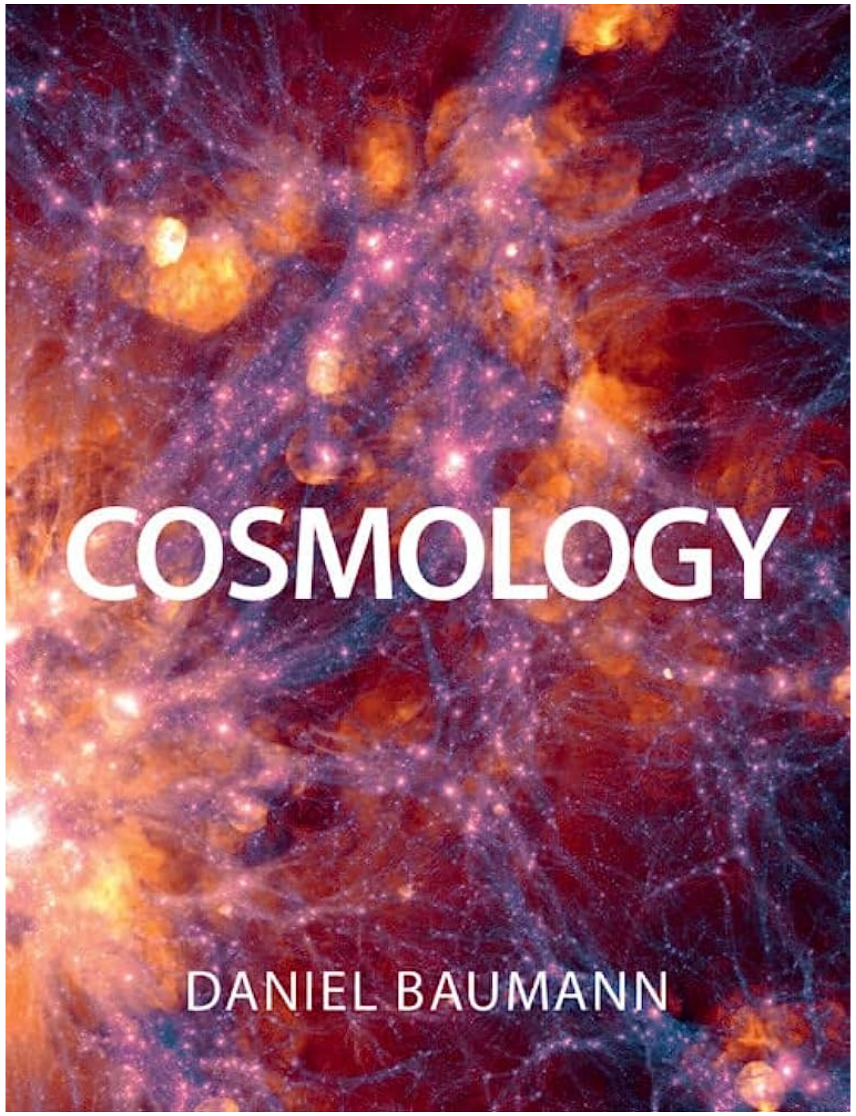
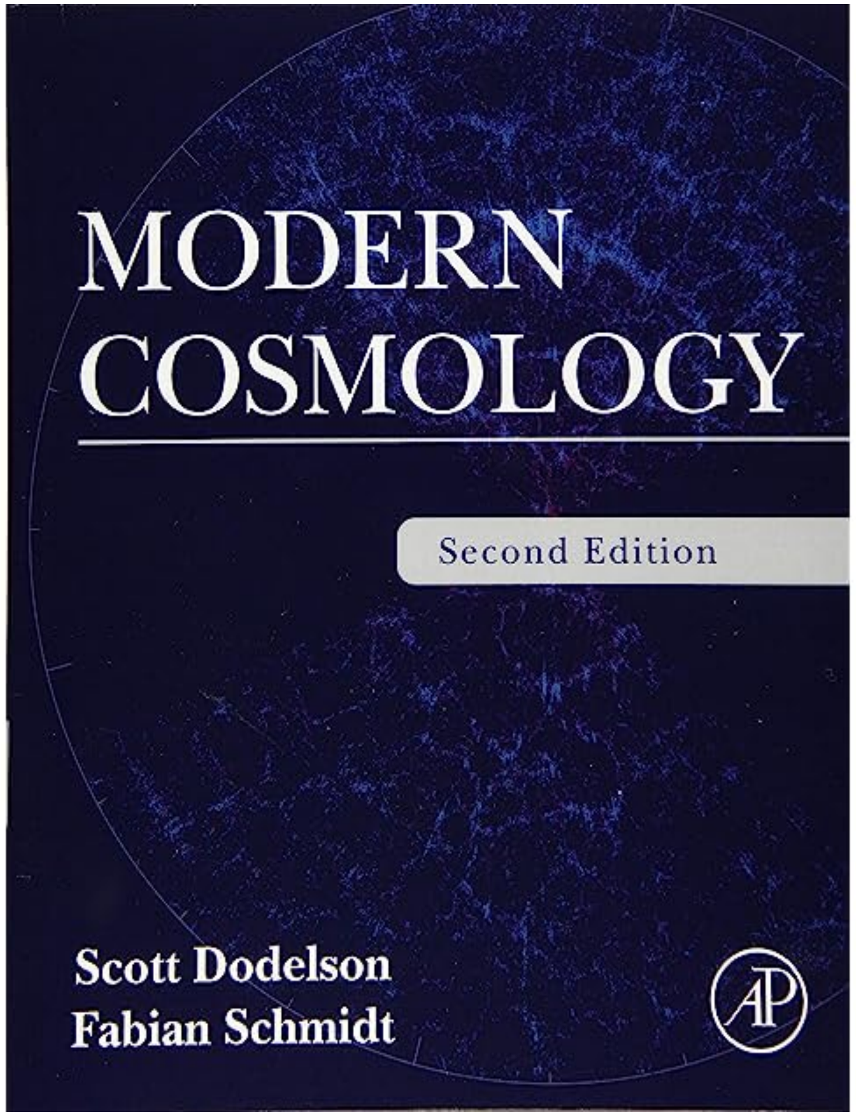
Cosmology

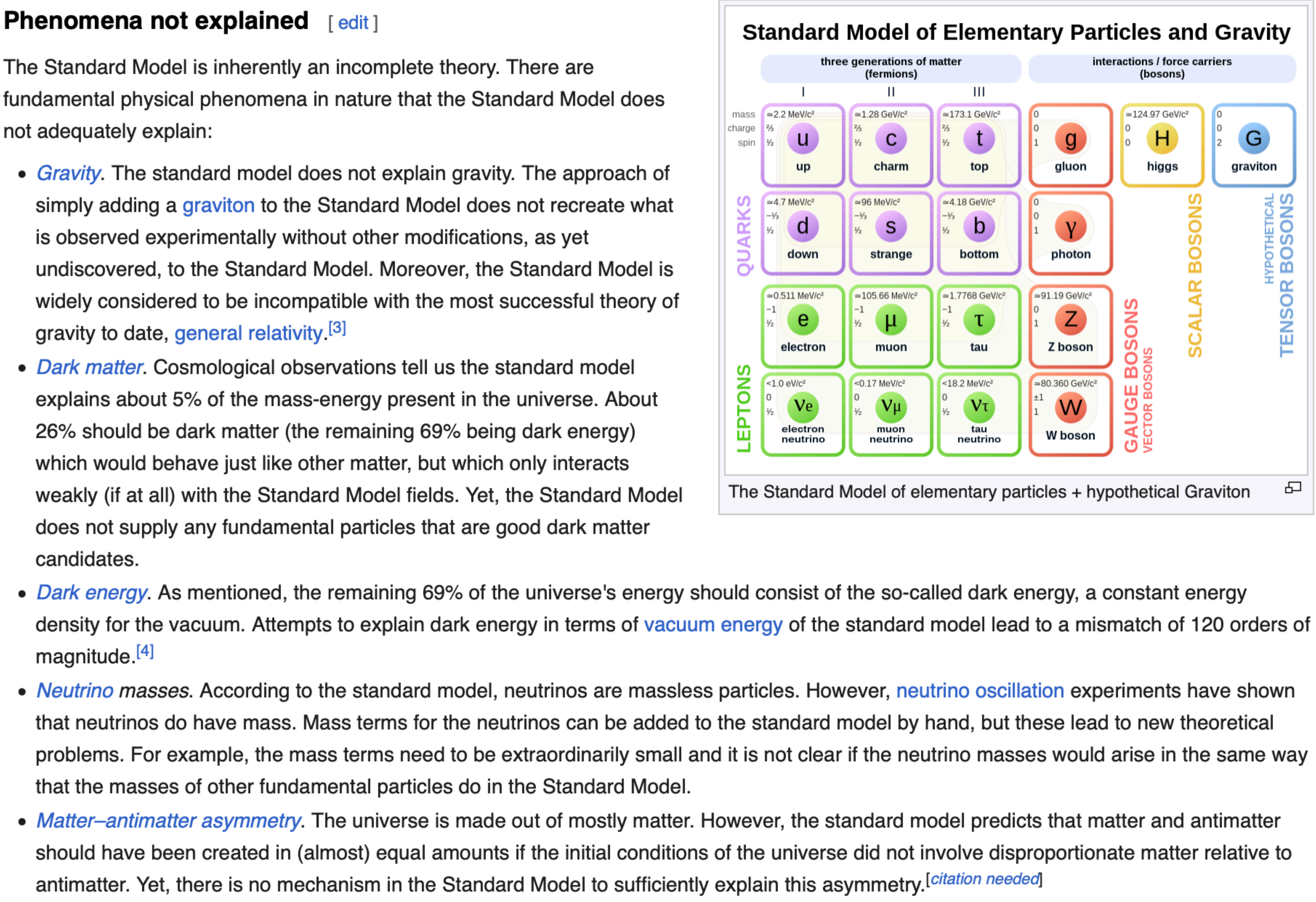
Lecture 1

Literature


COSMOLOGY
DANIEL BAUMANN


MODERN COSMOLOGY
Second Edition
Scott Dodelson
Fabian Schmidt
AP

Why cosmology in this school?



Phenomena not explained [edit]

The Standard Model is inherently an incomplete theory. There are fundamental physical phenomena in nature that the Standard Model does not adequately explain:

- *Gravity*. The standard model does not explain gravity. The approach of simply adding a graviton to the Standard Model does not recreate what is observed experimentally without other modifications, as yet undiscovered, to the Standard Model. Moreover, the Standard Model is widely considered to be incompatible with the most successful theory of gravity to date, general relativity.[3]
- *Dark matter*. Cosmological observations tell us the standard model explains about 5% of the mass-energy present in the universe. About 26% should be dark matter (the remaining 69% being dark energy) which would behave just like other matter, but which only interacts weakly (if at all) with the Standard Model fields. Yet, the Standard Model does not supply any fundamental particles that are good dark matter candidates.
- *Dark energy*. As mentioned, the remaining 69% of the universe's energy should consist of the so-called dark energy, a constant energy density for the vacuum. Attempts to explain dark energy in terms of vacuum energy of the standard model lead to a mismatch of 120 orders of magnitude.[4]
- *Neutrino masses*. According to the standard model, neutrinos are massless particles. However, neutrino oscillation experiments have shown that neutrinos do have mass. Mass terms for the neutrinos can be added to the standard model by hand, but these lead to new theoretical problems. For example, the mass terms need to be extraordinarily small and it is not clear if the neutrino masses would arise in the same way that the masses of other fundamental particles do in the Standard Model.
- *Matter–antimatter asymmetry*. The universe is made out of mostly matter. However, the standard model predicts that matter and antimatter should have been created in (almost) equal amounts if the initial conditions of the universe did not involve disproportionate matter relative to antimatter. Yet, there is no mechanism in the Standard Model to sufficiently explain this asymmetry.[*citation needed*]

Standard Model of Elementary Particles and Gravity

	three generations of matter (fermions)			interactions / force carriers (bosons)		
	I	II	III			
mass charge spin	≃2.2 MeV/c² ⅔ ½ u up	≃1.28 GeV/c² ⅔ ½ c charm	≃173.1 GeV/c² ⅔ ½ t top	0 0 1 g gluon	≃124.97 GeV/c² 0 0 H higgs	0 0 2 G graviton
QUARKS	≃4.7 MeV/c² −⅓ ½ d down	≃96 MeV/c² −⅓ ½ s strange	≃4.18 GeV/c² −⅓ ½ b bottom	0 0 1 γ photon	SCALAR BOSONS	HYPOTHETICAL TENSOR BOSONS
	≃0.511 MeV/c² −1 ½ e electron	≃105.66 MeV/c² −1 ½ μ muon	≃1.7768 GeV/c² −1 ½ τ tau	≃91.19 GeV/c² 0 1 Z Z boson		
LEPTONS	<1.0 eV/c² 0 ½ νe electron neutrino	<0.17 MeV/c² 0 ½ νμ muon neutrino	<18.2 MeV/c² 0 ½ ντ tau neutrino	≃80.360 GeV/c² ±1 1 W W boson	GAUGE BOSONS VECTOR BOSONS	

The Standard Model of elementary particles + hypothetical Graviton

Why cosmology in this school?

Together with observation of no new physics at the EW scale, cosmology had the biggest impact on particle physics in the last couple of decades

Lectures 1-4

Hot Big Bang

Matter-antimatter asymmetry

Dark Matter

Cosmological constant

Inflation

ΛCDM cosmological model

Lecture 5

What comes next?

Beyond standard model

How is this possible?

We integrate the signal over a very large volume

gravity, expansion of the universe, vacuum energy…

Evolution of the universe = scanning over (high) energies

helium, dark matter, density fluctuations…

Part 1

Cosmological principle, Hubble expansion

Newtonian cosmology —> GR interpretation

Light propagation in an expanding universe

Dynamics of an expanding universe

Hot Big Bang paradigm

(Discovery of the vacuum energy)

Beginning of cosmology

~1924. — discovery of galaxies

~1929. — discovery of expansion of the universe

$$v = H_0 r$$

Hubble (1929)

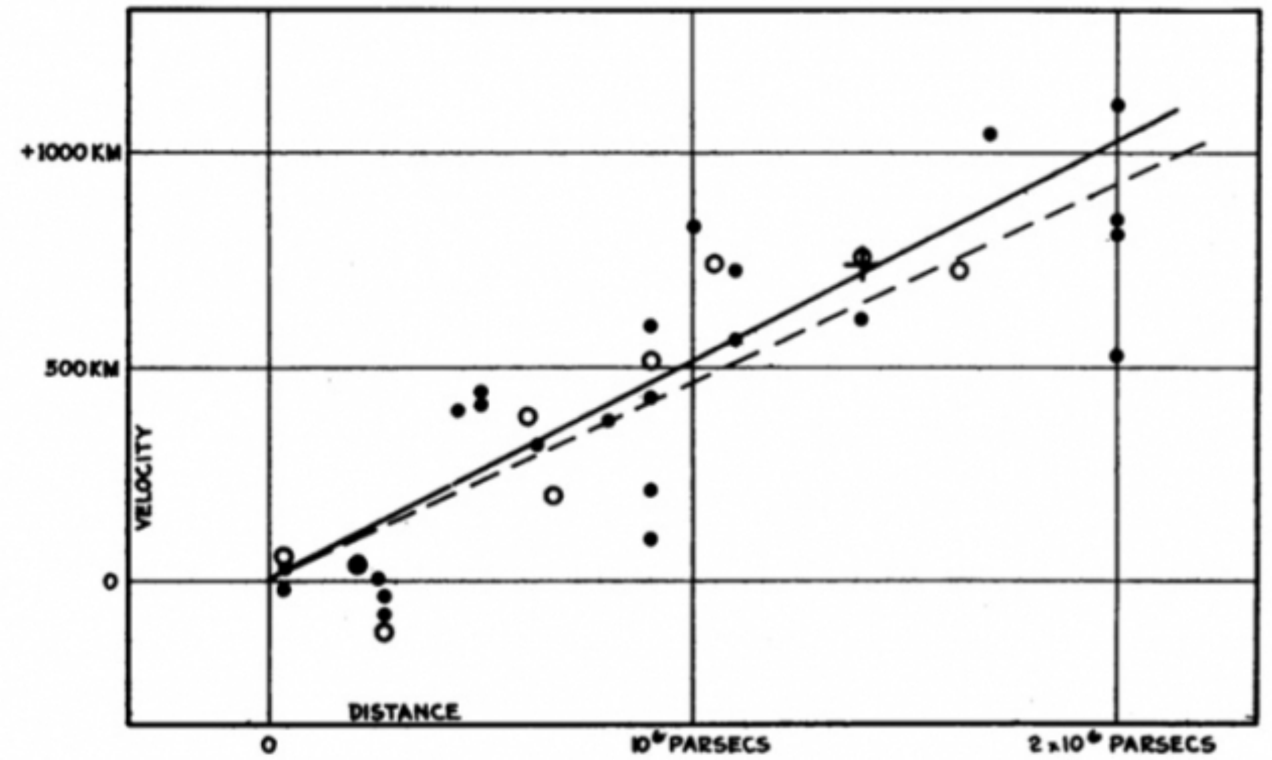


FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

$$1\,\mathrm{pc} = 3.26\,\mathrm{ly} = 3.1 \cdot 10^{13}\,\mathrm{km}$$

Beginning of cosmology

On large scales the universe is homogeneous and isotropic

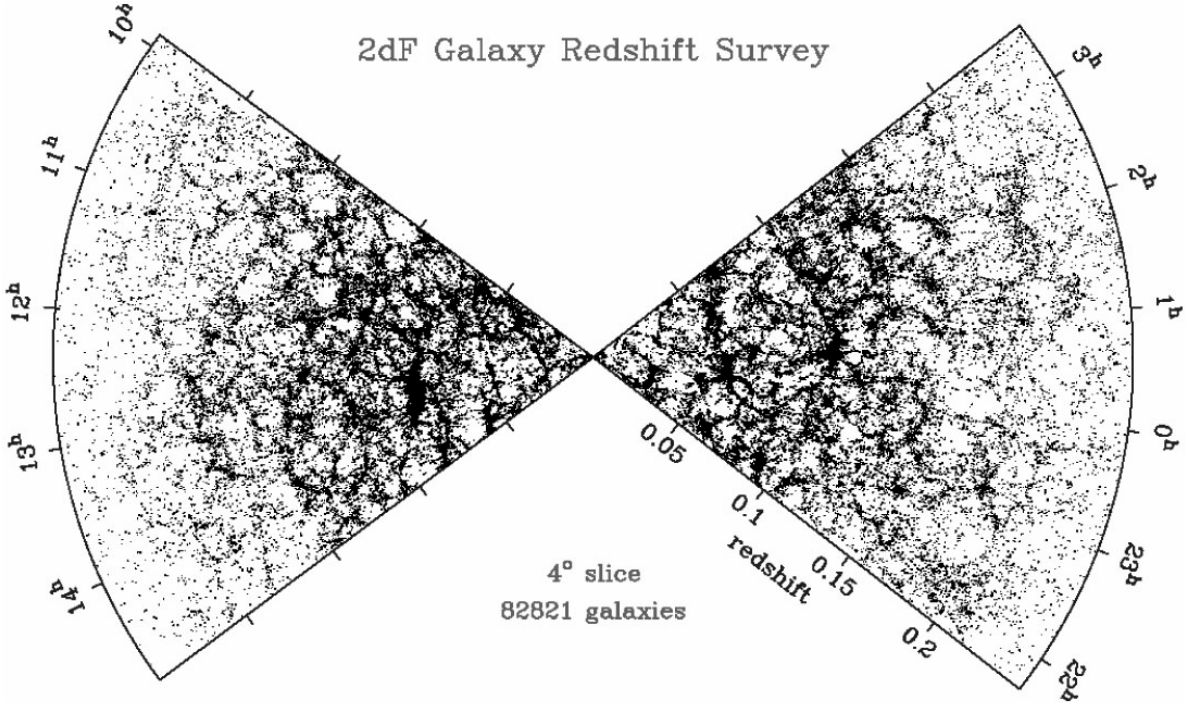
All galaxies are moving away from one another

Modern-day value of H_0

$H_0 \approx 69.8 \text{ km/s/Mpc}$

Impossible to measure in a laboratory

2dF galaxy survey (~2000)



~80000 galaxies

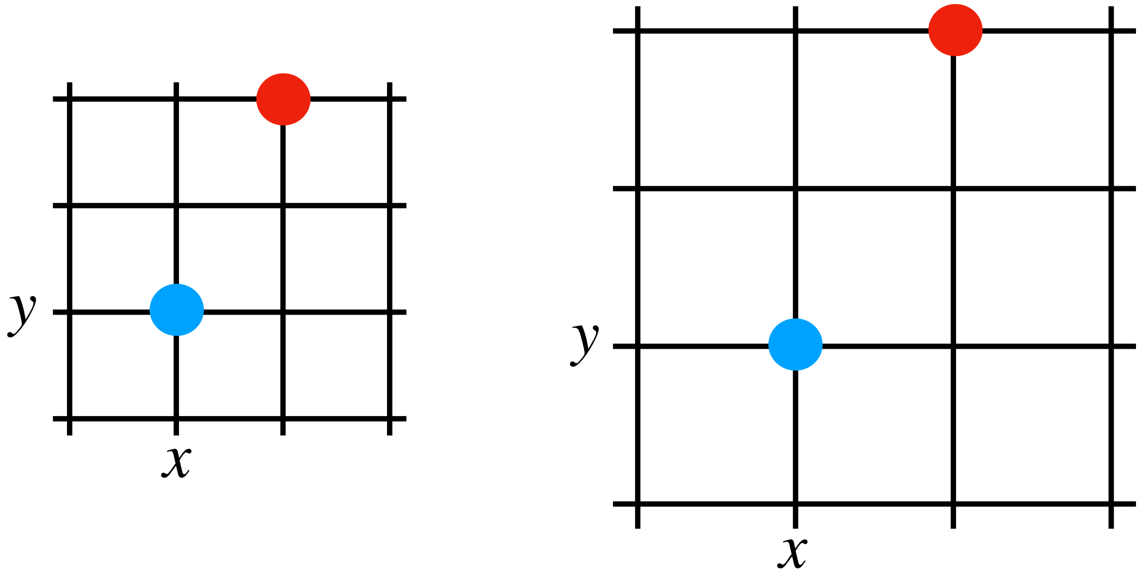
Explanation of the Hubble's law

scale factor

$$\boldsymbol{r} = a(t)\boldsymbol{x}$$

$$\boldsymbol{v} = \frac{\dot{a}}{a}\boldsymbol{r} + \cancelto{0}{\boldsymbol{v}_{\text{pec.}}}$$

Comoving coordinates



$$H(t) \equiv \frac{\dot{a}}{a} \qquad H_0 \equiv H(t_0) \qquad a(t_0) = 1$$

Newtonian cosmology

Equations of motion for the scale factor

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{C}{a^2}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$

} Friedmann equations

$$\dot{\rho} + 3H(\rho + p) = 0$$

Proper interpretation in General Relativity

Newtonian intuition breaks down at large scales

Friedmann eq. = Einstein eq. for a homogeneous and isotropic universe

FRW metric

$$ds^2 = -dt^2 + a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2\right]$$

Spatial curvature

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2}$$

Set $k = 0$ for the rest of the lectures

ρ and p are diagonal components of the stress-energy tensor

Propagation of light

Light propagates on the light cone

$$ds^2 = 0 \qquad \longrightarrow \qquad \int_{t_{\rm em}}^{t_{\rm det}} \frac{dt}{a(t)} = \int_{x_{\rm em}}^{x_{\rm det}} dx$$

Conformal time $\qquad d\tau \equiv \dfrac{dt}{a(t)}$

Cosmological redshift

$$z \equiv \frac{\lambda_{\rm det} - \lambda_{\rm em}}{\lambda_{\rm em}} = \frac{a(t_{\rm det})}{a(t_{\rm em})} - 1 = \frac{1}{a(t_{\rm em})} - 1$$

Solutions for matter and radiation

Energy density for matter and radiation

$$\rho_{\mathrm{m}} \sim a^{-3} \qquad\qquad \rho_{\mathrm{r}} \sim a^{-4}$$

Solutions for a generic fluid

$$p \equiv w\rho \qquad\qquad \rho \sim a^{-3(1+w)} \qquad\qquad a(t) = (t/t_0)^{\frac{2}{3(1+w)}}$$

Critical density and density fractions

$$\rho_c \equiv \frac{3H_0^2}{8\pi G} \qquad\qquad \Omega_i \equiv \frac{\rho_i}{\rho_c}$$

$$H^2 = H_0^2(\Omega_{\mathrm{m},0}a^{-3} + \Omega_{\mathrm{r},0}a^{-4} + \cdots)$$

Big Bang singularity and the age of the universe

$a(t) = (t/t_0)^{\frac{2}{3(1+w)}}$ for $t = 0$ there is a singularity!

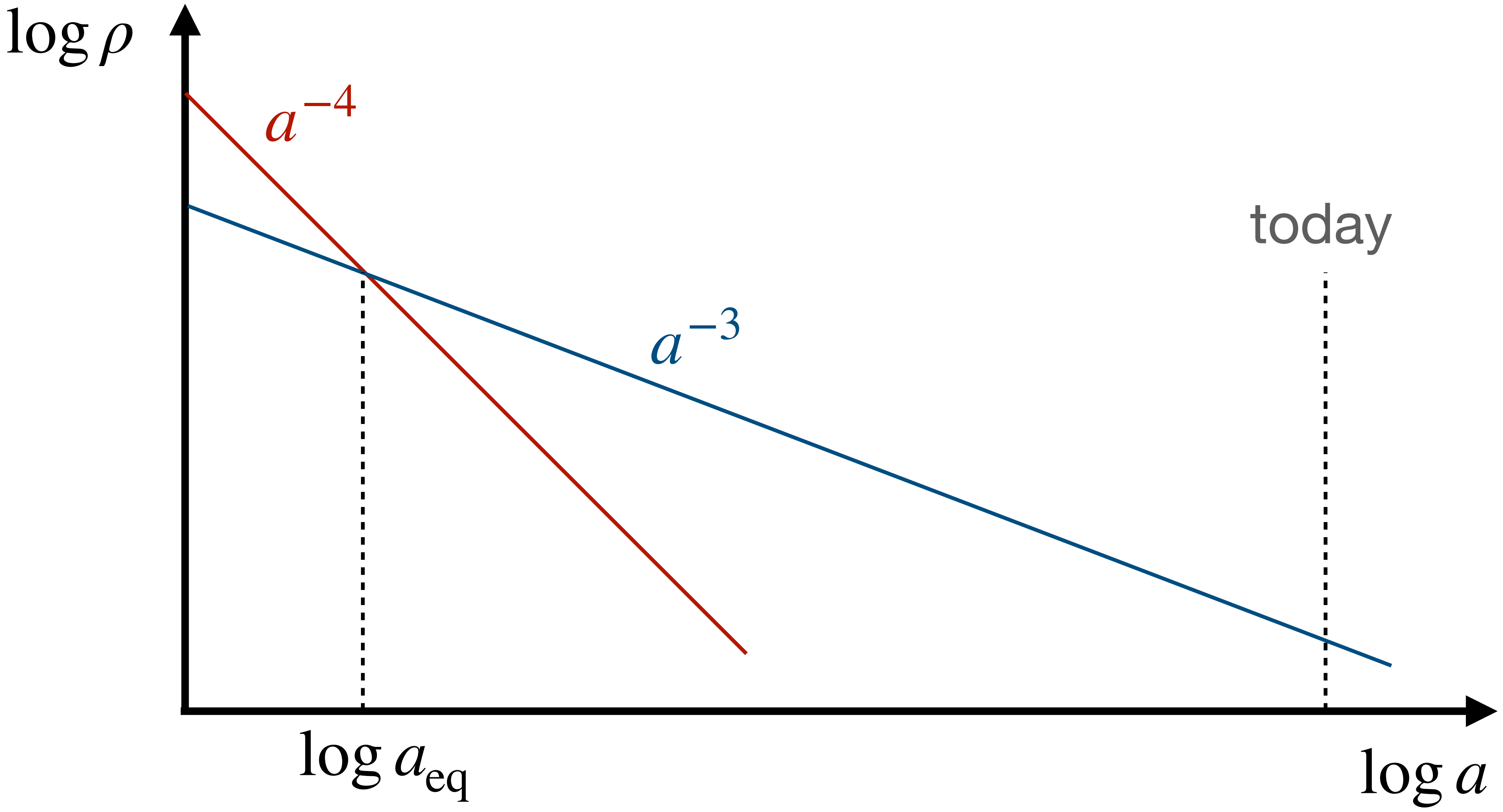
This implies a finite age of the universe

$$t_{\rm age} = \int_0^{t_{\rm age}} dt = \int_0^1 \frac{da}{aH(a)} = \frac{2}{3(1+w)} \frac{1}{H_0}$$

A rough estimate gives $t_{\rm age} \approx 14$ billion years

Conformal diagram and causal structure

Hot Big Bang and thermal history



Even a small amount of radiation today was dominating in the past!

Luminosity distance and deceleration

Luminosity distance

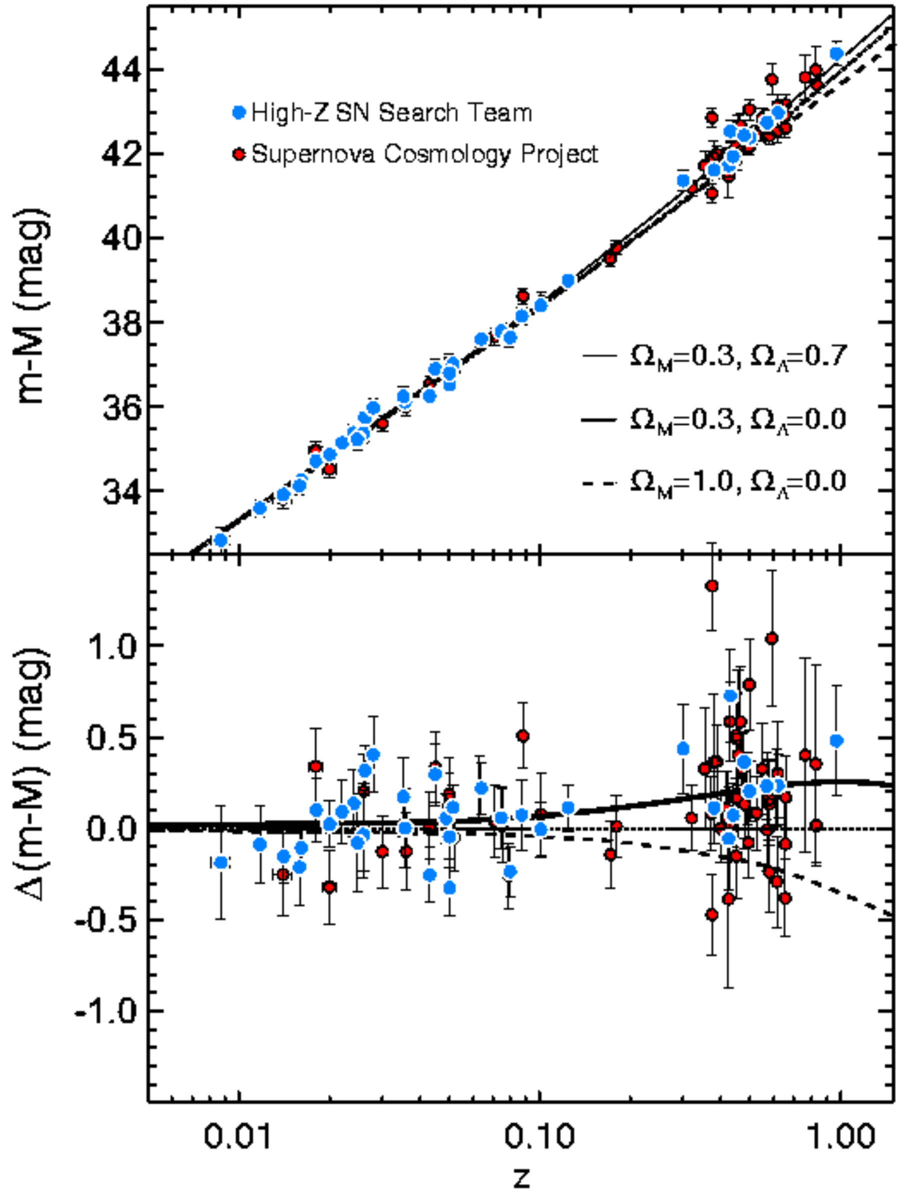
$$F \equiv \frac{L}{4\pi d_L^2} = \frac{L}{4\pi(1+z)^2 r^2} \longrightarrow d_L = (1+z)\int_0^z \frac{dz'}{H(z')}$$

Expanding around $z = 0$ we find

$$d_L = \frac{z}{H_0}\left(1 + \frac{1}{2}(1-q_0)z + \cdots\right) \qquad q(t) \equiv -\frac{\ddot{a}a}{\dot{a}^2}$$

For $\rho + 3p > 0$ we have $\ddot{a} < 0$ and $q_0 > 0$

Luminosity distance and deceleration



Observations give $q_0 < 0$

Only possible for $\rho + 3p < 0$

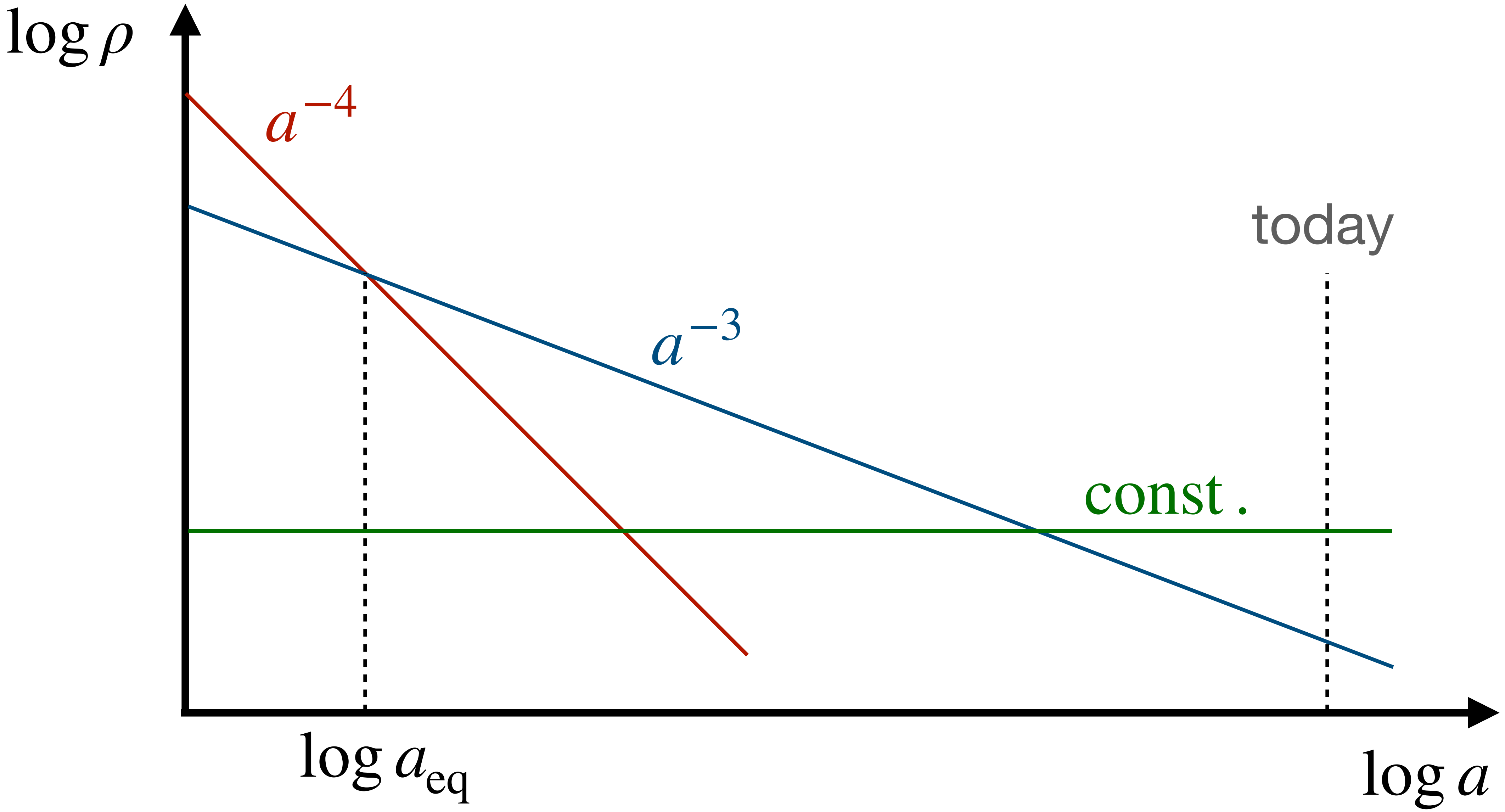
Natural candidate is vacuum energy

$$\rho = \text{const.} \qquad p = -\rho$$

$$\Omega_{\mathrm{m},0} \approx 0.3 \qquad \Omega_\Lambda \approx 0.7$$

This is Λ in ΛCDM cosmological model

Vacuum energy and its puzzles



Vacuum energy dominates the energy budget today!

Vacuum energy and its puzzles

Observed energy density of the vacuum is $\rho_\Lambda \approx (10^{-3}\ \mathrm{eV})^4$

We could never do it in a laboratory

O(100) orders of magnitude smaller than the naive expectations

Similar to the hierarchy problem, but much worse…

Resolution may have dramatic consequences:

Multiverse and anthropic principle

Giving up EFT paradigm

…