Week 1

First slide of each lecture will contain announcements / reminders

Syllabus; Course Introduction; Fundamental Observations; Historical Background

http://www.astro.utah.edu/~wik/courses/astr4080spring2021/

Course Outline and Grading

Course Schedule

[Jan19, Jan21] Introduction/Fundamental Observations (Ch. 1 & 2)
[Jan26, Jan28] Newton Versus Einstein (Ch. 3)
[Feb02, Feb04] Cosmic Dynamics (Ch. 4)
[Feb09, Feb11] Model Universes (Ch. 5)
[Feb16, ~~Feb18~~] Midterm 1 via Canvas, no Thurs. class
[Feb23, Feb25] Measuring Cosmological Parameters (Ch. 6)
[Mar02, Mar04] Dark Matter (Ch. 7)
[Mar09, Mar11] The Cosmic Microwave Background (Ch. 8)
[Mar16, Mar18] Nucleosynthesis and the Early Universe (Ch. 9)
[Mar30, ~~Apr01~~] Midterm 2 via Canvas, no Thurs. class
[Apr06, Apr08] Inflation and the Very Early Universe (Ch. 10)
[Apr13, Apr15] Structure Formation: Gravitational Instability / Baryons & Photons (Ch. 11 & 12)
[Apr20, Apr22] Structure Formation (cont.) / Student Presentations
[Apr27, (Apr29)] Student Presentations / Review (if time) [no class Thurs, but last HW due]
[Apr30] Final Exam 10:30am-12:30pm via Canvas

HW due

Grading

Homework:	40%
Participation:	10%
Midterm 1:	10%
Midterm 2:	10%
Presentation:	10%
Final Exam:	20%

Student Presentations

- Choose a current research area in modern (observational) cosmology
- Find and read a recent(ish) scientific paper(s) on that topic
- Make a ~15min powerpoint/keynote/pdf presentation
- Present presentation during last full week of class
- Answer questions afterward (also ask questions at end of other presentations)

Potential Topics:

- Bullet Cluster as direct proof of dark matter
- Measurement of CMB fluctuations
- Measurement of Baryon Acoustic Oscillations
- Constraints on the dark energy equation of state

What is Cosmology?

The study of the Universe → everything

Ancient cosmologies tied to religion/authority
- based on observations
- explanatory, not predictive
- unchangeable

Medicine Wheel in Bighorn National Forest, Wyoming

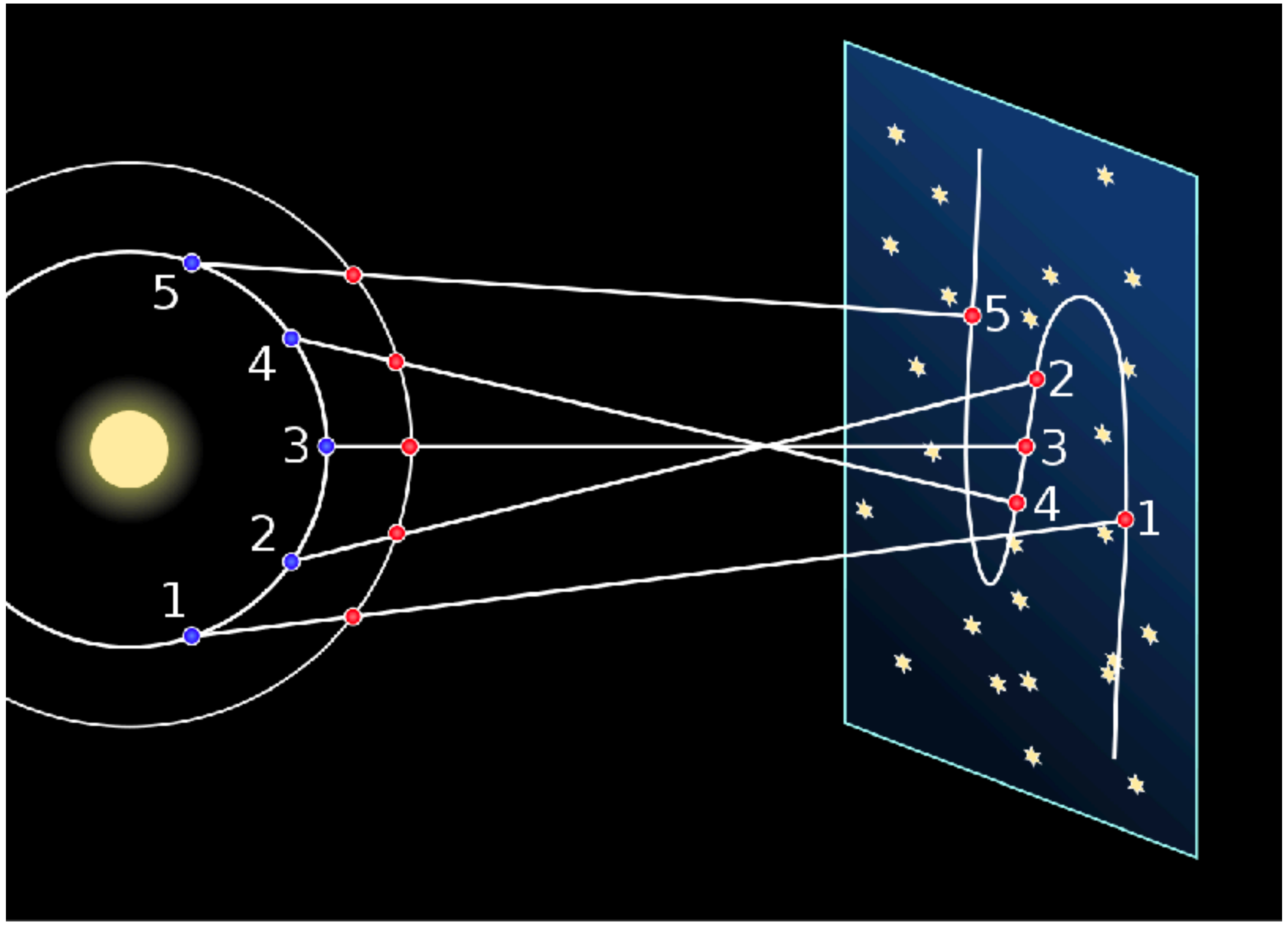
Attempt to put human life into the context of existence, but often turtles all the way down…

Scientific inquiries (at least that we know of) were rarely in vogue, often persecuted

Early Greeks (~600 BCE) performed/suggested experimental/observational investigations
- Estimated Earth-Moon distance
- Measured Earth's circumference
- suggested stars were very far away suns, based on their lack of parallax

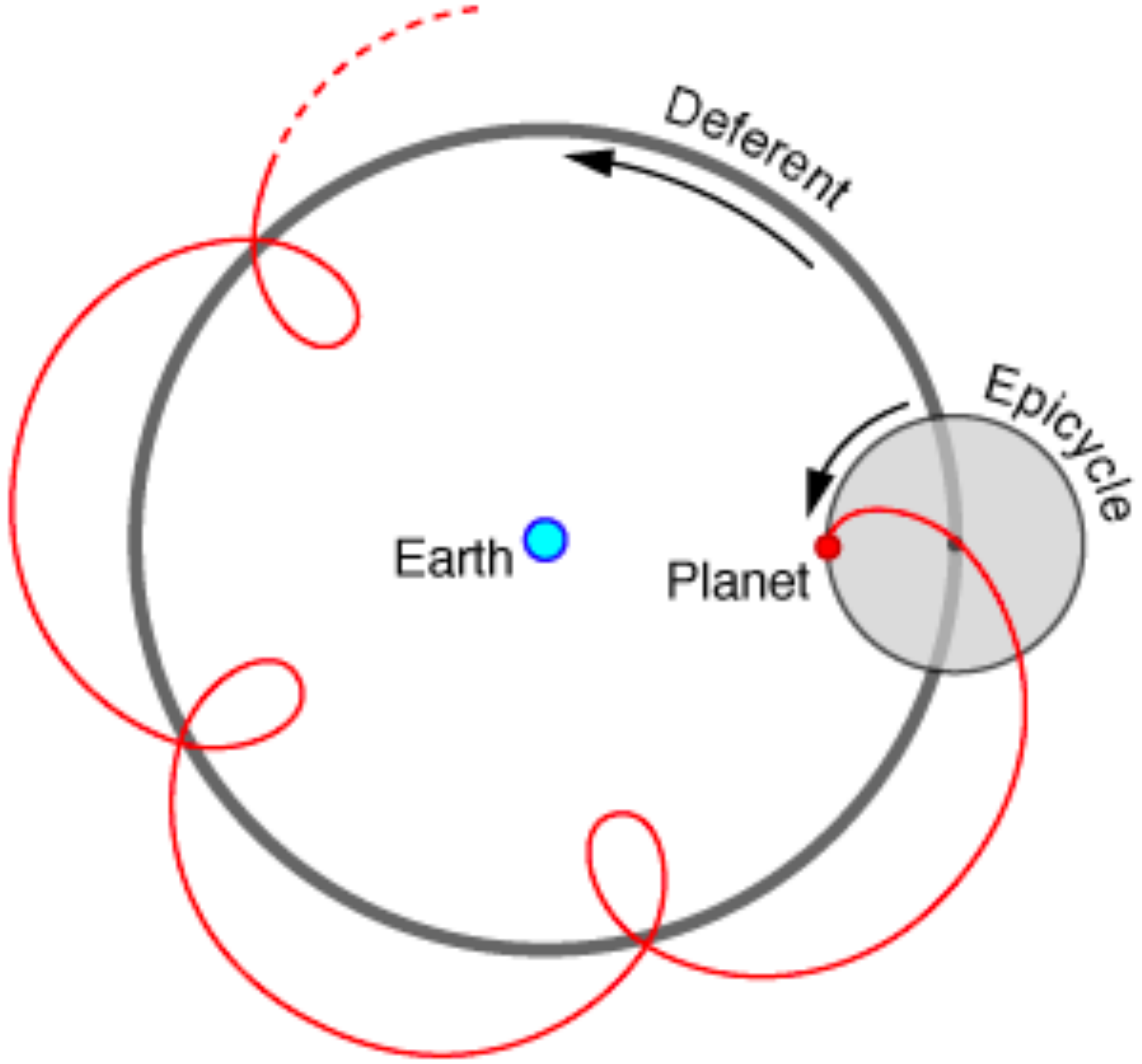
Ptolemic cosmology prevailed 1500 years in Europe and elsewhere

Epicycles



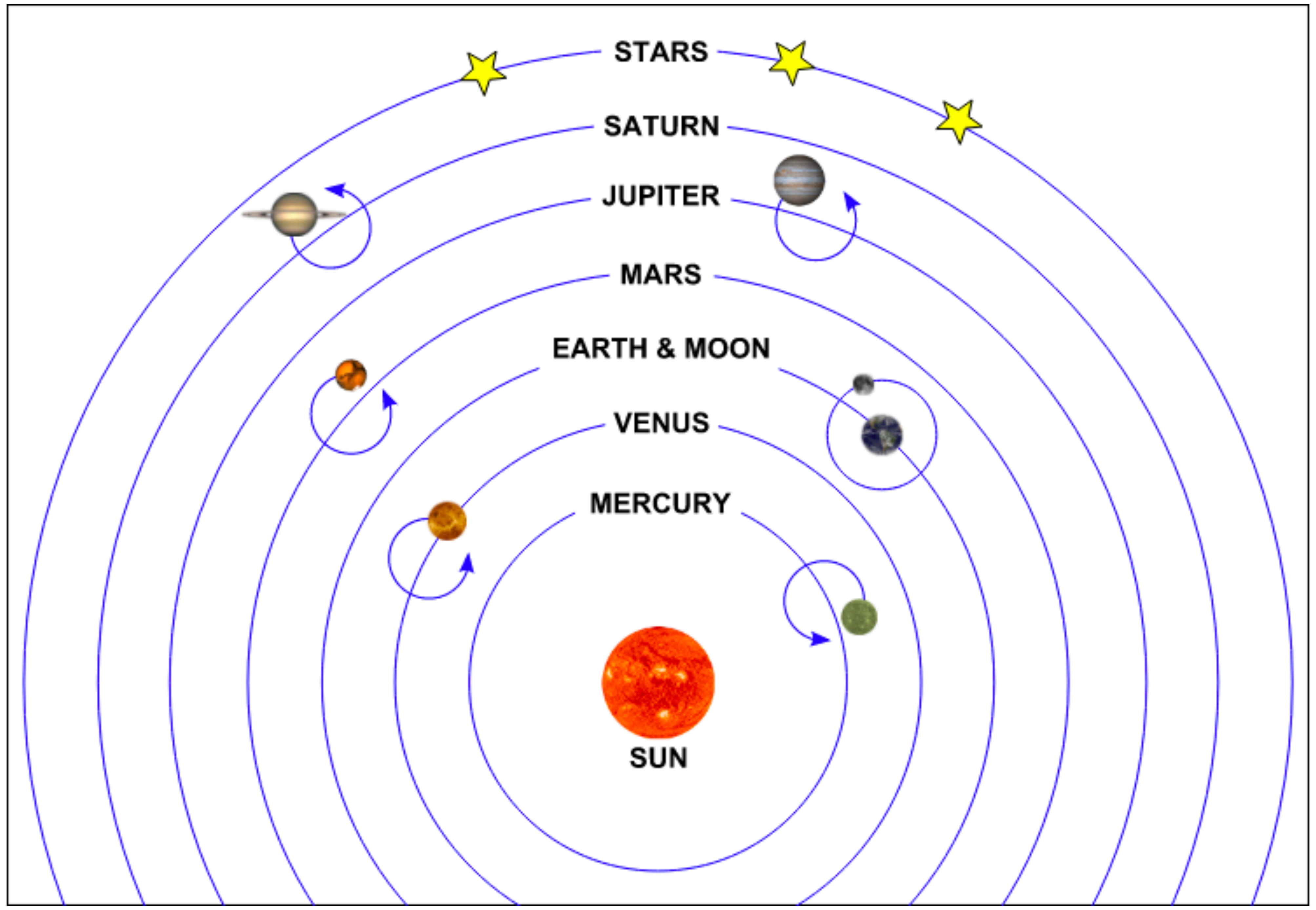
https://en.wikipedia.org/wiki/Apparent_retrograde_motion

Retrograde motion of Mars in 2005.
Credit astrophotographer Tunc Tezel

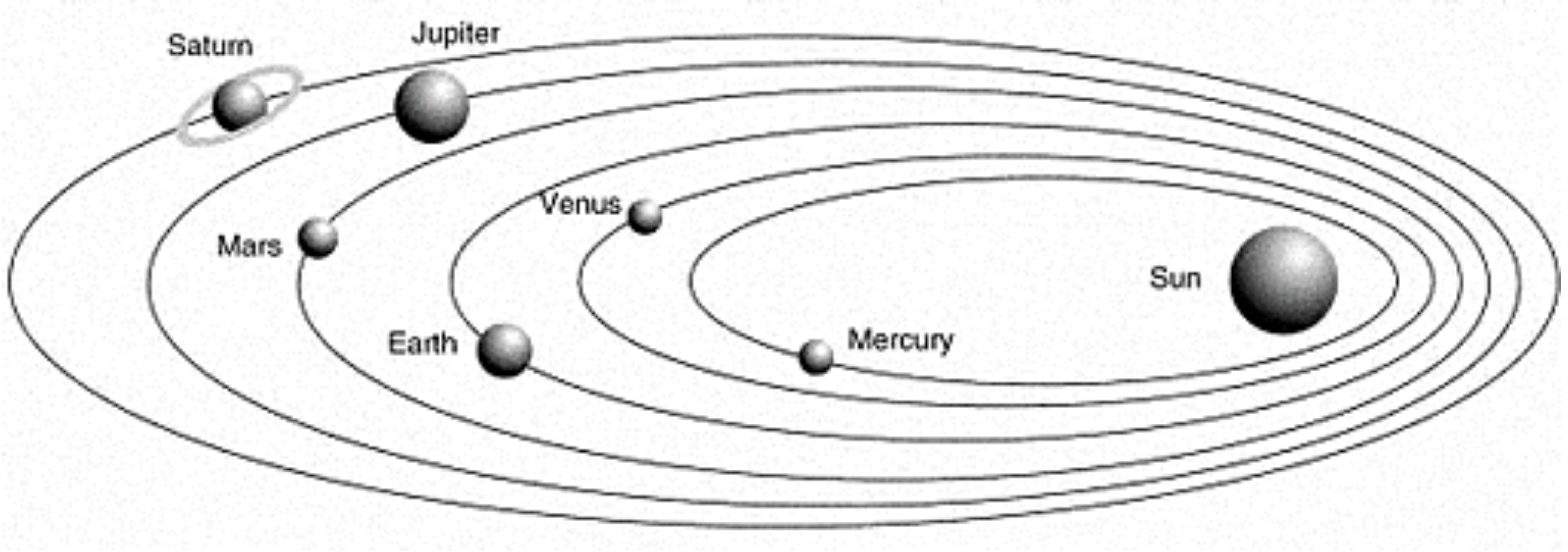


https://physics.weber.edu/schroeder/ua/BeforeCopernicus.html

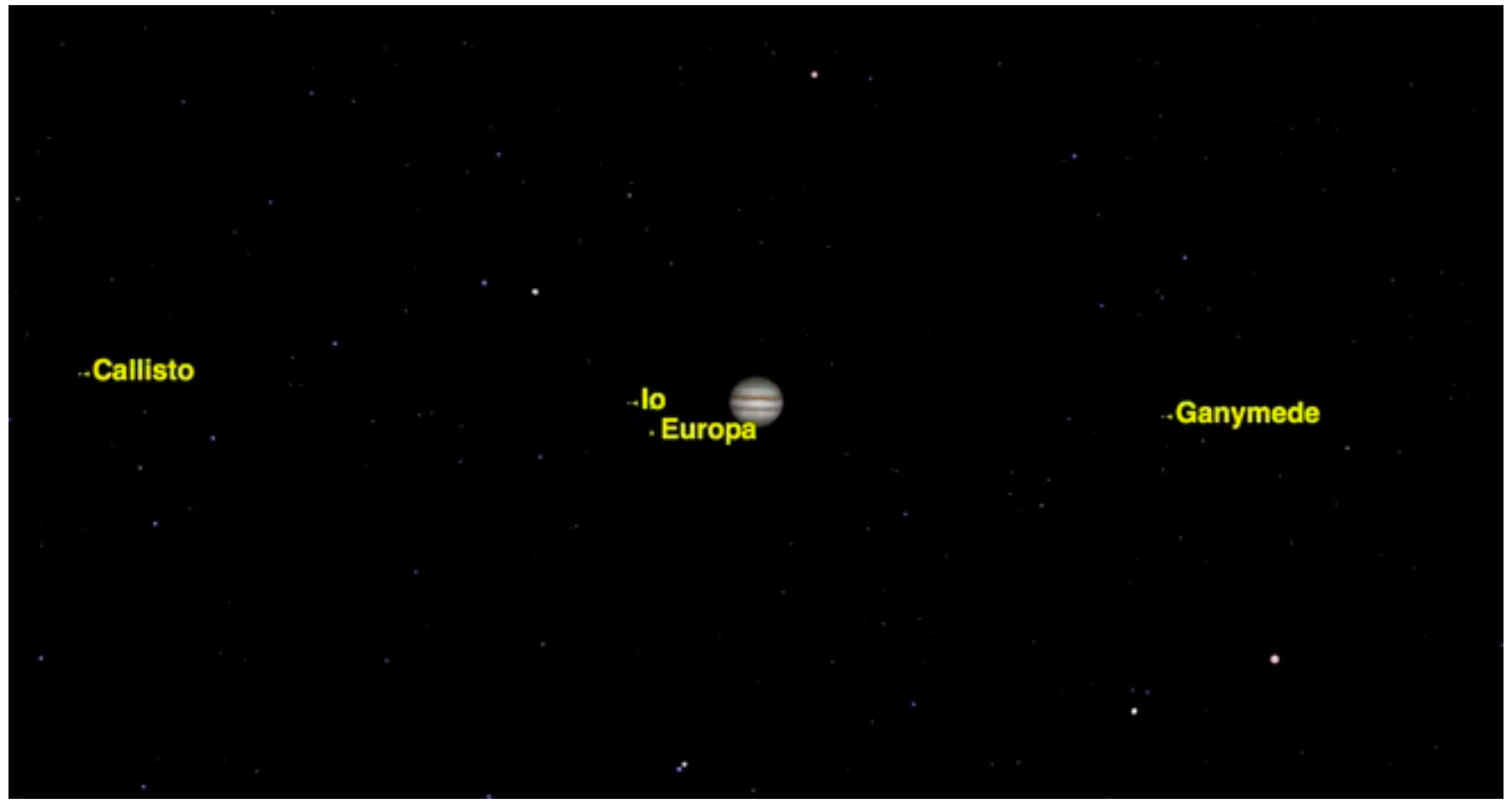
Copernicus, Brahe, Kepler, and Galileo



http://www.faithfulscience.com/science-and-faith/brief-history-of-faithful-science.html



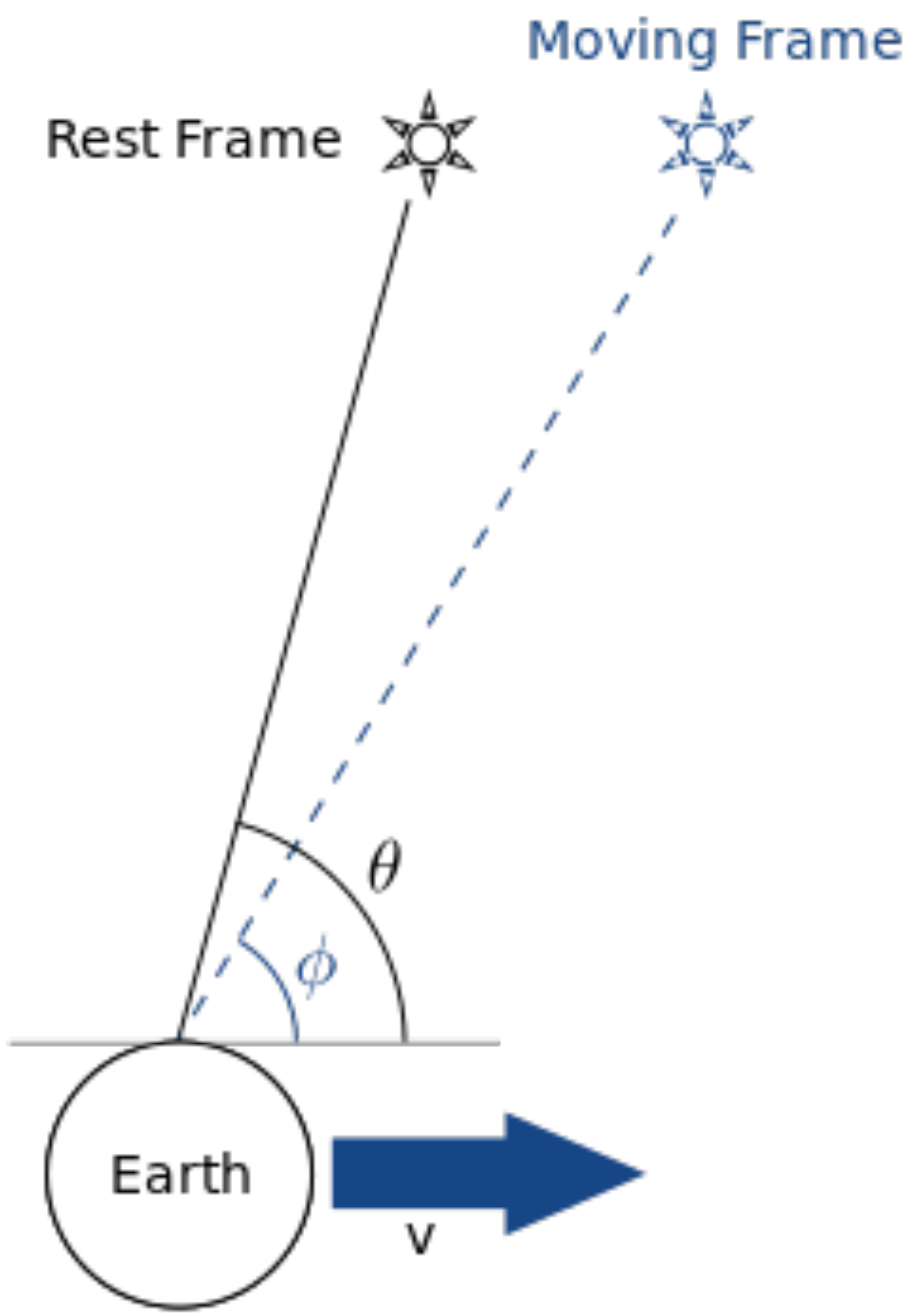
https://www.universetoday.com/55423/keplers-law/



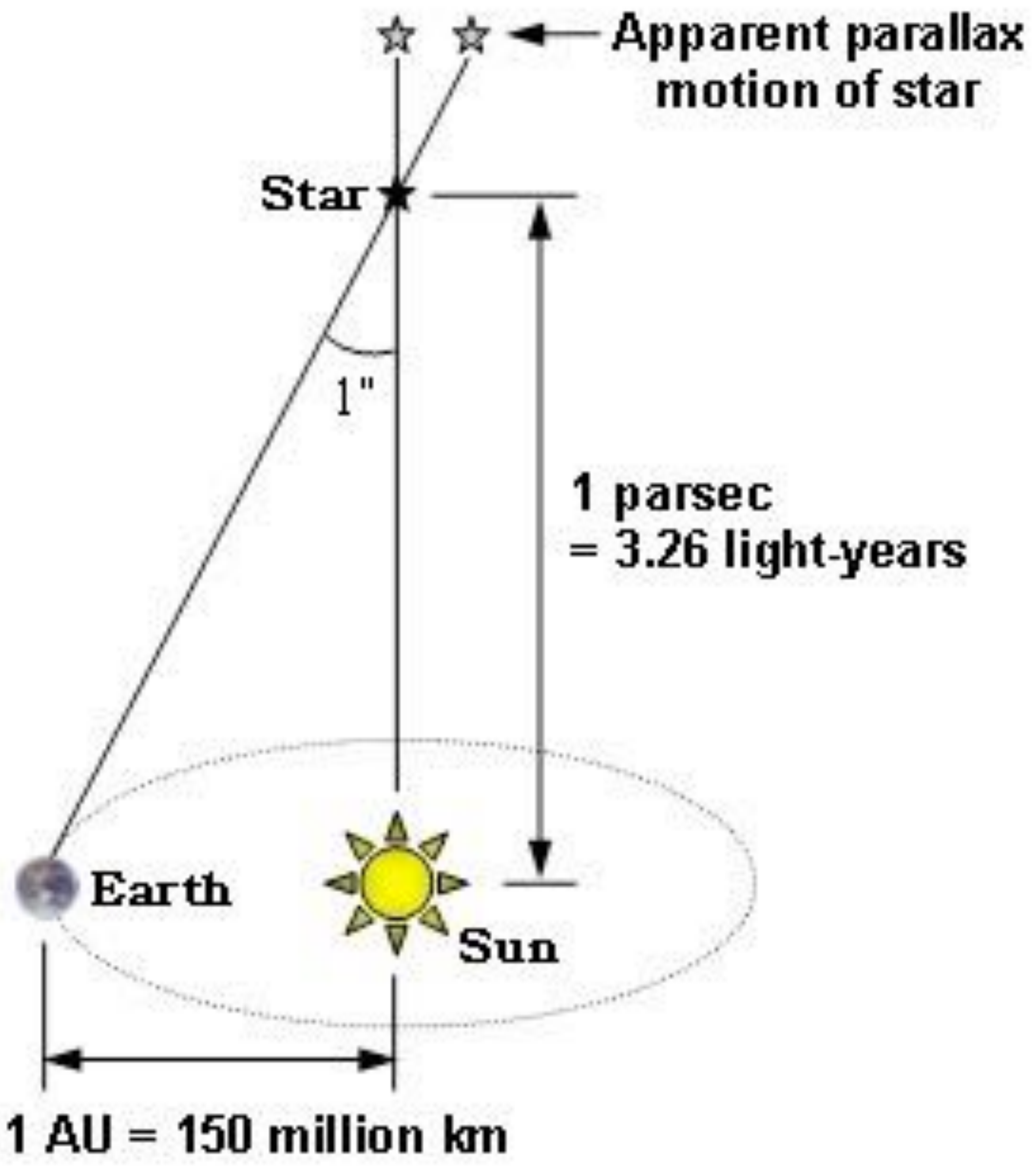
https://www.space.com/32221-spotting-shadows-of-jupiter-galilean-moons.html

Proofs of Heliocentric, Large Cosmos

1728: Stellar Aberration

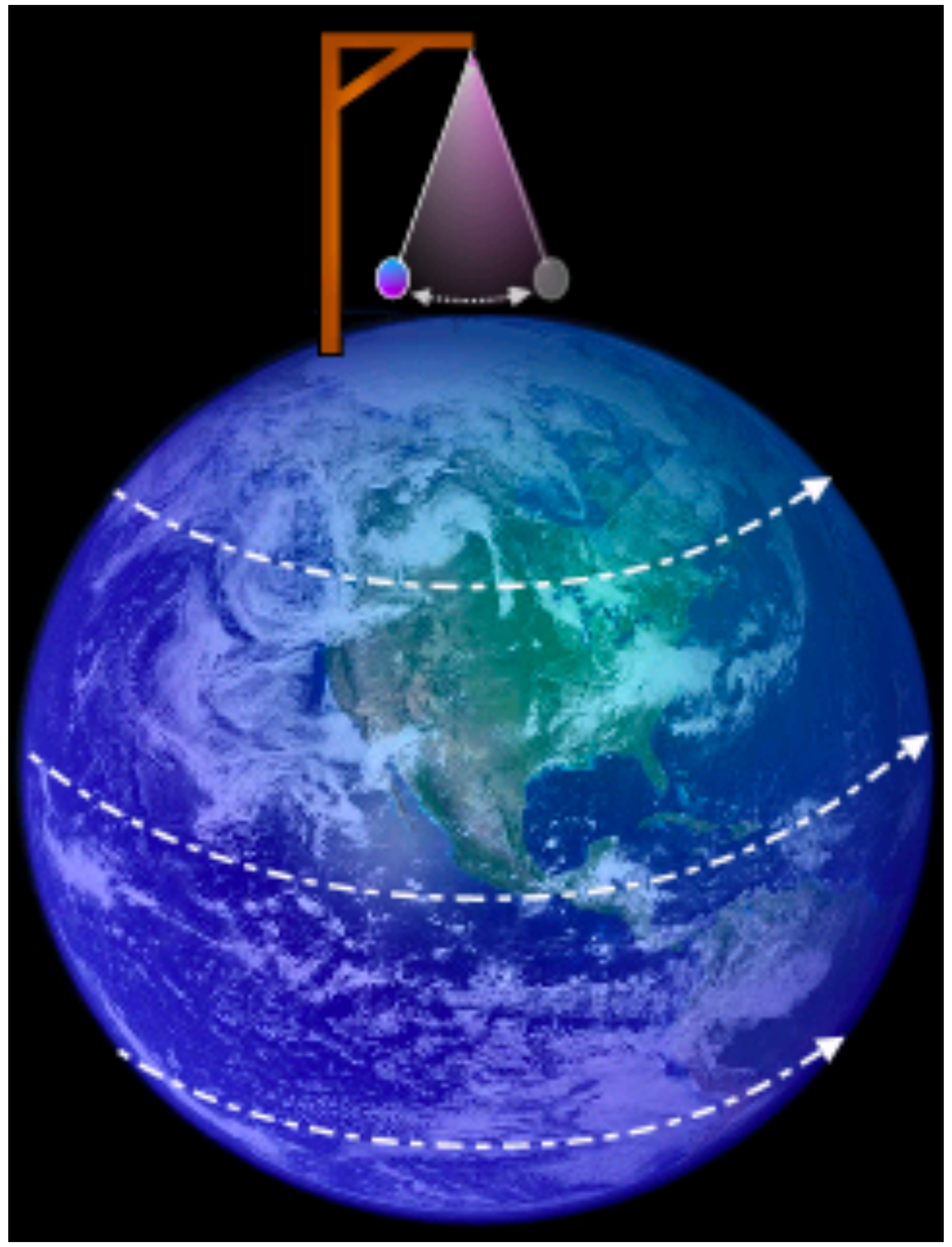


1838: Parallax



(only 60 measured by 1900!)

1851: Earth's Rotation

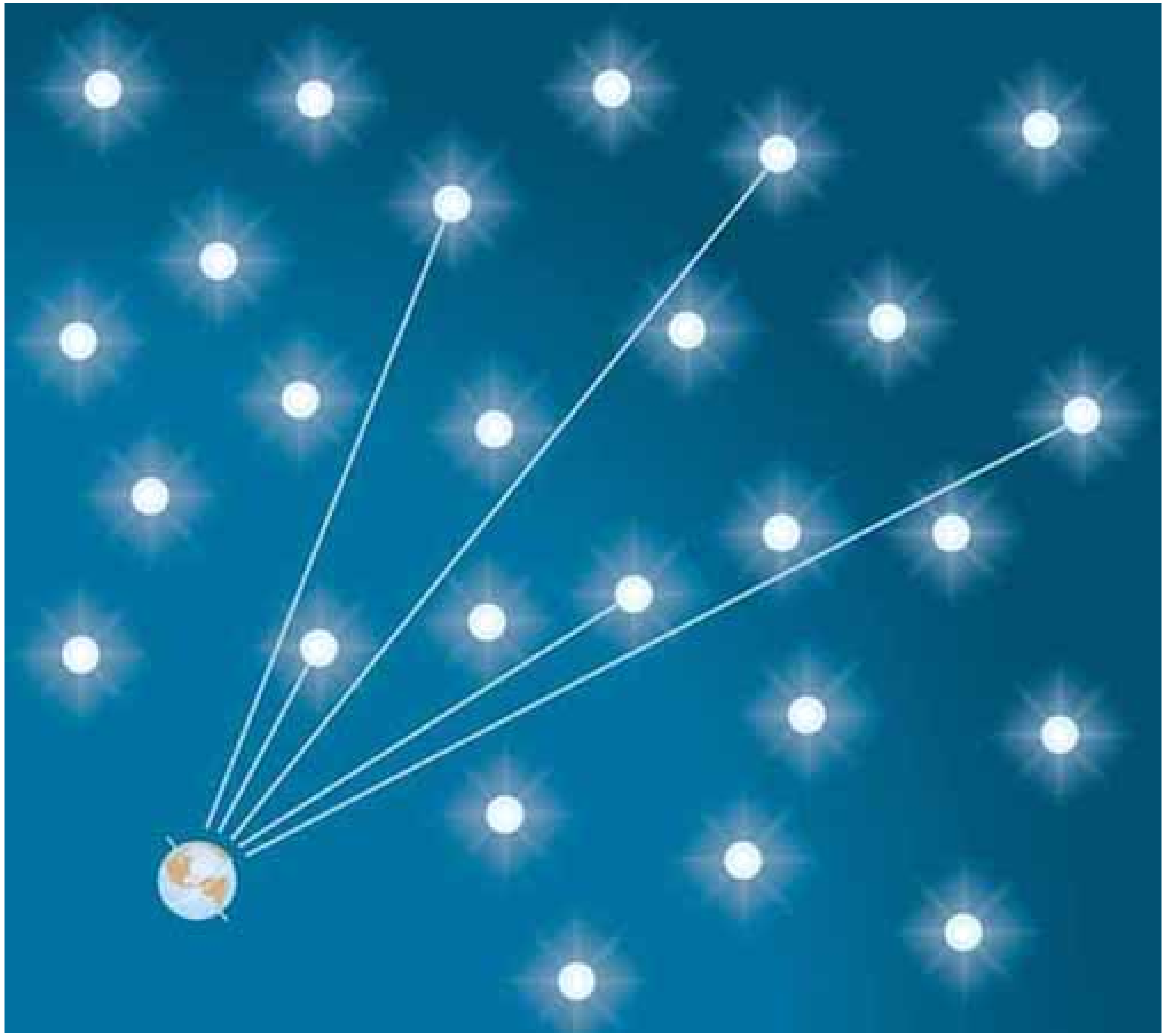


Olber's Paradox (1823)

Infinitely old, infinitely large universe full of stars

Sky should be as bright as the disk of the Sun!

[Whiteboard!]

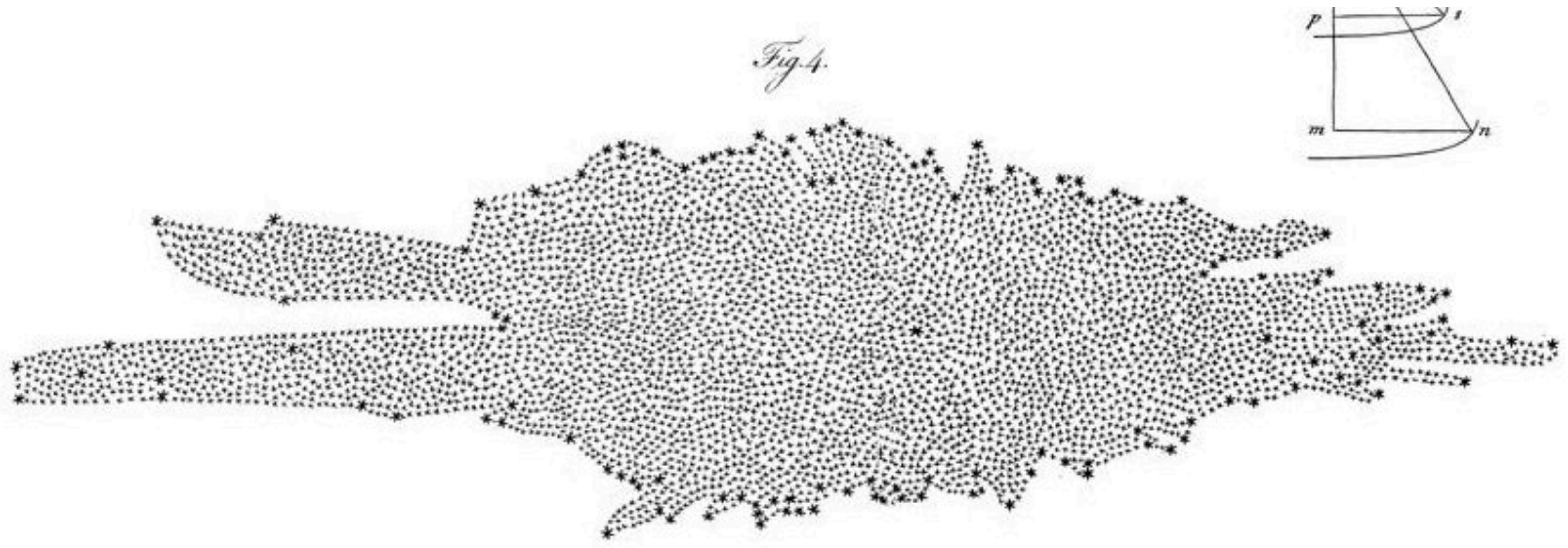


Stars and planets understood, but larger universe?

From invention of the telescope, efforts focused on searching the sky for new objects like nebulae, comets, and planets and measuring parallaxes

Progress hampered by high cost of big telescopes and limited means of recording data (i.e., drawing, counting)

Nature of the nebulae as separate “Milky Way”s suggested by Kant in 1755: “island universe theory”

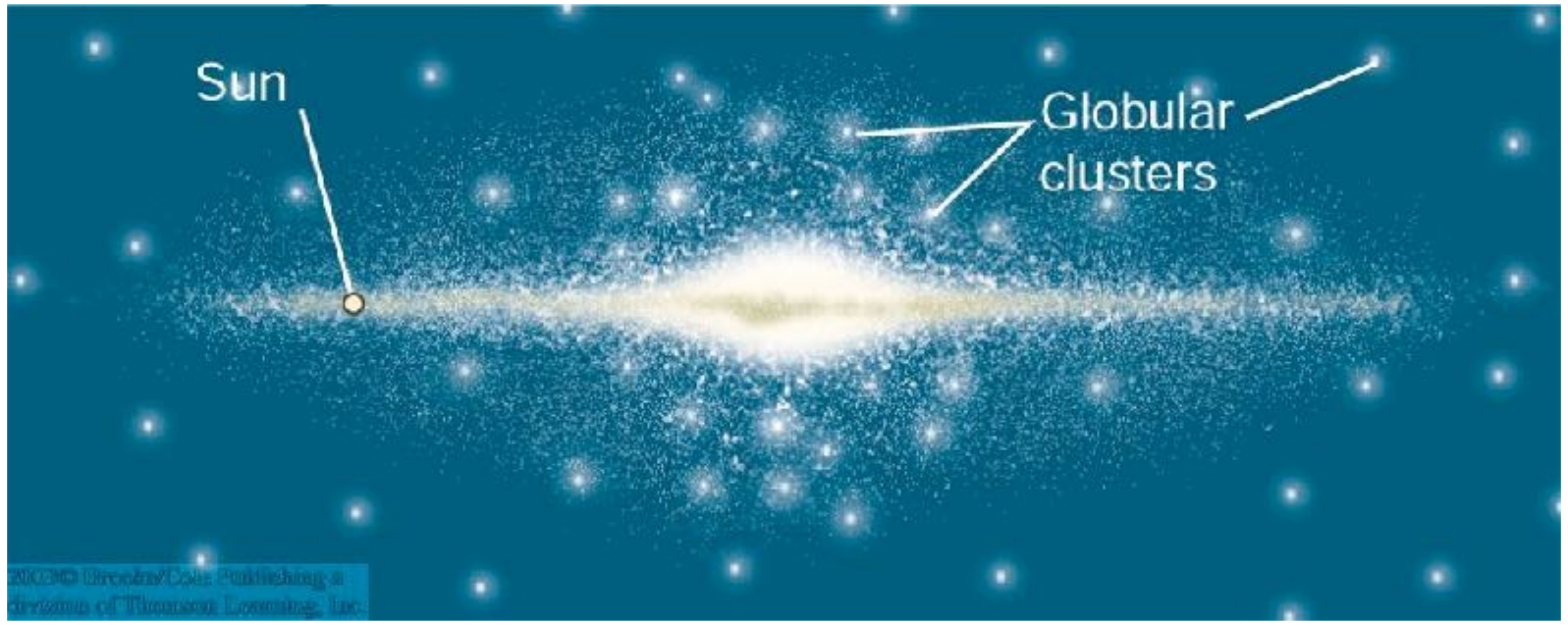


On the Construction of the Heavens by William Herschel, 1785

The Great Debate of 1920

Annual meeting of the National Academy of Sciences
at the Smithsonian Institution in Washington, D.C.

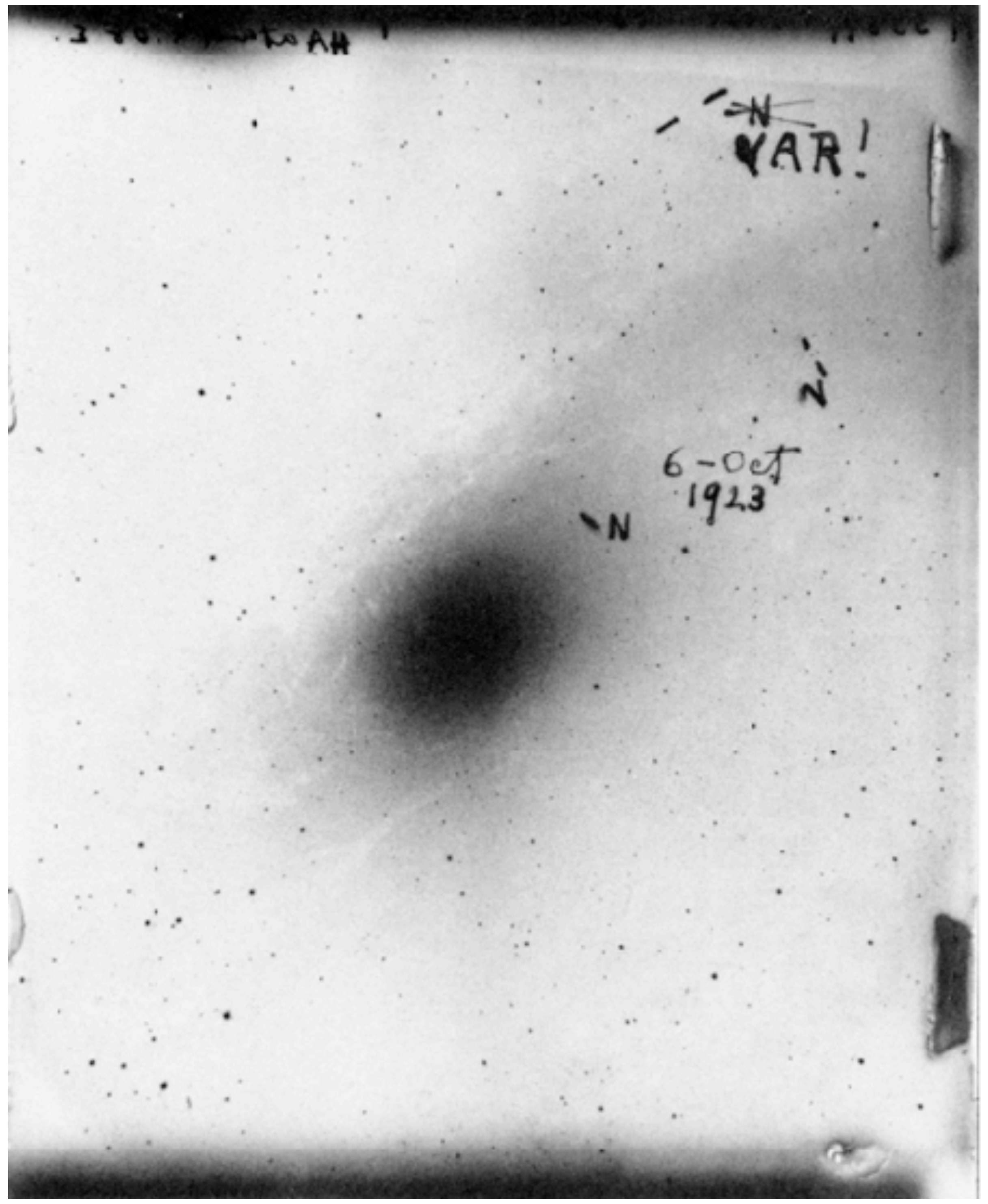
Shapely



Milky Way is entire universe

- Sun off-center, Galaxy big
- Nebulae would have to be impossibly far away to be external stellar systems
- Apparent rotation meant stars would be rotating way too fast

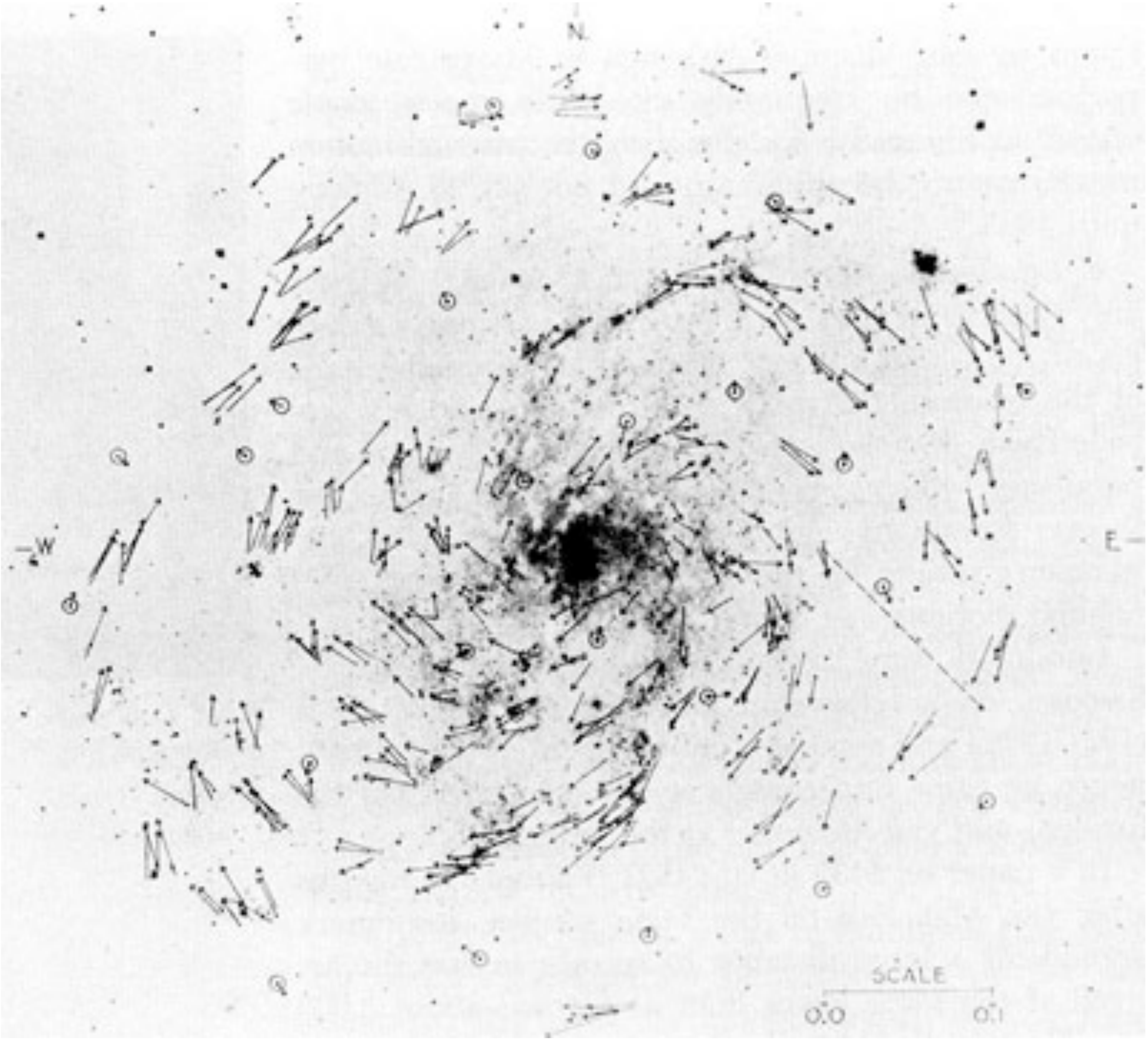
Curtis



Milky Way is one of many galaxies

- Novae brightnesses relative to Galactic novae implied 100x greater distance

The Great Debate of 1920



van Maanen measured proper motions in nebulae, implying incredible velocities that could not be supported by gravity if they were external galaxies

measurements just completely wrong, somehow

Expanding Universe

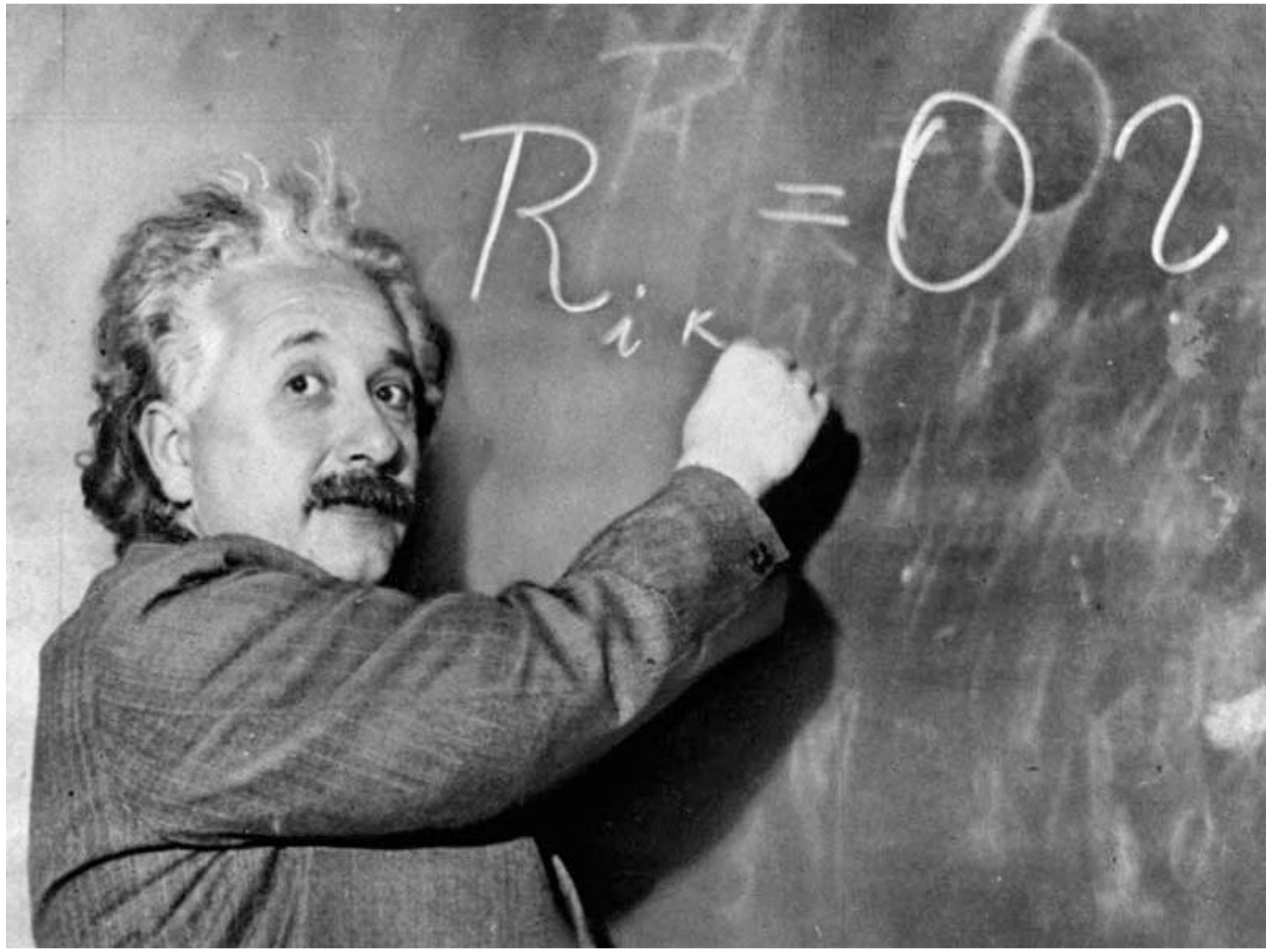
Special (1905) and general (1915) relativity upended Newtonian paradigm of space and time

Before the observation of expansion, astronomers told Einstein et al. the universe was static

GR predicts expansion (or contraction), so he and de Sitter added a constant to the equations to balance gravitational collapse in 1917

Friedmann (1922) solves GR for equation of expanding space, Lemaitre (1927) uses it to predict the distance-redshift relation

In 1929, Hubble measured a linear distance-redshift relation, establishing the expansion of the universe



Getting distances to the nebulae

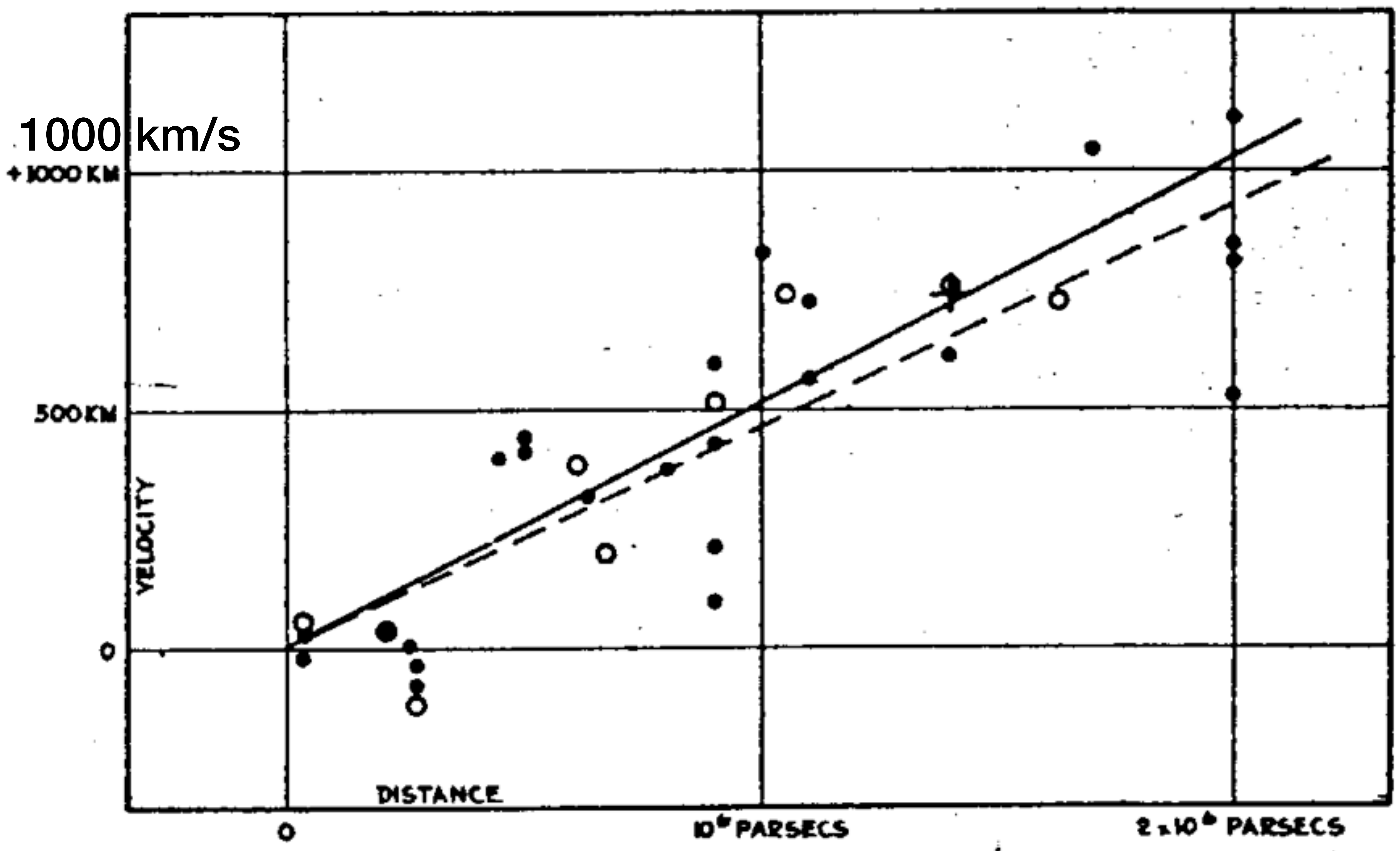


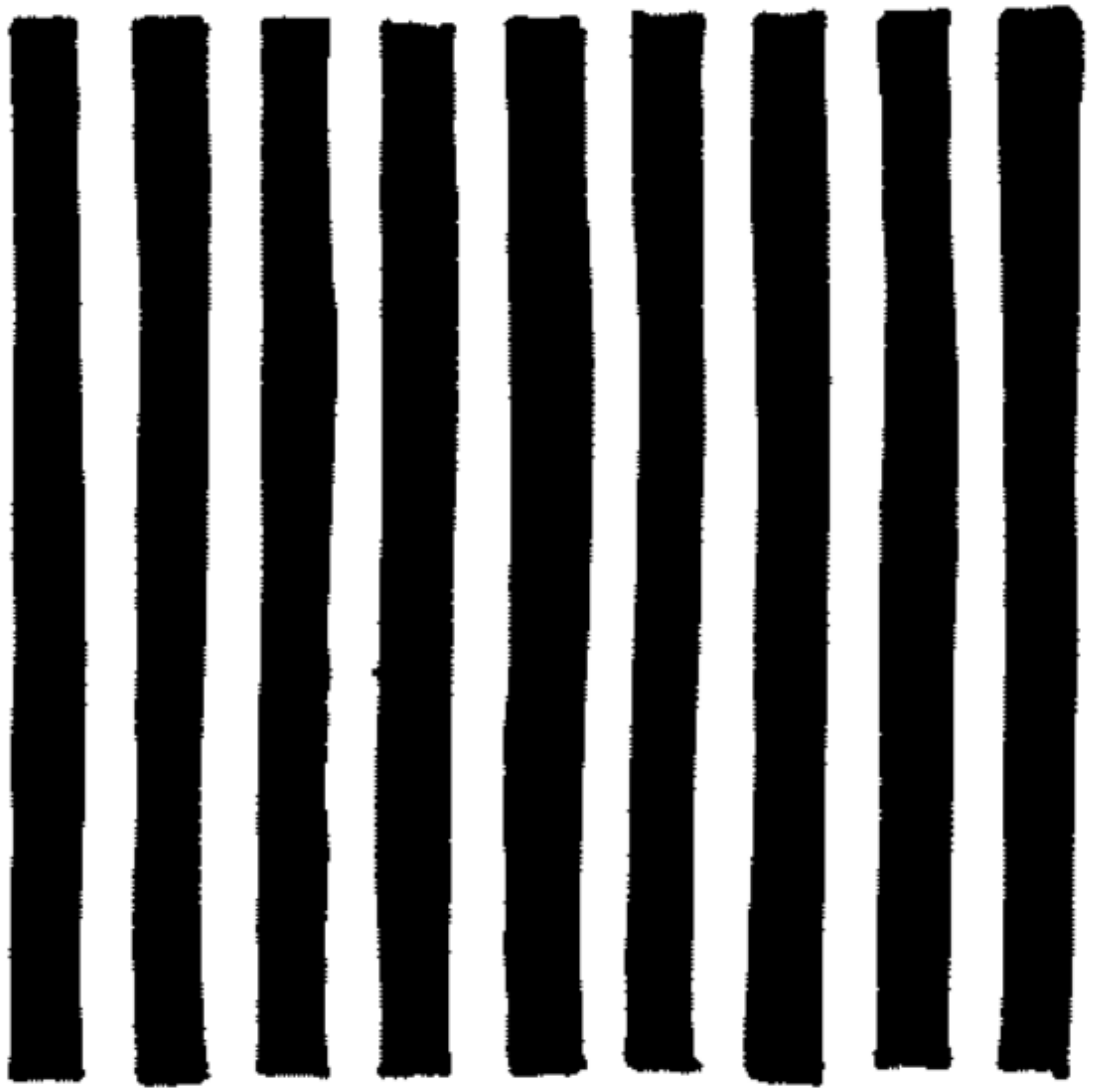
FIGURE 1

Hubble estimated distances to the nebulae, resolved in favor of Curtis and the island universe theory

Also, measurements of line shifts in spectra, interpreted as Doppler velocity shifts, demonstrated that farther away galaxies are “moving” away from us faster

[Whiteboard!]

Cosmological Principle



homogeneity & isotropy

Scale of the Universe

(log scale of course)

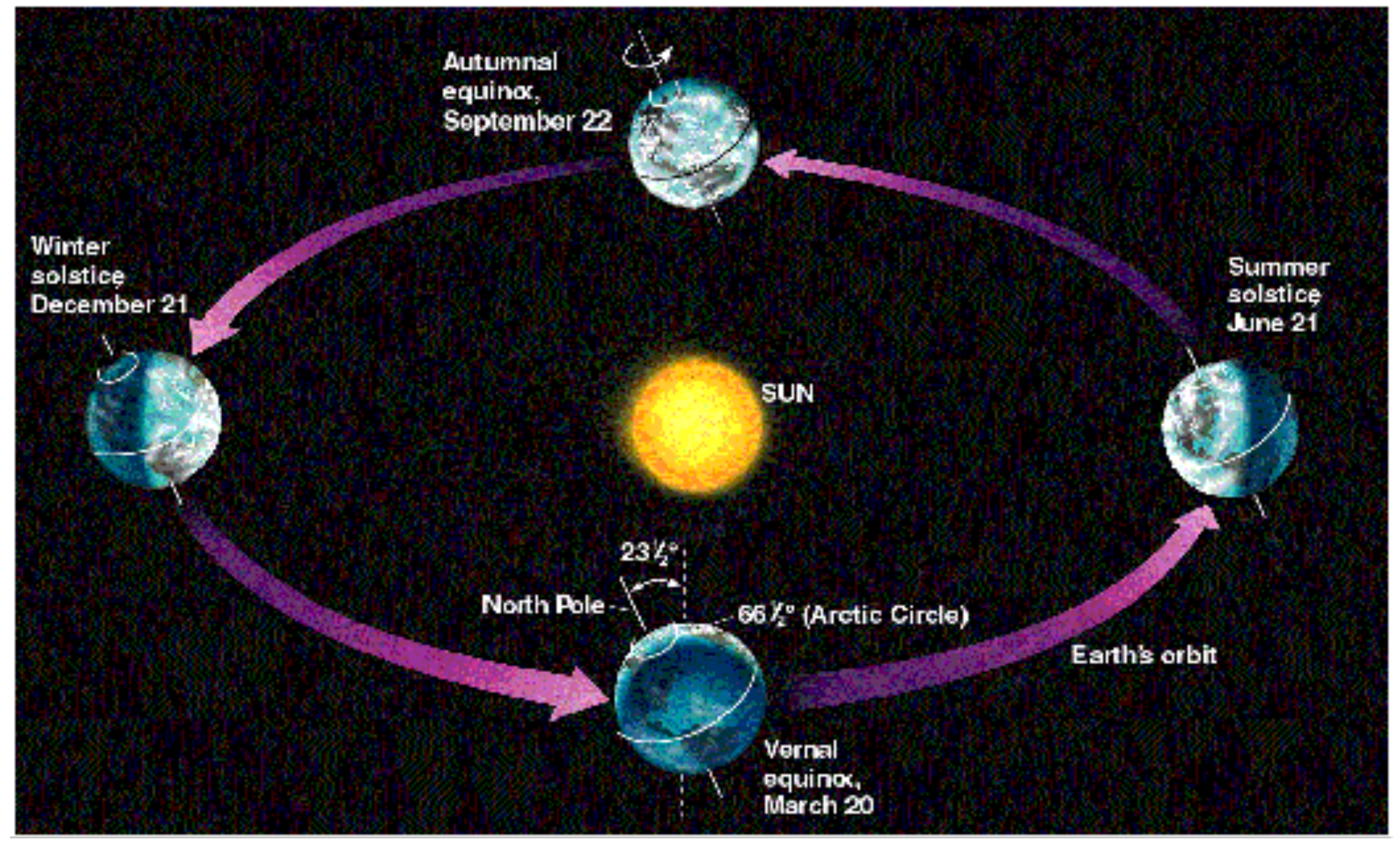
Powers of Ten (1977)
https://www.youtube.com/watch?v=0fKBhvDjuy0

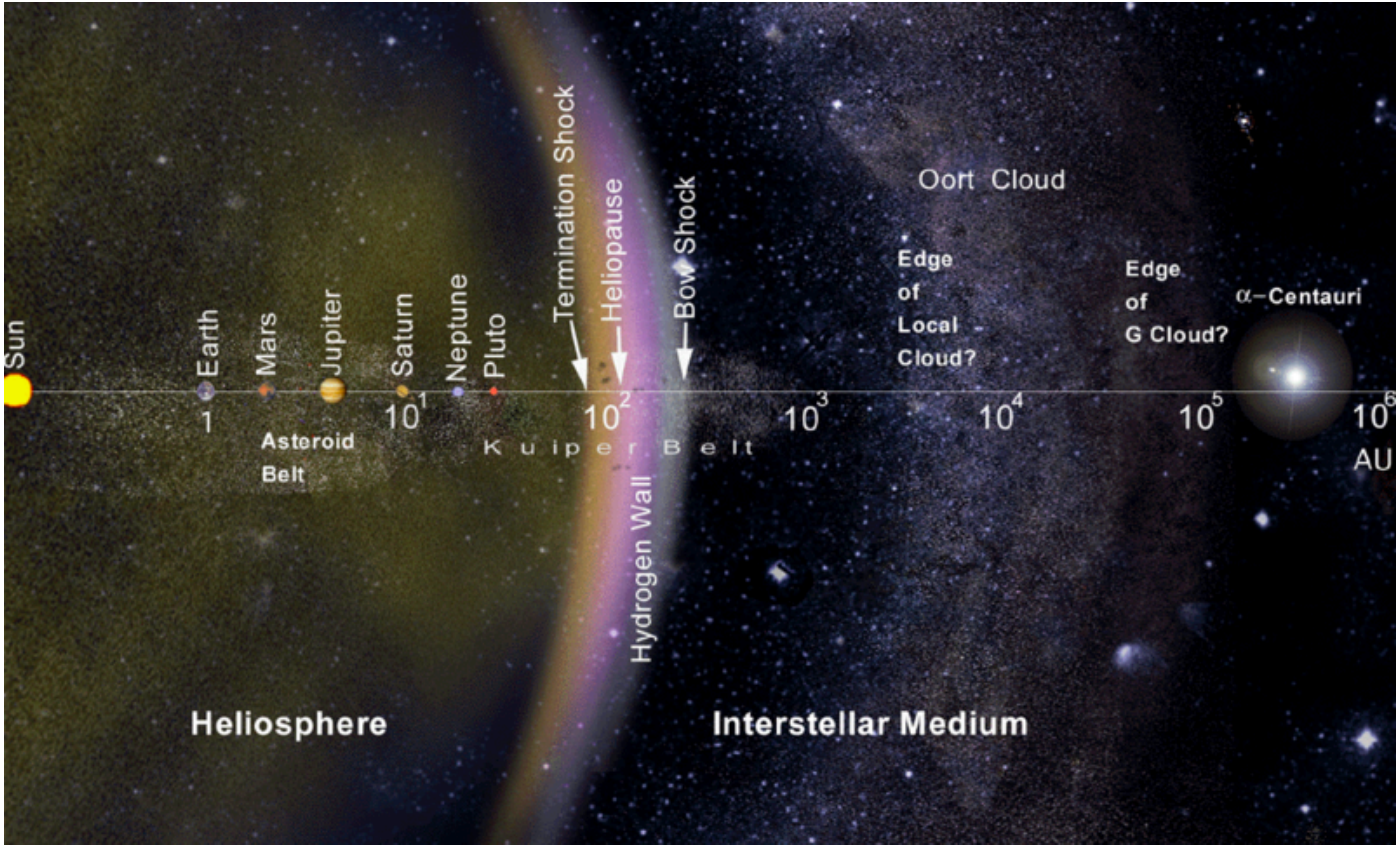
Contact intro (1997)
http://www.youtube.com/watch?v=BsTBbAMikPQ

Scale of the Universe

AU (Astronomical Unit)

1 AU = 1.496×10^{11} m
~ 8 light minutes

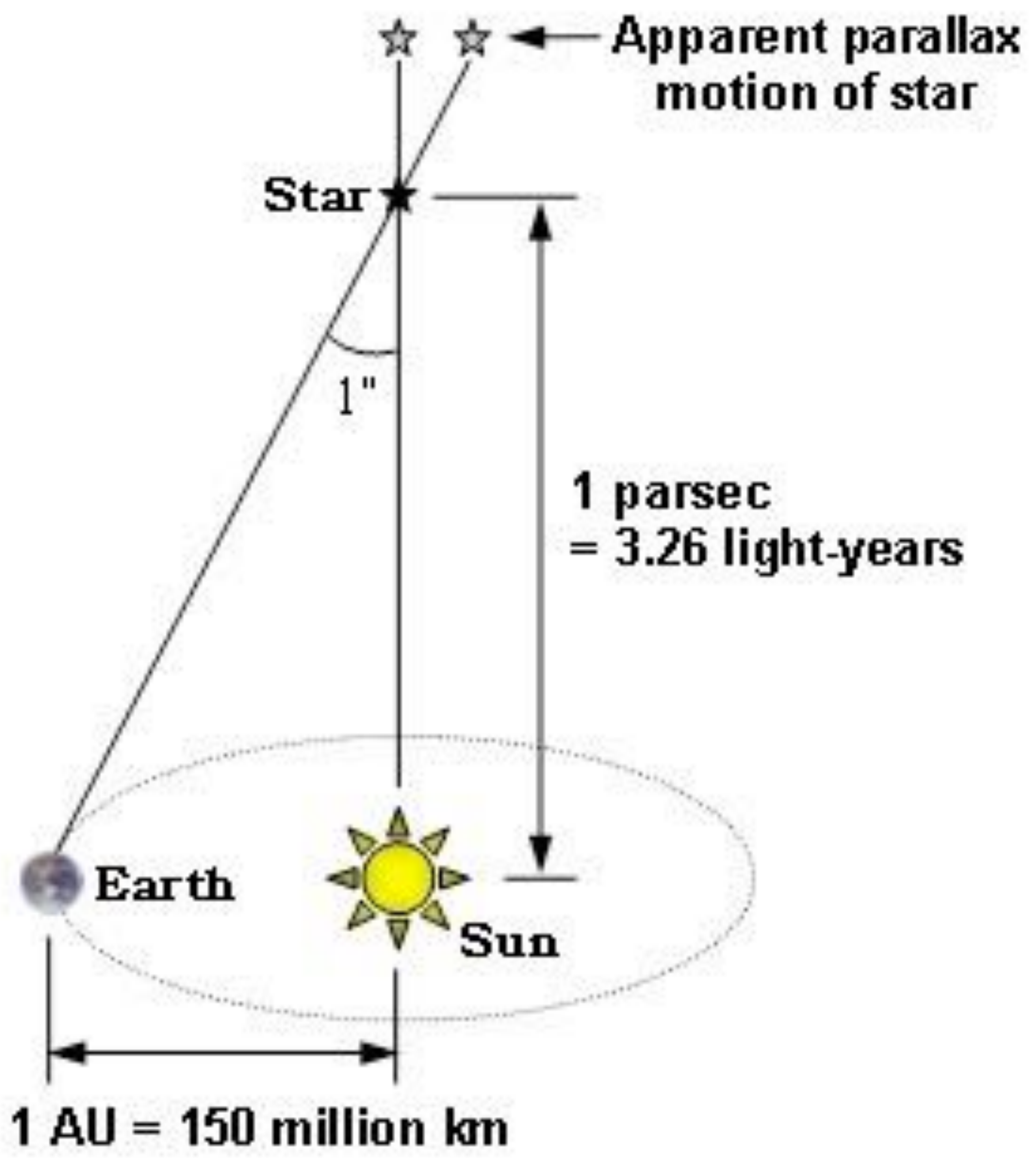


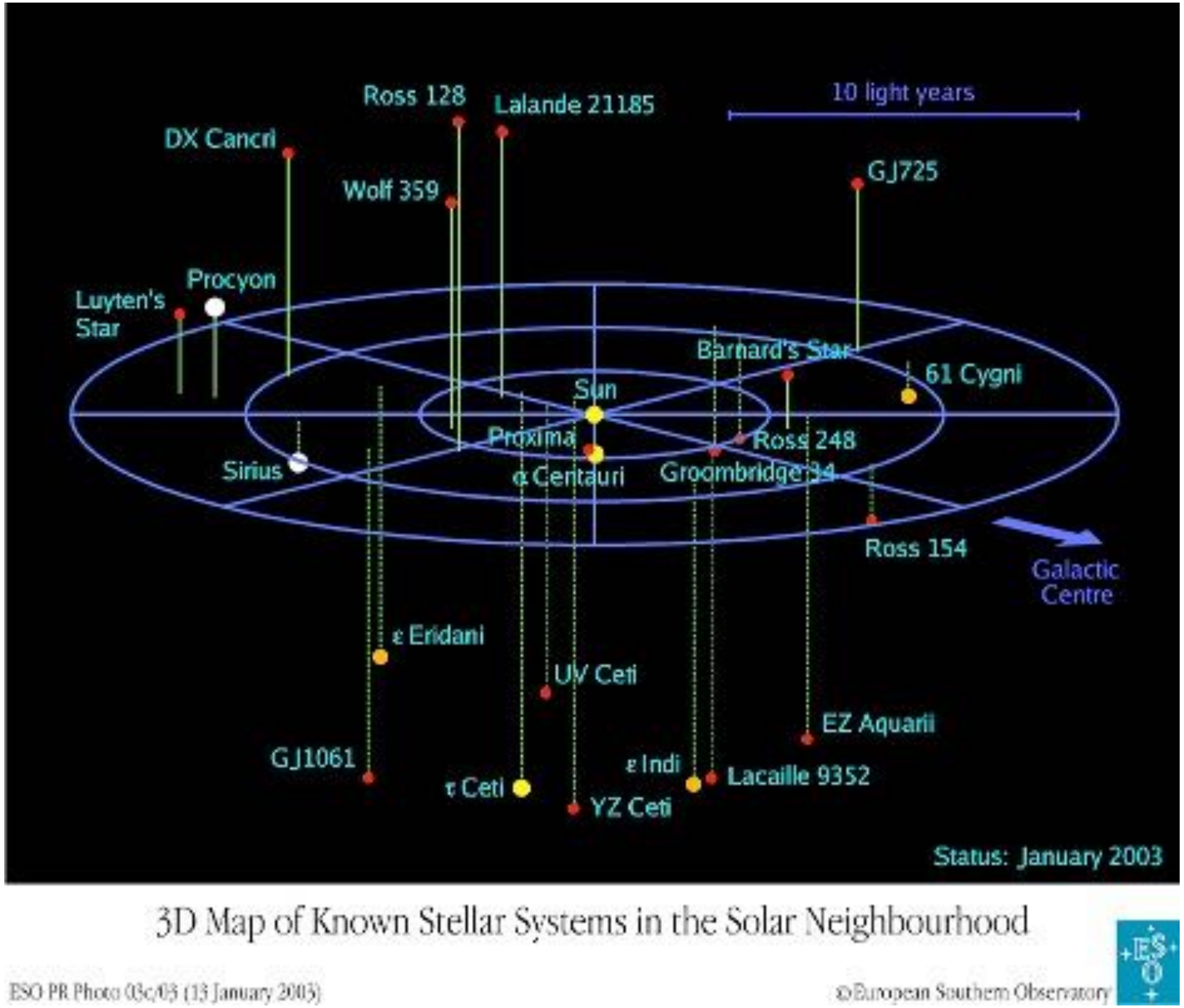


Scale of the Universe

pc (parsec)

1pc = 206265 AU = 3.086×10^{16} m = 3.26 light year

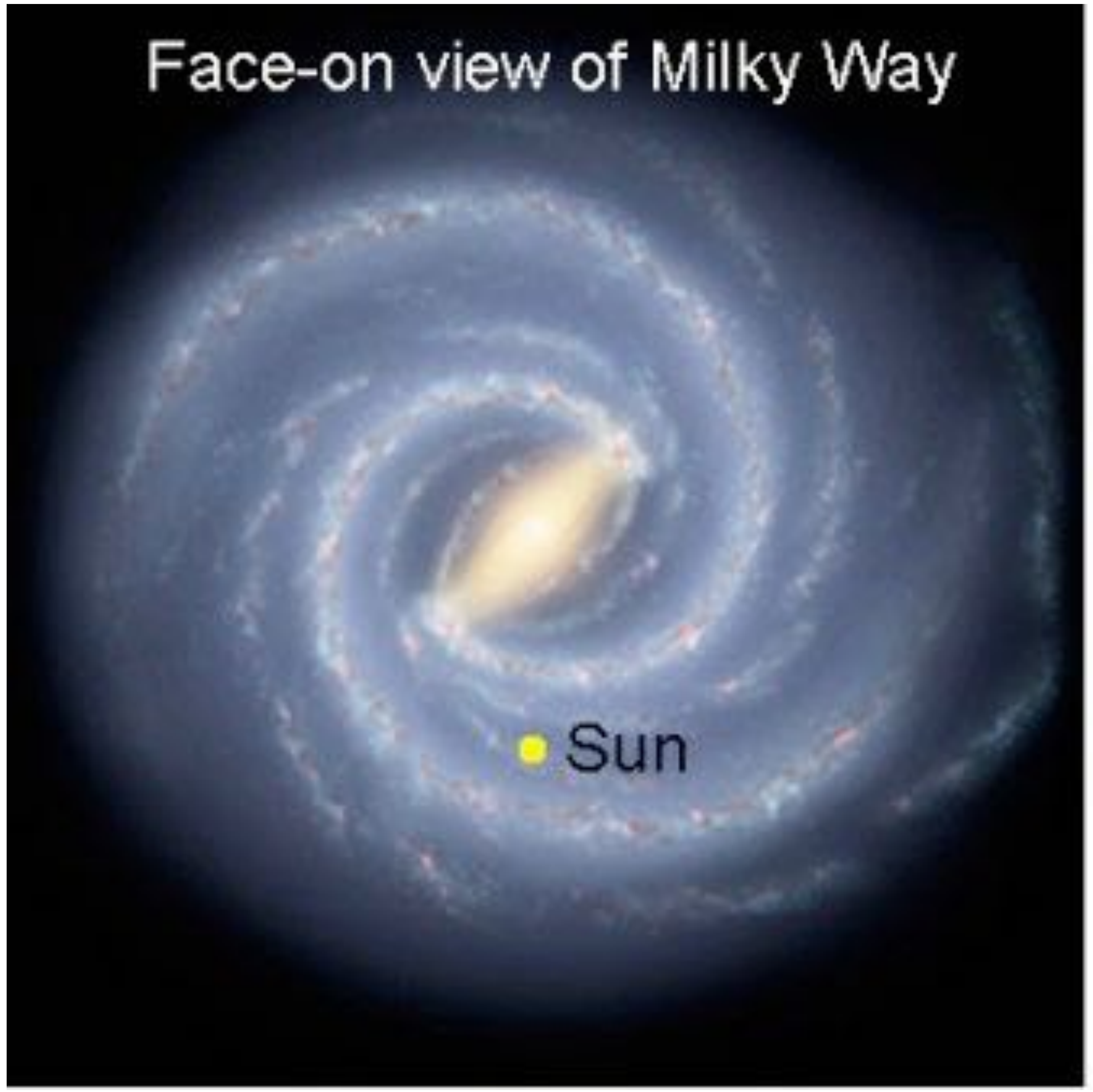


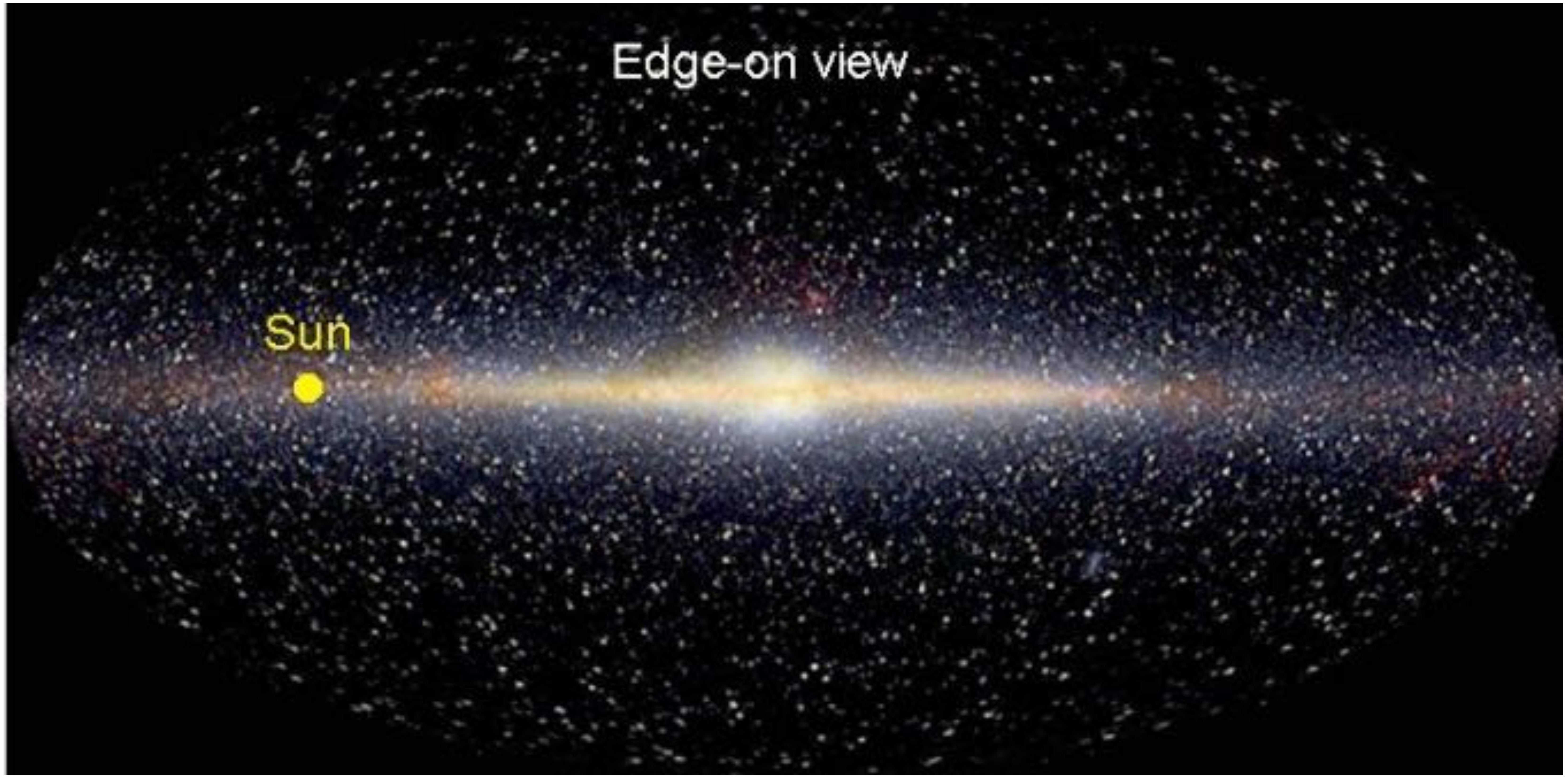


Scale of the Universe

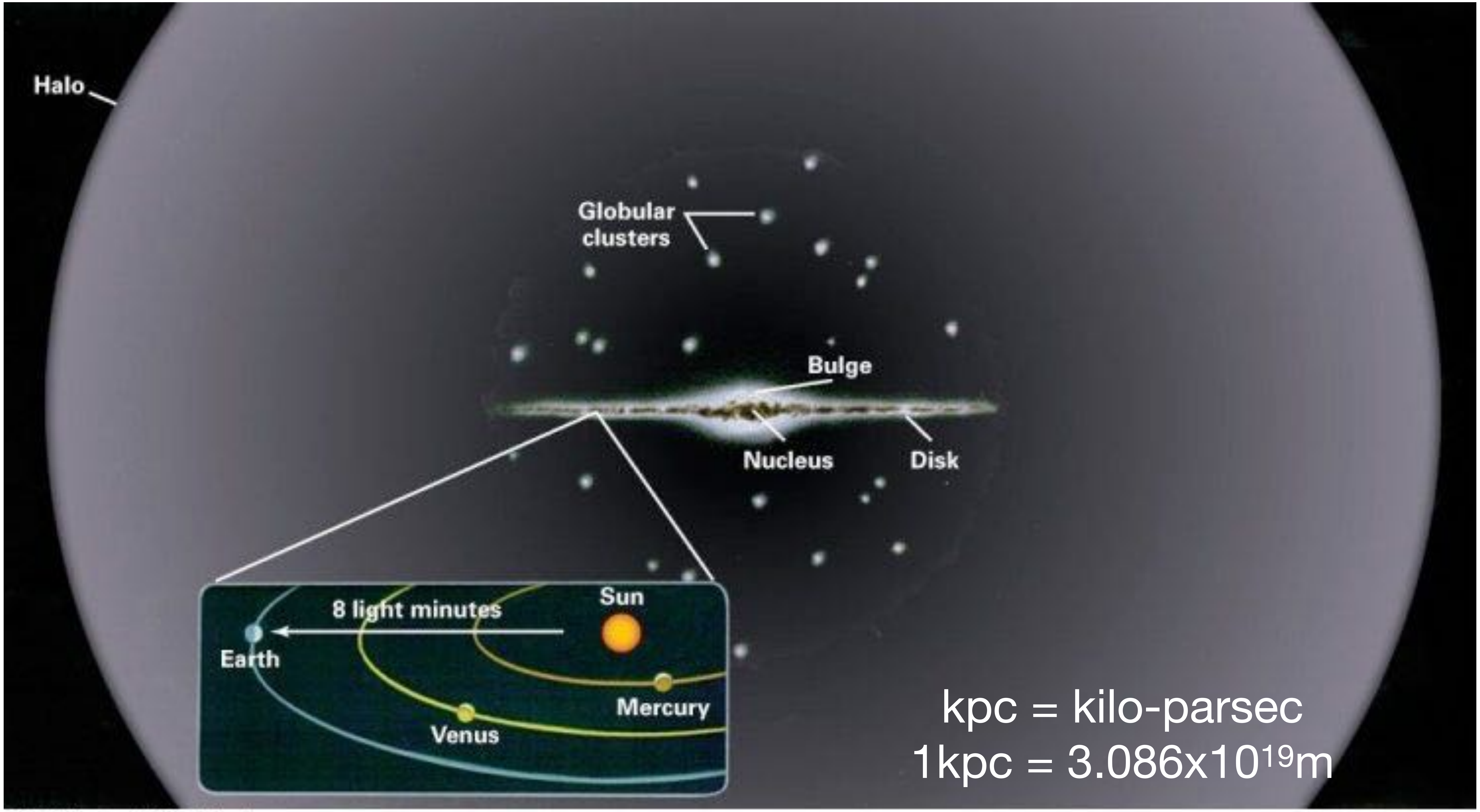
kpc = kilo-parsec

1kpc = 3.086×10^{19}m





Scale of the Universe



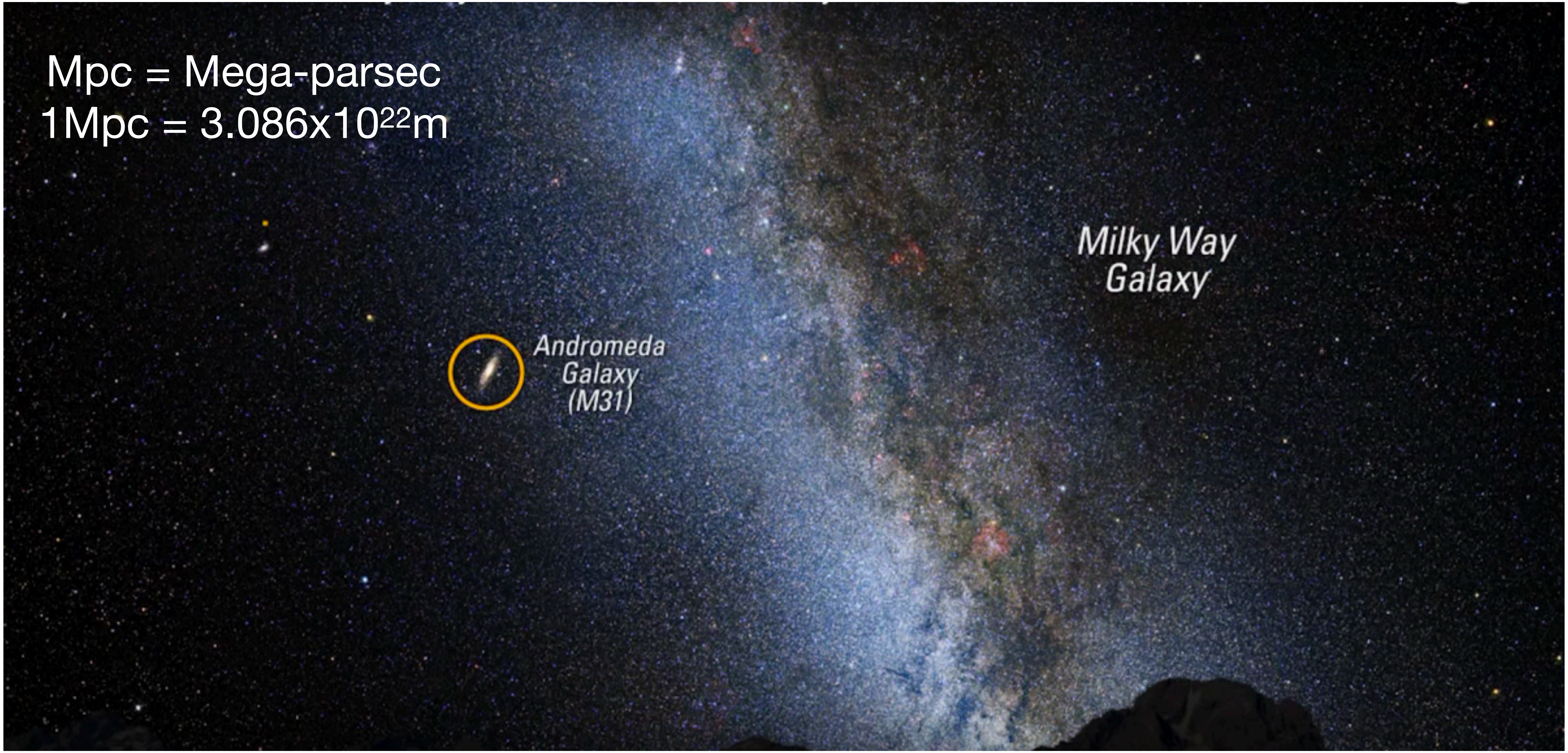
kpc = kilo-parsec

1kpc = 3.086×10^{19}m

Scale of the Universe

Mpc = Mega-parsec

$1\text{Mpc} = 3.086\times10^{22}\text{m}$



Scale of the Universe

Scale of the Universe

Scale of the Universe

Scale of the Universe

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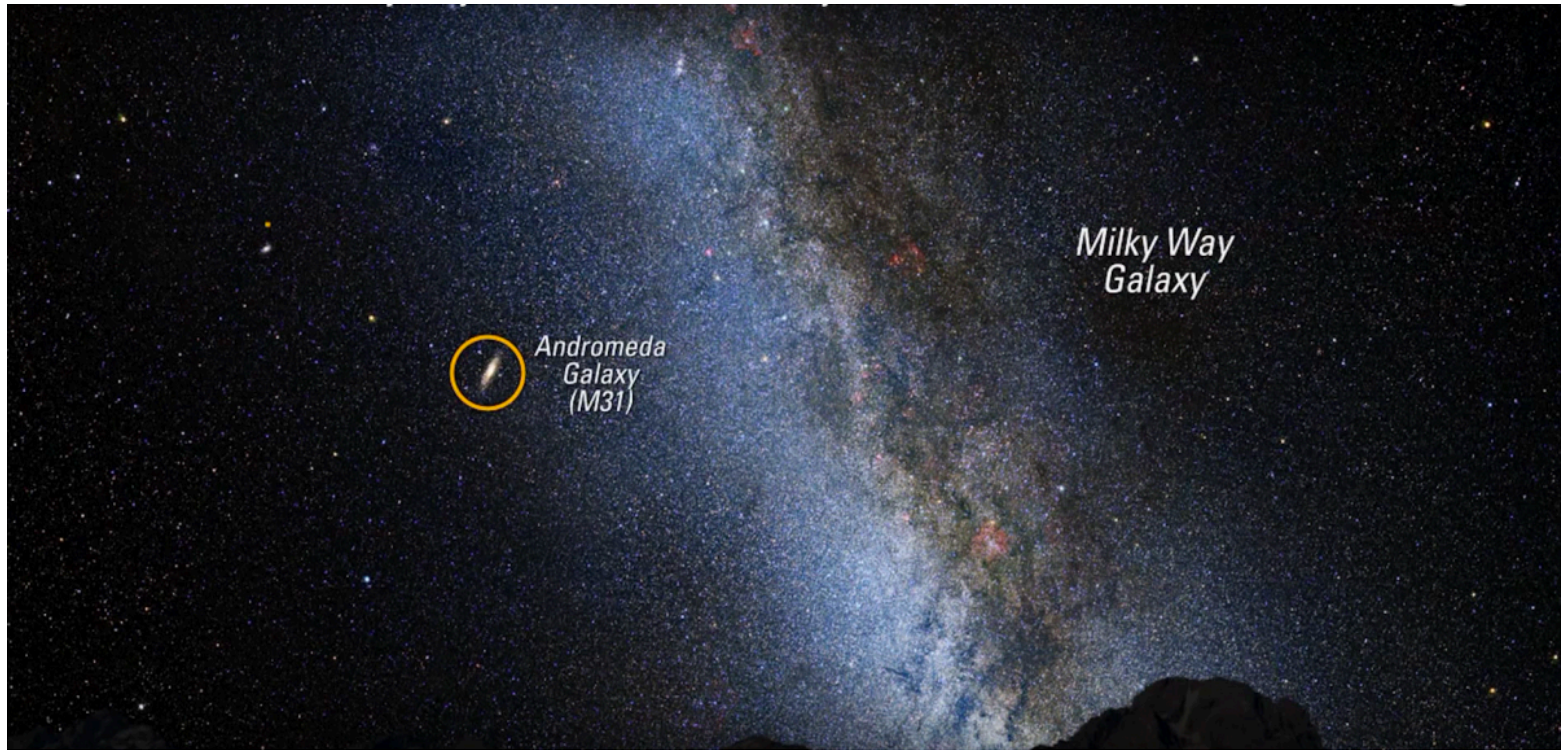
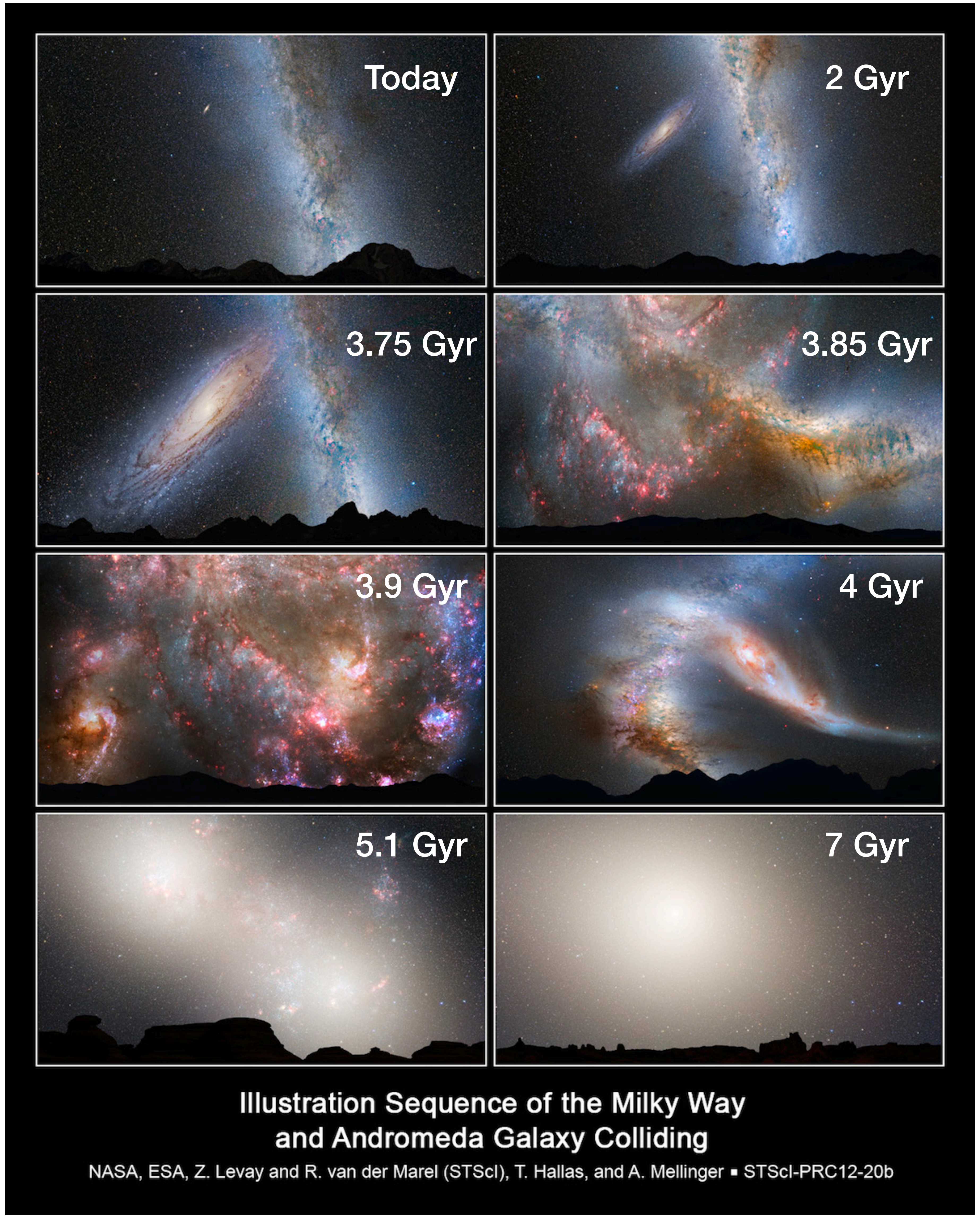
Scale of the Universe

Scale of the Universe

Mpc = Mega-parsec
1 Mpc = 3.086×10^{22} m



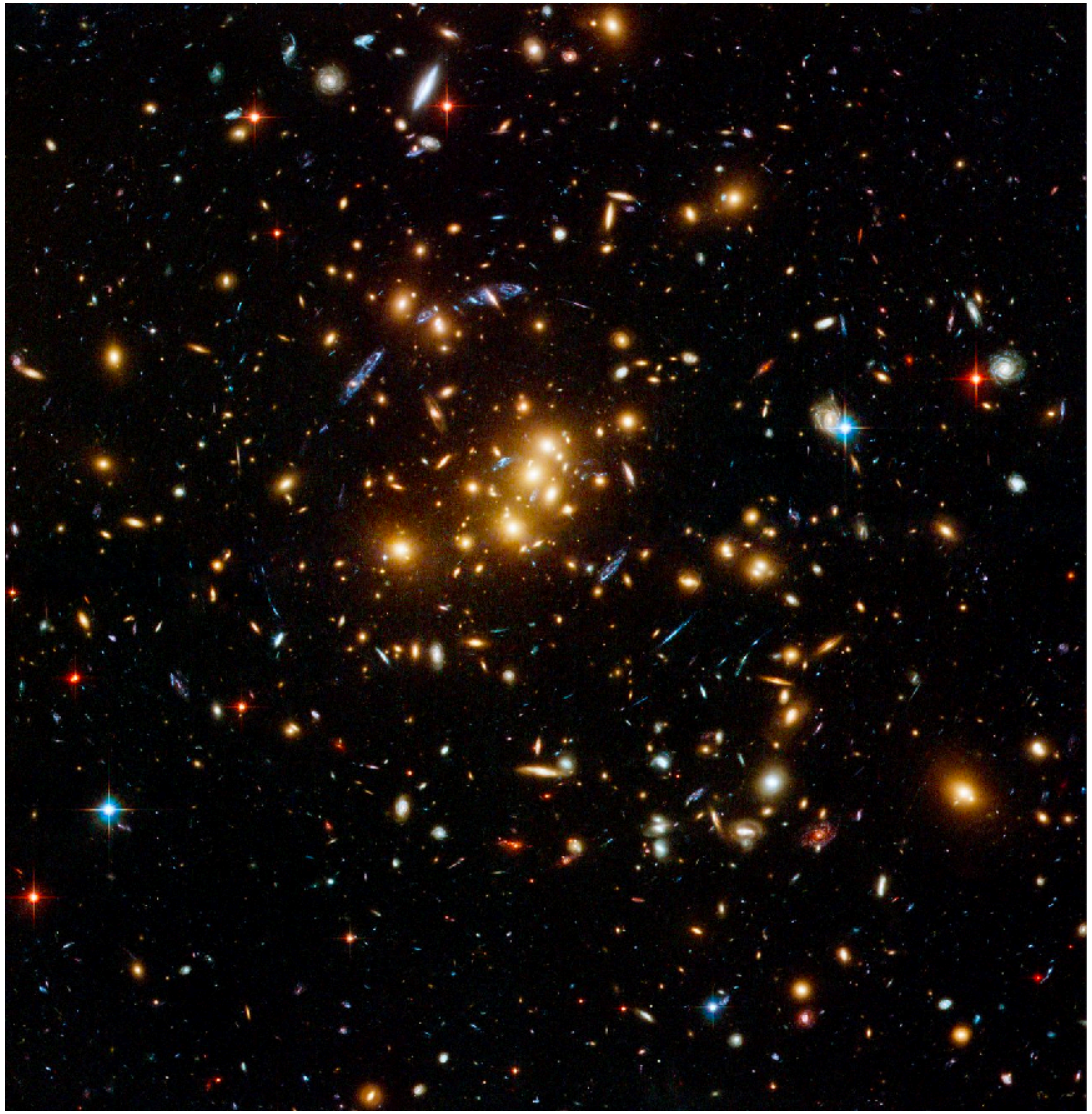
http://phenomena.nationalgeographic.com/2014/03/24/scientists-predict-our-galaxys-death/



Scale of the Universe

Mpc = Mega-parsec

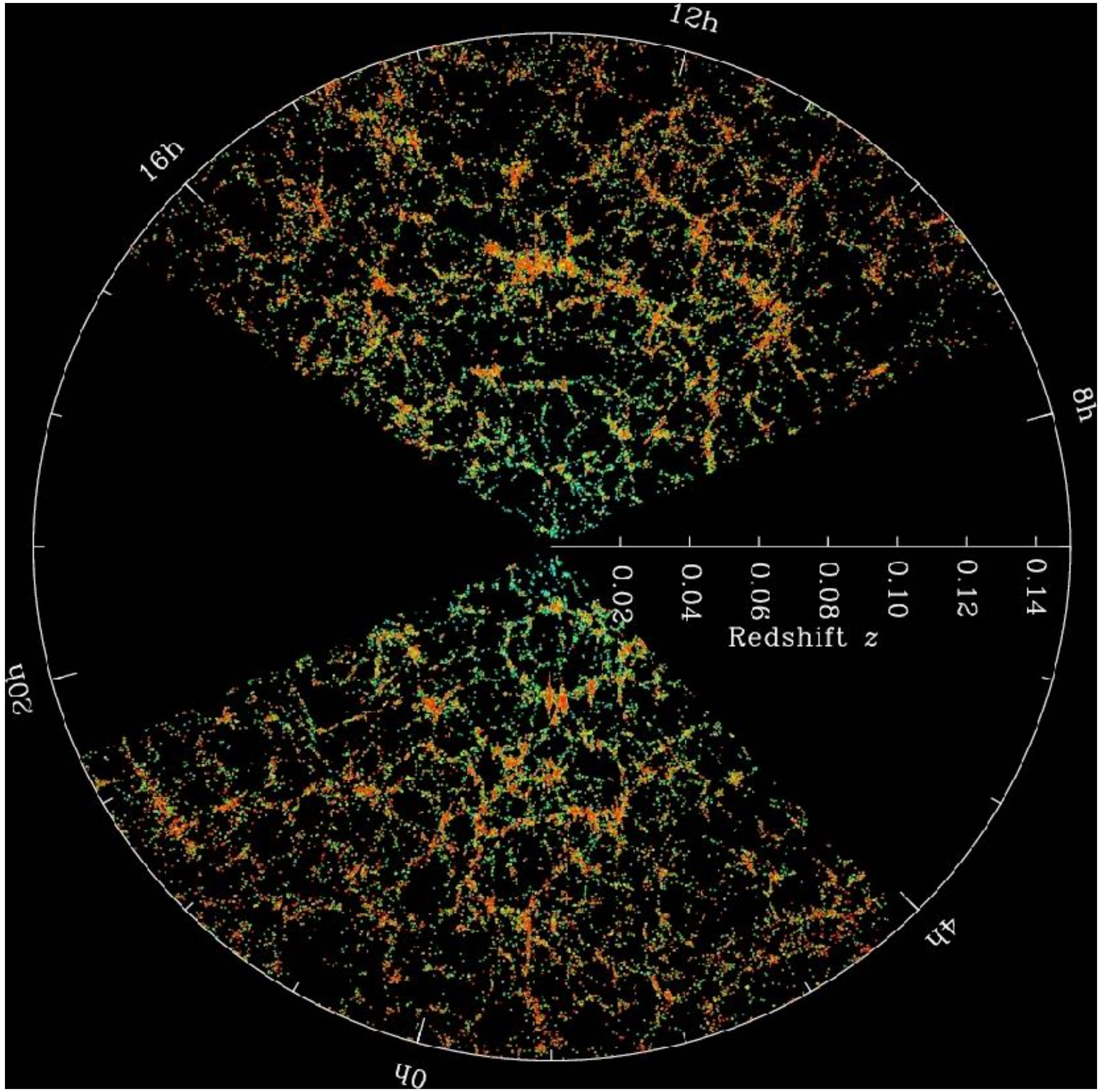
1 Mpc = 3.086×10^{22} m



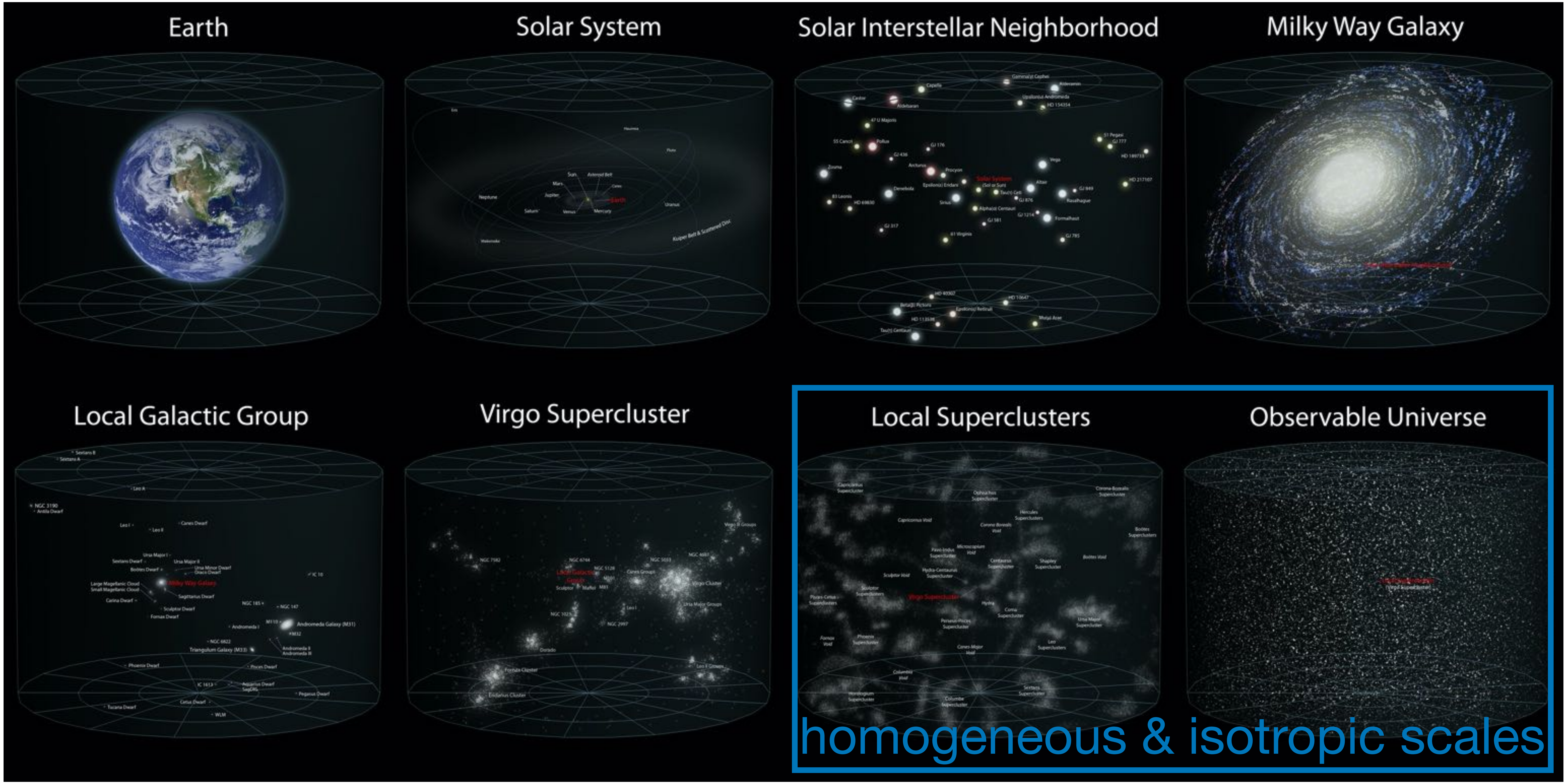
Scale of the Universe

Gpc = Giga-parsec

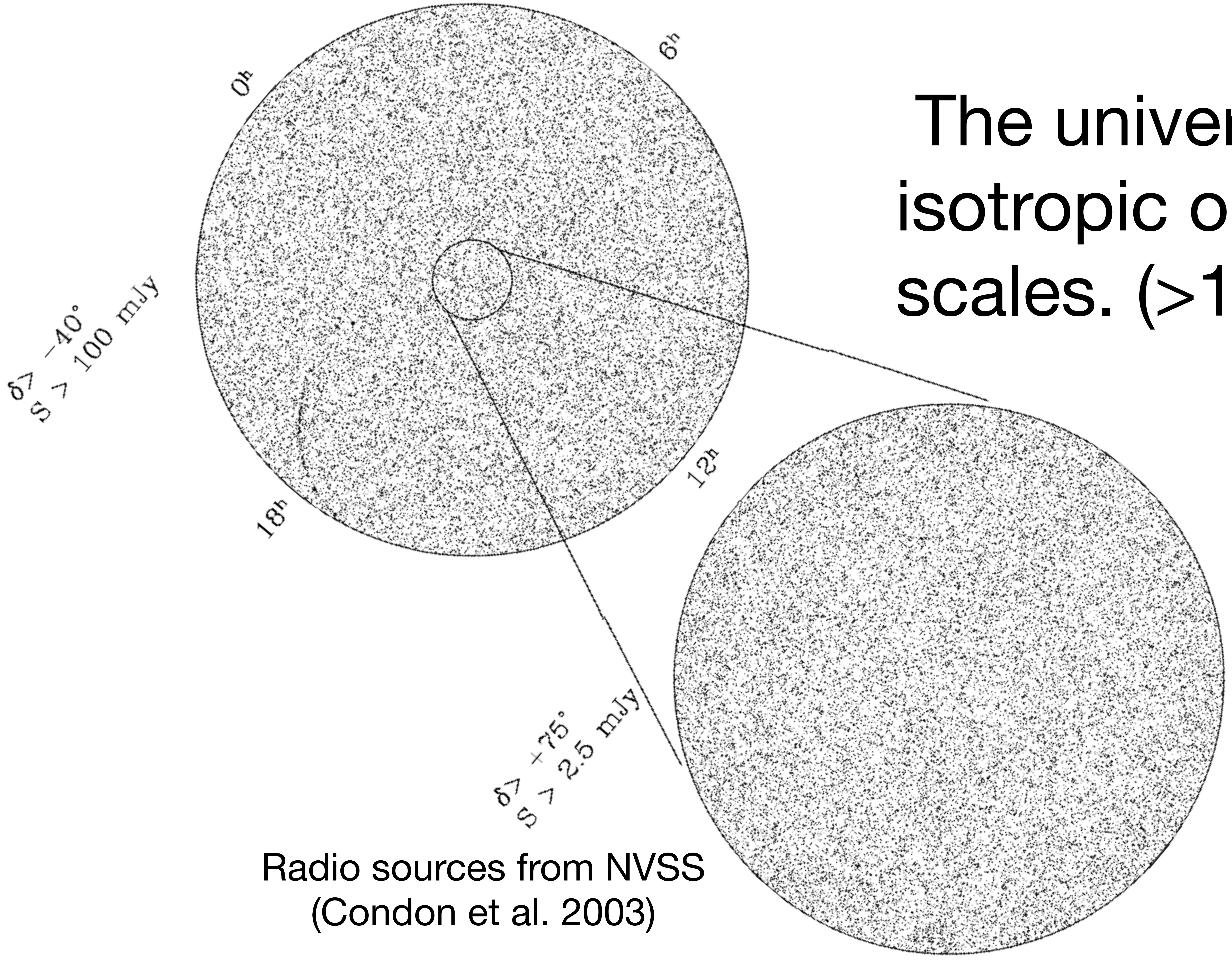
1 Gpc= 3.086×10^{25} m



Scale of the Universe



Cosmological Principle



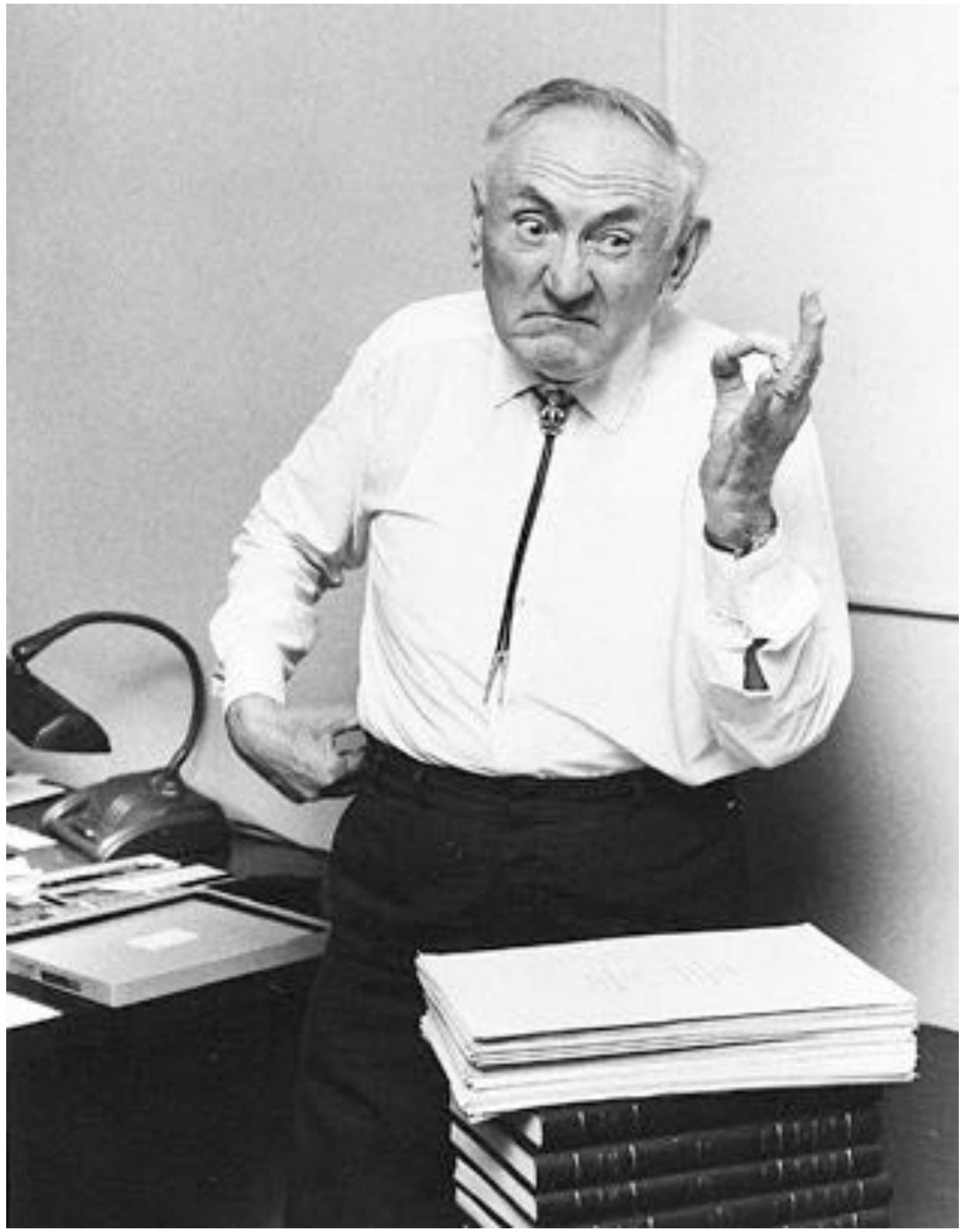
The universe is isotropic on very large scales. (>100 Mpc).

Copernican Principle
=> homogeneous & isotropic

(Cosmological Principle)

Radio sources from NVSS
(Condon et al. 2003)

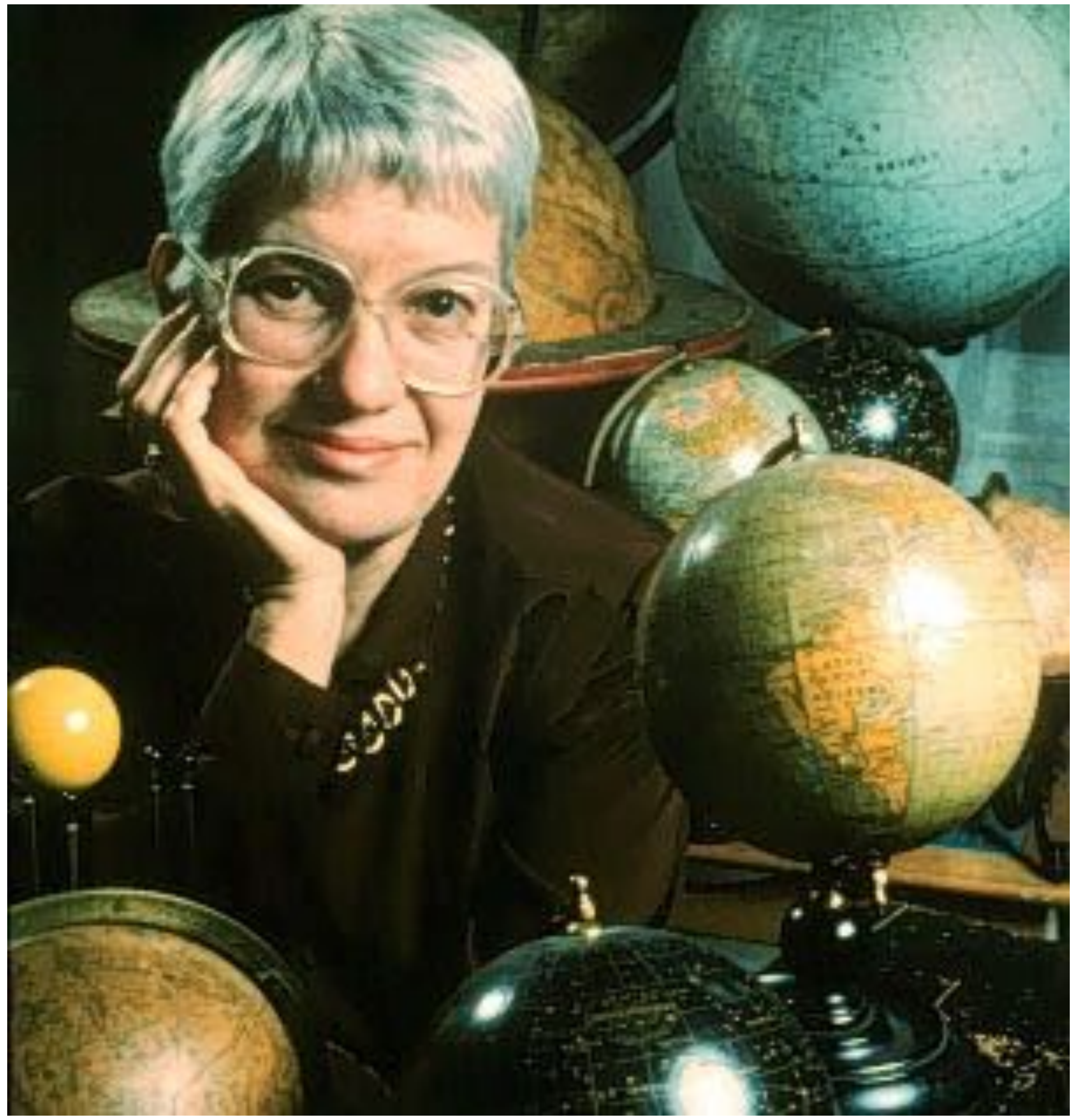
First Evidence of Dark Matter



1932: Need extra, non-luminous matter in the Milky Way to explain rotation (Jan Oort)

1933: Need dunkle materie to bound galaxies in galaxy clusters (Fritz Zwicky)

1970s: Vera Rubin and others showed dark matter necessary to explain galaxy rotation curves



Hot Big Bang Theory

1948: George Gamow, Ralph Alpher, Robert Herman extrapolate expansion back to very early times: predict element synthesis (formation of H and He, from primordial neutron soup)
[$\alpha\beta\gamma$ paper (Hans Bethe added for fun)]

—> primordial radiation as a result, the existence of cosmic background radiation

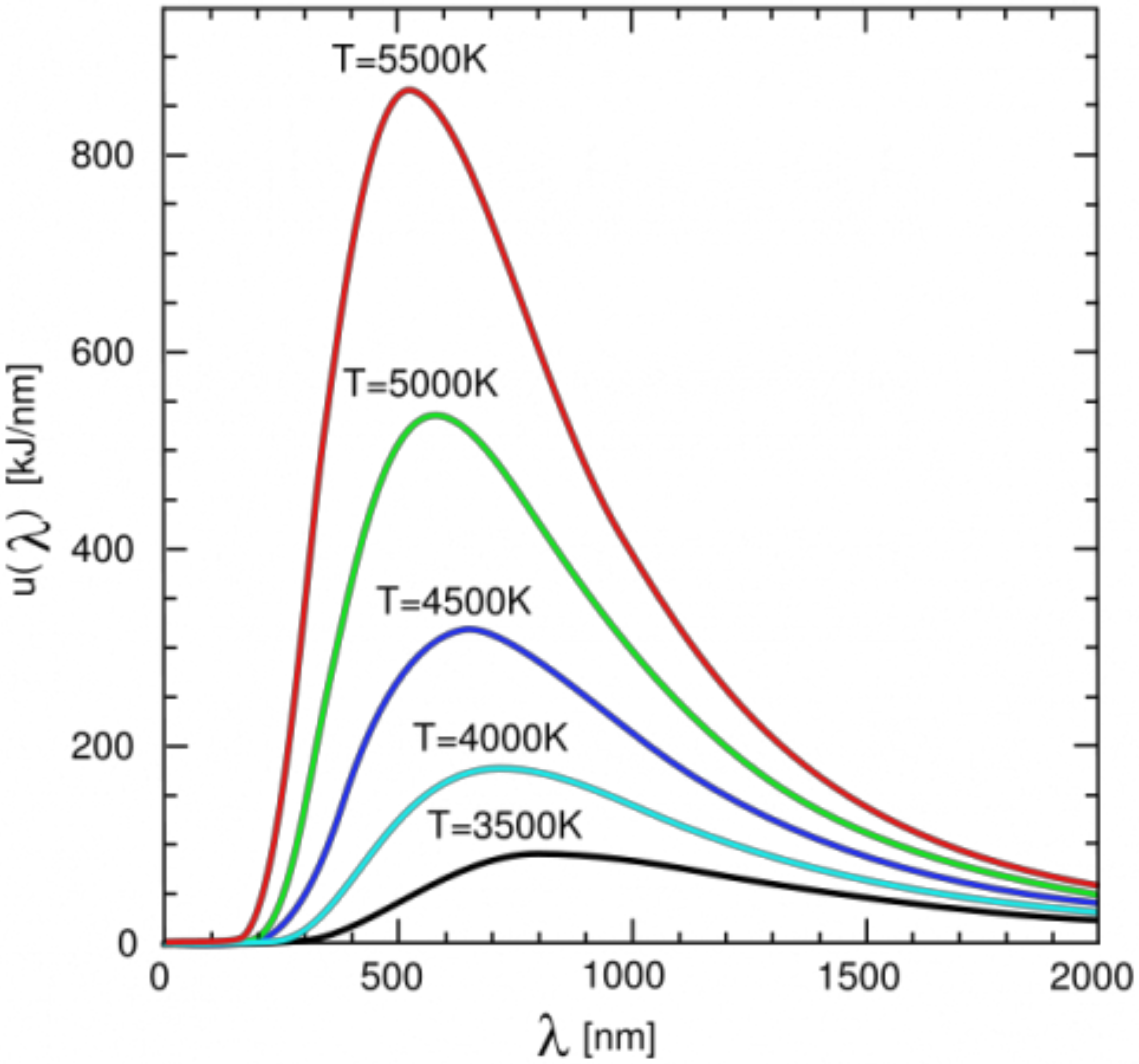
1948: Hermann Bondi, Thomas Gold, and Fred Hoyle, steady state cosmology from perfect cosmological principle

1950: Fred Hoyle coins term "Big Bang"

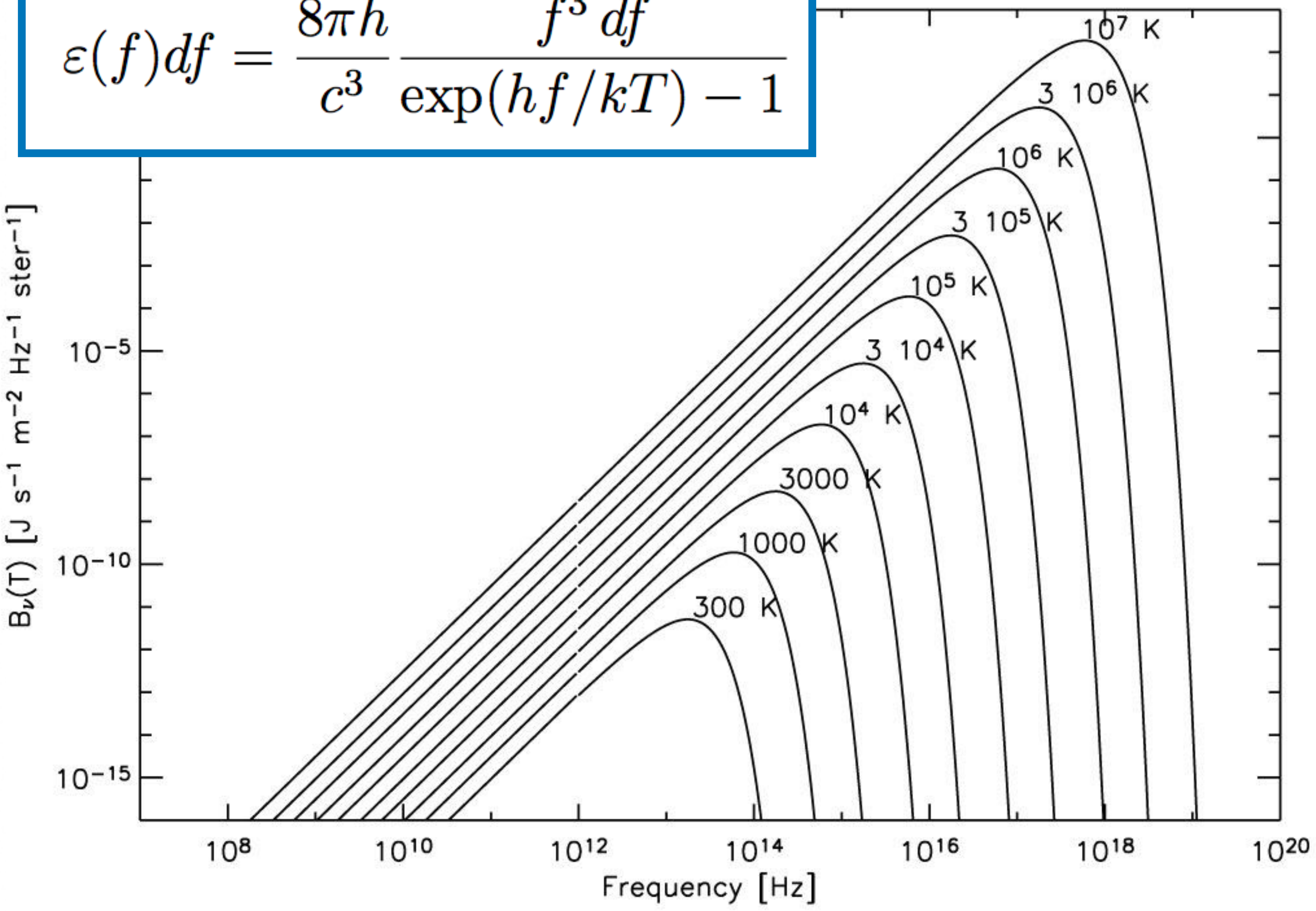
[Whiteboard!]

Cosmic Radiation

[Whiteboard!]



$$\varepsilon(f)df = \frac{8\pi h}{c^3} \frac{f^3\, df}{\exp(hf/kT) - 1}$$



Big Bang proven over Steady State

Nobel Prize in Physics (1978)

1965: Arno Penzias and Robert Wilson discover of the CMB (by accident)

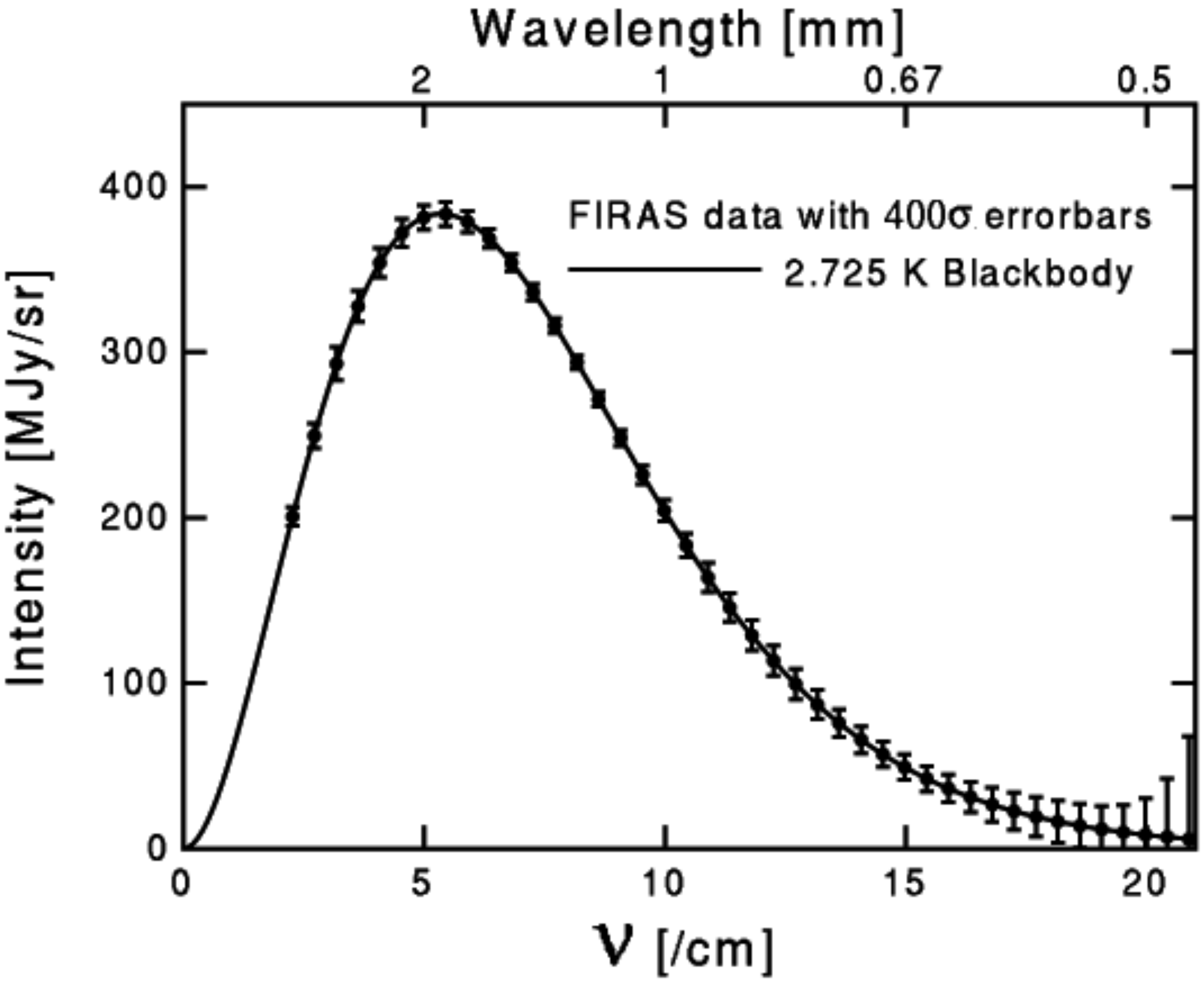
1965: Robert Dicke, James Peebles, Peter Roll, and David Wilkinson, CMB as relic from the Big Bang

CMB -> Perfect Blackbody

1990: NASA's COsmic Background Explorer (COBE) satellite confirms CMB as nearly perfect isotropic blackbody and discovers the anisotropies.

John Mather & George Smoot

Nobel Prize in Physics (2006)



Further Theoretical/Observational Concordance

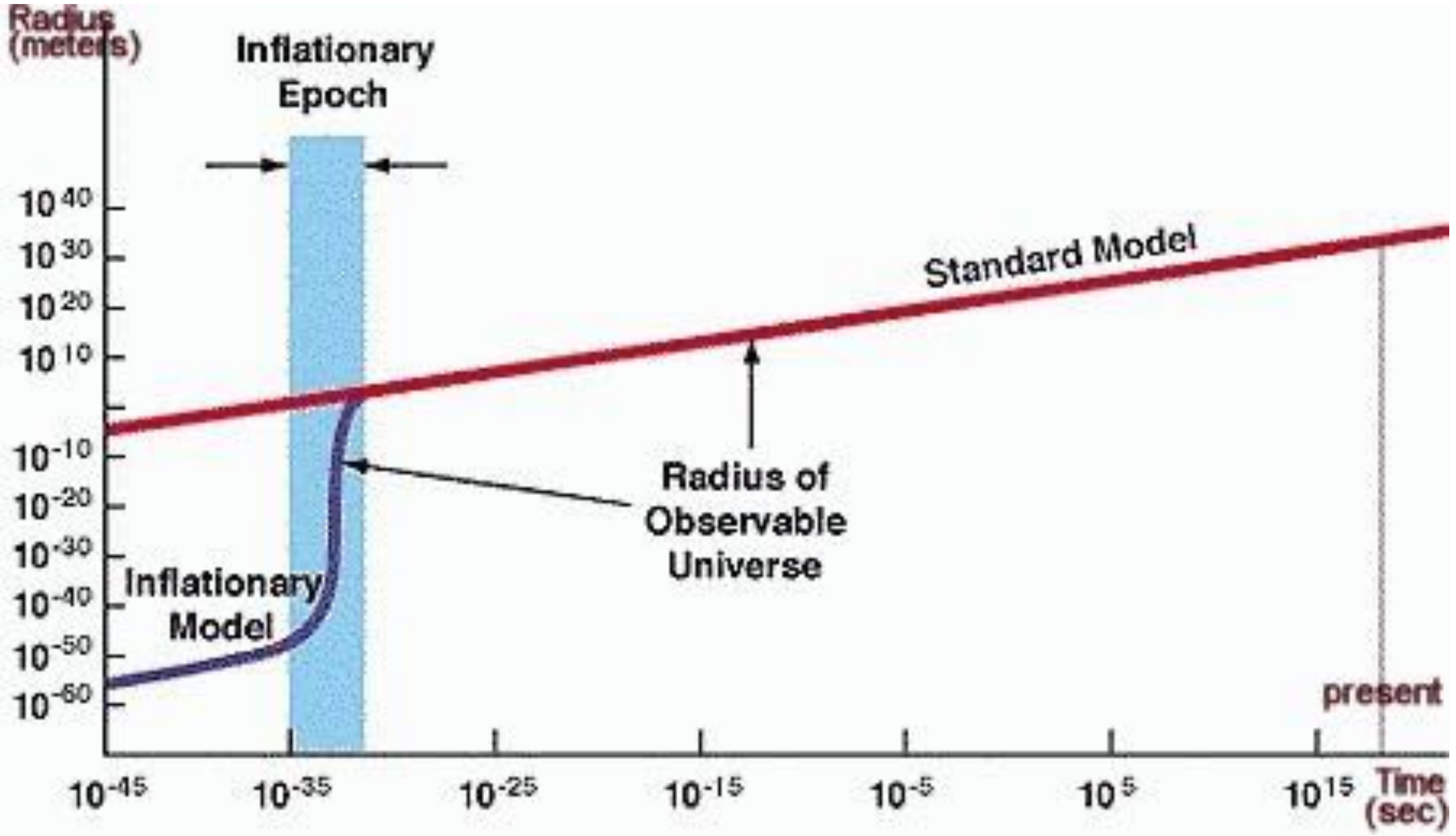
1966: James Peebles shows that the Big Bang predicts the correct helium abundance

1974: Robert Wagoner, William Fowler, and Fred Hoyle work out that the Big Bang predicts the correct deuterium and lithium abundance

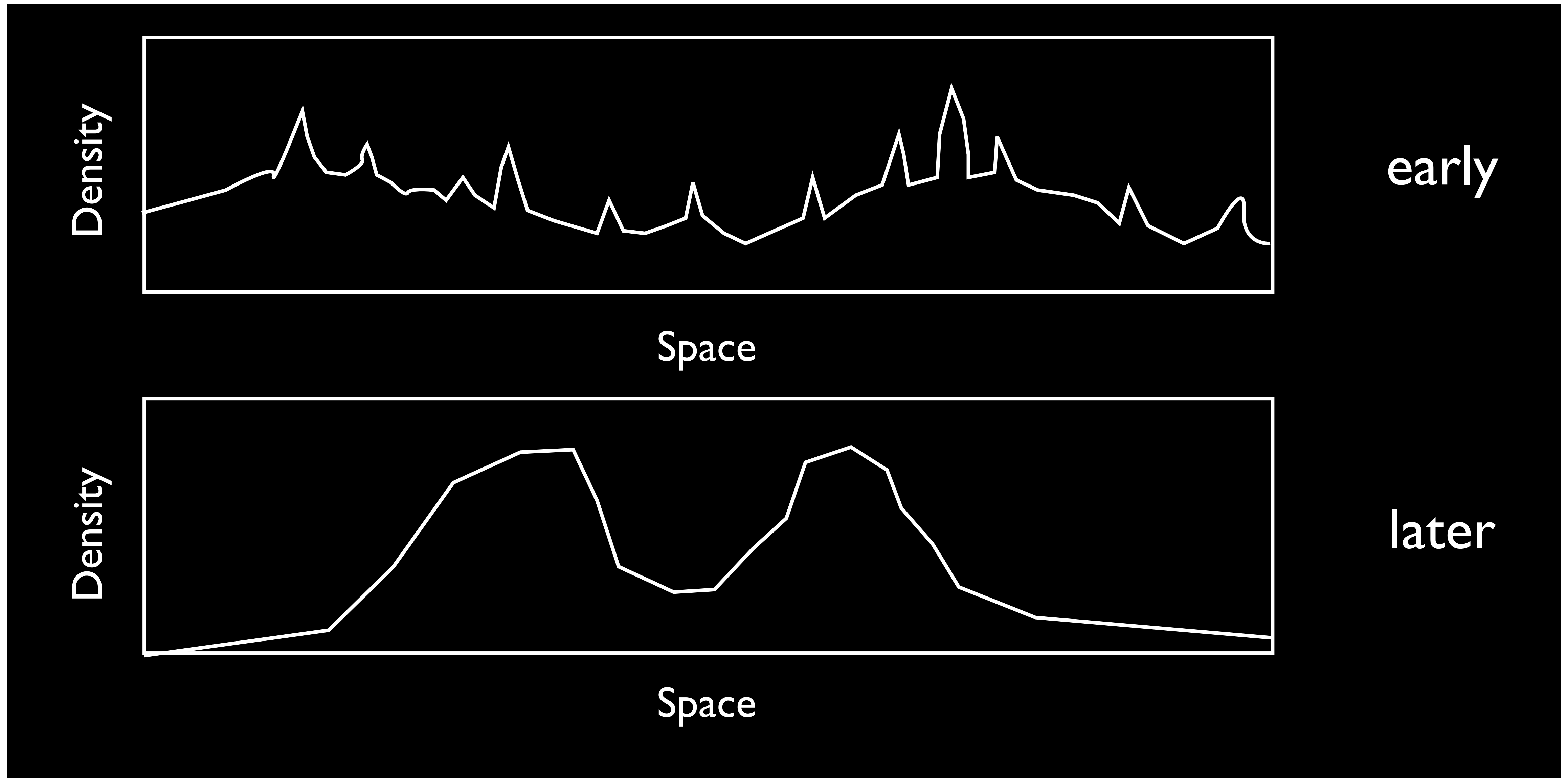
1969: Charles Misner, Big Bang horizon problem (?)
1969: Robert Dicke, Big Bang flatness problem (?)

1981: Viacheslav Mukhanov and G Chibisov, large scale structure from quantum fluctuations in an inflationary universe
1981: Alan Guth, inflation as solution to the horizon and flatness problems

Inflation and Origin of Structure



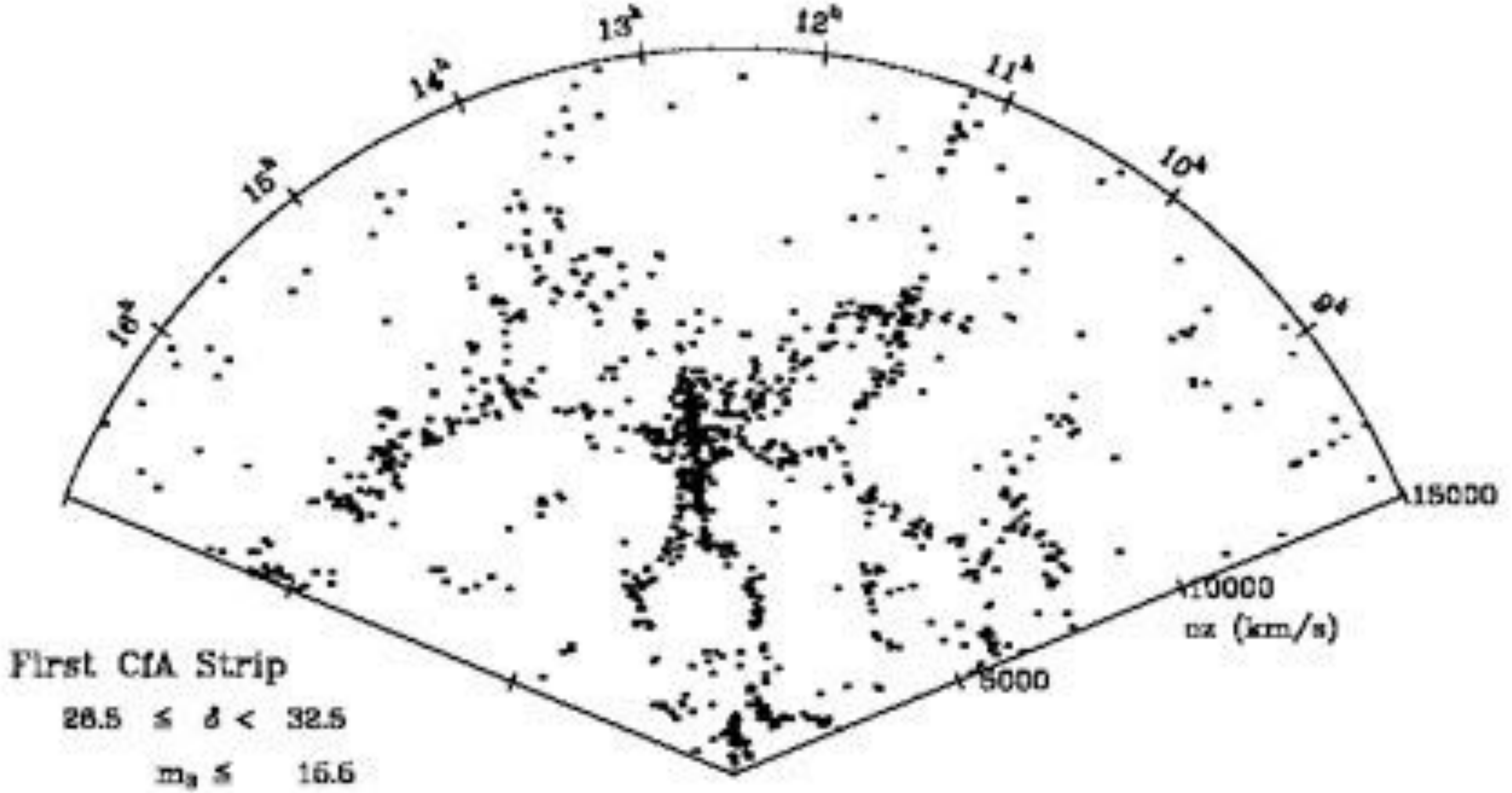
Initial quantum density perturbations amplified by Inflation after the Big Bang.



Called Hierarchical Structure Formation

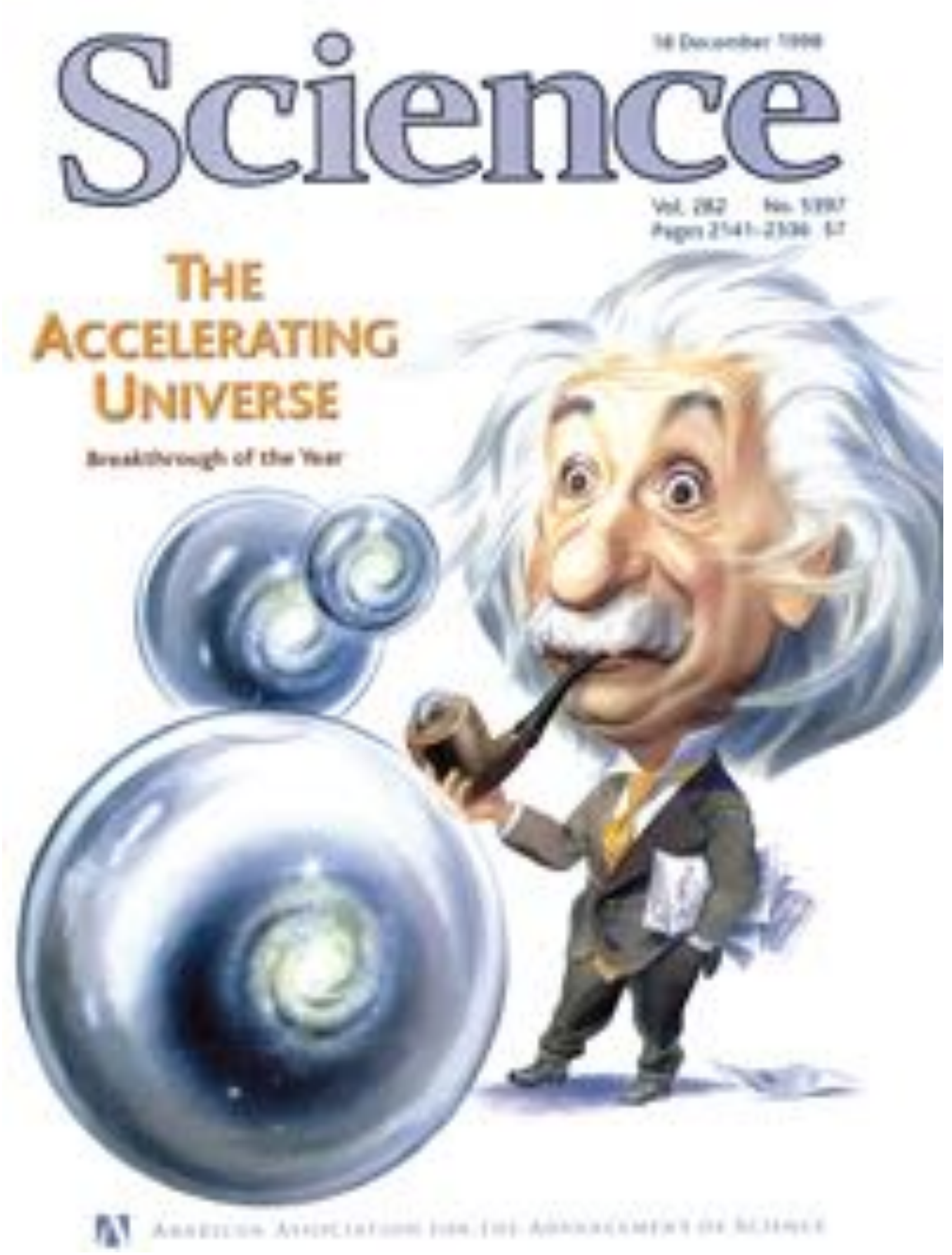
Structure seen in distribution of galaxies

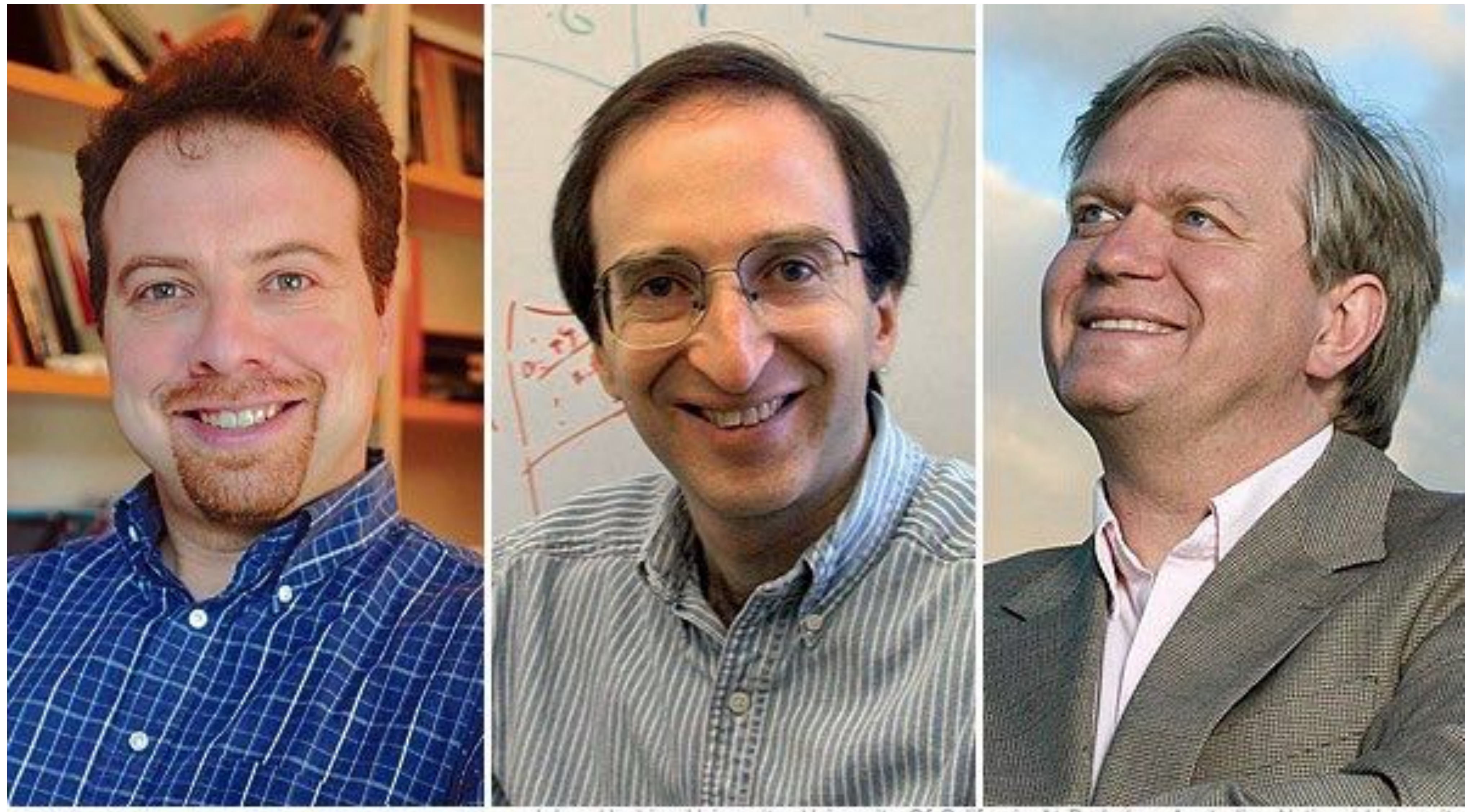
1977-1982: John Huchra, Margaret Geller et al. map galaxy 3D positions with the CfA galaxy redshift survey



Distant galaxies reveal expansion accelerating

1998: discovery that the expansion of the universe is accelerating from Supernova Ia observations (Supernova Cosmology Project and High-z Supernova Team); cosmological constant? dark energy?





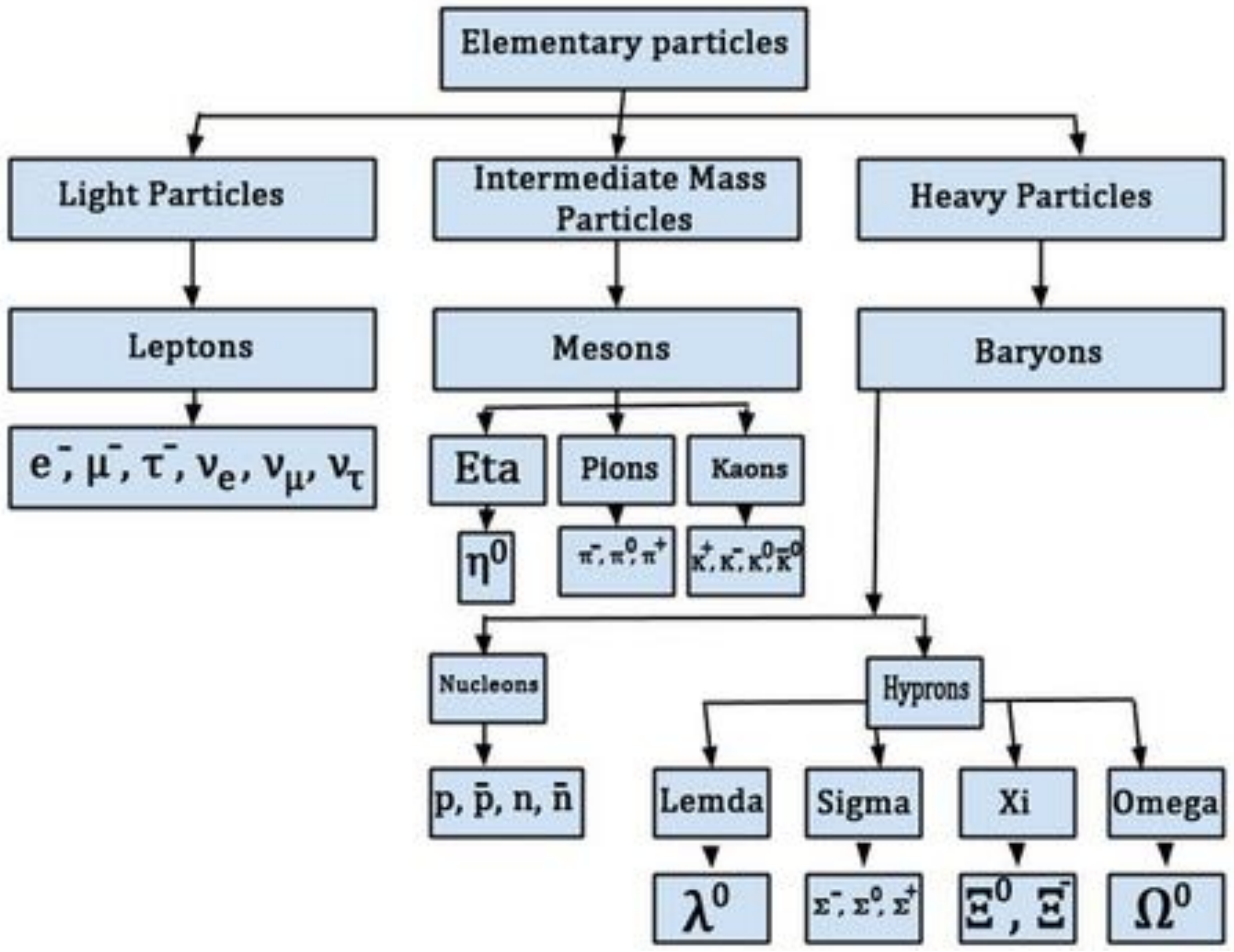
Johns Hopkins University; University Of California At Berkeley; Australian National University

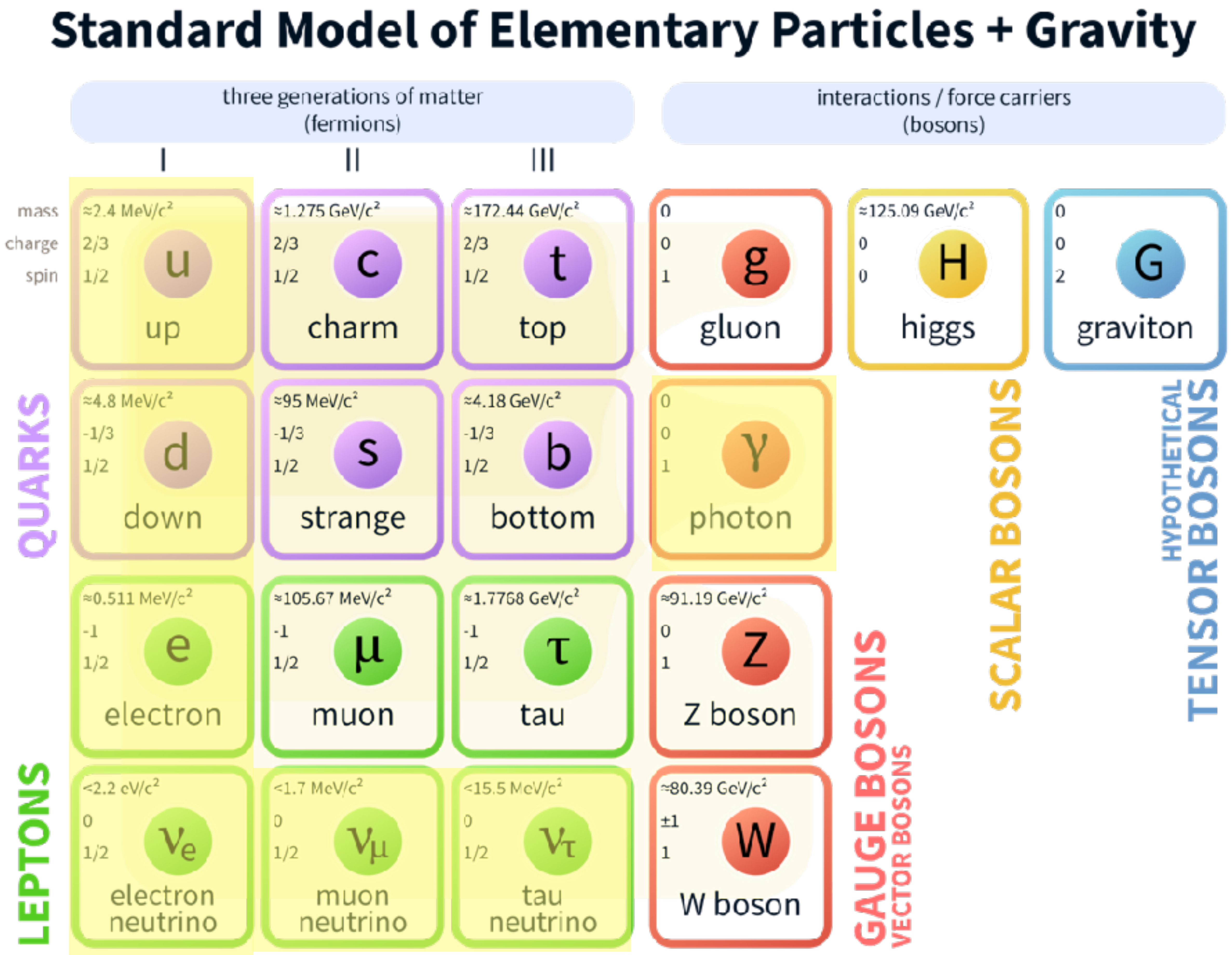
From left, Adam Riess, Saul Perlmutter and Brian Schmidt shared the Nobel Prize in physics awarded Tuesday.

Nobel Prize in Physics (2011)

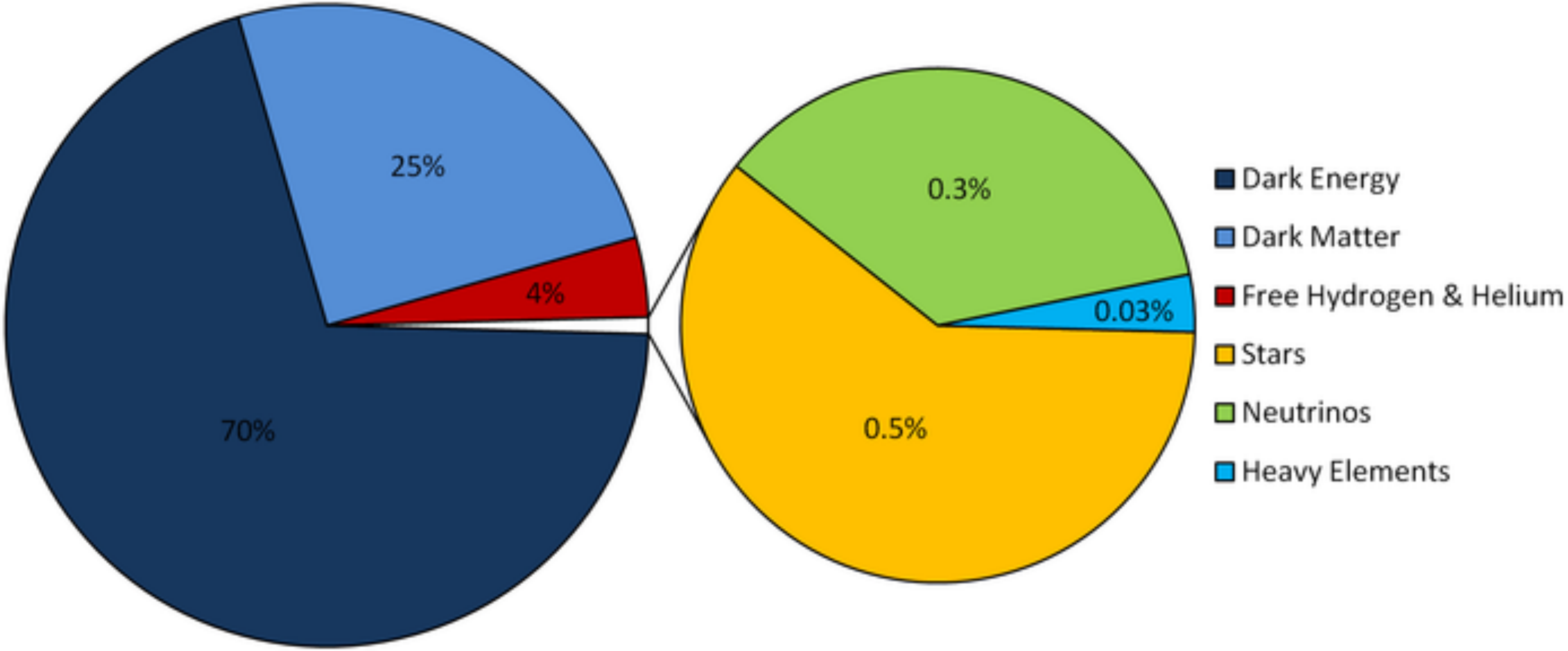
Elementary Particles

particle	symbol	rest energy (MeV)	charge
proton	p	938.3	+1
neutron	n	939.6	0
electron	e^-	0.511	-1
neutrino	ν_e,ν_μ,ν_τ	?	0
photon	γ	0	0
dark matter	?	?	0

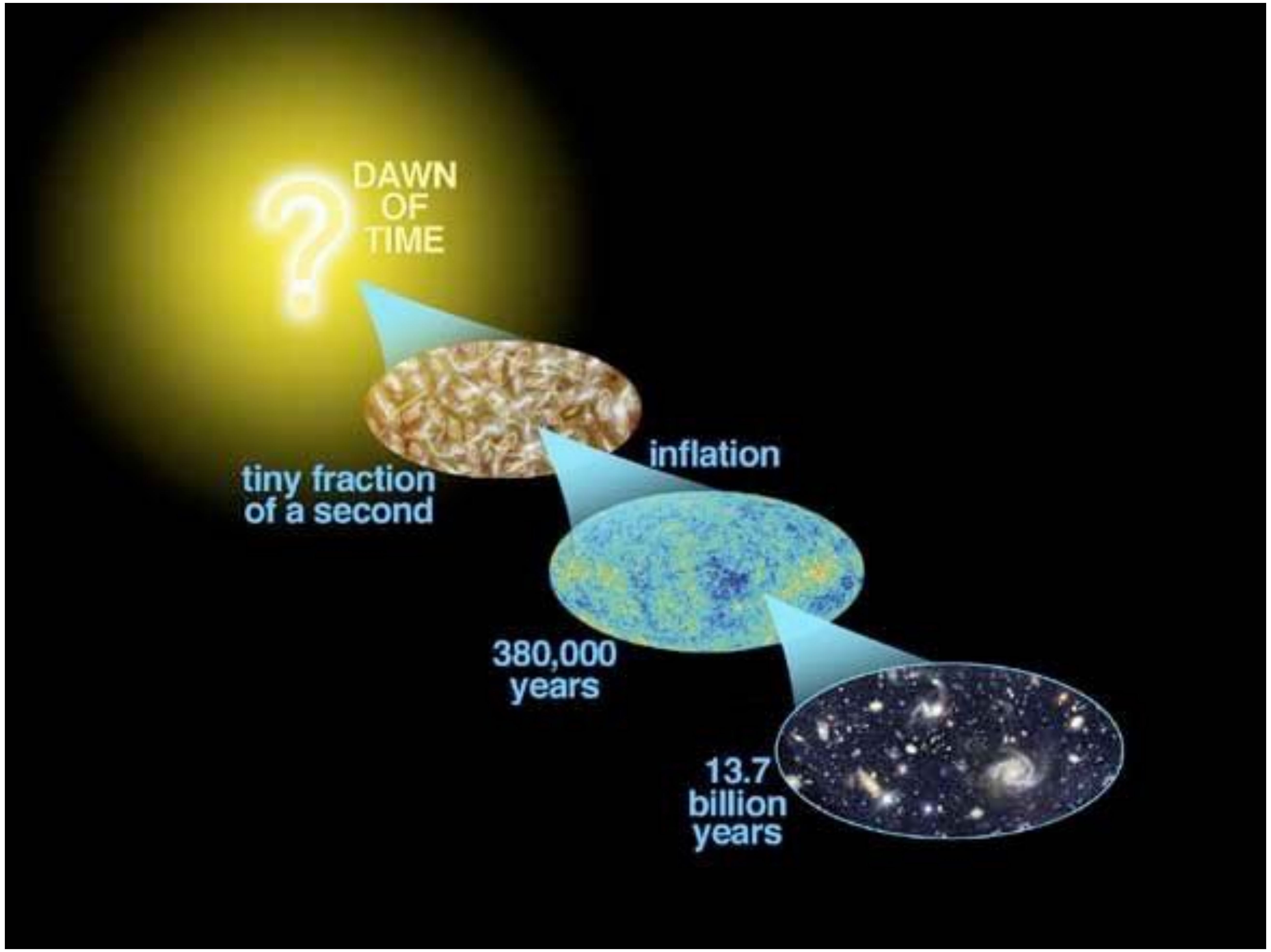




Relative Contents of Universe



Evolution of the Universe



Age of the universe: 13.7 Gyr = 4.3×10^{17} s

Planck time: $t_P \equiv \sqrt{\frac{\hbar G}{c^5}} \approx 5.39106(32) \times 10^{-44}$ s

Early Universe (Fundamental) Scales

Planck time: $t_p \equiv \left(\frac{G\hbar}{c^5}\right)^{1/2} = 5.4 \times 10^{-44}\mathrm{s}$

Planck length: $l_p \equiv \left(\frac{G\hbar}{c^3}\right)^{1/2} = 1.6 \times 10^{-33}\mathrm{cm}$

Planck mass: $M_p \equiv \left(\frac{\hbar c}{G}\right)^{1/2} = 2.2 \times 10^{-5}\mathrm{g}$

Planck energy: $E_p = M_p c^2 = \left(\frac{\hbar c^5}{G}\right)^{1/2} = 1.2 \times 10^{28}\mathrm{eV} = 1.2 \times 10^{19}\mathrm{GeV}$

Planck temperature: $T_p = E_p/k = 1.4 \times 10^{32}\mathrm{K}$

Planck units: $c = k = \hbar = G = 1$

Why Planck scale(s)?

General Relativity (GR) -- classical theory

- describes smooth space and time (or is valid for smooth space-time)
- does not include quantum effect in space-time
- applies to scales where quantum fluctuation << size of interest

At Planck scale, Compton wavelength $h/(M_P\ c) \sim l_p$.

- When the universe is at age $\sim t_p$, horizon scale $\sim ct_p \sim l_p$.
- We need gravity theory to study what's going on at scales of l_p.
- But quantum fluctuation is of order l_p.
- We no longer have smooth space-time.

- GR breaks down.

- We need quantum gravity (unification of GR and Quantum physics).
- Before we have such a theory, we can only in principle study the universe at age $> t_p$, or scale $> l_p$.