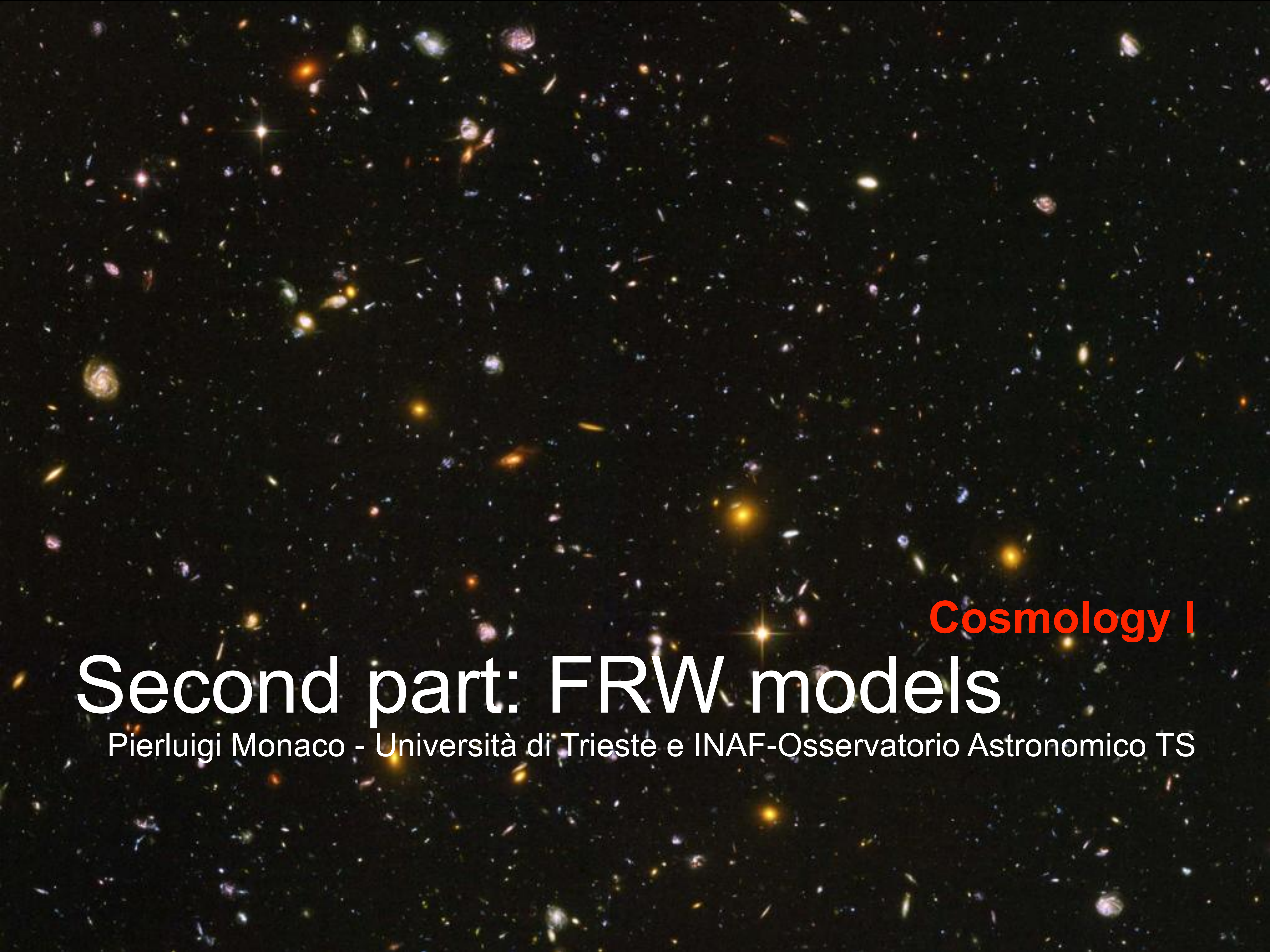


Cosmology I

Second part: FRW models

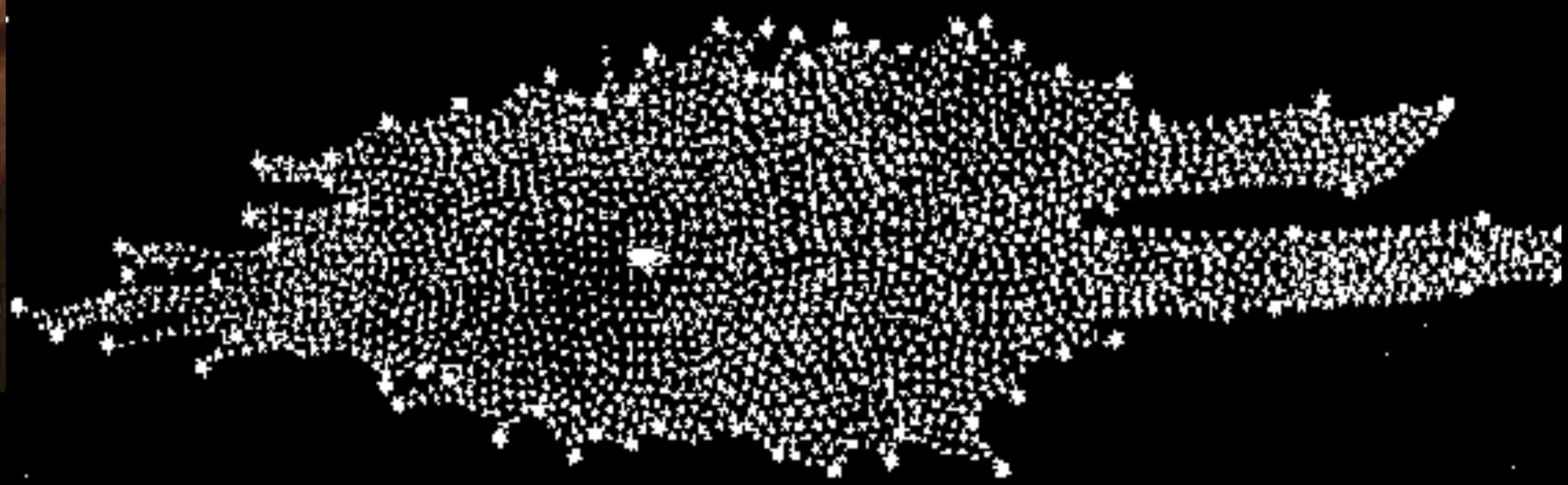
Pierluigi Monaco - Università di Trieste e INAF-Osservatorio Astronomico TS

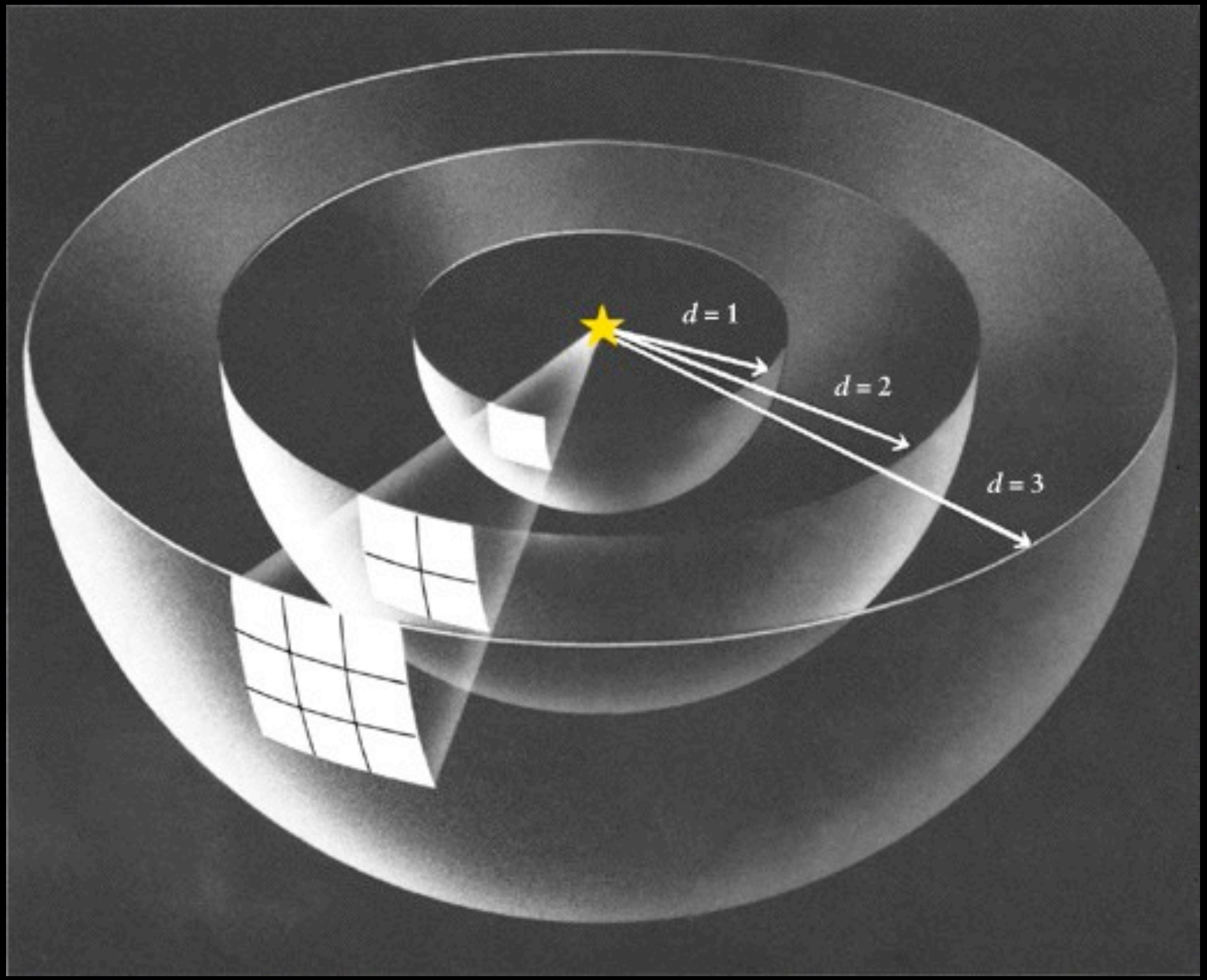
Epistemological facts:

- ⋆ The Universe is everything we can observe or experiment.
- ⋆ But we cannot observe to infinity, we have a horizon.
- ⋆ Under the hypothesis of cosmic homogeneity, we can follow the evolution of the Universe in time.
- ⋆ We need to take profit of all evidence.

William Herschel
1738-1822

1785



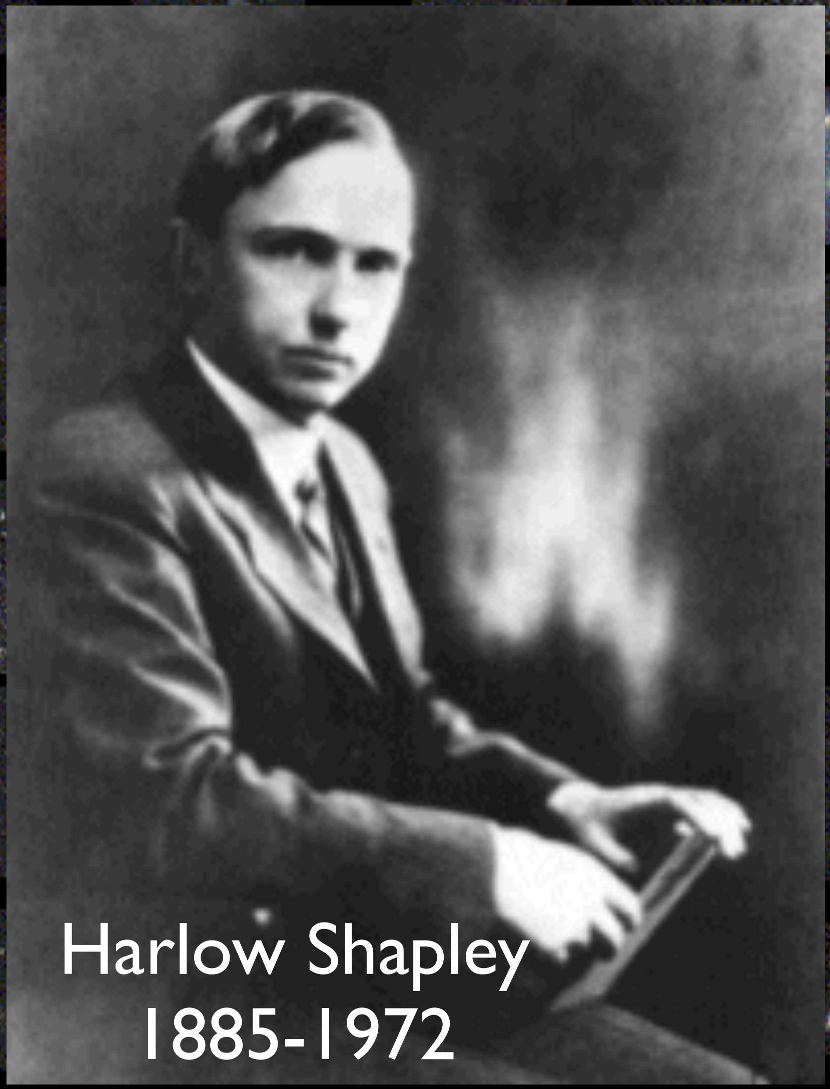


d = 1
d = 2
d = 3

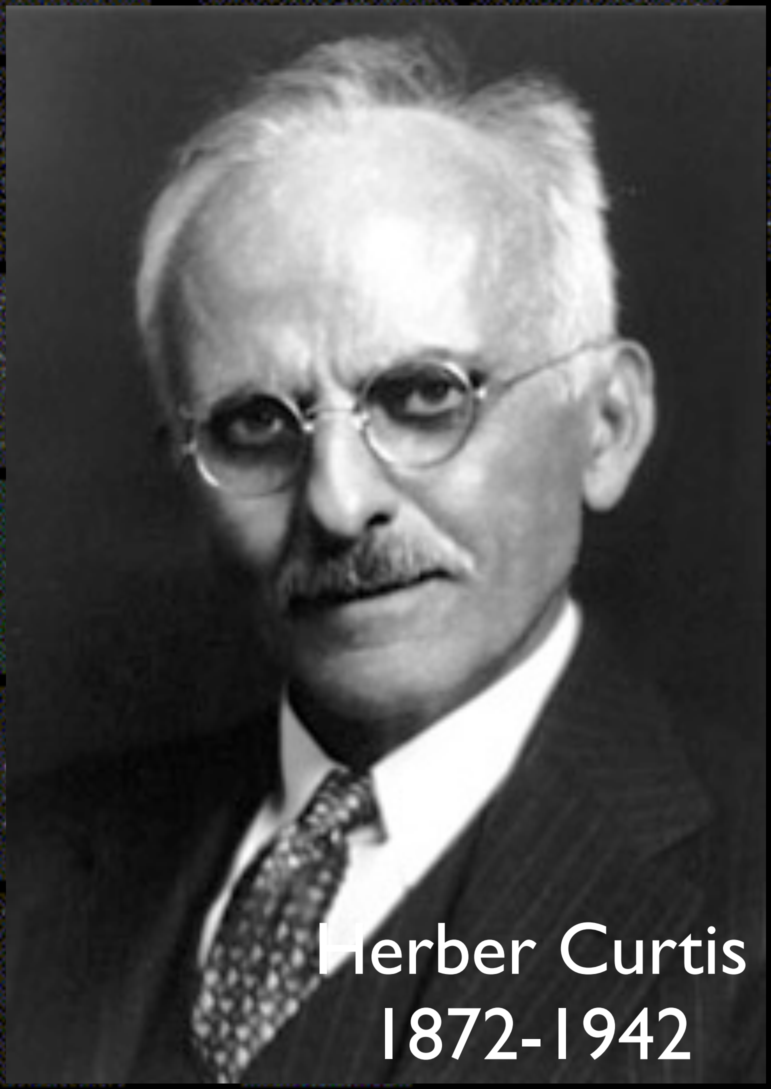
1916

Harlow Shapley
1885-1972

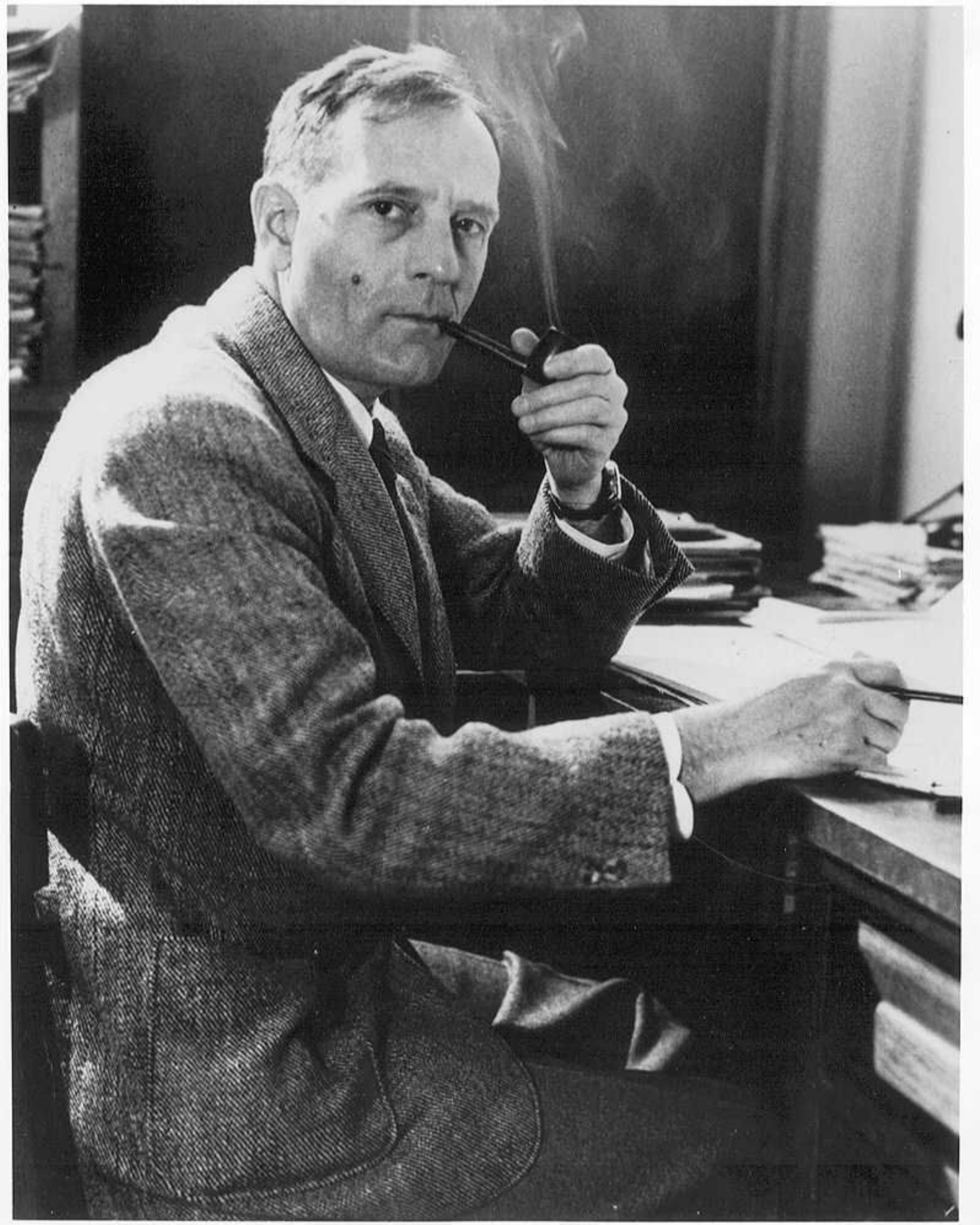
The great Shapley-Curtis debate
26 April 1920



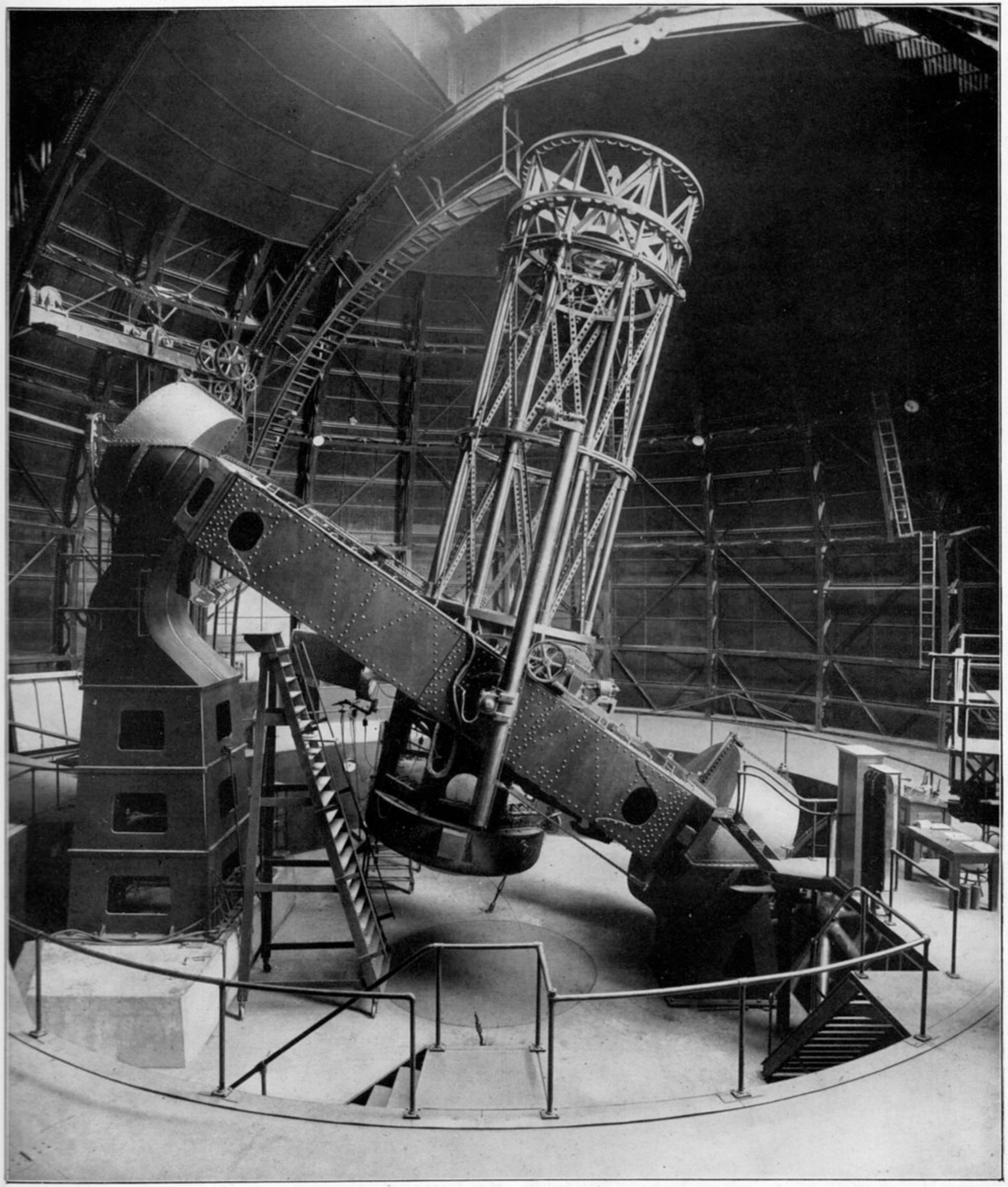
Harlow Shapley
1885-1972



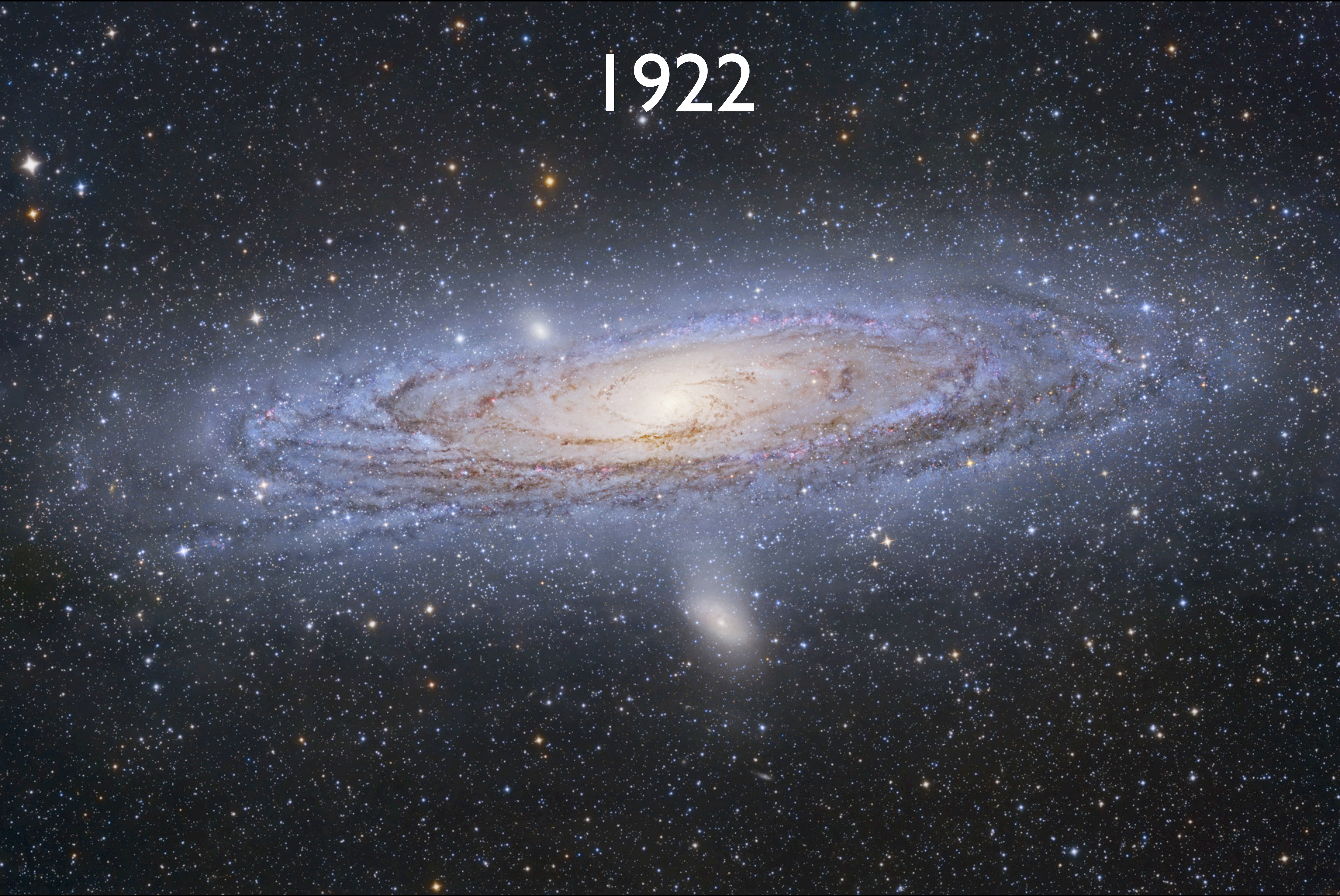
Herber Curtis
1872-1942



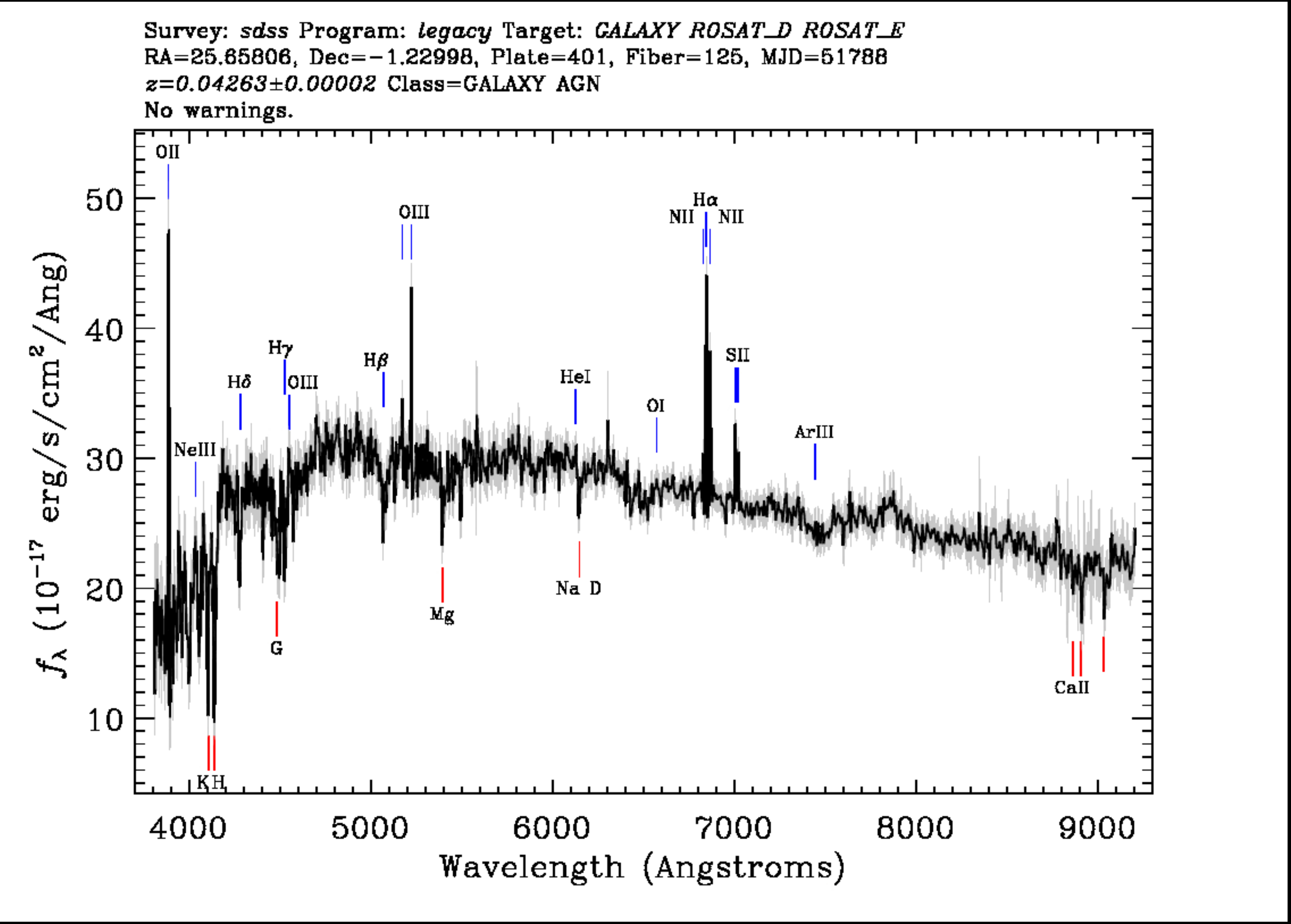
Edwin Hubble
1889-1953



1922



Line-of-sight velocity can be measured with Doppler shifts



1929: Expansion of the Universe, Hubble-Lemaitre law

$$cz = H_0 d$$

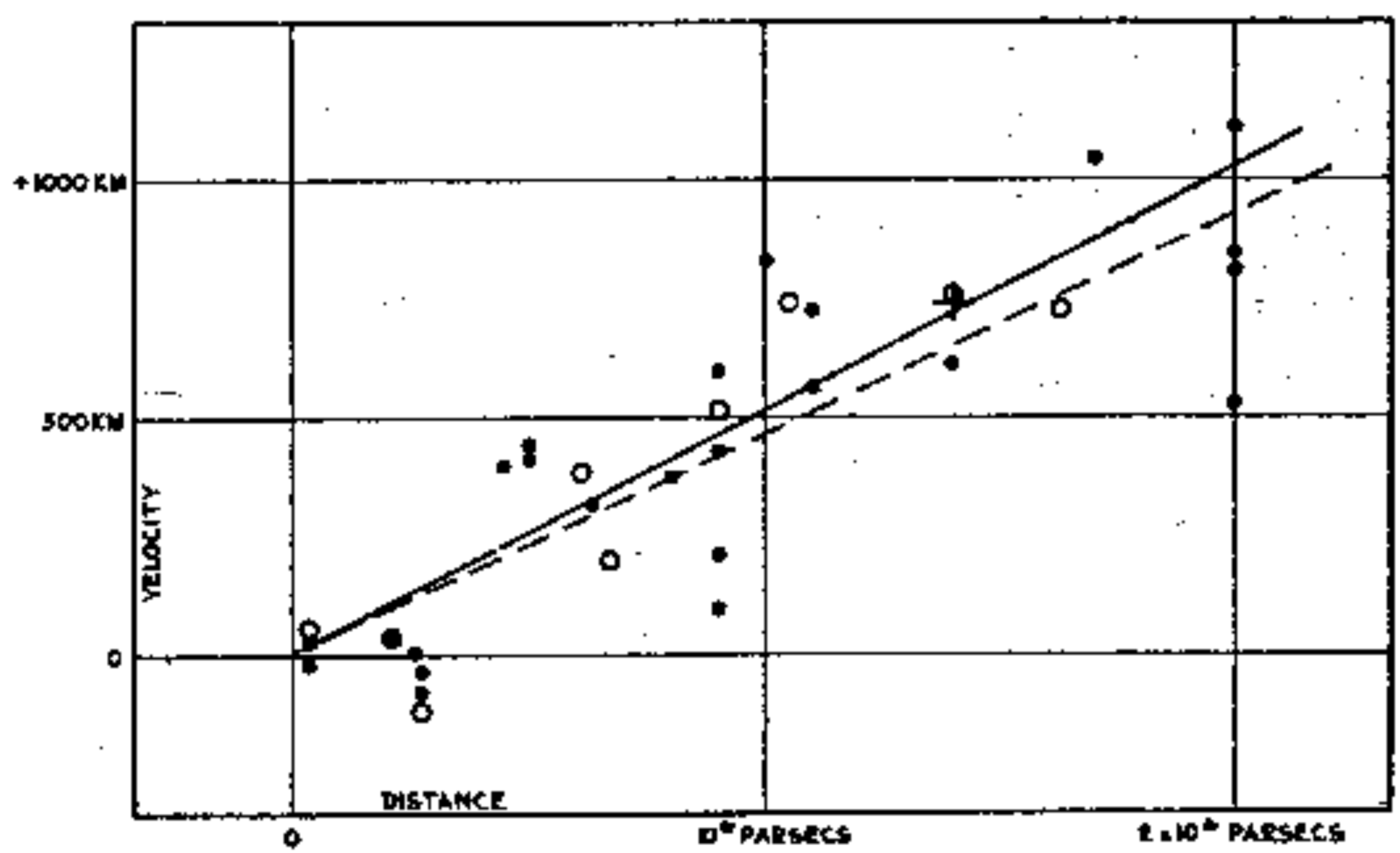
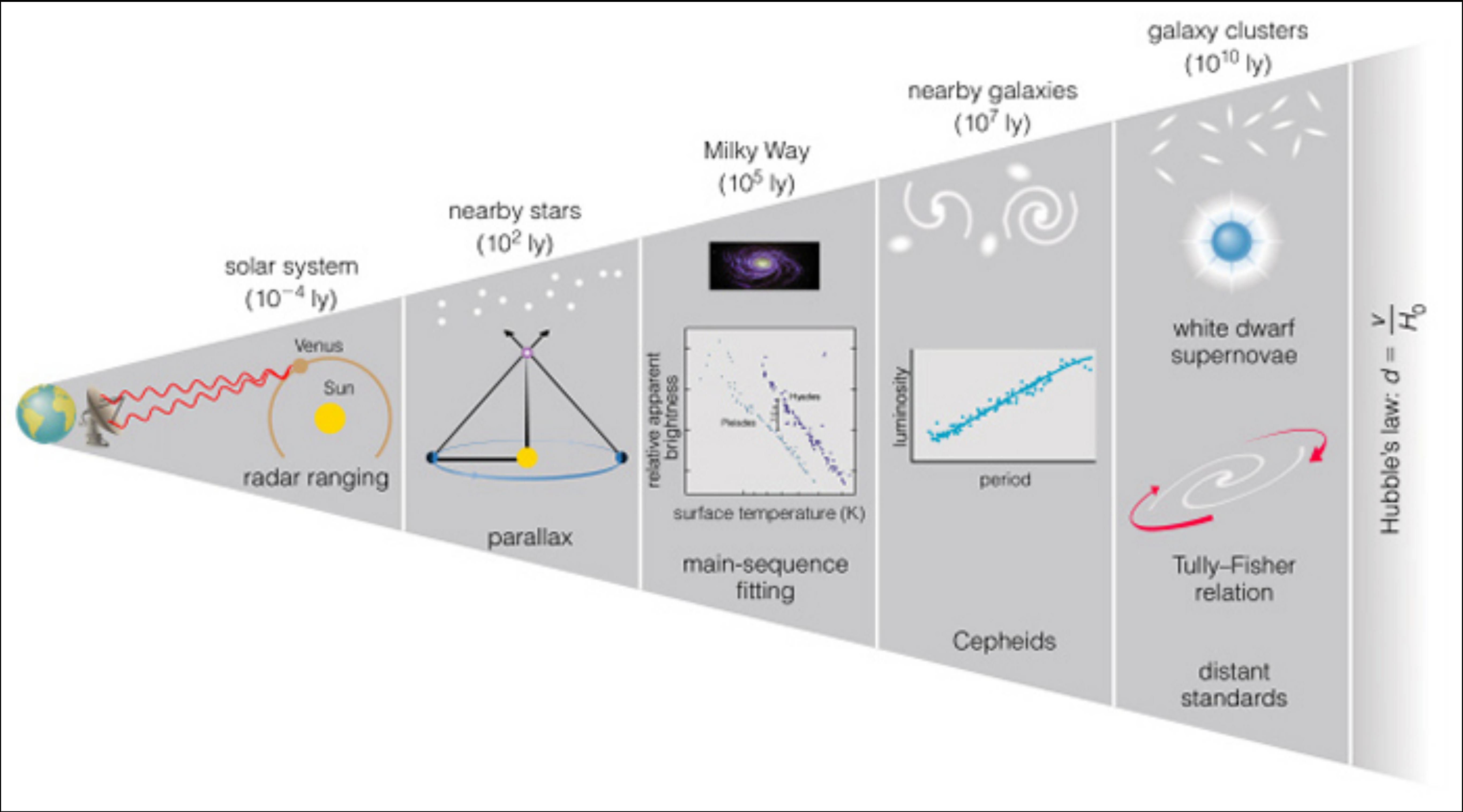
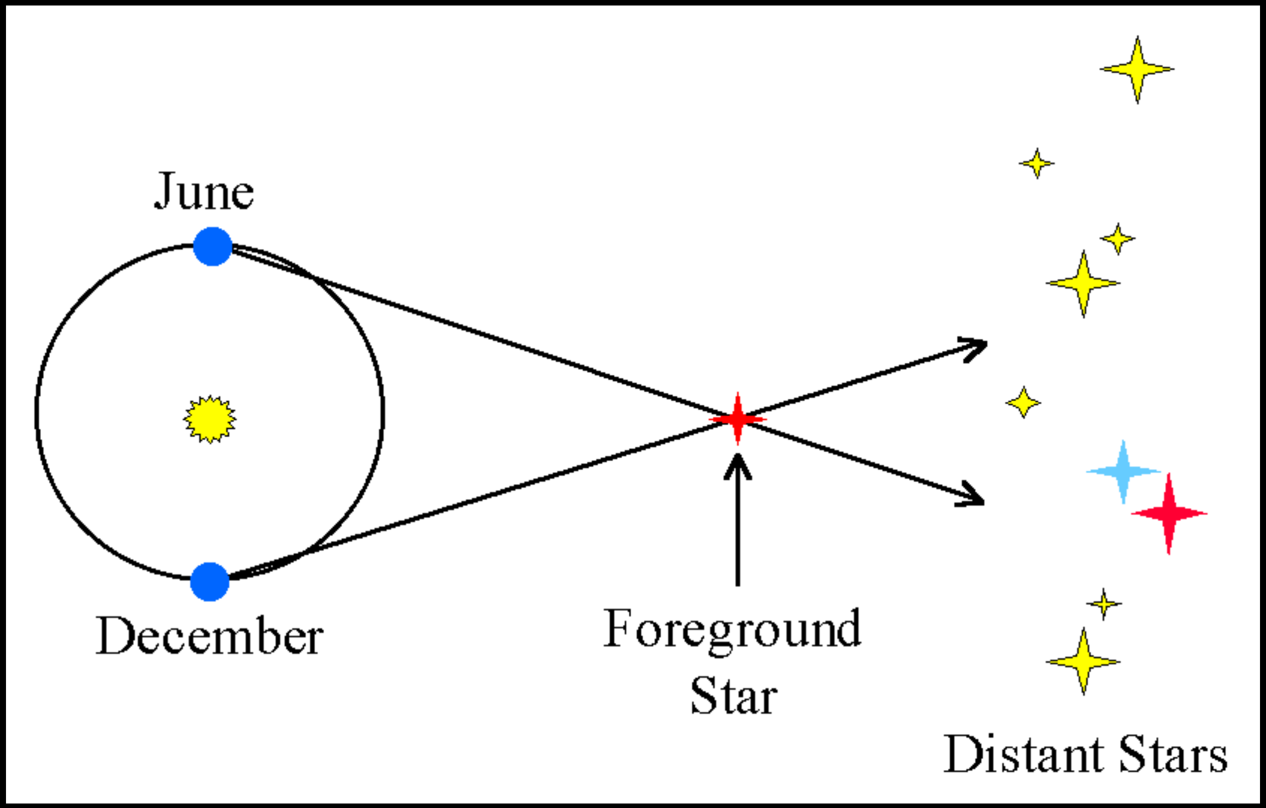


FIGURE 1

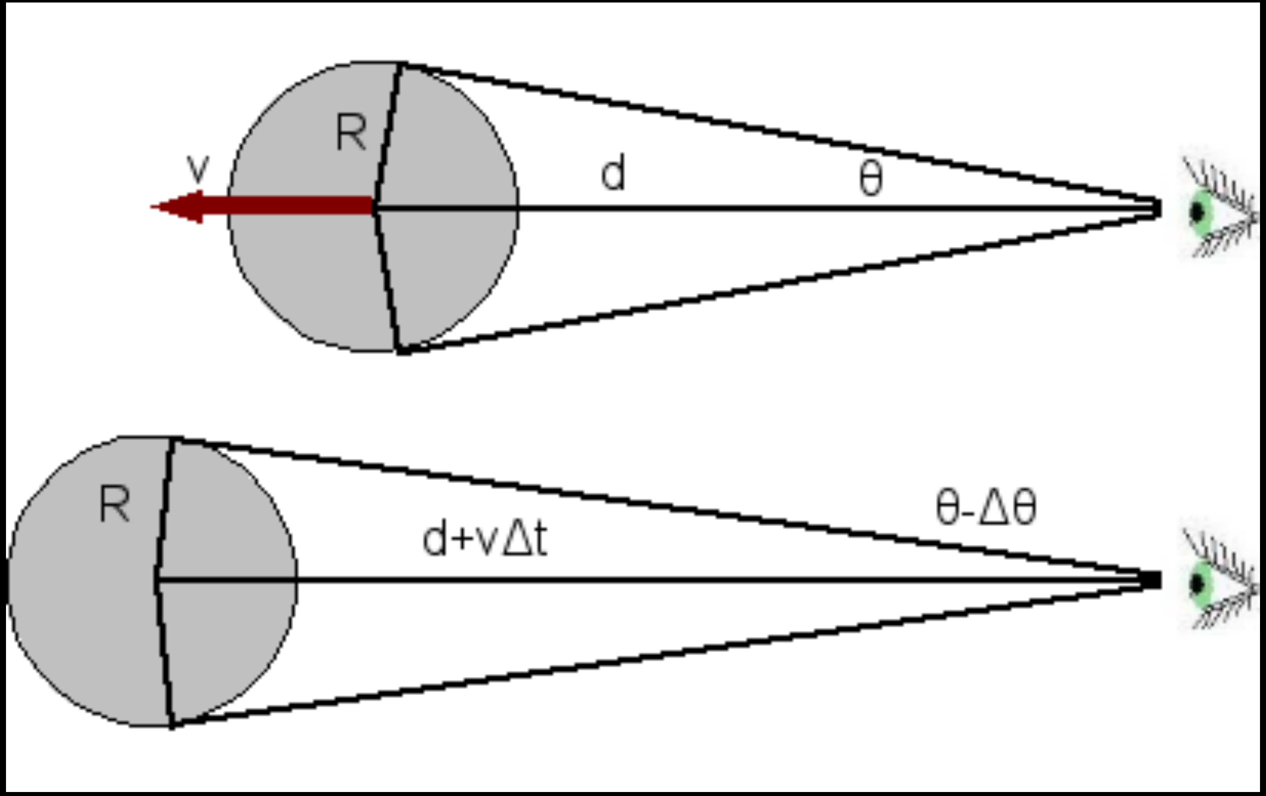
Distances require a “ladder” of measurements



parallax



moving cluster



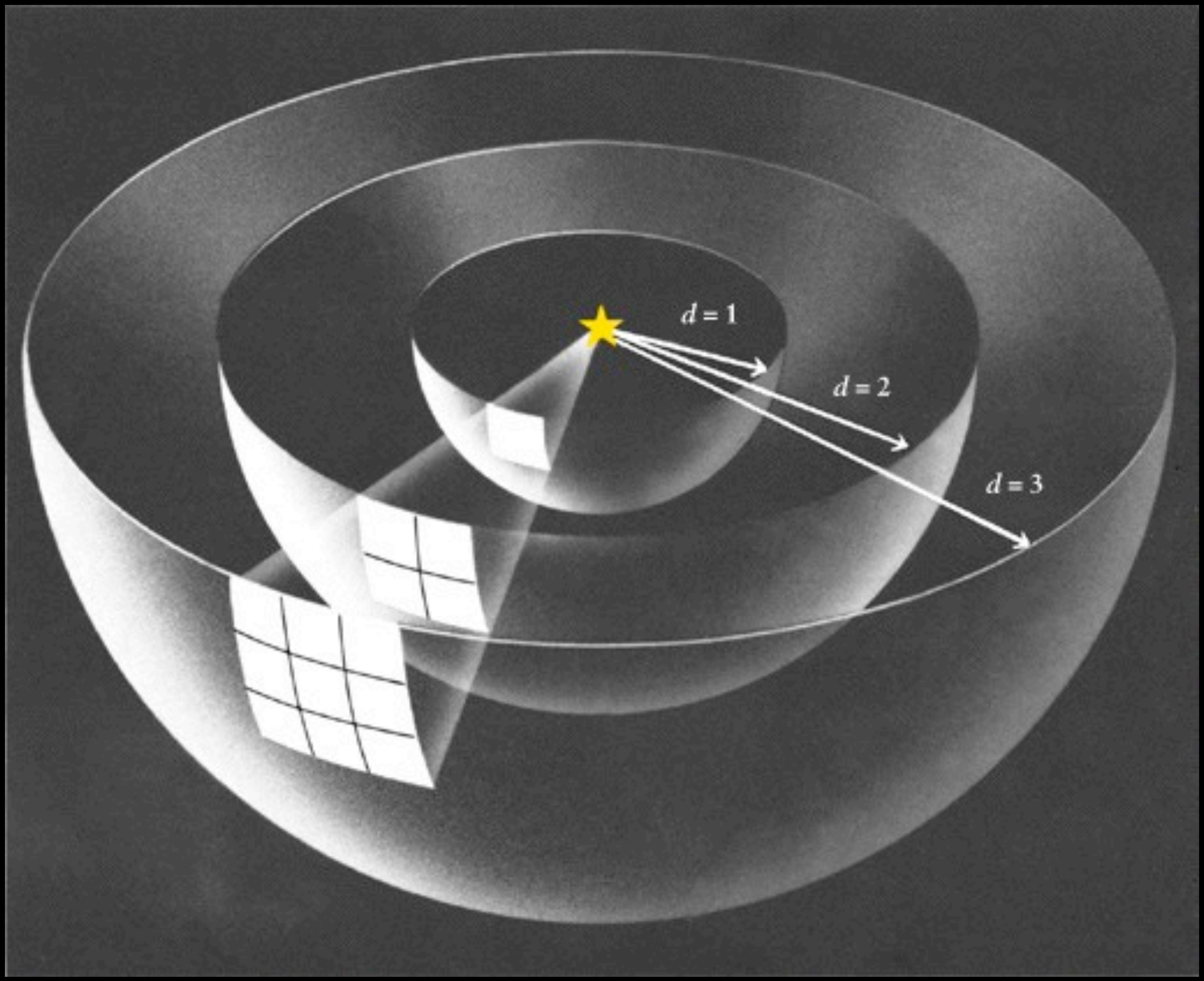
Distance indicators:

standard candle -

$$f = \frac{L}{4\pi d^2}$$

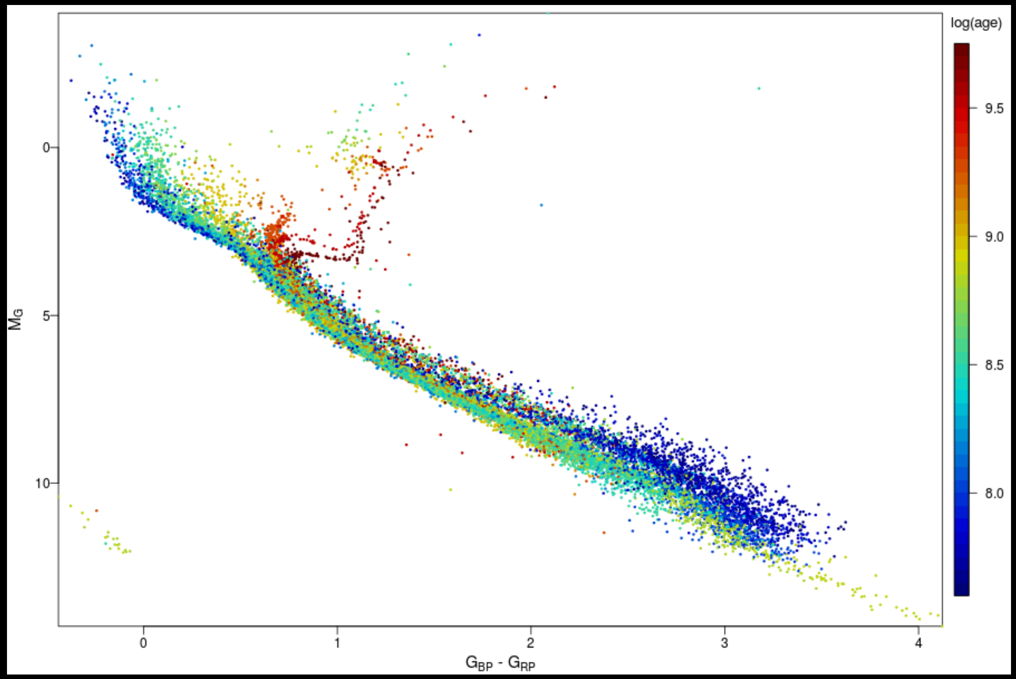
standard ruler -

$$\theta = \frac{D}{d}$$

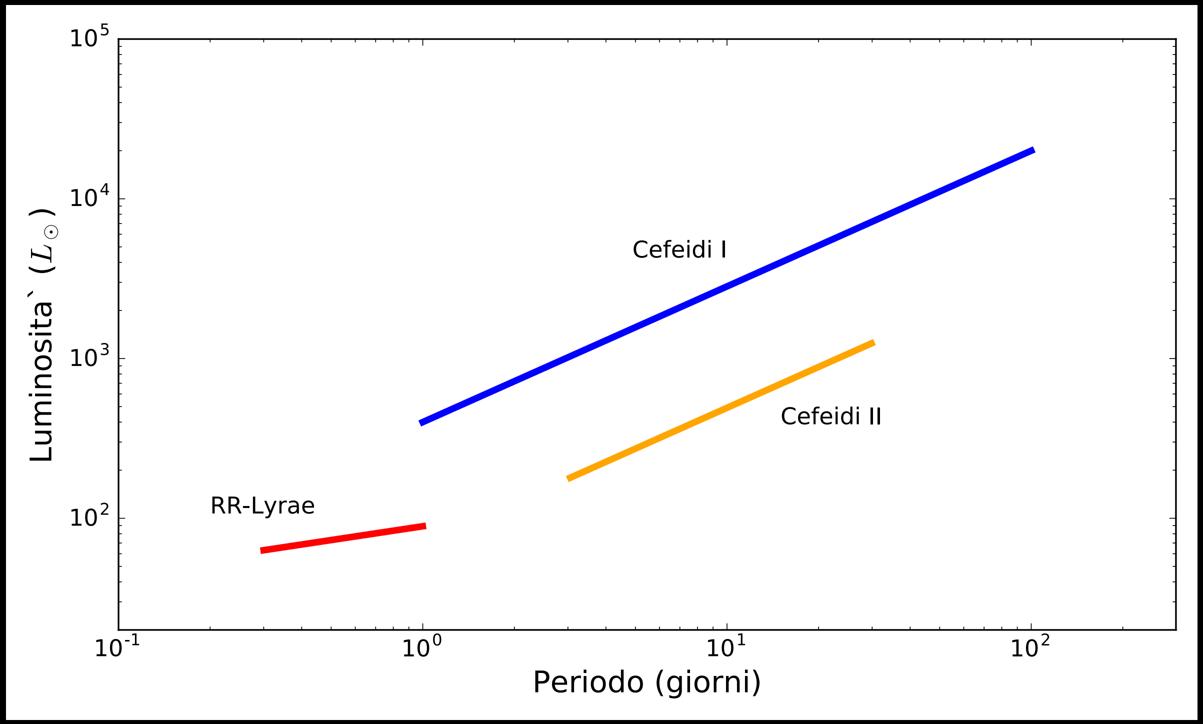


Alternatively, one can use a relation between a distance-independent and a distance-dependent quantity:

main-sequence fitting:

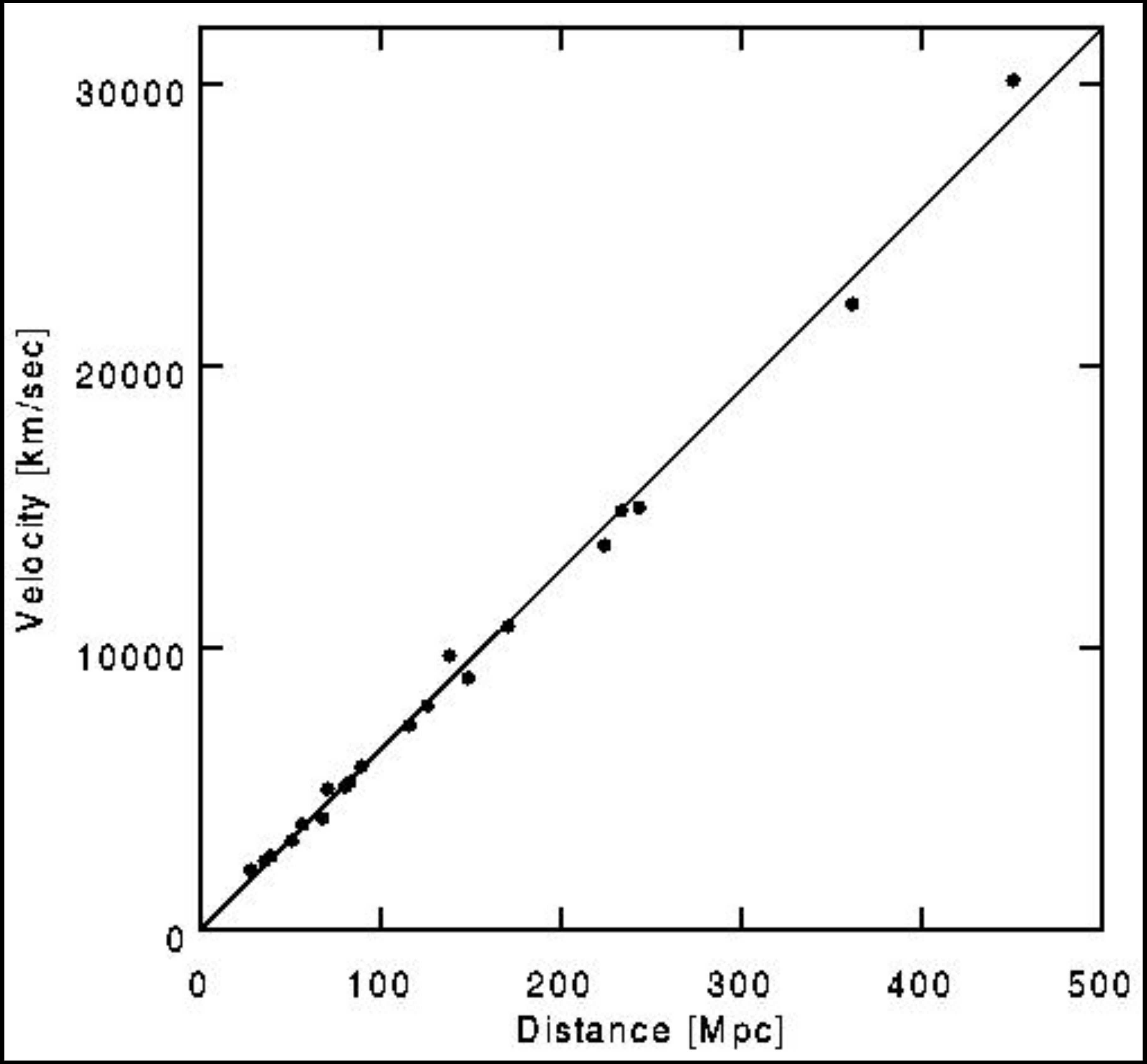


variable stars (cepheids):



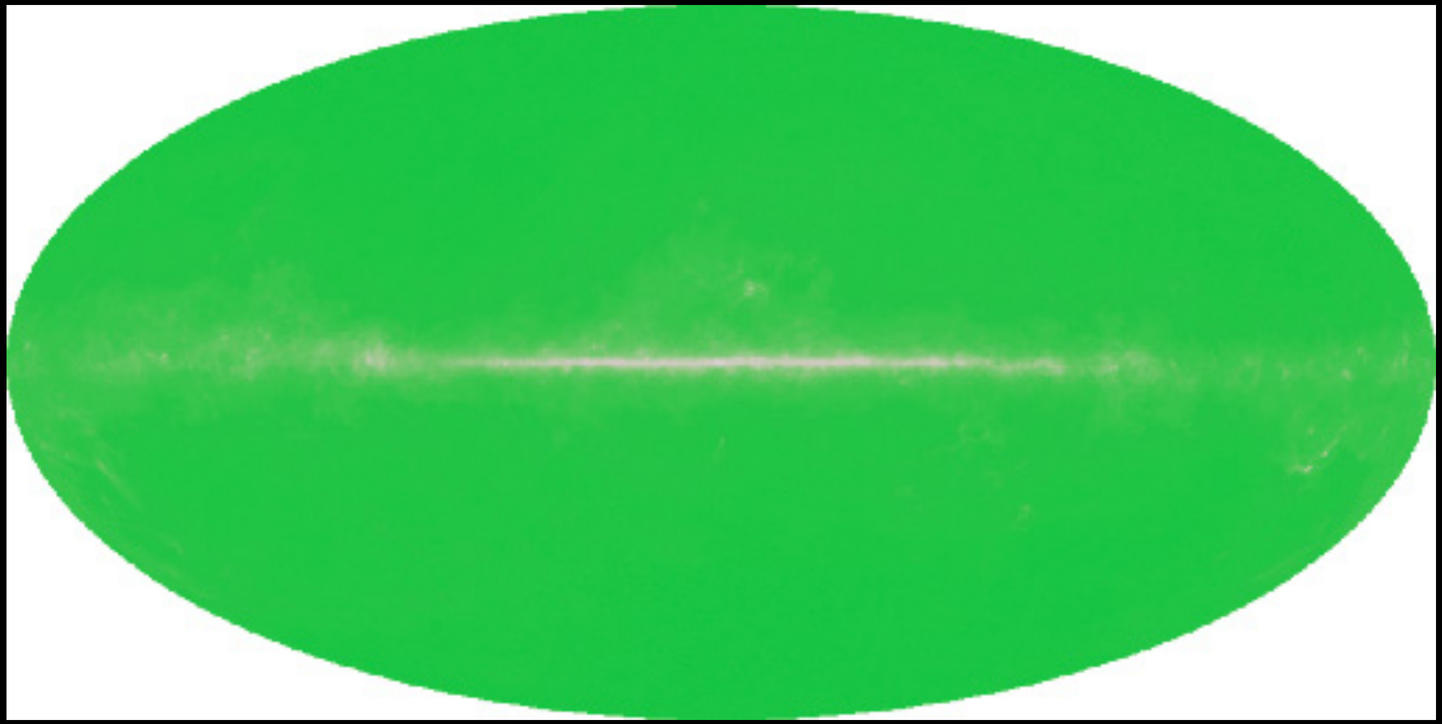
Standard candles: type Ia supernovae

Standard candles: type Ia supernovae



Cosmological principle:

There are no priviledged observers in the Universe. Observed on large scales, the Universe is **homogeneous** and **isotropic**.

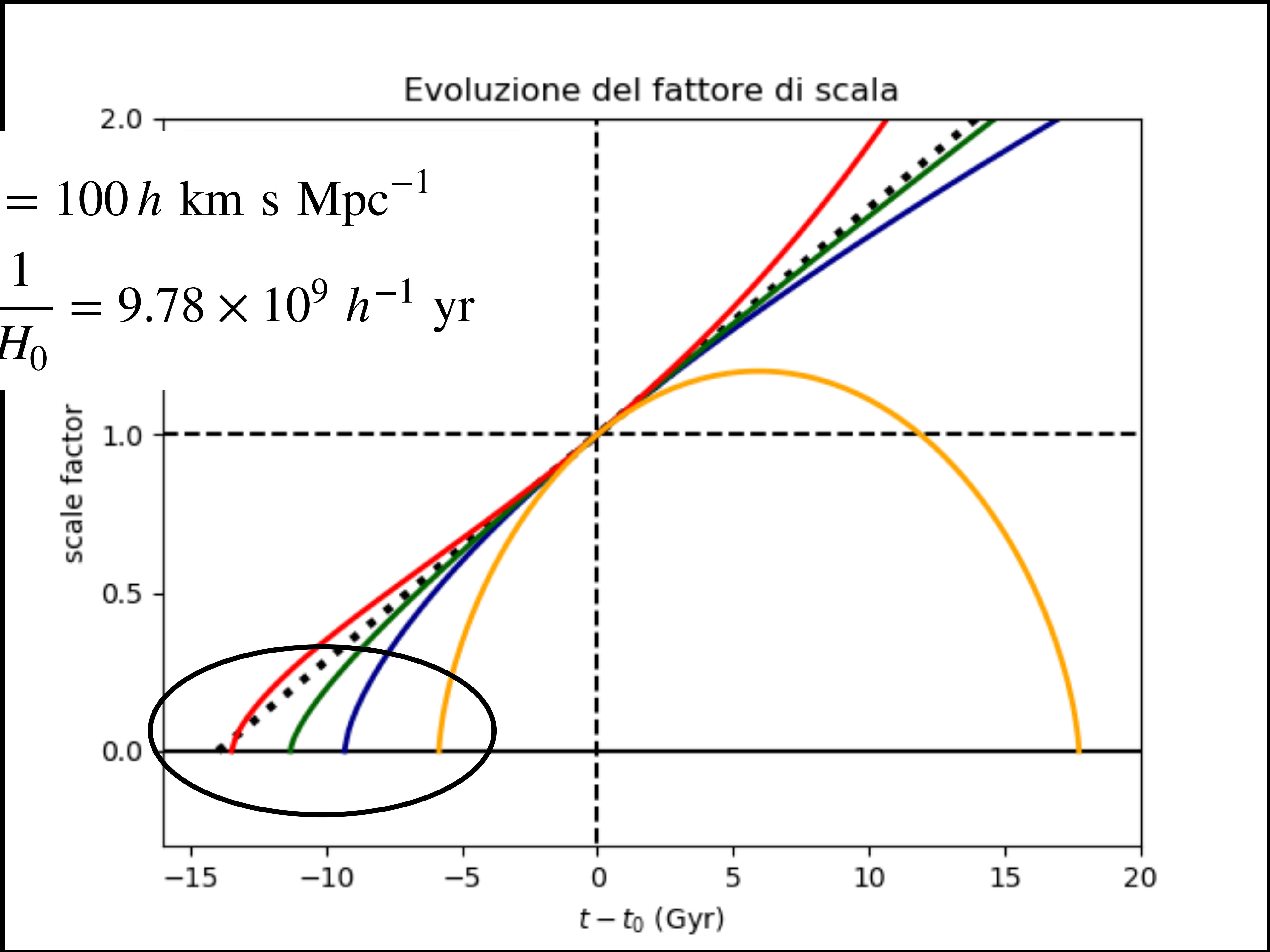


Observational evidence of isotropy: CMB.
Isotropy around a un-priviledged observer implies homogeneity (if the metric is analytic)

Hubble time

$$H_0 = 100\,h \text{ km s Mpc}^{-1}$$

$$t_{\rm H} = \frac{1}{H_0} = 9.78 \times 10^9\ h^{-1}\ \text{yr}$$



Big Bang

Hot Big Bang

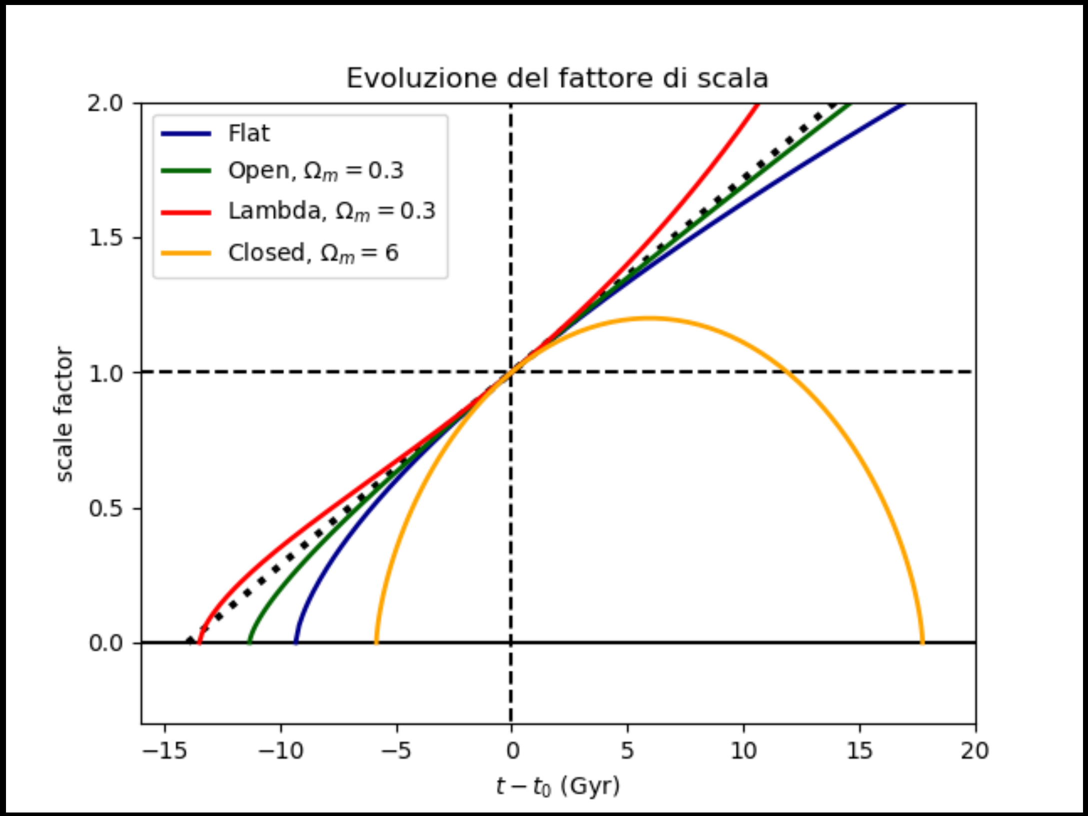
The universe was much denser and hotter in the distant past, density gets to infinity at t=0

This is a **naked singularity** (no EH)

Hubble law does **not** imply that the observer is at the center

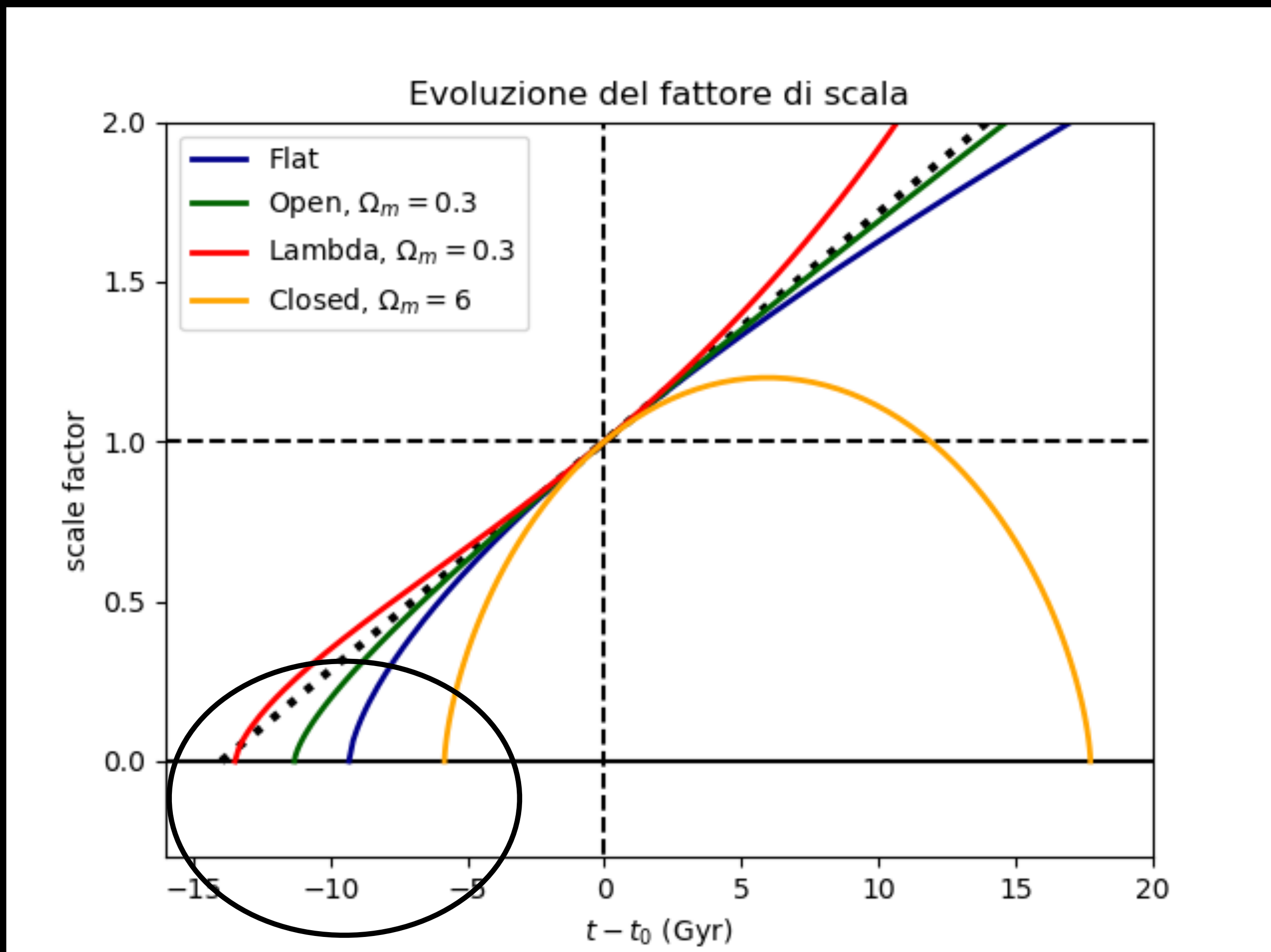
All the space expands, keeping homogeneity and isotropy

If the universe is infinite, it remains infinite at all times t>0



Because we do not understand physics at high energies, we should consider the Big Bang as an **extrapolation** of known physics

A problem with the age of the Universe?



$$H_0 = 100\,h \text{ km s Mpc}^{-1}$$

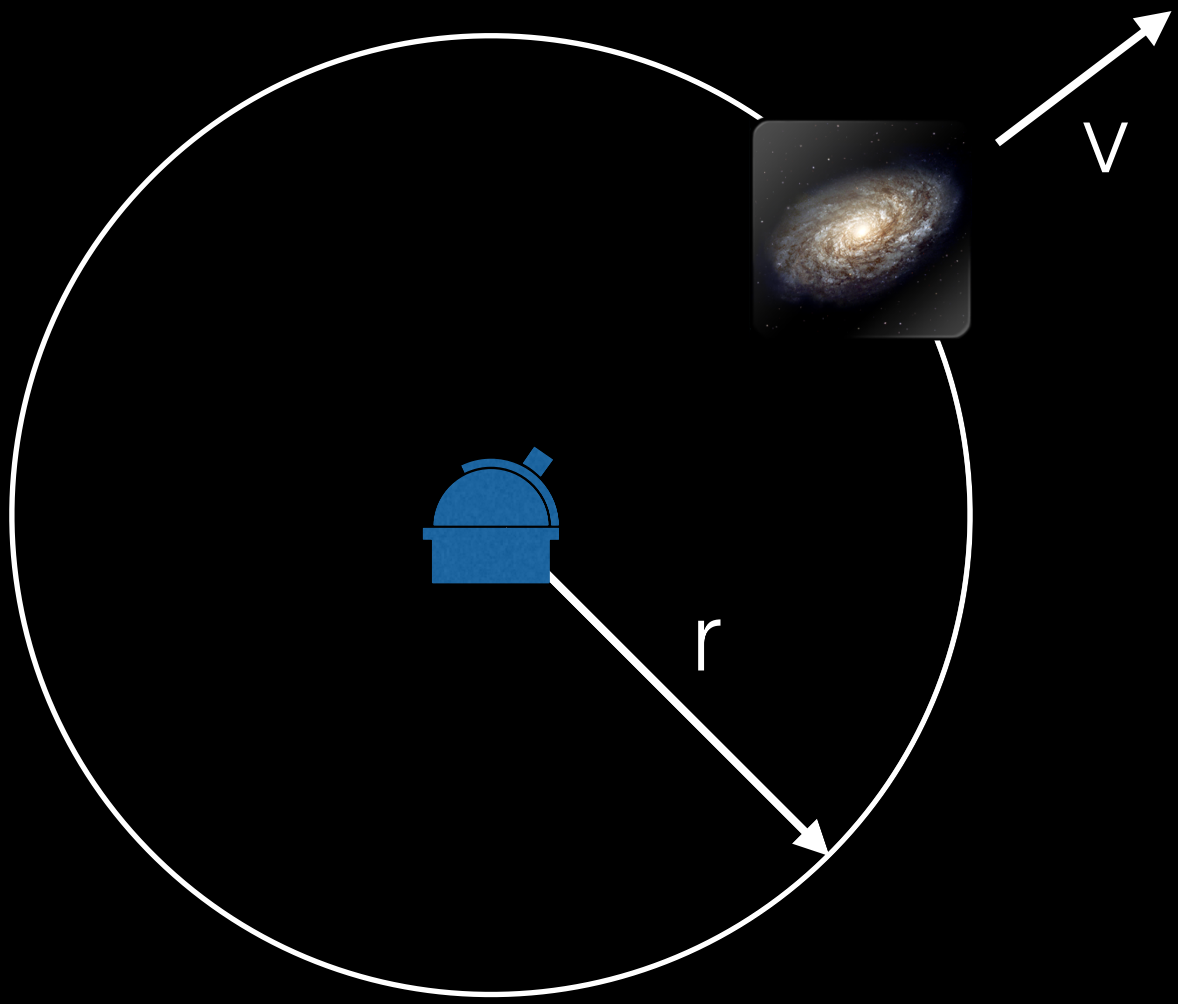
$$t_\mathrm{H} = \frac{1}{H_0} = 9.78 \times 10^9\ h^{-1}\ \mathrm{yr}$$

$$t_\mathrm{GC} \simeq 20\ \mathrm{Gyr}$$

Cosmology with Newtonian gravity

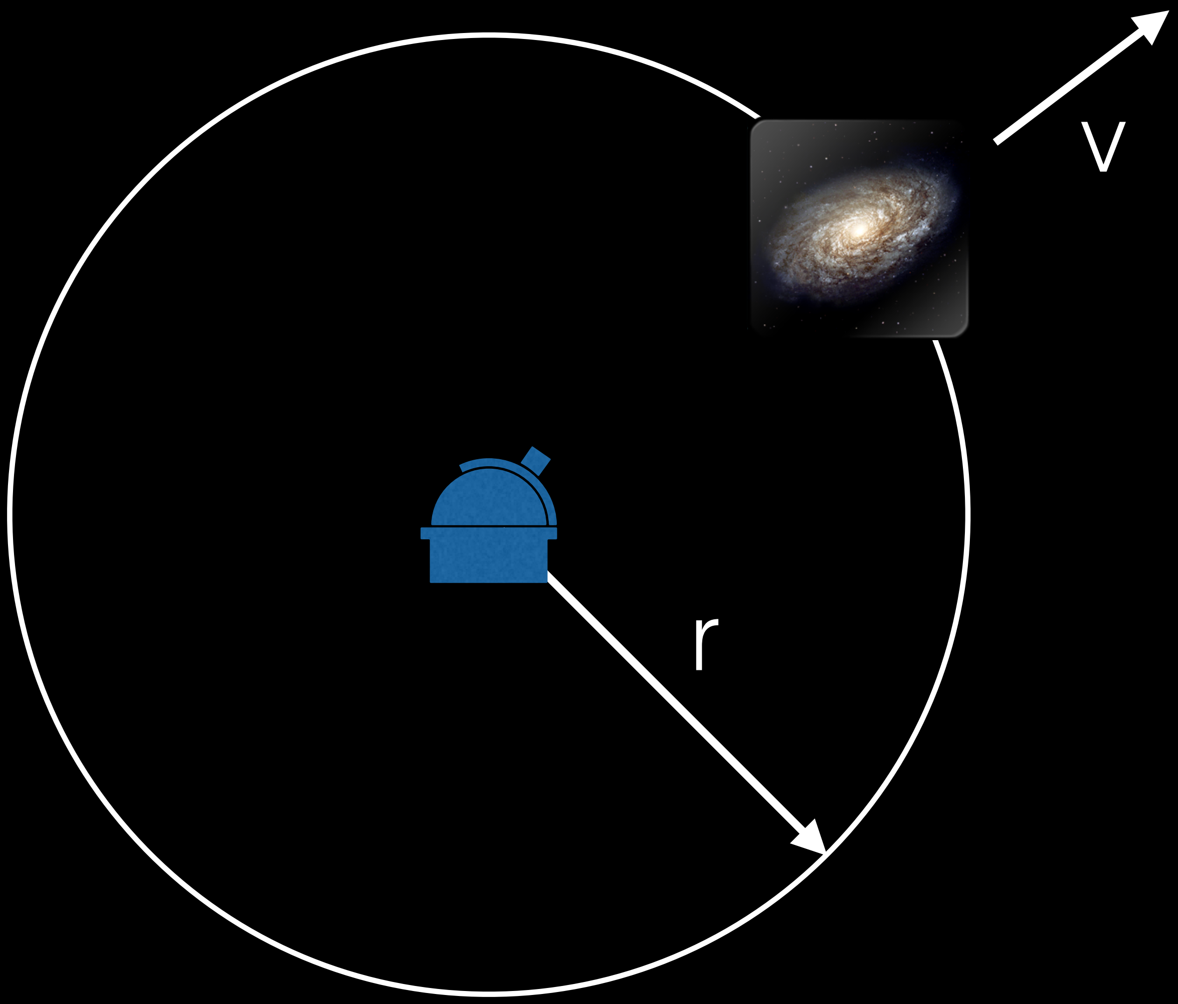
$$\nabla^2\Phi = 4\pi G\rho \quad \Longrightarrow \quad \Phi = \text{const} \times r^2$$

$$\text{cosmological principle} \quad \Longrightarrow \quad \rho = 0$$



Using a result of GR, Birkhoff's theorem, it is possible to demonstrate that in spherical symmetry matter outside a radius r does not influence the metric

Cosmology with Newtonian gravity



$$E = \frac{1}{2}mv^2 - \frac{GmM}{r} = \text{const}$$

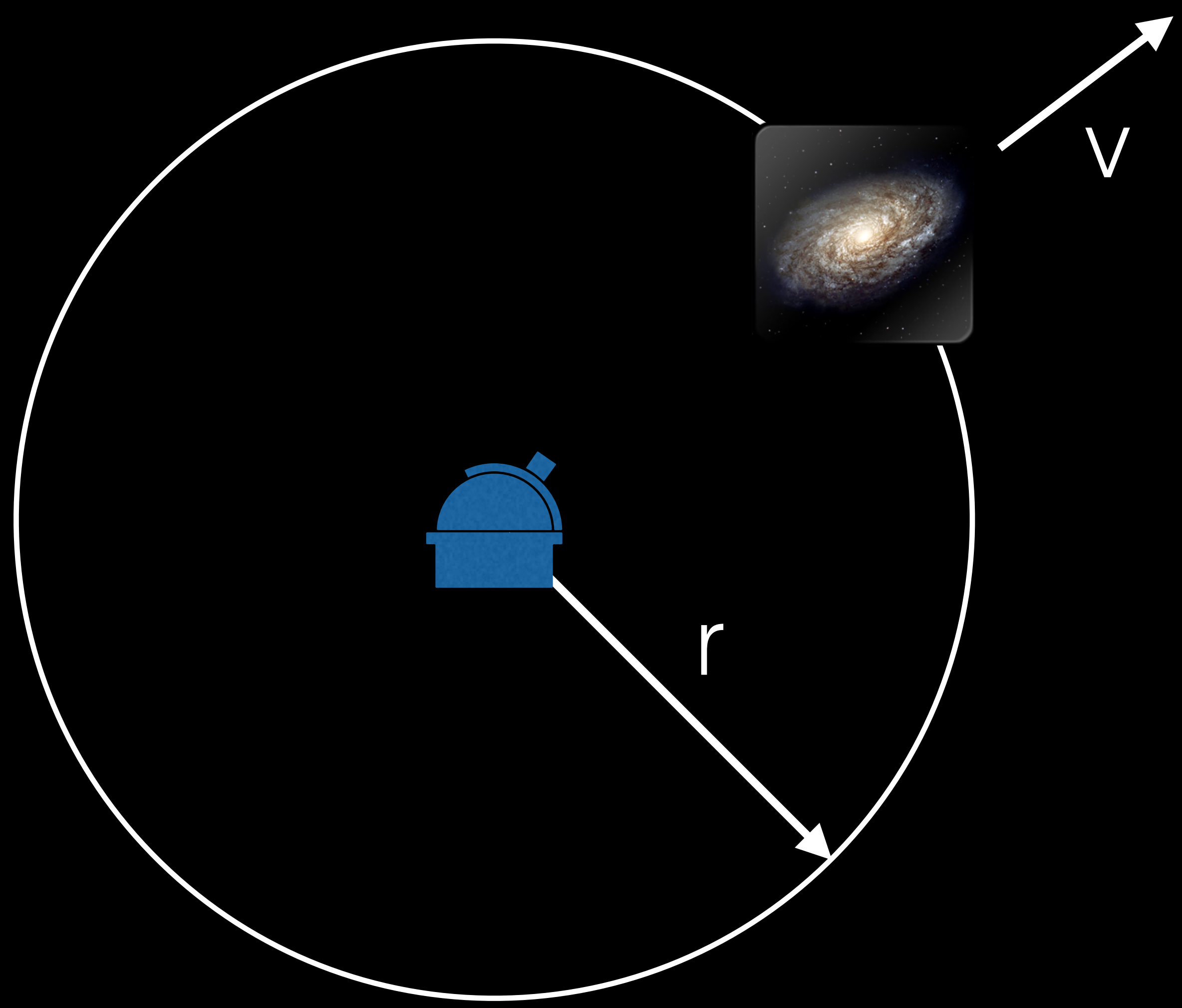
$$v = H_0\, r, \quad M = \frac{4\pi}{3} r^3 \rho$$

$$E = 0 \implies \rho = \rho_c = \frac{3H_0^2}{8\pi G}$$

critical density:

$$\rho_c = 2.77 \times 10^{11}\, h^2\ \mathrm{M}_\odot\ \mathrm{Mpc}^{-3} = 1.9 \times 10^{-29}\, h^2\ \mathrm{g\ cm}^{-3}$$

Cosmology with Newtonian gravity



scale factor : $a(t) = \frac{r}{r_0}$

density parameter : $\Omega_0 = \frac{\rho}{\rho_c}$

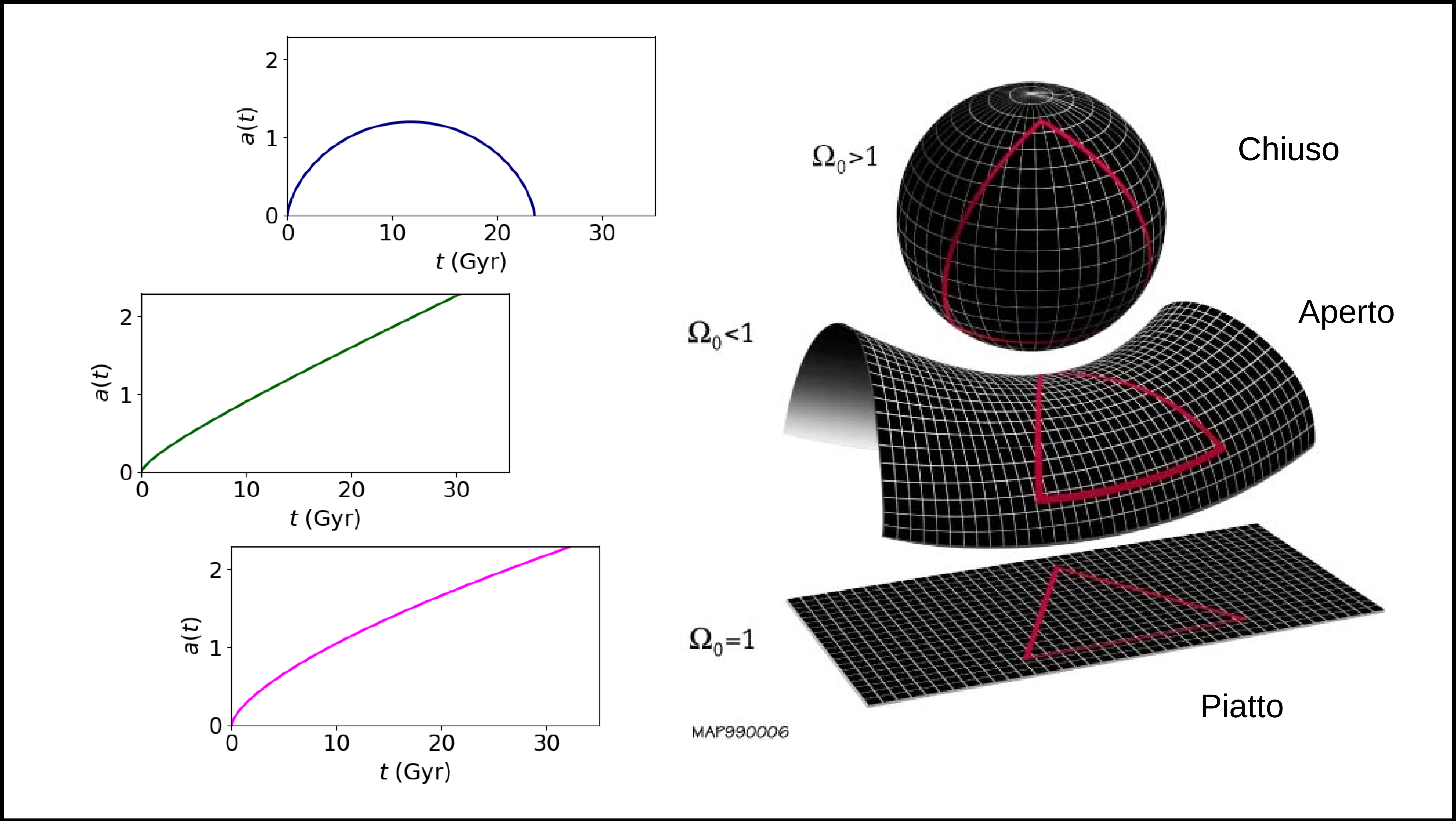
Hubble parameter : $H = \frac{1}{a}\frac{da}{dt}$

evolution with generic E:

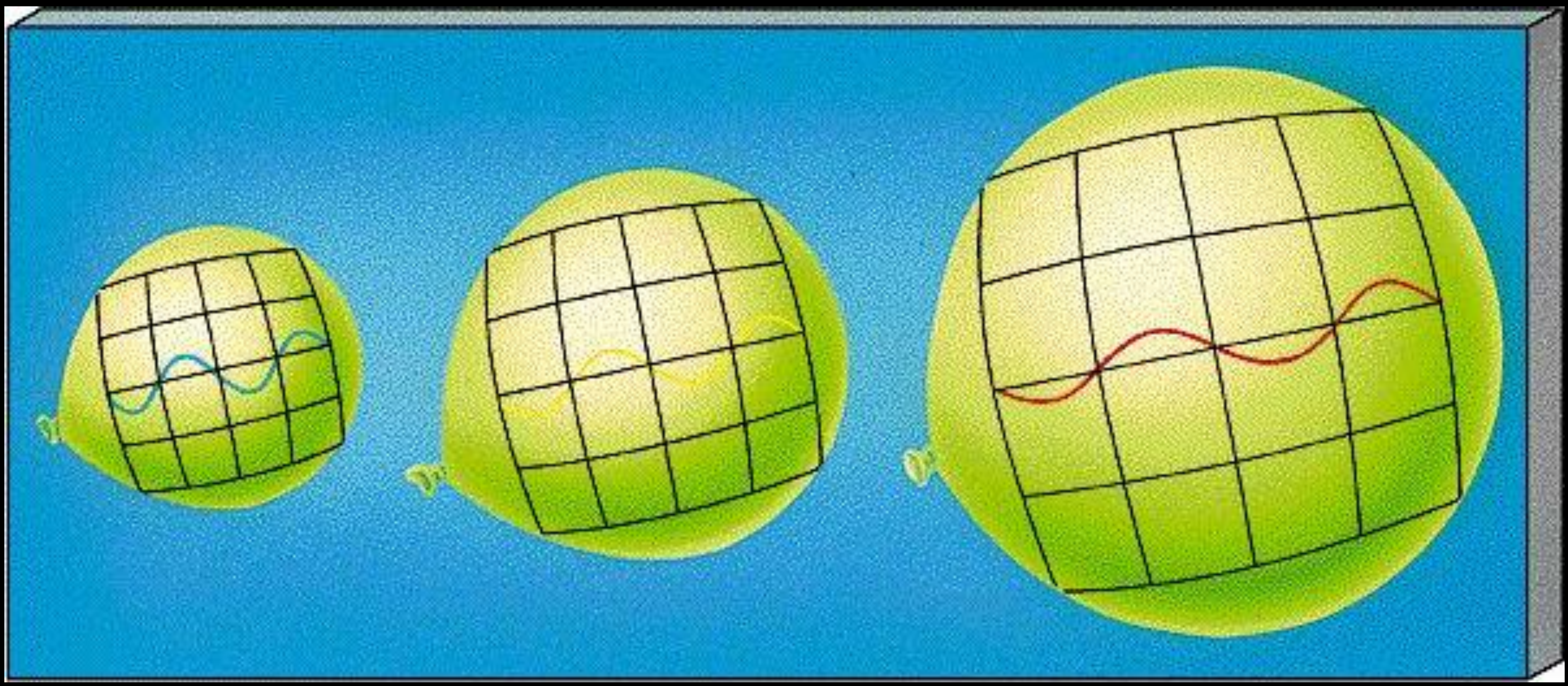
second Friedmann equation

$$\left(\frac{H}{H_0}\right)^2 = \frac{\Omega_0}{a^3} + \frac{1-\Omega_0}{a^2}$$

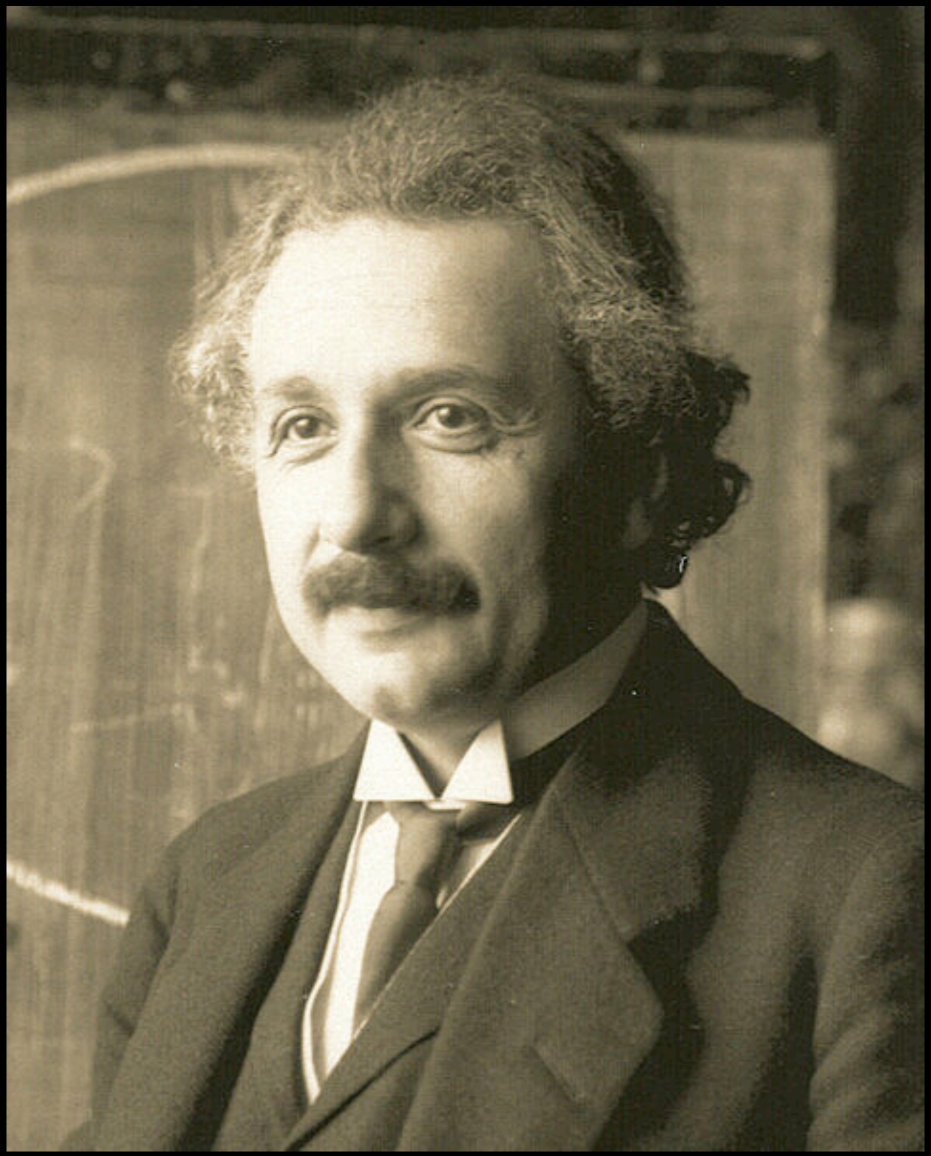
Fate of the universe



Cosmological redshift



The cosmological constant: 1, Einstein



The universe was thought to be maximally symmetric: homogeneous, isotropic, static

1915: $$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi G T_{\mu\nu}$$

The only way to obtain an (unstable) static solution is to add a cosmological constant:

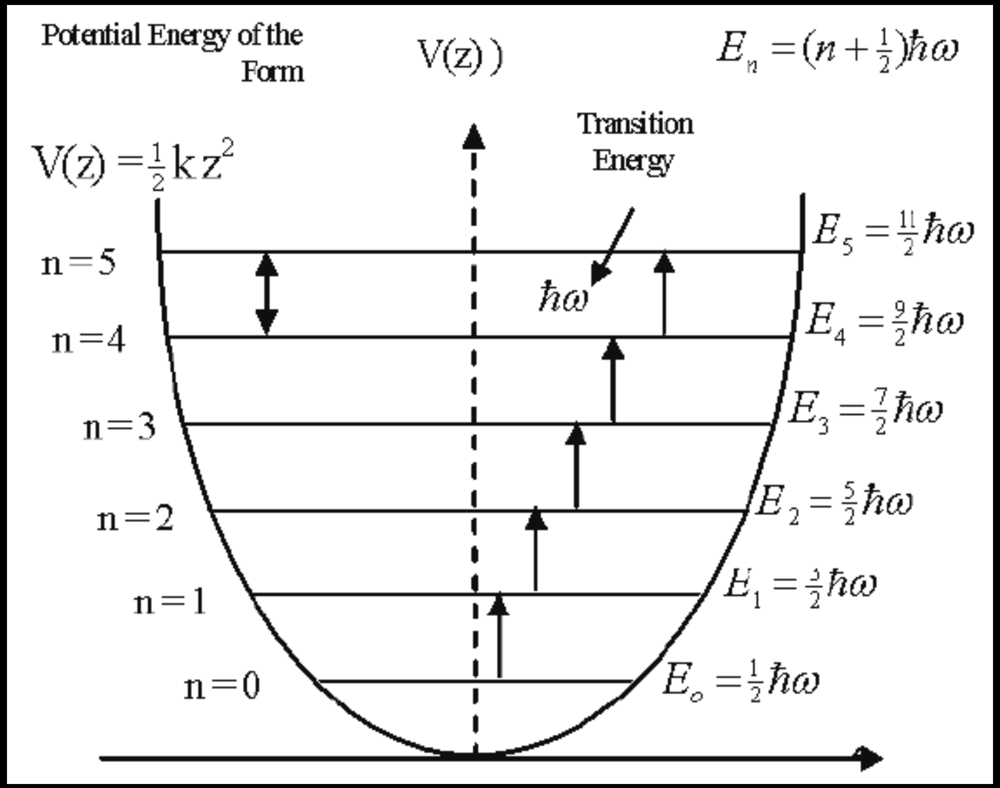
$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

1929: Hubble law, the static solution is ruled out

Lambda: Einsteins' biggest blunder!

The cosmological constant: 2, QFT ('80s)

$$p = -\rho$$



Suppose space is filled with a quantum field; void is associated with an energy $E = h\nu/2$ for each oscillation mode

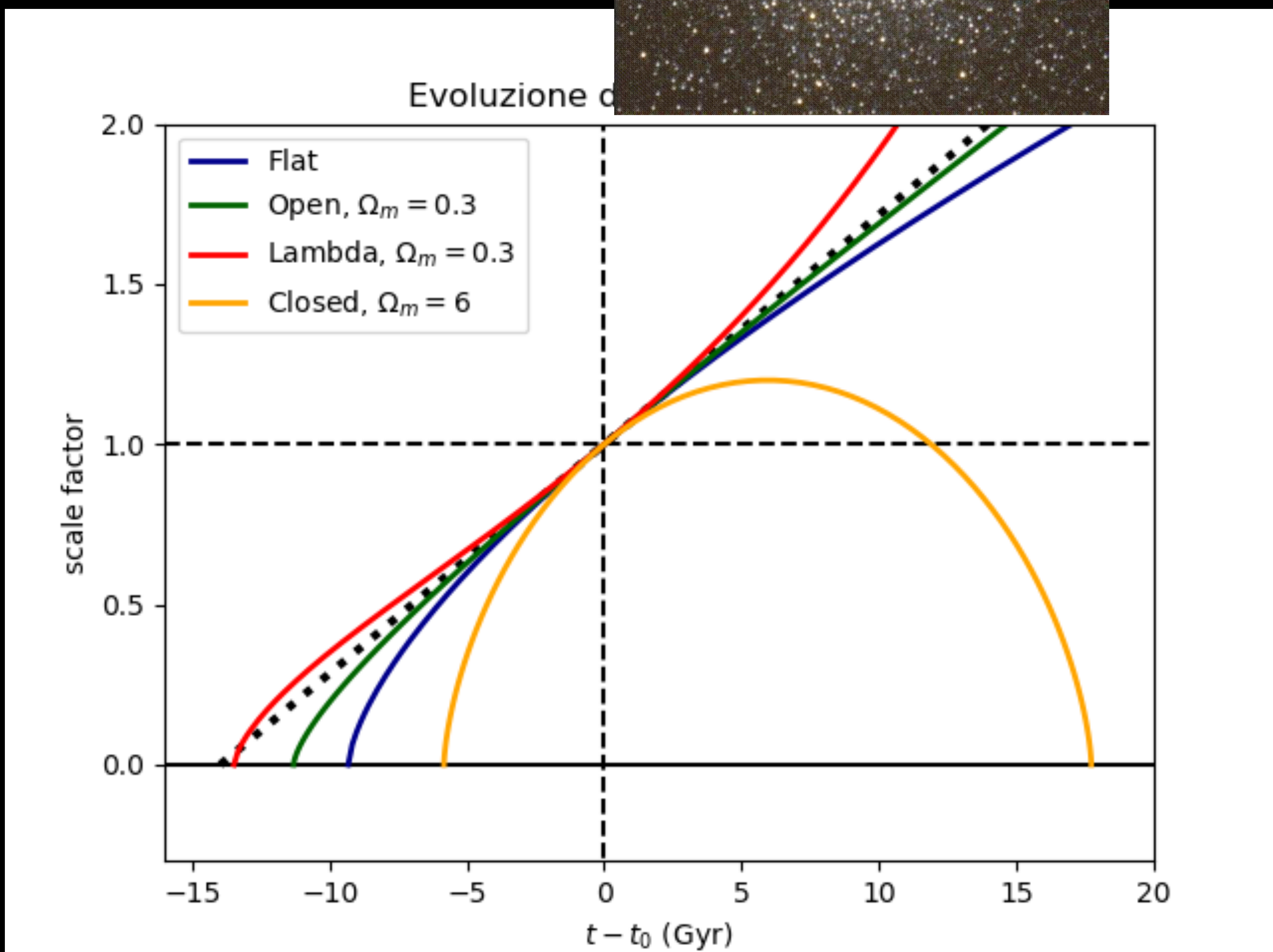
Quantum vacuum exerts a negative pressure, like in the Casimir effect

A constant vacuum energy is not measurable, but it contributes to the energy density

This gives an effective cosmological constant term, resulting in:

$$\Omega_\Lambda \sim 10^{120}$$

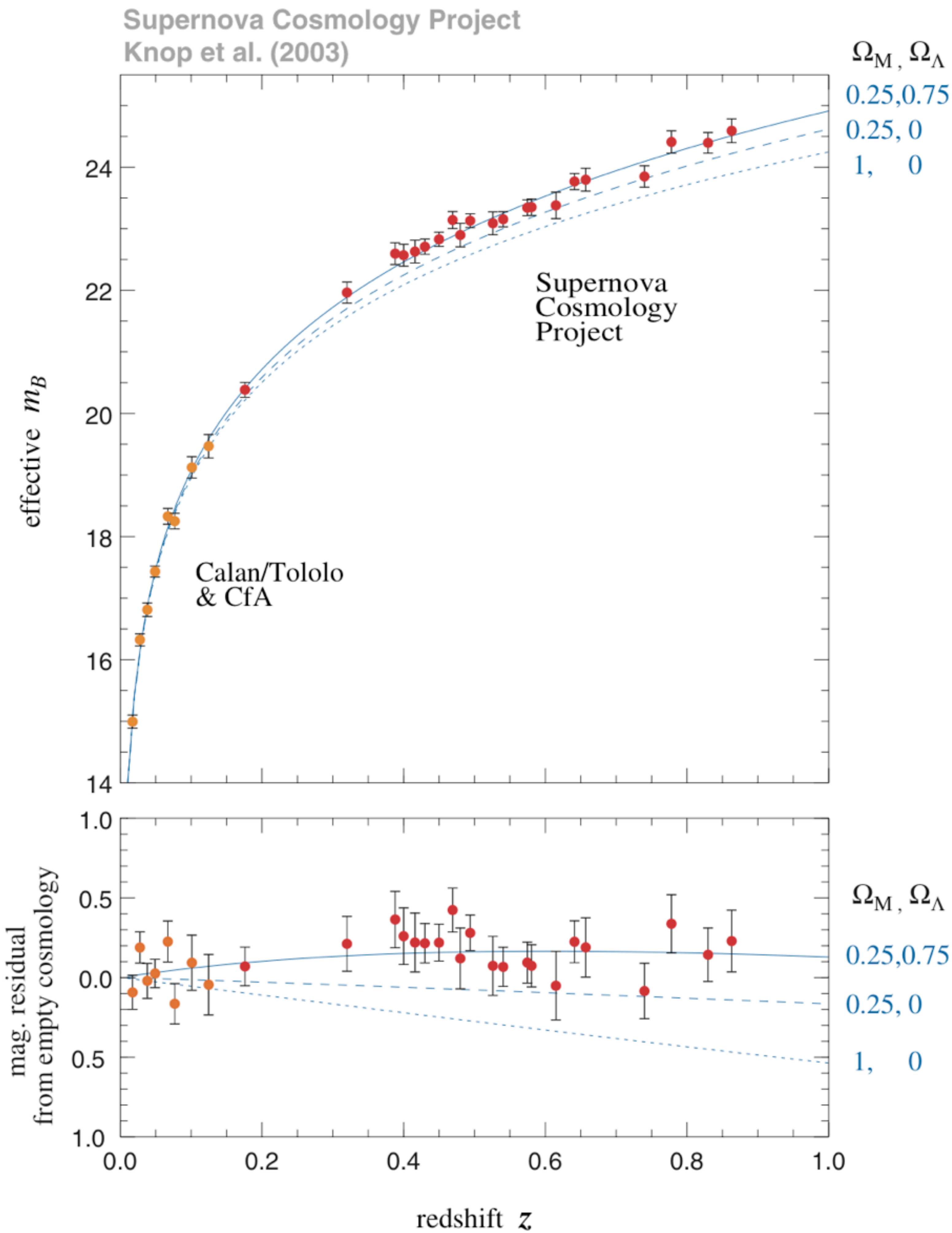
The cosmological constant: 3, FRW models ('90s)



Solution of age problem (and others):

- open universe
- cosmological constant

But cosmic inflation predicts a flat universe, so theoretical predjudice makes the open universe unattractive



Supernova Cosmology Project
Knop et al. (2003)
Ω_M, Ω_Λ
0.25,0.75
0.25, 0
1, 0
24
22
20
18
16
14
effective m_B
Supernova
Cosmology
Project
Calan/Tololo
& CfA
1.0
0.5
0.0
0.5
1.0
mag. residual
from empty cosmology
Ω_M, Ω_Λ
0.25,0.75
0.25, 0
1, 0
0.0
0.2
0.4
0.6
0.8
1.0
redshift z

The LambdaCDM model

Most matter is made up by a dark matter particle, that does not interact with light and starts with low velocity dispersion ("cold")

Most energy is in the form of a cosmological constant that accelerates the expansion at late times

An early phase of cosmic inflation produced the observed fluctuations

The universe is spatially flat

An anthropic argument on multi-verses could explain the unnatural value of the cosmological constant