Einführung in die Astronomie I

Jörn Wilms & Thomas Dauser

Wintersemester 2022/2023

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https://www.studon.fau.de/studon/goto.php?target=crs_4625333

Introduction

Astronomie/Astrophysik in BSc/MSc-Studiengängen

Zweisemestrige Module:

Nichtphysikalisches Wahlfach Astronomie im BSc. Physik: NW (10 ECTS): Vorlesung Einführung in die Astronomie I & II sowie Astronomisches Praktikum

Hinweis: Voraussetzung für Physikalisches Wahlfach (PW) Astrophysik im BSc Physik: Module für PW-1, PW-2 oder PW-3 (austauschbar mit MSc Modul)

WF im BSc/MSc Mathematik: Kombination mit Experimentalphysik: wie NW für BSc Physik (10 ECTS) & Auswahl PW1–3

WF im BSc/MSc Informatik: Modul: wie NW für BSc Physik & Übungen (15 ECTS, Praktikum durch PW Modul ersetzbar)

Astronomie/Astrophysik in BSc/MSc-Studiengängen

Einsemestrige Teilmodule:

WF im Lehramtsstudium: 2 Teilmodule: NW-WiSe & Übung (5 ECTS), NW-SoSe & Übung (5 ECTS), Astronomisches Praktikum (5 ECTS) ebenfalls möglich

WF im BSc Geowissenschaften: Teilmodul: NW-WiSe & Übung (5 ECTS)

Andere Fächer: je nach Studienordnung / Absprache mit Prüfungsamt und mir

Klausur und Übungen

ÜBUNGEN und Hausaufgaben: Dienstags nach der Vorlesung (3 Gruppen) und Mittwochs Dienstags nach der Vorlesung (HD, HE, HH) und Mittwoch (15:00, HF). Erster Termin: 25.11./26.11.

Verpflichtend für BSc Informatik, die meisten Nebenfächer, und Lehramt.

Übungsblätter gibt es auf StudOn im StudOn für die Vorlesung(!!)

Die verbindliche Klausur zum Modul NW findet am Ende des Sommersemesters 2021 statt. Inhalt: Astronomie 1 und 2.

KLAUSUR am 31. Januar 2023

verbindlich für Teilnehmer am Teilmodul NW-WiSe (z.B. LA, Geo).

Für alle anderen: freiwilliges Angebot zur Notenverbesserung; **Bonus** für die Abschlussklausur:

$$\text{Note } 3.0\text{–}2.3 \Longrightarrow \text{Bonus } 0.3,$$
$$\text{Note } 2.0\text{–}1.0 \Longrightarrow \text{Bonus } 0.7$$

Astronomisches Praktikum

Praktikum: Blockpraktikum an der Dr. Karl Remeis-Sternwarte, Bamberg, in den Semesterferien (März bzw. Sept./Okt)

Termine werden in den nächsten Wochen bekanntgegeben.

Vorbesprechung (voraussichtlich): 17.1.2023 (obligatorisch)

Anmeldung ab Mitte November

Frühjahrspraktikum: für Leute im $\geqslant$3. Semester
Herbstpraktikum: für Leute im $\geqslant$2. Semester

Textbooks

Karttunen, Kröger, Oja, Poutanen & Donner , 2007, *Fundamental Astronomy*, 5th ed., Heidelberg: Springer, € 68 (hardcover), 510 pp.

Good general overview of astronomy.
Recommended, especially for exam preparation.

Kutner, 2003, *Astronomy: A Physical Perspective*, 2nd ed., Cambridge: Cambridge Univ. Press, € 77, 600 pp.

Modern physics based textbook, easy to read. Recommended.

Bennett et al., 2009, *Astronomie: Die kosmische Perspektive*, Pearson Studium, € 89.95, 1200 pp.

Modern and good; German translation is not bad, Recommended.

Textbooks

Unsöld & Baschek, 2006, *Der neue Kosmos. Einführung in die Astronomie und Astrophysik*, 7. Auflage, Berlin: Springer, € 50, 577 pp.

Intermediate level: Good overview of stellar astronomy
Good secondary reading.

Zeilik & Gregory, 1998, *Introductory Astronomy & Astrophysics*, 4th ed., Thomson Learning, ca. € 85, 672 pp.

Intermediate level, self contained, but sometimes chaotic order.

Carroll & Ostlie, 2006, *An Introduction to Modern Astrophysics*, 2nd ed., Reading: Addison-Wesley, ca. € 72 (hardcover), 1400 pp.

Advanced level, expects good physics background.
Recommended if you want to specialize in astronomy.

Contents

18 Oct	**Organisation, Introduction**
25 Oct	History of Astronomy
08 Nov	Planets I
15 Nov	Planets II
22 Nov	Planets III
29 Nov	Planets IV
06 Dec	Planets V
13 Dec	Measurement Methods: Telescopes, Coordinates
20 Dec	Stars, Distances, Luminosity, HRD
10 Jan	Stars: Binaries, Masses & Radii
17 Jan	Exoplanets
24 Jan	Stars: Formation & Structure
31 Jan	*Exam!*
07 Feb	Stars: The Sun

History of Astronomy



J. Wilms

Newgrange (Ireland): 3200 BC; solar observatory?



J. Wilms

Newgrange (Ireland): 3200 BC; solar observatory?



Stonehenge: 2500 BC; solar observatory?



Disk of Nebra: 1600 BC

first reproduction of the night sky, constellation of Moon and Pleiades

measures solstices and equinoxes $\Longrightarrow$ calendar

History

Together with theology, astronomy is one of the oldest professions in the world.

Astronomical nomenclature is still strongly influenced by this tradition.

$\Longrightarrow$ appreciation of history of astronomy is required for understanding even of today's astronomy. Many terms used are based on this history, e.g., magnitudes by the greek astronomer Hipparcos (~150 BC)

Early Cosmology

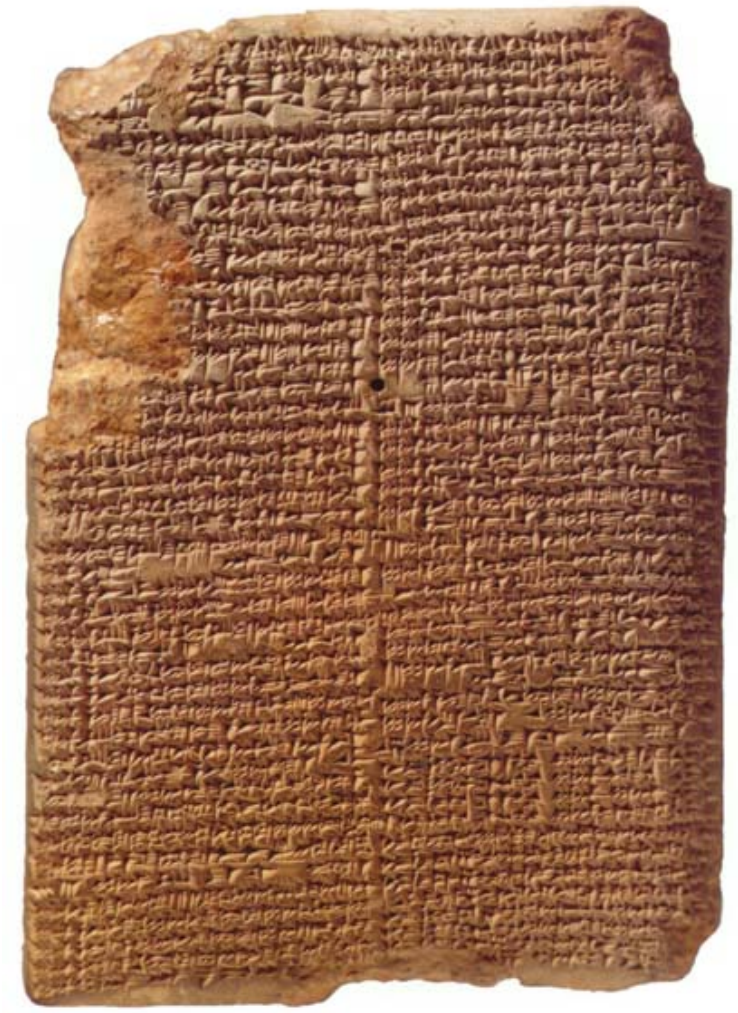


Composite of images of Mars spaced ~ a week apart – from late July 2005 (bottom right) through February 2006 (top left).

Explain observations:

- daily motions of Sun, Moon, planets & stars from E to W
- much slower motion of Sun & Moon with respect to stars
- occasional retrograde motions of planets (E to W)
- solar and lunar eclipses

Babylon



Babylonian astronomy: Earliest astronomy (flourish ∼700 BC) with influence on us:

$\Longrightarrow$ sexagesimal system [360:60:60], 24 h day, 12×30 d year,...

$\Longrightarrow$ Observations of Sun and Moon

$\Longrightarrow$ stellar constellations, 12 signs of zodiac

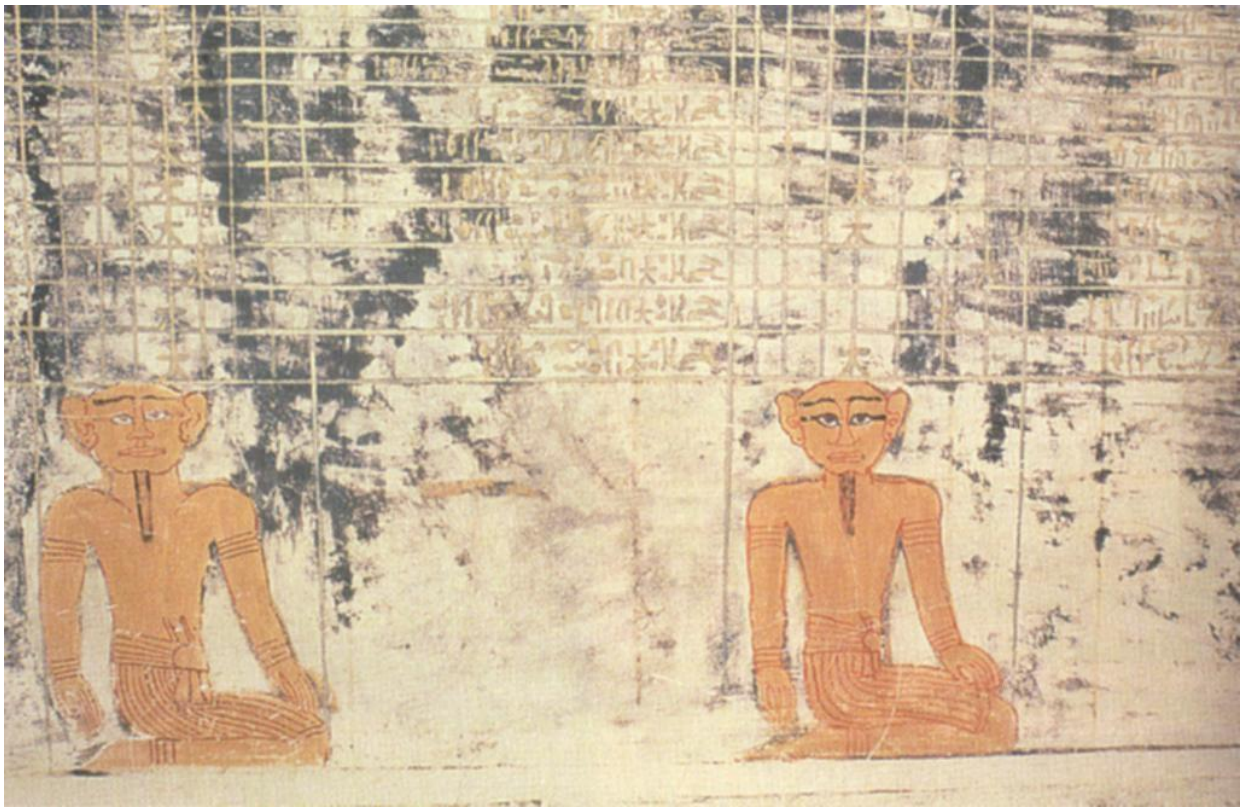
$\Longrightarrow$ bookkeeping on solar and lunar eclipses, Saros cycle: 18 yr 11 d

$\Longrightarrow$ description of planet movement

$\Longrightarrow$ cataloging stellar positions

Image: Mul.Apin cuneiform tablet (British Museum, BM 86378, 8 cm high); rising and setting of constellations through the babylonian calendar. Summarizes astronomical knowledge as of before ∼690 BC.

Egypt



Egyptian coffin lid showing two assistant astronomers, 2000. . . 1500 BC; hieroglyphs list stars (“decans”) whose rise defines the start of each hour of the night.

(Aveni, 1993, p. 42)

~2000 BC: 365 d calendar (12×30 d plus 5 d extra), fixed to Nile flood (heliacal rising of Sirius), star clocks.

heliacal rising: first appearance of star in eastern sky at dawn, after it has been hidden by the Sun.

Greece

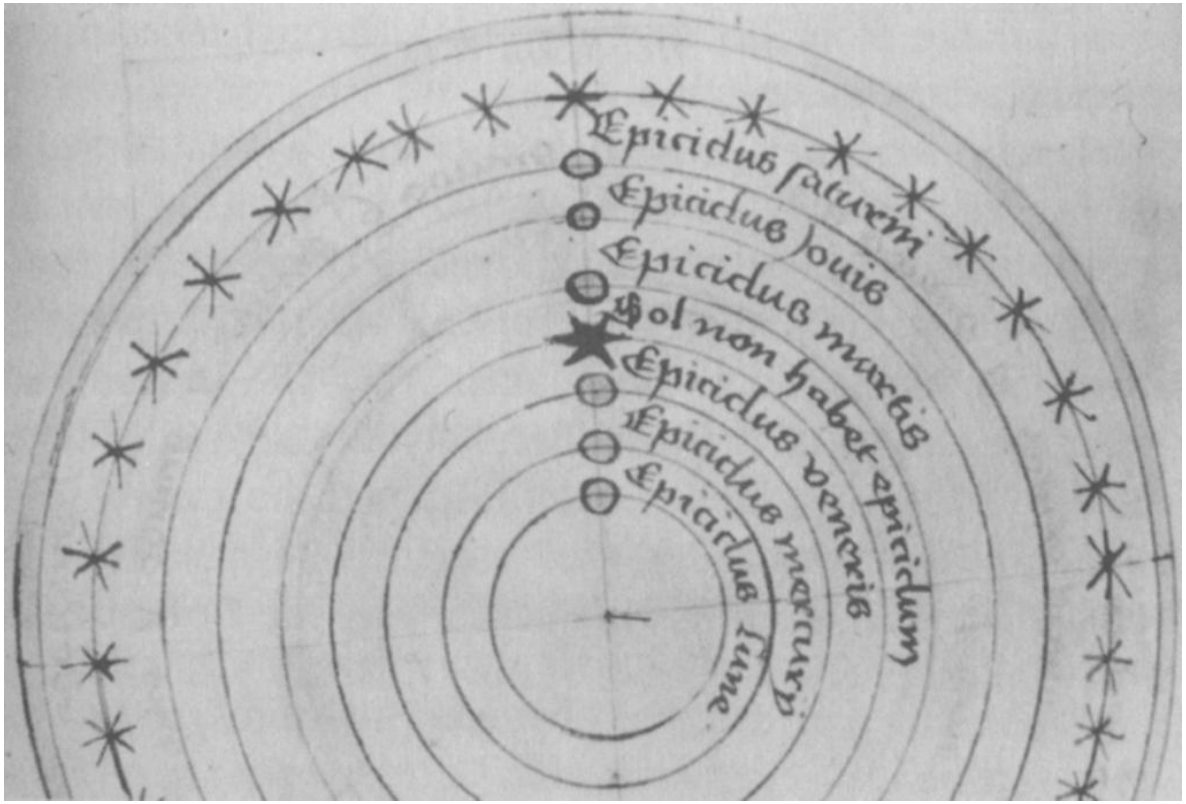


Atlas Farnese, 2c A.D., Museo Archeologico Nazionale, Napoli

Greek Astronomers: "Mathematicians"
development of the geocentric world model

- Thales (624–547 BC): Earth is flat, surrounded by water. Founder of Natural Philosophy
- Pythagoras (~570–510 BC): Earth is a sphere. "Everything is number" A harmonic universe (music) requires orbital motions in certain ratios of integer numbers (see Kepler: Harmonices mundi)
- Plato (427–347 BC): the circle is the perfect geometric form, uniform circular motion is eternal $\Longrightarrow$ "the hex of circles"
- Eudoxus (408–355 BC): Geocentric, planets affixed to concentric crystalline spheres. 27 spheres to account for non-uniform motions (does not work for Mars and Venus). First real model for planetary motion!

Greece



Aristotle (384–322 BC, *de caelo*): Refinement of Eudoxus model: add spheres to ensure correct motions of all planets: >50 nested and linked spheres, driven by the outermost sphere.

$\Longrightarrow$ Central philosophy until ~1450AD!

Greece

Hipparchus (?? – ~127 BC): First Greek observer:

- Star catalog: 850 stars
- Magnitudes of stars: $0^m \ldots 6^m$
- Parallax of the Moon
- Table of chords (early trigonometry)
- Discovery of precession (shift of the vernal equinox) by comparison with Babylonian star catalog
- Seasons have unequal length
- used geocentric world model of Aristotele to make predictions (Epicycle).

Greece

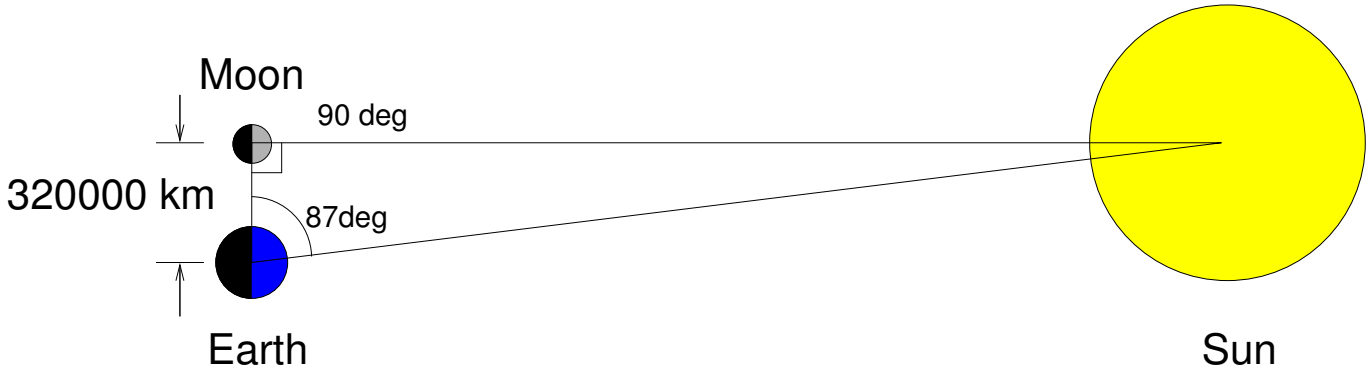


(Aveni, 1993, p. 58)

Ptolemaeus (~140AD): *Syntaxis* (aka Almagest): Refinement of Aristotelian theory into model useable for computations

$\Longrightarrow$ Ptolemaic System.

Greece



Development of the heliocentric world model: Aristarchus (310–230 BC) determines of the radius of the Sun

1st and last quarter of Moon:

observed $\angle(\text{Moon}, \text{Sun}) = 1/4\,\text{circle} - 1/30 \times 1/4\,\text{circle} = 87^\circ$

$$\Longrightarrow \text{distances: } D(\text{Sun} - \text{Earth}) = 19 \times D(\text{Moon} - \text{Earth})$$

Cassini (1672): Parallax of Mars, which gives $D(\text{Sun} - \text{Earth}) = 140$ Mio. km (using Kepler's 3rd law).

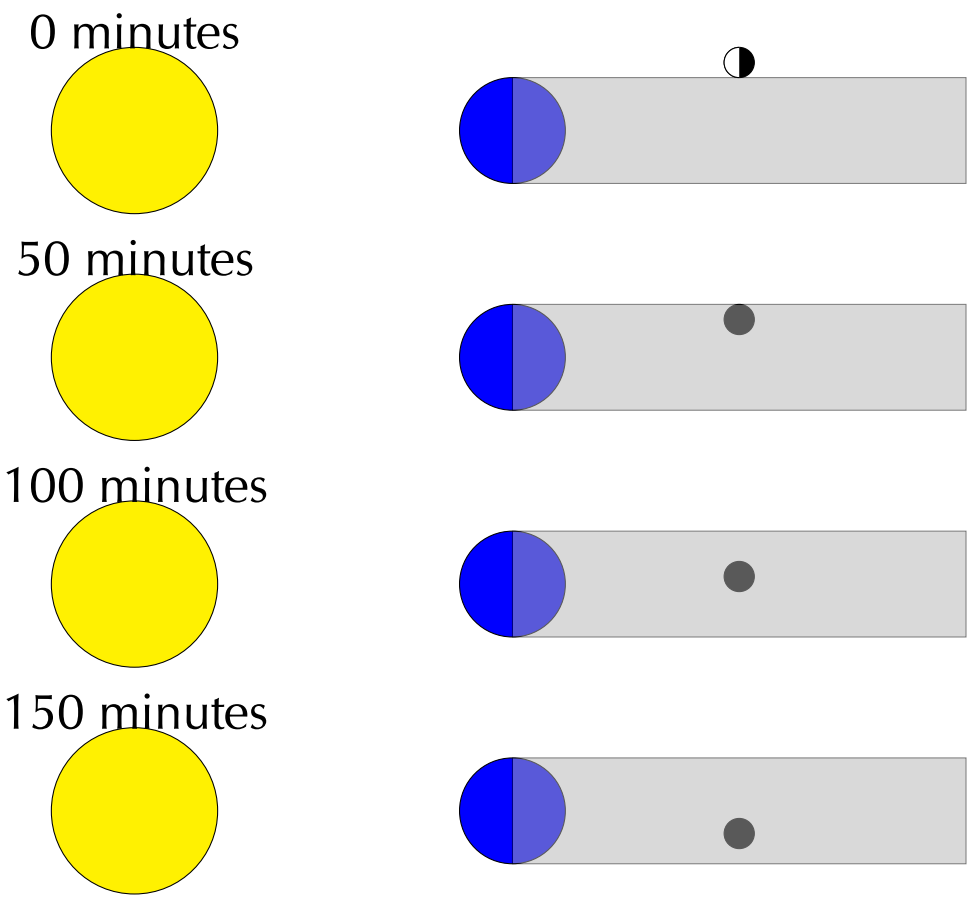
Since angular diameters of Sun and Moon are almost equal:

$$R(\text{Sun}) = 19 \times R(\text{Moon})$$

Greece

Development of the heliocentric world model:

Aristarchus (310–230 BC) radius of the Sun



lunar eclipses:

Moon fits twice into Earth's shadow

(in reality: 3.68×)

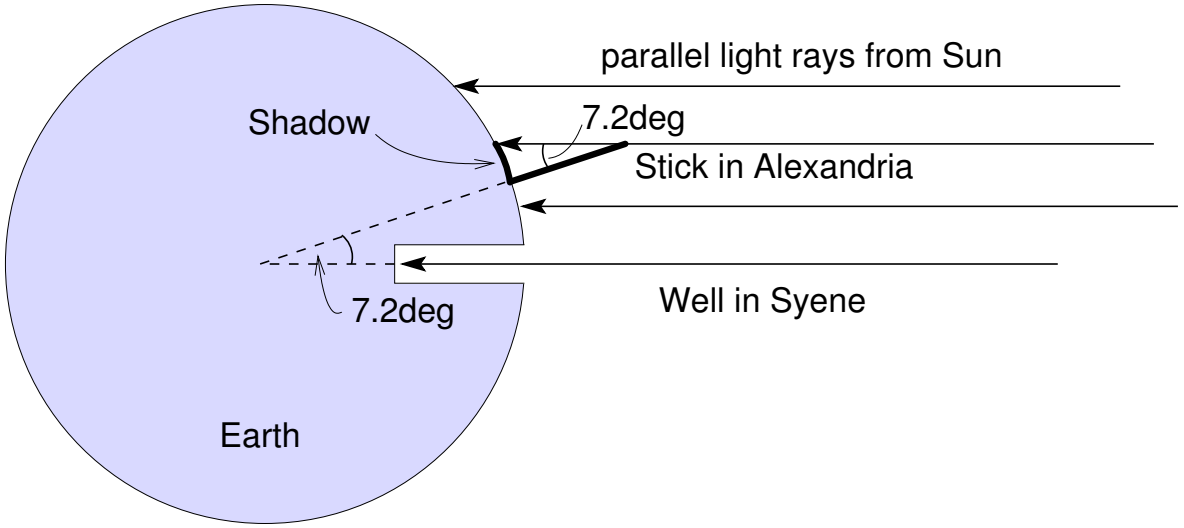
$\Longrightarrow$ Radii: $R(\text{Sun}) = 9.5 \times R(\text{Earth})$

common sense then implies: smaller body moves around the larger one!

Heliocentric world model

after Simon Singh

Greece



Eratosthenes (276–195 BC): measurement of the earth's radius

Idea: measure culmination of the Sun at two places of known distance (N to S) on the same day.

Syene: Sun at zenith, Alexandria: 7.2° away from Zenith

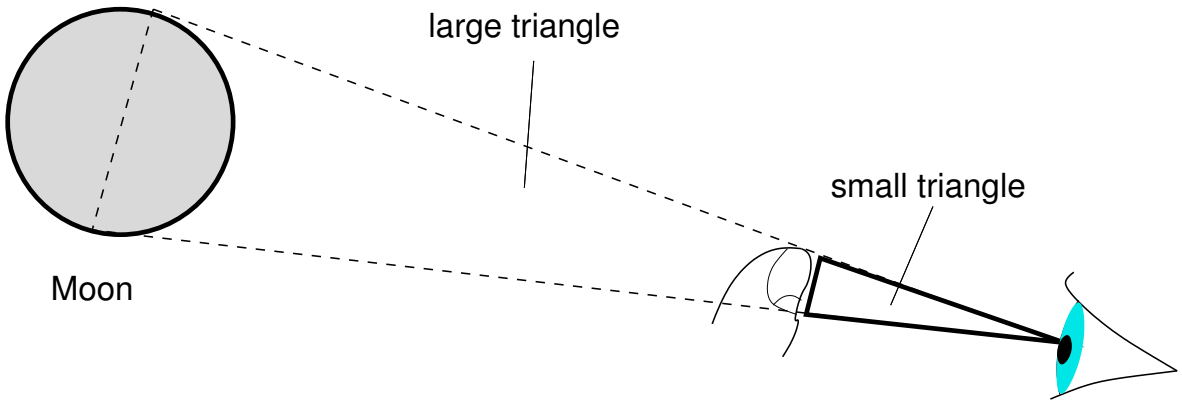
$\Longrightarrow$ Distance between Alexandria and Syene: $d/(2\pi R) = 7.2/360$

Measured: 5000 Stades

Some historians believe that this distance corresponds to ~820 km, so if true then the radius of the Earth would have been determined to 6264 km

in fact: 6378km; repeated: 1671: Paris-Amiens (J. Picard)

Greece



The distance to the Moon and the Sun:
angular diameter of the Moon equals width of finger as seen from 1 m away
$\Longrightarrow R_{moon}/d_{moon} = 1/200$

Lunar occultations: $R_{moon} = 1/2 R_{earth}$
$\Longrightarrow R_{earth}/d_{moon} = 1/100$

$$d_{moon} = 100 \times R_{earth} = 626400\,\text{km}$$

$\Longrightarrow$ distance to the Sun:

$$d_{sun} = 19 \times d_{moon} = 11.9\,\text{Mill km}$$

Renaissance



Regiomontanus: Johannes Müller from Königsberg (Franconia) (1436–1476):

- Studies at Leipzig (1447) and Vienna (1450): Mathematics and Astronomy
- *Epytoma Joanis de monte regio in almagesti ptolemei* (1461–1463): translation to latin with much improved maths
- *De triangulis omnimodis* (1462–1464): foundation of modern trigonometry
- *Ephemerides astronomicae ab anno 1475–1506*: most accurate ephemerides
  $\Longrightarrow$ Navigation: Columbus & Vasco da Gama

Renaissance



Nicolaus Copernicus (1473–1543): Earth centred Ptolemaic system is too complicated, a Sun-centred system is more elegant.

Renaissance



(Gingerich, 1993, p. 165)

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De revolutionibus orbium coelestium: "In no other way do we perceive the clear harmonious linkage between the motions of the planets and the sizes of their orbs."

Renaissance



(Gingerich, 1993, p. 165)

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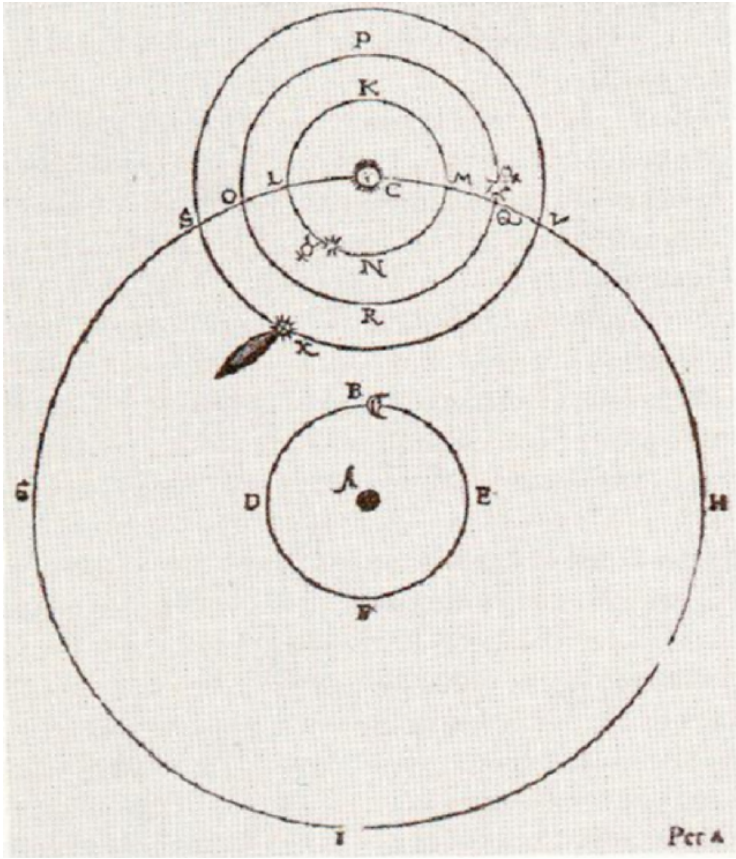
De revolutionibus orbium coelestium: "In no other way do we perceive the clear harmonious linkage between the motions of the planets and the sizes of their orbs."

Copernican principle: The Earth is not at the center of the universe.

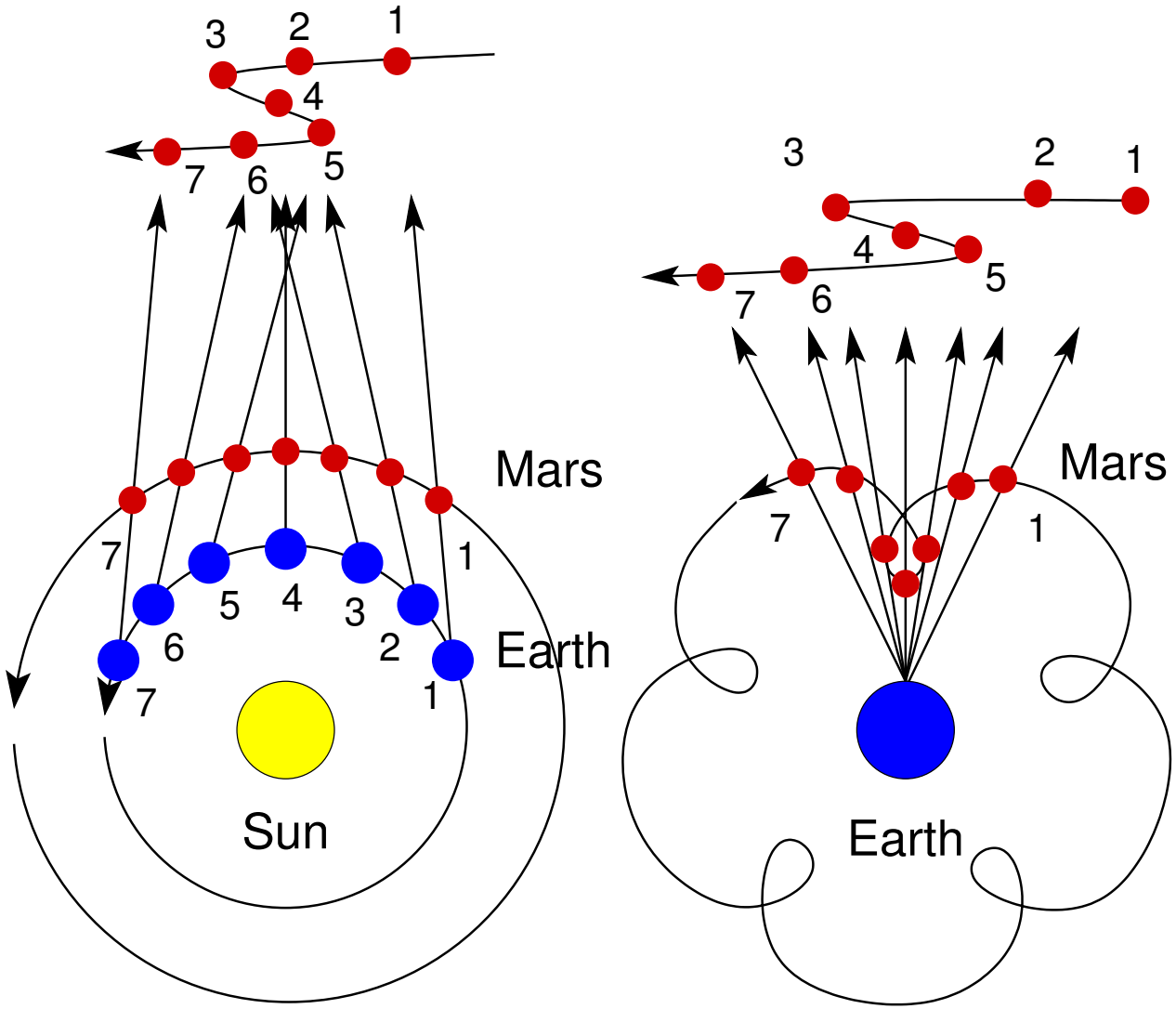
Renaissance



Tycho Brahe (1546–1601): Visual planetary positions of highest precision reveal flaws in Ptolemaic positions.



Renaissance



Retrograde motion: heliocentric vs. geocentric model

Galilei and Kepler





Johannes Kepler (1571–1630): Planets orbit on ellipses around Sun, not on circles, laws of motion.

Galileo Galilei (1564–1642): Telescopic observations, discovery of four moons of Jupiter

Galilei and Kepler

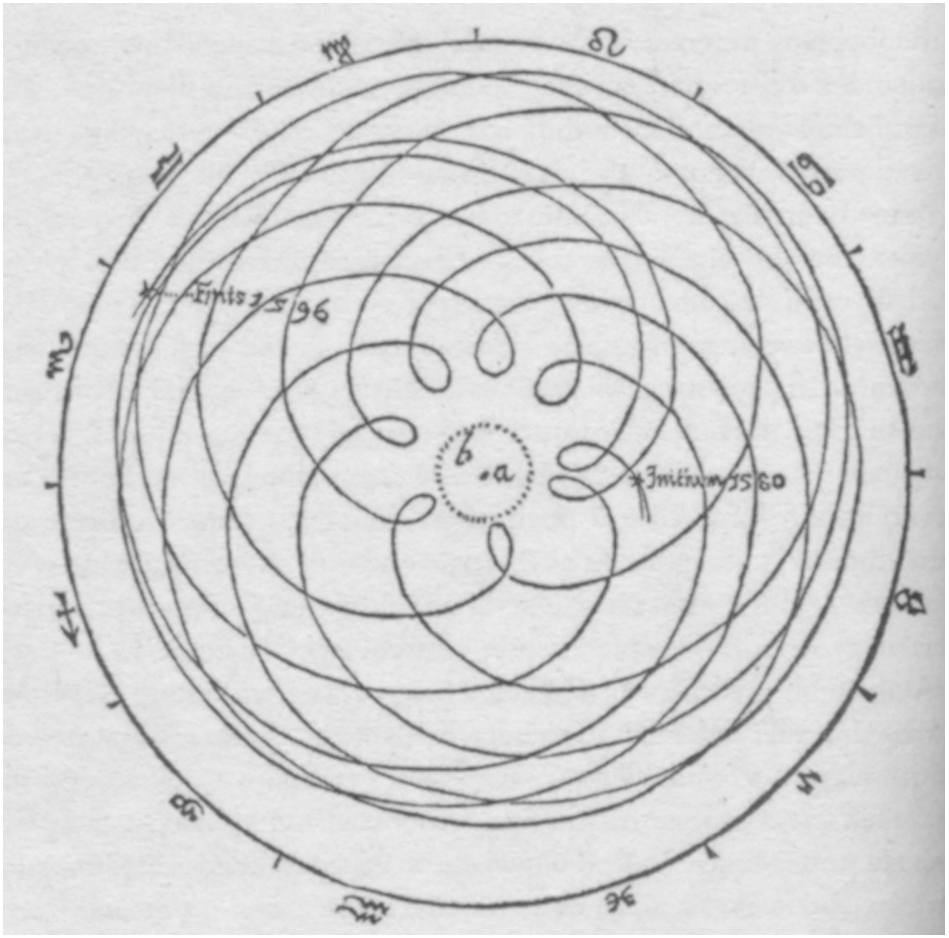


Johannes Kepler (1571–1630):

- born 27.12.1571, Weil der Stadt
- Studies Tübingen with Maestlin
- 1594–1600: Graz
- 1596: Mysterium Cosmographicum
- 1600–1612: Prag, assistant of Tycho Brahe, then Mathematician of emperor Rudolf II, discovered Supernova of 1604,...

1609: Astronomia Nova

Galilei and Kepler

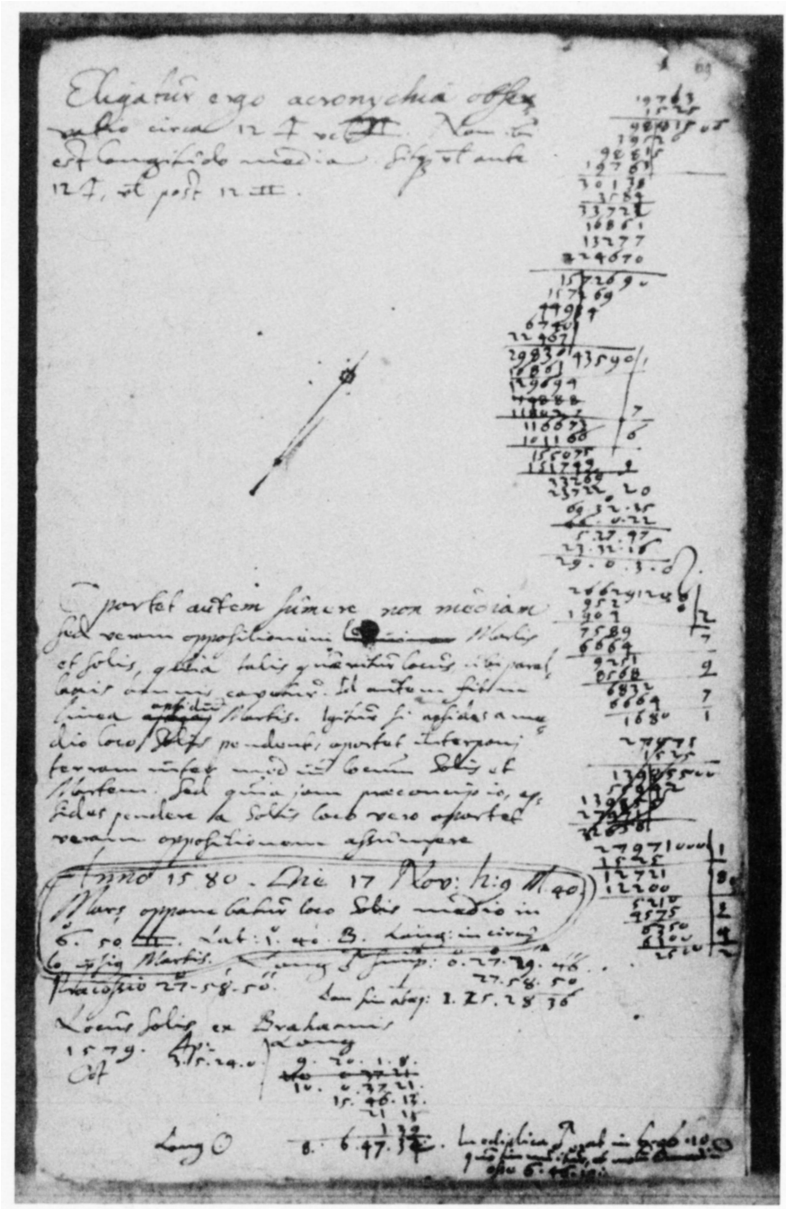


Astronomia Nova, Kapitel 1: motion of Mars in the epicycle theory between 1560 and 1596

Astronomia nova (Prag, 1609)

Critique of the epicycle theory:
“panis quadragesimalis”
(Osterbrezel)
$\Longrightarrow$ not elegant!

Galilei and Kepler



Result of Kepler's investigations:
The Keplerian laws:

1. Planets move on elliptical orbits, Sun in focus.

   ("Astronomia Nova", 1609)

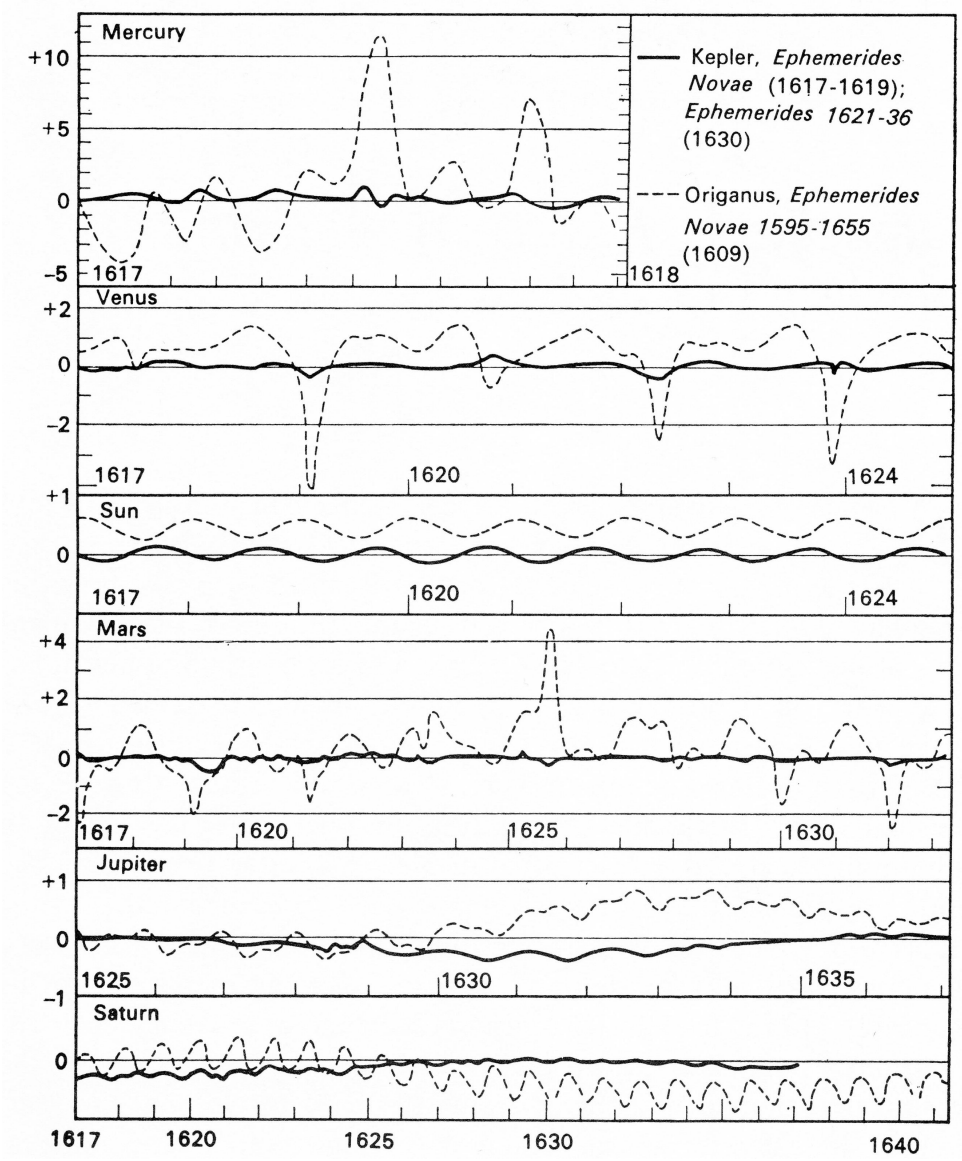
2. Motion is not uniform, planet moves fast when close to the Sun.

   ("Astronomia Nova", 1609)

3. Square of orbital period, P, is proportional to cube of the semimajor axis, a: $P^2 \propto a^3$

   ("Harmonice Mundi", 1619)

Galilei and Kepler



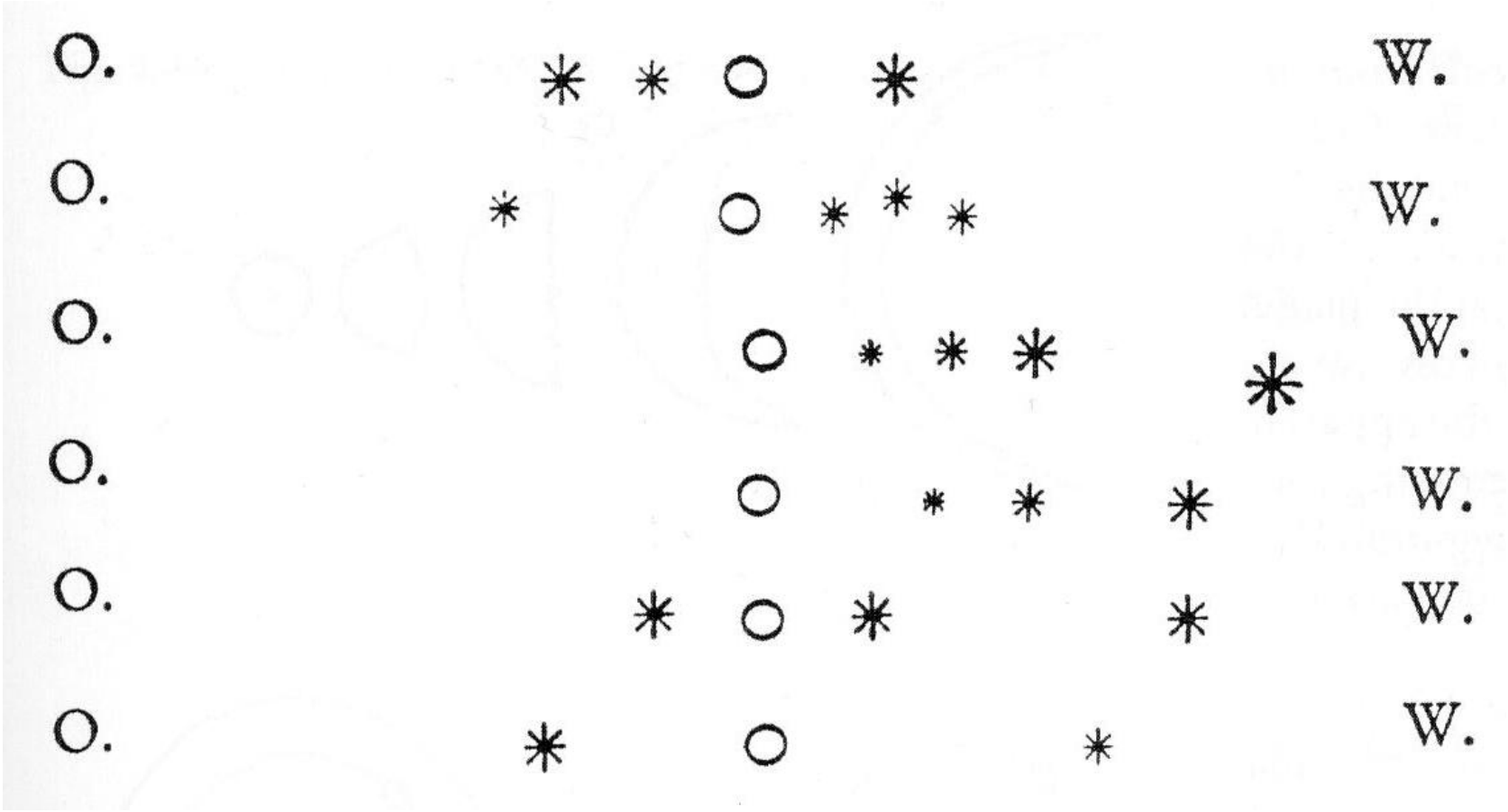


Tabulae Rudolphinae, 1627

Most precise positions of planets ever: 30× smaller errors than before

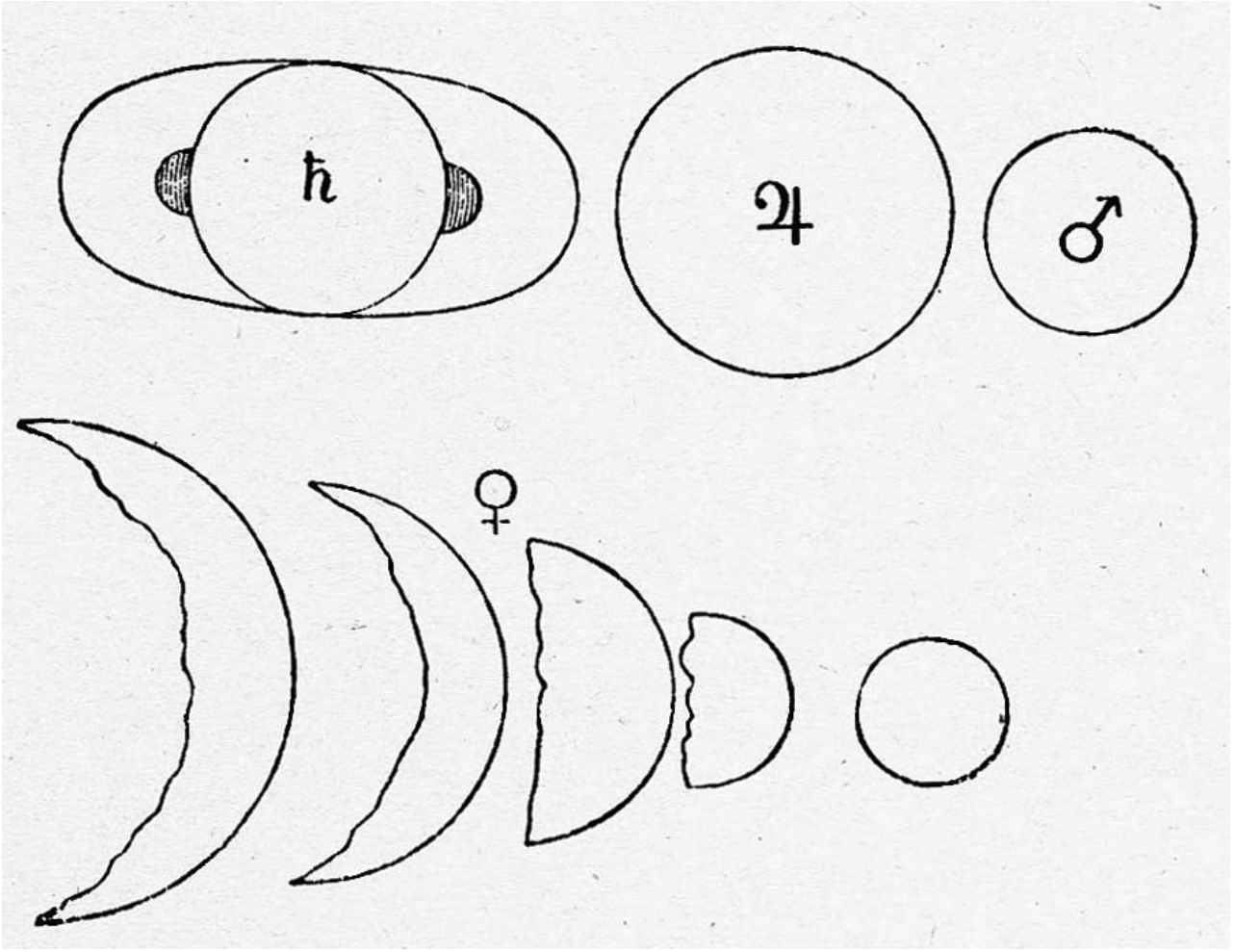
(Gingerich, 1993)

Galilei and Kepler



Moons move around Jupiter
($\Longrightarrow$ similar to heliocentric model!)...

Galilei and Kepler



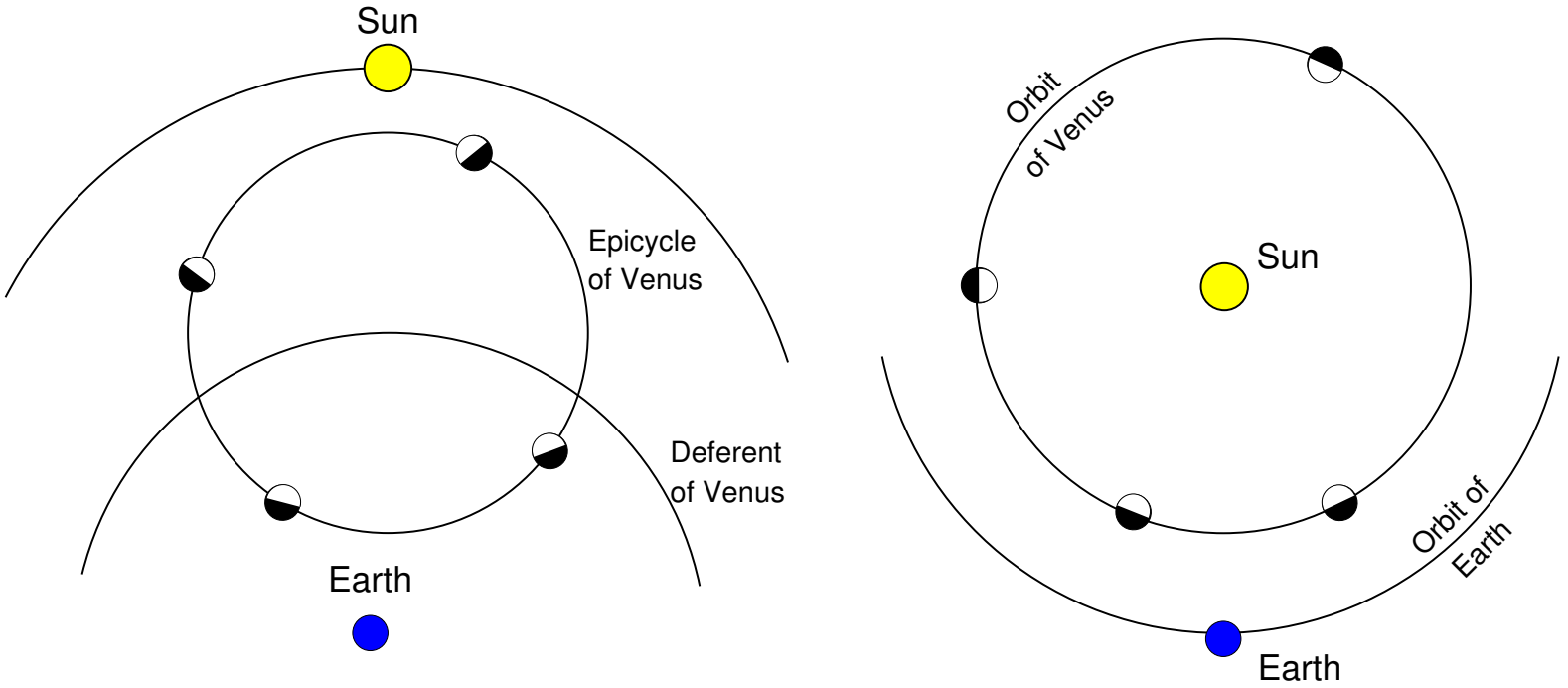
Discovery of phases of Venus (Il Saggiatore, 1623)

Observed phases and angular size changes of Venus



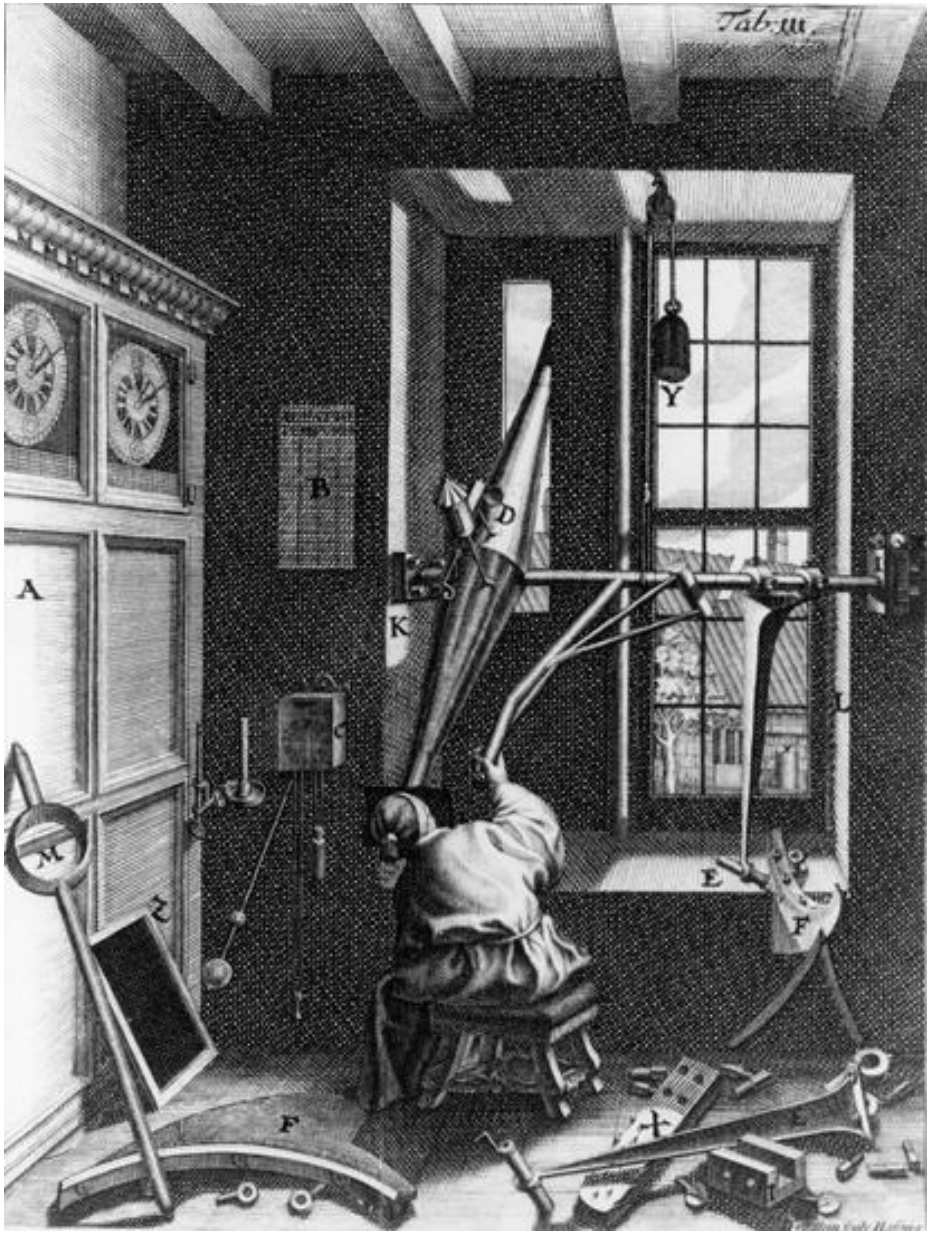
Statis Kalyvas & ESO

Galilei and Kepler



The observed phase changes of Venus can be explained by the heliocentric world model, but also in Tycho's geocentric one.

Rømer



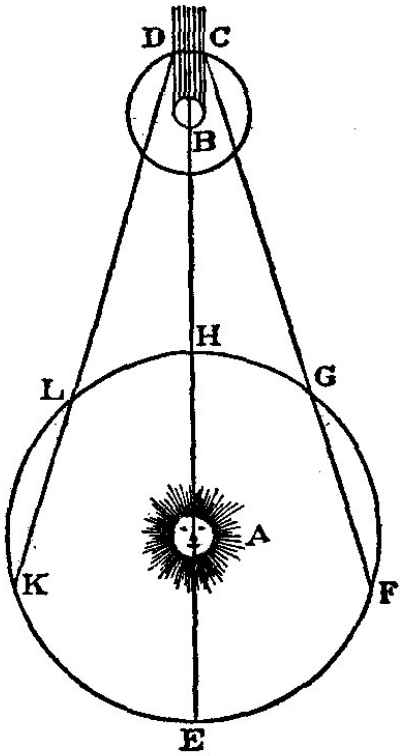


Fig. 70.

Rømer, 1676

Ole Rømer (1644–1710): measurement of the speed of light

Times of occultation of Io change by up to 20 minutes during the year.

(Peter Horrebouw, Basis astronomiae sive astronomiae machina, Kopenhagen, 1735)

Newton



(Newton, 1730)

Isaac Newton (1642–1727): Newton's laws, physical cause for shape of orbits is gravitation
(*De Philosophiae Naturalis Principia Mathematica*, 1687).

Gravitationsgesetz:

$$F = \frac{G m_1 m_2}{R^2} \tag{2.1}$$

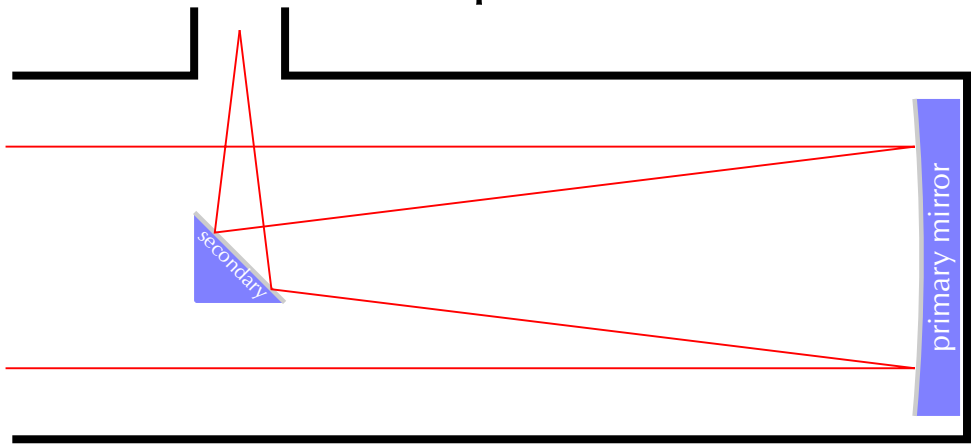
Newton's version of 3rd Kepler:

$$P^2 = \frac{4\pi^2}{G(m_1 + m_2)} a^3 \tag{2.2}$$

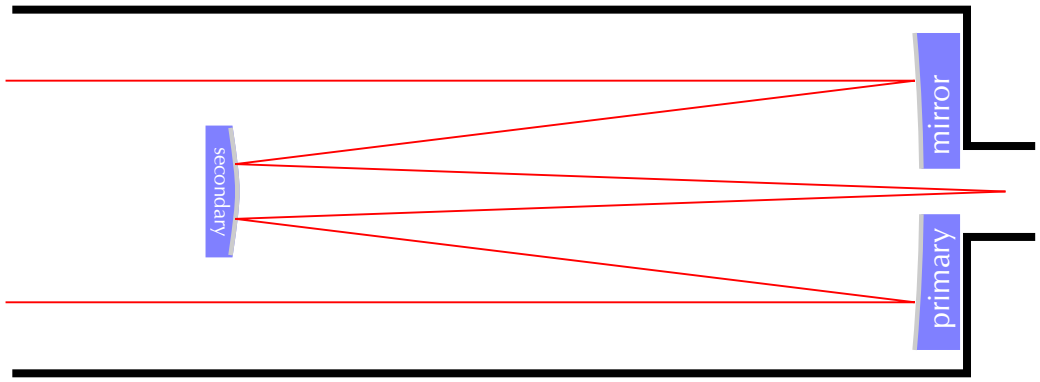
$\Longrightarrow$ Begin of modern physics based astronomy.

Telescopes

Newtonian telescope

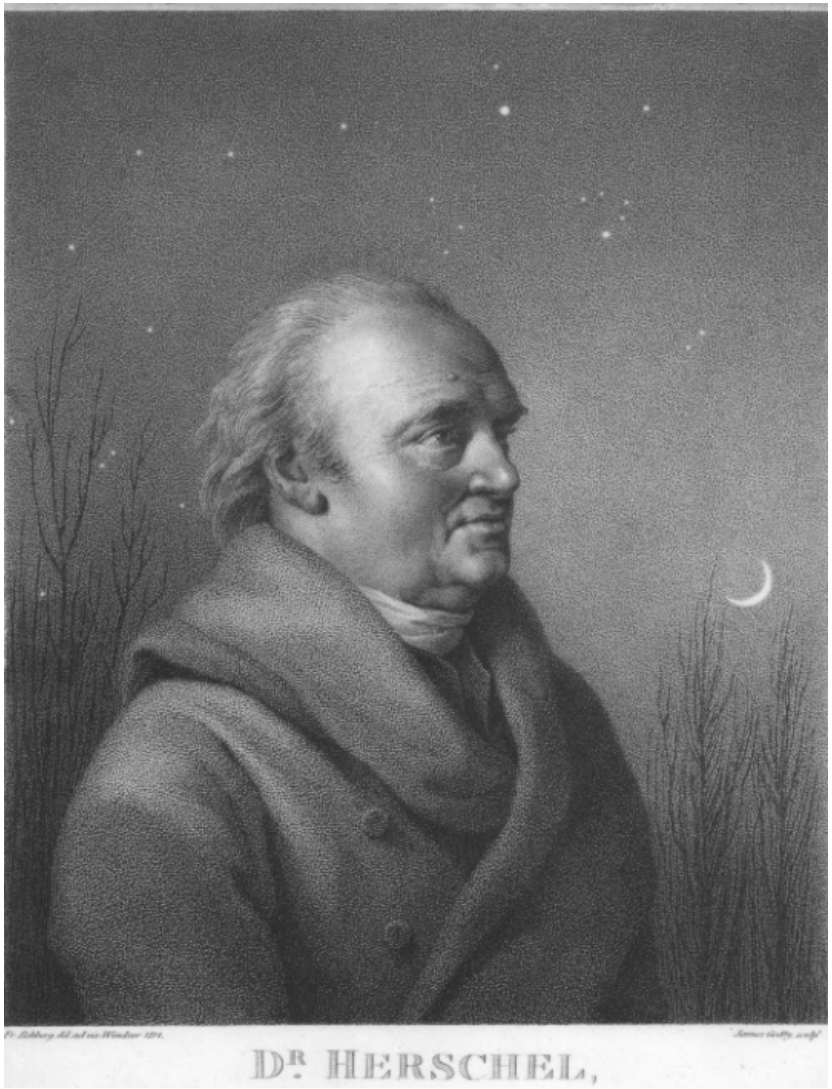


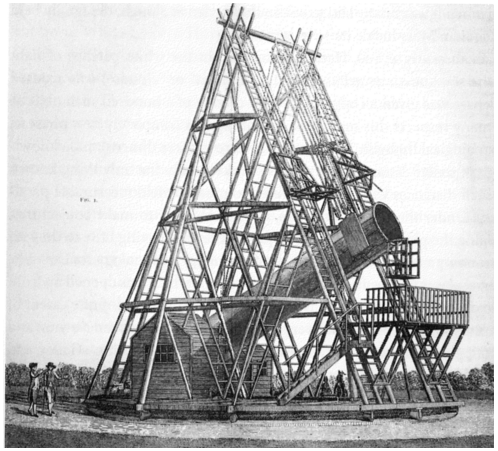
Cassegrain telescope



Newton (1668), Gregory (1670), Cassegrain (1672):
Telescopes with mirrors
(mirror made of polished metal [copper/zink alloy])

Herschel

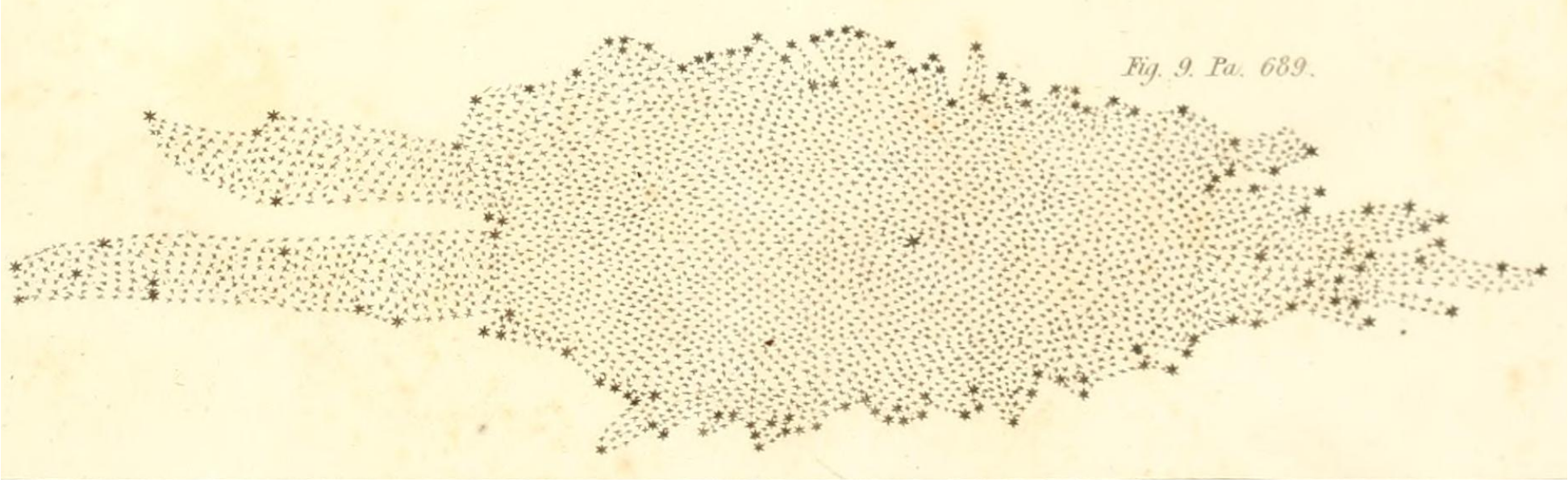




William Herschel (1738–1822):

- 15 Nov 1738: born in Hannover
- Musician (Oboist)
- 1759: emigration to England
- builds large reflecting telescopes
- 1781: Discovery of Uranus
- study of Nebulae
- Star counts (with his sister Caroline)

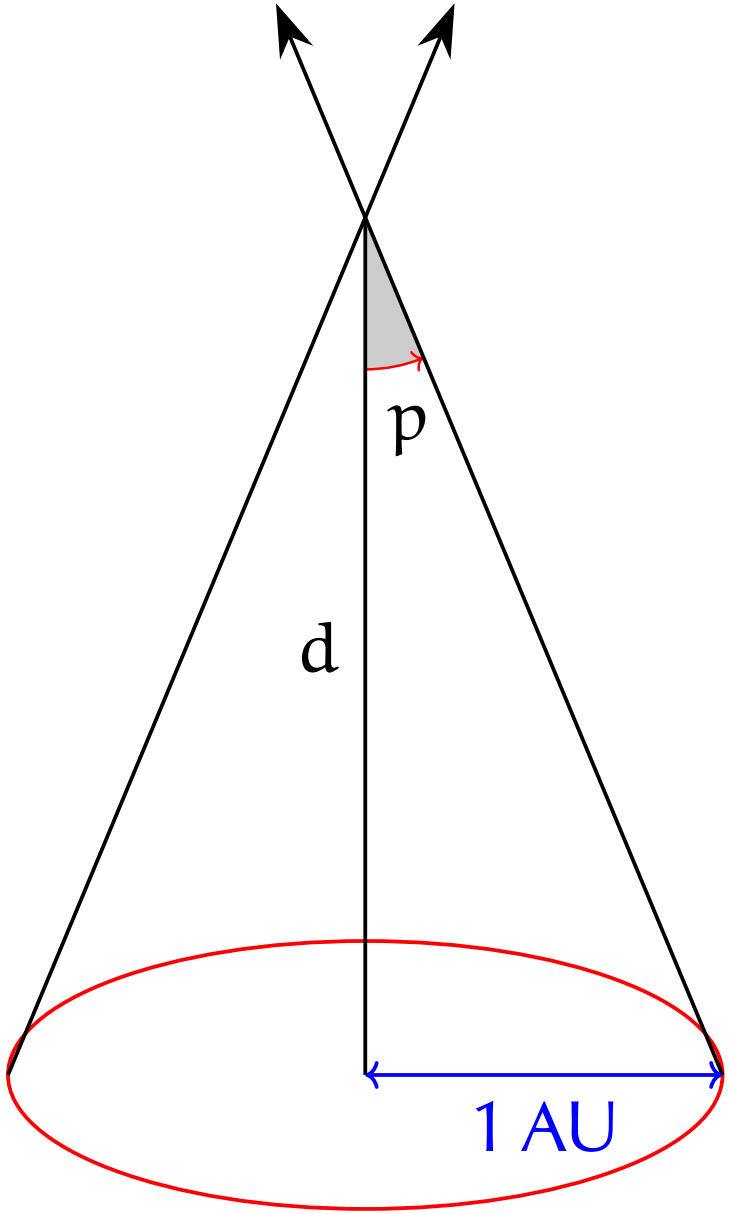
Herschel



Geometry of the Milky Way according to William Herschel (1785)

Sun is close to the center of the Milky Way

Herschel



$\Longrightarrow$ Wanted: Measurement of a yearly parallax of a star.

Parallax (small angles):

$$p = \frac{1\,\mathrm{AU}}{d}$$

(p measured in radian)

Problem since antiquity: p is small because the stars are so far away.

Bessel



Friedrich Wilhelm Bessel
(1784–1846)

Bessel (1839): first distance measurement of a star

ASTRONOMISCHE NACHRICHTEN.

№. 365. 366.

Bestimmung der Entfernung des 61sten Sterns des Schwans.

Von Herrn Geheimen-Rath und Ritter *Bessel*.

Als es *Bradley* gelungen war, seine Beobachtungen in *Kew* und *Wansted*, welche die Entdeckungen der Aberration und Nutation herbeiführten, durch diese allein genügend zu erklären, ohne dazu der Annahme einer jährlichen Parallaxe der beob-

ist nicht zu bezweifeln; allein wenn eine Untersuchung über die jährliche Parallaxe eines Fixsterns unternommen werden soll, so sind sie dennoch die einzigen, welche seine Wahl leiten können.

61 Cyg: Parallax $0.3''$

$\Longrightarrow$ distance 11 light years

The great debate



Whirlpool nebula
(Lord Rosse, ~1850)

19th century: Astronomy evolves into a modern natural science:

- precise stellar position ("Durchmusterungen" = surveys)
- Photography
- Spectroscopy (Astro*physics*)

The nature of the nebulae?

"The great debate": 26.04.1920

protoplanetary nebulae

or

island universe ("Welteninsel"):

Harlow Shapley vs. Heber Curtis

importance of debate mainly ignored until 1980s...

The great debate



Whirlpool nebula
(Hubble Space Telescope, 2005)

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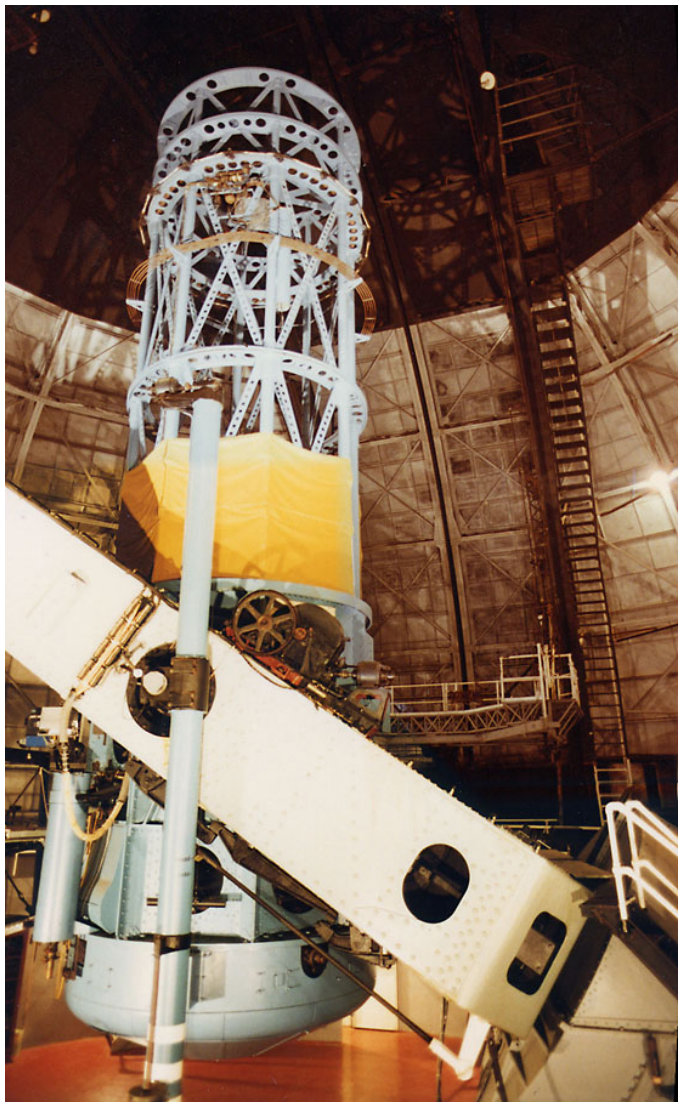
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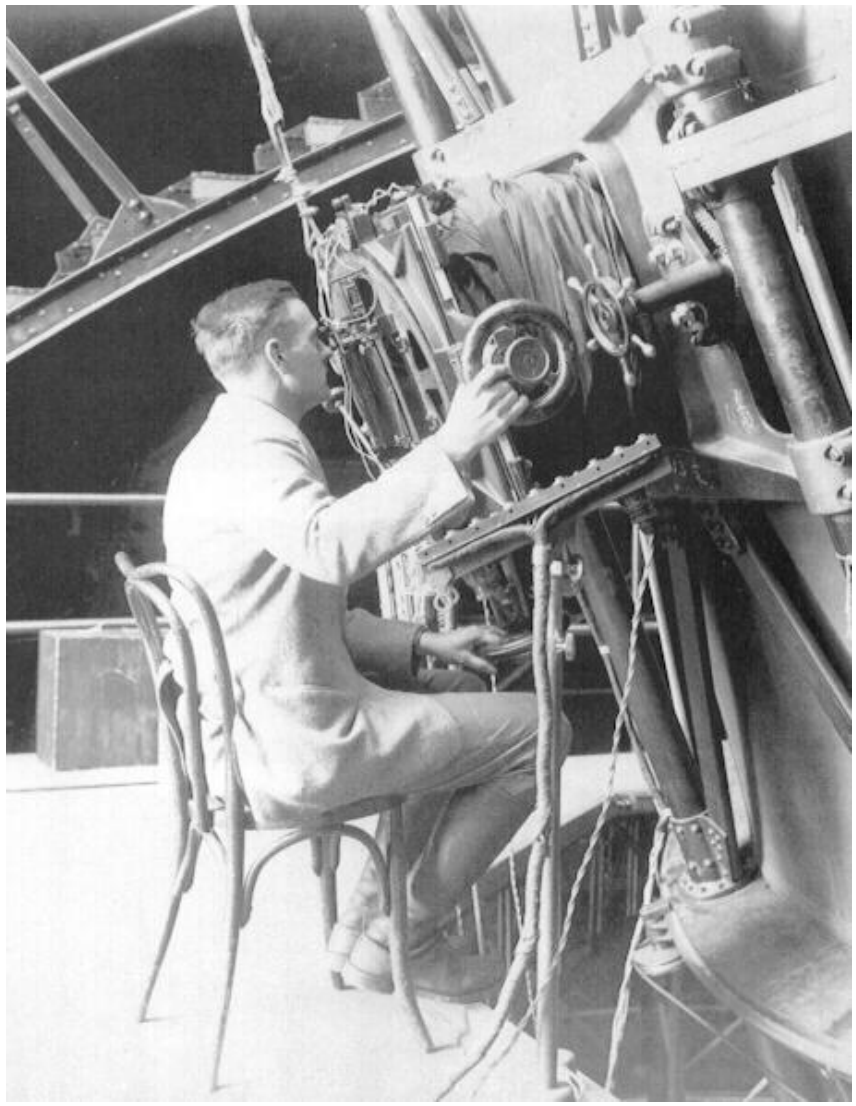
Harlow Shapley vs. Heber Curtis

importance of debate mainly ignored until 1980s...

Hubble



Mount Wilson 2.5 m “Hooker” Telescope



Edwin Hubble, 1922

Aveni, A. F., 1993, Ancient Astronomers, (Washington, D.C.: Smithsonian Books)
Gingerich, O., 1993, The Eye of Heaven – Ptolemy, Copernicus, Kepler, (New York: American Institute of Physics)
Newton, I., 1730, Opticks, Vol. 4th, (London: William Innys), reprint: Dover Publications, 1952

The Planets: Overview

What is a planet?

First, need to look at the definition of a planet.

- antiquity–1781: 6 planets: Mercury, Venus, Earth, Mars, Jupiter, Saturn

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- Sometime in late 1800s: Asteroids are not planets $\Longrightarrow$ 8 planets

What is a planet?

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Summer 2006: International Astronomical Union General Assembly, Prague

$\Longrightarrow$ Resolution GA26/5 and 6: Definition of a planet

$\Longrightarrow$ 8 planets

RESOLUTION 5

Definition of a Planet in the Solar System

Contemporary observations are changing our understanding of planetary systems, and it is important that our nomenclature for objects reflect our current understanding. This applies, in particular, to the designation "planets". The word "planet" originally described "wanderers" that were known only as moving lights in the sky. Recent discoveries lead us to create a new definition, which we can make using currently available scientific information.

The IAU therefore resolves that planets and other bodies, except satellites, in our Solar System be defined into three distinct categories in the following way:

(1) A planet[1] is a celestial body that
   (a) is in orbit around the Sun,
   (b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, and
   (c) has cleared the neighbourhood around its orbit.

(2) A "dwarf planet" is a celestial body that
   (a) is in orbit around the Sun,
   (b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape[2],
   (c) has not cleared the neighbourhood around its orbit, and
   (d) is not a satellite.

(3) All other objects[3], except satellites, orbiting the Sun shall be referred to collectively as "Small Solar System Bodies".

---

1 The eight planets are: Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune.

2. An IAU process will be established to assign borderline objects into either dwarf planet and other categories.

3. These currently include most of the Solar System asteroids, most Trans-Neptunian Objects (TNOs), comets, and other small bodies.

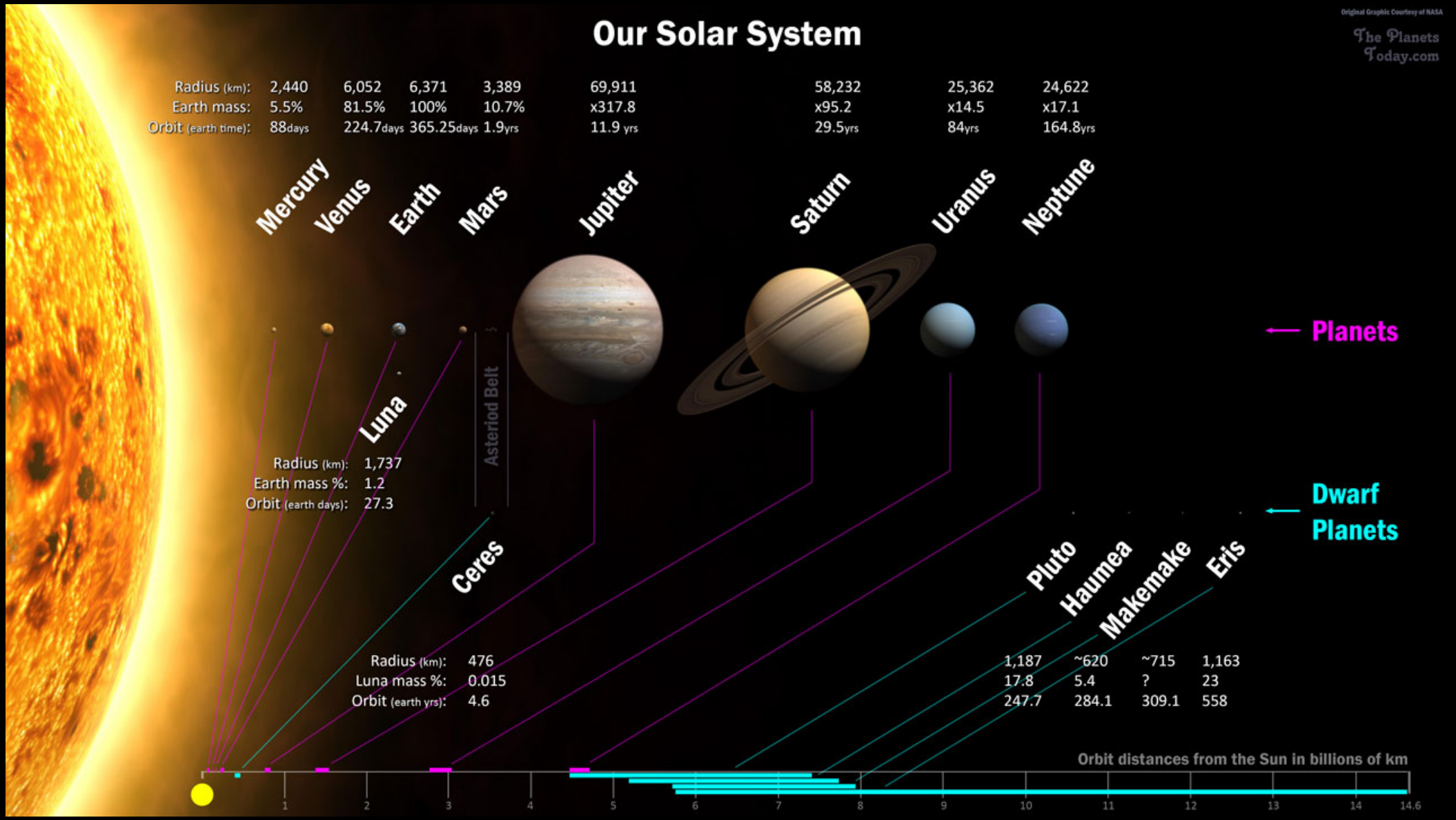
RESOLUTION 6

Pluto

The IAU further resolves:

Pluto is a "dwarf planet" by the above definition and is recognized as the prototype of a new category of Trans-Neptunian Objects[1].

1 An IAU process will be established to select a name for this category.



8 planets and 5 dwarf planets (and 10s of candidates)

Venus Transit, 2004 June 8



Elio Daniele, Palermo

Overview

Division of Solar System into two major types of planets:

1. Inner "Terrestrial" Planets: Mercury, Venus, Earth/Moon, Mars:
   $\Longrightarrow$ all similar to Earth ("rocks").
   $\Longrightarrow$ *no moons* (Earth/Moon better called "twins")

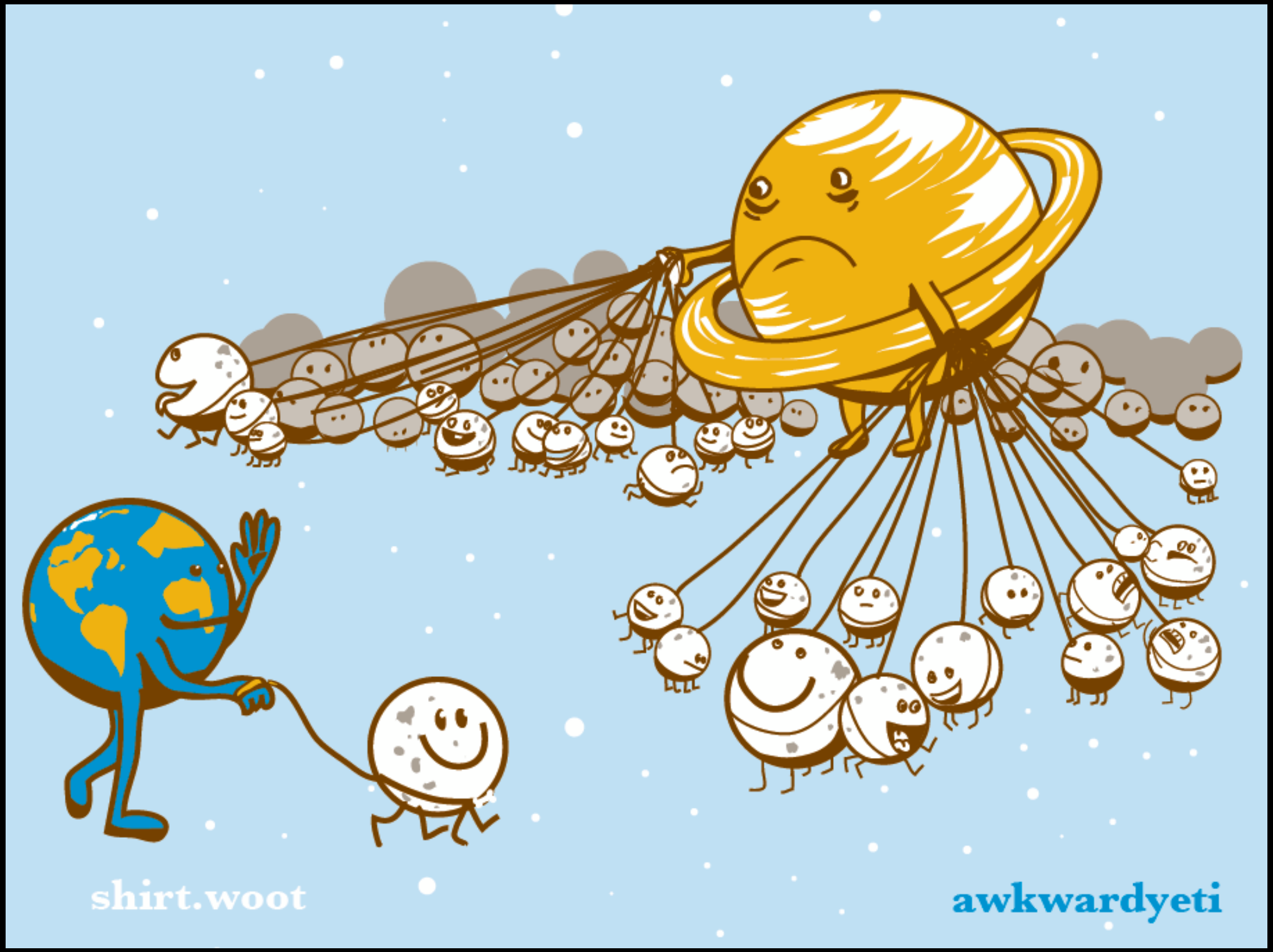
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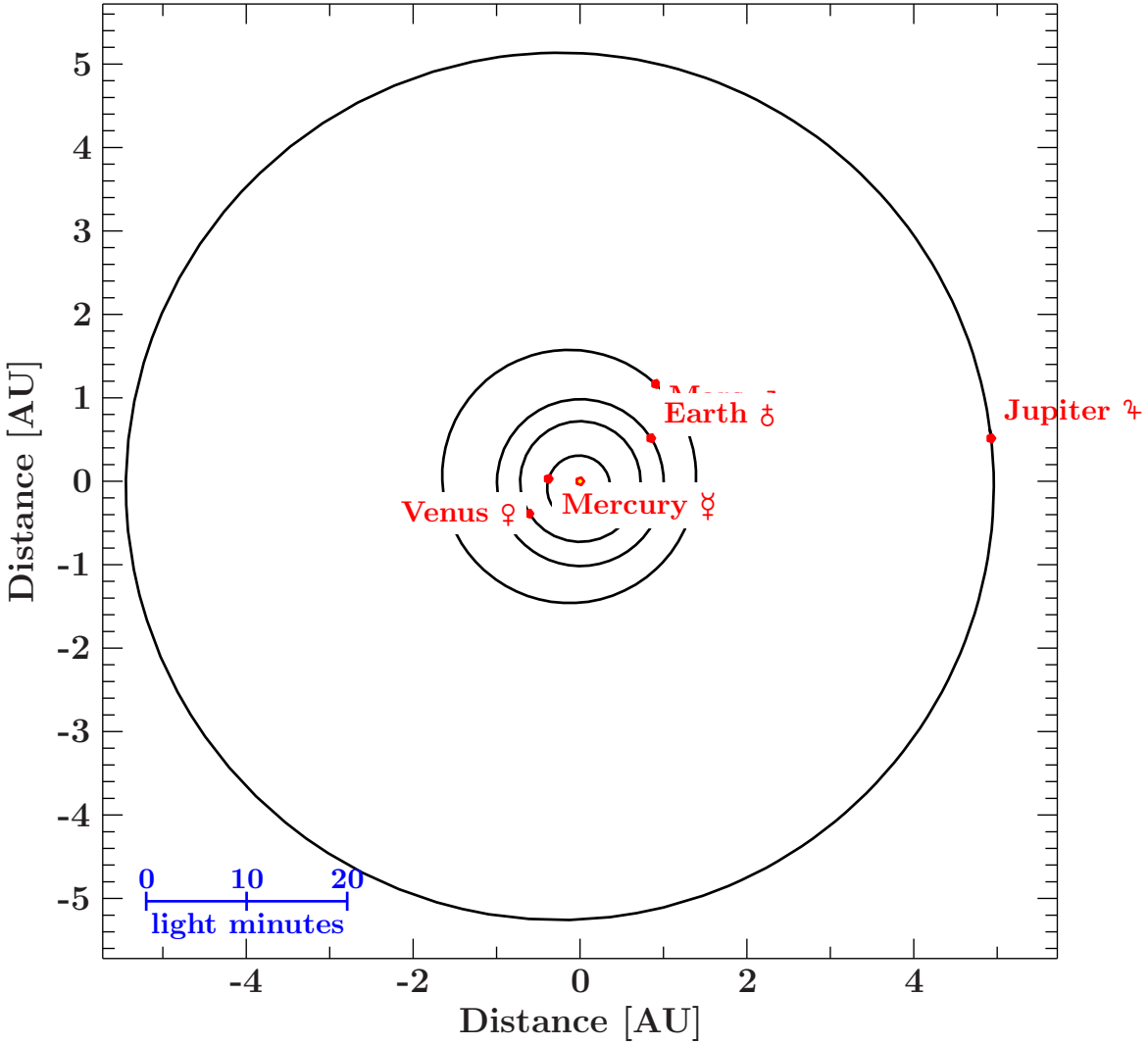
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2. Outer Planets: Jupiter, Saturn, Uranus, Neptune:
   $\Longrightarrow$ "gas giants"
   $\Longrightarrow$ all have *extensive moon systems*

Although not planets (i.e., motion not around Sun), large moons of gas giants are very similar in structure to terrestrial planets.

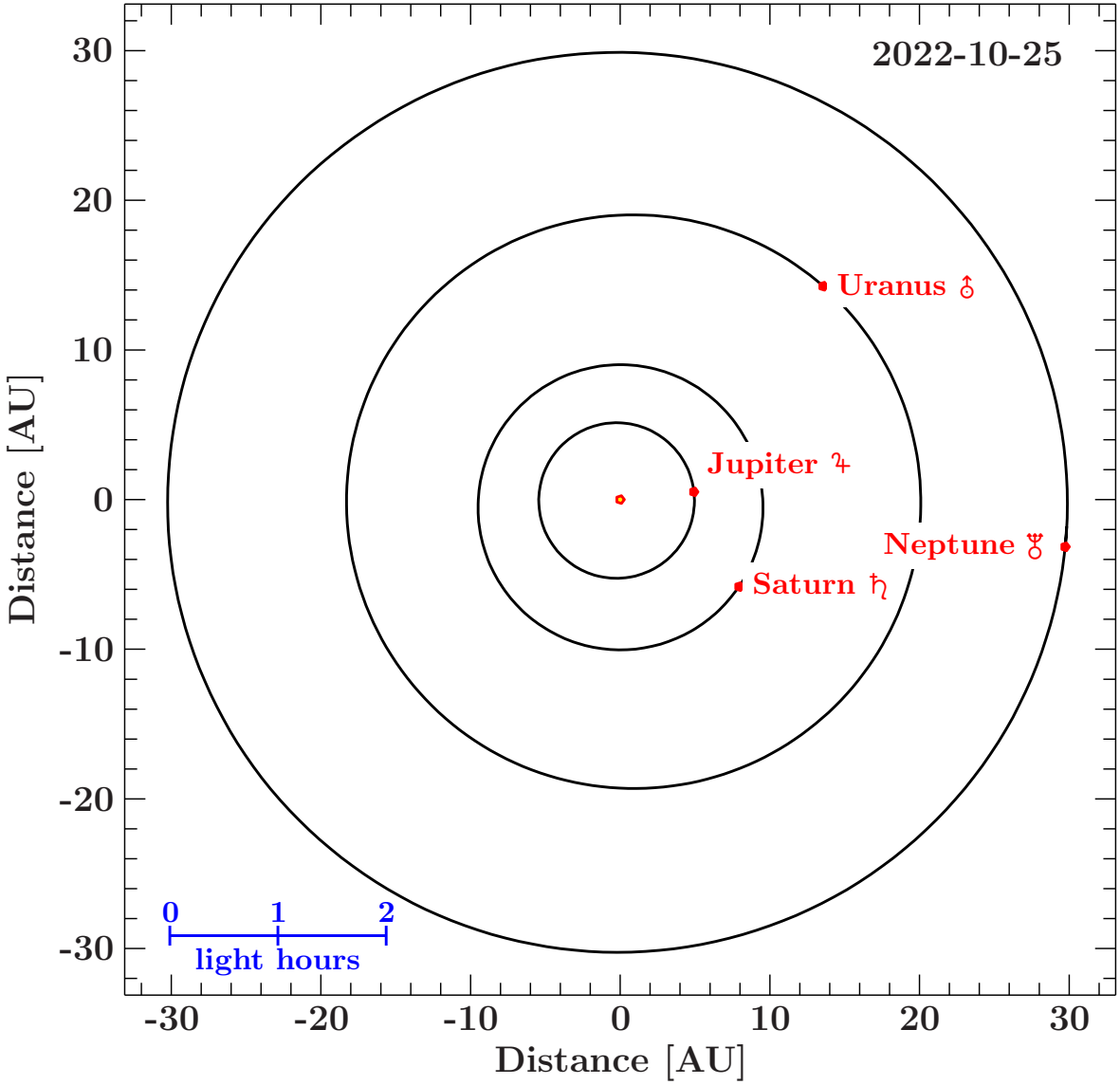

shirt.woot
awkwardyeti

Planetary Orbits



The Inner Planets

Planetary Orbits



The Outer Planets

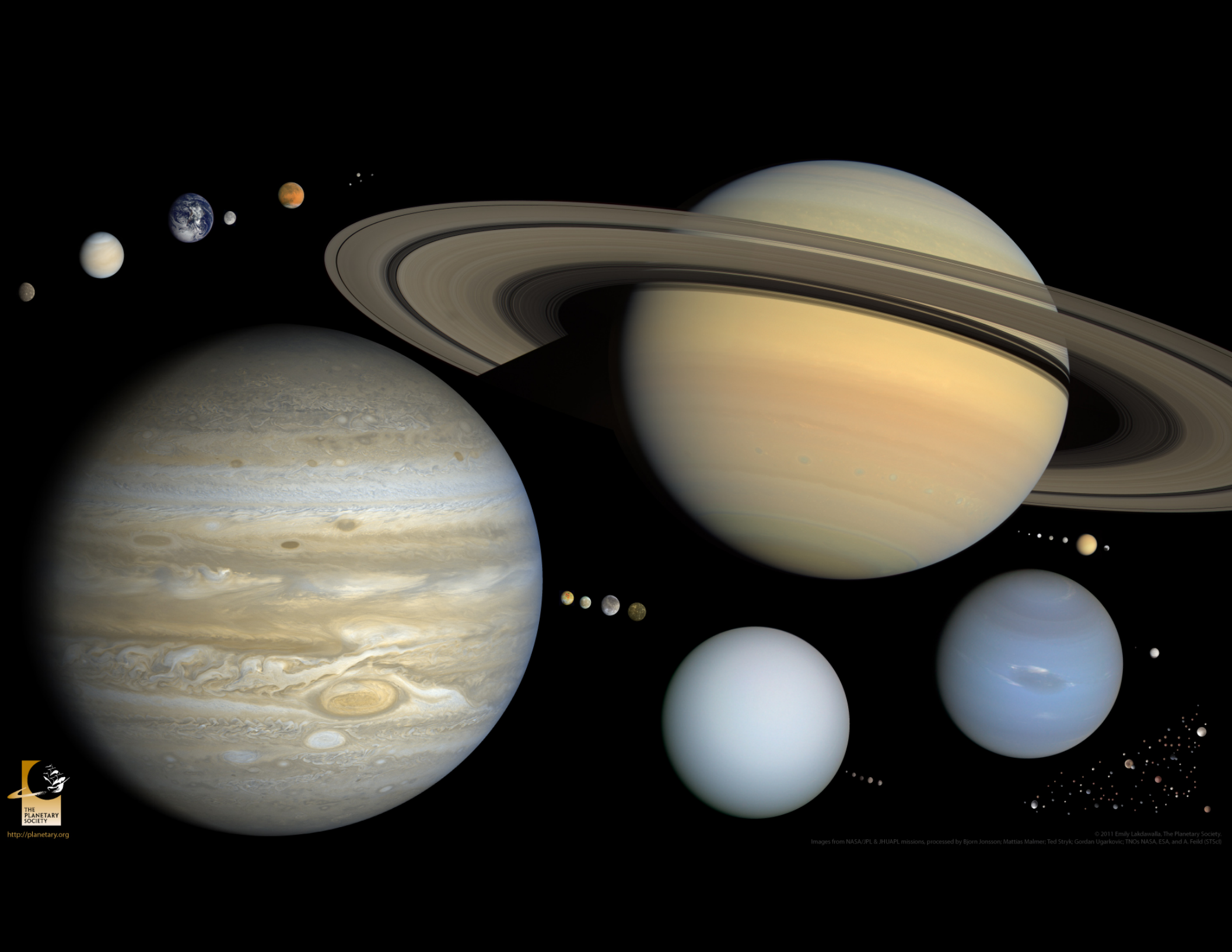
Planets: Properties

		a [AU]	P_{orb} [yr]	i [°]	e	P_{rot}	$M/M_\oplus$	$R/R_\oplus$
Mercury	☿	0.387	0.241	7.00	0.205	58.8 d	0.055	0.383
Venus	♀	0.723	0.615	3.40	0.007	−243.0 d	0.815	0.949
Earth	⊕	1.000	1.000	0.00	0.017	23.9 h	1.000	1.00
Mars	♂	1.52	1.88	1.90	0.094	24.6 h	0.107	0.533
Jupiter	♃	5.20	11.9	1.30	0.049	9.9 h	318	11.2
Saturn	♄	9.58	29.4	2.50	0.057	10.7 h	95.2	9.45
Uranus	♅	19.2	83.7	0.78	0.046	−17.2 h	14.5	4.01
Neptune	♆	30.1	164.8	1.78	0.011	16.1 h	17.1	3.88
(Pluto	♇	39.2	248	17.2	0.244	6.39 d	0.002	0.19)

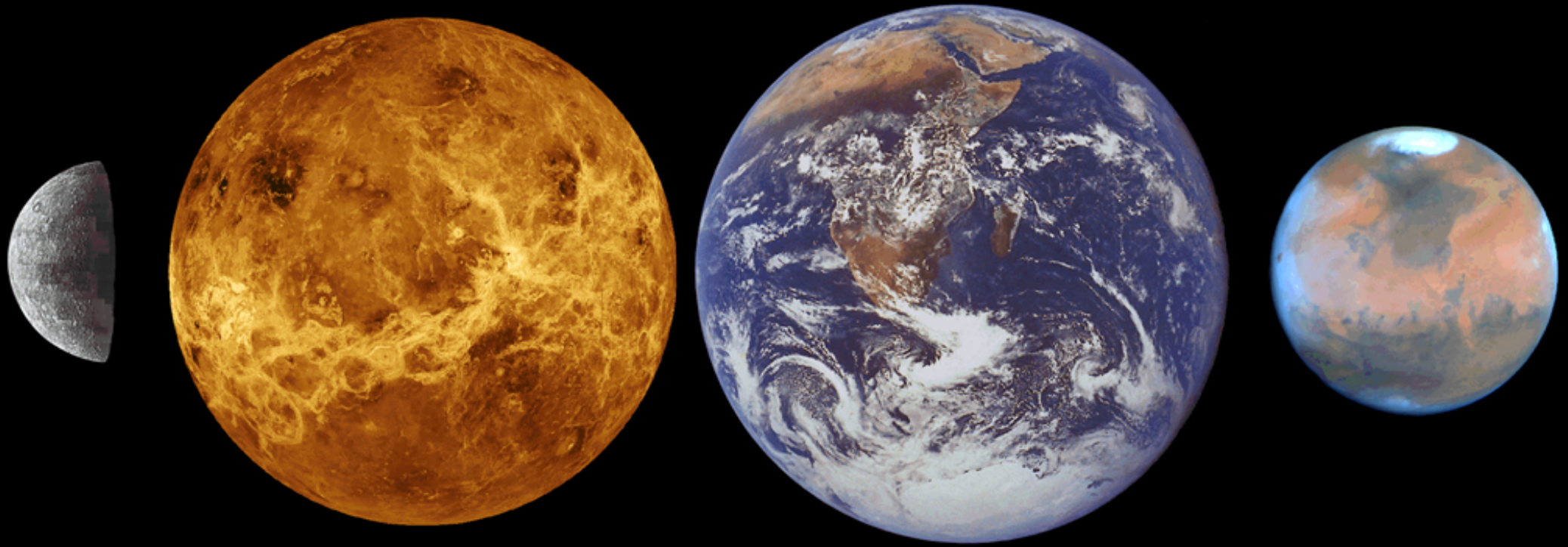
After Kutner, Appendix D;

a: semi-major axis
P_{orb}: orbital period
i: orbital inclination (wrt Earth's orbit)
e: eccentricity of the orbit
P_{rot}: rotational period
M: mass
R: equatorial radius

$1\,\mathrm{AU} = 1.496 \times 10^{11}\,\mathrm{m}$.

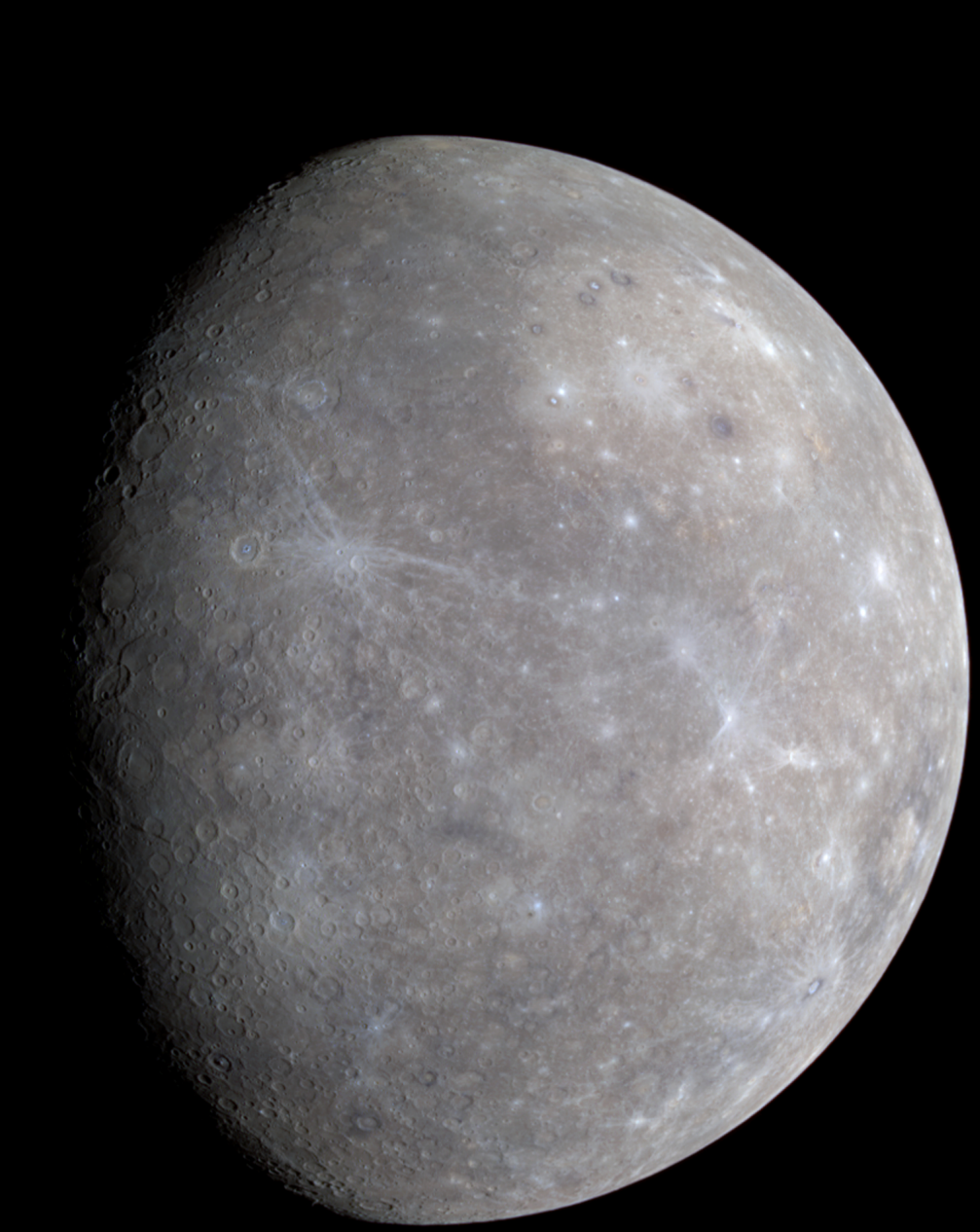

THE PLANETARY SOCIETY
http://planetary.org
© 2011 Emily Lakdawalla, The Planetary Society.
Images from NASA/JPL & JHUAPL missions, processed by Bjorn Jonsson; Mattias Malmer; Ted Stryk; Gordan Ugarkovic; TNOs NASA, ESA, and A. Feild (STScI)

Calvin J. Hamilton



esa

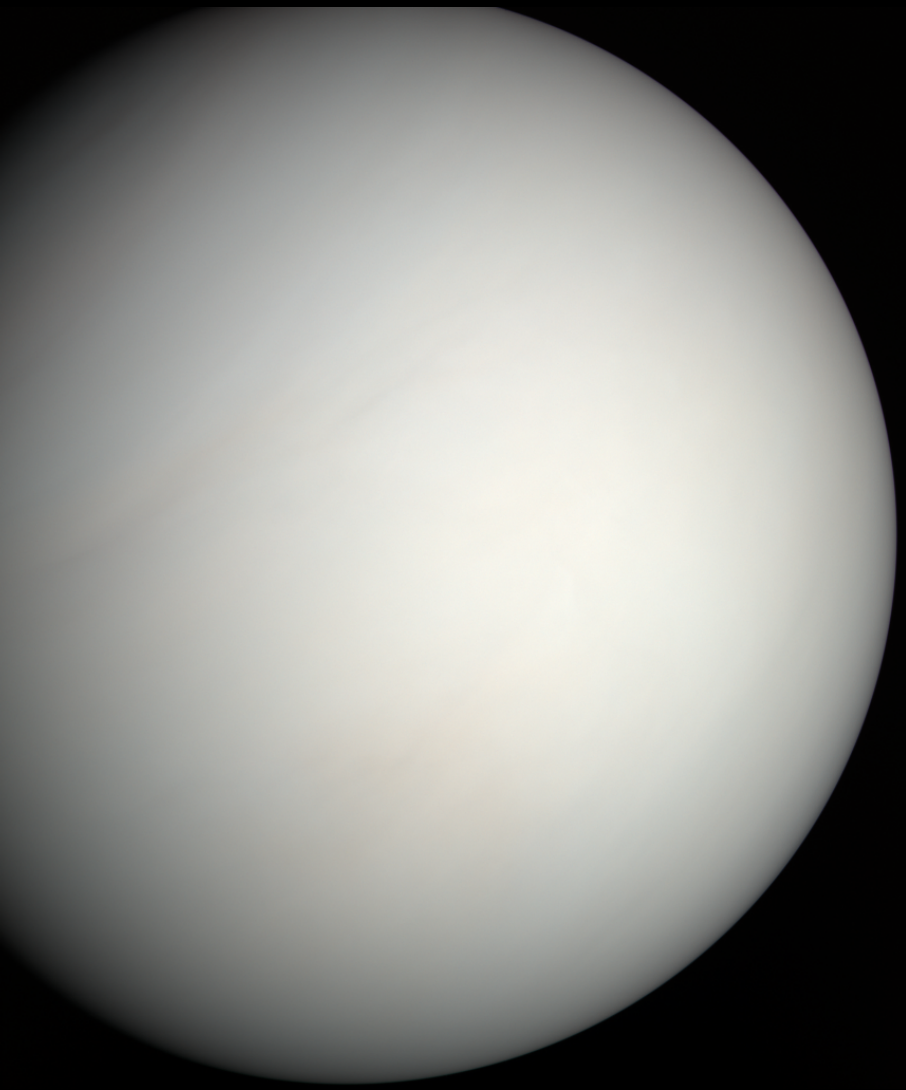
www.esa.int



NASA/MESSENGER, 2008 Jan

Mercury:

- not much larger than Moon
- densest of all terrestrial planets
- no evidence for atmosphere
- Rotation period: 59 d, 2/3 of orbital period.
- surface: impact craters
- Early information available from Mariner 10 (three flybys, 1974/1975)
- NASA mission “Messenger”
  (launched 2004 August 3, flybys 2008 and 2009, on orbit from 2011 until 2015 April 20 [impact on Mercury])
- ESA Mission Bepi Colombo, launched 2018 Oct 20, arrival on orbit 2025



NASA / JHUAPL / CIW / color composite by Gordan Ugarkovic

Venus:

- similar size to Earth, similar structure
- insolation $\sim 2\times$ Earth
- very slow rotation (243 d, retrograde;
  $\Longrightarrow$ no B-field)
- very dense atmosphere: surface pressure $\sim 90\times$ Earth
- atmosphere: 96.5% CO_2, 3.5% N
  $\Longrightarrow$ strong greenhouse effect
  $\Longrightarrow$ surface temperature $\sim 460^\circ$C.
- acid rain (yes, sulphuric acid!)

Information mainly from radar surveying from Earth and from Magellan (1990–1994), plus images from Pioneer Venus Probe (1979). Several landings (Venera, 1975/1981). Extensively studied by ESA's Venus Express probe (launch 04/2005, arrival 04/2006, mission ended 2014 Dec 16).



Earth/Moon, seen from Mars (NASA/Malin)

Earth:

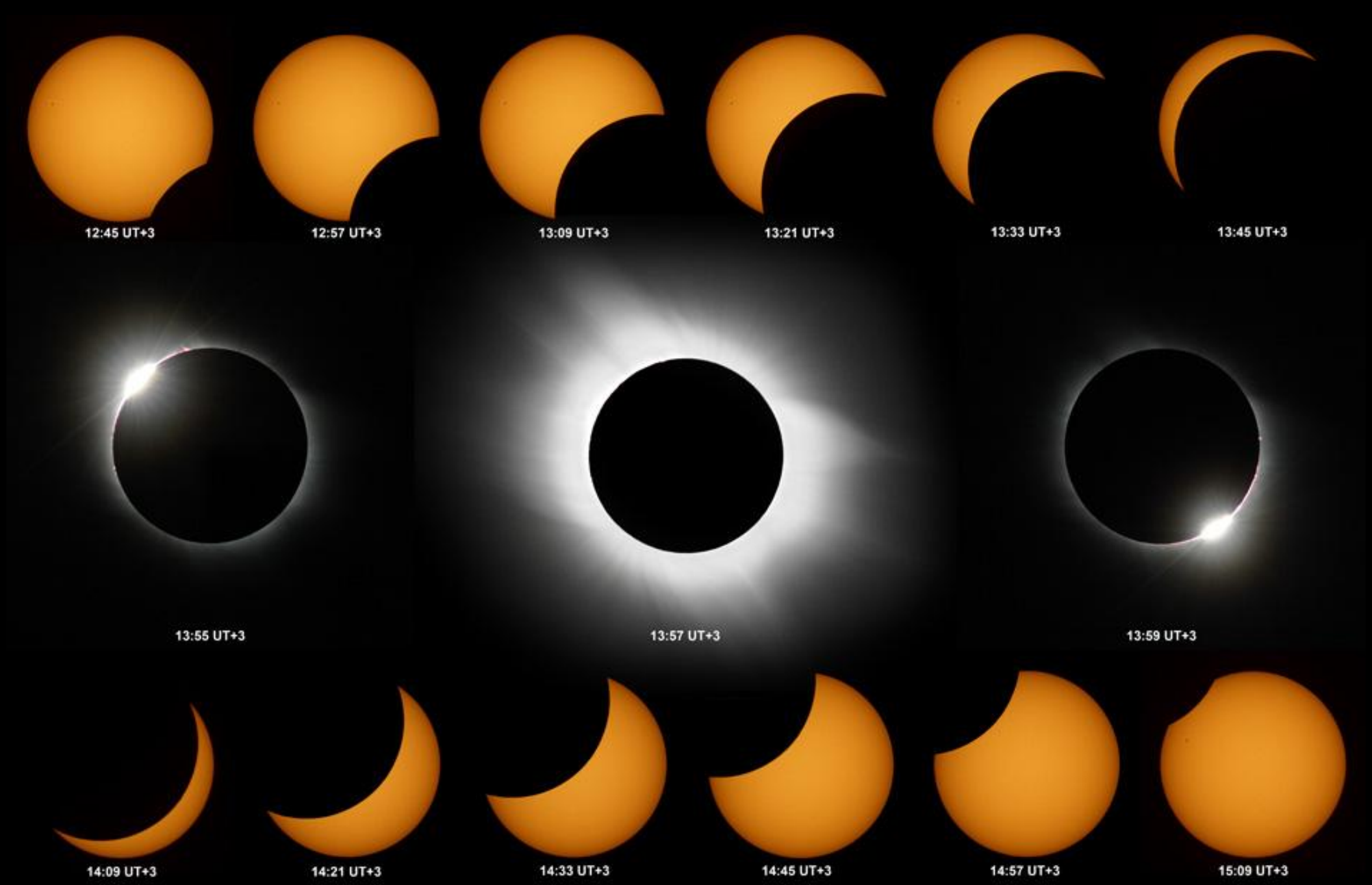
- double planet system
- Earth surface: *dominated by plate tectonics, erosion*
- atmosphere: 80% N_2, 20%O_2
  $\Longrightarrow$ moderate greenhouse effect
  $\Longrightarrow$ surface temperature $>0°C$.
- water present

Moon:

- very similar to Mercury, overall
- Mariae (plains from massive impacts) and impact craters
- Rotation synchronous with orbit around Earth



© High Power Rocketry blog 2013

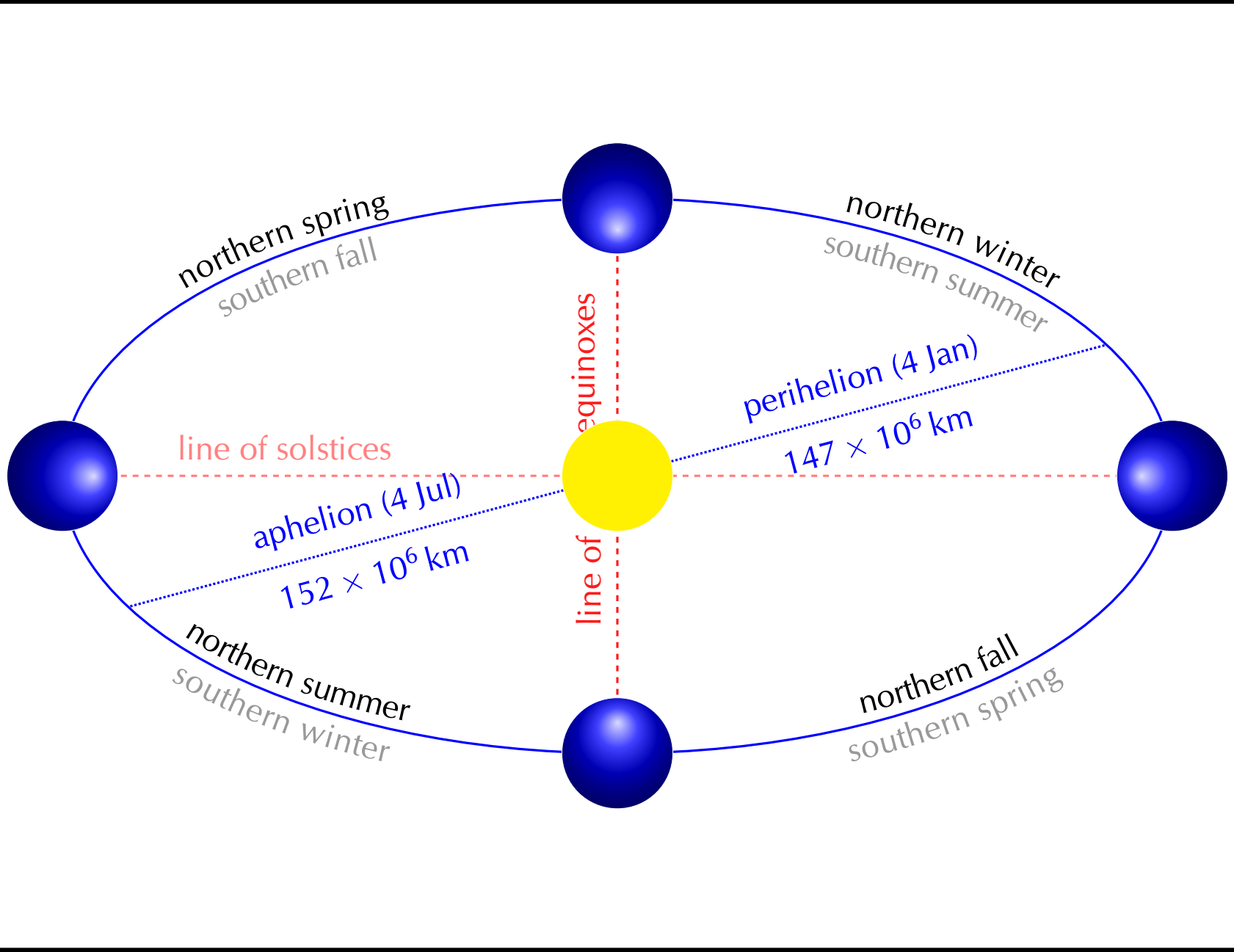


total solar eclipse 2006

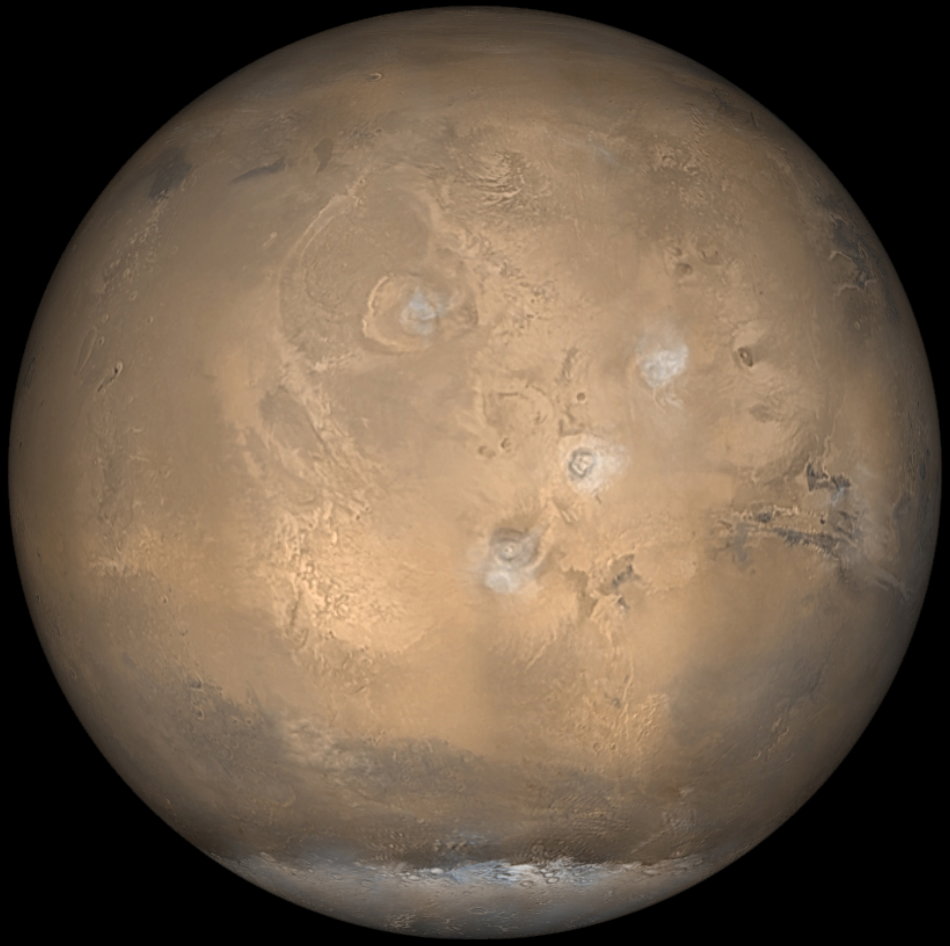
Moon and Sun have very similar apparent diameters: Eclipses



Lunar transit in front of Earth (2015 July 16, DISCOVR spacecraft, NASA; note we see the moon's back side); http://epic.gsfc.nasa.gov/



Earth's orbit, inclination of the rotation axis, and the seasons of the year.
Note: Perihelion is on January 4 $\Longrightarrow$ Sun is closest during northern winter!

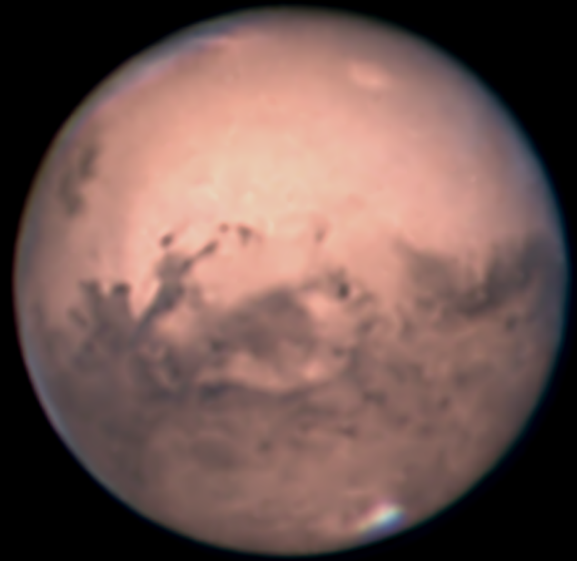


NASA, Mars Global Surveyor

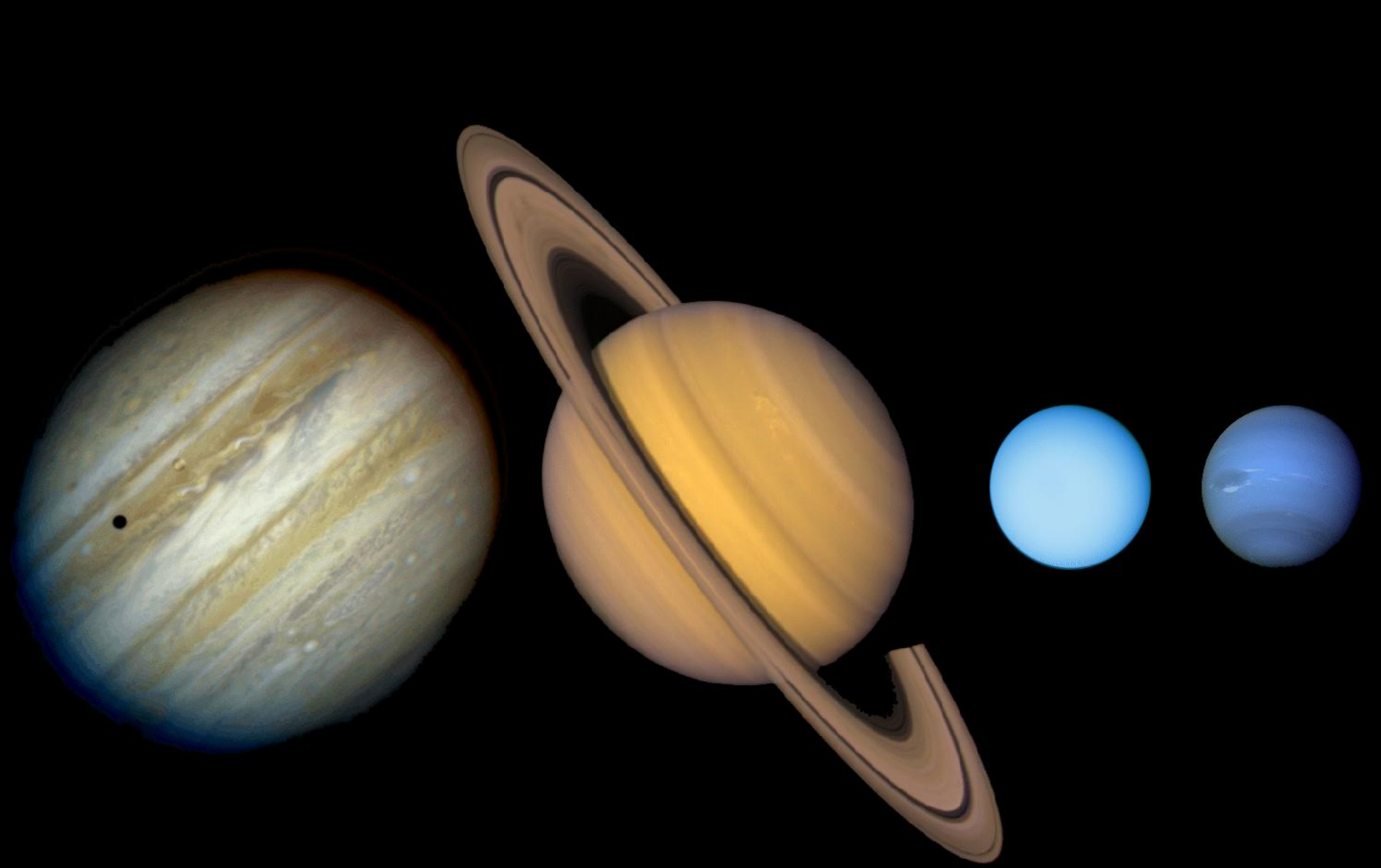
Mars:

- smaller than Earth
- very low density ($\langle\rho\rangle \sim 3\,\mathrm{g\,cm^{-3}}$)
  $\Longrightarrow$ small core, probably Fe and Fe_xS_y,
- polar caps, seasons
- thin atmosphere, clouds, fog,...
- water sublimes
  $\Longrightarrow$ no liquid water today
- Volcanism (large shield volcanoes
  $\Longrightarrow$ no (?) plate tectonics)
- atmosphere: 95% CO_2
  $\Longrightarrow$ weak greenhouse effect
- two moons (captured asteroids)

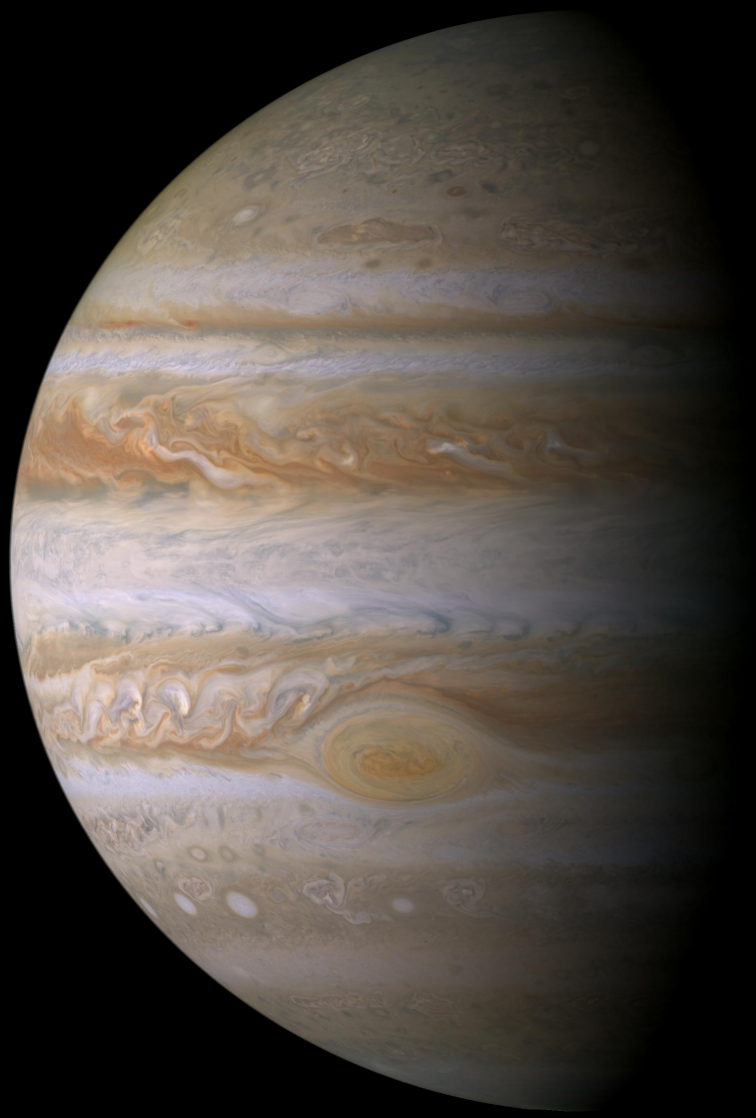
Early Exploration through Mariner missions and Viking 1 and Viking 2 orbiters and landers in 1970s, recently, strong interest (NASA Mars Global Surveyor [MGS], ESA Mars Express, India's Mangalyaan, plus four landers). Currently best surveyed planet except for Earth.



Mars 2020 (Opposition) [Remeis-Obs / P. Weber, S. Hämmerich et al.]



The jovian planets, ©C.J. Hamilton



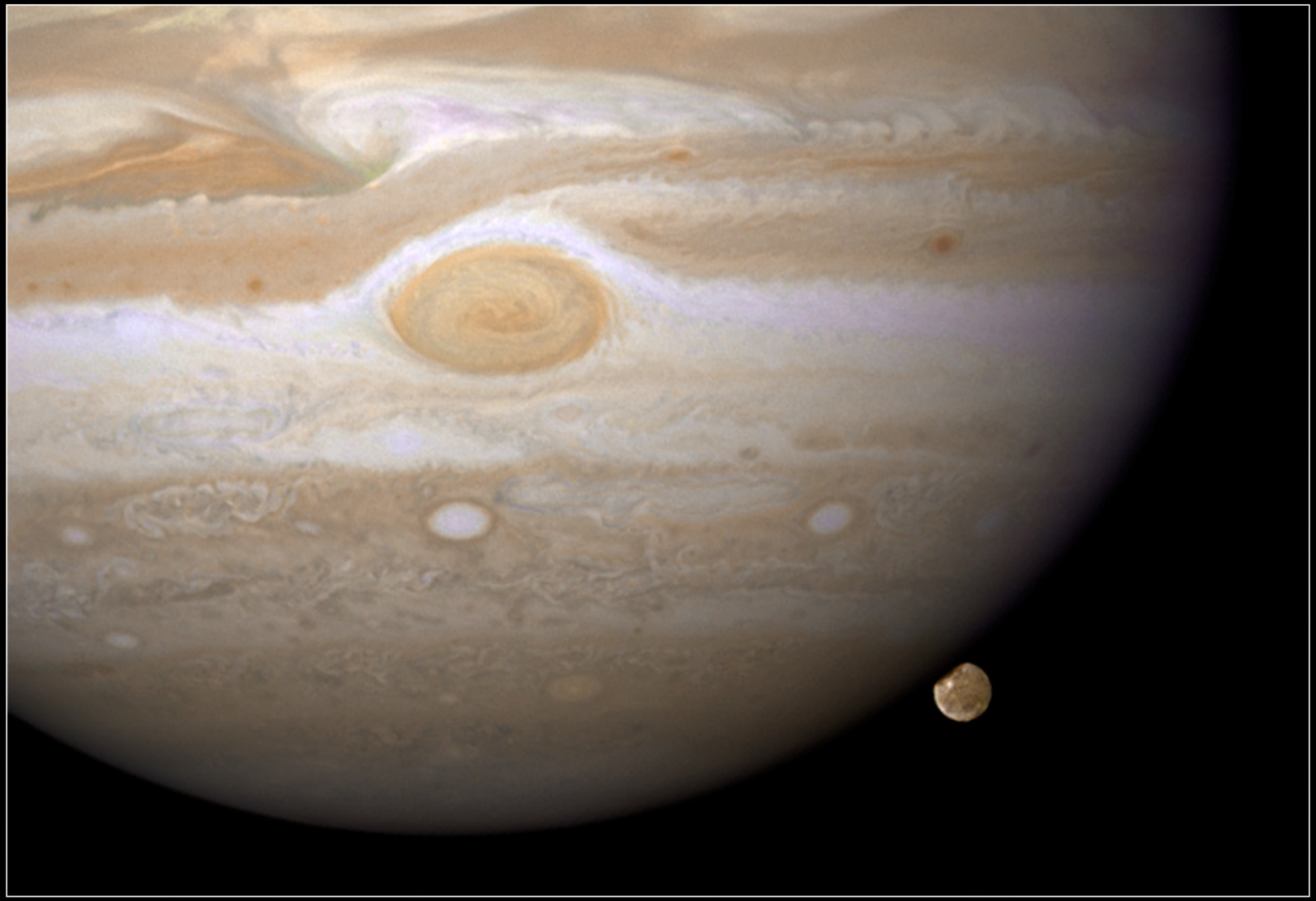
NASA/ESA, Cassini-Huyghens

Jupiter:

- Largest planet in solar system
- rapid rotation $\Longrightarrow$ severely flattened, banded atmosphere (Coriolis force), Great Red Spot
- strong magnetic field (strong radio emission)
- atmosphere: 75% H, 24% He (by mass), very close to solar
- differential rotation (rotation period 9 h 50 m at equator, 9 h 55 m at poles)
- strong magnetic field
- four major “Galilean” moons plus 75 small ones (as of Oct 2018; captured asteroids)

Early Exploration 1970s through Pioneer 11 and 12, and then through the Voyager probes. Intensively studied by NASA’s Galileo project (ended 2003 Sep 14), currently: NASA JUNO (since Jun 2016). Next mission: ESA JUICE (launch: 2022, arrival: 2030)

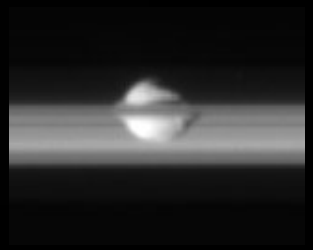
Jupiter and Ganymede • April 9, 2007 *Hubble Space Telescope* • WFPC2



NASA, ESA, and E. Karkoschka (University of Arizona) STScI-PRC08-42



NASA/ESA Cassini, 2004 Oct.



NASA/ESA Cassini

Saturn:

- similar to Jupiter, slightly smaller
- rapid rotation $\Longrightarrow$ flattened, banded atmosphere
- atmosphere: 75% H, 24% He (by mass), molecules etc. similar to Jupiter
- Rings!
- six major moons plus 76 small ones (as of Nov 2020; mainly captured asteroids)
- Early Exploration in 1970s with Pioneer 11 and 12 and the Voyager probes. Studied from 2004 July 1 until 2017 Sept 15 by NASA/ESA Cassini-Huygens project



2004–2009: 6 years of Saturn's orbit. Varying views on ring due to different inclinations of Saturn's and Earth's orbit



NASA Voyager 2, 1986 Jan 10

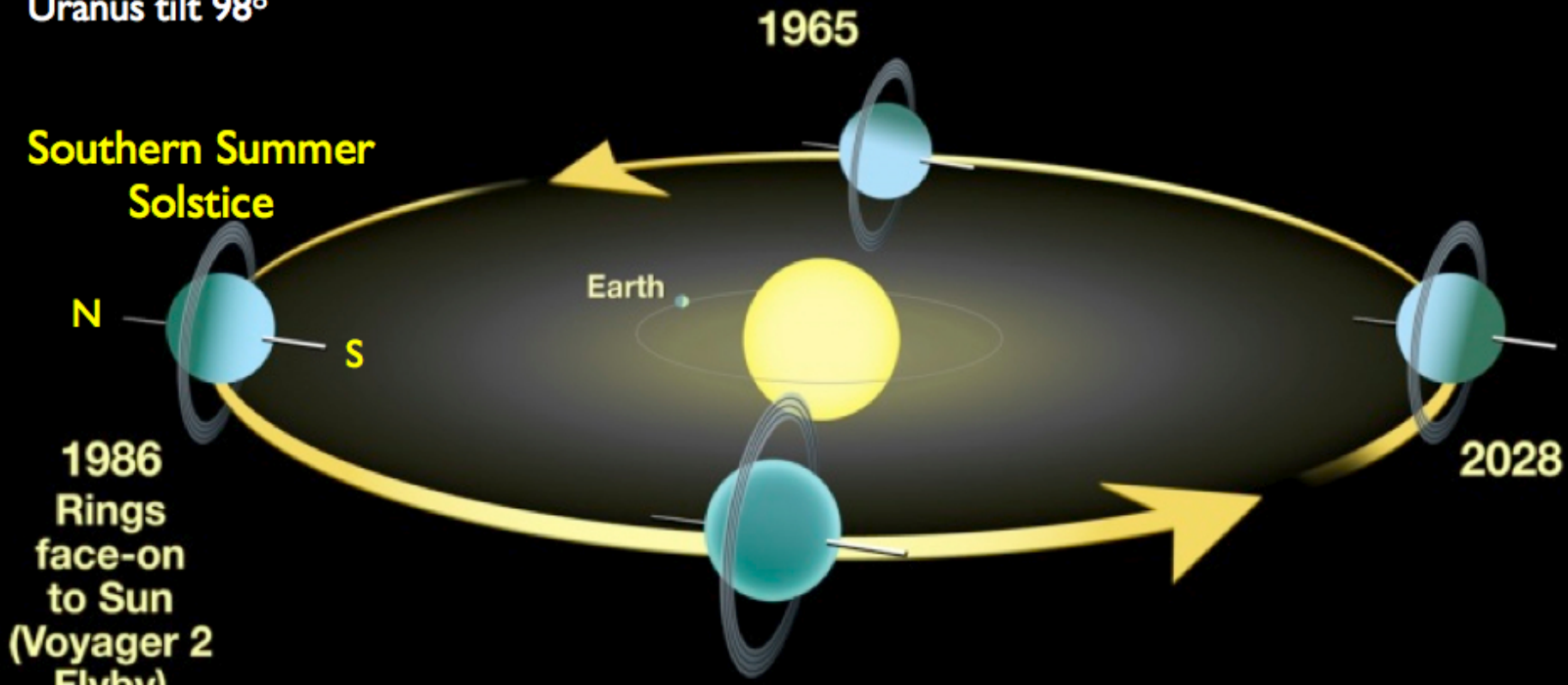
Uranus:

- atmosphere cold (59 K = −214°C) $\Longrightarrow$ ammonia has frozen out
- methane, hydrogen, and helium detected so far (less He than expected from Jupiter and Saturn!) $\Longrightarrow$ blueish color
- inclination of rotation axis: 98° ("rolling on ecliptic plane").
- small ring system
- five major moons in equatorial plane plus 22 small ones (as of Oct 2015; captured asteroids)

Flyby of Voyager 2 in 1986 January, since then only remote sensing from Hubble Space Telescope (HST) and ground based instruments.

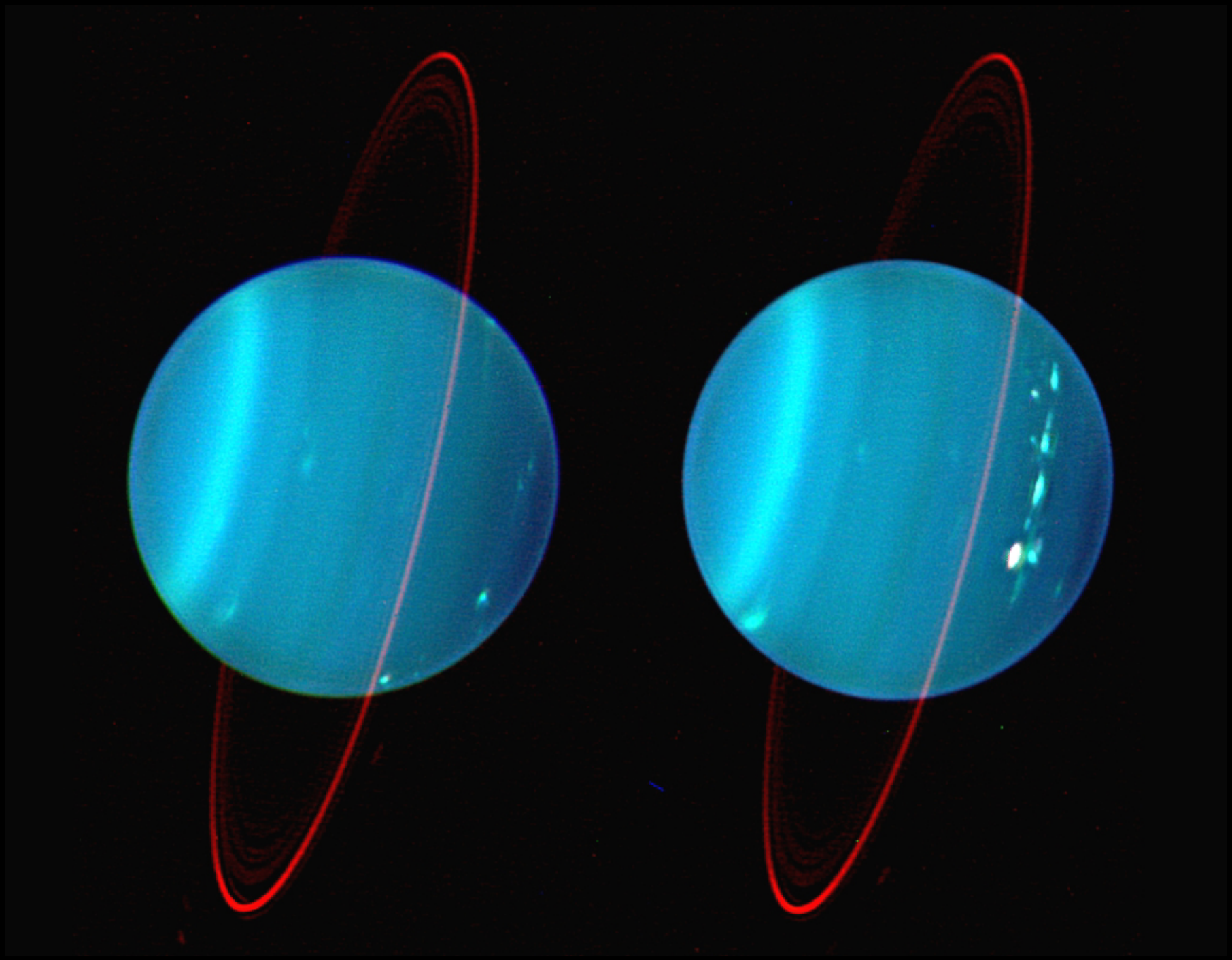
Seasons of Uranus

84 year orbit
spin axis tilt forces seasons
Jupiter tilt 3°
Earth tilt 23.5°
Uranus tilt 98°



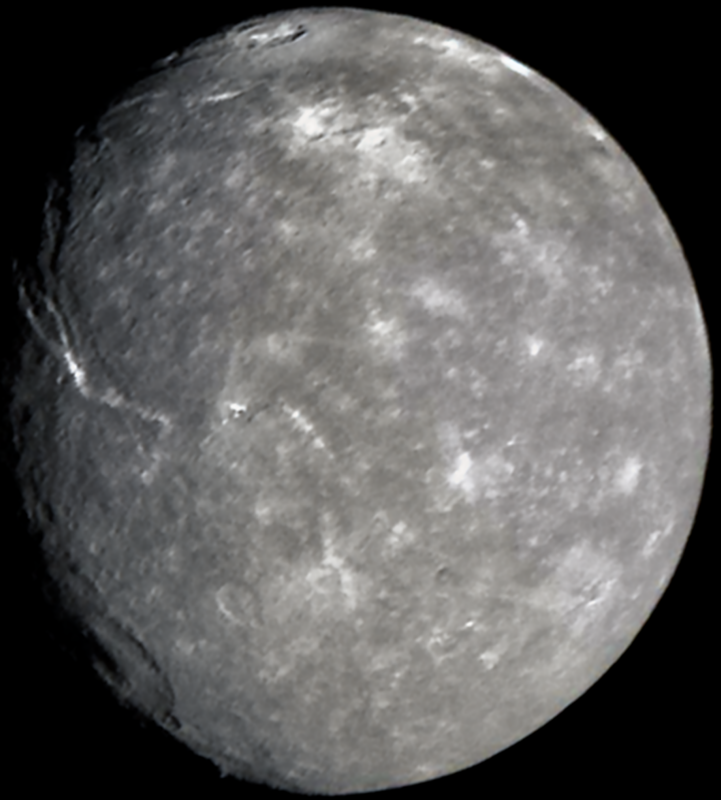
Objects and orbits are not to scale.

graphic from M. Showalter and M. Gordon, SETI Institute



Credit: Lawrence Sromovsky (Univ. Wisconsin-Madison), Keck Observatory

Uranus: rings and tilted rotation



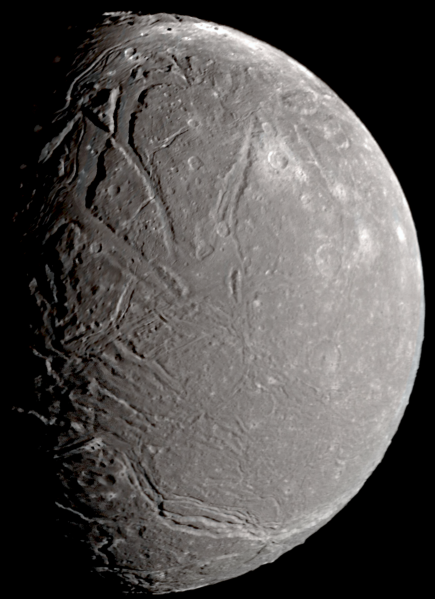
Titania



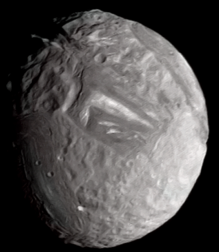
Oberon



Umbriel



Ariel



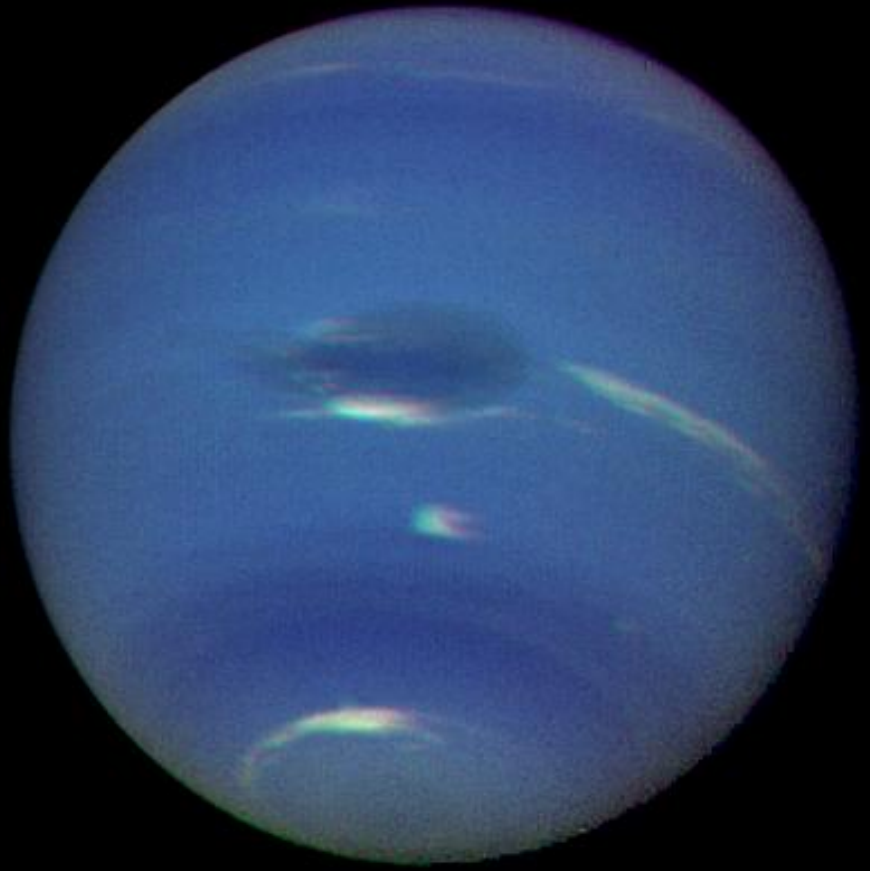
Miranda



Puck

Moons of Uranus confirmed to be larger than 150 km in diameter at 1 km/pixel

Data from Voyager 2 courtesy NASA/JPL Processed images and collage Copyright Ted Stryk



NASA Voyager 2

Neptune:

- atmosphere similar to Uranus, but more active; bright methane clouds above general cloud layer
- ring system (5 individual rings)
- Three major moons (Triton, 2720 km diameter(!), Proteus, 420 km, and Nereid, 355 km), 11 captured asteroids

Flyby in 1989 August by Voyager 2, only HST since then (showed in 1995 that dark spot has vanished, detected new storm system)



Moons of Neptune larger than 150 km in diameter at 1 km/pixel

Structure

Questions that we will deal with:

- How do the planets move?
  Kepler's laws and their physical interpretation
- What do planetary surfaces look like?
  craters, plate tectonics, volcanism
- What is the internal structure of the planets?
  hydrostatic structure
- How do planetary atmospheres work?
  hydrostatic structure (again)
- What is the nature of the minor bodies?
- How did the planetary system form?
- Is the solar system normal?
  Are there planets elsewhere? (Later)

The Planets: Dynamics

Introduction

Johannes Kepler: Motion of planets governed by three laws:

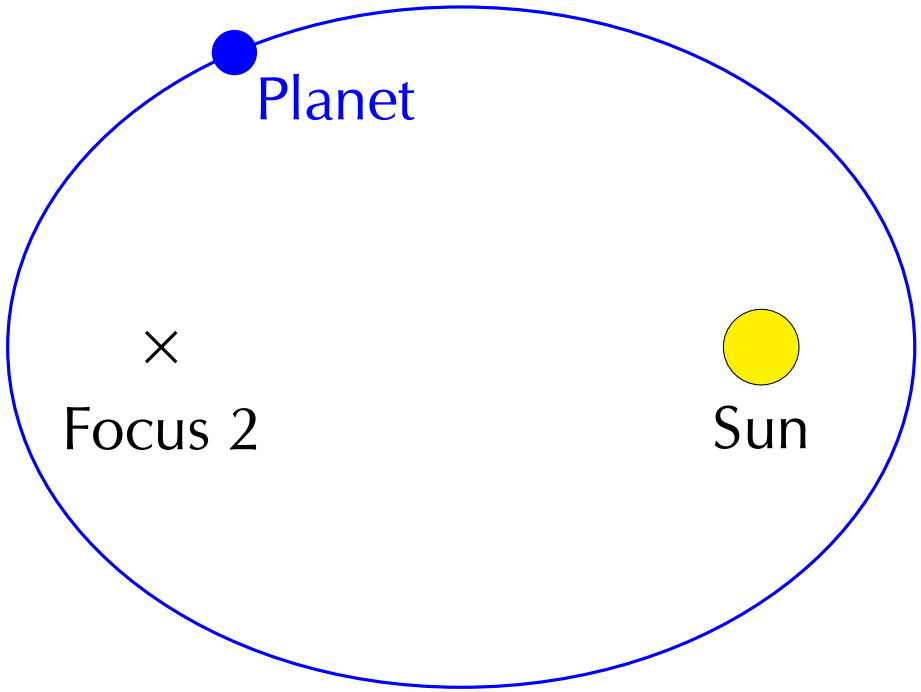
1. Each planet moves in an elliptical orbit, with the Sun at one focus of the ellipse. ("Astronomia Nova", 1609)
2. A line from the Sun to a given planet sweeps out equal areas in equal times. ("Astronomia Nova", 1609)
3. The square of the orbital periods of the planets is proportional to the cube of the major axes. ("Harmonice Mundi", 1619)

Isaac Newton ("Principia", 1687): Kepler's laws are consequence of gravitational interaction between planets and the Sun. The gravitational force is

$$\mathbf{F}_1 = -\frac{G m_1 m_2}{r_{12}^2}\frac{\mathbf{r}_{21}}{r_{12}} \tag{2.1}$$

where $\mathbf{F}_1$ is the gravitational force exerted on object 1, m_1, m_2 are the masses of the interacting objects, r their distance, and $\mathbf{r}_{21}/r_{12}$ the unit vector joining the objects, $\mathbf{r}_{21} = \mathbf{r}_2 - \mathbf{r}_1$, $\mathbf{r}_{12} = -\mathbf{r}_{21}$ and $r_{12} = |\mathbf{r}_{12}| = |\mathbf{r}_{21}|$.

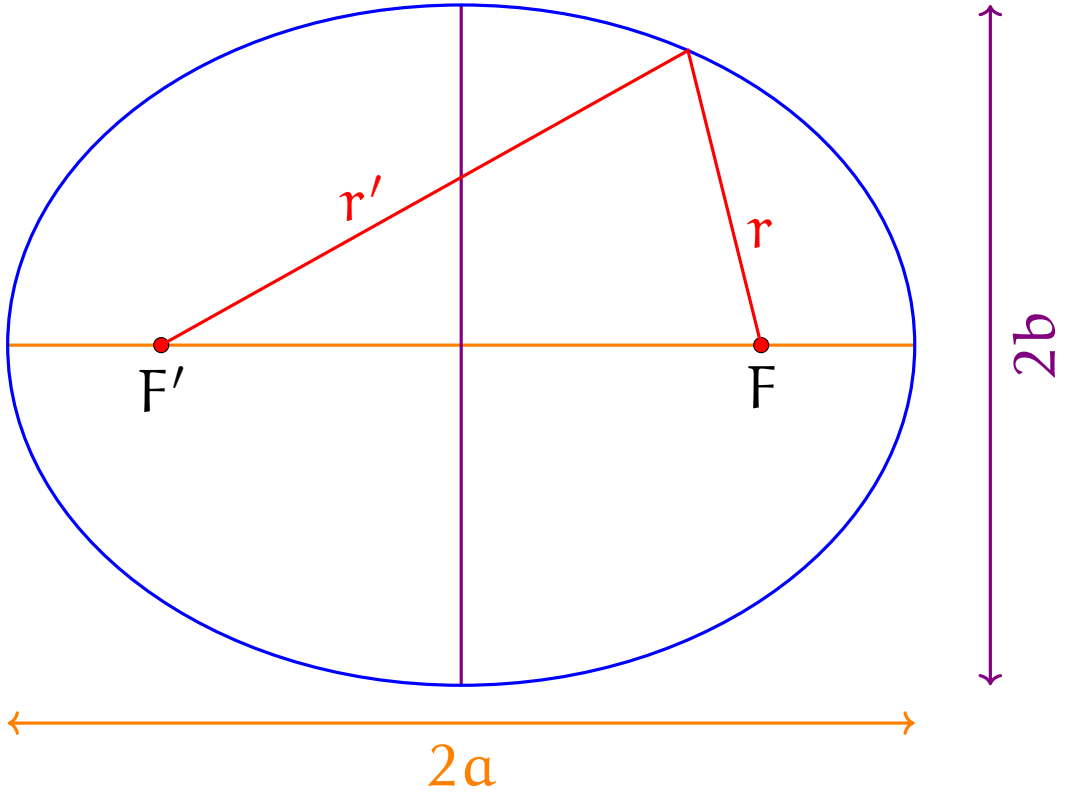
Kepler's 1st Law



Kepler's 1st Law: The orbits of the planets are ellipses and the Sun is at one focus of the ellipse.

For the planets of the solar system, the ellipses are almost circular, for comets they can be very eccentric.

Kepler's 1st Law

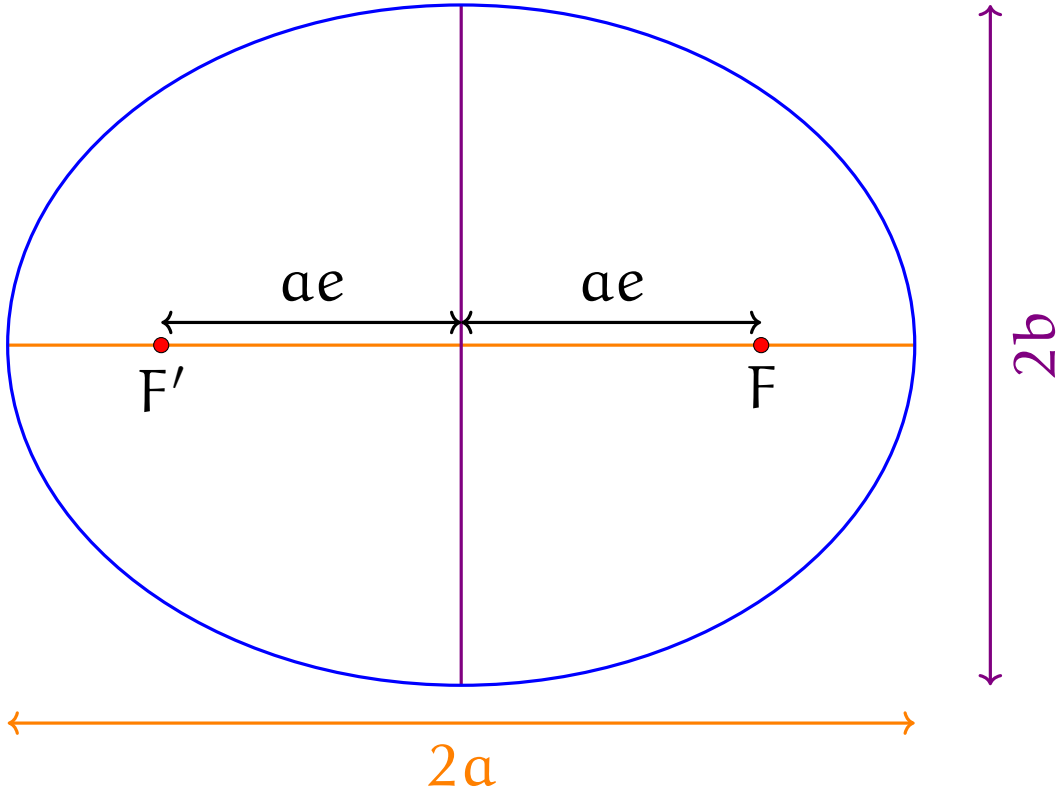


Definition: Ellipse = Sum of distances r, r' from any point on ellipse to two fixed points (foci, singular: focus), F, F′, is constant:

$$r + r' = 2a \tag{2.2}$$

where a is called the semi-major axis of the ellipse.

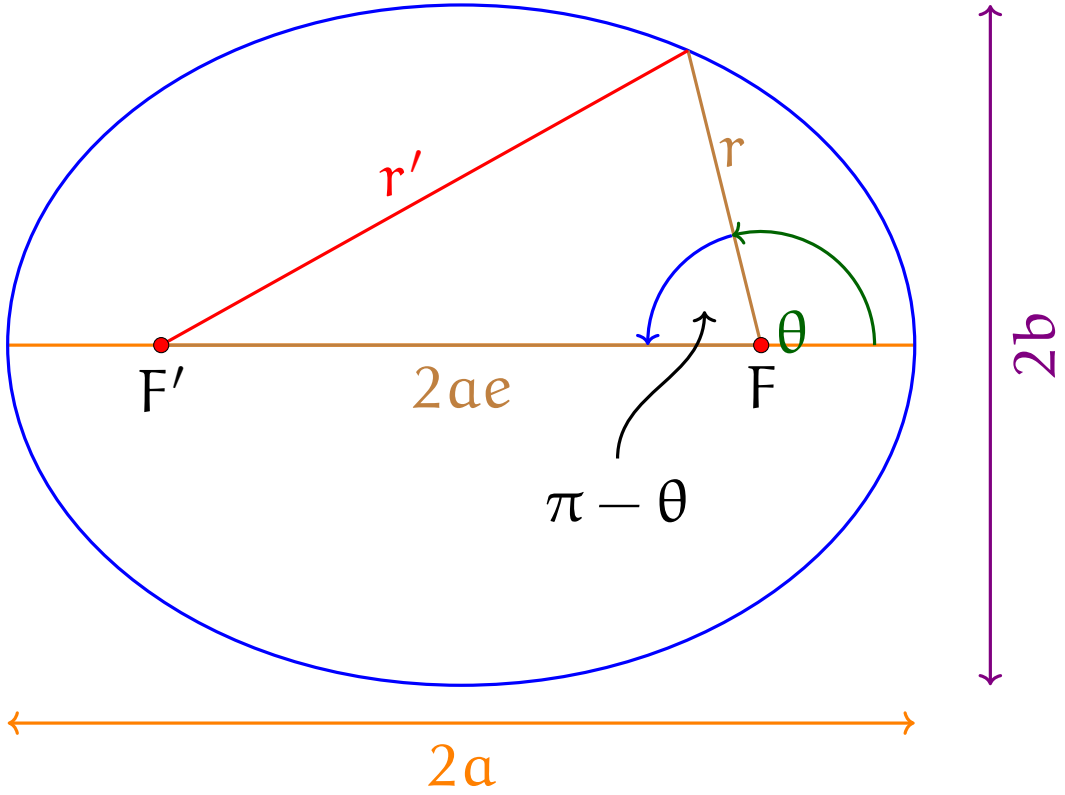
Kepler's 1st Law



Definition: Eccentricity e: ratio between distance from center of ellipse to focal point and semi-major axis.

So circles have $e = 0$.

Kepler's 1st Law

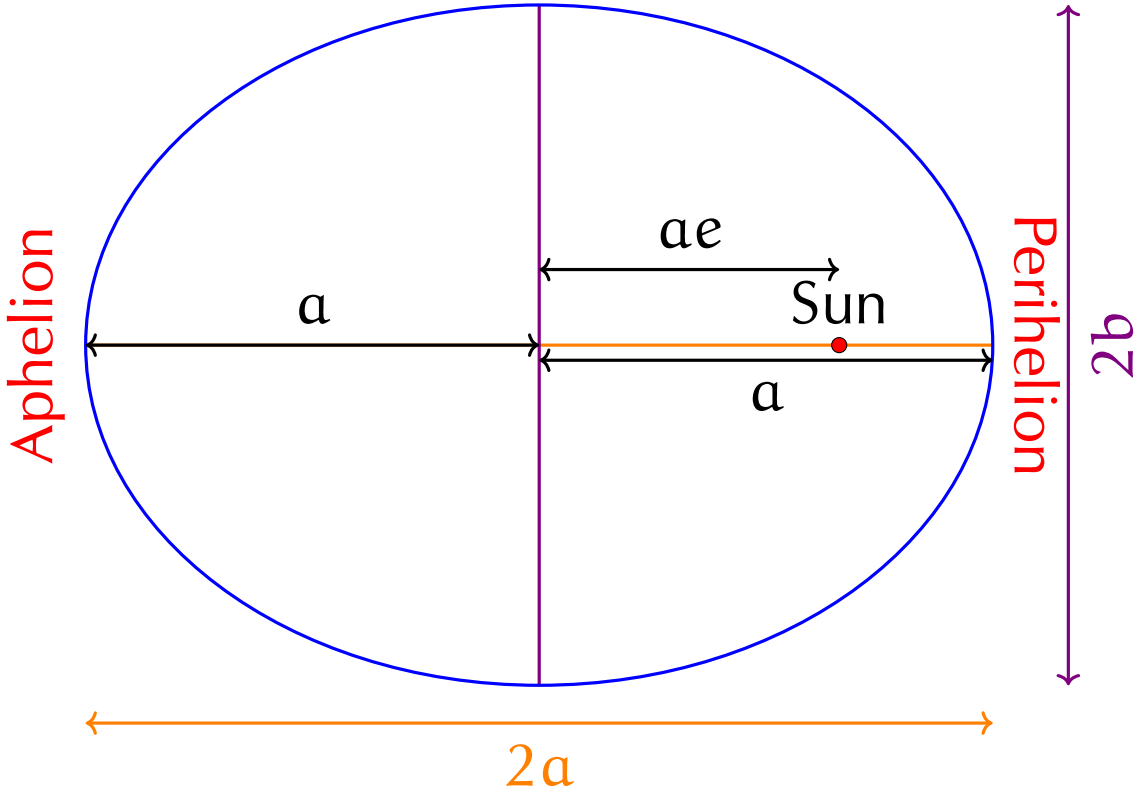


Law of cosines: $r'^2 = r^2 + (2ae)^2 - 2 \cdot r \cdot 2ae \cdot \cos(\pi - \theta)$
use $r + r' = 2a$ and solve for r to find the polar coordinate form of the ellipse:

$$r = \frac{a(1 - e^2)}{1 + e\cos\theta} \tag{2.3}$$

Check this for yourself! θ is called the *true anomaly*.

Kepler's 1st Law

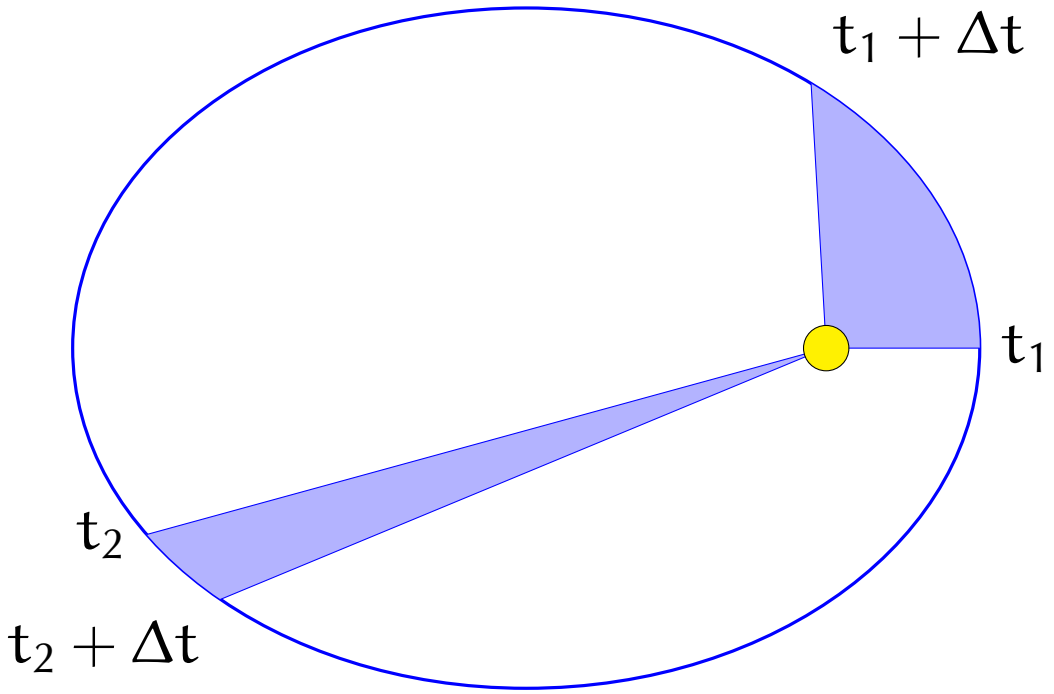


Finally, we need the closest and farthest point from a focus:

$$\begin{aligned} \text{closest point}: d_{\text{perihelion}} &= a - ae = a(1-e) \\ \text{farthest point}: d_{\text{aphelion}} &= a + ae = a(1+e) \end{aligned} \tag{2.4}$$

for stars: periastron and apastron,
for satellites circling the Earth: perigee and apogee.

2nd Law



Kepler's 2nd Law: The radius vector to a planet sweeps out equal areas in equal intervals of time.

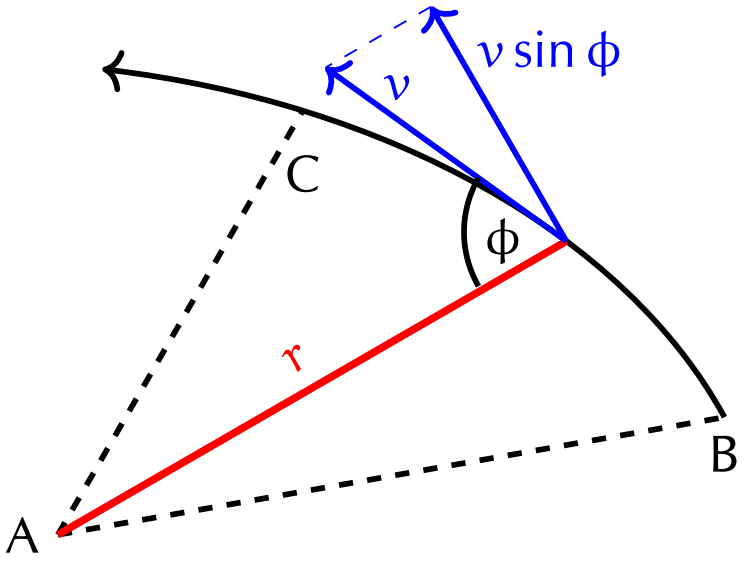
1. Kepler's 2nd Law is also called the *law of areas*.
2. perihelion: planet nearest to Sun $\Longrightarrow$ planet is fastest
3. aphelion: planet farthest from Sun $\Longrightarrow$ planet is slowest

Kepler's 2nd law is a direct consequence of the conservation of angular momentum. Remember that angular momentum is defined as

$$\mathbf{L} = \mathbf{r} \times \mathbf{p} = \mathbf{r} \times m\mathbf{v} \tag{2.5}$$

and its absolute value is

$$L = mrv \sin\phi \tag{2.6}$$



To interpret the angular momentum, look at the figure at the left. The projection of the velocity vector perpendicular to the radius vector r is $v \sin\phi$. The distance traveled by the planet in an infinitesimally short time Δt is given by $\Delta x = \Delta t \cdot v \sin\phi$. Therefore, the area of the triangle ABC is given by

$$\Delta A = \frac{1}{2} r \Delta x = \frac{1}{2} r \Delta t v \sin\phi = \frac{L}{2m} \Delta t \tag{2.7}$$

Kepler's 2nd law states that the "sector velocity" dA/dt is constant with time:

$$\frac{dA}{dt} = \lim_{\Delta t \to 0} \frac{\Delta A}{\Delta t} = \frac{L}{2m} = \text{const.} \tag{2.8}$$

To confirm that this claim is true, we need to prove that

$$\frac{d}{dt}\frac{dA}{dt} = \frac{1}{2m}\frac{dL}{dt} = 0 \tag{2.9}$$

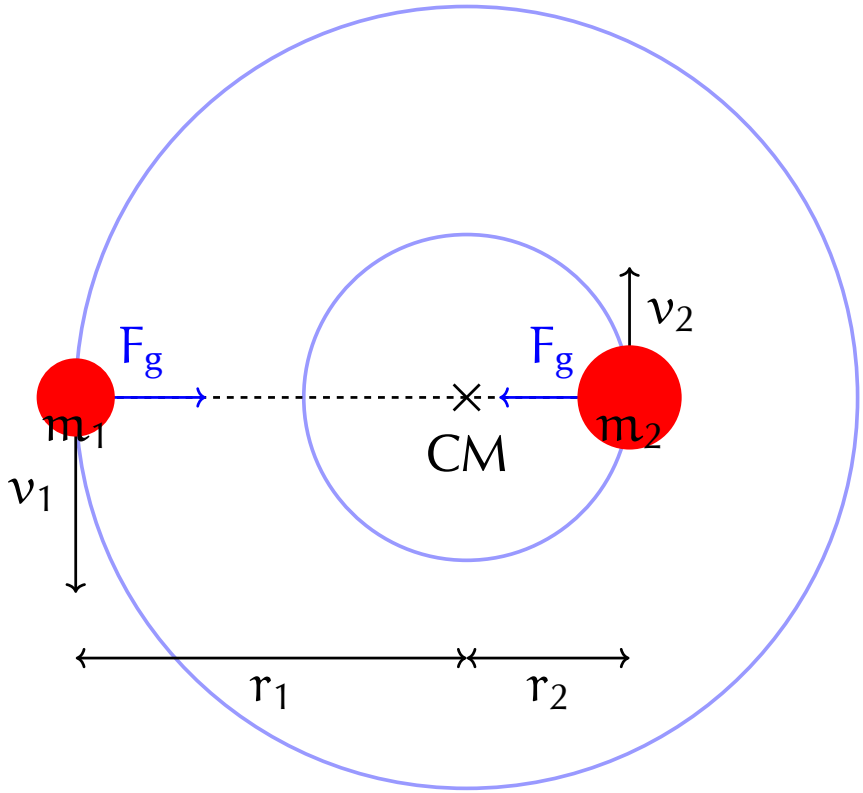
But dL/dt is given by

$$\frac{d\mathbf{L}}{dt} = \frac{d\mathbf{r}}{dt} \times \mathbf{p} + \mathbf{r} \times \frac{d\mathbf{p}}{dt} = \mathbf{v} \times \mathbf{p} + \mathbf{r} \times \mathbf{F} = \mathbf{v} \times m\mathbf{v} + \mathbf{r} \times \frac{GMm}{r^2} \frac{\mathbf{r}}{r} = 0 \tag{2.10}$$

since the cross product of a vector with itself is zero. Therefore, Kepler's 2nd law is true and is a consequence of the conservation of angular momentum for a central field.

3rd Law

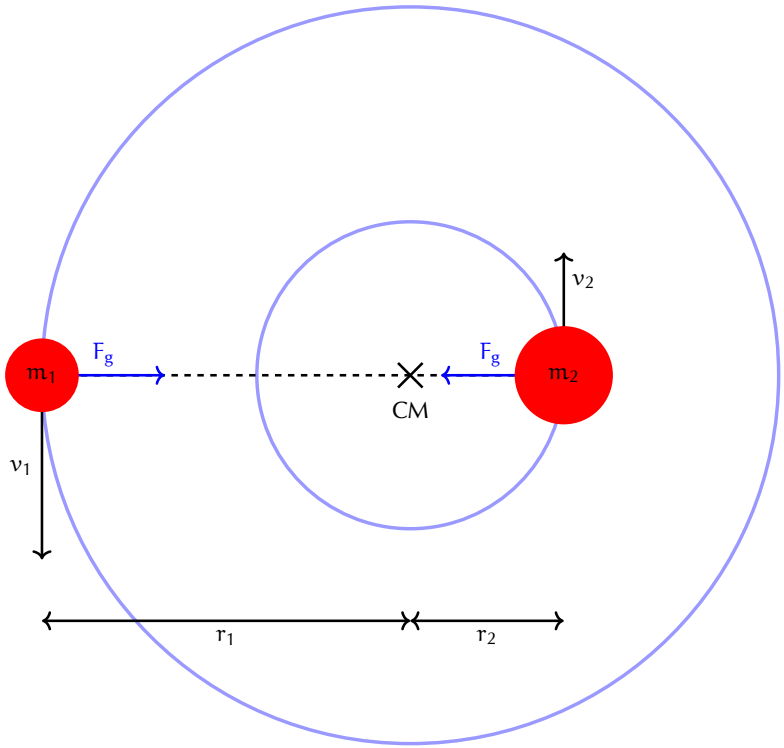
Kepler's 3rd Law: The squares of the periods of the planets, P, are proportional to the cubes of the semimajor axes, a, of their orbits: $P^2 \propto a^3$.



Calculating the motion of two bodies of mass m_1 and m_2 gives Newton's form of Kepler's third law:

$$P^2 = \frac{4\pi^2}{G(m_1 + m_2)} R^3 \tag{2.11}$$

where $r_1 + r_2 = R$ (for elliptical orbits: R is the semi-major axis).



For an interpretation of Kepler's third law, consider the motion of two bodies with masses m_1 and m_2 on circular orbits with radii r_1 and r_2 around a point CM (see figure).
The reason for doing the computation with circular orbits is that the following discussion will be easier, however, all results from this section also apply to the general case of elliptical motion. This will be proven later in the lectures on Theoretical Mechanics.
The attractive force between the two points is given by Newton's law:

$$F_g = G\frac{m_1 m_2}{R^2} = G\frac{m_1 m_2}{(r_1 + r_2)^2} \tag{2.12}$$

In order to keep the two bodies on circular orbits, the gravitational force needs to be equal the centripetal force keeping each body on its circular orbit.
The centripetal force is

$$\begin{aligned} F_{\text{cent},1} &= \frac{m_1 v_1^2}{r_1} = \frac{4\pi^2 m_1 r_1}{P^2} \\ F_{\text{cent},2} &= \frac{m_2 v_2^2}{r_2} = \frac{4\pi^2 m_2 r_2}{P^2} \end{aligned} \tag{2.13}$$

where $v = 2\pi r/P$ was used to determine the velocity of each of the bodies. Setting the centripetal force equal to the gravitational force gives

$$\begin{aligned} \frac{4\pi^2 m_1 r_1}{P^2} &= G\frac{m_1 m_2}{(r_1 + r_2)^2} \\ \frac{4\pi^2 m_2 r_2}{P^2} &= G\frac{m_1 m_2}{(r_1 + r_2)^2} \end{aligned} \tag{2.14}$$

canceling m_1 and m_2 results in

$$\begin{aligned} \frac{4\pi^2 r_1}{P^2} &= G\frac{m_2}{(r_1 + r_2)^2} \\ \frac{4\pi^2 r_2}{P^2} &= G\frac{m_1}{(r_1 + r_2)^2} \end{aligned} \tag{2.15}$$

Dividing these two equations by each other gives

$$\frac{r_1}{r_2} = \frac{m_2}{m_1} \quad \text{or} \quad m_1 r_1 = m_2 r_2 \tag{2.16}$$

This is the definition of the *center of mass*.

The total distance between the two bodies is

$$R = r_1 + r_2 = r_1 + \frac{m_1}{m_2} r_1 = r_1 \left(1 + \frac{m_1}{m_2}\right) \tag{2.17}$$

Inserting into one of the equations 2.15 gives

$$\frac{4\pi^2}{P^2} \cdot R \cdot \frac{m_2}{m_1 + m_2} = \frac{G m_2}{R^2} \tag{2.18}$$

such that

$$\frac{4\pi^2}{P^2} = \frac{G(m_1 + m_2)}{R^3} \quad \text{or} \quad P^2 = \frac{4\pi^2}{G(m_1 + m_2)} R^3 \tag{2.19}$$

This is *Newton's form of Kepler's 3rd law*.

3rd Law

Newton's form of Kepler's 3rd law is the most general form of the law.

However, often shortcuts are possible.

Assume one central body dominates, $m_1 = M \gg m_2$:

$$\frac{P^2}{a^3} = \frac{4\pi^2}{GM} = \text{const.} = k \tag{2.20}$$

So, if we know P and a for one body moving around m_1, can calculate k.

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For the Solar System, use Earth:

- $P_\oplus = 1$ year (by definition!)
- $a_\oplus = 1$ AU (Astronomical Unit, $1\,\text{AU} = 149.6 \times 10^6$ km)

$\Longrightarrow k = 1\,\text{yr}^2\,\text{AU}^{-3}$

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Jupiter: $a_{♃} = 5.2$ AU. What is its period?
Answer: $P_{♃}^2 = 1\,\text{yr}^2\,\text{AU}^{-3} \cdot 5.2^3\,\text{AU}^3 \sim 140\,\text{yr}^2$, or $P_{♃} \sim 12$ years
(with pocket calculator: $P_{♃} = 11.86$ years)

N-Body Problem

Apart from Sun, motion of planets also influenced by forces between planets:

Total equation of motion for the i-th object:

$$m_i \ddot{\mathbf{r}}_i = -\sum_{k=1}^{N} \frac{G m_i m_k}{r_{i,k}^2} \frac{\mathbf{r}_i - \mathbf{r}_k}{r_{i,k}} \tag{2.20}$$

$\Longrightarrow$ 3N differential equations of 2nd order, requiring 6N integrations for their solution.

Closed solution only possible for 10 of these (6: from motion of center of mass, 3: conservation of angular momentum, 1: conservation of energy).

Analytic solution: "Perturbation theory":

1. Assume two body motion around Sun for all planets
2. Evaluate force based on this motion.
3. Update positions with this "perturbation".
4. Iterate (i.e., goto step 2)

N-Body Problem

Perturbation theory yields two kinds of perturbations:

periodic perturbations: Terms containing time in sin- and cos-functions.

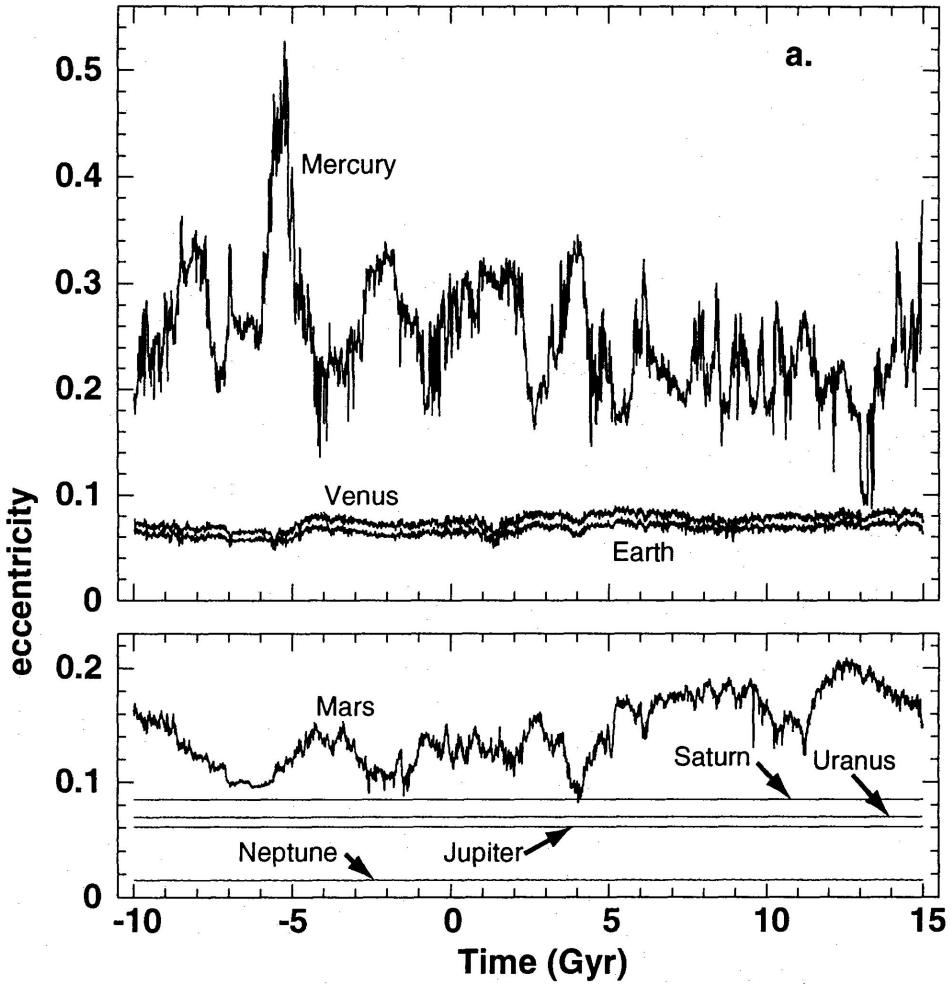
secular perturbations: Long term changes which depend on time (usually as a polynomial).

Analytical approach is very important for understanding the underlying physics, but mathematically *very* tedious. Series do not converge on long timescales (1000's of years).

$\Longrightarrow$ New high precision calculations are all based on numerical simulations, i.e., direct solution of equation of motion on computers.

Today's standard: DE102, DE405, DE414 from Jet Propulsion Laboratory, Pasadena, and INPOP06 from Laskar et al., IMCCE, Observatoire de Paris.

Long-Term Evolution of the Solar System



Laskar, J., 1989, Nature 338, 237, Laskar, J. 1990, Icarus 88, 266, Laskar, J. 1994, A&A 287, L9

Numerical simulations: obtain information about behavior of solar system for timescales of a few 10^7 years around the present $\Longrightarrow$ important, e.g., for paleoclimatology.

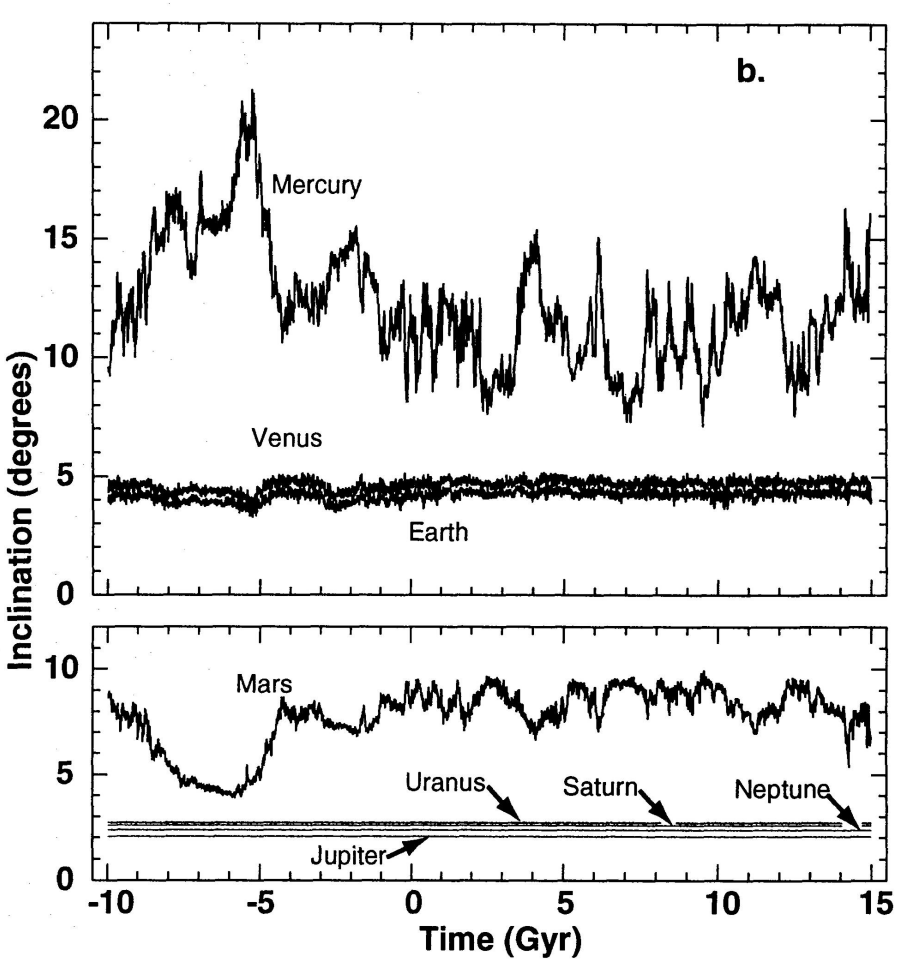
Laskar (1989, 1990): Motion of inner planets is chaotic.

"Chaotic": Initial errors get amplified exponentially, here by factor of 10 on time scales of ~10 million years.

Important, e.g., for climate variations on Earth ("Milankovitch cycles").

Also found with different methods by Wisdom and Suskind.

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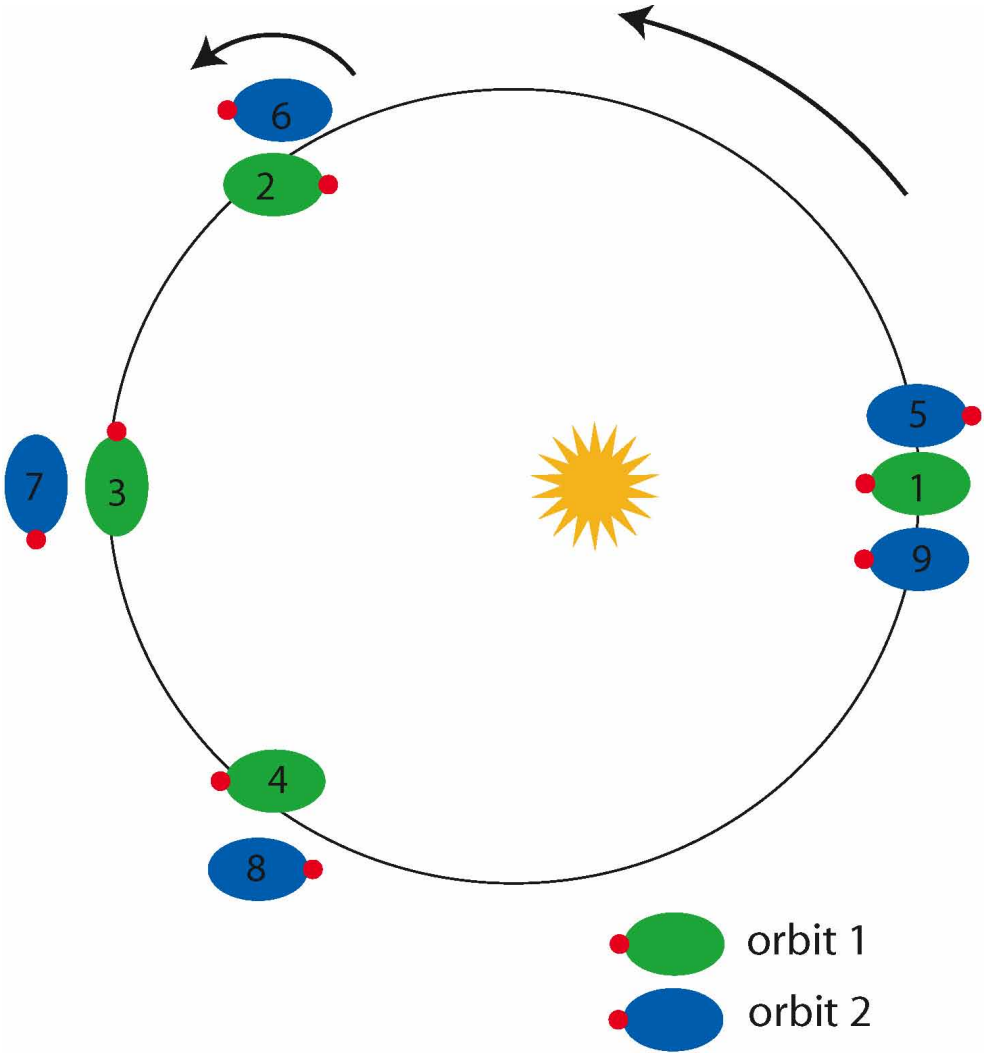
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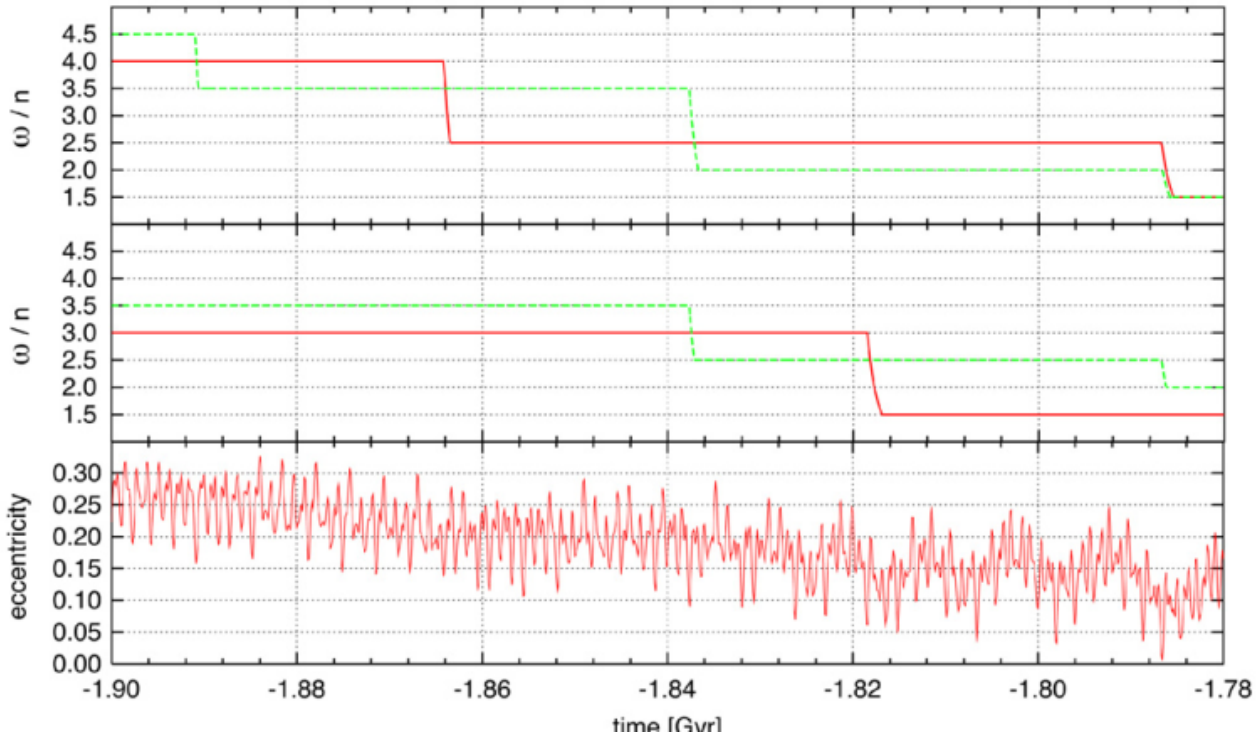
Long-Term Evolution of the Solar System



(courtesy J. Laskar/CNRS)

Rotation period and orbital period of Mercury are in a 3:2 resonance.

Long-Term Evolution of the Solar System

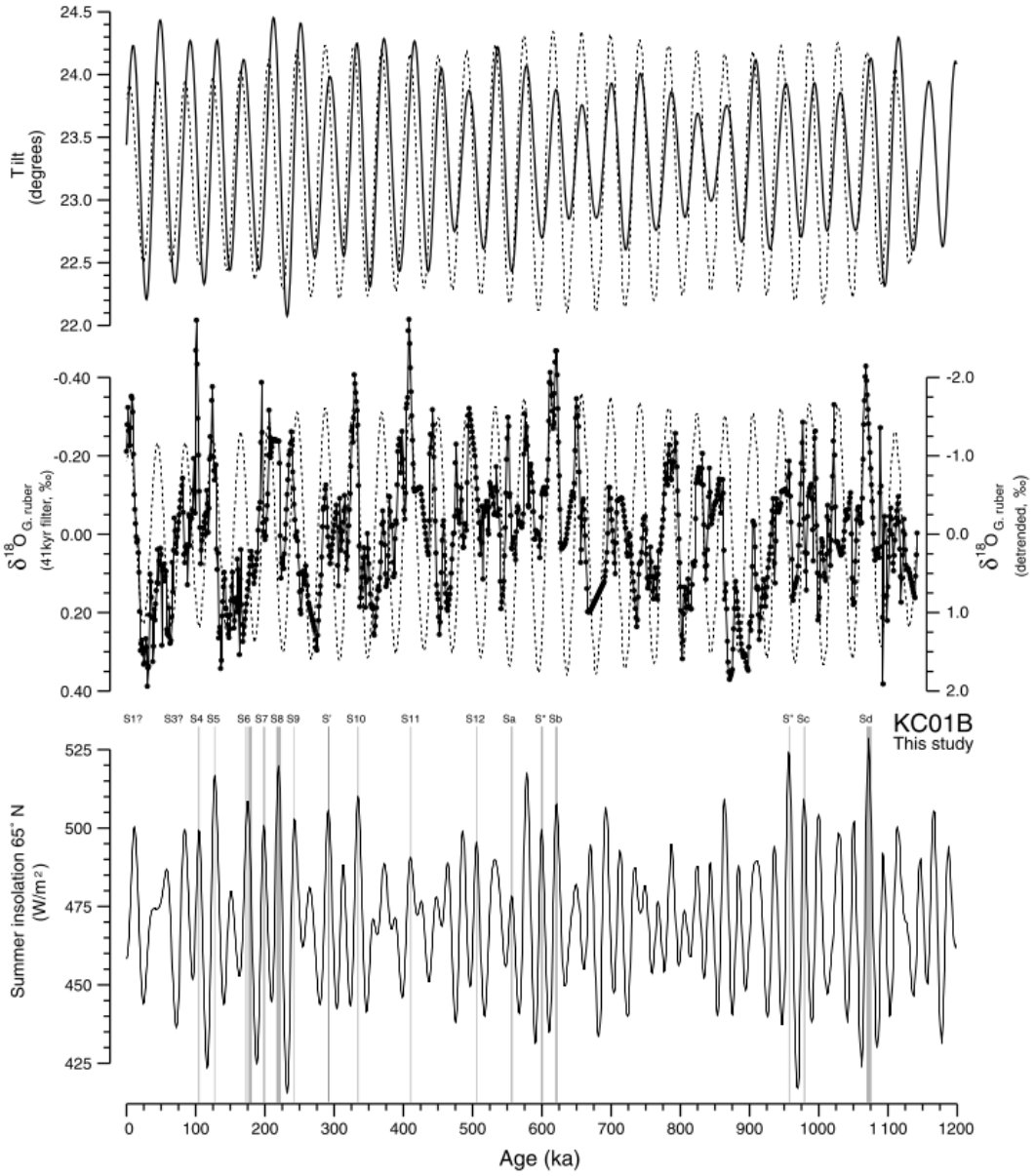


(Correia & Laskar, 2009, four different realizations of the long-term evolution)

Chaotic motion of Mercury's orbit increases probability of capturing Mercury in a resonance: 5:2 (22%), 2:1 (32%) or 3:2 (26%) via tidal dissipation.

Similar explanation also for retrograde rotation of Venus, Earth is saved from such a behavior because of the stabilizing influence of the Moon.

Paleoclimatology



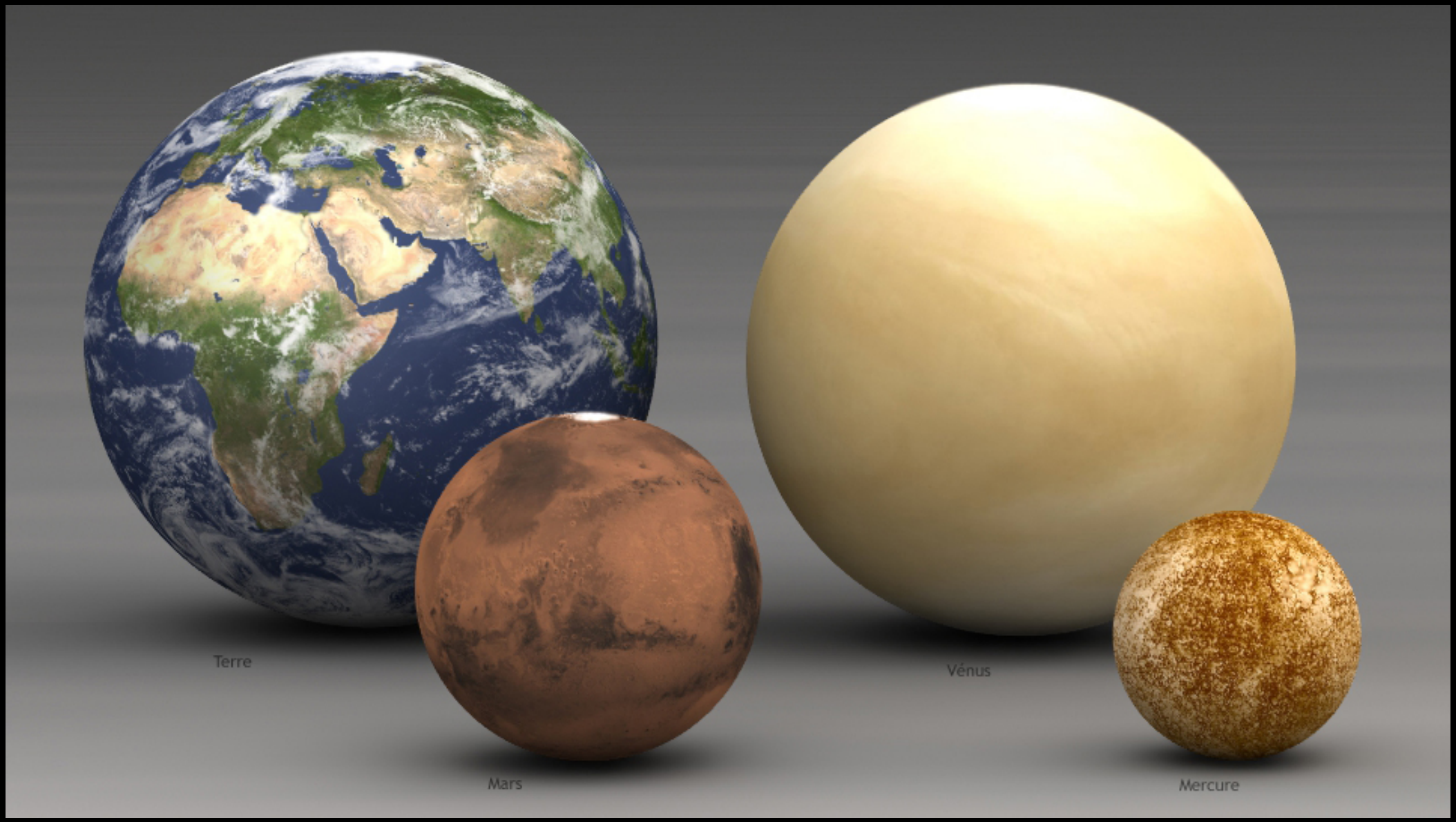
Simulations give inclination of Earth's axis: important quantity for insolation $\Longrightarrow$ paleoclimatology

Correllation between predicted insolation from astronomical models and measured sea surface temperature (correlates to δ^{18}O-value [related to relative abundance of ^{16}O and ^{18}O]).

(Lourens, 2004)

Correia, A. C. M., & Laskar, J. 2009, Icarus, 201, 1
Laskar, J., 1989, Nature, 338, 237
Laskar, J., 1990, Icarus, 88, 266
Lourens, L. J., 2004, Paleoceanography, 19, PA3010

The Planets: Special Topics



http://www.lesud.com/lesud-astronomy_pageid81.html

The Not-Planets

Many large round worlds are not currently classified as planets: the solar system's major moons, the largest asteroids, and large Kuiper belt objects. These are the ones spacecraft have visited.

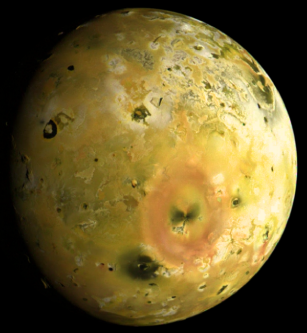
Images from Galileo (Jupiter's moons), Cassini (Saturn's moons), Voyager 2 (Uranus and Neptune's moons). New Horizons (Pluto), Dawn (asteroids). Data from NASA/JPL/JHUAPL/SwRI/UCLA/MPS/DLR/IDA processed by Ted Stryk, Gordan Ugarkovic, Emily Lakdawalla, and Jason Perry. Earth's Moon photo by Gari Arrillaga. Montage by Emily Lakdawalla, The Planetary Society, blog@planetary.org.

Earth's Moon:

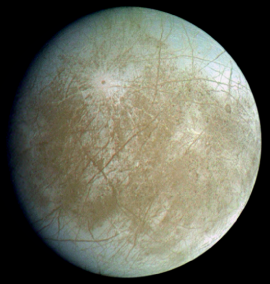


The Moon

Jupiter satellites:



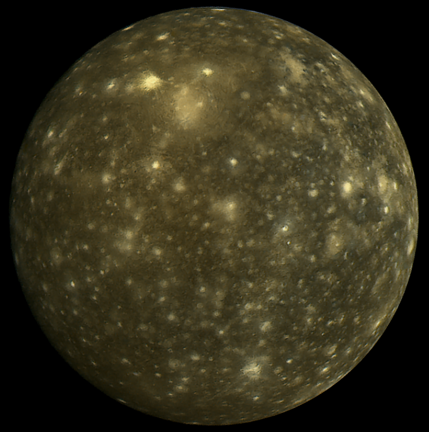
Io



Europa



Ganymede



Callisto

Saturn satellites:



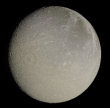
Mimas



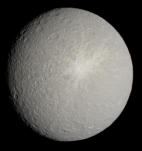
Enceladus



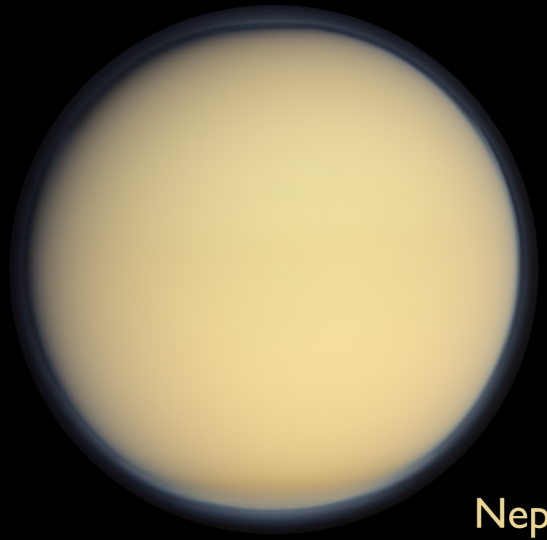
Tethys



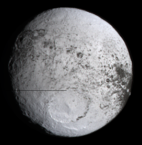
Dione



Rhea

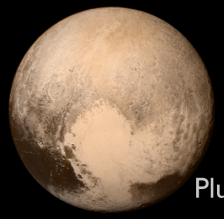


Titan

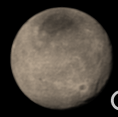


Iapetus

Pluto system:



Pluto



Charon

Asteroids:



Vesta



Ceres

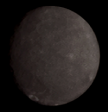
Uranus satellites:



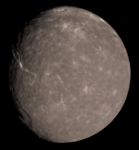
Miranda



Ariel



Umbriel



Titania



Oberon

Neptune satellites:



Triton

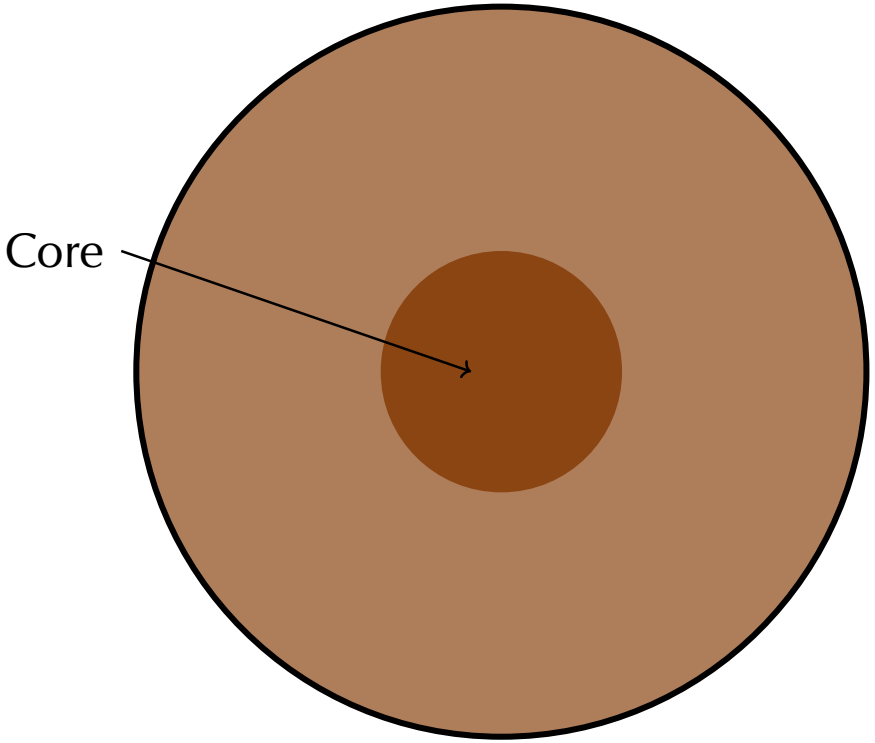


Proteus

CC BY NC SA

THE PLANETARY SOCIETY

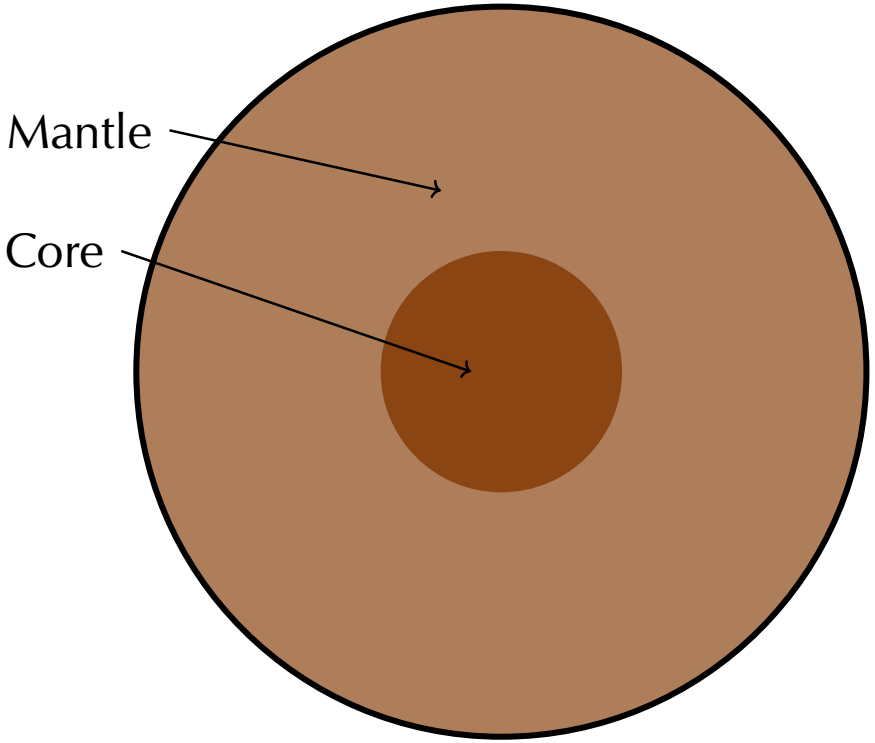
Terrestrial Planets: Structure



Structure of terrestrial planets:

- Core: high-density material (Fe)

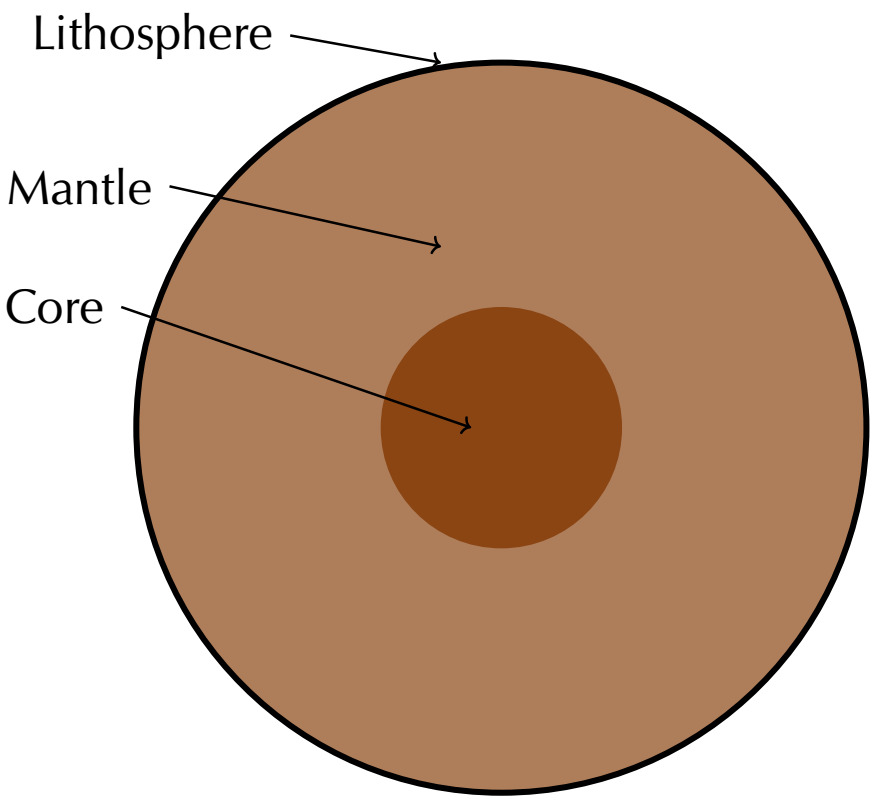
Terrestrial Planets: Structure



Structure of terrestrial planets:

- Core: high-density material (Fe)
- Mantle: plastic materials, hot (e.g., Earth: molten rocks)

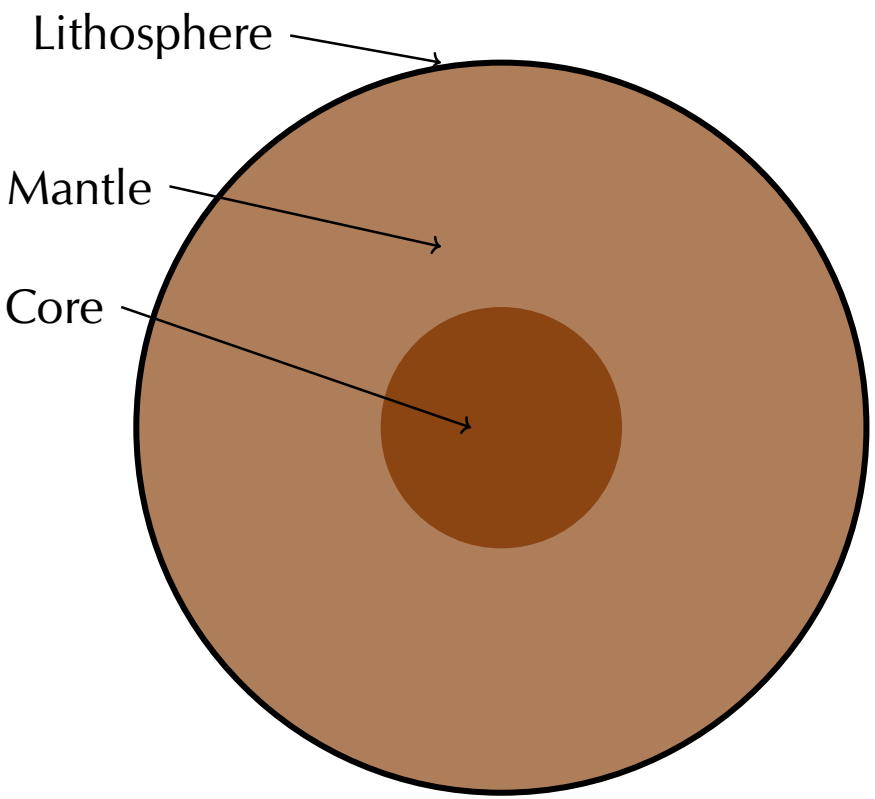
Terrestrial Planets: Structure



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- Lithosphere: rigid material, e.g., Silicates

Terrestrial Planets: Structure

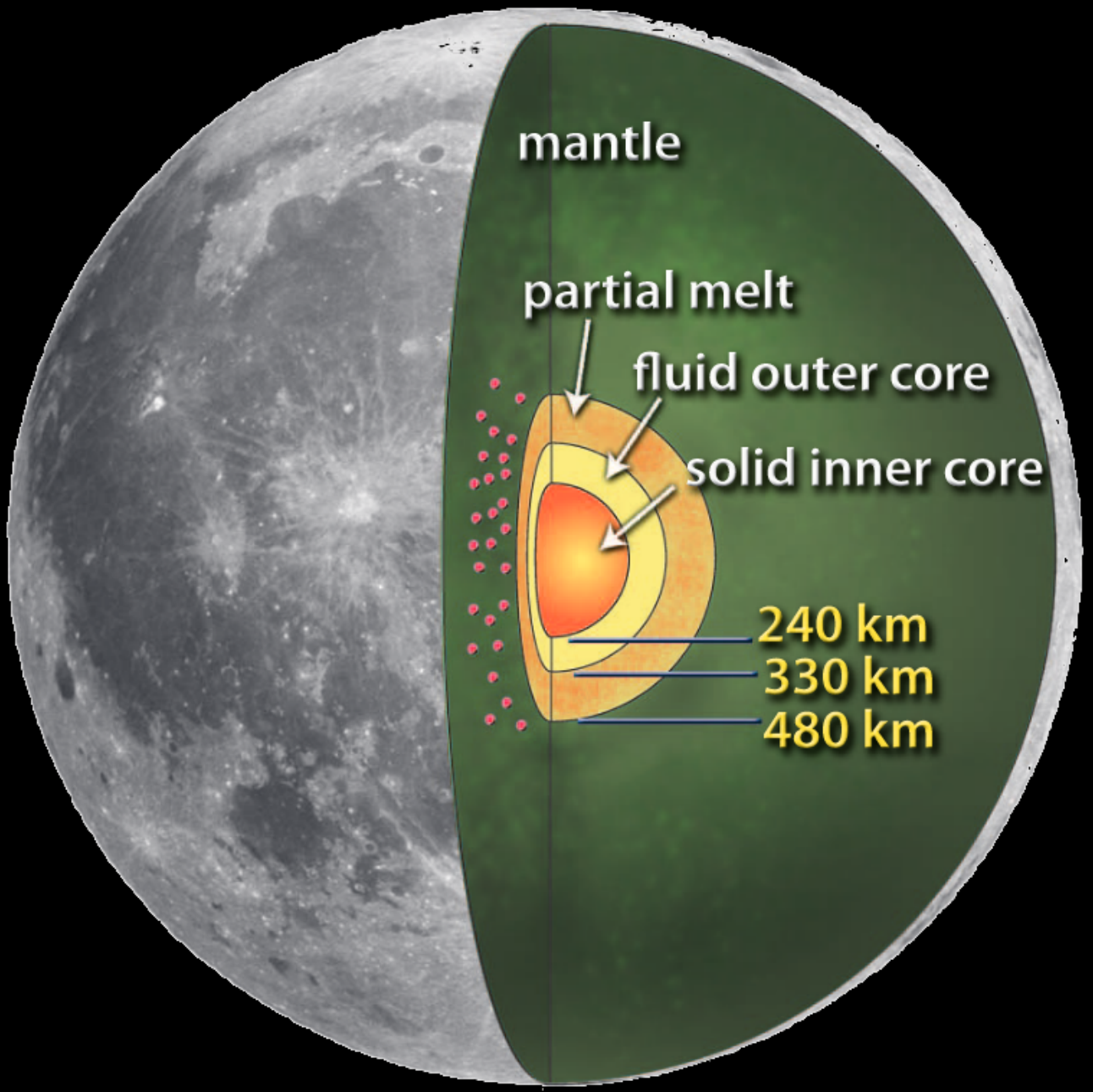


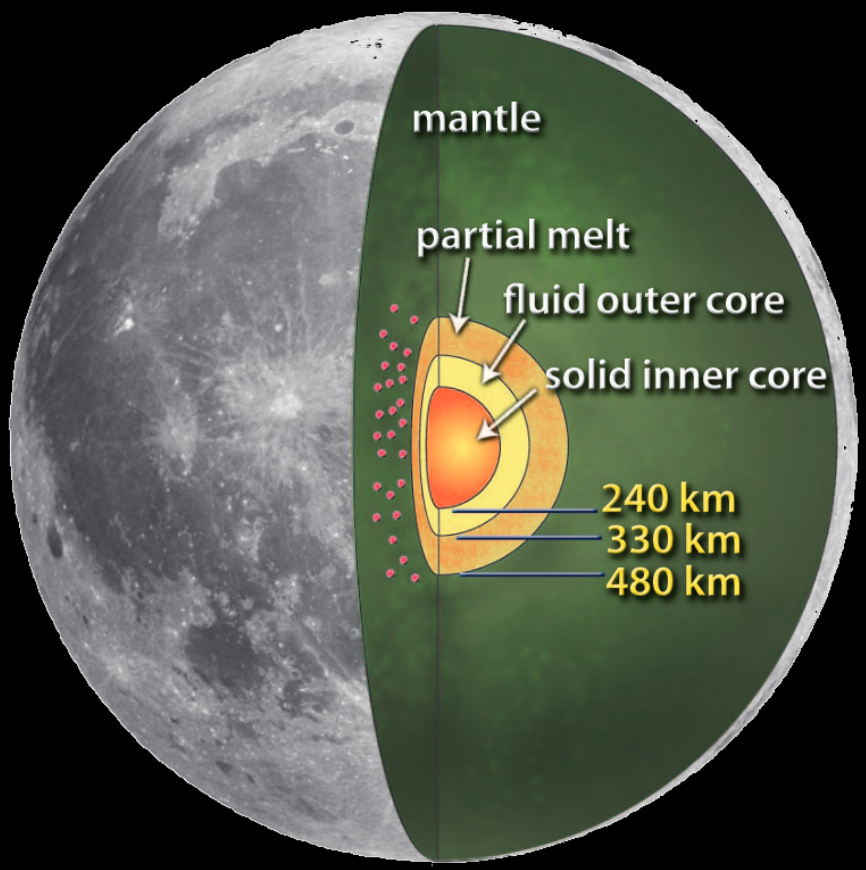
Structure of terrestrial planets:

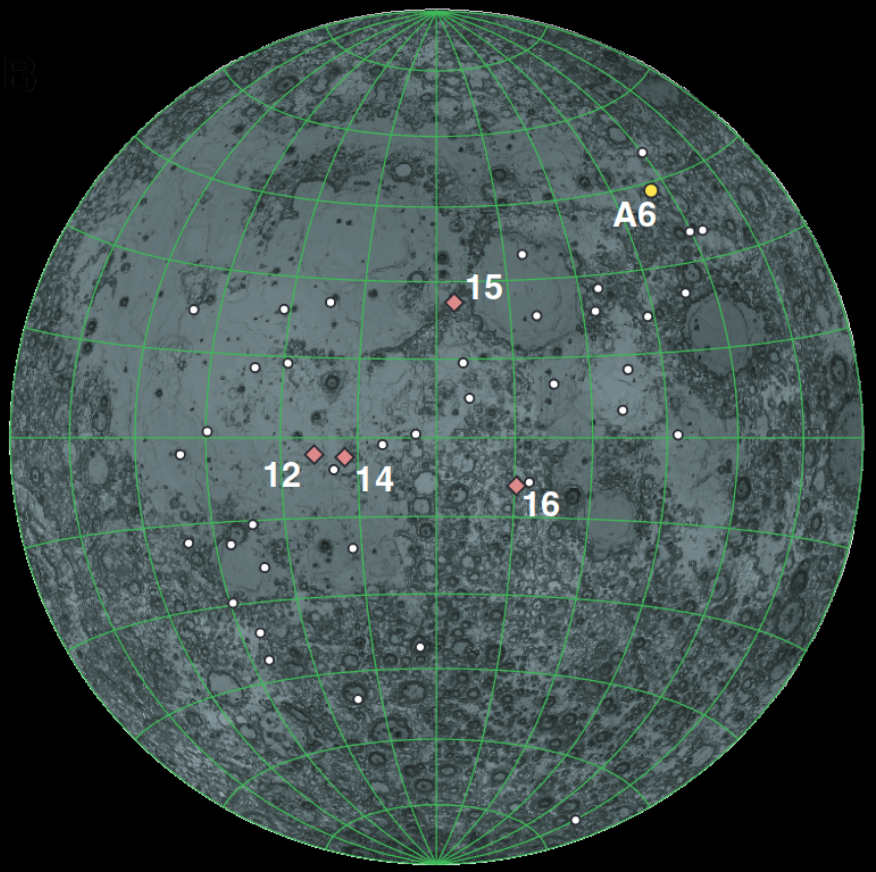
- Core: high-density material (Fe)
- Mantle: plastic materials, hot (e.g., Earth: molten rocks)
- Lithosphere: rigid material, e.g., Silicates

Knowledge of structure important for, e.g.,

- atmospheric composition (molten mantle $\Longrightarrow$ volcanism $\Longrightarrow$ CO_2, CH_4,...)
- origin of magnetic fields (thought to be caused by molten core $\Longrightarrow$ currents $\Longrightarrow$ B-field ["dynamo"]. Details unknown).


mantle
partial melt
fluid outer core
solid inner core
240 km
330 km
480 km

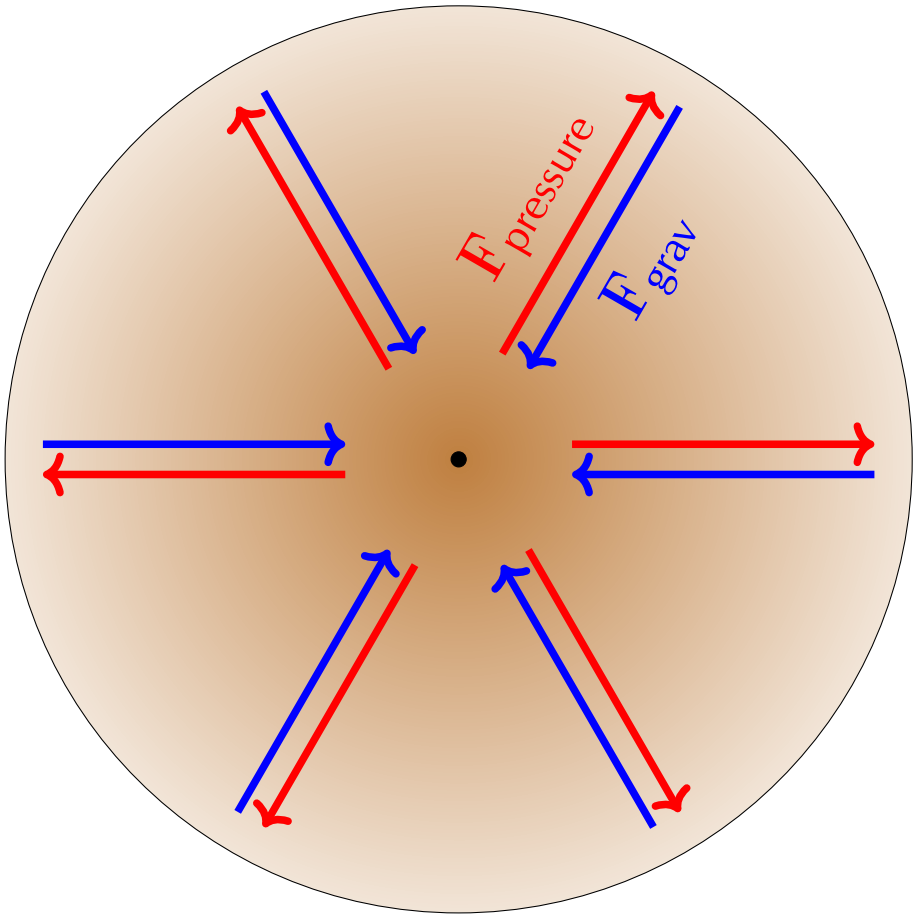




Structure of the Moon:

- gravimetric measurements
- seismometry from Apollo 12, 14, 15 & 16: mild moonquakes from 800–1000 km depth; generated by tidal forces?
- center of mass off-set by 2 km from center of sphere
- crust much thicker on the far side (100 km) than on the near side (60 km)
- small iron core (Weber et al., 2011)

Hydrostatic Equilibrium



Planets are round: Structure of planet defined by self-gravitation: plastic (deformable) material in hydrostatic equilibrium.

Gravitational force pulling planet inwards equals pressure force pushing outwards:

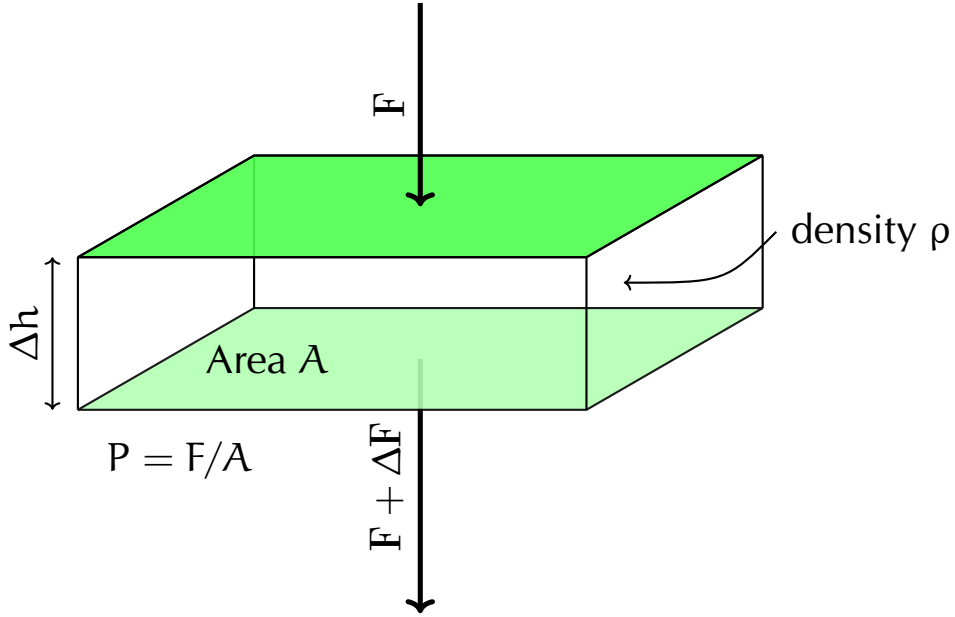
$$\mathbf{F}_{\text{grav}} = -\mathbf{F}_{\text{pressure}} \qquad (3.1)$$

"hydro": since material is deformable; "static": since structure is not time variable

substructure of planet [e.g., lithosphere–mantle–core] due to changes in behavior of material and chemical composition

Hydrostatic Equilibrium

Structure of planet defined through hydrostatic equilibrium:



Gravitational force on an area A contributed by a block of area A and height Δh:

$$\Delta F = mg = \rho V g = A\rho g \Delta h \tag{3.2}$$

where g: gravitational acceleration.

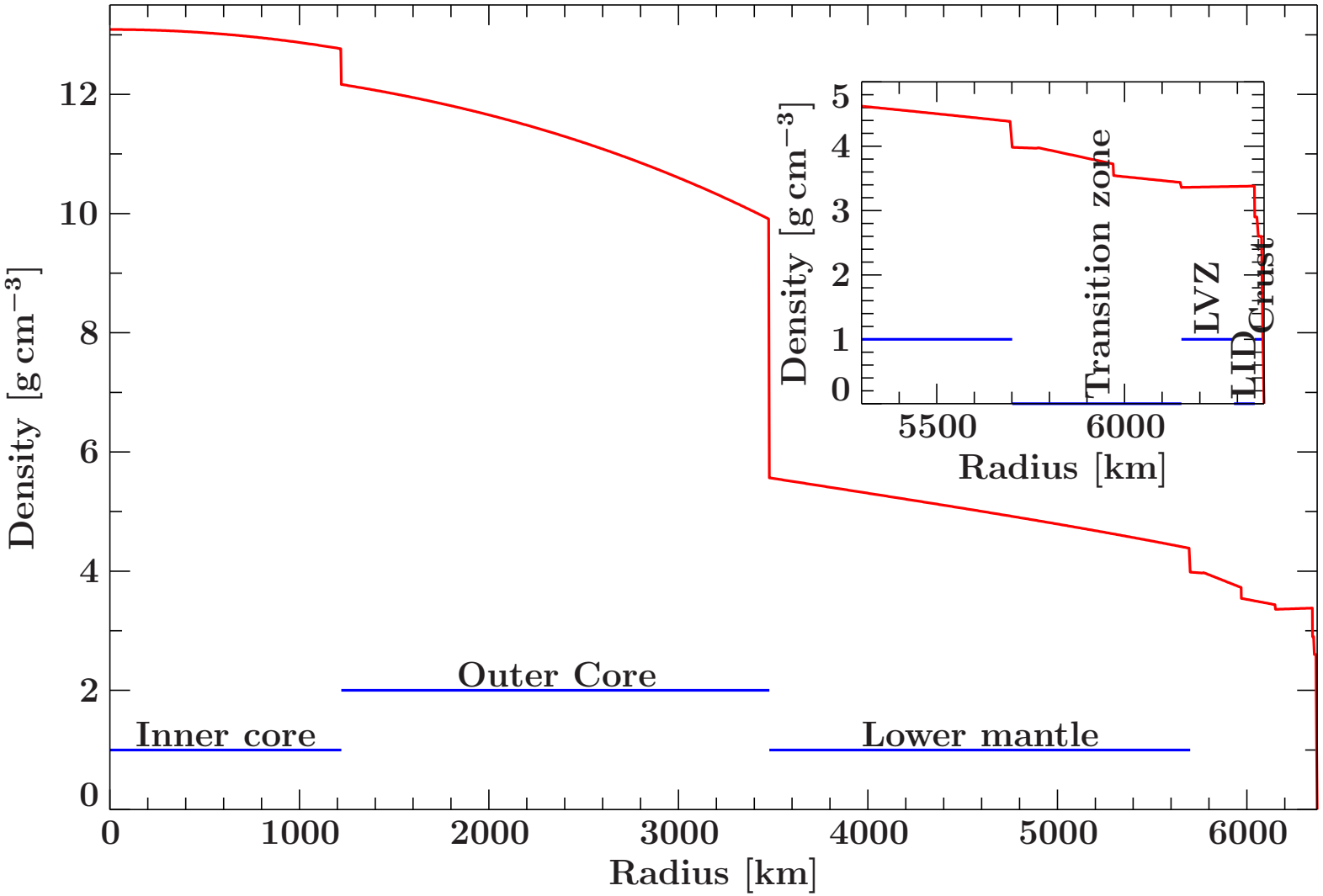
But $P = F/A \Longrightarrow$ change in pressure with height:

$$\frac{\Delta P}{\Delta h} = -\rho g \quad \Longrightarrow \quad \lim \Delta h \longrightarrow 0 \quad \Longrightarrow \quad \frac{dP}{dh} = -\rho g \tag{3.3}$$

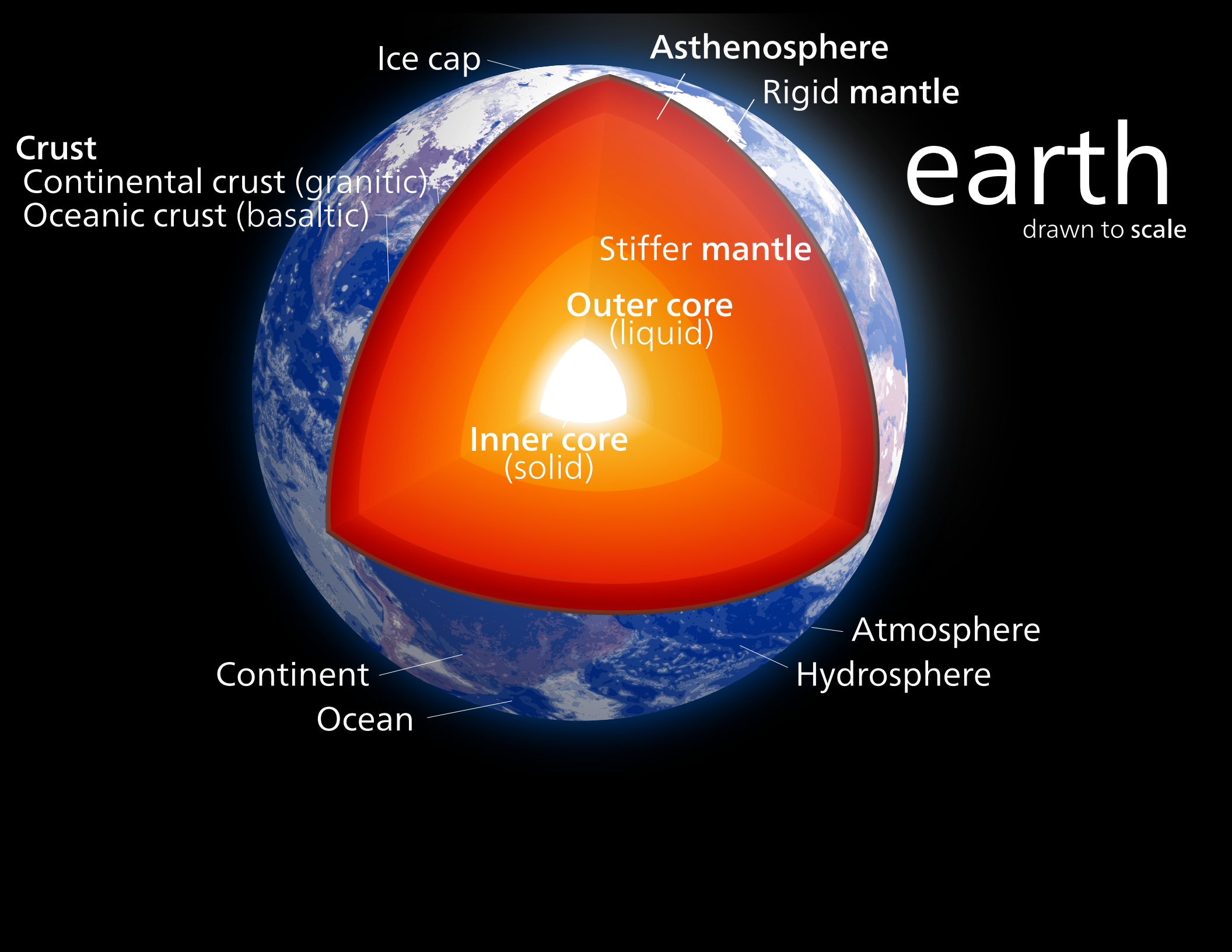
where ρ and g: functions of h

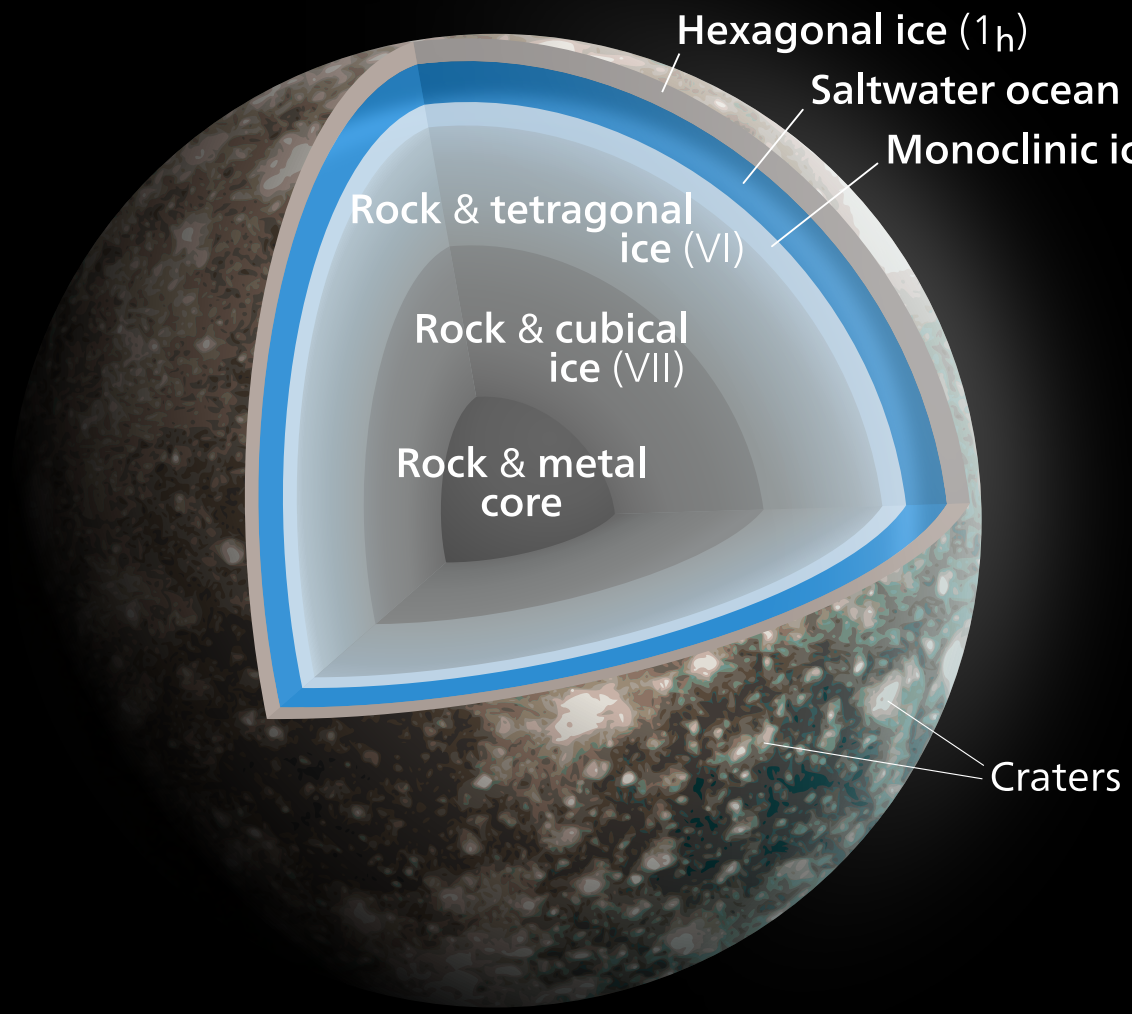
solution of differential equation requires knowledge of material properties, e.g., iron oxides at high temperature and pressure, as this determines $\rho(h)$ *and* $g(h)$

Hydrostatic Equilibrium



density in Earth after the PREM model (based on seismology; Dziewonski & Anderson, 1981, Phys. Earth Plan. Interiors 25, 297)


Ice cap
Asthenosphere
Rigid mantle
Crust
Continental crust (granitic)
Oceanic crust (basaltic)
earth
drawn to scale
Stiffer mantle
Outer core
(liquid)
Inner core
(solid)
Atmosphere
Hydrosphere
Continent
Ocean



Callisto

SATMOD monoclinic ice model
layers drawn **to scale**



Structure of Jupiter's Galilean Moons similar to terrestrial planets

(but some also have very thick ice layer on top)

Distant Horizons - Different Surfaces

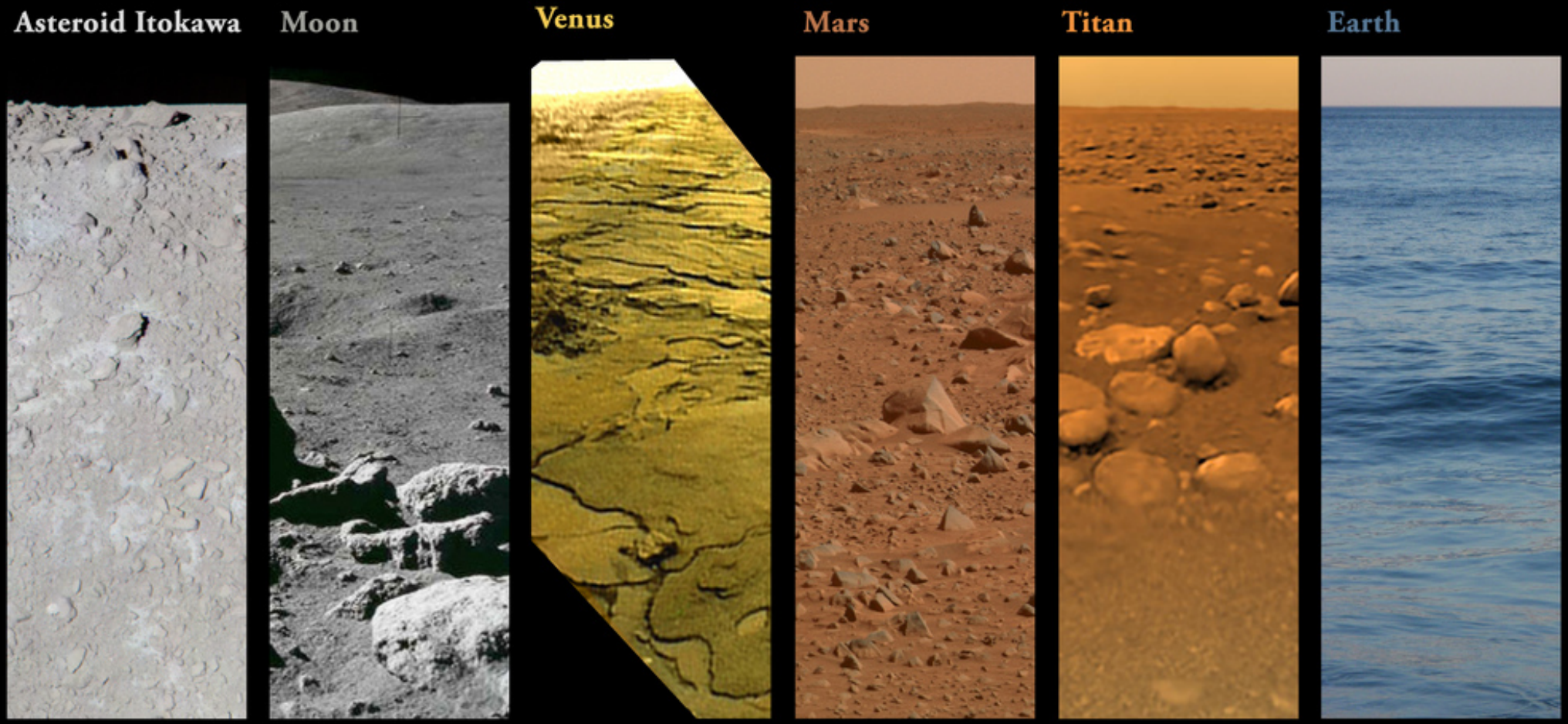
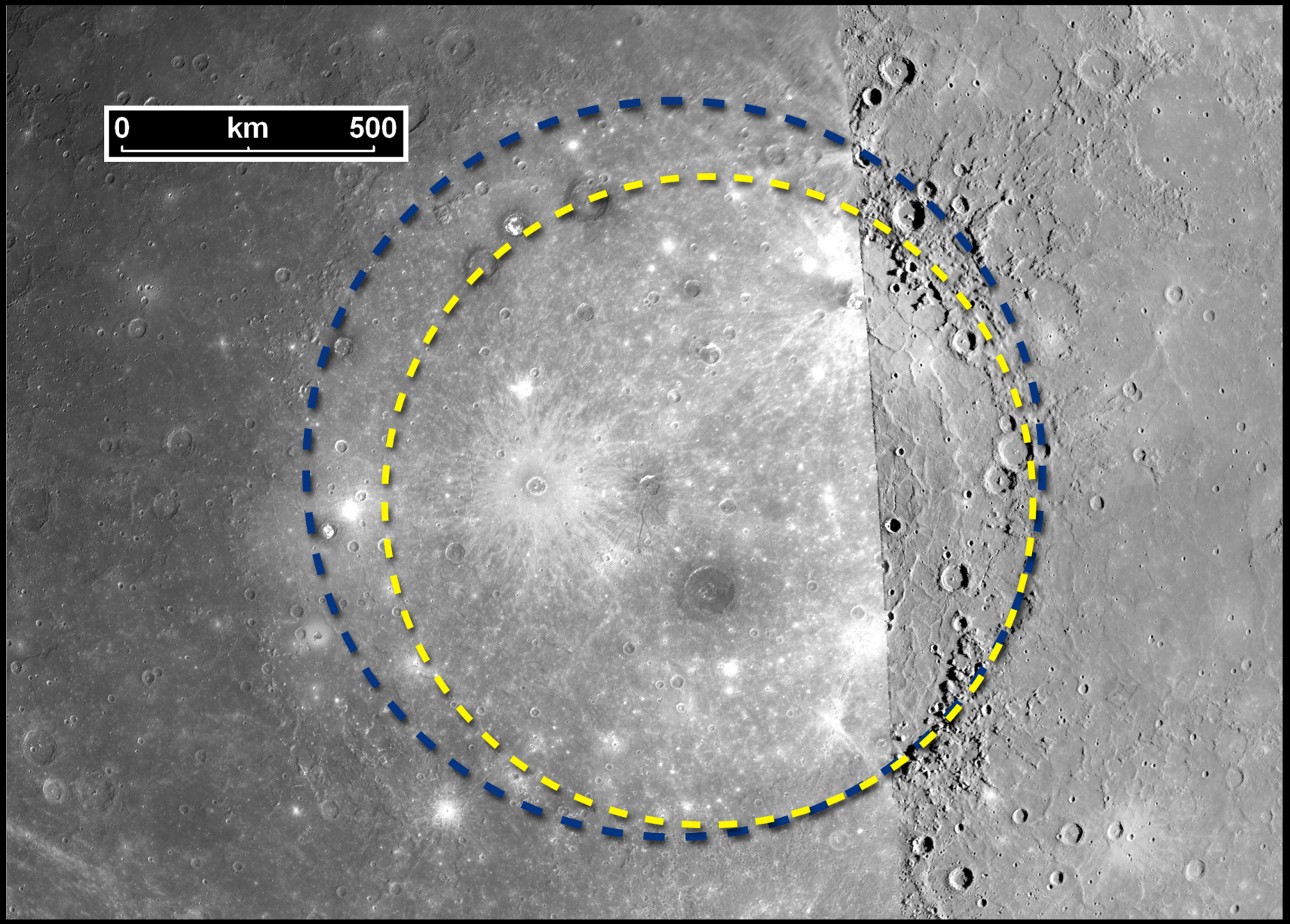


Image Credits:
Asteroid Itokawa [Hayabusa]: ISAS / JAXA / Gordan Ugarkovic
Moon [Apollo 17]: NASA
Venus [Venera 14]: IKI / Don Mitchell / Ted Stryk / Mike Malaska
Mars [Mars Exploration Rover Spirit]: NASA / JPL / Cornell / Mike Malaska
Titan [Cassini Huygens]: ESA / NASA / JPL / University of Arizona
Earth: Mike Malaska

Composition by Mike Malaska



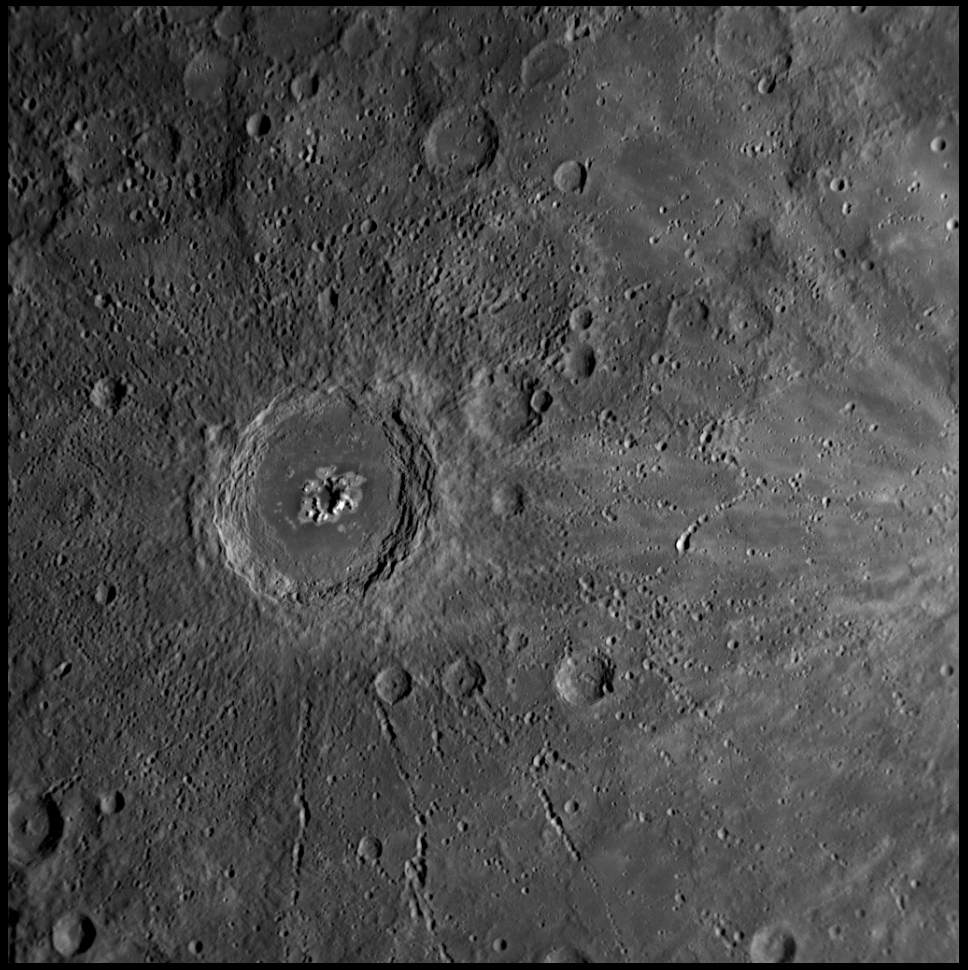
NASA/MESSENGER

Mercury: Caloris Basin (1300 km diameter)

close to sub-solar point at perihelion $\Longrightarrow$ hot! ($T > 400°C$ on day, $T \sim -170°C$ during night)

Basin: result of *large* impact event

Major landforms: Craters



NASA/MESSENGER

Terraced craters, with central mountains.



S-Pole; NASA/JPL (Mariner)

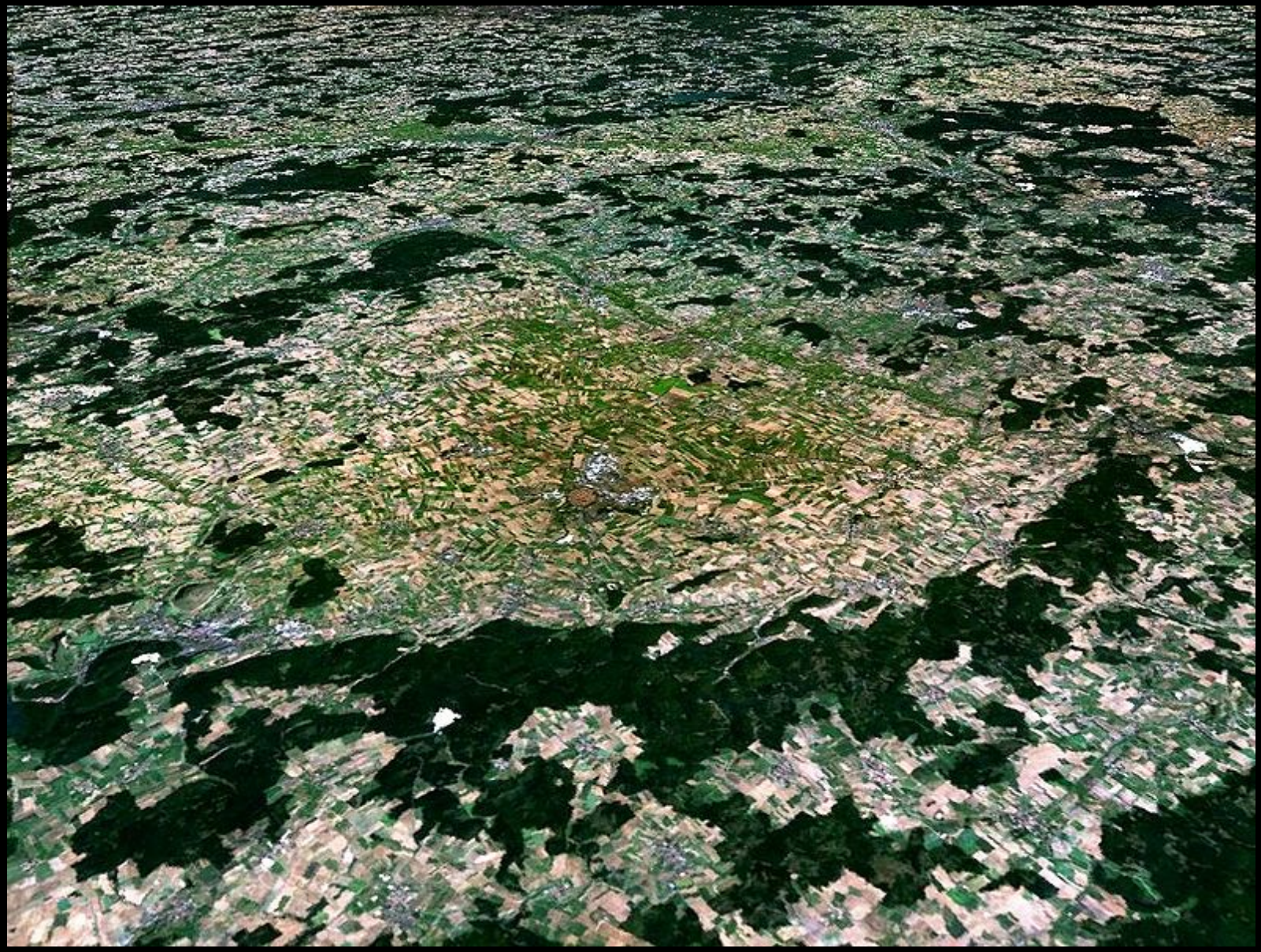
50 km diam craters with rays (remains from impact)



V. L. Sharpton

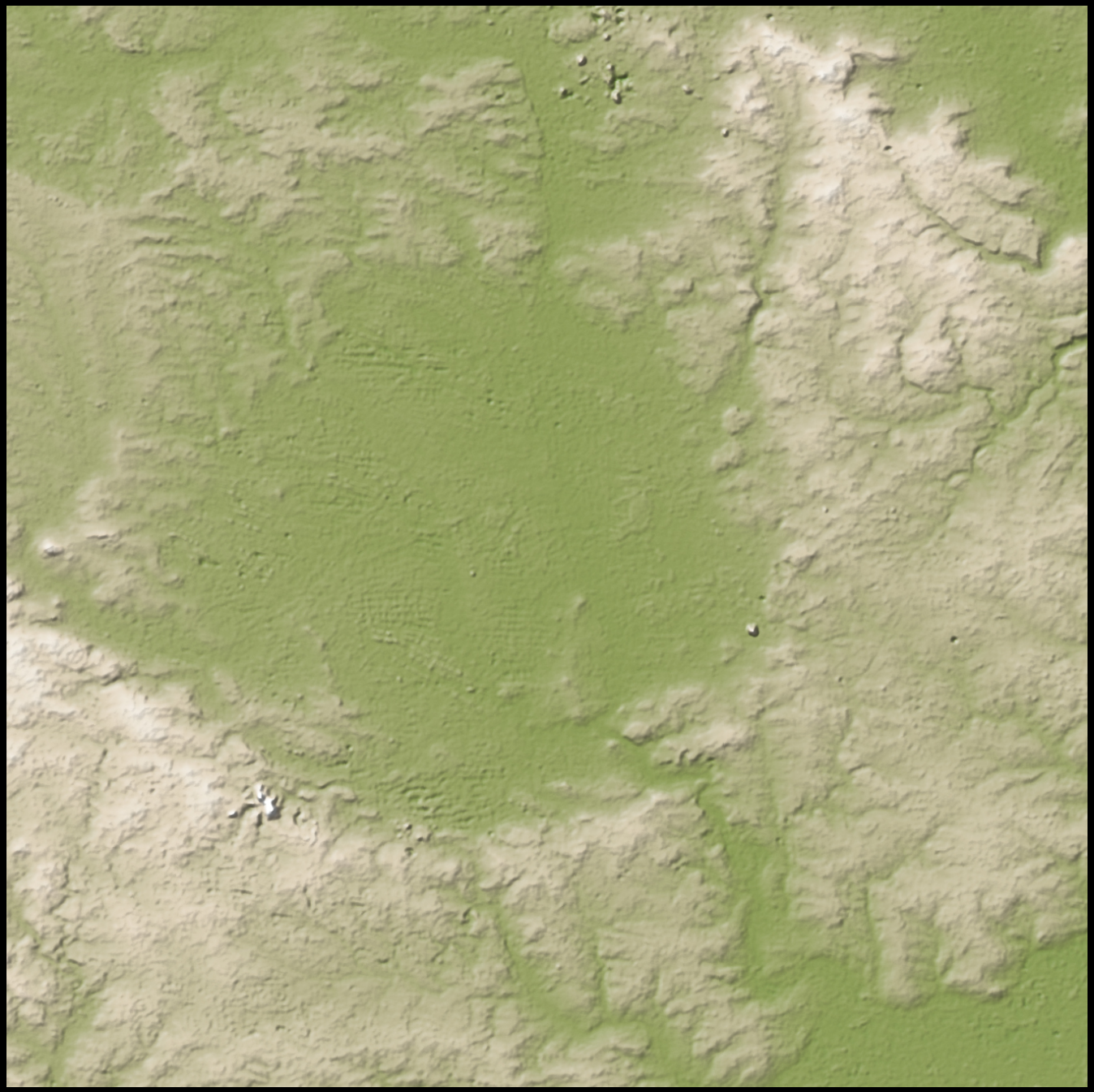
Earth: Wolf Creek Crater, Australia

Currently 180 confirmed impact structures on Earth



Earth: Nördlinger Ries

Impact crater identified by Shoemaker in 1960s



Earth: Elevation image Nördlinger Ries

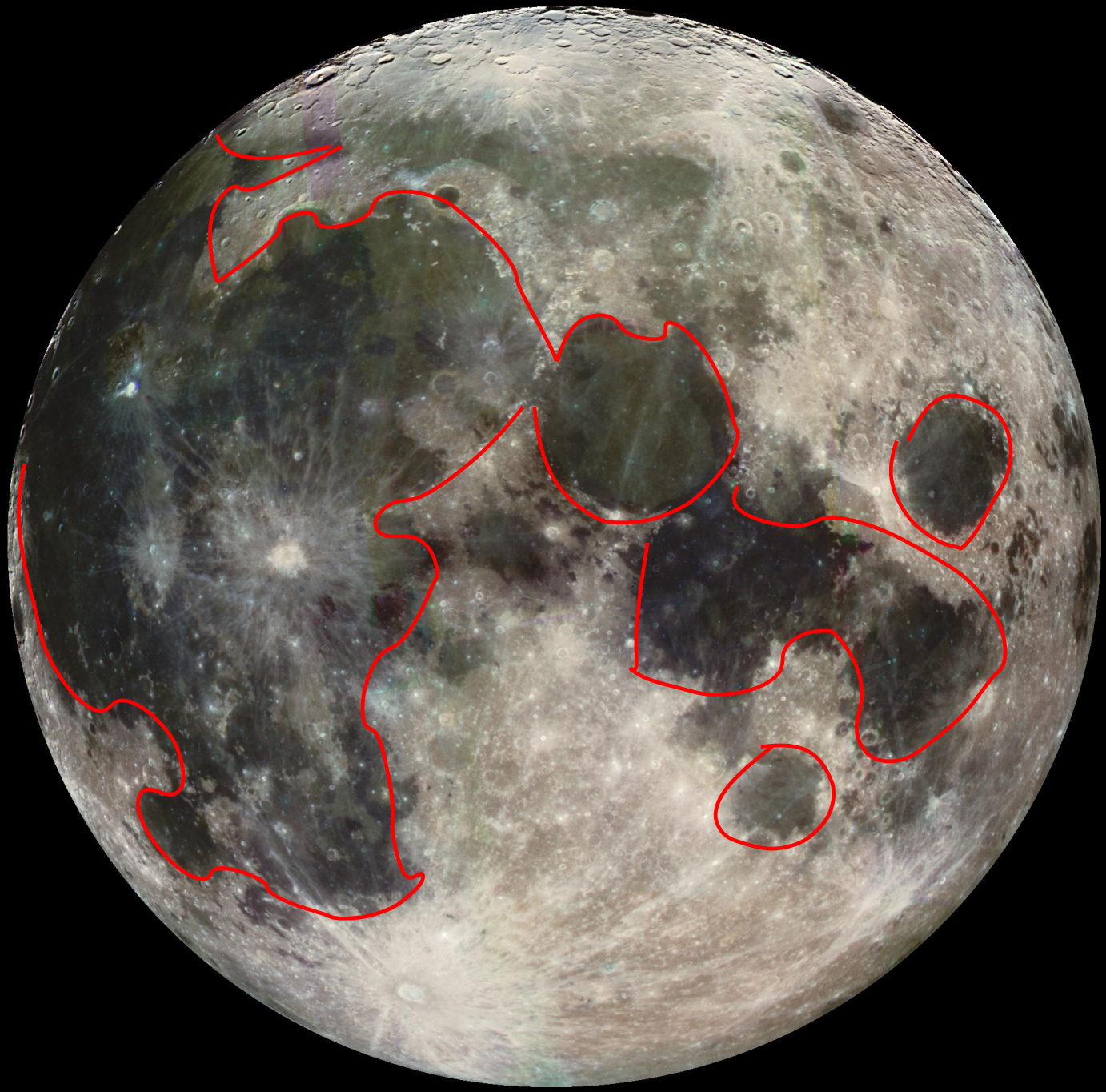
Thermal Emission and Reflection Radiometer on NASA Terra satellite, credit: NASA



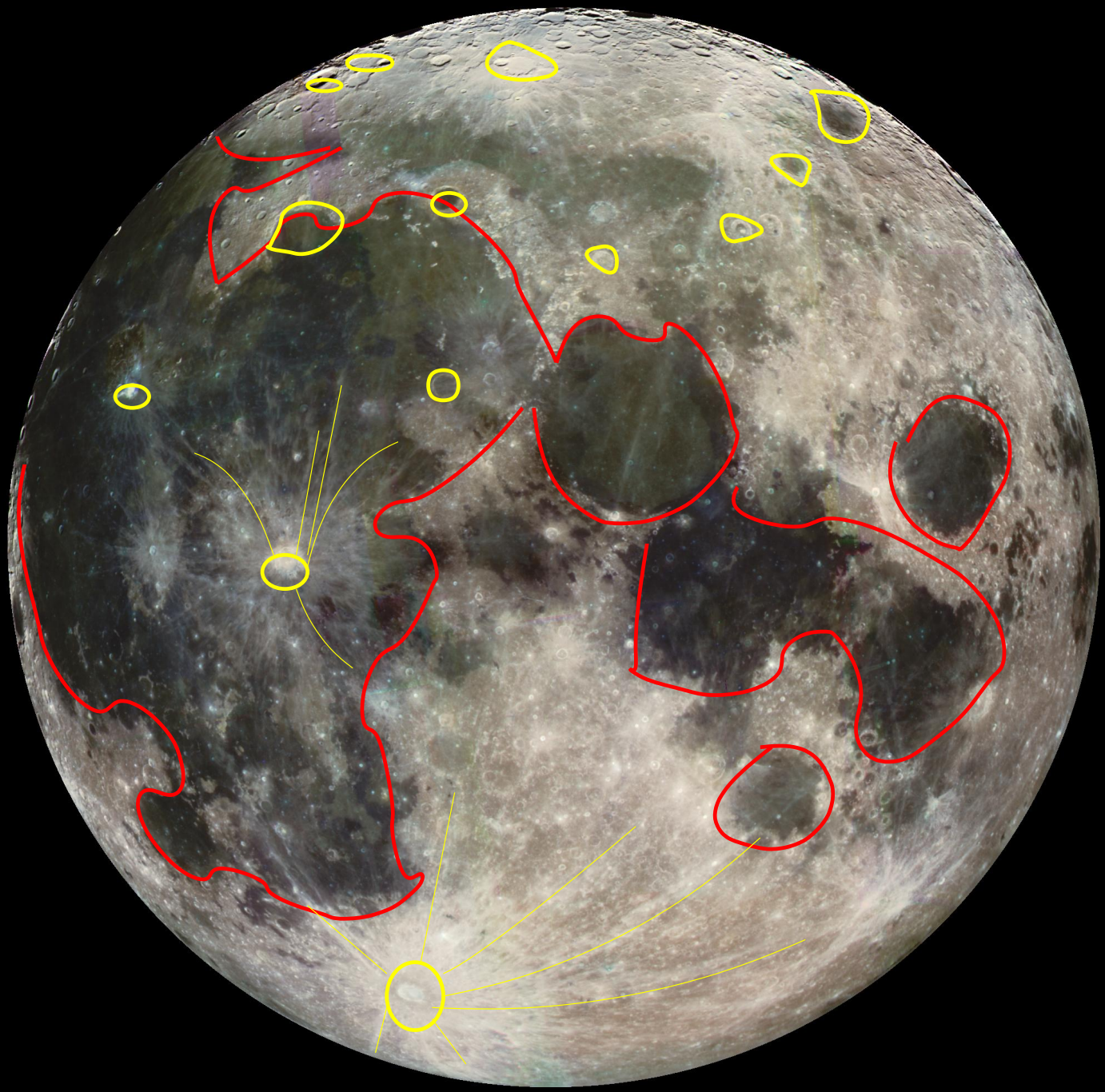
St. Lawrence river and Manicouagan crater, Canada, from ISS (NASA/Chris Hatfield)



Earth’s Moon



Earth's Moon : surface dominated by mariae (large, dark lava basins)



Earth's Moon : surface dominated by mariae (large, dark lava basins) and craters (only most prominent shown).



Moon: Crater Copernicus



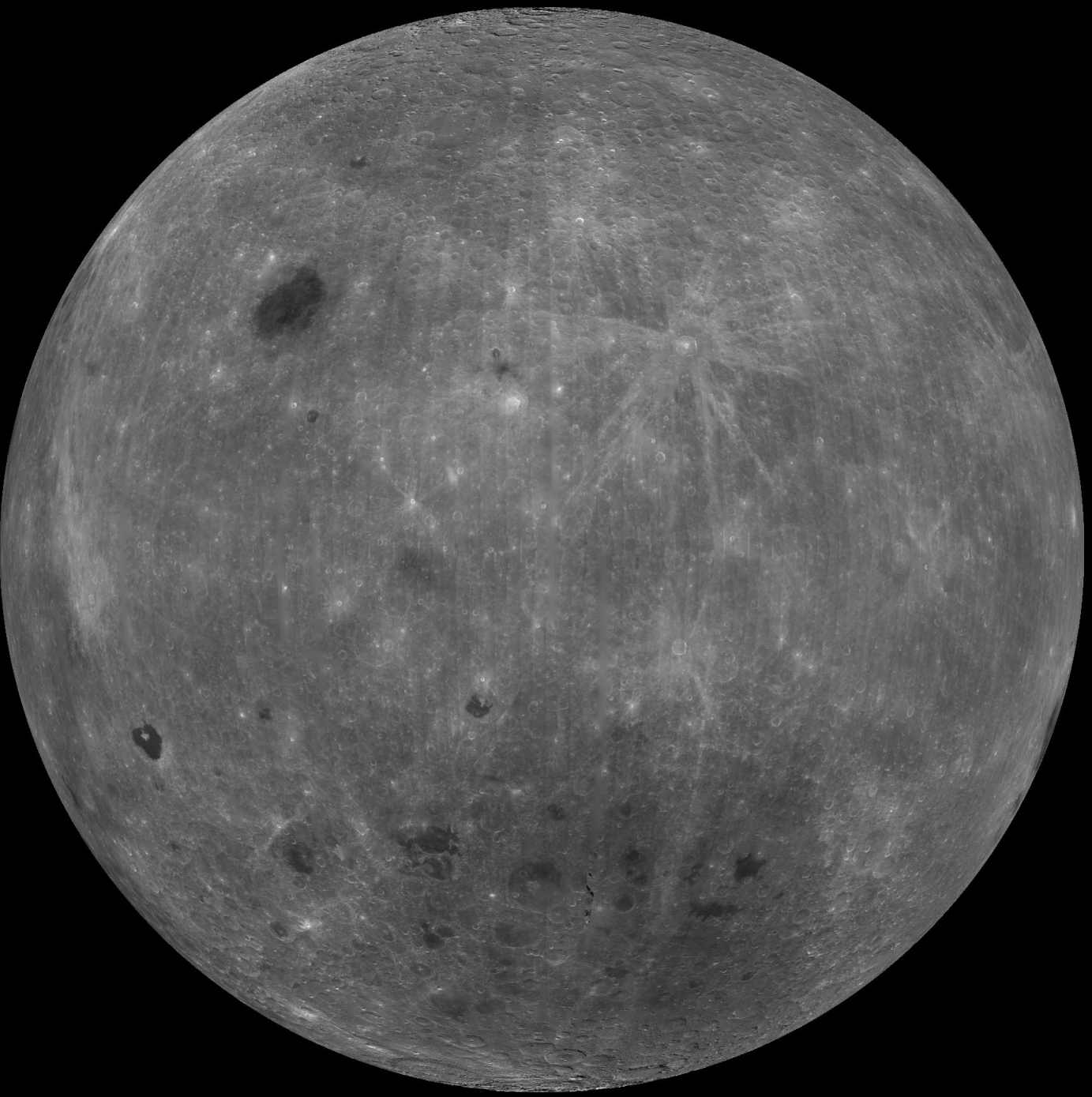
Moon: Apollo 16, 1972 Apr, Descartes Highlands



Apollo 16, 1972 Apr, C. Duke



Yutu Rover (China, 2014; Crater in Mare Imbrium)



Far side of the Moon:

- few maria
- stronger relief (16 km roughness, compared to 5–6 km on near side)
- Aitkin basin near South pole: 12 km deep

NASA/Clementine

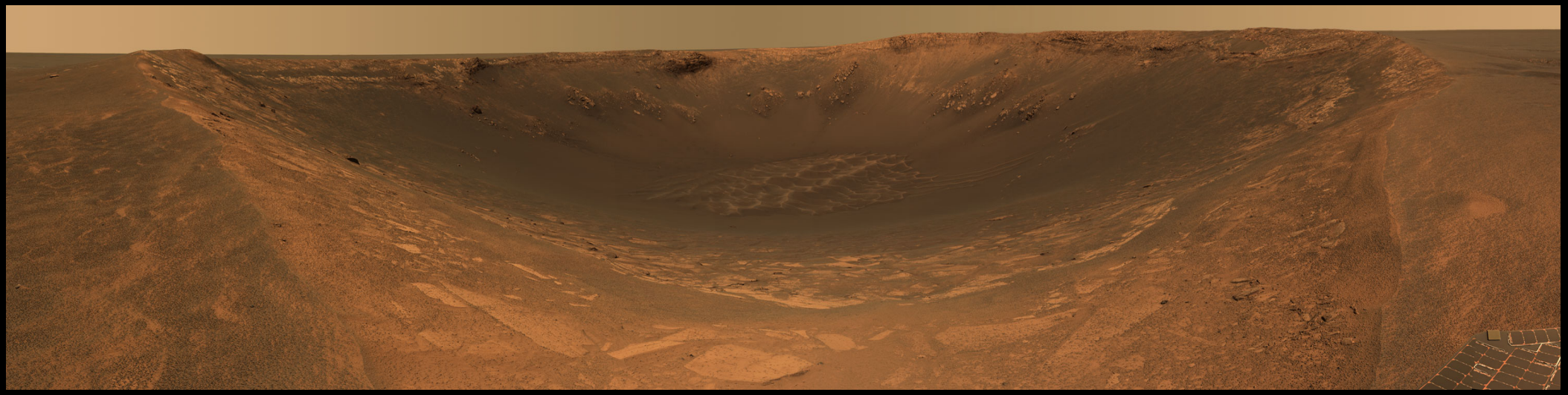


2008 May 25, Lander Phoenix on parachute in front of Crater Heimdall; NASA/JPL/University of Arizona

Mars' surface can also be studied *in situ*.



Mars: Surface panorama, Exploration Rover “Opportunity” looks back to lander (2004 Feb 09)



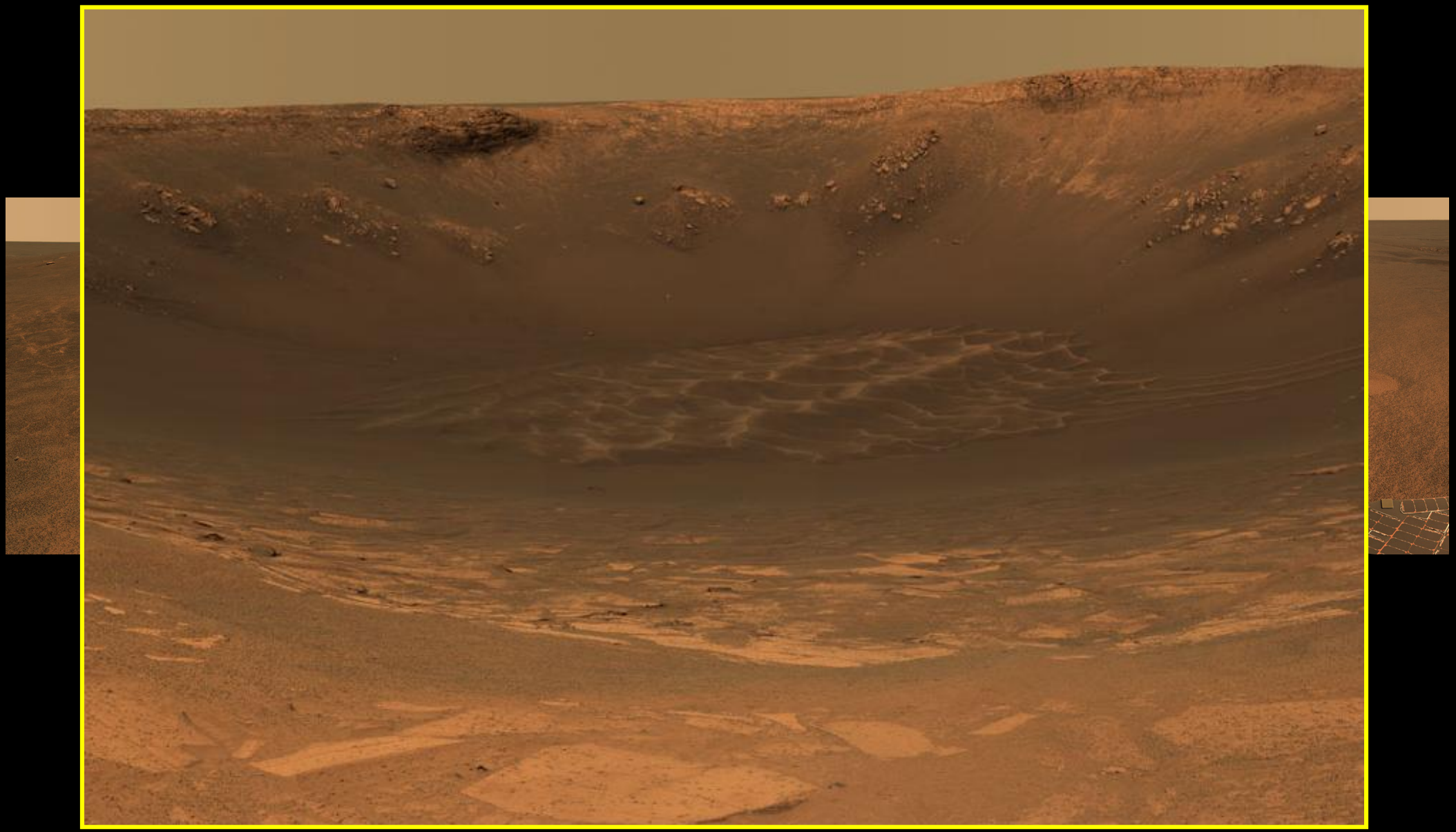
NASA/JPL/Cornell

Mars: Crater Endurance



NASA/JPL/Cornell

Mars: Crater Endurance

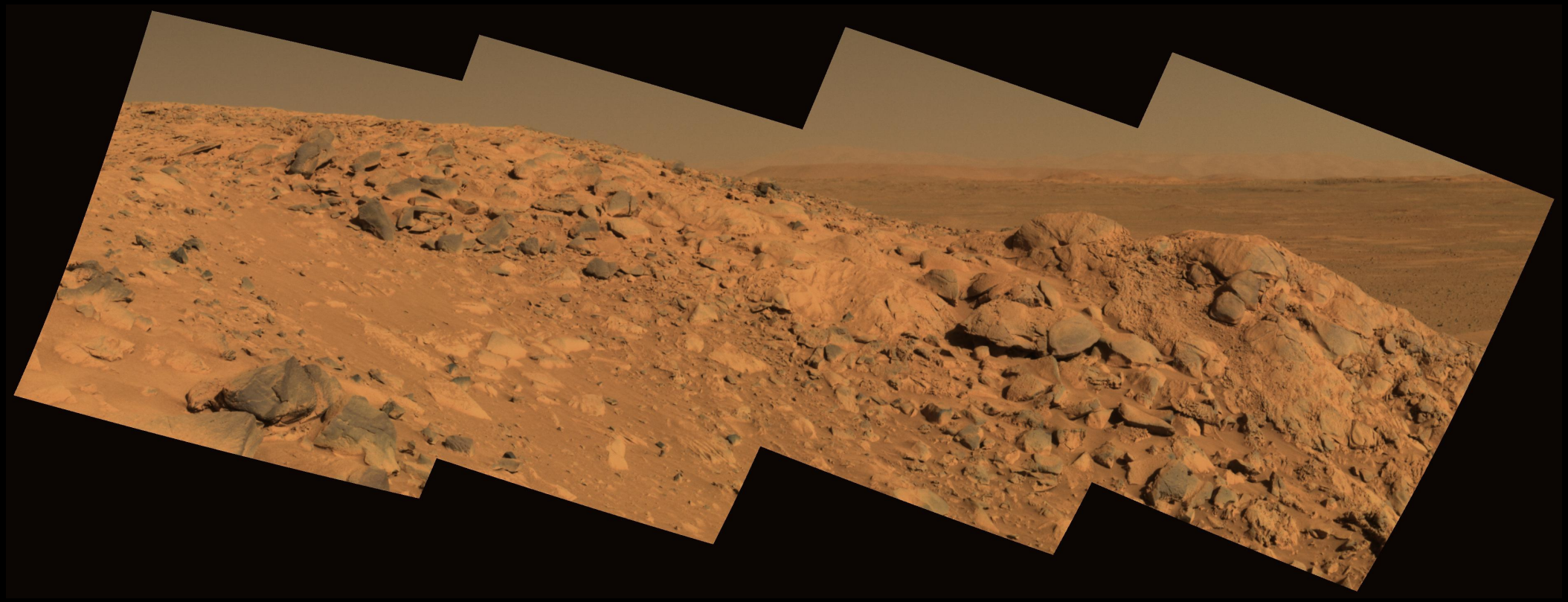


NASA/JPL/Cornell

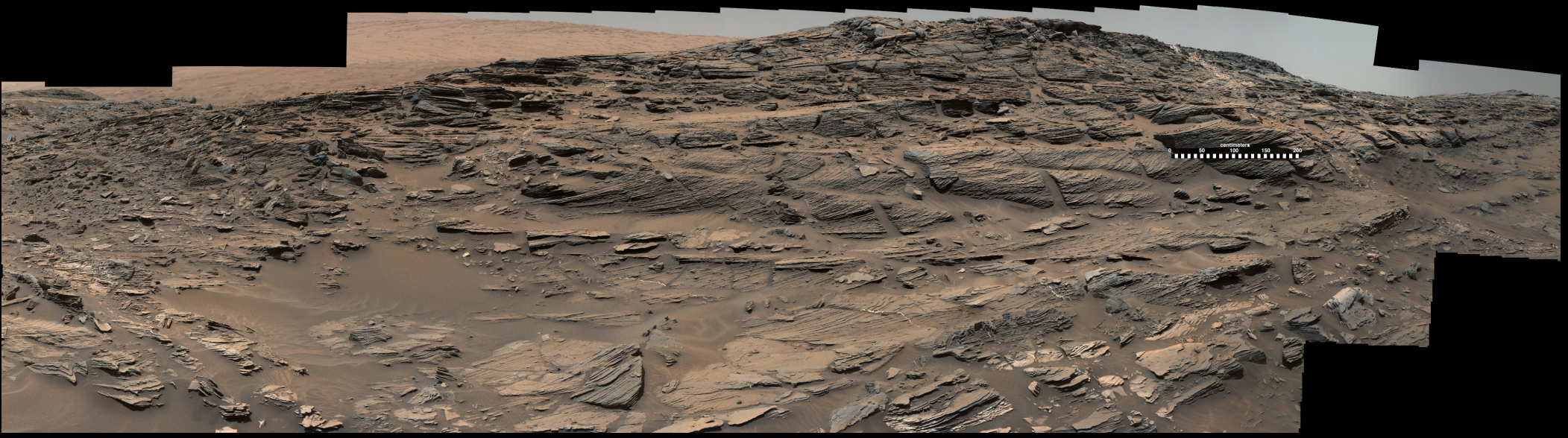
Mars: Crater Endurance



Mars: “Spirit” rolls towards Columbia Hills
(2004 June)



Mars: “Spirit” looks from Columbia Hills towards Gusev crater
(2004 Aug)

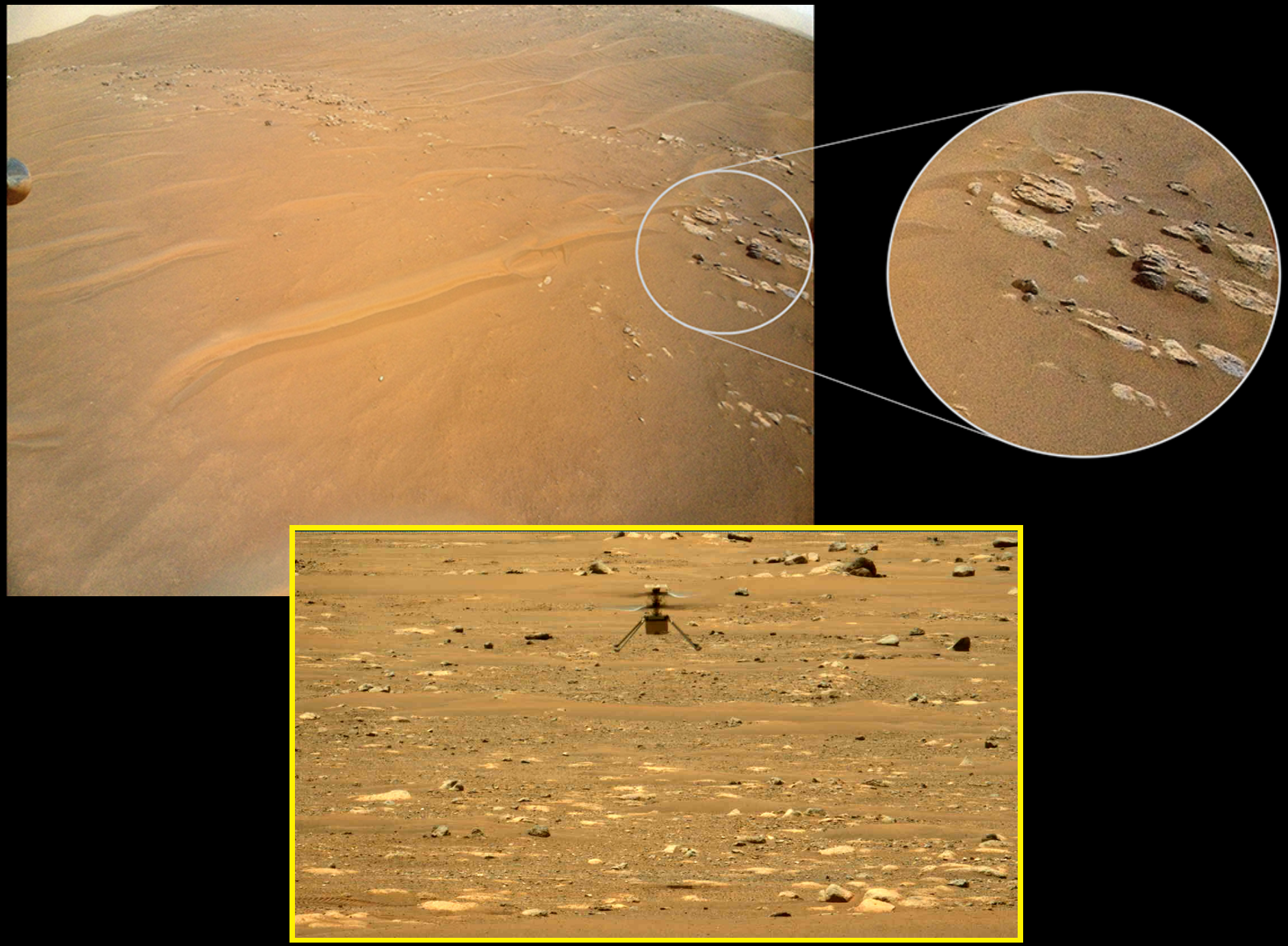


Mars: lower slope of Mount Sharp
wind blown sand dunes that have petrified (2015)

NASA/JPL/MSSS



Climbing Vera Rubin Ridge - sol 1812 - NASA/JPL-Caltech/MSSS/Thomas Appéré



Fortune Ridge as seen by Ingenuity (Perserverance, 2022) NASA/JPL



Mars: evidence for ancient lakes
Strata in foreground indicate flow of water toward a basin (2015)

NASA/JPL/MSSS

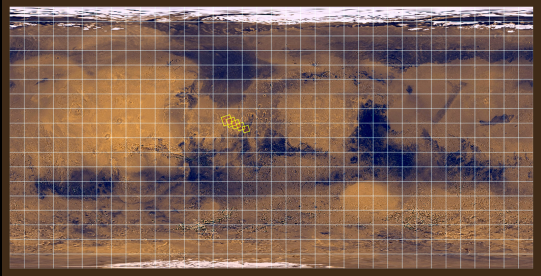
Ares Vallis, Mars

Mars Orbiter Mission Mars Colour Camera
Orbit 288, 16 September 2016

Processed by Emily Lakdawalla
for The Planetary Society
planetary.org/isromom

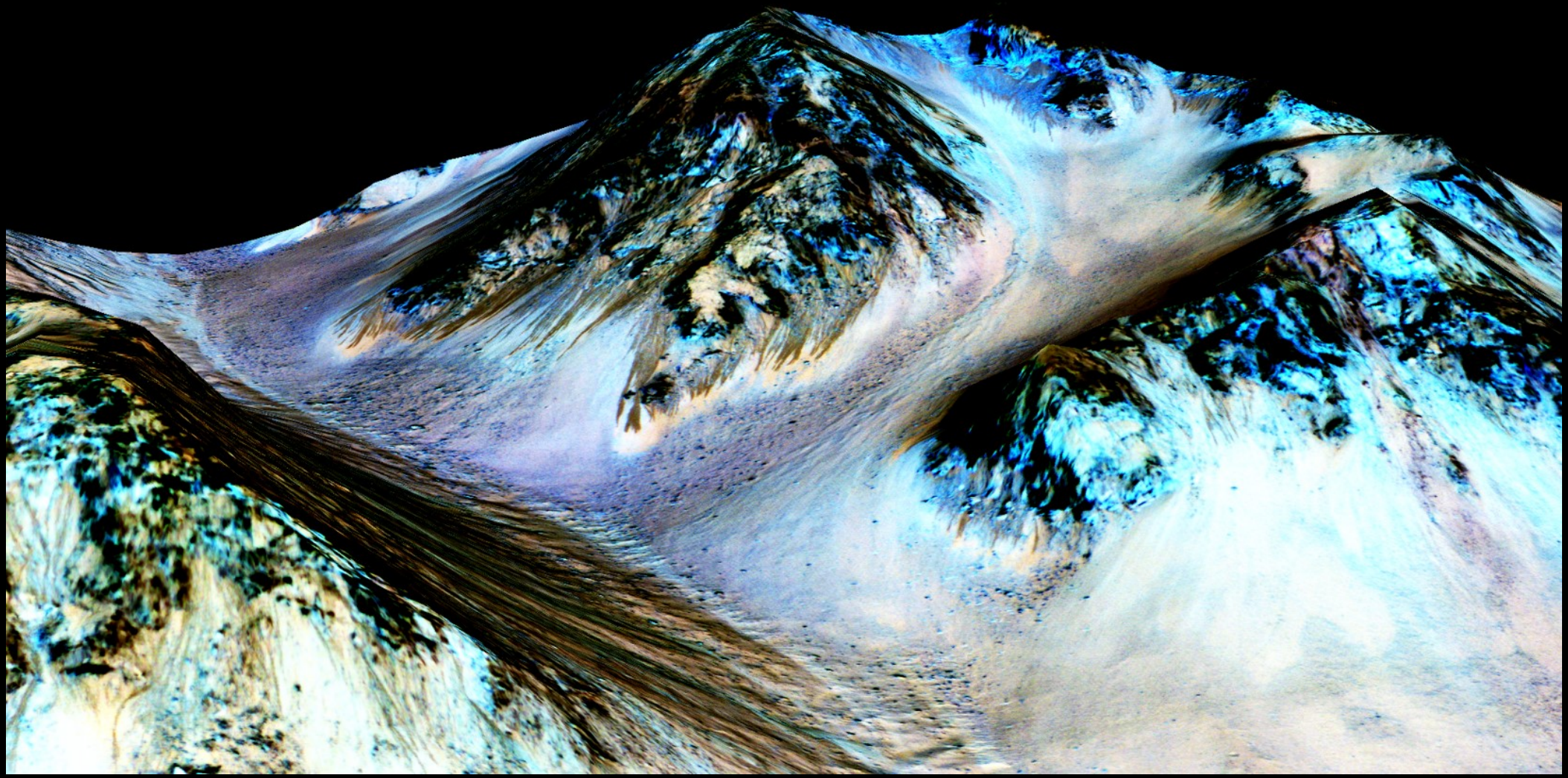
© reserved ISRO

100km



Data sources:
MCC_MRC_20160916T185359639_D_GDS
MCC_MRC_20160916T185600642_D_GDS
MCC_MRC_20160916T185801644_D_GDS
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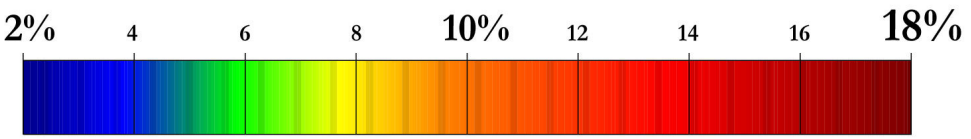
OK to reshare for noncommercial purposes with attribution: ISRO / MOM / ISSDC / Emily Lakdawalla



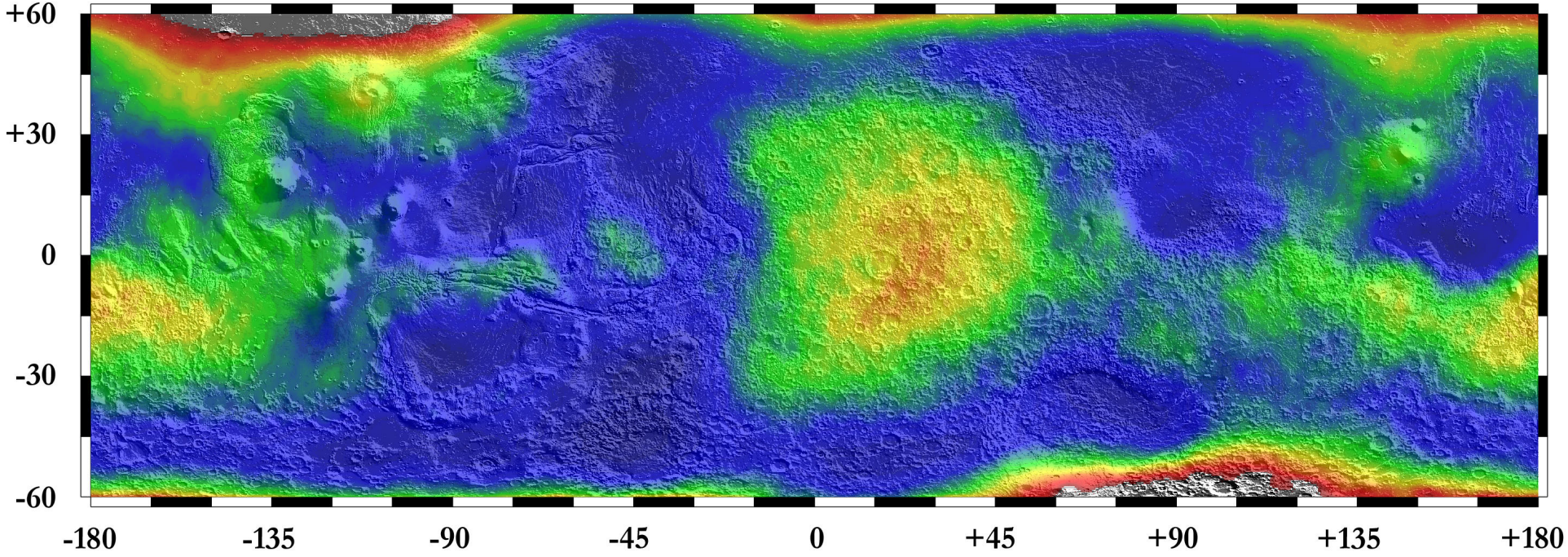
Mars: 100 m long streaks (recurring slope lineae)
formed by contemporary flowing water (height scale enhanced)

NASA/JPL/University of Arizona

Water Equivalent Hydrogen Abundance



Los Alamos NATIONAL LABORATORY

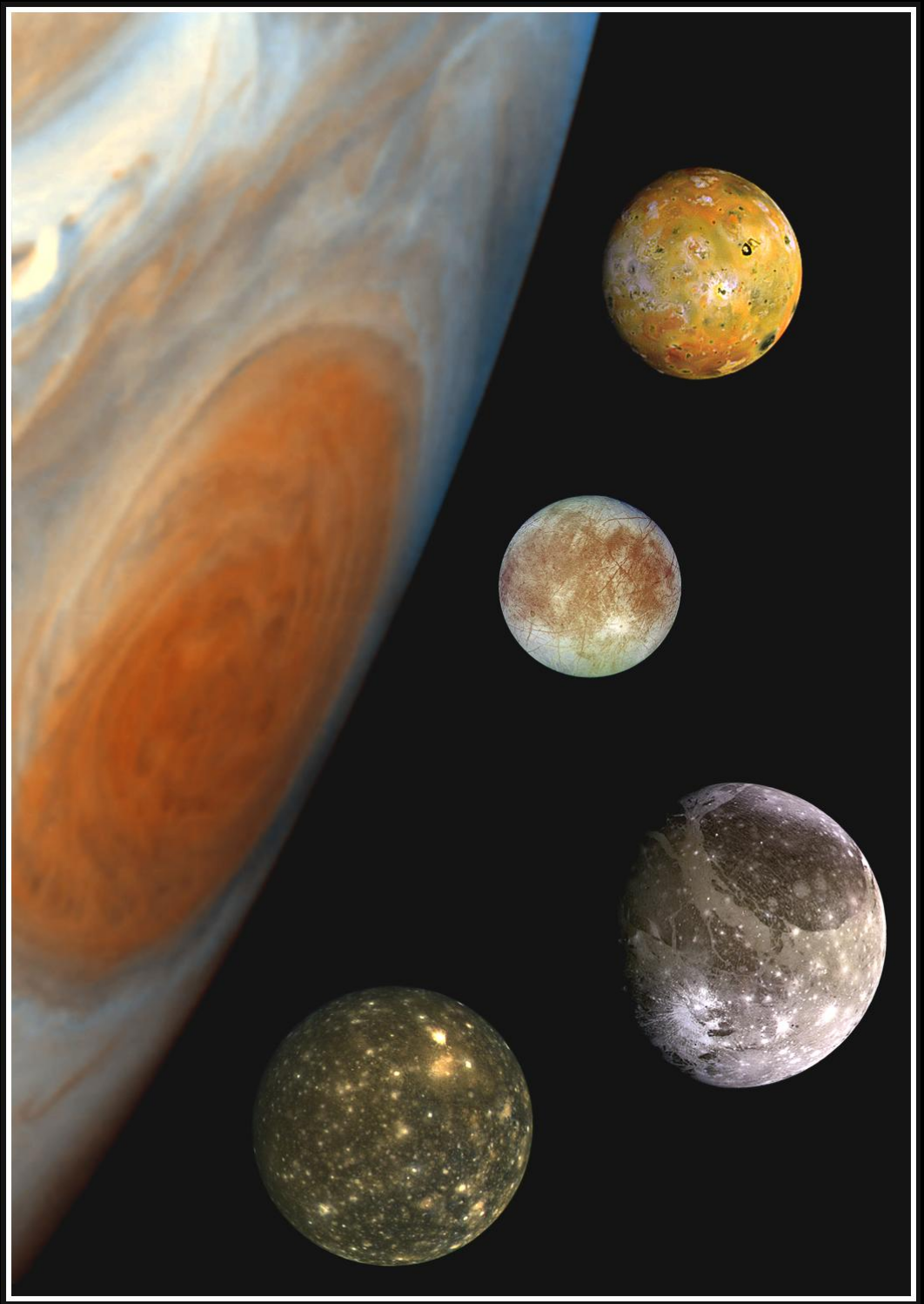


Distribution of Water on Mars: Overlay of water equivalent hydrogen abundances and a shaded relief map derived from MOLA topography. Mass percents of water were determined from epithermal neutron counting rates using the Neutron Spectrometer aboard Mars Odyssey between Feb. 2002 and Apr. 2003.

Reference: Feldman W. C., T. H. Prettyman, S. Maurice, J. J. Plaut, D. L. Bish, D. T. Vaniman, M. T. Mellon, A. E. Metzger, S. W. Squyres, S. Karunatillake, W. V. Boynton, R. C. Elphic, H. O. Funsten, D. J. Lawrence, and R. L. Tokar, The global distribution of near-surface hydrogen on Mars, *JGR-planets*, submitted July 2003.

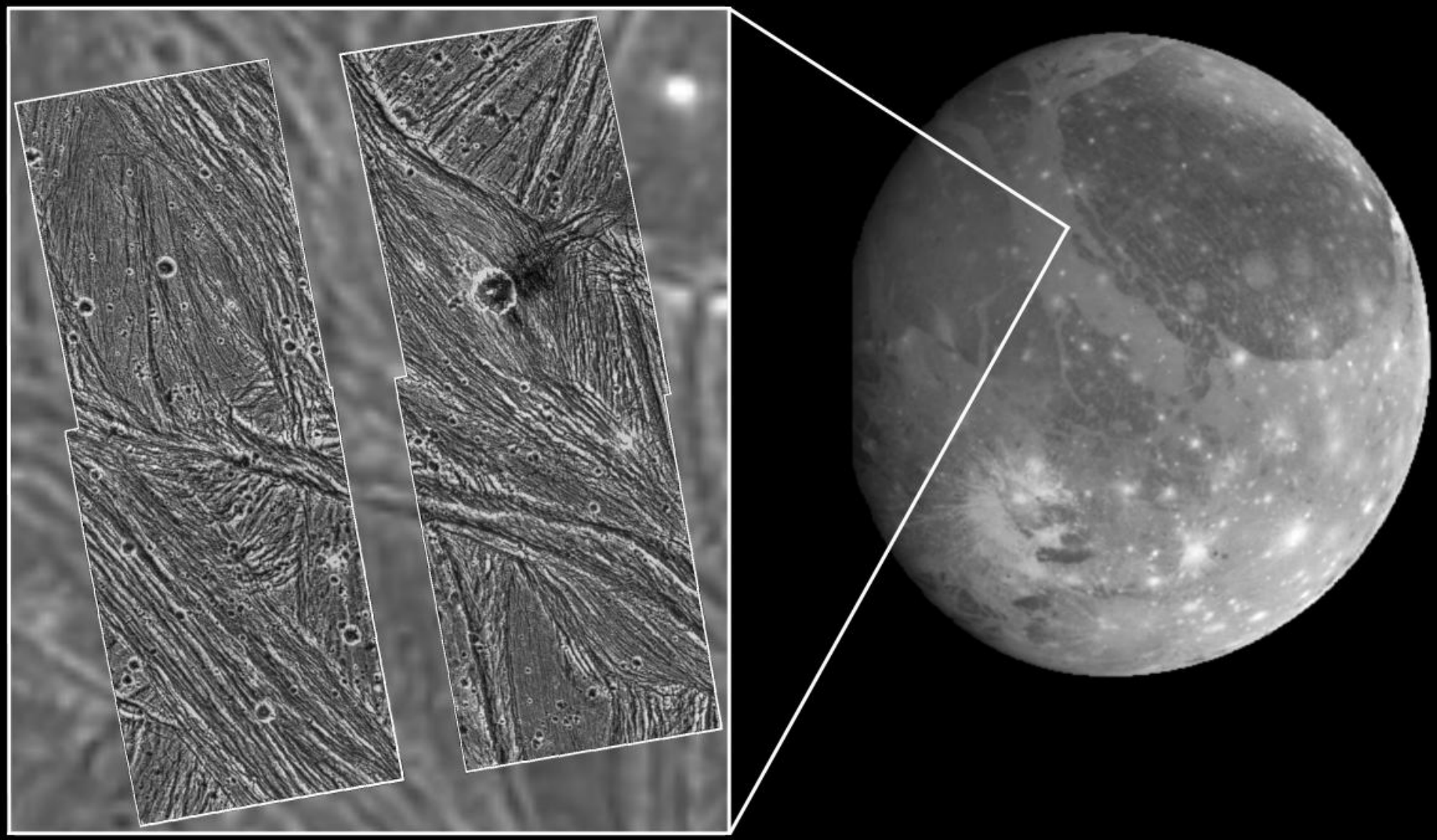
These data were generated by the Planetary Science Team at Los Alamos: B. Barraclough, D. Bish, D. Delapp, R. Elphic, W. Feldman, H. Funsten, O. Gasnault*, D. Lawrence, S. Maurice*, G. McKinney, K. Moore, T. Prettyman, R. Tokar, D. Vaniman, and R. Wiens. * Also at Observatoire Midi-Pyrenees, France

The neutron spectrometer aboard Mars Odyssey, a component of the Gamma-ray Spectrometer suite of instruments, was designed and built by the Los Alamos National Laboratory and is operated by the University of Arizona in Tucson. The Mars Odyssey mission is managed by the Jet Propulsion Laboratory.



Montage of Jupiter and Galilean Moons: top to bottom: Io, Europa, Ganymede and Callisto.

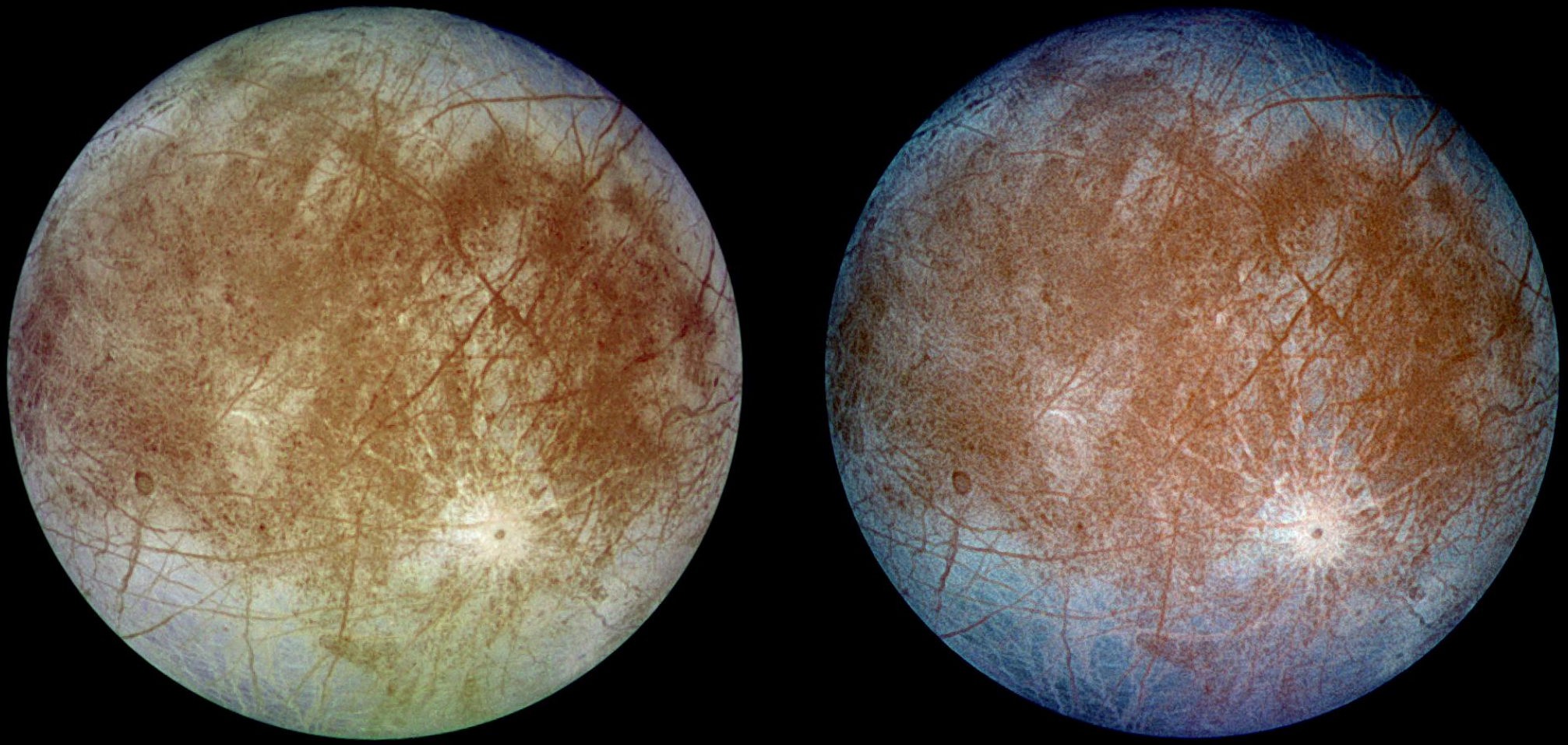
(N.B.: All Galilean moons are tidally locked to Jupiter – Jupiter always faced by same side)



NASA Galileo / DLR, inset: 120×110 km

Ganymede – icy surface, ice hills and valleys, craters

Radius: 2634 km (largest moon in solar system, larger than Mercury!)



NASA Galileo / DLR, 1996 September 7

Europa – icy surface with ridges (colors: different kinds of ice)
Radius: 1565 km (~ Earth Moon)
possibility of water ocean below surface



Callisto: “pock faced”, mainly impact craters.
white: ice
dark: ice-poor material

Radius: 2406 km (similar to Mercury!)

Cratering Physics

Physics of impact cratering:

Kinetic energy:

$$E = \frac{1}{2}mv^2 = \frac{1}{2} \cdot \frac{4}{3}\pi r^3 \rho v^2 = \frac{\pi d^3 \rho v^2}{12}$$

Important numbers:

- Velocity of impact: several times orbital speed of planet
- Impacting body: rock or Fe, several meters to kilometers in size

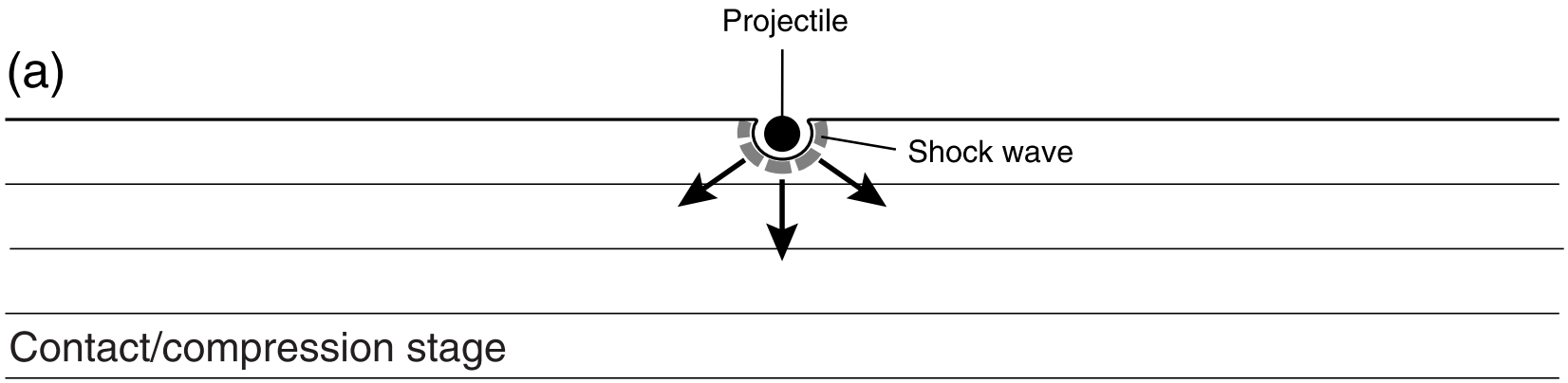
Example:

E.g., $v = 10\,\mathrm{km\,s^{-1}}$, $d = 25\,\mathrm{m}$, $\rho = 7900\,\mathrm{kg\,m^{-3}}$

$\Longrightarrow E = 3 \times 10^{15}\,\mathrm{J}$ (~1 Megaton of TNT)

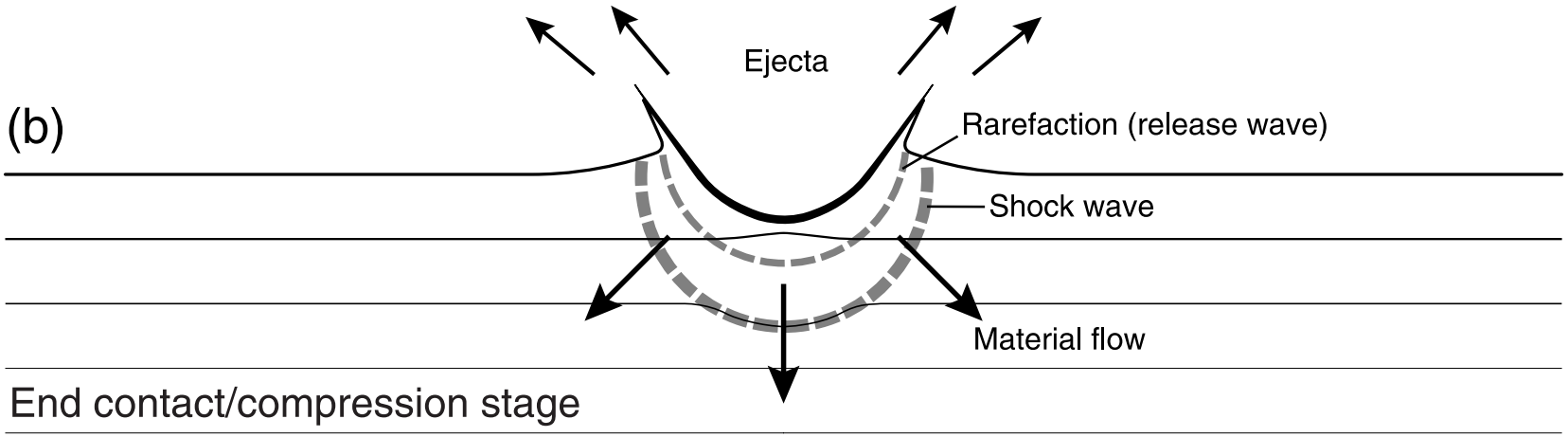
1 Megaton TNT is typical strength of US nuclear bombs [B-83 bomb]

Cratering Physics



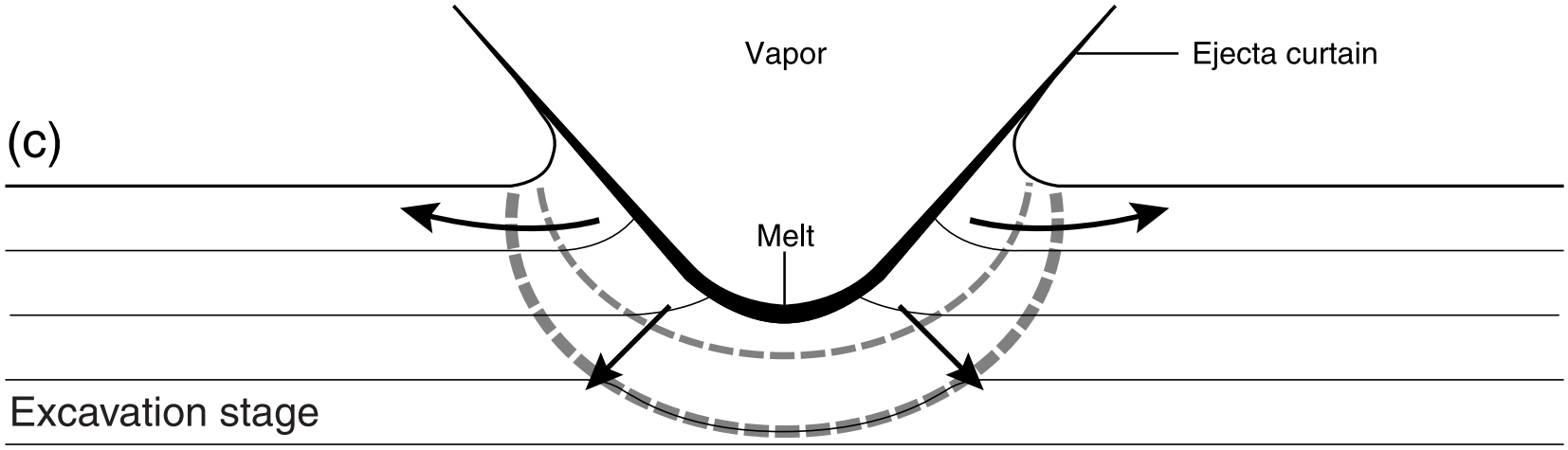
French, 1998, LPI Contribution 954, p. 21

Cratering Physics



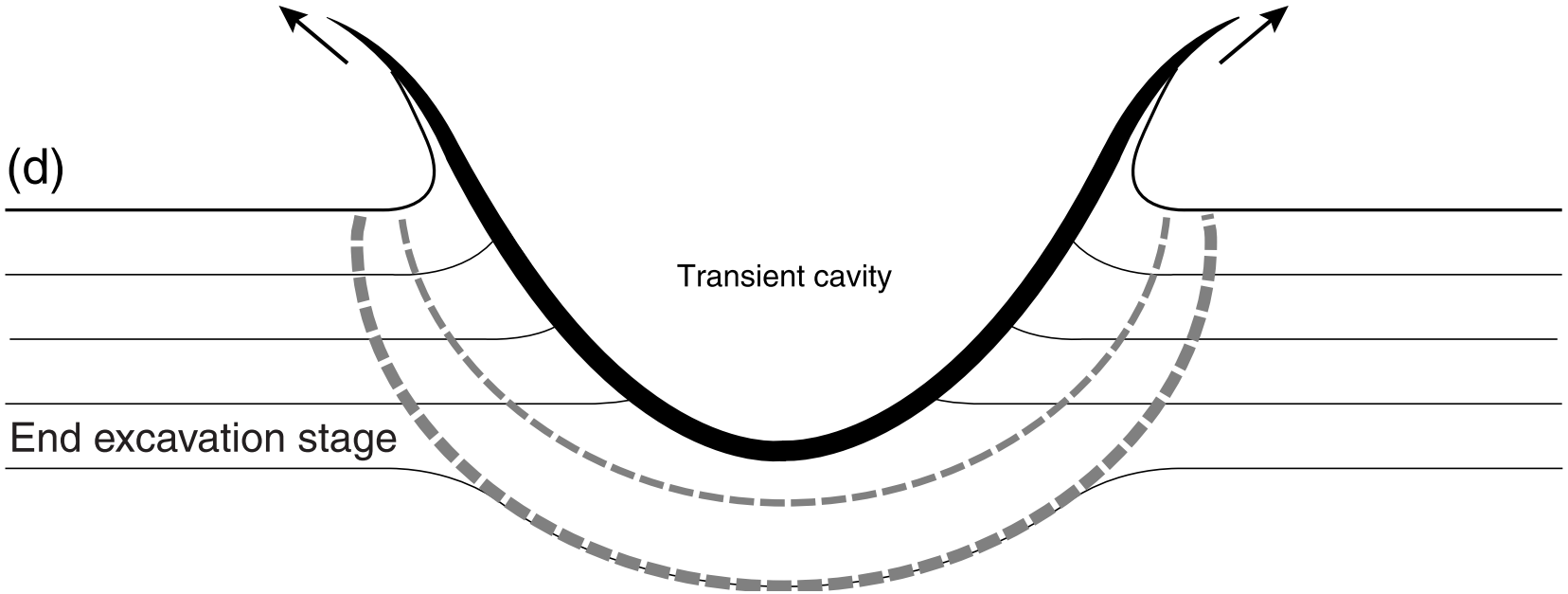
French, 1998, LPI Contribution 954, p. 21

Cratering Physics



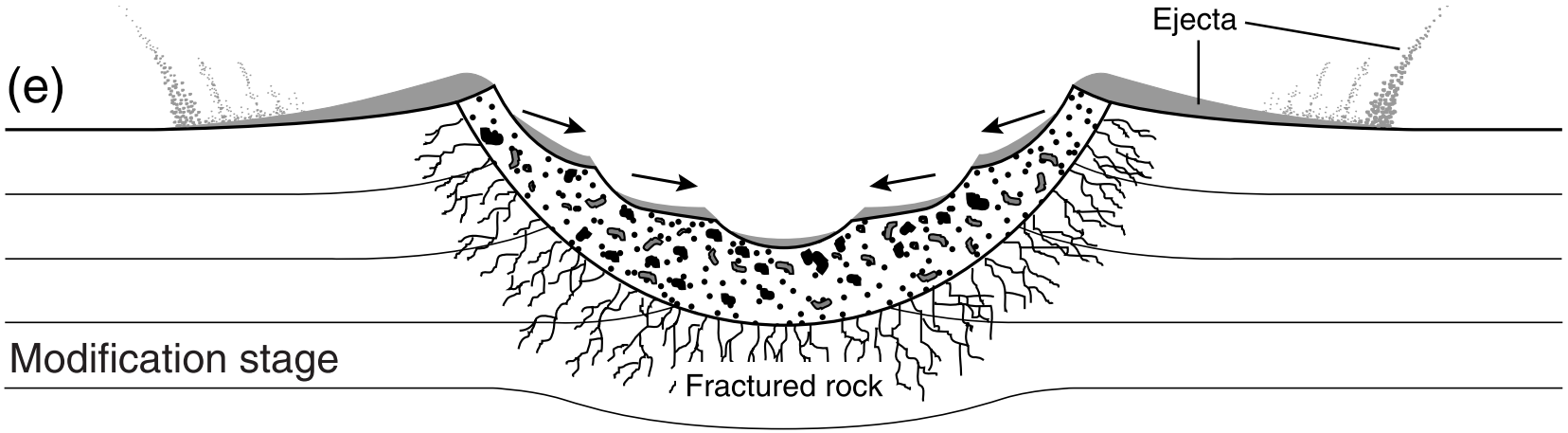
French, 1998, LPI Contribution 954, p. 21

Cratering Physics



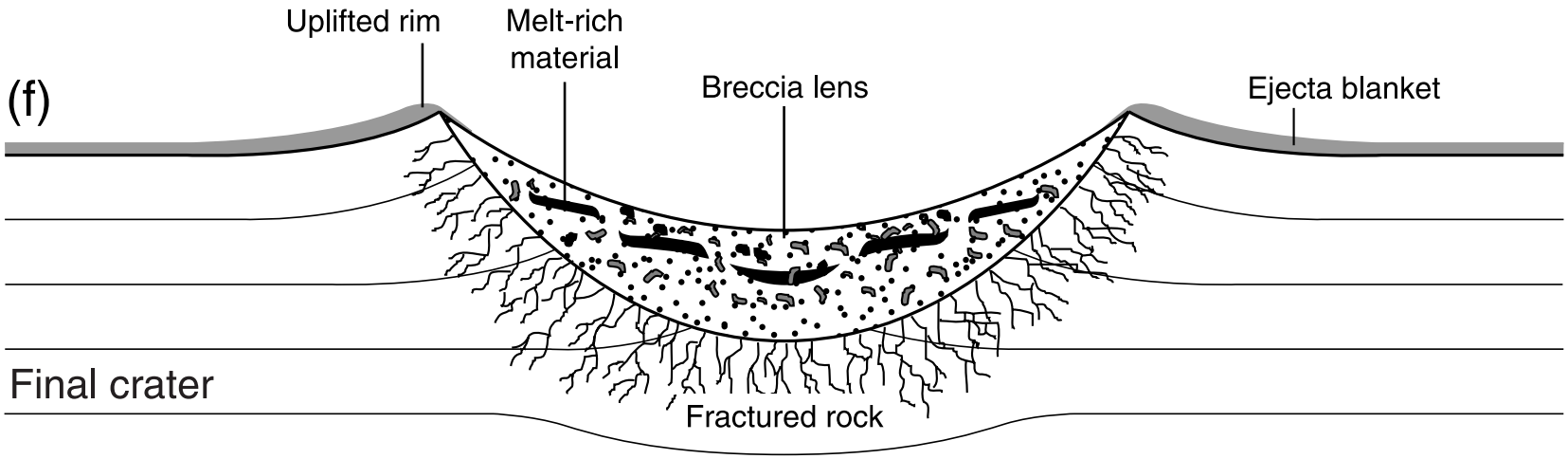
French, 1998, LPI Contribution 954, p. 21

Cratering Physics

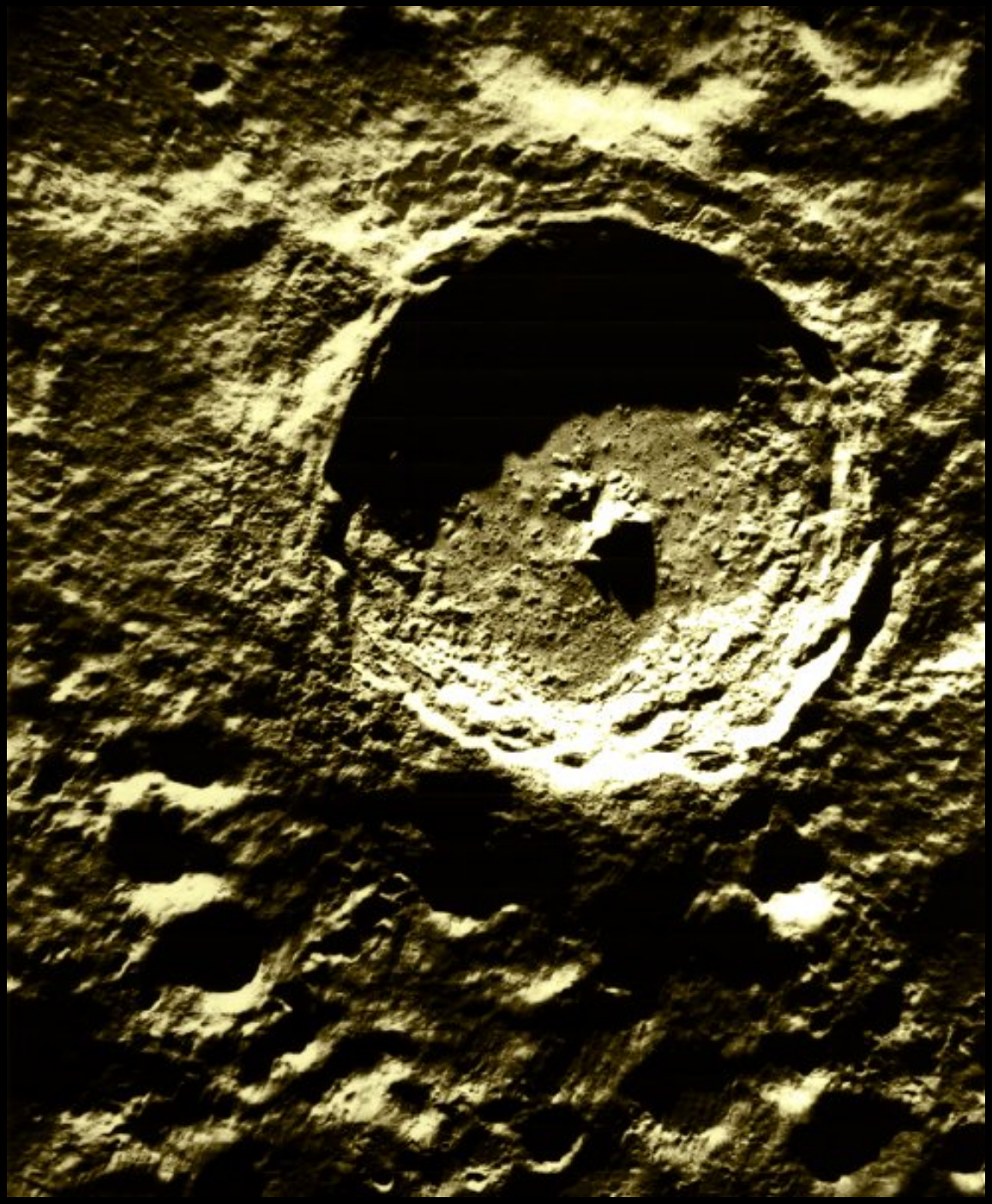


French, 1998, LPI Contribution 954, p. 21

Cratering Physics



French, 1998, LPI Contribution 954, p. 21



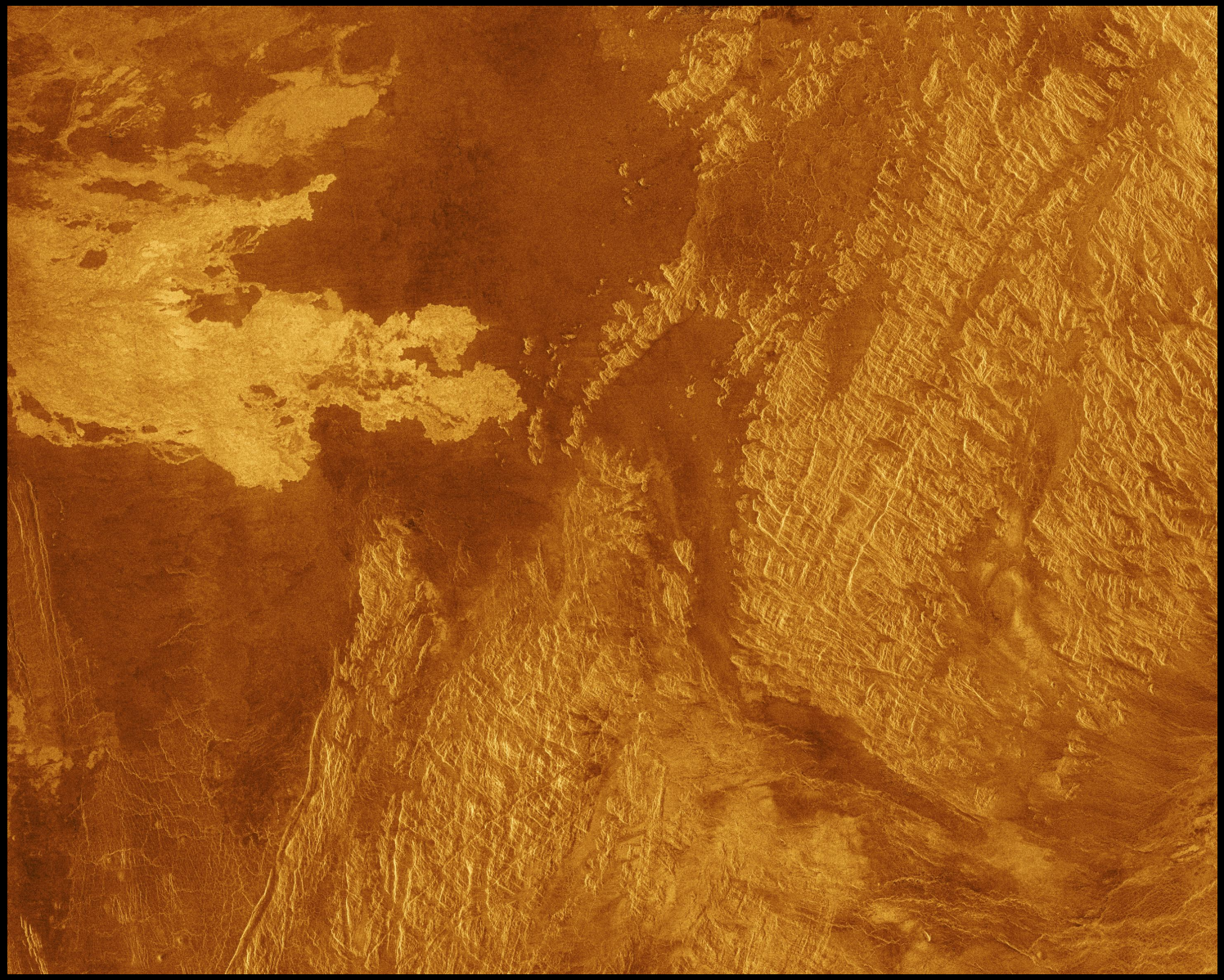
NASA

Crater Tycho on Moon

large craters:
complex craters with
central peak or
ring structures:

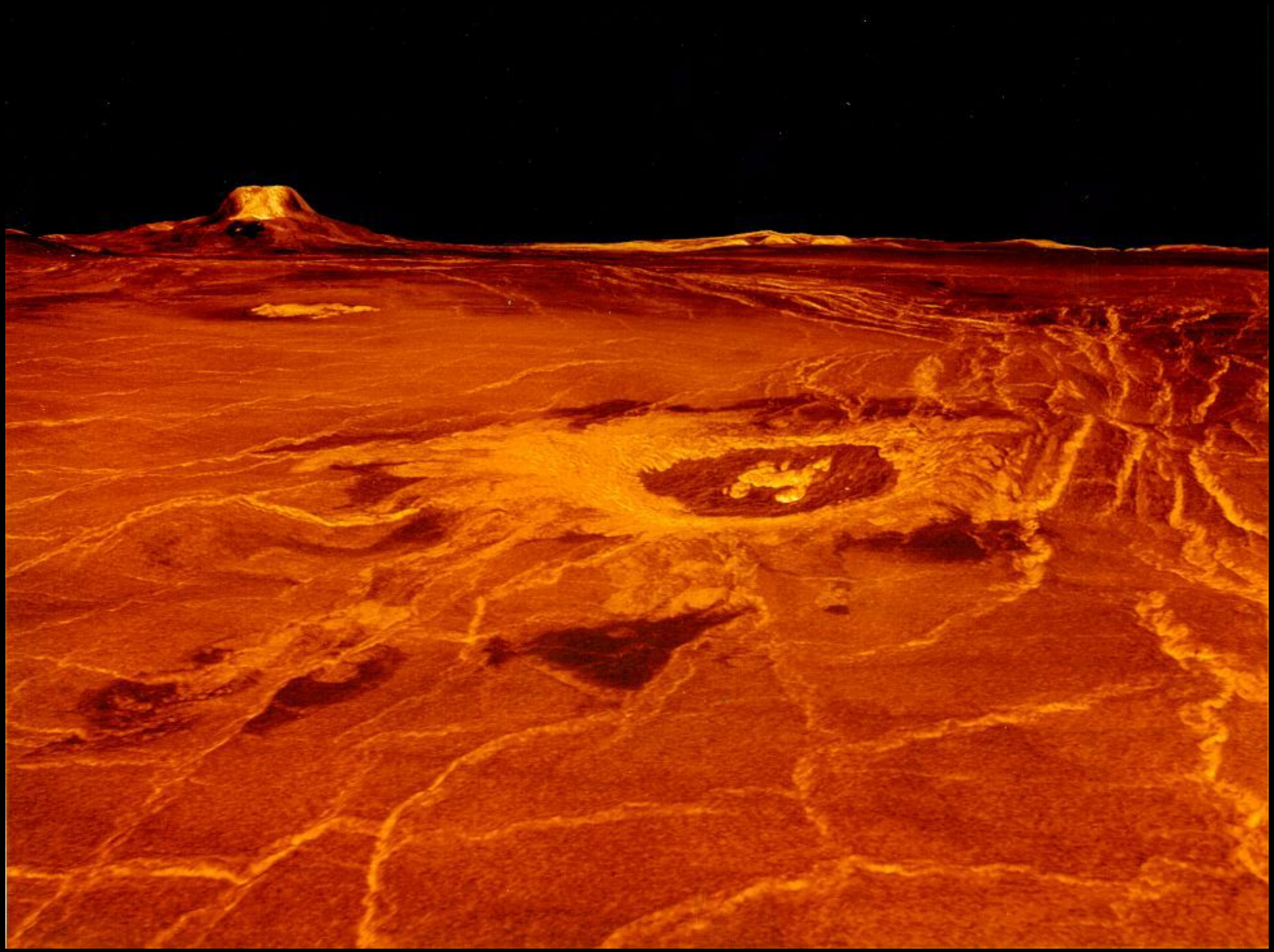
"soft" material tries to reach equilibrium with gravitation again

Venus



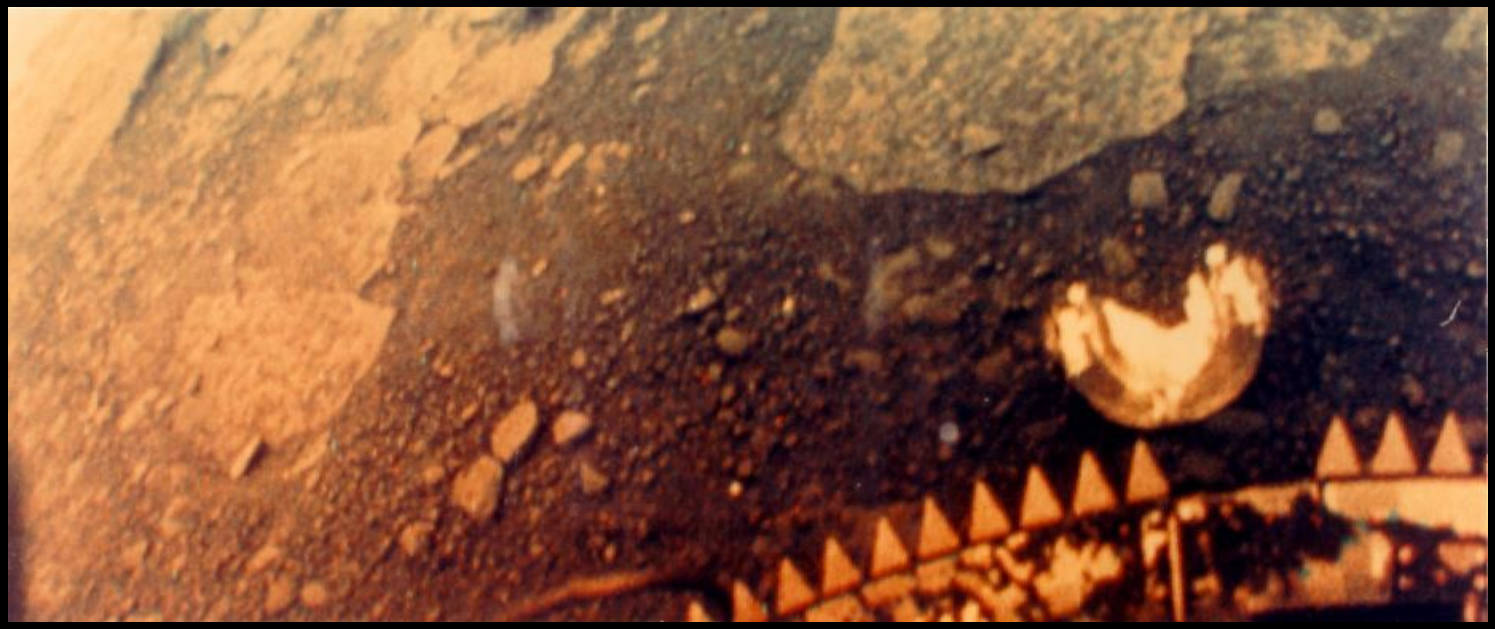
NASA, Magellan

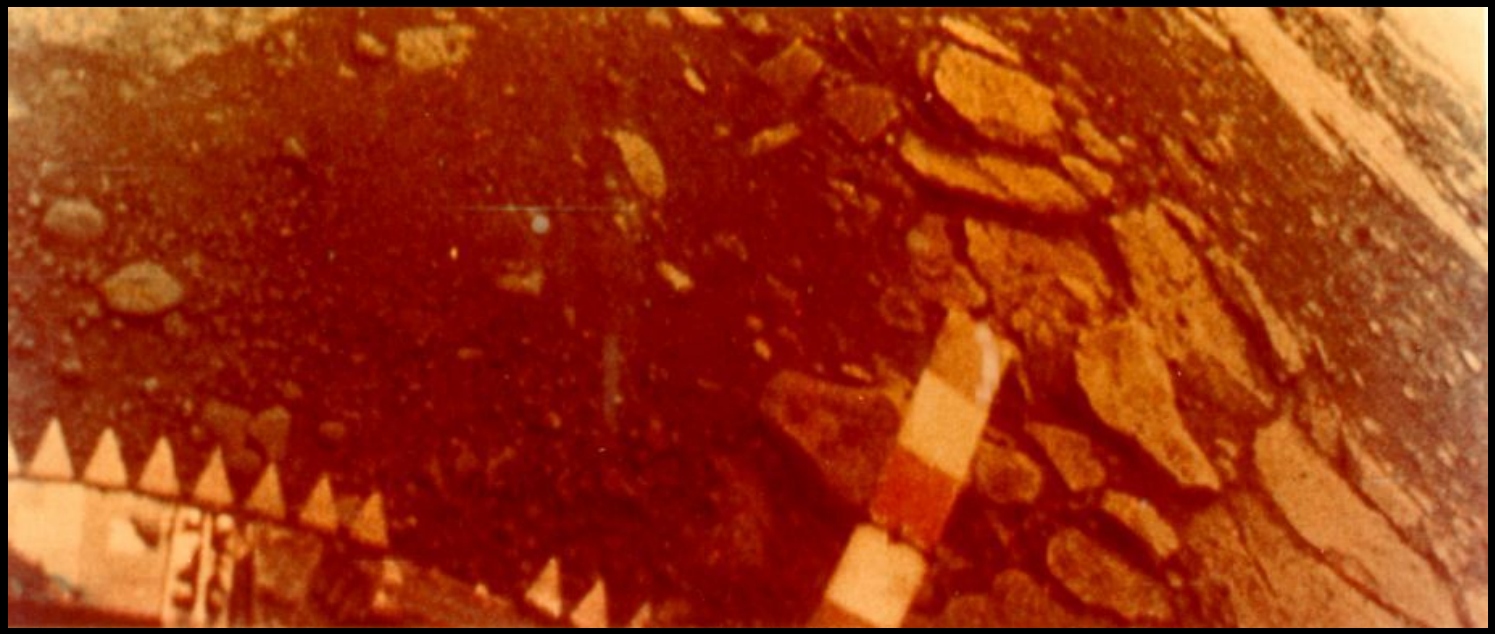
$440 \times 350\,\mathrm{km}^2$ area in Eistla Regio, shows basic stratigraphy (sequence of geologic events): right half: old highlands, fractured structure (~15% of surface), left part: lowlands, younger area, origin in volcanism?
Craters (note: strong erosion $\Longrightarrow$ fewer craters overall)



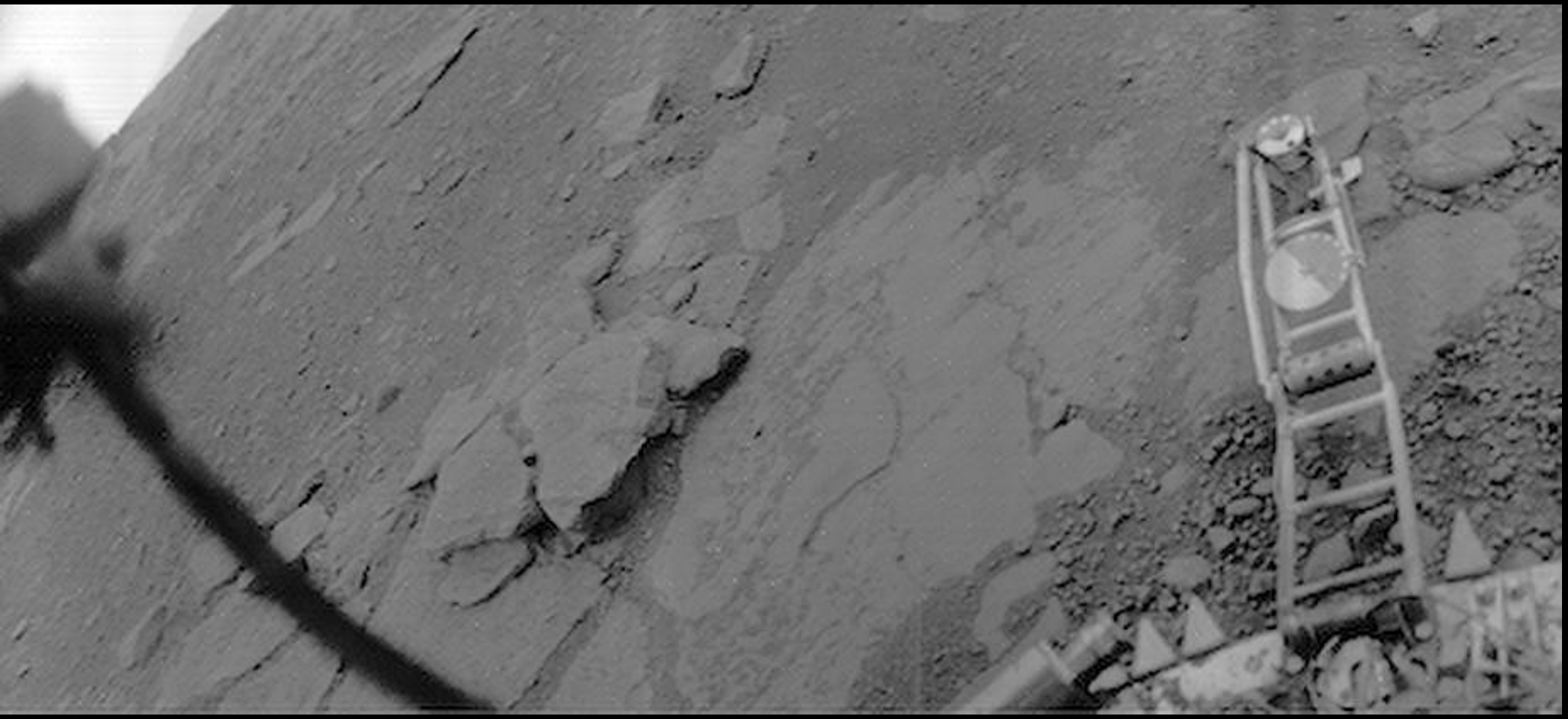
Eistla Regio; heights exagerrated by factor 22.5

Venus surface images:





Venera 13 (3 March 1982): images from color TV camera

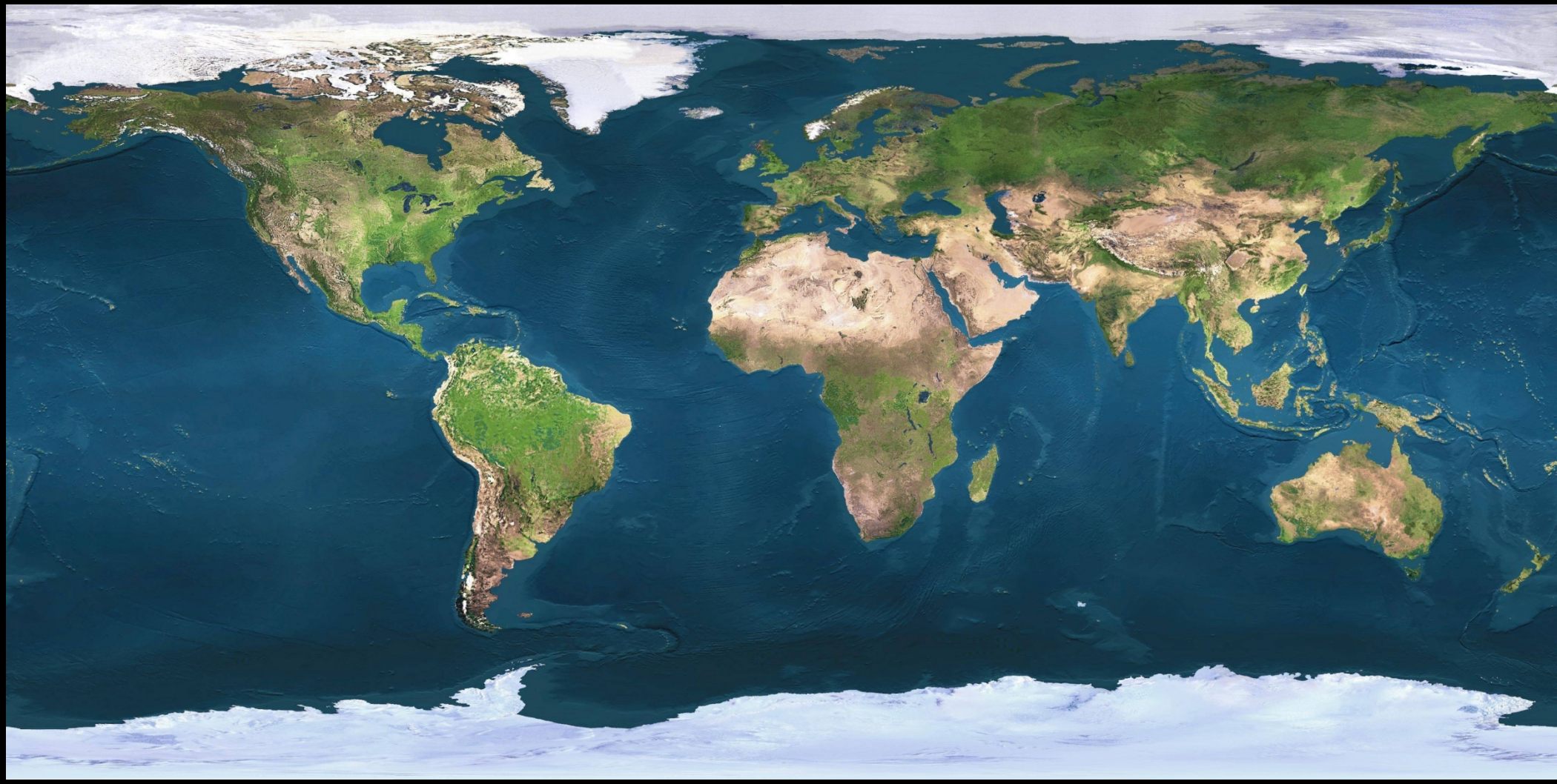


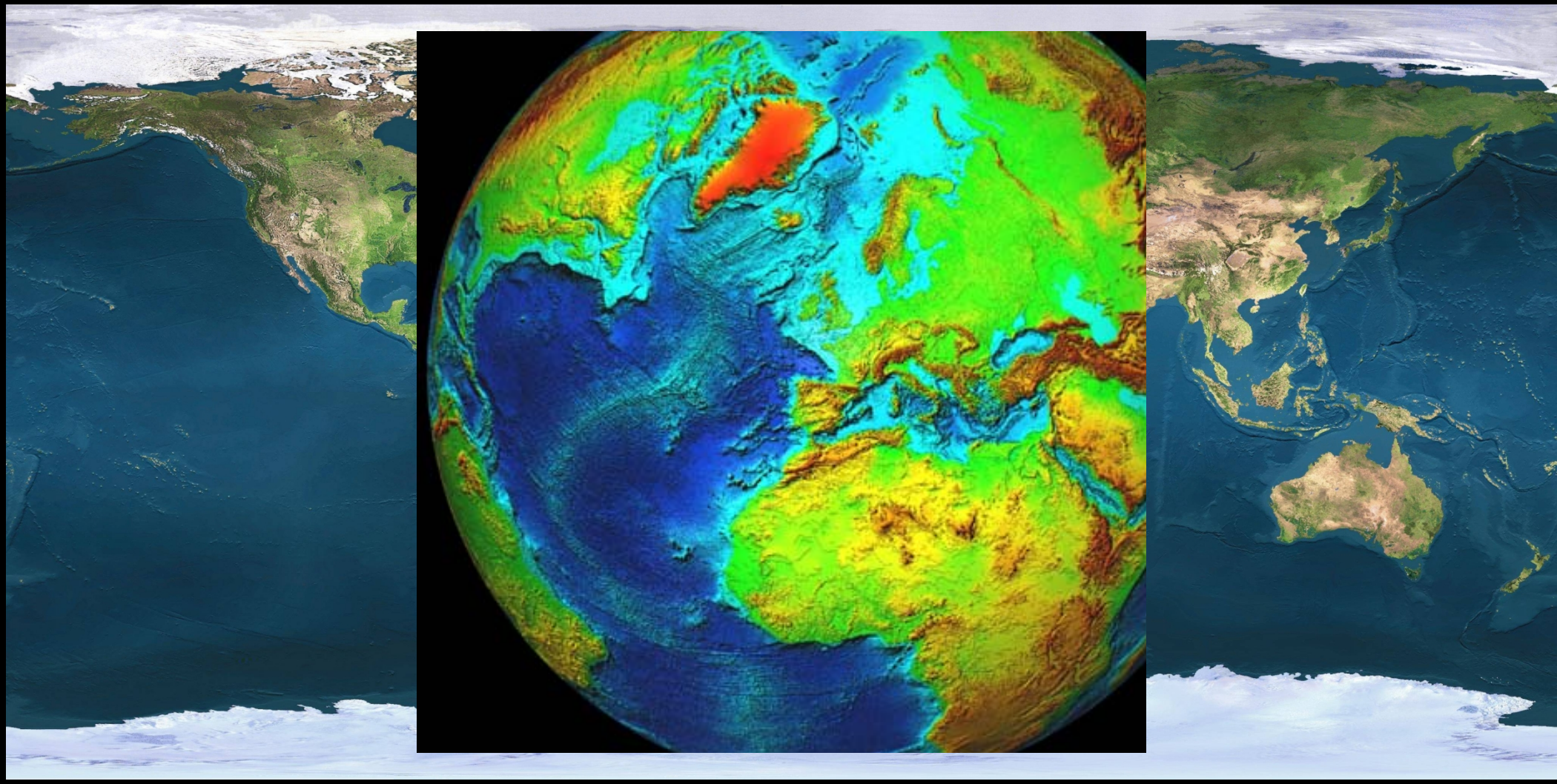
courtesy D.P. Mitchell

Venera 13 (1982 March 3): reanalysed image without camera distortion

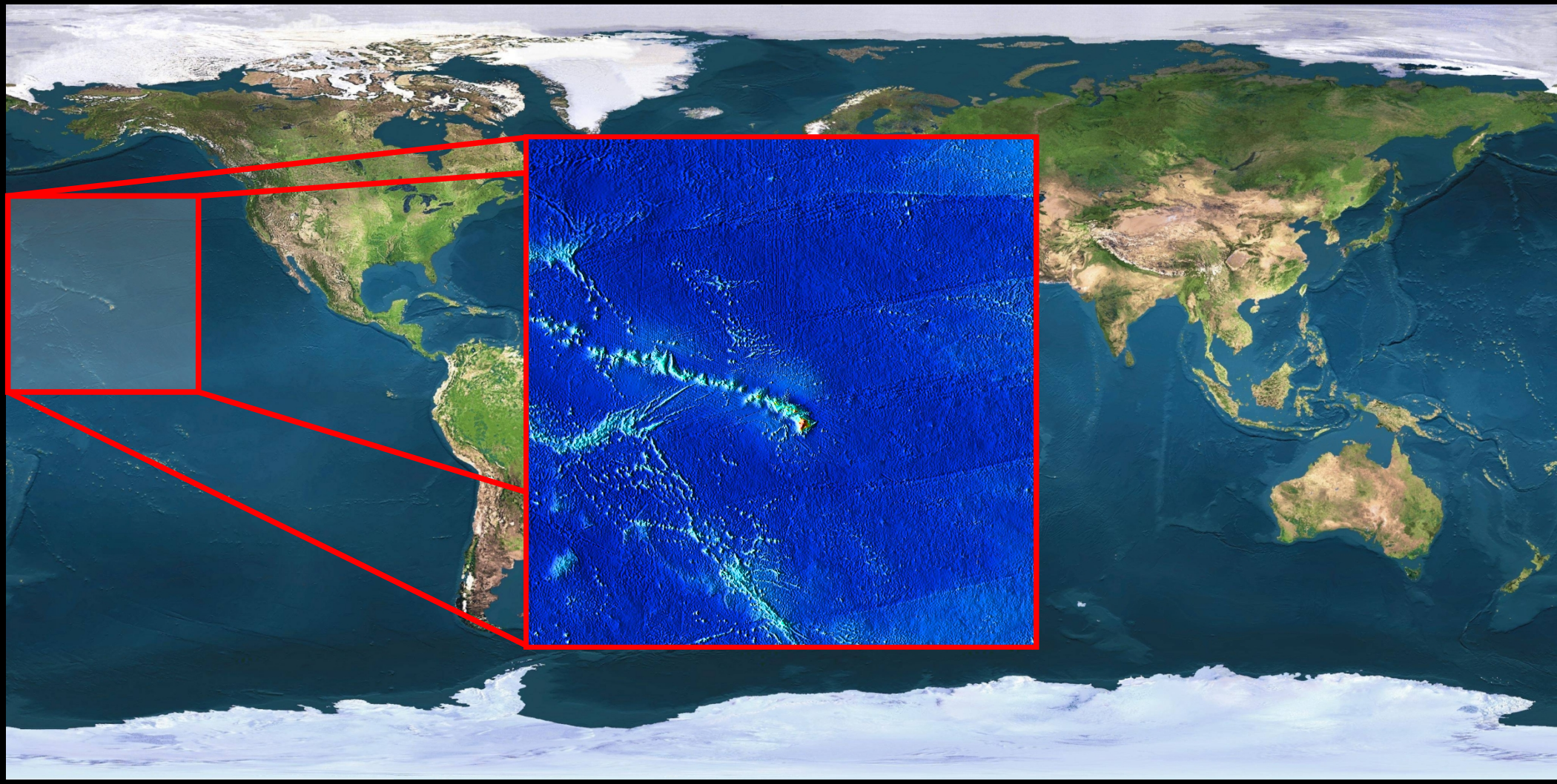


Venera 14 (1982 May 5)

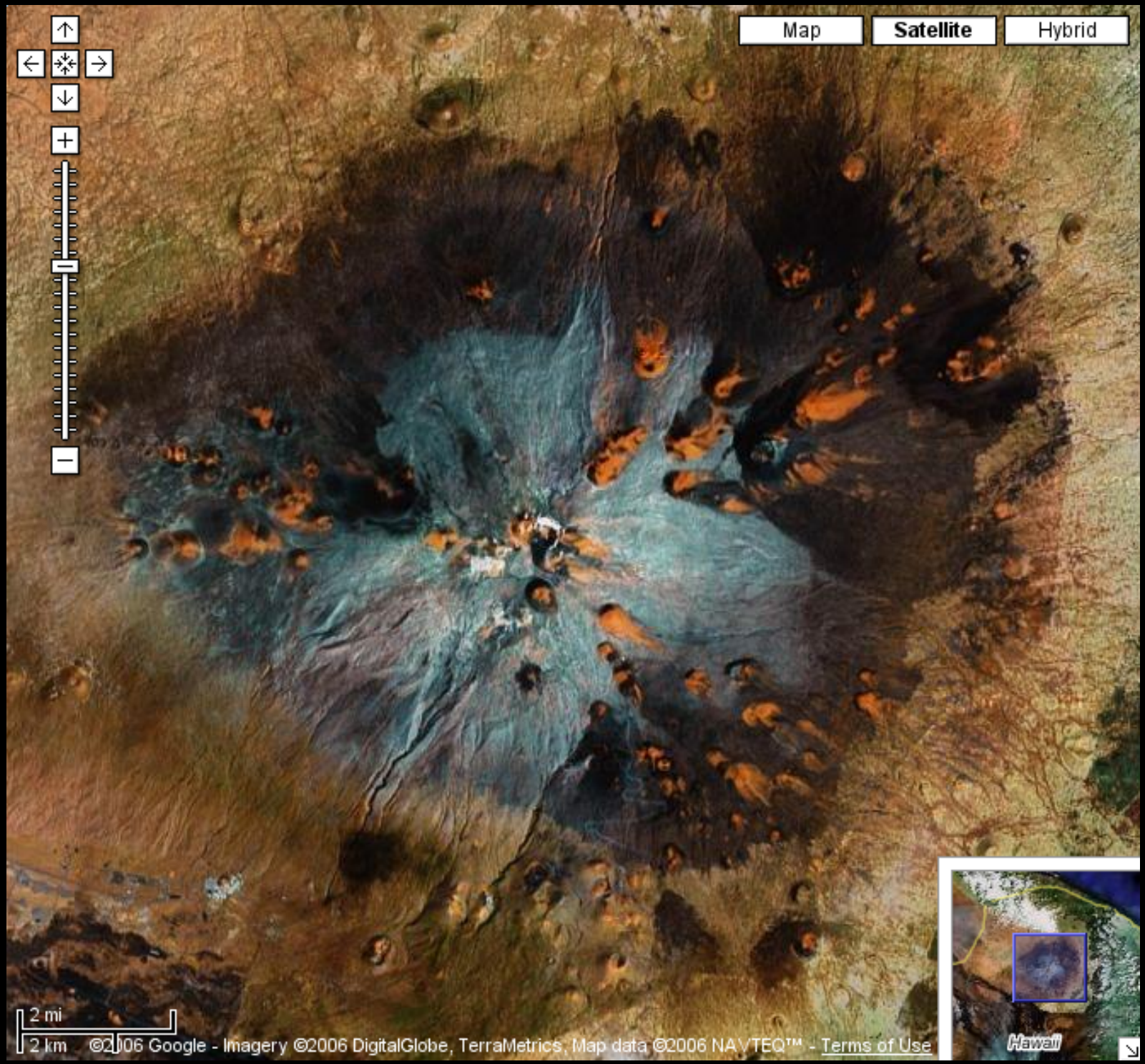




Evidence for plate tectonics (few craters!)



Evidence for plate tectonics (few craters!) , volcanism,. . .


Map
Satellite
Hybrid
2 mi
2 km
©2006 Google - Imagery ©2006 DigitalGlobe, TerraMetrics, Map data ©2006 NAVTEQ™ - Terms of Use
Hawaii

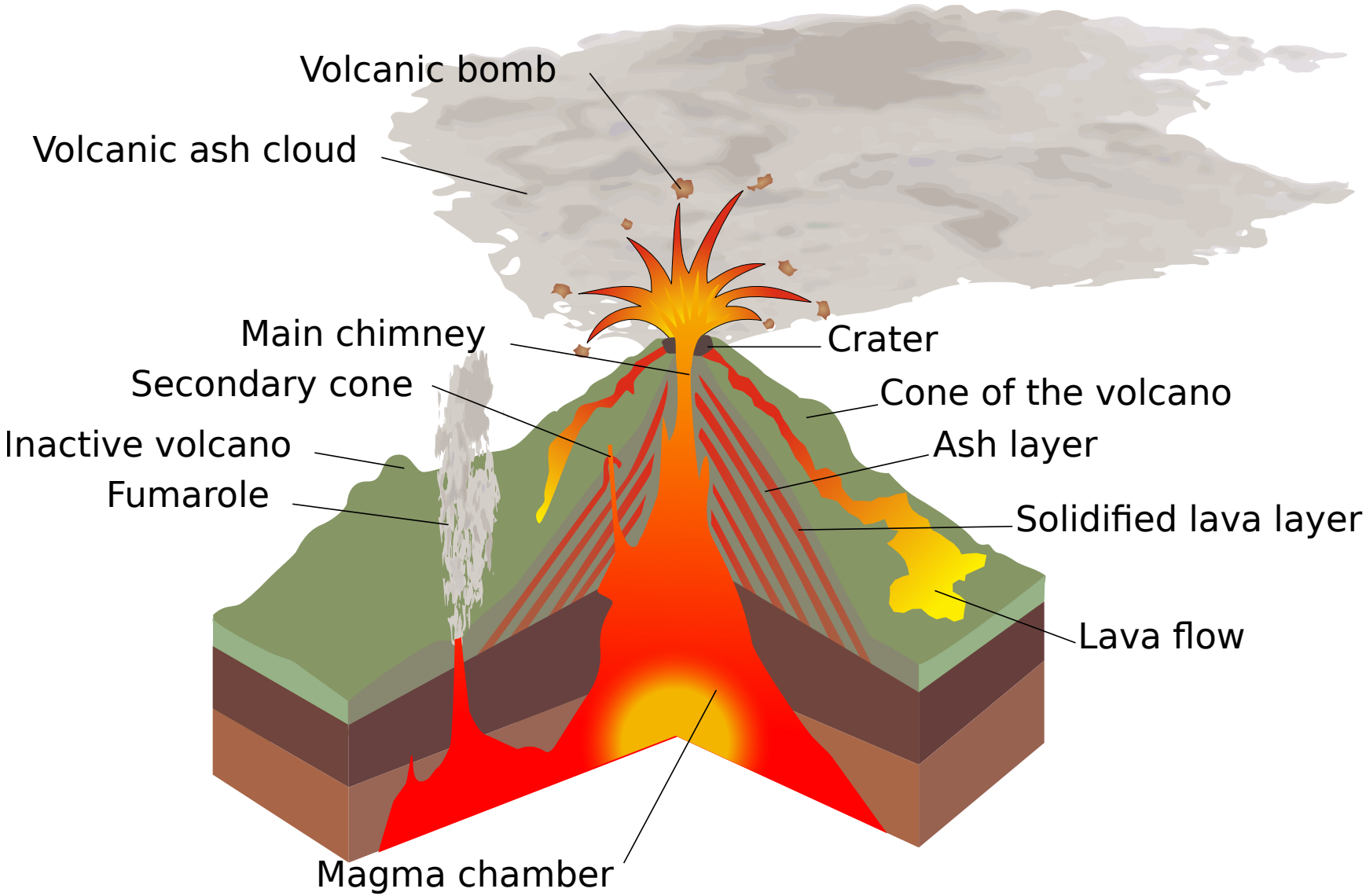
© Google



© J. Wilms

Hawaii

Volcanism on Earth





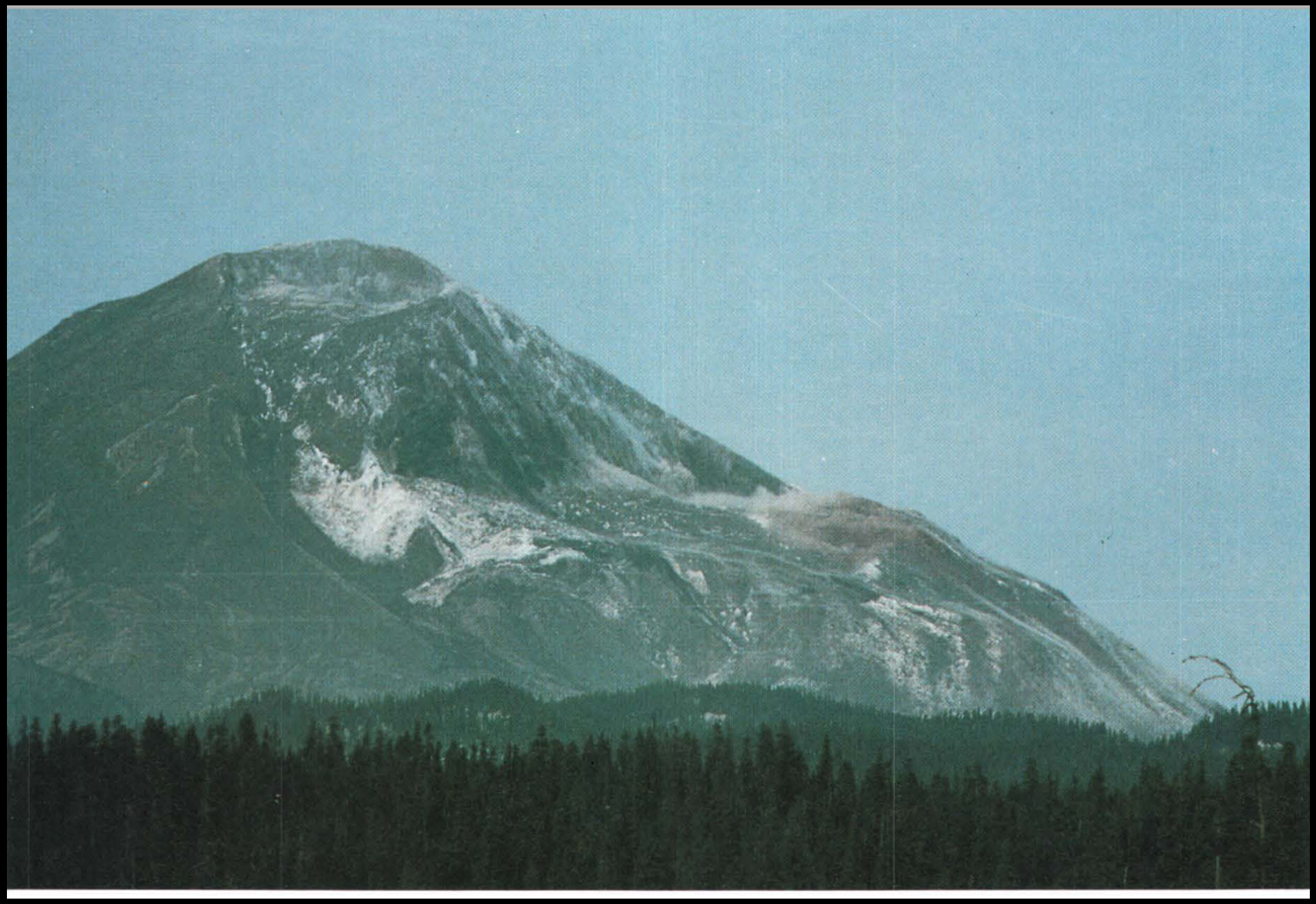
Mt. St. Helens, 17 May 1980 (H. Glicken, USGS)



Mt. St. Helens, 18 May 1980, 8:27PDT
5 minutes pre eruption, (USGS prof. paper 1250, © G. Rosenquist)



Mt. St. Helens, 18 May 1980, 8:32:47PDT
(USGS prof. paper 1250, © G. Rosenquist)



Mt. St. Helens, 18 May 1980, 8:32:47PDT + 0.8 s
(USGS prof. paper 1250, © G. Rosenquist)



Mt. St. Helens, 18 May 1980, 8:32:47PDT + 2.4 s
(USGS prof. paper 1250, © G. Rosenquist)



Mt. St. Helens, 18 May 1980, 8:32:47PDT + 6.3 s
(USGS prof. paper 1250, © G. Rosenquist)



Mt. St. Helens, 18 May 1980, 8:32:47PDT + 10.0 s
(USGS prof. paper 1250, © G. Rosenquist)



Mt. St. Helens, 18 May 1980, 8:32:47PDT + 13.0 s
(USGS prof. paper 1250, © G. Rosenquist)



Mt. St. Helens, 18 May 1980, 8:32:47PDT + 16.7 s
(USGS prof. paper 1250, © G. Rosenquist)



Mt. St. Helens, 18 May 1980, 8:32:47PDT + 31.8 s
(USGS prof. paper 1250, © G. Rosenquist)



Mt. St. Helens, 27 Aug 2015 (© J. Wilms)

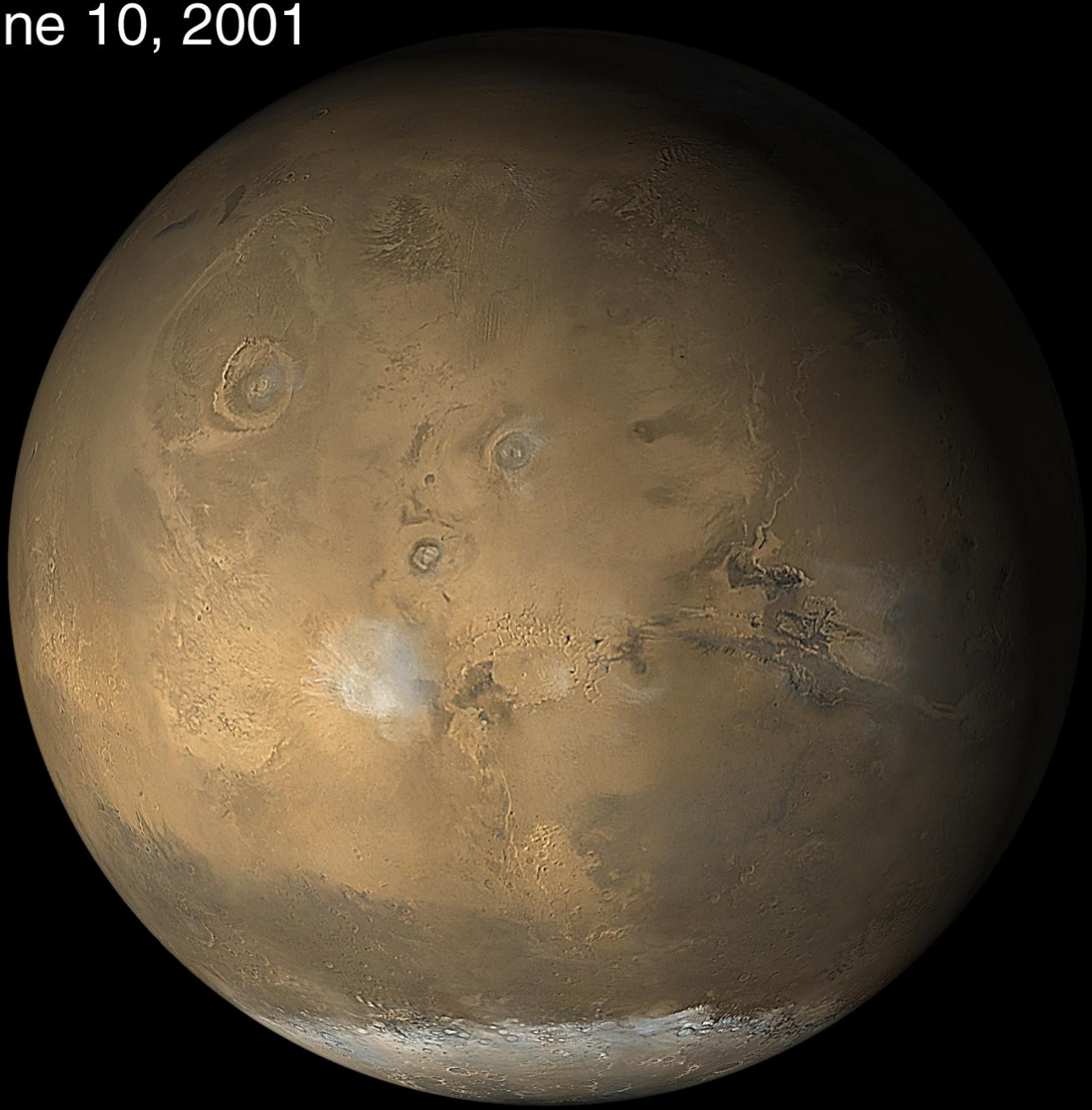


Mt. St. Helens, 10 Sept 1980 (H. Glicken, USGS)

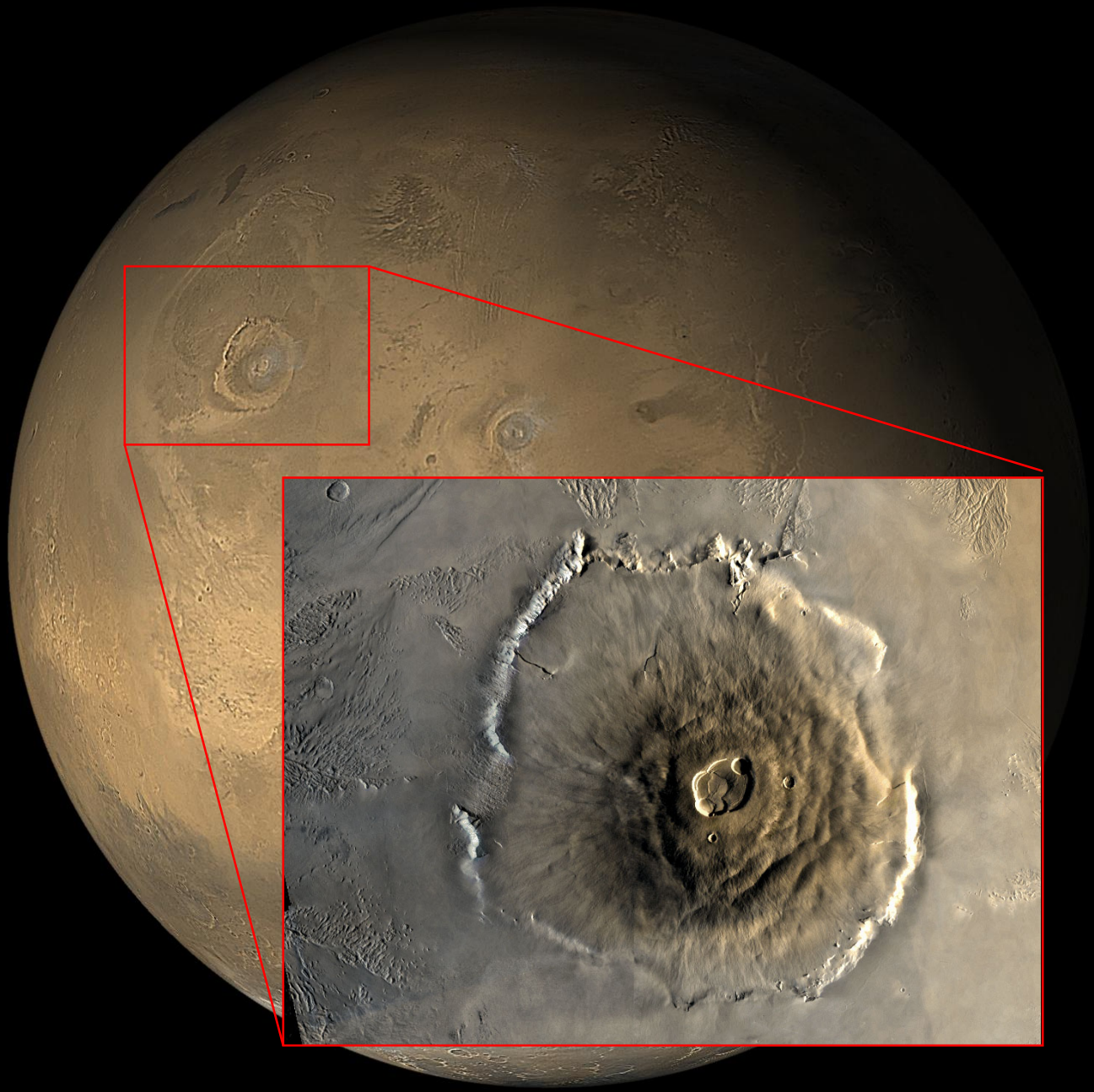


© J. Wilms

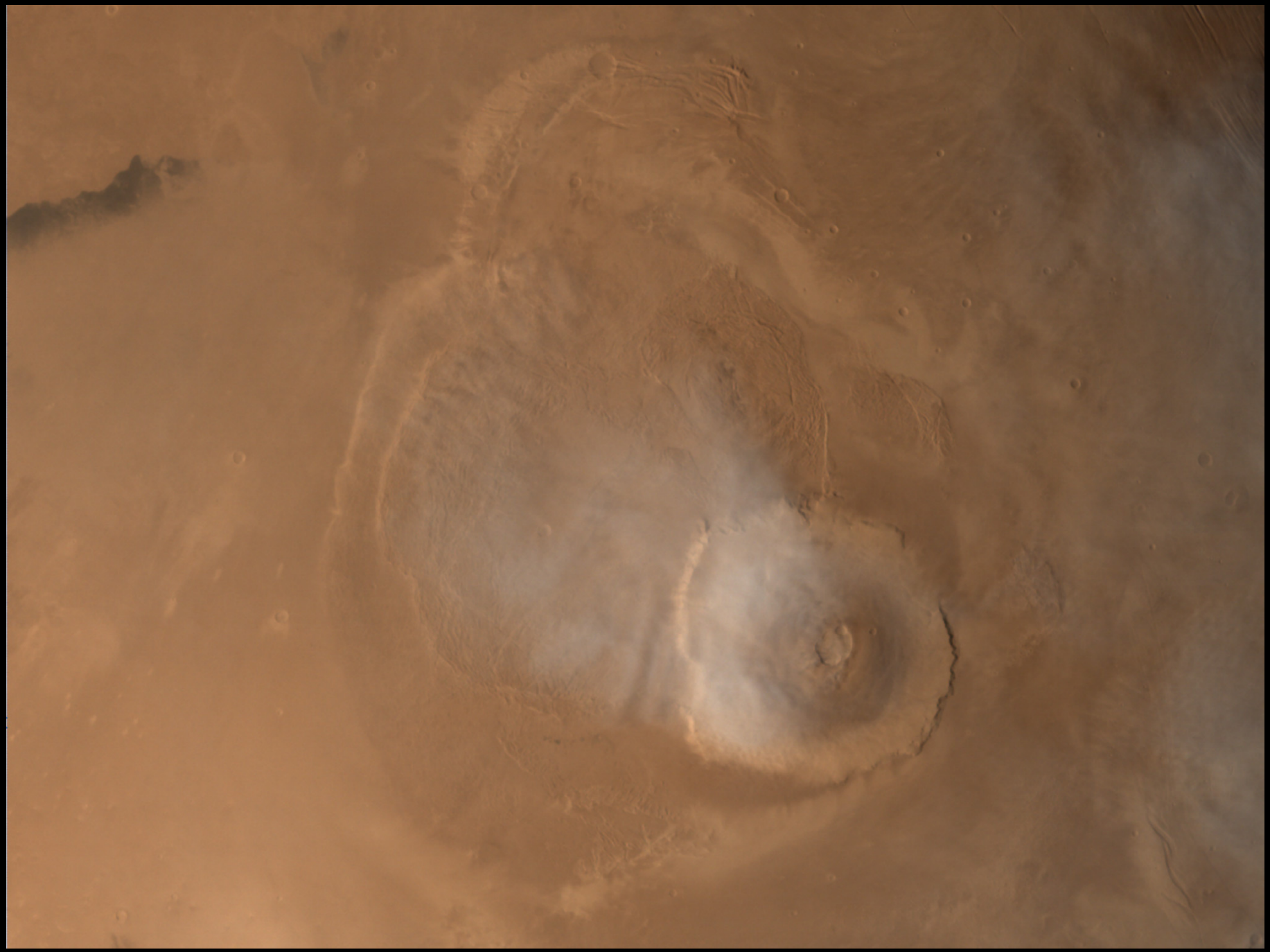
Mt. St. Helens in 2015



Mars: Tharsis vulcanos: Large shield vulcanos, now extinct
$\Longrightarrow$ no plate tectonics $\Longrightarrow$ Mars interior is colder than Earth.

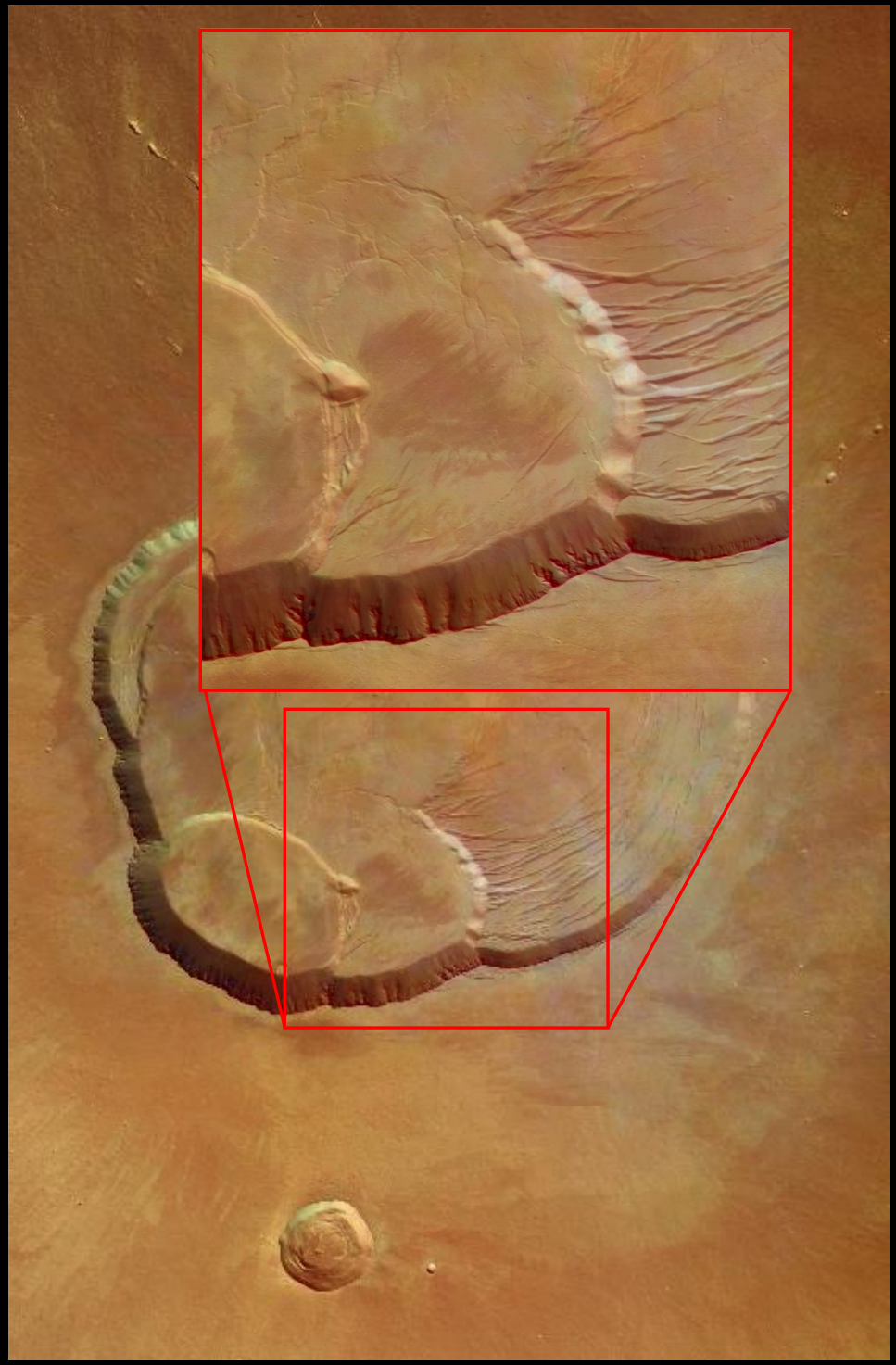


Olympus Mons: highest volcano in solar system
(25 km above surrounding plain; but slope only 2° to 5°).





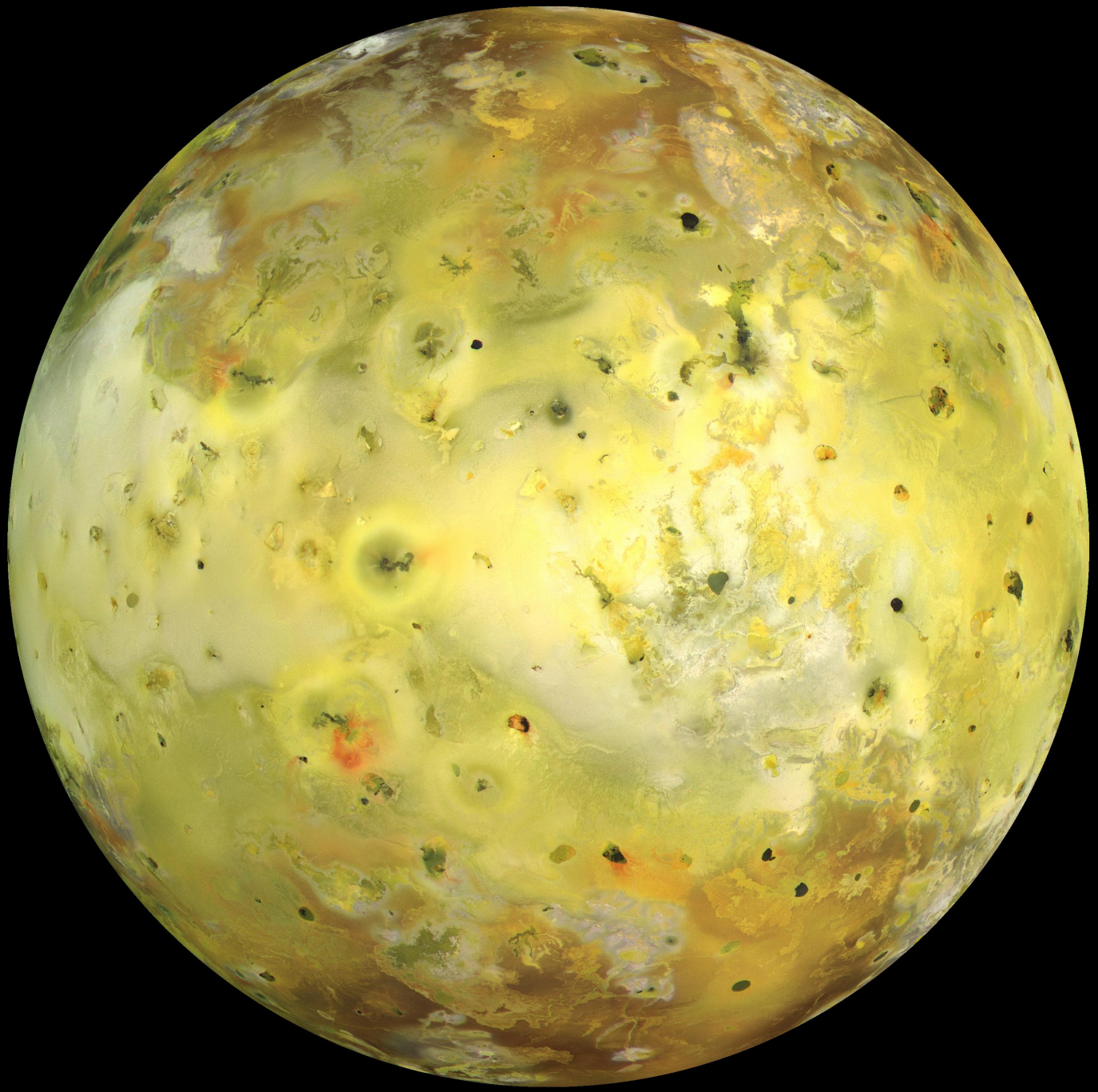
ESA/Mars Express, HRSC, 11.02.2004



ESA/Mars Express, HRSC, 11.02.2004

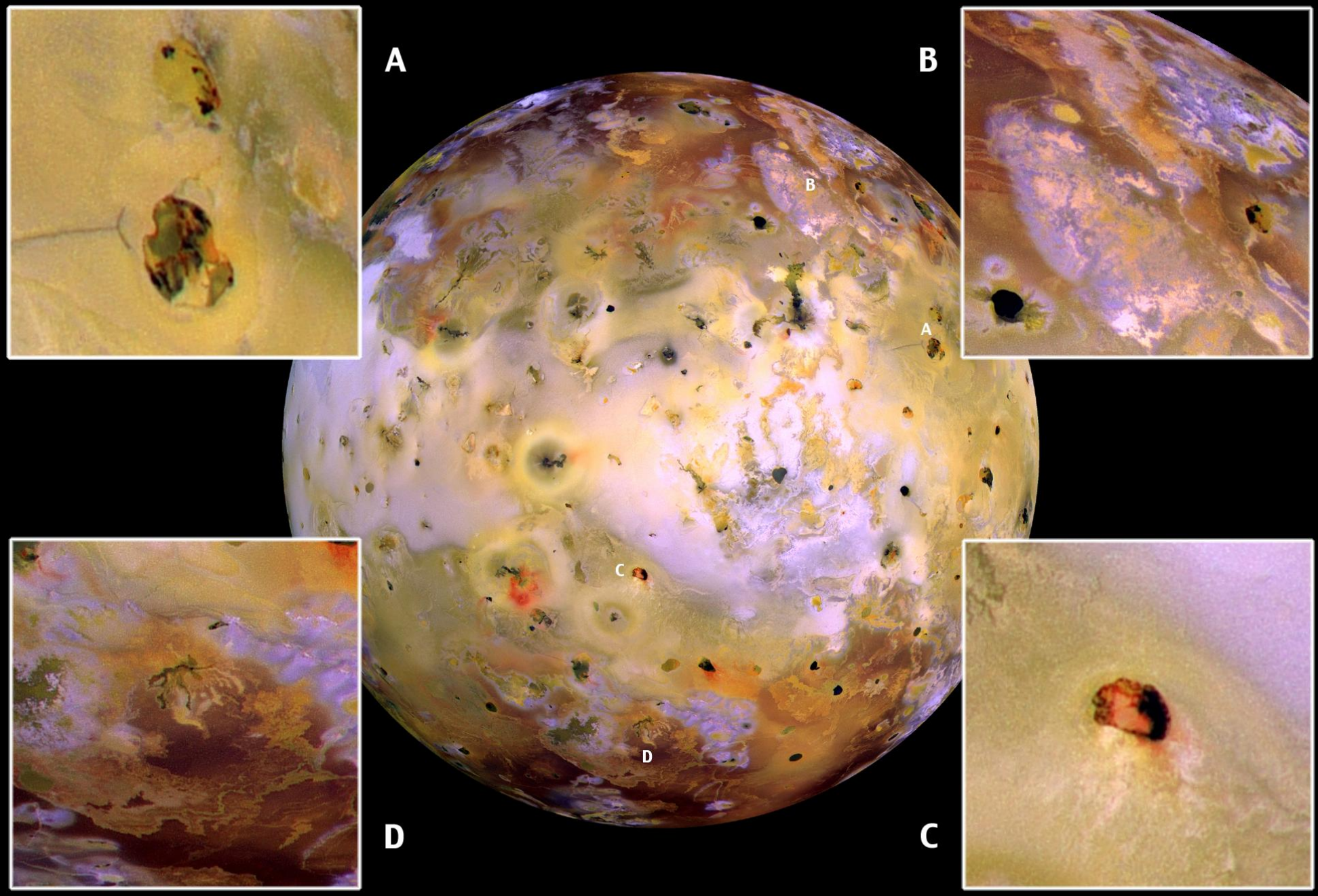


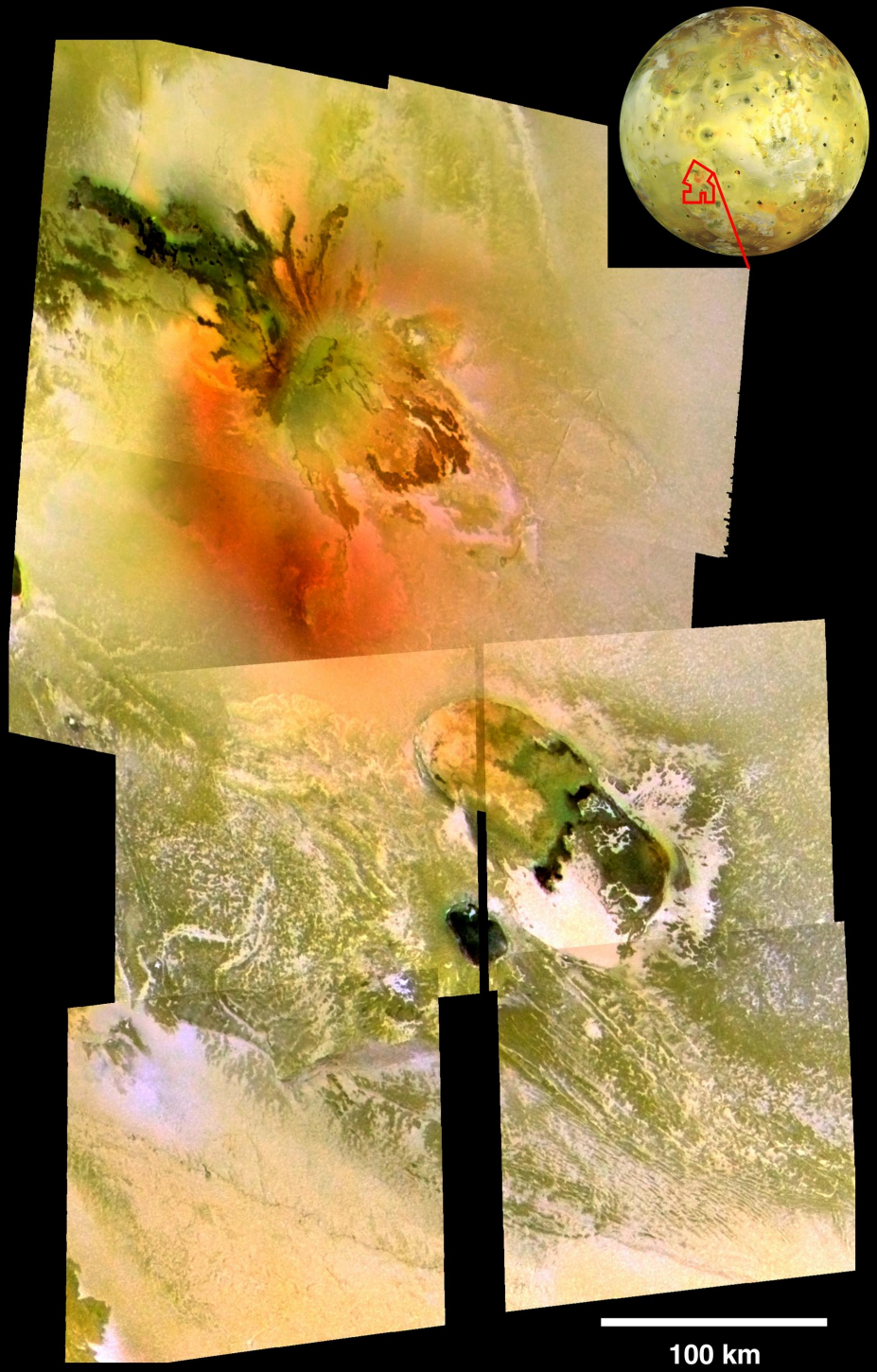
ESA/Mars Express, HRSC, 11.02.2004



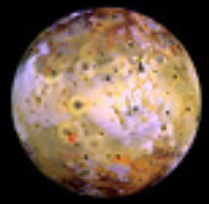
NASA/Galileo (true color)

Jupiter's moon Io – the vulcano moon (Diam. 1821 km [Earth moon: 1738 km])


A
B
C
D
A
B
C
D



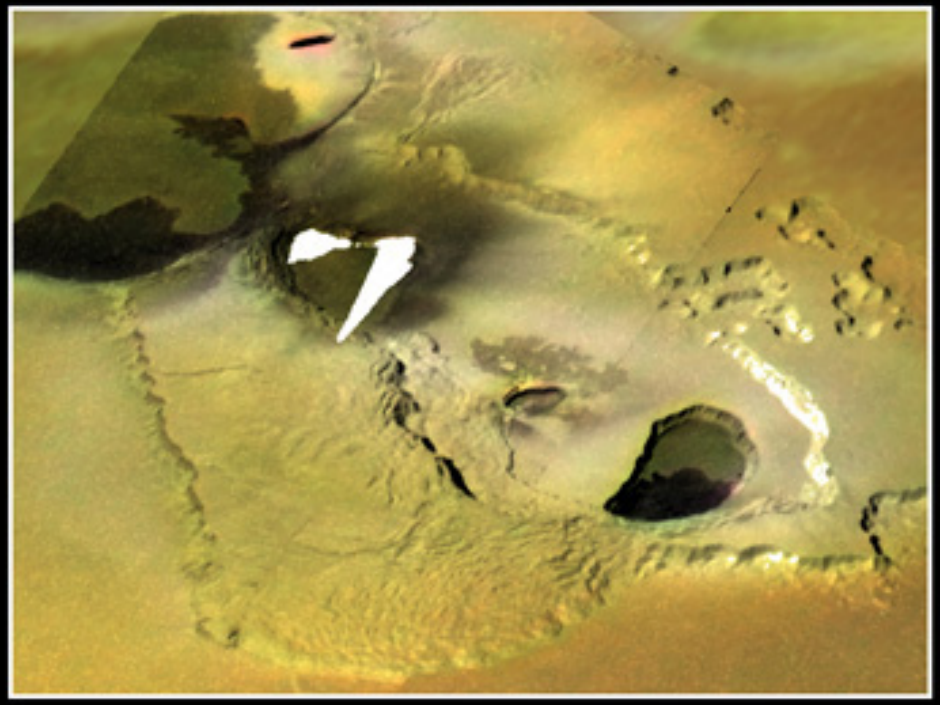
Active vulcanoes on Io (interior heated by tidal forces from Jupiter), color due to large contents of sulphur and sulphur oxides in lava. Height of vulcanoes: 6 km or higher

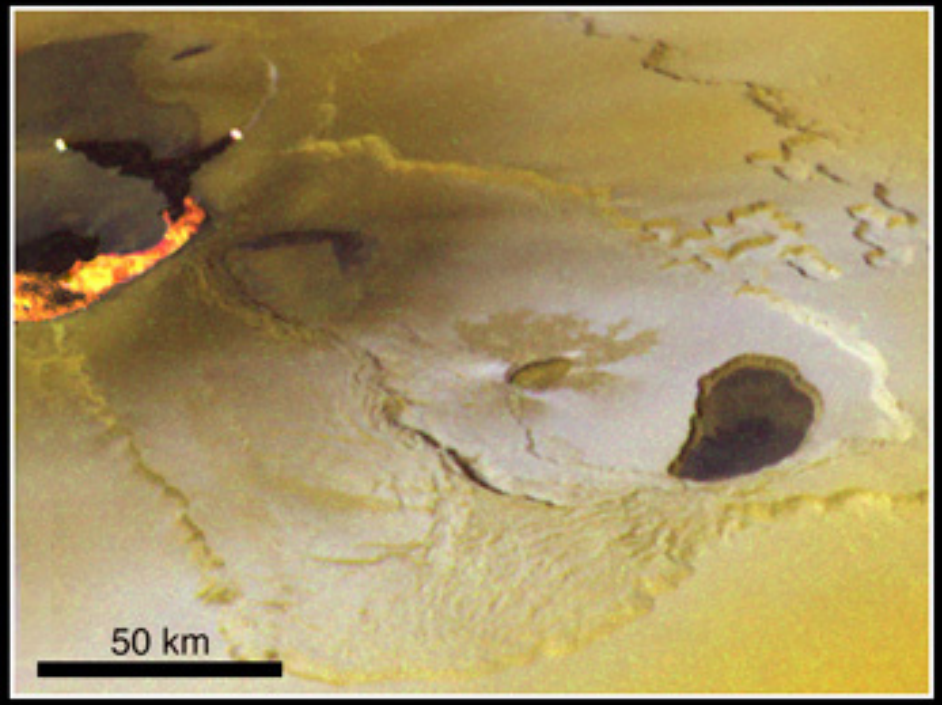


Io — Tvashtar Catena

I25 (26 Nov 1999)
+ C21 low-resolution color

I27 (22 Feb 2000)
visible wavelength data
+ IR data of active lava flow

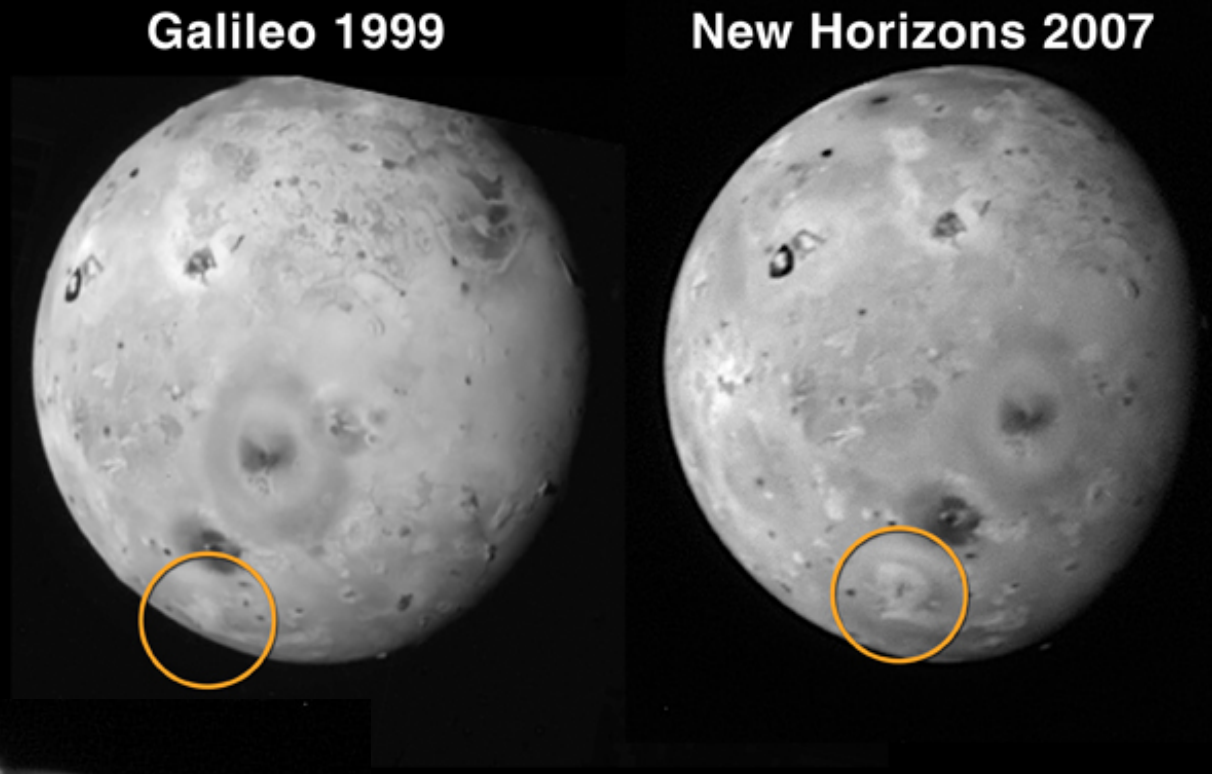


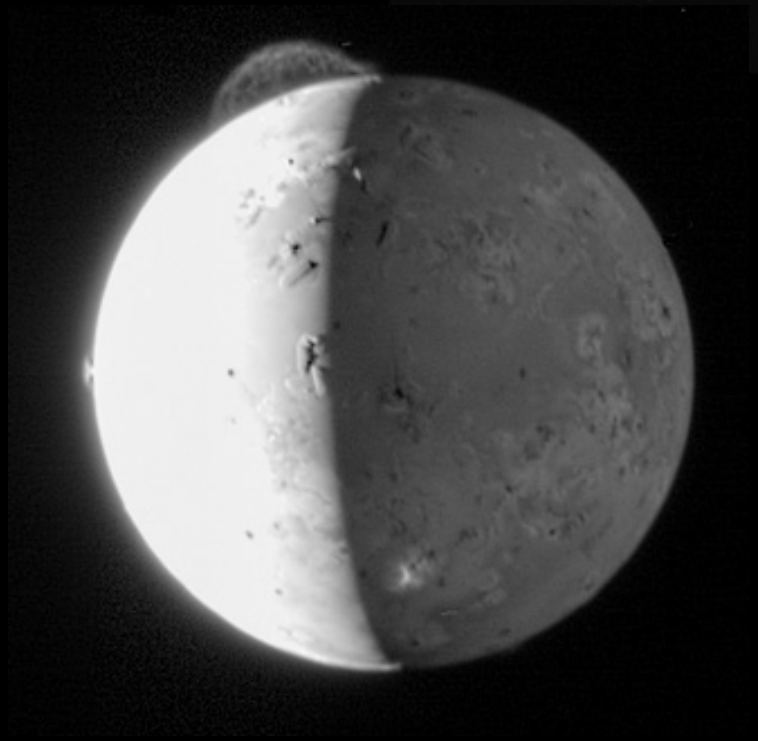


curtains of lava fountains [white: overexposed]
NASA Galileo, 1999 Nov 26, Tvashtar vulcano

High temperature volcanism (2000 K; hotter than on Earth [1700 K]!)

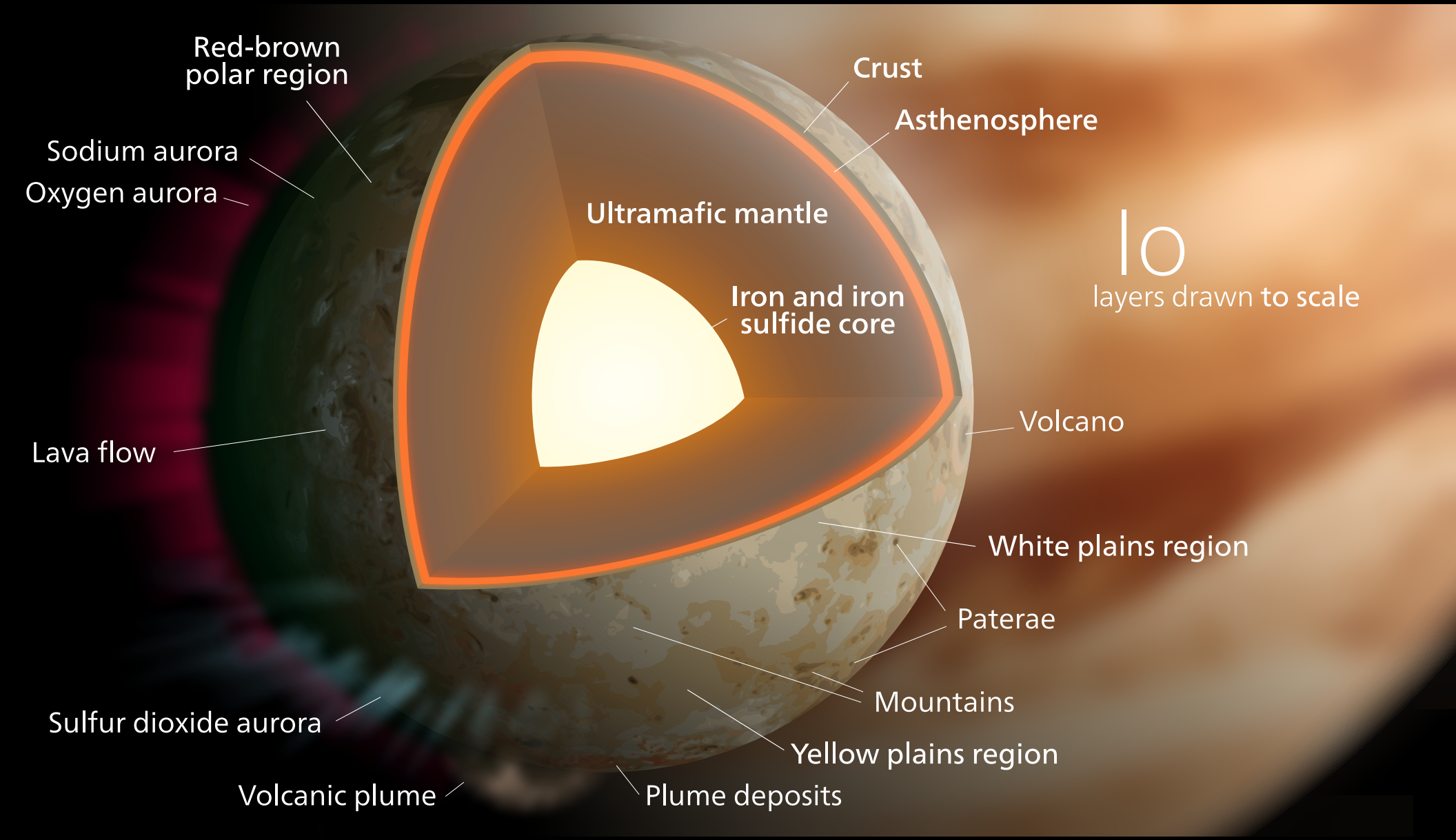
Io Surface Changes



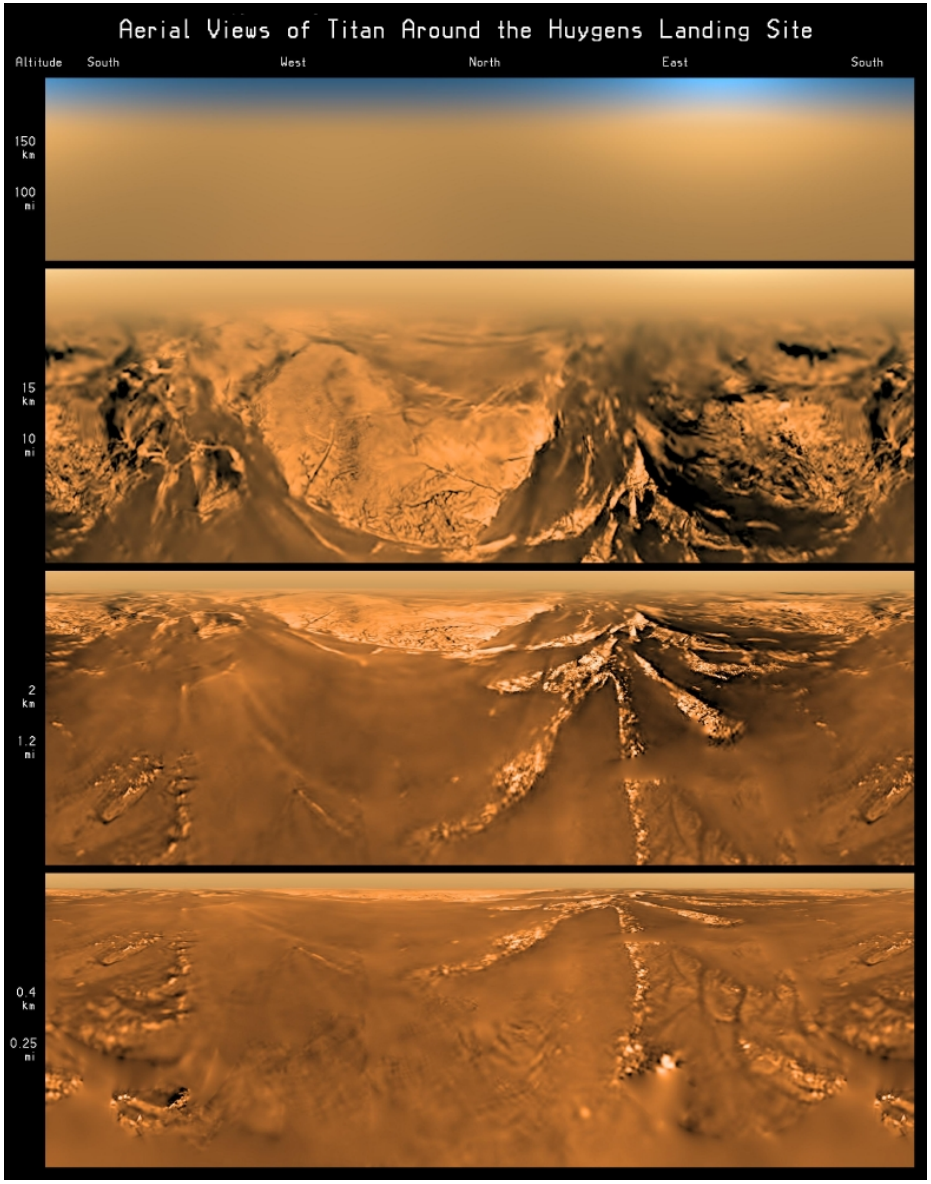


Eruption of Tvashtar during 2007 New Horizons Fly By

Plumes: very symmetric, as Io does not have an atmosphere
$\Longrightarrow$ parabolic trajectories


Red-brown polar region
Sodium aurora
Oxygen aurora
Crust
Asthenosphere
Ultramafic mantle
Iron and iron sulfide core
Io
layers drawn to scale
Lava flow
Volcano
White plains region
Paterae
Mountains
Sulfur dioxide aurora
Yellow plains region
Volcanic plume
Plume deposits

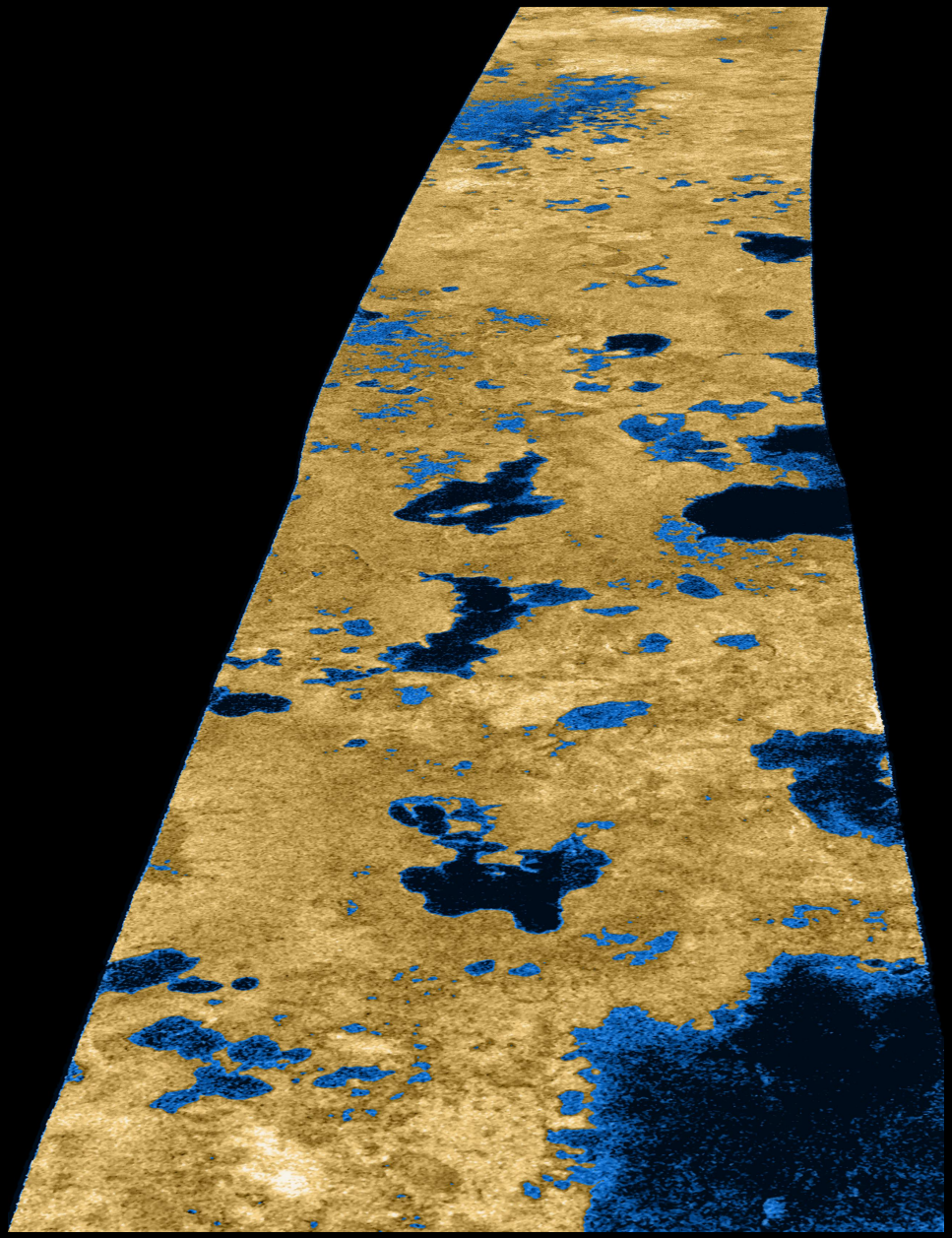
Titan



Titan:

- Huyghens lander: pictures from descent
- Radius: 2575 km second largest moon, larger than Mercury!

Credit: ESA/NASA/JPL



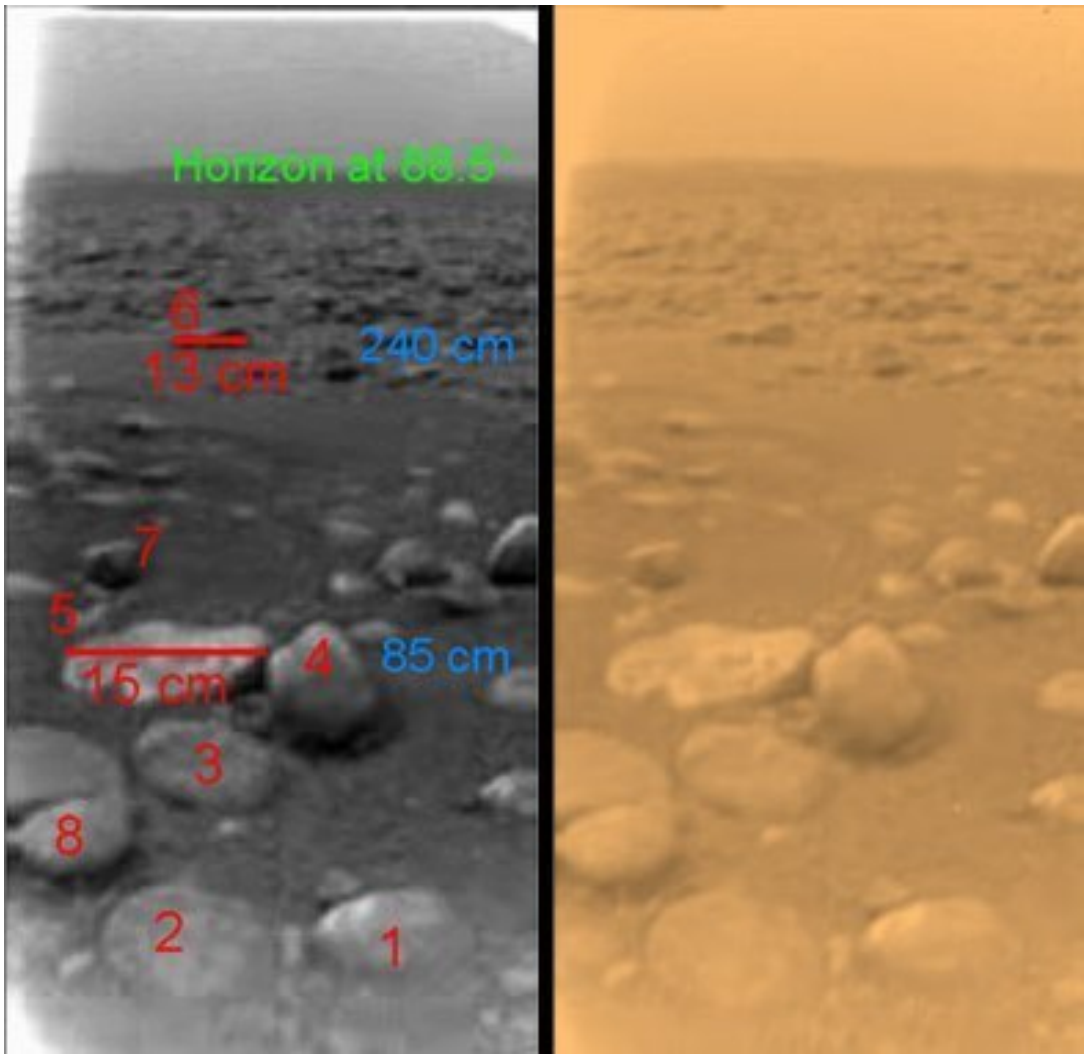
Cassini-Huygens, ESA/NASA/JPL

Saturn's Moon Titan:

Methane lakes.

Cryovolcanism (methane geysers)

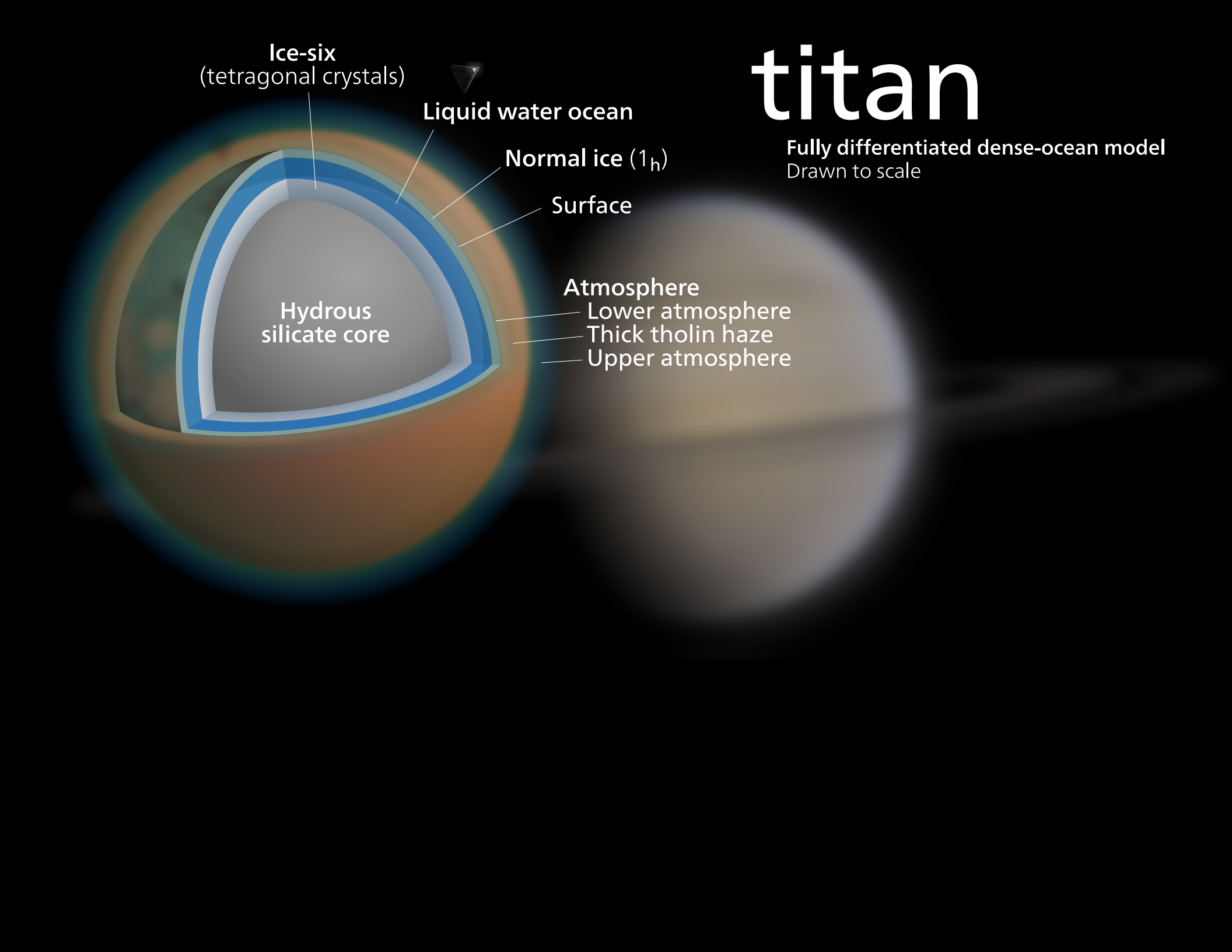
Titan

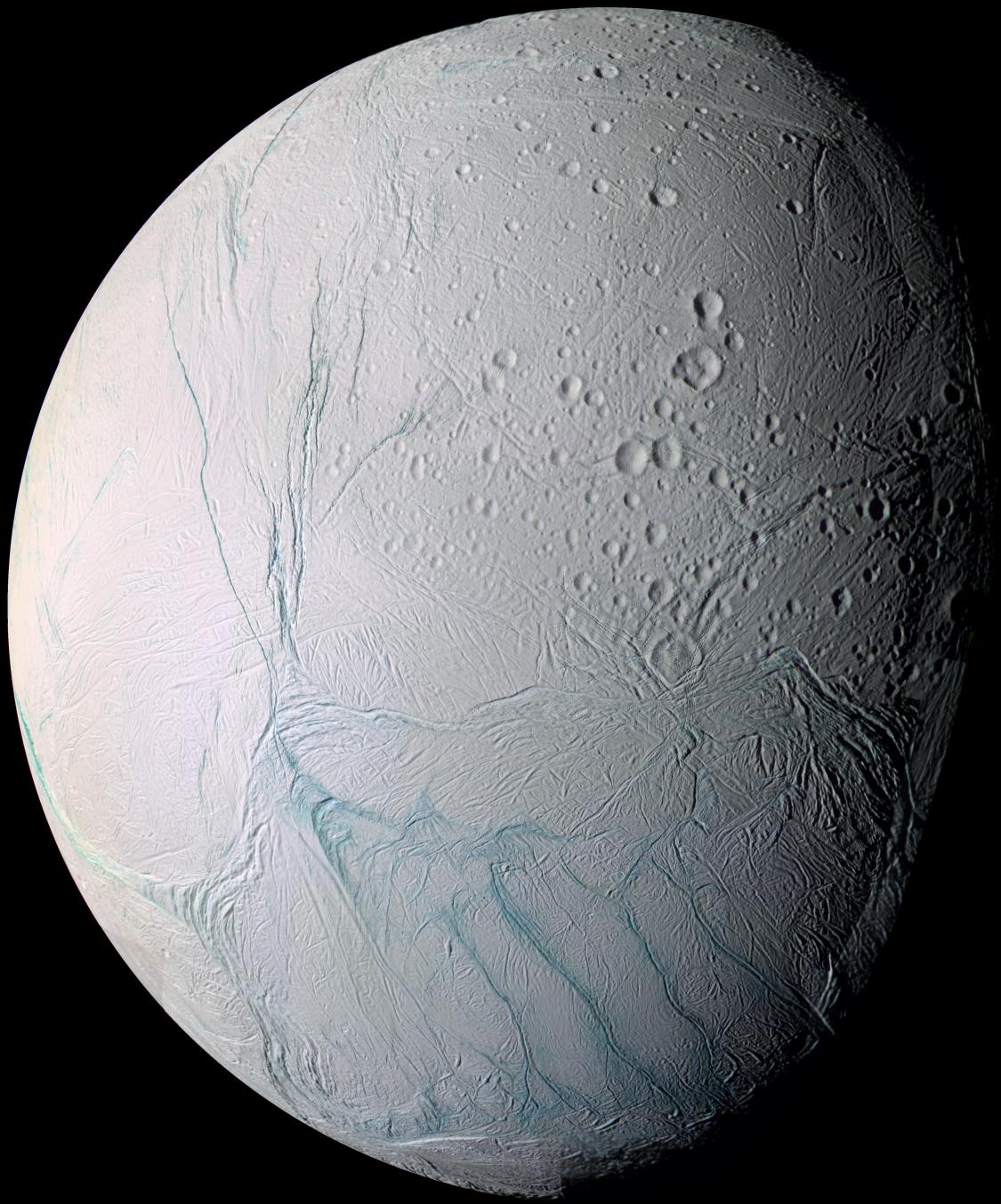


Titan:

- Huyghens lander: pictures from landing site.
- Methan/water ice
- River bed?

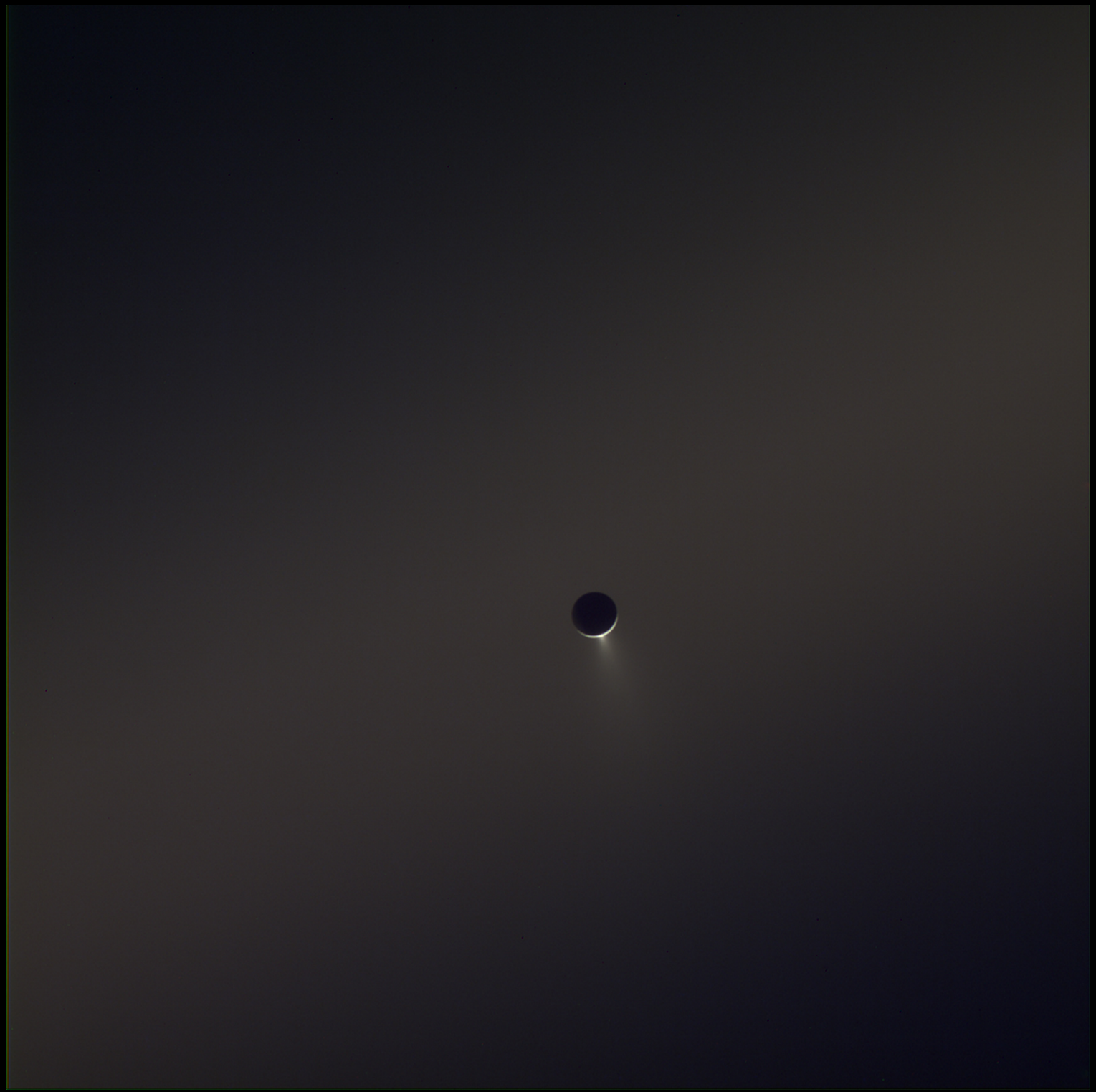
Credit: ESA/NASA/JPL

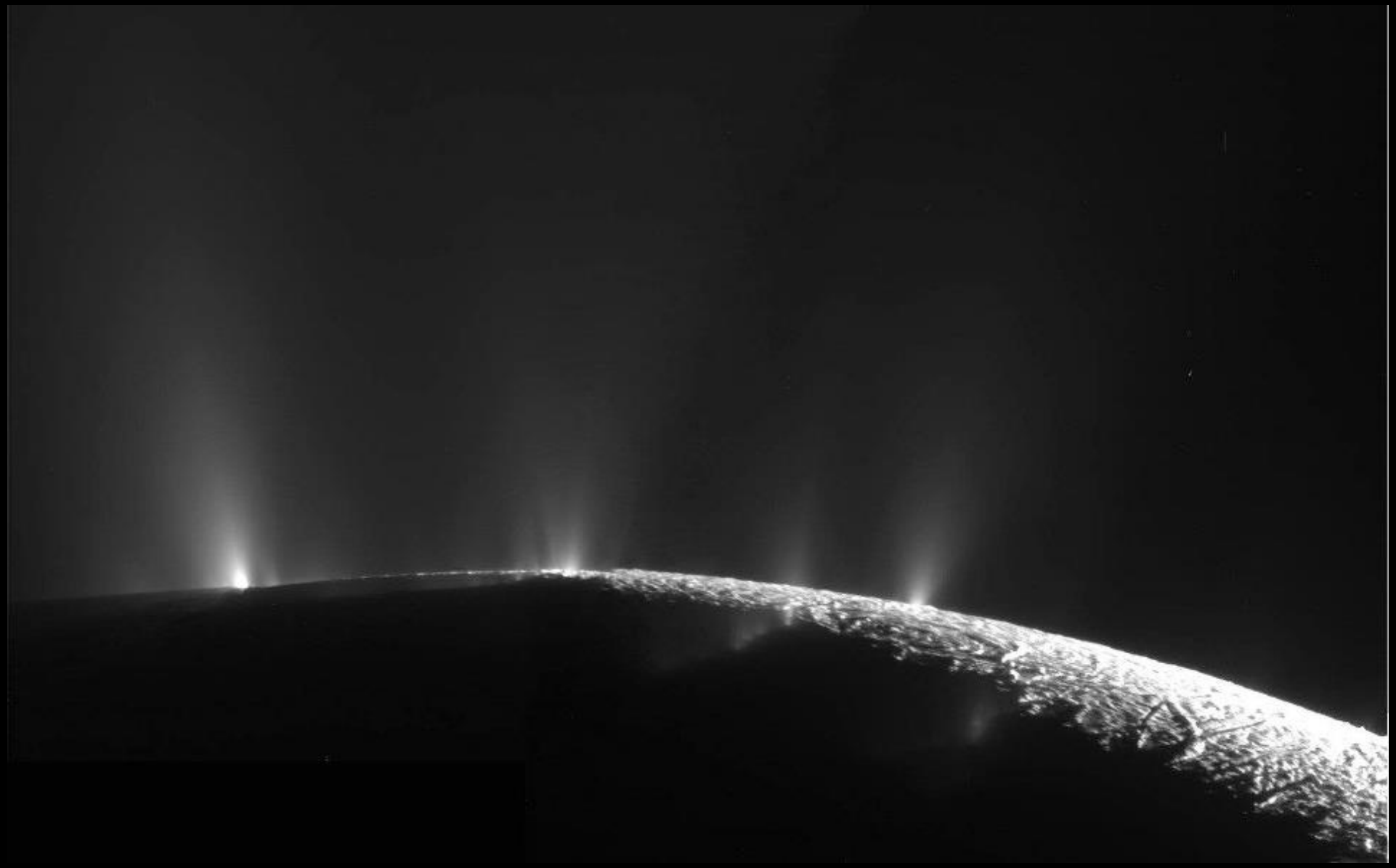

Ice-six
(tetragonal crystals)
Liquid water ocean
Normal ice (1_h)
Surface
Hydrous
silicate core
Atmosphere
Lower atmosphere
Thick tholin haze
Upper atmosphere
titan
Fully differentiated dense-ocean model
Drawn to scale



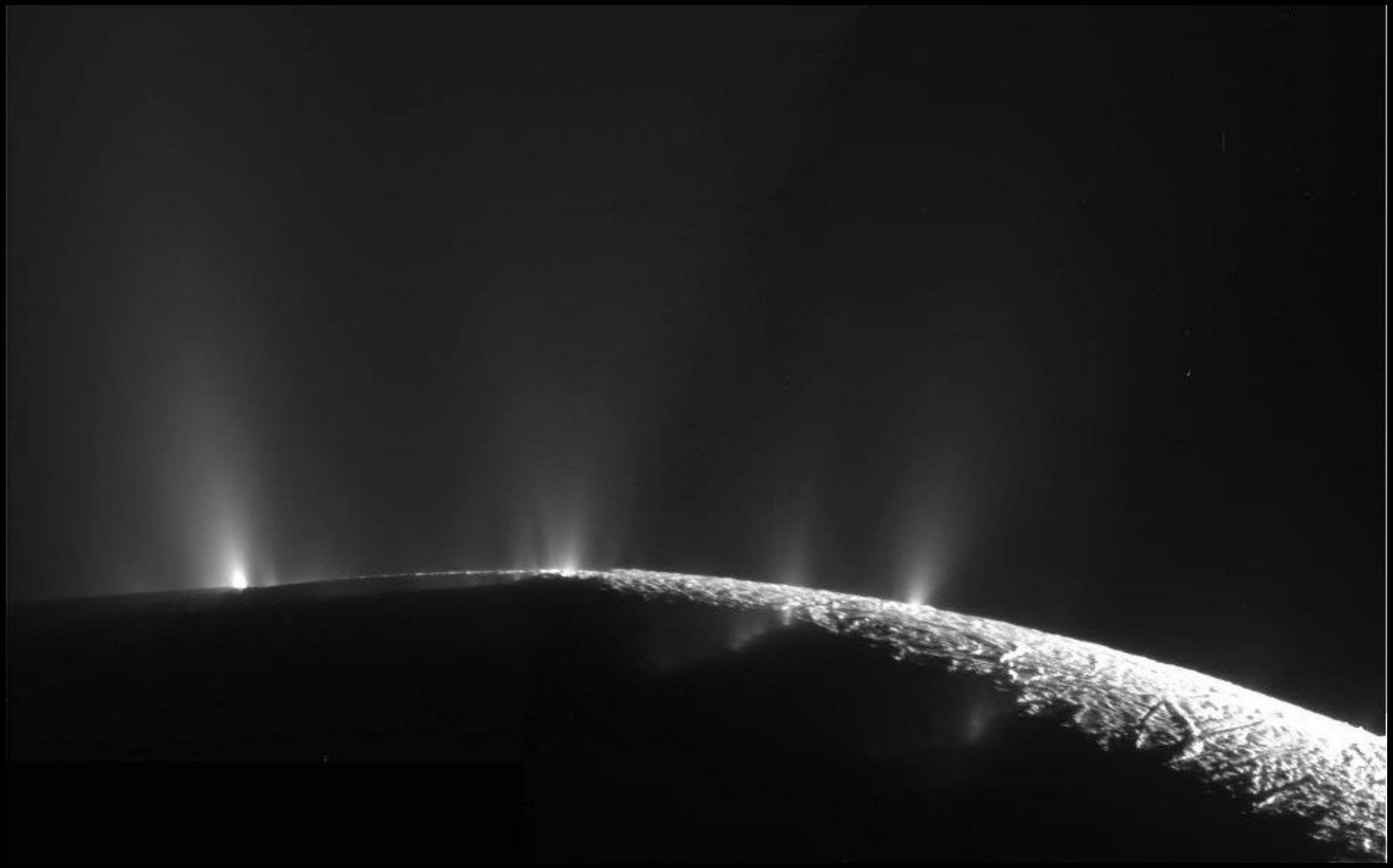
Saturn: Enceladus: ice surface w/cracks – evidence for an ocean below?

similar to Europa





Enceladus' cracks appear to show geyser activity



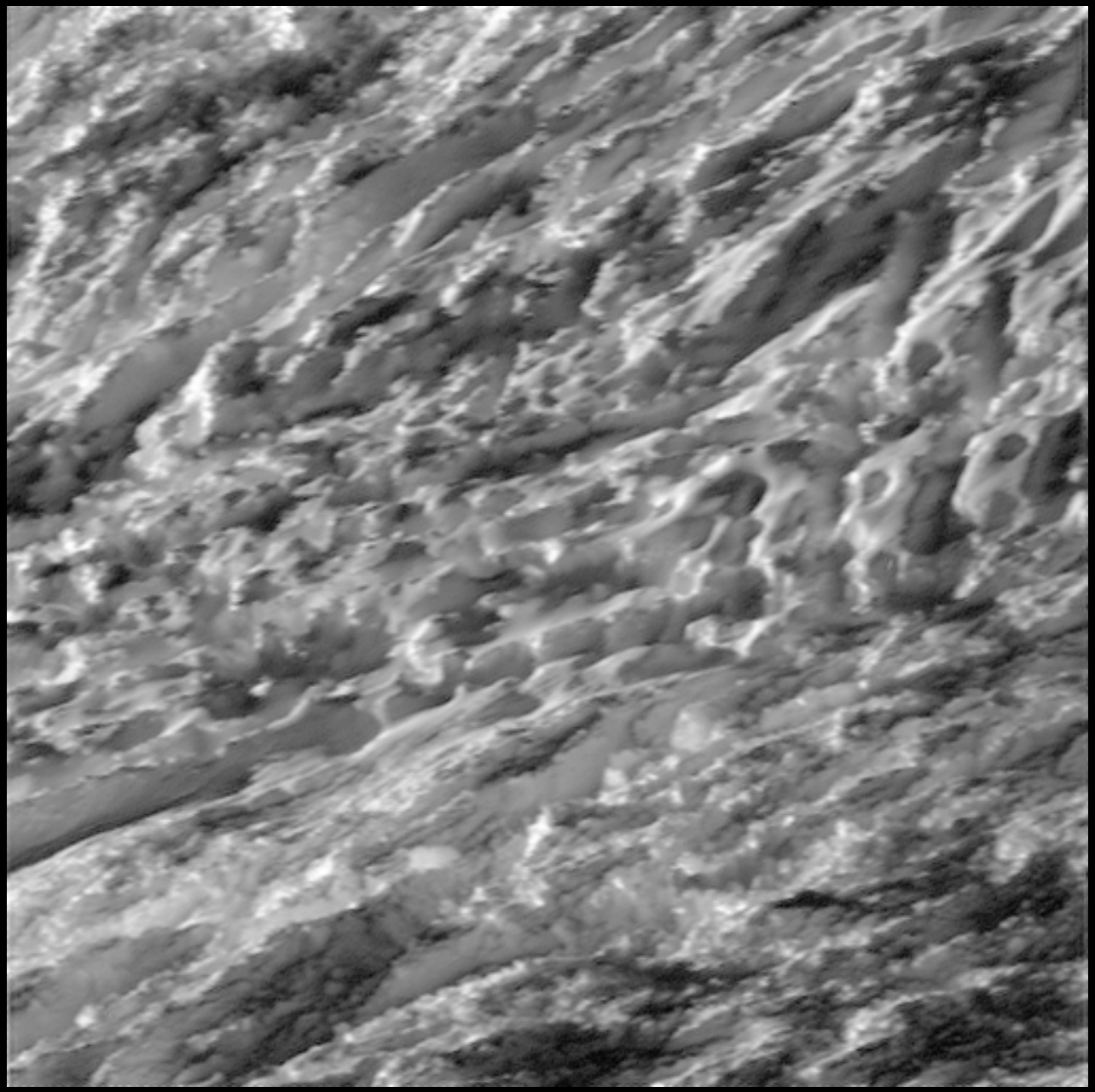
Enceladus' cracks appear to show geyser activity

Flyby of Cassini on 2015-10-28: dive through active plume



NASA/JPL

Deep dive through active plume



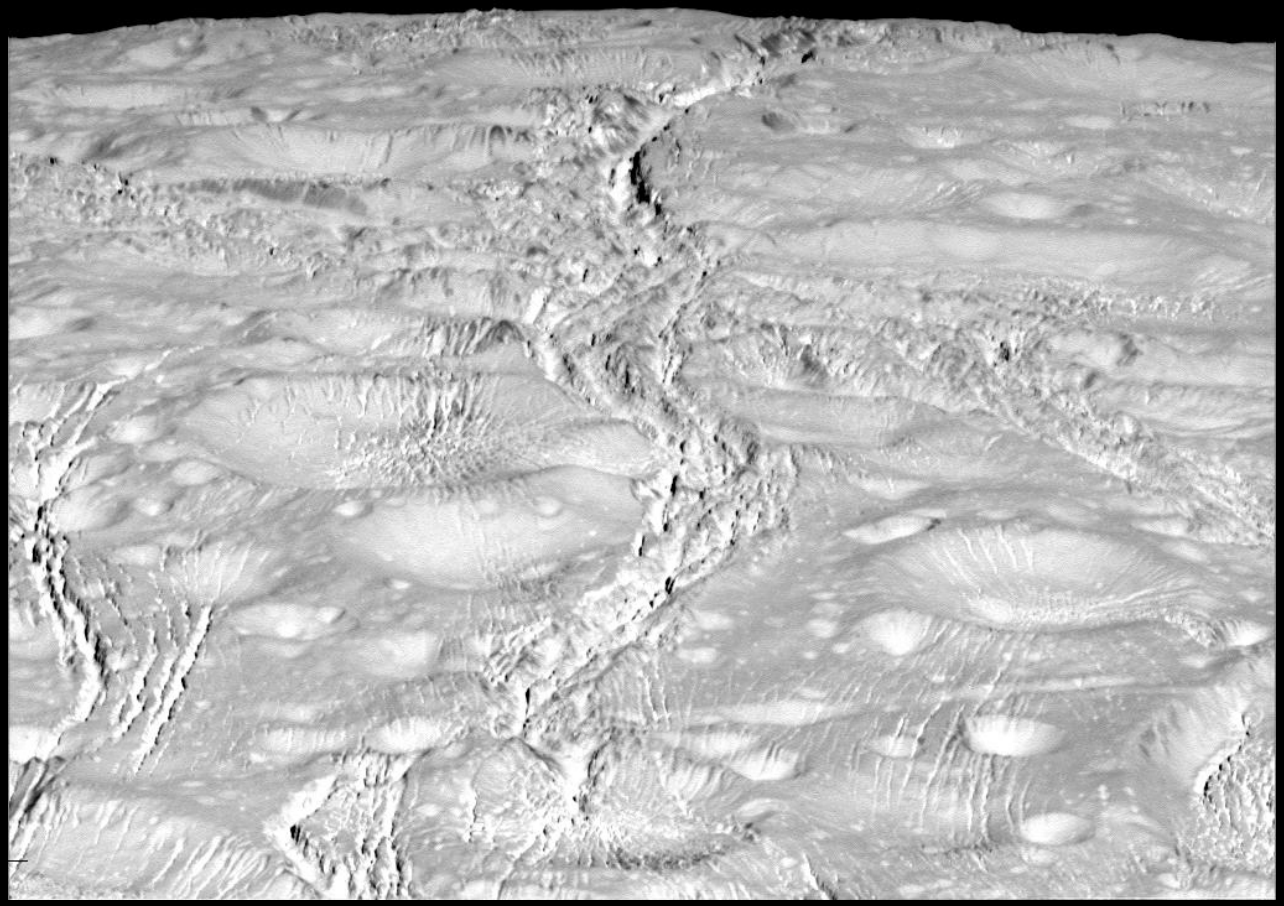
NASA/JPL

Surface near south pole of Enceladus



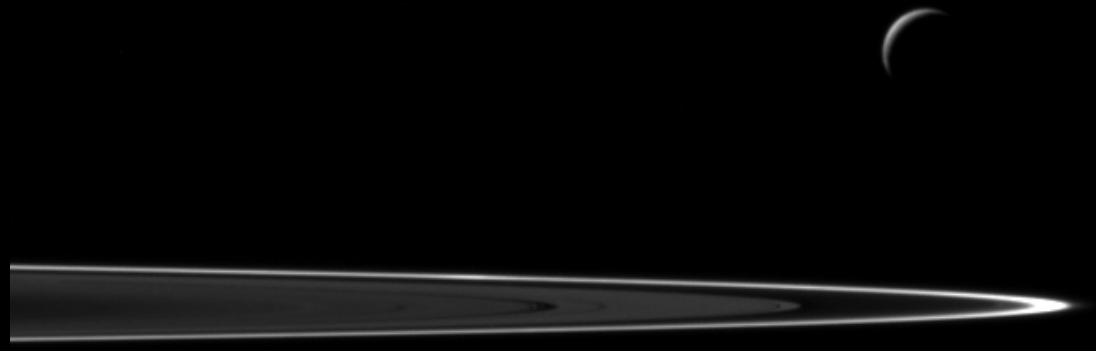
NASA/JPL

Craters and thin fractures (northern hemisphere)



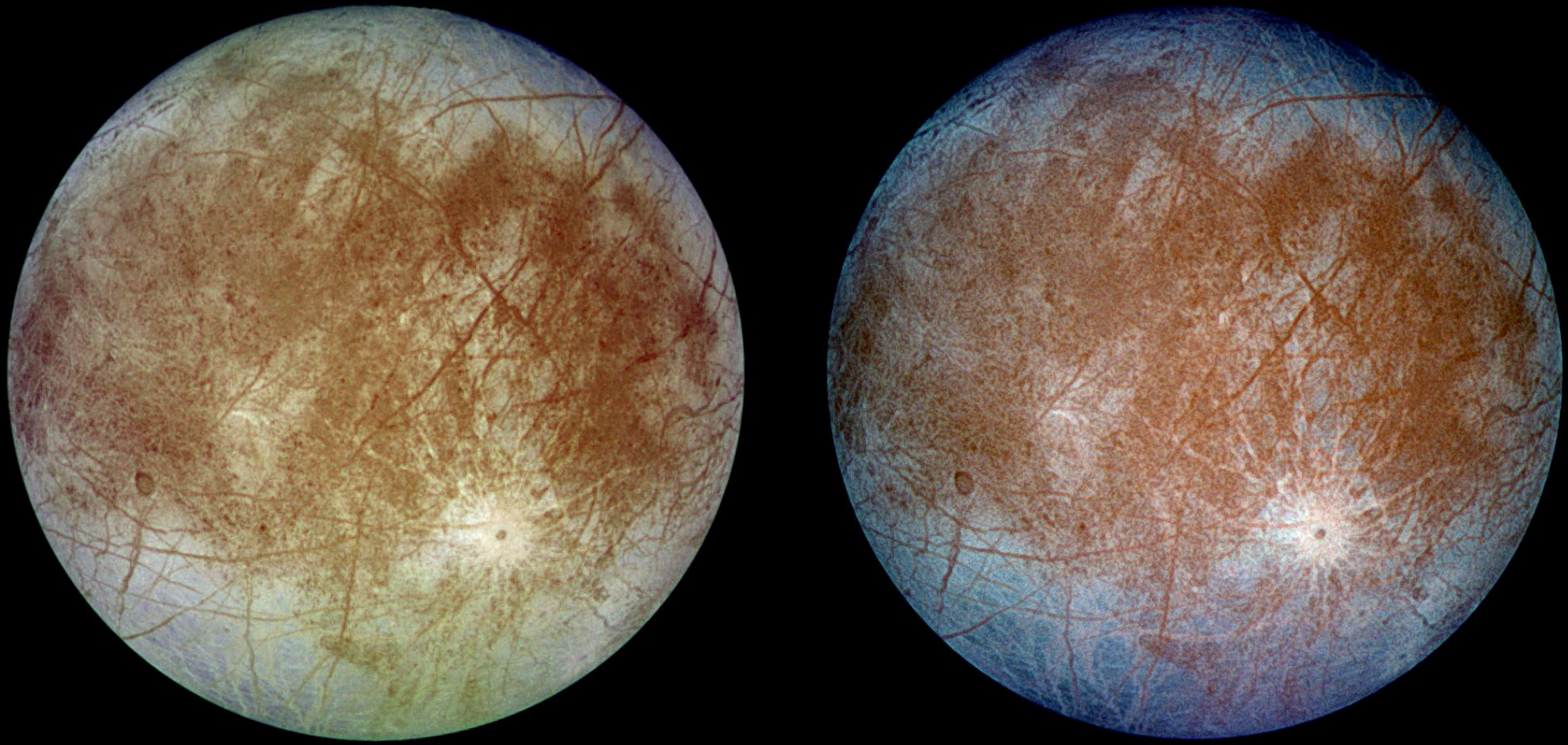
NASA/JPL

Surface near north pole of Enceladus

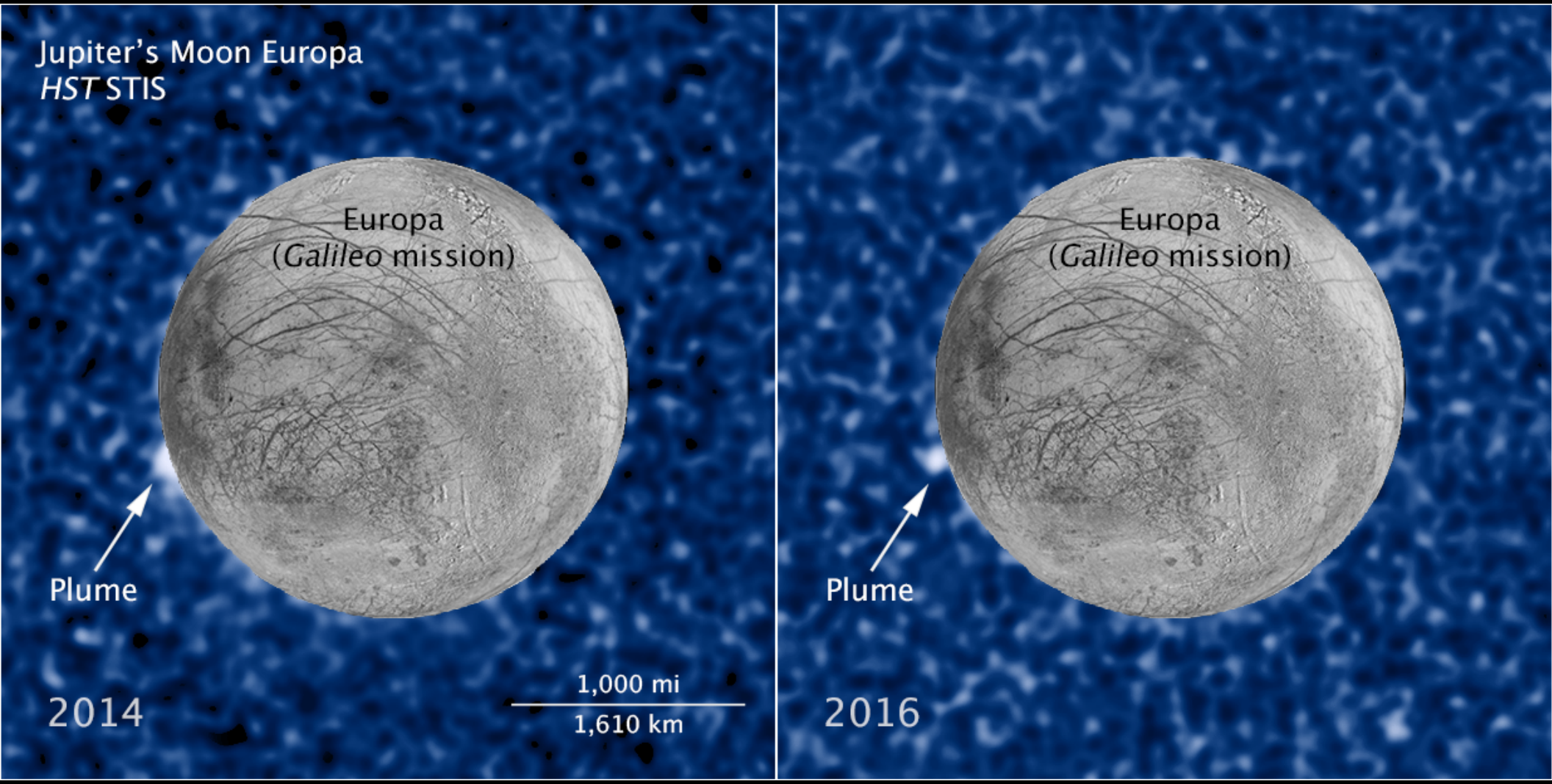


NASA/JPL

Good bye!



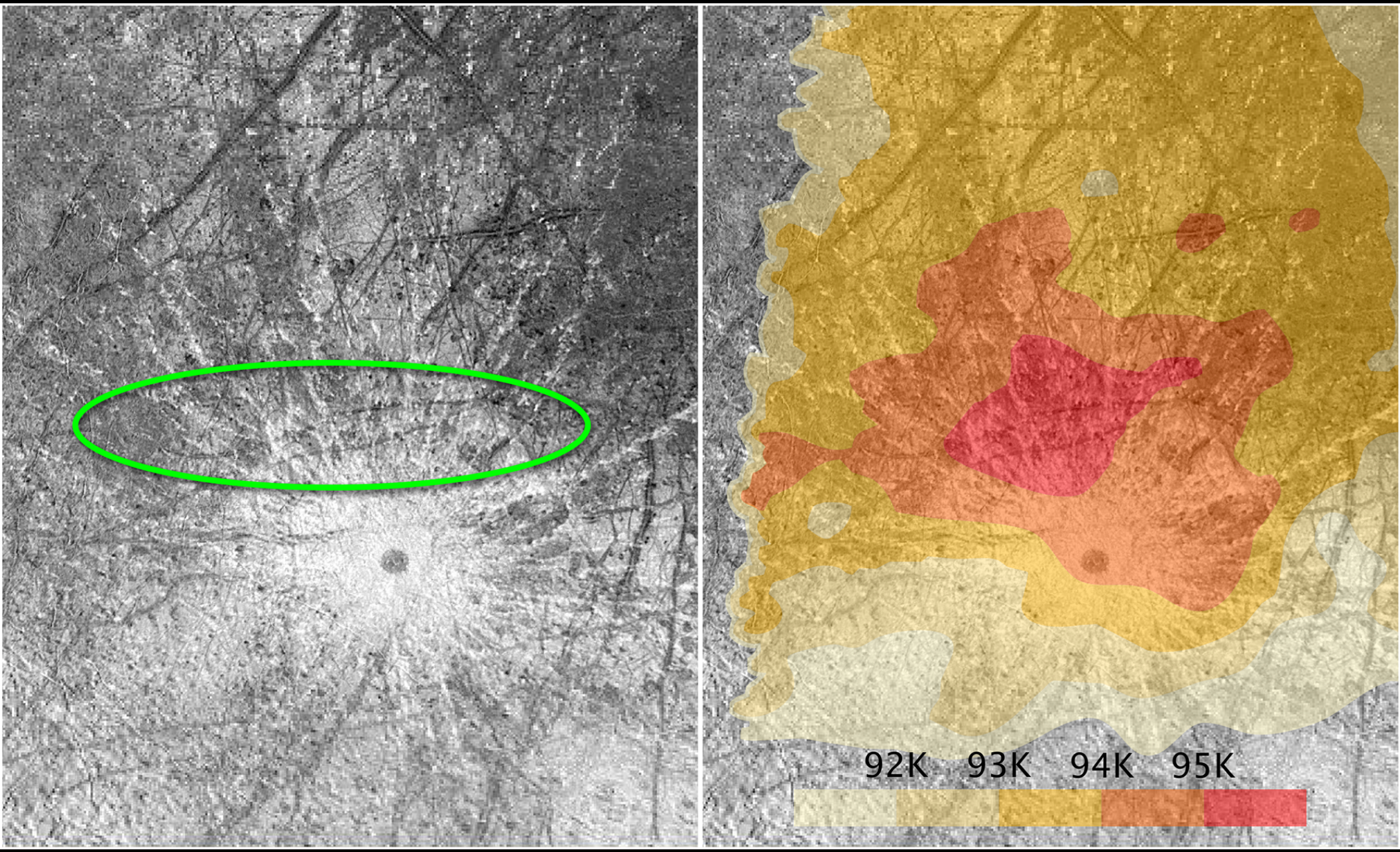
Jupiter Moon Europa: Ice World



STScI

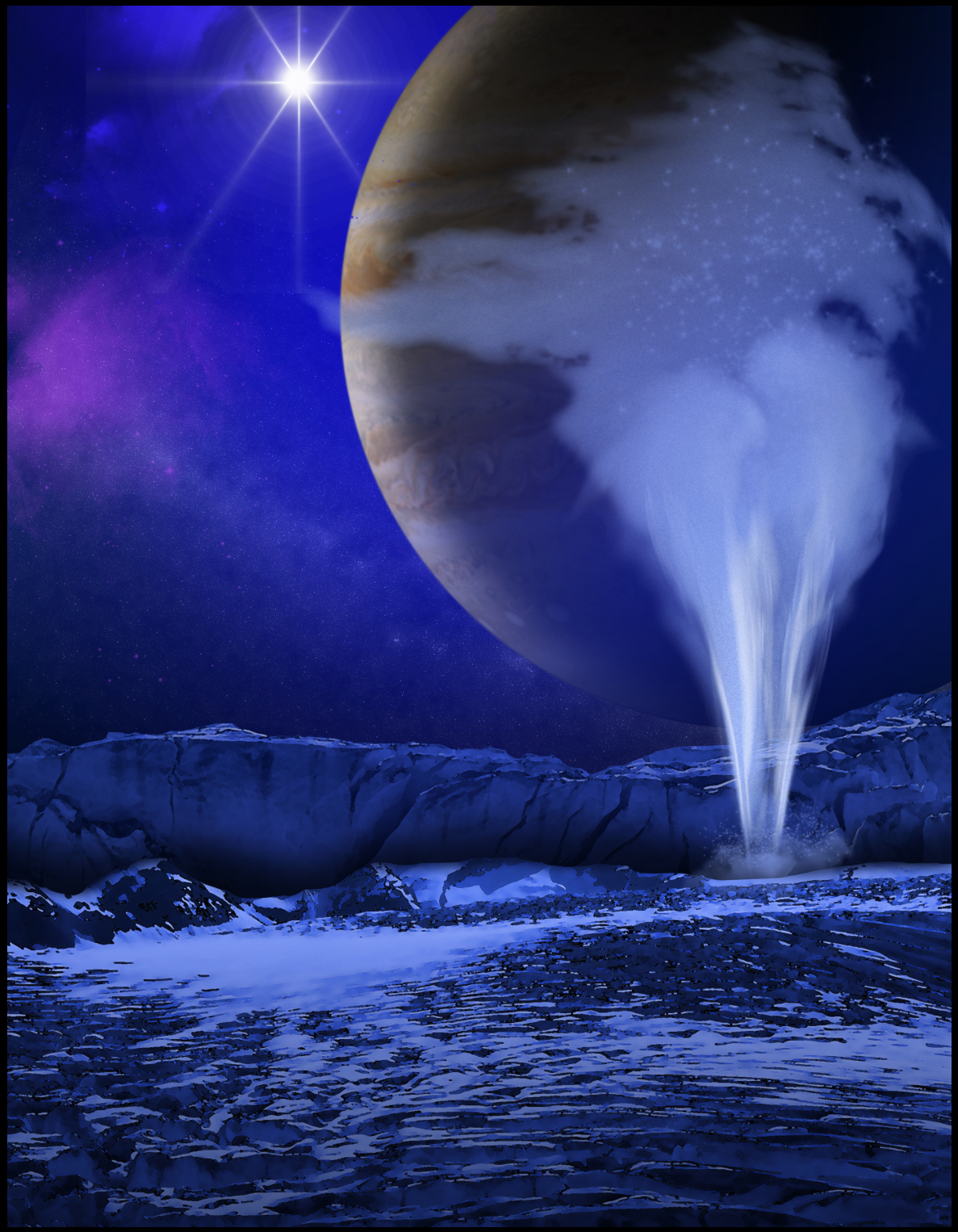
Possible evidence for geysers (similar to Enceladus)

Target of NASA's Europa Clipper mission (launch: ~2025)

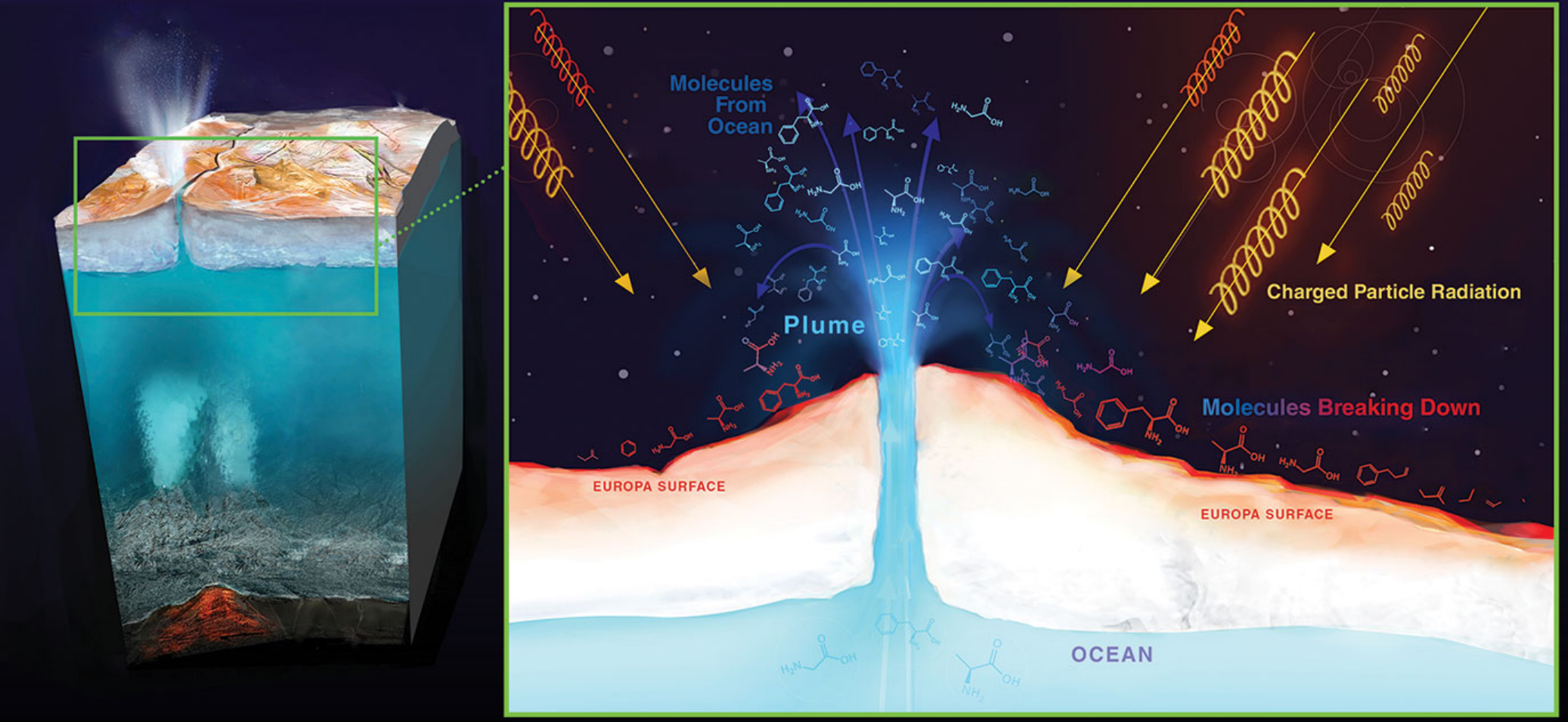


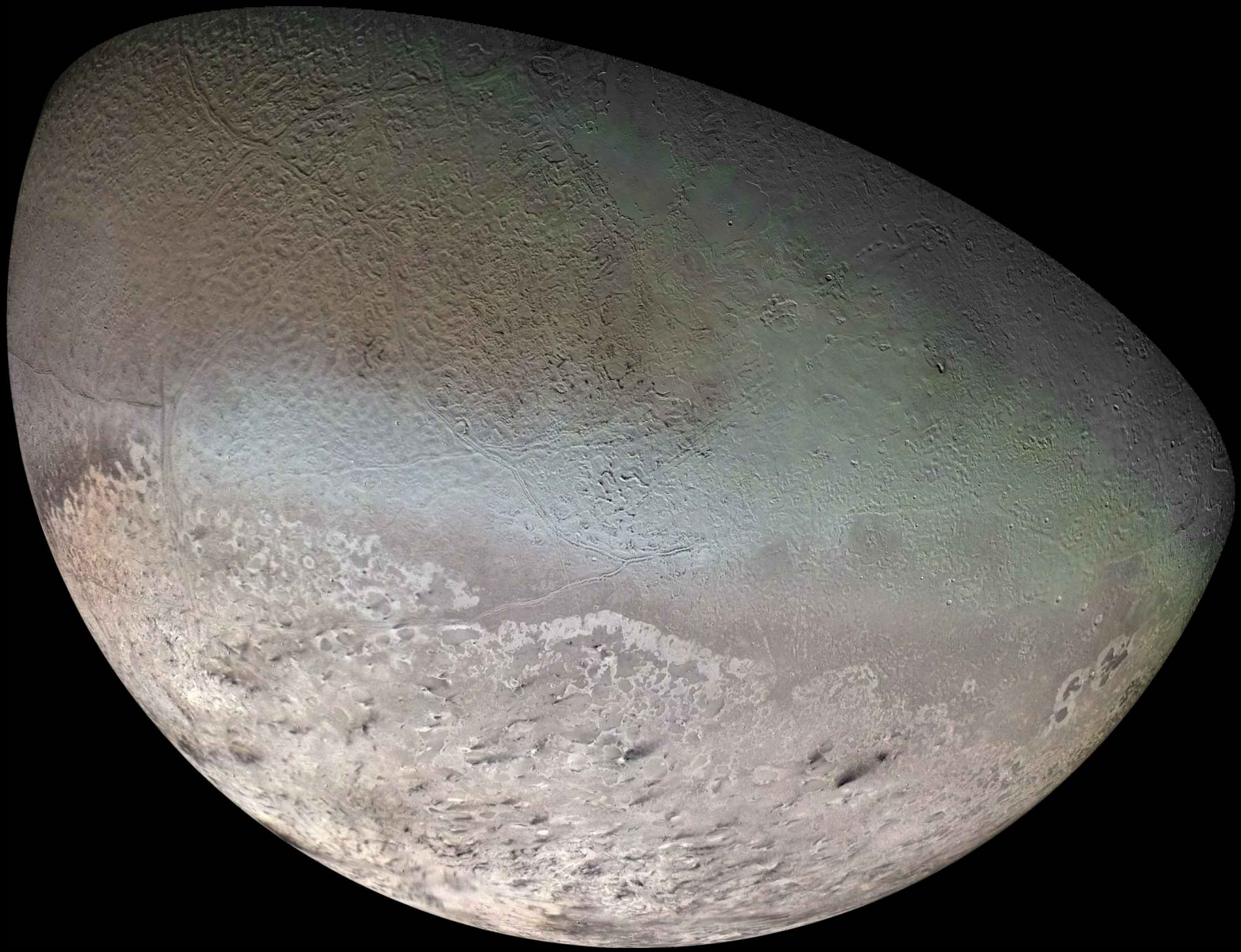
STScI

Plumes associated with known “warm spot” on Europa



NASA/ESA/K. Retherford/SWRI


Molecules From Ocean
Plume
Charged Particle Radiation
Molecules Breaking Down
EUROPA SURFACE
EUROPA SURFACE
OCEAN



NASA/Voyager 2/Calvin J. Hamilton

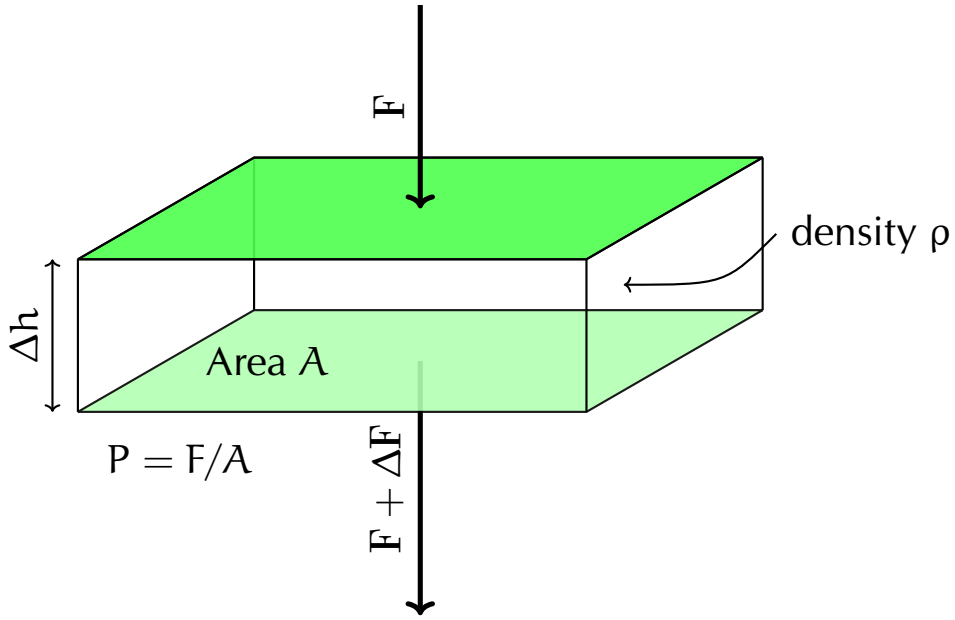
Neptune's Moon Triton:

ice cap of frozen methane (freezing point 90 K) and frozen nitrogen (freezing point 60 K).

Few impact craters $\Longrightarrow$ young surface $\Longrightarrow$ volcanism (dark spots: nitrogen geysers with T $\sim$ 70 K)

Atmospheres

Structure of atmosphere defined through hydrostatic equilibrium:



Force on area A by slab of gas of area A and density ρ:

$$F = mg = \rho V g = A h \rho g \qquad (3.4)$$

With $P = F/A$ one finds:

$$\frac{dP}{dh} = -\rho g \qquad (3.5)$$

where g gravitational acceleration.

Atmospheres

$$\frac{dP}{dh} = -\rho g \tag{3.6}$$

First assume: thin atmosphere $\Longrightarrow$ $g = \text{const.}$.

Need to relate ρ to P: equation of state.

For an "ideal gas":

$$P = (\rho/\mu)kT \tag{3.7}$$

where T is the Temperature (K!), μ the average mass of a gas particle, and k is Boltzmann's constant ($k = 1.38 \times 10^{-23}\,J\,K^{-1}$). Therefore:

$$\frac{dP}{dh} = -\left(\frac{\mu g}{kT}\right) P \tag{3.8}$$

where $P = P_0$ at $h = 0$.

Atmospheres

To solve

$$\frac{dP}{dh} = -\left(\frac{\mu g}{kT}\right) P \tag{3.9}$$

we use the method of "separation of variables":

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First, divide by P and integrate both sides of the equation with respect to height:

$$\int_0^h \frac{1}{P}\frac{dP}{dh}\,dh = -\int_0^h \left(\frac{\mu g}{kT}\right) dh$$

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$$\int_0^h \frac{1}{P}\frac{dP}{dh}\,dh = -\int_0^h \left(\frac{\mu g}{kT}\right) dh$$

Substitute $P(h)$ for h on the left hand side. Using the chain rule gives

$$\int_{P_0}^{P(h)} \frac{dP'}{P'} = -\int_0^h \left(\frac{\mu g}{kT}\right) dh$$

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$$\ln\left(\frac{P(h)}{P_0}\right) = -\left(\frac{\mu g}{kT}\right) h$$

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Exponentiating then gives

$$P(h) = P_0 \exp\left(-\frac{\mu g}{kT}\cdot h\right) = P_0 \exp\left(-\frac{h}{H}\right) \tag{3.10}$$

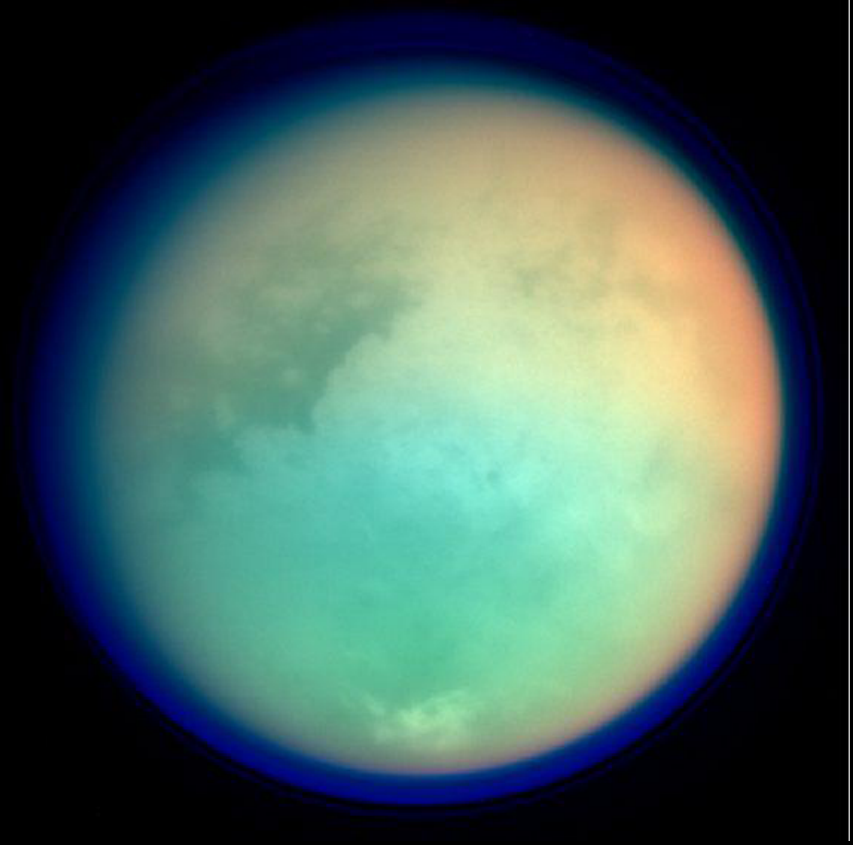
Atmospheres

Typical H for the inner planets (Karttunen)

Gas	μ	Venus km	Earth km	Mars km
H_2	2	360	120	290
O_2	32	23	7	81
H_2O	18	40	13	32
CO_2	44	16	5	13
N_2	28	26	8	20
T [K]		750	275	260
g [$m\,s^{-2}$]		8.61	9.81	3.77



NASA Voyager



27.10.2004, false colour IR/UV; NASA/ESA

Titan: dense atmosphere, 99% nitrogen, 1% methane, some hydrocarbons, thought to be similar to primordial atmosphere of Earth!

Radius: 2575 km (~ Mercury!)

ESA probe *Huygens* landed on Titan on 2005 January 14

Atmospheric Composition

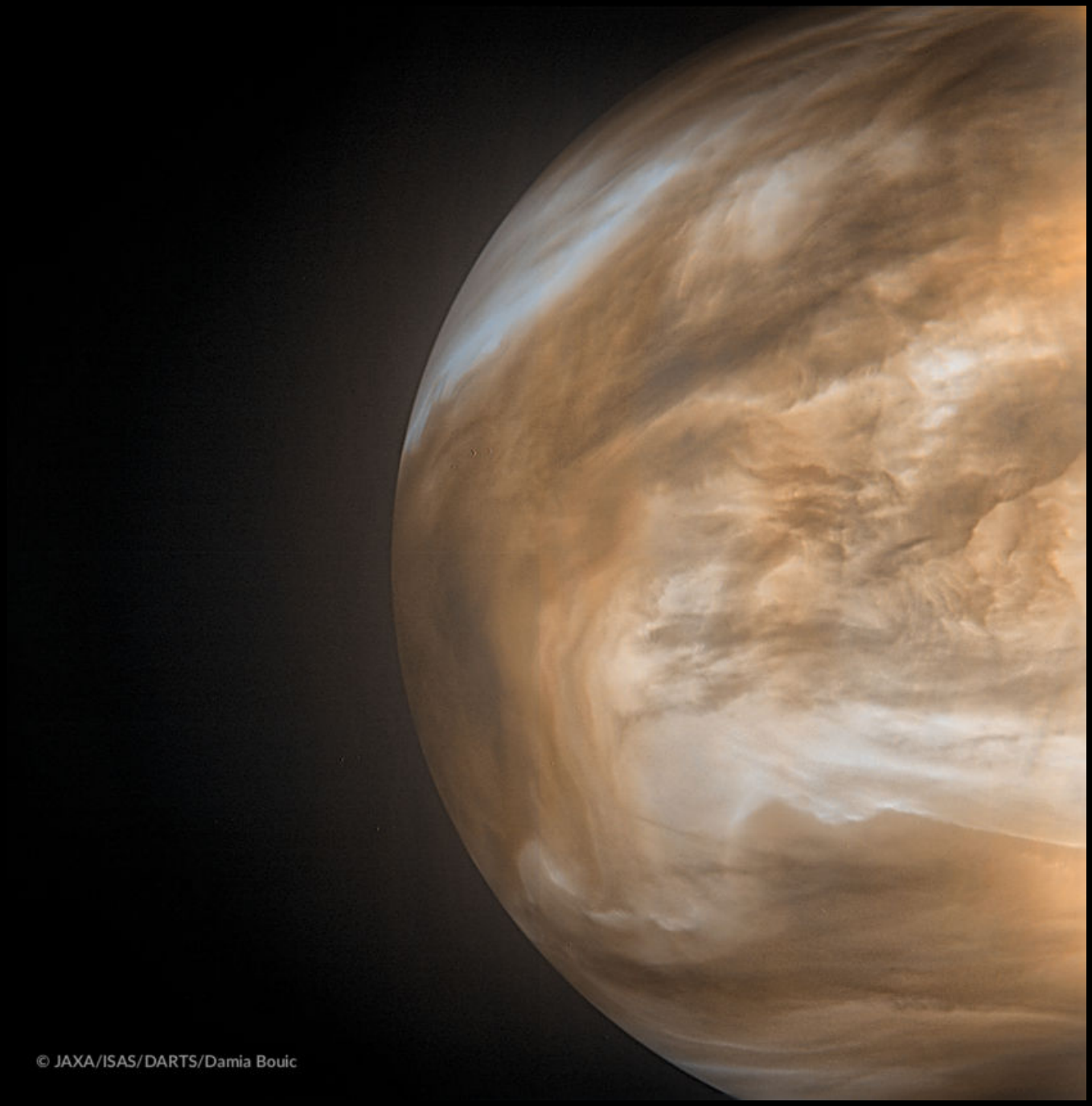
Atmospheric composition of selected terrestrial objects

	Venus	Earth	Mars	Titan
O_2	0.0	21.0	0.0	0.0
H_2O	50ppm	1.0	$<$ 100ppm	0.4ppb
CO_2	96.5	0.0	95.3	10ppb
N_2	3.5	78.0	2.7	90
Ar	0.0	0.9	1.6	

Values are given as percentages by volume.

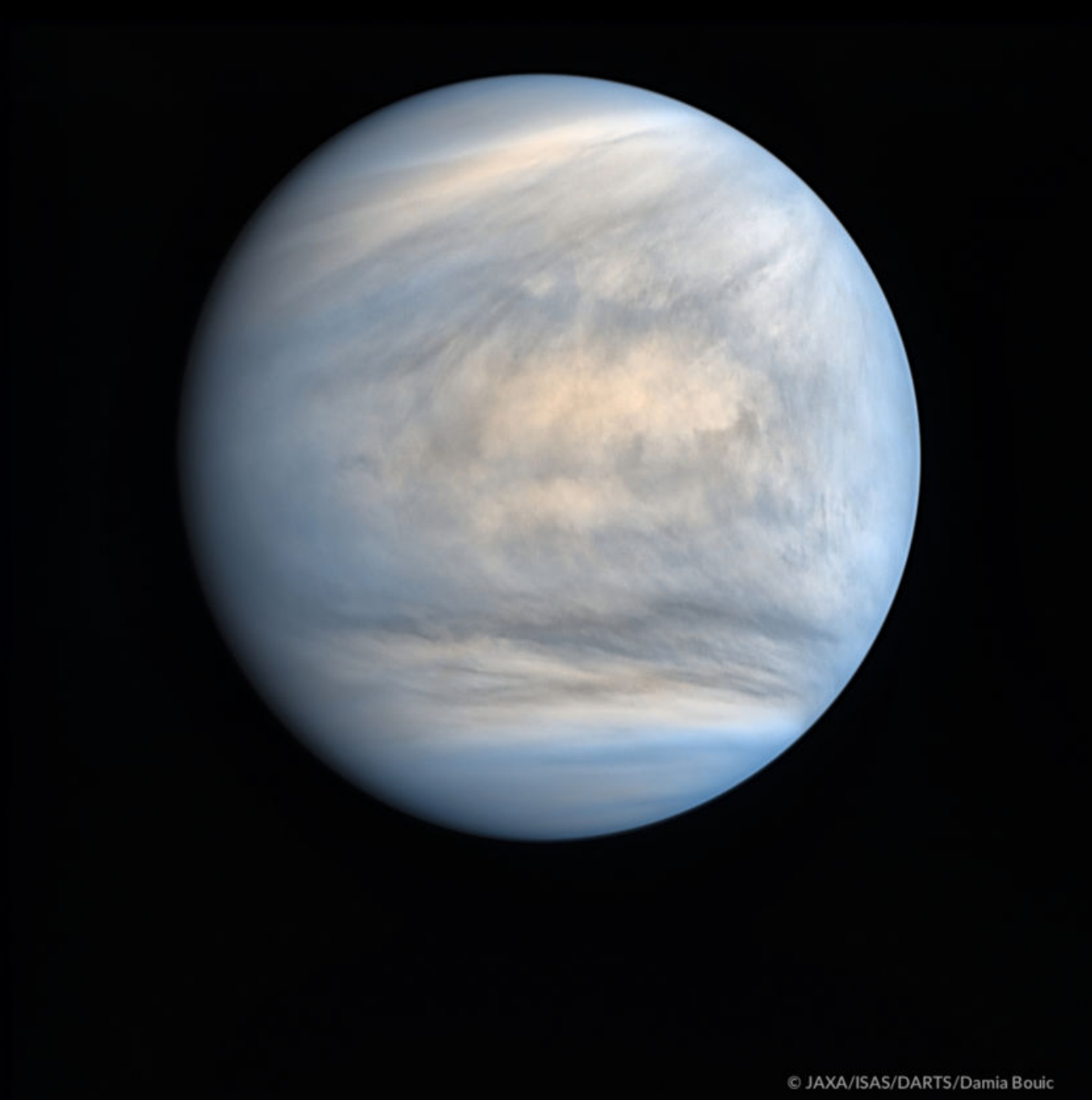
Titan has atmospheric structure similar to Earth!

after de Pater and Lissauer



IR (pseudo color)

Venus



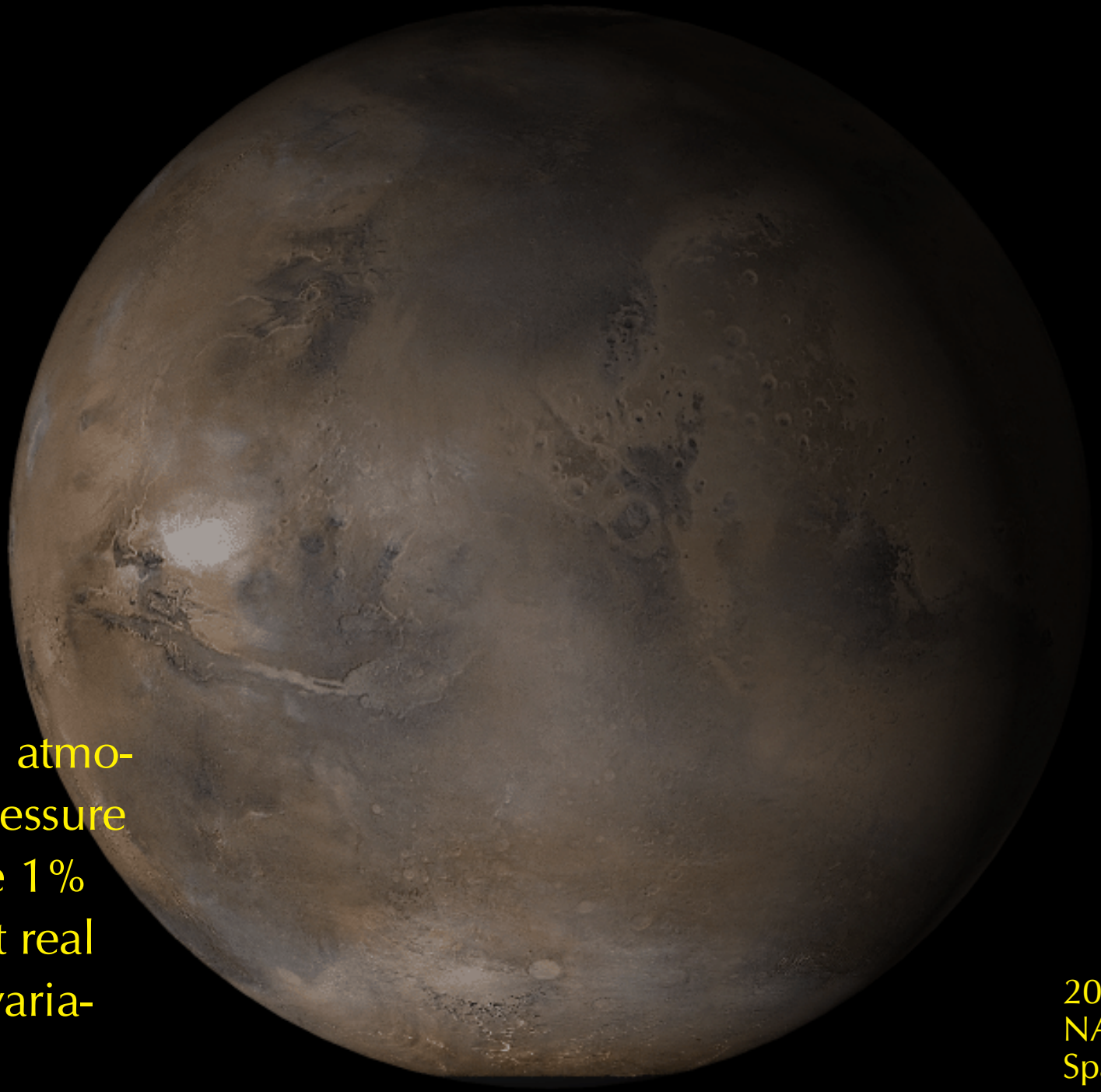
UV (pseudo color)

Venus



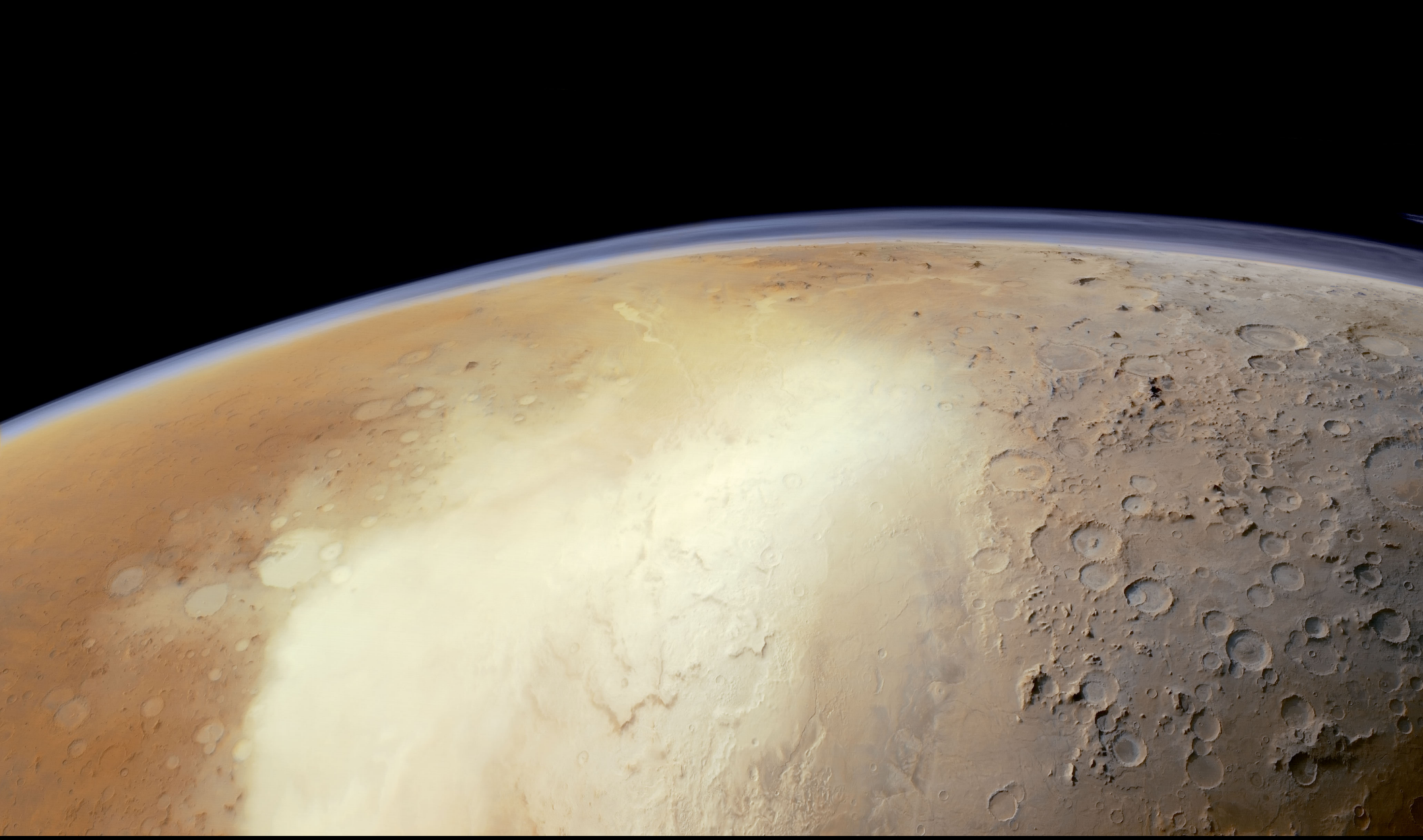
NASA/NOAO

Earth on 2012 October 28 with Hurricane Sandy



Mars: thin atmosphere (pressure on surface 1% Earth), but real seasonal variations.

2005 Feb 7, NASA/Malin Space Systems

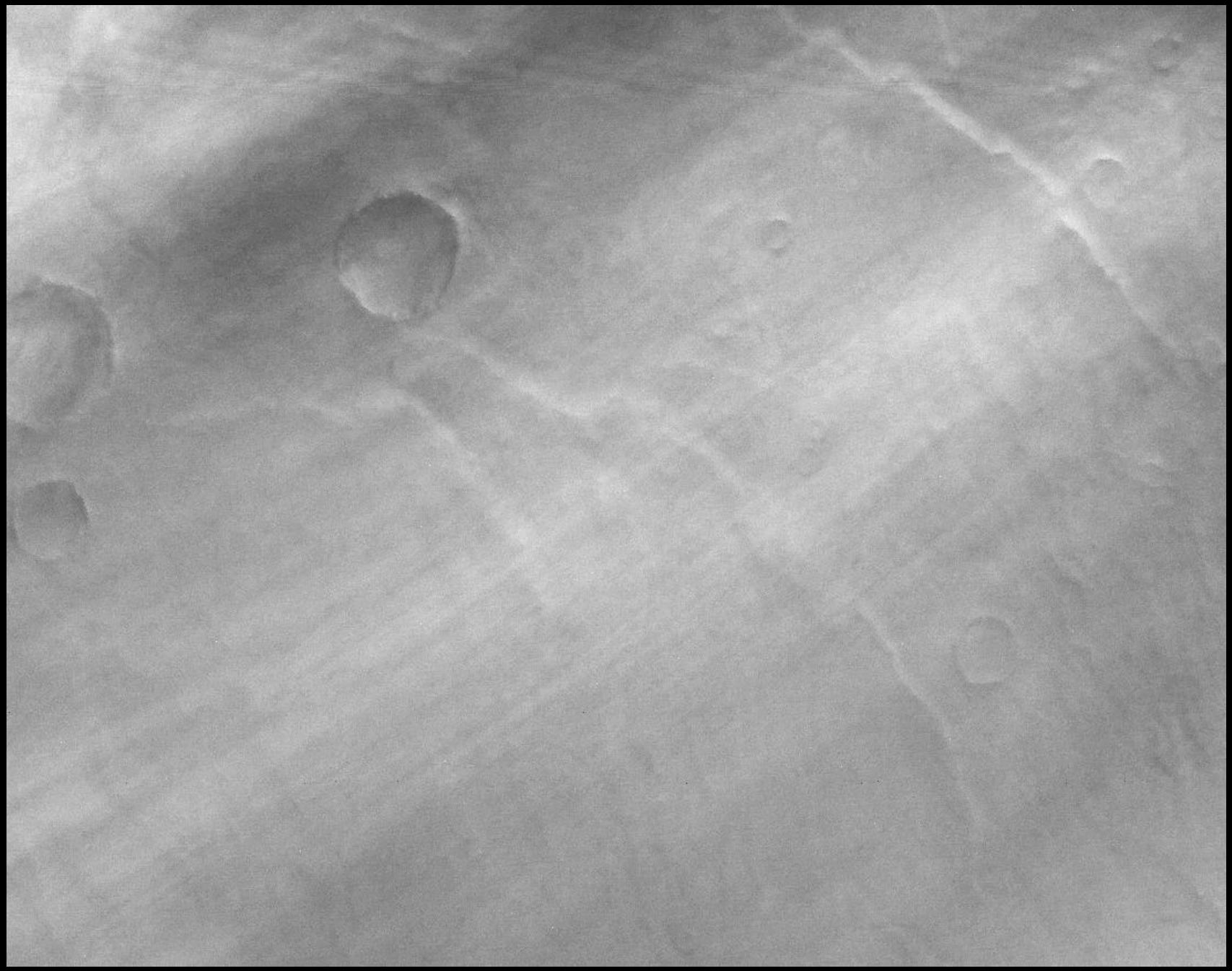


Weather



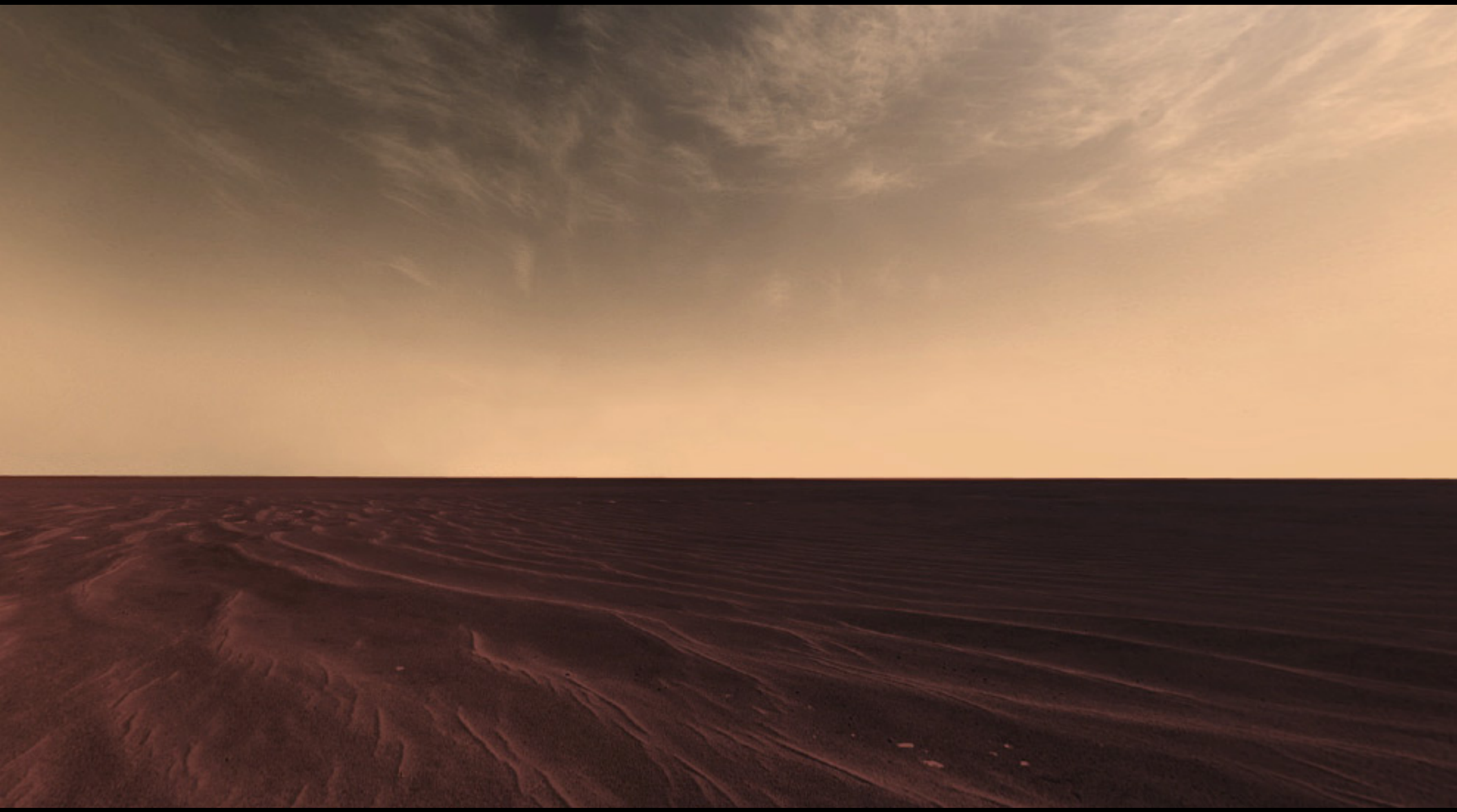
Dust Devil on Mars

Note: false color image!



NASA/C.J.Hamilton

Mars: Streaky clouds

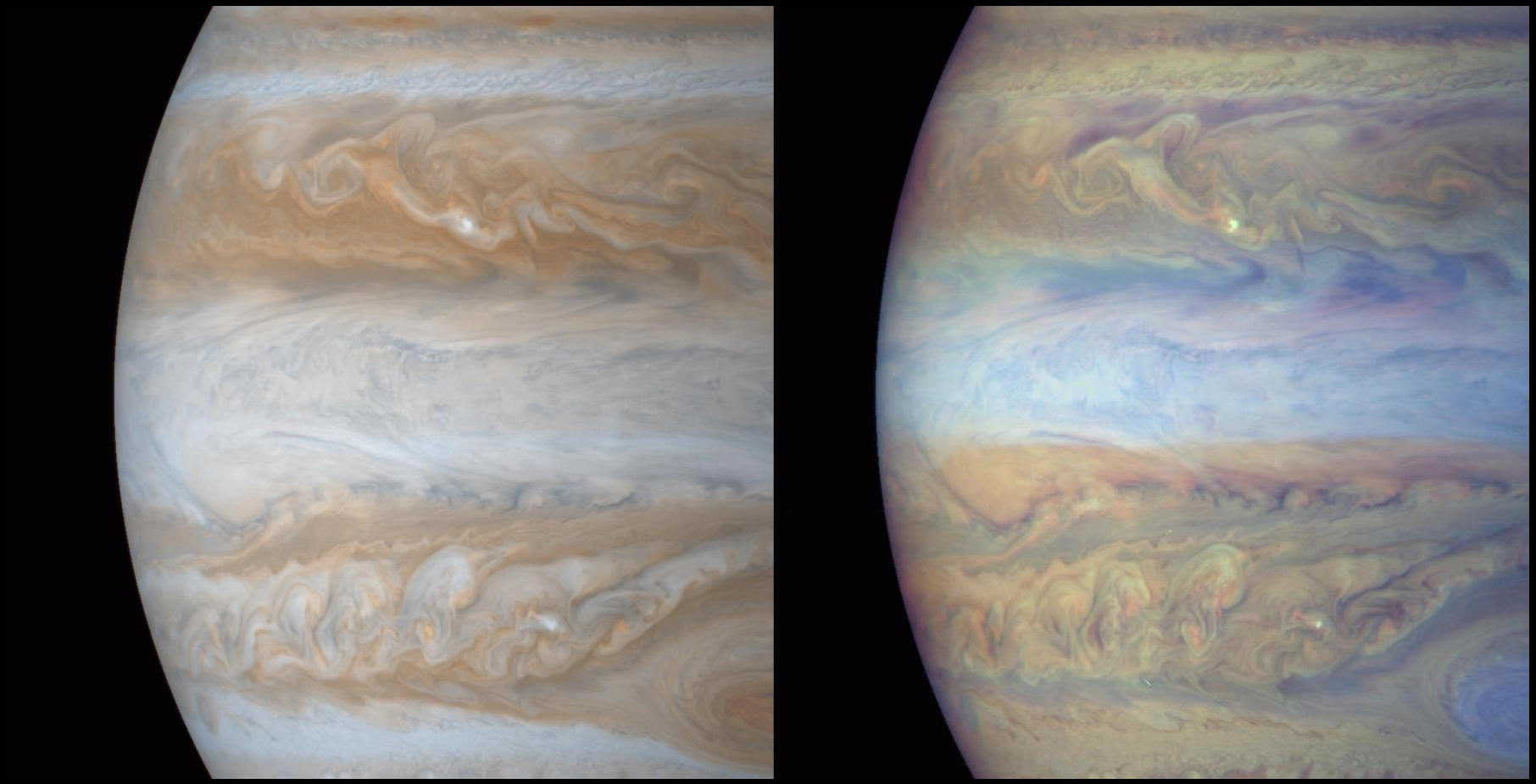


color enhanced, NASA/JPL/Cornell

Mars: Clouds from below



2005 May 19: Sunset on Mars (NASA/JPL/Texas A&M/Cornell)



NASA/JPL, Cassini, 2000 Dec 31

Jupiter: true color image; colors likely from trace content of organic compounds in atmosphere

false color image,
red: waterclouds,
dark spots: deep hot spots

Overall atmospheric structure: three layers:

Ammonia – ammonia hydrosulfide (NH_4HS) – water ice/water (deepest)

Gas Giants

Atmospheric composition of gas giants and the Sun

	Sun	Jupiter	Saturn	Uranus	Neptune
H_2	83.5	86.4	96.3	85±5	85±5
He	19.5	15.7	3.4	18±5	18±5

H: volume percent relative to total atmosphere
He: volume percent relative to H

Gas giants have approximately same composition as the Sun.

after de Pater and Lissauer

Gas Giants

In general, gas giants have very different properties from terrestrial planets:

- average density is low, e.g.,
  - Jupiter: $\langle\rho\rangle \sim 1.3\,\mathrm{g\,cm^{-3}}$
  - Saturn: $\langle\rho\rangle \sim 0.7\,\mathrm{g\,cm^{-3}}$

  (compare to terrestrial planets: $\langle\rho\rangle \sim 5.5\,\mathrm{g\,cm^{-3}}$; H_2O has $\rho = 1\,\mathrm{g\,cm^{-3}}$).
- elemental composition similar to stars (by mass):
  - 75% H
  - 24% He
  - 1% rest ("metals")

$\Longrightarrow$ expect fundamentally different internal structure!

Gas Giants

Structure of a gas giant from equation of hydrostatic equilibrium:

$$\frac{dP}{dr} = -\rho(r)\frac{GM(r)}{r^2} \tag{3.5}$$

To solve, need $\rho(r)$, $M(r) \Longrightarrow$ complicated, but doable if properties of material are known.

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Acceleration:

$$g(r) = \frac{GM(r)}{r^2} \tag{3.11}$$

where $M(r)$ is the mass of the planet contained within a radius r

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$$g(r) = \frac{GM(r)}{r^2} \tag{3.11}$$

where $M(r)$ is the mass of the planet contained within a radius r

$$M(r) = \int_0^r 4\pi\rho(r)r^2 dr \tag{3.12}$$

Interpretation: integrate over onion shells of thickness dr and density $\rho(r)$; M in each of these shells is $4\pi\rho(r)dr$, summing over all onion shells gives the answer.

Gas Giants

Equation of state for gas under high pressure is much more complex than ideal gas ($P \propto \rho T$).

$\Longrightarrow$ Do order of magnitude estimate.

Earth: $\rho \sim$ const. (by factor 10).

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So: assume the same for Jupiter.

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$\langle \ldots \rangle$ means “average”

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$$\rho(r) = \langle\rho\rangle = \text{const.} \tag{3.13}$$

$\langle \ldots \rangle$ means "average"

Such that

$$M(r) = \frac{4}{3}\pi r^3 \langle\rho\rangle \tag{3.14}$$

and thus the equation of hydrostatic equilibrium

$$\frac{dP}{dr} = -\frac{4}{3}\langle\rho\rangle^2 G\pi r \tag{3.15}$$

Gas Giants

We had

$$\frac{dP}{dr} = -\frac{4}{3}\langle\rho\rangle^2 G\pi r \tag{3.16}$$

This differential equation is separable $\Longrightarrow$ can use "separation of variables"

same procedure as for isothermal atmosphere!

To solve, integrate both sides of the equation from $r = 0$ to the surface of the planet at $r = R$:

$$\int_0^R \frac{dP}{dr}\,dr = -\frac{4}{3}\int_0^R \langle\rho\rangle^2 G\pi r\,dr \tag{3.17}$$

Now need to look at the integrals on both sides of the equation

Gas Giants

To solve:

$$\int_0^R \frac{dP}{dr}\,dr = -\frac{4}{3}\int_0^R \langle\rho\rangle^2 G\frac{4}{3}\pi r\,dr \tag{3.18}$$

Gas Giants

To solve:

$$\int_0^R \frac{dP}{dr}\,dr = -\frac{4}{3}\int_0^R \langle\rho\rangle^2 G\frac{4}{3}\pi r\,dr \tag{3.18}$$

Integrate left hand side:

Substitute $r \longrightarrow P(r)$ where $P(r)$ (pressure at radius r) is unknown:

$$\int_0^R \frac{dP}{dr}\,dr = \int_{P(r=0)}^{P(r=R)} \frac{dP}{dr}\frac{dr}{dP}\,dP = \int_{P(r=0)}^{P(r=R)} dP \tag{3.19}$$

Where the "boundary conditions":

- center: $P(r=0) = P_{\text{central}}$
- surface: $P(r=R) = 0$

such that:

$$\int_0^R \frac{dP}{dr}\,dr = P(R) - P(0) = -P(0) =: -P_c \tag{3.20}$$

Gas Giants

To solve:

$$\int_0^R \frac{dP}{dr}\,dr = -\frac{4}{3}\int_0^R \langle\rho\rangle^2 G\frac{4}{3}\pi r\,dr \tag{3.18}$$

Integrate right hand side:

$$-\int_0^R \langle\rho\rangle^2 G\frac{4\pi}{3} r\,dr = -\langle\rho\rangle^2\frac{4\pi}{3}G\int_0^R r\,dr \tag{3.19}$$

$$= -\langle\rho\rangle^2\frac{4\pi}{3}G\frac{R^2}{2} \tag{3.20}$$

$$= -\frac{2\pi}{3}\langle\rho\rangle^2 R^2 \tag{3.21}$$

Gas Giants

Combining results gives: Central Pressure:

$$P_{central} = \frac{2\pi}{3} G \langle \rho \rangle^2 R^2 \tag{3.22}$$

Rule of thumb: P_c estimates correct central pressure to better than factor of 10

Gas Giants

Combining results gives: Central Pressure:

$$P_{\text{central}} = \frac{2\pi}{3} G \langle \rho \rangle^2 R^2 \tag{3.22}$$

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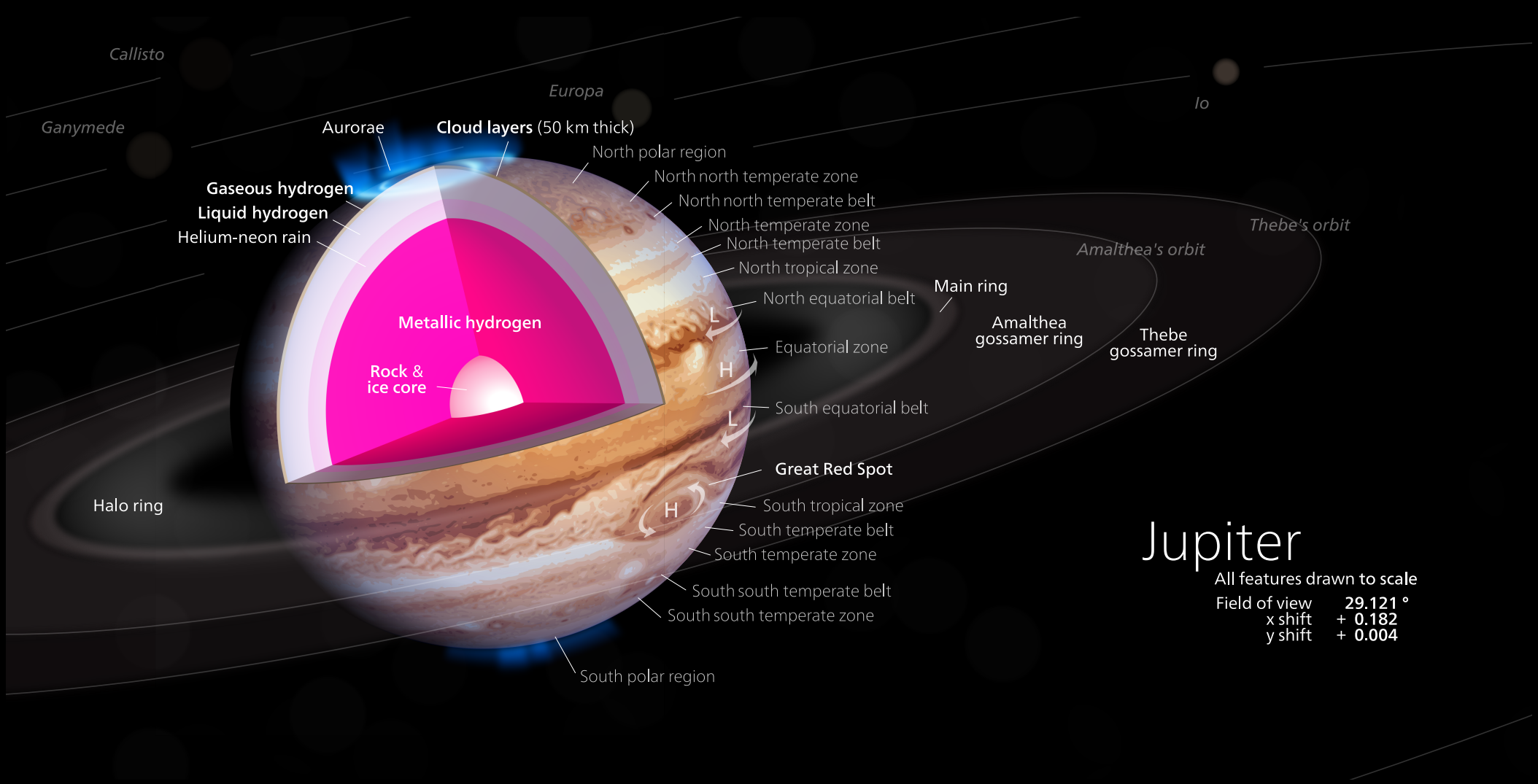
Plug in numbers for Jupiter:

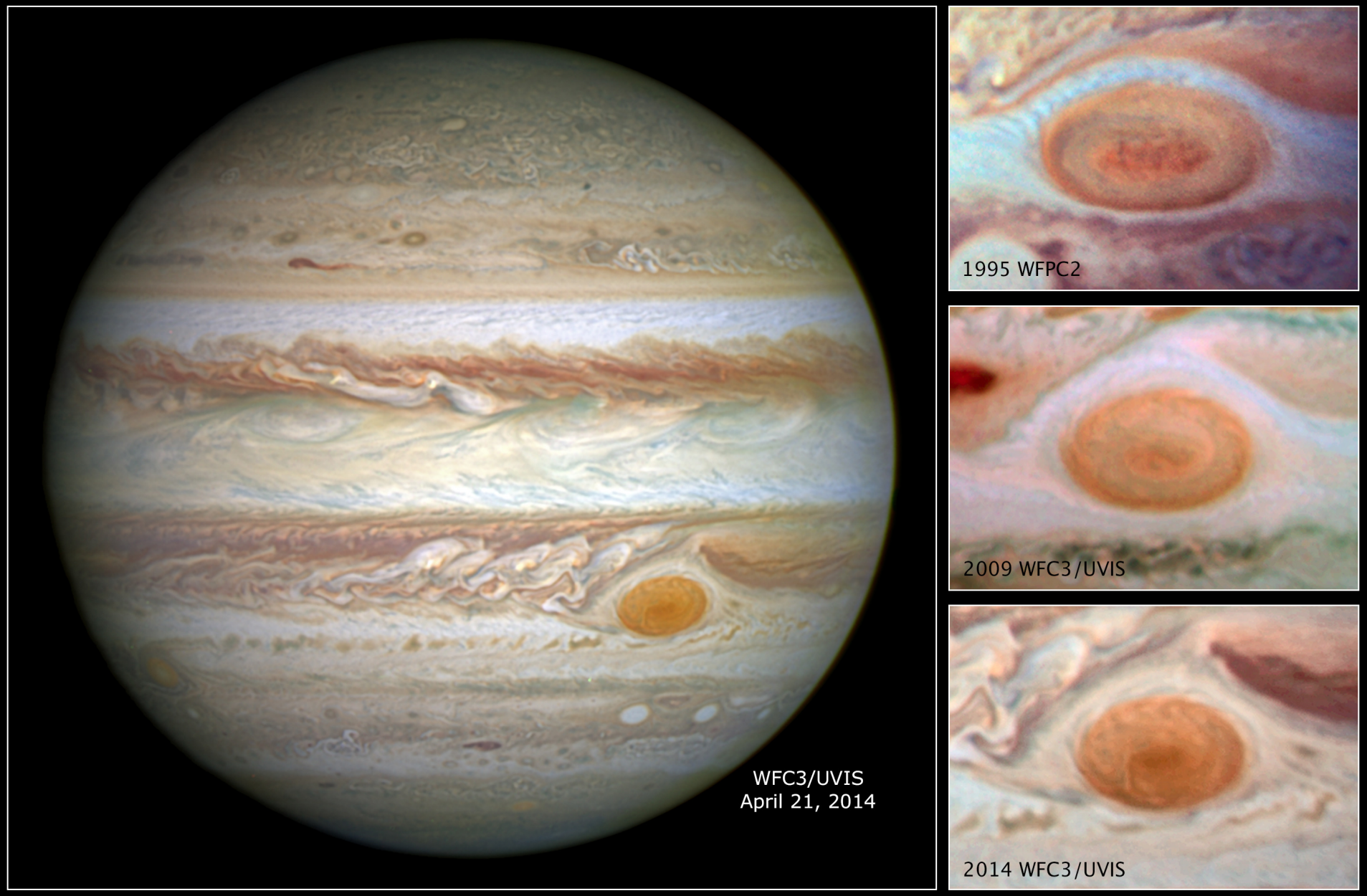
- $R = 70000\,\text{km}$,
- $\langle \rho \rangle = 1.3\,\text{g}\,\text{cm}^{-3}$

$\Longrightarrow P_{\text{central}} = 1.2 \times 10^{12}\,\text{Pa}$ ($10\times$ Earth).

At this pressure: existence of metallic hydrogen (i.e., electrons can move freely around).

More detailed computations: metallic hydrogen from 14000–45000 km away from center

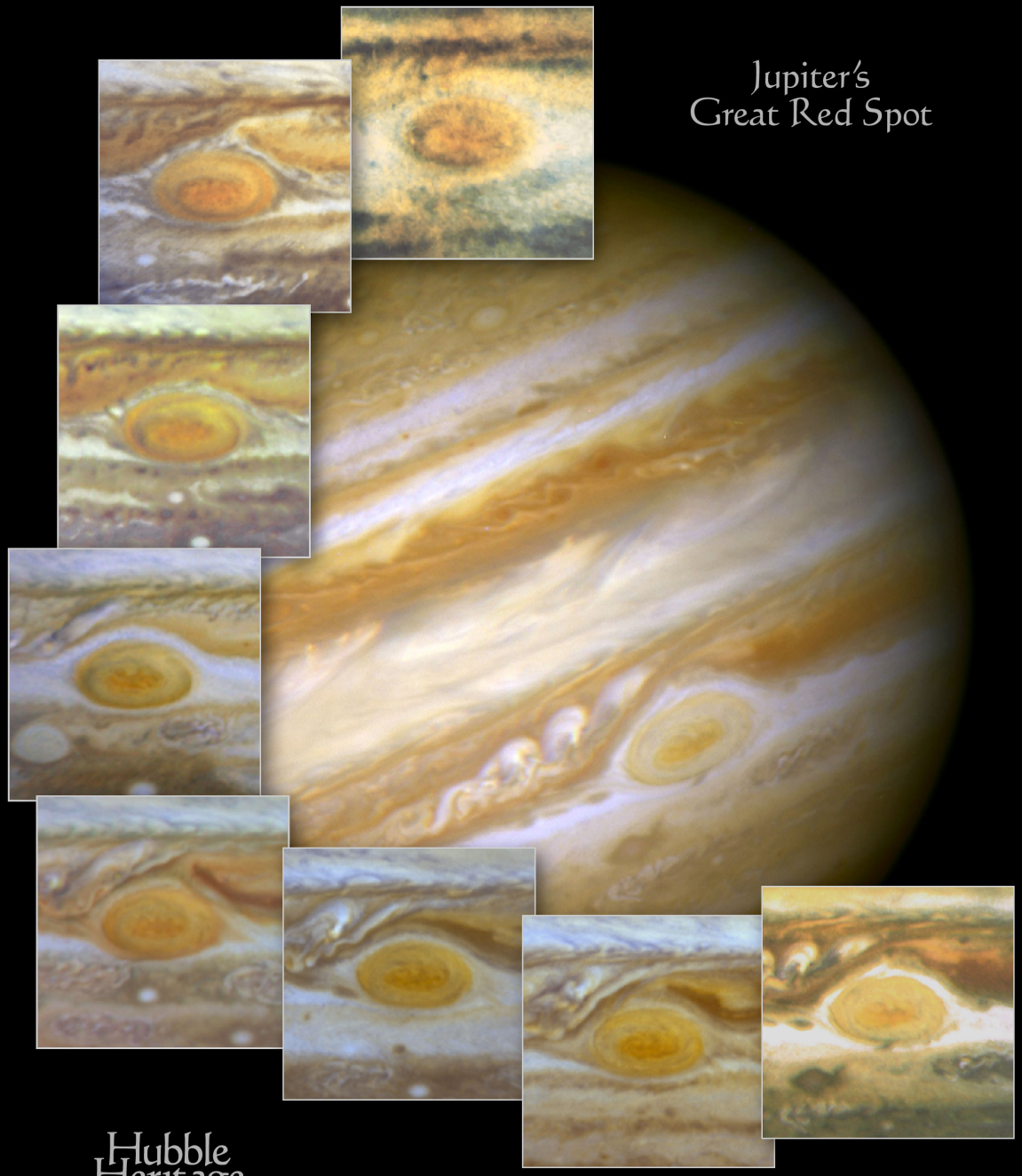

Callisto
Europa
Io
Ganymede
Aurorae
Cloud layers (50 km thick)
North polar region
North north temperate zone
North north temperate belt
North temperate zone
North temperate belt
North tropical zone
North equatorial belt
Equatorial zone
South equatorial belt
Great Red Spot
South tropical zone
South temperate belt
South temperate zone
South south temperate belt
South south temperate zone
South polar region
Gaseous hydrogen
Liquid hydrogen
Helium-neon rain
Metallic hydrogen
Rock & ice core
Thebe's orbit
Amalthea's orbit
Main ring
Amalthea gossamer ring
Thebe gossamer ring
Halo ring
L
H
L
H
Jupiter
All features drawn to scale
Field of view 29.121 °
x shift + 0.182
y shift + 0.004



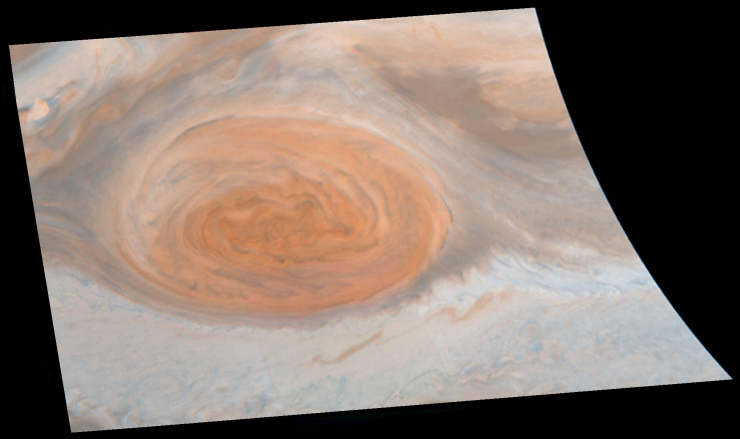
Jupiter and the Great Red Spot
Hubble Space Telescope WFC3/UVIS WFPC2

NASA and ESA

STScI-PRC14-24a

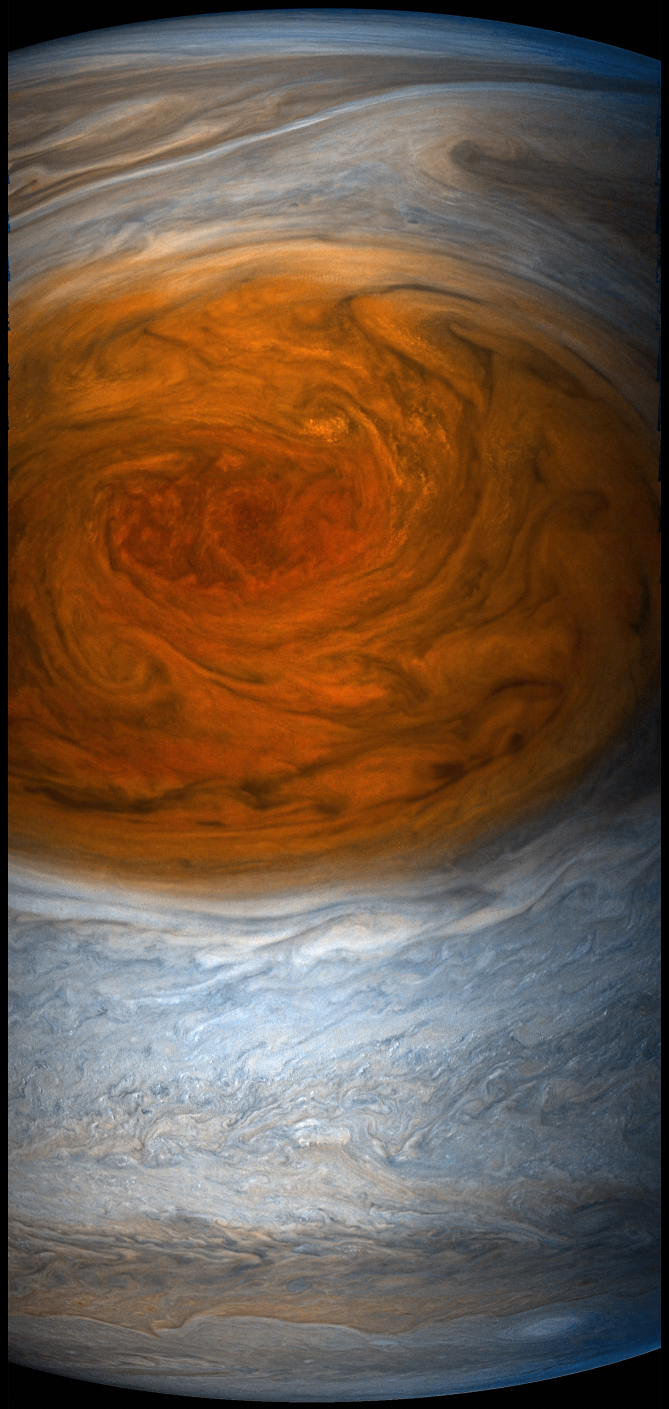


PRC99-29 • Hubble Space Telescope WFPC2 • Hubble Heritage Team (AURA/STScI/NASA)

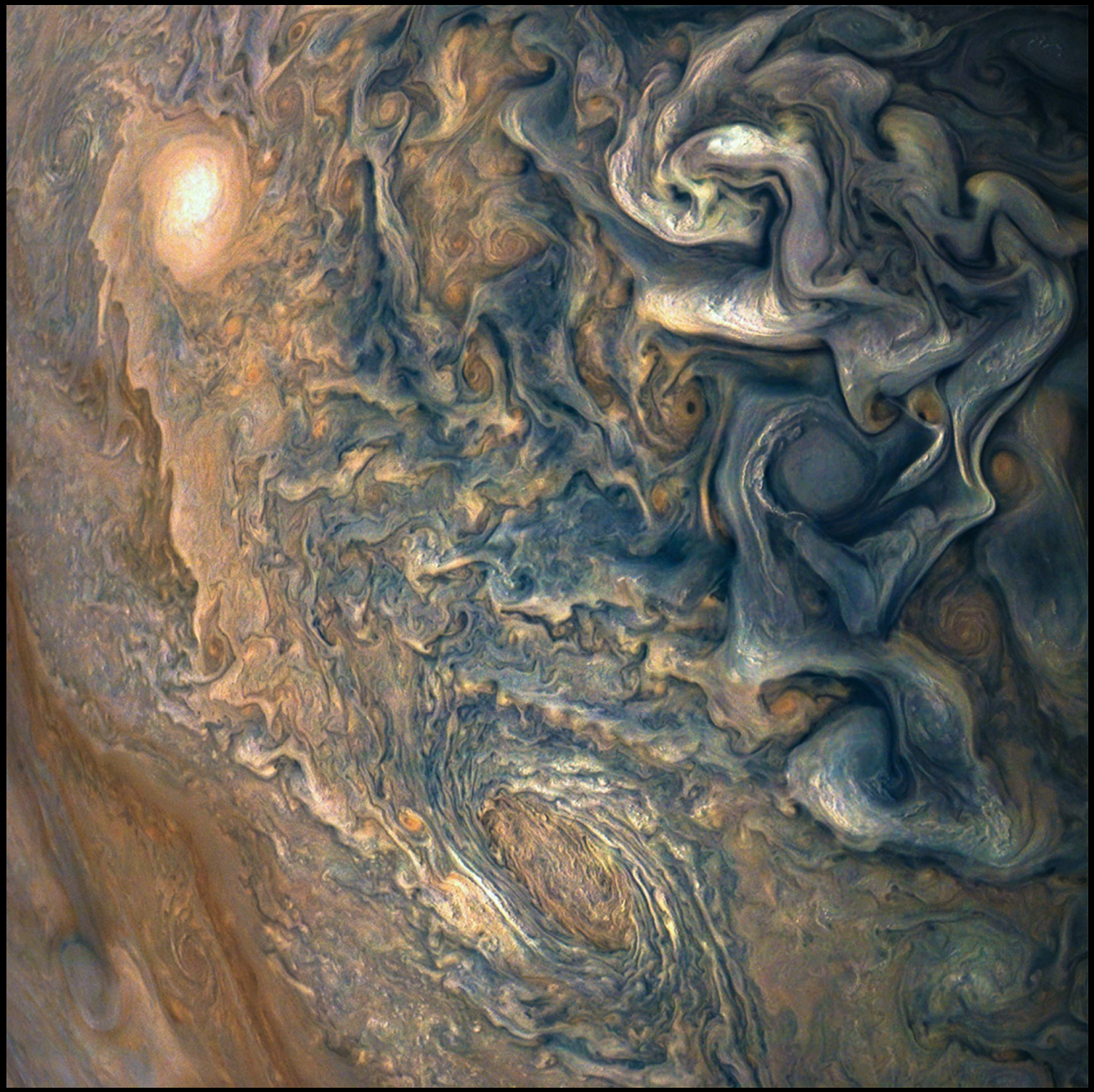


NASA Galileo, 1996 June 26

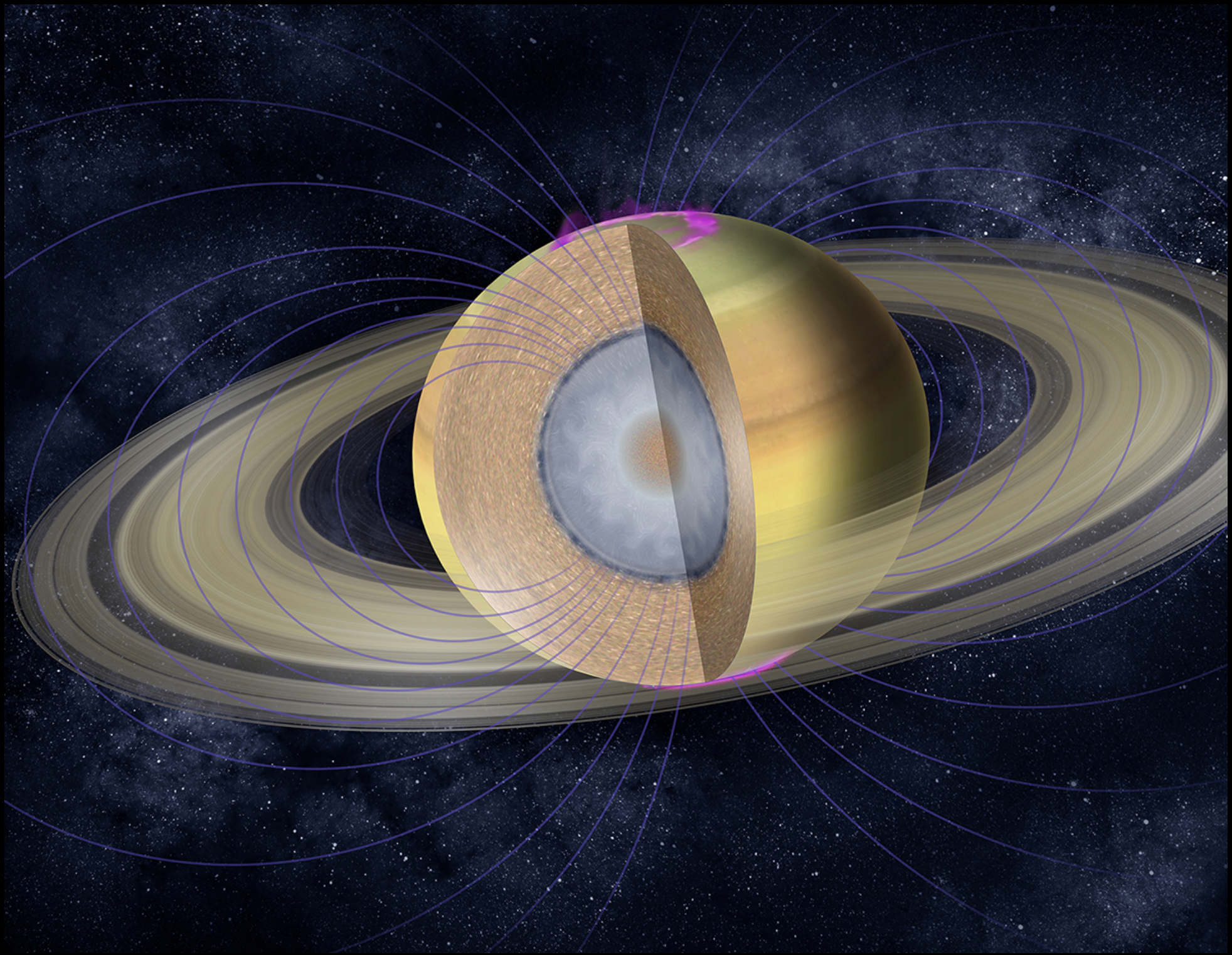
Jupiter's Great Red Spot: Storm System, ~2× Earth diameter, exists since more than 300 years, 8 km above and 10° cooler than surrounding region (rising high pressure region), rotates counterclockwise (Coriolis force on Southern hemisphere).

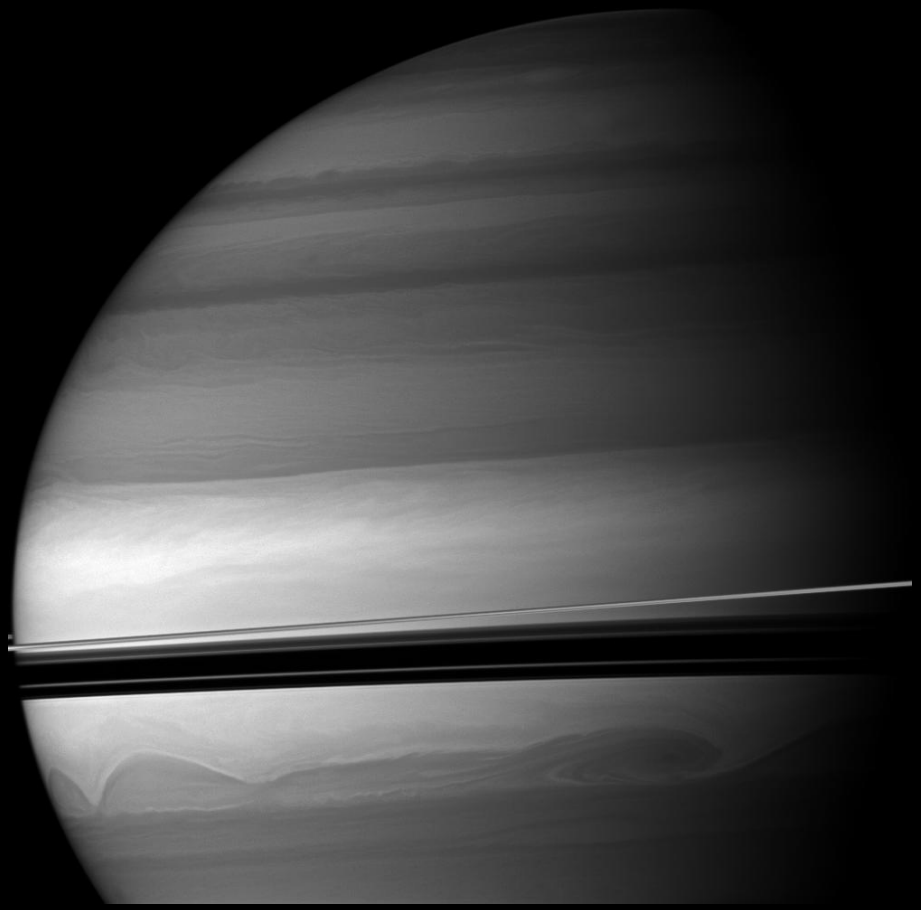


NASA (Juno probe, 2017)

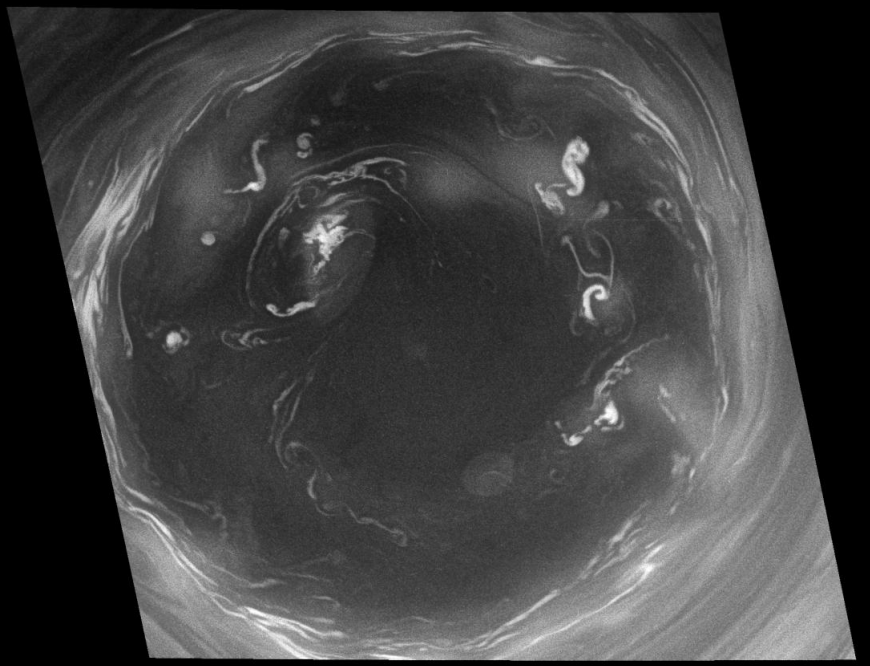


NASA/JPL-Caltech/SwRI/MSSS/Gerald Eichstaedt/Seán Doran

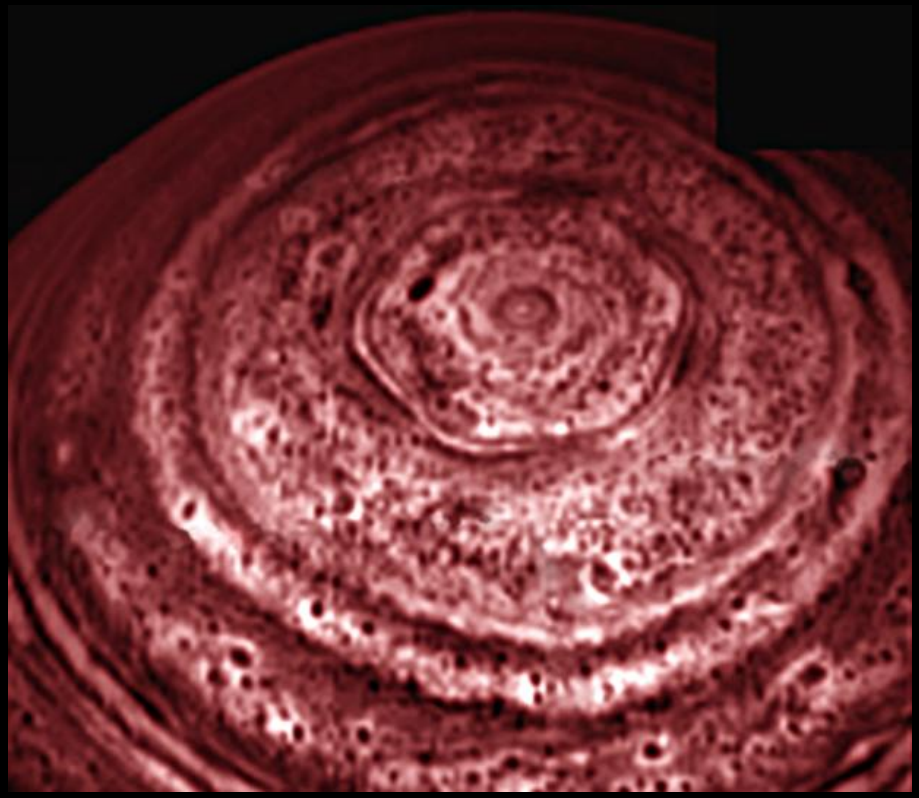




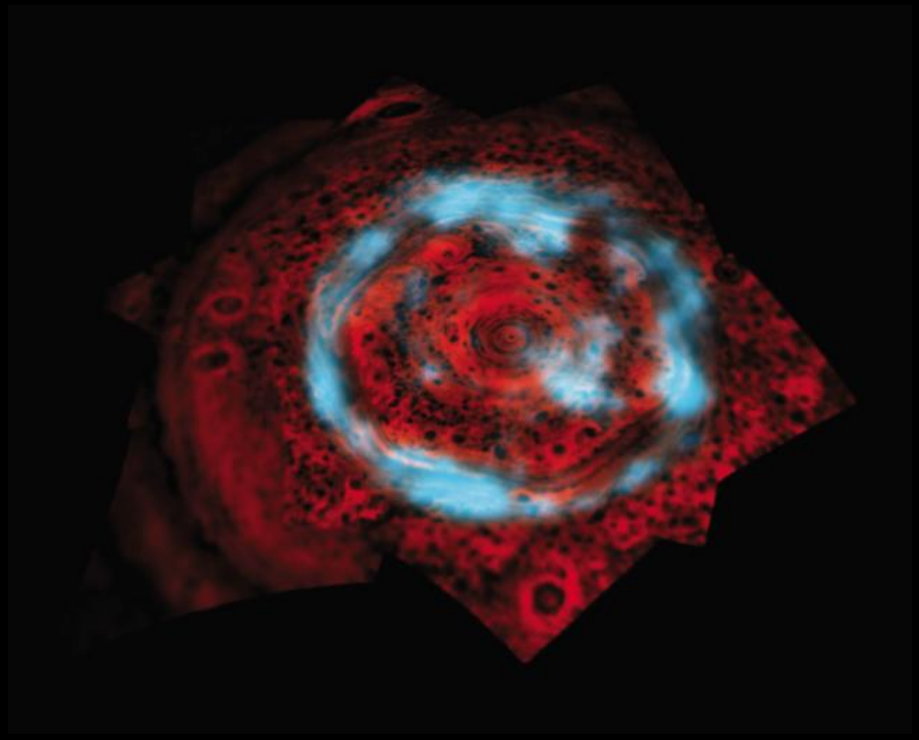
NASA/ESA Cassini



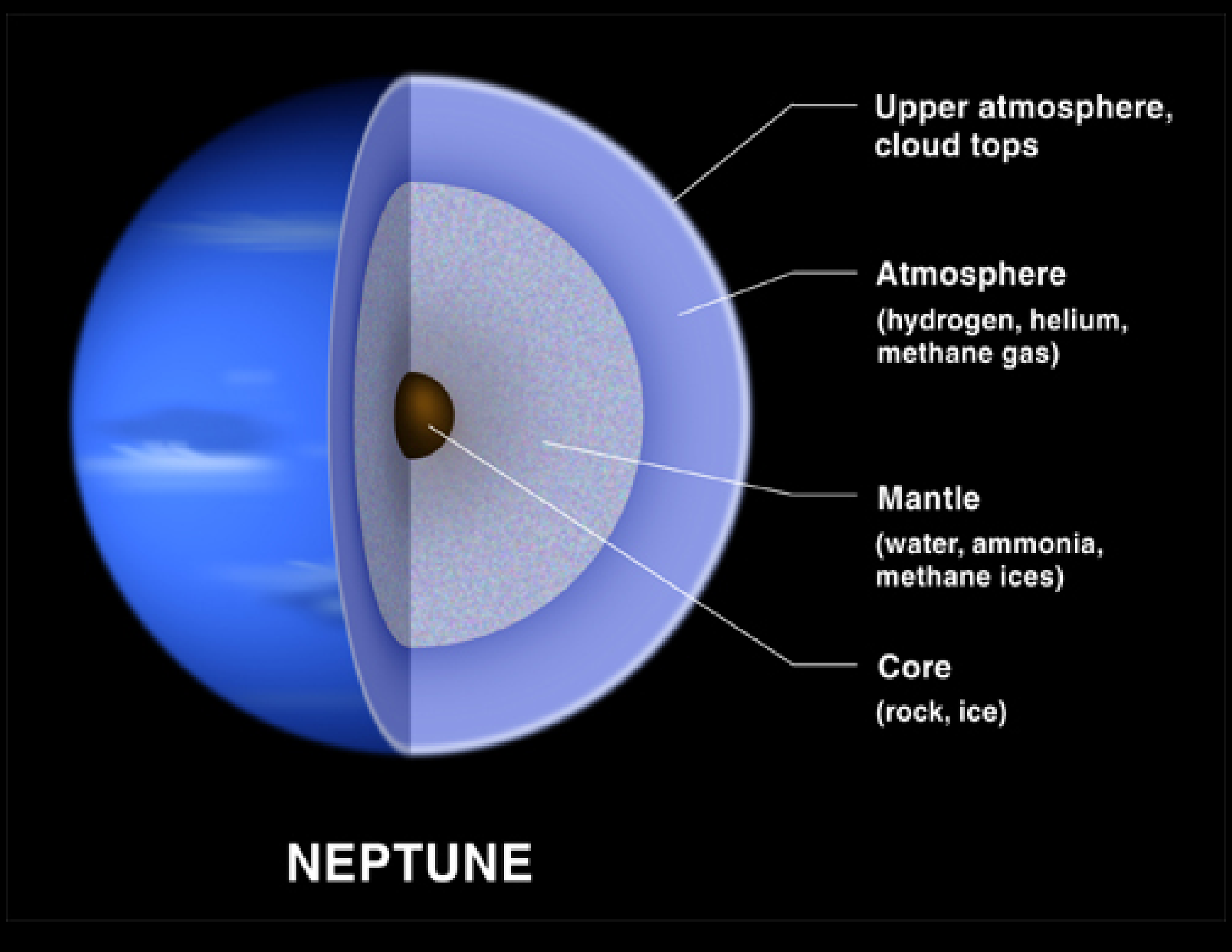
Saturn: Bands and south pole

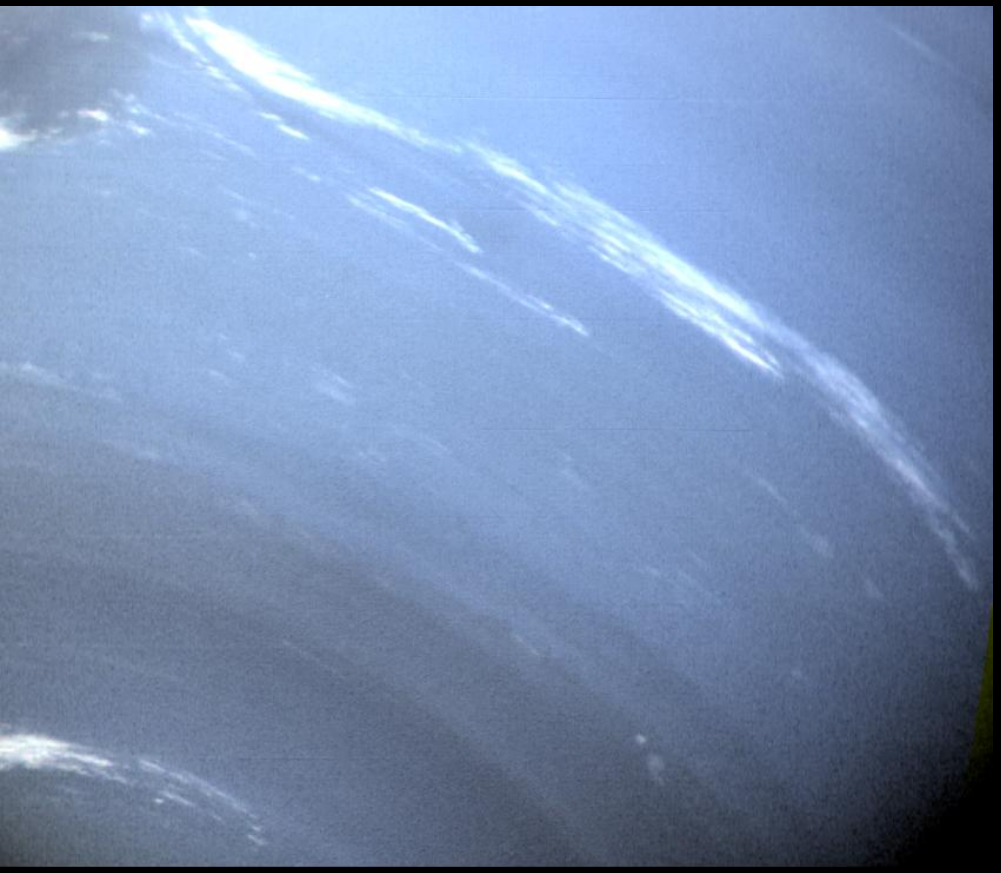


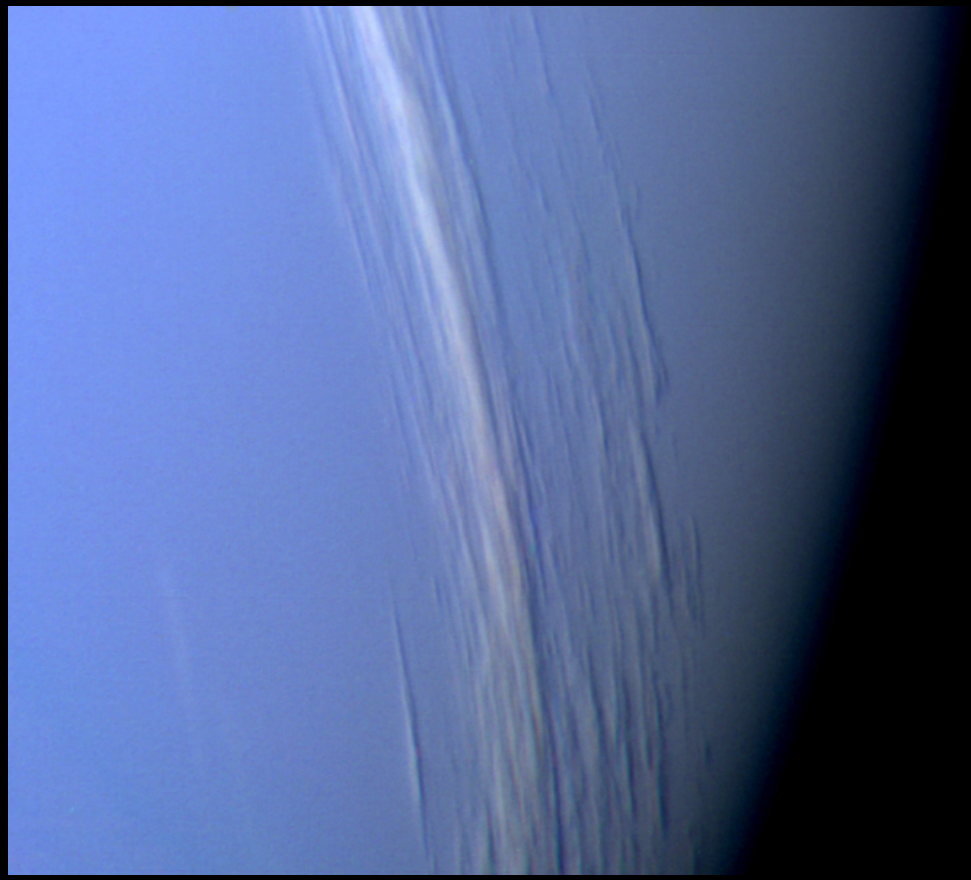
NASA/ESA Cassini



Saturn: North pole: Hexagon & Aurora

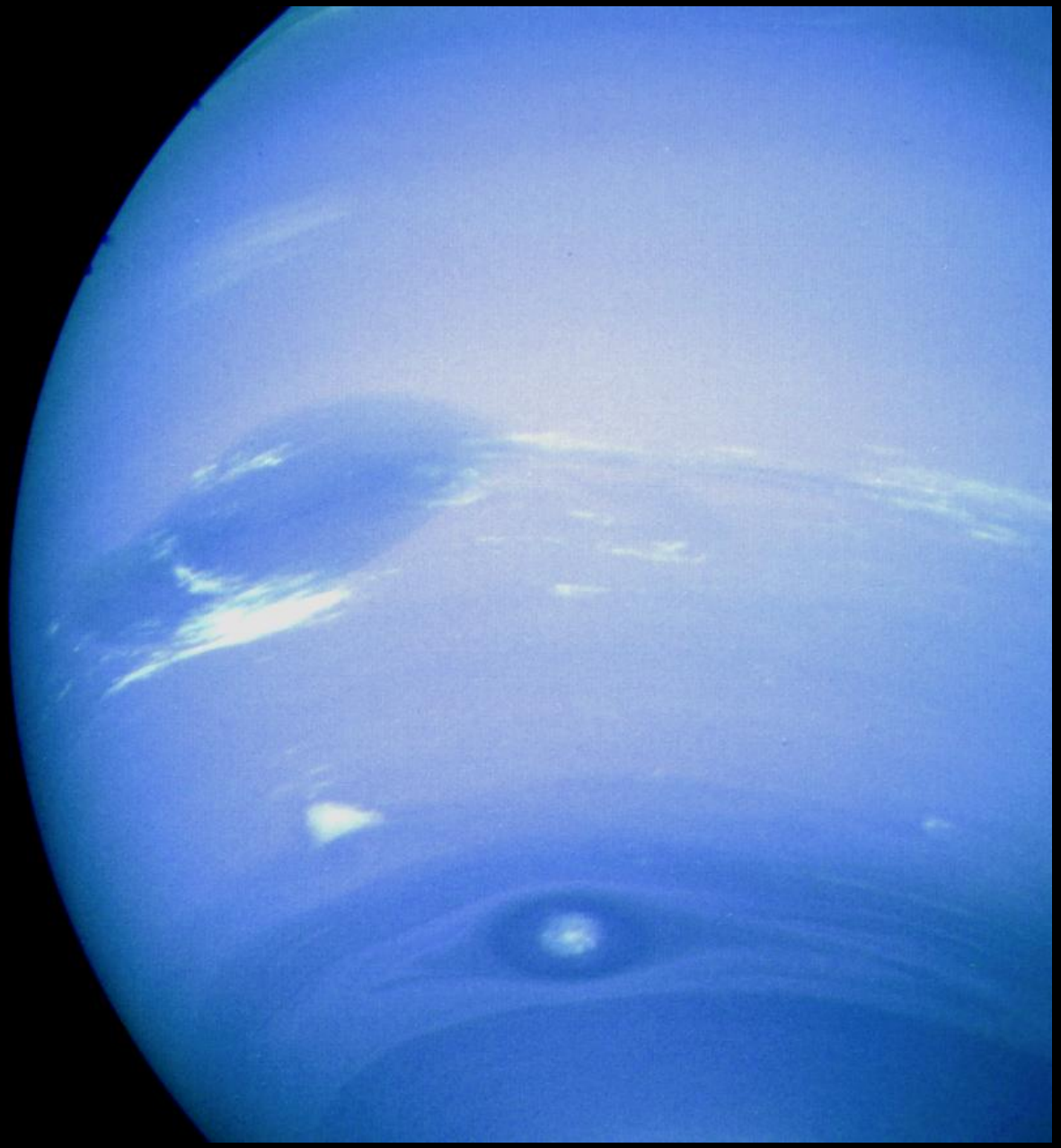

Upper atmosphere, cloud tops
Atmosphere
(hydrogen, helium, methane gas)
Mantle
(water, ammonia, methane ices)
Core
(rock, ice)
NEPTUNE





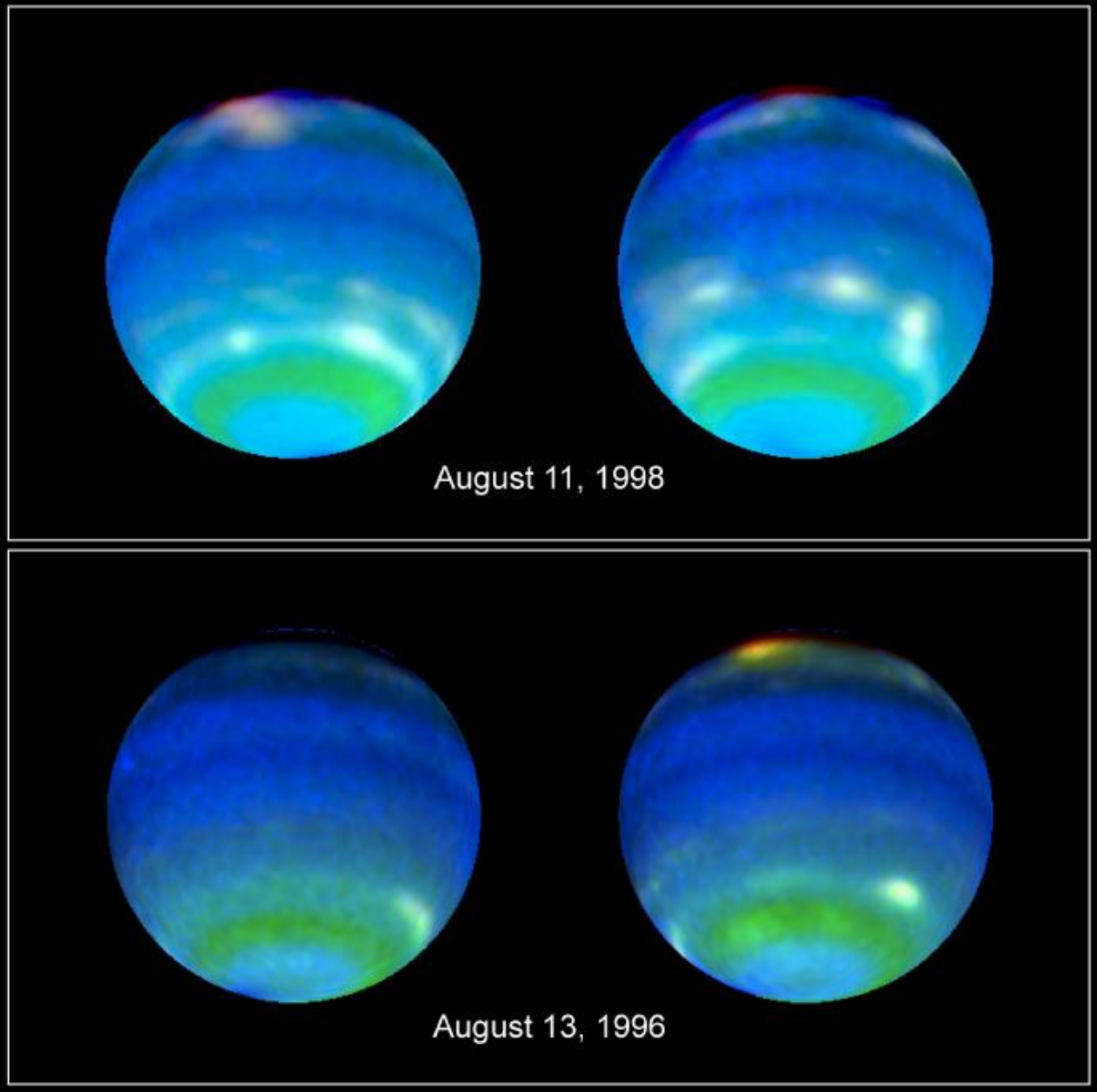
NASA/JPL

Neptune: True color image of clouds



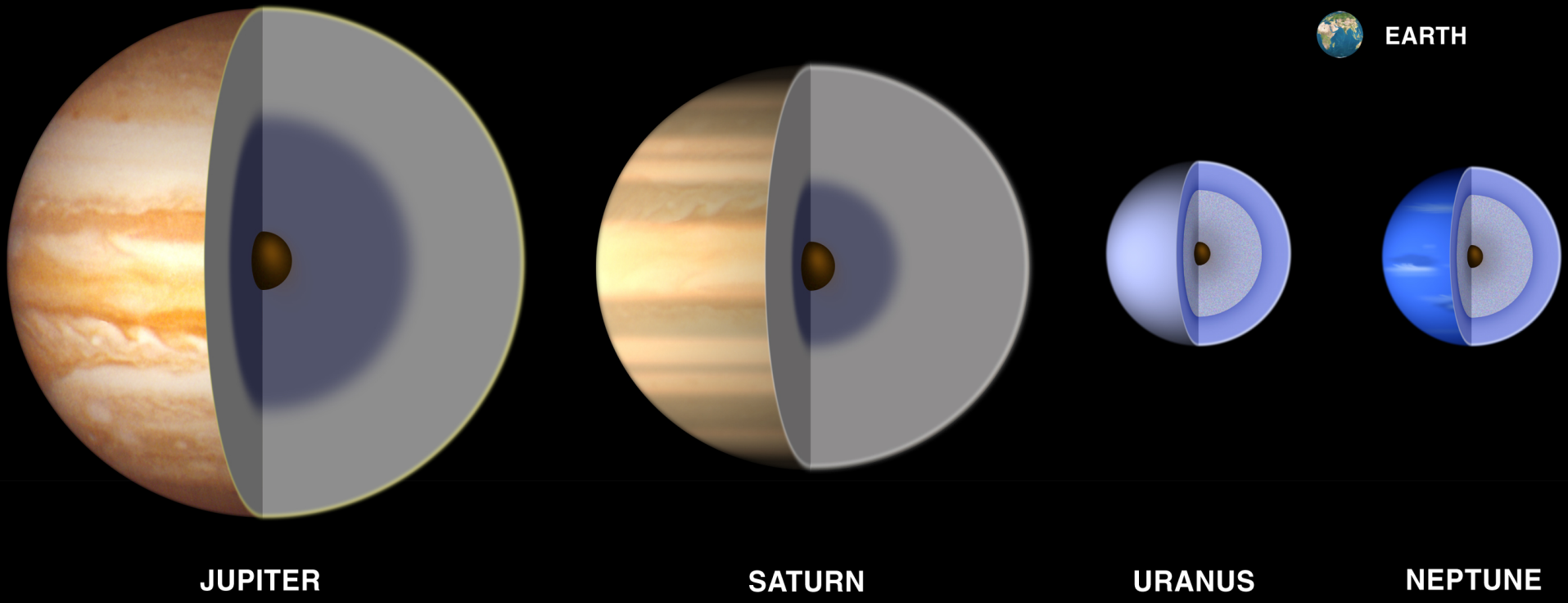
NASA/JPL, Voyager 2

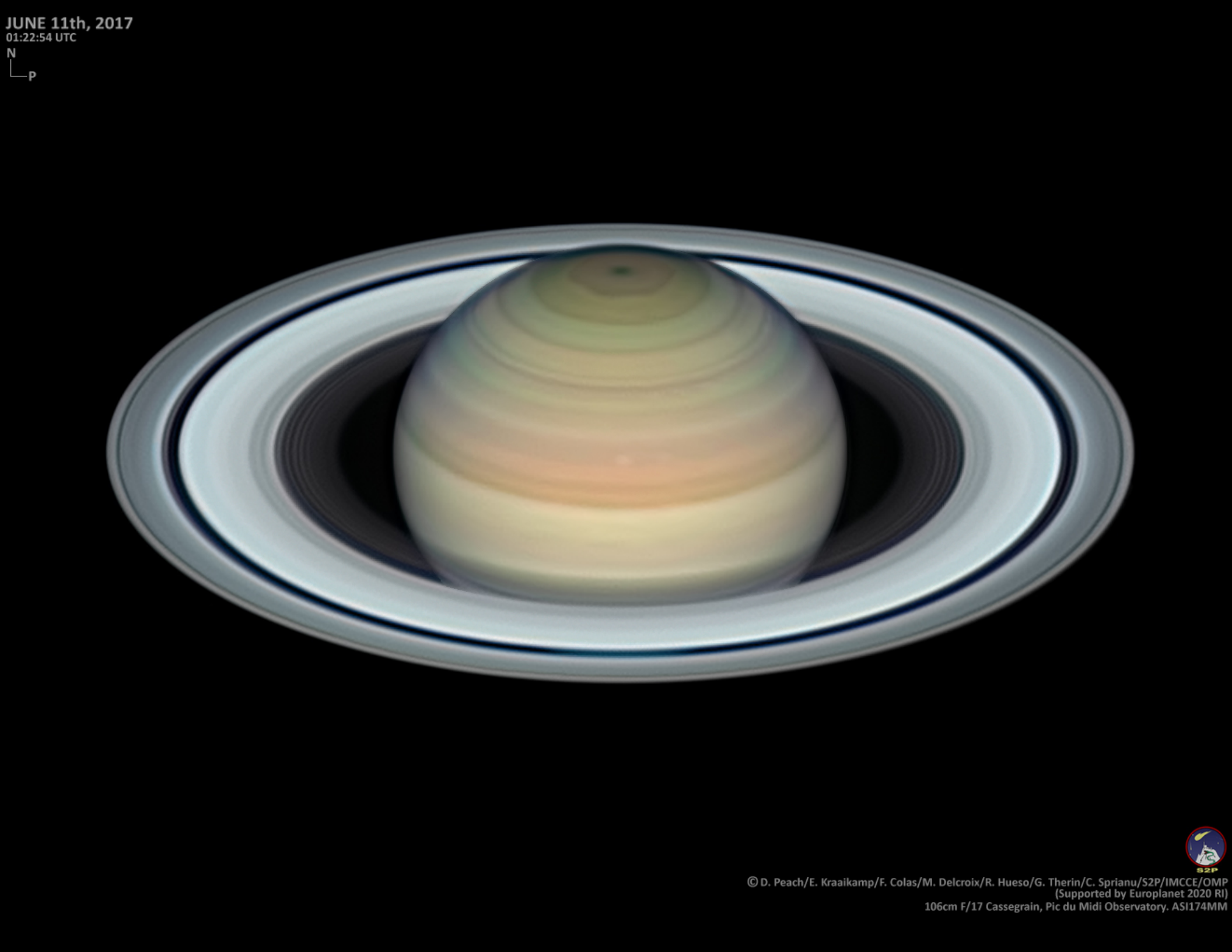
Neptune: Similar large-scale storms as the "Great Red Spot" also exist on other planets



STScI, HST

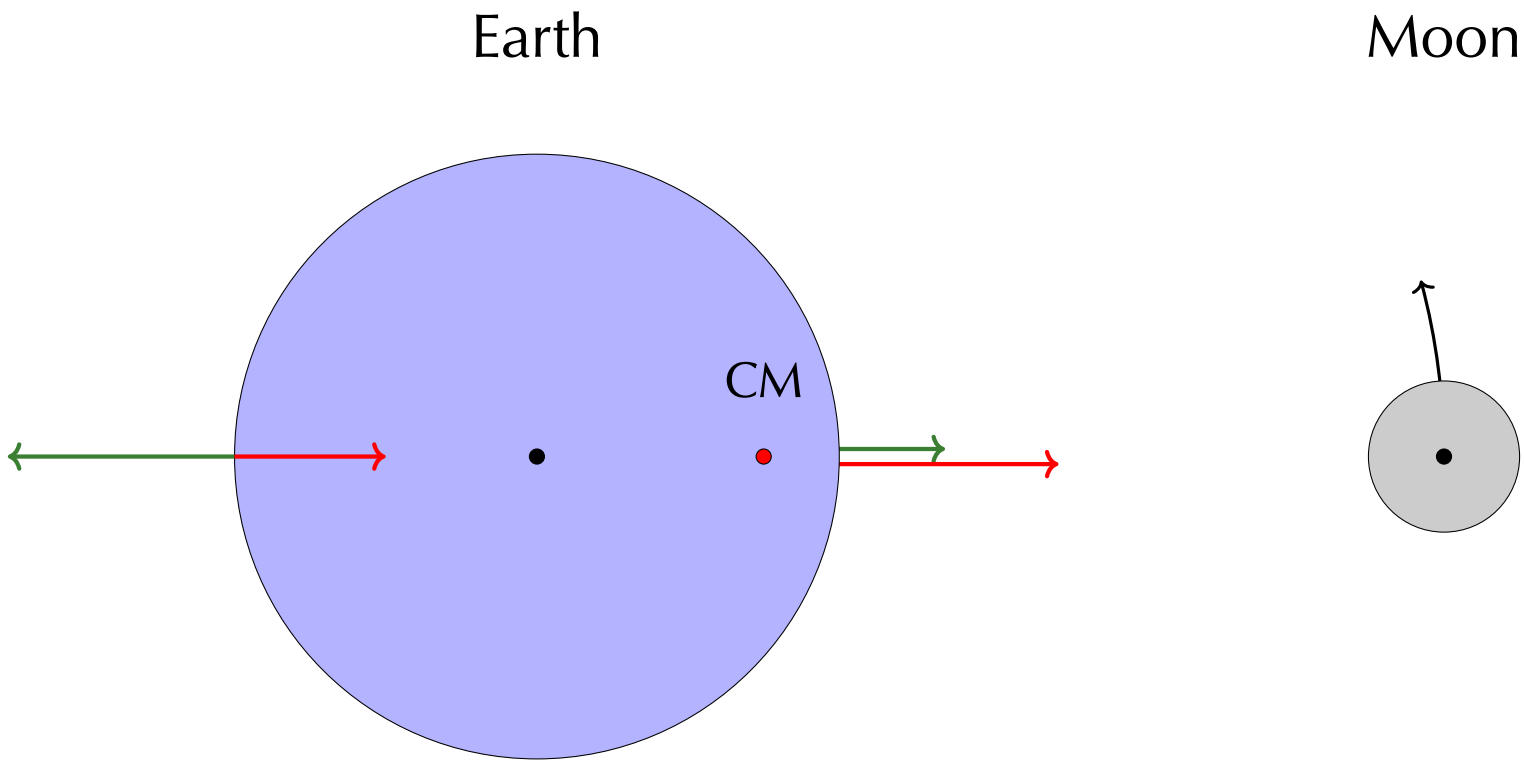
Neptune: Storm systems are much less stable on Neptune than on Jupiter (less heating from the inside)


EARTH
JUPITER
SATURN
URANUS
NEPTUNE
Molecular hydrogen
Metallic hydrogen
Hydrogen, helium, methane gas
Mantle (water, ammonia, methane ices)
Core (rock, ice)



© D. Peach/E. Kraaikamp/F. Colas/M. Delcroix/R. Hueso/G. Therin/C. Sprianu/S2P/IMCCE/OMP
(Supported by Europlanet 2020 RI)
106cm F/17 Cassegrain, Pic du Midi Observatory. ASI174MM

Tides in the Earth–Moon system

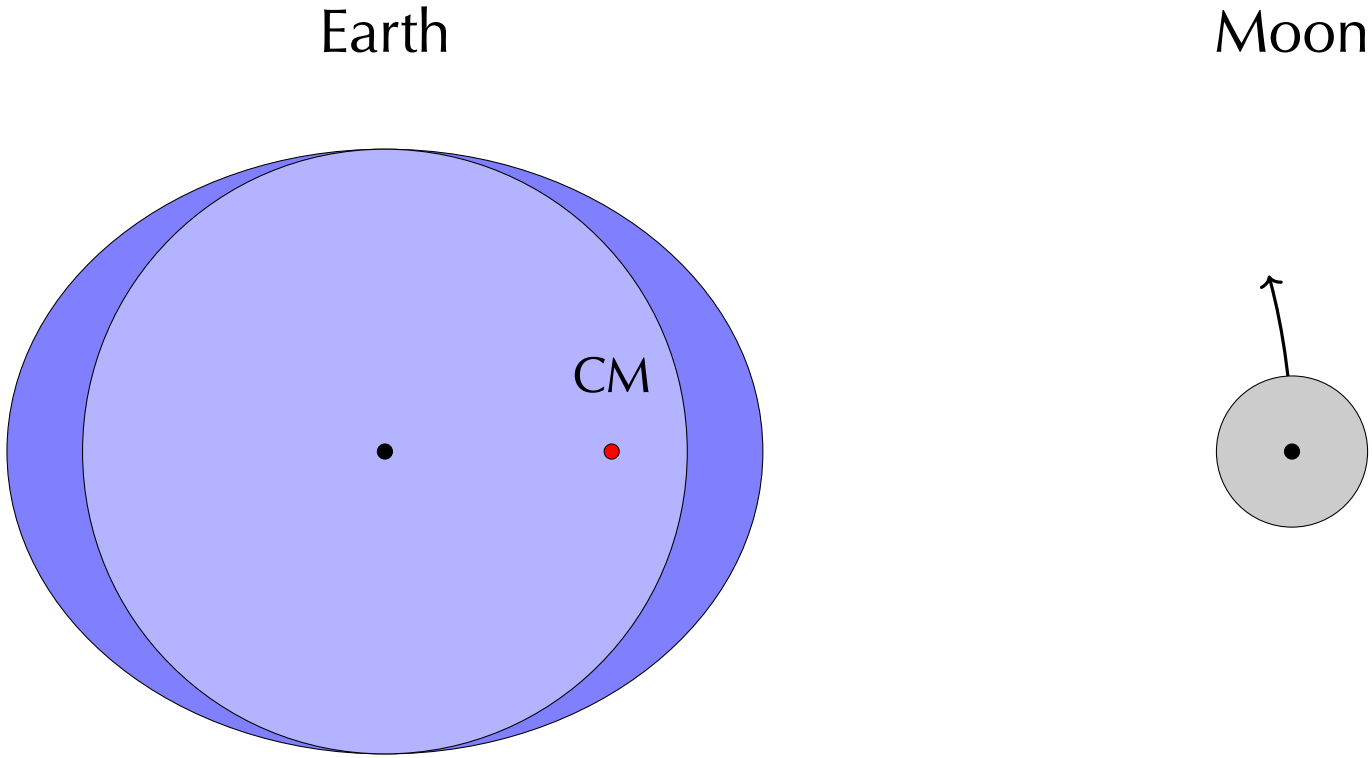


Motion of the Earth-Moon system:

red: gravitational force of the Moon onto the Earth

green: centrifugal force of Earth around the center of mass (CM)

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Gravitational acceleration for center of Earth and for the point closest to a gravitating body:

$$a_{\text{center}} = \frac{GM}{r^2} \quad \text{and} \quad a_{\text{closest}} = \frac{GM}{(r - R_\oplus)^2} \tag{3.23}$$

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use $(1 - \epsilon)^{-2} \sim 1 + 2\epsilon$

$$\sim \frac{GM}{r^2}\left(1 + 2\frac{R_\oplus}{r} - 1\right) = \frac{2GMR_\oplus}{r^3} \tag{3.25}$$

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Therefore the tides due to the Moon and Sun are

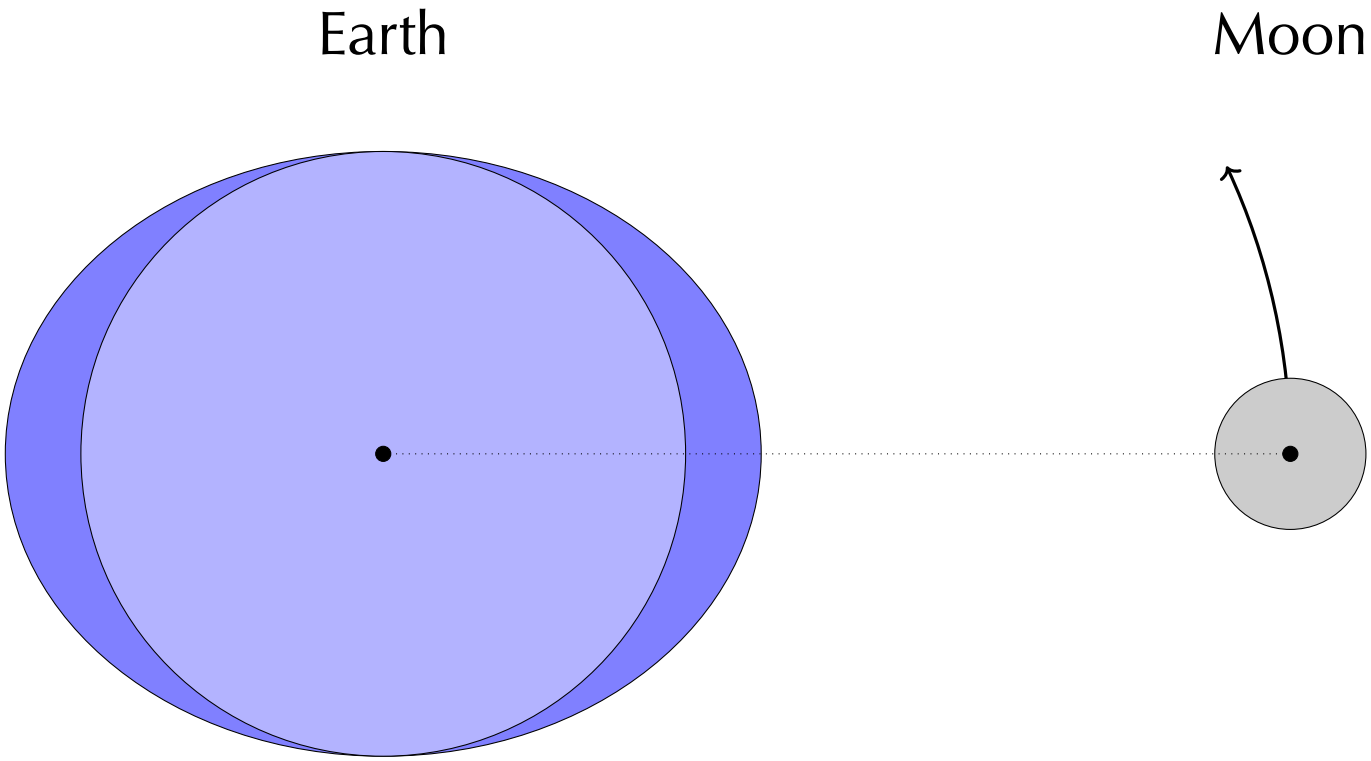
$$\Delta a_{☾} = \frac{2GM_{☾}\,R_\oplus}{r_{☾}^3} \quad \text{and} \quad \Delta a_{\odot} = \frac{2GM_{\odot}R_\oplus}{(1\,\text{AU})^3} \tag{3.26}$$

Since $M_{☾} \sim M_\oplus/81$ and $r_{☾} \sim 60 \times R_\oplus$

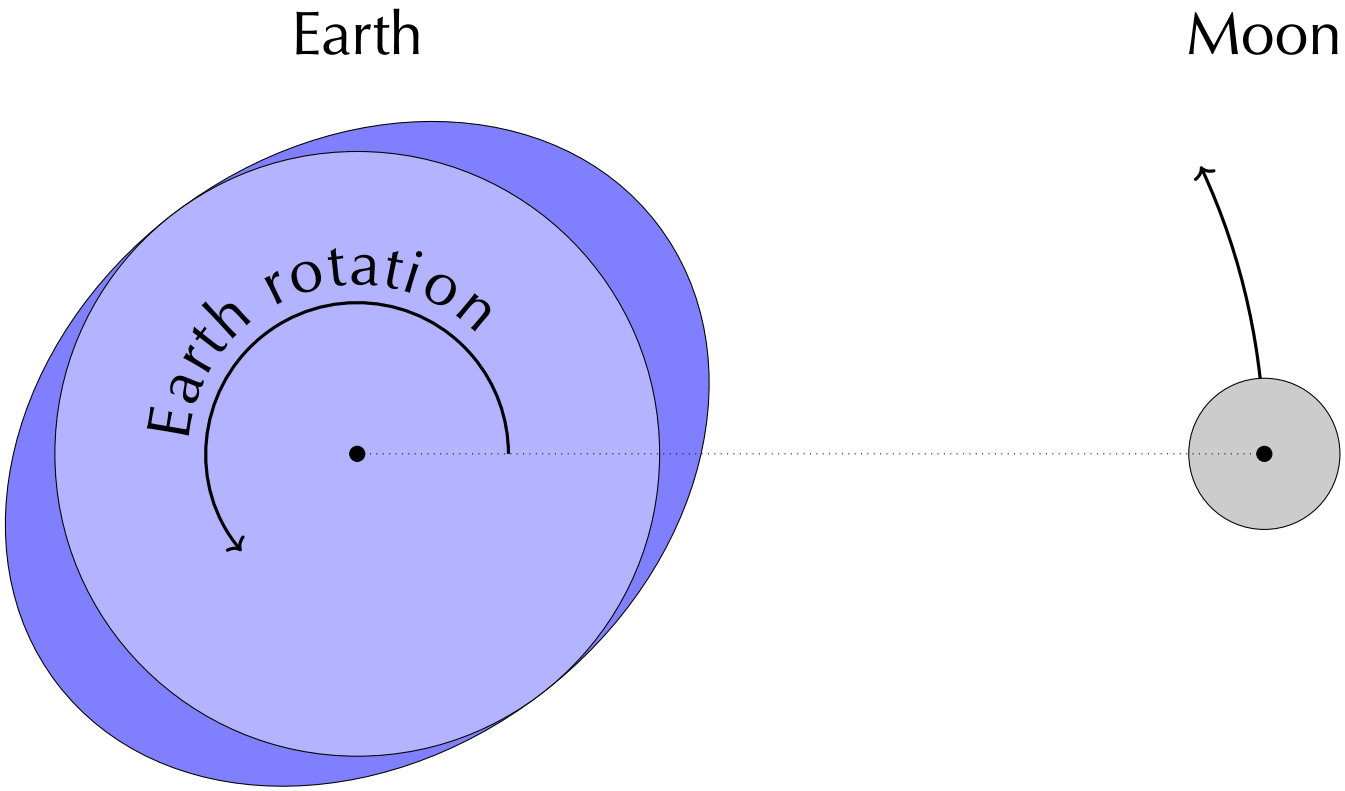
$\Longrightarrow \Delta a_{\odot}/\Delta a_{☾} = 0.46$

$\Longrightarrow$ Moon twice as important as Sun; two sets of tidal bulges, spring-tides when they align

Bound Rotation

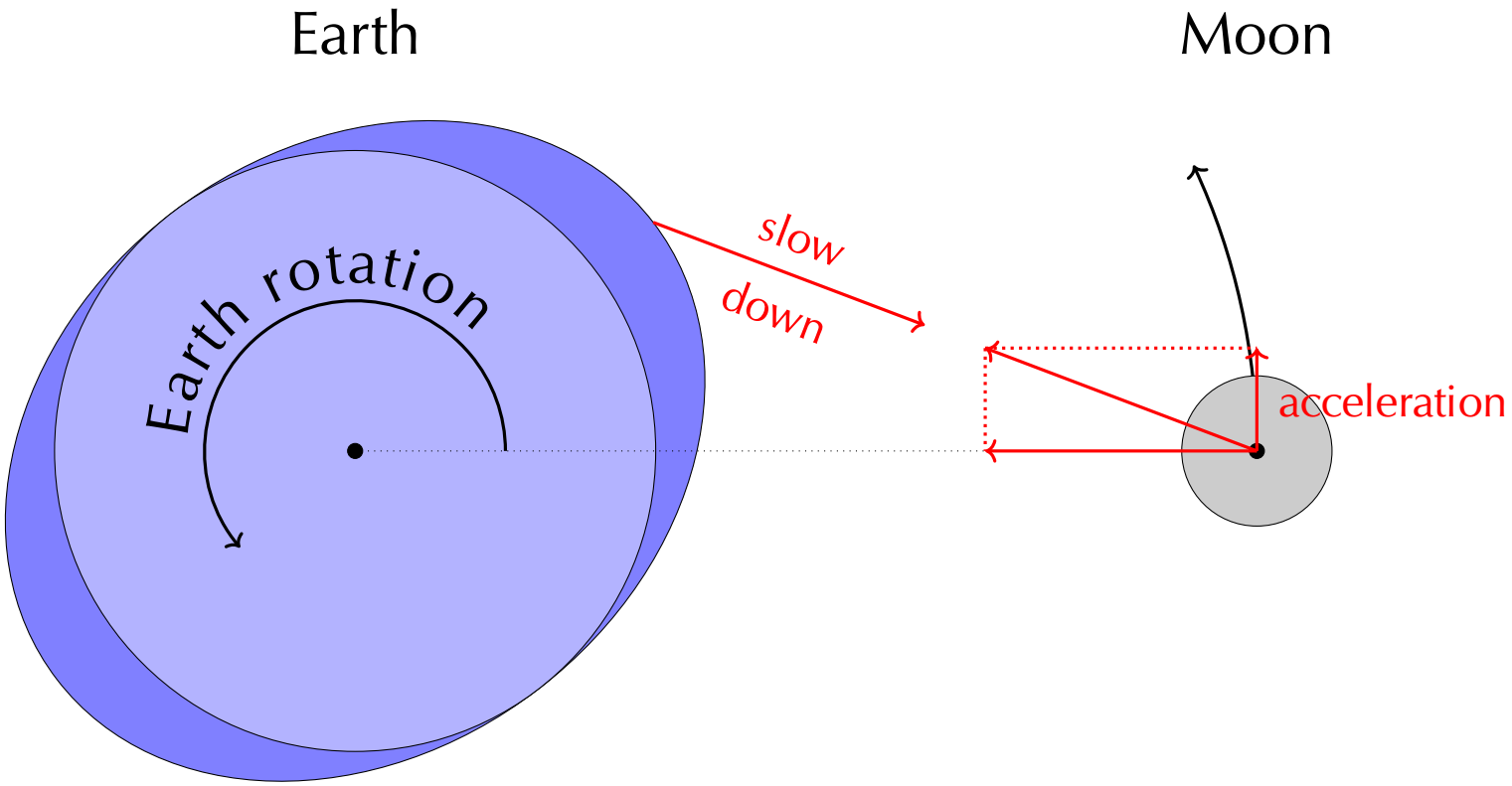


Bound Rotation



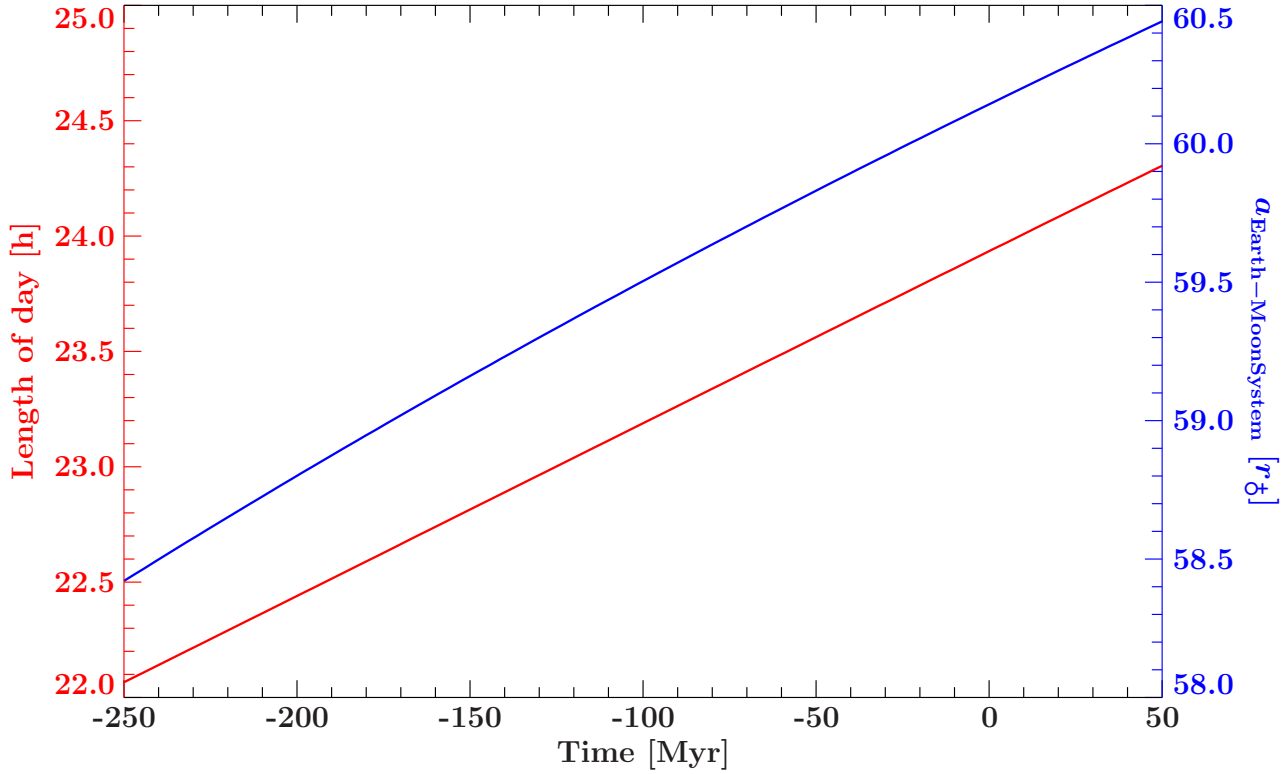
Friction Earth–Ocean: Tidal bulges preceed rotation by 2.5 h

Bound Rotation



- $P_{rot,\oplus}$ increases: length of day increases by $2.68\,\mathrm{ms\,century^{-1}}$
  confirmed by historic solar eclipse observations (e.g., Thales, 585 B.C., eclipse observations by Chinese astronomers)

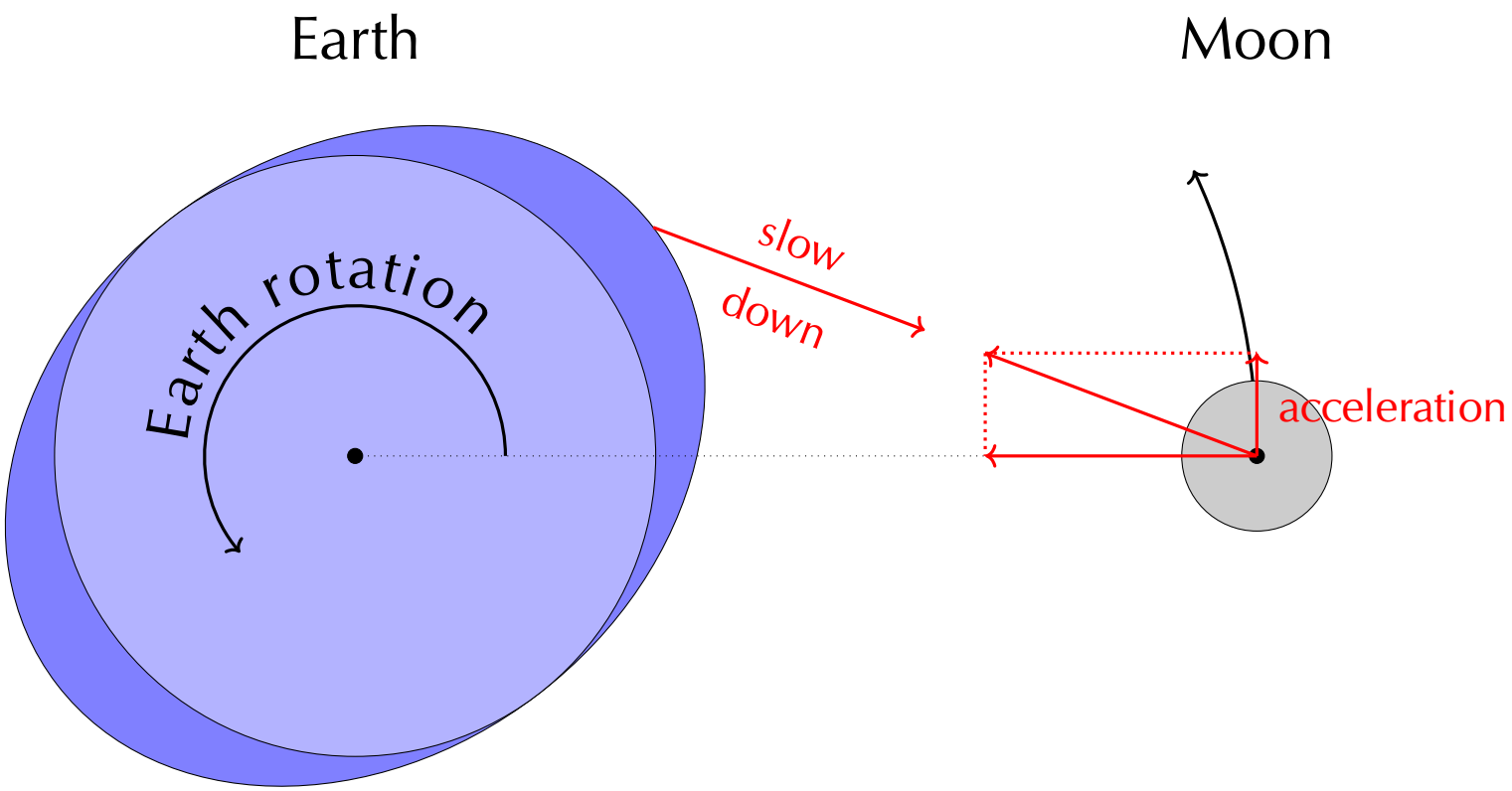
Bound Rotation



after Laskar et al. (2002)

- 370 Mio. yr ago (Devon): 1 Year$\sim$400 d
  (from coral growth; “rhythmites”; Williams et al., 2000, Rev. Geophys. 38(1), 37)
- Moon is accelerated: d increases by $3.82(7)\,\mathrm{cm\,yr^{-1}}$ (Dickey et al., 1994) $\Longrightarrow$ length of month grows
  (measured with Lunar Laser Ranging)

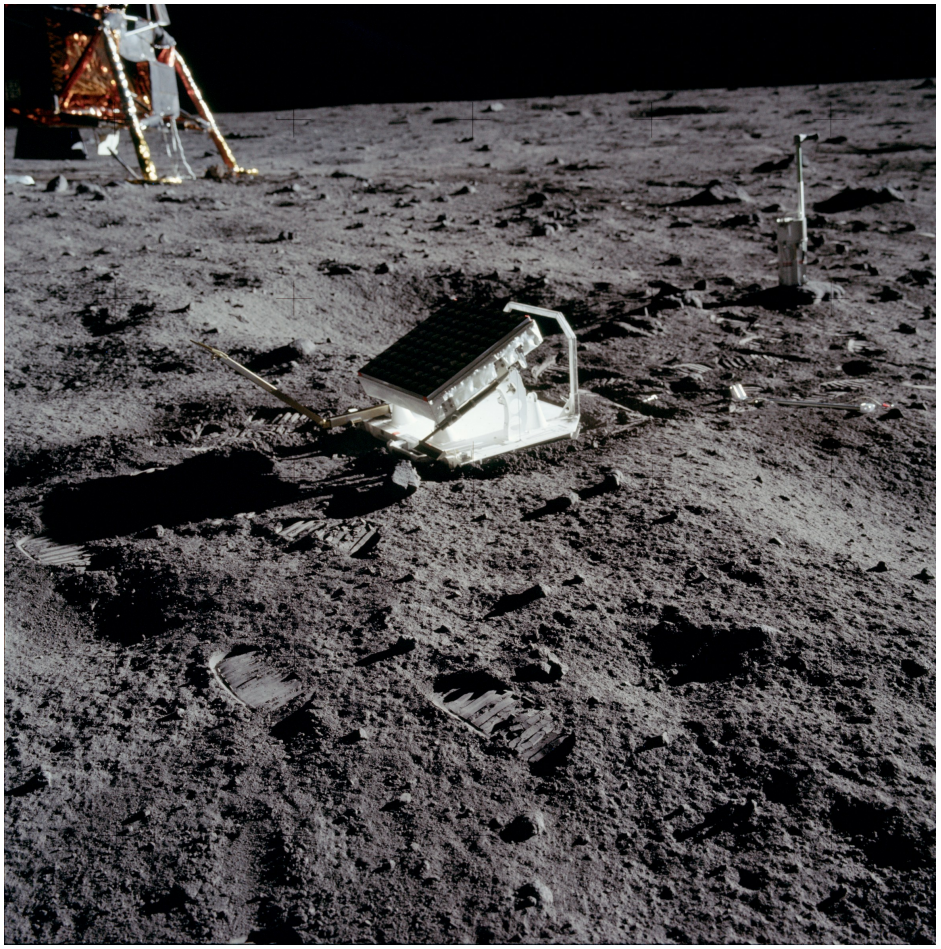
Bound Rotation



- Earth will reach equilibrium (bound rotation) once 1 rotation $=$ 1 month$(\mathrm{synodic})$ $=$ 50 d (today).
  reached in $\sim 10^{12}$ years
- Moon: $P_{rot} \simeq P_{orb}$ soon after formation (tidal friction on liquid interior)
  Many other satellites are also synchronized (due to work on planetary body): e.g. Galilean moons of Jupiter, Pluto/Charon

Bound Rotation

Appolo 11: Lunar Laser Ranging Experiment



NASA



Geodetic Observatory Wettzell (©H. Raab)

Stability of Satellites

Tidal forces: important for the stability of small bodies (e.g., moons) moving around a central body at a distance r.

Notation: mass $M_{p,s}$, radius $R_{p,s}$, density $\rho_{p,s}$ where p: planet, s: satellite.

Satellite: bound by its own gravitational force. Not ripped apart if:

$$\text{binding force } F_G > \text{tidal force } F_T$$

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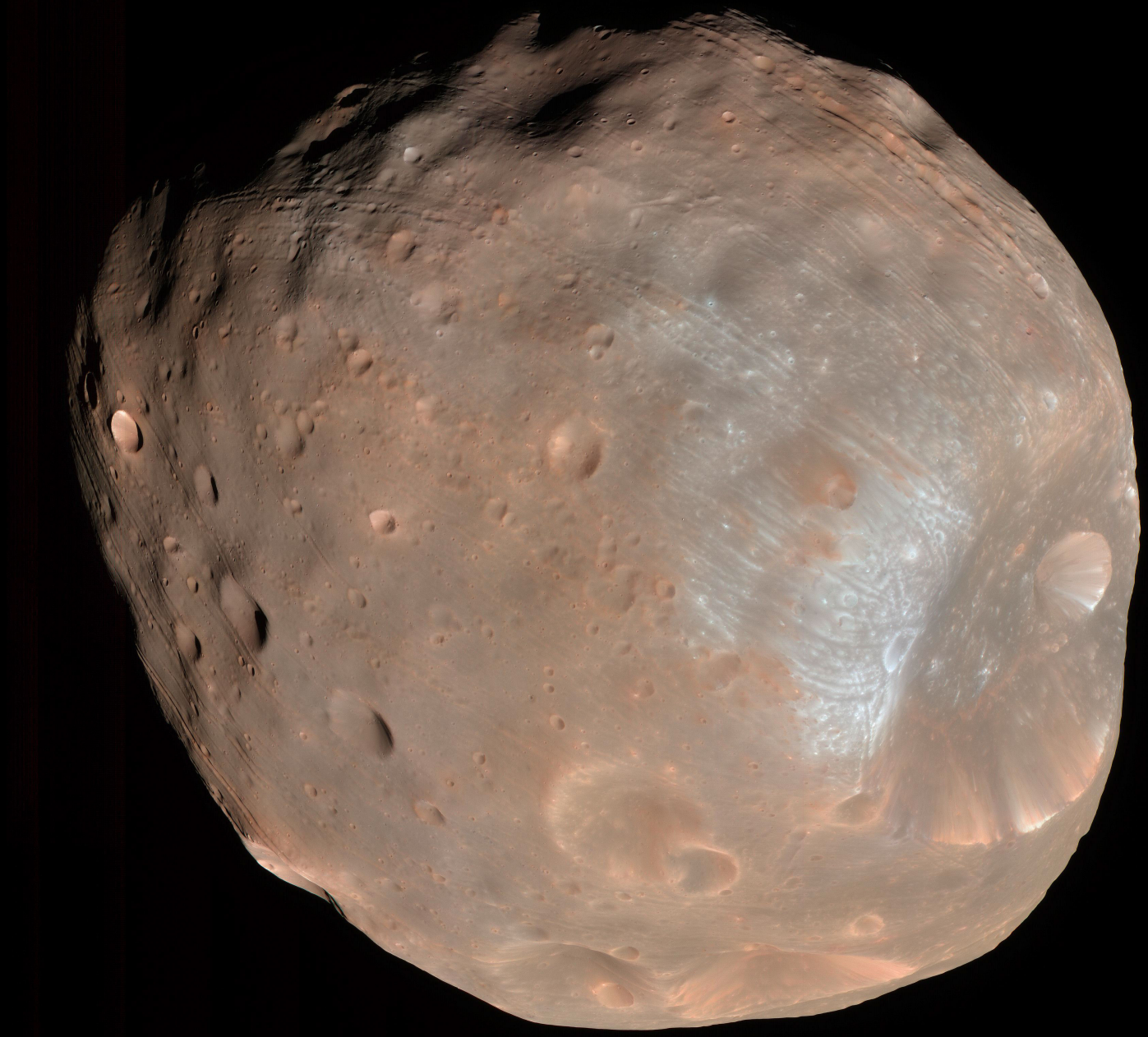
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$\exists$ a critical distance (Roche, 1850):

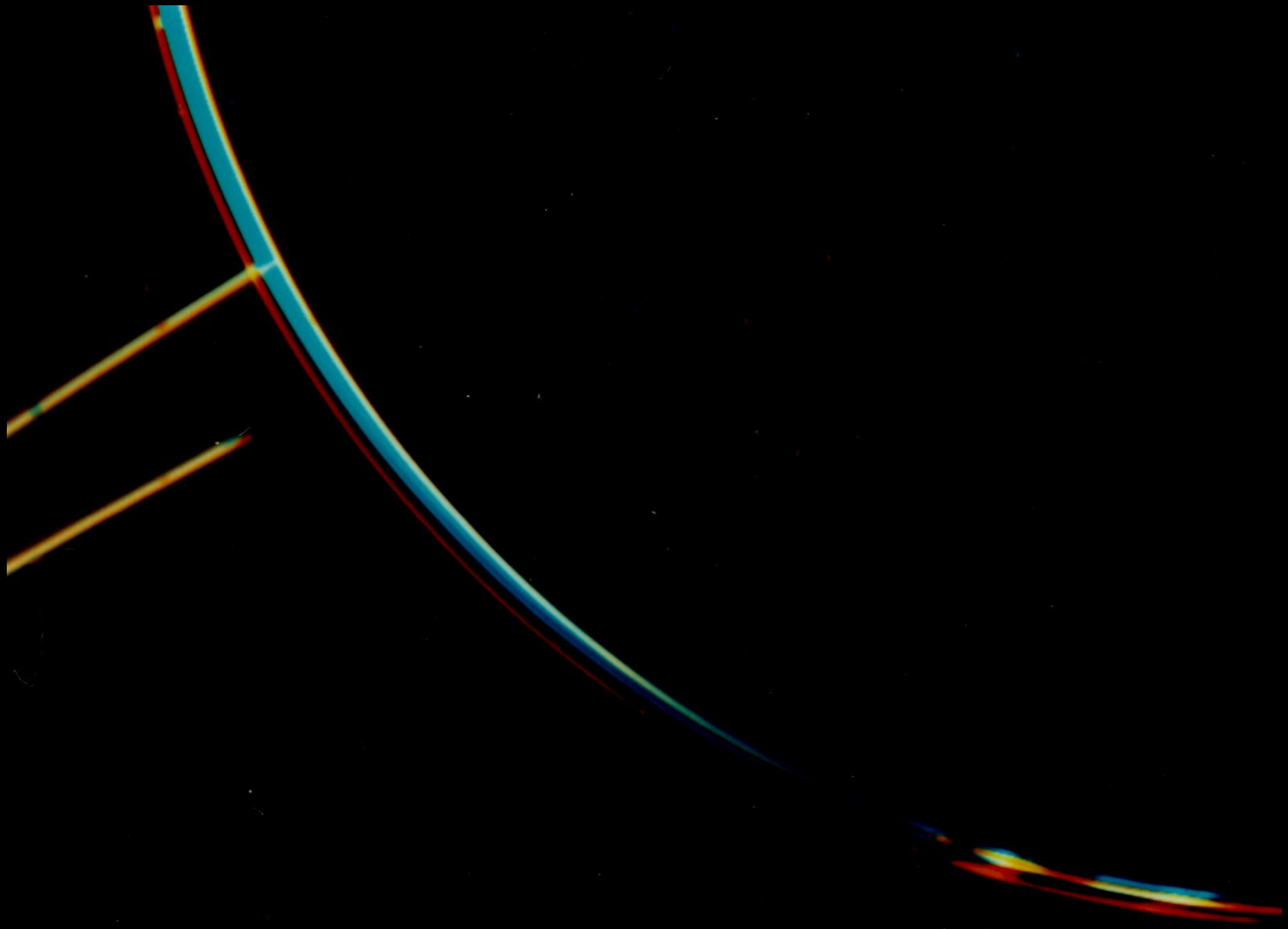
$$\frac{r_c}{R} = \sqrt[3]{\frac{4\rho_p}{\rho_s}} \quad \xrightarrow{\text{exact calculation}} \quad \frac{r_c}{R} = 2.46\sqrt[3]{\frac{\rho_p}{\rho_s}} \tag{3.29}$$

$\Longrightarrow$ If $\rho_p \sim \rho_s$: moon must be more distant than 2.44 planetary radii from the planet to avoid disruption. This is important, e.g., for the formation of rings.



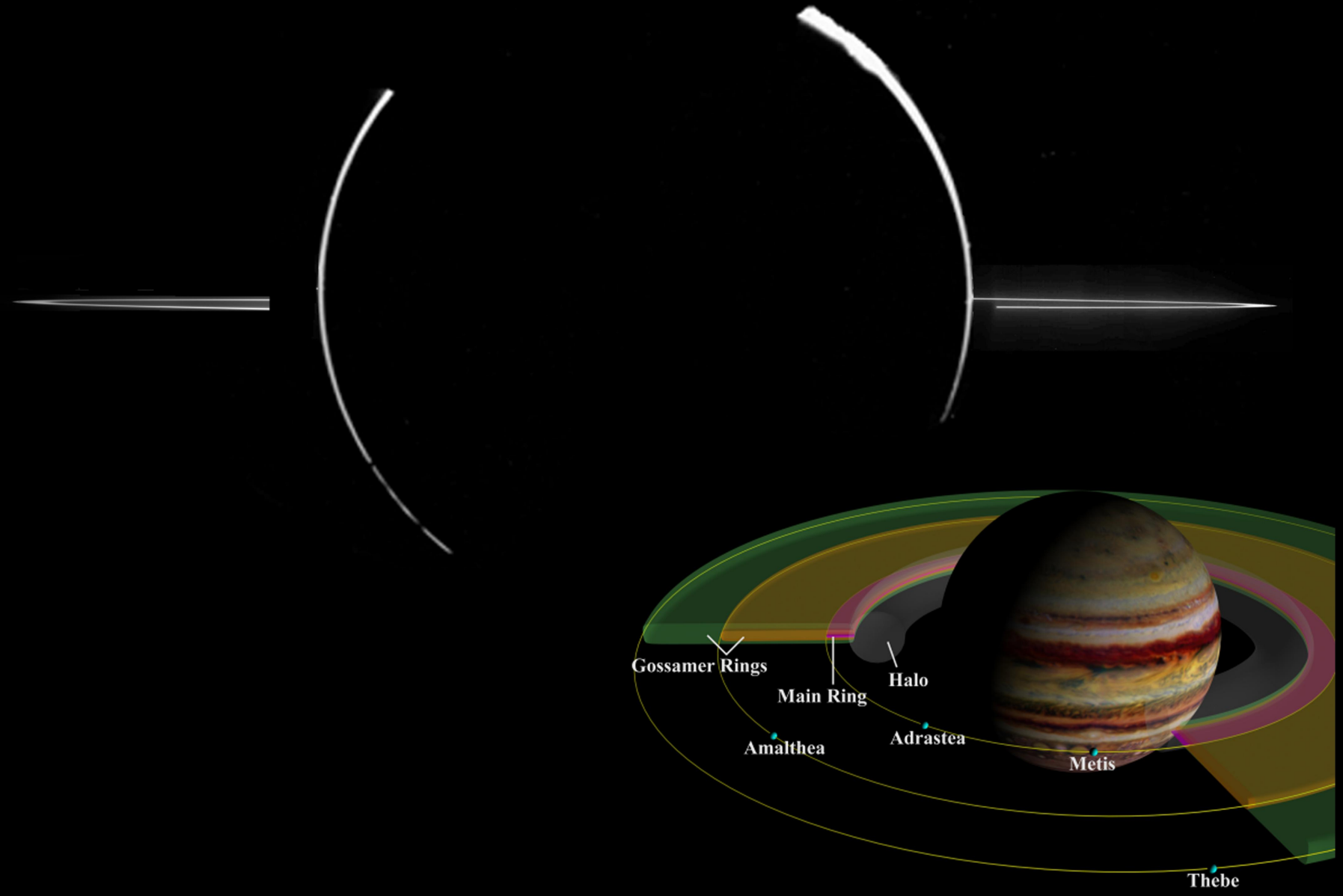
NASA/JPL-Caltech/University of Arizona

Mars' moon Phobos is example of moon that is located close to Roche limit (note ridges!)



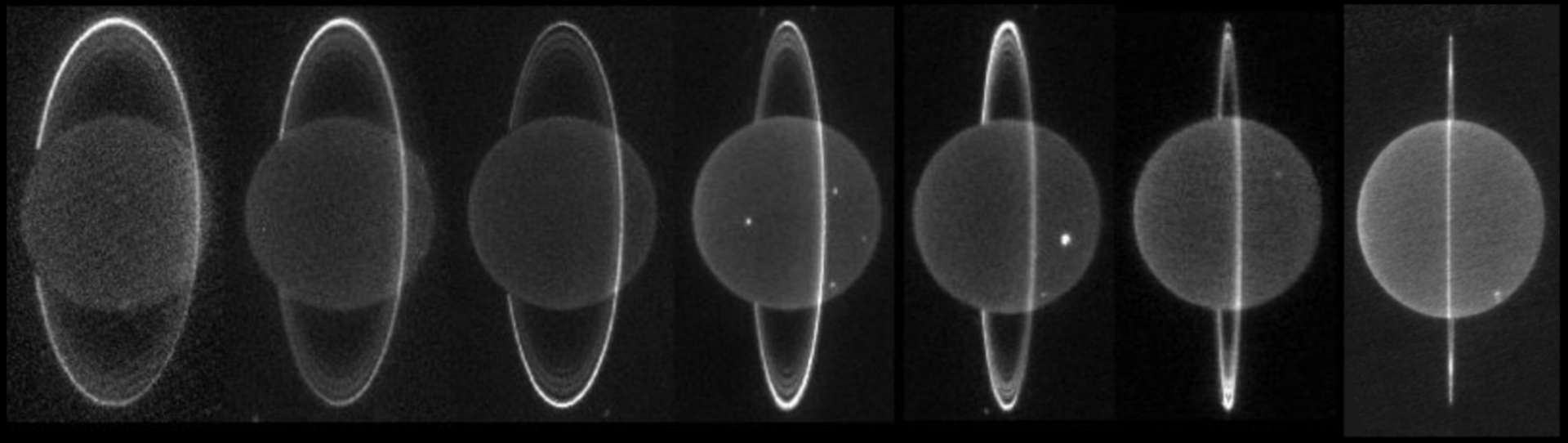
colors in atmosphere: parallax due to motion of Voyager 2

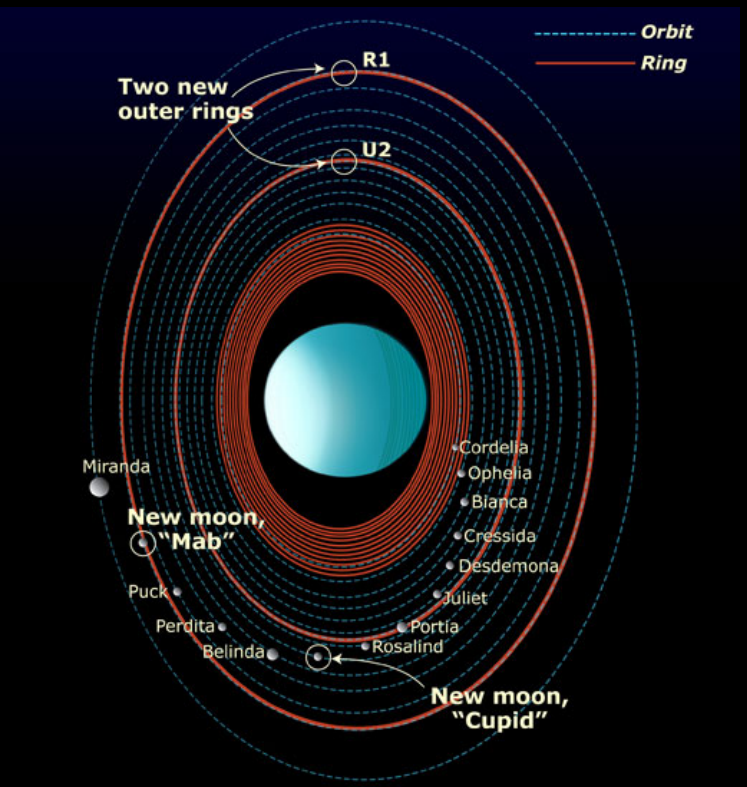
Jupiter’s rings (Voyager 2, 1979 March)



NASA/JPL/UofArizona

Jupiter's Rings from Galileo





Uranus' rings (IR; strongly enhanced)
Imke de Pater, Seran Gibbard, Heidi Hammel / W. M. Keck Observatory

Structure of Uranus' ring system and moonlets

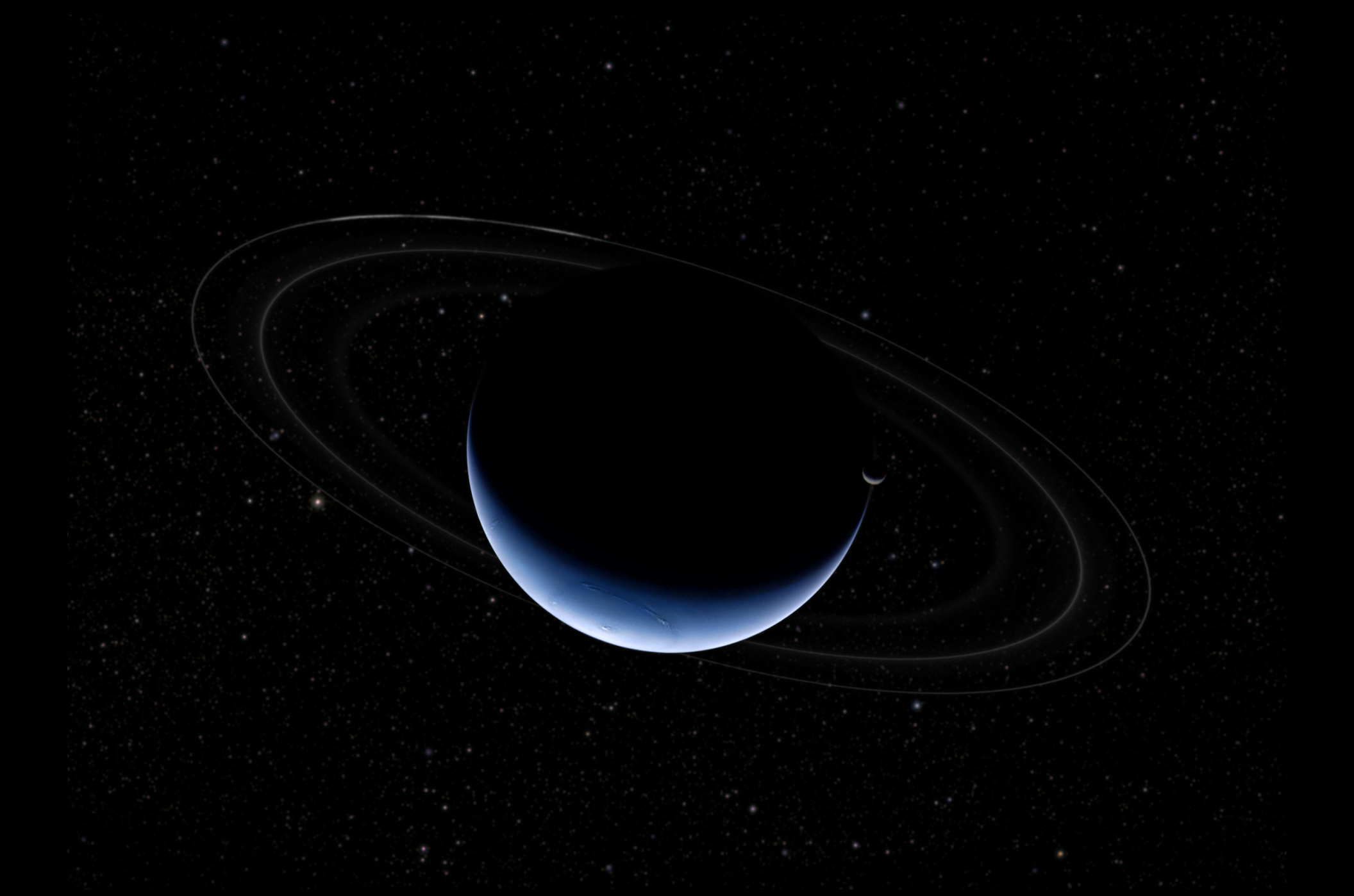
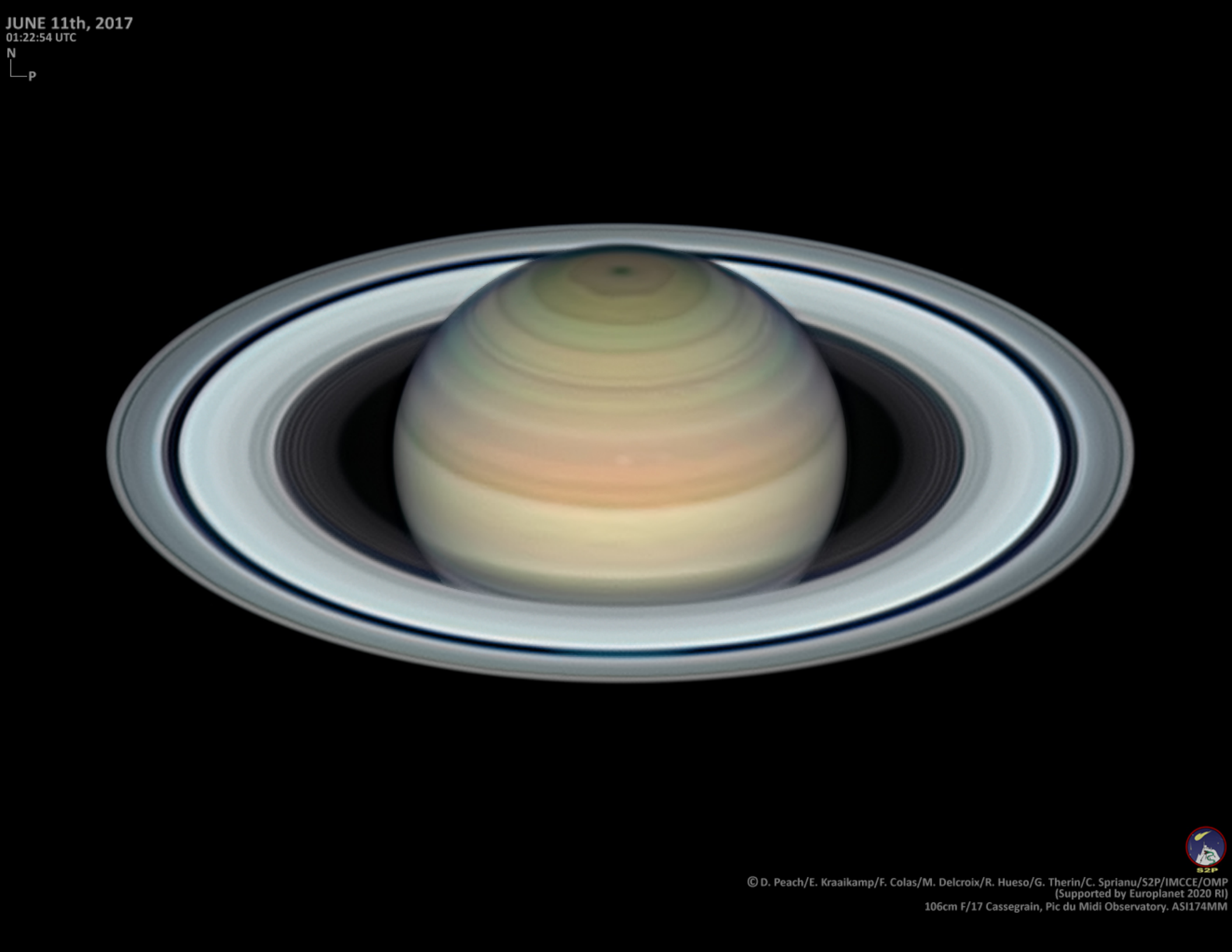
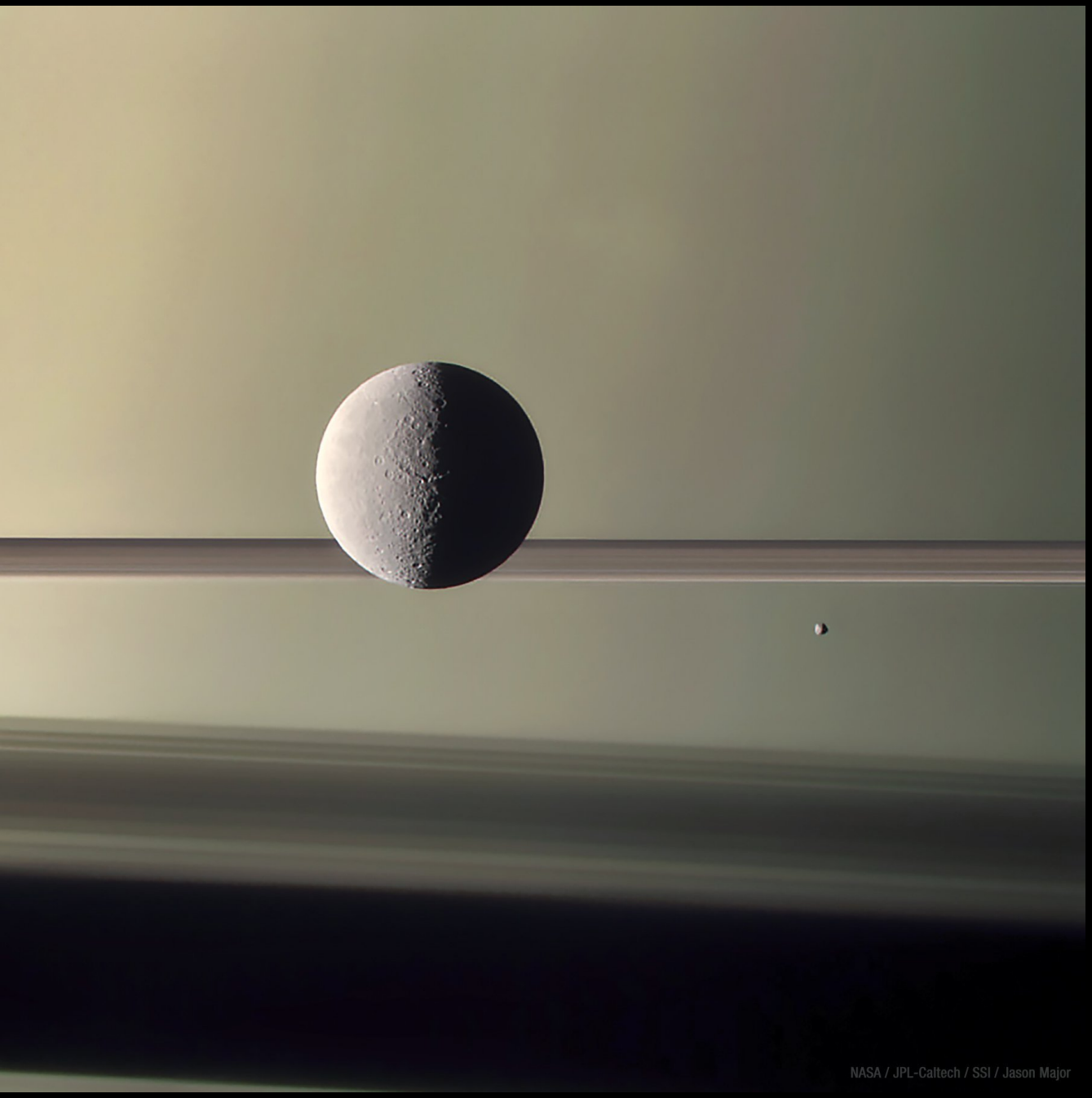


Image Assembly & Processing: Rolf Wahl Olsen
Image Data: NASA/JPL (Voyager 2, NASA Planetary Data System)

Neptune: 1989 August 25: note dense sub-structures in ring!

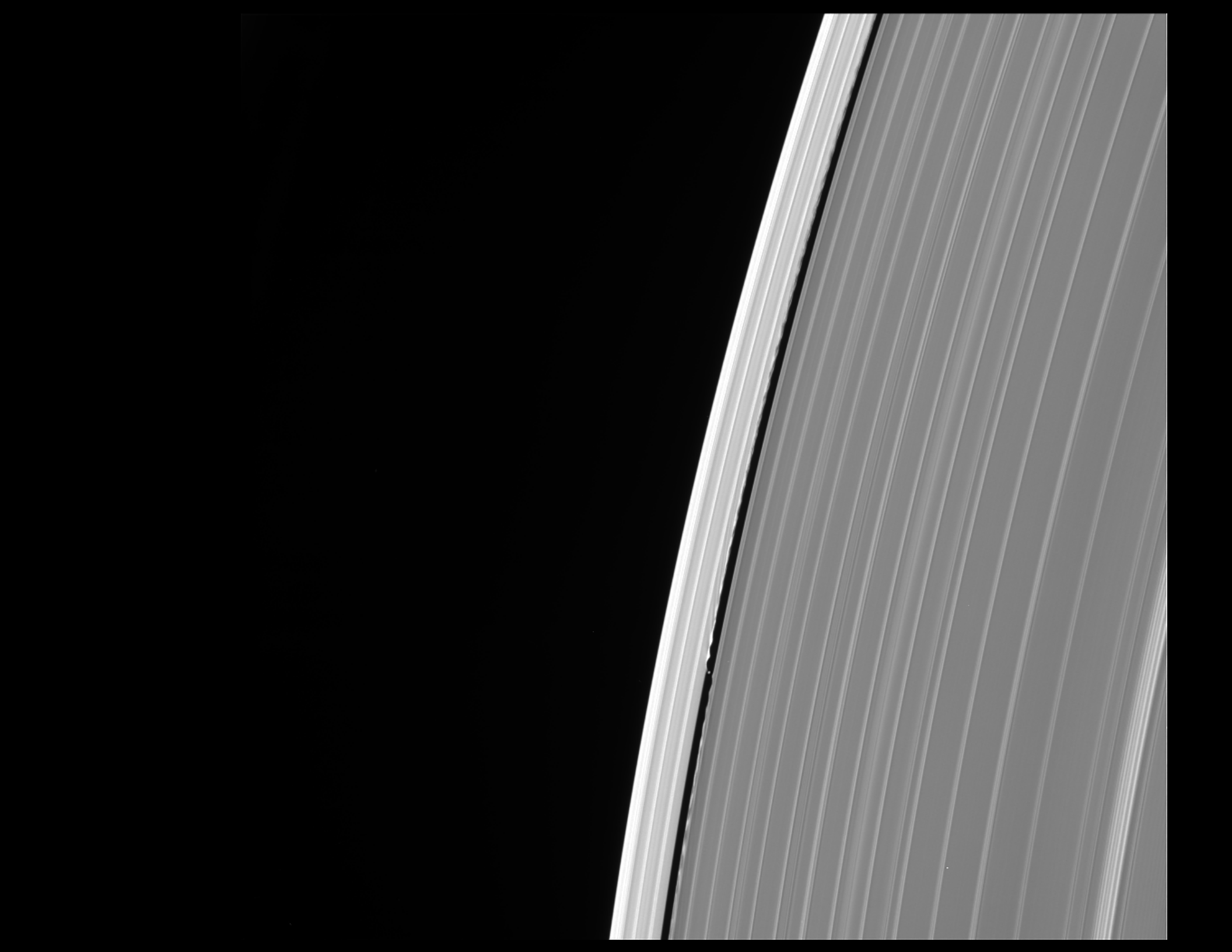


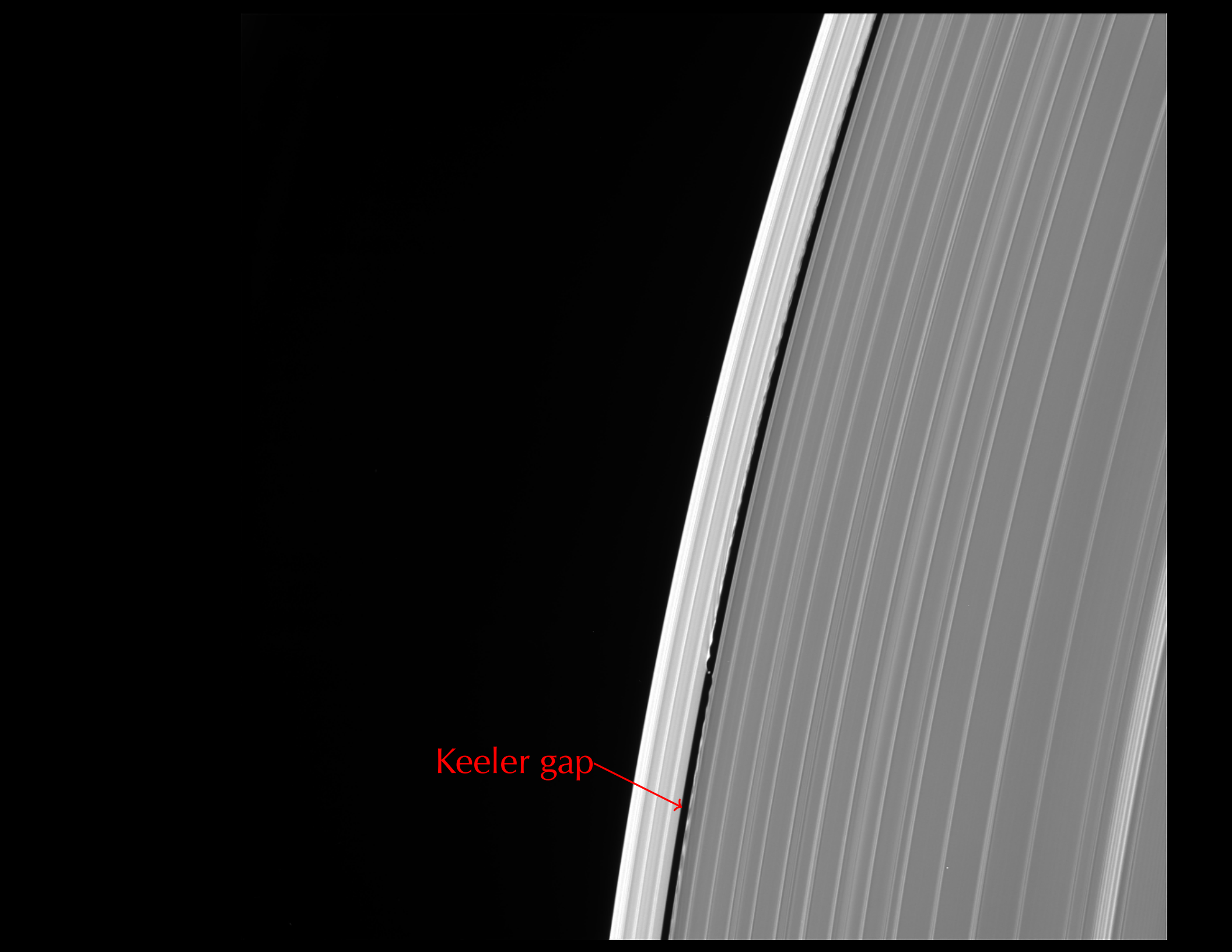
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(Supported by Europlanet 2020 RI)
106cm F/17 Cassegrain, Pic du Midi Observatory. ASI174MM

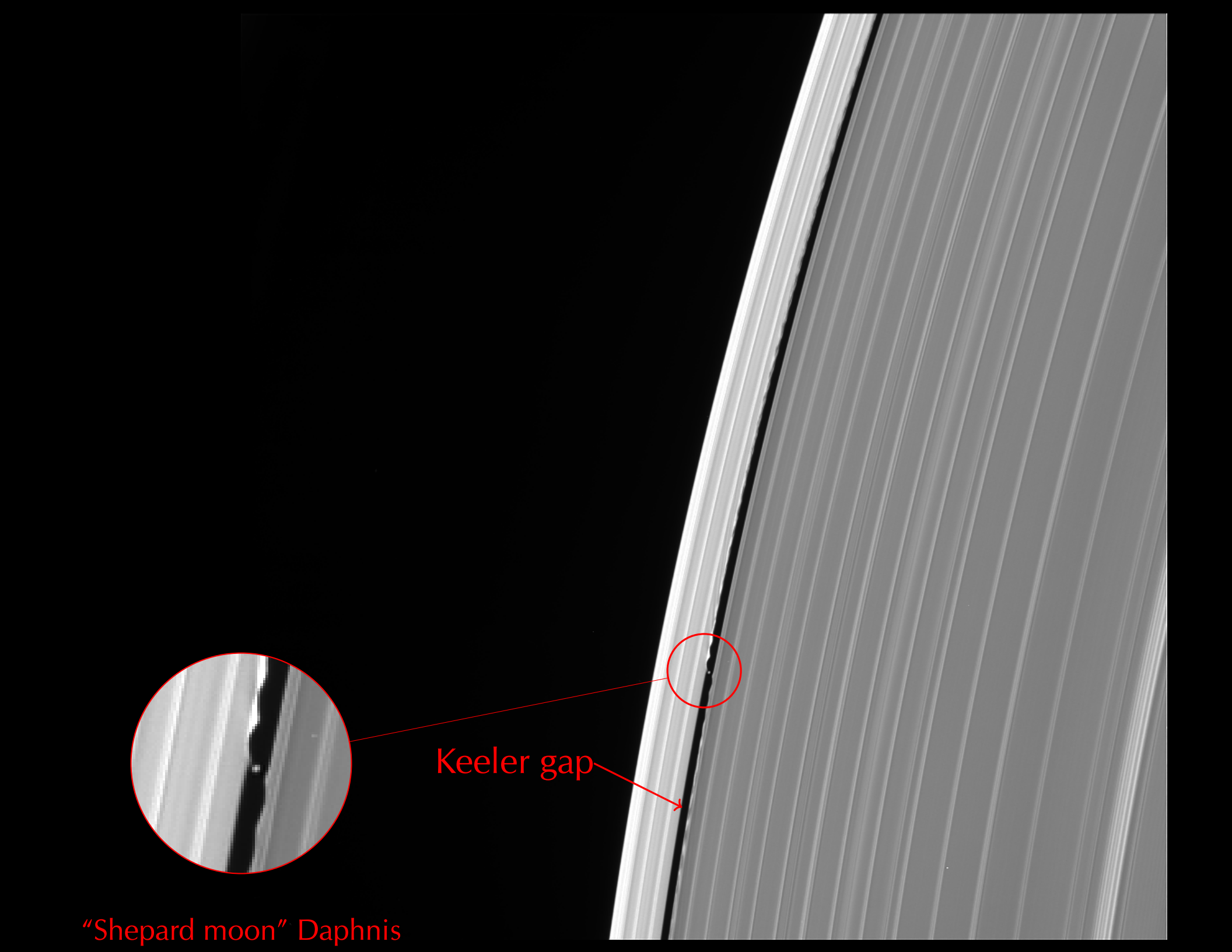


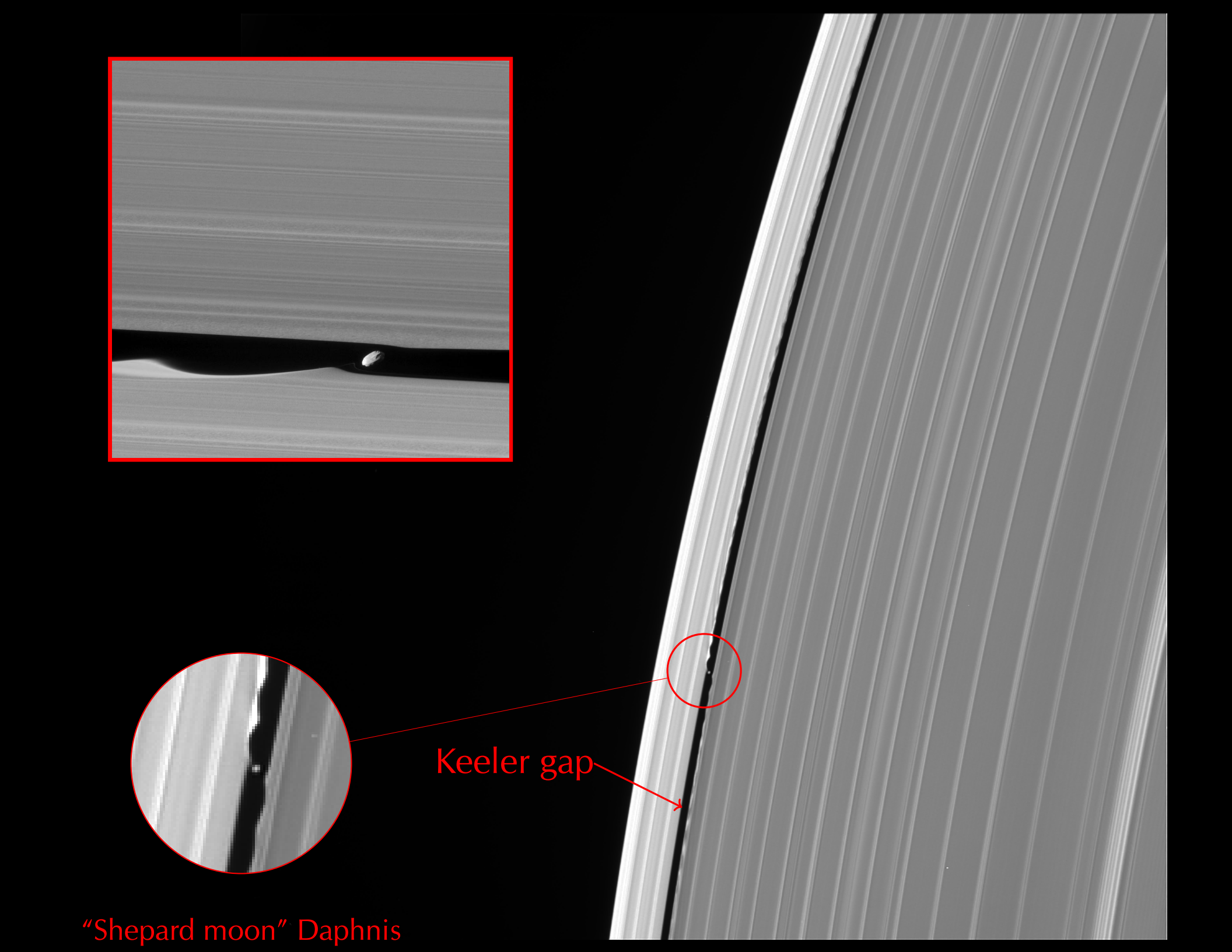
Rings are very thin (10 m inner ring, few km outer rings), consist of dust, ice, and rocks

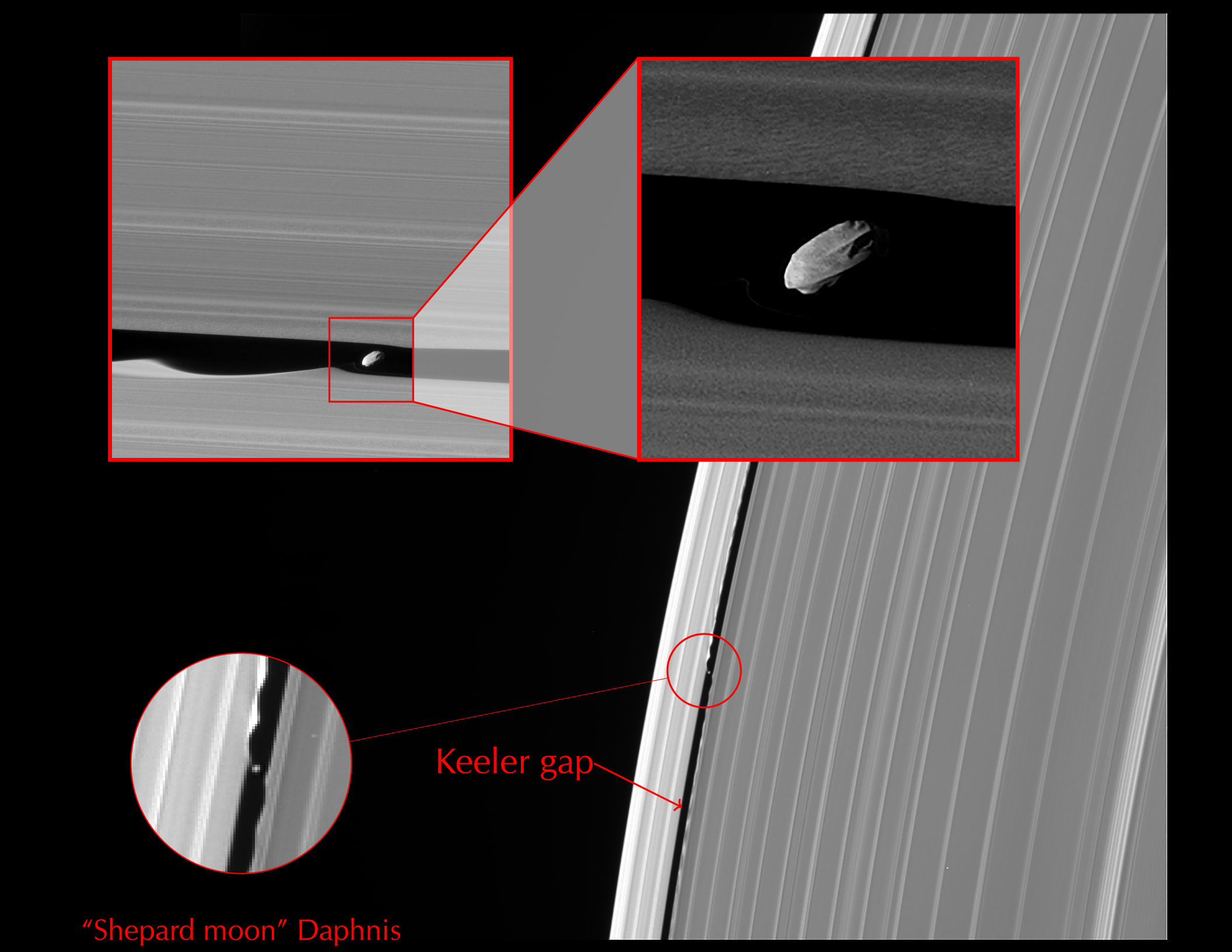
Rhea and Epimetheus in front of Saturn

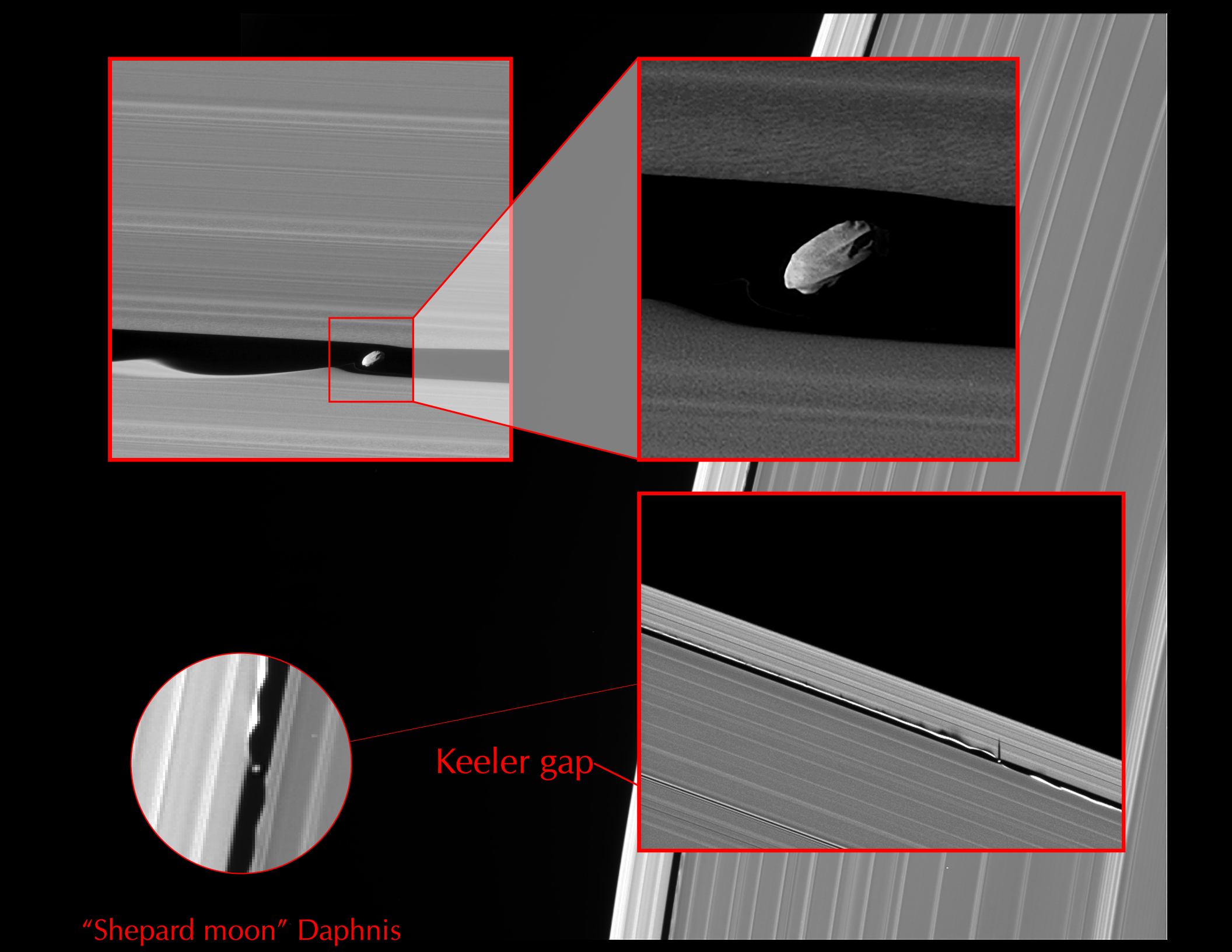


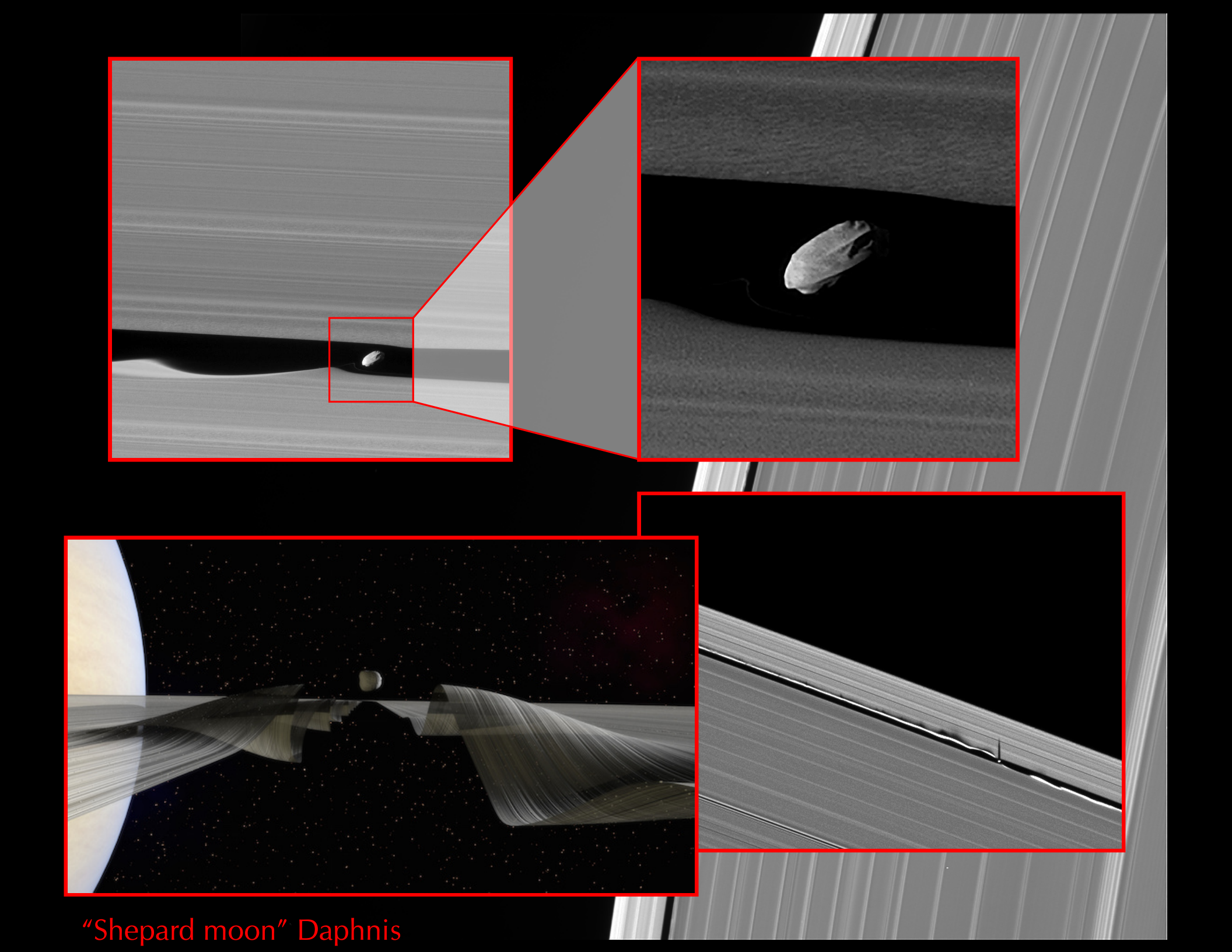

Keeler gap


Keeler gap
"Shepard moon" Daphnis

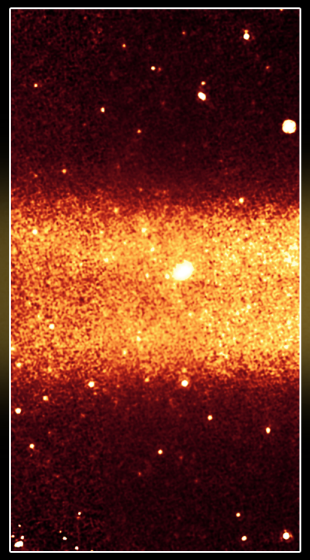

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Saturn

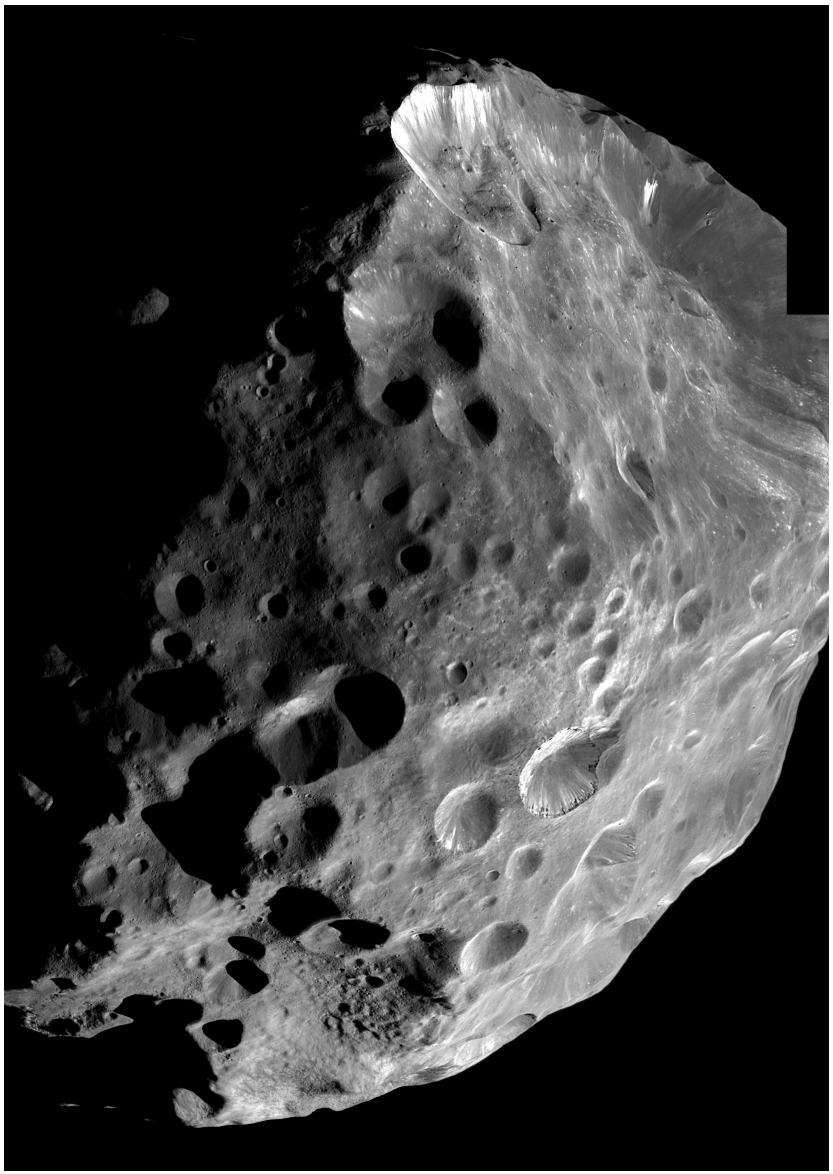
Dust Ring

Infrared View of Saturn's Largest Ring
NASA / JPL-Caltech / A. Verbiscer (Univ. of Virginia)

Spitzer Space Telescope • MIPS
ssc2009-19a

Saturn's dust ring (NASA Spitzer): extends from 128 to 207 R_{η}, 40 R_{η} thick.

Saturn's Rings

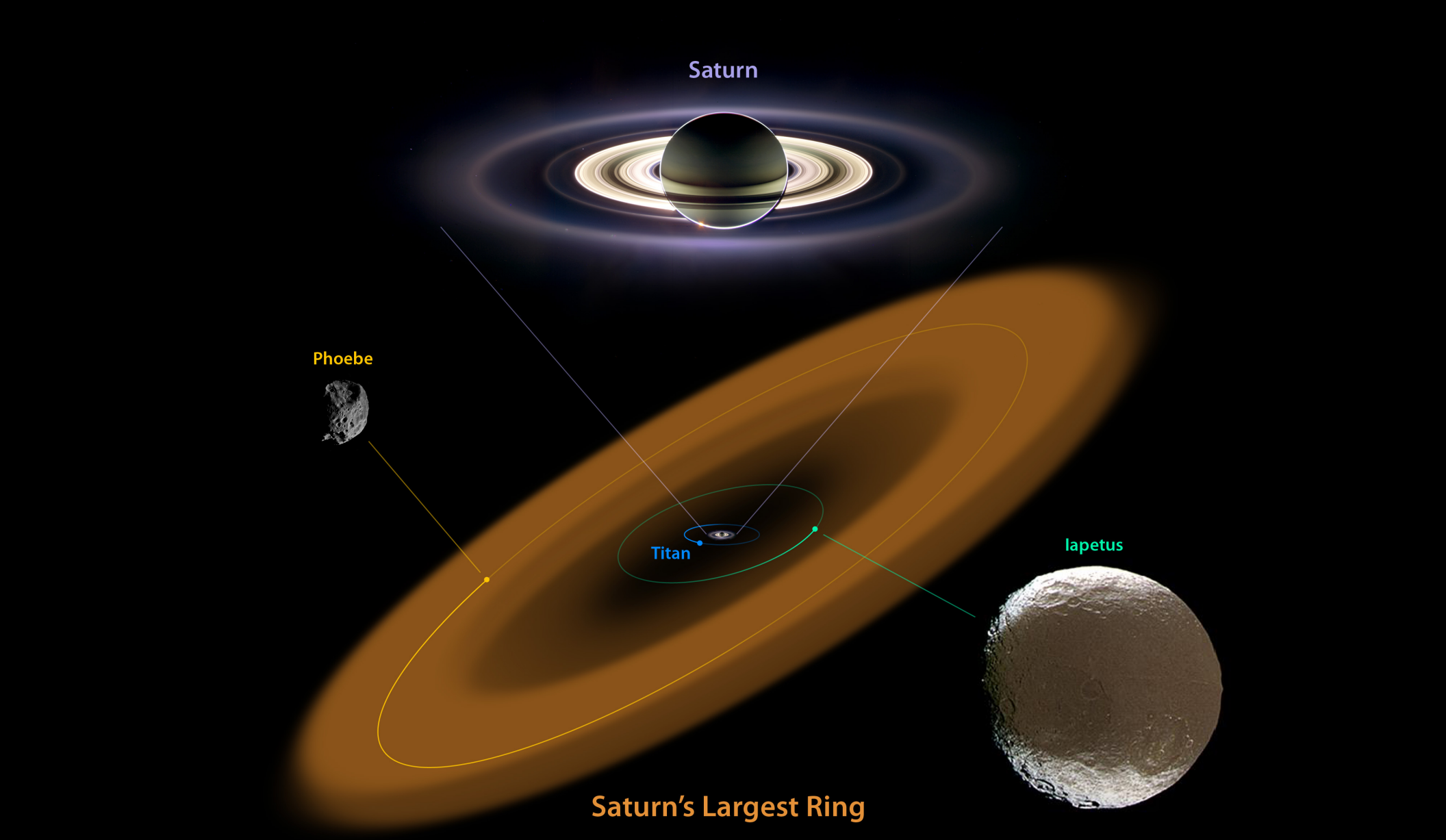


Phoebe:

- small moon of Saturn: radius 220 km.
- dark surface: albedo = 0.08

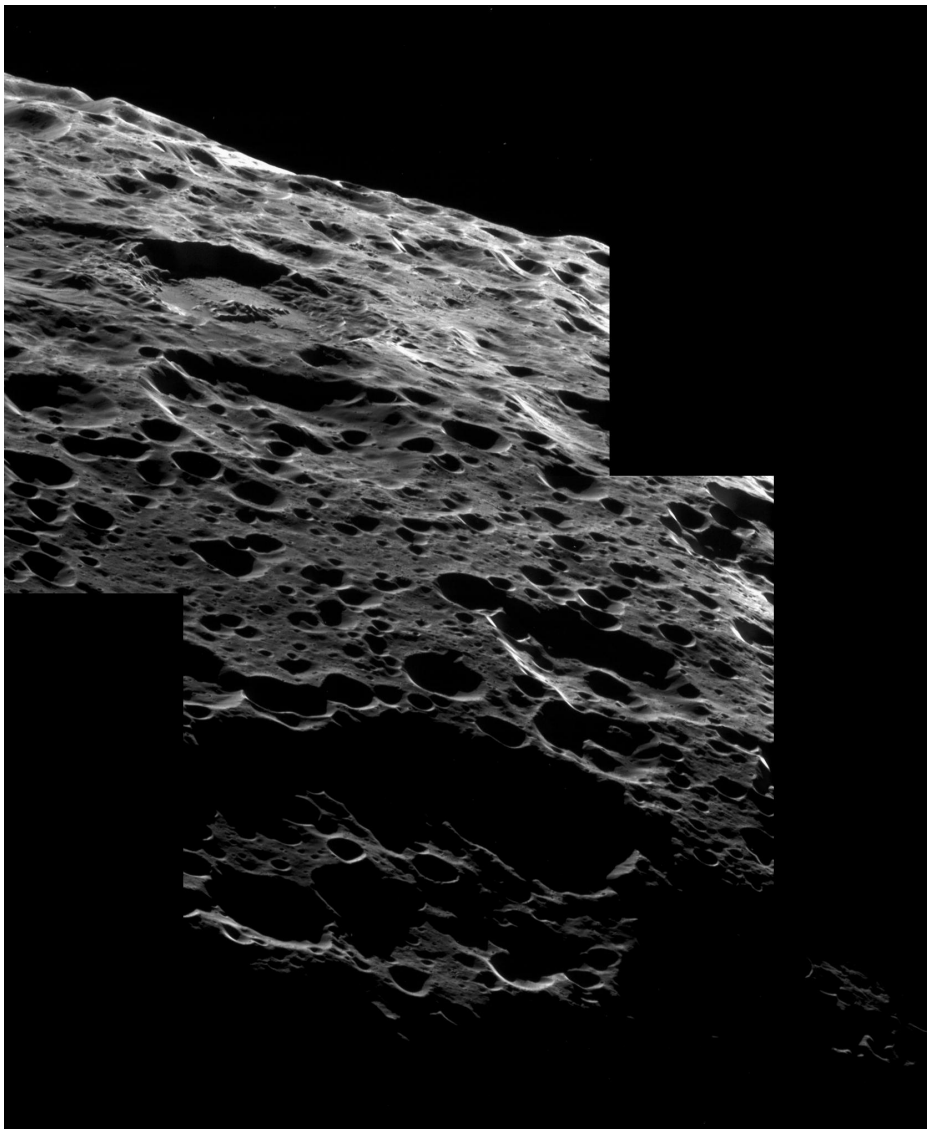
orbits inside the enormous dust ring of Saturn

Surface details from Cassini spacecraft. Credit: ESA/NASA/JPL



Dust supply through impacts on Phoebe, dust particles then migrate inwards and are swept up by Iapetus

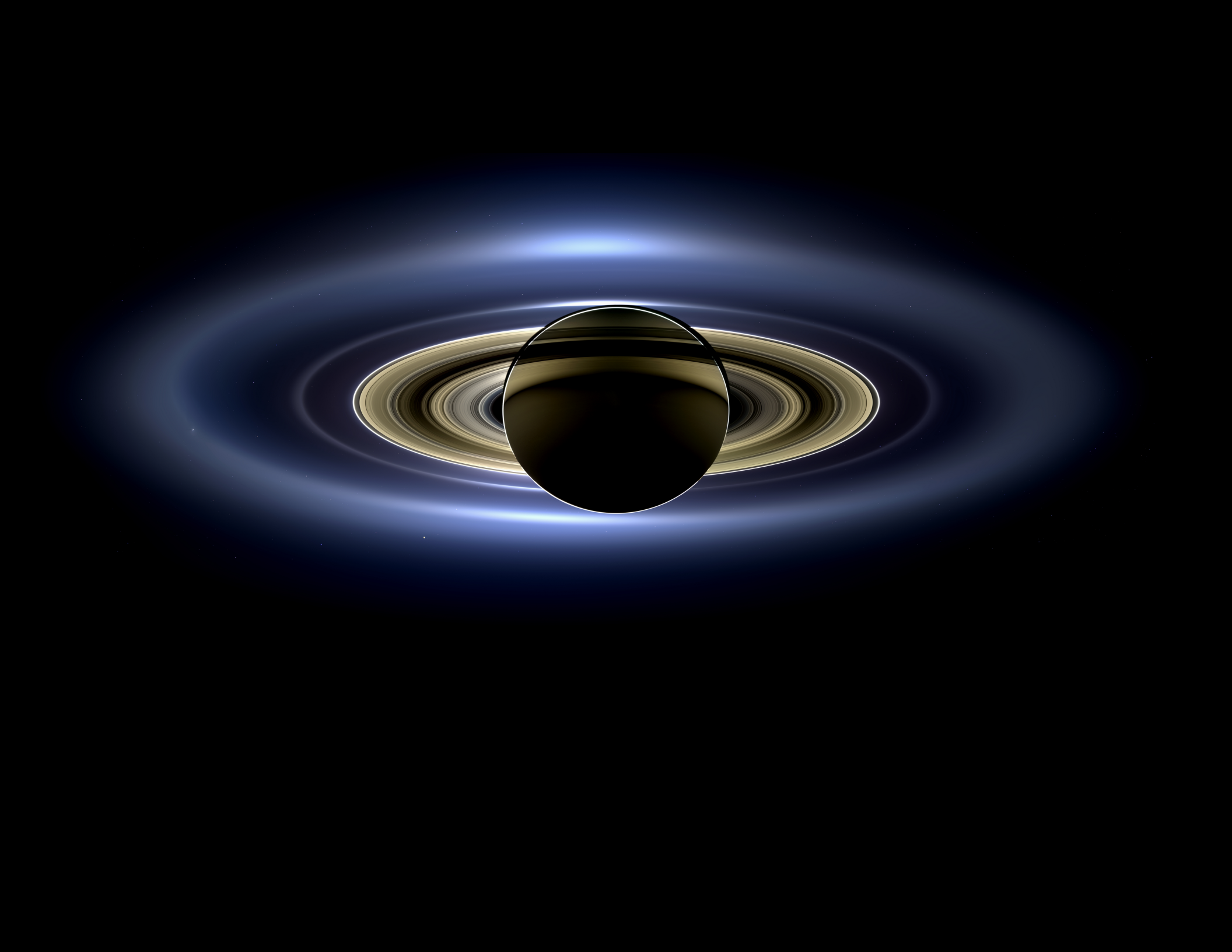
Saturn's Rings

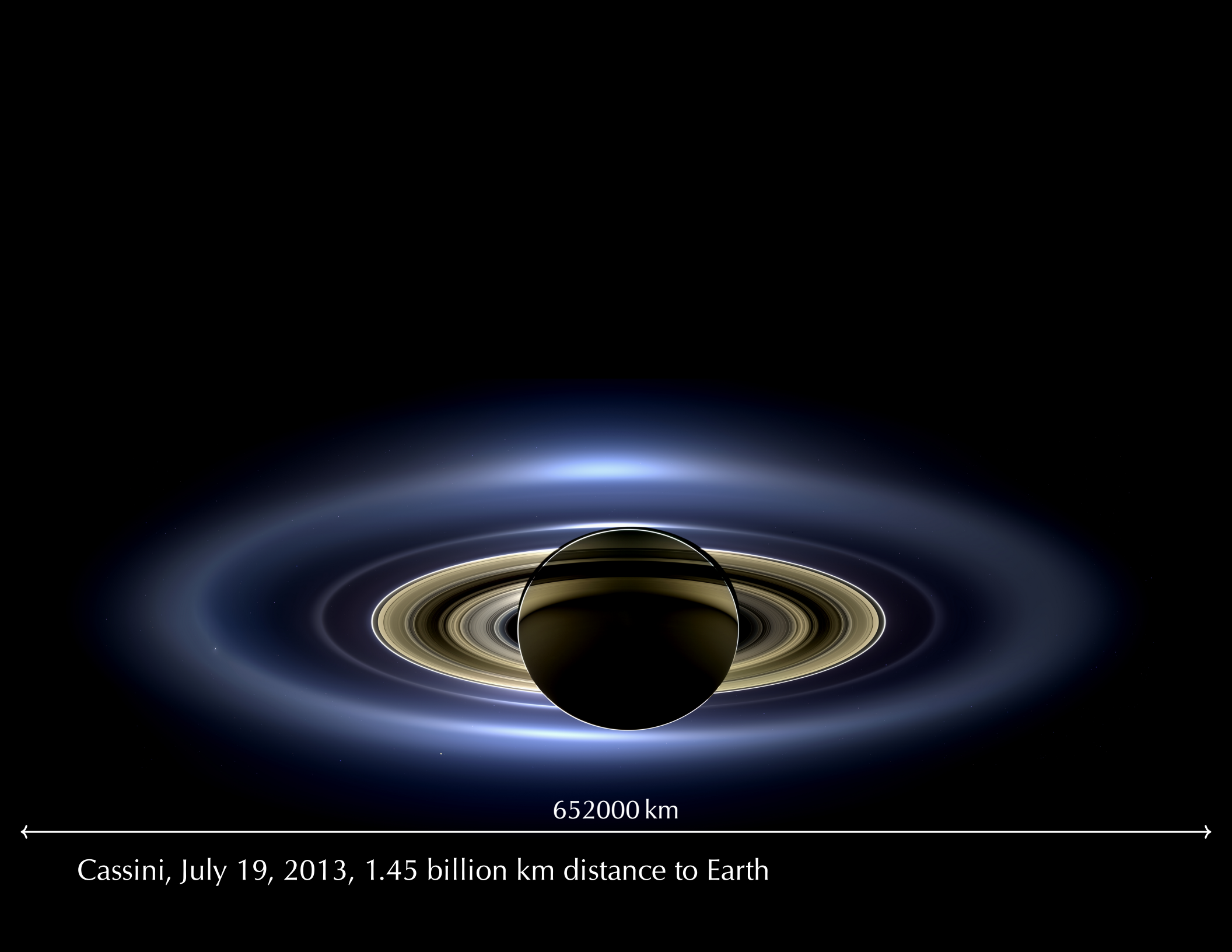


Iapetus:

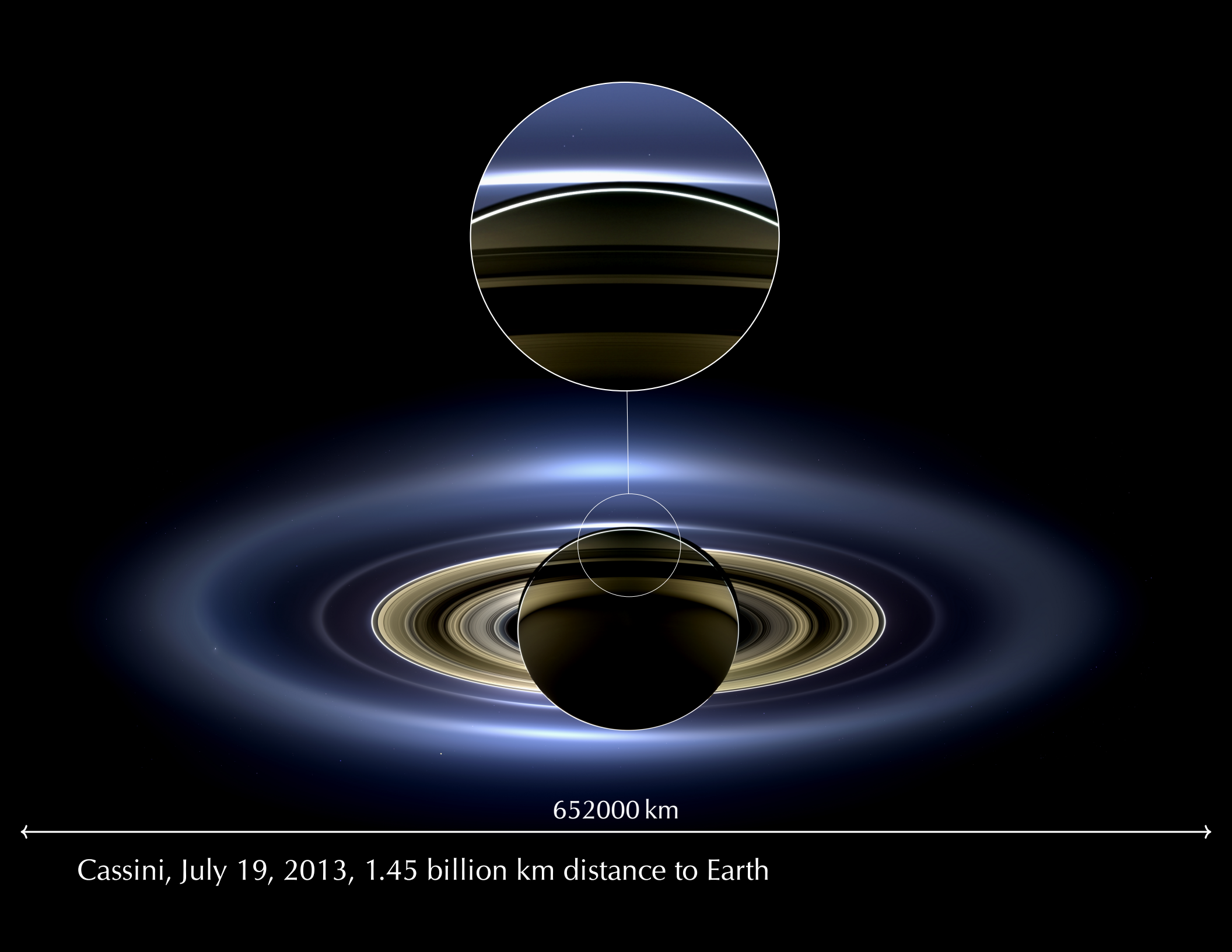
- Radius: 1436 km
- Two hemispheres:
  Cassini Regio: very dark (albedo~0.05)
  Roncevaux Terra: bright like Europa (albedo~0.5)
- low density: 1.27 g cm^{-3}
  large fraction of water ice?
- Dark material accreted from Saturn's dust ring

Surface details from Cassini spacecraft.
Credit: ESA/NASA/JPL

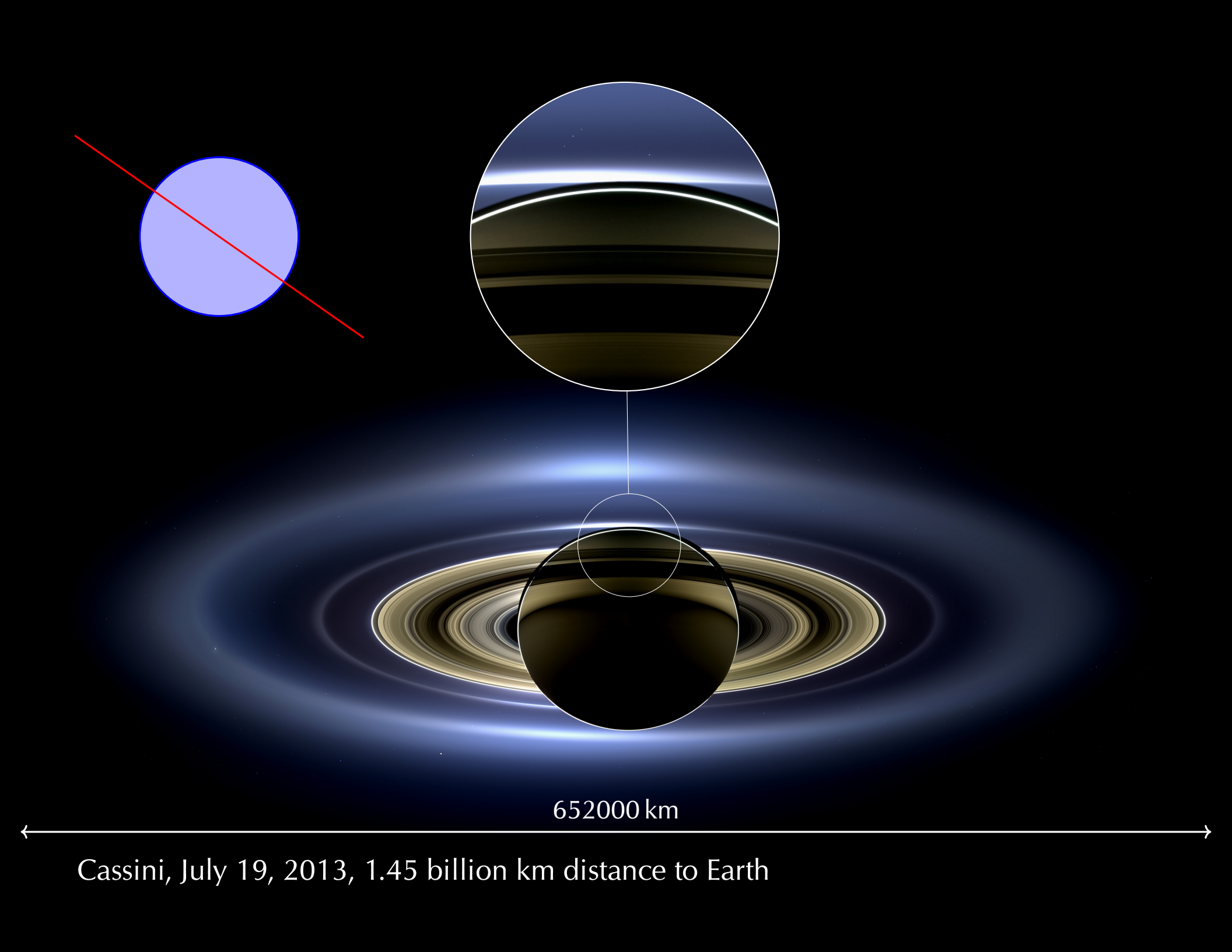




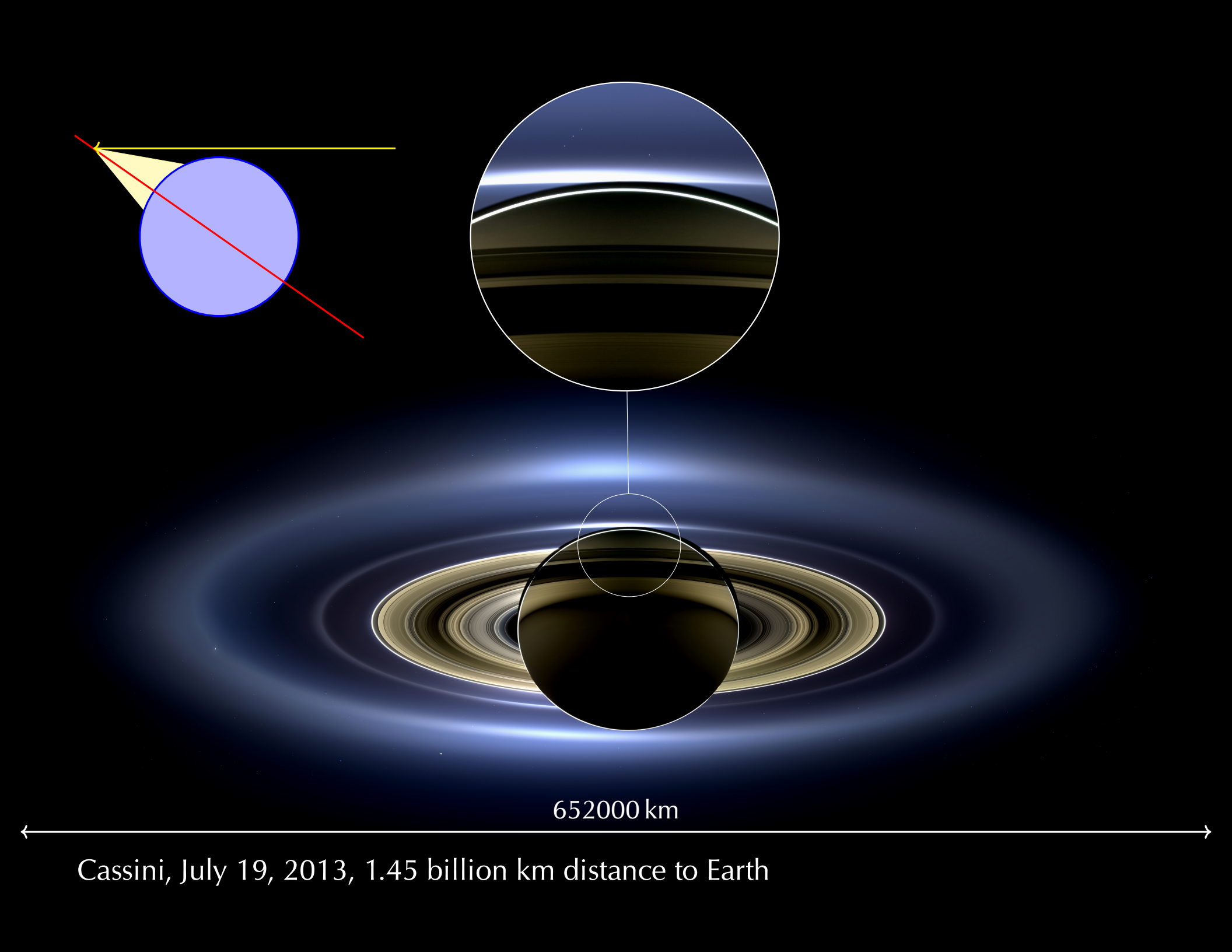
Cassini, July 19, 2013, 1.45 billion km distance to Earth



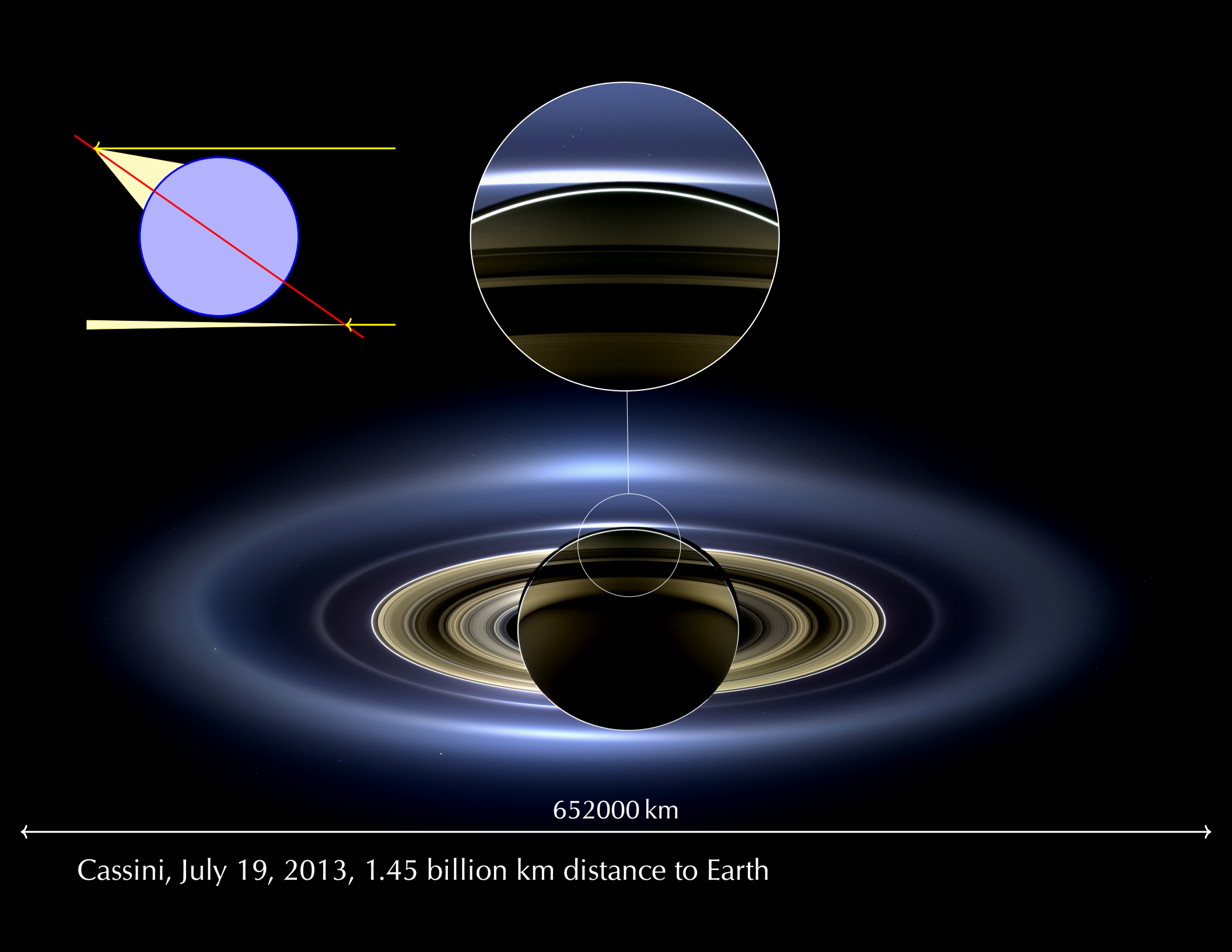
Cassini, July 19, 2013, 1.45 billion km distance to Earth



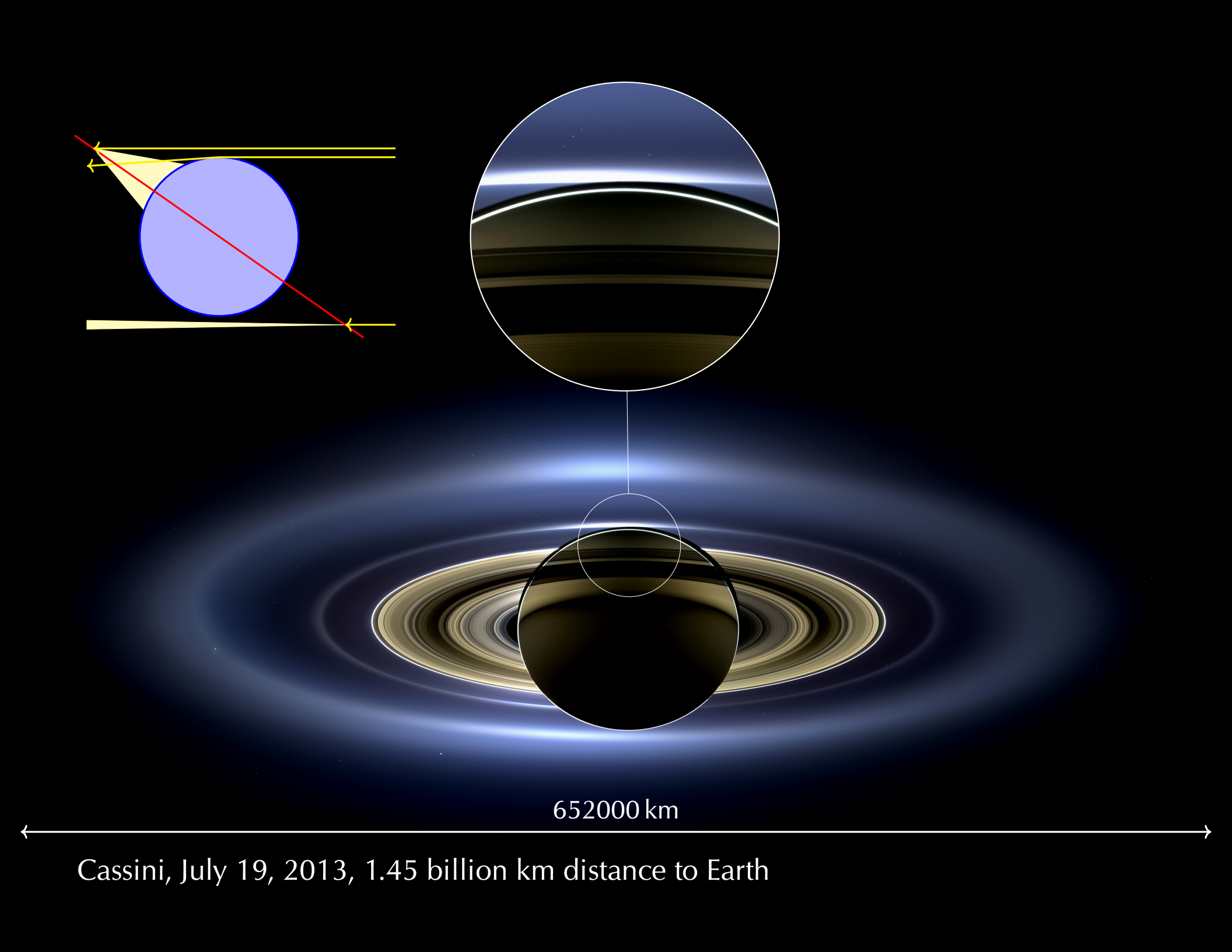
Cassini, July 19, 2013, 1.45 billion km distance to Earth



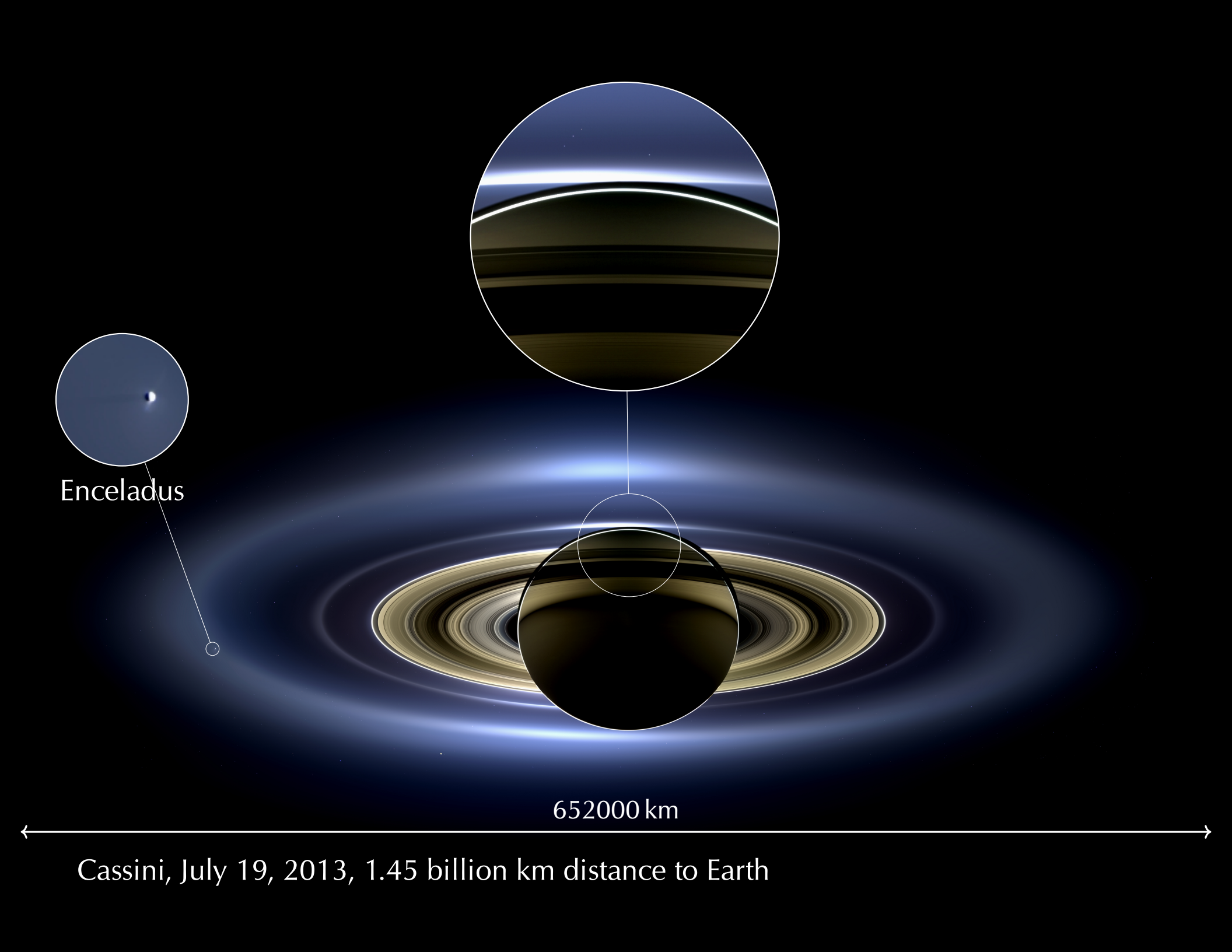
Cassini, July 19, 2013, 1.45 billion km distance to Earth

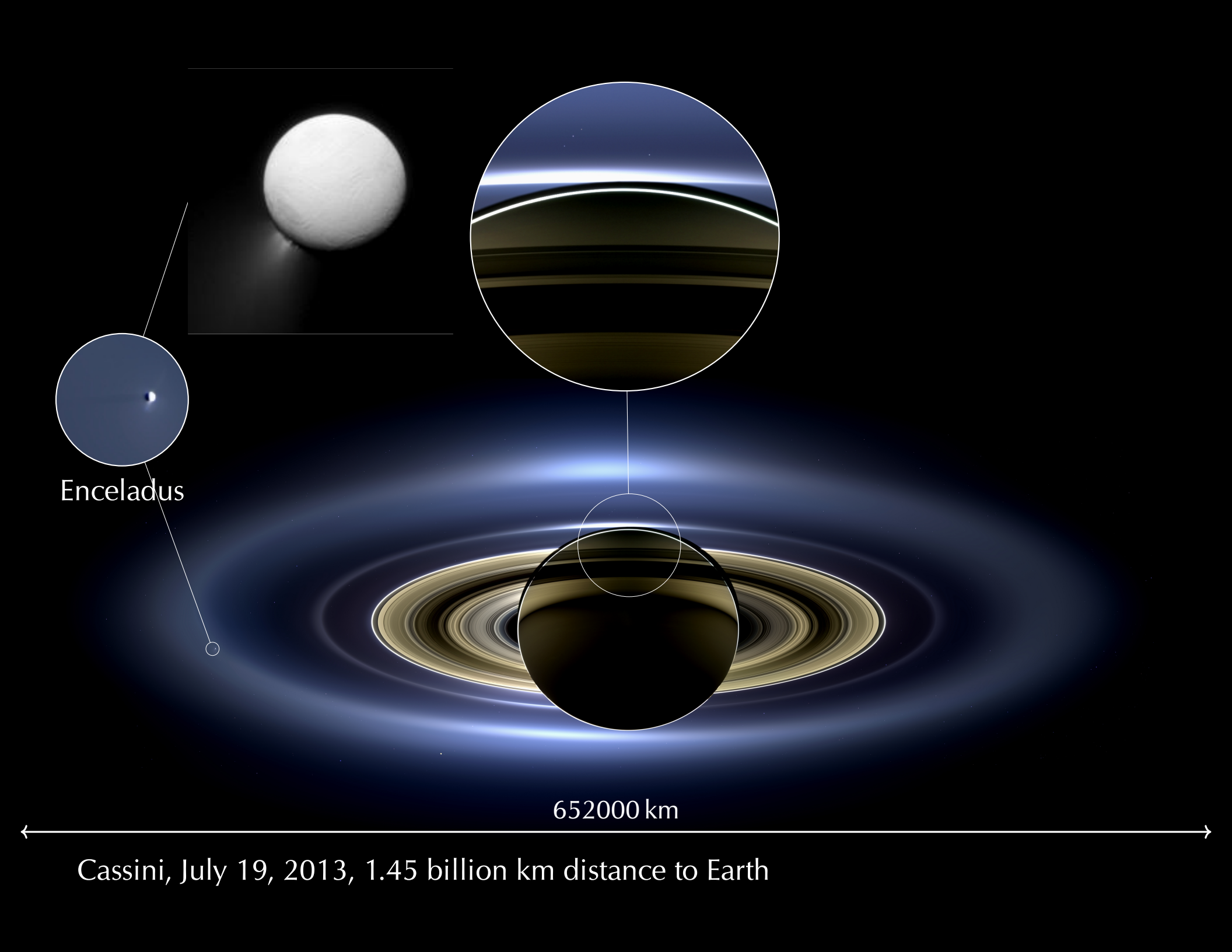


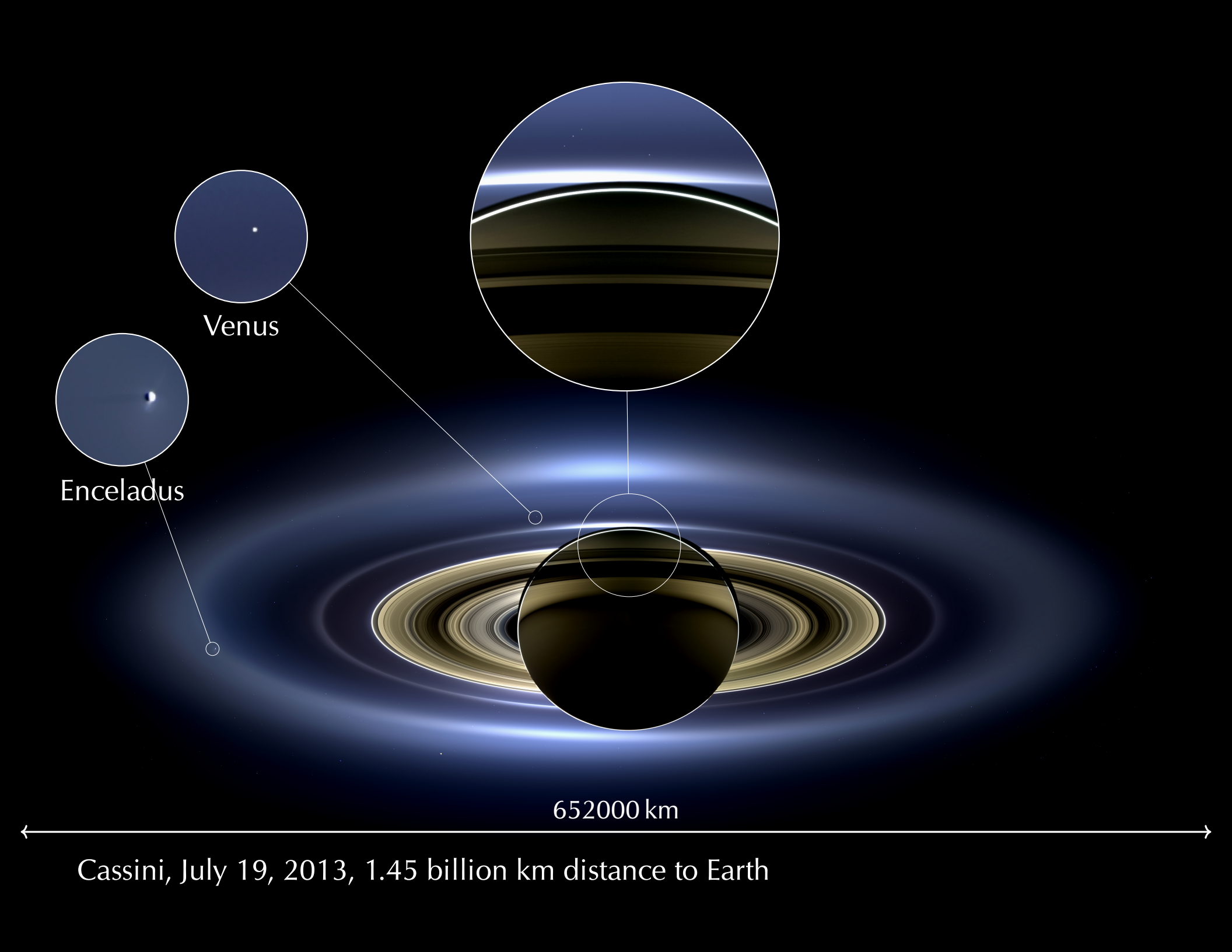
Cassini, July 19, 2013, 1.45 billion km distance to Earth



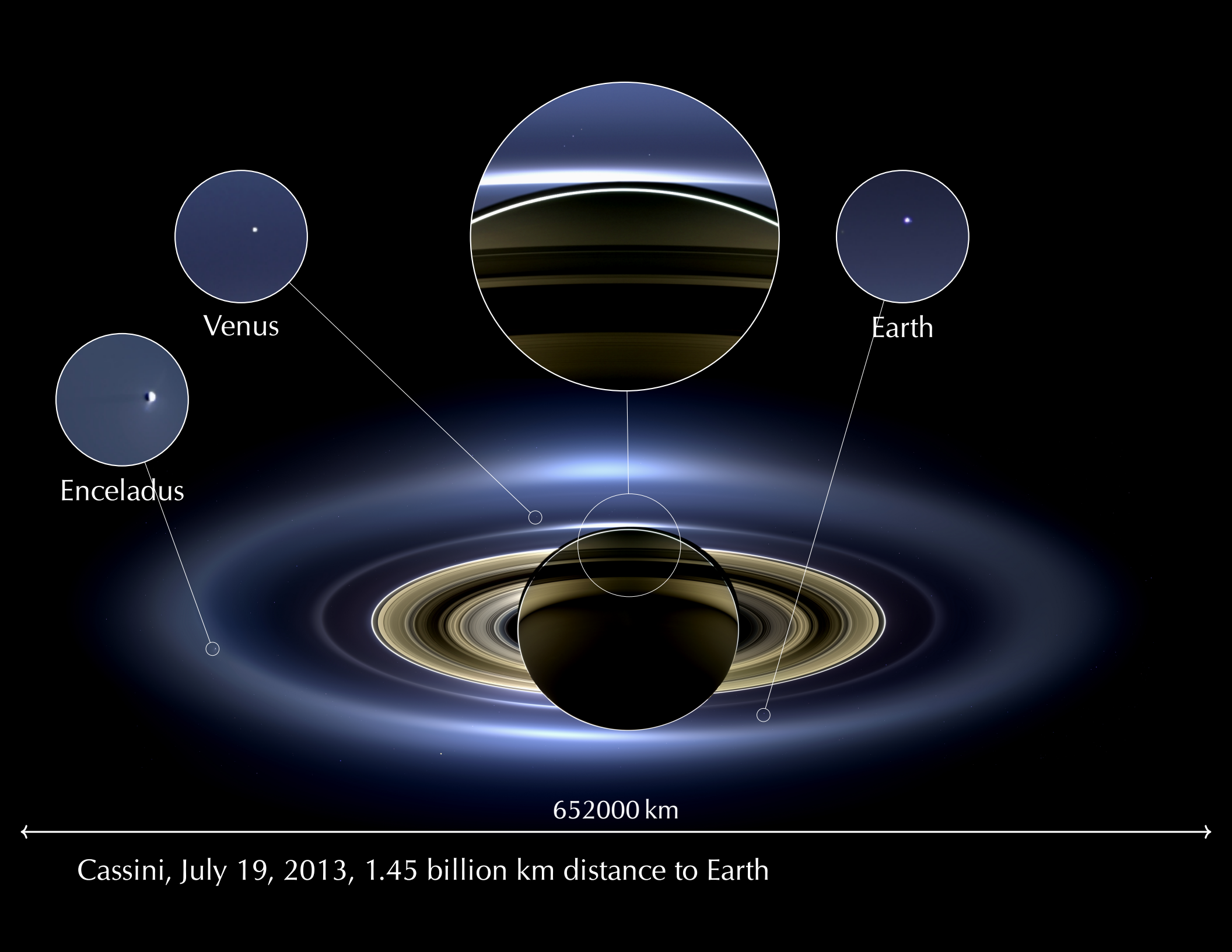
Cassini, July 19, 2013, 1.45 billion km distance to Earth


Enceladus
652000 km
Cassini, July 19, 2013, 1.45 billion km distance to Earth

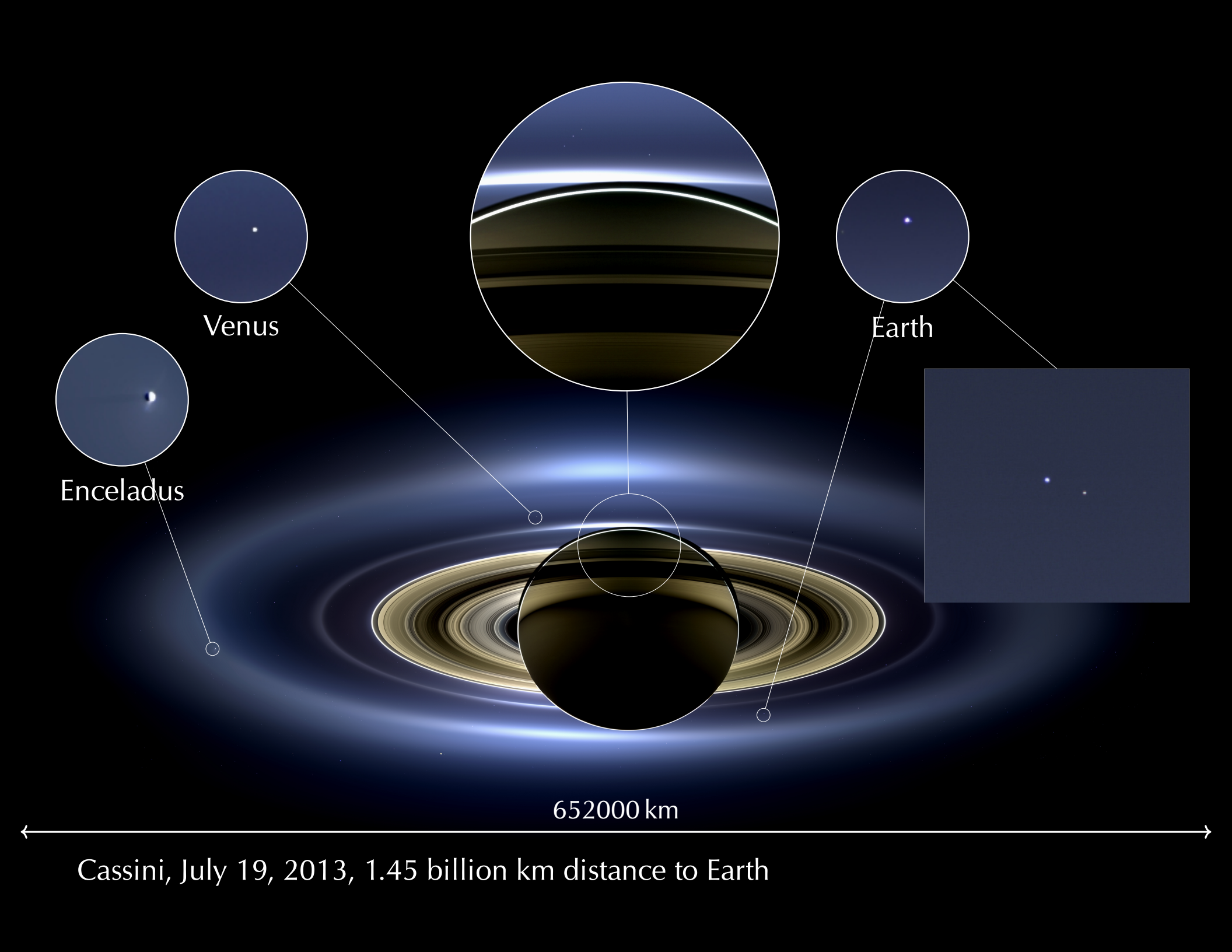

Enceladus
652000 km
Cassini, July 19, 2013, 1.45 billion km distance to Earth



Cassini, July 19, 2013, 1.45 billion km distance to Earth



Cassini, July 19, 2013, 1.45 billion km distance to Earth



Cassini, July 19, 2013, 1.45 billion km distance to Earth

Weber, R. C., Lin, P.-Y., Garnero, E. J., Williams, Q., & Lognonné, P. 2011, Science, 331, 309

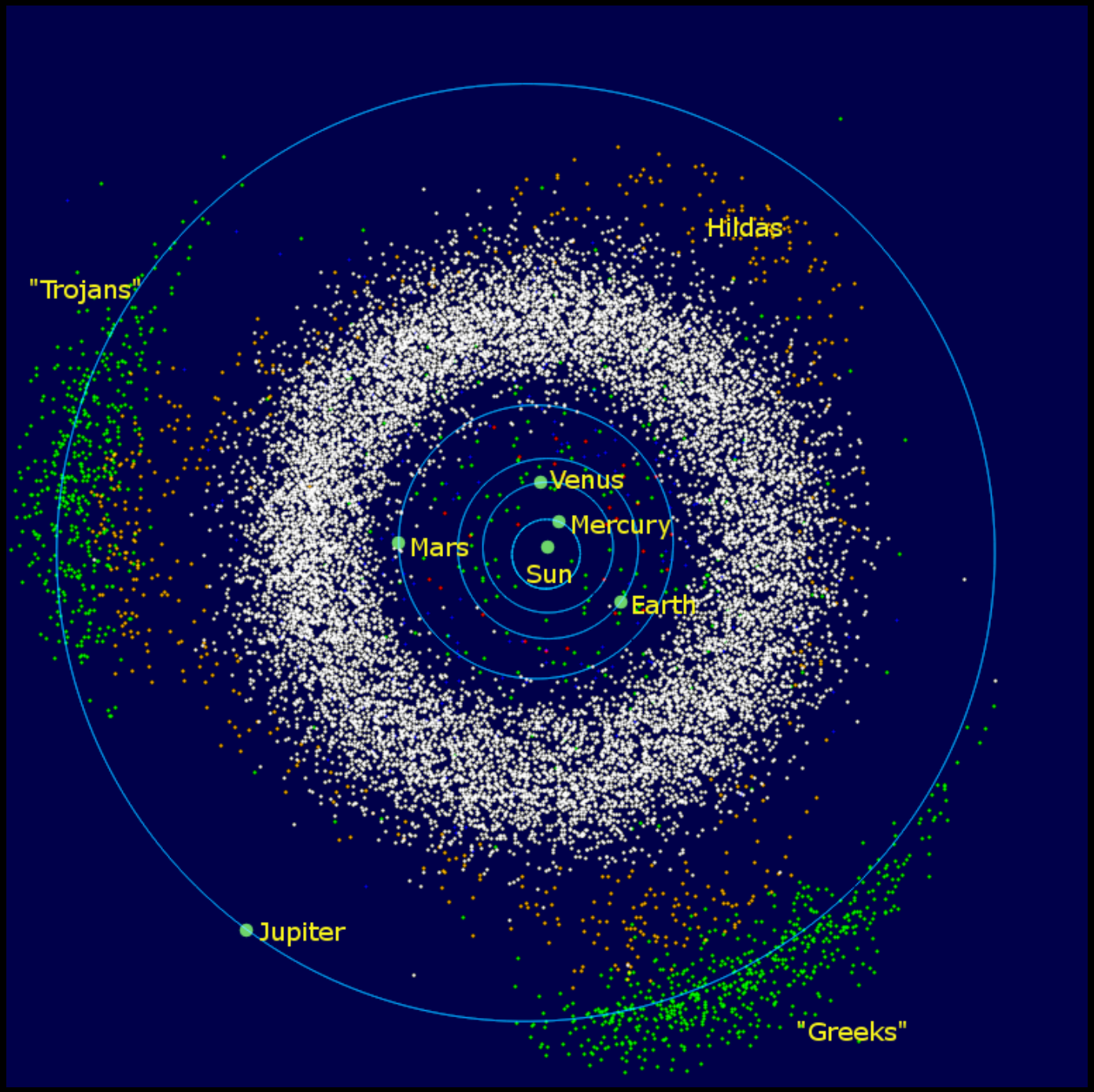
Small Solar System Bodies: Asteroids, Comets, and Trans Neptunian Objects



951 Gaspra (NASA)

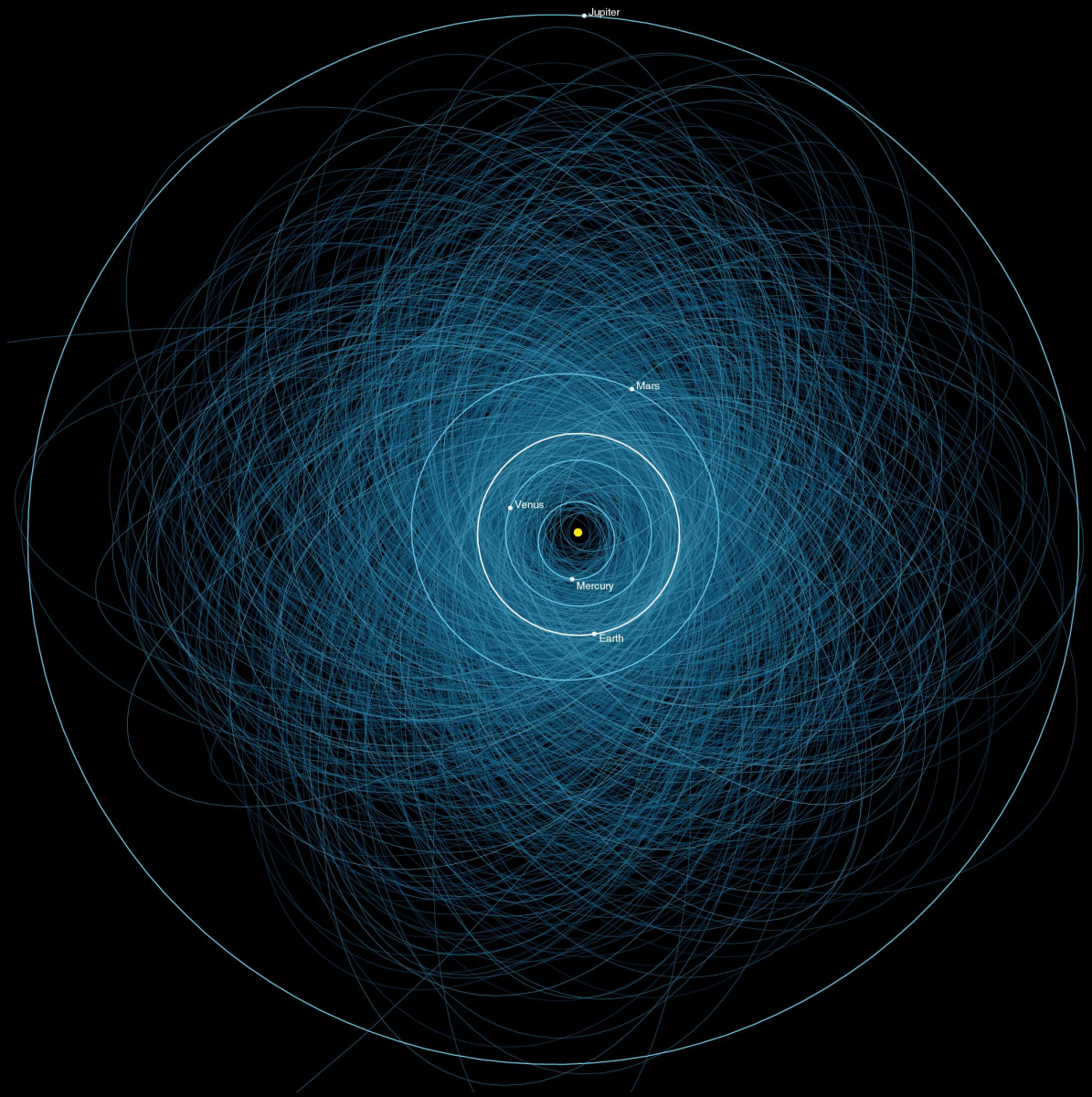
Asteroids: Minor planets mostly between Mars and Jupiter (main belt), diameters <1000 km

First discovery in 1801 (Piazzi: Ceres, diam. 1000 km)
Today >100000 known, only 7 with diameters >300 km
Total mass $\sim$0.5% of Earth (40% of moon), of which $\sim$30% in Ceres, 75% are C-type (carbonaceous), 17% S-type (silicaceous), and 8% M-type (metallic) asteroids.



Wikipedia

Orbit dynamics leads to structuring of the asteroid belt: asteroid families.



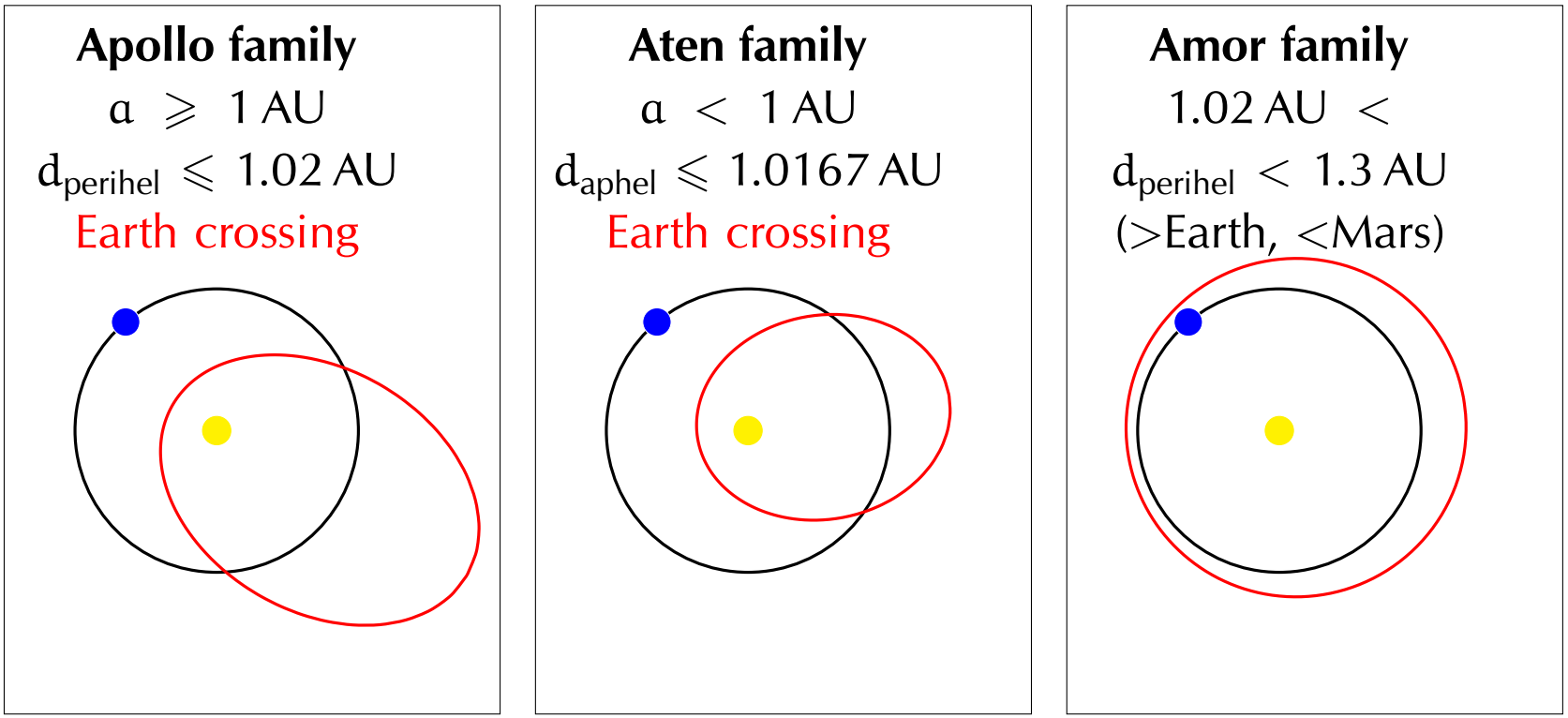
http://photojournal.jpl.nasa.gov/catalog/PIA17041

Orbits of all 1400 potentially hazardous asteroids; >140m, d <0.05 AU

see http://neo.jpl.nasa.gov/index.html

Estimate: there are >1000000 Earth orbit crossing asteroids

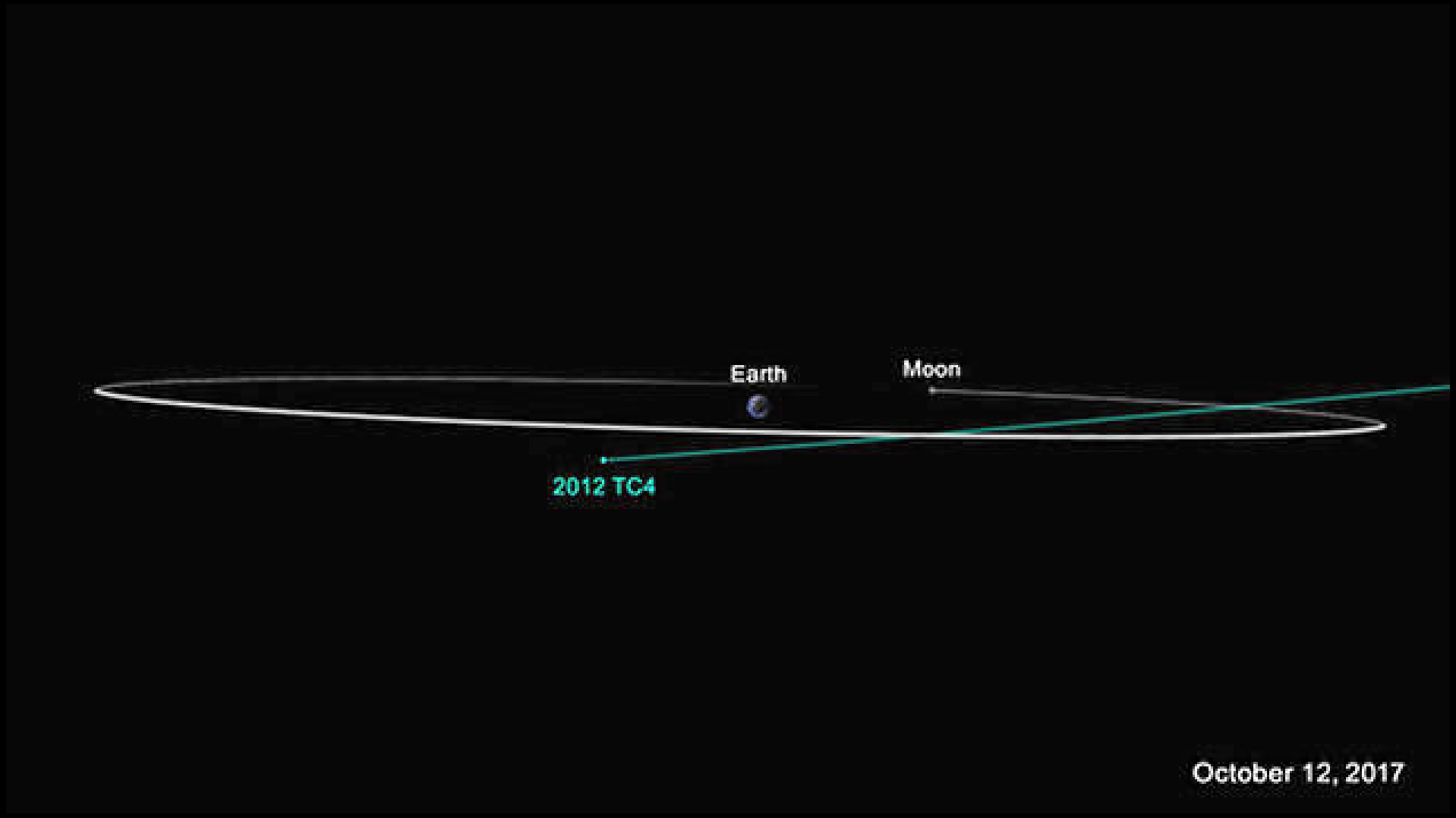
Asteroid Families



after `http://neo.jpl.nasa.gov/neo/groups.html`

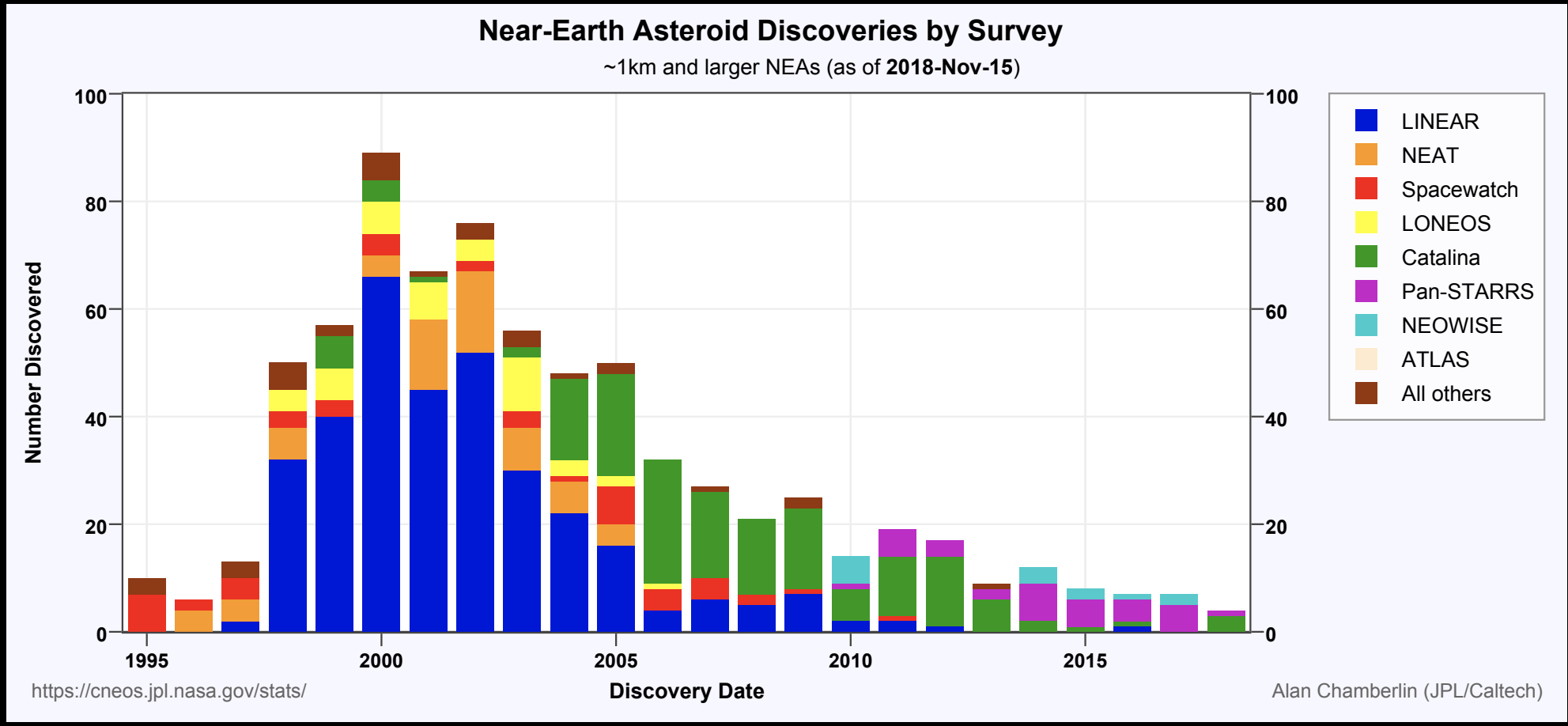
Several types asteroids can get close to Earth

Definition of Potentially Hazardous Asteroids: Earth minimum orbit intersection distance <0.05 AU *and* size >150 m



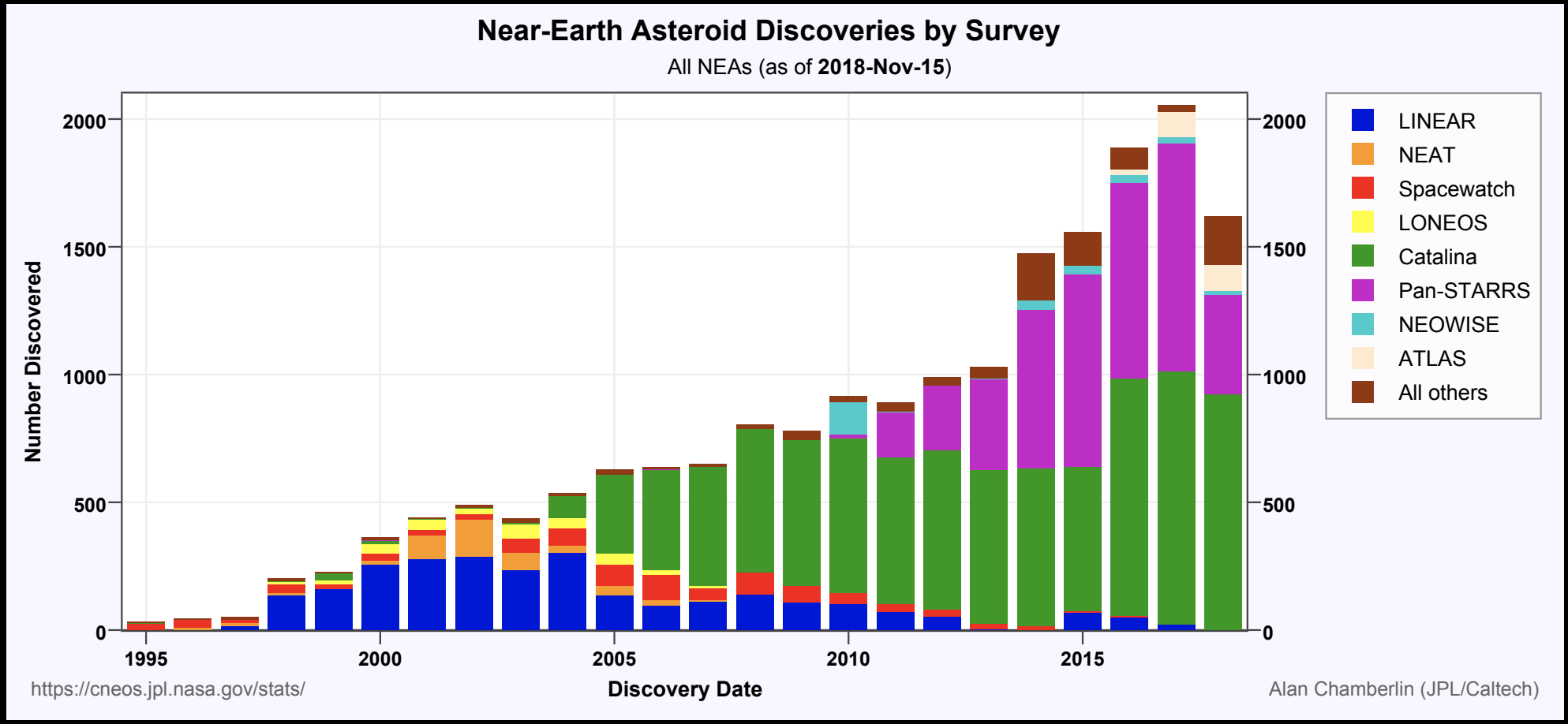
Asteroid 2012 TC4, Oct. 12, 2017: Apollo group, ~15 m, flyby at 42000 km distance.

NASA/JPL-Caltech



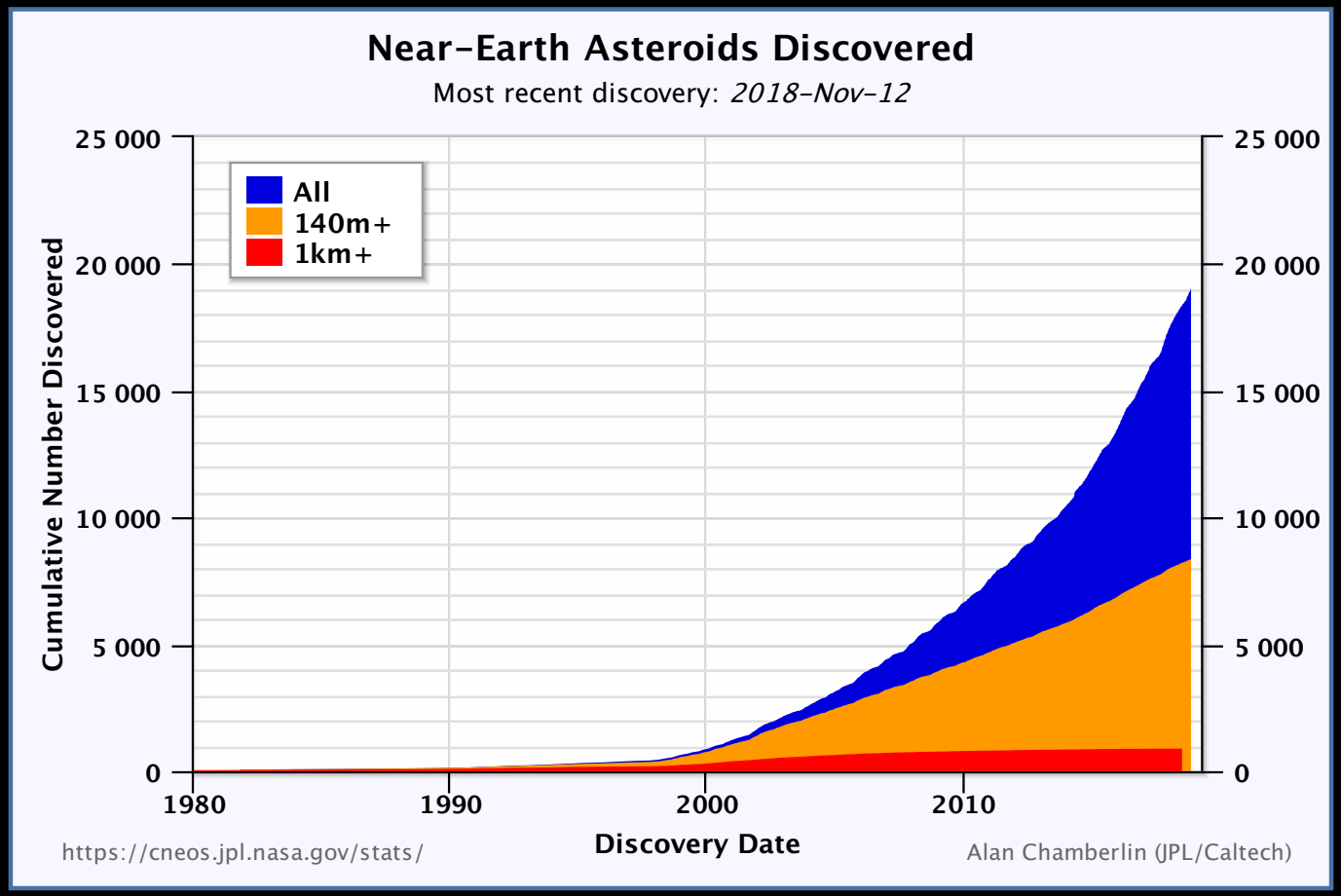
http://neo.jpl.nasa.gov/stats/

not many >km NEAS found recently



http://neo.jpl.nasa.gov/stats/

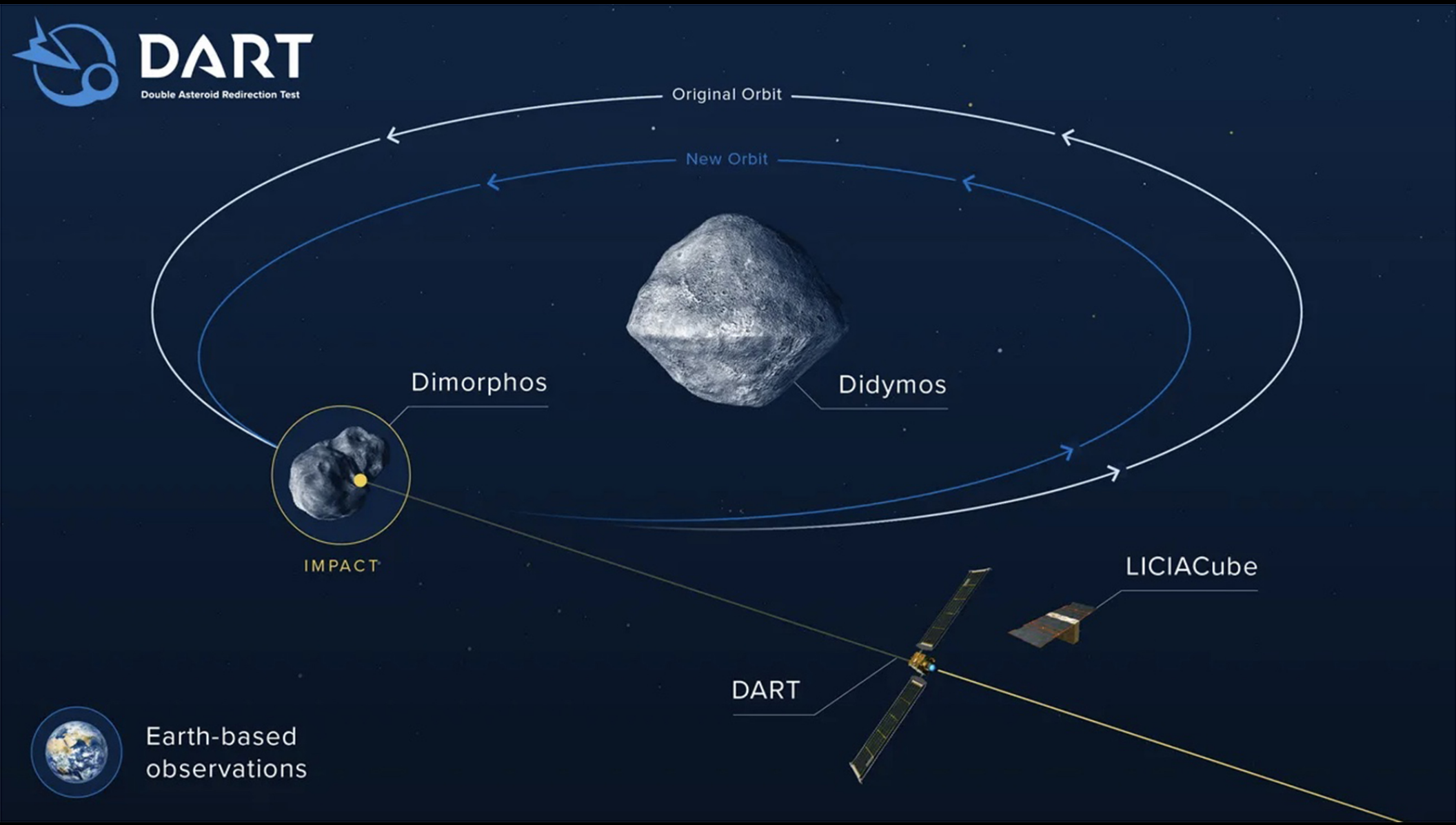
number of total discoveries increasing as surveys progress



http://neo.jpl.nasa.gov/stats/

estimate >1000000 Near Earth Asteroids

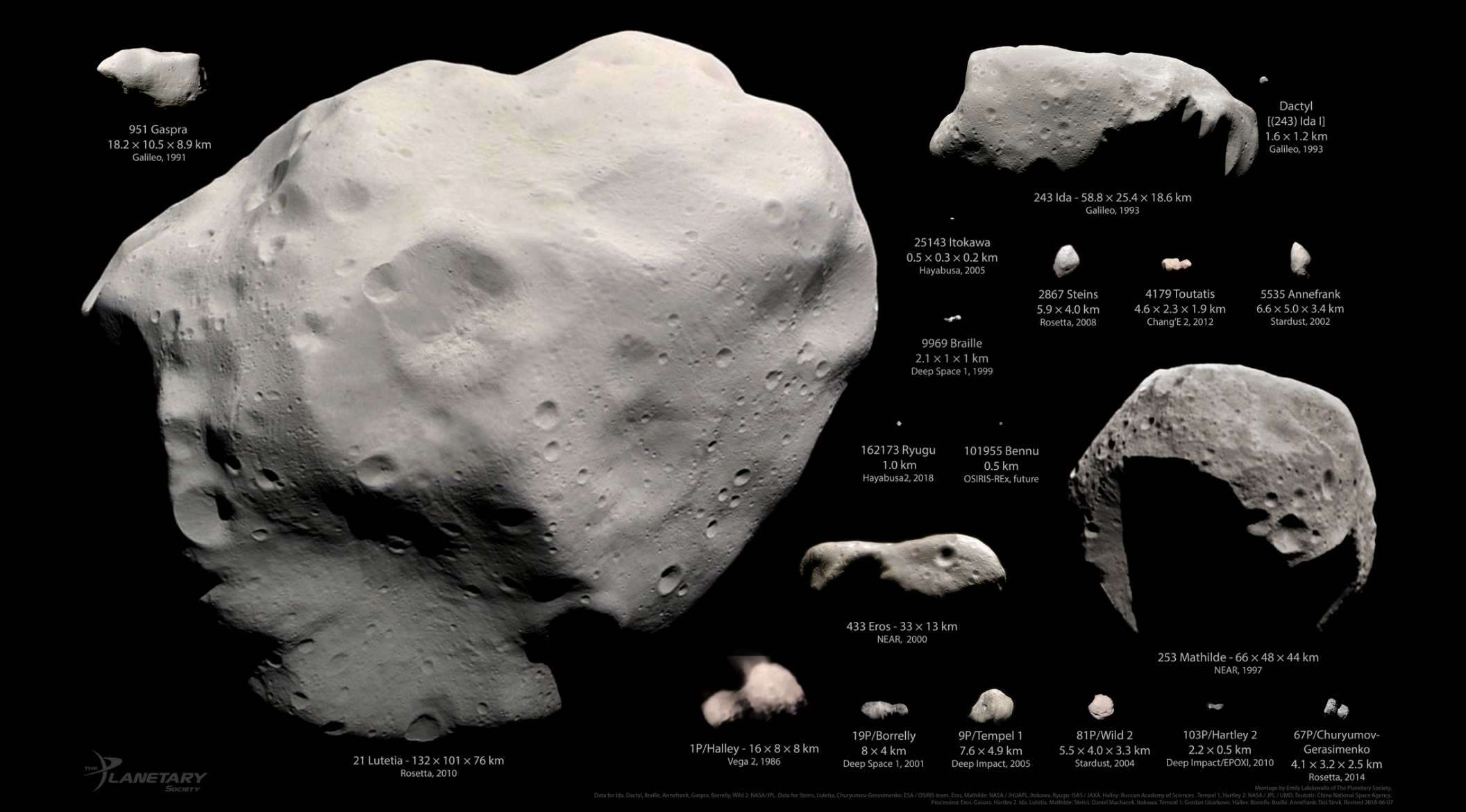
DART:first planetary defense test mission



planned crash of NASA DART into Dimorphos on 26 of Sept. 2022



image taken by DART before crashing into Dimorphos (150m diameter, credit: NASA/Eydeet)



ESA/Planetary Society

past 25 years: many asteroids and comets surveyed by interplanetary probes

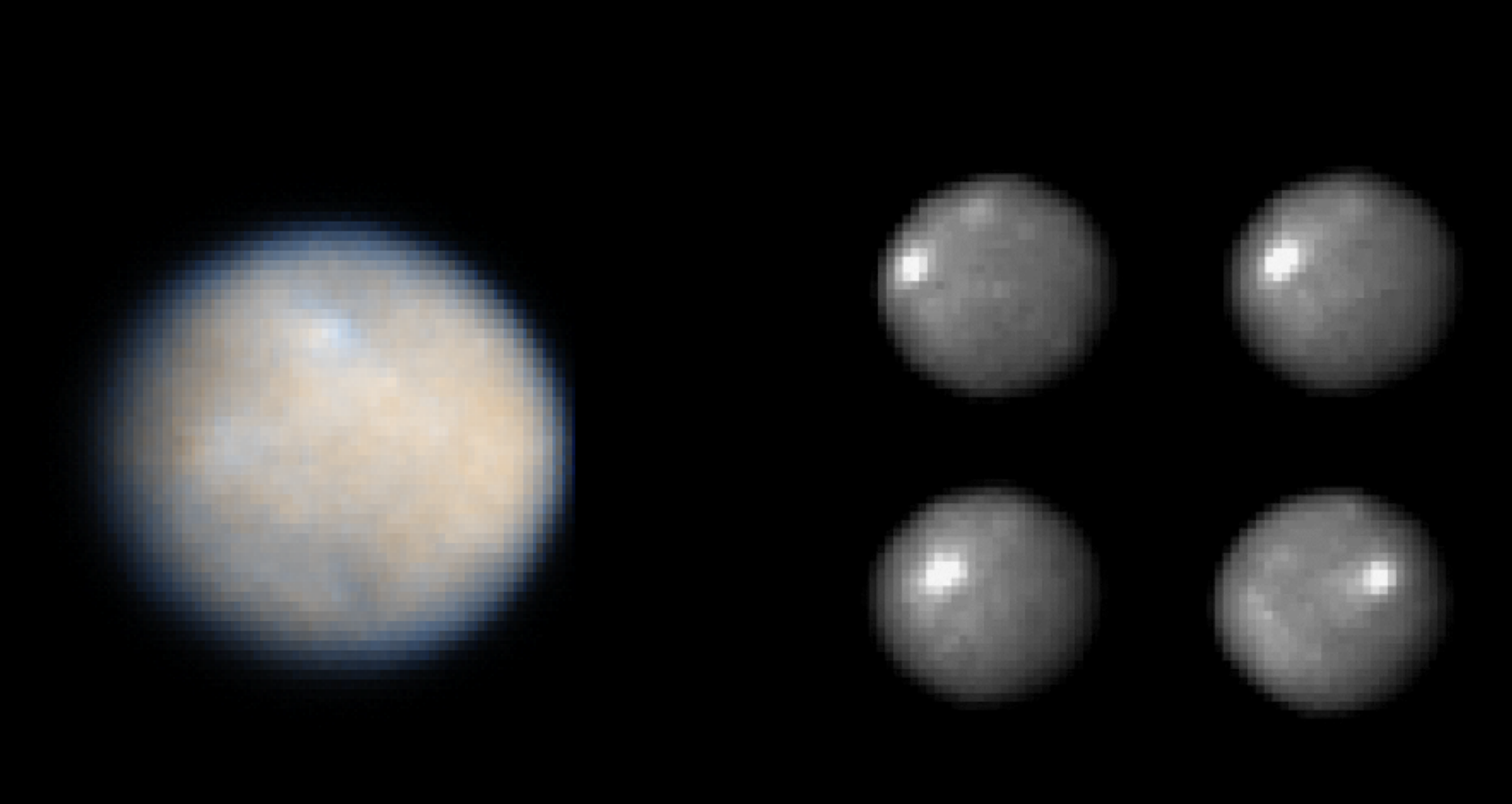


2001 Feb 12: NEAR lands on Eros



MOVIE TIME:

- `http://near.jhuapl.edu/iod/20010205/index.html`: Rotation of Eros [2000 Dec 3/4]
- `http://near.jhuapl.edu/iod/20010731/index.html`: descent onto Eros

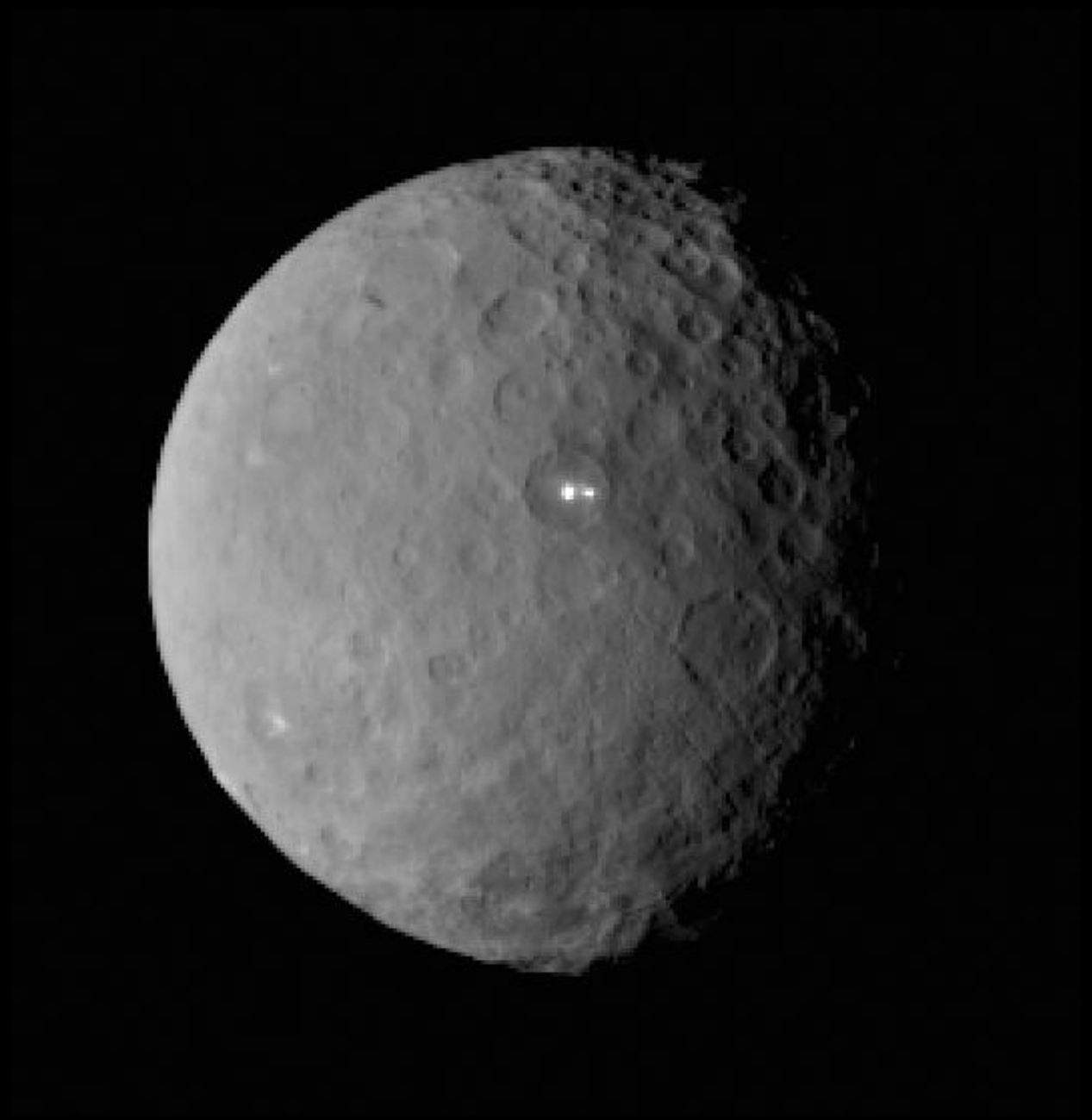


Dec 2003/Jan 2004: Ceres from Earth (Hubble Space Telescope)

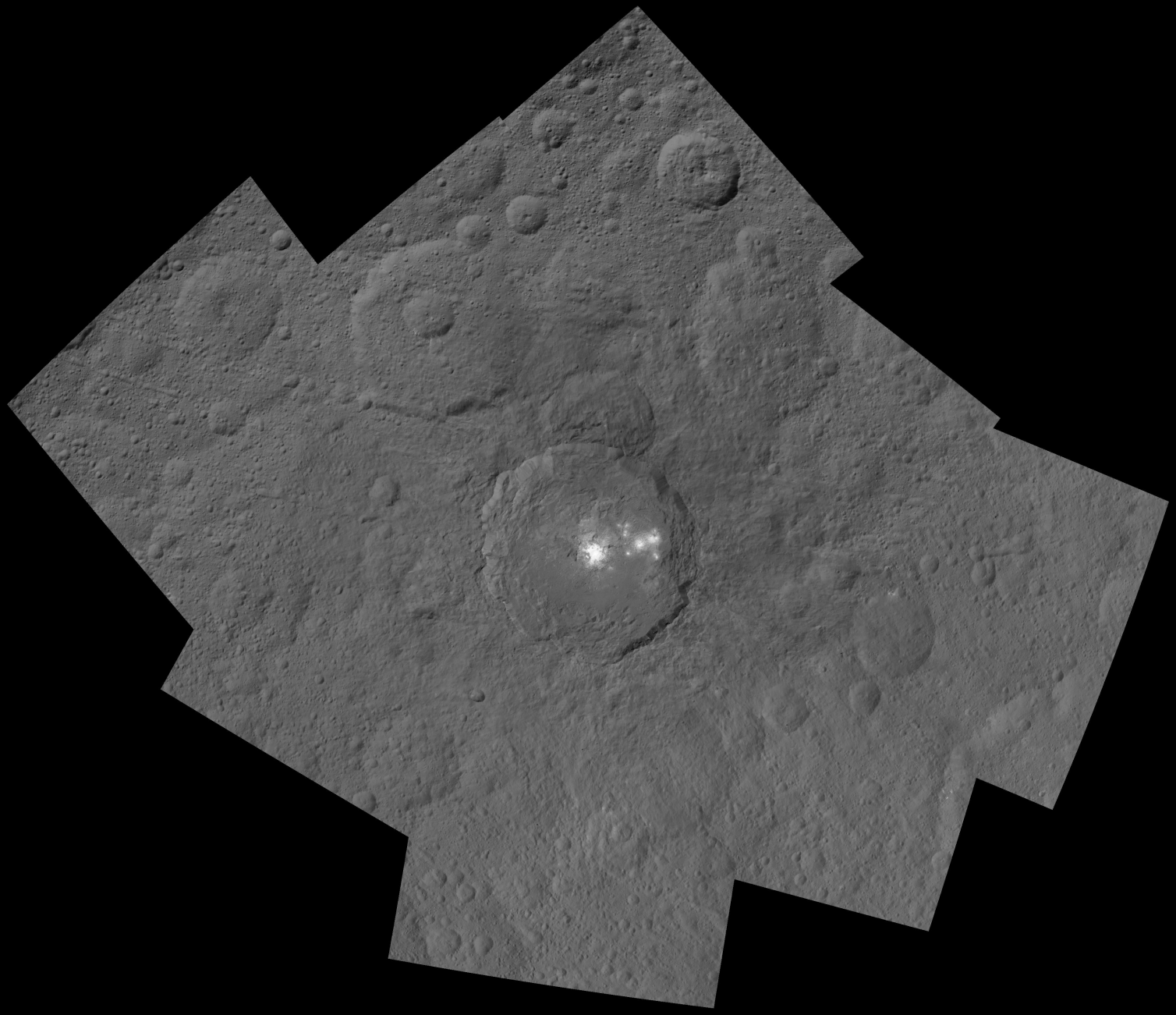


2015 Feb 19, 46000 km distance

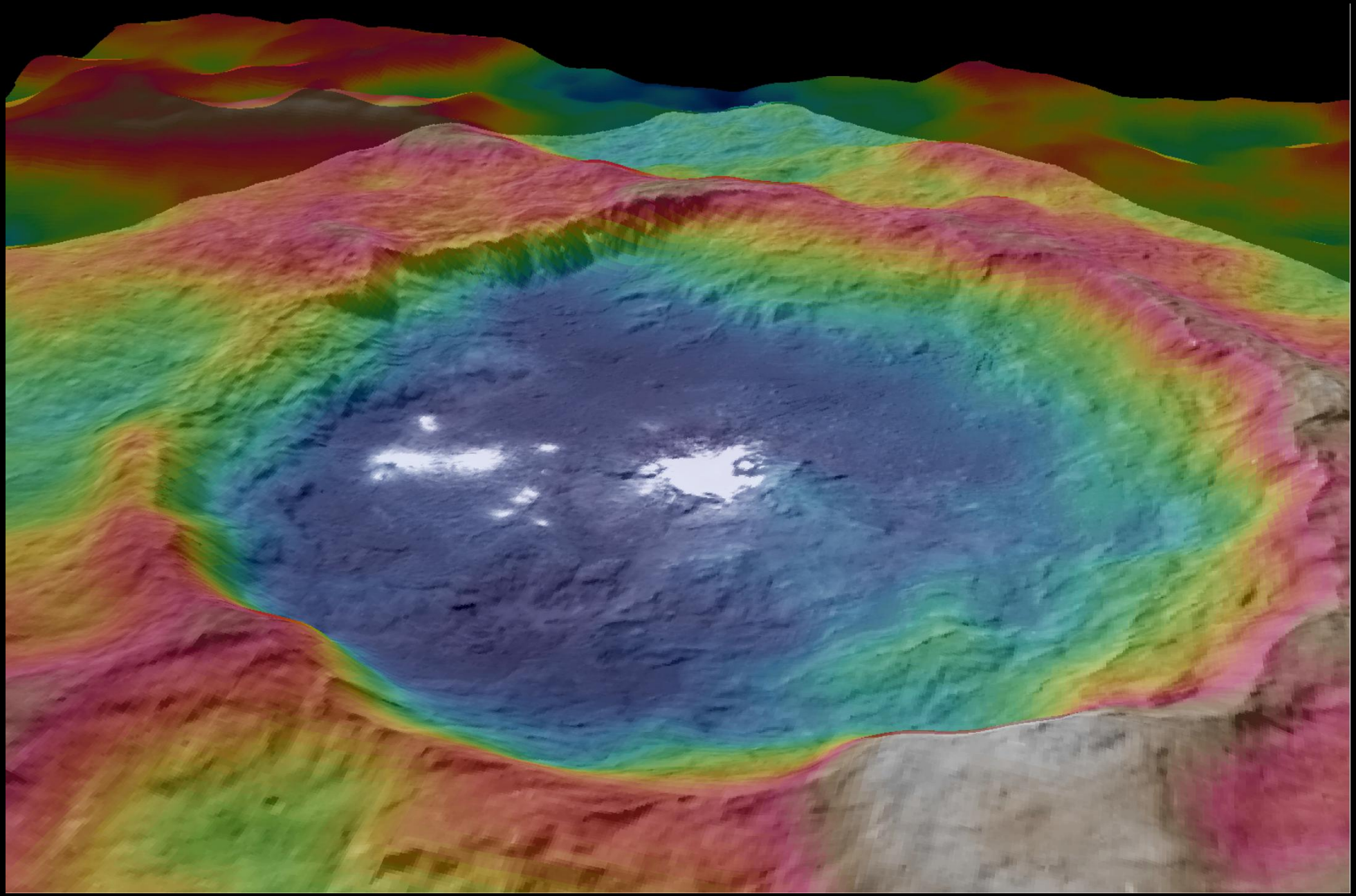
2015 Feb–Dec: NASA's Dawn mission studies Ceres



Occator Crater

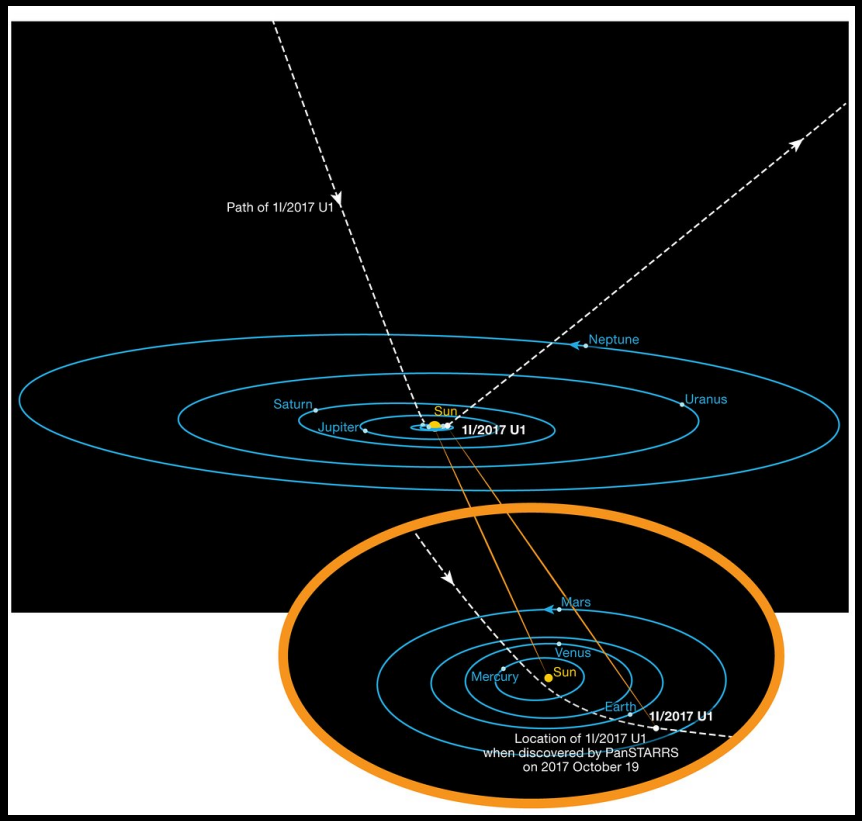


2015 Oct: Occator Crater (diam: 90 km) from 1470 km

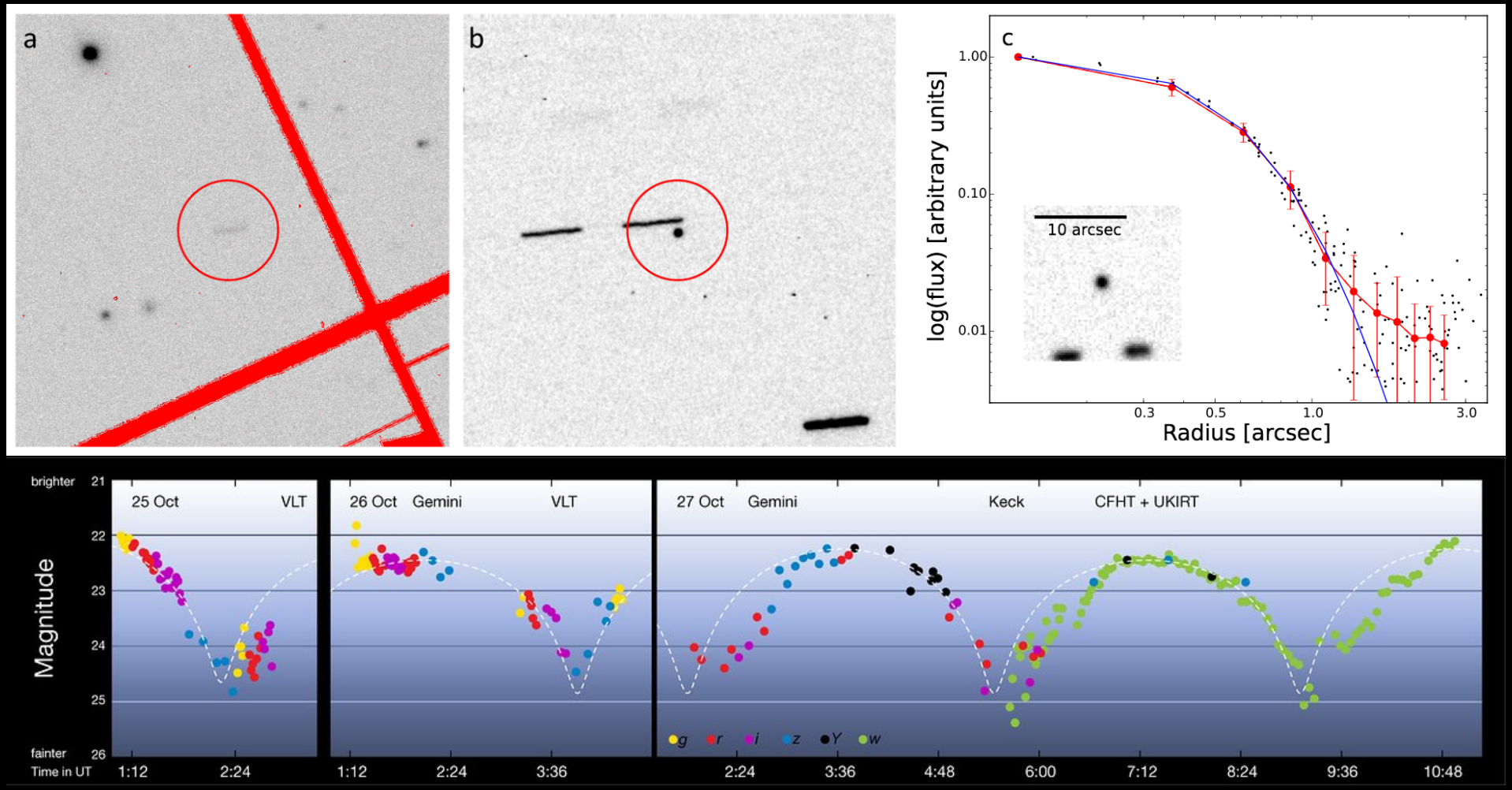


Occator Crater topography





The first interstellar asteroid ever observed: 1I/'Oumuamua.
Discovered on 2017 October 19 with Pan-STARRS 1 on Hawaii.



Upper left: Discovery image of 1I/'Oumuamua taken with Pan-STARRS 1. Exposure: 45 s. Middle: Observation with CFHT on Oktober 22, 2017. Right: Mosaic of Gemini and VLT images and radial profile. Lower panel: light curve of 1I/'Oumuamua. (Meech et al., 2017)

Comets



153P/Ikeya-Zhang (©M. Jäger)

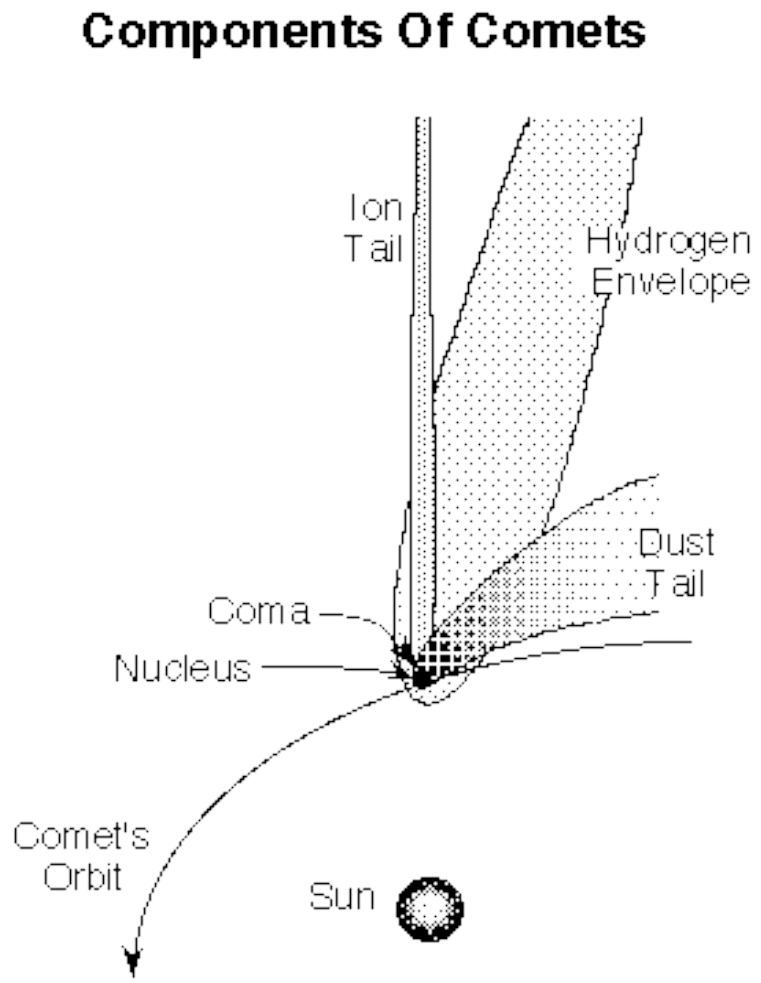


Comet Hale Bopp over Bamberg, 1997 spring



Comet Hale Bopp, 1997 March 30

Structure



NASA

Major components of a comet:

- Nucleus: "Dusty Snowball" (Whipple, 1951), 1–50 km
  dominated by water ice, plus up to 15–20% CO_2 and CO
- Coma: 10^4–10^5 km, evaporated gas surrounding nucleus
  includes H_2O, CO_2, CO, but also H_2S, CH_3OH, H_2CO, NH_3, HCN, CH_4, S_2
- Ion tail: Ionized gas, typical extent up to 10^8 km, often bluish
- Dust tail: Dust evaporated away from nucleus, typical size ~10^6–10^7 km.

High volatility species indicate origin in cool regions of solar system and "storage" out there until recently.

Structure



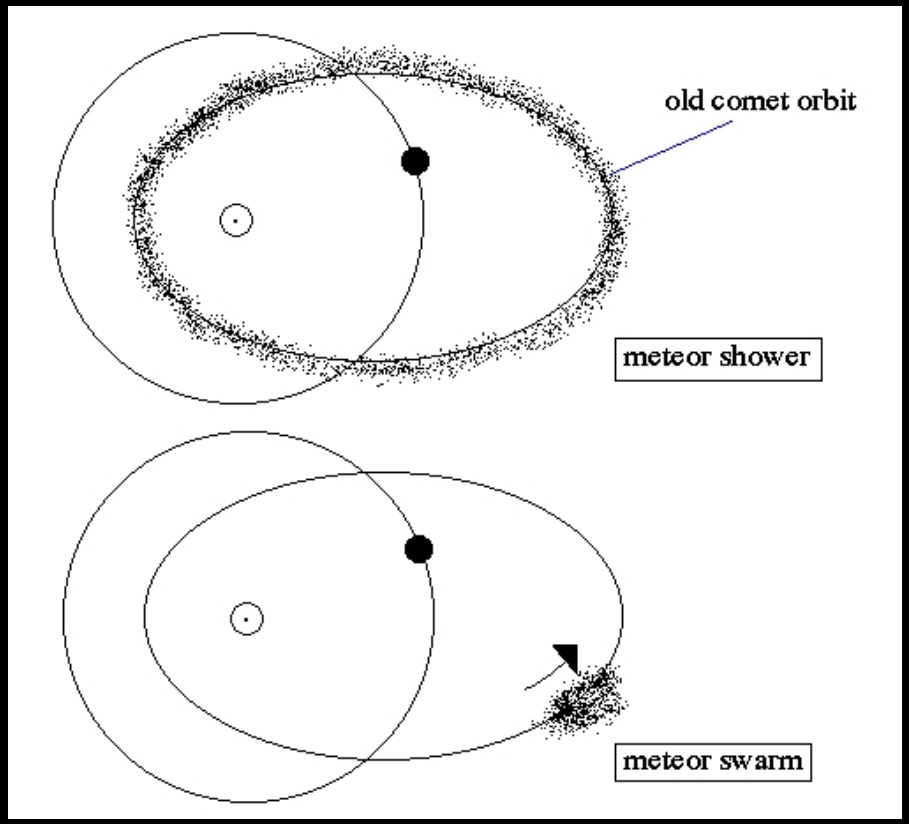
Bust of Apian
(Ruhmeshalle, Munich)

How do cometary tails form?

- tails always point away from the Sun (Apianus, 1531) $\Longrightarrow$ Sun causes the phenomenon
- Dust tail: scattered Sun light.
  - Dust particles are accelerated by radiation pressure
- Gas tail: ionized plasma, ions emit light by fluorescence
  - Wurm (1943): plasma can not be accceleratated by radiation pressure
  - Biermann (1951): There must be a solar wind of particles

Meteors

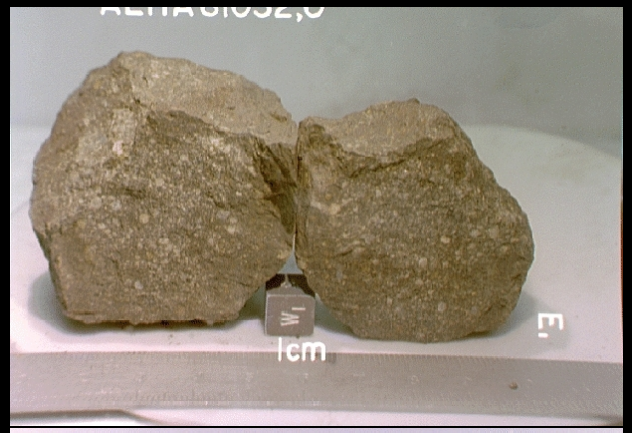




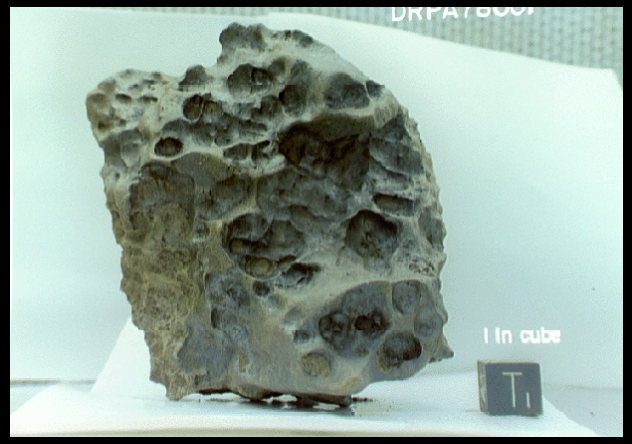
Meteors:

- ≈25 Mio./day hit Earth's atmosphere.
- most burn up
- ≈1 Mio. kg/day to Earth's surface.
- large ones break into pieces, are ablated, but reach the surface as meteorites
- origin: debris of comets: dust tails
- showers/swarms when earth crosses a comet's orbit named after constellation of radiant
- e.g., Leonids due to 55P/Tempel-Tuttle (mid of November).

Meteorites







three major types:

- Chondrites: most common, stone, radiometric dating: age = 4.55 billion years
- Pallasites: stone with metals
- iron meteorites: 13 subclasses: iron-nickel alloys

Meteorite in Winchcombe (UK) in Feb 2021





- around 11% of the weight is water plus extraterrestrial amino acids
- isotope ratio of hydrogen close to the one at earth

$\Rightarrow$ further evidence that water and organic material come from asteroids (note, comets are found to have a different isotope ratio)









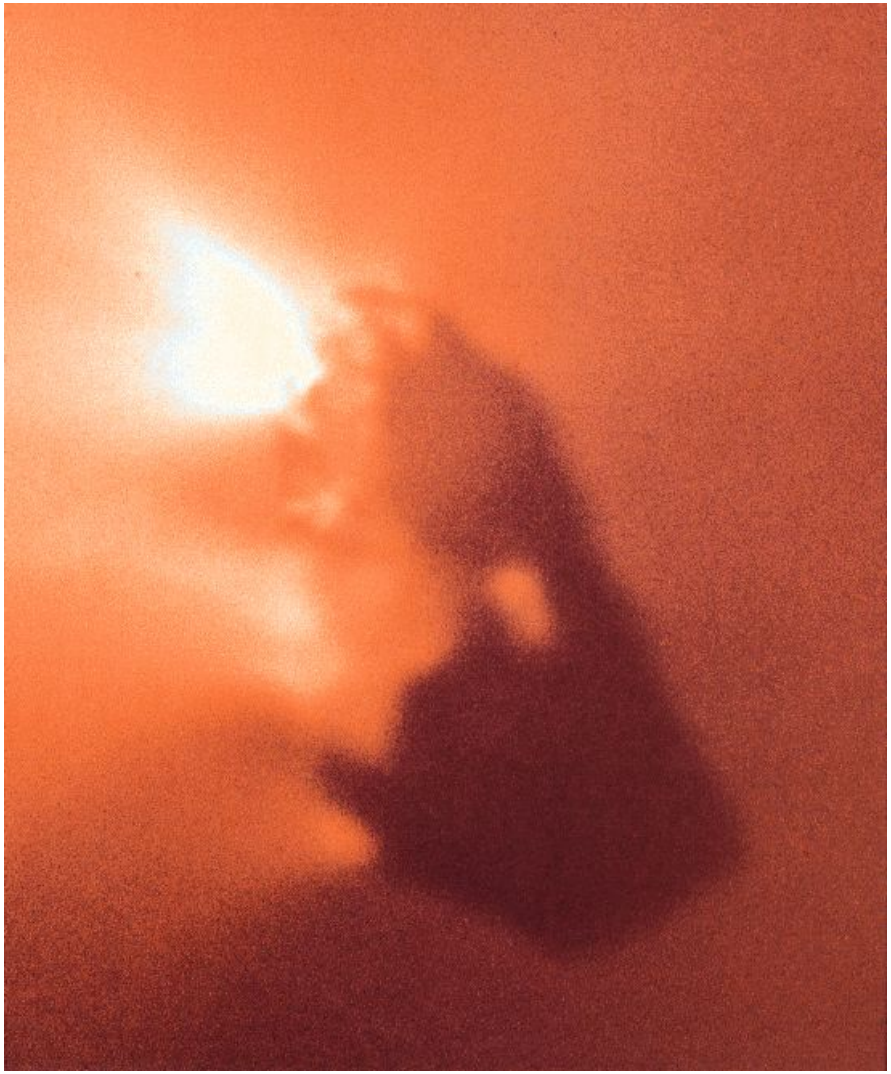
Enceladus, Earth, Moon, 67P/Churyumov-Gerasimenko

Next pages: Results from several comets studied in situ with space probes
Interpretation of pictures: comets are “dirty snow”: very(!) low albedo

albedo: reflectivity of surface

ESA

Halley

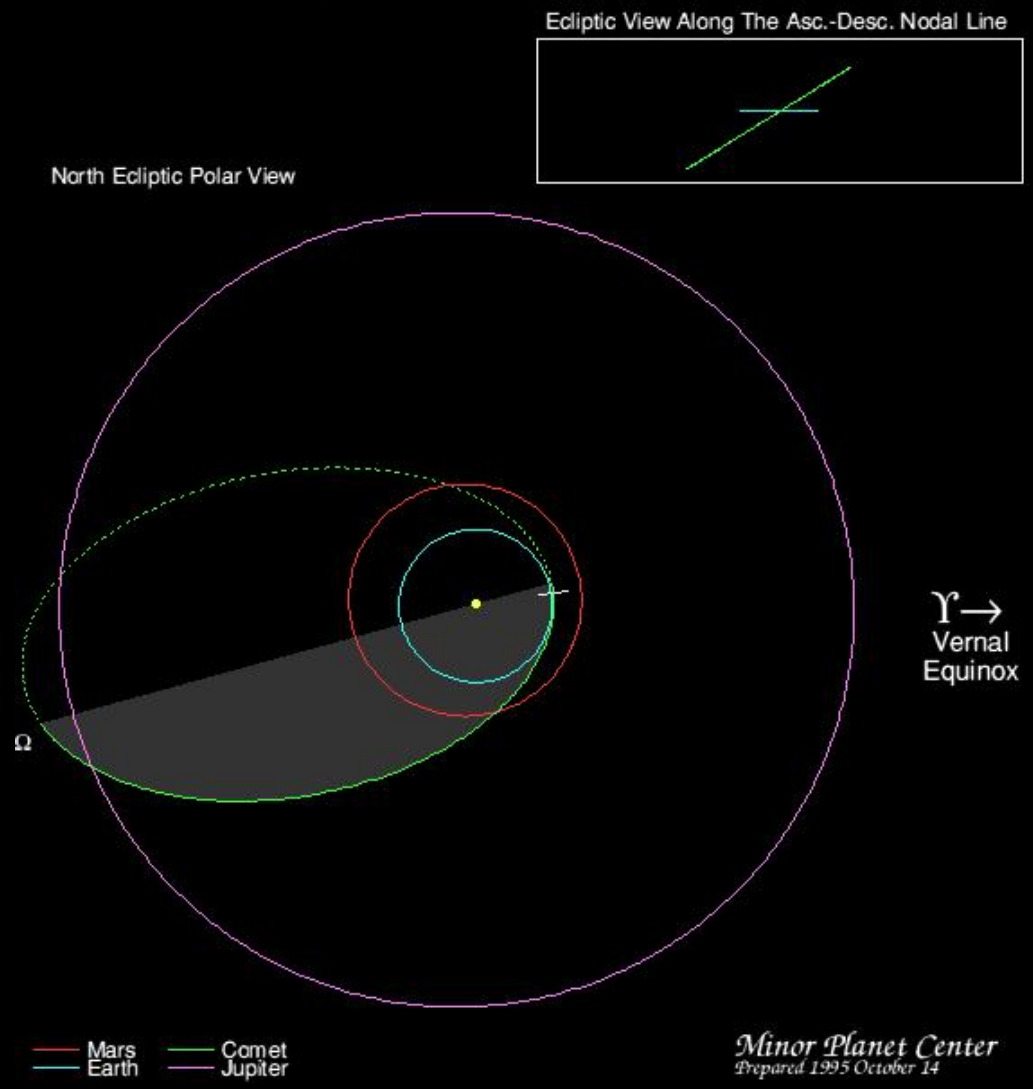


ESA

1P/Halley:

- Orbital period: 76–79.3 year orbit (earliest recorded appearence: 239 B.C, famous: 1066, Tapestry of Bayeux).
- Analyzed in detail during 1986 return, flyby of ESA's Giotto spacecraft close to nucleus, further analysis by Russian Vega 1 and 2 probes, Japanese Suisei and Sakigake, and NASA's International Cometary Explorer.
- "International Halley Watch" with strong contributions from Bamberg observatory.

21P/Giacobini-Zinner



siderial period: 6 yr 227 d, perihel: 1.037 AU, aphel: 6.015 AU

rediscovered by Ernst Zinner, Assistant at Bamberg (later its 2nd director)

first comet observed by a space probe: 1985: ICE (International Comet Explorer)

flys through tail in 7800 km distance from core

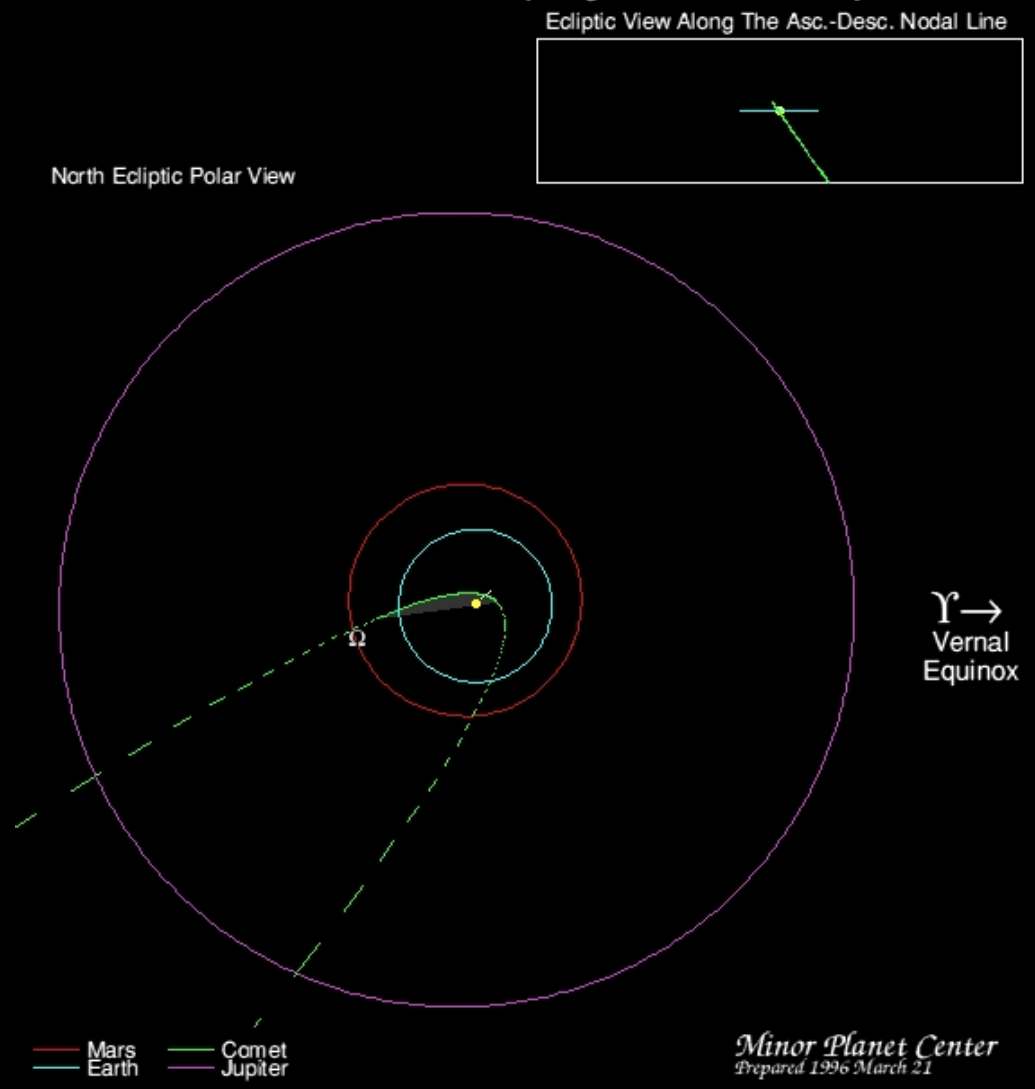


Comet Hyakutake • C/1996 B2

Hubble Space Telescope • Wide Field Planetary Camera 2

PRC96-14 • ST ScI OPO • March 27, 1996 • H. Weaver (ARC), NASA

C/1996 B2 (Hyakutake)



Original Semi-major axis: ~400 AU, closest approach to Earth: 0.1 AU

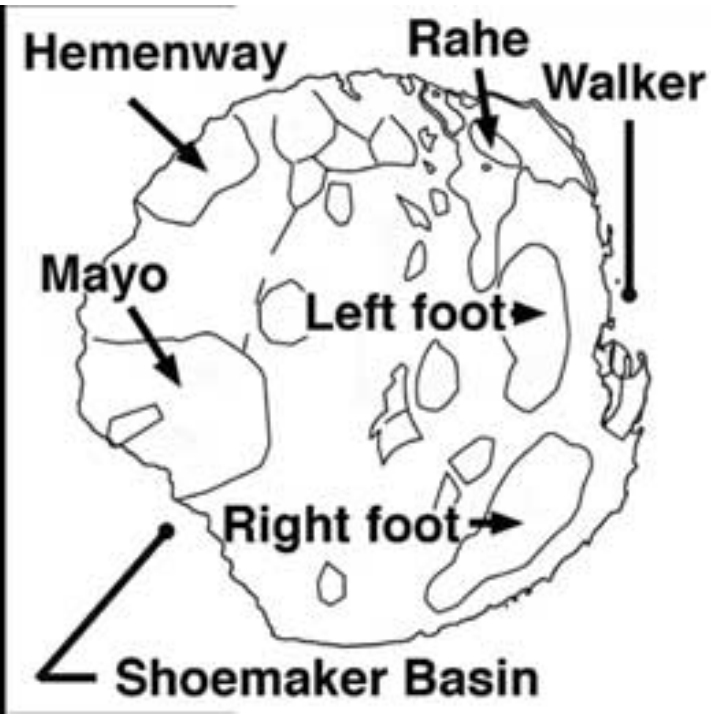
$i = 125°$; $e > 0.999784$

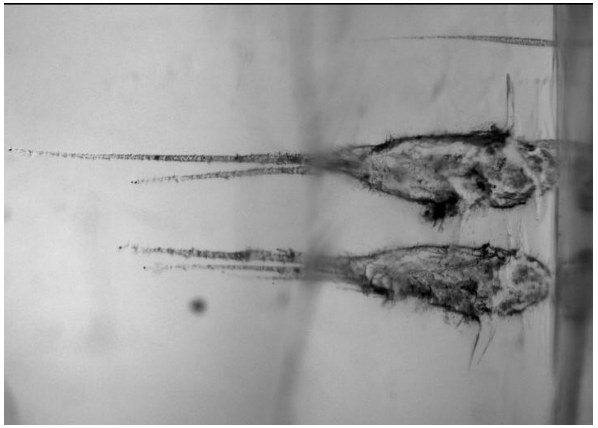
Pre-perihelion Orbital period: ~8000 years

Post-perihelion Orbital period: ~140000 years

Comet Wild 2



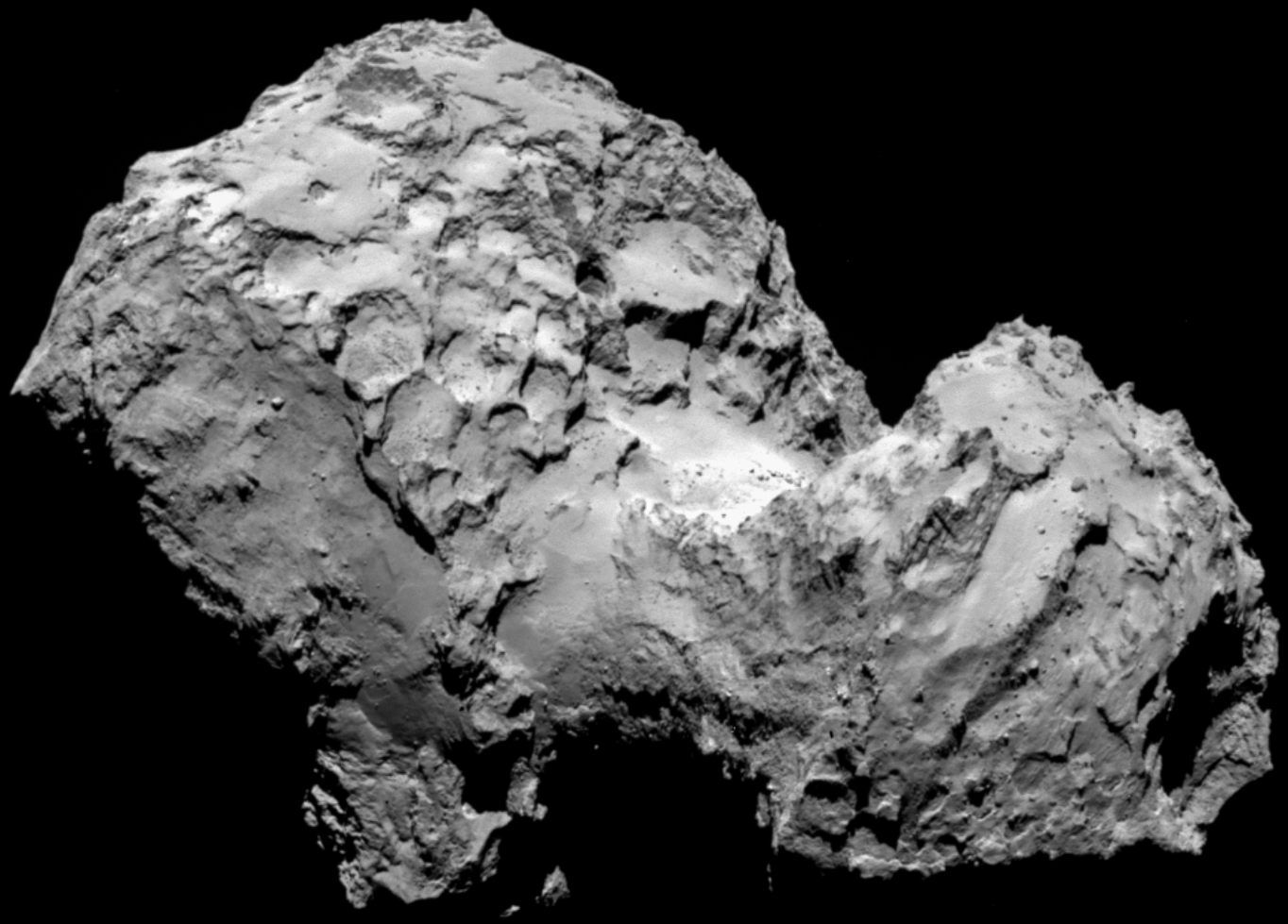




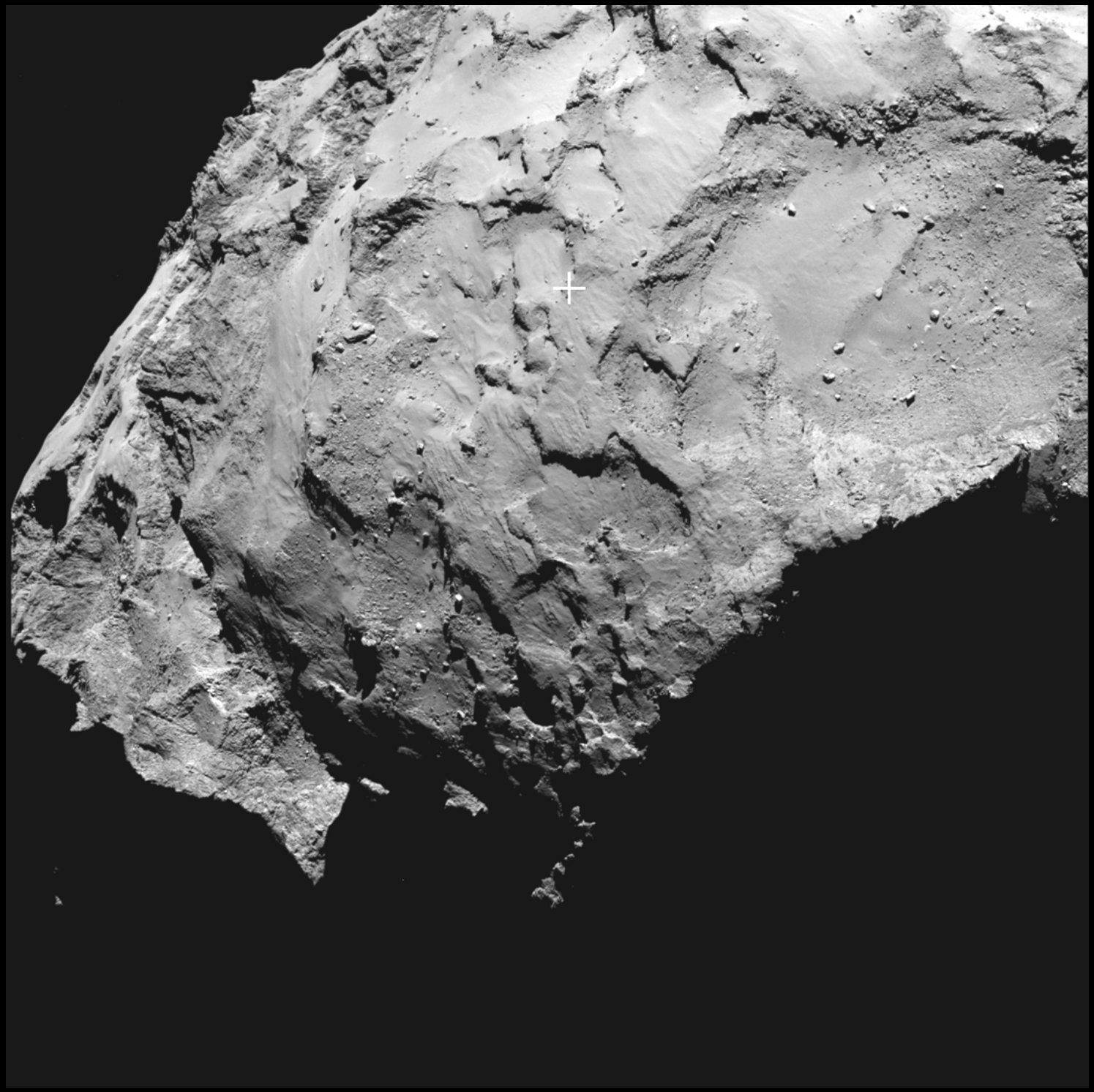
NASA, stardust mission, size ∼5 km

NASA's Stardust mission: flyby at comet Wild 2 on 2004 January 2, collection of particles from vicinity of comet's nucleus (closest approach: 240 km), impacted with samples in Utah on 2006 January 15

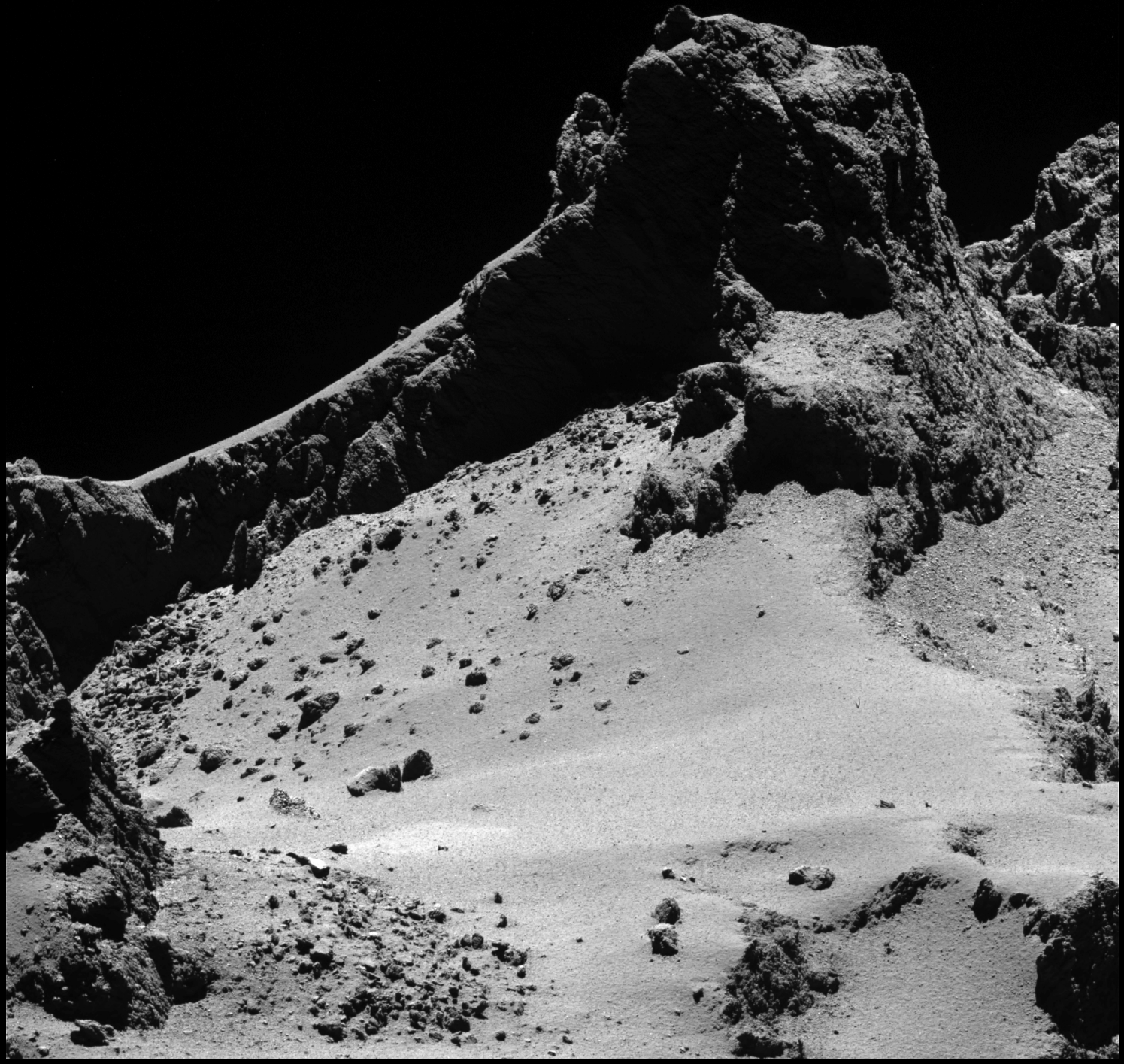
P/Wild 2: large semi-major axis, perihelion outside Mars after Jupiter encounter in 1974 (∼ Jupiter before that) $\Longrightarrow$ Material has not been processed by Sun before sample return.



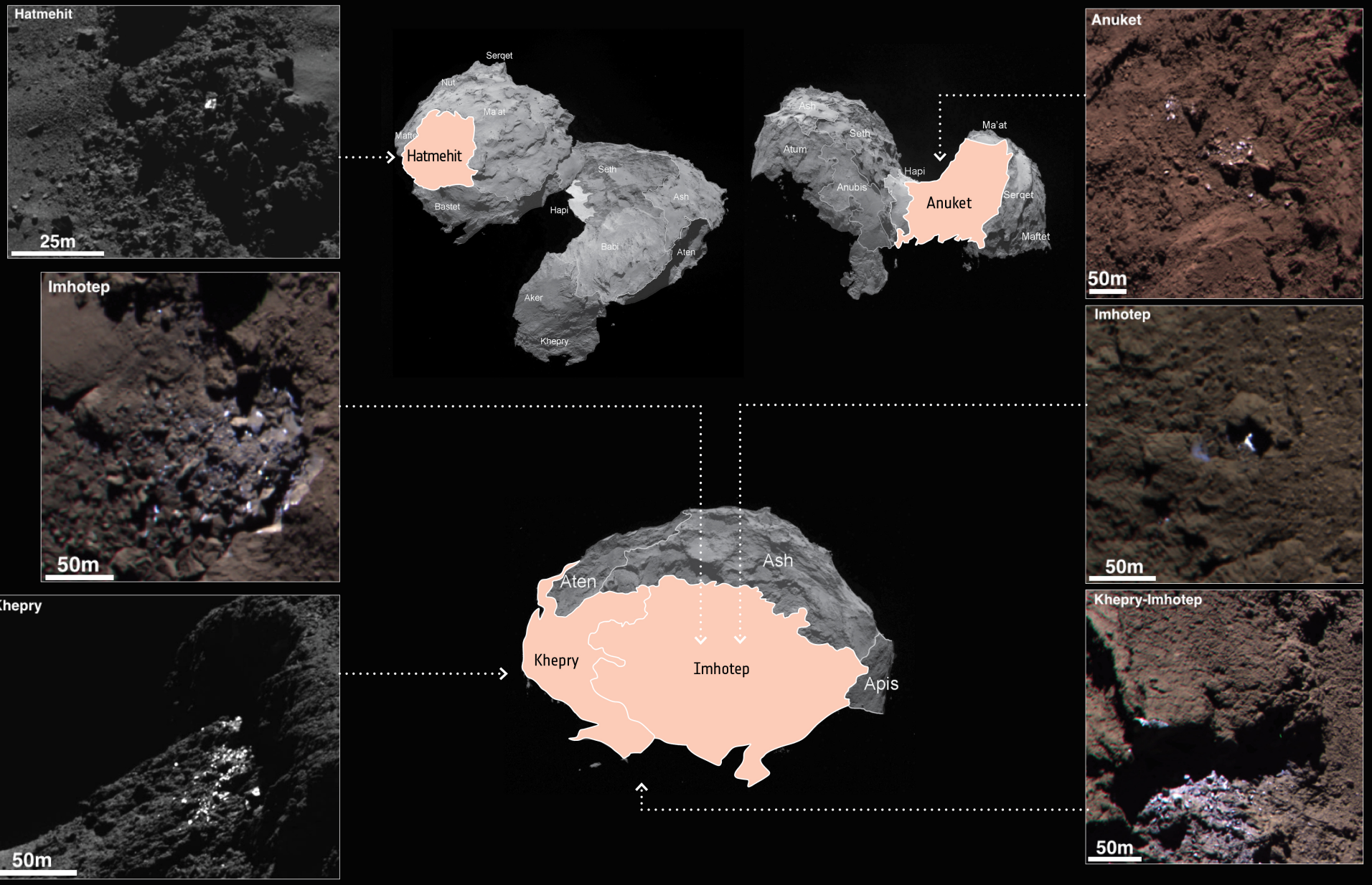
2014 Aug – 2015 Dec: Comet 67P/Churyumov-Gerasimenko studied with ESA's Rosetta mission (launch: 2004 March 2)



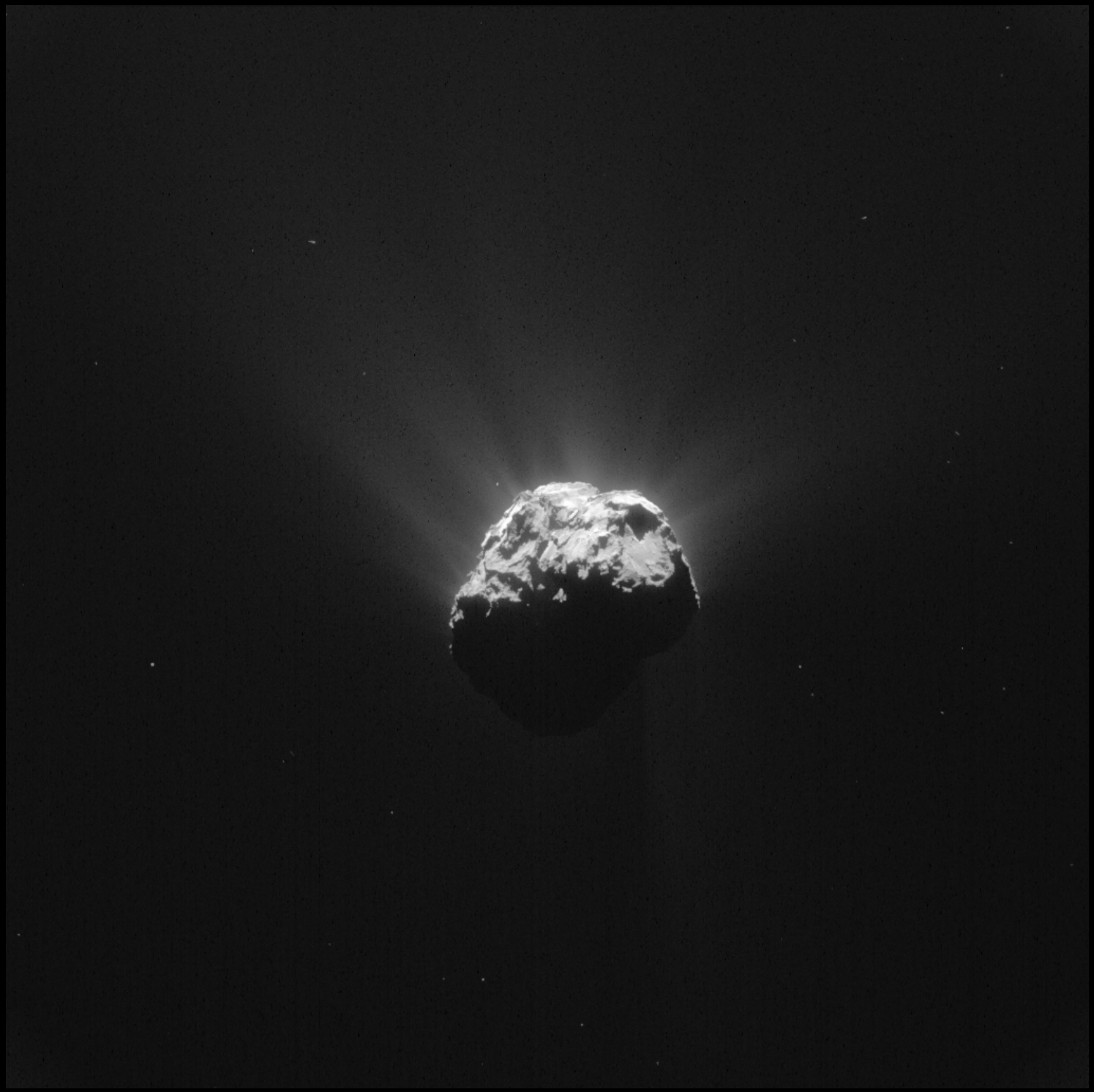
2014 Nov 12: Lander Philae landed on comet; cross: landing site



High resolution (15 cm/pixel) surface from 8 km distance (ESA)



Exposed water ice (ESA)



ESA, Churyumov-Gerasimenko on 2015 June 13 (ESA)

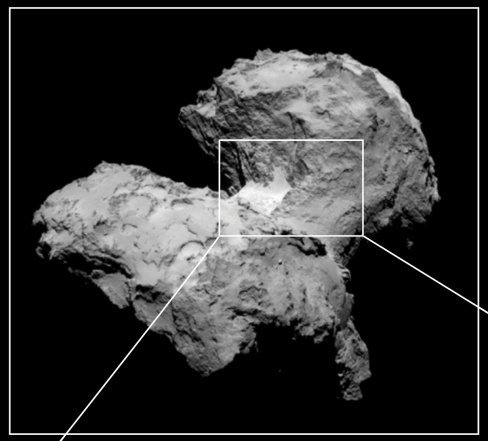


ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA

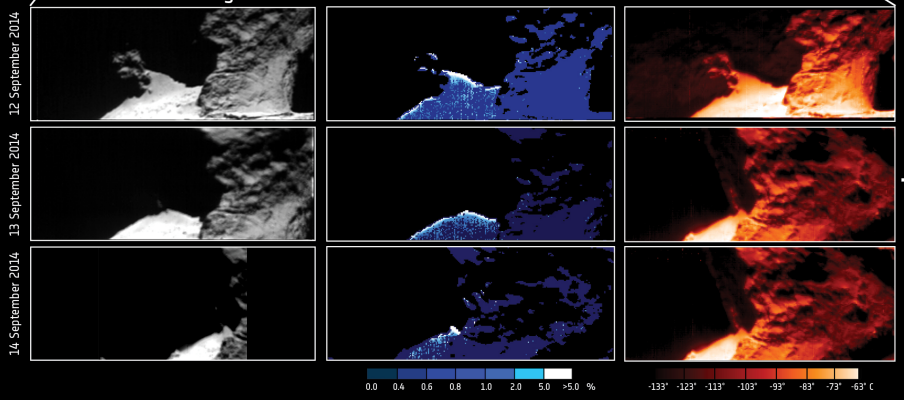
2015 August 12: perihelion – strongest activity

→ THE CYCLE OF WATER ICE AT COMET 67P/CHURYUMOV–GERASIMENKO

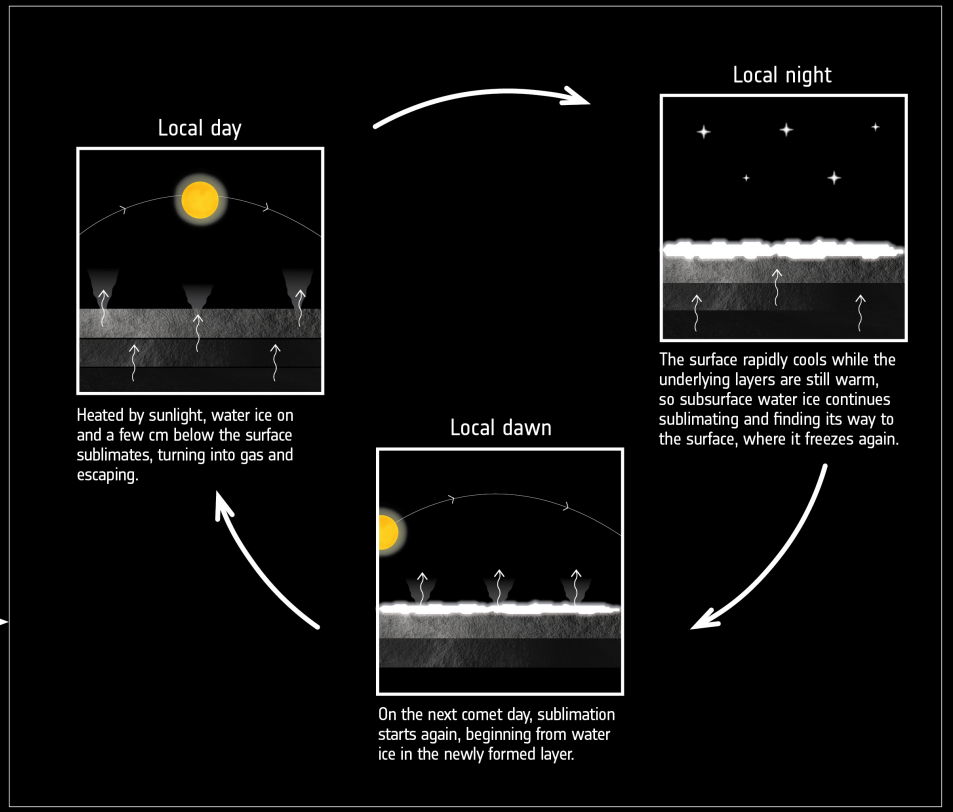
Comet on 2 September 2014



VIRTIS images | Ice abundance map | Temperature map



Water ice cycle at the comet



Data: ESA/Rosetta/VIRTIS/INAF-IAPS/OBS DE PARIS-LESIA/DLR; M.C. De Sanctis et al (2015); Comet: ESA/Rosetta/NAVCAM – CC BY-SA IGO 3.0

Comet P/Shoemaker-Levy 9 (1993e) • May 1994



SPACE TELESCOPE SCIENCE INSTITUTE

Hubble Space Telescope • Wide Field Planetary Camera 2

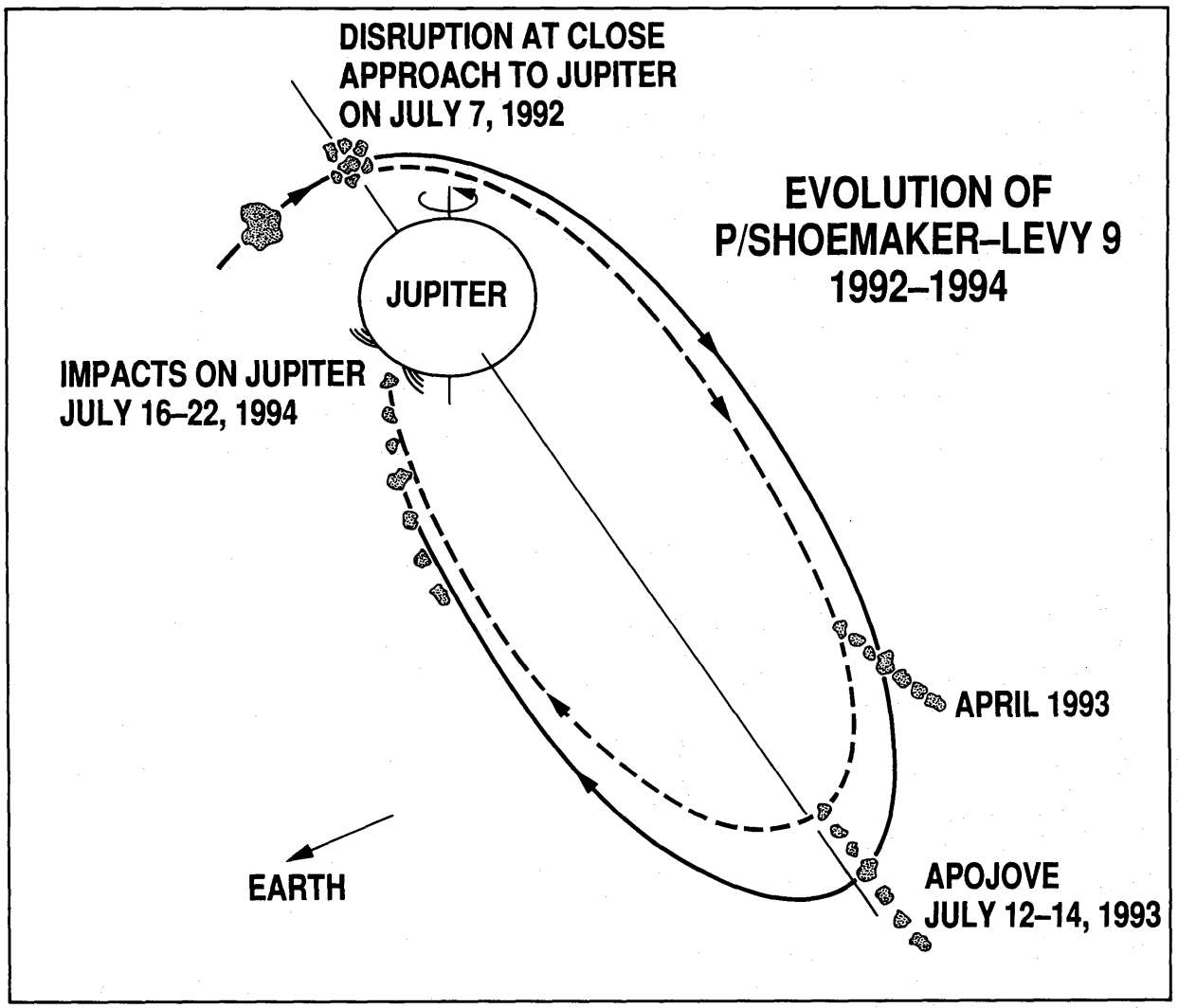
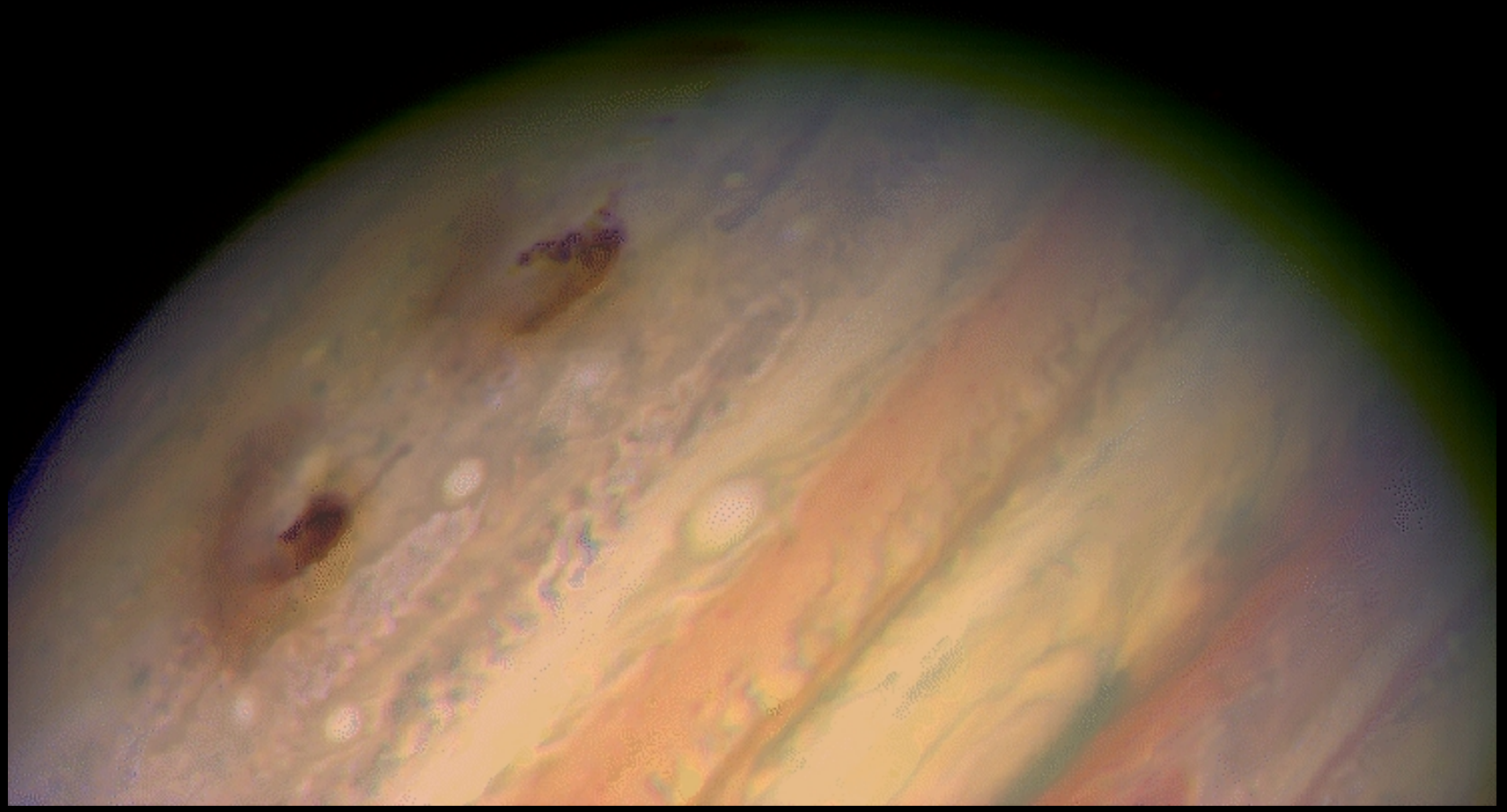
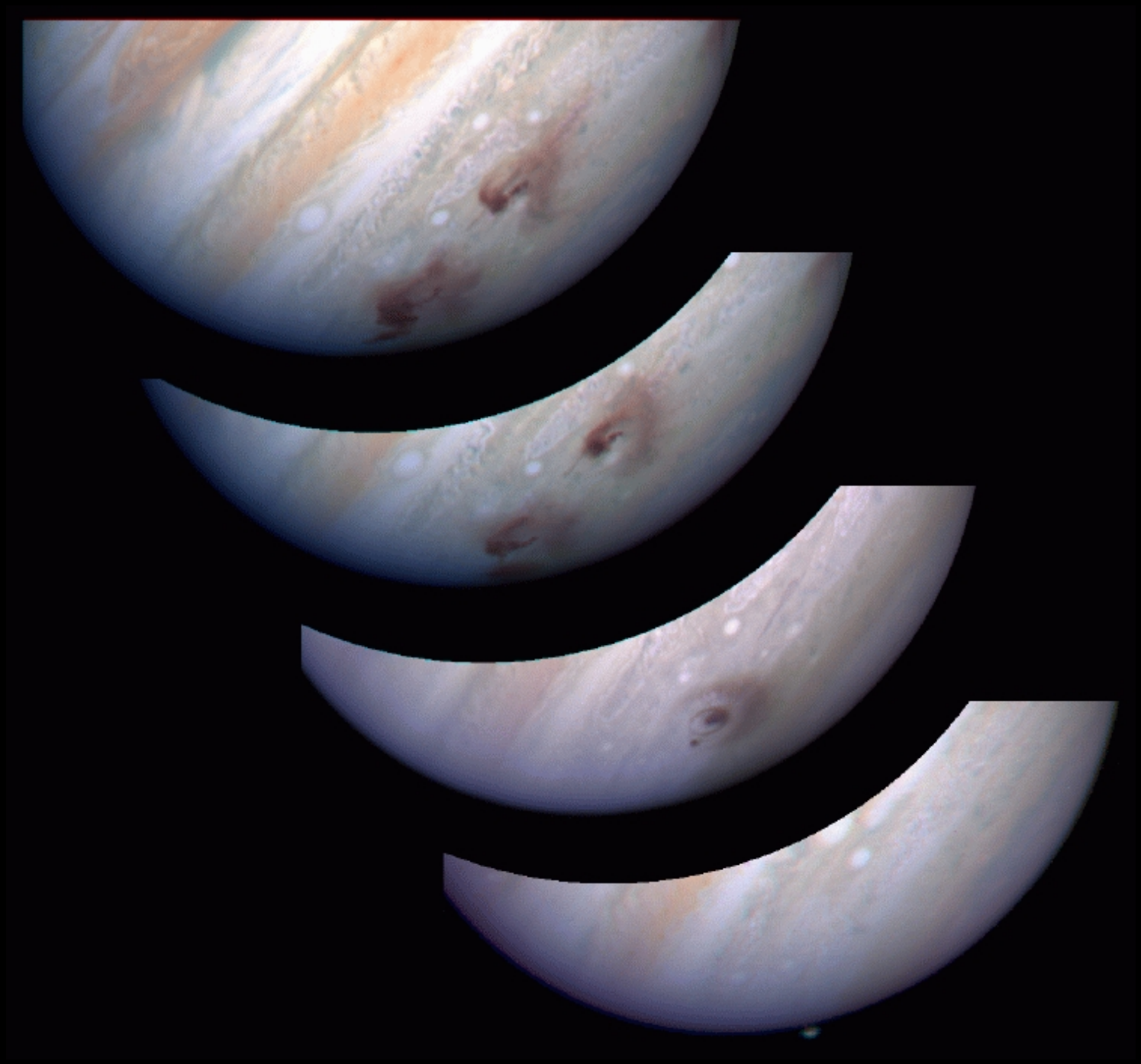


Fig. 9. Schematic representation of the tidal breakup of the parent nucleus of P/Shoemaker–Levy 9 in July 1992, the orbital evolution of its fragments, and their collision with Jupiter in July 1994. It should be remembered that the orbital dimensions and the sizes of Jupiter and the fragment chain are not drawn to scale. The apojove distance in July 1993 was in reality ~520 times the perijove distance in July 1992

Sekanina et al. (1994, A&A 289, 607)



HST: Impact of fragments D and G. Outer ring: $d \sim 12000$ km (Earth!).



Evolution of impact G: bottom to top: 1994 July 18, 5′ after impact of fragment (plume!), until 5 d after impact).

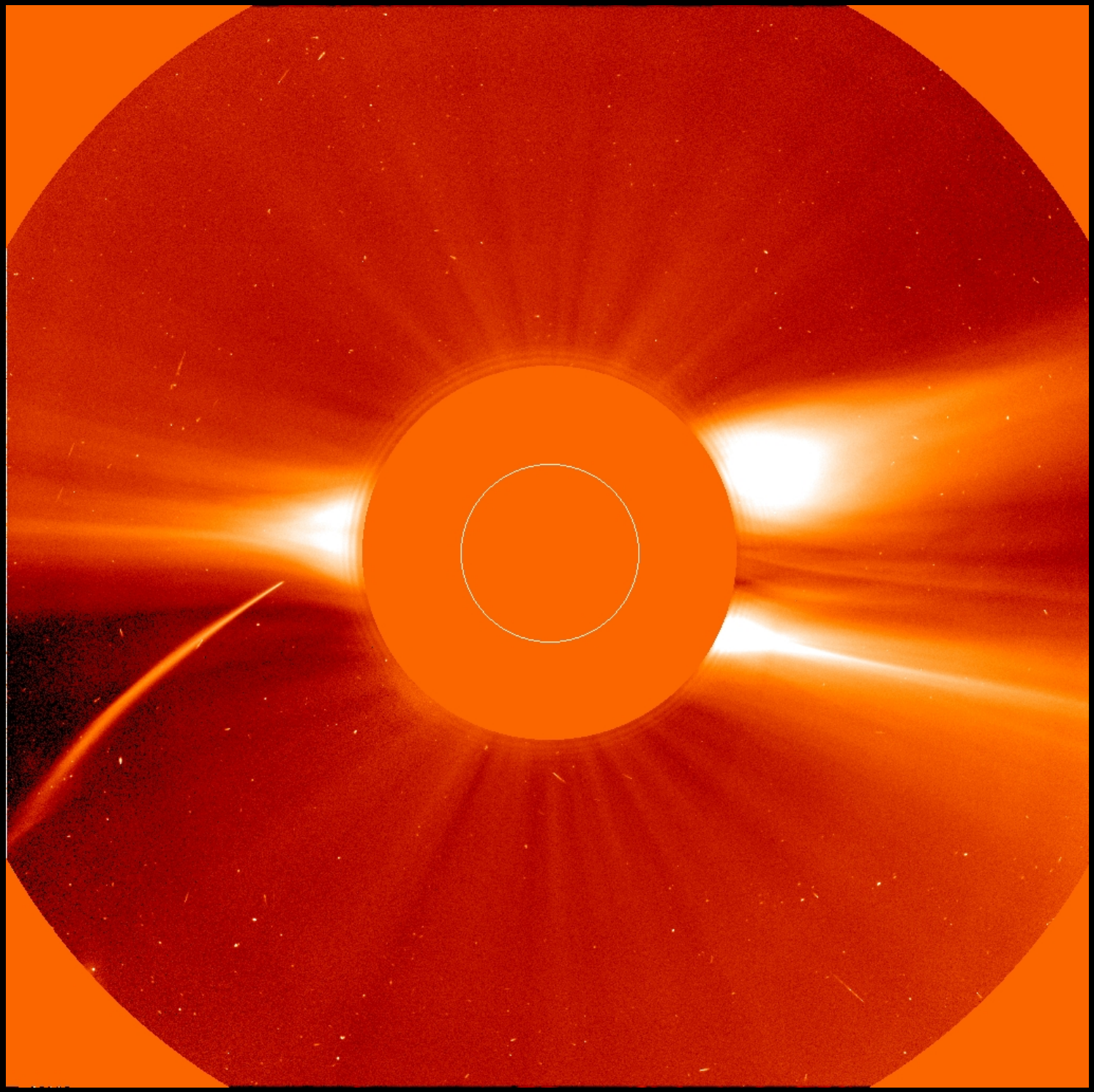


HST image of Jupiter after the impacts



NASA, ESA, & H. Hammel

Similar impact also happened in 2009 (discovered by amateur astronomer) $\Longrightarrow$ "normal"?



Sungrazers

Sungrazing comets: . . . the unlucky ones, members of the Kreutz group of comets, which come within ∼50000 km of the Sun.

Named after Heinrich Kreutz, who discovered these comets in the late 1800s.

Until 1979: 9 comets known.

Since then: solar observations from satellites, more comets found.

Since 1996: >1800 sungrazers discovered with instruments onboard ESA's SOHO spacecraft and recently also by NASA's STEREO.

SOHO: Launched 1995 December 2, STEREO: launched in 2006 October

Sungrazers

MOVIE TIME:

- `Hyakutake.mpg`: Perihelion passage of P/Hyakutake. Note dust tail and plasma tail!
- `cometM.mpg`: perihelion passage of comet P/Macholz
- `c2002v1.mpg`: perihelion passage of another comet in 2002
- `C3_2comets_CME.mpg`: two comets hitting the sun, followed by an (unrelated!) coronal mass ejection

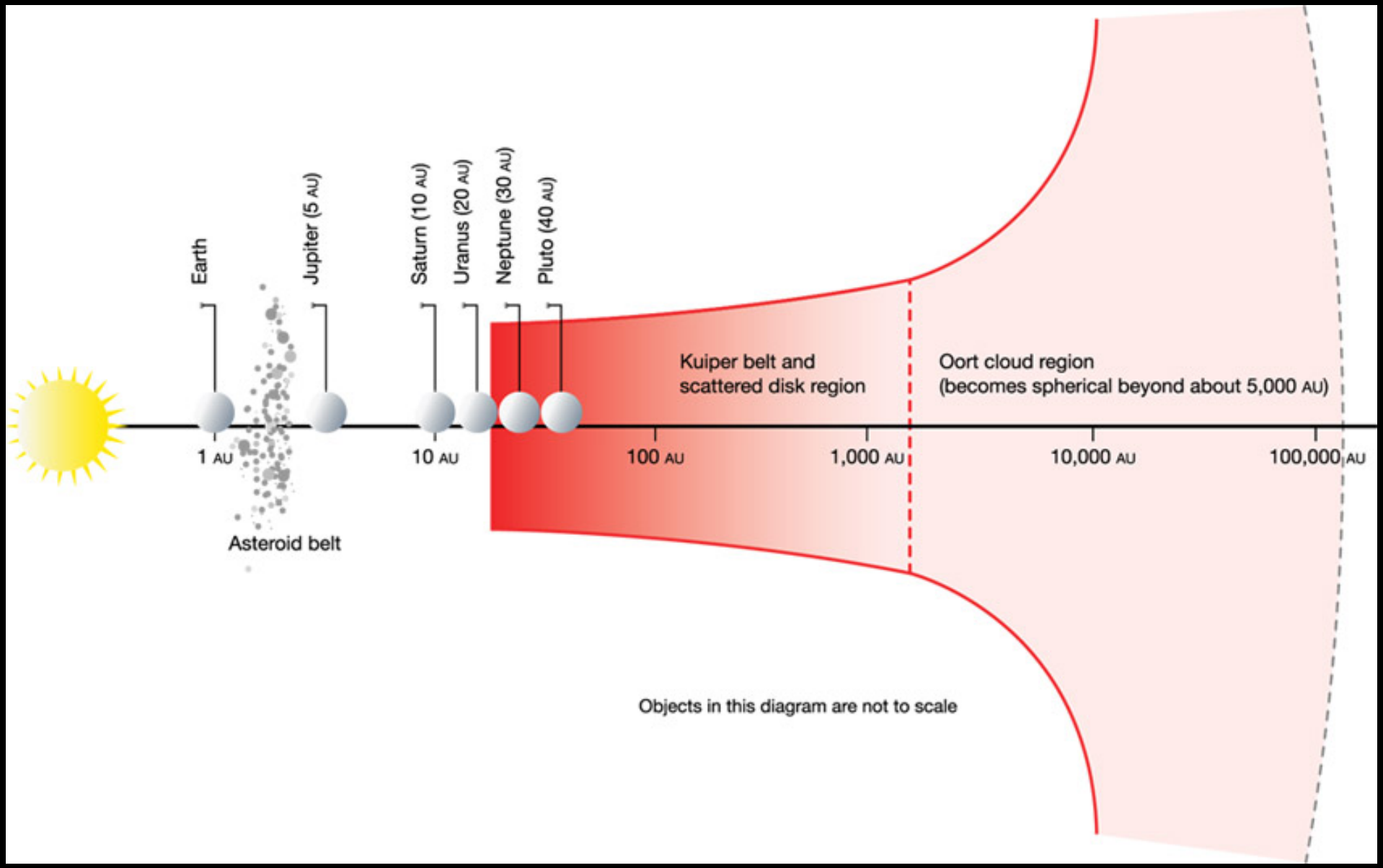
Origin of Comets

Long period comets: P $\geqslant$ 200 years, have very eccentric orbits with huge semi-major axes, all angular momenta and inclinations observed.

Jan Oort (1950) suggested the presence of a large cloud of comets at *huge* distances around the Sun (Oort cloud).

Formal definition: Oort cloud is ensemble of all comets with semi-major axis $a \geqslant 10^4$ AU; estimated content $\sim 10^{11}$ to 10^{12} objects, total mass 1–50 Earth masses, temperature 5–10 K.

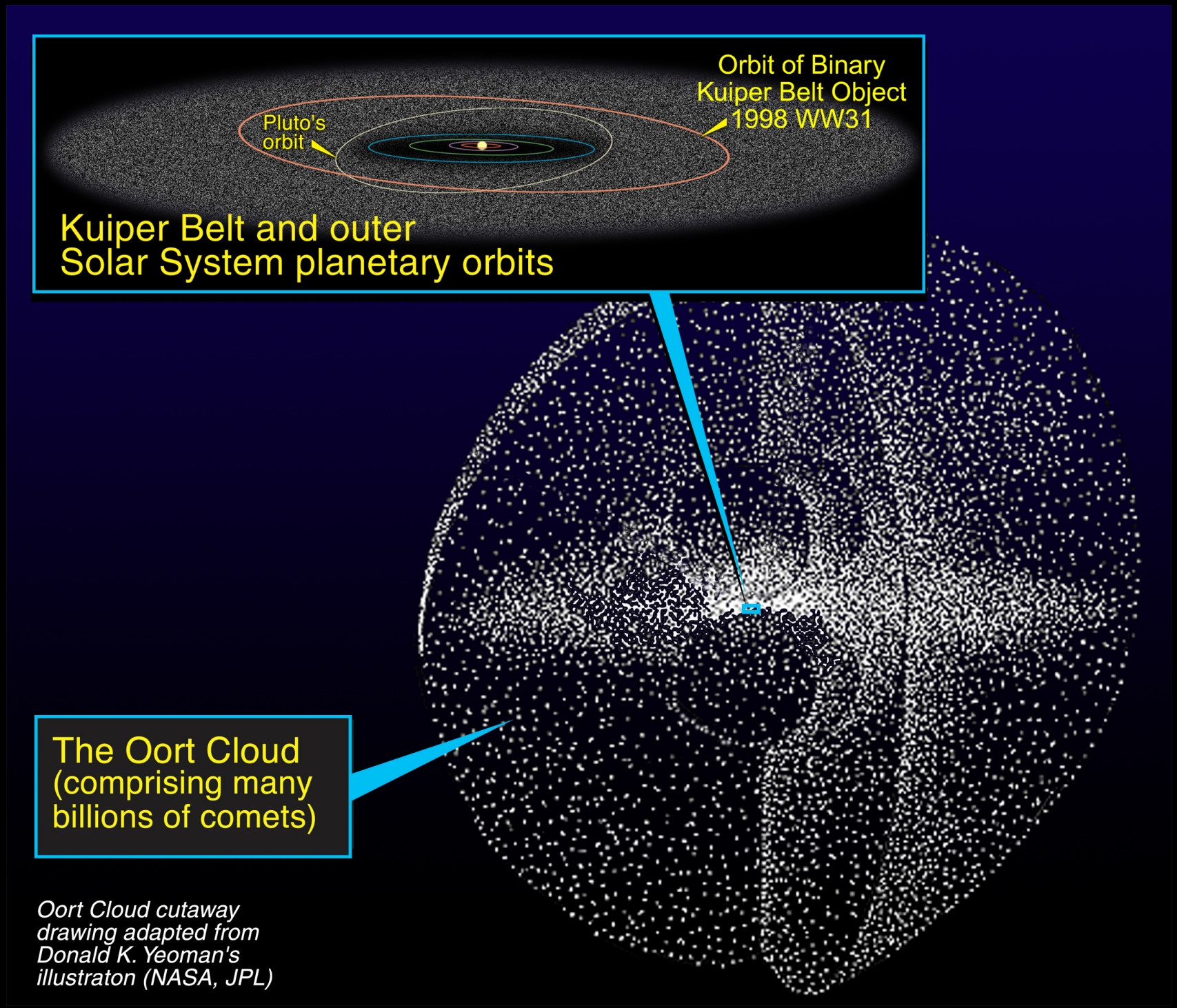
Long period comets originate in Oort cloud, orbits are disturbed by passing stars or Giant Molecular Clouds.



S.A. Stern (2003, Nature 424, 639–642)

short period comets: P $<$ 200 years: orbital angular momenta similar to planets, mainly found in plane of solar system.

$\Longrightarrow$ probably from Kuiper belt, high collision rates there fragment objects, leading to cometary debris.



NASA/A. Feild(STScI)

Trans Neptunian Objects

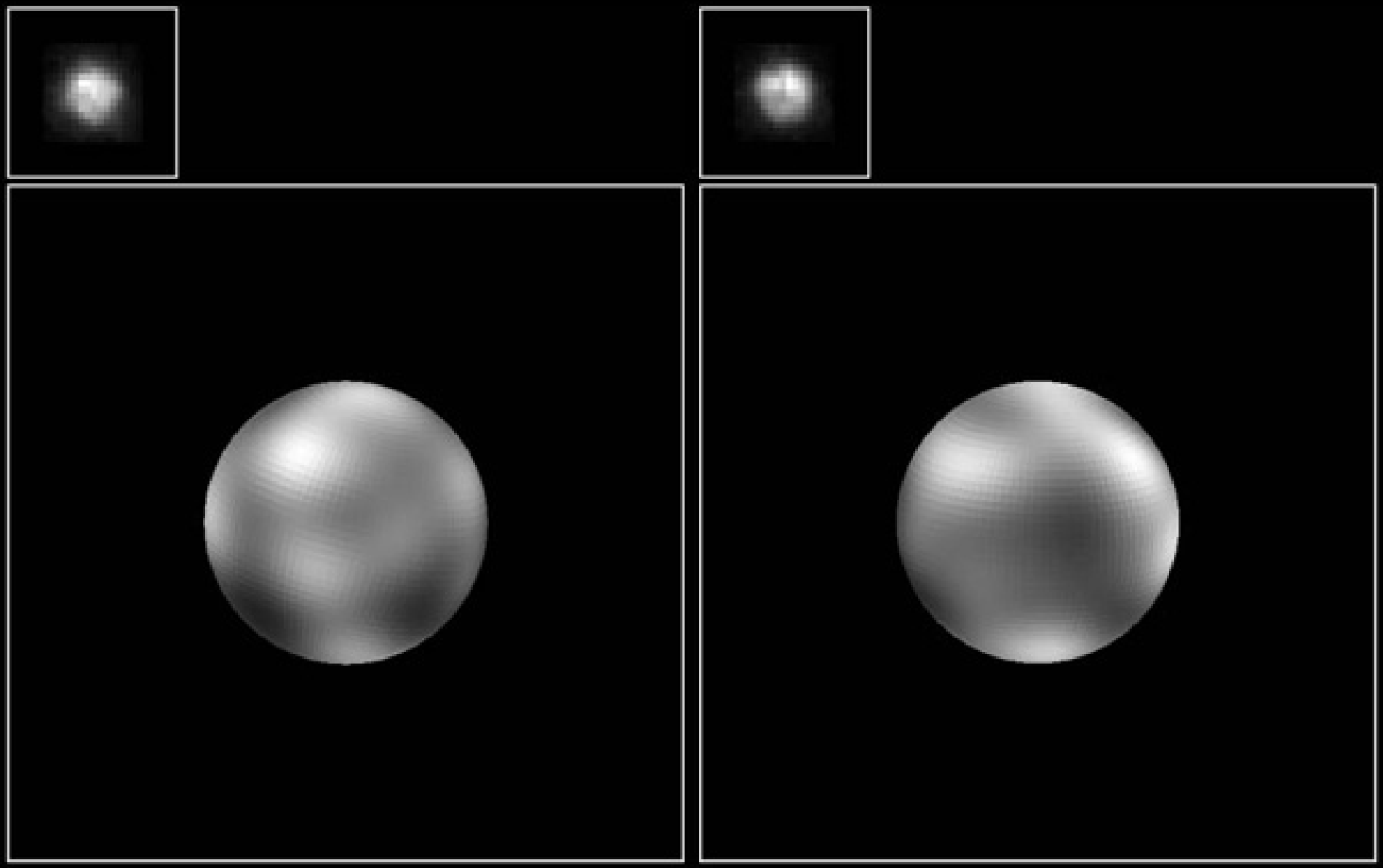
Pluto – the dwarf planet



NASA/ESA HST

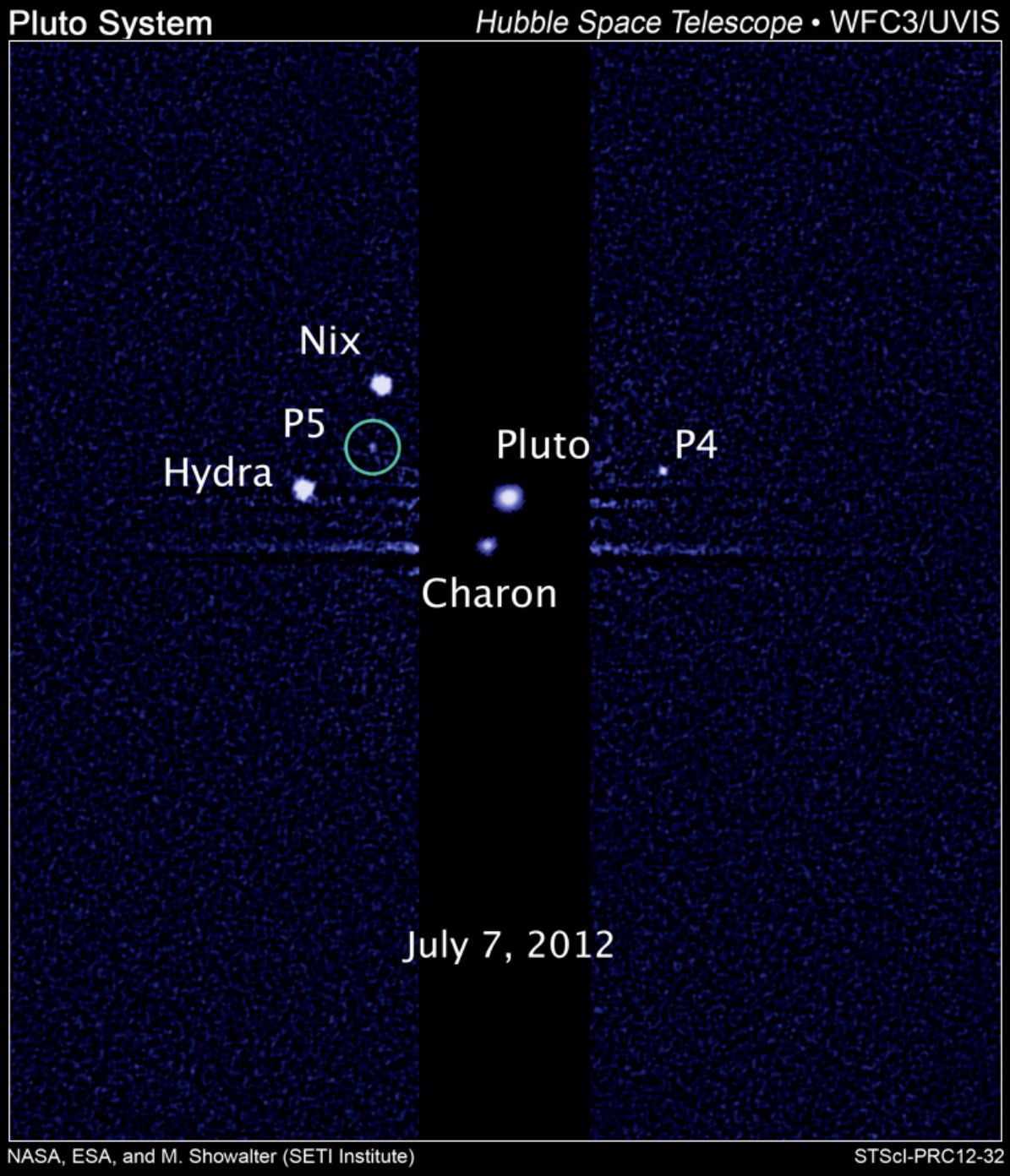
Pluto/Charon:

- discovered 1930/1978
- double system (Pluto: D = 2320 km, Charon: D = 1270 km), plus moons (Kerberos, Styx, Nix, Hydra)
- icy surface, probably cratered
- one of the largest trans neptunian objects, member of the Kuiper belt



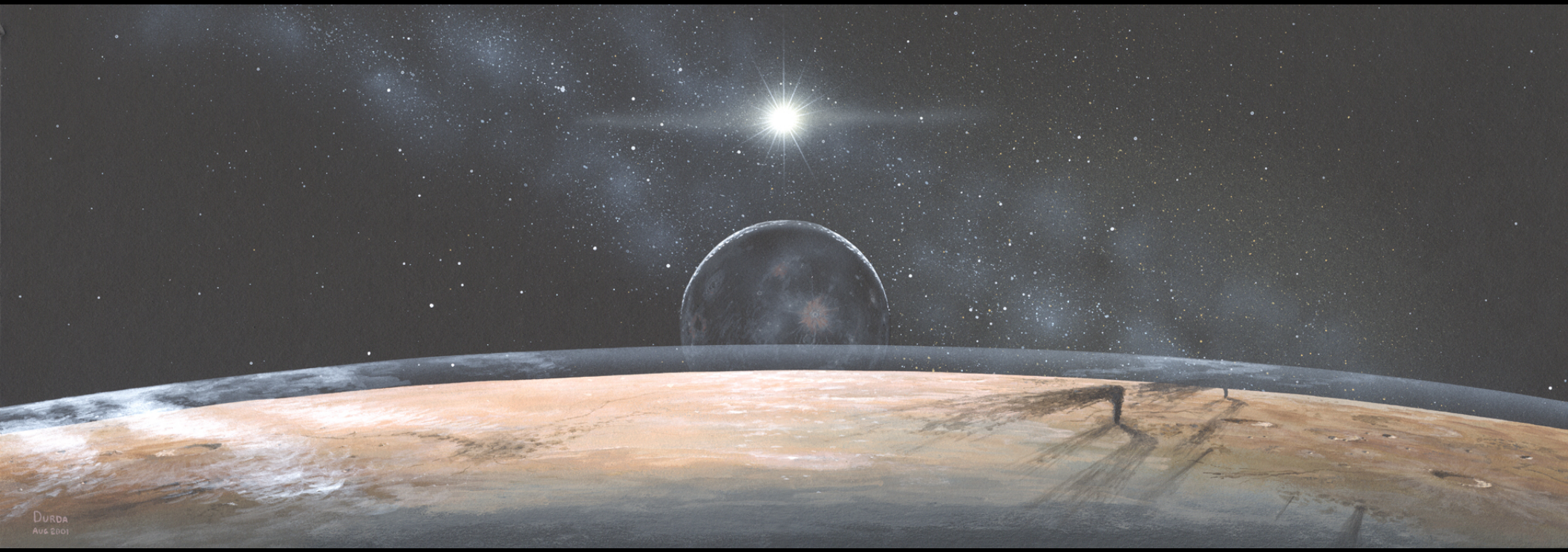
Pluto HST • FOC

PRC96-09a · ST ScI OPO · March 7, 1996 · A. Stern (SwRI), M. Buie (Lowell Obs.), NASA, ESA

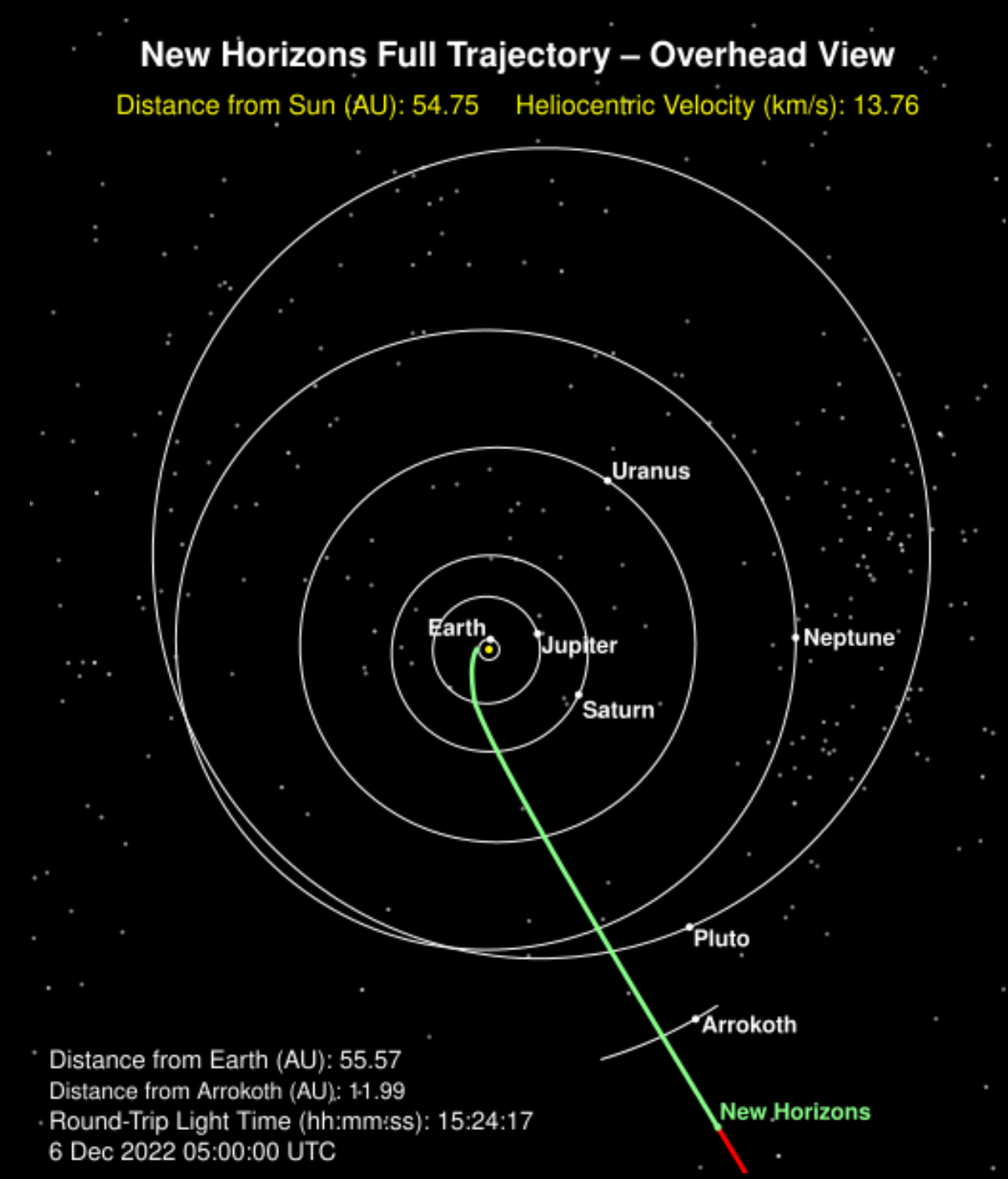


5 moons of Pluto:

https://www.nasa.gov/mission_pages/hubble/science/new-pluto-moon.html

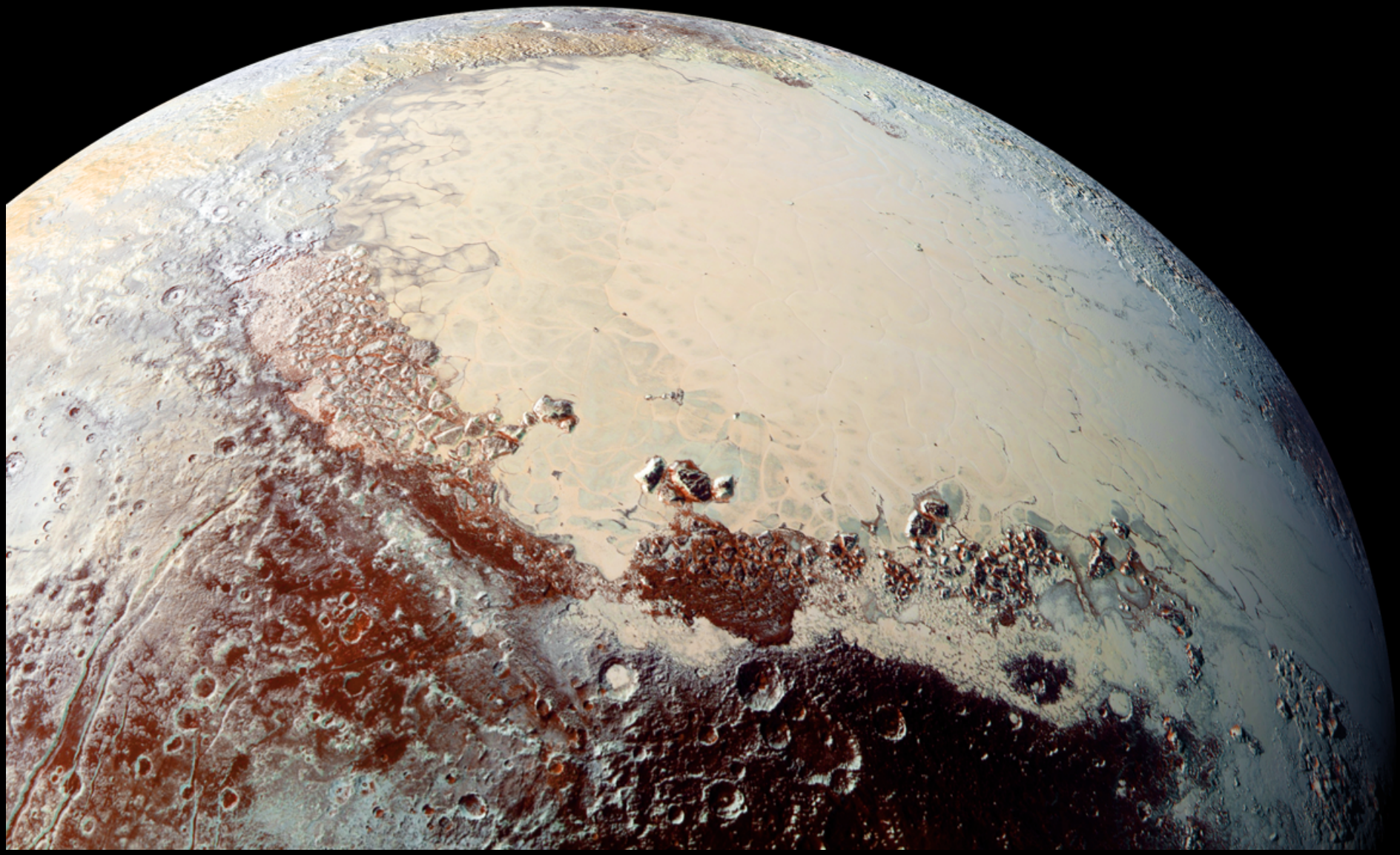


Artist's impression of Pluto and Charon (D. Durda, SWRI; before New Horizons mission)



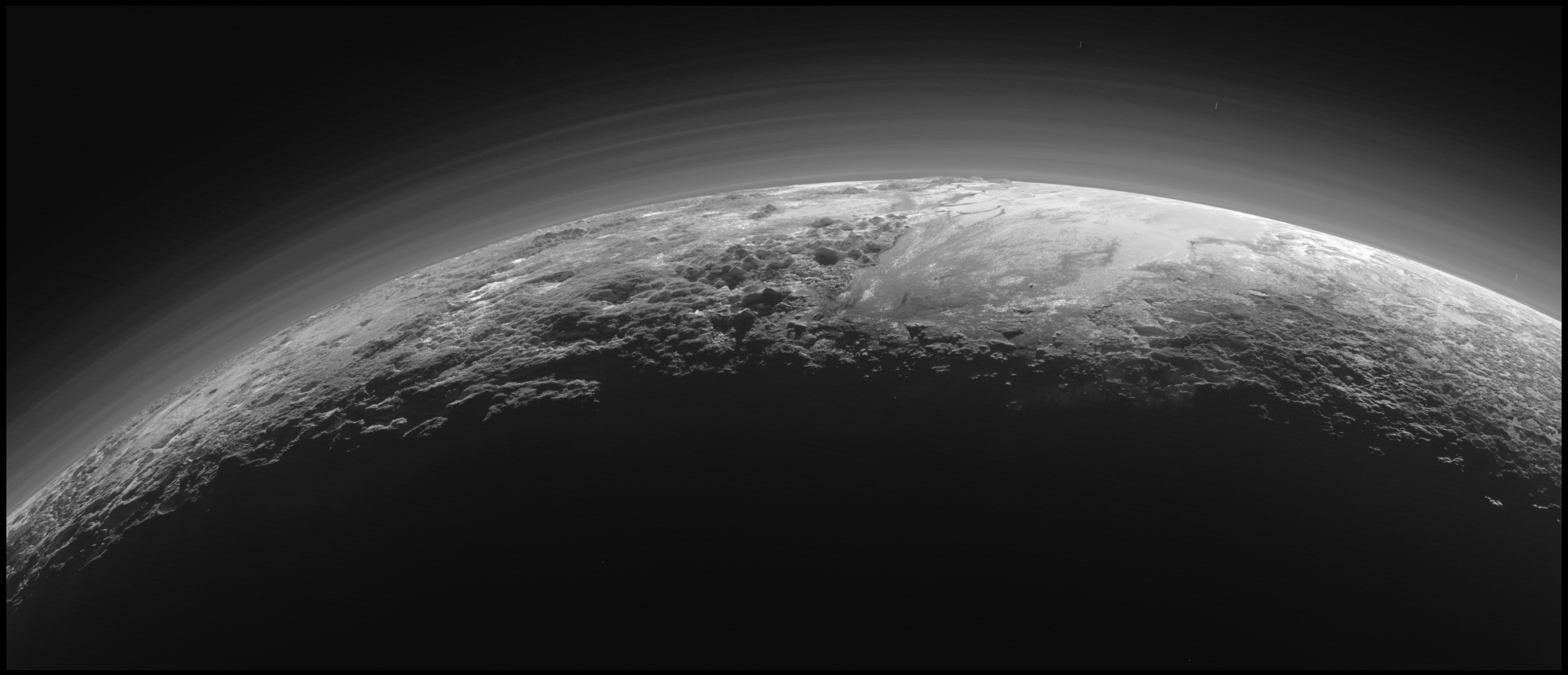
New Horizons: NASA Mission to Pluto and beyond launched 2006 January 19,
2007 February: Jupiter gravity assist,
2015 July: Flyby at Pluto and Charon,
Kuiper Belt mission: flyby of Arrokoth in 2019 Jan



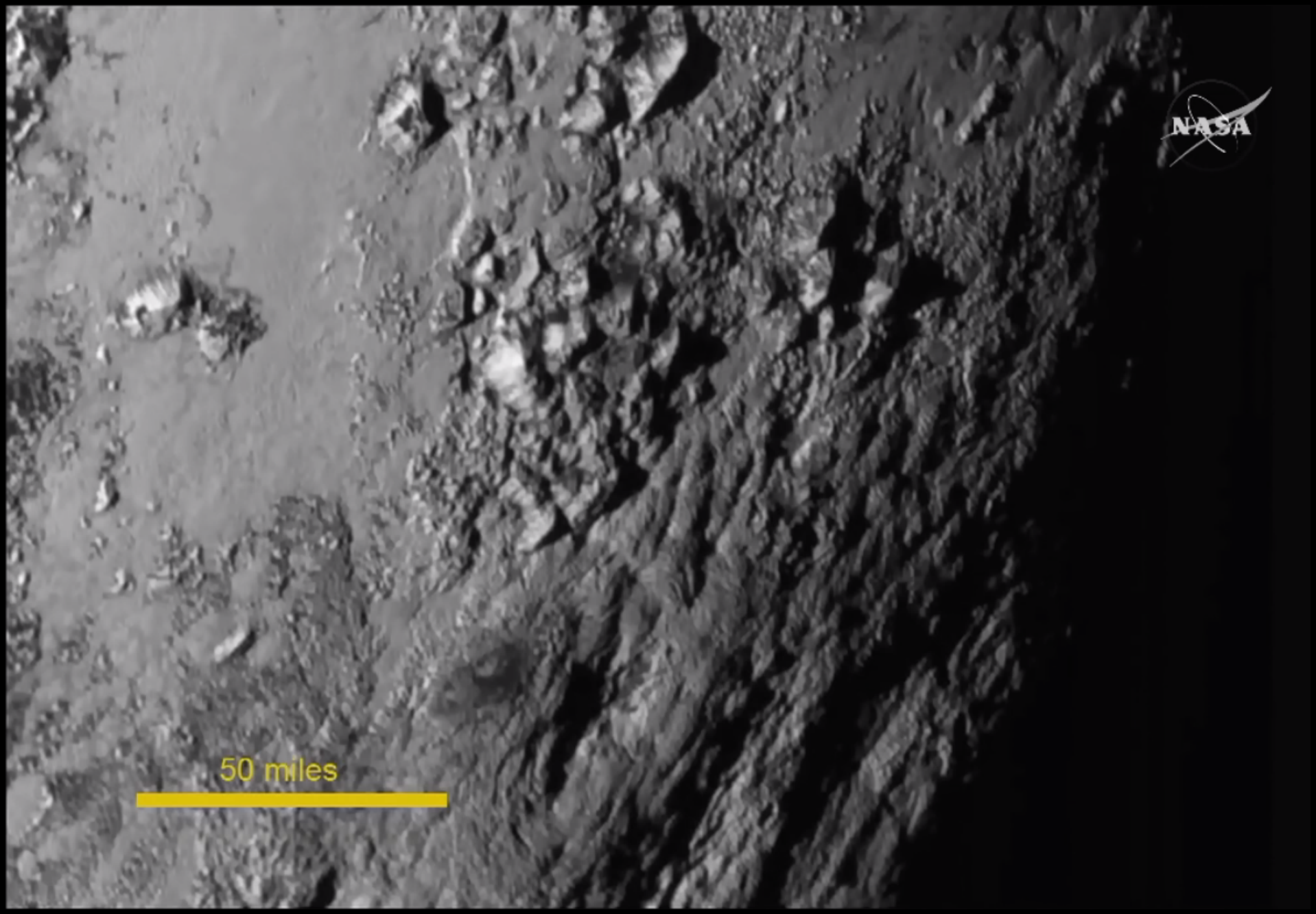


NASA/JHUAPL/SwRI

Closeup on Sputnik Planum
(color enhanced + infrared)



NASA/JHUAPL/SwRI

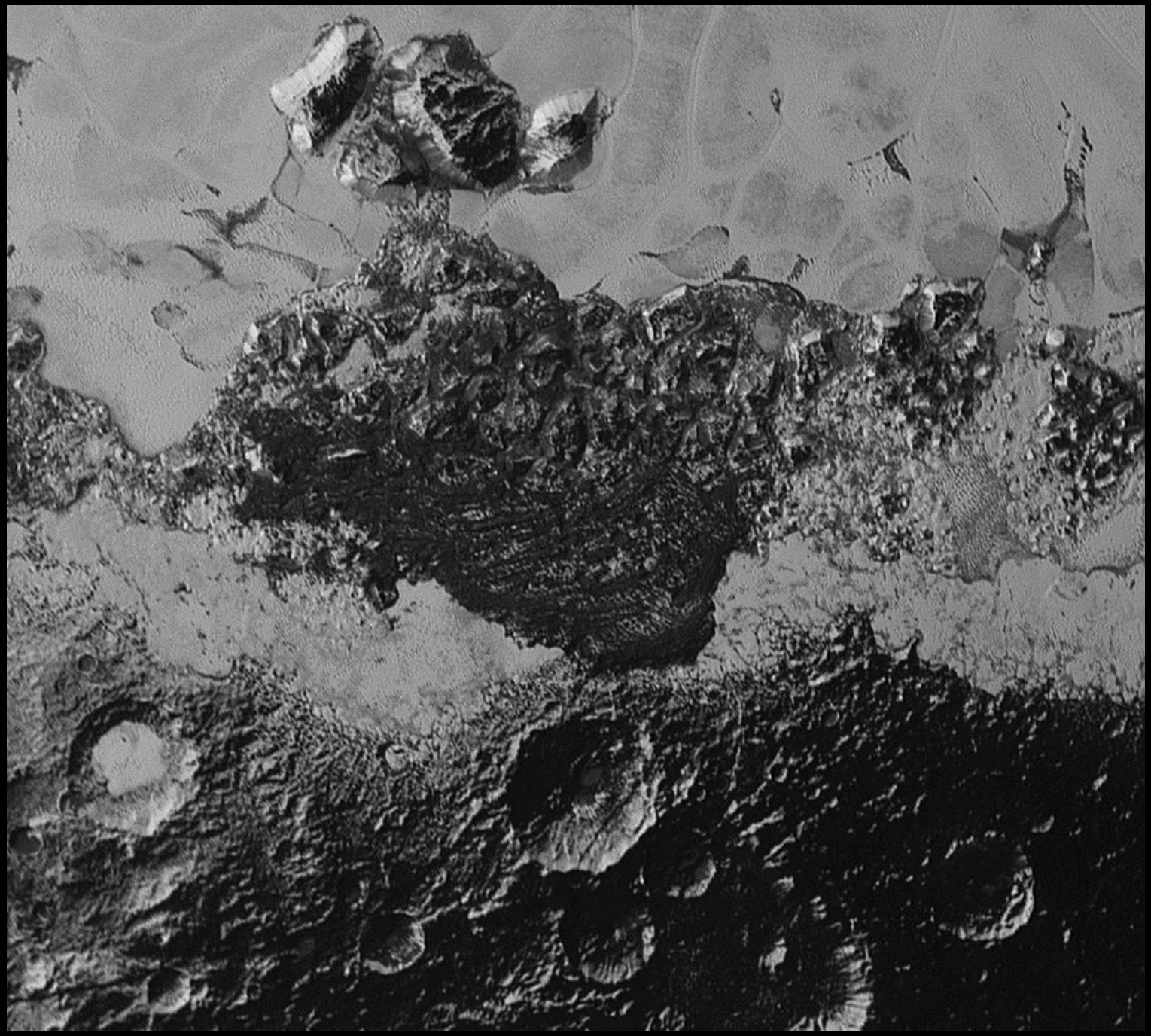


Norgay mountains

NASA

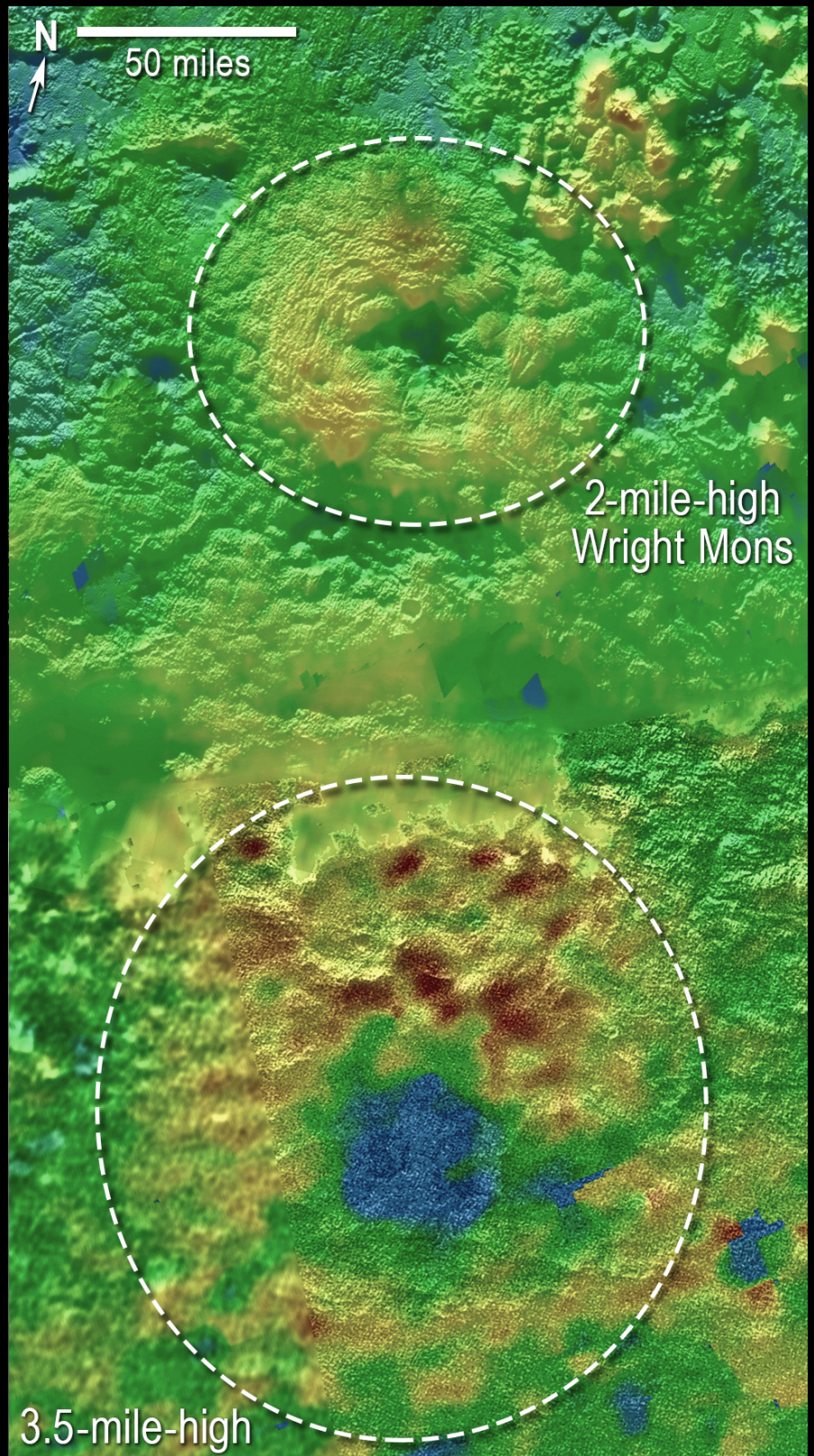
3.4 km high, water ice, 100 million years old

$\Longrightarrow$ geologically young! $\Longrightarrow$ Pluto still active?



Surface details of Pluto
(distance: 80 000 km, resolution: 800 m)

NASA/JHUAPL/SwRI



Kryovulcanos!

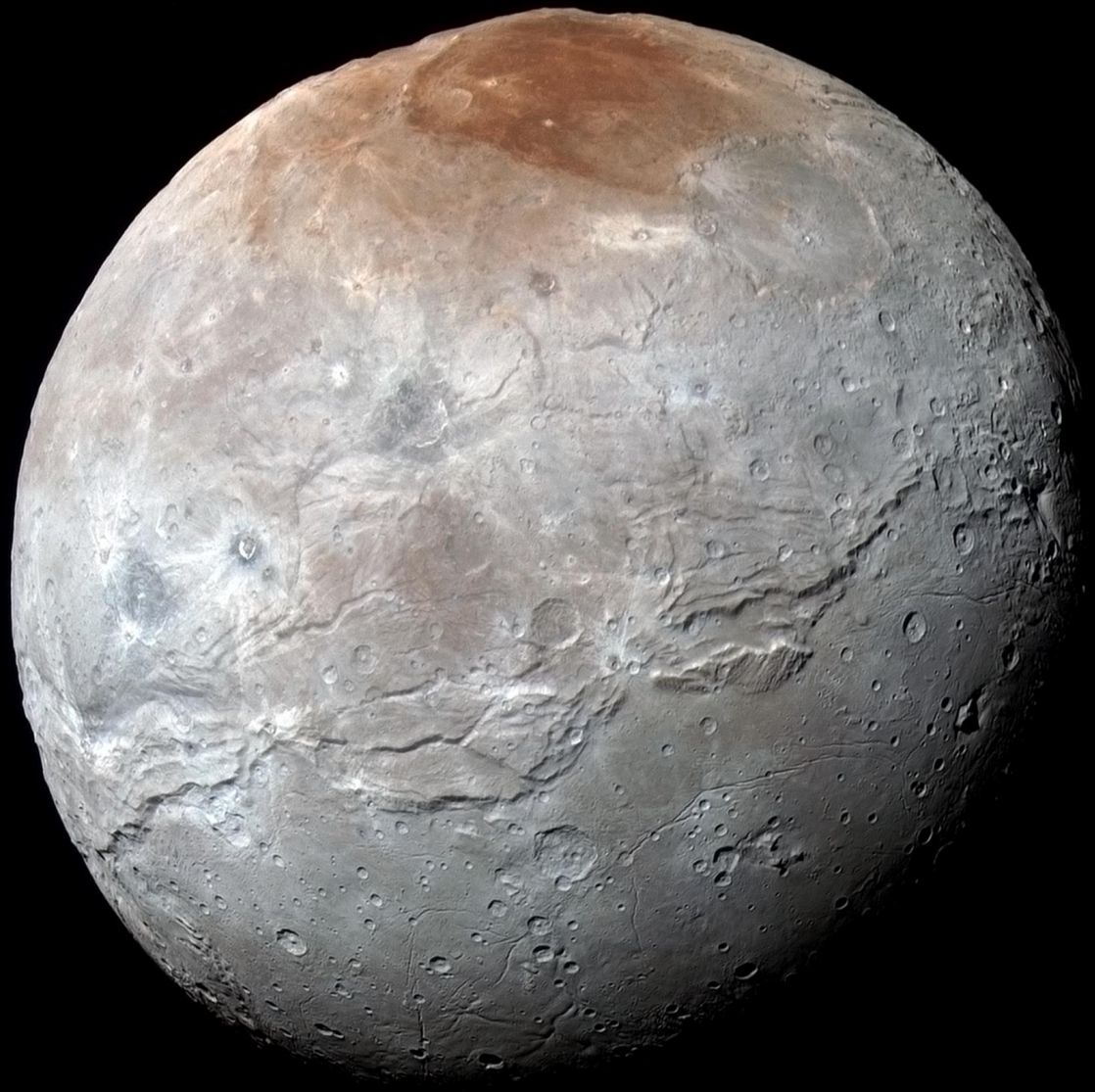
- craters
- liquid material ejected
- vulcanoc flows on the outside
- unseen before in outer solar system!

NASA/JHUAPL/SwRI



Blue Sky of Pluto!

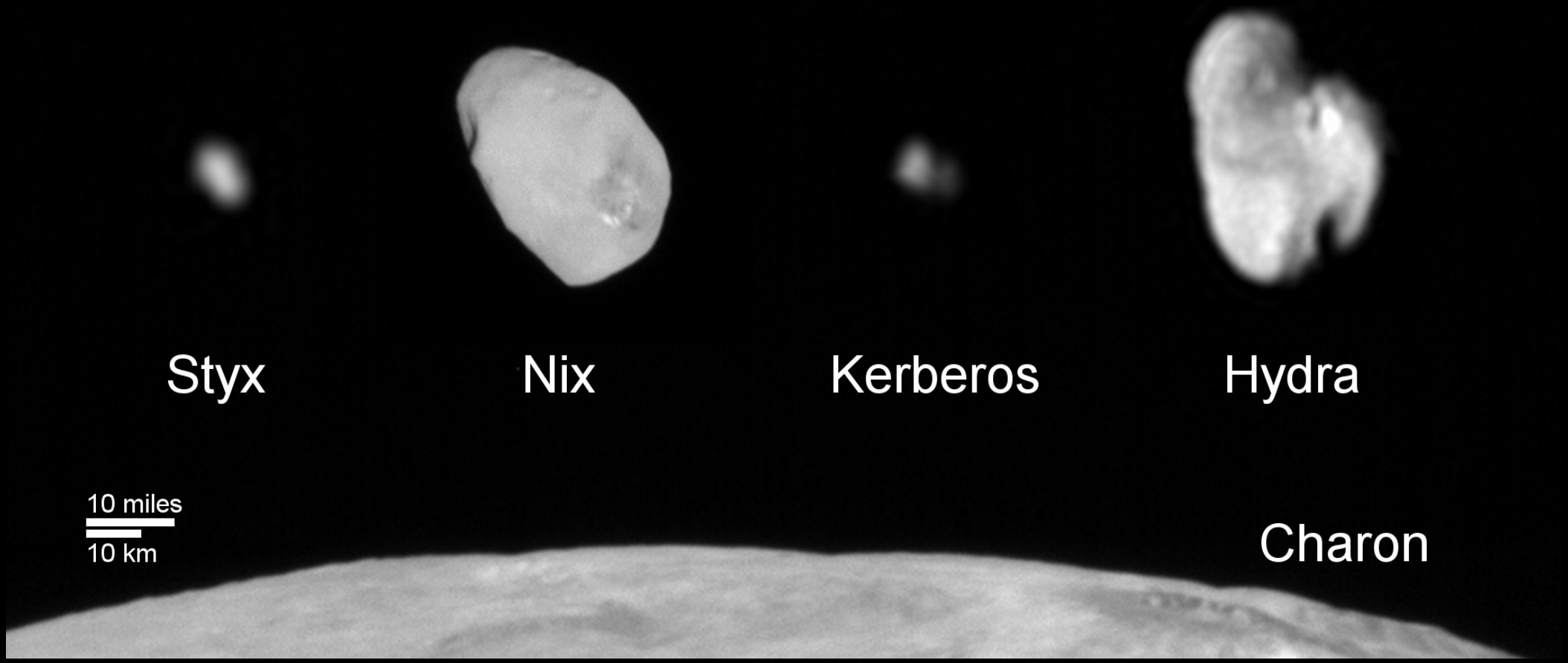
NASA/JHUAPL/SwRI



Charon (diameter: 1200 km)
tectonic fractures, mountains, plains

NASA/JHUAPL/SwRI

Charon and the Small Moons of Pluto



NASA/JHUAPL/SwRI

Elongated shape: Kuiper belt bodies caught by interaction w/Pluto!

Arrokoth (2014 MU69): a typical pristine Trans-Neptunian Object

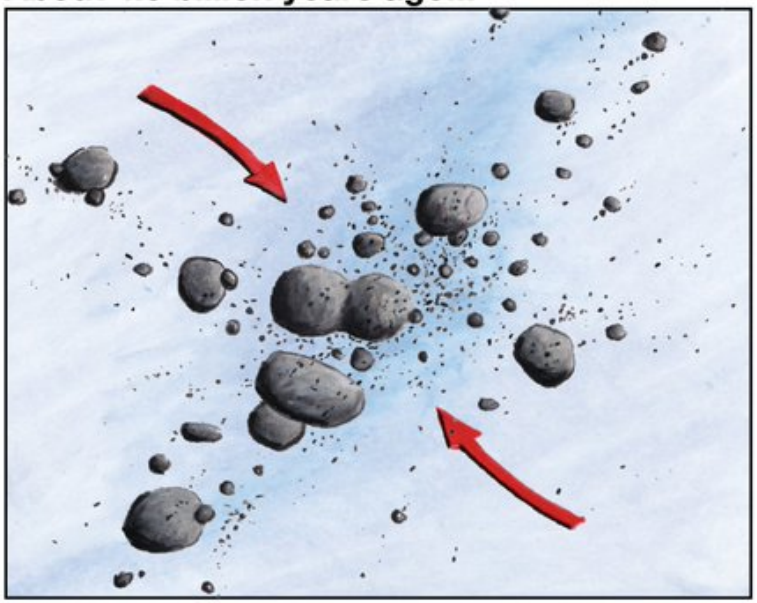


NASA/JHUAPL/SwRI

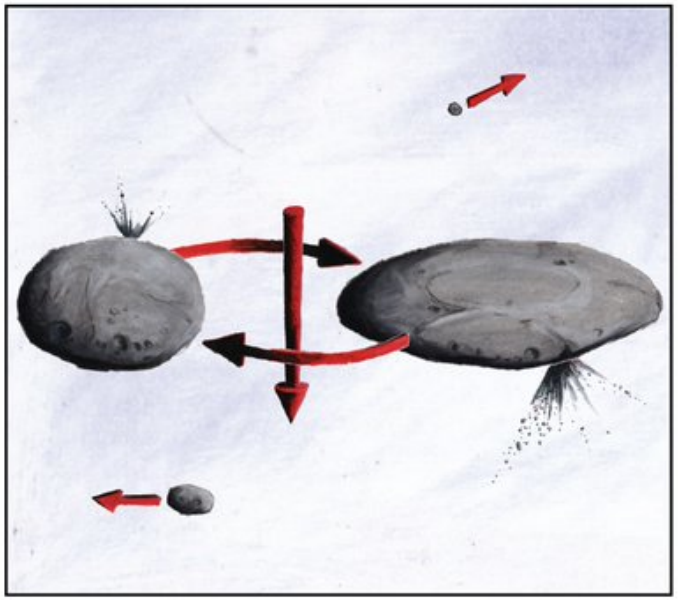
the farthest and most primitive object visited by a spacecraft (~45 AU)

The Formation of 2014 MU69

About 4.5 billion years ago...



A rotating cloud of small, icy bodies starts to coalesce in the outer solar system.



Eventually two larger bodies remain.

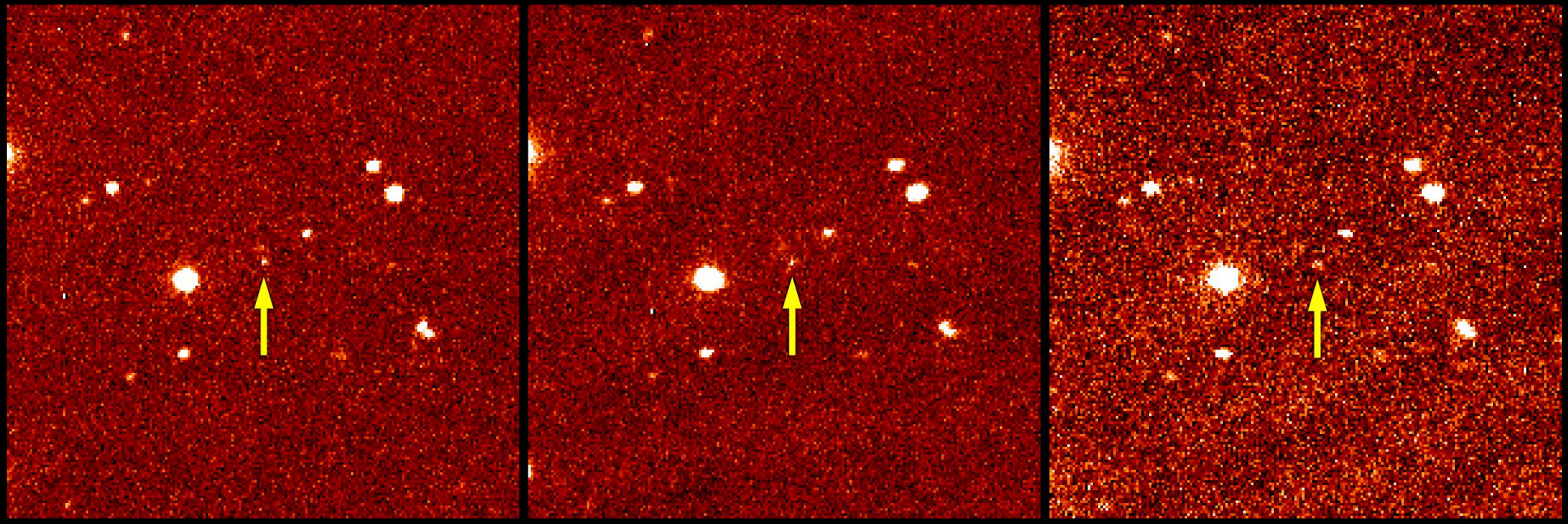
...1 January 2019.



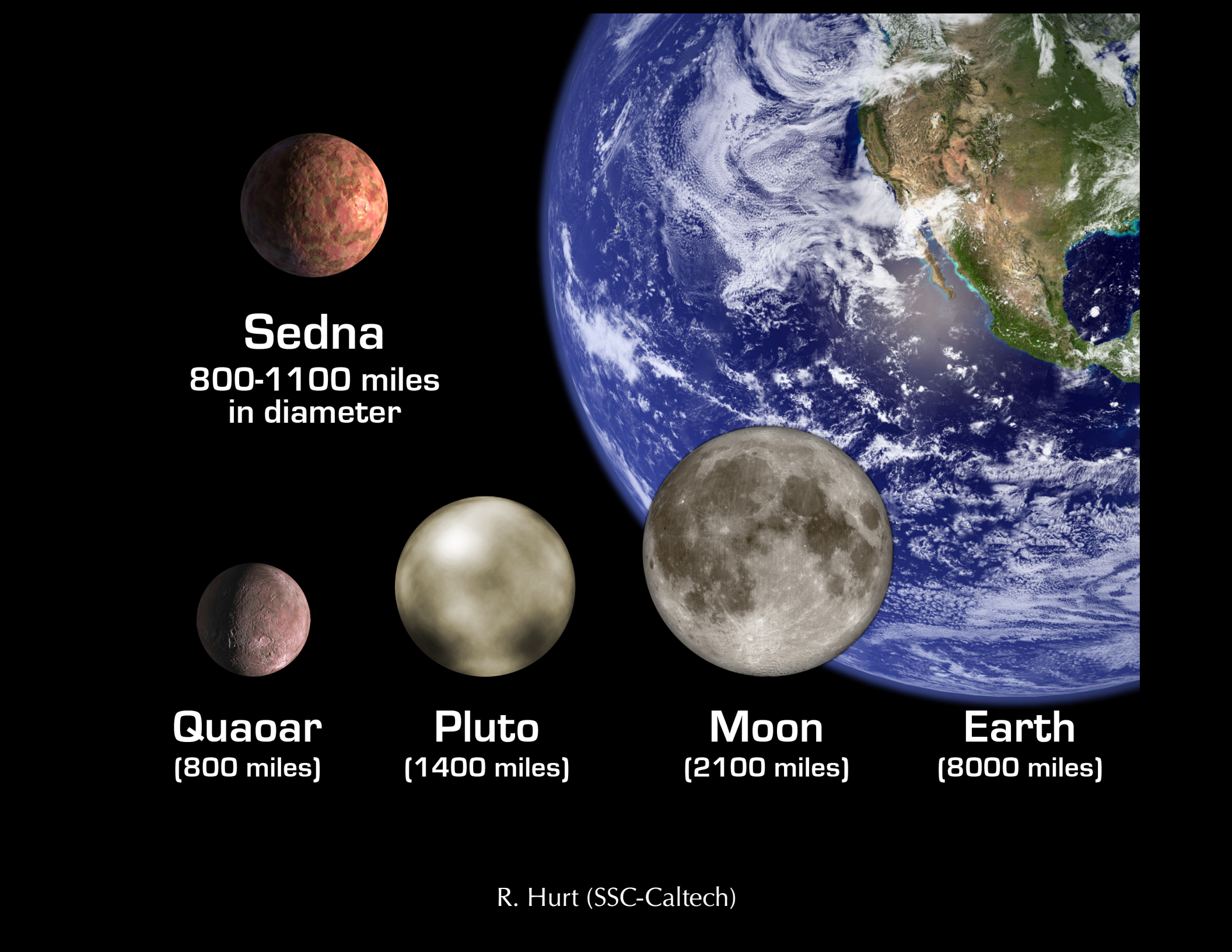
The two bodies slowly spiral closer until they touch, forming the bi-lobed object we see today.

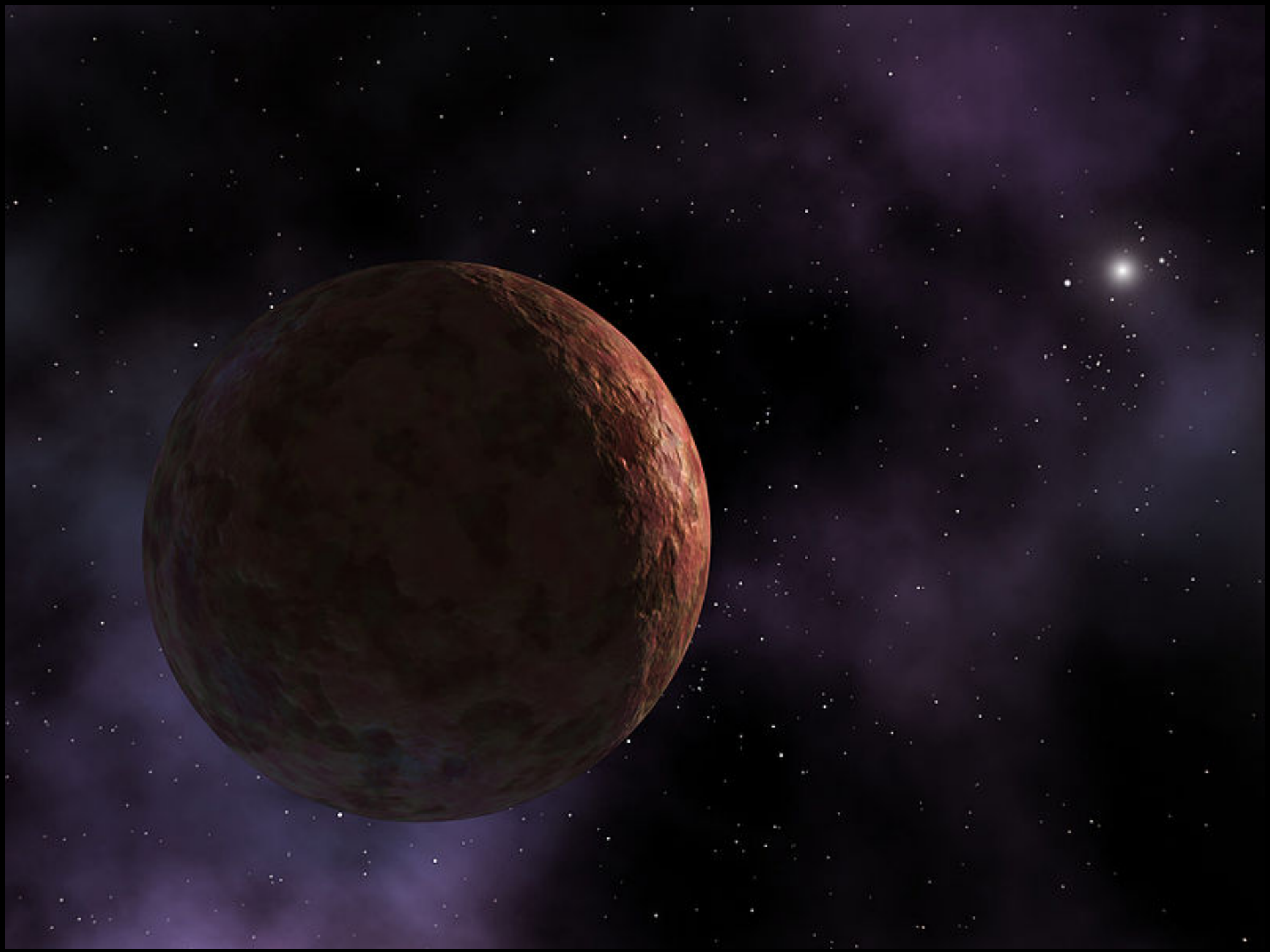
New Horizons / NASA / JHUAPL / SwRI / James Tuttle Keane

NASA/JHUAPL/SwRI

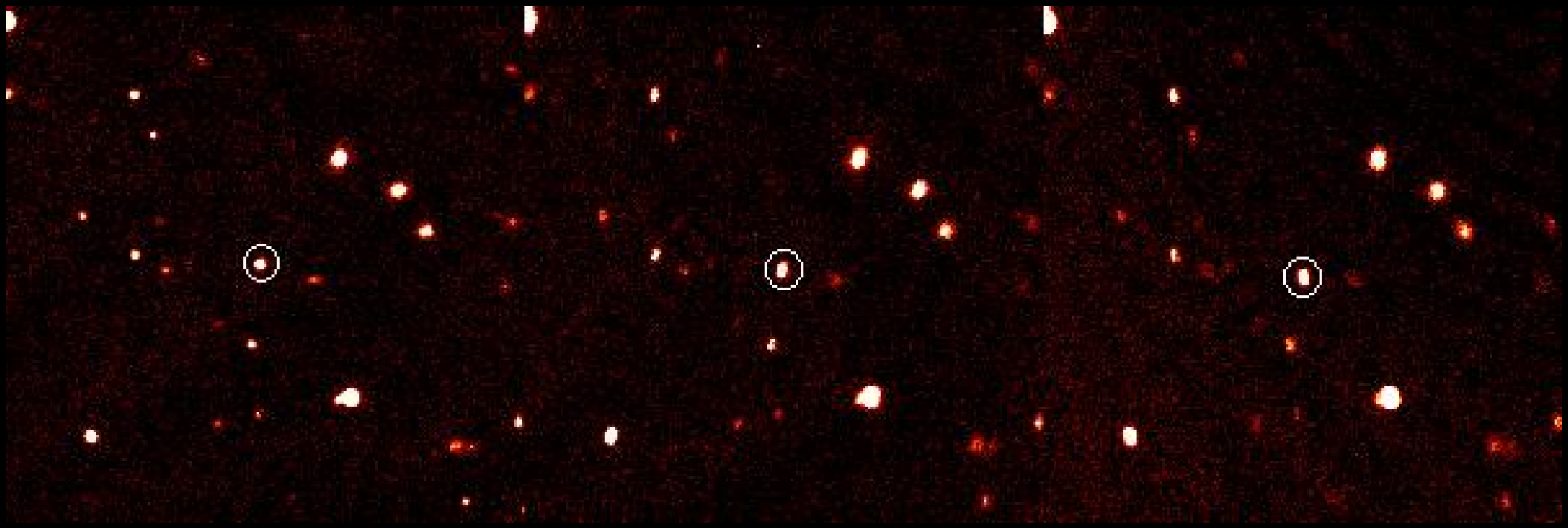


Nov. 14th, 2003 6:32 (UT) 8:03 (UT) 9:38 (UT)


Sedna
800-1100 miles
in diameter
Quaoar
(800 miles)
Pluto
(1400 miles)
Moon
(2100 miles)
Earth
(8000 miles)
R. Hurt (SSC-Caltech)



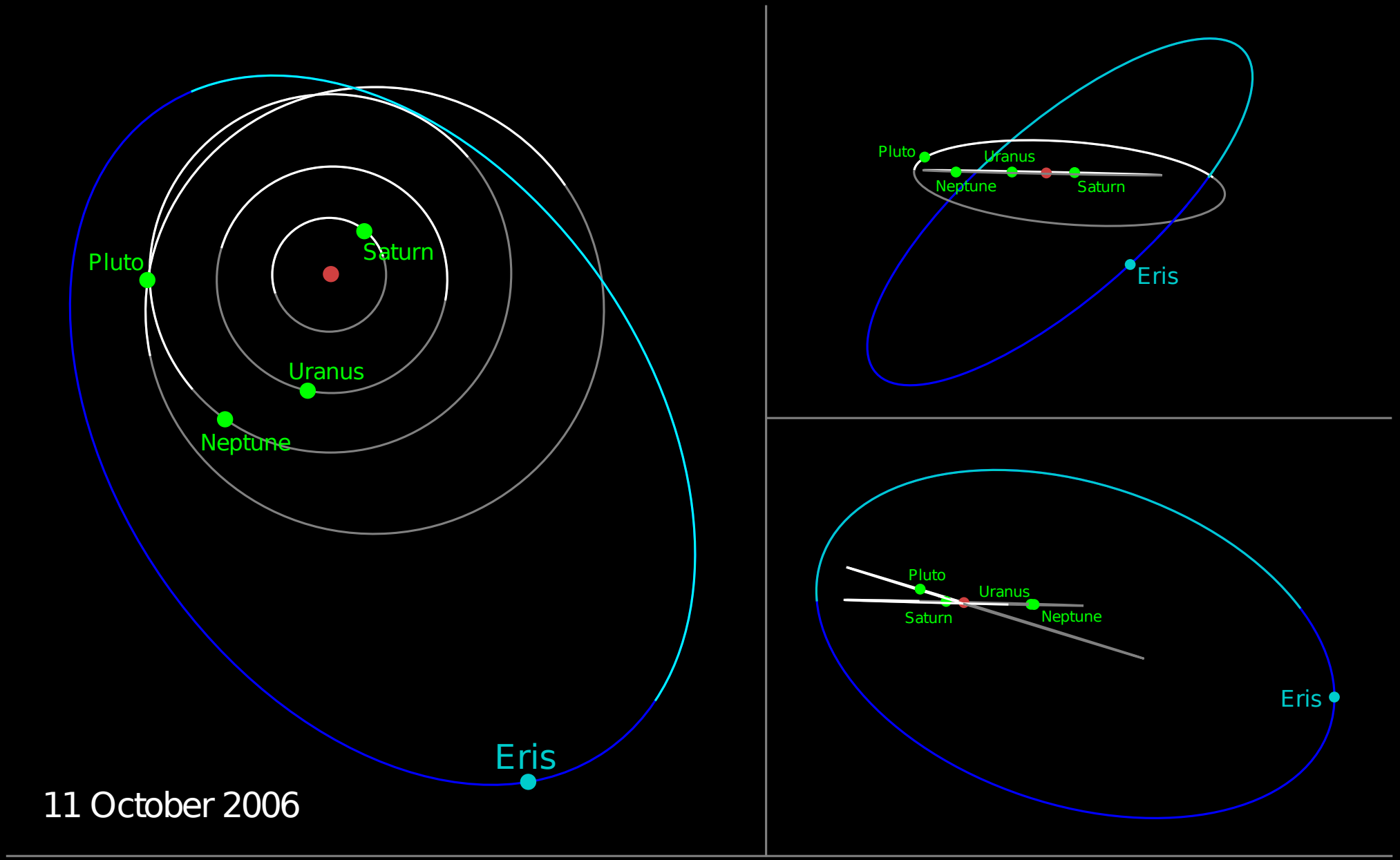
Viewing inwards from Sedna (NASA/JPL)



Discovery images of the dwarf planet Eris. The three images were taken 1.5 h apart on 2003 October 21. (M. Brown et al. Caltech)

Eris (2003 UB_{313}): discovered 2005: distance ~100 AU (today: ~95 AU), brightness similar to Pluto

$\Longrightarrow$ larger than Pluto, unless it is 100% reflective (unlikely)!

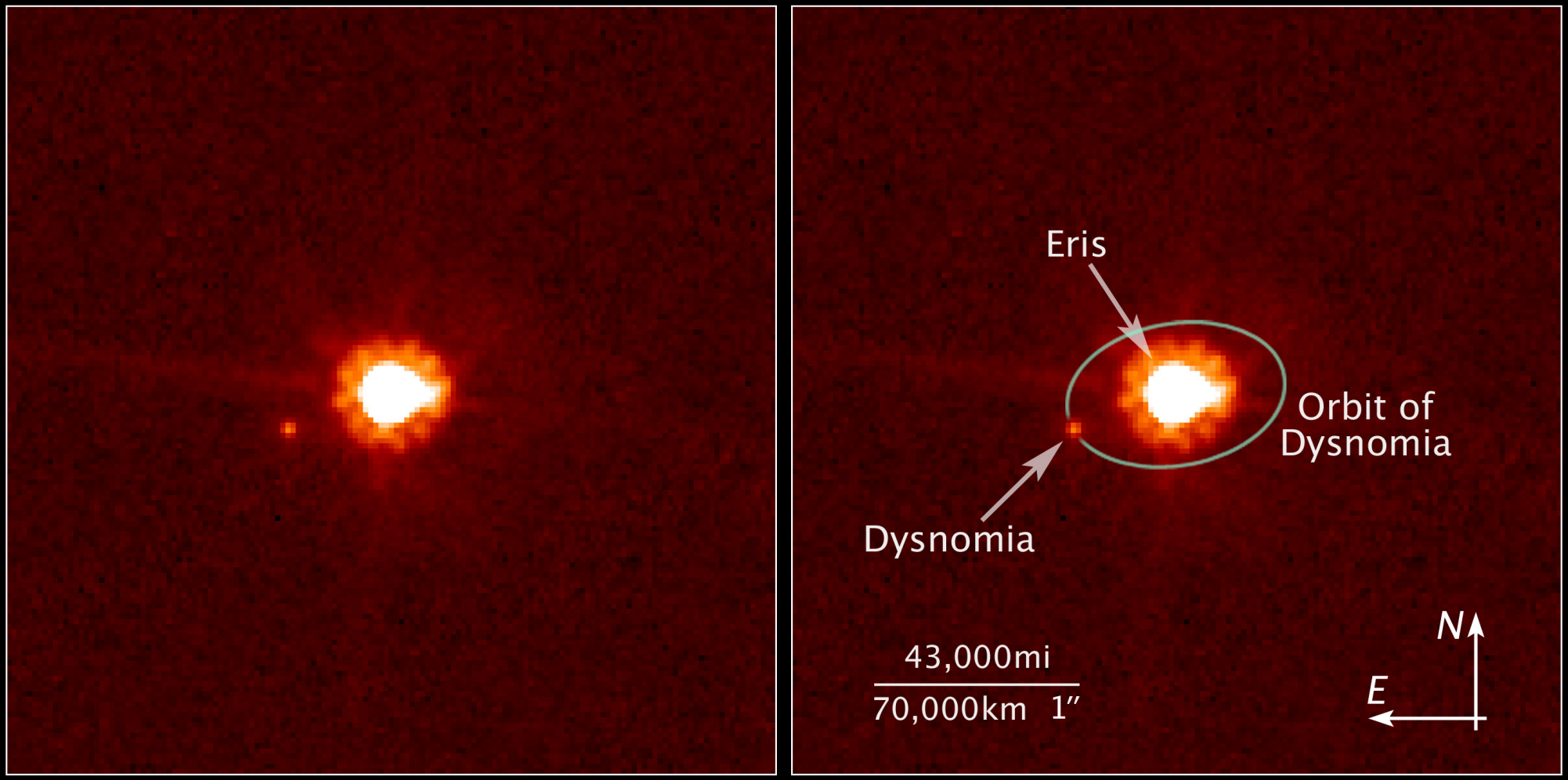


Orbit of Eris

(136199 Eris)

Perihelion: 37.77 AU
Aphelion: 97.56 AU
Eccentricity: 0.44
Inclination: 44°
Orbital period: 557 years

Wikipedia



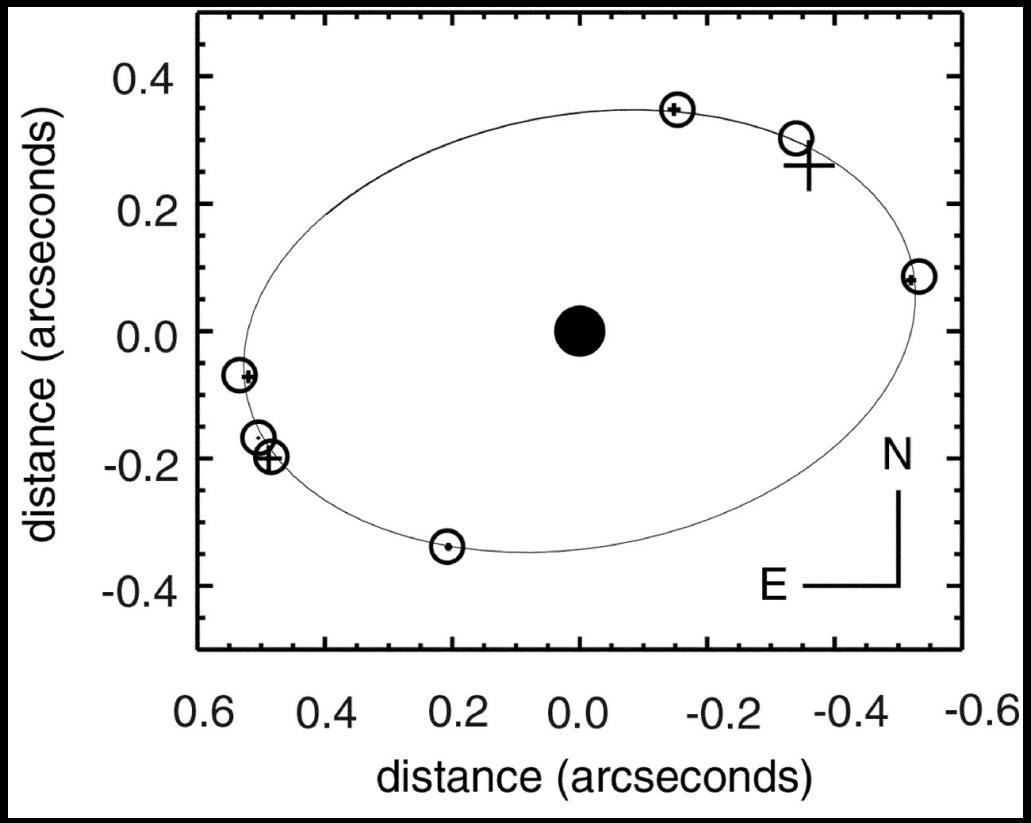
Dwarf Planet Eris and Satellite Dysnomia • August 30, 2006

Hubble Space Telescope • ACS/HRC

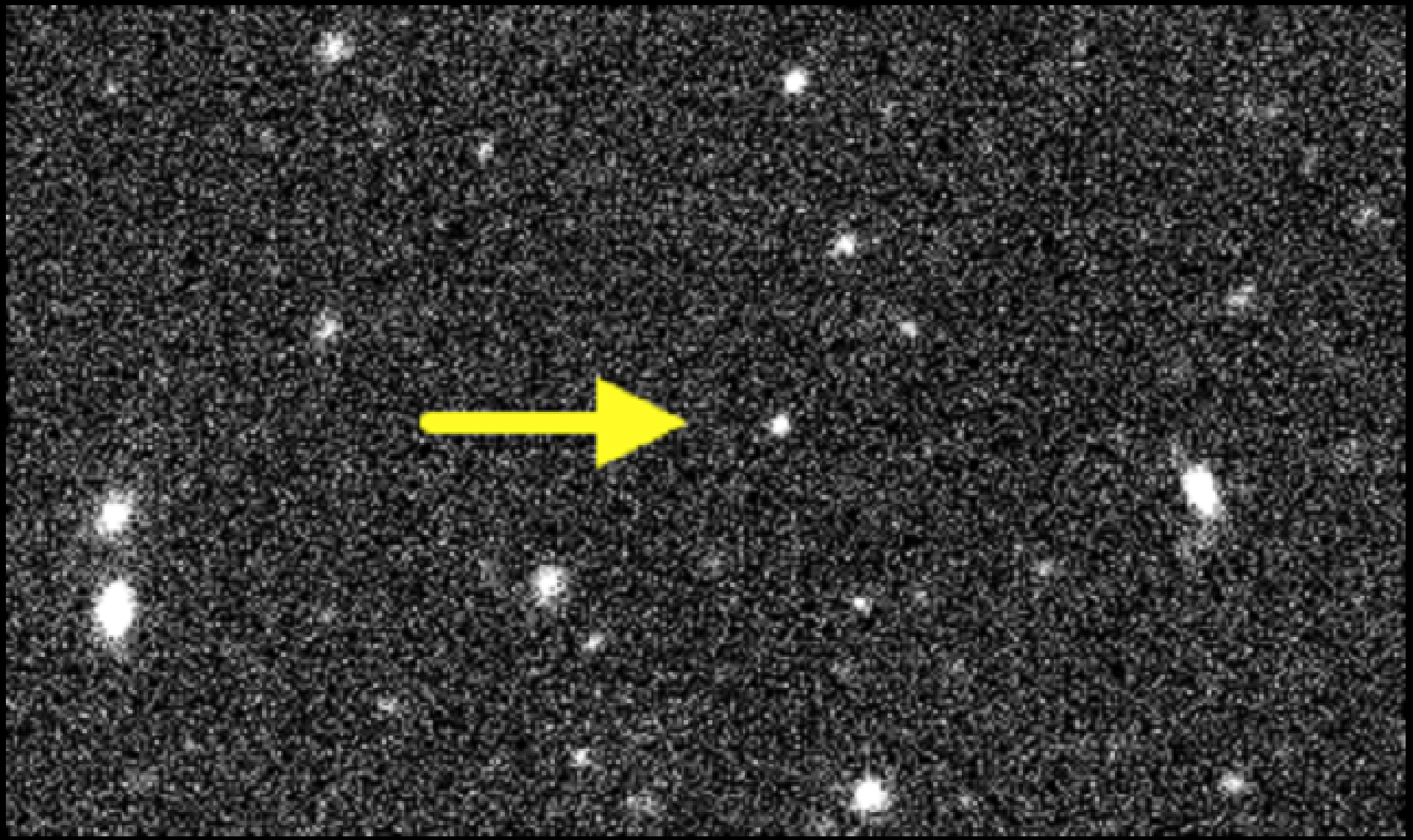
NASA, ESA, and M. Brown (California Institute of Technology)

STScI-PRC07-24

The orbit of Dysnomia around Eris:



- circular orbit
- Period $P = 15.773$ days
- Orbital radius: $R = 37400$ km
  (Brown & Schaller, Science Vol 316, 15 June 2007)

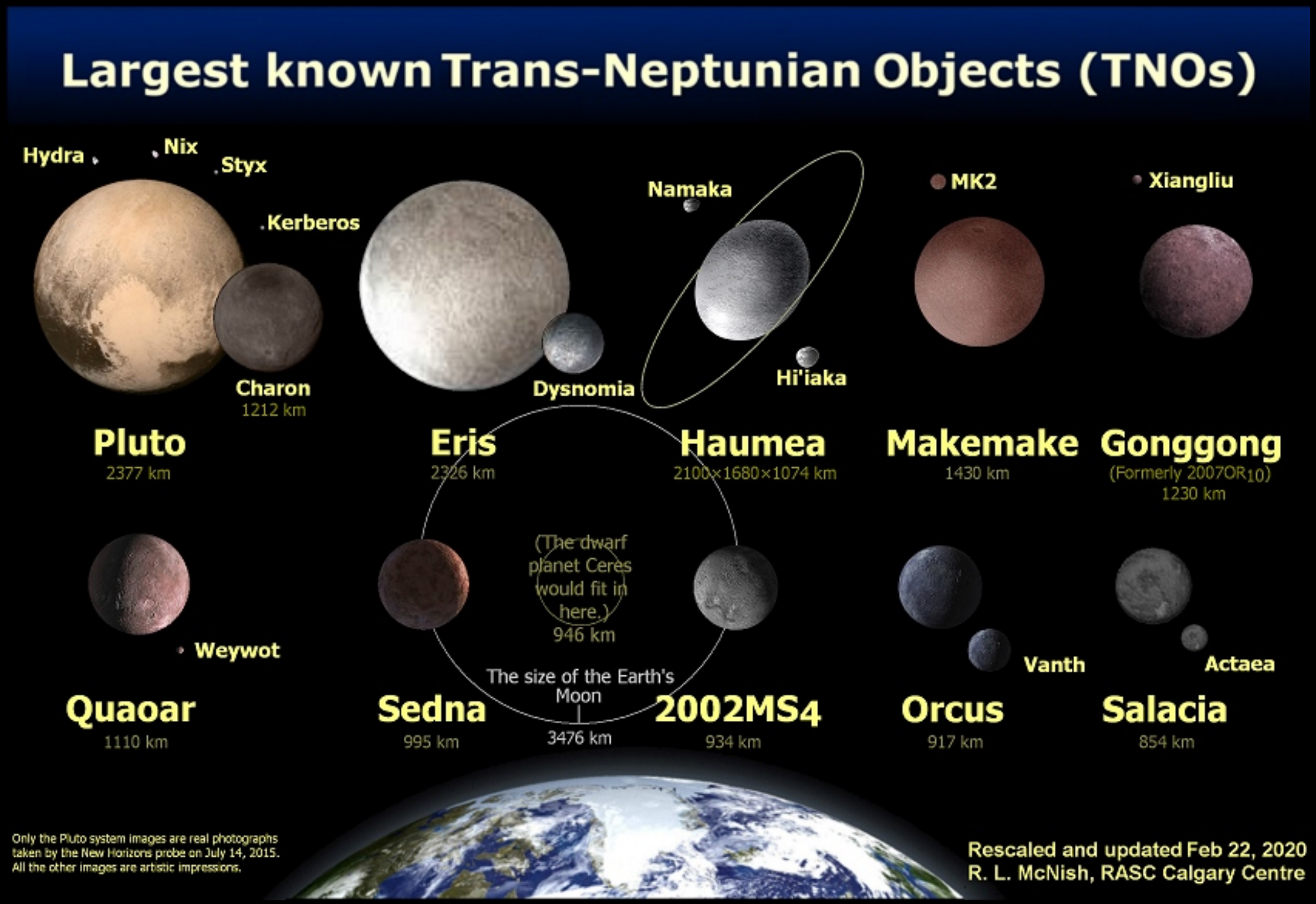


Subaru

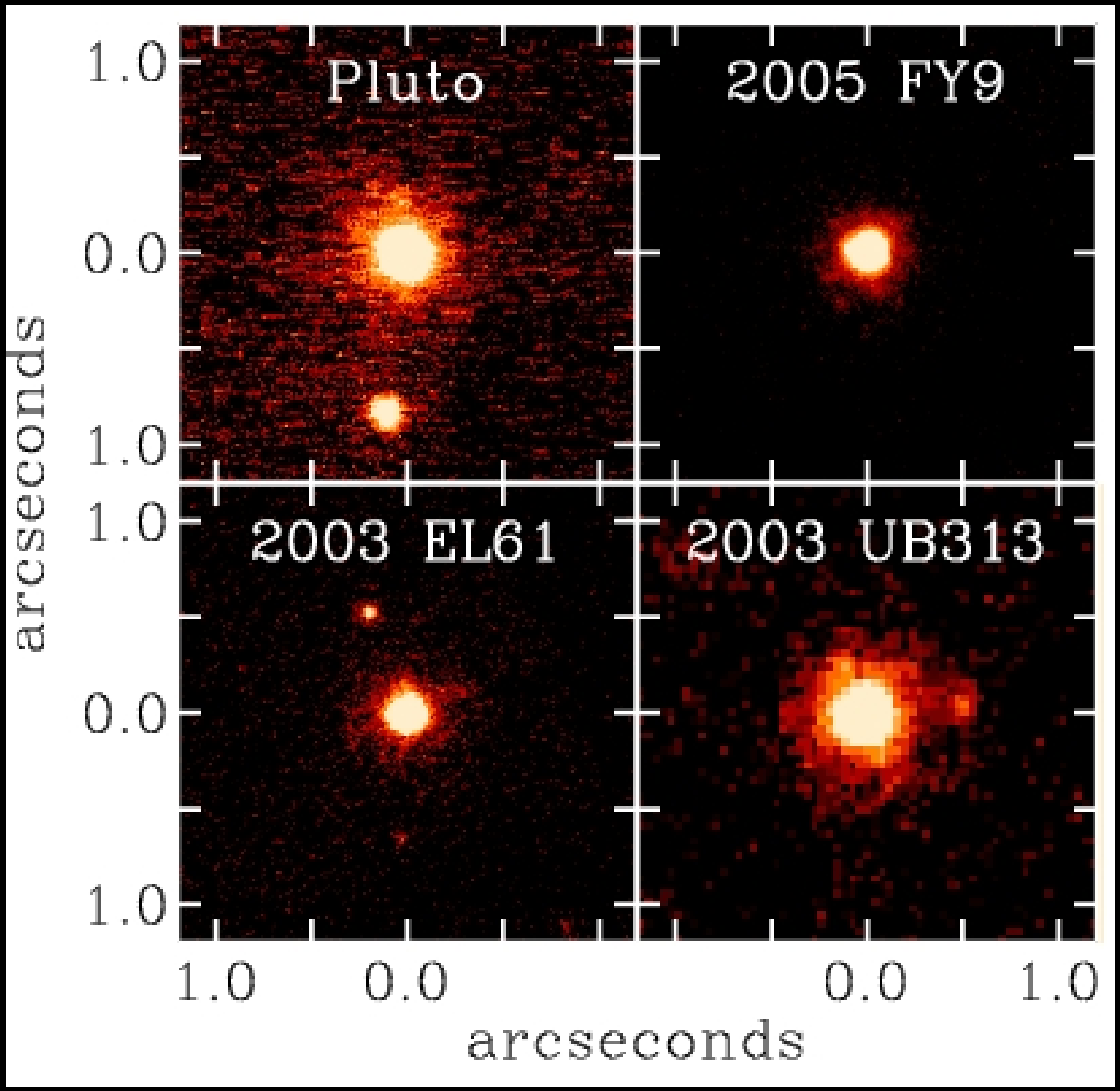
V774104

distance: 103 AU, diameter 500 km–1000 km

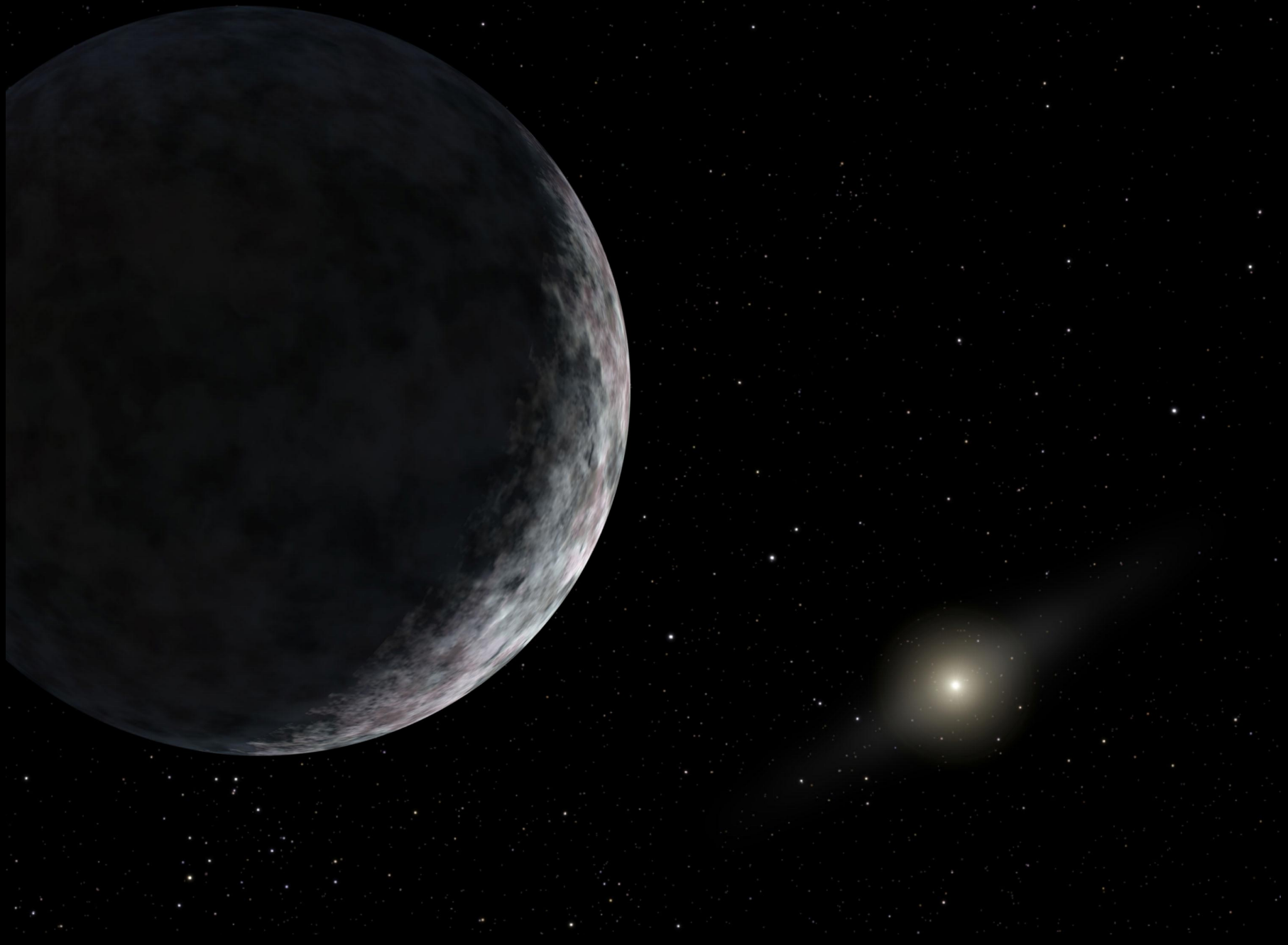
most distant solar system object!



today >4000 TNOs are known



Many dwarf planets have moons



Eris: View of the Solar System

(drawing courtesy M. Brown et al./NSF/NASA)

Measurement Methods and Coordinates

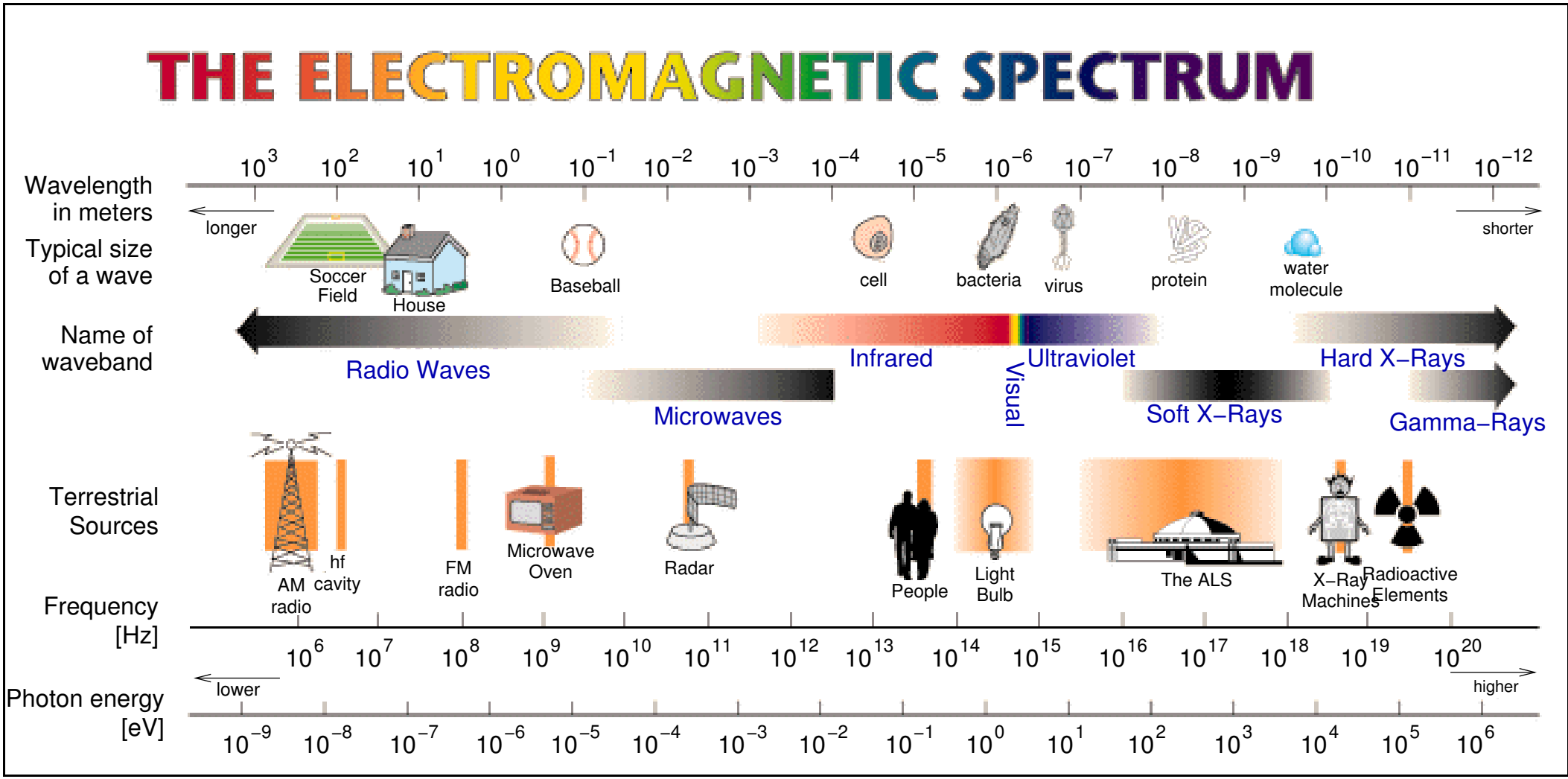
Introduction

We now move away from the solar system

$\Longrightarrow$ before we can continue with science, we need to understand

- where astronomical objects are $\Longrightarrow$ coordinate systems
- how astronomical measurements are made $\Longrightarrow$ telescopes

THE ELECTROMAGNETIC SPECTRUM



Electromagnetic Spectrum

As we all know, light can be characterized by

Wavelength: λ, measured in m, mm, cm, nm, Å.

Frequency: ν, measured in Hz, MHz.

Energy: E, measured in J, erg, Rydbergs, eV, keV, MeV, GeV.

These quantities are related:

$$\lambda\nu = c \qquad E = h\nu \tag{7.1}$$

where

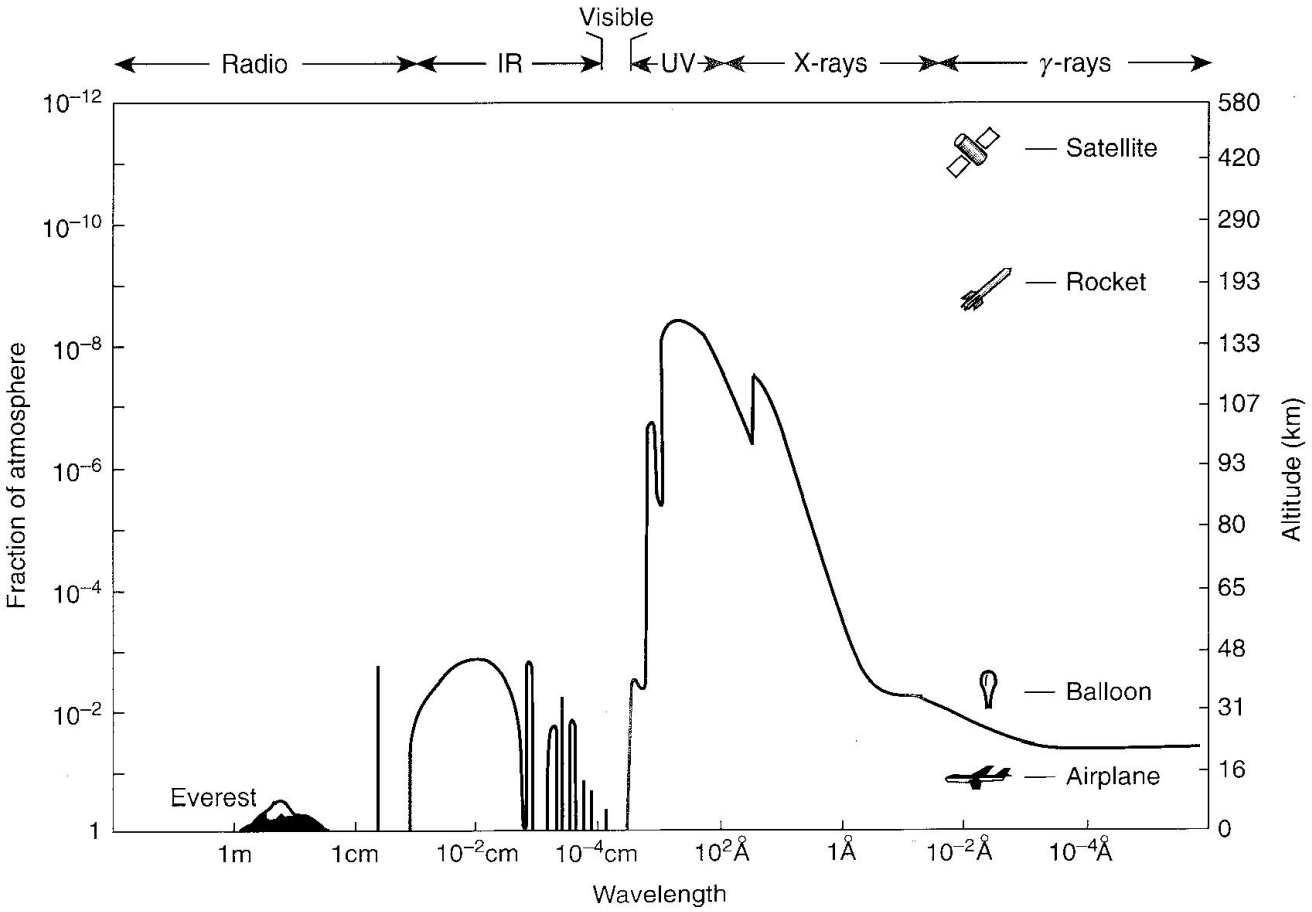
$$c = 299792458\,\mathrm{m\,s^{-1}} \tag{7.2}$$

$$h = 6.626070150 \times 10^{-34}\,\mathrm{J\,s} \tag{7.3}$$

(7.4)

Constants are the 2018 BIPM values and defined to be exact.

Earth's Atmosphere



Charles & Seward, Fig. 1.12

Earth's atmosphere is opaque for all types of EM radiation except for optical light and radio.

$\Longrightarrow$ Astronomy is today multi-wavelength astronomy, although optical studies are still very important

$\Longrightarrow$ For time reasons only optical telescopes will be discussed.

Introduction

Scientific purposes of a telescope:

1. Collect light, lots of light, to show faint objects ("Light bucket")
2. Resolve small features

Instrumentation used...

1. to make images
   $\Longrightarrow$ Imaging (Charge Coupled Devices [CCDs], earlier also with film)
2. to measure spectra
   $\Longrightarrow$ Spectrographs
3. to measure stellar brightness
   $\Longrightarrow$ Photometers (often CCDs, there are also dedicated photometers for msec-resolution photometry)

For physics of instrumentation $\longrightarrow$ Astronomy Laboratory

Types of Telescopes

To collect light, we have two possibilities:

1. Lenses: Refractors

   Disadvantage: lens cannot be supported from the back

   $\Longrightarrow$ limits max. diameter to $\lesssim 1\,\mathrm{m}$

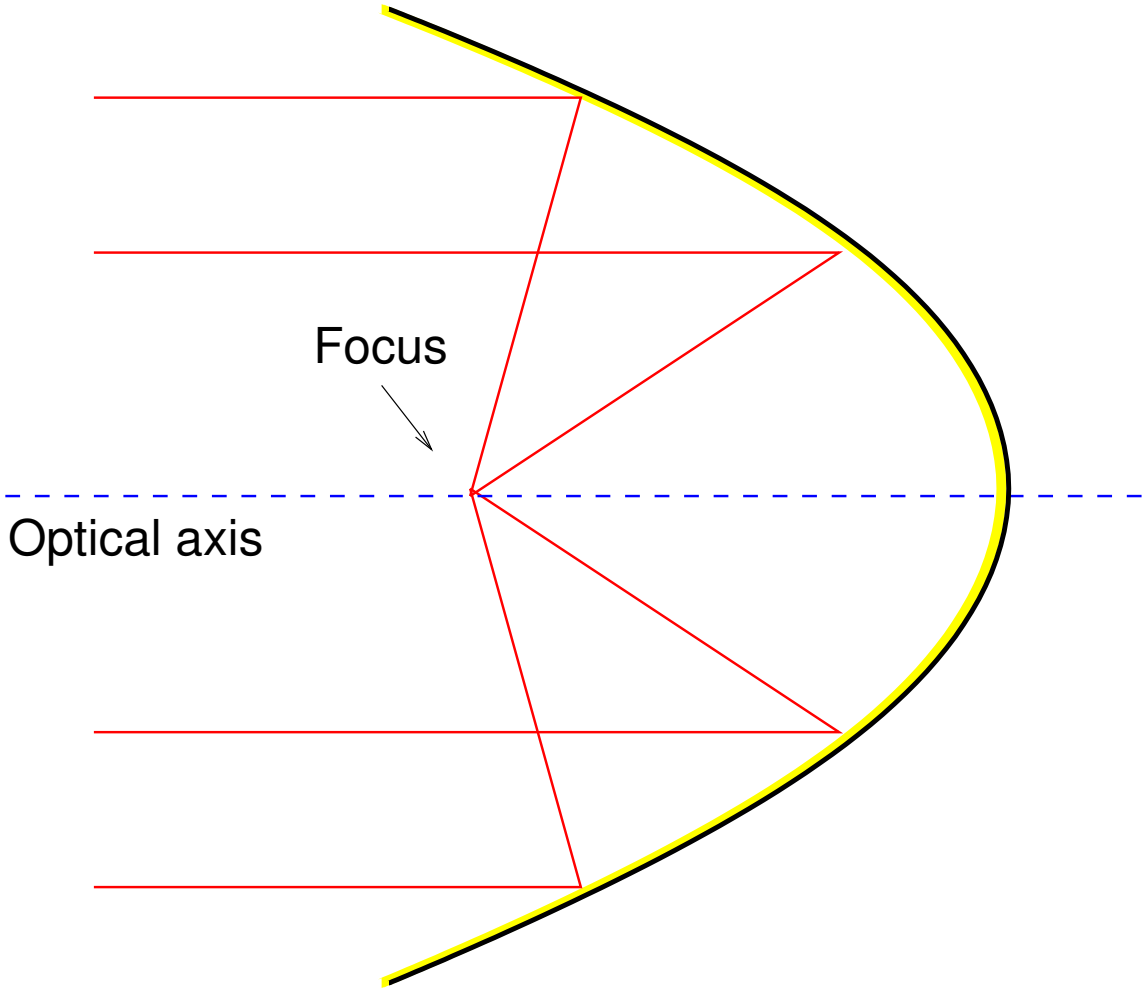
   largest refractor at Yerkes Observatory (University of Chicago): $\mathrm{d} = 1.02\,\mathrm{m}$

   $\Longrightarrow$ not of interest for science

2. Mirrors: Reflectors

   Mirrors can be supported, instrument of choice for today, with diameters up to 11 m

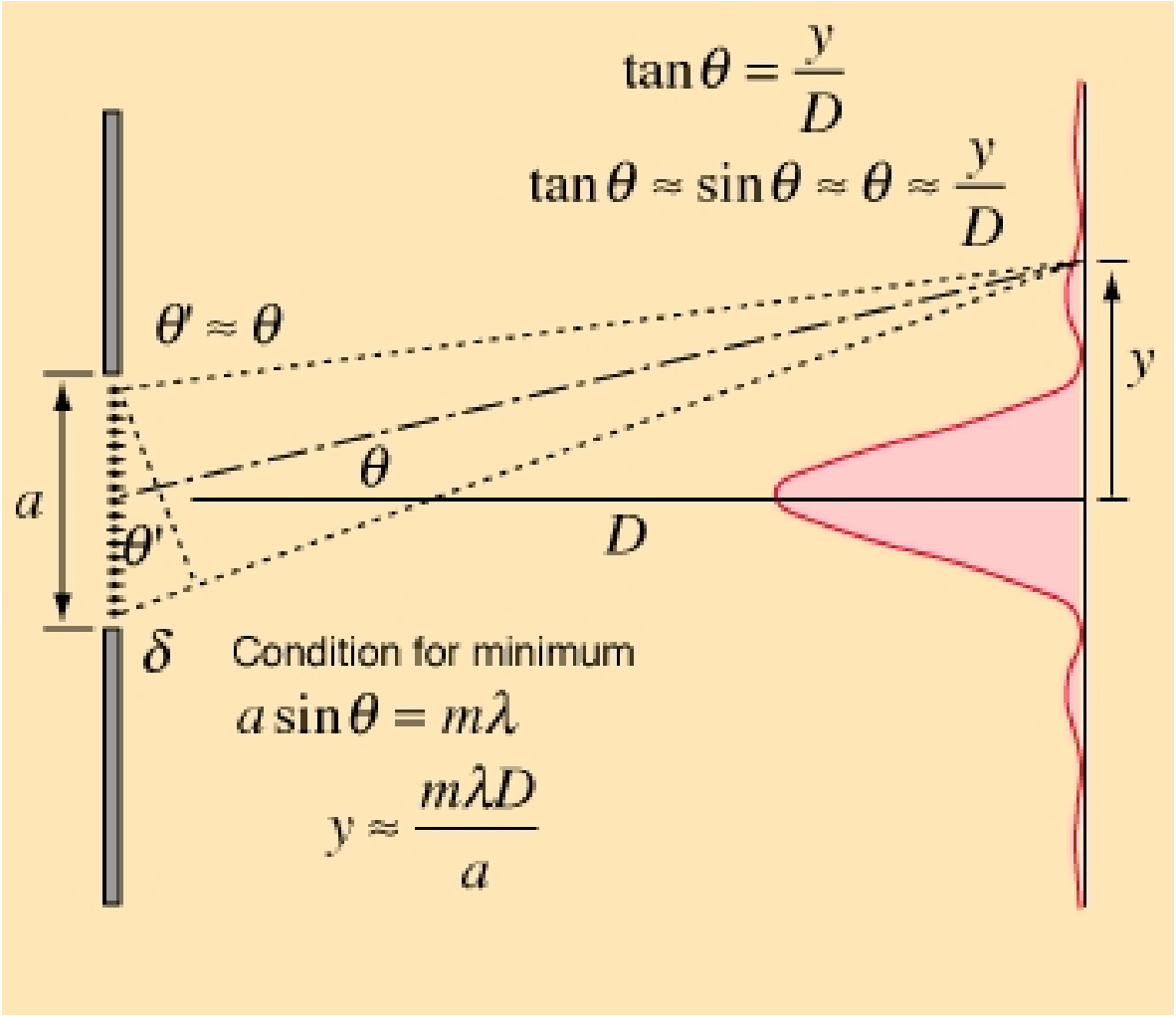
Types of Telescopes



To form image: focus light with a parabolic mirror

Spherical mirrors show spherical aberration
$\Longrightarrow$ *not* suited for astronomical telescopes (at least not without correction).

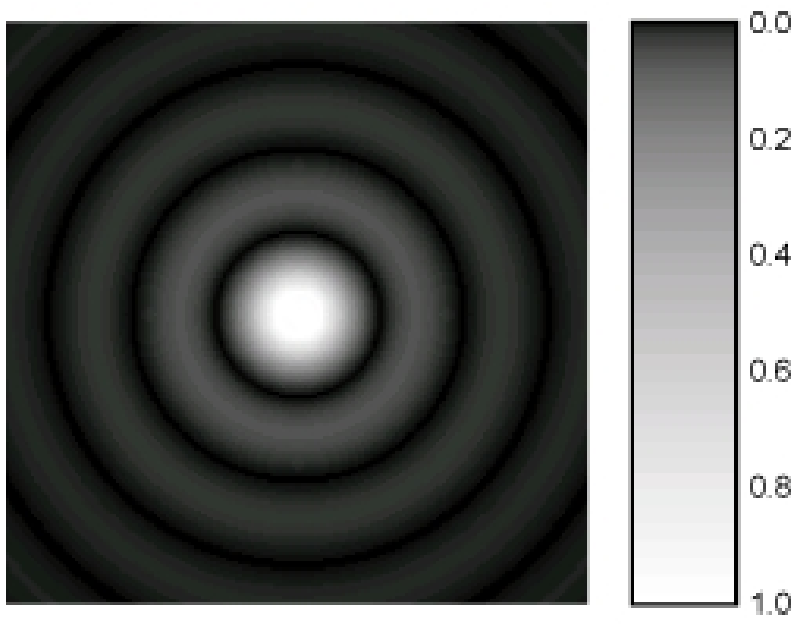
Resolution



GSU

Wave nature of light results in interference pattern caused by diffraction on optical elements in telescope (mainly aperture).

Resolution



Diffraction pattern on telescope aperture: Airy pattern

For a circular aperture with radius r:

$$I(\theta) \propto \pi^2 r^4 \left[\sum_{n=0}^{\infty} (-1)^n \frac{1}{n+1}\left(\frac{m^n}{n!}\right)^2\right]^2 \propto \frac{\pi^2 r^4}{m^2}\left(J_1(2m)\right)^2 \tag{7.5}$$

where $m = \pi(r/\lambda)\sin\theta$ and where $J_1(x)$ s the Bessel function of the first kind of order unity.

$I(\theta)$ has minima for $m = 1.916, 3.508, 5.087, \ldots$, or

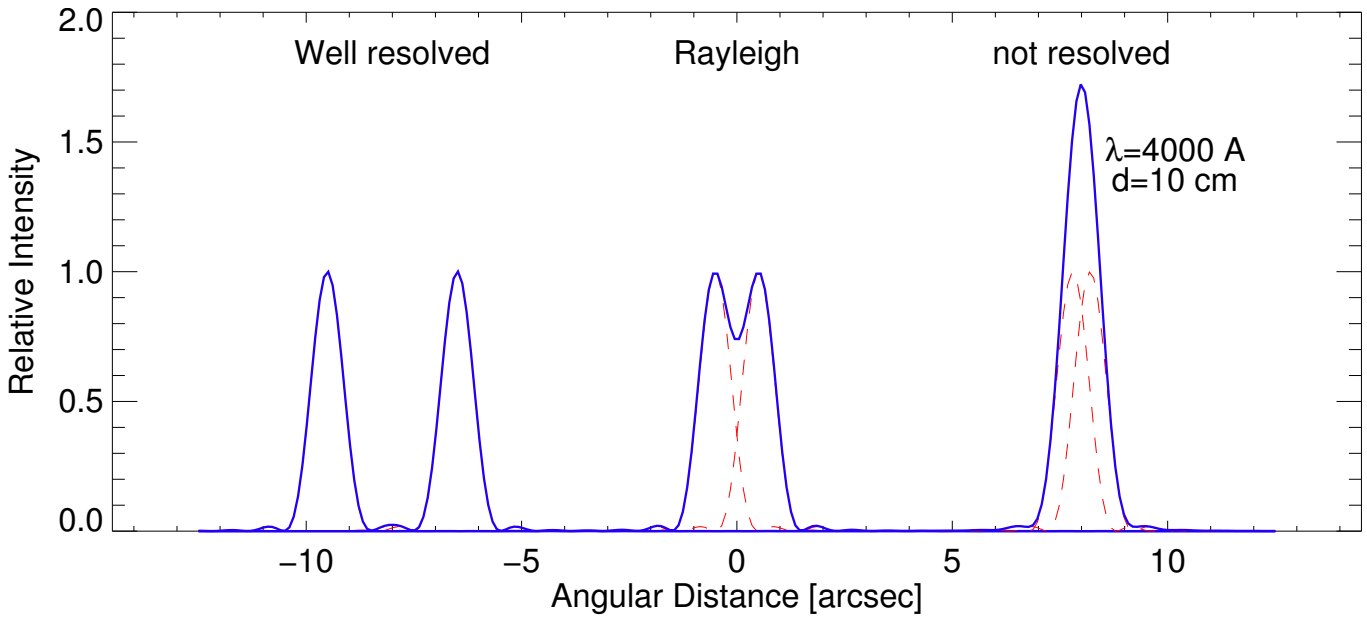
$$\sin\theta = \frac{1.916\lambda}{\pi r}, \frac{3.508\lambda}{\pi r}, \frac{5.087\lambda}{\pi r}, \ldots \tag{7.6}$$

or for θ small ($\sin\theta \sim \theta$) minima are found at:

$$\theta = \frac{1.220\lambda}{d}, \ldots \tag{7.7}$$

where d: diameter.

Resolution



Resolution of telescope: ability to separate two (point-like) light sources

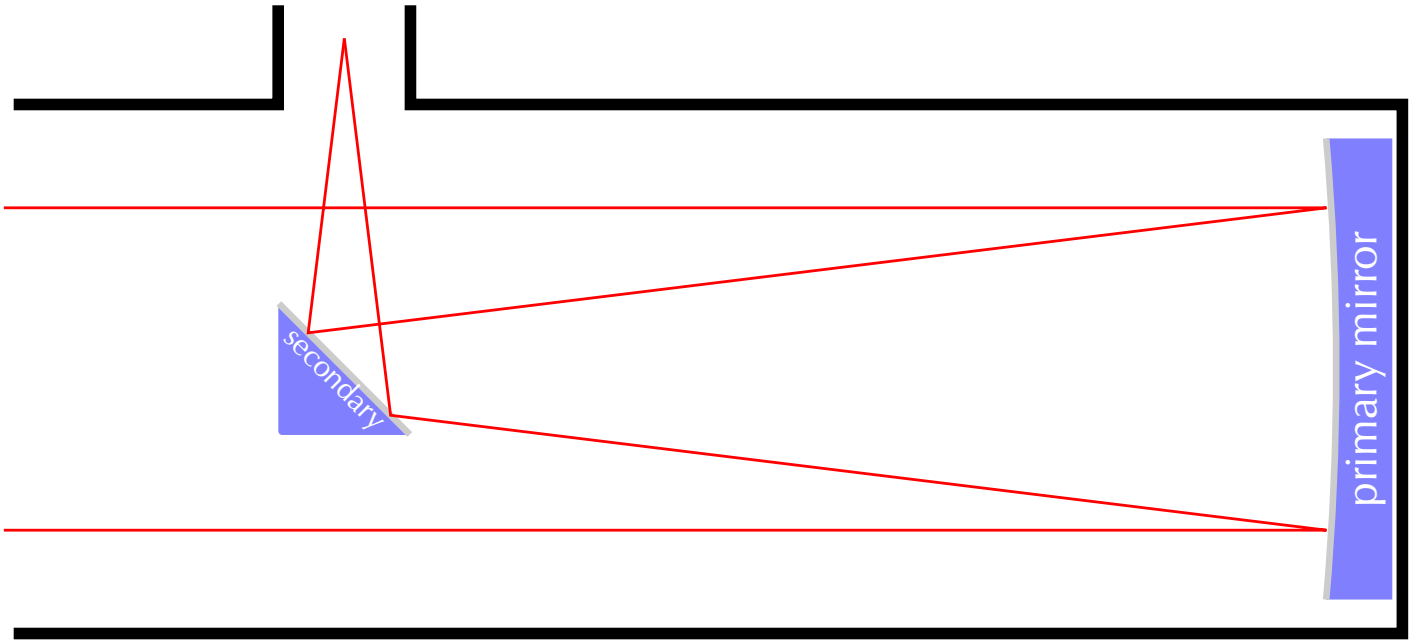
Rayleigh criterion for resolution: maximum of diffraction pattern of one source must fall into minimum of diffraction pattern of other source.

Therefore the diffraction limited resolution is

$$\alpha = \frac{1.220\lambda}{d} = \frac{12''}{D/1\,\mathrm{cm}} \quad \text{for optical light} \tag{7.8}$$

Note: Rayleigh criterion is a criterion, *not* a law. Detailed object separability depends on ratio of intensities of two objects, in practice resolutions up to $3\times$ smaller are achievable.

Newtonian Telescope

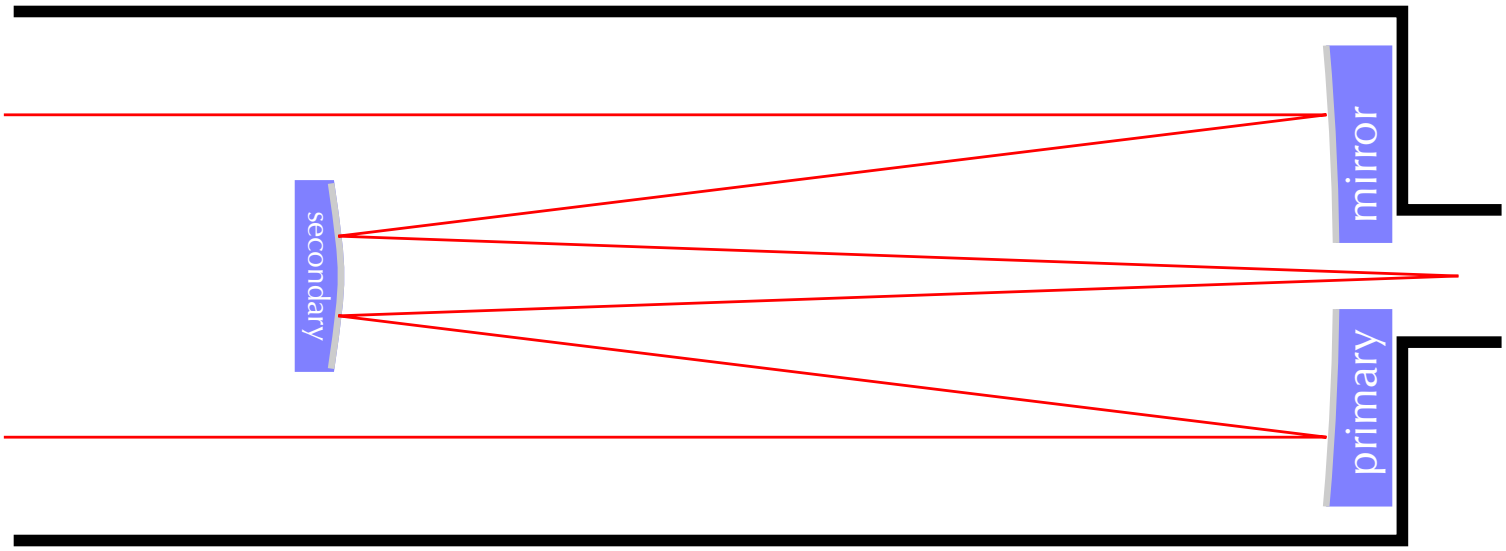


Newtonian telescope: reflector with parabolic mirror.

Common in cheaper telescopes.

Disadvantage: large size (~ focal length)

Cassegrain Telescope



Cassegrain telescope: reflector with “folded optical path”

(primary: paraboloid, secondary: hyperboloid)

$\Longrightarrow$ Much shorter than Newtonian

$\Longrightarrow$ Telescope of choice for modern instruments

Schmidt Telescope



Bernhard Schmidt (Hamburg)
http://www.sky-win.de/

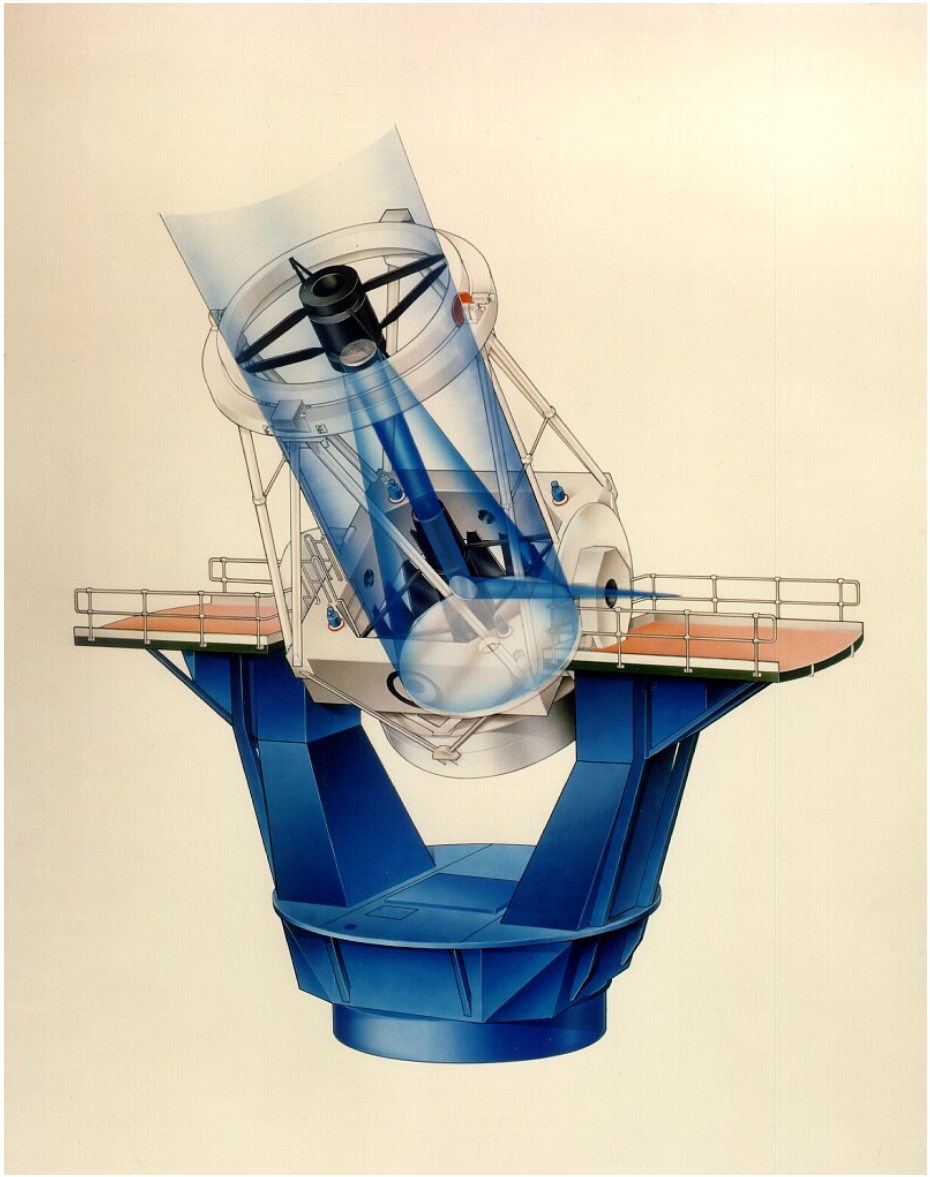


2m Schmidt telescope at the Landesternwarte Thüringen in Tautenburg near Jena:
largest Schmidt telescope in the world.

Uses spherical mirror for larger field view, correction plate used to correct for spherical aberration.

Many amateur telescopes are combination of Schmidt telescope and Cassegrain telescope
$\Longrightarrow$ Schmidt-Cassegrain telescopes.

Schmidt Telescope



Nasmyth Focus:

light reflected through axis

- ideal for modern azimutal mountings

  e.g., European Southern Observatory's Very Large Telescope

- two stationary platforms
- can host large instruments
- very stable

William Herschel Telescope, La Palma

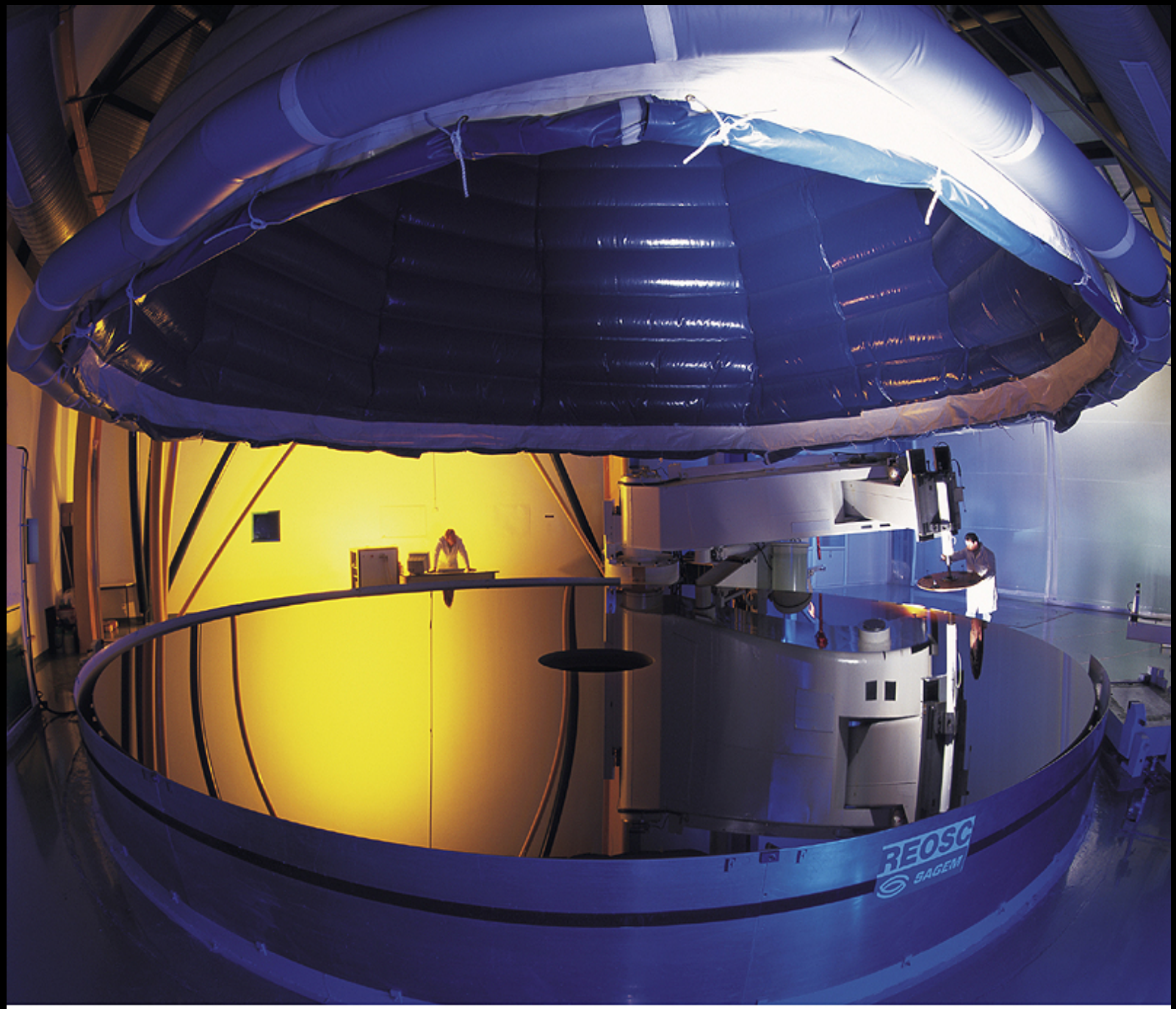

© J. Wilms



Example: Building of the European Southern Observatory's Very Large Telescope



ESO



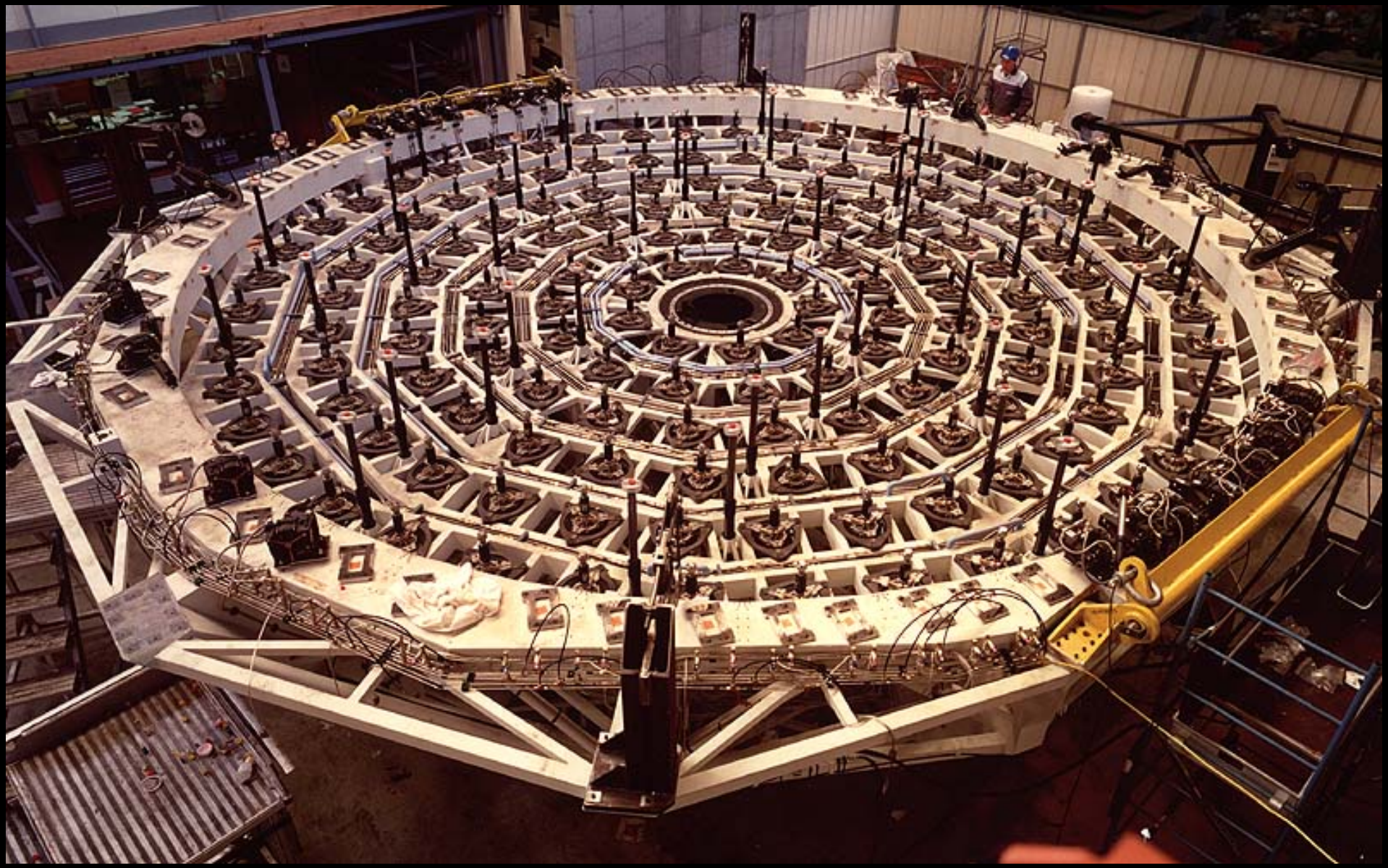
The Polished Fourth VLT 8.2-m Mirror at REOSC

Photo: SAGEM

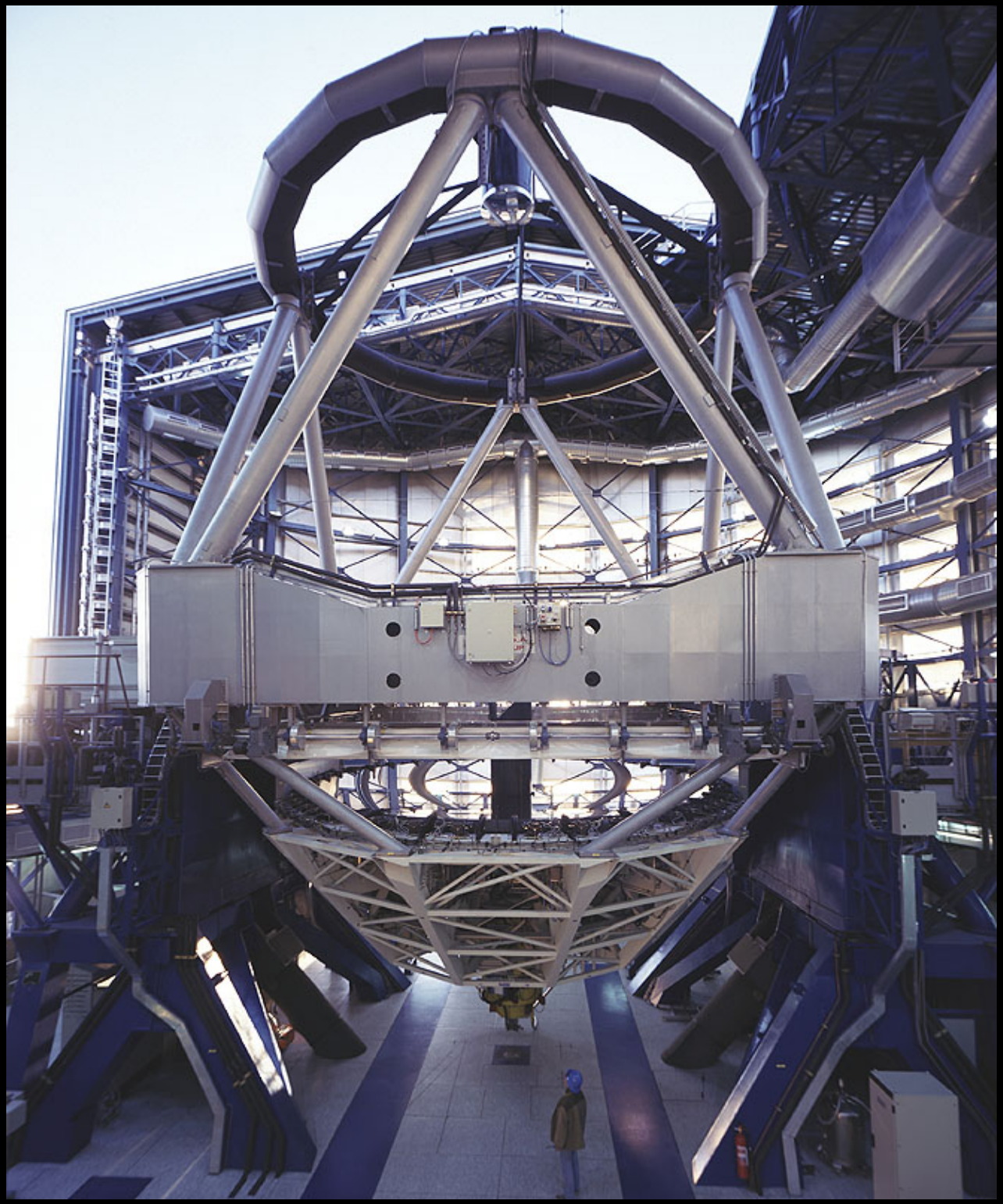
ESO PR Photo 44/99 (14 December 1999)

European Southern Observatory


VERY
LARGE
TELESCOPE
REOSC
GOODRUND
GOODRUND
REOSC
GOODRUND



Mirror cell supporting the mirror, actuators keep mirror in shape ("active optics", correcting all possible deformations of the mirror).





VLT at Paranal

ESO PR Photo 43a/99 (8 December 1999)

© European Southern Observatory

Adaptive Optics

From Eq. 7.8, the resolution of a telescope of diameter d is

$$\alpha = \frac{1.220\lambda}{d} = \frac{12''}{D/1\,\mathrm{cm}} \tag{7.8}$$

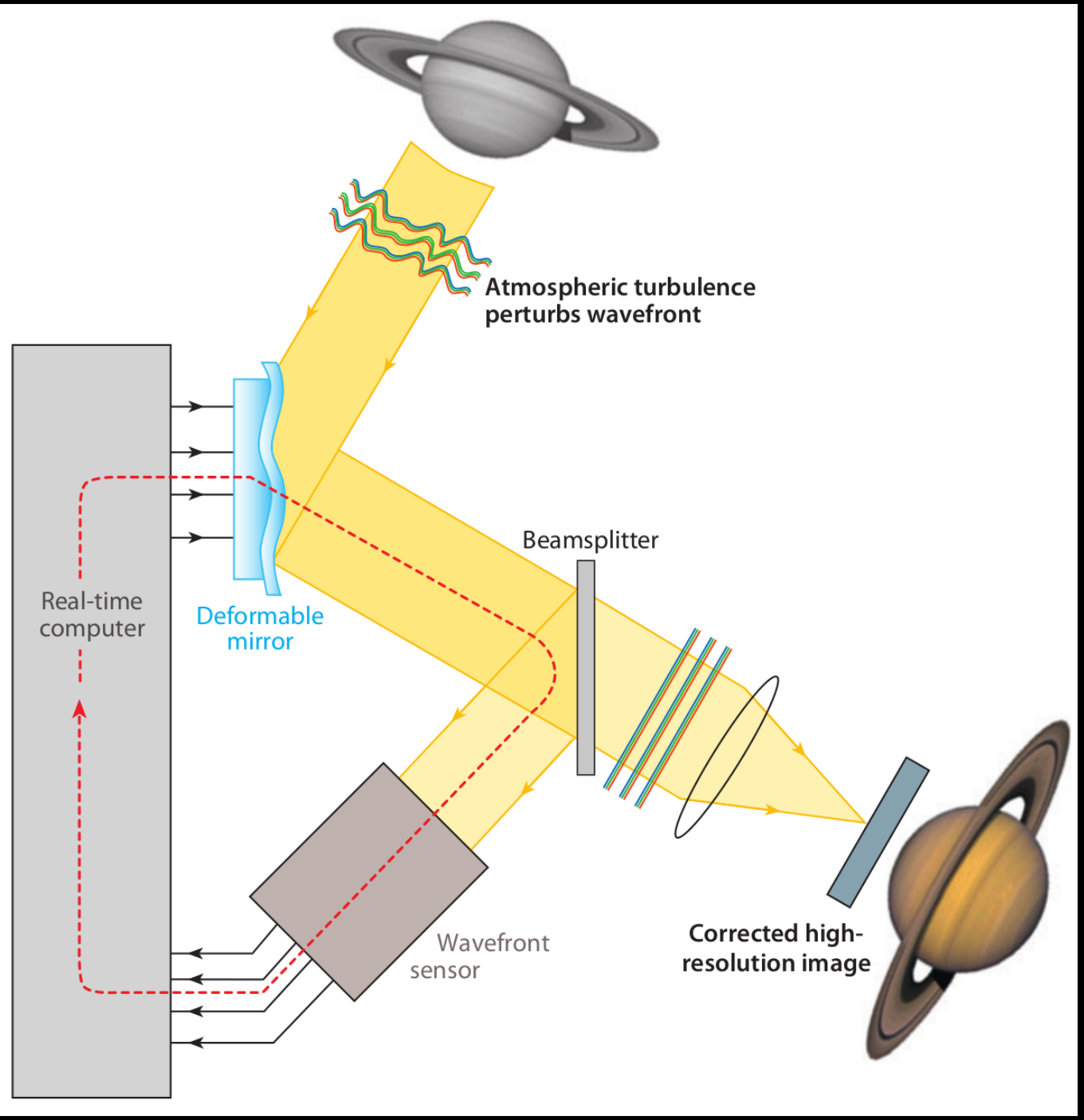
Problem: astronomical seeing

$\Longrightarrow$ turbulence in atmosphere smears pictures of stars to disks with $\theta \gtrsim 0.3''$

$\Longrightarrow$ Increasing telescope diameter to $\gtrsim$40 cm does *not* result in increase in resolution!

Solution to seeing problem: adaptive optics

. . . which only works in the IR so far, need to go to space for optical and UV



Schematic principle of an adaptive optics system

(Davies & Kasper, 2012, ARAA 50, 305 and Sterne und Weltraum/S. Hippler)



The AO system of Mt. Hopkins observatory, a 30 W laser (©G. Furesz).



The AO system of Mt. Hopkins observatory, a 30 W laser (©G. Furesz).



AO on the ESO-VLT

Adaptive Optics



Gemini North/AURA

Picture of the galactic center in the IR taken with the Gemini North

Adaptive Optics



Gemini North/AURA

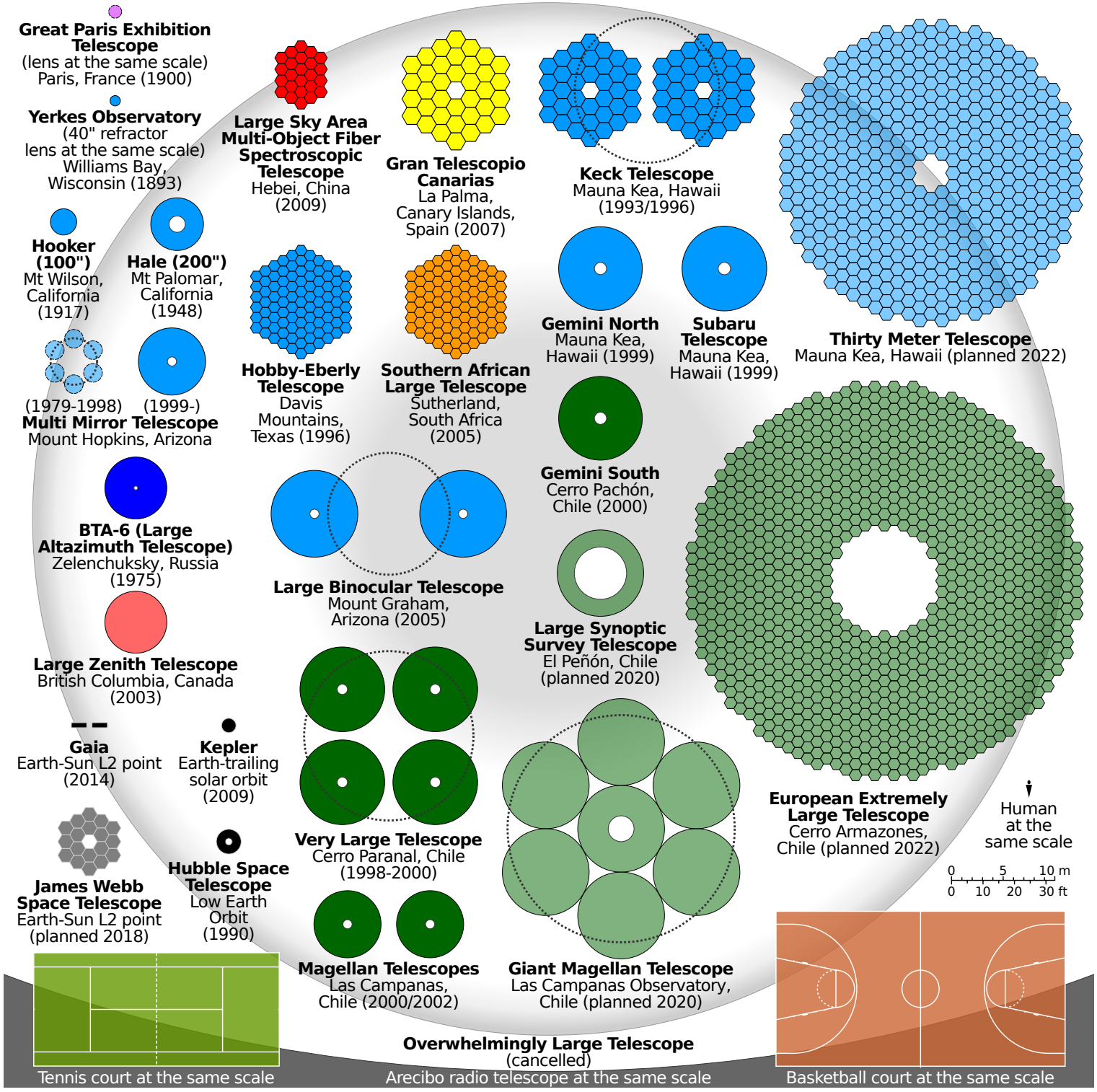
Picture of the galactic center in the IR taken with the Gemini North

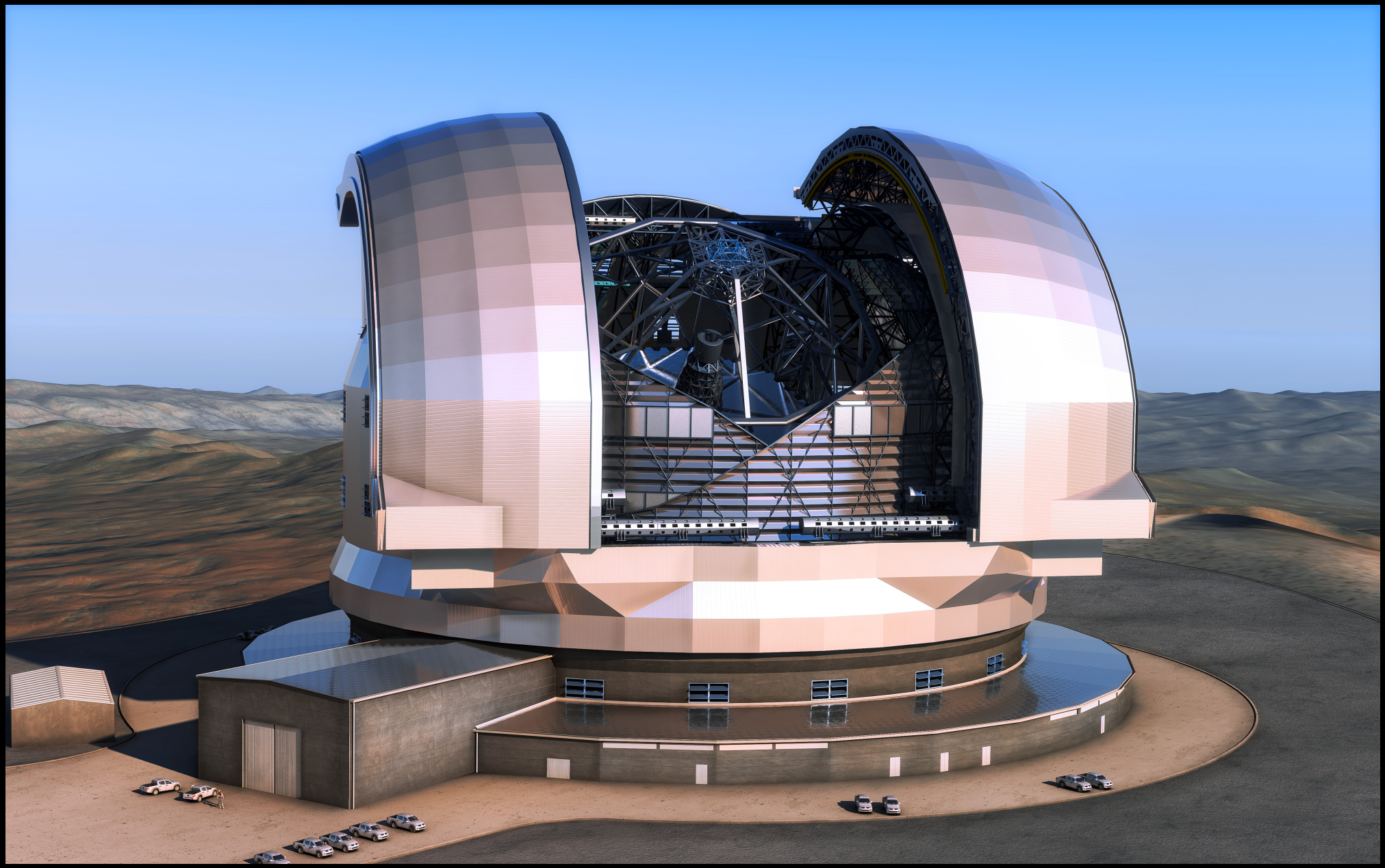
...and corrected with adaptive optics

$\Longrightarrow$ Resolution: diffraction limited!

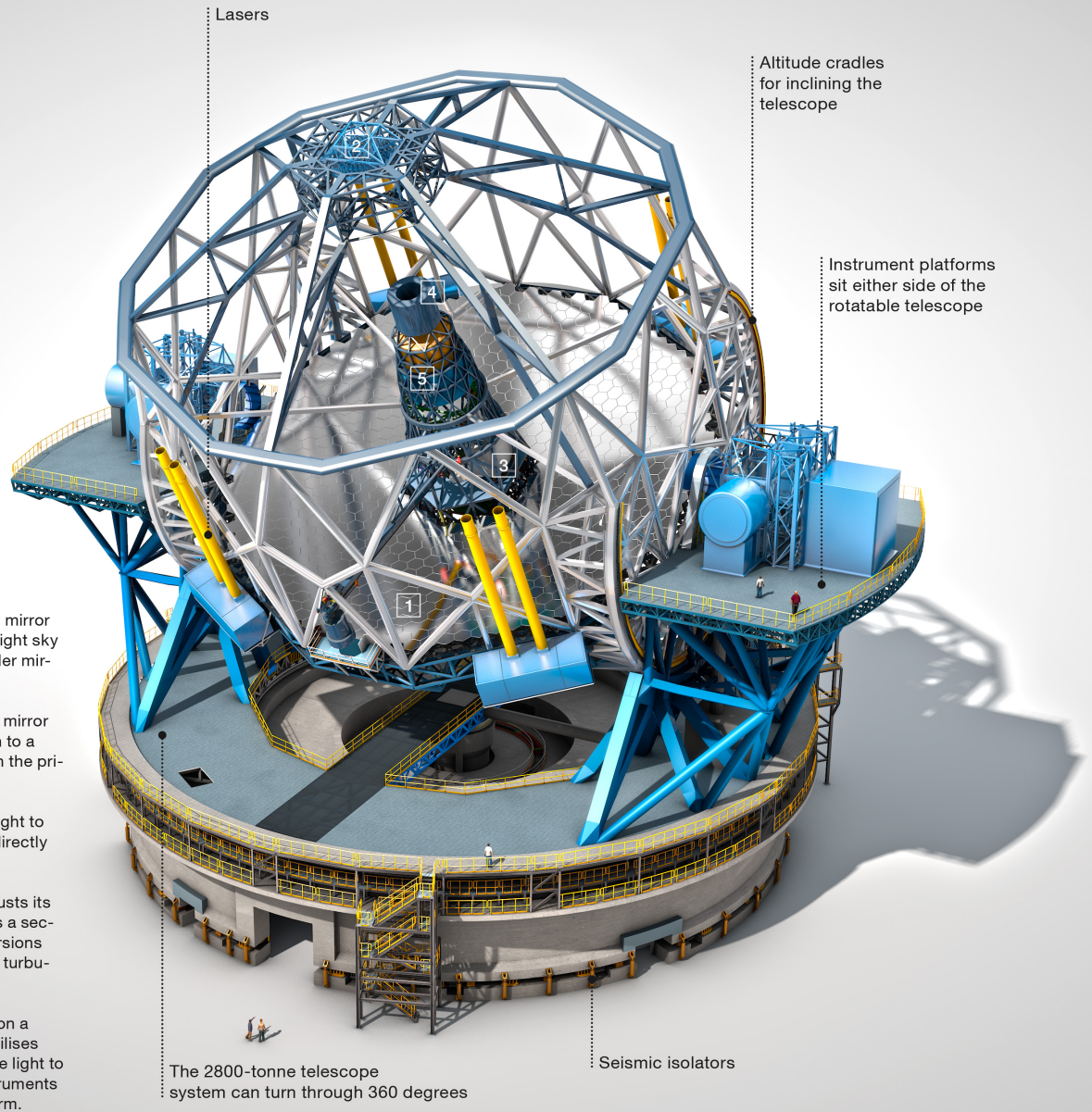
$$\theta = 1.22\,\text{rad} \cdot \lambda/d \sim 70\,\text{mas} \quad (7.9)$$

(for $d = 8\,\text{m}$, $\lambda = 2.2\,\mu\text{m}$)


Great Paris Exhibition Telescope
(lens at the same scale)
Paris, France (1900)
Yerkes Observatory
(40" refractor
lens at the same scale)
Williams Bay,
Wisconsin (1893)
Large Sky Area Multi-Object Fiber Spectroscopic Telescope
Hebei, China
(2009)
Gran Telescopio Canarias
La Palma,
Canary Islands,
Spain (2007)
Keck Telescope
Mauna Kea, Hawaii
(1993/1996)
Thirty Meter Telescope
Mauna Kea, Hawaii (planned 2022)
Hooker (100")
Mt Wilson,
California
(1917)
Hale (200")
Mt Palomar,
California
(1948)
Hobby-Eberly Telescope
Davis
Mountains,
Texas (1996)
Southern African Large Telescope
Sutherland,
South Africa
(2005)
Gemini North
Mauna Kea,
Hawaii (1999)
Subaru Telescope
Mauna Kea,
Hawaii (1999)
(1979-1998)
(1999-)
Multi Mirror Telescope
Mount Hopkins, Arizona
Gemini South
Cerro Pachón,
Chile (2000)
BTA-6 (Large Altazimuth Telescope)
Zelenchuksky, Russia
(1975)
Large Binocular Telescope
Mount Graham,
Arizona (2005)
Large Synoptic Survey Telescope
El Peñón, Chile
(planned 2020)
Large Zenith Telescope
British Columbia, Canada
(2003)
Gaia
Earth-Sun L2 point
(2014)
Kepler
Earth-trailing
solar orbit
(2009)
European Extremely Large Telescope
Cerro Armazones,
Chile (planned 2022)
Human at the same scale
0 5 10 m
0 10 20 30 ft
Very Large Telescope
Cerro Paranal, Chile
(1998-2000)
James Webb Space Telescope
Earth-Sun L2 point
(planned 2018)
Hubble Space Telescope
Low Earth
Orbit
(1990)
Magellan Telescopes
Las Campanas,
Chile (2000/2002)
Giant Magellan Telescope
Las Campanas Observatory,
Chile (planned 2020)
Overwhelmingly Large Telescope
(cancelled)
Tennis court at the same scale
Arecibo radio telescope at the same scale
Basketball court at the same scale



The future: The European Extremely Large Telescope (E-ELT).
39 m diameter on Cerro Armazones in Chile (3060 m altitude)
Construction started 2014 June. First light expected 2024.



Five-mirror design

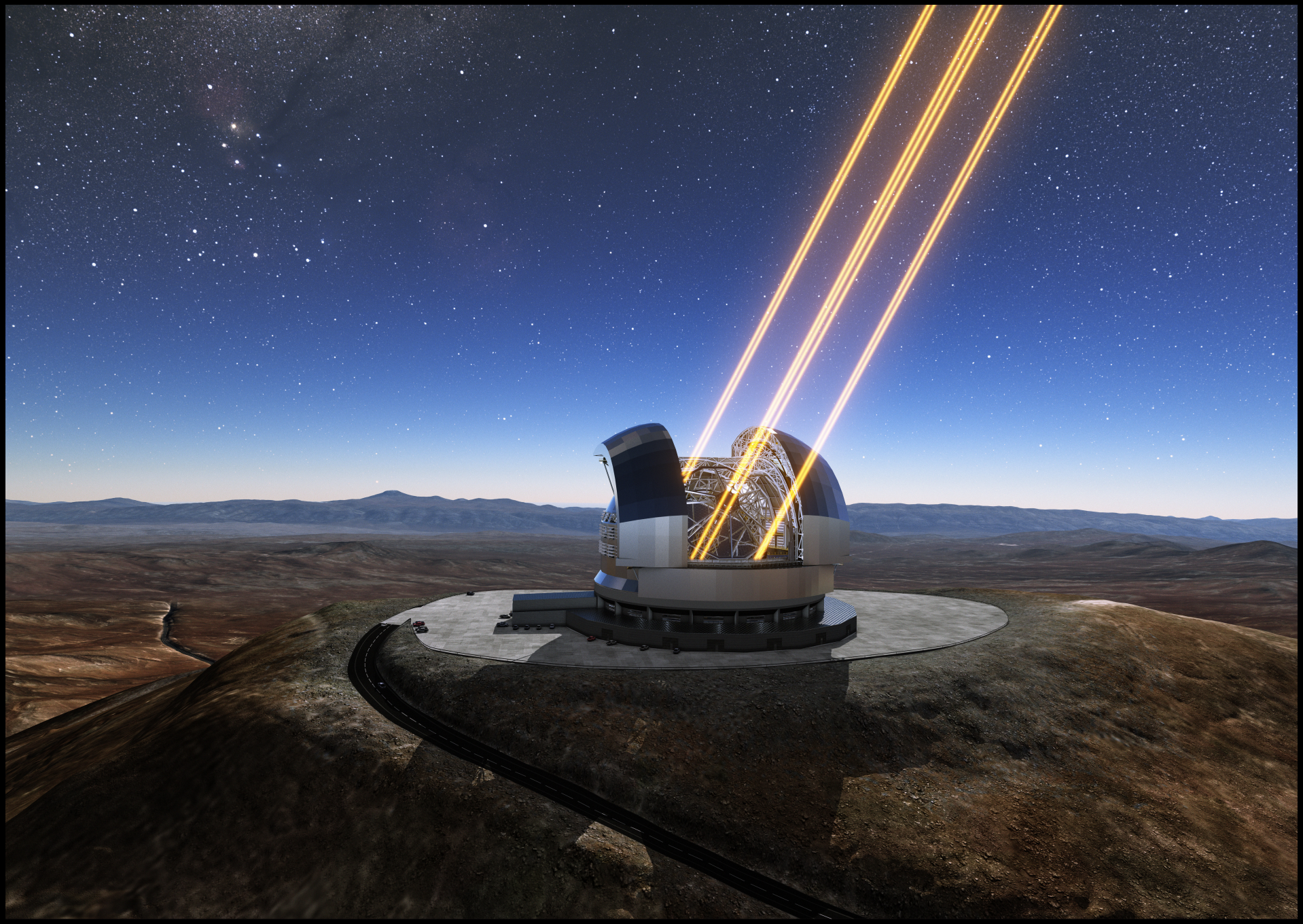
1. The 39.3-metre primary mirror collects light from the night sky and reflects it to a smaller mirror located above it.

2. The 4-metre secondary mirror reflects light back down to a smaller mirror nestled in the primary mirror.

3. The third mirror relays light to an adaptive flat mirror directly above.

4. The adaptive mirror adjusts its shape a thousand times a second to correct for distorsions caused by atmospheric turbulence.

5. A fifth mirror, mounted on a fast-moving stage, stabilises the image and sends the light to cameras and other instruments on the stationary platform.





Status 2014 December



Status 2018 December

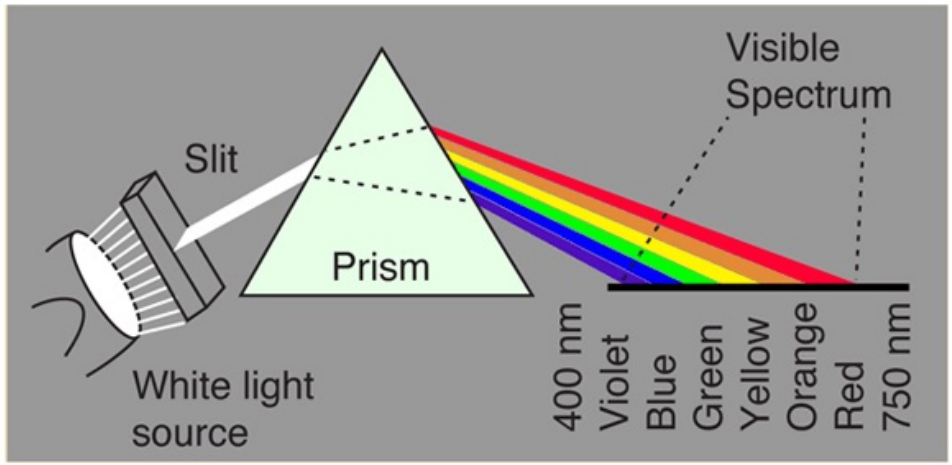


Status 2022 December 05



Status 2022 December 05

Spectroscopy

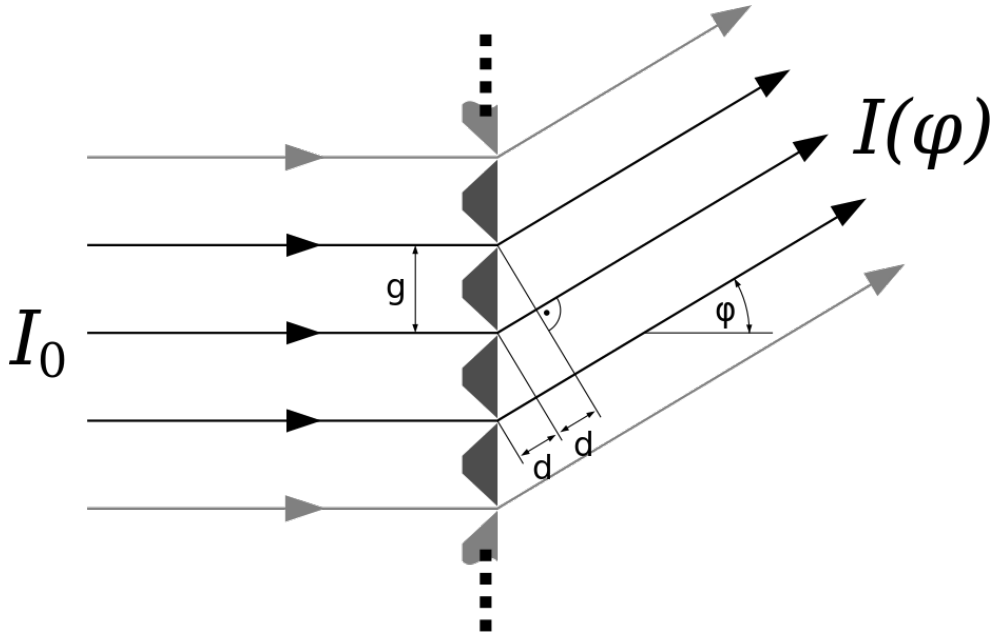


http://hyperphysics.phy-astr.gsu.edu/hbase/vision/specol.html

Light: Superposition of waves with different wavelengths.
Disassemble light into its spectrum (for different wavelength, i.e., colors).
Dispersion: change of physical parameter in dependence of wavelength (or frequency).
Detect the diffracted light.

Prisms are usually not used in Astronomy.

Spectroscopy



Wikipedia

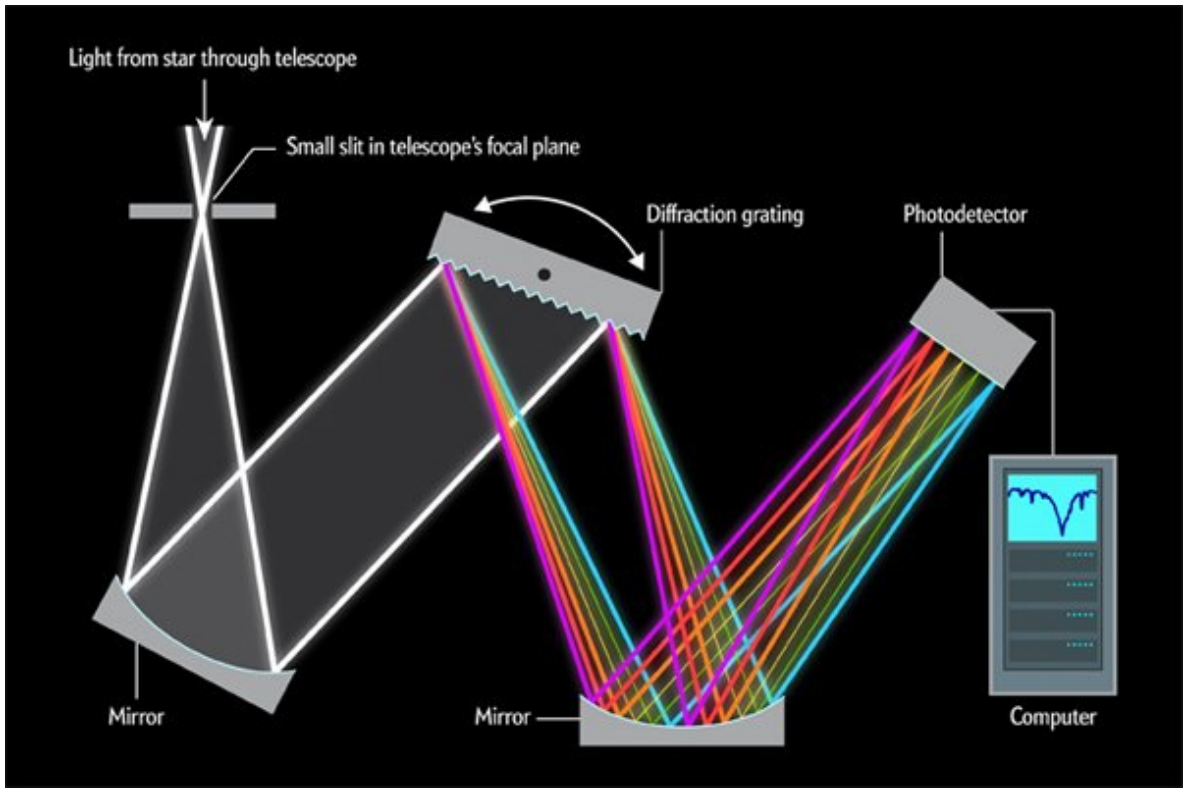
Transmission grating:

Constructive interference at

$$\sin\phi = \frac{m\lambda}{g}, m = \pm 1, \pm 2, ...$$

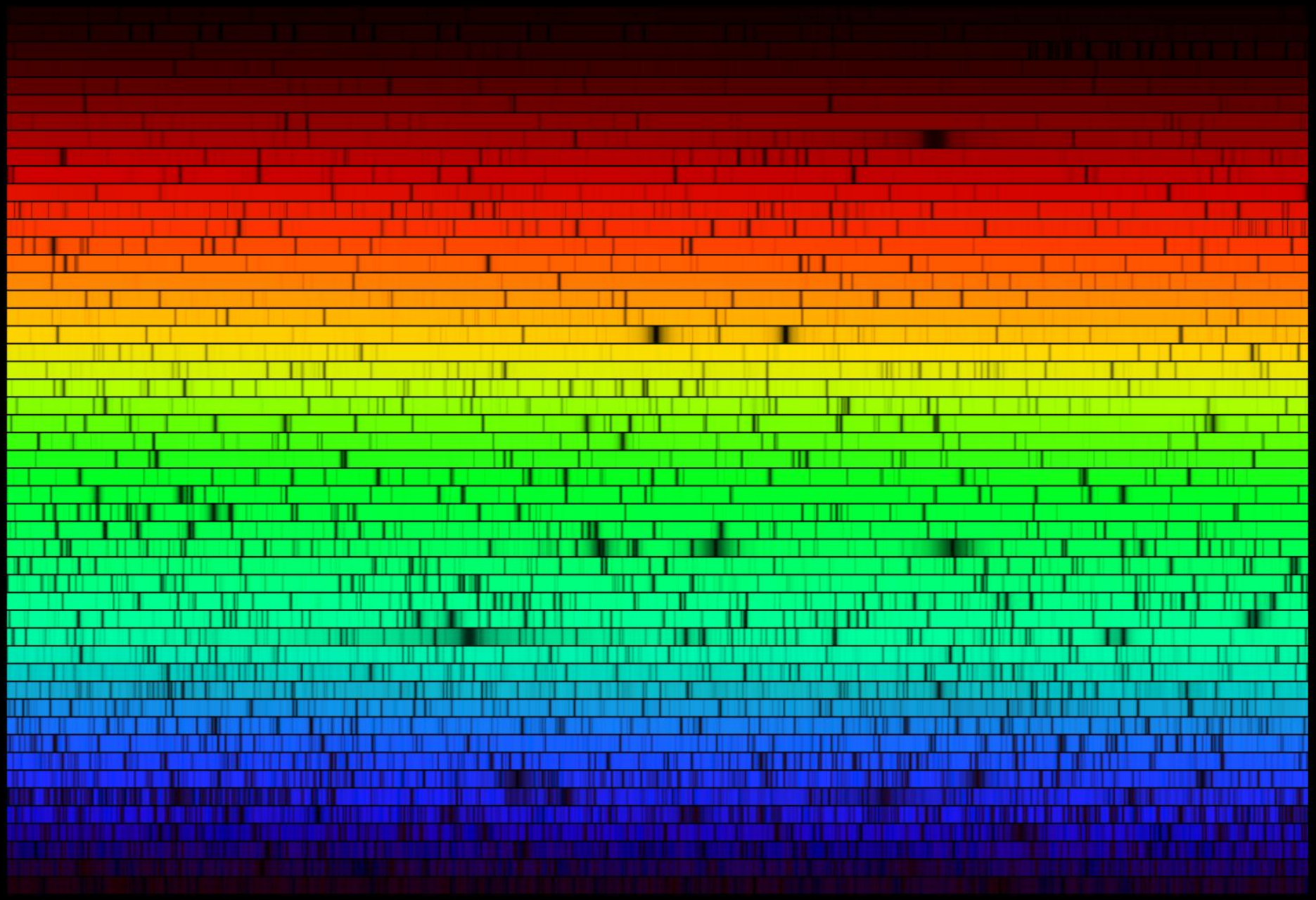
Position (angle ϕ) depends on λ.

Spectroscopy



Scientific American, illustration by George Retseck

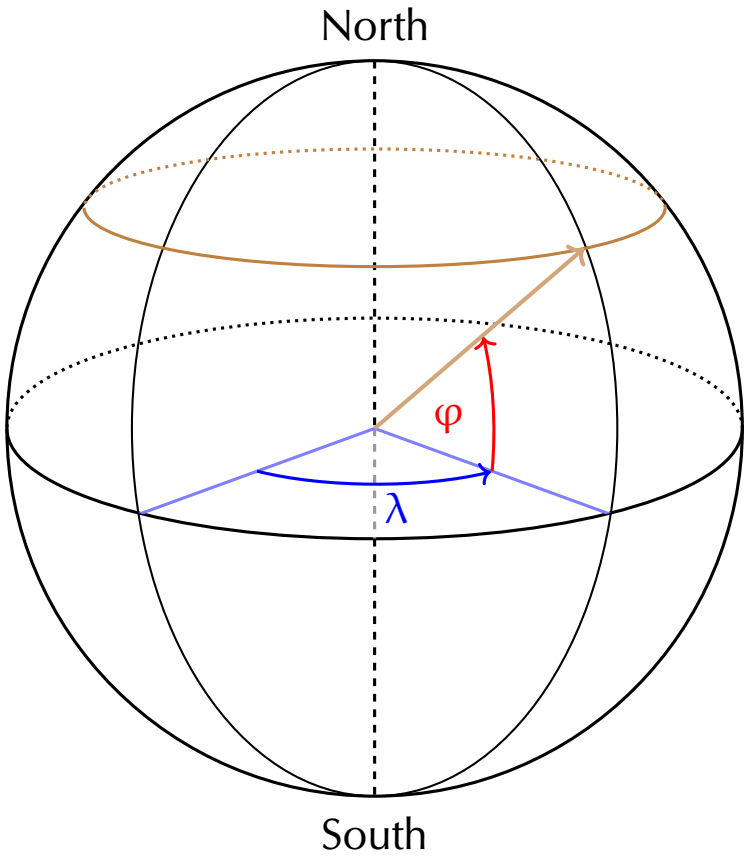
"Blaze" grating: 'grazing'.
More light at higher m.
$\Longrightarrow$ high efficiency for high dispersion.



N.A.Sharp, NOAO/NSO/Kitt Peak FTS/AURA/NSF

Solar spectrum

Positions on Earth



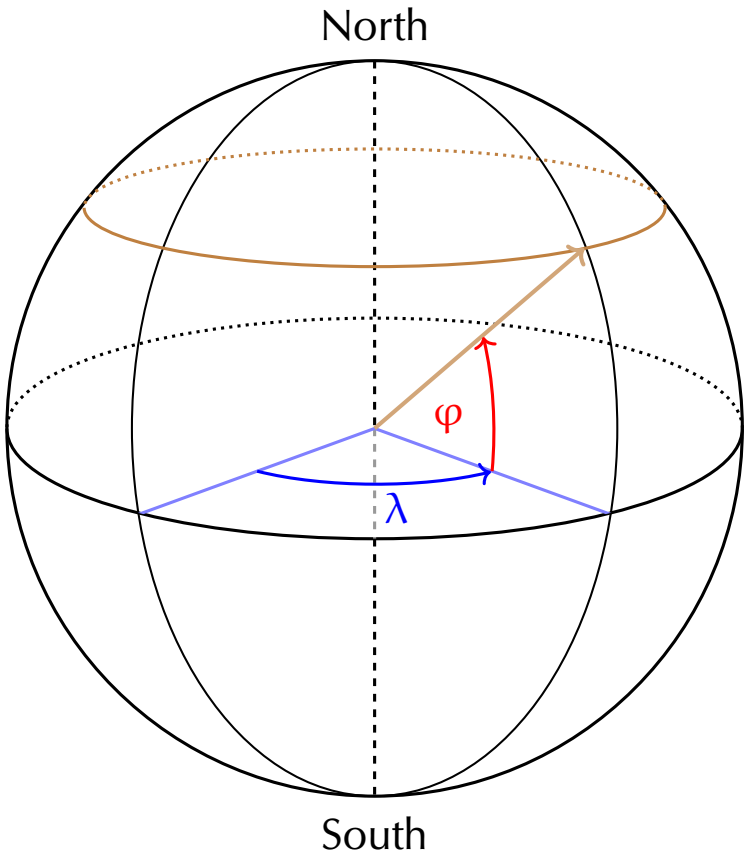


λ: geographic longitude (deg),

φ: geographic latitude (deg)

$\lambda = 0°$ defined by position of a meridian circle in Greenwich (London)

Positions on Earth



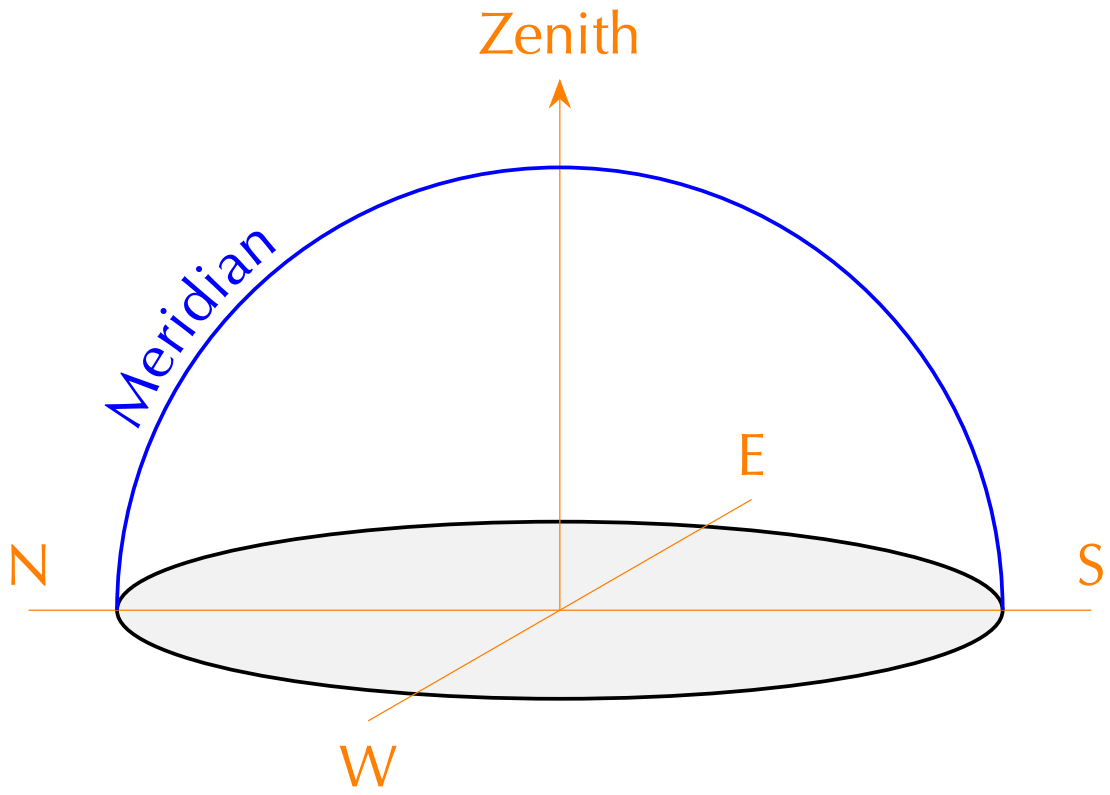


λ: geographic longitude (deg),

φ: geographic latitude (deg)

$\lambda = 0°$ defined by position of a meridian circle in Greenwich (London)

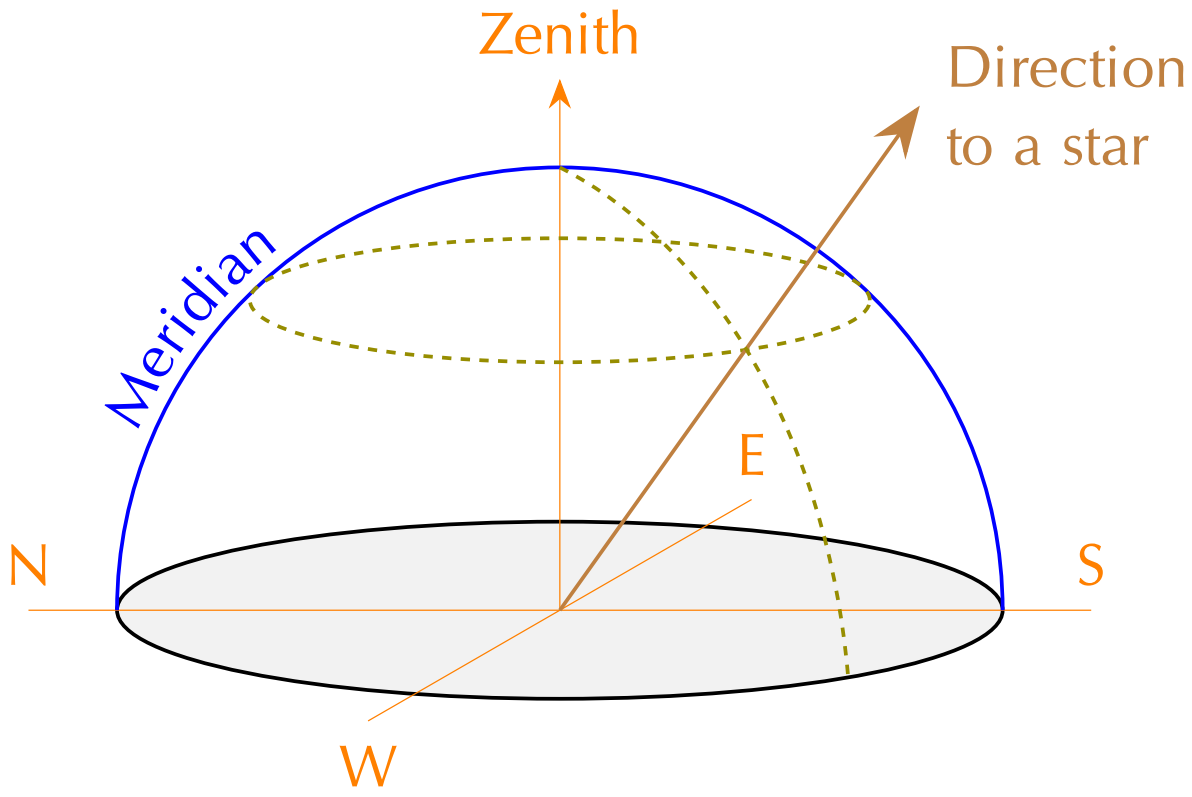
Horizon System



after Giese

Horizon system:

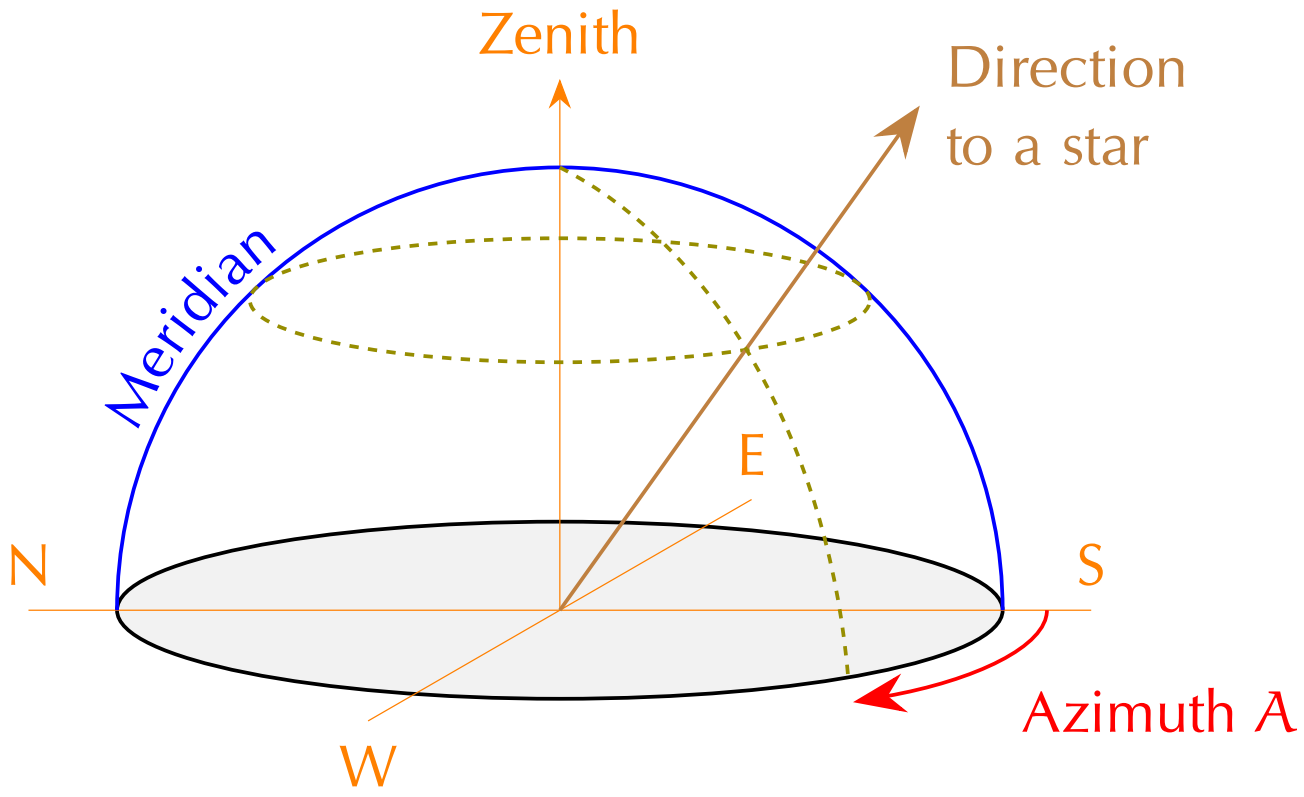
Horizon System



after Giese

Horizon system: Direction to a star

Horizon System

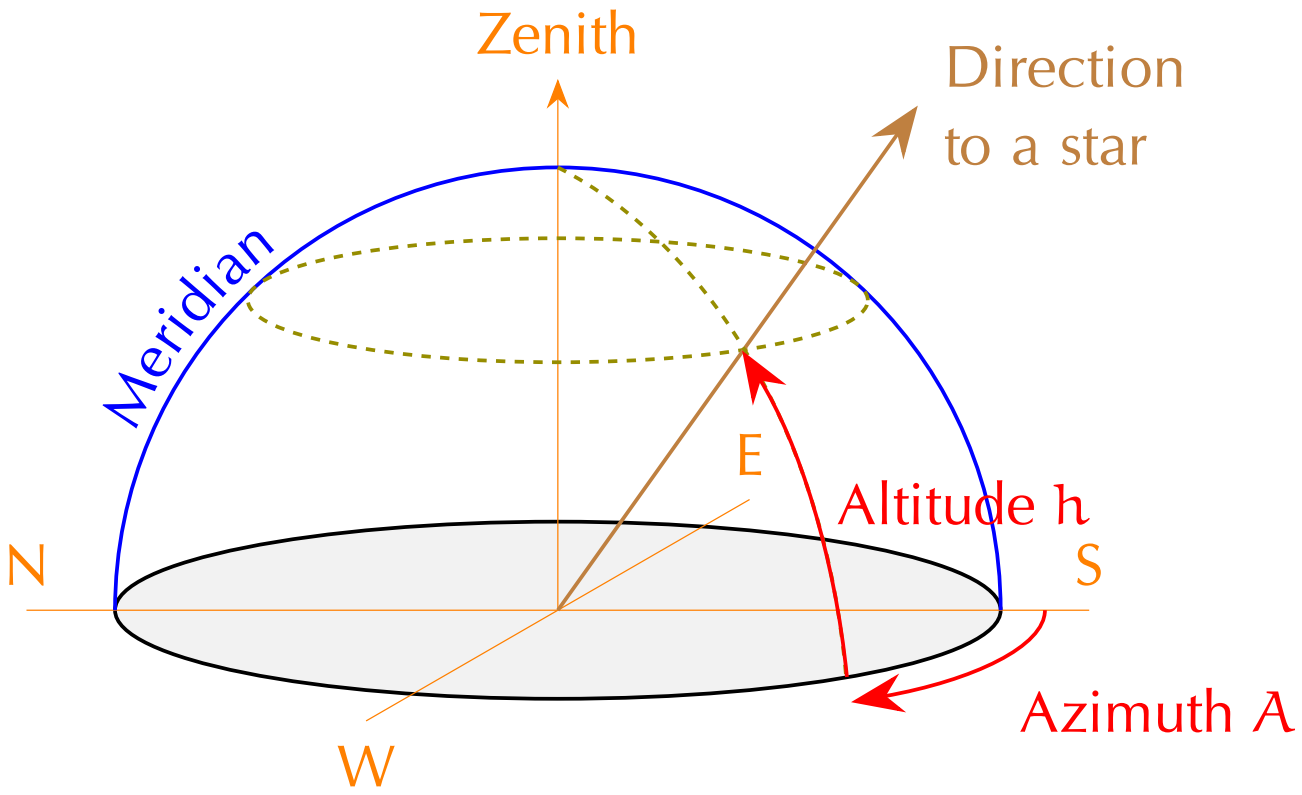


after Giese

Horizon system: Direction to a star

- Azimuth A: angle in horizontal S-W-N-E

Horizon System

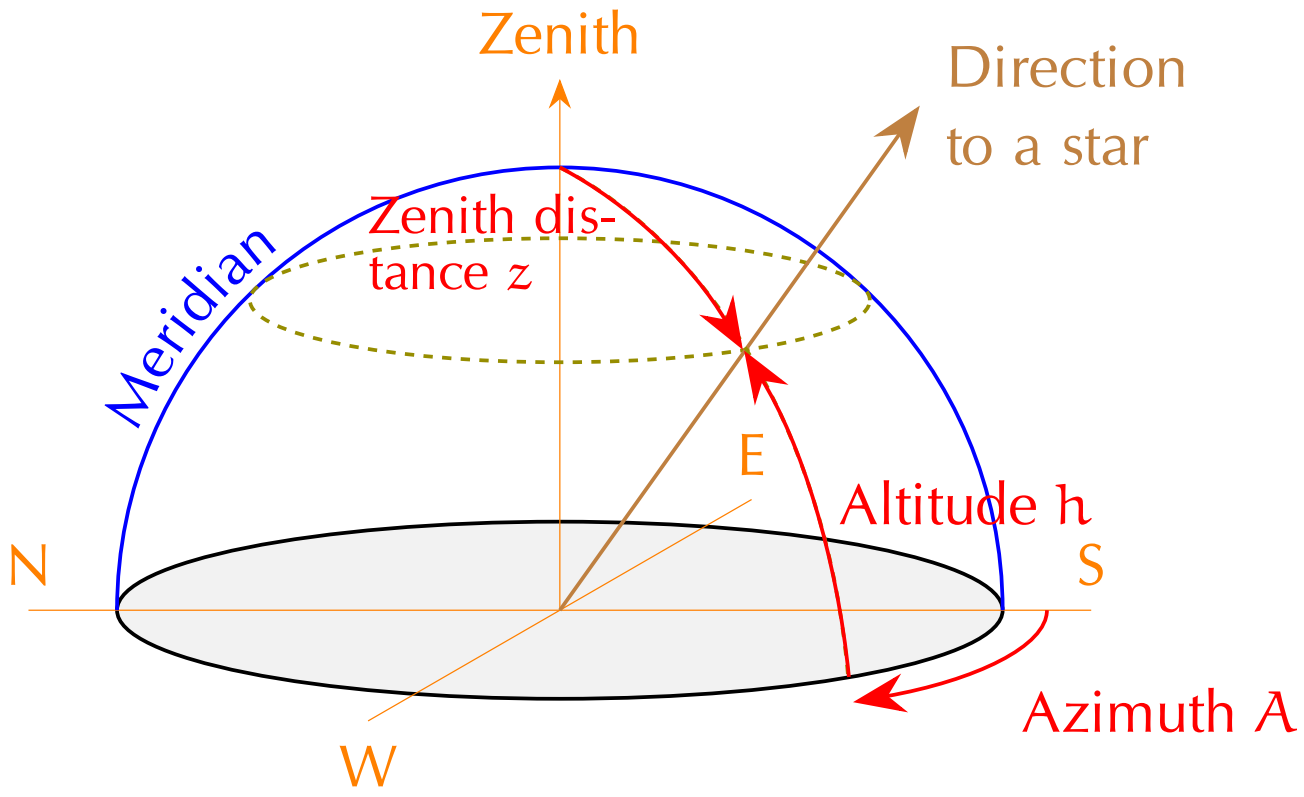


after Giese

Horizon system: Direction to a star

- Azimuth A: angle in horizontal S-W-N-E
- Altitude h: angle from horizon towards zenith

Horizon System



after Giese

Horizon system: Direction to a star

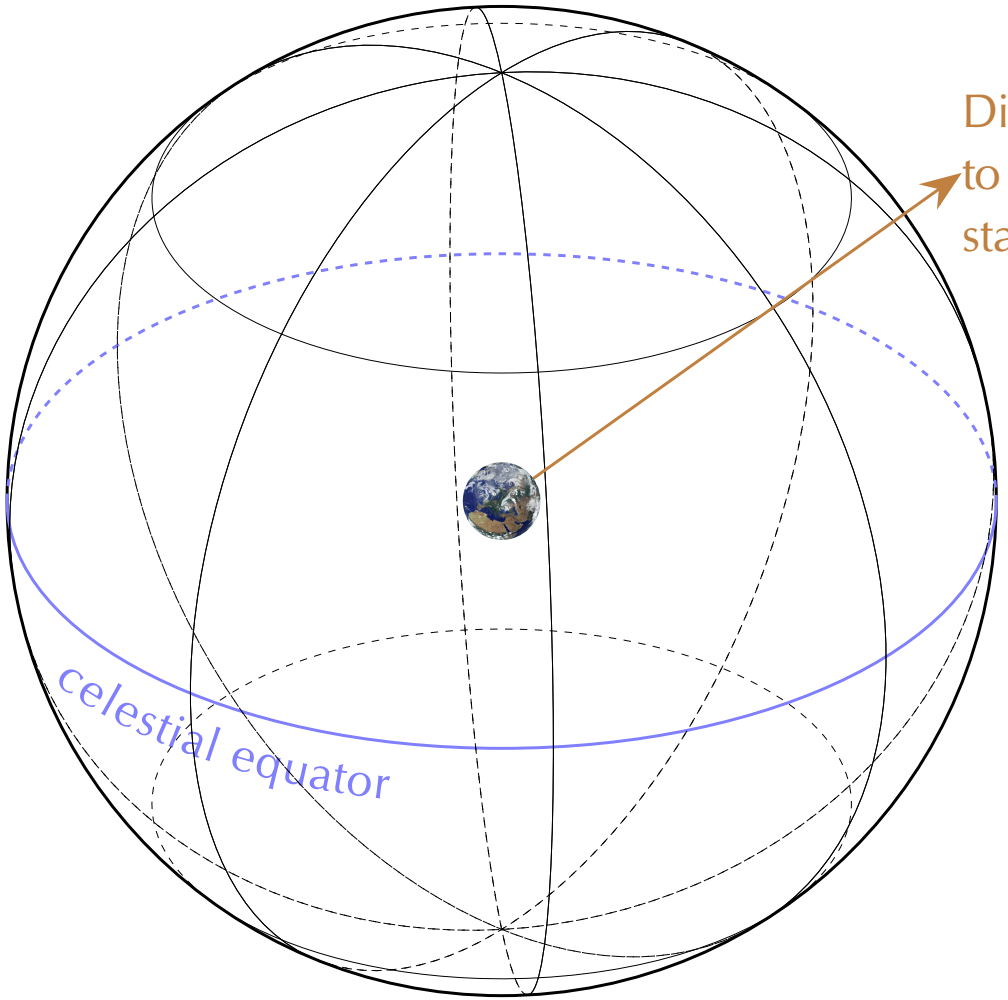
- Azimuth A: angle in horizontal S-W-N-E
- Altitude h: angle from horizon towards zenith
- Zenith distance z: $z = 90° - h$



http://joeorman.shutterace.com/Trails/Trails_021227_5.html

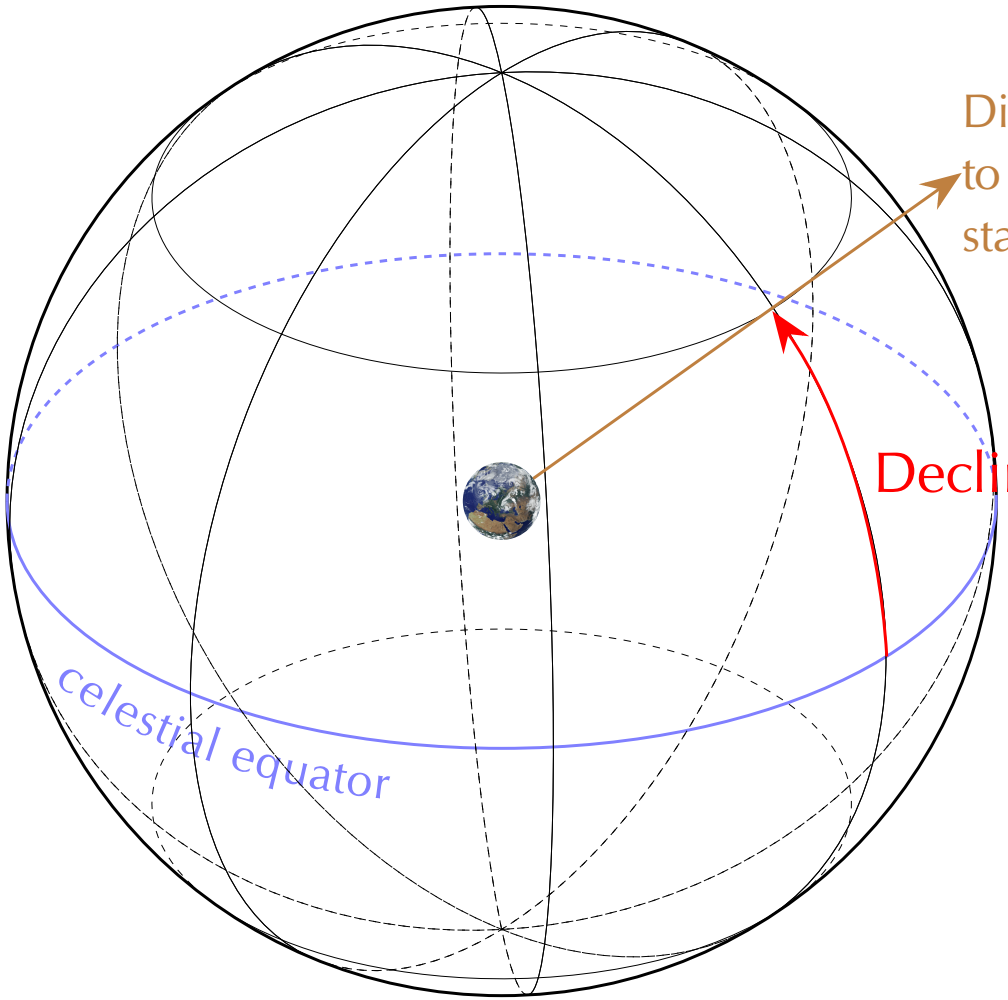
Earth rotates: A, $\mathfrak{h}$ do not define position of stars at any time

Equatorial System



Fixed coordinates to star

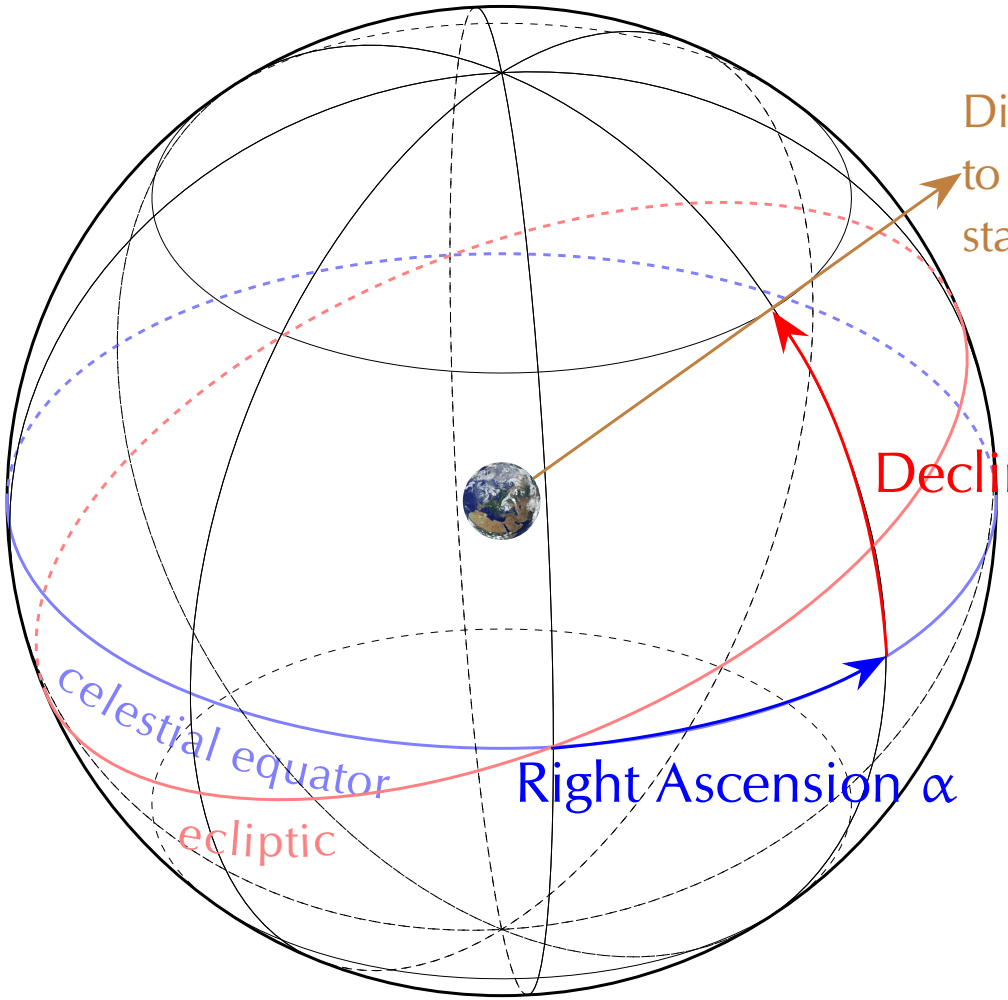
Equatorial System



Fixed coordinates to star:

- Declination δ:
  $\angle$(celestial equator, star)
  Measured in °, ′, ″

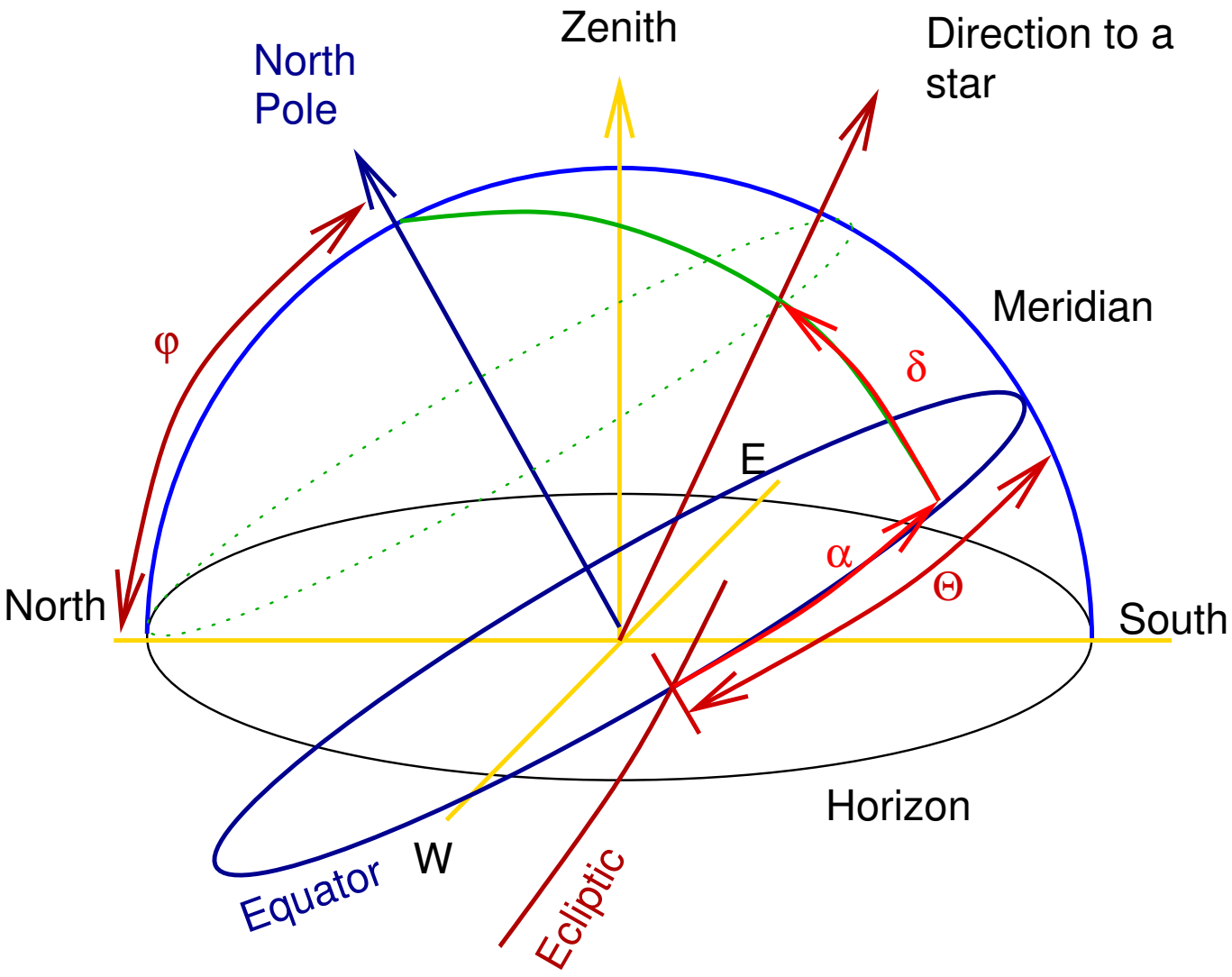
Equatorial System



Fixed coordinates to star:

- Declination δ:
  $\angle$(celestial equator, star)
  Measured in °, ′, ″
- Right ascension α: angle along equator from ascending node of Sun (vernal equinox) to star
  Measured in h, m, s

Siderial Time



Define siderial time: 24 h correspond one rotation of the celestial sphere.

0 h siderial time = time when vernal equinox passes through meridian.

$\Longrightarrow$ Local siderial time: Right ascension of stars passing through meridian.

Right Ascension is measured in hours, minutes, and seconds

1 h corresponds to 15°.
α increases towards East.

Siderial Time

Note: Siderial time $\neq$ common time

Common time: 24 h between culminations of the Sun (i.e., passes of Sun through meridian).

BUT

Sun moves on sky towards east

$\Longrightarrow$ one "solar day" takes slightly longer than one rotation of the Earth

Angular speed of Sun: 360° degrees in 365.25 days, i.e., $0.9856^\circ\,\mathrm{d}^{-1}$.

$\Longrightarrow$ During 365.25 days the Earth rotates 366.25 times

$\Longrightarrow$ Earth's rotation takes $24\,\mathrm{h} \times 365.25/366.25 = 23\,\mathrm{h}\ 56\,\mathrm{minutes}$.

Precession and Nutation

Earth is ~ rotational ellipsoid, orbits of Sun and Moon are *not* in plane of equator

(Earth's axis has tilt of ~23.5°, Moon's orbit tilted by 7° against ecliptic)

$\Longrightarrow$ Sun and Moon exert torques onto Earth

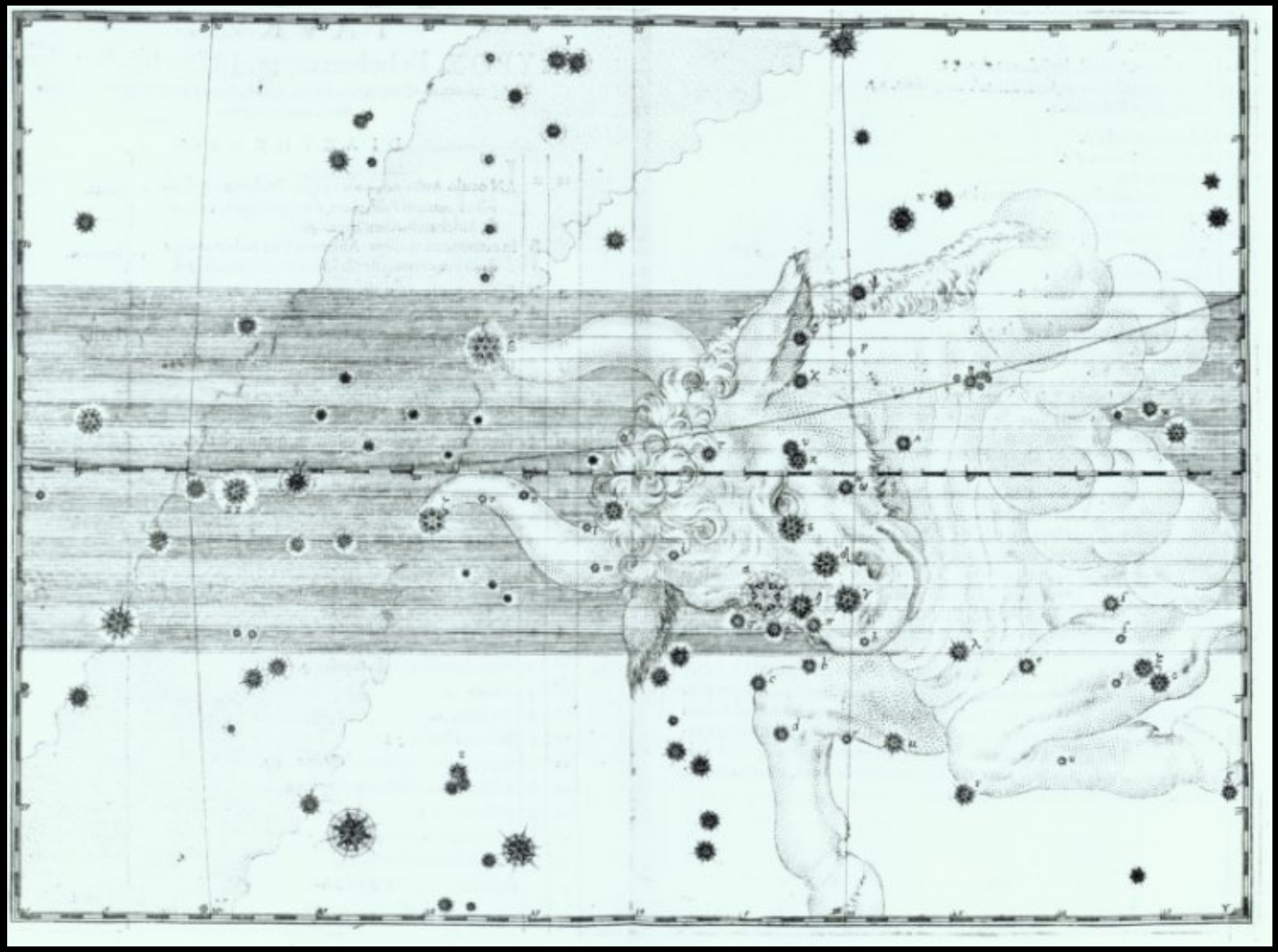
Earth's rotational axis is not stable in space.

Two major effects:

luni-solar precession: Earth's axis rotates around pole of ecliptic once every 25800 years (~50″ per year).

Already discovered by Hipparcos in ~200 BC!

nutation: "Wobble" with ~18 year periodicity caused by short-term perturbations caused by Moon and Sun.



Bayer's Uranometria (1603; University of Illinois collections)

Because of precession and nutation: need to state epoch of coordinate!

Aldebaran = α Tau: $\alpha_{\mathrm{J2000.0}} = 04^{\mathrm{h}}35^{\mathrm{m}}55.2387^{\mathrm{s}}$, $\delta_{\mathrm{J2000.0}} = +16^{\circ}30'33.485''$

corresponding to $\alpha_{\mathrm{B1950.0}} = 04^{\mathrm{h}}33^{\mathrm{m}}02.9^{\mathrm{s}}$, $\delta_{\mathrm{B1950.0}} = +16^{\circ}24'37.6''$

Measurement Methods and Coordinates

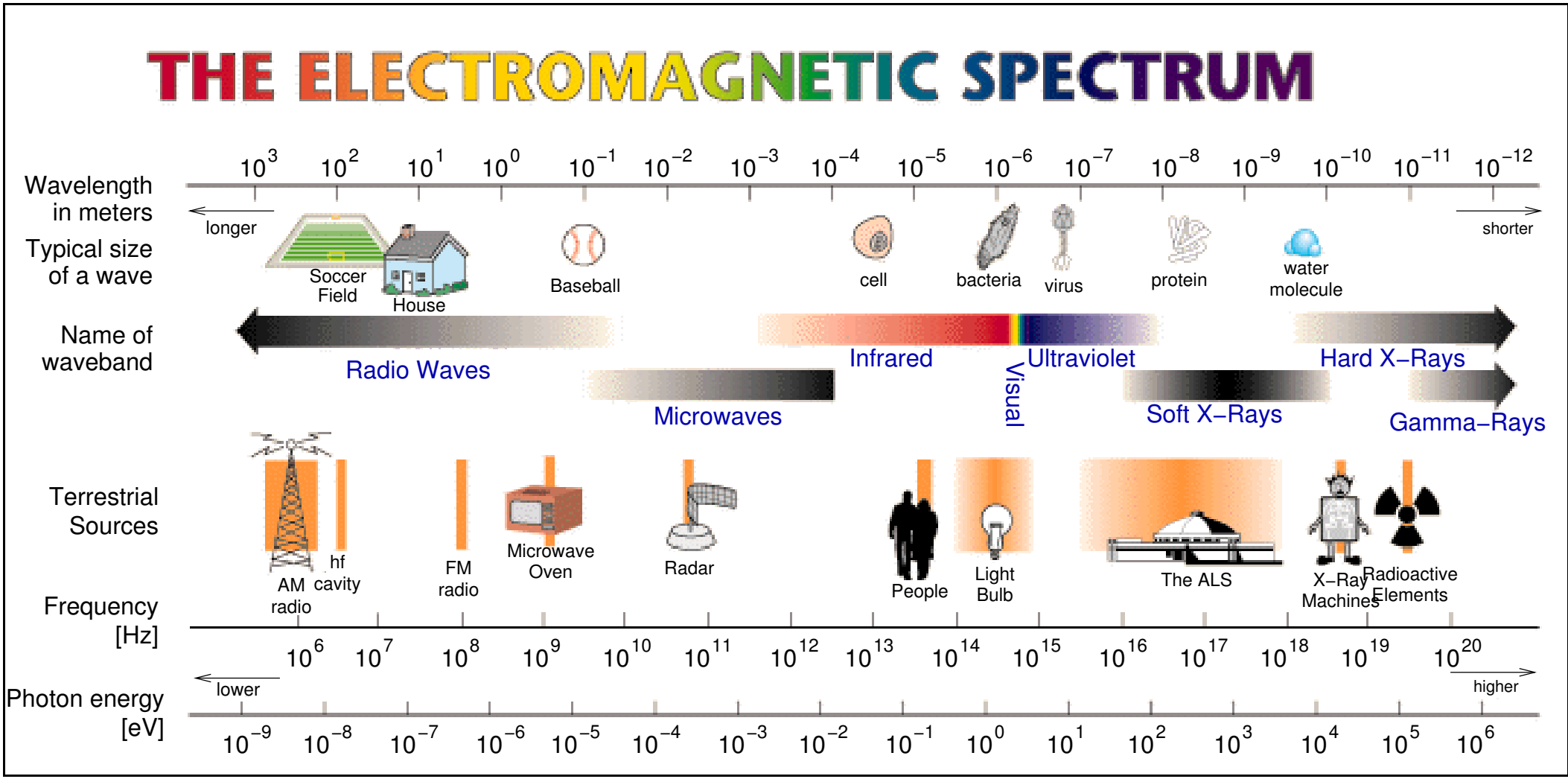
Introduction

We now move away from the solar system

$\Longrightarrow$ before we can continue with science, we need to understand

- where astronomical objects are $\Longrightarrow$ coordinate systems
- how astronomical measurements are made $\Longrightarrow$ telescopes

THE ELECTROMAGNETIC SPECTRUM



Electromagnetic Spectrum

As we all know, light can be characterized by

Wavelength: λ, measured in m, mm, cm, nm, Å.

Frequency: ν, measured in Hz, MHz.

Energy: E, measured in J, erg, Rydbergs, eV, keV, MeV, GeV.

These quantities are related:

$$\lambda\nu = c \qquad E = h\nu \tag{5.1}$$

where

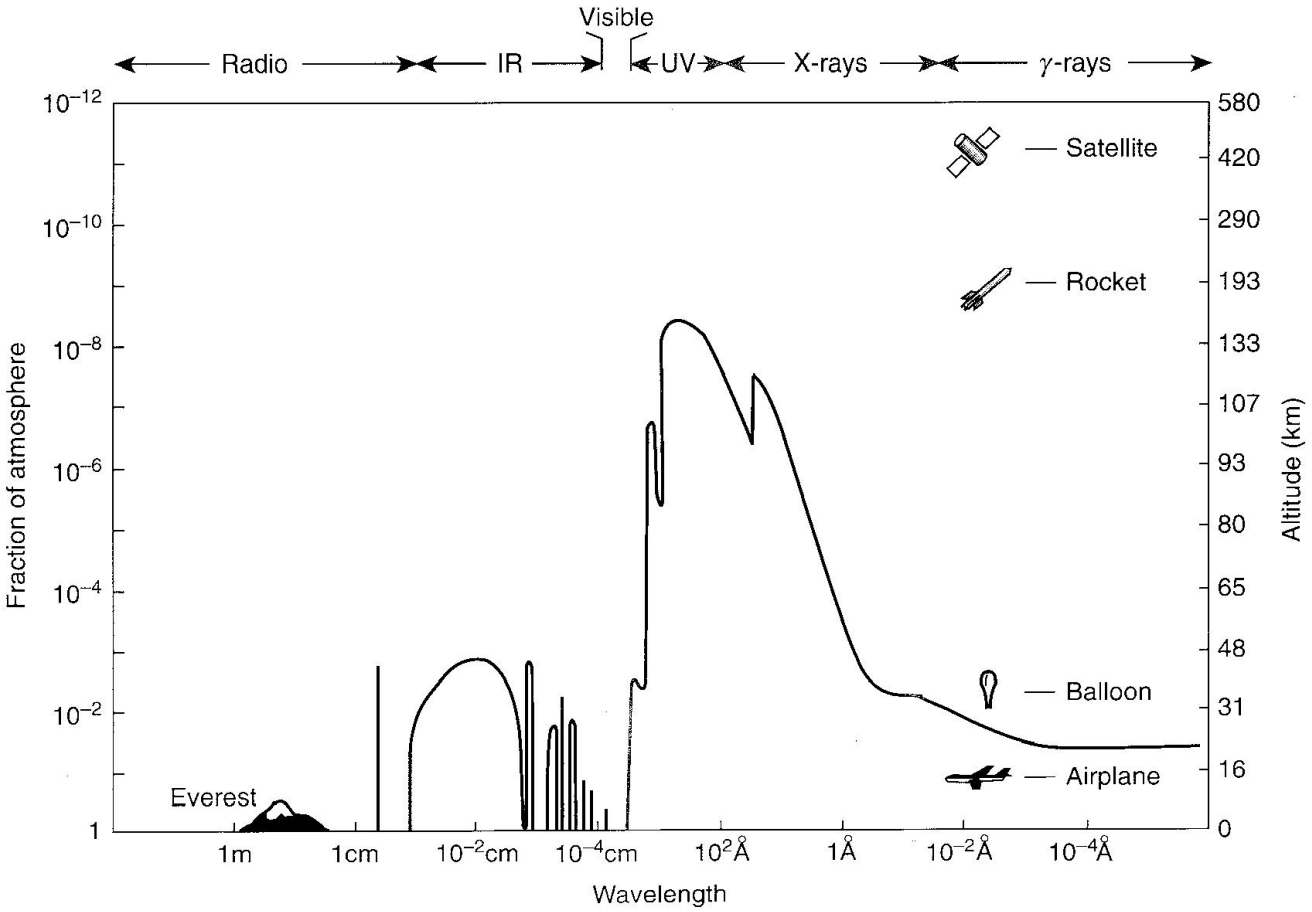
$$c = 299792458\,\mathrm{m\,s^{-1}} \tag{5.2}$$

$$h = 6.626070150 \times 10^{-34}\,\mathrm{J\,s} \tag{5.3}$$

(5.4)

Constants are the 2018 BIPM values and defined to be exact.

Earth's Atmosphere



Charles & Seward, Fig. 1.12

Earth's atmosphere is opaque for all types of EM radiation except for optical light and radio.

$\Longrightarrow$ Astronomy is today multi-wavelength astronomy, although optical studies are still very important

$\Longrightarrow$ For time reasons only optical telescopes will be discussed.

Introduction

Scientific purposes of a telescope:

1. Collect light, lots of light, to show faint objects ("Light bucket")
2. Resolve small features

Instrumentation used...

1. to make images
   $\Longrightarrow$ Imaging (Charge Coupled Devices [CCDs], earlier also with film)
2. to measure spectra
   $\Longrightarrow$ Spectrographs
3. to measure stellar brightness
   $\Longrightarrow$ Photometers (often CCDs, there are also dedicated photometers for msec-resolution photometry)

For physics of instrumentation $\longrightarrow$ Astronomy Laboratory

Types of Telescopes

To collect light, we have two possibilities:

1. Lenses: Refractors

   Disadvantage: lens cannot be supported from the back

   $\Longrightarrow$ limits max. diameter to $\lesssim 1\,\mathrm{m}$

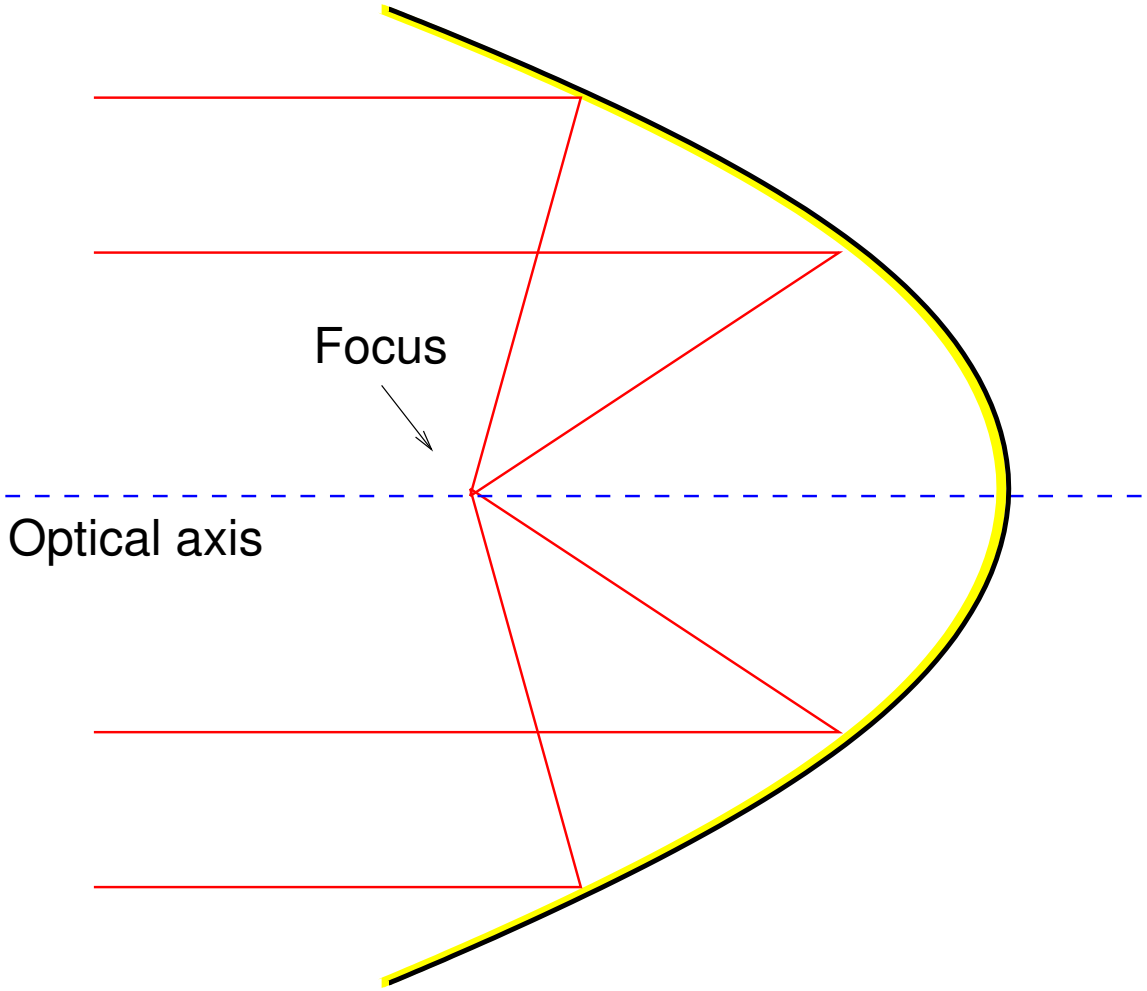
   largest refractor at Yerkes Observatory (University of Chicago): $\mathrm{d} = 1.02\,\mathrm{m}$

   $\Longrightarrow$ not of interest for science

2. Mirrors: Reflectors

   Mirrors can be supported, instrument of choice for today, with diameters up to 11 m

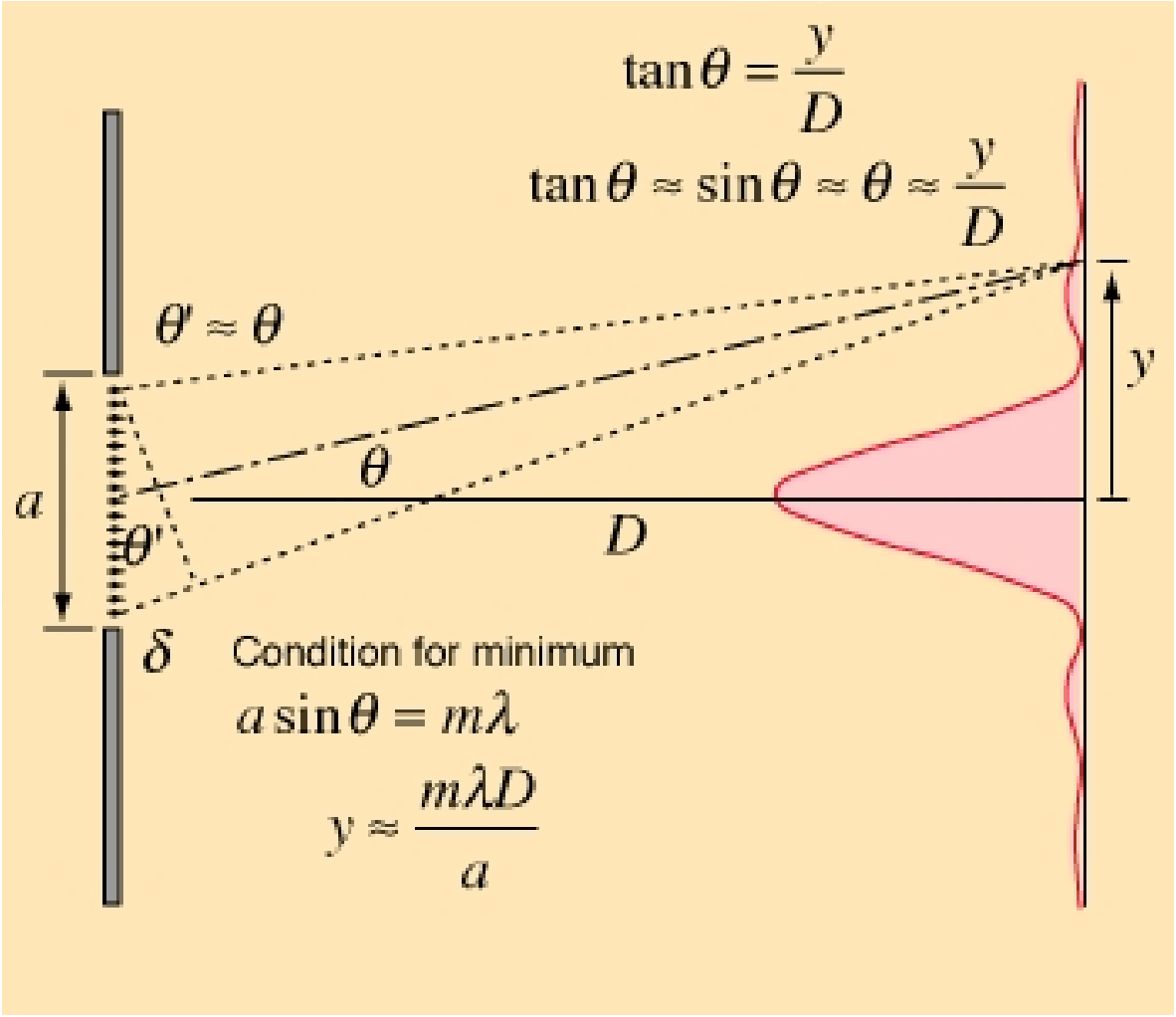
Types of Telescopes



To form image: focus light with a parabolic mirror

Spherical mirrors show spherical aberration
$\Longrightarrow$ *not* suited for astronomical telescopes (at least not without correction).

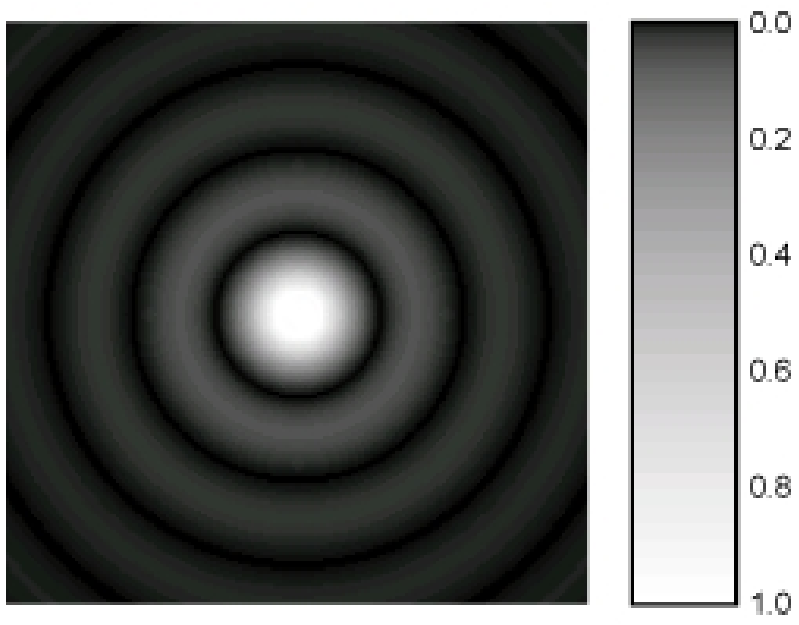
Resolution



GSU

Wave nature of light results in interference pattern caused by diffraction on optical elements in telescope (mainly aperture).

Resolution



Diffraction pattern on telescope aperture: Airy pattern

For a circular aperture with radius r:

$$I(\theta) \propto \pi^2 r^4 \left[\sum_{n=0}^{\infty} (-1)^n \frac{1}{n+1}\left(\frac{m^n}{n!}\right)^2\right]^2 \propto \frac{\pi^2 r^4}{m^2}\left(J_1(2m)\right)^2 \tag{5.5}$$

where $m = \pi(r/\lambda)\sin\theta$ and where $J_1(x)$ s the Bessel function of the first kind of order unity.

$I(\theta)$ has minima for $m = 1.916, 3.508, 5.087, \ldots$, or

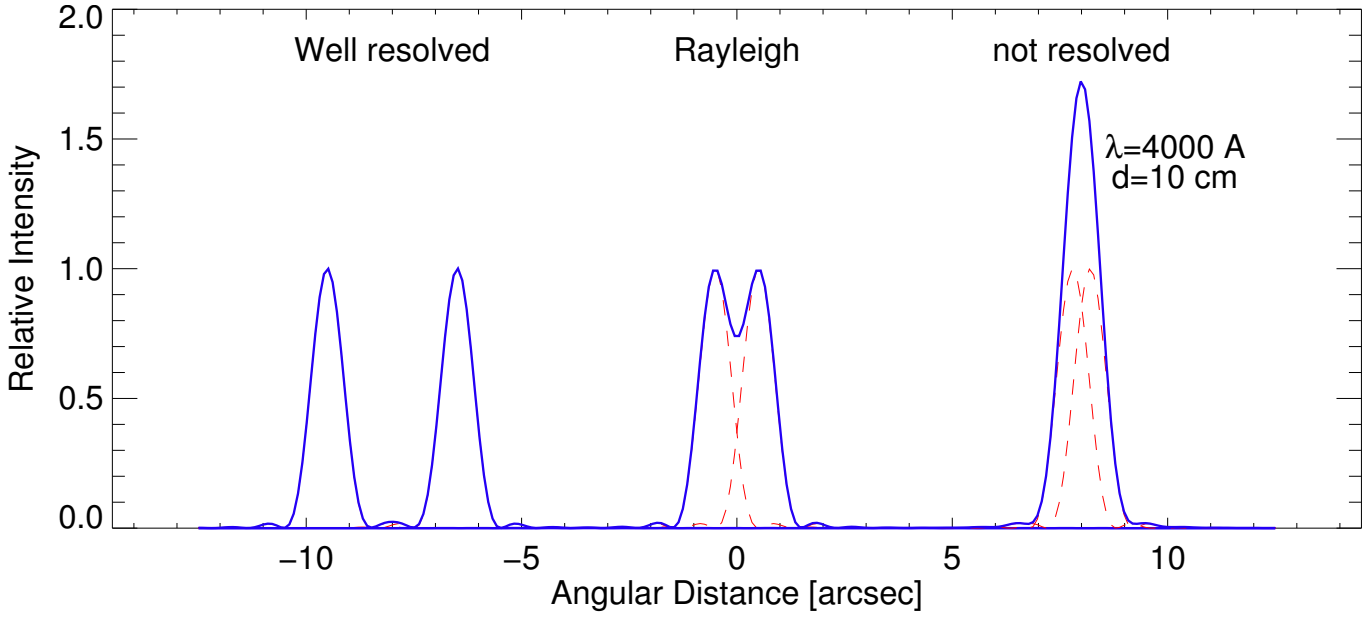
$$\sin\theta = \frac{1.916\lambda}{\pi r}, \frac{3.508\lambda}{\pi r}, \frac{5.087\lambda}{\pi r}, \ldots \tag{5.6}$$

or for θ small ($\sin\theta \sim \theta$) minima are found at:

$$\theta = \frac{1.220\lambda}{d}, \ldots \tag{5.7}$$

where d: diameter.

Resolution



Resolution of telescope: ability to separate two (point-like) light sources

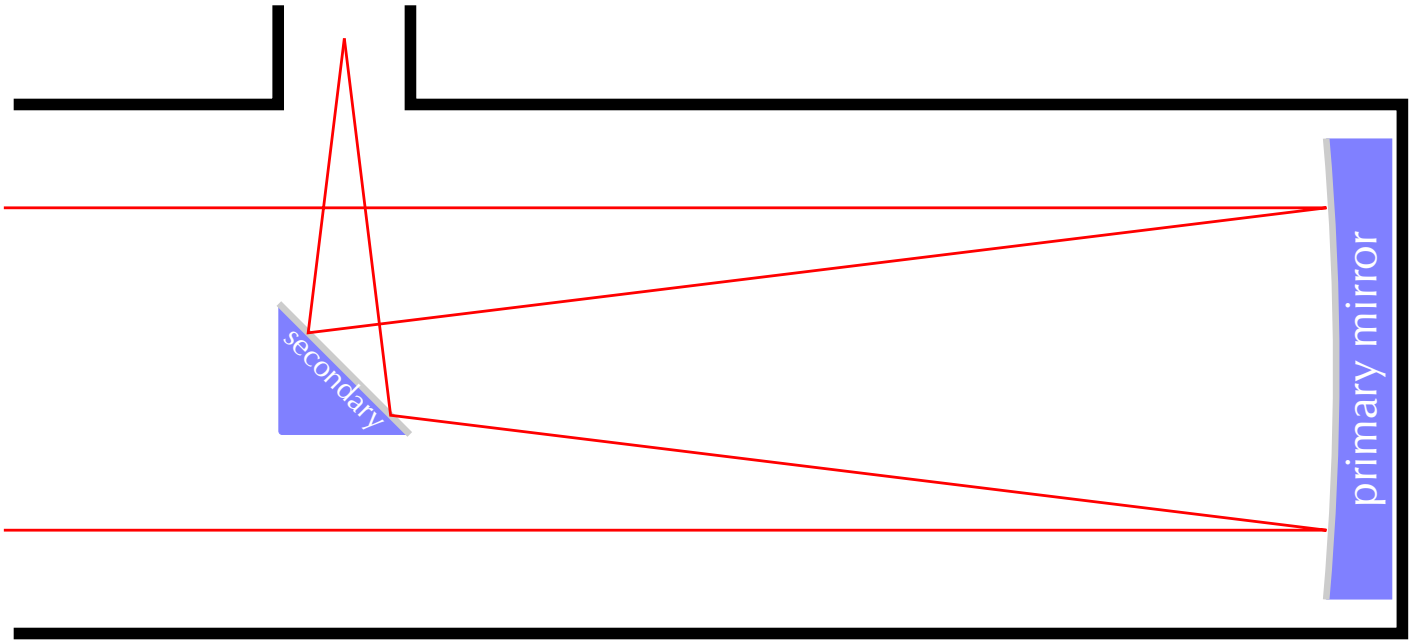
Rayleigh criterion for resolution: maximum of diffraction pattern of one source must fall into minimum of diffraction pattern of other source.

Therefore the diffraction limited resolution is

$$\alpha = \frac{1.220\lambda}{d} = \frac{12''}{D/1\,\mathrm{cm}} \quad \text{for optical light} \tag{5.8}$$

Note: Rayleigh criterion is a criterion, *not* a law. Detailed object separability depends on ratio of intensities of two objects, in practice resolutions up to $3\times$ smaller are achievable.

Newtonian Telescope

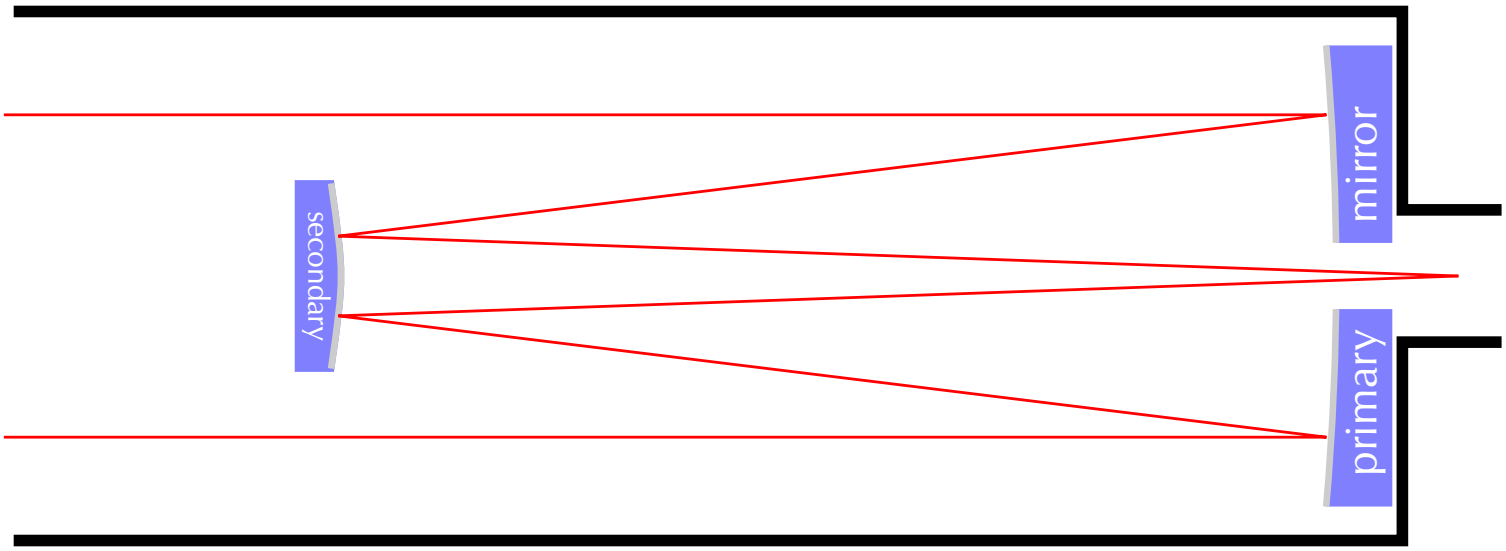


Newtonian telescope: reflector with parabolic mirror.

Common in cheaper telescopes.

Disadvantage: large size (~ focal length)

Cassegrain Telescope



Cassegrain telescope: reflector with “folded optical path”

(primary: paraboloid, secondary: hyperboloid)

$\Longrightarrow$ Much shorter than Newtonian

$\Longrightarrow$ Telescope of choice for modern instruments

Schmidt Telescope



Bernhard Schmidt (Hamburg)
`http://www.sky-win.de/`

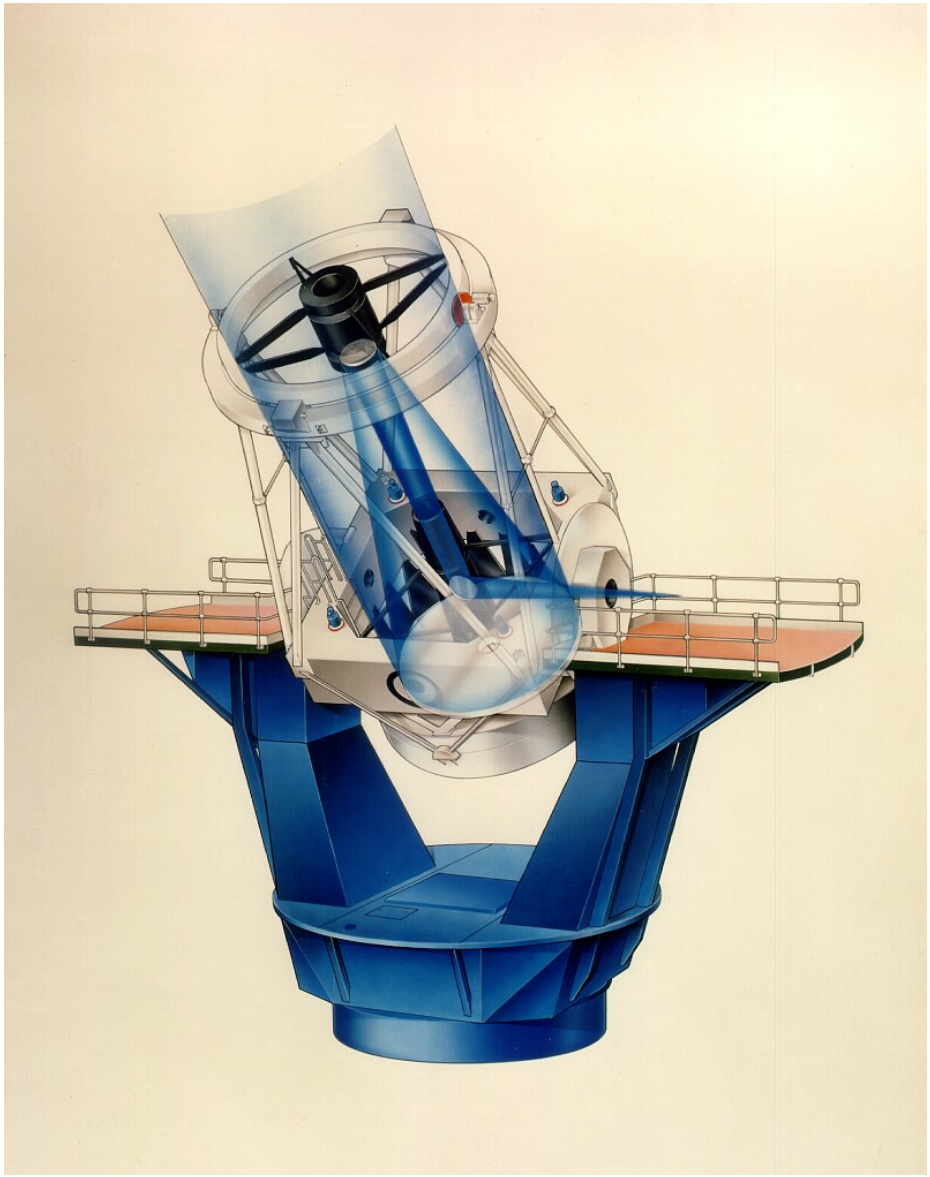


2m Schmidt telescope at the Landesternwarte Thüringen in Tautenburg near Jena:
largest Schmidt telescope in the world.

Uses spherical mirror for larger field view, correction plate used to correct for spherical aberration.

Many amateur telescopes are combination of Schmidt telescope and Cassegrain telescope
$\Longrightarrow$ Schmidt-Cassegrain telescopes.

Schmidt Telescope



Nasmyth Focus:

light reflected through axis

- ideal for modern azimutal mountings

  e.g., European Southern Observatory's Very Large Telescope

- two stationary platforms
- can host large instruments
- very stable

William Herschel Telescope, La Palma

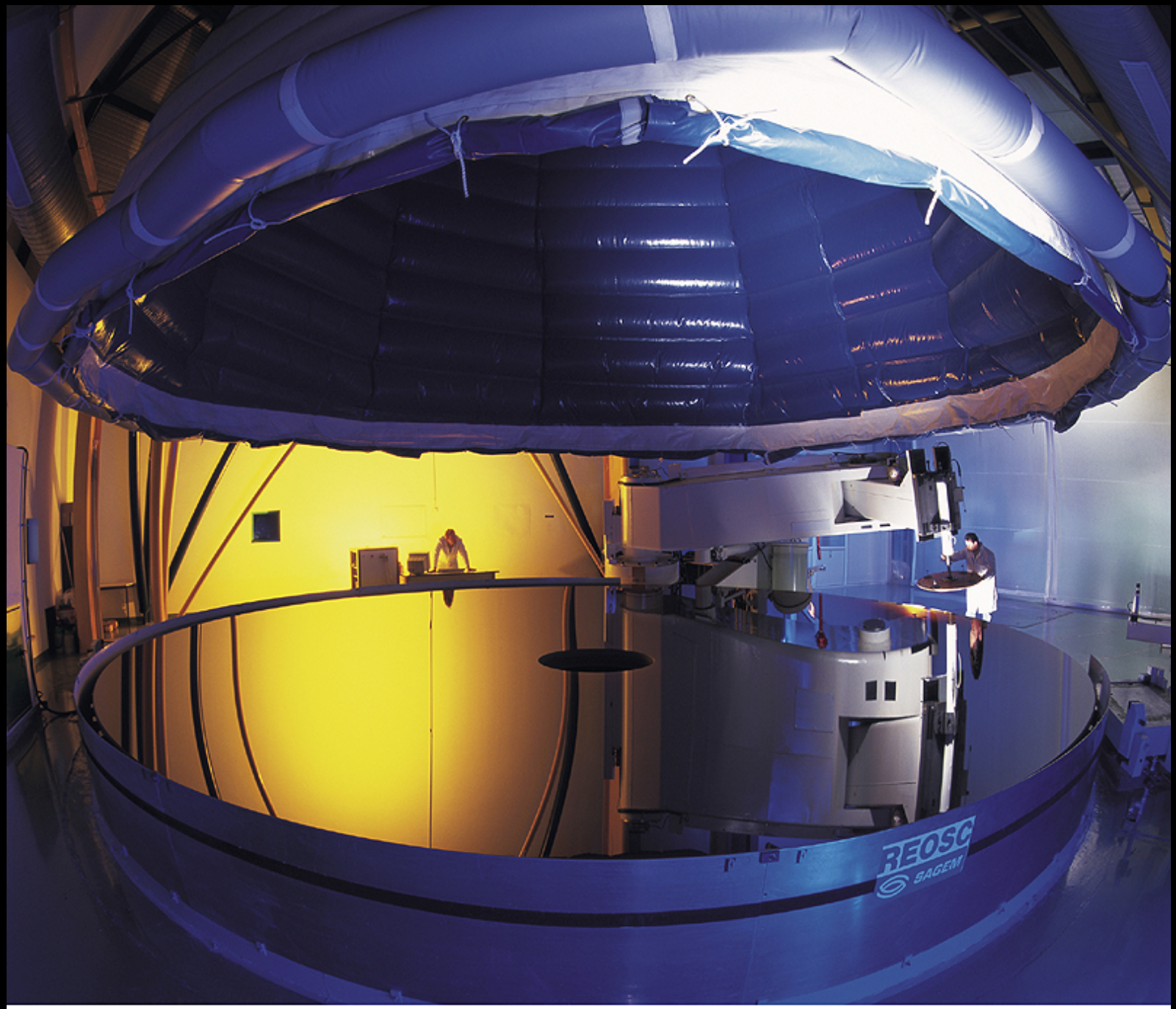

© J. Wilms



Example: Building of the European Southern Observatory's Very Large Telescope



ESO



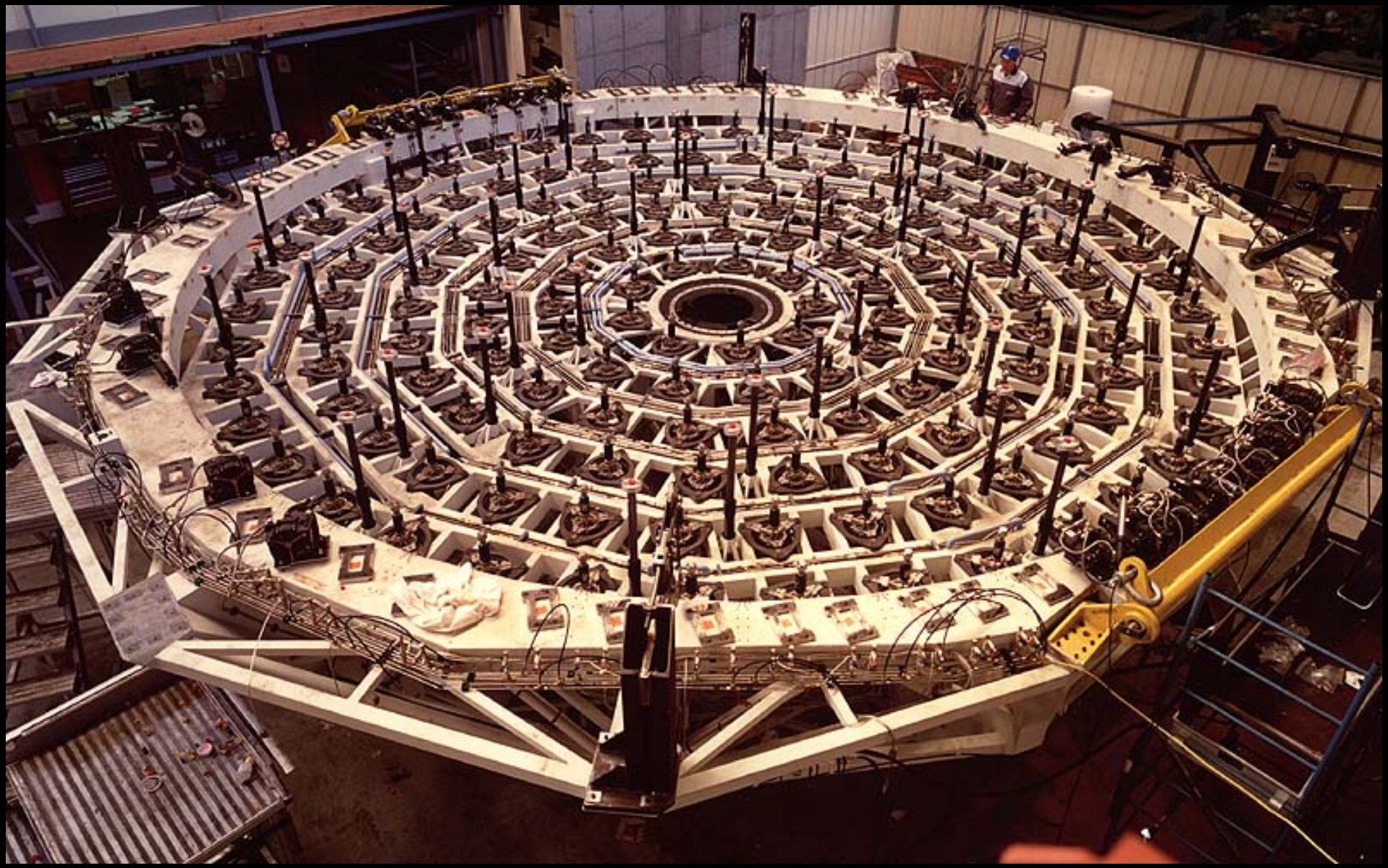
The Polished Fourth VLT 8.2-m Mirror at REOSC

Photo: SAGEM

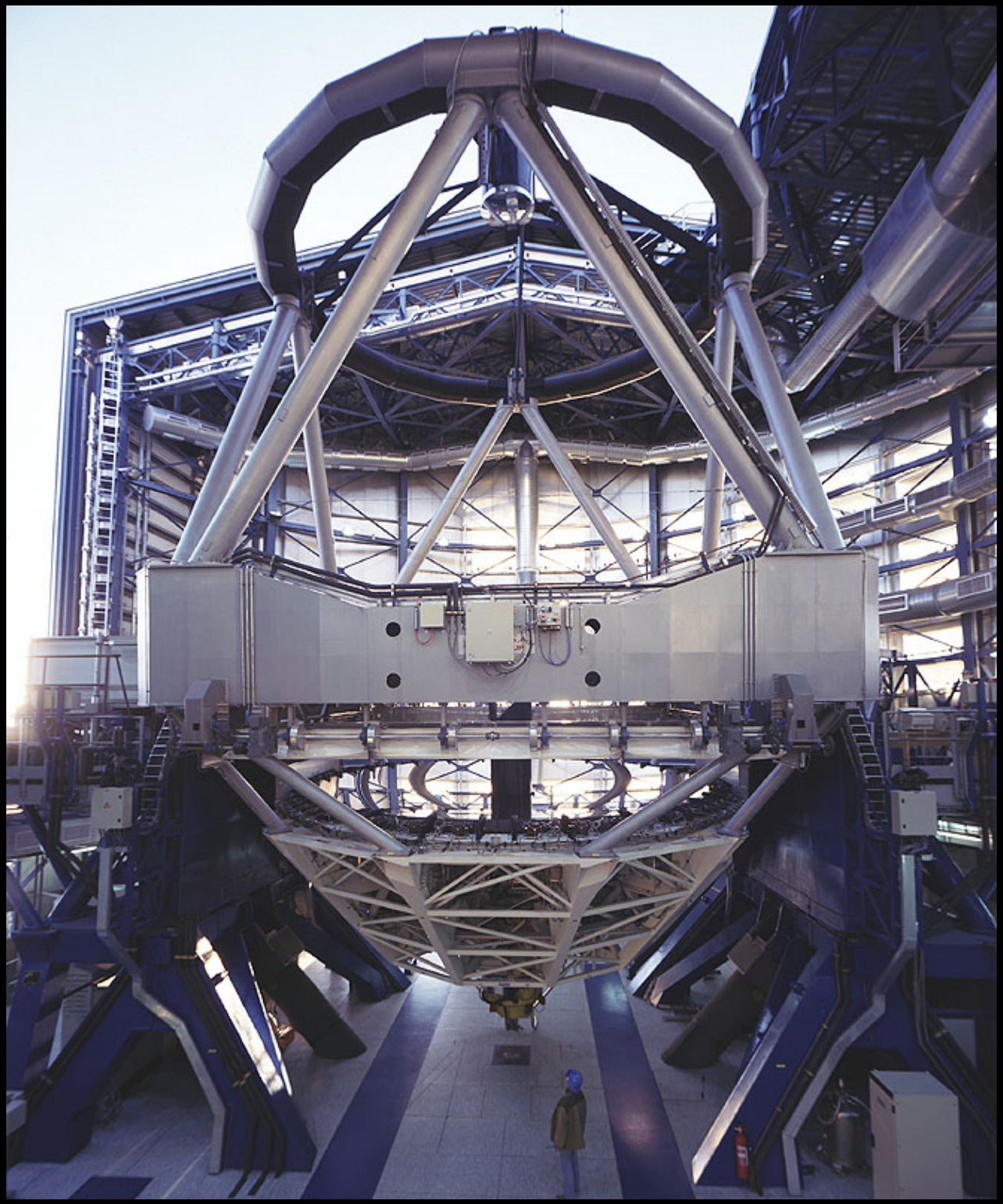
ESO PR Photo 44/99 (14 December 1999)

European Southern Observatory


VERY
LARGE
TELESCOPE
REOSC
GOODRUND
GOODRUND
REOSC
GOODRUND



Mirror cell supporting the mirror, actuators keep mirror in shape ("active optics", correcting all possible deformations of the mirror).





VLT at Paranal

ESO PR Photo 43a/99 (8 December 1999)

© European Southern Observatory

Adaptive Optics

From Eq. 5.8, the resolution of a telescope of diameter d is

$$\alpha = \frac{1.220\lambda}{d} = \frac{12''}{D/1\,\mathrm{cm}} \tag{5.8}$$

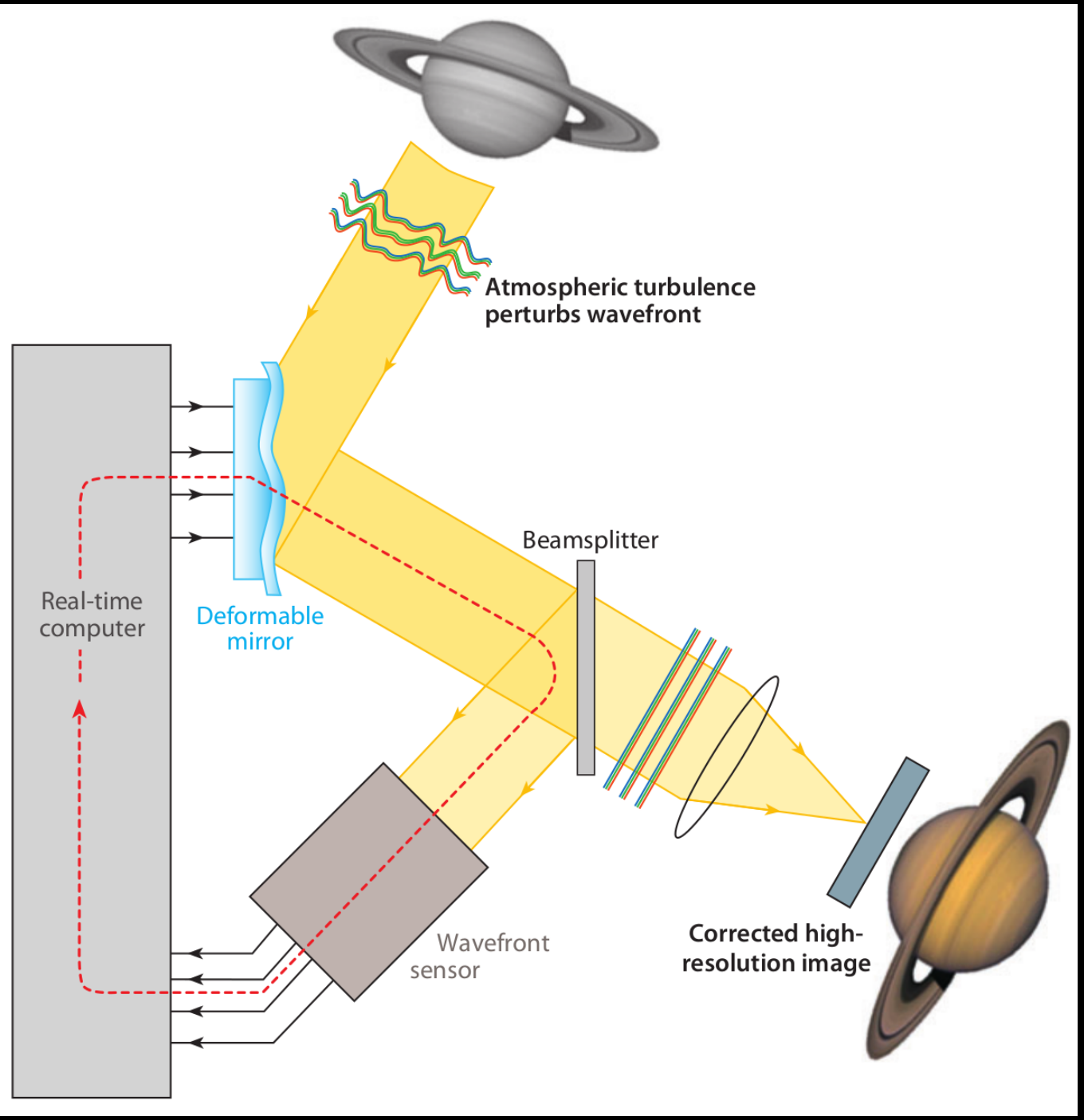
Problem: astronomical seeing

$\Longrightarrow$ turbulence in atmosphere smears pictures of stars to disks with $\theta \gtrsim 0.3''$

$\Longrightarrow$ Increasing telescope diameter to $\gtrsim$40 cm does *not* result in increase in resolution!

Solution to seeing problem: adaptive optics

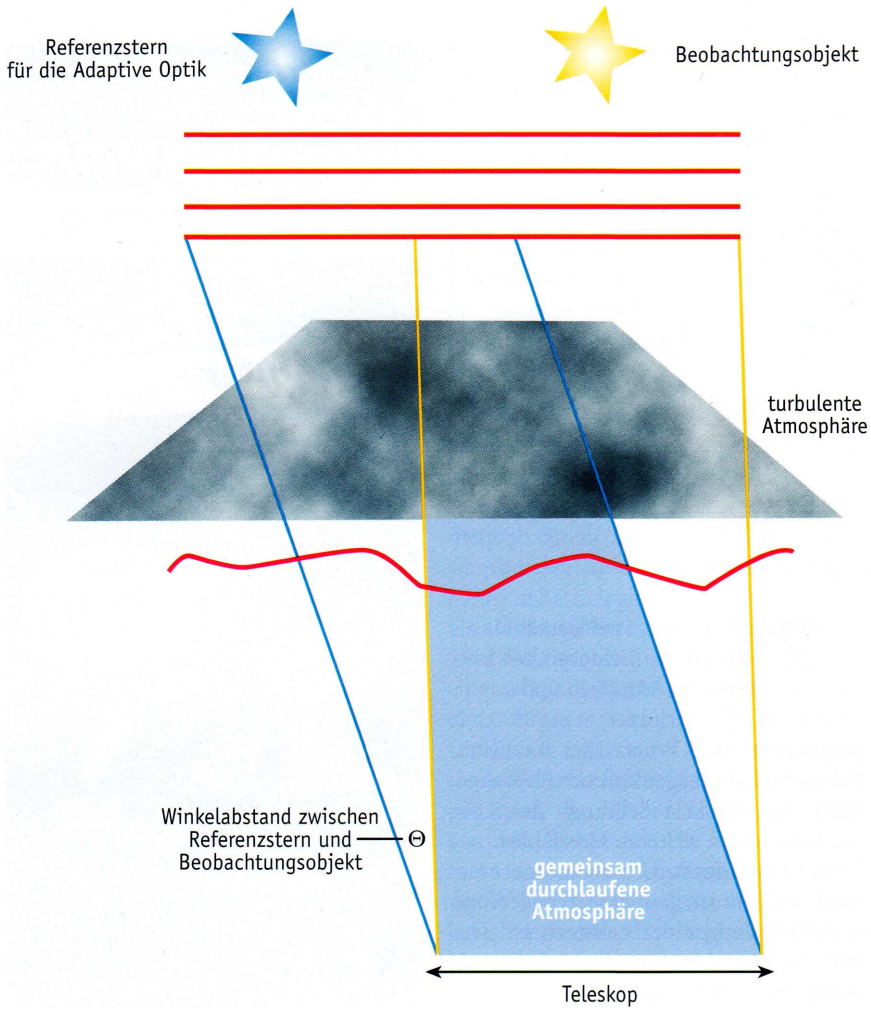
. . . which only works in the IR so far, need to go to space for optical and UV



Schematic principle of an adaptive optics system

(Davies & Kasper, 2012, ARAA 50, 305 and Sterne und Weltraum/S. Hippler)

Adaptive Optics



Hippler & Kasper, 2004, SuW 43,10,32

Giuding star: usual a guiding star is needed, as the observed object is not bright enough.

$\Longrightarrow$ wave front correction by using a neighboring star



If no natural guiding star is in the field of view, use an artificial laser guiding star.
The AO system of Mt. Hopkins observatory, a 30 W laser (©G. Furesz).



AO on the ESO-VLT

Adaptive Optics



Gemini North/AURA

Picture of the galactic center in the IR taken with the Gemini North

Adaptive Optics



Gemini North/AURA

Picture of the galactic center in the IR taken with the Gemini North

...and corrected with adaptive optics

$\Longrightarrow$ Resolution: diffraction limited!

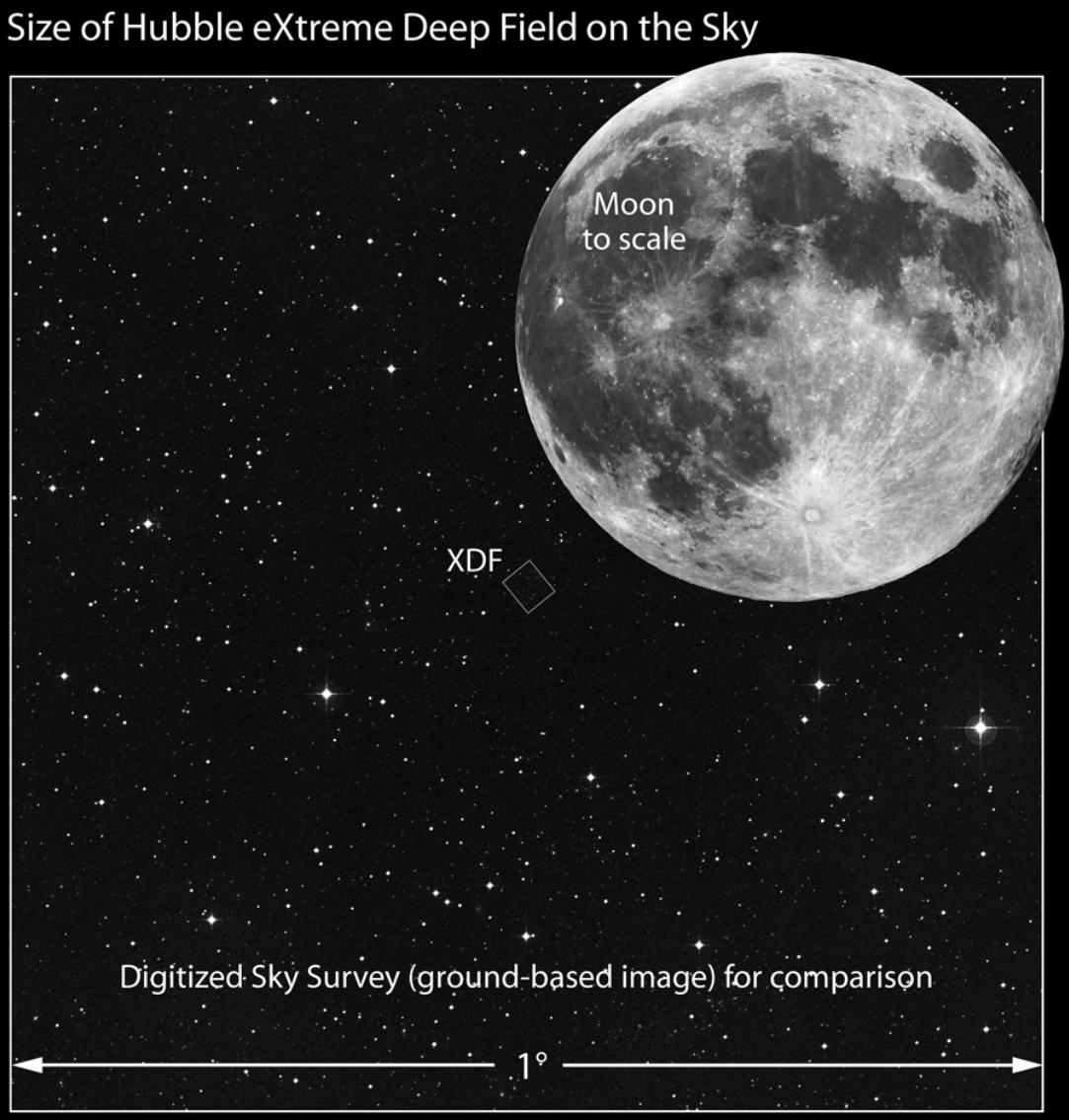
$$\theta = 1.22\,\text{rad} \cdot \lambda/d \sim 70\,\text{mas} \quad (5.9)$$

(for $d = 8\,\text{m}$, $\lambda = 2.2\,\mu\text{m}$)

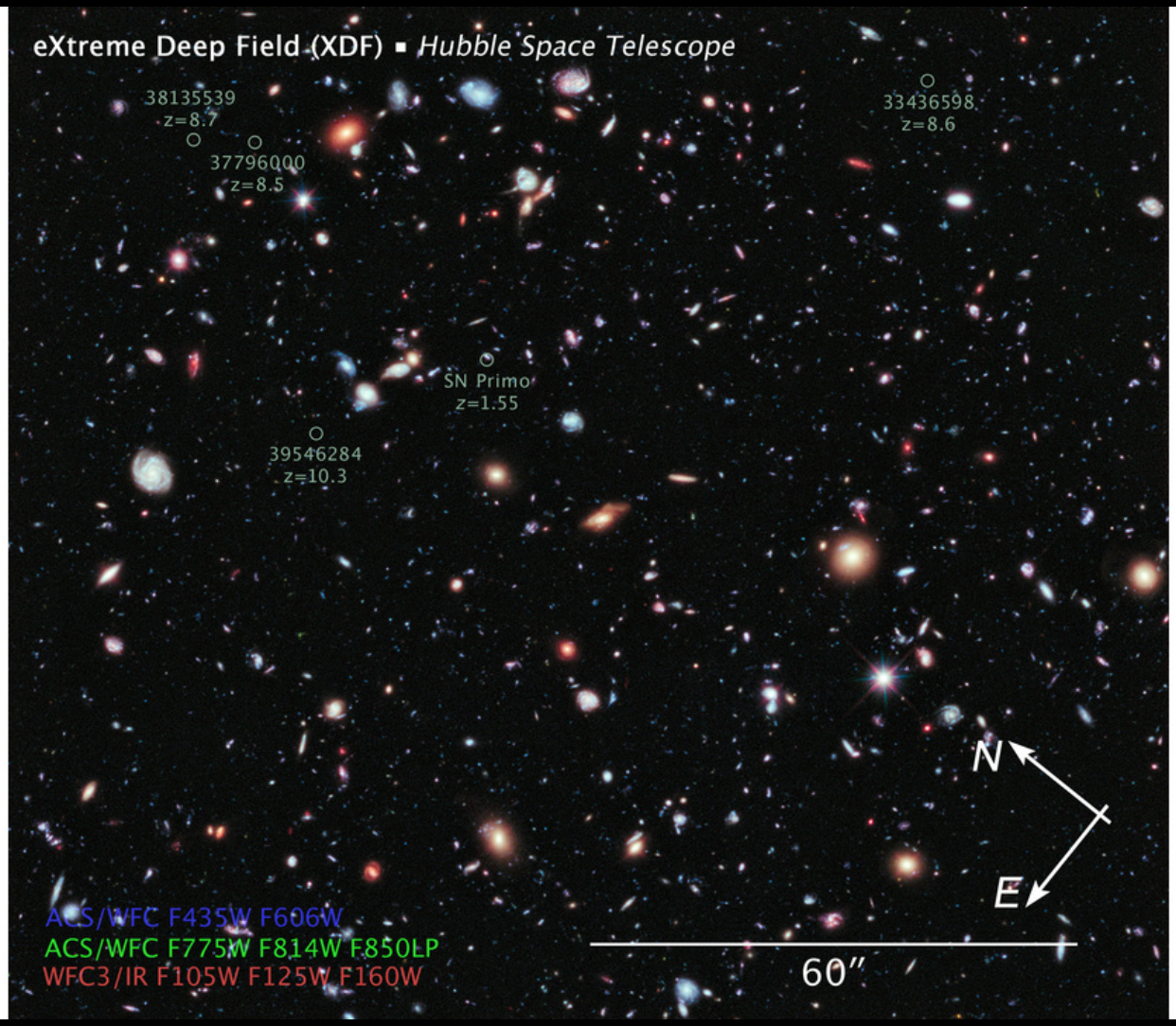


Hubble Space Telescope: Infraret to UV (Launched 1990)
2.4m Ritchey-Chrétien mirror telescope, length 13.1 m, mass 11.6 t

story of NASA astronaut Mike Massimino: `http://themoth.org/posts/stories/a-view-of-the-earth`

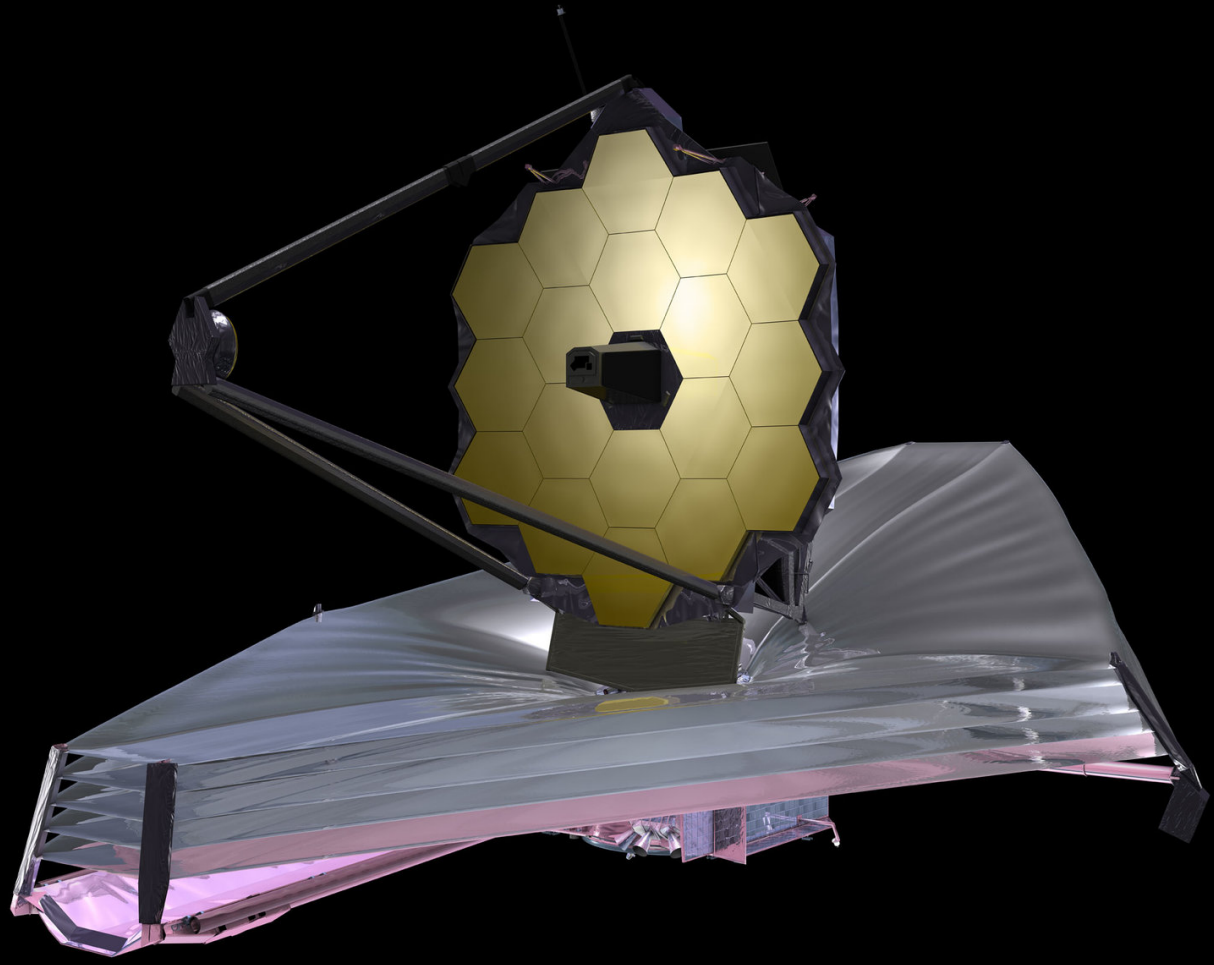


G. Illingworth, D. Magee, and P. Oesch (University of California, Santa Cruz), R. Bouwens (Leiden University), and the HUDF09 Team



Advanced Camera for Surveys & Wide Field Camera 3: 50 Tage Belichtungszeit

G. Illingworth, D. Magee, and P. Oesch (University of California, Santa Cruz), R. Bouwens (Leiden University), and the HUDF09 Team



James Webb Space Telescope: infrared-observatory (successor of Hubble)
Launched on 25.12.2021; costs: 8.8 billion US dollar

Comparing Hubble with JWST

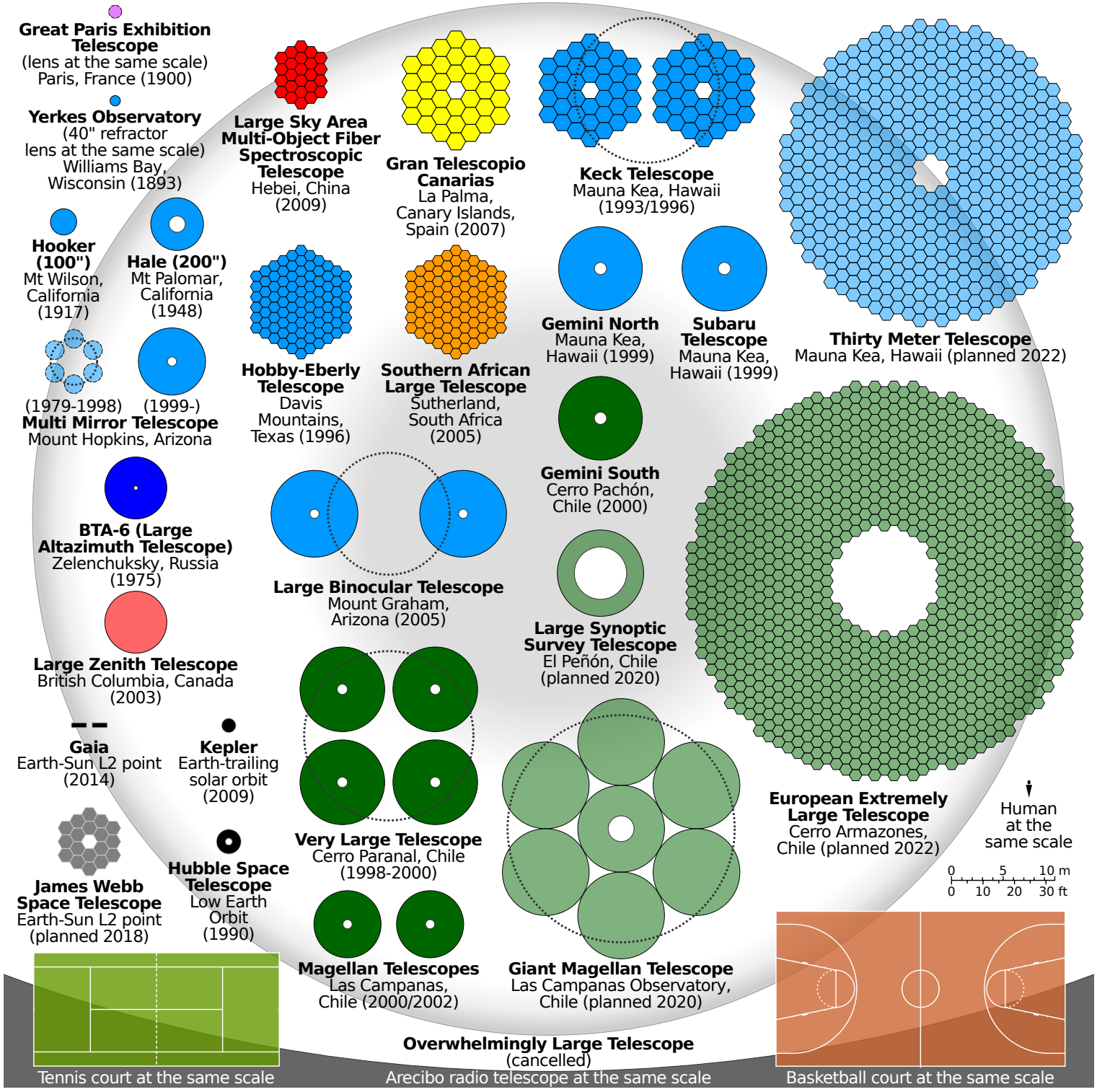


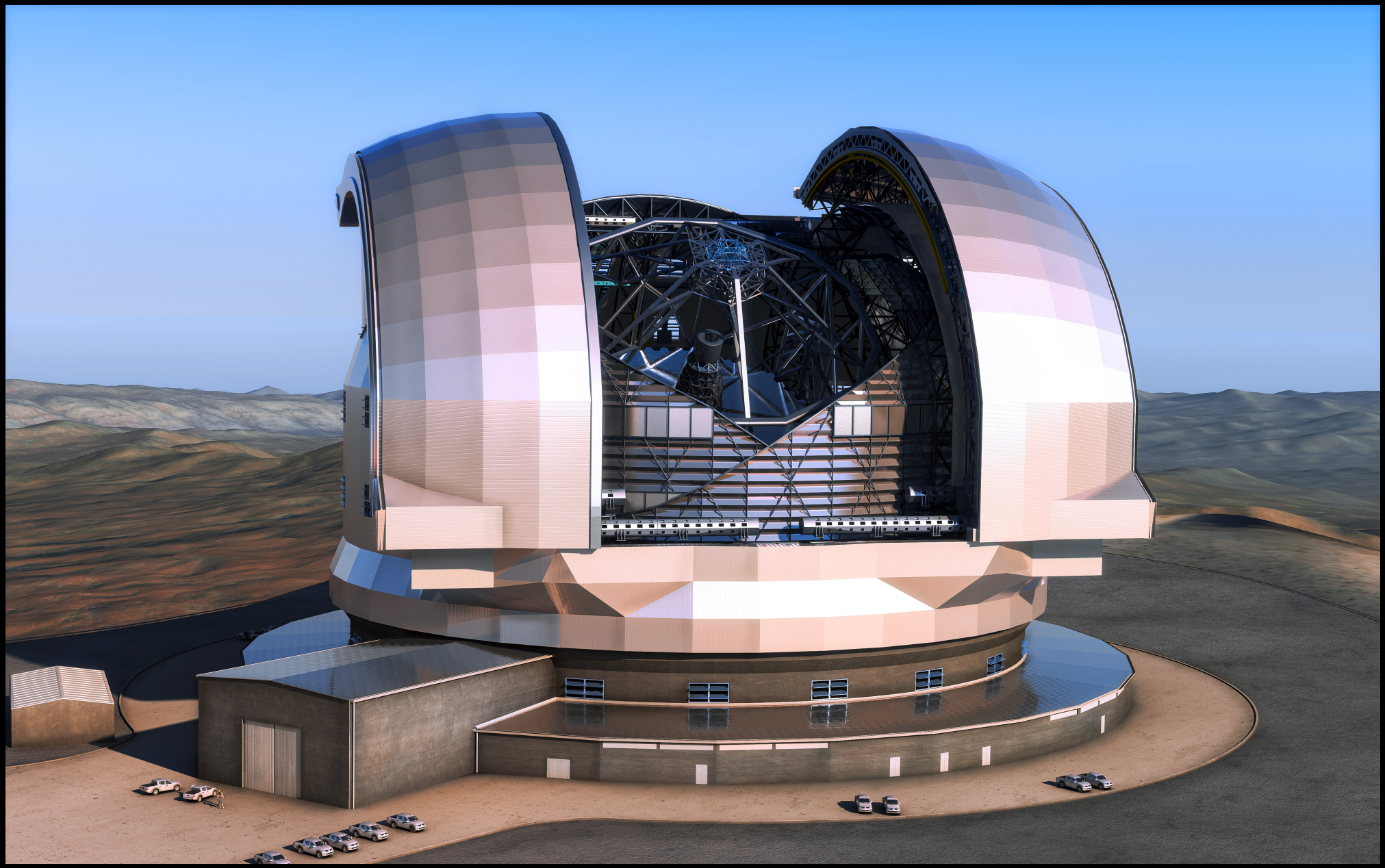
Lensed galaxy cluster SMACS 0723 (credit: NASA/ESA/CSA/STScI)

Comparing Hubble with JWST

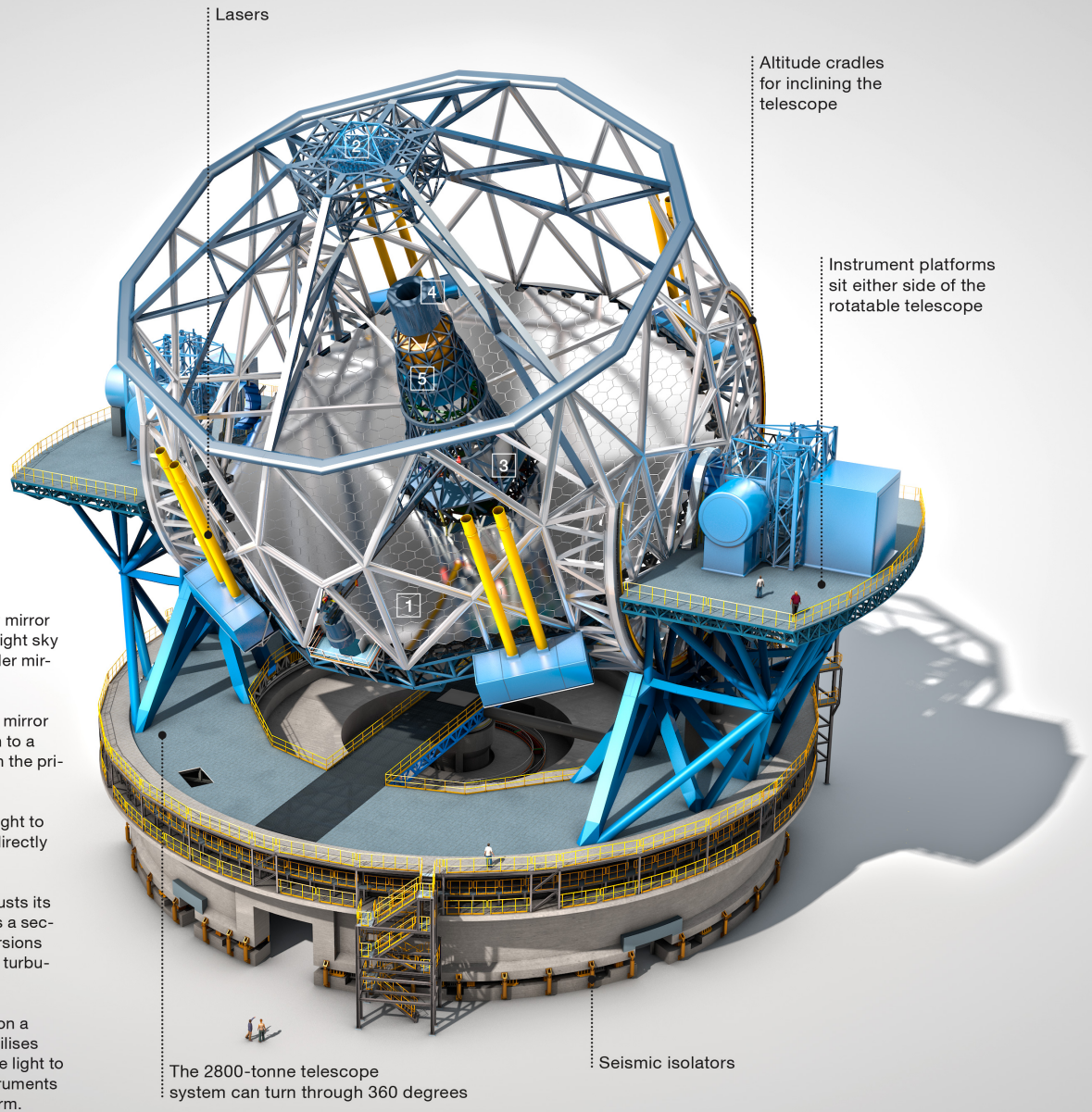


Lensed galaxy cluster SMACS 0723 (credit: NASA/ESA/CSA/STScI)


Great Paris Exhibition Telescope
(lens at the same scale)
Paris, France (1900)
Yerkes Observatory
(40" refractor
lens at the same scale)
Williams Bay,
Wisconsin (1893)
Large Sky Area Multi-Object Fiber Spectroscopic Telescope
Hebei, China
(2009)
Gran Telescopio Canarias
La Palma,
Canary Islands,
Spain (2007)
Keck Telescope
Mauna Kea, Hawaii
(1993/1996)
Thirty Meter Telescope
Mauna Kea, Hawaii (planned 2022)
Hooker (100")
Mt Wilson,
California
(1917)
Hale (200")
Mt Palomar,
California
(1948)
Hobby-Eberly Telescope
Davis
Mountains,
Texas (1996)
Southern African Large Telescope
Sutherland,
South Africa
(2005)
Gemini North
Mauna Kea,
Hawaii (1999)
Subaru Telescope
Mauna Kea,
Hawaii (1999)
(1979-1998)
(1999-)
Multi Mirror Telescope
Mount Hopkins, Arizona
Gemini South
Cerro Pachón,
Chile (2000)
BTA-6 (Large Altazimuth Telescope)
Zelenchuksky, Russia
(1975)
Large Binocular Telescope
Mount Graham,
Arizona (2005)
Large Synoptic Survey Telescope
El Peñón, Chile
(planned 2020)
Large Zenith Telescope
British Columbia, Canada
(2003)
Gaia
Earth-Sun L2 point
(2014)
Kepler
Earth-trailing
solar orbit
(2009)
European Extremely Large Telescope
Cerro Armazones,
Chile (planned 2022)
Human at the same scale
0 5 10 m
0 10 20 30 ft
Very Large Telescope
Cerro Paranal, Chile
(1998-2000)
James Webb Space Telescope
Earth-Sun L2 point
(planned 2018)
Hubble Space Telescope
Low Earth
Orbit
(1990)
Magellan Telescopes
Las Campanas,
Chile (2000/2002)
Giant Magellan Telescope
Las Campanas Observatory,
Chile (planned 2020)
Overwhelmingly Large Telescope
(cancelled)
Tennis court at the same scale
Arecibo radio telescope at the same scale
Basketball court at the same scale



The future: The European Extremely Large Telescope (E-ELT).
39 m diameter on Cerro Armazones in Chile (3060 m altitude)
Construction started 2014 June. First light expected 2024.



Five-mirror design

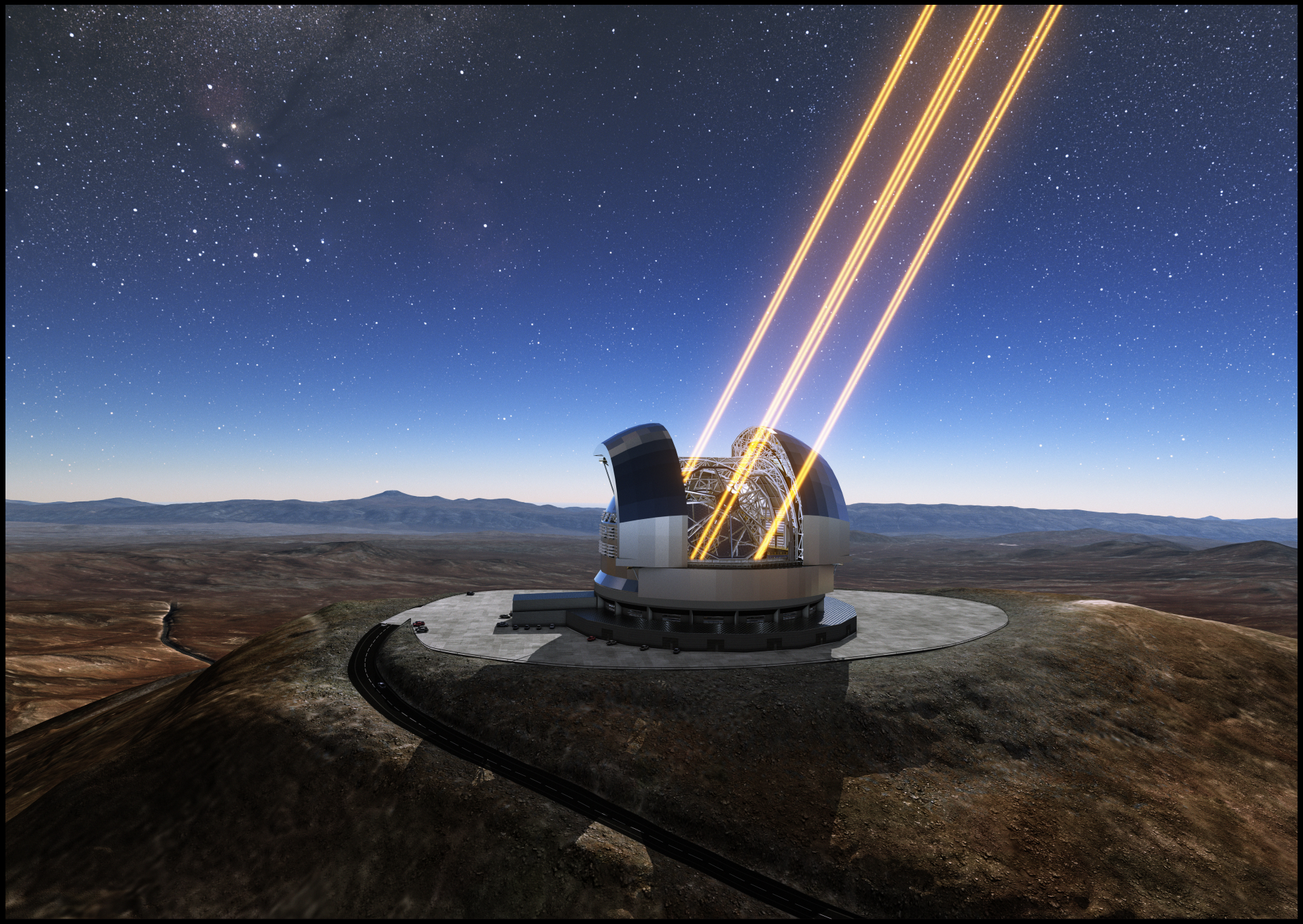
1. The 39.3-metre primary mirror collects light from the night sky and reflects it to a smaller mirror located above it.

2. The 4-metre secondary mirror reflects light back down to a smaller mirror nestled in the primary mirror.

3. The third mirror relays light to an adaptive flat mirror directly above.

4. The adaptive mirror adjusts its shape a thousand times a second to correct for distorsions caused by atmospheric turbulence.

5. A fifth mirror, mounted on a fast-moving stage, stabilises the image and sends the light to cameras and other instruments on the stationary platform.





Status 2014 December



Status 2018 December

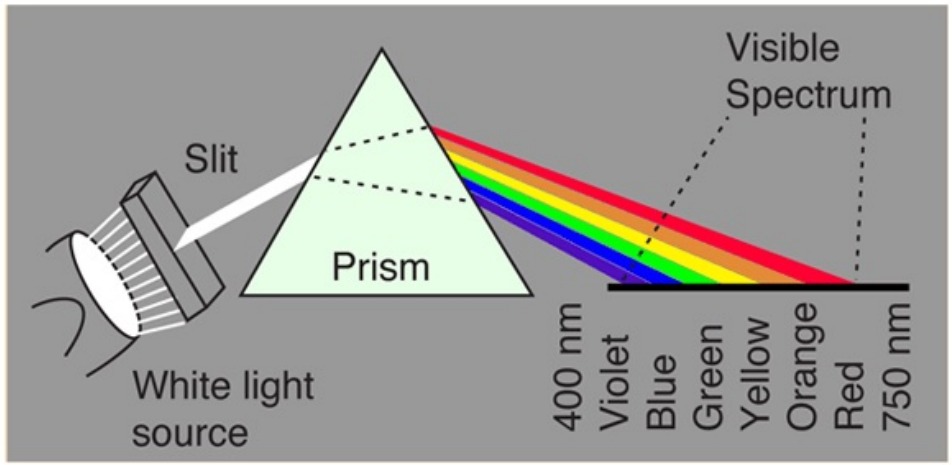


Status 2022 December 05



Status 2022 December 05

Spectroscopy

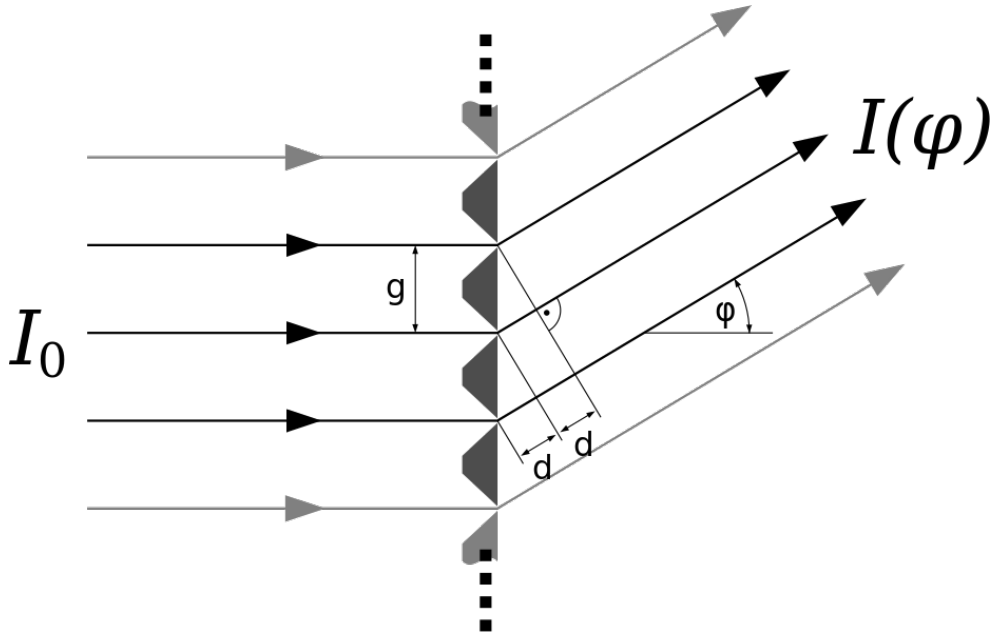


http://hyperphysics.phy-astr.gsu.edu/hbase/vision/specol.html

Light: Superposition of waves with different wavelengths.
Disassemble light into its spectrum (for different wavelength, i.e., colors).
Dispersion: change of physical parameter in dependence of wavelength (or frequency).
Detect the diffracted light.

Prisms are usually not used in Astronomy.

Spectroscopy



Wikipedia

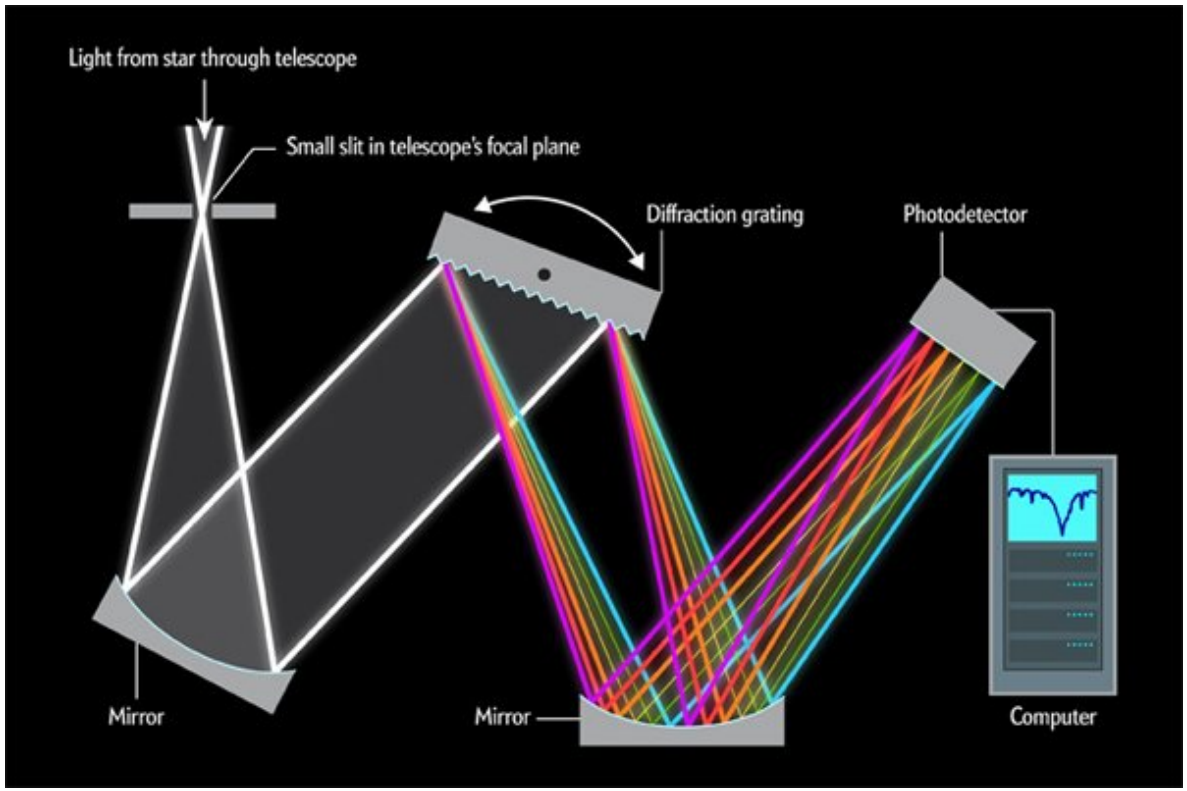
Transmission grating:

Constructive interference at

$$\sin\phi = \frac{m\lambda}{g}, m = \pm 1, \pm 2, ...$$

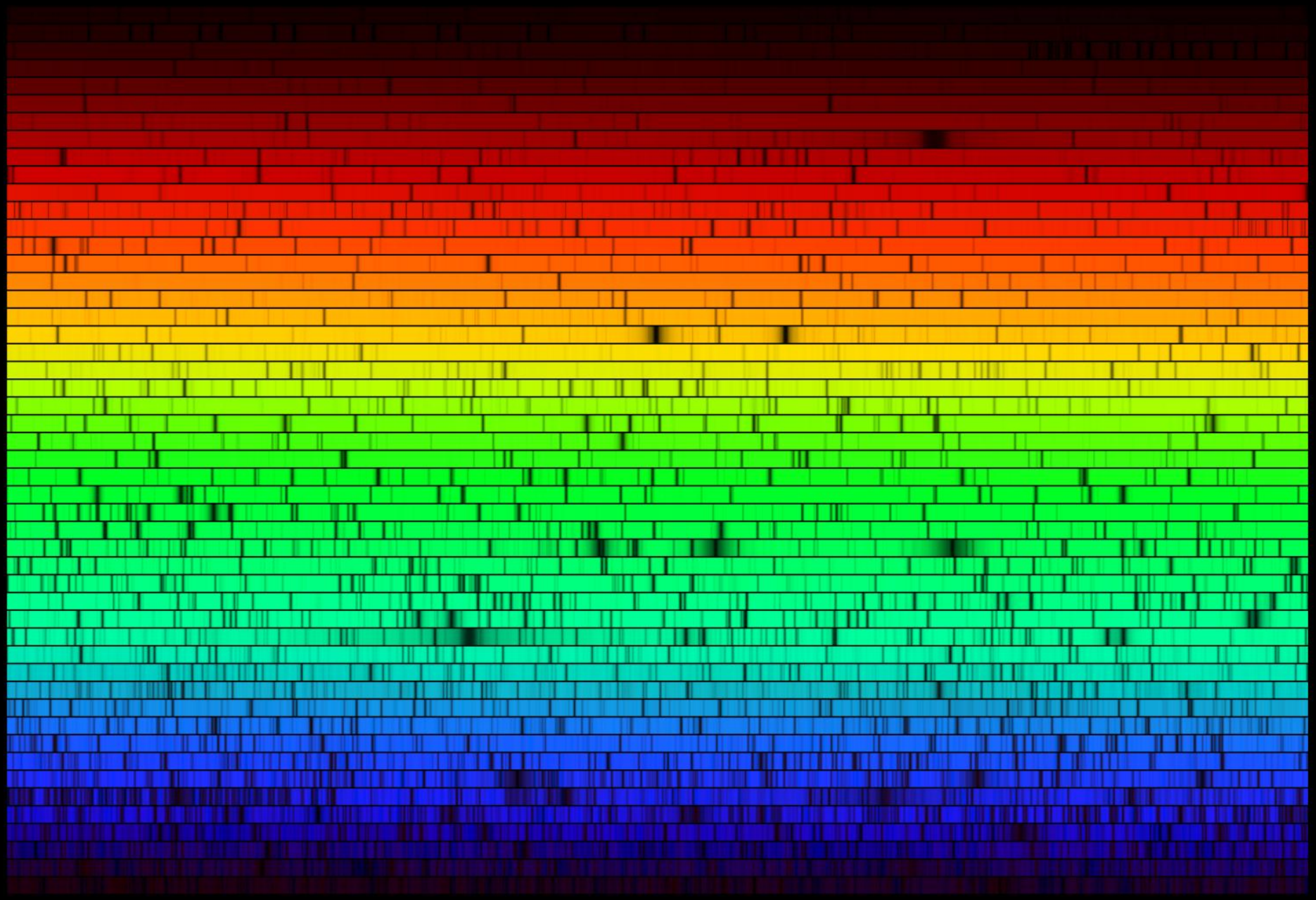
Position (angle ϕ) depends on λ.

Spectroscopy



Scientific American, illustration by George Retseck

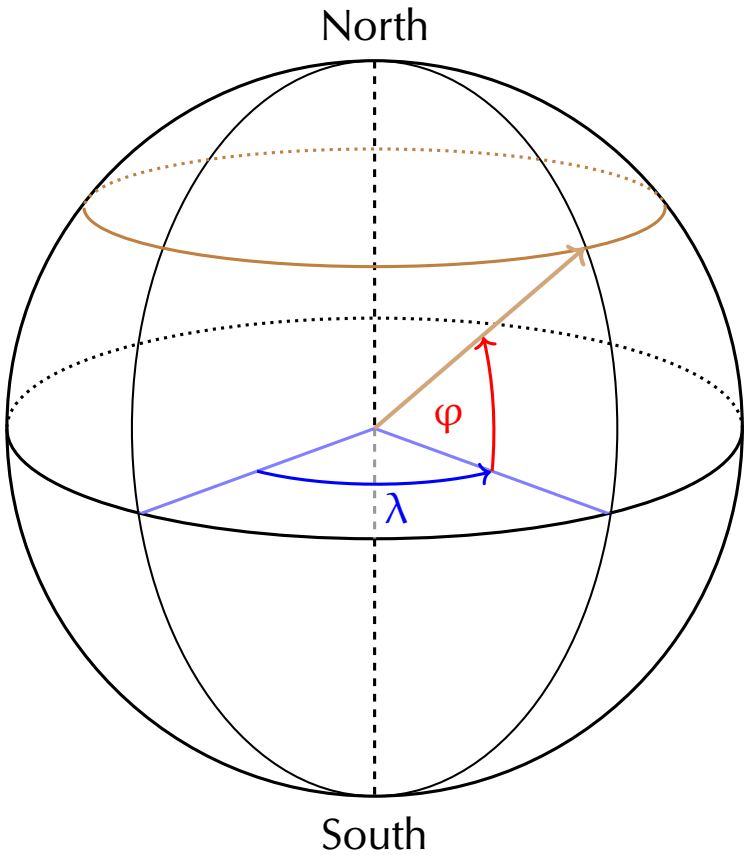
"Blaze" grating: 'grazing'.
More light at higher m.
$\Longrightarrow$ high efficiency for high dispersion.



N.A.Sharp, NOAO/NSO/Kitt Peak FTS/AURA/NSF

Solar spectrum

Positions on Earth



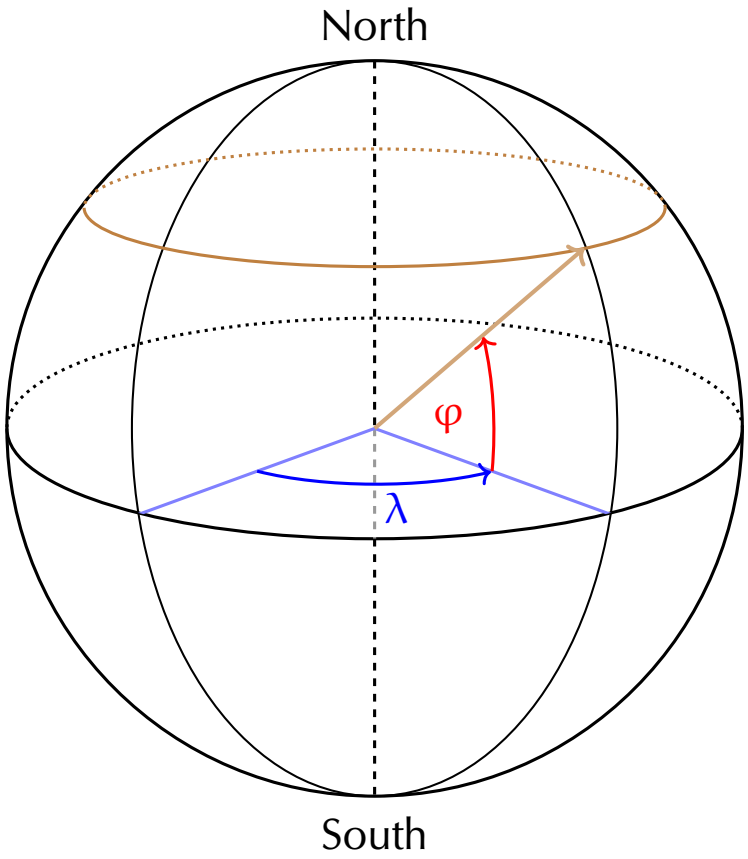


λ: geographic longitude (deg),

φ: geographic latitude (deg)

$\lambda = 0°$ defined by position of a meridian circle in Greenwich (London)

Positions on Earth



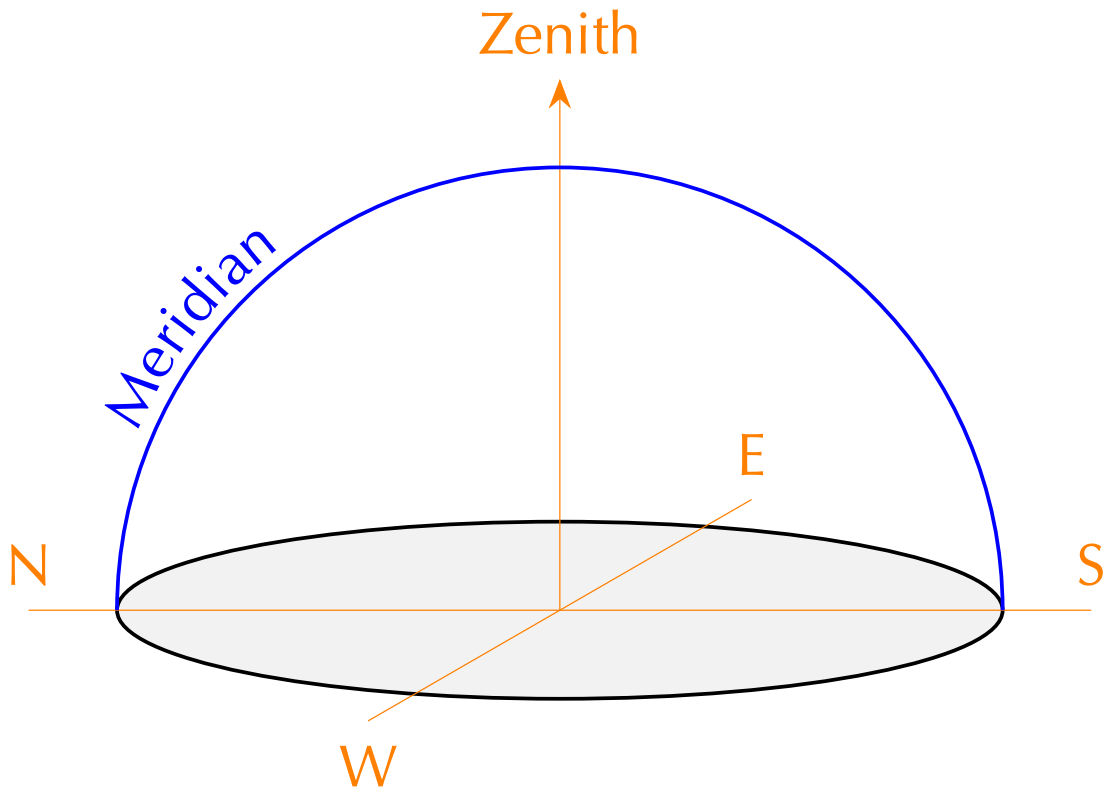


λ: geographic longitude (deg),

φ: geographic latitude (deg)

$\lambda = 0°$ defined by position of a meridian circle in Greenwich (London)

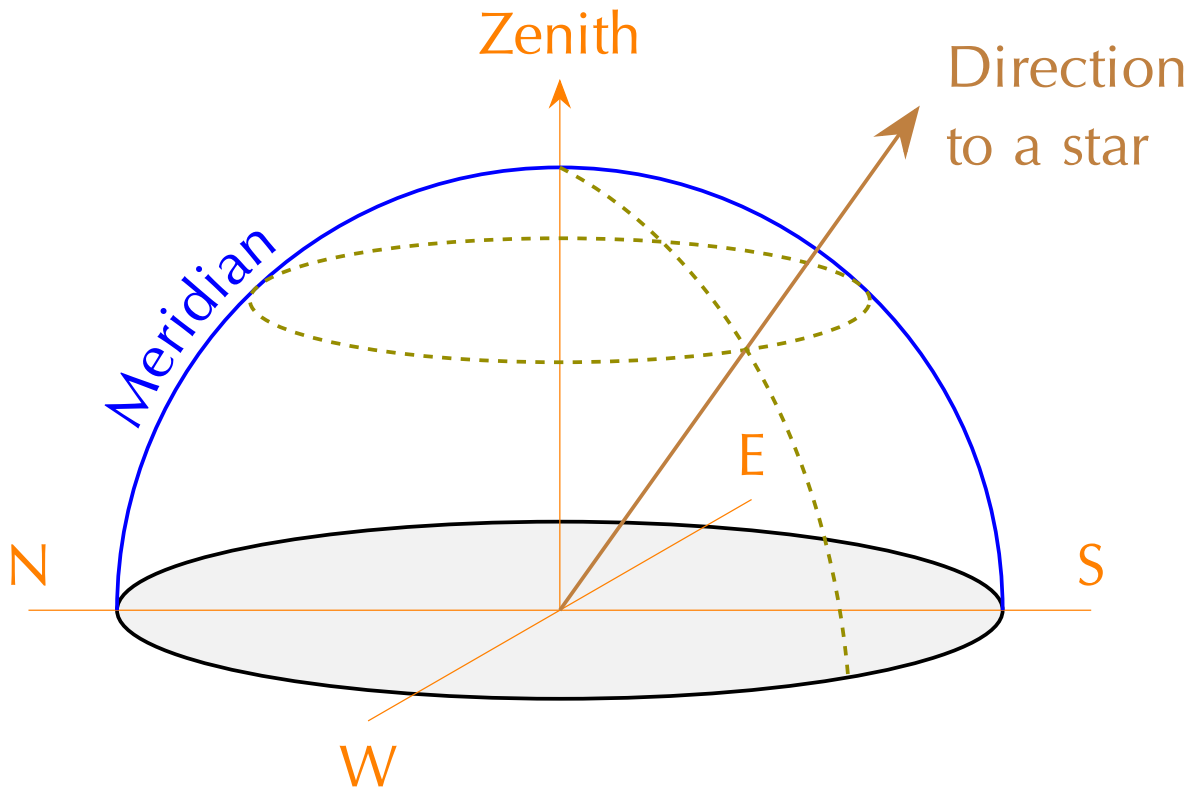
Horizon System



after Giese

Horizon system:

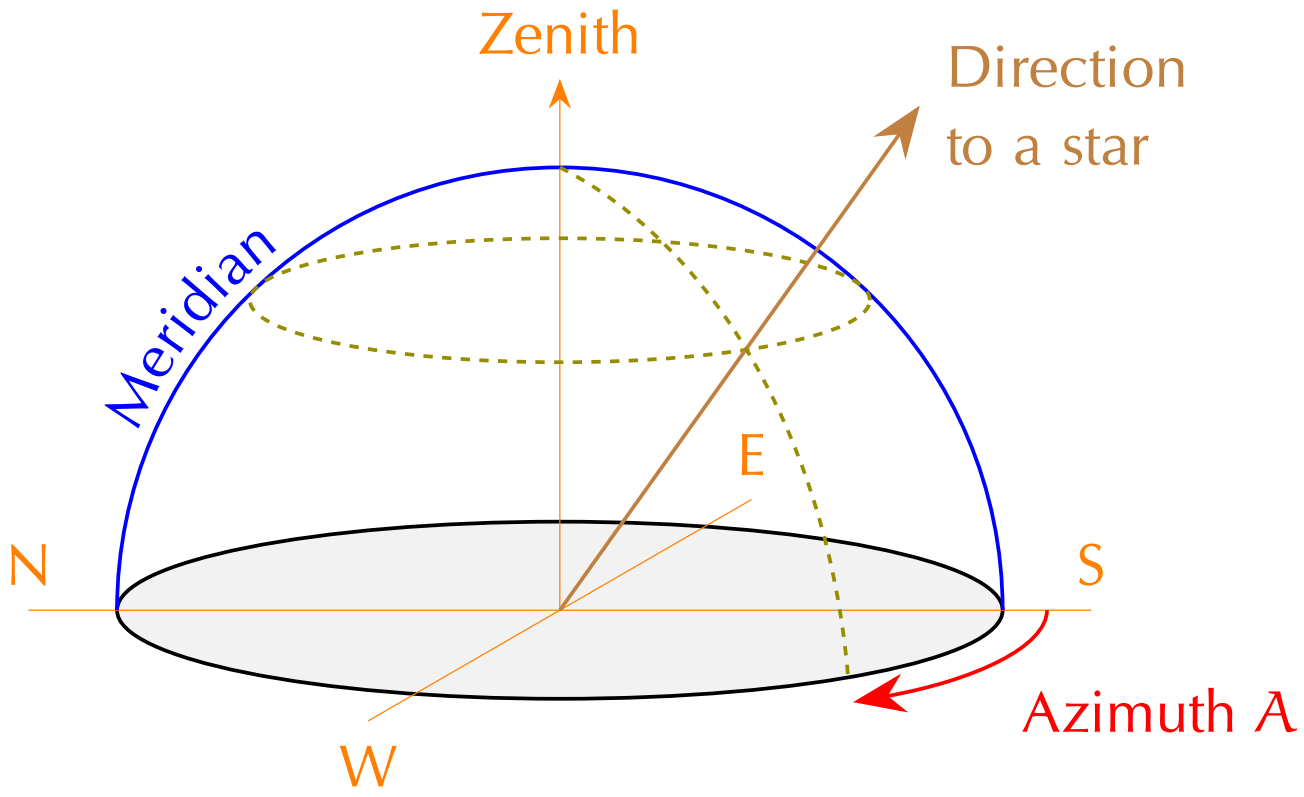
Horizon System



after Giese

Horizon system: Direction to a star

Horizon System

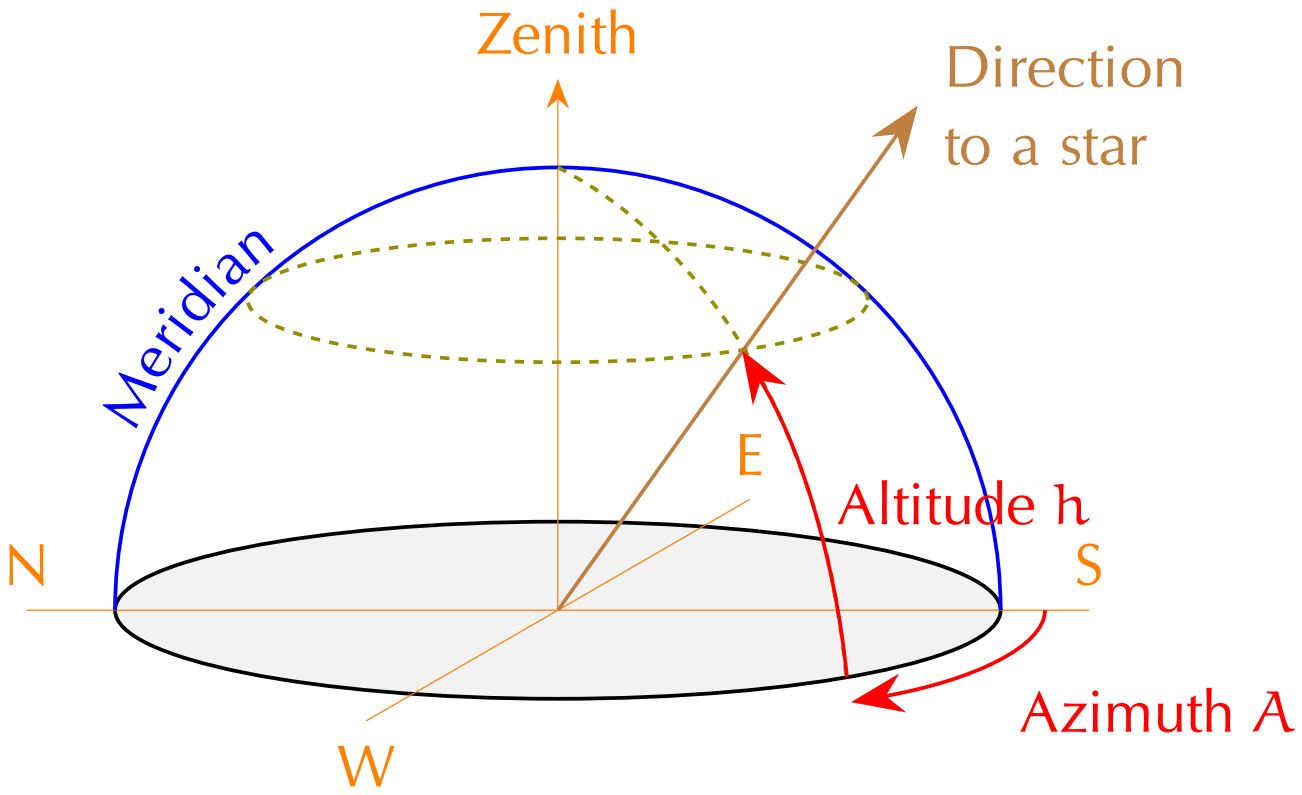


after Giese

Horizon system: Direction to a star

- Azimuth A: angle in horizontal S-W-N-E

Horizon System

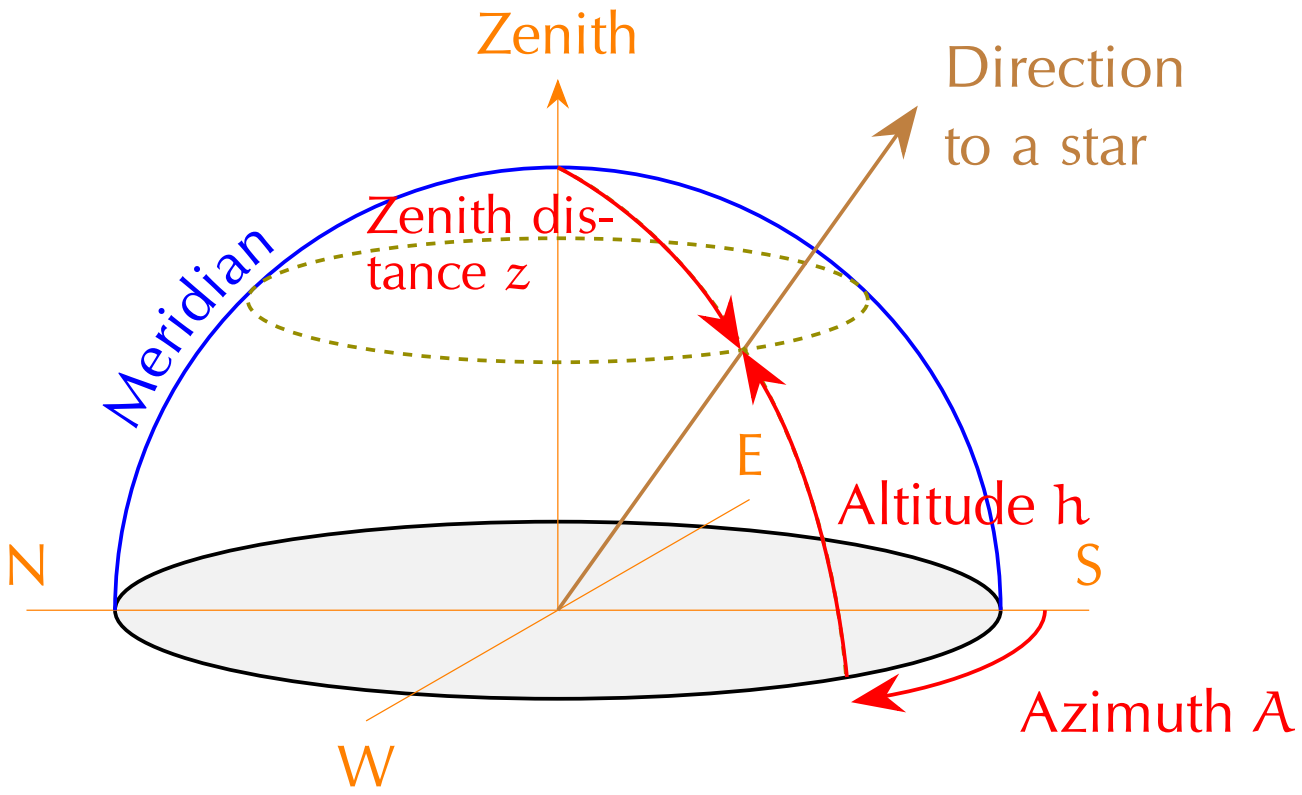


after Giese

Horizon system: Direction to a star

- Azimuth A: angle in horizontal S-W-N-E
- Altitude h: angle from horizon towards zenith

Horizon System



after Giese

Horizon system: Direction to a star

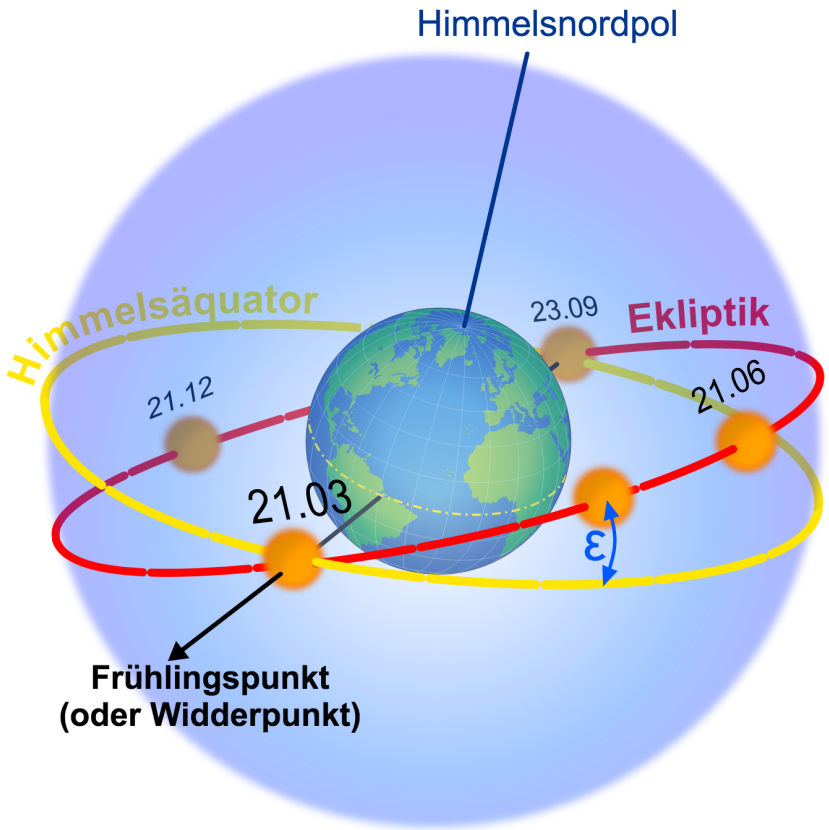
- Azimuth A: angle in horizontal S-W-N-E
- Altitude h: angle from horizon towards zenith
- Zenith distance z: $z = 90° - h$



http://joeorman.shutterace.com/Trails/Trails_021227_5.html

Earth rotates: A, $\mathfrak{h}$ do not define position of stars at any time

Equinox



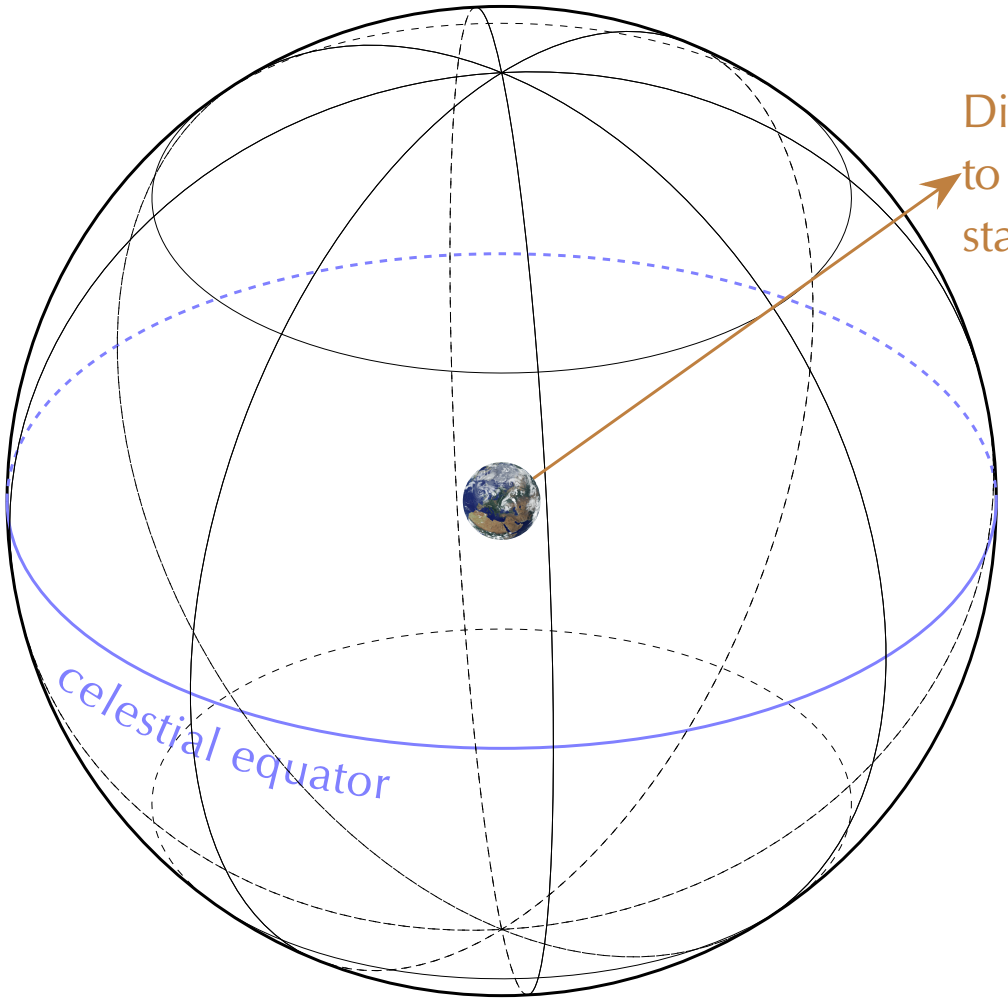
Wikipedia

Two planes defined by Earth:
Equator and ecliptic

Intersection defines the spring equinox
(first point of Aries):
Sun crosses equator from S to N
20/21 March; start of spring

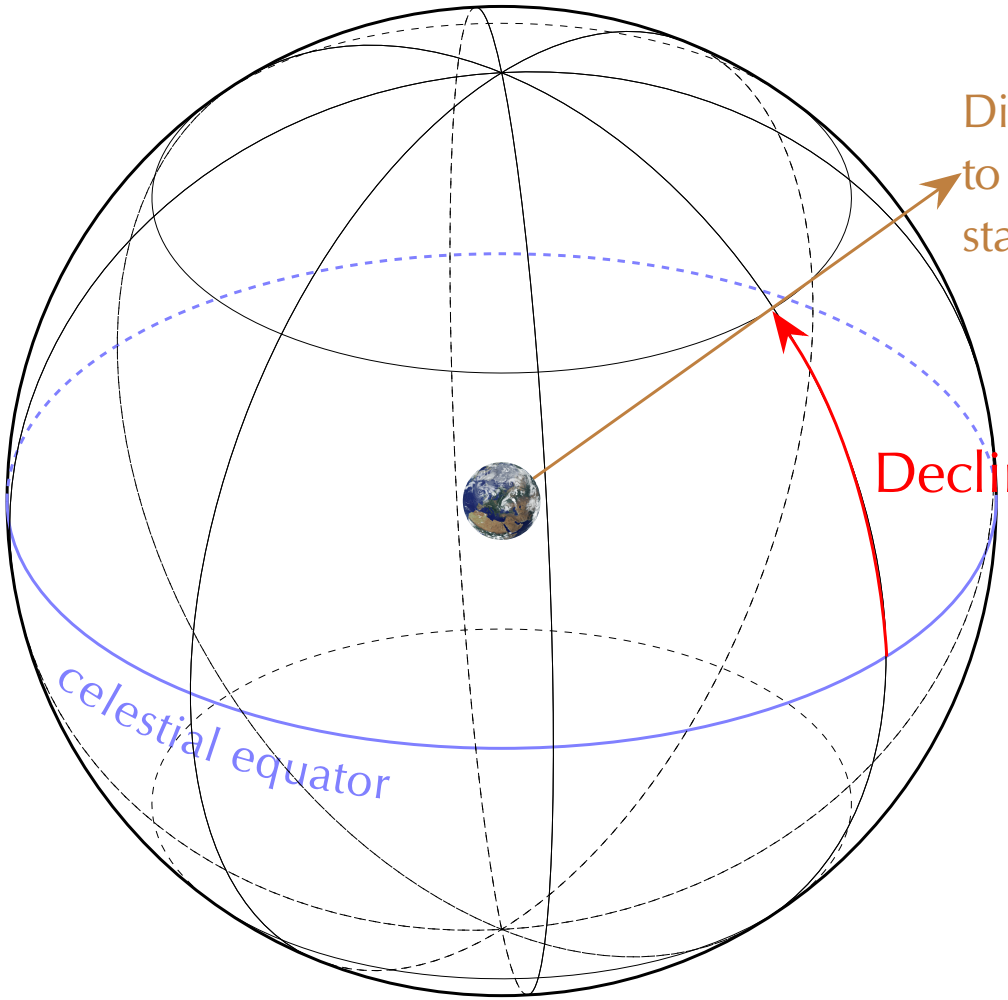
Obliquity of the ecliptic: $\epsilon = 23.5°$.

Equatorial System



Fixed coordinates to star

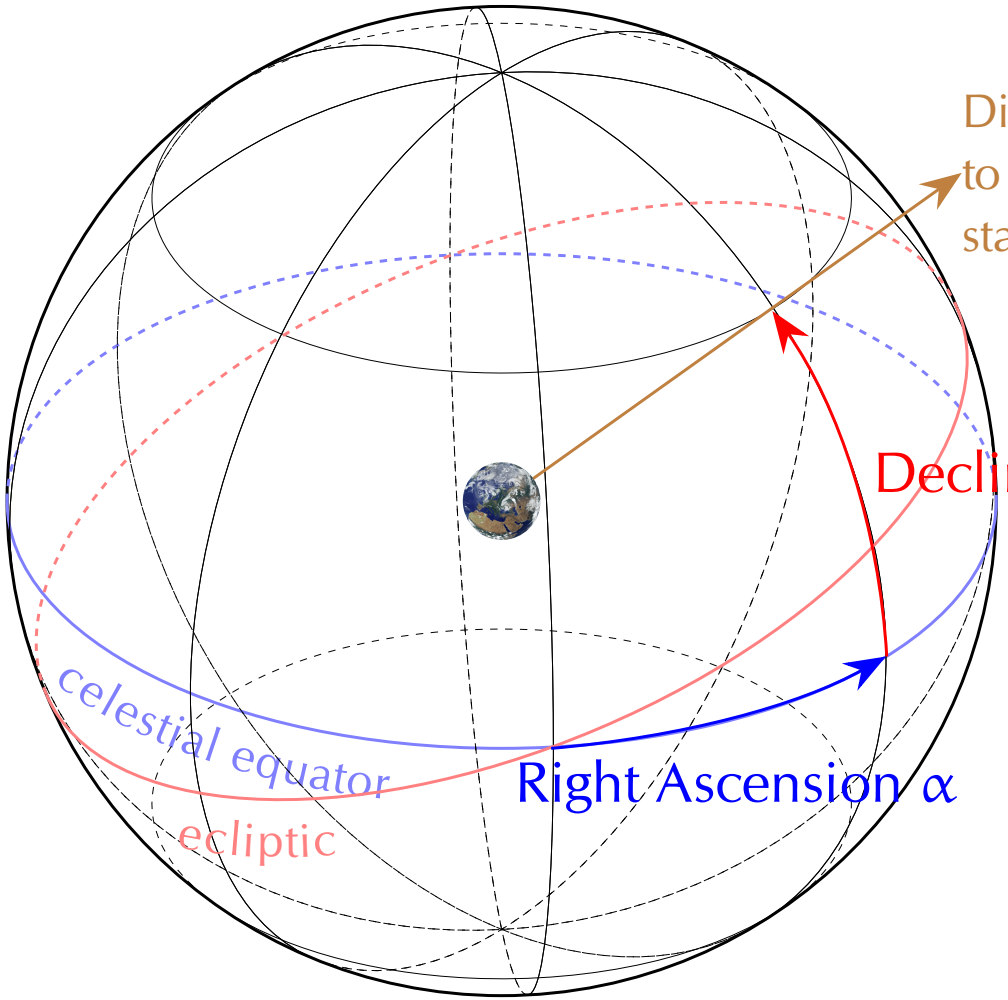
Equatorial System



Fixed coordinates to star:

- Declination δ:
  $\angle$(celestial equator, star)
  Measured in °, ′, ″

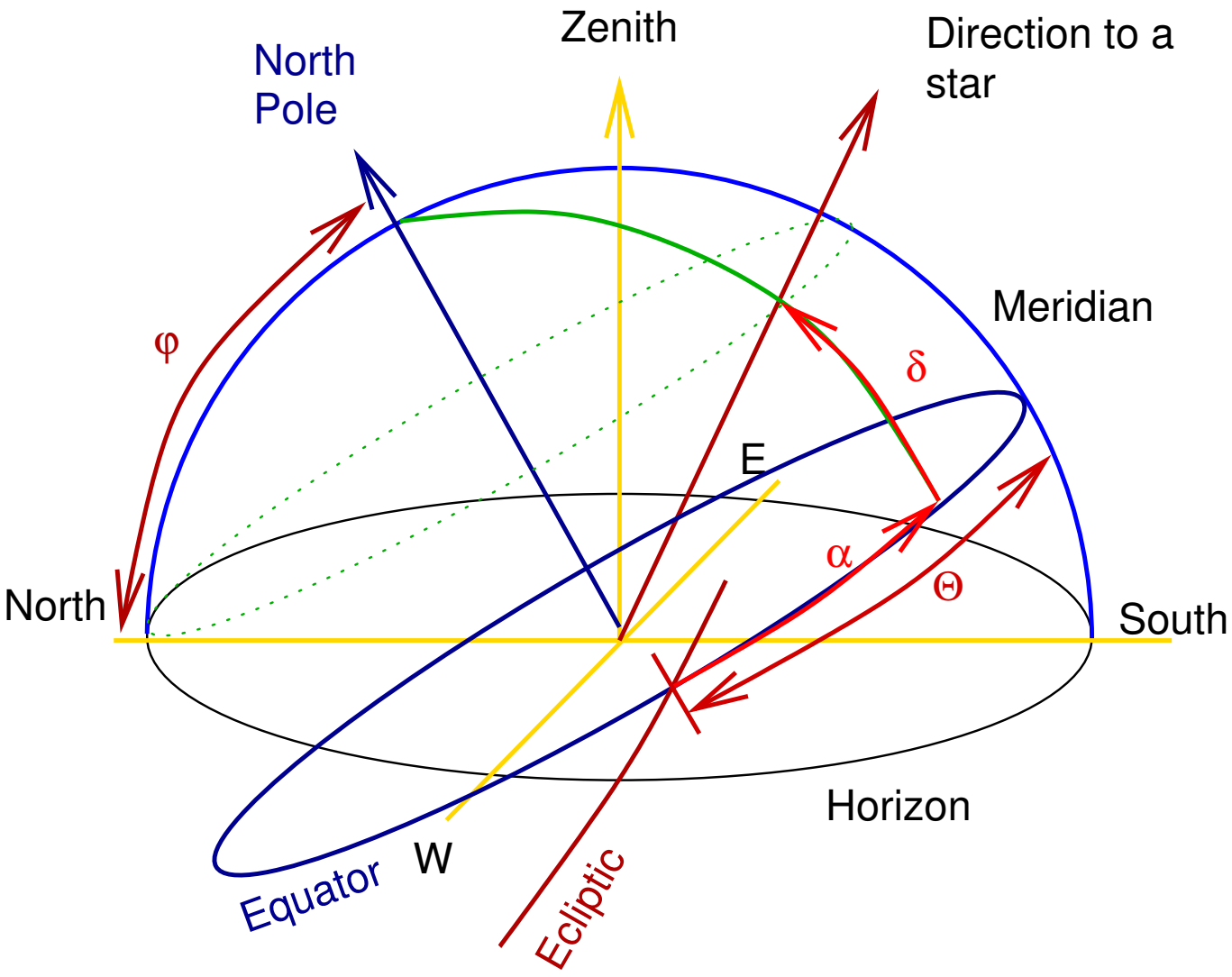
Equatorial System



Fixed coordinates to star:

- Declination δ:
  $\angle$(celestial equator, star)
  Measured in °, ′, ″
- Right ascension α: angle along equator from ascending node of Sun (vernal equinox) to star
  Measured in h, m, s

Siderial Time



Define siderial time: 24 h correspond one rotation of the celestial sphere.

0 h siderial time = time when vernal equinox passes through meridian.

$\Longrightarrow$ Local siderial time: Right ascension of stars passing through meridian.

Right Ascension is measured in hours, minutes, and seconds

1 h corresponds to 15°.
α increases towards East.

Siderial Time

Note: Siderial time $\neq$ common time

Common time: 24 h between culminations of the Sun (i.e., passes of Sun through meridian).

BUT

Sun moves on sky towards east

$\Longrightarrow$ one "solar day" takes slightly longer than one rotation of the Earth

Angular speed of Sun: 360° degrees in 365.25 days, i.e., $0.9856^\circ\,\mathrm{d}^{-1}$.

$\Longrightarrow$ During 365.25 days the Earth rotates 366.25 times

$\Longrightarrow$ Earth's rotation takes $24\,\mathrm{h} \times 365.25/366.25 = 23\,\mathrm{h}\ 56\,\mathrm{minutes}$.

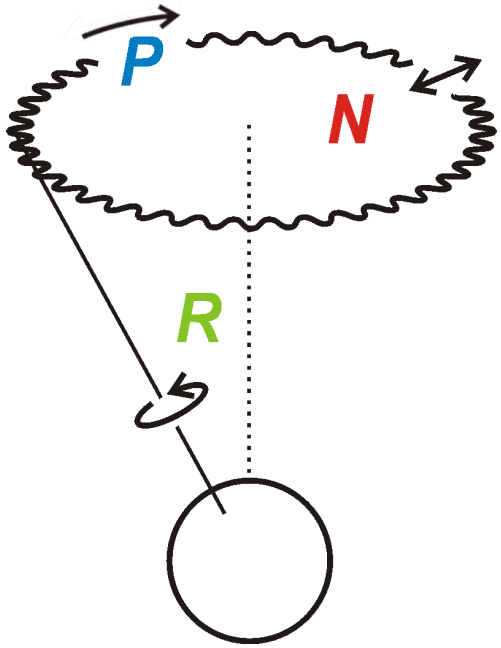
Precession and Nutation

Earth is ~ rotational ellipsoid, orbits of Sun and Moon are *not* in plane of equator

(Earth's axis has tilt of ~23.5°, Moon's orbit tilted by 7° against ecliptic)

$\Longrightarrow$ Sun and Moon exert torques onto Earth

Earth's rotational axis is not stable in space.

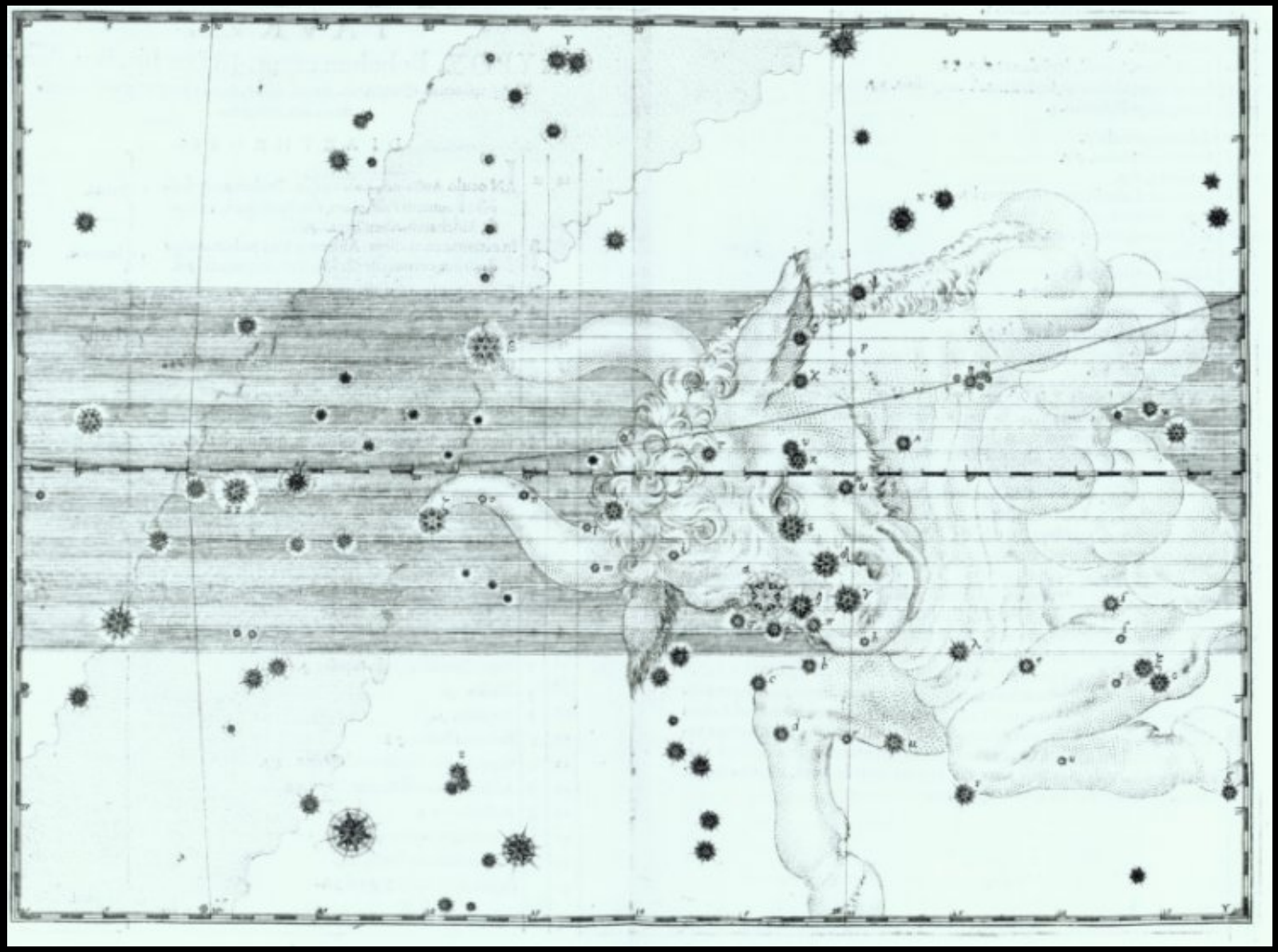


Two major effects:

luni-solar precession: Earth's axis rotates around pole of ecliptic once every 25800 years (~50″ per year).
Discovered by Hipparcos in ~200 BC!

nutation: "Wobble" with ~18 year periodicity caused by short-term perturbations caused by Moon and Sun.

Note: both effects are due to the same physical mechanism, terminology is mainly historical.



Bayer's Uranometria (1603; University of Illinois collections)

Because of precession and nutation: need to state epoch of coordinate!

Aldebaran = α Tau: $\alpha_{\mathrm{J2000.0}} = 04^{\mathrm{h}}35^{\mathrm{m}}55.2387^{\mathrm{s}}$, $\delta_{\mathrm{J2000.0}} = +16^{\circ}30'33.485''$

corresponding to $\alpha_{\mathrm{B1950.0}} = 04^{\mathrm{h}}33^{\mathrm{m}}02.9^{\mathrm{s}}$, $\delta_{\mathrm{B1950.0}} = +16^{\circ}24'37.6''$

Extrasolar Planets

Formation of the solar system

Facts to be explained:

- planetary orbits all lie almost in the same plane, parallel to the Sun's equator, almost circular

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$$a_n = 0.4 + 0.3 \times 2^n \tag{8.1}$$

for $n = -\infty, 0, 1, \ldots, n = 3$: asteroid belt (Ceres))

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- terrestrial and giant planets are physically and chemically different
- satellite systems resemble miniature solar systems in structure

Nebula Hypothesis

"Nebula hypothesis": Formation of solar system by collapse of an interstellar cloud (first discussed by I. Kant in 1755)

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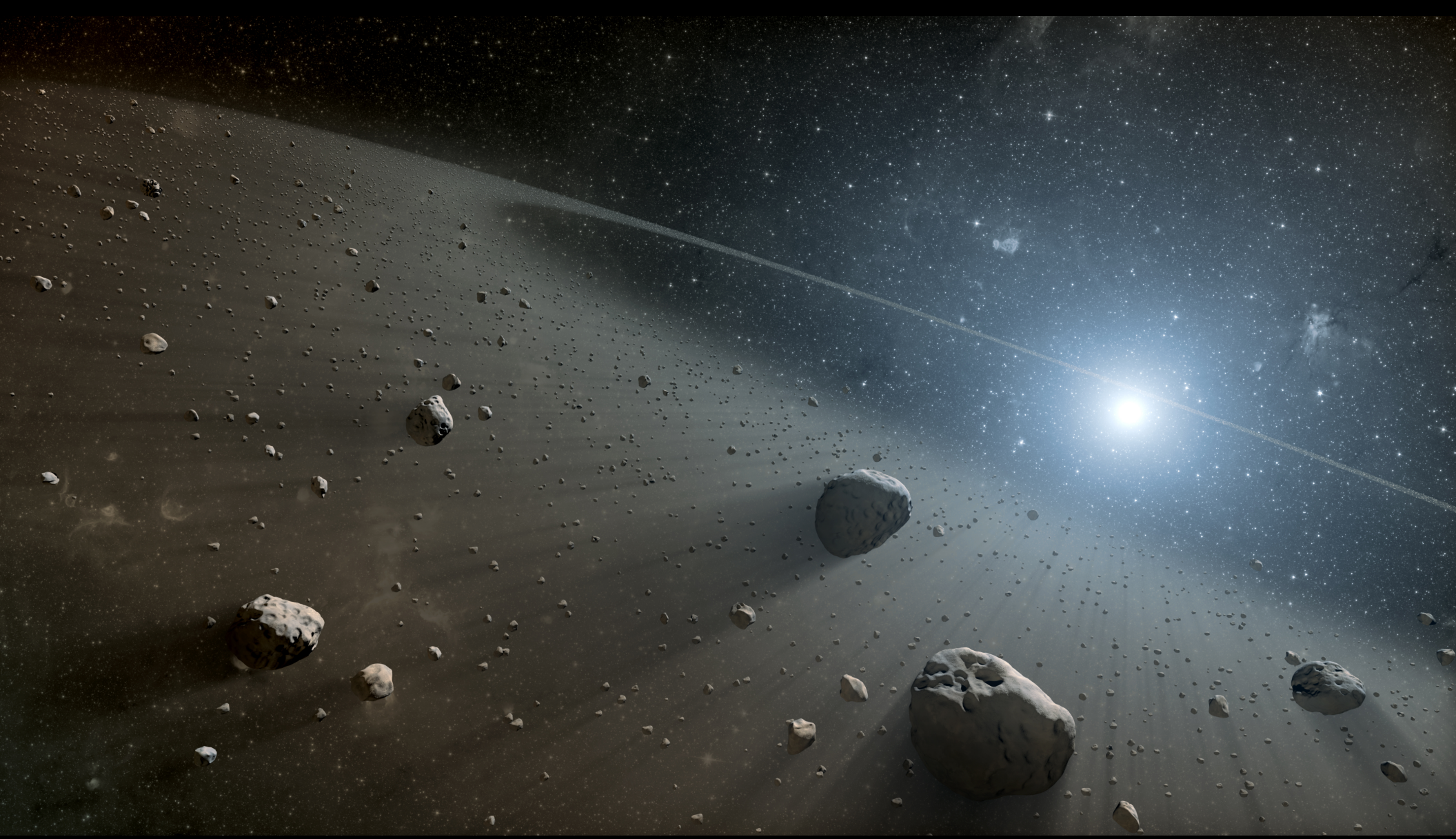
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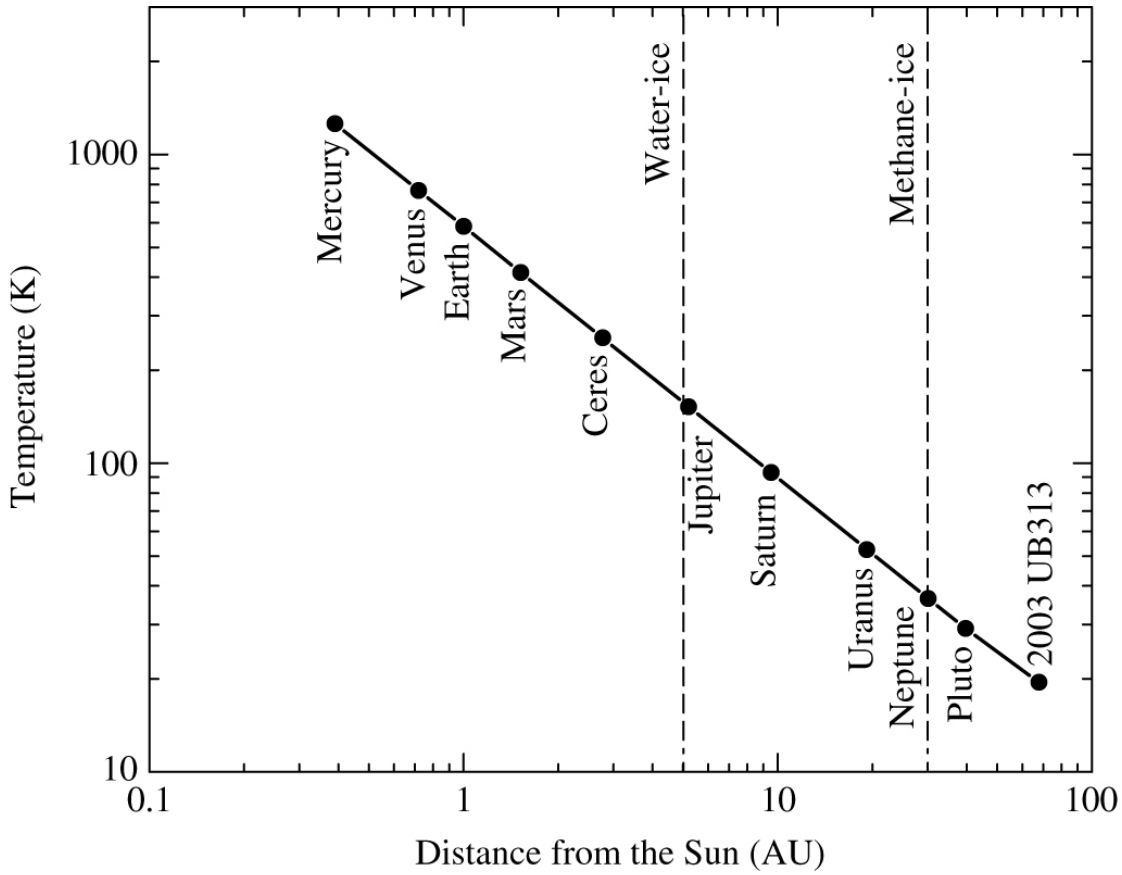
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- ~1 Myr after the nebula cooled, star generates a very strong solar wind, gas left in the protoplanetary nebula is swept away.
- "Planetesimals" collide with each other and become more massive.
- After 10 to 100 Myr: planets in stable orbits $\Longrightarrow$ solar system formed



Nebula Hypothesis

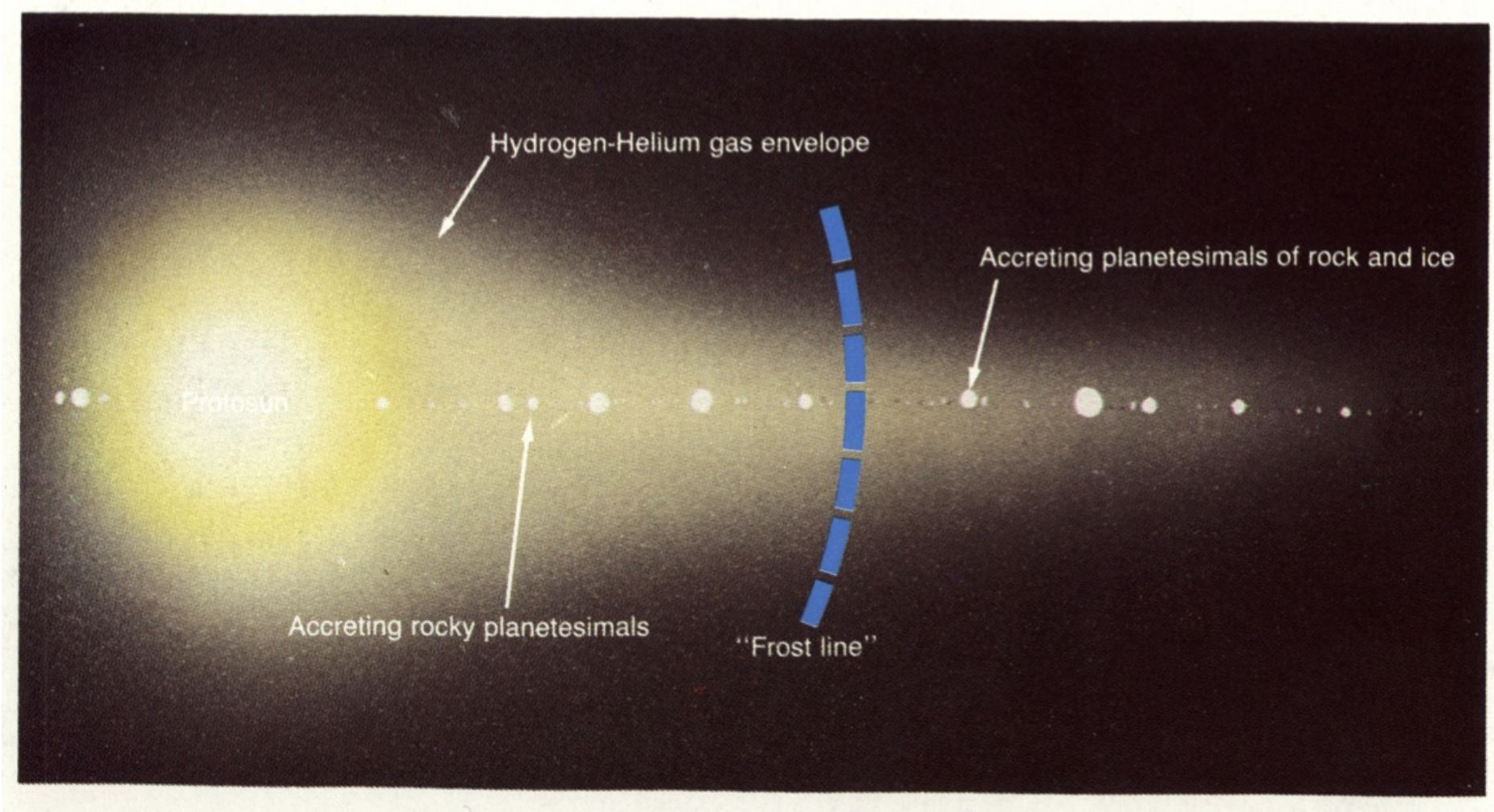


Temperature gradient in the early solar nebula (Carroll & Ostlie)

Condensation of dust and ices: Chemical differentiation according to temperature:

- $T > 1500\,K$: Fe, Ni, CaO, AlO condense
- $1500\,K > T > 1000\,K$: Silicates (e.g., feldspar)
- $1000\,K > T > 800\,K$: FeS
- $800\,K > T > 500\,K$: Metallic Oxides
- $T < 150\,K$: Water ice

Nebula Hypothesis



"frostline": change in expected planet structure



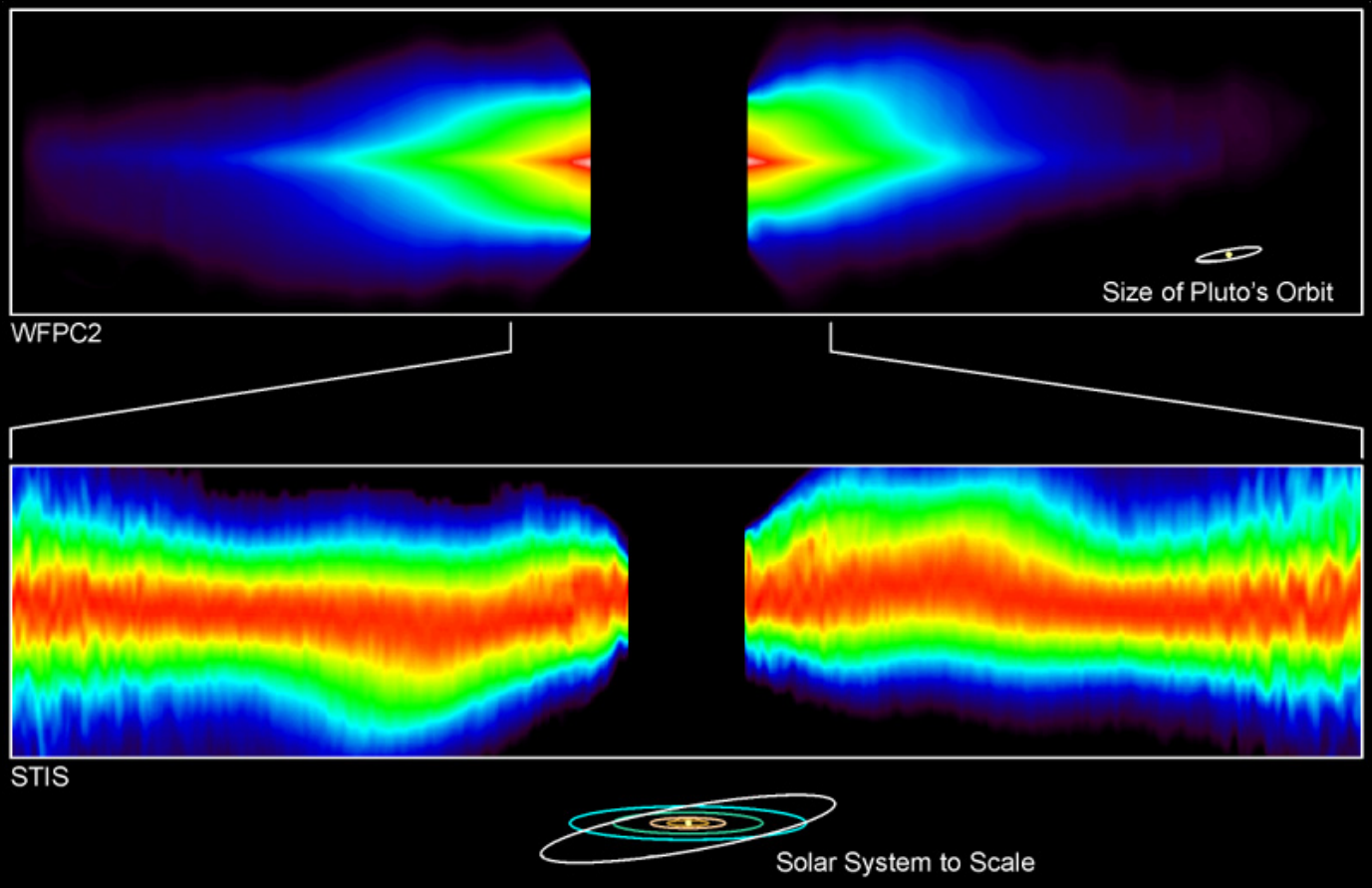
Edge-On Protoplanetary Disk
Orion Nebula

HST • WFPC2

PRC95-45c • ST ScI OPO • November 20, 1995

M. J. McCaughrean (MPIA), C. R. O'Dell (Rice University), NASA

Disk around the young star



Beta Pictoris HST • WFPC2 • STIS

PRC98-03 • January 8, 1998 • ST ScI OPO

A. Schultz (Computer Sciences Corp.), S. Heap (NASA Goddard Space Flight Center) and NASA

"False color" image: gradations in the brightness of the disk scattering the starlight.
Warps in the disk: gravitational pull of one or more unseen planets.

Introduction

So far: have looked at planets around our Sun

Physics question:

Is our Solar System normal?

$\Longrightarrow$ Are there planets around other stars?

can then compare solar system with other systems.

To answer these questions, we need to detect extrasolar planets.

Detection Methods

Possible ways to detect extrasolar planets:

Direct Method:

- . . . direct imaging of planet (visual binary)

Indirect Methods: search for evidence for. . .

- . . . radial velocity: Motion of host star (spectroscopic binary)
- . . . periodic variation of proper motion of the star (like Sirius; astrometric binary)
- photometry: light curves: occultation (transits)
- others (not discussed here):
  - . . . influence of planet on light from behind planet (gravitational lensing)
  - . . . time of flight variations (pulsars, pulsating stars)

Direct Imaging

In order to make an image of an extrasolar planet, need to separate images of star and planet with telescope

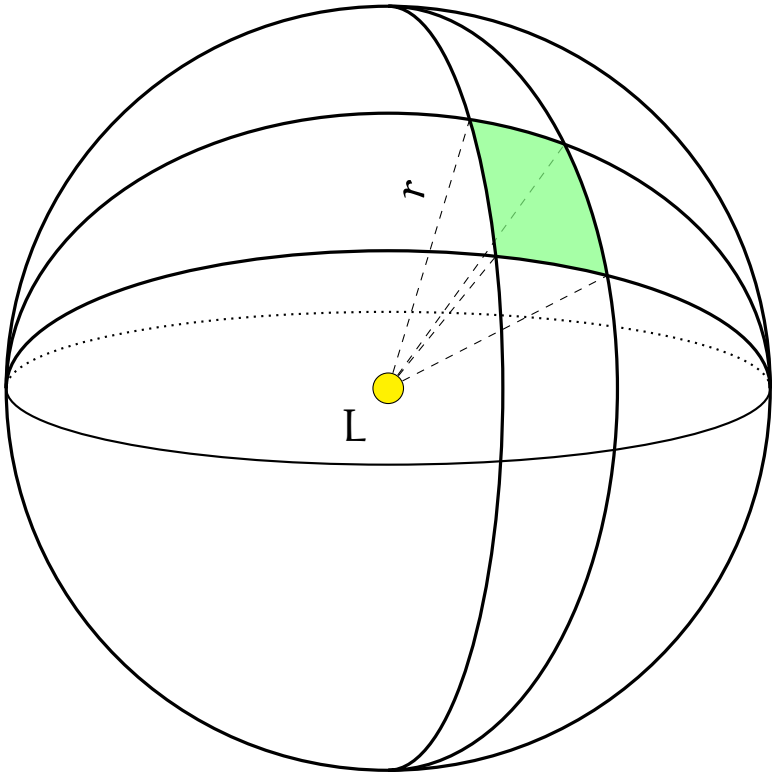
$\Longrightarrow$ Requires two ingredients:

1. "contrast" (relative intensity of star and planet)
2. "resolving power" of telescope (angular distance between star and planet)

Direct Imaging: Contrast

Estimate intensity contrast between star and planet:

Solar system: Luminosity of Sun $L = 3.90 \times 10^{26}\,W =: L_\odot$

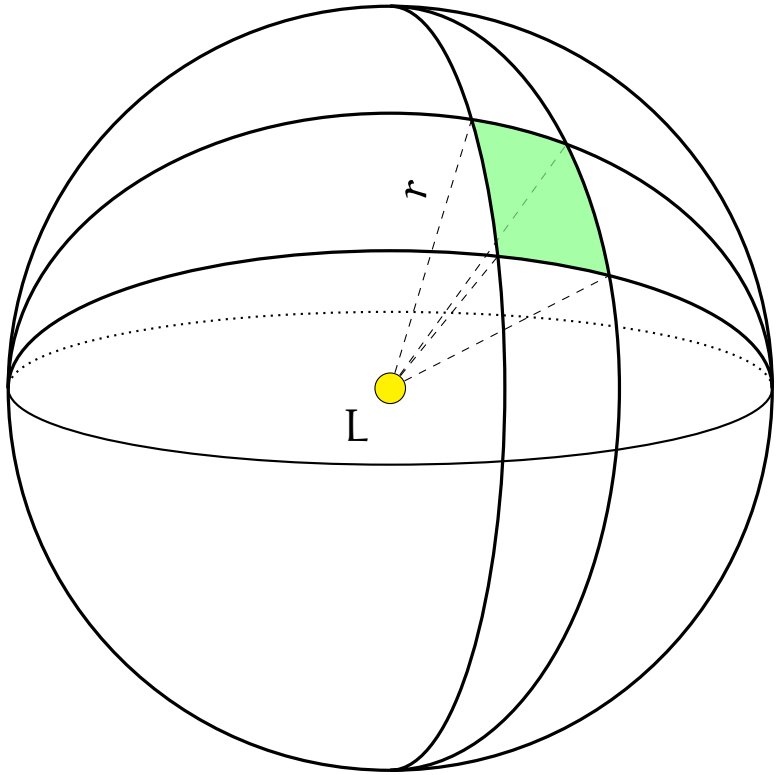


This power is emitted isotropically into all directions.

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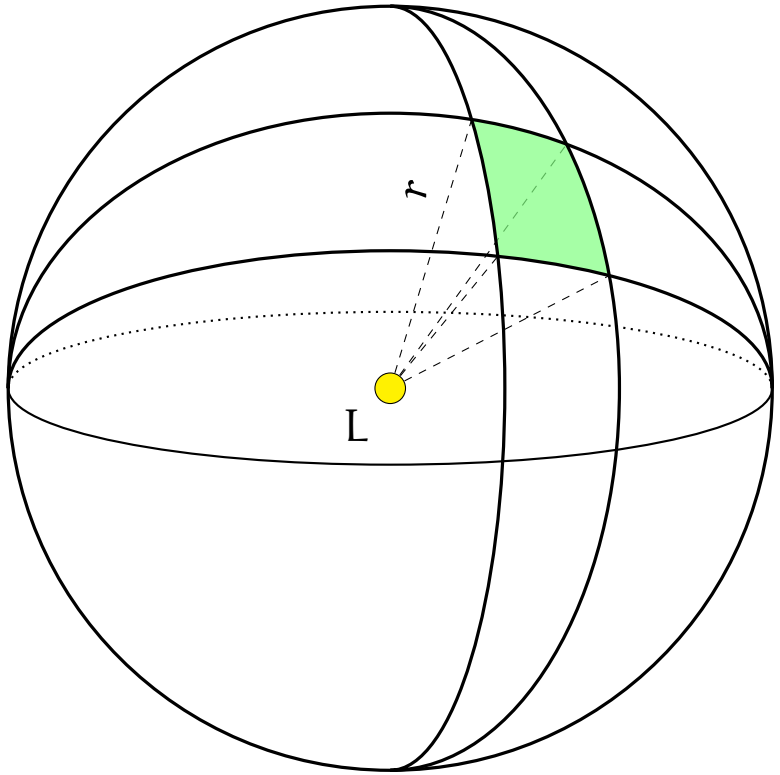
This power is emitted isotropically into all directions.

$\Longrightarrow$ Energy received per second on whole area of sphere of radius r (area $A = 4\pi r^2$) equals L as well!

Direct Imaging: Contrast

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This power is emitted isotropically into all directions.

$\Longrightarrow$ Energy received per second on whole area of sphere of radius r (area $A = 4\pi r^2$) equals L as well!

$\Longrightarrow$ Energy falling per second on area of $1\,m^2$ at distance r ("flux"):

$$F = \frac{L}{4\pi r^2}$$

units: $W\,m^{-2}$ or $erg\,cm^{-2}\,s^{-1}$

Direct Imaging: Contrast

Plugging in typical numbers:

Earth:

distance: $r = 1\,\mathrm{AU} = 150 \times 10^6\,\mathrm{km}$
$\Longrightarrow P \sim 1380\,\mathrm{W\,m^{-2}}$ ("solar constant").

Total power received by Earth: projected solar facing area $A = \pi r_\oplus^2 = 1.26 \times 10^{14}\,\mathrm{m^2}$

$\Longrightarrow$ Total power received: $P_{\mathrm{total},\oplus} = 1.74 \times 10^{17}\,\mathrm{W}$.
Of this, about 30% is reflected, i.e., $L_\oplus = 5.2 \times 10^{16}\,\mathrm{W} \sim 10^{-10}\,L_\odot$.

The luminosity of the Earth is 10 billion times weaker than that of the Sun.

in infrared, luminosity contrast is only 10 million, but still rather weak...

Direct Imaging: Contrast

Plugging in typical numbers:

Jupiter:

distance: $r = 5.2\,\mathrm{AU} = 7.8 \times 10^8\,\mathrm{km} \Longrightarrow P \sim 51\,\mathrm{W\,m^{-2}}$

Total power received by Jupiter: projected solar facing area $A = \pi r_{♃}^2 = 1.6 \times 10^{16}\,\mathrm{m^2}$

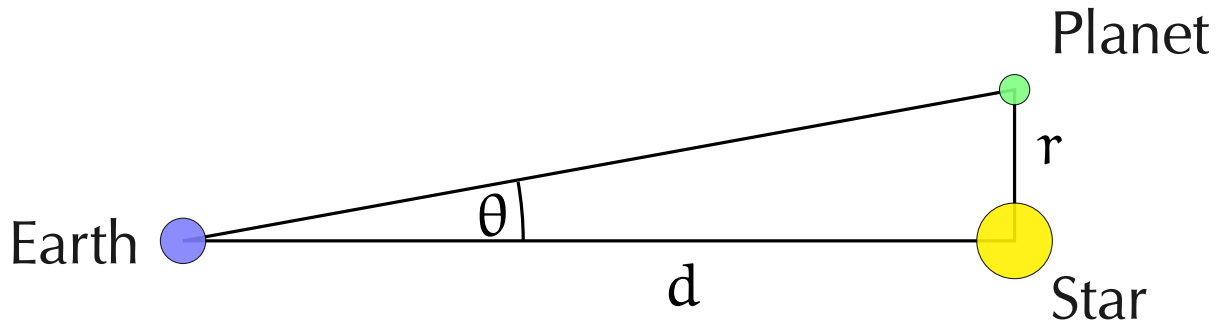
$\Longrightarrow$ Total power received: $P_{\mathrm{total},♃} = 8.2 \times 10^{17}\,\mathrm{W}$.
Of this, about 30% is reflected, i.e., $L_{♃} = 2.5 \times 10^{17}\,\mathrm{W} \sim 6 \times 10^{-10}\,L_\odot$.

The luminosity of Jupiter is ∼1 billion times weaker than that of the Sun.

$\Longrightarrow$ For typical planets around solar type stars, we need to be able to detect intensity contrasts of better than 1:1 billion.

$\Longrightarrow$ Not doable now, achievable in your lifetime (“coronagraphs”)...

Direct Imaging: Angular Separation



How close on the sky are the images of a star and its planet?

$$\tan\theta = \frac{r}{d} \quad \Longrightarrow \quad \theta \sim \frac{r}{d}$$

(for small θ: Taylor series: $\tan\theta \sim \theta + (1/3)\theta^3 + \ldots$; "small angle approximation")

Typical distances to nearby stars: $d \sim 100\,\mathrm{Ly} = 9.5 \times 10^{17}\,\mathrm{m}$,
typical distances in planetary system: $r \sim 1\,\mathrm{AU} = 1.5 \times 10^{11}\,\mathrm{m}$,

$$\Longrightarrow \qquad \theta = \frac{r}{d} = 1.57 \times 10^{-7}\,\mathrm{rad} = 9 \times 10^{-6}\,\mathrm{deg} = 0.03''$$

reminder: $1'' = 1\,\mathrm{arcsec} = 1/3600\,\mathrm{deg}$.

Direct Imaging: Angular Separation

Optics: resolving power of telescope with diameter D:

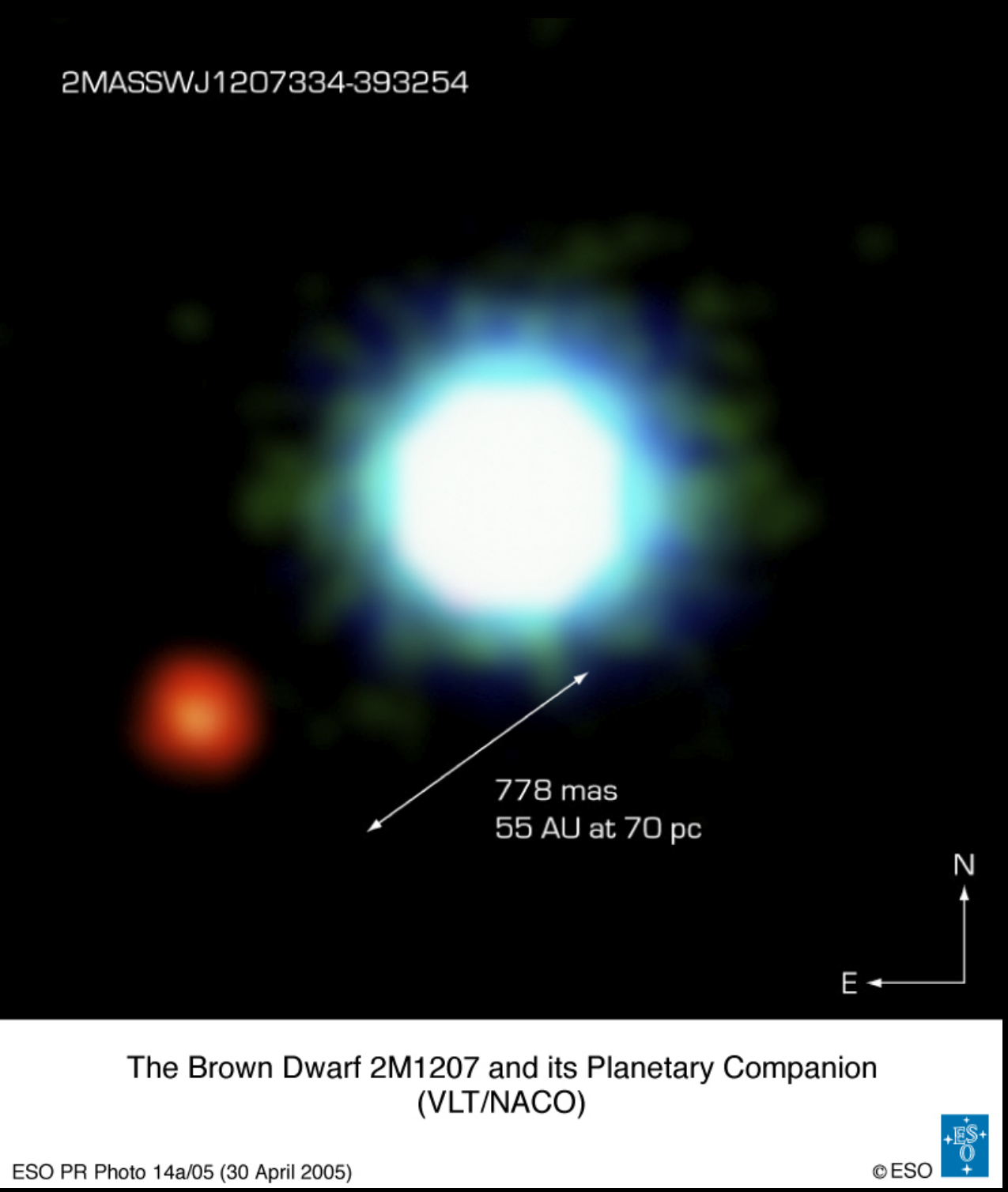
$$\alpha = \frac{12''}{D/1\,\mathrm{cm}} \tag{8.2}$$

$\Longrightarrow$ to resolve $0.03''$, need $D = 4\,\mathrm{m}$, so doable

BUT

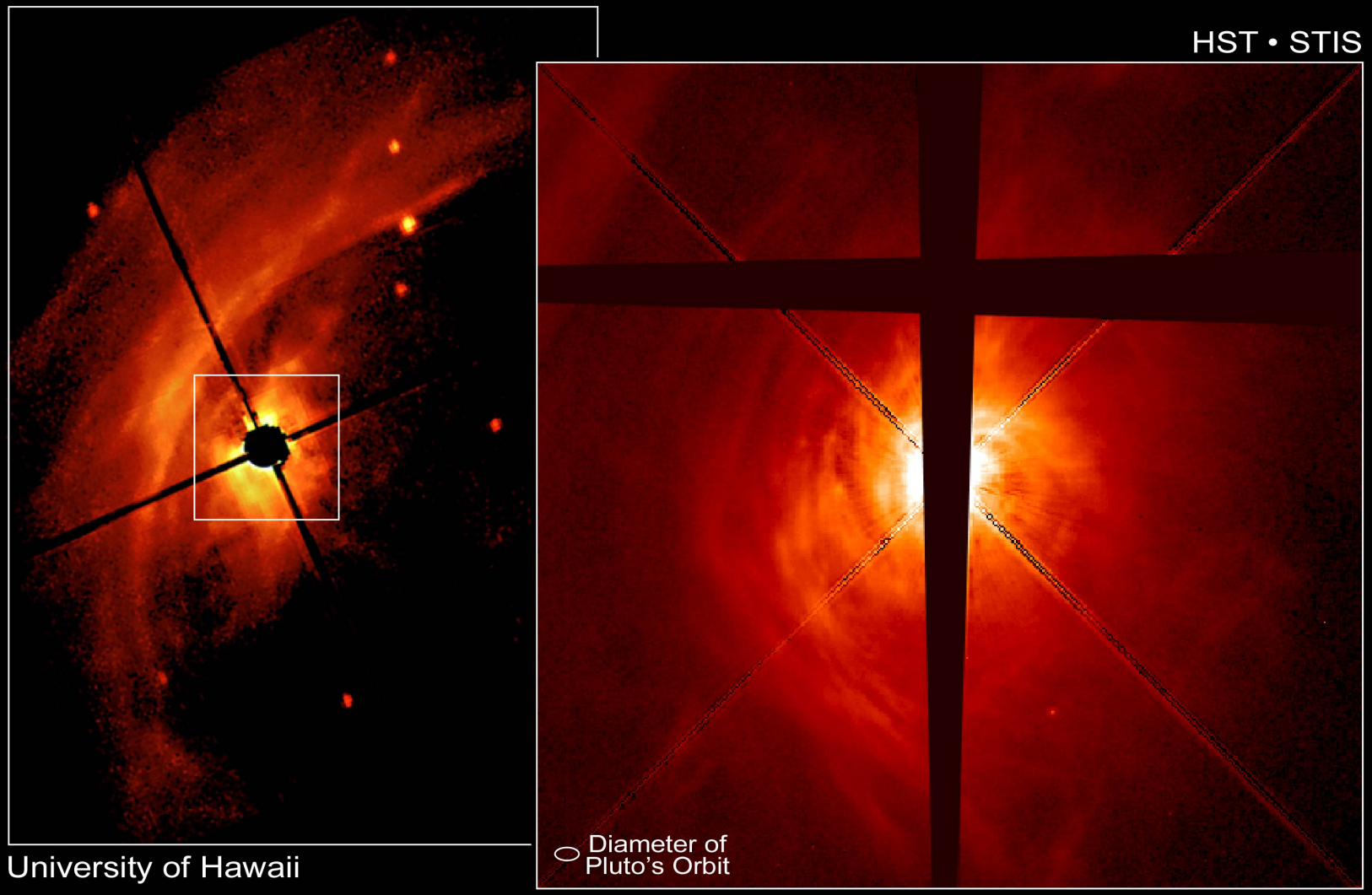
Earth atmosphere limits resolution to $\sim 0.5''$ ("seeing")

Currently, direct detection of extrasolar planets around solar-type stars is doable from ground only in exceptional circumstances. It is technologically feasible from space.

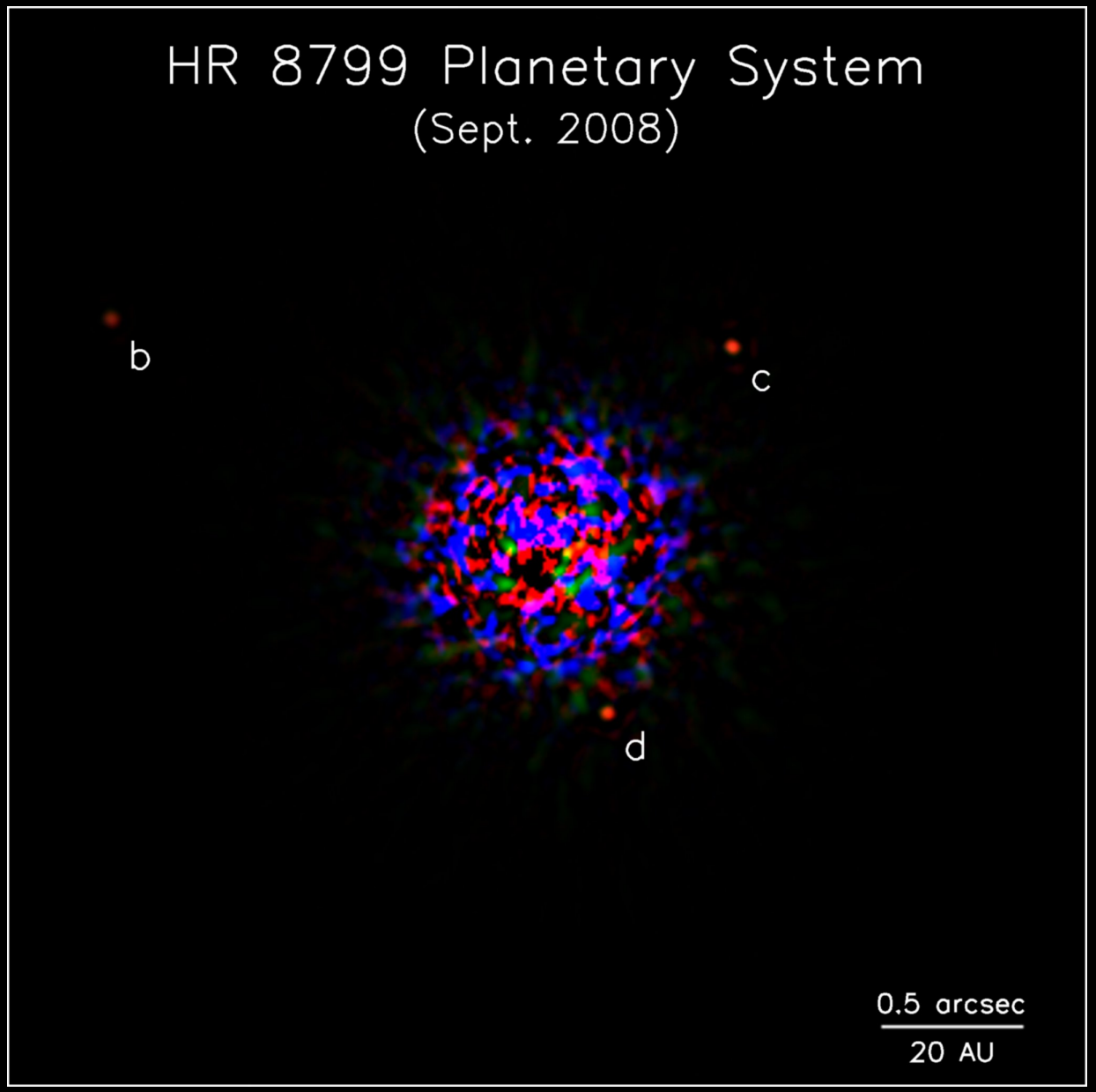


Adaptive optics: obtain diffraction limited resolution in the near infrared.
Contrast still a problem. For one very dim star (a "brown dwarfs") a planetary companion was detected in early 2005 with the VLT and confirmed in 2006 with HST.

Distance between star and planet: $\sim 2\times$ Neptune distance, distance to system 59 ± 7 pc.

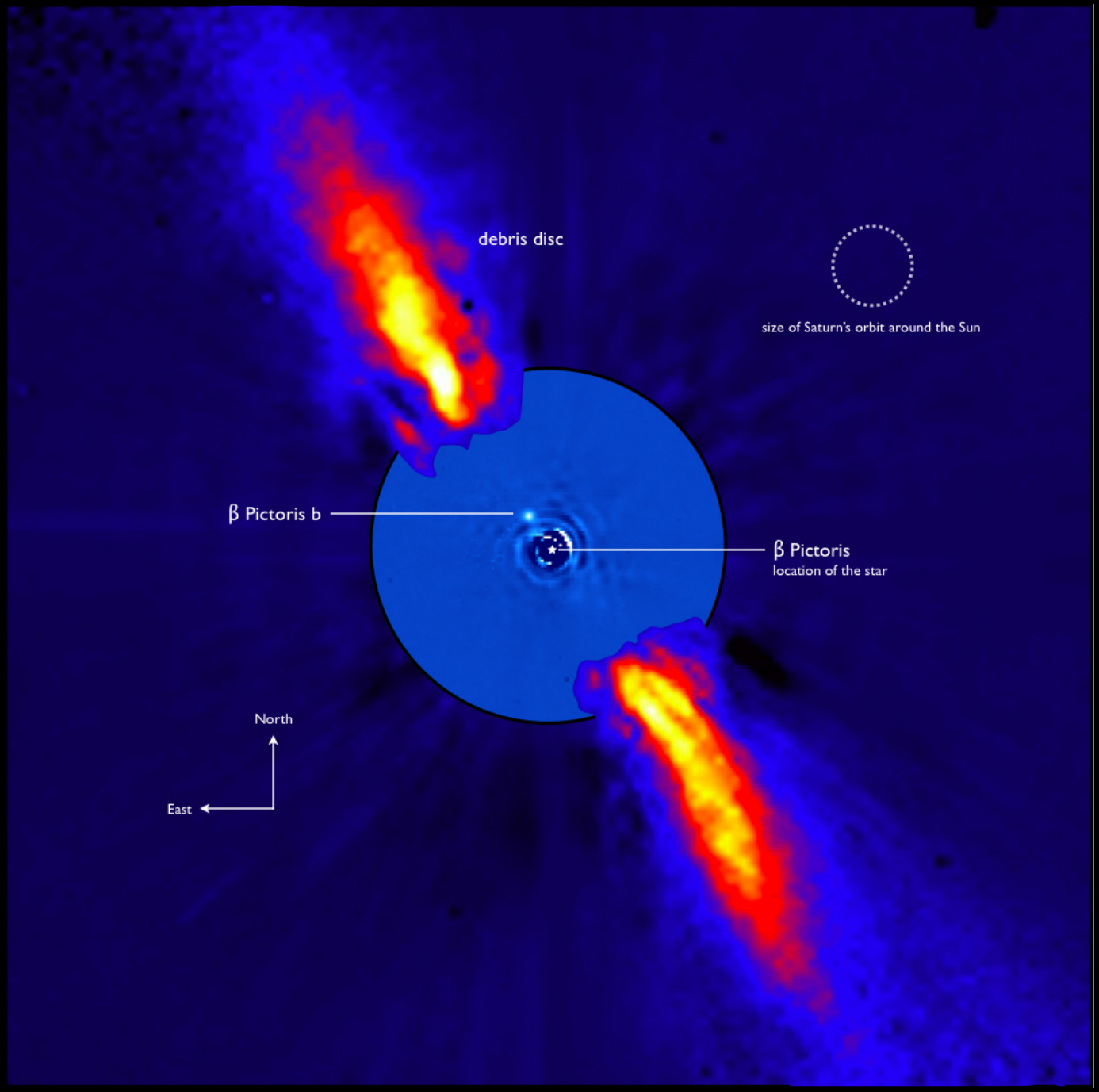


. . . direct imaging of the region close to a star is in principle doable with modern technology (HST, VLT, et al.)



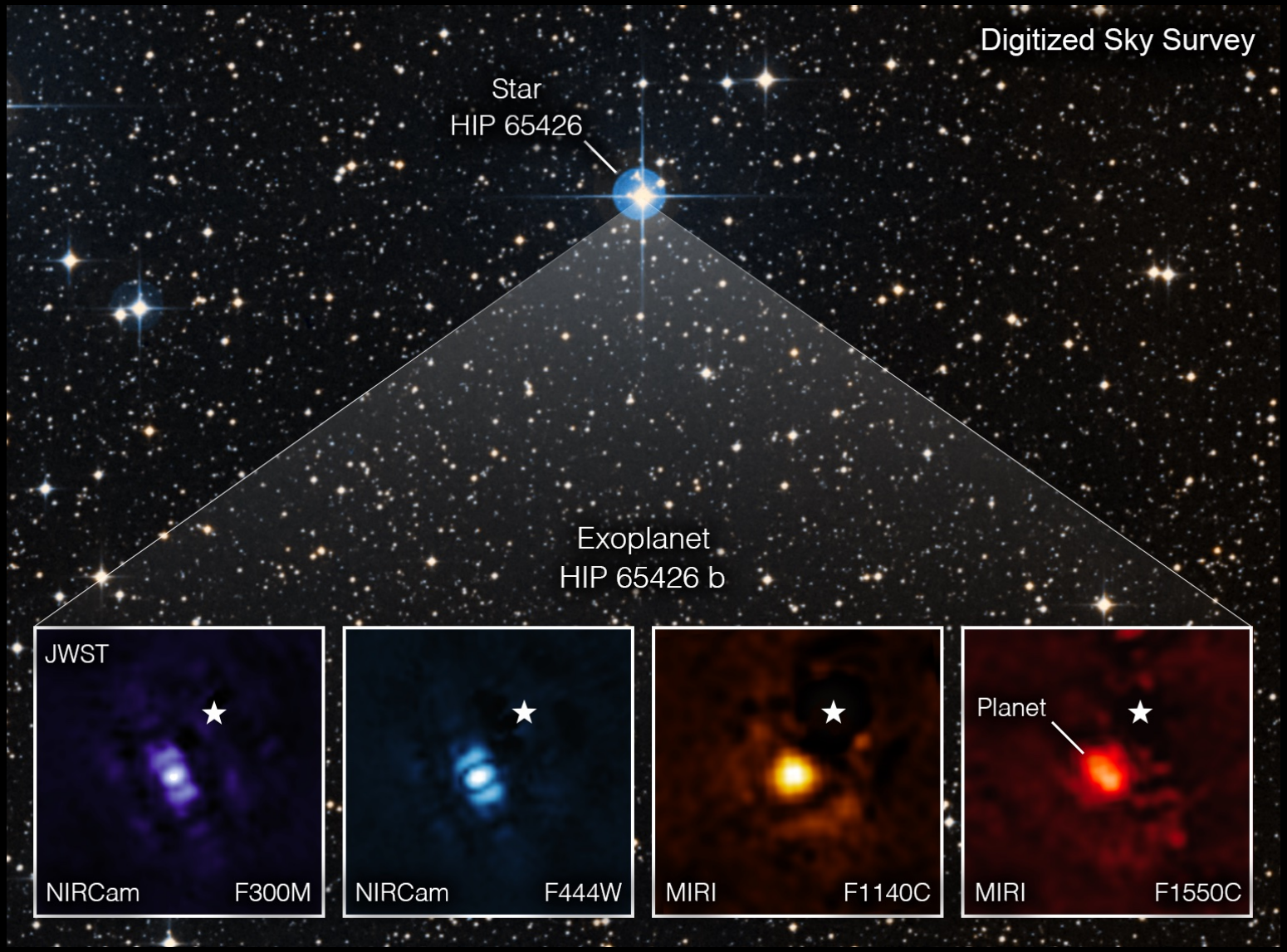
C. Marois (NRC-HIA), IDPS survey and Keck Observatory

13.11.2008: Direct imaging of planetary system around HR 8799 announced; distances 70, 40, and 25 AU from star (constellation Pegasus; $d = 110$ Ly).



ESO

21.11.2008: Direct imaging of planet with ESO-VLT and NACOS instrument announced (planet around β Pictoris, 1000× fainter than star).

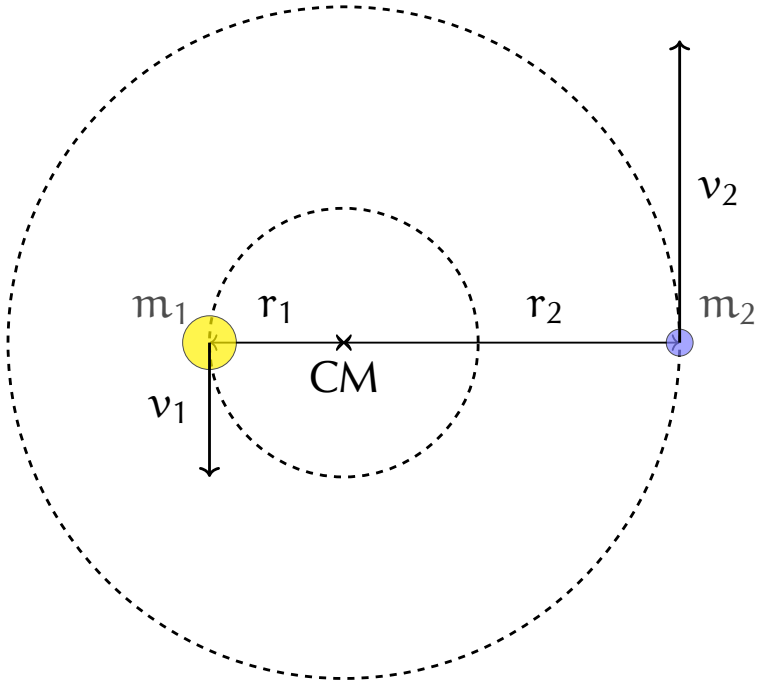


JWST: capable of taking direct images of planets
(coronagraphs blocks the light of the star, credit: NASA/ESA/CSA)

$\rightarrow$ 62 planets detected by imaging (Dec 2022) $\Rightarrow$ mainly (super-) Jupiters

Radial Velocity Measurements

If we cannot see planet directly $\Longrightarrow$ use indirect methods.



Two-body problem: Star and planet move around common center of mass:

$$m_1 r_1 = m_2 r_2$$

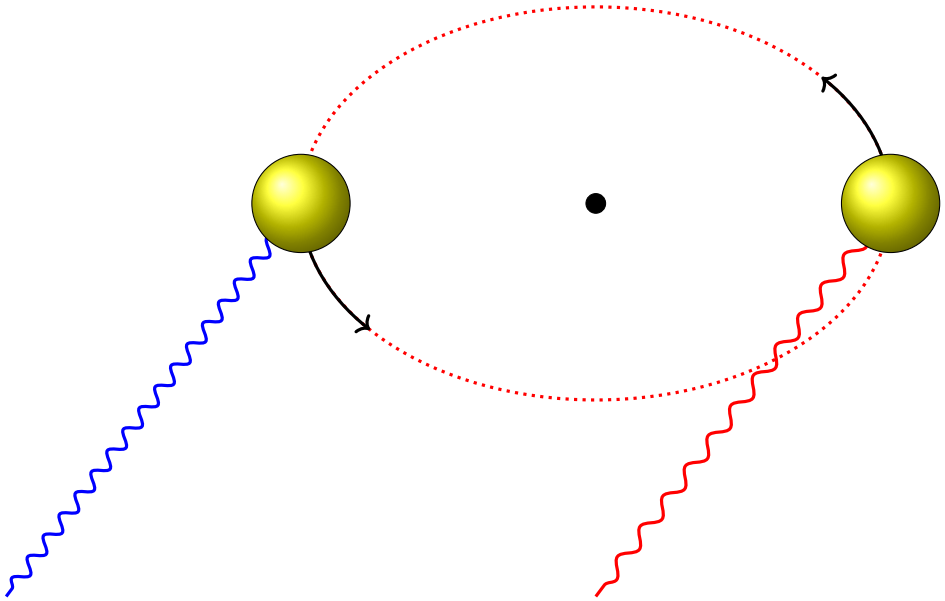
For circular orbits and orbital period P, velocity of star due to action of planet is

$$v_1 = \frac{2\pi r_1}{P} = \frac{2\pi}{P} \cdot \frac{m_2}{m_1} \cdot r_2$$

Example: Sun vs. Jupiter:
$m_1 = 2 \times 10^{30}\,\mathrm{kg}$, $m_2 = 2 \times 10^{27}\,\mathrm{kg}$, $r_2 = 5.2\,\mathrm{AU} = 7.8 \times 10^{11}\,\mathrm{m}$, $P_J = 11.9\,\mathrm{yr} = 3.76 \times 10^8\,\mathrm{s}$
$\Longrightarrow v_1 = 13.1\,\mathrm{m\,s^{-1}} \sim 50\,\mathrm{km\,h^{-1}}$

Example: Sun vs. Earth gives $v_1 = 10\,\mathrm{cm\,s^{-1}} \sim 0.8\,\mathrm{km\,h^{-1}}$

Radial Velocity Measurements



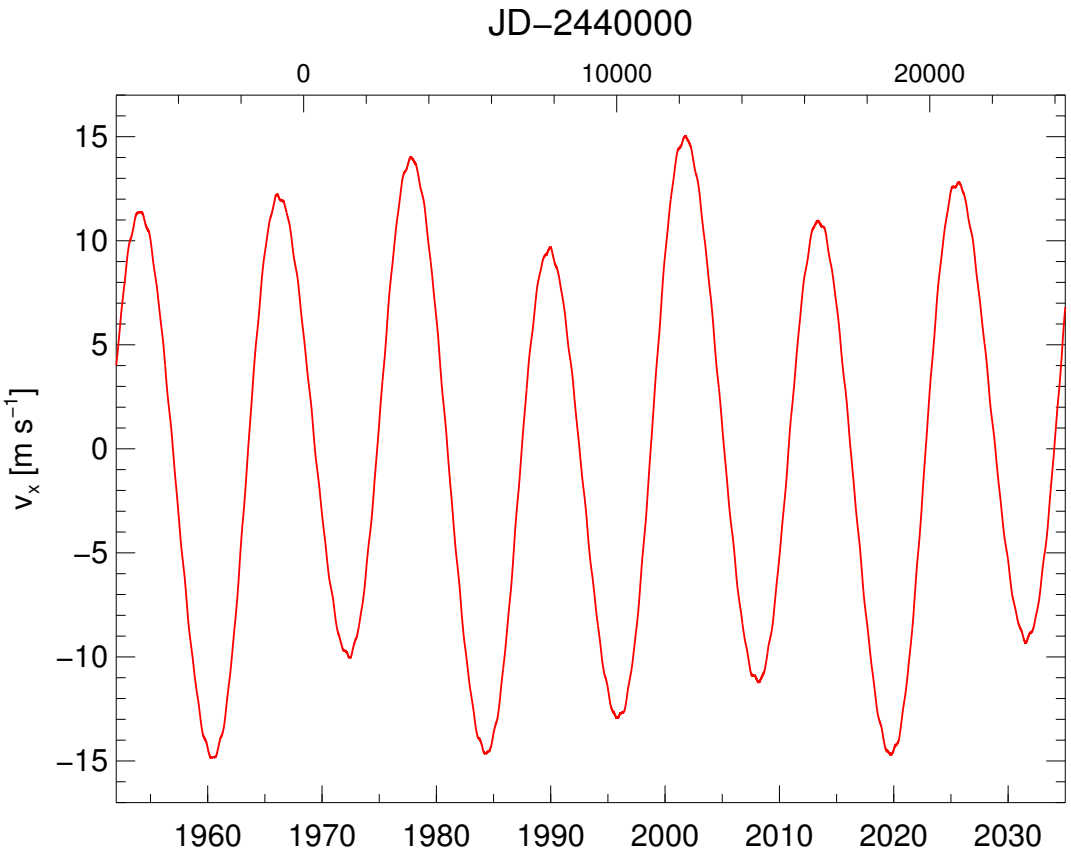
to observer

How to hunt extrasolar planets using the Doppler Detection Method:

1. get access to *lots* of telescope time
2. get access to *very good* spectrograph
3. measure for years, to determine changes in velocity of stars due to motion of star around CM

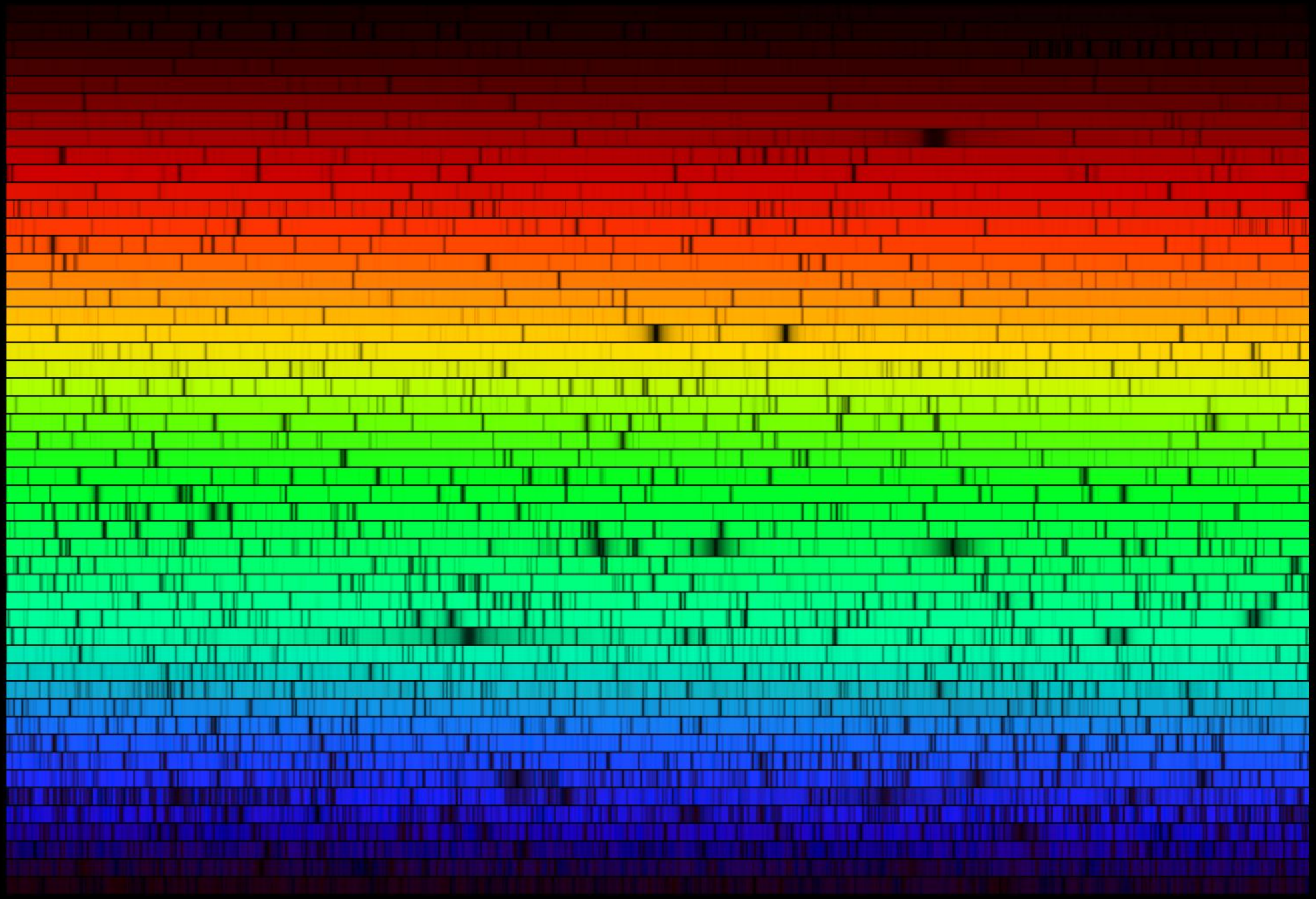
Radial Velocity Measurements

Doppler motion of the sun due to all planets in the solar system as an observer in the ecliptic would have measured:



- Superposition of sinusoidal radial velocity curves.
- amplitude = 13 m s^{-1} (~47 km/h)
- Largest effect due to Jupiter.

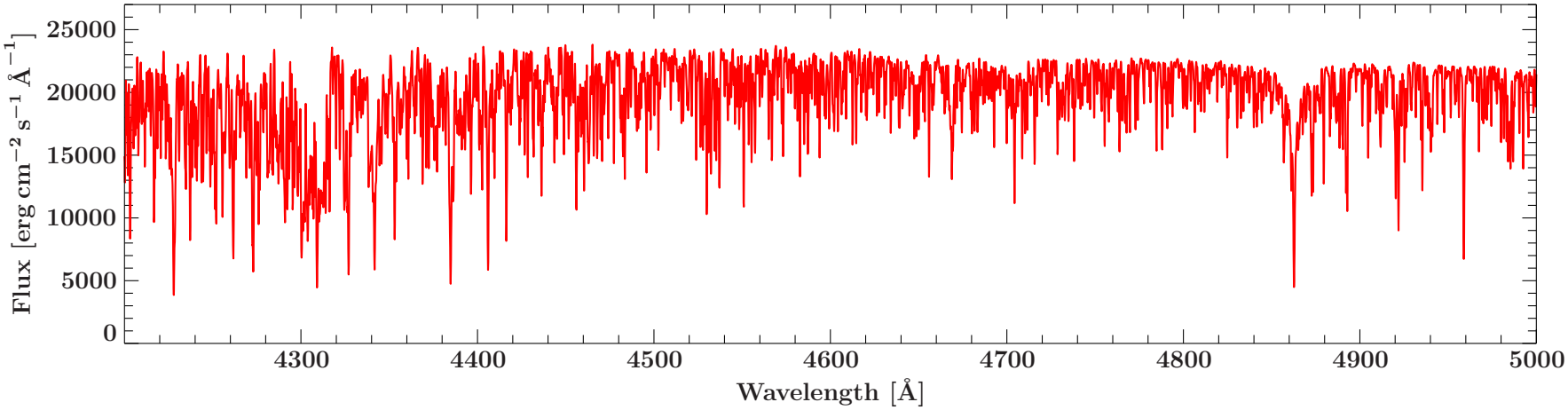
Need to measure stellar radial velocity to much better than 13 m s^{-1}.



N.A. Sharp, NOAO/NSO/Kitt Peak FTS/AURA/NSF

Absorption line spectrum of the Sun: Fraunhofer Lines

Radial Velocity Measurements



data from Chance & Kurucz (2010)

Doppler motion of the Sun:

$$\frac{\lambda_{\text{observed}} - \lambda_{\text{emitted}}}{\lambda_{\text{emitted}}} = \frac{v}{c} \quad \text{with } v = 13\,\text{m s}^{-1}: \quad \Delta\lambda/\lambda = 4 \times 10^{-8} \tag{8.3}$$

Line broadening due to thermal motion of the light emitting ions:

$$v_{\text{therm}}^2 = \frac{2kT}{Am_H} \Longrightarrow \frac{\Delta\lambda}{\lambda} = \sqrt{\frac{2kT}{Am_Hc^2}} \tag{8.4}$$

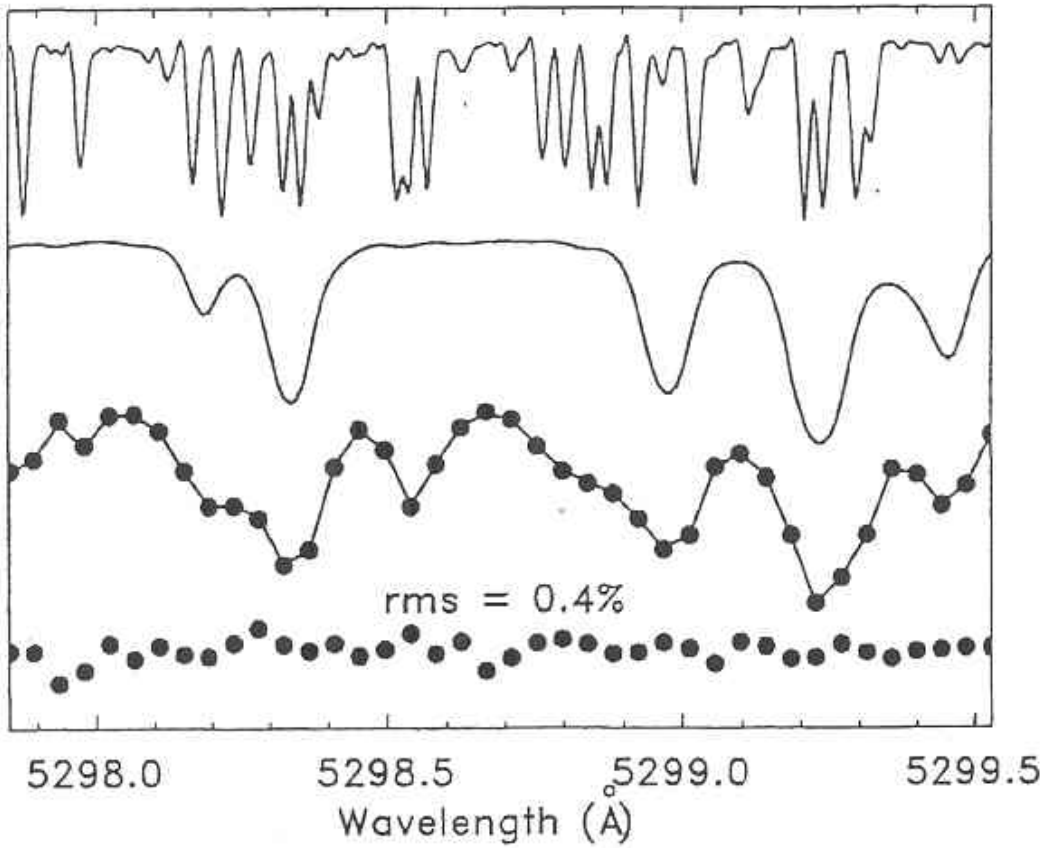
where A: atomic weight in atomic mass units (m_H)

For the Sun ($T = 5780\,\text{K}$):

- Hydrogen: $v_{\text{therm}}(\text{H}) = 9.8\,\text{km s}^{-1} \Longrightarrow \frac{\Delta\lambda}{\lambda} = 3 \times 10^{-5}$
- Iron: $v_{\text{therm}}(\text{Fe}) = 1.9\,\text{km s}^{-1} \Longrightarrow \frac{\Delta\lambda}{\lambda} = 6 \times 10^{-6}$ (prefer heavy elements!)

Intrinsic line widths are 400–3000 times broader than expected Doppler velocity.

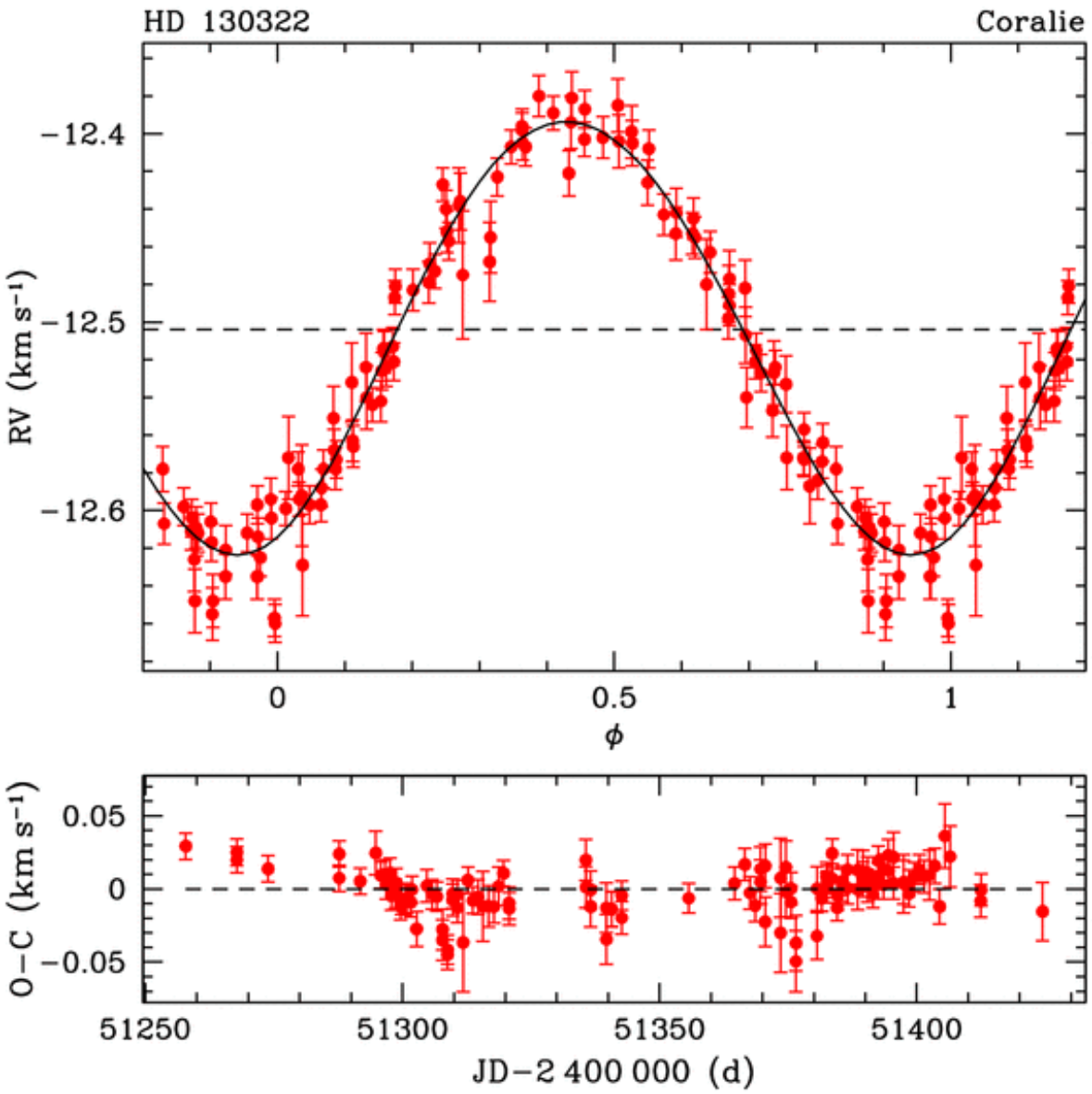
Radial Velocity Measurements



- accuracy can only be reached by measuring tens of thousands of lines
- long term stability: very stable wavelength standard needed
- Iodine cell in front of spectrograph: Iodine vapor at ~50° C. High mass (127), low temperature $\Longrightarrow$ sharp lines.

- cross correlation of spectra.
- works with cool stars, e.g., solar-like (sufficient number of lines).

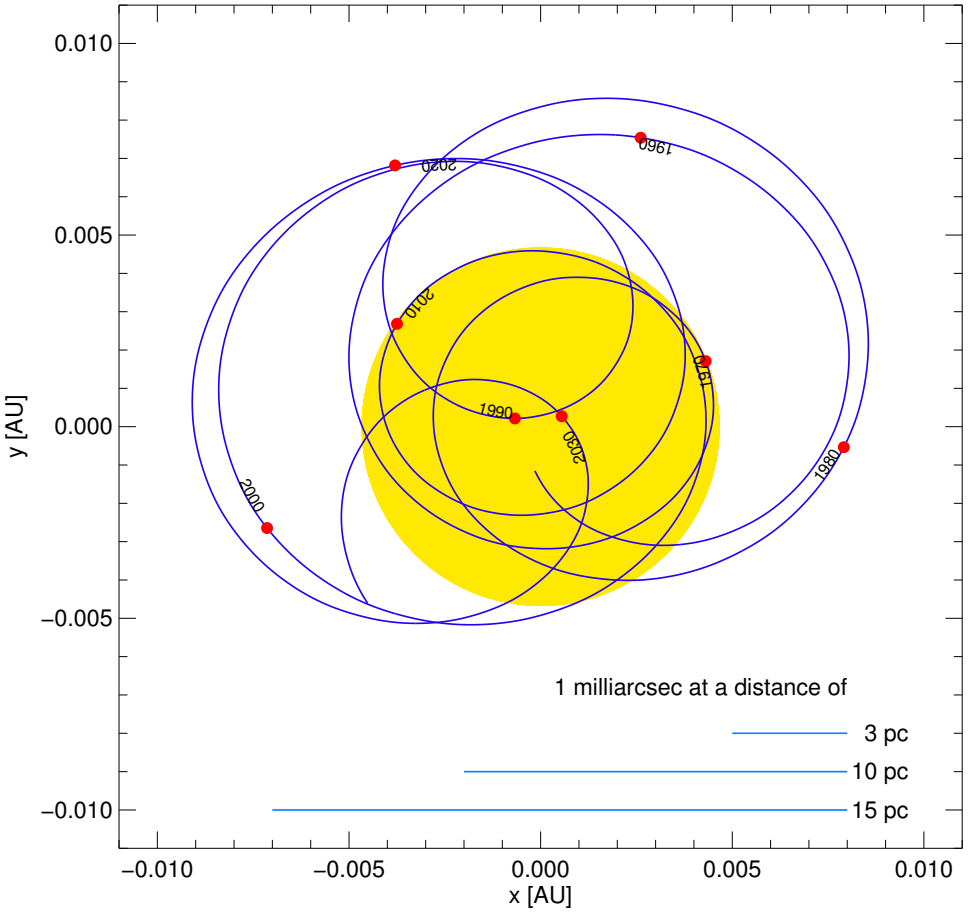
Radial Velocity Measurements



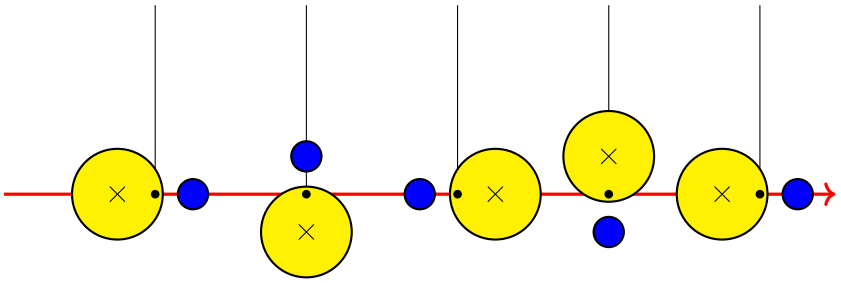
Example: Changing radial velocity of HD 130322 results in discovery of Jupiter-mass planet (Udry et al., 2000).
Here: velocity amplitude: 115 m s^{-1}.

Radial velocity = velocity along our line of sight.

Astrometry



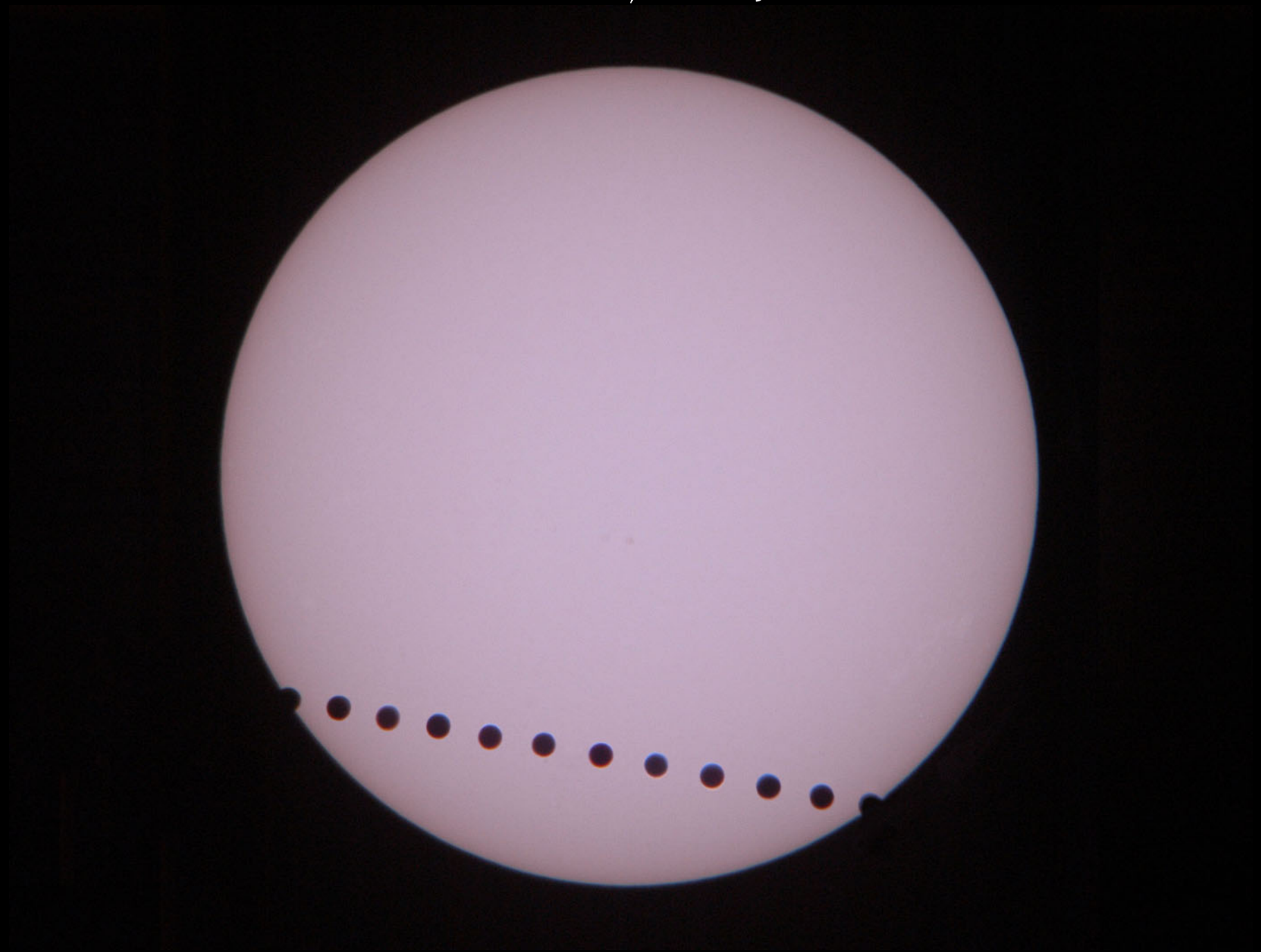
Motion of the sun around the barycenter of the solar system viewed from the north pole of the ecliptic



Outlook:

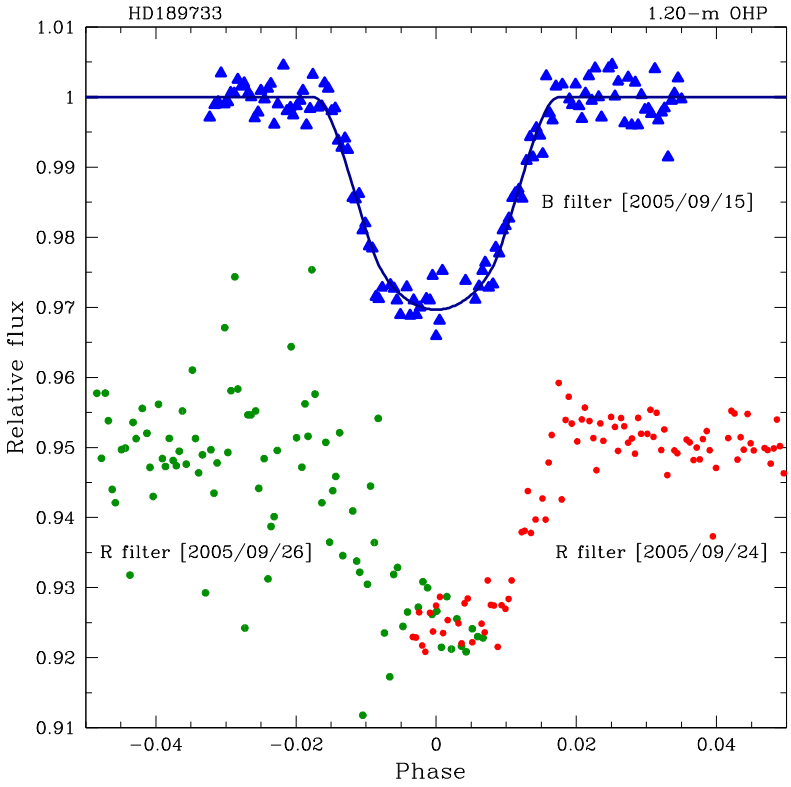
- planet + star: astrometric binary
- measure periodic wobble of the proper motion
- need precision <1 mas
- *GAIA* astrometric mission of ESA

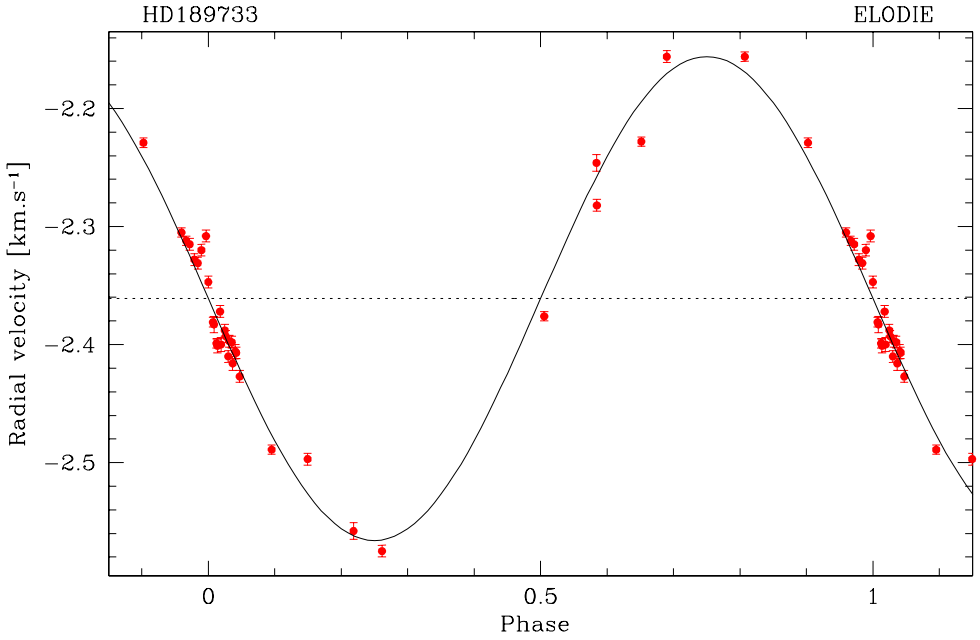
Venus Transit, 2004 June 8



Elio Daniele, Palermo

Transits





Planetary transit: occultation of the star by the planet

$\Longrightarrow$ inclination known

Can determine mass *and* radius of the planet!

Kepler

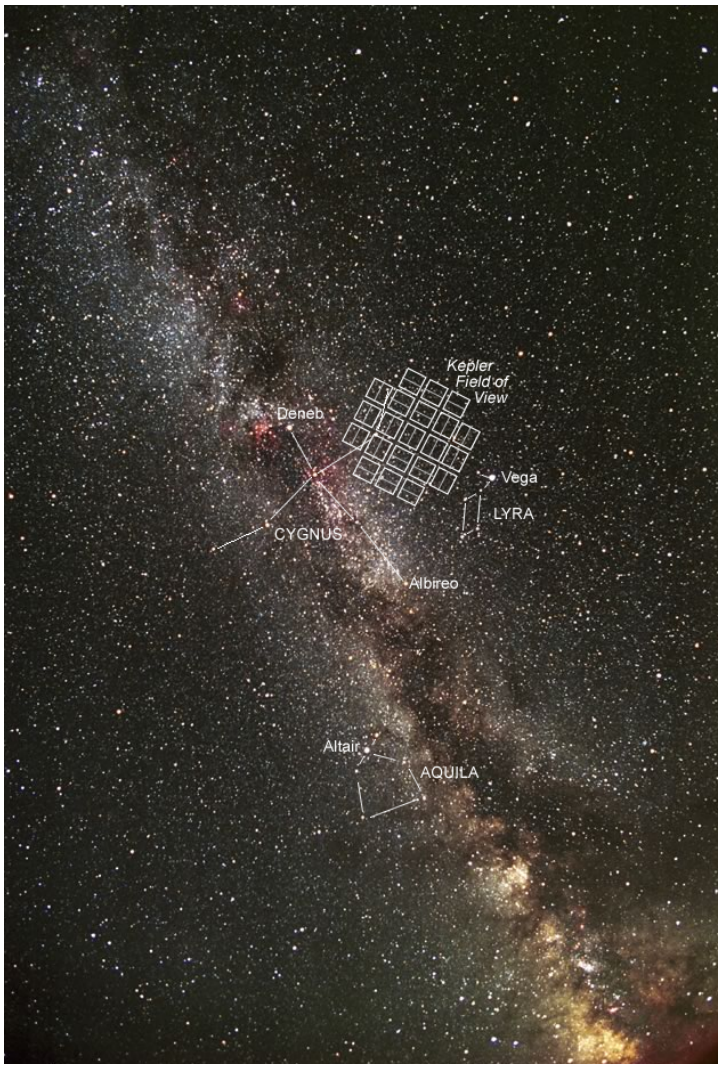


Occultation technique *very* difficult from ground $\Longrightarrow$ go to space!
NASA: Kepler spacecraft, launch 2009 March 07, end of mission 2018

Continuous photometry of 145000 stars in 12° field of view using 45 CCDs with 2200×1024 pixel each (95 Megapixel)
Reaches 20 ppm at 12 mag in 6.5 h integration
(Earth-like planet: ~100 ppm)

Kepler found a total of 2394 confirmed exoplanets.

Kepler



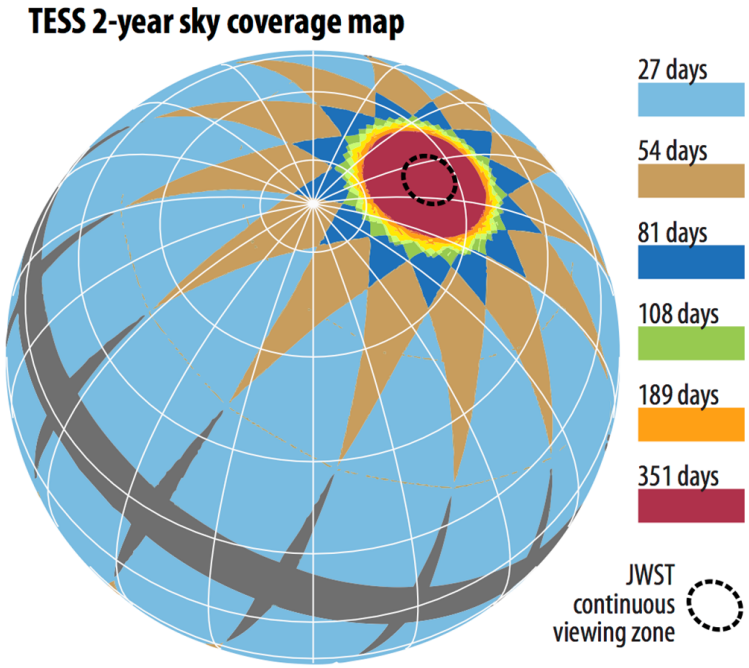
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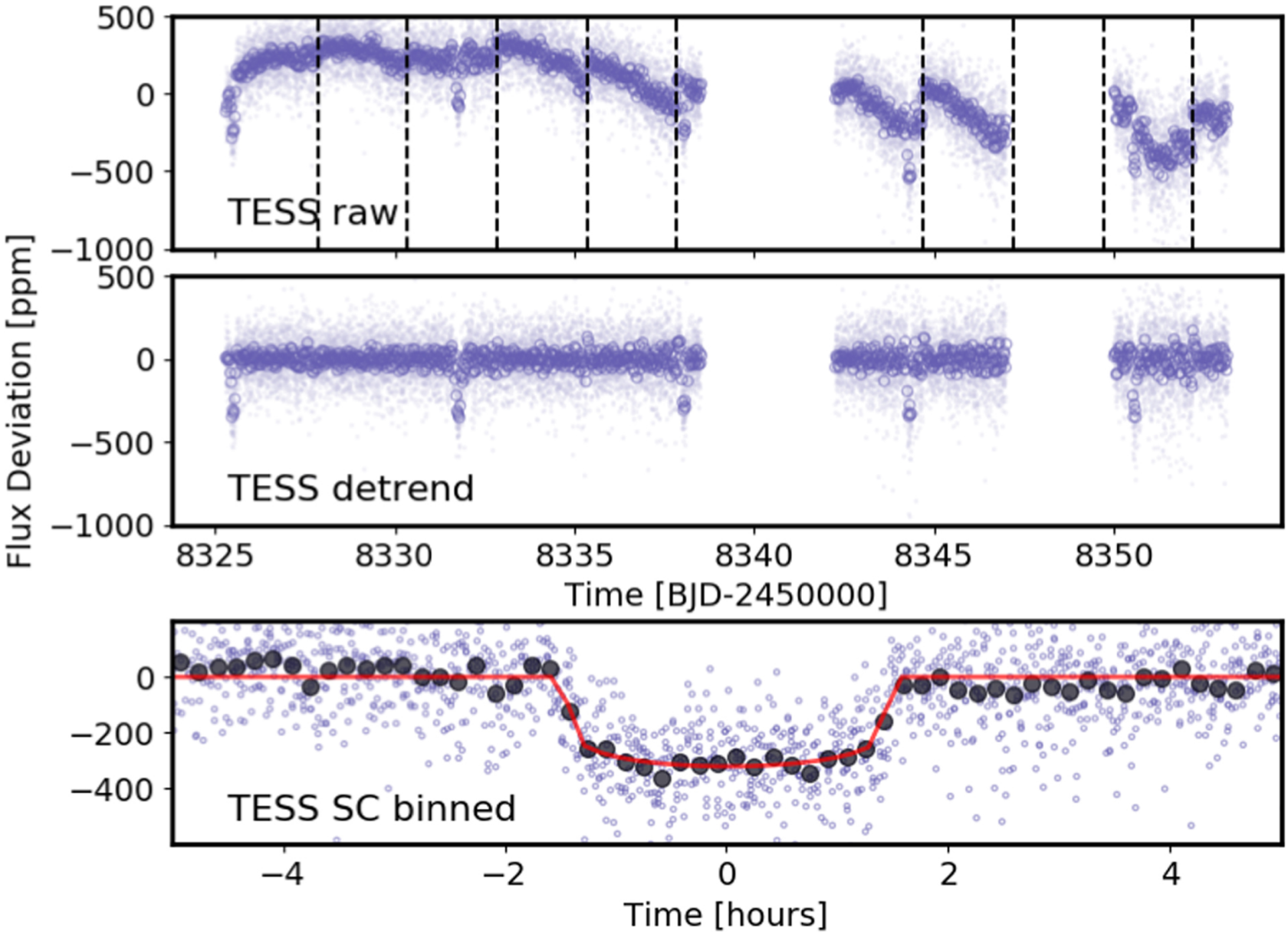
TESS



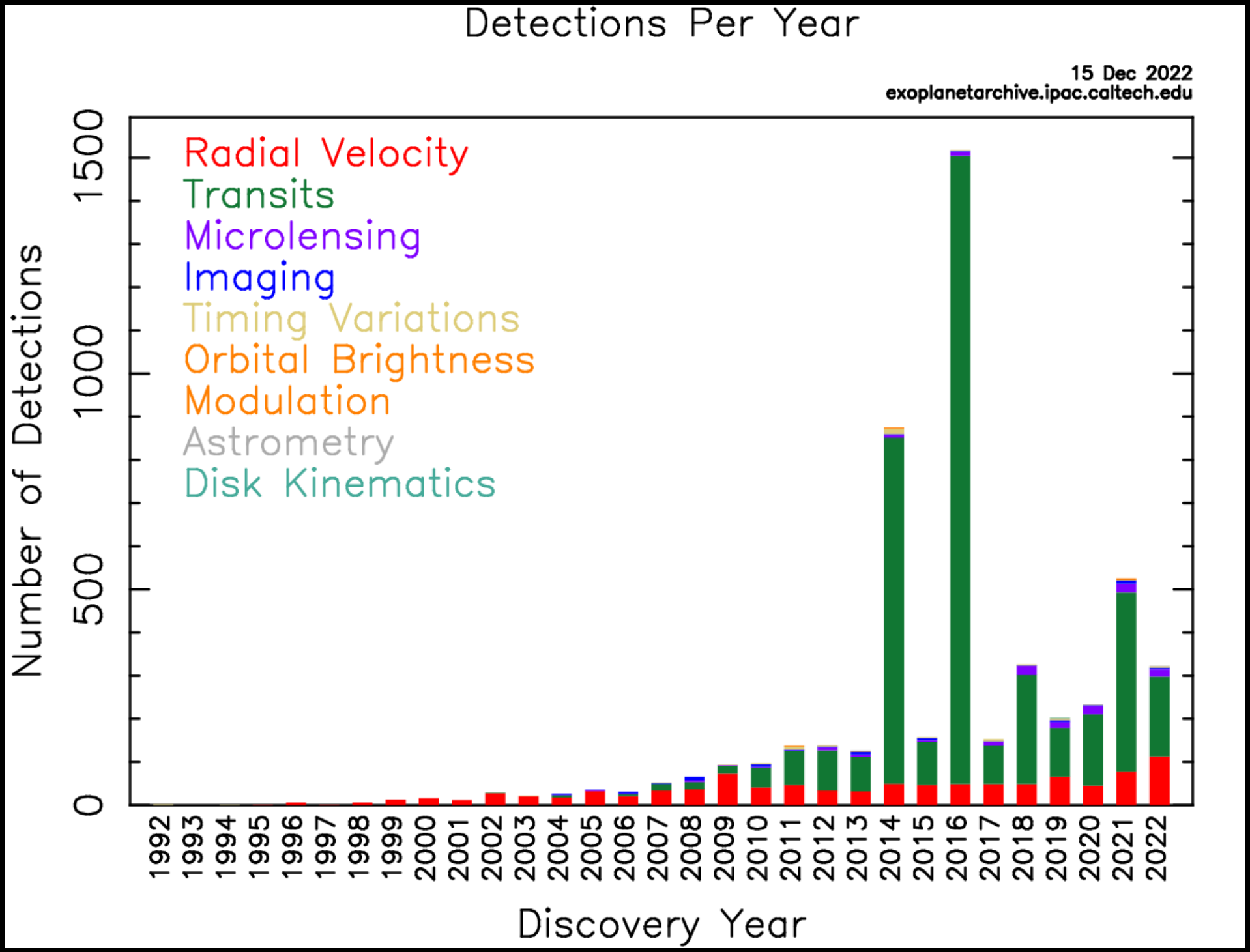


Since 2018 April 18: Transiting Exoplanet Survey Satellite (TESS):

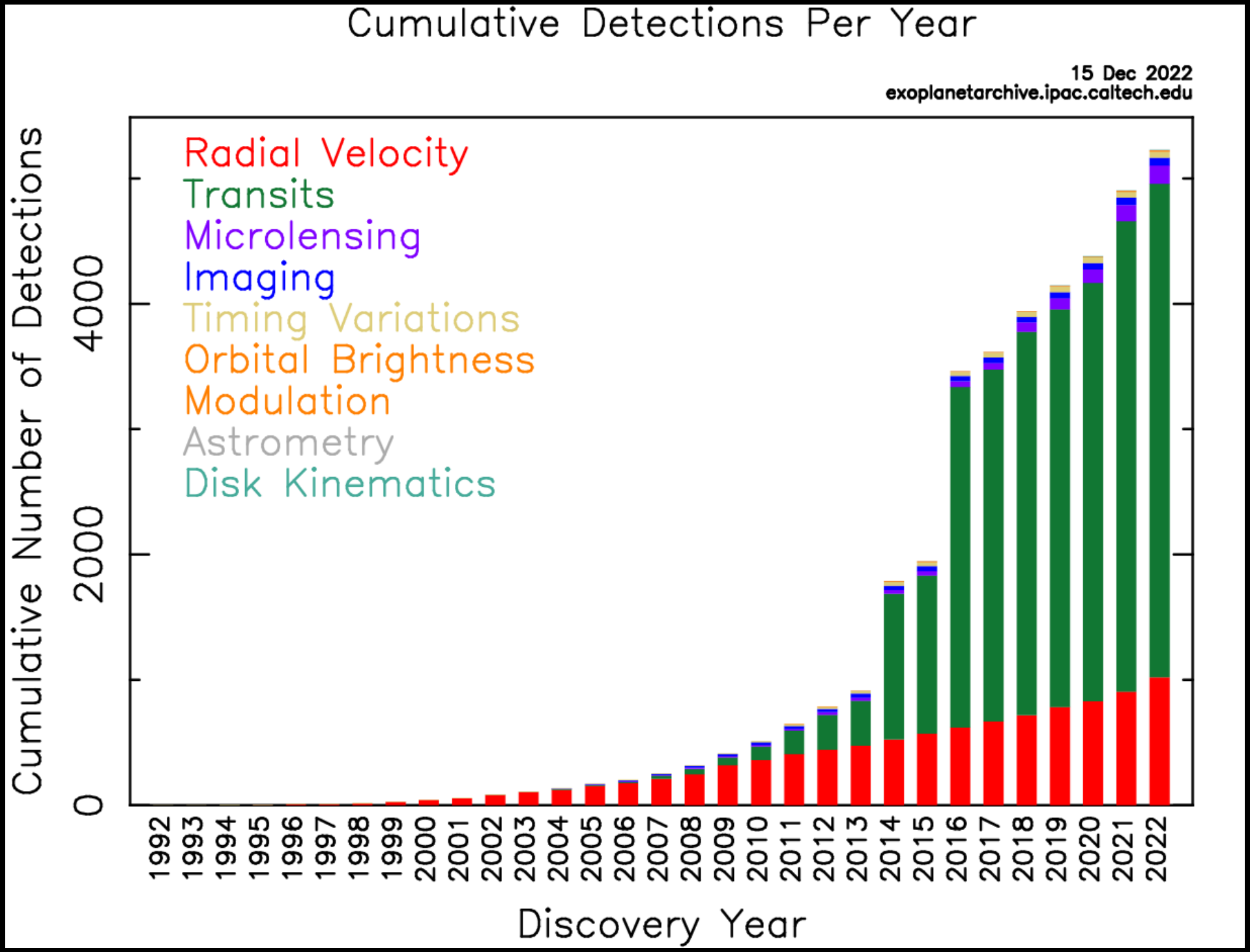
- 13.7 d cislunar orbit
- 4 cameras, 24° × 96° combined field of view
  → monitor whole sky in 26 segments
- Monitoring of 200000 stars for transits



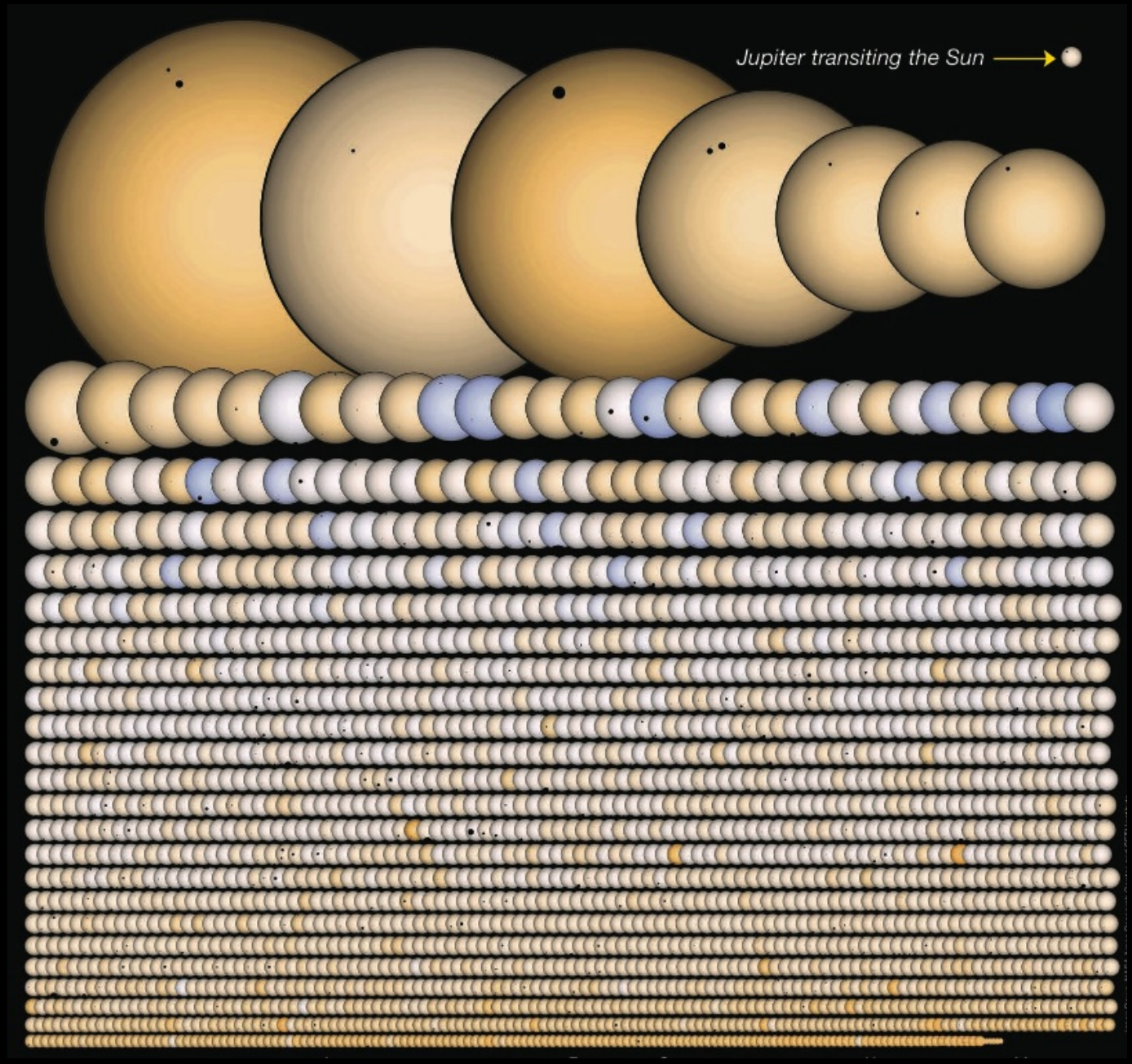
example of an exoplanet discovery by TESS (Huang et al., 2018)



see also http://www.exoplanet.eu



see also http://www.exoplanet.eu

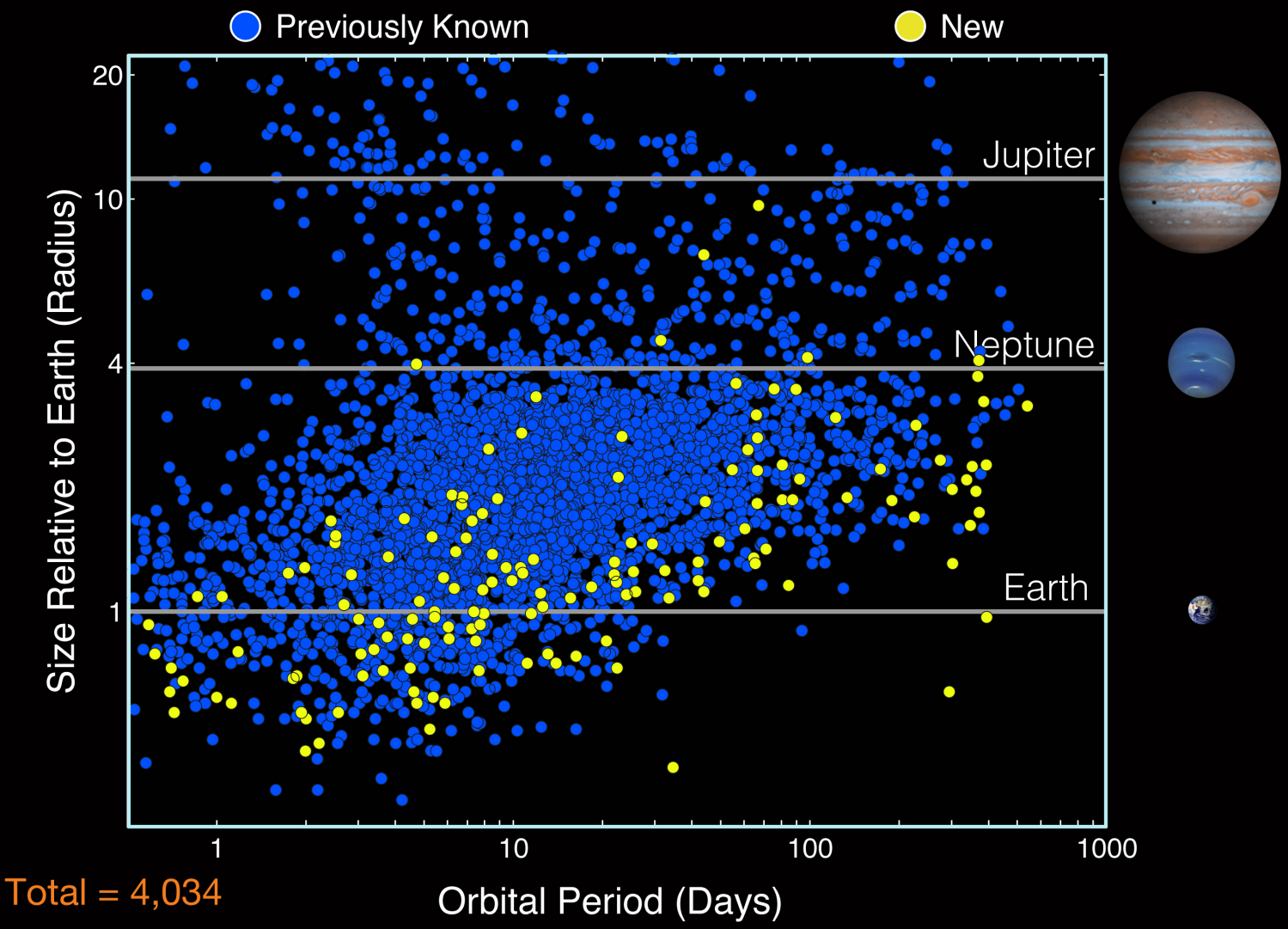


NASA/Rowe

1235 candidates from Kepler

New Kepler Planet Candidates

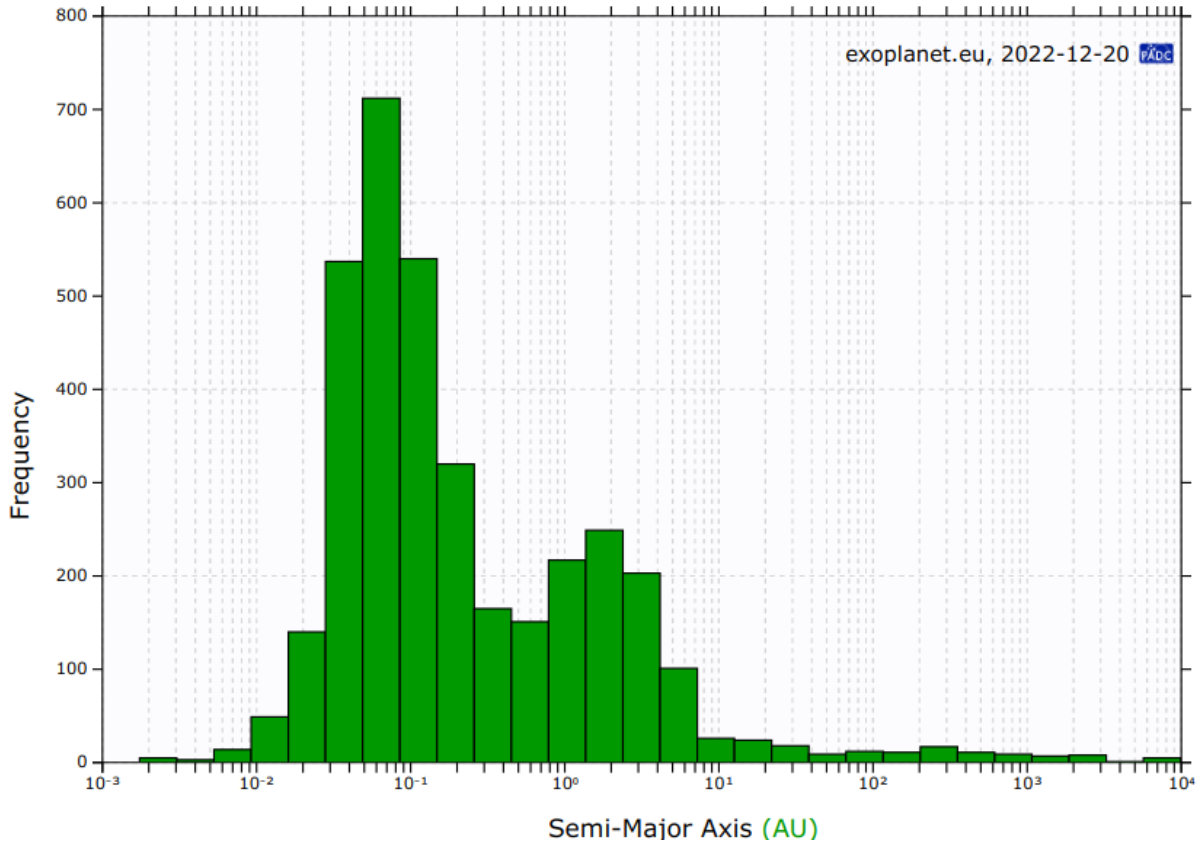
As of June 2017



Total = 4,034

Kepler Orrery: https://apod.nasa.gov/apod/ap151205.html

Results: Semimajor Axis



Note:
bimodal distribution!
Due to different detection techniques:

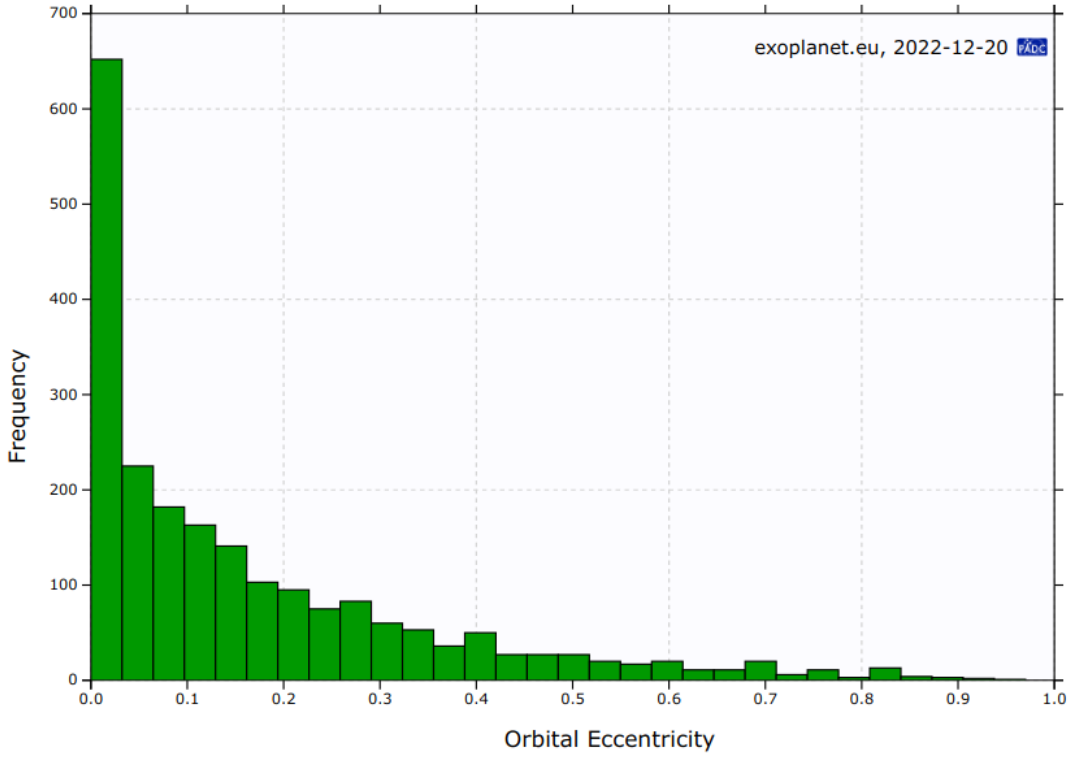
- transits (small $a \sin i$)
- radial velocity (large $a \sin i$)

Most planets found are close to companion star!

Selection effect: small $a \Longrightarrow$ short period

$\Longrightarrow$ detectable in small amount of time (years, not decades)

Results: Eccentricity



Many planets are in eccentric orbits!

different from solar system!

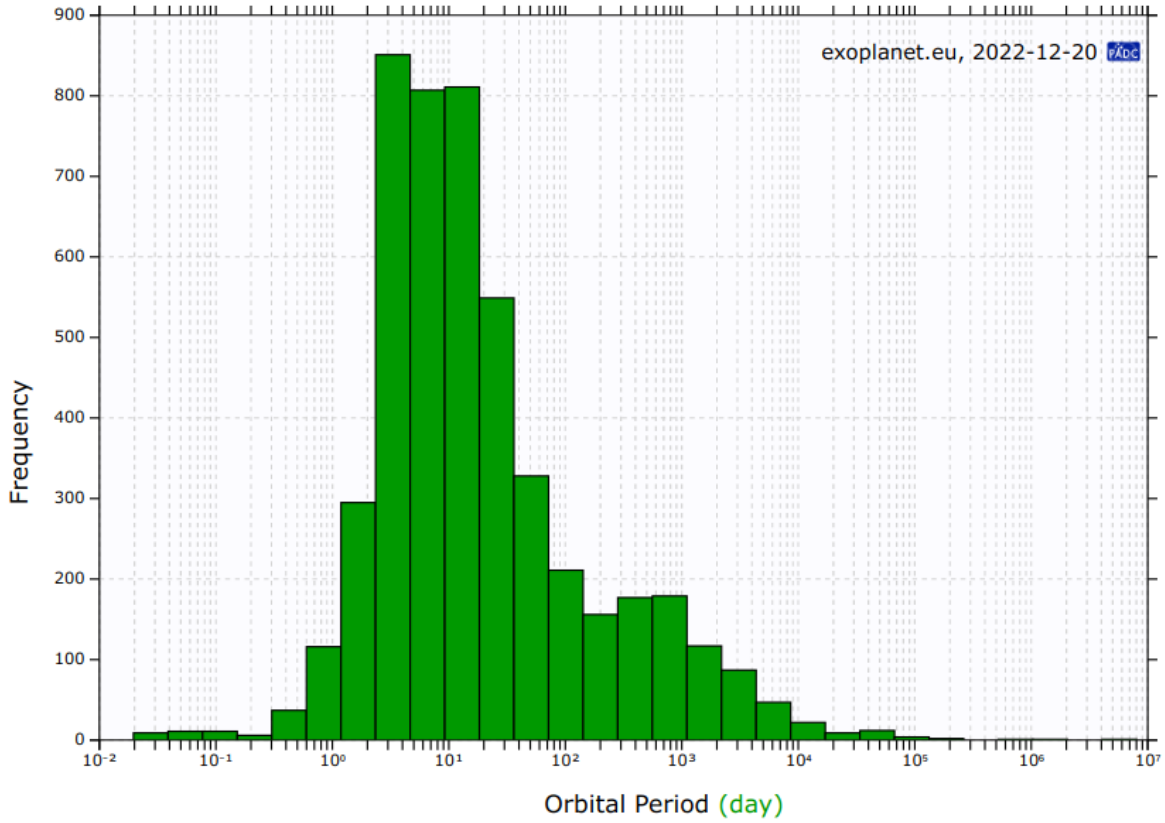
Might be selection effect due to our existence:

Jupiter in eccentric orbit in our solar system

$\Longrightarrow$ strong disturbances of Earth's orbit $\Longrightarrow$ no life!

So, in some sense Copernican principle does *not* always seem to hold!

Results: Period



Most planets found in short orbits!

Again, selection effect: short period planets are detectable during typical durations of observing runs...

Planetary properties

Measurable quantities:

- radial velocity amplitude

$$K_s = v_s \sin i, \tag{8.5}$$

- Orbital period, P,
- stellar mass M_s (from spectral type, see later)

i: inclination (angle line of sight and normal of planetary orbit)

$i = 0°$: look onto system, i.e., $K_s = 0$, $i = 90°$: edge on view of system, i.e., $K_s = v_s$

If the planet is on a circular orbit with distance a from star:

Eccentric orbits give same results, but more complicated derivation

Distance of planet and star from center of mass:

$$a_p = \frac{M_s}{M_s + M_p} a \quad \text{and} \quad a_s = \frac{M_p}{M_s + M_p} a \tag{8.6}$$

Planetary velocity:

$$v_p = \frac{2\pi a_p}{P}. \tag{8.7}$$

Planetary properties

Kepler 3:

$$P^2 = \frac{4\pi^2}{G(M_s + m_p)}(a_s + a_p)^3 \tag{8.8}$$

Therefore:

$$a = a_s + a_p = \left(\frac{P^2}{4\pi^2}G(M_s + M_p)\right)^{1/3}. \tag{8.9}$$

In addition (center of mass!):

$$a_s M_s = a_p M_p \tag{8.10}$$

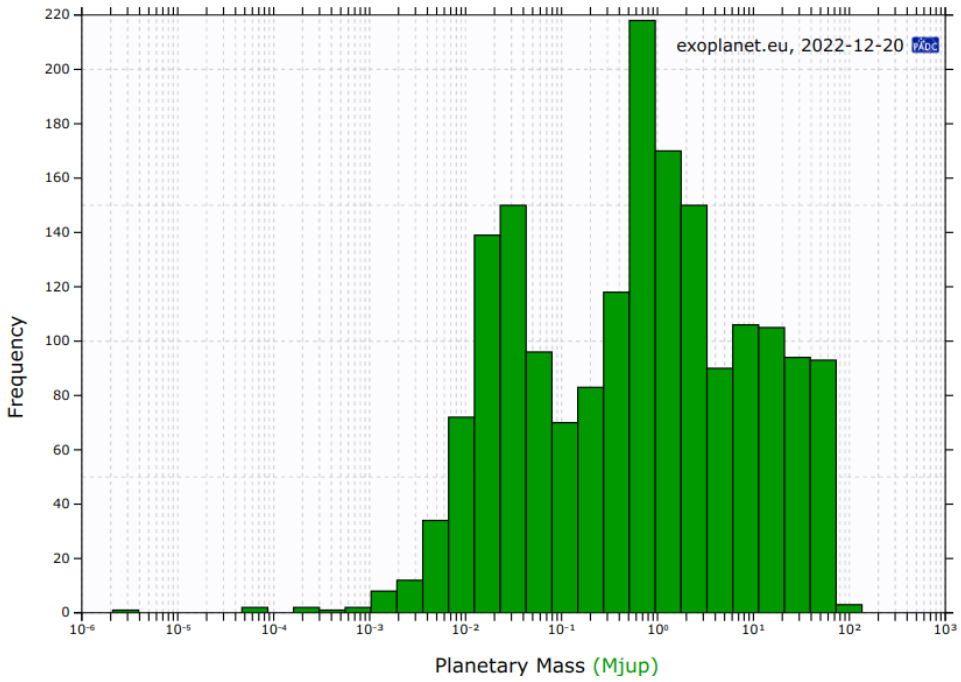
such that

$$v_s M_s = v_p M_p. \tag{8.11}$$

Therefore

$$M_p \sin i = K_s \left(\frac{P(M_s + M_p)^2}{2\pi G}\right)^{1/3}. \tag{8.12}$$

Results: Mass limits



- Except for transits: Only mass function can be directly derived:

$$f(M) = \frac{M_p \,(\sin i)^3}{\left(1 + \frac{M_s}{M_p}\right)^2} = \frac{P\, K_s^3}{2\pi G} \qquad (8.13)$$

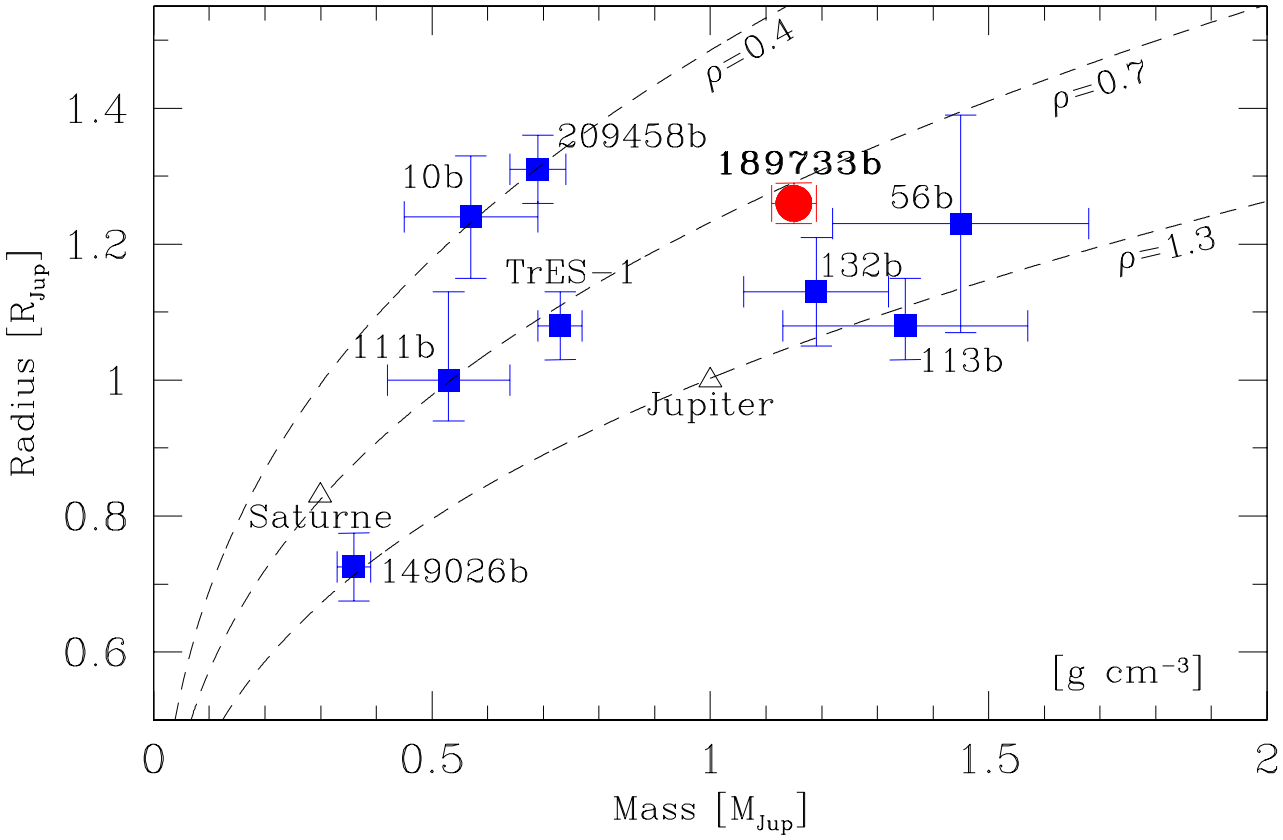
- mass of the star M_s from spectroscopy $\Longrightarrow M_p \sin i$, i.e., lower limit to the planet's mass M_p; inclination remains indetermined
- Many (most!) Planets found have $M_p \sin i > M_{♃}$ ($M_{♃} = 318\, M_\oplus$)

Selection effect: large M $\Longrightarrow$ larger velocity amplitude $\Longrightarrow$ easier to detect!

So, the fact that we have seen not many Earth-like planets does not mean that they do not exist, just that we cannot detect them. Smallest mass found so far: $0.01\, M_\oplus$ (Kepler 37b)

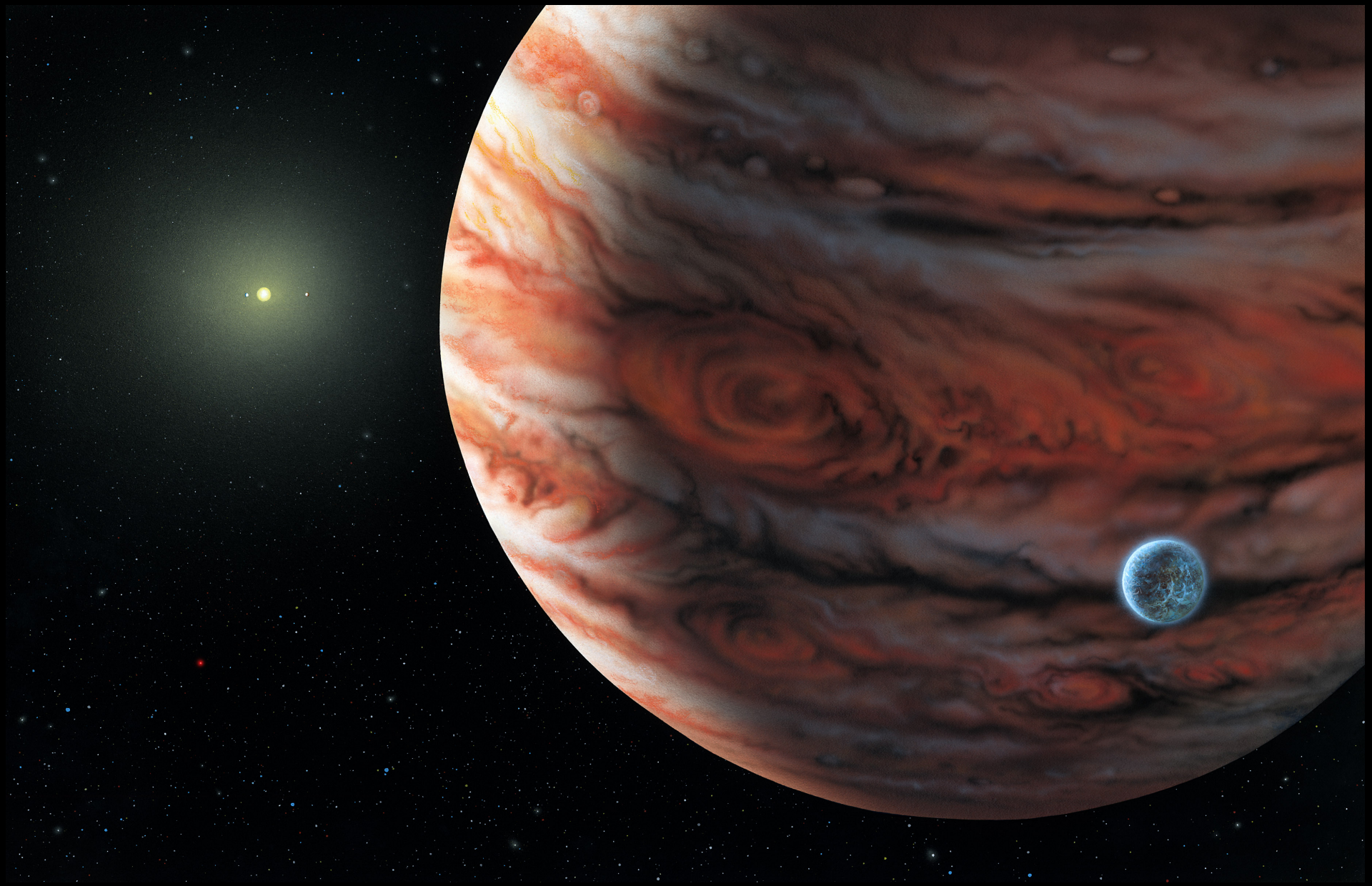
bimodal distribution: caused by detection techniques (transits versus radial velocity)

Results: Density



- Masses and radii: $\Longrightarrow$ density
- many similar to Saturn and Jupiter
- several less dense than Saturn and Jupiter
- inflated by heating by host star

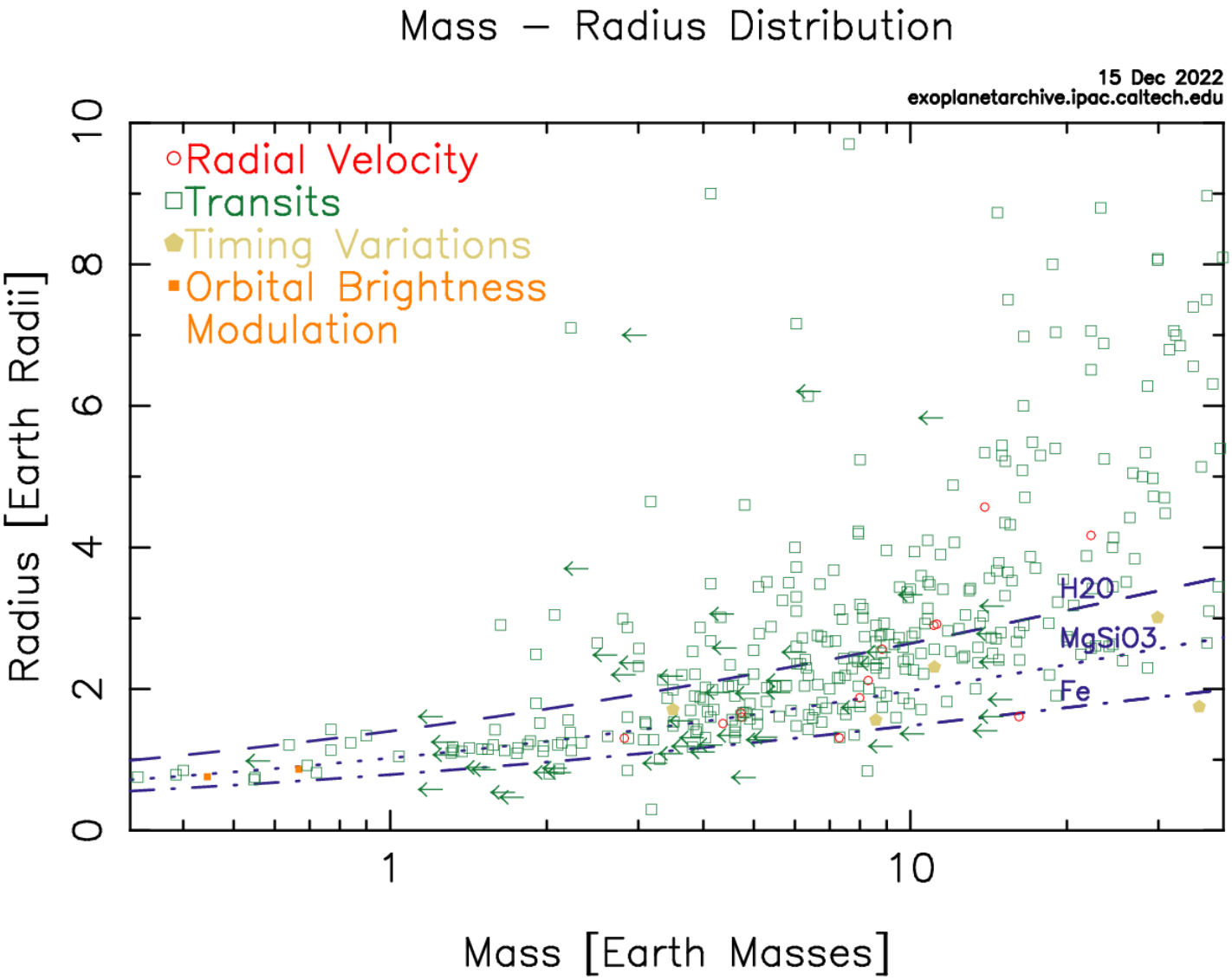
Low densities $\Longrightarrow$ these planets are made of gas!



ESA press release, copyright 2002 Lynette Cook, `http://extrasolar.spaceart.org/`.

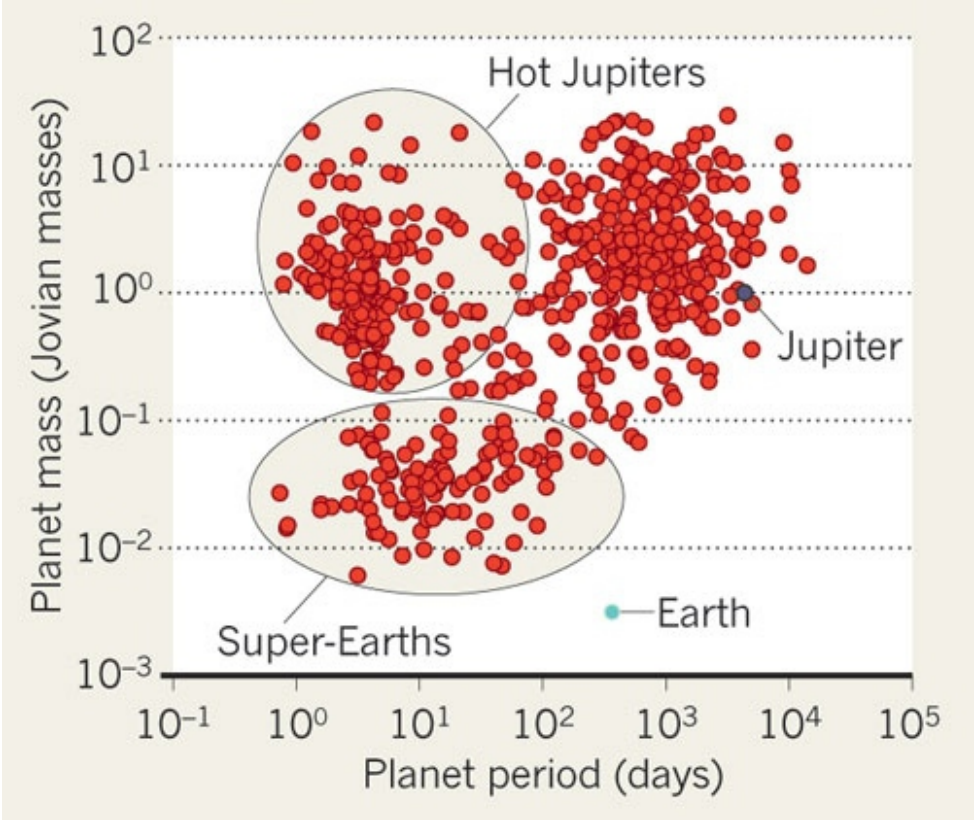
Jupiter-sized planet plus minor planets (left: detected, Jupiter-scale planet, right: hypothetical planet) around 55 Cancri.

Results: Density



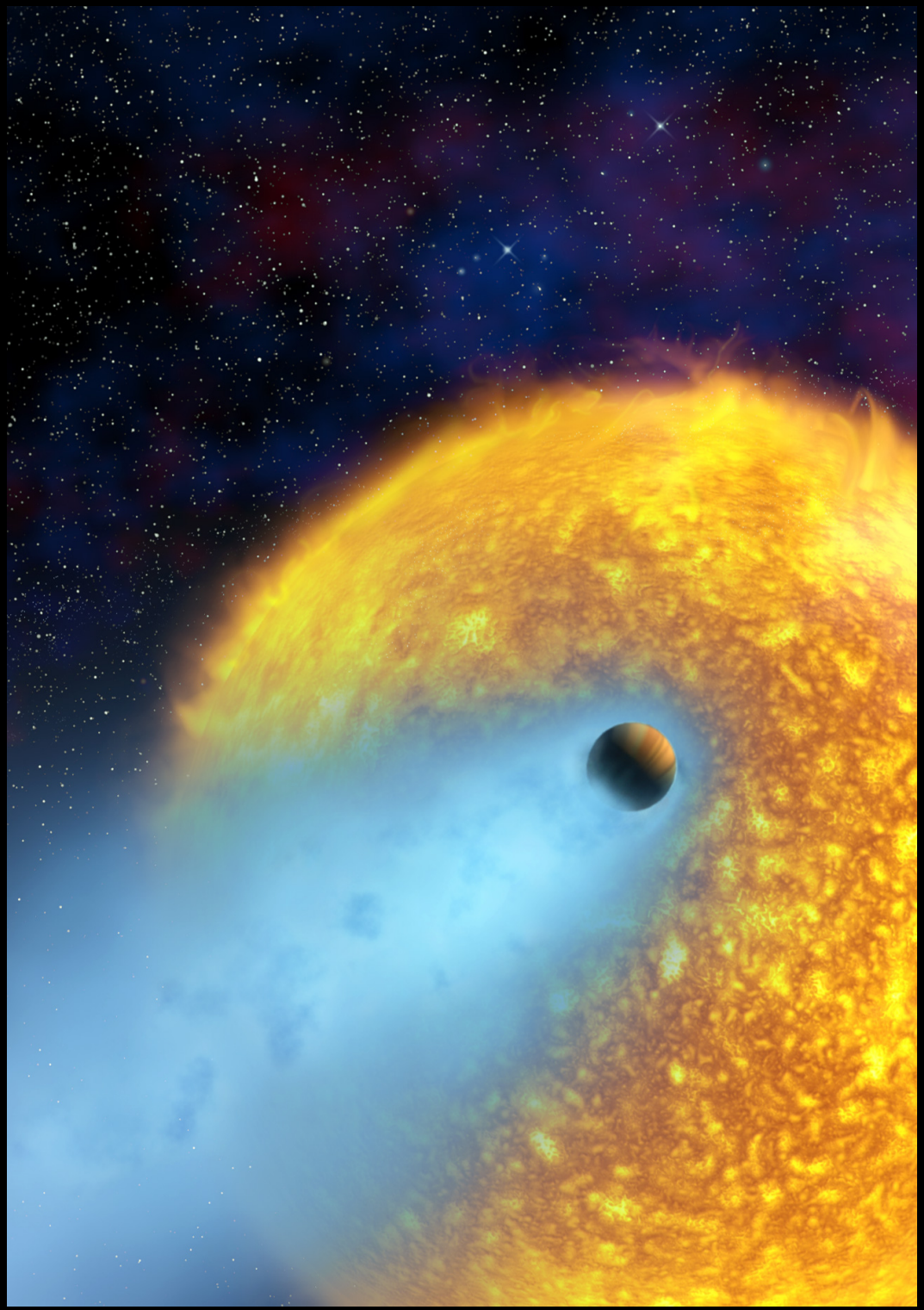
There are planets with large densities: Super-Earths

Results: Density



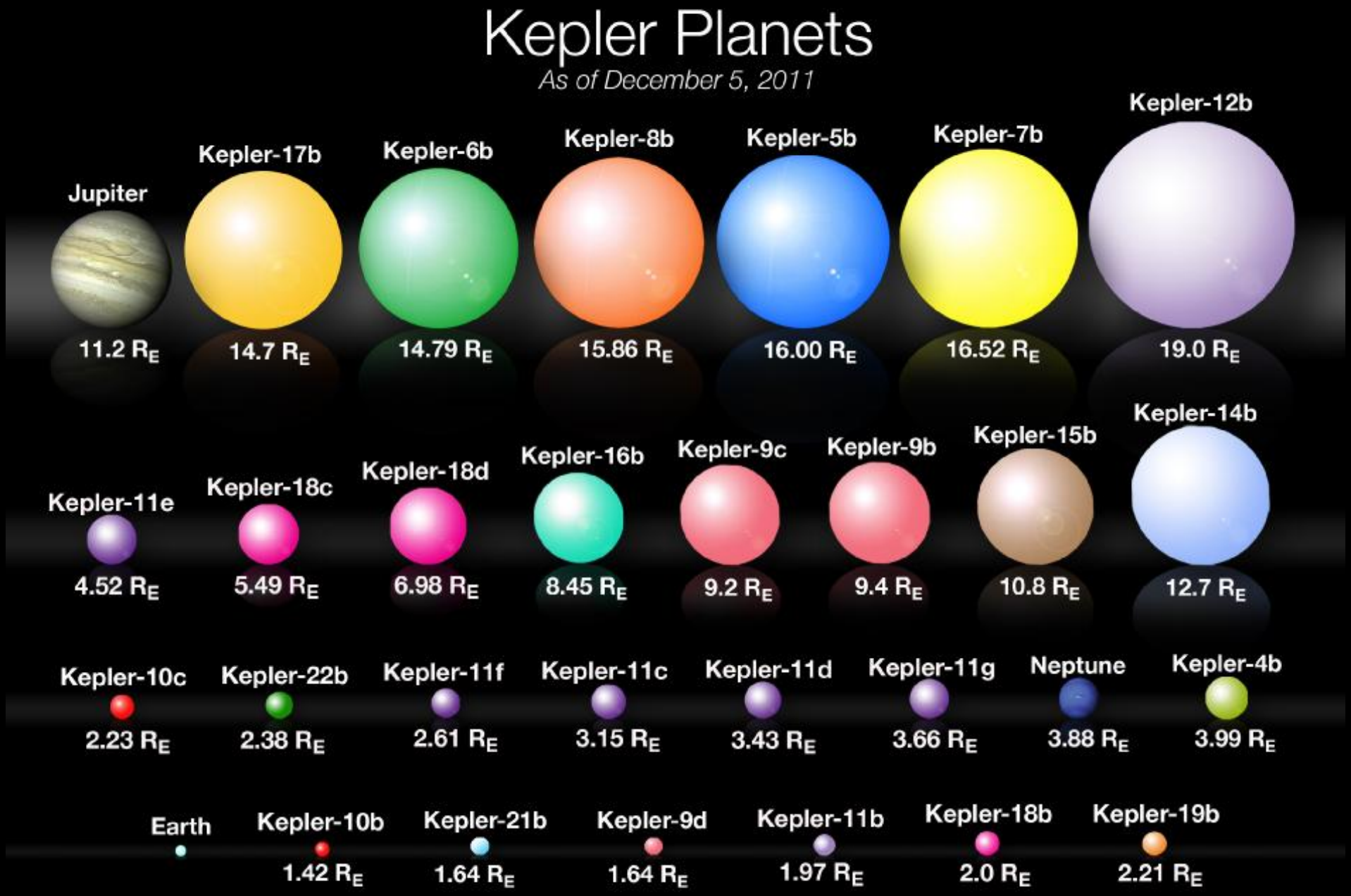
Super-Earth: CoRoT-7b

- Mass and radius
  $\Longrightarrow$ density
- radius small, mass large
- density larger than Earth
- CoRoT-7b:
  Mass: $7.42 \pm 1.21\,M_{\oplus}$,
  Density: $10.4 \pm 1.4\,\mathrm{g\,cm^{-3}}$,
  (Hatzes et al. 2011, ApJ 743, 75)
  $\Longrightarrow$ possible composition similar to Marcury: 2/3 Fe core, 1/3 silicate mantle
  (Wagner et al. 2012, A&A, 541, A103)

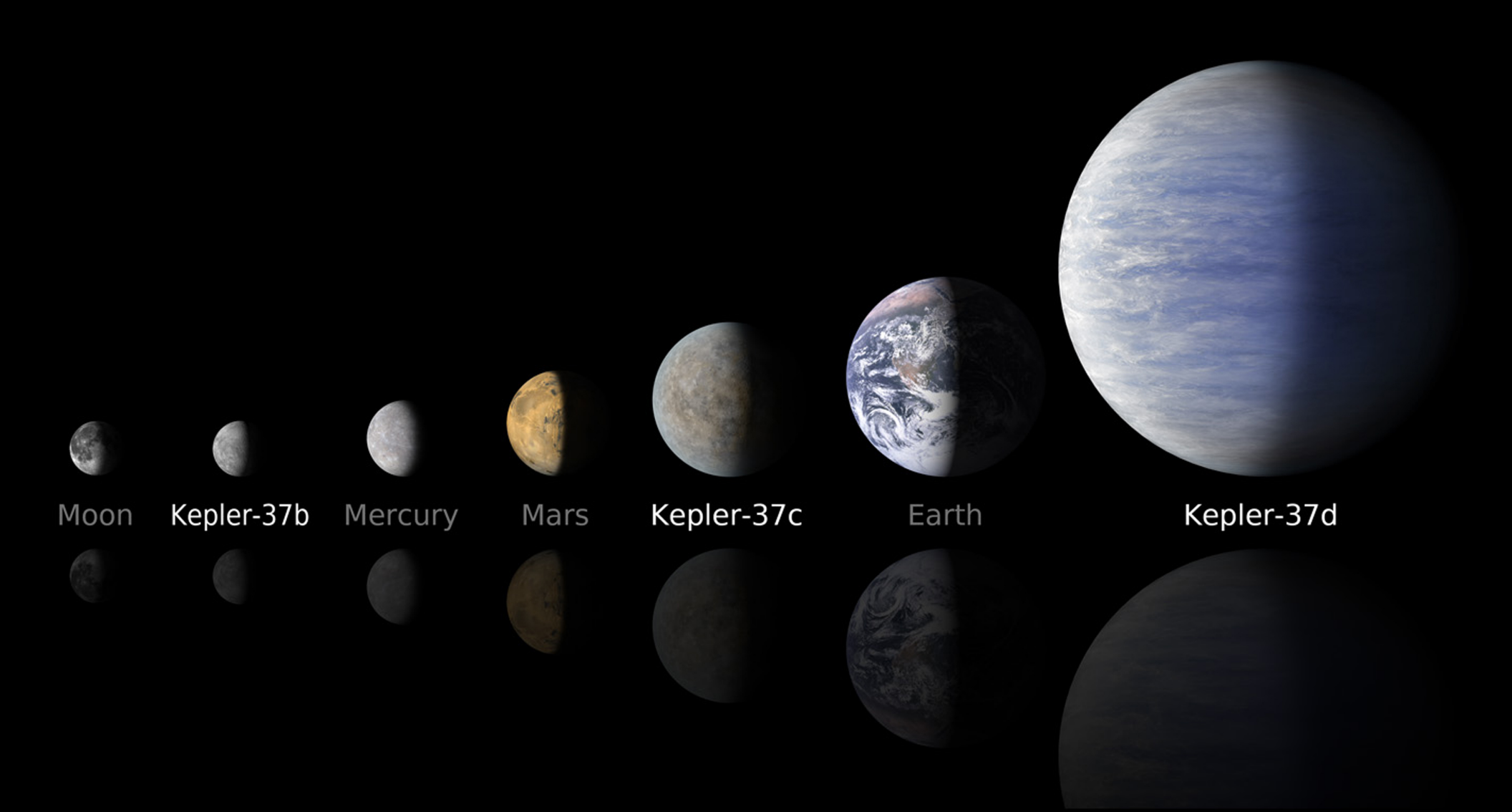


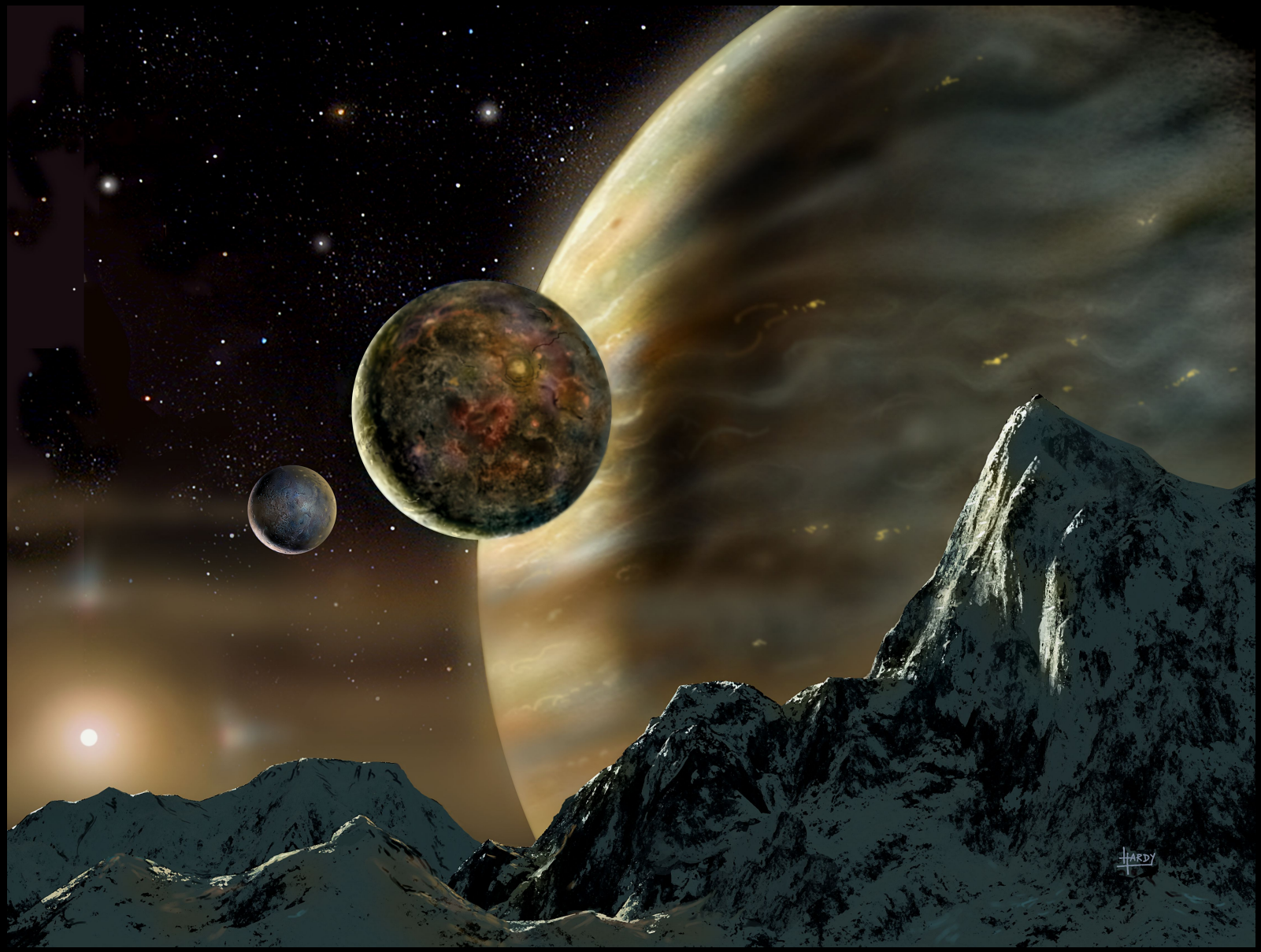
ESA

Jupiter-scale planets close to stars: “hot Jupiters”
e.g., HD 209458b, only 7 Million km from star: planet is evaporating (HST spectroscopy: mass loss is $10^7\,\mathrm{kg\,s^{-1}}$)!



Discovering many Jupiter- and Earth-like planets!

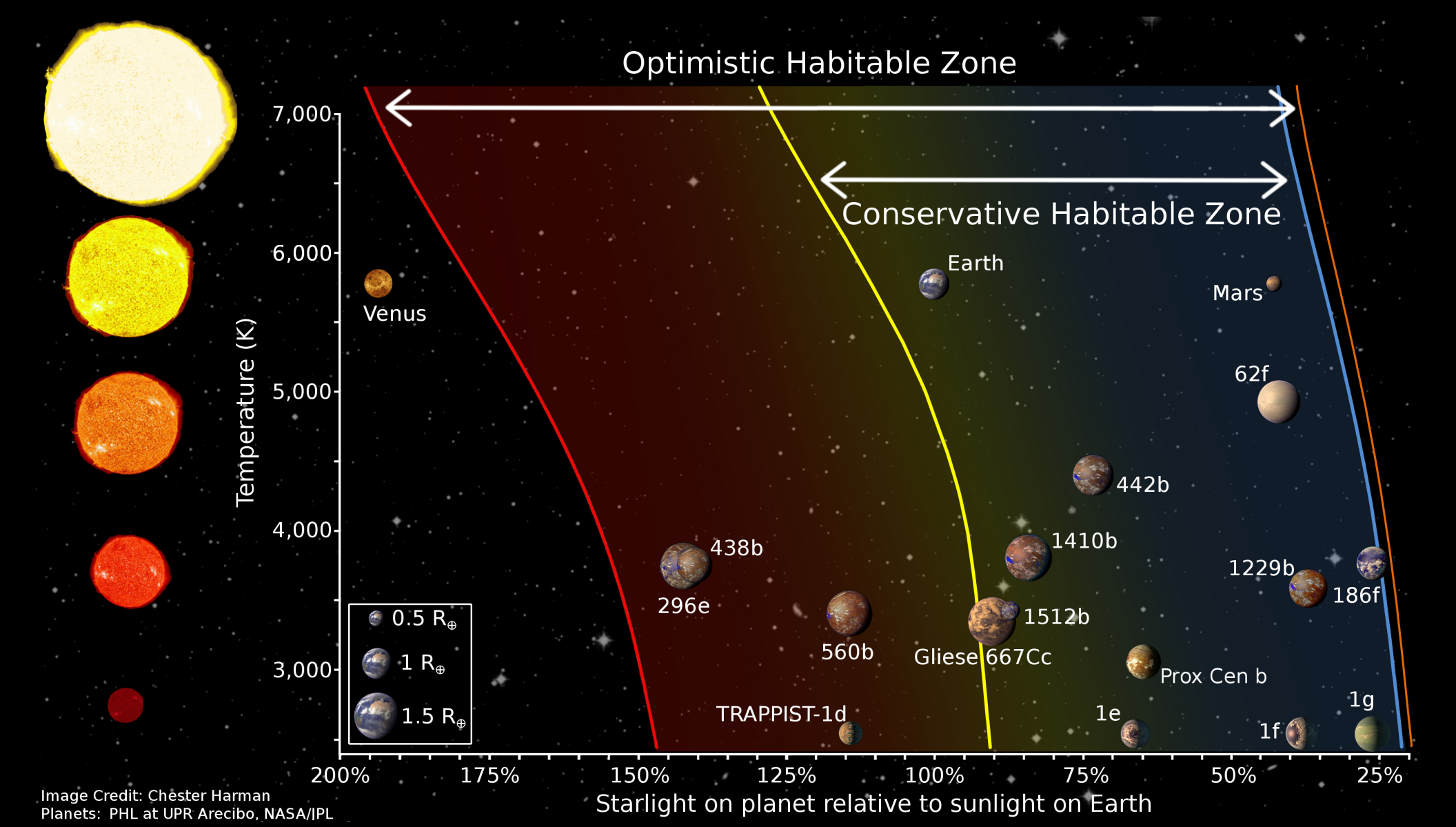

Moon
Kepler-37b
Mercury
Mars
Kepler-37c
Earth
Kepler-37d



D.M.Hardy / PPARC

Some Earth-like planets found on long-period orbits – HD 70642 ($\mathrm{d} = 90\,\mathrm{ly}$): discovered by Hugh Jones (Liverpool John Moores University): Jupiter mass planet at 3 AU from solar-like star in circular orbit

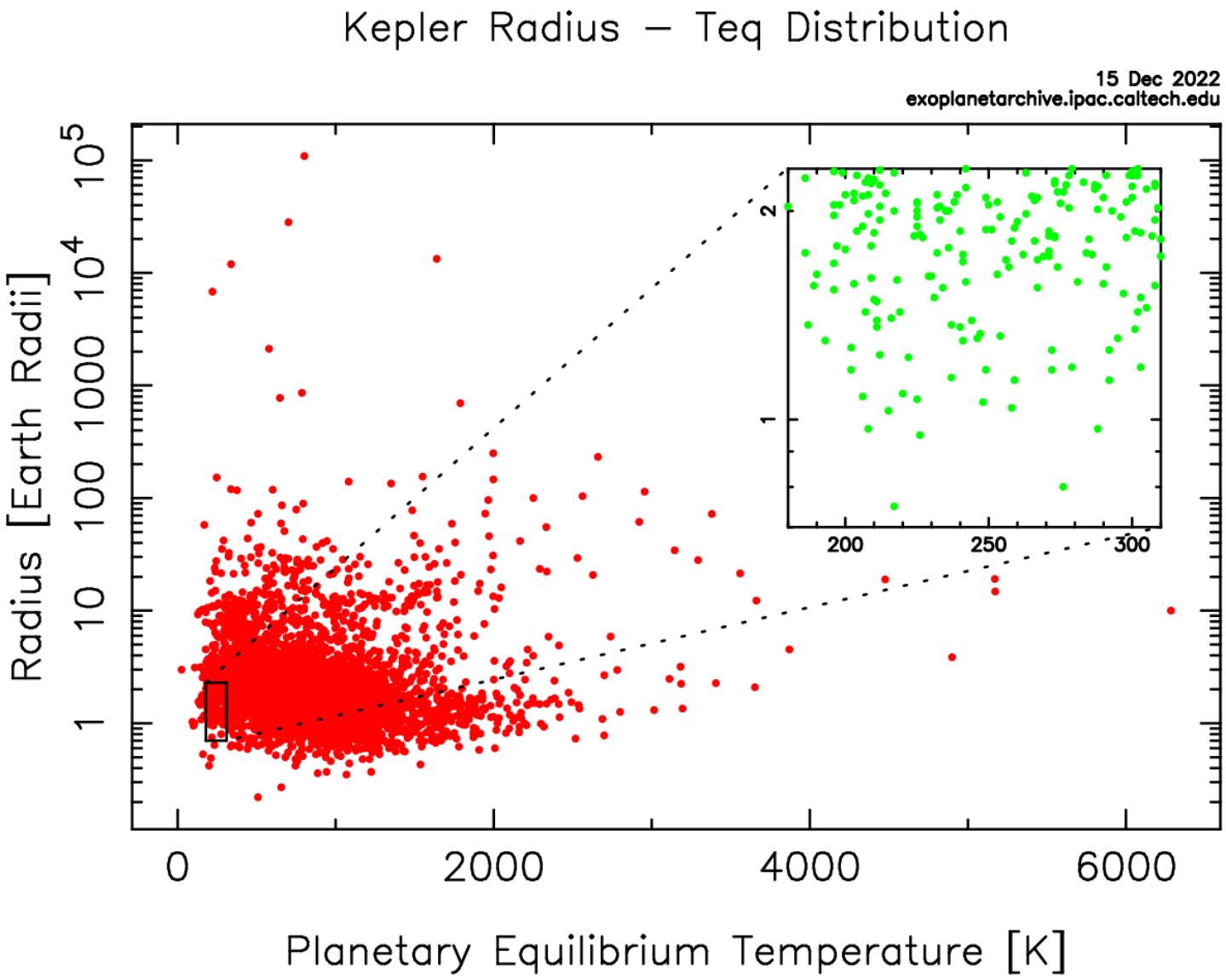
$\Longrightarrow$ stable Earths are possible.



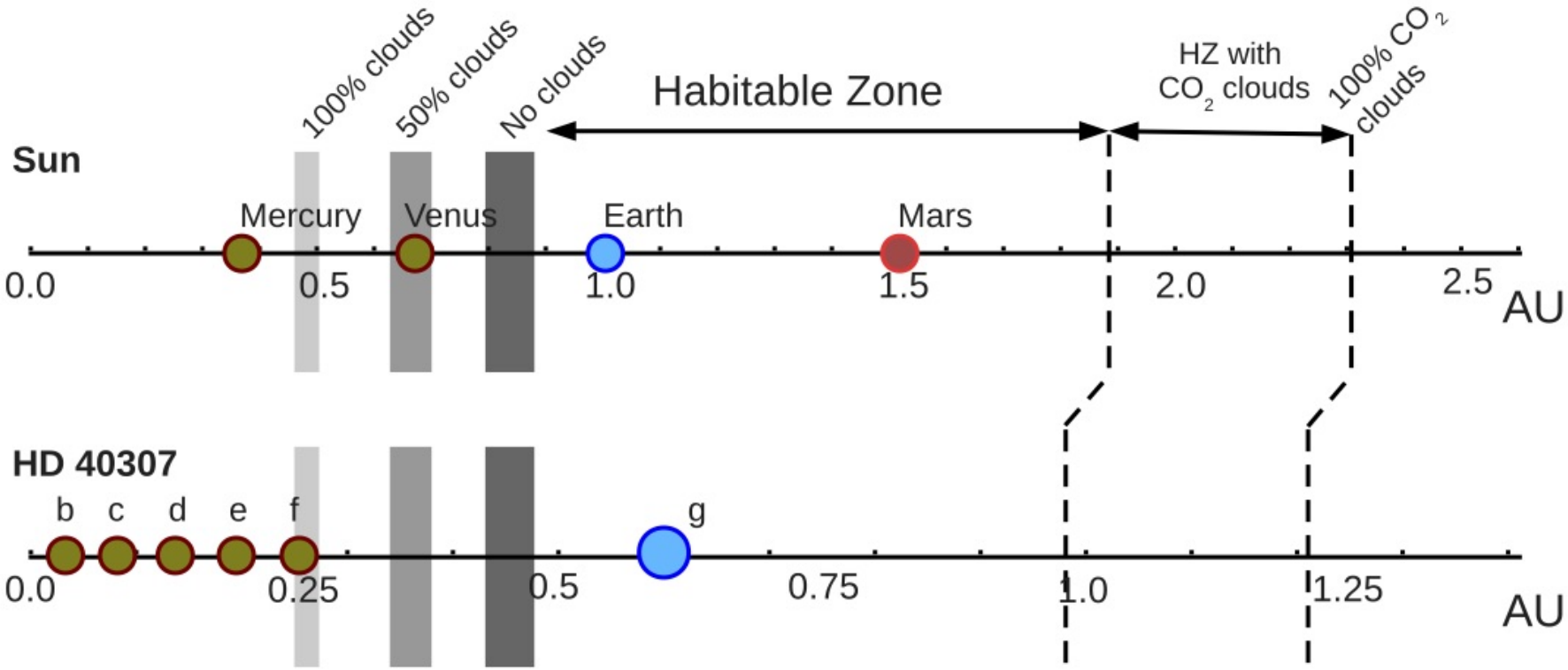
Chester Harman

habitable zone: region in which water could exist as a liquid

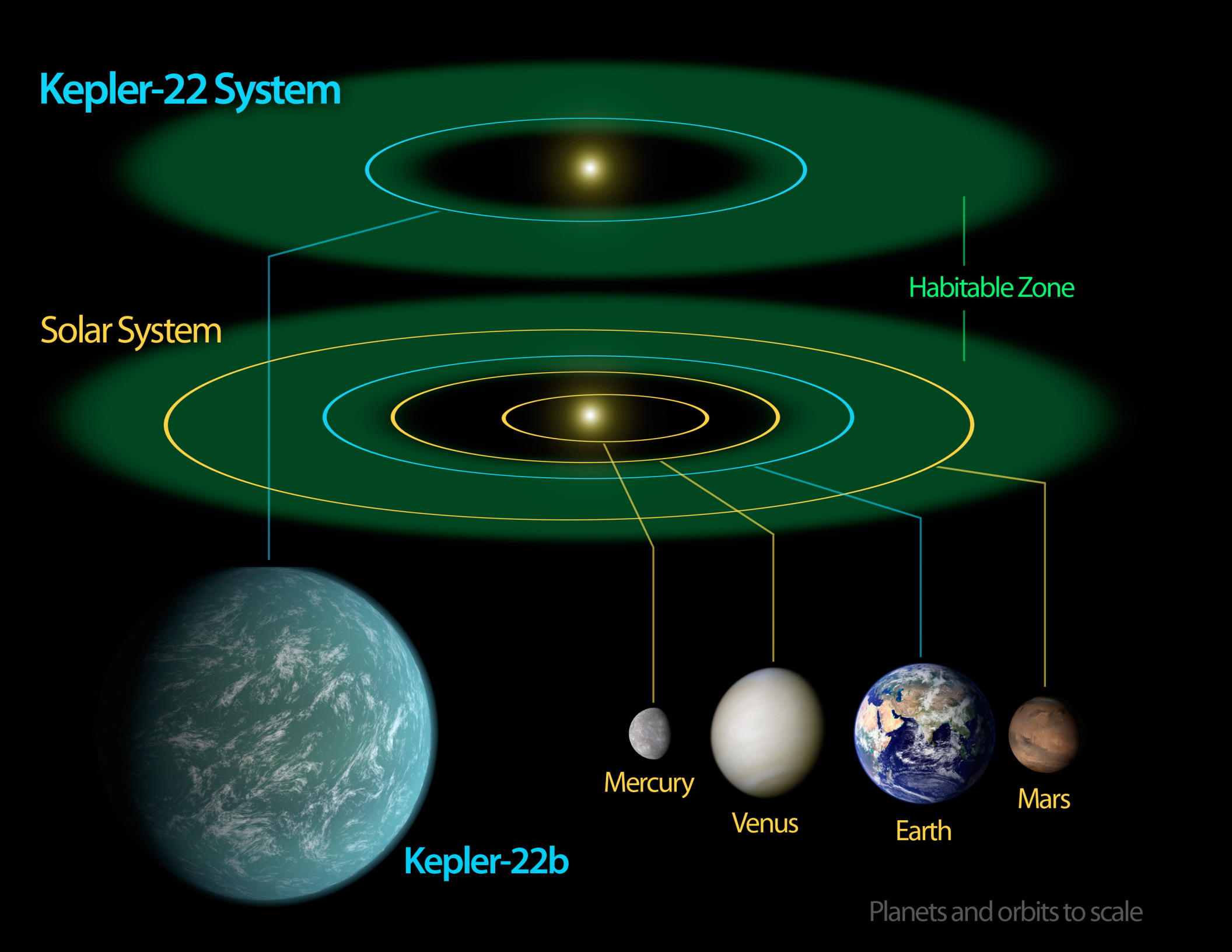
Habitable Zone



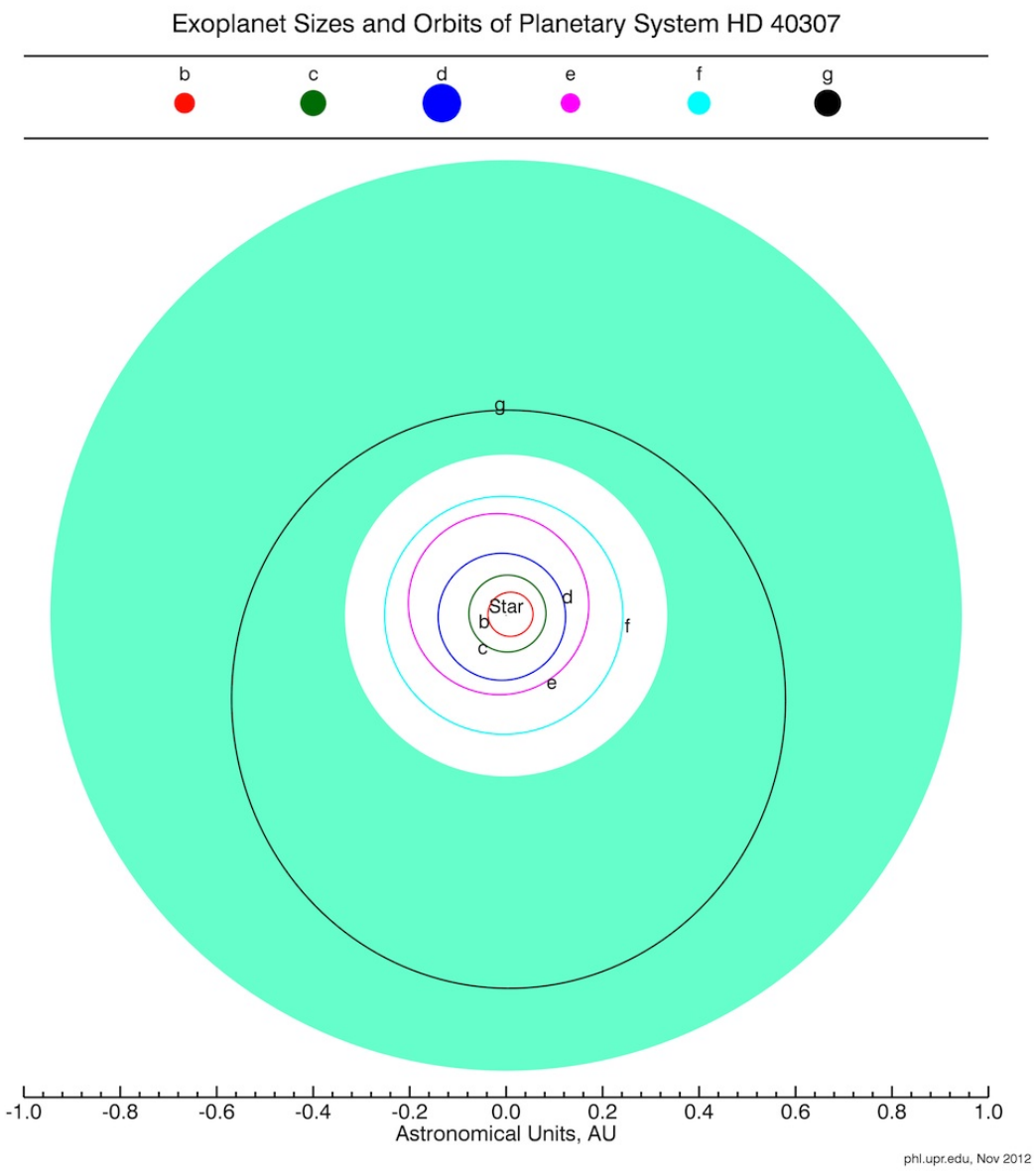
Habitable Zone



Note: Habitable Zone depends of properties of the planets, especially clouds (reflectivity, green house effect,...)

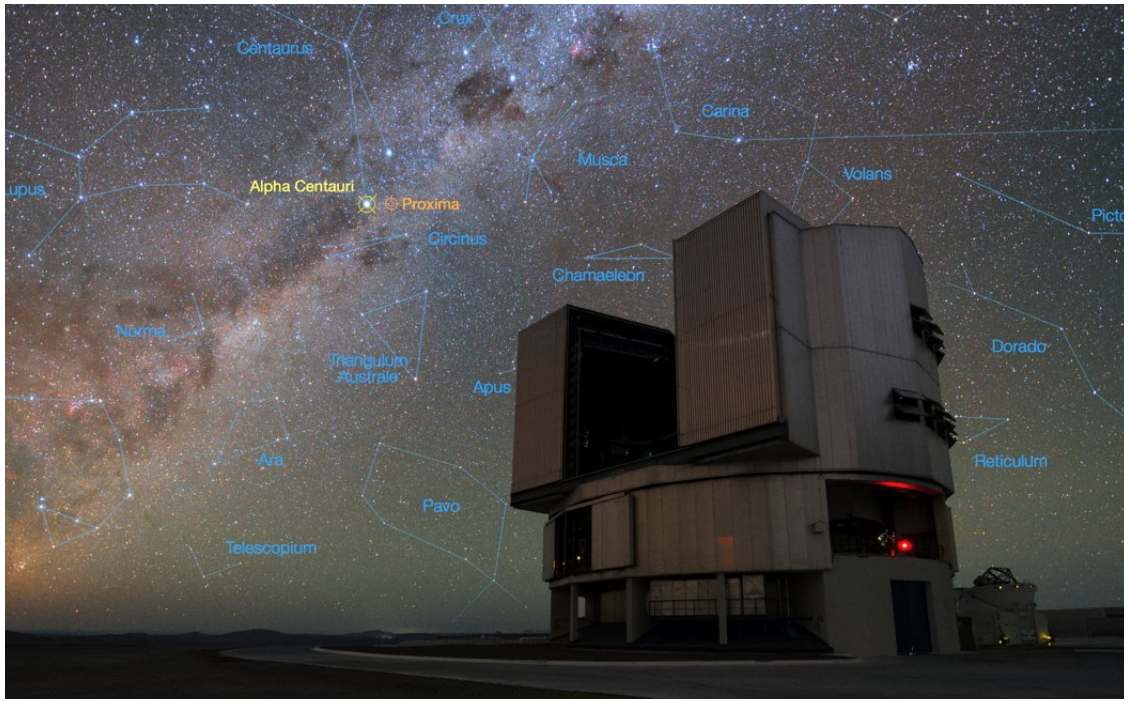

Kepler-22 System
Habitable Zone
Solar System
Mercury
Venus
Earth
Mars
Kepler-22b
Planets and orbits to scale

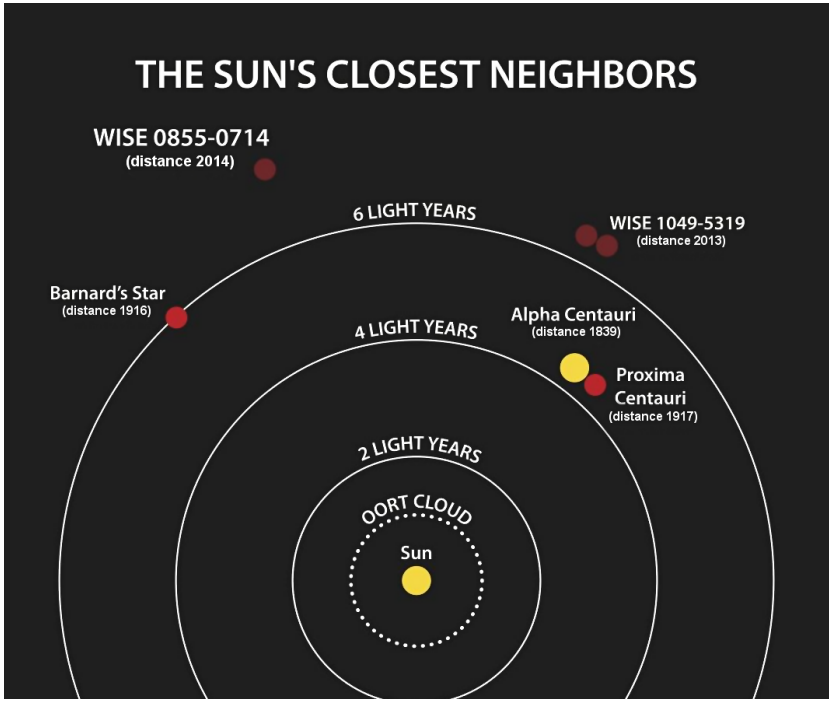
The planets of HD40307



- Six planets, of which 3 are super earths
- HD40307g, $M > 7.1 M_\oplus$, $P = 197.8$ d, in habitable Zone.
  dynamical analysis: mass cannot be much larger than minimum mass

Proxima Centauri b



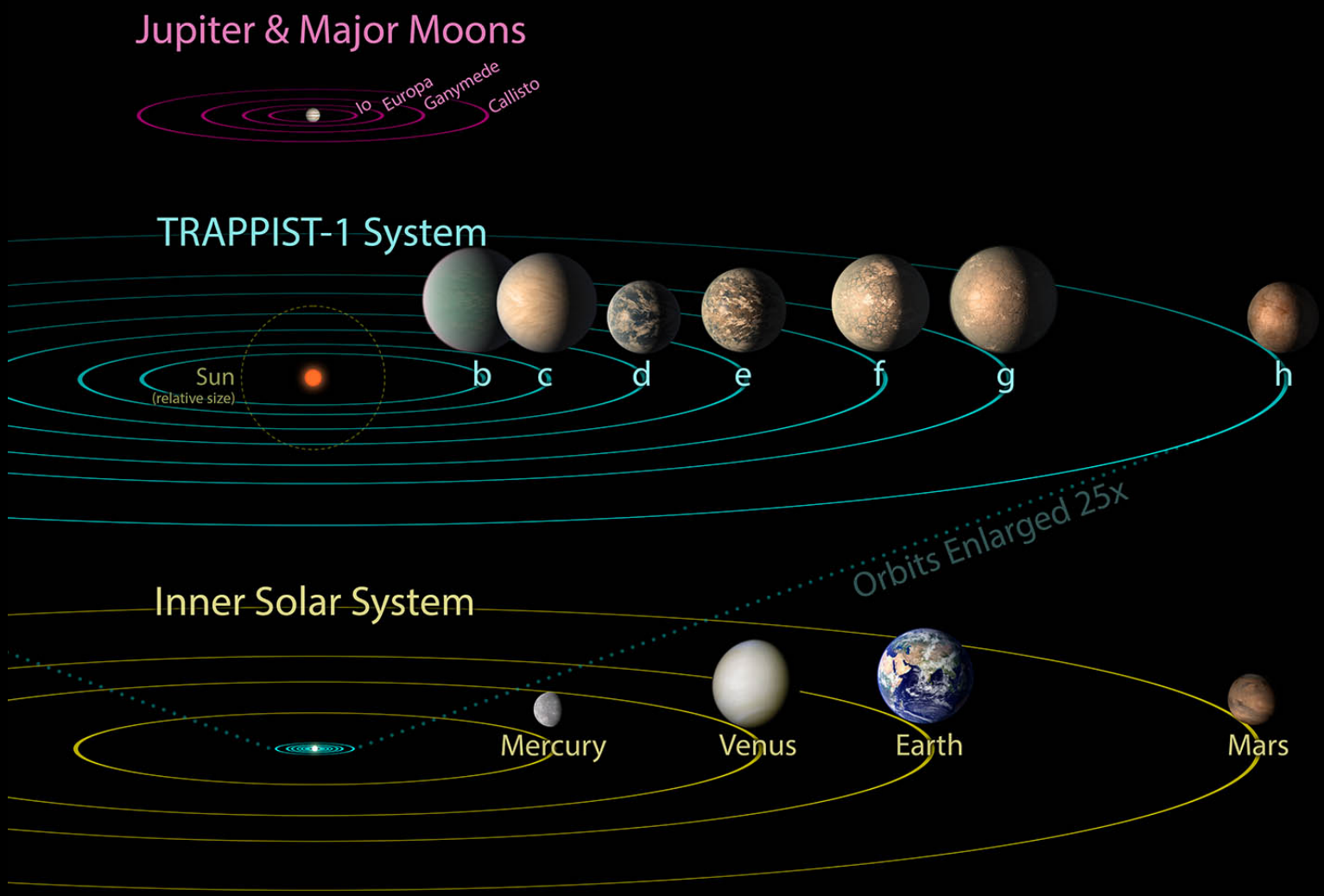


Proxima Centauri: red dwarf with $0.12 M_\odot$.

closest star to sun, distance 1.3 pc (4.24 light years)

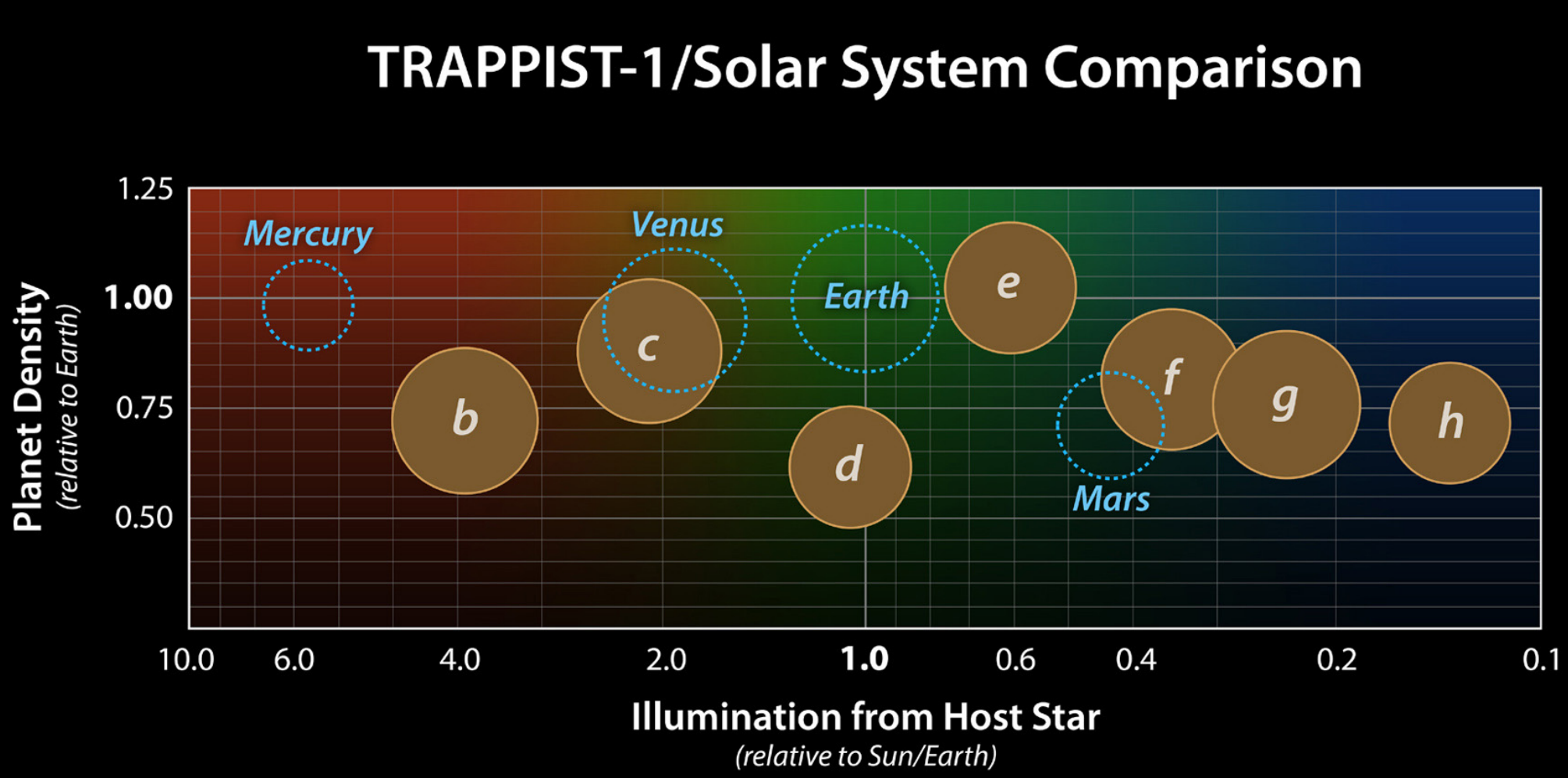
Planet Proxima Centauri b: closest exo planet, is in habitable zone

but: red dwarfs show flaring which would sterilize planetary surface



NASA/JPL-Caltech/R. Hurt, T. Pyle (IPAC)

TRAPPIST-1 ($d = 39.6$ ly): system of 7 planets around M-dwarf (ultra cool star; $M = 0.09\,M_\odot$).

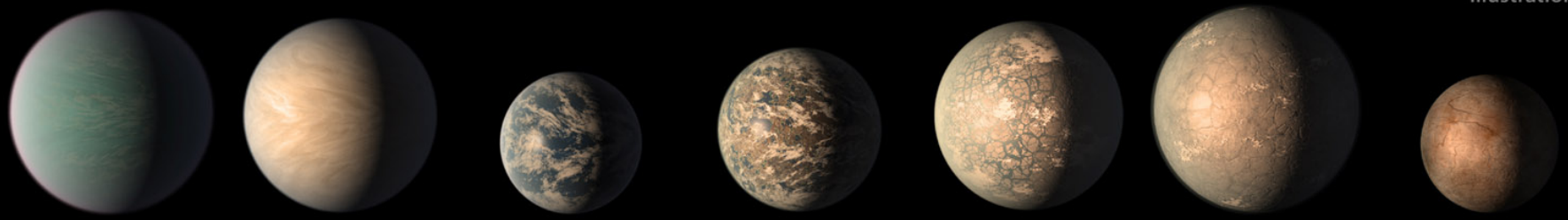


NASA/JPL-Caltech

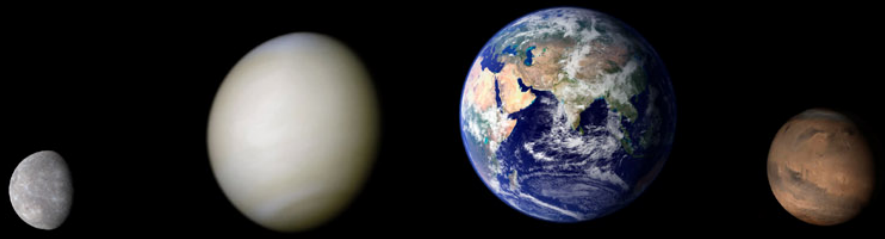
Conditions on planets similar to Earth

$\Longrightarrow$ searches for atmospheres, water are ongoing

Illustrations



TRAPPIST-1 System (Feb. 2018)	b	c	d	e	f	g	h
Orbital Period	1.51 days	2.42 days	4.05 days	6.10 days	9.21 days	12.36 days	18.76 days
Distance to Star	0.0115 AU	0.0158 AU	0.0223 AU	0.0293 AU	0.0385 AU	0.0469 AU	0.0619 AU
Planet Radius	1.12 R_{earth}	1.10 R_{earth}	0.78 R_{earth}	0.91 R_{earth}	1.05 R_{earth}	1.15 R_{earth}	0.77 R_{earth}
Planet Mass	1.02 M_{earth}	1.16 M_{earth}	0.30 M_{earth}	0.77 M_{earth}	0.93 M_{earth}	1.15 M_{earth}	0.33 M_{earth}
Planet Density	0.73 ρ_{earth}	0.88 ρ_{earth}	0.62 ρ_{earth}	1.02 ρ_{earth}	0.82 ρ_{earth}	0.76 ρ_{earth}	0.72 ρ_{earth}
Surface Gravity	0.81 g	0.96 g	0.48 g	0.93 g	0.85 g	0.87 g	0.55 g



Solar System Rocky Planets	Mercury	Venus	Earth	Mars
Orbital Period	87.97 days	224.70 days	365.26 days	686.98 days
Distance to Star	0.387 AU	0.723 AU	1.000 AU	1.524 AU
Planet Radius	0.38 R_{earth}	0.95 R_{earth}	1.00 R_{earth}	0.53 R_{earth}
Planet Mass	0.06 M_{earth}	0.82 M_{earth}	1.00 M_{earth}	0.11 M_{earth}
Planet Density	0.98 ρ_{earth}	0.95 ρ_{earth}	1.00 ρ_{earth}	0.71 ρ_{earth}
Surface Gravity	0.38 g	0.90 g	1.00 g	0.38 g

NASA/JPL-Caltech

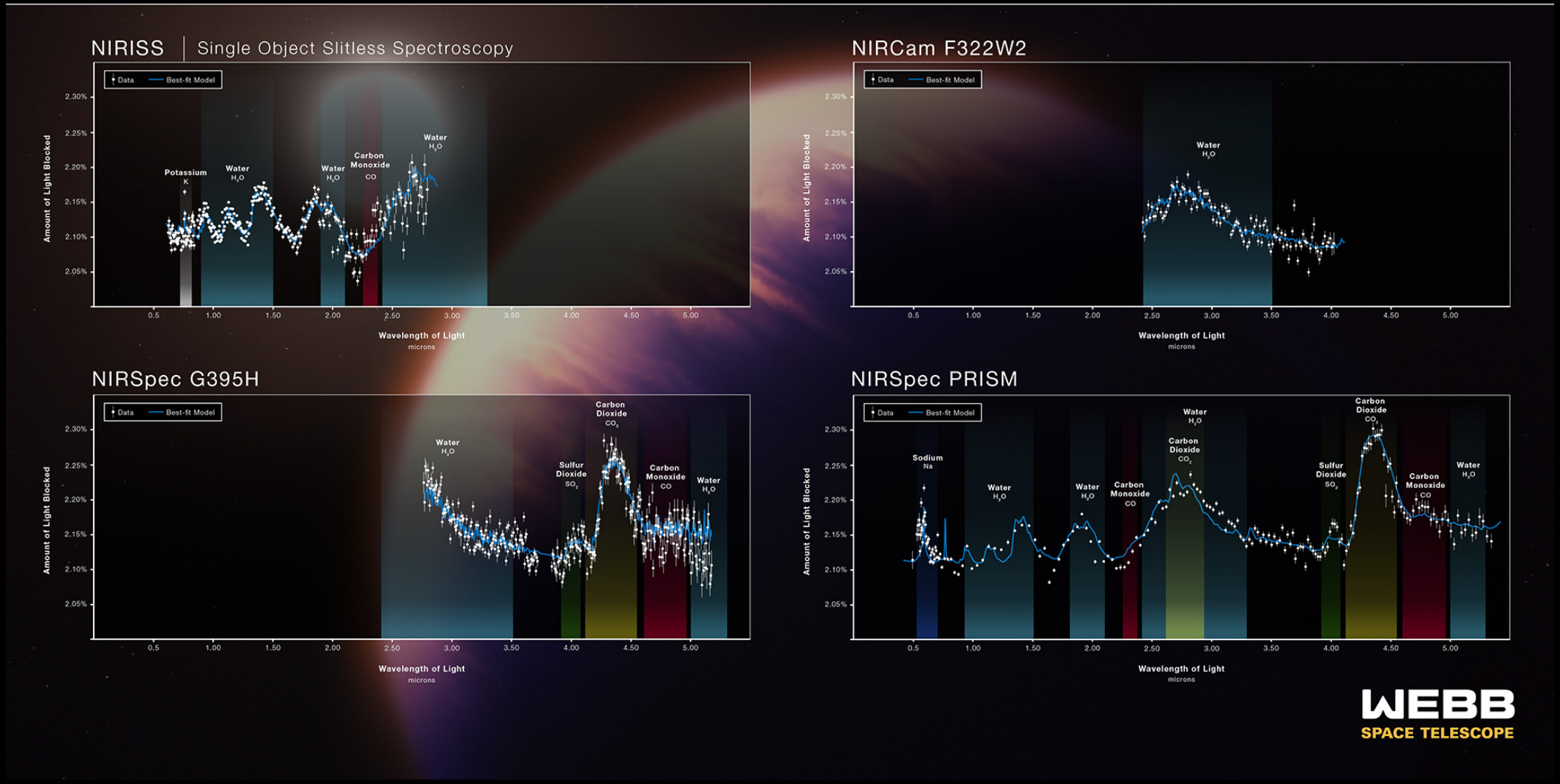
Possibility of oceans and/or ice has been discussed for some of the Earth-like objects



Artist's view from surface of Trappist-1f
(see homework)

HOT GAS GIANT EXOPLANET WASP-39 b

ATMOSPHERE COMPOSITION



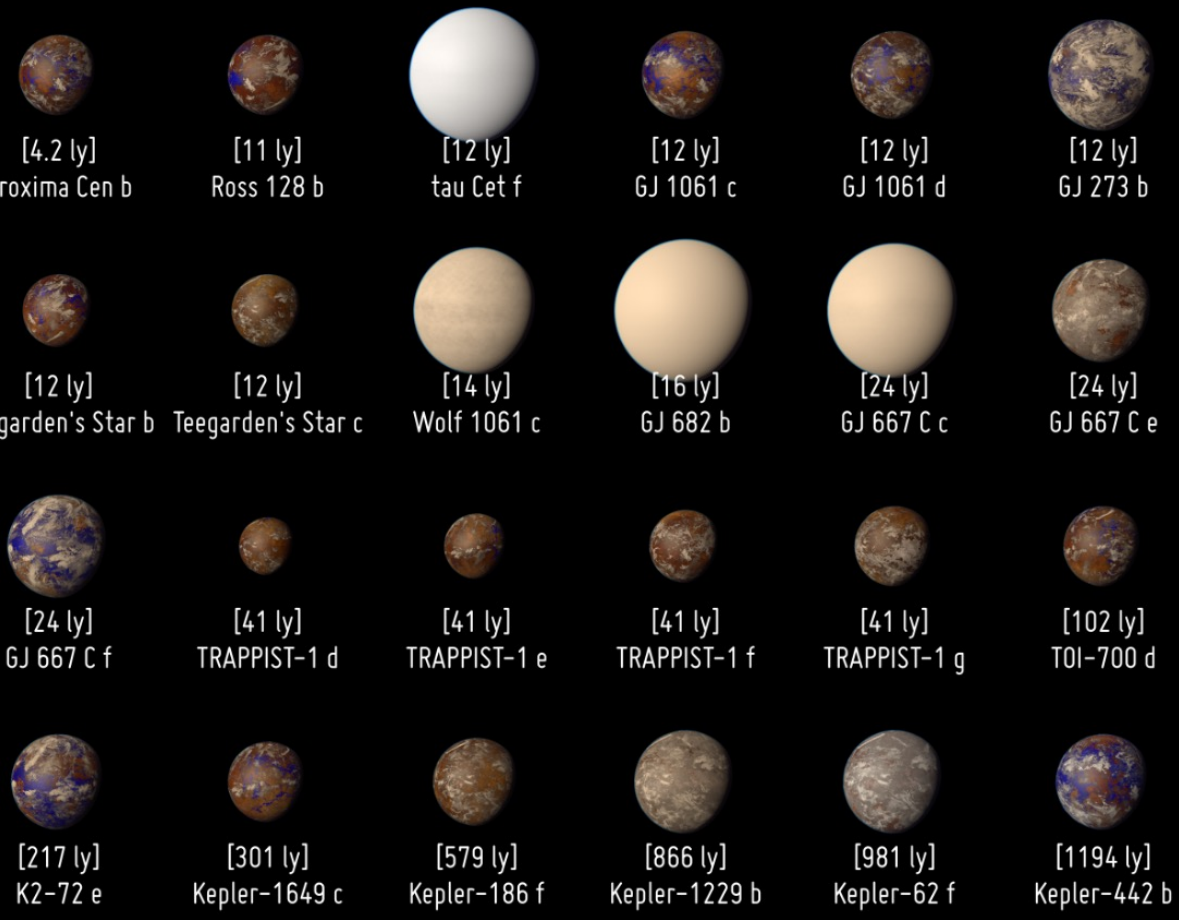
WEBB
SPACE TELESCOPE

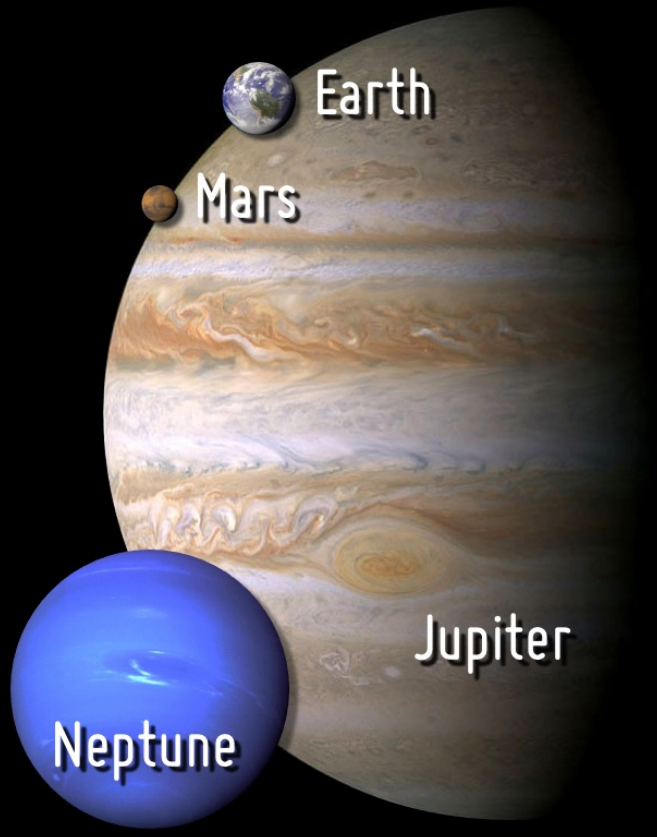
Hot Jupiter WASP-39 b: H_2O, CO_2, SO_2, CO detected this year by JWST

Potentially Habitable Exoplanets

Ranked by Distance from Earth (light years)

PHL





Artistic representations. Earth, Mars, Jupiter, and Neptune for scale. Distance from Earth is between brackets.

CREDIT: PHL @ UPR Arecibo (phl.upr.edu) Oct 5, 2020

Stars: Observations

What are stars?

Most important building blocks of the universe: stars

Proper definition:

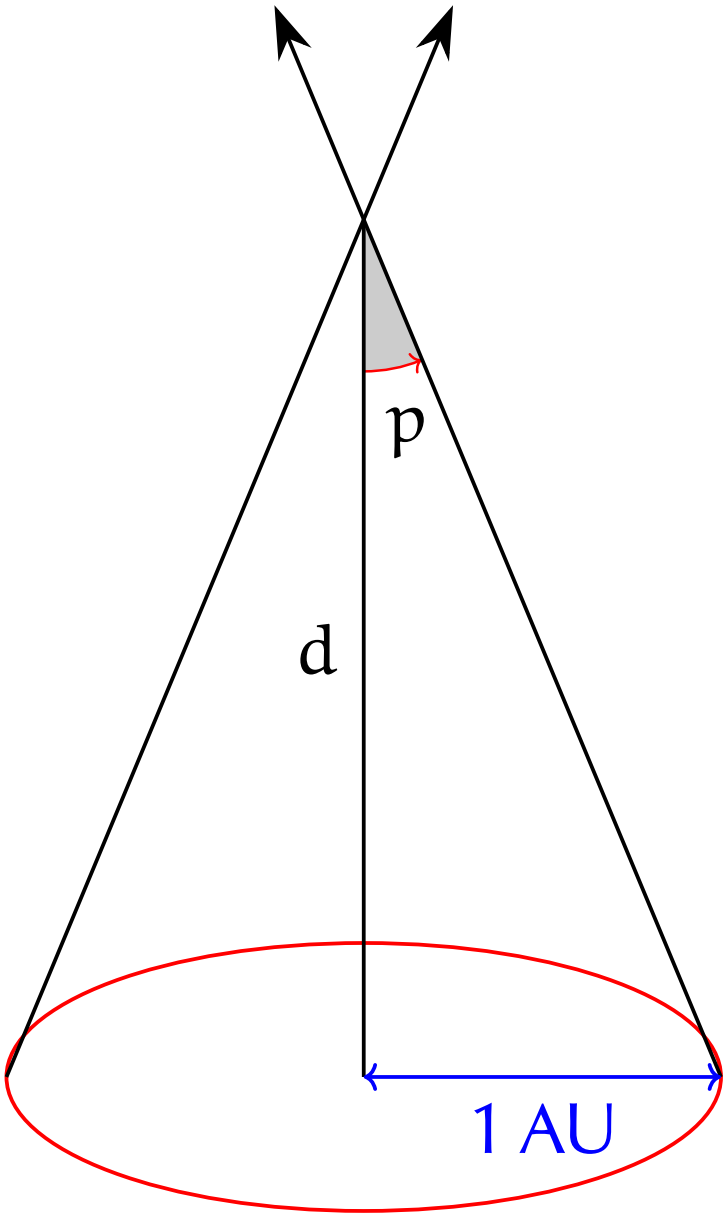
> Stars are gas balls consisting mainly of hydrogen and helium, which produce energy by fusion.

We will now look at observable properties of stars:

1. Distance
2. Motions
3. Brightness and luminosity
4. Spectrum and Temperature
5. Masses

. . . and later deduce from these data how they live.

Distances



Direct distance measurements: parallax measurement:

$\Longrightarrow$ Measure stellar position several times over year with respect to background stars.

Parallax angle (small angle approximation):

$$p = \frac{1\,\mathrm{AU}}{d}$$

(p is measured in *radians*)

Typical values for p are arcseconds

$\Longrightarrow$ define distance unit "Parsec" ("parallax second") such that $d = 1\,\mathrm{pc}$ for $p = 1''$:

The parsec is the distance at which 1 AU subtends an angle of $1''$.

Some people use π instead of p for the parallax...

Distances

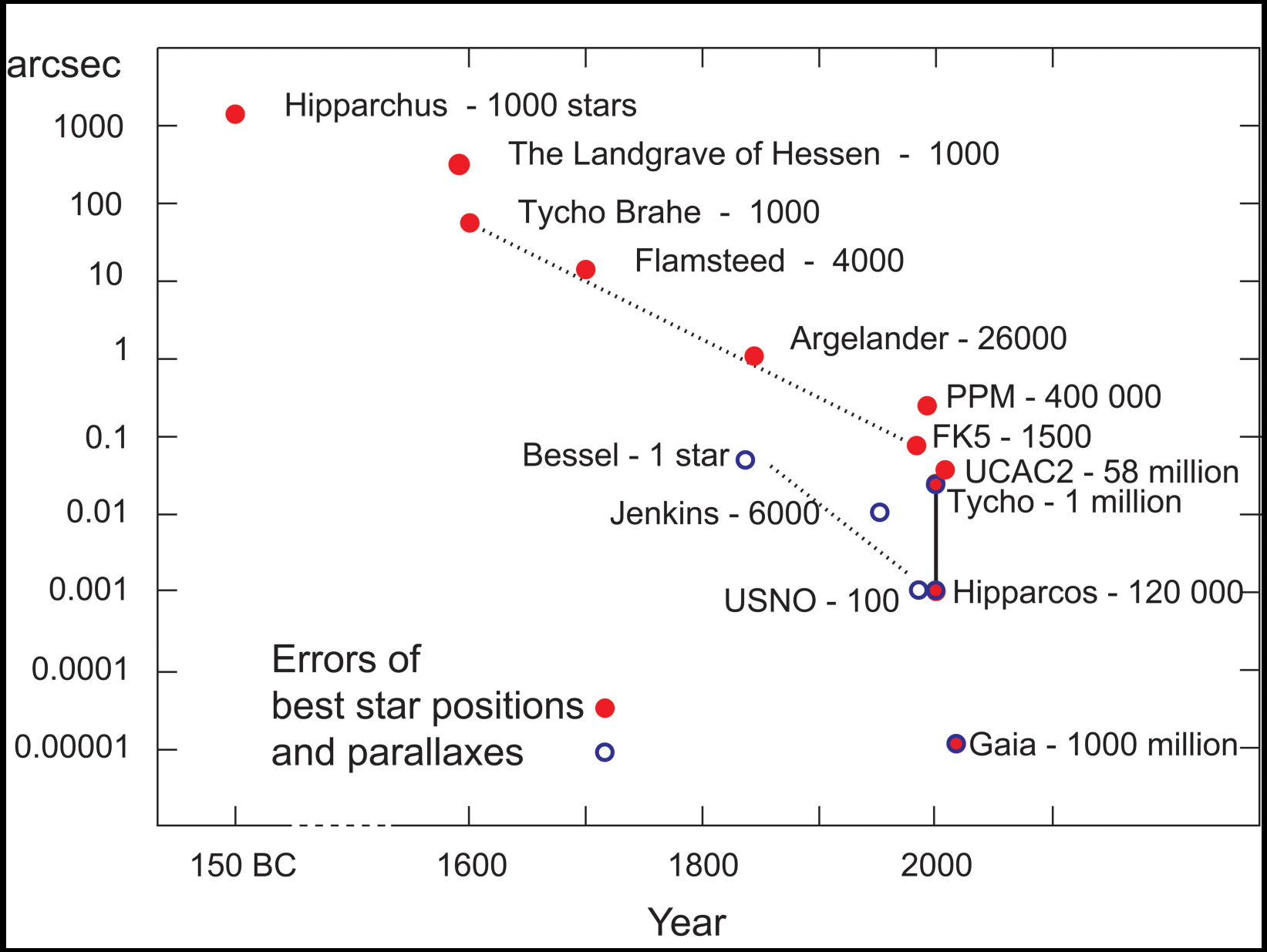
How far is one parsec?

From $p = 1\,\mathrm{AU}/d$ follows with $p = 1''$:

$$d = 1\,\mathrm{pc} = \frac{1\,\mathrm{AU}}{1''} = \frac{1\,\mathrm{AU}}{\pi/(180 \cdot 3600)} = 206264\,\mathrm{AU} = 3.086 \times 10^{16}\,\mathrm{m} \sim 3.26\,\mathrm{ly}$$

Note: If parallax p is known and given in arcseconds, then distance can be immediately calculated:

$$\frac{d}{1\,\mathrm{pc}} = \frac{1}{p/1''} \quad \text{or (sloppy notation)} \quad d = \frac{1}{p}$$



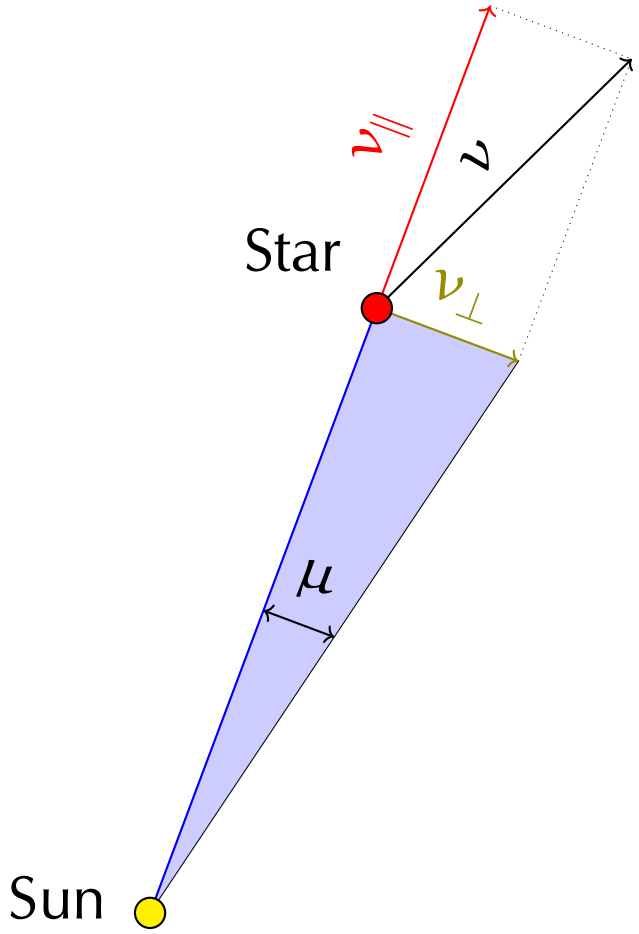
ESA/E. Høg

Today: positional accuracy ~0.01″ from ground, and better than 1 mas (10^{-3}″) from space

$\Longrightarrow$ can measure parallax out to ~1 kpc

further out: "secondary distance estimators" $\Longrightarrow$ see later lectures

Proper Motion



Stars are not fixed to the sky: 3D-motion:

1. Radial velocity, $v_\parallel$: velocity along the line of sight
   (determined using Doppler shift of stellar spectrum)
2. Tangential velocity, $v_\perp$: velocity perpendicular to the line of sight
3. Proper motion μ: Change of star's position with time.
   (μ is measured in *arcsec/year*)
   Typical values for μ are mas/yr

Tangential velocity $= \mu \times d$

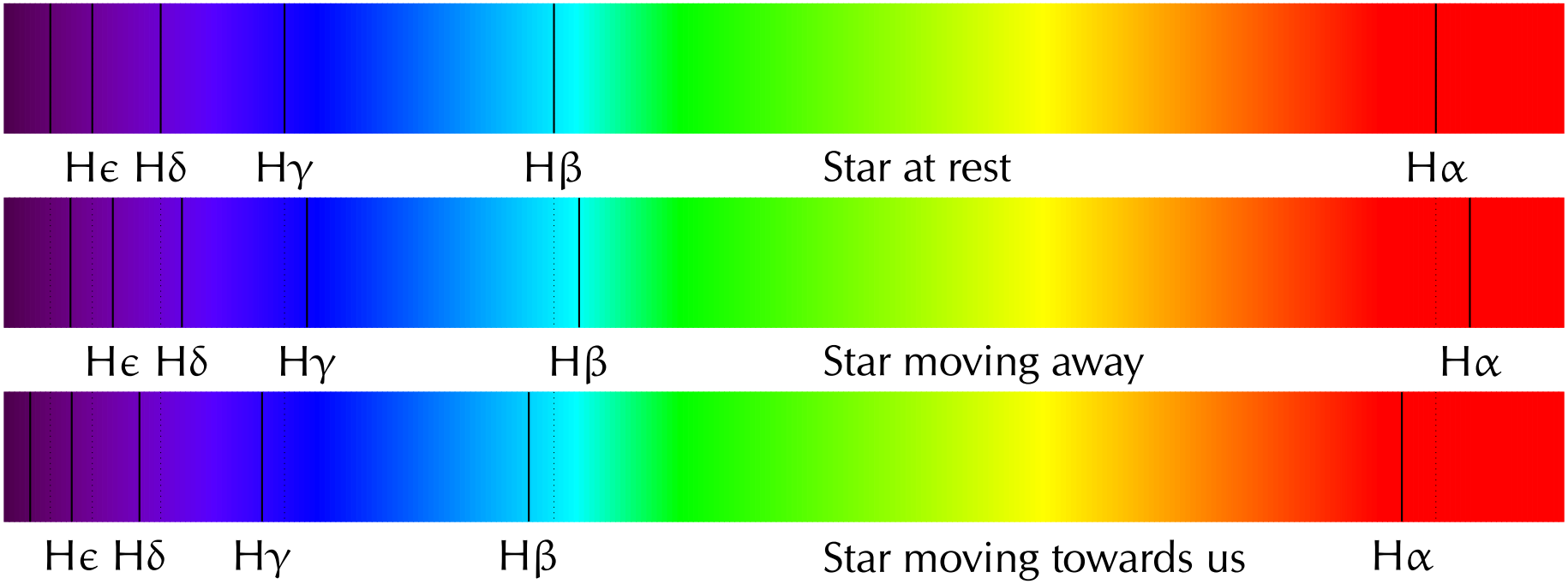
(Distance d needs to be known!)



Credit: Mortfield & Cancelli

Largest proper motion: Barnard's star, $\mu = 10.3\,\mathrm{arcsec\,yr^{-1}}$

Radial Velocity



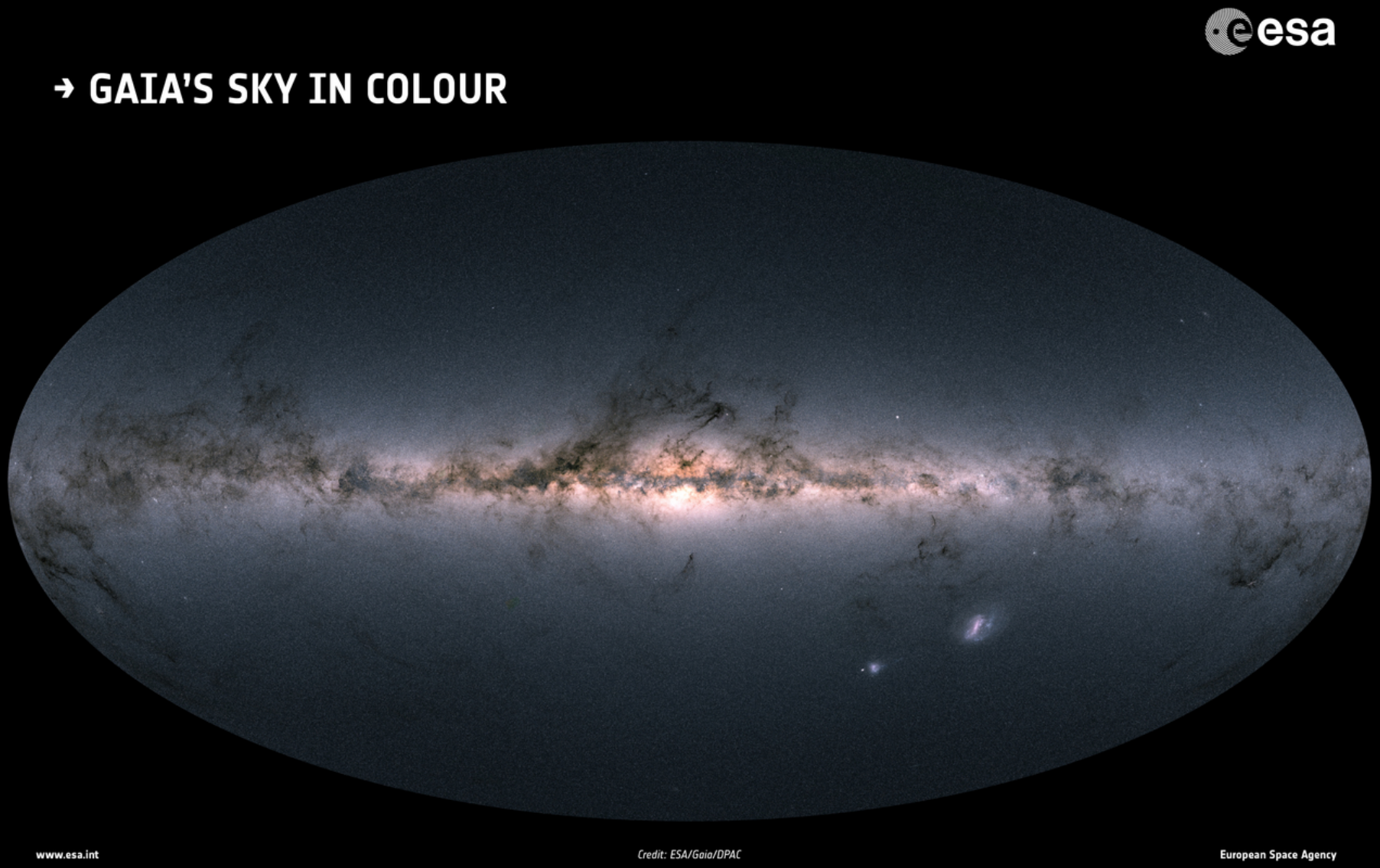
Doppler-Formula:

$$\frac{\Delta\lambda}{\lambda} = \frac{v_{\text{rad}}}{c} \tag{9.1}$$

$\Longrightarrow$ measure radial velocity, v_{rad}, spectroscopically

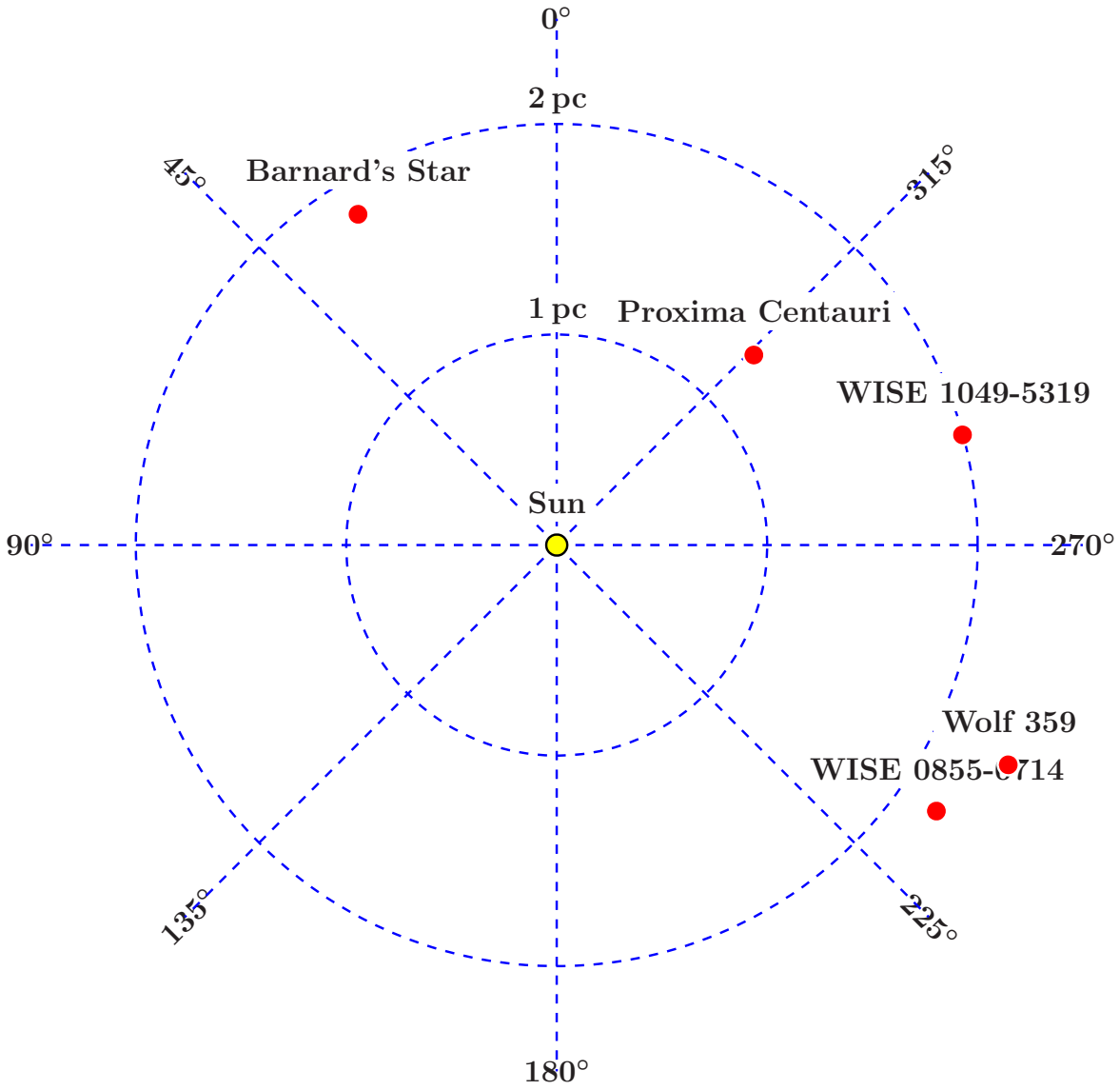
w/tangential velocity (from distance and proper motion): 3D spatial motion

c: speed of light



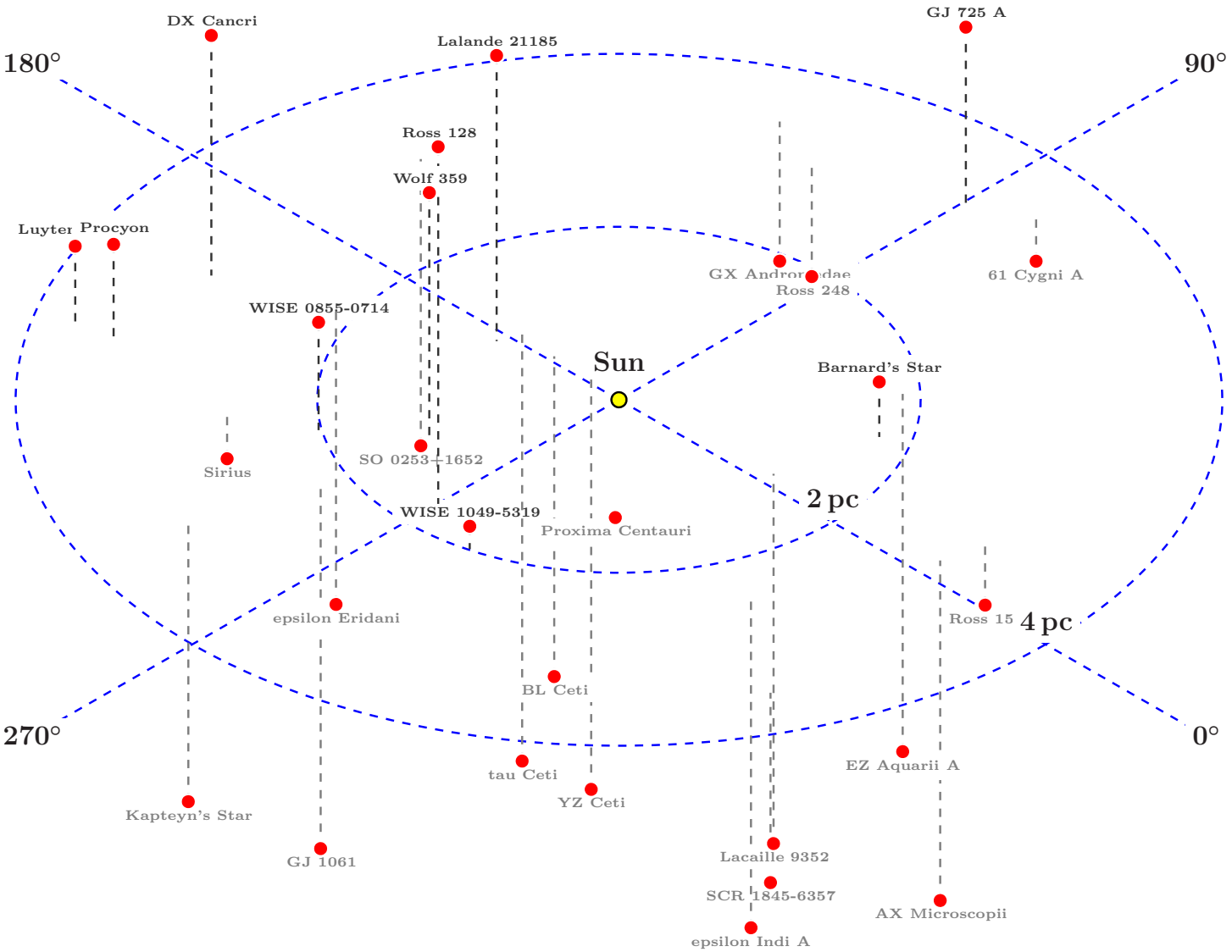
Gaia (ESA mission, launched 29 July 2014):
Data release 2 (25 April 2018): positions, parallaxes, proper motions for 1.3×10^9 stars (precision: 0.04 mas for brighter objects, going down to 0.7 mas at the limit, pm: $\sim$1 mas yr^{-1}); radial velocities for 7.2 million stars; brightness measurements for 1.38×10^9 objects; high precision astrometry for 14099 solar system objects; classifications for 550000 variable stars

Solar Neighborhood

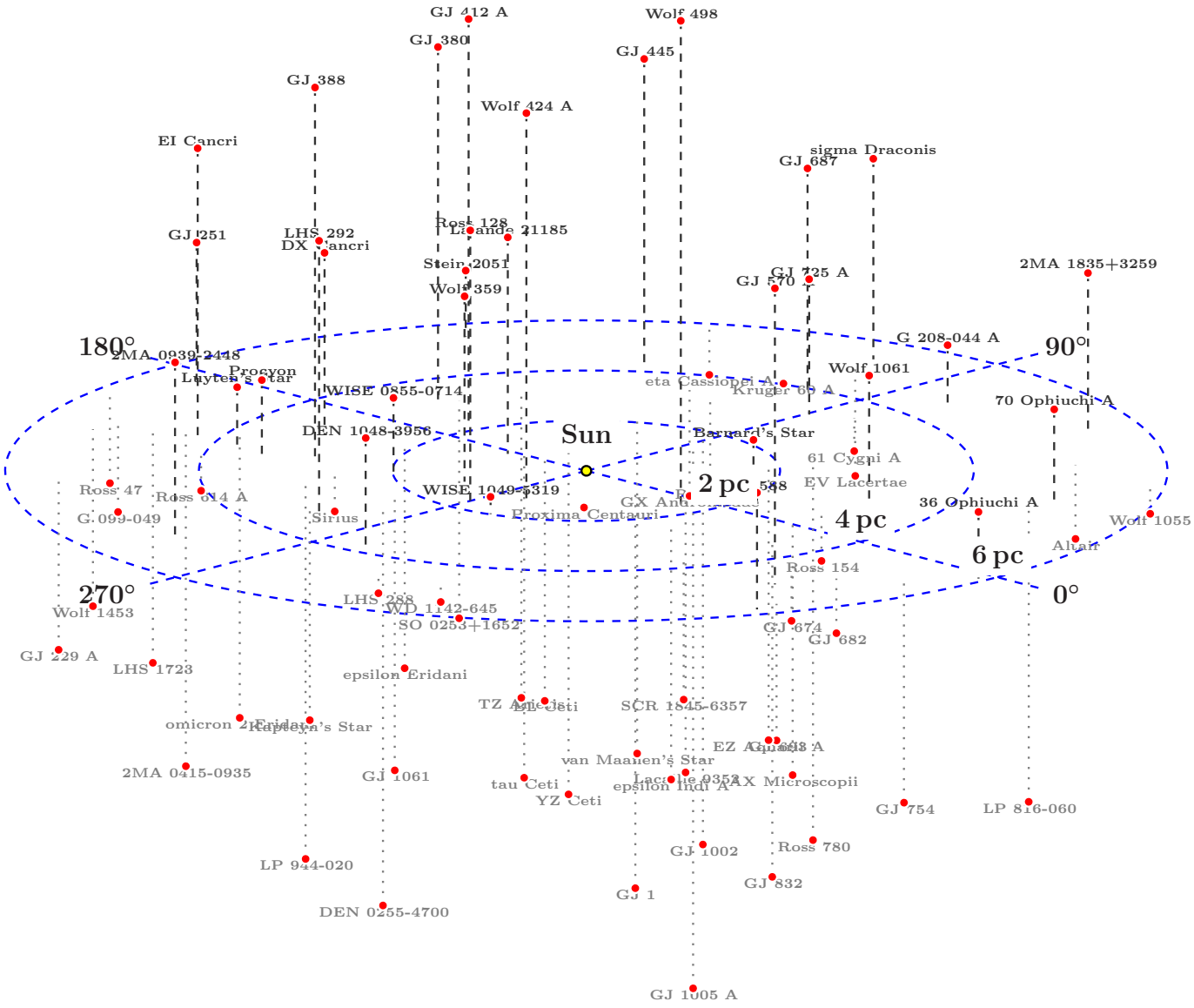


3rd closest stellar system (WISE 1049−5319) was only discovered in 2013

Solar Neighborhood



Solar Neighborhood



Known stars within 6.1 pc (20 ly): 115 star systems (only 10 brown dwarfs)

Note: We are probably missing many faint stars already in this small volume!

Data from the RECONS project (`http://recons.org/TOP100.posted.htm`)

Luminosity

Definition: Luminosity of a star:

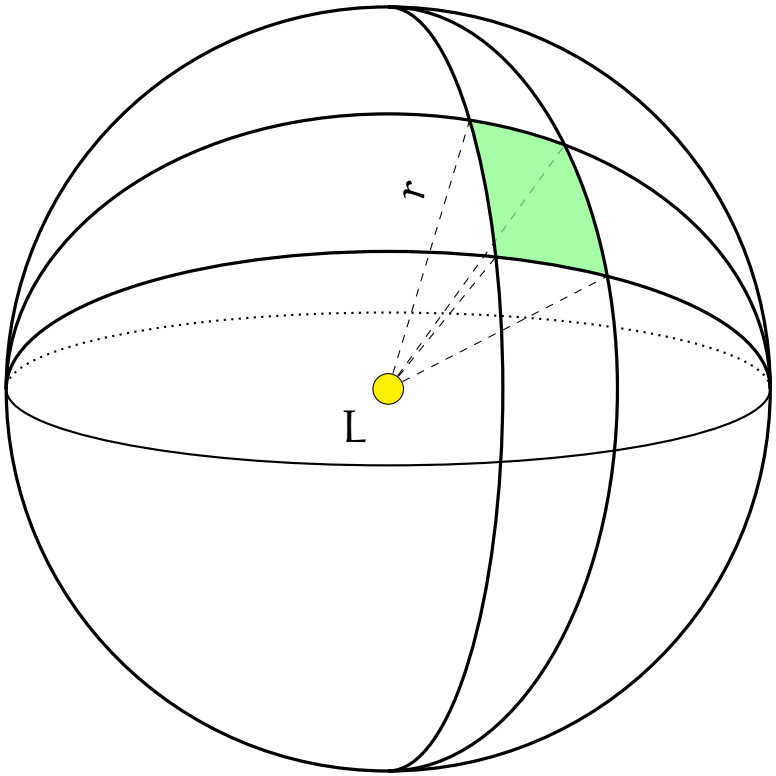
The total energy emitted by a star per second is called its luminosity.

(= luminosity is a power)

In astronomy, luminosities are often measured in units of the solar luminosity,

$$L_\odot = 3.90 \times 10^{26}\,\mathrm{J\,s^{-1}} = 3.90 \times 10^{26}\,\mathrm{W} = 3.9 \times 10^{33}\,\mathrm{erg\,s^{-1}}$$

Flux



Assumption: star emits its radiation isotropically.

Flux: energy passing per second through area of 1 m^2 at distance r:

$$F = \frac{L}{4\pi r^2}$$

(unit: $W\,m^{-2}$ or $erg\,cm^{-2}\,s^{-1}$).

Flux

Fluxes from stars (apart from the Sun) are *very small*.

Example: α Centauri (closest star to the Sun).

- distance: $1.3\,\mathrm{pc} \sim 4 \times 10^{16}\,\mathrm{m}$
- luminosity: similar to the Sun ($4 \times 10^{26}\,\mathrm{W}$).

Flux arriving on Earth:

$$F = \frac{L}{4\pi r^2} = \frac{3.9 \times 10^{26}\,\mathrm{W}}{4\pi \cdot 16 \cdot 10^{32}\,\mathrm{m}^2} = 2 \times 10^{-8}\,\mathrm{W\,m^{-2}}$$

(compare with solar constant, $F = 1380\,\mathrm{W\,m^{-2}}$!)

$\Longrightarrow$ your eye detects a power of

$$P = A_{\mathrm{eye}} F = 5 \times 10^{-13}\,\mathrm{W}$$

from α Cen (assuming $A_{\mathrm{eye}} \sim 25\,\mathrm{mm}^2$)!

weakest visible stars: ~100× weaker!

Magnitudes



Hipparchus
(~190–~120 BC)

First classification of stars:

- Stars of "magnitude 1": brightest (visible) stars
- Stars of "magnitude 6": faintest (visible) stars
- apparent visual magnitude: m_V = magnitude as observed with the naked eye
- Unit: magnitudo (plural: magnitudines): ^{m}
  examples: Castor (α Gem): $m_V = 1^m.59$

`http://www-gap.dcs.st-and.ac.uk/~history/Mathematicians/Hipparchus.html`

Magnitudes

Studies in early 19th century: Eye sensitivity is logarithmic.

Pogson (1856):

> A brightness *difference* of 5 magnitudes corresponds to a *ratio* of 100 in detected flux

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So, if magnitudes of two stars are m_1 and m_2, then

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This means:

$$\log_{10}(f_1/f_2) = \frac{m_2 - m_1}{5} \log_{10} 100 = \frac{2}{5}(m_2 - m_1)$$

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or

$$m_2 - m_1 = 2.5 \log_{10}(f_1/f_2) = -2.5 \log_{10}(f_2/f_1)$$

Note: Larger Magnitude = *FAINTER* Stars

Luminosity (revisited)

The inverse square law links flux f at distance d to flux F measured at another distance D:

$$\frac{F}{f} = \frac{L/4\pi D^2}{L/4\pi d^2} = \left(\frac{d}{D}\right)^2$$

Define the absolute visual magnitude M_V as the visual magnitude measured at distance $D = 10\,\mathrm{pc}$:

$$m_V - M_V = 2.5\log(F_V/f_V) = 2.5\log(d/10\,\mathrm{pc})^2 = 5\log d - 5$$

$m_V - M_V$ is called the distance modulus, d is measured in pc.

absolute bolometric magnitude M_{bol}: magnitude corresponding to flux integrated over all wavelengths: $M_{bol} = 4.74 - 2.5\log\frac{L}{L_\odot}$

bolometric correction B.C. $= M_{bol} - M_V$ from model atmospheres

Spectral Classification

Next fundamental parameter: Temperature

Obtained using spectroscopy

In the following: rough outline, as stellar spectroscopy is rather complicated

Outline:

1. Spectral Classification
2. Planck's Radiation Laws
3. Atomic line transitions
4. Spectral line formation

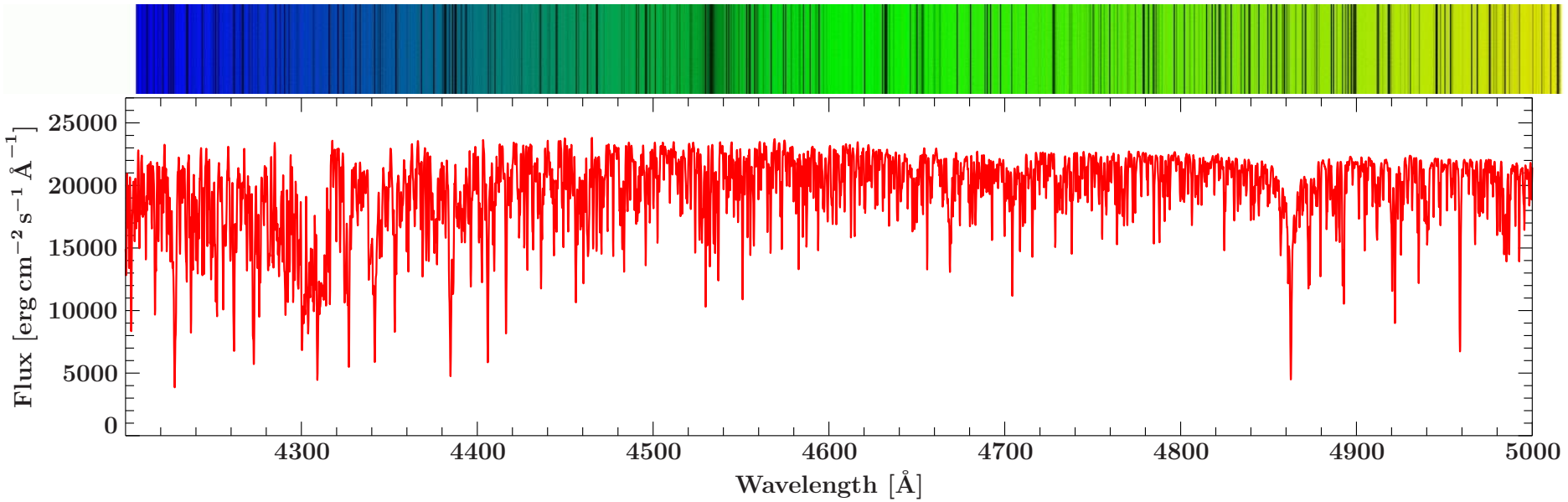
Stellar spectra

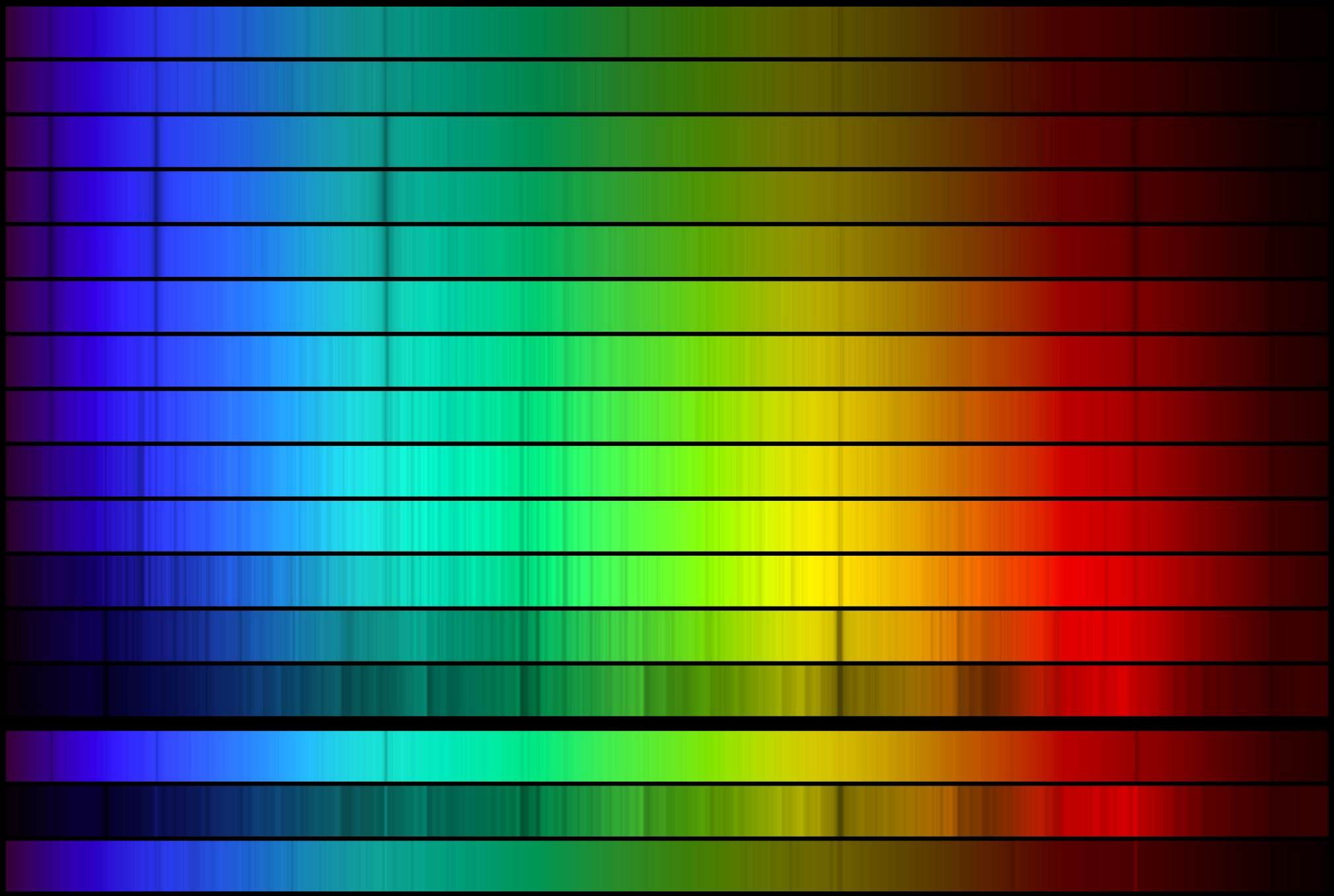
The spectrum of the Sun:

Newton (1666): first solar spectrum obtained with a prism: contains all colors (wavelengths).

Fraunhofer (1814): more than 500 dark absorption lines: strongest marked A . . . L

Kirchhoff-Bunsen (1860): some Fraunhofer lines are emitted by chemical elements (″fingerprints″)





Edward Pickering (around 1890): Stars have different spectra. NOAO

Stellar spectra



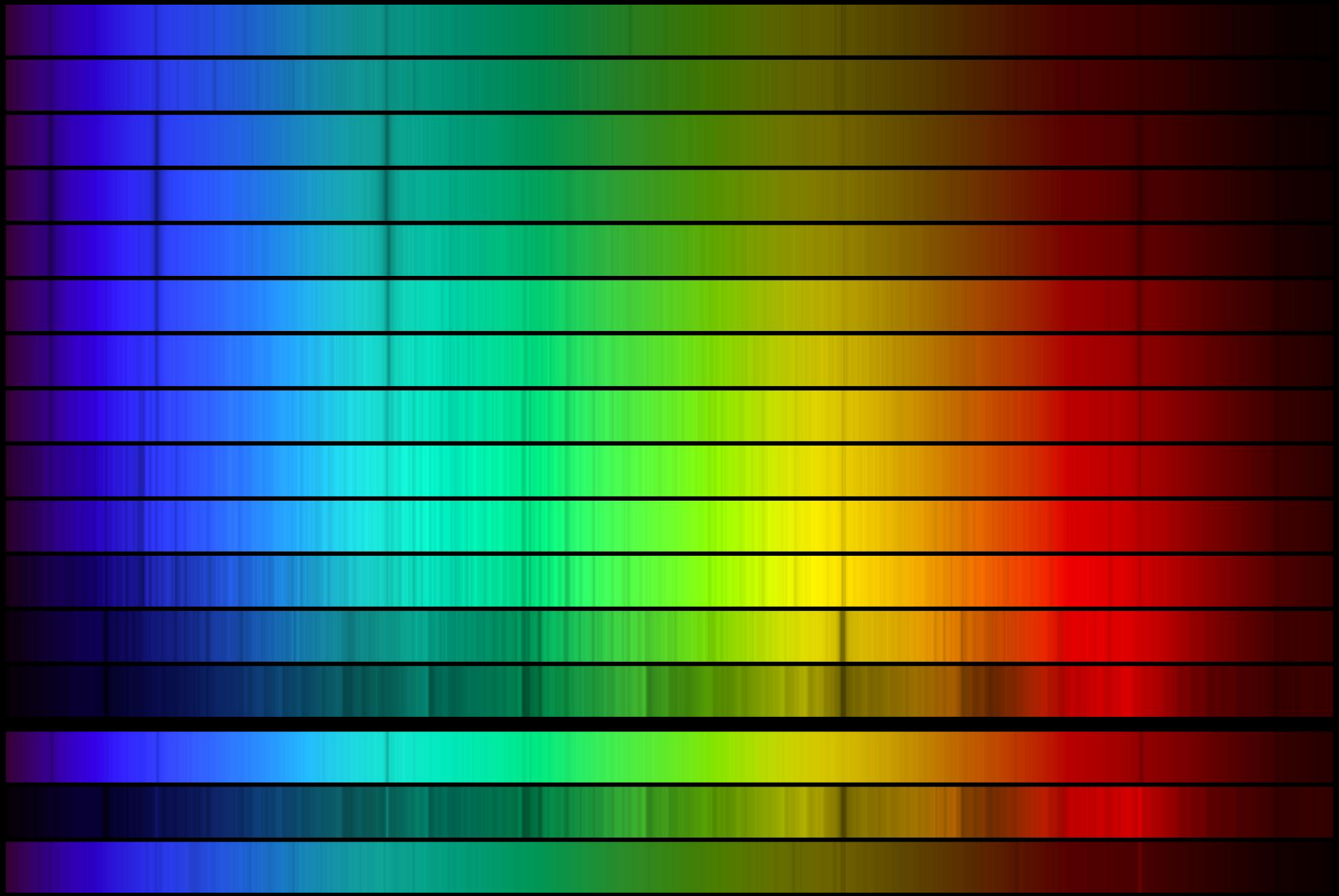
Annie Jump Cannon (1863–1941)

Biography: `http://www.sdsc.edu/ScienceWomen/cannon.html`

Annie Jump Cannon: There are spectral types.

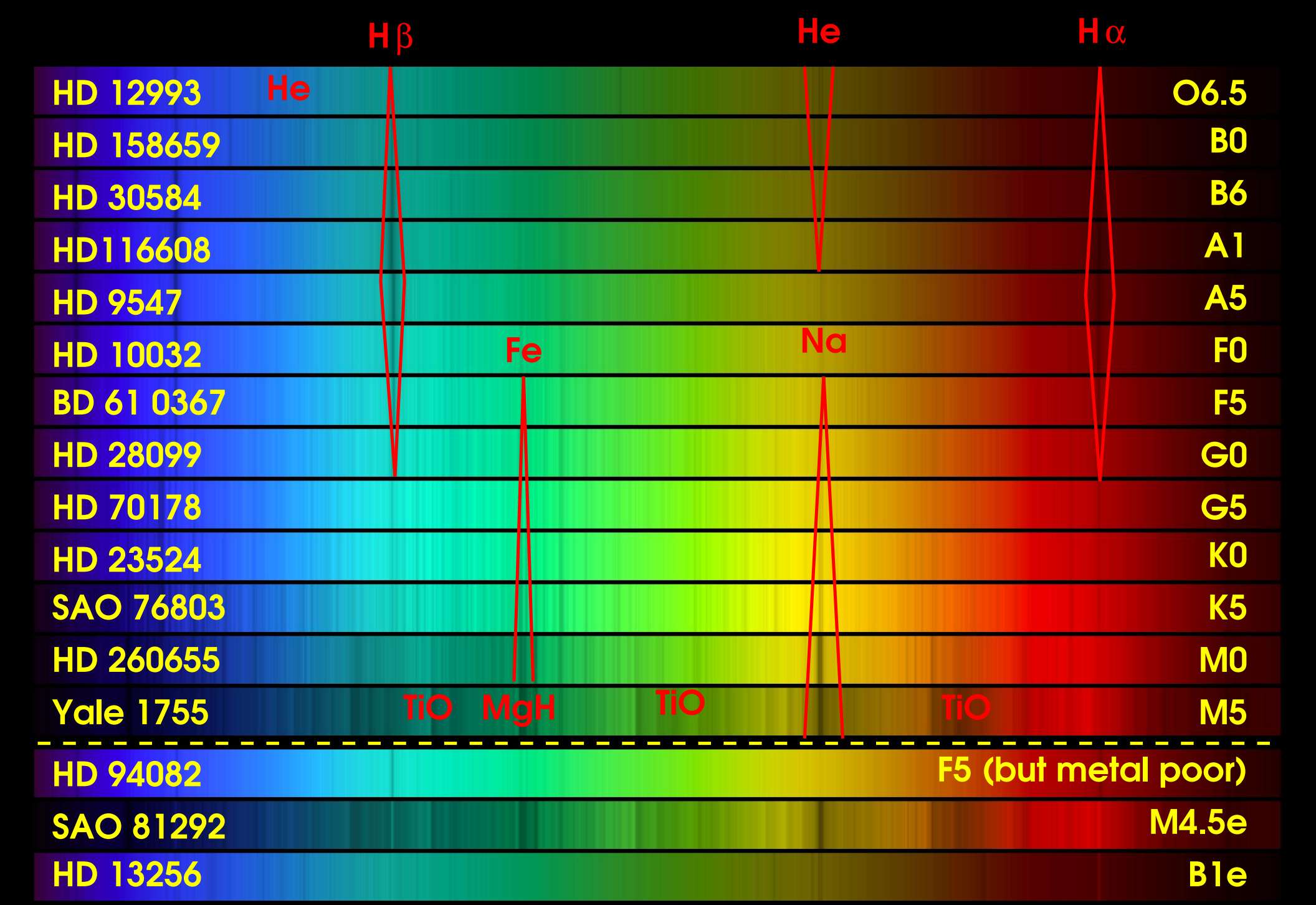
Henry Draper catalogues (Cannon plus ~10 female "computers"): 225000 spectral classifications.





Cannon: Strength of absorption lines varies with spectral type.

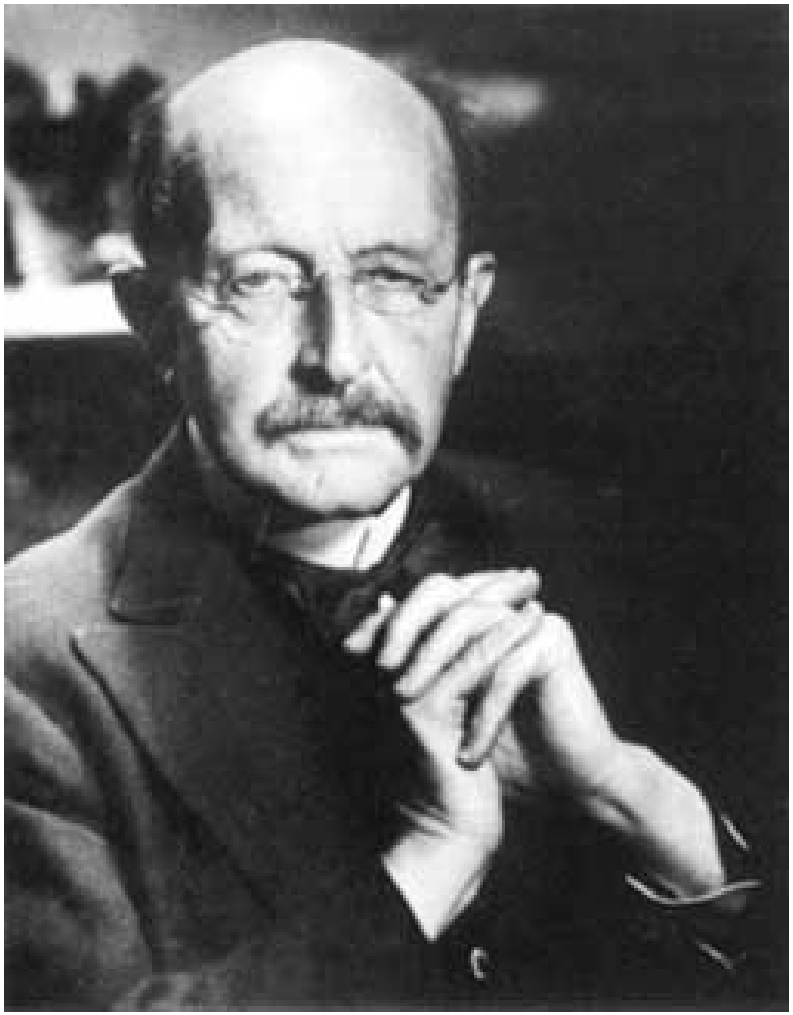
NOAO



Cannon: Strength of absorption lines varies with spectral type.

NOAO

Planck's Radiation Law



Max Planck (1858–1947)

Stars are big glowing gas balls.

In zeroth order: thermodynamic equilibrium.

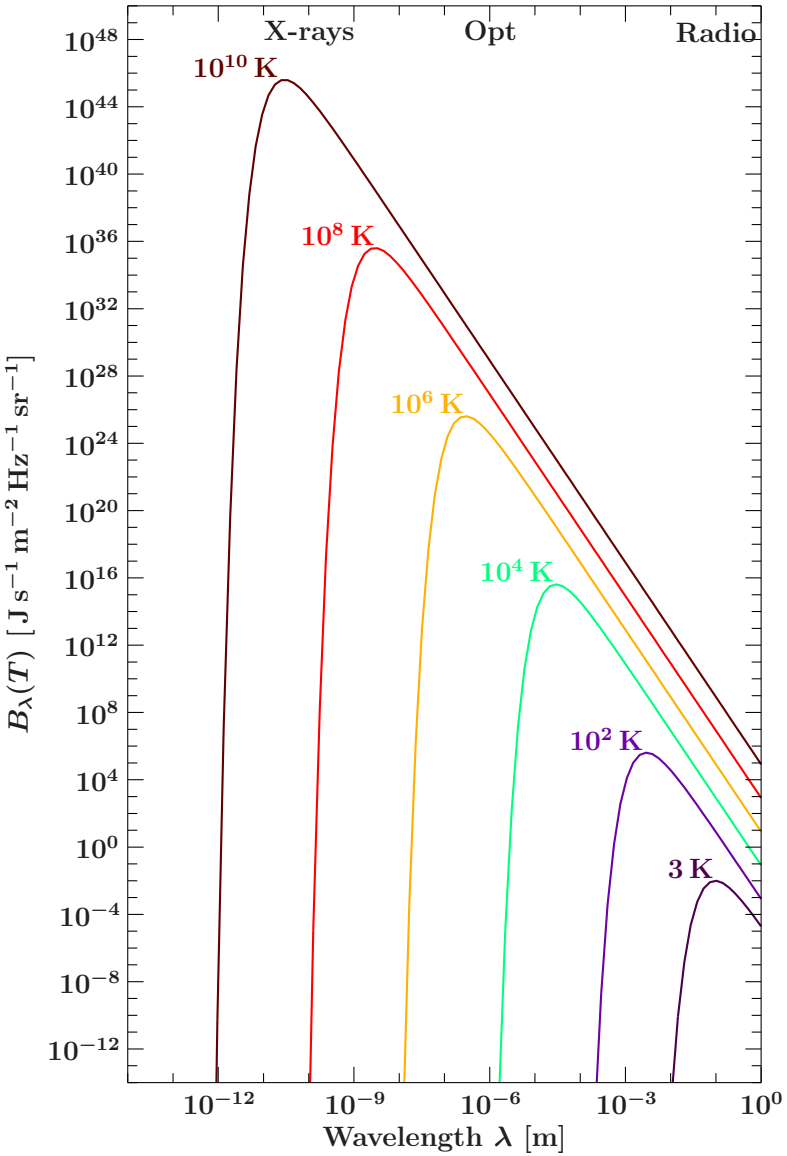
Max Planck: under these circumstances: emitted flux spectrum is blackbody radiation:

$$B_\lambda = \frac{2hc^2/\lambda^5}{\exp(hc/\lambda kT) - 1} \qquad (9.2)$$

B_λ: Energy emitted per second and wavelength interval and unit area into 1 sr.

- $h = 6.623 \times 10^{-34}\,\mathrm{J\,s}$: Planck's constant
- $k = 1.38 \times 10^{-23}\,\mathrm{J\,K^{-1}}$: Boltzmann constant

Planck's Radiation Law



Without proof, the following two important relationships hold for blackbody radiation:

Stefan-Boltzmann law: Flux (power emitted per square-meter surface) of a blackbody:

$$F = B = \int_0^\infty B_\lambda(\lambda)\,d\lambda = \sigma T^4$$

where $\sigma = 5.67 \times 10^{-8}\,\mathrm{W\,m^{-2}\,K^{-4}}$

"hotter bodies have a much higher luminosity"

Wien's displacement law: Wavelength of maximum blackbody emission:

$$\lambda_{max} T = 2.898 \times 10^{-3}\,\mathrm{m\,K}$$

"hotter bodies radiate higher energetic radiation"

Stellar Spectra: interpretation



Cecilia Payne-Gaposchkin
(1900–1979)

BSc, Cambridge, left UK because of situation of women in astronomy

1st person to obtain PhD in Astronomy at Radcliffe/Harvard: "Stellar Atmospheres, A Contribution to the Observational Study of High Temperature in the Reversing Layers of Stars"
`https://ui.adsabs.harvard.edu/abs/1925PhDT.....1P/abstract`

Otto Struve: "undoubtedly the most brilliant Ph.D. thesis ever written in astronomy."

Stars mainly consist of Hydrogen. Spectral types are a temperature sequence.

later: 1st female full professor at Harvard

Biography: `https://mathshistory.st-andrews.ac.uk/Biographies/Payne-Gaposchkin/`

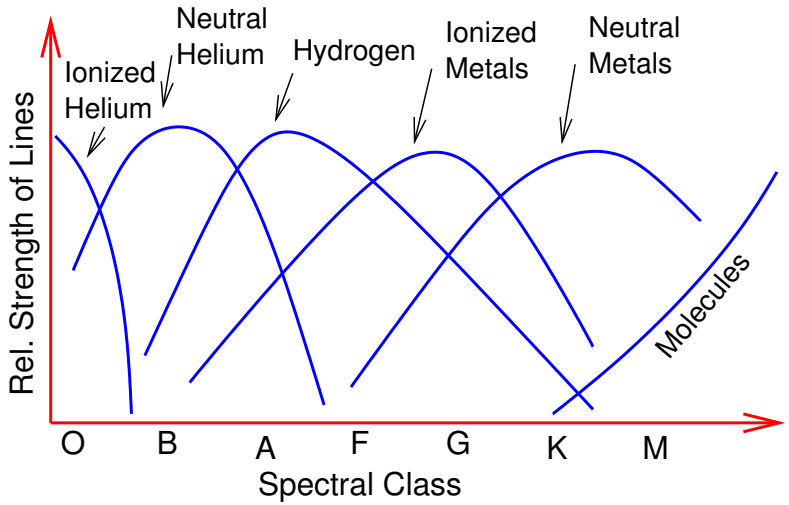
Stellar Spectra: interpretation

Punchline of Payne-Gaposchkin's results:
spectral classes are a temperature sequence.

O - B - A - F - G - K - M

30 000 K 3 000 K

"early type" "late type"



plus subtypes: B0…B9, A0…A9, etc.

Sun is G2.

Note: "early" and "late" has *nothing* to do with age!

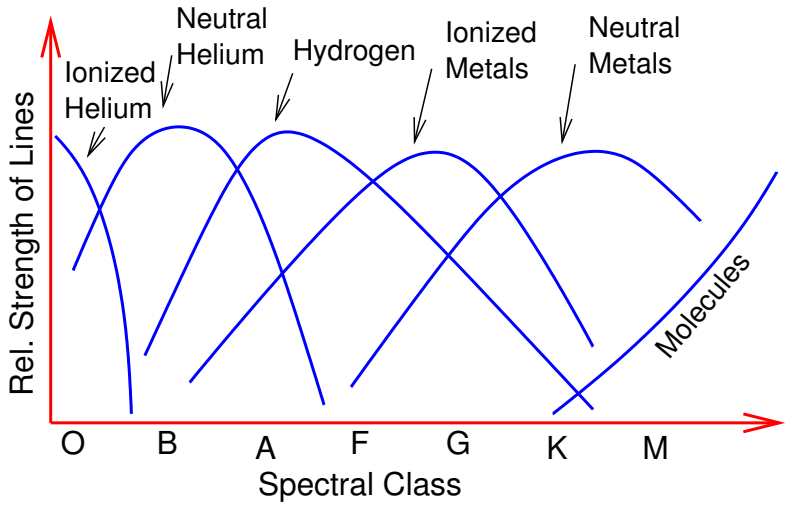
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Mnemonics:

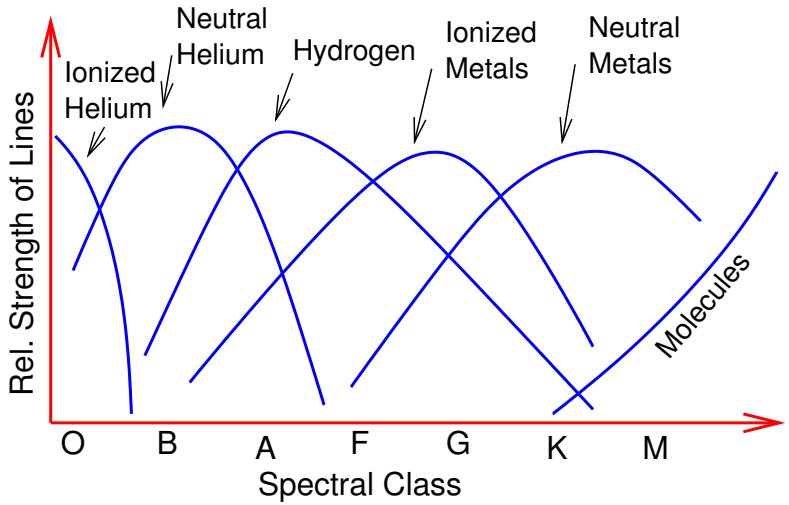
(`http://www.star.ucl.ac.uk/~pac/obafgkmrns.html`)

O Be A Fine Girl Kiss Me

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O Be A Fine Girl / Guy Kiss Me

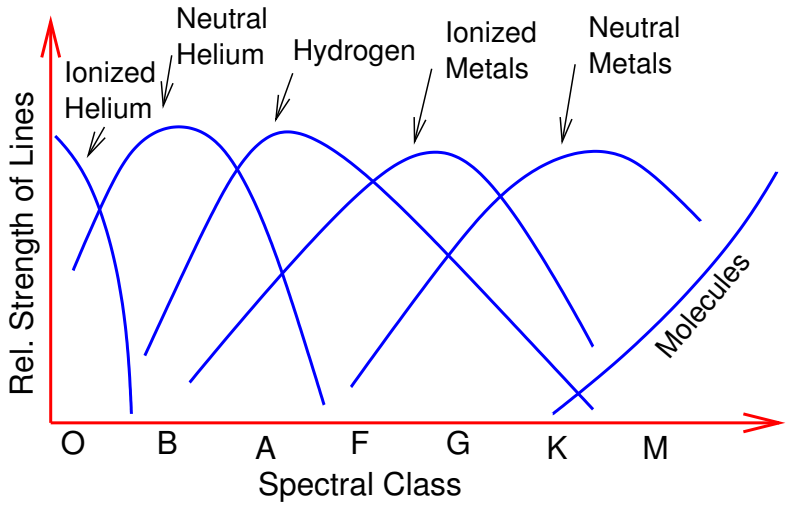
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plus subtypes: B0...B9, A0...A9, etc.

Sun is G2.

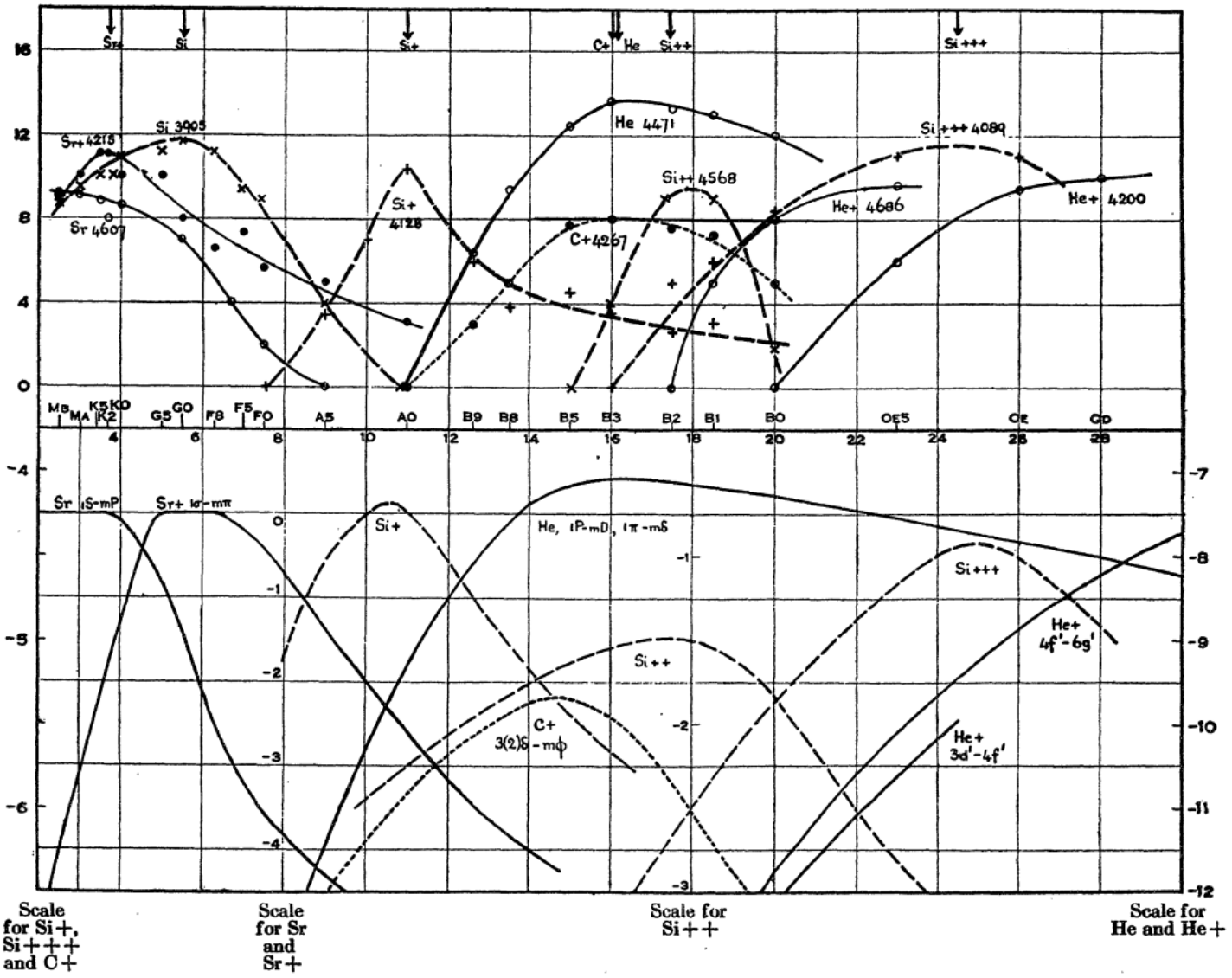
Note: "early" and "late" has *nothing* to do with age!

Mnemonics:

(`http://www.star.ucl.ac.uk/~pac/obafgkmrns.html`)

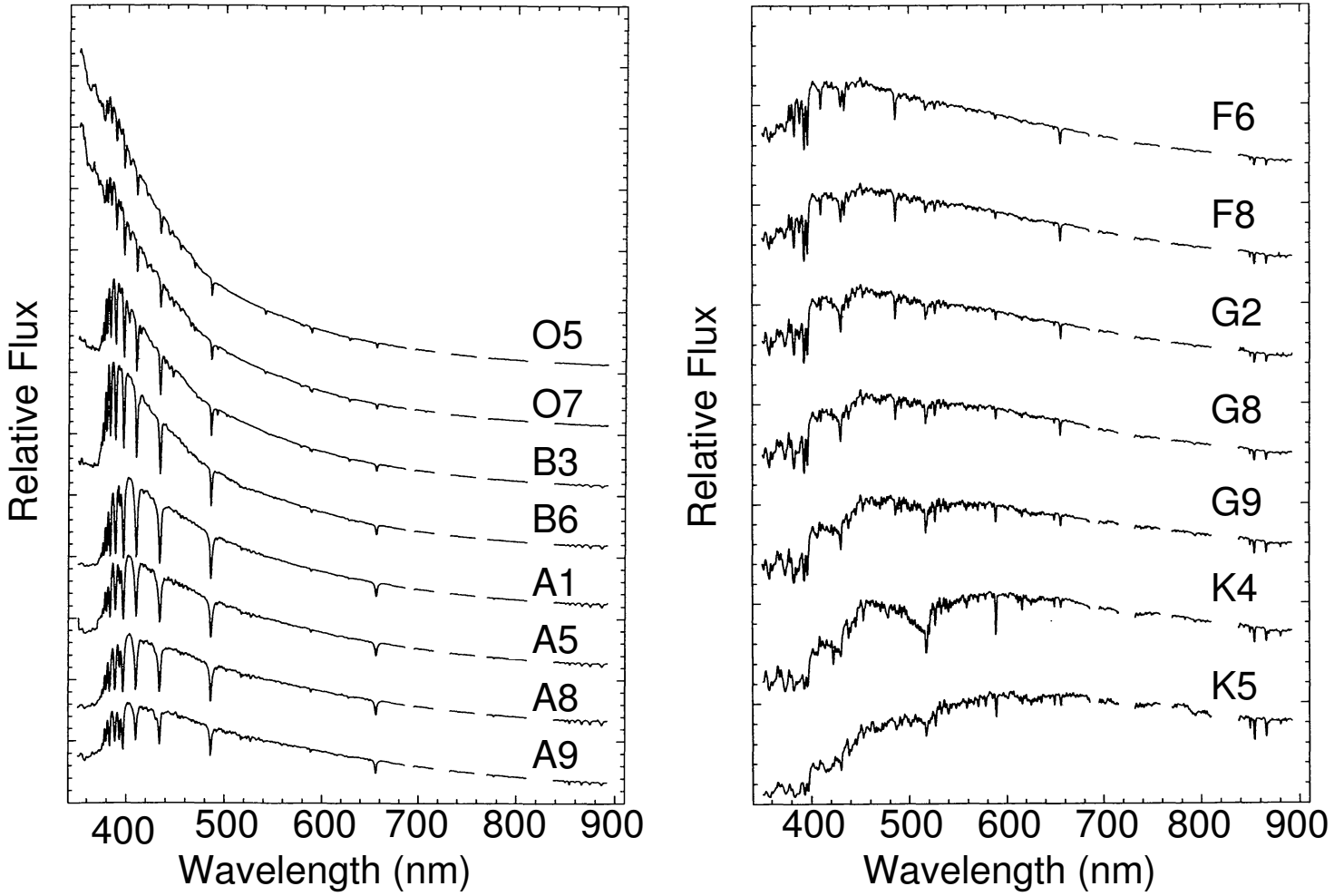
O Be A Fine Girl Guy Kiss Me Only Boys Accepting Feminism Get Kissed Meaningfully

Stellar Spectra: interpretation



Payne, 1924, Harvard Circ. 256, Fig. 1

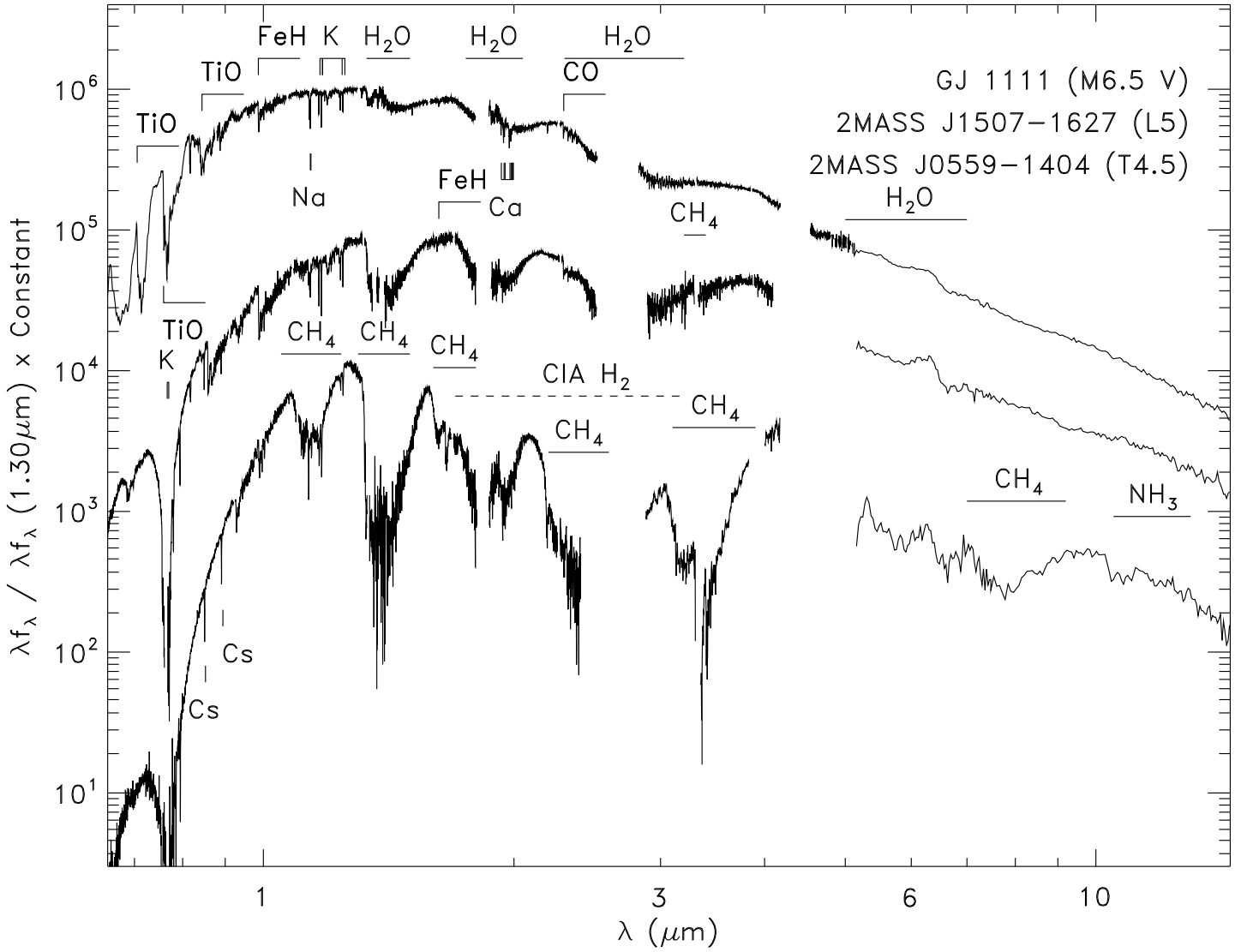
Stellar Spectra: interpretation



Silva & Cornell, 1992, ApJ Suppl. 81, 865

Spectral Atlas for classification purposes.

L- and T-Stars



1995 ff.: discovery of brown dwarfs (low mass, low temperature objects).

Cushing et al., 2006

L- and T-Stars

Brown Dwarfs $\Longrightarrow$ extension of spectral types to lower temperature objects

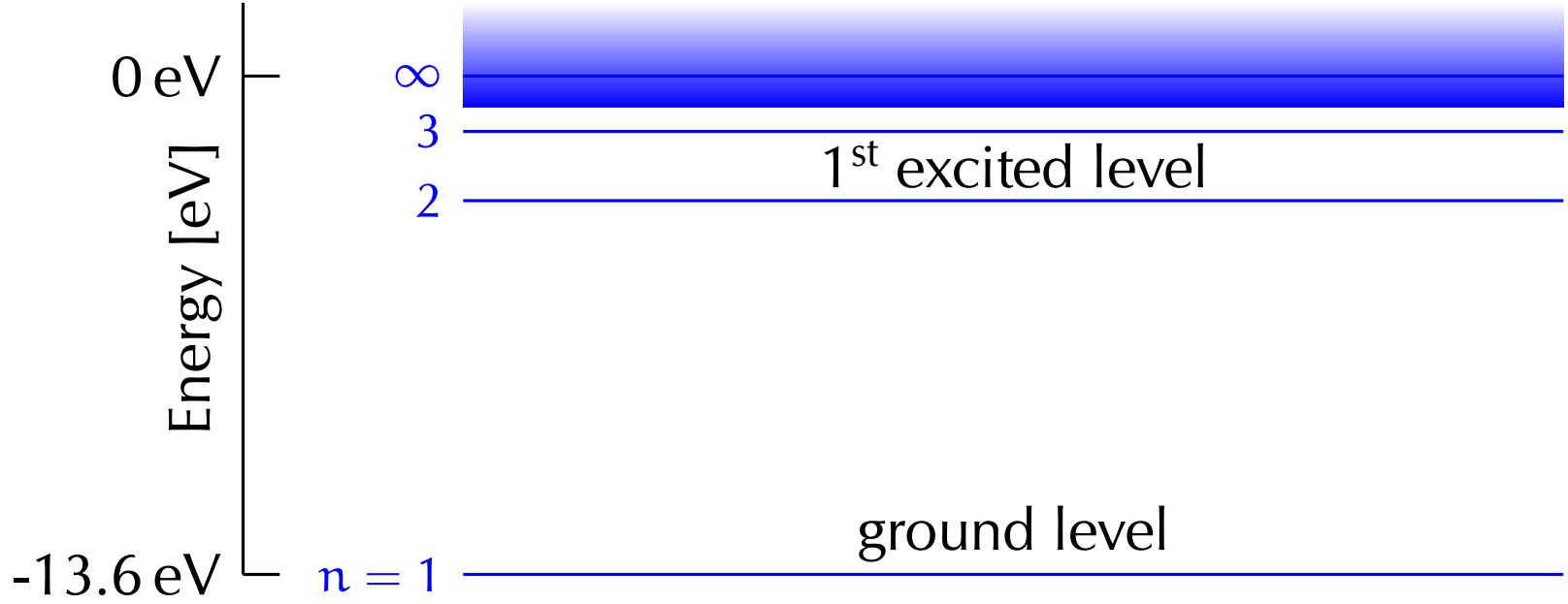
L dwarfs: objects with temperatures of 1200–2500 K, low mass, some do not support fusion. Spectra peak in IR, optical spectra contain prominent lines from metal hydrides and alkali metals.

Designation: L is character closest to M that was still available.

T dwarfs: brown dwarfs with temperatures of ∼1000 K, strong lines from molecules such as methane in the spectrum.

See Kirkpatrick (2005, Ann. Rev. Astron. Astrophys., 43, 195) for an overview and the formal definition of these spectral types.

Spectroscopy



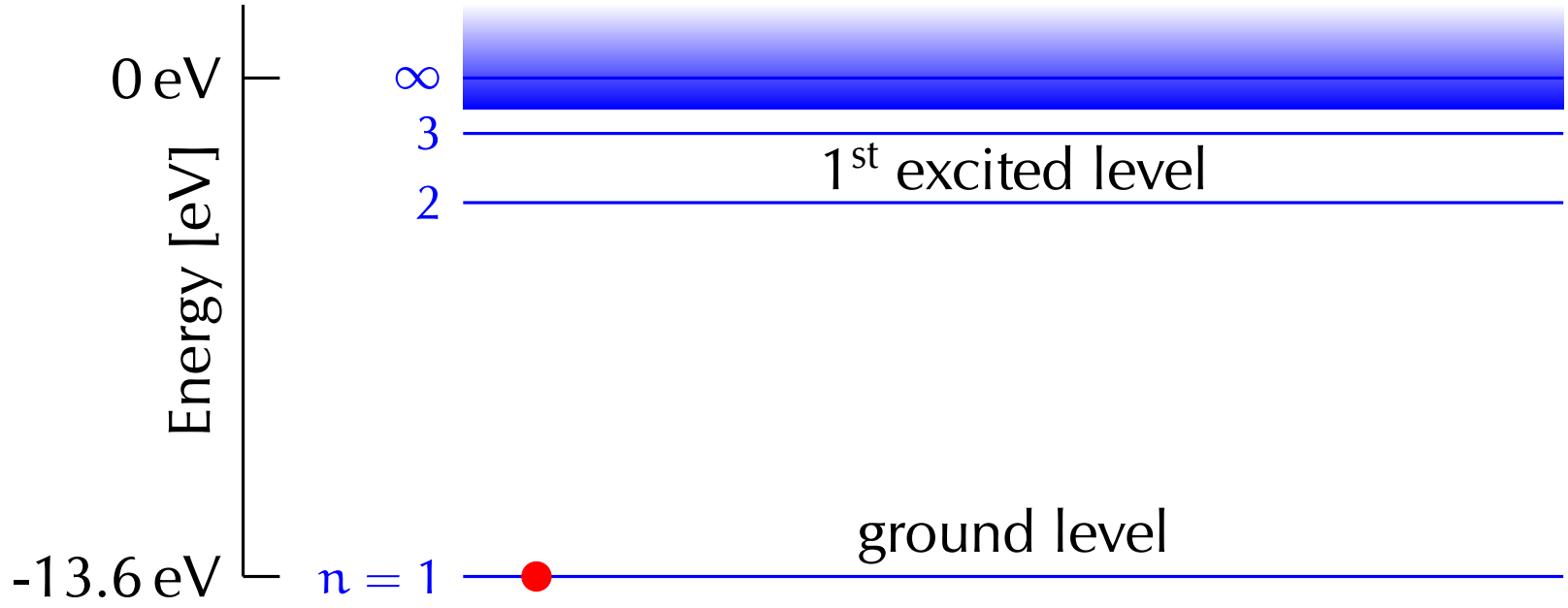
Quantum mechanics: atoms have discrete energy levels

Energy levels in Hydrogen:

$$E_n = -\frac{2\pi^2 \mu e^4}{\hbar^2} \cdot \frac{1}{n^2} \propto -\frac{1}{n^2}$$

($n \in \mathbb{N}$; Balmer formula)

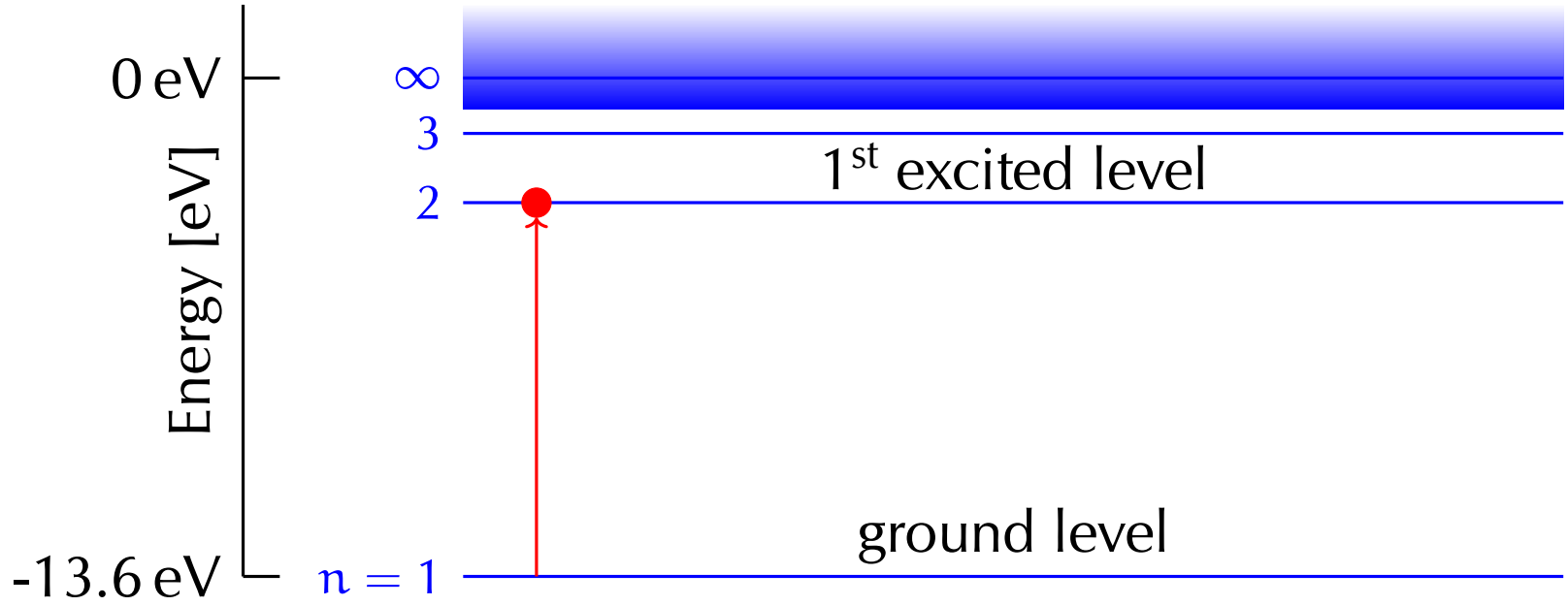
Spectroscopy



In hydrogen atom: electrons typically found in ground state.

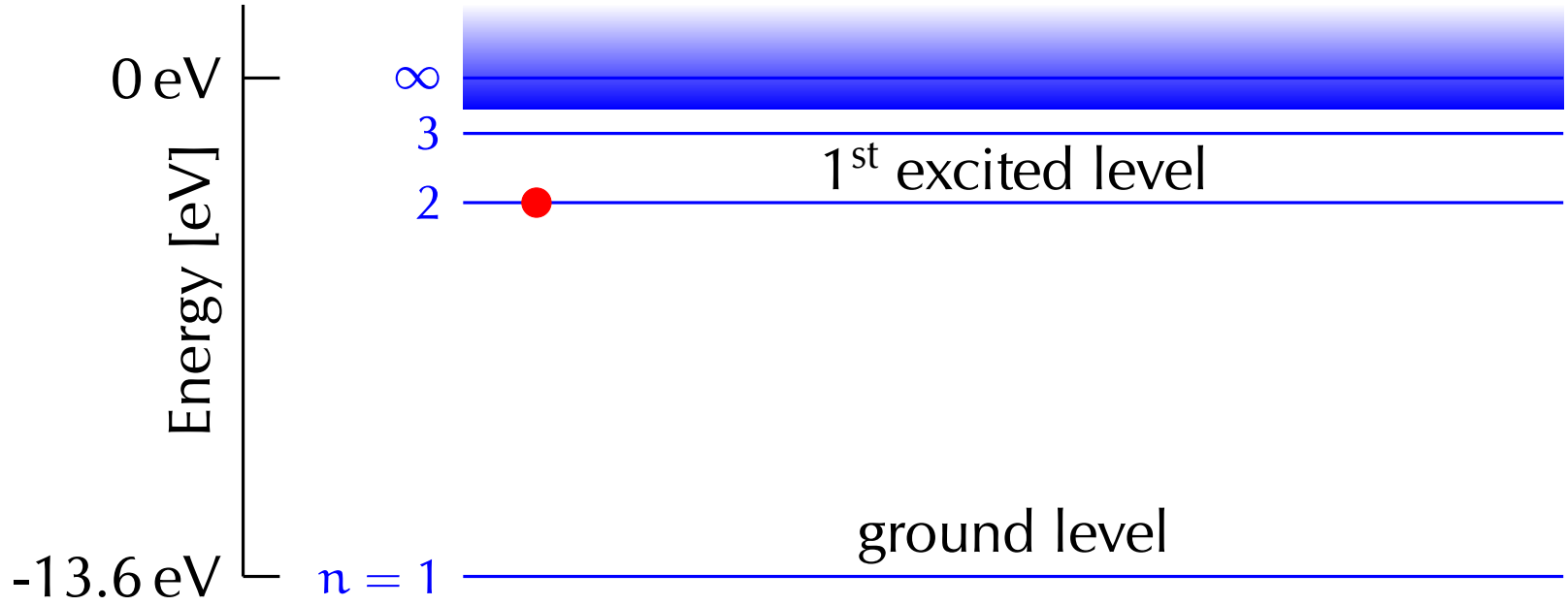
if temperature is higher, can also be in 1st excited state, but the physical principles following remain the same.. . .

Spectroscopy



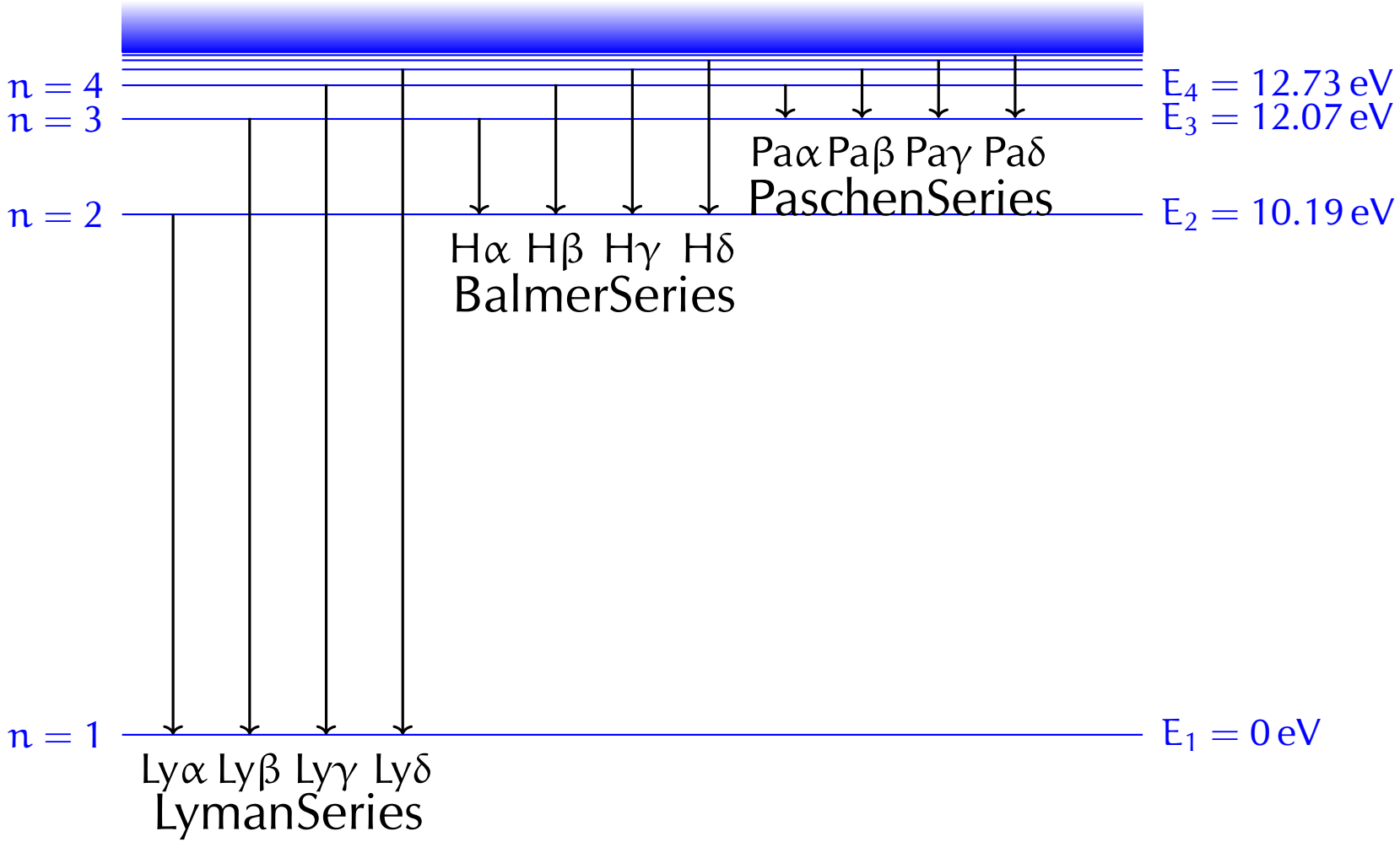
Photon hitting atom has energy $E_{phot} = h\nu = hc/\lambda$. If $E_{phot} = E_2 - E_1$, then photon can be absorbed...

Spectroscopy



After absorption event, absorbing photon has disappeared and hydrogen atom remains in excited state.

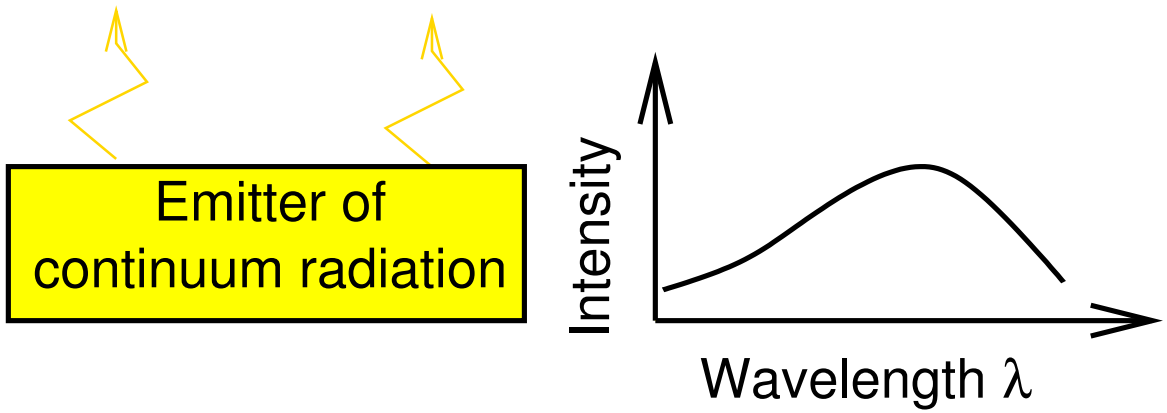
Spectroscopy



Hydrogen lines in the visual (Balmer lines) arise from absorbing photons by atoms in the first excited state.

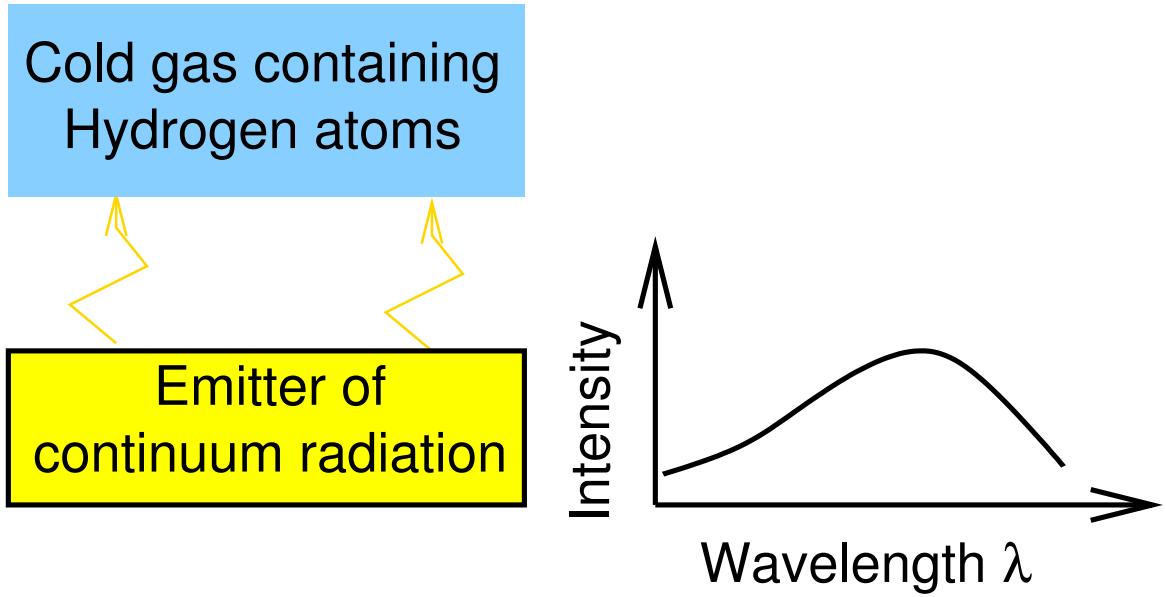
Spectroscopy

1. Assume stellar surface has continuum spectrum (Planck).

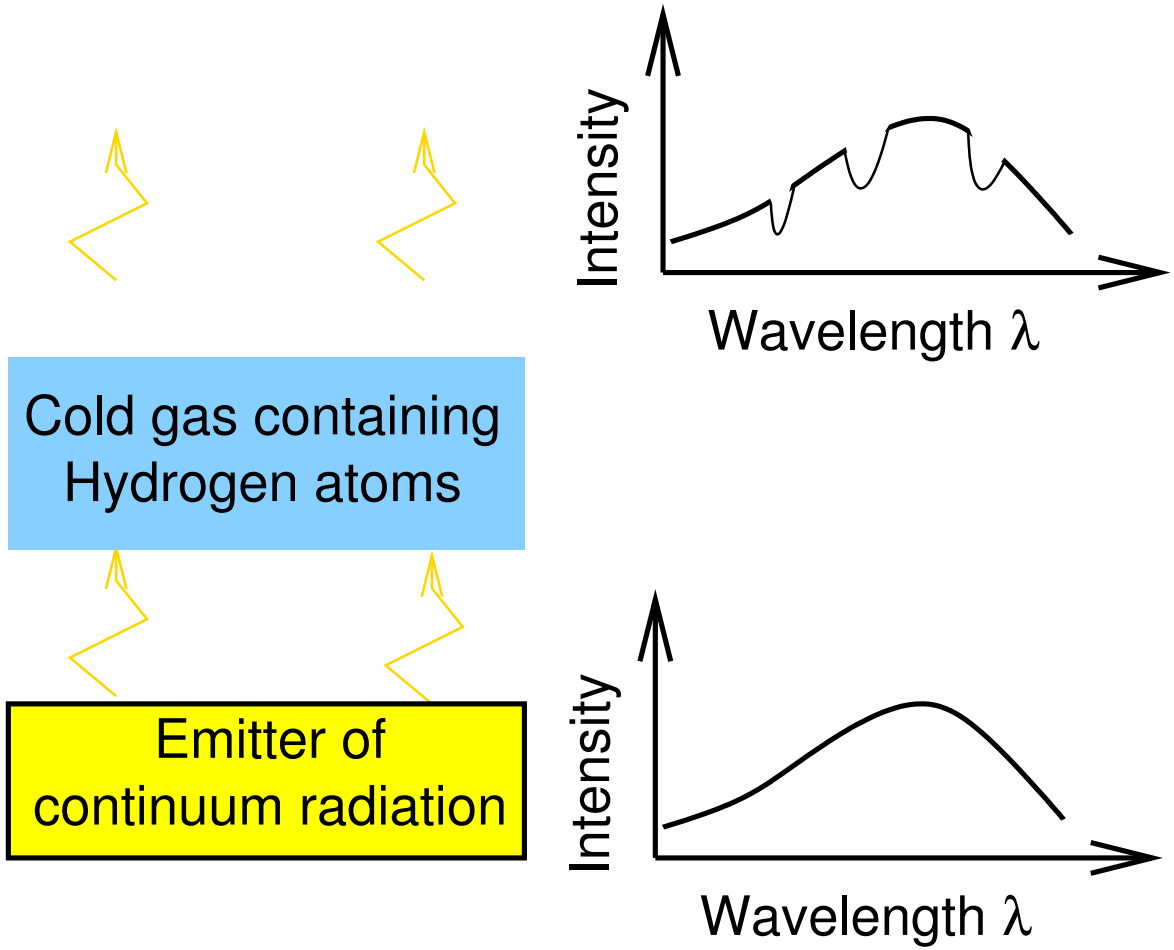


Spectroscopy

1. Assume stellar surface has continuum spectrum (Planck).
2. Assume surface is below atmosphere of colder gas.



Spectroscopy

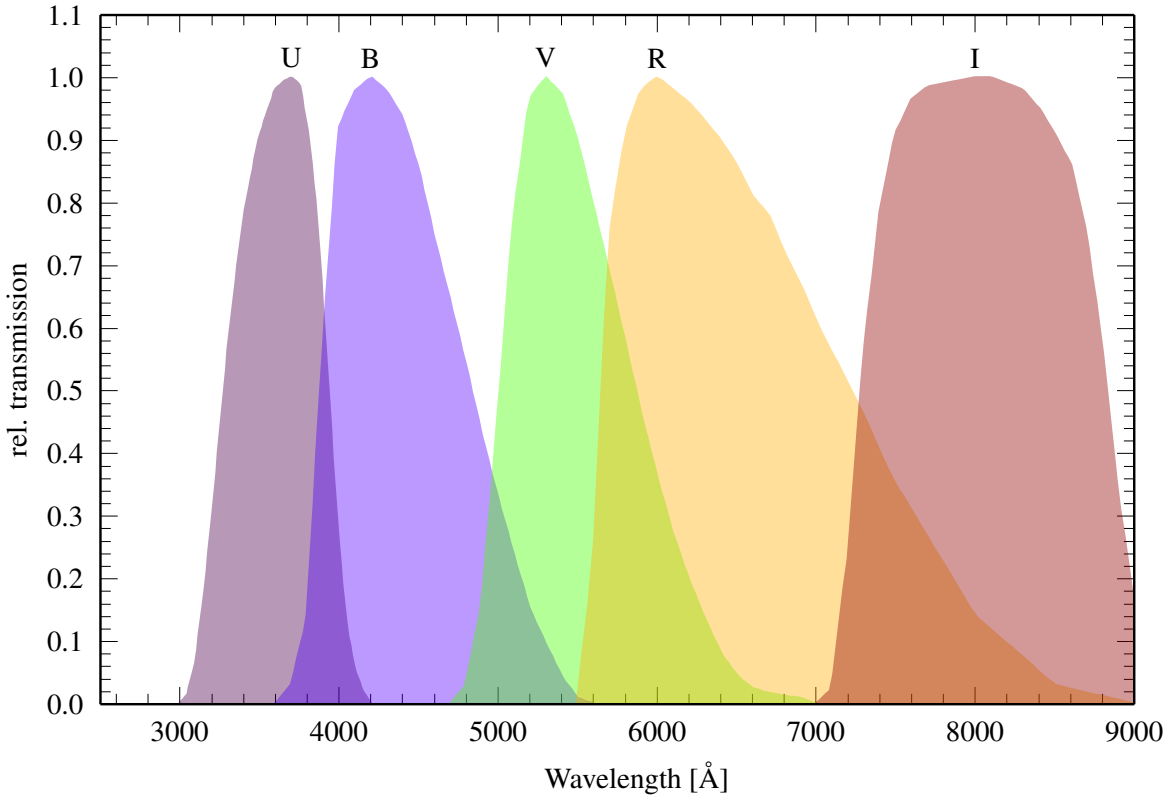


1. Assume stellar surface has continuum spectrum (Planck).
2. Assume surface is below atmosphere of colder gas.

$\Longrightarrow$ Atmosphere absorbs photons at wavelengths characteristic for the elements present in stellar atmosphere.

$\Longrightarrow$ Formation of absorption line spectrum.

Colors



photometry: use filters to measure intensity in specific wavebands
UBVRI photometry: 3 filter system (Johnson-Cousins system):

m_U = U = ultraviolet m_B = B = blue m_V = V = visual
m_R = R = red m_I = I = infrared

etc. has been extended further into the infrared (J, H, K,...) as these wavelength ranges became accessible

Colors

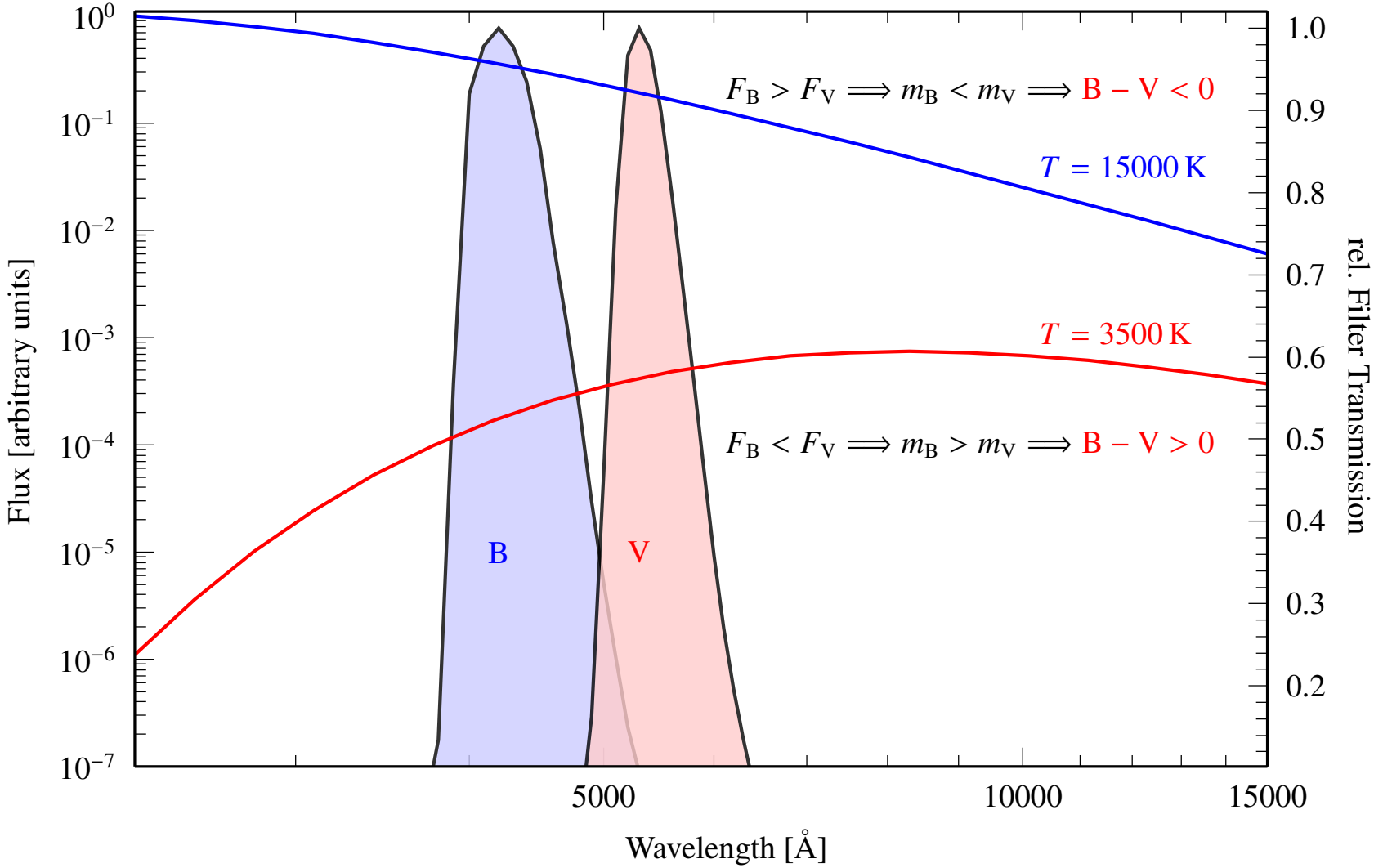
"Color": difference between magnitudes in two bands

normally: shorter wavelength − longer wavelength magnitude

e.g.,

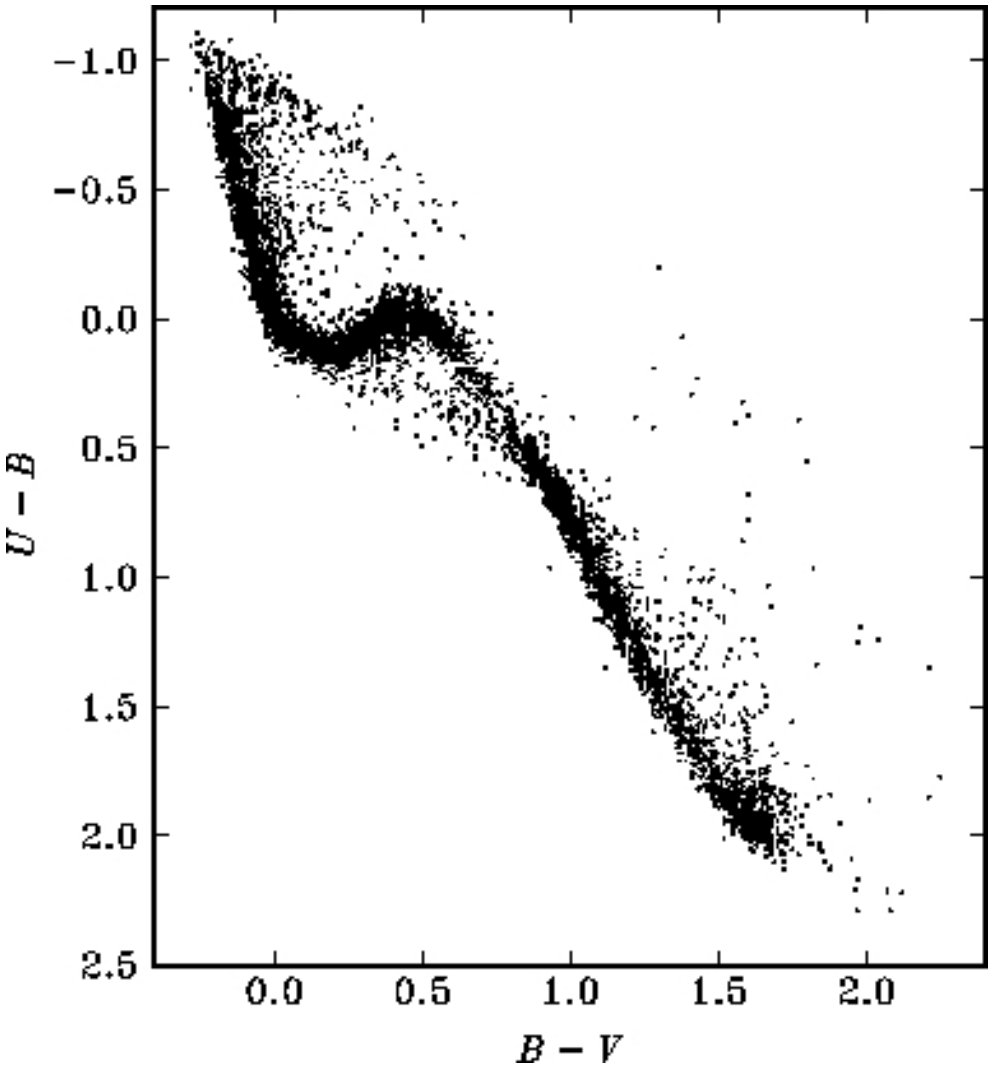
$$B - V = m_B - m_V = -2.5 \log(f_B/f_V) \tag{9.3}$$

Colors



Colors are temperature indicators: U − B, B − V, . . .

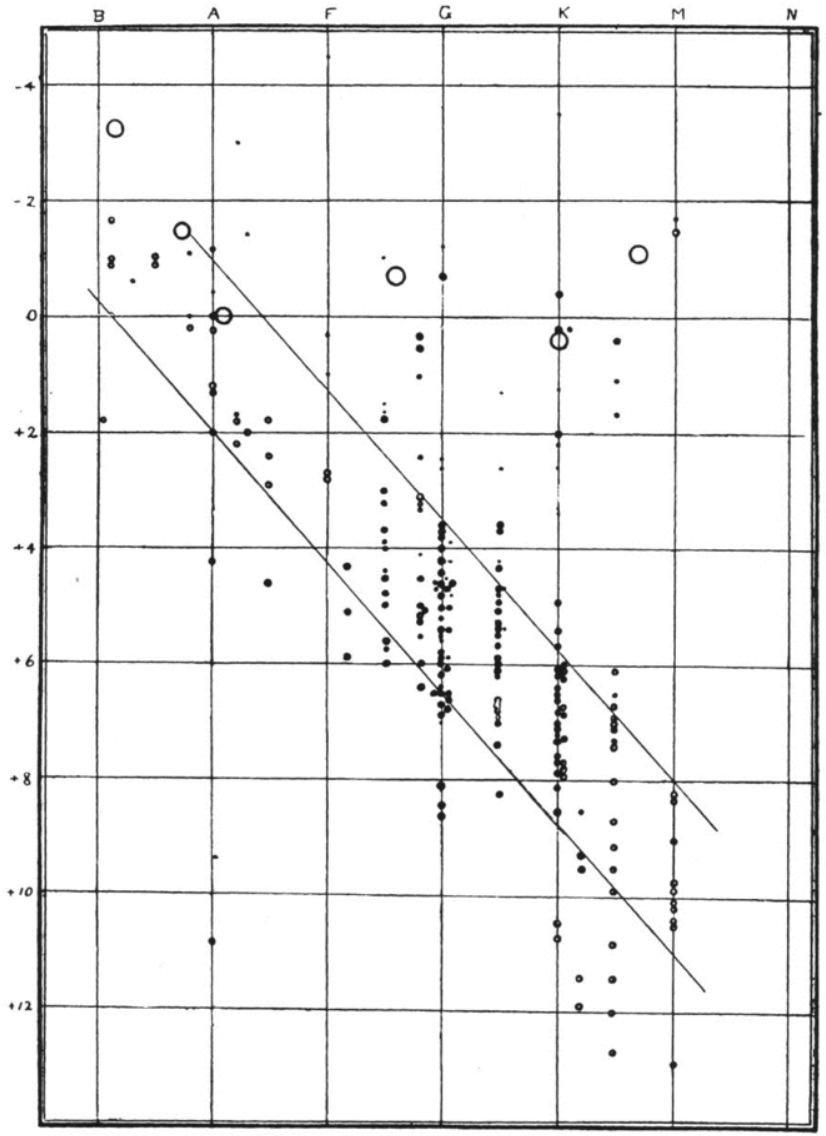
Colors



color-color diagram of the brighest stars (V $< 6^{m}.6$)
`http://images.astronet.ru/pubd/2006/03/01/0001211924/img416.gif`

- Colors: compute magnitude difference: e.g., B − V, U − B
- Color-magnitude diagram (CMD): plot one color versus magnitude, often used (V vs. B − V)
- color-color diagram: e.g., B − V vs. U − B.

Hertzsprung Russell Diagram



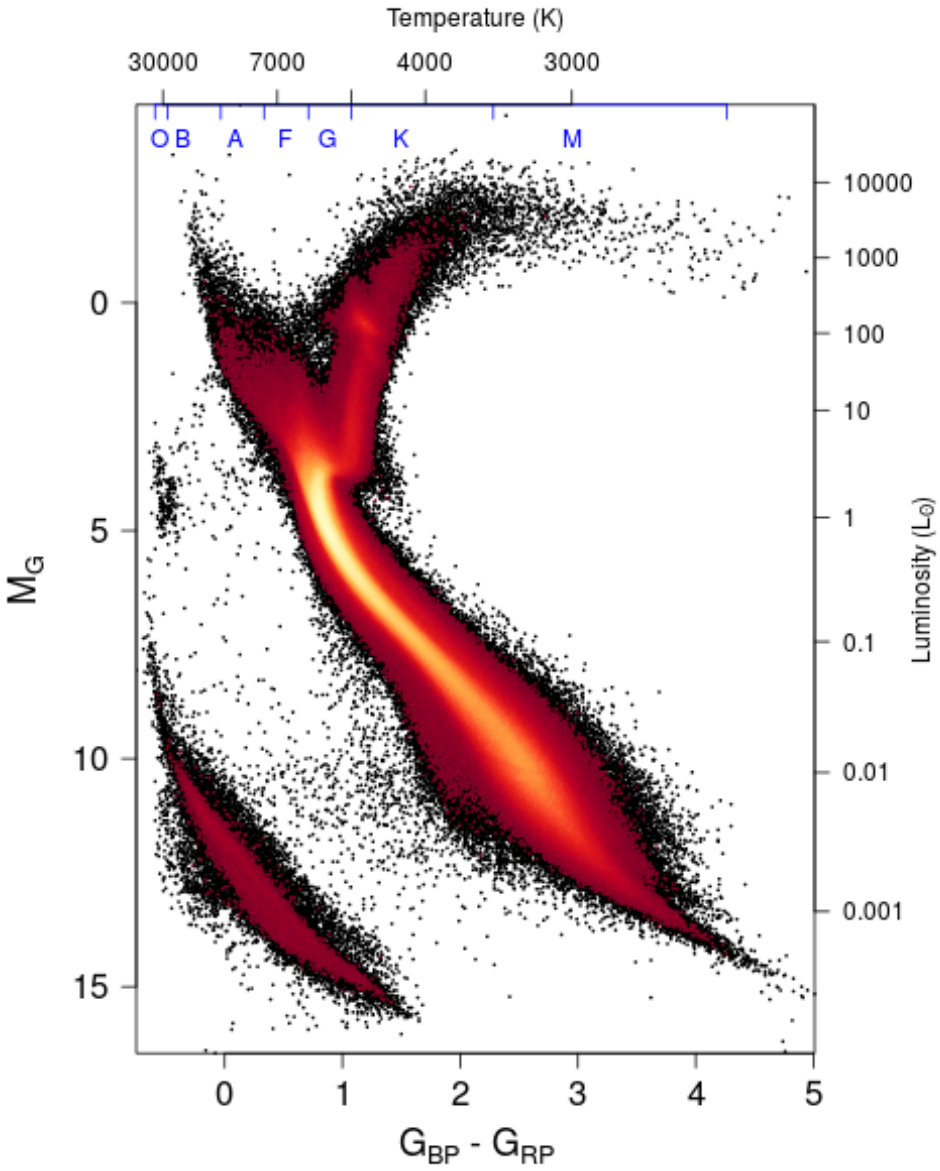
Russell, Nature 93, 252 (1914)

Hertzsprung Russell Diagram (HRD):
after Ejnar Hertzsprung and Henry Norris Russell

absolute visual magnitude versus spectral type shows systematic behavior

Most important phase diagram in stellar astrophysics

Hertzsprung Russell Diagram



Photometric HRD:

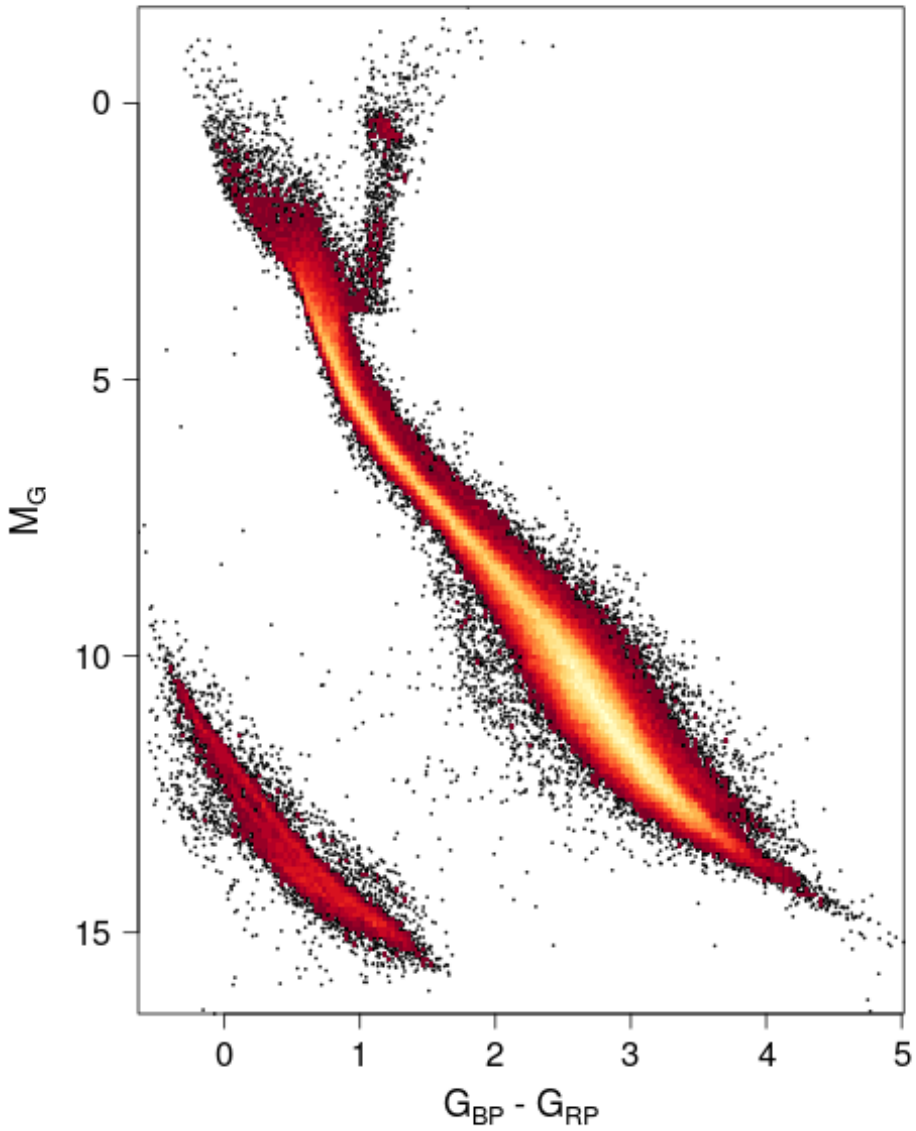
plot absolute visual magnitude versus B—V color

HRD from Gaia

4 276 690 stars w/low extinction

Gaia cons., 2018, A&A 616, A10

Hertzsprung Russell Diagram



Photometric HRD:

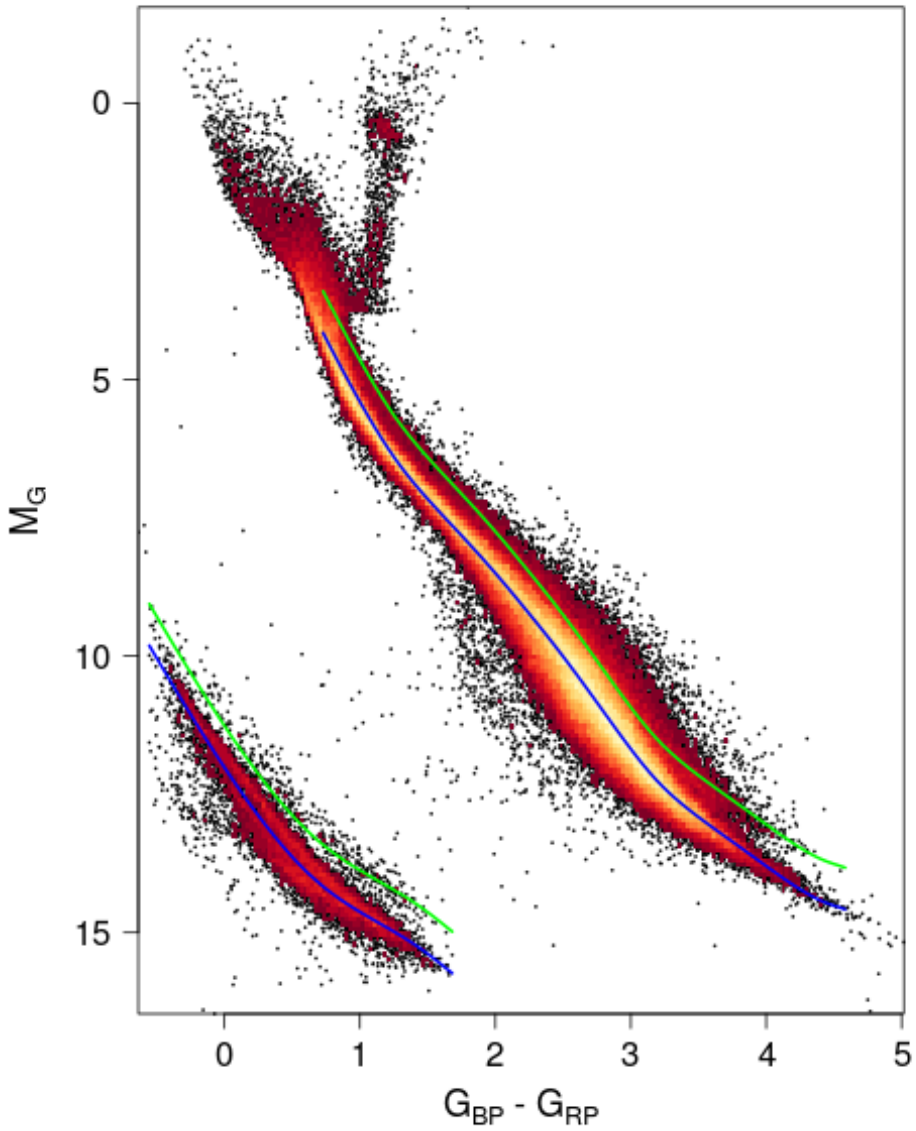
plot absolute visual magnitude versus B−V color

HRD from Gaia

212 728 stars within 100 pc

Gaia cons., 2018, A&A 616, A10

Hertzsprung Russell Diagram



Photometric HRD:

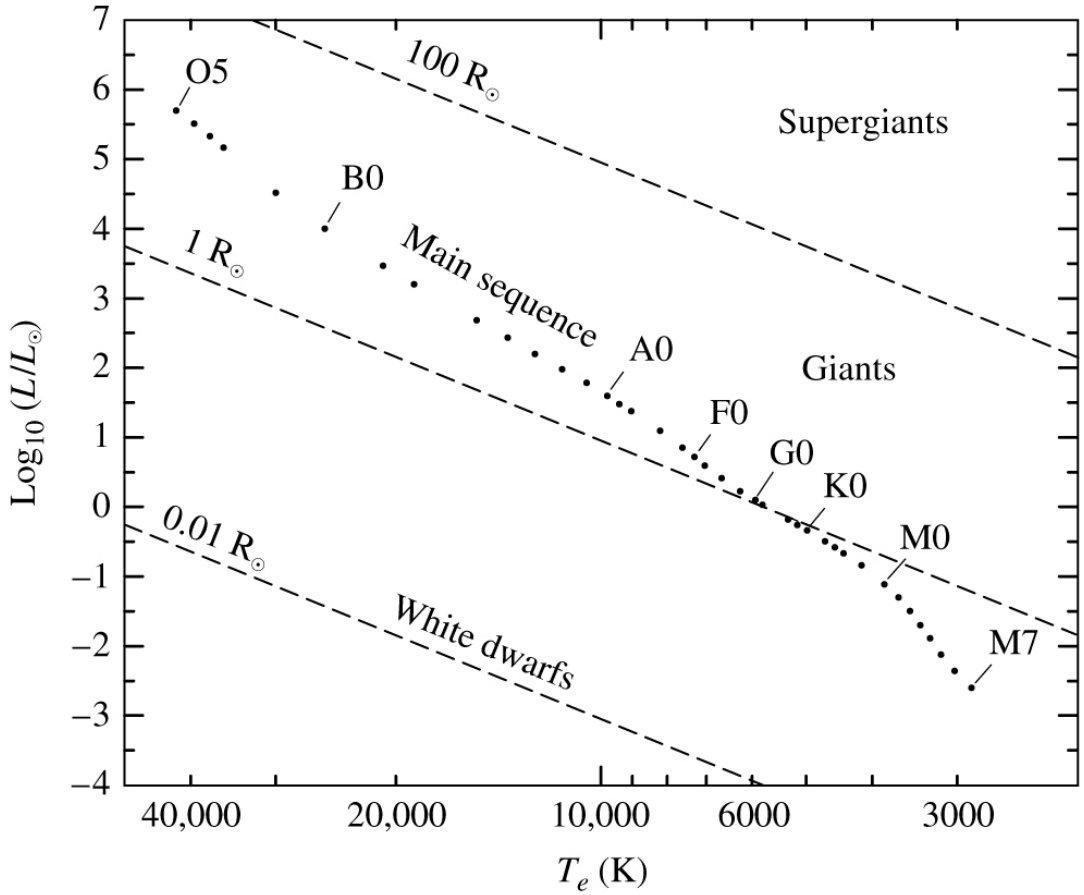
plot absolute visual magnitude versus B−V color

HRD from Gaia

stars within 100 pc, effect of binaries

Gaia cons., 2018, A&A 616, A10

Yerkes classification



Carroll & Ostlie

Stellar Luminosity:

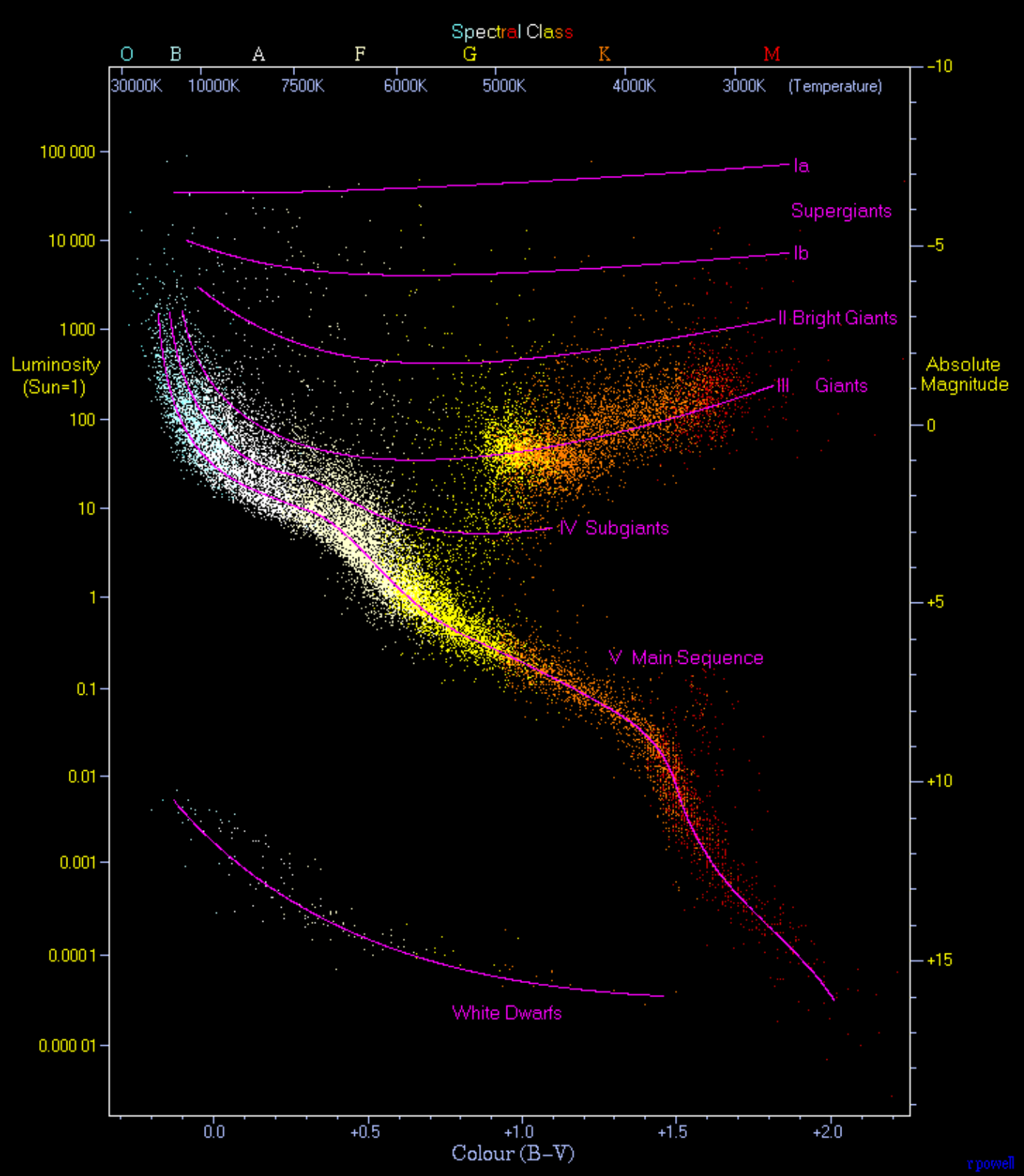
$$L = 4\pi R^2 \sigma T_{\mathrm{eff}}^4 \propto R^2 T_{\mathrm{eff}}^4 \quad (9.4)$$

Lines of constant radius:

$$\log \frac{L}{L_\odot} = 2 \log \frac{R}{R_\odot} + 4 \log \frac{T_{\mathrm{eff}}}{T_{\mathrm{eff},\odot}} \quad (9.5)$$

$\Longrightarrow$ hot (early type) main sequence stars are larger than the Sun

$\Longrightarrow$ cool (late type) main sequence stars are smaller than the Sun

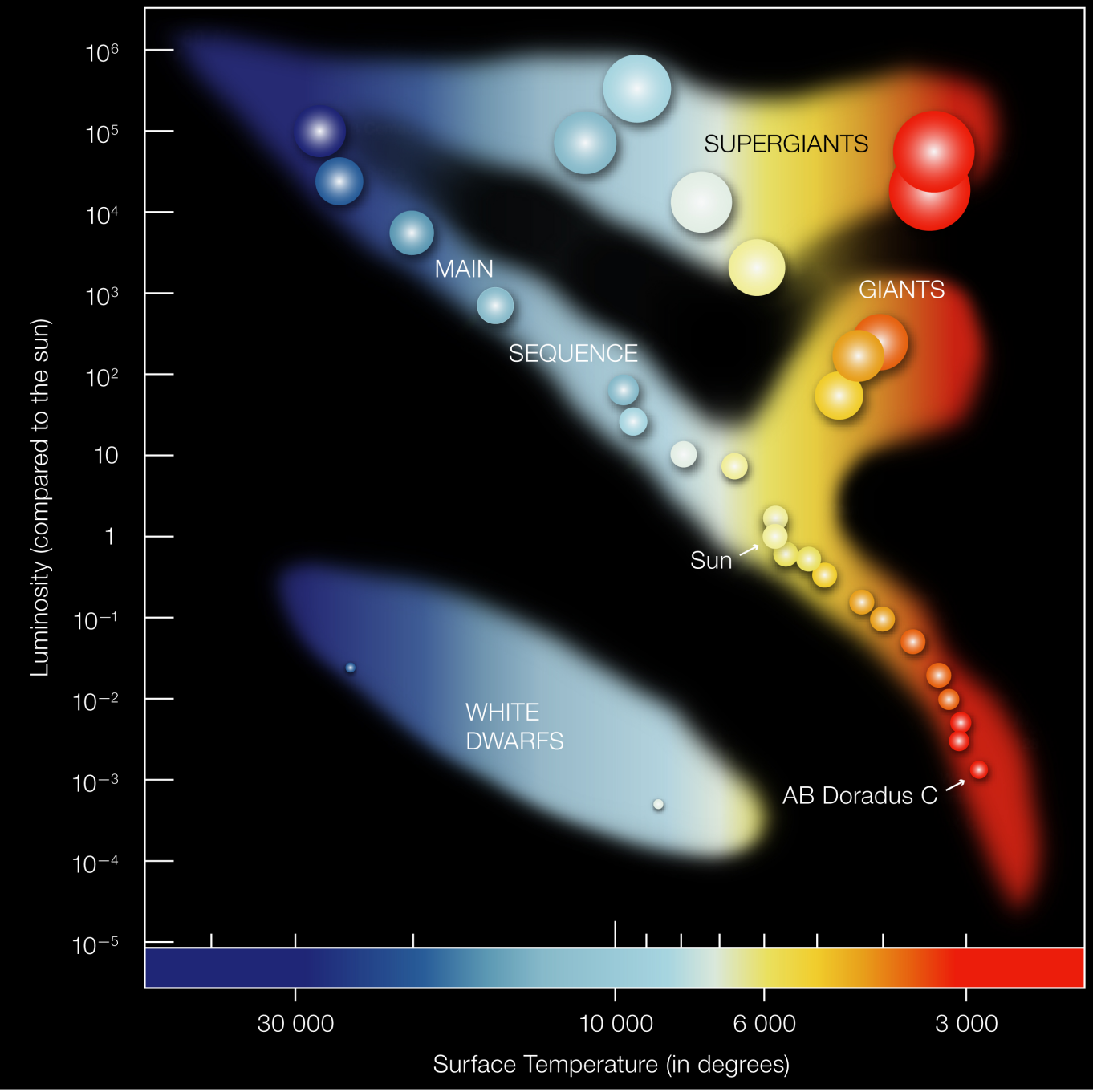


Size of stars influences spectral lines: "Morgan-Keenan classes" or "luminosity classes":

- Ia = hypergiant,
- Ib = supergiant,
- II = bright giant,
- III = giant,
- IV = subgiant,
- V = dwarf,
- VI = subdwarf

Notation: Append "Morgan-Keenan classes" to spectral class: Sun: G2 V, Betelgeuse: M2 Iab

R. Powell/Wikipedia



The Hertzsprung-Russell Diagram

ESO Press Photo 28c/07 (19 June 2007)
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Hertzsprung-Russell Diagram (HRD):

Note:

x-axis can be:

- temperature
- color
- spectral type

y-axis can be:

- luminosity
- absolute magnitude

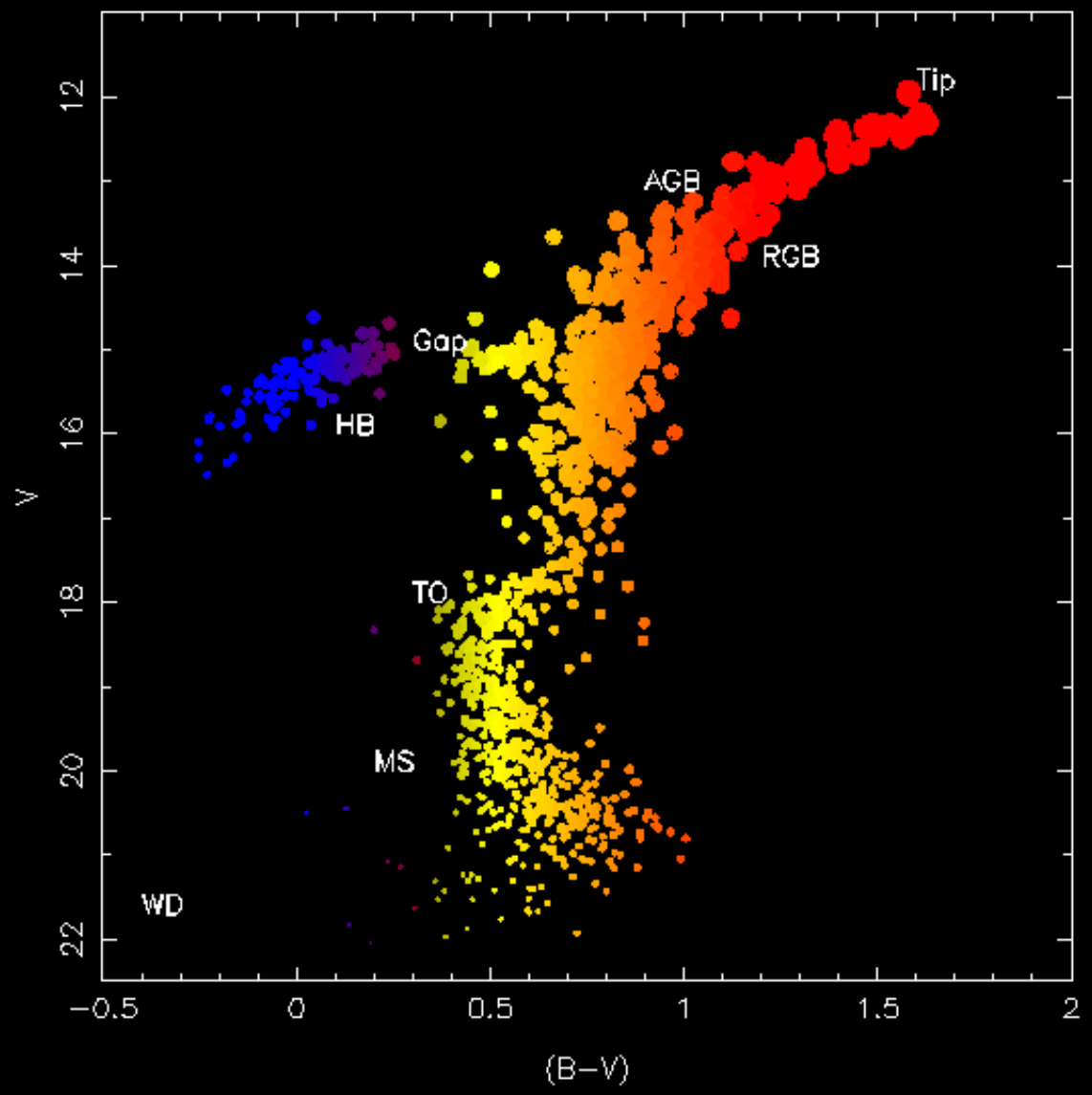
Statistics:

- Most stars on Main Sequence ("dwarfs")
- Few stars are Giants

Globular Cluster NGC 6093



Hubble Heritage



HRD of Globular Cluster M5 (UNSW, Sydney)
(B-V: ~ spectral class; V is a magnitude)

Globular Clusters: HRD is *very* different of solar neighbourhood

MS: Main Sequence

TO: Turn-Off point

HB: Horizontal Branch

RGB: Red Giant Branch

AGB: Asymptotic Giant Branch

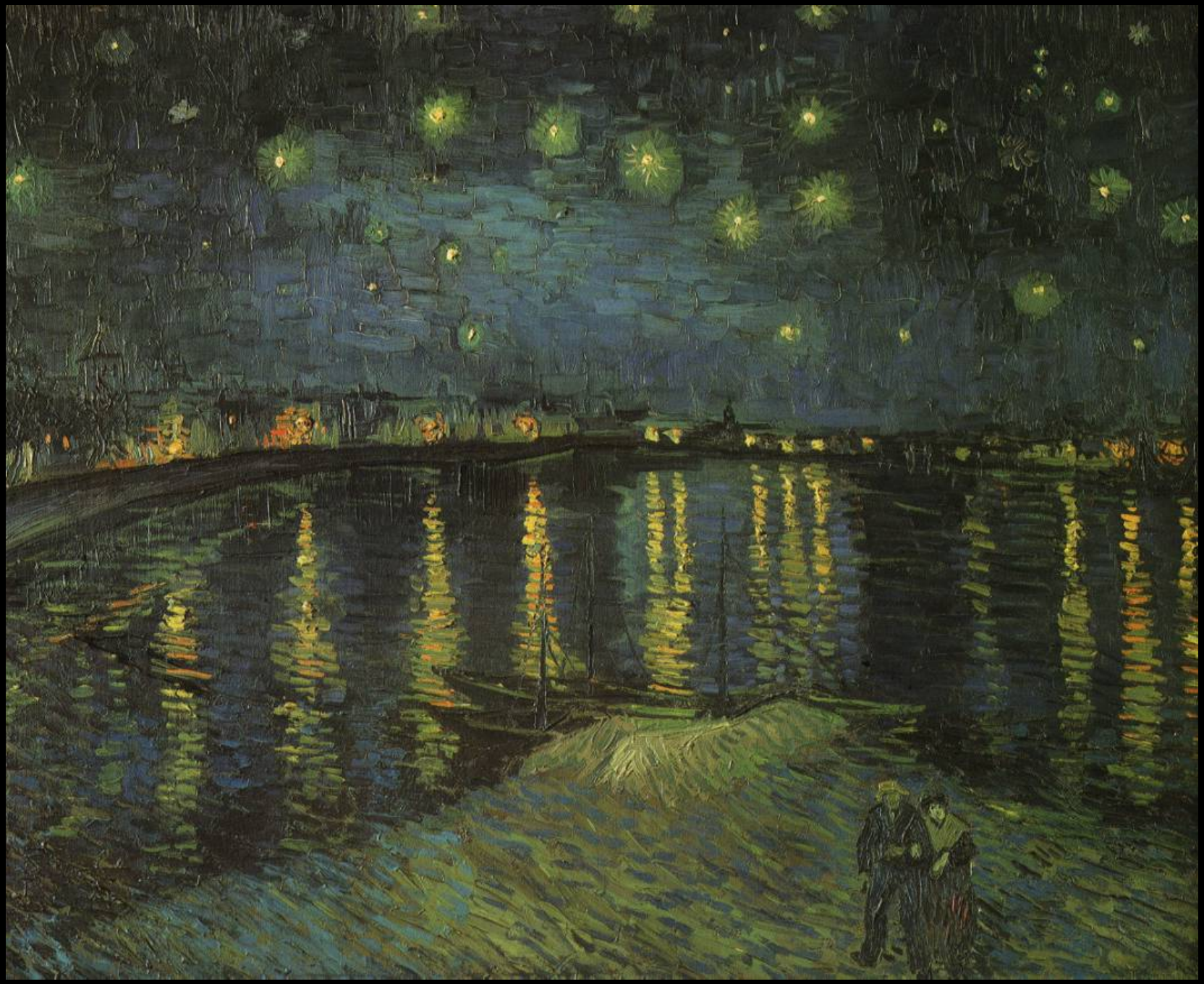
WD: White Dwarfs

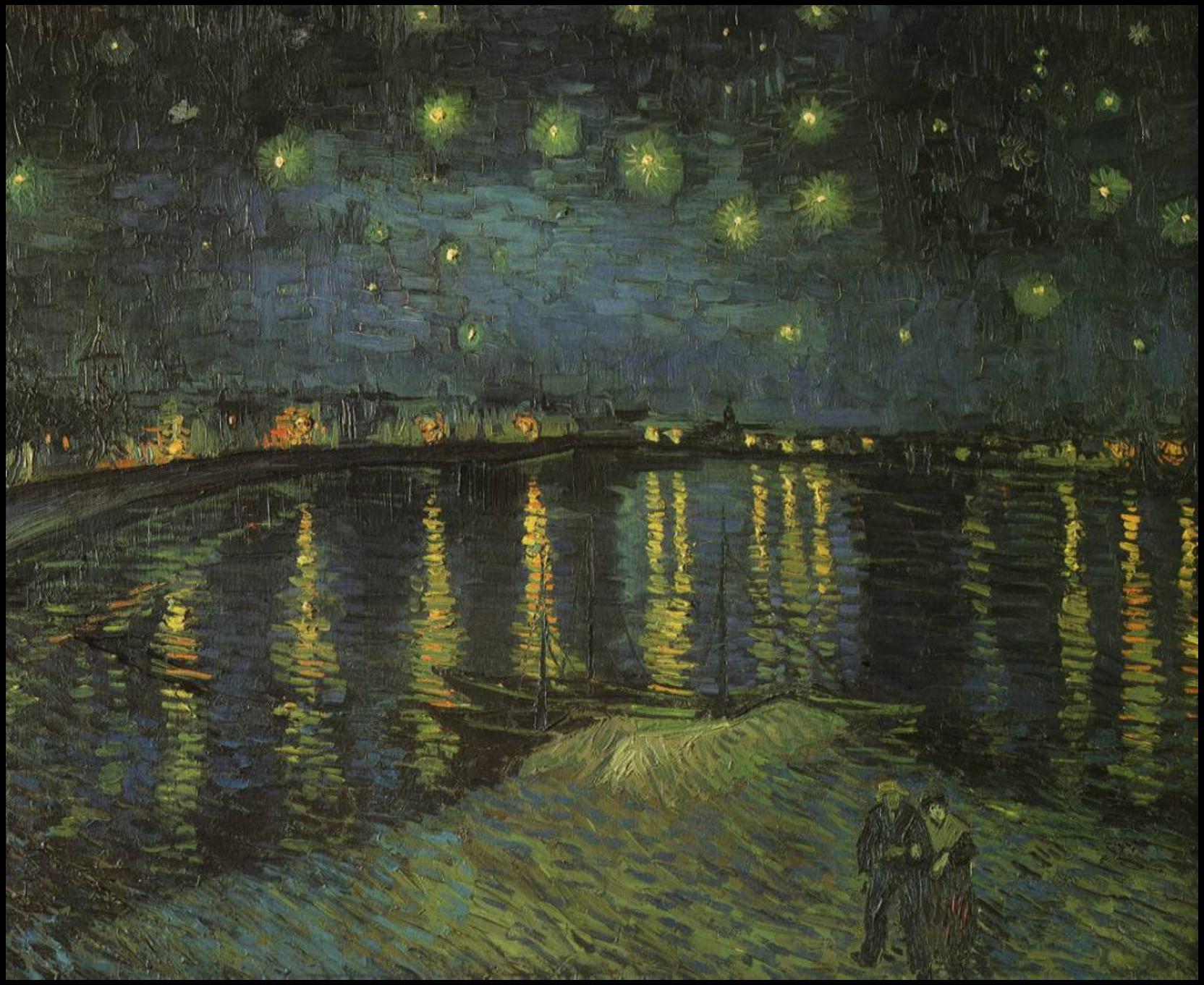
All stars in globular cluster born at the same time

$\Longrightarrow$ HRD shows evidence for stellar evolution

Terms to know:

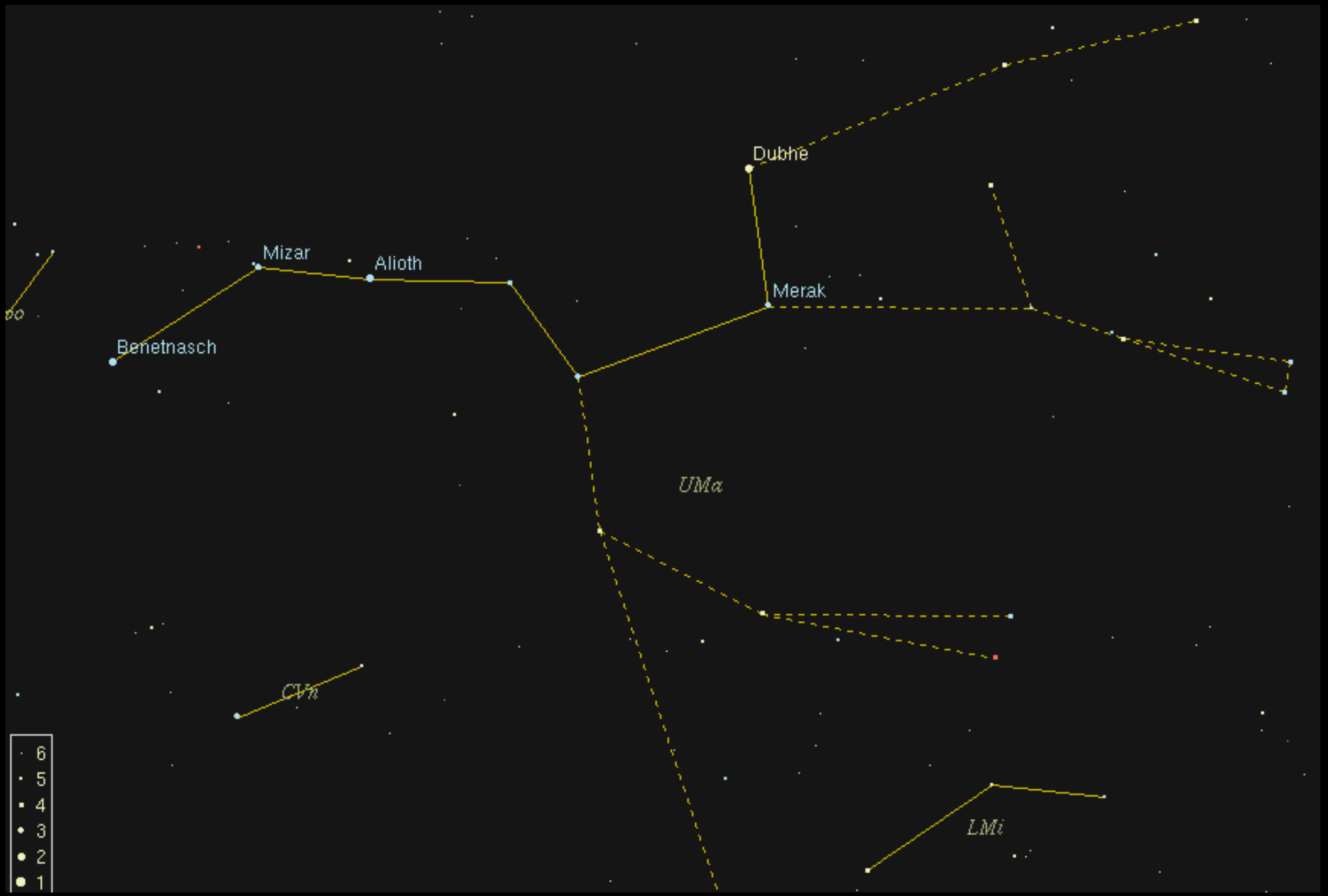
- Astrometry:
  parallax mesurements yield distances: $p = \frac{1\,\mathrm{AU}}{d}$ (unit: pc)
- Photometry:
  - Flux, luminosity and the inverse square law: $F = \frac{L}{4\pi r^2}$
  - The magnitude scale:
    * apparent visual magnitude m_V: $\frac{f_{V,1}}{f_{V,2}} = 100^{(m_{V,2}-m_{V,1})/5}$
    * absolute visual magnitude M_V = magnitude at $D = 10\,\mathrm{pc}$
    * distance modulus: $m_V - M_V = 2.5\log(F_V/f_V) = 2.5\log(d/10\,\mathrm{pc})^2 = 5\log d - 5$
    * bolometric absolute magnitude $M_{bol} = -2.5\log\frac{L}{L_\odot} + 4.74$
    * bolometric correction: $B.C. = M_{bol} - M_V$
    * color indices, e.g., UBV: $B - V = m_B - m_V$, $U - B = m_U - m_B$
- Planck's law:
  - Effective temperature: $T_{eff}^4 = F/\sigma = L/(4\pi R^2\sigma)$
  - color indices are temperature indicators
- Spectroscopy: two dimensional classification scheme
  - 1. Harvard: spectral types: O, B, A, F, G, K, M
  - 2. Yerkes (Morgan-Keenan): luminosity classes Ia, Ib, II, III, IV, V, VI
  - Spectral sequence is caused by excitation (Boltzmann equation) and ionization (Saha equation) of atoms $\Longrightarrow$ temperature sequence
  - luminosity classes are density indicators (without proof)
- Hertzsprung-Russell-Diagram: Three versions:
  - classical: M_V vs. spectral type
  - photometric: Color-magnitude diagram (CMD): V vs. (B−V), M_V vs. color index (usually B−V)
  - physical: Luminosity vs. effective temperature: L vs. T_{eff}
    * most stars are on the main sequence
    * various types of giants above the main sequence
    * white dwarfs below the main sequence

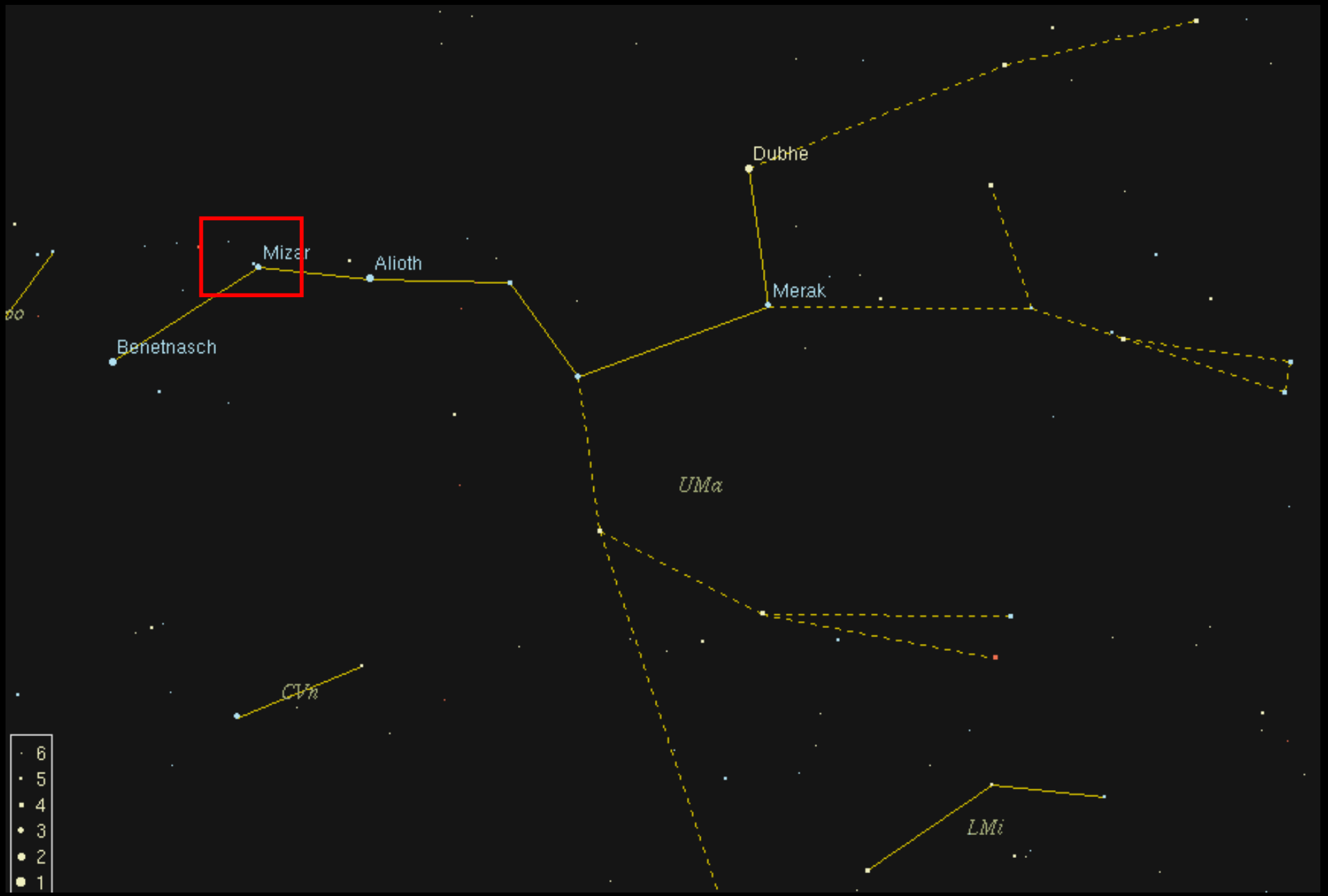


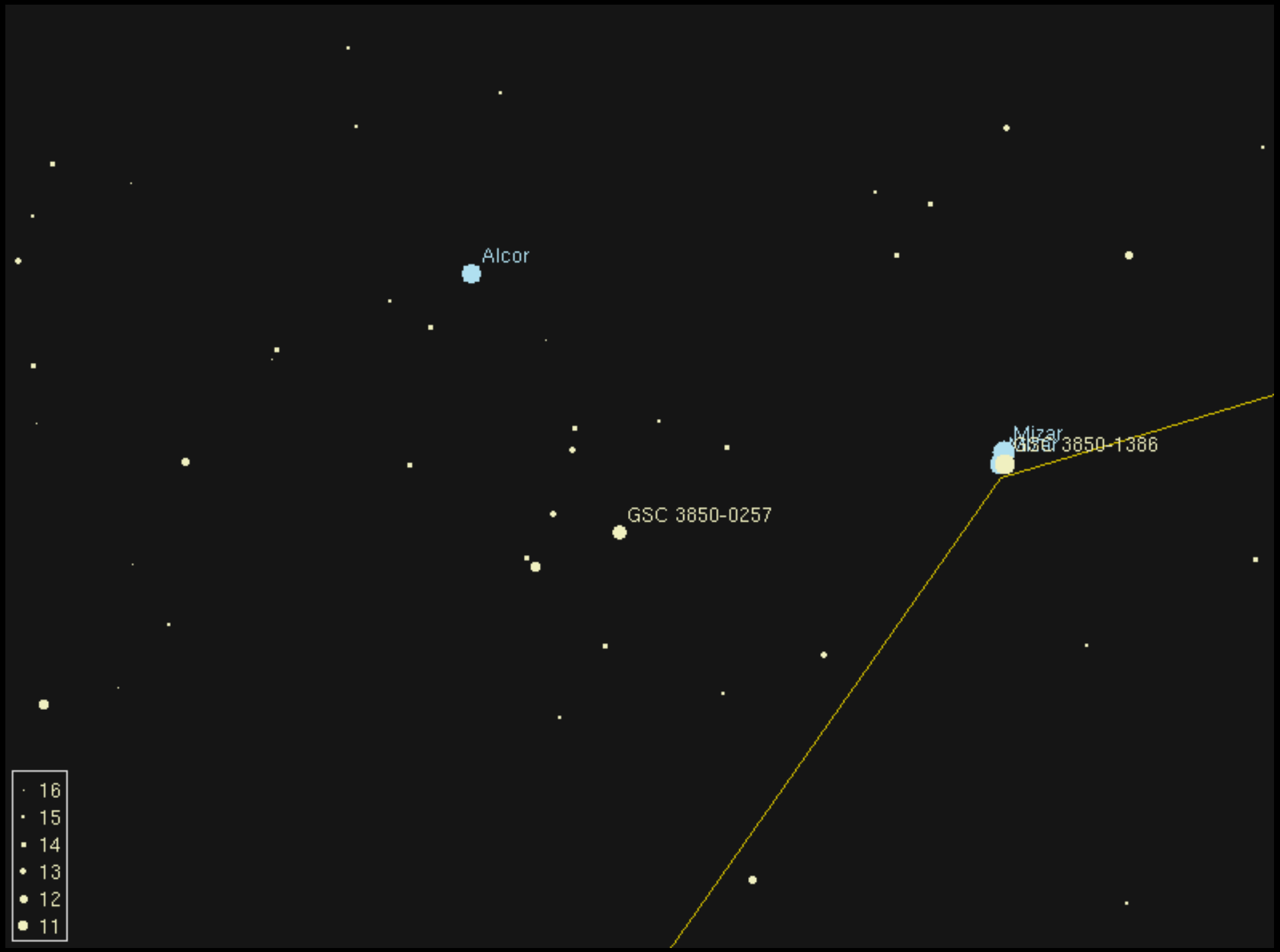


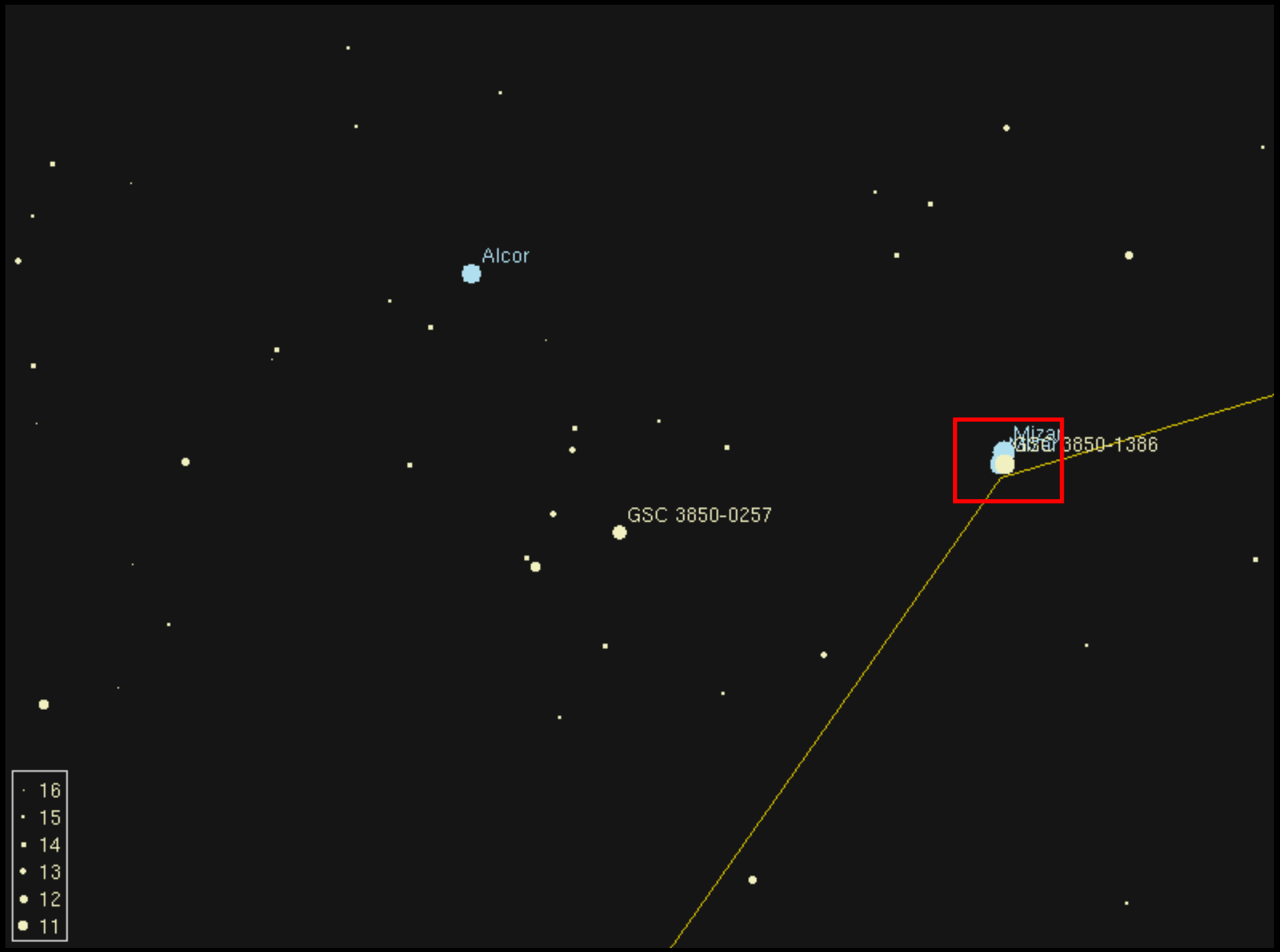
V. van Gogh: Starry Night over the Rhône (1888)

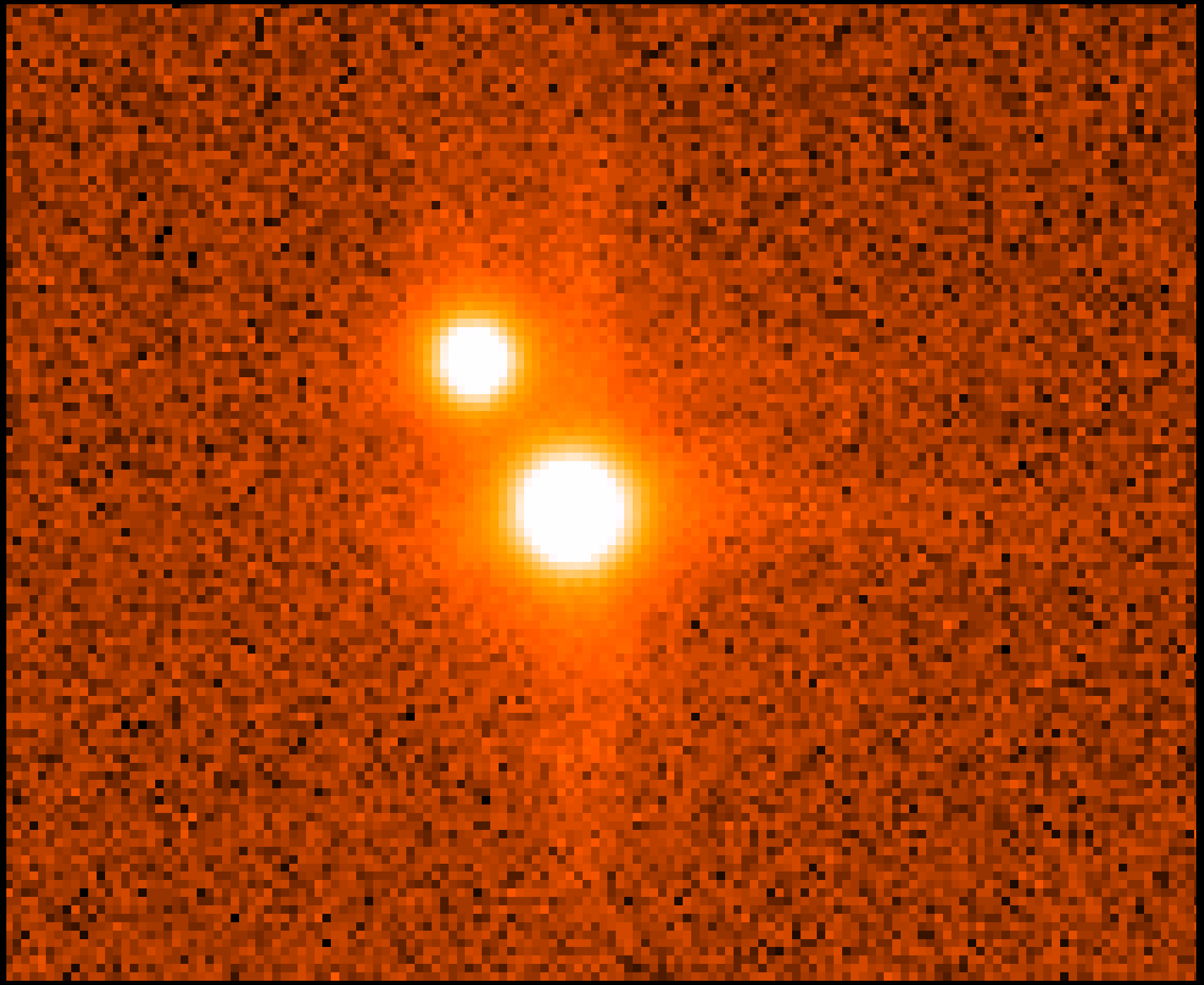
The WebMuseum (`http://www.ibiblio.org/wm/`; original: Paris, Musée d'Orsay)

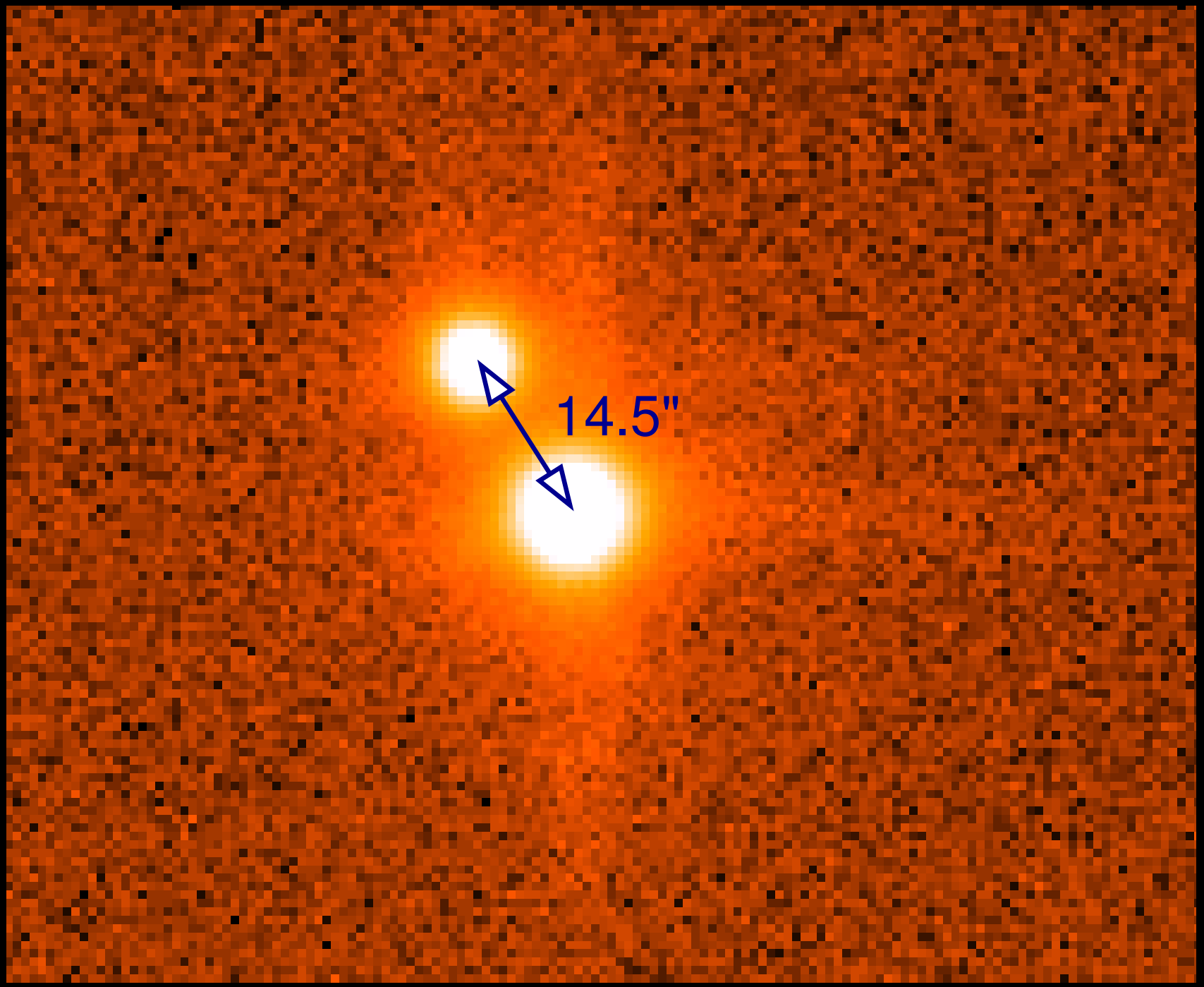

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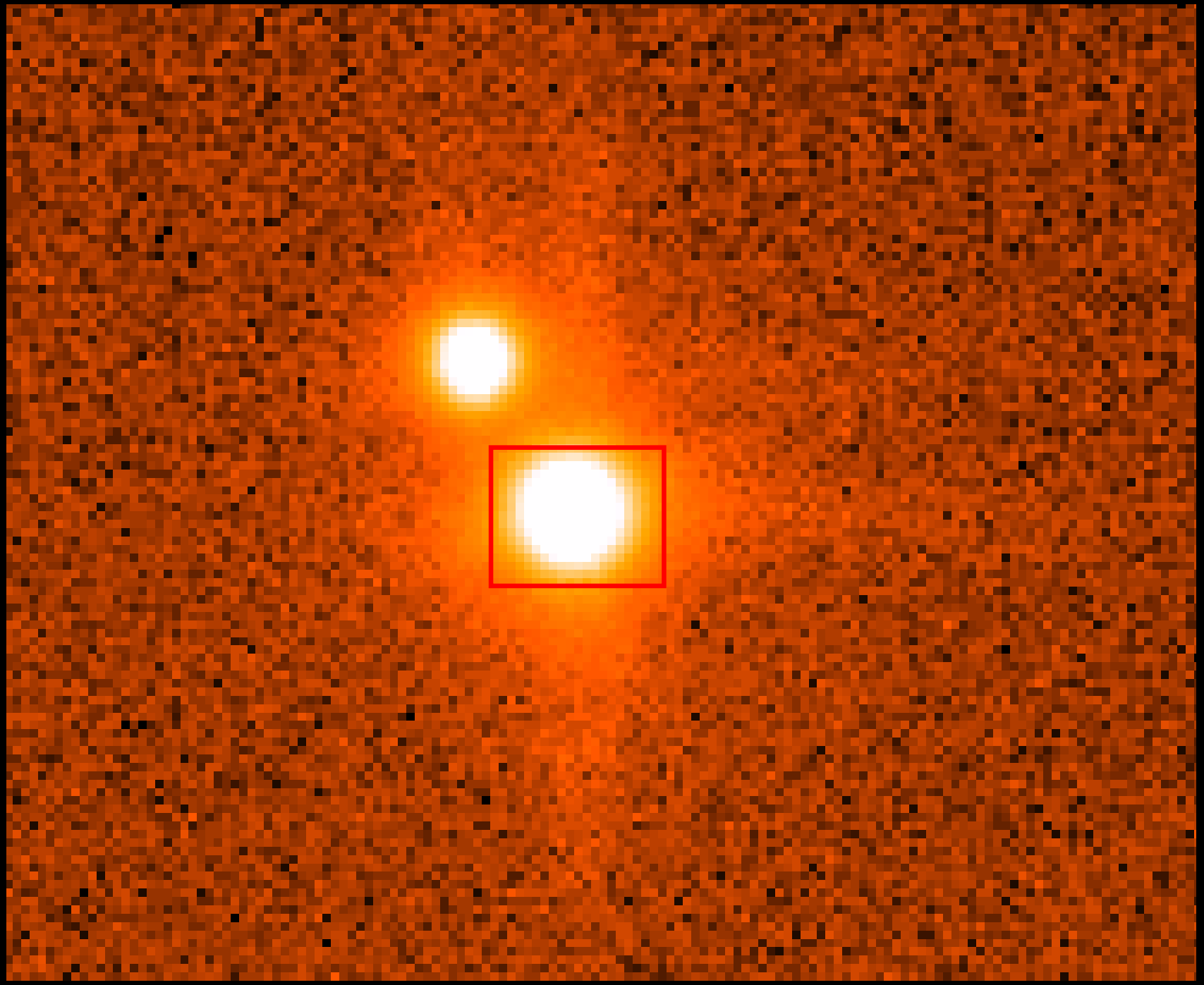

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Alcor
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GSC 3850-0257
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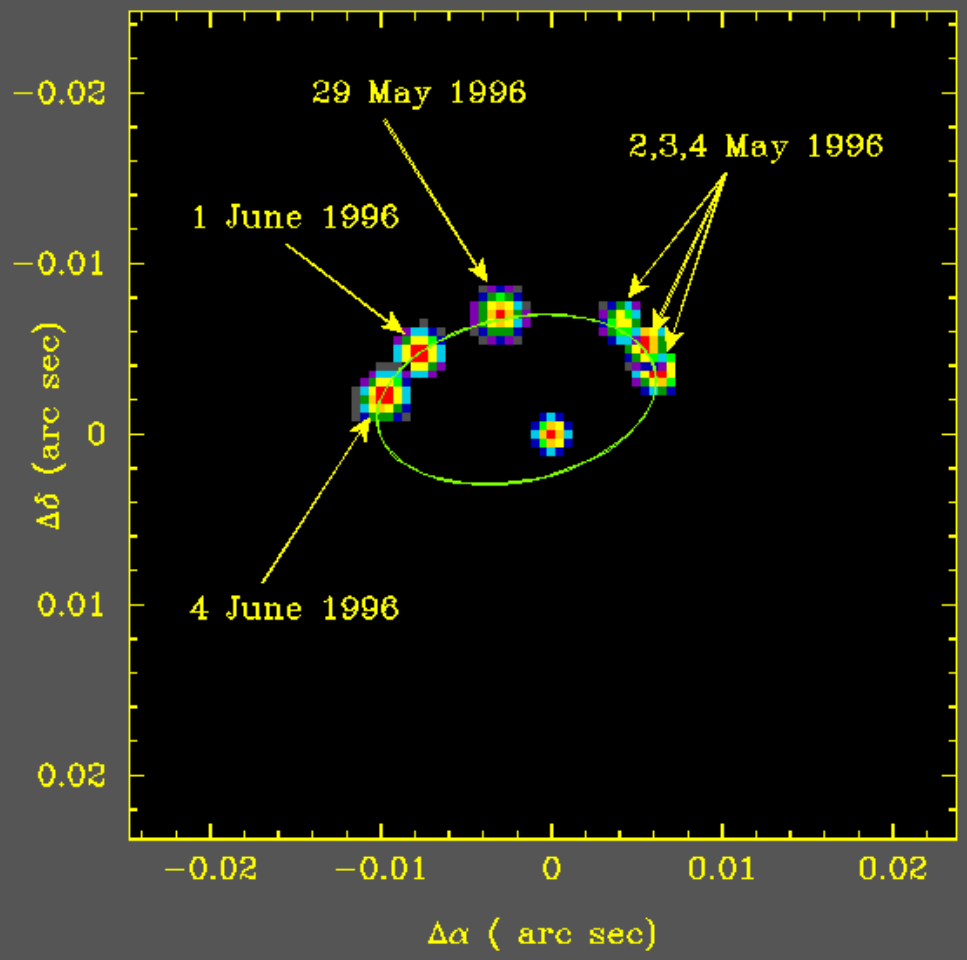

Alcor
GSC 3850-0257
16
15
14
13
12
11




14.5"



ζ^1 Ursae Majoris



Mark III optical interferometer on Mount Wilson, California,
Credit: J. Benson et al., NPOI Group, USNO, NRL

Mizar A is a binary itself

Masses

Mizar A and B are rather typical stars:

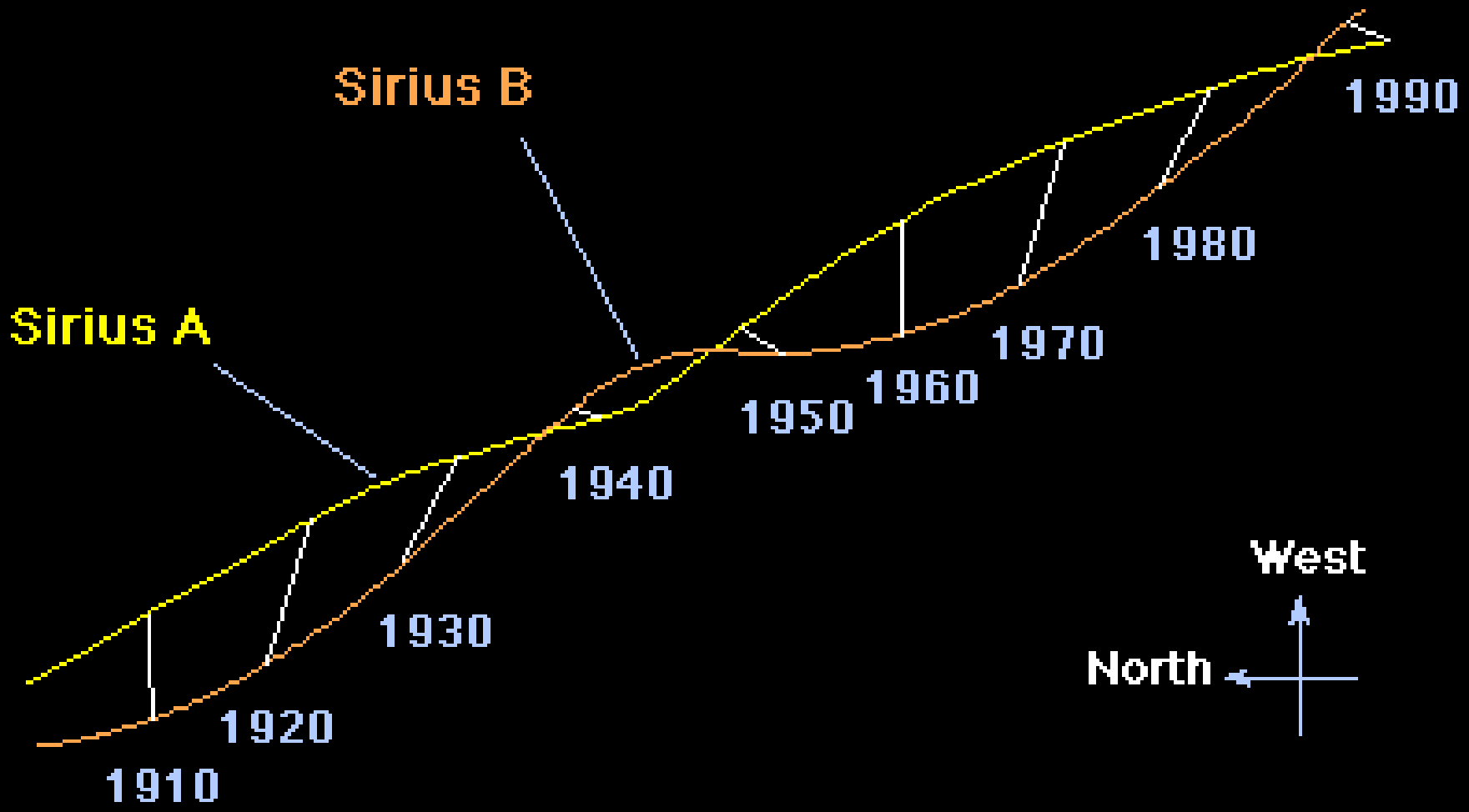
> 50% – 80% of all stars in the solar neighbourhood belong to multiple systems.

Rough classification:

apparent binaries: stars are *not* physically associated, just happen to lie along same line of sight ("optical doubles").

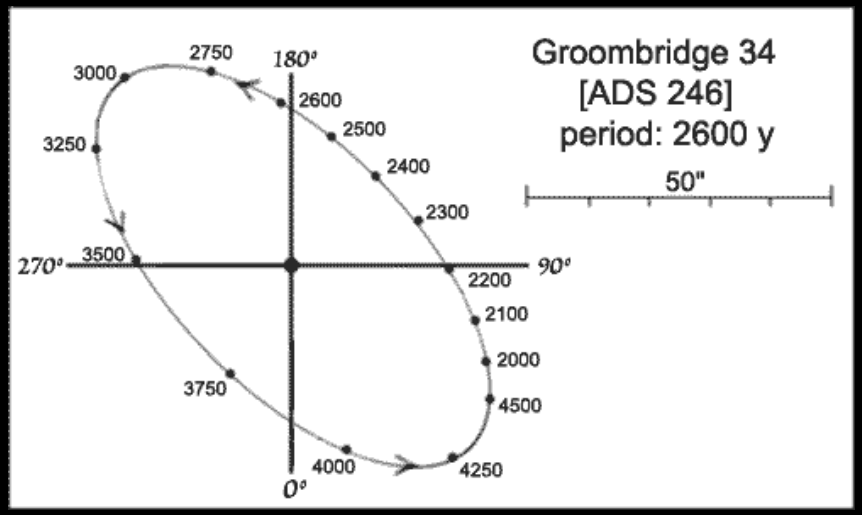
visual binaries: bound system that can be resolved into multiple stars (e.g., Mizar); can image orbital motion, periods typically 1 year to several 1000 years.

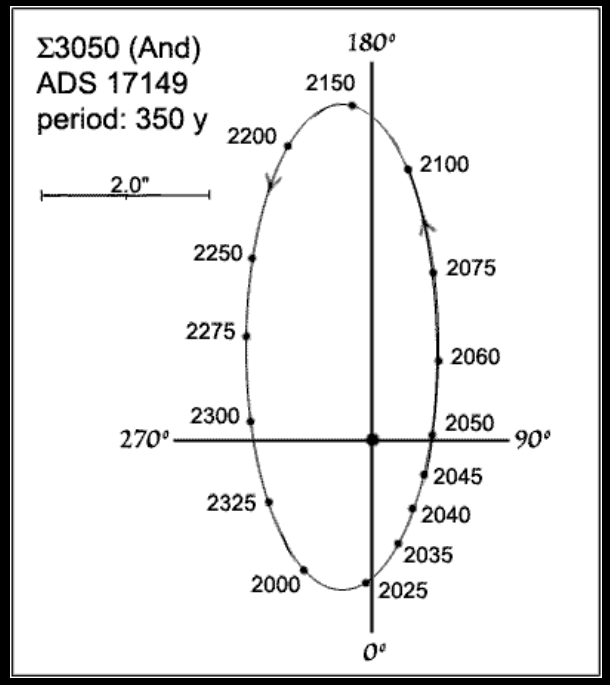
spectroscopic binaries: bound systems, cannot resolve image into multiple stars, but see Doppler effect in stellar spectrum; often short periods (hours. . . months).

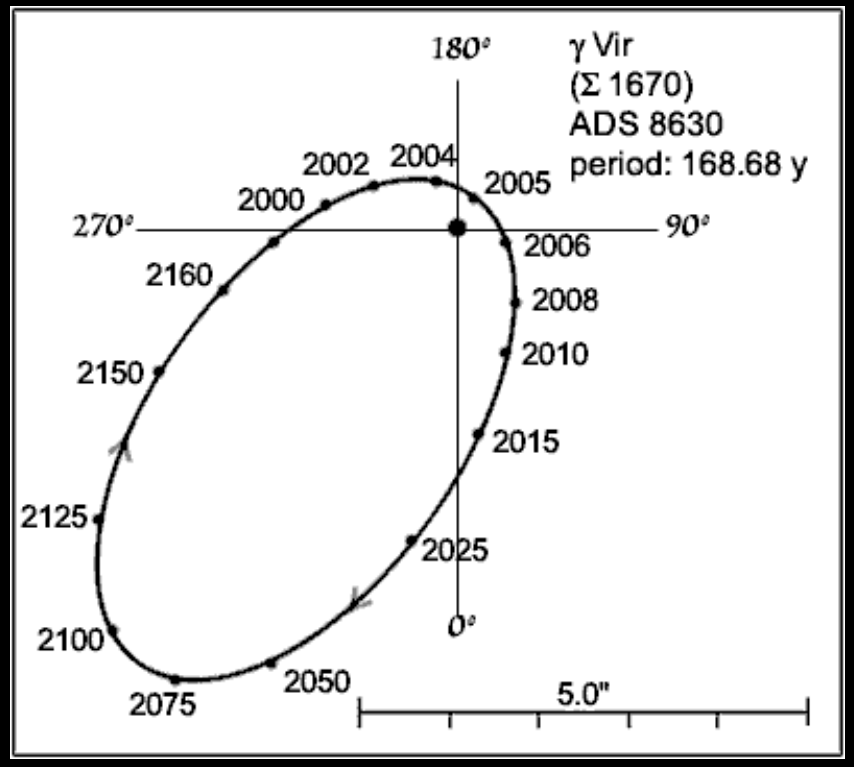


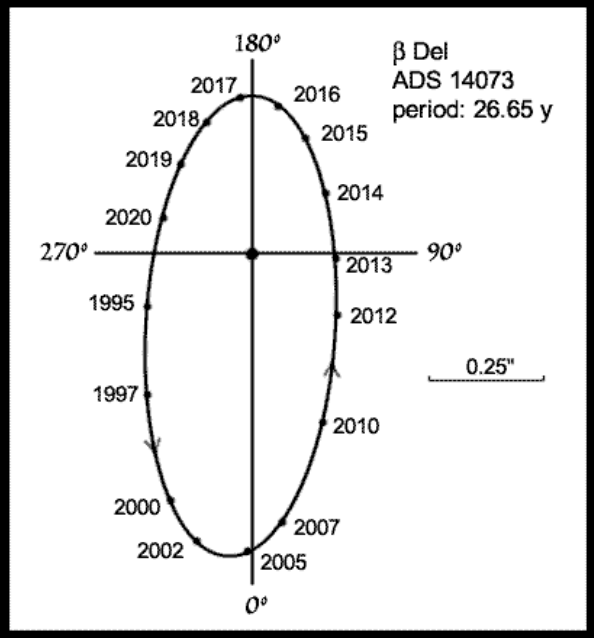
http://csep10.phys.utk.edu/astr162/lect/binaries/astrometric.html

Astrometric binaries: Motion of stars around common center of mass results in a "wobble" around the CM (since CM is moving along a straight line).









Taking out proper motion leaves us with binary star orbits.

Masses

To determine stellar masses, use Kepler's 3rd law:

$$\frac{a^3}{P^2} = \frac{G}{4\pi^2}(m_1 + m_2)$$

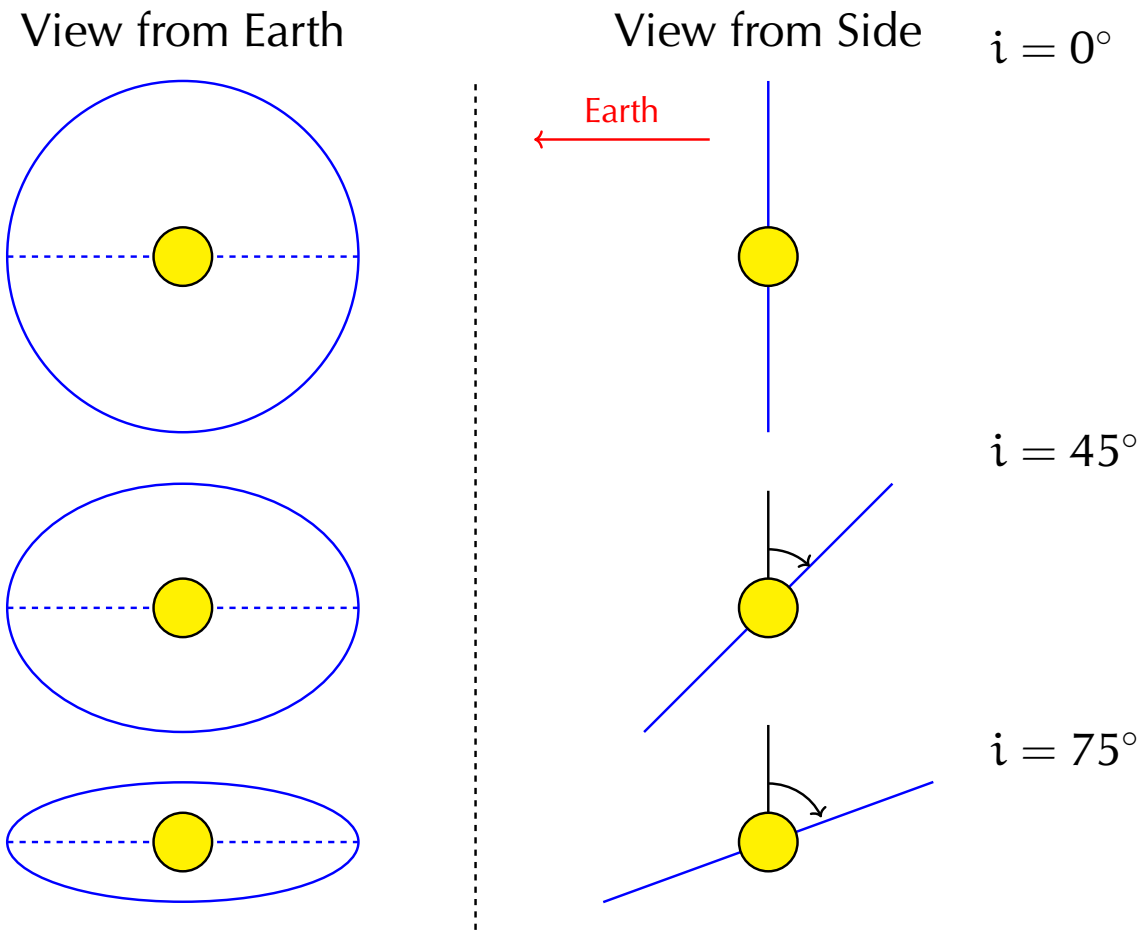
where

- $M_{1,2}$: masses
- P: period
- a semimajor axis

Observational quantities:

- P – directly measurable
- a – measurable from image *if and only if* distance to binary and the inclination are known

Masses



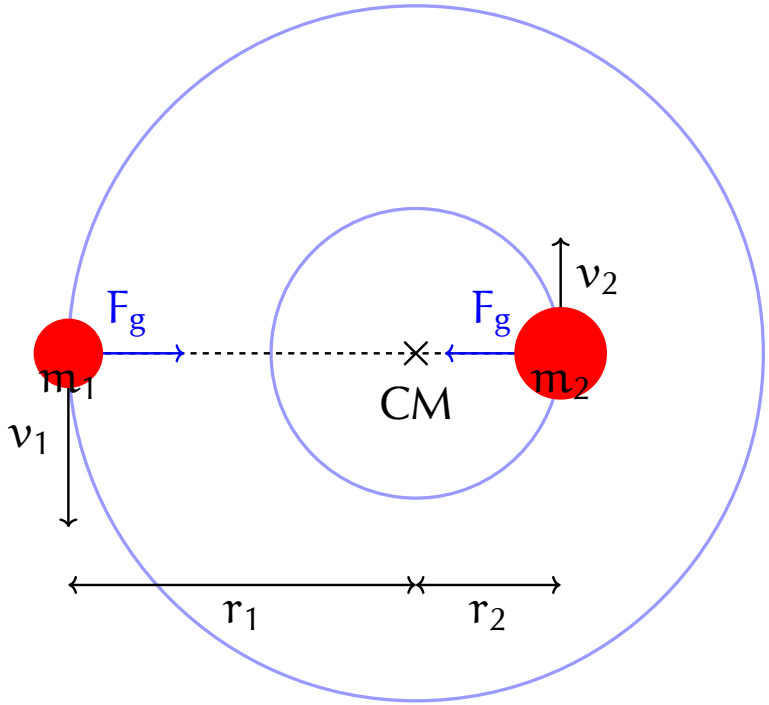
Problem when analyzing orbits: orientation of orbit in space: "inclination"

In simplest case: real semi-major axis:

$$a_{observed} = a_{real} \cos i$$

Inclination typically found using Kepler's 2nd law plus geometry...

Masses



Kepler's 3rd law gives $m_1 + m_2$.

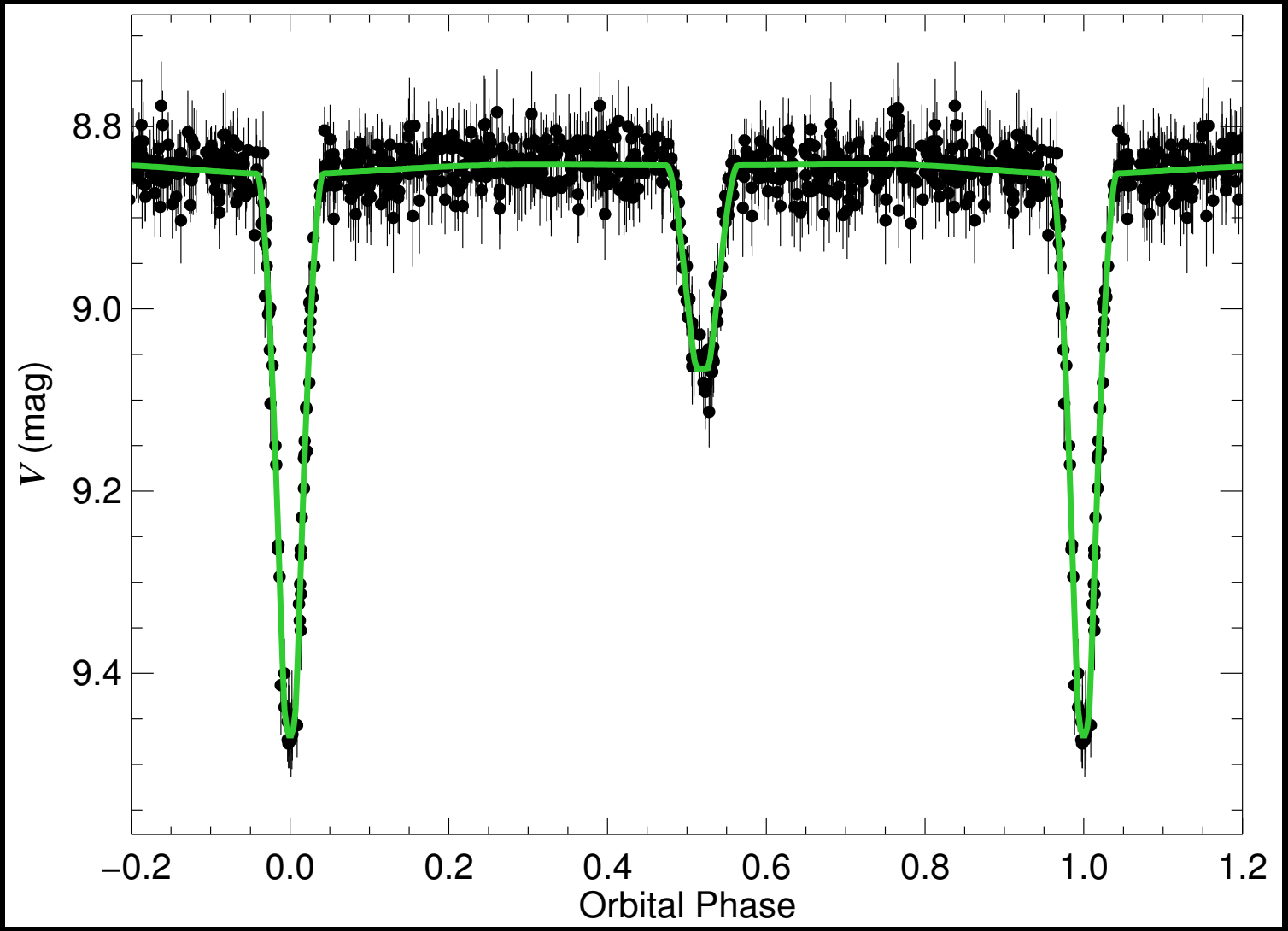
To determine individual masses, m_1 and m_2, we make use of the fact that the stars move around their common center of mass (CM):

$$m_1 a_1 = m_2 a_2 \quad \text{such that} \quad \frac{m_1}{m_2} = \frac{a_2}{a_1}$$

where a_1, a_2: semi-major axes of orbits around CM (observable from imaging).

MOVIE TIME: vbin0.mpg, vbin4.mpg

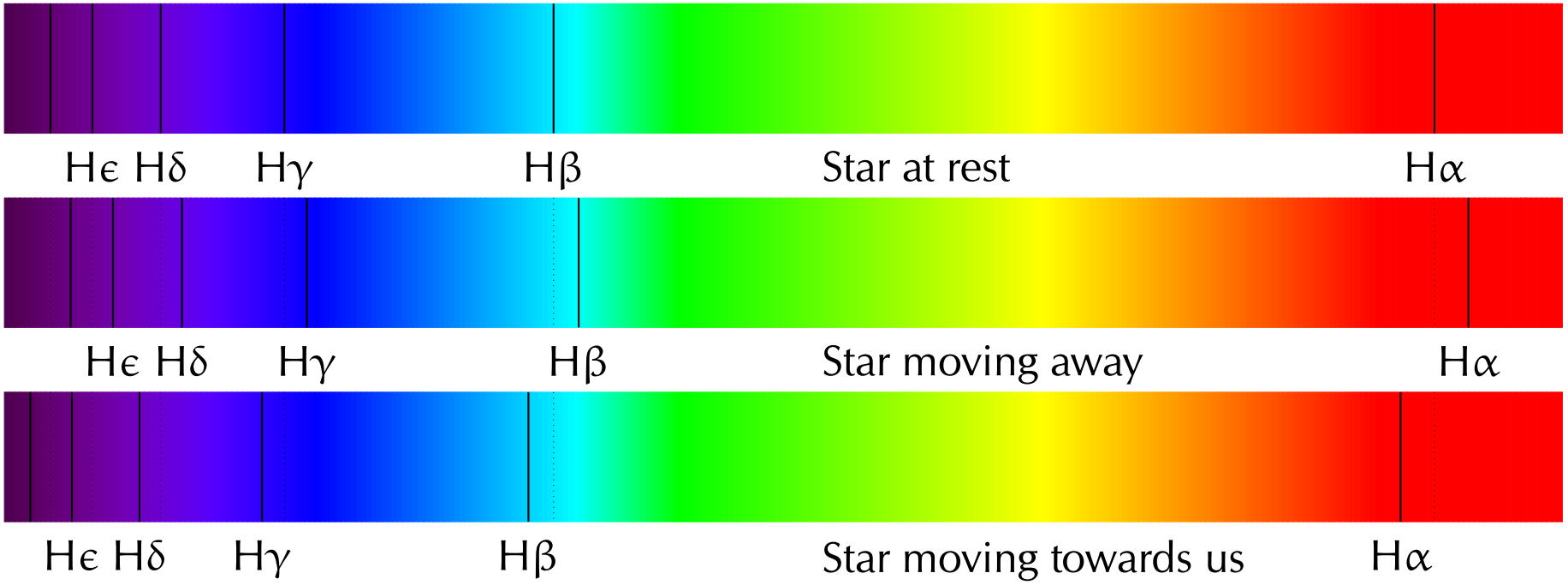
Also recommended: Interactive program: `http://astro.ph.unimelb.edu.au/central/Mirrors/binary/binary.htm`



HD 252416, Williams et al., 2011, AJ 142, 5

Eclipsing binaries: photometric binaries where the orbital plane is perpendicular to the celestial plane.

Spectroscopic Binaries



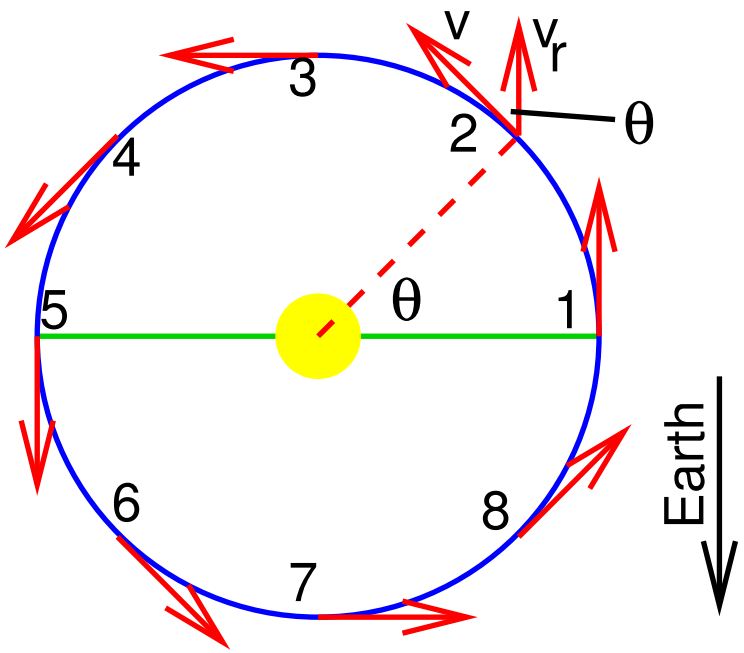
Doppler formula:

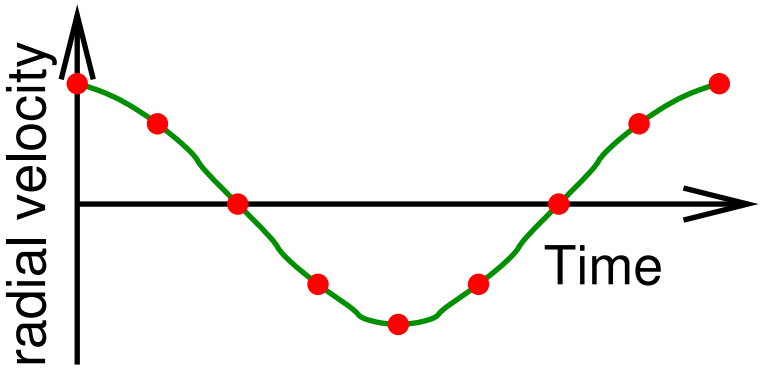
$$\frac{\Delta\lambda}{\lambda} = \frac{v_{\text{rad}}}{c} \tag{9.6}$$

allows to measure the radial velocity v_{rad} from line shifts
plus tangential velocity (from distance and proper motion)

c: speed of light

Spectroscopic Binaries





For spectroscopic binaries: can only measure radial velocity along line of sight
For circular orbit, angle θ on orbit:

$$\theta = \omega t$$

where $\omega = 2\pi/P$.
Observed radial velocity:

$$v_r = v \cos(\omega t)$$

If orbit has inclination i, then

$$v_r(t) = v \sin i \cos(\omega t) =: K \cos(\omega t)$$

From observation of $v_r(t) \Longrightarrow v \sin i$.
("velocity amplitude", K)

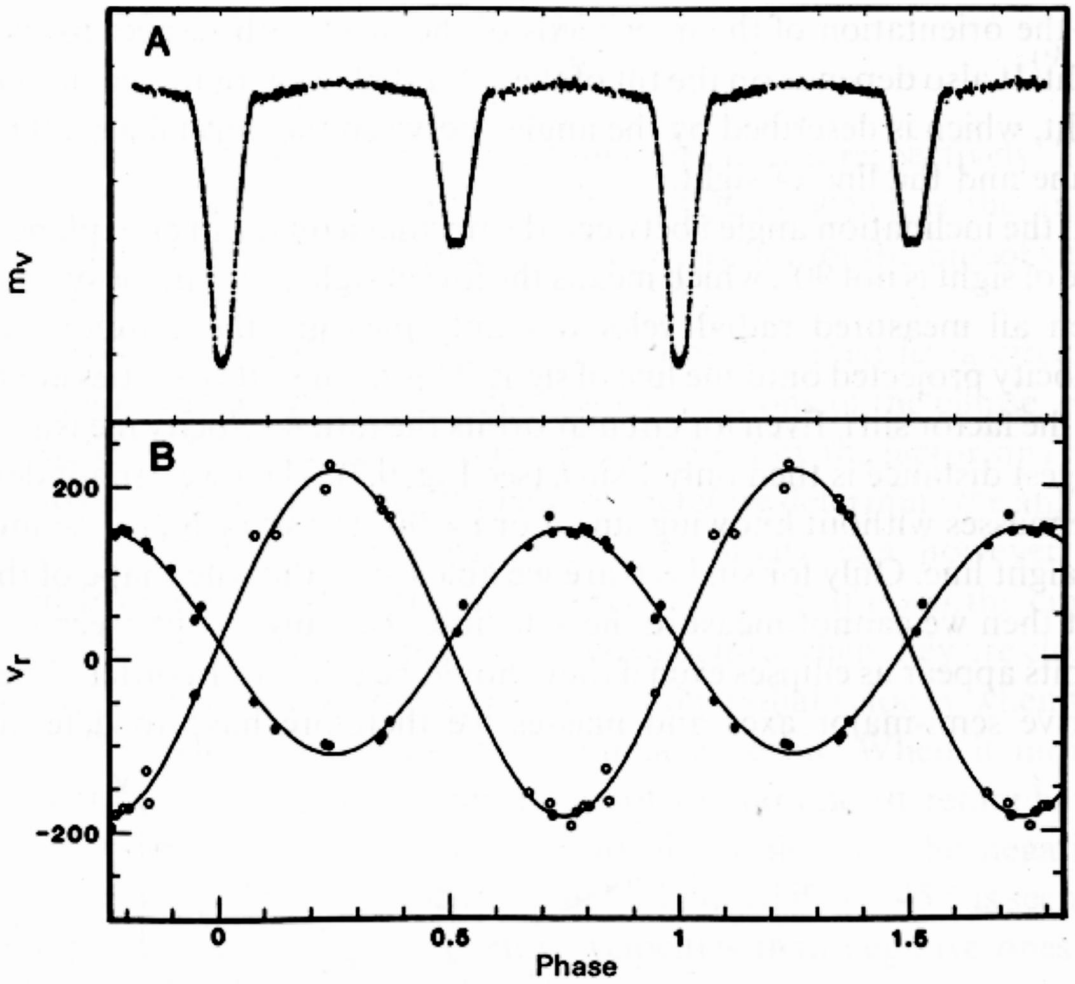


Fig. 9.6. Light and velocity curves for the eclipsing binary ζ Phoenicis are shown as a function of orbital phase. During the times when one star is behind the other we see a reduced light intensity. This happens twice during one period, once if star 1 is in front of star 2, and once if star 2 is in front of star 1. If star 2 has the larger surface brightness, i.e., if star 2 emits more light per cm^2, then less light will be received when star 2 is eclipsed during the first eclipse than will be received when star 1 is eclipsed, i.e., during the second eclipse. The first light minimum is then deeper than the second one. (From Paczinski 1985.)

Mass function

If only one star is visible: obtain mass limits from the mass function (derivation: see homework):

$$f_M := \frac{PK_1^3}{2\pi G} = \frac{M_2^3 \sin^3 i}{(M_1 + M_2)^2} \tag{9.7}$$

where the observables: K_1 & P
and the unknowns: M_1: mass of "primary star", M_2: mass of (unseen) "secondary star" & i: inclination

$\Longrightarrow$ f_M is lower limit for M_2, since for $M_1 = 0$: $M_2 = f_M / \sin^3 i \geqslant f_M$

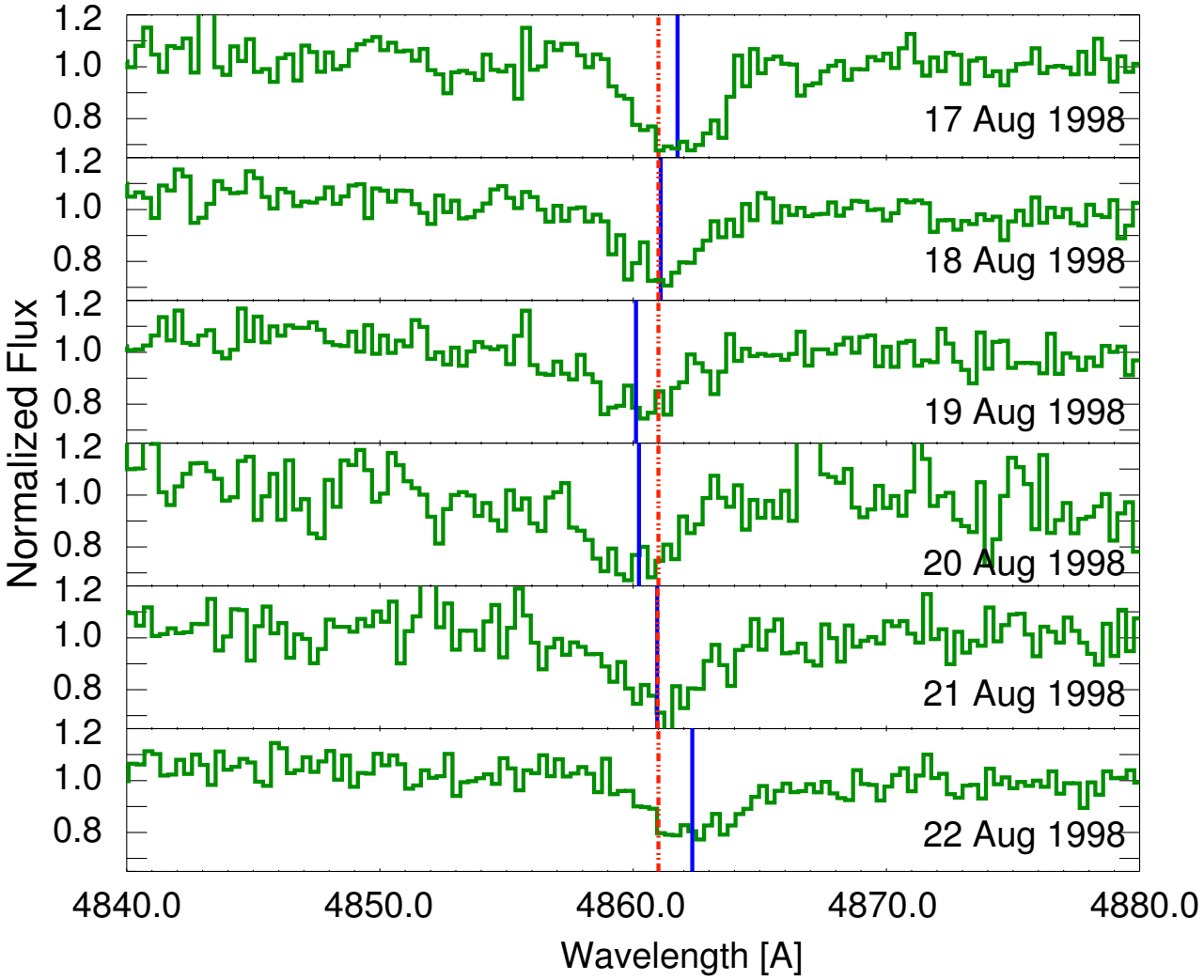
In some cases, knowing $f(M)$ is enough to determine M_2:

Often, the mass of the primary, M_1, can be derived from a quantitative spectral analysis. In this case two unknowns remain: M_2 and $\sin i$.

As $|\sin i| \leqslant 1$: improved lower limit for M_2.

Determine lower mass limits for all types of invisible faint companions: Exoplanets, brown dwarfs, faint normal stars, neutron star and black hole binaries.

Mass function



HDE 226868/Cyg X-1; Pottschmidt (2001)

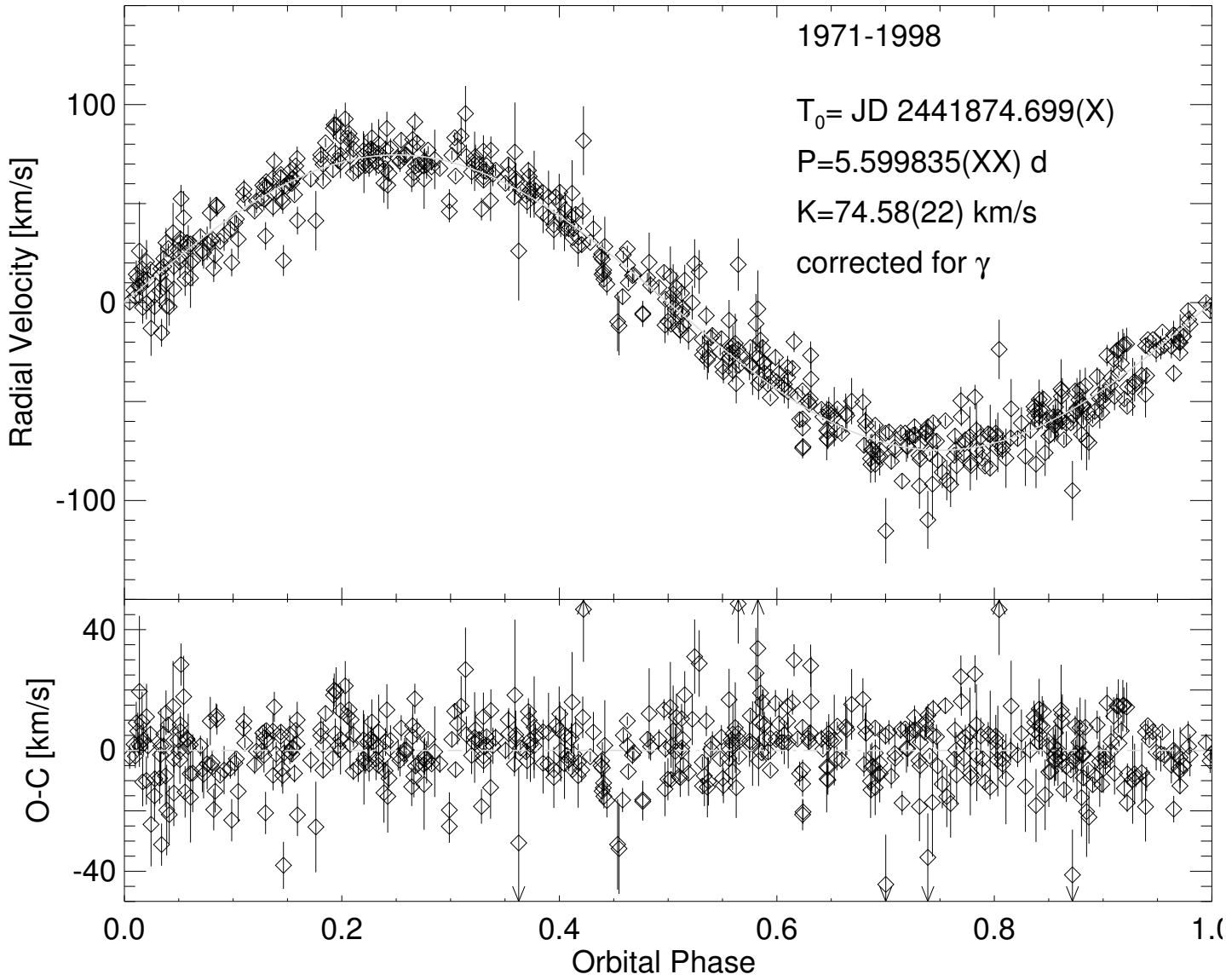
Motion of star visible through Doppler shift in stellar spectrum:

$$\frac{\Delta\lambda}{\lambda} = \frac{v_r}{c} = \frac{v}{c}\sin i \cos \omega t$$

For virtually all stars, classical Doppler effect is enough; once $v \gtrsim 0.1c$, however, use relativistic Doppler effect,

$$\nu_{obs} = \nu_{em}\sqrt{\frac{1+v/c}{1-v/c}}$$

Mass function

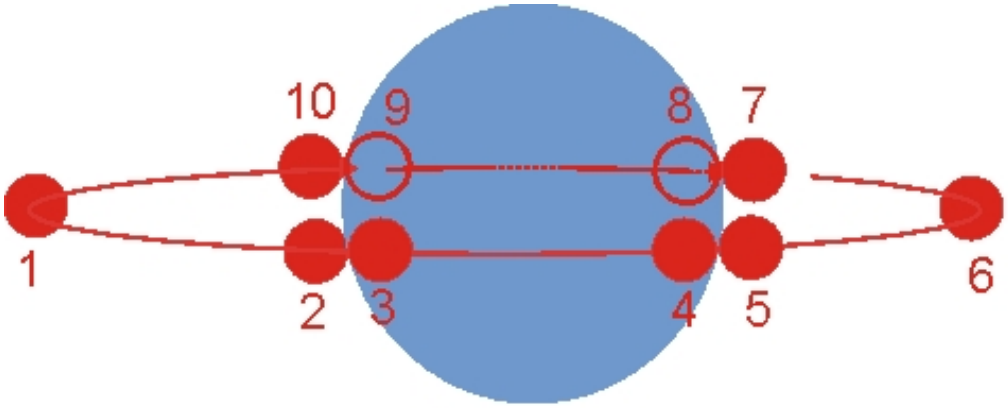


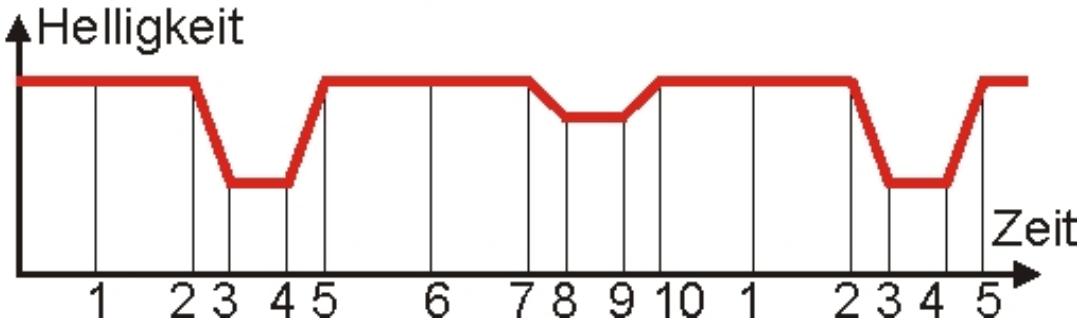
Best fit radial velocity curve of HDE 226868/Cyg X-1 using data spanning more than 30 years.

Pottschmidt et al. (2001)

Stellar Diameters

Eclipsing Binaries





Determination of diameters d_A and d_B from eclipse timing:

Duration of eclipse:

$$d_A + d_B = v(t_5 - t_2) \qquad (9.8)$$

Duration of eclipse egress:

$$d_A - d_B = v(t_4 - t_3) \qquad (9.9)$$

therefore:

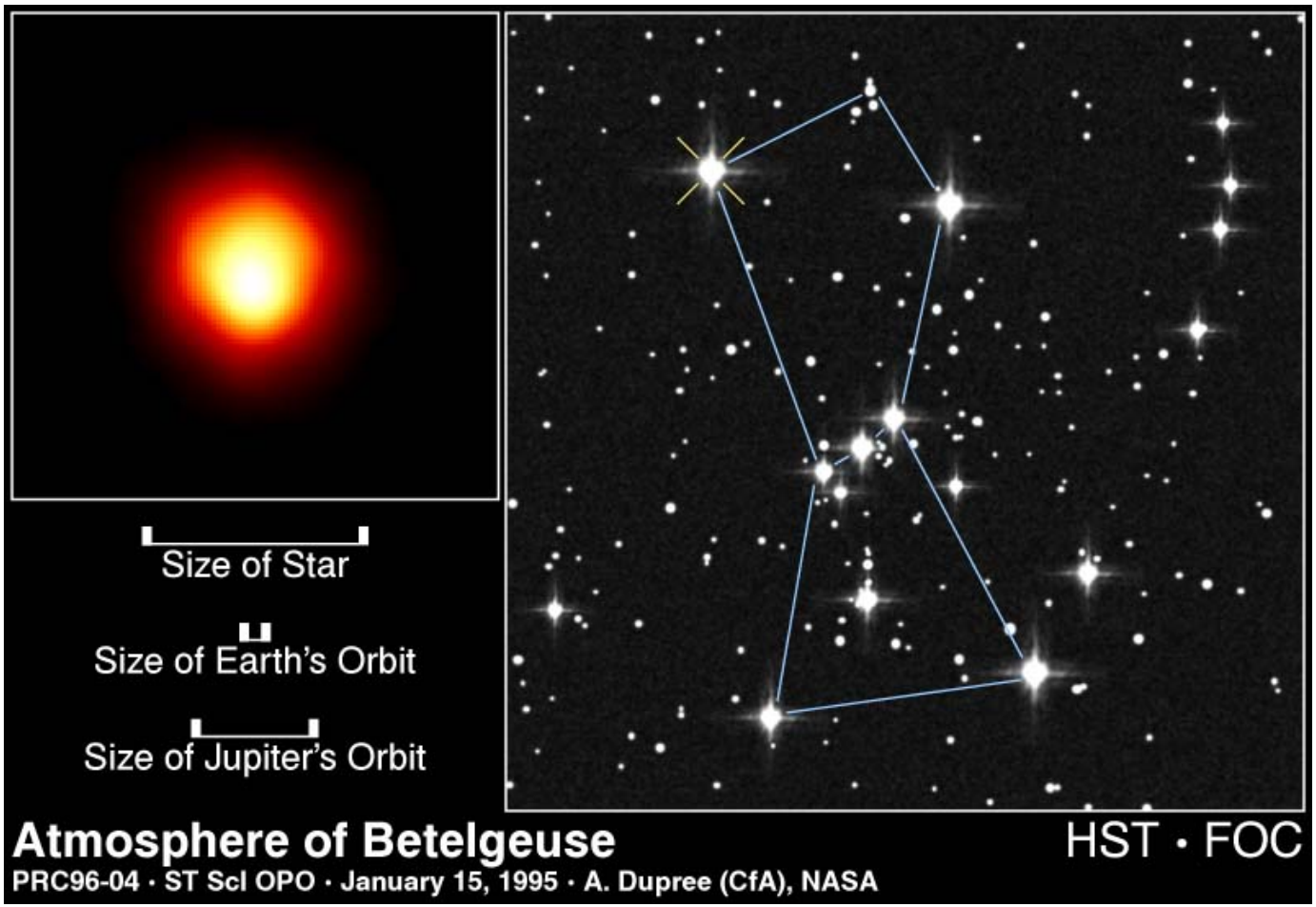
$$d_A = v(t_5 - t_2 + t_4 - t_3) \qquad (9.10)$$

$$d_B = v(t_5 - t_2 + t_4 + t_3) \qquad (9.11)$$

Note: requires extremely accurate photometry

Resulting radii are independent of distance

Stellar Angular Diameters



direct imaging:

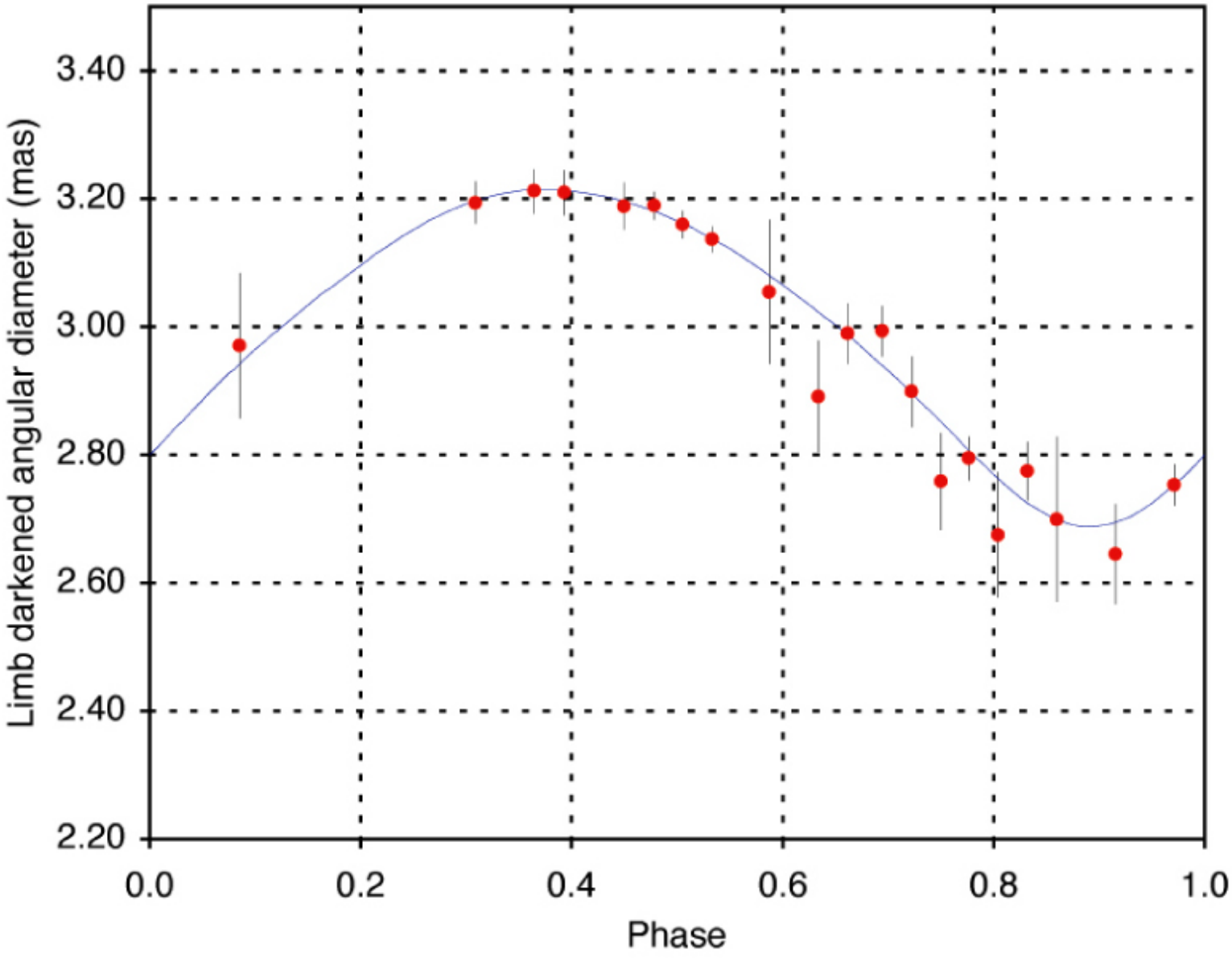
- requires very high resolution
- Betelgeuse: angular diameter: 54 mas
- distance needs to be known to determine the linear diameter



The Four Auxiliary Telescopes at Paranal

ESO PR Photo 51c/06 (22 December 2006)

© ESO

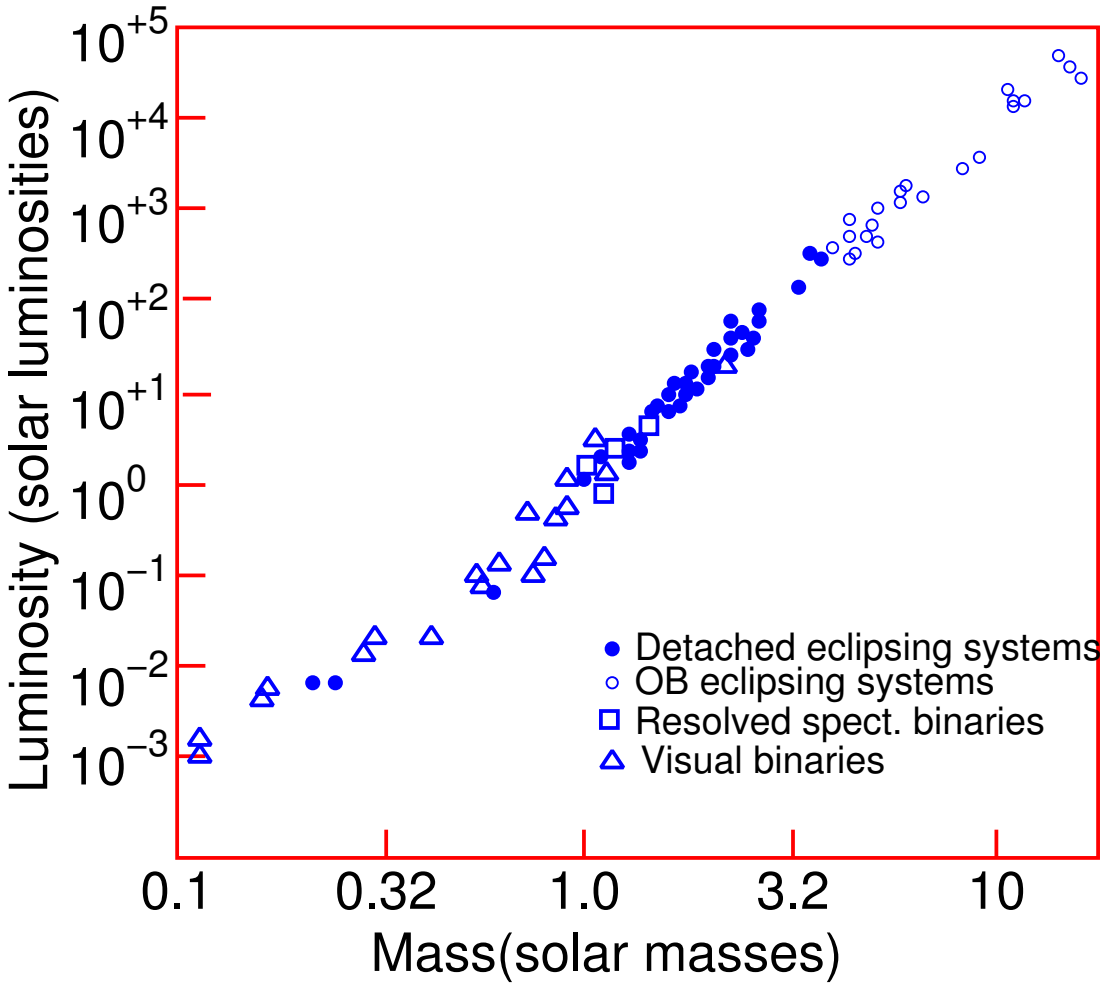


Pulsation of the Cepheid Star L Carinae
(VLTI + VINCI)

ESO PR Photo 30c/04 (29 October 2004)

© European Southern Observatory

Mass-Luminosity Relation



$\Longrightarrow$ determine mass-luminosity relationship

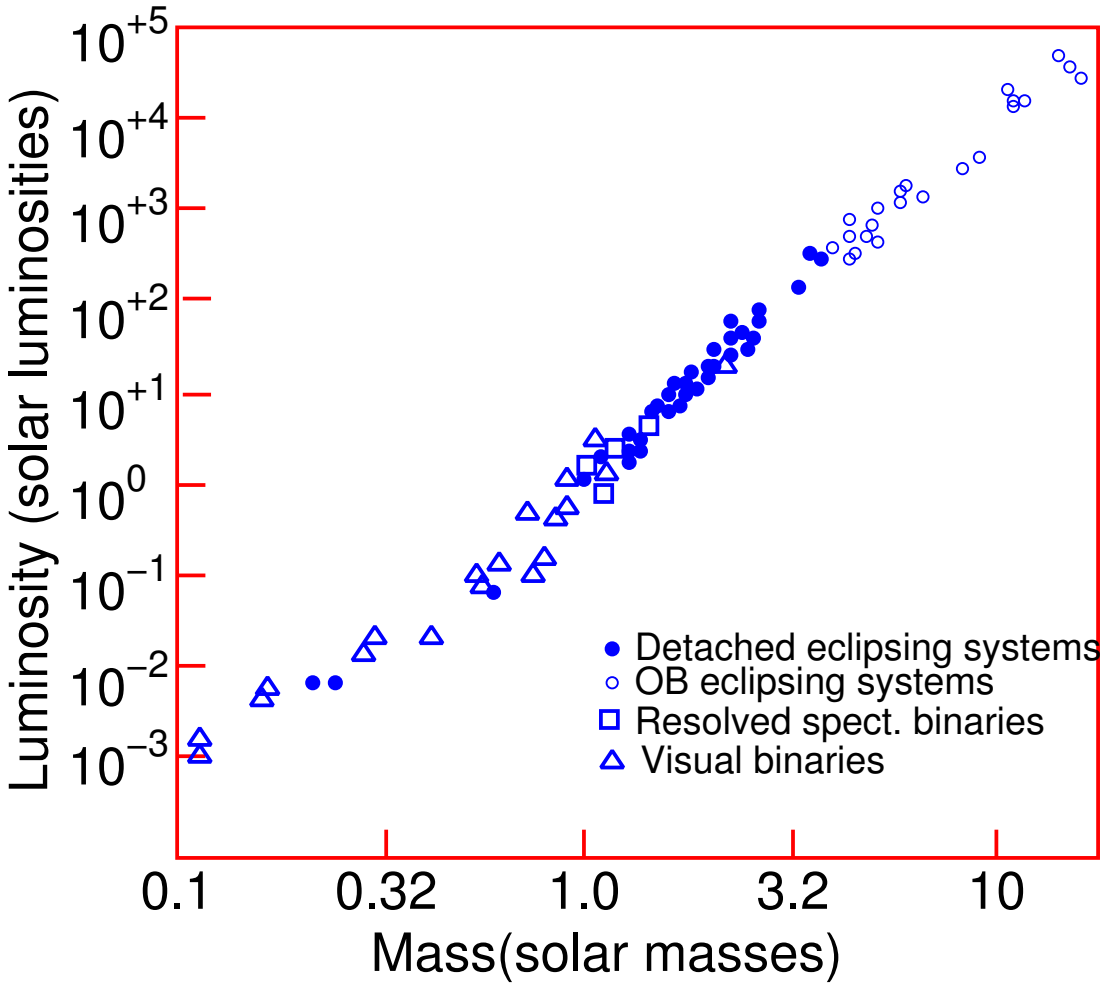
Masses and Radii of binary stars:

Radii R *and* temperatures T_{eff} give the luminosity:

$$L = 4\pi R^2 \sigma_{SB} T_{eff}^4 \qquad (9.12)$$

Mass measured from binaries

Mass-Luminosity Relation



Empirical result:

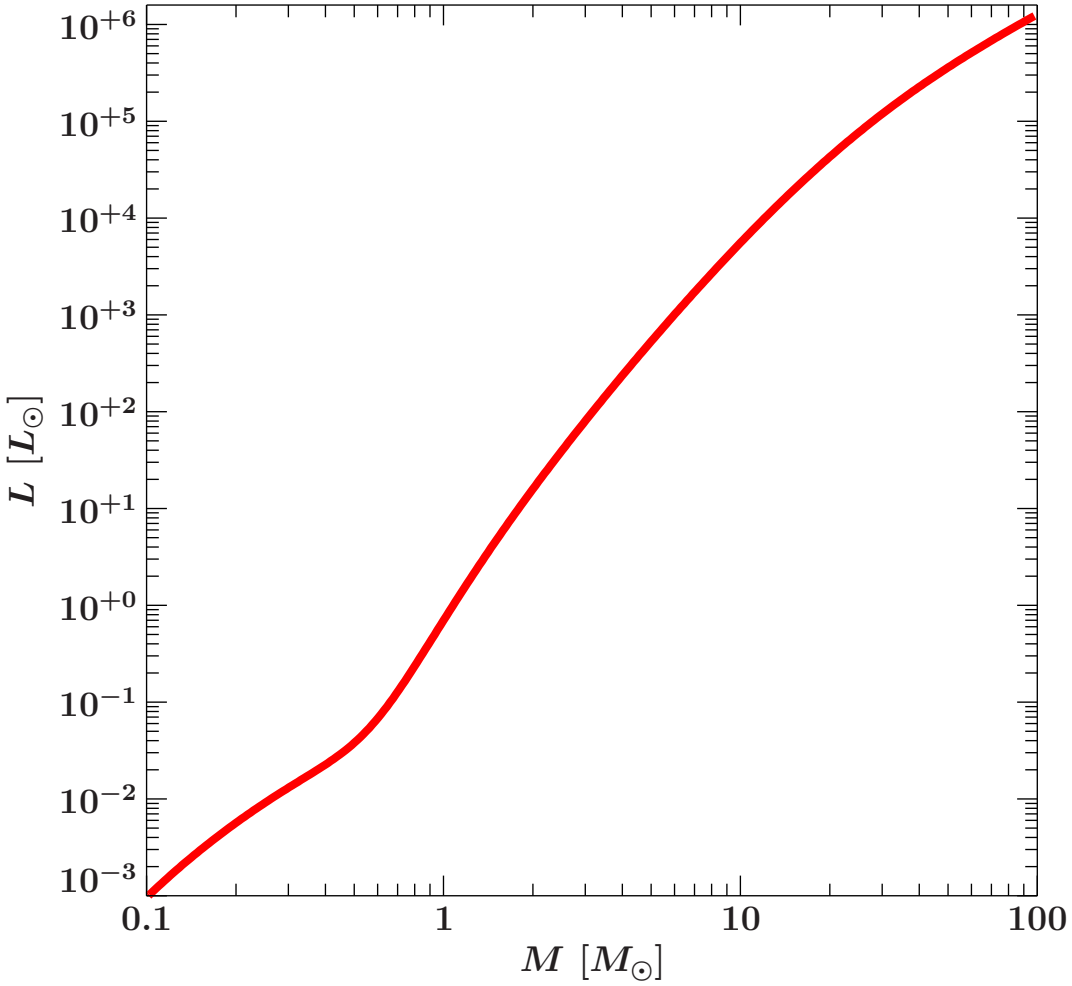
$$\frac{L}{L_\odot} = \begin{cases} 0.23 \left(\frac{M}{M_\odot}\right)^{2.3} & (M < 0.43\, M_\odot) \\ \left(\frac{M}{M_\odot}\right)^{4.0} & (M \geqslant 0.43\, M_\odot) \end{cases}$$

$\Longrightarrow$ more massive stars have extremely larger luminosities!
(factor 2 in M $\rightarrow$ factor 16 in L).
sometimes, one also sees $L \propto M^{3.3}$...

Direct consequence:

More massive stars live much shorter lives

Mass-Luminosity Relation



Empirical result:

$$\frac{L}{L_\odot} = \begin{cases} 0.23 \left(\frac{M}{M_\odot}\right)^{2.3} & (M < 0.43\,M_\odot) \\ \left(\frac{M}{M_\odot}\right)^{4.0} & (M \geqslant 0.43\,M_\odot) \end{cases}$$

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More massive stars live much shorter lives

Stars: Structure



The Sun: A typical star (ESA/NASA SOHO)

Stellar Structure

The structure of stars is defined by a set of four coupled differential equations which express the basic conservation and transport quantities always encountered in physics:

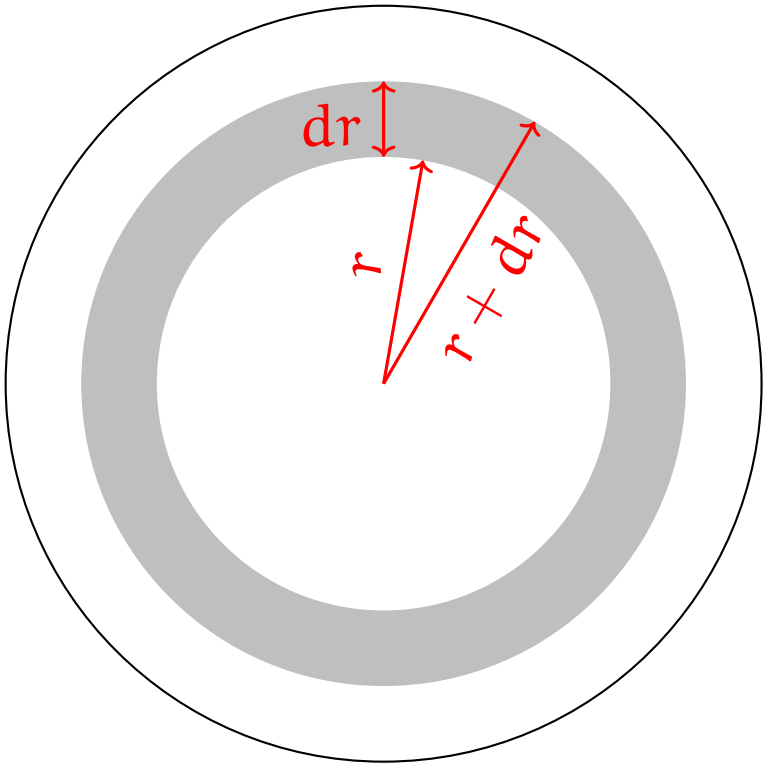
1. Mass conservation
2. Momentum conservation (=hydrostatic equilibrium)
3. Energy conservation
4. Energy transport

and quantities expressing the physical properties of material, mainly:

1. Energy generation
2. Equation of state (=dependence of density of material from physical conditions)

Mass Conservation

Density stratification of a star is defined through mass conservation:



Define M_r as the mass contained within radius r:

$$M(r) = M_r = \int_0^r 4\pi r^2 \rho(r)\, dr \qquad (8.1)$$

Thus the mass within a spherical shell is

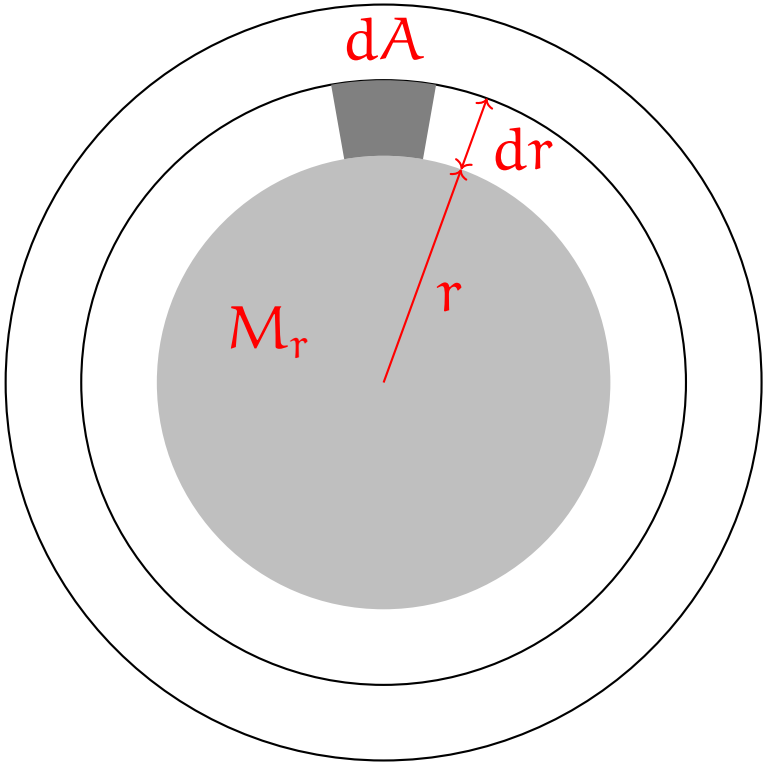
$$dM_r = 4\pi r^2 \rho\, dr \qquad (8.2)$$

and therefore

$$\frac{dM_r}{dr} = 4\pi r^2 \rho \qquad (8.3)$$

Hydrostatic Equilibrium

Pressure stratification of a star is defined through hydrostatic equilibrium:



Force on area A by slab of gas of area dA and density ρ:

$$dF_g = -\frac{GM_r dm}{r^2} = -\frac{GM_r \rho}{r^2} dA\, dr \qquad (8.4)$$

Bouyancy:

$$F_P = dA(P(r + \Delta r) - P(r)) = dA\Delta P \qquad (8.5)$$

Balance of forces:

$$-\frac{GM_r \rho}{r^2} dA\, dr = dP\, dA \qquad (8.6)$$

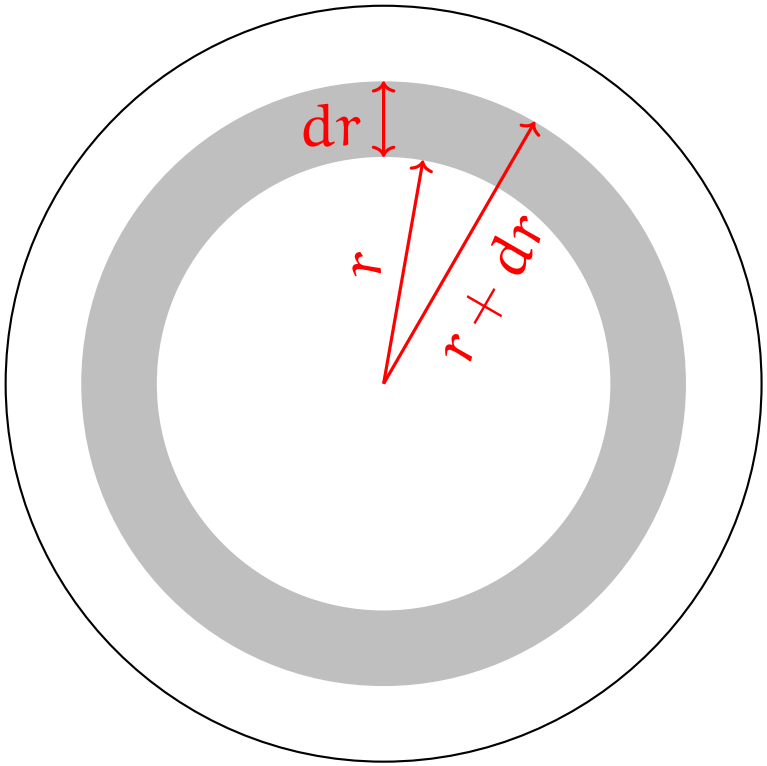
such that

$$\frac{dP}{dr} = -\rho(r)\frac{GM_r}{r^2} \qquad (8.7)$$

Note: in virtually all stars, hydrostatic equilibrium is the balance between graviation and the gas pressure. Radiation pressure or centrifugal forces are *not* important!

Energy Conservation

Temperature stratification of a star is defined through energy conservation:



Let ϵ = energy production coefficient, i.e., the energy released per time and unit mass.
Luminosity produced within a spherical shell is

$$dL_r = \epsilon dM_r = 4\pi r^2 \rho \epsilon \, dr \qquad (8.8)$$

and therefore

$$\frac{dL_r}{dr} = 4\pi r^2 \rho \epsilon \qquad (8.9)$$

Energy Transport

Energy is transported in stars by

- radiation
- convection
- conduction

In most stars, radiation and convection are important, conduction usually not.

Radiative Transport = diffusive process:

- radiation produced by nuclear fusion (γ-rays)
- mean free path l_{phot} of a photon in center of the sun: few cm
- photons do random walk to the stellar surface absorbed by ions and reemitted
- # of "scatterings": $N = (R/l_{phot})^2$: e.g., $R_\odot = 700000\,\mathrm{km}$: $N \approx 10^{20}$
- Diffusion theory:

$$\frac{dT}{dr} = -\frac{3}{4ac}\frac{\kappa(r)\rho(r)}{T^3}\frac{L(r)}{4\pi r^2} \tag{8.10}$$

Energy Transport



CXC/M. Weiss

Convection is much more difficult to deal with, no self-consistent hydrodynamical treatment, approximate (so called mixing-length) theory

$$\frac{dT}{dr} = \left(1 - \frac{1}{\gamma}\right) \frac{T}{P} \frac{dP}{dr} \tag{8.11}$$

Energy Transport

Stellar structure governed by four coupled differential equations:

Mass structure
(mass conservation)

$$\frac{dM}{dr} = 4\pi r^2 \rho(r)$$

Pressure structure
(hydrostatic equilibrium)

$$\frac{dP}{dr} = -\rho(r)\frac{GM(r)}{r^2}$$

Temperature structure
(e.g. radiative transfer)

$$\frac{dT}{dr} = -\frac{3}{4ac}\frac{\kappa\rho(r)}{T^3}\frac{L(r)}{4\pi r^2}$$

Energy conservation

$$\frac{dL}{dr} = 4\pi r^2 \rho(r)\epsilon(r)$$

plus "equation of state" ($P = P(T, \rho)$), Opacities $\kappa(T, \rho, Z)$ = interaction of radiation with gas, energy generation ($\epsilon = \epsilon(T, \rho, Z)$),...

Stellar model: numerical solution of stellar structure equations.

Overview

Main sequence: Nuclear fusion of Hydrogen into Helium:

$$4p \longrightarrow {}^4_2\mathrm{He} + E$$

How much energy is gained?

Particle physics: express mass as "rest energy equivalent" via $E = mc^2$

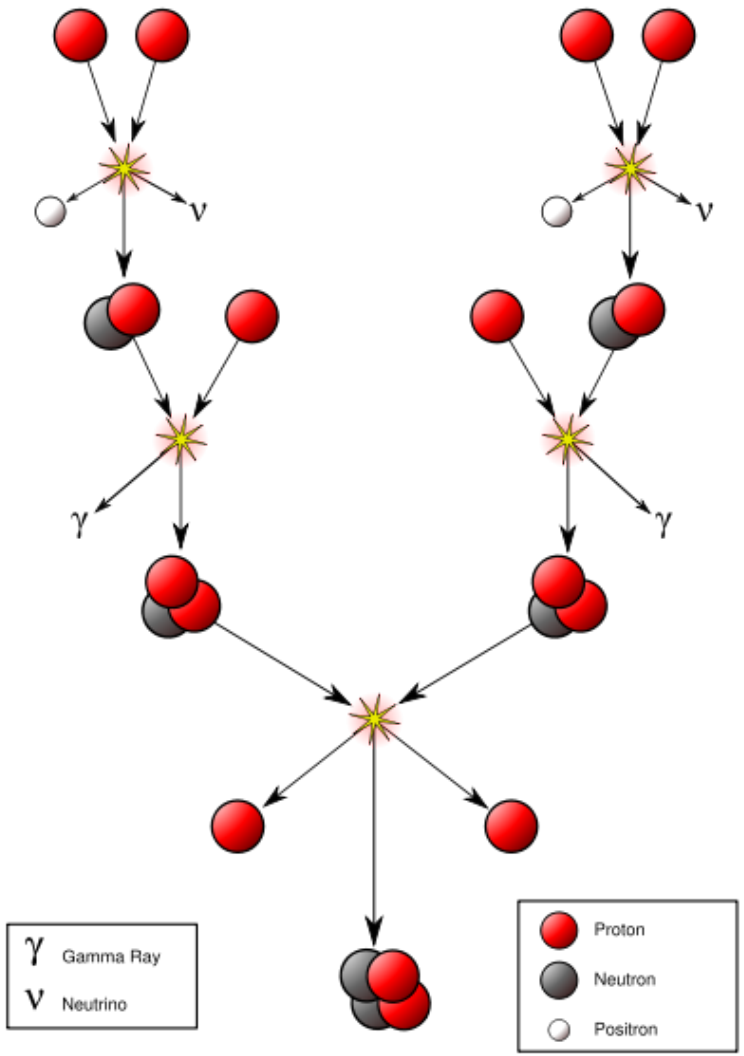
(and call it "mass"...); usually use energy units of MeV, $1\,\mathrm{MeV} = 1.602 \times 10^{-13}\,\mathrm{J}$

	mass of 4 protons ($4 \times 938\,\mathrm{MeV}$):	$3752\,\mathrm{MeV}$
$-$	mass of ${}^4_2\mathrm{He}$:	$3727\,\mathrm{MeV}$
	mass defect Δmc^2:	$25\,\mathrm{MeV}$

In the fusion of hydrogen to helium, 0.7% of the available rest mass energy is converted to energy.

Two main burning cycles: proton-proton chain and the CNO cycle.

Proton-Proton chain



For moderate central temperatures, He is produced using the proton proton chain.

First, two protons create a deuteron:

$$^1\mathrm{H} + {}^1\mathrm{H} \longrightarrow {}^2\mathrm{H} + \mathrm{e}^+ + \nu_\mathrm{e} \qquad (8.12)$$

This process is slow (happens once for a nucleon per 10^{10} years)
Then an additional proton is attached:

$$^2\mathrm{H} + {}^1\mathrm{H} \longrightarrow {}^3\mathrm{He} + \gamma \qquad (8.13)$$

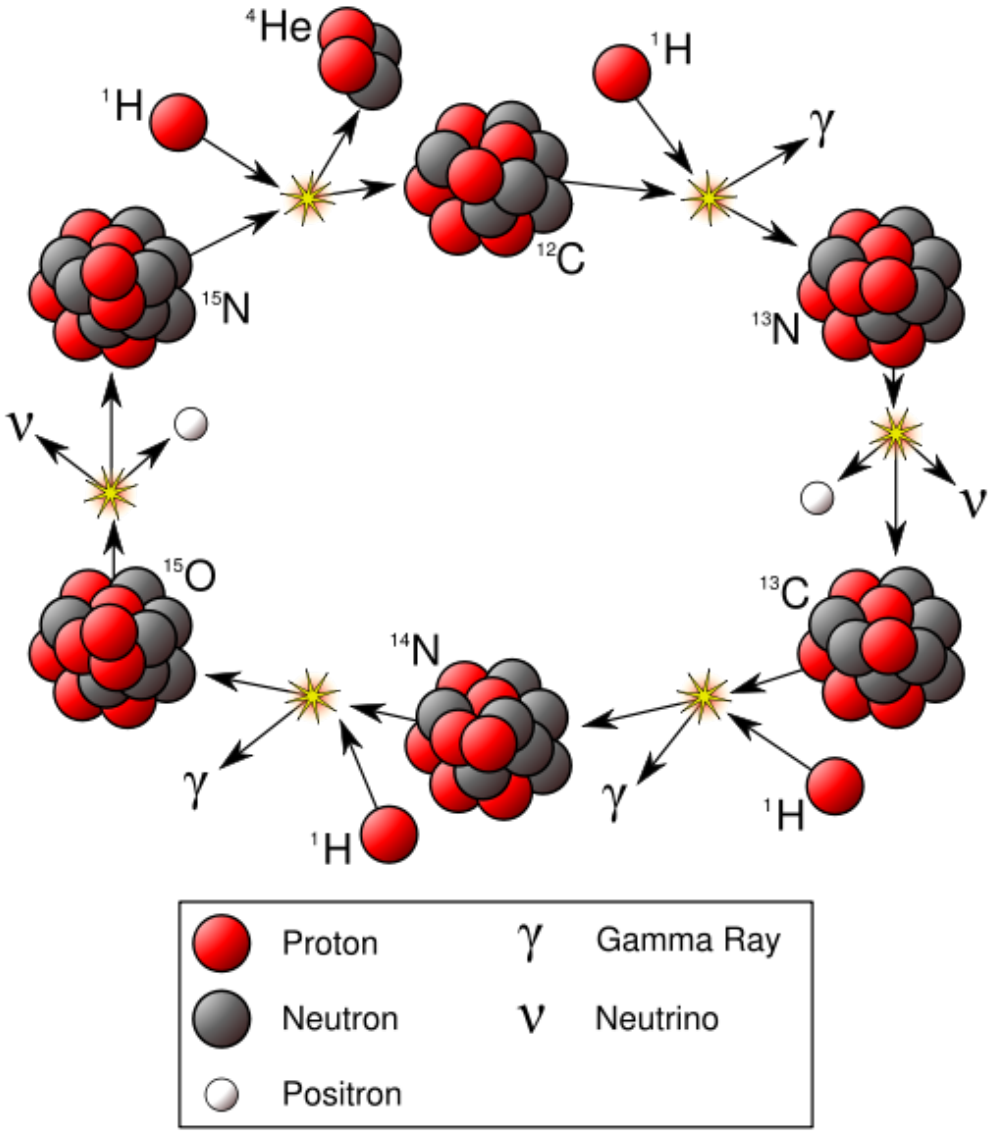
and two helium nuclei can form an alpha particle:

$$^3\mathrm{He} + {}^3\mathrm{He} \longrightarrow {}^4\mathrm{He} + 2\,{}^1\mathrm{H} \qquad (8.14)$$

This is the so called pp i-cycle, minor variations of the theme exist (pp ii, pp iii cycles), but pp i dominates.

pp chain dominates for $T \lesssim 2 \times 10^7$ K, $\epsilon_{pp} \propto T^5$; Sun: 98.4%.

CNO cycle



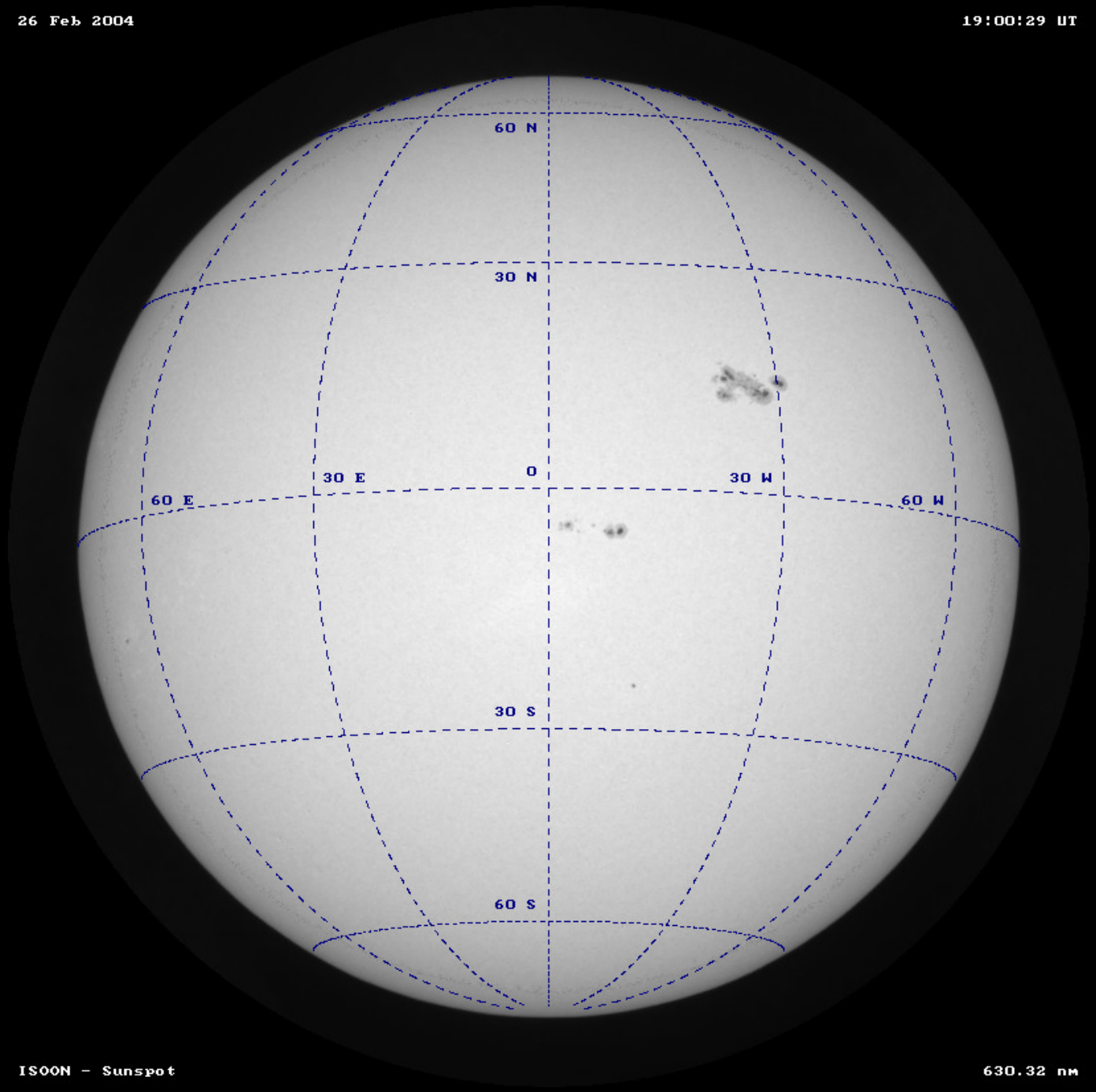
The CNO cycle (Bethe-Weizsäcker-cycle) requires the presence of C, N, and O isotopes as catalysts.

CNO cycle has slightly smaller energy release than pp-cycle because of higher neutrino losses.

Reaction $^{14}\mathrm{N} + \mathrm{p} \longrightarrow {}^{15}\mathrm{O} + \gamma$ is th slowest reaction (one million years).

CNO cycle dominates above 2×10^7 K, $\epsilon_{\mathrm{CNO}} \propto T^{17}$;
Sun: 1.6%.

Wikipedia


26 Feb 2004
19:00:29 UT
60 N
30 N
30 E
0
30 W
60 E
60 W
30 S
60 S
ISOON - Sunspot
630.32 nm

The Sun

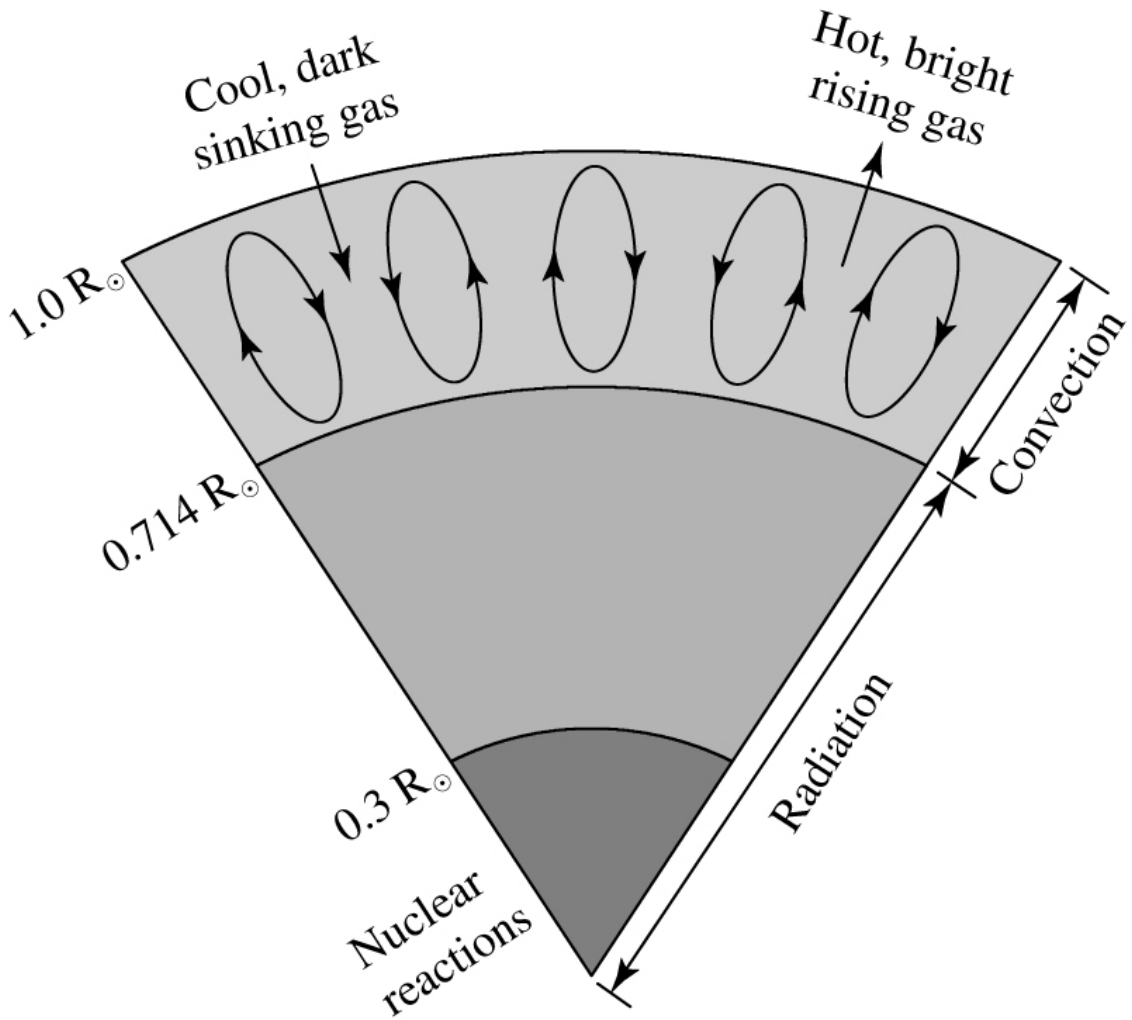
Solar Structure

Based on observations of

- Solar Mass: $1\,M_\odot = 1.997 \times 10^{30}\,\mathrm{kg} = 1.997 \times 10^{33}\,\mathrm{g}$
- Solar Luminosity: $1\,L_\odot = 3.846 \times 10^{26}\,\mathrm{W} = 3.846 \times 10^{33}\,\mathrm{erg\,s^{-1}}$
- age: $t = 4.5 \times 10^9$ yrs
- Solar chemical composition (=elemental abundances) at the surface: 73.81% H, 24.85% He, 1.34% metals (by mass)

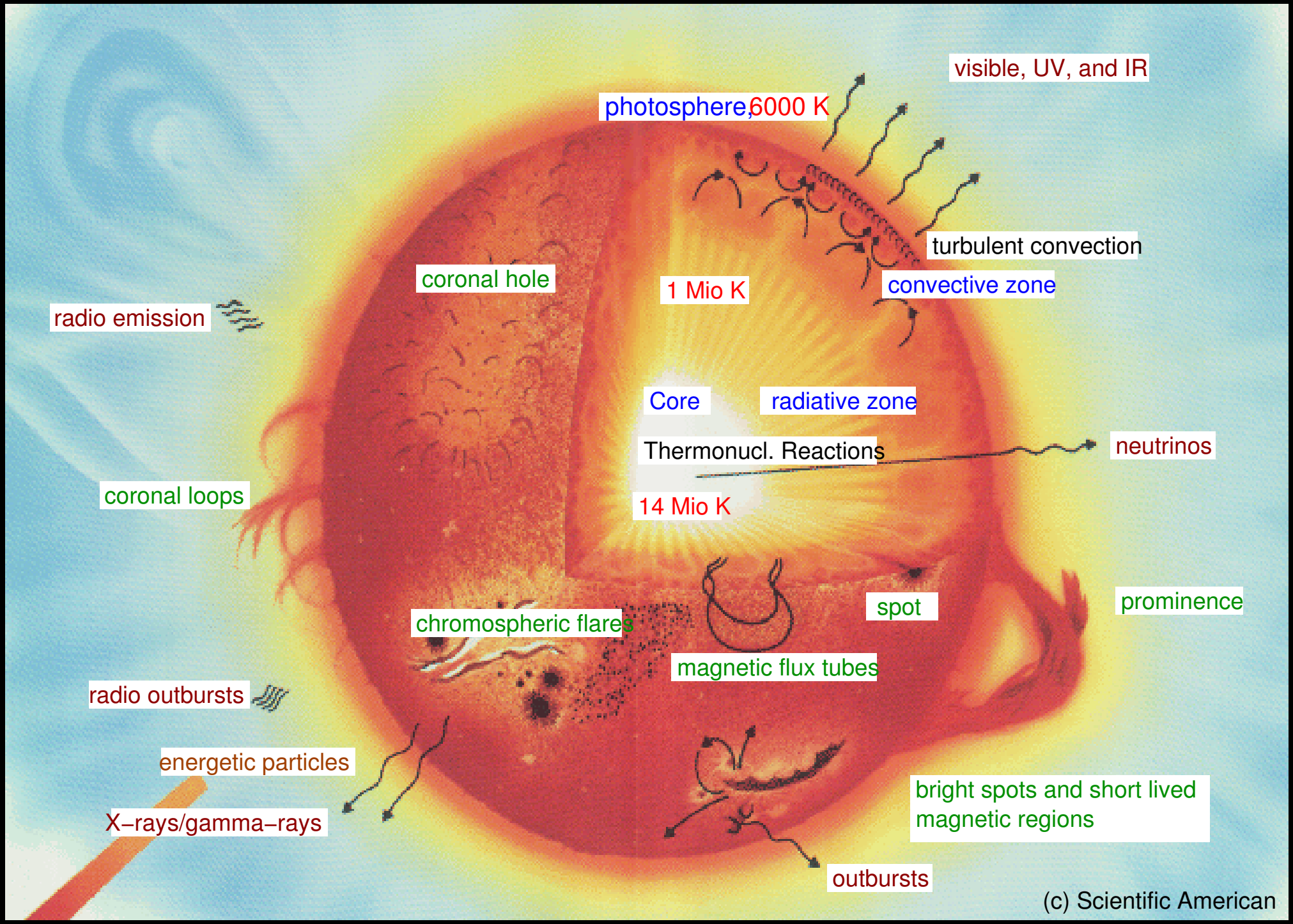
it is possible to use the equations of stellar structure to determine a model for the structure of the Sun, i.e., M_r, L_r, $\rho(r)$, $T(r)$, abundances(r) starting with a homogenous model and allow for 4.5 Gyrs of evolution.

Solar Structure

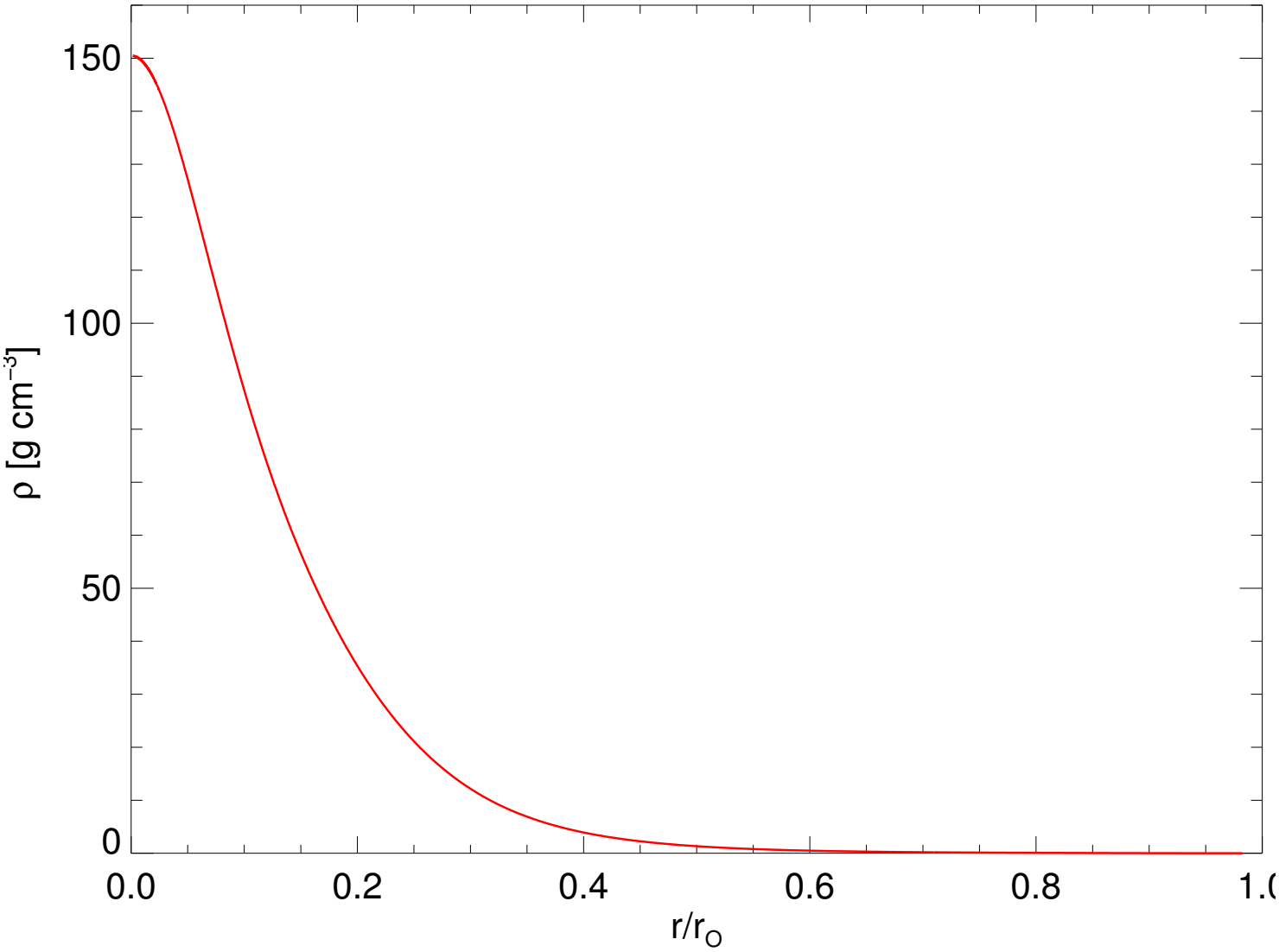


central conditions in the sun:

- $T_c = 1.57 \times 10^7\,\mathrm{K}$
- $P_c = 2.34 \times 10^{16}\,\mathrm{N\,m^{-2}}$
- $\rho_c = 1.53 \times 10^5\,\mathrm{kg\,m^{-3}}$
- Hydrogen fraction:
  $X = 0.34$ (by mass)
- Helium fraction:
  $Y = 0.64$ (by mass)

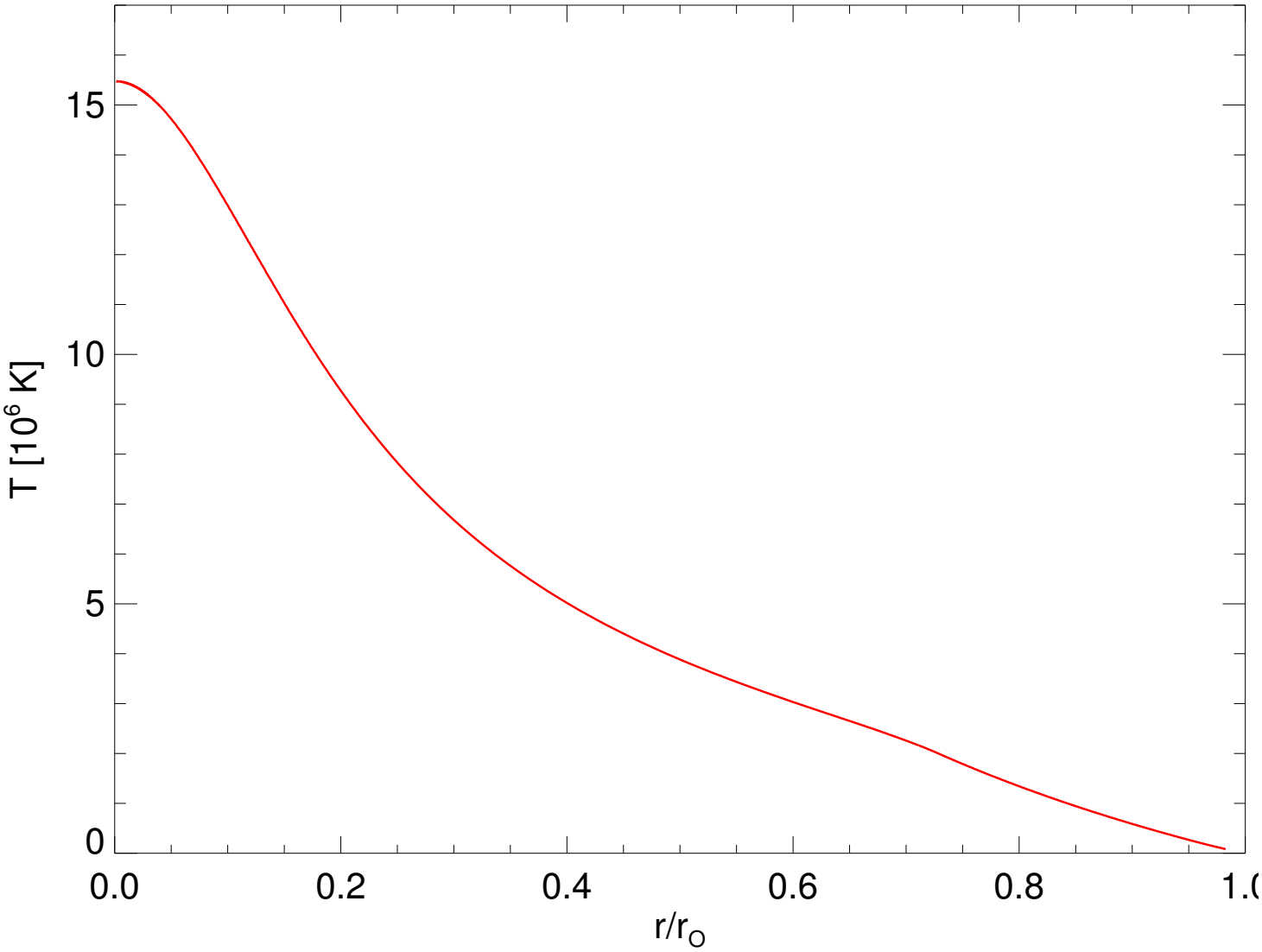

visible, UV, and IR
photosphere, 6000 K
turbulent convection
coronal hole
1 Mio K
convective zone
radio emission
Core
radiative zone
Thermonucl. Reactions
neutrinos
coronal loops
14 Mio K
spot
prominence
chromospheric flares
magnetic flux tubes
radio outbursts
energetic particles
bright spots and short lived magnetic regions
X–rays/gamma–rays
outbursts
(c) Scientific American

Standard Solar Model



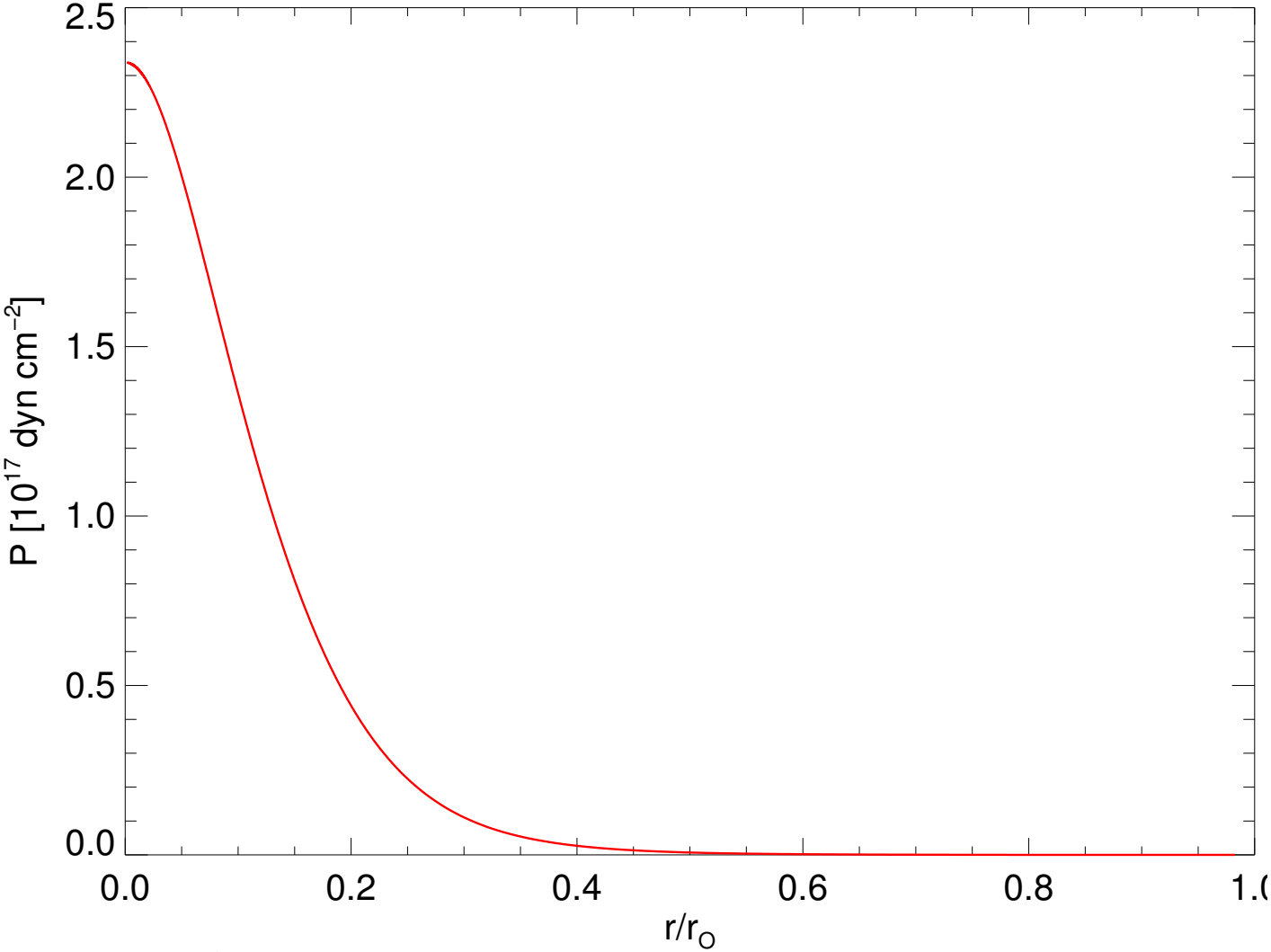
Standard solar model of Bahcall & Serenelli (2005, ApJ 626, 530)

Standard Solar Model



Standard solar model of Bahcall & Serenelli (2005, ApJ 626, 530)

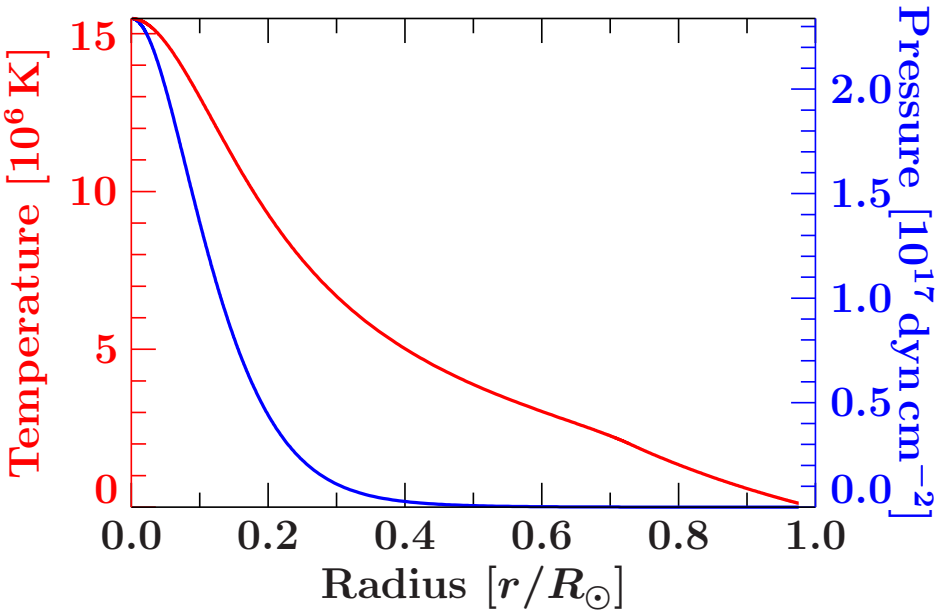
Standard Solar Model



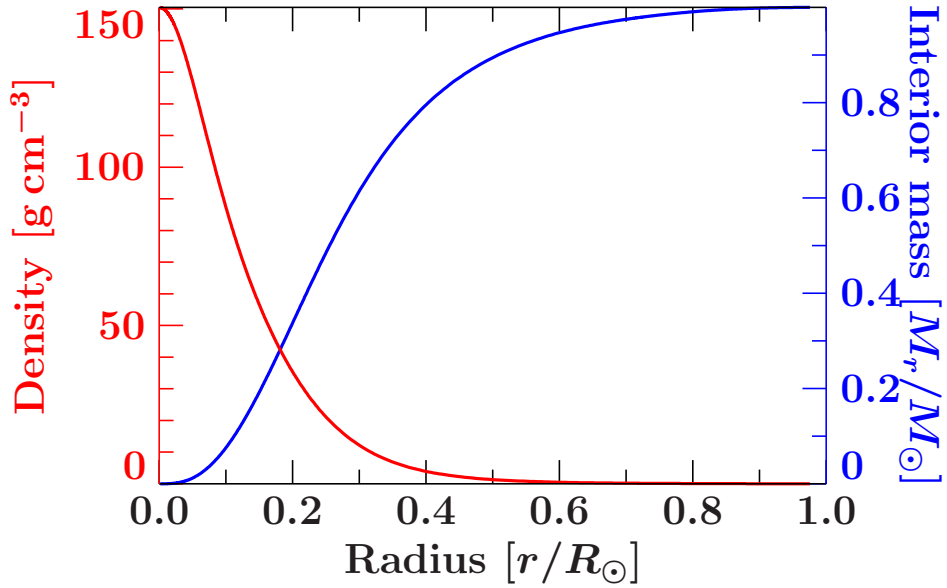
Standard solar model of Bahcall & Serenelli (2005, ApJ 626, 530; 1 dyn $=$ 10^{-5} N, 1 dyn cm^{-2} $=$ 0.1 Pa)

Standard Solar Model

Standard solar model:



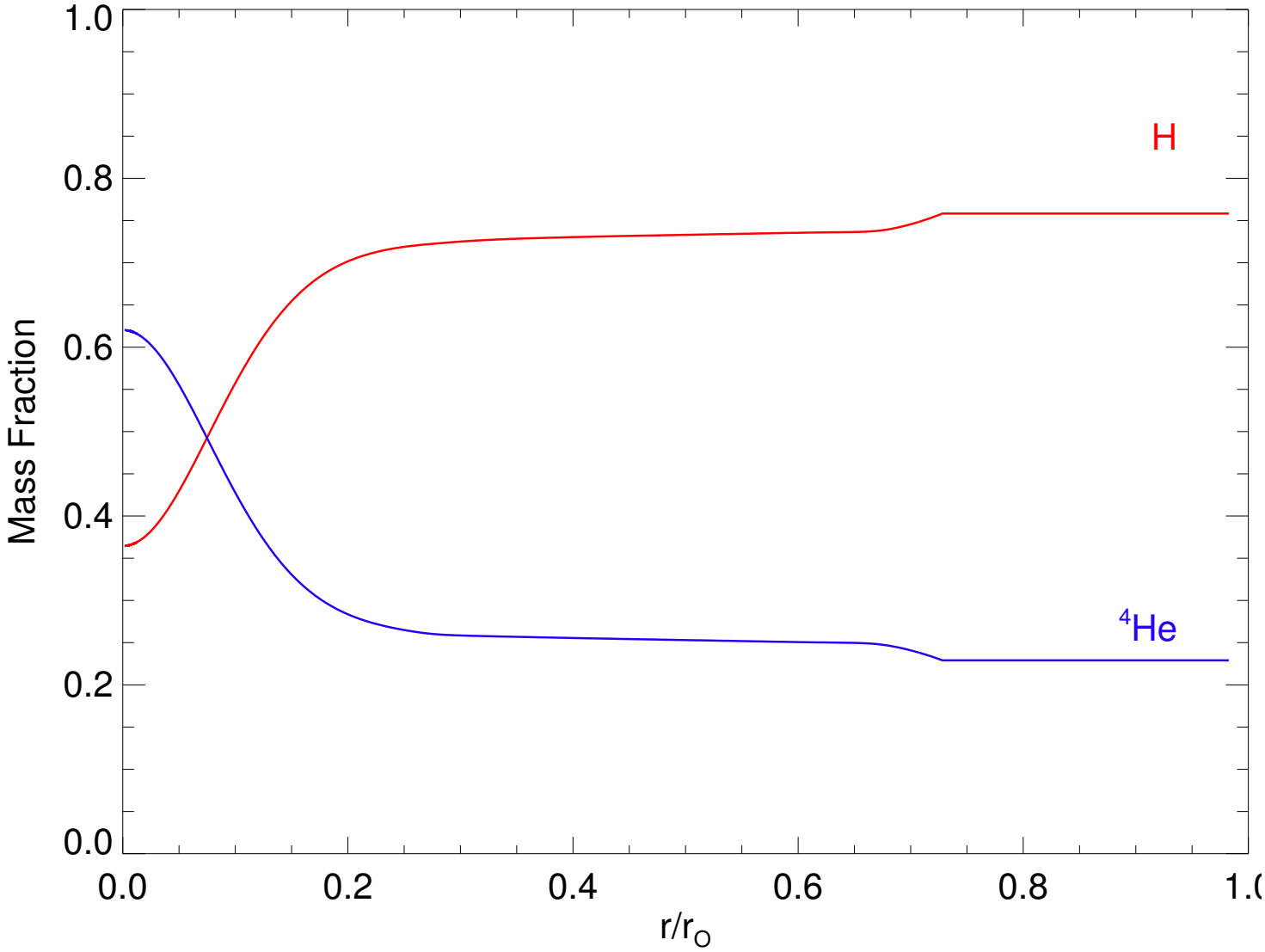
Temperature & pressure profile



Density & interior mass profile

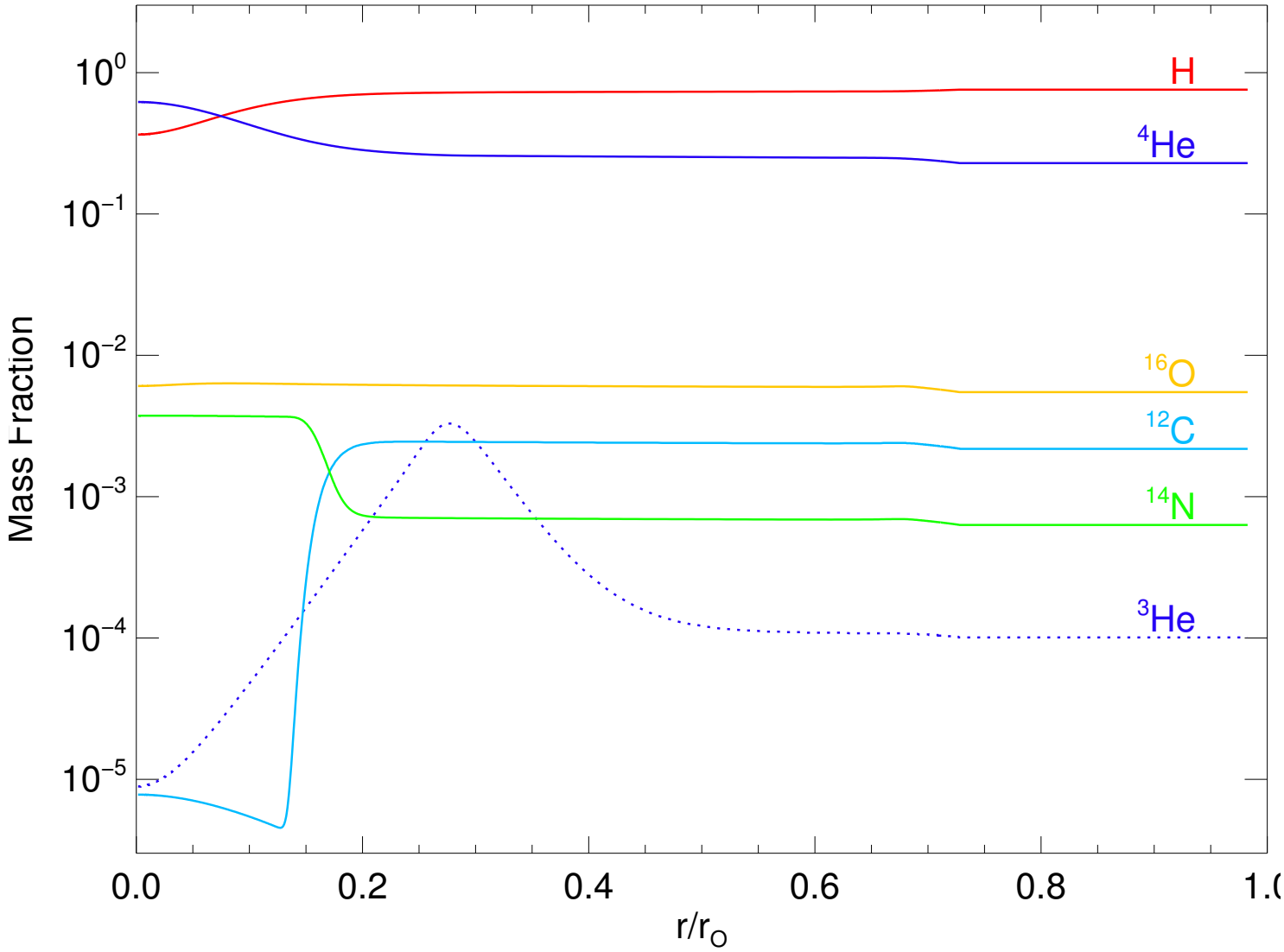
Values from Bahcall, Pinsonneault & Basu (ApJ 555,990, 2001)

Standard Solar Model



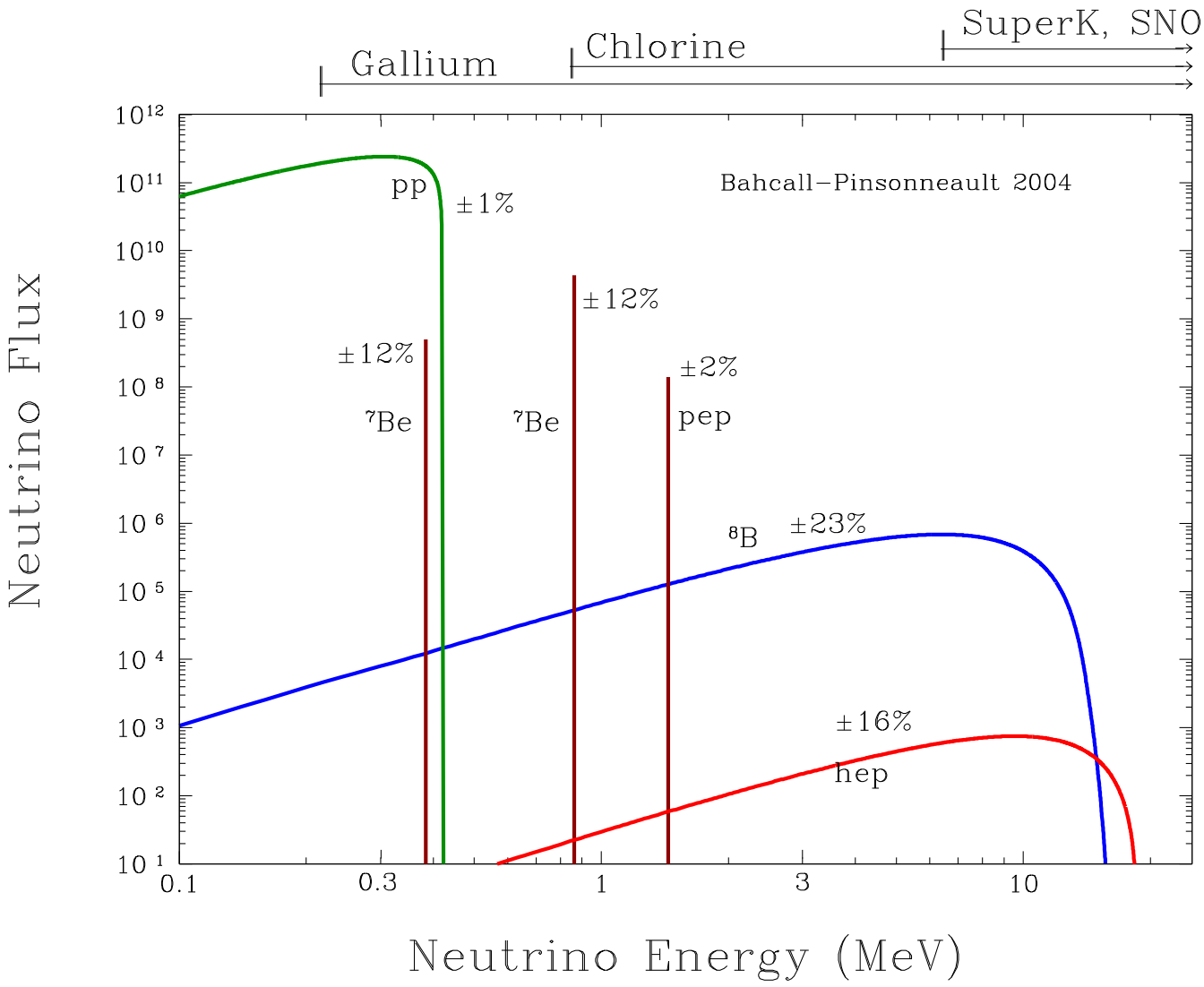
Standard solar model of Bahcall & Serenelli (2005, ApJ 626, 530)

Standard Solar Model



Standard solar model of Bahcall & Serenelli (2005, ApJ 626, 530)

Solar Neutrinos



after Bahcall

The solar model predicts a solar neutrino spectrum that can be compared with Earth based measurements. This is the most direct test of theory of stellar structure known.

Problem: Neutrinos are difficult to detect since their interaction cross section is *very small*

$\Longrightarrow$ large detectors are needed.



The first neutrino experiment in the Homestake mine (J. Davis et al., 1968ff.).

Based on reaction

$$\nu_e + {}^{37}\mathrm{Cl} \longrightarrow {}^{37}\mathrm{Ar} + e^-$$

Use Chlorine in large tetrachloroethylene tank (615 T), detect Ar with radiochemical methods.

Sensitive for electron neutrinos at energies above ~0.8 MeV, which are rare.

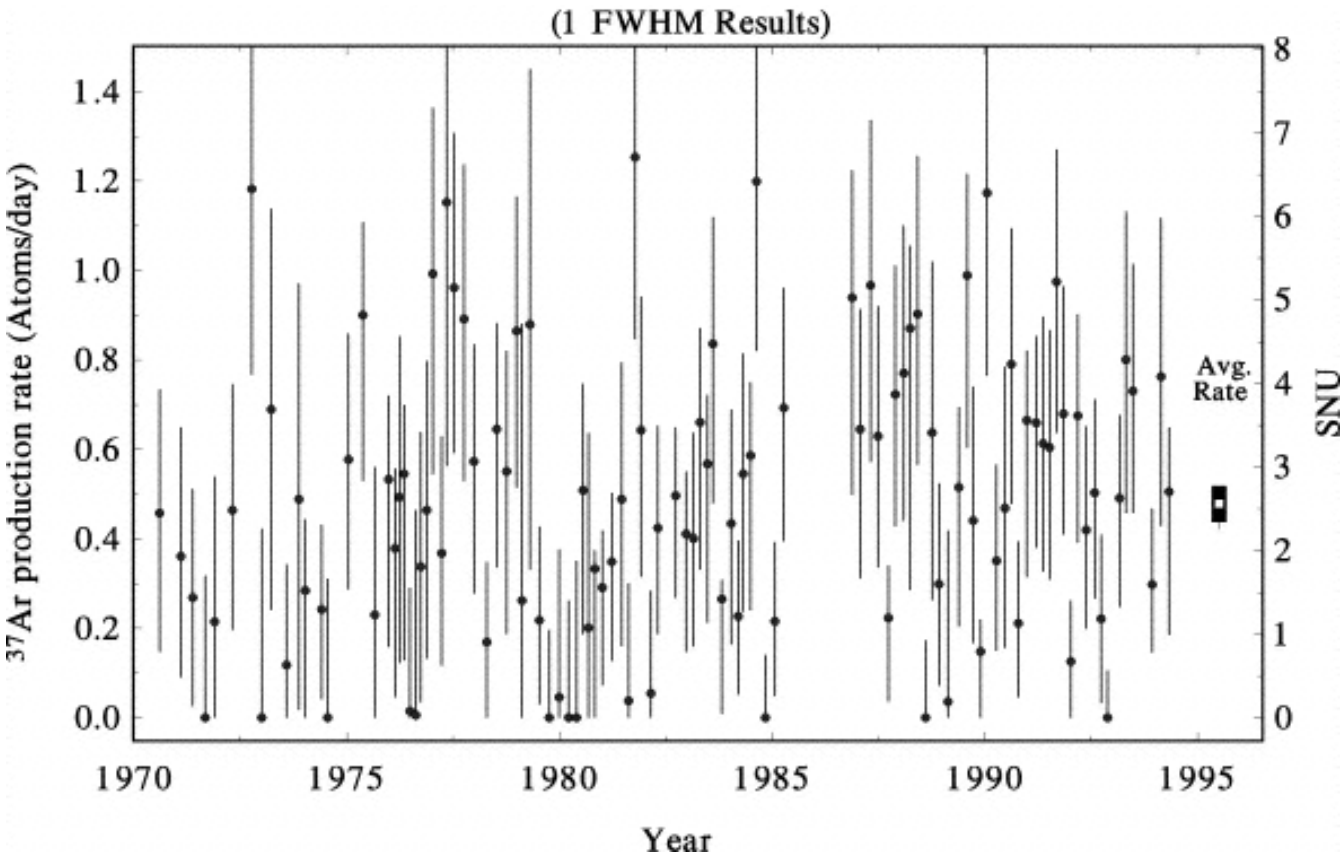
Expected rate: 8.5 ± 1.9 SNU

Detected rate: 2.6 ± 0.2 SNU

1 SNU: 10^{-37} captures target atom^{-1} s^{-1}.

Brookhaven National Laboratory

Solar Neutrinos



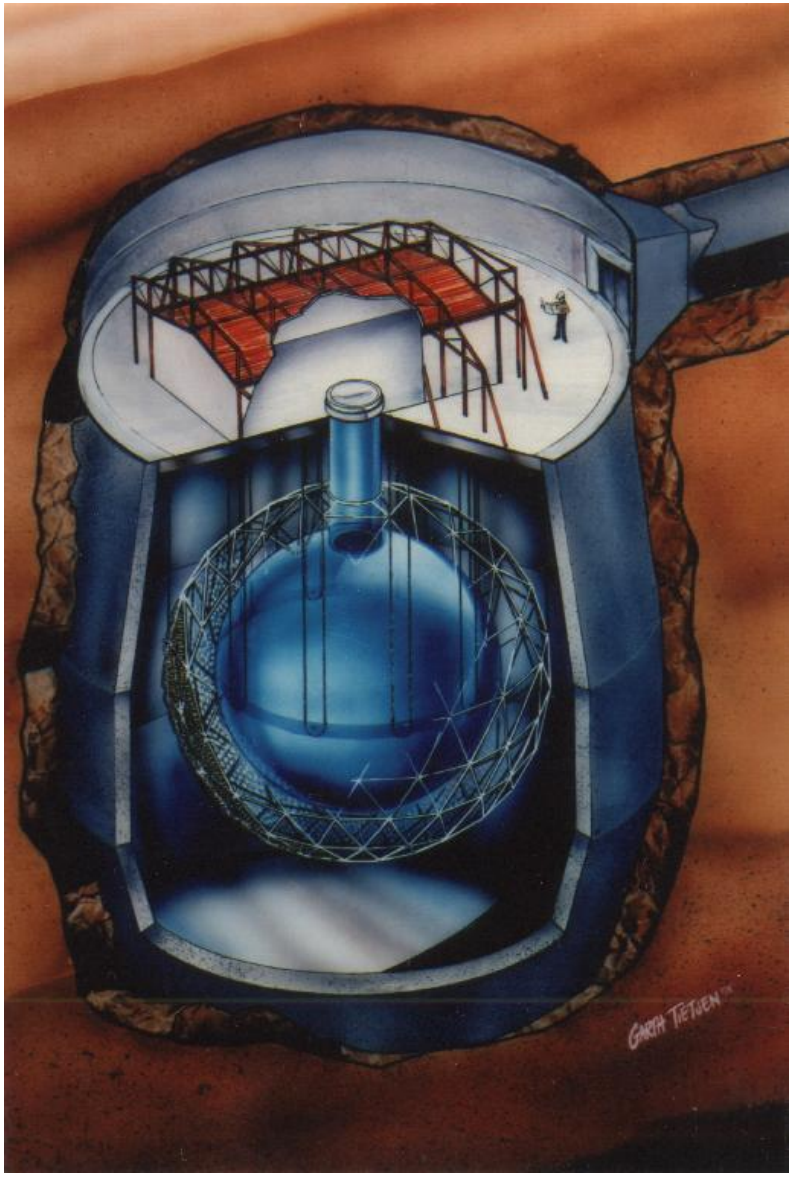
Cleveland et al. (1998, ApJ 596, 505; a total of 875 ^{37}Ar atoms were detected in the experiment, 766 of which were solar)

Low flux from early Homestake runs was confirmed in the early 1990s by Kamiokande.

Solar Neutrino Problem: Solar neutrino flux is ~ 1/3 of predicted neutrino flux.

Most particle physicists believed that reason for the solar neutrino problem is that the standard solar model is wrong. They were wrong.

Solar Neutrinos



Sudbury Neutrino Observatory: uses 1000 T of heavy water, i.e., D_2O, 2000 m below ground.

Possible neutrino reactions:

charged current: $\nu_e + D \rightarrow p + p + e^- - 1.442\,\text{MeV}$

neutral current: $\nu + D \rightarrow p + n + \nu - 2.224\,\text{MeV}$

elastic scattering: $\nu + e^- \rightarrow \nu + e^- - 2.224\,\text{MeV}$

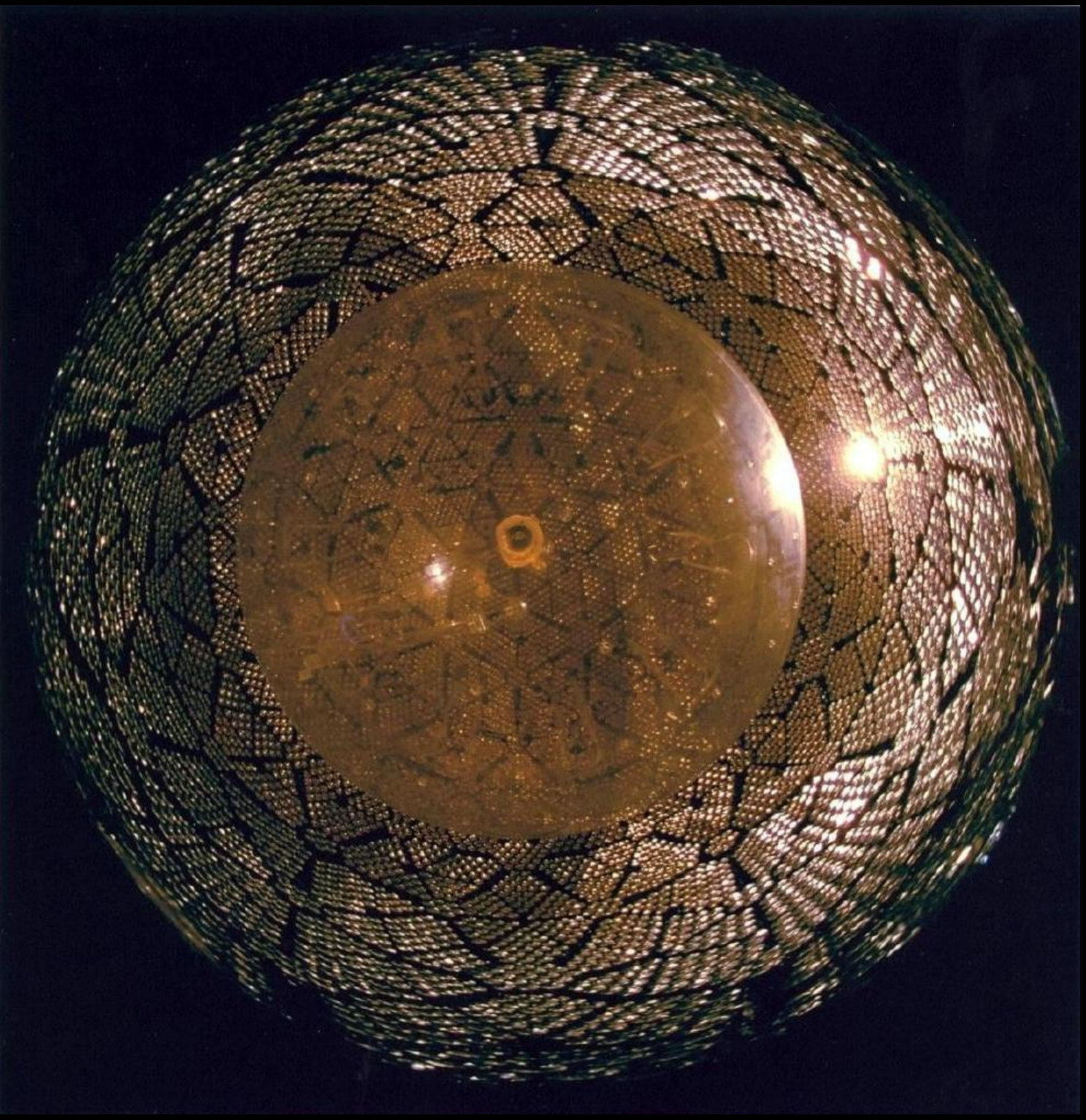
The neutral current reaction is sensitive to *any* flavor of neutrino.

SNO detects ~5000 neutrino events per year.

courtesy SNO



courtesy SNO



Acrylic vessel surrounded by photomultiplier tubes.

View through fisheye lens.

courtesy SNO

Measurement of the Rate of $\nu_e + d \rightarrow p + p + e^-$ Interactions Produced by ^{8}B Solar Neutrinos at the Sudbury Neutrino Observatory

Q. R. Ahmad,[15] R. C. Allen,[11] T. C. Andersen,[12] J. D. Anglin,[7] G. Bühler,[11] J. C. Barton,[13,*] E. W. Beier,[14] M. Bercovitch,[7] J. Bigu,[4] S. Biller,[13] R. A. Black,[13] I. Blevis,[3] R. J. Boardman,[13] J. Boger,[2] E. Bonvin,[9] M. G. Boulay,[9] M. G. Bowler,[13] T. J. Bowles,[6] S. J. Brice,[6,13] M. C. Browne,[15] T. V. Bullard,[15] T. H. Burritt,[15,6] K. Cameron,[12] J. Cameron,[13] Y. D. Chan,[5] M. Chen,[9] H. H. Chen,[11,†] X. Chen,[5,13] M. C. Chon,[12] B. T. Cleveland,[13] E. T. H. Clifford,[9,1] J. H. M. Cowan,[4] D. F. Cowen,[14] G. A. Cox,[15] Y. Dai,[9] X. Dai,[13] F. Dalnoki-Veress,[3] W. F. Davidson,[7] P. J. Doe,[15,11,6] G. Doucas,[13] M. R. Dragowsky,[6,5] C. A. Duba,[15] F. A. Duncan,[9] J. Dunmore,[13] E. D. Earle,[9,1] S. R. Elliott,[15,6] H. C. Evans,[9] G. T. Ewan,[9] J. Farine,[3] H. Fergani,[13] A. P. Ferraris,[13] R. J. Ford,[9] M. M. Fowler,[6] K. Frame,[13] E. D. Frank,[14] W. Frati,[14] J. V. Germani,[15,6] S. Gil,[10] A. Goldschmidt,[6] D. R. Grant,[3] R. L. Hahn,[2] A. L. Hallin,[9] E. D. Hallman,[4] A. Hamer,[6,9] A. A. Hamian,[15] R. U. Haq,[4] C. K. Hargrove,[3] P. J. Harvey,[9] R. Hazama,[15] R. Heaton,[9] K. M. Heeger,[15] W. J. Heintzelman,[14] J. Heise,[10] R. L. Helmer,[10,‡] J. D. Hepburn,[9,1] H. Heron,[13] J. Hewett,[4] A. Hime,[6] M. Howe,[15] J. G. Hykawy,[4] M. C. P. Isaac,[5] P. Jagam,[12] N. A. Jelley,[13] C. Jillings,[9] G. Jonkmans,[4,1] J. Karn,[12] P. T. Keener,[14] K. Kirch,[6] J. R. Klein,[14] A. B. Knox,[13] R. J. Komar,[10,9] R. Kouzes,[8] T. Kutter,[10] C. C. M. Kyba,[14] J. Law,[12] I. T. Lawson,[12] M. Lay,[13] H. W. Lee,[9] K. T. Lesko,[5] J. R. Leslie,[9] I. Levine,[3] W. Locke,[13] M. M. Lowry,[8] S. Luoma,[4] J. Lyon,[13] S. Majerus,[13] H. B. Mak,[9] A. D. Marino,[5] N. McCauley,[13] A. B. McDonald,[9,8] D. S. McDonald,[14] K. McFarlane,[3] G. McGregor,[13] W. McLatchie,[9] R. Meijer Drees,[15] H. Mes,[3] C. Mifflin,[3] G. G. Miller,[6] G. Milton,[1] B. A. Moffat,[9] M. Moorhead,[13,5] C. W. Nally,[10] M. S. Neubauer,[14] F. M. Newcomer,[14] H. S. Ng,[10] A. J. Noble,[3,‡] E. B. Norman,[5] V. M. Novikov,[3] M. O'Neill,[3] C. E. Okada,[5] R. W. Ollerhead,[12] M. Omori,[13] J. L. Orrell,[15] S. M. Oser,[14] A. W. P. Poon,[5,6,10,15] T. J. Radcliffe,[9] A. Roberge,[4] B. C. Robertson,[9] R. G. H. Robertson,[15,6] J. K. Rowley,[2] V. L. Rusu,[14] E. Saettler,[4] K. K. Schaffer,[15] A. Schuelke,[5] M. H. Schwendener,[4] H. Seifert,[4,6,15] M. Shatkay,[3] J. J. Simpson,[12] D. Sinclair,[3] P. Skensved,[9] A. R. Smith,[5] M. W. E. Smith,[15] N. Starinsky,[3] T. D. Steiger,[15] R. G. Stokstad,[5] R. S. Storey,[7,†] B. Sur,[1,9] R. Tafirout,[4] N. Tagg,[12] N. W. Tanner,[13] R. K. Taplin,[13] M. Thorman,[13] P. Thornewell,[6,13,15] P. T. Trent,[13,*] Y. I. Tserkovnyak,[10] R. Van Berg,[14] R. G. Van de Water,[14,6] C. J. Virtue,[4] C. E. Waltham,[10] J.-X. Wang,[12] D. L. Wark,[13,6,§] N. West,[13] J. B. Wilhelmy,[6] J. F. Wilkerson,[15,6] J. Wilson,[13] P. Wittich,[14] J. M. Wouters,[6] and M. Yeh[2]

(SNO Collaboration)

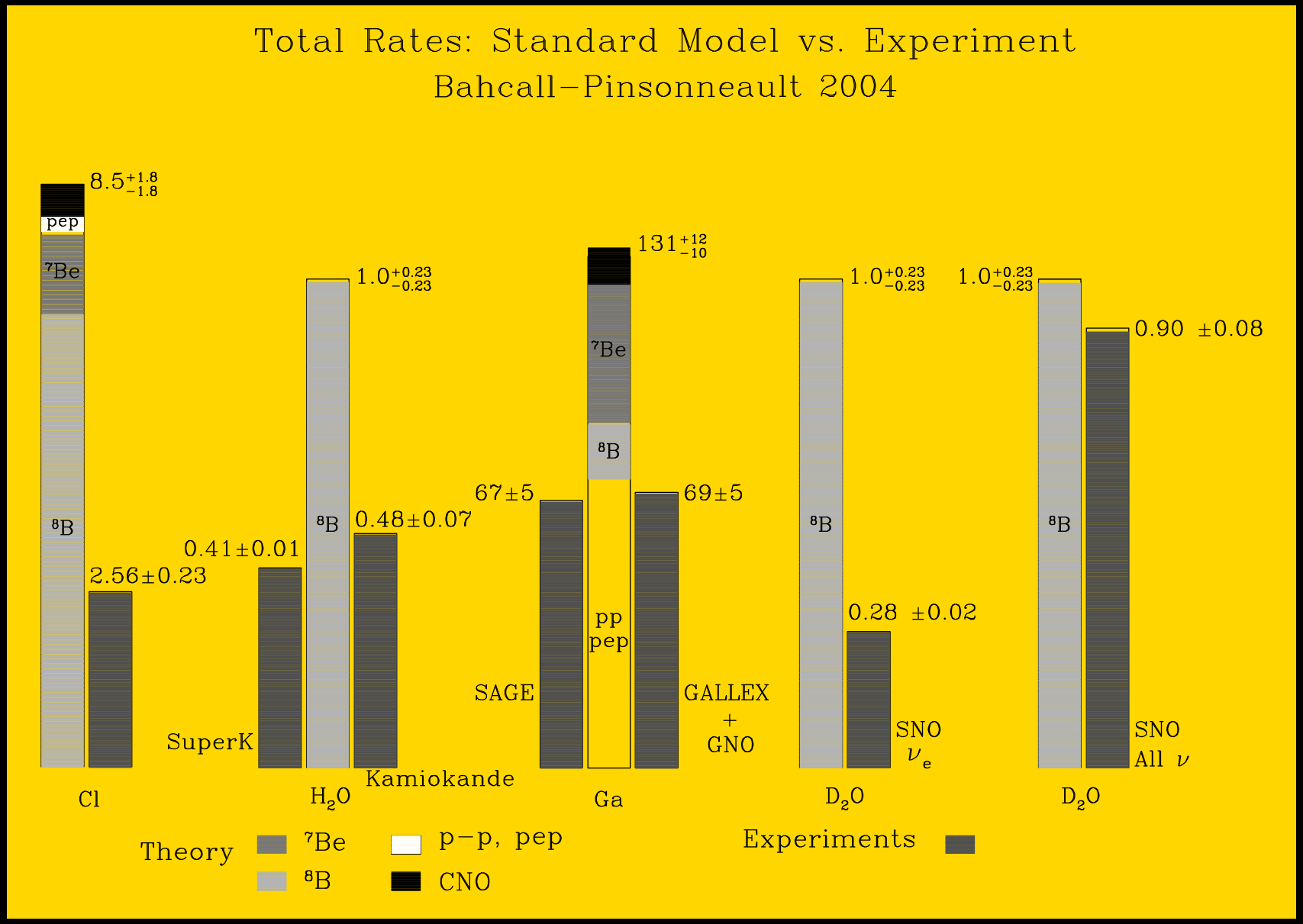
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[13]*Nuclear and Astrophysics Laboratory, University of Oxford, Keble Road, Oxford, OX1 3RH, United Kingdom*
[14]*Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania 19104-6396*
[15]*Center for Experimental Nuclear Physics and Astrophysics, and Department of Physics, University of Washington, Seattle, Washington 98195*

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Solar neutrinos from ^{8}B decay have been detected at the Sudbury Neutrino Observatory via the charged current (CC) reaction on deuterium and the elastic scattering (ES) of electrons. The flux of ν_e's is measured by the CC reaction rate to be $\phi^{\mathrm{CC}}(\nu_e) = 1.75 \pm 0.07(\mathrm{stat})^{+0.12}_{-0.11}(\mathrm{syst}) \pm 0.05(\mathrm{theor}) \times 10^6\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. Comparison of $\phi^{\mathrm{CC}}(\nu_e)$ to the Super-Kamiokande Collaboration's precision value of the flux inferred from the ES reaction yields a 3.3σ difference, assuming the systematic uncertainties are normally distributed, providing evidence of an active non-ν_e component in the solar flux. The total flux of active ^{8}B neutrinos is determined to be $5.44 \pm 0.99 \times 10^6\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.

DOI: 10.1103/PhysRevLett.87.071301 PACS numbers: 26.65.+t, 14.60.Pq, 95.85.Ry

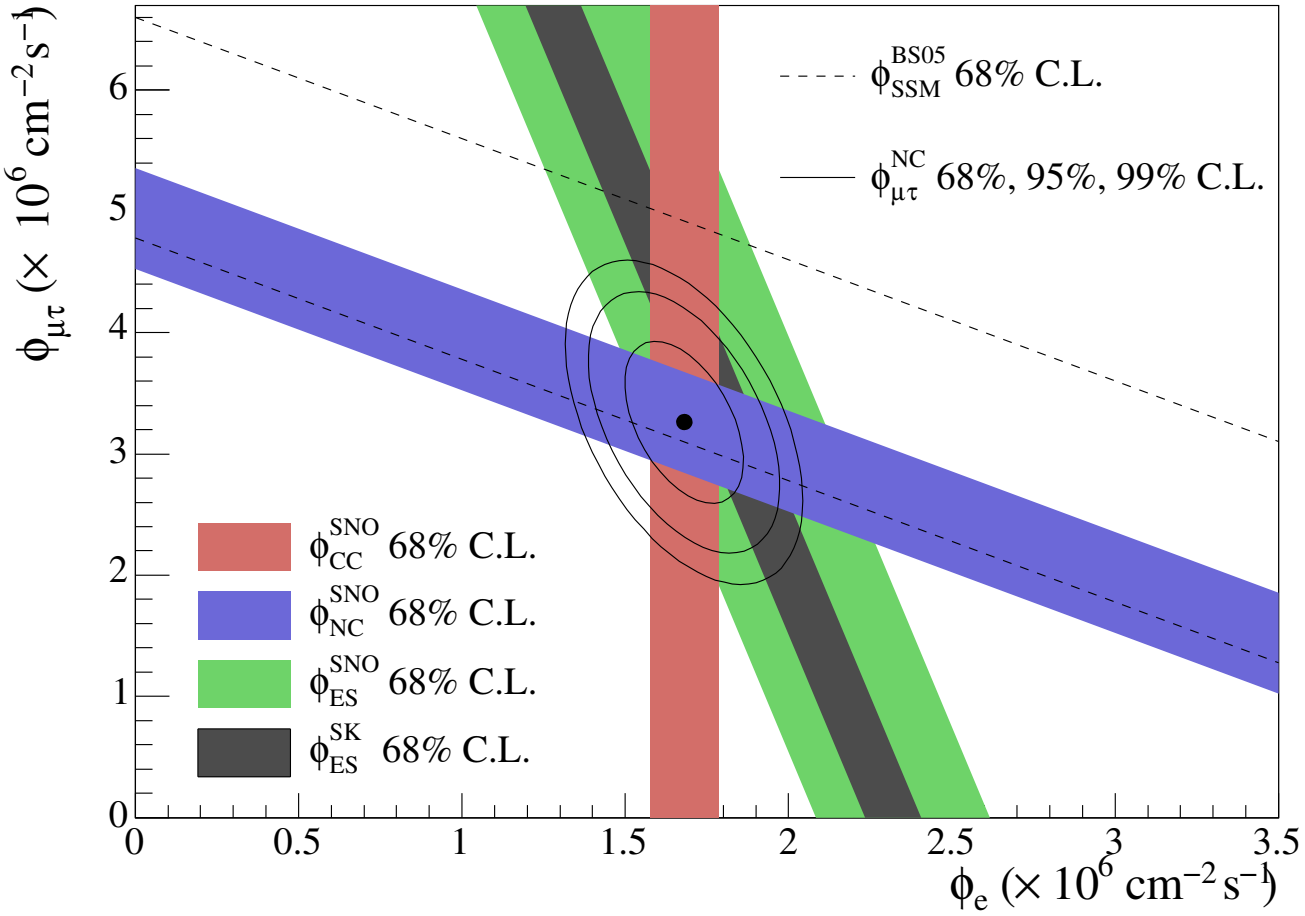
 © 2001 The American Physical Society



Bahcall

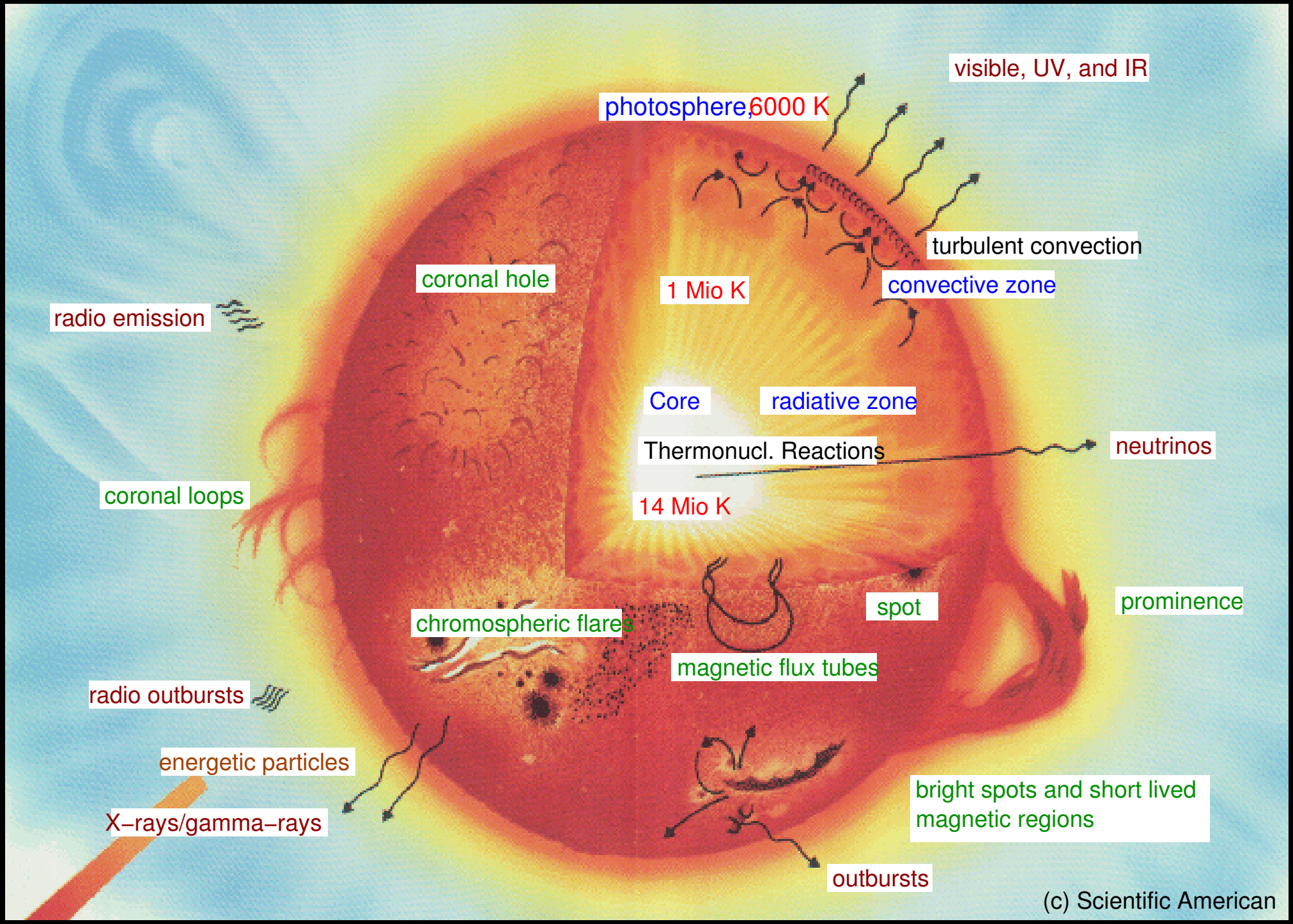
SNO (2001): When taking *all* neutrino flavors into account, the measured and predicted neutrino fluxes agree $\Longrightarrow$ Neutrinos change their flavor.

Solar Neutrinos



Aharmin et al., 2005 (dashed line: prediction of standard solar model)

SNO (2001): 2/3 of all ν_e produced in Sun change into ν_τ or ν_μ on their way from Sun to Earth: neutrino oscillations $\Longrightarrow$ physics beyond the standard model of particle physics!


visible, UV, and IR
photosphere, 6000 K
turbulent convection
coronal hole
1 Mio K
convective zone
radio emission
Core
radiative zone
Thermonucl. Reactions
neutrinos
coronal loops
14 Mio K
spot
prominence
chromospheric flares
magnetic flux tubes
radio outbursts
energetic particles
bright spots and short lived magnetic regions
X–rays/gamma–rays
outbursts
(c) Scientific American

Sun as a Star

- main sequence star (dwarf star), Type G2 V.
- $T_{eff} = 5780\,K$
- $R_\odot = 696\,000\,km$
- $M_\odot = 1.99 \times 10^{33}\,g$
- rotational speed: $P_{rot} = 25\,d$ (equator), $P_{rot} = 29\,d$ at latitude 60°
  Differential rotation until ~200000 km depth, below that rotation like solid body
- Atmosphere:
  Monotonous decrease with height in photosphere down to ~5000 K
  Increase to 10000 K (chromosphere) and then to $> 10^6$ K (corona)
  Heating probably through magnetic reconnection and magnetohydrodynamical waves excited in convection zone

Photosphere

Density of photosphere: scale height $H = kT/gAm_p = 180\,\mathrm{km}$.

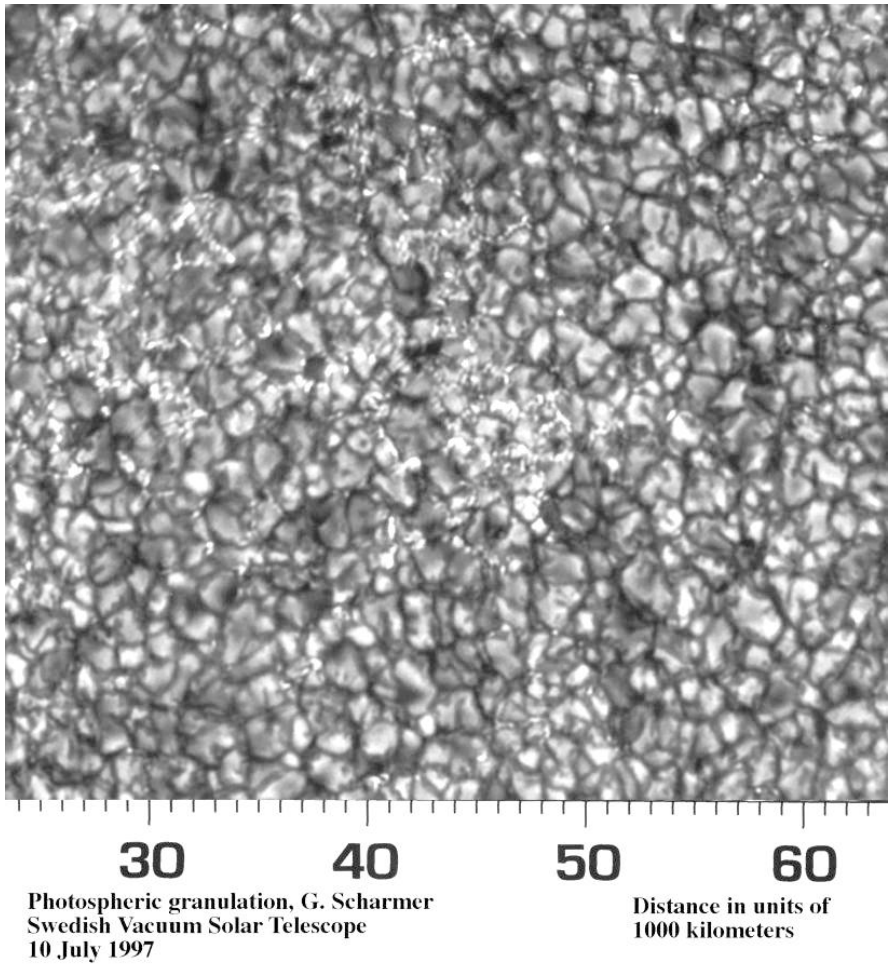
assuming $T = 6000\,\mathrm{K}$, $g = 274\,\mathrm{m\,s^{-2}}$ (surface acceleration, often written as: $\log g = 4.44$), $A = 1$ (assuming H only)

So $H/R_\odot \sim 3 \times 10^{-4} \Longrightarrow H \ll R_\odot$.

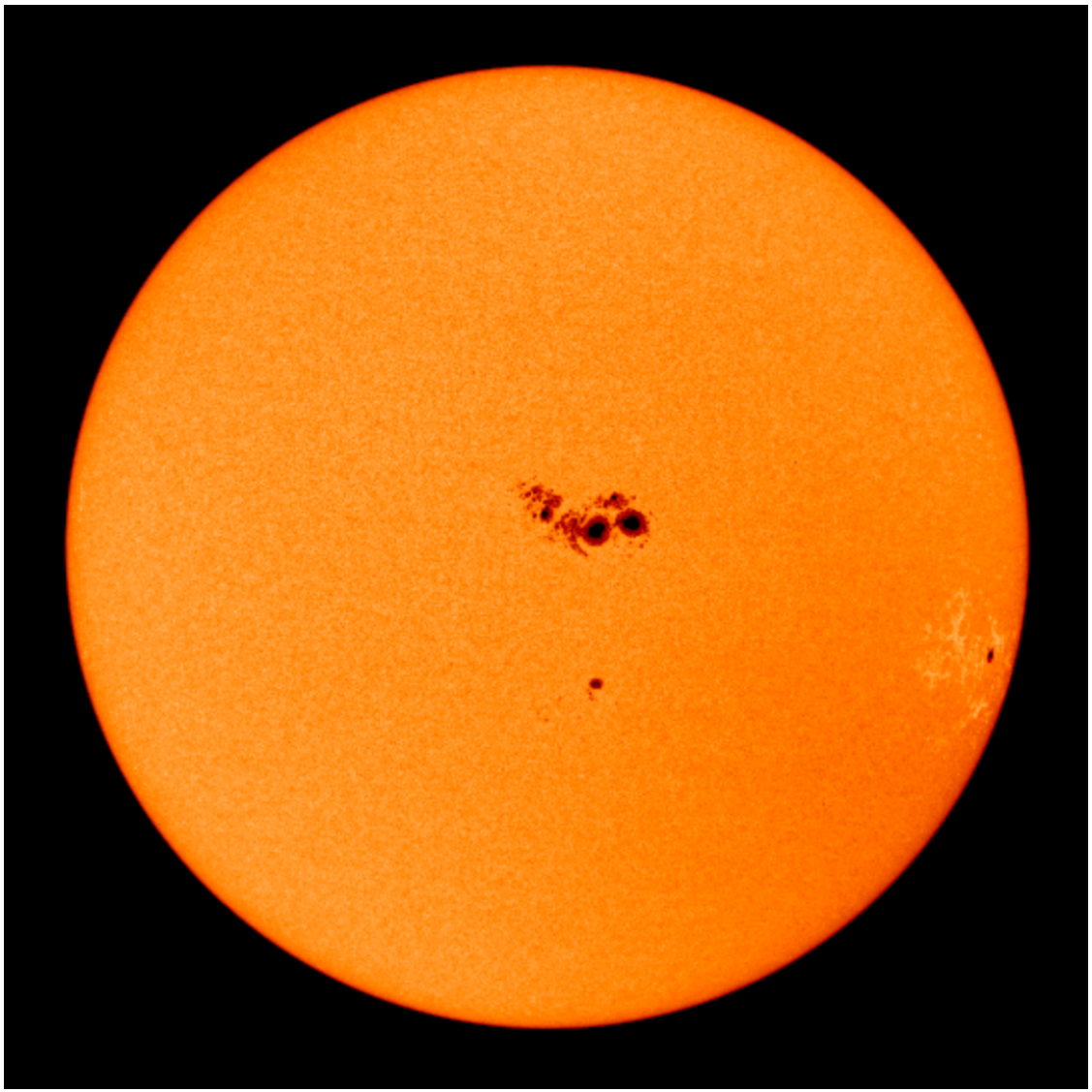
Granular structure of "surface" due to convection zone

Bright center of granules: rising hot material

Dark space between granules: colder material moving downwards



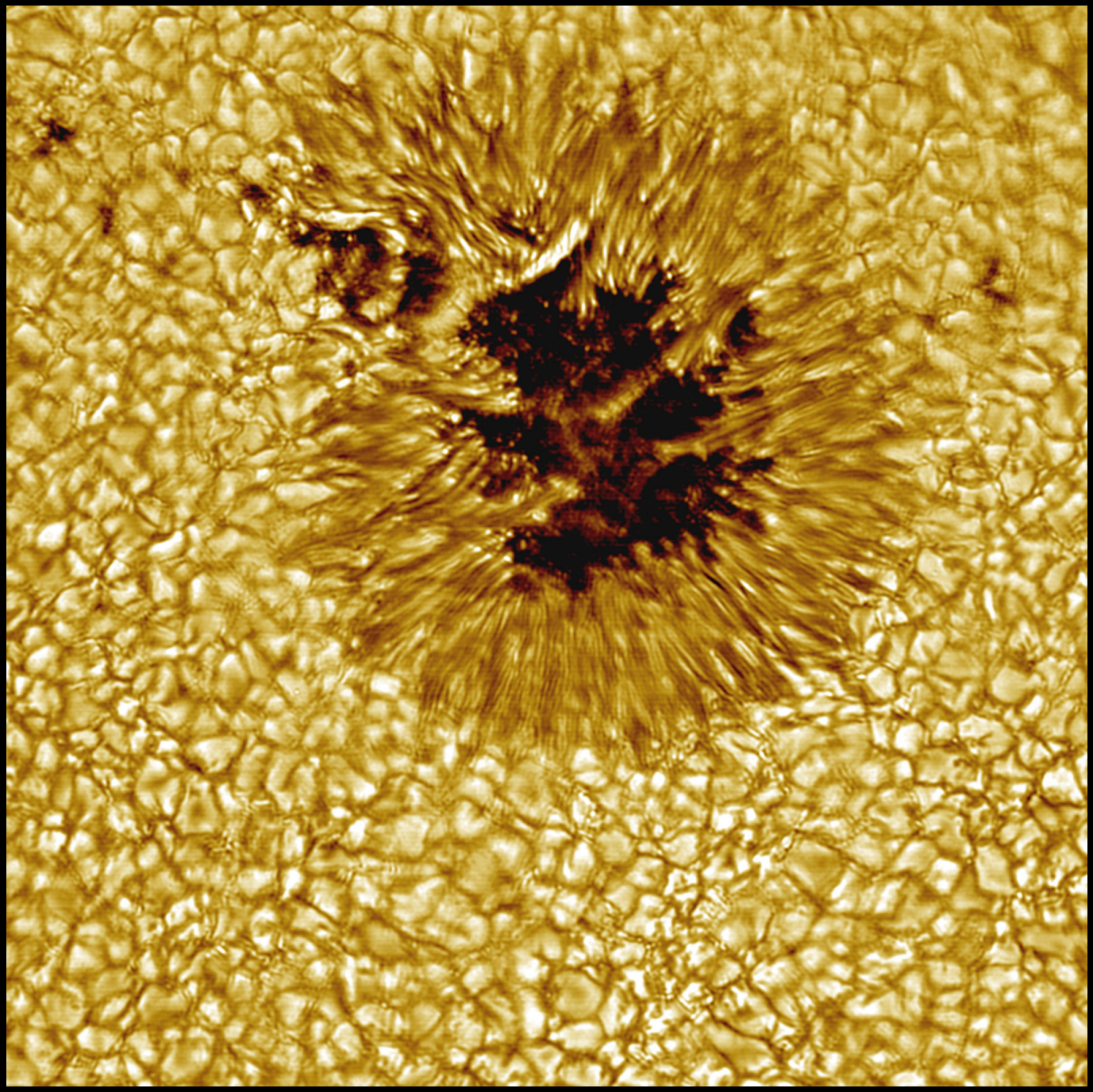
Photosphere



Sun spots:

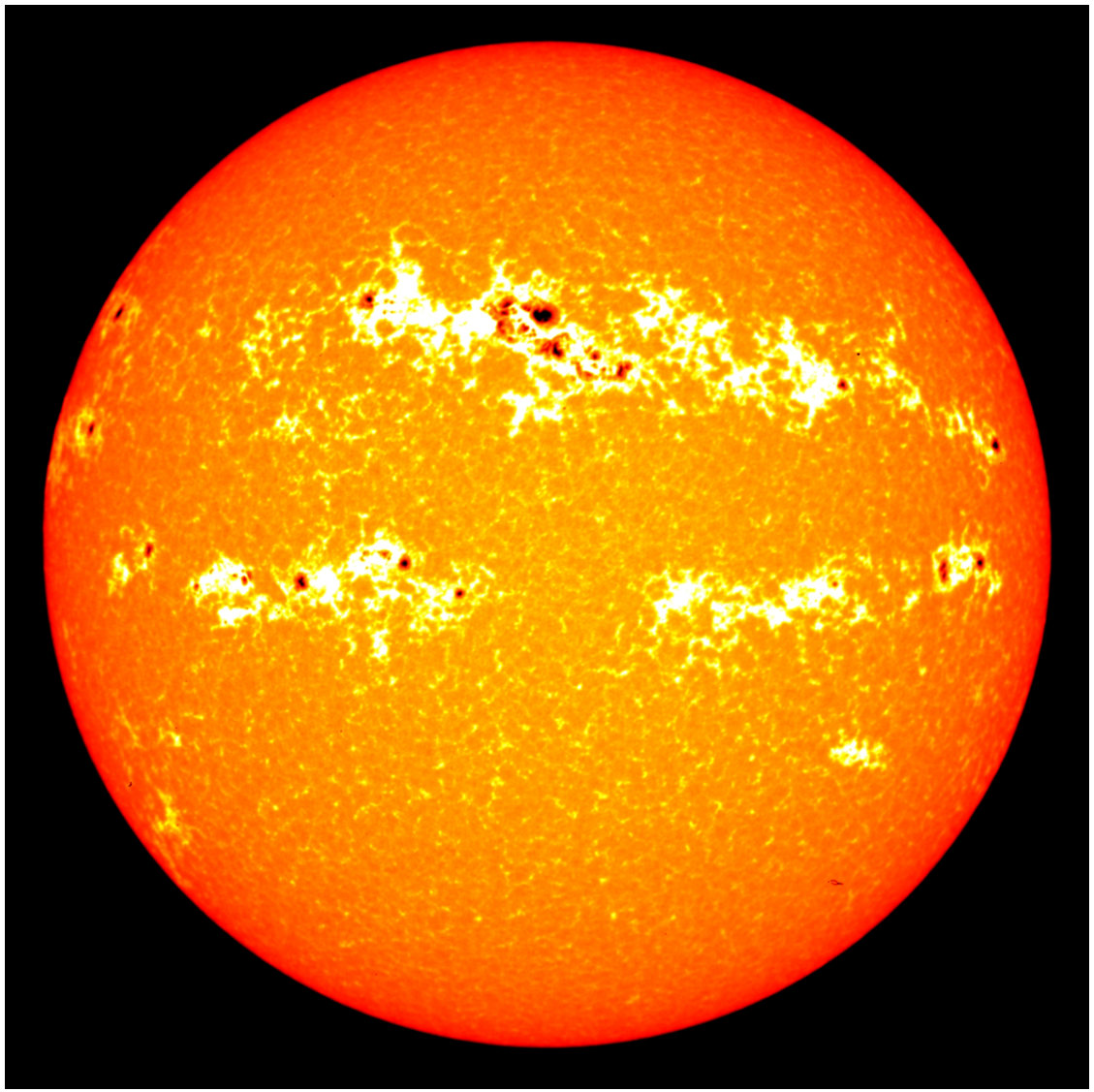
- Dark spots on surface
- Depending on size, exist for days to weeks
- Temperature in center: ~3700 K
  ~2000 K colder than remaining photosphere
- Due to strong magnetic fields which hinder convection (and thus energy transport)
- Internal B-fields are distorted, move outwards

Courtesy NASA/ESA SOHO team



Vacuum Tower Telescope, NSO, NOAO

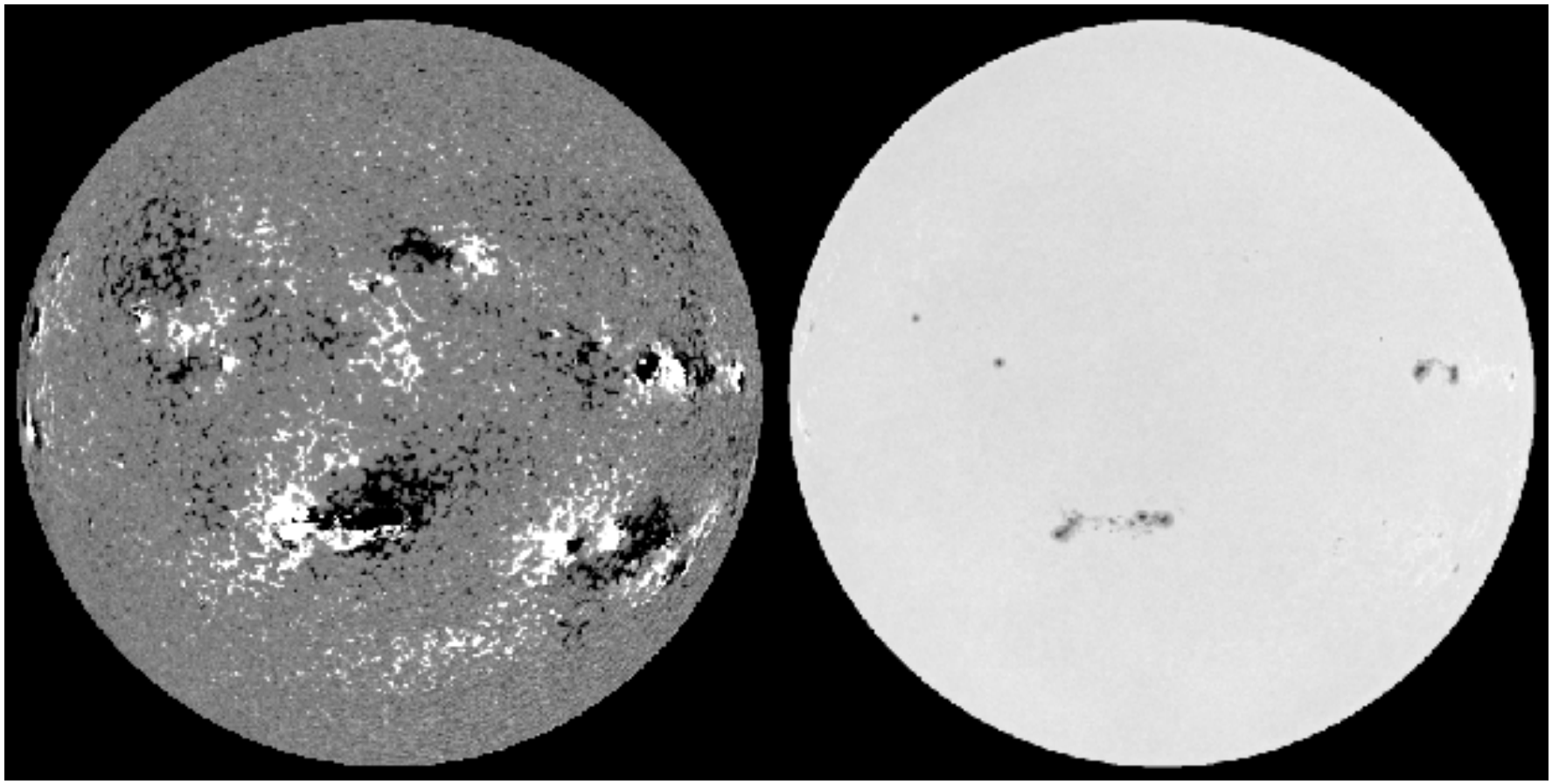
Photosphere



- Umbra: dark core, ~10000 km in size, region of strongest B-field, $\mathbf{B} \perp$ surface
- Penumbra: bright region around umbra, B-fields have angle with respect to surface
- Faculae: Regions of increased brightness and temperature (~7000 K)
- B-fields in sun spots up to ~5000 G
  (solar surface: 1 G, Earth: 0.6 G)

NASA/Goddard/SORCE

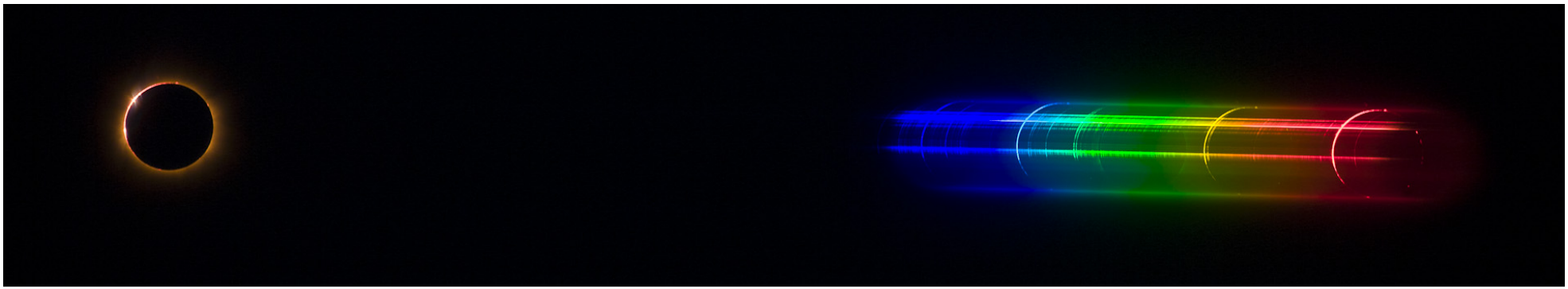
Photosphere



Wenzler et al., 2004, SOHO

Left: Magnetogram: Bright and dark spots show regions with strong magnetic fields of opposite polarity

Chromosphere



APOD, Copyright: C. Emmanouilidi

"Flash spectrum": spectrum of the solar chromosphere

Chromosphere: Above photosphere, ~2000 km thickness

Particle density decreases from $10^{17}\,\mathrm{cm}^{-3}$ to $10^{9}\,\mathrm{cm}^{-3}$

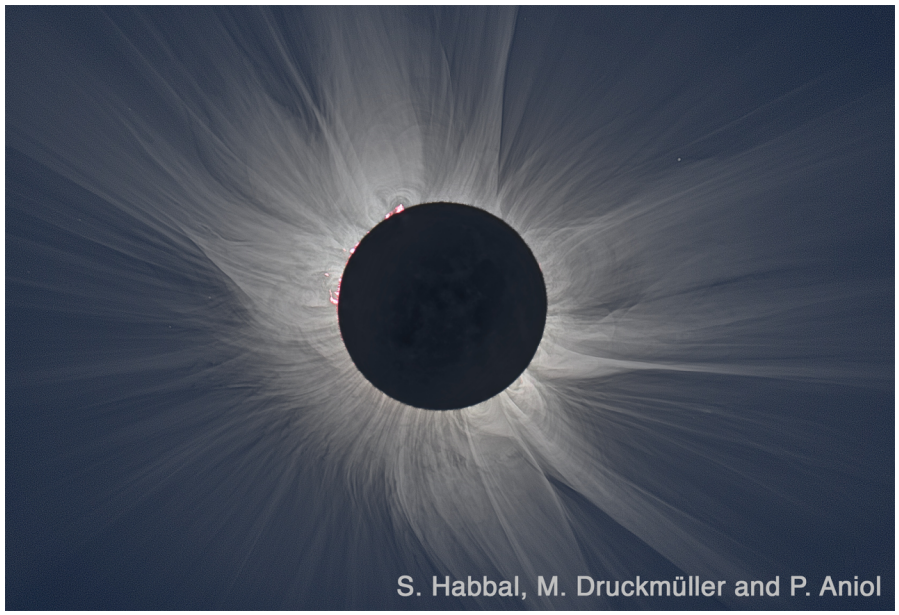
Earth's atmosphere on surface: $10^{19}\,\mathrm{cm}^{-3}$

Temperature: 6000 K–20000 K.

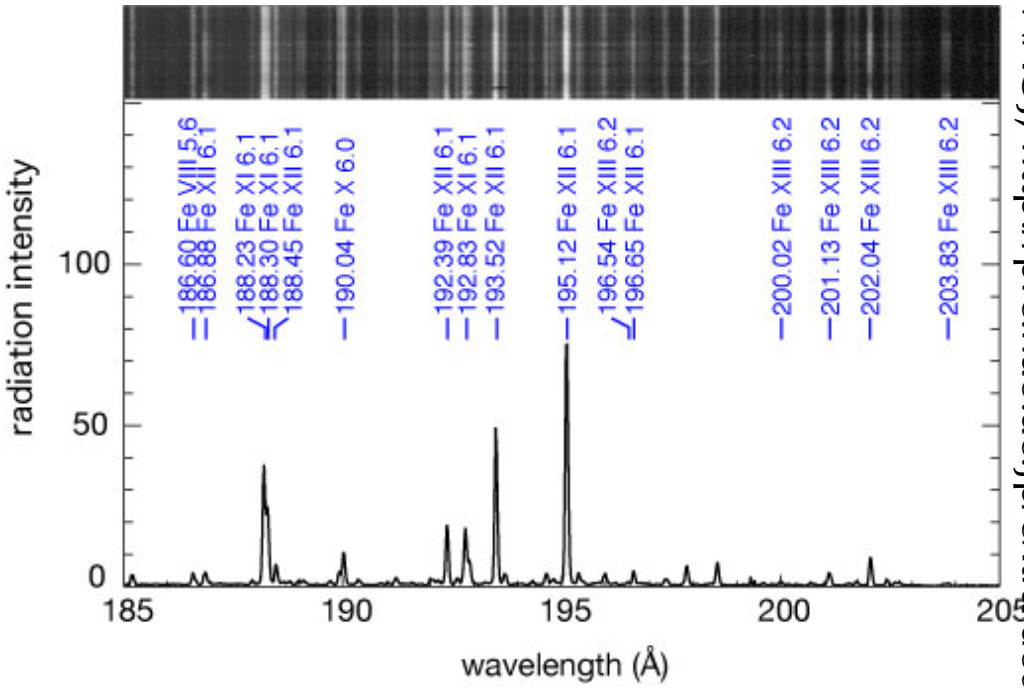
H is fully ionized on top

Strong Hα-Emission $\Longrightarrow$ light is "reddish" $\Longrightarrow$ "color-sphere"

Corona



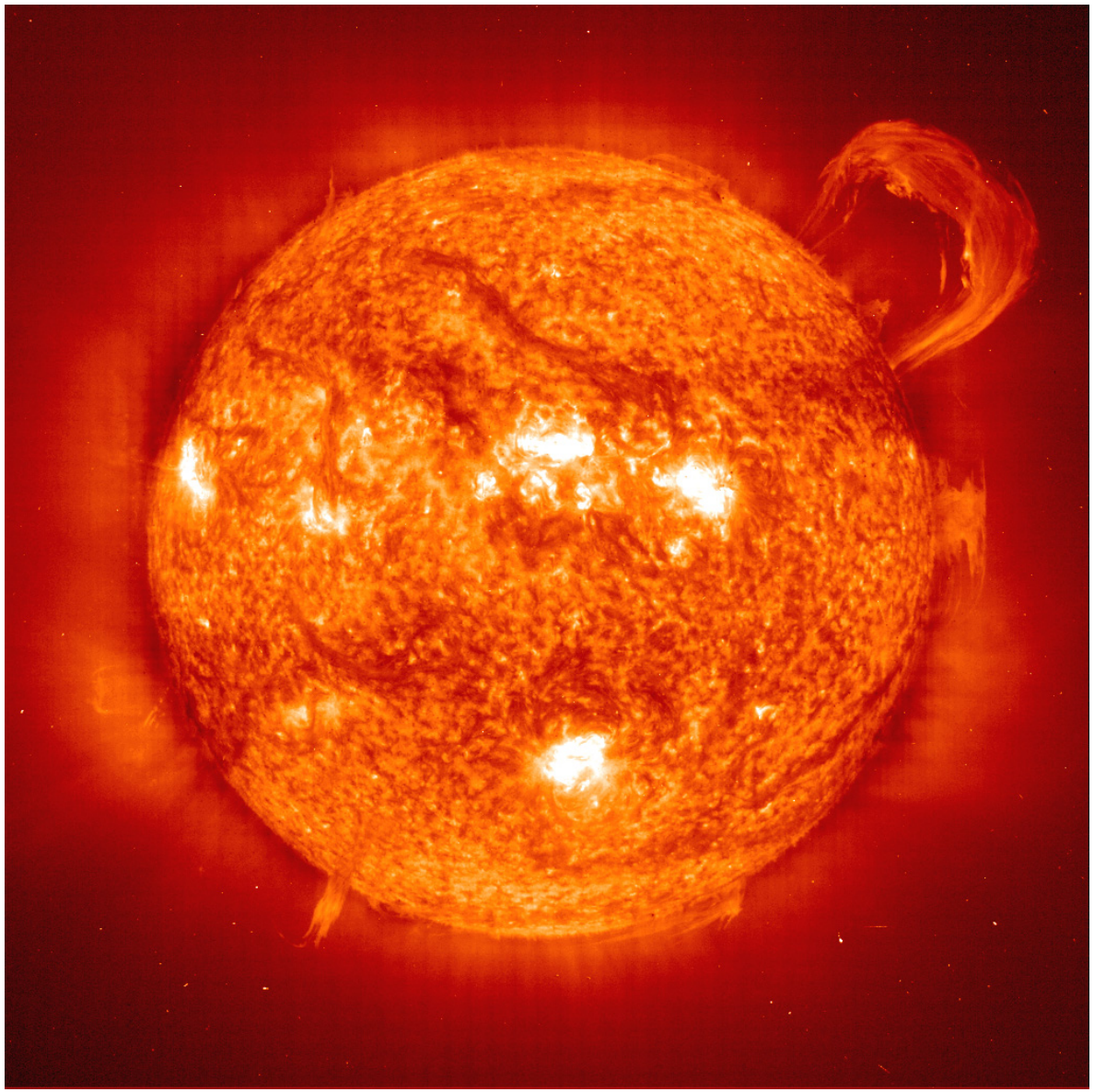
Solar corona (eclipse, 21 Aug 2017)



NAOJ, http://prc.nao.ac.jp/extra/uos/en/

- Corona: outermost area of solar atmosphere
- decrease of density to $n \sim 10^5\,\mathrm{cm}^{-3}$ at distance $10R_\odot$. Temperature: $1\text{–}2 \times 10^6\,\mathrm{K}$.
- transits into solar wind
  speed a few $100\,\mathrm{km\,s}^{-1}$
- Emission lines: atoms are highly ionized
  up to H- and He-like, visible in UV- and X-rays
- coronal holes: B-field lines reaching into interplanetary medium

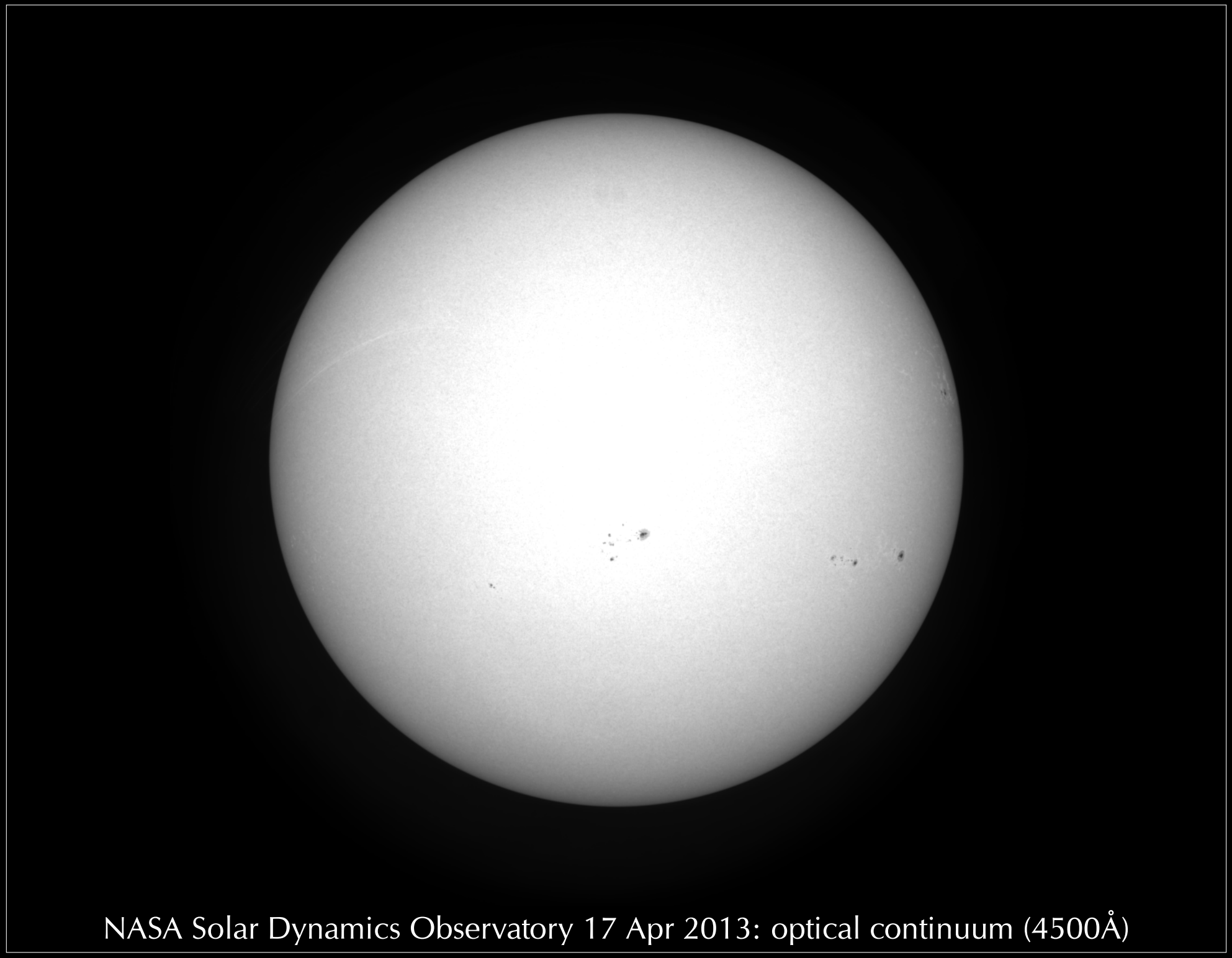
Corona



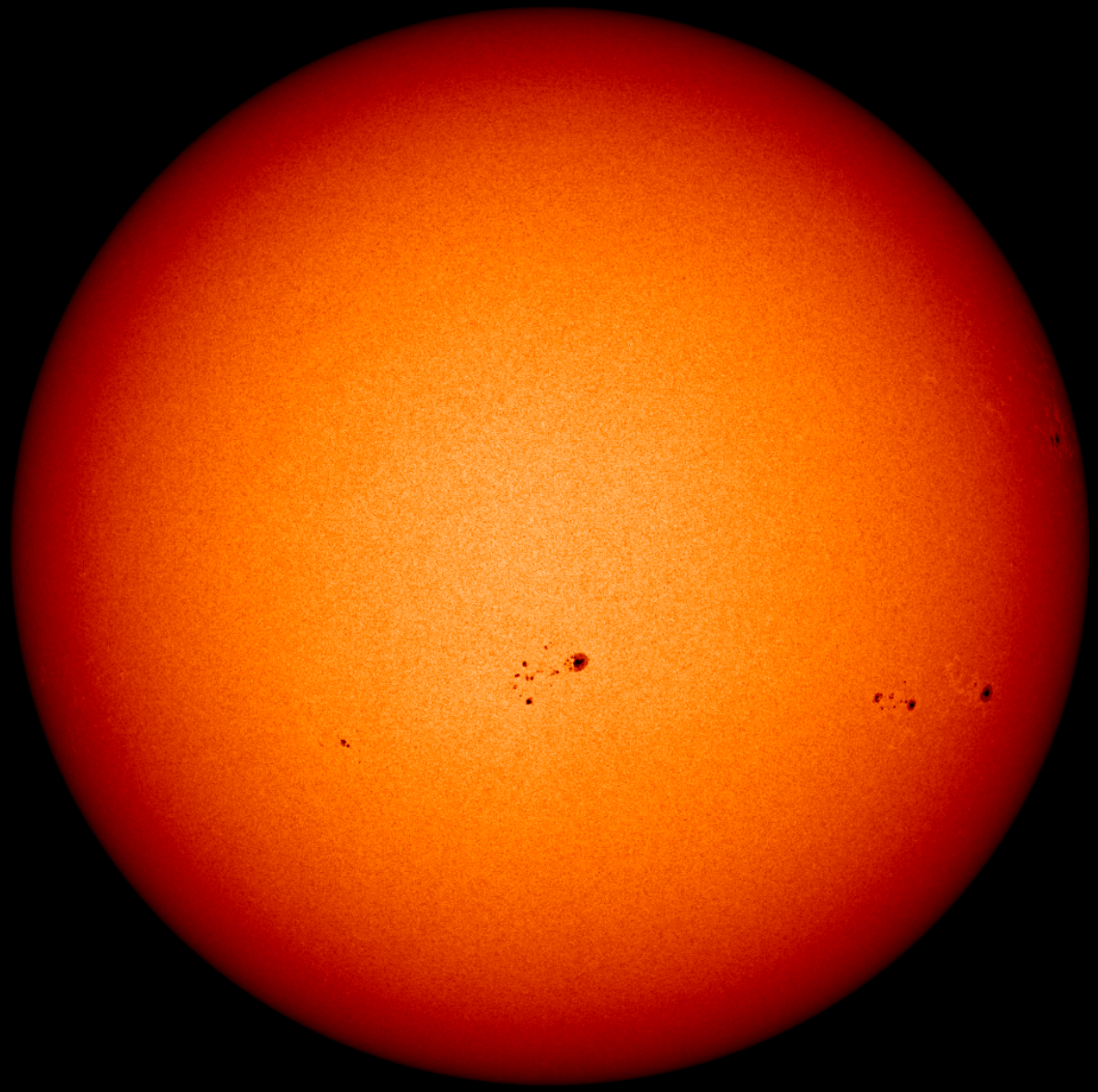
Protuberances:

- bright, long structures in the corona
- Spectra, T, and n similar to Chromosphere
  $T = 5000\,\mathrm{K}–12000\,\mathrm{K}$, $n = 10^{11}\,\mathrm{cm}^{-3}$
- cold and dense plasma embedded in the hotter and less dense corona
- explanation: charged particles moving along B-field lines. B-field is “frozen”, allowing plasma to be situated above sun spots

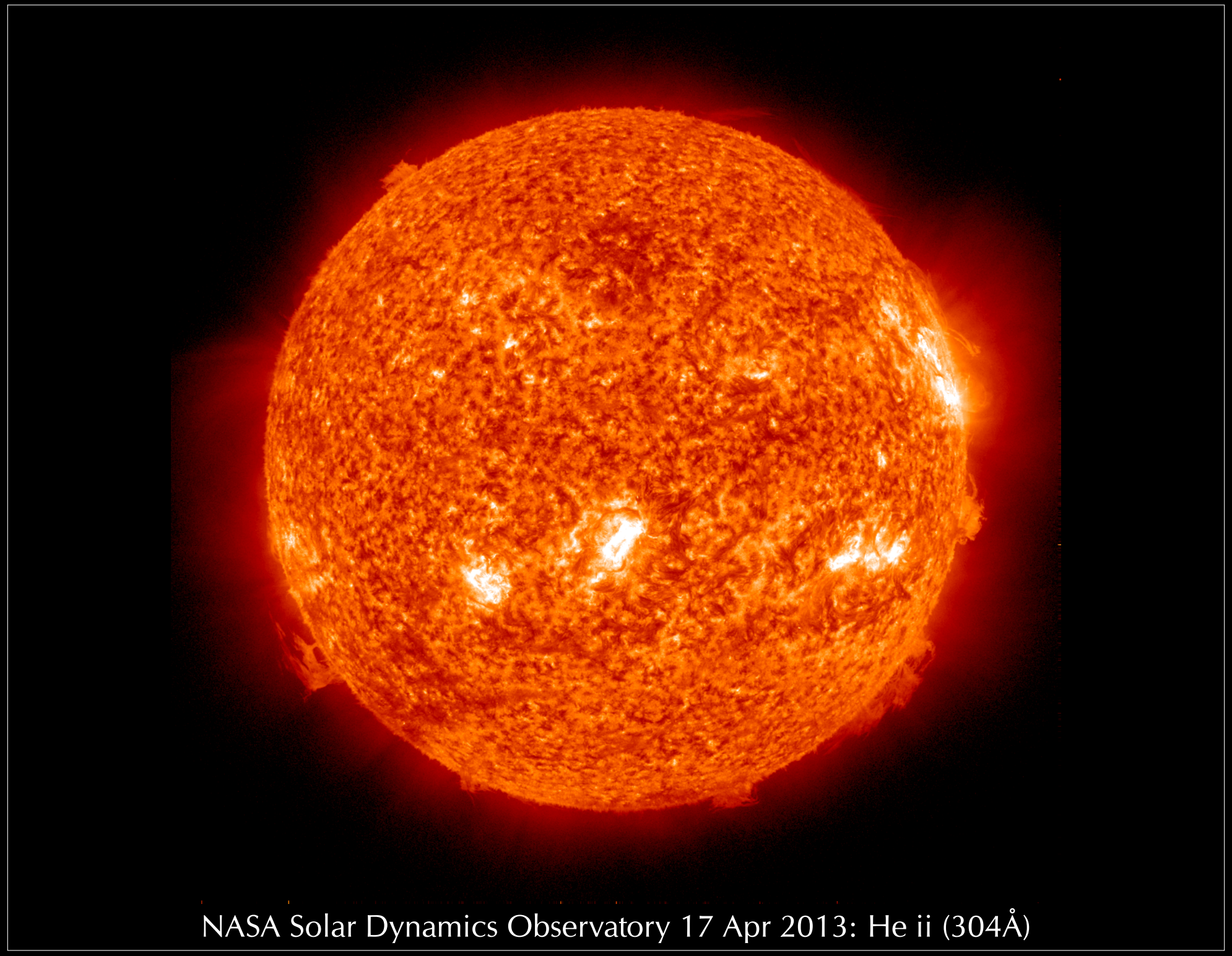
Credit: SOHO-EIT Consortium, ESA, NASA



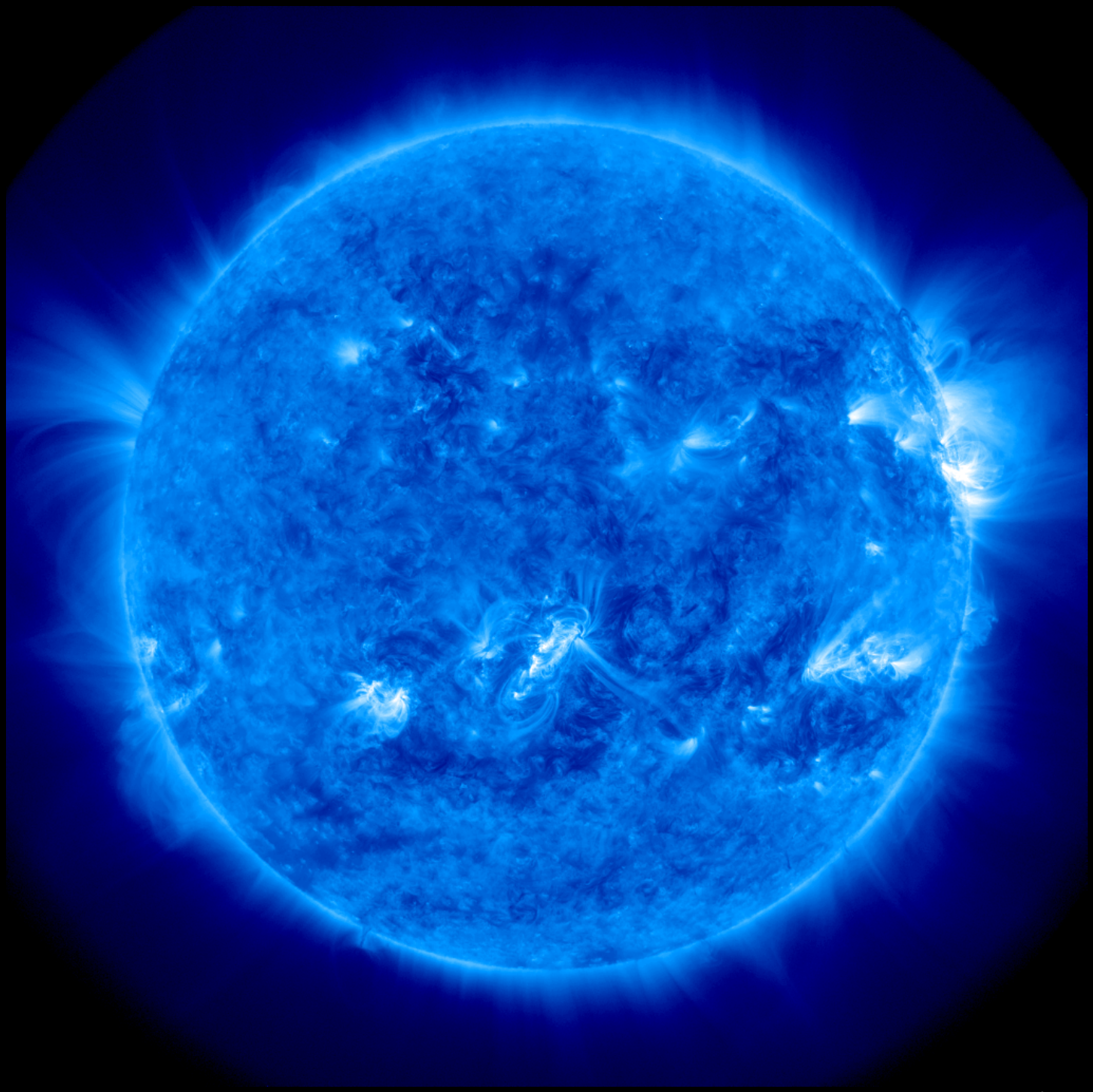
NASA Solar Dynamics Observatory 17 Apr 2013: optical continuum (4500Å)



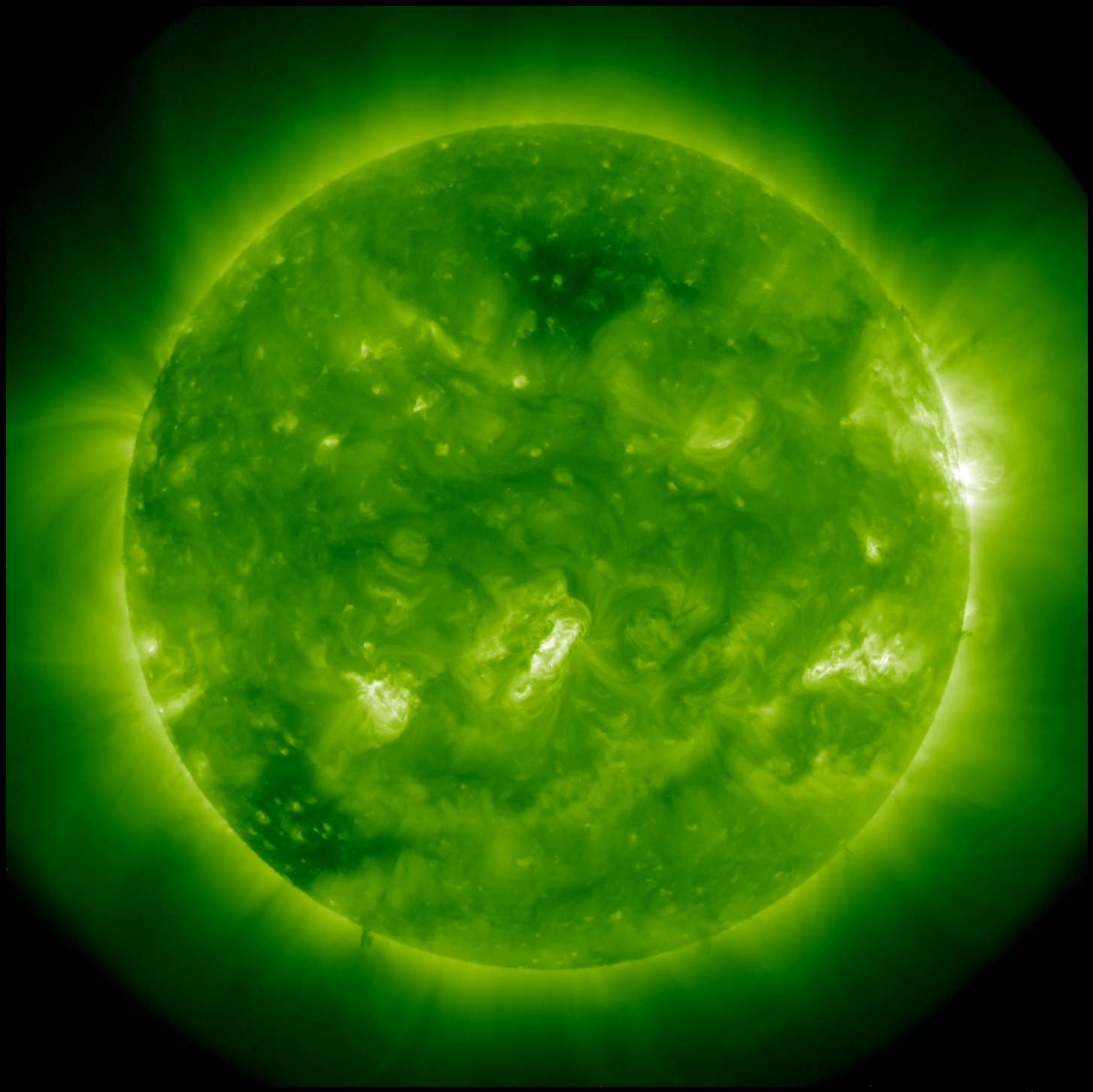
NASA Solar Dynamics Observatory 17 Apr 2013: optical continuum (6173Å)



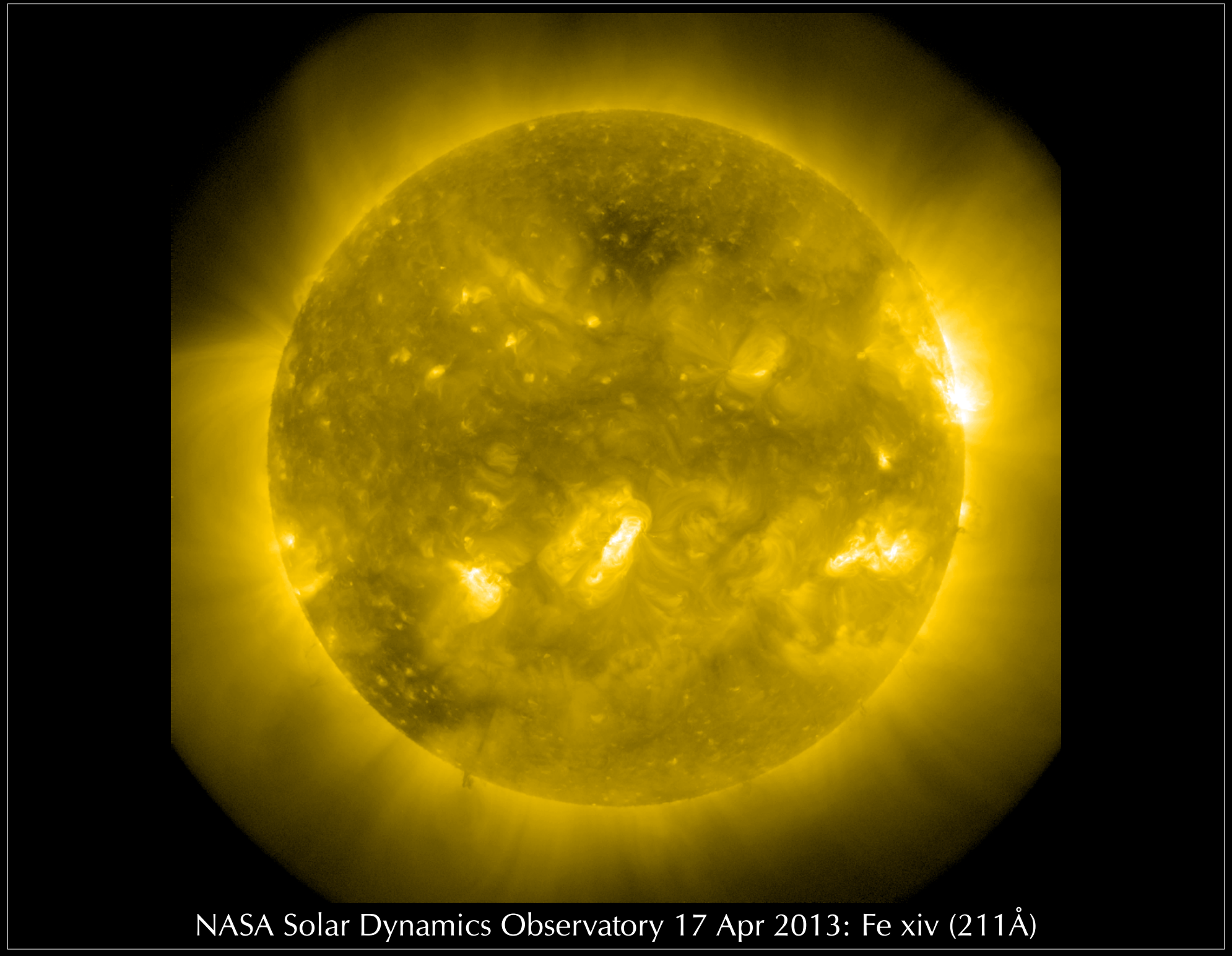
NASA Solar Dynamics Observatory 17 Apr 2013: He ii (304Å)



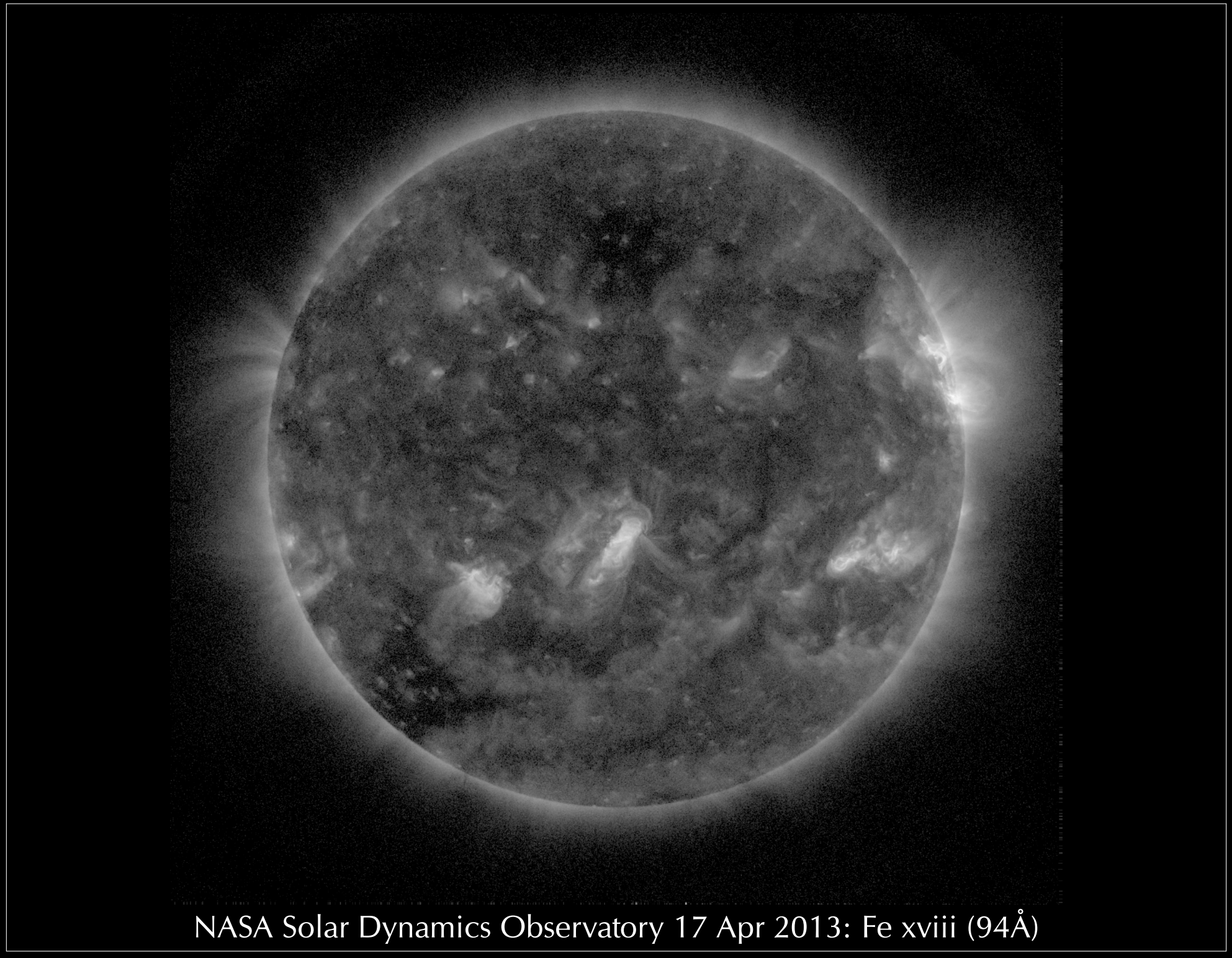
NASA Solar Dynamics Observatory 17 Apr 2013: Fe ix/x (171Å)



NASA Solar Dynamics Observatory 17 Apr 2013: Fe xii (193Å)

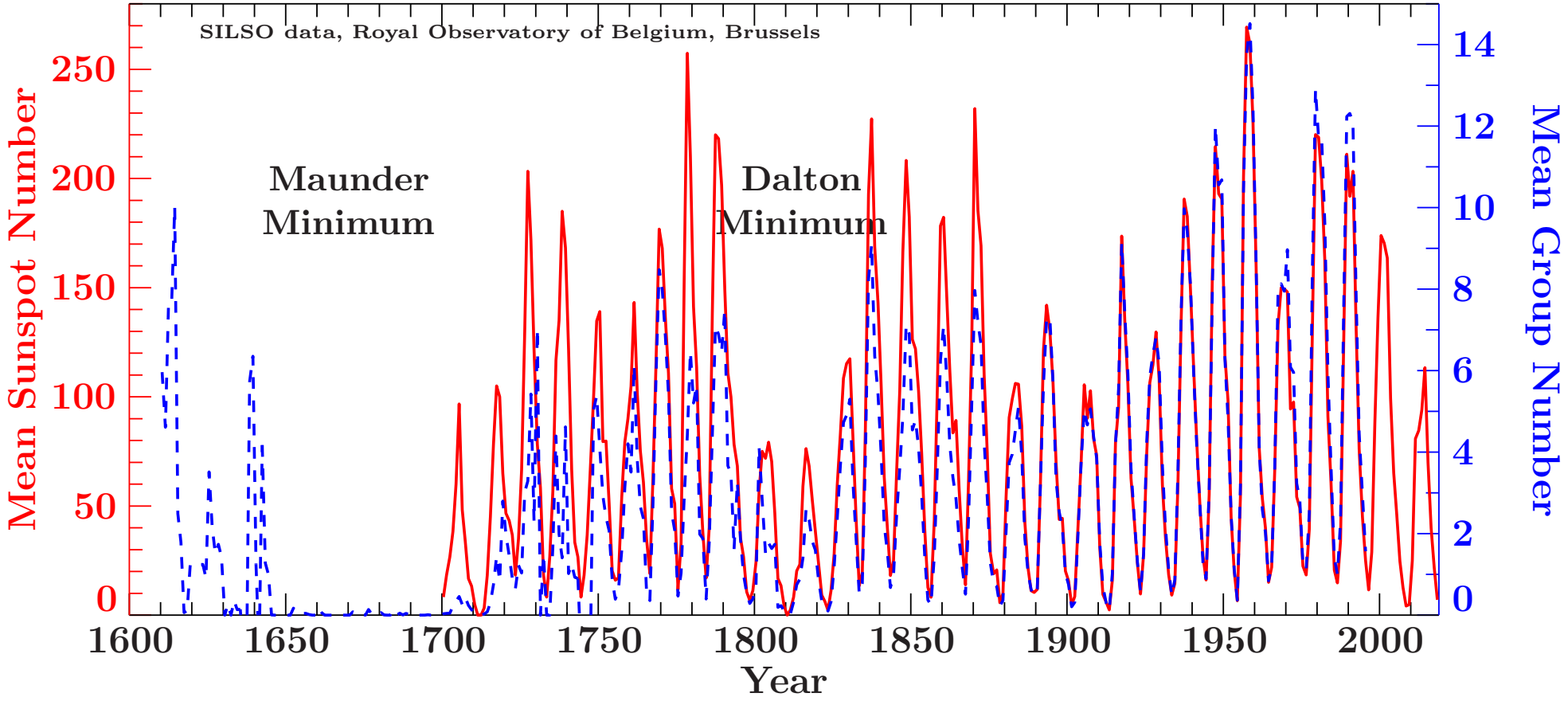


NASA Solar Dynamics Observatory 17 Apr 2013: Fe xiv (211Å)



NASA Solar Dynamics Observatory 17 Apr 2013: Fe xviii (94Å)

Solar Activity

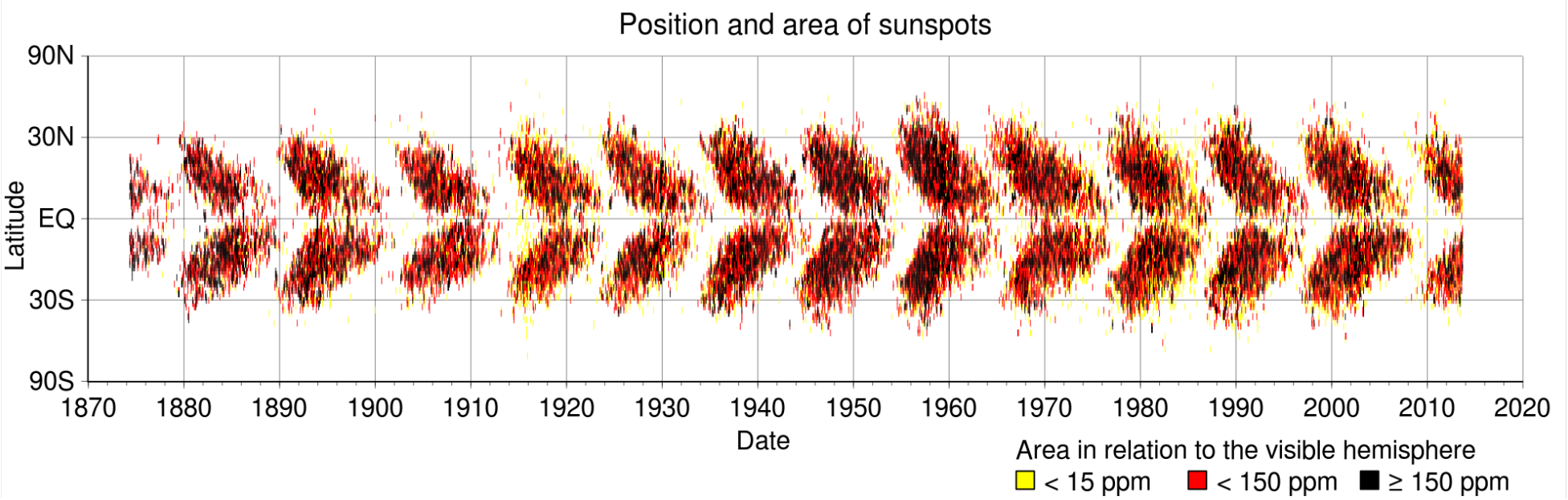


Periodic change in number of sunspots and sunspot groups with P = 11 years

discovered by H. Schwabe (1843)

Activity cycles are strongly variable, almost no activity in 17th century

Solar Activity



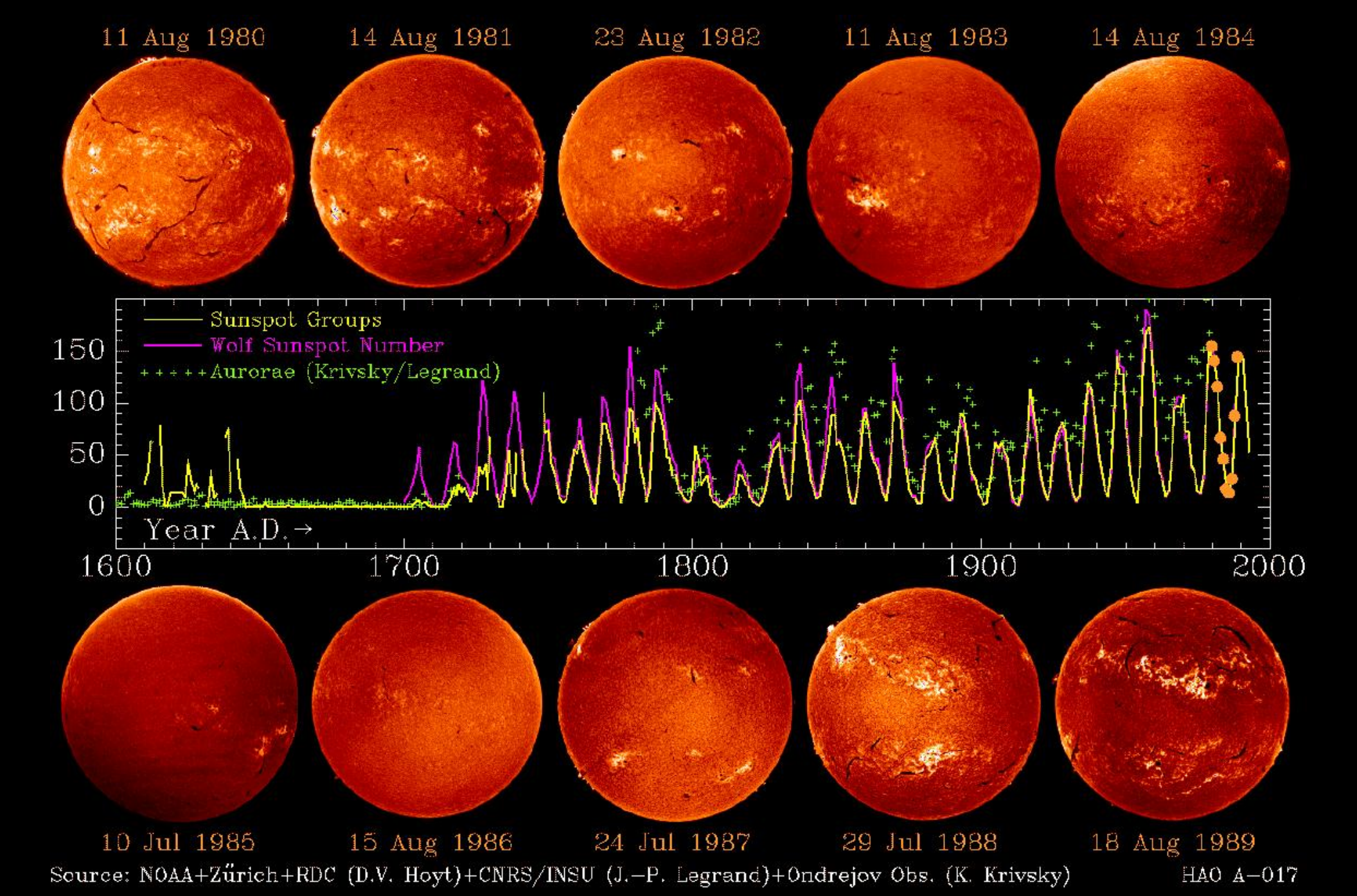
Wikipedia

Position of sunspots changes over cycle: “butterfly diagram”

Early cycle: spots at large heliographic latitude, moves towards equator during cycle

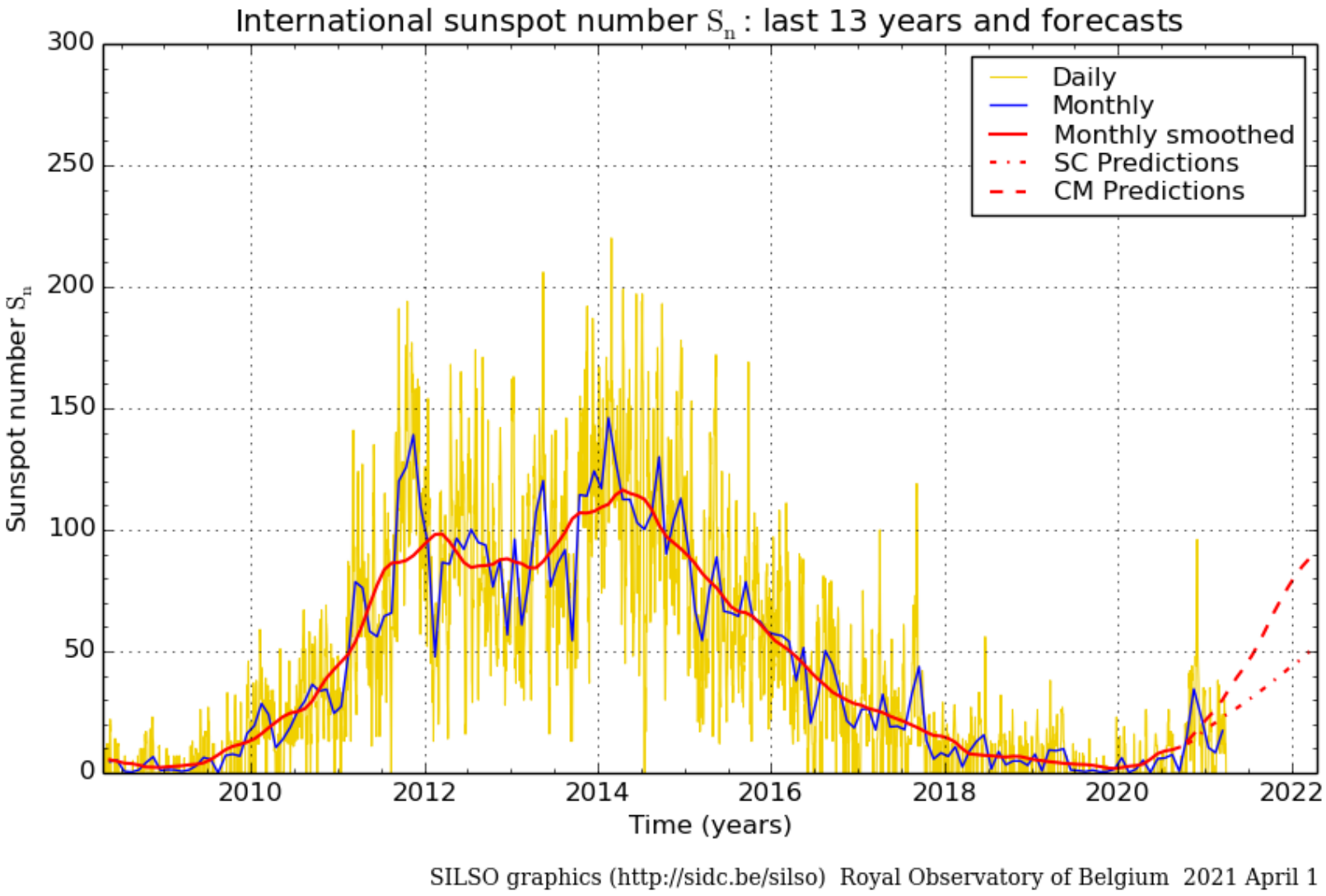
No spots at $|b| > 45°$

Polarity of solar B-field changes every 11 years $\Longrightarrow$ activity cycle is 22 years



Source: NOAA+Zűrich+RDC (D.V. Hoyt)+CNRS/INSU (J.-P. Legrand)+Ondrejov Obs. (K. Krivsky) HAO A-017

Solar Activity



Currently we are just after a minimum of the solar cycle

Einführung in die Astronomie II

Jörn Wilms

Sommersemester 2023

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Skript zugänglich über FAU StudiumOnline Portal:
http://www.studon.uni-erlangen.de/studon/

FRIEDRICH-ALEXANDER
UNIVERSITÄT
ERLANGEN-NÜRNBERG
NATURWISSENSCHAFTLICHE
FAKULTÄT

Stars: Evolution

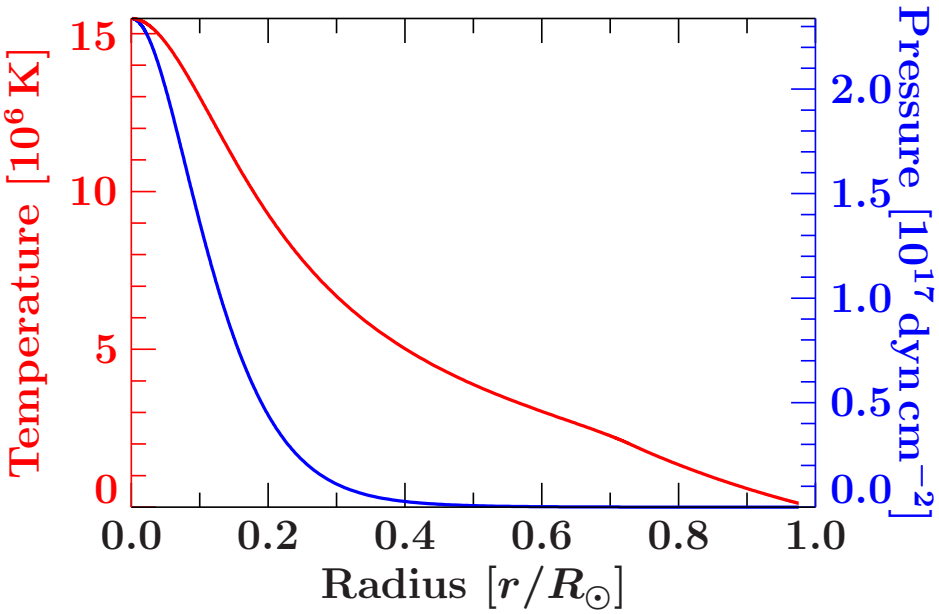
Stellar Evolution

Principle:

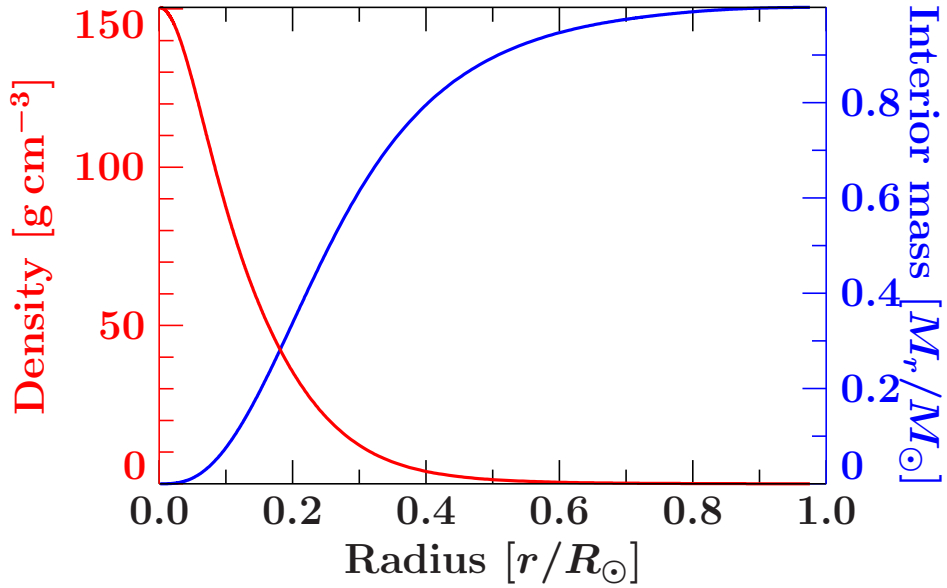
1. Construct stellar model by solving equations of stellar structure for given radial abundances.
2. Evaluate change in elemental abundances as a function of radius based on the local fusion processes.
3. Change abundances appropriately for a time step Δt.
4. goto step 1

Solar Structure

Standard solar model:



Temperature & pressure profile



Density & interior mass profile

Values from Bahcall, Pinsonneault & Basu (ApJ 555,990, 2001)

Evolution: Timescales

Main sequence: Hydrogen burning at the center.

Evolution timescale dominated by the nuclear timescale = timescale needed to use the fuel in the center of the star.

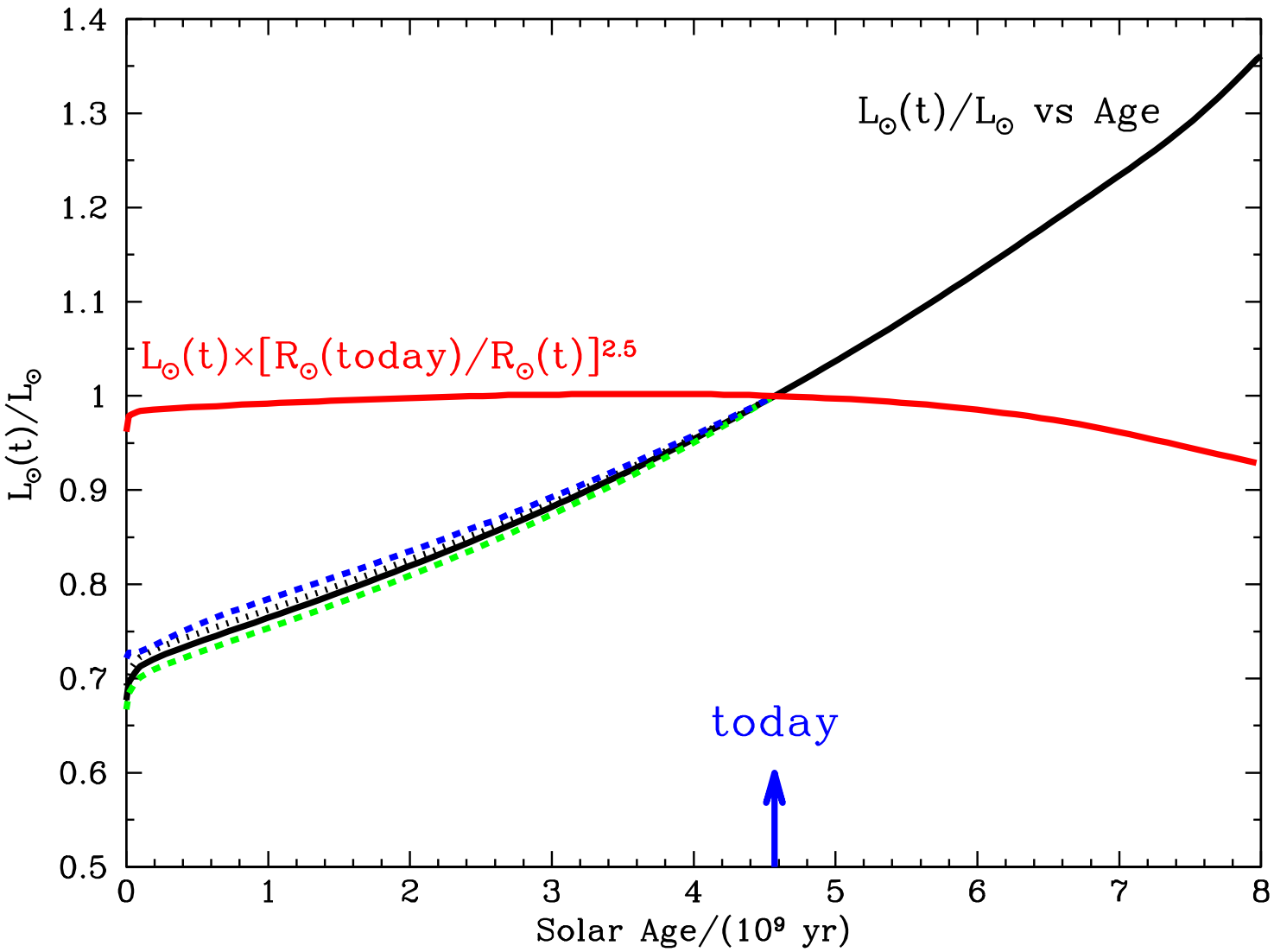
According to simulations, this is ~10% of the available Hydrogen.
Since 0.7% of $M_{core}c^2$ converted into He, the nuclear timescale is

$$t_n = \frac{0.007 \cdot 0.1 M c^2}{L} = \frac{M/M_\odot}{L/L_\odot} \cdot 10^{10}\,\text{years} \tag{1.1}$$

A second important timescale is the timescale the star would need to radiate its stored thermal energy: thermal timescale.
Roughly given as

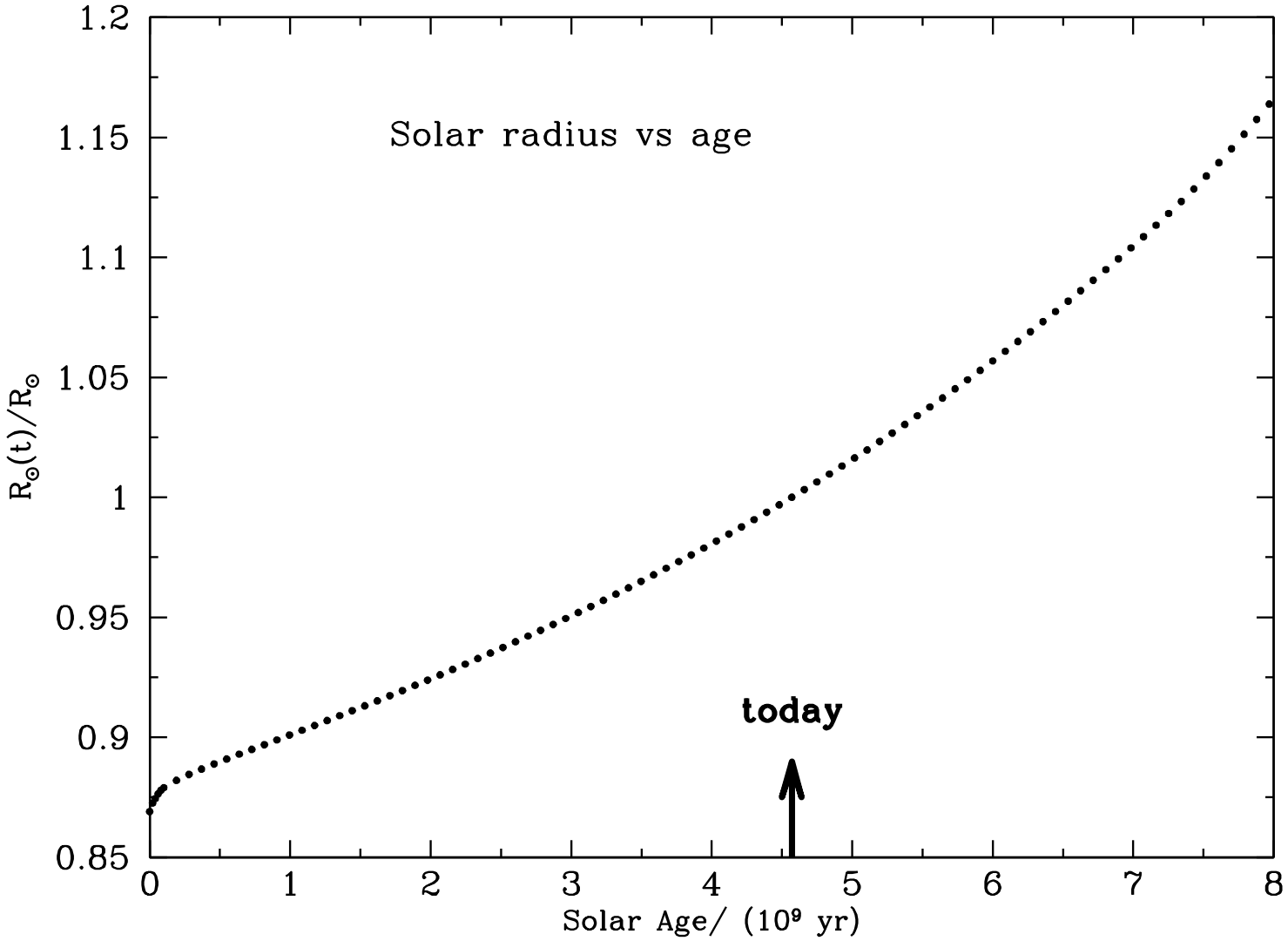
$$t_t = \frac{0.5 G M^2/R}{L} = \frac{(M/M_\odot)^2}{(R/R_\odot)(L/L_\odot)} \cdot 2 \times 10^7\,\text{years} \tag{1.2}$$

Solar Evolution: Luminosity



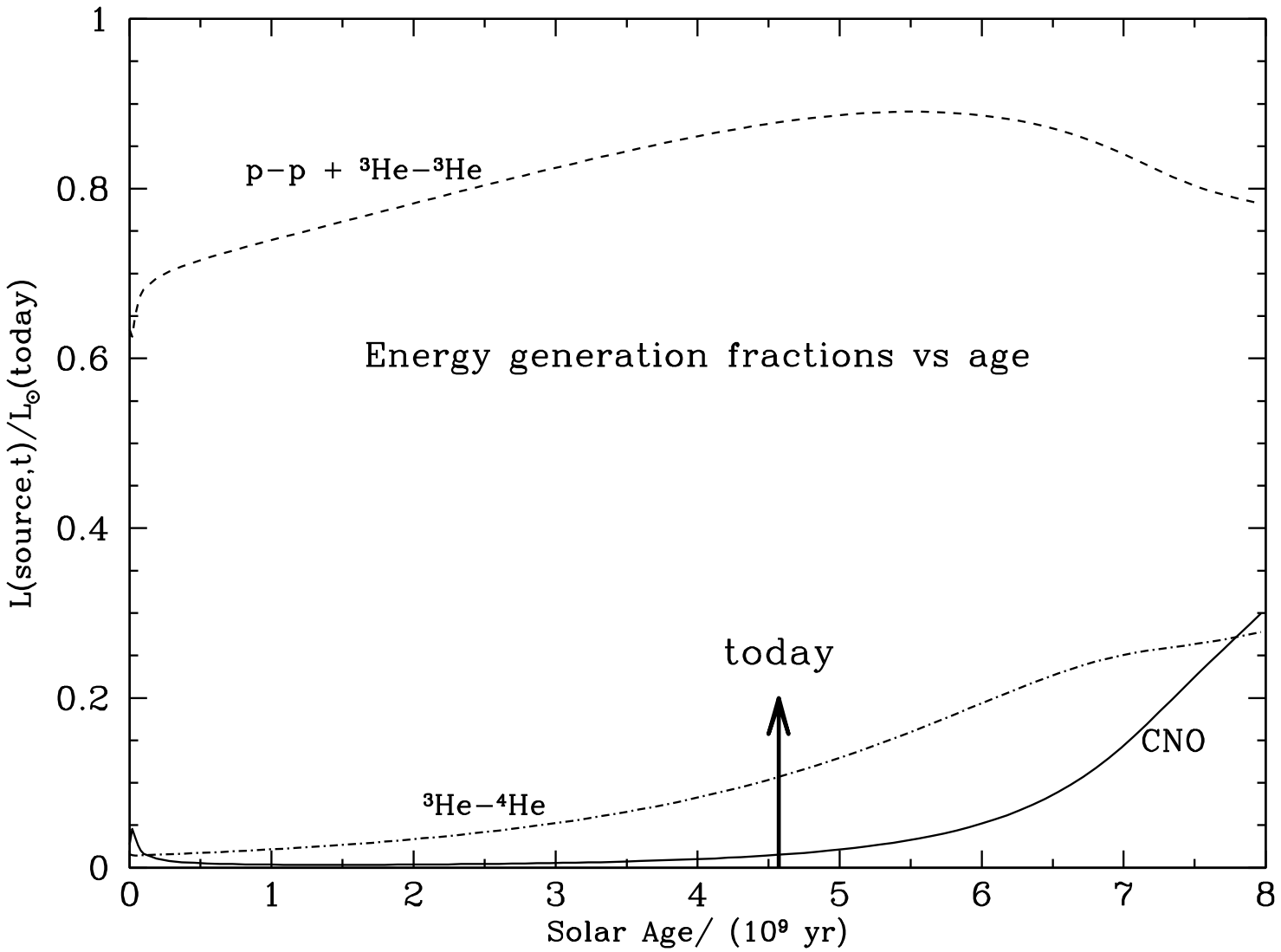
Bahcall, Pinsonneault & Basu (2001, ApJ 555, 990)

Solar Evolution: Radius



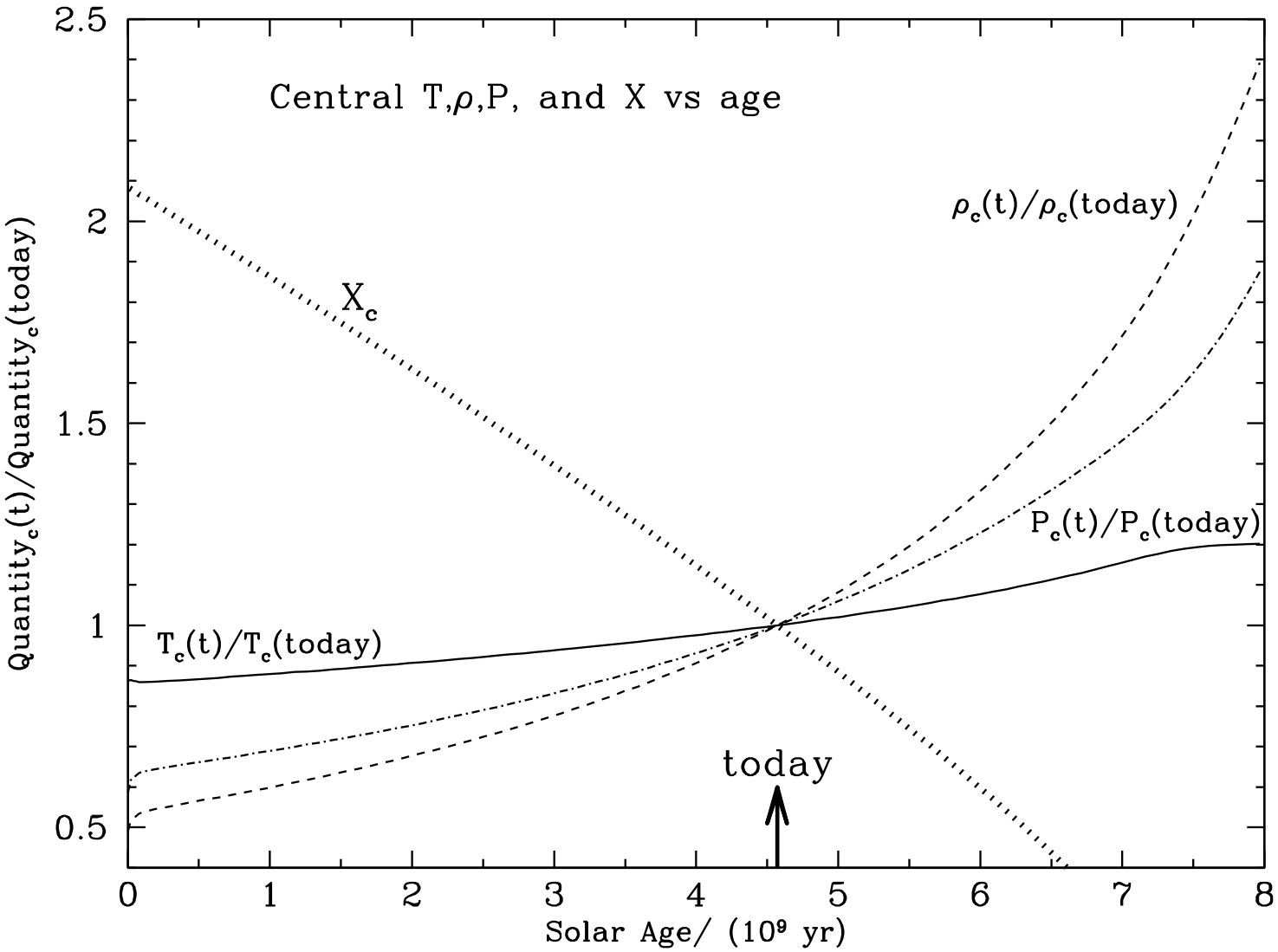
Bahcall, Pinsonneault & Basu (2001, ApJ 555, 990)

Solar Evolution: Energy Generation



Bahcall, Pinsonneault & Basu (2001, ApJ 555, 990)

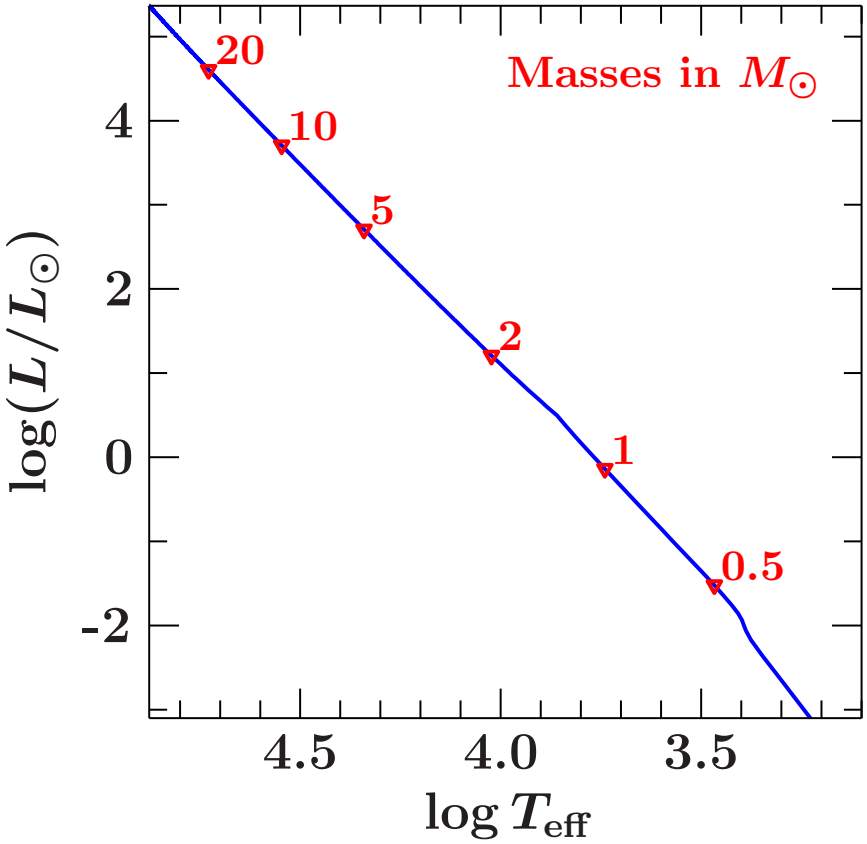
Solar Evolution: Center

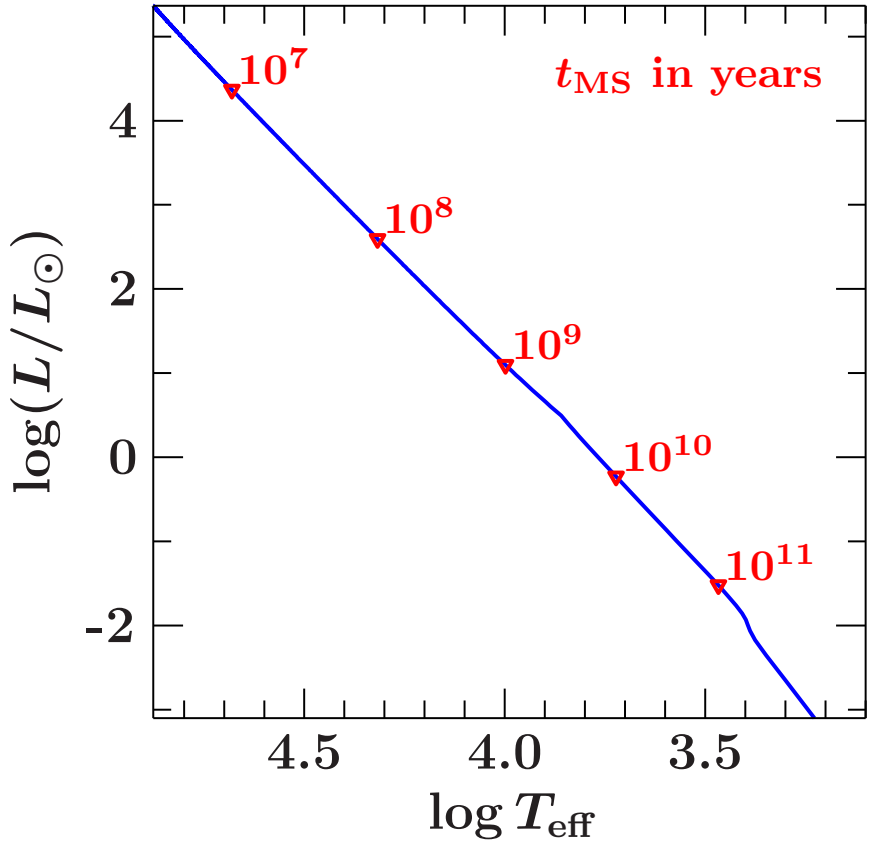


Bahcall, Pinsonneault & Basu (2001, ApJ 555, 990; X_c is the central H fraction)

Main Sequence

Main Sequence in the Hertzsprung-Russell-Diagram:





After Eggleton et al. (1989)

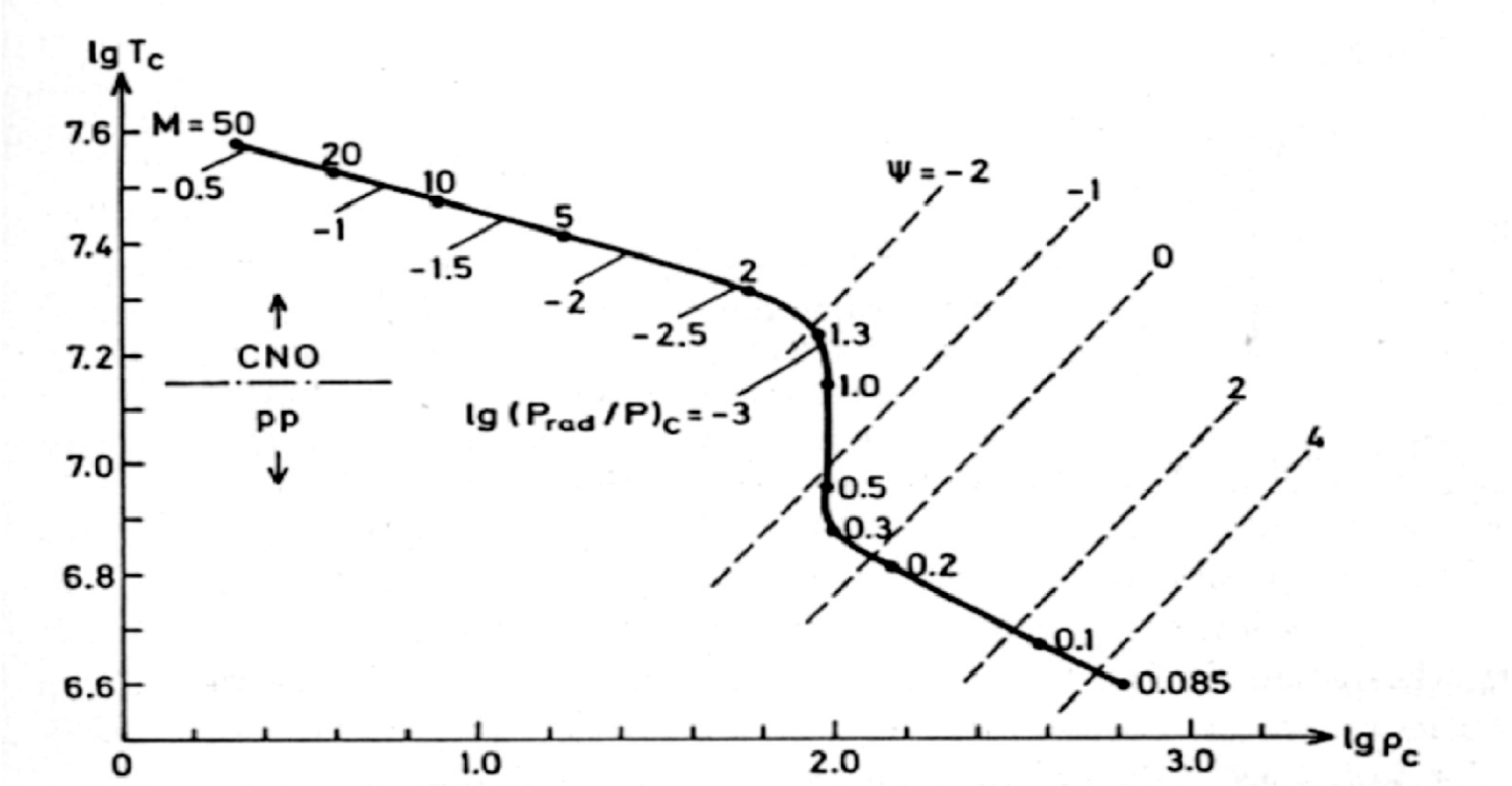
Masses along the HRD

life times along the HRD

mass limits: Min.: 0.08$M_\odot$ (no H-burning for lower masses)

Max.: ~100 $M_\odot$ (radiation pressure too high, $p_{rad} \sim T_{eff}^4$)

Main Sequence



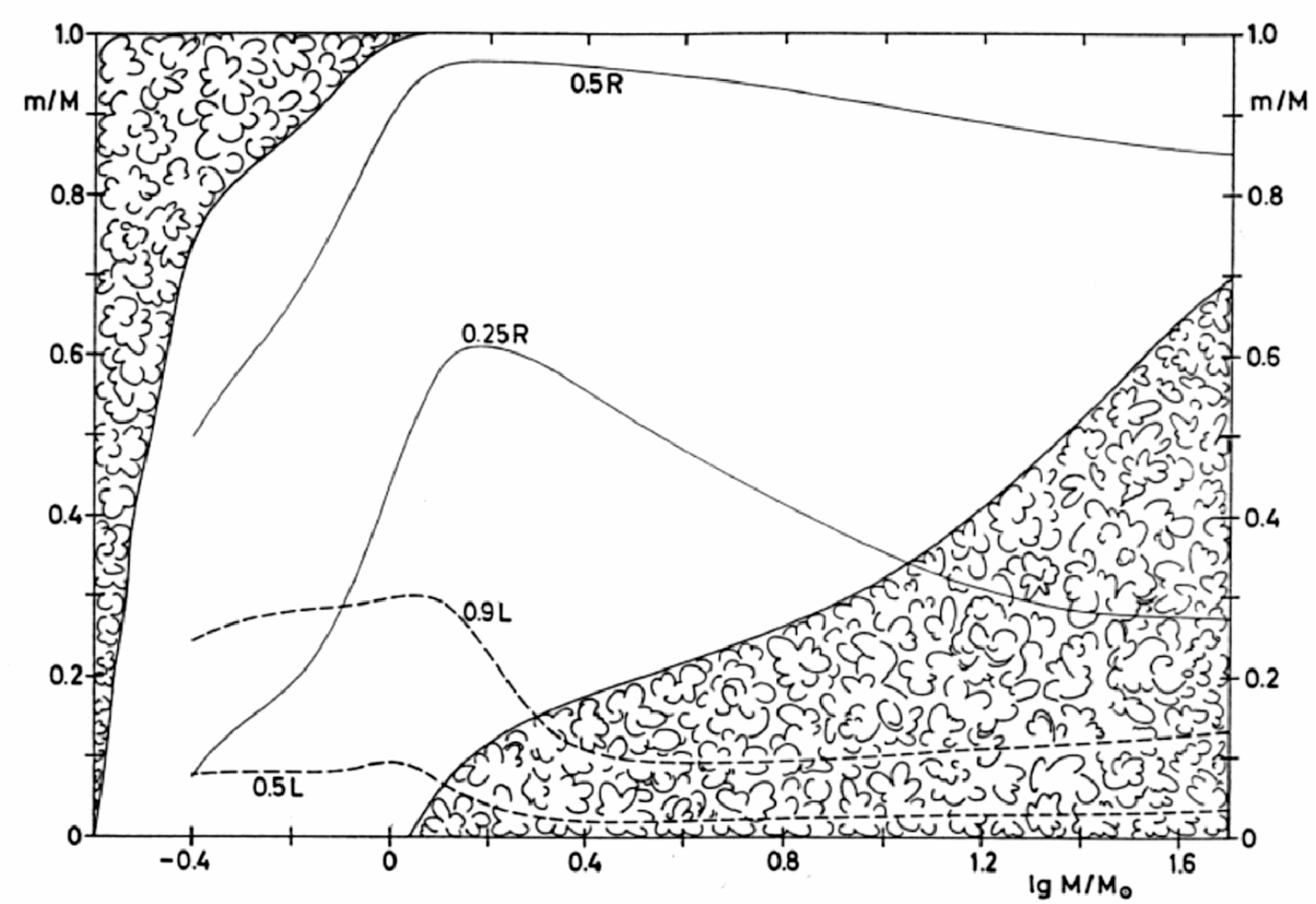
Central temperatures & densities

Strong change at $\sim 1\,M_\odot$:

- $M < 0.5 M_\odot$: low temperature, very high density
- $M > 1.3 M_\odot$: high temperature, low density

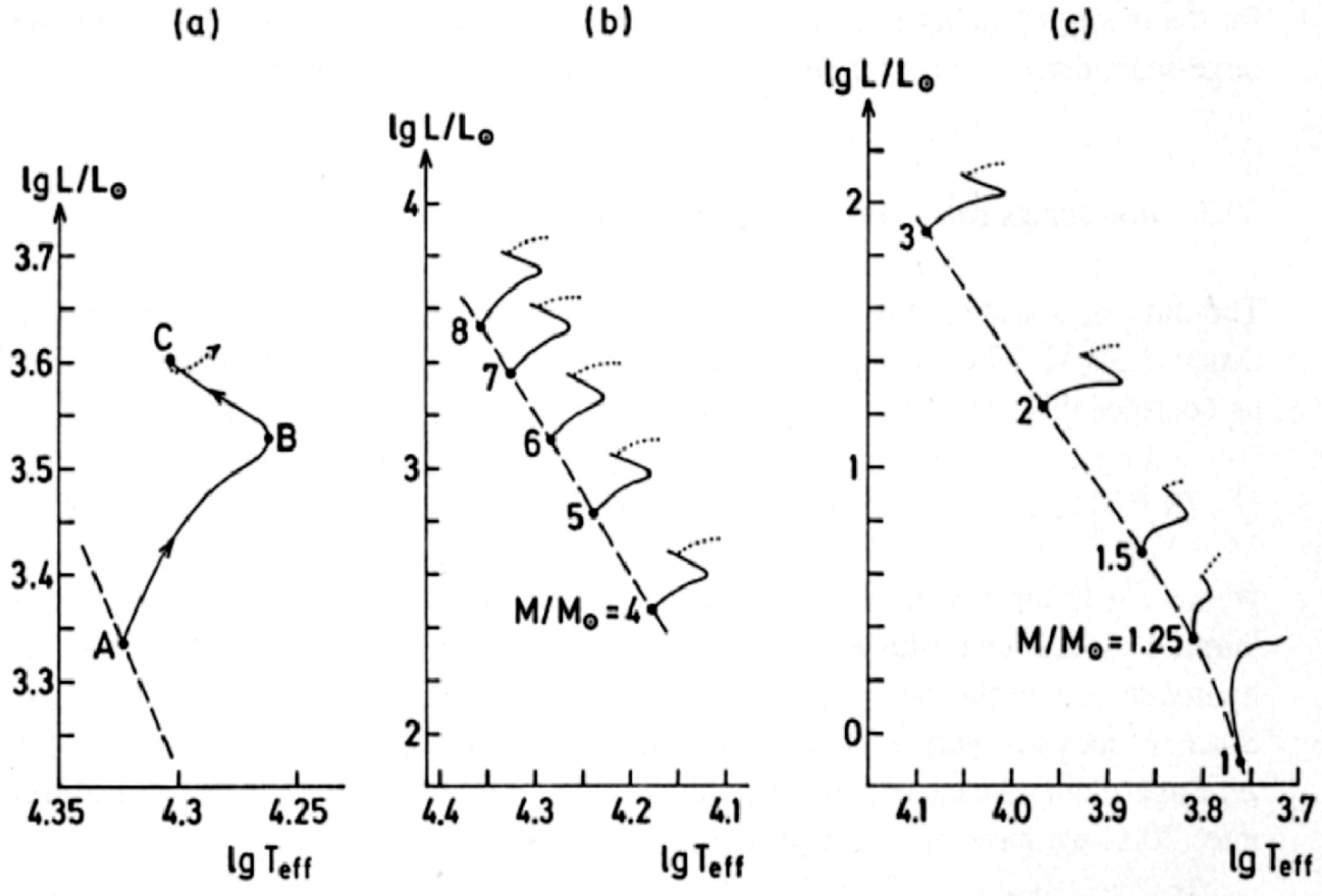
Low mass stars: H burned in pp-chains, High mass: H burned in the CNO-cycle

Main Sequence



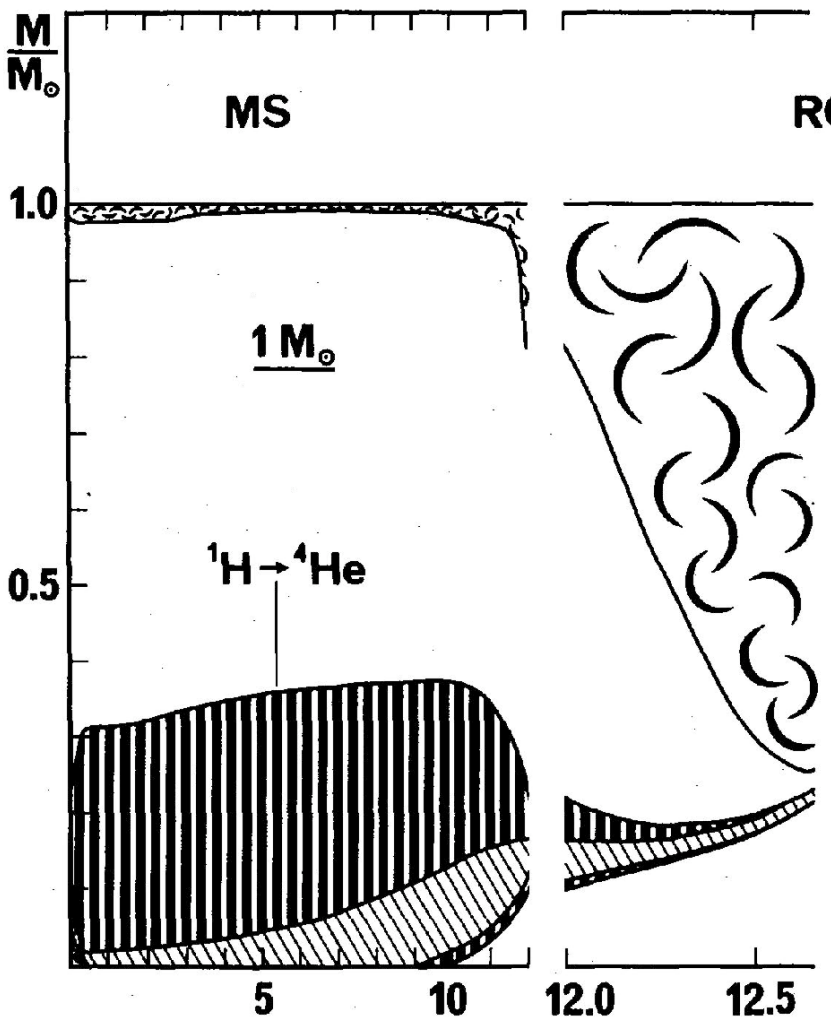
Kippenhahn-diagram: Internal Structure of Main Sequence stars

Main Sequence Evolution



main sequence evolution from zero age to helium exhaustion

Post Main Sequence

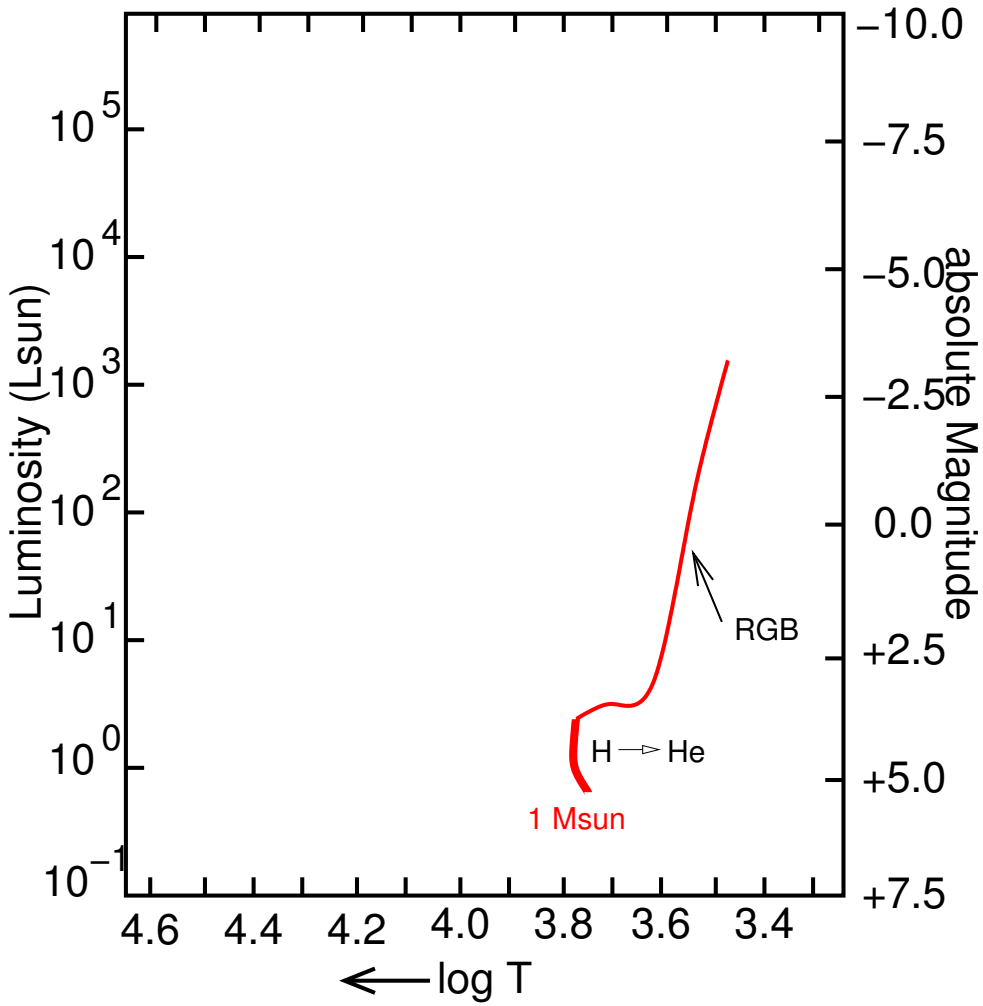


(Maeder & Meynet, 1989)

Once H is exhausted in center: H continues to burn in a shell around the He core ("shell burning").

For stars with $M \lesssim 1\,M_\odot$: Star reacts by expanding convective envelope until it is almost fully convective.

Post Main Sequence



(after Iben, 1991)

Once H is exhausted in center: H continues to burn in a shell around the He core ("shell burning").

For stars with $M \lesssim 1\,M_\odot$:

Star reacts by expanding convective envelope until it is almost fully convective.

$\Longrightarrow$ luminosity increases, temperature decreases

$\Longrightarrow$ motion in HRD horizontally towards the right, then upwards to higher L: red giant stage.

Post Main Sequence

Reminder: stars are in hydrostatic equilibrium: inwards gravitational pressure balanced by outwards gas pressure

Since the gas pressure is $P = nkT$: energy source needed to heat gas (=fusion).

This is a problem for the core during the red giant stage, as virtually no fusion ongoing

$\Longrightarrow$ Core gets compressed

$\Longrightarrow$ ρ and T increase

BUT:

collapse cannot continue indefinitely!

$\Longrightarrow$ once ρ has increased appreciably, there must be a point where quantum mechanical effects become important.

QM interlude

Quantum mechanics: The Pauli exclusion principle:

> For particles such as electrons ("Fermions"), at least one of their quantum numbers must be different.

Quantum numbers are, e.g.,

- position (x, y, z),
- momentum p ($p_x = mv_x$, $p_y = mv_y$, $p_z = mv_z$),
- angular momentum,
- spin (s)

All of these numbers are "quantized", i.e., can only have discrete values (e.g., spin: $+1/2, -1/2$).

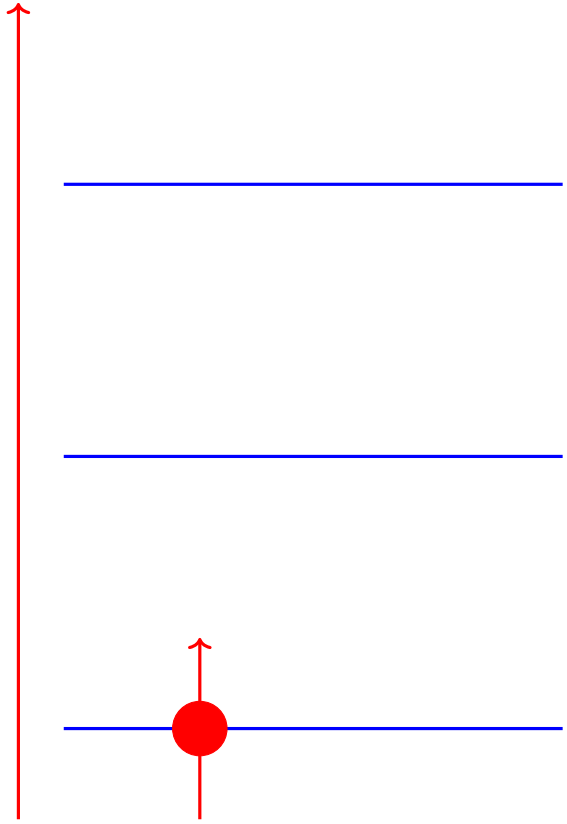
Heisenberg's principle: (6-d) phase space is quantized: $\Delta p \times \Delta V \approx h^3$

Each cell in phase space can host two electrons of different spin

In a typical gas, this is not a problem ("phase space is (almost) empty") once it becomes dense $\Longrightarrow$ exclusion principle kicks in.

QM interlude

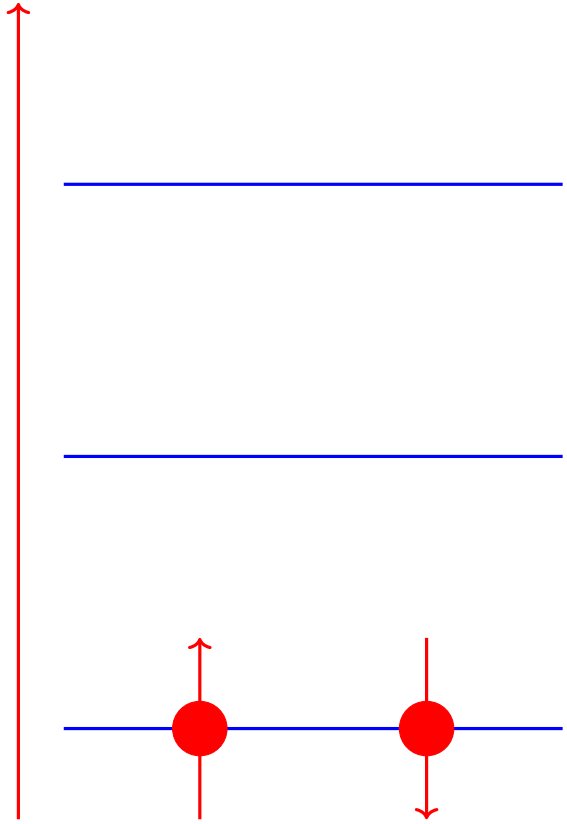
Effect of high density on electron energy



Energy of electrons at the same position in space

QM interlude

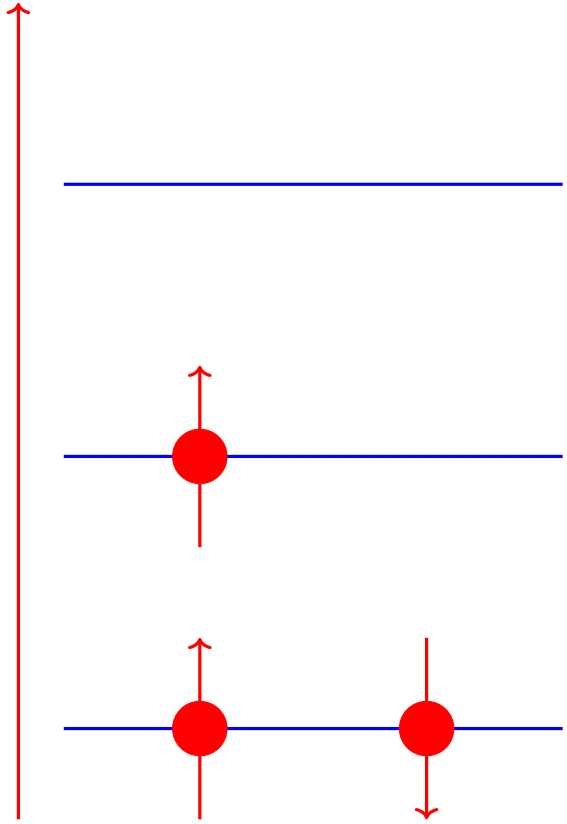
Effect of high density on electron energy



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QM interlude

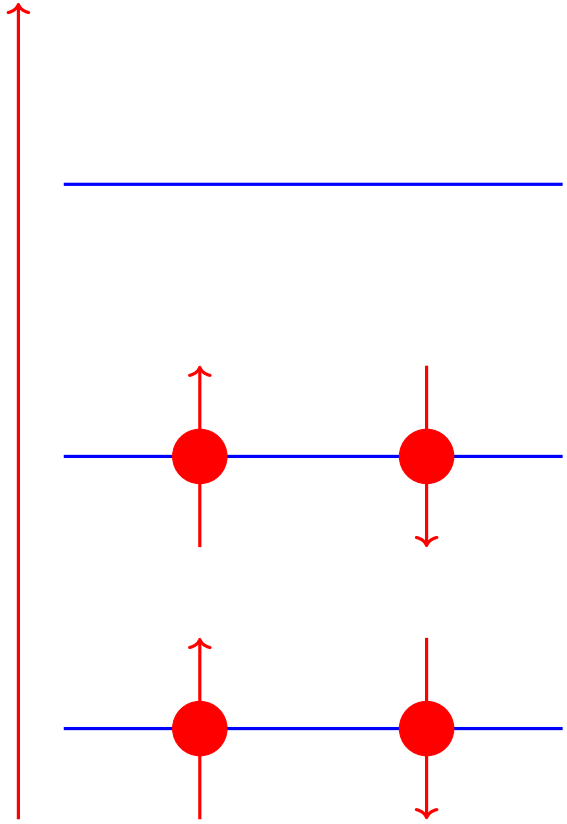
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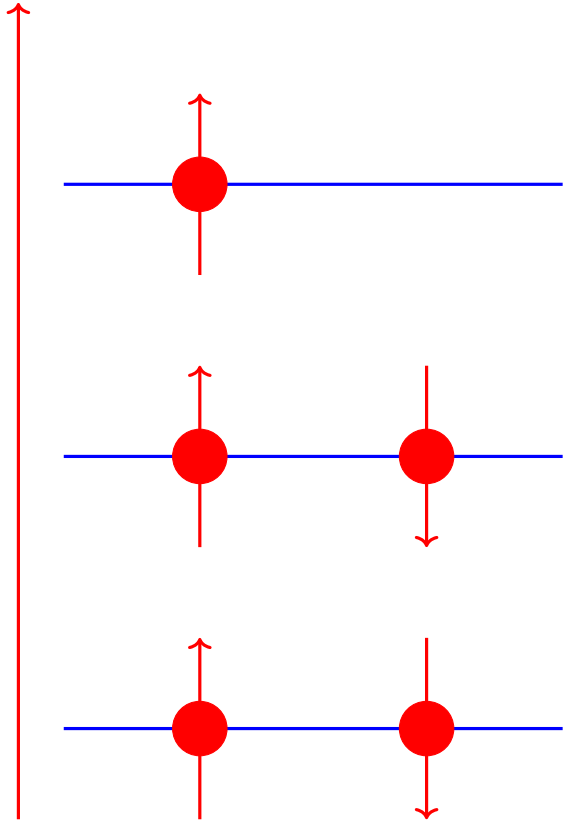
Effect of high density on electron energy



Energy of electrons at the same position in space

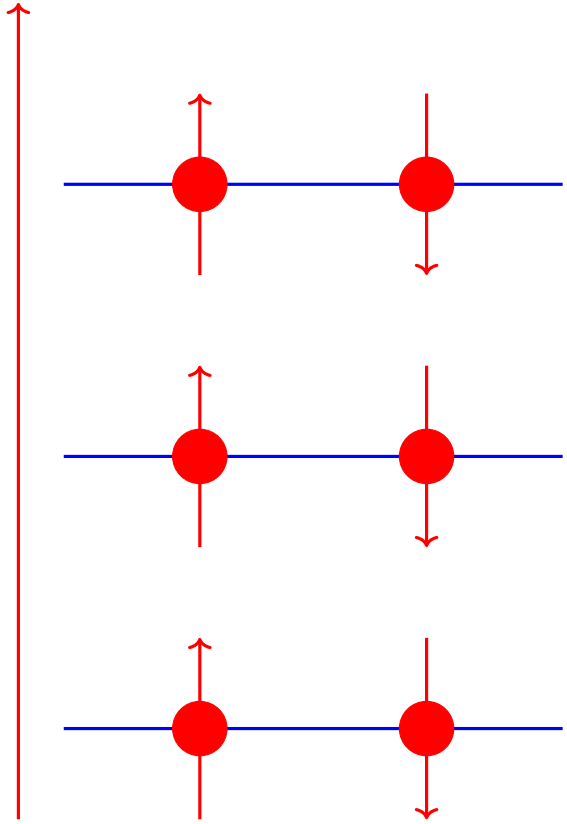
QM interlude

Effect of high density on electron energy



Energy of electrons at the same position in space

QM interlude

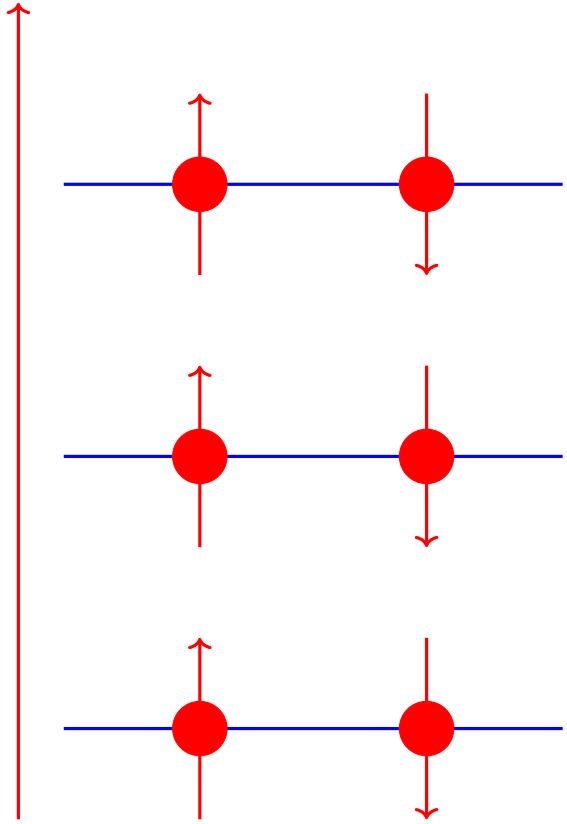


Energy of electrons at the same position in space

Effect of high density on electron energy:

In degenerate electron gases, electrons have much higher energies than in thermal gas.

QM interlude



Energy of electrons at the same position in space

Effect of high density on electron energy:

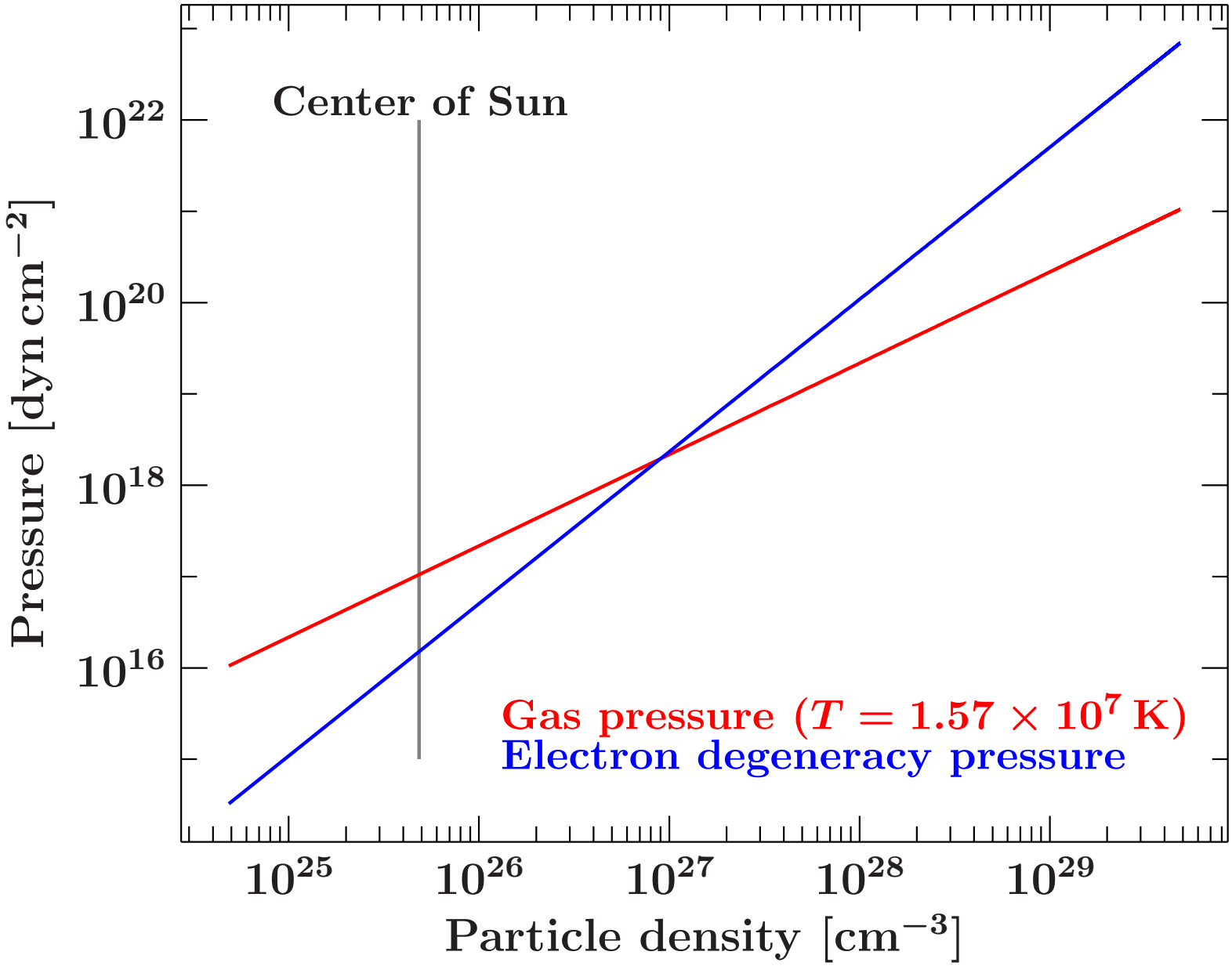
In degenerate electron gases, electrons have much higher energies than in thermal gas.

Interaction of electrons results in degeneracy pressure:

$$P = \frac{\hbar^2}{m_e} n_e^{5/3} \propto \rho^{5/3}$$

Note: The degeneracy pressure is independent of the temperature!

QM interlude



Post Main Sequence

Differences in stellar behavior between equation of states (EoS):

EoS of ideal gas: $P \propto \rho T$

Energy production increases:

$\Longrightarrow$ Temperature increases

$\Longrightarrow$ Pressure increases

$\Longrightarrow$ Expansion

$\Longrightarrow$ Temperature decreases

Closed loop system

"self stabilizing"

Post Main Sequence

Differences in stellar behavior between equation of states (EoS):

EoS of ideal gas: $P \propto \rho T$

Energy production increases:

$\Longrightarrow$ Temperature increases

$\Longrightarrow$ Pressure increases

$\Longrightarrow$ Expansion

$\Longrightarrow$ Temperature decreases

EoS of degenerate gas: $P \propto \rho^{5/3}$

Energy production increases:

$\Longrightarrow$ Temperature increases

$\Longrightarrow$ Pressure *does not* increase

$\Longrightarrow$ Energy production increases

$\Longrightarrow$ Temperature increases

$\Longrightarrow \ldots$

Thermal run-away

Closed loop system

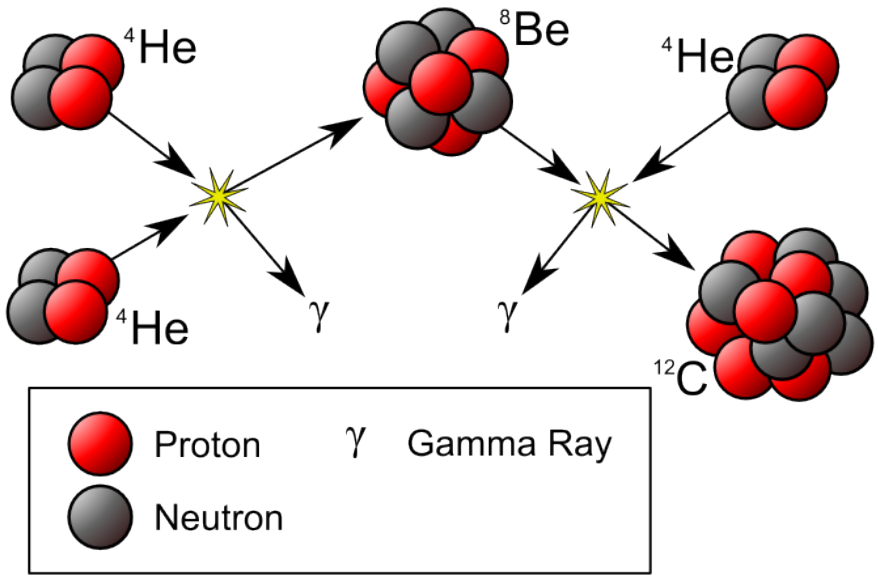
Open control loop

"self stabilizing"

It is only after the thermal energy $>$ Fermi energy that the degeneracy is suspended

In German: "Regelkreis" versus "Teufelskreis"

Post Main Sequence



In the degenerate core, once $T_{core} \sim 100 \times 10^6$ K: Triple alpha process starts:

$$^4\text{He} + {}^4\text{He} \leftrightarrow {}^8\text{Be}$$
$$^8\text{Be} + {}^4\text{He} \rightarrow {}^{12}\text{C}$$

Since ^{8}Be has a half life of only 2.6×10^{-16} s: this can only work effectively if 3 α-particles collide.

But core is degenerate:

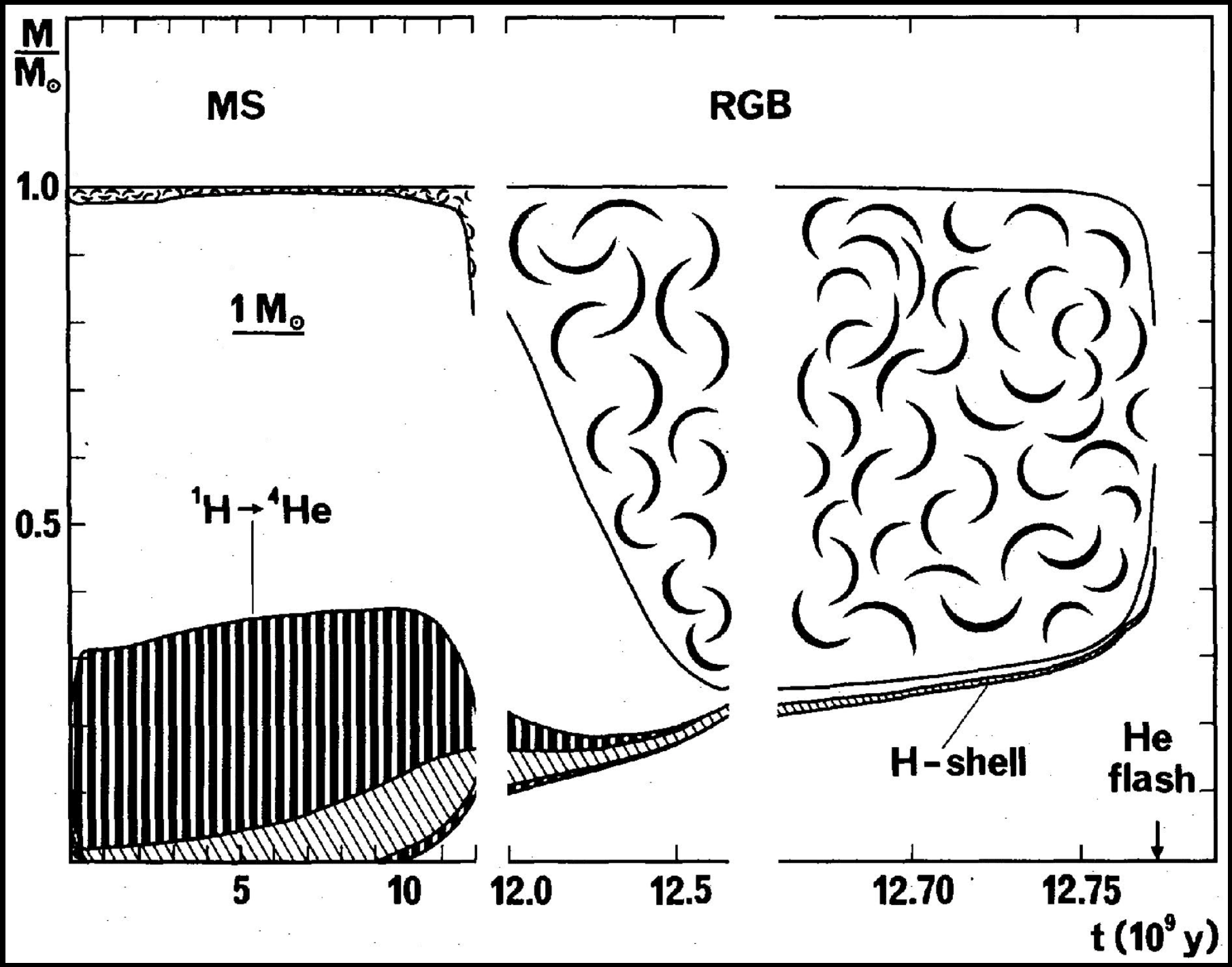
$\Longrightarrow$ High thermal conductivity of electrons

$\Longrightarrow$ core has uniform temperature

$\Longrightarrow$ 3α onset is rapid

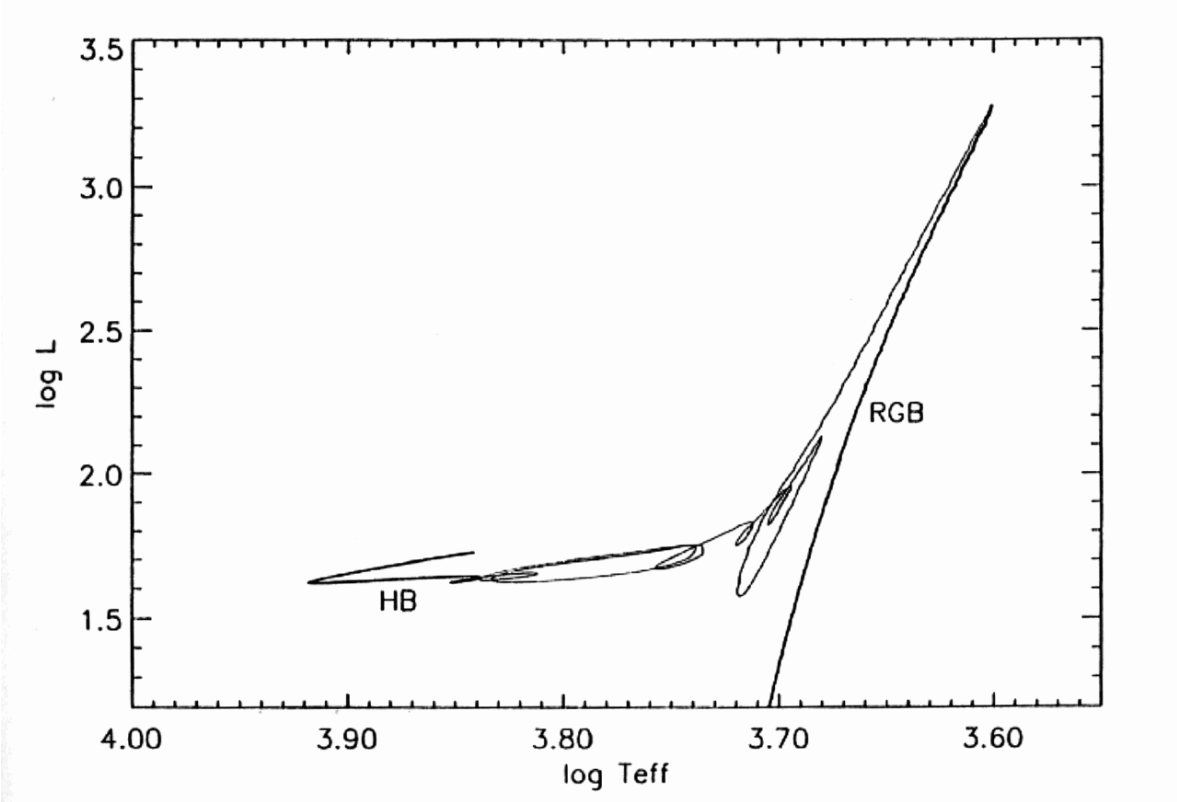
$\Longrightarrow$ He flash

Not seen on surface ("buffered" by convective envelope).



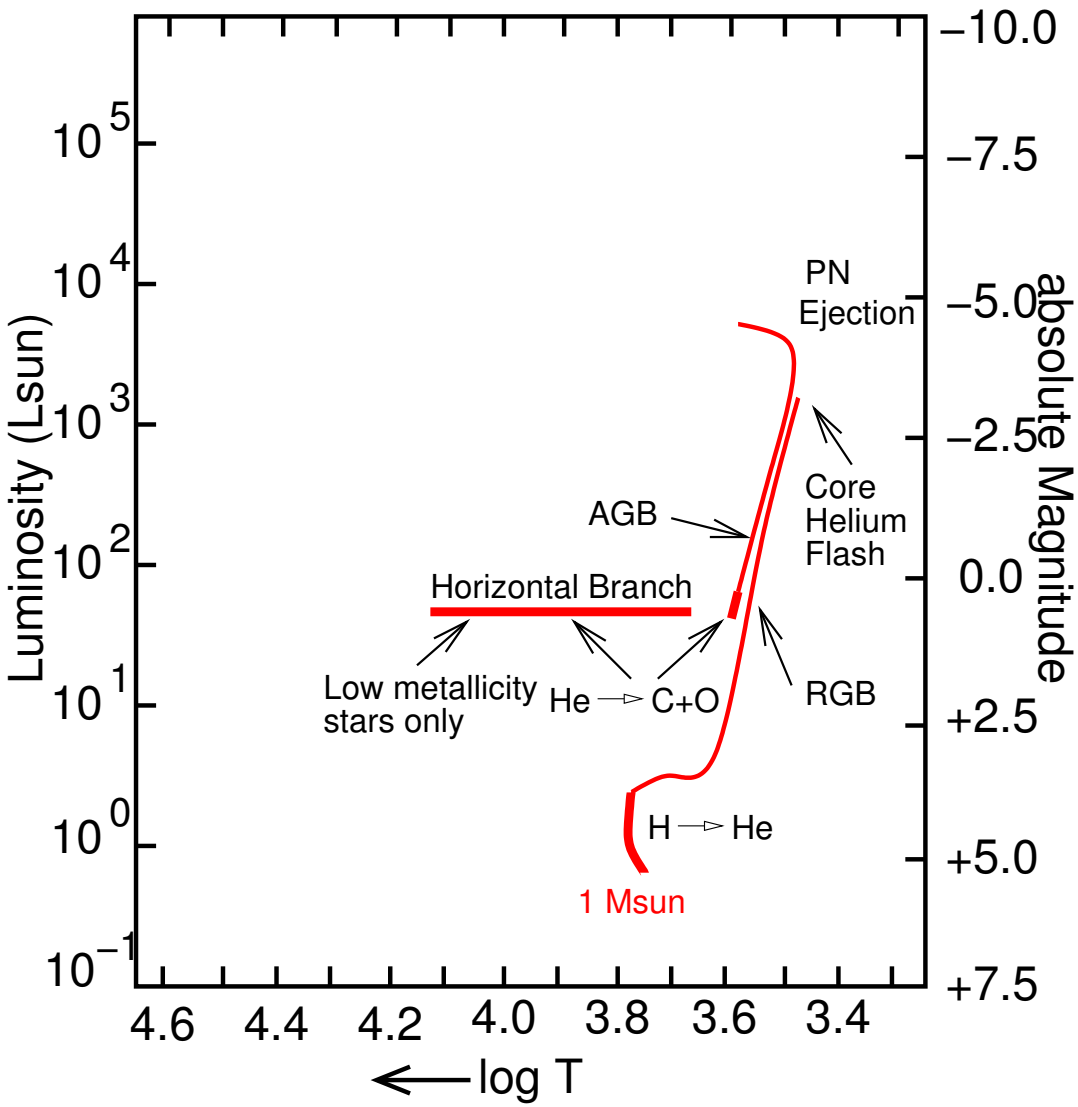
Evolution of the structure of a 1 $M_\odot$ star to the Helium flash (Maeder & Meynet, 1989).

Post Main Sequence



- In reality: multiple flashes (total duration ~1.5 × 10^6 years)
- He-burning in core, H-burning in a shell ("horizontal branch")
- Life time on horizontal branch: 1–2 × 10^8 years

Post Main Sequence

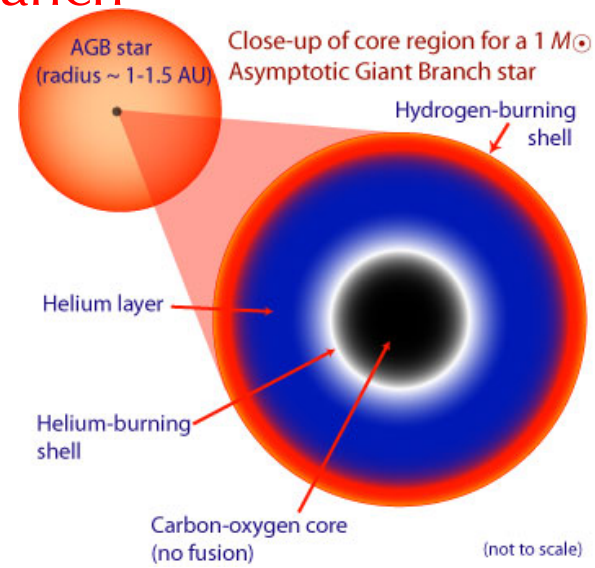


after Iben, 1991

After He-flash: star has He burning core and H burning shell

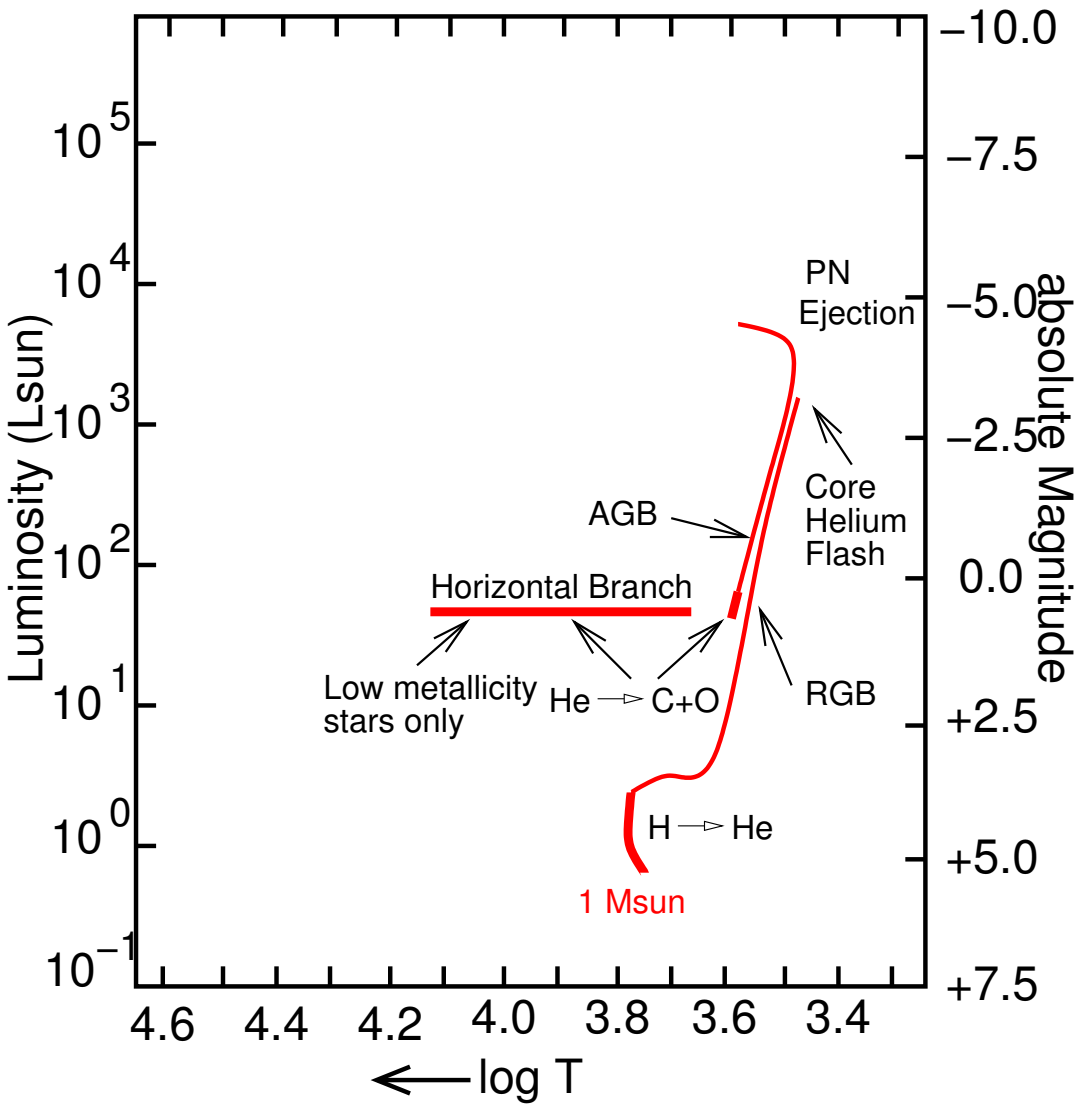
$\Longrightarrow$ starts to expand again

$\Longrightarrow$ "asymptotic giant branch"



CSIRO

Post Main Sequence



after Iben, 1991

Shell sources are not stable: cyclical H- and He-burning ("thermal pulses")

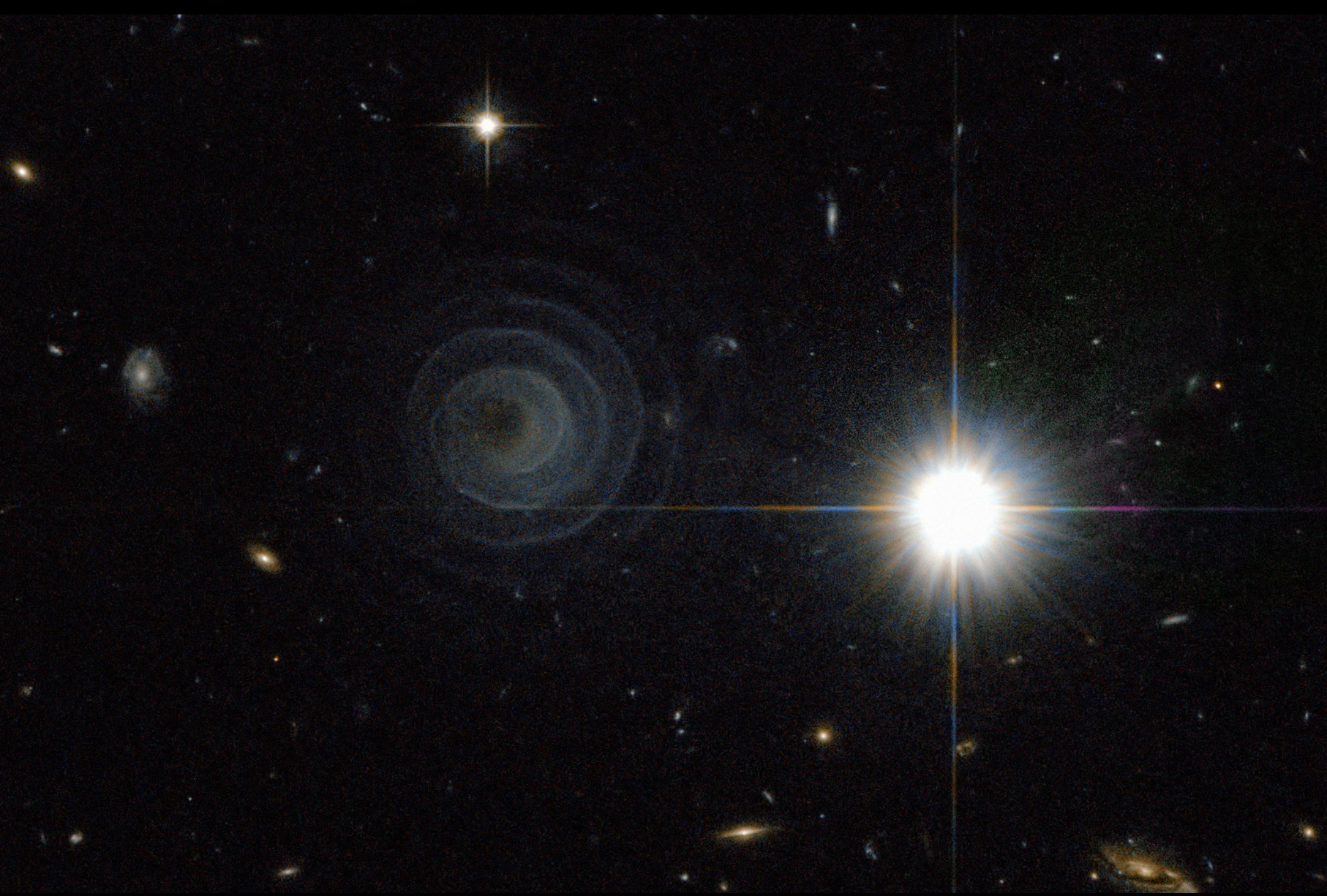
Effect of He core being unable to transport energy away quickly enough.

Outer layers are very weakly bound

$\Longrightarrow$ ejection of outer layers

~50% of total mass!

$\Longrightarrow$ inner (hotter) parts of star become visible.



Pre-planetary nebula: IRAS 23166+1655 around the star LL Pegasi

(NASA/ESA/HST/HLA; Copyright: Pestana & Villaverde)



Abell 39 (WIYN, AURA, NOAO, NSF)

planetary nebulae: material ejected during AGB phase, photoionized once remaining core of former star has shed enough mass to emit UV photons.



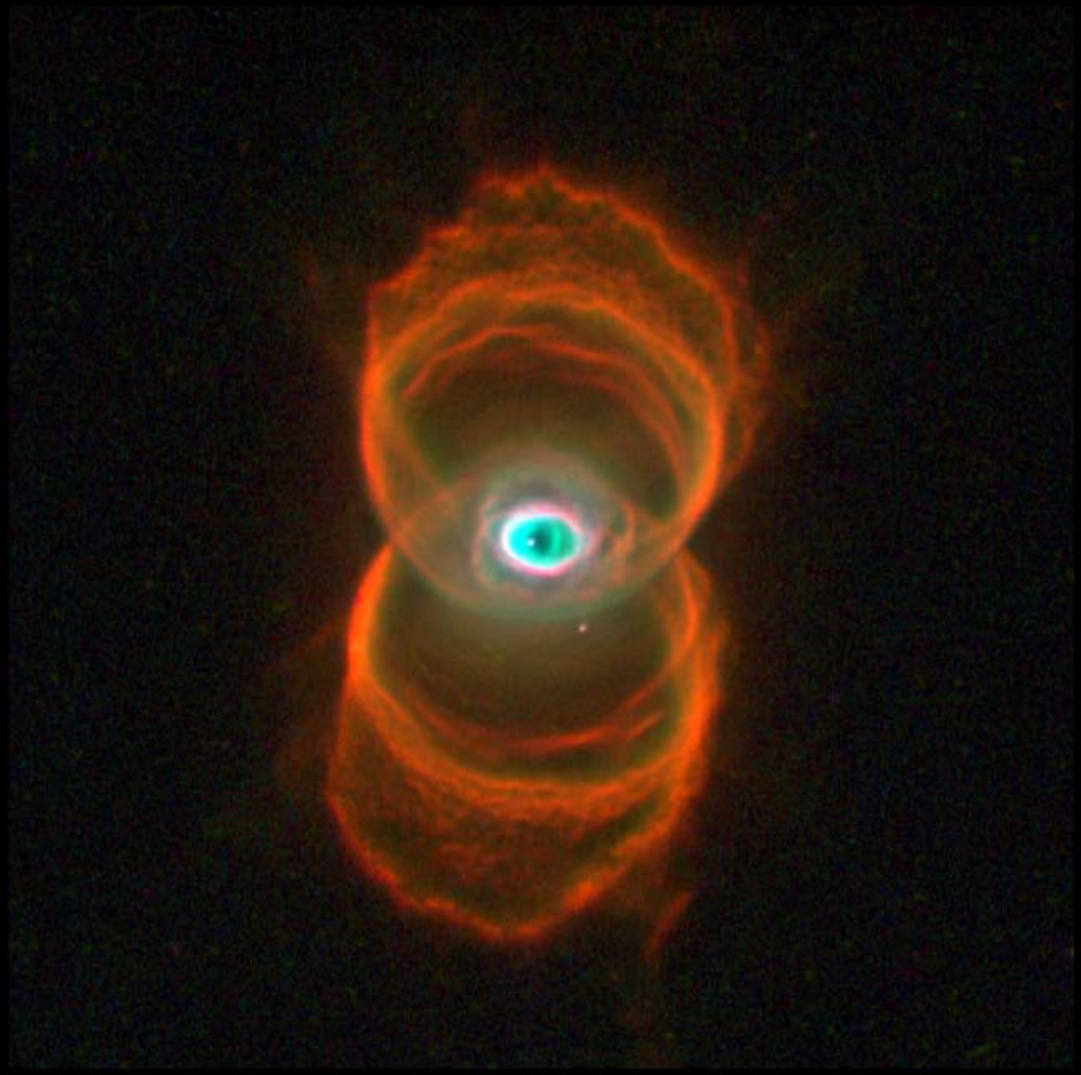
Ring Nebula (HST/STScI/NASA)

planetary nebulae: material ejected during AGB phase, photoionized once remaining core of former star has shed enough mass to emit UV photons.

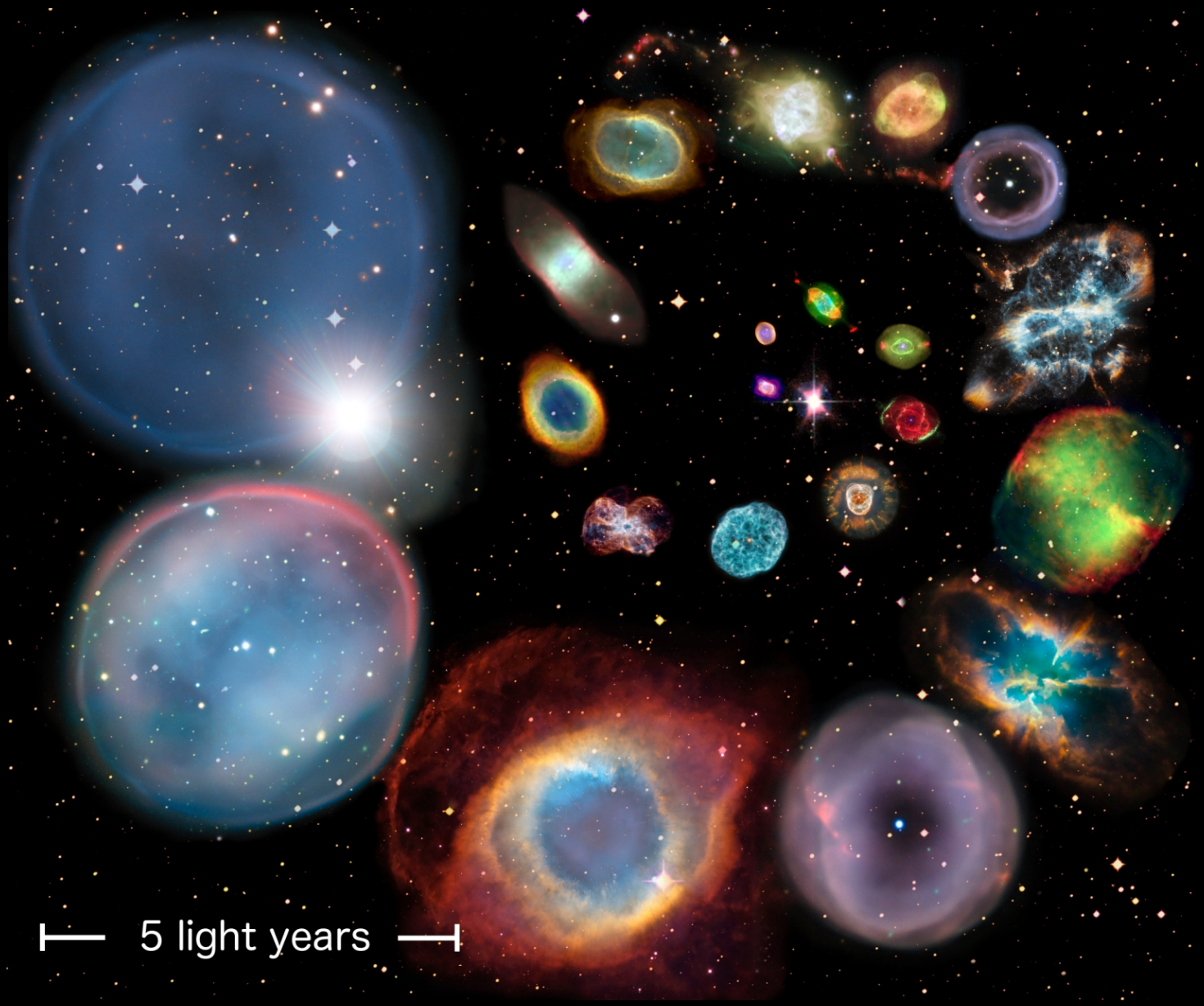


ESP PR 21/98

planetary nebulae: material ejected during AGB phase, photoionized once remaining core of former star has shed enough mass to emit UV photons.



planetary nebulae: material ejected during AGB phase, photoionized once remaining core of former star has shed enough mass to emit UV photons.

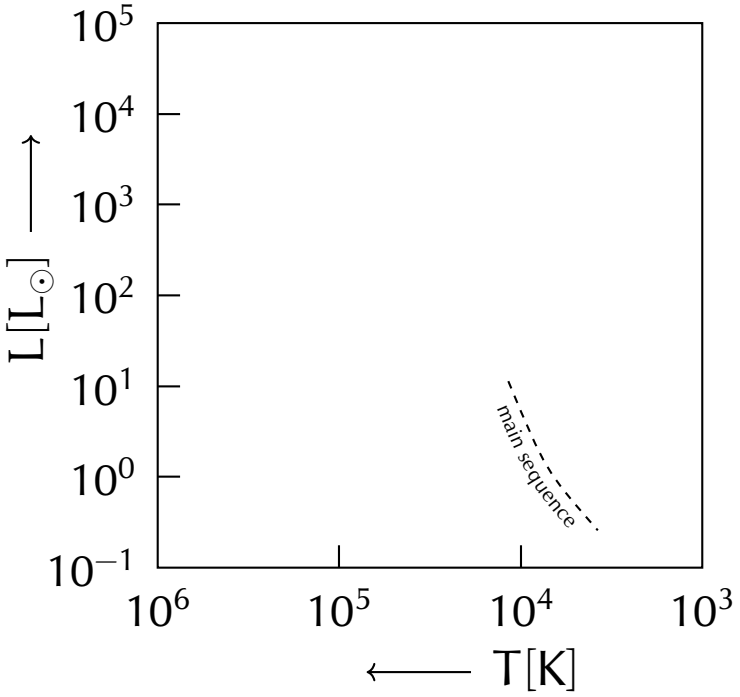


(HKU Physics, NASA/ESA)

planetary nebulae: material ejected during AGB phase, photoionized once remaining core of former star has shed enough mass to emit UV photons.

The Overall Picture of Low Mass Stellar Evolution

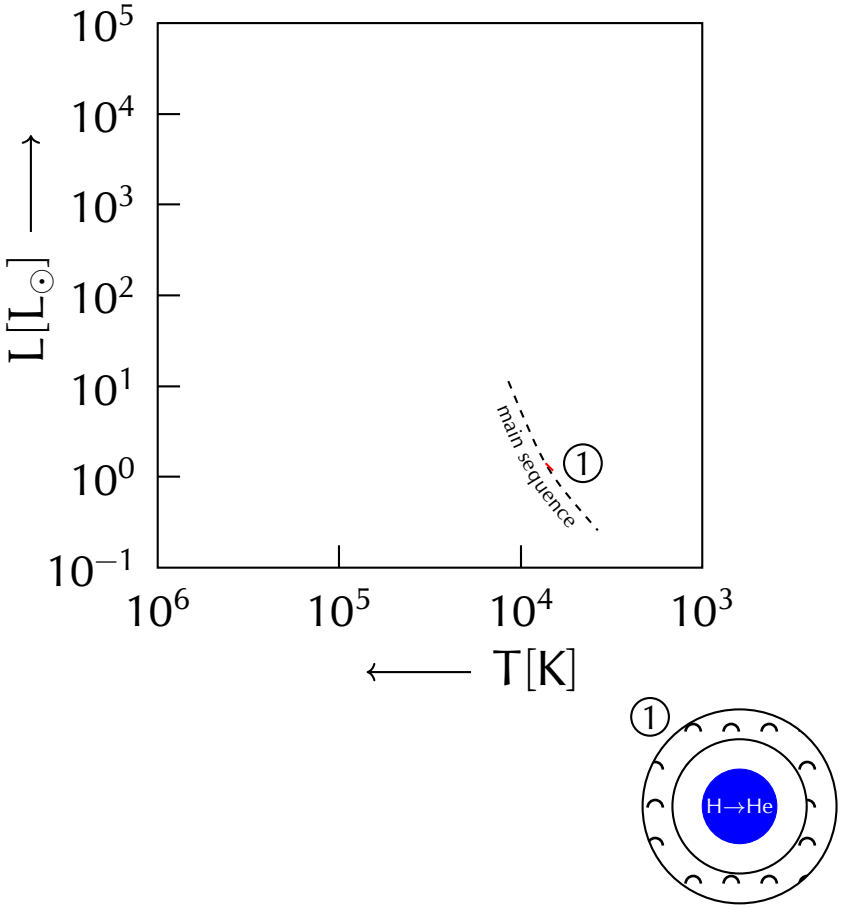
Summary: Evolution of Low Mass Stars:



The Overall Picture of Low Mass Stellar Evolution

Summary: Evolution of Low Mass Stars:

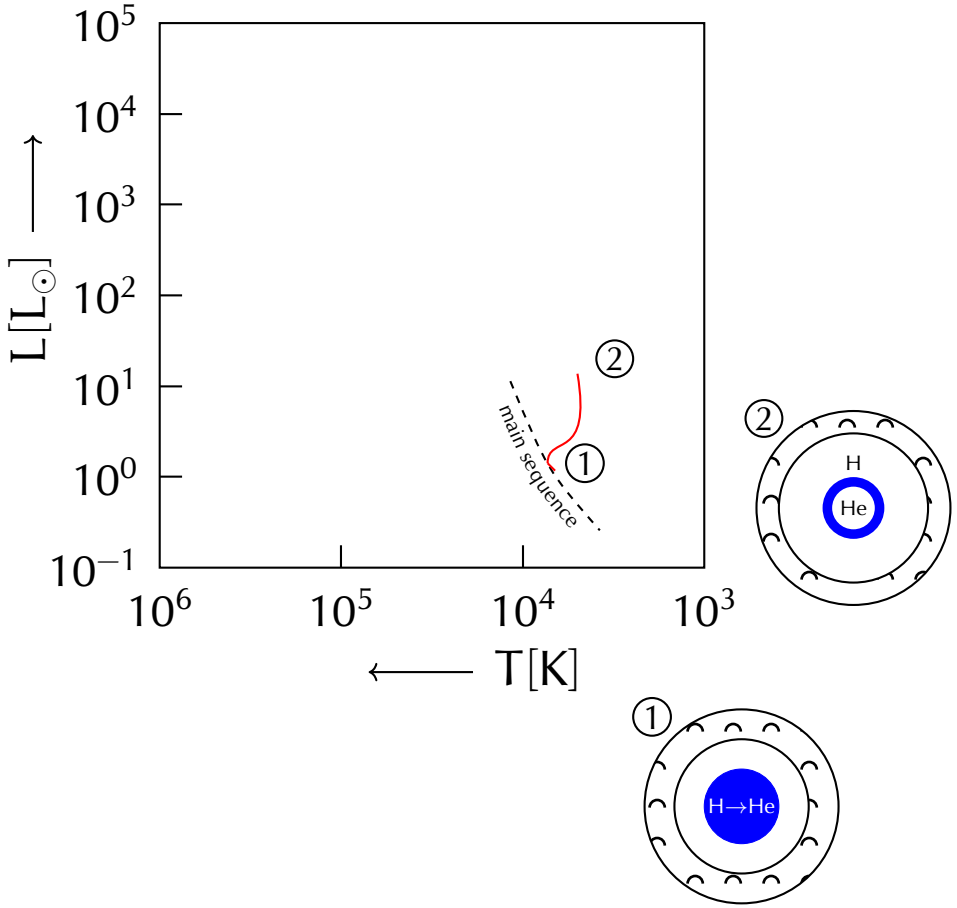
1. Main Sequence (MS) = Core H burning



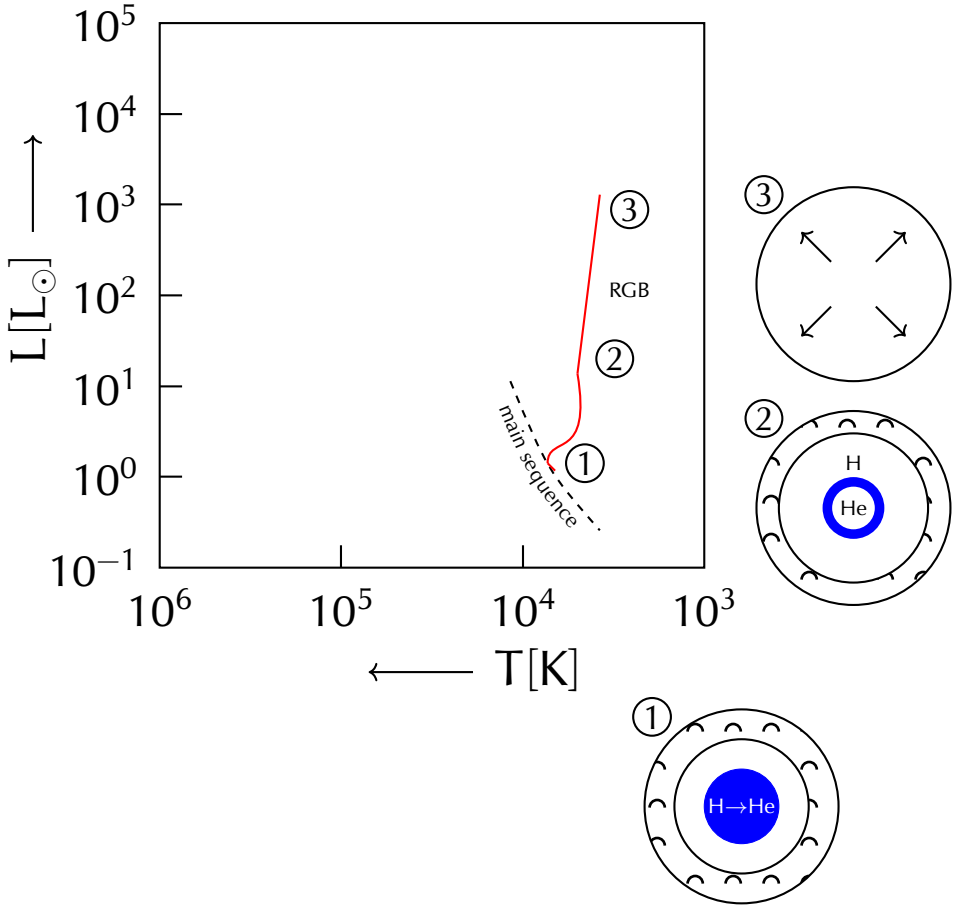
The Overall Picture of Low Mass Stellar Evolution

Summary: Evolution of Low Mass Stars:

1. Main Sequence (MS) = Core H burning
2. Red Giant Branch (RGB)
   = H shell burning



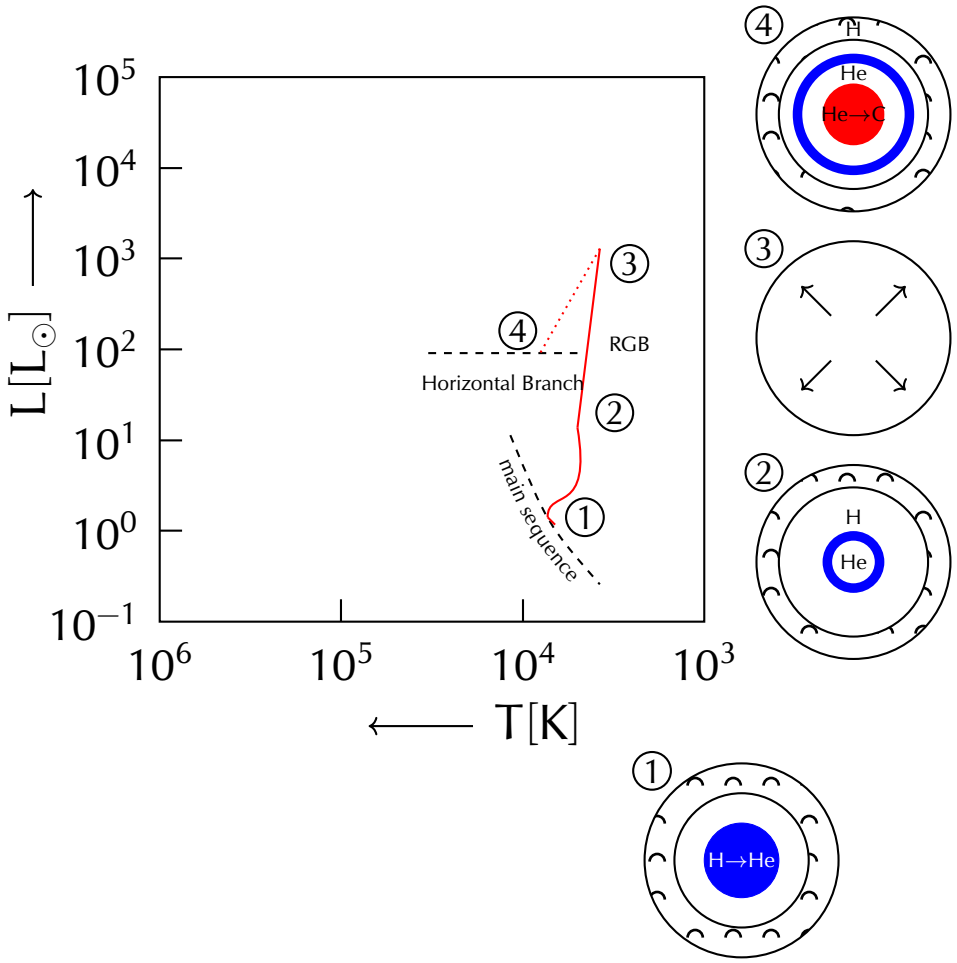
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Summary: Evolution of Low Mass Stars:

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   = helium ignition in degenerate electron gas

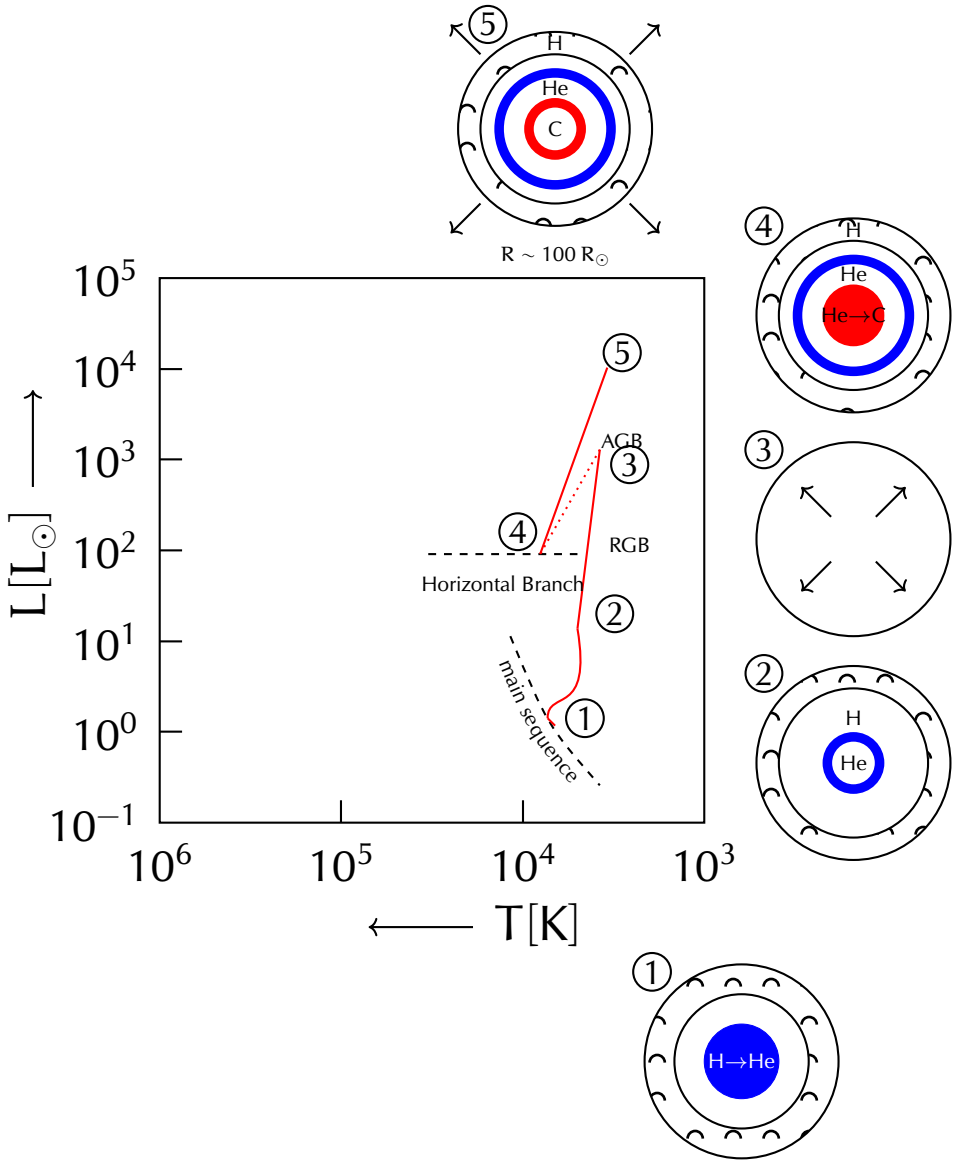
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Summary: Evolution of Low Mass Stars:

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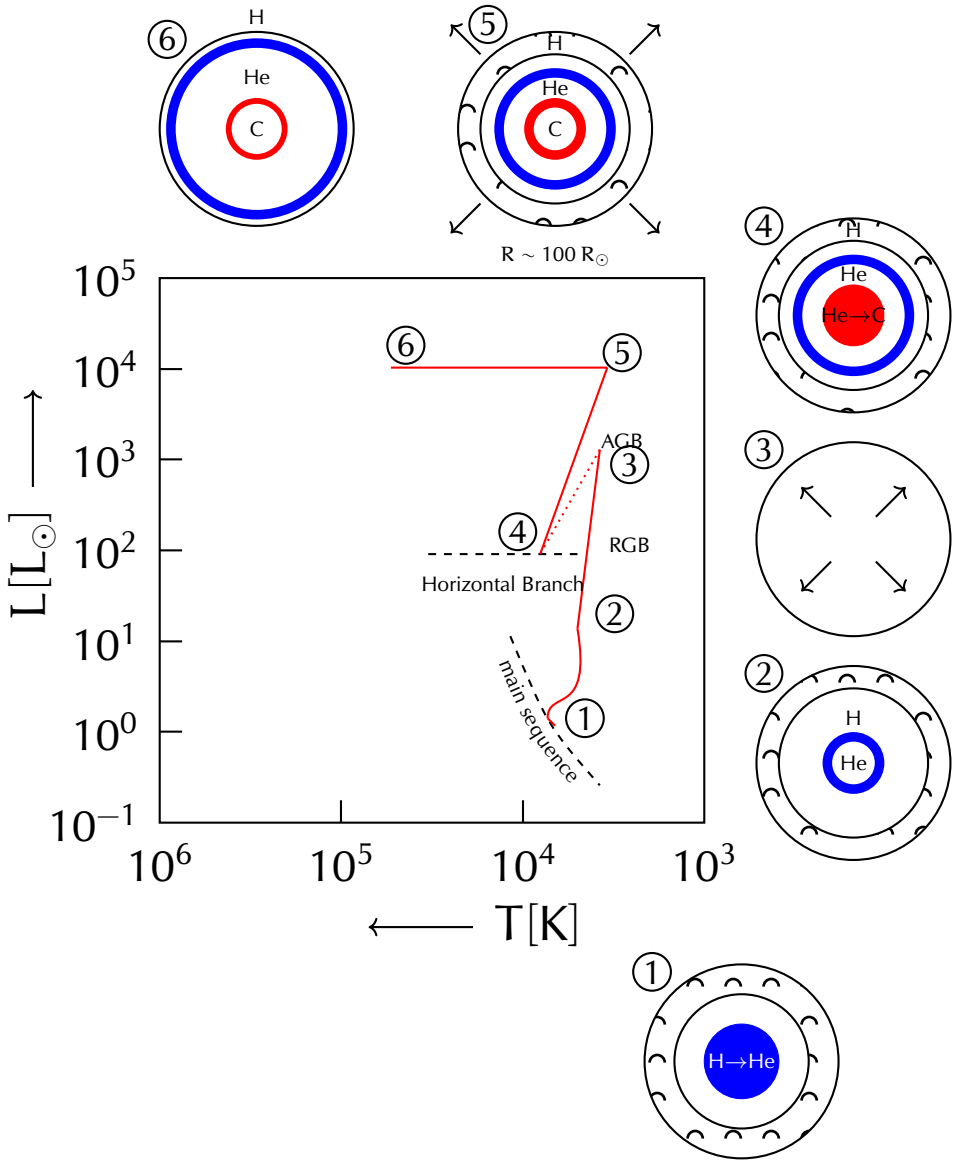
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5. Asymptotic Giant Branch (AGB) = 2 shell burning (H + He) Tip of AGB: envelope ejection through dust formation & pulsations

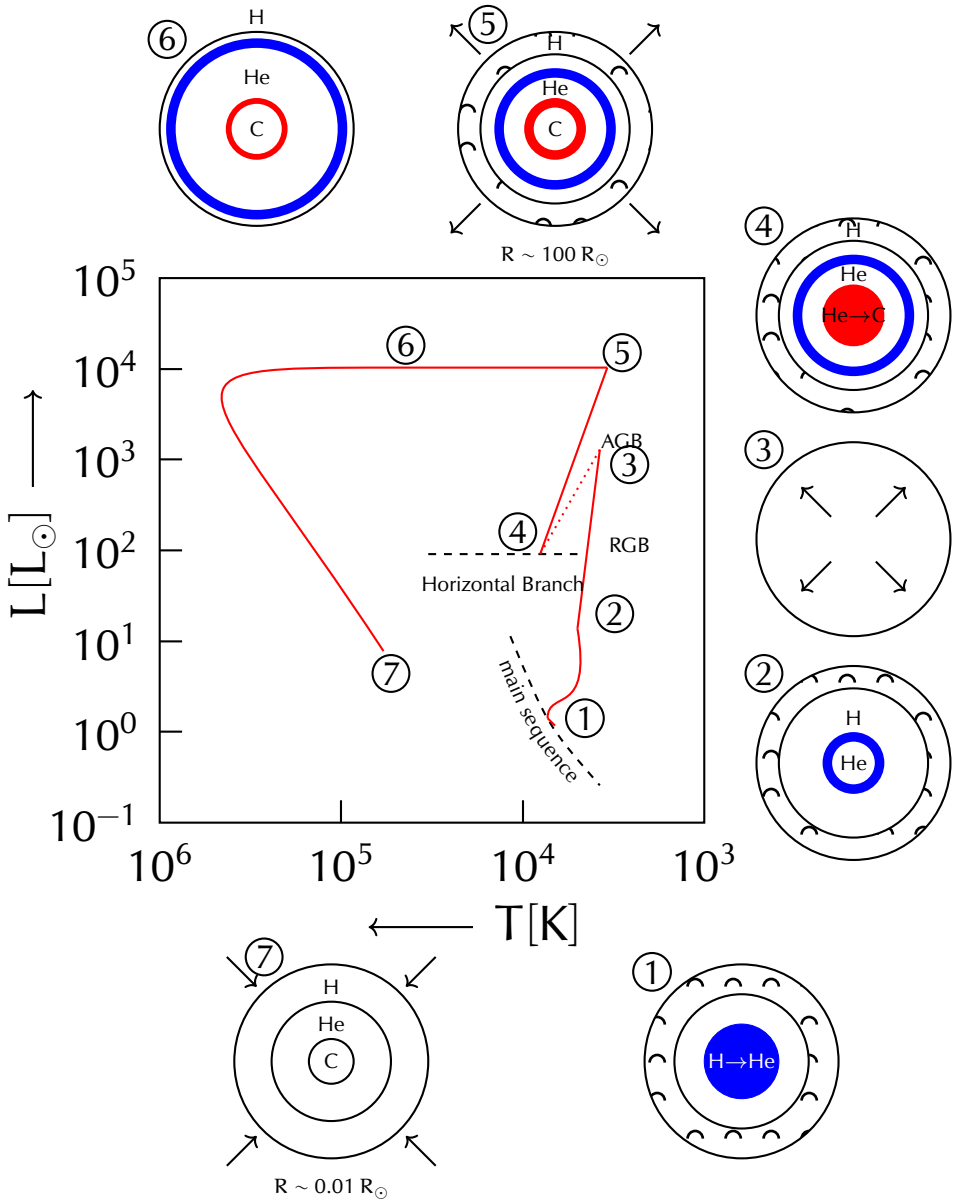
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The Overall Picture of Low Mass Stellar Evolution



Summary: Evolution of Low Mass Stars:

1. Main Sequence (MS) = Core H burning
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6. Planetary nebula (PN): hot star excites the ejected envelope to shine
7. White Dwarf = degenerate C/O remnant

Reminder: Main Sequence

Structure on the Main Sequence: Simulations show existence of two regimes:

lower main sequence : stars have structure similar to Sun:

- energy generation: pp-chain ($\epsilon \propto T^5$)
- inner radiative core
- convective envelope

upper main sequence : for central temperatures of 18×10^6 K (1.5 $M_\odot$ stars): pp-chain and CNO-cycle produce equal amounts of energy. Above that: CNO dominates.

- energy generation: CNO-cycle ($\epsilon \propto T^{17}$)
- inner convective core since energy generation from CNO cycle strongly peaked towards center.
- outer radiative envelope

Stars born with masses $> 8\,M_\odot$

Evolution on MS similar, however, faster than for low mass stars.

More massive stars reach threshold temperature for 3α and subsequent nuclear burning before reaching degeneracy

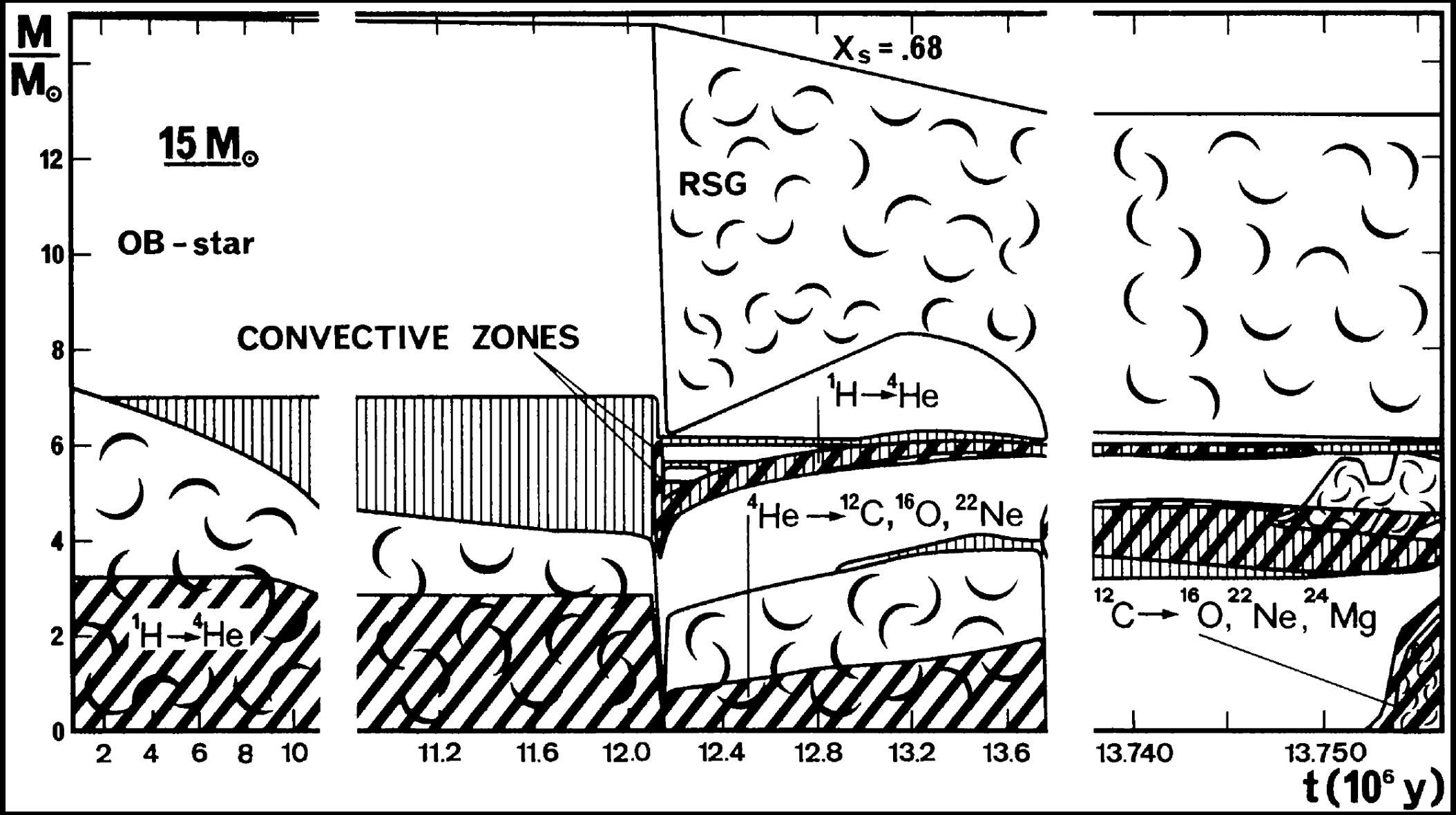
$\Longrightarrow$ He just starts to burn.

In these objects, higher order fusion processes can kick in (but are energetically unimportant): alpha reactions

$$^{12}\mathrm{C} + {}^{4}\mathrm{He} \rightarrow {}^{16}\mathrm{O} + \gamma$$
$$^{16}\mathrm{O} + {}^{4}\mathrm{He} \rightarrow {}^{20}\mathrm{Ne} + \gamma$$
$$^{20}\mathrm{Ne} + {}^{4}\mathrm{He} \rightarrow {}^{24}\mathrm{Mg} + \gamma$$

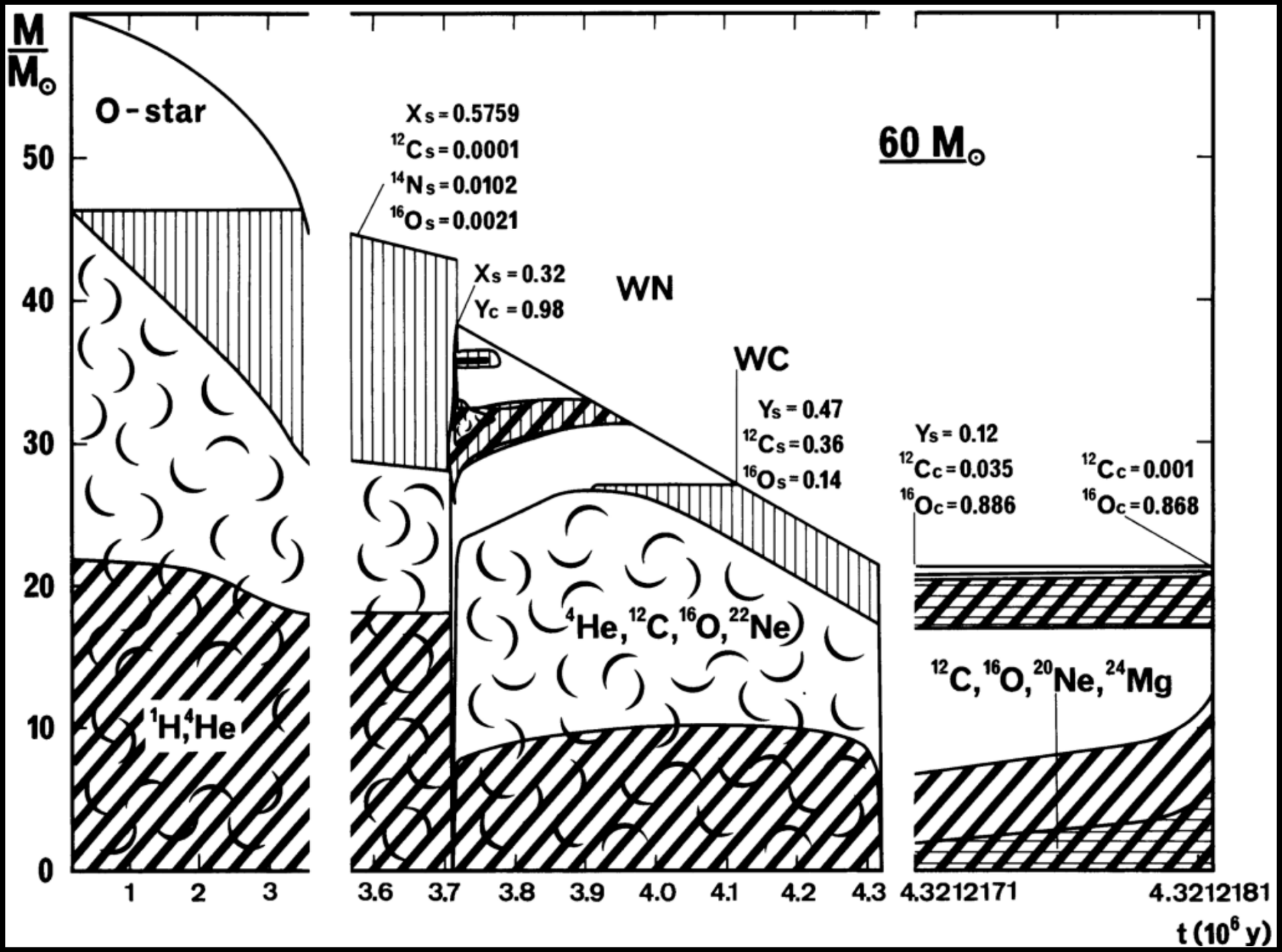
Outer layers continue H shell burning.

During evolution of star on red giant branch: convective envelope moves deeper into core, can mix fusion products into outer layers.



(Maeder & Meynet, 1987; RSG: Red Super Giant)

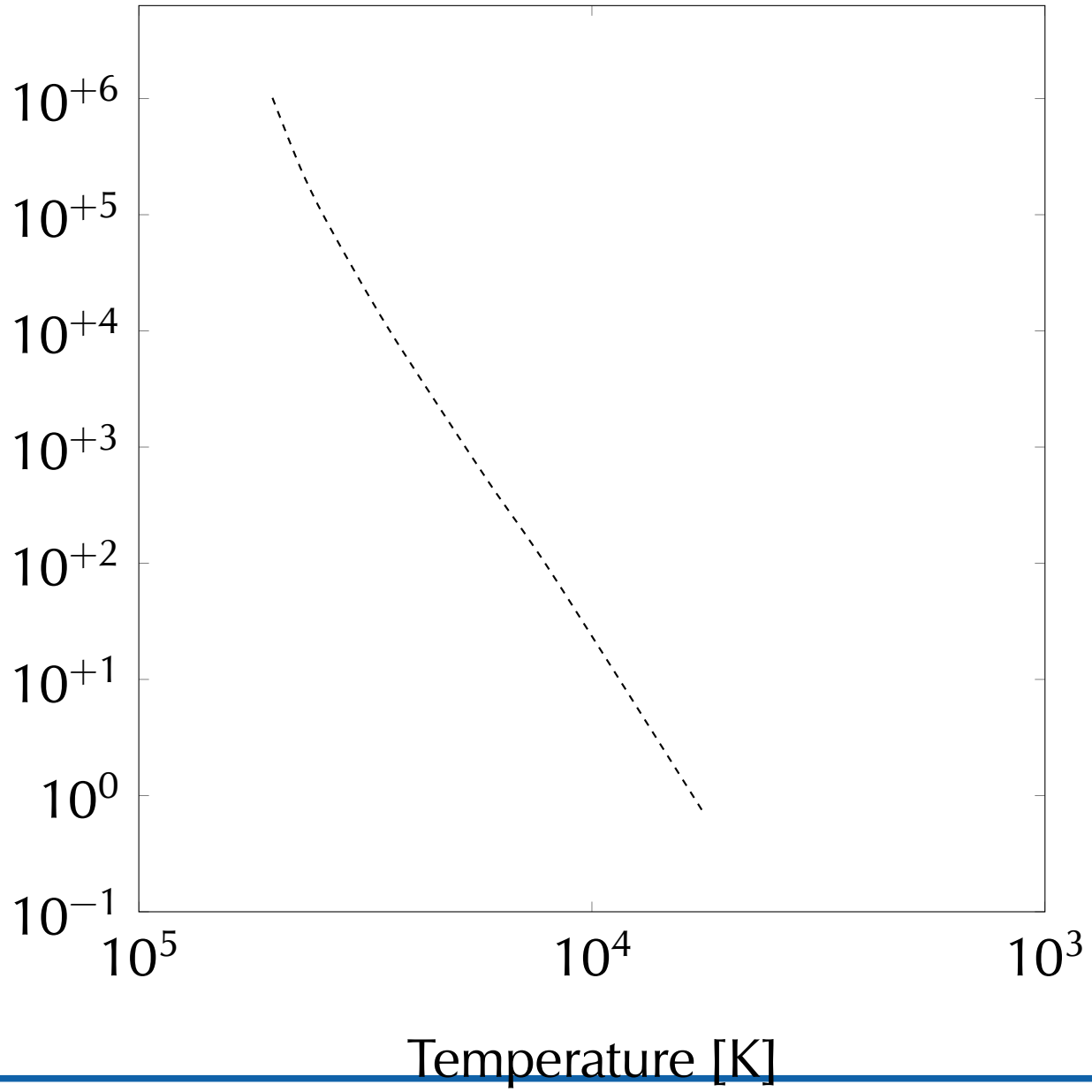
Evolution of the internal structure of a 15 $M_\odot$ star.



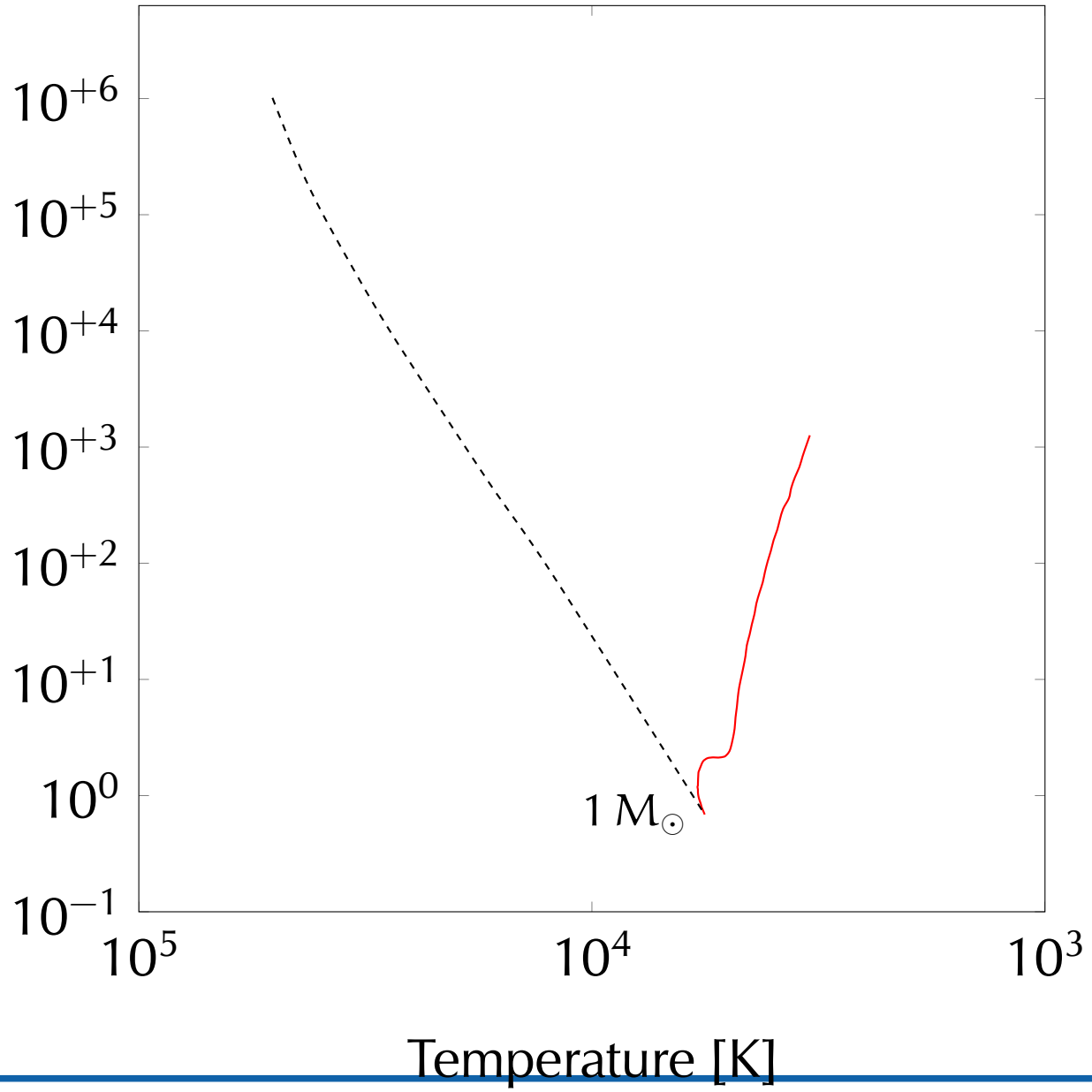
(Maeder & Meynet, 1987)

Evolution of the internal structure of a 60 $M_\odot$ star.

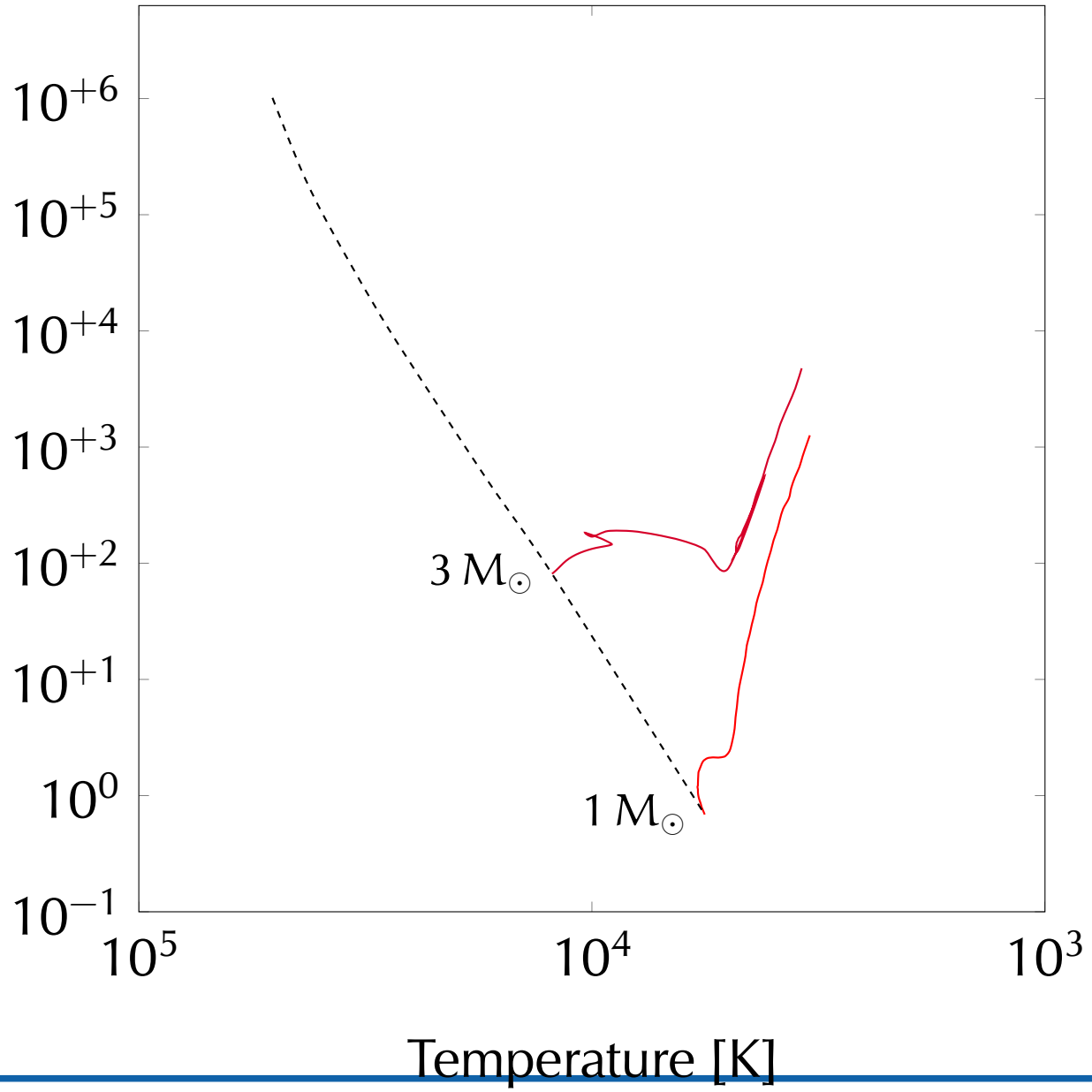
Stars born with masses $> 8\,M_\odot$



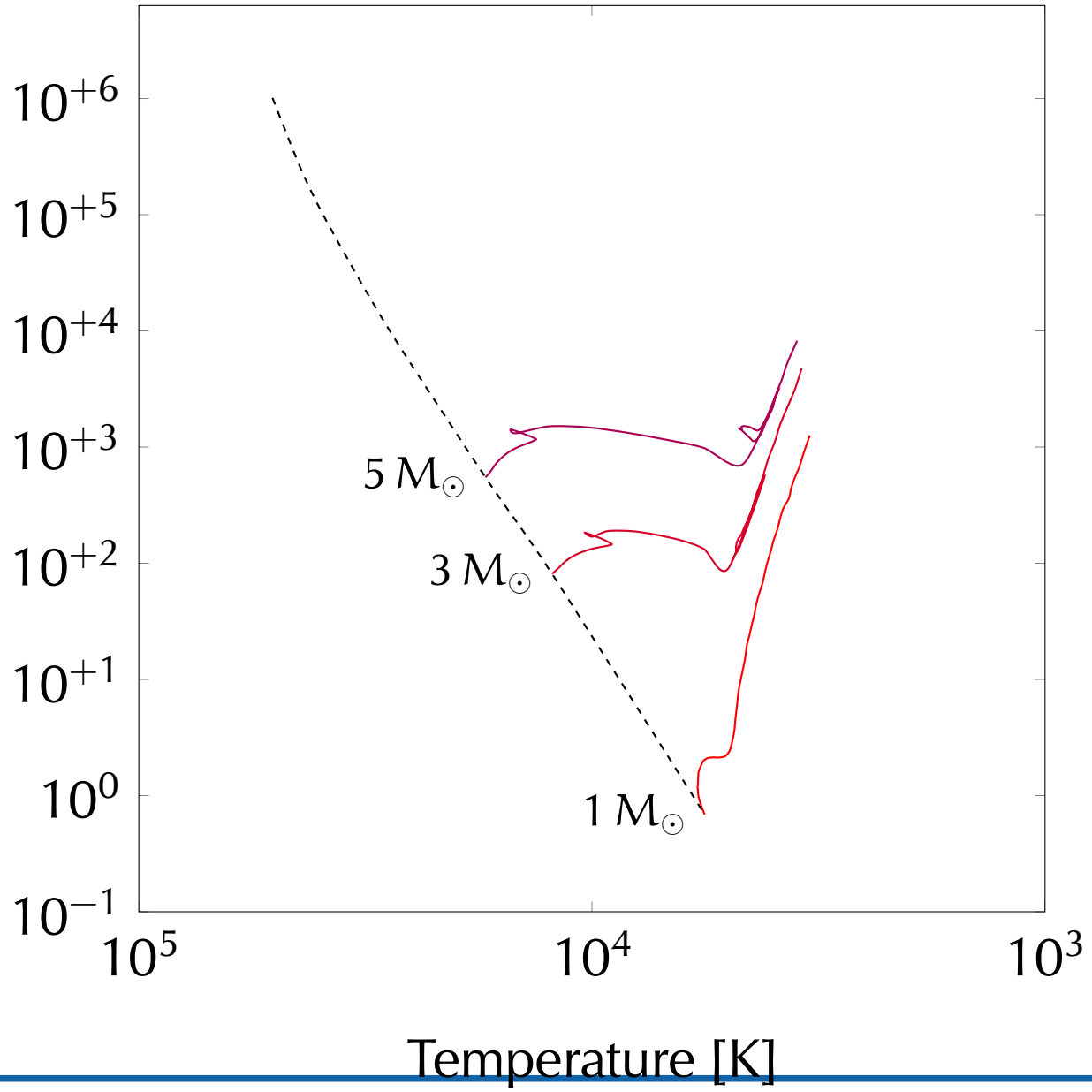
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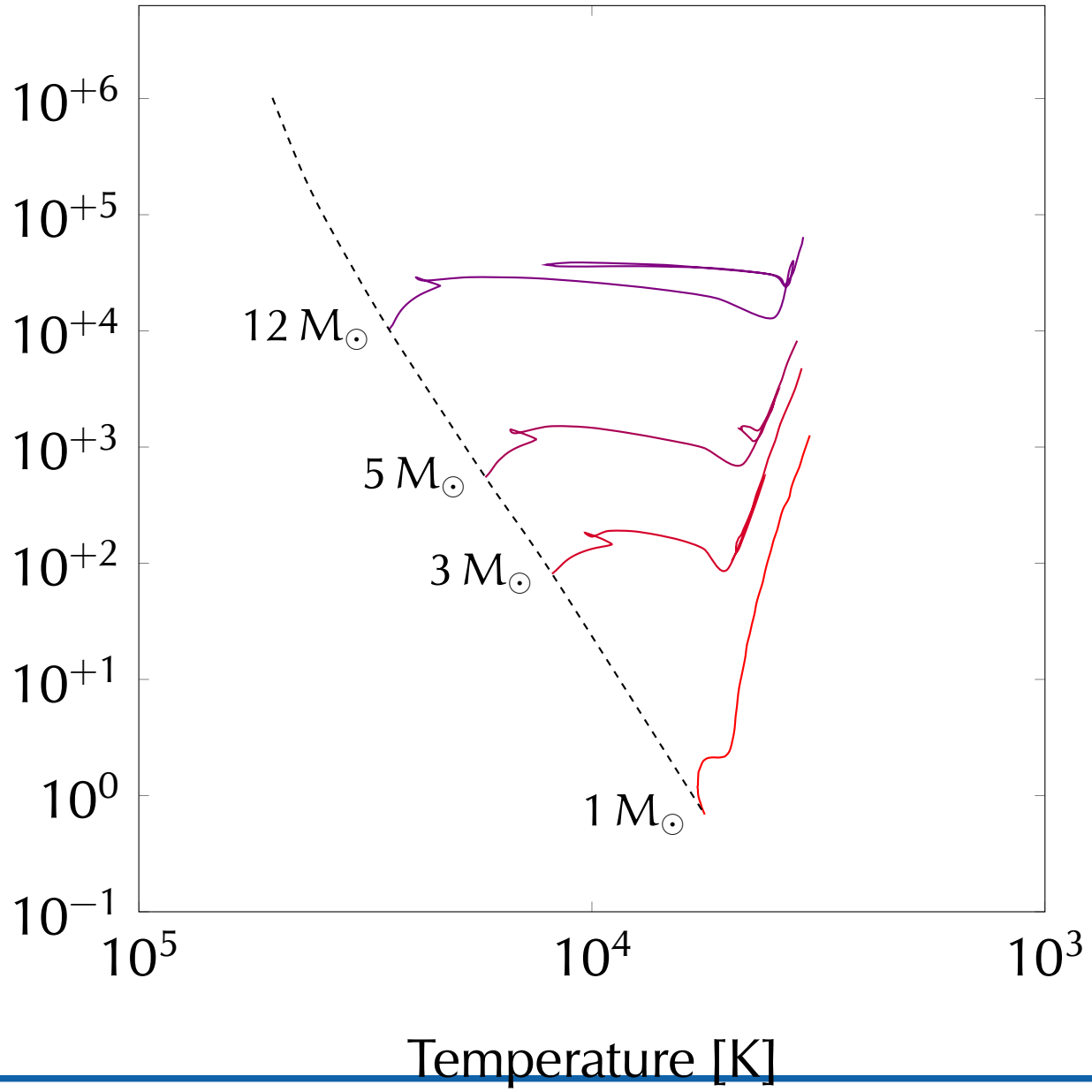
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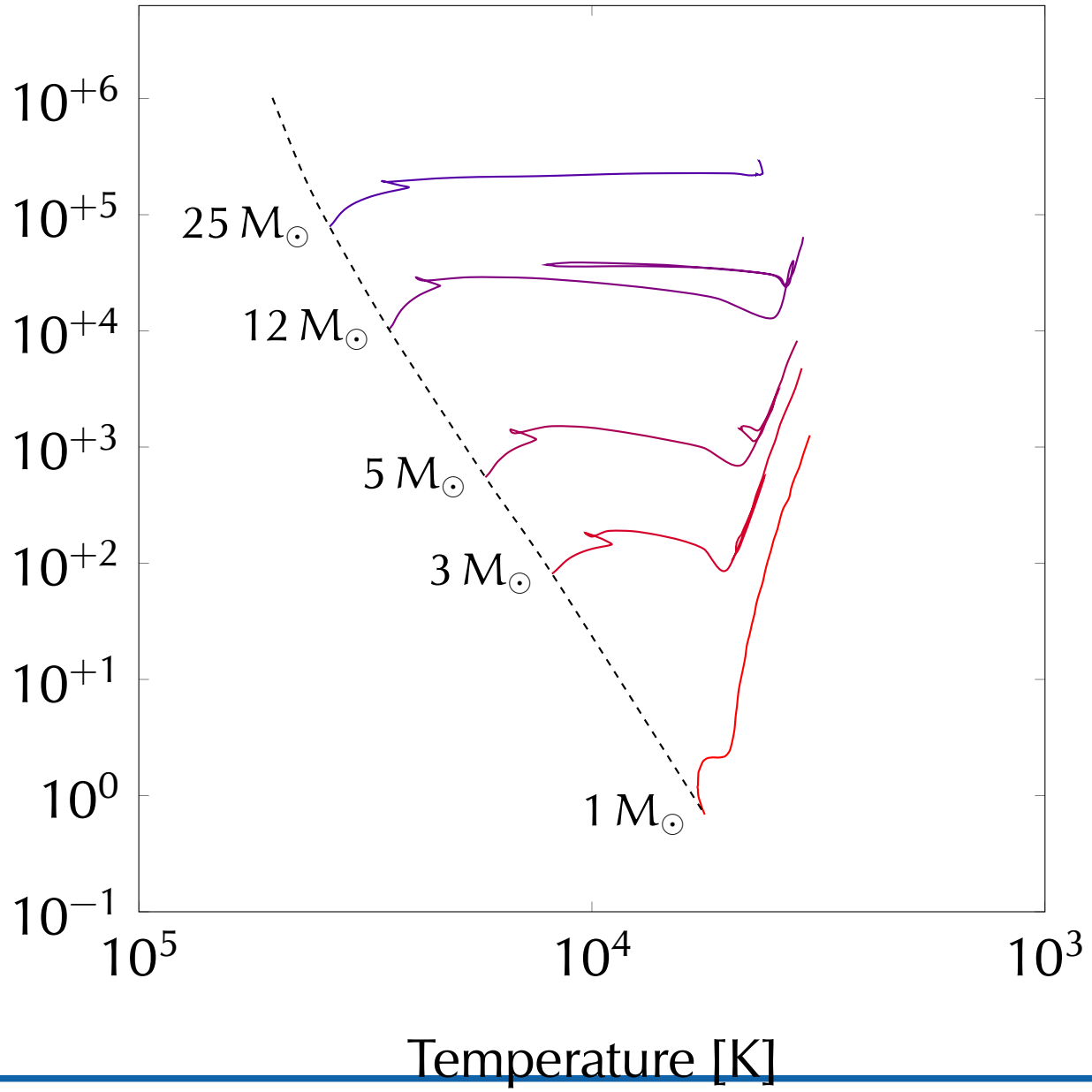
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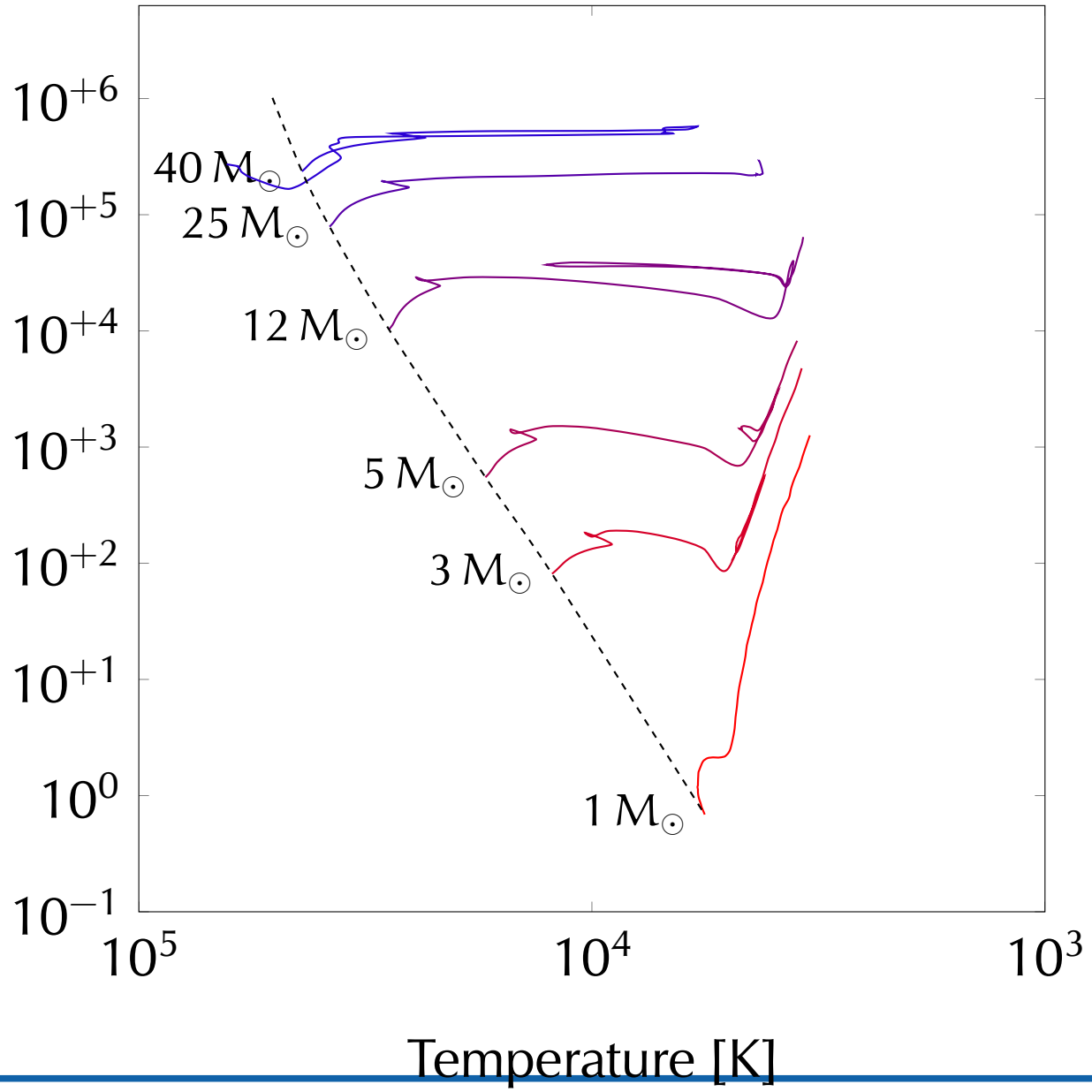
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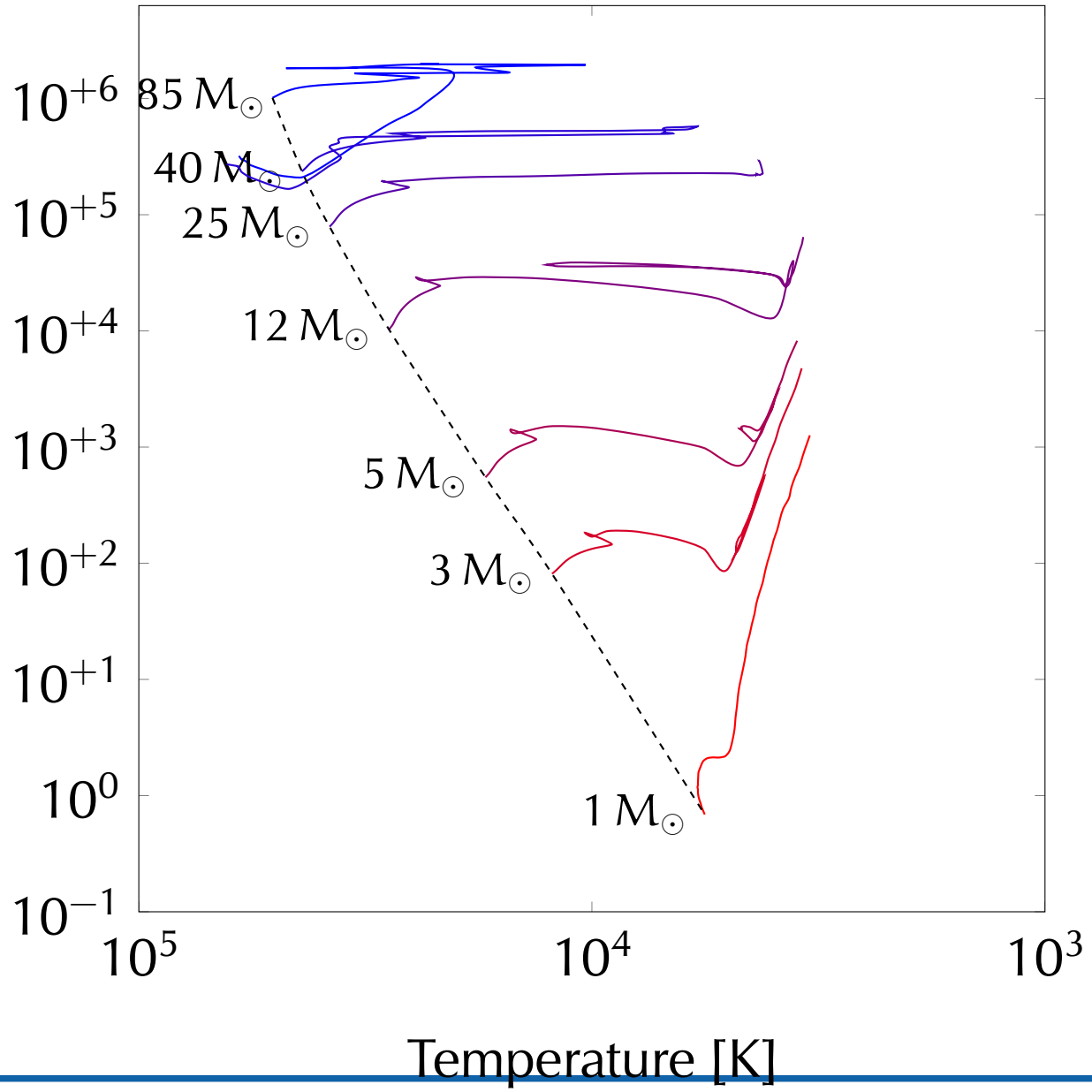
Stars born with masses $> 8\,M_\odot$



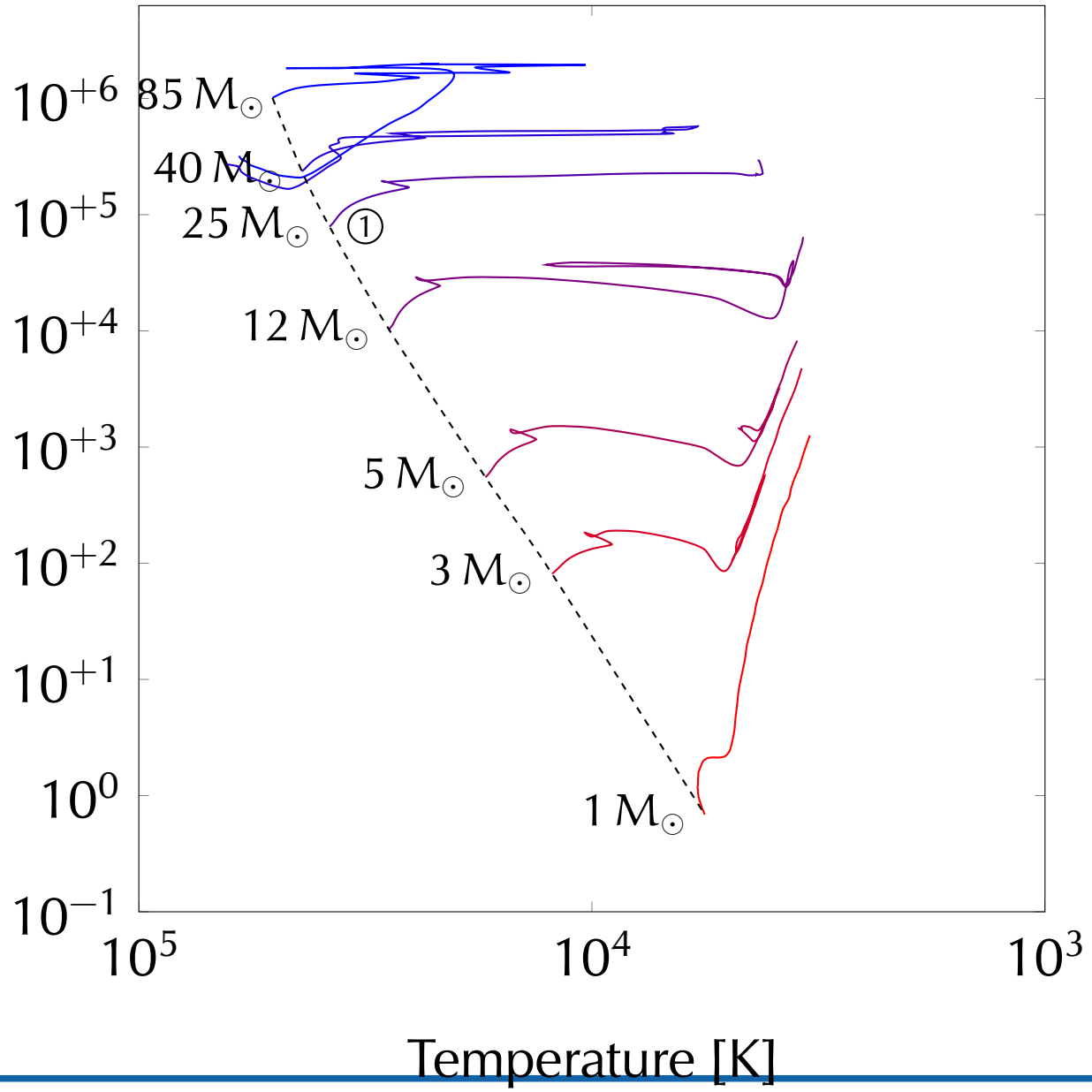
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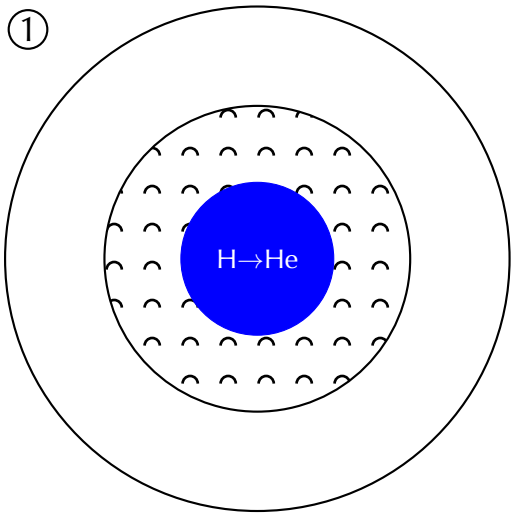


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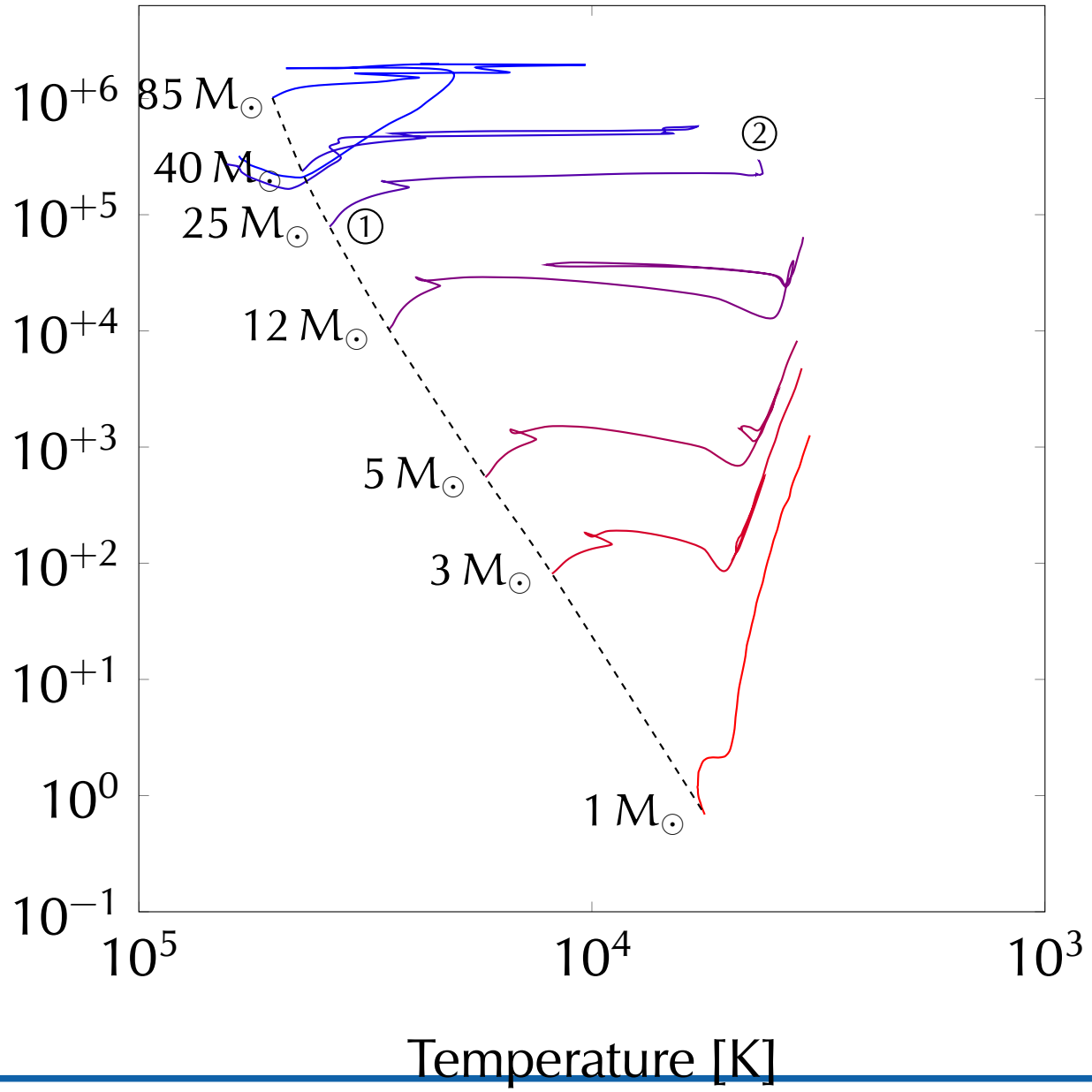


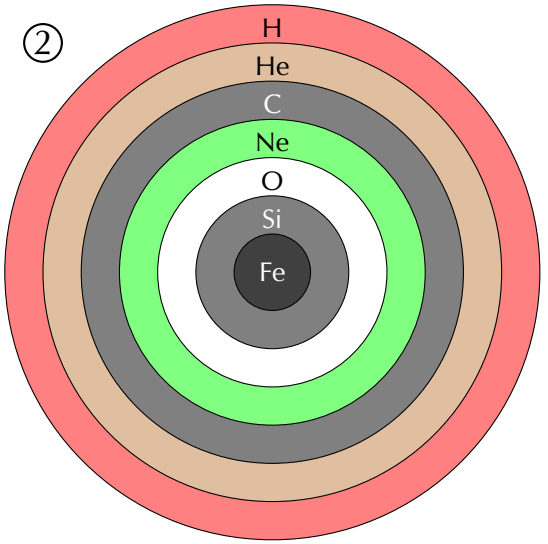
Stars born with masses $> 8\,M_\odot$

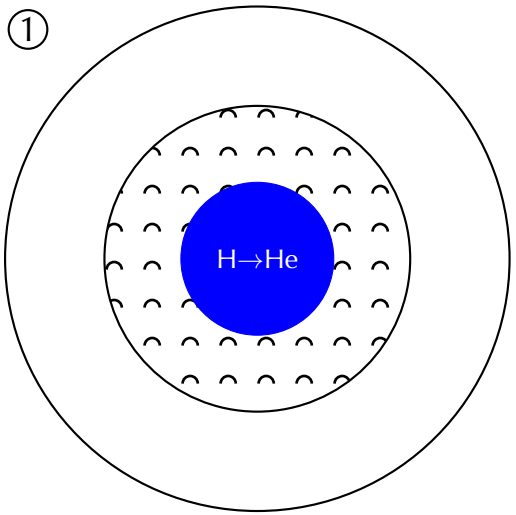




Stars born with masses $> 8\,M_\odot$





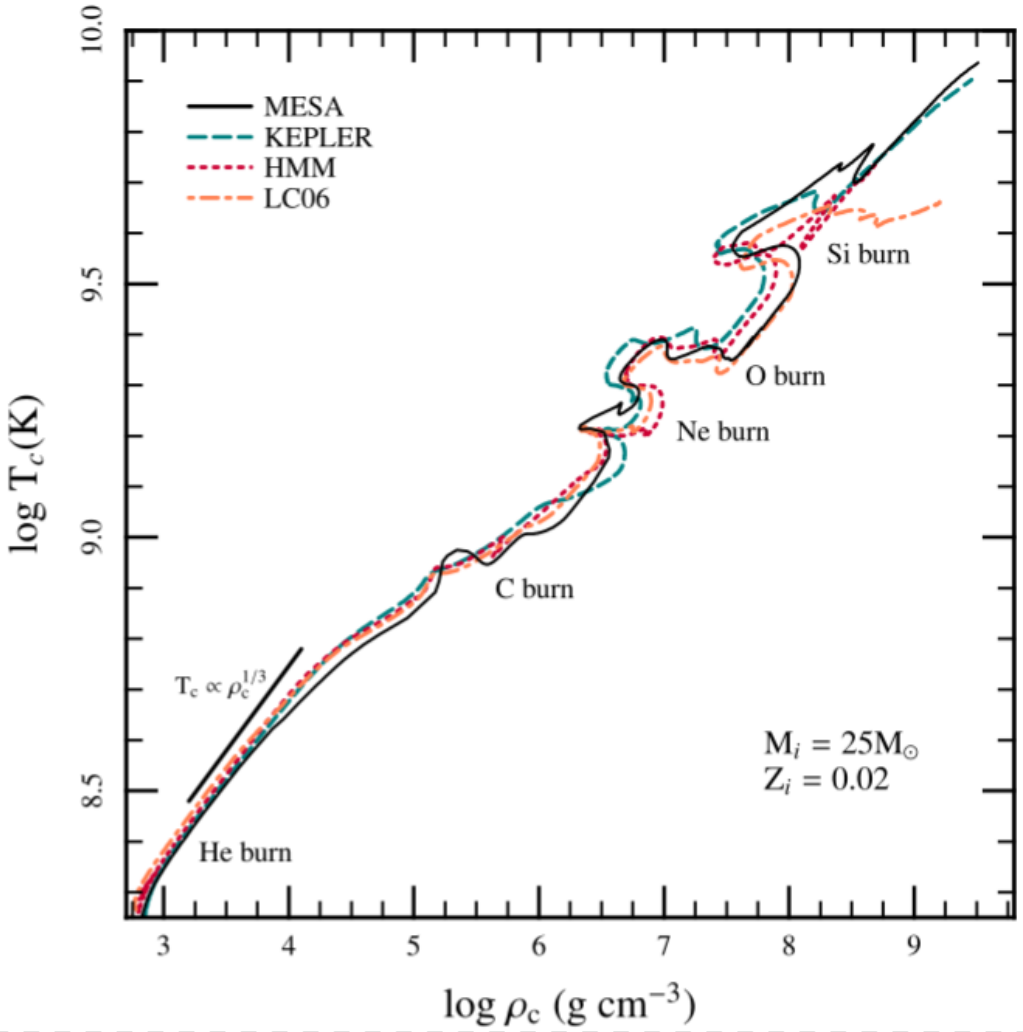


Stars born with masses $> 8\,M_\odot$

Nuclear reactions in massive ($> 8\,M_\odot$) stars:

Reaction	above T [10^6 K]	Energy gain [MeV]
Hydrogen burning		
$4\,^1H \longrightarrow {}^4He$	4	6.55
Helium burning		
$3\,^4He \longrightarrow {}^8Be + {}^4He \longrightarrow {}^{12}C$	100	<0.61
Carbon burning		
${}^{12}C + {}^4He \longrightarrow {}^{16}O$	600	<0.54
$2\,^{12}C \longrightarrow {}^4He + {}^{20}Ne$		
${}^{20}Ne + {}^4He \longrightarrow n + {}^{23}Mg$		
Oxygen burning		
$2\,^{16}O \longrightarrow {}^4He + {}^{28}Si$	1000	<0.3
$2\,^{16}O \longrightarrow 2\,^4He + {}^{24}Mg$		
Silicon burning		
$2\,^{28}Si \longrightarrow {}^{56}Fe$	3000	< 0.18

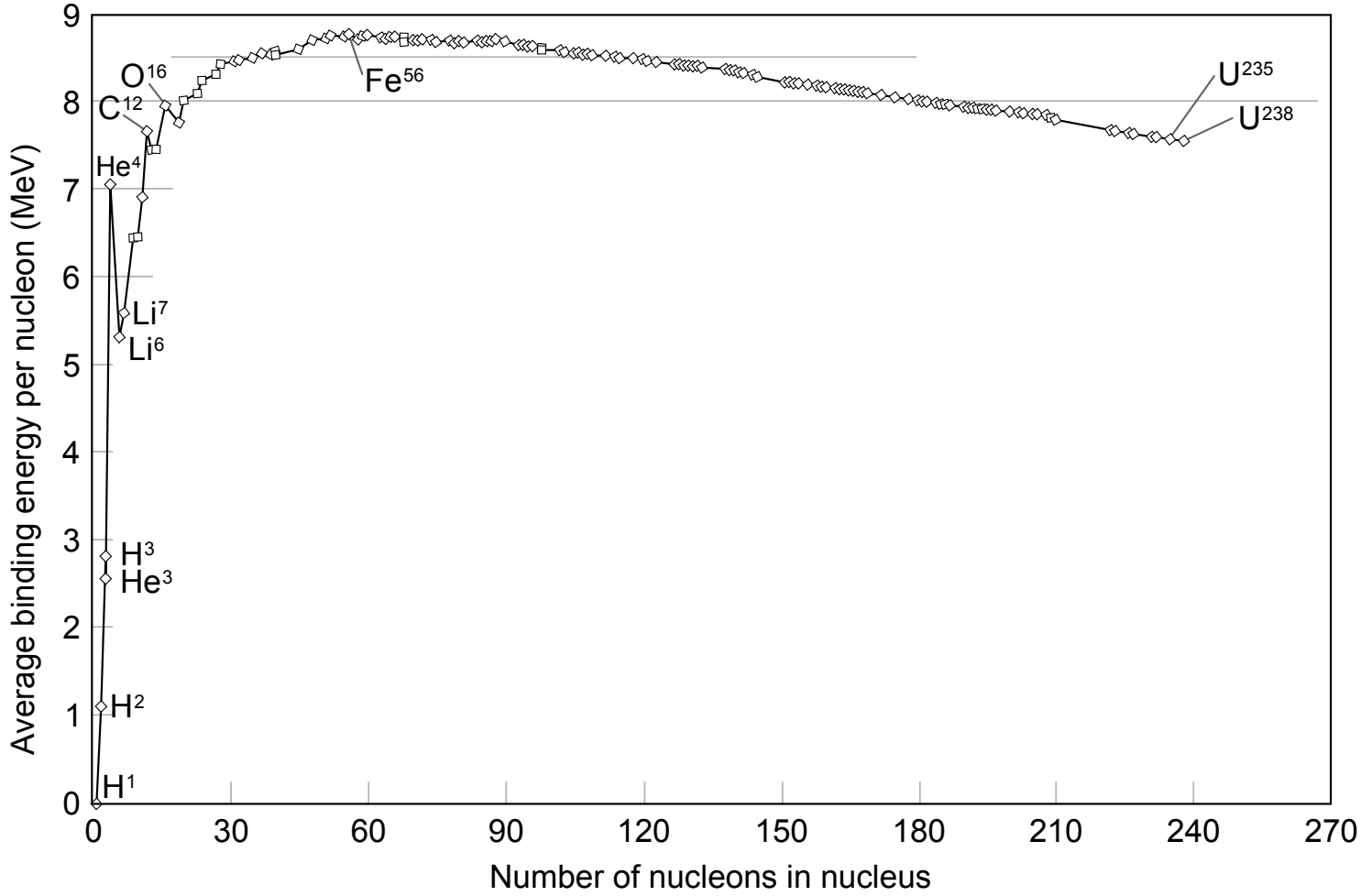
Stars born with masses $> 8\,M_\odot$



Evolution of central temperature and density of a $25\,M_\odot$ star

(Paxton et al., 2011, Fig. 30)

Stars born with masses $> 8\,M_\odot$

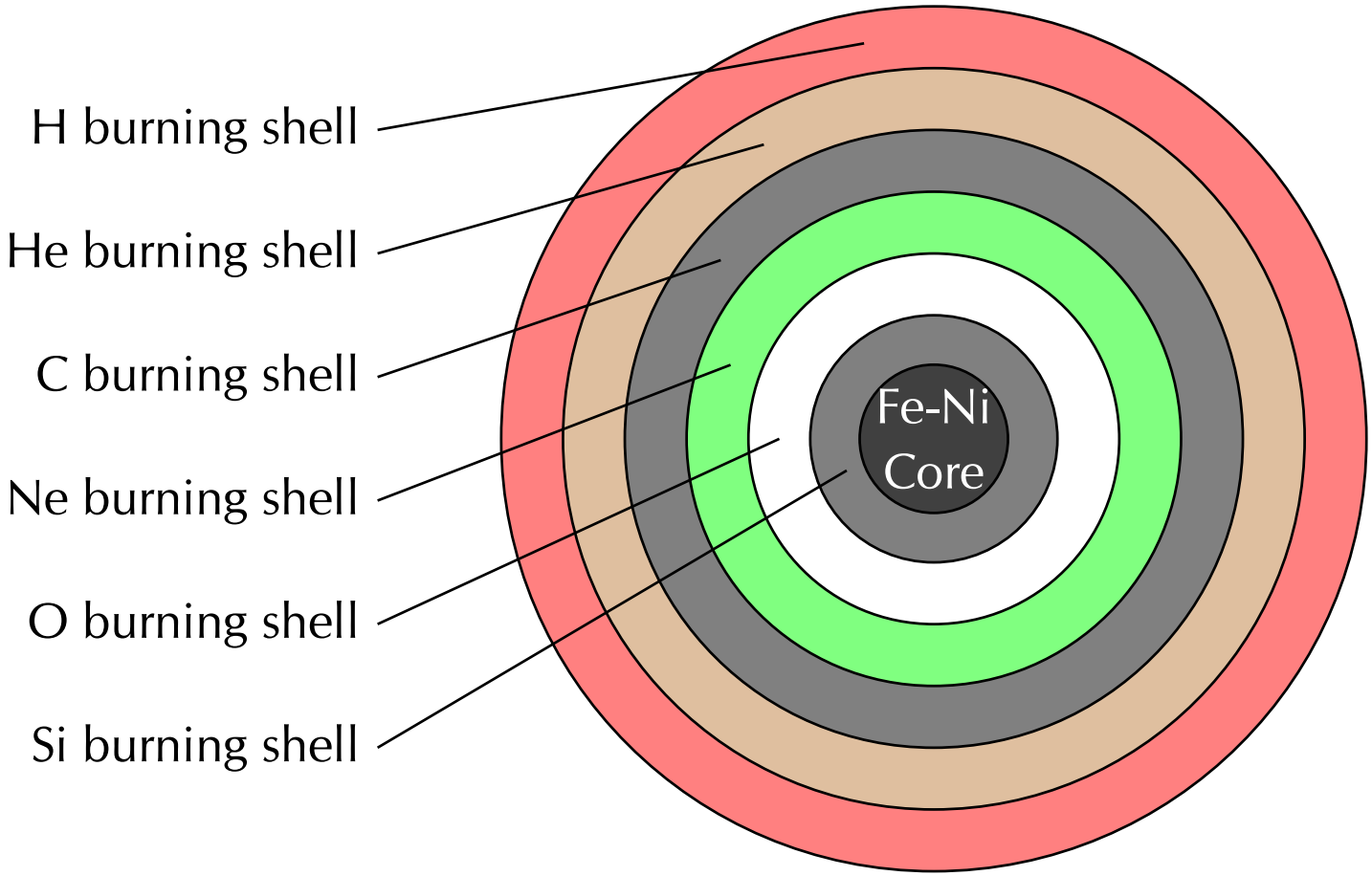


Wikipedia

^{56}Fe is one of the most tightly bound nucleons

$\Longrightarrow$ Star has a problem once ^{56}Fe reached: fusion becomes endotherm

Stars born with masses $> 8\,M_\odot$



successive stages of nuclear burning: final state: onion-shell model

1. H burning, ash: He
2. He burning, ashes: C, O, Ne, Mg
3. C burning, ashes: Ne, Na, Mg
4. Ne burning, ashes: O, Mg . . .
5. O burning, ashes: Si, P, S, . . .
6. Si burning, ashes: Fe, Ni

Summary: massive versus low mass stars

stellar evolution: central density and temperature scale with mass

low mass stars

Main sequence: low $T_{central}$, high $\rho_{central}$, radiative core, convective hull

$\Longrightarrow$ post main sequence: degenerate electron gas

$\Longrightarrow$ He flash

$\Longrightarrow$ low T_c

$\Longrightarrow$ no carbon burning

$\Longrightarrow$ planetary nebulae

C/O core stabilized by degeneracy pressure

high mass stars

Main sequence: high $T_{central}$, low $\rho_{central}$, convective core, radiative hull

$\Longrightarrow$ post main sequence: no degeneracy

$\Longrightarrow$ no He-flash

$\Longrightarrow$ high T_c

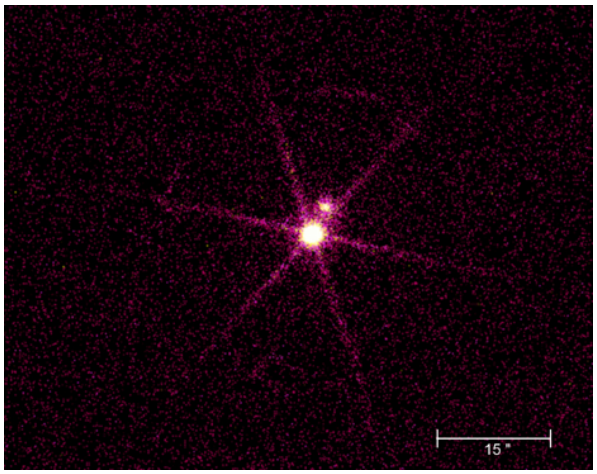
$\Longrightarrow$ C-burning

$\Longrightarrow$ higher burning stages

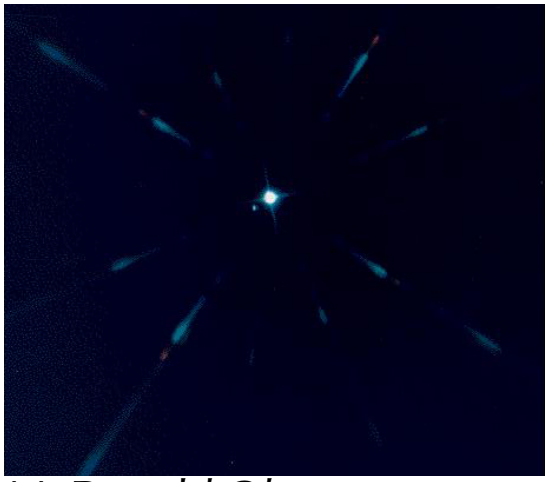
Fe core, not really stabilized by degeneracy

Stellar Death

White Dwarfs



Sirius A+B: *Chandra*
(X-rays; *WD is bright*)

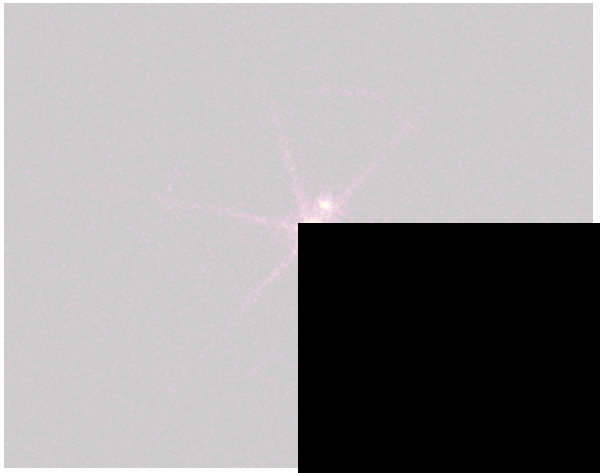


McDonald Observatory
(optical; *WD is faint*)

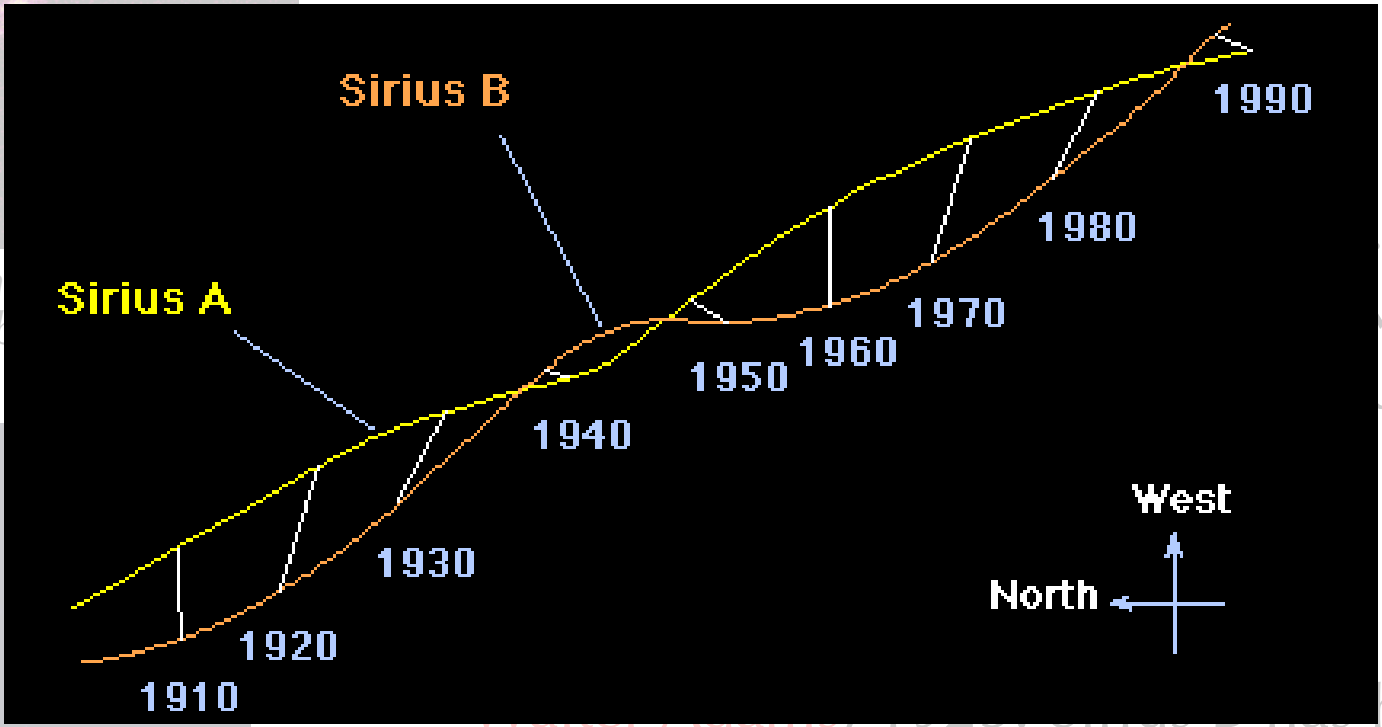
White Dwarfs: Sirius B

- Companion to the brightest star Sirius
- cannot be seen with the naked eye.
- Friedrich Wilhelm Bessel (1844): Motion of Sirius from 1833 to 1844: Sirius must have unseen companion.
- Alvan Graham Clark, 1862 Jan 31: discovery of Sirius B
- Walter Adams, 1925: Sirius B has high temperature, small size, large density

White Dwarfs



Sirius A+B: *Ch*
(X-rays; *WD is b*





McDonald Observatory
(optical; *WD is faint*)

us

Motion of

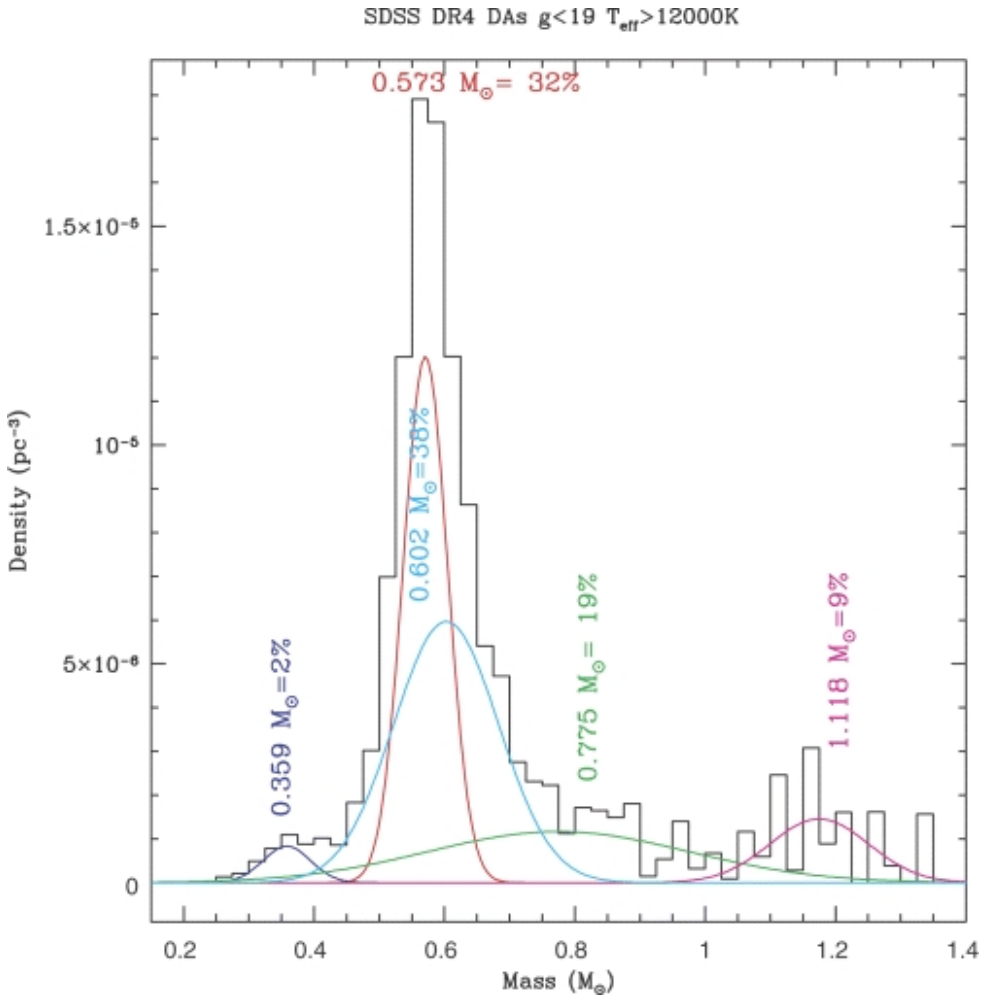
ust have un-

discovery

high tem-

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White Dwarfs

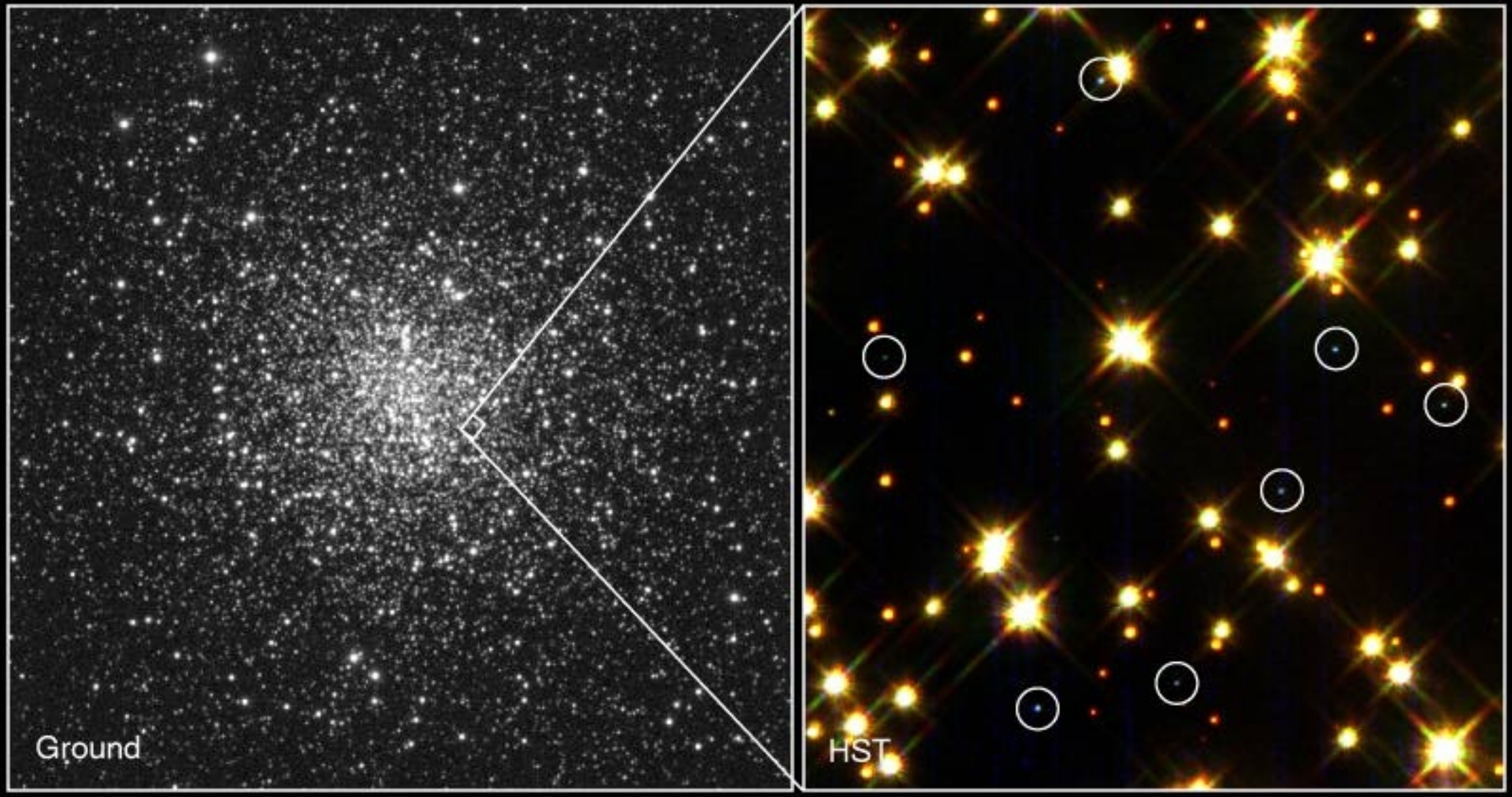


mass distribution of 1733 white dwarfs

(Kepler et al. 2007, MNRAS 375, 1315)

White Dwarfs

1. End stages of evolution of stars born with $M \lesssim 8\,M_\odot$
2. typically $M \sim 0.6 M_\odot$
3. mainly consist of C and O
4. Radius ~ Earth
5. typical density $\rho \sim 10^6\,\mathrm{g\,cm^{-3}}$



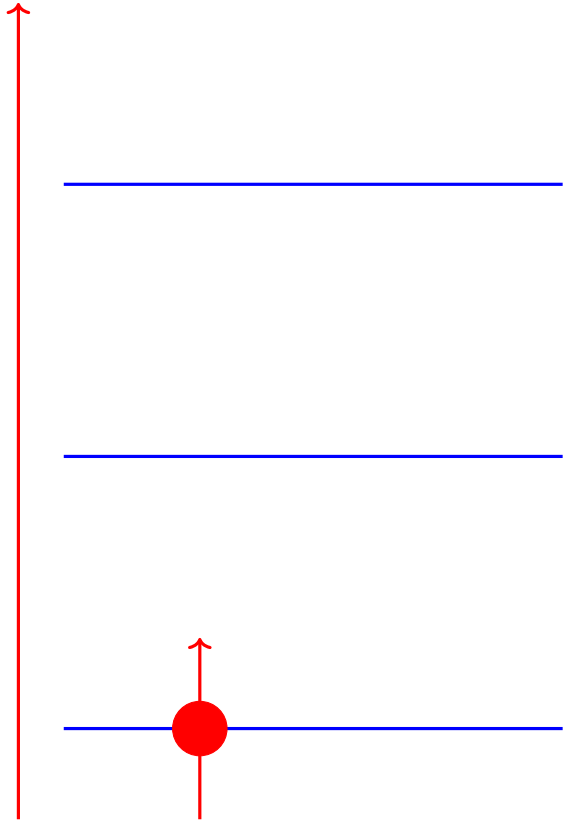
White Dwarf Stars in M4

HST · WFPC2

PRC95-32 · ST ScI OPO · August 28, 1995 · H. Bond (ST ScI), NASA

White Dwarfs

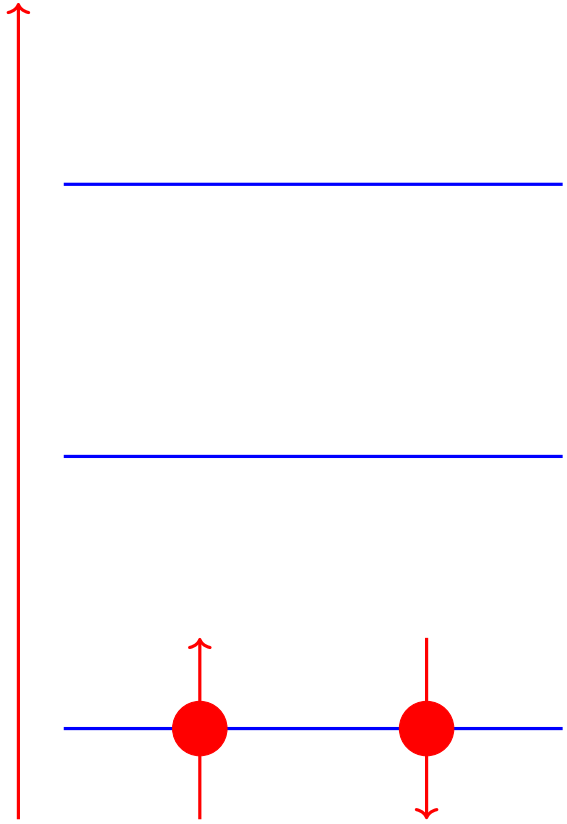
Effect of high density on electron energy



Energy of electrons at the same position in space

White Dwarfs

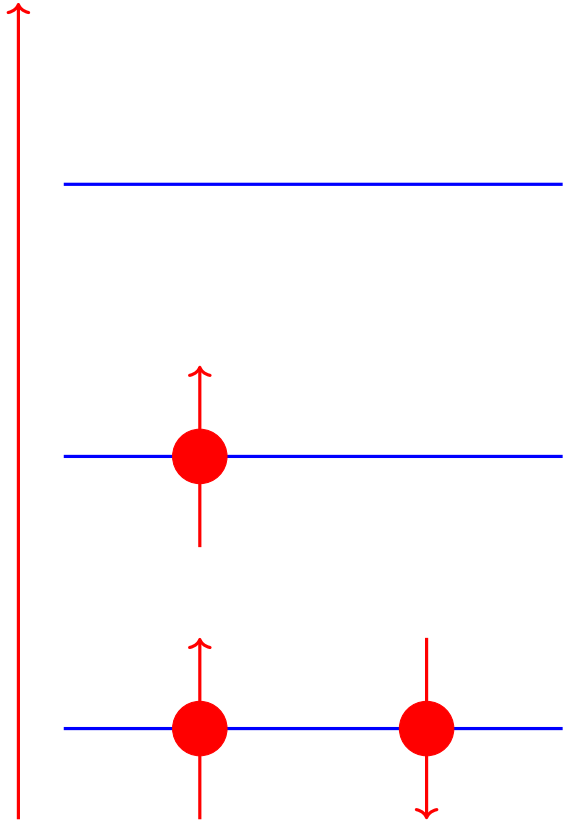
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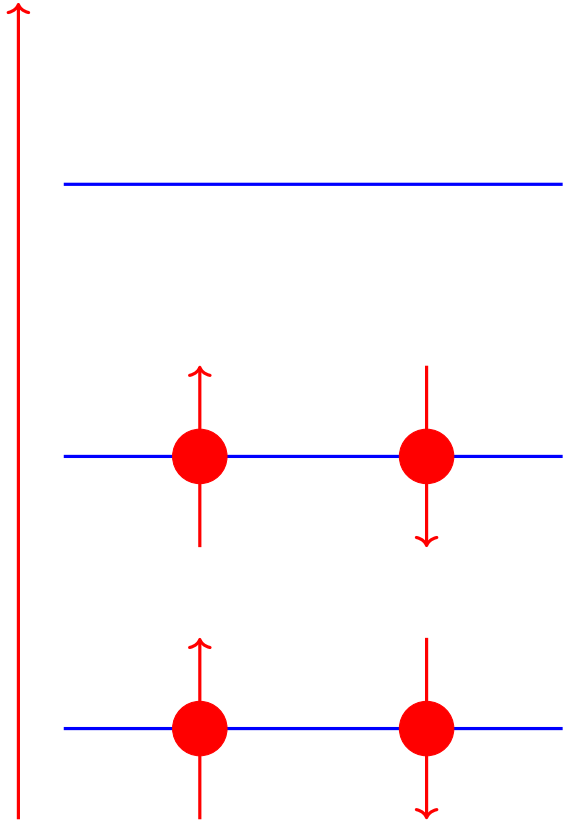
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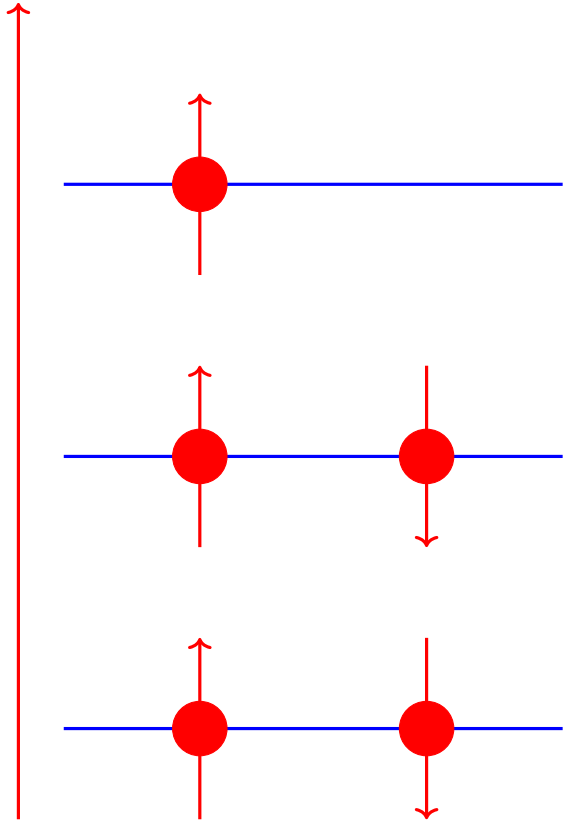
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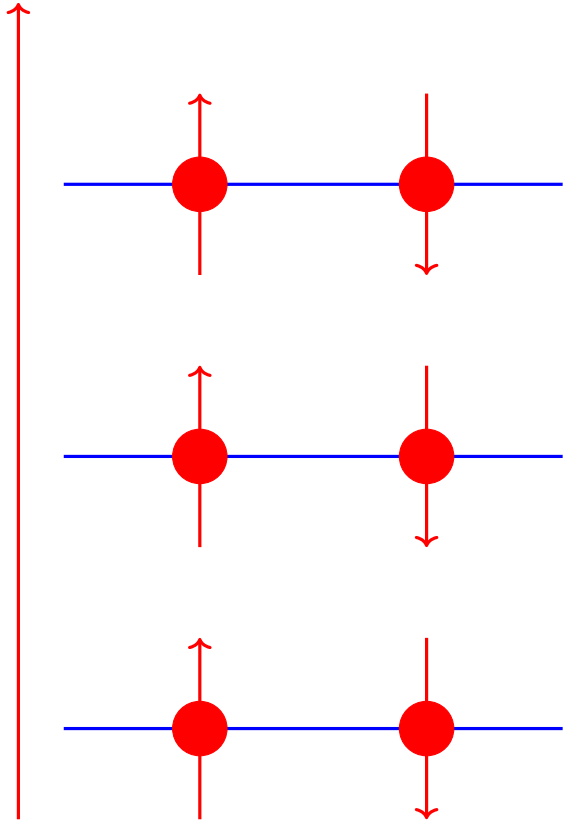
White Dwarfs

Effect of high density on electron energy



Energy of electrons at the same position in space

White Dwarfs

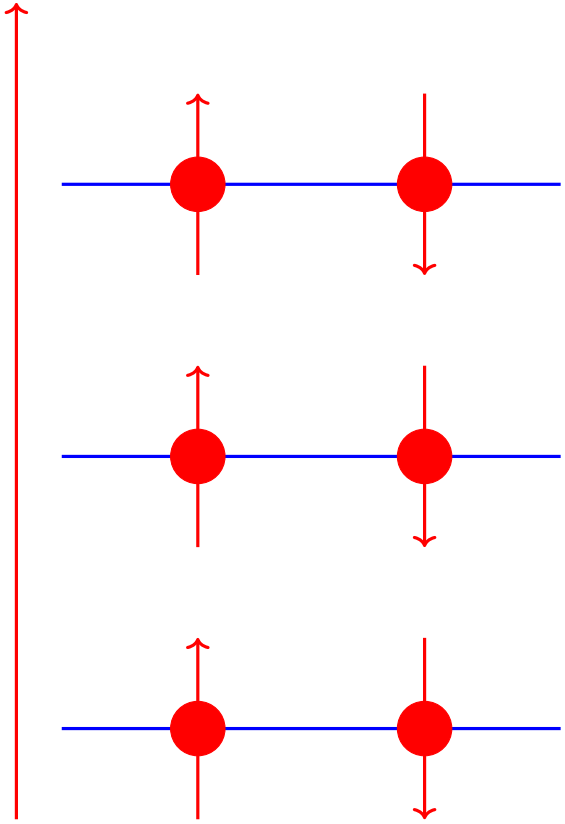


Energy of electrons at the same position in space

Effect of high density on electron energy:

In degenerate electron gases, electrons have much higher energies than in thermal gas.

White Dwarfs



Energy of electrons at the same position in space

Effect of high density on electron energy:

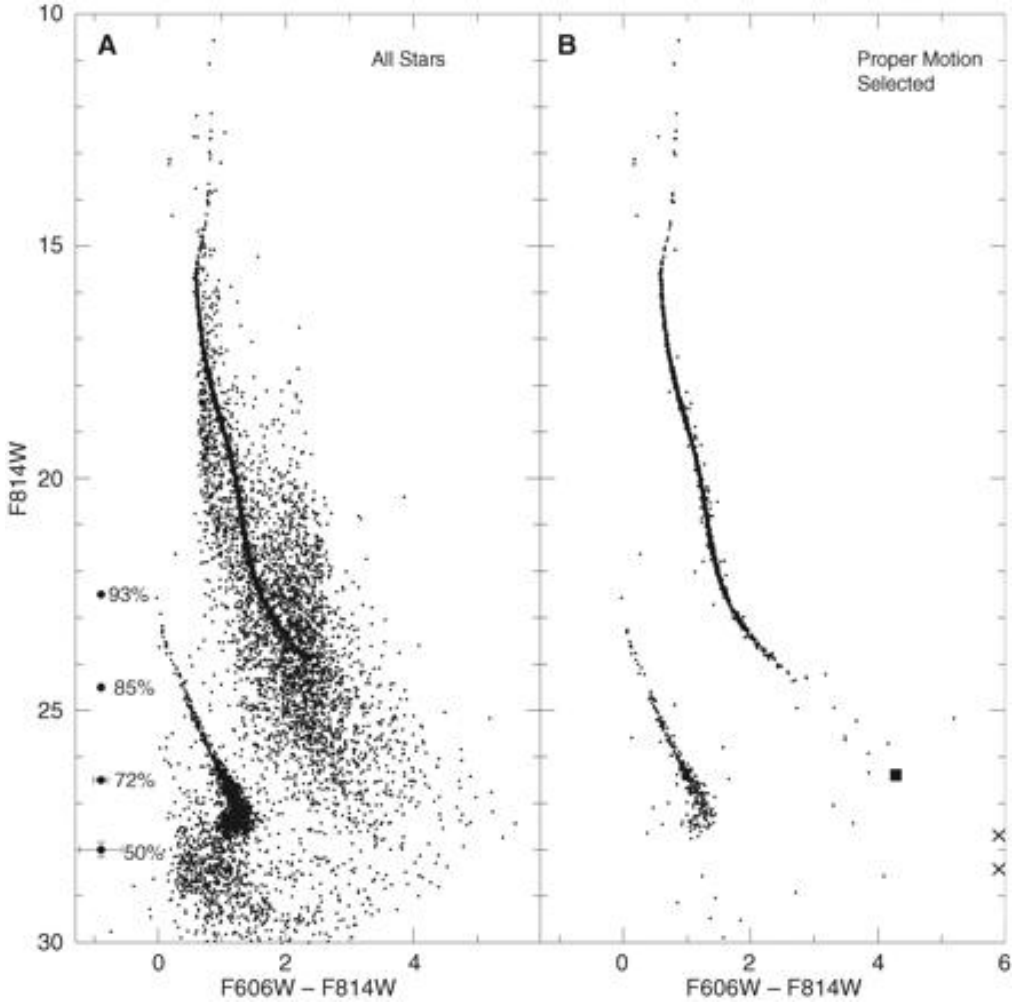
In degenerate electron gases, electrons have much higher energies than in thermal gas.

Interaction of electrons results in degeneracy pressure:

$$P = \frac{\hbar^2}{m_e} n_e^{5/3} \propto \rho^{5/3}$$

Note: The degeneracy pressure is independent of the temperature!

White Dwarfs



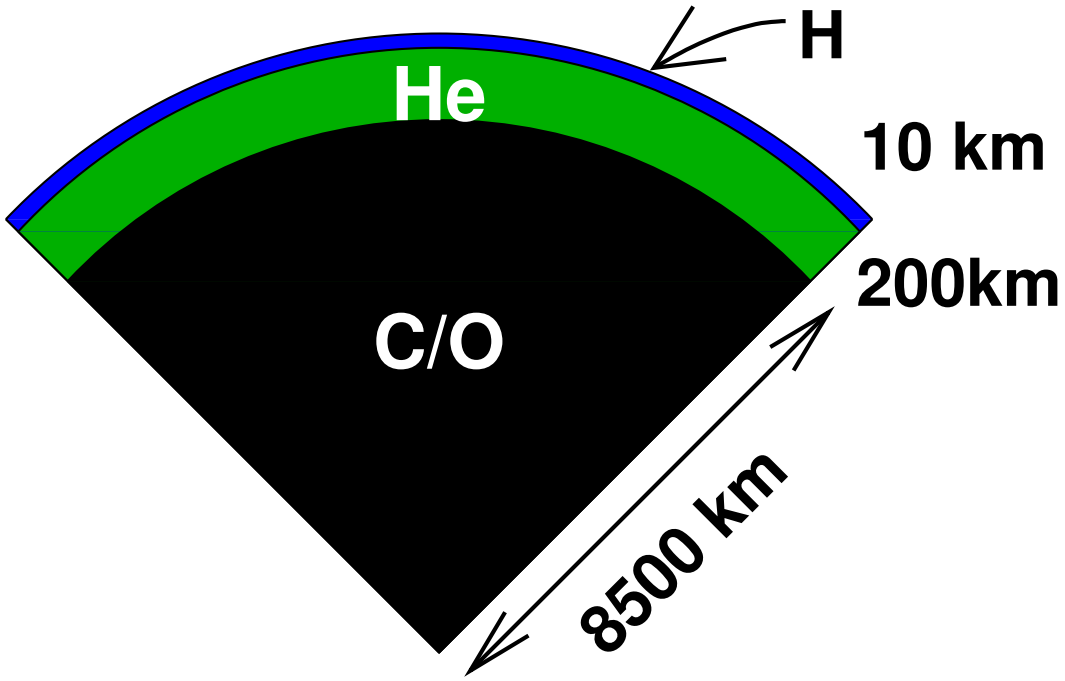
Color-magnitude diagram of the NGC 6397 White Dwarf sequence (Richer et al. 2006, Science 313, 936)

globular clusters are the oldest building blocks of the Galaxy

$\Longrightarrow$ many stars have already died

$\Longrightarrow$ GCs must host a large number of white dwarfs

White Dwarfs



White dwarfs come in two flavors:

DA: H present in spectrum
(~80% of all WD)

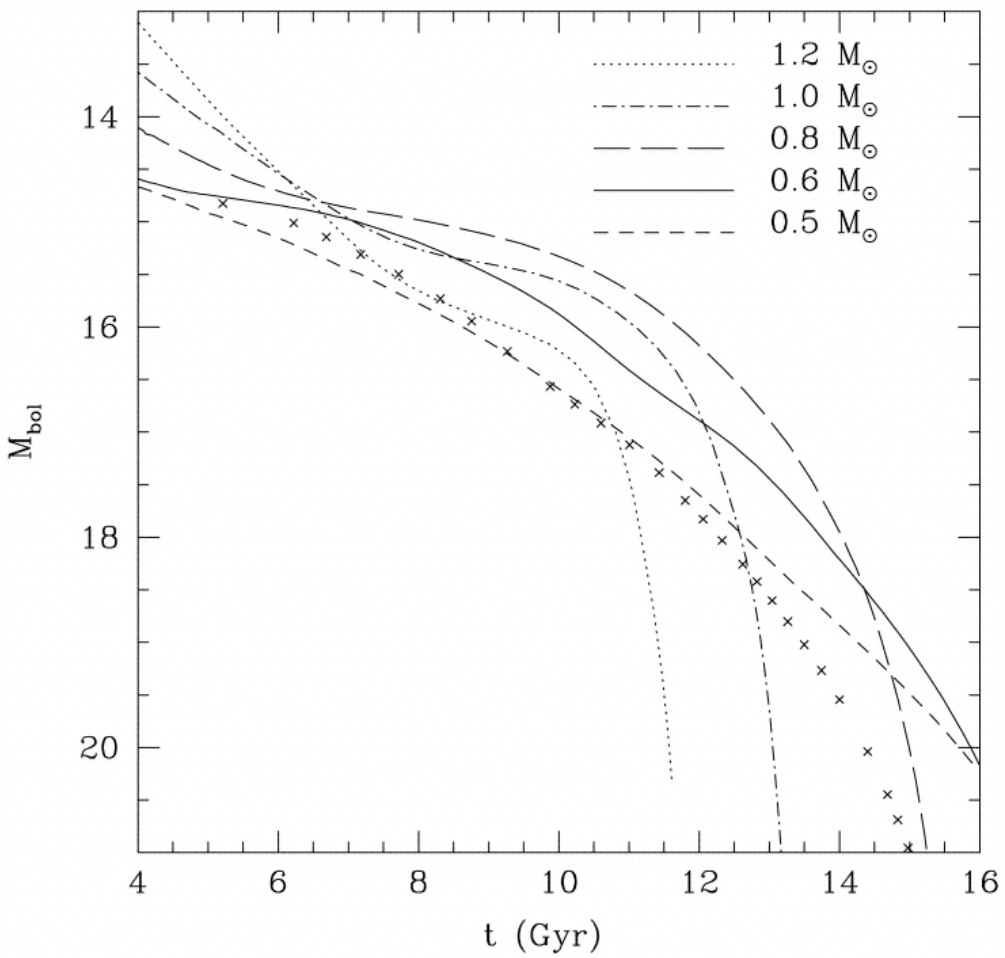
DB: He present in spectrum
(~ the rest)

plus a few oddballs

Structure: gravitationally settled, so DB's really do not have any H since it would "swim on top"

$\Longrightarrow$ layered, "onion-like" structure

White Dwarfs



white dwarf cooling tracks
Chabrieyer et al. 2005 (ApJ 542, 216)

- white dwarfs are stabilized by the pressure of the degenerate electron gas
- they can not shrink
- cooling of the ionic gas takes a very long time
- at low temperature: crystalization, crystal structure similar to diamond

"White dwarfs are diamonds in the sky"

White Dwarfs

For a degenerate gas, the equation of state ($P = P(T, \rho)$) is

$$P \propto \begin{cases} \rho^{5/3} & \text{(non-relativistic gas)} \\ \rho^{4/3} & \text{(relativistic gas)} \end{cases} \tag{2.1}$$

independent of T!

WD structure can be determined from hydrostatic equilibrium alone:

Mass structure
(mass conservation)

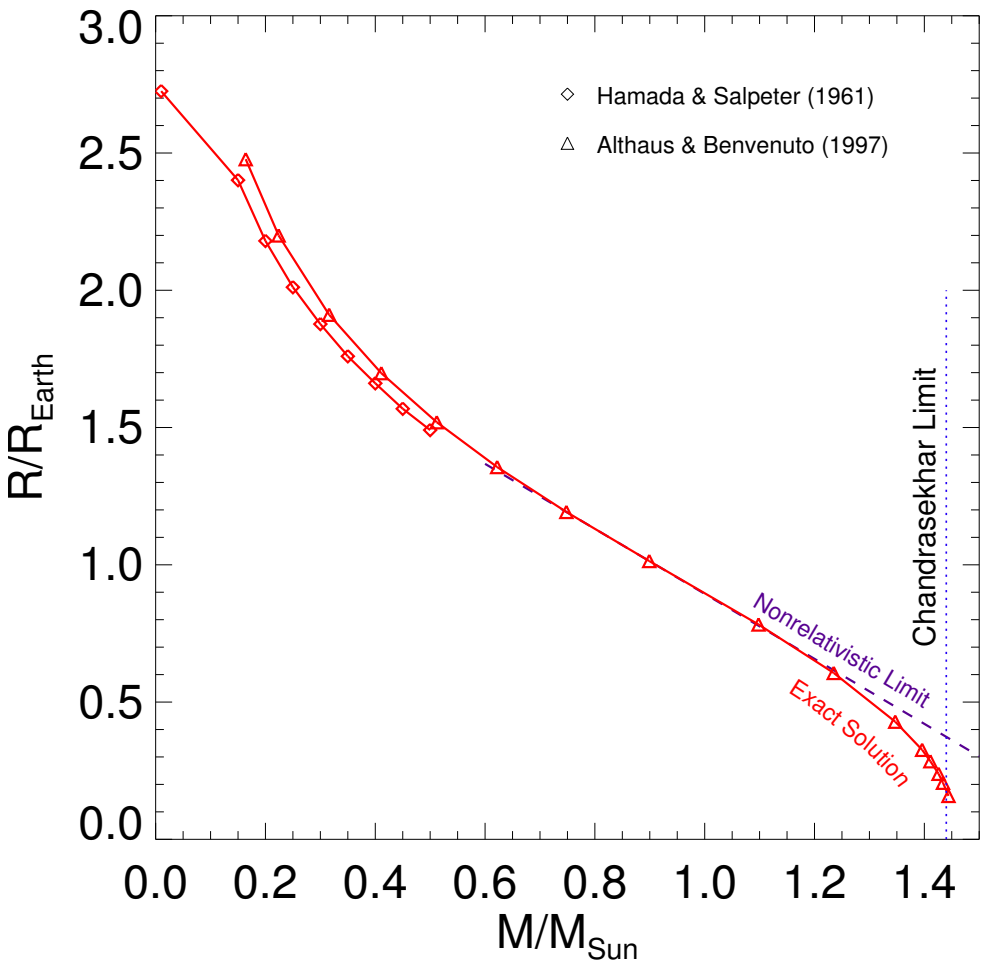
$$\frac{dM}{dr} = 4\pi r^2 \rho(r)$$

Pressure structure
(hydrostatic equilibrium)

$$\frac{dP}{dr} = -\rho(r)\frac{GM(r)}{r^2}$$

Can derive mass–radius-relationship

White Dwarfs





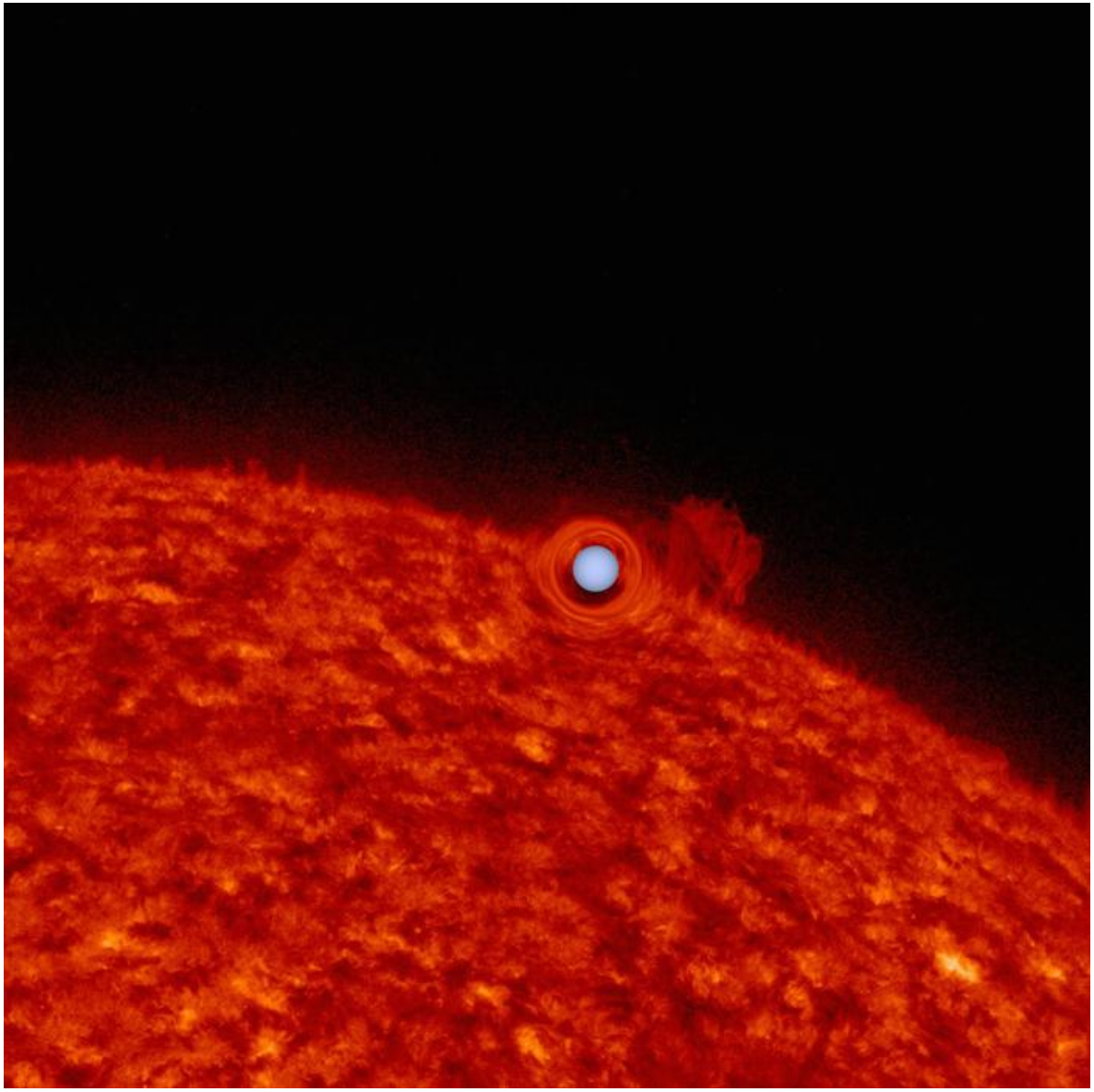
©Univ. Chicago

Subrahmanyan Chandrasekhar, 1910–1995 (Nobel prize 1983)

Radius of White Dwarfs decreases with increasing mass: $R \propto M^{1/3}$

Chandrasekhar limit: Mass of White Dwarfs must be less than $1.44\,M_\odot$

White Dwarfs

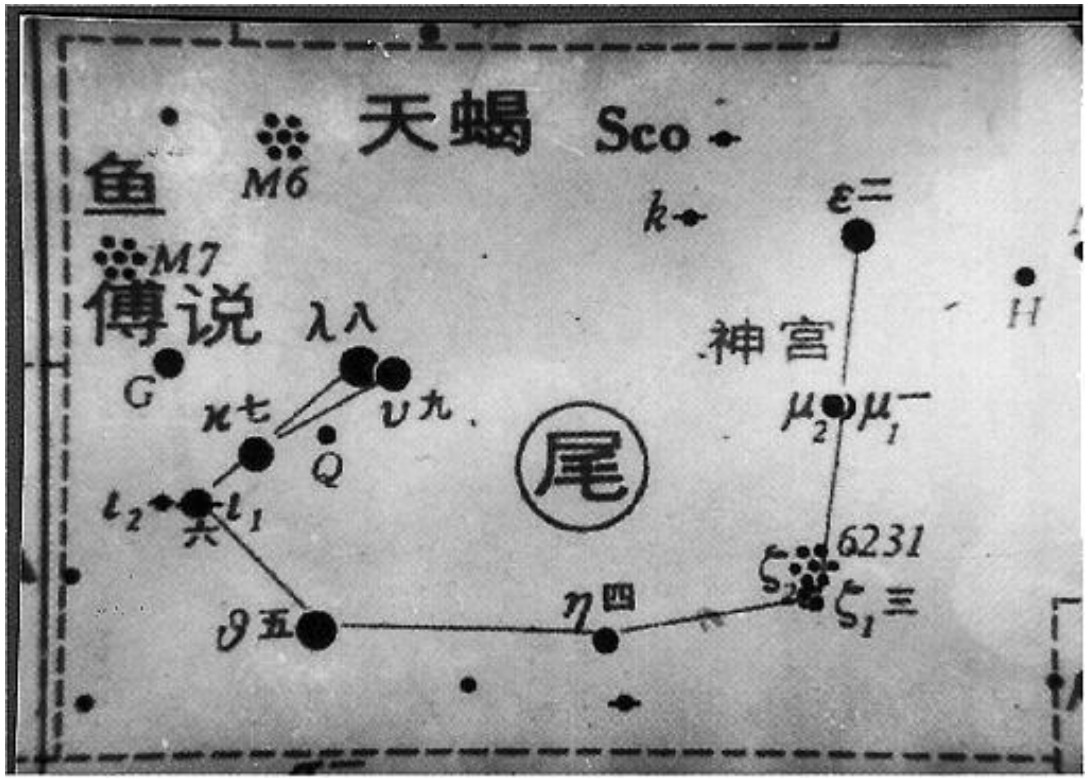


White dwarfs are very small compared to stars
$\Longrightarrow$ mass bends space
$\Longrightarrow$ "self lensing"
(i.e., star with WD can get slightly brighter if WD moves in front of it)
has been seen very nicely by Kruse & Agol (2014) in the object KOI-3278

Historical Supernovae

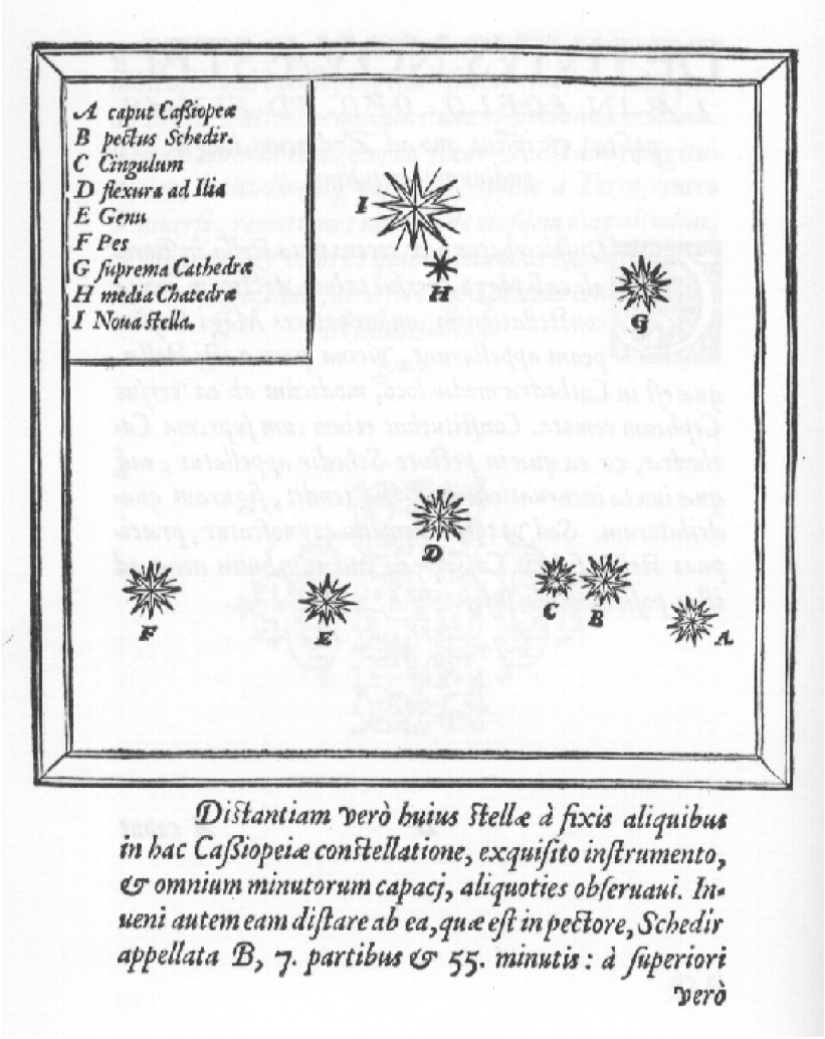
Supernovae: stars which increase suddenly by ~20 mag

(term coined by Baade & Zwicky, 1934)

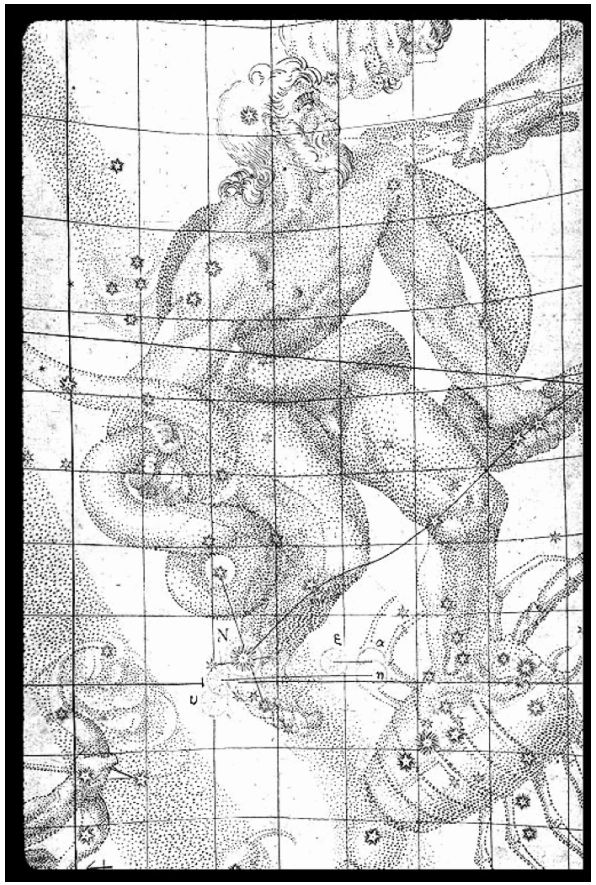


The guest star of AD 386, Wang, Yu & Chen (1997, A&A 318, L59)

Historical Supernovae



Tycho Brahe's Supernova 1572

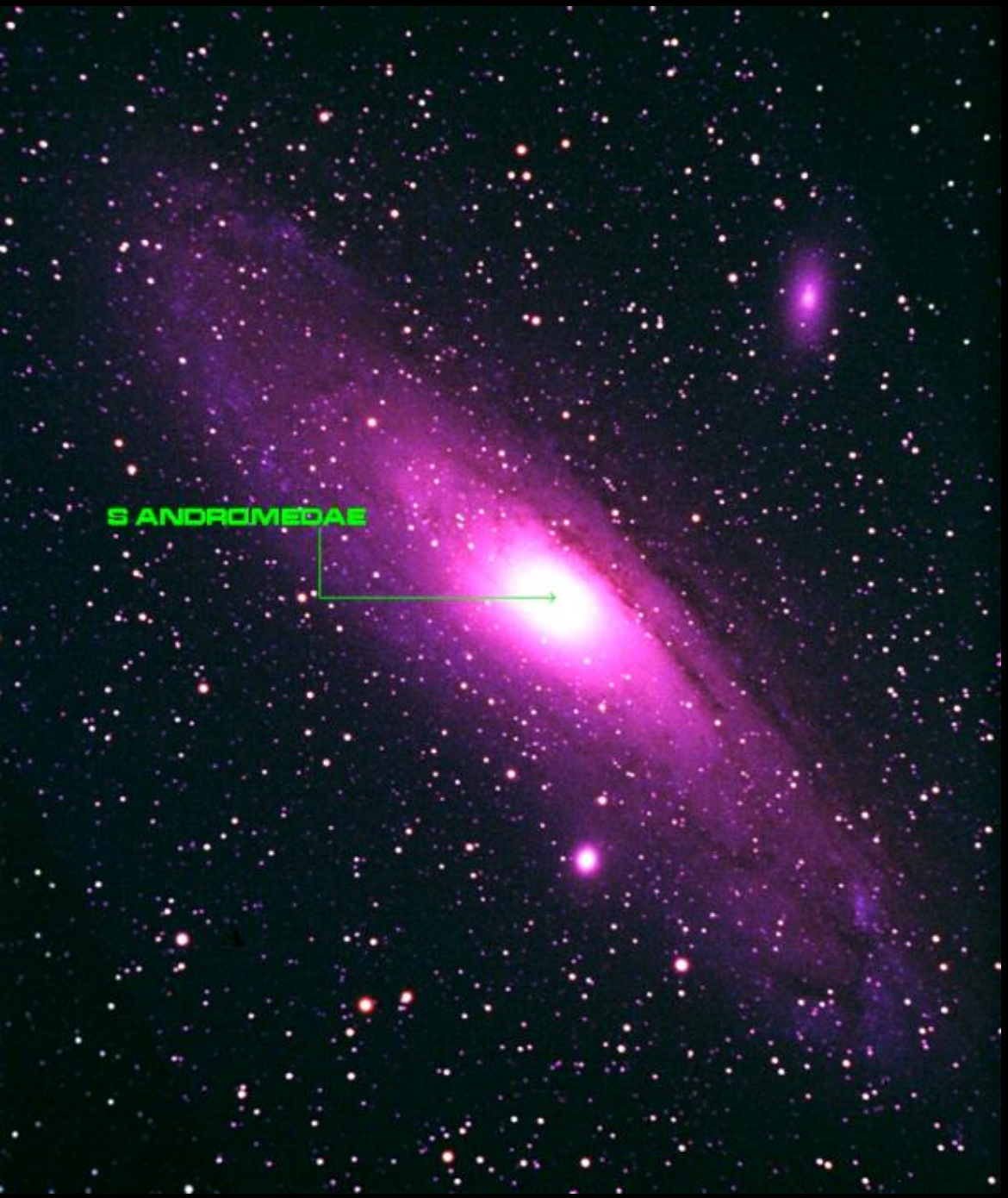


Johannes Kepler's Supernova 1604

Galactic supernovae

Year of appearance	constellation	magnitude	visibility months
185	Centaurus	−8	6?
386	Sagitarius	+1.5	
393	Scorpius	0	
1006	Lupus	−7.5	24
1054	Taurus	−6	24
1181	Cassiopeia	0	6
1572	Cassiopeia	−6	16
1604	Ophiuchus	−3	12
1667	Cassiopeia	obscured	-
~1850	G1.9+0.3	obscured	–

S Andromedae = Supernova 1885 in Andromeda Galaxy





Ernst Hartwig (Dorpat = Tartu)

20.08.1885:

Discovery of S And

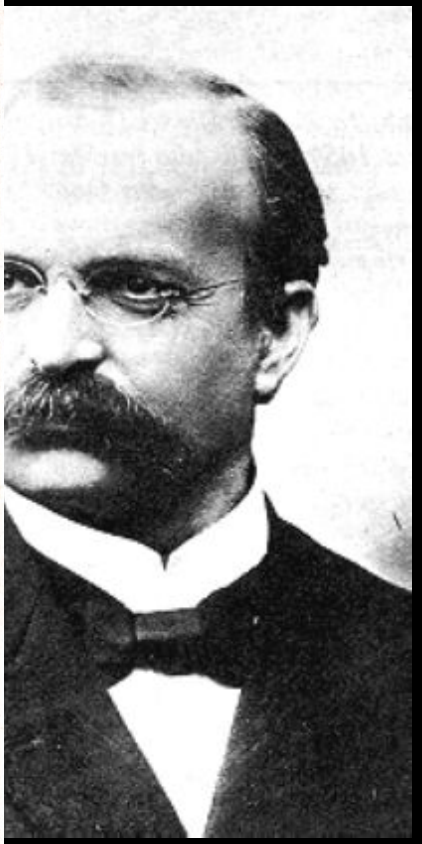
01.01.1886:

Director of Remeis-Observatory

S Andromedae = Supernova 1885 in Andromeda Galaxy





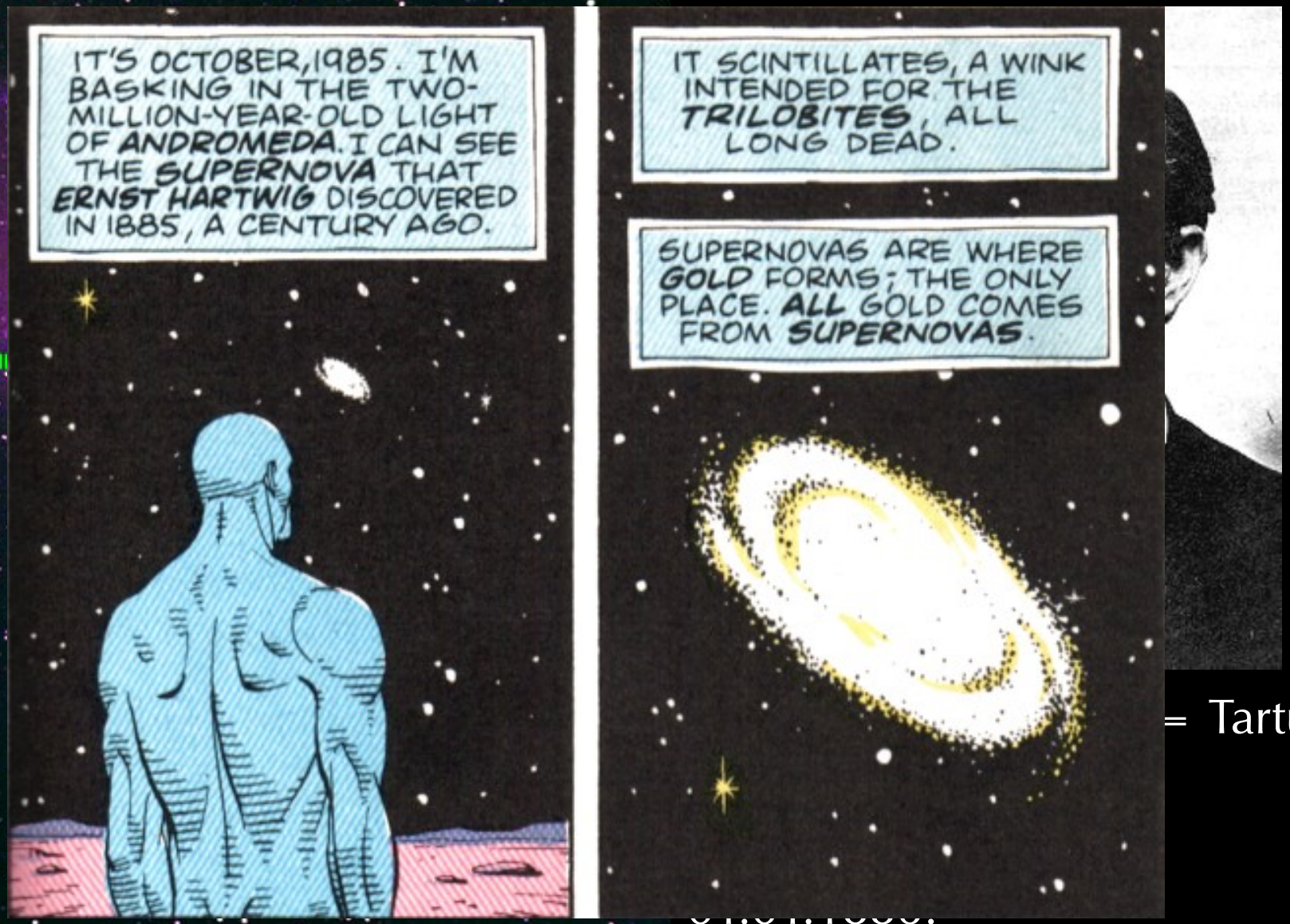


(Dorpat = Tartu)

of S And

f Remeis-Observatory

S Andromedae = Supernova 1885 in Andromeda Galaxy



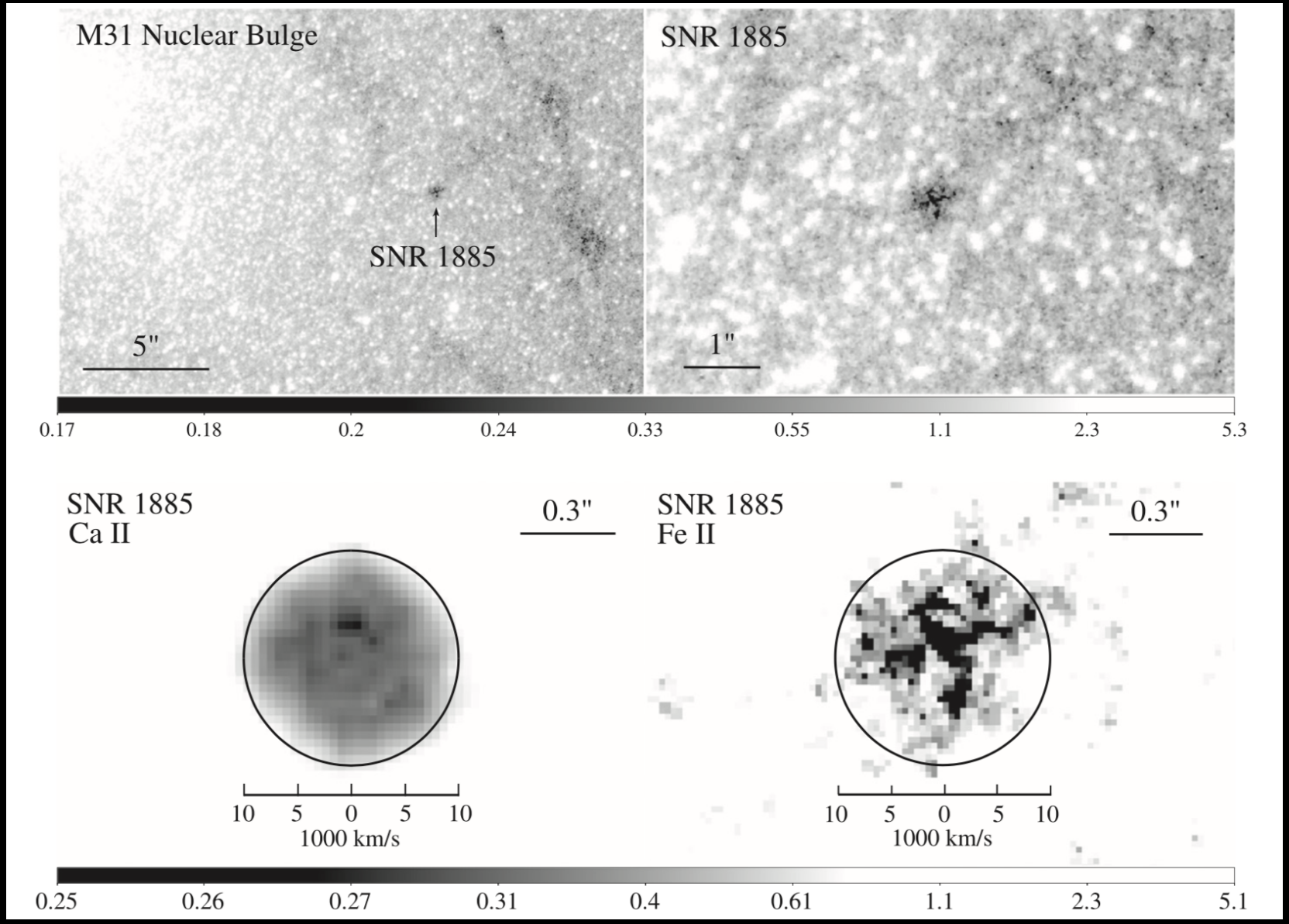
= Tartu)

Director of Remeis-Observatory



HST observation of the remnant ~ 120 years later
(Fesen et al., 2015)

S Andromedae = Supernova 1885 in Andromeda galaxy

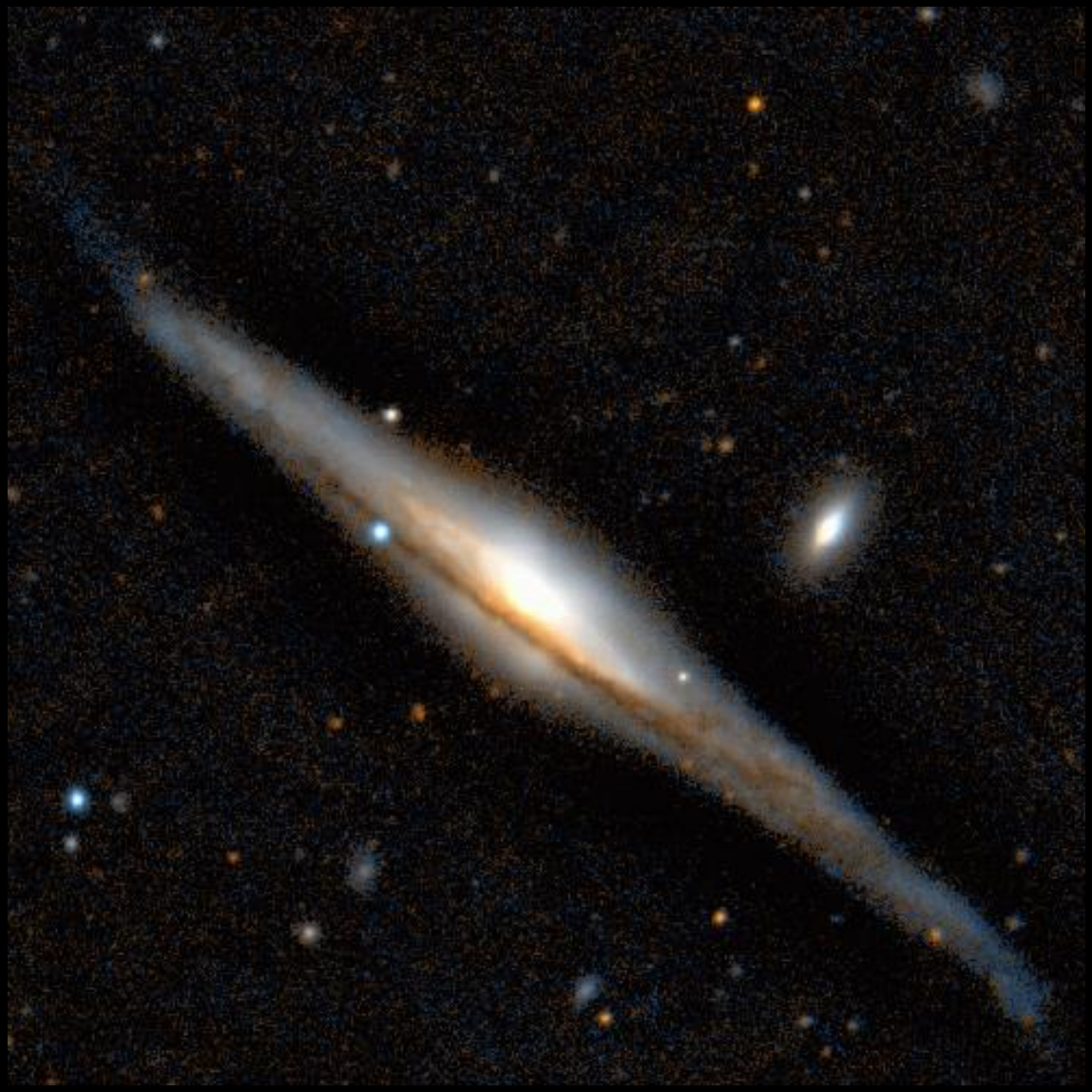


HST observation of the remnant ~ 120 years later
(Fesen et al., 2015)

S Andromedae = Supernova 1885 in Andromeda galaxy



SN1994d (HST WFPC)



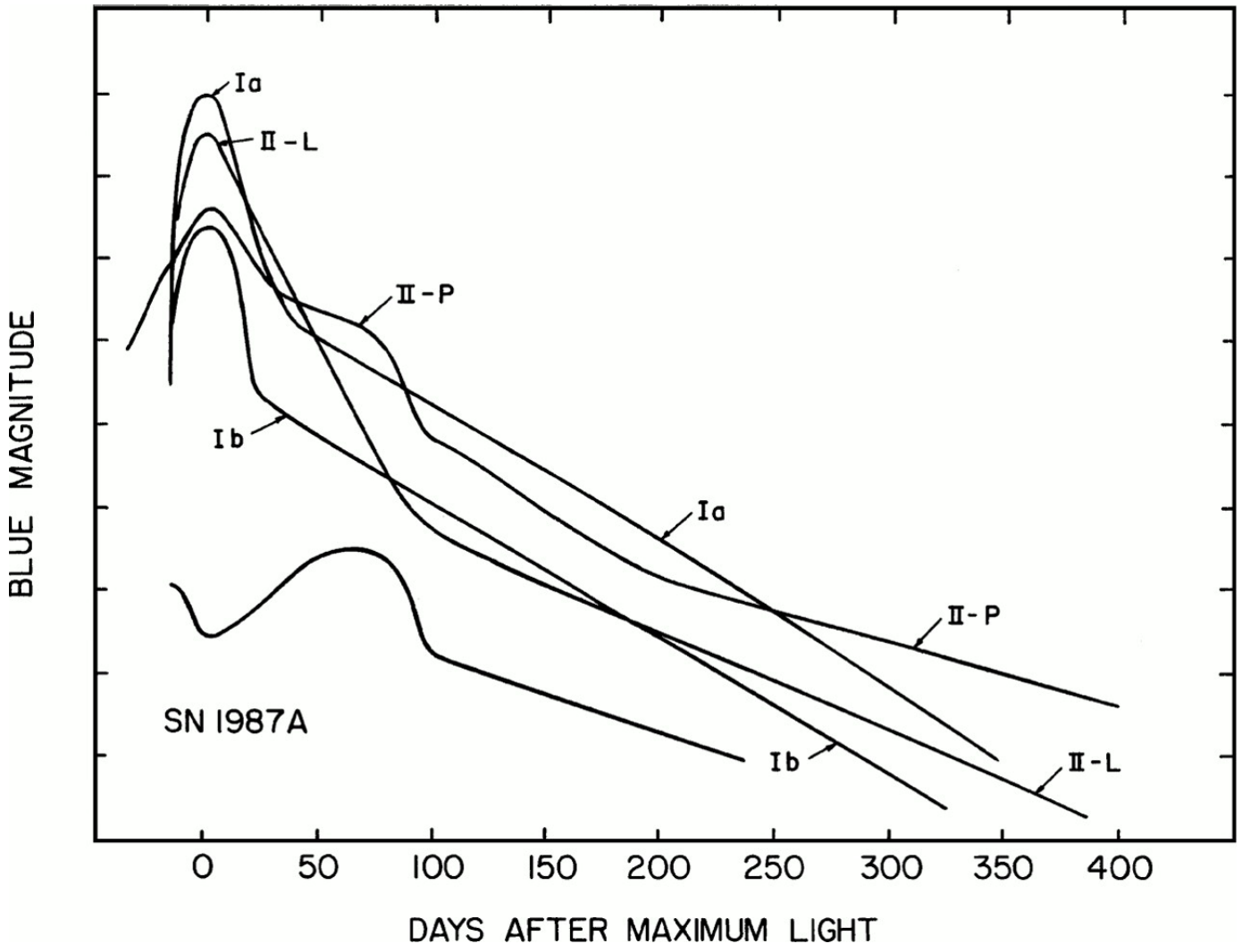
Type II SN2001cm in NGC5965 (2.56 m NOT, Håkon Dahle; NORDITA)



(left: M. Hirsch/M. Hanke, 2009 May 02, right: M. Wille, 2011 Jun 27; Remeis-Obs)

SN 2011dh in M 51

Extragalactic Supernovae

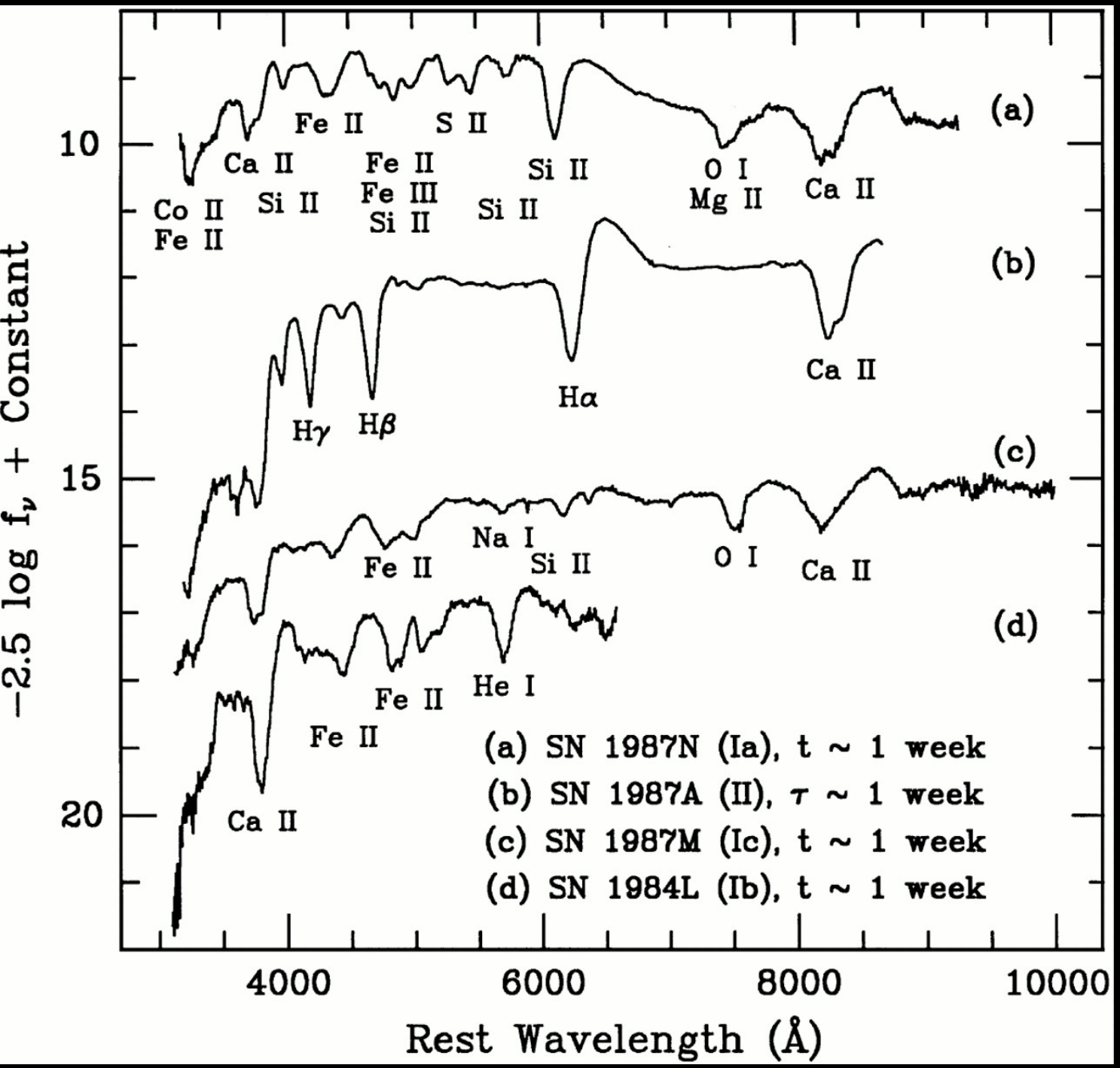


(Wheeler & Harkness, 1990, Fig. 2)

Light curves of SNe I all very similar, SNe II have much more scatter.

SNe II-L ("linear") resemble SNe I

SNe II-P ("plateau") have const. brightness to within 1 mag for extended period of time.



(Filippenko et al., 1997, Fig. 2); t: time after maximum light; τ: time after explosion; P Cyg profiles give $v \sim 10000\,\mathrm{km\,s^{-1}}$

Rough classification (Minkowski, 1941):

Type I: no hydrogen in spectra; subtypes Ia, Ib, Ic

Type II: hydrogen present, subtypes II-L, II-P

Note: pre 1985 subtypes Ia, Ib had different definition than today $\Longrightarrow$ beware when reading older texts.

Supernova Statistics

Clue on origin from supernova statistics:

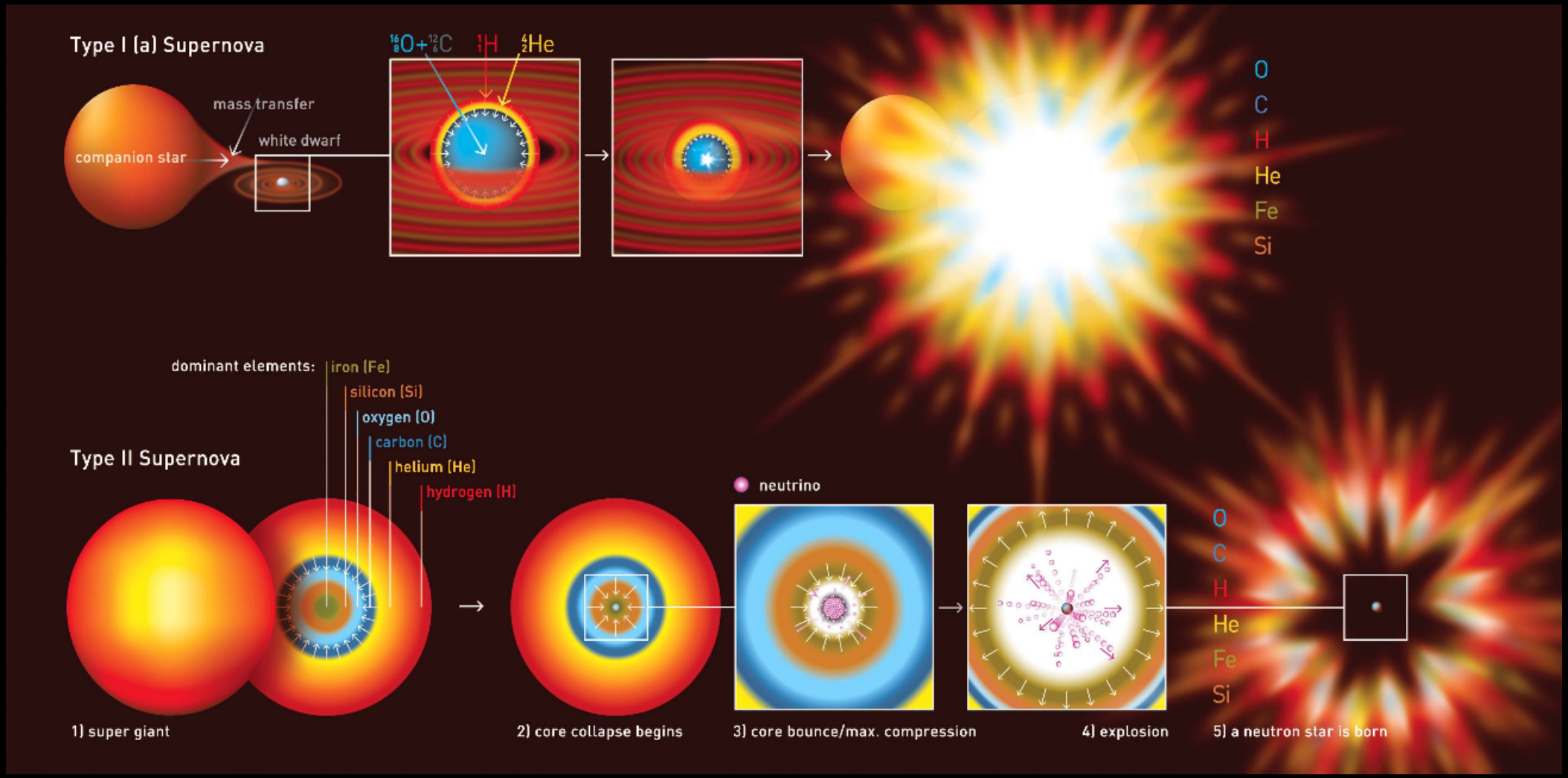
- SNe II, Ib, Ic: never seen in elliptical galaxies, which are void of gas and have no new star formation; generally associated with spiral arms and H II regions in spiral galaxies, i.e., with star forming regions

$\Longrightarrow$ progenitor of SNe II, Ib, Ic: massive stars ($\gtrsim 8\,M_\odot$)
$\Longrightarrow$ "core collapse supernova"

- SNe Ia: all types of galaxies, coming from both young and old stellar populations.

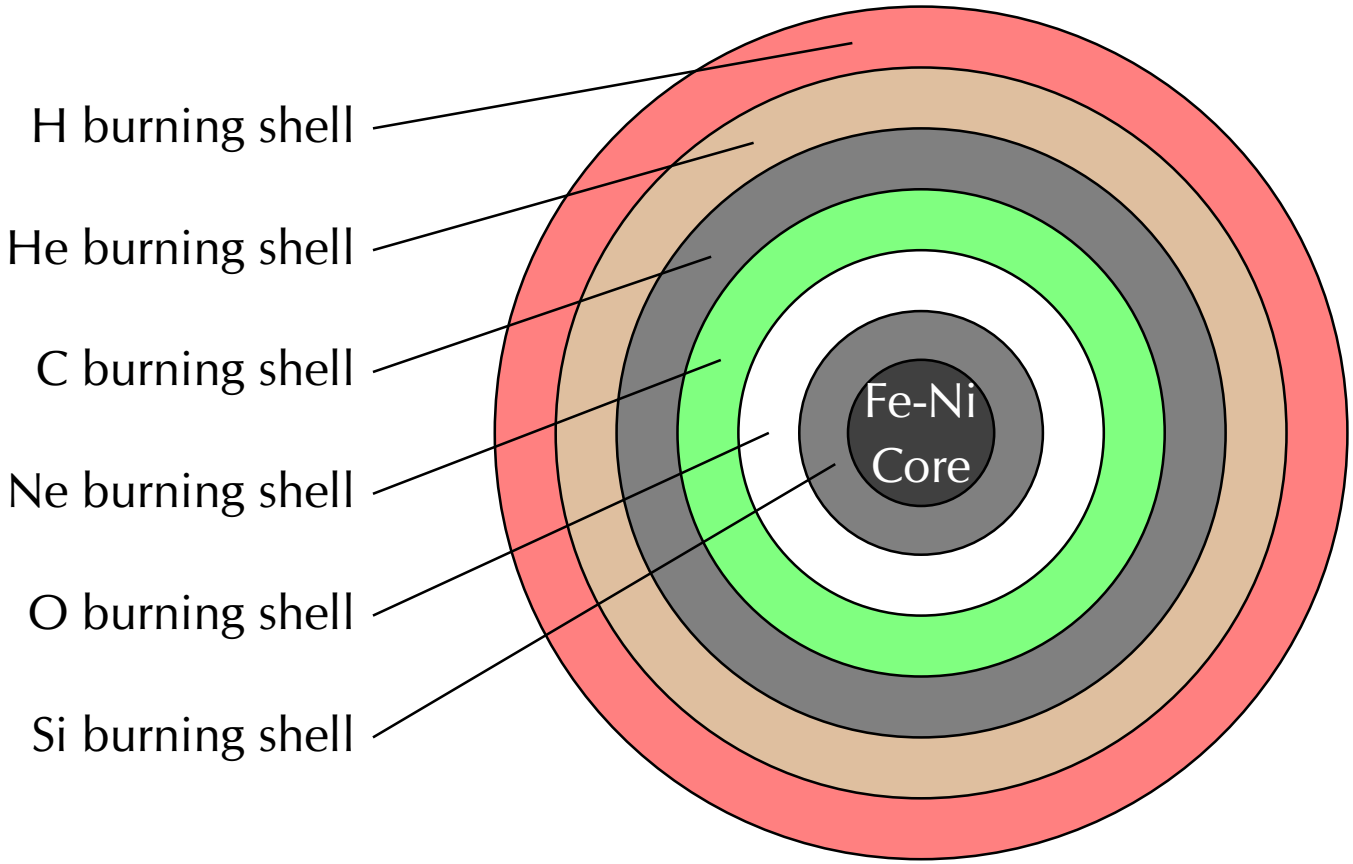
$\Longrightarrow$ stellar progenitors of SNe Ia can not be massive stars, because such stars do no longer exist in old stellar populations.

common model: accreting carbon-oxygen white dwarfs undergoing thermonuclear runaway



F.K. Thielemann

Core Collapse Supernovae

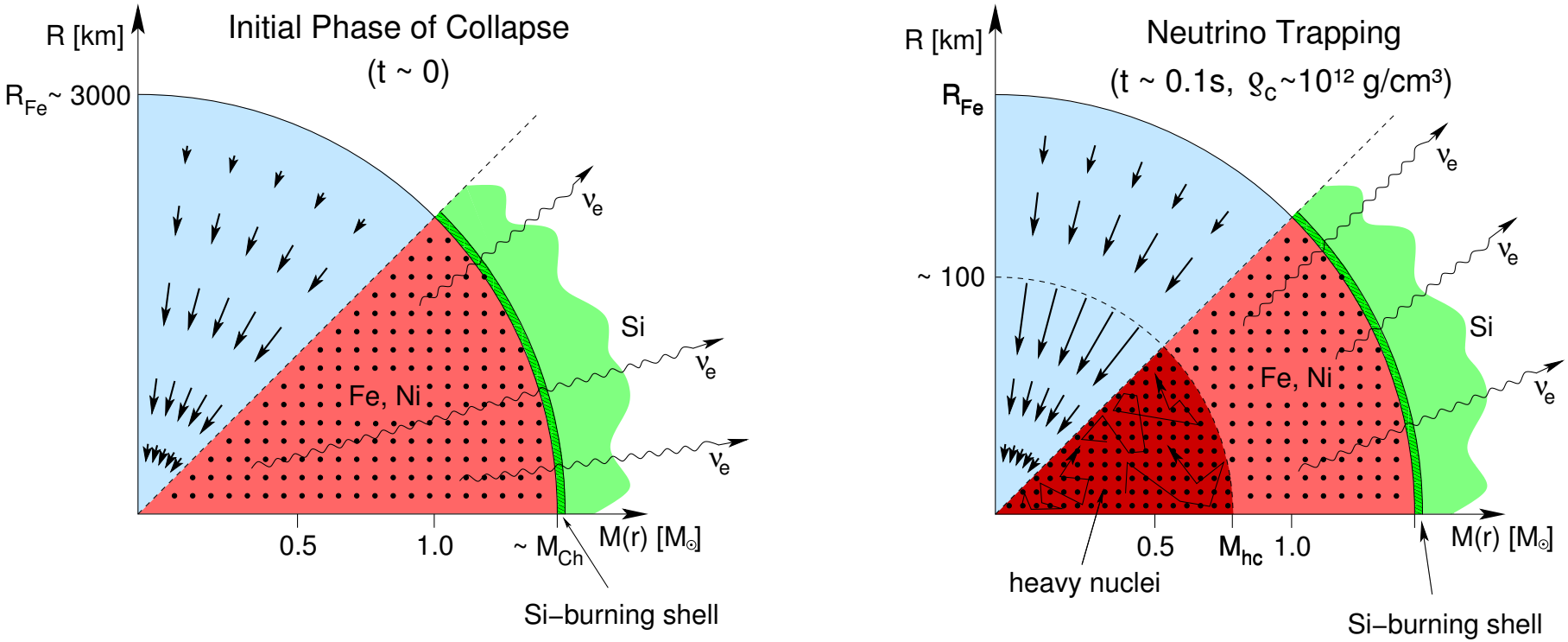


Successive stages of nuclear burning in a massive star:

1. H burning, ash: He
2. He burning, ashes: C, O, Ne, Mg
3. C burning, ashes: Ne, Na, Mg
4. Ne burning, ashes: O, Mg . . .
5. O burning, ashes: Si, P, S, . . .
6. Si burning, ashes: Fe, Ni

Final state: "onion-shell"

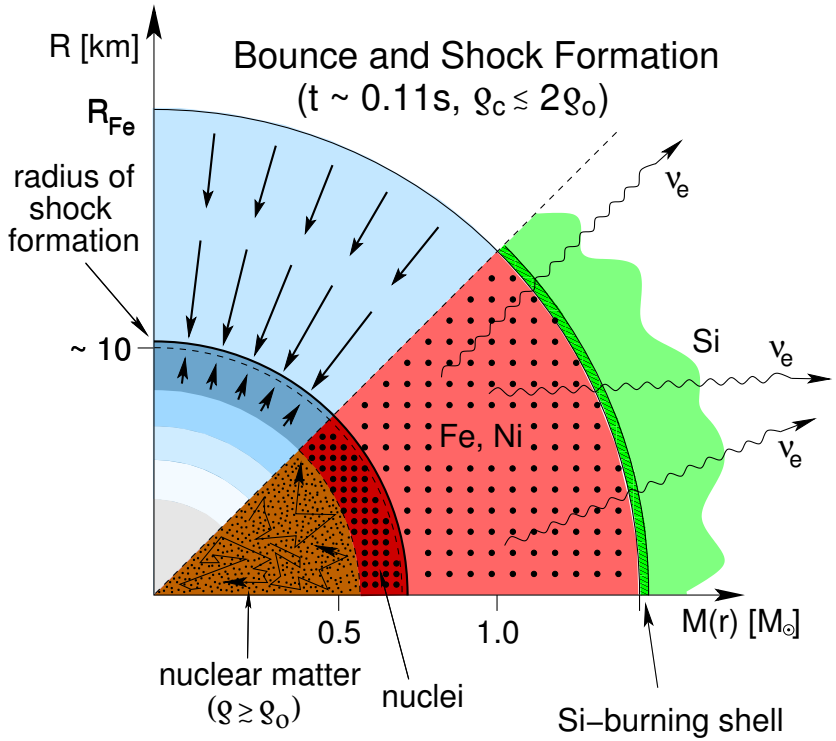
Core Collapse Supernovae

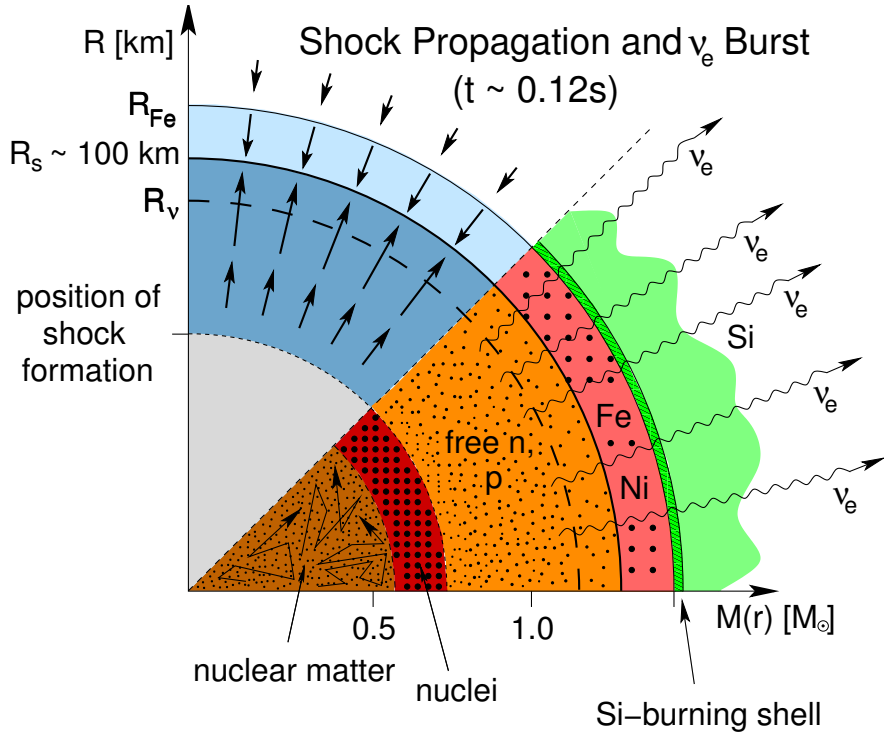


Janka et al. (2007, Phys. Rep. 442, 38; Fig. 1)

$t = 0\,\mathbf{s}$: Collapse of Fe/Ni core of star with main sequence mass $>10\,M_\odot$, triggered by electron capture and photodisintegration of Fe ($T \sim 10^{10}\,\mathrm{K}$, $\rho \sim 10^{10}\,\mathrm{g\,cm^{-3}}$).

Core Collapse Supernovae



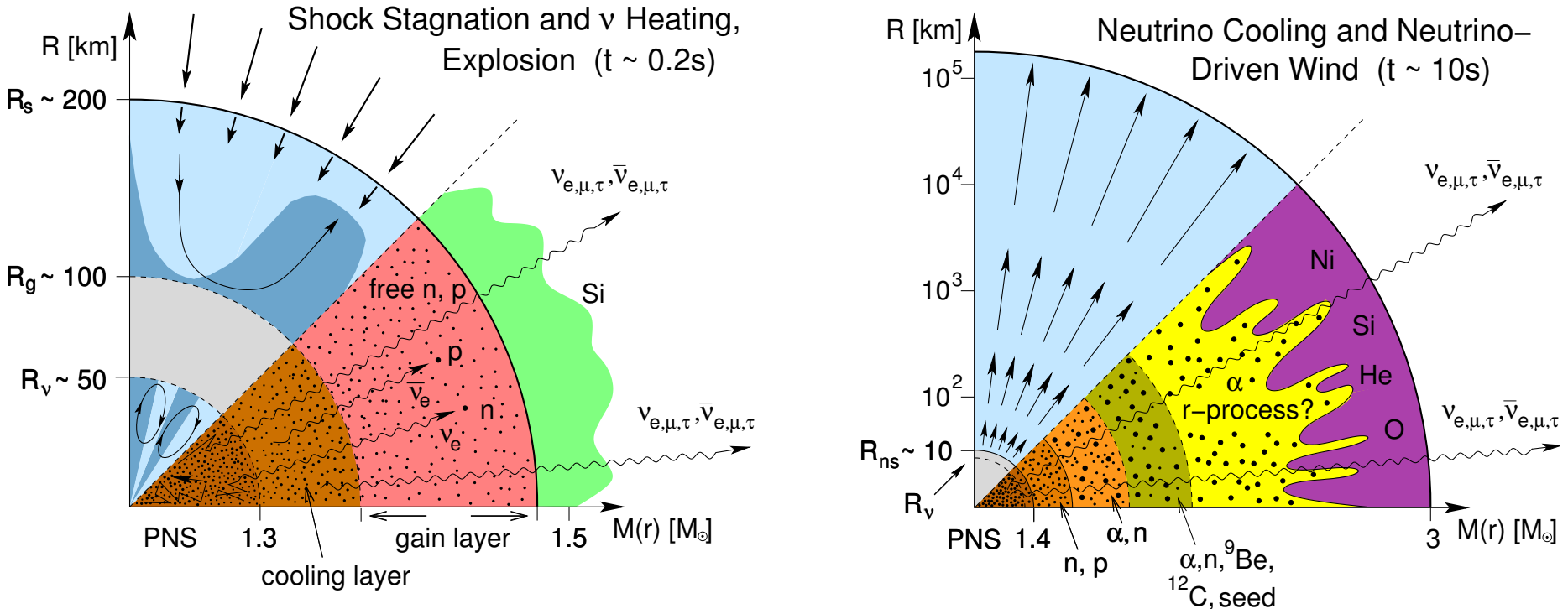


Janka et al. (2007, Phys. Rep. 442, 38; Fig. 1)

rebound: outer material rebounds off core, looses velocity because of photodisintegration and neutrino loss

$t = 0.1\,\mathbf{s}$: proto-neutron star formed with $R \sim 30\,\mathrm{km}$, $M = 1.4\,M_\odot$, standing shock ~150 km above neutron star

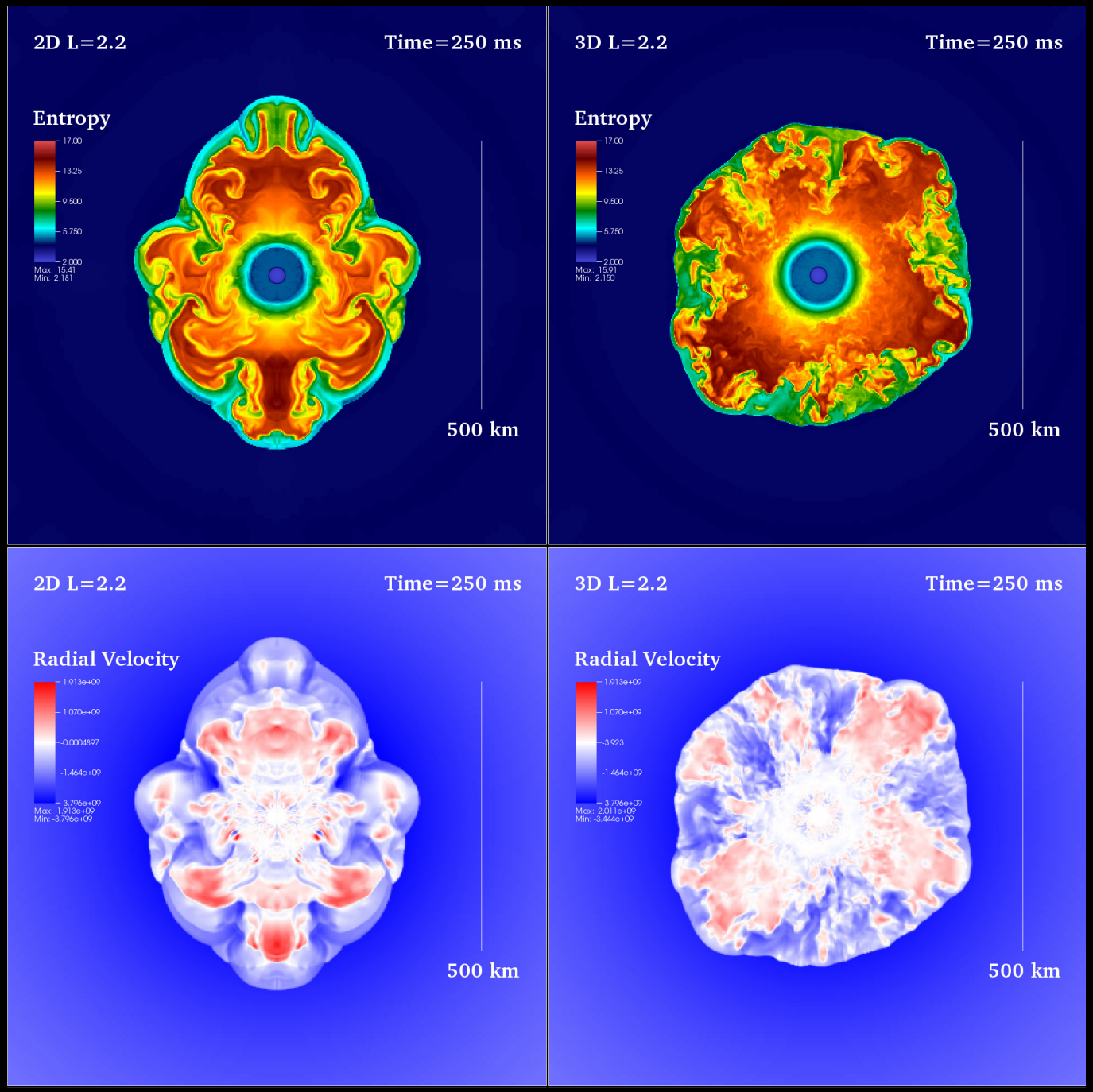
Core Collapse Supernovae



Janka et al. (2007, Phys. Rep. 442, 38; Fig. 1)

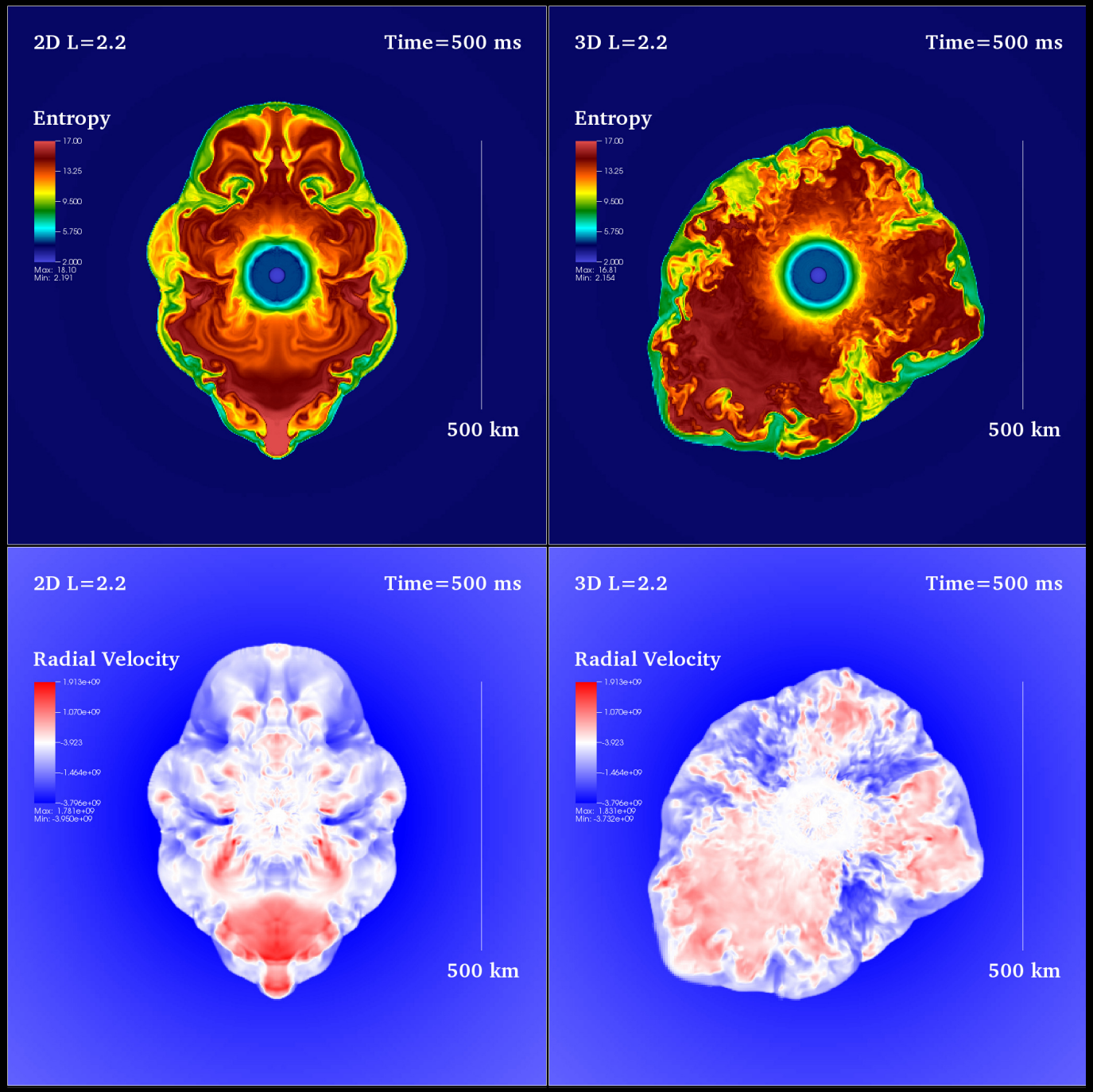
until $t = 0.2$ **s:** start to radiate $\sim 10^{53}$ erg s^{-1} as neutrinos, triggers convection, heats material by depositing 10^{51} erg ($\longrightarrow$ convection)

$t = 0.2$ **s:** SN explosion is triggered



comparison of 2D and 3D SN simulations (Dolence et al. 2012, ApJ 765, 110, Fig. 2)

Understanding of SNe is strongly limited by available computing resources!

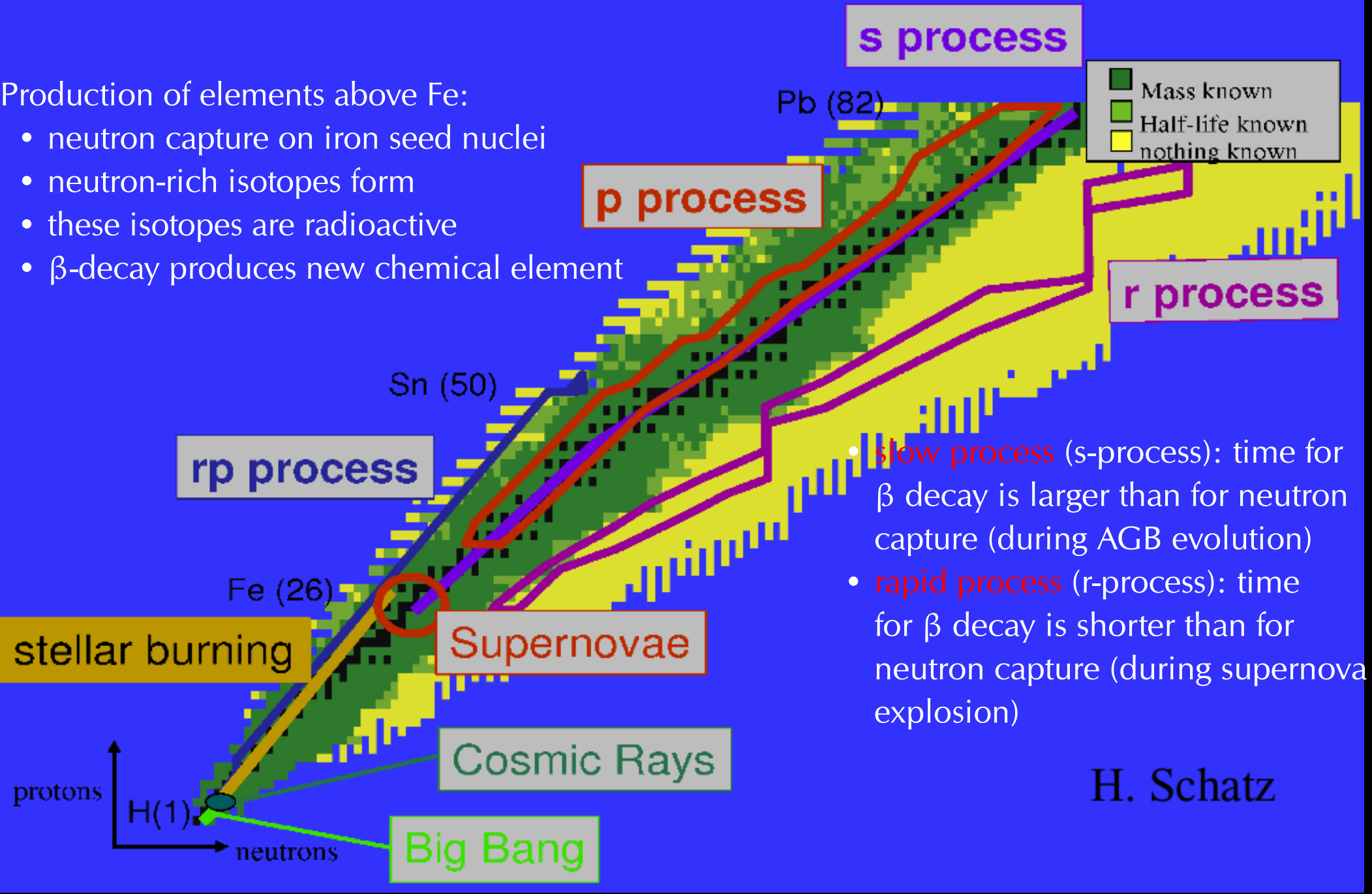


comparison of 2D and 3D SN simulations (Dolence et al. 2012, ApJ 765, 110, Fig. 3)

Understanding of SNe is strongly limited by available computing resources!

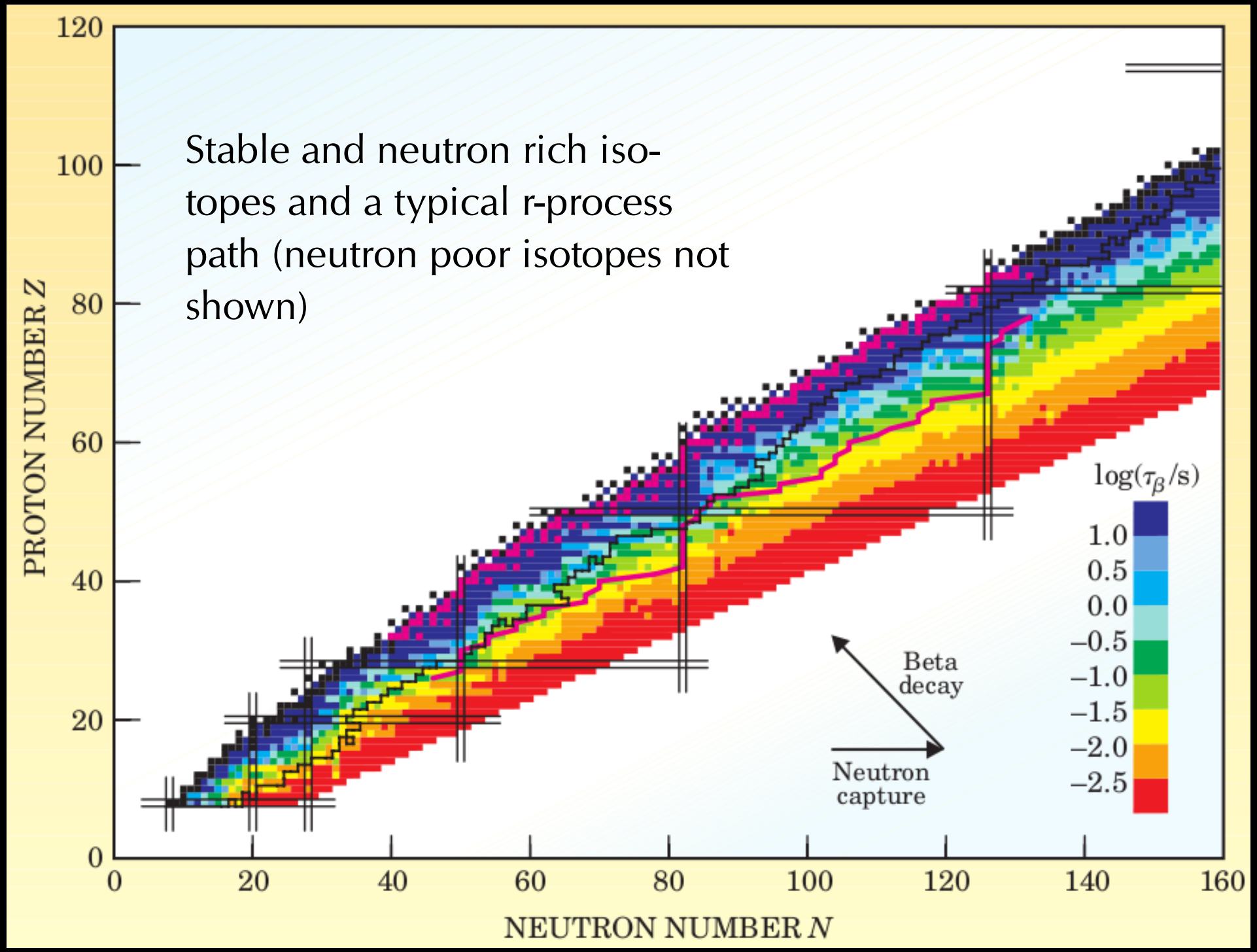
Production of elements above Fe:

- neutron capture on iron seed nuclei
- neutron-rich isotopes form
- these isotopes are radioactive
- β-decay produces new chemical element



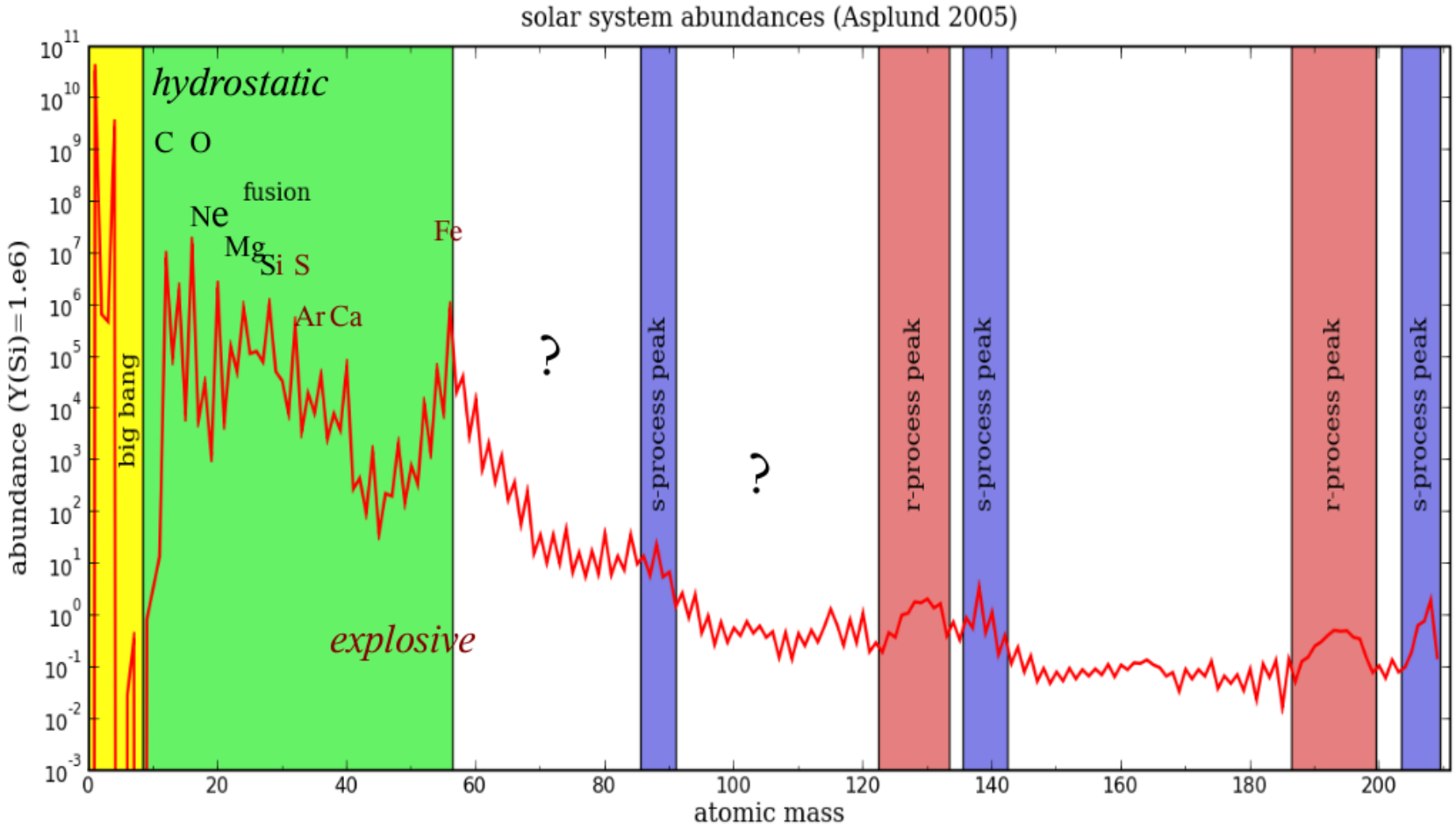
- slow process (s-process): time for β decay is larger than for neutron capture (during AGB evolution)
- rapid process (r-process): time for β decay is shorter than for neutron capture (during supernova explosion)

H. Schatz



(Cowan & Thielemann, 2004, Physics Today, 46; after P. Möller)

Nucleosynthesis



With SN calculations and fusion mechanisms in stars, it is possible to explain the observed elemental abundance pattern of the solar system.

First work on these processes: Burbidge, Burbidge, Fowler, Hoyle, 1957 (B^2FH)


© Anglo-Australian Observatory

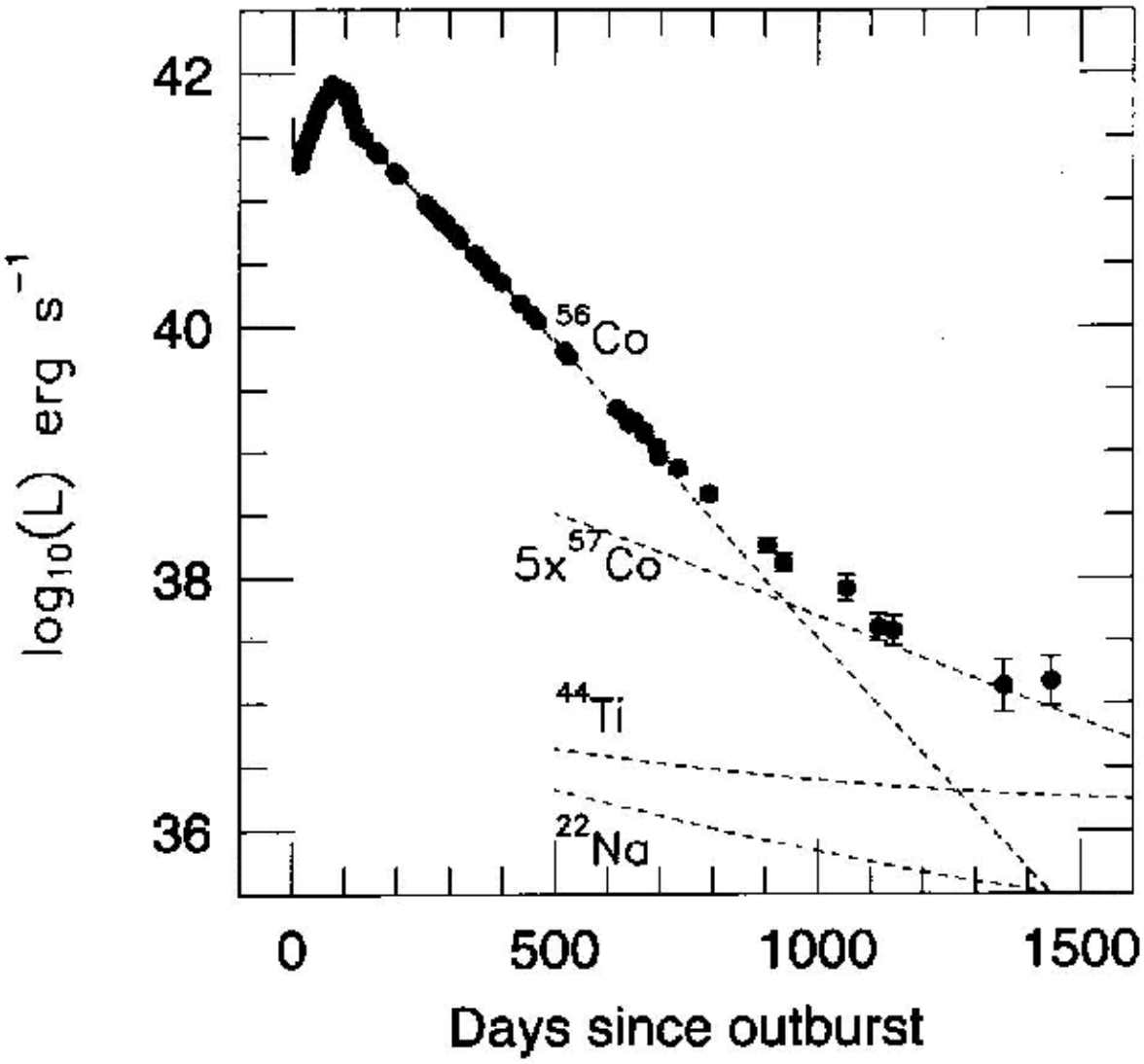

© Anglo-Australian Observatory

SN1987a

SN1987A in the Large Magellanic Cloud, 1987 February 23

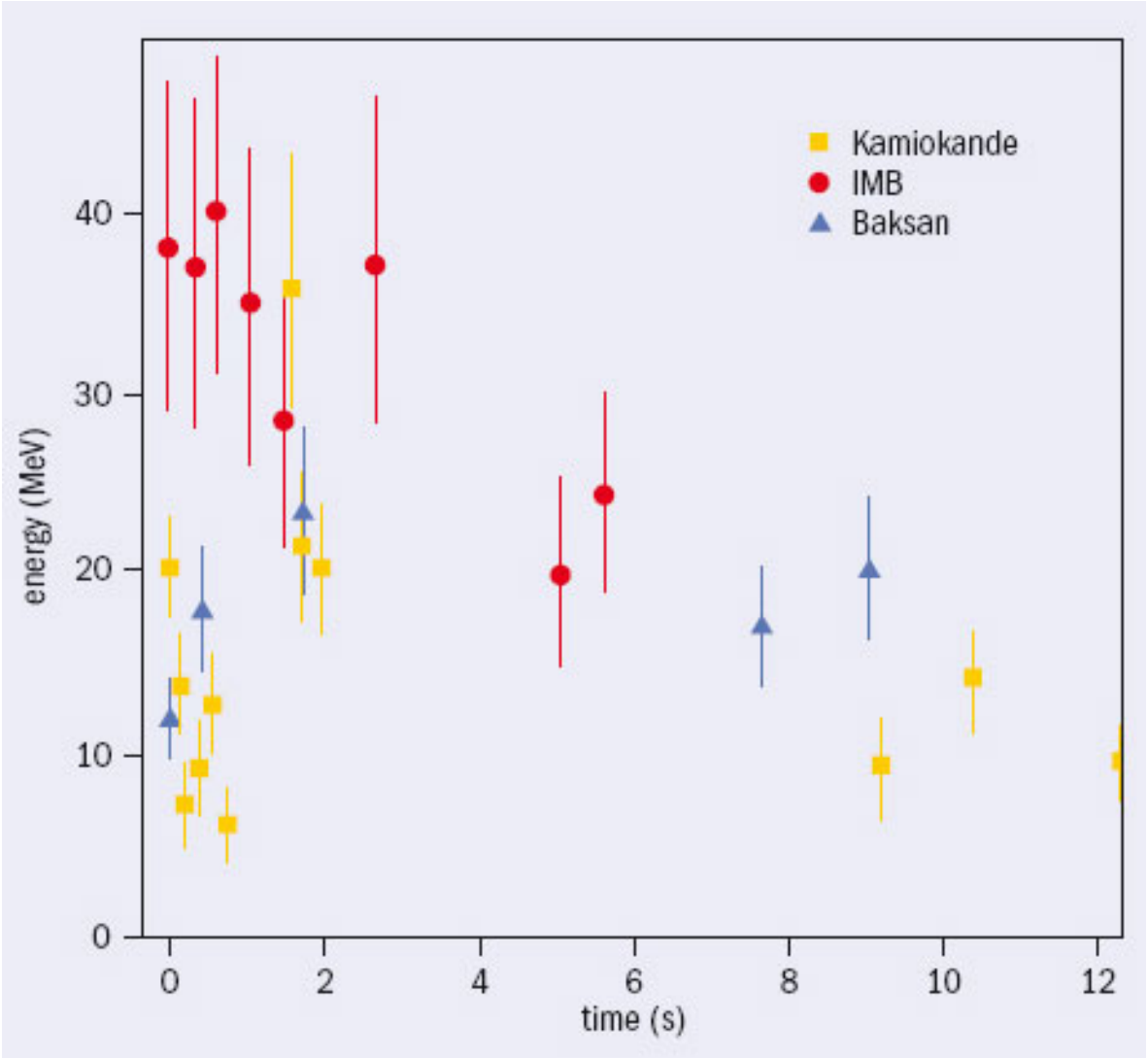
- distance well known = 50 kpc
- visible to the naked eye ($V_{max} = 4.5$ mag), first after 300 yrs
- for the first time it was possible to identify the progenitor star
- progenitor Sanduleak −69 202 = massive star, i.e., blue supergiant
- supports core collapse model
- light curve has been measured over 20 yrs, presently V = 21 mag
- spectral changes have been monitored over many years

SN1987a



Expanding envelope powered by radioactive decay of short lived isotopes created in the core collapse

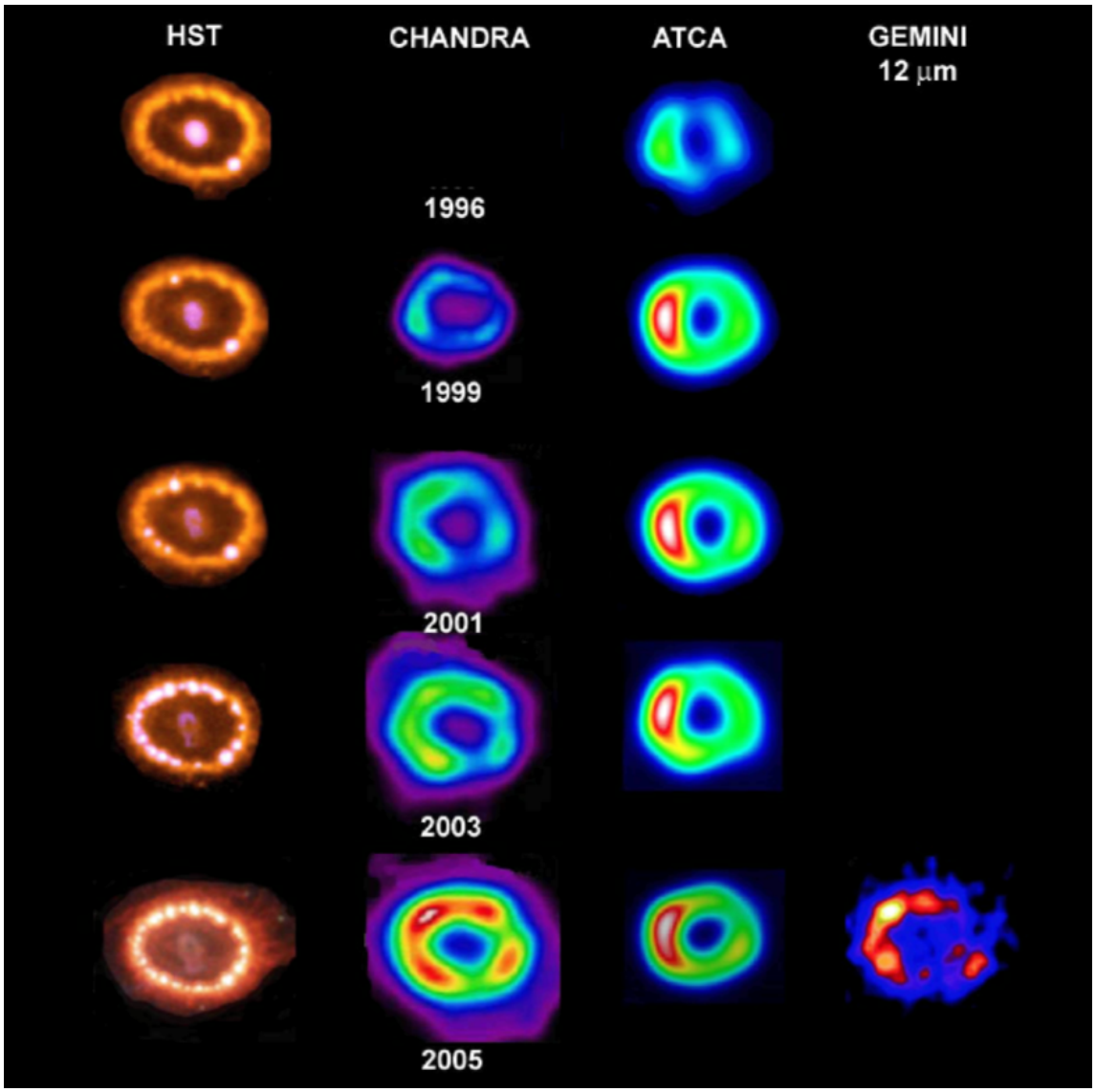
SN1987a



Neutrinos detected as predicted by core collapse model

Cern Courier

SN1987a

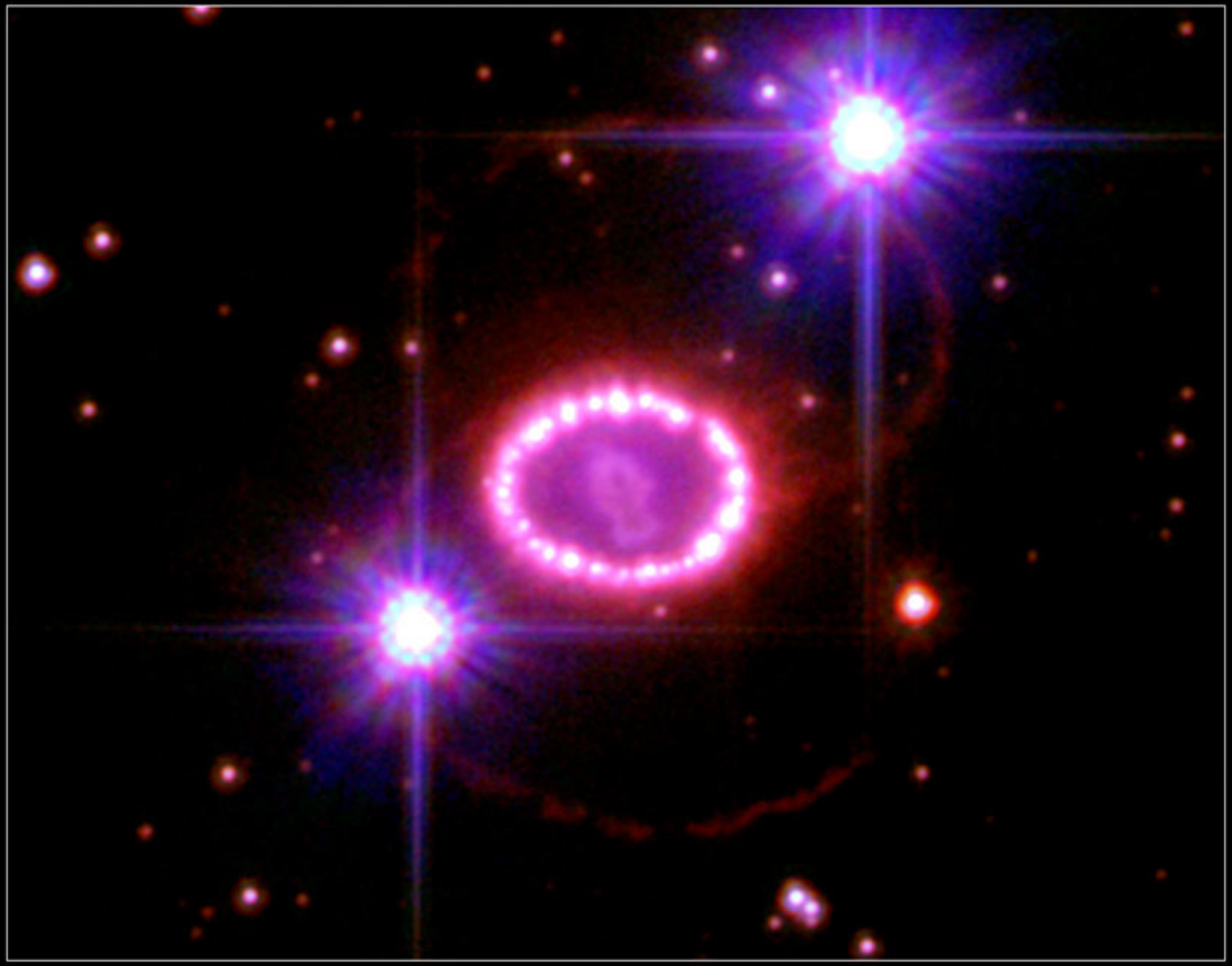


McCray 2007, Fig. 6

Late time light curve due to radioactive decay of Cobalt.

- Day 125–1100: dominated by decay of ^{56}Co
- After ~3 years: radioactive decays of long-lived ^{57}Co and later ^{44}Ti start to heat the system
- Today: Light curve almost flat and $\sim 10^{-7}$ fainter than at maximum! Ring still brightening!

SN 1987A has made the transition to a young Supernova Remnant!



Supernova 1987A • December 2006

Hubble Space Telescope • Advanced Camera for Surveys

NASA, ESA, P. Challis, and R. Kirshner (Harvard-Smithsonian Center for Astrophysics)

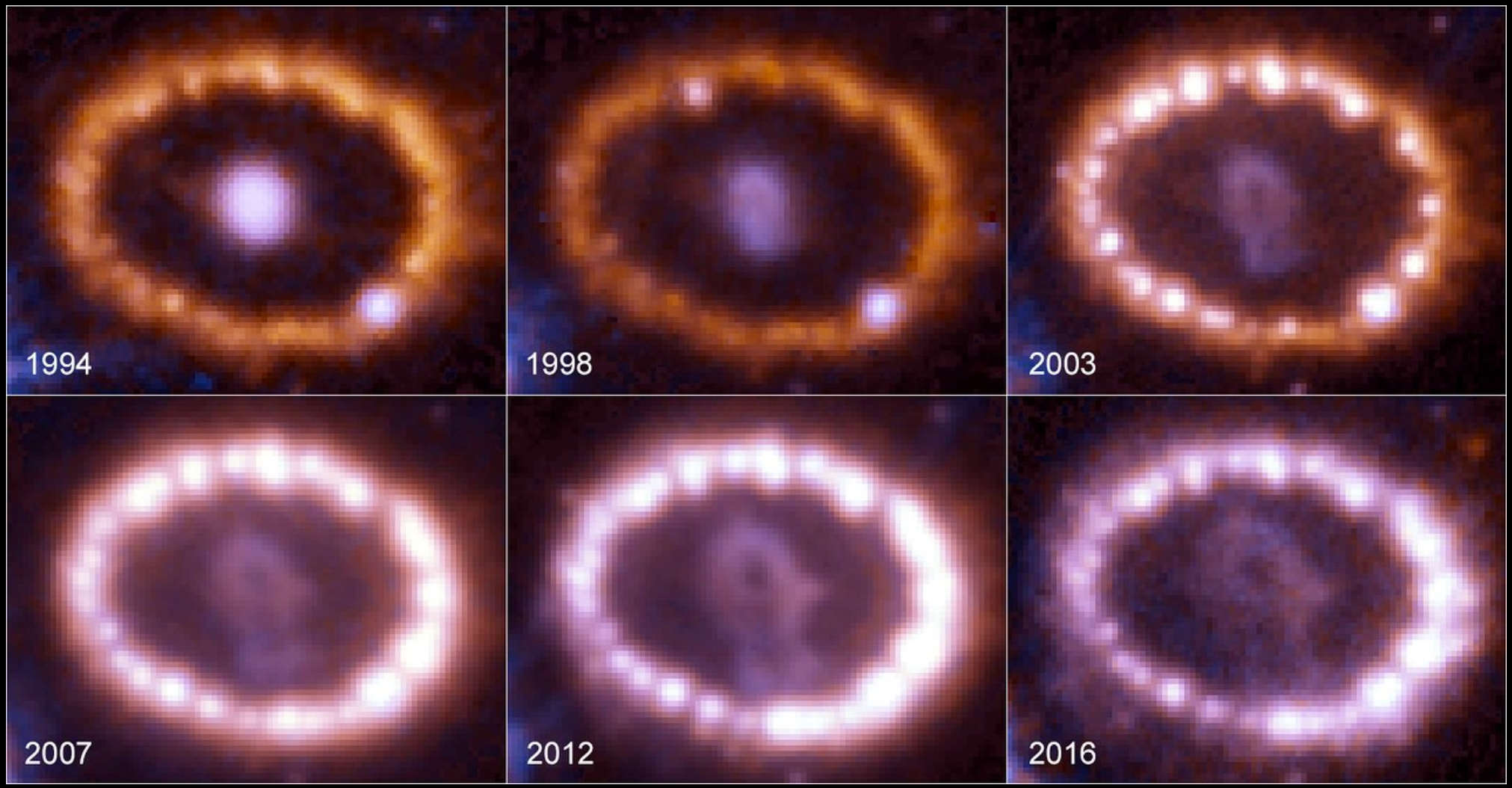
STScI-PRC07-10

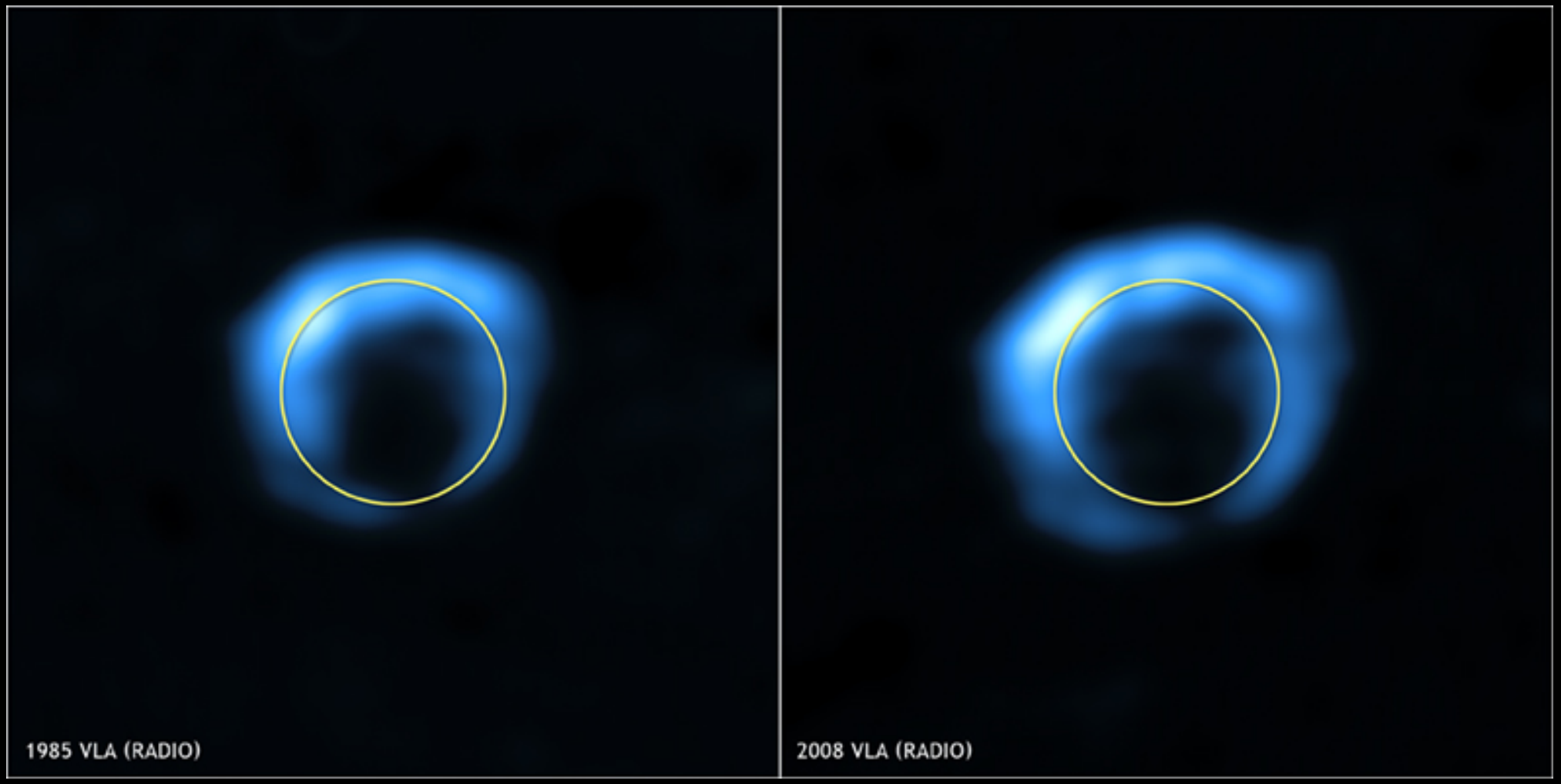


Additional features:
rings

- central ring, light year across; due to impact of a shock wave on circumstellar material ejected from progenitor star; started to glow $\gtrsim$15 years after explosion.
- outer rings: due to ionization of material illuminated by SN? Material possibly from bipolar outflow during blue supergiant phase (fast blue SG wind colliding with slower RG wind); material ejected $\sim$20000 years before explosion.

NASA, ESA, and R. Kirshner (Harvard-Smithsonian Center for Astrophysics and Gordon and Betty Moore Foundation) and P. Challis (Harvard-Smithsonian Center for Astrophysics)


1994
1998
2003
2007
2012
2016



G1.9+0.3: Youngest Galactic SN remnant. While known since long time, it was only in 2008 that the fast expansion was noted $\Longrightarrow$ age: 140 ± 30 years

Due to strong extinction by dust in MW, explosion was not observed.



(ESO VLT/FORS 2)

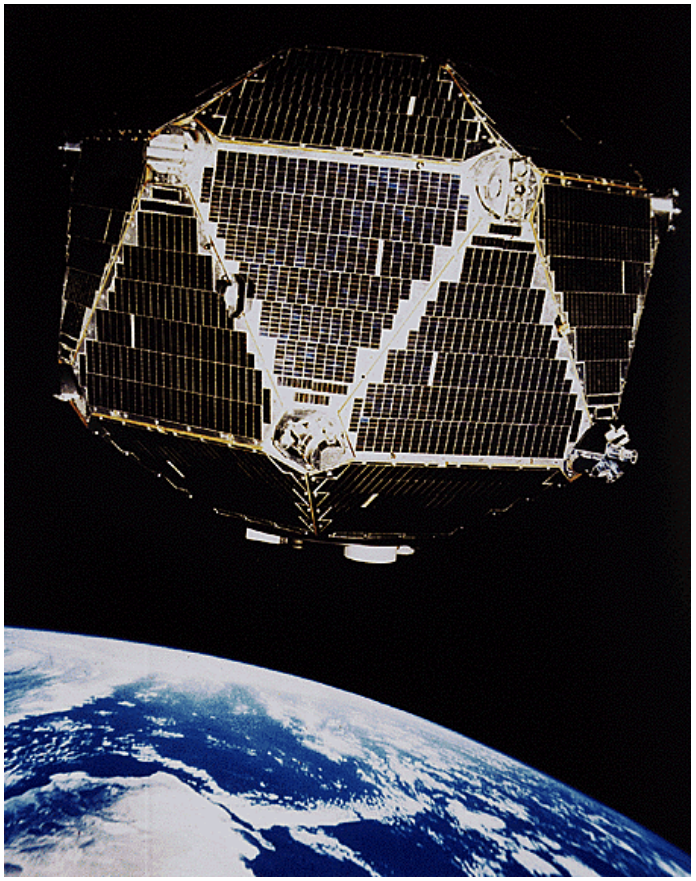
Crab nebula: young remnant of SN of 1054, observed light due to synchrotron radiation (radiation emitted by electrons accelerated in magnetic field)



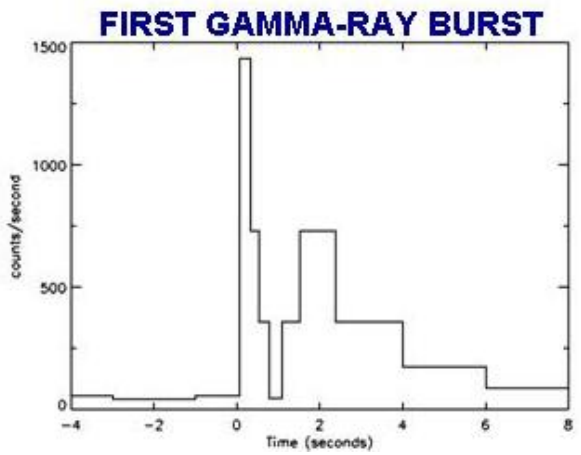
5000–10000 year old IC 1340/Veil Nebula/Cygnus Loop (©Loke Kun Tan)

Older supernova remnants: "wispy structure" due to interaction with interstellar medium, radiation (line emission) mainly caused by heating due to shocks.

Gamma-Ray Bursts



Sketch of one of the Vela satellites to search for violations of the nuclear test ban treaty.



1967: Vela satellites find extremely bright flares from the sky, with durations of a few seconds: Gamma-Ray Bursts (GRBs; total of 73 GRBs found between).

Reported in 1973 only (Klebesadel et al., 1973).

During the burst, GRBs are the *brightest* gamma-ray objects in the sky, brighter than the Sun!

1990s: CGRO era



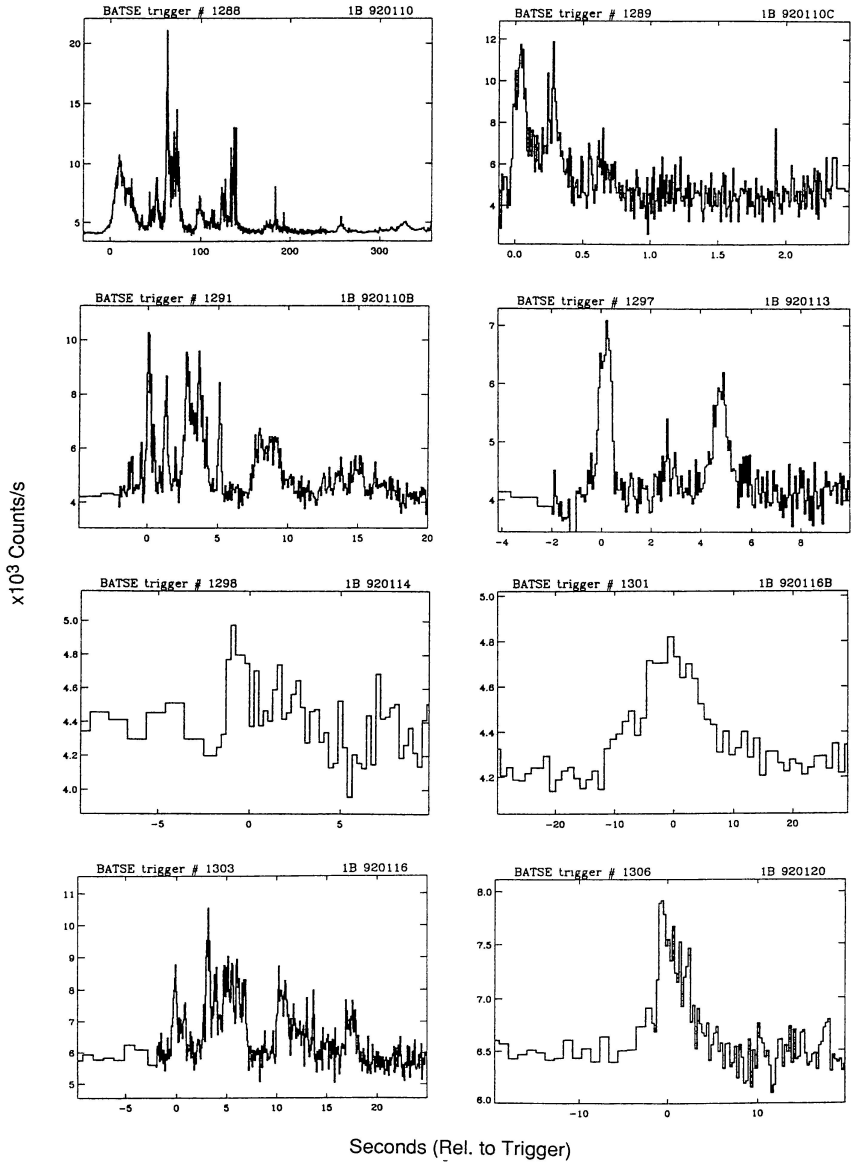
Due to short duration of bursts, no detailed studies were available for a long time.

This changed with the Burst and Transient Science Experiment (BATSE) on the Compton Gamma-Ray Observatory (*CGRO*; launch 1991): All Sky Monitor, first systematic study of Gamma-Ray Bursts.

Gamma-Ray Bursts are very common: BATSE saw 1 GRB day^{-1}, taking into account BATSE covering factor: 600 GRB year^{-1}

Movie time: `grbmovies/grb_animation.gif`

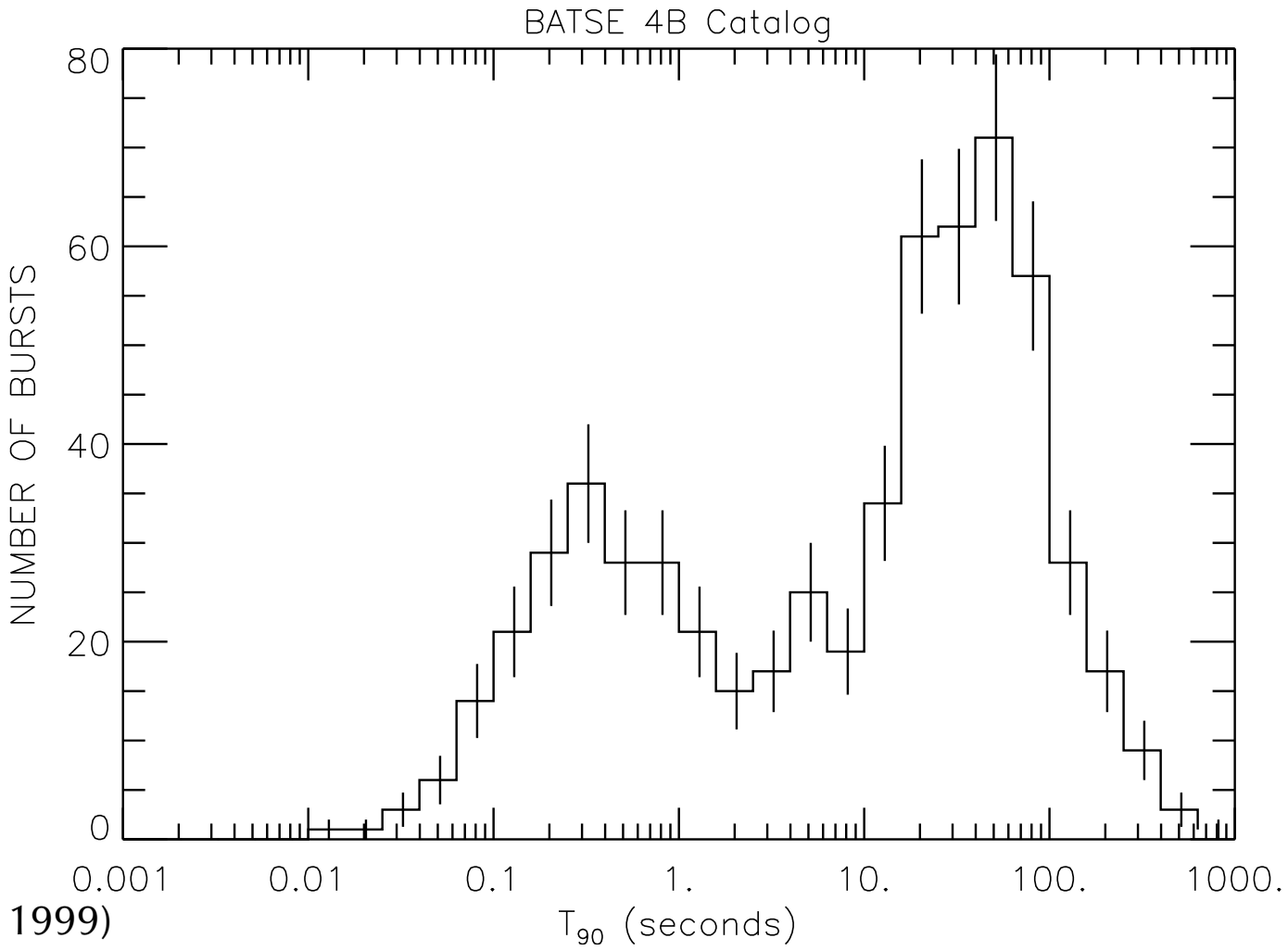
1990s: CGRO era



There is a wide variety of burst lightcurves, both in duration and morphology.

(Fishman et al., 1995, Fig. 1)

1990s: CGRO era

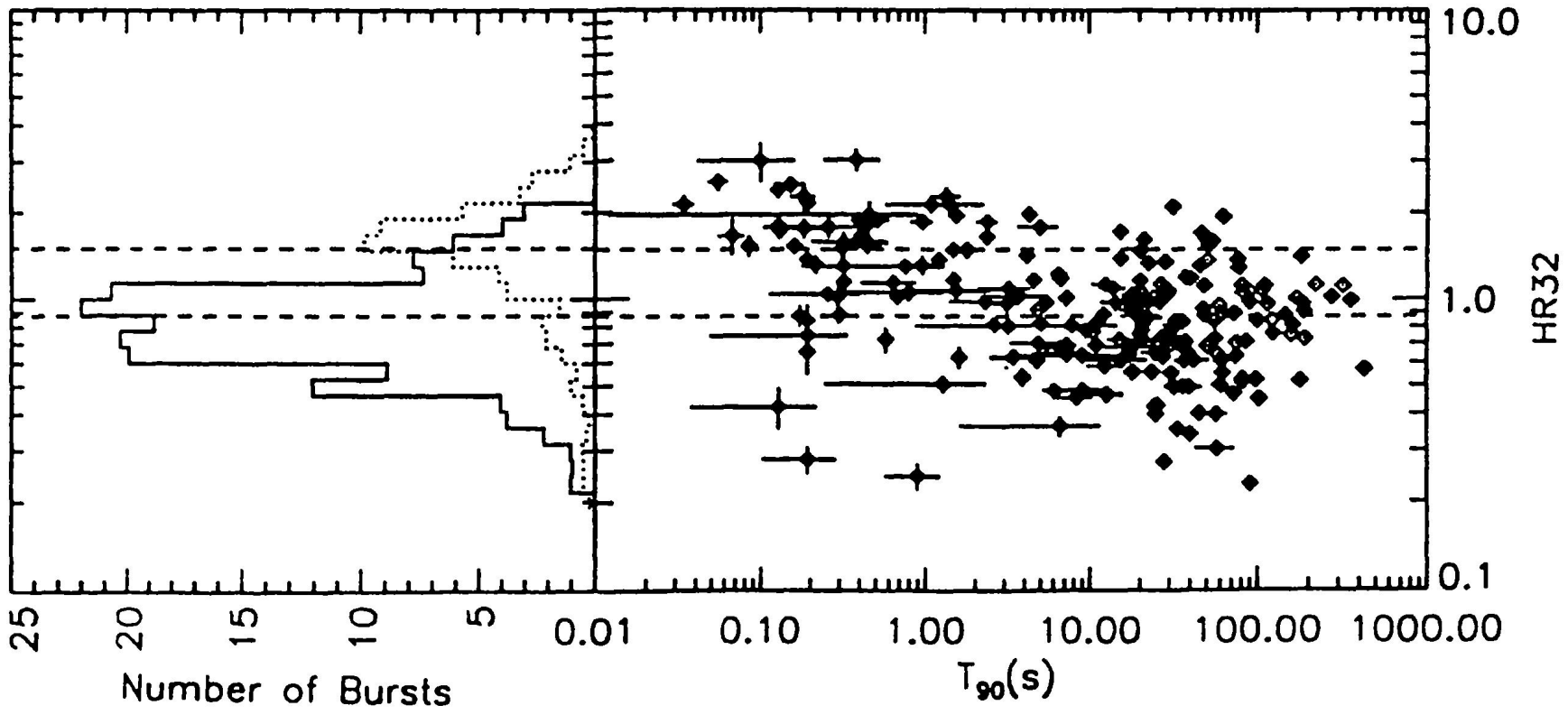


(Paciesas et al. 1999)

Kouveliotou et al. (1993): There are two classes of Gamma-Ray Bursts:

long bursts ($t_\gamma > 2$ s) and short bursts ($t_\gamma < 2$ s).

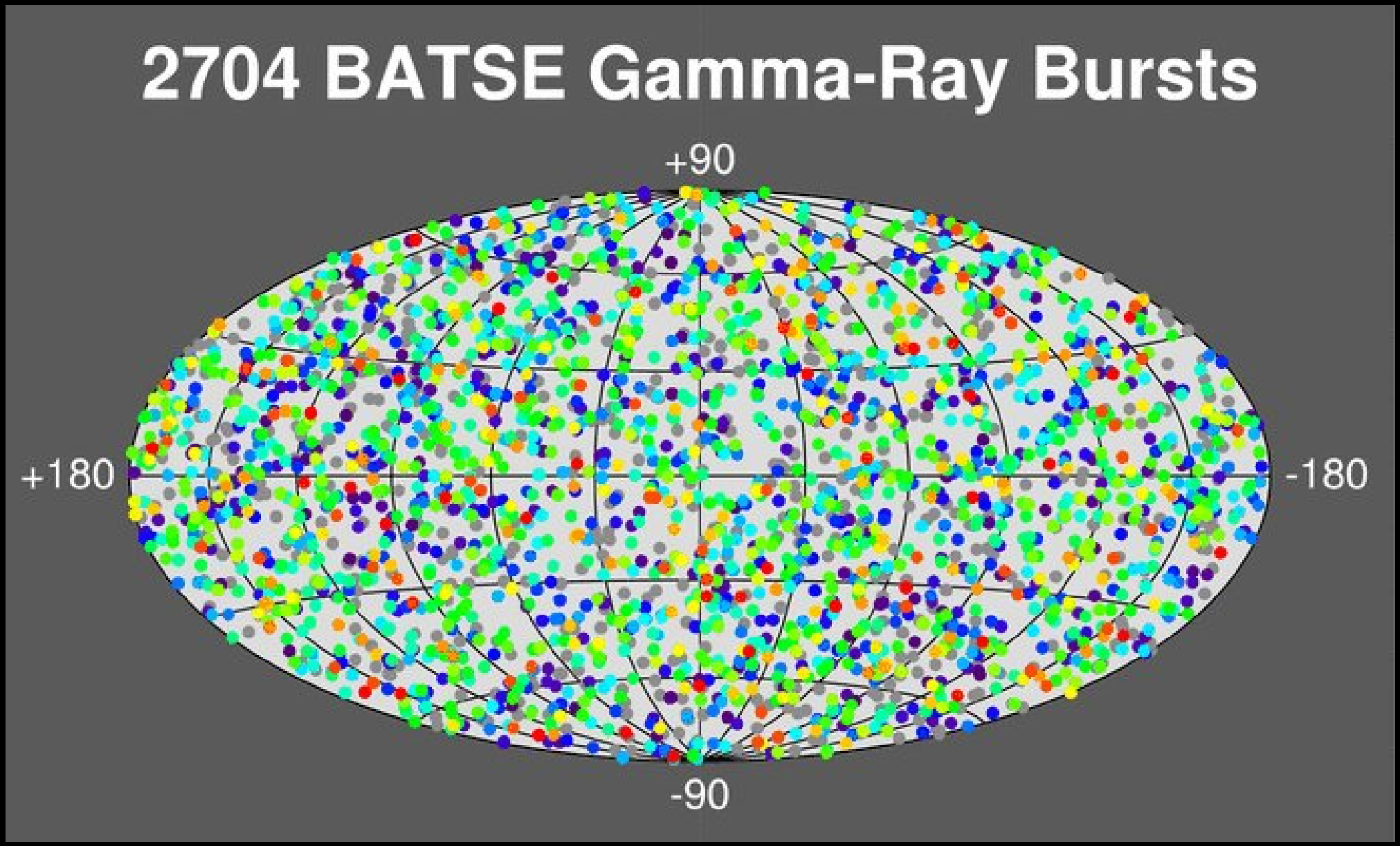
1990s: CGRO era



(Kouveliotou et al., 1993)

There is a correlation between spectral shape and duration of the burst:

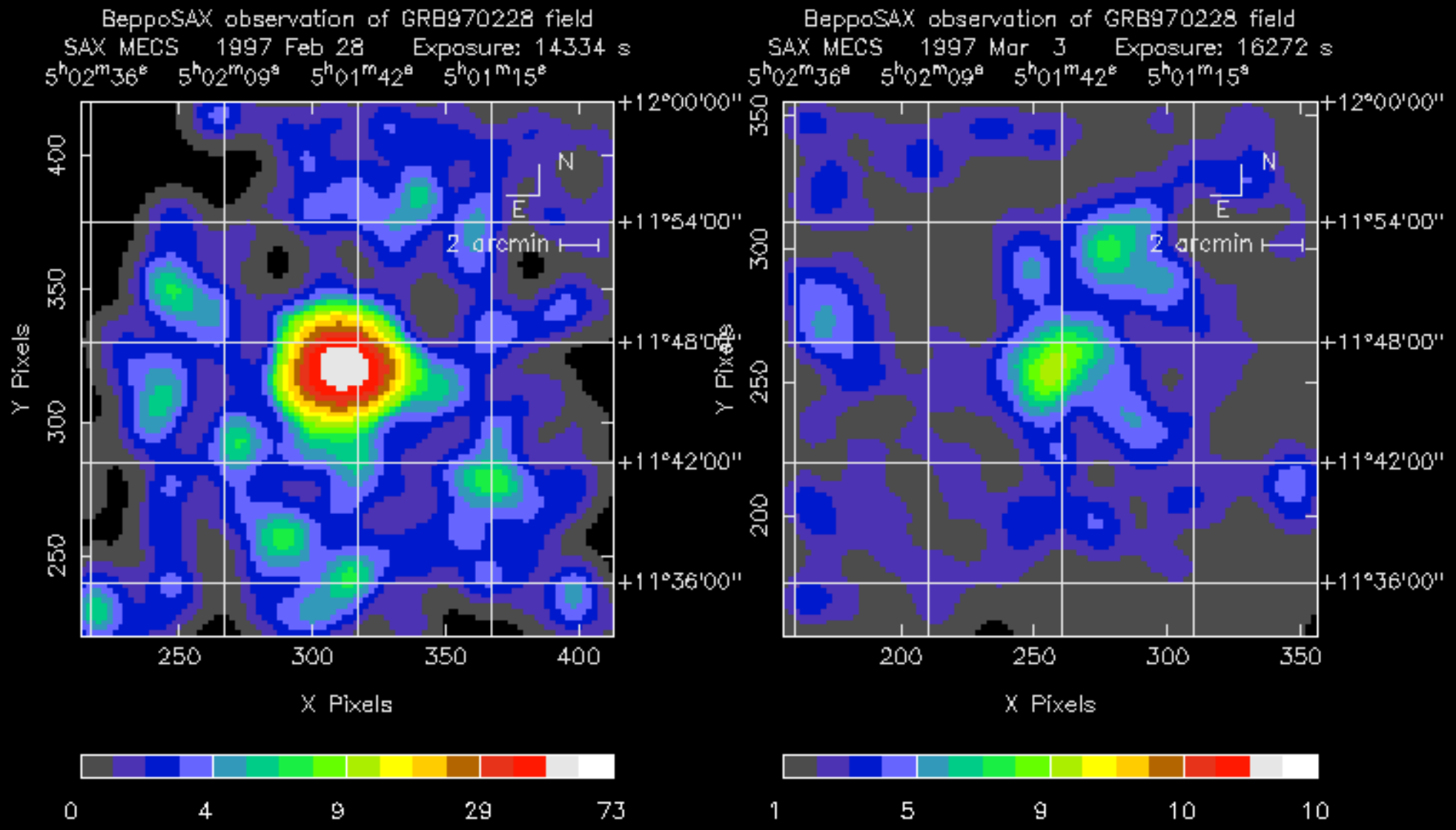
Shorter bursts tend to have harder X-ray/gamma-ray spectra.



9 years of *CGRO*-BATSE GRBs

Bursts are distributed isotropically on sky:

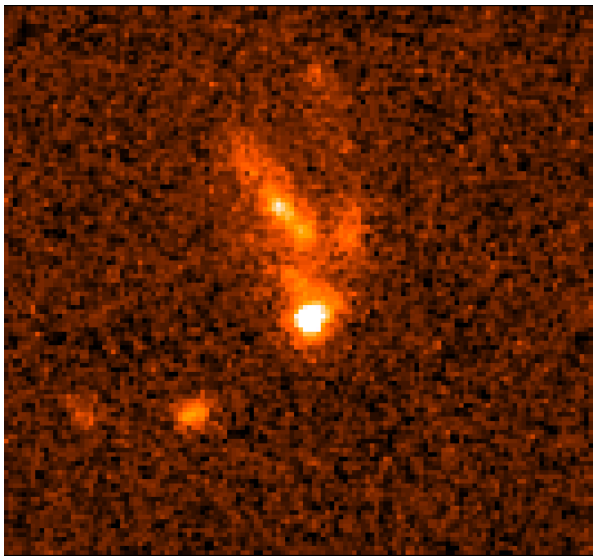
they are either very close (solar system) or at cosmological distances.



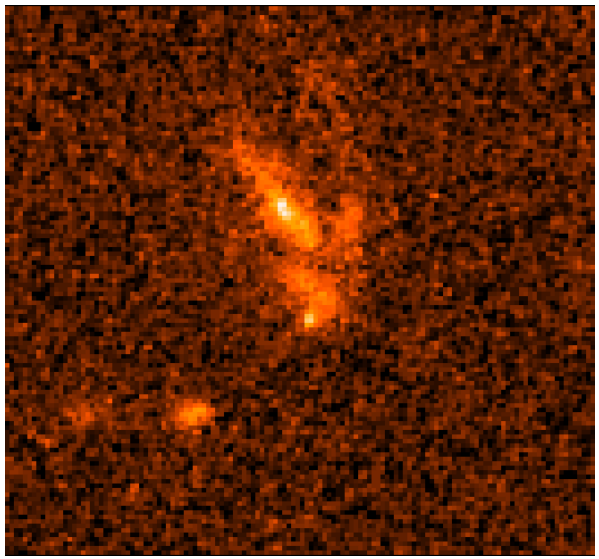
GRB 970228: *BeppoSAX* finds first GRB afterglow (Costa et al., 1997)

$\Longrightarrow$ Allows precise localization of burst

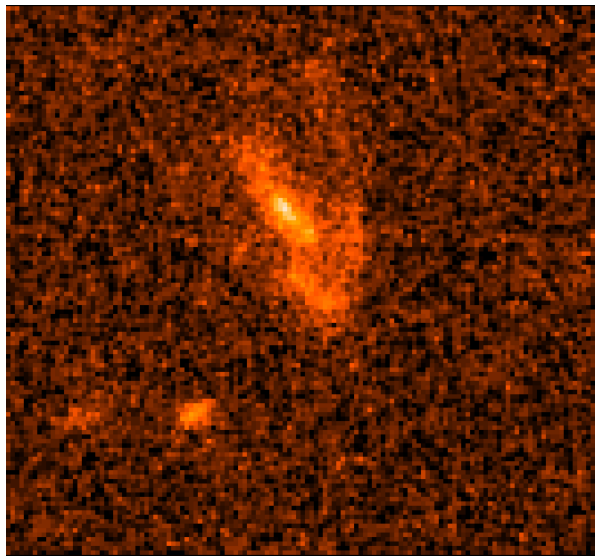
GRB 990123



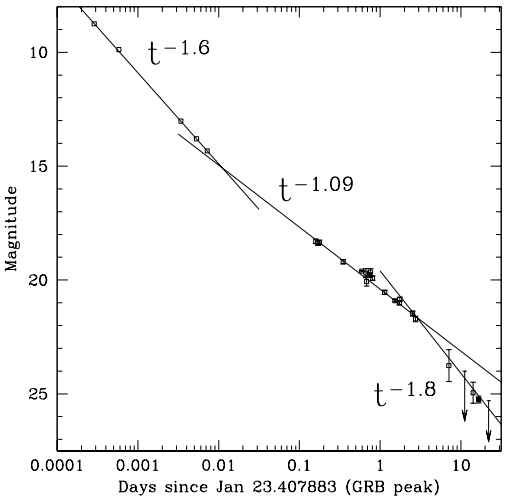
Feb 1999



Mar 1999

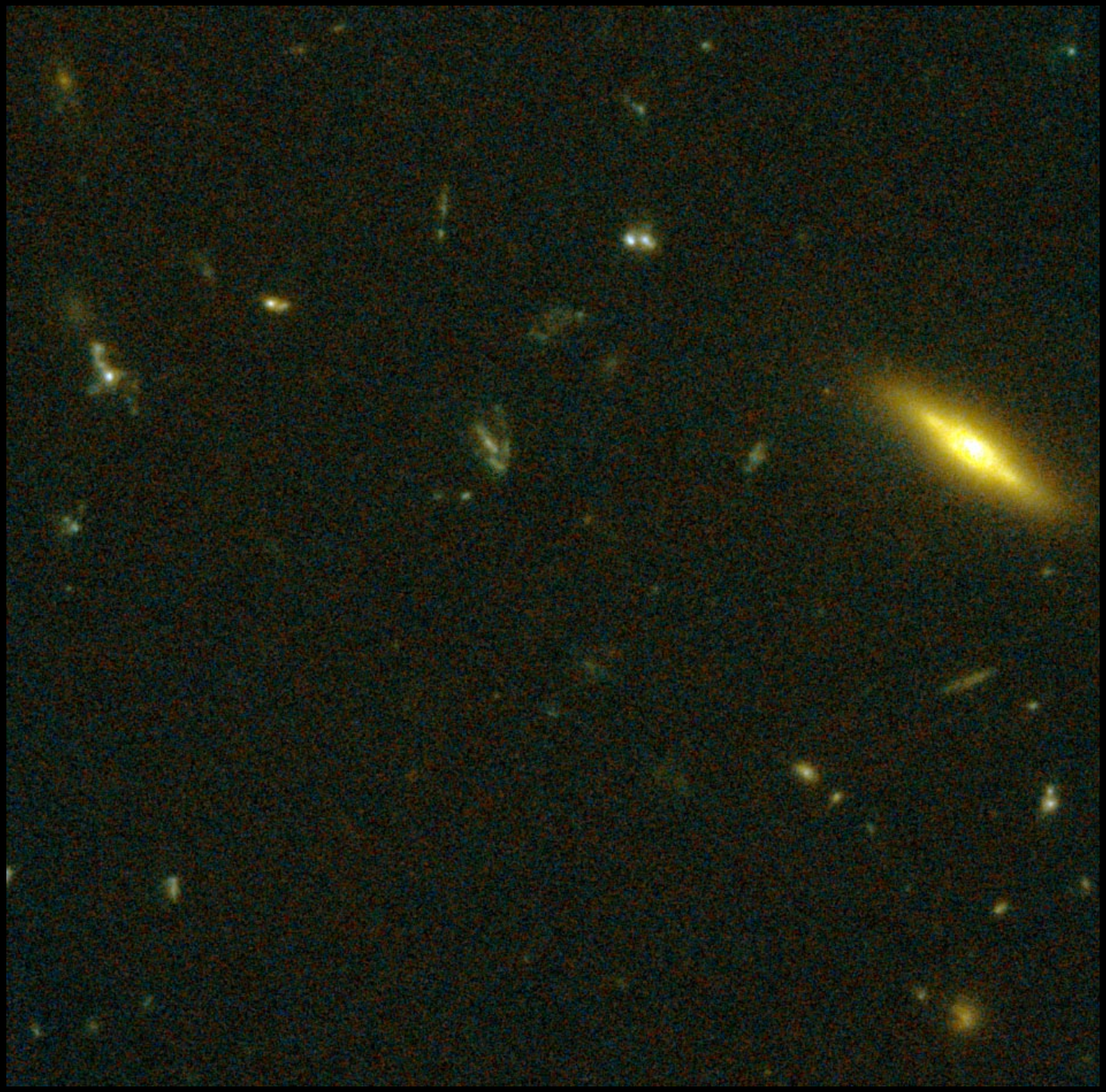


Feb 2000



Fading of the optical transient of GRB 990123.
Lightcurve is also a power law.

Fruchter et al. (1999) and `http://www.stsci.edu/~fruchter/GRB/990123/index.html`



26.3″ × 26.3″ HST image of field of GRB 990123 (A. Fruchter; priv. comm.)

Host galaxy is peculiar, blueish

GRB 990123

Bright and prompt optical flashes and radio flares are associated with some GRBs

First seen for GRB 990123

X-ray afterglows (seen in long bursts) allow localization of GRB

BeppoSaX/ground based: Galaxies hosting GRB 970508 and GRB 971214 have large redshifts

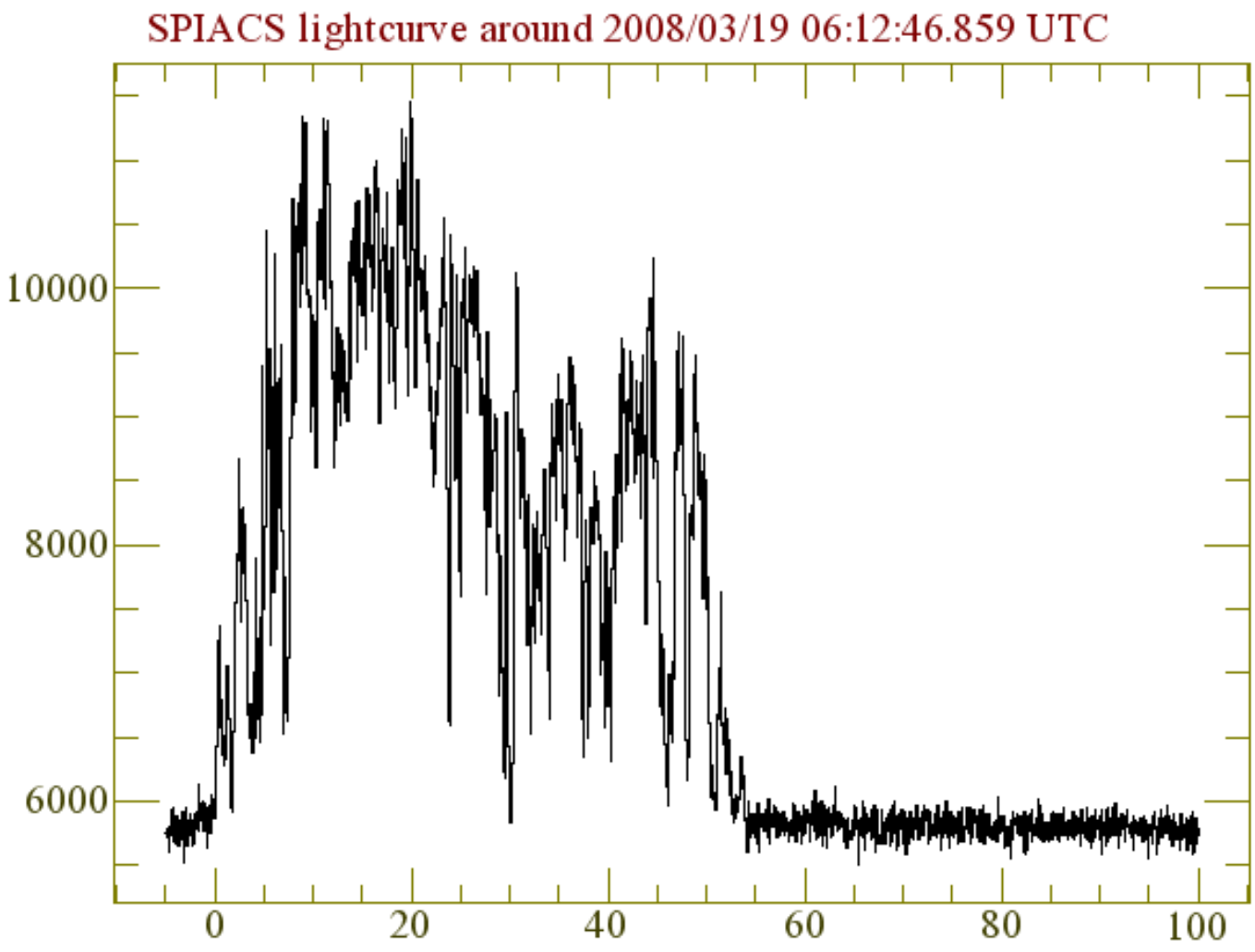
Gamma-Ray Bursts are at cosmological distances.

Redshifts known for >50 GRBs to date, typical $z \sim 1$, but there are extremes, e.g., GRB 050904 with $z = 6.29$ (end of cosmological dark ages!).

$\Longrightarrow$ Gives fluences $\sim 10^{53...54} (\Omega_\gamma / 4\pi)$ erg, varying by about 1 order of magnitude.

Ω_γ is correction factor for beaming.

GRB 080319



INTEGRAL/V. Beckmann

GRB 080319B (one of four GRBs seen on that date!)

GRB 080319

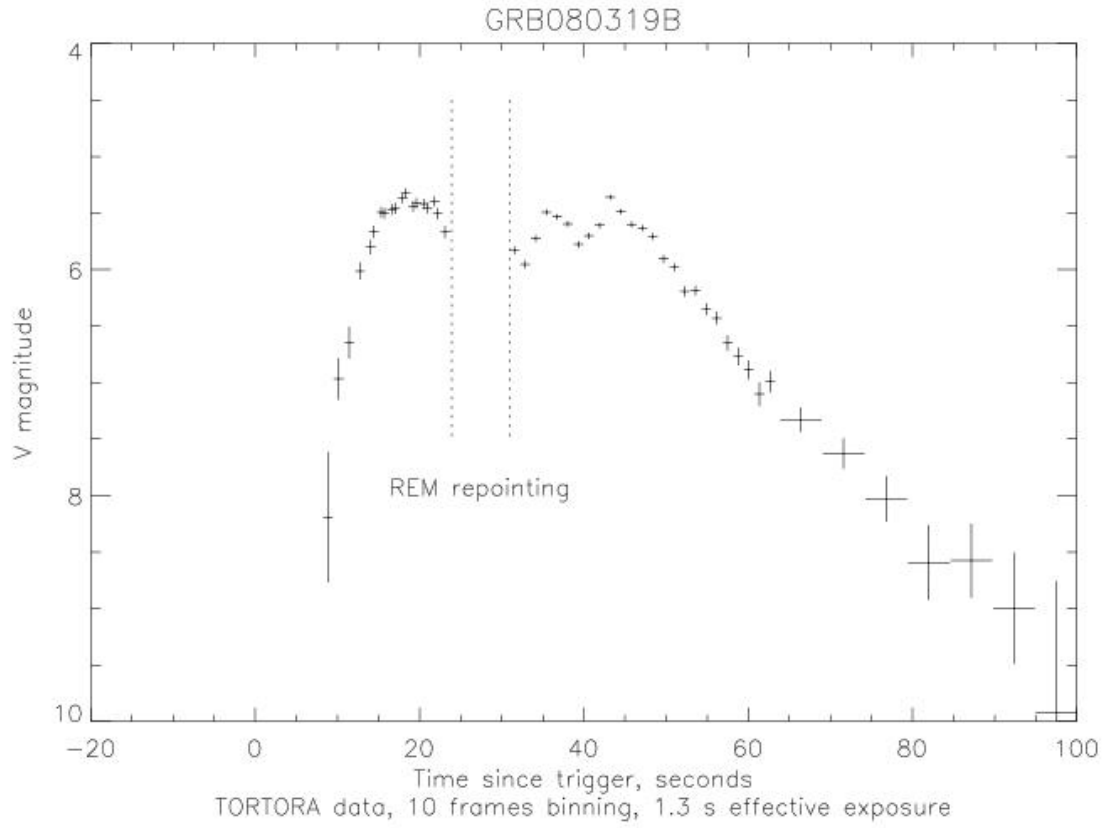


REM and TORTORA

ESO Press Photo 08a/08 (2 April 2008)

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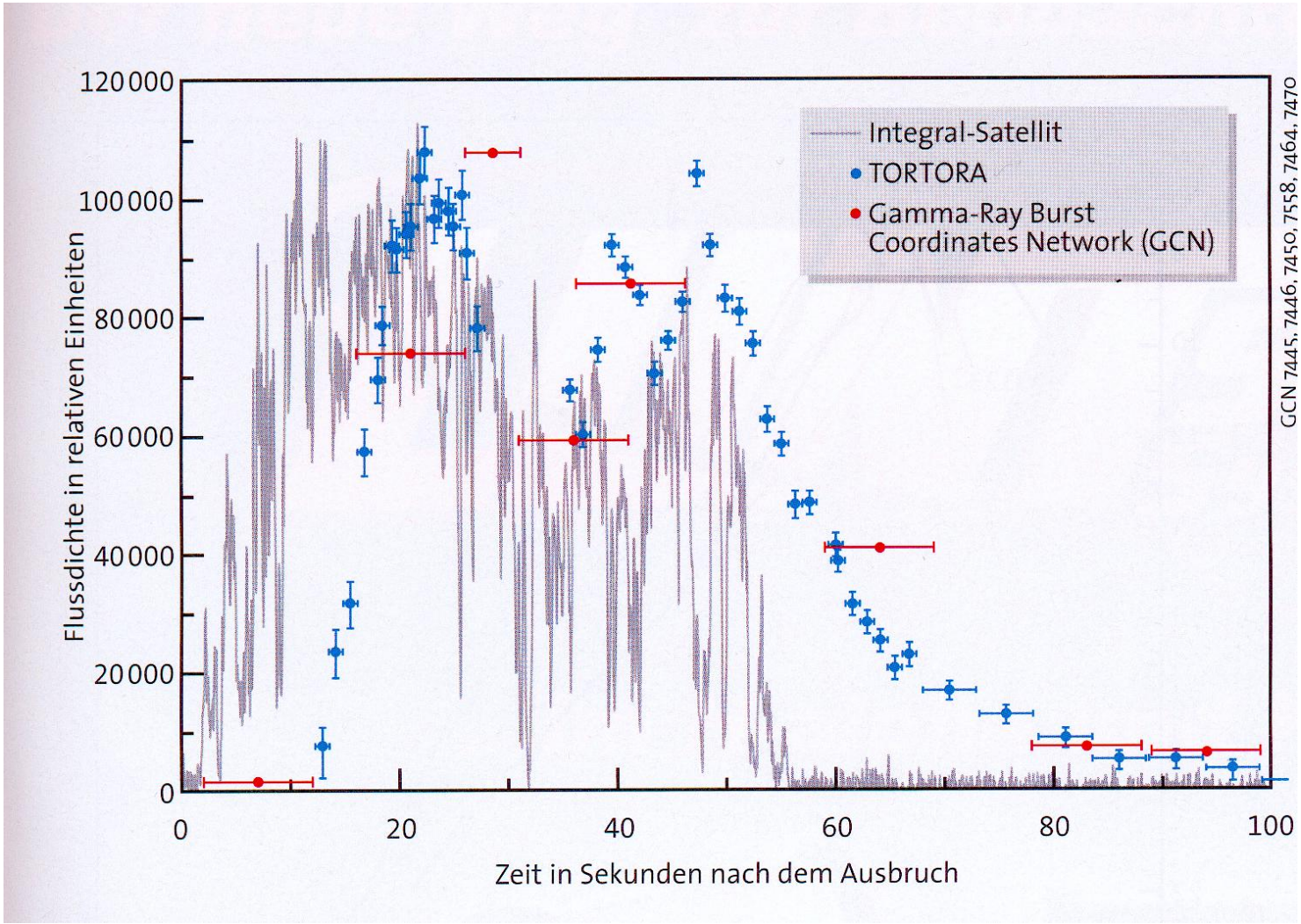
Tortora Video camera on REM: one image every 0.13 s



Karpov et al. (2008; GCN 7558)

GRB080319B: 1st GRB confirmed to be visible to the naked eye!

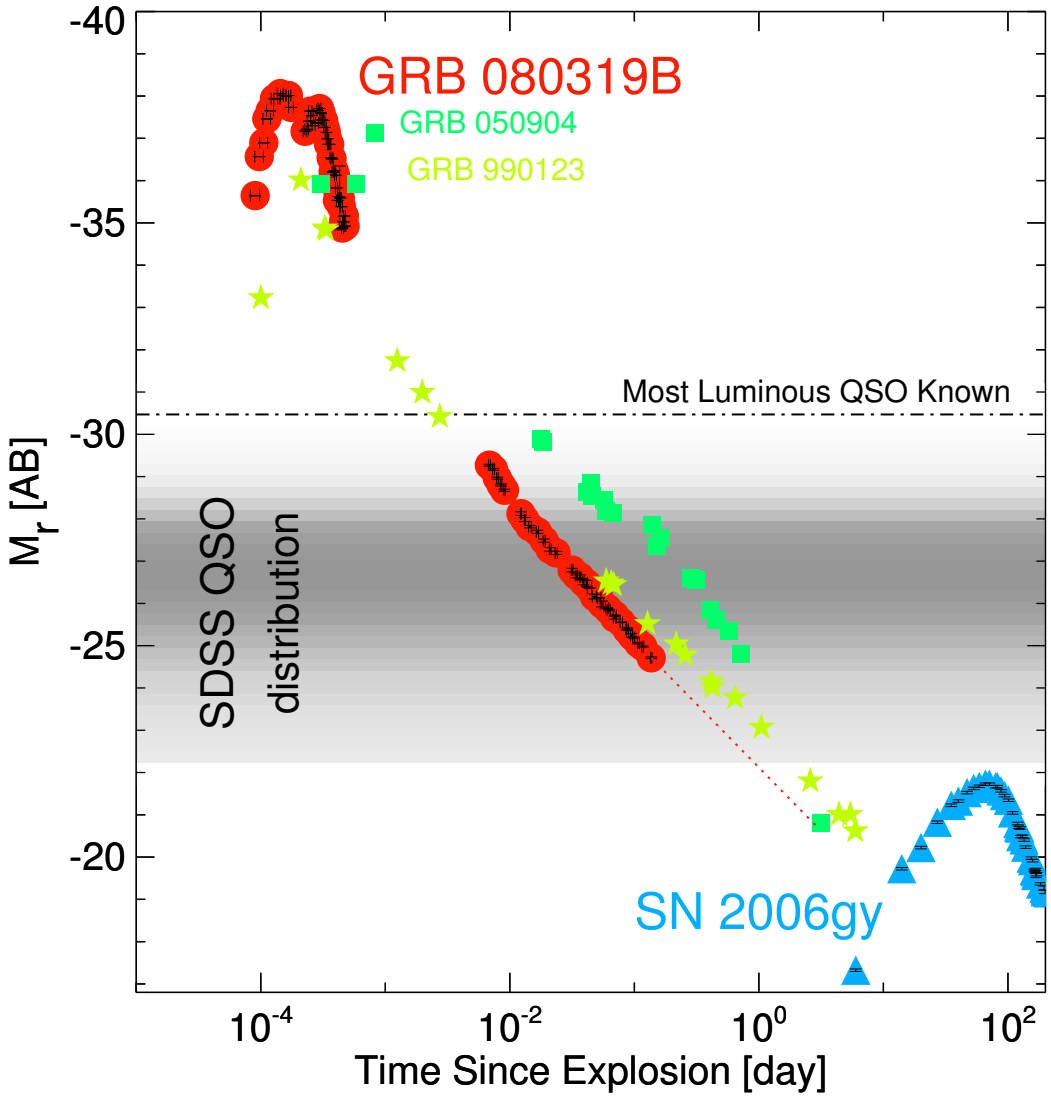
GRB 080319



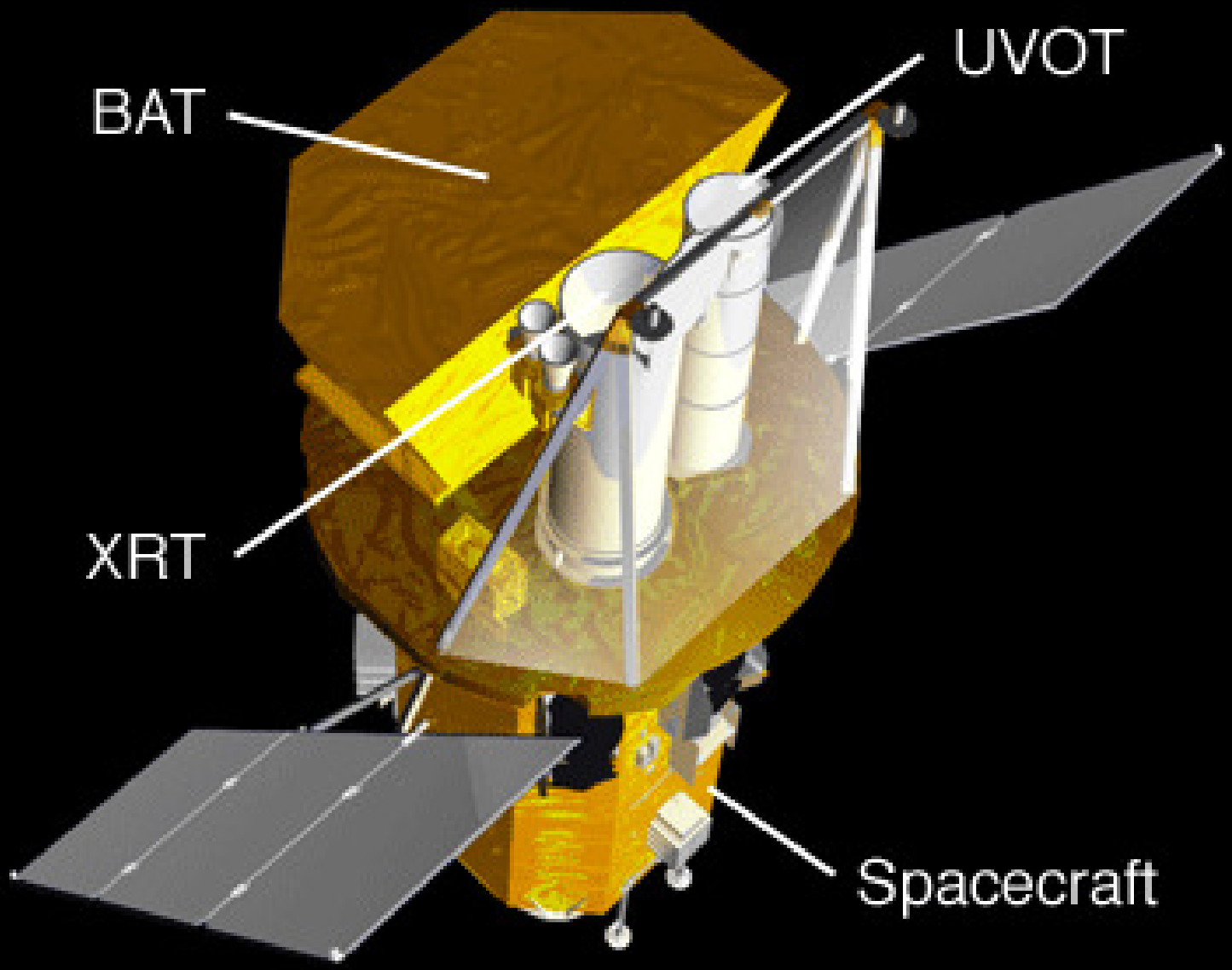
Long duration GRB, optical afterglow 6 s after the GRB (SuW 5/2008)

Movie time: grb080319b.avi (`http://vo.astronet.ru/~karpov/`)

GRB 080319



GRB080319B = the biggest bang since the Big Bang

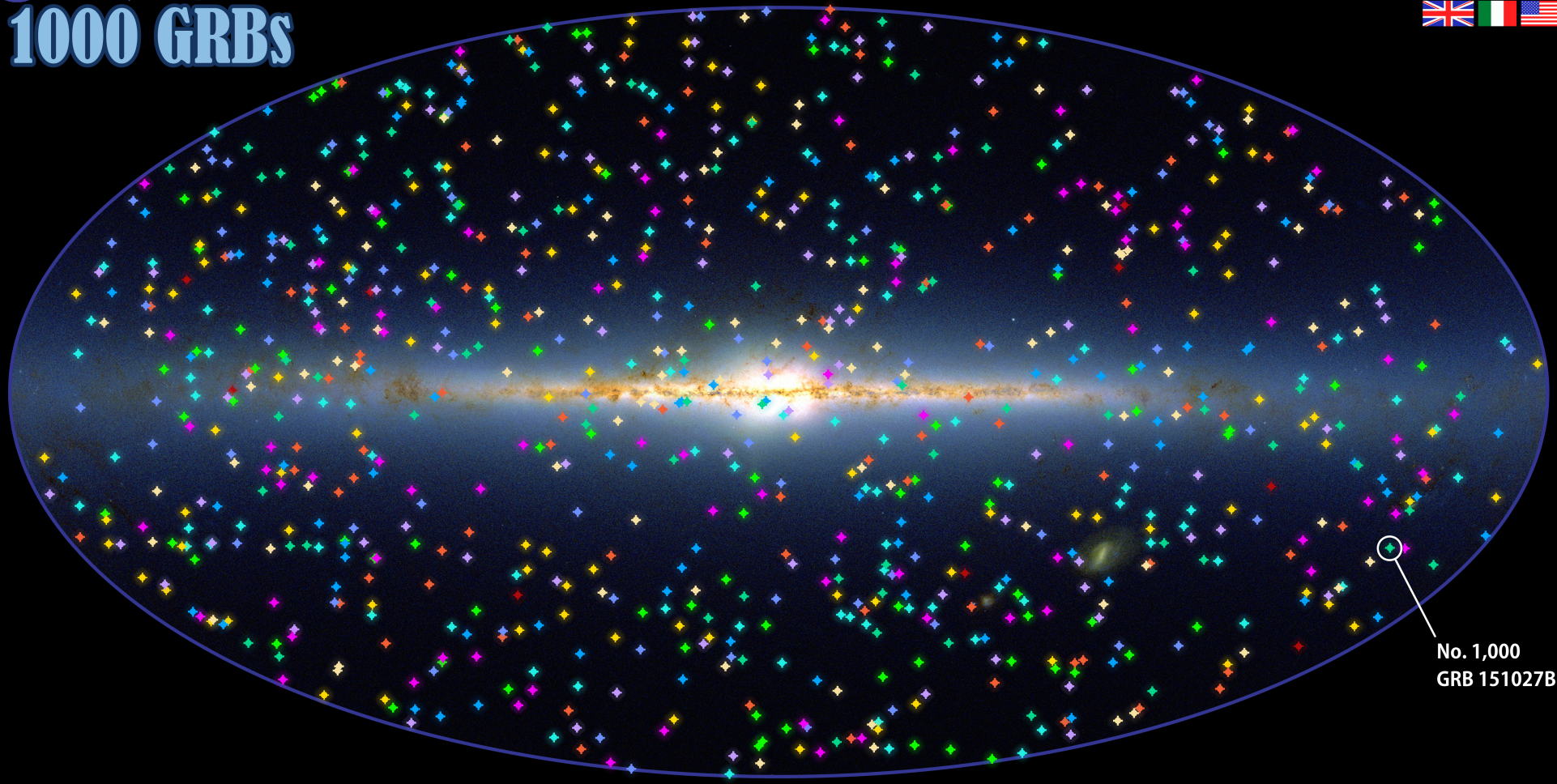


(Gehrels et al., 2004, Fig. 2)

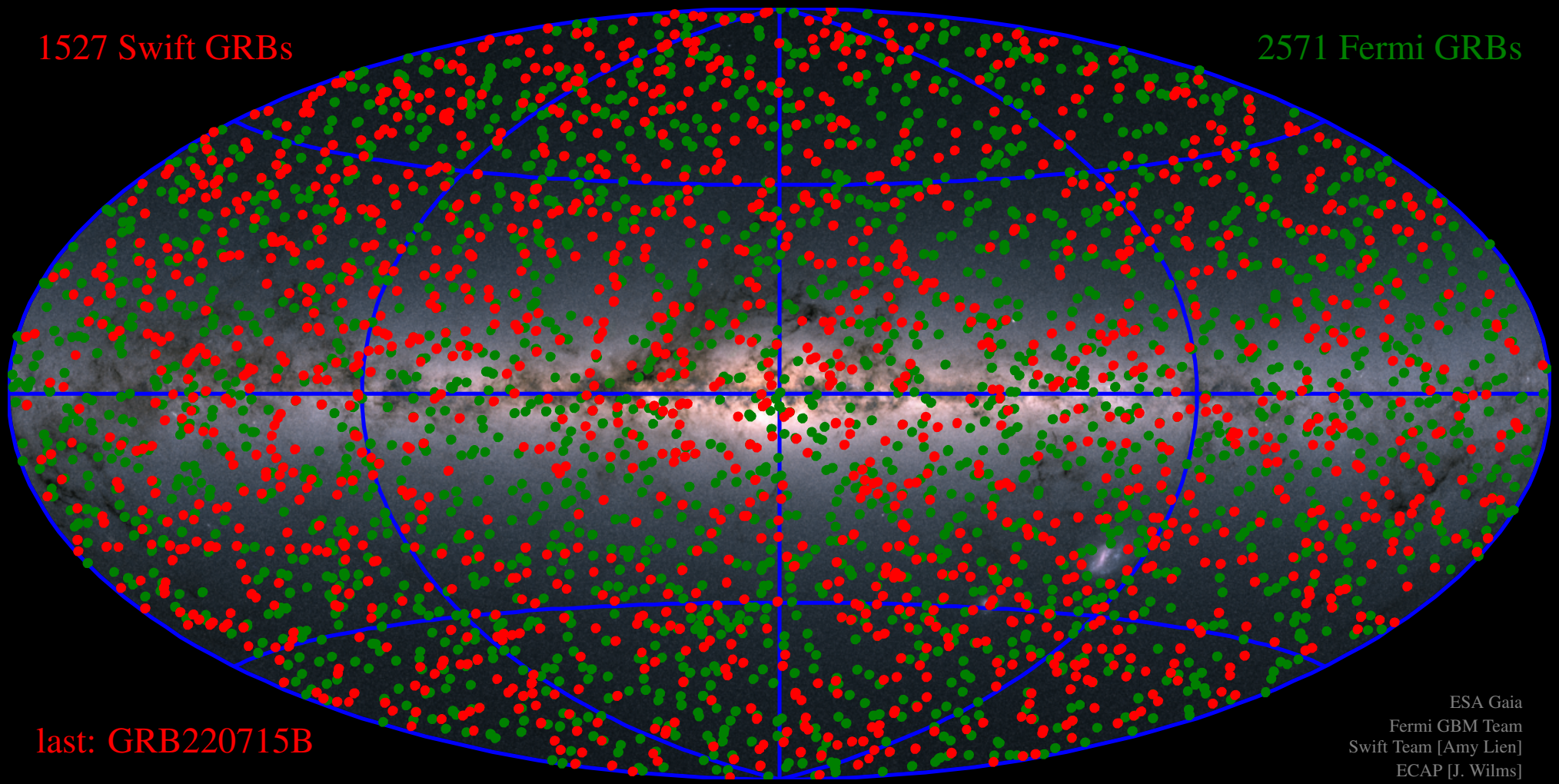
Swift: Launch November 2004, allows broad band monitoring of GRBs

Since *CGRO* and *Beppo-SAX* only some progress through observations with *HETE*-2 and Gamma-ray detectors on interplanetary probes; now renamed "Neil Gehrels Swift Observatory"

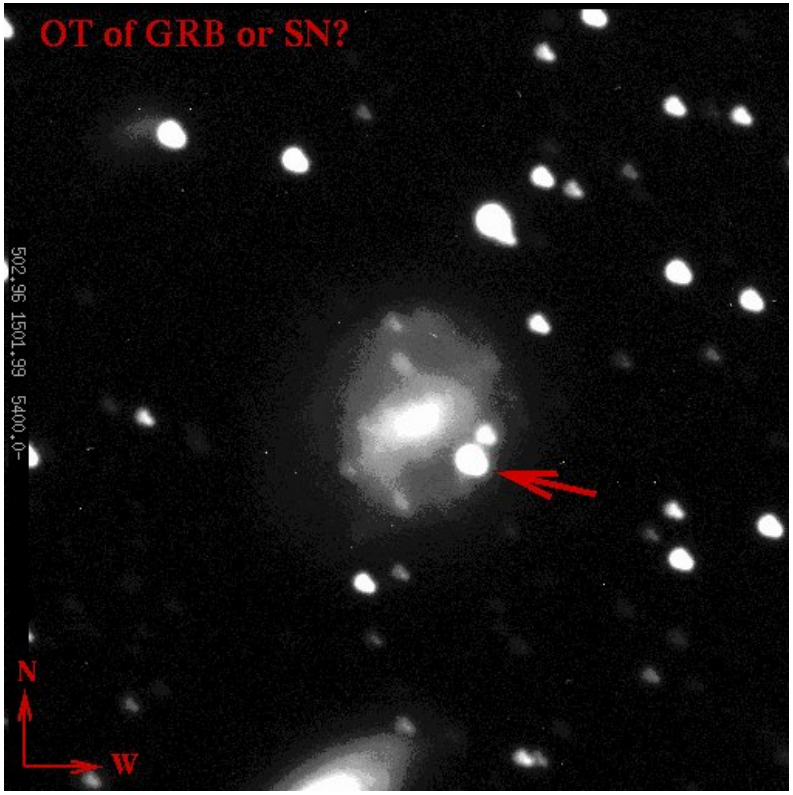
Swift 1000 GRBs



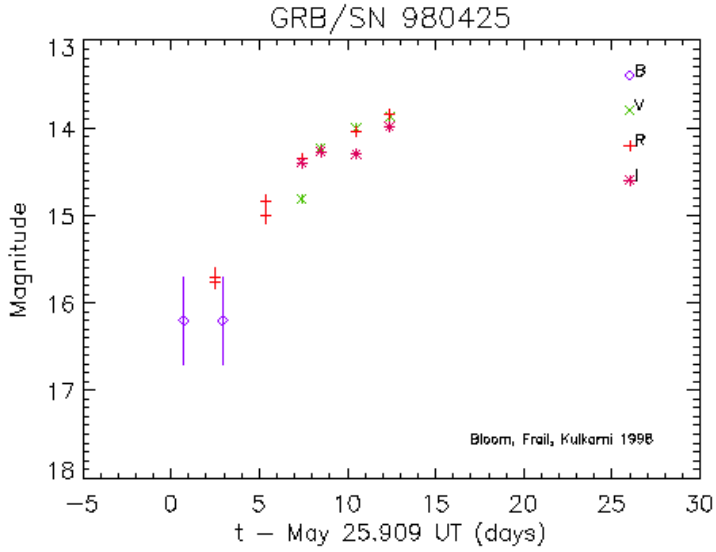
2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
9	88	102	86	103	89	84	81	92	96	95	75 to Oct. 27


1527 Swift GRBs
2571 Fermi GRBs
last: GRB220715B
ESA Gaia
Fermi GBM Team
Swift Team [Amy Lien]
ECAP [J. Wilms]

GRB–SN association



UvA

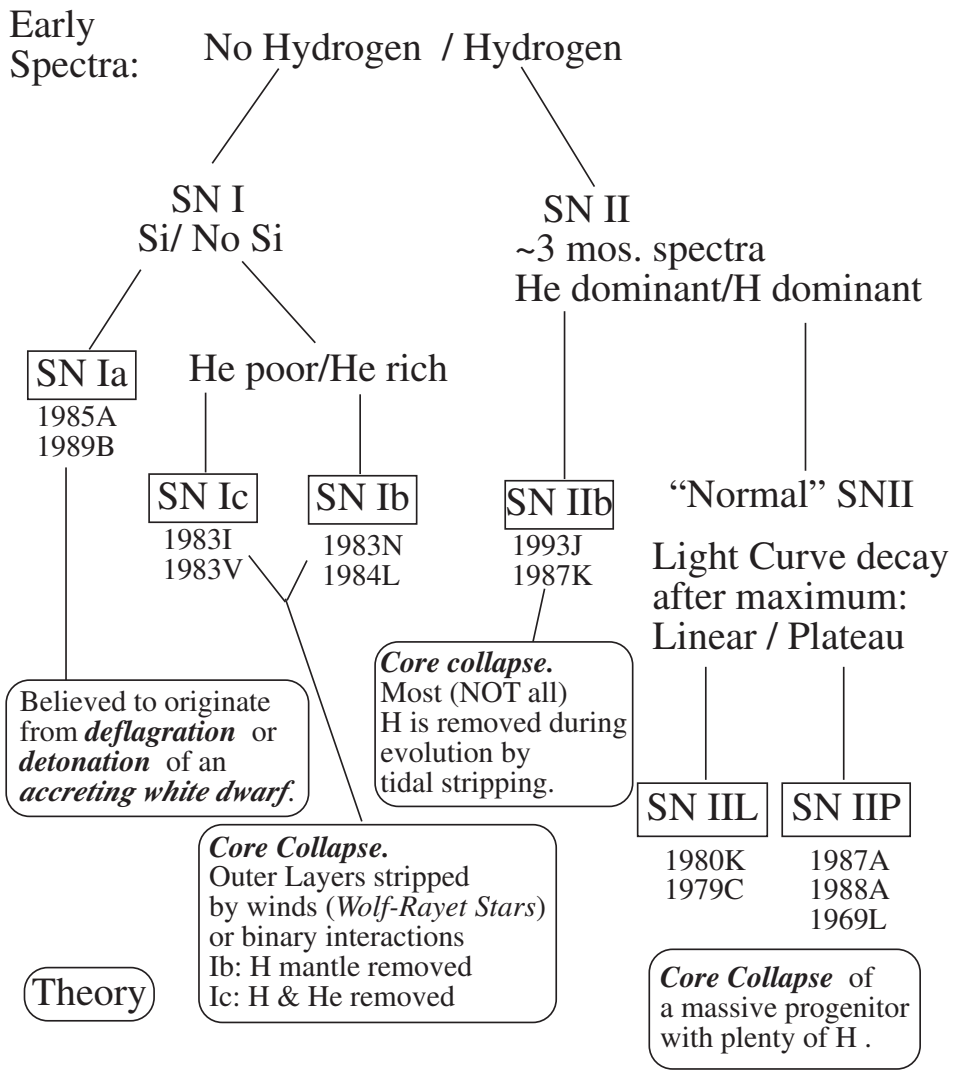


Bloom et al. (IAUC 6899)

- 26 April 1998: IAUC 6884: GRB 980425 detected with *BeppoSAX*-WFC
- 29 April 1998: Galama et al. (GCN Report 60): GRB 980425 located off center on arms of in barred spiral ESO 184-82

- Several GCNs: nothing seen in optical
- 7 May 1998: Galama et al. (IAUC 6895): Point source at GRB position, brightens

GRB–SN association

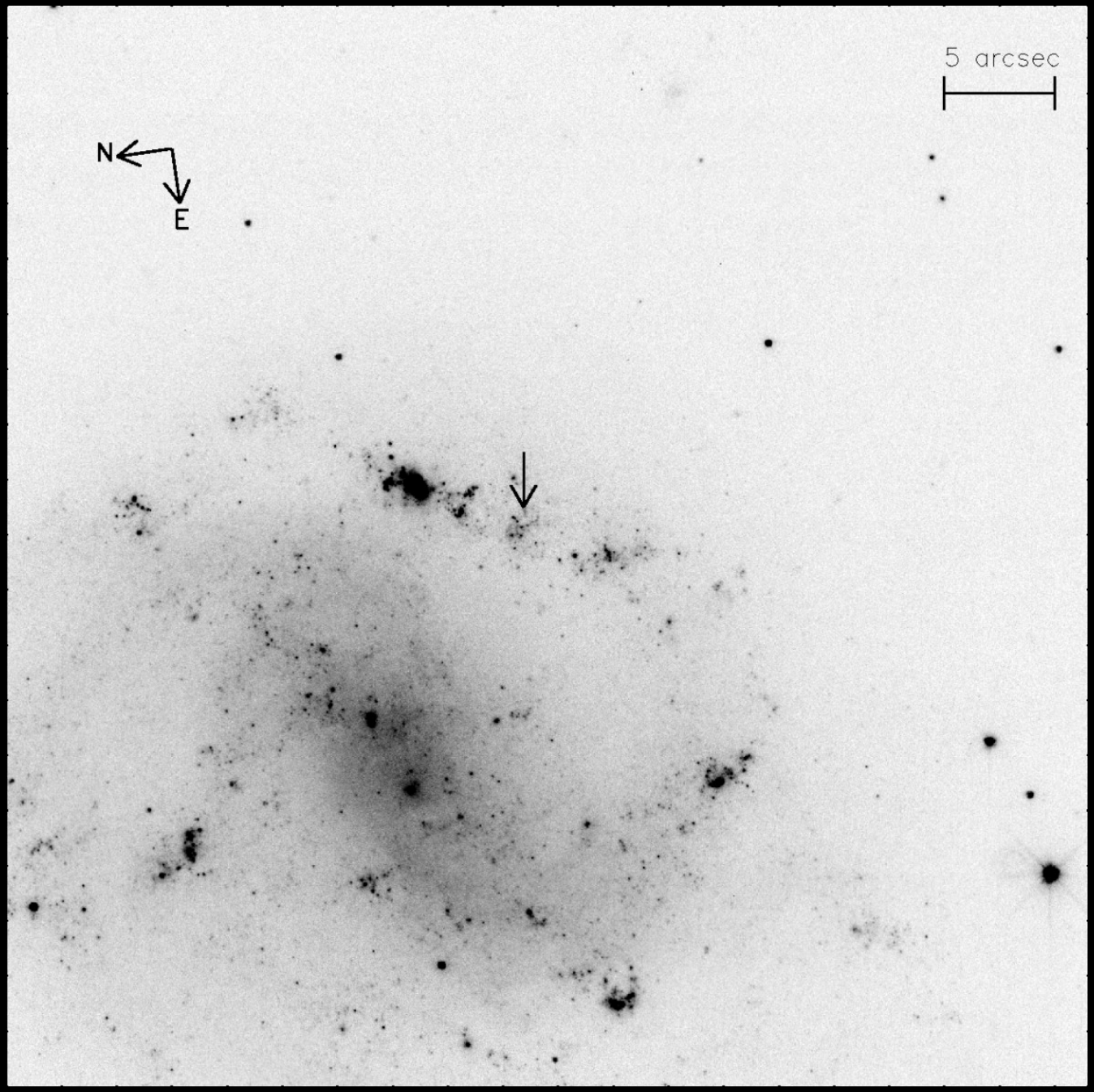


courtesy M.J. Montes

- 7 May 1998: Lidman et al. (IAUC 6895): Spectroscopy: point source at location of GRB 980425 is possibly a supernova, designated *SN 1998bw*:
  - no H-lines
    $\Longrightarrow$ not a type-II supernova
  - no Si lines
    $\Longrightarrow$ not regular Ia Supernova.

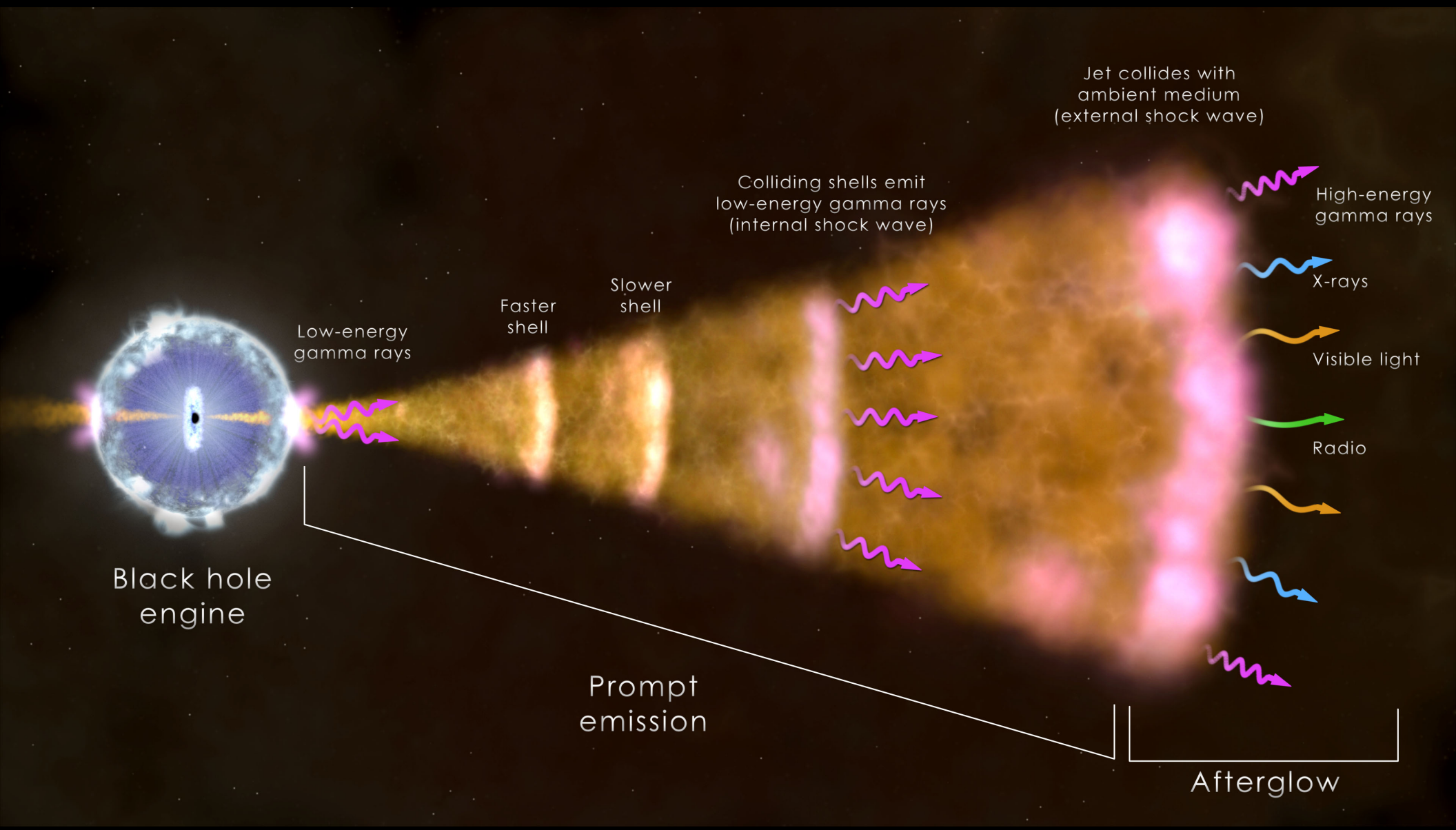
$\Longrightarrow$ peculiar SN Ic

"The nature of this puzzling object still evades identification, as does its relation to GRB 980425 or to the galaxy.".



Fynbo et al. (2000): ESO 184-G82 is a star-forming SBc galaxy

GRB was located in star forming region



http://www.nasa.gov/feature/goddard/nasas-swift-spots-its-thousandth-gamma-ray-burst

GRB model: Relativistic fireball model (Rees & Mészáros, 1992)

Neutron Stars

Neutron stars form after the core collapse of massive stars.

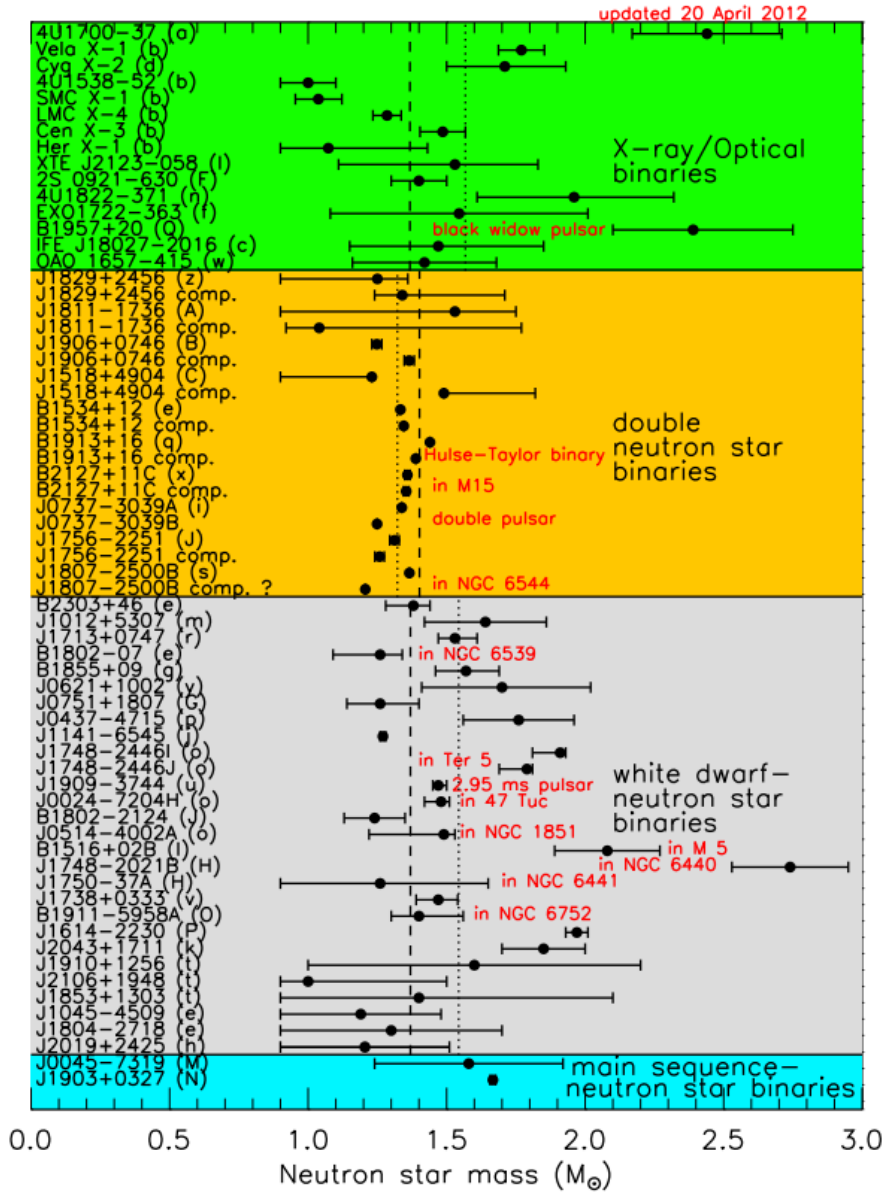
During the supernova, densities get so high that neutronization sets in:

$$p + e^- \longrightarrow n + \nu_e$$

General properties:

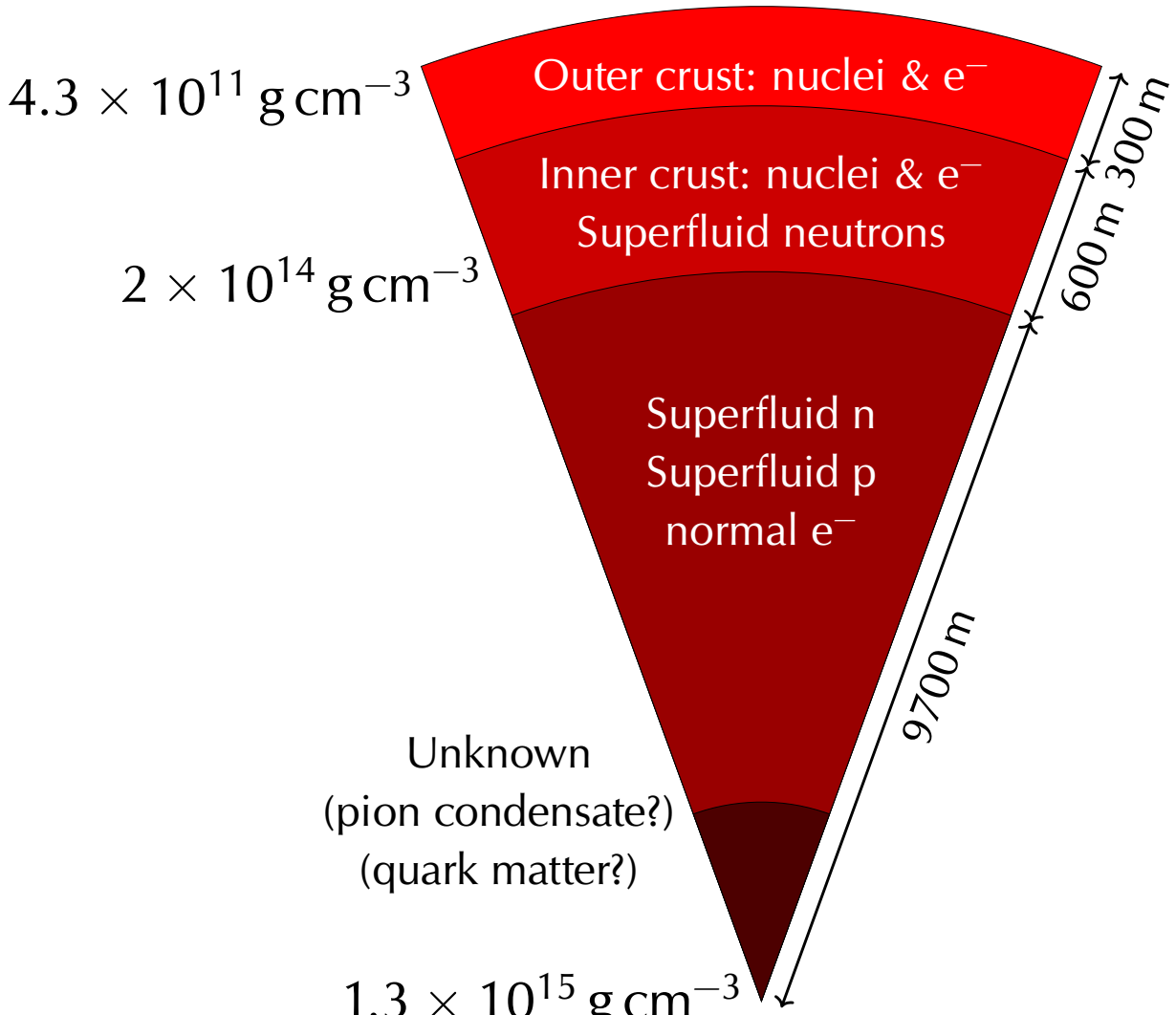
- Pressure mainly through degenerate neutrons (similar to degenerate electrons for WD!).
- Typical density: $\rho \sim 10^{14}\,\mathrm{g\,cm^{-3}}$ (nuclear densities)
- Typical radius: $10 \ldots 15\,\mathrm{km}$ (Nuremberg!)
- Surface gravity $\sim 10^{11} \times$ Earth
- Detailed structure not yet fully understood

Neutron Stars: Masses



Lattimer (2013)

Neutron Stars: Structure



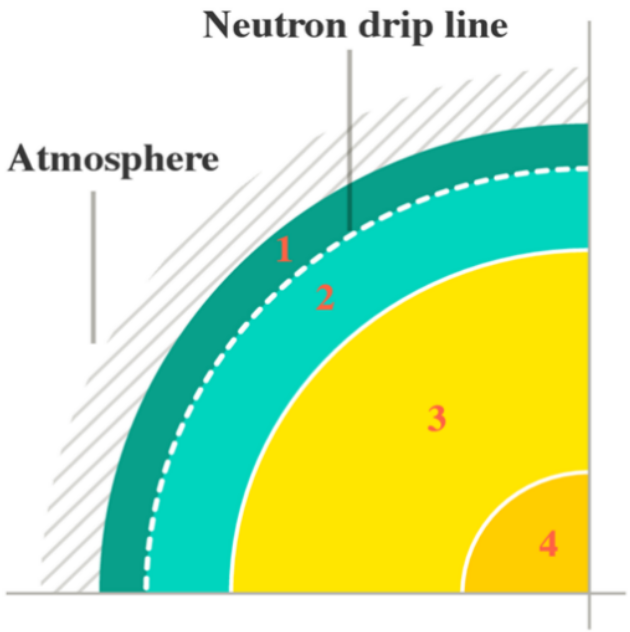
(after Shapiro & Teukolsky)

Crust: perhaps crystallized?

Atoms become elongated along B-field line on surface

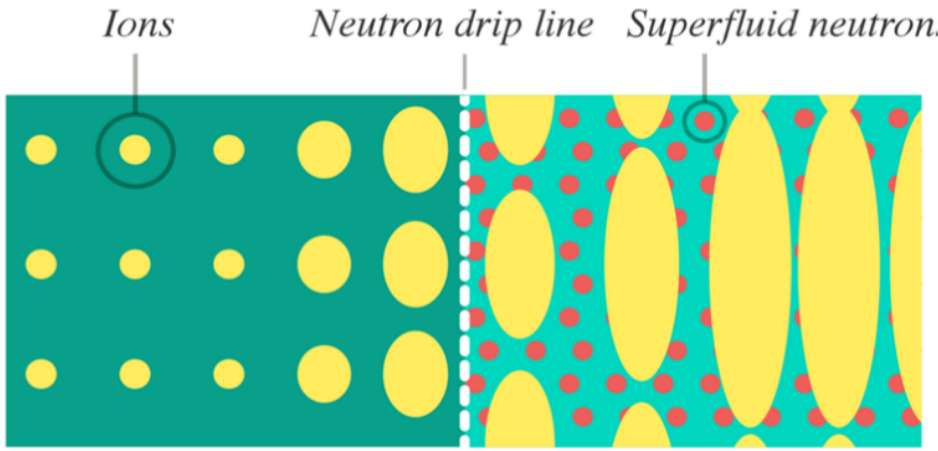
Internal structure unclear:

- Supraconducting matter
- Suprafluidity (i.e., fluid with no viscosity)
- central composition unknown



1) OUTER CRUST

2) INNER CRUST



Down quark

Up quark

Strange quark

3) OUTER CORE



Nucleons
(neutrons and protons) expected to be superfluid/superconducting. Also contains electrons and muons (not shown).

4) INNER CORE

May contain, in addition to or instead of nucleons:



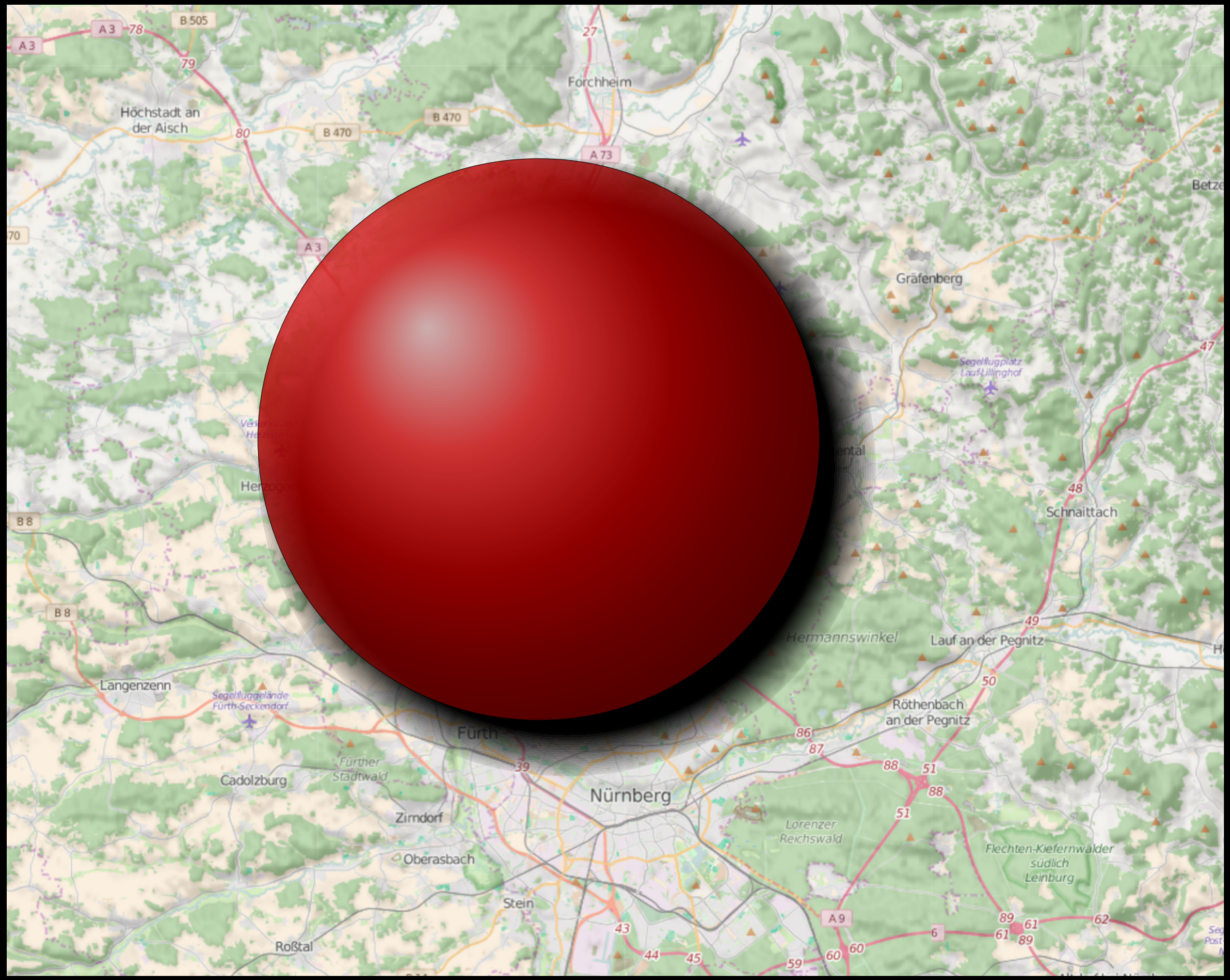
Hyperons



Free quarks

These states of matter may also be in a superfluid or superconducting state.

LOFT yellow book (ESA_SRE_2013_3_LOFT)



Neutron stars are small!

Neutron Stars: Rotation

During collapse, angular momentum is conserved (Explosion: symmetric)

Total angular momentum of homogeneous sphere:

$$J = I\omega \quad \text{where} \quad I = \frac{2}{5}MR^2$$

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Angular momentum conservation ($J_{before} = J_{NS}$):

$$\frac{2}{5}M_{before}R_{before}^2\omega_{before} = \frac{2}{5}M_{NS}R_{NS}^2\omega_{NS}$$

or

$$\omega_{NS} = \left(\frac{M_{before}}{M_{NS}}\right)\left(\frac{R_{before}}{R_{NS}}\right)^2\omega_{before} \quad \text{or} \quad P_{NS} \sim \left(\frac{R_{NS}}{R_{before}}\right)^2 P_{before}$$

(where P: rotation period)

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(where P: rotation period)

Example: $R_{before} = 700000\,\text{km}$ (sun), $R_{NS} = 15\,\text{km}$, $P_{Sun} = 27\,\text{d} \Longrightarrow P_{NS} = 0.001\,\text{s}$

Neutron Stars are extremely fast rotators.

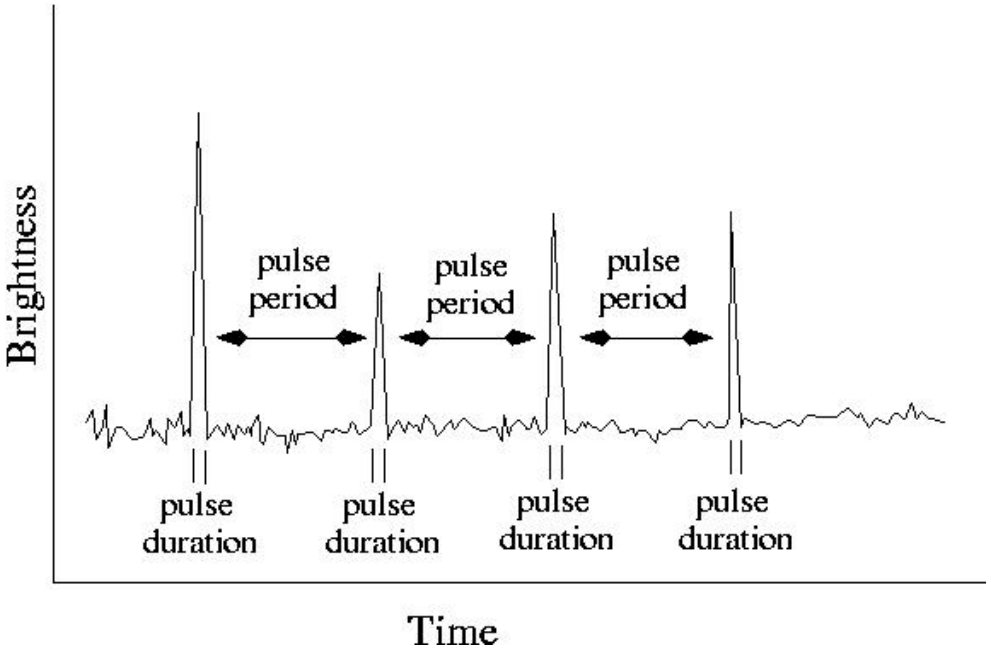
close to break-up speed!

Pulsars



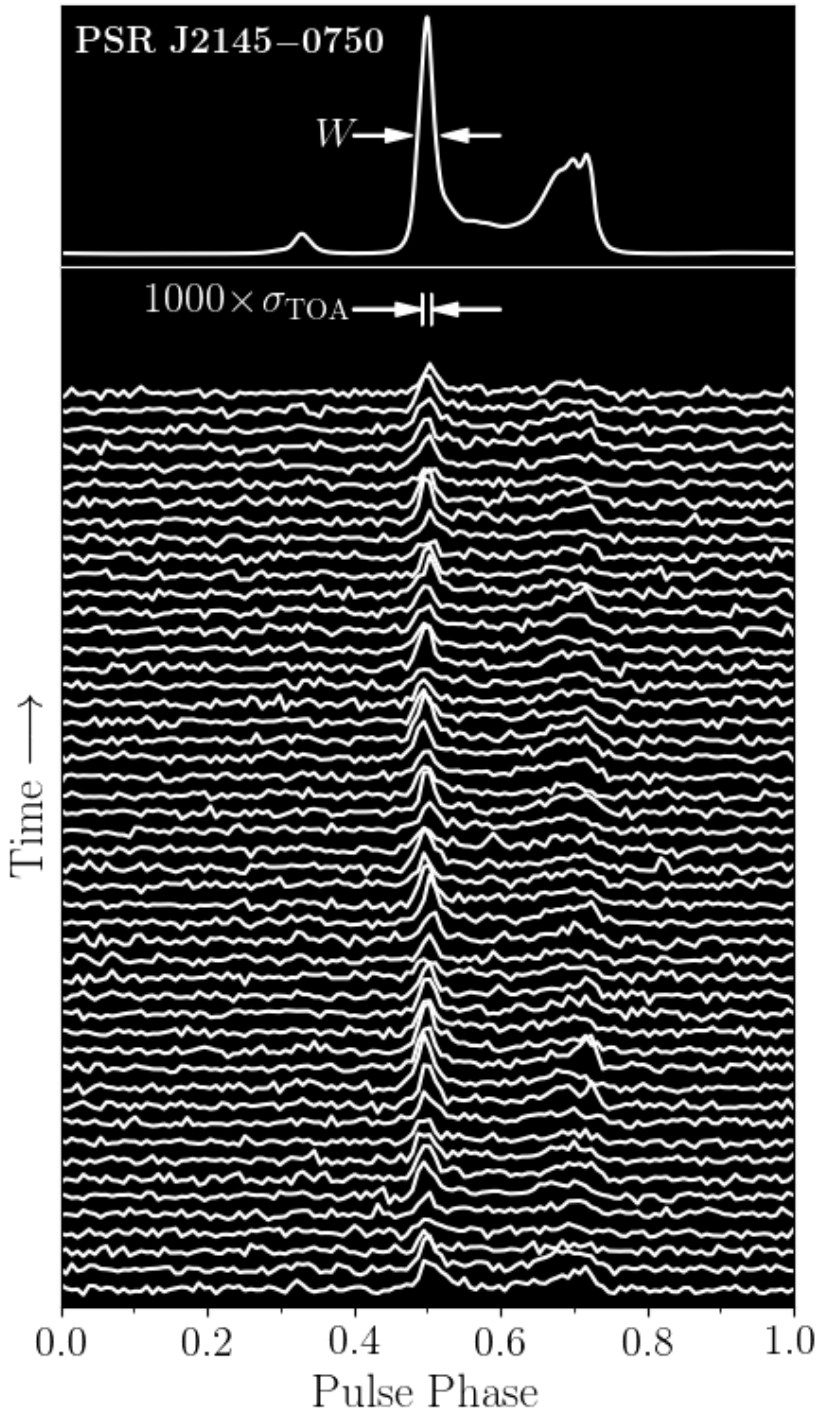
Discovery: Bell & Hewish (1967):

Radio Pulsar



radio emission is pulsed,

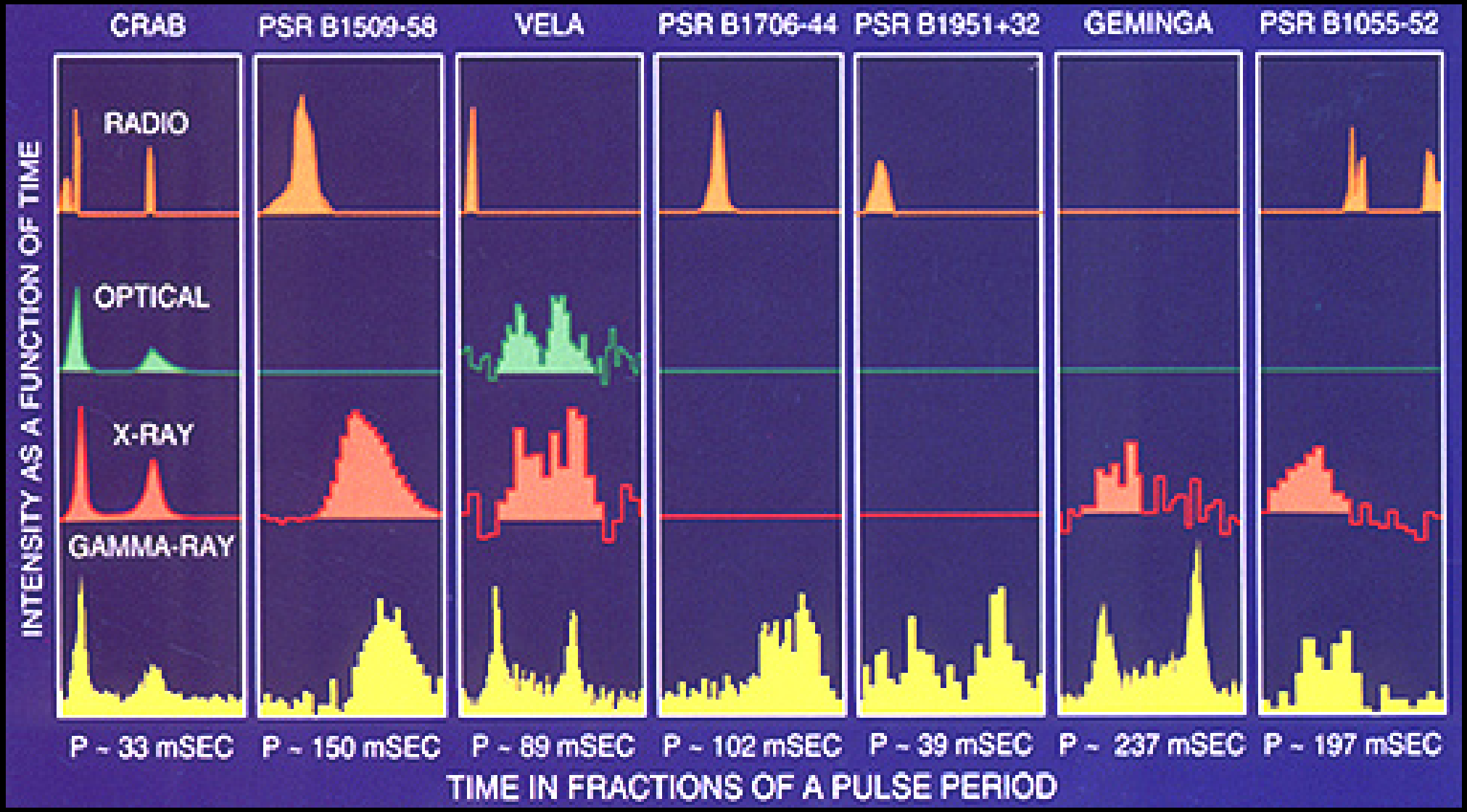
very short periods: milliseconds to a few seconds



Pulse profile: individual pulses vary, but average is very stable

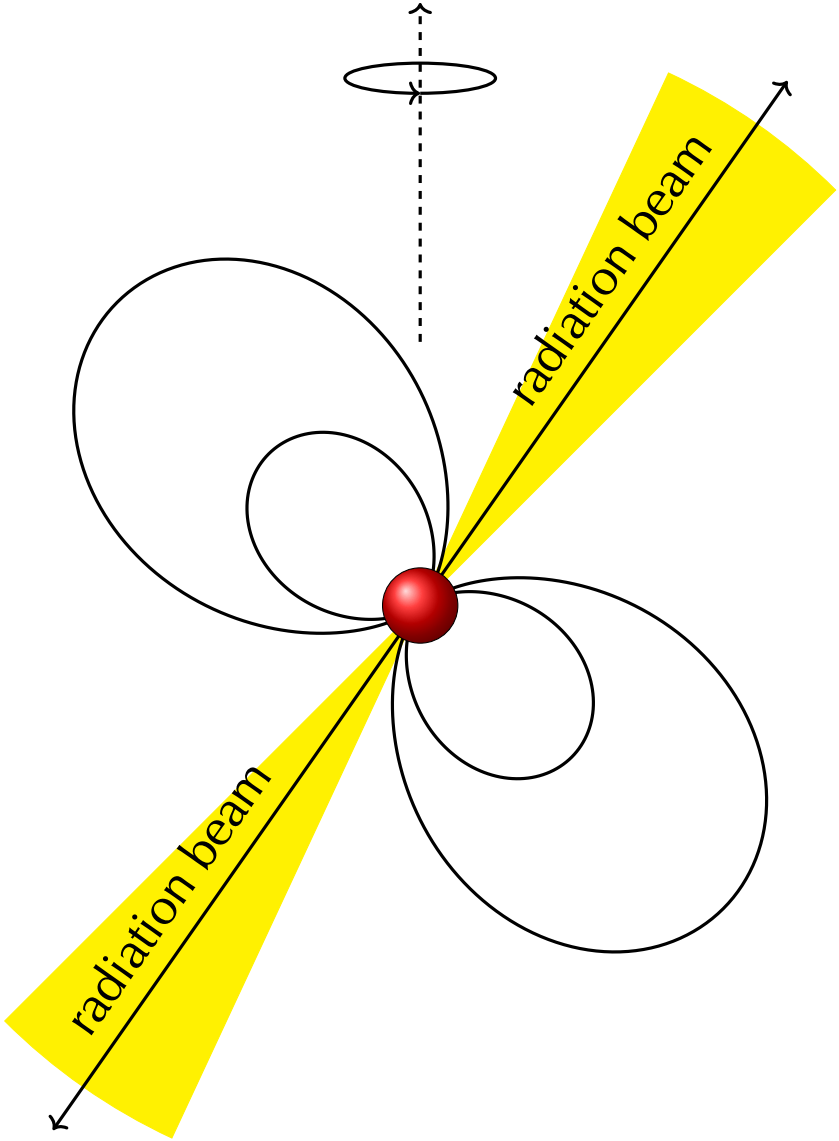
PSR J2145−0750 (NANOGrav, arXiv:1810.06594)

Pulsars at different wavelengths



Pulsations not only in the radio regime, but also at optical, X-ray, and γ-ray wavelength, but not in all cases.

Pulsars



"Lighthouse model" for pulsars

Another conserved observable:
magnetic flux: $\Phi = BR^2$

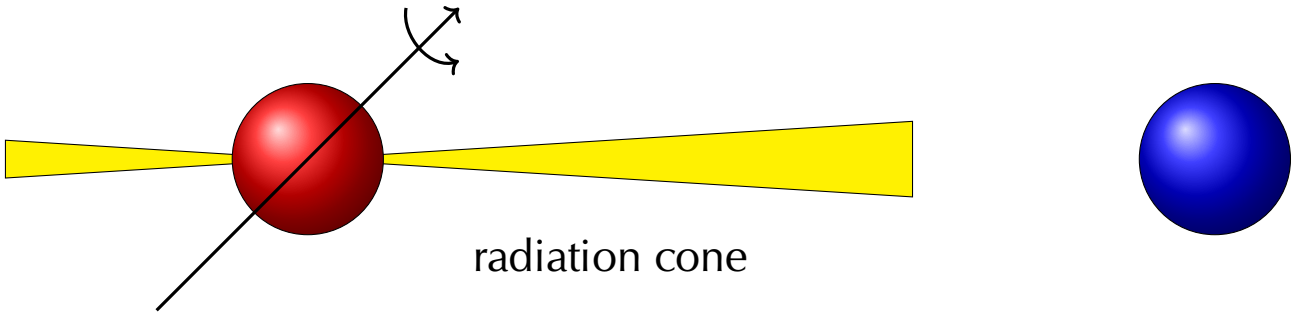
Magnetic field after SN:

$$B_{NS} = \left(\frac{R_{before}}{R_{NS}}\right)^2 B_{before}$$

$\Longrightarrow$ neutron stars have strong magnetic fields (typical: $B \sim 10^6 \ldots 10^8$ T)

Radio pulsars are fast rotating (isolated) neutron stars with strong magnetic fields.

Pulsars



Pulses caused by the lighthouse effect

Pulsar rotation period:

$$P = \frac{2\pi R}{v_{rot}} \tag{2.2}$$

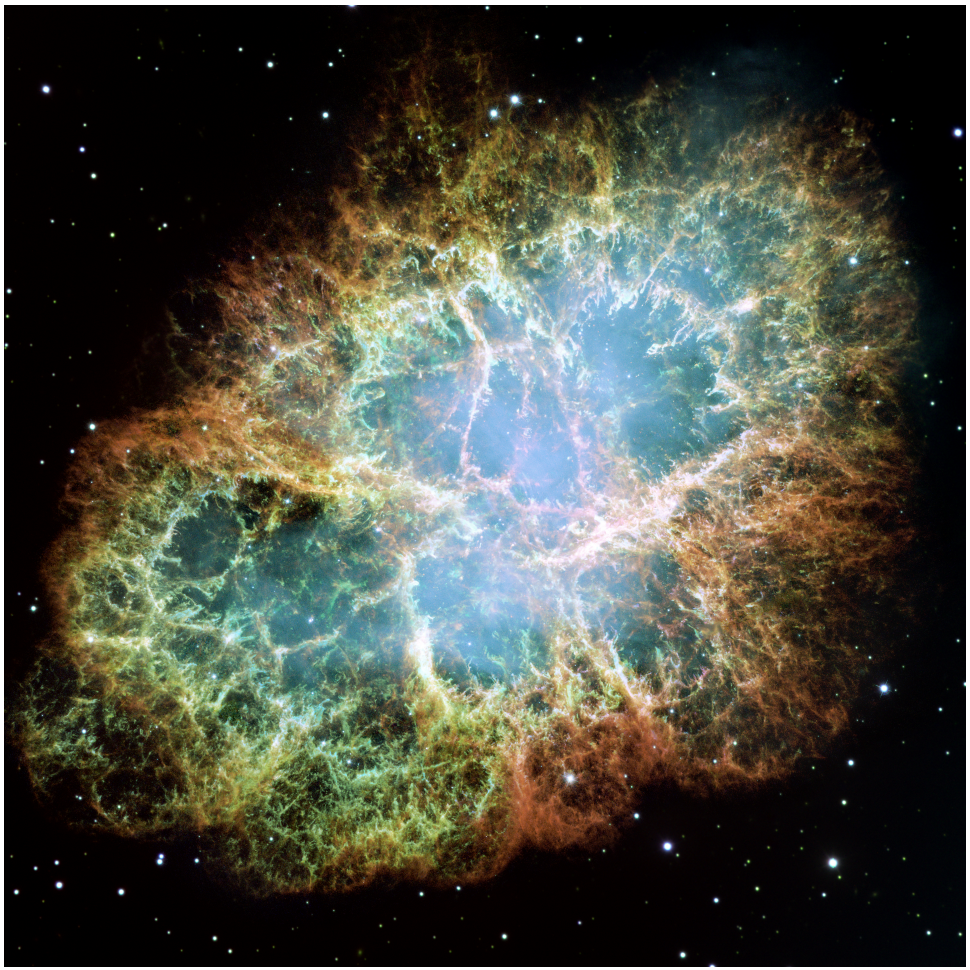
Rotation speed at the surface must be smaller the speed of light. $\Longrightarrow R < \frac{Pc}{2\pi}$

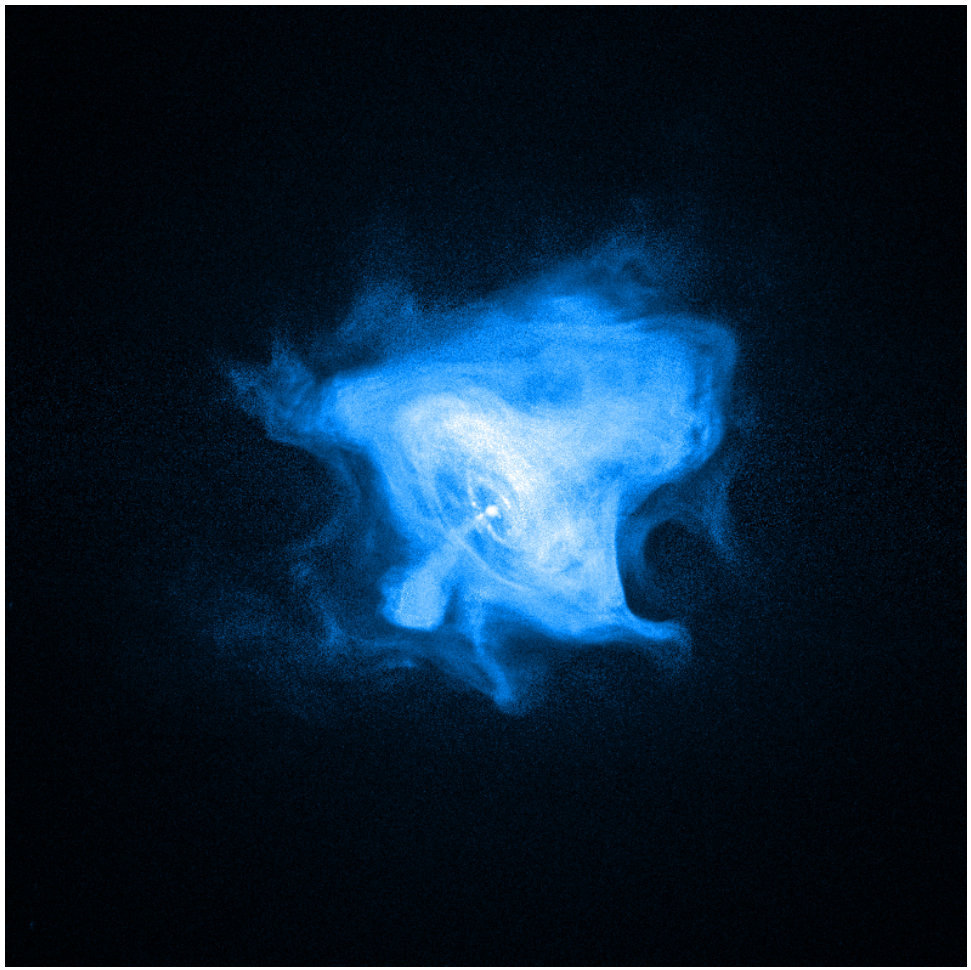
Shortest periods observed: $P \sim 1\,\text{ms}$

$\Longrightarrow R < 50\,\text{km}$

Pulsars are neutron stars!

Pulsarwindnebel

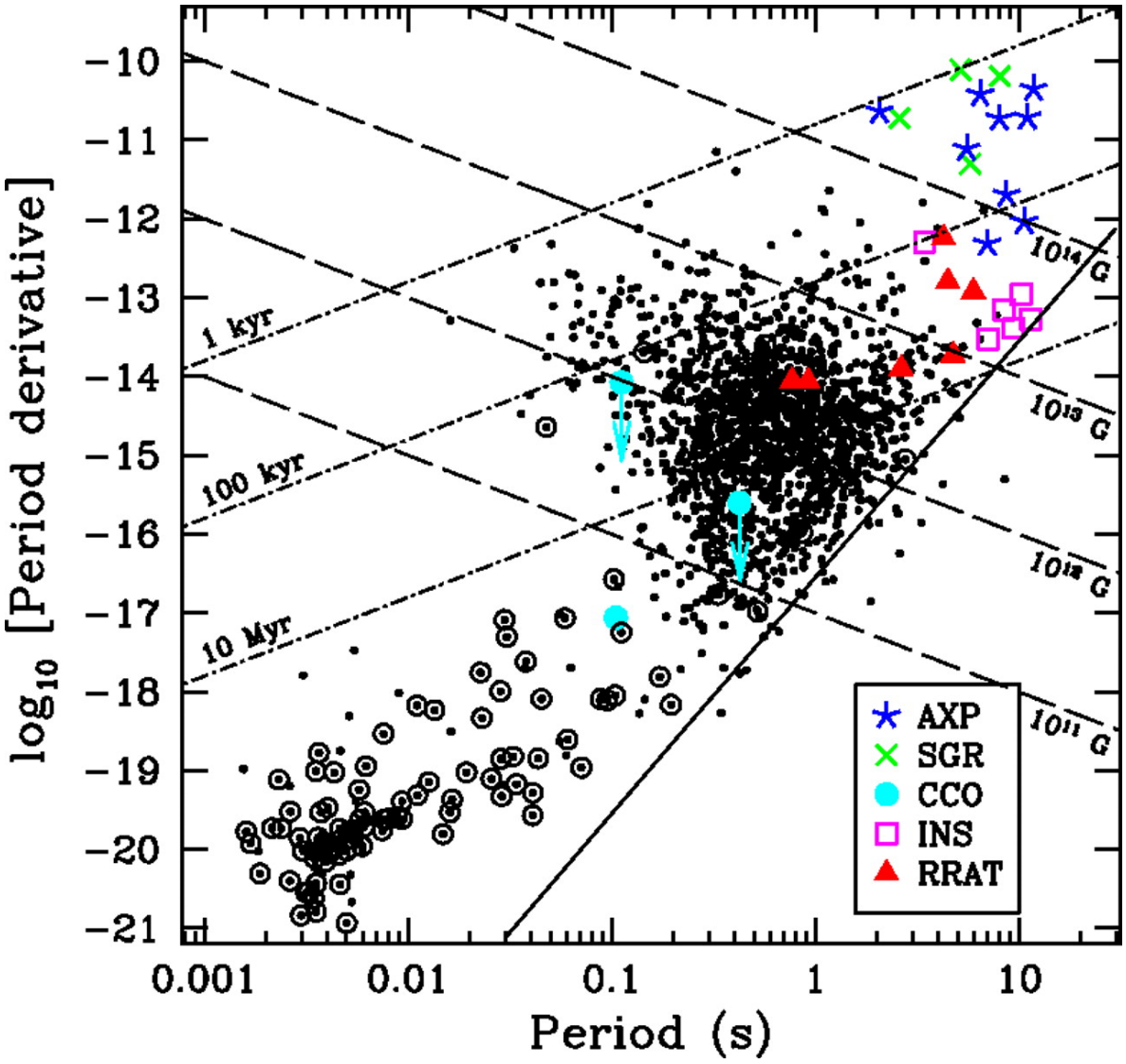




Crab nebula: left: optical (HST), right: X-rays (Chandra)

Synchrotron radiation of relativistic electrons in a magnetic field

Rotational periods



Kaspi (2010)

The sounds of pulsars

- PSR 0329 – a normal pulsar ($P = 0.714519\,s$)
- PSR 0833 – the Vela pulsar, a faster, younger pulsar in the Vela supernova remnant ($P = 89\,msec$)
- Crab pulsar – the youngest pulsar ($P = 33\,ms$)
- B1937 – one of the fastest pulsars ($P = 0.00155780644887275\,s$)

See/hear `http://www.jb.man.ac.uk/~pulsar/Education/Sounds/sounds.html` for more examples.

Black Holes

Degenerate neutron gas: Chandrasekhar theory applies, but must include relativistic effects due to relativity

$\Longrightarrow$ equation of state much more complicated than for white dwarfs

Neutron stars also have upper mass limit: Oppenheimer Volkoff limit.

Detailed mass limit unknown, causality considerations give $M \sim 3\,M_\odot$

(for "stiff equation of state": at this mass: $v_{\text{sound}} \gtrsim c$)

Compact objects with mass above Oppenheimer Volkoff limit: Black Holes

More conservative astronomers: "Black Hole Candidates".

Black Holes

In more modern usage (but still Newtonian!):

Total energy of a mass m:

$$E = E_{pot} + E_{kin} = -\frac{GMm}{R} + \frac{1}{2}mv^2$$

Mass m is unbound if $E > 0$, i.e., for

$$v \geqslant v_{escape} = \sqrt{\frac{2GM}{R}}$$

Black Hole: Body of mass M and radius R for which $v_{escape} > c$, where c is the speed of light.

This is the case if

$$R \leqslant R_S = \frac{2GM}{c^2} \sim 3\,\mathrm{km}\frac{M}{M_\odot}$$

the Schwarzschild Radius.

Einstein



Albert Einstein (1879–1955)

Special relativity (1905):

- Speed of light has the same value in *all* frames of reference
- Observer with constant velocity measure the same physical laws

From these axioms follows:

$\Longrightarrow$ Space and time are relative

("4D-space-time")

$\Longrightarrow E = mc^2$

("Mass and Energy are equivalent")

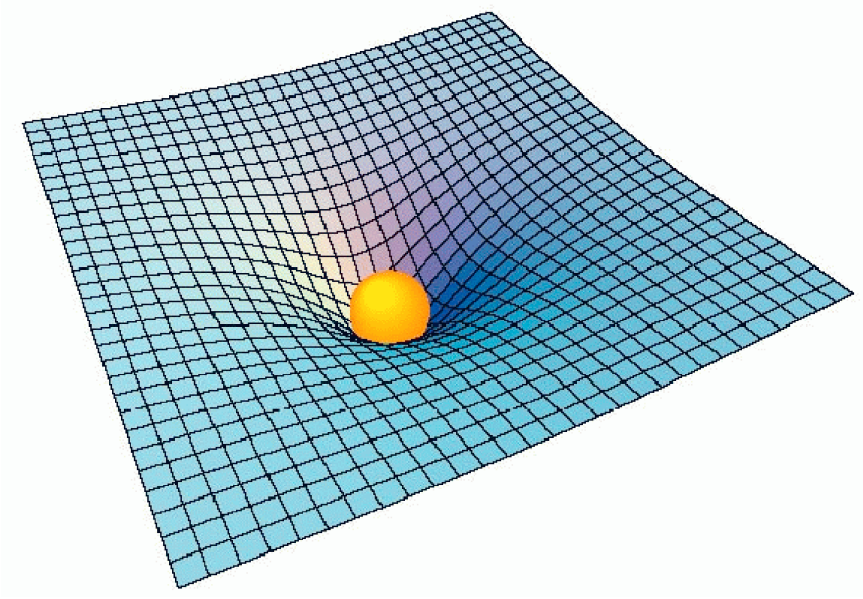
Einstein



Albert Einstein (1879–1955)

General relativity (1916):

- Mass curves space (“Metric”)



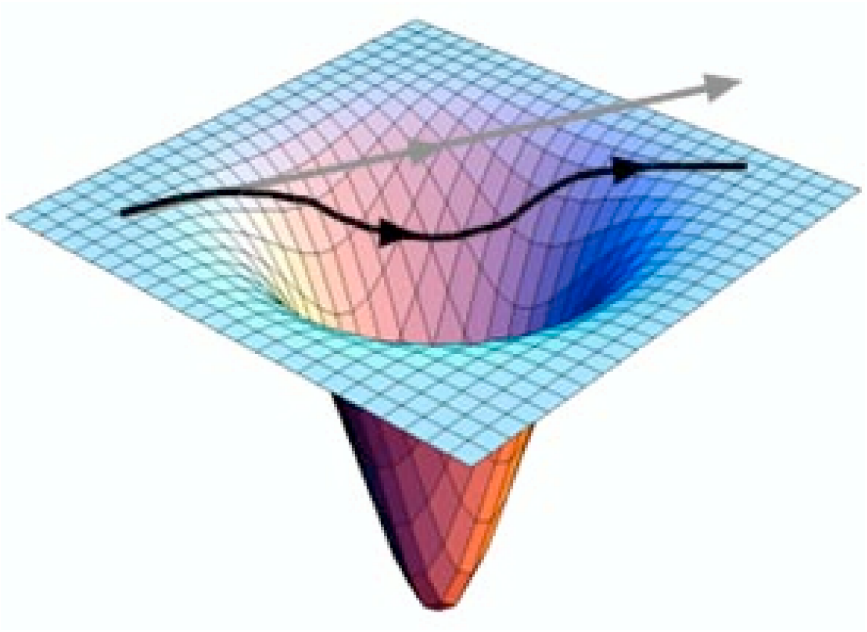
Einstein



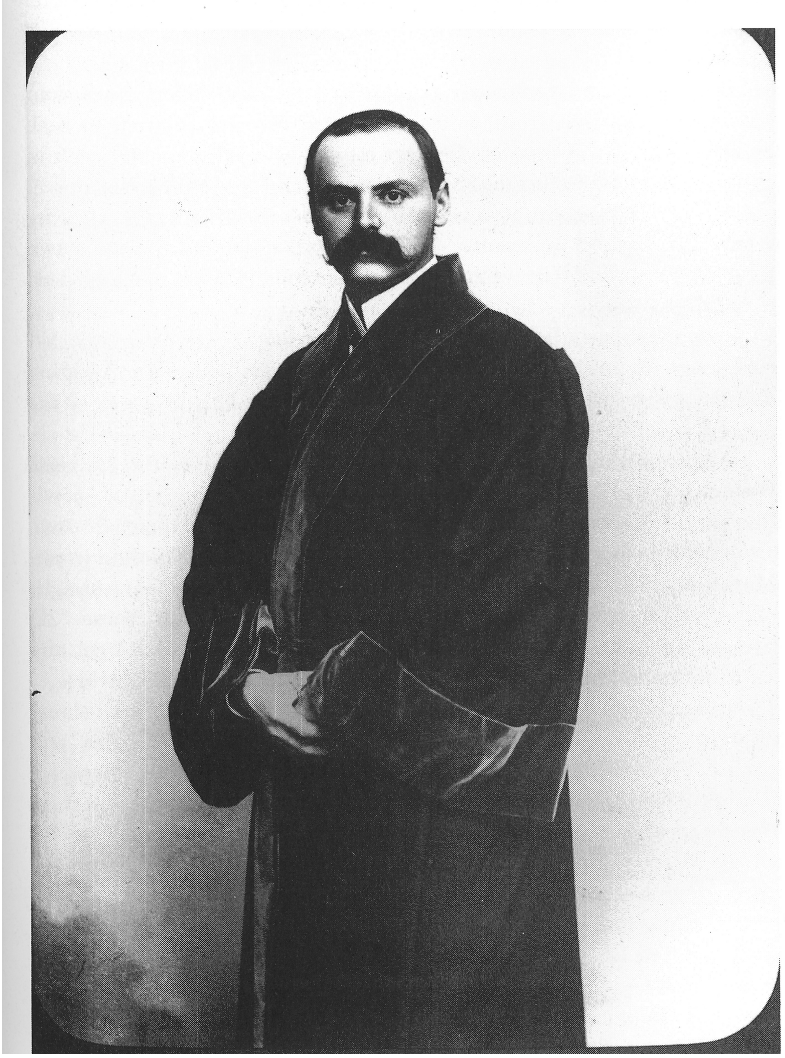
Albert Einstein (1879–1955)

General relativity (1916):

- Mass curves space (“Metric”)
- Light moves through curved space



post-Einstein



Karl Schwarzschild (1873–1916)

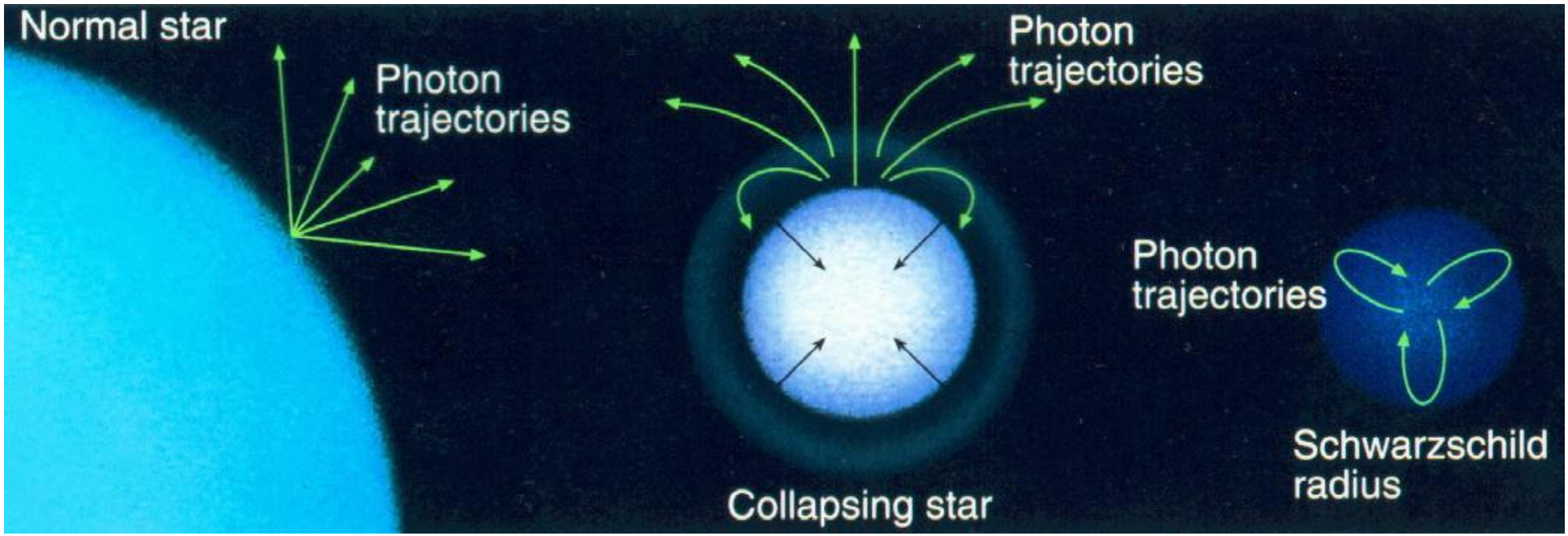
Directly after publication of GRT:

$$ds^2 = \left(1 - \frac{2GM}{c^2 r}\right) c^2 dt^2 - \left(1 - \frac{2GM}{c^2 r}\right)^{-1} dr^2$$

(Schwarzschild Metric).

Describes “shape of space” in vicinity of mass M.

post-Einstein



$R > R_S$ $R \sim R_S$ $R < R_S$

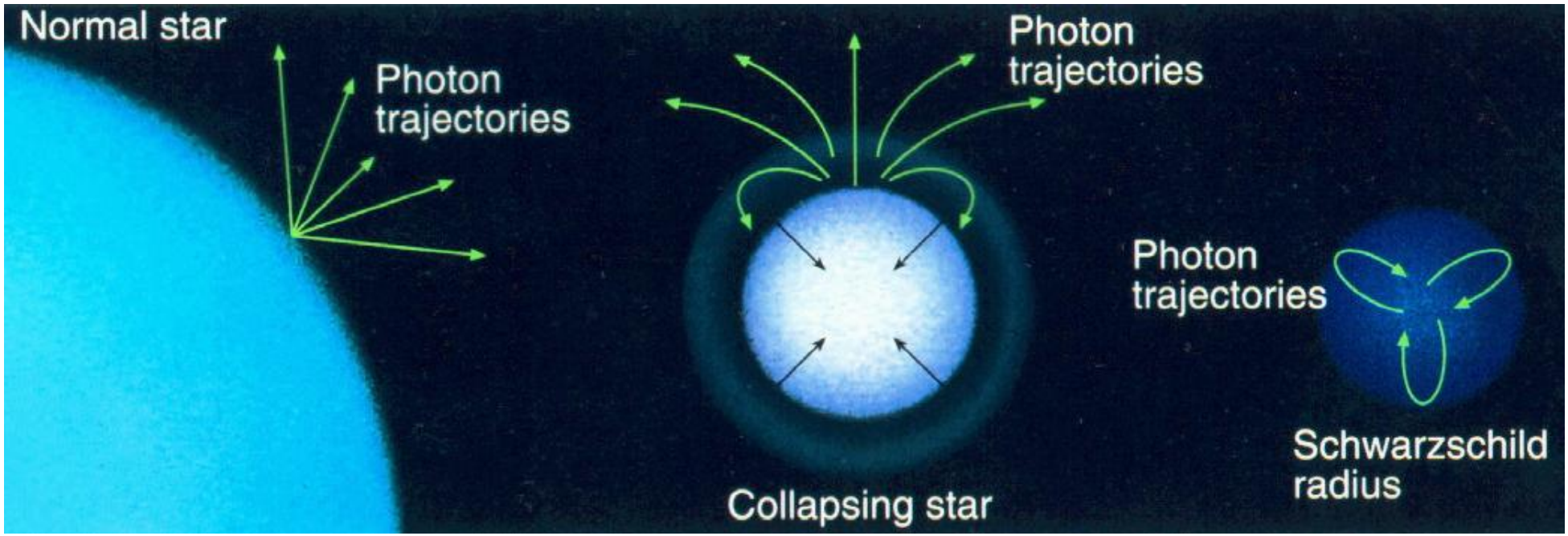
Behavior of light is determined from location of emission, in dependence from the Schwarzschild Radius:

$$R_S = \frac{2GM}{c^2} \sim 3\,\mathrm{km}\,\frac{M}{M_\odot}$$

Same value as in Newtonian derivation!

J.N. Imamura

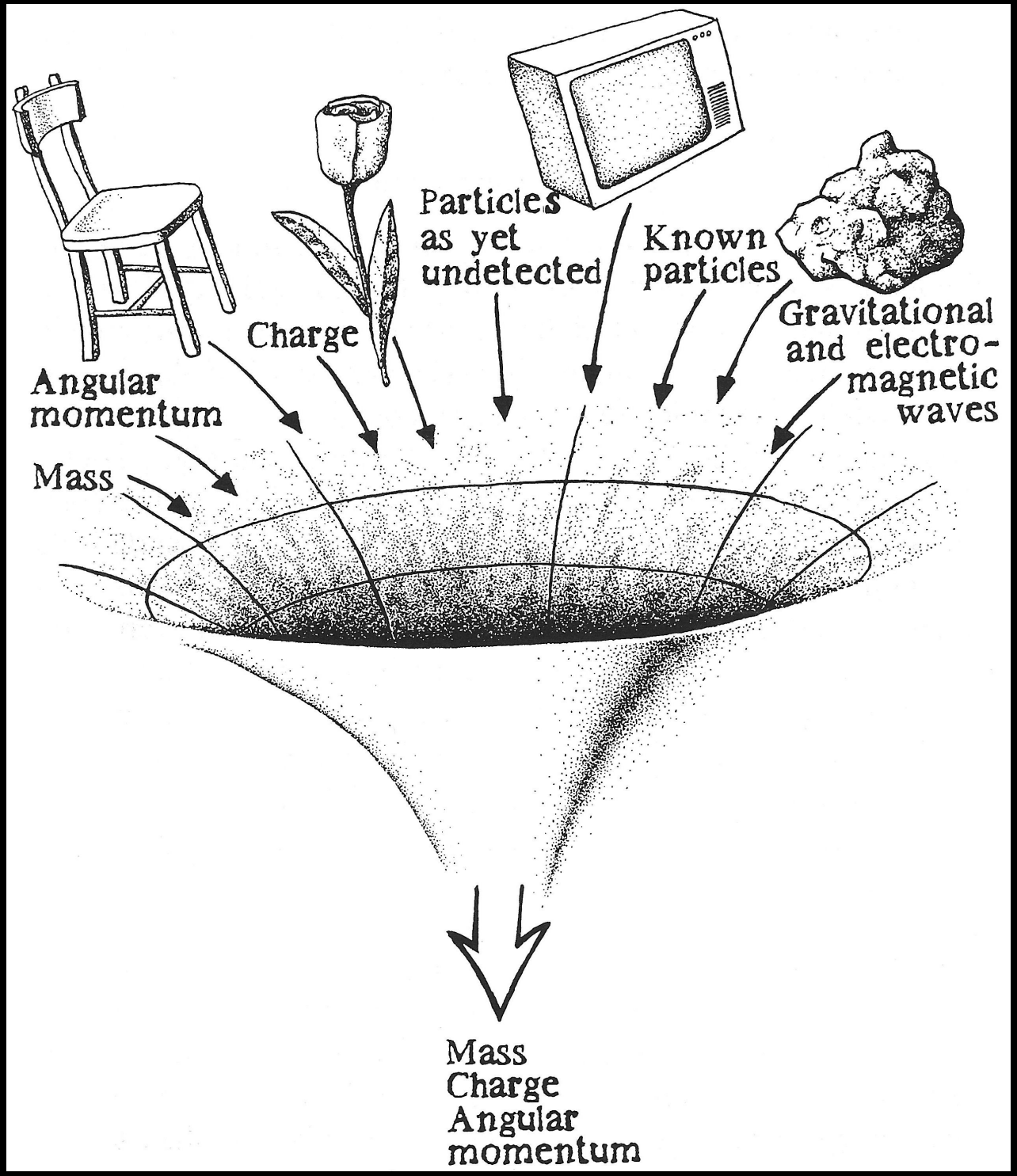
post-Einstein



$R > R_S$ $R \sim R_S$ $R < R_S$

Black hole in GRT: Bodies smaller than their Schwarzschild radius.

J.N. Imamura



Black holes are very simple physical objects, determined by

- Mass
- (Charge)
- Angular momentum

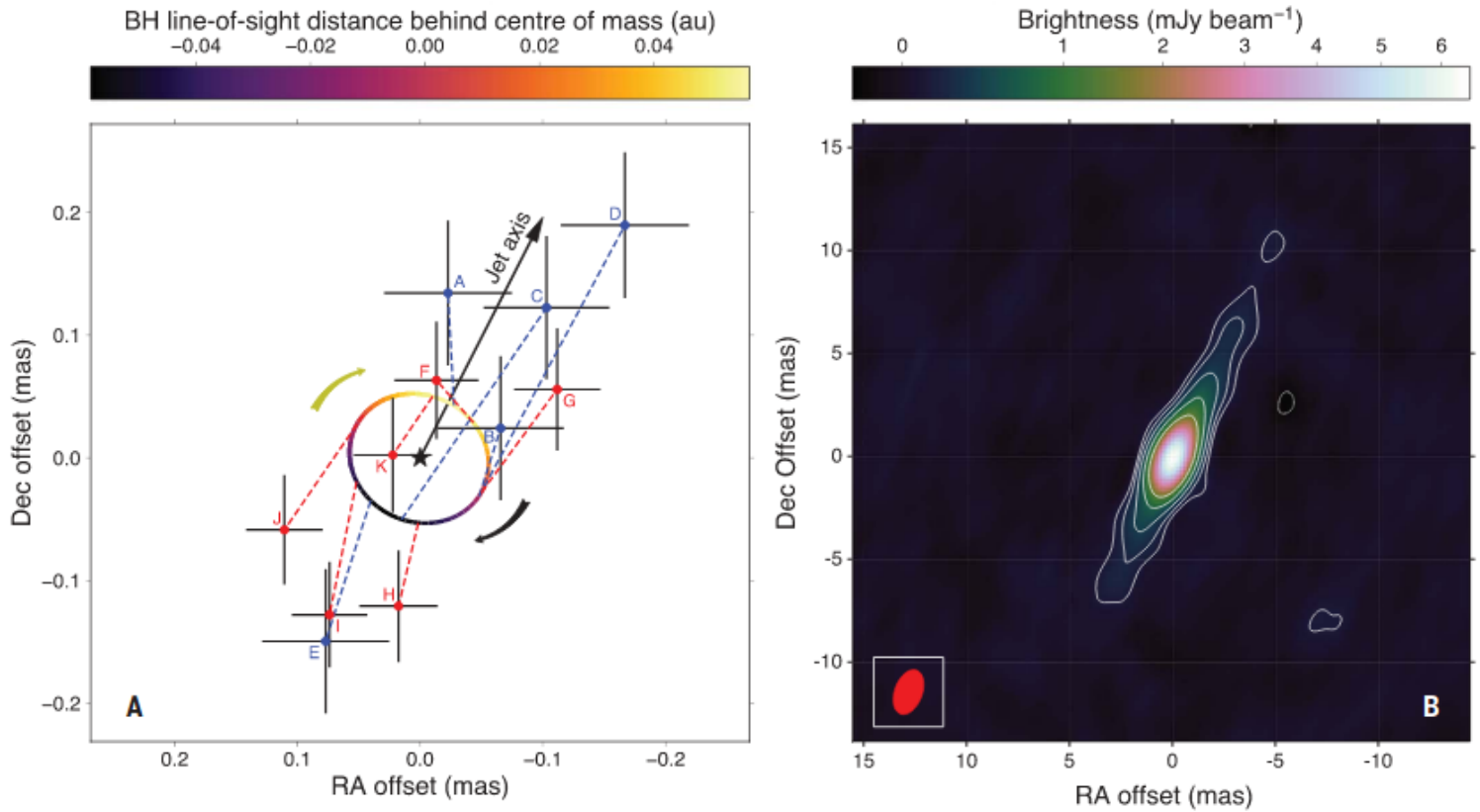


Material flows from normal star onto compact object via inner Lagrange point, L_1

$\Longrightarrow$ Formation of an accretion disk, with temperature $\sim 10^7$ K

$\Longrightarrow$ X-rays and gamma-rays.

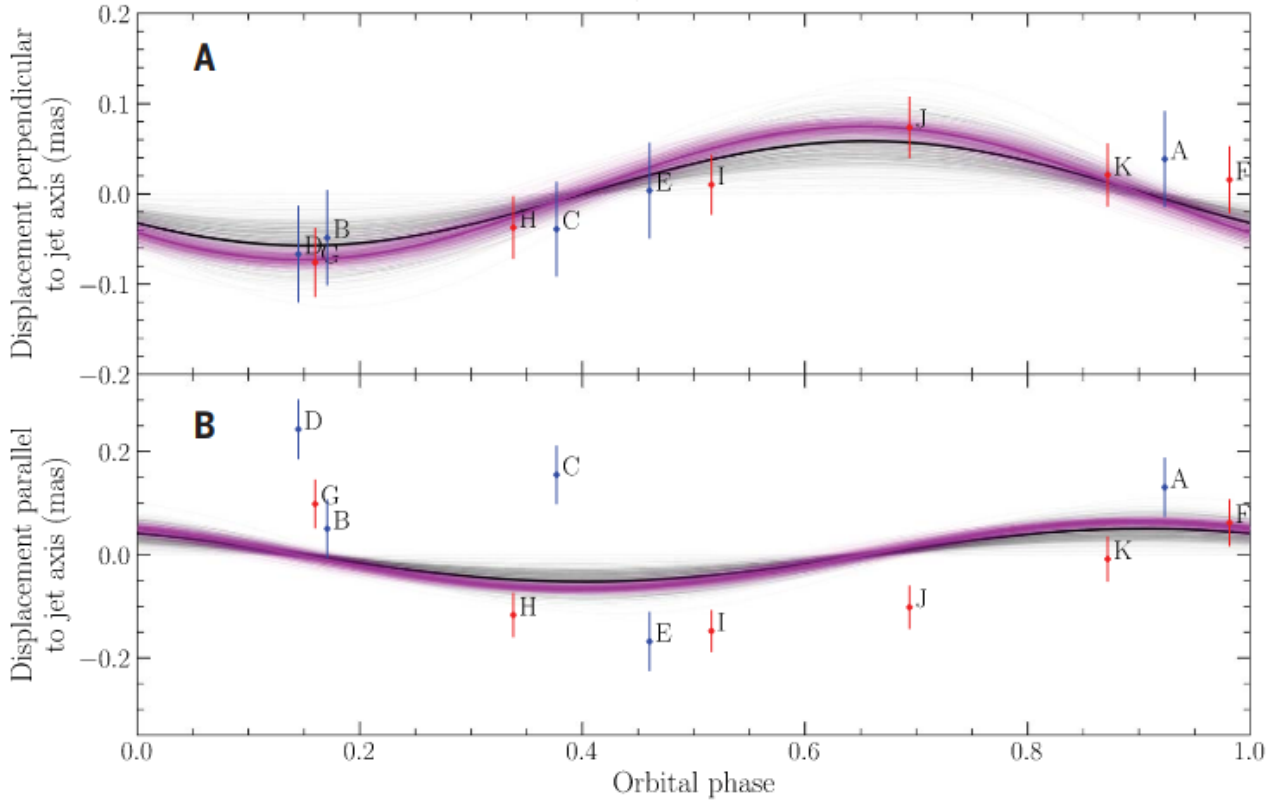
post-Einstein



Miller-Jones et al. (incl. JW), 2021, Science 371, 1046

To get mass: determine M_* from stellar models, or from direct measurement. Cyg X-1: $d = 2.22^{+0.18}_{-0.17}$ kpc, $M_{BH} = 21.2 \pm 2.2\,M_\odot$, $M_* = 40.6^{+7.7}_{-7.1}\,M_\odot$

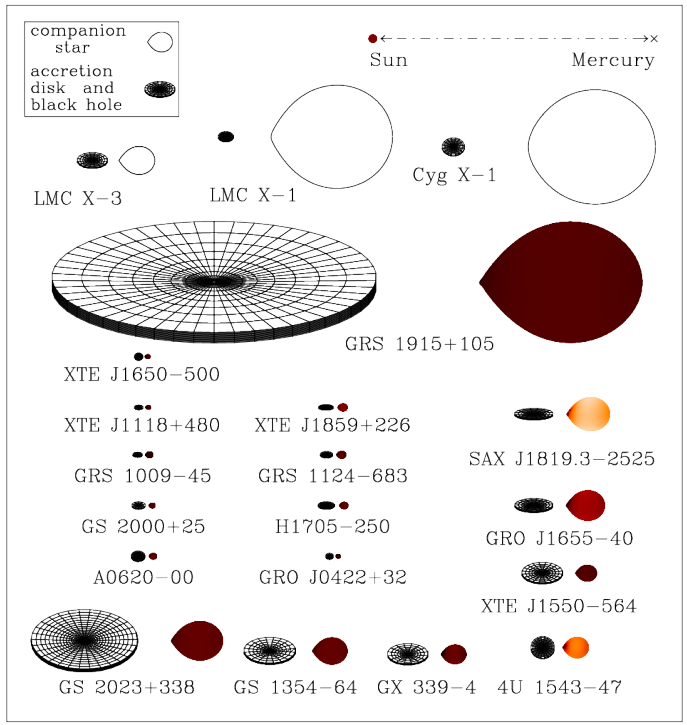
post-Einstein



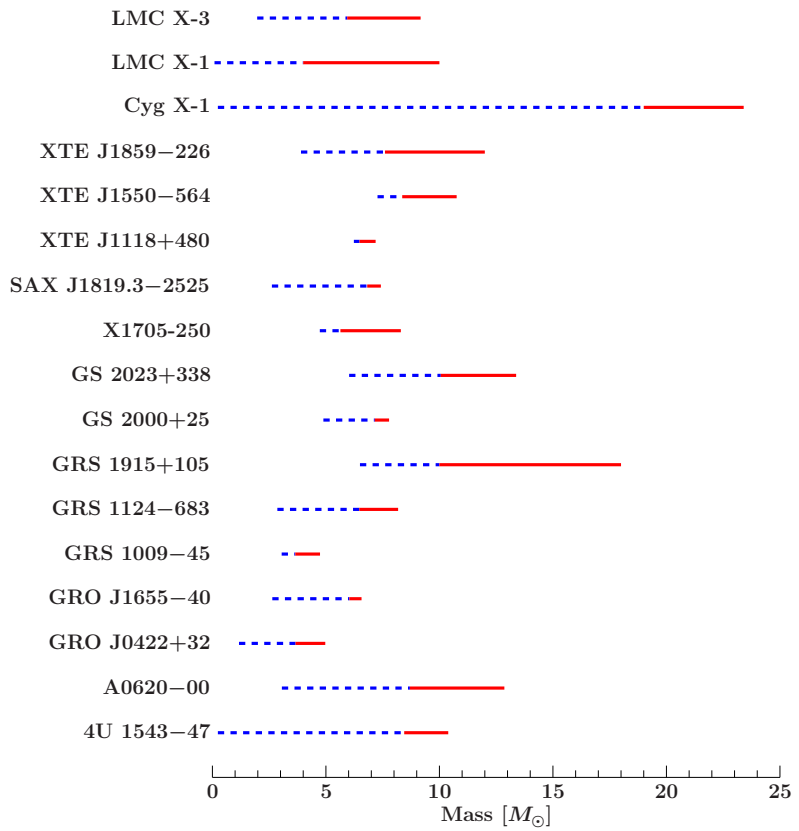
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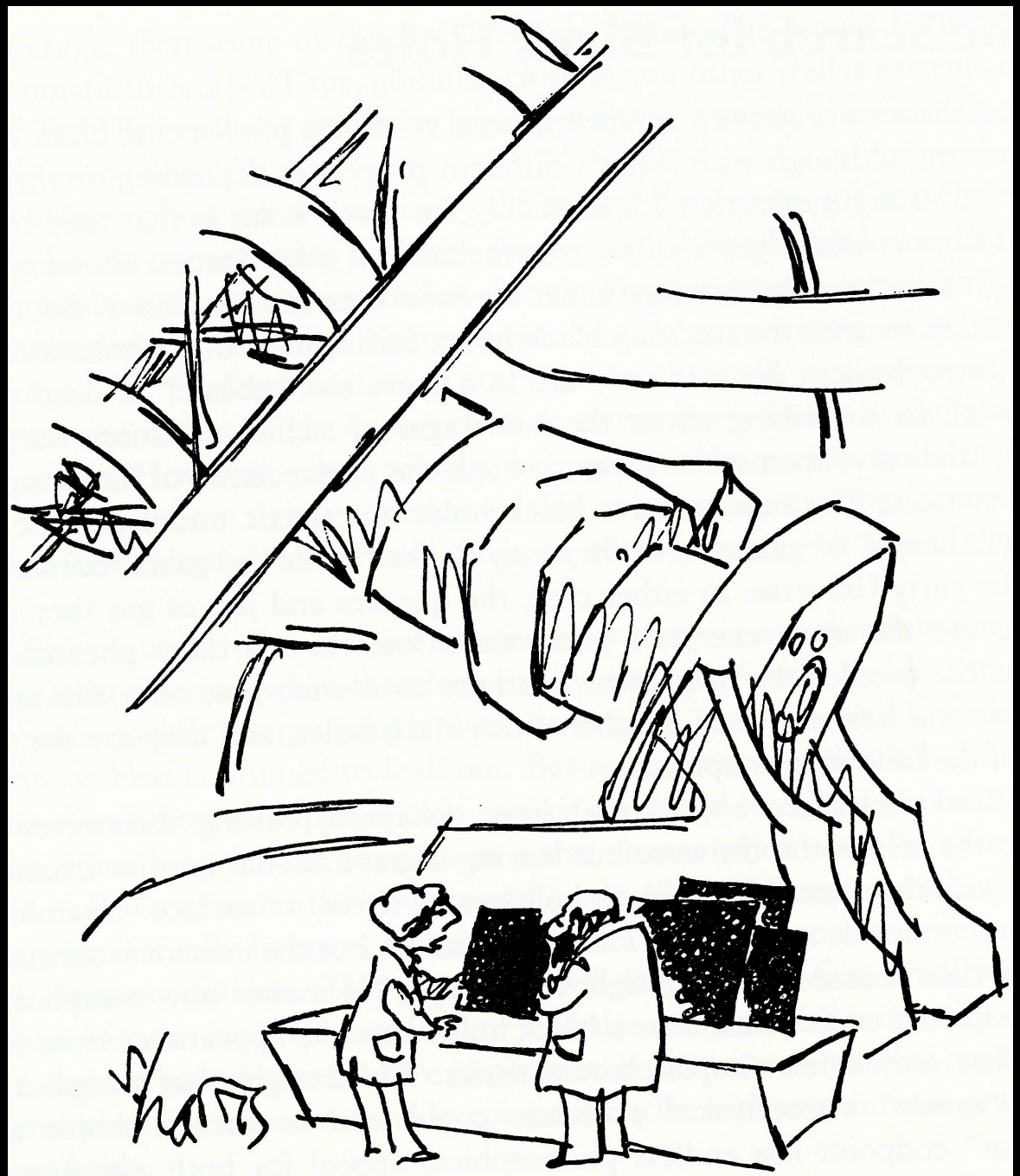
post-Einstein



Orosz, priv. comm.



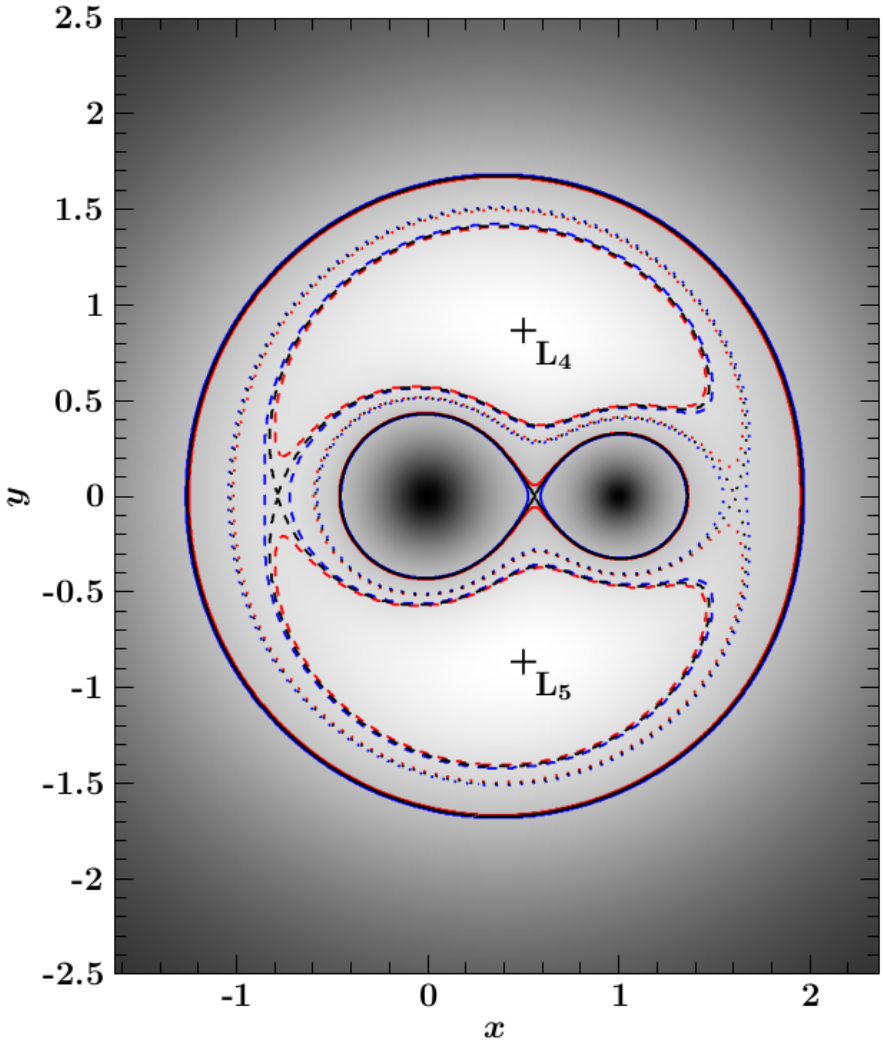
We know about 20 black holes with dynamically determined masses in our own Galaxy.

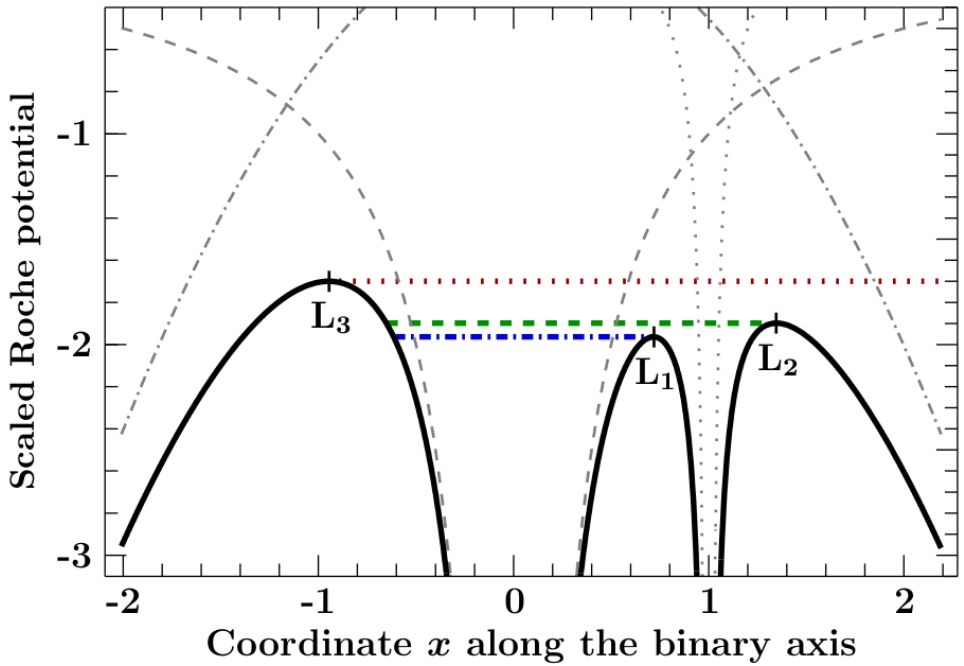


"It's black, and it looks like a hole. I'd say it's a black hole."

Binary Systems

Close Binaries





M. Hanke

Gravitational potential of a binary.

$L_1, \ldots, L_5$: Lagrange points.

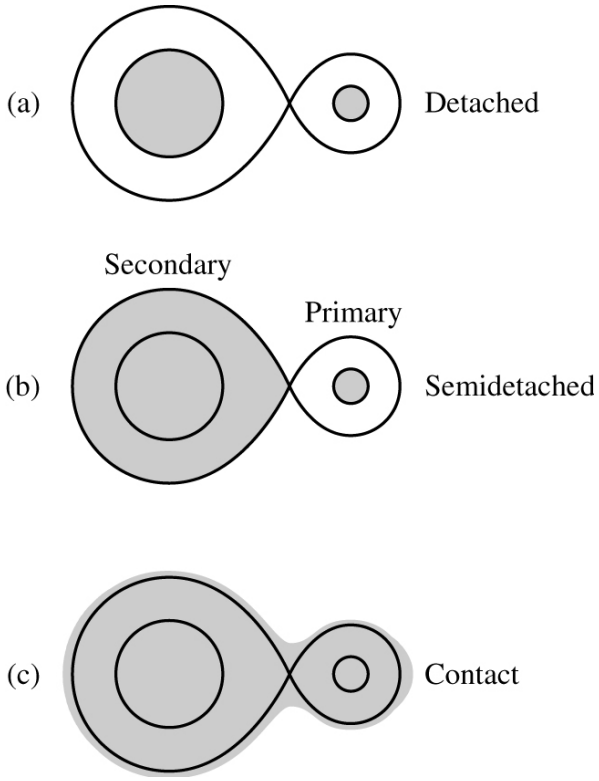
Dashed line: Total energy required for material to flow through L_1.

M. Hanke

Close Binaries

How to detect a compact object?

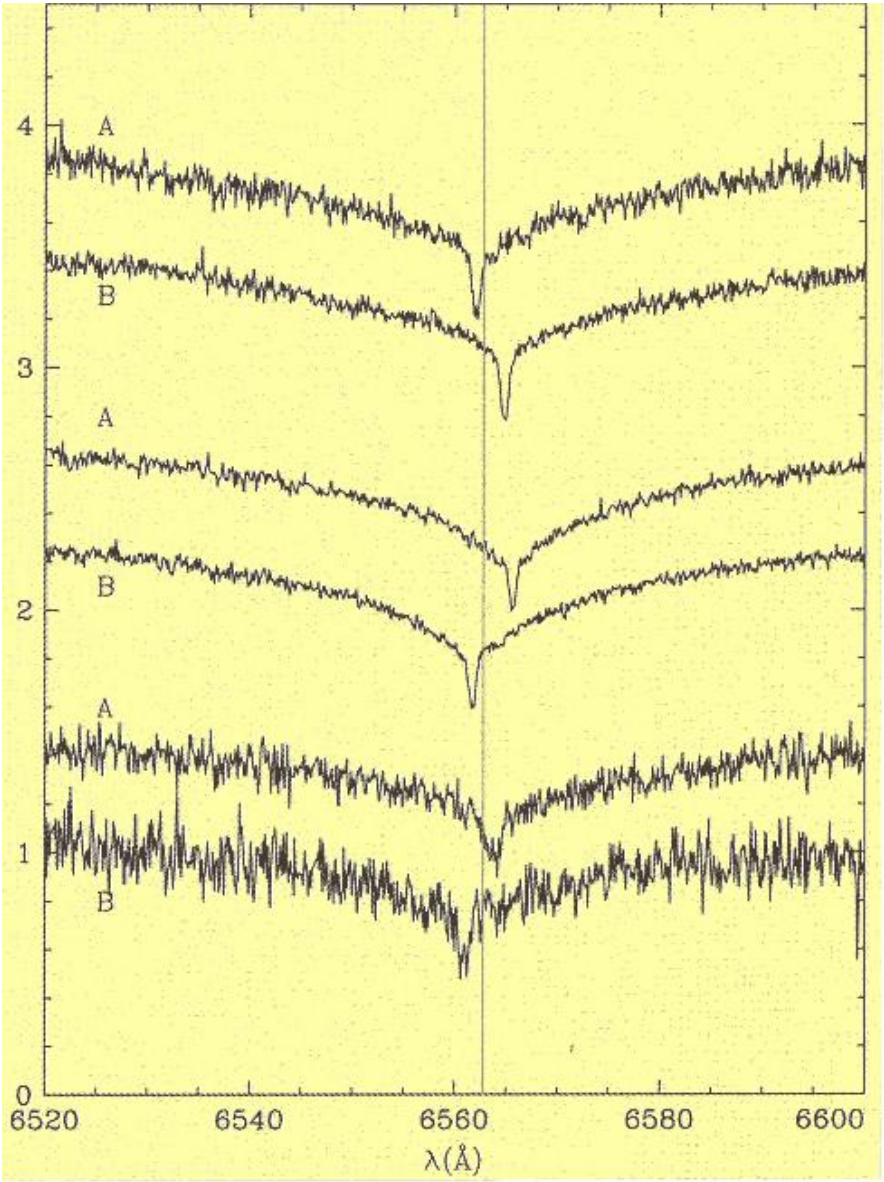
Binaries!



Carroll & Ostlie Fig. 18.4

- Detached binaries:
  Doppler motion of the visible star (as for Exo-Planets).
- Interacting binaries (semi-detached):
  Mass transfer from the normal star and accretion onto the companion

Close Binaries



Reminder: Spectroscopic binaries: Mass of compact invisible object (as for the exo-planets) from 3rd Kepler:

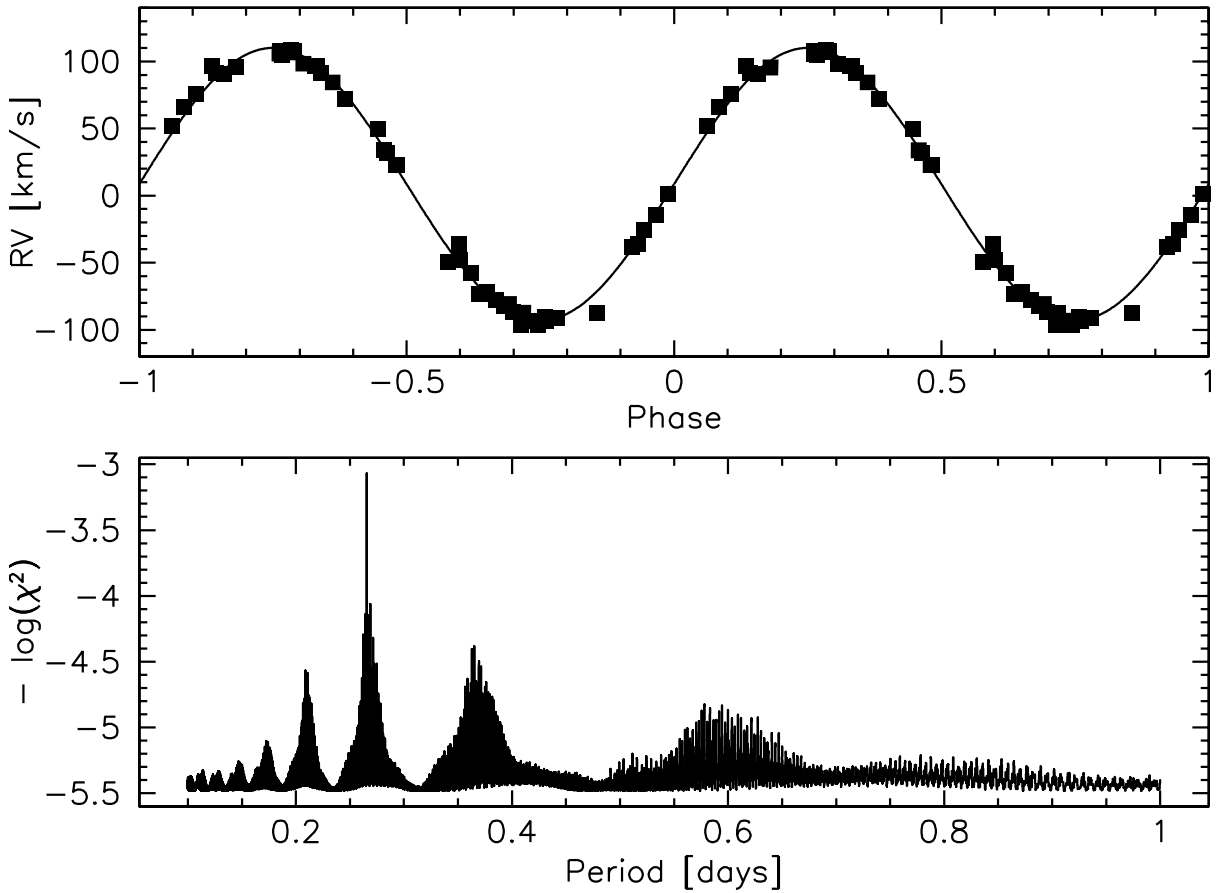
$$\frac{a^3}{P^2} = \frac{G(M_1 + M_2)}{4\pi^2} \tag{3.1}$$

(a: semi-major axis, P: orbital period, $M_{1,2}$: Masses).

Derive from this: Mass function

$$MF = \frac{M_2^3 \sin^3 i}{(1 + (M_1/M_2))^2} = \frac{K_1^2 P}{2\pi G} \tag{3.2}$$

Close Binaries



Karl et al., Balt. Ast. 15, 1

Measurement K_2 : velocity amplitude, P: period (power spectrum)

Mass function, f, gives lower limit for M_2

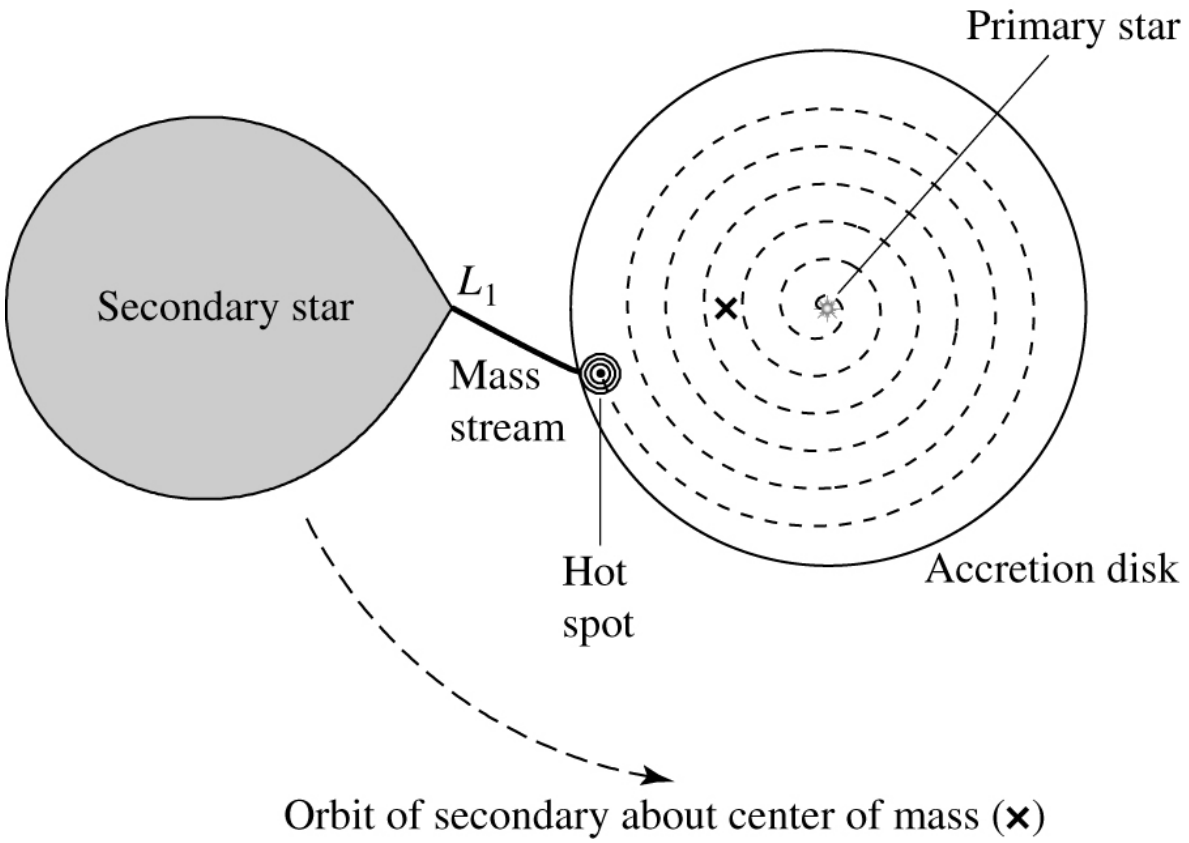
Close Binaries

How do we distinguish between white dwarf, neutron star and black hole?

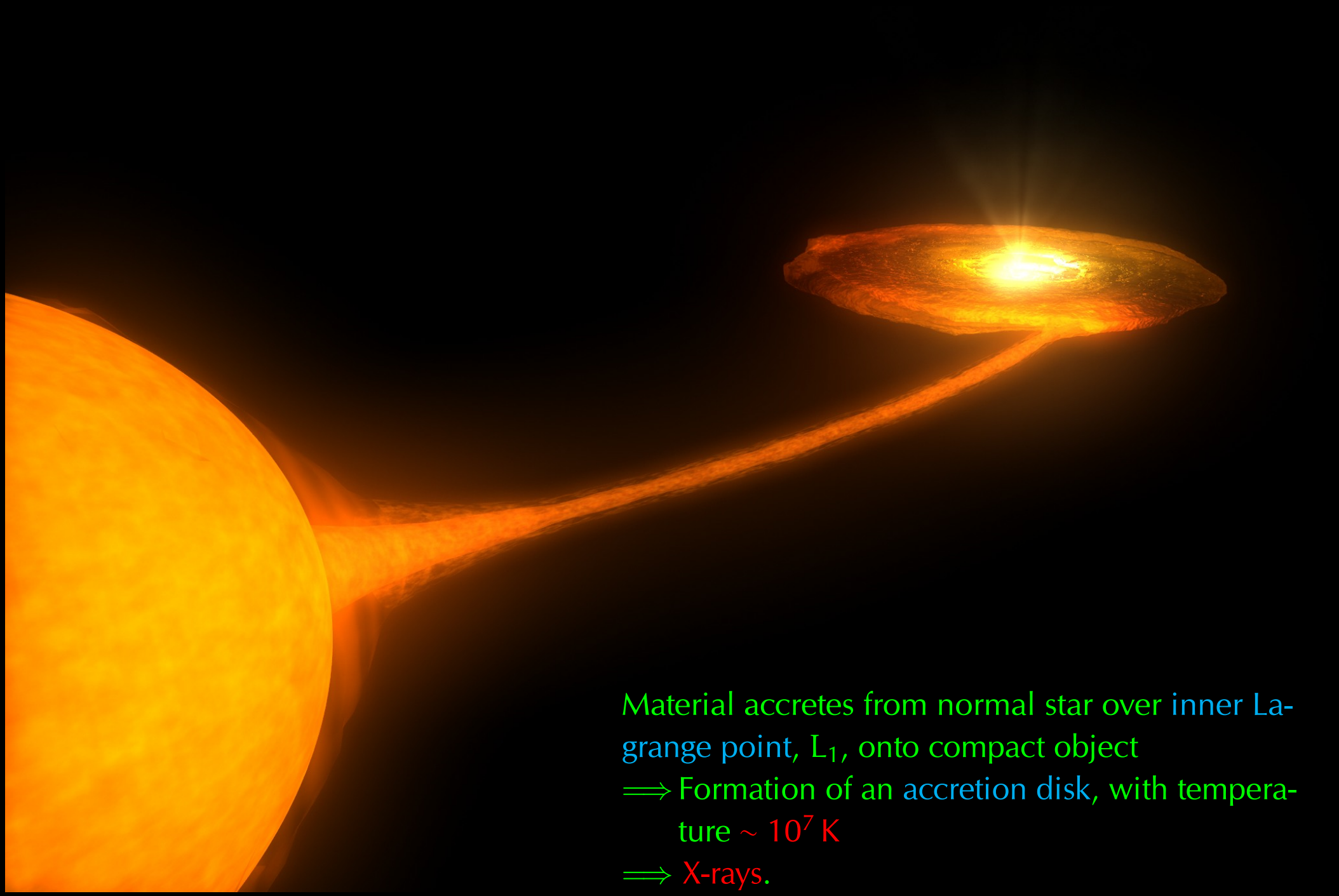
This is done using the mass function, f:

- $f < 1.44\,M_\odot = M_{Ch}$: no distinction possible.
- $M_{Ch} < f < M_{OV}$: Neutron star or black hole
- $f > M_{OV}$: black hole
- If the companion is a pulsar: neutron star

Semi-detached systems



- Visible star = "secondary" = normal star
- Cataclysmic variable: primary is white dwarf
- X-ray binary: primary is a neutron star or black hole.



Material accretes from normal star over inner Lagrange point, L_1, onto compact object

$\Longrightarrow$ Formation of an accretion disk, with temperature $\sim 10^7$ K

$\Longrightarrow$ X-rays.

Accretion

Astrophysical energy sources:

1. Nuclear fusion

Reactions à la

$$4p \longrightarrow {}^4He + \Delta E_{nuc}$$

Energy released:

Fusion produces $\sim 6 \times 10^{11}\,J\,g^{-1}$

(i.e., $\Delta E_{nuc} \sim 0.007 m_p c^2$)

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2. Gravitation

Accretion of mass m from ∞ to R_S on black hole with mass M gives

$$\Delta E_{acc} = \frac{GMm}{R_S} \text{ where } R_S = \frac{2GM}{c^2}$$

Accretion produces $\sim 10^{13}\,J\,g^{-1}$

(i.e., $\Delta E_{acc} \sim 0.1\, m_p c^2$)

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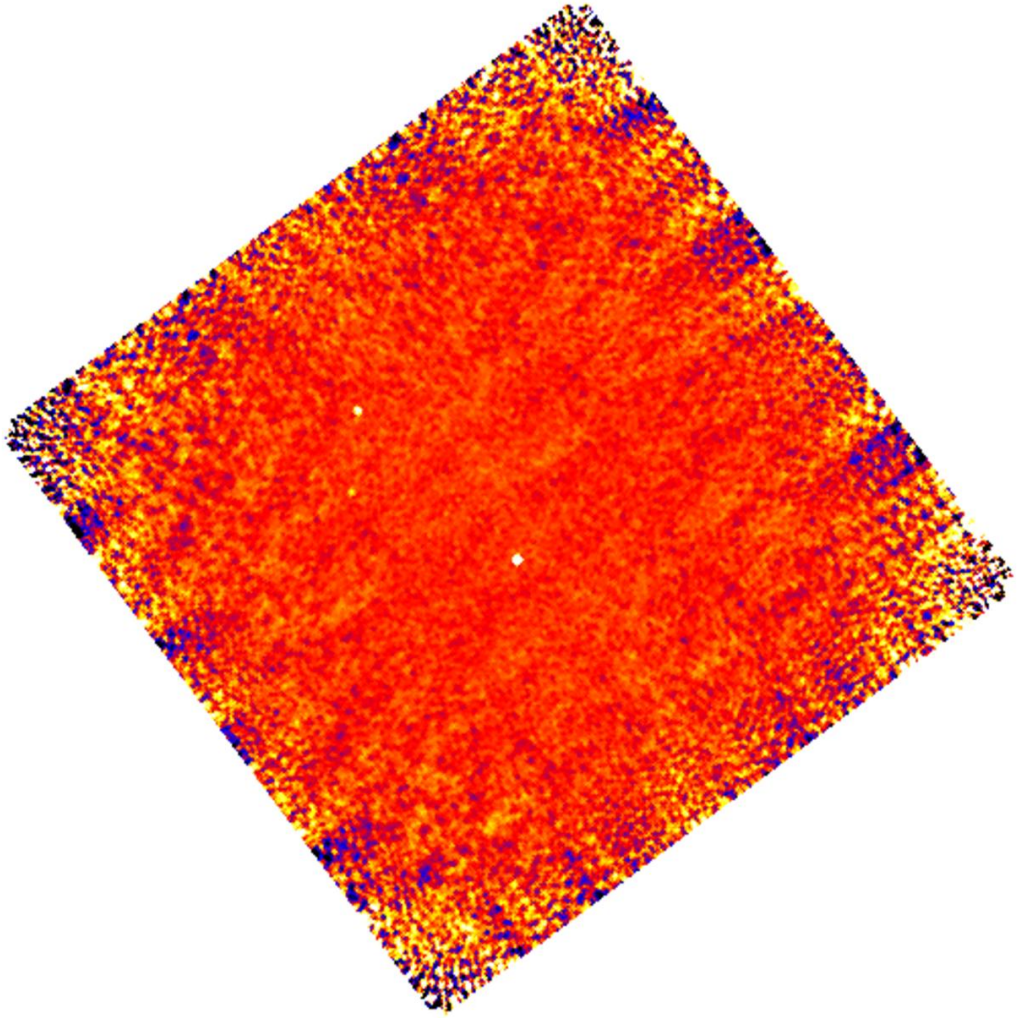
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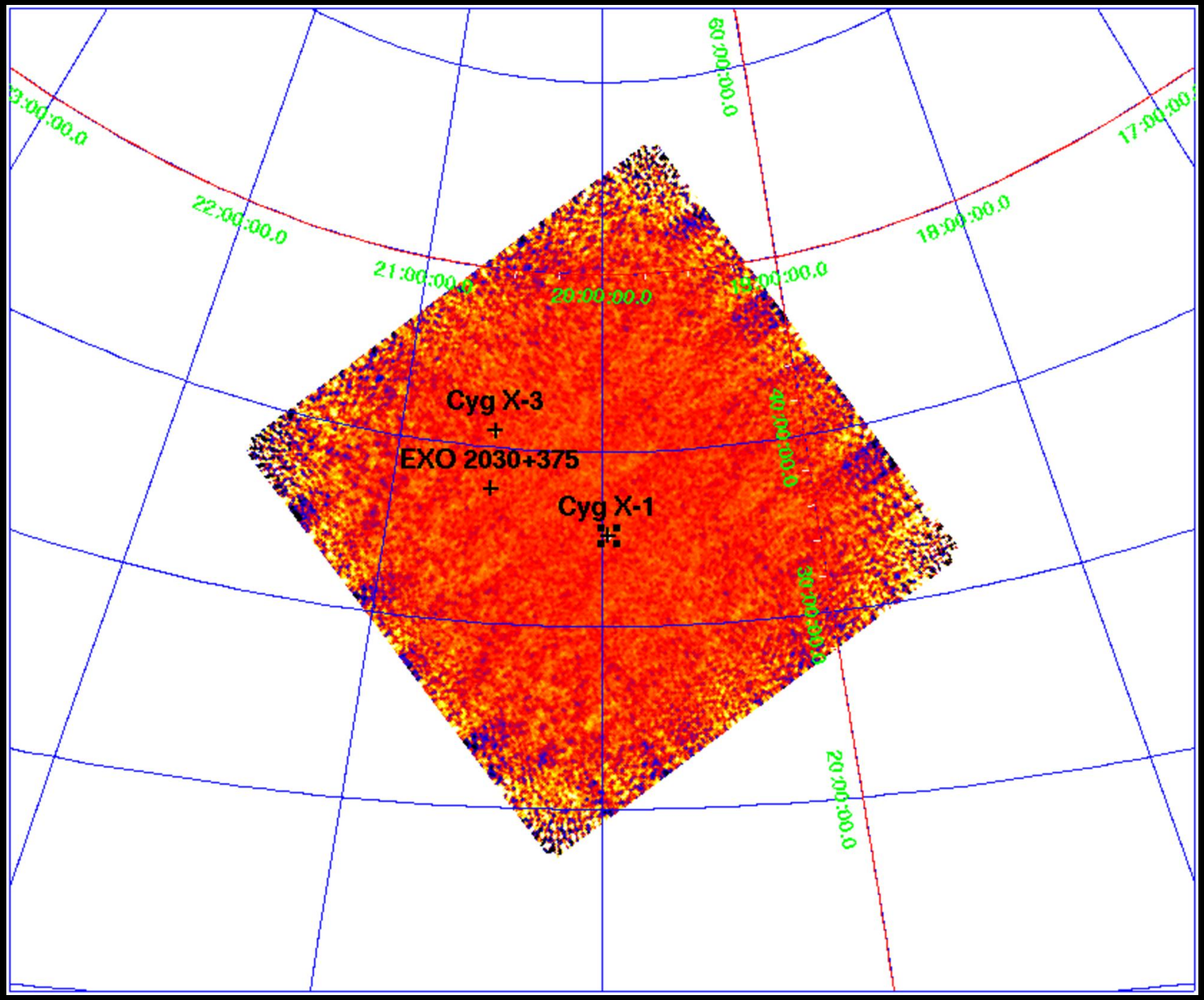
$\Longrightarrow$ Accretion of material is the most efficient astrophysical energy source.

. . . thus accreting objects are the most luminous in the whole universe.

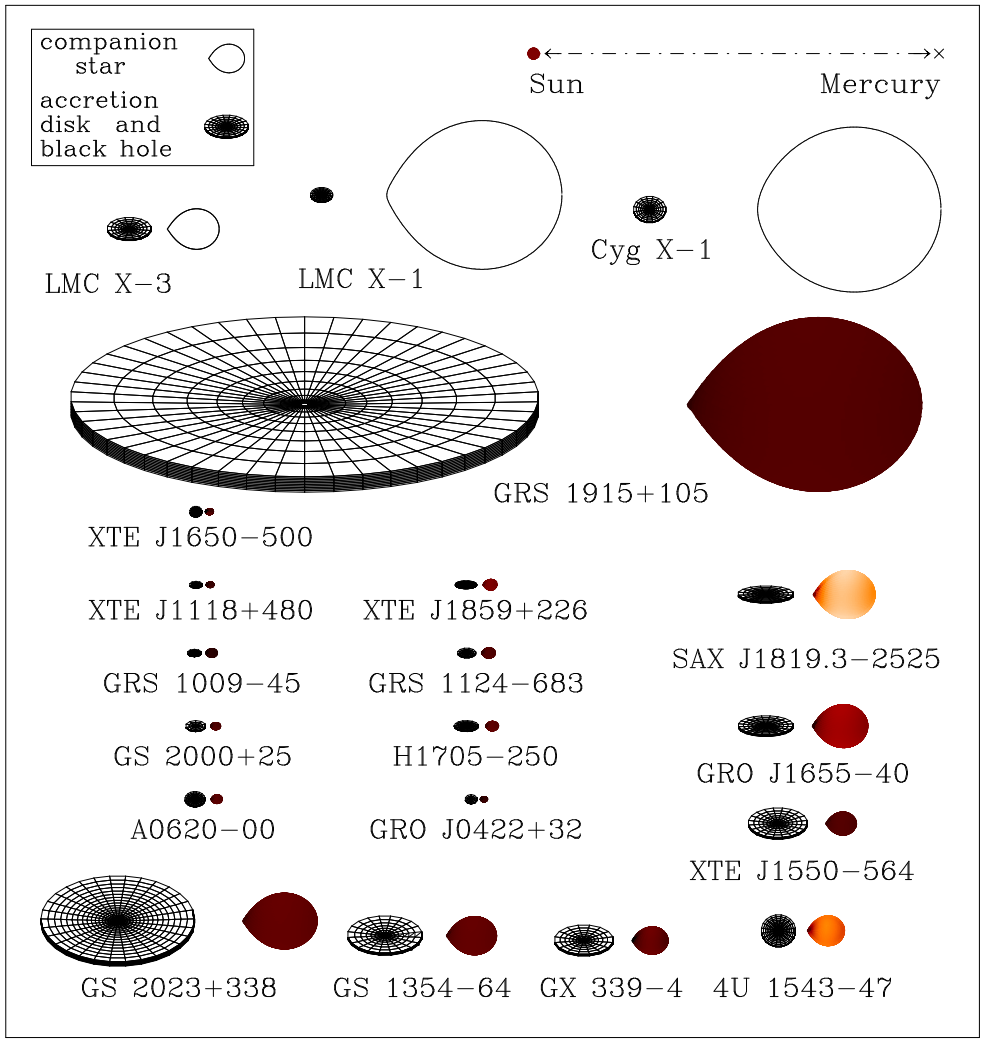
Note: energy gets radiated away from *outside* the Schwarzschild radius!

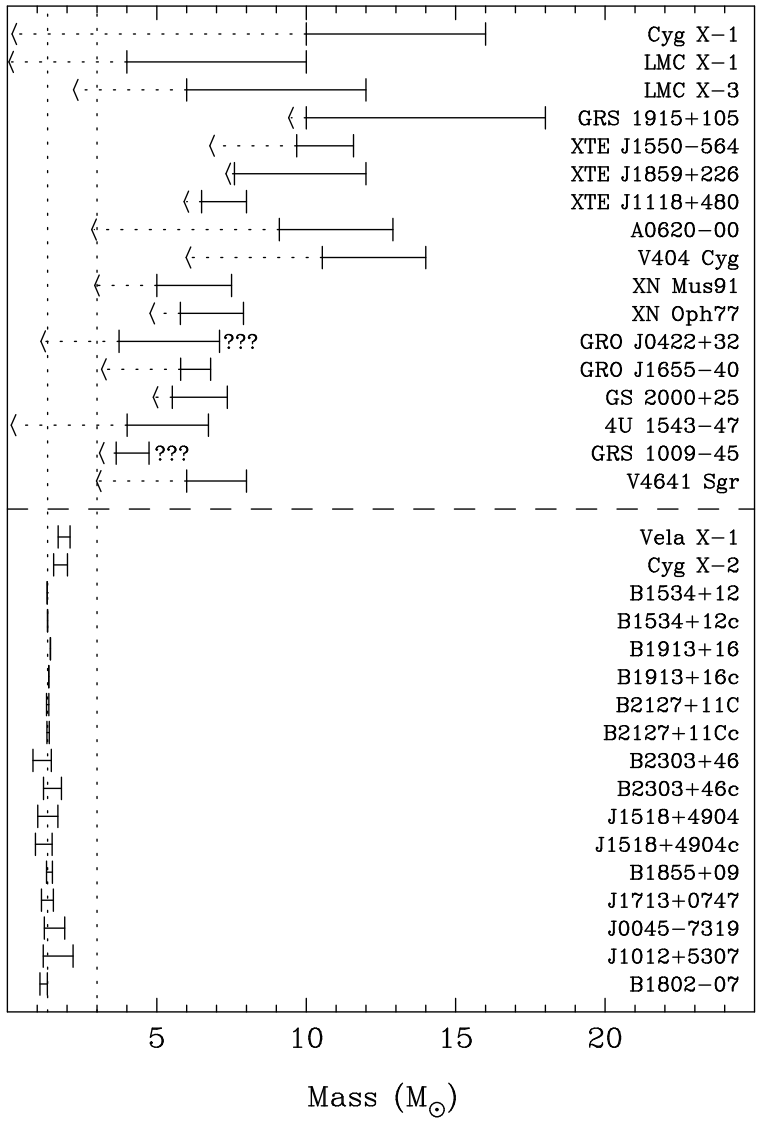





Cyg X-3
EXO 2030+375
Cyg X-1
23:00:00.0
22:00:00.0
21:00:00.0
20:00:00.0
19:00:00.0
18:00:00.0
17:00:00.0
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30:00:00.0
20:00:00.0

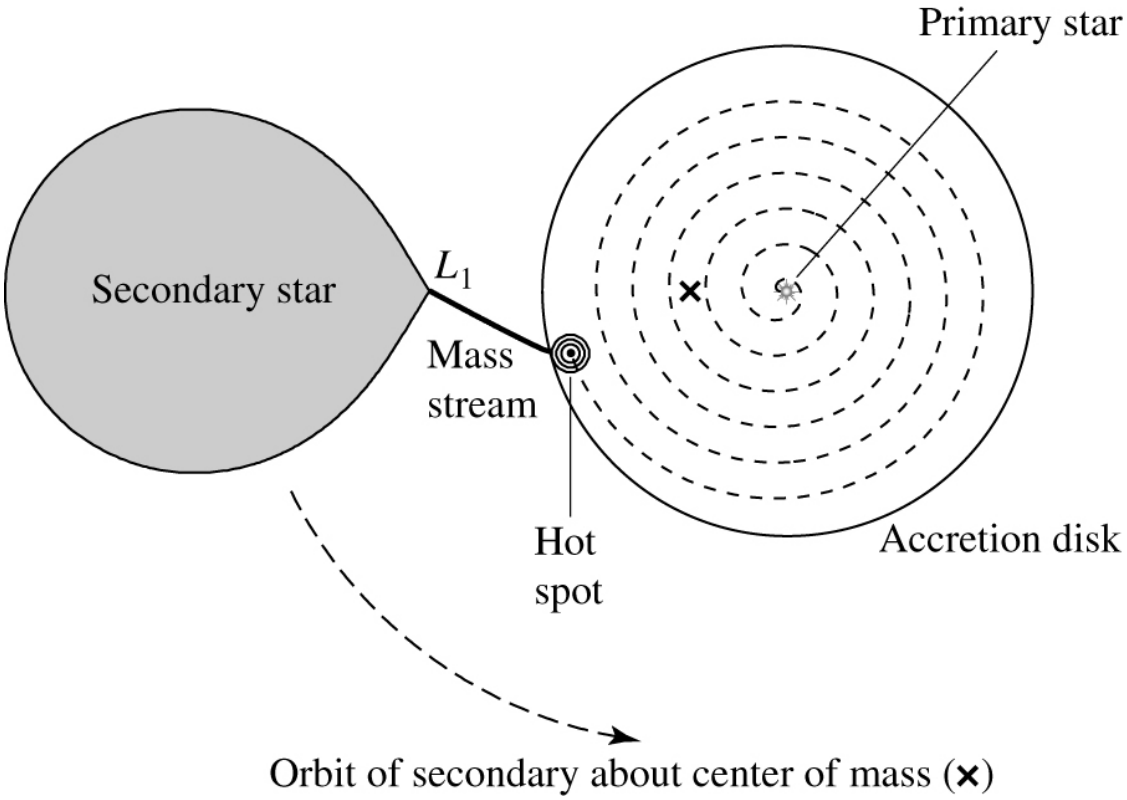
Mass determination





Orosz, 2003, priv. comm.

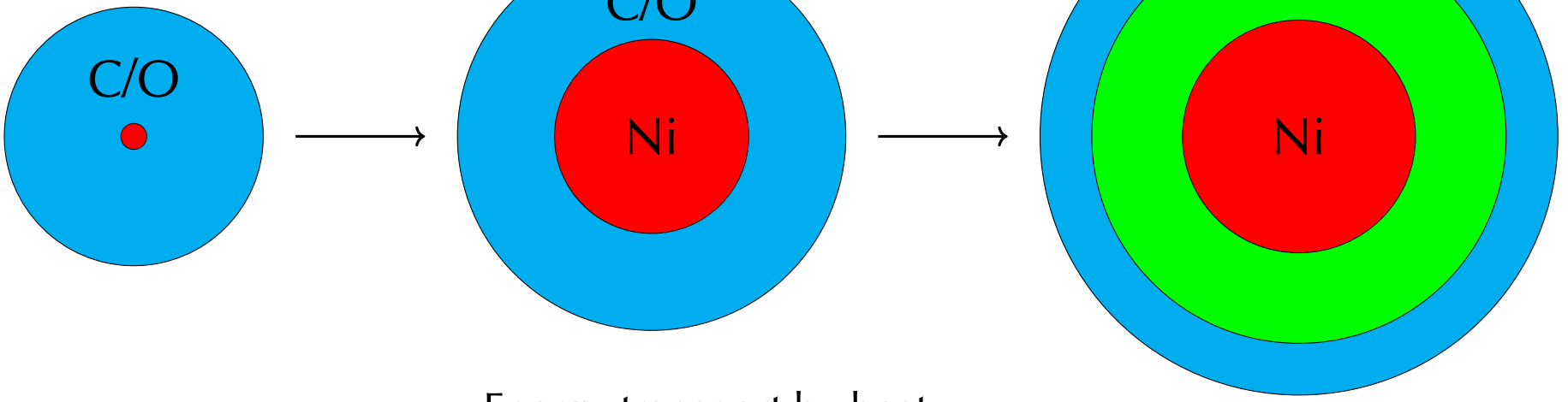
Explosions in binary systems: Novae



Novae: accretion of hydrogen onto the surface of a white dwarf:

- $10^{-5}M_\odot \ldots 10^{-4}M_\odot$ Hydrogen accumulate. Electron gas is degenerate, Temperature of a few million K
- hydrogen burning in the CNO cycle starts
- thermal run-away (similar to core He flash at the tip of the RGB)
- explosion expels almost all accreted material

Explosions in binary systems: Supernovae– Type Ia



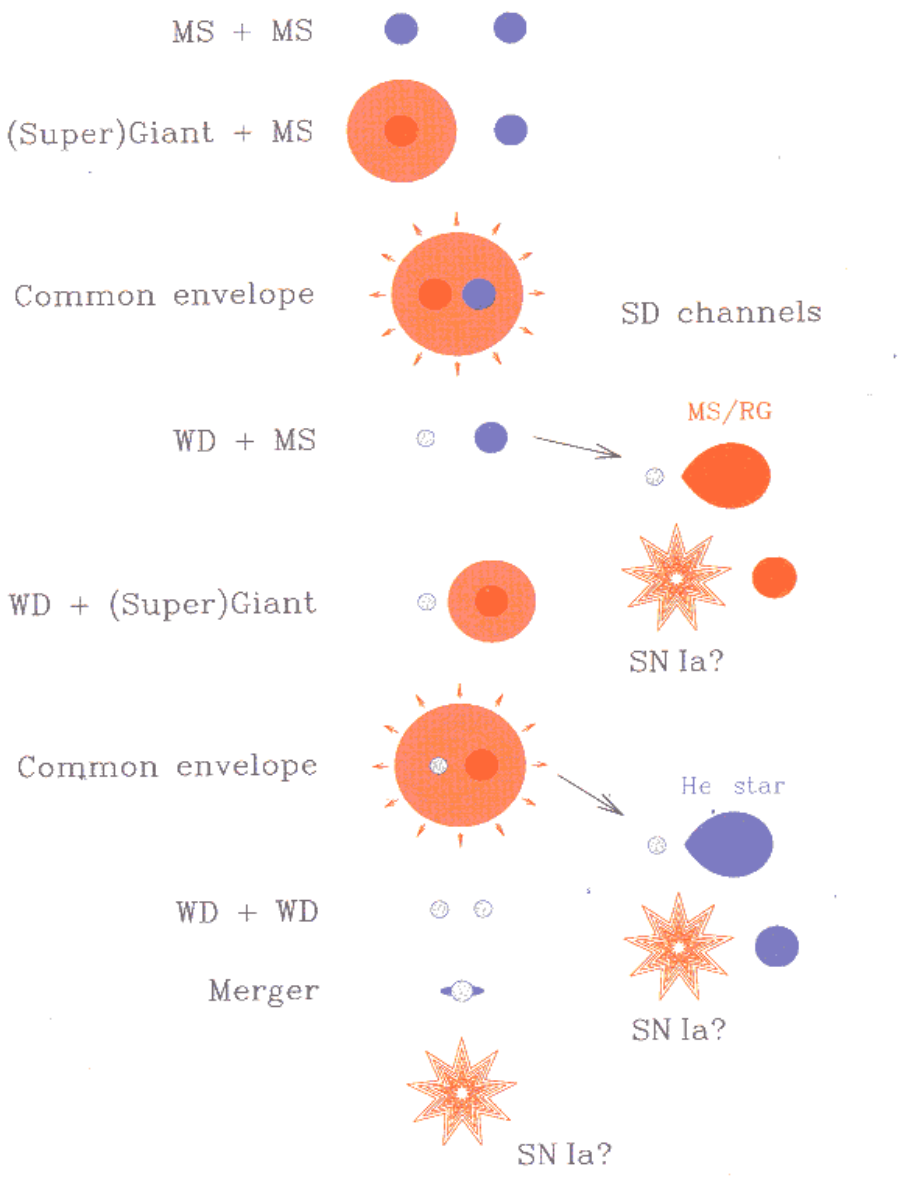
after P. Höflich

Energy transport by heat conduction over front ($v \ll c_{sound}$) ignition of unburned fuel

ignition of unburned fuel by compression in detonation

SNe Ia: thermonuclear runaway in carbon-oxygen white dwarfs close to Chandrasekhar limit

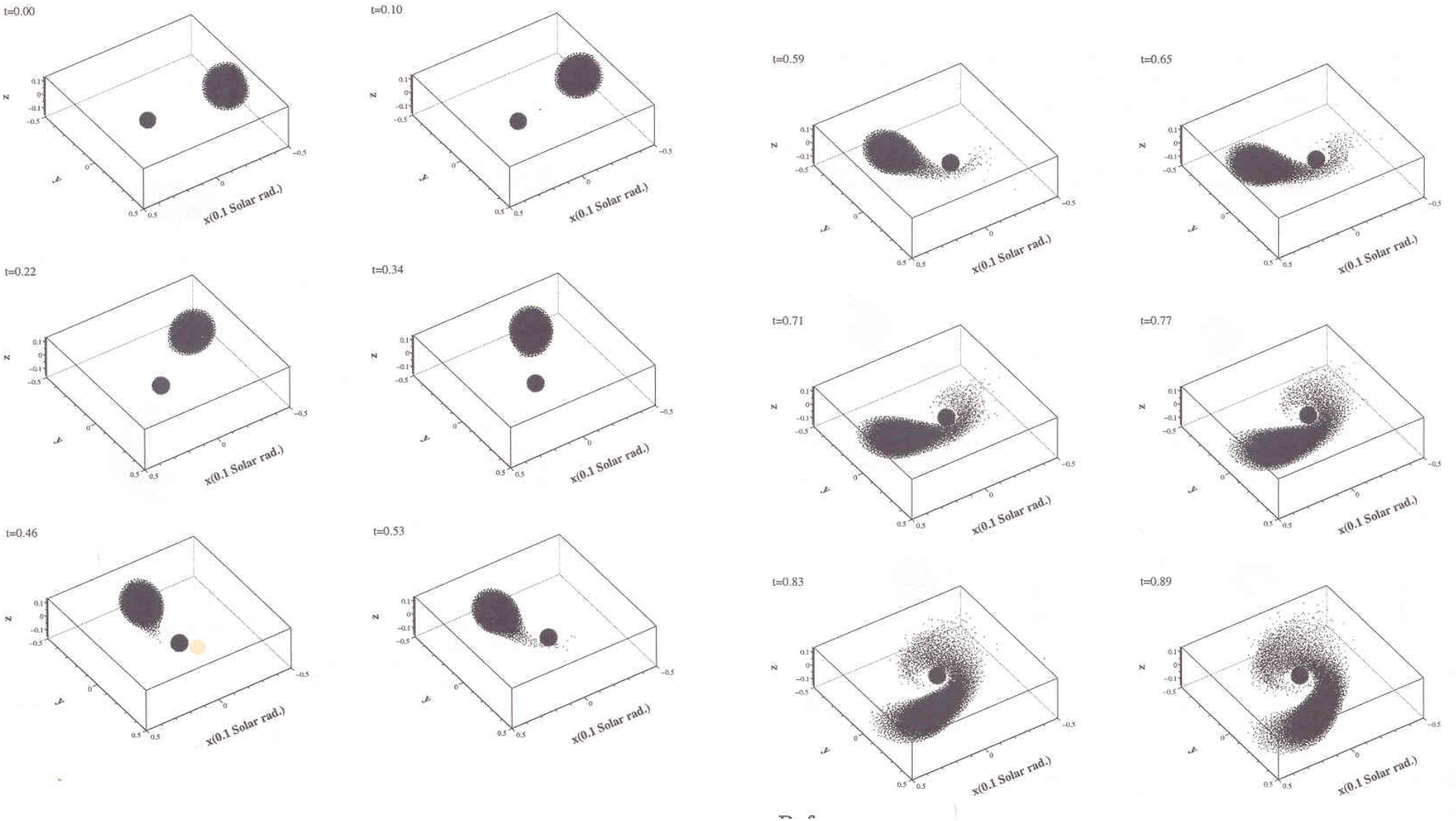
Explosions in binary systems: Supernovae– Type Ia



Path to SN Ia:

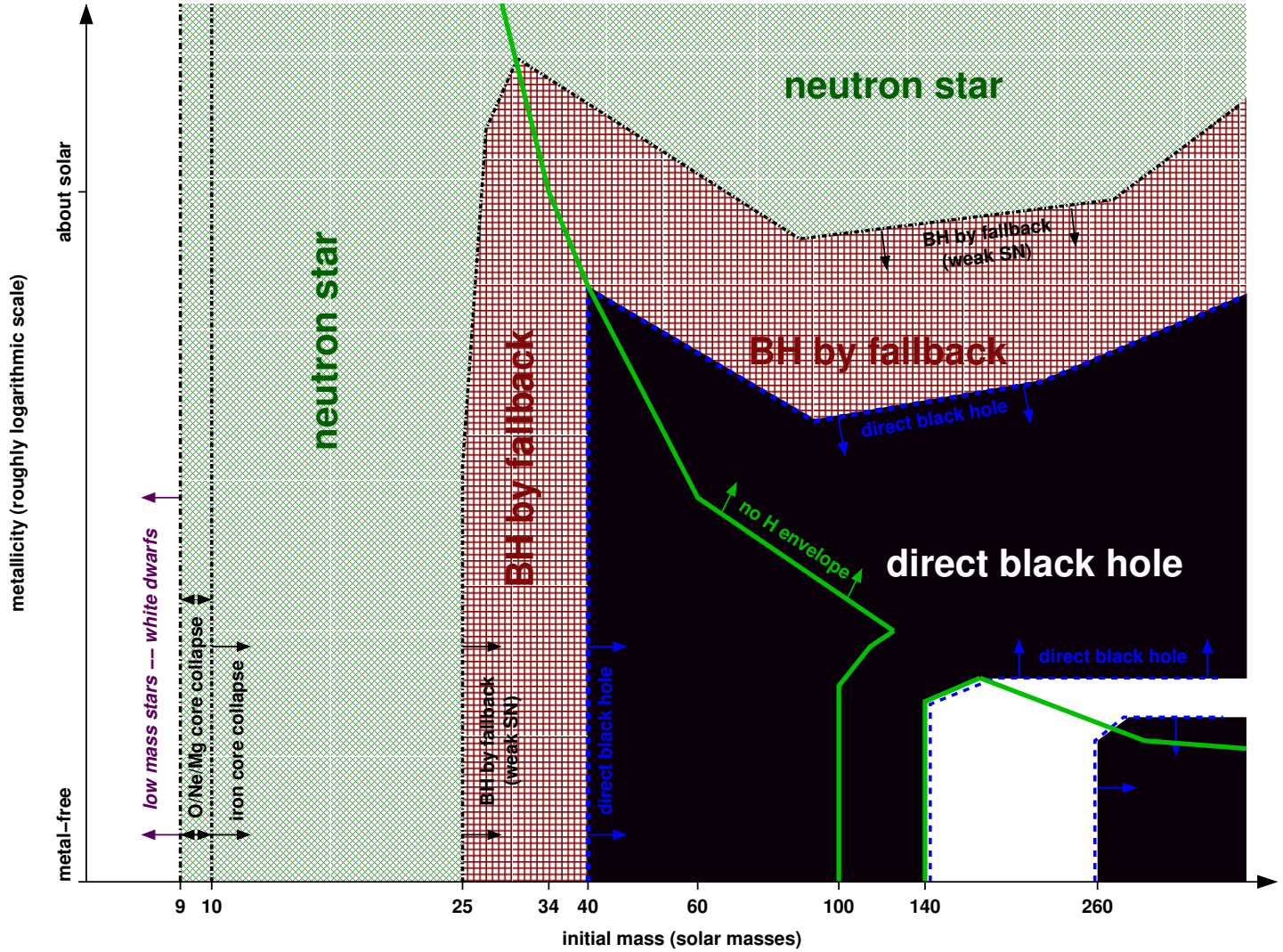
- orbital shrinkage by common envelope ejection
- single degenerate scenario: continous mass transfer to the white dwarf
  - white dwarf & normal star
  - white dwar & helium star
- Double degenerate scenario:
- two white dwarfs: orbital shrinkage by gravitational wave radiation: white dwarf merger.

White dwarf merger



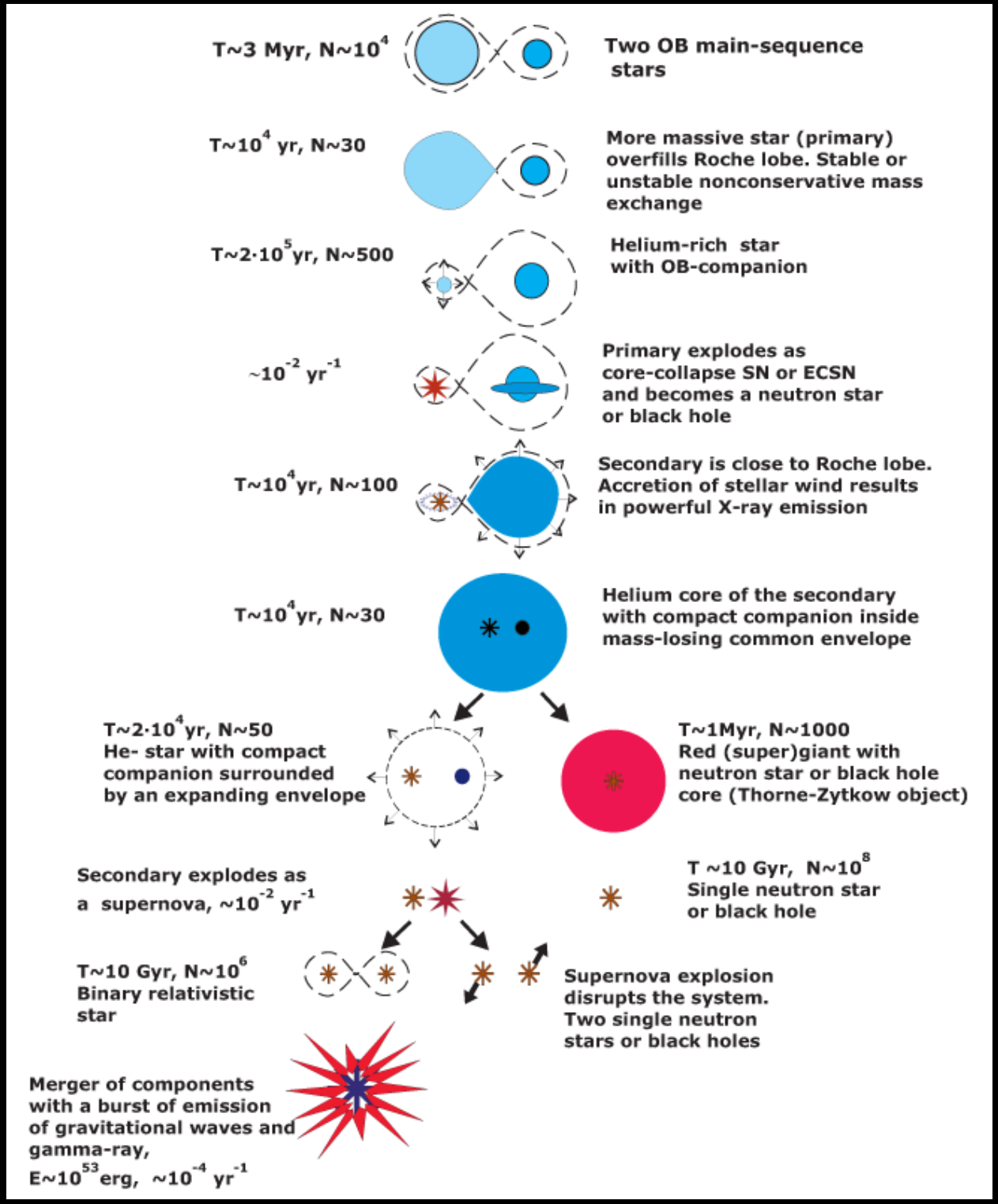
The less massive (larger) white dwarf is disrupted with in one final orbit and acrreted by the more massive one. Explosion starts when approaching the Chandrasekhar limit.

SN results (revisited)



(Heger et al., 2003, ApJ 591, 288, Fig. 1)

SN result depends on metallicity and initial stellar mass



(Postnov & Yungelson, 2014, Living Rev. Relativity 17, 3; N: Number of objects in Galaxy)

SN results (revisited)

How do we detect a
NS + NS or NS + BH or BH + BH binary?

Gravitational Waves!

Orders of magnitude

What are gravitational waves?

GW: space-time distortion caused by motion of masses

Analogy to electro magnetism:

- Static field:
  - Radial and transversal components
  - Decreases as r^{-n}, $n \geqslant 2$ possible
- Radiation:
  - Only transversal component
  - Decreases as r^{-1}

$\Longrightarrow$ In the “far field” radiation dominates

Orders of magnitude

Electromagnetism:

- Monopole terms: q: charge

$$E \propto \frac{q}{r^2} \quad , \quad \frac{\dot{q}}{r} \tag{3.3}$$

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- Dipole-Term: $P = \sum q_i s_i$

$$E \propto \frac{P}{r^3} \quad , \quad \frac{\dot{P}}{r^2} \quad , \quad \frac{\ddot{P}}{r} \tag{3.4}$$

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$\Longrightarrow \ddot{P} \neq 0$: time variable dipole moment produces electromagnetic radiation.

Orders of magnitude

Gravitation: Waves as “tidal forces”

- Monopole term: M: Mass

$$g' \propto \frac{M}{r^3} \quad , \quad \frac{\dot{M}}{r^2} \quad , \quad \frac{\ddot{M}}{r} \tag{3.5}$$

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- dipole term: $P = \sum M_i s_i$

$$g' \propto \frac{P}{r^3} \quad , \quad \frac{\dot{P}}{r^2} \quad , \quad \frac{\ddot{P}}{r} \tag{3.6}$$

Orders of magnitude

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$$g' \propto \frac{M}{r^3} \quad , \quad \cancel{\frac{\dot{M}}{r^2}} \quad , \quad \cancel{\frac{\ddot{M}}{r}} \tag{3.5}$$

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$$g' \propto \frac{P}{r^3} \quad , \quad \frac{\dot{P}}{r^2} \quad , \quad \cancel{\frac{\ddot{P}}{r}} \tag{3.6}$$

but conservation of momentum:

$$\ddot{P} = \sum M_i \ddot{r}_i = \sum M_i a_i = 0 \tag{3.7}$$

No dipole radiation possible!

Orders of magnitude

- Quadrupole-Term: quadrupole moment $I = \sum M_i s_i \otimes s_i$ (quadratic in s)

$$g' \propto \frac{I}{r^5} \quad , \quad \frac{\dot{I}}{r^4} \quad , \quad \frac{\ddot{I}}{r^3} \quad , \quad \frac{\dddot{I}}{r^2} \quad , \quad \frac{\ddddot{I}}{r} \tag{3.8}$$

A time dependent quadrupole moment can produce gravitational waves.

Orders of magnitude: $\ddddot{I}$ contains terms such as

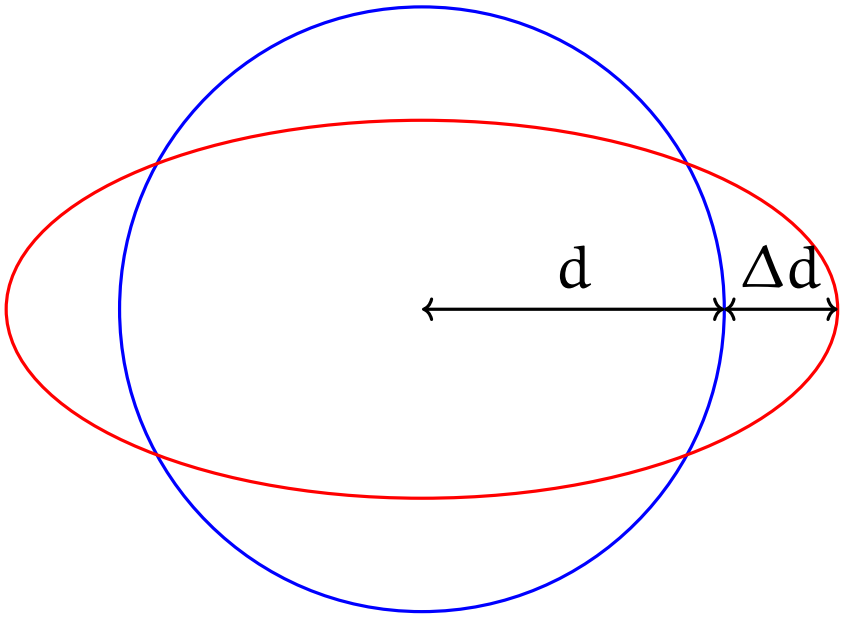
$s\frac{\partial^2 a}{\partial T^2} \sim s\frac{s}{T^2}\frac{1}{T^2} = \frac{s^2}{T^4}, \quad v\frac{\partial a}{\partial T} = \frac{s}{T}\frac{a}{T^2}\frac{1}{T} = \frac{s^2}{T^4}, \quad a^2 = \left(\frac{s}{T^2}\right)^2 = \frac{s^2}{T^4}$

For a periodic system: terms are $\propto s^2/T^4$.

Therefore amplitude scales as

$$g' \propto \frac{1}{r} \cdot \frac{GM}{c^4} \cdot \frac{s^2}{T^4} = \frac{1}{r} \cdot \frac{GM}{c^4} \cdot s^2 f^4 \tag{3.9}$$

Orders of magnitude



Gravitational waves:
g' is gradient of gravitation
$\Longrightarrow$ difference in gravitational acceleration between two points with distance d is $g'd$.
Therefore

- velocity difference of the points: $\int d \cdot g' \, dt$
- displacement of the points: $\Delta d = \iint d \cdot g' \, d^2t$:

Define strain:

$$h = 2 \iint g' d^2t \sim 2\frac{\Delta d}{d} \tag{3.10}$$

Extra factor 2 will simplify life later

Orders of magnitude

Order of magnitude for the strain:

$$h = 2\iint g' d^2t \sim \frac{2}{r}\frac{GM}{c^4}s^2 f^4 T^2 = \frac{1}{r}\frac{2GM}{c^4}s^2\left(\frac{1}{T}\right)^2 = \frac{1}{r}\frac{2GM}{c^2}\left(\frac{v}{c}\right)^2 \quad (3.11)$$

Orders of magnitude

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typical distances: $$r = \text{kpc} \ldots \text{Mpc} = 3 \times 10^{21\ldots24}\,\text{cm} \quad (3.12)$$

mass term: $$\frac{2GM}{c^2} = 3\,\text{km}\frac{M}{M_\odot} \quad (3.13)$$

velocity (Kepler): $$\frac{v}{c} = \frac{1}{c}\sqrt{\frac{GM}{s}} = 10^{-4}\left(\frac{M}{M_\odot}\right)^{1/2}\left(\frac{s}{1\,\text{AU}}\right)^{-1/2} \quad (3.14)$$

Orders of magnitude

Order of magnitude for the strain:

$$h = 2\iint g' d^2t \sim \frac{2}{r}\frac{GM}{c^4} s^2 f^4 T^2 = \frac{1}{r}\frac{2GM}{c^4} s^2 \left(\frac{1}{T}\right)^2 = \frac{1}{r}\frac{2GM}{c^2}\left(\frac{v}{c}\right)^2 \tag{3.11}$$

typical distances: $$r = \text{kpc} \ldots \text{Mpc} = 3 \times 10^{21\ldots24}\,\text{cm} \tag{3.12}$$

mass term: $$\frac{2GM}{c^2} = 3\,\text{km}\frac{M}{M_\odot} \tag{3.13}$$

velocity (Kepler): $$\frac{v}{c} = \frac{1}{c}\sqrt{\frac{GM}{s}} = 10^{-4}\left(\frac{M}{M_\odot}\right)^{1/2}\left(\frac{s}{1\,\text{AU}}\right)^{-1/2} \tag{3.14}$$

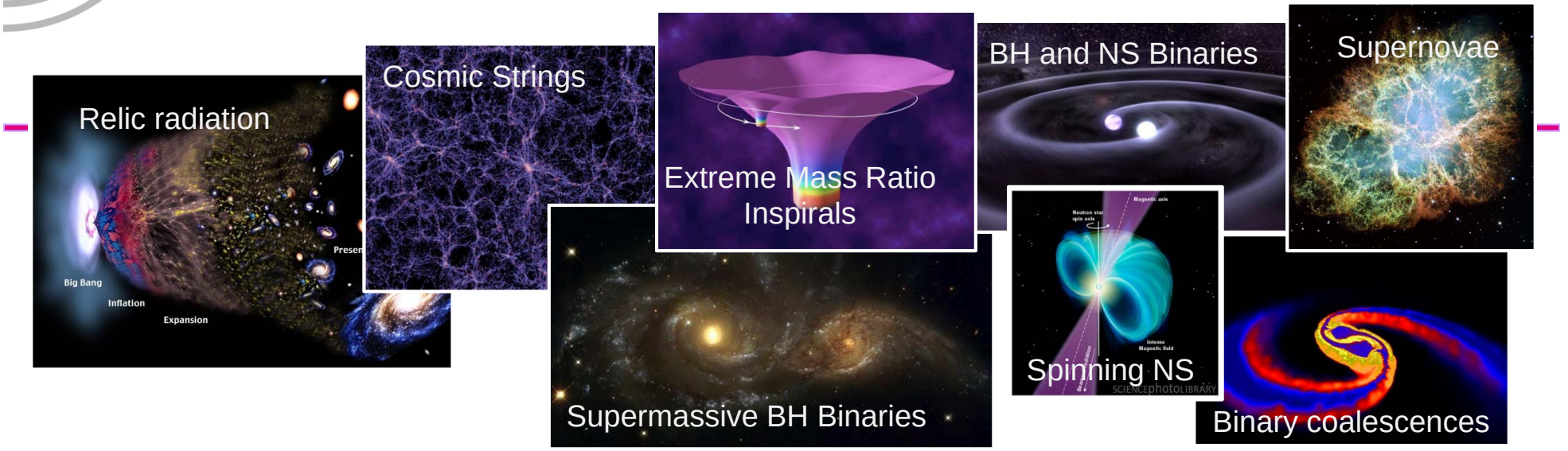
$$h = 10^{-28}\left(\frac{M}{1\,M_\odot}\right)^2\left(\frac{s}{1\,\text{AU}}\right)^{-1}\left(\frac{r}{1\,\text{kpc}}\right)^{-1} \tag{3.15}$$

very small: change of Earth's diameter: $\Delta d = 10^{-28} \cdot 6300\,\text{km} \cdot 2 \sim 10^{-21}\,\text{m}$ (nucleus: $10^{-15}\,\text{m}$)

$\Longrightarrow$ we need: large mass, *very* small systems ($s \sim$ km, not AU)!

$\Longrightarrow$ compact objects!

The GW Spectrum



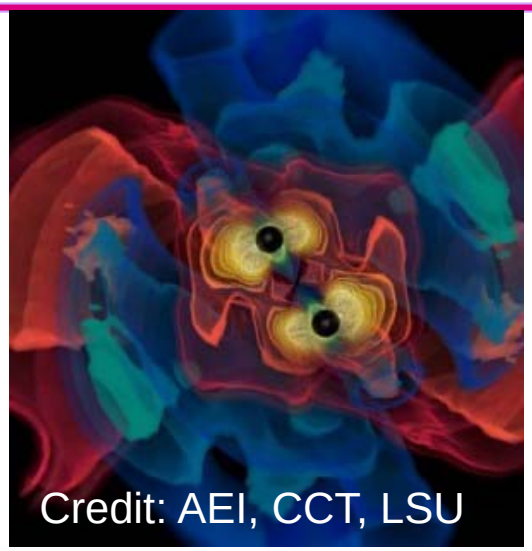


10^{-16} Hz | 10^{-9} Hz | 10^{-4} Hz | 10^{0} Hz | 10^{3} Hz

Inflation Probe | Pulsar timing | Space detectors | Ground interferometers

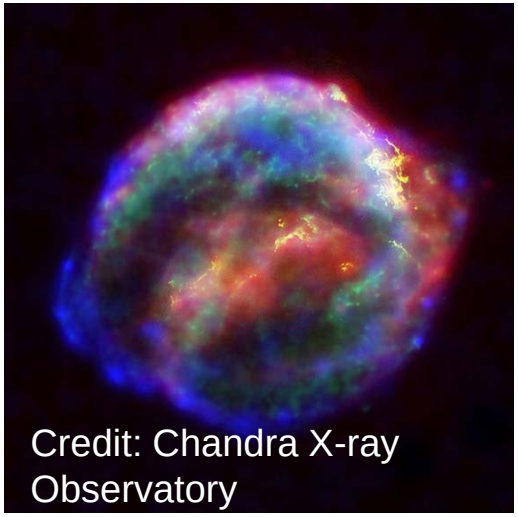


GW sources for ground-based detectors: The most energetic processes in the universe



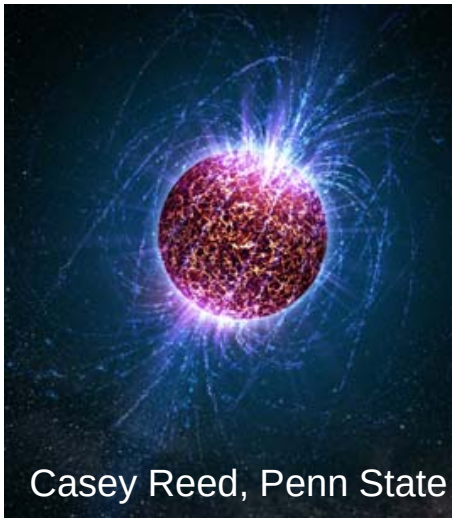
Coalescing Compact Binary Systems: Neutron Star-NS, Black Hole-NS, BH-BH

- Strong emitters, well-modeled,
- (effectively) transient



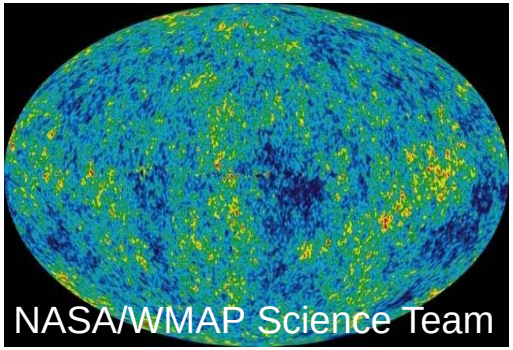
Asymmetric Core Collapse Supernovae

- Weak emitters, not well-modeled ('bursts'), transient
- Cosmic strings, soft gamma repeaters, pulsar glitches also in 'burst' class



Spinning neutron stars

- (effectively) monotonic waveform
- Long duration



Cosmic Gravitational-wave Background

- Residue of the Big Bang, long duration
- Long duration, stochastic background

Indirect detection

Orbital energy in a binary

$$E_{orb} \sim -G\frac{\mu M}{2r} \tag{3.16}$$

where the reduced mass $\mu = M_1 M_2/(M_1 + M_2)$.

Radiated power in gravitational wave:

$$L_{GW} \sim \frac{32}{5}\frac{c^5}{G}\left(\frac{\mu}{M}\right)^2\left(\frac{GM}{c^2 s}\right)^5 \tag{3.17}$$

Therefore change of distance:

$$\frac{dr}{dt} = -\frac{L_{GR}}{dE(r)/dr} \tag{3.18}$$

here: r: separation of the objects

Since $dr/dt < 0$: orbital period increases due to radiation of gravitational waves.

More precise equations for the radiation of gravitational waves in binary systems were first published by Peters & Mathews (1963, Phys. Rev. 131, 435) and Peters (1964, Phys. Rev. 136, 1224) for a system of two point masses m_1, m_2 moving on an elliptical orbit with eccentricity e and semi-major axis a.

The power radiated per orbital period is

$$\langle P \rangle = -\frac{32}{5}\frac{G^4}{c^5}\frac{m_1^2 m_2^2 (m_1+m_2)}{a^5(1-e^2)^{7/2}}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right) \tag{3.19}$$

The radiation of gravitational waves then leads to a change of a and e (the eccentricity is changed since gravitational waves also transport angular momentum):

$$\left\langle \frac{da}{dt} \right\rangle = -\frac{64}{5}\frac{G^3}{c^5}\frac{m_1 m_2 (m_1+m_2)}{a^3(1-e^2)^{7/2}}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right) \tag{3.20}$$

$$\left\langle \frac{de}{dt} \right\rangle = -\frac{304}{15}e\frac{G^3}{c^5}\frac{m_1 m_2 (m_1+m+2)}{a^4(1-e^2)^{5/2}}\left(1+\frac{121}{304}e^2\right) \tag{3.21}$$

Therefore a system that was initially on a circular orbit ($e = 0$) with an initial orbital radius of $a = a_0$ will change the radius

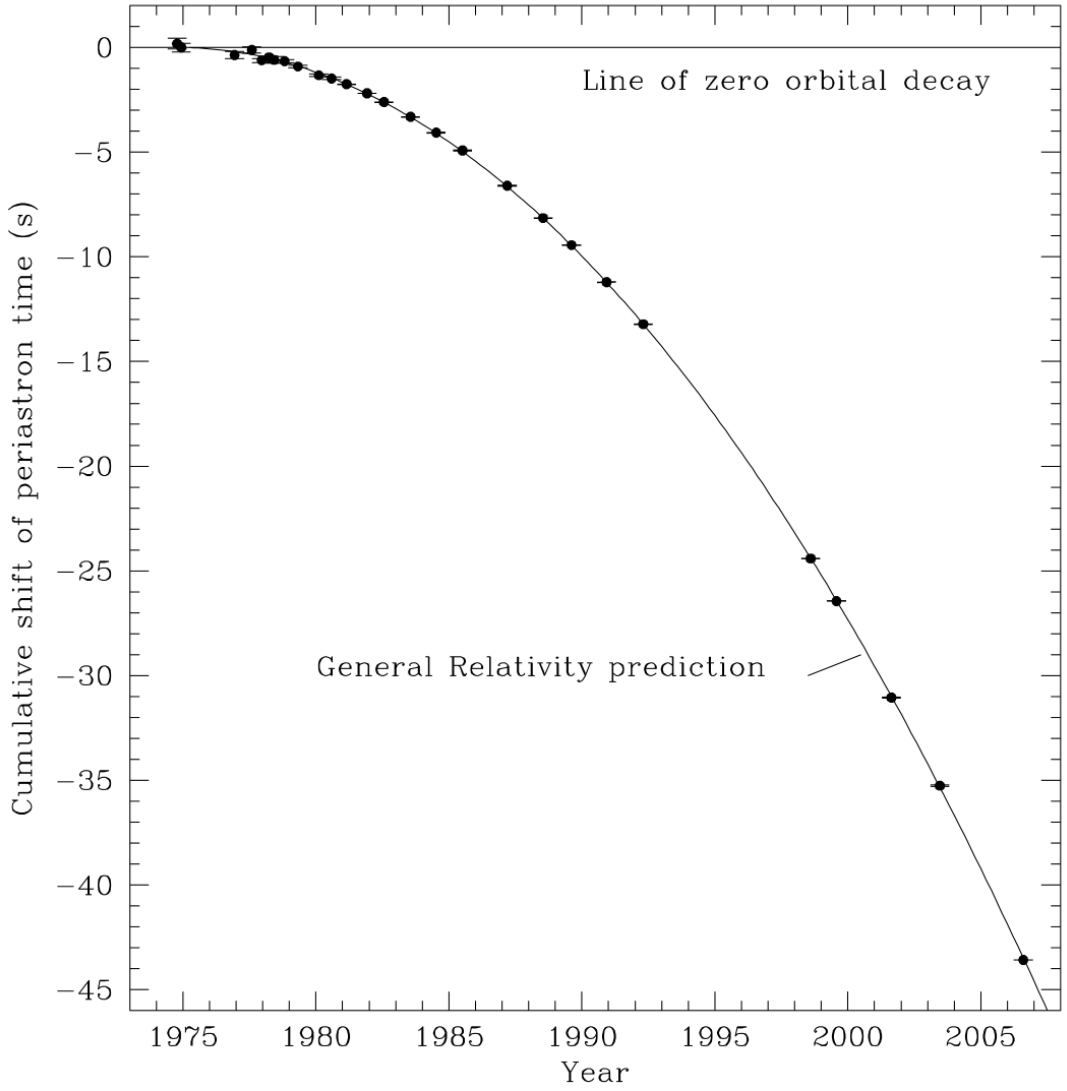
$$a(t) = (a_0 - 4\beta t)^{1/4} \quad \text{where} \quad \beta = \frac{64}{5}\frac{G^3}{c^5} m_1 m_2 (m_1+m_2) \tag{3.22}$$

It will therefore merge in a time

$$T_c(a_0) = \frac{a_0^4}{4\beta} \tag{3.23}$$

For small initial eccentricities e this time is increased by a factor of approximately $e^{2.5}$.

Indirect detection



PSR B1913+16: 1. NS+NS System:
$P_{orb} = 7.75\,h$, $\nu \sin i = 300\,km\,s^{-1}$.
Hulse& Taylor (1975, ApJ, 195, L51)

Change or orbital period completely in agreement with power radiated in gravitational waves. Other explanations can be excluded.

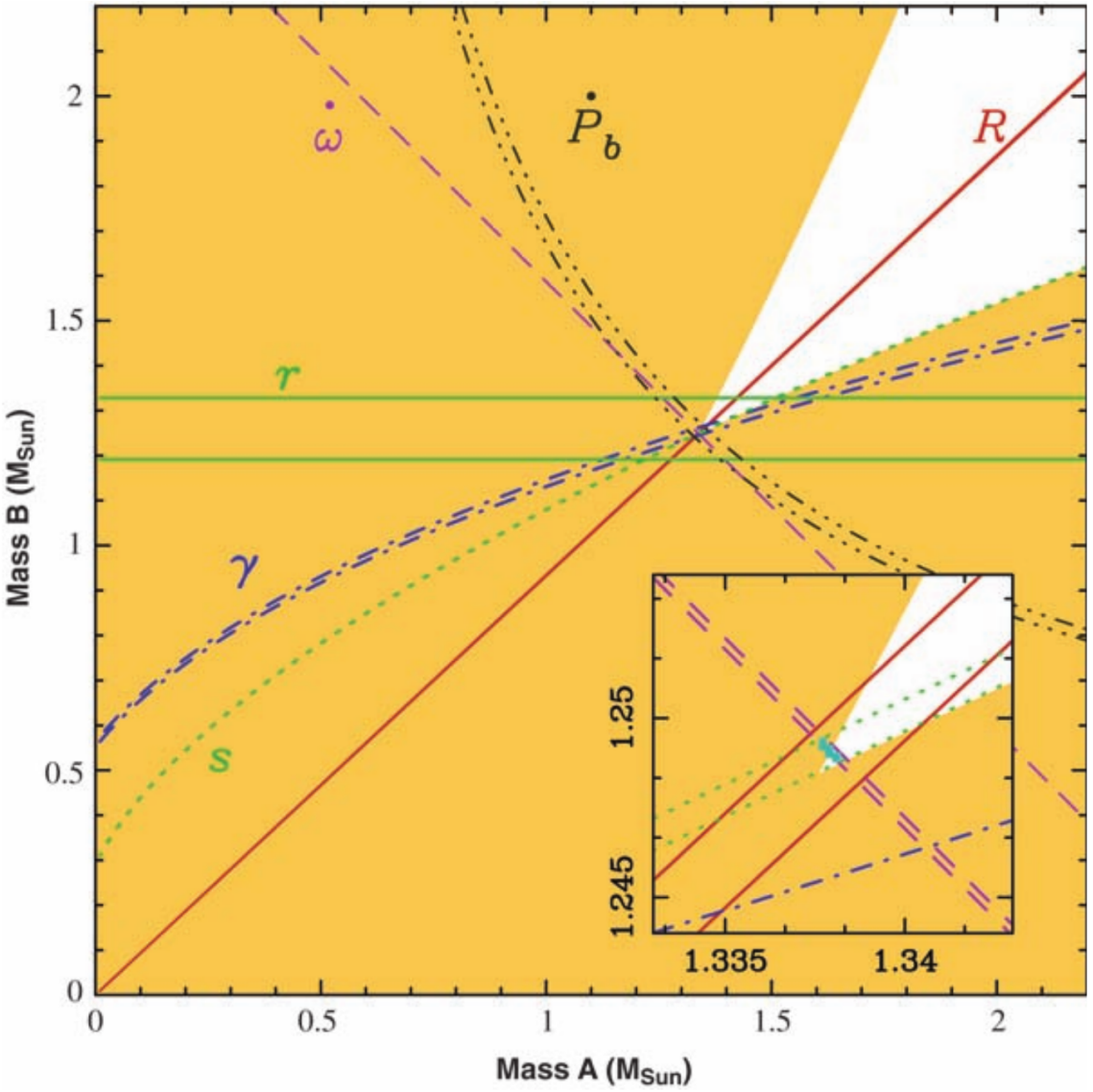
$\Longrightarrow$ indirect detection of gravitational waves

$\Delta a \sim 7\,mm\,d^{-1}$ is in agreement with GR at a level of 0.1%

Nobel Prize 1993: "for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation"

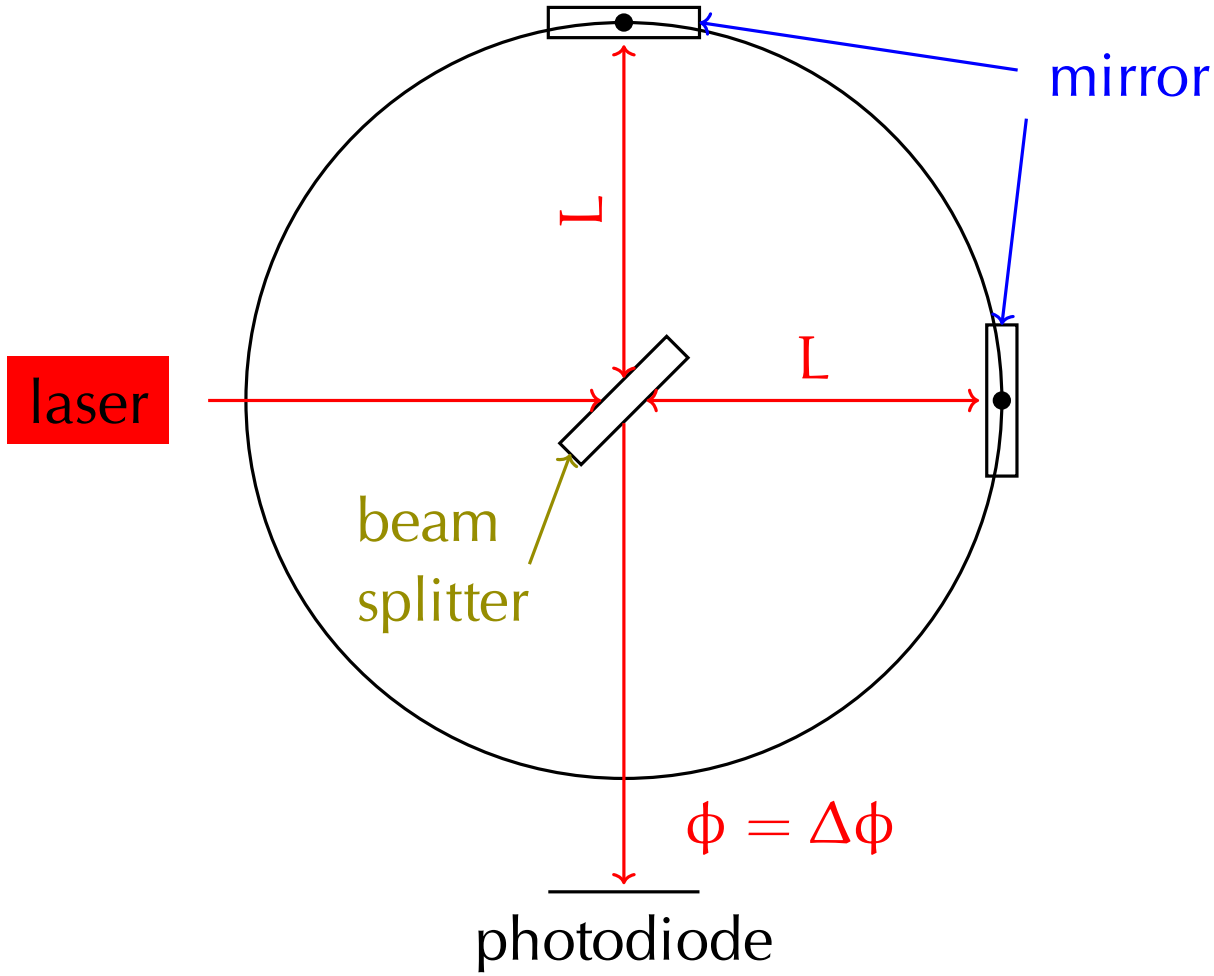
Weisberg et al., 2010, ApJ 722, 1030

Indirect detection



(Kramer et al., 2006, Science 314, 97)

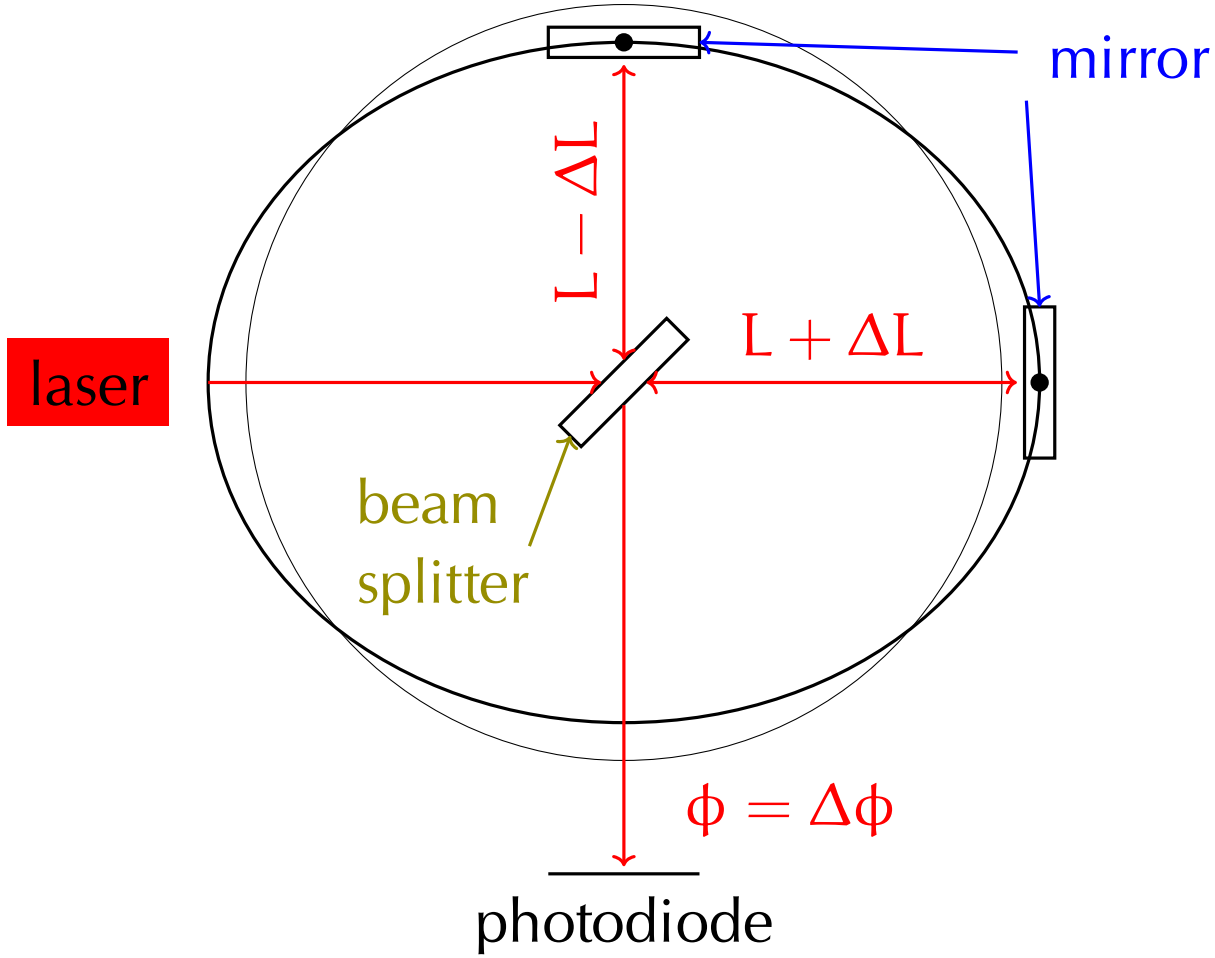
Direct detection



Direct detection: interferometry

$$h = \frac{\Delta L}{L} \quad \Longrightarrow \quad \text{For fixed } \Delta L, \text{ L must be as large as possible!} \tag{3.24}$$

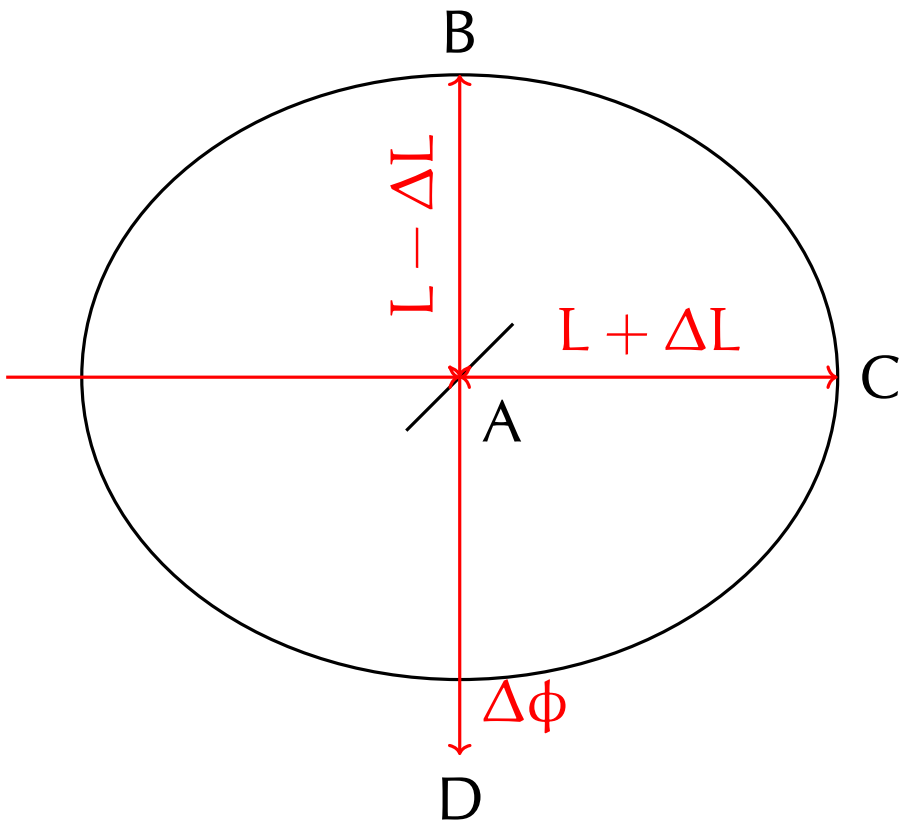
Direct detection



Direct detection: interferometry

$$h = \frac{\Delta L}{L} \quad \Longrightarrow \quad \text{For fixed } \Delta L, \text{ L must be as large as possible!} \tag{3.24}$$

Direct detection



Displacement:

$$\Delta L = hL \tag{3.25}$$

careful: h has implicit factor 2!

Difference in arrival time at D:

$$\Delta t = 2hL/c \tag{3.26}$$

Corresponding a phase difference

$$\Delta\Phi = \frac{2\pi c}{\lambda}\Delta t = h\frac{2L}{c}\frac{2\pi c}{\lambda} \tag{3.27}$$

Relativistic calculation: $\int dt = \frac{1}{c}\int 1 + \frac{h_{11}}{2}dx$ yields identical result

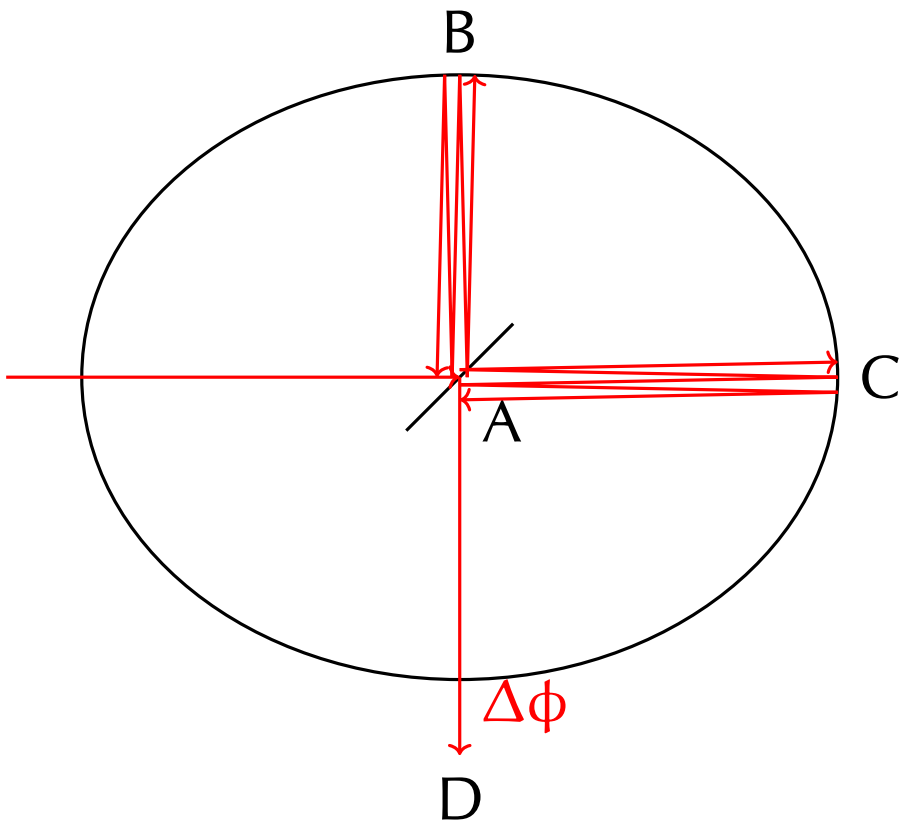
Required precision of measurement for very close NS-NS system (ISCO):

$s = 25.6\,\text{km}$, $v/c = 0.4$, $r = 1\,\text{kpc}$: $h \sim 6 \times 10^{-23}$

$\Longrightarrow$ for $L = 4\,\text{km}$: $\Delta L = hL \sim 2.3 \times 10^{-19}\,\text{m}$ resp. $\Delta\Phi \sim 10^{-13}$ $\Longrightarrow$ too small.

(reminder: atomic nucleus: $10^{-15}\,\text{m}$)

Direct detection



Displacement:

$$\Delta L = hL \tag{3.25}$$

careful: h has implicit factor 2!

Difference in arrival time at D:

$$\Delta t = 2hL/c \tag{3.26}$$

Corresponding a phase difference

$$\Delta\Phi = \frac{2\pi c}{\lambda}\Delta t = h\frac{2L}{c}\frac{2\pi c}{\lambda} \tag{3.27}$$

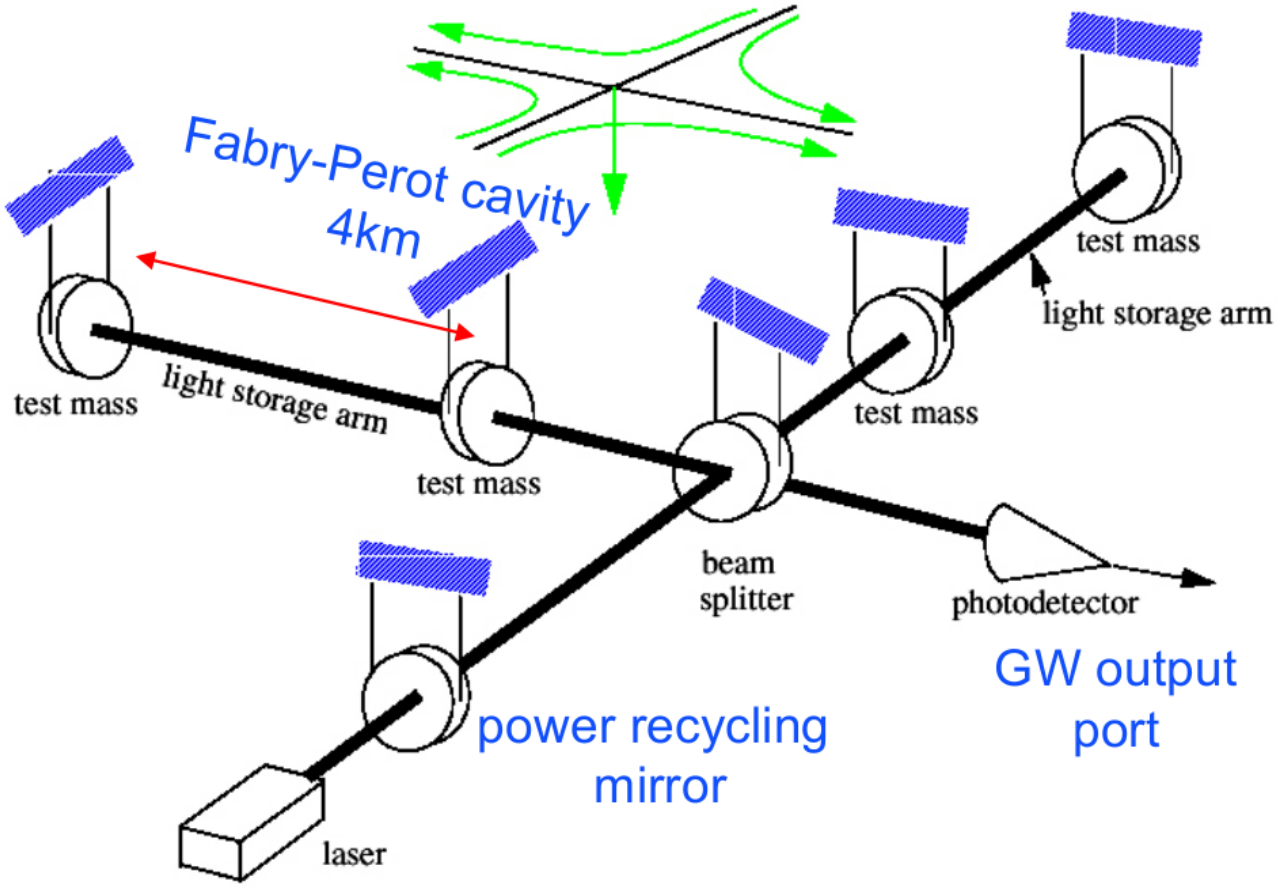
Relativistic calculation: $\int dt = \frac{1}{c}\int 1 + \frac{h_{11}}{2}dx$ yields identical result

Solution: pass N times through A–B, A–C (Fabry-Pérot Interferometer)

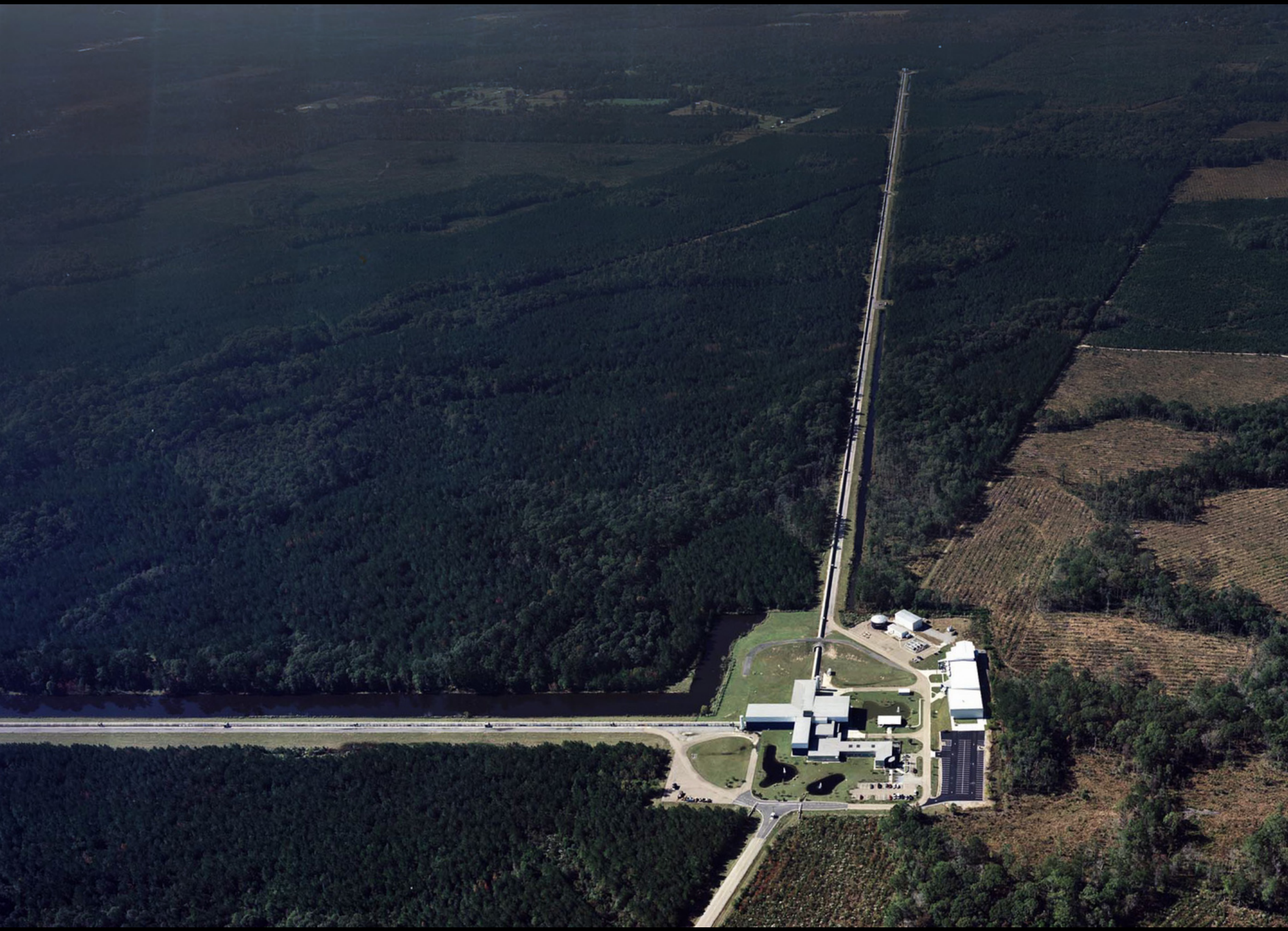
Possible as long as $h \sim$ const., i.e. $\Delta t \ll$ characteristic time scale of change of h (otherwise need to consider $h(t)$ in calculation...)

N can be chosen large enough such that $\Delta\Phi$ can be measured.

Direct detection

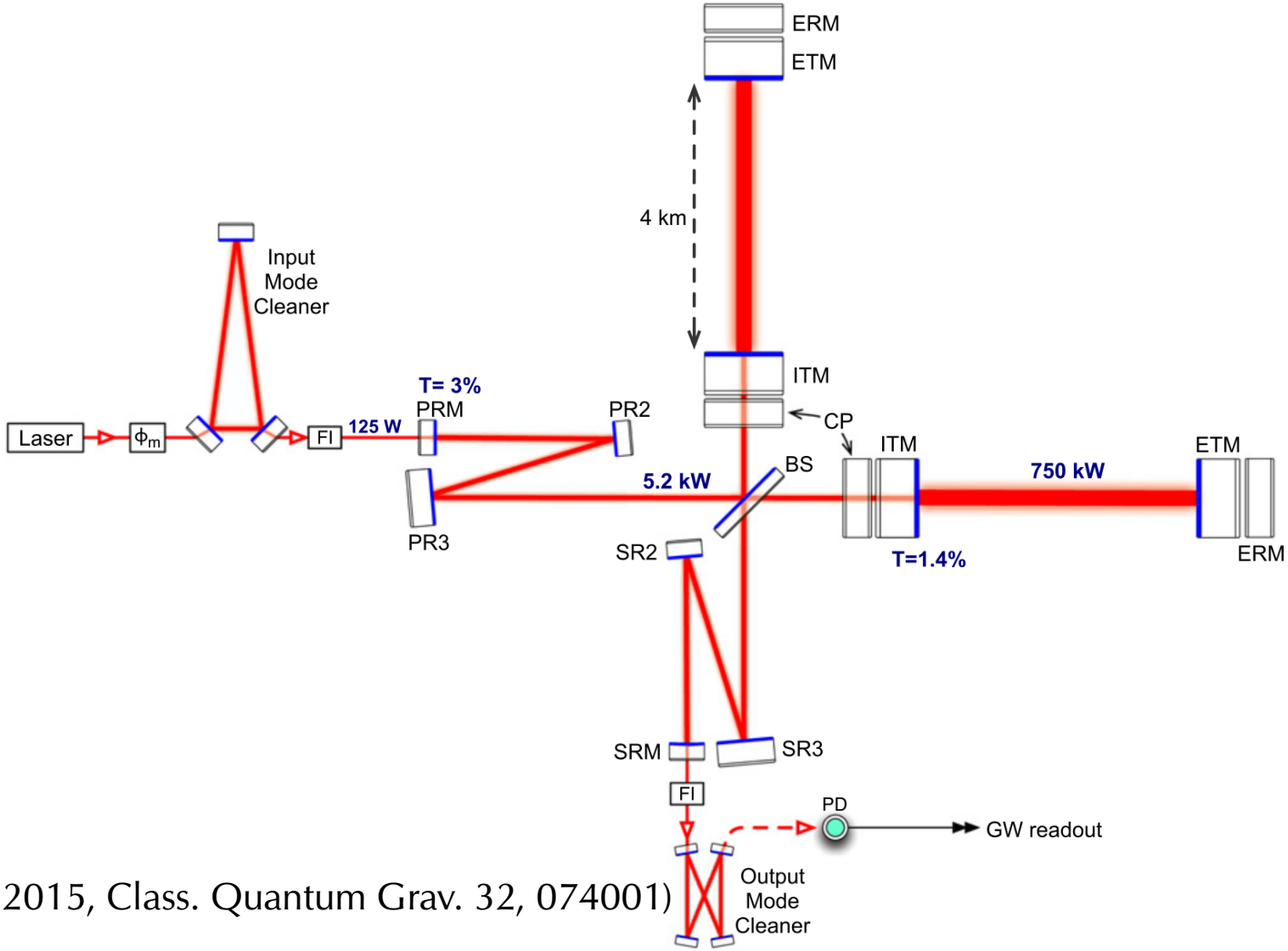


In real life: separate Fabry-Pérot and beam splitter



LIGO

Direct detection

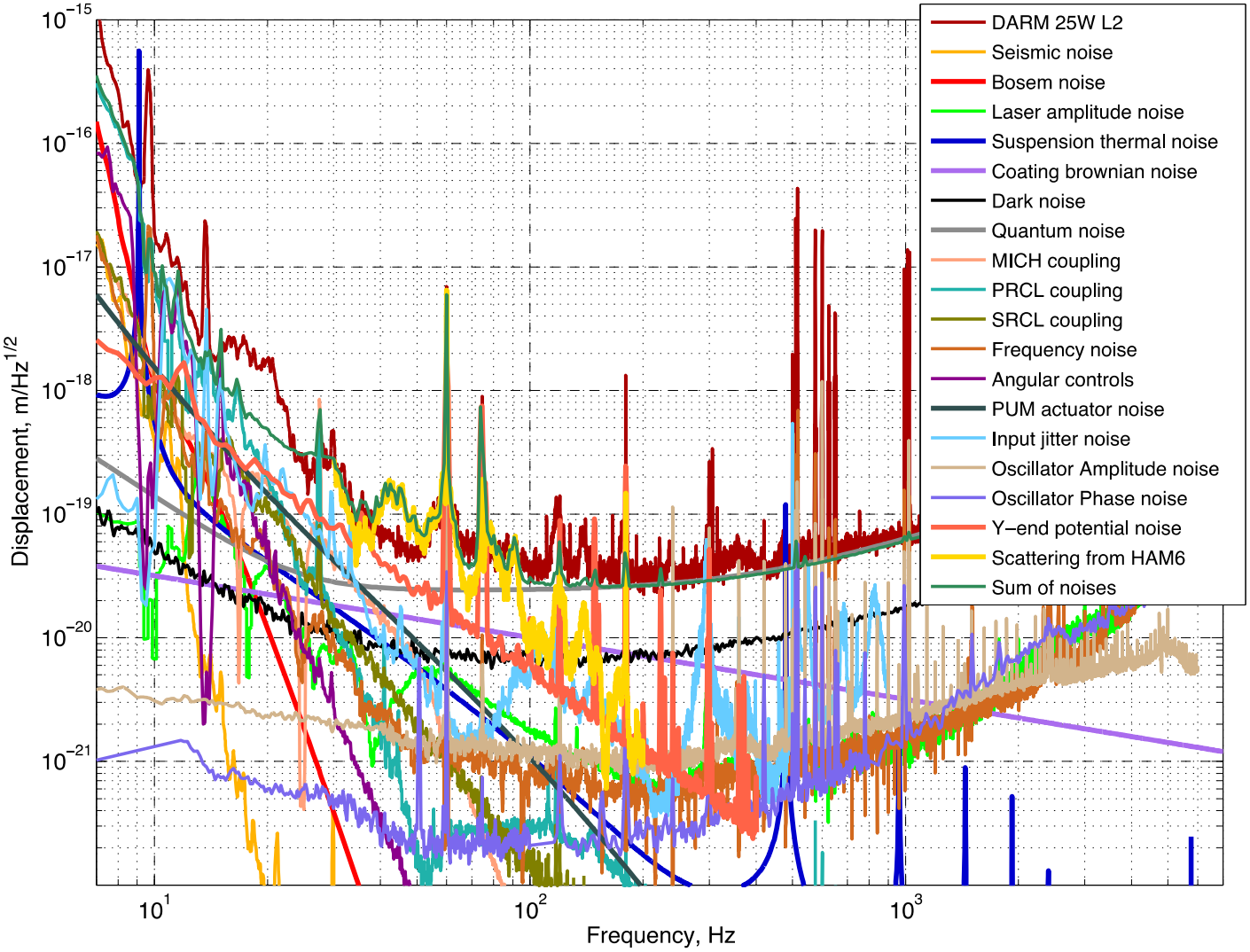


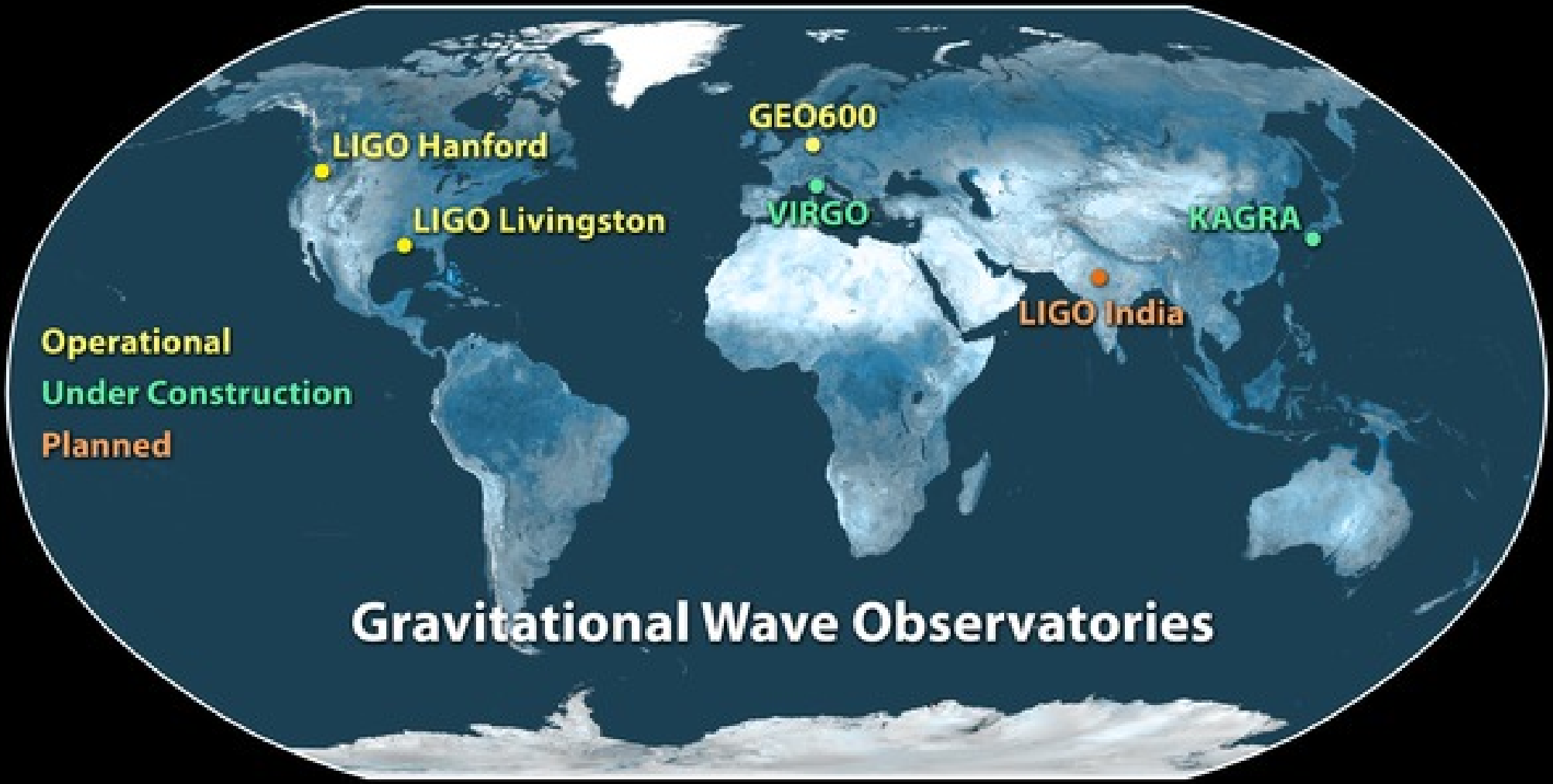
(Aasi et al., 2015, Class. Quantum Grav. 32, 074001)

More detailed structure: optimized with respect to basic principle

LLO noise model

- Many anticipated noise sources
- Explains most current limitations to performance
- Many susceptible to improvement through controls modifications
- Some require changes in vacuum





∃ large network of GW observatories

Inspiral

Radiation of GW once system is very close:

Quadrupole solution for $f = f_{orb}$:

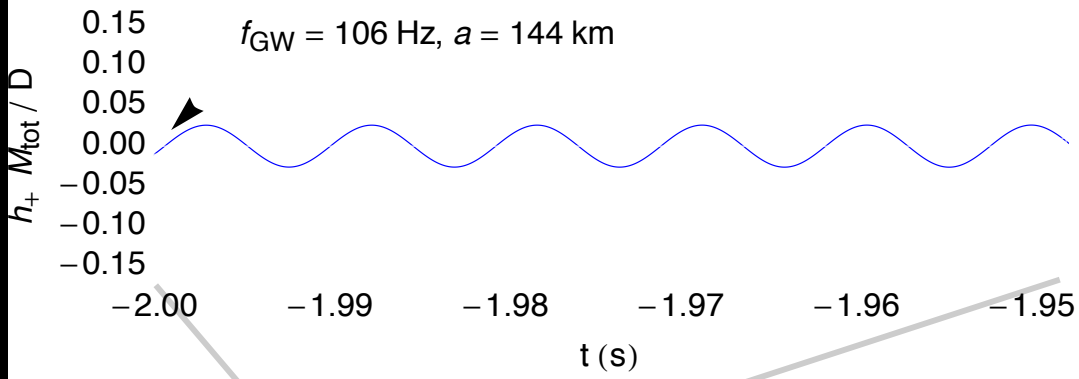
$$h(t) = h_0 \cos\phi(t) \quad \text{wo} \quad \phi(t) = 2\pi\left(ft + \frac{1}{2}\dot{f}t^2\right) + \phi_0 \tag{3.28}$$

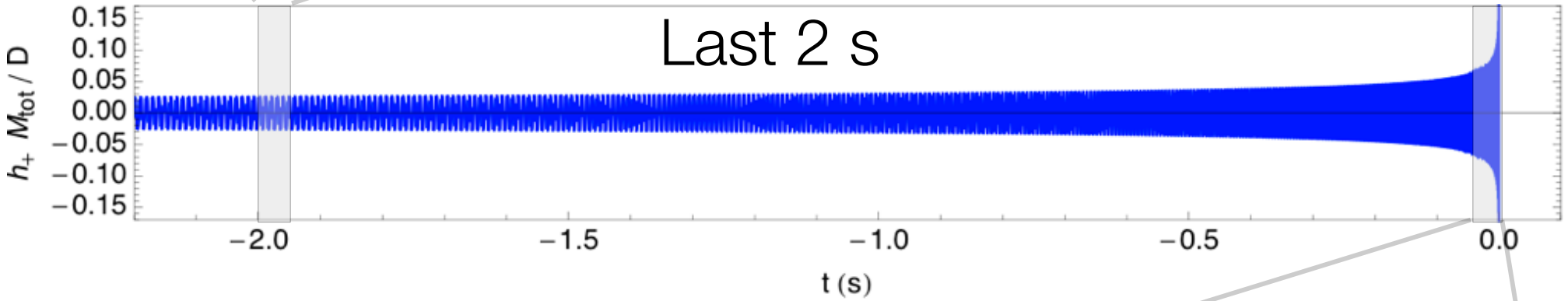
where

"chirp Mass": $$M_c = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} \tag{3.29}$$

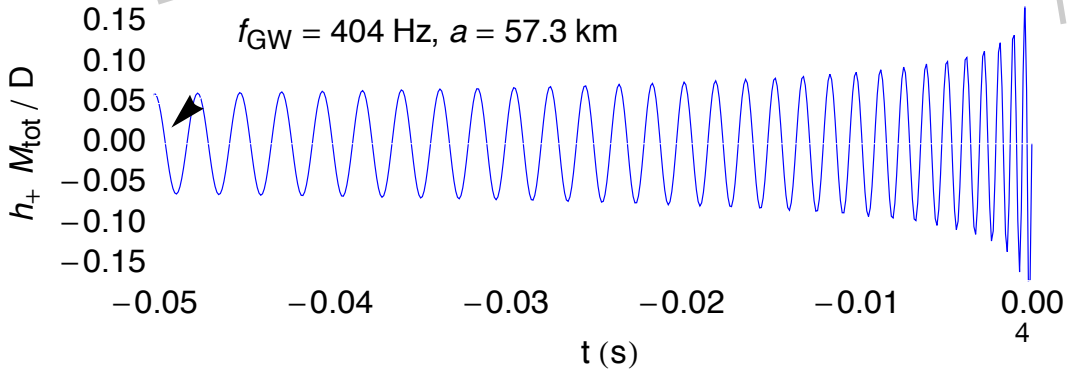
Amplitude: $$h_0 = 4\frac{GM}{c^4 r}\left(G\pi f M\right)^{2/3} \tag{3.30}$$

chirp: $$\dot{f} = \frac{96}{5}\frac{c^3}{G}\frac{f}{M}\left(\frac{G}{c^3}\pi f M\right) \tag{3.31}$$





Last 0.05 s



J. Read, CGWAS 2015

Inspiral

astrophysical application: signal yields $\dot{f}$ and h_0

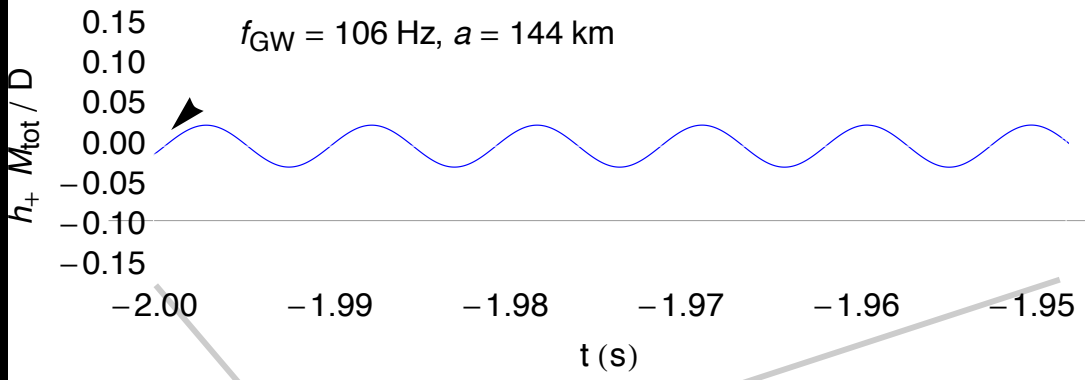
But then: can determine chirp mass:

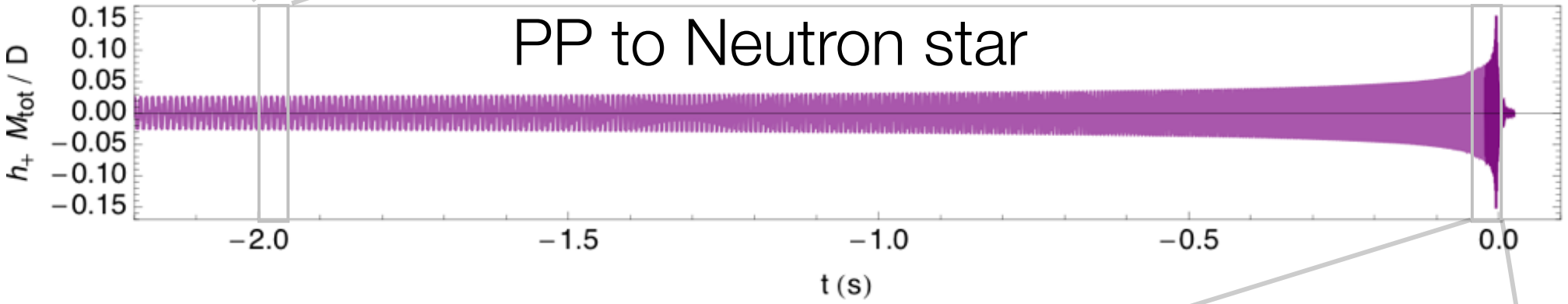
$$M = \frac{c^3}{G}\left(\frac{5}{96}\pi^{-8/3} f^{-11/3}\dot{f}\right)^{3/5} \tag{3.32}$$

Combine M with amplitude to yield distance of source:

$$r = \frac{5}{96\pi^2}\frac{c}{h_0}\frac{\dot{f}}{f^3} \tag{3.33}$$

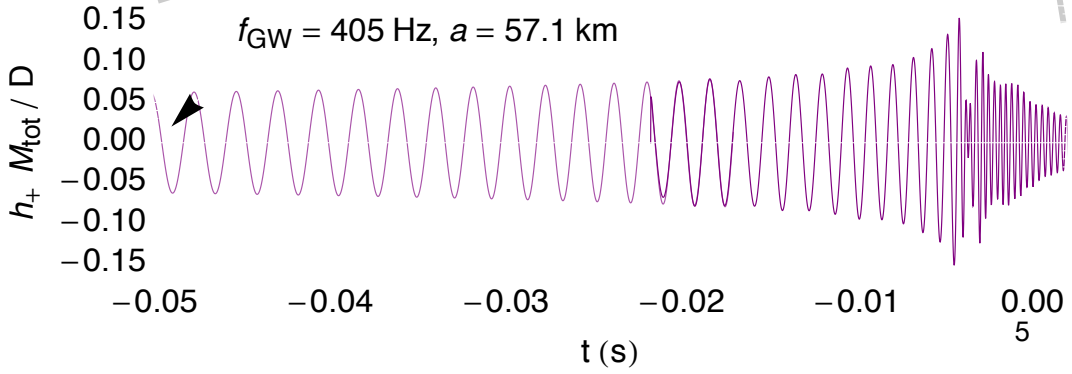
$\Longrightarrow$ independent of other astrophysical assumptions



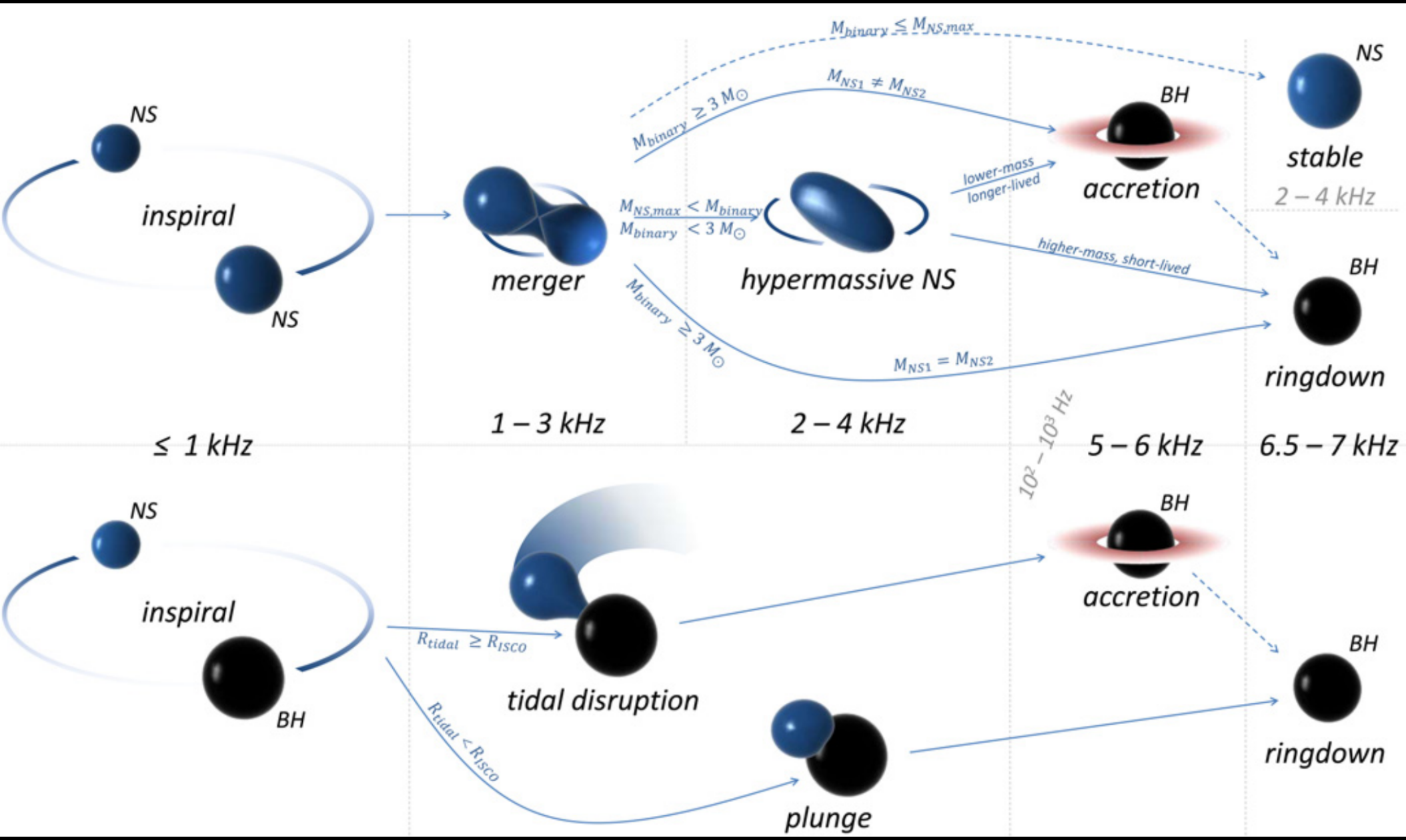


PP to Neutron star

Numerical simulation required for the last orbits



J. Read, CGWAS 2015

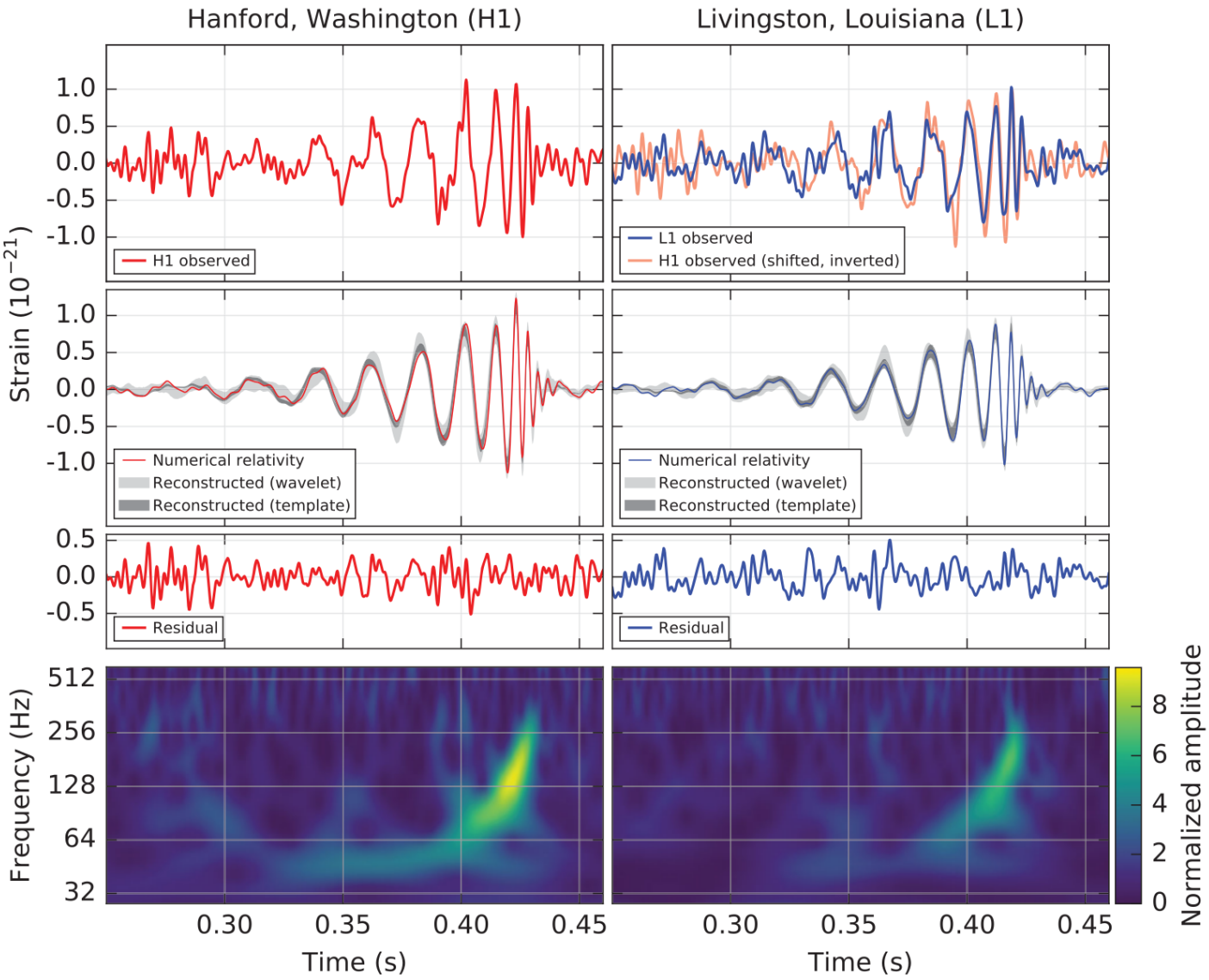


Bartos (2013, Class. Quantum Grav. 30, 123001)

Time before merger is astrophysically very interesting, but requires numerical simulations ("Templates").

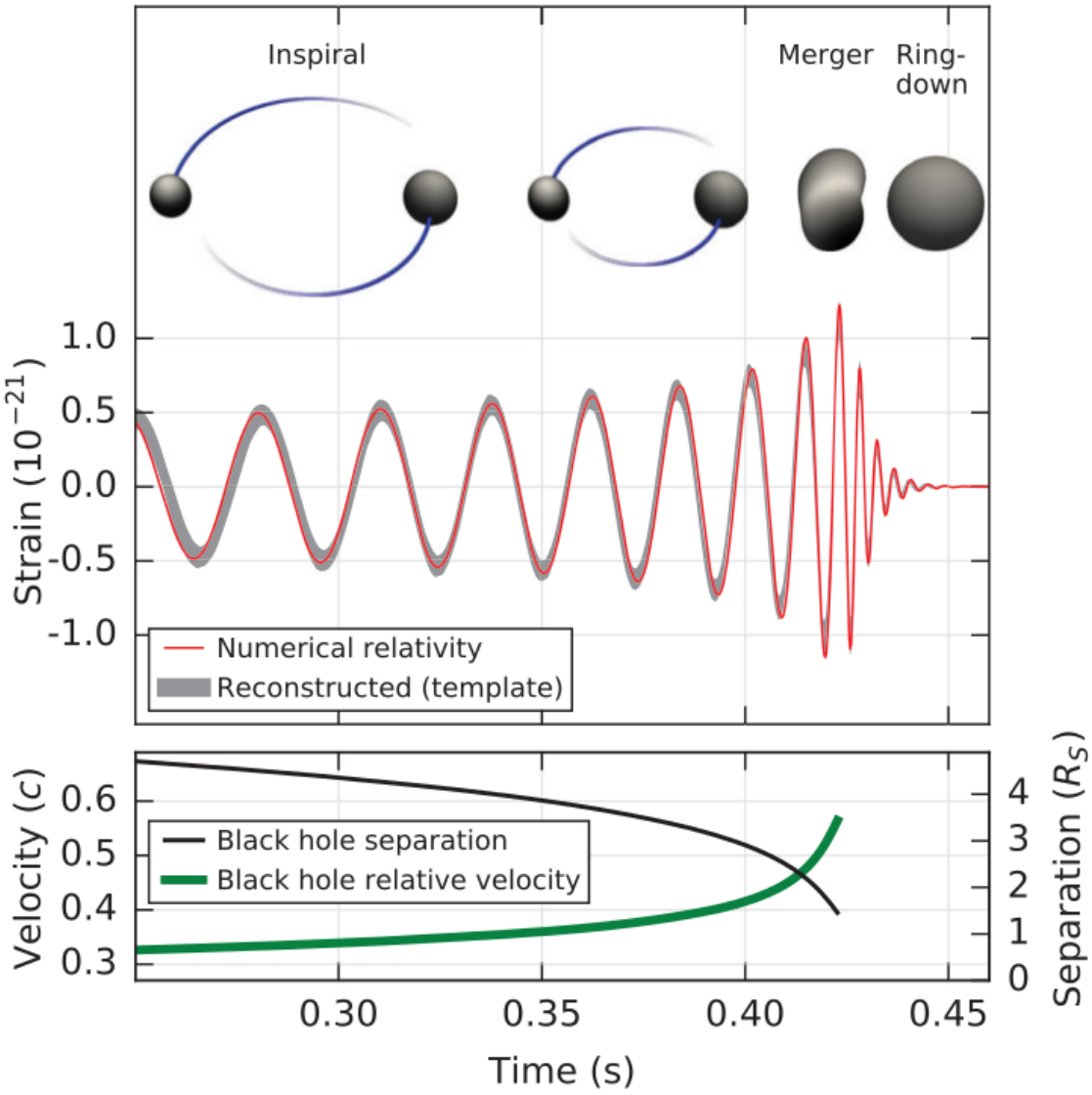
This is where astrophysics can be done with GWs

GW150914



(Abbott et al., 2016, PRL 116, 061102)

GW150914



Chirp properties: f increases in 0.2 s from 35 to 150 Hz

Modeling signal yields chirp mass of $M_c = 30\,M_\odot$

$\Longrightarrow m_1 + m_2 \gtrsim 70\,M_\odot$

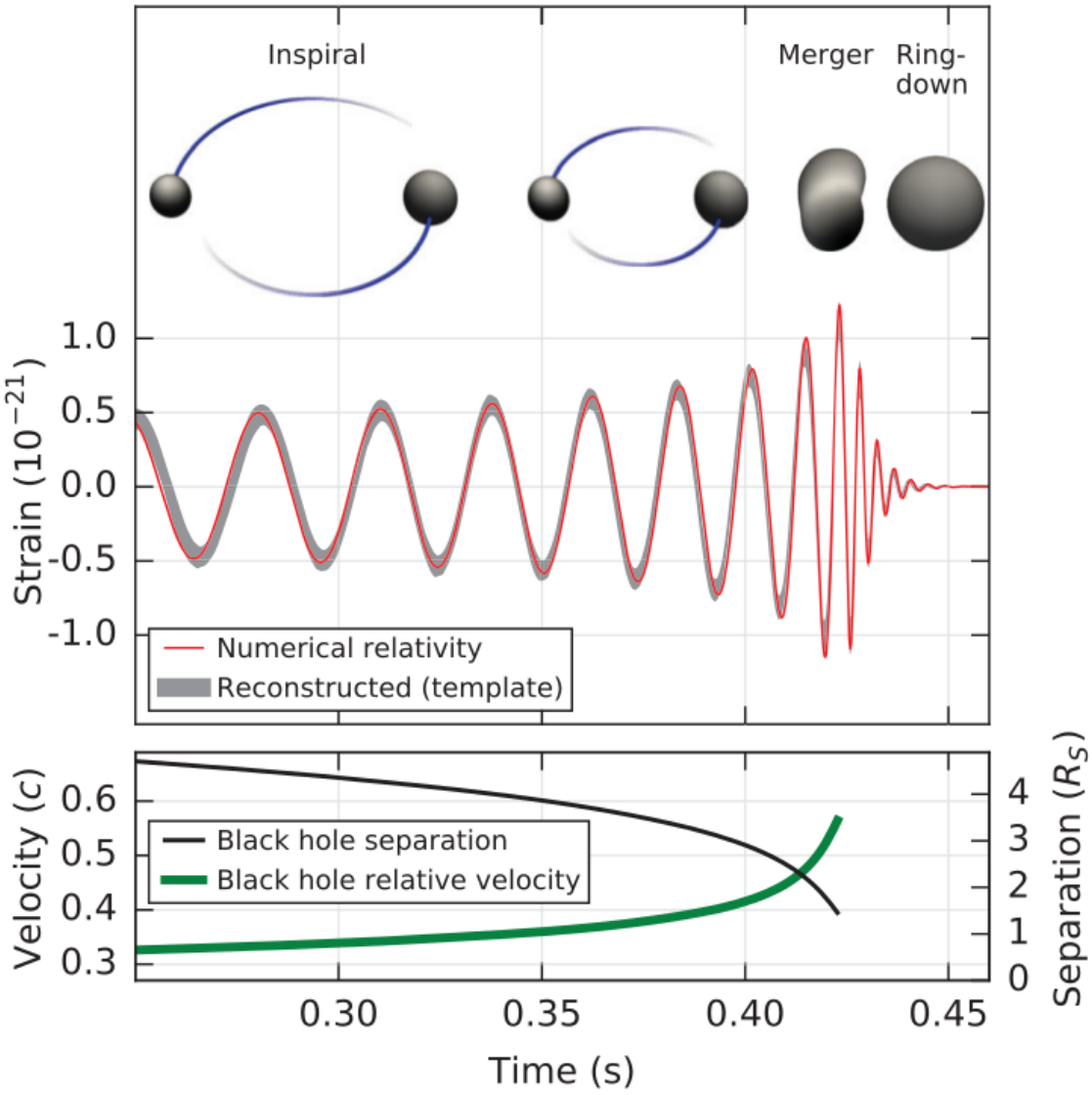
Final orbital frequency: 75 Hz

$\Longrightarrow$ system must have been *very* close (Newton: 350 km)

Only possible with BH + BH merger!

(Abbott et al., 2016, PRL 116, 061102)

GW150914



Detailed modeling:

Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

total radiated energy:
$3.0 \pm 0.5 M_\odot c^2$,
maximum luminosity
$L = 3.6^{+0.5}_{-0.4} \times 10^{56}\,\mathrm{erg\,s^{-1}}$

(Abbott et al., 2016, PRL 116, 061102)

Astrophysical Consequences

Currently: 10 BH-BH mergers, 1 NS-NS-merger (GW 170817)

Although astrophysically not predicted: $\exists$ BH + BH-systems with masses $> 20\,M_\odot$

But good $\Longrightarrow$ large signal!
Normally: Signal ~ Noise $\Longrightarrow$ *much* more complicated measurement $\Longrightarrow$ "matched filtering".

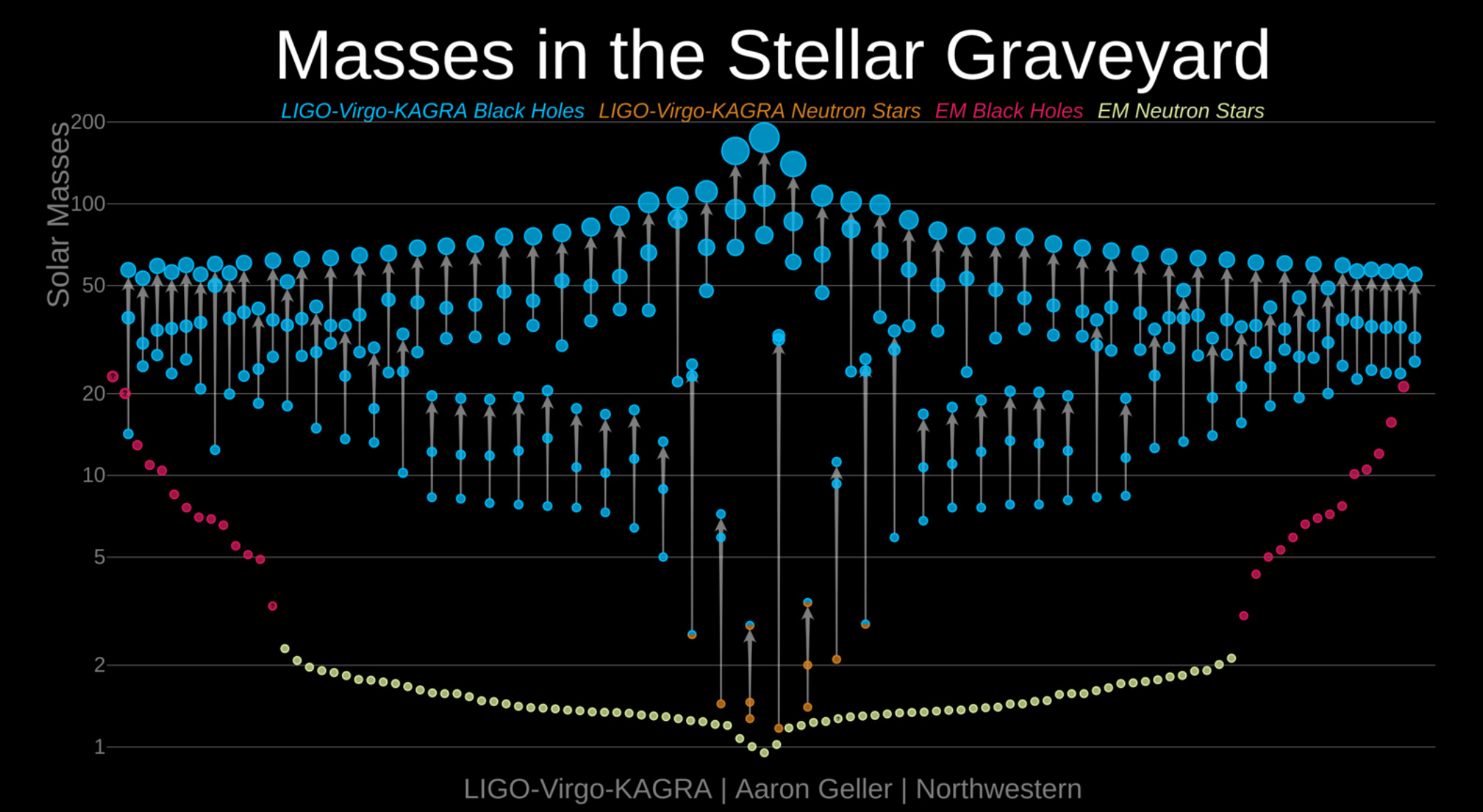
$\Longrightarrow$ Only possible with stars with very low metallicity, i.e., first generation

Large Z: strong winds $\Longrightarrow$ mass los before SN-explosion

Table 1. Rates for sources of interest for GW searches. For binary mergers, a range of possible rates is given, following the detailed discussion in [46]. Detection rates with advanced GW detectors are also given (based on [46]). For core-collapse SNe (CCSNe), the rate range represents the local rate (lower limit, $z \approx 0$) and a more distant rate (upper limit, $z \approx 1$).

Source	Rate ($\mathrm{Gpc^{-3}\ yr^{-1}}$)	GW detection rate ($\mathrm{yr^{-1}}$)	Ref.
NS–NS	$10 - 10^4$	0.4–400	[44–46]
BH–NS	$0.6 - 10^3$	0.2–300	[226, 46]
Short GRB	$\sim 10^3$		[227]
Long GRB	~ 30		[228]
LL GRB	$10^2 - 10^3$		[229]
SN Ibc	2×10^4		[229]
CCSN	$7 \times 10^4 - 7 \times 10^5$		[230]

Bartos (2013, Class. Quantum Grav. 30, 123001)


Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

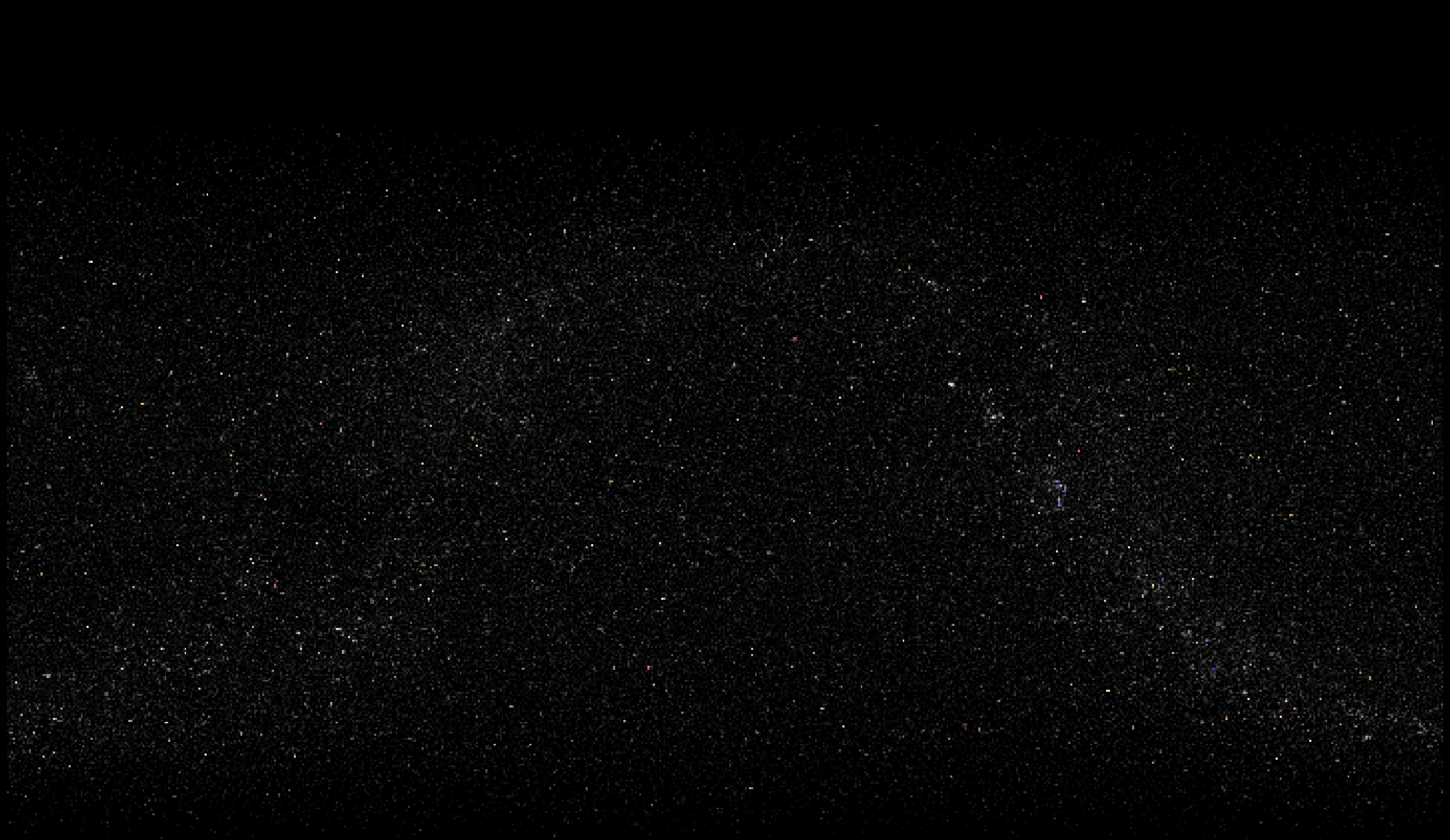
The Galaxy


(c)WallyPacholka / AstroPics.com



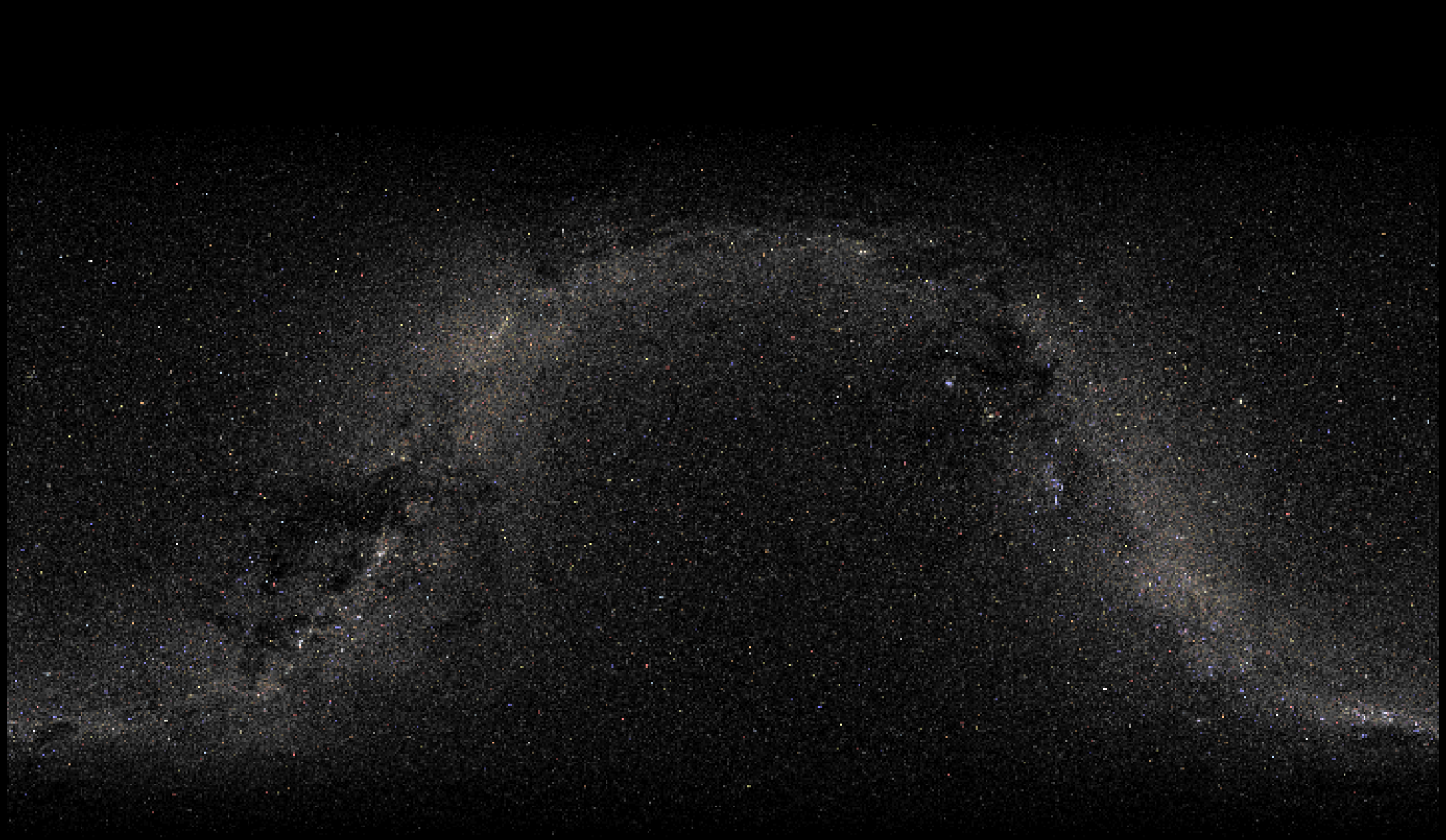
D.Seal/JPL

The Yale Bright Star Catalogue (9110 brightest stars)



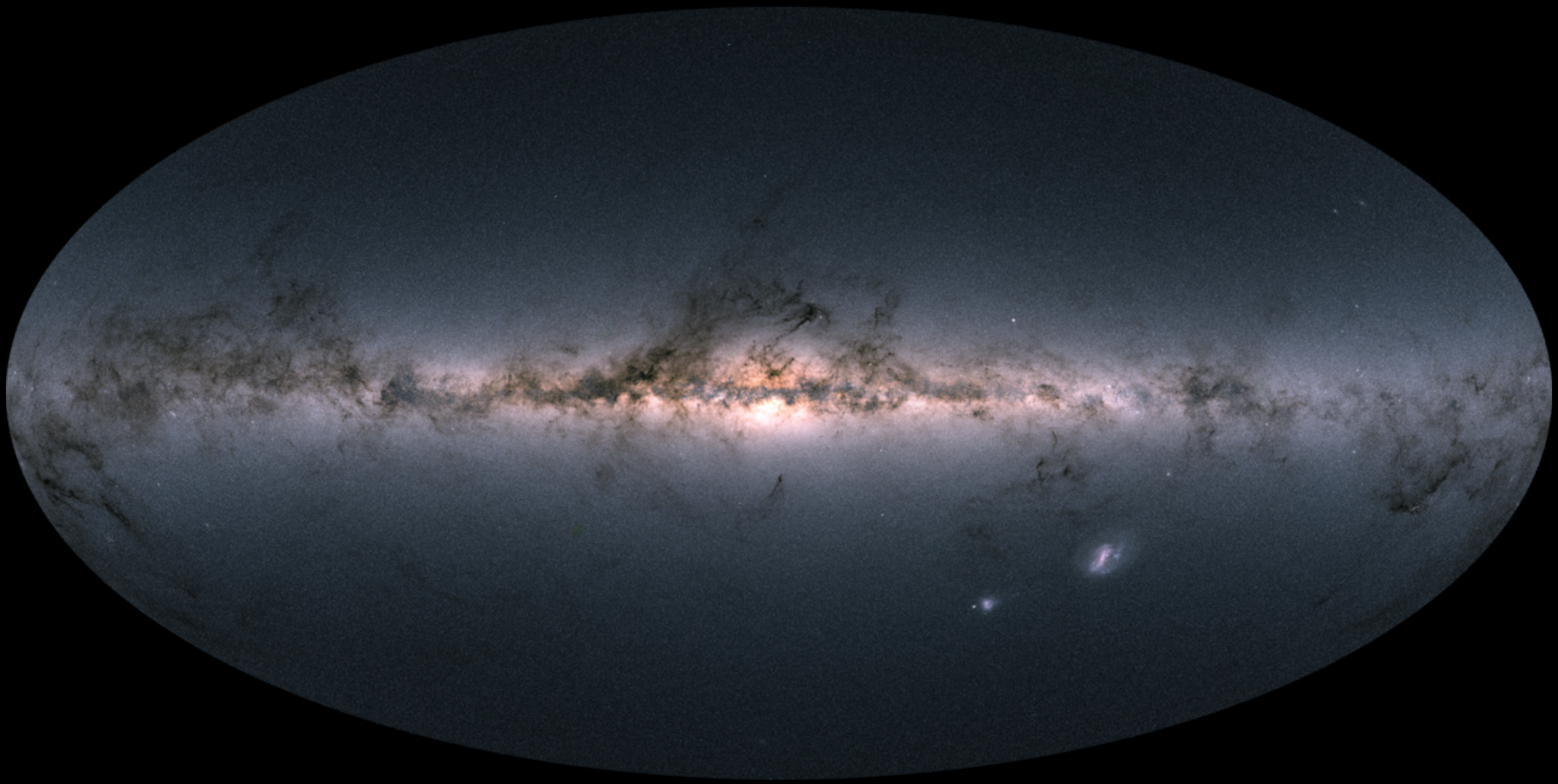
D.Seal/JPL

The Hipparcos Catalogue (118000 stars)



D.Seal/JPL

The second Tycho Catalogue (2.5 million stars)



The 2nd Gaia catalogue (1.7 billion stars)



The Night Sky





Galileo Galilei (1564–1642; Sidereus Nuncius): Telescope resolves (part of) the milky way in stars, discovers new stars $\Longrightarrow$ Milky way is not “milky”!

The Night Sky

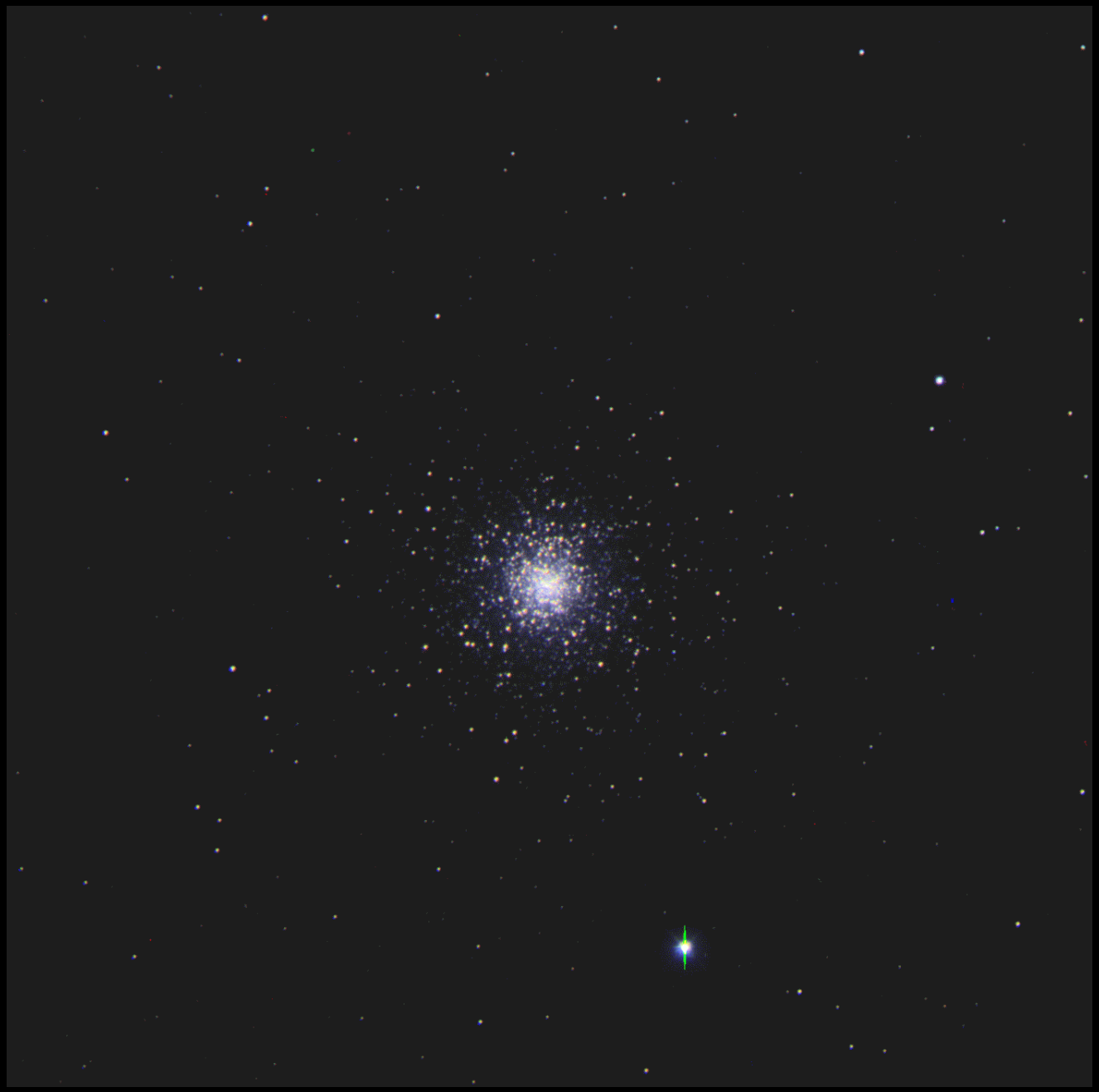


Charles Messier (1730–1817) searched for comets but found nebula which did not move.
Created a catalog of 110 nebulae.

- diffuse nebulae: M 42 = Orion nebula
- Planetary nebulae: M 57 = Ring nebula
- Supernova remnants M 1 = Crab nebula
- Open star clusters: M 45 = Pleiades
- Globular clusters: M 13 in Hercules
- Galaxies: M31 = Andromeda galaxy



Open clusters = Galactic clusters, young, e.g., Pleiades 100 Myr



Globular clusters: very old: 9–12 Gyr



http://www.cosmic-lab.eu/Cosmic-Lab/image_gallery_files/mosaic_poster.jpg

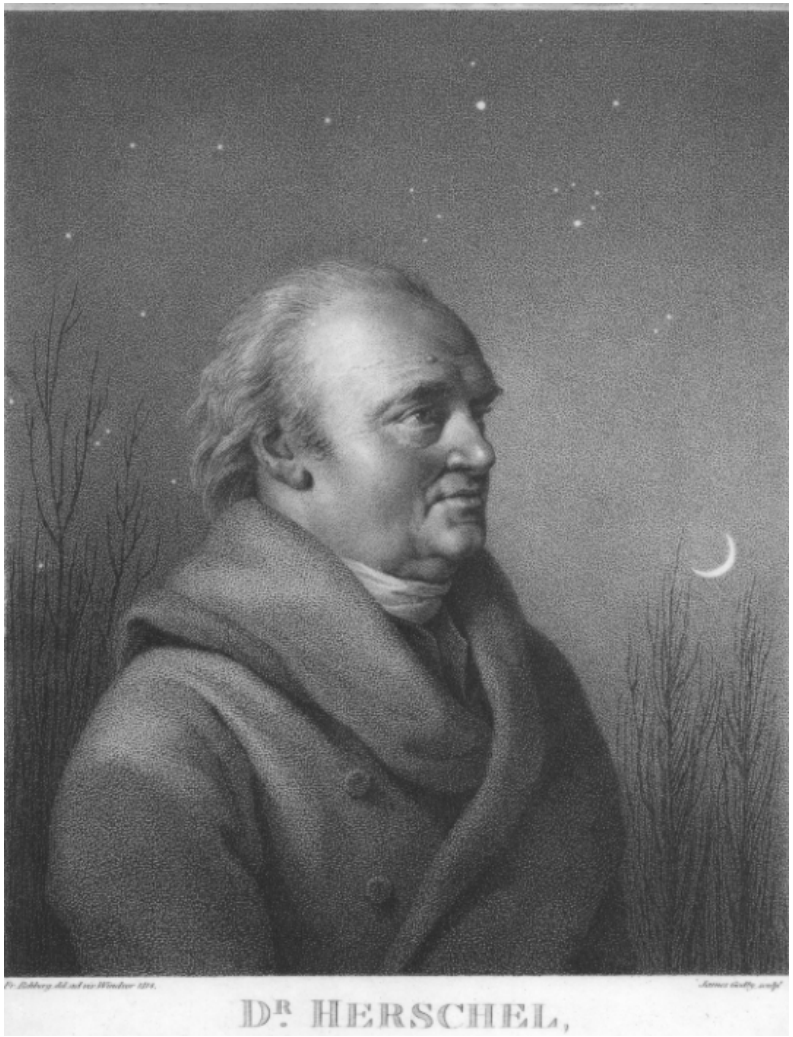
Globular Cluster M15

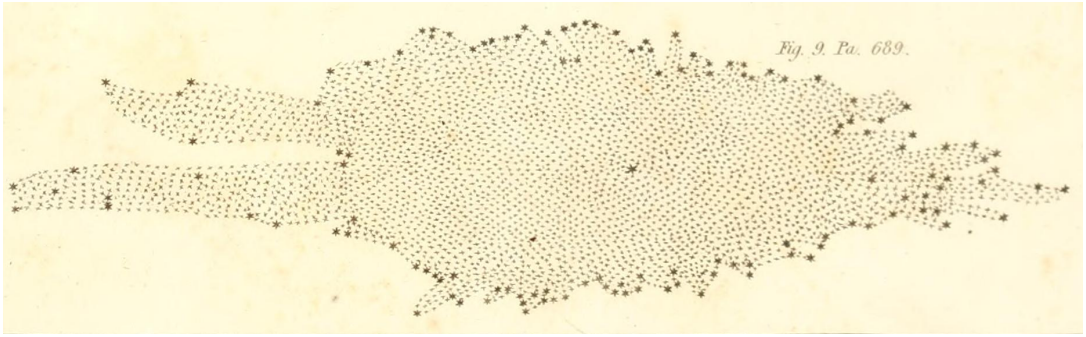


Hubble Heritage

NASA and The Hubble Heritage Team (STScI/AURA) • Hubble Space Telescope WFPC2 • STScI-PRC00-25

The Night Sky



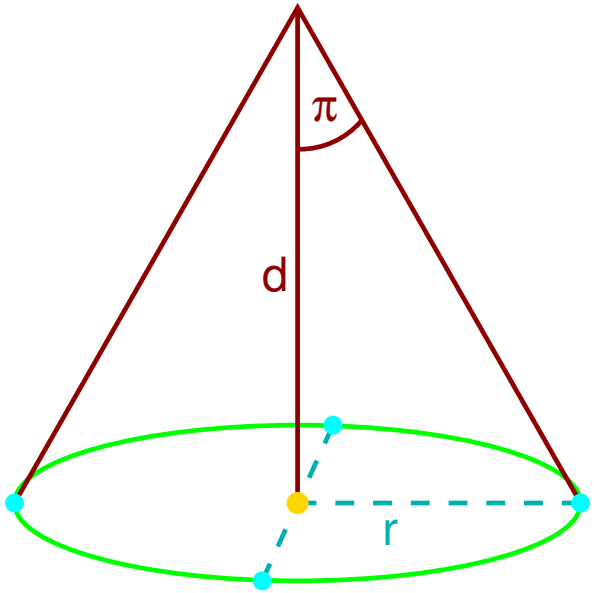


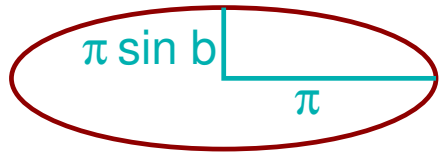
William Herschel (1738–1822): First attempts to determine morphology of the Galaxy.

Note: heliocentric!

The Night Sky



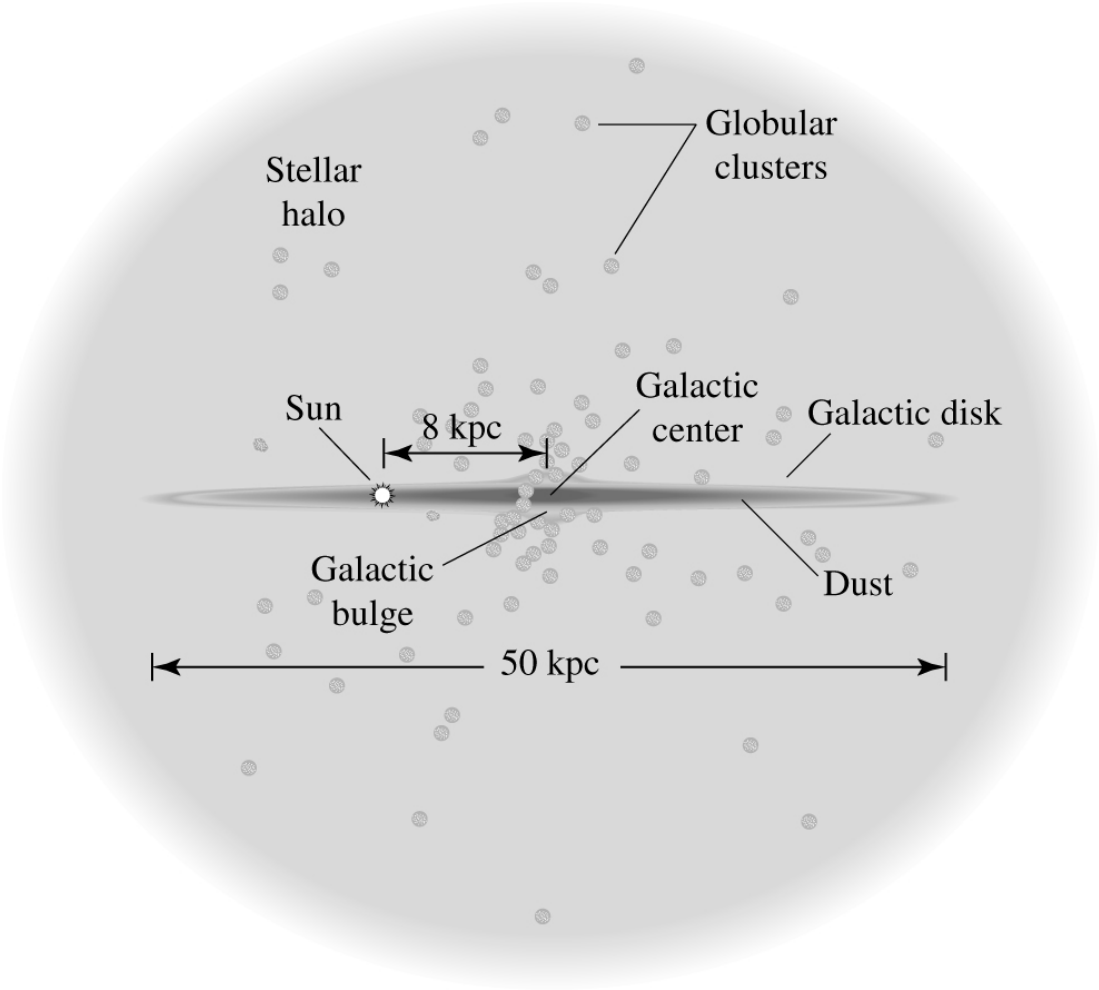




Wilhelm Bessel (1784–1846): First determination of a stellar parallax

reminder: 1 parsec = 3.26 Lj = 3×10^{13} km

The Milky Way



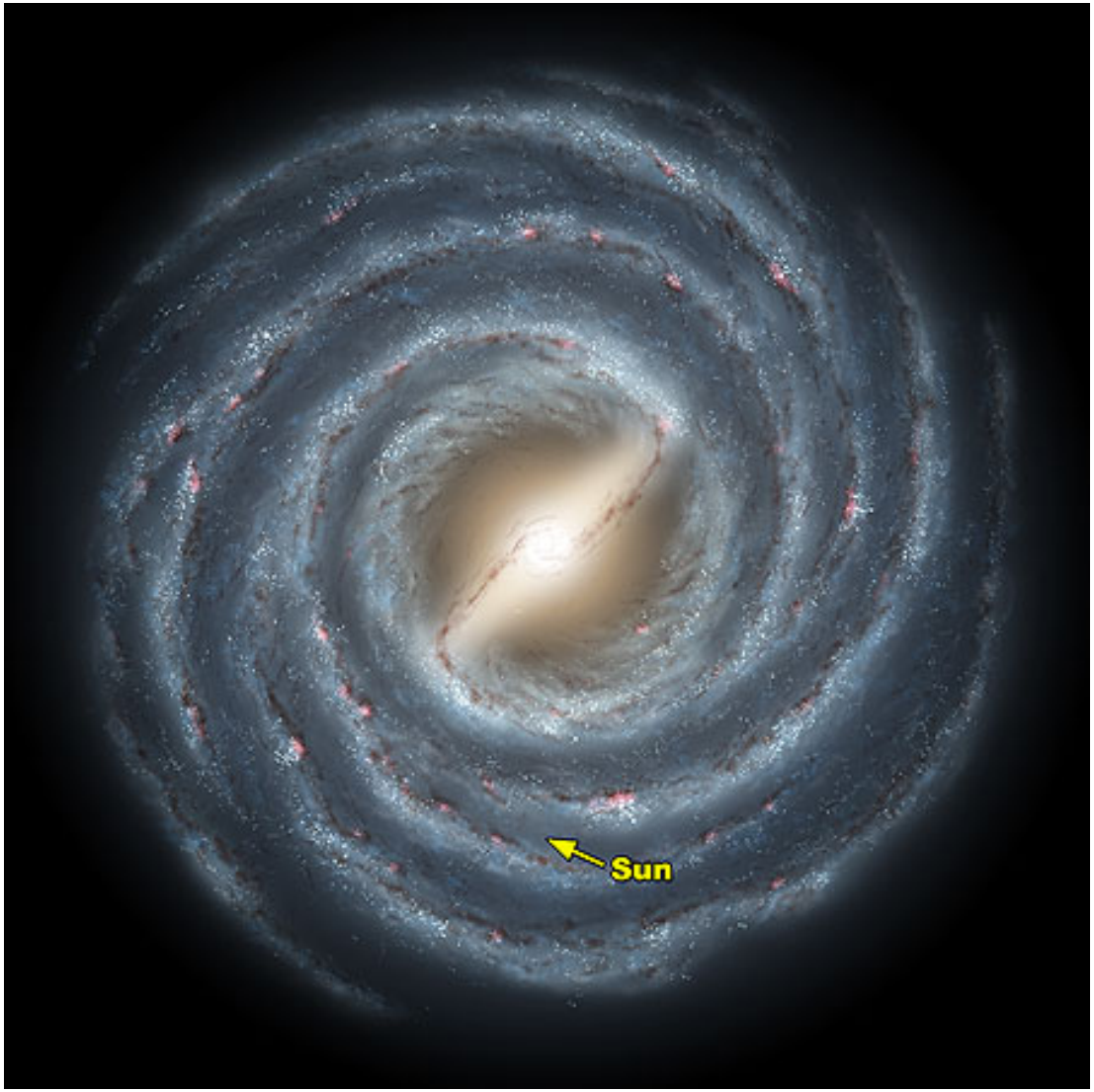
components of the Milky Way:

- Galactic disk:
  - rotating
  - young & old stars, open star clusters
  - gas & dust
- Galactic halo:
  - non-rotating,
  - old stars only, globular clusters
  - no gas, no dust
- Galactic bulge: rigid rotation

Typical Numbers

Diameter	30 kpc
Number of stars	3×10^{11}
Visible mass	$10^{11} M_\odot$
Total (gravitating) mass	$10^{12} M_\odot$
Thickness of the young ($< 10^9$ yr) thin disk	200 pc
Thickness of the old ($10^{9\ldots10}$ yr)thin disk	600 pc
Thickness of thethick disk ($> 10^{10}$ yr)	3 kpc
Distance of Sun from the Galactic center	8 kpc
Orbital period of Sun around Galactic center	240 Myr

Typical Numbers



Milky Way is a barred spiral galaxy Luminosity: $\sim 2 \times 10^{10}\,L_\odot$

Mass: $\sim 10^{11}\,M_\odot$ (radiating)
$\sim 10^{12}\,M_\odot$ (total)

Stellar density: $\sim 0.3\,M_\odot\,pc^{-3}$

$1\,M_\odot = 2 \times 10^{33}\,g = 2 \times 10^{30}\,kg$,
$1\,L_\odot = 4 \times 10^{33}\,erg\,s^{-1} = 4 \times 10^{26}\,W$

Interstellar Medium

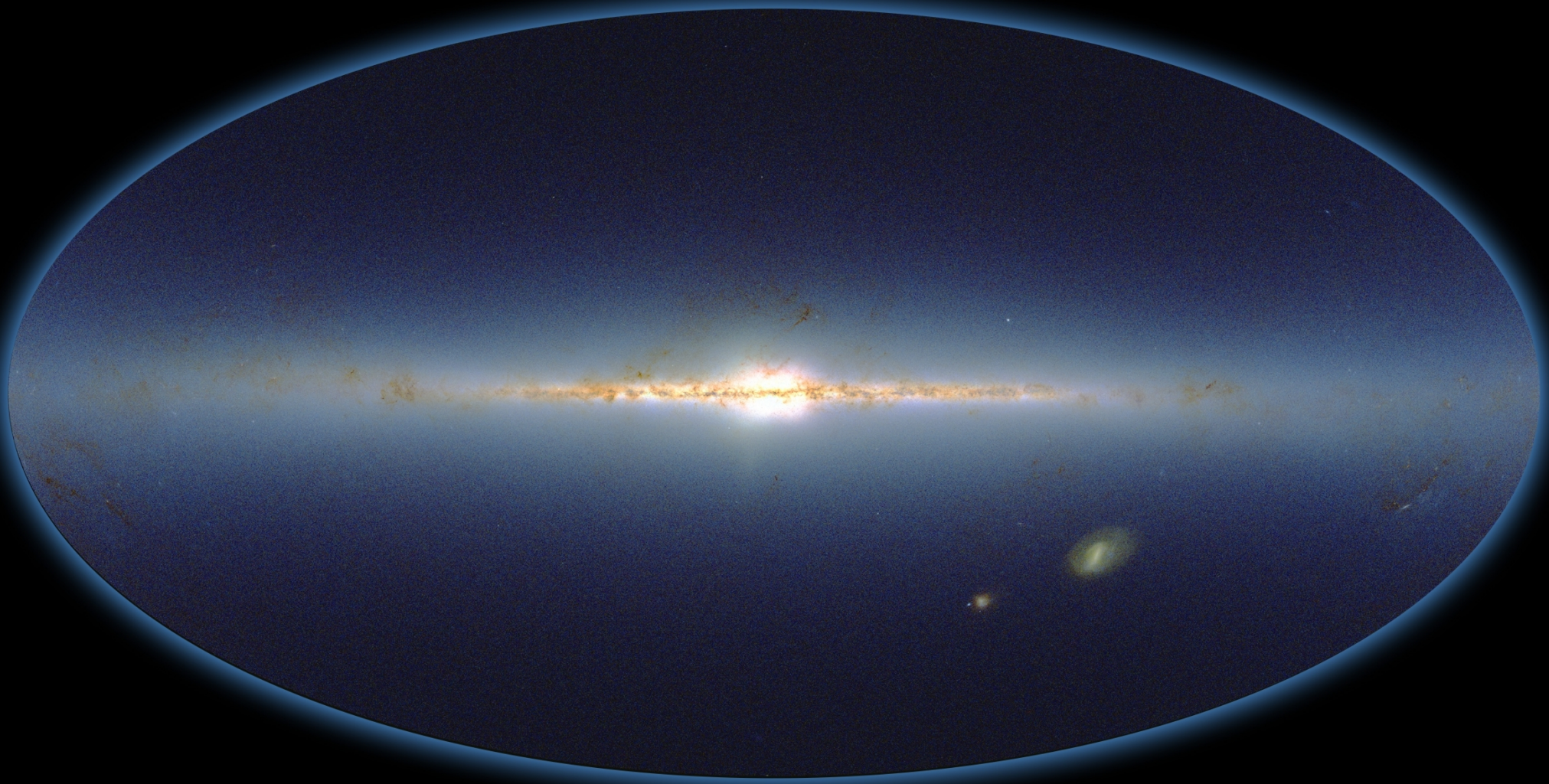
The space between the stars is filled with matter, radiation, and magnetic fields: Interstellar medium (ISM):

Components of the ISM:

- Gas (atoms, molecules, ions and free electrons)
- Dust (small solids),
- Cosmic rays (relativistic charged particles)
- electromagnetic radiation,
- magnetic fields, and
- dark matter.

To get full inventory of the medium, need to look at the galaxy in all wave-bands

2MASS Covers the Sky



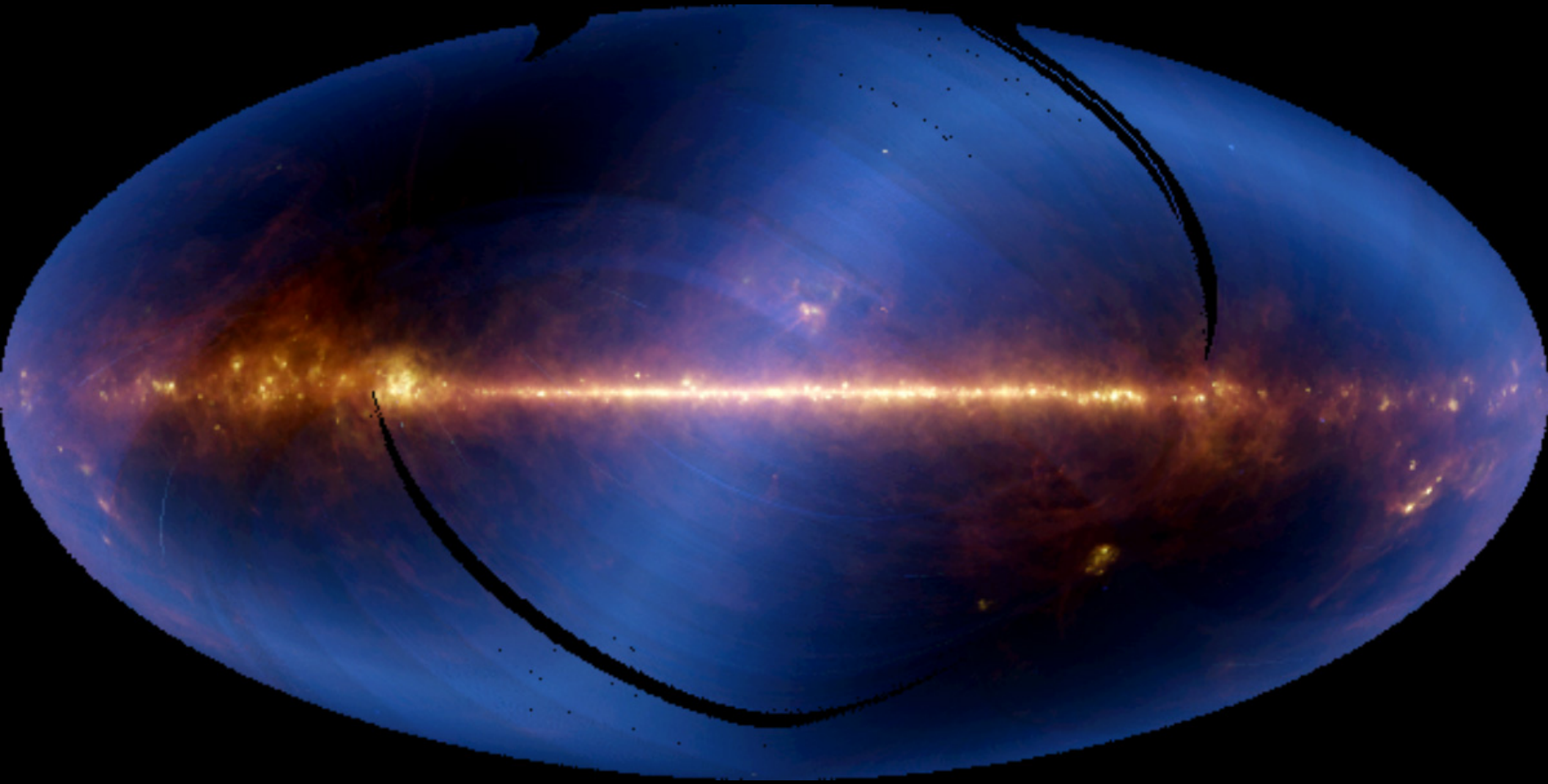
The Two Micron All Sky Survey

Infrared Processing and Analysis Center/Caltech & Univ. of Massachusetts

Infra red: Dust becomes transparent!

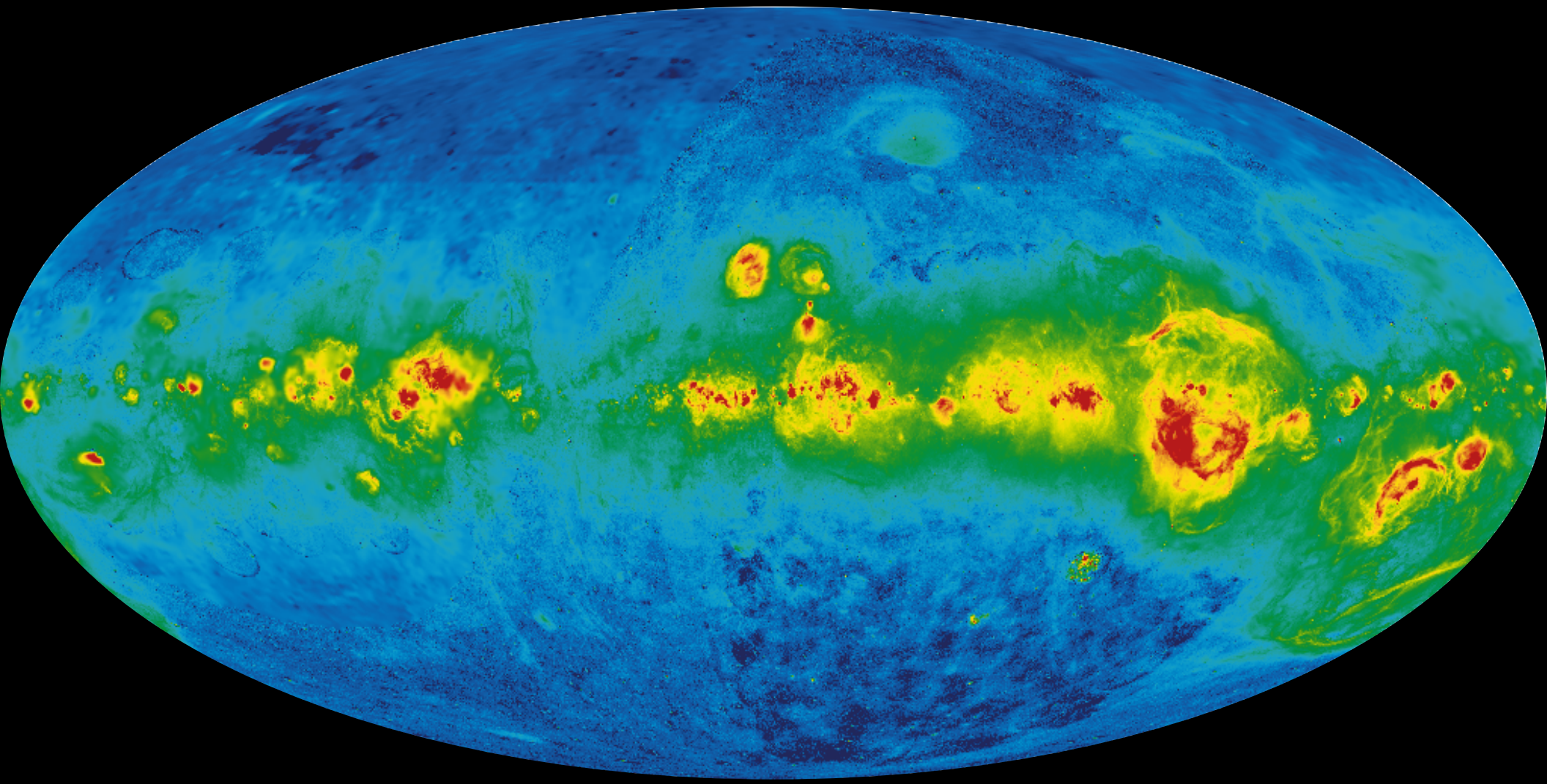
2MASS: 3 IR Bands: J (1.25 μm), H (1.65 μm), K_s (2.17μm)

Milky Way in Near Infra Red



Milky Way in far Infra Red

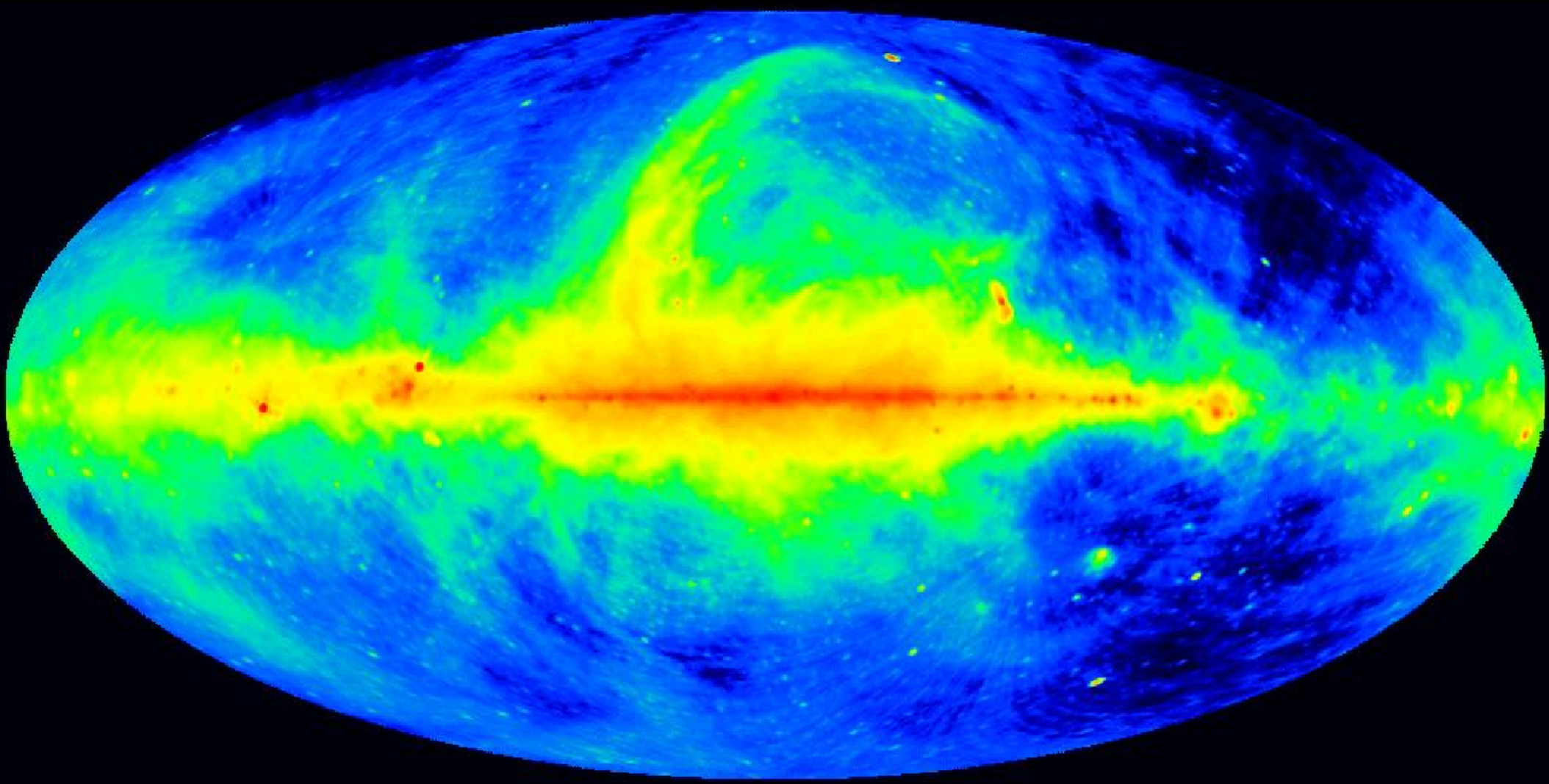
IRAS: 3 IR Bands: blue (12 μm), green (60 μm), red (100 μm)



Finkbeiner, 2003, HEASARC/LAMBDA

Galaxy in Hα

H II-Regions



G.T. Haslam et al., MPI für Radioastronomie 1982

Milky Way in radio ($\lambda = 73\,\mathrm{cm}$, $\nu = 408\,\mathrm{MHz}$)
Continuum radiation (bremsstrahlung, synchrotron radiation)

Multi Wavelength

Phase	Temperature [K]	Density [cm^{-3}]	Observation
Molecular clouds	10–50	10^3–10^6	sub-mm, FIR
diffuse molecular gas (H_2)	~50	~10^2	Radio, IR, optisch
cold neutral gas (HI)	~100	20–50	HI 21 cm emission
warm neutral gas (HI)	~5000	~0.6	HI 21 cm emission
warm ionized gas (HII)	~10^4	0.2–0.5	Hα emission
HII-regions	10^4	10^2–10^4	Hα emission, radio
Hot plasma	10^5–10^7	~0.001	UV, X-rays

The cold regions of gas cause absorption of Infrared, optical, and UV-radiation, and X-rays.

Structure of the Milky Way

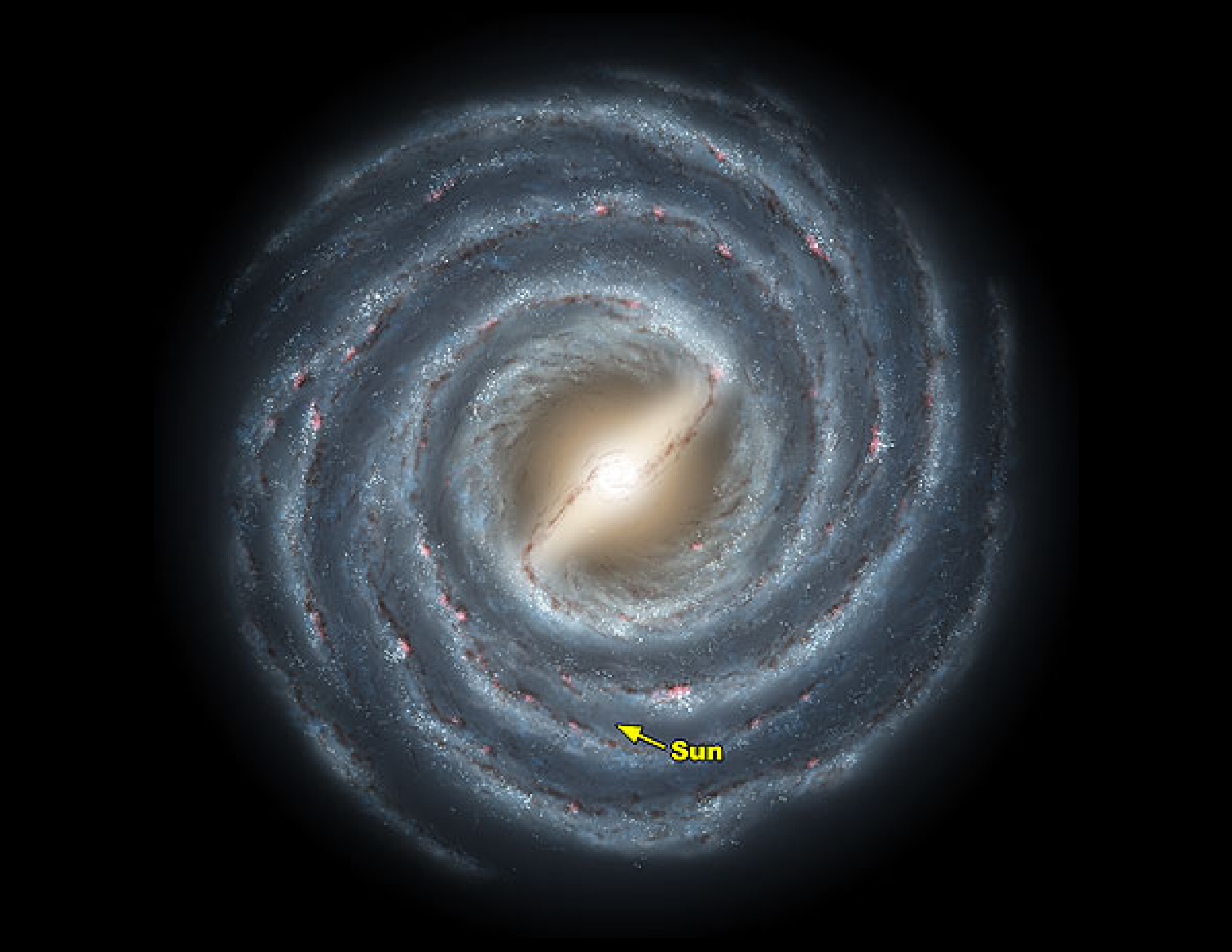
From the available maps the Galaxy looks like a spiral galaxy.

$\Longrightarrow$ How can we determine the structure of the Galaxy in more detail?

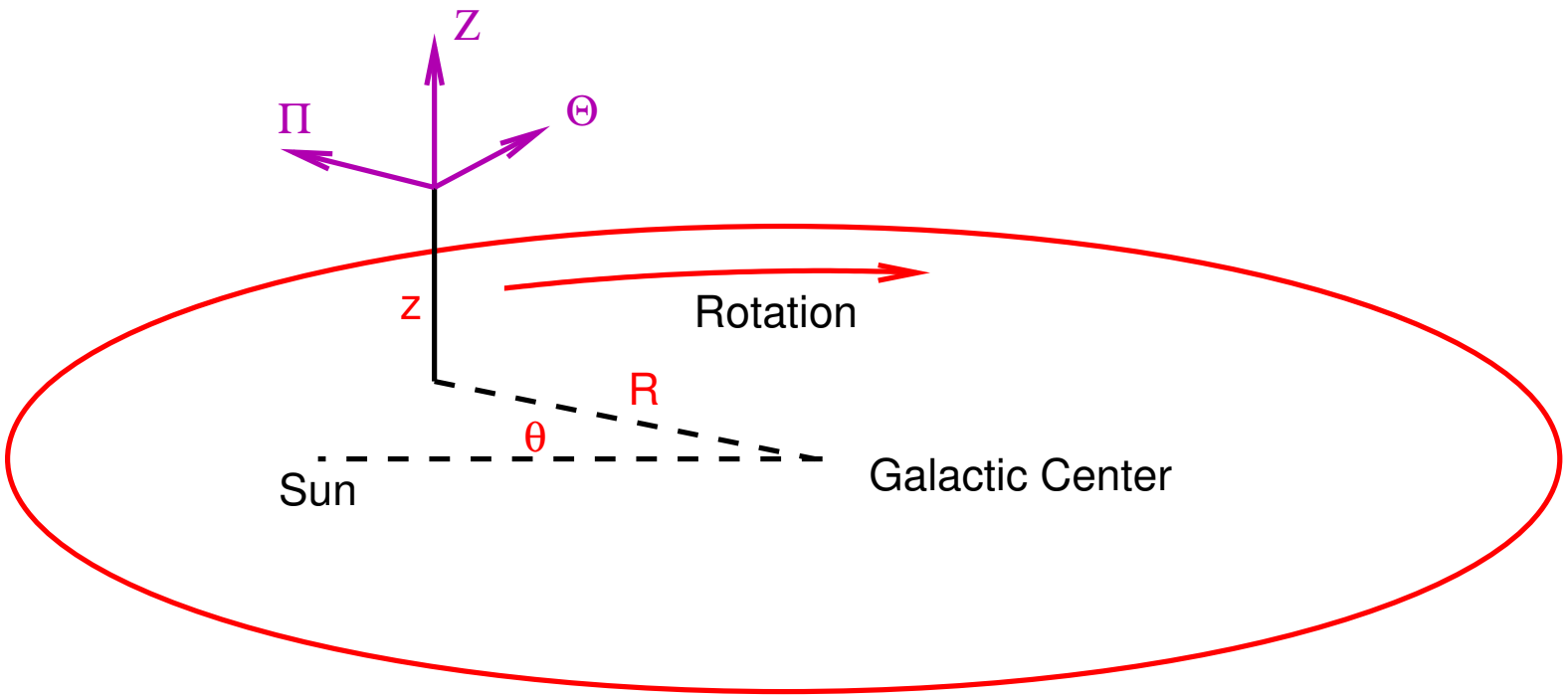
Derivation of Galactic structure: complicated since we are sitting in it and since solar system participates with the motion of the Galaxy.

$\Longrightarrow$

1. Galactic Rotation Curve
2. Distribution of gas
3. Evidence for spiral arms


Sun

Galactic Rotation



after Carroll & Ostlie (Fig. 22.21)

Introduce cylindrical coordinate system R, θ, z

$\Longrightarrow$ Velocity components of a star in a cartesian coordinate system:

$$\Pi = \frac{dR}{dt} \qquad \Theta = R\frac{d\theta}{dt} \qquad Z = \frac{dz}{dt} \tag{4.1}$$

Galactic Rotation

All observations of Galaxy are made from position of Sun.

But Sun moves through space

$\Longrightarrow$ define a *local* coordinate system centered on Sun, which moves on a circular orbit around the center of the Galaxy: Local Standard of Rest (LSR)

By definition, velocity components of the LSR are:

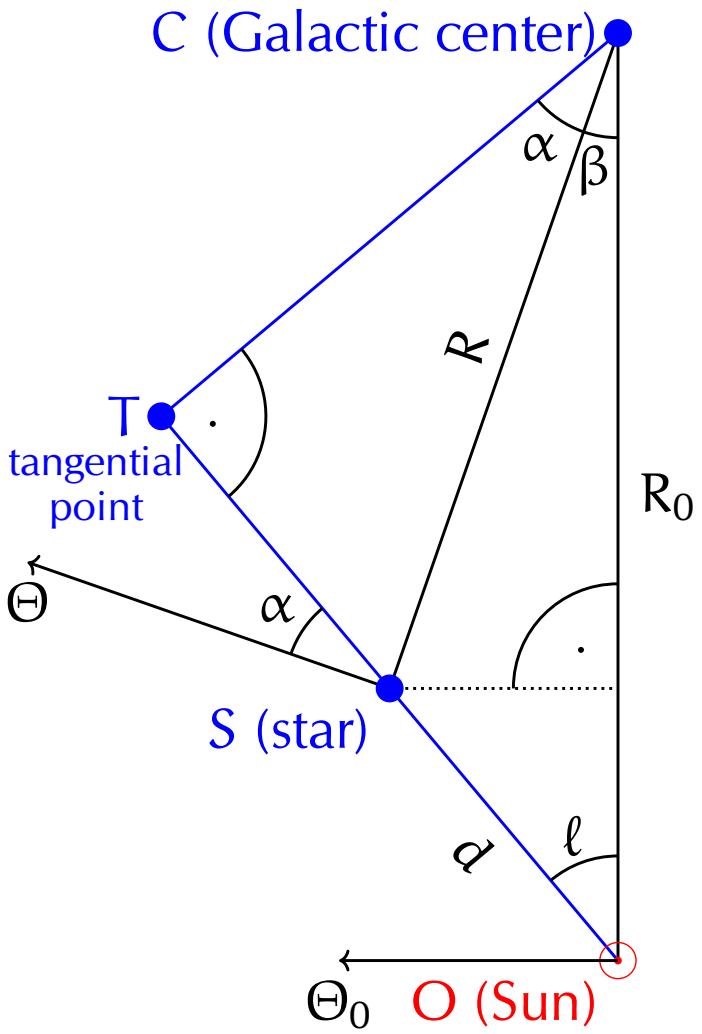
$$\Pi_{LSR} = 0 \qquad \Theta_{LSR} =: \Theta_0 \qquad Z = 0 \tag{4.2}$$

Therefore, after measuring motion with respect to LSR, we can convert to Galactic system provided we know Θ_0.

Note that Sun *moves with respect to LSR*!

Measurement: statistics of stellar motions surrounding the Sun

Galactic Rotation



after Carroll & Ostlie (Fig. 22.24)

To determine rotation of Galaxy ($= \Theta(R)$), our observables are the radial velocities and the transversal velocities of a star S:

$$v_r = \Theta \cos\alpha - \Theta_0 \sin\ell = \Omega R \cos\alpha - \Omega_0 R_0 \sin\ell \tag{4.3}$$

$$v_t = \Theta \sin\alpha - \Theta_0 \cos\ell = \Omega R \sin\alpha - \Omega_0 R_0 \cos\ell \tag{4.4}$$

where ℓ: galactic longitude, $\Omega = \Theta/R$: angular velocity

But from geometry of $\triangle$OTC:

$$R\cos\alpha = R_0 \sin\ell \tag{4.5}$$

$$R\sin\alpha = R_0 \cos\ell - d \tag{4.6}$$

such that

$$v_r = (\Omega - \Omega_0) R_0 \sin\ell \tag{4.7}$$

$$v_t = (\Omega - \Omega_0) R_0 \cos\ell - \Omega d \tag{4.8}$$

$\Longrightarrow$ We can determine Ω from v_r!

Gas Distribution

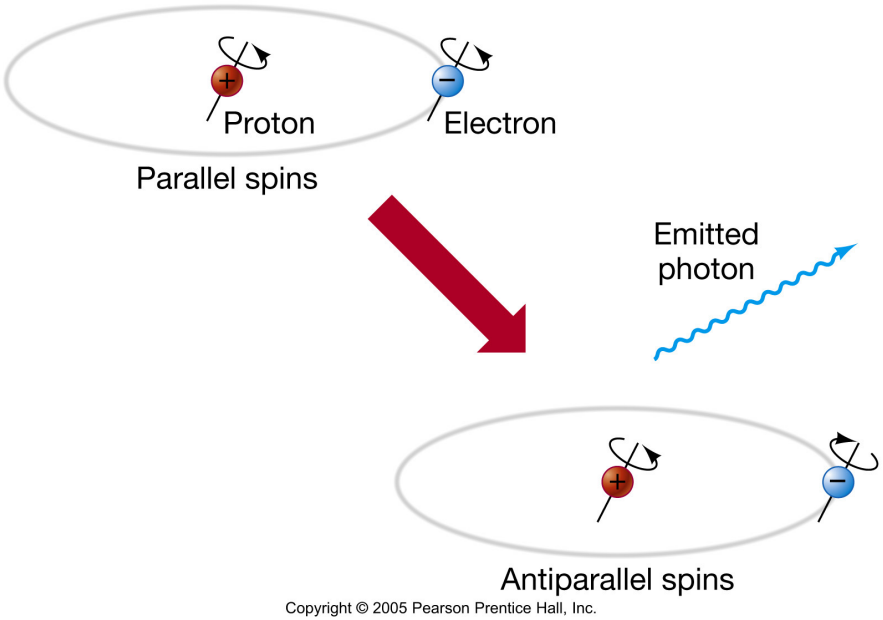


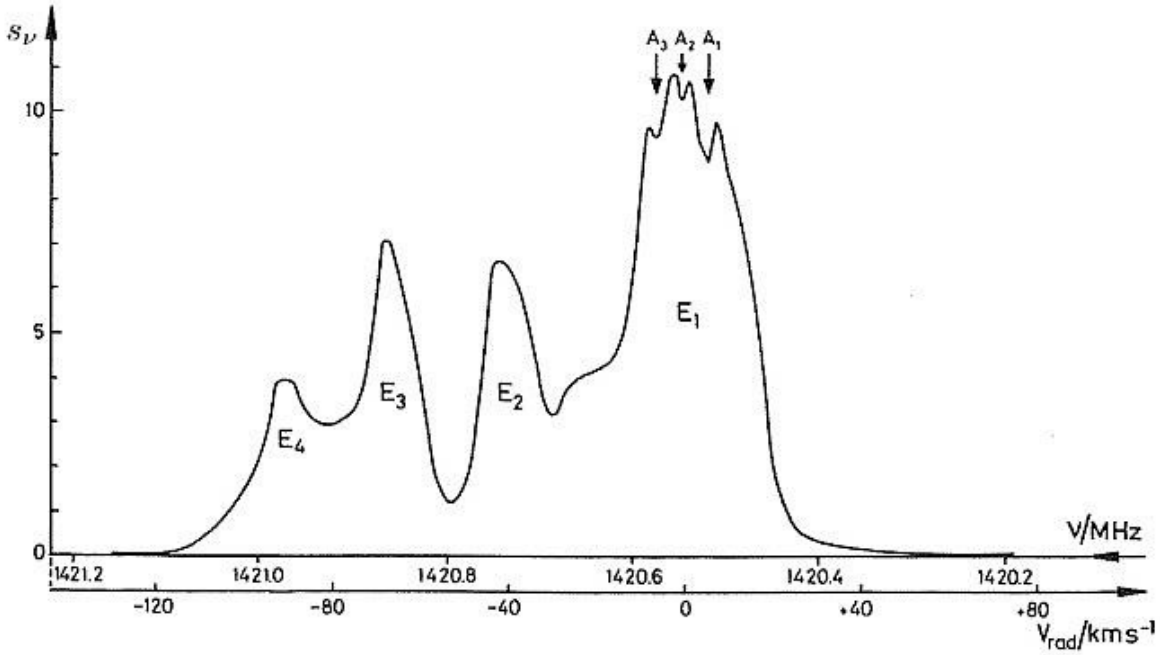
Image: 2005, Pearson Prentice Hall, Inc.

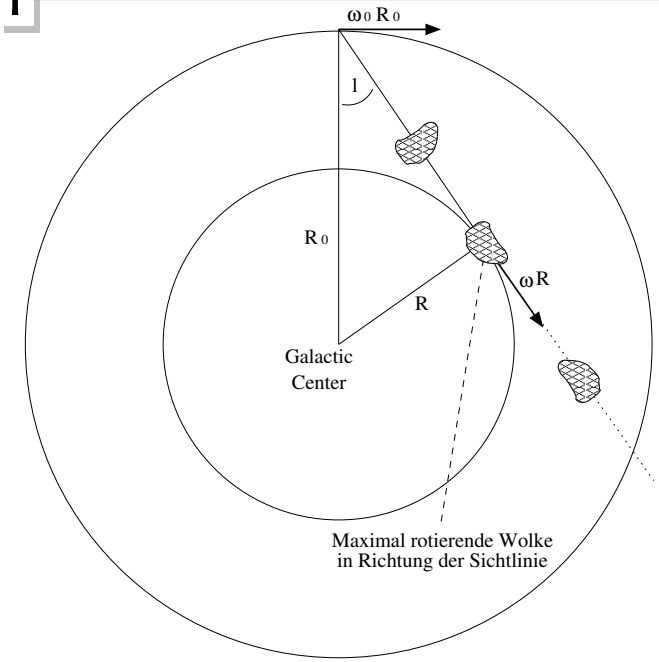
- Spins of electron and proton may be parallel ($F = 1$) or antiparallel ($F = 0$) ("hyperfine levels");
- Energy difference of $\Delta E \sim 6 \times 10^{-6}$ eV, corresponding to $\lambda = 21$ cm or $\nu = 1.4$ GHz.
- $F = 1$: metastable, i.e., long life time (10^7 years)

  transition to $F = 0$ *dipole forbidden* in quantum mechanics, transition rate 10^{-6} smaller than for permitted transitions
- Laboratory: $F = 1$ state is depopulated by collisions; no line is seen.
- ISM: low densities, i.e., no collisions; radiative transitions possible.

Because of the ubiquity of hydrogen, 21 cm line traces gas extremely well. Self-absorption of the line is extremely unlikely $\Longrightarrow$ line visible from everywhere except for the most dense regions.

Gas Distribution





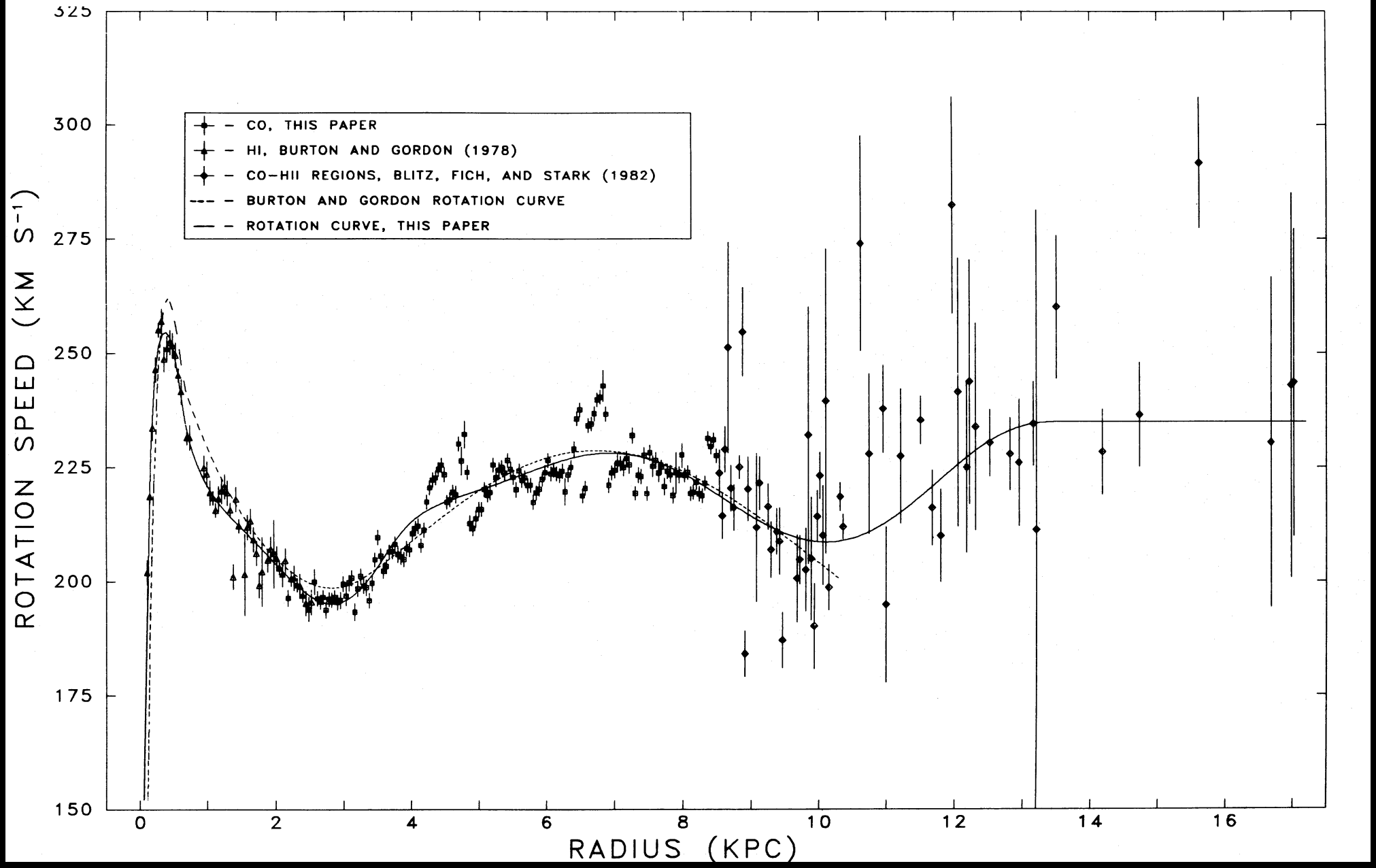
Sketch of a typical H I emission line profile. Note: v-axis has wrong sign!

In general multiple hydrogen clouds along the line of sight. Differential rotation $\Rightarrow$ Differential Doppler shift, allows to obtain $\Omega(R)$ (note: maximum v_r at $R = R_0 \sin \ell$!).

Overall: Probe of ISM structure and dynamics!

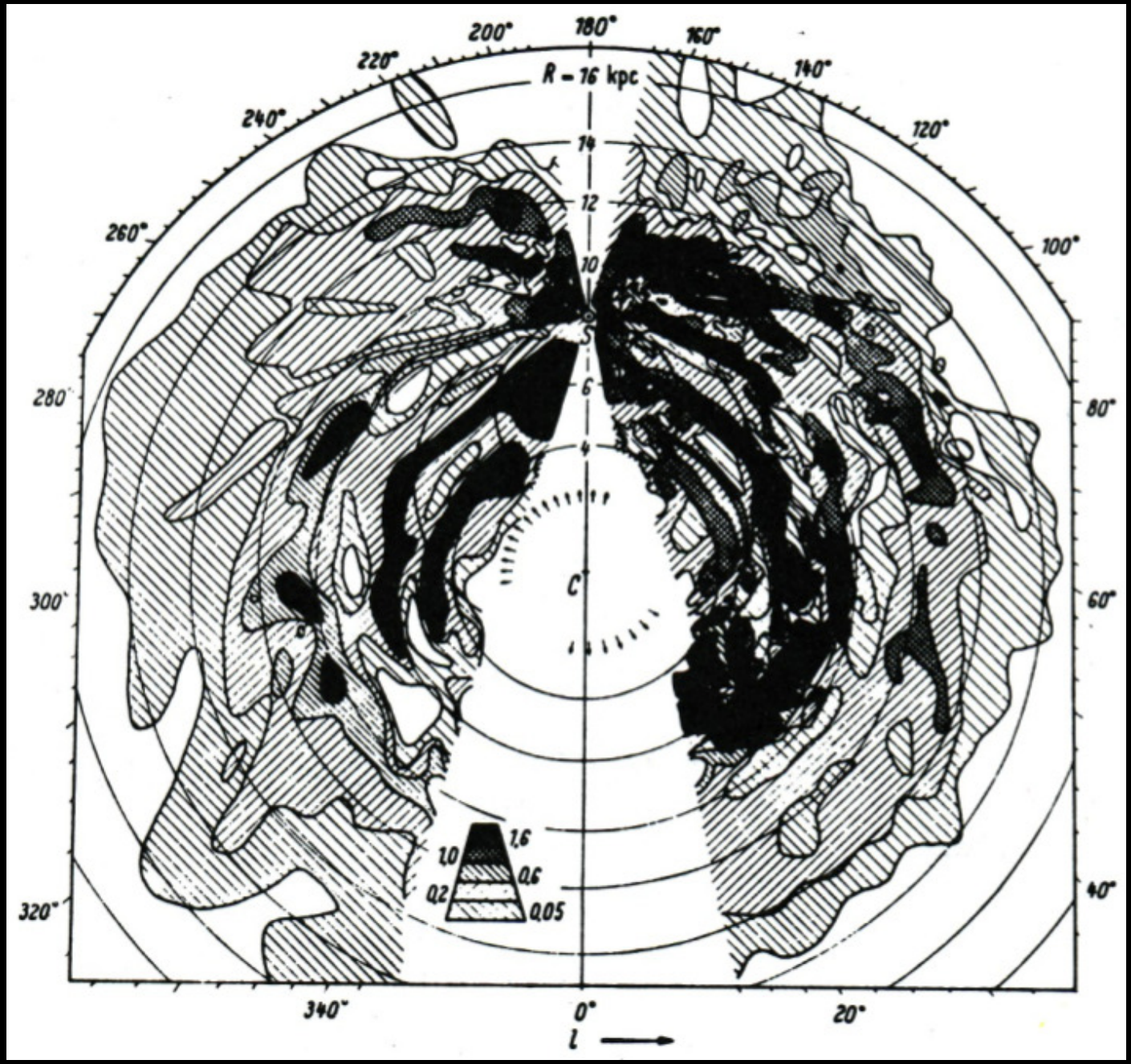
Integration over the full profile gives the column density of neutral hydrogen in this direction. Typical values: $10^{18}\,\mathrm{cm}^{-2}$ (at large gal. latitudes) to $10^{22}\,\mathrm{cm}^{-2}$ (in the gal. plane).

State of the art is the Leiden-Argentine-Bonn Survey (Kalberla et al., 2005).



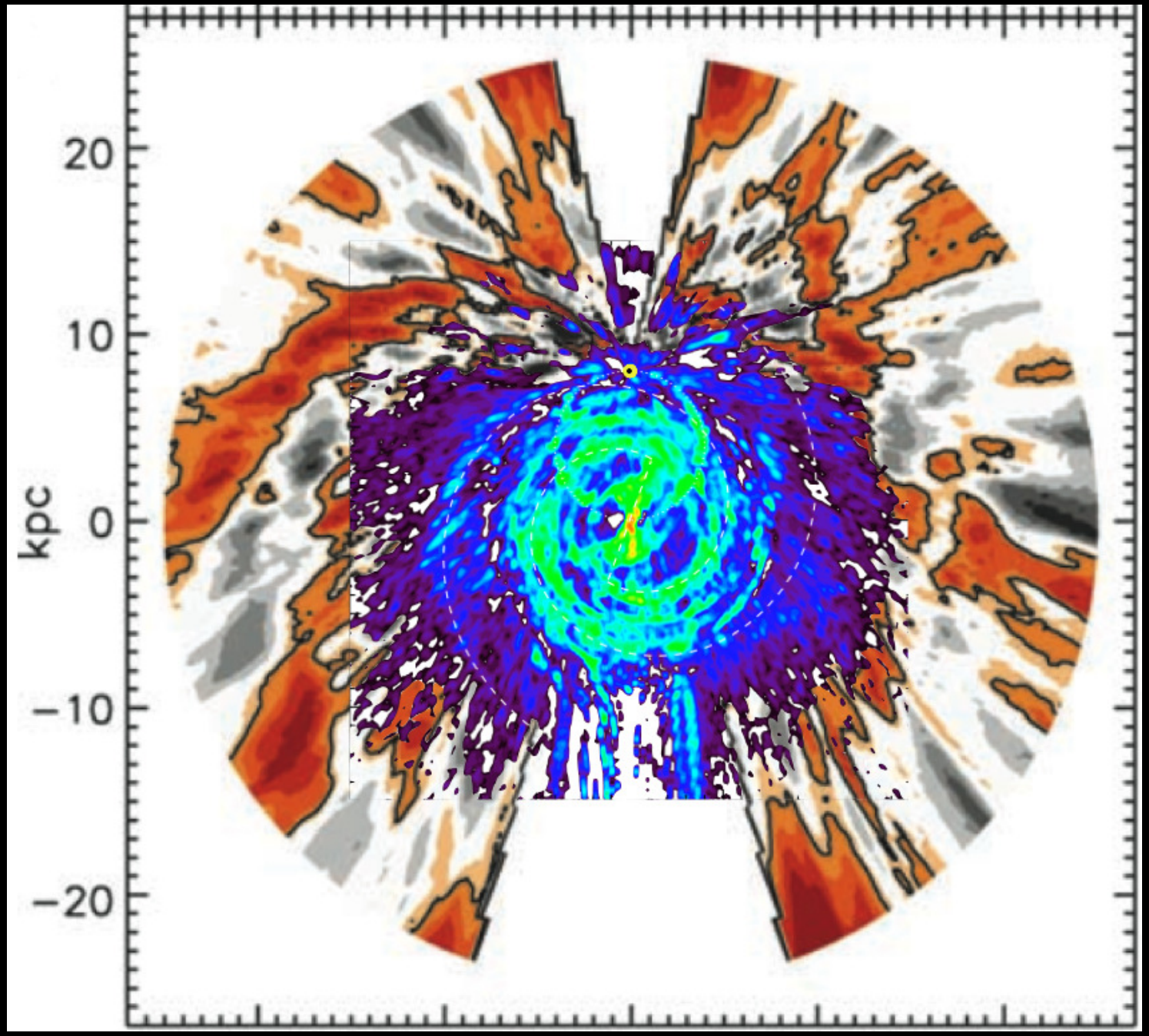
Clemens (1985, Fig. 3)

The rotation curve of the galaxy is approximately flat.



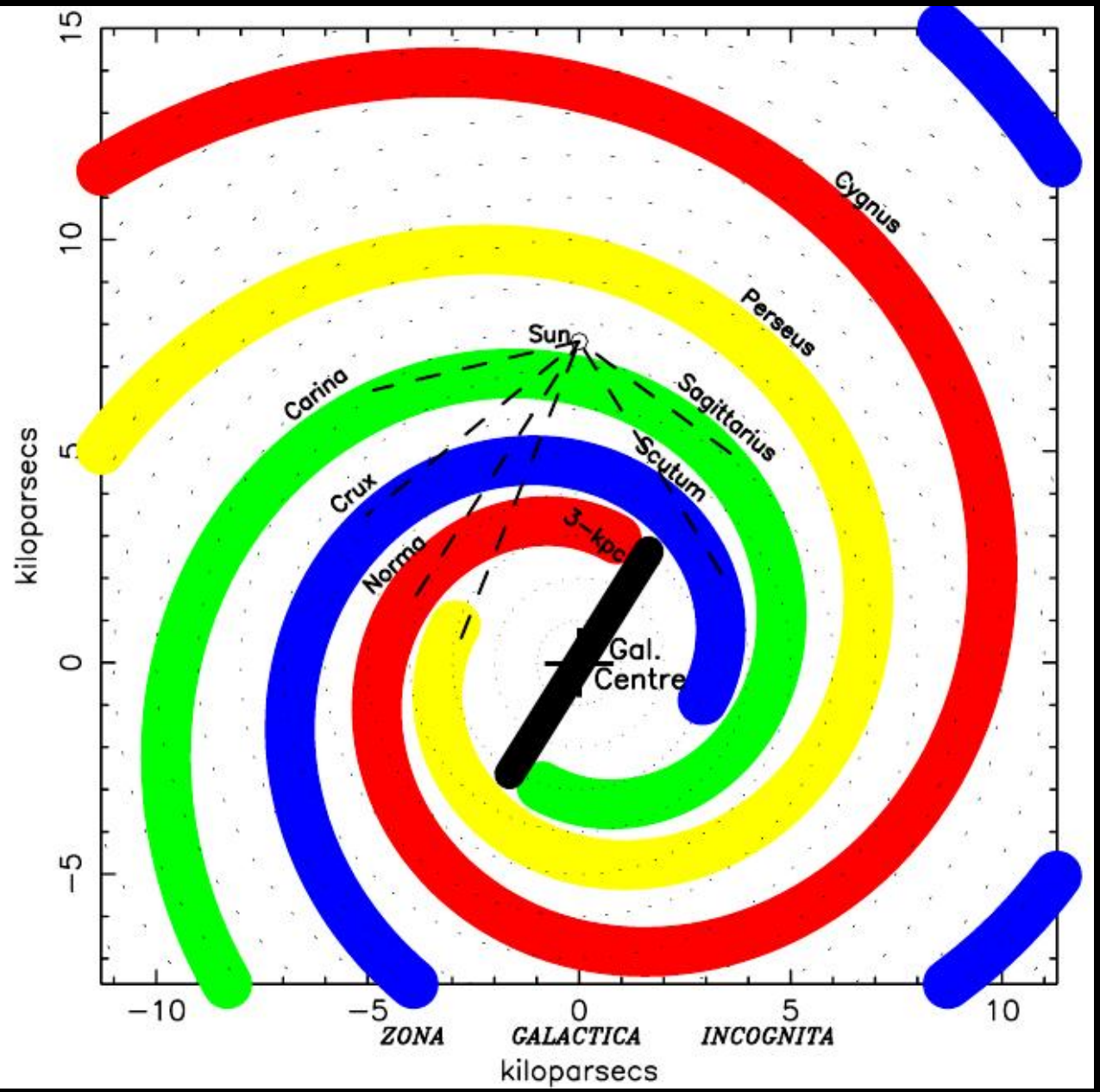
from Englmaier, Pohl, Bissanz (2008, Fig. 1)

Oort (1958): First map of H distribution in Galaxy: structure!



from Englmaier, Pohl, Bissanz (2008, Fig. 2; Sun is yellow dot)

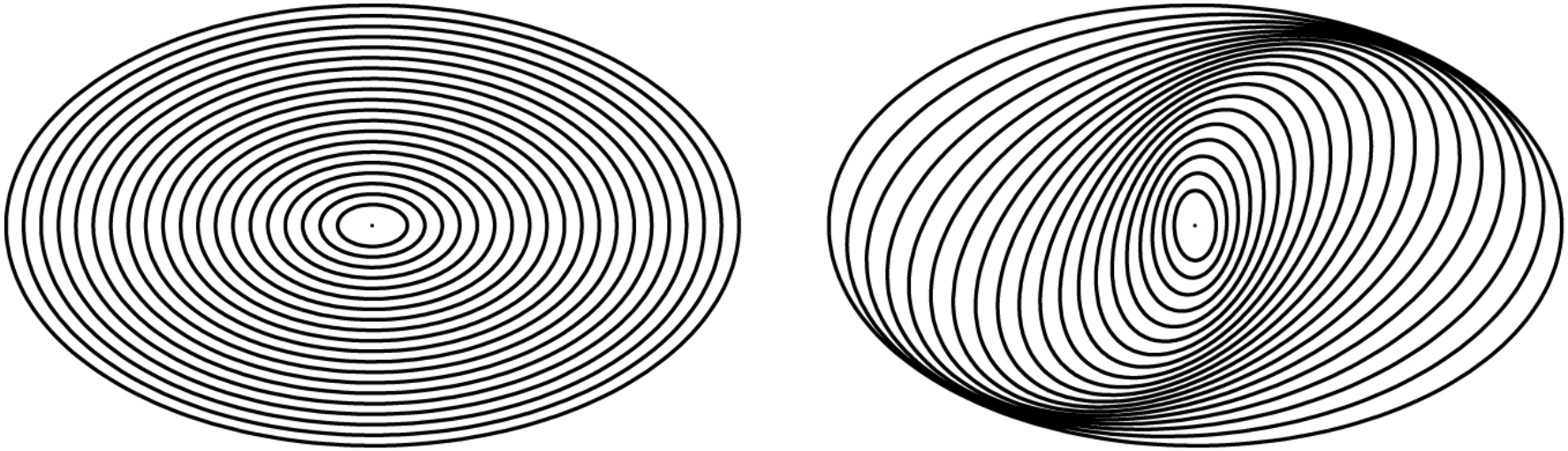
Distribution of CO and H gas shows clearly the spiral structure.



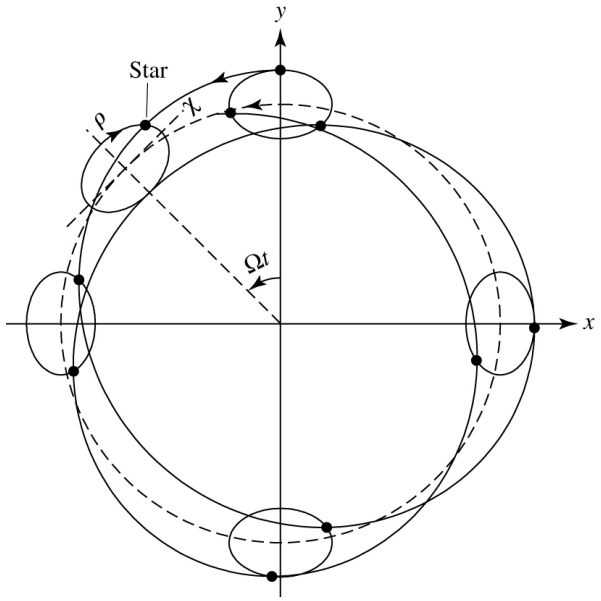
The spiral arm structure of Galaxy is now rather well understood

Vallee (2008)

Spiral Arms



(a) (b)



Carroll & Ostlie

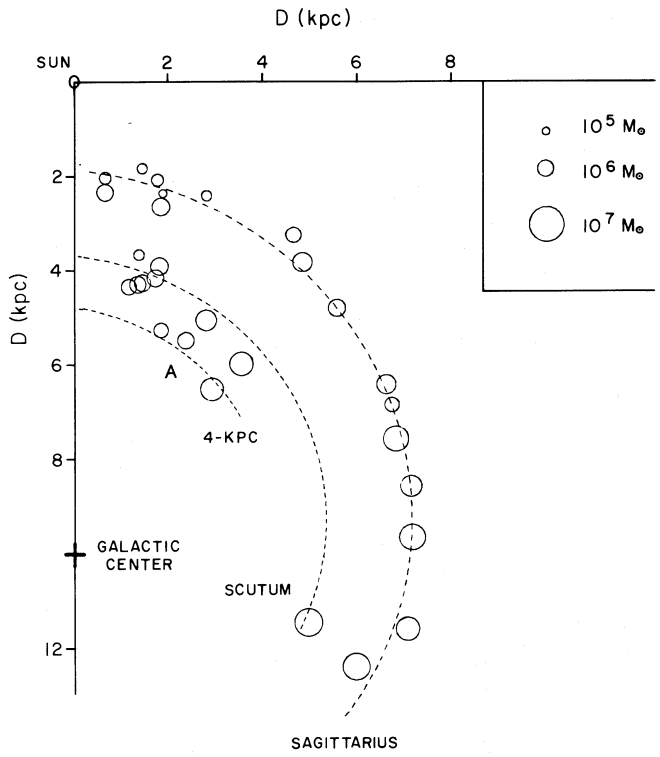
Spiral structure and density waves:

Stars move on on "nested ovals", not circles

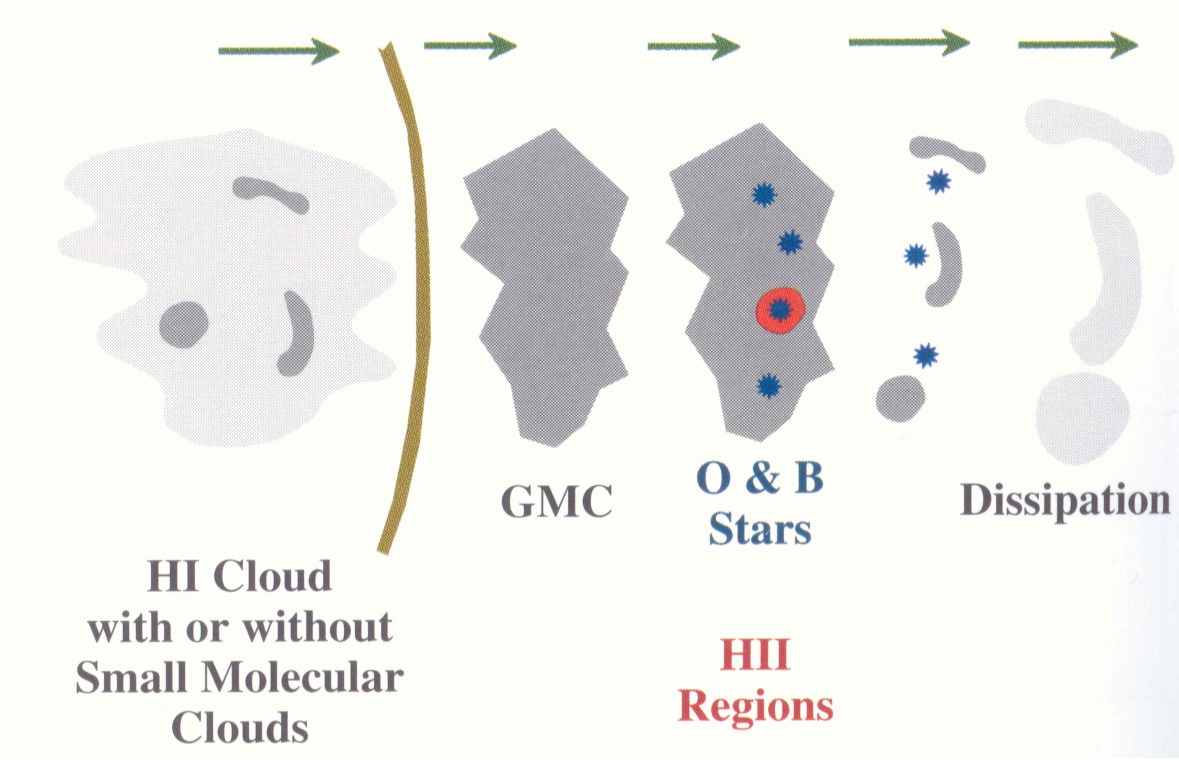
If each oval is rotated relative to the orbit immediately interior to it: spiral density wave

First order approximation: combination of a retrograde motion about an epicycle and a prograde circular orbit of the epicycle centre

Spiral Arms



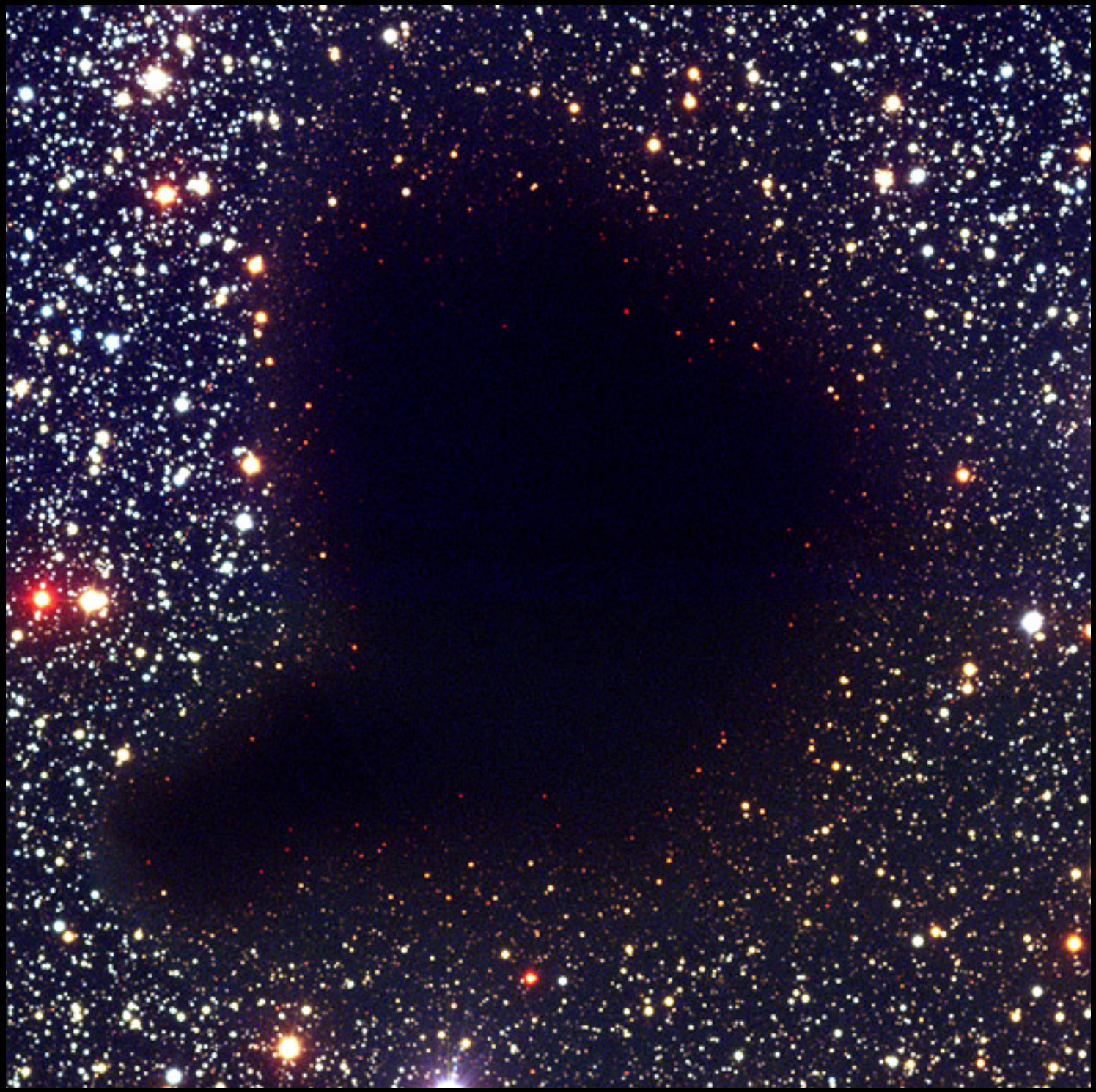
Dame et al. (1986, Fig. 9)



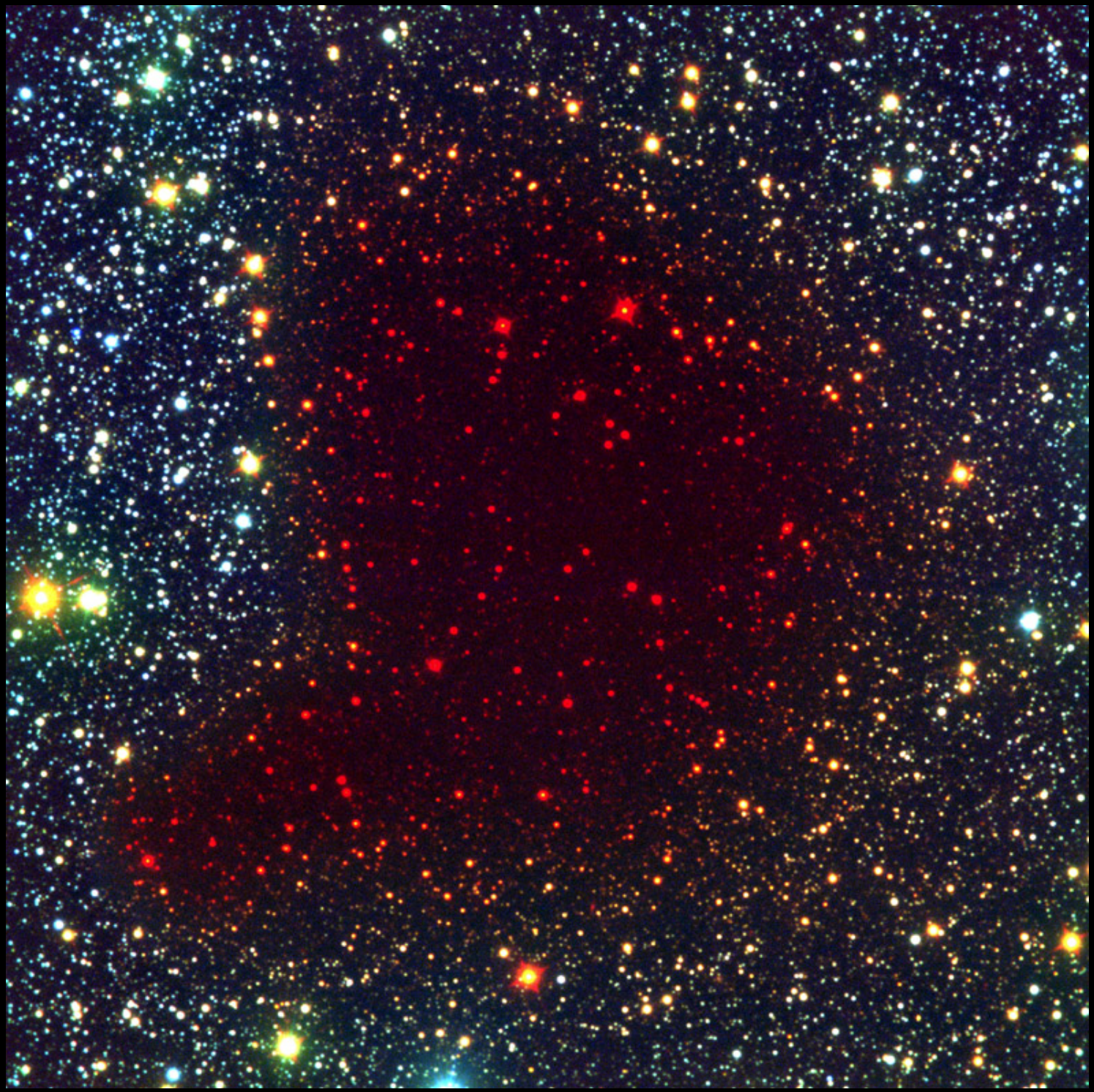
Carroll & Ostlie

Star formation induced by density wave:

- A cloud of gas passes through a density wave
- compression induces collapse
- stars of all masses form
- massive stars dissipate the cloud by their strong UV radiation



Optical View of B68 (ESO; VLT/FORS1)



IR View of B68 (ESO; VLT/FORS1 + NTT/SOFI)

Stellar Birth

Stars are born in "Giant Molecular Clouds"

Typical GMC parameters (e.g., Orion):

- large clouds: typical diameters 50–100 pc
- contain lots of molecular gas (H_2, CO, alcohol,...).
- typical temperatures: 10–20 K (coolest regions in the interstellar medium)
- typical particle densities $n \sim 10^6$–$10^{10}\,\mathrm{cm}^{-3}$

Stars are born in groups out of collapsing Molecular Clouds.

Collapse triggered, e.g., by collisions of clouds or shocks caused by nearby supernovae.

Stellar Birth

Criterion for collapse: Cloud is instable, i.e., gravitation is stronger than thermal pressure.

In terms of thermal and gravitational energies, this means

$$\frac{3}{5}\frac{GM^2}{R} \geqslant \frac{3}{2}\frac{M}{m_p}kT \tag{4.9}$$

which can be expressed as

$$\frac{M}{R} \geqslant \frac{5}{2}\frac{kT}{Gm_p} \quad \text{or} \quad \frac{4\pi}{3}\rho R^2 \geqslant \frac{5}{2}\frac{kT}{Gm_p} \tag{4.10}$$

$\Longrightarrow$ Collapse thus possible for

$$R > R_J = \sqrt{\frac{15kT}{8\pi G m_p \rho}} \sim \sqrt{\frac{kT}{G m_p \rho}} \tag{4.11}$$

where R_J is called the Jeans radius.

Stellar Birth

Plugging in typical typical numbers, i.e., $T \sim 50\,\mathrm{K}$, particle density $n = 10^5\,\mathrm{H\text{-}atoms\,cm^{-3}}$ (=a mass density of $\rho = n m_p \sim 1.7 \times 10^{-19}\,\mathrm{g\,cm^{-3}}$) gives $R_J \sim 0.2\,\mathrm{pc}$.

For a given Jeans radius, the mass within R_J is the Jeans mass

$$M_J \sim \frac{4\pi}{3} R_J^3 \rho$$

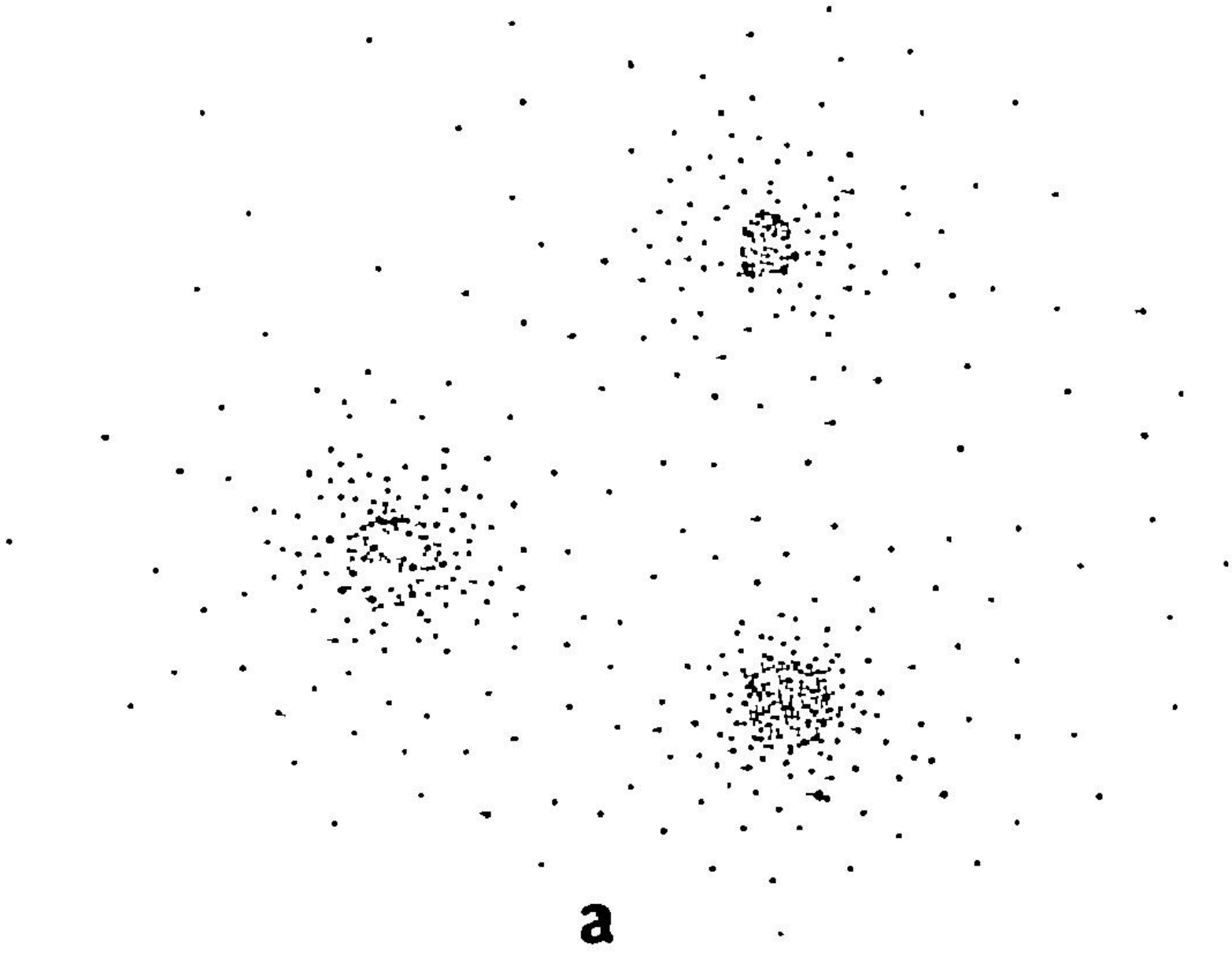
...which has typical values of $50\text{–}100\,M_\odot$, i.e., larger than one star!

In reality things are more complicated: ISM contains magnetic fields
$\Longrightarrow$ Particle motion $\perp$ B-field lines difficult
$\Longrightarrow$ stops gas from collapsing.

This is good since Jeans formalism alone predicts too strong star formation.

$\Longrightarrow$ Need star formation with magnetic fields

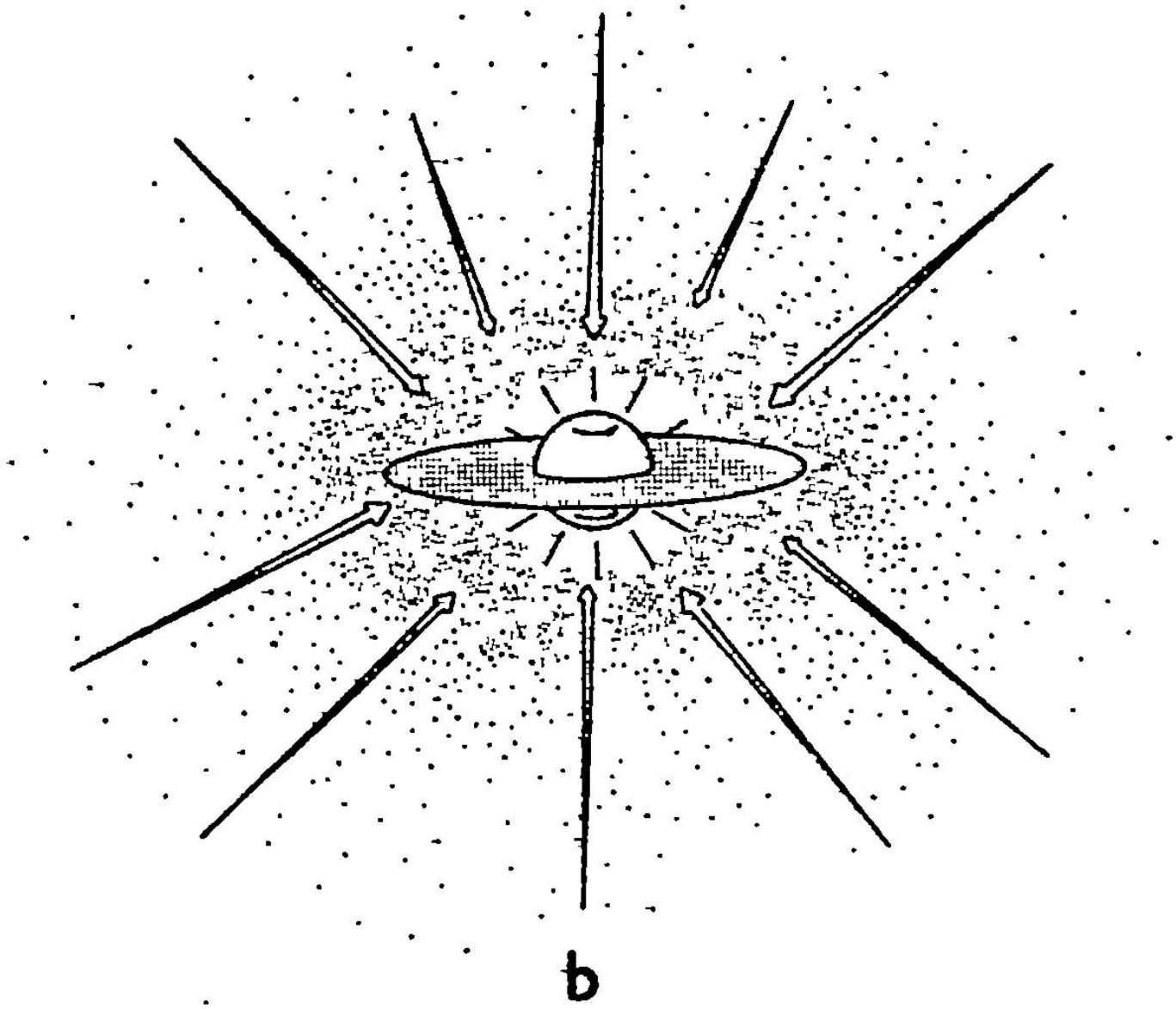
See Shu et al. (1987, Annual Reviews of Astronomy and Astrophysics 25, 23) for the gory details.



Shu et al. (1987, ARAA 25, 23, Fig. 7)

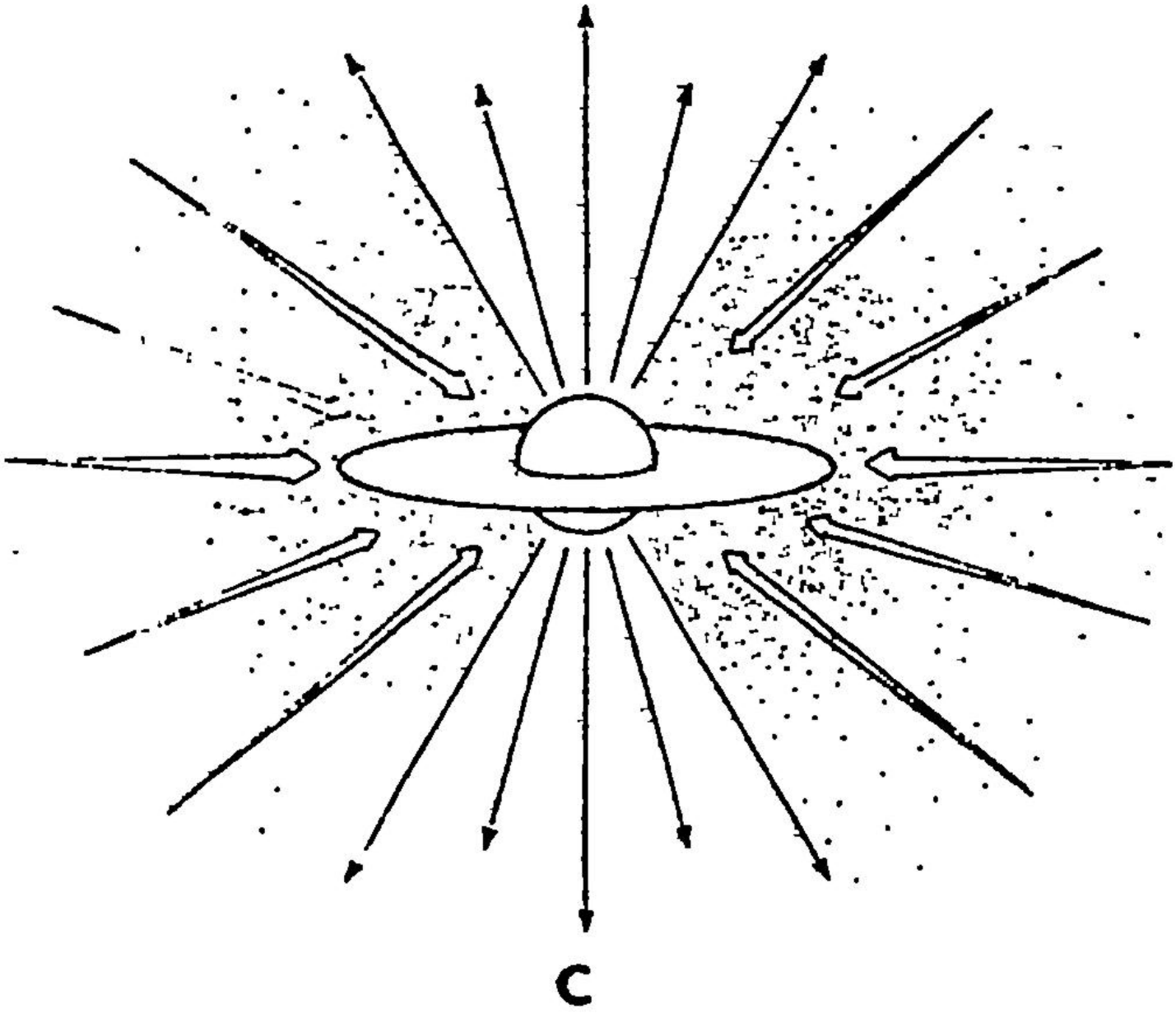
Stellar mass cores form from fragmentation of larger pieces.

Note: fragmentation only along B-field lines.



Shu et al. (1987, ARAA 25, 23, Fig. 7)

Protostar forms with surrounding disk ("inside out collapse") once core hot enough to allow fusion ($T > 10^6$ K)

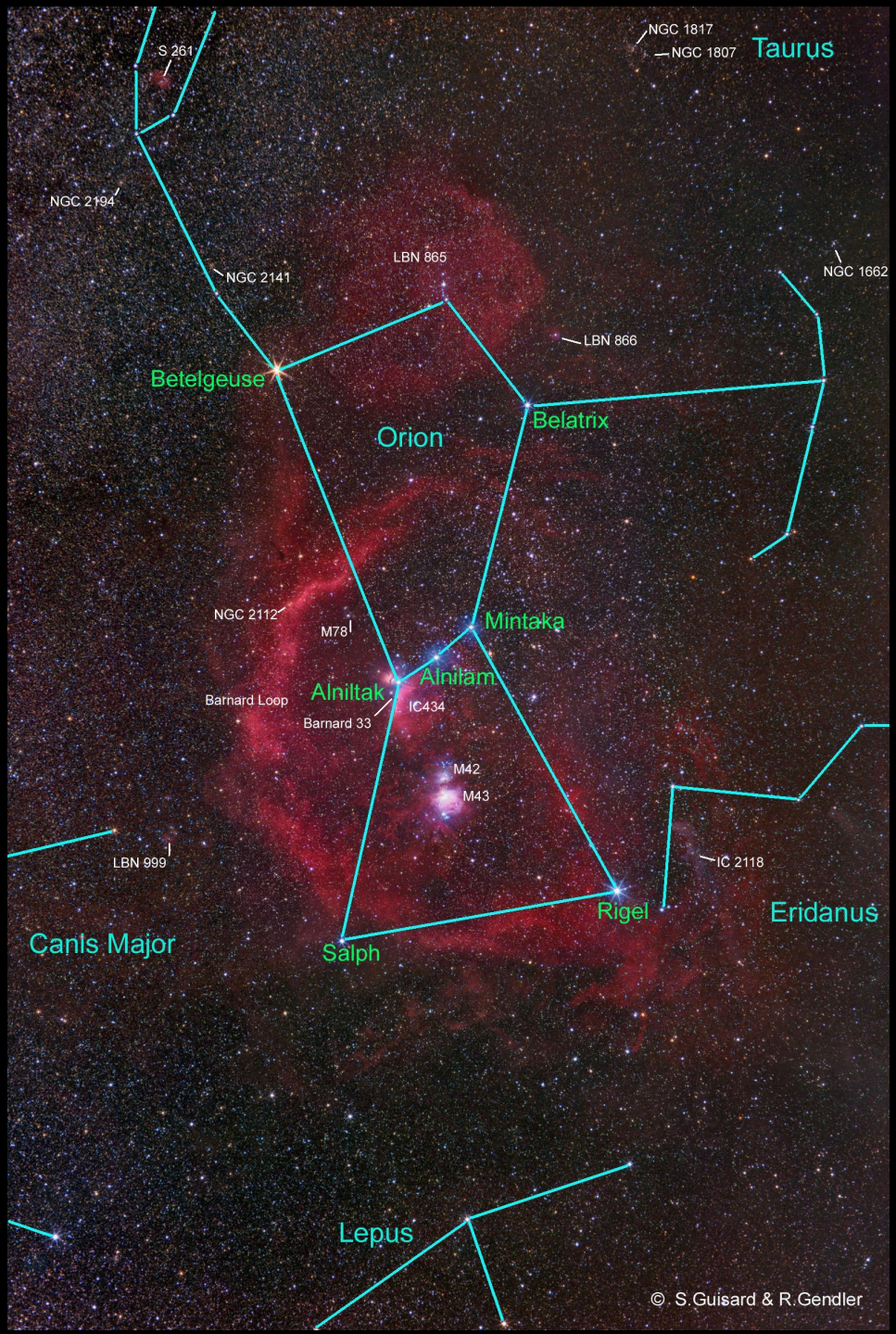


Shu et al. (1987, ARAA 25, 23, Fig. 7)

Stellar wind forms bipolar outflow



Orion (Bayer's Uranometria; image ©USNO)


S 261
NGC 1817
NGC 1807
Taurus
NGC 2194
NGC 2141
LBN 865
NGC 1662
LBN 866
Betelgeuse
Belatrix
Orion
NGC 2112
M78
Mintaka
Alnilam
Alniltak
Barnard Loop
IC434
Barnard 33
M42
M43
LBN 999
IC 2118
Rigel
Eridanus
Canis Major
Salph
Lepus
© S.Guisard & R.Gendler



Movie Time: `movies/starformation_movies/orion_zoom.mov` from `http://hubblesite.org/newscenter/archive/releases/2006/01/`



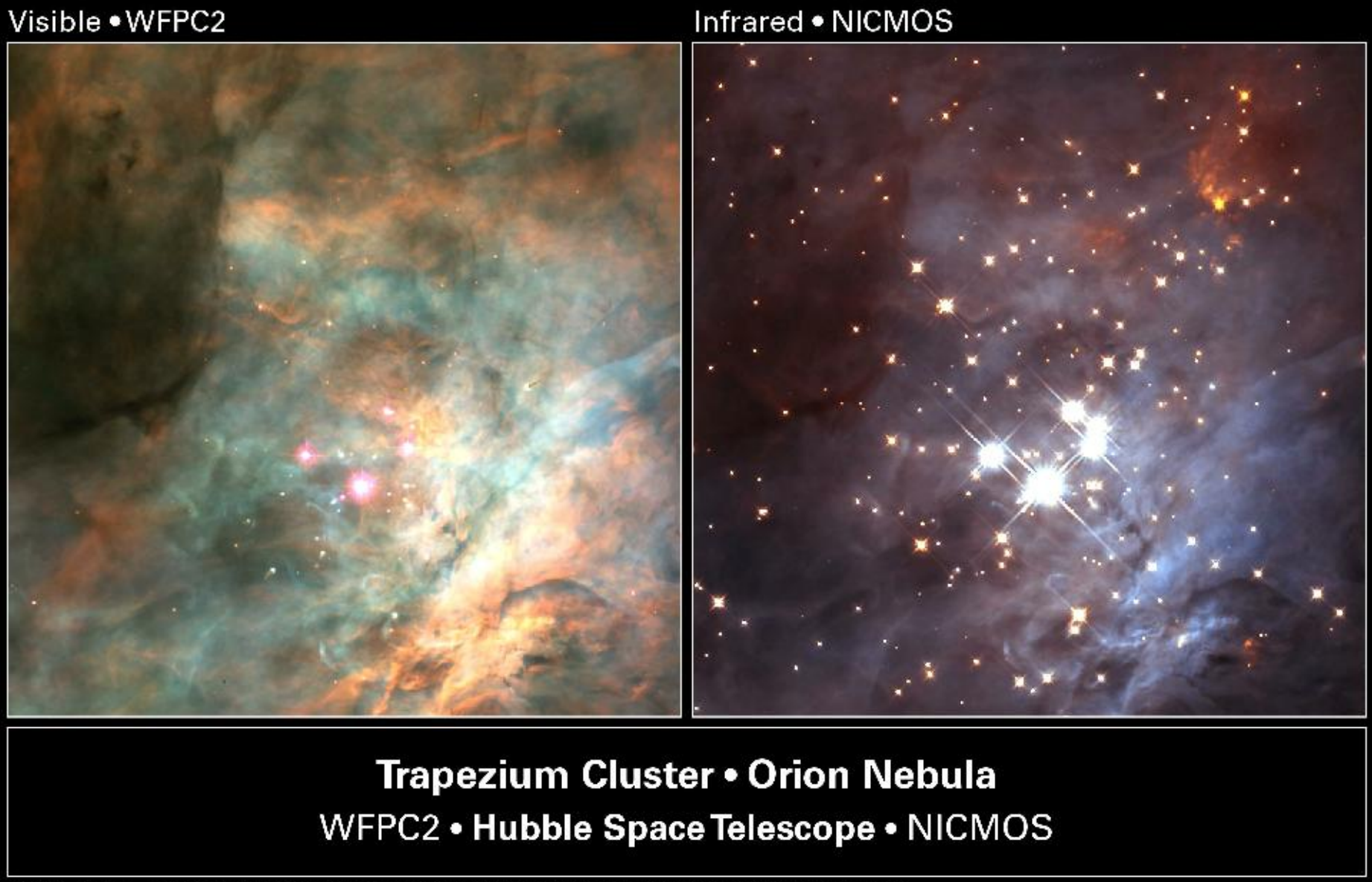

Orion Nebula
M42, M43
HST ACS/WFC
F658N Hα
F775W *i* + F850LP *z*
F555W *V*
F435W *B*
5 light-years
1.5 parsecs
11′
N
E



Orion Nebula; R. Gendler



Orion Nebula; R. Croman



Trapezium cluster: source of ionizing radiation

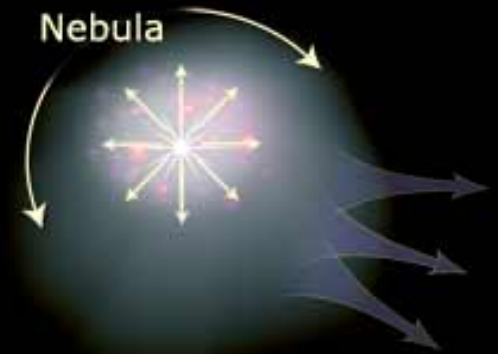


Evolution of the Orion Nebula (M42)*

Radiation and wind from a nebula's stars push surrounding gas away, creating cavities within the nebula's cloud. In the Orion Nebula, several hot, young central stars, called the Trapezium, have carved out the core of the nebula. This cavernous core has broken through the part of the cloud that faces Earth, enabling Hubble and other telescopes to observe within.



The central (Trapezium) stars begin to burn hydrogen. Ultraviolet radiation ionizes the central environment and produces a bubble.



The bubble swells until it reaches the edge of the neutral nebula and then opens, allowing material to flow away.

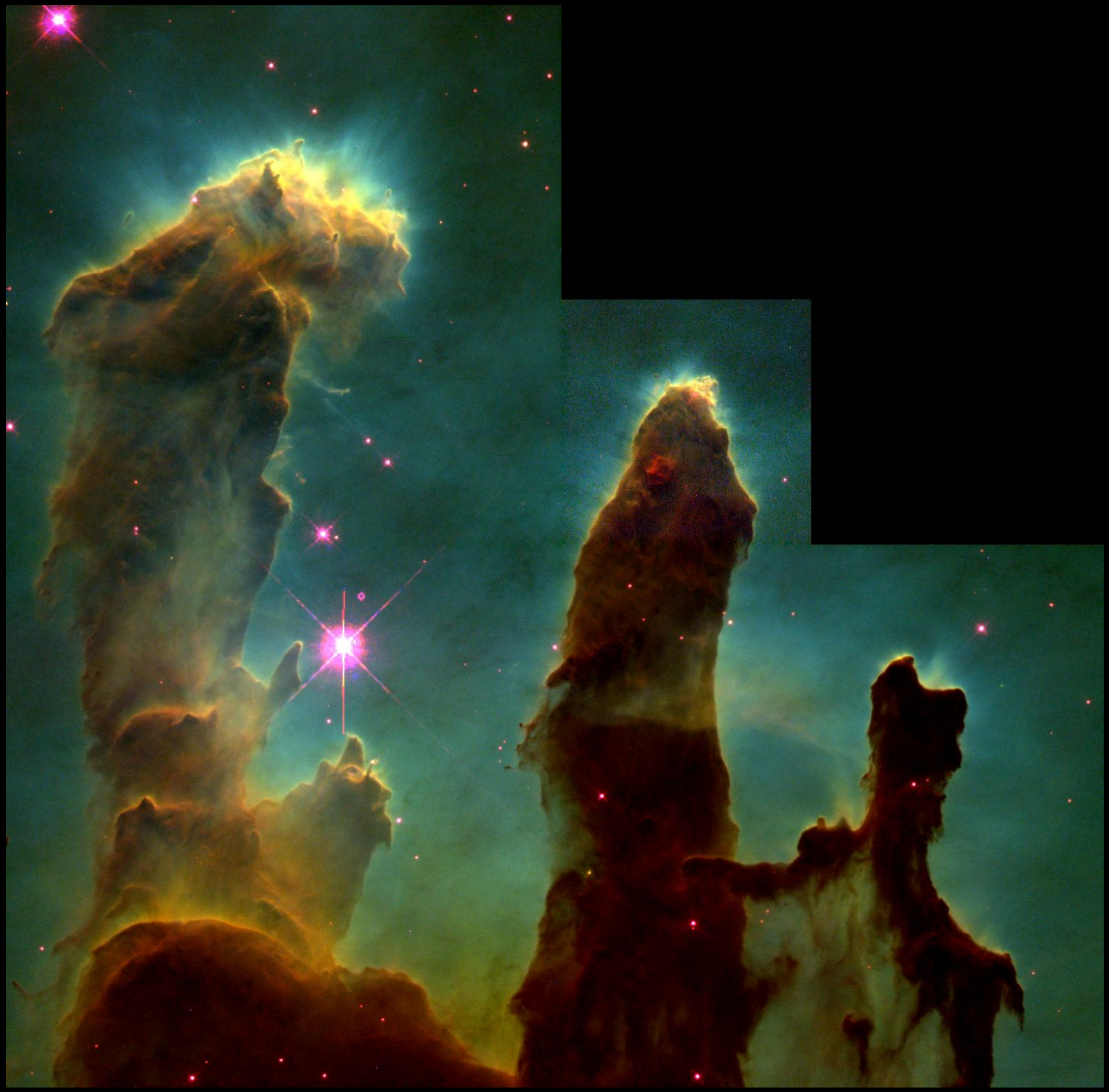


What remains is an empty cavity filled by ultraviolet light and winds from the stars and the cavity walls.

**The Orion Nebula is approximately 1,500 light-years from Earth.*



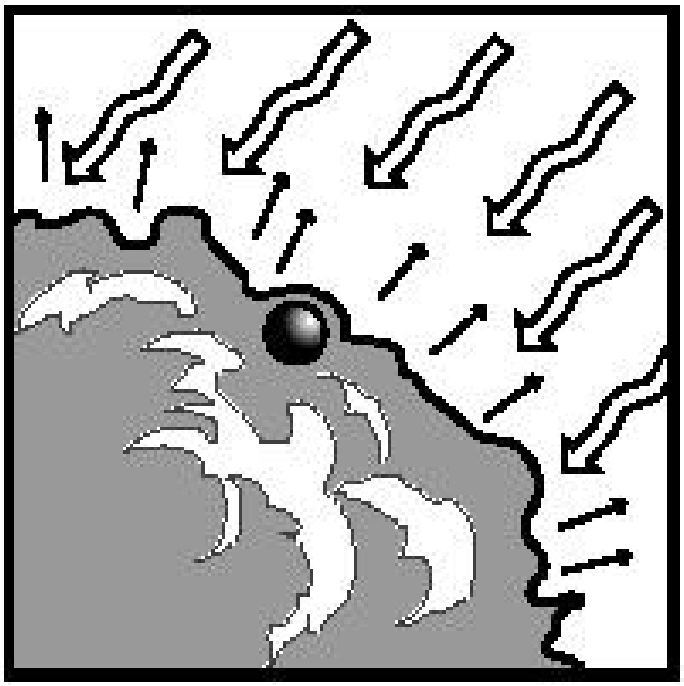
Eagle-nebula (M16)



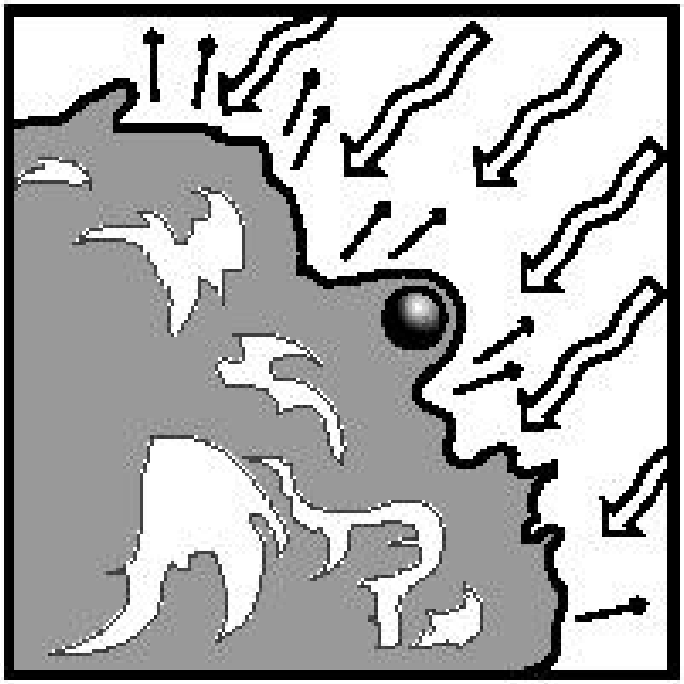
"pillars of creation" in Eagle Nebula (M16)

also known as evaporating gaseous globules (EGGs)

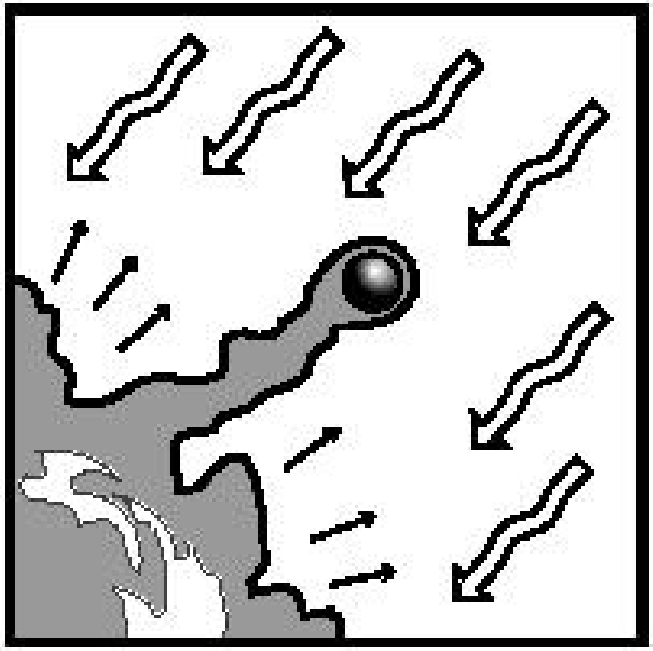
Stellar EGGs in M16



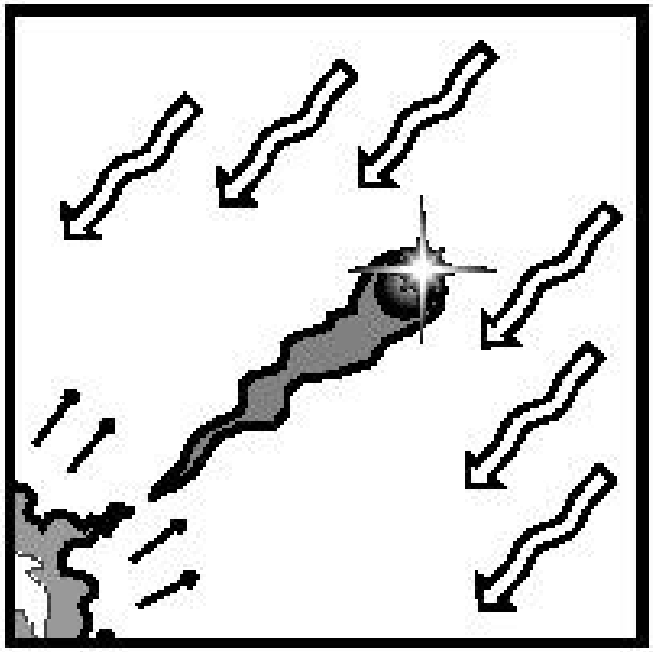
The surface of a molecular cloud is illuminated by intense ultraviolet radiation from nearby hot stars. The radiation evaporates material off of the surface of the cloud.



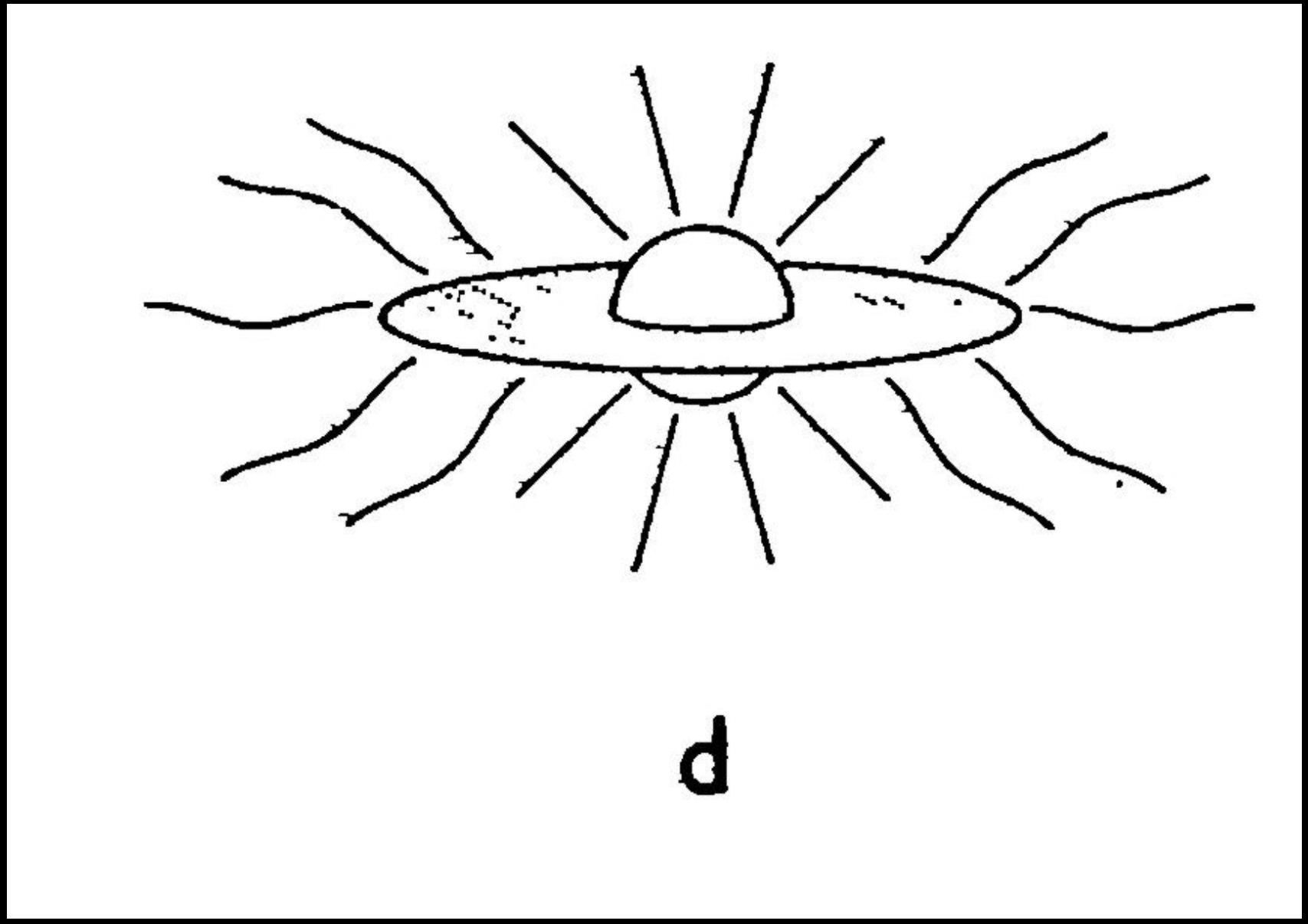
As the cloud is slowly eaten away by the ultraviolet radiation, a denser than average globule of gas begins to be uncovered



The EGG has now been largely uncovered. The shadow of the EGG protects a column of gas behind it, giving it a fing er-like appearance.



Eventually the EGG may become totally separated from teh molecular cloud in which it formed. As the EGG itself slowly evaporates, the star within is uncovered and may appear sitting on the front surface of the EGG.



Shu et al. (1987, ARAA 25, 23, Fig. 7)

Star has reached zero age main sequence (ZAMS) plus circumstellar disk.
Some disks produce fast collimated outflows (jets): Herbig Haro Objects



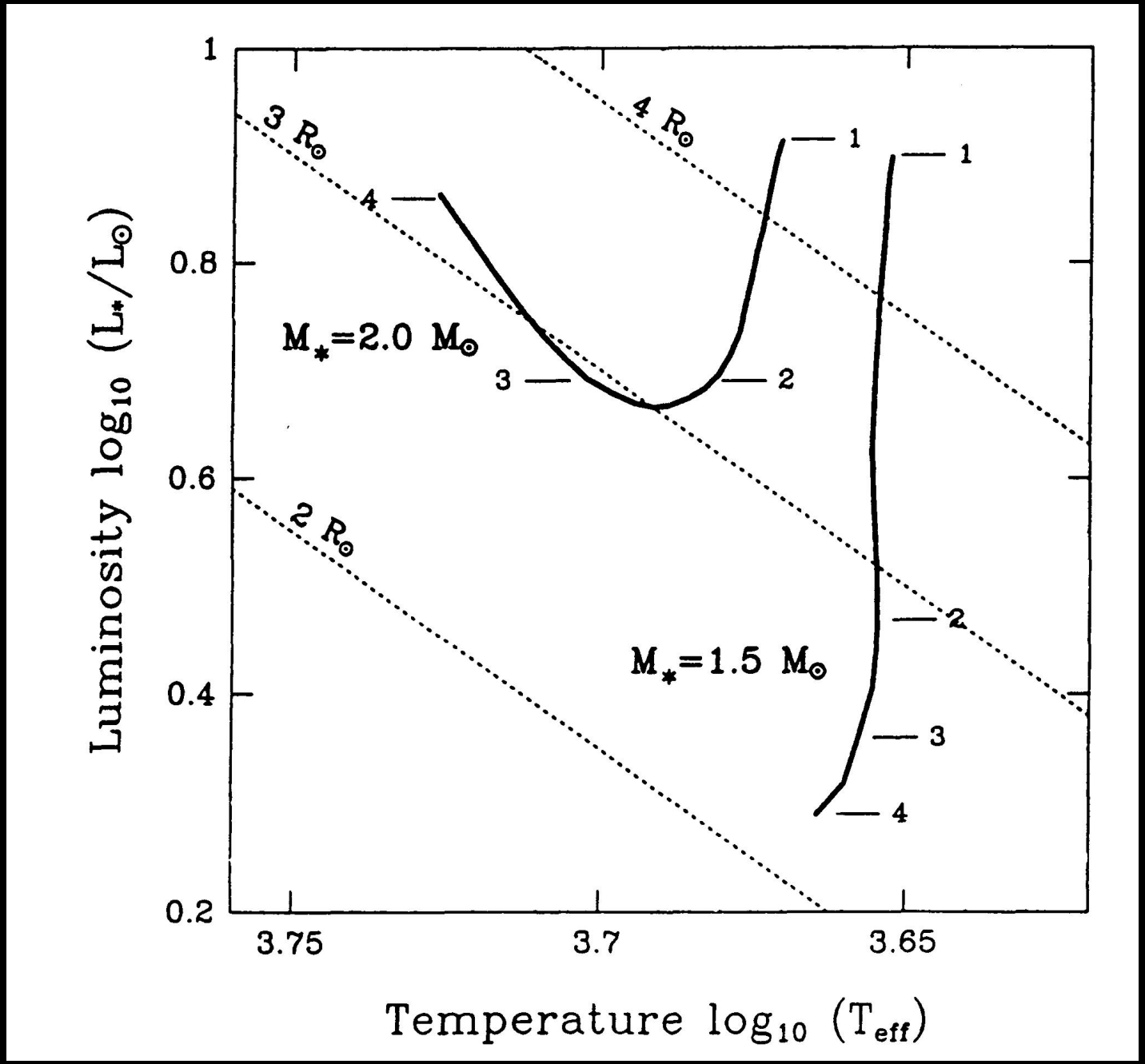
HH34 in Orion (ESO VLT KUEYEN/FORS2)

Herbig Haro Objects: shocks and jets/outflows produced during formation of stars.



Pleiades (R. Gendler; $d = 150\,pc$, diameter: $5\,pc$, 3000 stars

Once stars have formed, strong UV radiation removes residual dust (still seen as a reflection nebula) and an open cluster is formed.

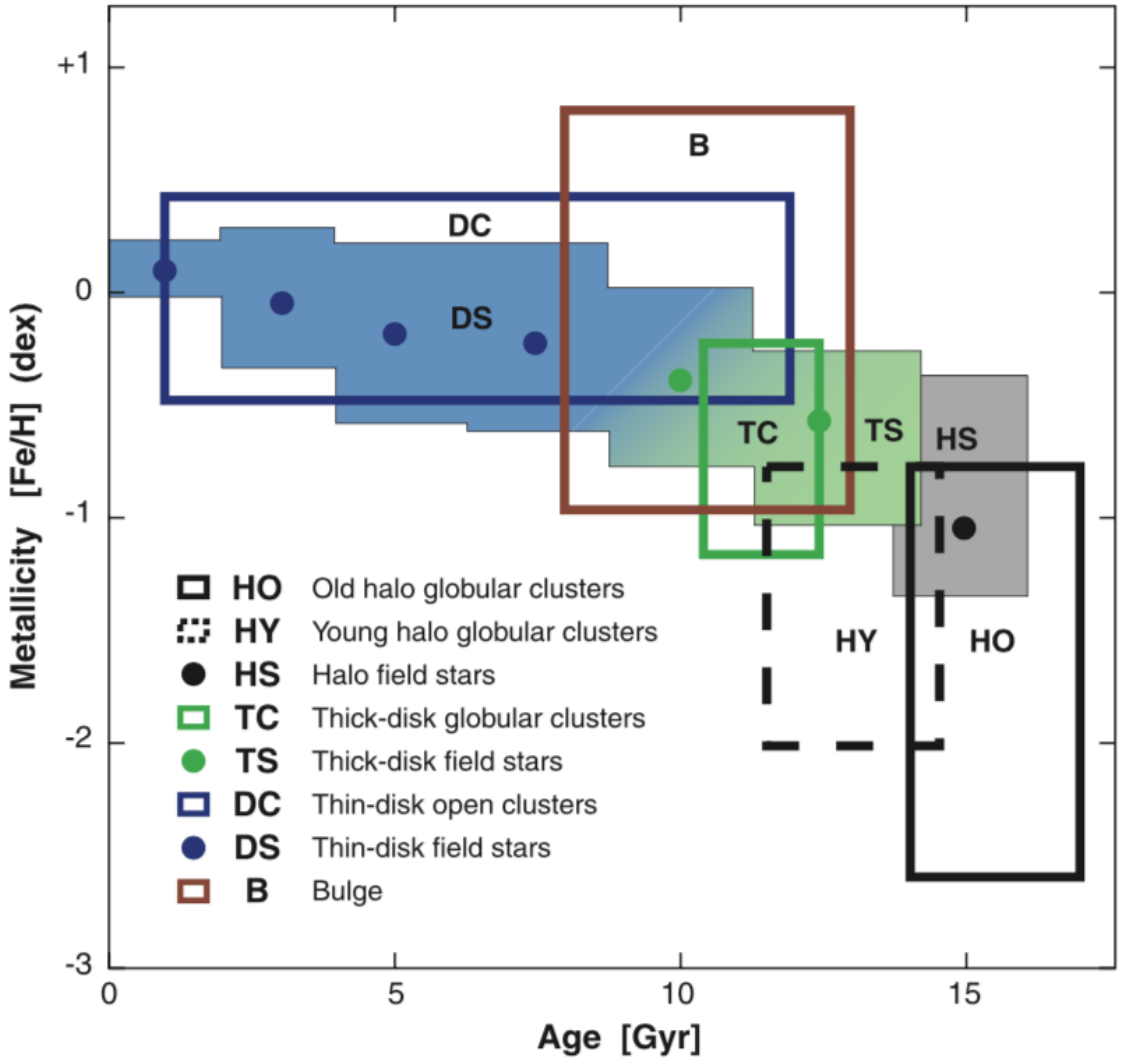


Palla & Stahler (1993, ApJ 418, 414; numbers are time in 10^6 years)

Stellar Evolution from protostar to ZAMS takes a few million years.

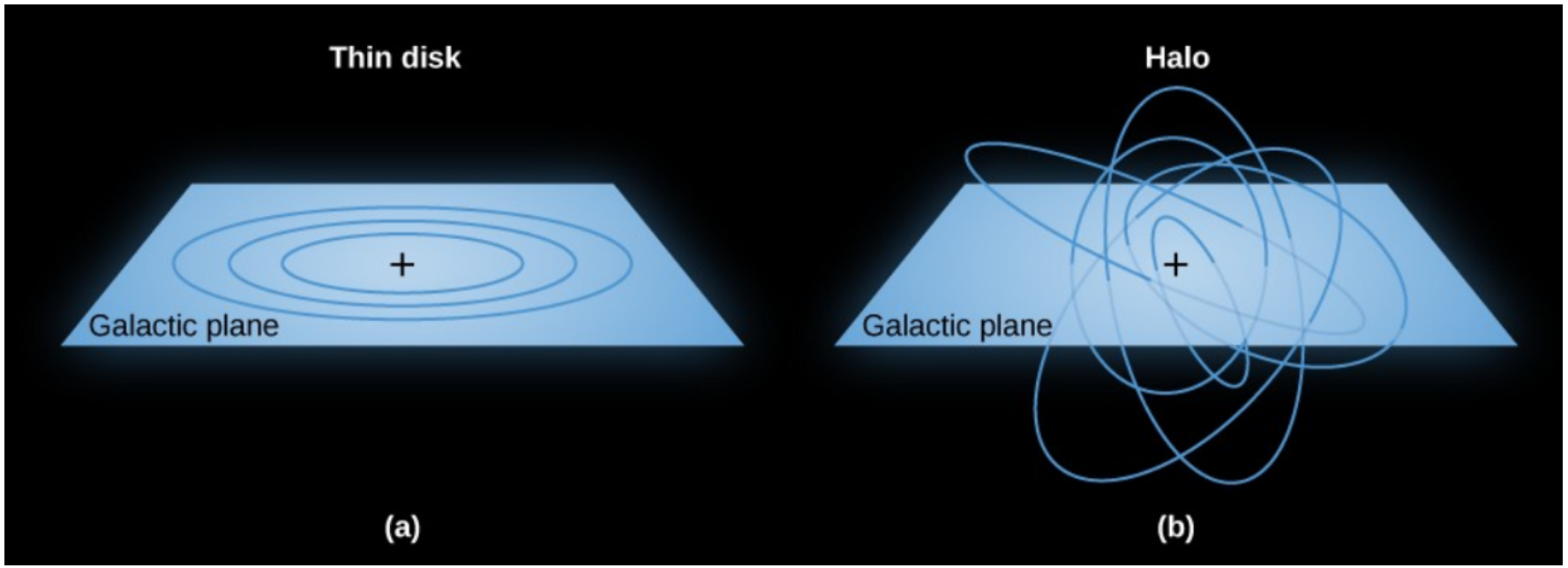
After that: normal evolution

Stellar populations



Buser (2000)

Stellar populations



Orbits of stars of population I (left) und Population II (right)

http://cnx.org/contents/2e737be8-ea65-48c3-aa0a-9f35b4c6a966@10.1

Population I: rich in metals, young. In spiral arms (disk). Sun belongs to it
Population II: poor in metals, old. In globular clusters or in bulge. On elliptical, inclined orbits in halo. High velocities.

The Path to the Galactic Center



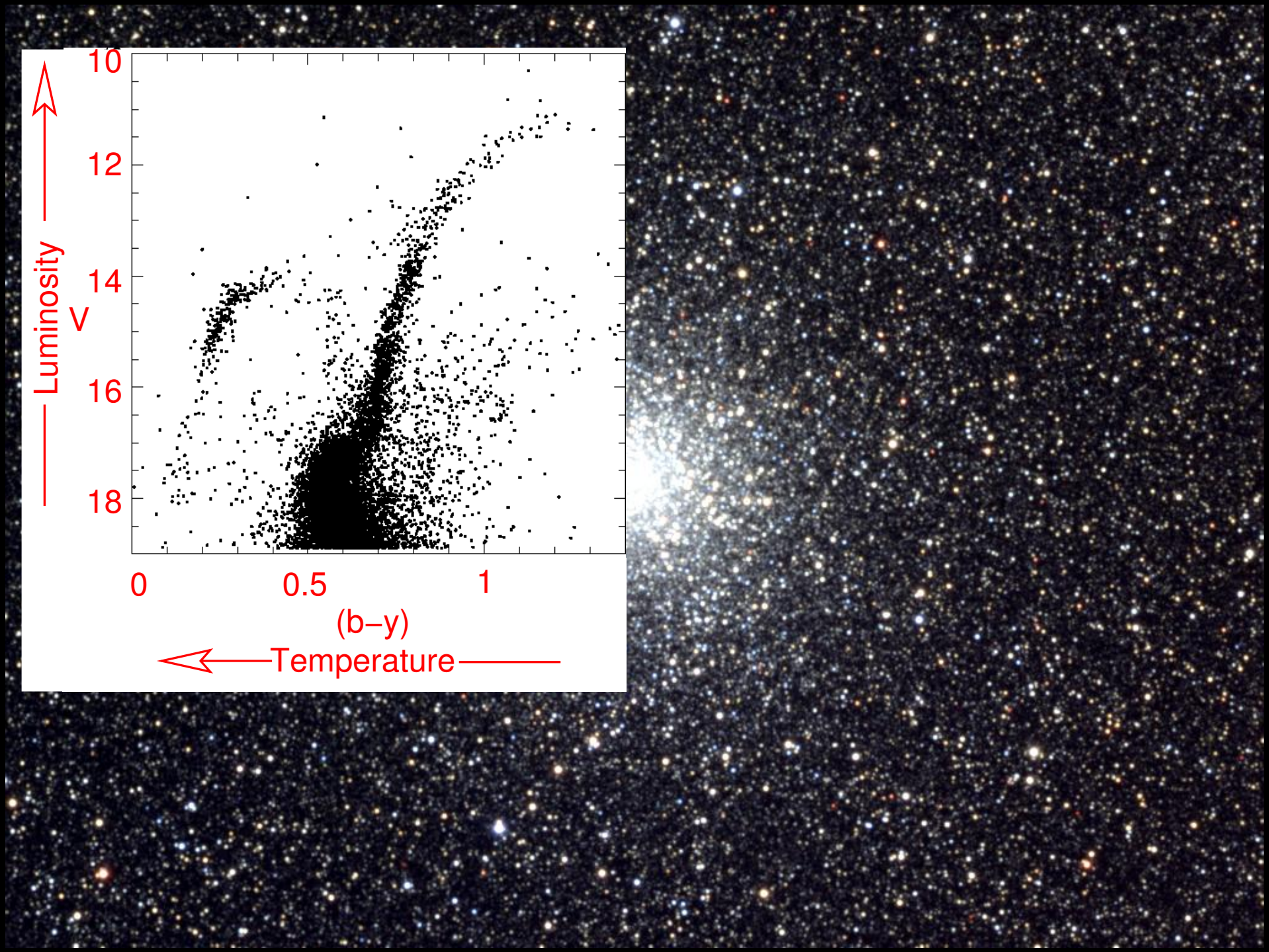
http://www.phys-astro.sonoma.edu/brucemedalists/Shapley/index.html

1918: Harlow Shapley determines distances to globular clusters using RR Lyrae stars

- Spatial distribution: spherical symmetry
- *Center of the Galaxy*: ~center of the distribution
- *Center* is located in the constellation Sagittarius

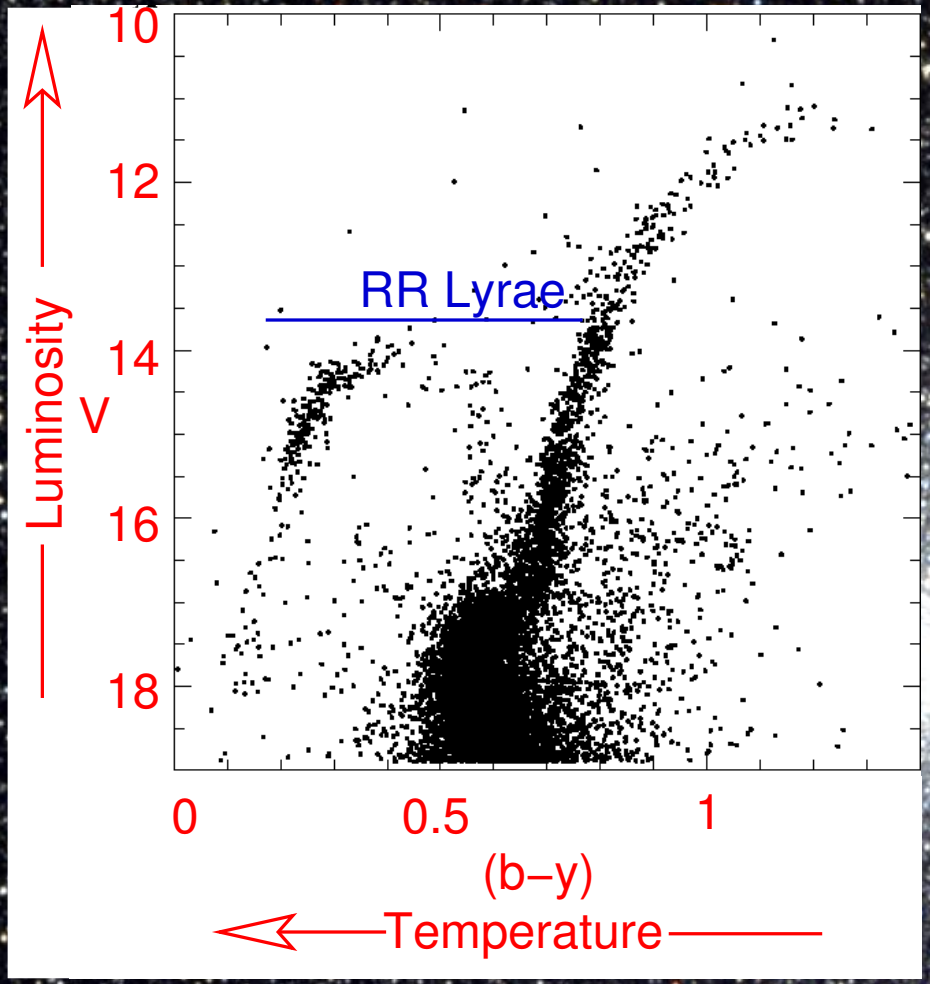


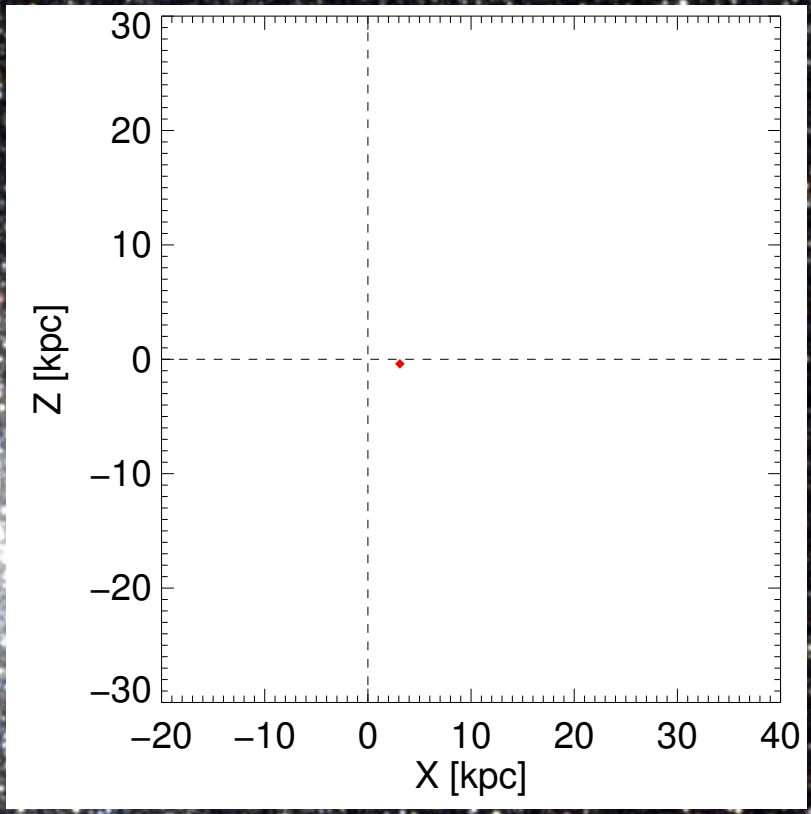
M22, KPNO (N.A.Sharp, REU program/NOAO/AURA/NSF)



Richter et al., 1999, A&A 350, 476

M22, KPNO (N.A.Sharp, REU program/NOAO/AURA/NSF)

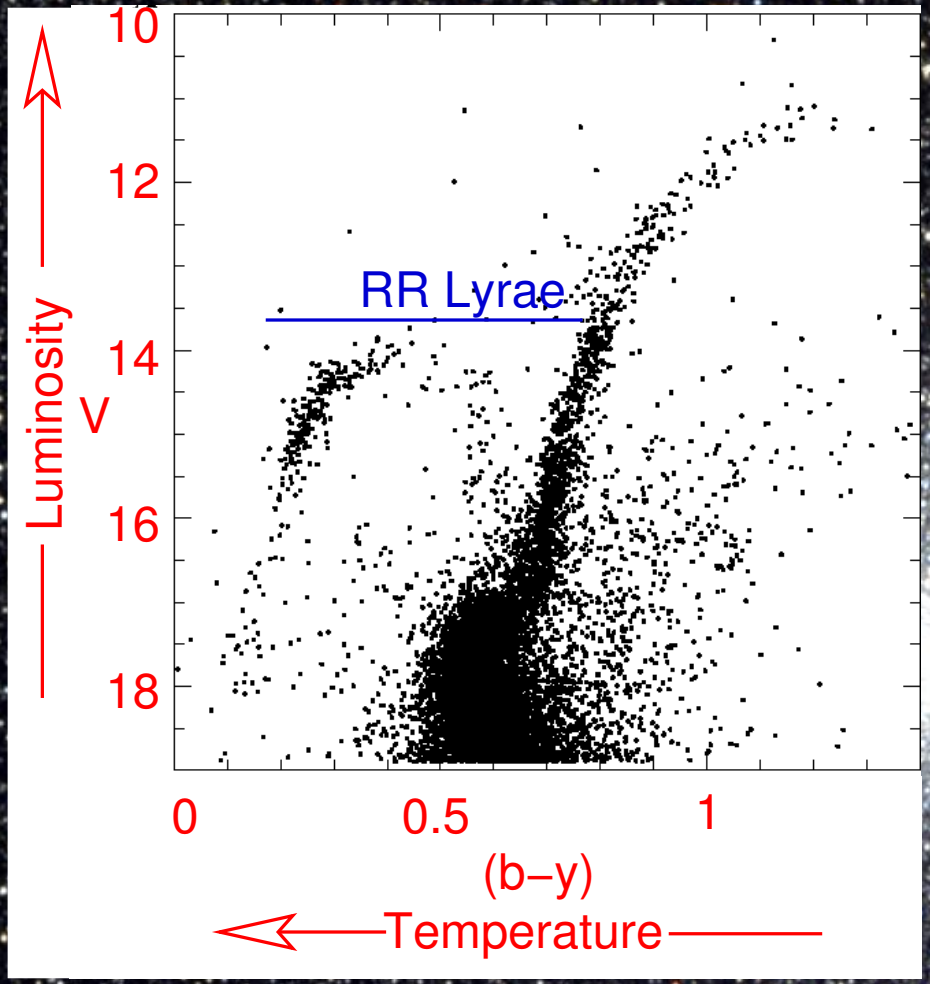


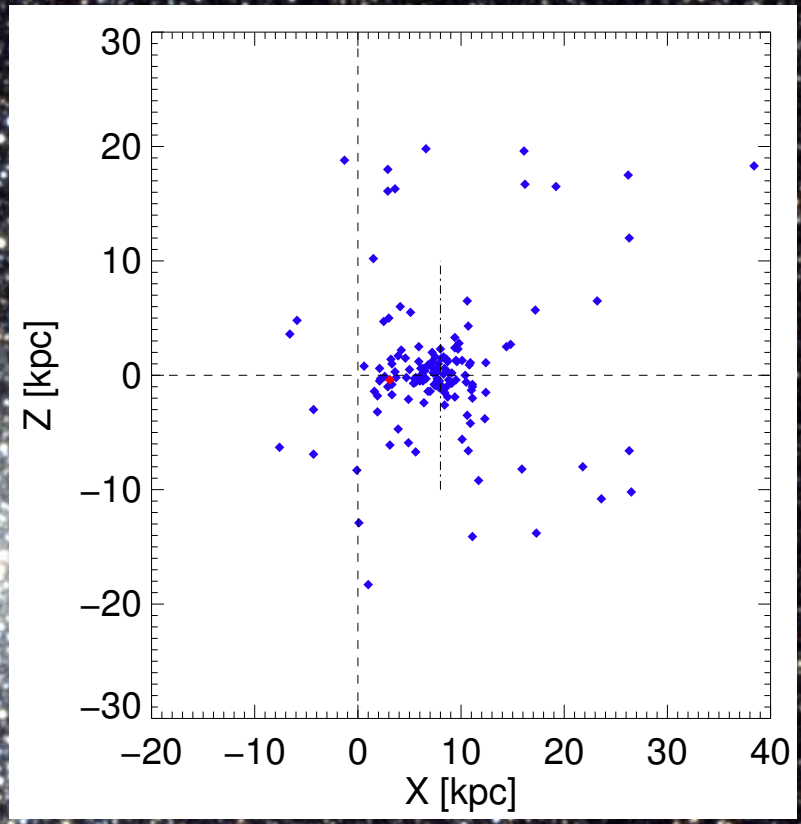


M22 has a distance of 3.2kpc

Richter et al., 1999, A&A 350, 476

M22, KPNO (N.A.Sharp, REU program/NOAO/AURA/NSF)





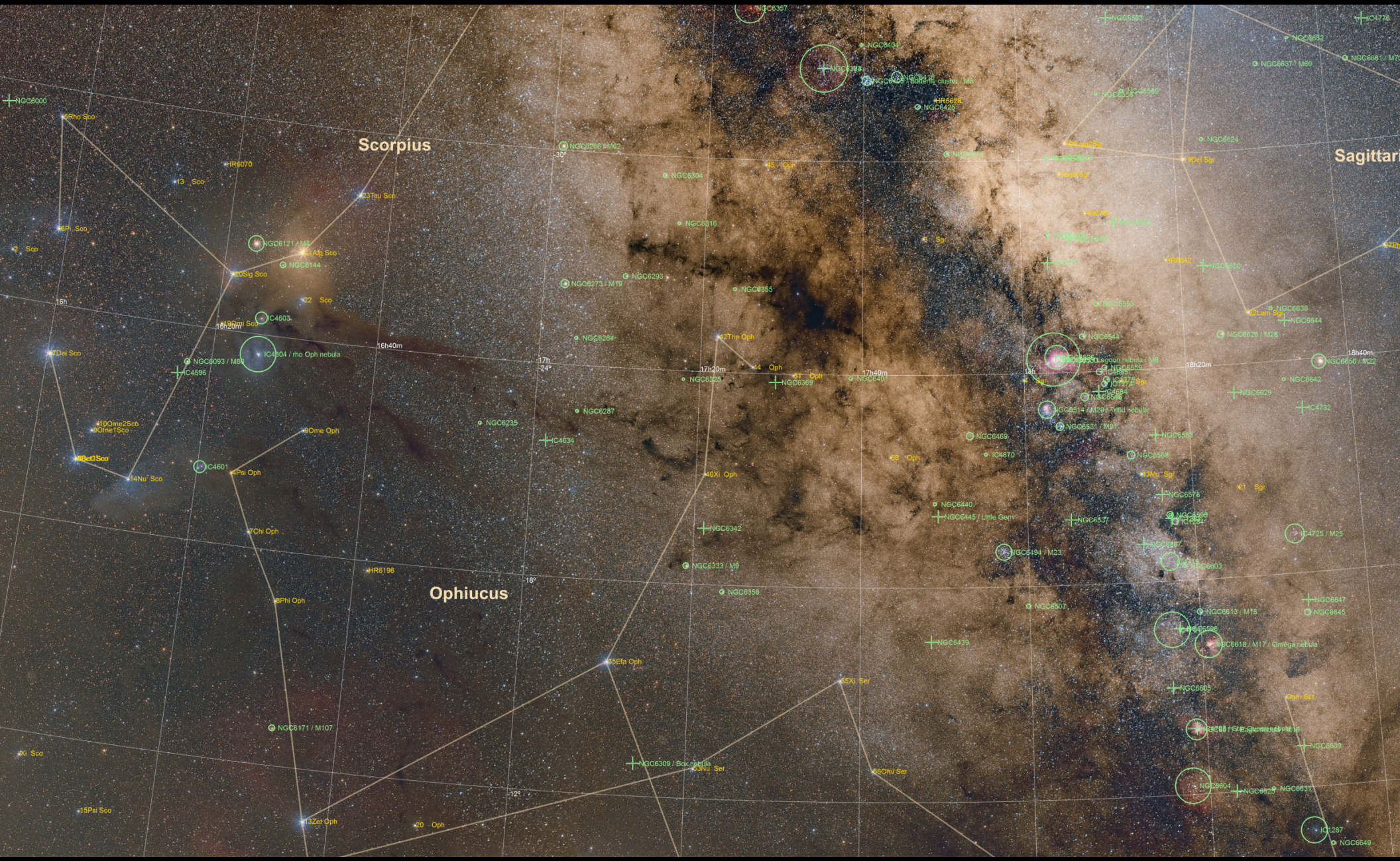
Galactic center has a distance of 8kpc

Richter et al., 1999, A&A 350, 476

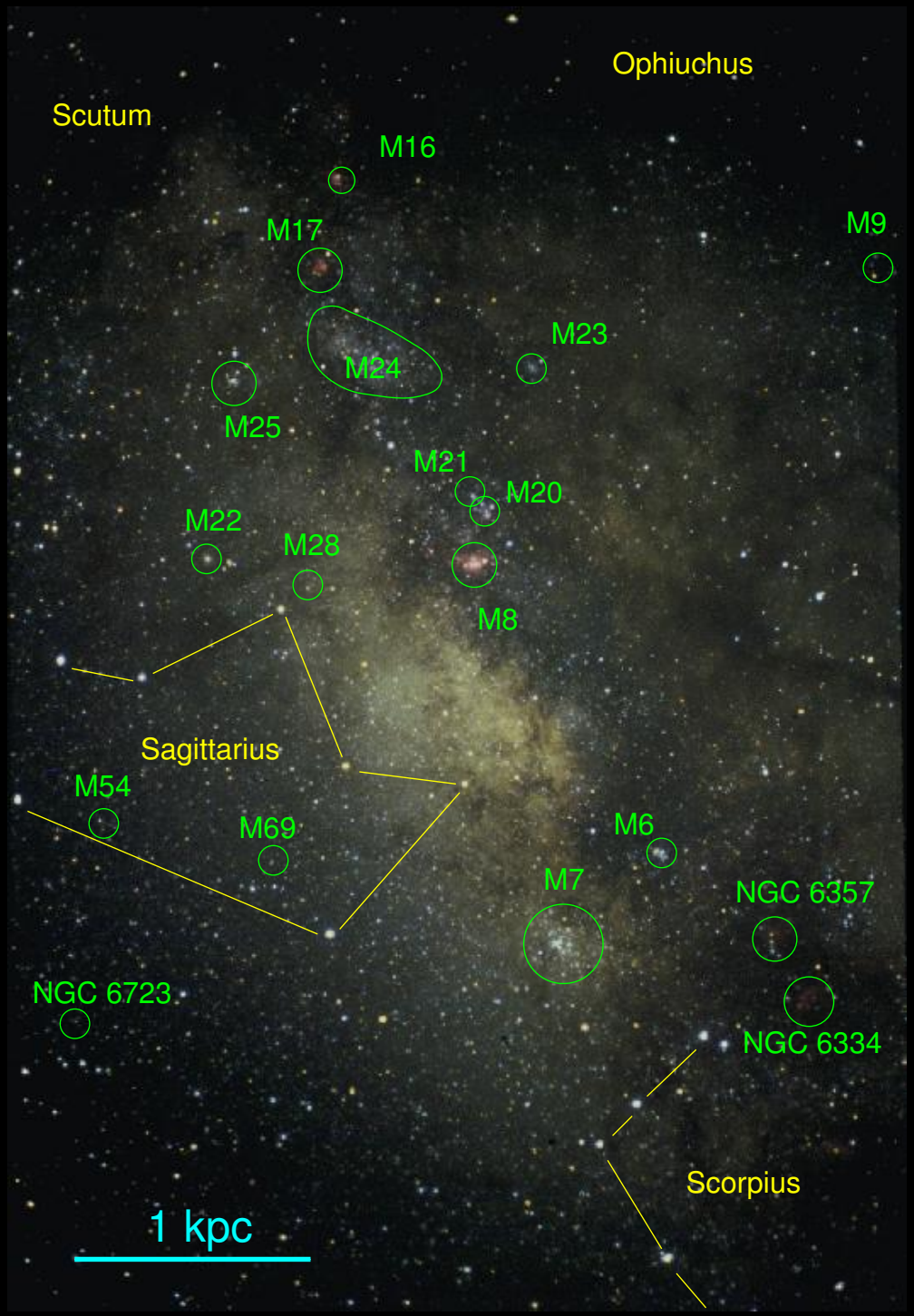
M22, KPNO (N.A.Sharp, REU program/NOAO/AURA/NSF)



http://www.pampaskies.com/gallery3/Wide-Field/orion-1317612650 (Ignacio Diaz Bobillo)



http://www.pampaskies.com/gallery3/Wide-Field/orion-1317612650 (Ignacio Diaz Bobillo)



W. Keel (U Alabama)

Milky way in Sagittarius

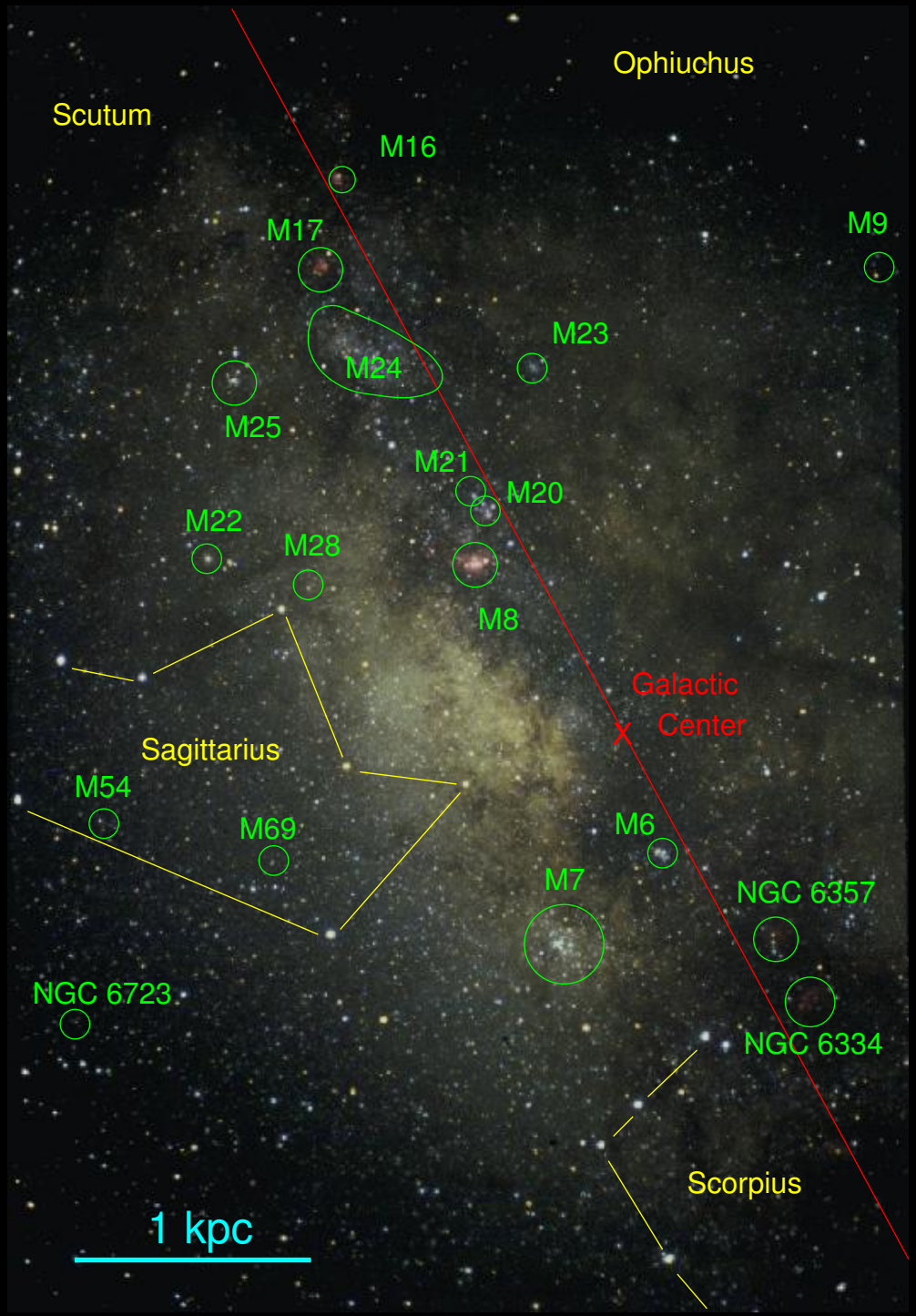
$27^\circ \times 40^\circ$

Distance: 8 kpc

$\Longrightarrow 1^\circ \sim 140$ pc

$\Longrightarrow 1' \sim 2$ pc

$\Longrightarrow 1'' \sim 0.03$ pc



W. Keel (U Alabama)

Milky way in Sagittarius

$27^\circ \times 40^\circ$

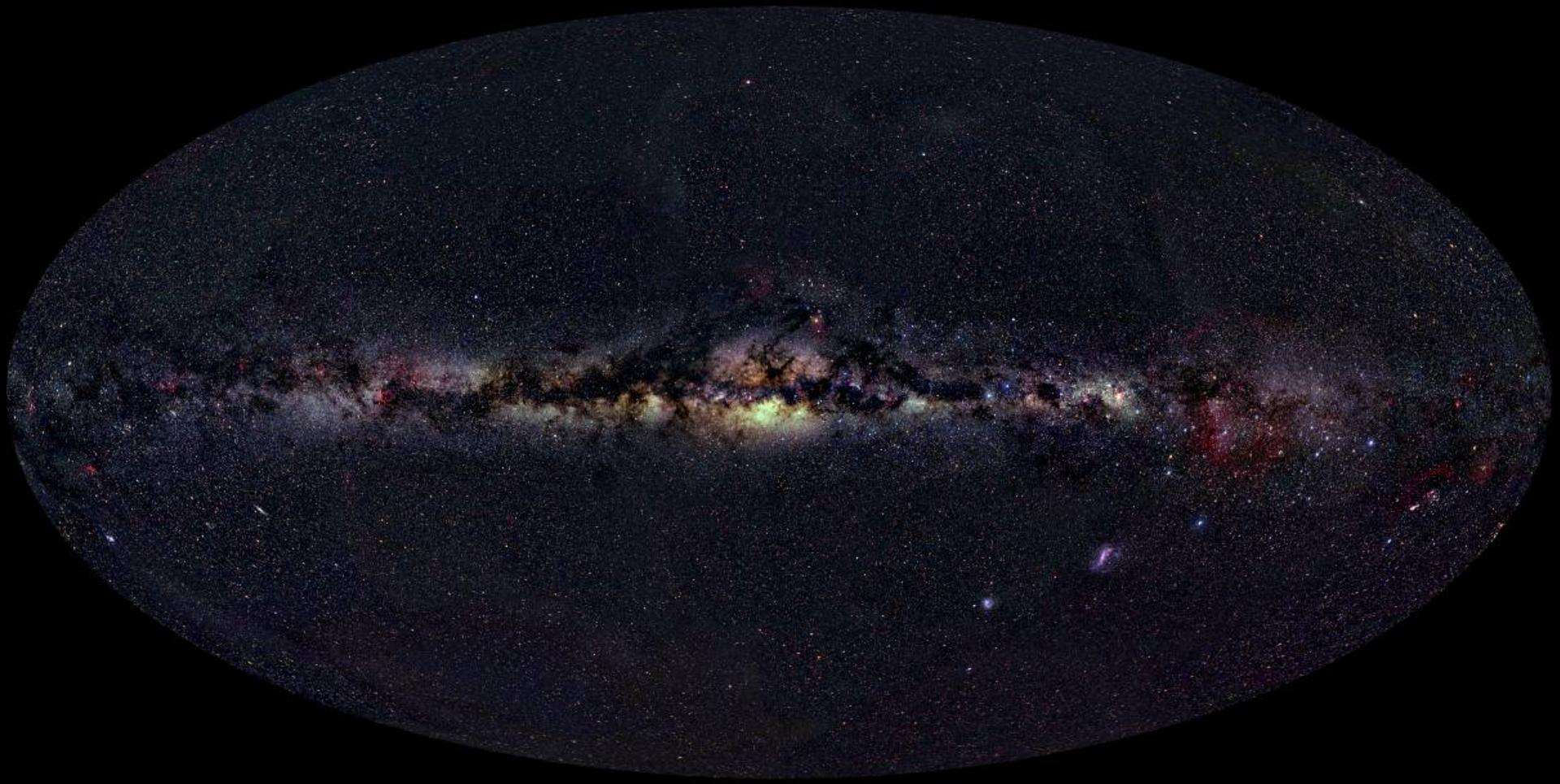
Distance: 8 kpc

$\Longrightarrow 1^\circ \sim 140$ pc

$\Longrightarrow 1' \sim 2$ pc

$\Longrightarrow 1'' \sim 0.03$ pc

The Deep Sky

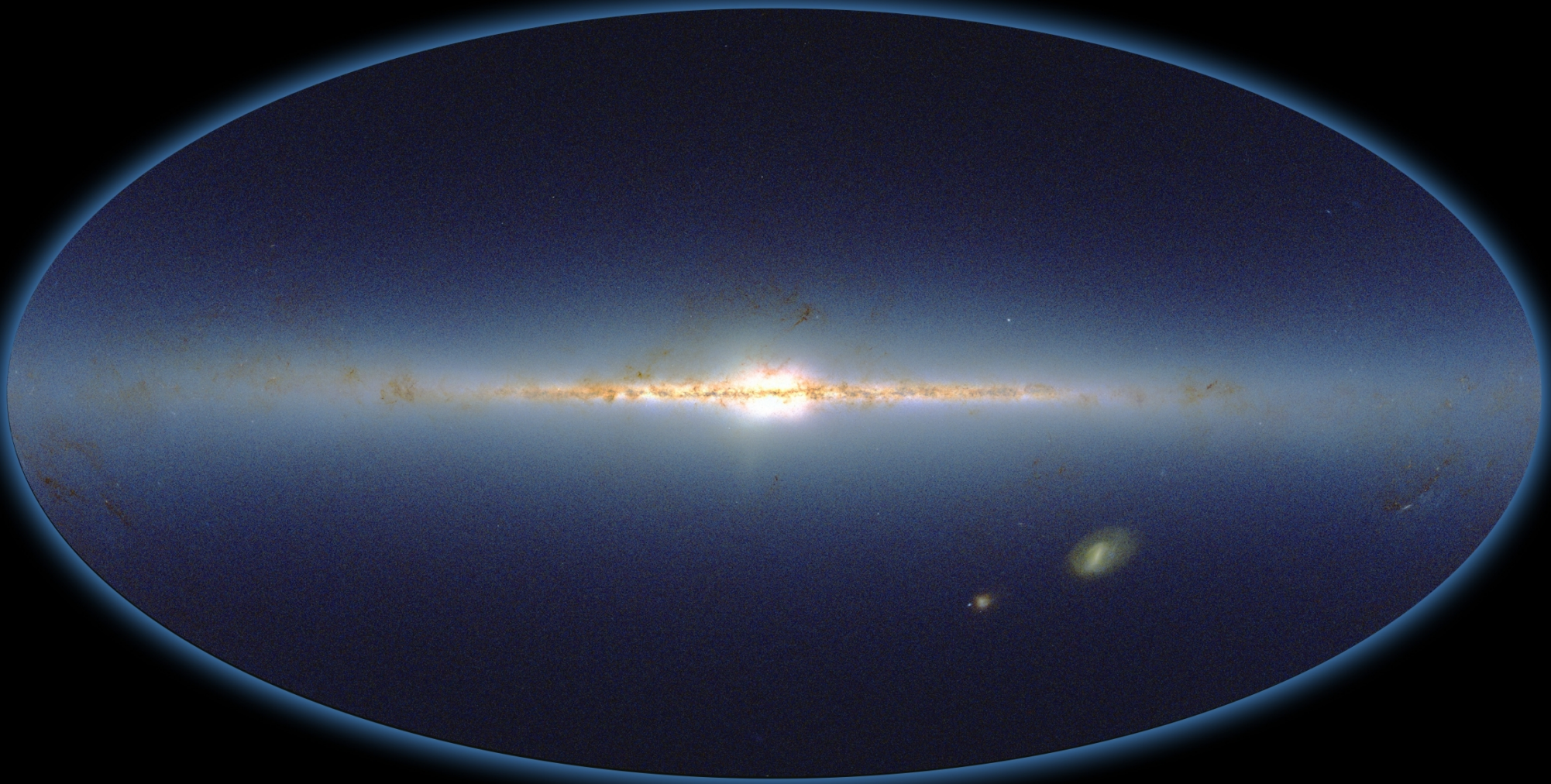


Problem: strong extinction due to dust

($A_V \sim 30$ mag: 10^{12} times reduction in the optical!)

$\Longrightarrow$ Multiwavelength astronomy!

2MASS Covers the Sky

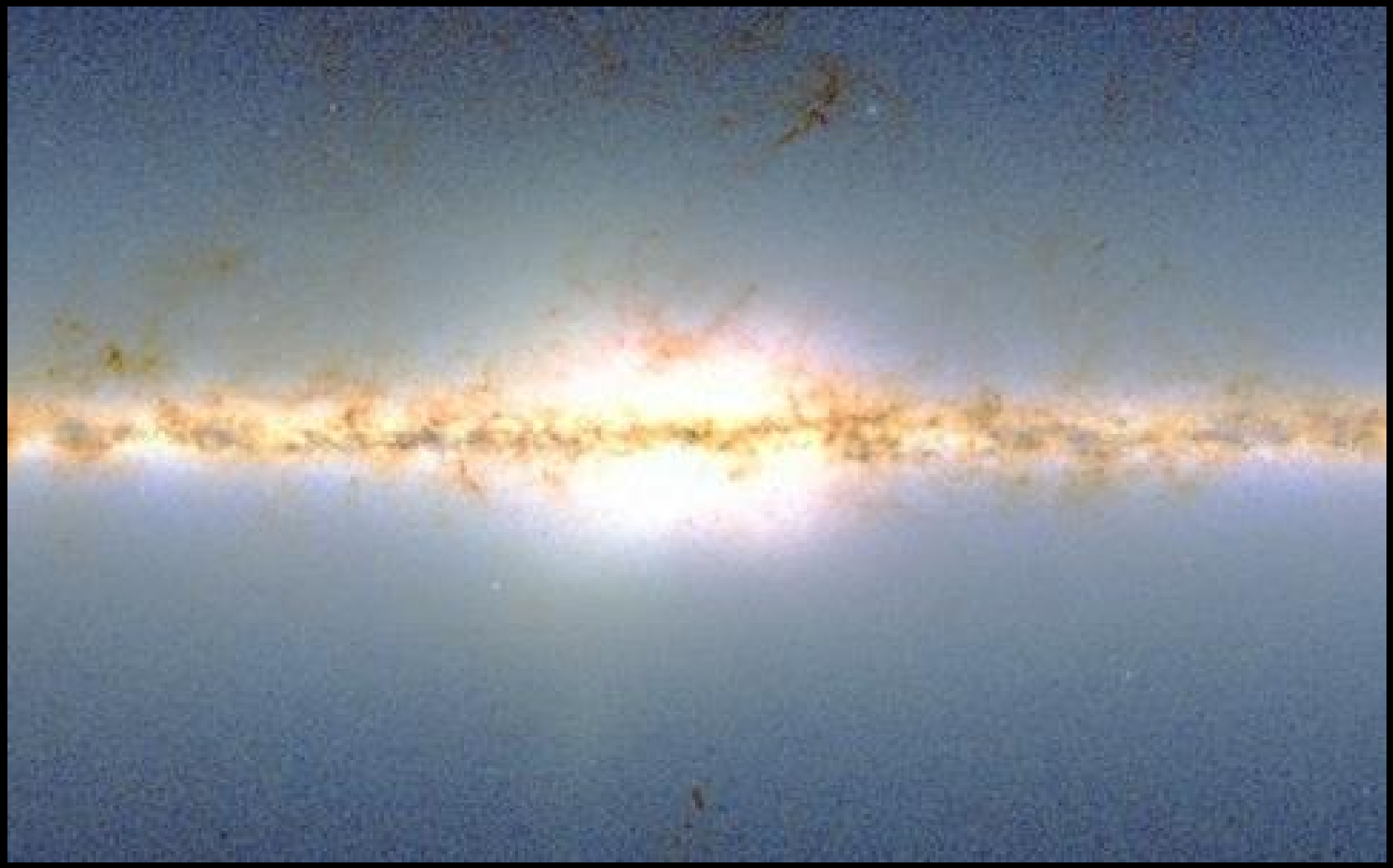


The Two Micron All Sky Survey

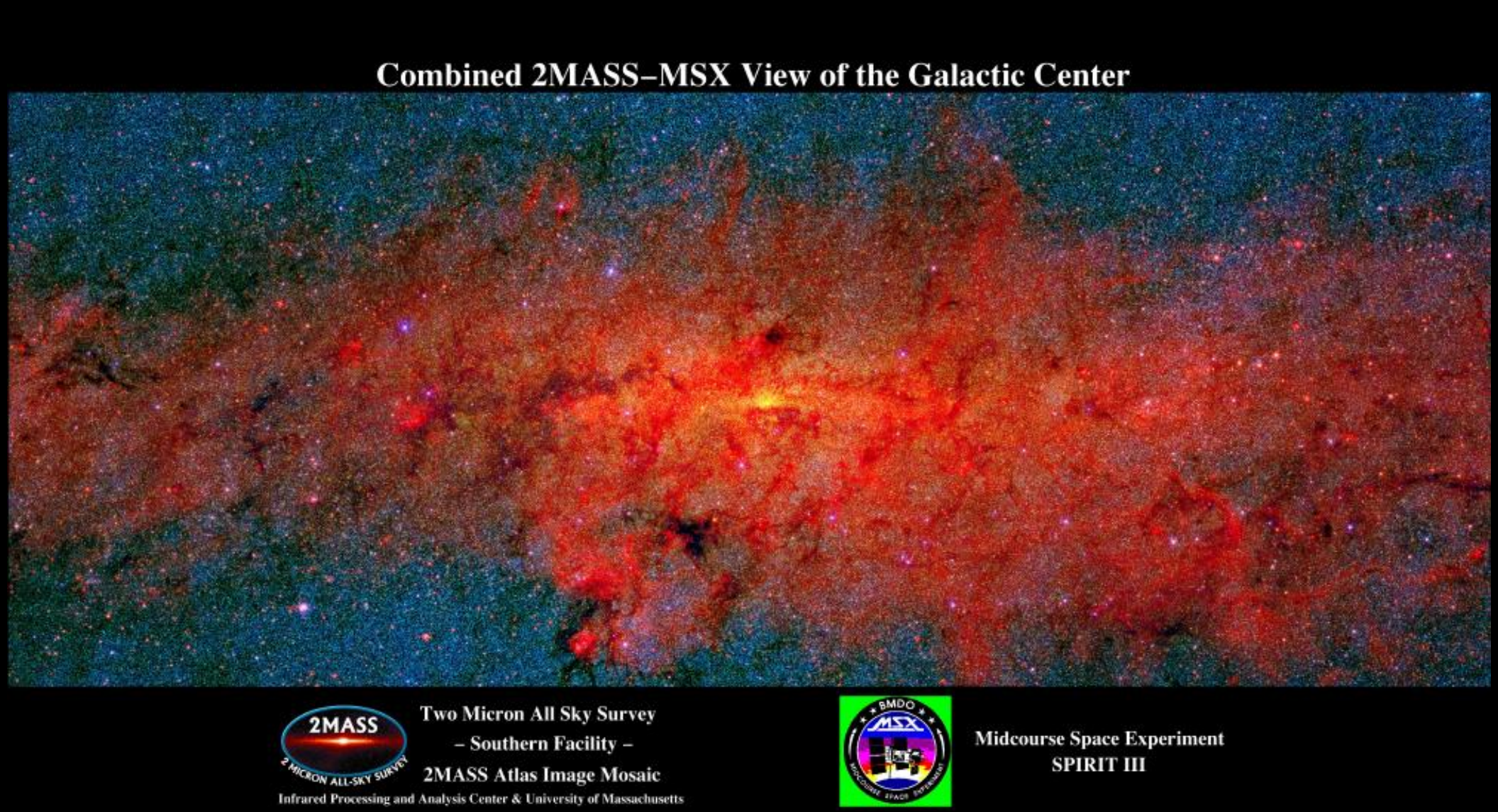
Infrared Processing and Analysis Center/Caltech & Univ. of Massachusetts

Infra red: Dust becomes transparent!

2MASS: 3 IR Bands: J (1.25 μm), H (1.65 μm), K_s (2.17μm)

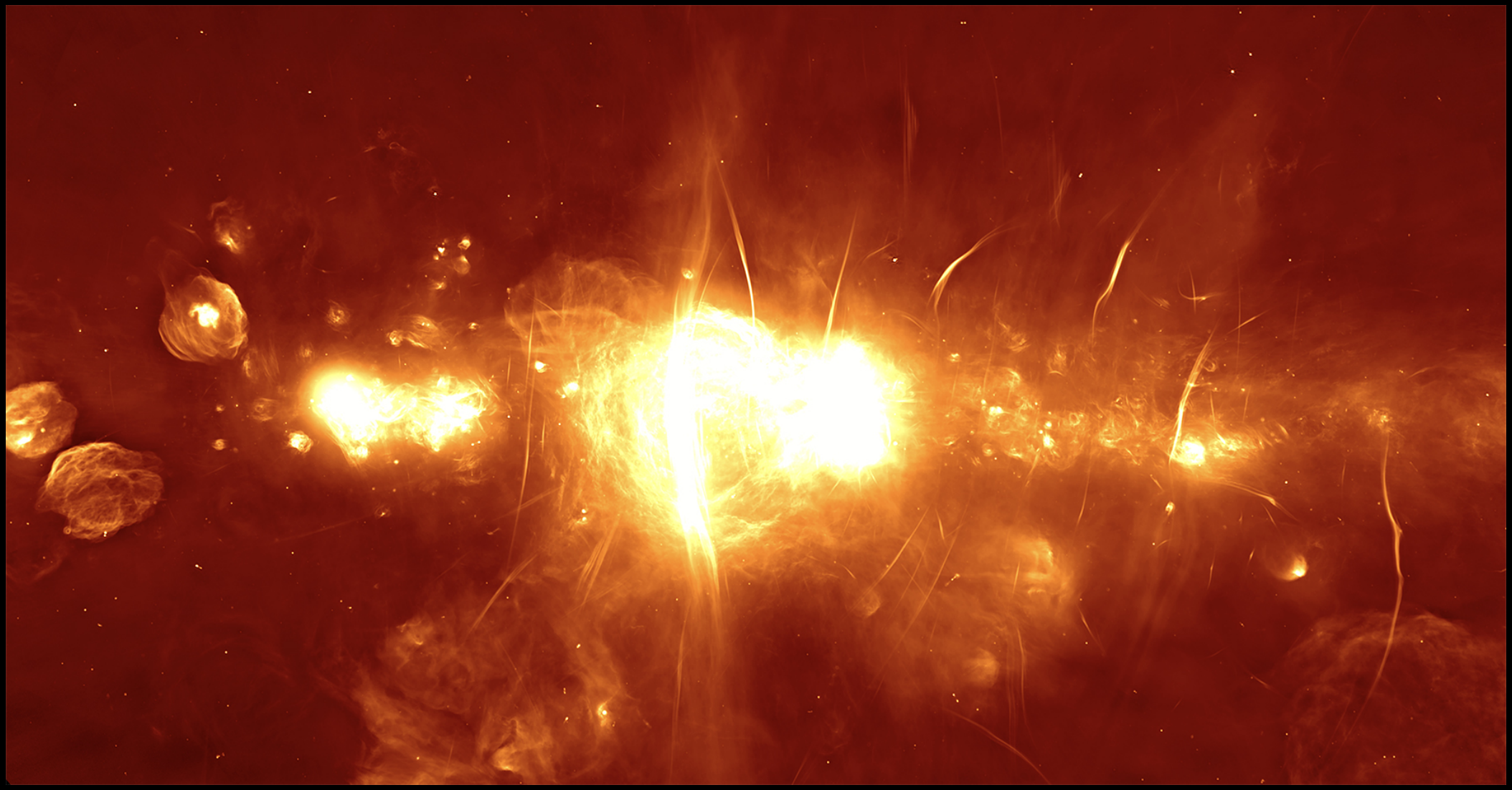


2MASS: inner $60^\circ \times 45^\circ$



2MASS/MSX: Inner $4^\circ \times 2^\circ$

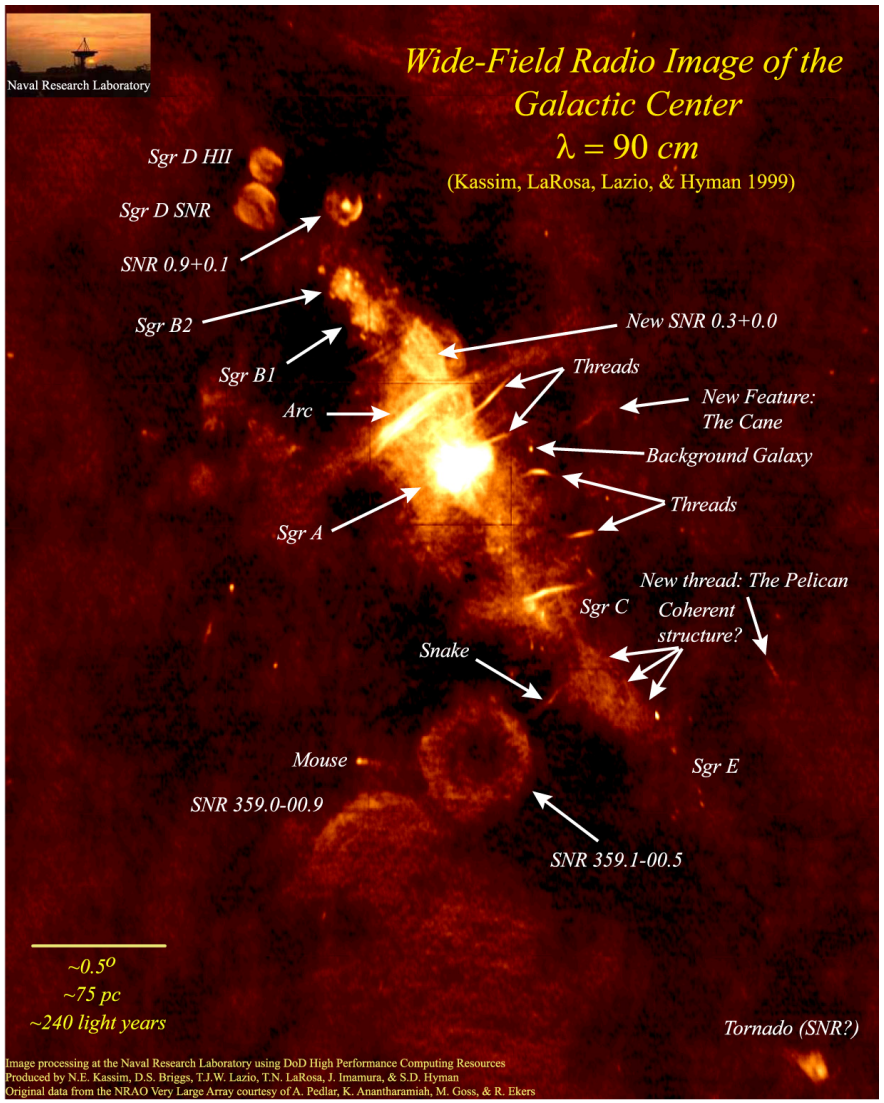
2MASS (J [1.25 μm], red), (K [2.17 μm], green), MSX (A [6–11 μm], blue)



MeerKAT

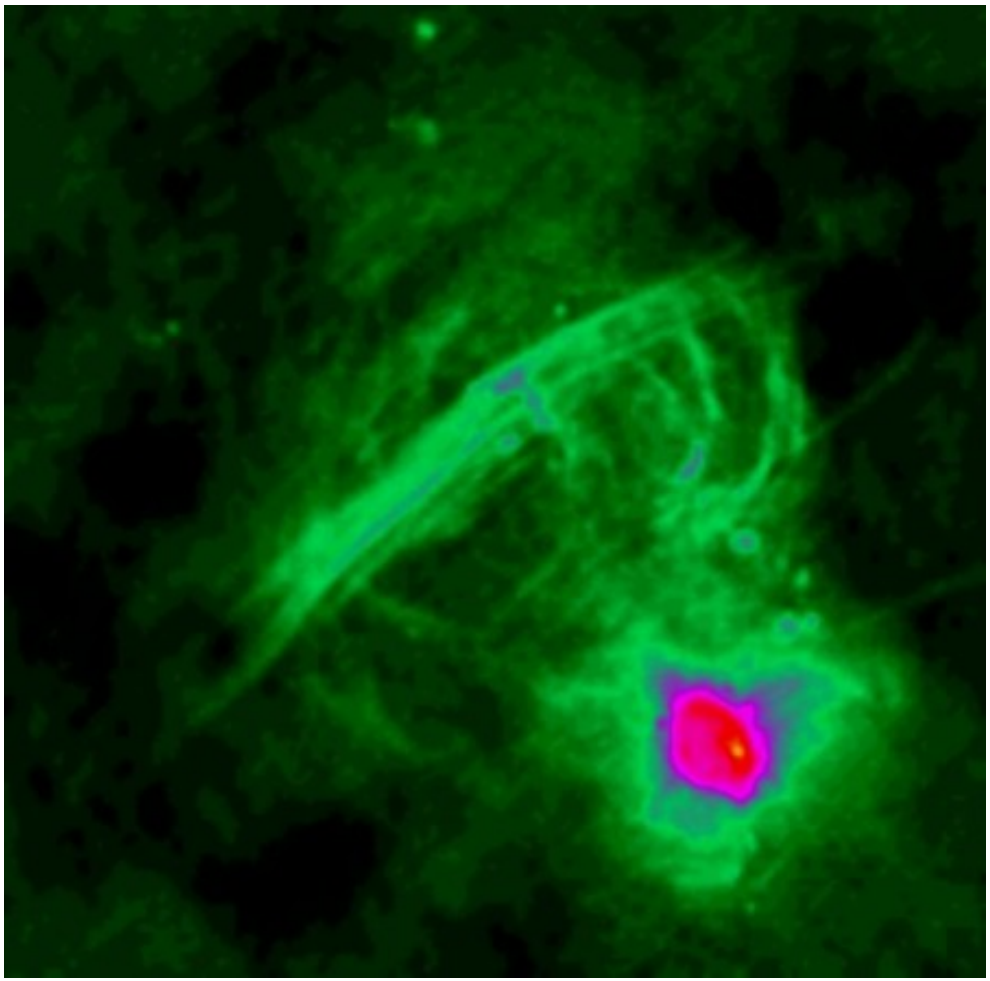
Radio image of the Galactic Center region

The Galactic center



- the stellar density rises towards a sharp central peak.
- Galactic gas disc has a central hole of 3 kpc radius
- dense nuclear gas disc (R = 1.5 kpc) within the central gas hole
  - neutral hydrogen
  - mostly molecular clouds concentrated within central 300pc: 10^8 $M_\odot$ = 5% of the total Galactic molecular mass!
  - embedded in very hot gas (10^8K)
  - supernova remnants
- central 10pc are dominated by radio source Sgr A

The Galactic center

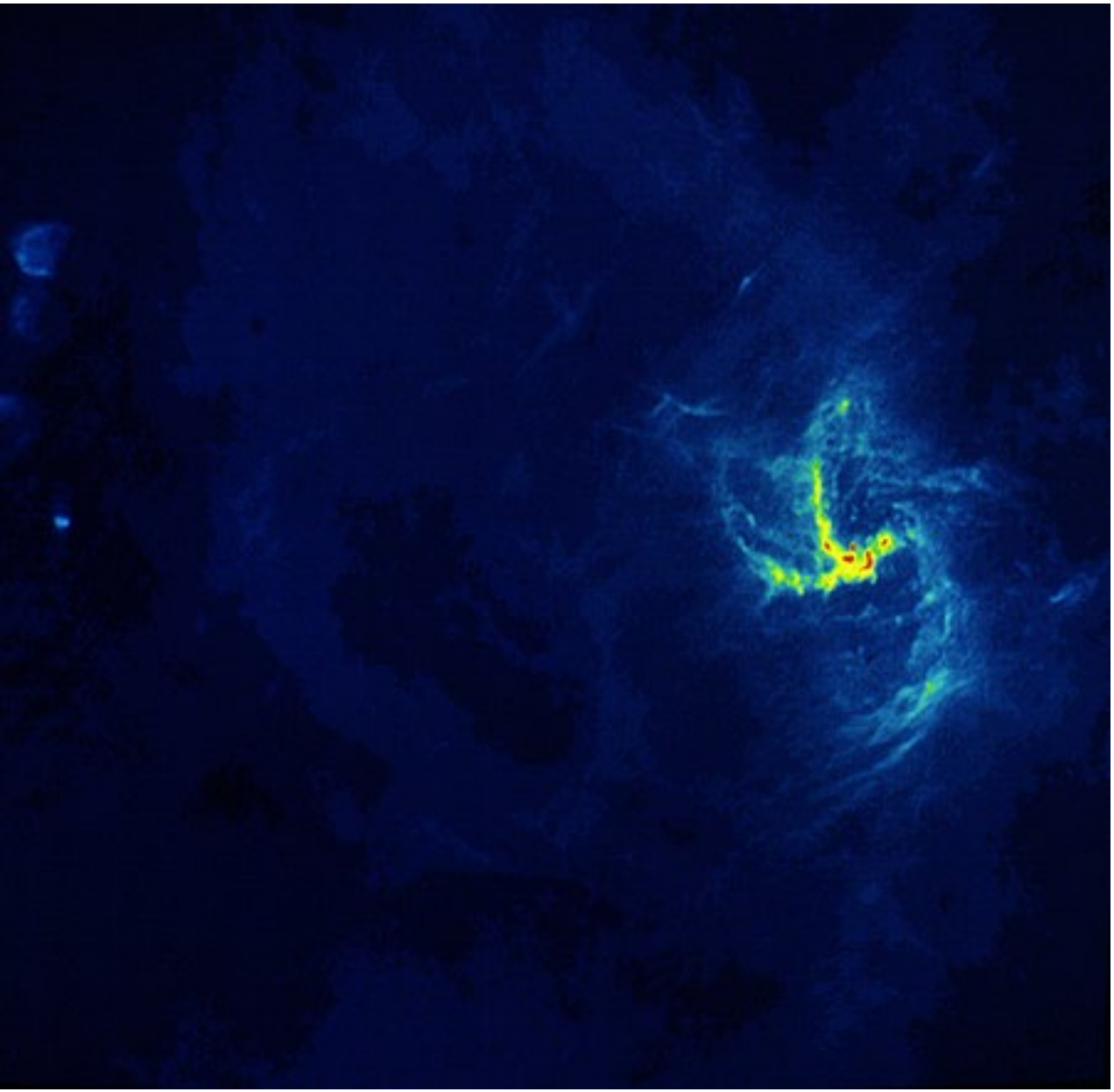


70 pc × 70 pc, VLA (F. Yusef-Zadeh et al., 1982–1984)
©NRAO/AUI

Radio source Sgr A:
Sgr A (West) (Arc): broad radio filaments, part of a much larger Ω-shaped structure ⊥ galactic plane.

polarized, steep radio spectrum $\Longrightarrow$ synchrotron radiation (nonthermal electrons; $n_e(E) \propto E^{-p}$)!
caused by shocks from supernovae?

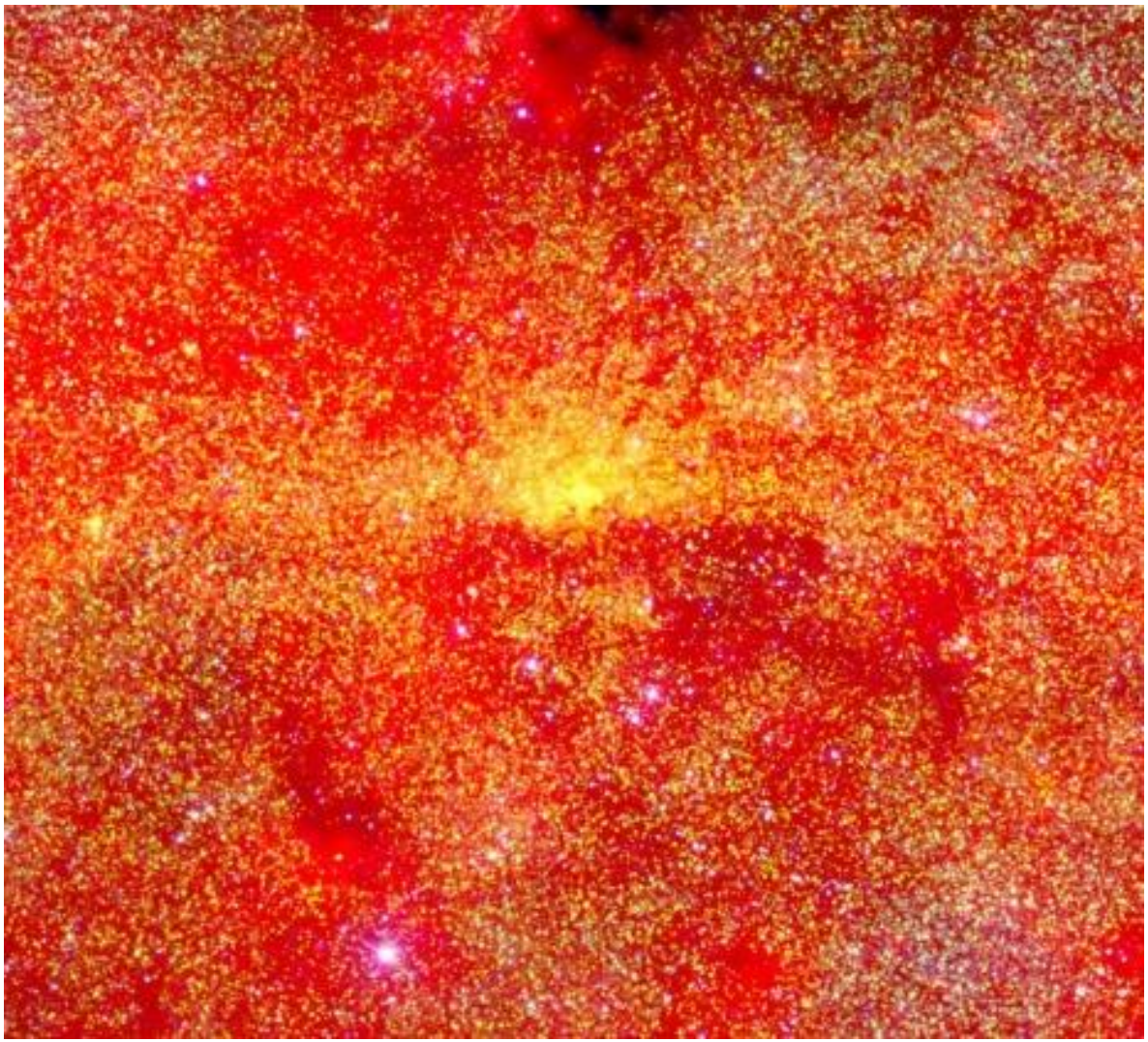
central radio point source, unresolved: Sgr A*



Sgr A (3.6 cm, courtesy K.Y. Lo/NRAO/AUI)

Sgr A West ("spiral"):
2 pc diameter,
$\sim$ 60 $M_\odot$ ionized gas, shaped by tidal forces
northern arm falls on centre, east and south arms rotate.

The Inner Parsec: Central Cluster



Centre of Sgr A contains massive and dense cluster
($> 10^6\,M_\odot\,pc^{-3}$, compare solar neighborhood: $0.1\,M_\odot\,pc^{-3}$)
Spectroscopy: Stars are rich in Helium, early type (=massive), strong winds ($v_{Wind} \sim 1000\,km\,s^{-1}$).

The Inner Parsec: Central Cluster



Gemini North/AURA

Observations are difficult because of astronomical seeing ($\sim 0.7'' = 0.2$ pc)

The Inner Parsec: Central Cluster



Gemini North/AURA

Observations are difficult because of astronomical seeing ($\sim 0.7'' = 0.2$ pc)

...which can be corrected by adaptive optics

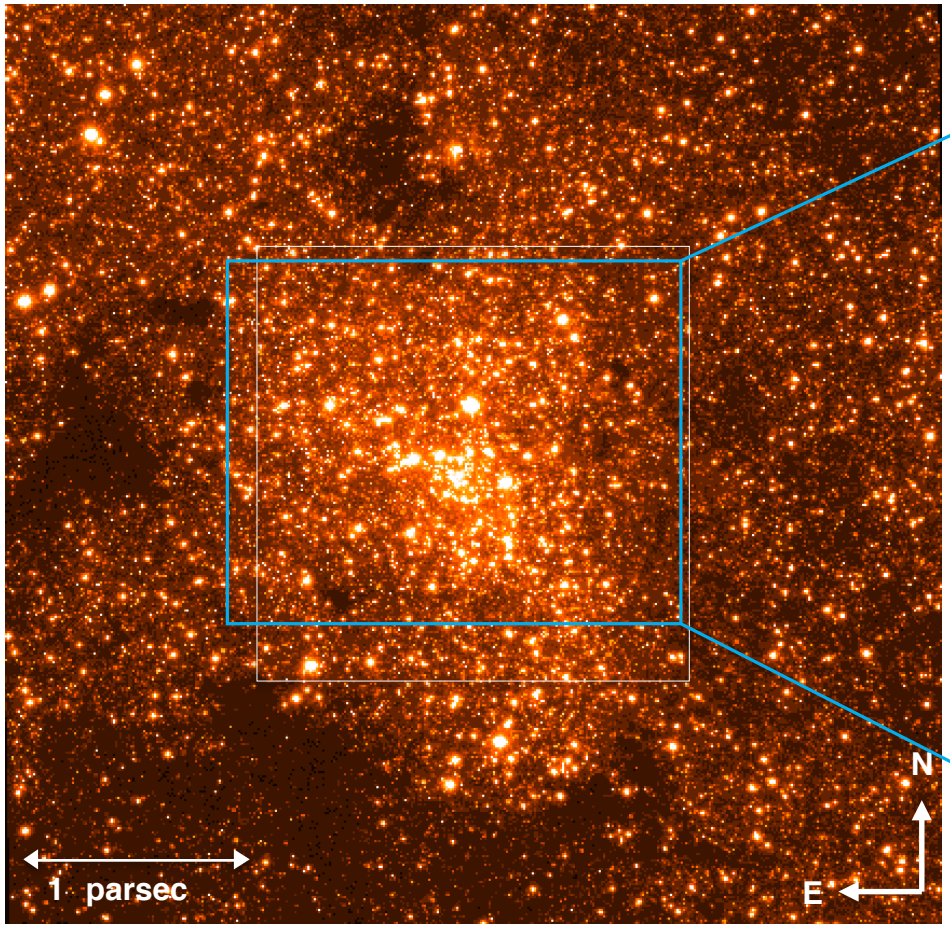
$\Longrightarrow$ resolution: diffraction limit!

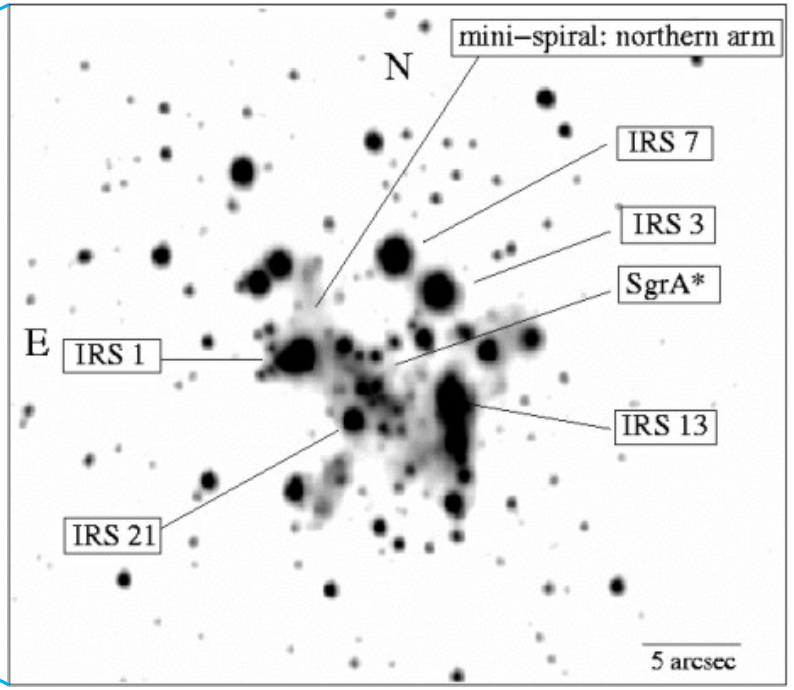
$$\theta = 1.22\,\text{rad} \cdot \lambda/d \sim 1\,\text{mas}$$

(for $d = 8$ m, $\lambda = 2.2\,\mu$m)

$\Longrightarrow$ 140 AU for gal. centre!

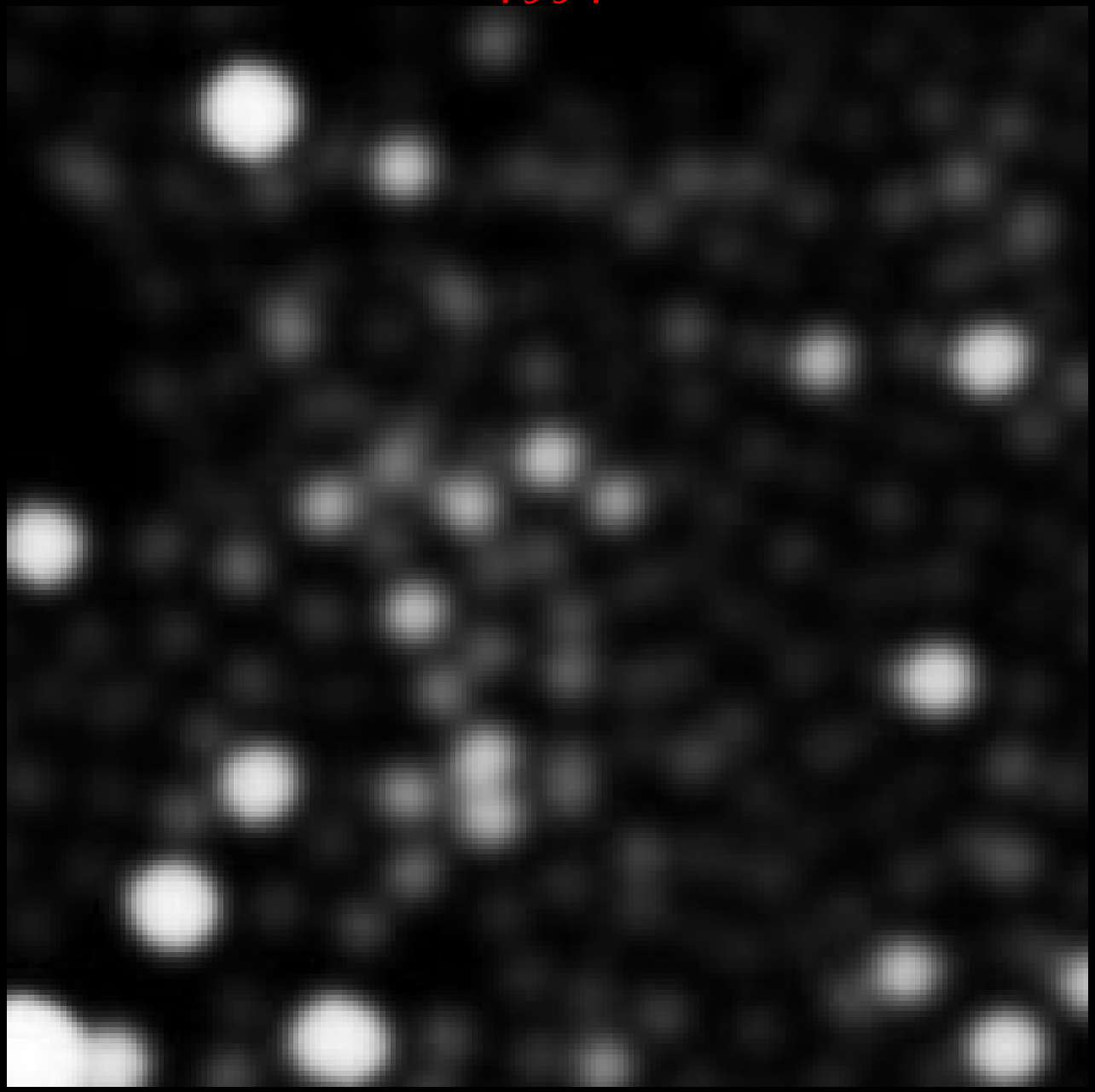
The Inner Parsec: Central Cluster





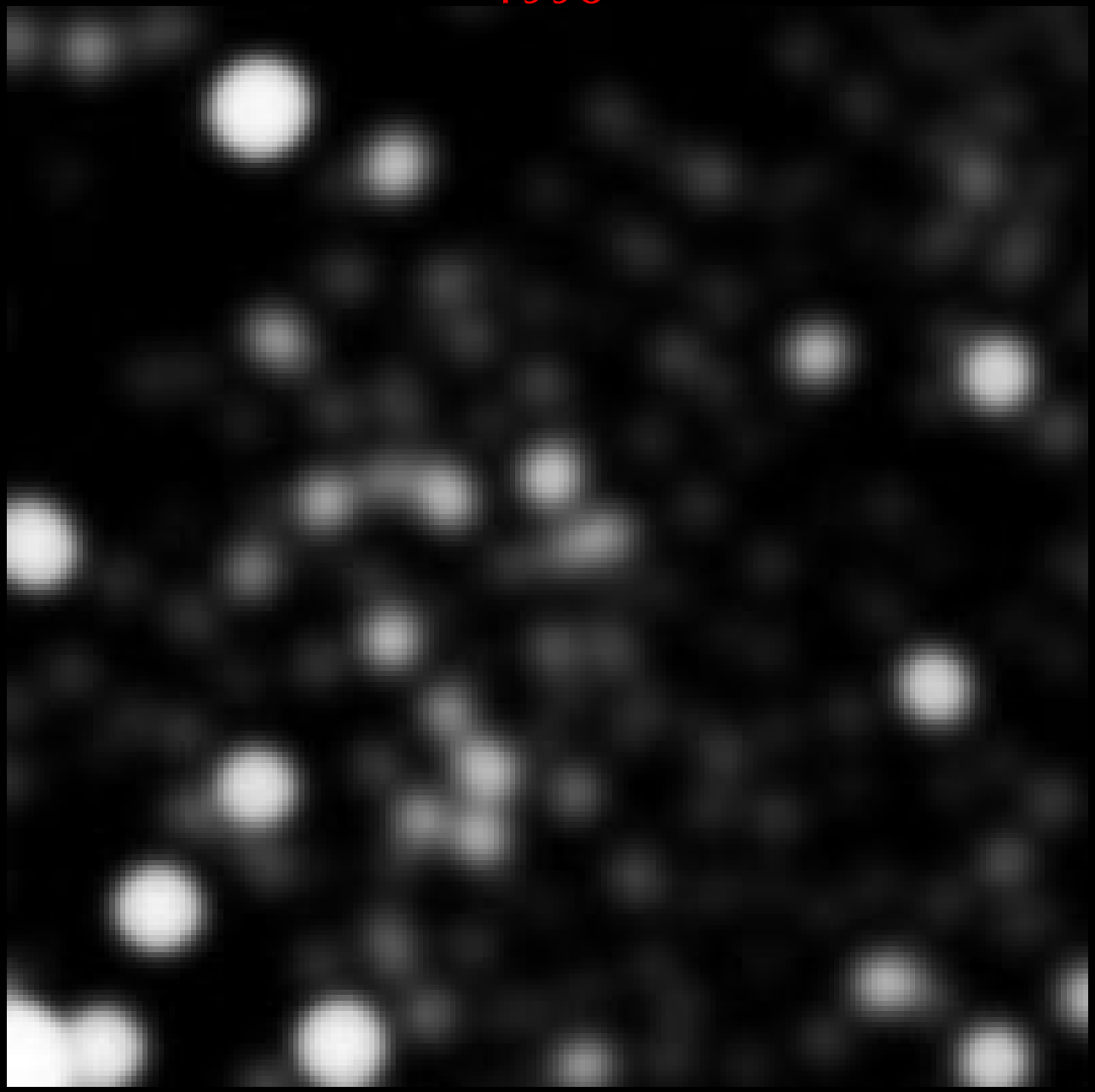
Gallego-Cano et al., 2018, A&A 609, A26; VLT ISAAC K-Band (2.2 μm)(Genzel/Eckart)

1994



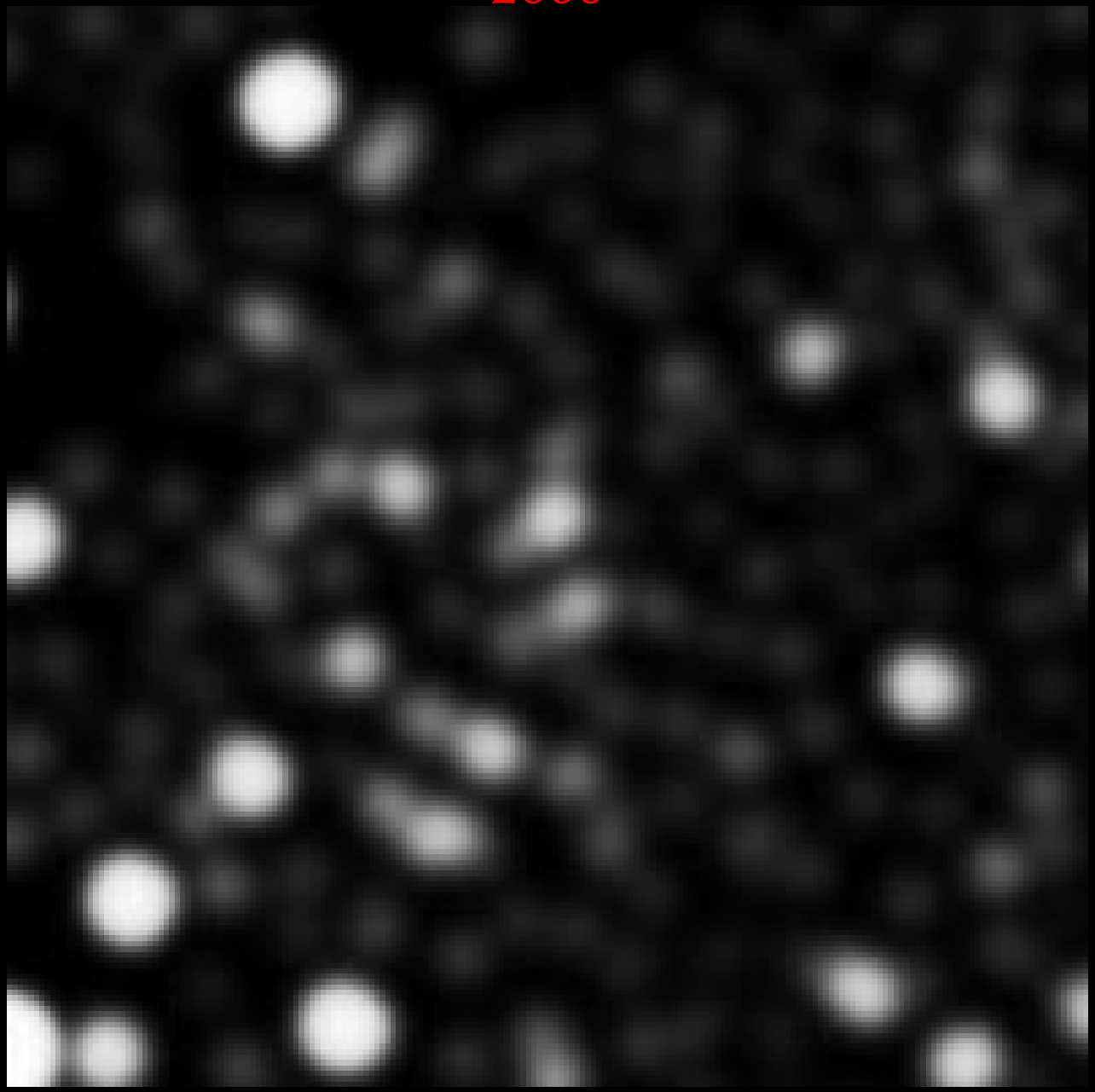
Genzel/Eckart

1996

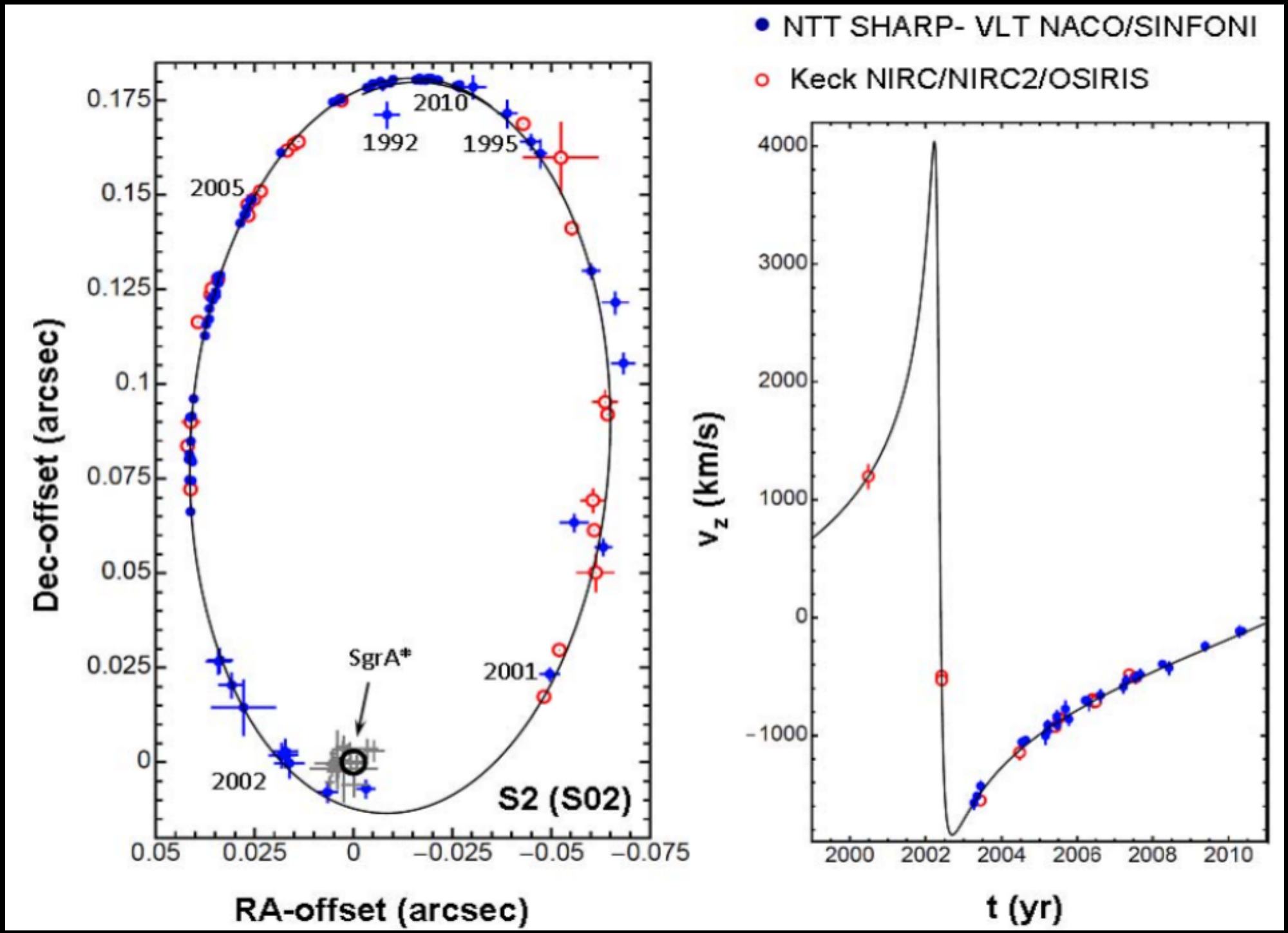


Genzel/Eckart

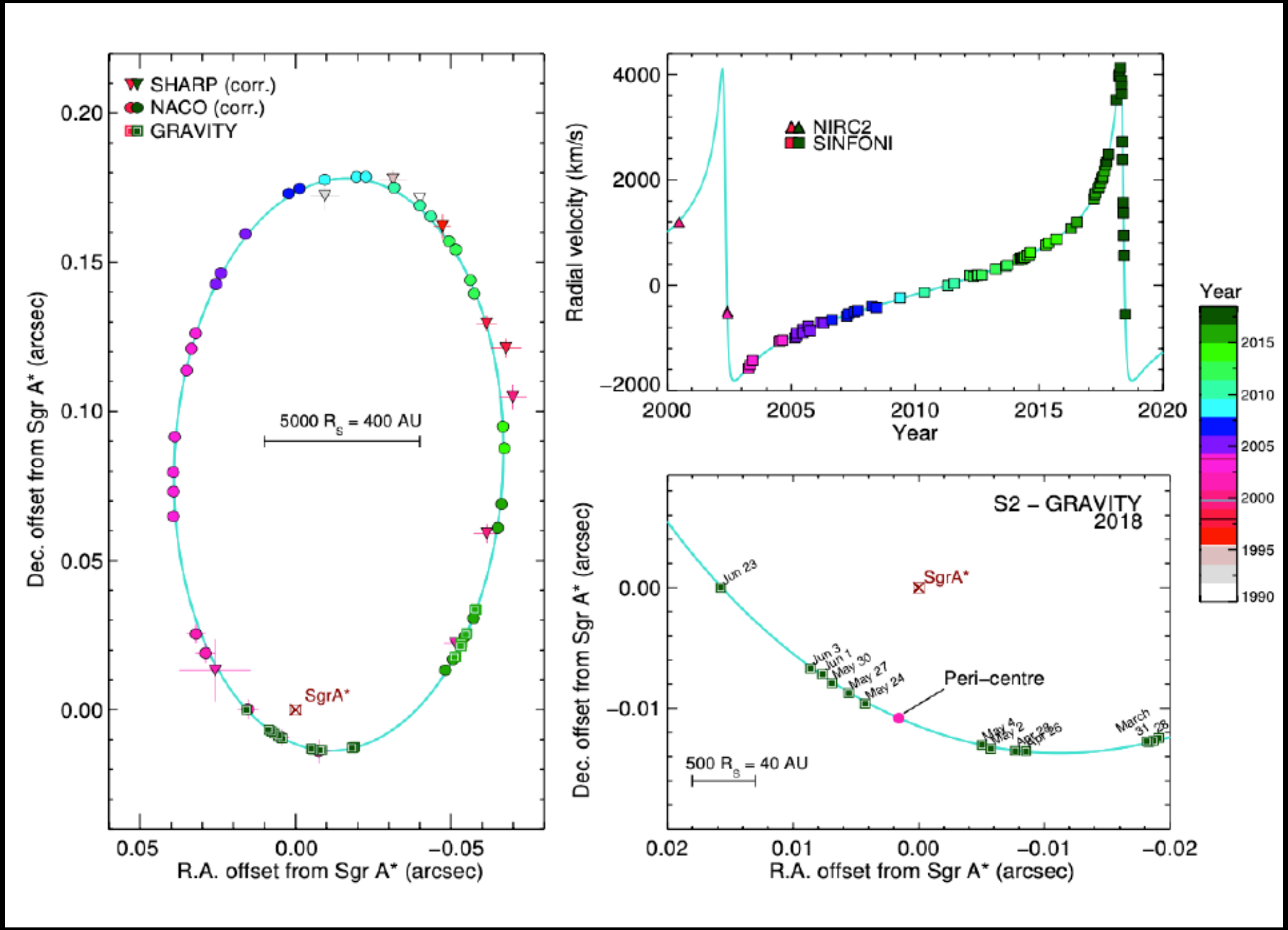
2000



Genzel/Eckart

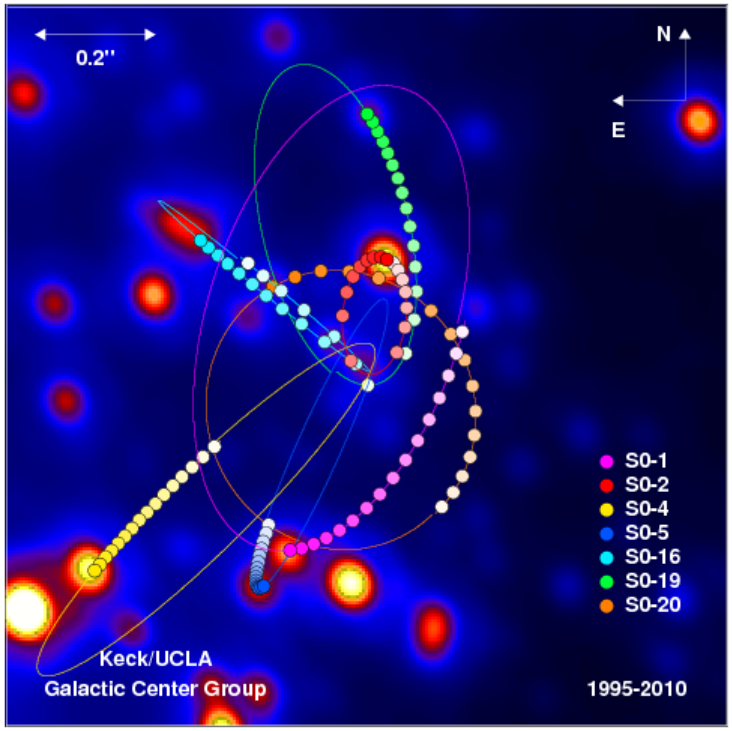


Genzel, Eisenhauer, Gillessen (2010), data from Genzel et al. and Ghez et al.

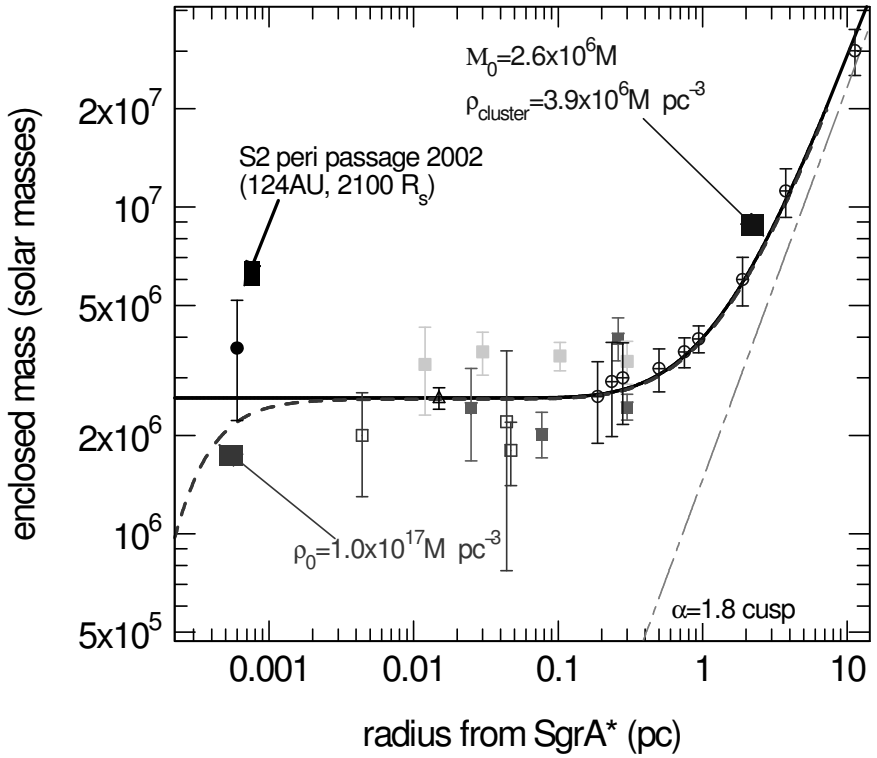


Arbuter et al., 2018

The inner parsec: mass determination



Ghez, priv. comm.

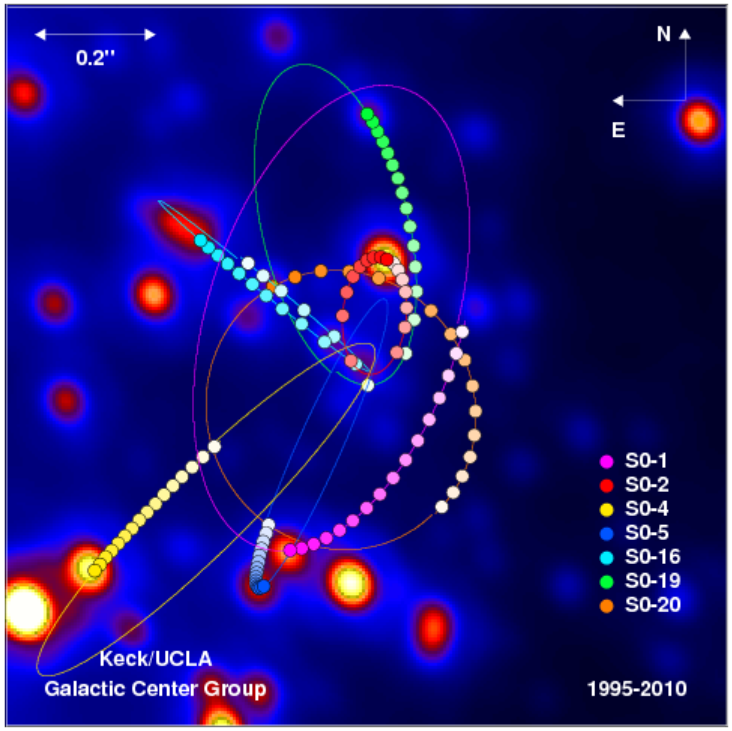


Schödel et al. (2002)

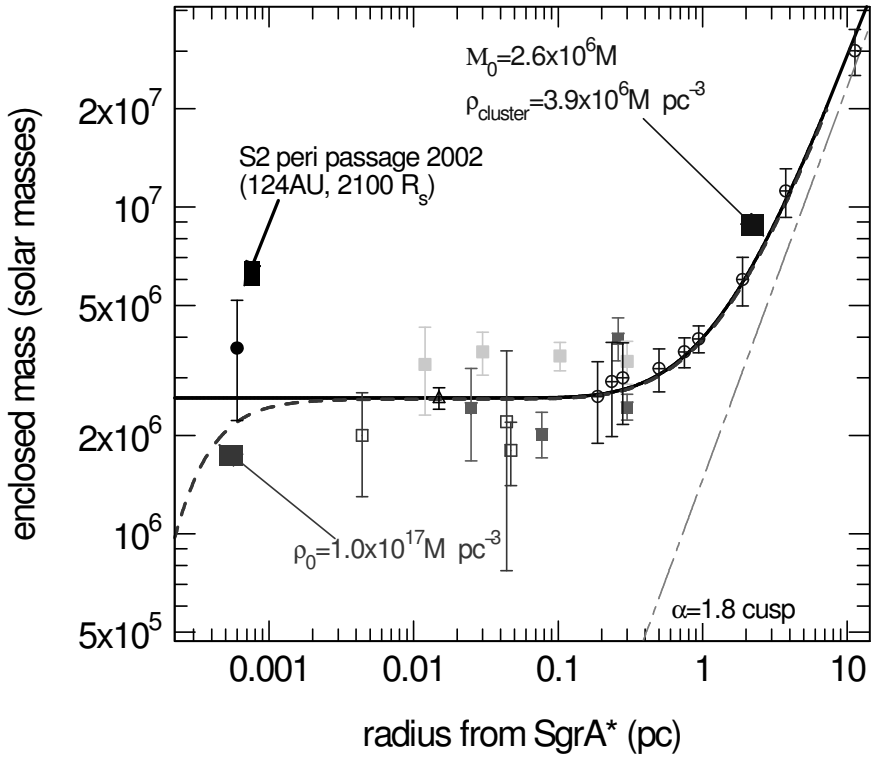
Mass: 3rd Kepler:

$$\left.\begin{aligned} a &= 5.5\,\text{Light days} \\ P &= 15.2\,\text{Years} \end{aligned}\right\} \Longrightarrow \quad \frac{P^2}{a^3} = \frac{4\pi^2}{G(m_* + M_{BH})}$$

The inner parsec: mass determination



Ghez, priv. comm.



Schödel et al. (2002)

The center of the Galaxy contains a black hole w/ $M_{BH} = (4.154 \pm 0.014) \times 10^6\, M_\odot$

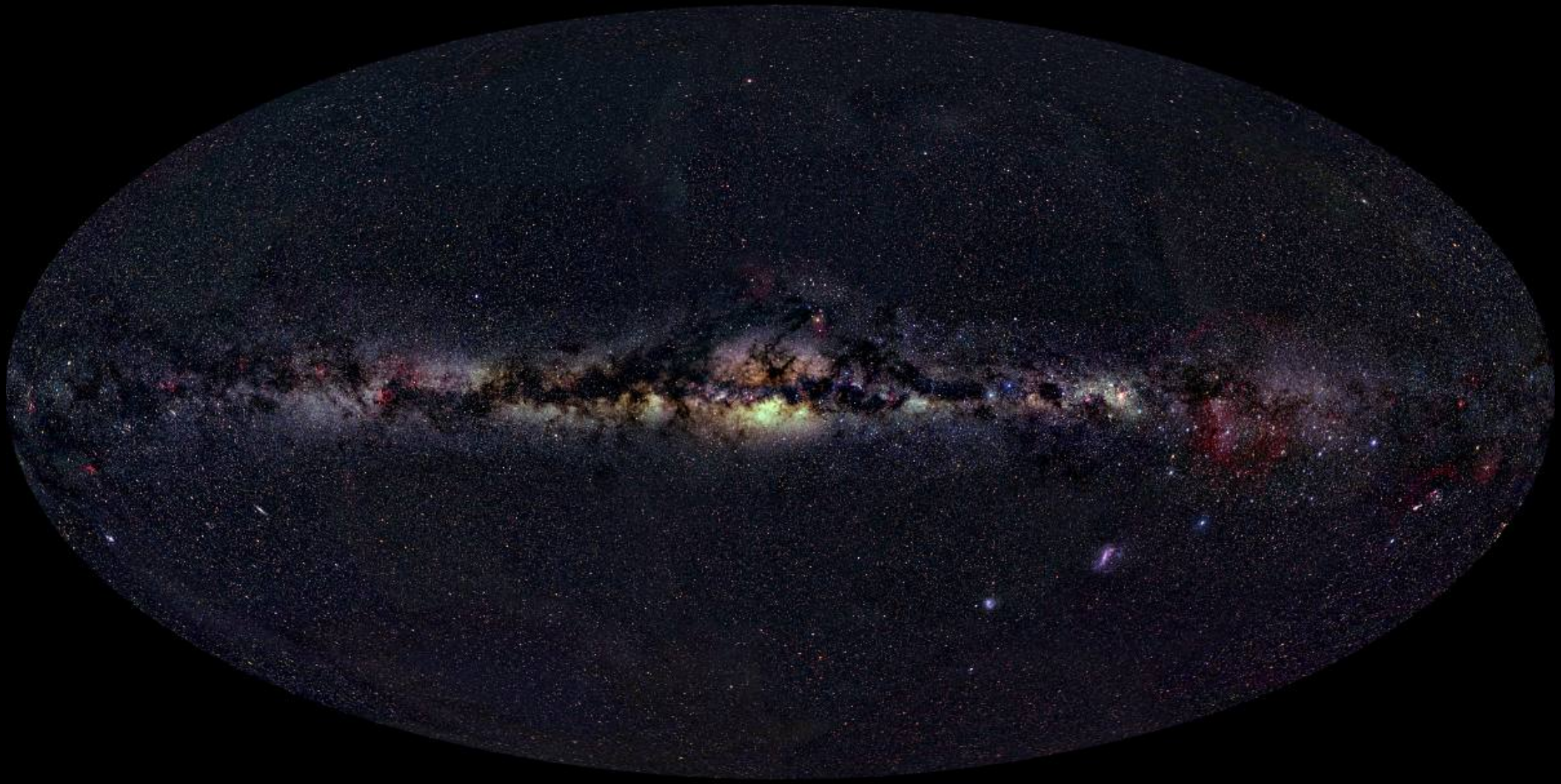




Nobel Prize 2020 for Andrea Ghez and Reinhard Genzel

Galaxies

The Deep Sky



Optical image of the whole sky

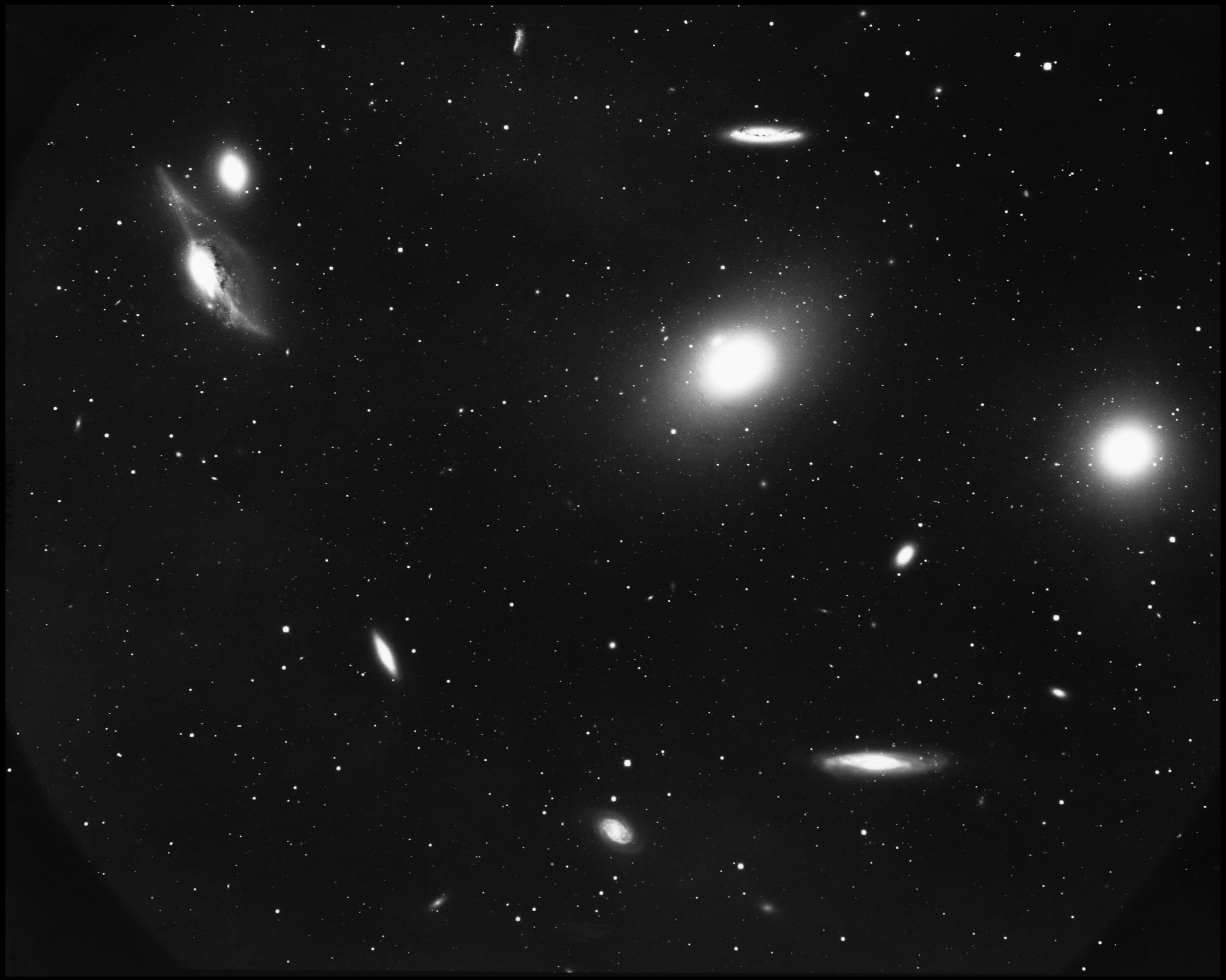


Andromeda galaxy (closest real neighbor galaxy, diam. 70 kpc, distance: 780 kpc), NOAO/AURA/NSF



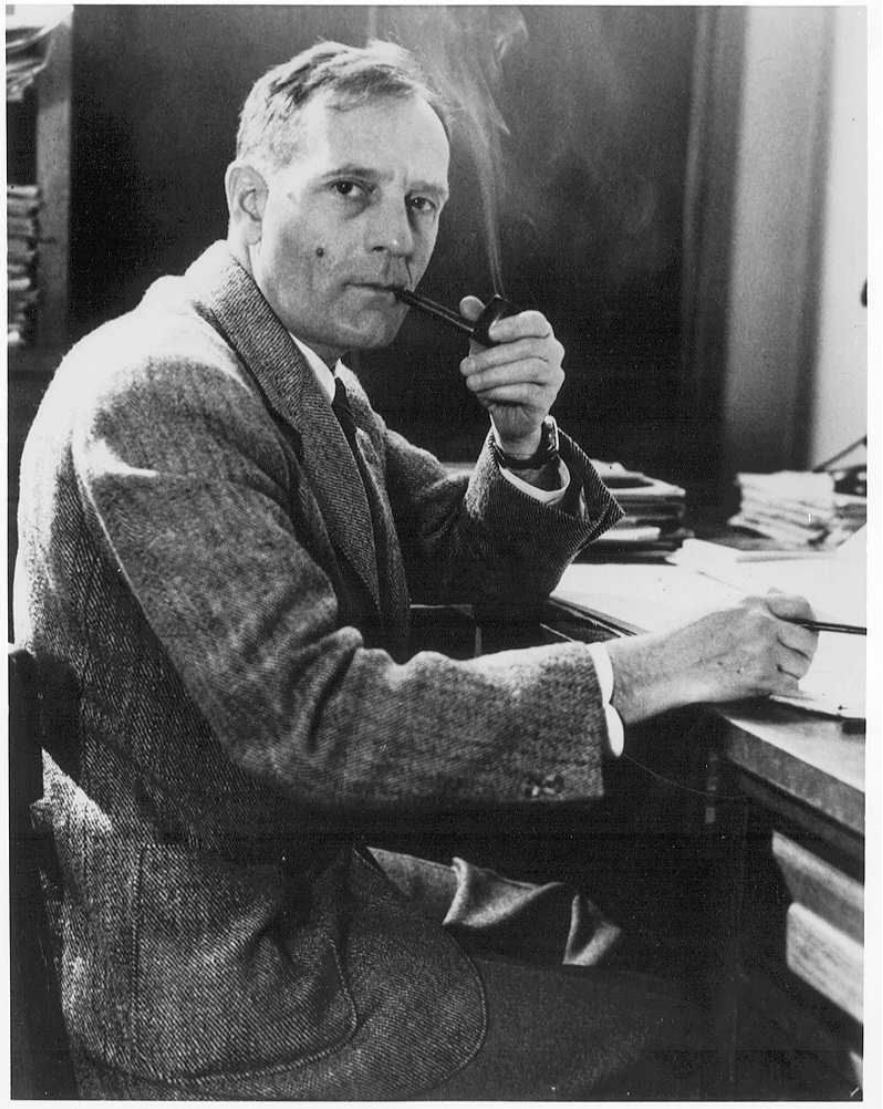
Virgo cluster, Burnell Schmidt telescope, NOAO/AURA/NSF

Deep looks in the universe: galaxies as building blocks



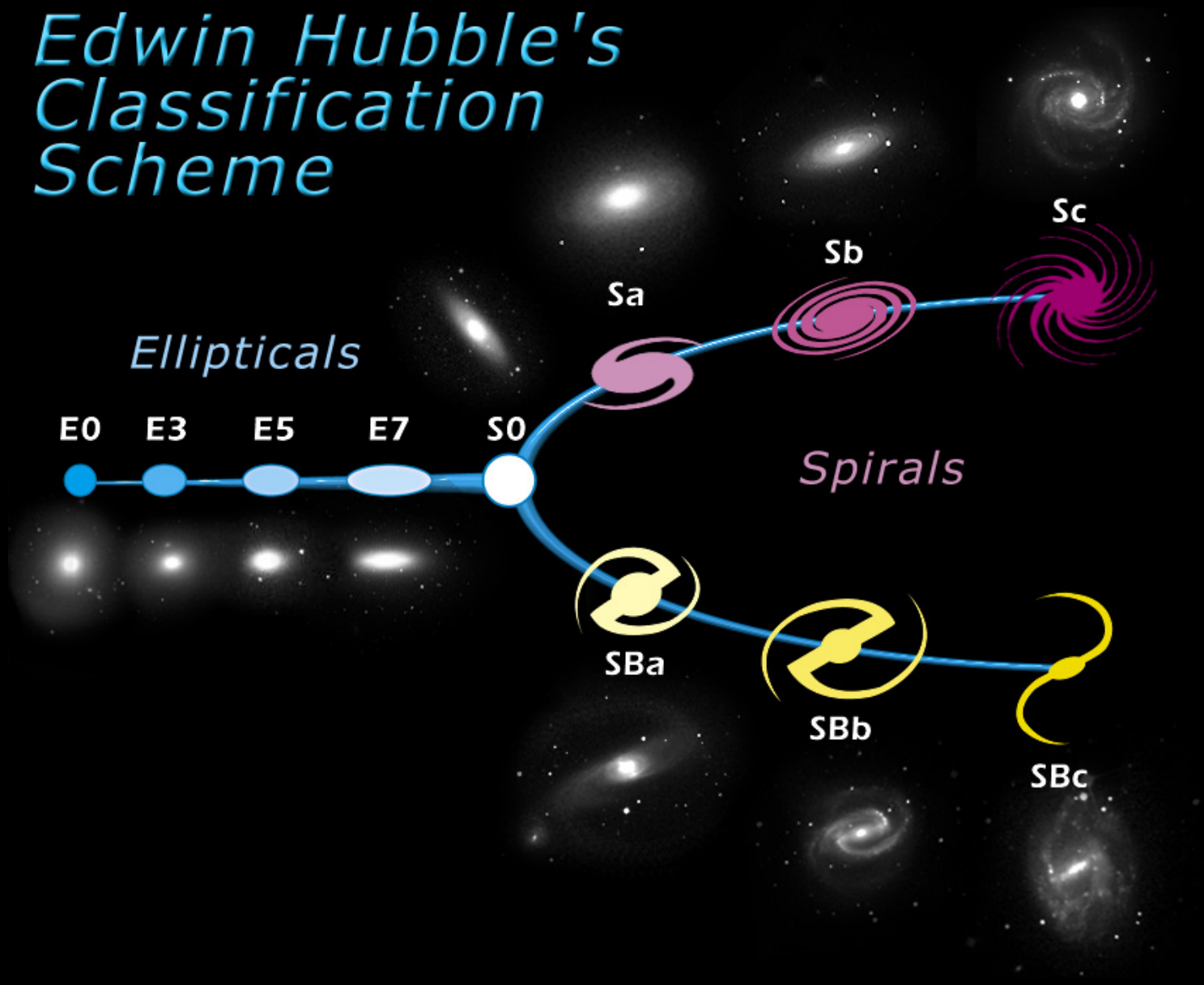
Deep image of Virgo cluster, 4 m Mayall telescope, NOAO/AURA/NSF

Galaxy Classification



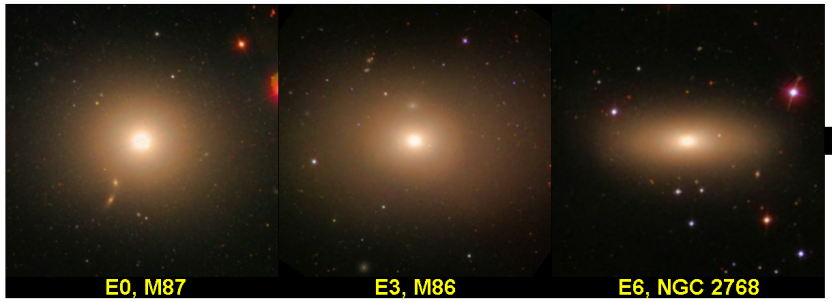
1920s: Hubble and others: classification of galaxies

- Morphology: Appearance on photographs, photographic emulsion is blue sensitive
- *Warning:* scheme is in parts not so well defined, incomplete, and not unique
- Note: photometric (colors) and spectroscopic information are not part of the Hubble scheme.

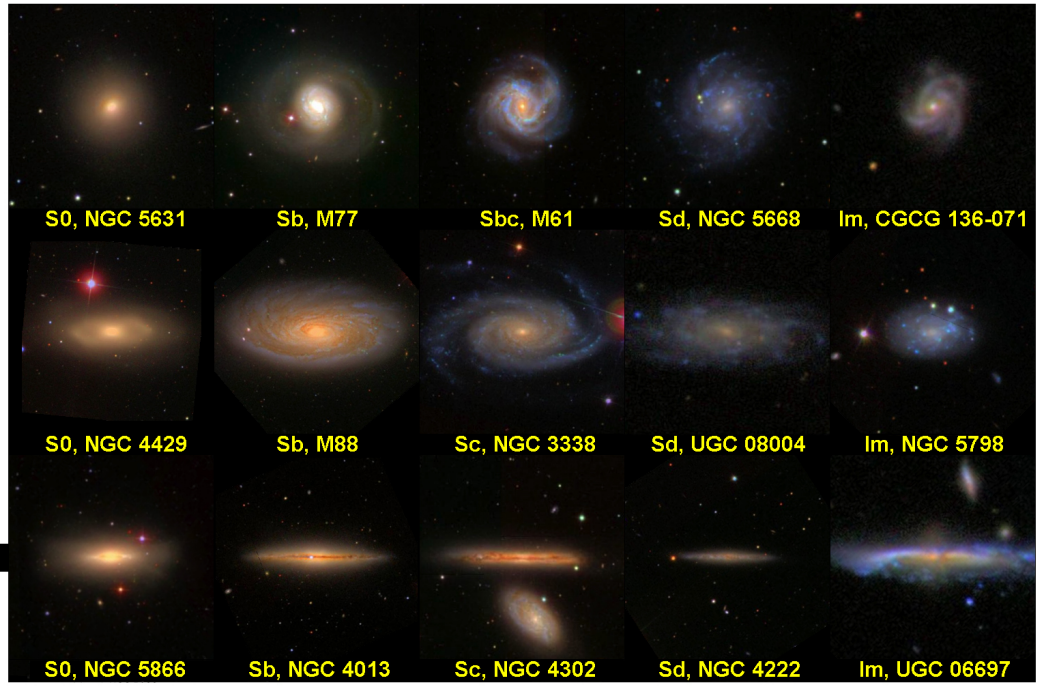


SDSS

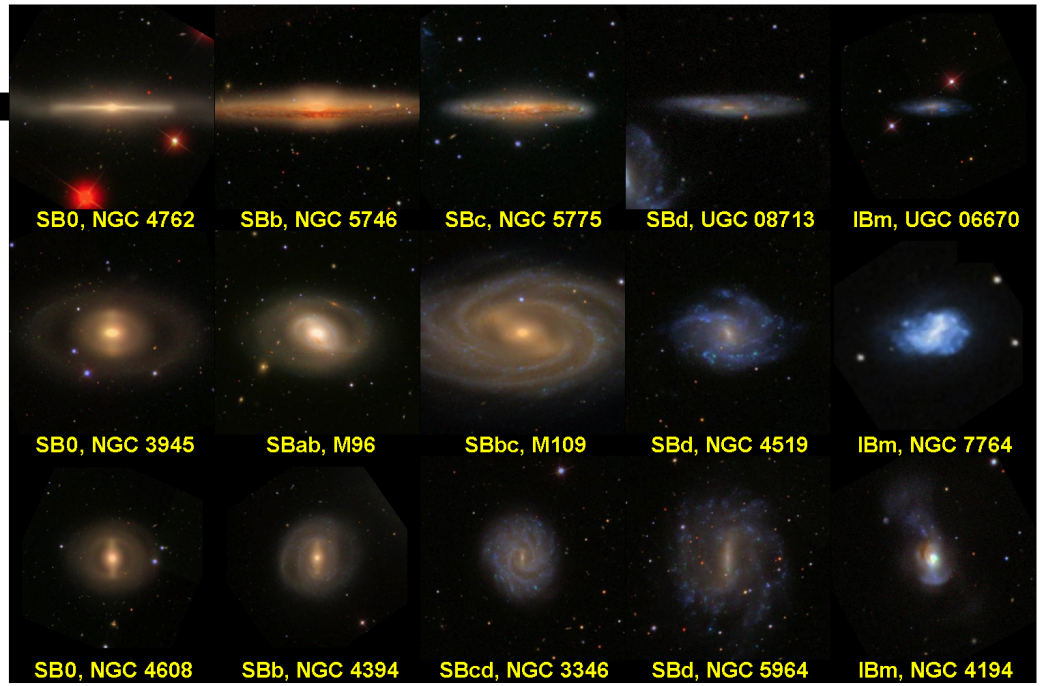
Galaxy classification via the Hubble "tuning fork diagram": "early types": elliptical galaxies; "late types": spiral galaxies, Not an evolutionary sequence!



Elliptical (E) galaxies



Normal Lenticular (S0), Spiral (S), and Irregular (Im) galaxies



Barred Lenticular (SB0), Spiral (SB), and Irregular (IBm) galaxies

0 10 20 kpc

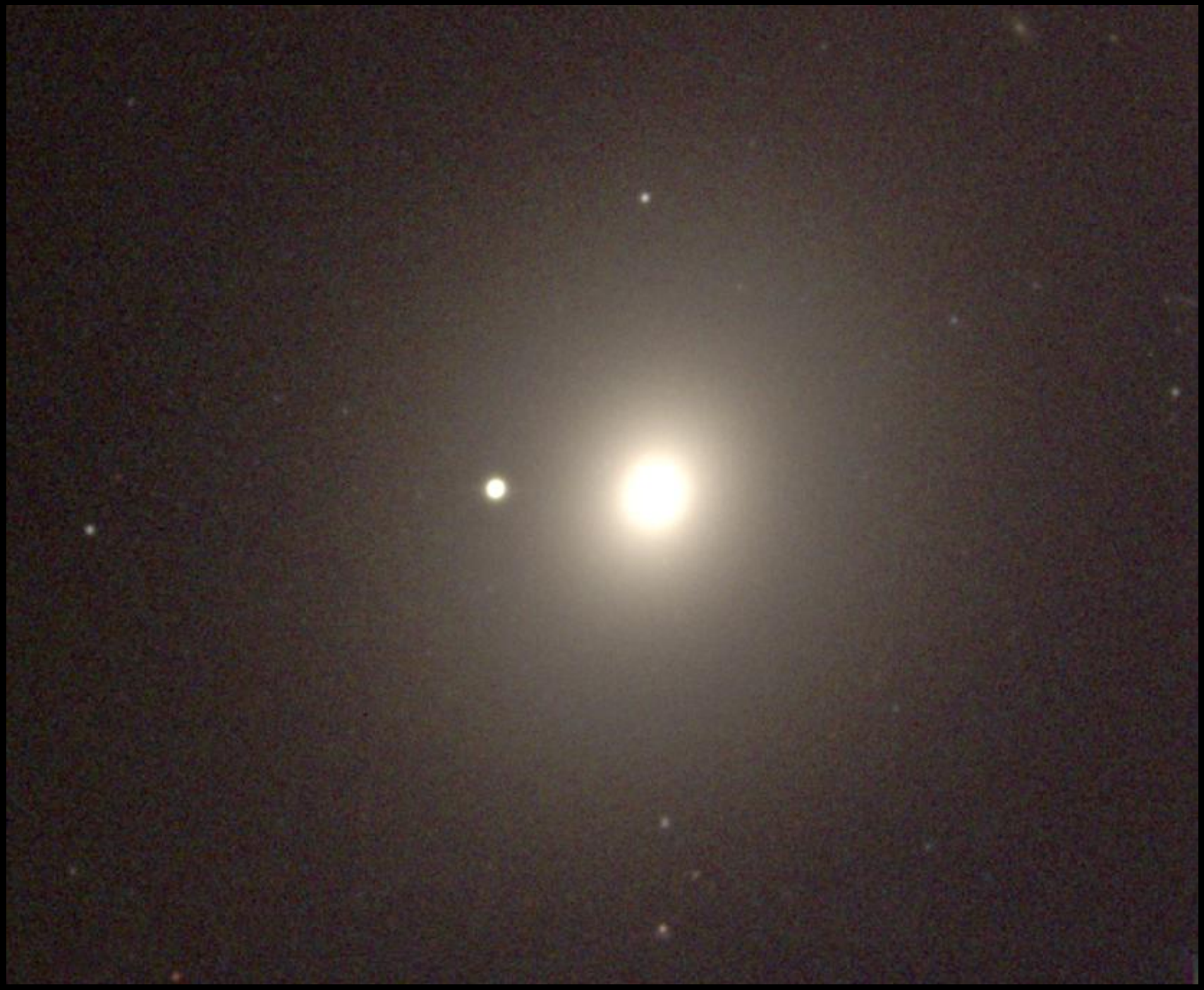
0 25 50 ly x 1000

Ian Steer/NED-D ©2011

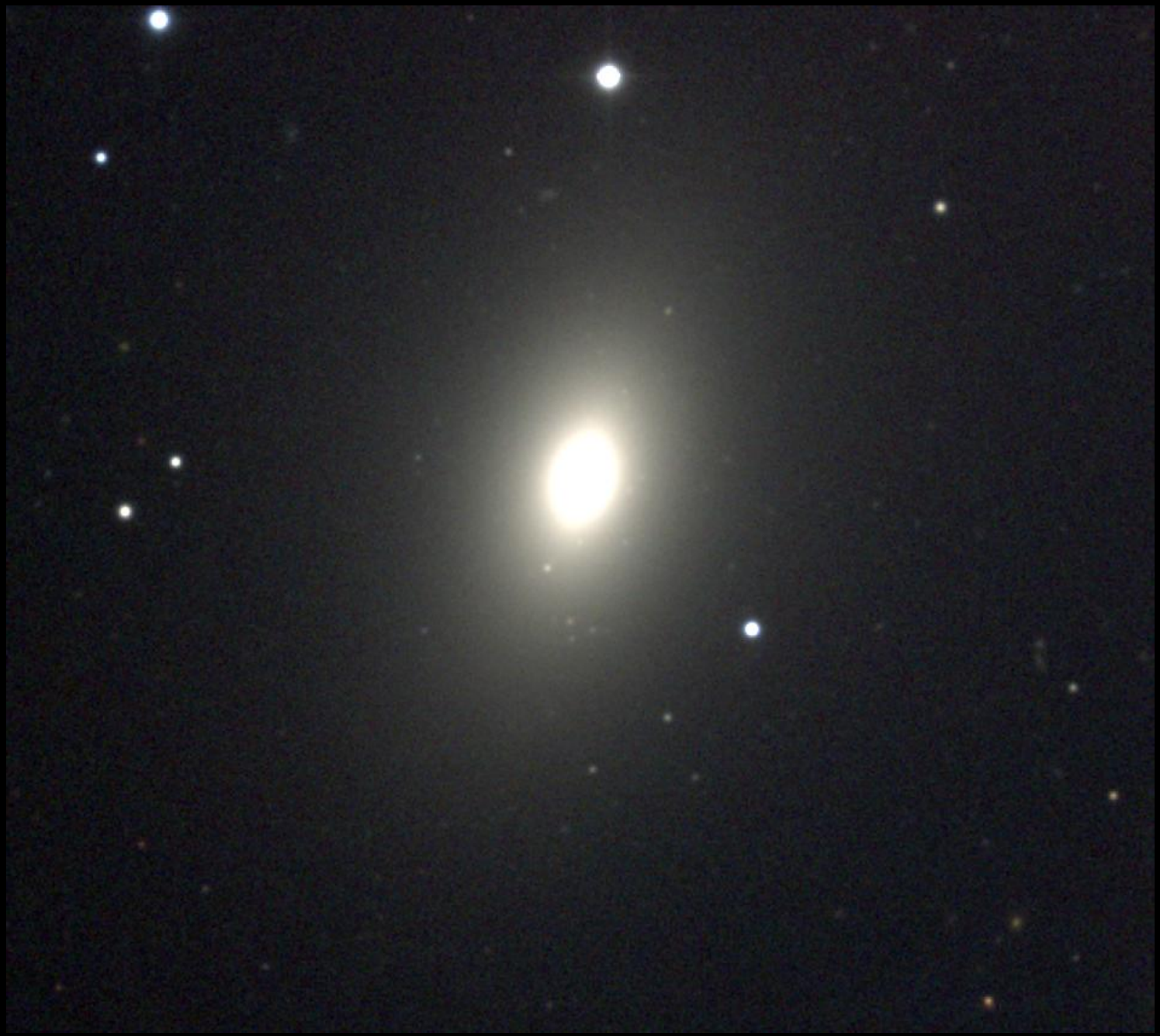
http://ned.ipac.caltech.edu/Library/Distances/hubtf.html



M87 (= Virgo A, note jet; E0), NOAO/AURA/NSF

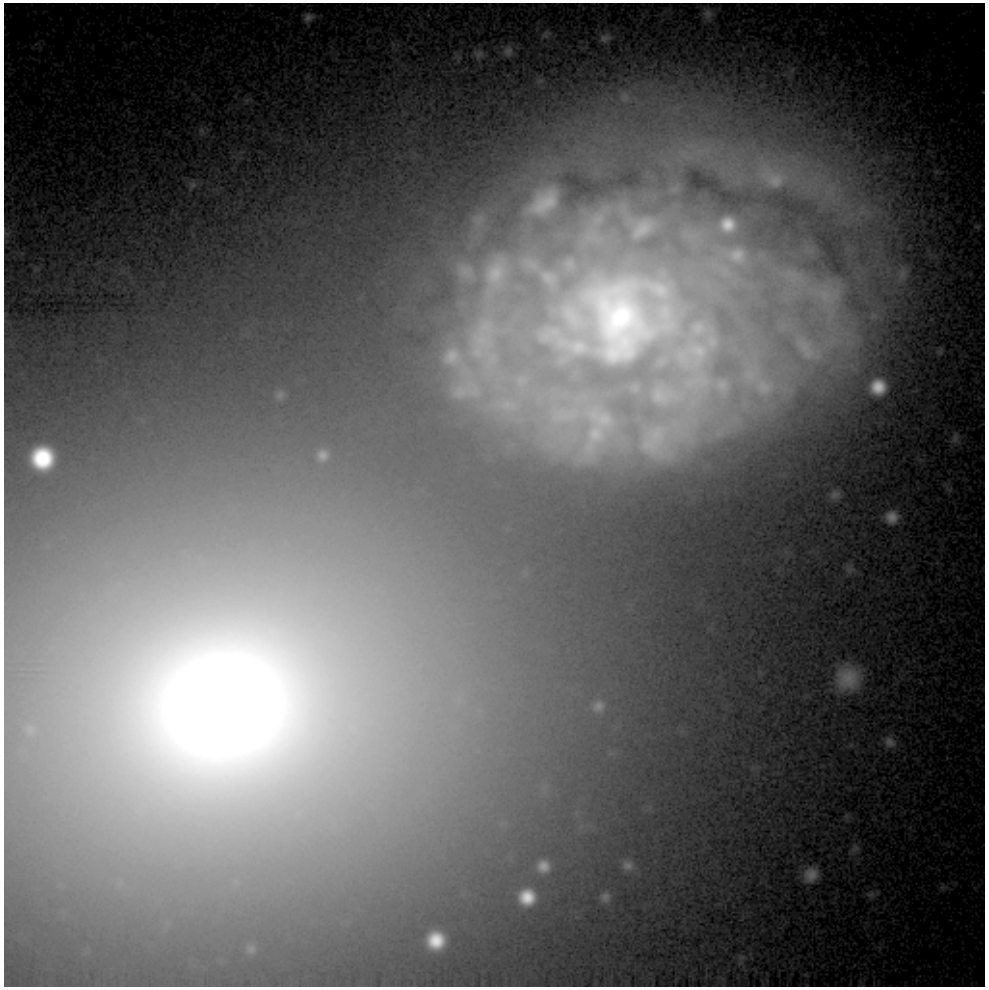


M49 (E4), NOAO/AURA/NSF

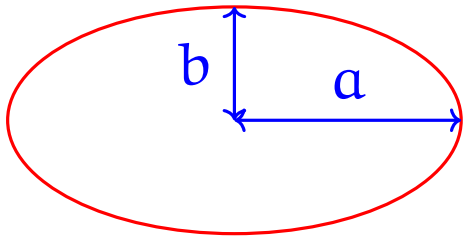


M59 (E5; color image), NOAO/AURA/NSF

Elliptical Galaxies

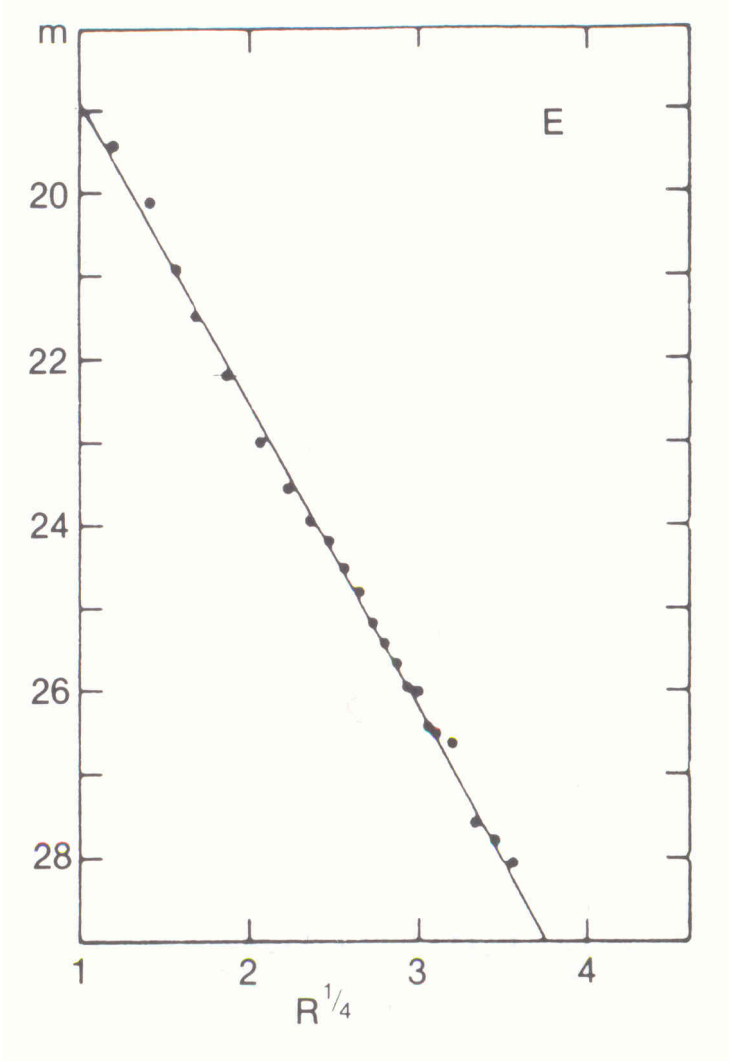


M60 (NGC 4649), E1, U. of Alabama



Elliptical galaxies: Classification as Ex where $x = 10(a - b)/a$ (integer part; between 0 and 7)
Ellipticals are low on dust and gas, reddish color (=old stars!), typically low luminosity and low mass ($10^6\,M_\odot$)
Monsters: Also elliptical, from mergers in galaxy clusters (e.g., M87 in Virgo), M up to $10^{12}\,M_\odot$, designated cD.

Elliptical Galaxies



Radial brightness distribution in ellipticals is given by de Vaucouleurs' law:

$$\log\left(\frac{I(R)}{I_e}\right) = -3.3307\left[\left(\frac{R}{R_e}\right)^{1/4} - 1\right] \tag{5.1}$$

where

- $I(R)$: surface brightness, e.g., in $L_\odot\,pc^{-2}$
- R_e: effective radius, i.e., radius containing in half of the total luminosity

Sombrero Galaxy • M104



Hubble Heritage

Edge-On Galaxy NGC 4013



Hubble Heritage

NASA and The Hubble Heritage Team (STScI/AURA)
Hubble Space Telescope WFPC2 • STScI-PRC01-07

edge on Spiral NGC 4013
(Sa; NASA/HST)



NGC 4565 (Sb, seen edge on), McLaughlin



M51 (Sc, “Whirlpool galaxy”), NOAO/AURA/NSF, T. Rector

Whirlpool Galaxy • M51



Hubble Heritage

NASA and The Hubble Heritage Team (STScI/AURA)
Hubble Space Telescope WFPC2 • STScI-PRC01-10

M51 (Sc; center), HST/NASA

Spiral Galaxies



M51 (NGC 5194 and 5195), Sc and Irr, Kitt Peak 0.9 m

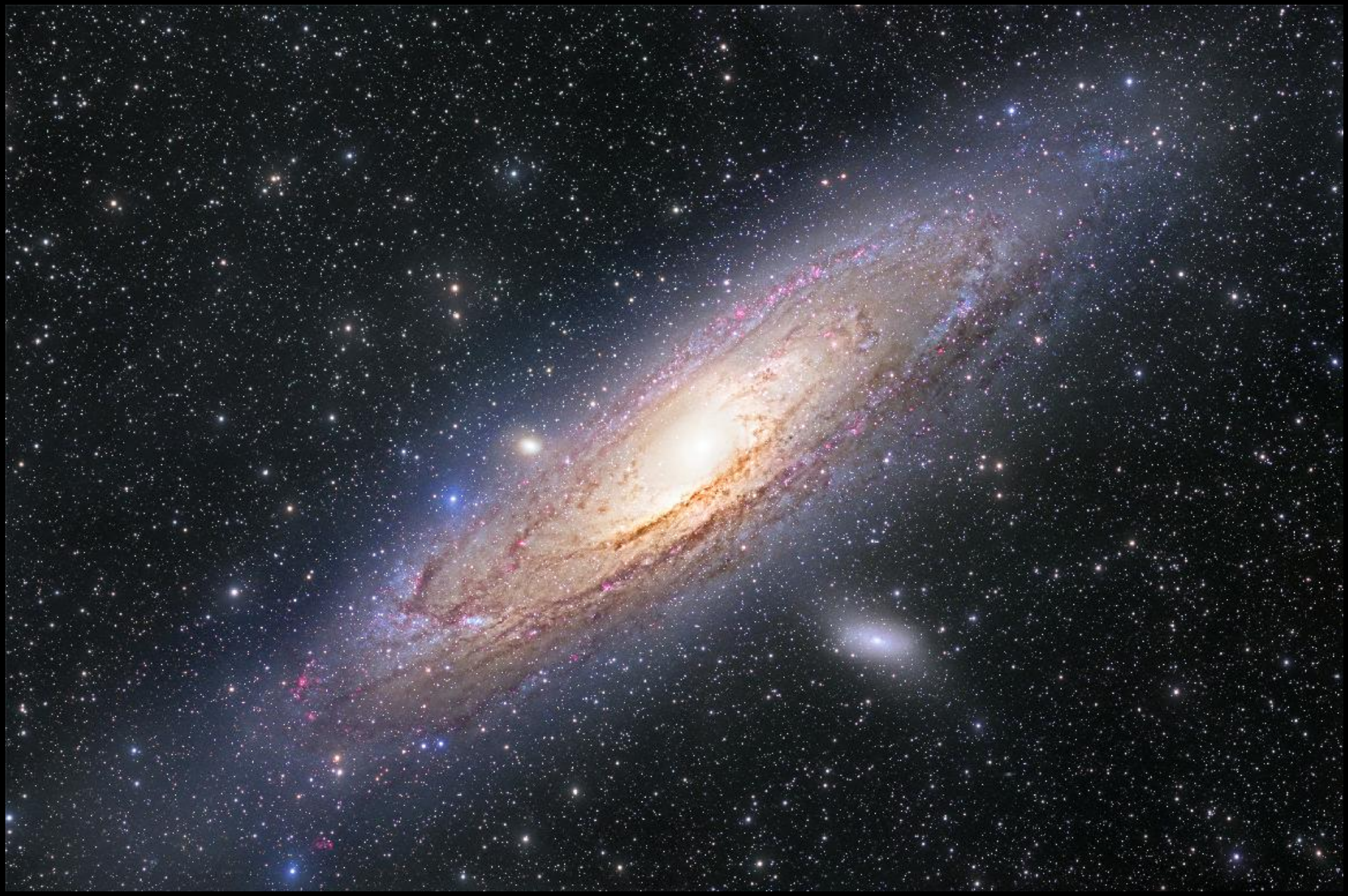
Spiral Galaxies: Elliptical nucleus ("bulge") plus disk with spiral arms, designated Sa, Sb, Sc depending on opening angle of spiral (Sa: $\sim 10°$, Sc: $\sim 20°$) and dominance of nucleus.

Bluer than ellipticals.

Mass content $\sim 3 \times 10^{11}\,M_\odot$, with $M/L \sim 20$,

Gas content increases from Sa to Sc from 1% to 8%.

Spiral arms probably due to density wave.



M31 (Sb; “Andromeda galaxy”),
http://www.rosa-obs.com/images/ccd/M31C_karel_full.jpg



M90 (Sb), NOAO/AURA/NSF

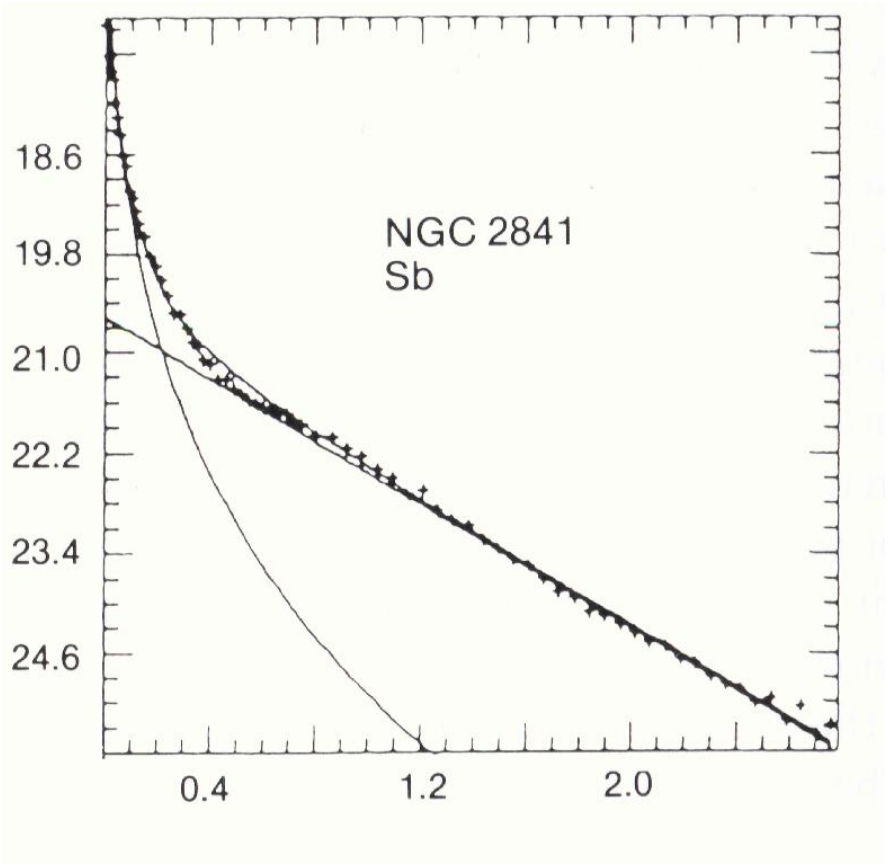


Spiral Galaxy NGC 300
(MPG/ESO 2.2-m + WFI)

ESO PR Photo 18a/02 (7 August 2002)

© European Southern Observatory

Spiral Galaxies



Radial intensity profile:

Bulge: de Vaucouleurs' law (same as ellipticals!):

$$\log\left(\frac{I(R)}{I_e}\right) = -3.3307\left[\left(\frac{R}{R_e}\right)^{1/4} - 1\right] \tag{5.2}$$

where

- $I(R)$: surface brightness, e.g., in $L_\odot\,pc^{-2}$
- R_e: effective radius, i.e., radius containing in half of the total luminosity

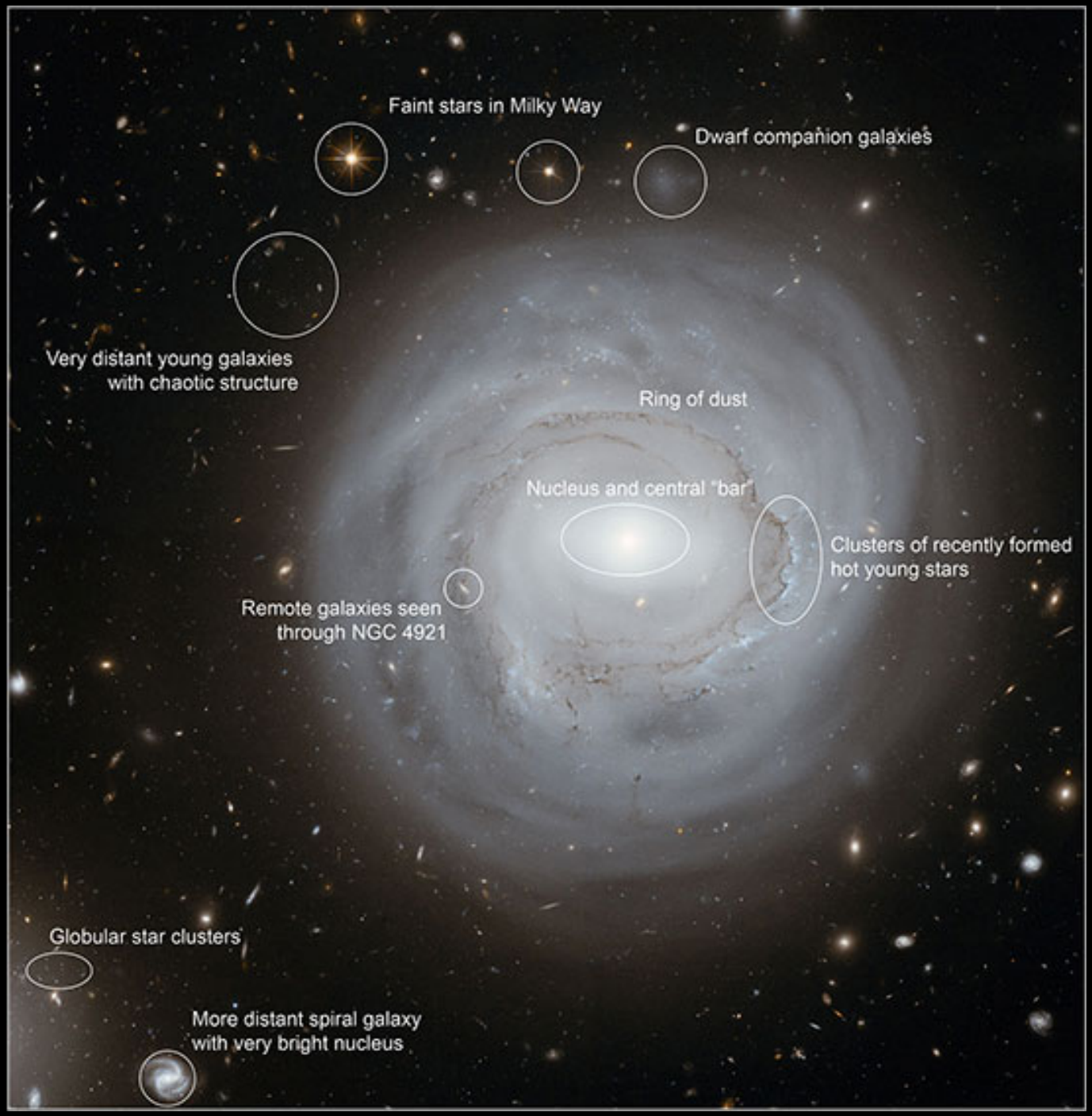
Disk: Exponential law:

$$I(R) = I_0 \exp -R/R_0 \tag{5.3}$$

where R_0: scale length (typical, e.g., thin disk of Milky Way: 3 kpc)



NGC 4921 (SBab; but note low star formation! HST/STScI)



NGC 4921 (SBab; but note low star formation! HST/STScI)



M58 (SBb), NOAO/AURA/NSF



M83 (SBc, ESO)

Barred Galaxies



M95 (NGC 3351), SBb, INT

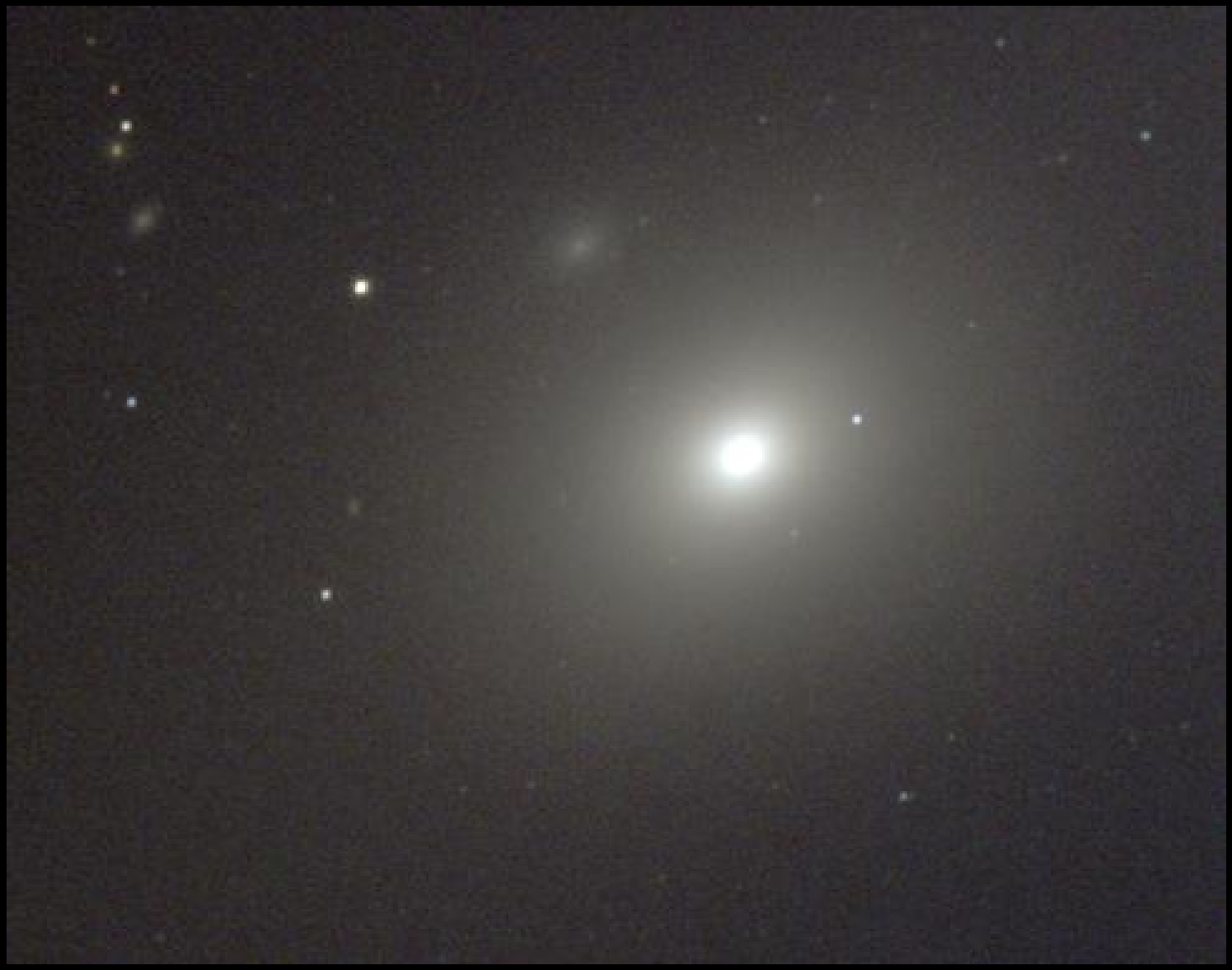
Barred Galaxies: Classification as SBa, SBb, SBc similar to Sx galaxies, but additional presence of a bar (cause of bar production and stability are still debated).

Similar masses and gas content as in normal spirals.

Milky Way is a barred spiral.



NGC 1365 (SBb, VLT/FORS/ANTU): note old “reddish” bar, young spiral arms

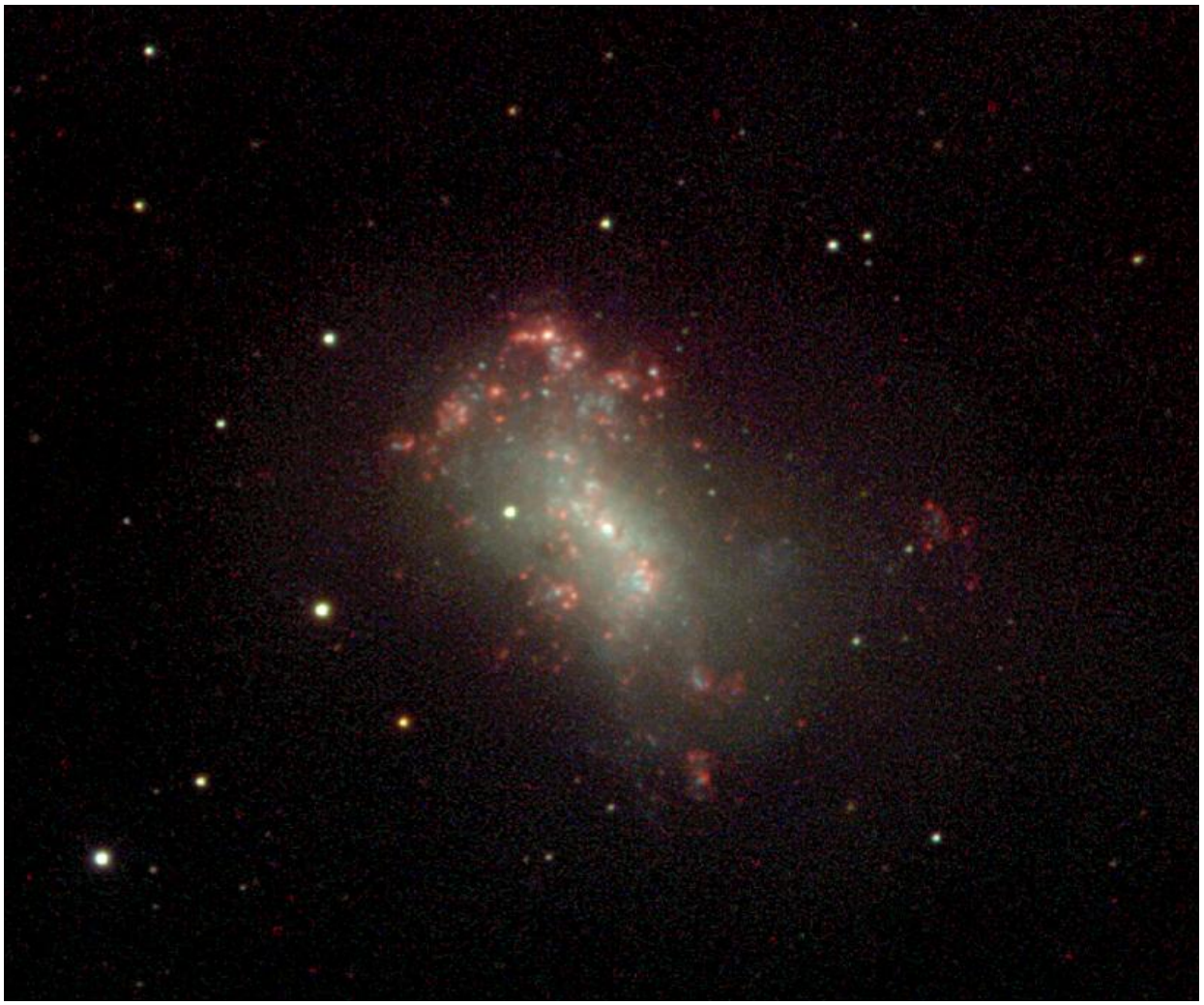


M86 (lenticular, S0), NOAO/AURA/NSF

S0 = eliptical galaxy + disk

S0 = spiral galaxy without spirals

Irregular Galaxies: Irr I



NGC 4449, Univ. Bonn

Irr I: no symmetry or spiral arms, bright knots of O- and B-type stars, very blue ($B - V \sim 0.5$), high dust content ($\sim$ 16%), $M/L \sim 3$, masses vary appreciably from 10^6 to $10^{10}\,M_\odot$.

Examples: SMC, LMC

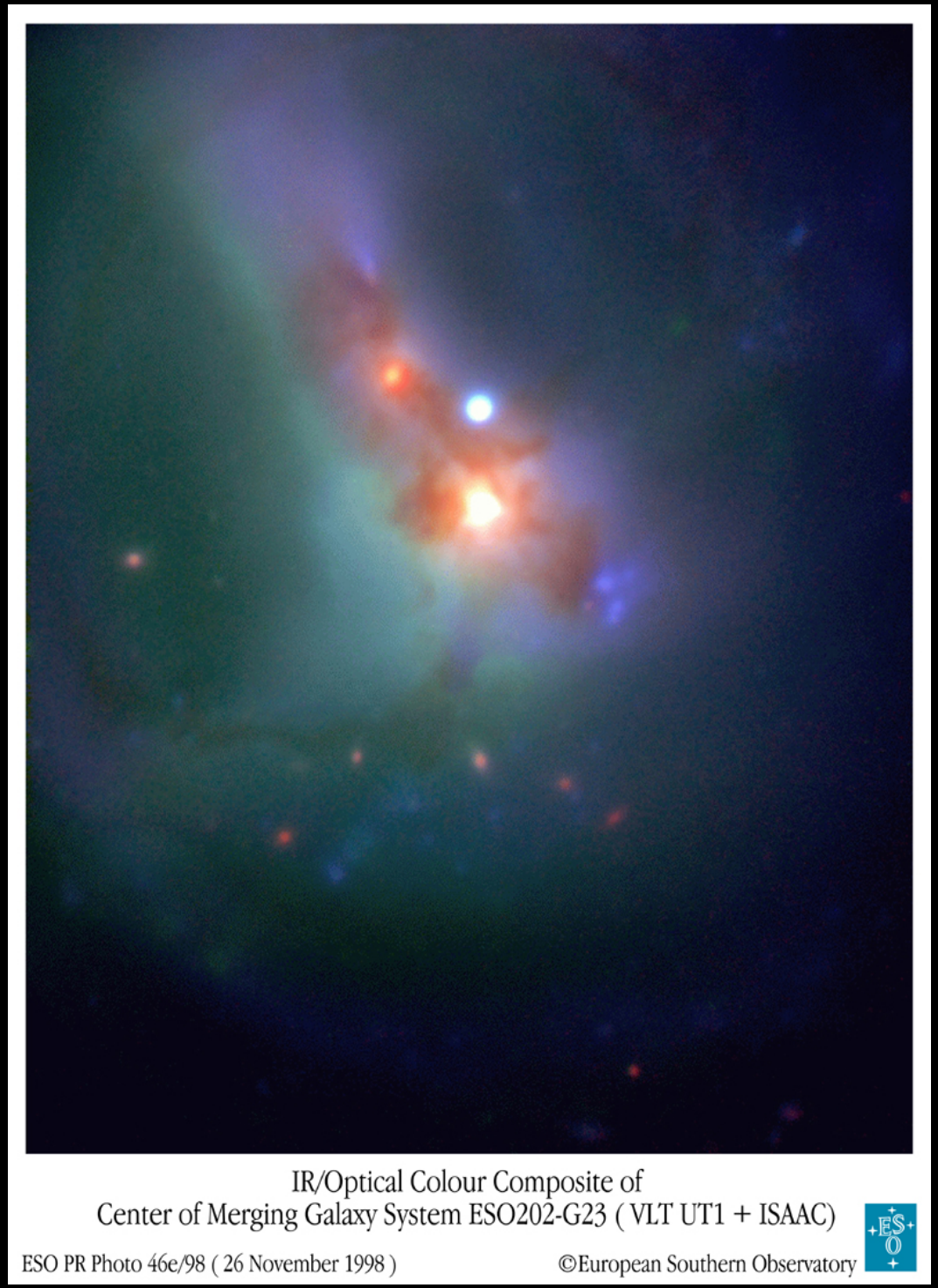
$\Longrightarrow$ "Magellanic type irregulars".



Large Magellanic Cloud (LMC; Irr I), Loke Kun Tan



Large Magellanic Cloud (LMC; Irr I), AURA/NOAO/NSF



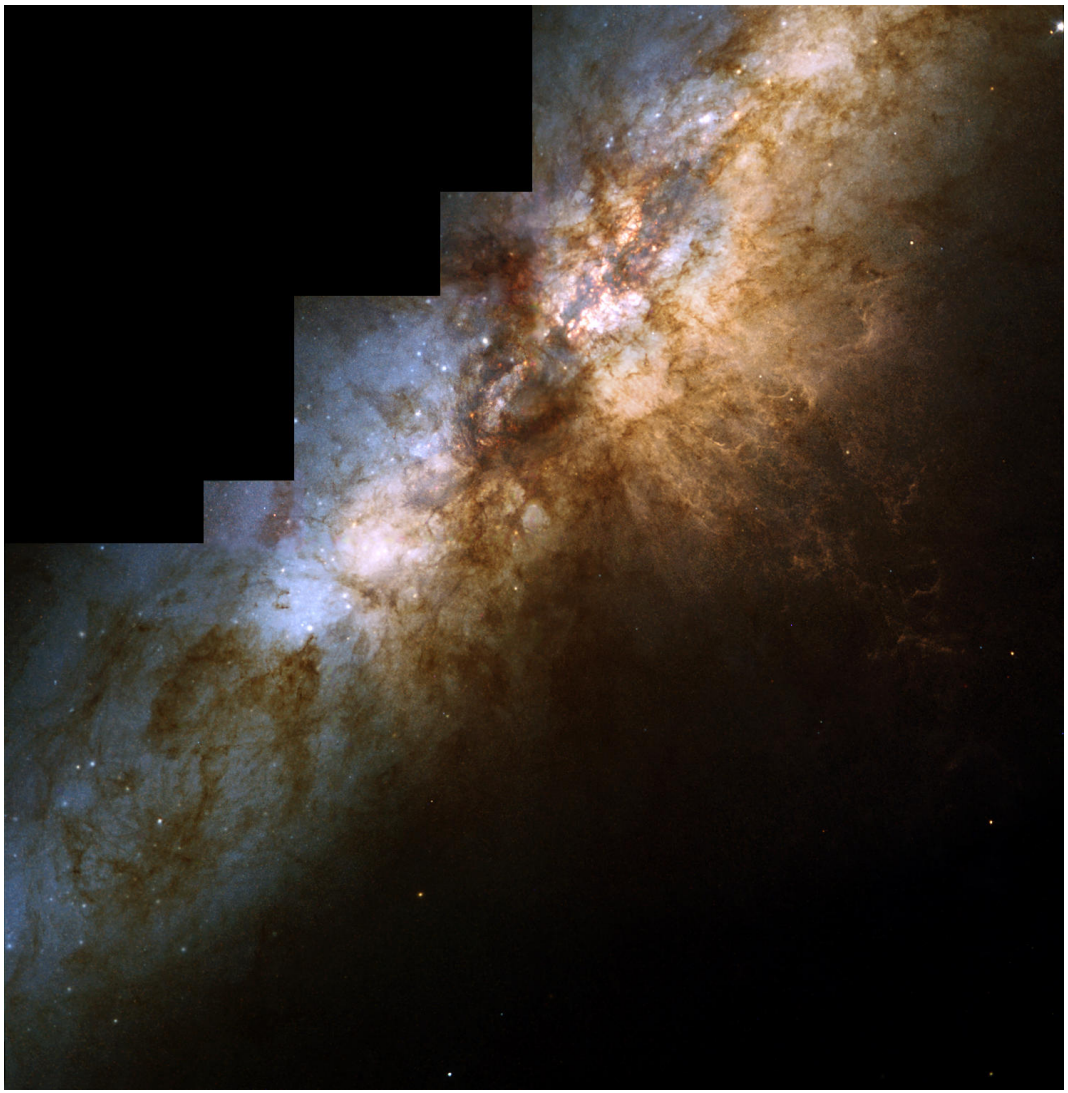
IR/Optical Colour Composite of
Center of Merging Galaxy System ESO202-G23 (VLT UT1 + ISAAC)

ESO PR Photo 46e/98 (26 November 1998)

©European Southern Observatory

ESO202-G23 (VLT UT1/ISAAC/ESO)

Irregular Galaxies: Irr II



M82, HST-WFPC

Irr II: asymmetrical and "abnormal"

$\Longrightarrow$ All objects that do not fit in the rest of the classification: starburst galaxies, interacting galaxies, Seyfert galaxies,...



NGC 6946, T. Rector/AURA/Gemini



NGC 6946, T. Rector/AURA/Gemini

NGC 6946 is a SABc galaxy (note very small bar).



I Zwicky 18, Y. Izotov/T. Thuan/HST



I Zwicky 18, Y. Izotov/T. Thuan/HST

I Zw 18 is a irregular galaxy

(and one of the smallest galaxies known, merely 1.2 kpc across).



Hoag's Object, HST



Hoag’s Object, HST

Hoag’s object an irregular galaxy



NGC 2841 (Robert Gendler, NASA/ESA, Subaru, and DSS)



NGC 2841 (Robert Gendler, NASA/ESA, Subaru, and DSS)

NGC 2841 is a Sb galaxy

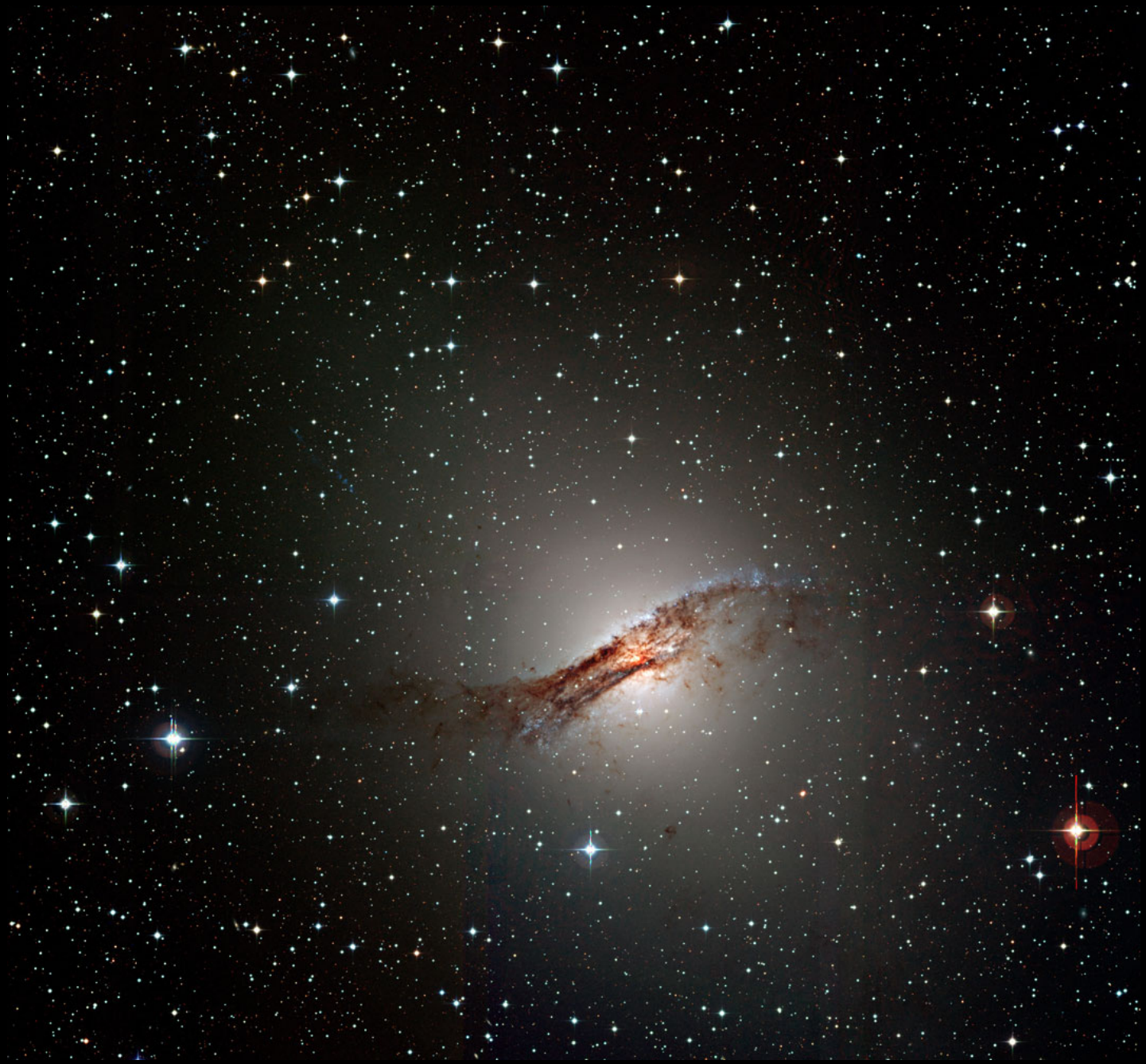


NGC 1300, HST

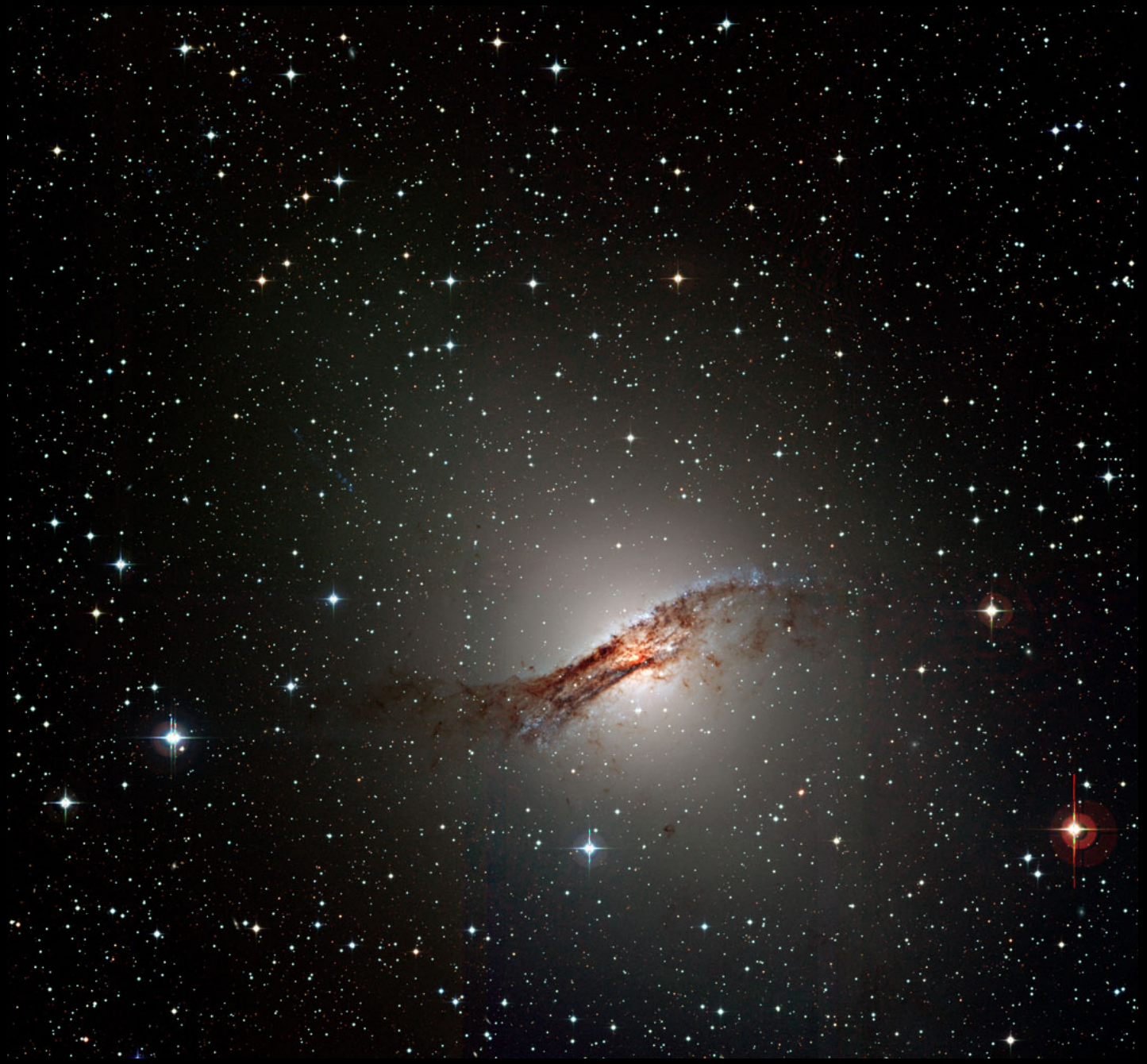


NGC 1300, HST

NGC 1300 is a SBbc galaxy



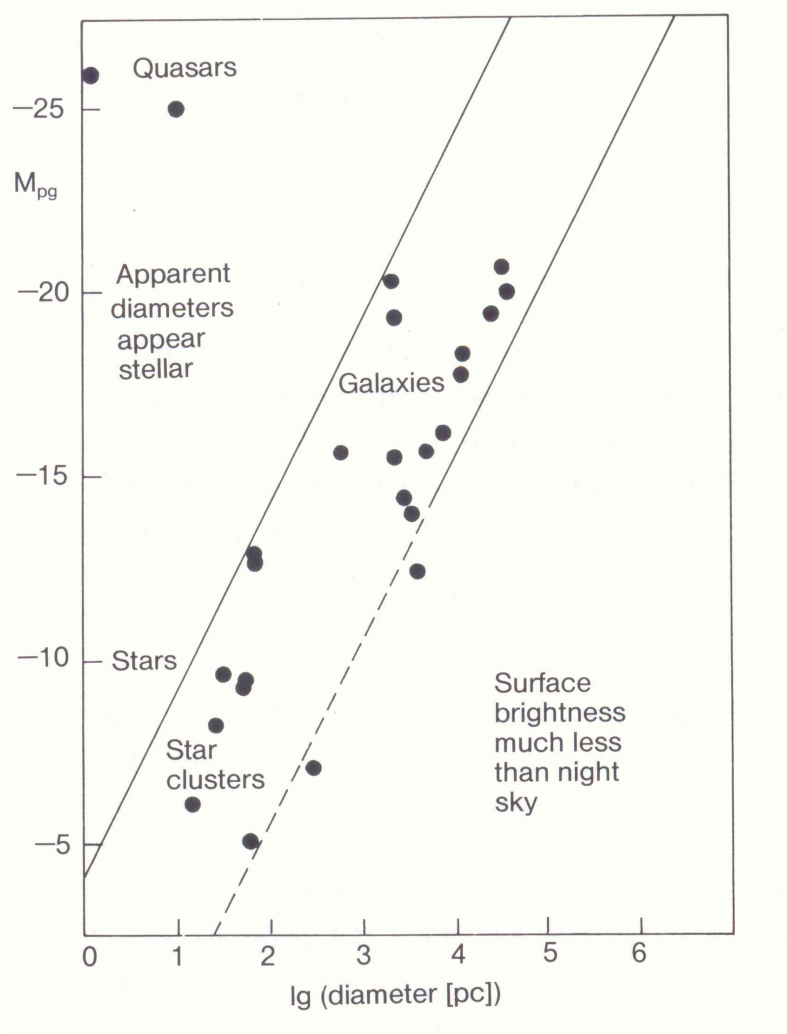
Cen A, ESO/WFI



Cen A, ESO/WFI

Cen A is a (peculiar) S0 galaxy

Caveats: Selection Effects



Karttunen

- diameter: edge of a galaxy is not well defined as intensity decreases strongly from center.

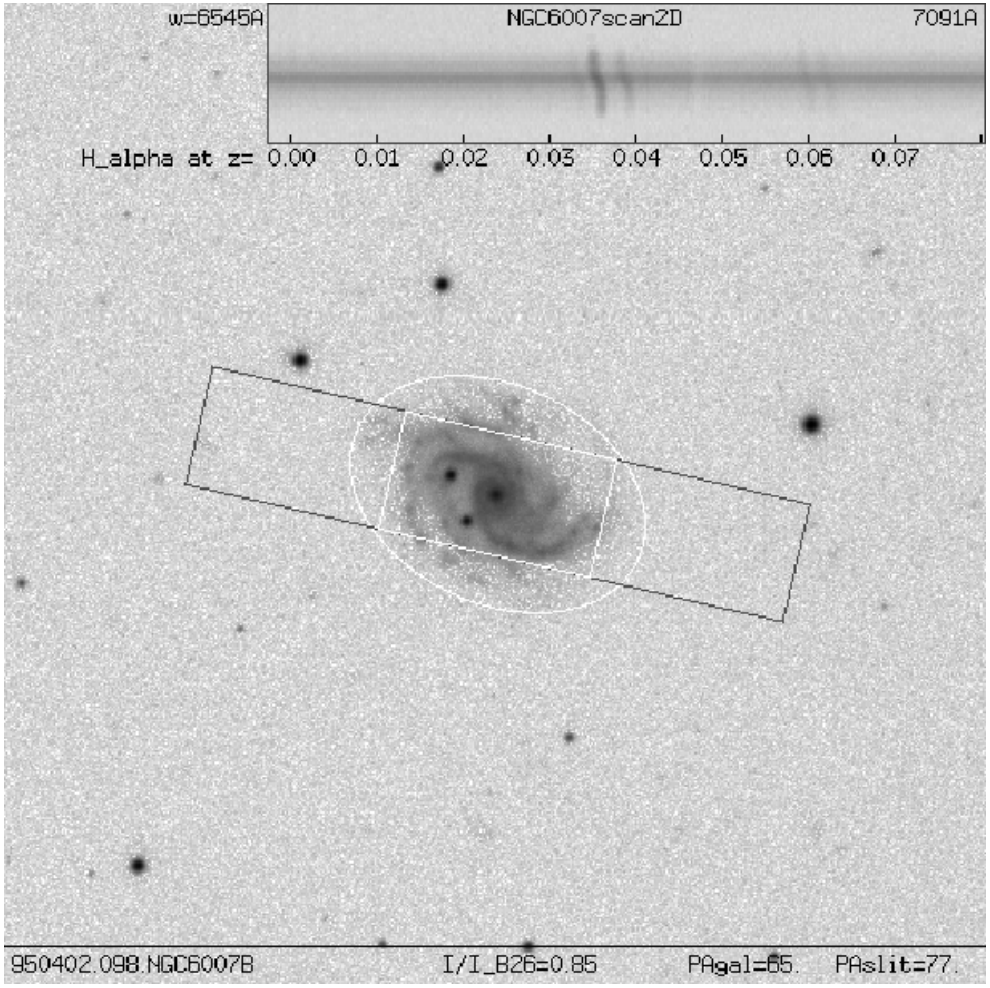
  Wide range of observed radii: 0.1 . . . 10 kpc (dwarf galaxies) to 30 kpc (normal spirals) and 50 kpc (ellipticals)

- Angular diameters depend on sky brightness

  Often used: D_{25} contour (= isophotal contour where galaxy becomes fainter than 25 mag arcsec^{-2})

- Small Galaxies can not be distinguished from stars
- Low surface brightness galaxies can not be seen against sky background.

Spiral Galaxies



NGC 6007 (Jansen; `http://www.astro.rug.nl/~nfgs/`)

Spectra of galaxies: sum of all constituent spectra (mainly stars plus some contribution from nebulae).

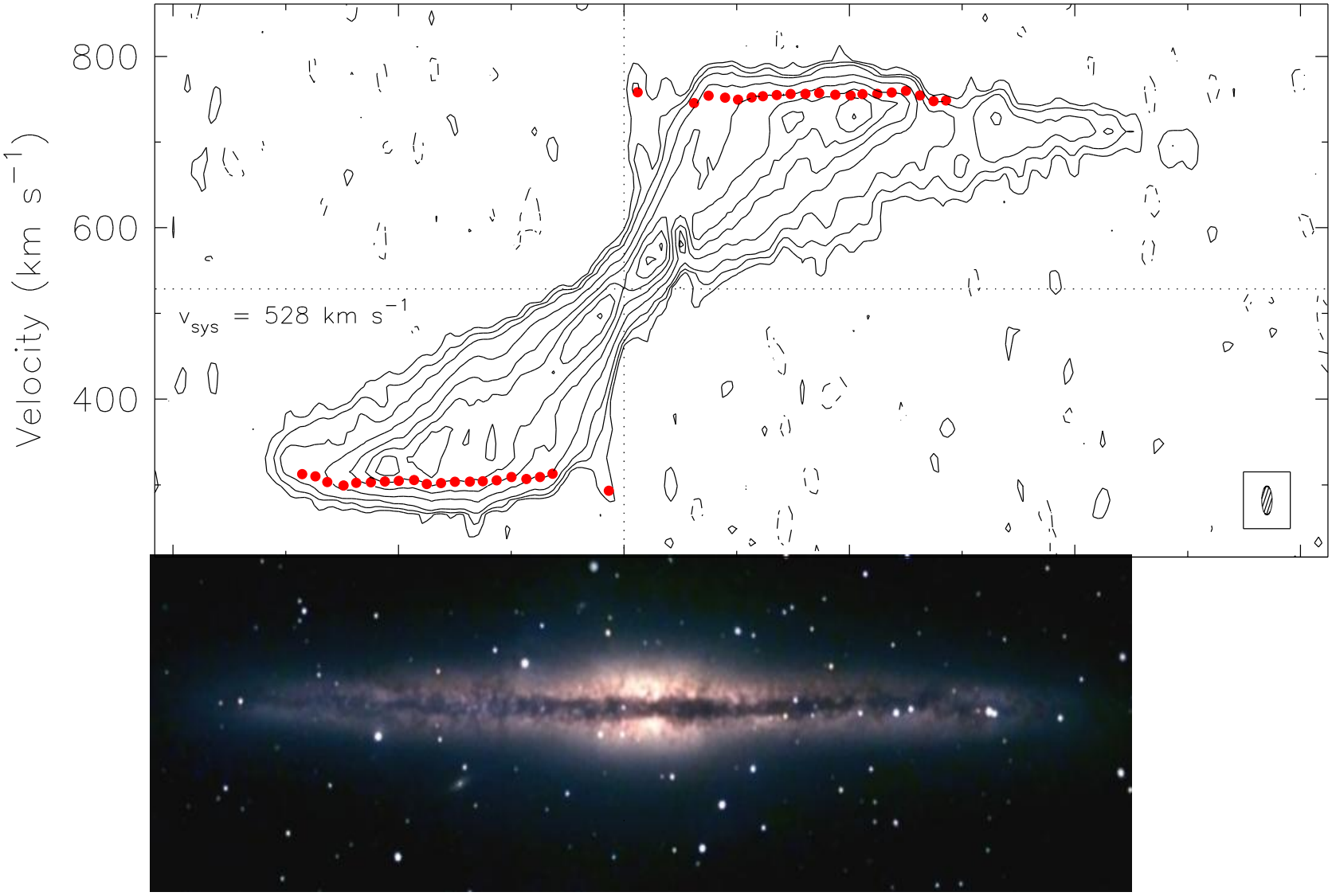
Absorption lines show clear shift $\Longrightarrow$ Doppler effect due to motion of stars around centre:

$$\frac{\Delta\lambda}{\lambda} = \frac{v_r}{c} = \frac{v}{c}\sin i$$

where v_r: radial velocity, i: inclination (angle measured with respect to plane of sky).

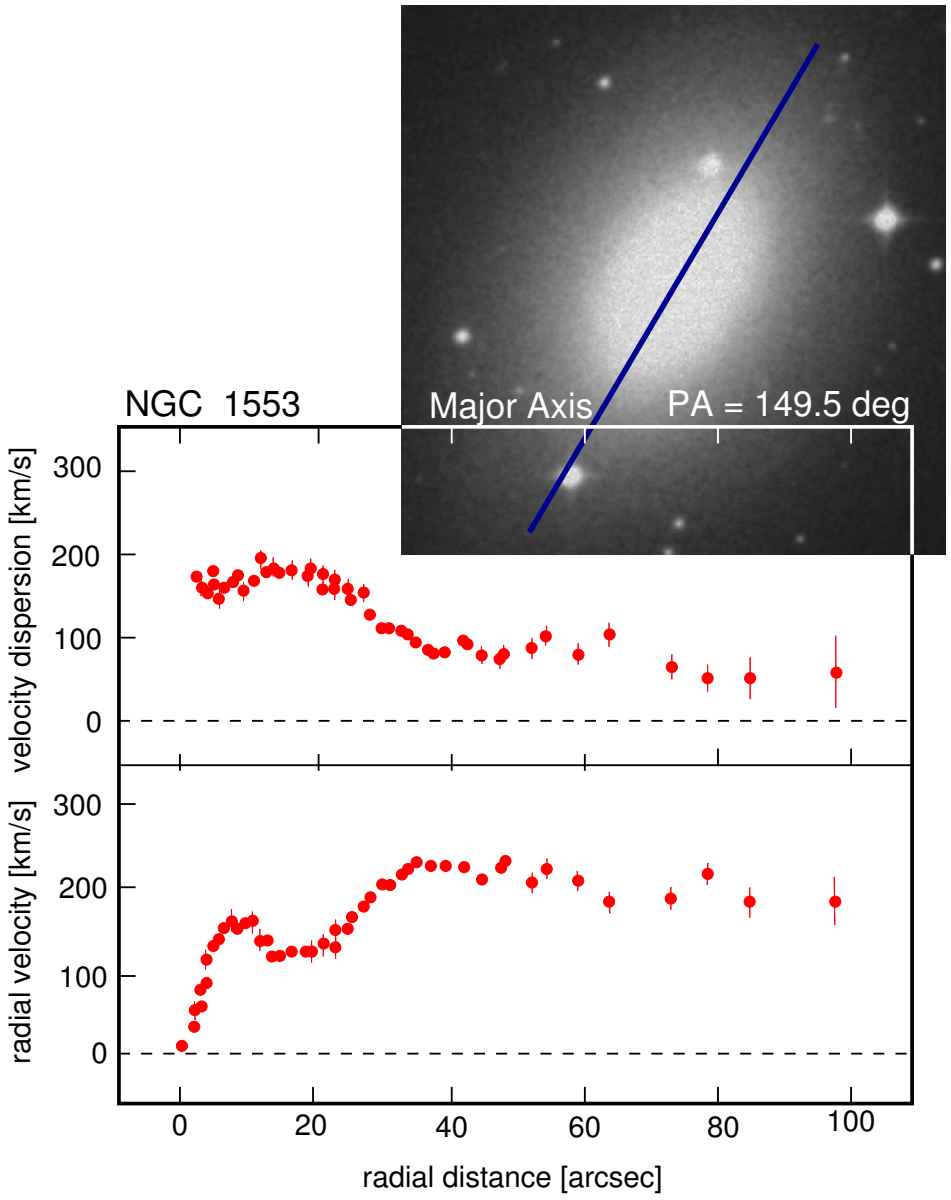
Typical rotation speeds are a few $100\,\mathrm{km\,s^{-1}}$.

Spiral Galaxies



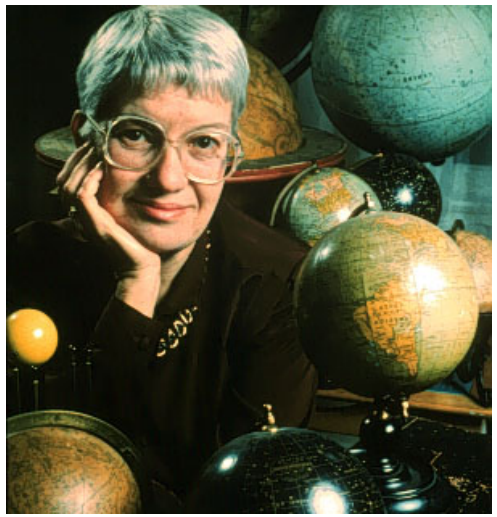
NGC 891 (Swaters et al., 1997, ApJ 491, 140 / Paul LeFevre, S&T Nov. 2002)

Spiral Galaxies



Spiral galaxy rotation curves are flat!

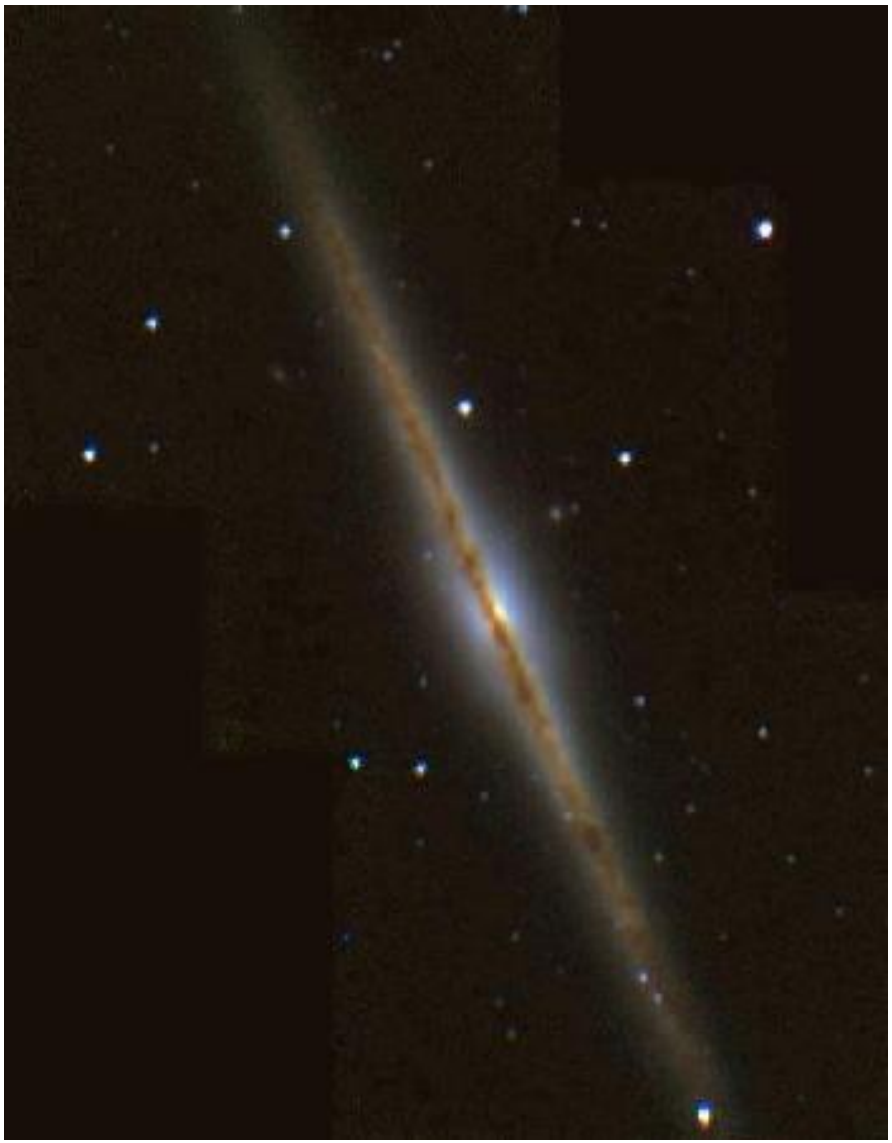
"Galaxy rotation problem", first discovered by Vera Rubin (1970)



©Astron. Soc. Pacific

← NGC 1553 (S0) (after Kormendy, 1984, ApJ 286, 116)

Rotation Curves: Interpretation



Newtonian interpretation of galaxy rotation curves:

Motion because of mass within r:

$$\frac{GM(\leqslant r)}{r^2} = \frac{v_{rot}^2(r)}{r}$$

such that

$$M(\leqslant r) = \frac{v_{rot}^2 r}{G}$$

therefore:

$v \sim$ const. implies $M(\leqslant r) \propto r$.

This assumption is approximately true even for nonspherical mass distributions.

NGC 891, KPNO 1.3 m
Barentine & Esquerdo

Rotation Curves: Interpretation

What mass distribution do we expect?

Intensity profile of disk in spiral galaxies can be well described by

$$I(r) = I_0 \exp(-r/h)$$

where r: distance from centre, h: "scale length".

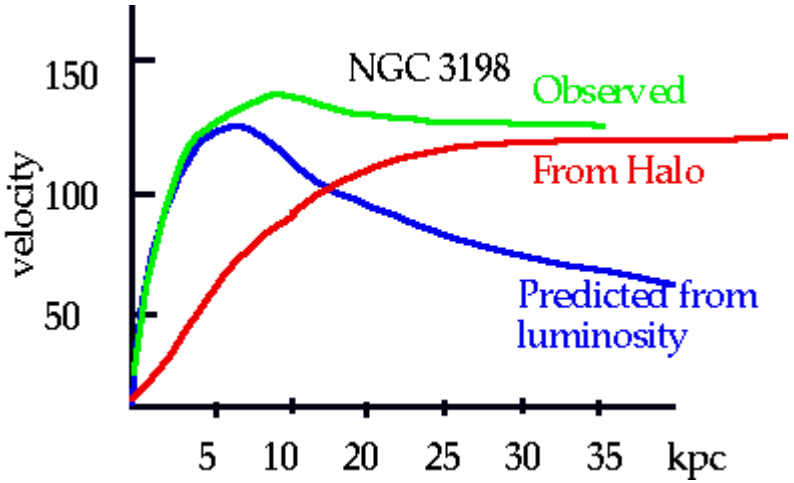
Luminosity emitted within radial distance r_0:

$$L(r < r_0) = I_0 \int_0^{r_0} \exp(-r/h)\, 2\pi r\, dr = 2\pi I_0 \left(h^2 - \exp(-r_0/h) h (h + r_0)\right)$$

i.e., for $r_0 \longrightarrow \infty$: $L(r < r_0) \rightarrow$ const..

If all light comes from stars, i.e., light traces mass,
and the population of stars does not change with position
then $M/L \sim$ const., such that $M(< r) \sim$ const. outside a certain radius and
$v \propto r^{-1/2} \Longrightarrow$ not what is observed!

Rotation Curves: Interpretation



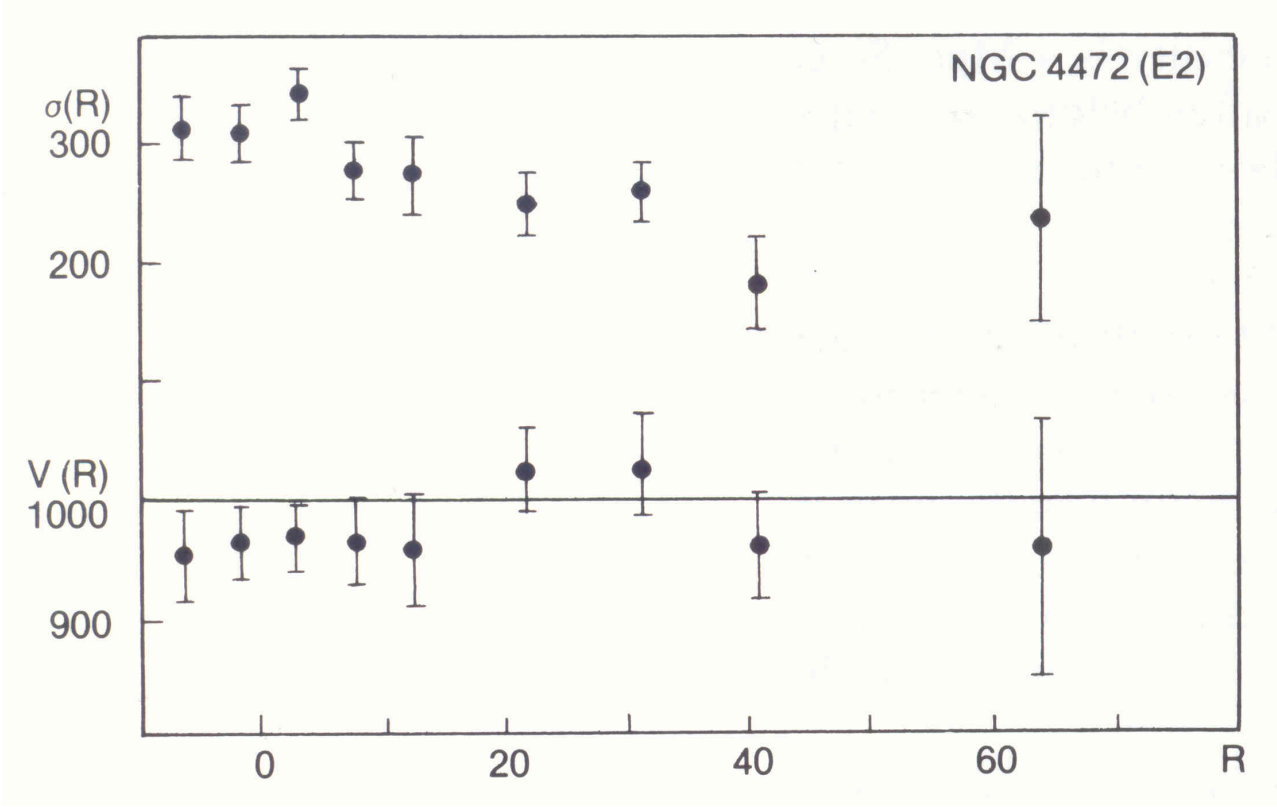
Distribution of dark matter

- luminosity to mass ratio: $L/M = 4$ (solar neighbourhood)
- convert luminosity to mass
- compute expected rotation curve form the mass distribution $v_{lum}(R)$
- distribution of dark matter: $M_{dark}(R) = \frac{M}{G}[v^2(R) - v^2_{lum}(R)]$

Canonical interpretation: a large fraction of gravitating material does not emit light $\Longrightarrow$ spiral galaxies have large and massive halos made of dark matter

Elliptical Galaxies

What determines the shape of elliptical galaxies?



Karttunen

No rotation!

Large velocity dispersion

statistical motion of stars

correlation of the central velocity dispersion with absolute brightness $L \sim \sigma_c^4$ (Faber-Jackson-relation)

Masses of Elliptical Galaxies

Ellipticals do not rotate. We can estimate their masses from the virial theorem assuming that the stars in ellipticals are in statistical equilibrium:

The virial theorem says that on average

$$\langle E_{kin} \rangle = -\frac{1}{2} \langle E_{pot} \rangle \tag{5.4}$$

For an elliptical galaxy,

$$M_G \langle v^2 \rangle = G \int_0^{R_G} \frac{M(R) dM(R)}{R} = a \frac{G M_G^2}{R_G} \tag{5.5}$$

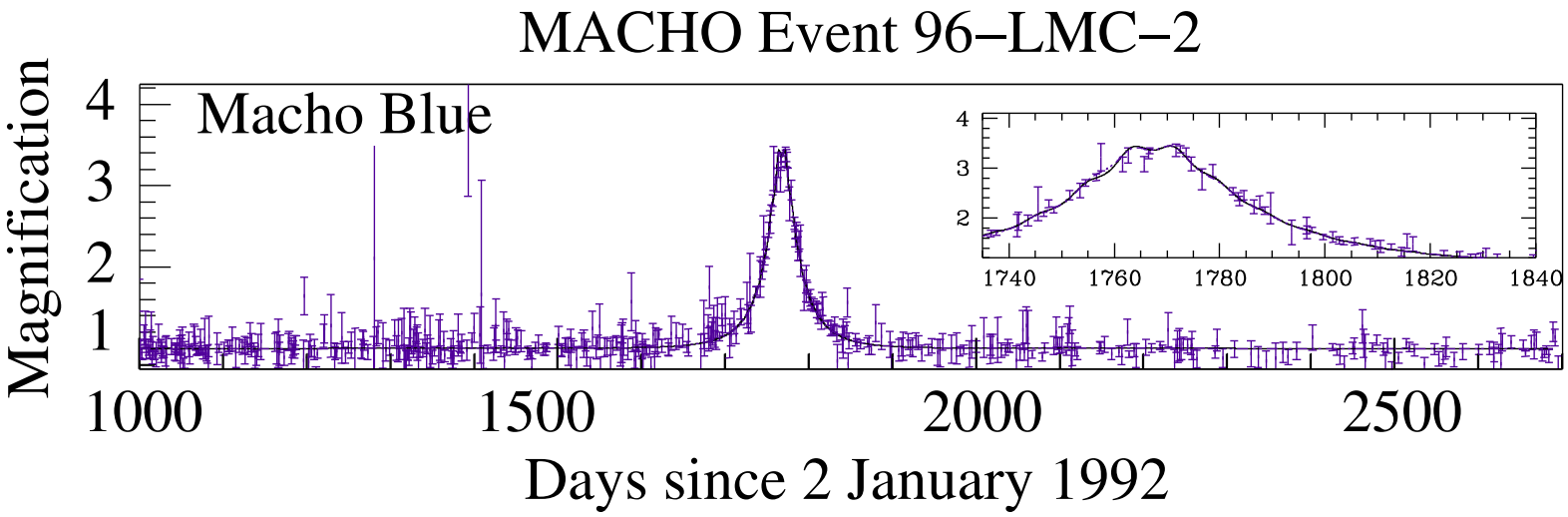
where for a homogeneous sphere $a = 3/5$. Therefore

$$\langle v^2 \rangle = \sigma^2 = a \frac{G M_G}{R_G} \tag{5.6}$$

Measurements show that also for ellipticals the kinematical mass is significantly larger than the mass of luminous matter.

Dark Matter is present also in Elliptical Galaxies

Dark Matter: MACHOS



after Alcock et al. (2001, Fig. 2)

MACHOS (Massive Compact Halo Objects): White dwarfs in the galaxy's halo

Pro:

1. very low luminosity objects $\Longrightarrow$ *very* difficult to detect
2. detected by microlensing towards SMC and LMC (see figure) $\Longrightarrow$ MW halo consists of 50% white dwarfs

Contra:

1. possible "self-lensing" (by stars in MW or SMC/LMC; confirmed for a few cases)
2. inferred white dwarf formation rate too high (100 $\text{year}^{-1}\,\text{Mpc}^{-3}$ instead of <1 as previously assumed)

Dark Matter: Nonbaryonic

Nonbaryonic dark matter:

Requirements:

- gravitating
- no or very weak other interaction with baryons (= "us")

$\Longrightarrow$ Grab-box of elementary particle physics:

1. Neutrinos with non-zero mass

   Pro: It exists, mass limits are a few eV, need only $\langle m_\nu c^2 \rangle \sim 10\,\mathrm{eV}$

   Contra: ν are relativistic ($v \sim c$), this has implications for galaxy formation that make it unlikely that they form a major part of dark matter.

2. Axions ($mc^2 \sim 10^{-5\ldots-2}\,\mathrm{eV}$) and WIMPs (weakly interacting massive particles; masses $mc^2 \sim \mathrm{GeV}$)

   Pro: help with cosmology as well

   Contra: We do not know they exist... (but they might soon be detectable)

$\Longrightarrow$ Jury is still out, question on origin of flat rotation curves is still open.

MOND

Modified Newtonian Dynamics (Milgrom, 1983ff.; MOND): Alternative to Dark Matter

Reviews: Sanders & McGaugh, 2002, Ann. Rev. Astron. Astrophys. 40, 263; Milgrom, 2001, astro-ph/0112069

Idea: Modify Newton's Laws:

Acceleration on particle in gravitational field:

$$a = \frac{GM}{r^2} \cdot \frac{1}{\mu(a/a_0)} \quad \text{with} \quad \mu(x) \longrightarrow \begin{cases} 1 & \text{for } x \to \infty \\ x & \text{for } x \to 0 \end{cases}$$

i.e., for accelerations $a \ll a_0$, $a \longrightarrow \sqrt{GMa_0/r^2}$, giving circular motion in the limit of small accelerations:

$$\sqrt{\frac{GM(\leqslant r)a_0}{r^2}} = \frac{v^2}{r} \quad \Longrightarrow \quad M(\leqslant r) = \frac{v^4}{Ga_0}$$

and therefore independent of r!

MOND can explain the flat rotational curves (by construction!).

MOND

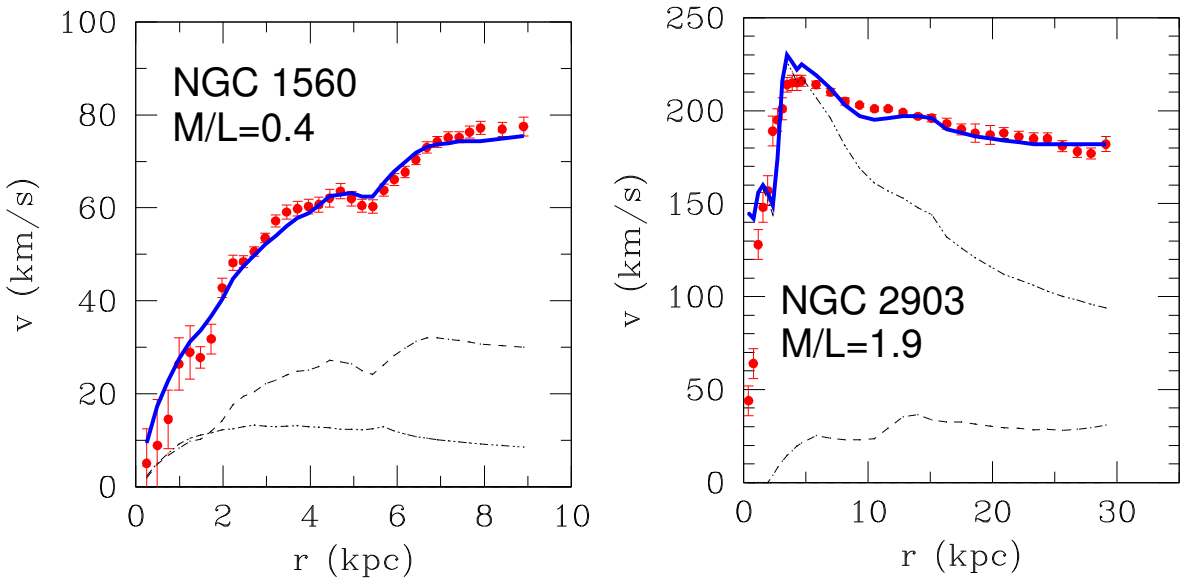
Fits of rotational curves give

$$a_0 = 1.2 \times 10^{-8}\,\mathrm{cm\,s^{-2}}$$

and $M/L \sim 1$, so not bad!

BUT:

- where is the physics behind a_0?



after Sanders & McGaugh (2002)

- violation of the strong equivalence principle

  ("outcome of any physical experiment is independent of where and when in the universe it is performed, and it is independent on whether the experimental apparatus is free falling or stationary")

$\Longrightarrow$ At the moment MOND does not seem to be a viable alternative to other theories of dark matter.

...but it shows that even today people are not afraid to attack Newton's laws, and this is good for progress of physics as a whole

The Astronomical Distance Ladder

Introduction

Distances are required to determine properties such as the luminosity or the size of an astronomical object.

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Only *direct* method:

1. Trigonometric parallax

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Only *direct* method:

1. Trigonometric parallax

Most other methods based on "standard candles", i.e., use known absolute magnitude of an object to derive distance via distance modulus.

2. Main Sequence Fitting
3. Variable stars: RR Lyrae and Cepheids
4. Type Ia Supernovae
5. Tully-Fisher for spiral galaxies
6. D_n-σ for ellipticals
7. Brightest Cluster Galaxies

Introduction

Distances are required to determine properties such as the luminosity or the size of an astronomical object.

Only *direct* method:

1. Trigonometric parallax

Most other methods based on "standard candles", i.e., use known absolute magnitude of an object to derive distance via distance modulus.

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For the farthest objects, can also use expansion of universe:

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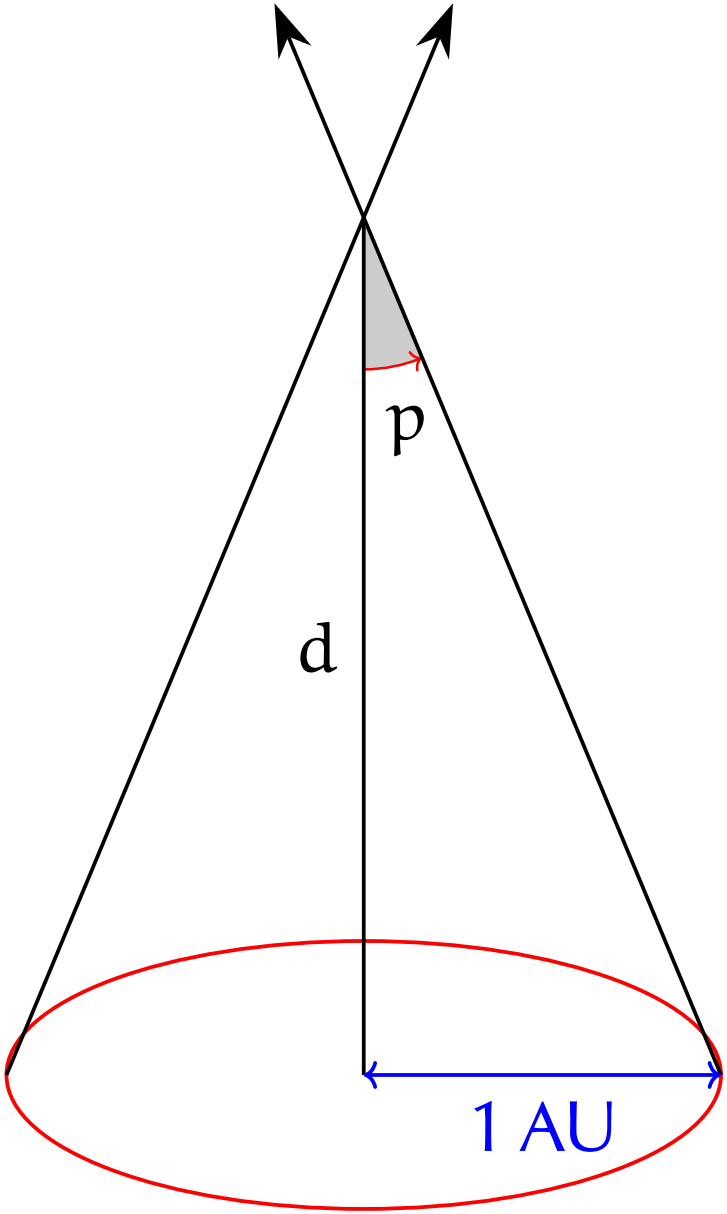
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For the farthest objects, can also use expansion of universe:

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Methods are calibrated using distances from the previous step of the distance ladder.

Trigonometric Parallax



Motion of Earth around Sun $\Longrightarrow$ Parallax
Produces apparent motion of star; projected on sky see angular motion, opening angle

$$\tan p \sim p = \frac{r_\oplus}{d} = \frac{1\,\mathrm{AU}}{d}$$

p is called the trigonometric parallax.

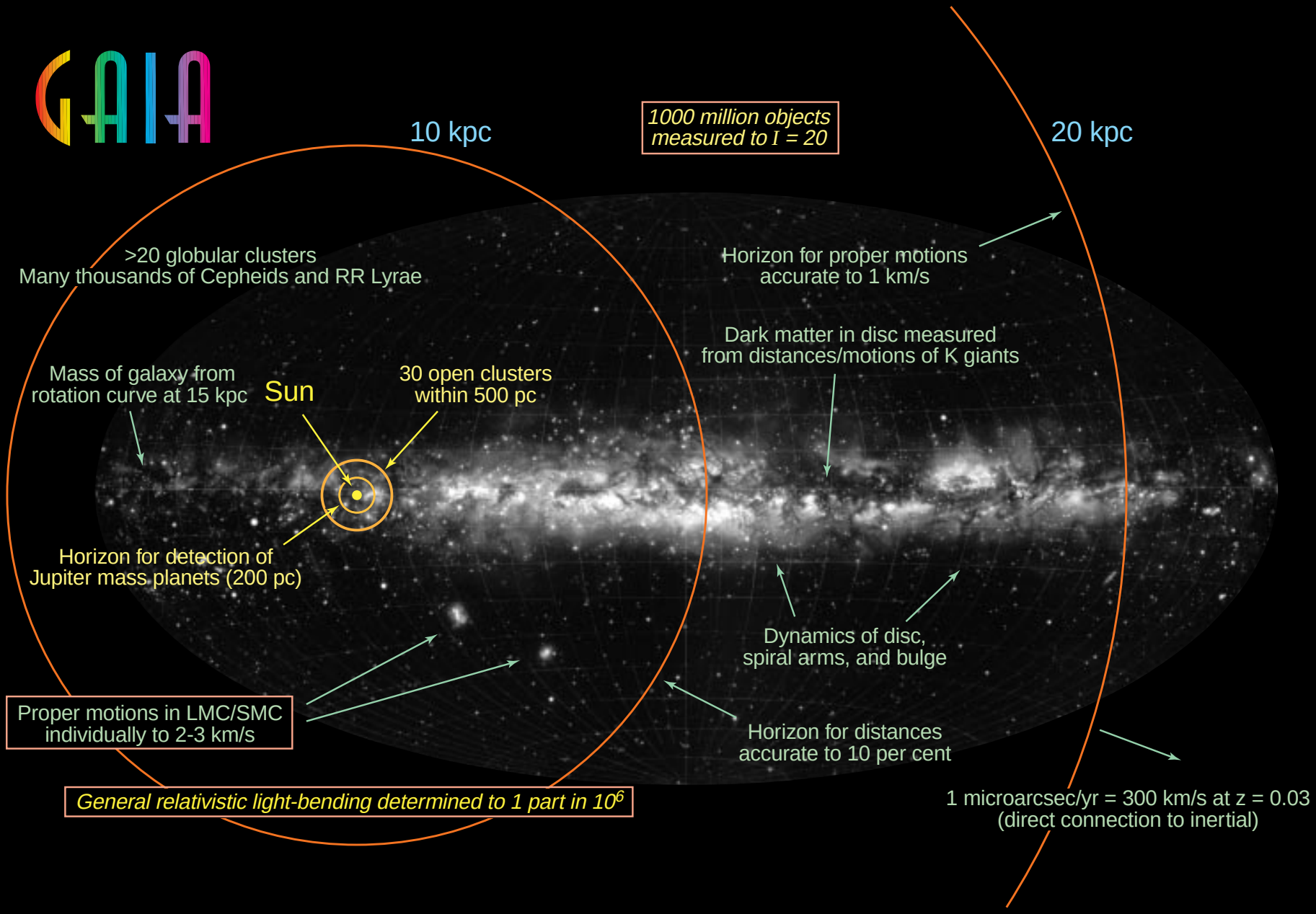
Note: requires several measurements at several positions of the Earth

Measurement difficult: $p \lesssim 0.76''$ (α Cen).

Define unit for distance:
Parsec: Distance for which $p = 1''$.

$$1\,\mathrm{pc} = 206265\,\mathrm{AU} = 3.086 \times 10^{16}\,\mathrm{m} = 3.26\,\mathrm{ly}$$

Gaia (ESA mission)



GAIA: ~ 4μarcsec precision, 4 color to $V = 20$ mag, 10^9 objects.

Standard Candles

Assuming isotropic emission, the flux measured at distance d from object with luminosity L is given by the "inverse square law",

$$f(d) = \frac{L}{4\pi d^2}$$

note that f is a function of the d.

Remember that the magnitude is defined through comparing two fluxes,

$$m_2 - m_1 = 2.5 \log_{10}(f_1/f_2) = -2.5 \log_{10}(f_2/f_1)$$

To allow the comparison of sources at different distances, define

absolute magnitude M = magnitude if star were at distance 10 pc

Because of this

$$M - m = -2.5 \log_{10}\left(f(10\,\mathrm{pc})/f(d)\right) = -2.5 \log_{10}\left(\frac{L/(4\pi(10\,\mathrm{pc})^2)}{L/(4\pi d^2)}\right) = -2.5 \log_{10}\left(\frac{d}{10\,\mathrm{pc}}\right)^2$$

The difference $m - M$ is called the distance modulus,

$$m - M = 5 \log_{10}\left(\frac{d}{10\,\mathrm{pc}}\right)$$

Standard Candles

To obtain distance, use standard candles

> Standard candles are defined to be objects for which their absolute magnitude is known.

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Requirements:

- physics of standard candle well understood (i.e., need to know *why* object has certain luminosity).
- absolute magnitude of standard candle needs to be calibrated, e.g., by measuring its distance by other means (this is a *big problem*)

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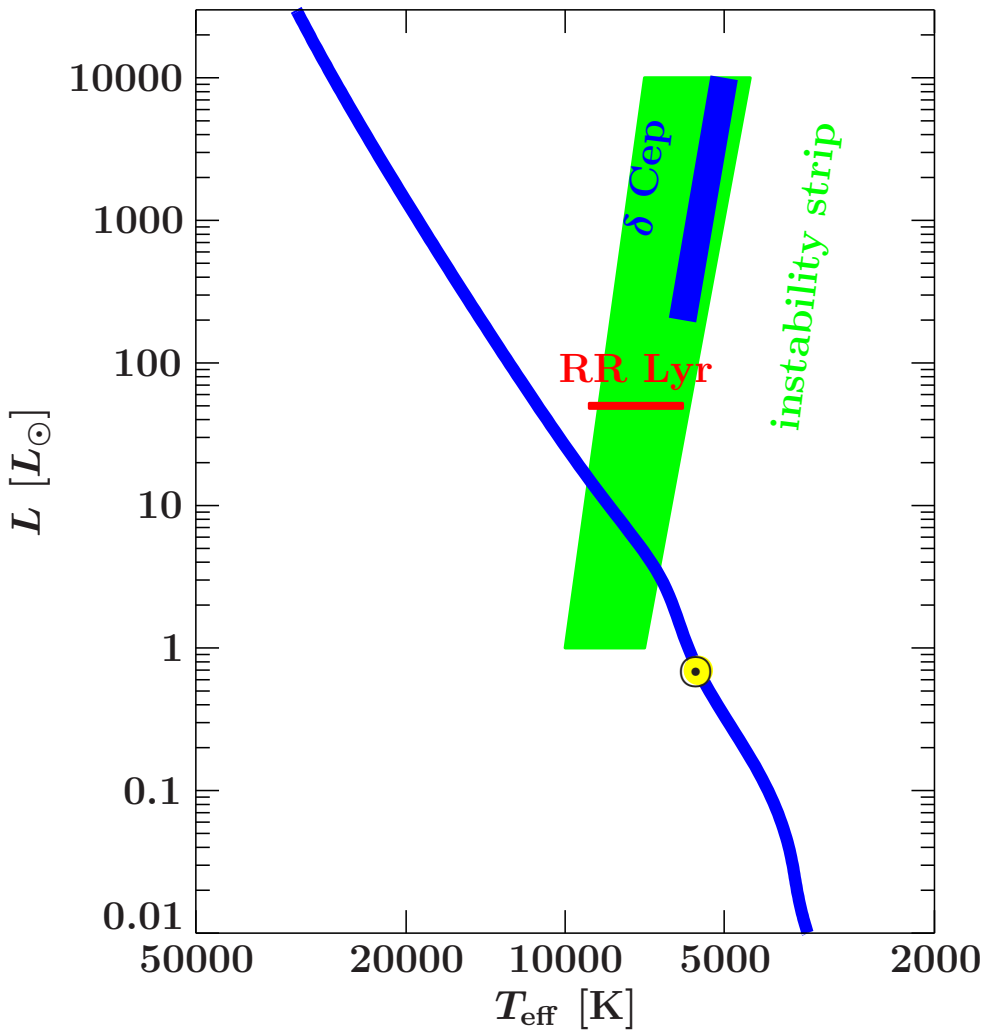
- physics of standard candle well understood (i.e., need to know *why* object has certain luminosity).
- absolute magnitude of standard candle needs to be calibrated, e.g., by measuring its distance by other means (this is a *big problem*)

To determine distance to astronomical object:

1. find standard candle(s) in object,
2. measure their m
3. determine $\mathrm{m} - \mathrm{M}$ from known M of standard candle
4. compute distance d

Often, distances are given in terms of $\mathrm{m} - \mathrm{M}$, and not in pc, so last step is not always performed.

Variable stars



Instability strip in the Hertzsprung-Russell Diagram

Certain regions of HRD: stars prone to instability:

Ionization of Helium: transparency of outer parts of star changes

$\Longrightarrow$ size of star changes

$\Longrightarrow$ surface temperature and luminosity variations

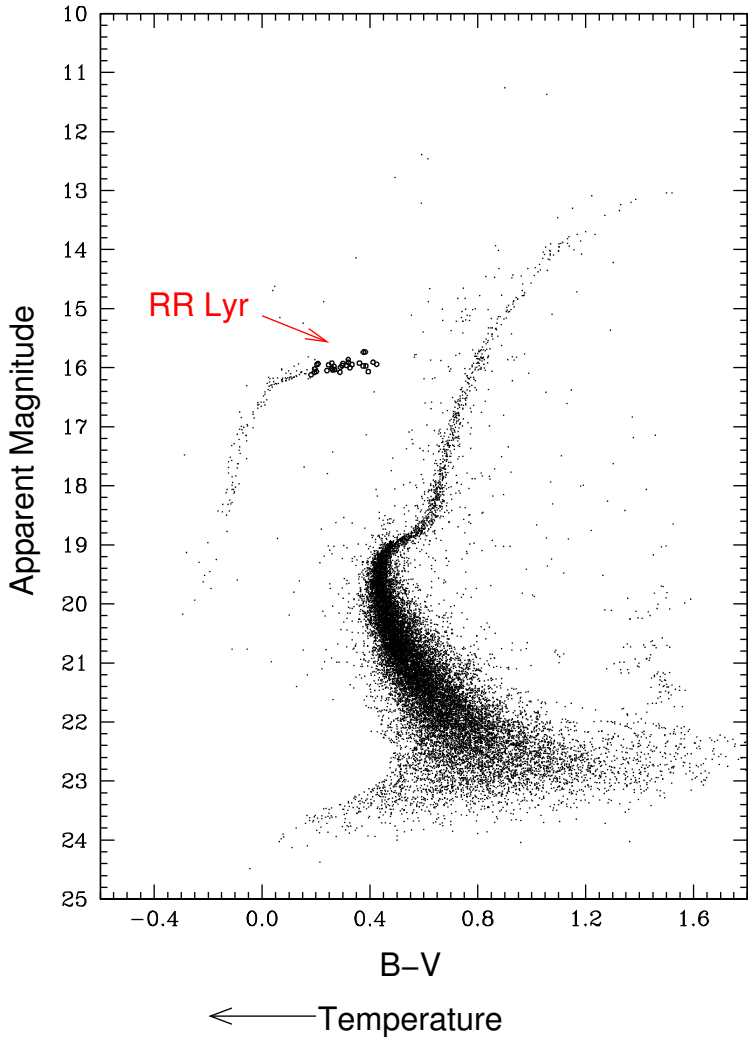
Most important variables of this kind:

1. RR Lyr variables

   mainly in globular clusters: lower metallicity of clusters ("population II") allows stars to enter instability strip

2. δ Cepheids

RR Lyrae



HRD of Globular Cluster M2
(after Lee et al., 1999, Fig. 2)

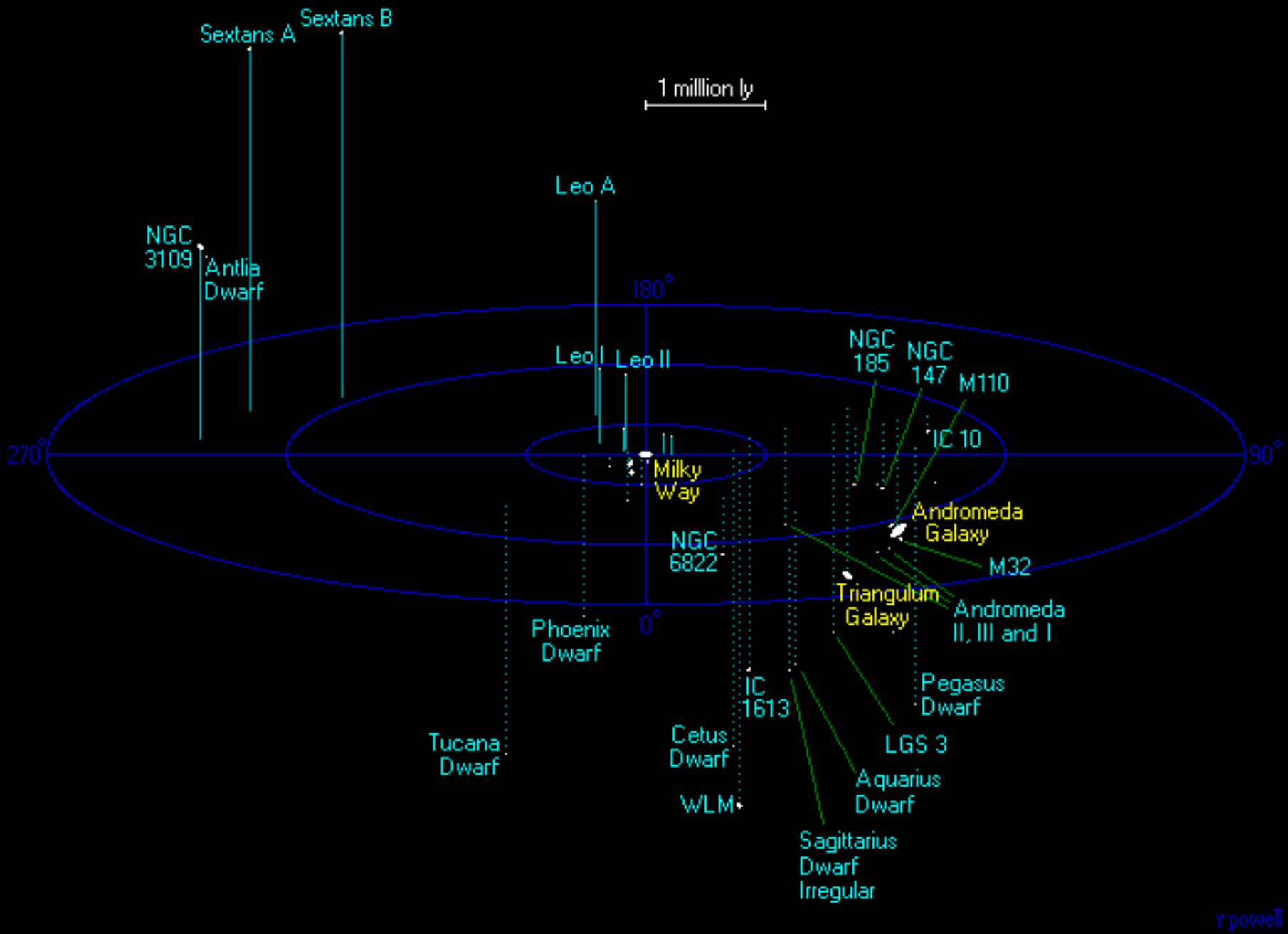
RR Lyrae variables:

- Variability ($P \sim 0.2 \ldots 1\,d$)
- Mainly temperature change
- RR Lyr gap clearly observable in globular cluster HRD

Absolute magnitude of RR Lyr gap:
$M_V = 0.6\,mag$, $M_B = 0.8\,mag$, i.e., $L_{RR} \sim 50\,L_\odot$.

Works out to LMC ($d \sim 50\,kpc$) and other dwarf galaxies of local group, mainly used for globular clusters and local group.

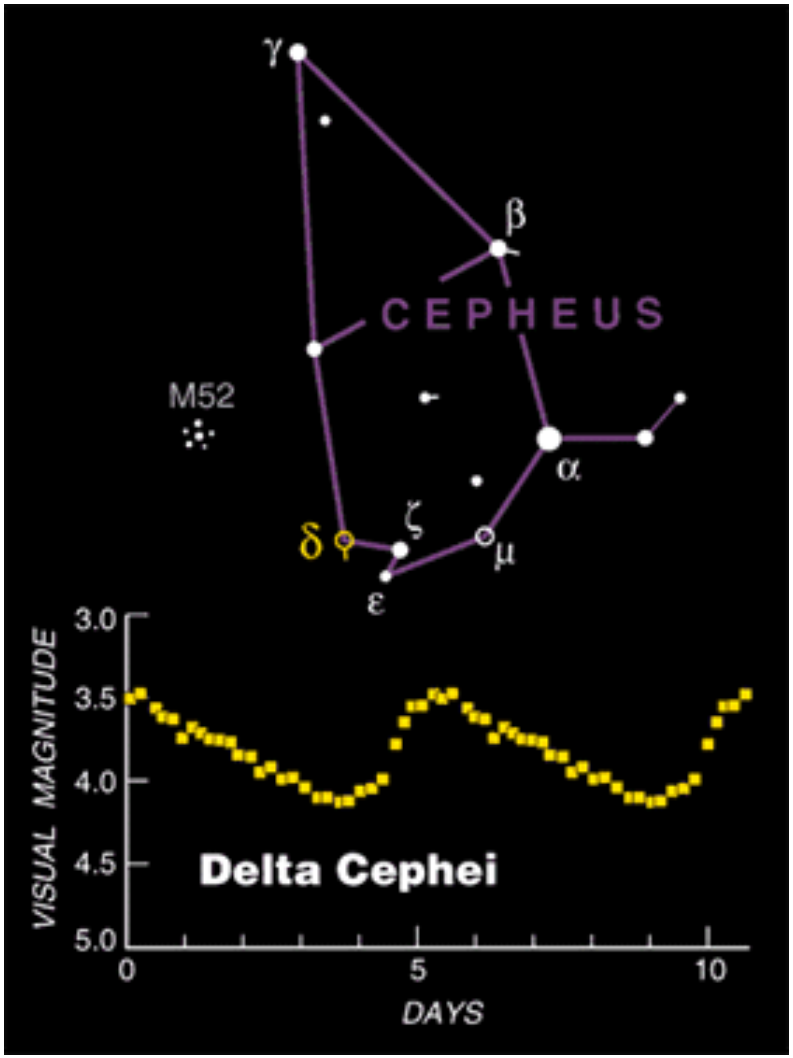
Example: M5: gap at $m = 16\,mag \Longrightarrow m - M = 15.4\,mag \Longrightarrow d = 12\,kpc$.



source: `http://www.atlasoftheuniverse.com`

The neighbourhood of the Milky Way: the Local Group

Cepheids





John Goodricke (1764–1786):

- deaf after scarlet fever at the age of five
- special education at Edinburgh
- at the age of 13 academy near York
- 1781: worked with Edward Pigott as astronomer
- 1782: discovery of Algol as eclipsing binary
- 1784: discovery of δ Cep

Cepheids



© ASP

Henrietta Leavitt (1868–1921):

- Graduated from Radcliffe College
- from 1895: volunteer at Harvard Observatory
- was ill and partially deaf from that
- 1902: back at Harvard Obs
- discovered 1777 variable stars in LMC
- 1912: discovered Period-Luminosity relation of Cepheids in SMC, but was not allowed (!) to follow this up

- later: defined Harvard photographic magnitude system
- died of cancer in 1921

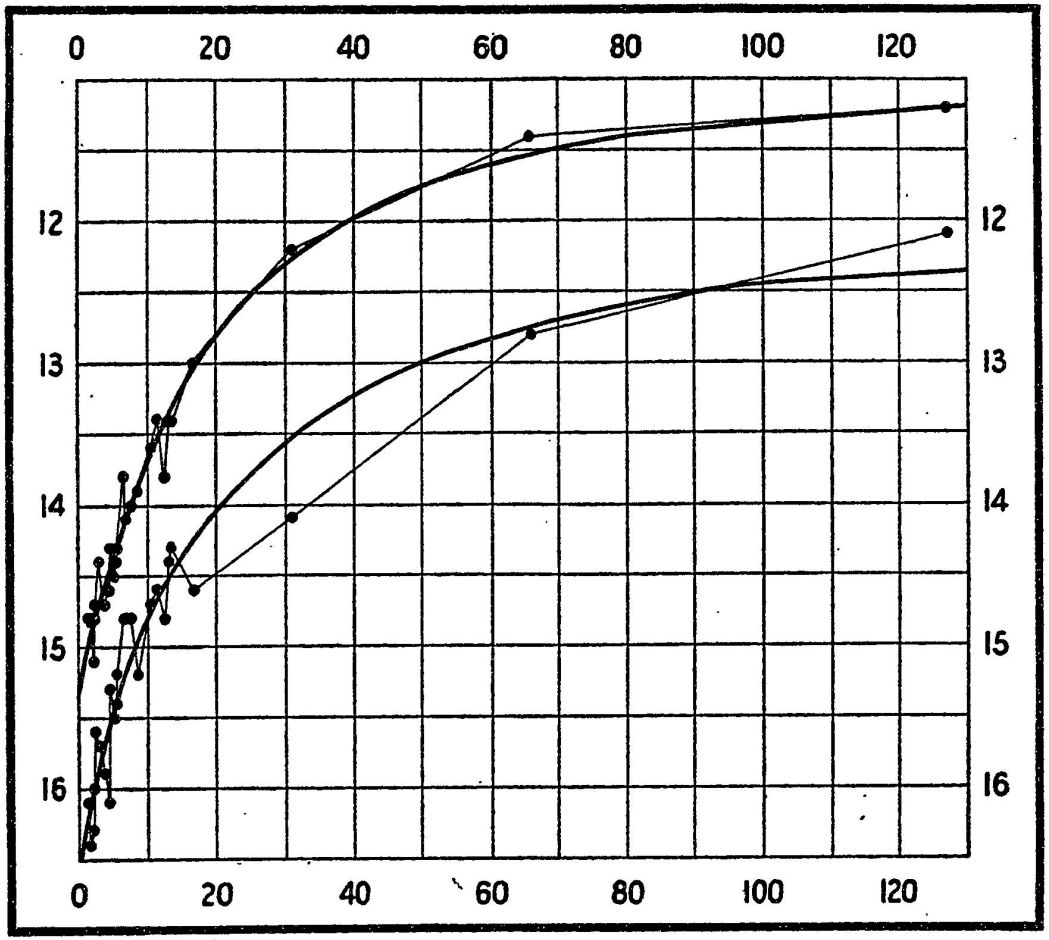


FIG. 1.

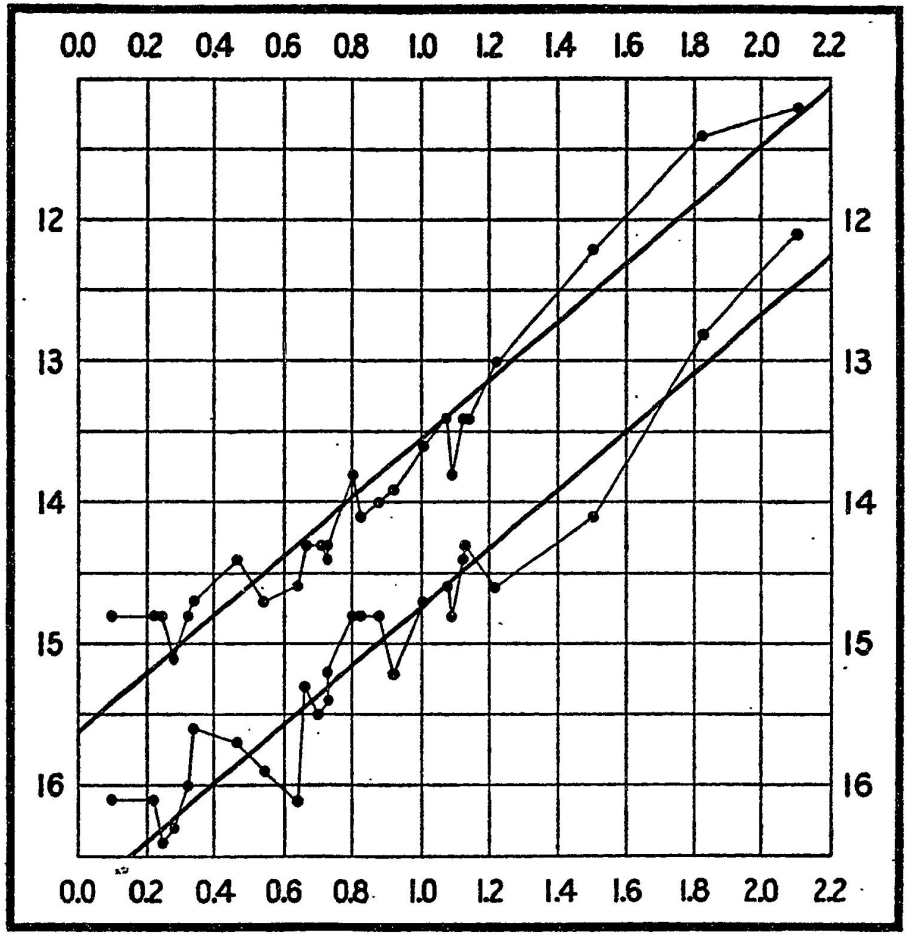
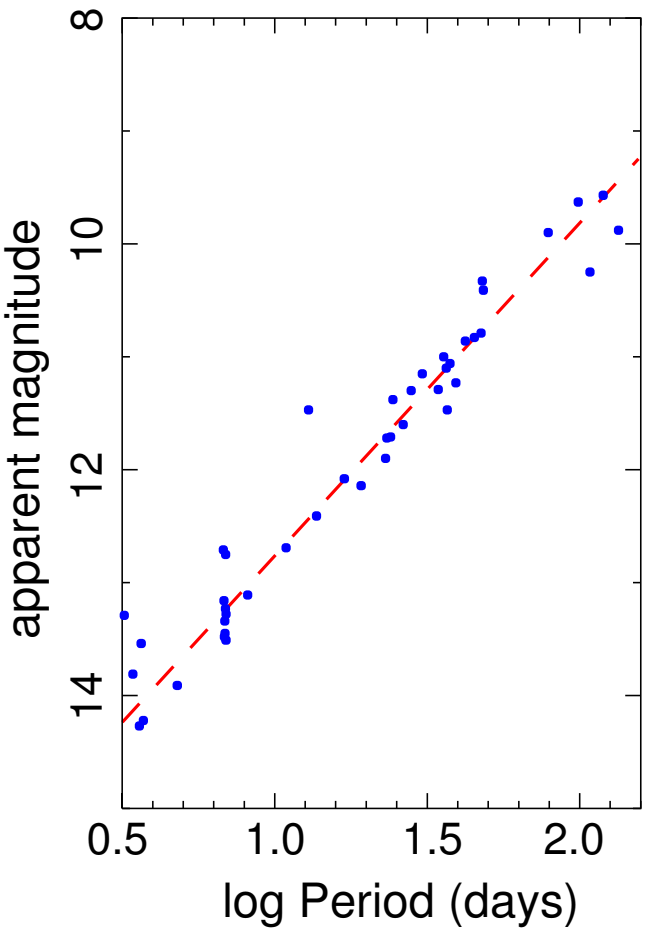


FIG. 2.

x-axis: period in days, y-axis: magnitude

Leavitt & Pickering, 1912, Periods of 25 Variable Stars in the Small Magellanic Cloud, Harvard College Observatory Circular, vol. 173, pp. 1–3

Cepheids



Period-Luminosity relation for the LMC Cepheids
after Mould et al. (2000, Fig. 2)

Henrietta Leavitt(1912):

Cepheids have a period luminosity relationship: $M \propto -\log P$

Low luminosity Cepheids have lower period

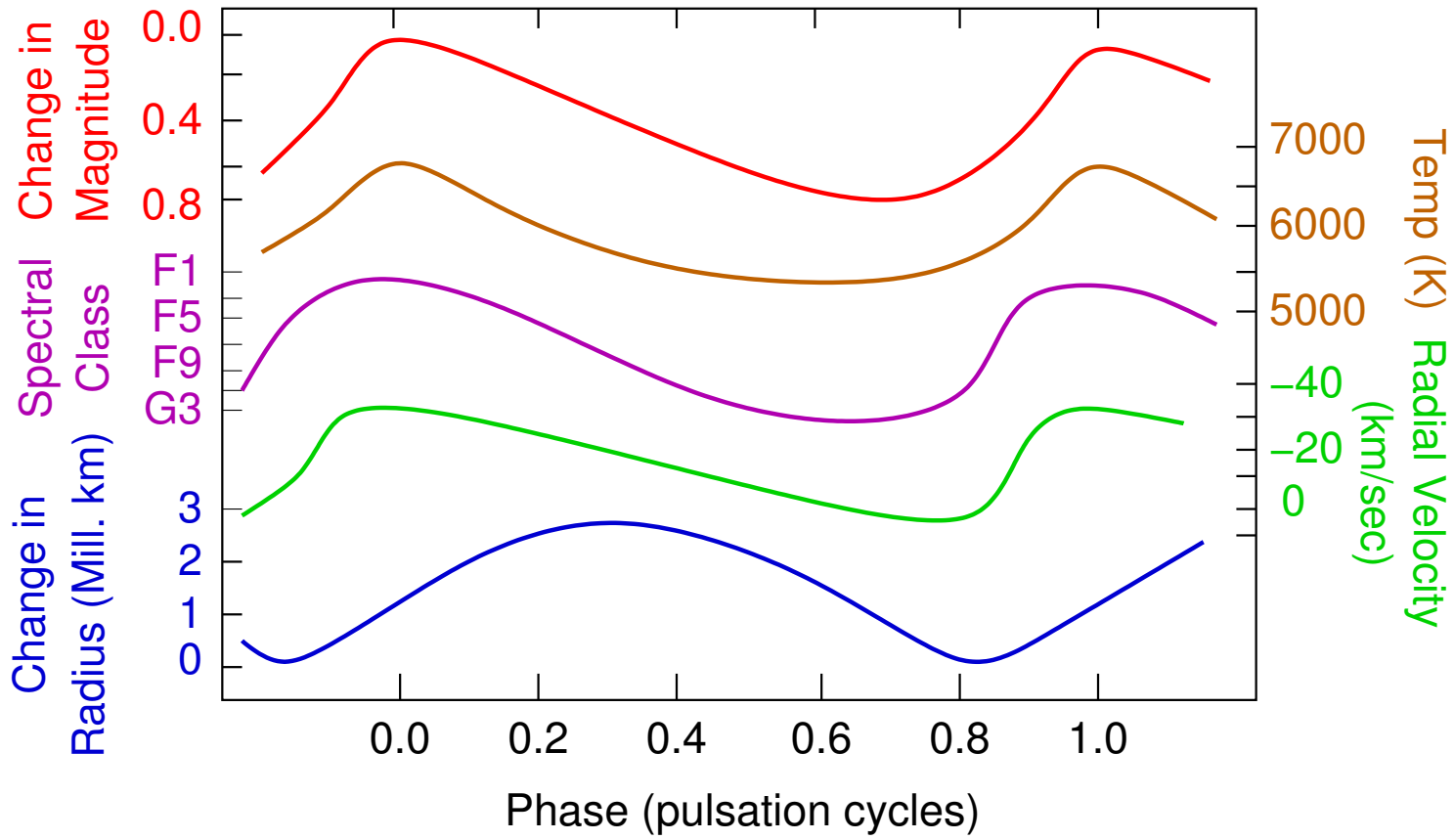
Observations find:

$$\langle M \rangle = -2.76 \log P - 1.40$$

(P in days)
Calibrated from observing Large Magellanic Cloud Cepheids (see figure), and determining LMC distance from other means (MS fitting, RR Lyr,...) to find absolute magnitudes...

With HST: works out to Virgo cluster ($d = 18.5$ Mpc).

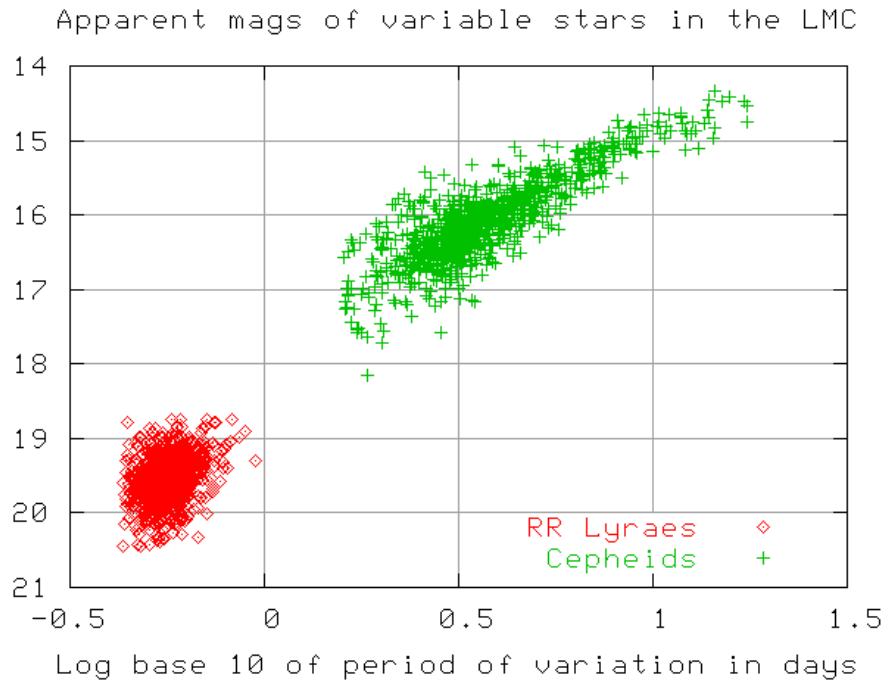
Cepheids



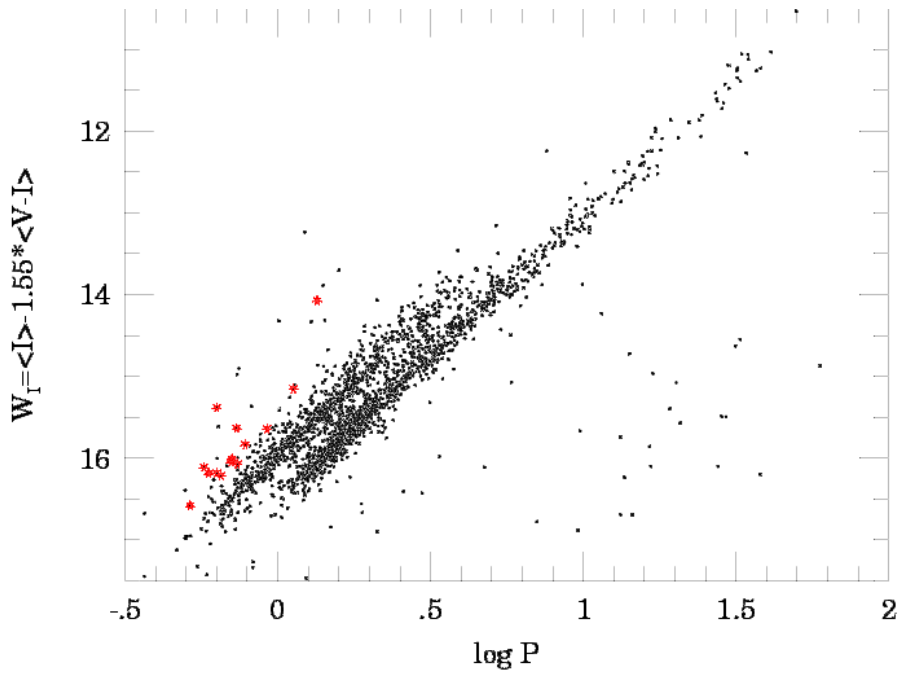
after `http://csep10.phys.utk.edu/astr162/lect/index.html`

Cepheids: Luminous stars ($L \sim 1000\,L_\odot$) in instability strip with large luminosity amplitude variation, $P \sim 2 \ldots 150$ d (easily measurable).

The distance to the LMC



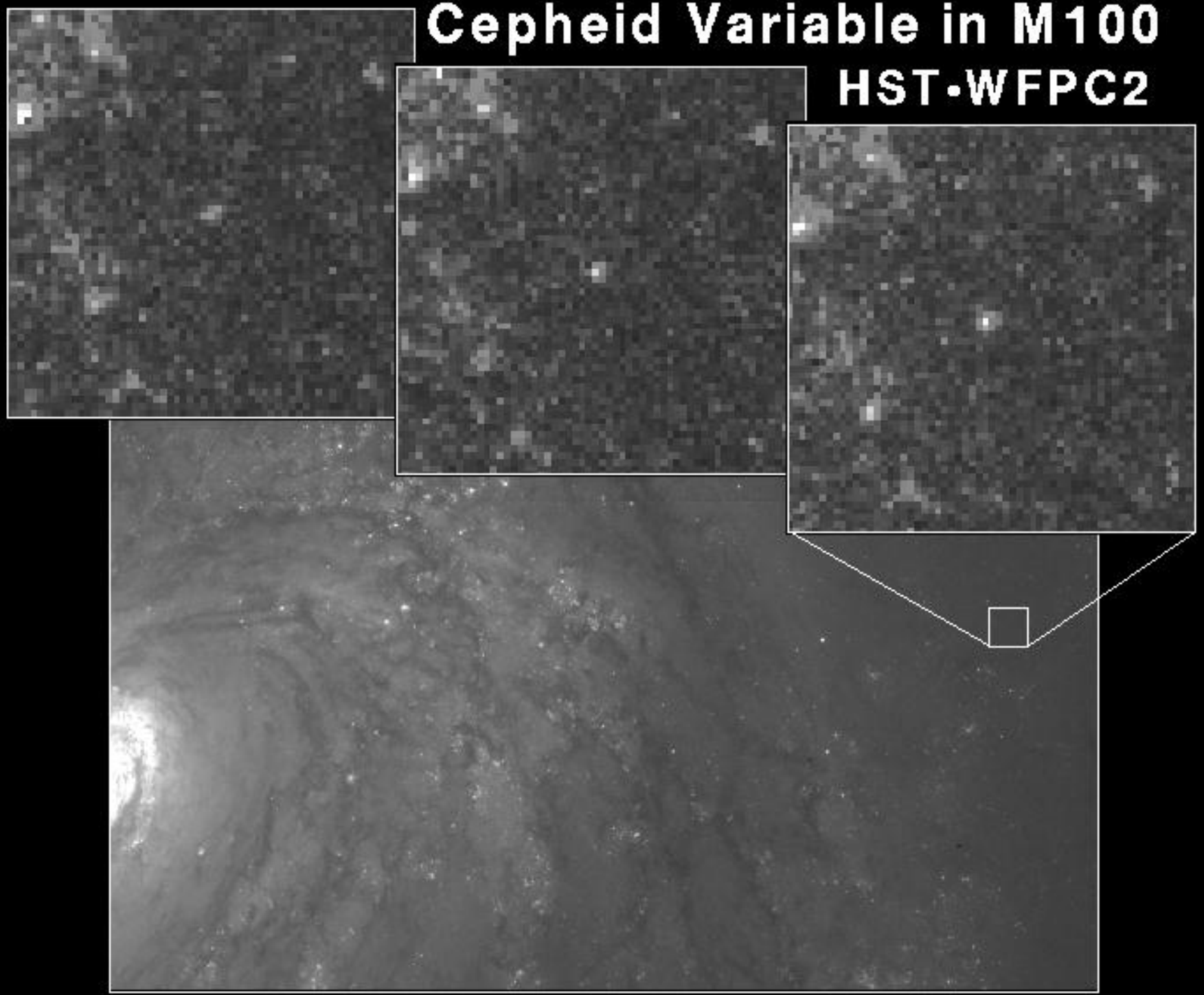
RR Lyra (old stellar population) & δ Cep stars (young population)



problem: overtone pulsators

Additional methods: Eclipsing binaries, star clusters, Miras, tip of red giant branch, Supernova 1987A,...

Distance to the LMC: 50 kpc


Cepheid Variable in M100
HST•WFPC2



Movie: movies/cosmomovies/1999-19-b-low_quicktime.mov

The origin of the Period-Luminosity relationship is in the Helium ionization instability discussed before. The details of this are rather messy, however, it is easy to see that a Period-Luminosity relationship as that observed for the Cepheids is a simple consequence of the fact that the pulsating star is not disrupted by its oscillation.

For the outer parts of the star to remain bound, the kinetic energy of the pulsating outer parts of the stars has to remain smaller than their binding energy:

$$\frac{1}{2}mv^2 \lesssim \frac{GMm}{R}$$

But we know that for the velocity

$$v < \frac{2R}{P}$$

where P is the period of the star and R its radius at maximum extension (we observe the star to expand to a radius R once every P seconds, so the maximum distance the expanding material can go during that time is 2R). Inserting v into the above equation gives

$$\frac{1}{2}\frac{4R^2}{P^2} \lesssim \frac{GM}{R} \quad \Longleftrightarrow \quad P^2 \gtrsim \frac{2}{G}\frac{R^3}{M} = \frac{2}{G}\frac{1}{M/R^3}$$

If we assume that the pulsation is close to the break-up speed, and noting that M/R^3 is proportional to the average density of the star, then it is easy to see that

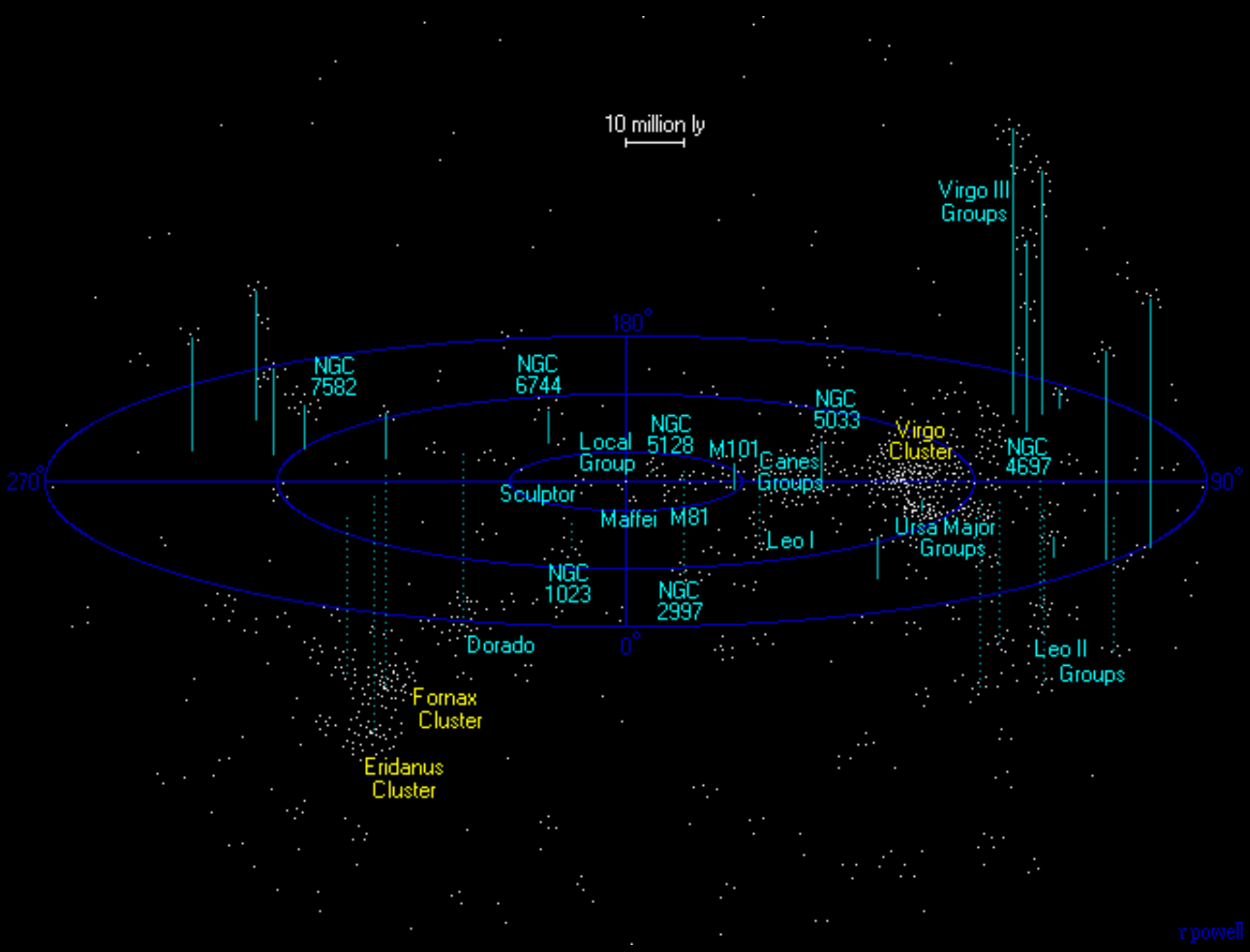
$$P \propto (G\rho)^{-1/2}$$

In the homework for this week you are asked to convince yourself that $(G\rho)^{-1/2}$ has the dimension of a period, i.e., for all gas balls oscillating close to the break up speed, we expect that $P \propto \rho^{-1/2}$. To obtain the period luminosity relationship, you need to remember that the emissivity per square-metre of the surface of a star with temperature T is σT^4 (per the Stefan-Boltzmann law), while the surface of the star is proportional to R^2. Therefore, the luminosity of the star is $L \propto R^2T^4$.

This week's homework asks you to use $L \propto R^2T^4$ and $P \propto \rho^{-1/2}$ to show that from these the absolute magnitude of a pulsating star is related to the period through

$$\log P \propto -m$$

as observed for Cepheids.



The universe out to the Virgo Cluster

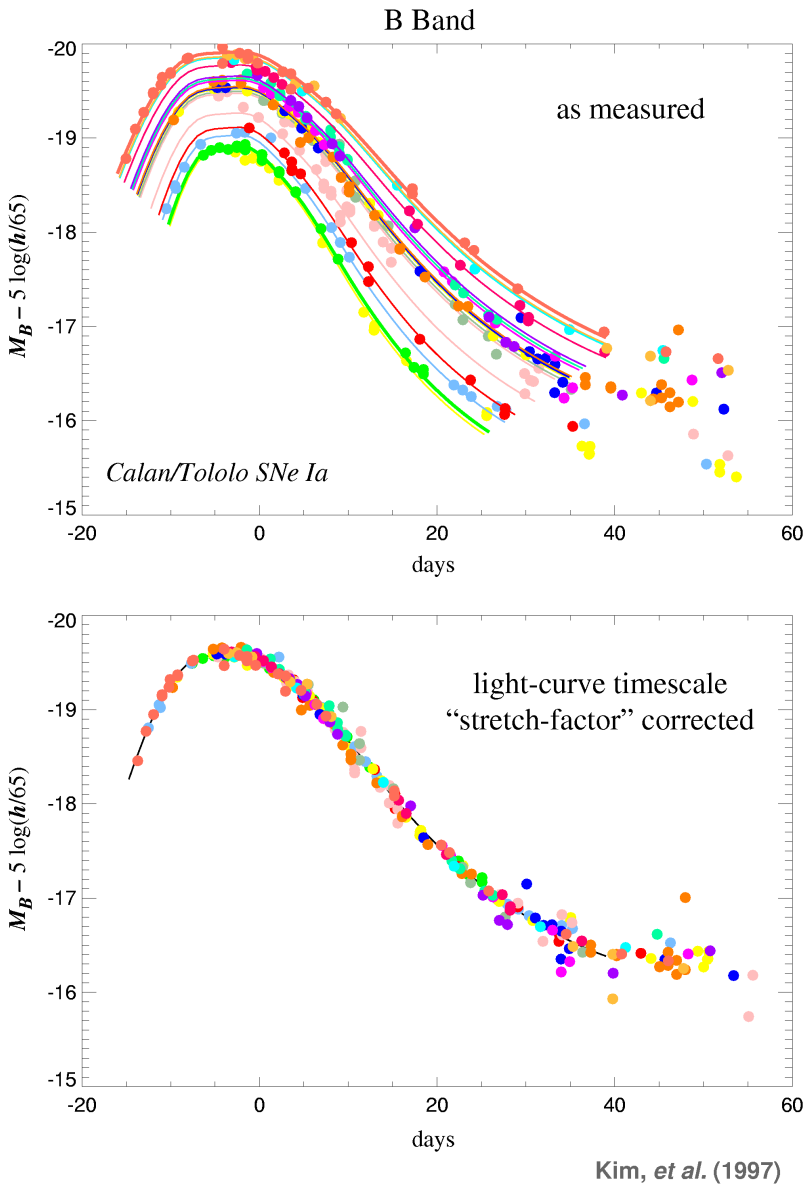
source: `http://www.atlasoftheuniverse.com`



SN1994d (HST WFPC)

Supernovae have luminosities comparable to whole galaxies: $\sim 10^{51}$ erg/s in light, $100\times$ more in neutrinos.

Supernovae



After correction of systematic effects and time dilatation (expansion of the universe, see later):

SN Ia lightcurves all look the same

$\Longrightarrow$ standard candle

Supernovae

SN Ia: Explosion of CO white dwarf when pushed over Chandrasekhar limit ($1.4\,M_\odot$) (via accretion?).

$\Longrightarrow$ Always similar process

$\Longrightarrow$ Very characteristic light curve: fast rise, rapid fall, exponential decay ("FRED") with half-time of 77 d.

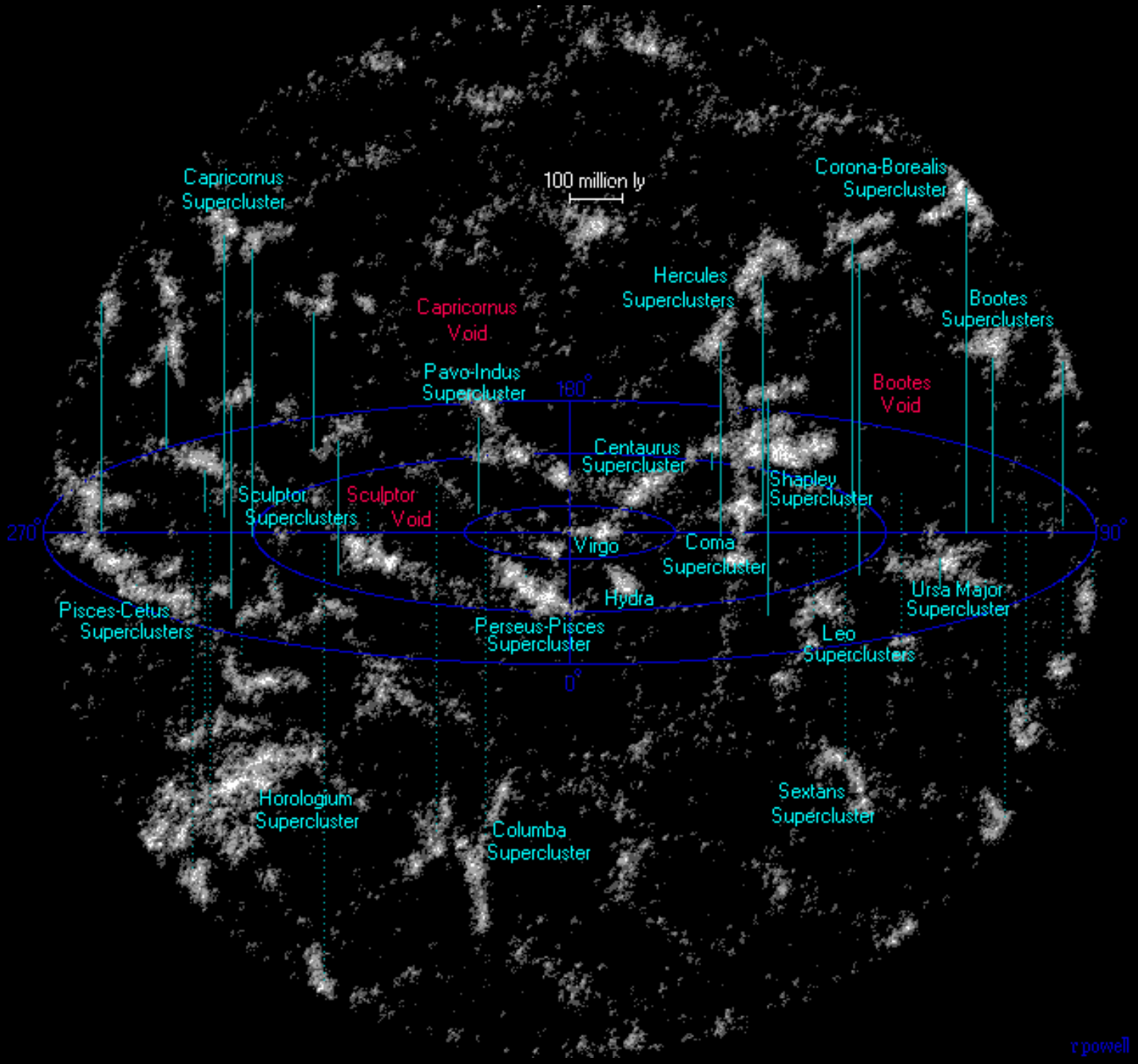
77 d time scale from radioactive decay $Ni^{56} \to Co^{56} \to Fe^{56}$
("self calibration" of lightcurve if same amount of Ni^{56} produced everywhere)

Calibration: SNe Ia in nearby galaxies where Cepheid distances known.

At maximum light:

$$M_B = -19.3 \pm 0.11 \quad \Longleftrightarrow \quad L \sim 10^{9\ldots10}\,L_\odot$$

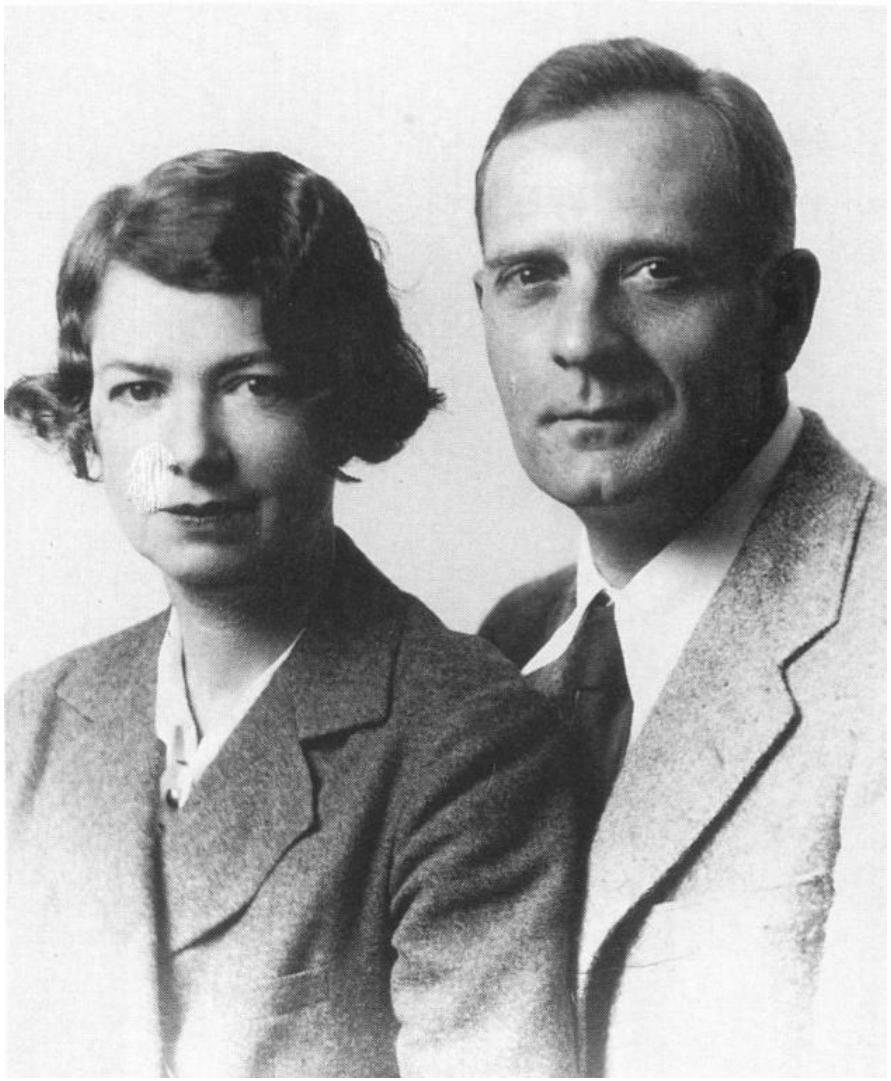
Observable out to $\gtrsim$1 Gpc $\Longrightarrow$ covers almost the whole universe...



Superclusters in our vicinity

source: `http://www.atlasoftheuniverse.com`

Edwin Hubble



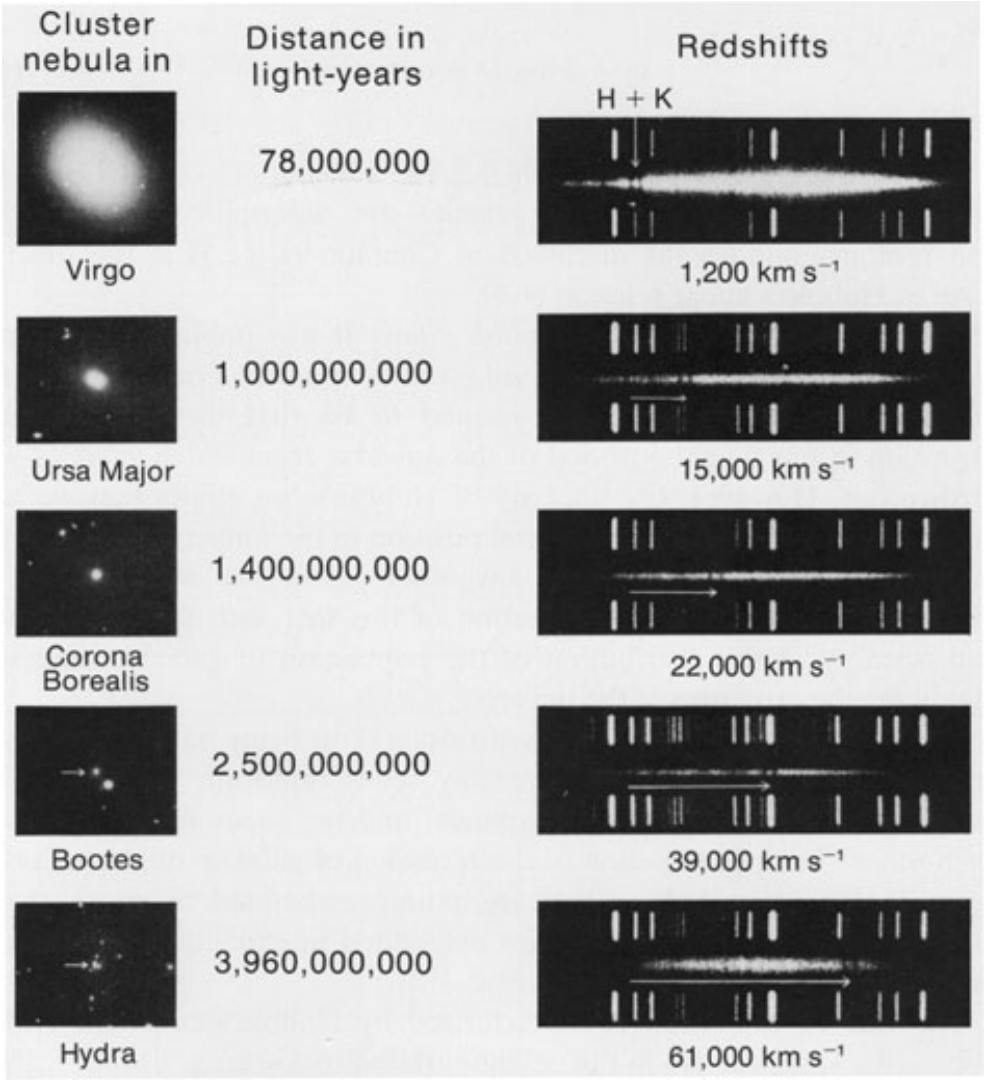
Christianson, 1995, p. 165

Edwin Hubble (1889–1953):

- Realization of galaxies as being outside of the Milky Way
- Discovery that universe is expanding

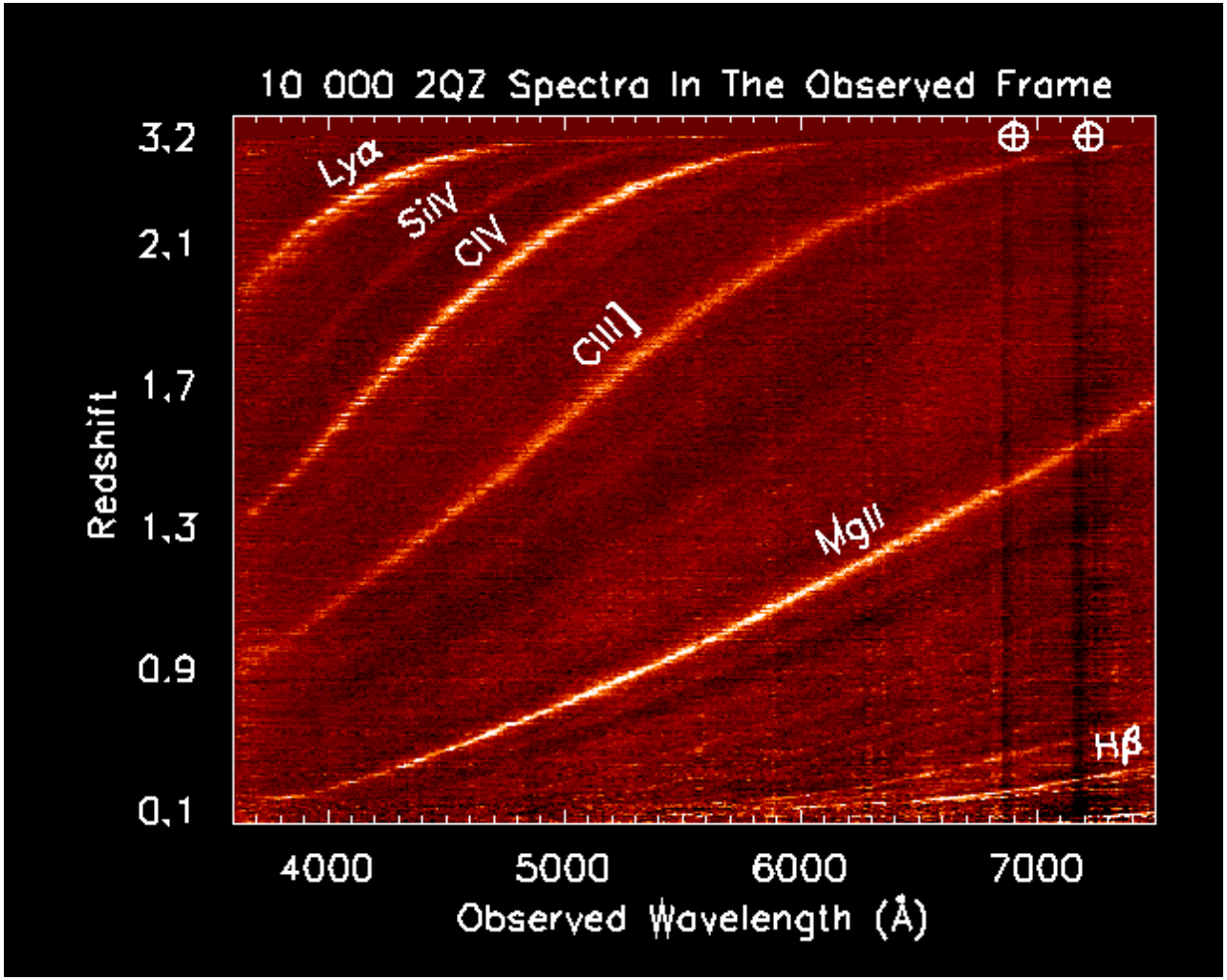
Founder of modern extragalactic astronomy

Redshifts



Hubble: spectral lines in galaxies are more and more redshifted with increasing distance.

Redshifts



2dF QSO Redshift survey

Redshift:

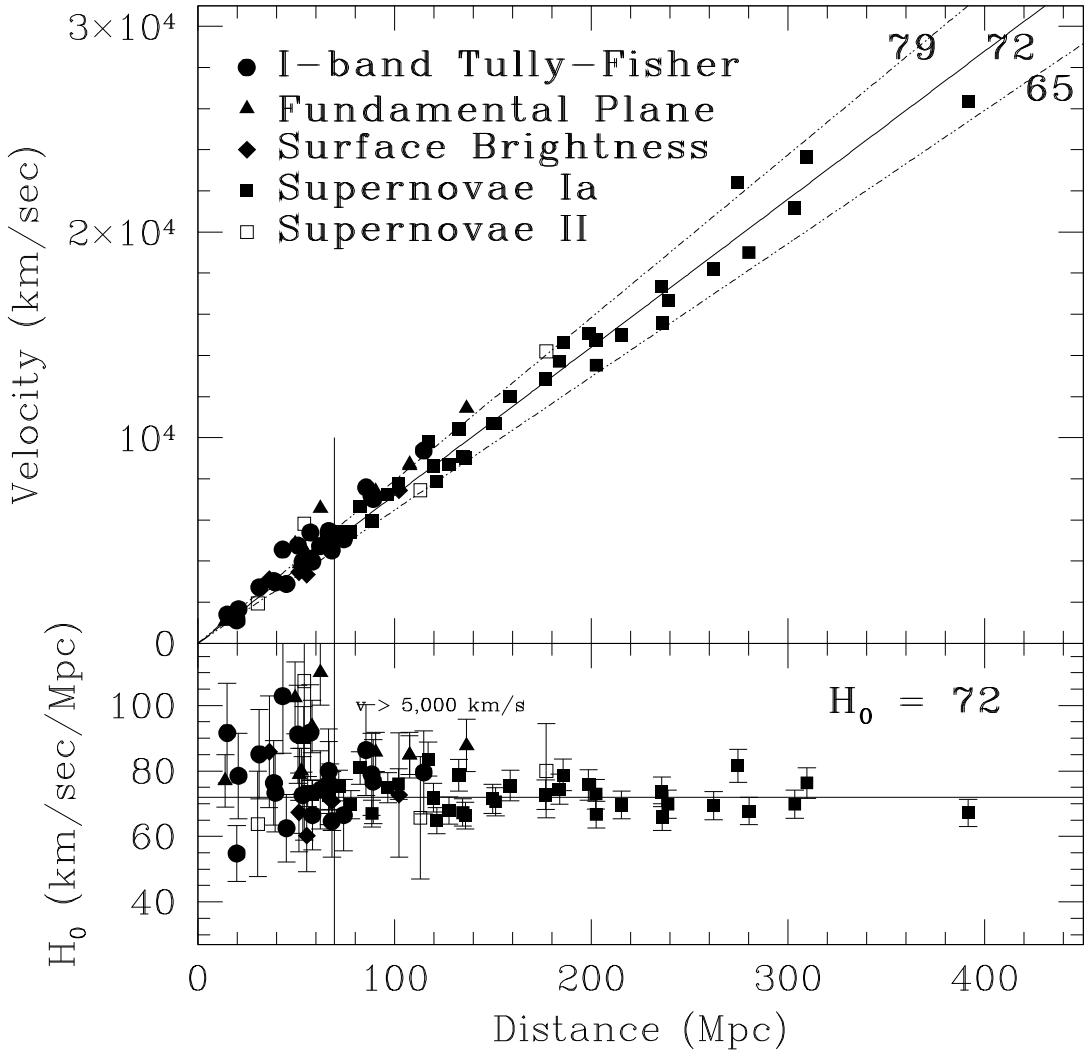
$$z = \frac{\lambda_{\text{observed}} - \lambda_{\text{emitted}}}{\lambda_{\text{emitted}}}$$

interpreted as velocity:

$$v = cz$$

where $c = 300000\,\text{km}\,\text{s}^{-1}$ (speed of light)

Hubble Relation



(Freedman, 2001, Fig.4)

Hubble relation (1929):

The redshift of a galaxy is proportional to its distance: $v = cz = H_0 d$

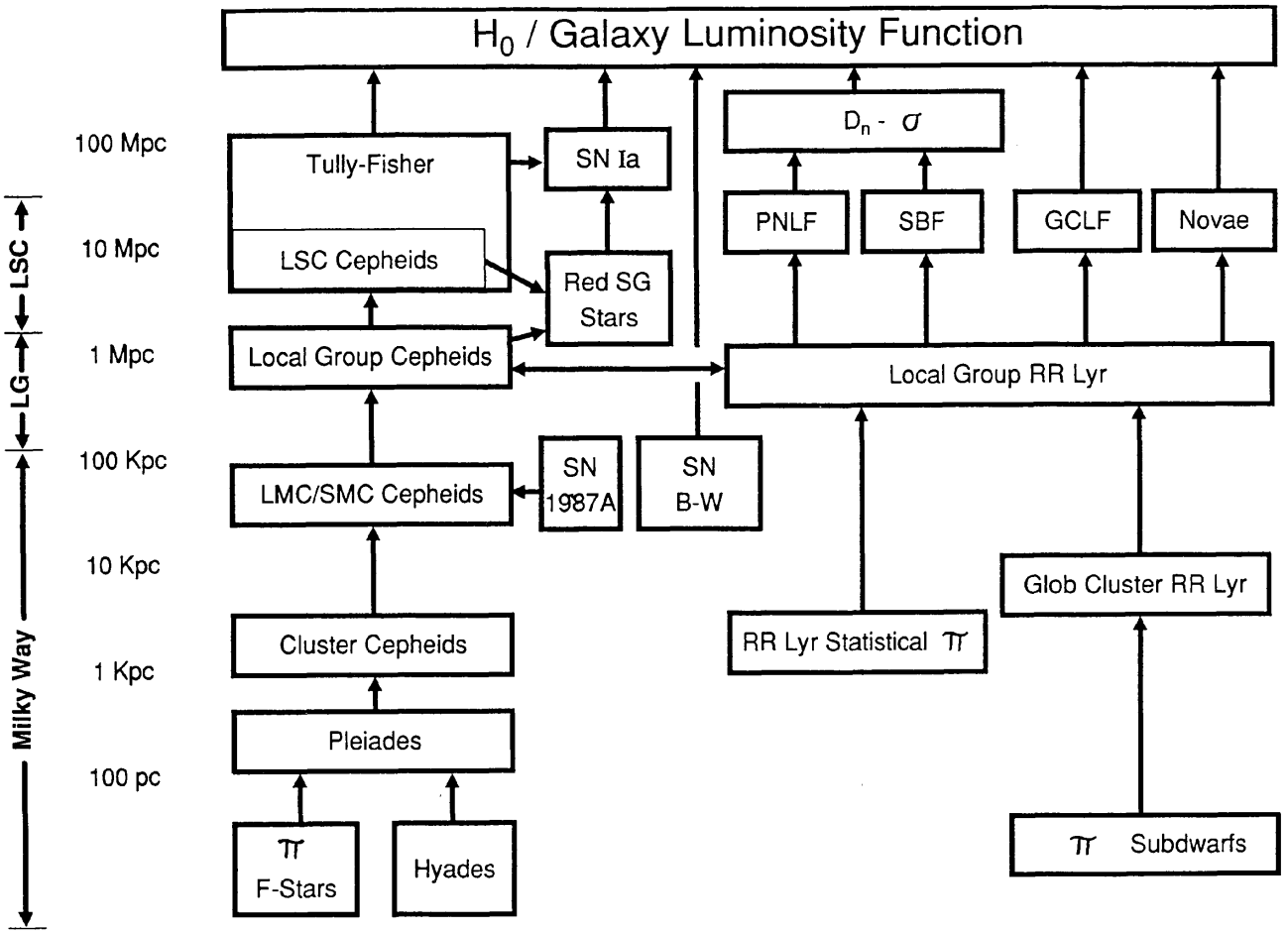
where H_0: "Hubble constant".

Measurement: determine v from redshift (easy), d with standard candles (difficult) $\Longrightarrow$ H_0 from linear regression.

Hubble Space Telescope key project finds

$$H_0 = 72 \pm 8\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

Summary: Distance Ladder



Pathways to Extragalactic Distances

Jacoby (1992, Fig. 1)

World Models

Introduction

Cosmology: science of the universe as a whole

> How did the universe evolve to what it is today?

Based on four basic facts:

> The universe
> - expands,
> - is isotropic,
> - and is homogeneous.

Isotropy and homogeneity of the universe: "*cosmological principle*".

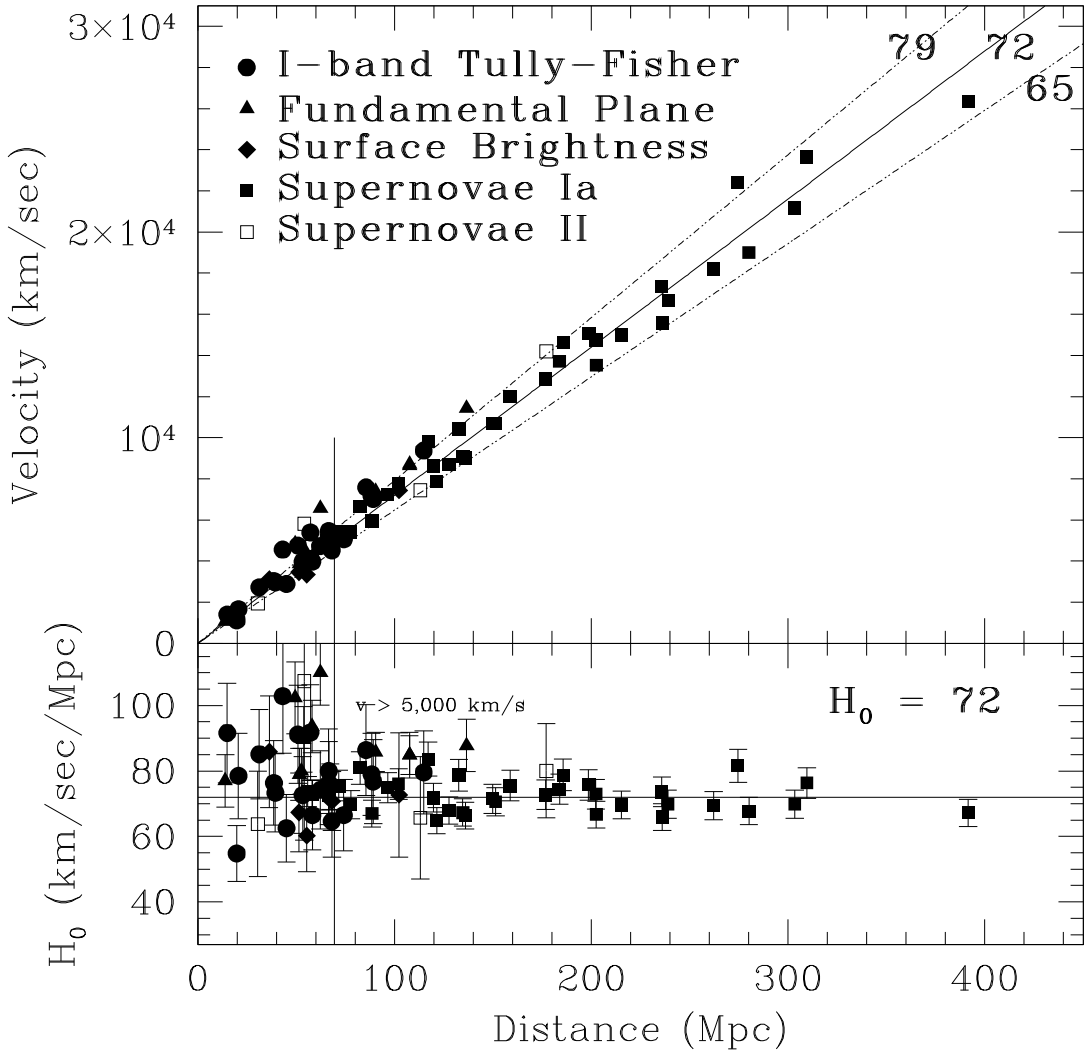
Perhaps (for us) the most important fact is:

> - The universe is habitable for humans.

("*anthropic principle*")

The one question cosmology does not attempt to answer is: How came the universe into being? $\Longrightarrow$ Realm of theology!

Hubble Relation



(Freedman, 2001, Fig.4)

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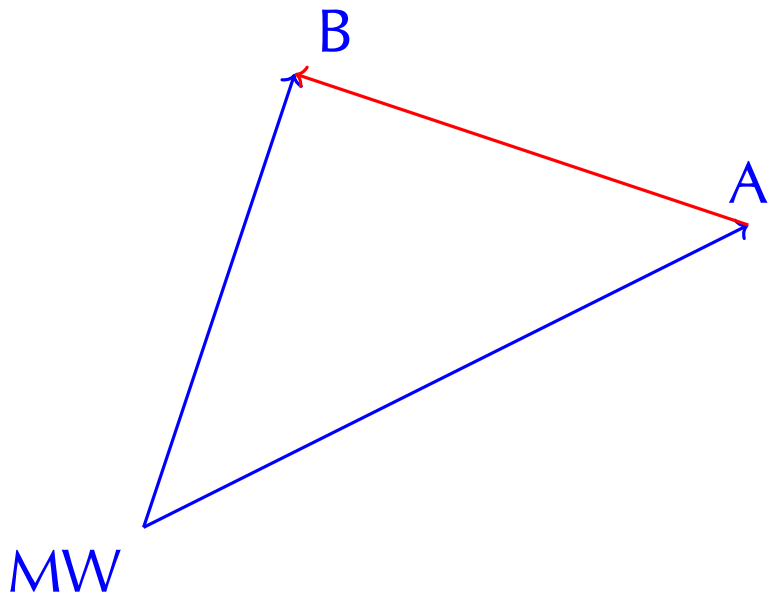
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Hubble Relation



The expansion law $\mathbf{v} = H_0\mathbf{r}$ is unchanged under rotation and translation: isomorphism.

Proof: consider two galaxies at positions $\mathbf{r}_A$ and $\mathbf{r}_B$:

Hubble: $\mathbf{v}_A = H_0\,\mathbf{r}_A$ and $\mathbf{v}_B = H_0\,\mathbf{r}_B$

Galaxy B as seen from galaxy A:

$\mathbf{v}_B - \mathbf{v}_A = H_0\,\mathbf{r}_B - H_0\,\mathbf{r}_A = H_0\,(\mathbf{r}_B - \mathbf{r}_A)$

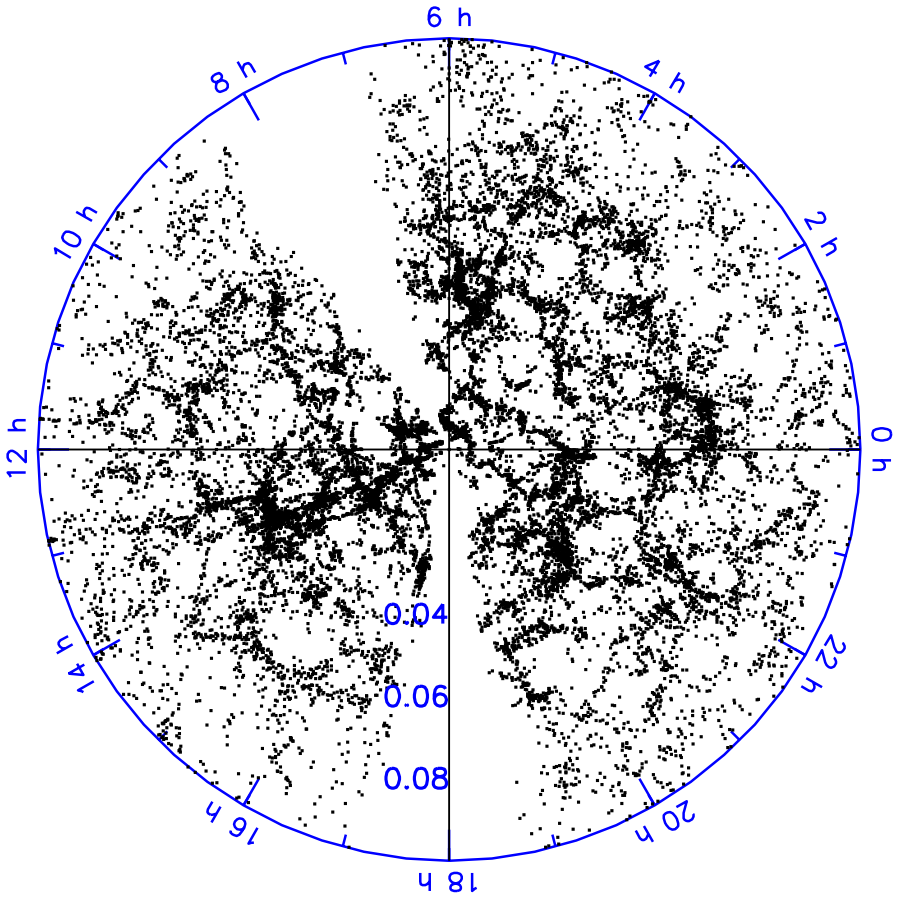
$\Longrightarrow$ observer at A derives the same Hubble law as we on Milky Way.

This is a direct consequence of the homogeneity of the universe.

Despite everything receding from us, we are not at the center of the universe $\Longrightarrow$ Copernicus principle still holds.

Copernicus principle: We are not at a special place in the universe in time or space.

Homogeneity

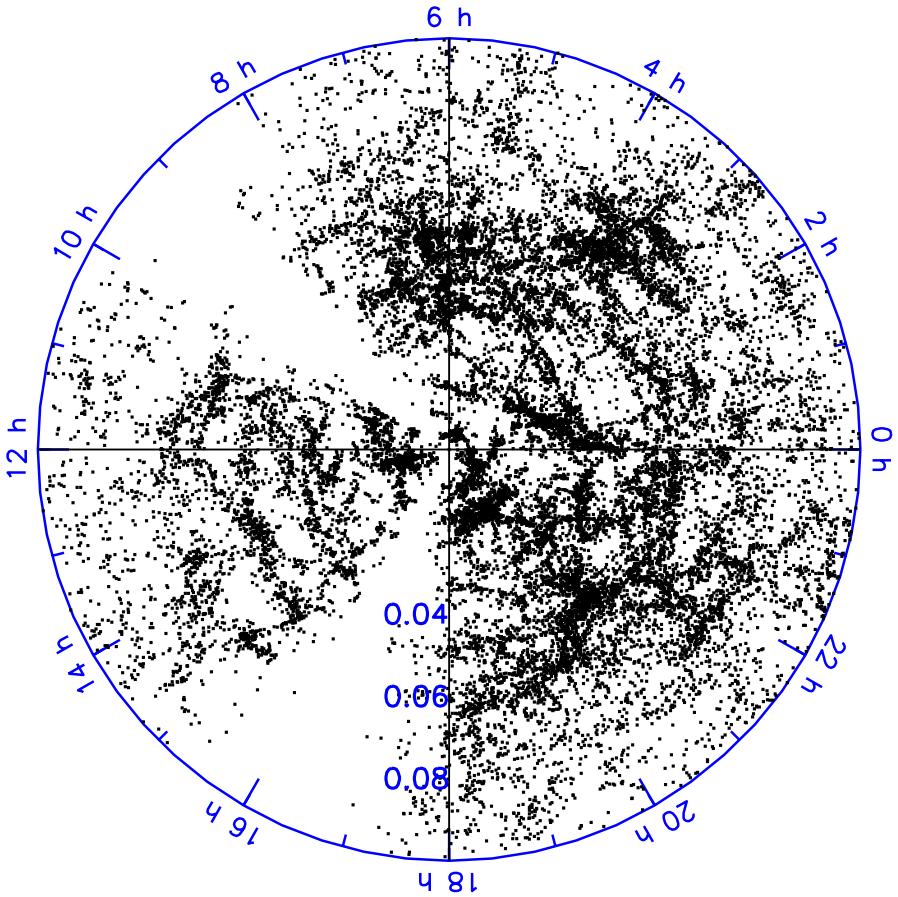


$-30^\circ < \delta < -20^\circ$

Homogeneity: "The universe looks the same, regardless from where it is observed" (on scales $\gg$100 Mpc).

6dF QSO Redshift survey

Homogeneity

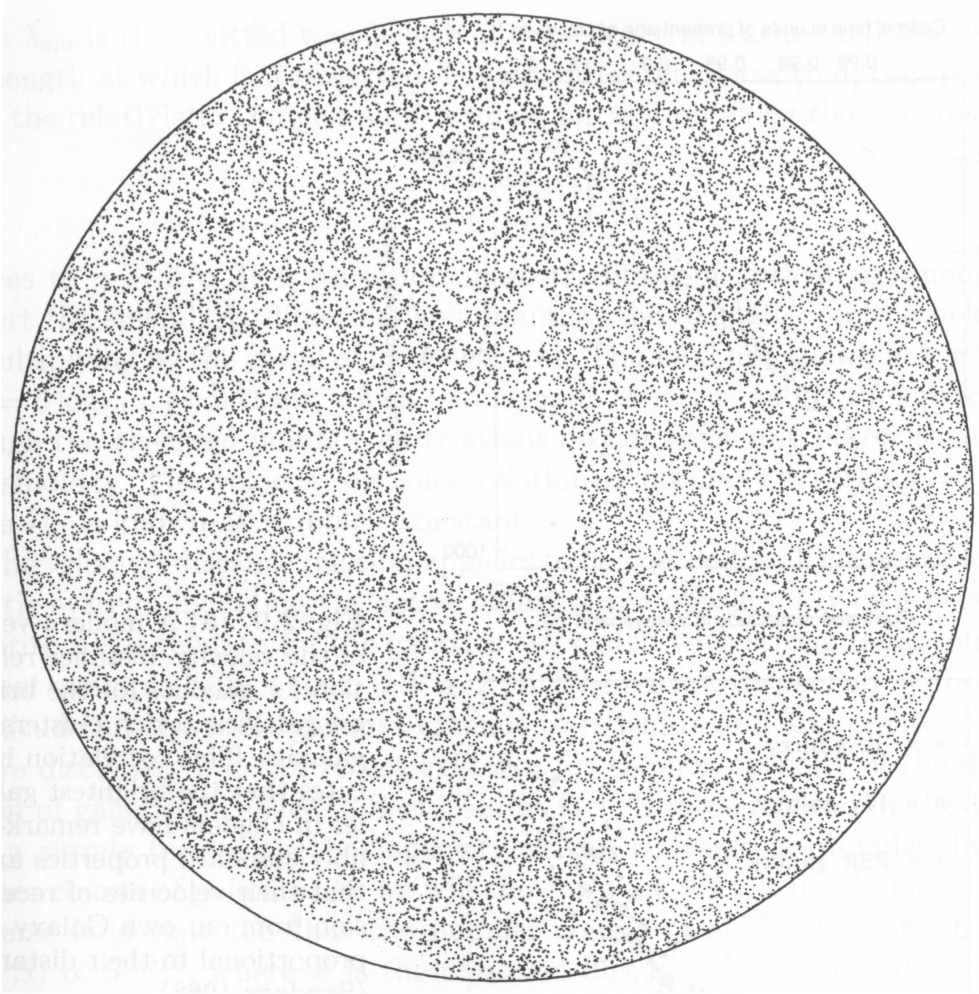


$-60^\circ < \delta < -40^\circ$

Homogeneity: "The universe looks the same, regardless from where it is observed" (on scales $\gg$100 Mpc).

6dF QSO Redshift survey

Isotropy



Peebles (1993): Distribution of 31000 radio sources on northern sky (wavelength $\lambda = 6\,\mathrm{cm}$)

Isotropy $\Longleftrightarrow$ The universe looks the same in all directions.

N.B. Homogeneity *does not* imply isotropy, and isotropy around one point does not imply homogeneity!

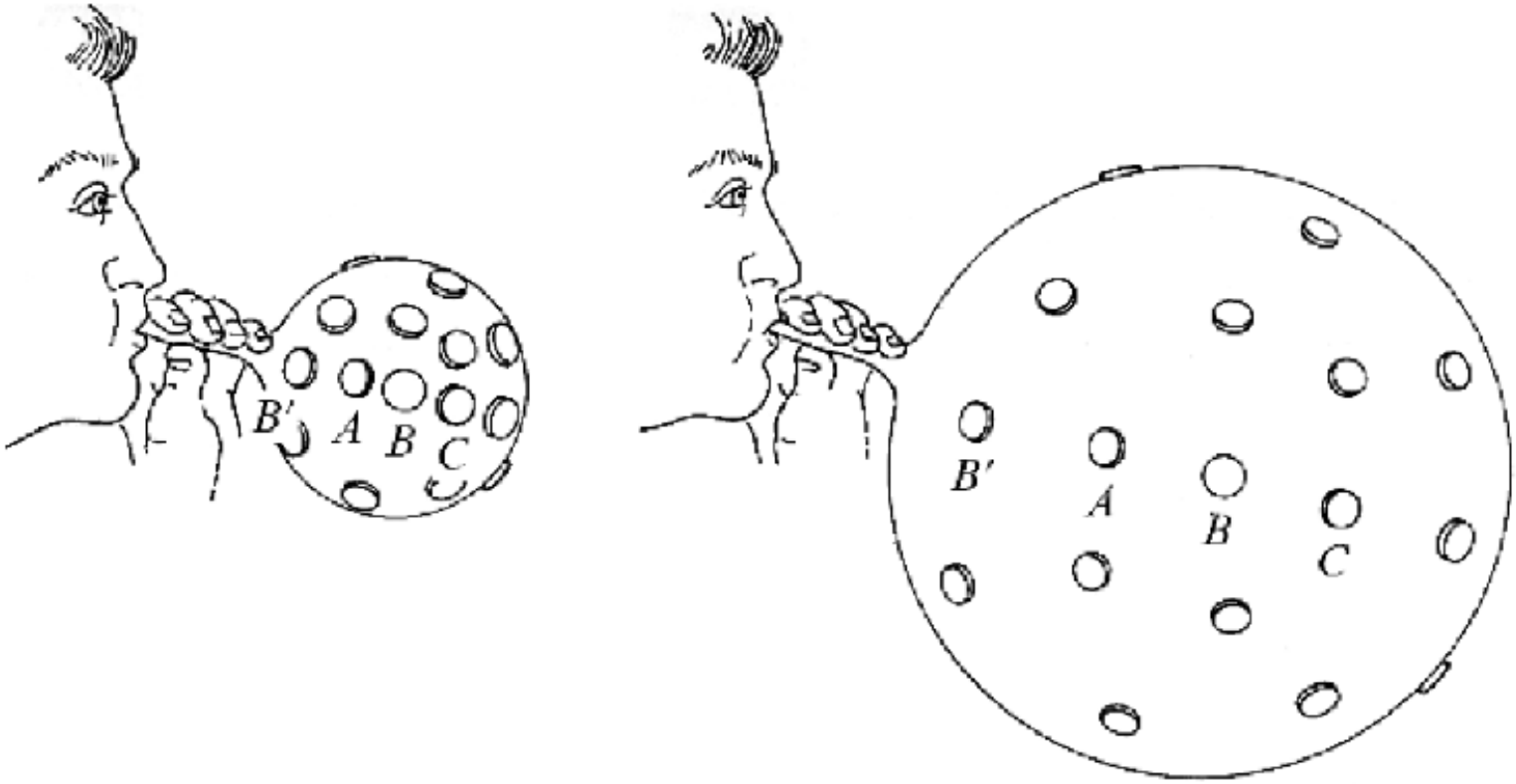
World Models



A.A. Friedmann (1888–1925)

Friedmann: Mathematical description of the Universe using normal “fixed” coordinates (“comoving coordinates”), plus scale factor R which describes evolution of the Universe.

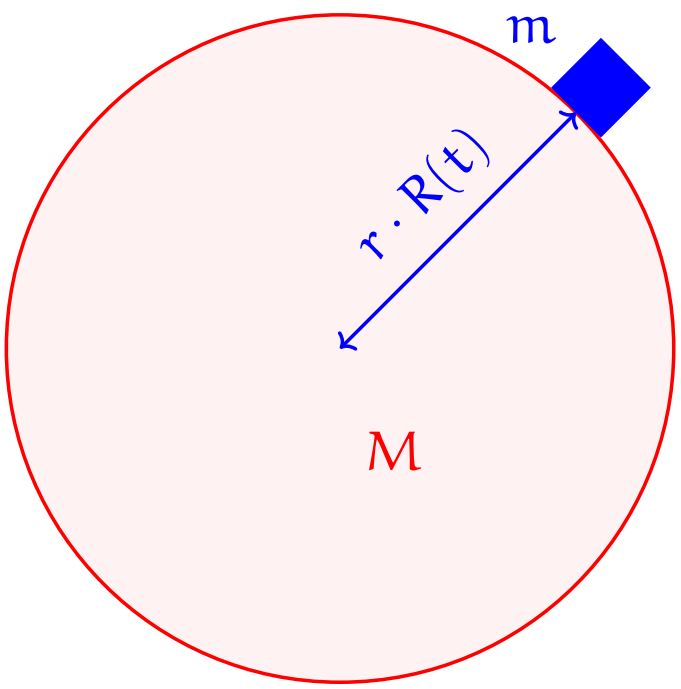
World Models



R small R large

Friedmann: Mathematical description of the Universe using normal “fixed” coordinates (“comoving coordinates”), plus scale factor R which describes evolution of the Universe.

Friedmann Equations



Evolution of universe described with Friedmann equations: Dynamics of a mass element on the surface of sphere of density $\rho(t)$ and comoving radius d, i.e., proper radius $d \cdot R(t)$ (McCrea, 1937)

Mass of sphere:

$$M = \frac{4\pi}{3}(d\,R)^3\rho(t) = \frac{4\pi}{3}d^3\rho_0 \quad \text{where} \quad \rho(t) = \frac{\rho_0}{R(t)^3} \tag{19.1}$$

Force on mass element:

$$m\frac{d^2}{dt^2}(d\,R(t)) = -\frac{GMm}{(dR(t))^2} = -\frac{4\pi G}{3}\frac{d\rho_0}{R^2(t)}\,m \tag{19.2}$$

Canceling $m \cdot d$ gives momentum equation:

$$\ddot{R}(t) = -\frac{4\pi G}{3}\frac{\rho_0}{R(t)^2} = -\frac{4\pi G}{3}\rho(t)R(t) \tag{19.3}$$

Multiplying Eq. (19.3) with $\dot{R}$ and integrating yields the energy equation:

$$\frac{1}{2}\dot{R}(t)^2 = +\frac{4\pi G}{3}\frac{\rho_0}{R(t)} + \text{const.} = +\frac{4\pi G}{3}\rho(t)R^2(t) + \text{const.} \tag{19.4}$$

where the constant can only be obtained from GR.

Friedmann Equations

General relativistic approach: Insert metric into Einstein equation to obtain differential equation for $R(t)$:

Einstein equation:

$$\underbrace{R_{\mu\nu} - \frac{1}{2}\mathscr{R} g_{\mu\nu}}_{G_{\mu\nu}} = \frac{8\pi G}{c^4} T_{\mu\nu} + \Lambda g_{\mu\nu} \tag{19.5}$$

where

$g_{\mu\nu}$: Metric tensor ($ds^2 = g_{\mu\nu}\, dx^\mu\, dx^\nu$)

$R_{\mu\nu}$: Ricci tensor (function of $g_{\mu\nu}$)

$\mathscr{R}$: Ricci scalar (function of $g_{\mu\nu}$)

$G_{\mu\nu}$: Einstein tensor (function of $g_{\mu\nu}$)

$T_{\mu\nu}$: Stress-energy tensor, describing curvature of space due to fields present (matter, radiation,...)

Λ: Cosmological constant

$\Longrightarrow$ greatly simplified by cosmolgical principle: Robertson-Walker metric

Friedmann Equations

The exact GR derivation of Friedmanns equation gives:

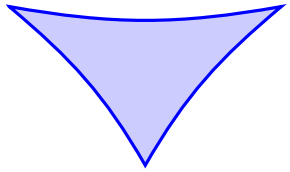
$$\ddot{R} = -\frac{4\pi G}{3} R \left(\rho + \frac{3p}{c^2} \right) + \left[\frac{1}{3} \Lambda R \right]$$
$$\dot{R}^2 = +\frac{8\pi G \rho}{3} R^2 - kc^2 + \left[\frac{1}{3} \Lambda c^2 R^2 \right] \qquad (19.6)$$

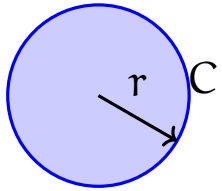
Notes:

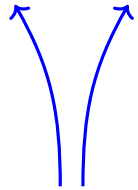
1. For $k = 0$: Eq. (19.6) $\longrightarrow$ Eq. (19.4).
2. k determines the curvature of space:
   - $k > 0$: closed universe (finite volume)
   - $k = 0$: flat universe
   - $k < 0$: open universe (infinite volume)
3. The density, ρ, includes the contribution of all different kinds of energy (remember mass-energy equivalence!).
4. cosmological constant Λ introduced by Einstein to ensure stability of the universe. Physics unknown.

Friedmann Equations

negative curvature
$k = -1$

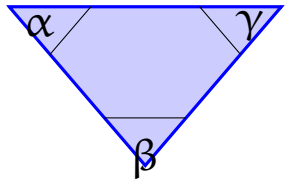


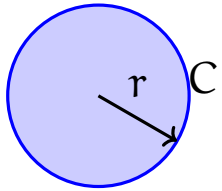


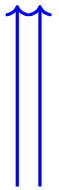


$\alpha + \beta + \gamma < \pi$ $C > 2\pi r$ Nearby straight parallel lines may diverge

zero curvature
$k = 0$

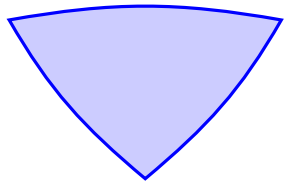


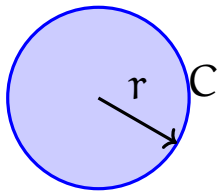


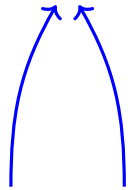


$\alpha + \beta + \gamma = \pi$ $C = 2\pi r$ Nearby straight parallel lines remain parallel

positive curvature
$k = +1$





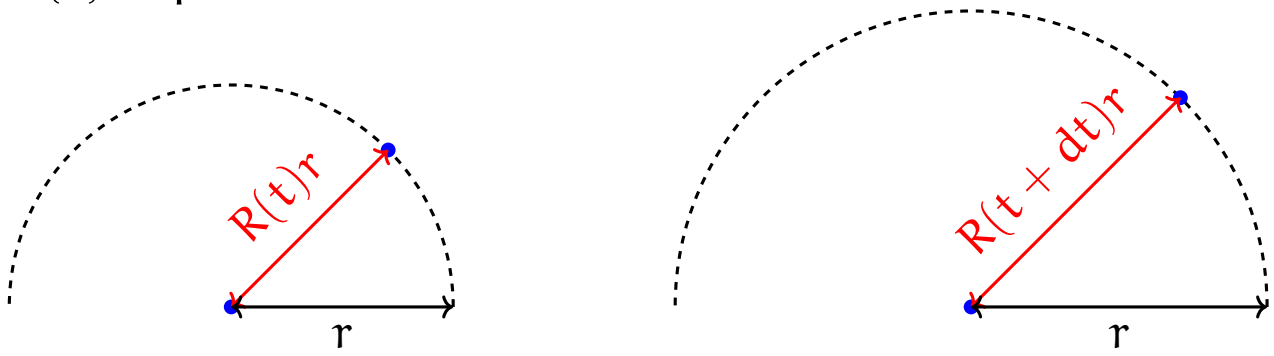


$\alpha + \beta + \gamma > \pi$ $C < 2\pi r$ Nearby straight parallel lines may converge

after Jones & Lambourne: An Introduction to Galaxies and Cosmology

Hubble's Law

The variation of $R(t)$ implies Hubble's Law:



Small scales $\Longrightarrow$ Euclidean geometry

Proper distance between two observers with comoving distance d:

$$D(t) = d \cdot R(t) \tag{19.7}$$

Expansion $\Longrightarrow$ D changes:

$$\frac{\Delta D}{\Delta t} = \frac{R(t+\Delta t)d - R(t)d}{\Delta t} \quad \text{and for} \lim_{\Delta t \to 0} \quad v = \frac{dD}{dt} = \dot{R}\, d = \frac{\dot{R}}{R} D =: H D \tag{19.8}$$

$\Longrightarrow$ Identify local Hubble "constant" as

$$H = H(t) = \frac{\dot{R}(t)}{R(t)} \tag{19.9}$$

$\Longrightarrow$ Hubble "constant" is time-dependent! $\Longrightarrow$ "Hubble parameter"

Hubble's Law

The cosmological redshift is a consequence of the expansion of the universe:

The comoving distance is constant, thus in terms of the proper distance:

$$d = \frac{D(t = \text{today})}{R(t = \text{today})} = \frac{D(t)}{R(t)} = \text{const.} \tag{19.10}$$

Set $a(t) = R(t)/R(t = \text{today})$, then eq. (19.10) implies

$$\lambda_{\text{obs}} = \frac{\lambda_{\text{emit}}}{a_{\text{emit}}} \tag{19.11}$$

(λ_{obs}: observed wavelength, λ_{emit}: emitted wavelength)

Thus the observed redshift is

$$z = \frac{\lambda_{\text{obs}} - \lambda_{\text{emit}}}{\lambda_{\text{emit}}} = \frac{\lambda_{\text{obs}}}{\lambda_{\text{emit}}} - 1 = \frac{\nu_{\text{emit}}}{\nu_{\text{obs}}} - 1 \tag{19.12}$$

$$\Longrightarrow \qquad 1 + z = \frac{1}{a_{\text{emit}}} = \frac{R(t = \text{today})}{R(t)} = \frac{\nu_{\text{emit}}}{\nu_{\text{obs}}} \tag{19.13}$$

Light emitted at $z = 1$ was emitted when the universe was half as big as today!

z: measure for *relative size* of universe at time the observed light was emitted.

Critical Density

Looking at the energy equation for $\Lambda = 0$,

$$\dot{R}^2 = +\frac{8\pi G\rho}{3}R^2 - kc^2 \tag{19.14}$$

we find that the evolution of the Hubble parameter is:

$$\left(\frac{\dot{R}}{R}\right)^2 = H(t)^2 = \frac{8\pi G\rho(t)}{3} - \frac{kc^2}{R^2} \tag{19.15}$$

and therefore

$$k \cdot \frac{c^2}{R(t)^2 H(t)^2} = \frac{8\pi G}{3H(t)^2}\rho(t) - 1 = \frac{\rho(t)}{\rho_{crit}} - 1 = \Omega - 1 \tag{19.16}$$

where Ω is called the critical density:

$$\Omega = \frac{\rho}{\rho_{crit}} \qquad \text{where} \qquad \rho_{crit} = \frac{3H^2}{8\pi G} \tag{19.17}$$

currently: $\rho_{crit} \sim 1 \times 10^{-23}\,\mathrm{g\,cm^{-3}}$ ($3 \ldots 10$ H-Atoms $\mathrm{m^{-3}}$).

Ω describes the curvature of the universe:

$$\Omega > 1 \Longrightarrow k > 0 : \text{closed} \quad | \quad \Omega = 1 \Longrightarrow k = 0 : \text{flat} \quad | \quad \Omega < 1 \Longrightarrow k < 0 : \text{open}$$

Critical Density

World Model: Evolution of R as a function of time

Solution of Friedmann equations depends on boundary conditions:

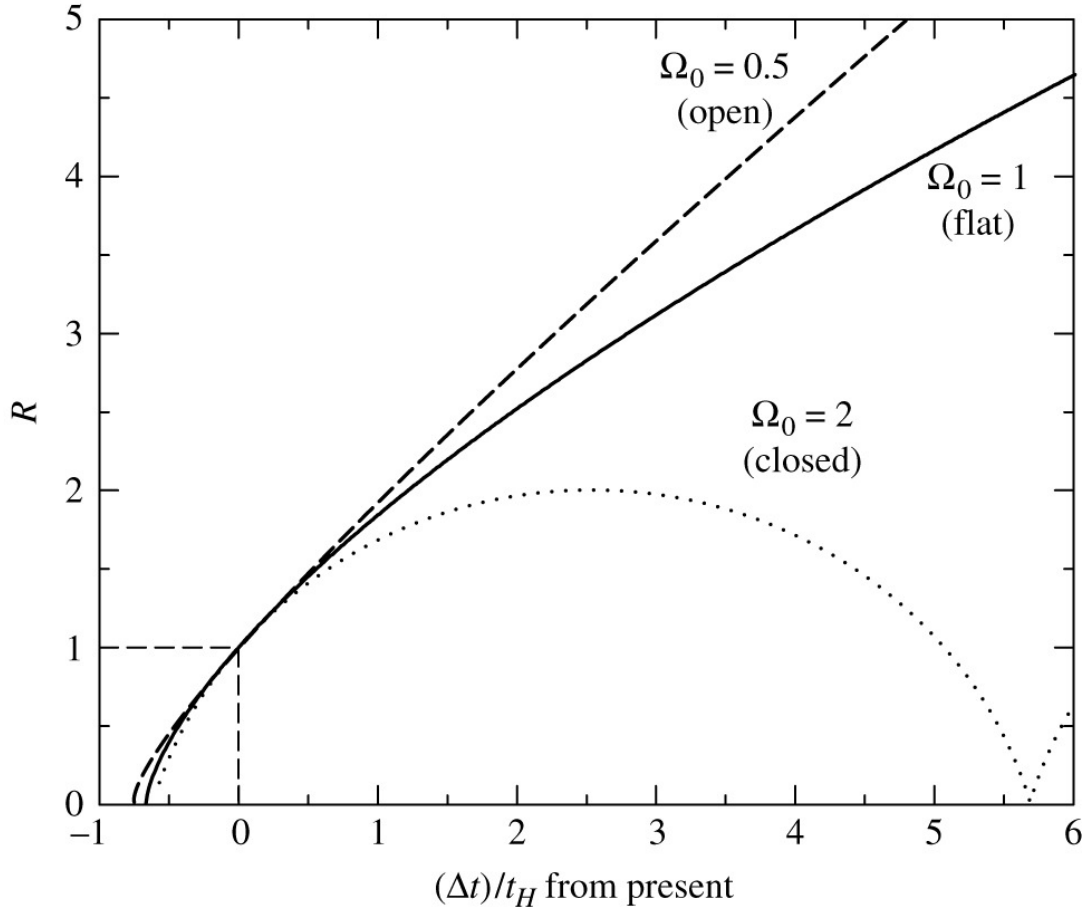
1. Value of H as measured today (H is time dependent!)
2. Density Parameter of universe

Note: total Ω is sum of:

1. Ω_m: Matter, i.e., everything that leads to gravitative effects
   Ω_m in baryonic matter is $\lesssim 3\%$, but note there might be "nonbaryonic dark matter" as well!
2. $\Omega_\Lambda = \Lambda c^2/3H^2$: contribution by cosmological constant Λ
   (Λ is often called "dark energy" for PR reasons)

Hubble time: Assume an empty universe ($\omega = 0$): linear expansion
$\Longrightarrow$ age of the Universe: $t_H = v/d = 1/H_0$ is called Hubble time

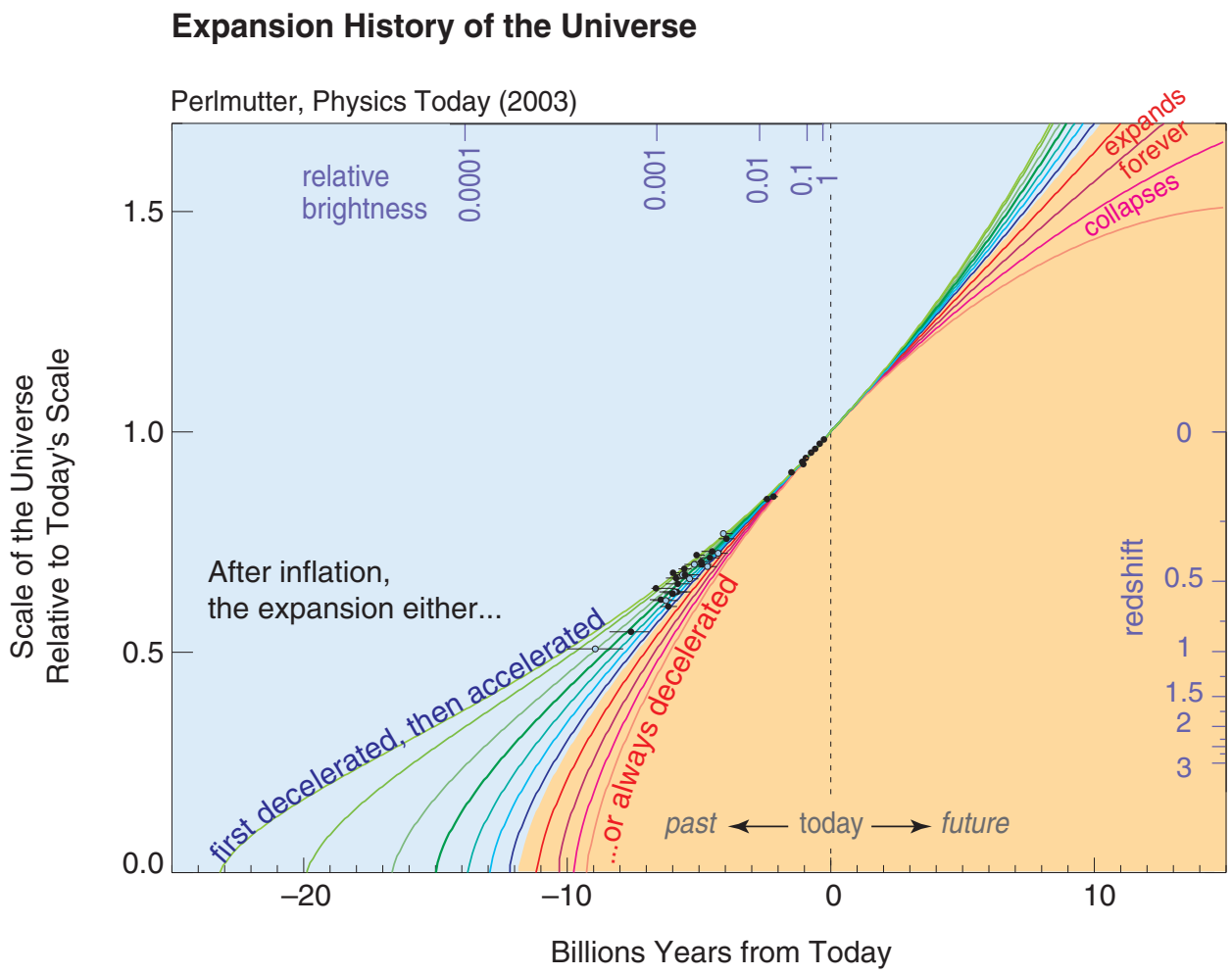
Critical Density



Carroll & Ostlie, Fig. 29.5

- $\Omega > 1 \Longrightarrow$ finite life
- $\Omega = 1 \Longrightarrow$ expands forever
- $\Omega < 1 \Longrightarrow$ expands forever

Age of the Universe

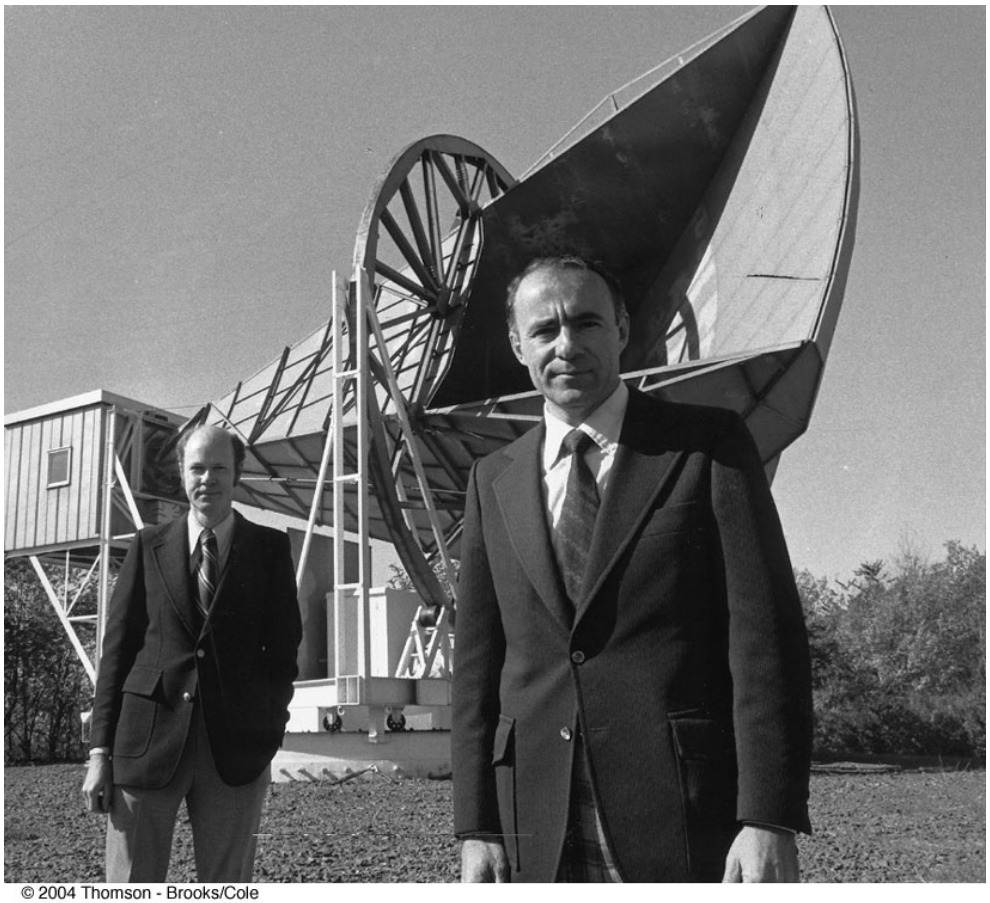


Note: Extrapolation backwards gives age of universe as *roughly* $1/H_0$!

for $H_0 = 72\,\mathrm{km\,s^{-1}\,Mpc^{-1}} = 2.3 \times 10^{-18}\,\mathrm{s^{-1}}$, giving an age of 13.6 Gyr.

The Big Bang

CMBR

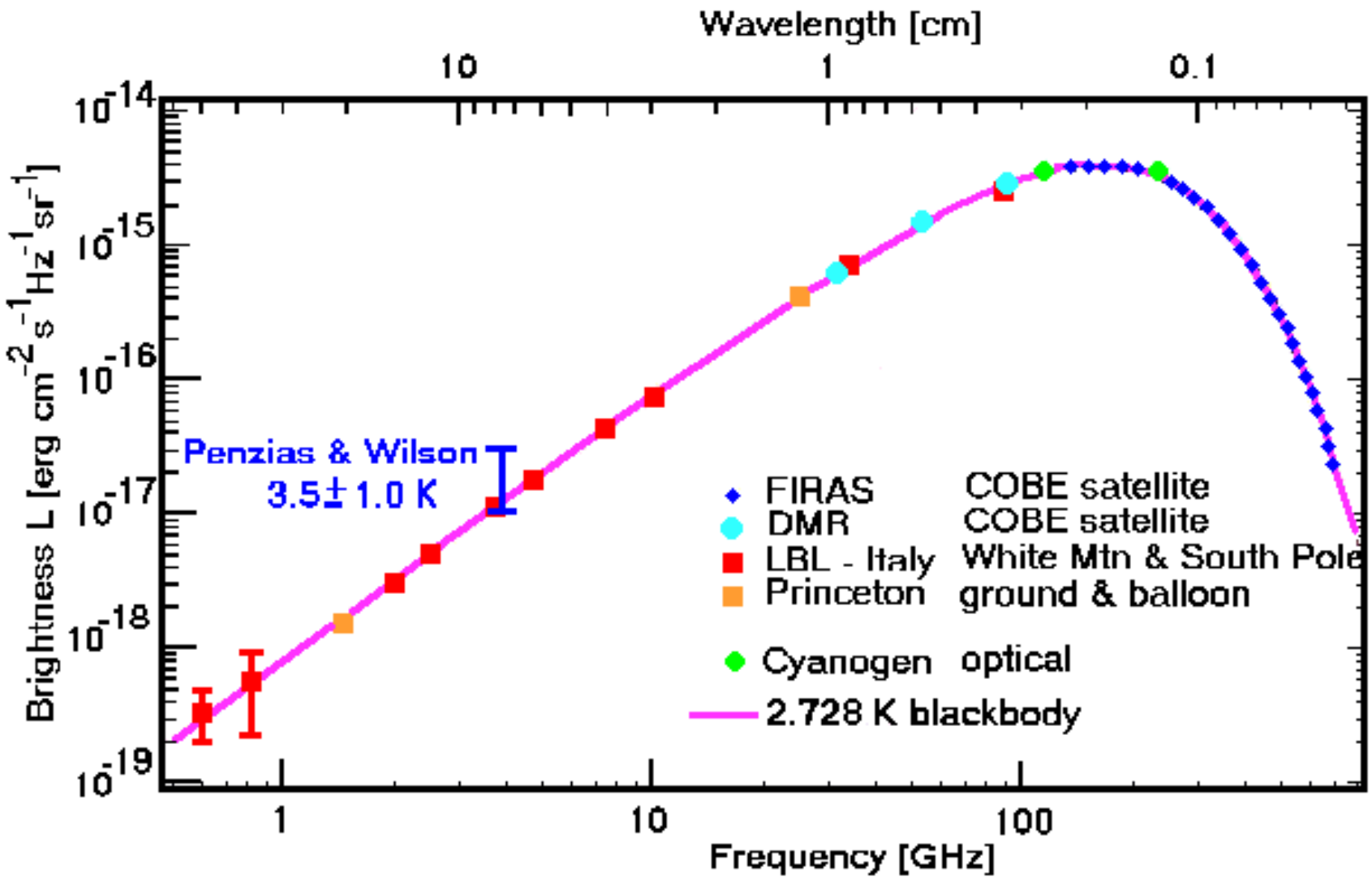

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Arno Penzias & Robert Wilson
(Nobel prize 1978)

Discovery of the Cosmic Microwave Background (CMB):

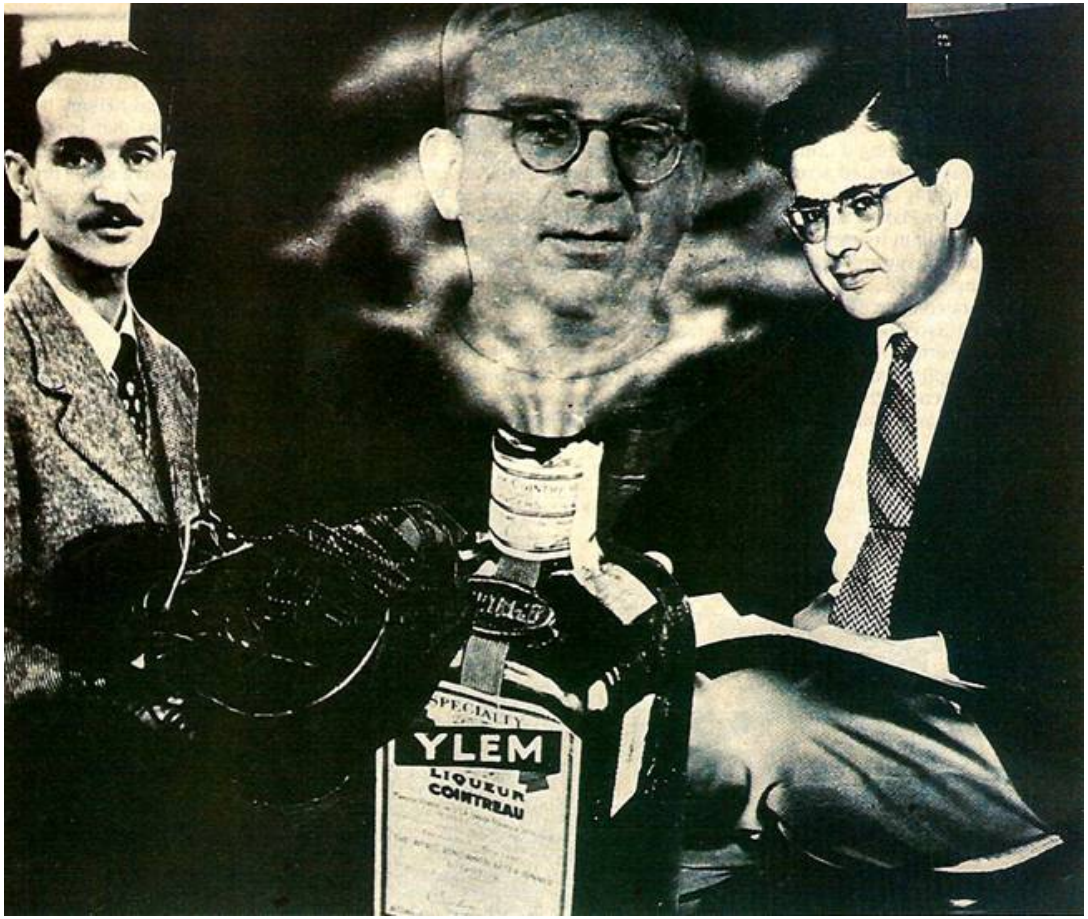
"A Measurement of Excess Antenna Temperature at 4080 Mc/s."
A.A. Penzias & R.W. Wilson (1965, ApJ 142, 419):
Abstract: *Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna . . . at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value of about 3.5 K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and free from seasonal variations (July, 1964 – April, 1965). A possible explanation for the observed excess noise temperature is the one given by Dicke, Peebles, Roll, and Wilkinson (1965) in a companion letter in this issue.*

CMBR



NASA COBE: CMB is a perfect black body with $T = 2.725 \pm 0.002\,K$

CMBR



George Gamov: Thermodynamics implies that the young, dense Universe must have been extremely hot

$\Longrightarrow$ The Big Bang

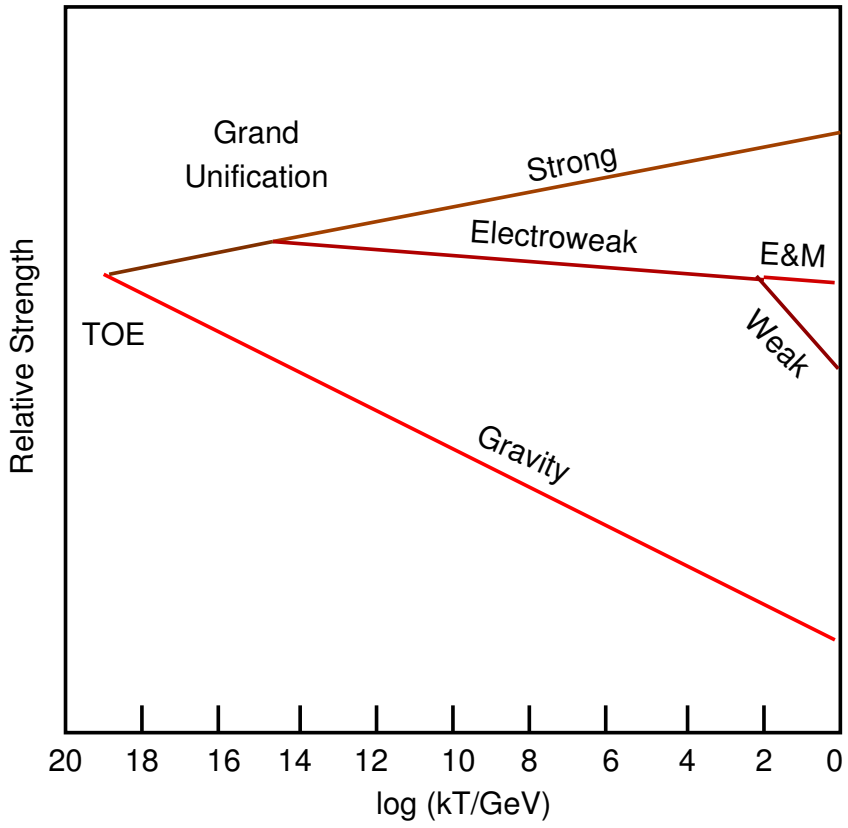
Temperature then decreased after BB as universe expanded,

$$T(z) = T_0(1+z) \qquad (20.1)$$

Gamov called original state the ylem. This term has (thankfully) not caught on.

The very early universe

Big Bang Theory: Initially, the universe was very hot and as it expanded, it cooled down. Theory gives $T(t) = 1.52 \times 10^{10}\,\mathrm{K} \cdot (t/1\,\mathrm{s})^{-1/2}$



after Carroll & Ostlie, Fig. 30.2

Fundamental physics: unification of forces

- $t = 10^{-44}$ s: GUT & gravitation
  $\Longrightarrow$ Theory of Everything (TOE)
- $t = 10^{-34}$ s: electroweak & strong nuclear force
  $\Longrightarrow$ Grand Unifying Theory (GUT)
- $t = 10^{-11}$ s: electromagnetic & weak nuclear forces
  $\Longrightarrow$ electroweak force

Physics is understood from $t = 10^{-11}$ s after the Big Bang

The hot Big Bang

- 10^{-4} s after Big Bang: Temperature has decreased to $T = 10^{12}$ K, corresponding energy $E = kT = 86$ MeV
- Universe consists of only a few particle types:
  - photons γ, electrons e^-, positrons e^+, neutrinos: ν_e, ν_μ, ν_τ and anti-neutrinos $\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$
  - few hadrons: protons p & neutrons n: $N(p) \sim 5 \times 10^{-10} N(\gamma)$
- reactions at work:
  - pair formation and annihilation:

$$\gamma \rightleftharpoons e^- + e^+ \quad \text{and} \quad \gamma \rightleftharpoons \nu_e + \bar{\nu}_e$$

  - transformation of particles:

$$n \rightleftharpoons p + e^- + \nu_e$$
$$n + e^+ \rightleftharpoons p + \bar{\nu}_e$$
$$n + \nu_e \rightleftharpoons p + e^-$$

- resulting thermodynamic equilibrium: neutron-proton-ratio:

$$\frac{N(n)}{N(p)} = \exp\left(-\frac{(m_p - m_n)c^2}{kT}\right) \tag{20.2}$$

where $(m_p - m_n)c^2 = 1.293\,\text{MeV} \Longrightarrow N_n/N_p = 0.985$

The hot Big Bang

- $t \sim 2\,s$: Temperature has decreased to $T \sim 2 \times 10^{10}\,K$.
  At this time: Timescale for nuclear reactions $<$ Expansion time scale

  Result: End of thermodynamical equilibrium, "freeze out"

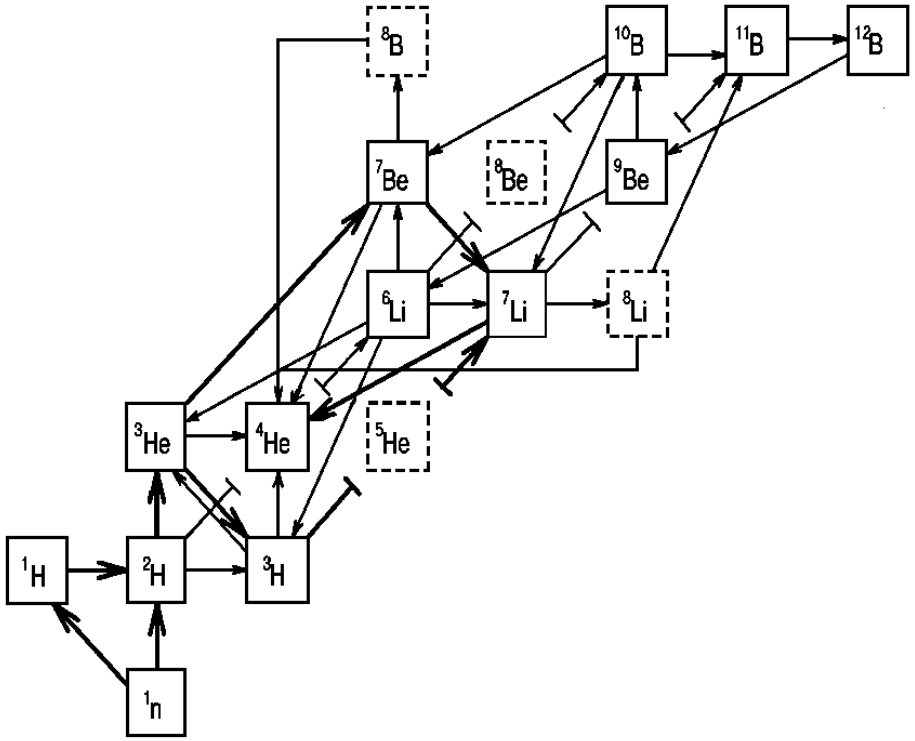
  – neutron-proton ratio now $N_n/N_p = 0.223$
  – Neutrino freeze-out: neutrinos decouple, no interaction with other particles
  – electron-positron pair formation stops at threshold 1.22 MeV ($1.4 \times 10^{10}\,K$)
  – electrons and positrons annihilate $\Longrightarrow$ very few electrons remain
  – $\Longrightarrow$ no neutrons can be formed neutrons decay to protons (half-life: 10.3 min.)
- $t = 230\,s \sim 4\,min$, $T = 10^9\,K$:
  – Deuterium formation: $p + n \rightleftharpoons d + \gamma$
  – Helium formation:

$$d + d \rightleftharpoons t + p \quad \text{and then} \quad t + d \rightleftharpoons {}^4He + n$$

and also

$$d + d \rightleftharpoons {}^3He + n \quad \text{and} \quad {}^3He + d \rightleftharpoons {}^4He + p$$

The hot Big Bang



Ohio State University

- Helium formation:
- neutrons start to decay

$$N_n(t) = 0.223 \exp(-\lambda t) \qquad (20.3)$$

where $\lambda = \ln 2/\tau$. Nucleosynthesis starts once $N_n/N_p = 0.164$.
Most neutrons still around manage to get bound in He before they decay:

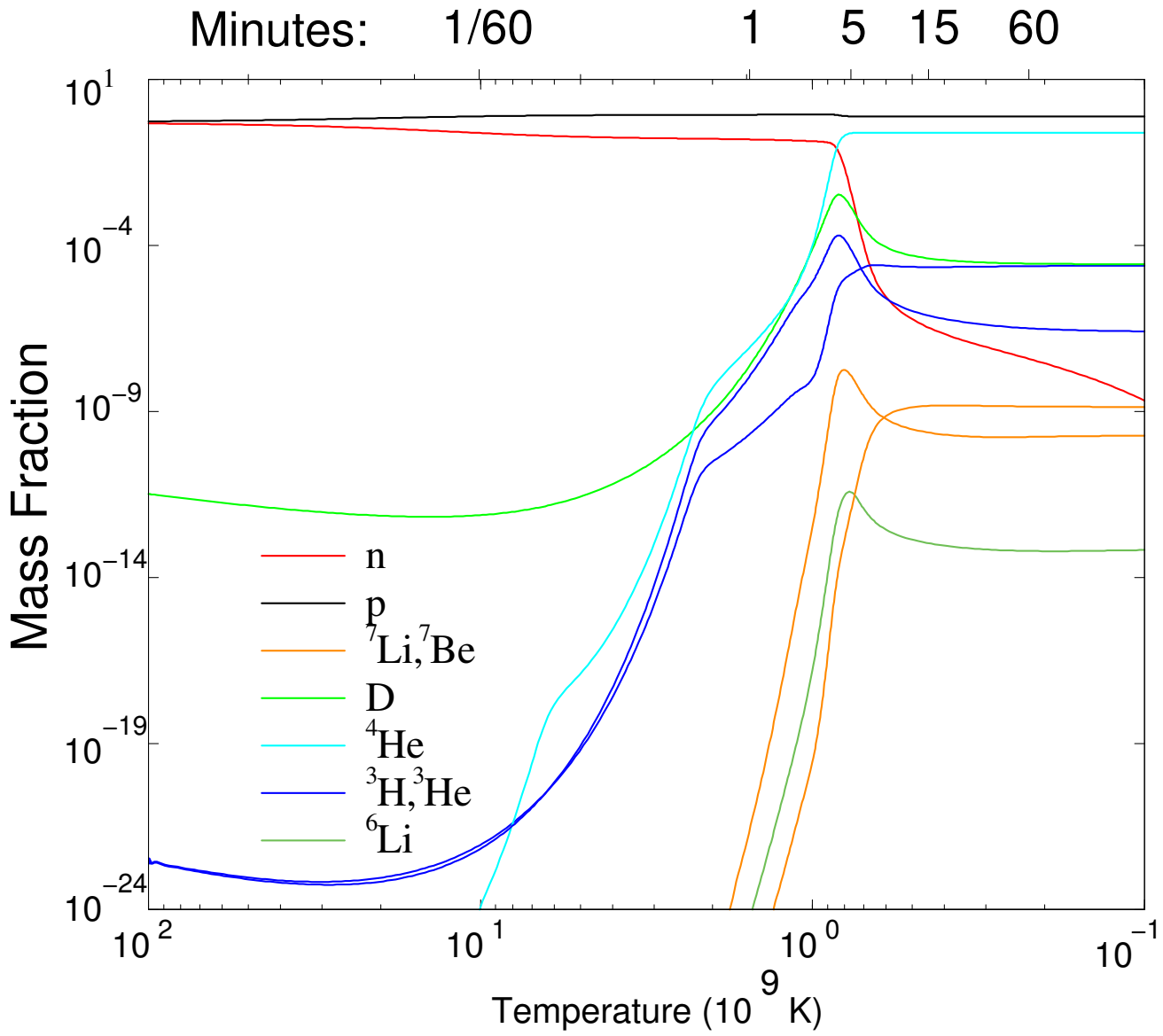
$$N_{He}/N_H \sim 0.1 \qquad (20.4)$$

(turns out to be almost independent of Ω)

- Some higher elements are also formed, especially ^{7}Li Abundances of deuterium, tritium, ^{3}He and ^{7}Li are strongly dependent on Ω

Since there are no stable nuclei with $A = 5$ and 8, more massive elements can not form in Big Bang Nucleosynthesis.

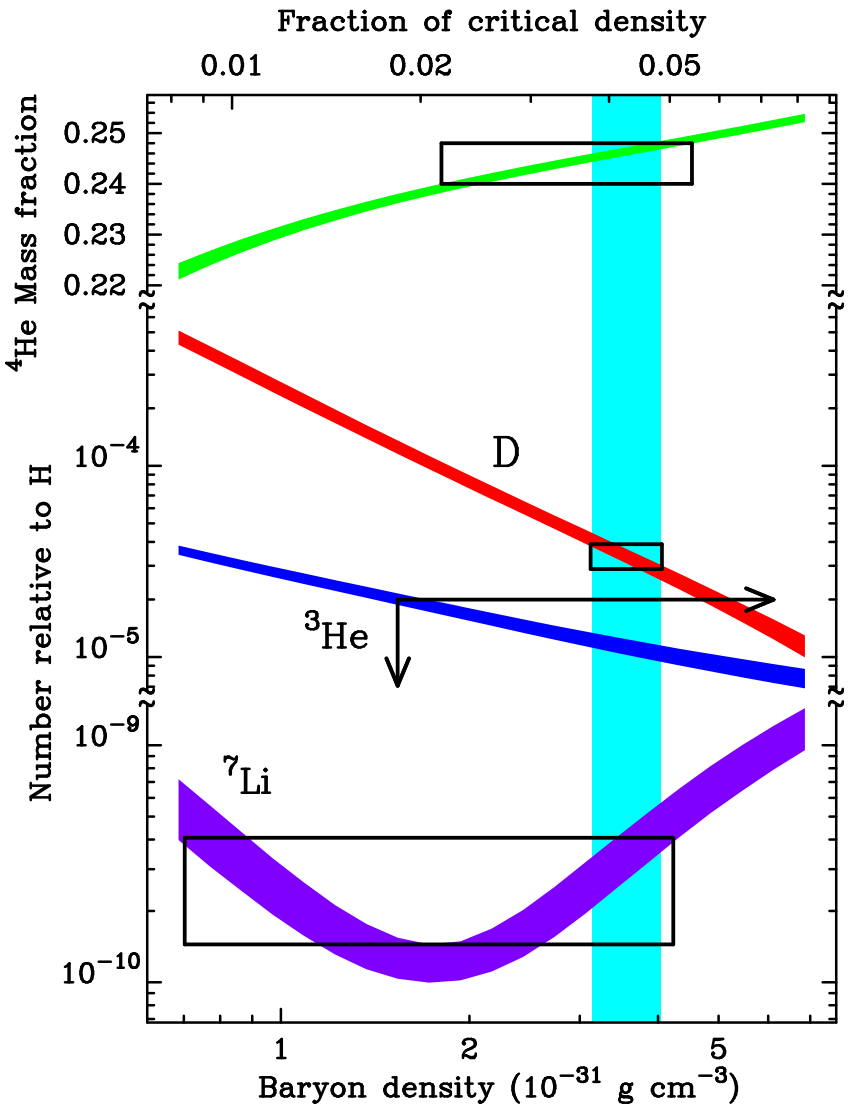
The hot Big Bang



Big Bang Nucleosynthesis finishes after a quarter of an hour!

(Burles, 1999)

The hot Big Bang



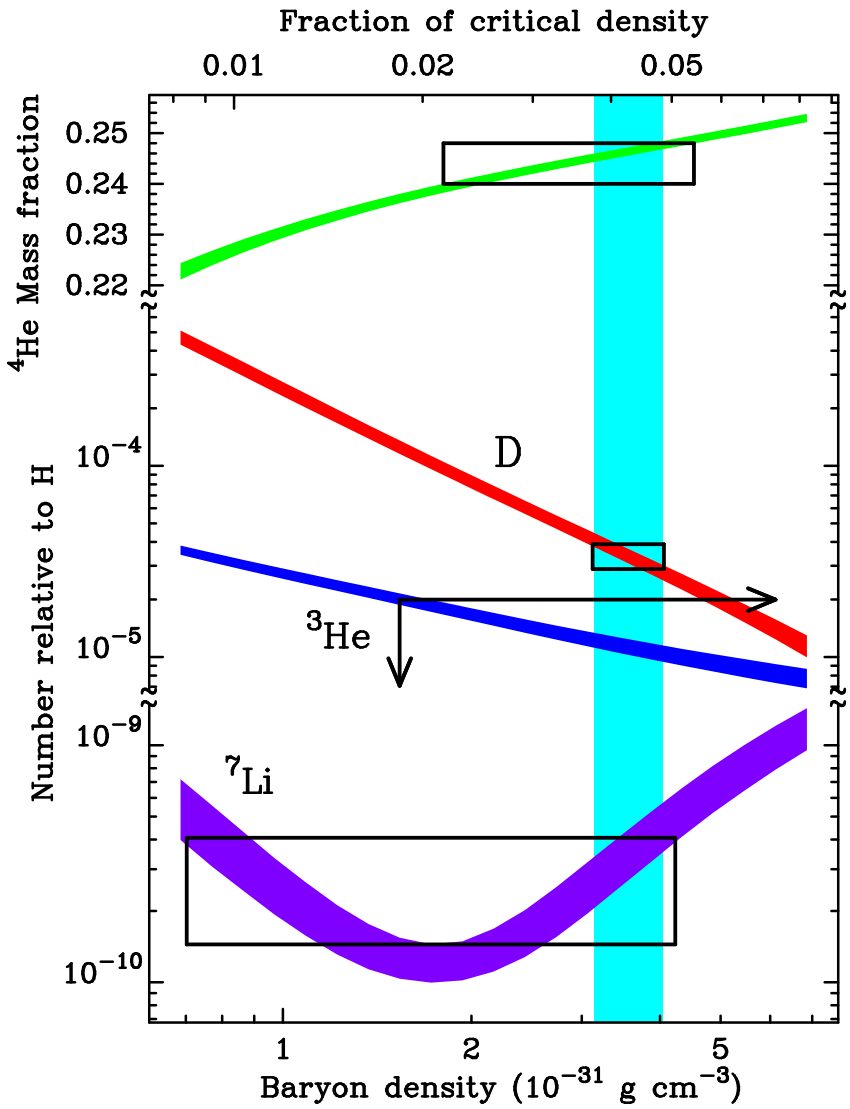
(Burles, 1999)

Synthesis of the elements in stars: Burbidge, Burbidge, Fowler & Hoyle (1957, B^{2}FH):

Stars produce much less He than observed

$\Longrightarrow$ The helium (^{4}He) abundance is a smoking gun for the hot big bang

The hot Big Bang



(Burles, 1999)

Deuterium, ^{3}He & Lithium abundances: primordial abundances are very difficult to determine as these elements are easily destroyed in stars by thermonuclear reactions.

Can be approximately measured from old stars and the intergalactic medium

Result:

Density parameter $\Omega_b = 0.04$: Normal matter ("baryons") contributes 4% of the critical density.

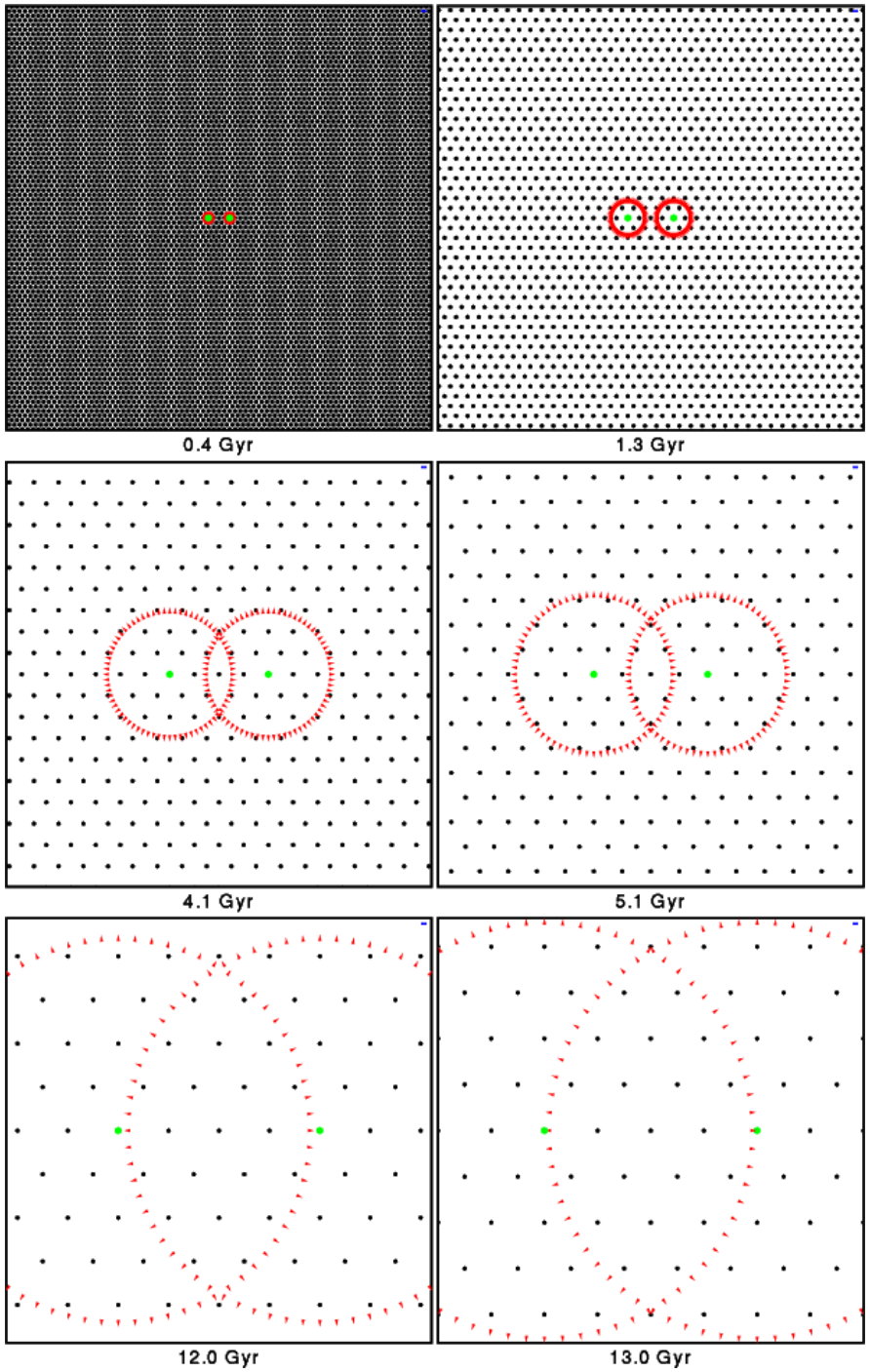
The hot Big Bang

BB works remarkably well in explaining the observed universe.

However, there are many problems with classical BB theory:

- Horizon problem:
  Why ist the CMB so isotropic?
- Flatness problem:
  Why is and was the density so close to critical, i.e., $\Omega = 1$?
- Baryogenesis:
  Why is there virtually no antimatter in the universe?
- What is the nature of Dark Matter & Dark Energy?
- Structure formation:
  The fluctuations of the cosmic microwave background are too small to allow stars & galaxies to form as early as observed. Why?

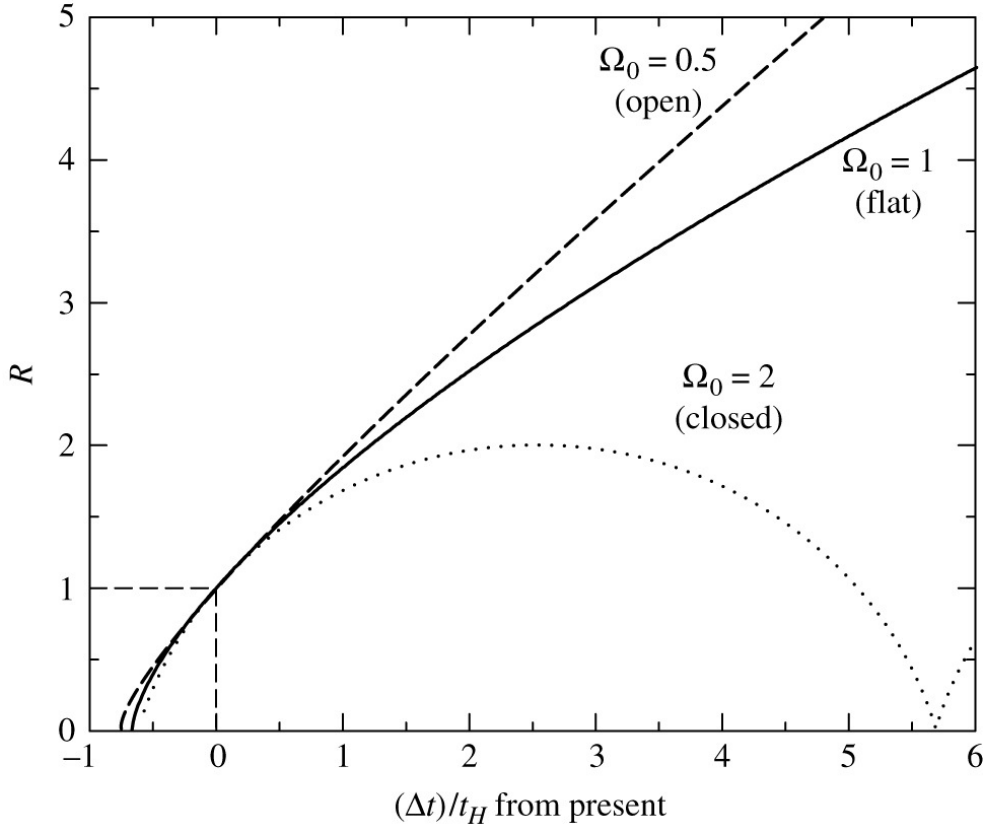
Inflation attempts to answer all of these questions.



courtesy E. Wright.

Expansion of horizon in an expanding universe.

The Flatness Problem



Carroll & Ostlie, Fig. 29.5

Because of expansion, Ω is changing with time:

$$\frac{1}{\Omega_0} - 1 = \left(\frac{1}{\Omega} - 1\right) \cdot (1 + z) \qquad (20.5)$$

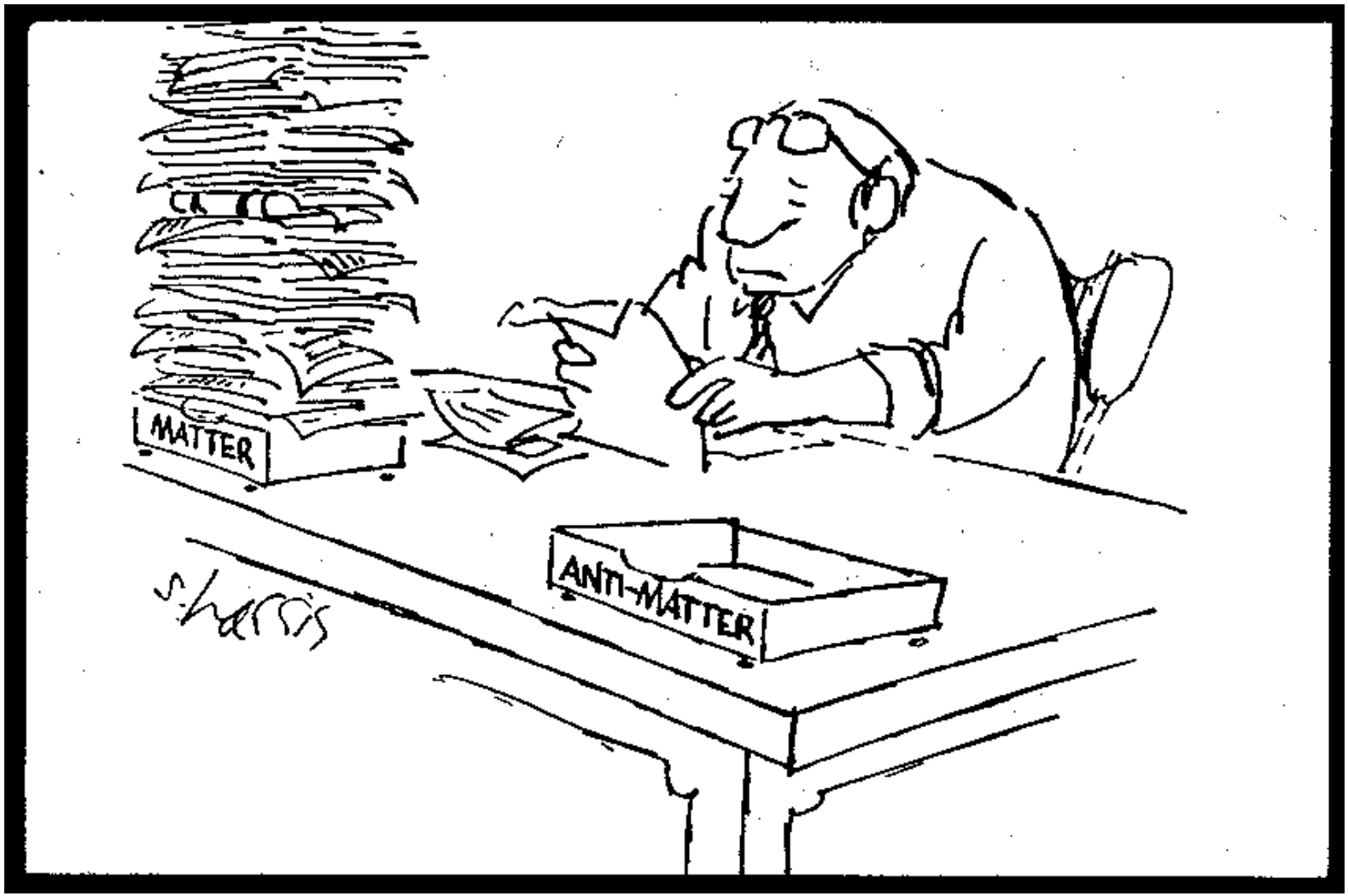
What was Ω at time when radiation and matter decoupled ($T_{dec} = 380000$ yrs; $z = 1100$)?

$\Longrightarrow$ assume $\Omega(T_{dec}) = 2$:
Results in big crunch after $\sim$ 3 million years

$\Longrightarrow$ assume $\Omega(T_{dec}) = 0.5$:
Results in a very fast evolution of the universe, no stars & galaxies can form.

Why is the universe (nearly) flat?

The matter/antimatter problem



The matter/antimatter problem

Early universe was in thermodynamic equilibrium

$\Longrightarrow$ there should have been as much matter as antimatter

But: If there were as much matter as antimatter formed in the Big Bang, they would have annihilated very soon.

$\Longrightarrow$ Only photons would have remained, we should not exist.

Observations of Big Bang nucleosynthesis: ratio of hadrons to photons: $\sim 5 \cdot 10^{-10}$

$\Longrightarrow$ slightly more matter than antimatter must have been formed.

There is no observational evidence for antimatter

(except for production by high energy cosmic rays)

$\Longrightarrow$ There must have been some kind of symmetry breaking in the production of elementary particles in the very early universe!

Inflation

Possible solution of these problems: inflation

Basic assumption of inflationary cosmology:

> During the big bang there was a phase where Λ dominated the Friedmann equation.

Use the Friedmann equation with a cosmological constant:

$$H^2(t) = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho}{3} - \frac{k}{a^2} + \frac{\Lambda}{3} \tag{20.6}$$

where $a = R(t)/R_0$

For $\Lambda = \text{const.}$ this gives

$$H(t) = \frac{\dot{a}}{a} = \sqrt{\frac{\Lambda}{3}} = \text{const.} \tag{20.7}$$

Solution of Eq. (20.7):

$$a \propto e^{Ht} \tag{20.8}$$

Inflation

When and why did inflation happen?

Typical assumption: Inflation = phase transition of a scalar field ("inflaton") associated with Grand Unified Theories = GUT.

(GUT predicts that the electromagnetic, weak nuclear, and strong nuclear forces are fused into a single unified field at energies above 10^{14} GeV)

$\Longrightarrow$ temperature $kT_{GUT} = 10^{15}\,GeV$, when $1/H \sim 10^{-34}\,sec$ ($t_{start} \sim 10^{-34}\,s$).

$\Longrightarrow$ inflation lasted for 100 Hubble times, i.e., for $\Delta T = 10^{-32}\,s$.

With Eq. (20.8): Inflation: Expansion by factor $e^{100} \sim 10^{43}$ . . . corresponding to a volume expansion by factor $\sim 10^{130}$

$\Omega \neq 1$ (curved) before inflation $\Longrightarrow \Omega = 1$ (flat) thereafter.

Universe was so small before inflation that all parts of it were in causal contact.

Inflation solves horizon, antimatter, and flatness problem.

. . . but it was *constructed* to do so, and the real physical cause for inflation is still unclear.