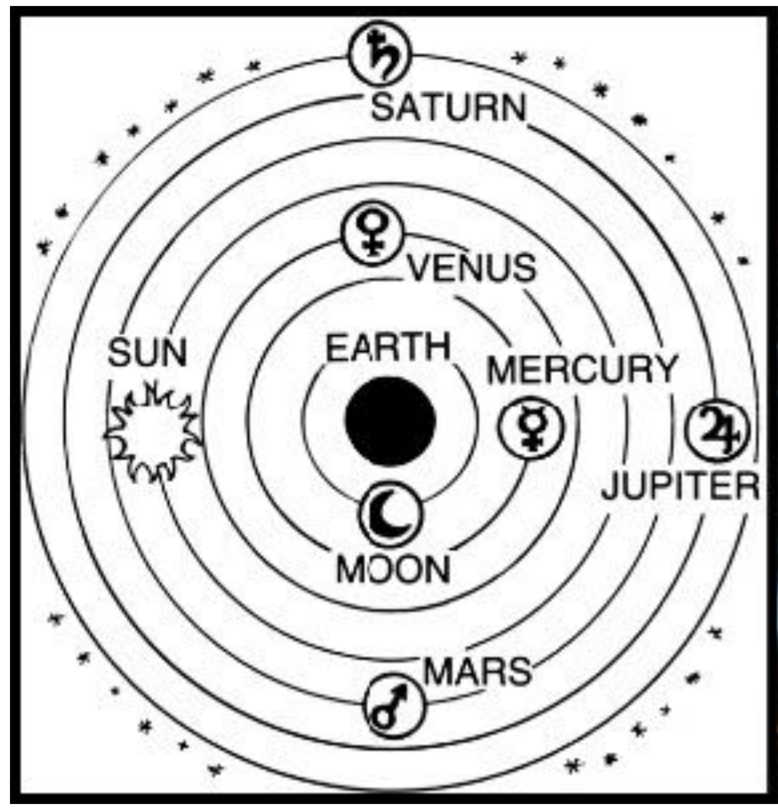


ASTR/PHYS 4080: Introduction to Cosmology

Week 2

Read Chapters 1-3 ASAP IF YOU HAVEN’T ALREADY
Also read the Key Concepts for those chapters

Today: Finish Chapter 2 & History of Modern Cosmology
Start Chapter 3

HW 1 due Thursday

Getting distances to the nebulae

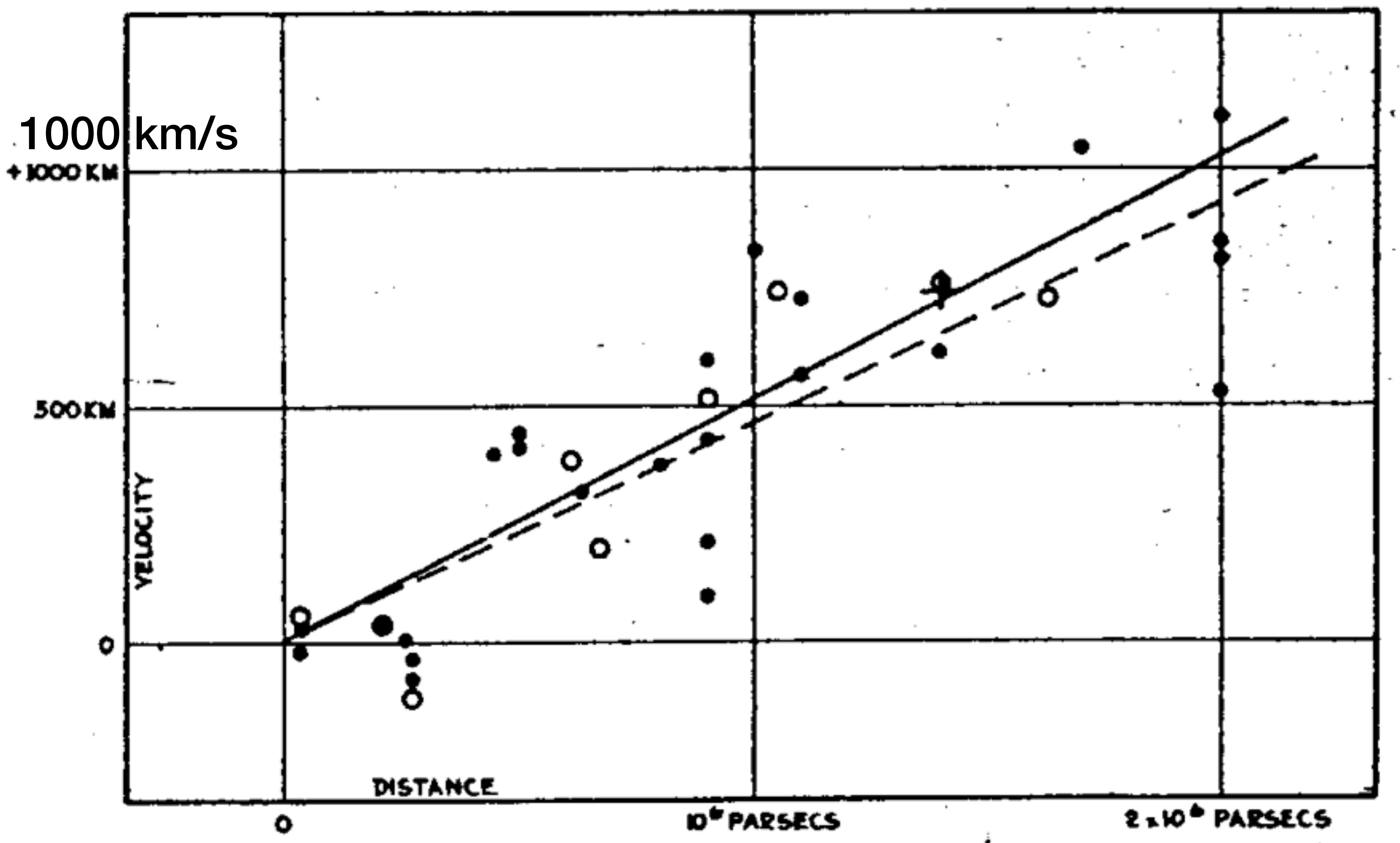


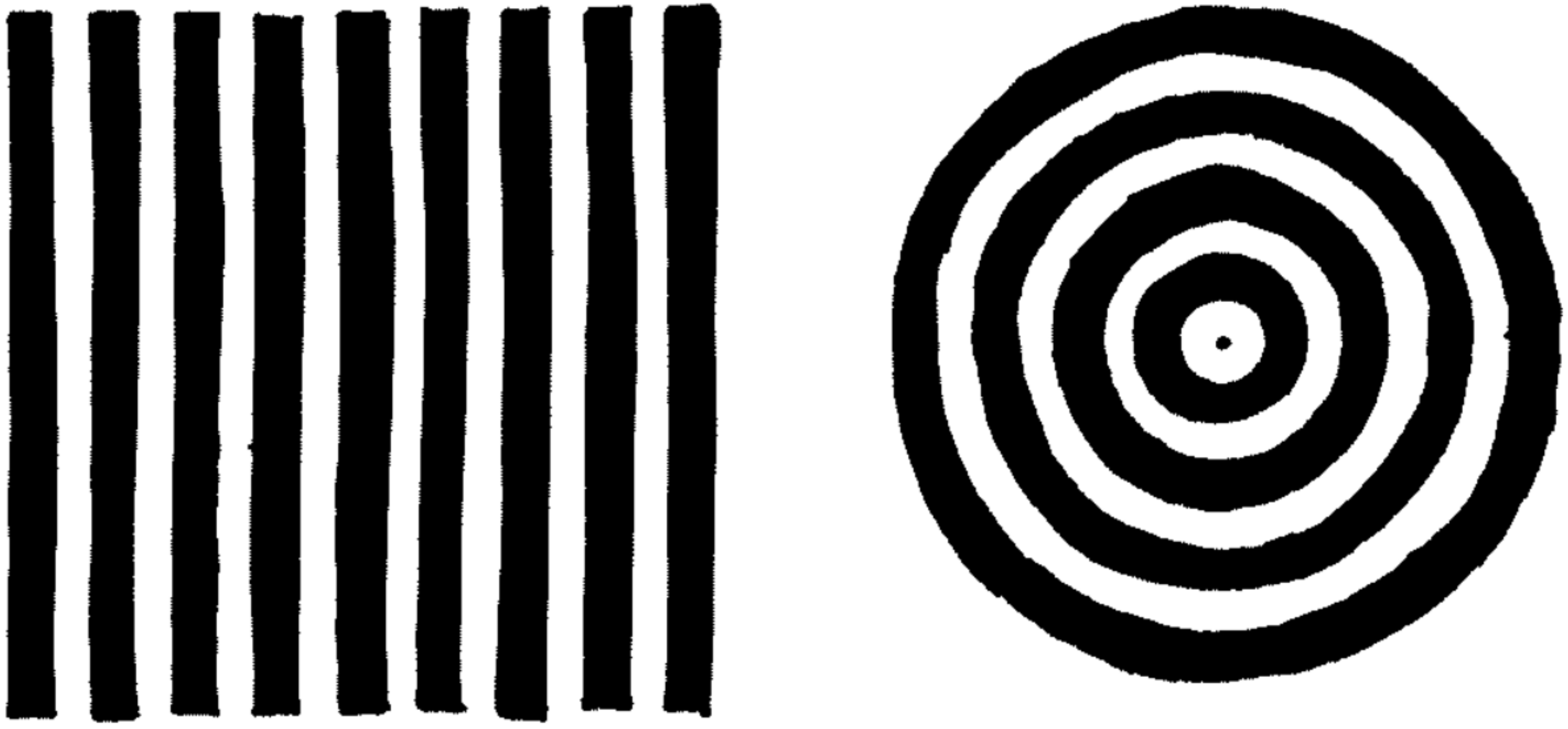
FIGURE 1

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)

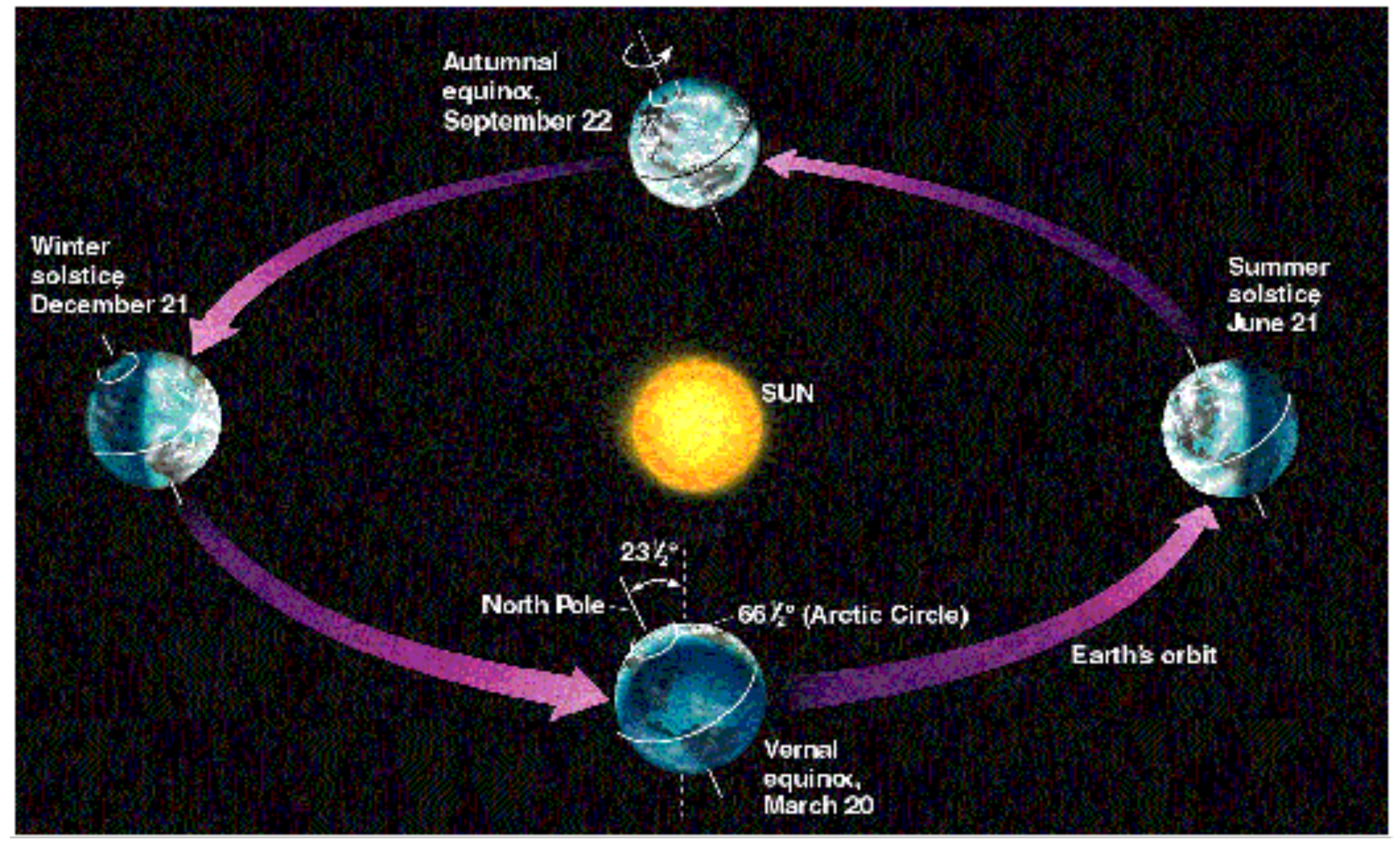
Powers of Ten (1977)
https://www.youtube.com/watch?v=0fKBhvDjuy0

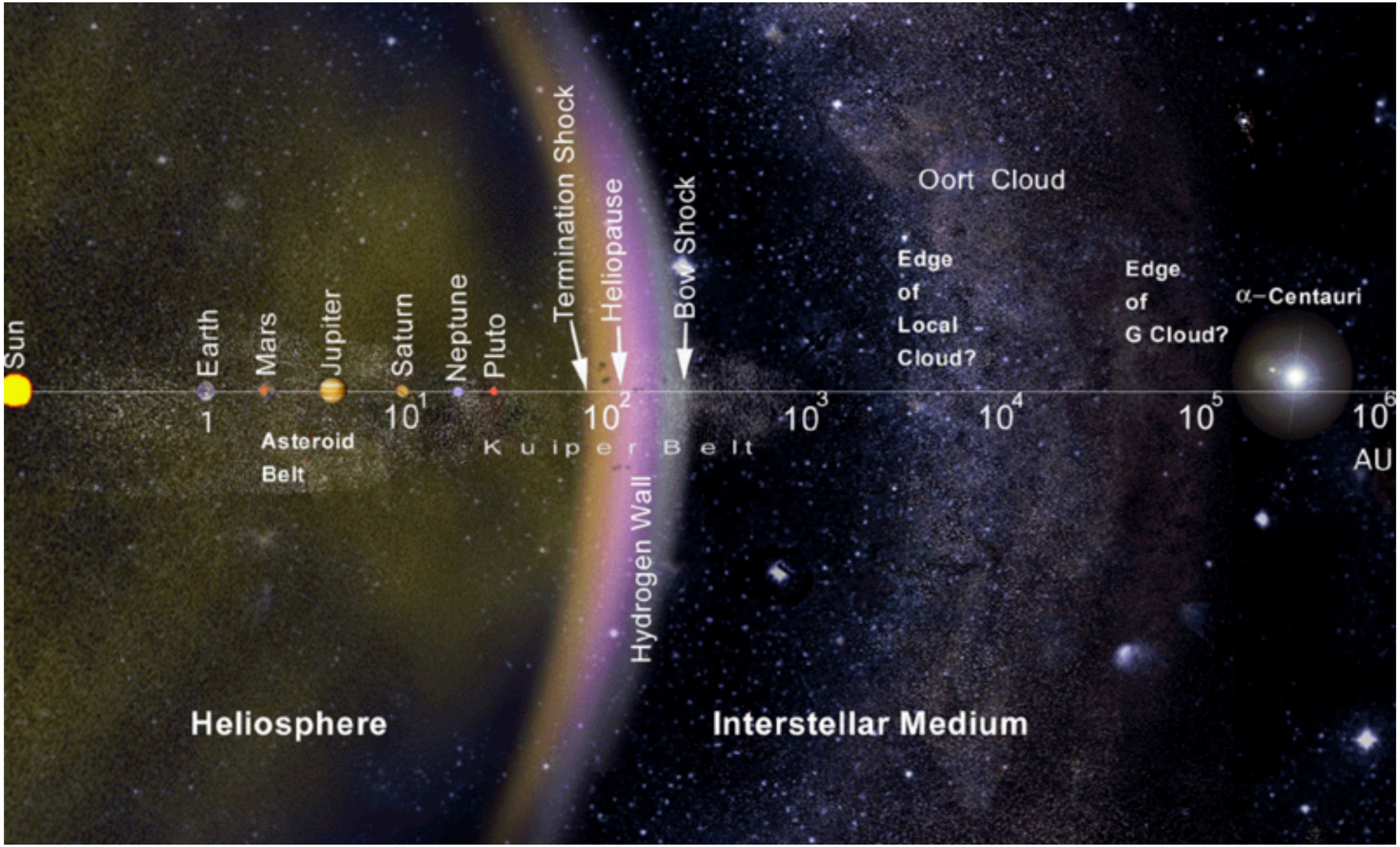
Contact intro (1997)
http://www.youtube.com/watch?v=BsTBbAMikPQ

Scale of the Universe

AU (Astronomical Unit)

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

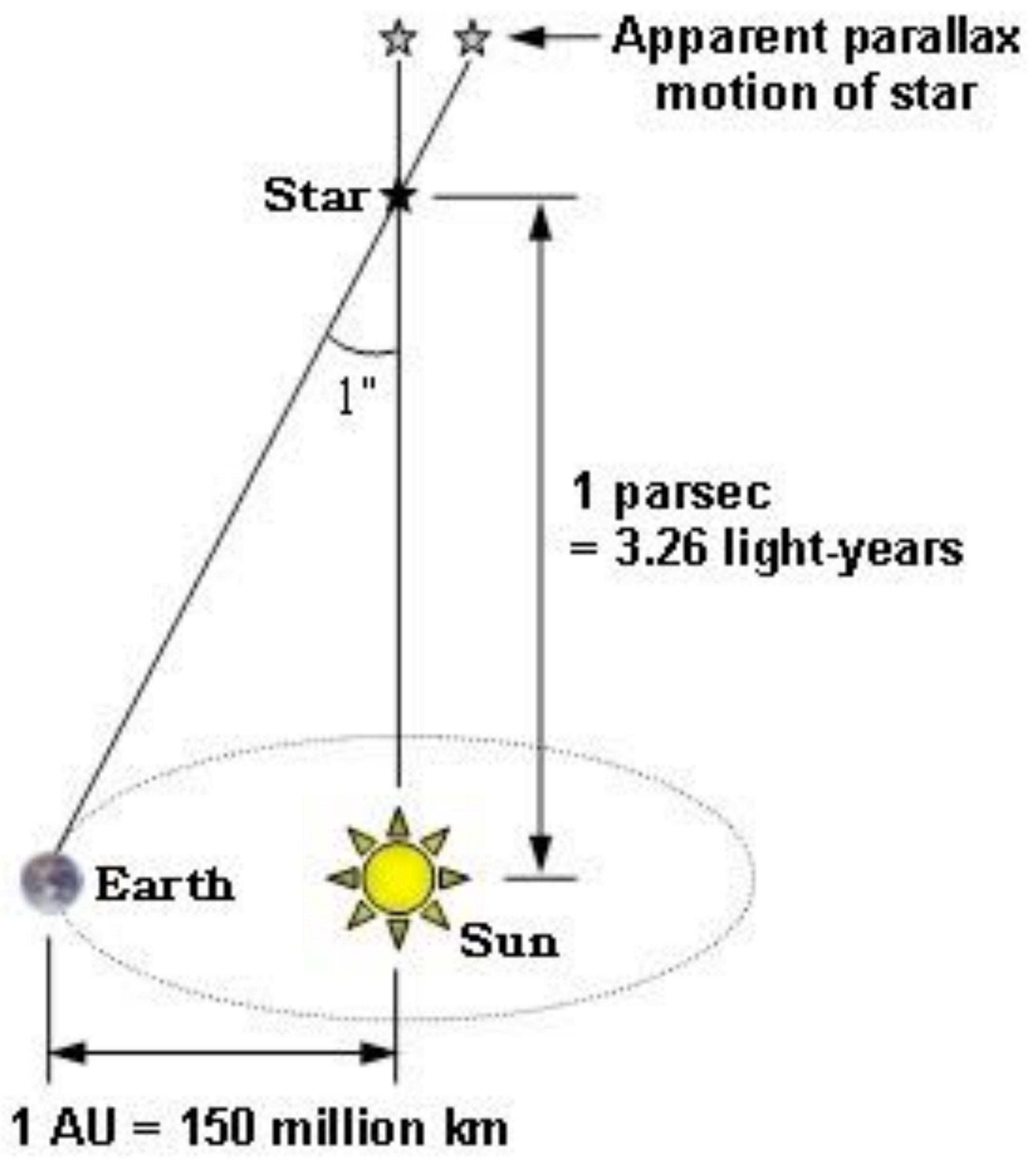


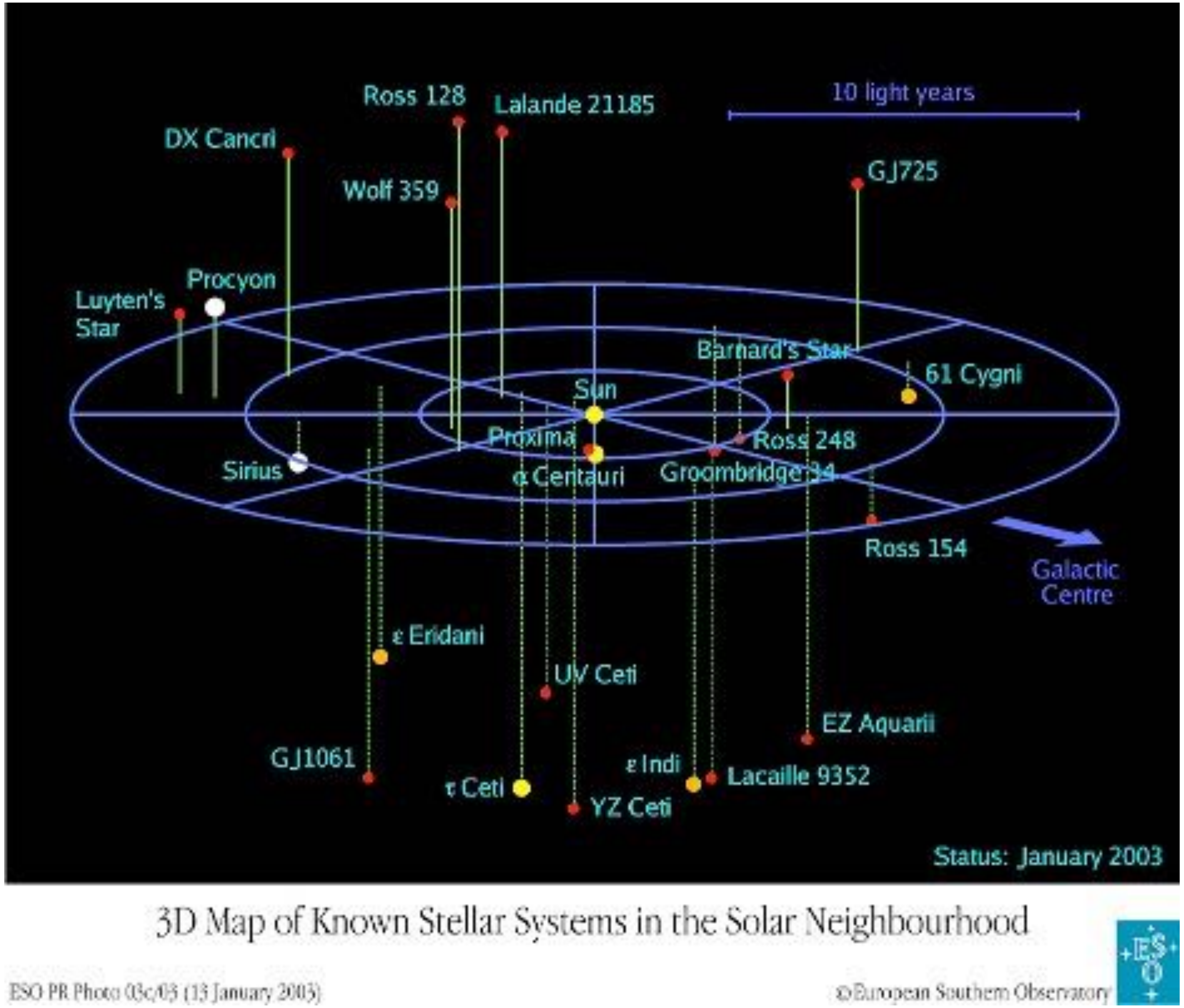


Scale of the Universe

pc (parsec)

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

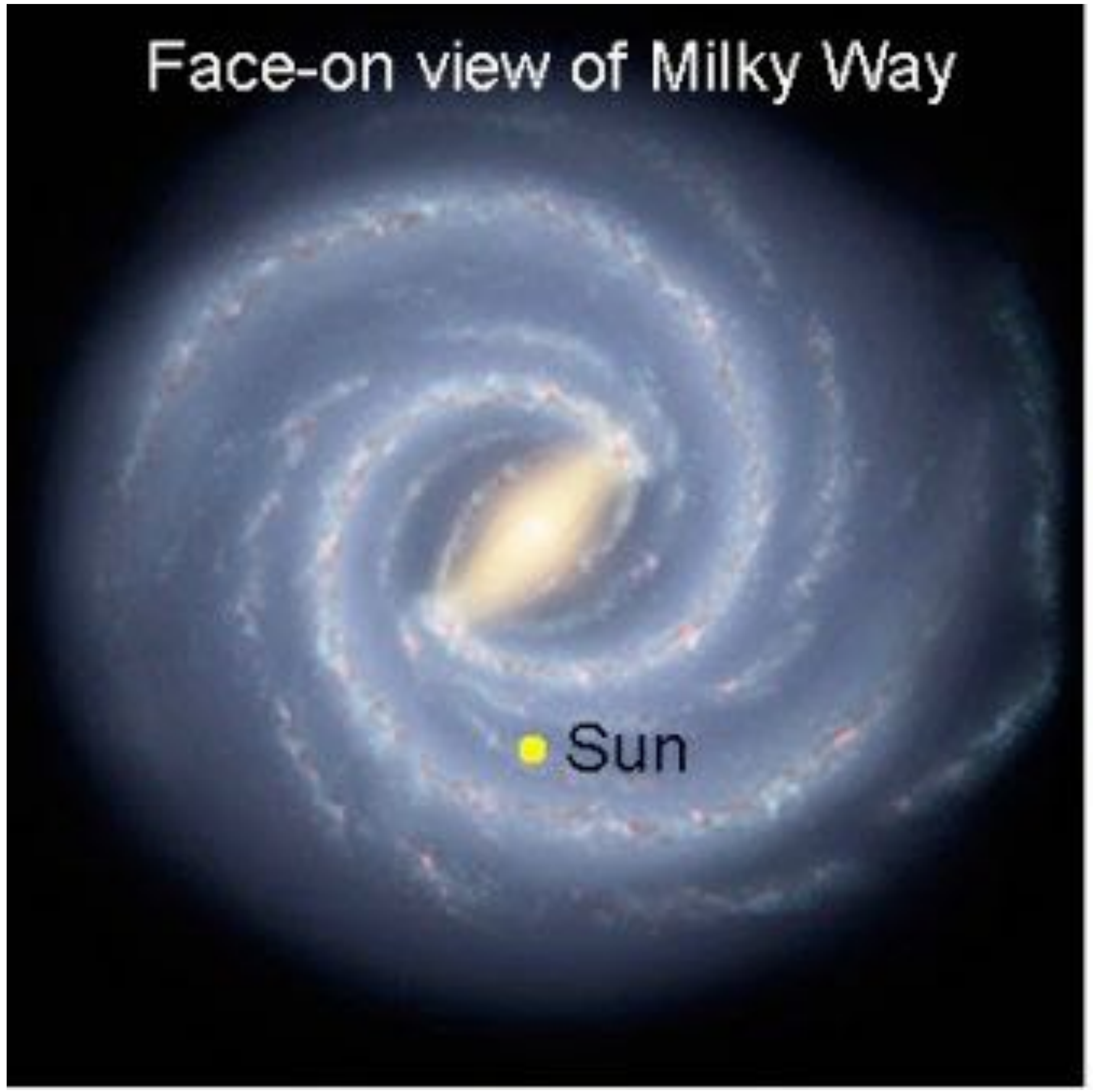


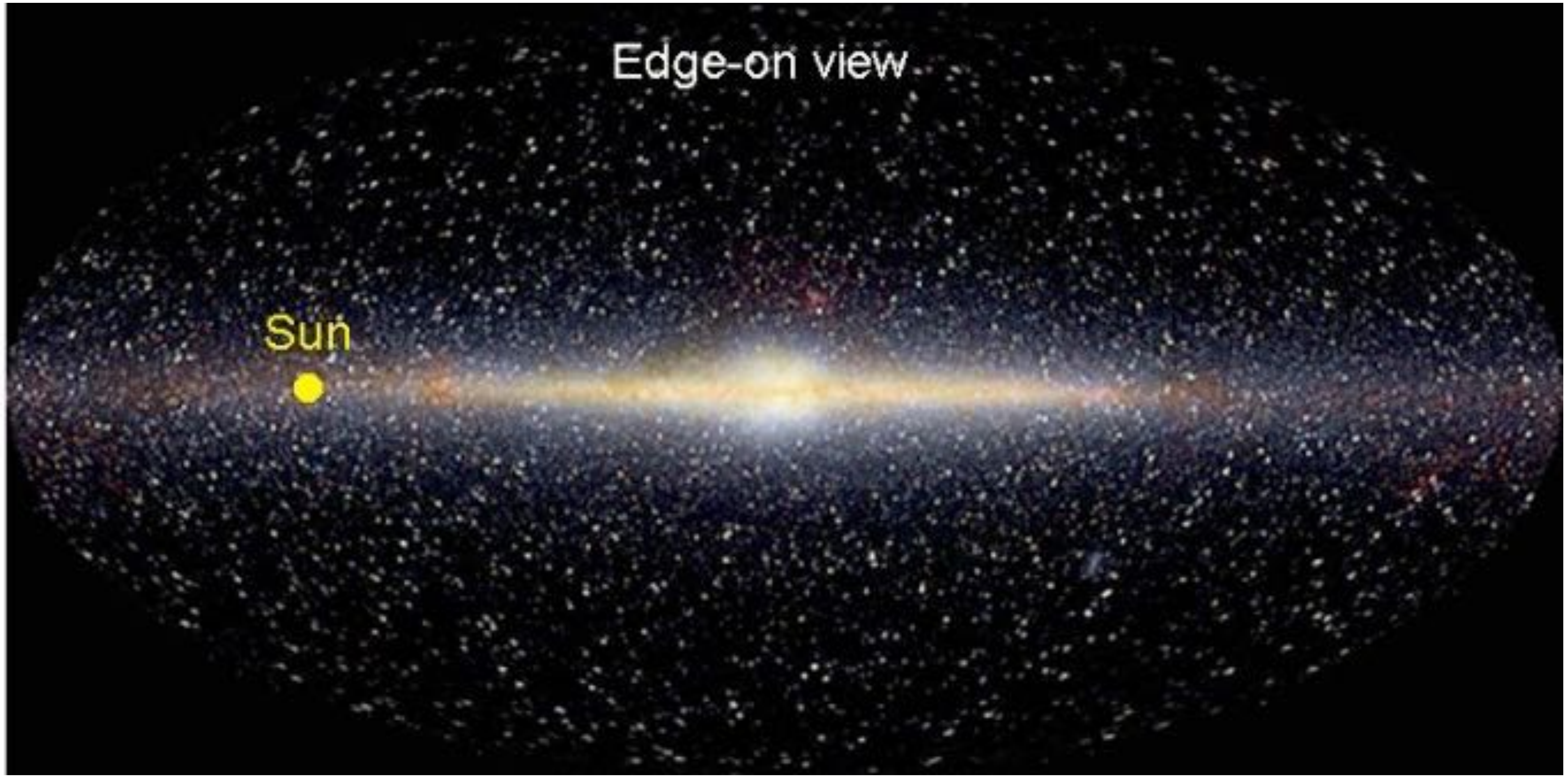


Scale of the Universe

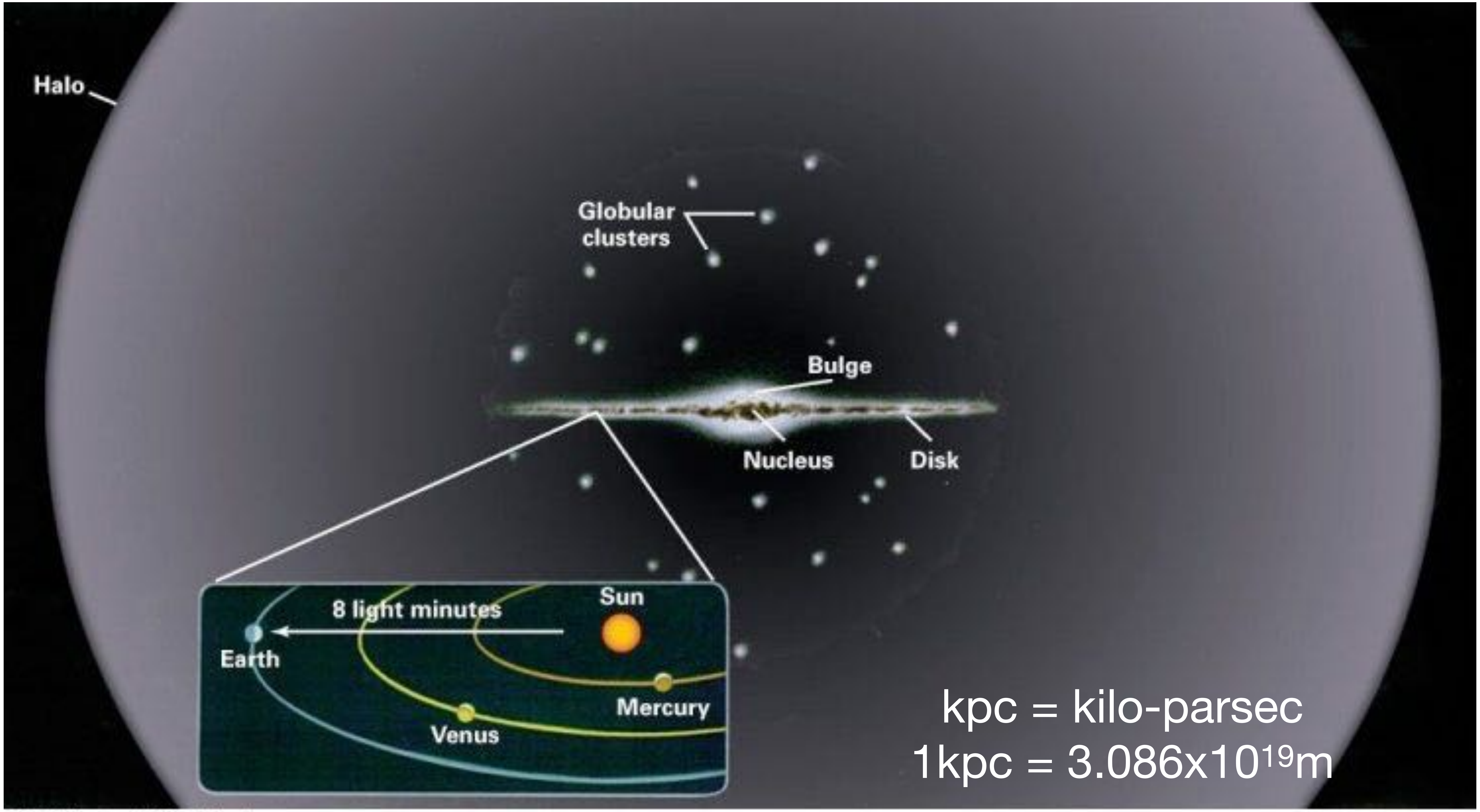
kpc = kilo-parsec

1kpc = 3.086×10^{19}m





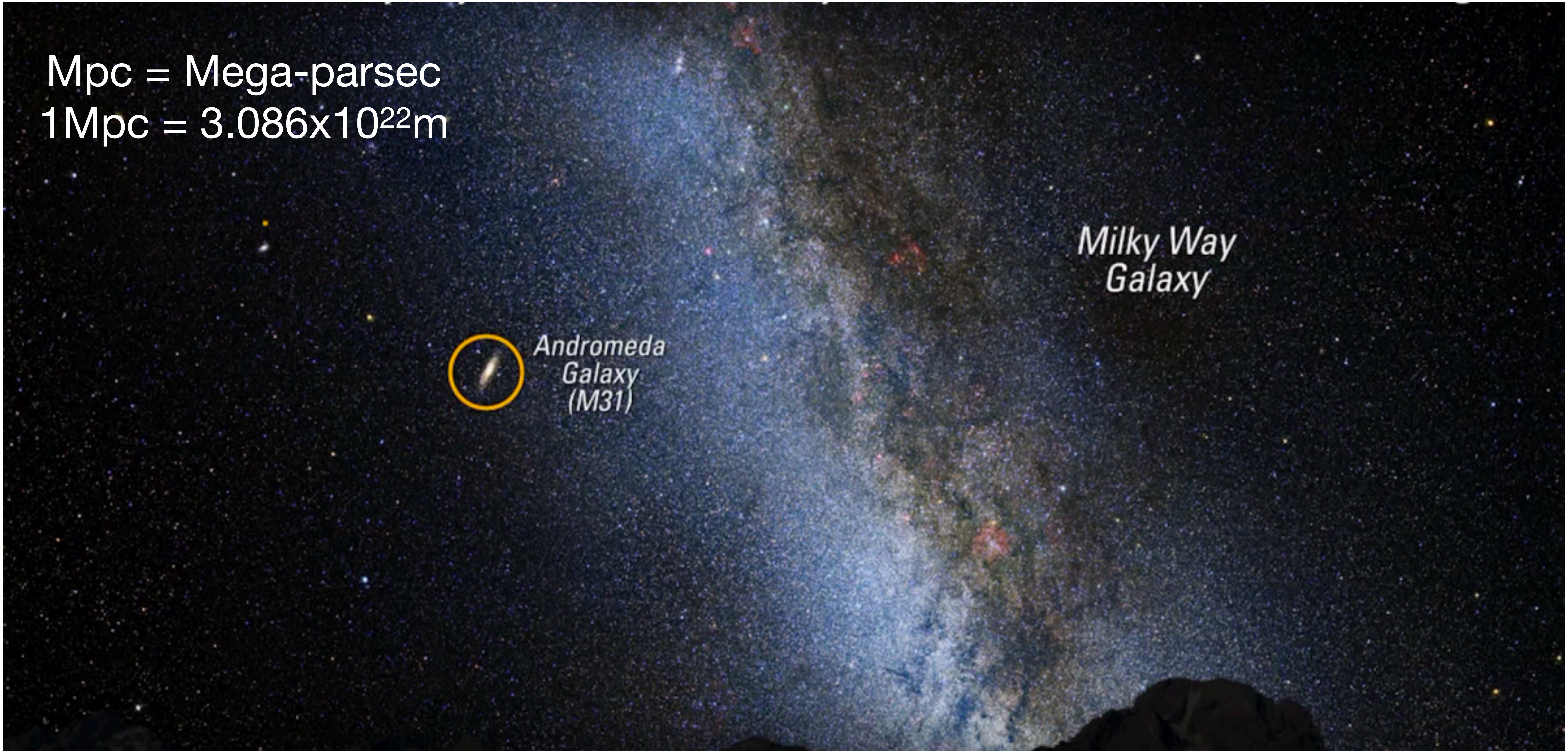
Scale of the Universe



Scale of the Universe

Mpc = Mega-parsec

1Mpc = 3.086×10^{22}m



Scale of the Universe

Scale of the Universe

Scale of the Universe

Scale of the Universe

Scale of the Universe

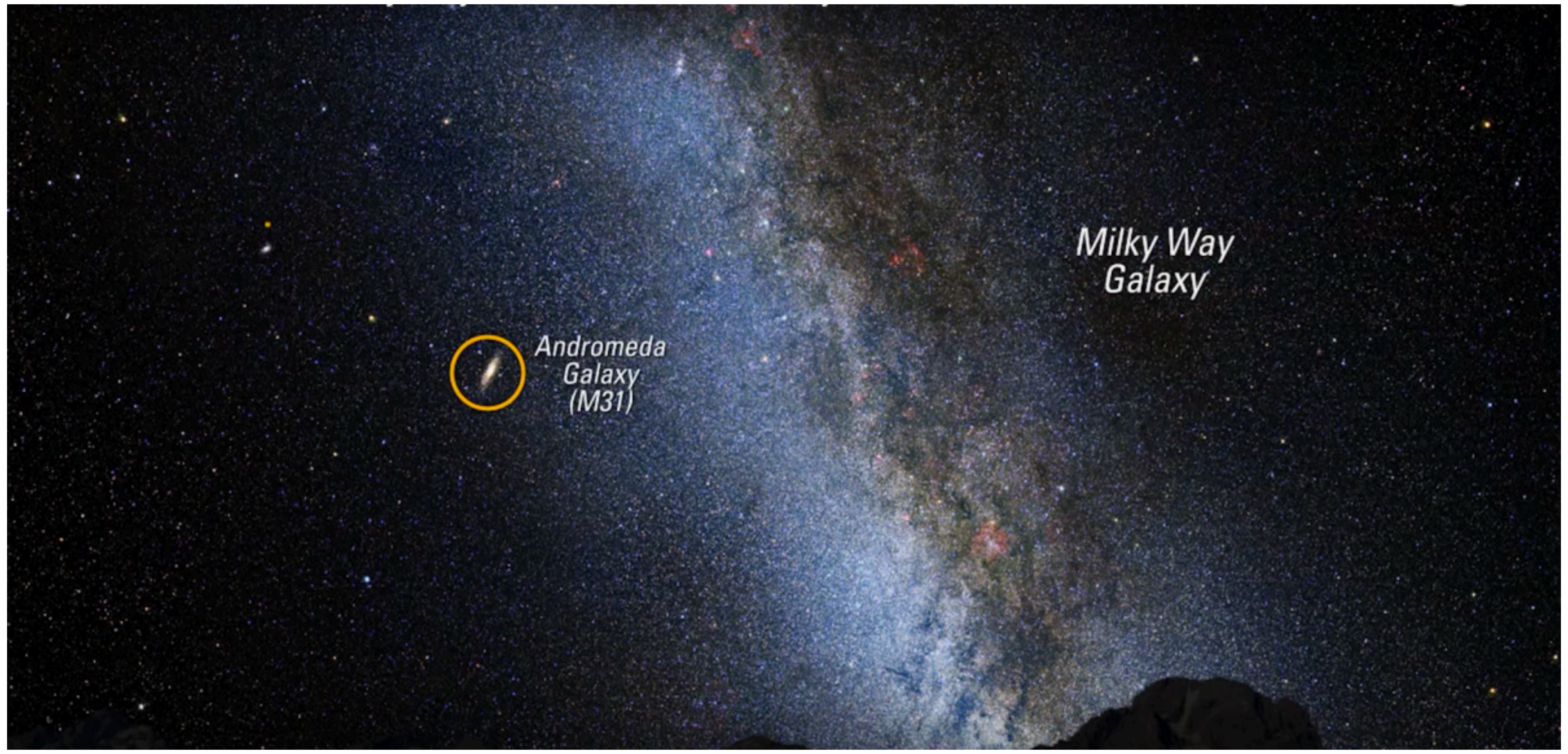
Scale of the Universe

Scale of the Universe

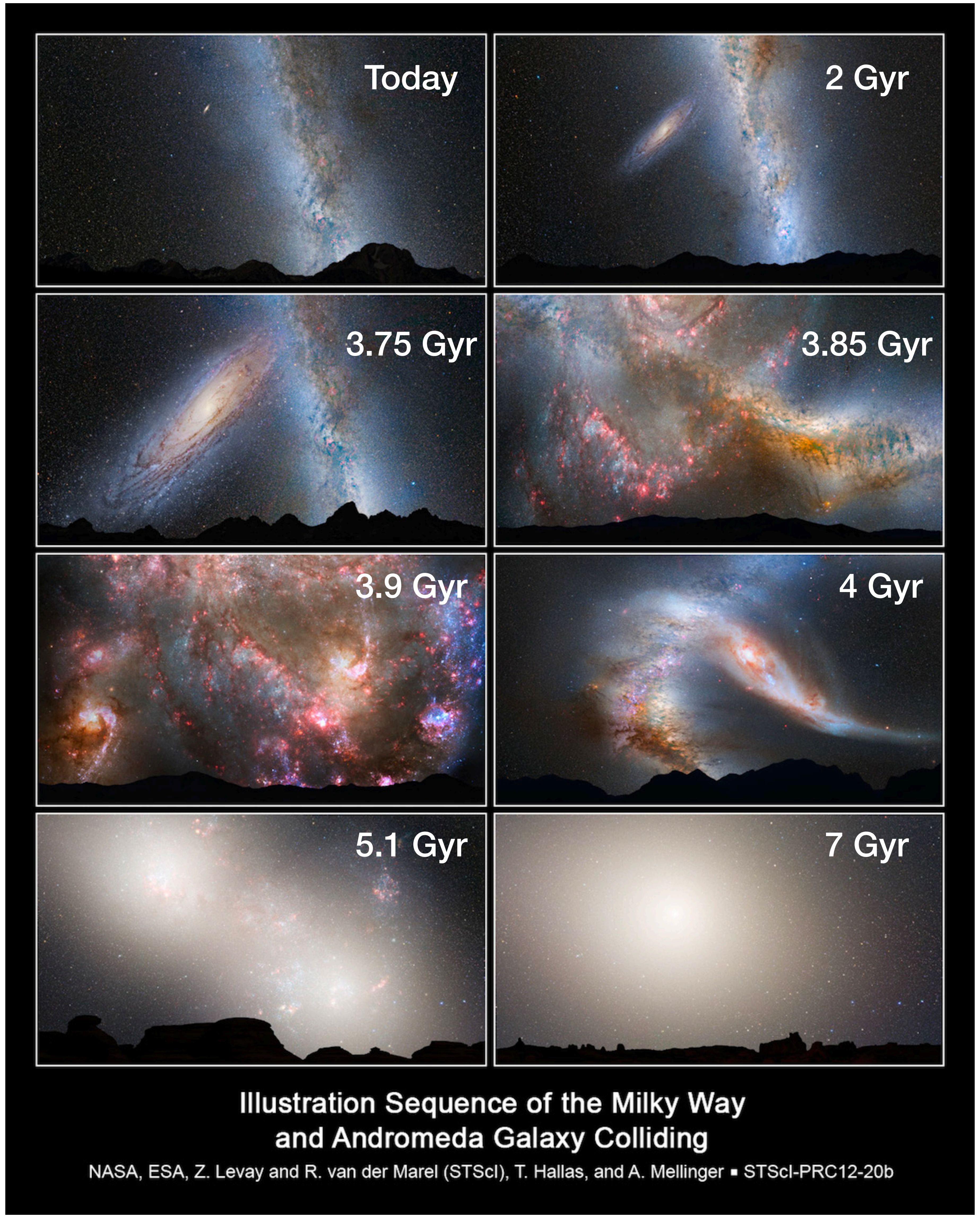
Scale of the Universe

Scale of the Universe

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



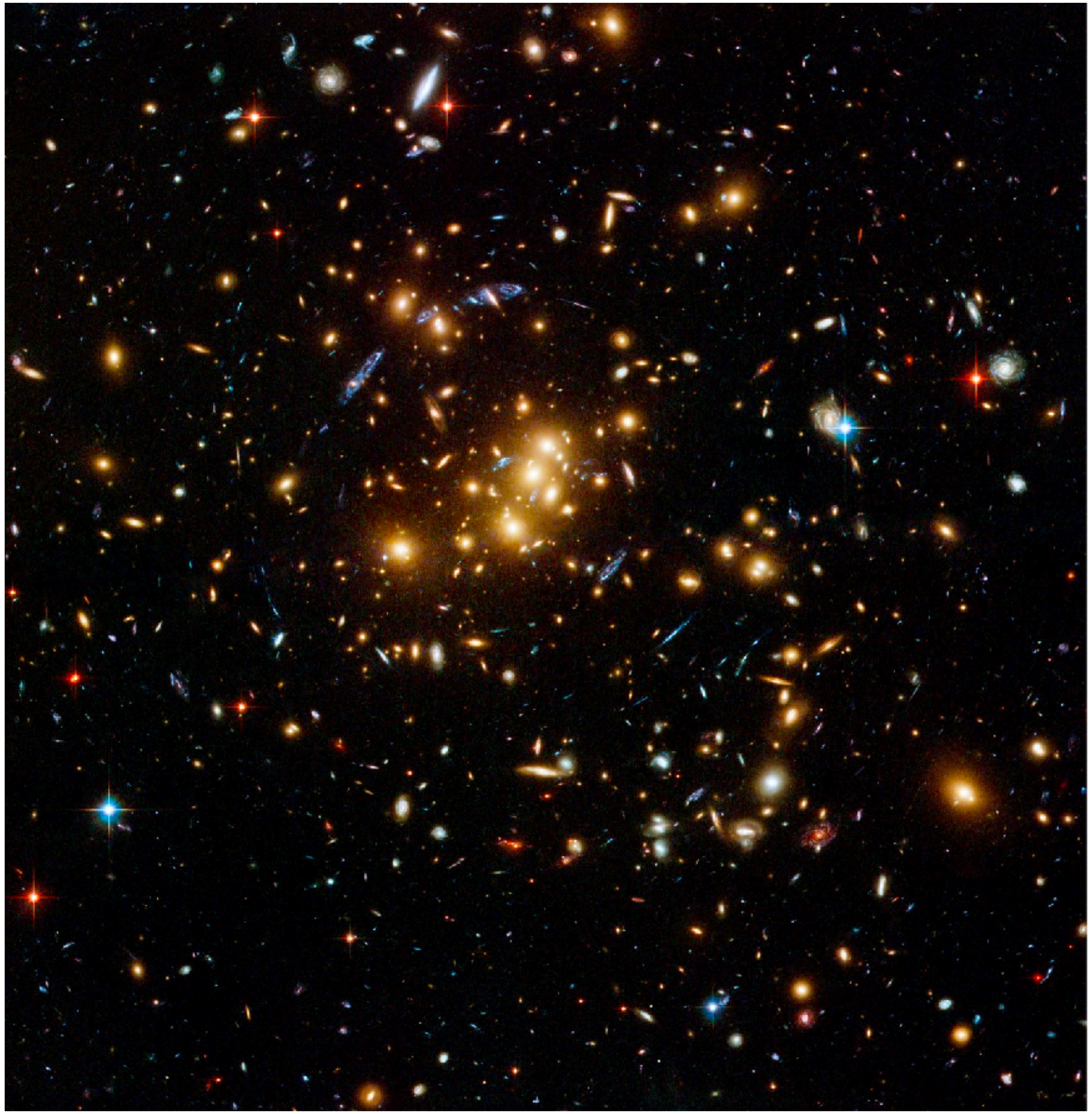
http://phenomena.nationalgeographic.com/2014/03/24/scientists-predict-our-galaxys-death/



Scale of the Universe

Mpc = Mega-parsec

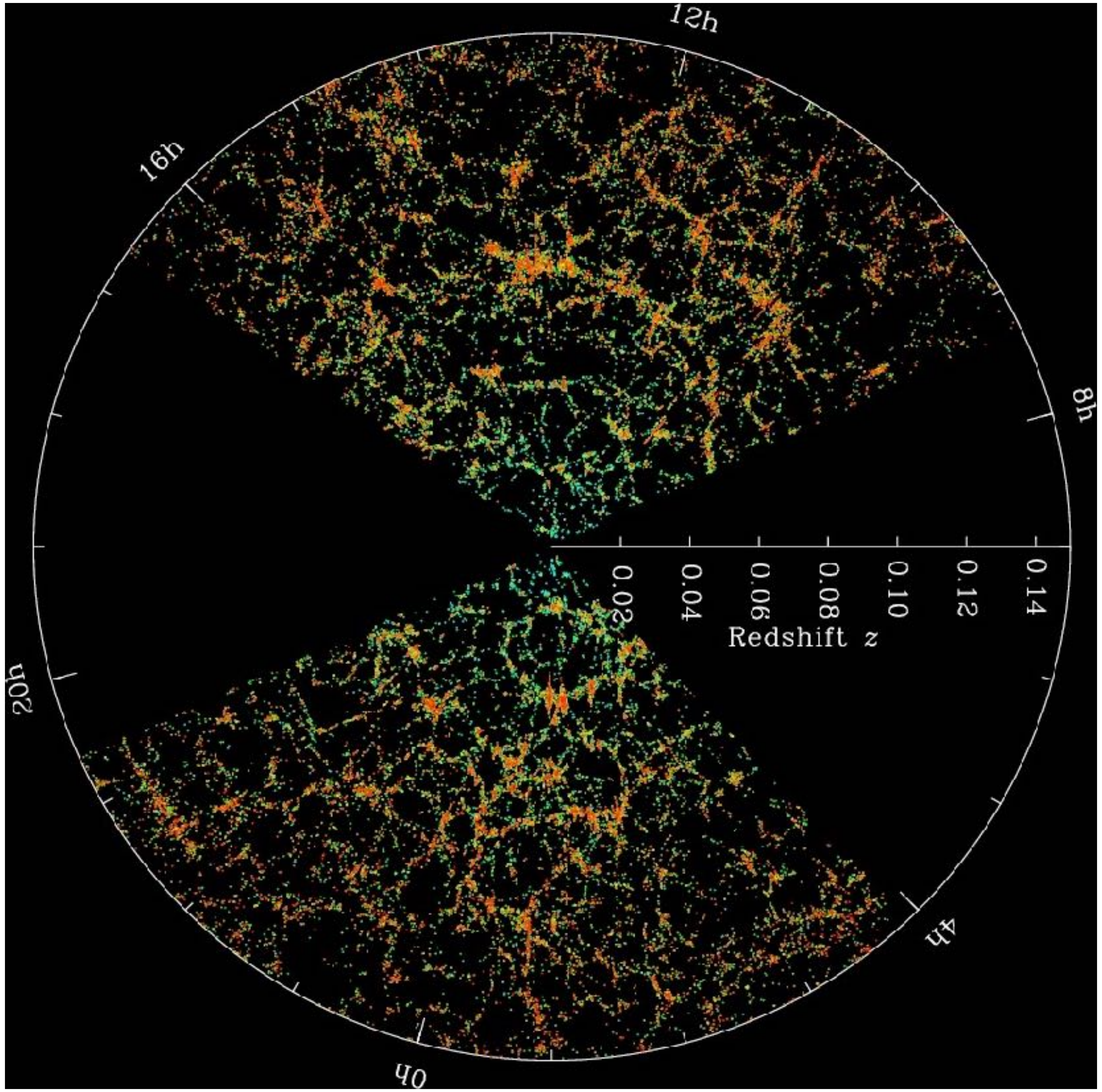
1 Mpc = 3.086×10^{22} m



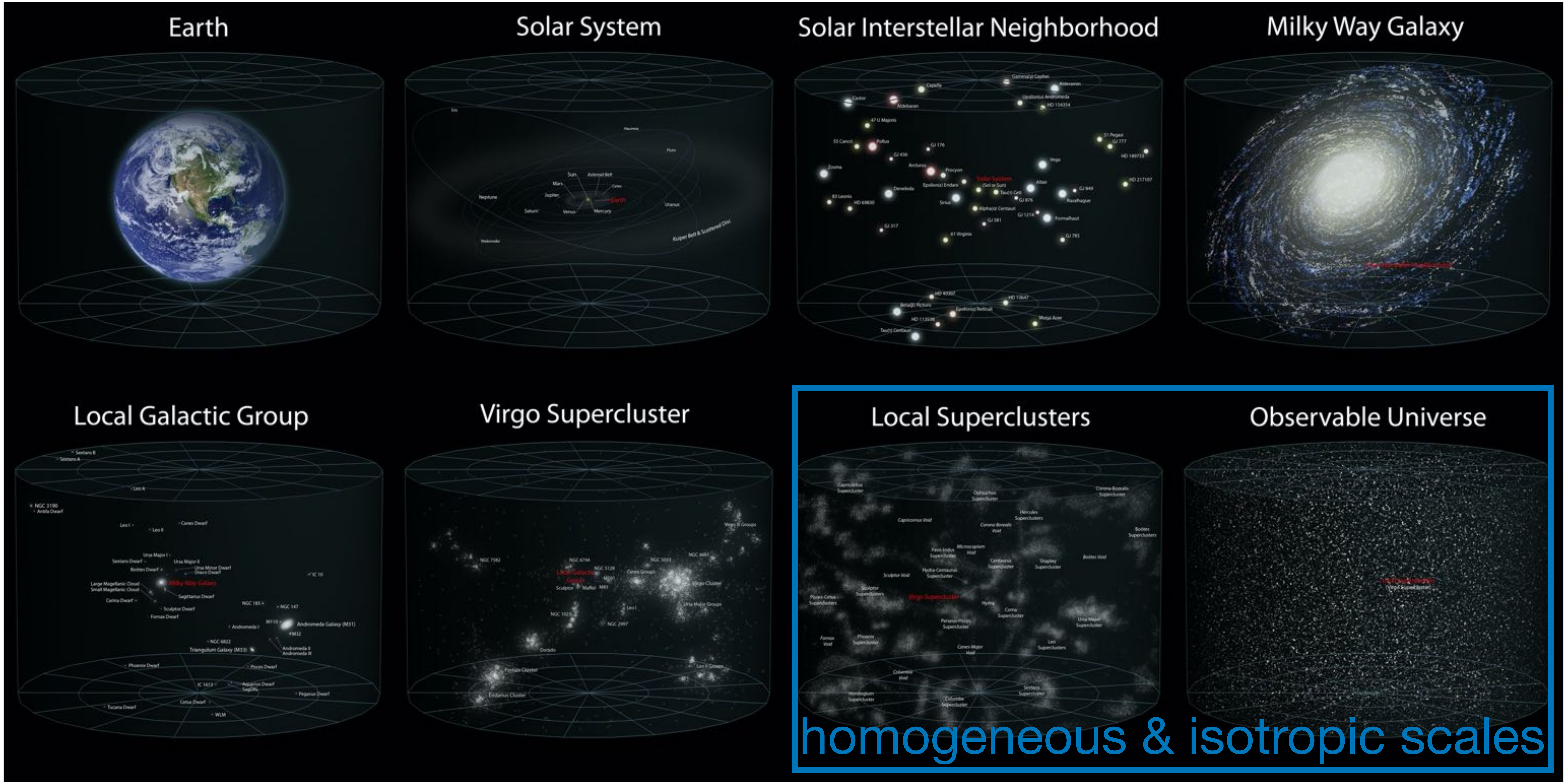
Scale of the Universe

Gpc = Giga-parsec

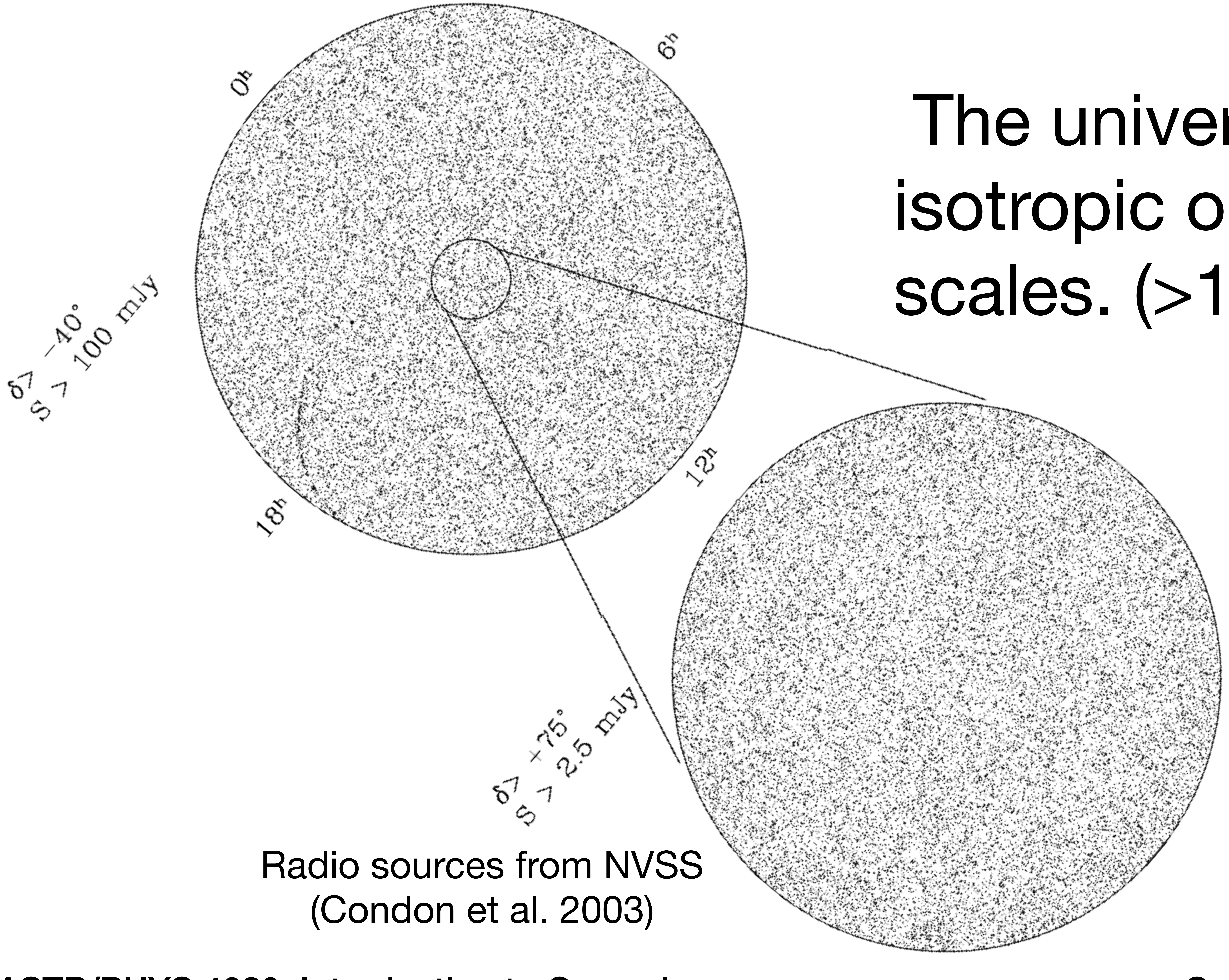
1 Gpc= 3.086×10^{25} m



Scale of the Universe



Cosmological Principle



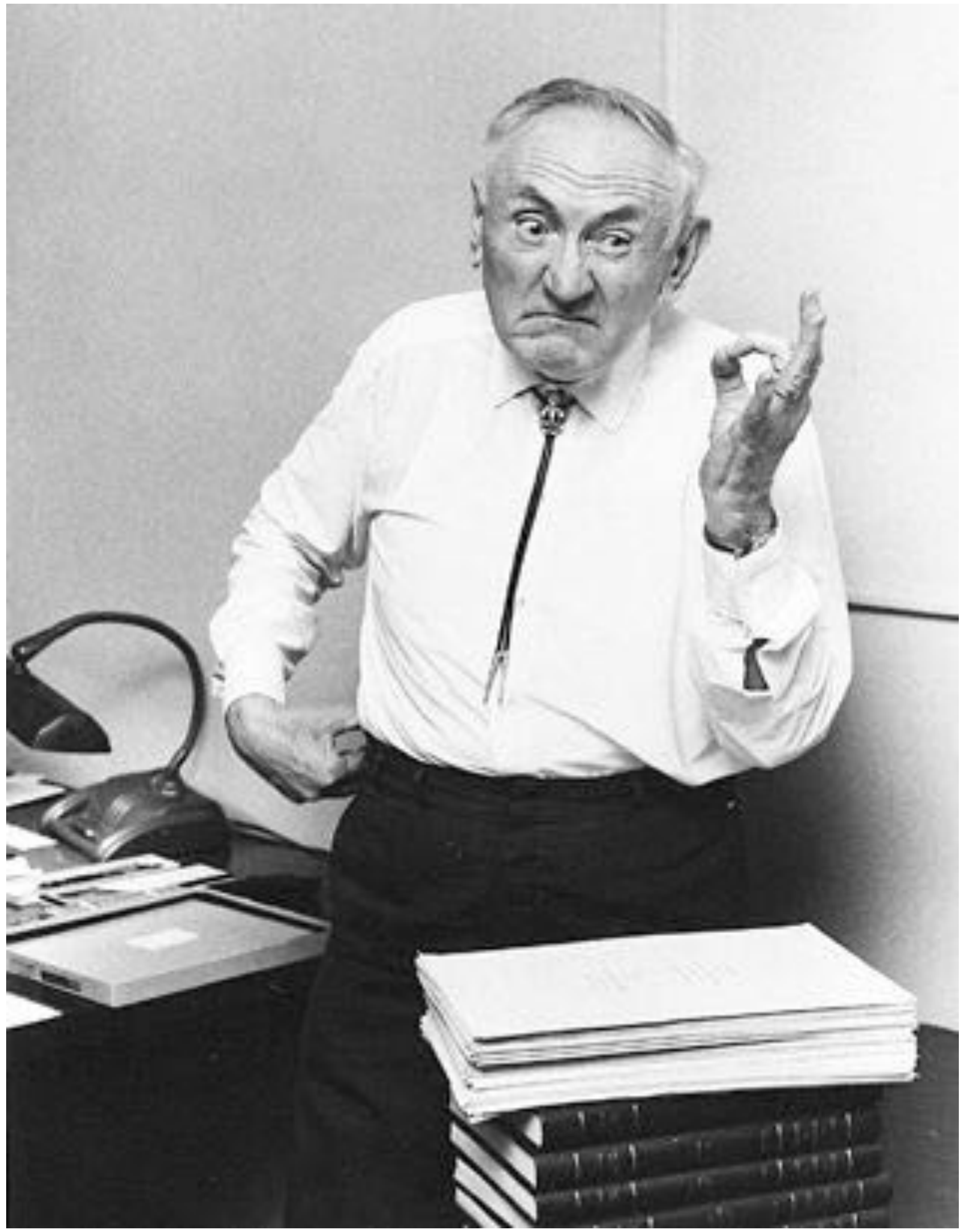
Radio sources from NVSS
(Condon et al. 2003)

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

Copernican Principle
=> homogeneous & isotropic

(Cosmological Principle)

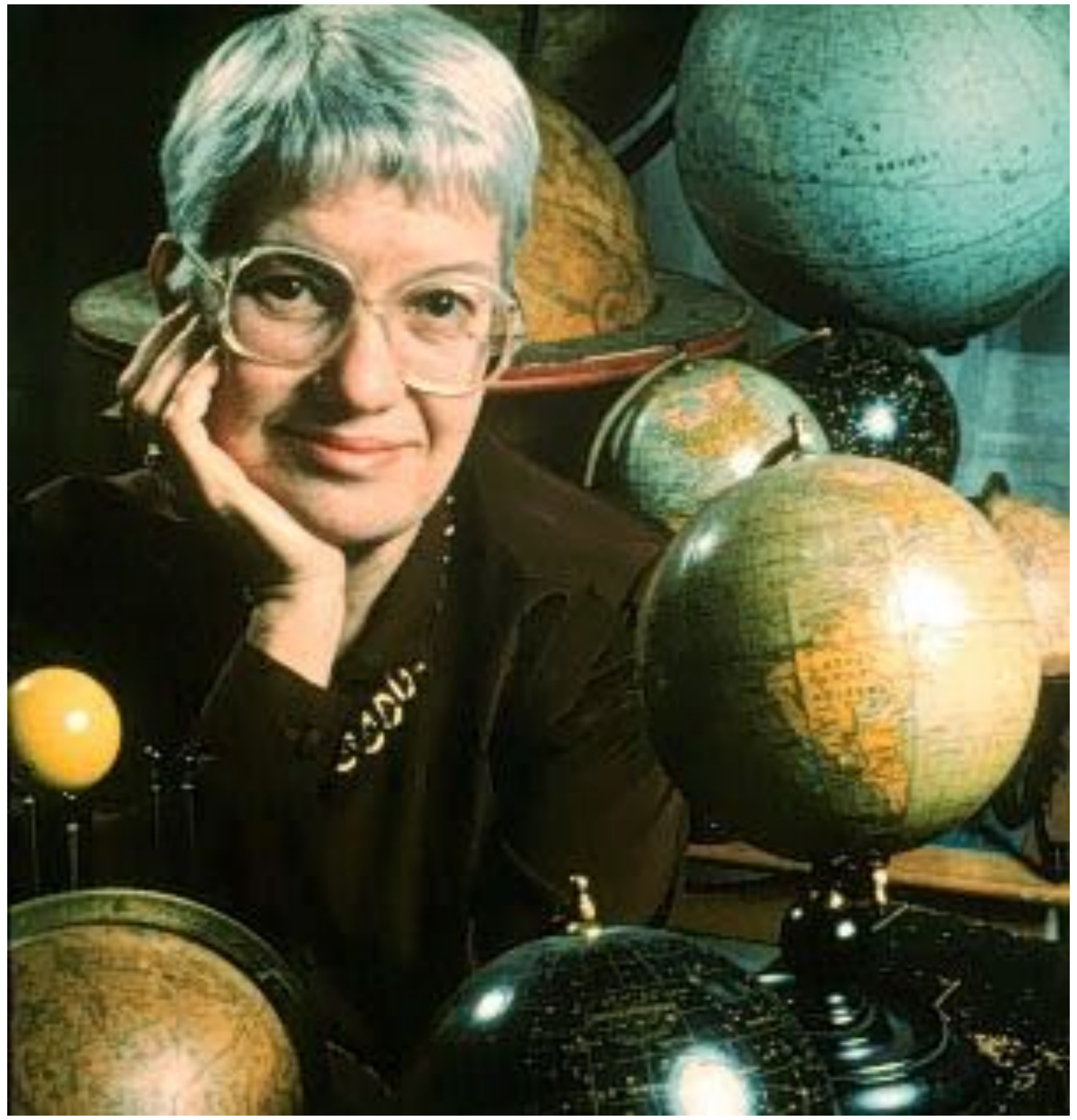
First Evidence of Dark Matter



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

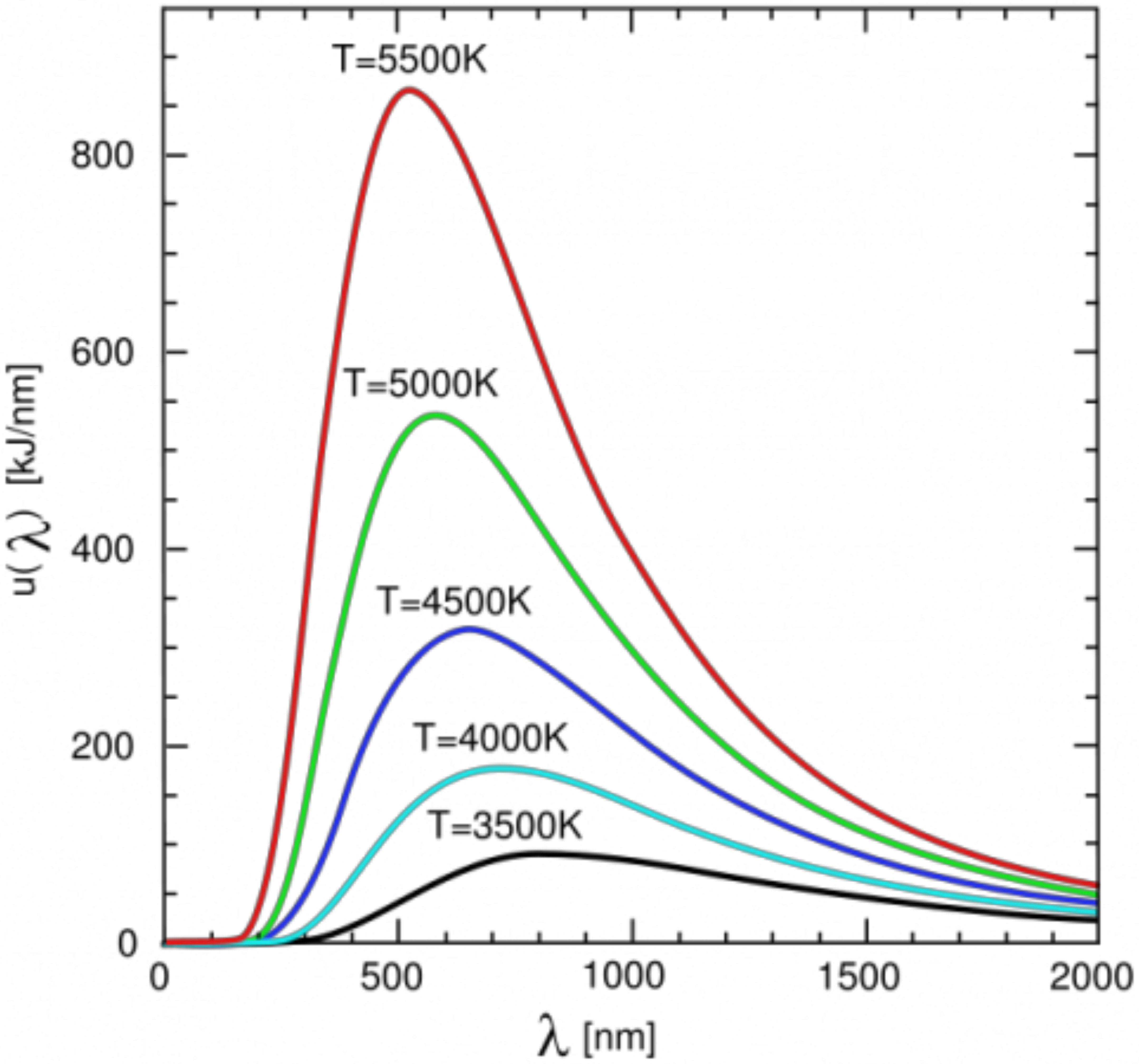
1948: Hermann Bondi, Thomas Gold, and Fred Hoyle, steady state cosmology from perfect cosmological principle

1950: Fred Hoyle coins term “Big Bang”

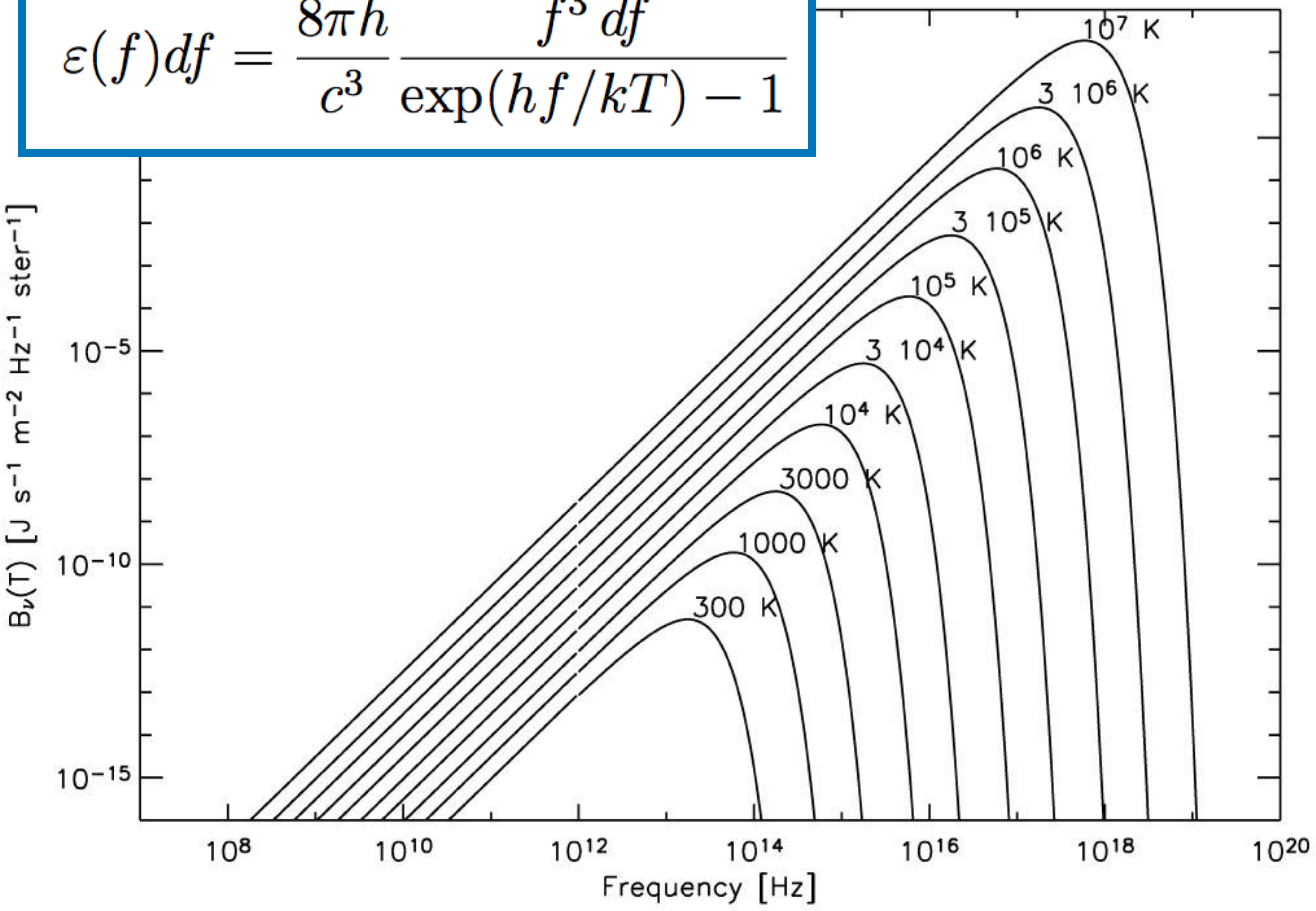
[Whiteboard!]

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)

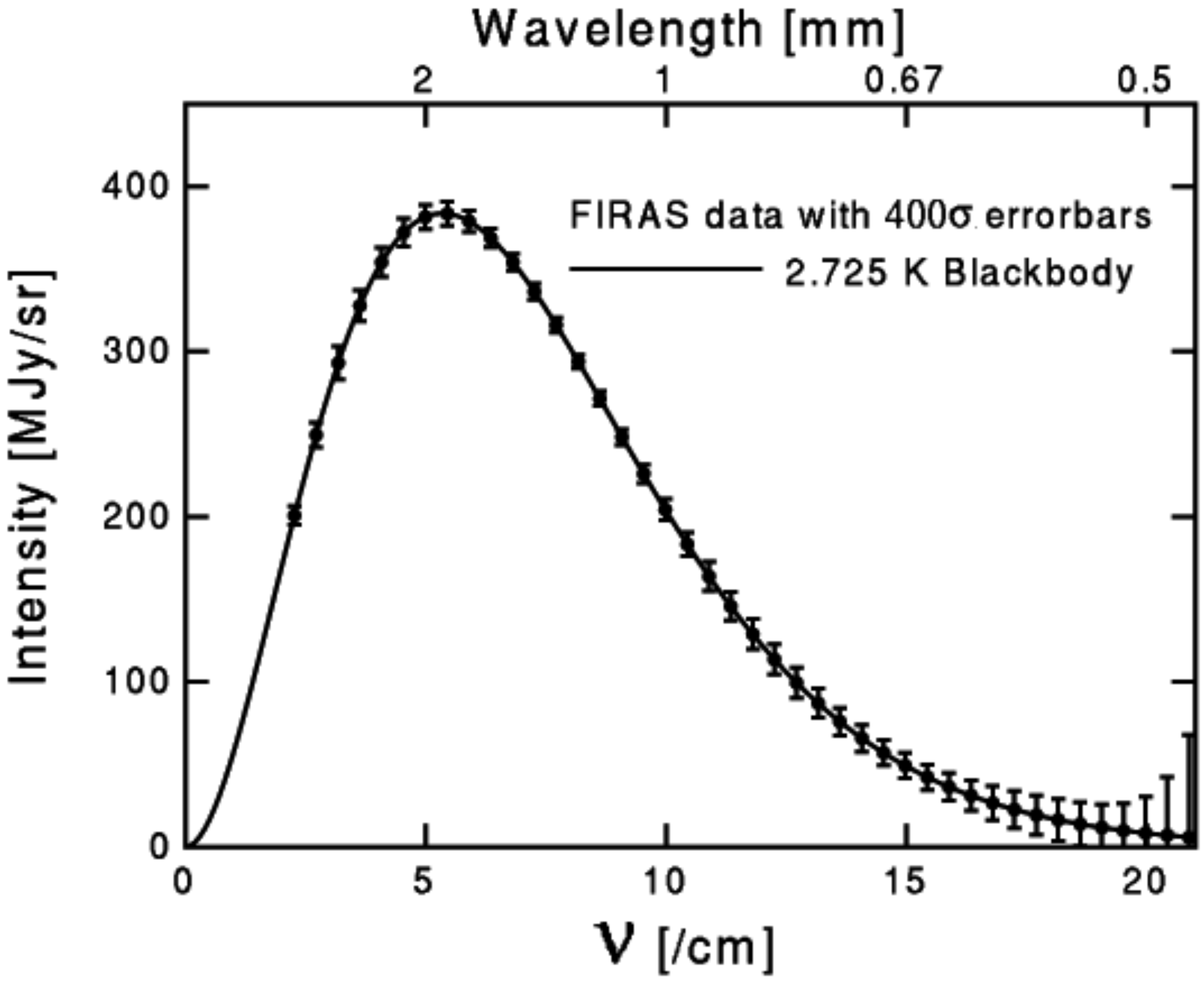
1965: Arno Penzias and Robert Wilson discover of the CMB (by accident)

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

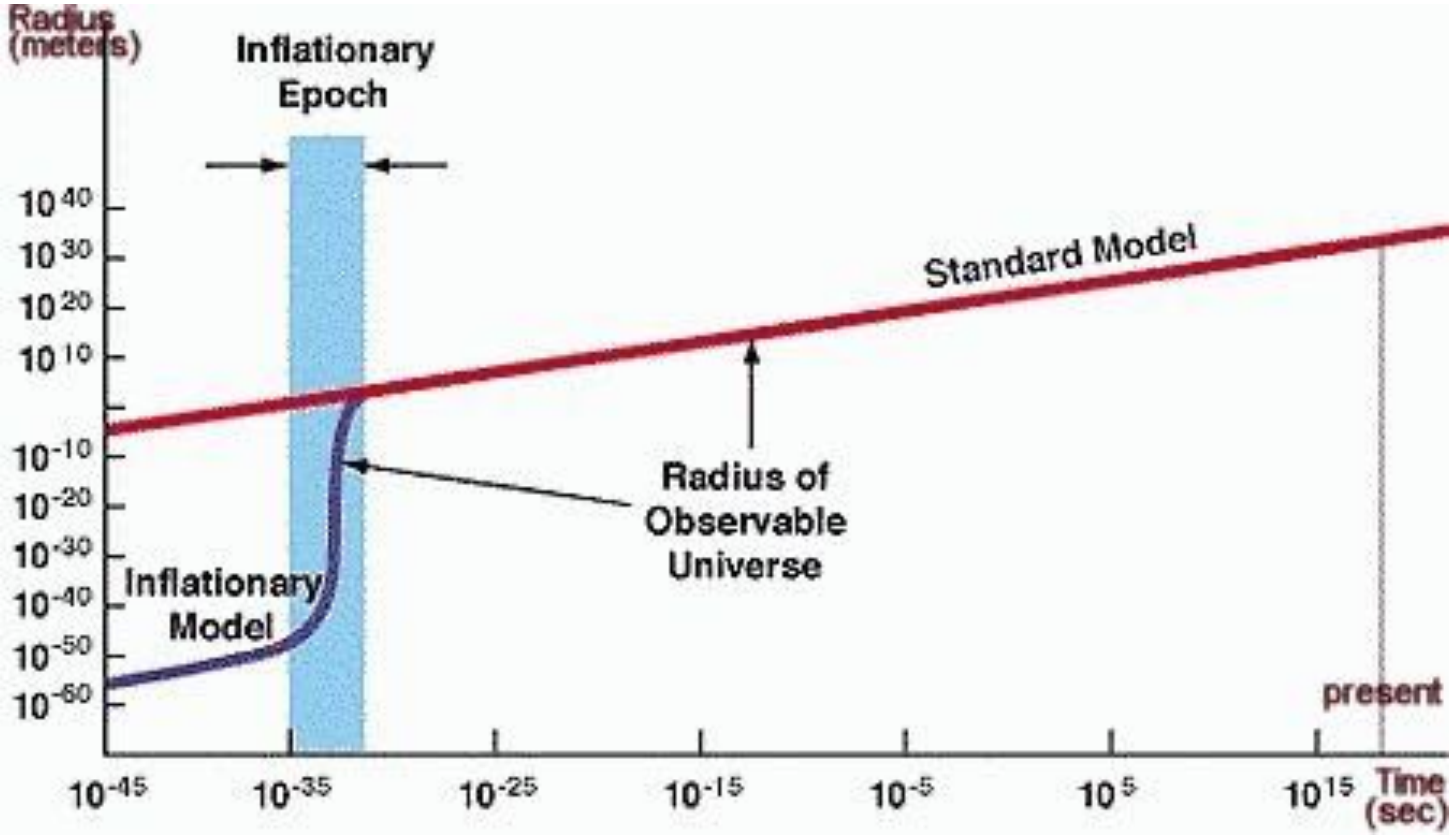
1966: James Peebles shows that the Big Bang predicts the correct
helium abundance

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

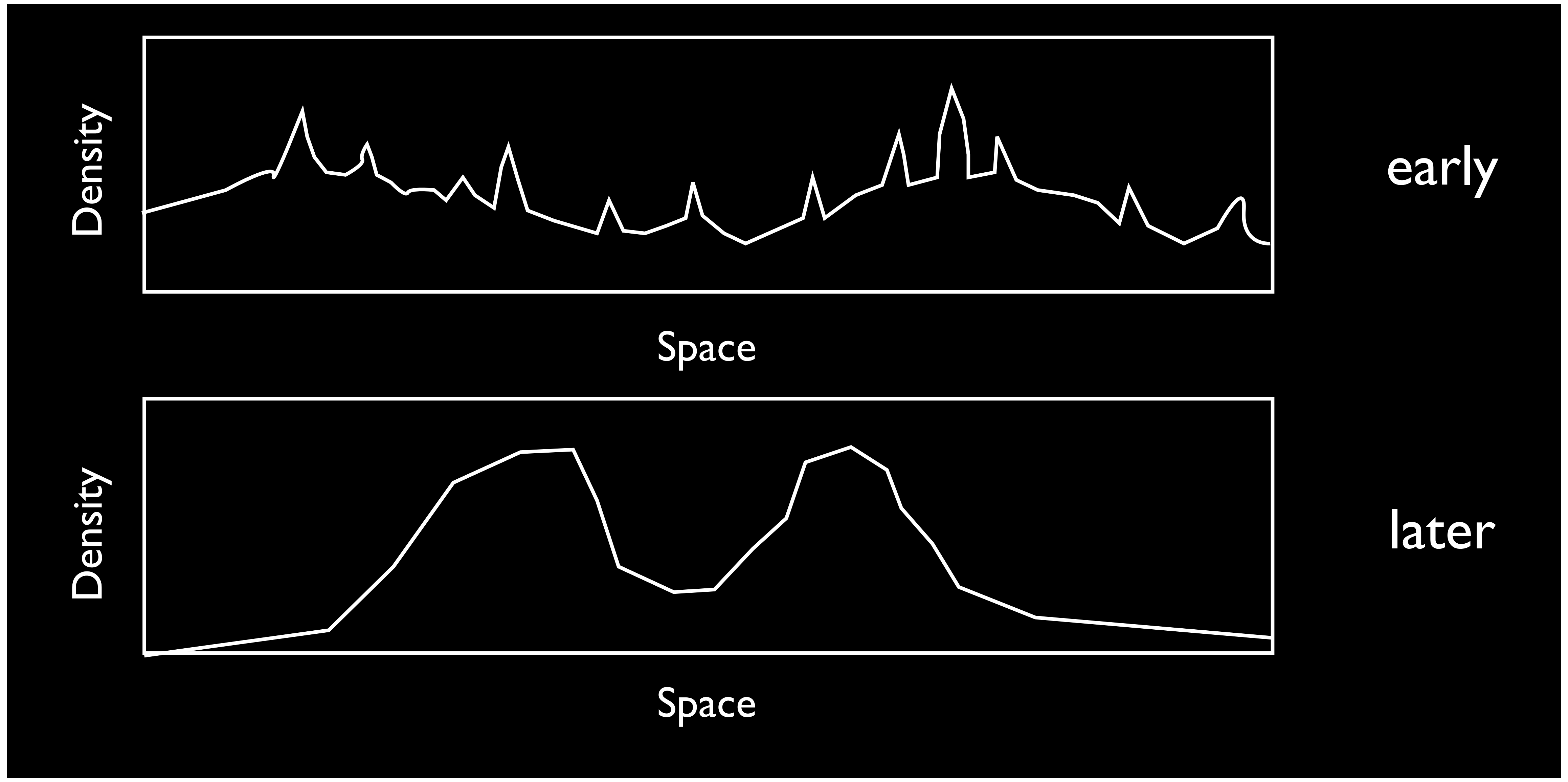
1969: Charles Misner, Big Bang horizon problem (?)
1969: Robert Dicke, Big Bang flatness problem (?)

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



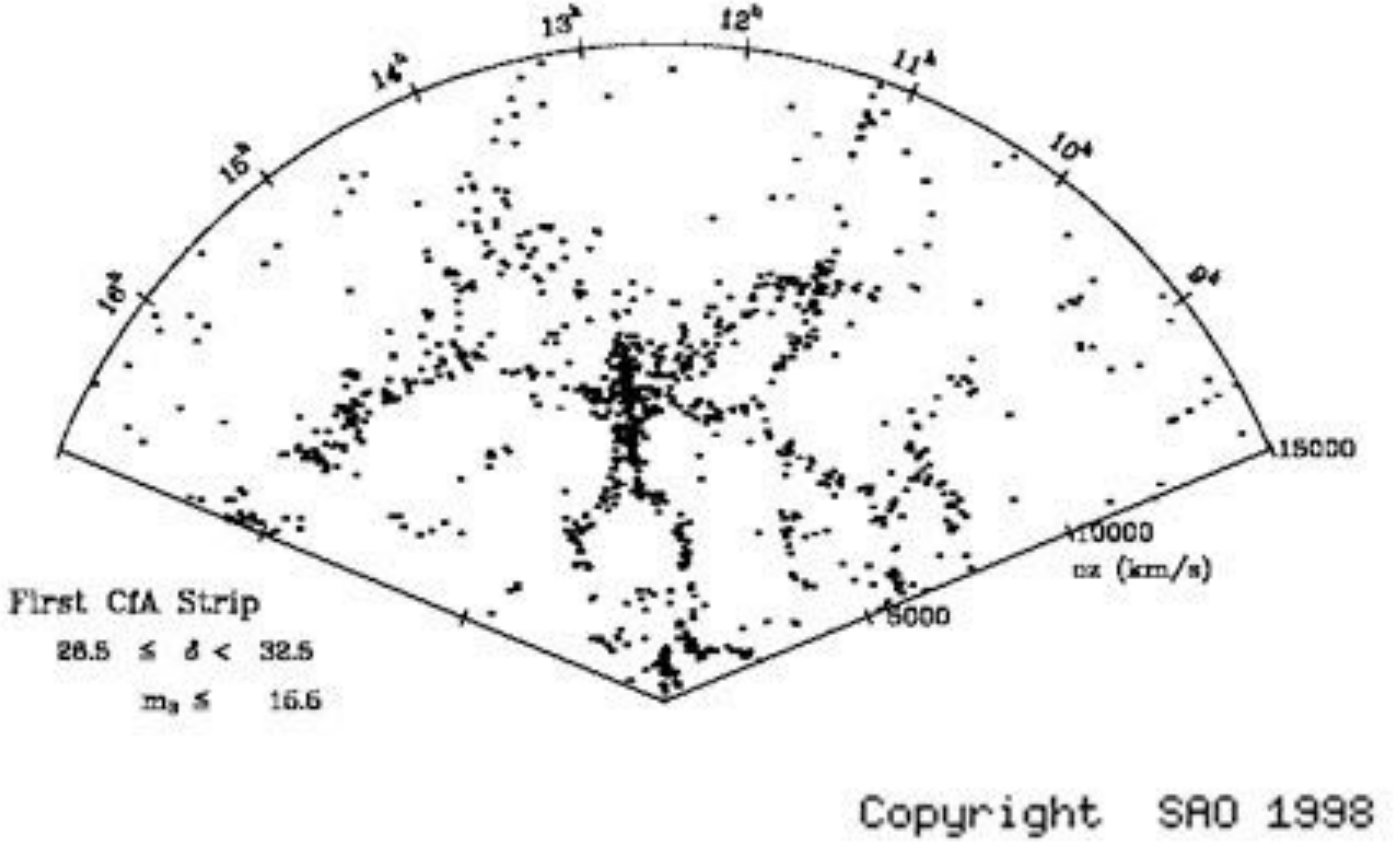
Initial quantum density perturbations amplified by Inflation after the Big Bang.



Called Hierarchical Structure Formation

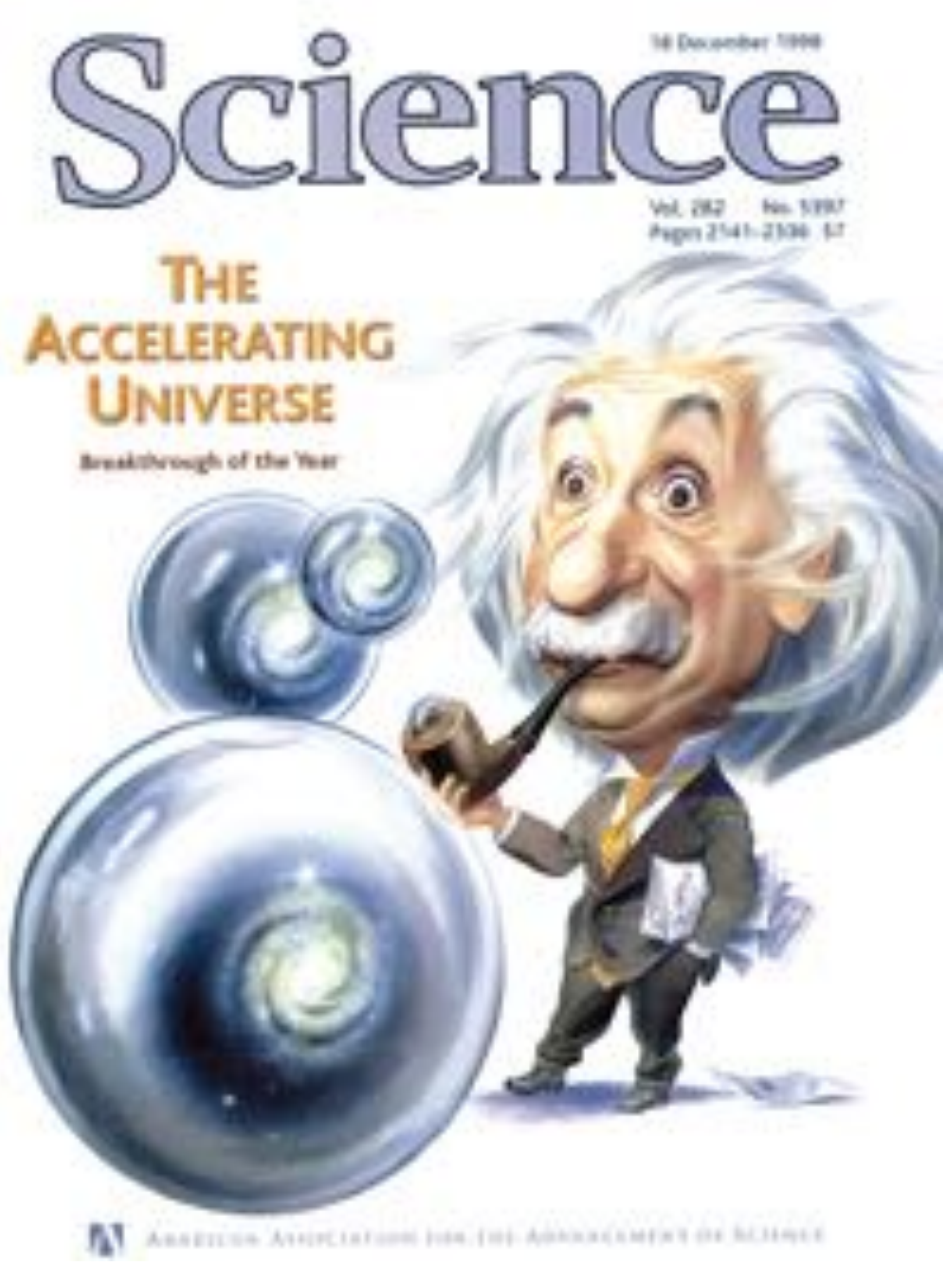
Structure seen in distribution of galaxies

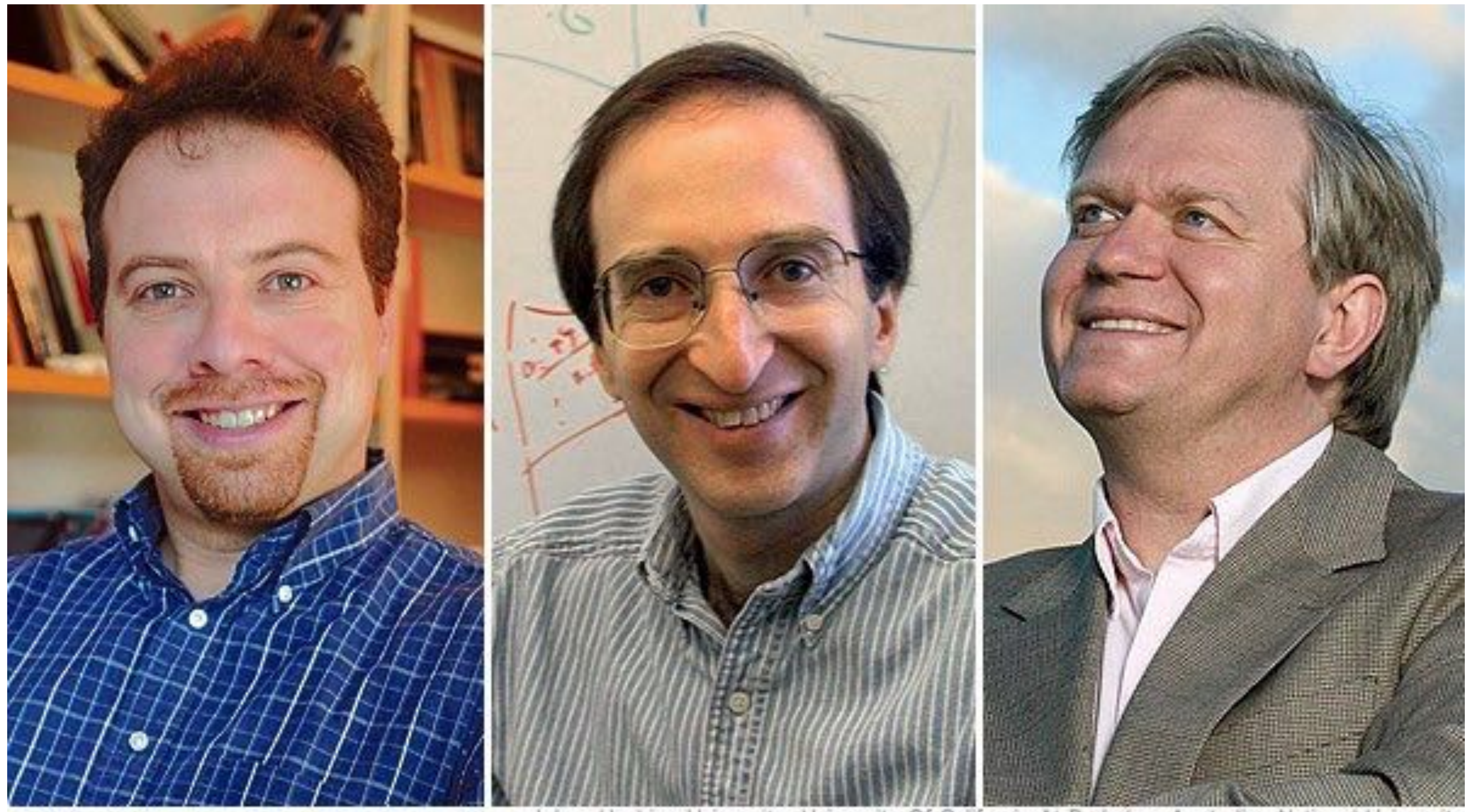
1977-1982: John Huchra, Margaret Geller et al. map galaxy 3D positions with the CfA galaxy redshift survey



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?





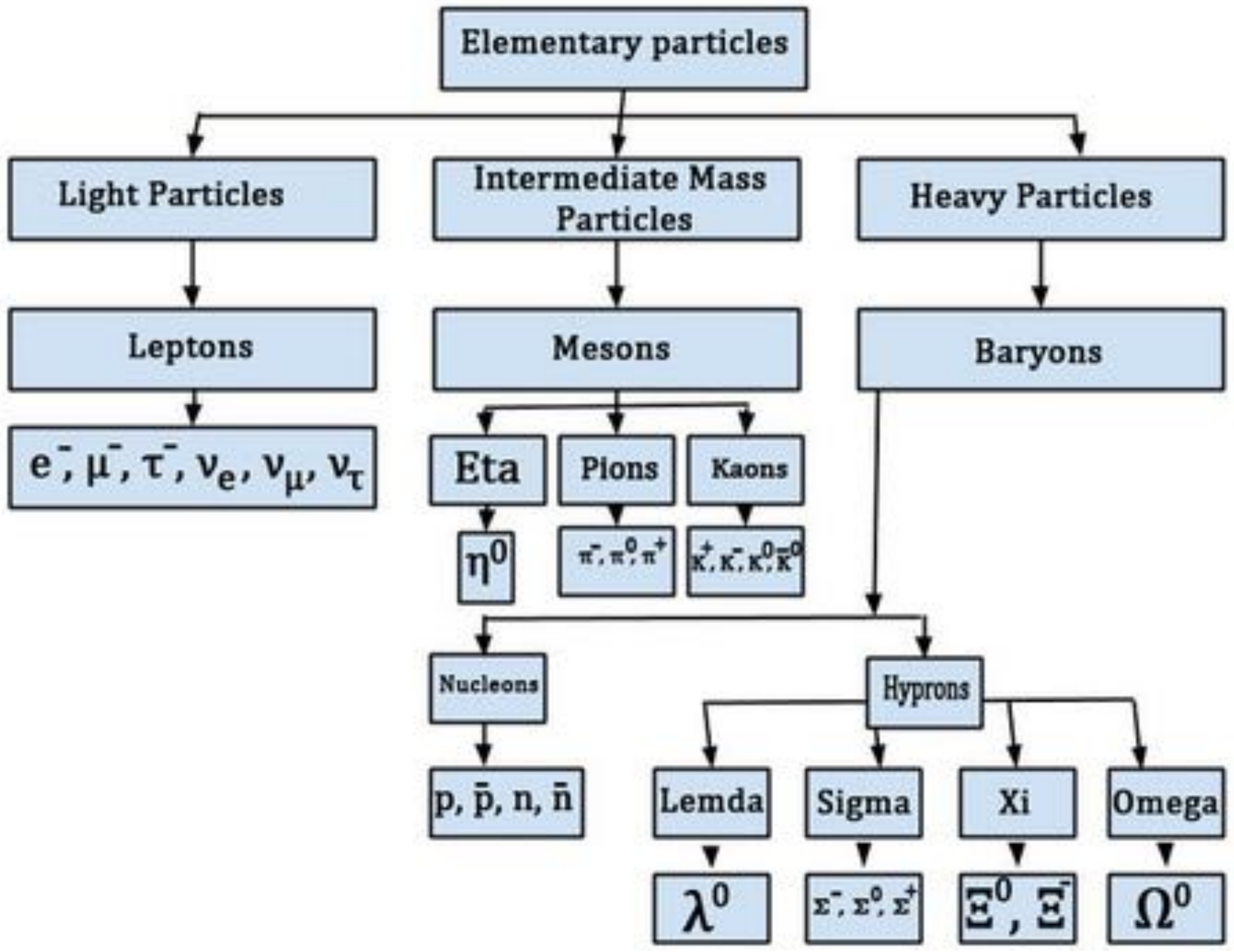
Johns Hopkins University; University Of California At Berkeley; Australian National University

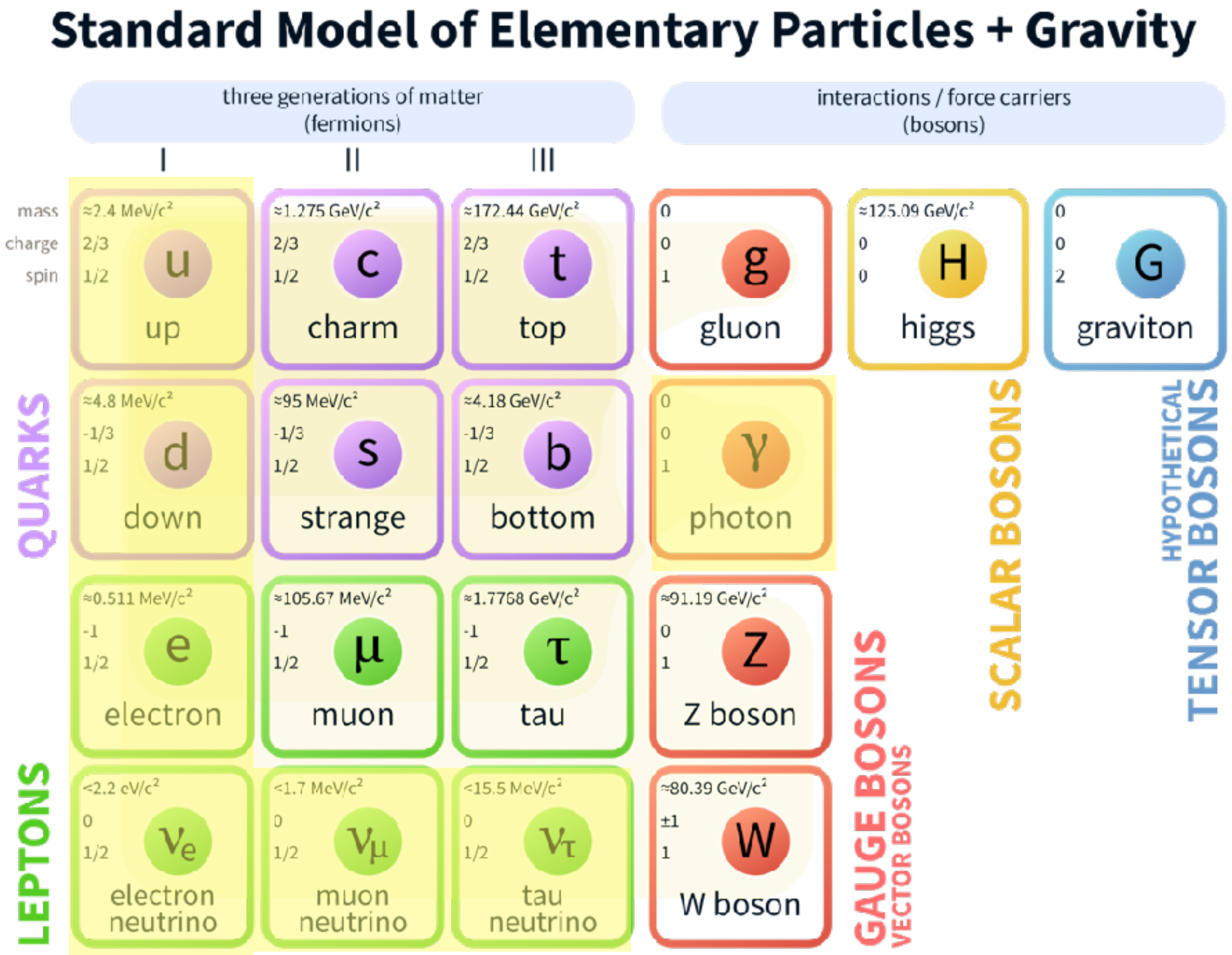
From left, Adam Riess, Saul Perlmutter and Brian Schmidt shared the Nobel Prize in physics awarded Tuesday.

Nobel Prize in Physics (2011)

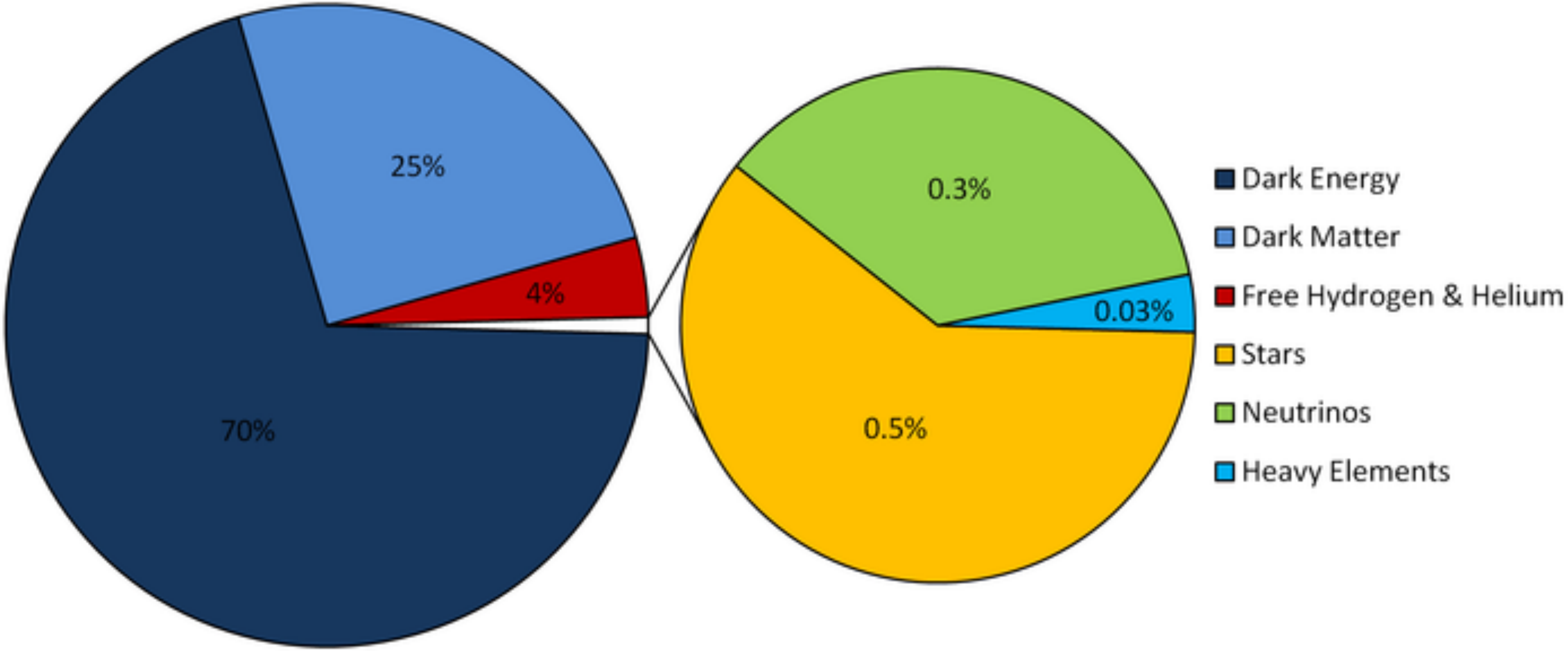
Elementary Particles

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

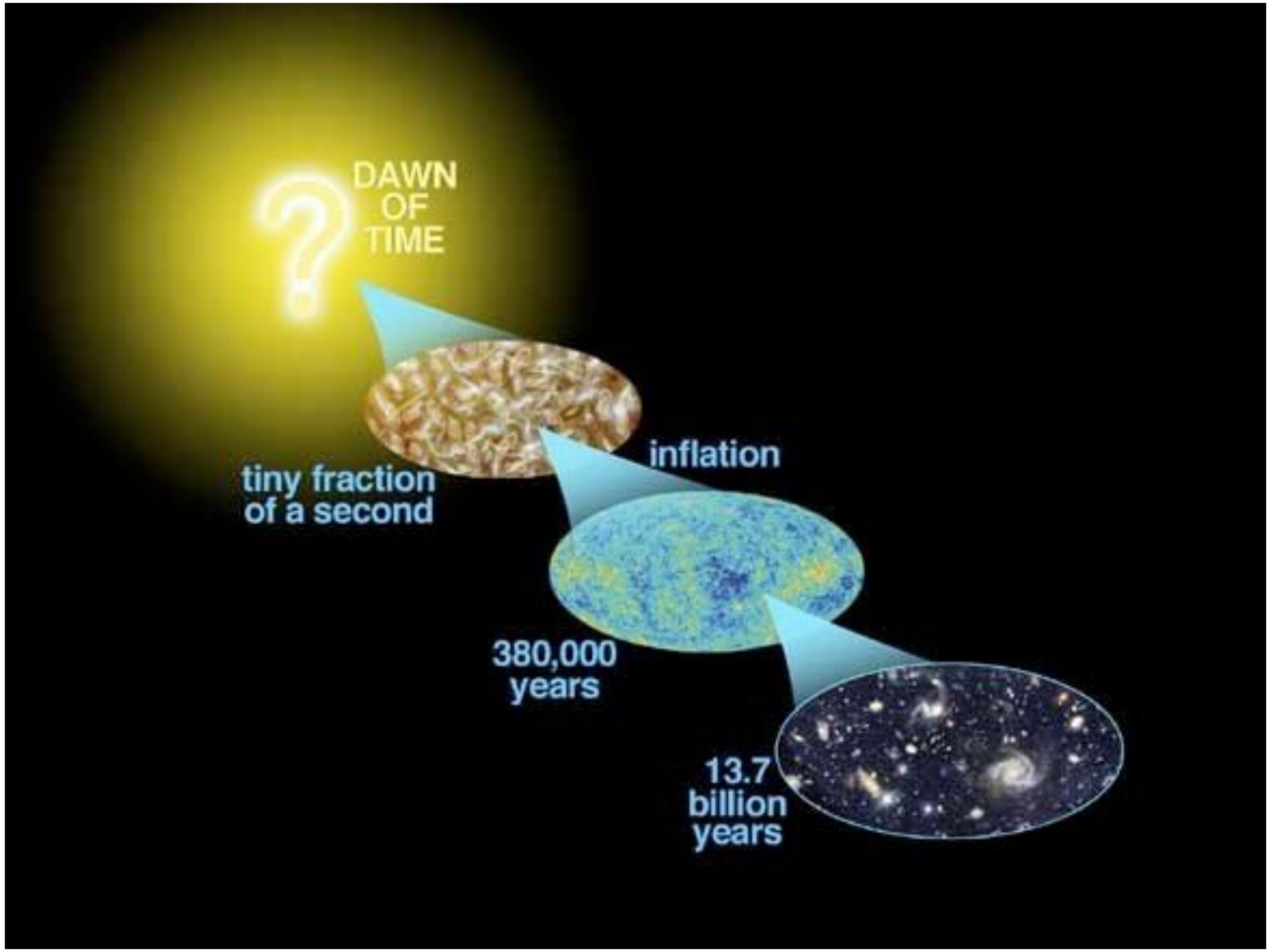




Relative Contents of Universe



Evolution of the Universe



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

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

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 $h/(M_P\, c) \sim l_p$.

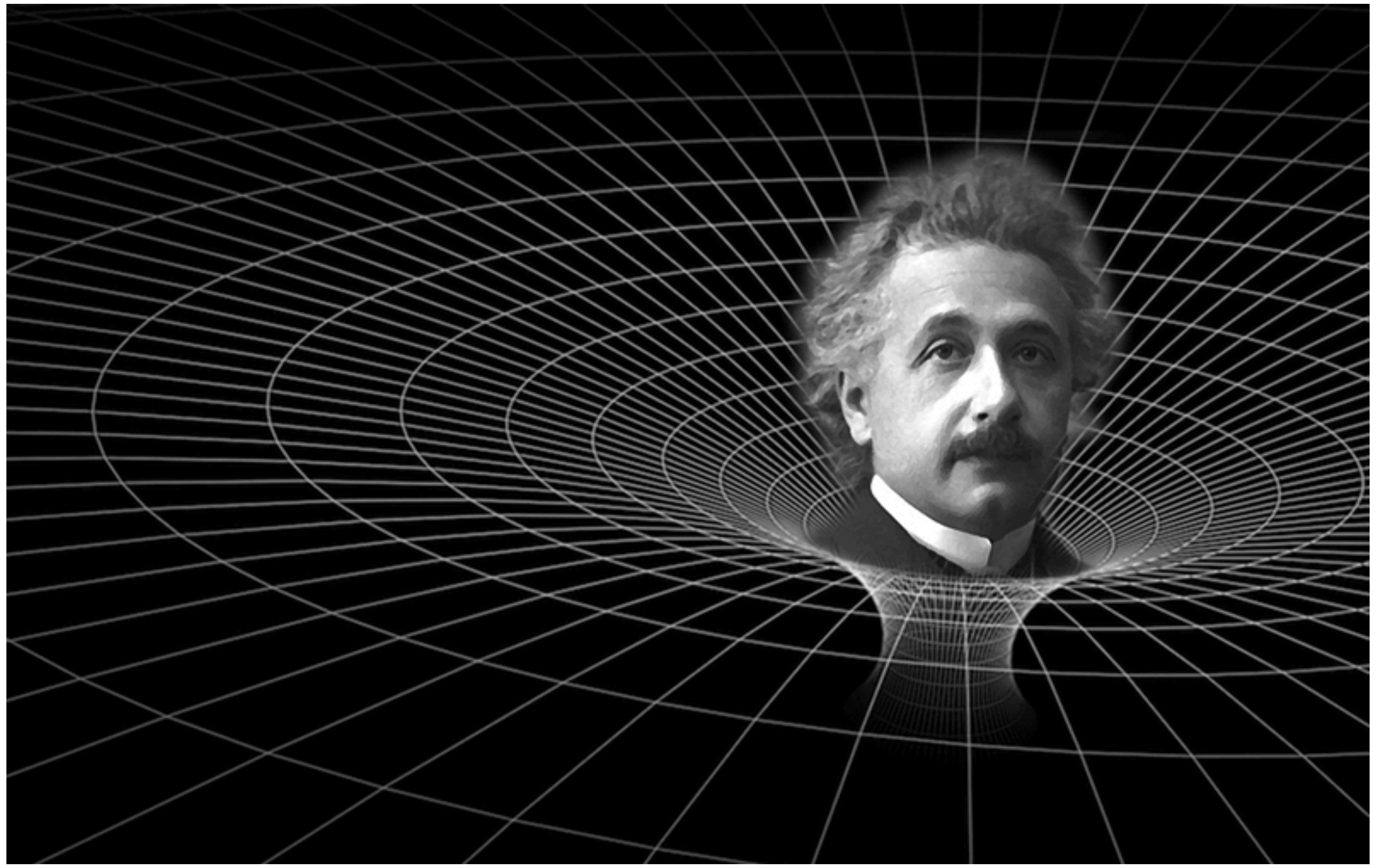
- When the universe is at age $\sim t_p$, horizon scale $\sim ct_p \sim l_p$.
- We need gravity theory to study what's going on at scales of l_p.
- But quantum fluctuation is of order l_p.
- We no longer have smooth space-time.

- GR breaks down.

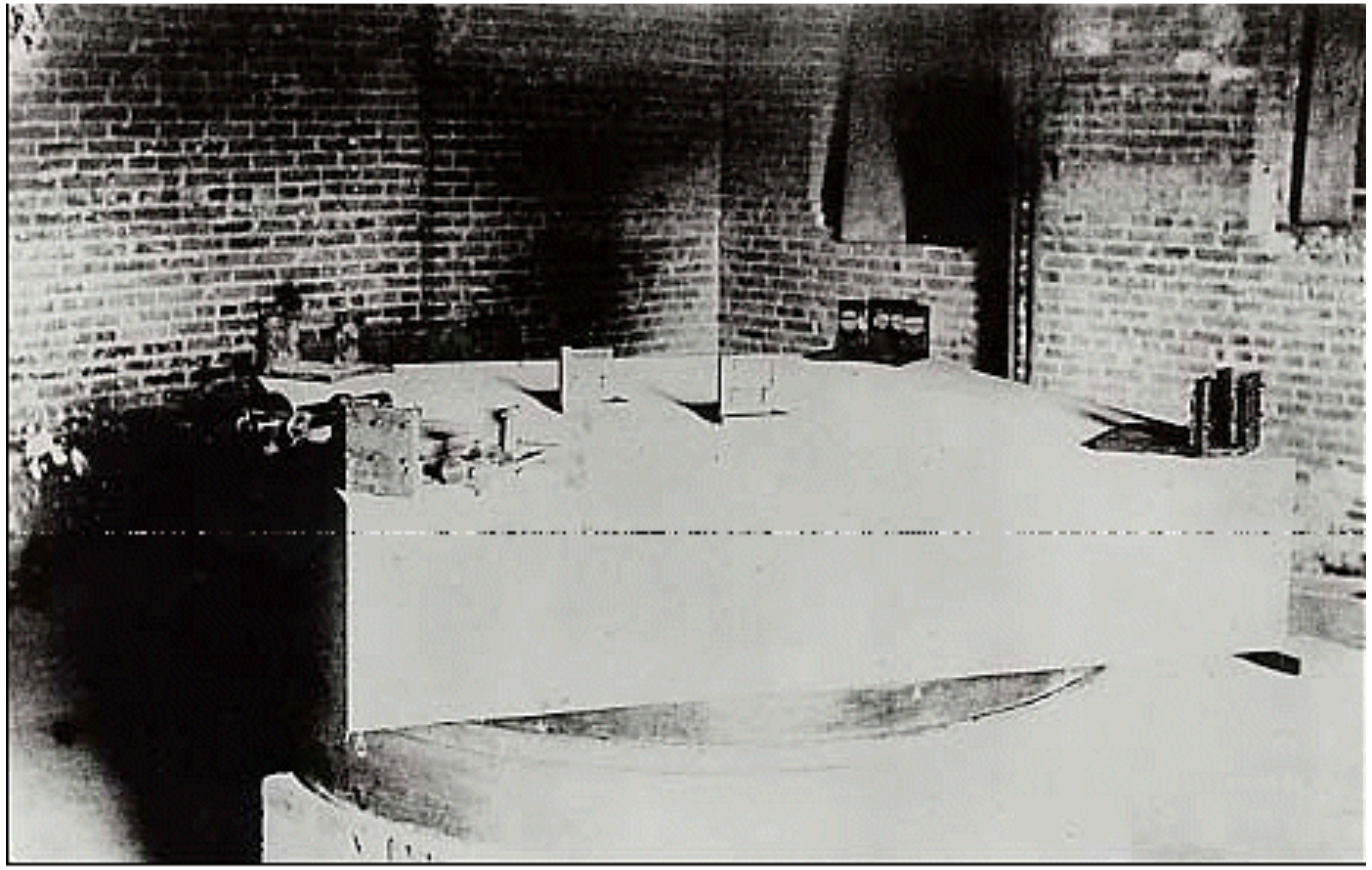
- We need quantum gravity (unification of GR and Quantum physics).
- Before we have such a theory, we can only in principle study the universe at age > t_p, or scale > l_p.

Special & General Relativity

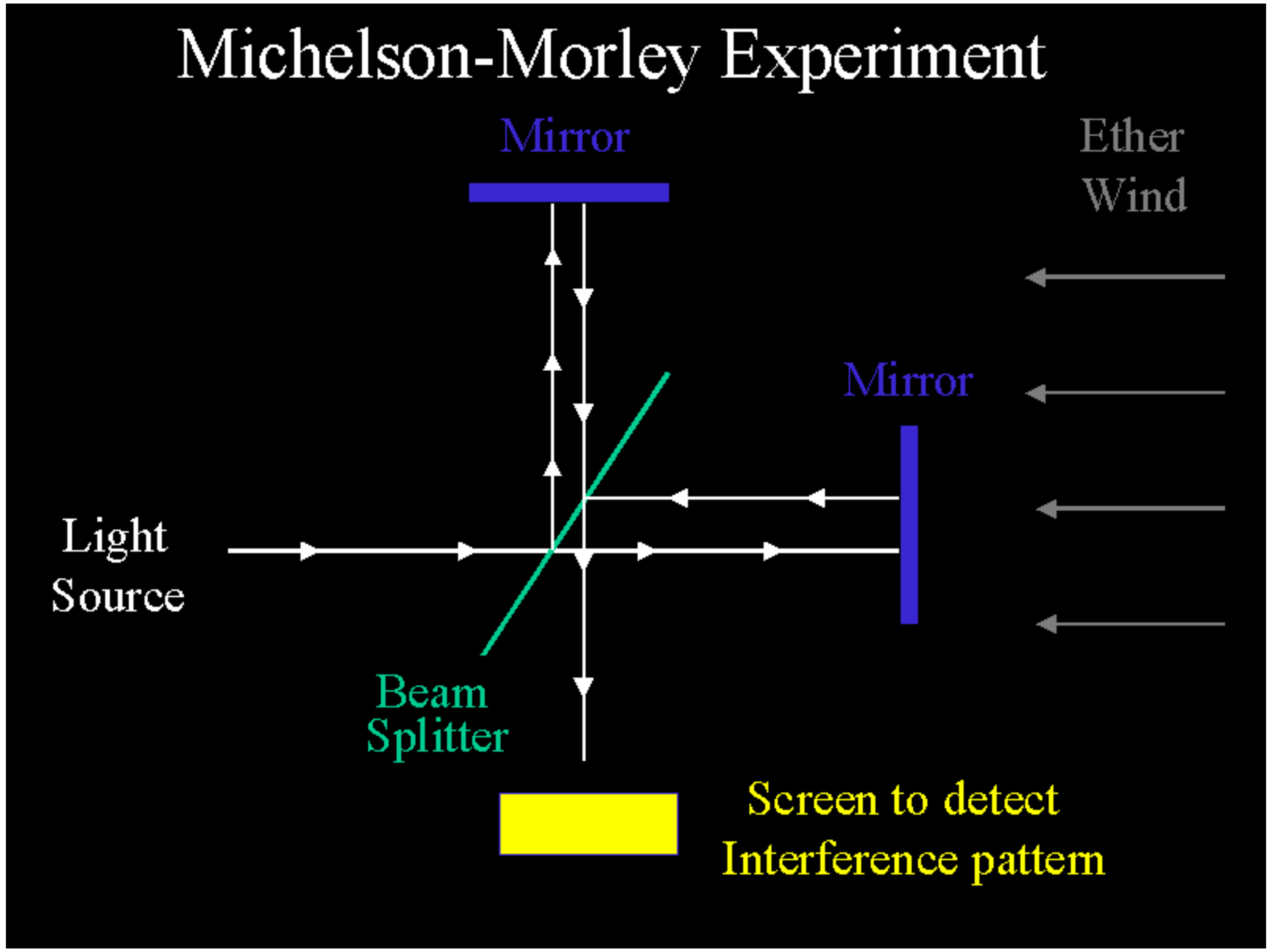
Chapter 3



Special Relativity: no "ether"



Michelson & Morley's 1887 interferometer
built in the basement of Western Reserve
Photo: Case Western Reserve Archive



Presumes absolute space and time, light is a vibration of some medium: the ether

Equivalence Principle(s)

$$\mathbf{F} = m_I \mathbf{a}$$

reflect an object's inertia
(how hard to make it move)

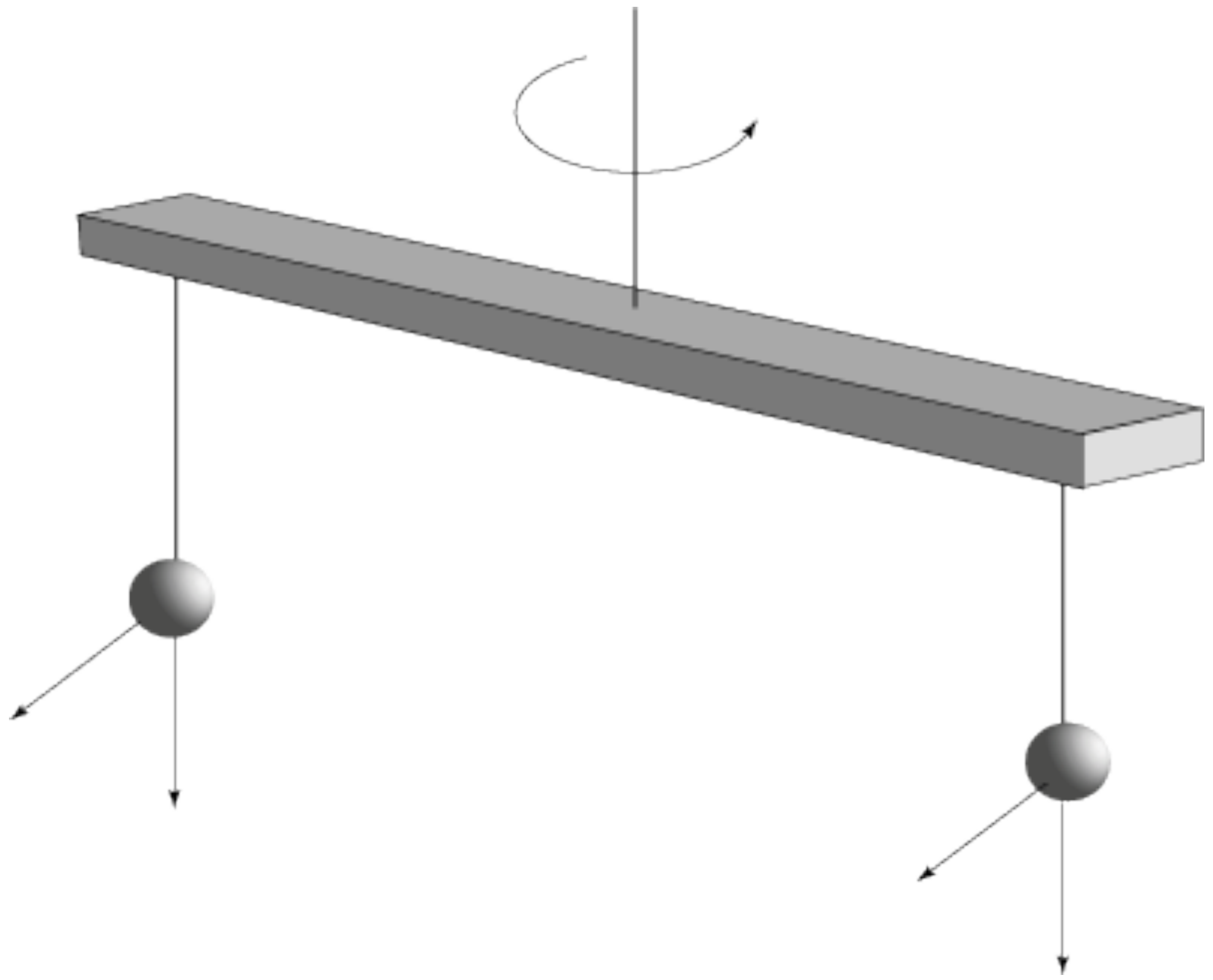
$$\mathbf{F} = -\frac{GM_G m_G}{r^2}\hat{r} = m_G \mathbf{g}$$

reflect the strength of the grav. interaction;
nothing to do with inertia at all;
may just call it "gravity charge" (like electric charge)

Galileo, and later Eötvös, experimentally demonstrated that:

$$m_I = m_G$$

suspicious…



Special relativity resulted from realizing the laws of physics must be identical in any inertial frame

How can a similar realization lead to the consequences of general relativity?

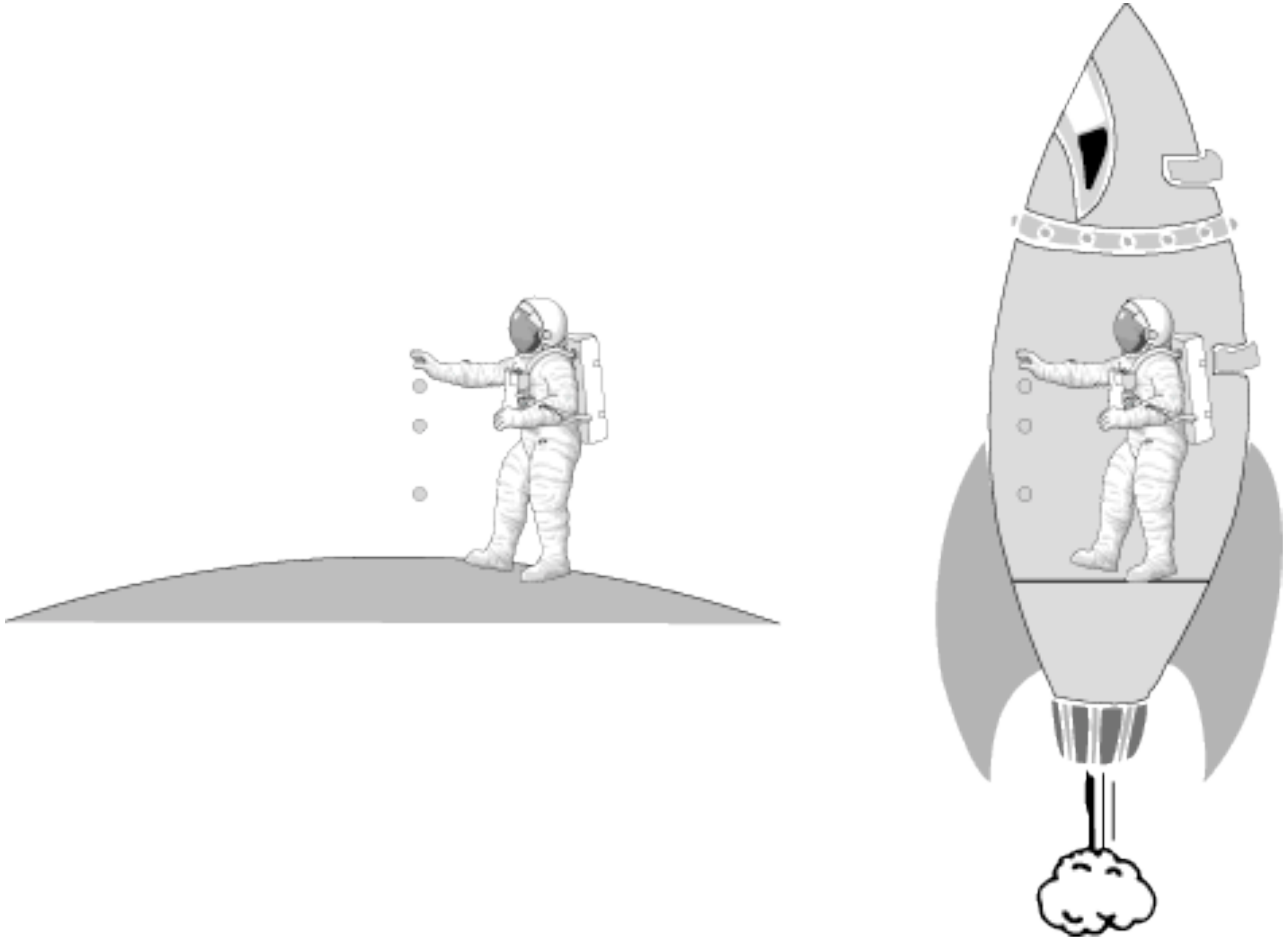
Equivalence Principle: Newton

"Gravitational mass" and "inertial mass" are equivalent

You cannot distinguish gravity from any other acceleration

Gravity even affects massless particles like light

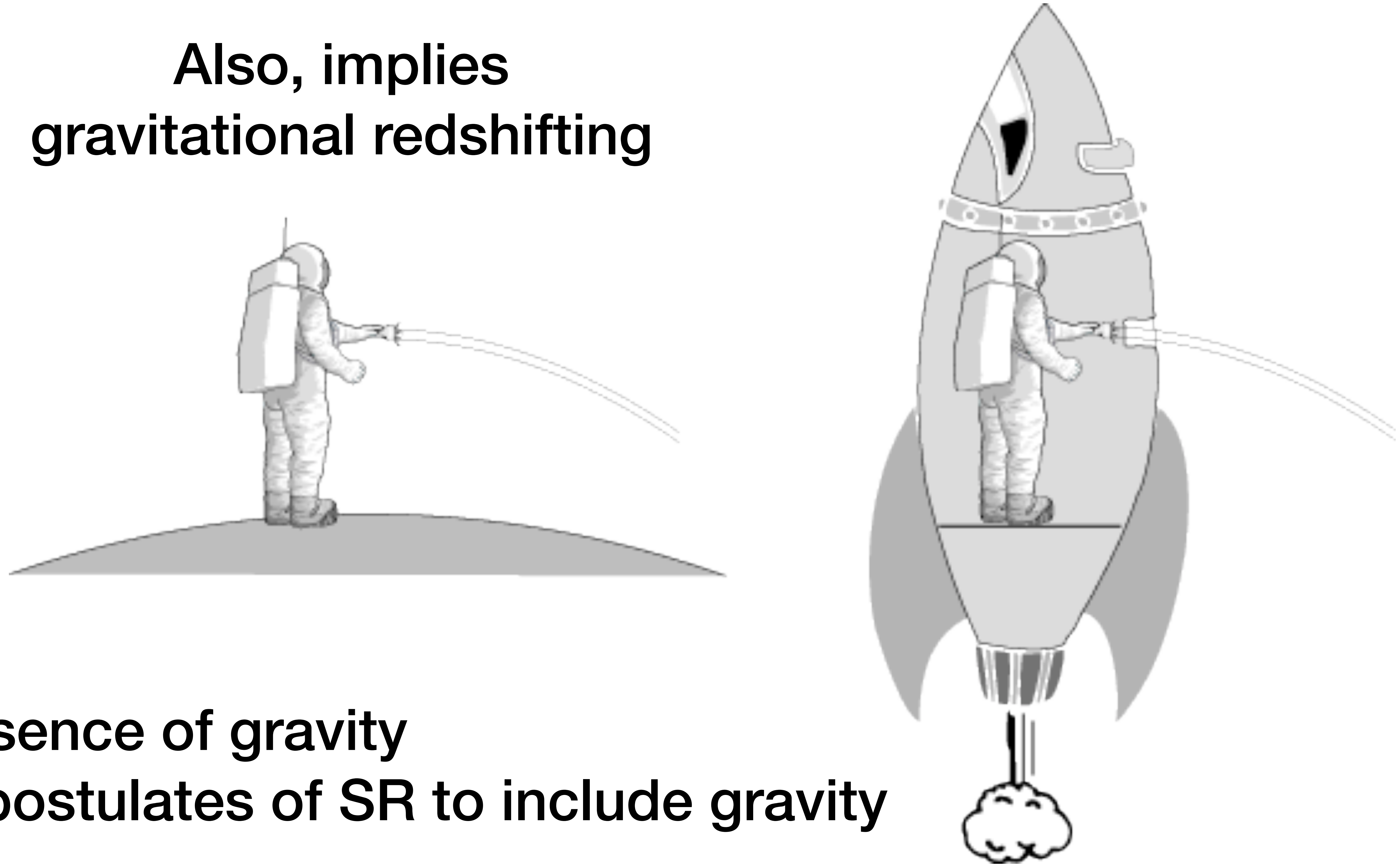
Only applies to mechanics: E&M not included until special relativity



Equivalence Principle: Einstein

No experiment can distinguish between an accelerated frame and a gravitational field – they are completely equivalent

Also, implies gravitational redshifting



“Special” relativity applies in the absence of gravity
“General” relativity generalizes the postulates of SR to include gravity

Mach’s Principle: inertial frames aren’t absolute, but determined by the distribution of matter — can’t have motion without something else a thing is moving relative to

Implication of Stricter Equivalence for Light

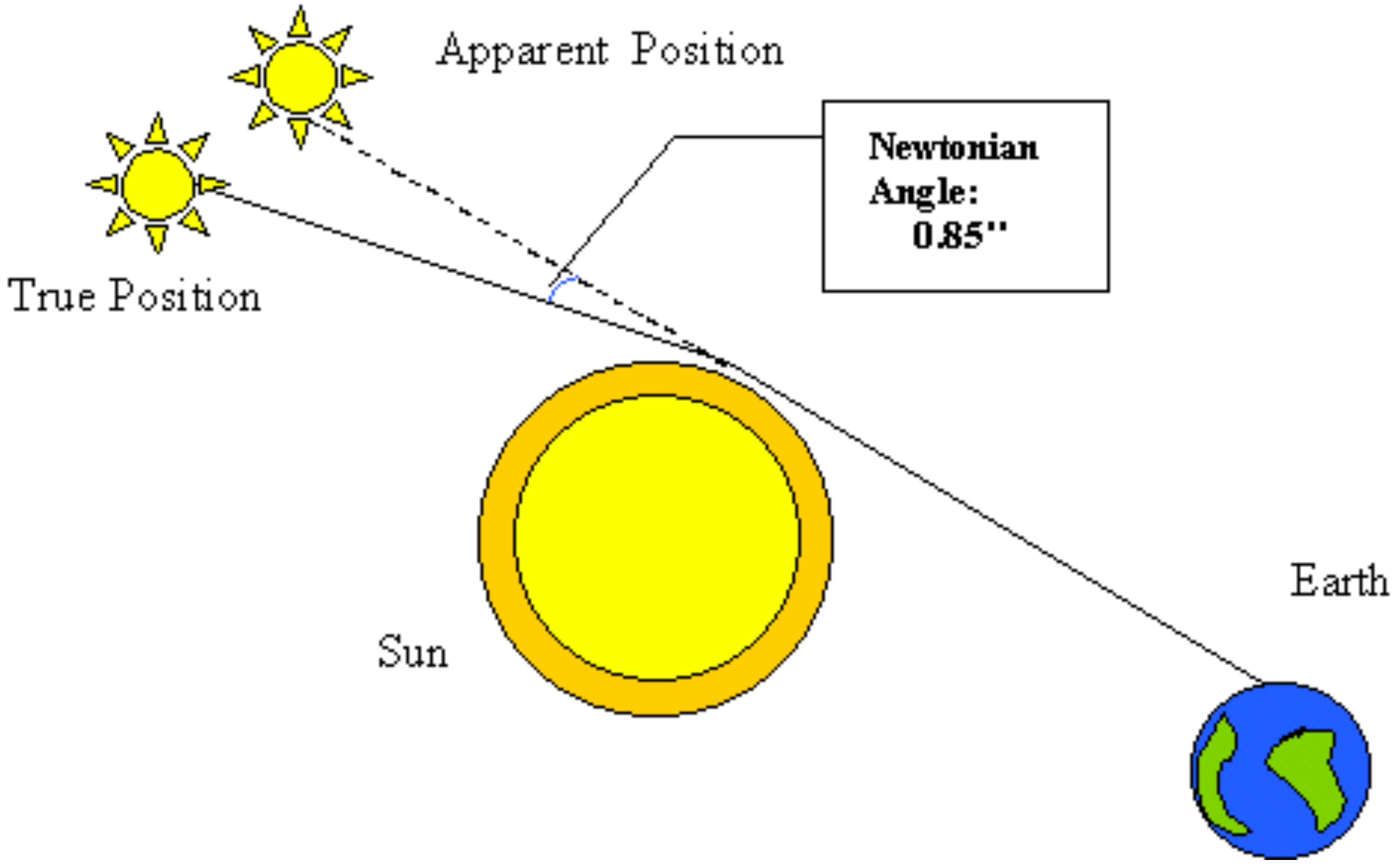
Fermat's Principle in optics states that light travels the maximal (general the minimum) distance between two points

If light takes a curved path, space cannot be Euclidean (flat) because the shortest path in Euclidean geometry is a straight line

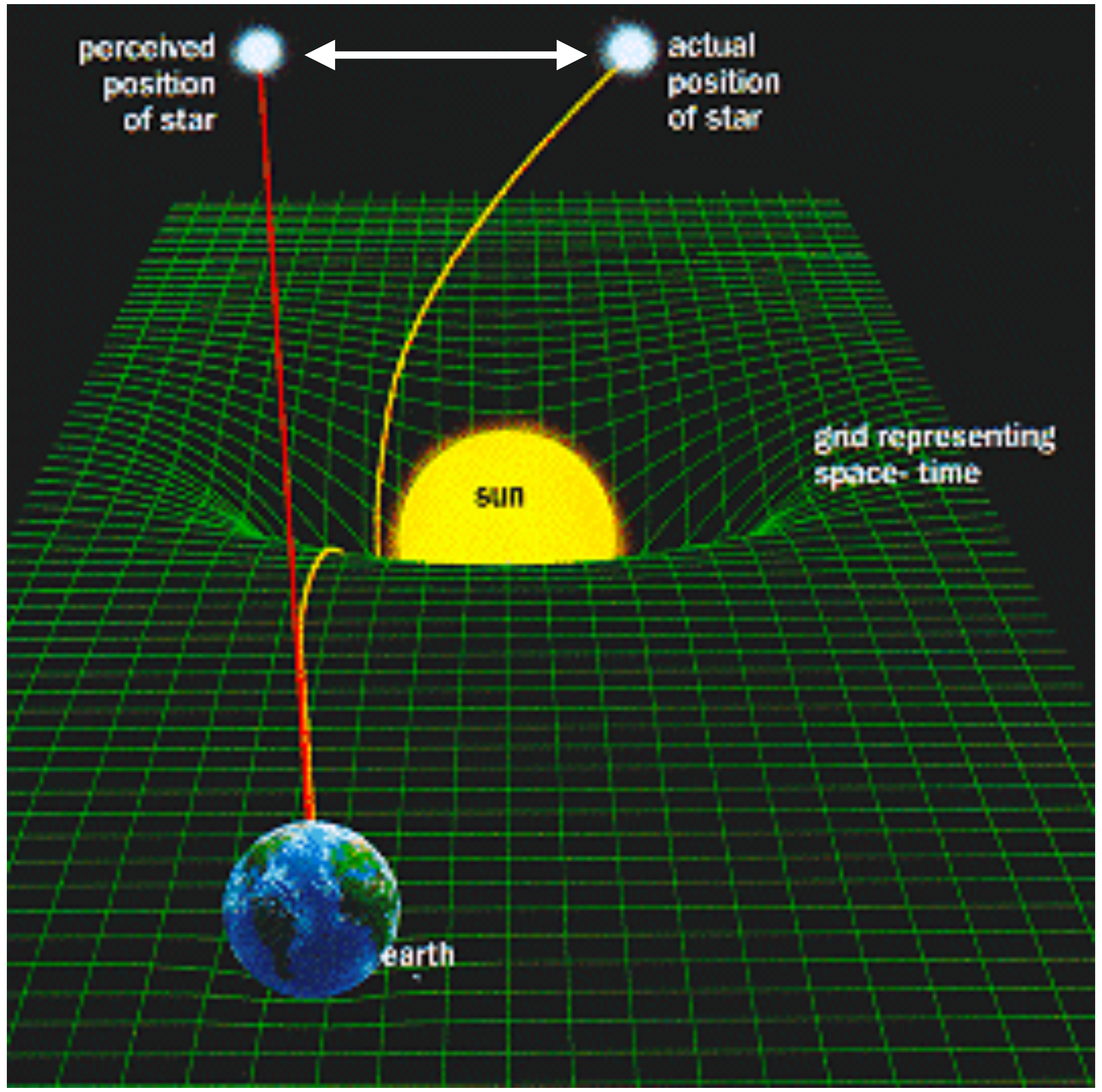
If space is curved (like surface of a sphere), then Fermat's Principle may still hold

—> Matter (and Energy, b/c $E=mc^2$) tells spacetime how to curve, and curved spacetime tells matter (and energy) how to move

Experimental Confirmation of GR



Angle in GR is ~1.75”:
additional deflection due to curved space-time

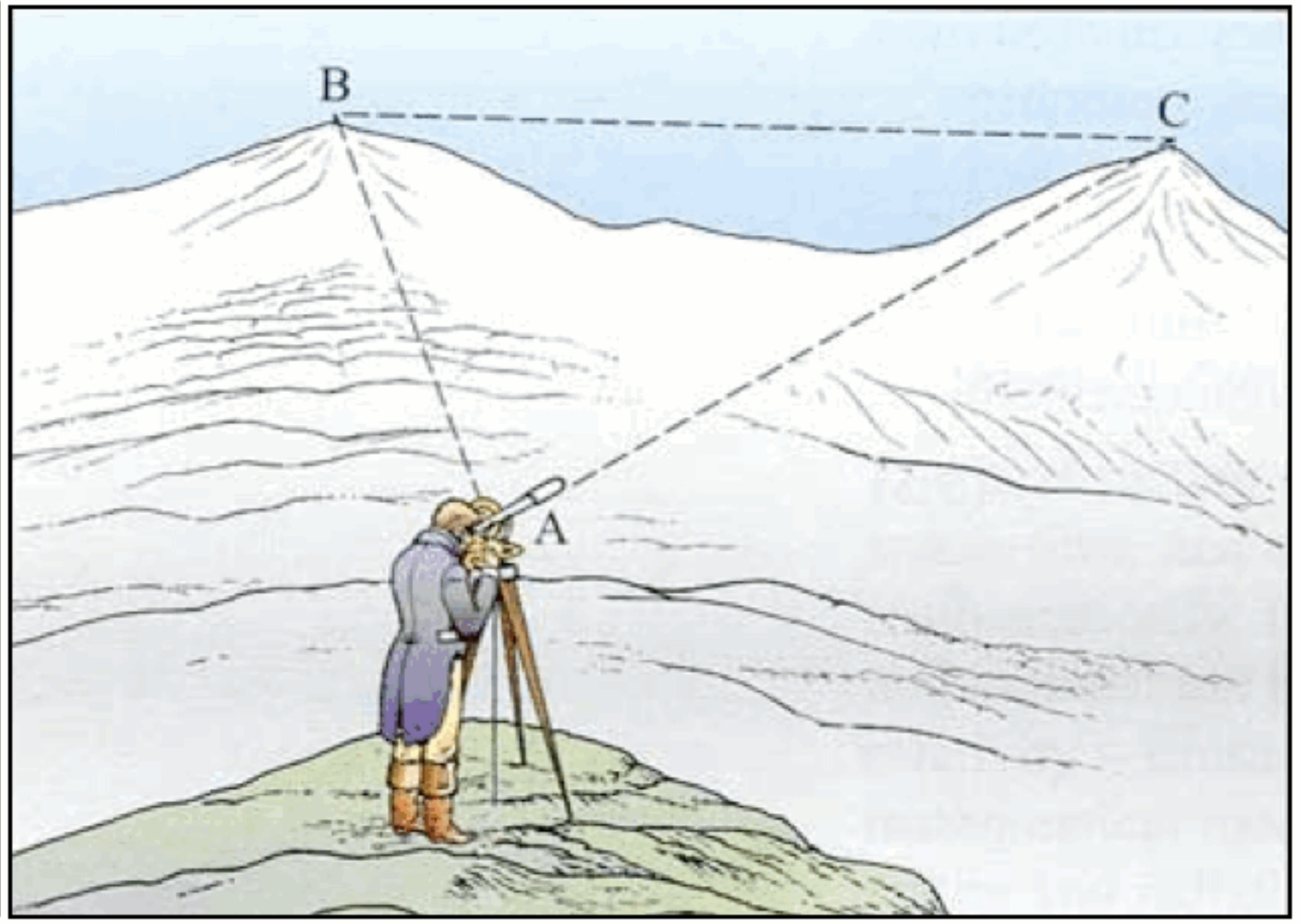


“Confirmed” by Arthur Eddington during the 1919 solar eclipse
—> reason Einstein became famous

Curvature

How can we measure the curvature of spacetime?

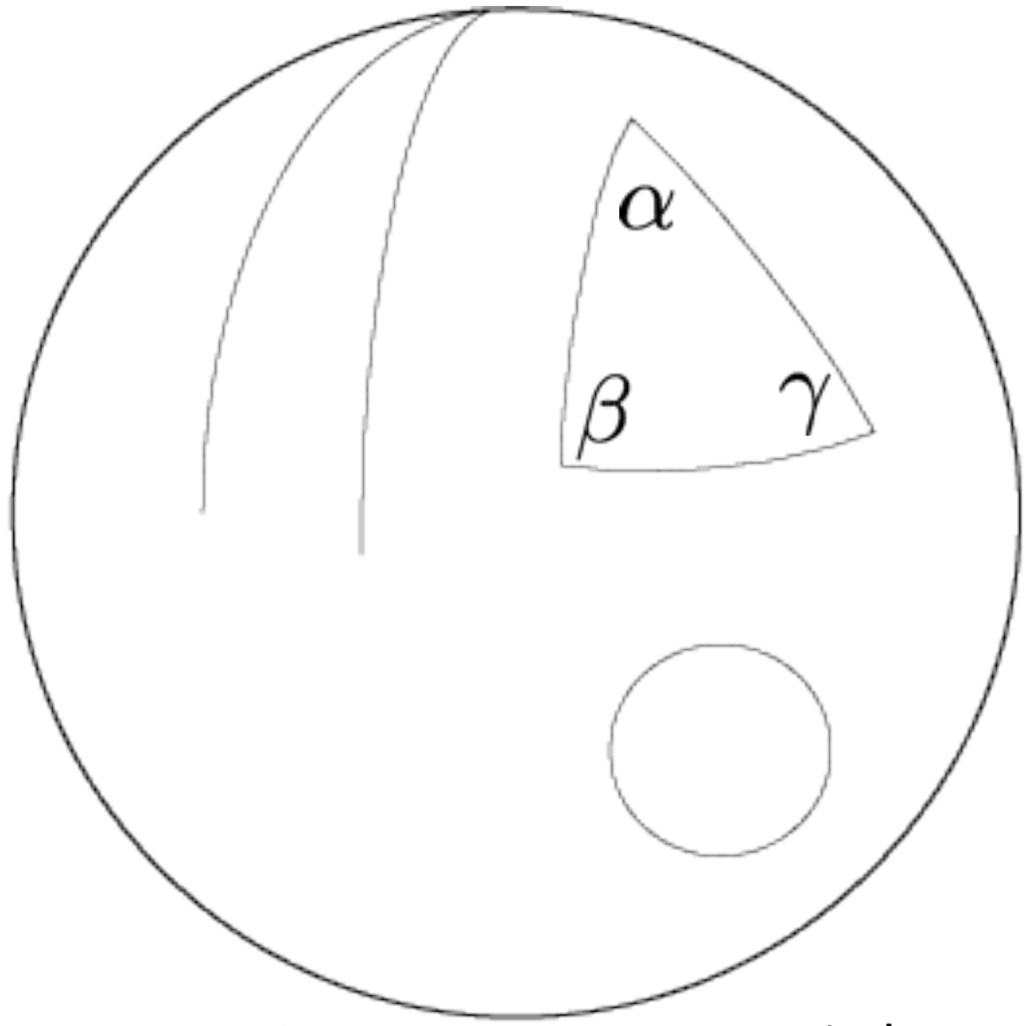
Carl Friedrich Gauss
1777 - 1855



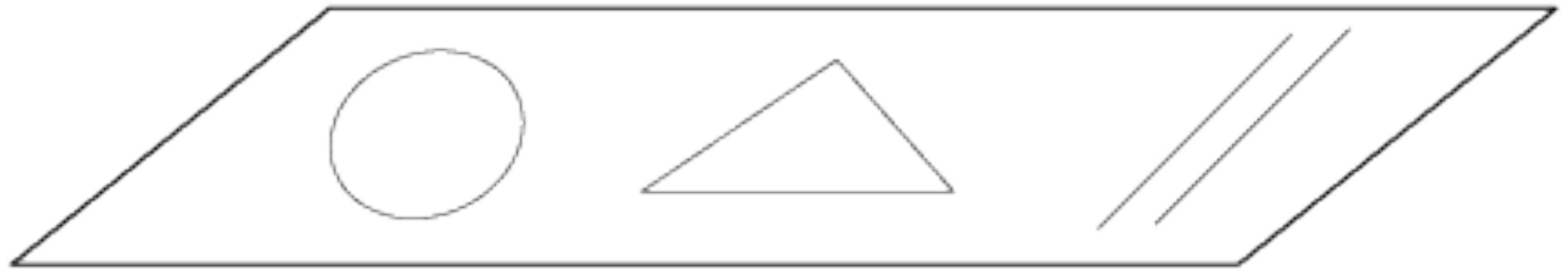
Gauss finds 180 degrees in large survey triangles:
Space is not (grossly) non-Euclidean

A = area of triangle R = Radius of Curvature

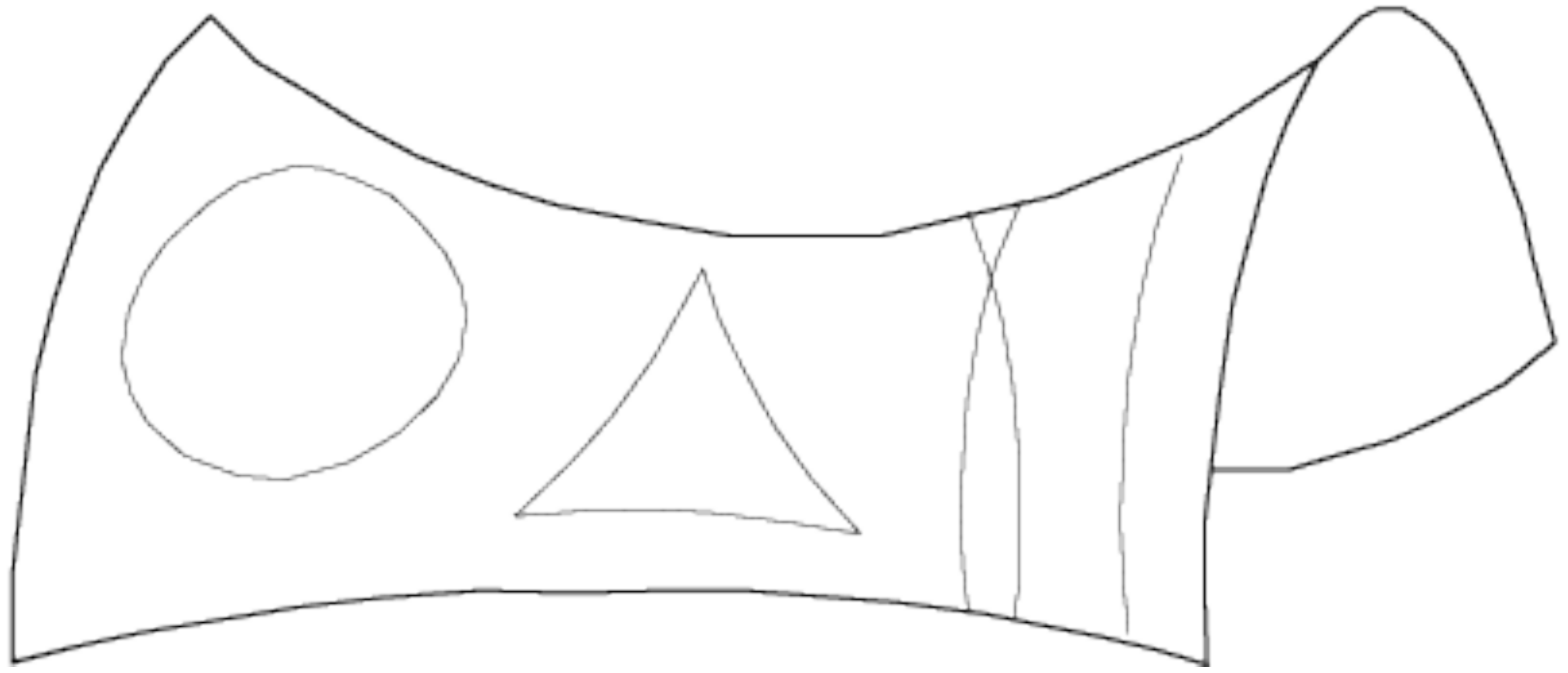
Only possible geometries that are homogeneous/isotropic



$$\alpha + \beta + \gamma = \pi + A/R$$

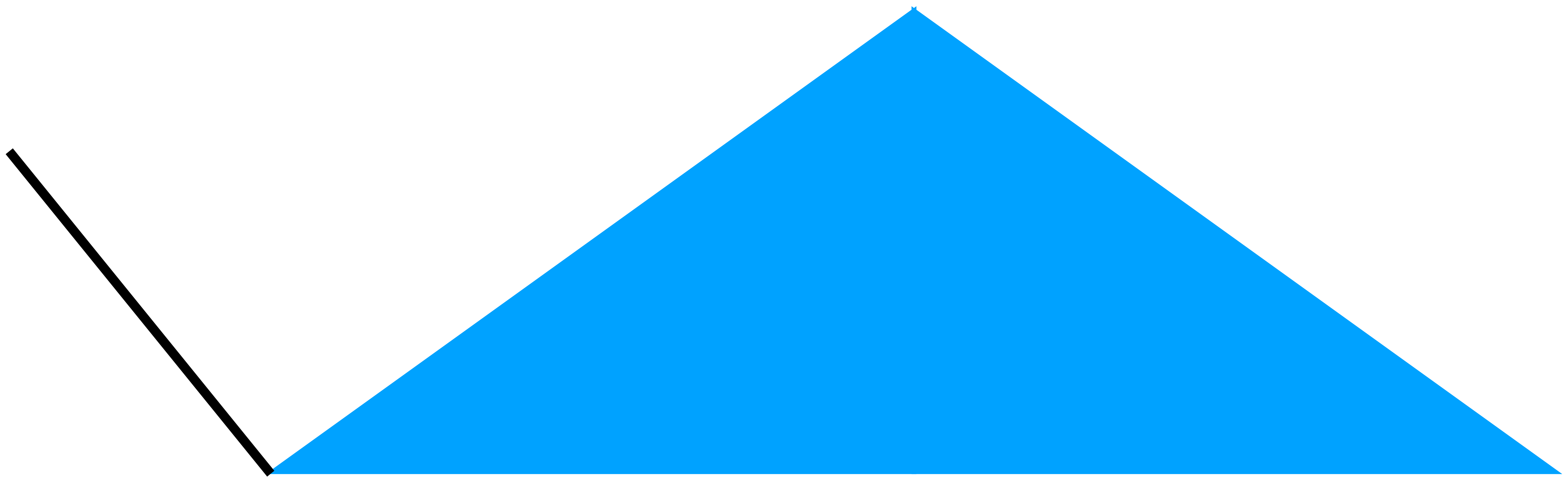


$$\alpha + \beta + \gamma = \pi$$



$$\alpha + \beta + \gamma = \pi - A/R$$

Characterizing Curvature

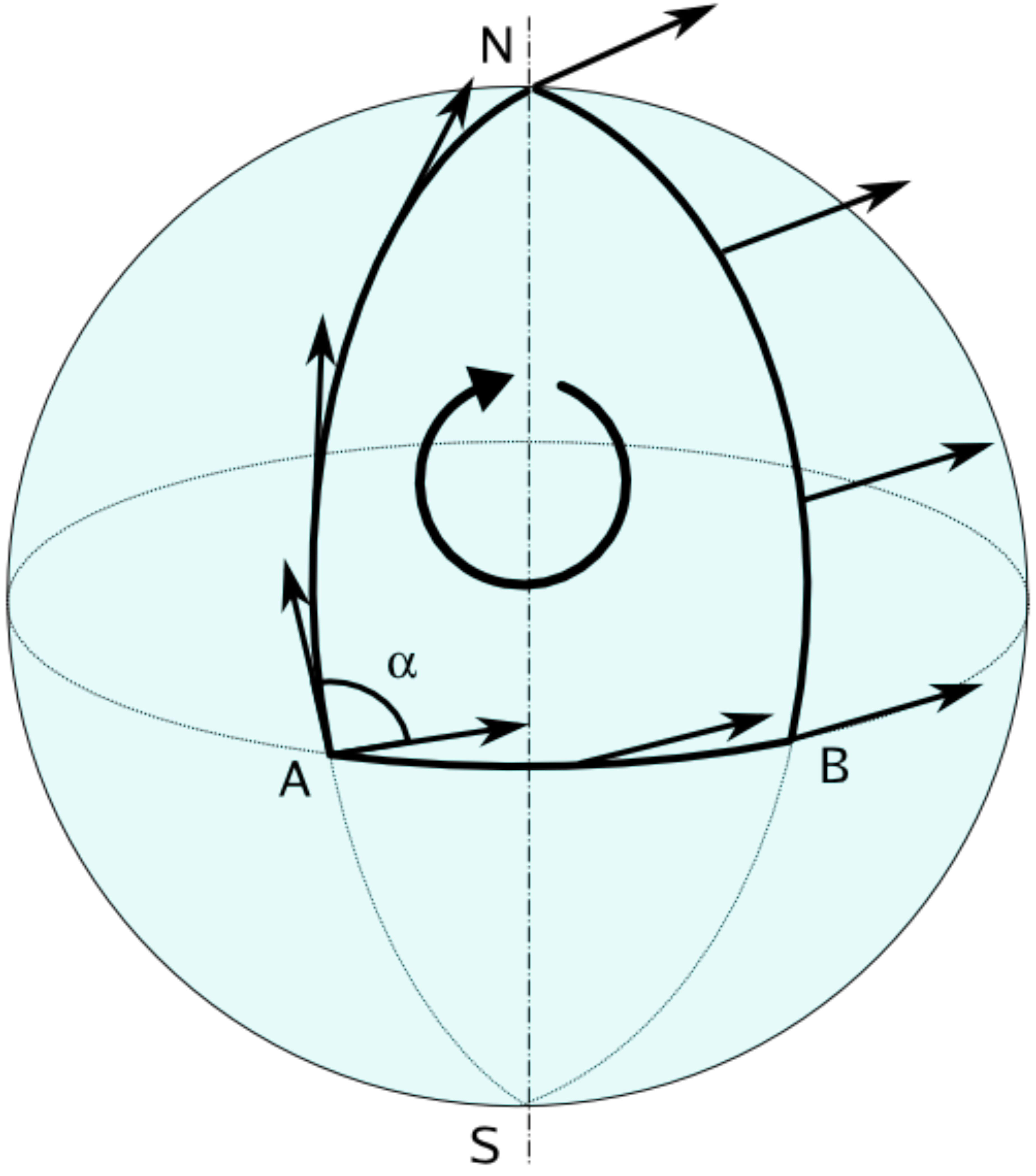


Characterizing Curvature

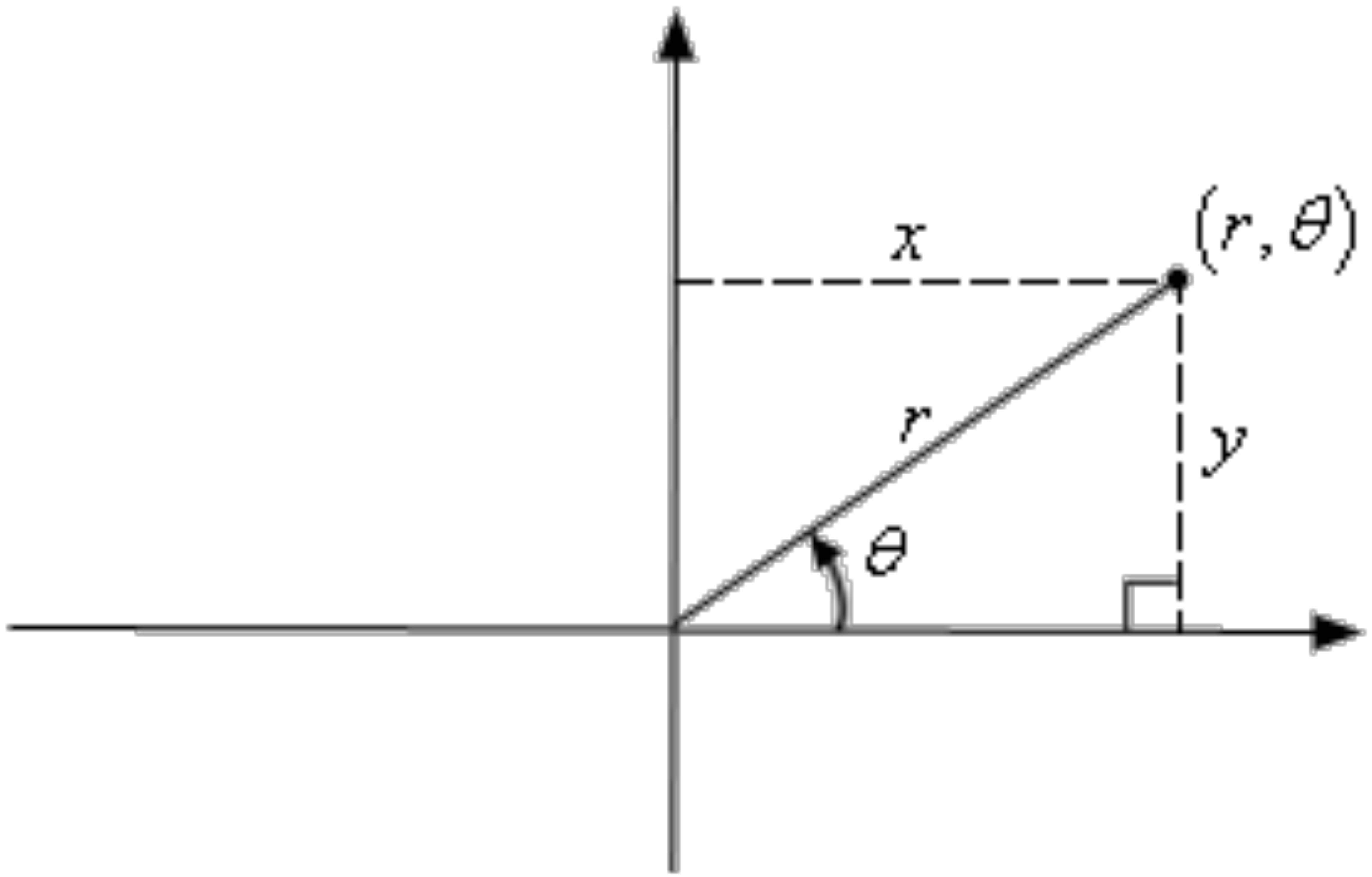
<u>Parallel Transport</u>

transport a vector around a triangle, keeping the vector at the same angle wrt your path at all times

change in vector when you arrive back at your starting position ⟶ curved space



Length of a (Euclidean) Line



$$(x, y) \rightarrow (x + dx, y + dy)$$

$$d\ell^2 = dx^2 + dy^2$$

$$(r, \theta) \rightarrow (r + dr, \theta + d\theta)$$

$$d\ell^2 = dr^2 + r^2 d\theta^2$$

$$x = r\cos\theta, y = r\sin\theta$$

Lengths of Geodesics (3D, polar coords)

→ straight lines in a given geometry

$$d\Omega^2 \equiv d\theta^2 + \sin^2\theta d\phi^2$$

flat or Euclidean space:

$$d\ell^2 = dr^2 + r^2 d\Omega^2$$

elliptical or spherical space:

$$d\ell^2 = dr^2 + R^2 \sin^2 \frac{r}{R} d\Omega^2$$

hyperbolic space:

$$d\ell^2 = dr^2 + R^2 \sinh^2 \frac{r}{R} d\Omega^2$$

<OR>

$$d\ell^2 = dr^2 + S_\kappa(r)^2 d\Omega^2$$

$$S_\kappa(r) = \begin{cases} R\sin\frac{r}{R} & (\kappa = +1) \\ r & (\kappa = 0) \\ R\sinh\frac{r}{R} & (\kappa = -1) \end{cases}$$

Minkowski & Robertson-Walker Metrics

metrics define the distance between events in spacetime

Minkowski (no gravity: metric in SR)

$$ds^2 = -c^2dt^2 + dr^2 + r^2d\Omega^2$$

Robertson-Walker (with gravity, if spacetime is homogeneous & isotropic)

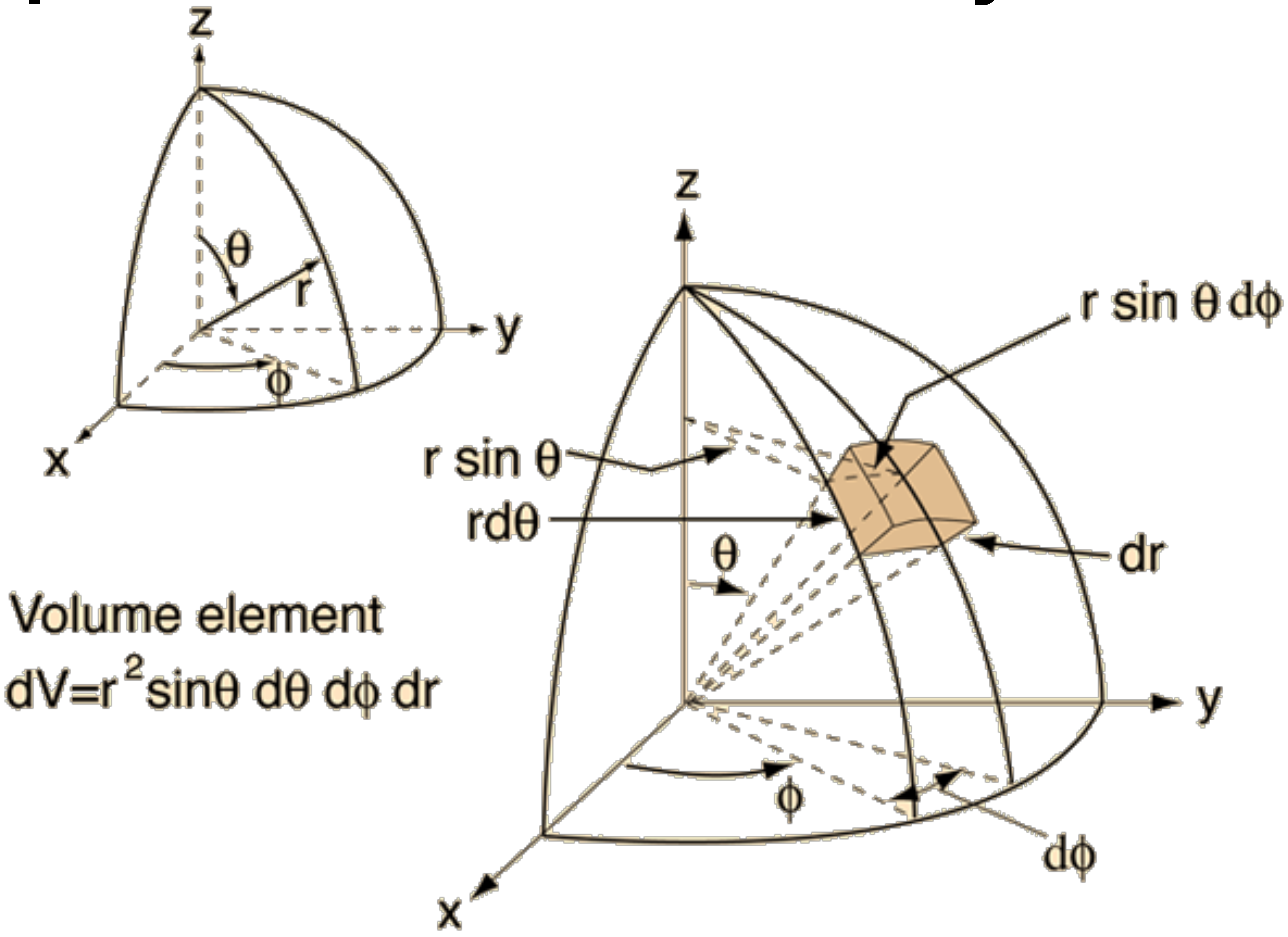
$$ds^2 = -c^2dt^2 + a(t)[dr^2 + S_\kappa(r)^2d\Omega^2]$$

light travels along null geodesics, i.e.: $ds^2 = 0$

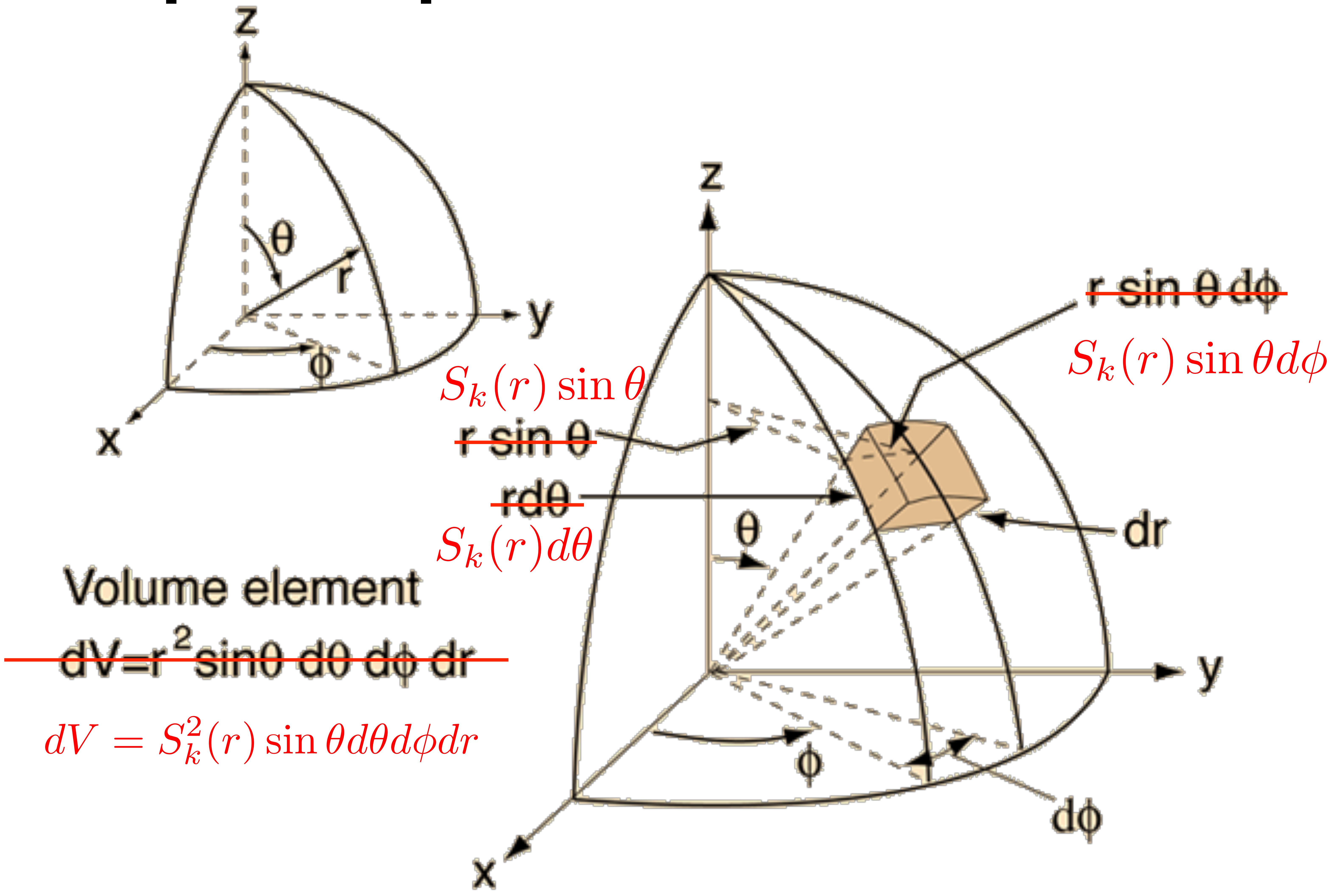
cosmological proper time or cosmic time

(r, θ, ϕ) comoving coordinates

Spherical Coordinate System



Spatial part of RW metric



At time t, $adr, \;\; aS_k(r)d\theta, \;\; aS_k(r)\sin\theta d\phi$

Proper Distance

In an expanding universe, how do we define the distance to something at a cosmological distance?

The distance between 2 objects at the same instant of time is given by the RW metric: called the "proper distance"

$$ds = a(t)dr$$

$$d_p(t) = a(t)\int_0^r dr = a(t)r$$

$$\dot{d}_p = \dot{a}r = \frac{\dot{a}}{a}d_p$$

$$v_p(t_0) \equiv H_0 d_p(t_0) \rightarrow d_H(t_0) \equiv c/H_0$$

Redshift and Scale Factor

Proper distance is not usually a practical distance measure.
For example, you might rather want to know the distance light has traveled from a distant object so you know the "lookback time" or how far you're looking into the past.

Relatedly, we measure redshift, but would like to know how redshift is related to the change in scale factor between emission and observation, which is:

$$1 + z = \frac{a(t_0)}{a(t_e)} = \frac{1}{a(t_e)}$$