The Universe: What We Know and What we Don’t

Fundamental Physics

- Cosmology
- Elementary Particle Physics

Cosmology

Study of the universe at the largest scale

- How big is the universe?
- Where did the universe come from?
- What is the fate of the universe?
- Are there other universes? How many?
- What is dark matter?
- What is dark energy?

Elementary Particle Physics

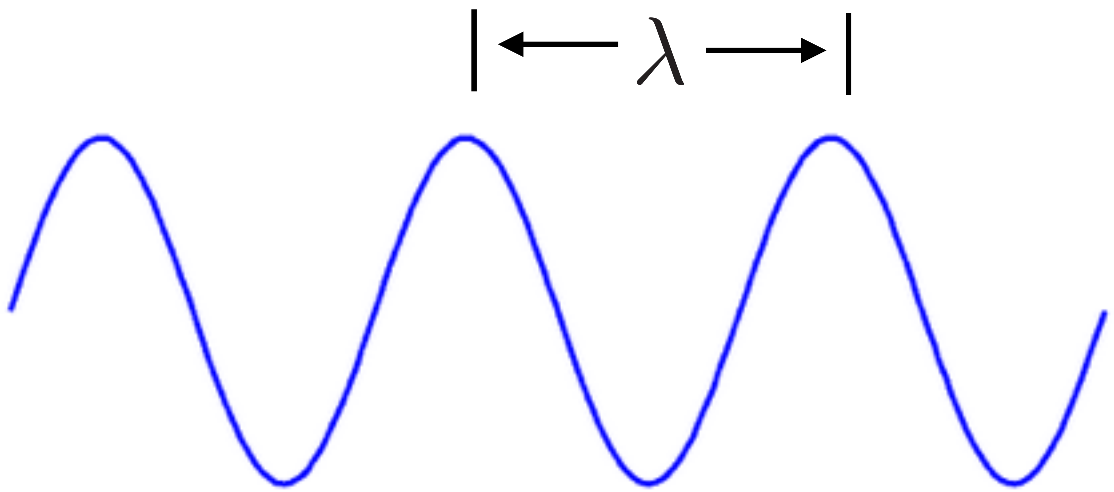
Study of the small scale structure of the universe

- What are the basic building blocks?
- How do they interact with one another?
- Is there a smallest amount of space and time?
- Is there a theory of everything?

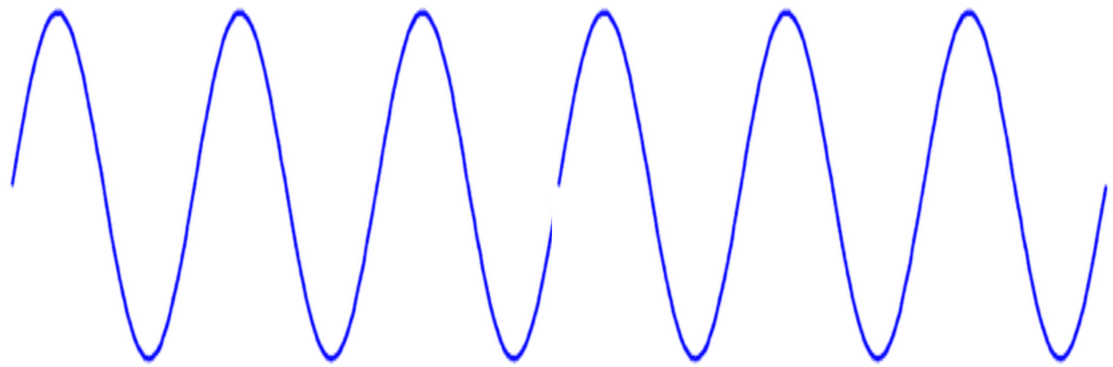
Particle-Wave Duality

Energy inversely proportional to wavelength

$$E \propto \frac{1}{\lambda}$$



lower energy



higher energy

Study of small distances requires high energy probes

Large Hadron Collider

Energy scale

10^3 GeV

Distance scale

10^{-19} m

Temperature

10^{16} K

Big Bang

14 billion years ago the universe was much denser and hotter than today

Has been expanding and cooling ever since

To know the state of the universe at earlier and earlier times, need to know physics at higher and higher energy scales (smaller and smaller distances)

10^{16} K → 10^{-12} s after Big Bang

What we Know

- Physics down to a distance scale of

$$10^{-19}\ \mathrm{m}$$

- Physics down to a time of

$$10^{-12}\ \mathrm{s}$$ after the Big Bang

How big is the universe?

We don't know

- At least about 100 times larger than the visible universe
- Could be infinite

Steady State Universe

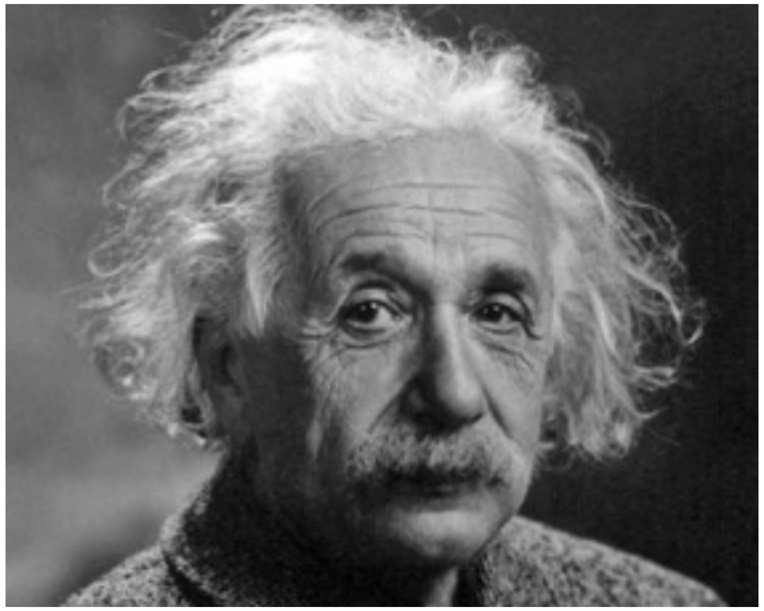
Pre 20th century

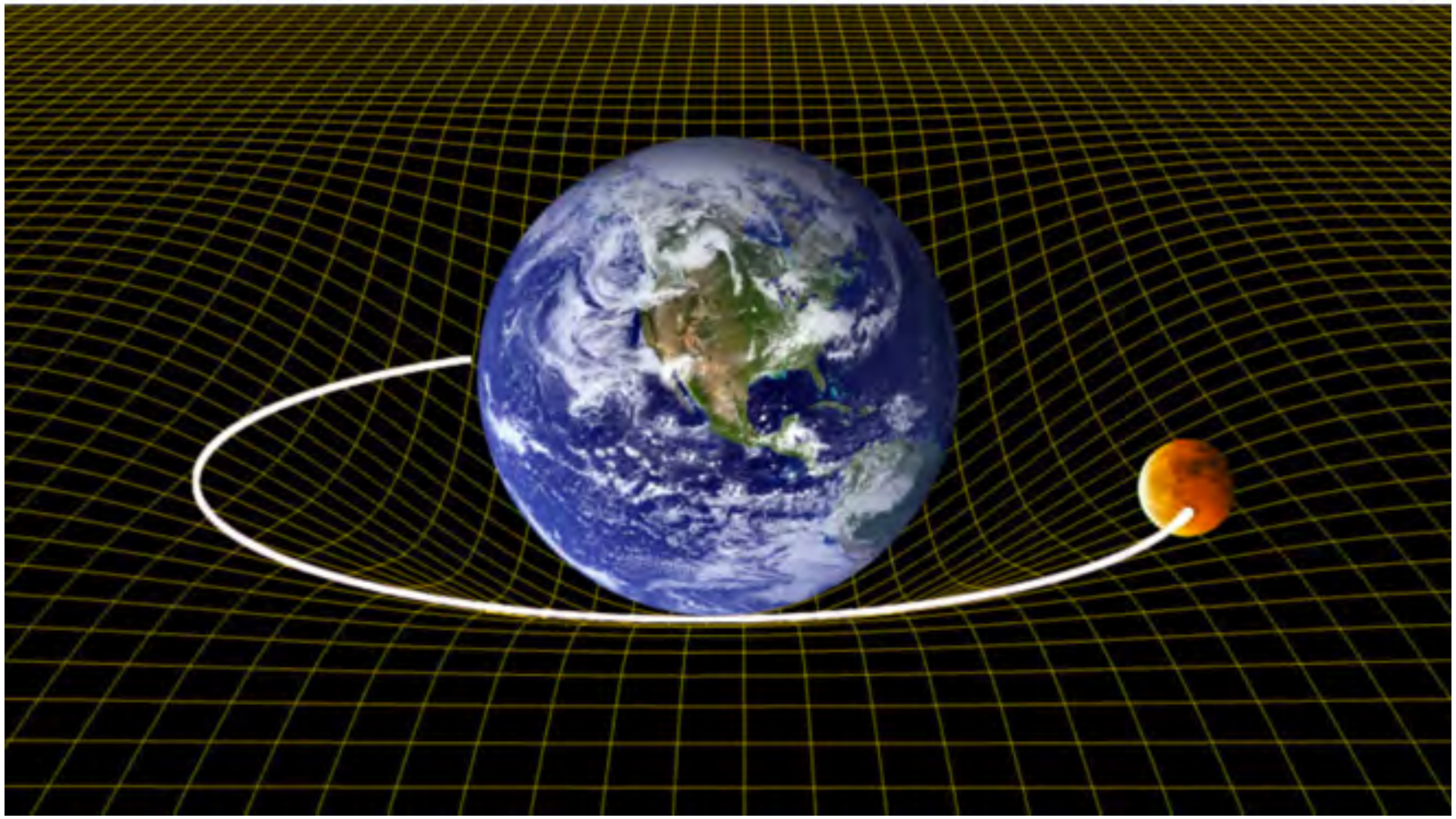
- Stars fixed points in space
- Universe unchanging

General Relativity

Eistein 1915

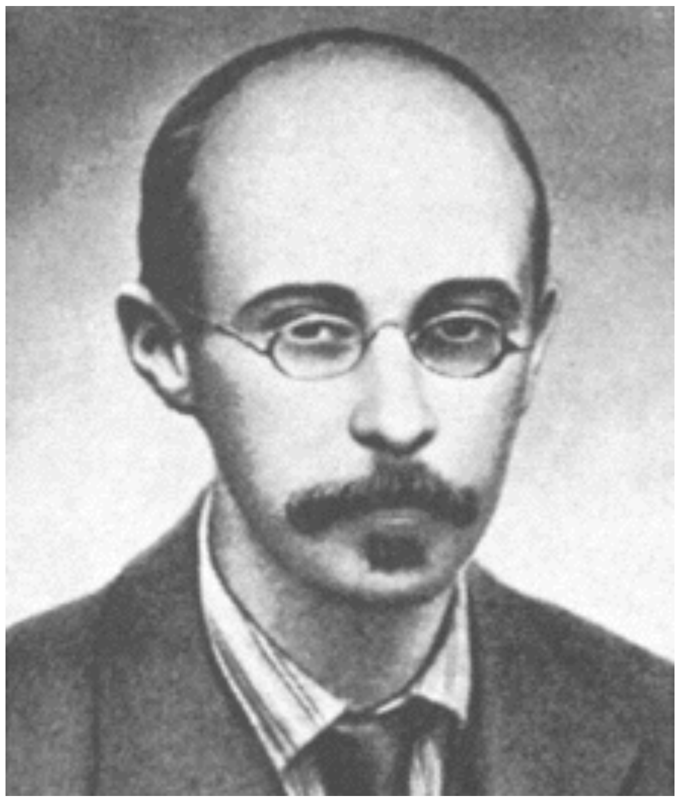
- Gravity due to curvature of space-time





Friedman Equation

Alexander Friedman 1922



Applied general relativity to the whole universe

$$\left(\frac{v}{r}\right)^2 \sim \text{ energy density}$$

What is energy density due to ?

$$E = mc^2$$

about one hydrogen atom per cubic meter

$$1 \text{ GeV} \ / \ m^3$$

Cosmological Constant

fudge factor

$$\left(\frac{v}{r}\right)^2 = \frac{8\pi G}{3}\rho_m - \Lambda$$

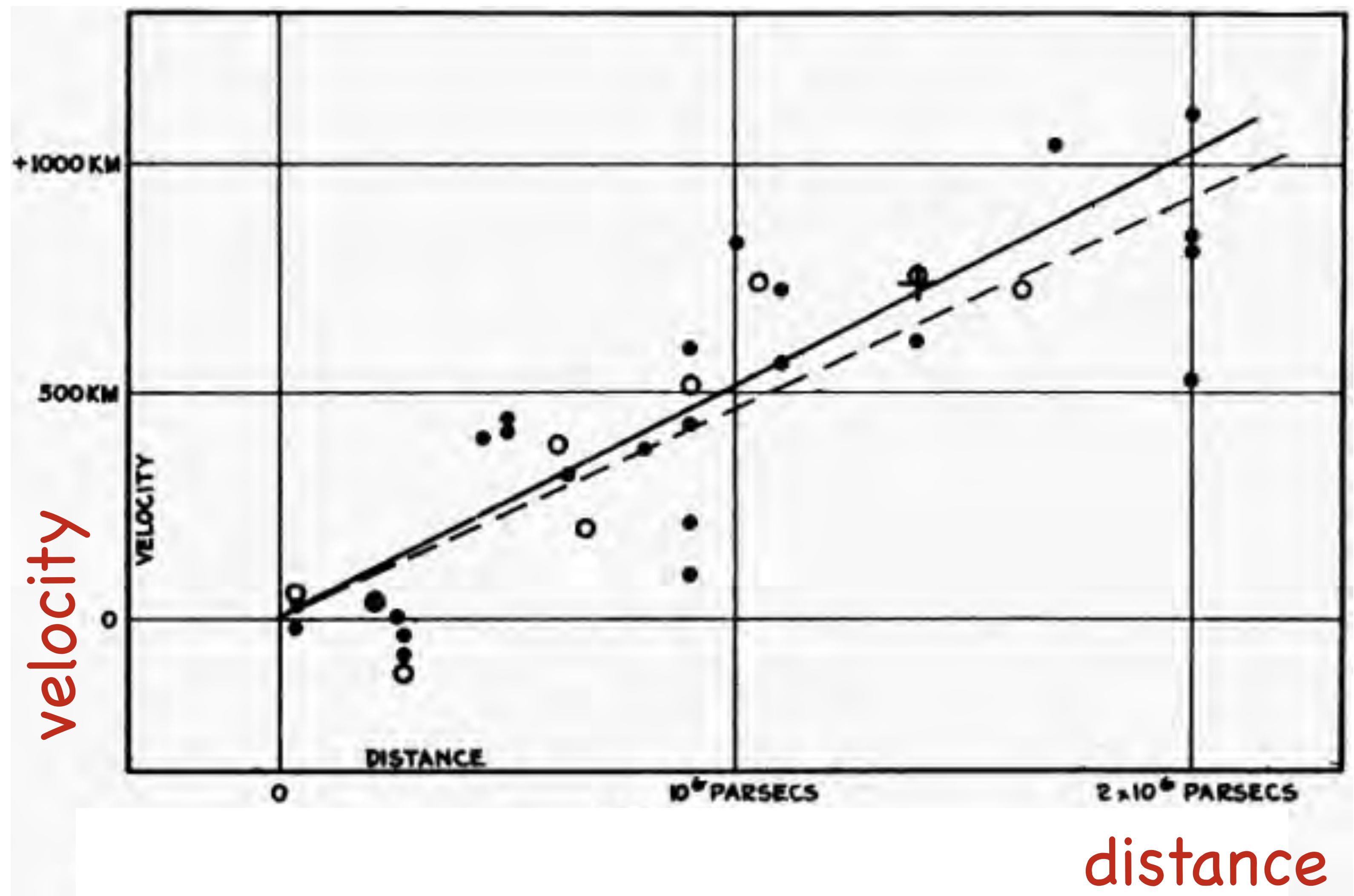
matter energy density

Prevents the universe from expanding (or contracting)

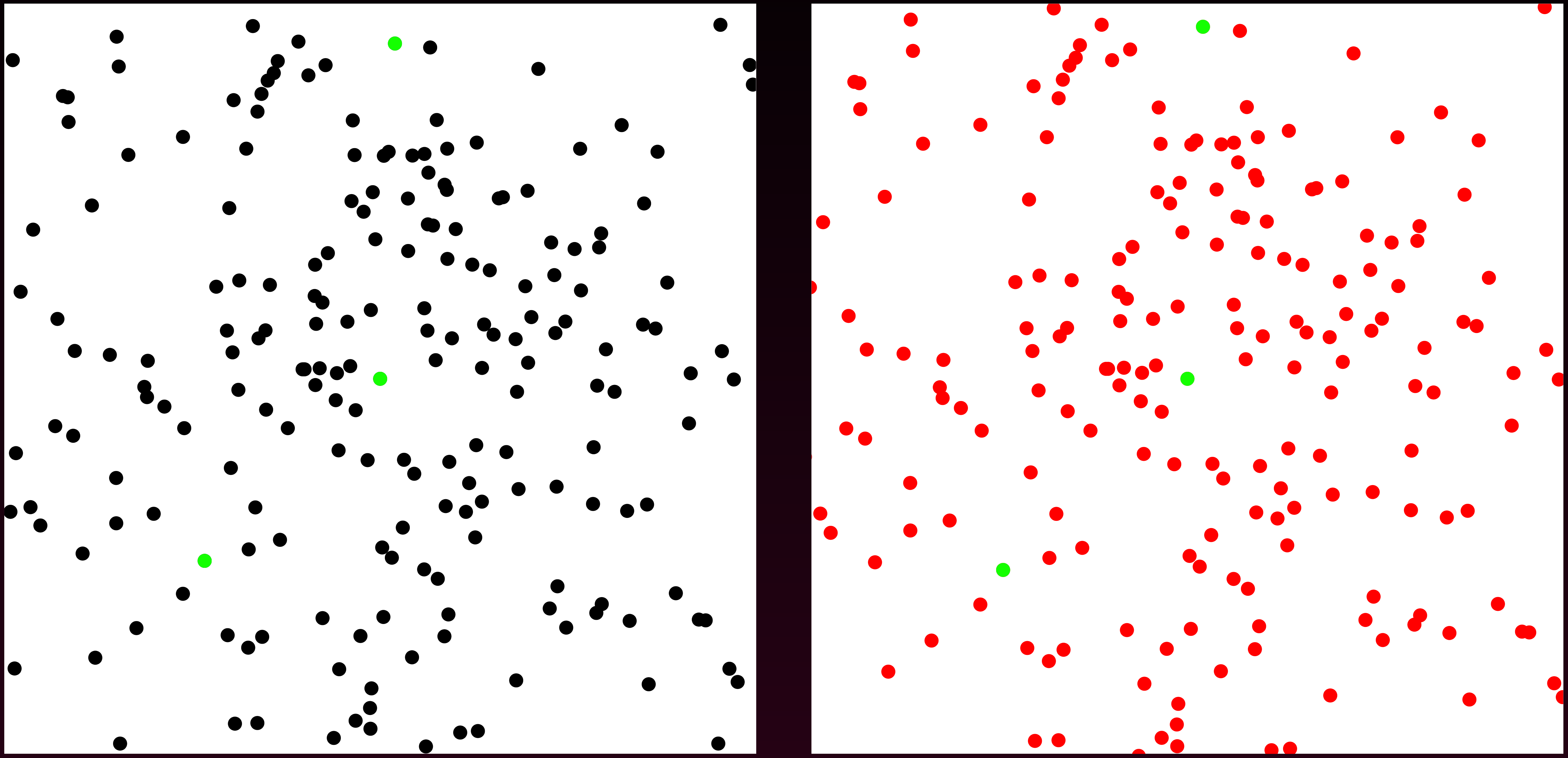
Hubble Expansion

Hubble 1927

The universe is expanding



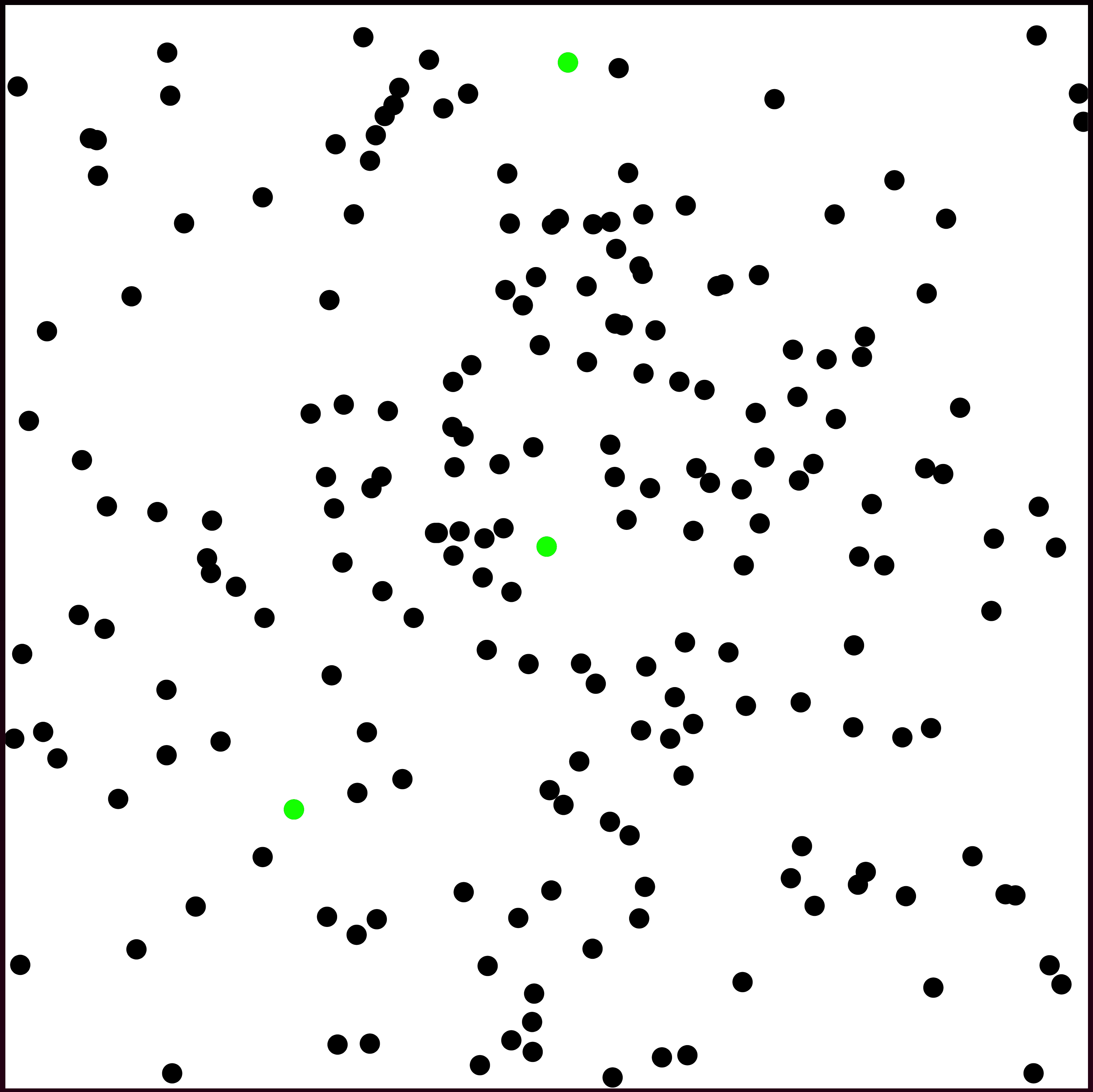
An Expanding Universe



original | expanded by 5%

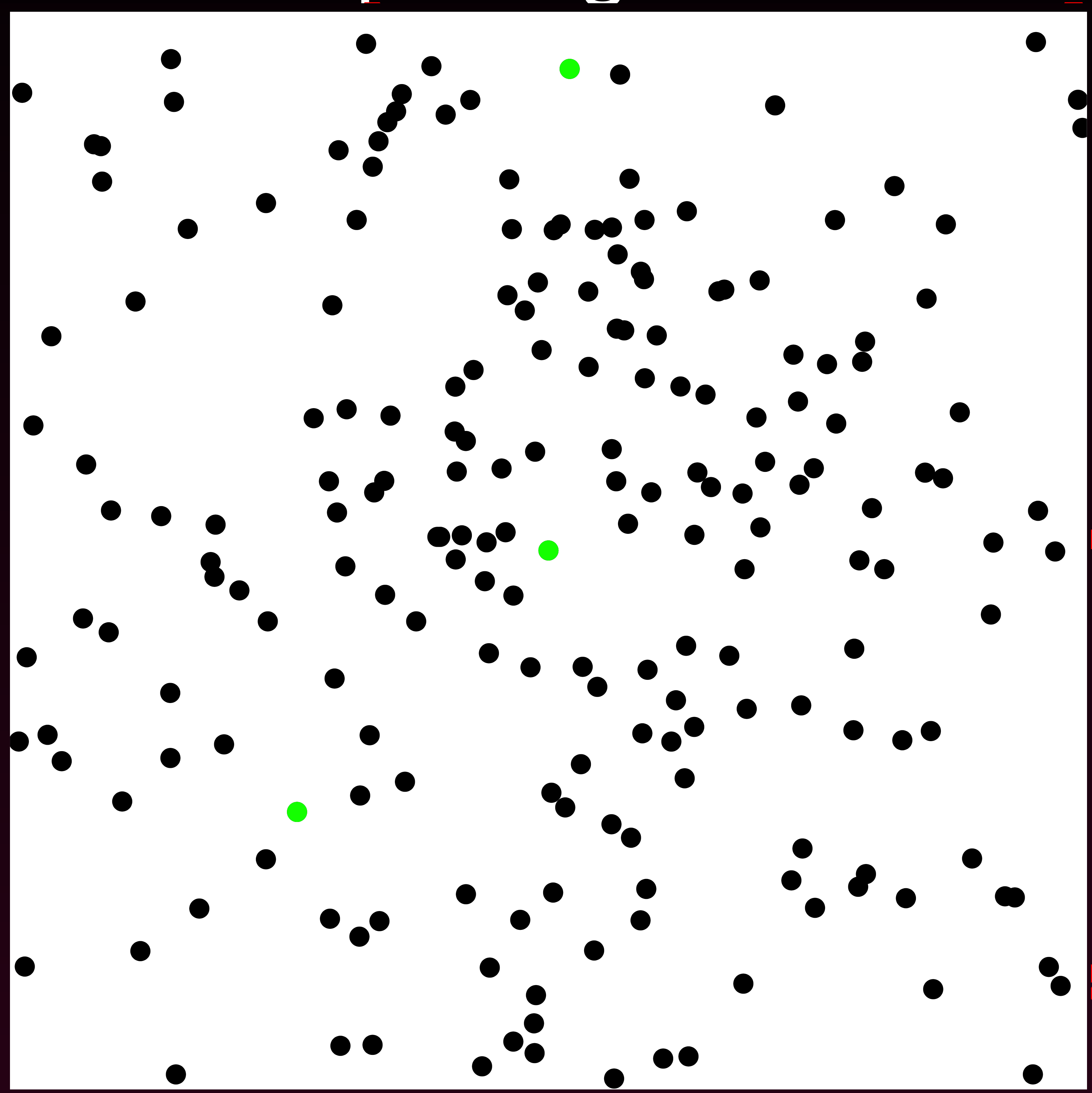
each dot represents a galaxy in the Universe

An Expanding Universe



"velocity" is proportional to distance: Hubble's Law!

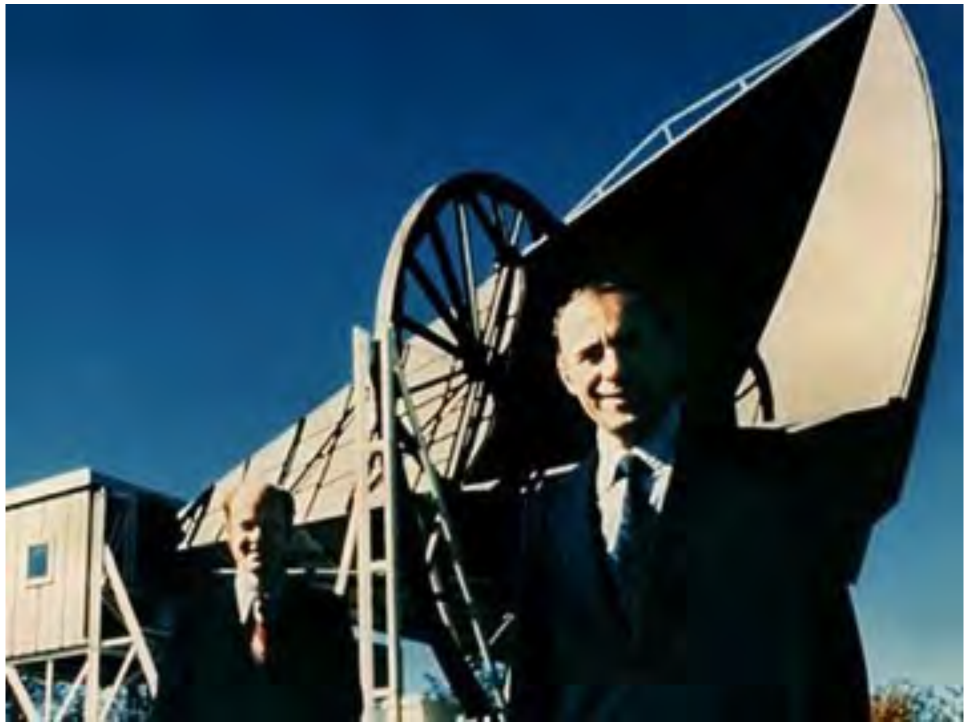
An Expanding Universe



everyone sees the same relationship: Hubble's Law is universal!

Cosmic Microwave Background Radiation

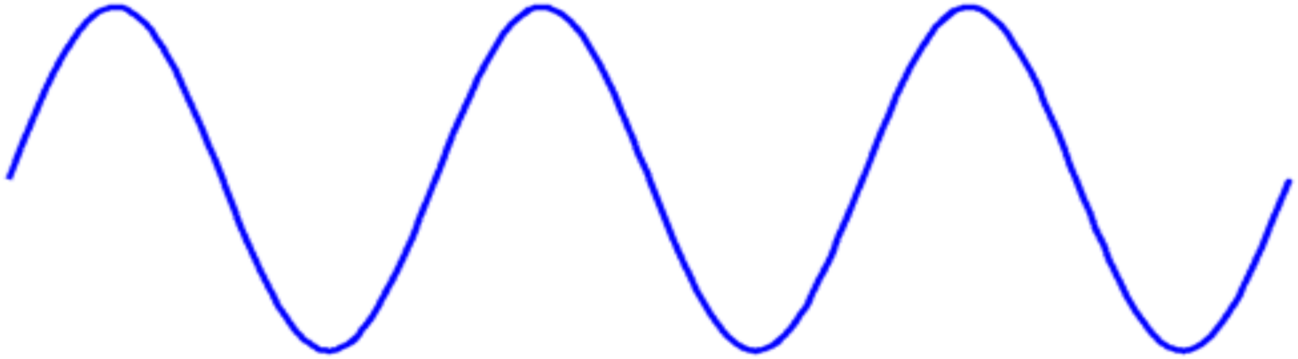
Penzias and Wilson 1965



Remnant radiation (photons) left over from 380,000 years after the Big Bang

Cooled from 3000 K to 2.7 K

Why?



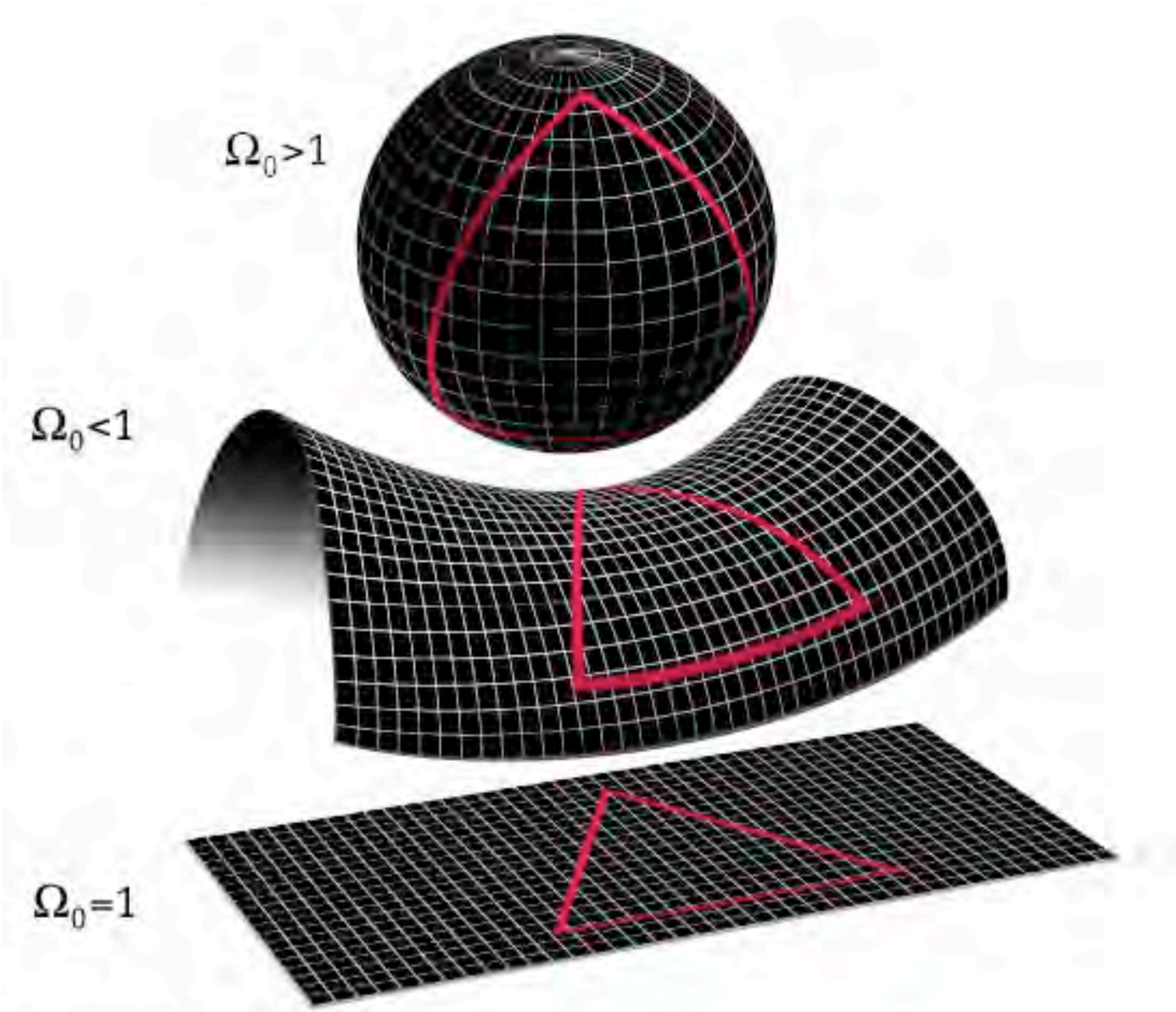
Something Wrong

$$H_0^2 = \left(\frac{v}{r}\right)^2 = \frac{8\pi G}{3}\,\rho_m$$

$$H_0^2 \,/\, H_0^2 = \frac{8\pi G}{3}\,\rho_m \,/\, H_0^2 = \Omega_m$$

$$\Omega_m = 0.05$$

Curvature



positive curvature

negative curvature

zero curvature (flat)

$$\Omega_K = -\frac{Kc^2}{R^2} / H_0^2$$

Cosmology in 1970

$$1 = \Omega_m + \Omega_K$$

0.05 0.95

- Expansion dominated by negative curvature
- Relatively small R

This is wrong

Dark Matter

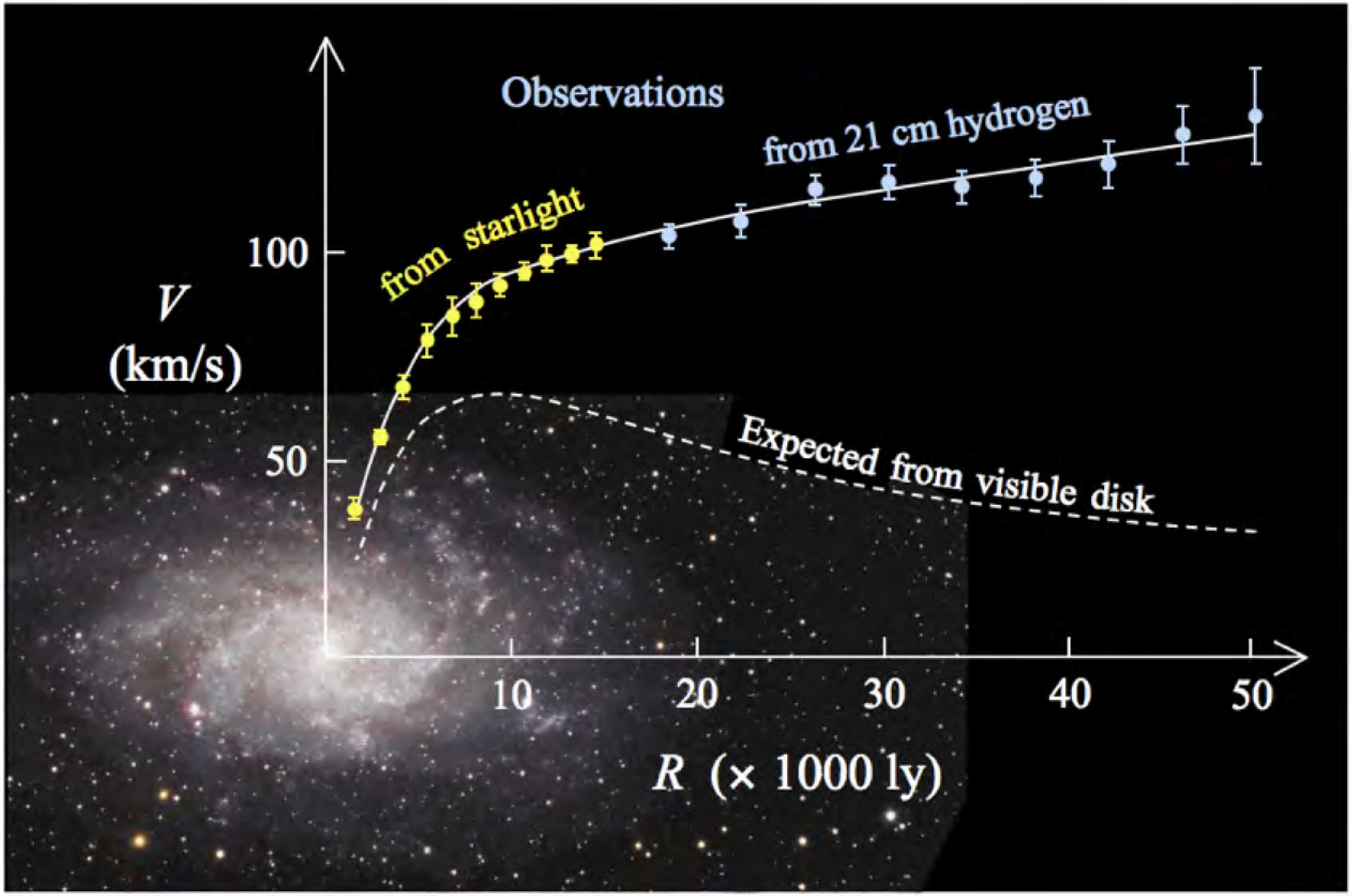
Dark Energy

Dark Matter

About 80% of the matter
in the universe is dark

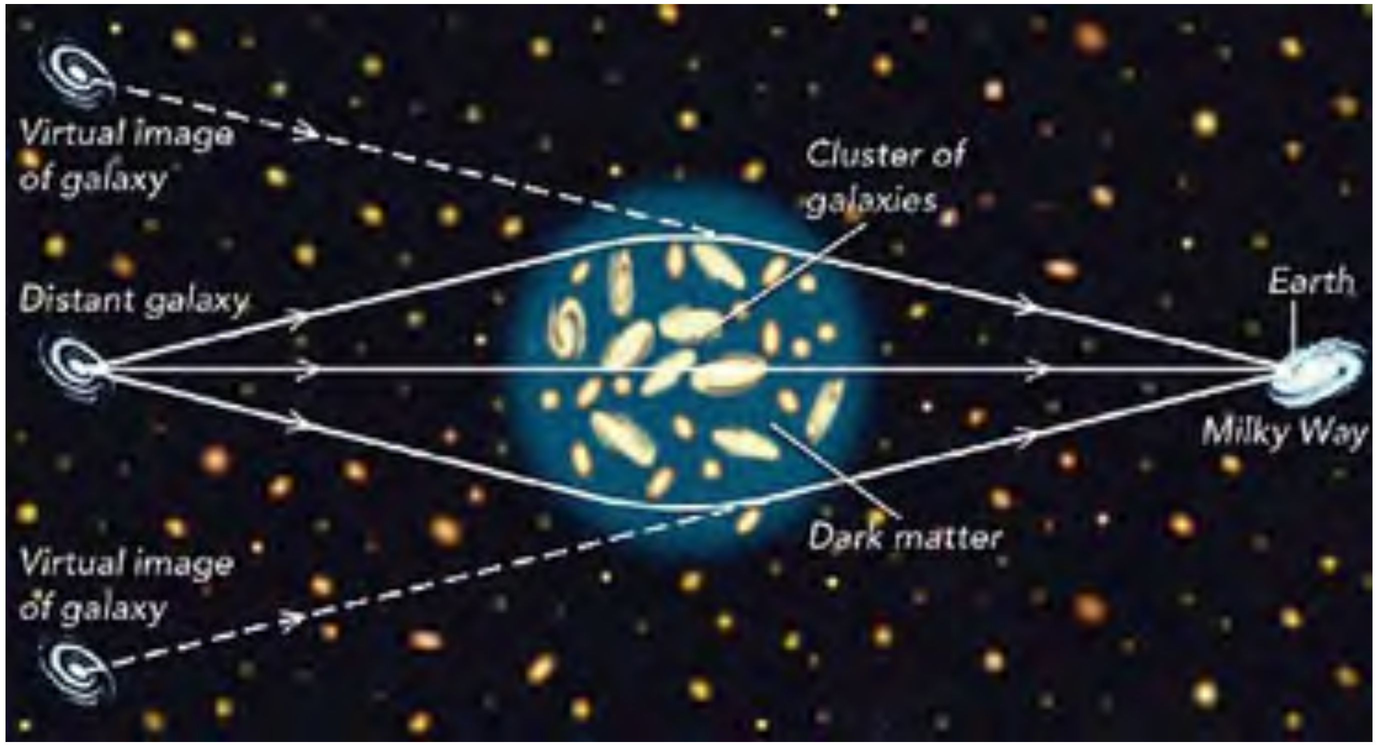
Evidence for Dark Matter (1)

Rotational curve of galaxy



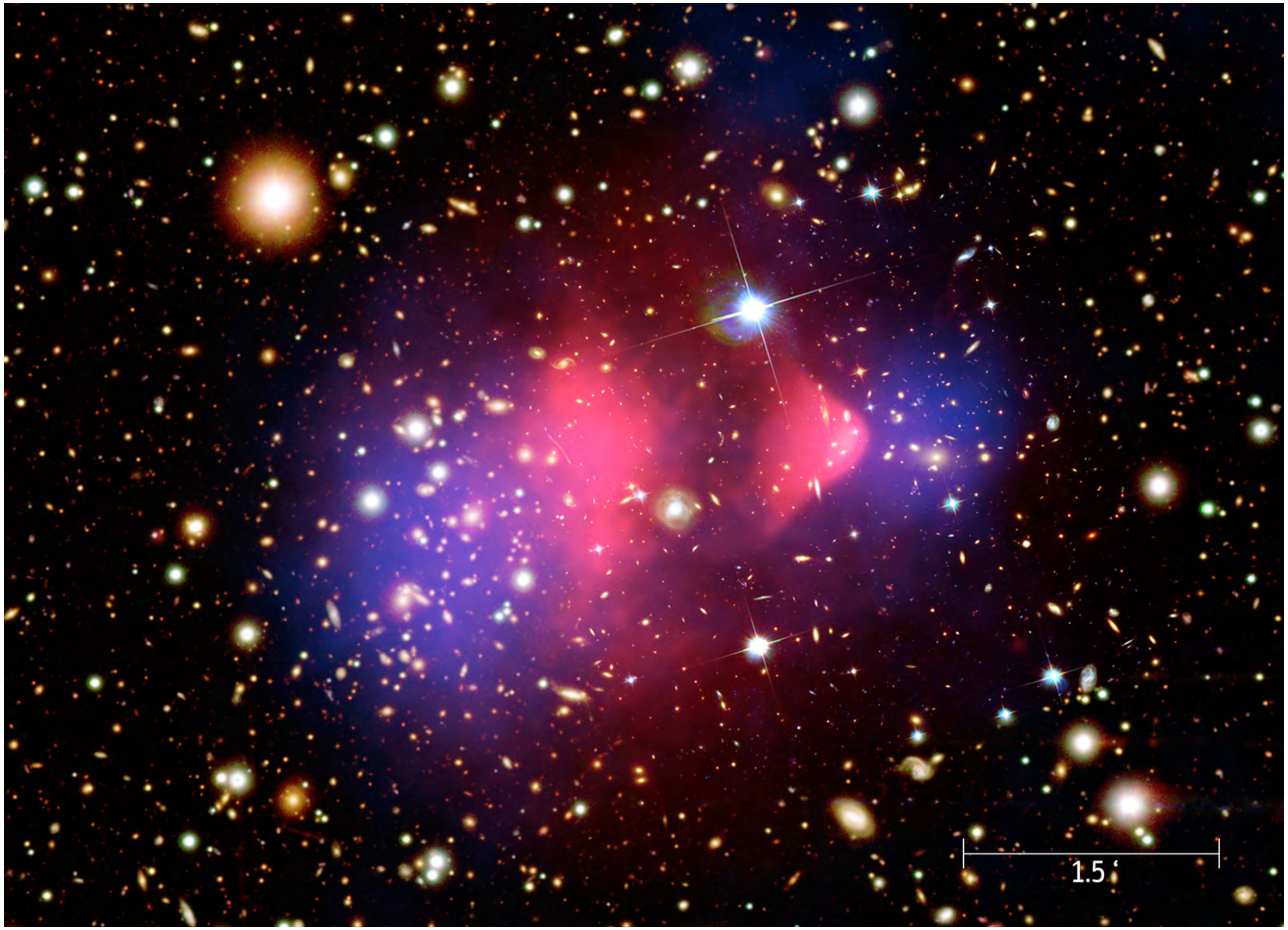
Evidence for Dark Matter (2)

Gravitational lensing

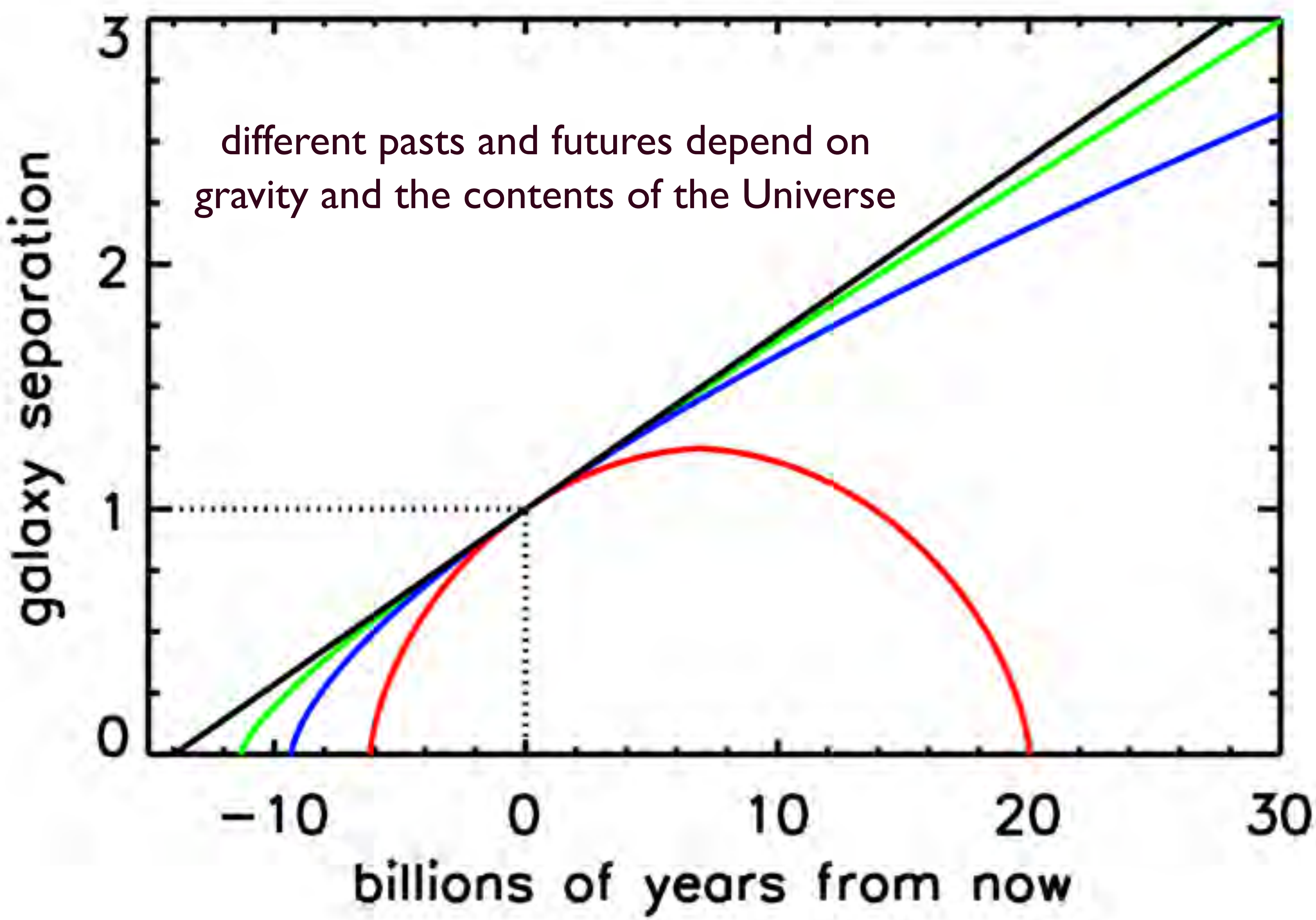


Evidence for Dark Matter (3)

Bullet Cluster

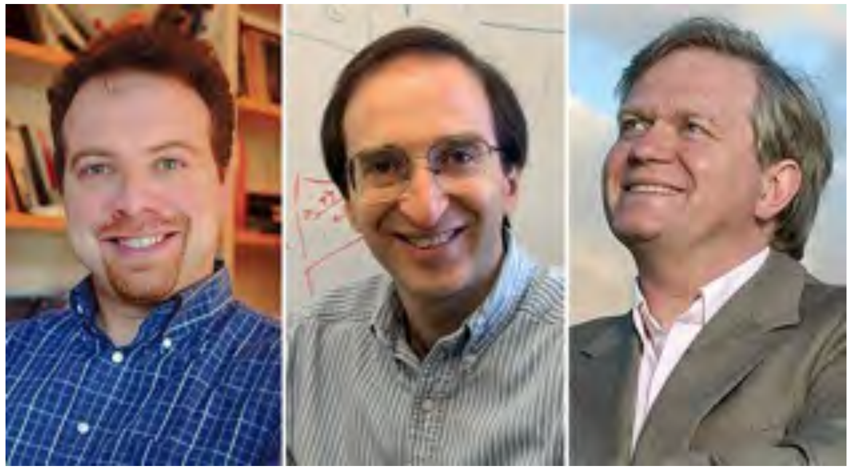


Evolution of the Universe

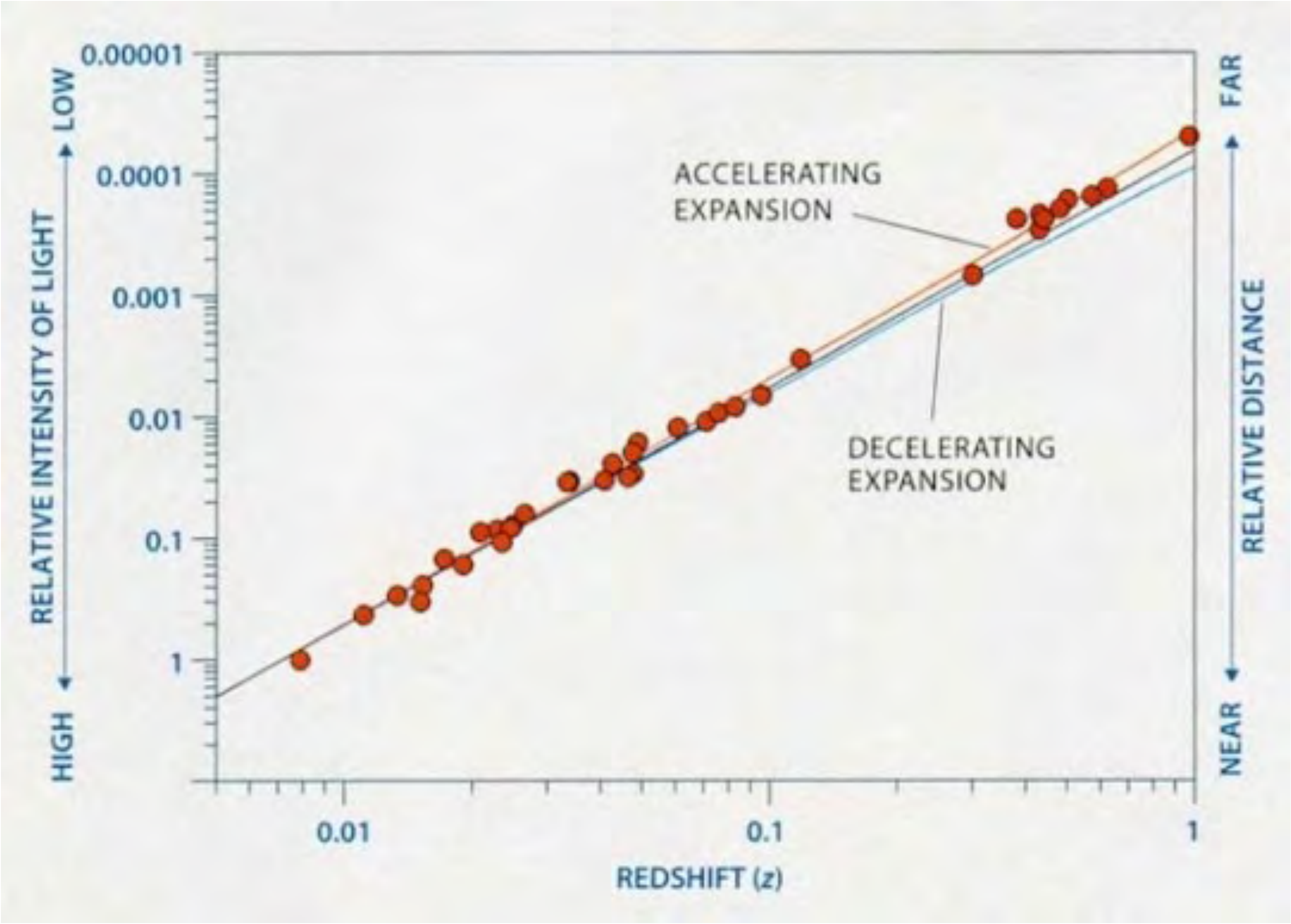


Dark Energy

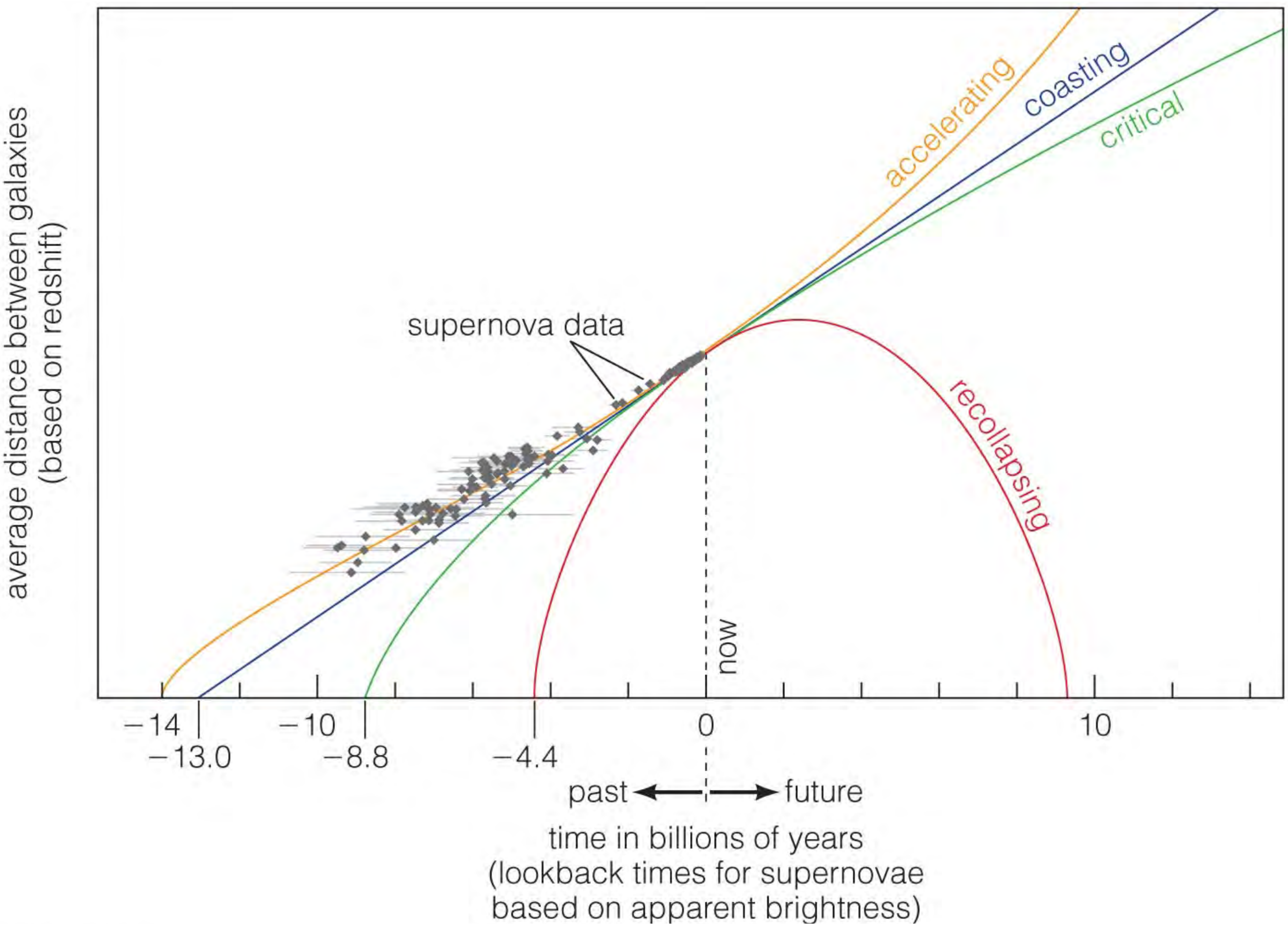
Riess, Perlmutter, Schmidt 1998



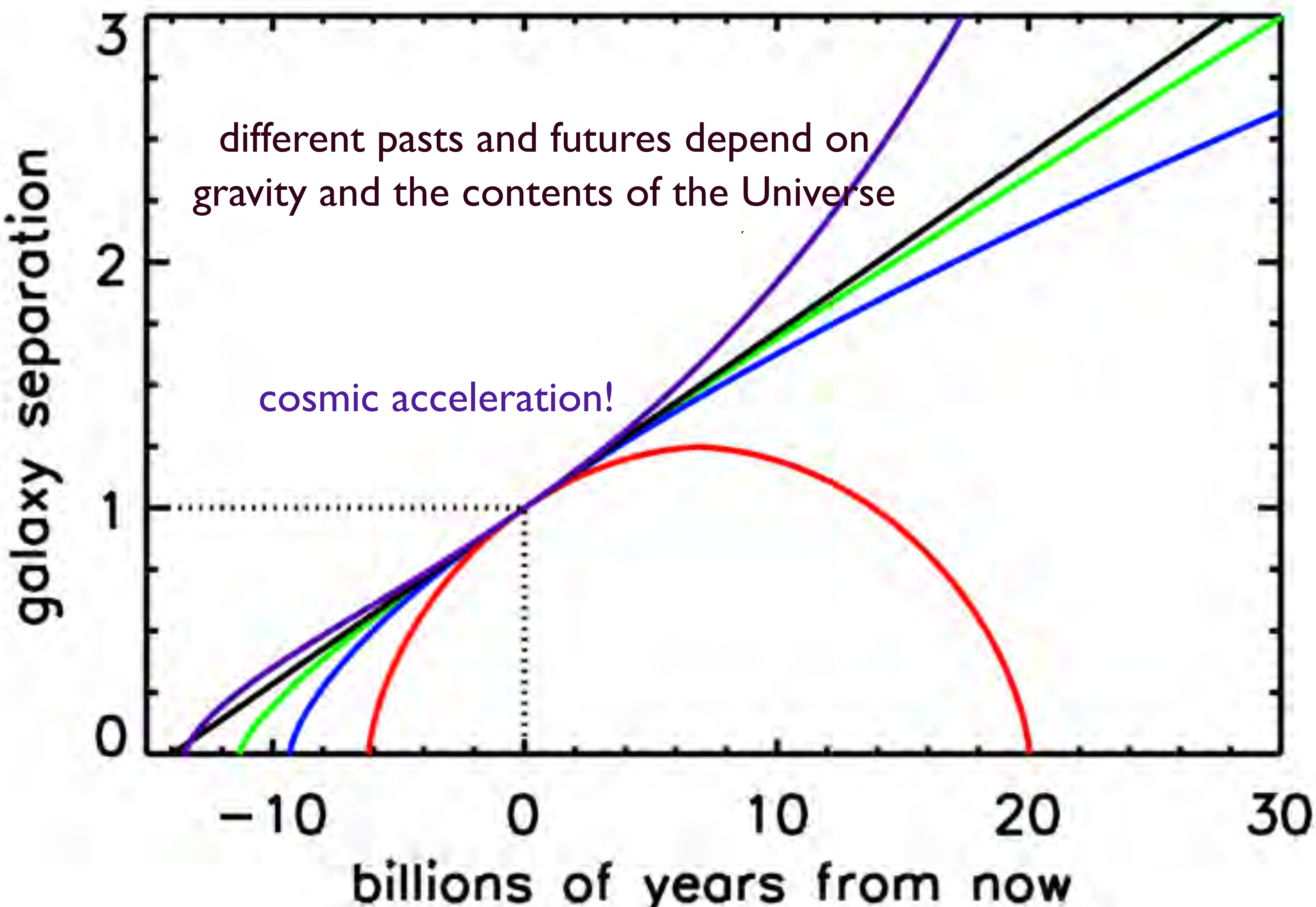
Type Ia supernova



Accelerated Expansion of Universe



Evolution of the Universe



Cosmology in 2017

$$1 = \Omega_m + \Omega_{dm} + \Omega_\Lambda + \Omega_K$$

$$0.05 \qquad 0.25 \qquad 0.7 \qquad \approx 0$$

- Dark Energy largest contribution to expansion
- Universe is nearly or completely flat

How big is the universe?

Vacuum Energy

- Dark energy is the energy of vacuum

- It has a fixed energy density that doesn't change as the universe expands

Ω_Λ is constant

20 Billion Years from Now

$$\Omega_m = \frac{8\pi G}{3}\rho_m \sim \frac{1}{a^3}$$

$$\Omega_{dm} = \frac{8\pi G}{3}\rho_{dm} \sim \frac{1}{a^3}$$

$$\Omega_\Lambda = \frac{8\pi G}{3}\rho_\Lambda$$

constant

$$1 = \Omega_m + \Omega_{dm} + \Omega_\Lambda + \Omega_K$$

≈ 0 $\quad 0.01 \quad 0.99 \quad \approx 0$

Expansion completely dominated by Dark Energy

Exponential Expansion

Far in the future

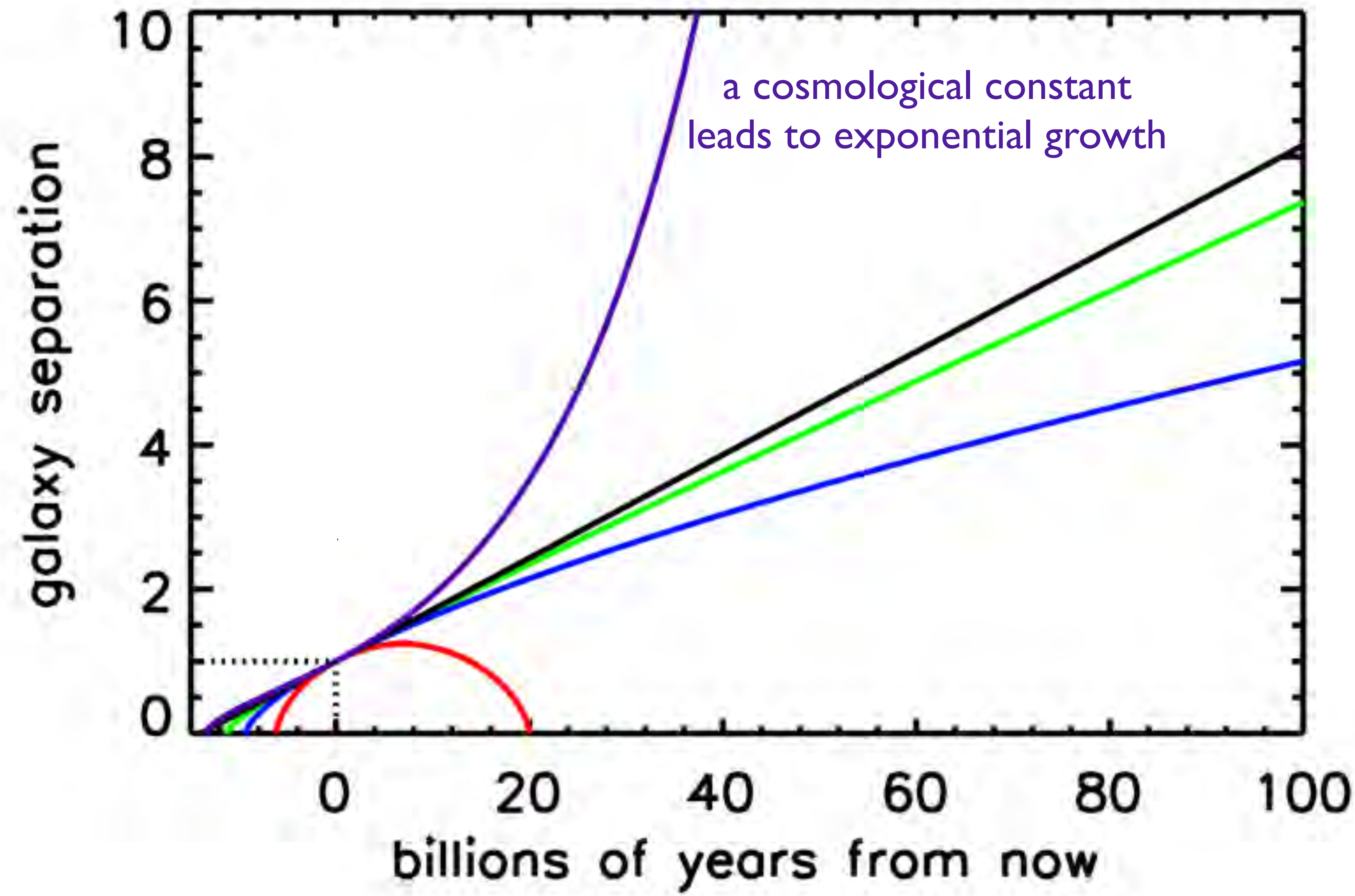
$$\Omega_{dm} = \Omega_m = 0 \qquad \Omega_\Lambda = 1$$

$$\left(\frac{v}{r}\right)^2 = \frac{8\pi G}{3}\rho_\Lambda = \Lambda$$

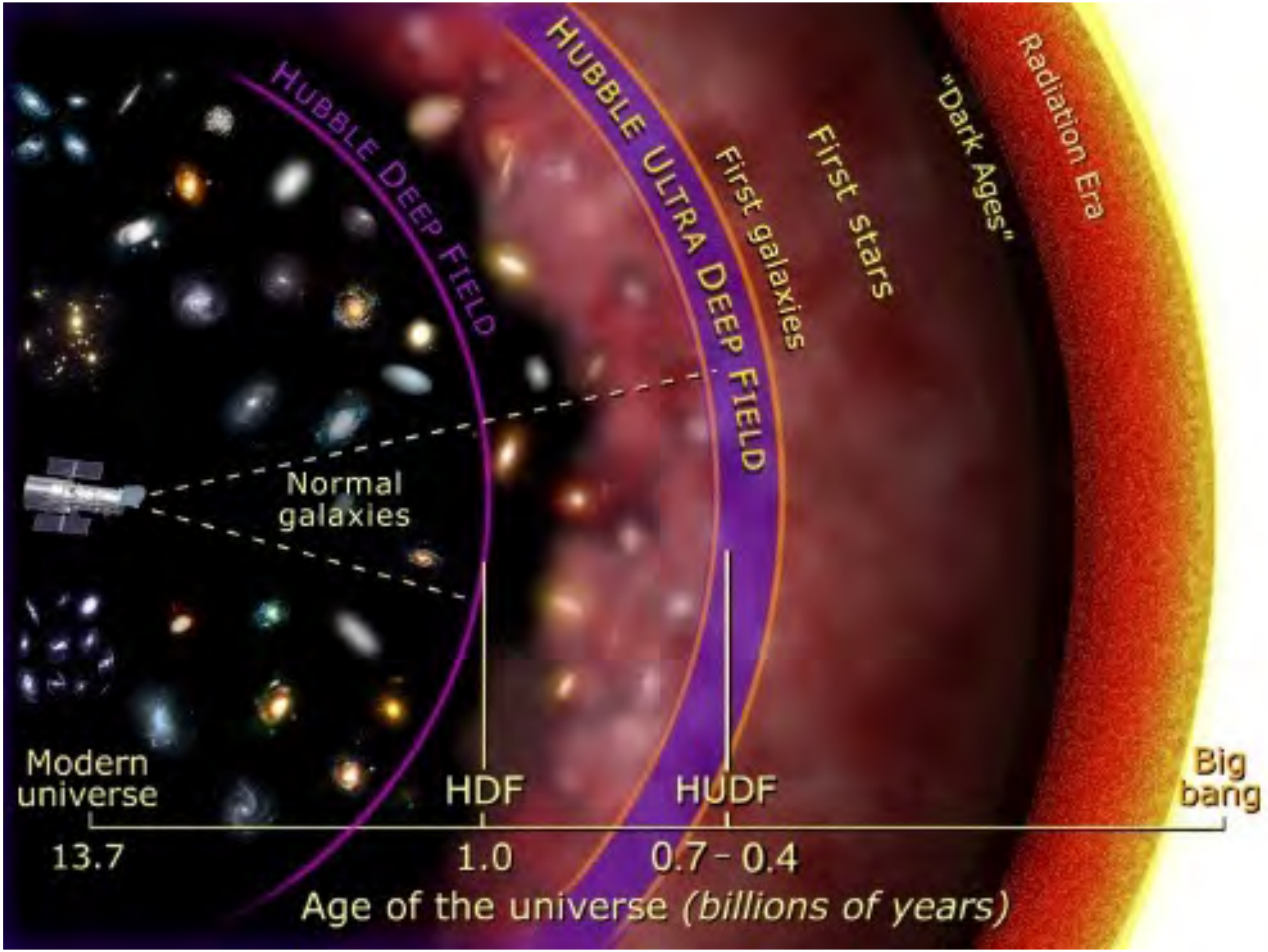
$$\left(\frac{v}{r}\right) = \sqrt{\Lambda} \qquad v = \frac{dr}{dt} = \sqrt{\Lambda}\, r$$

$$r \sim e^{\sqrt{\Lambda}\, t}$$

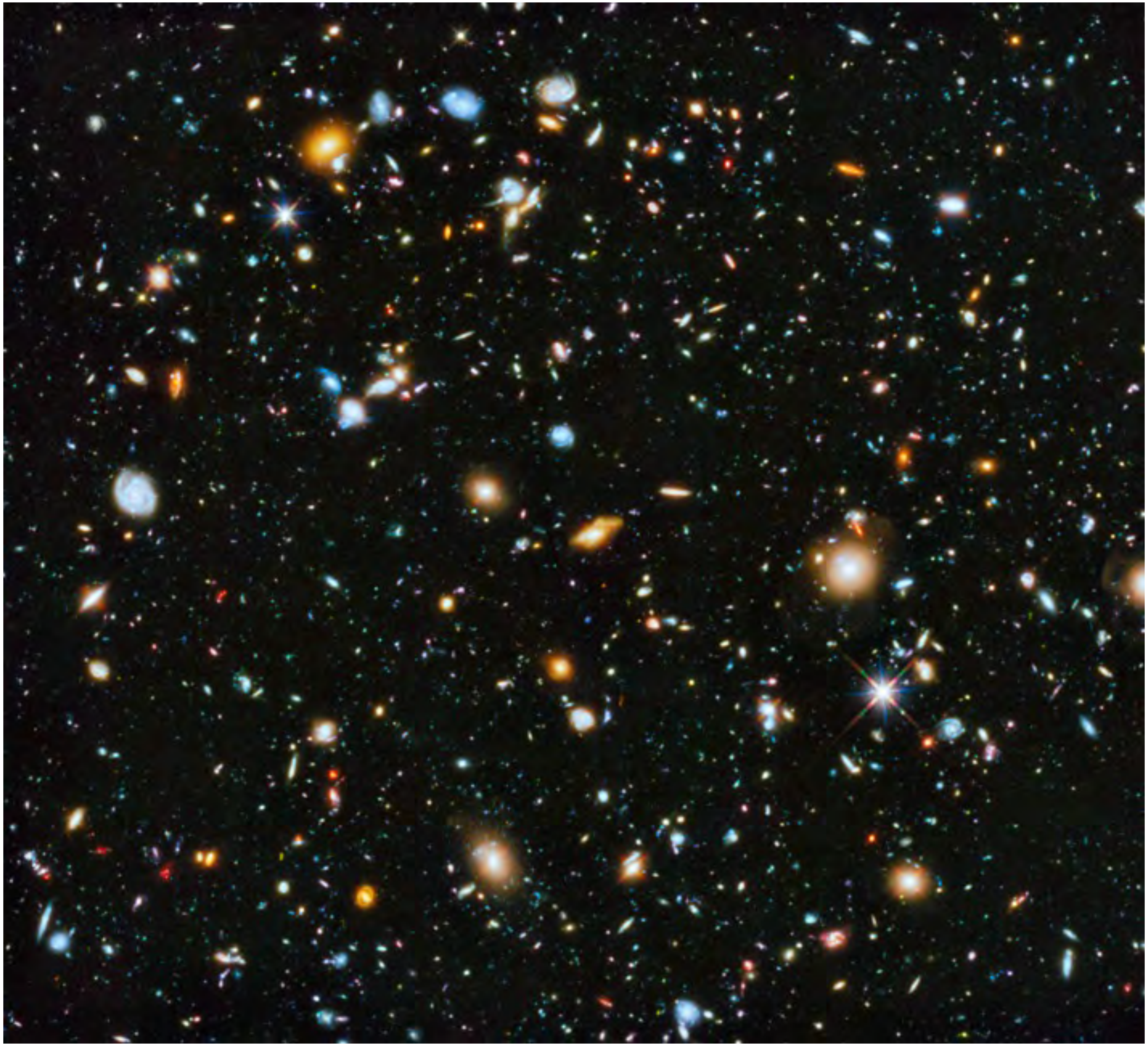
The Future of the Universe



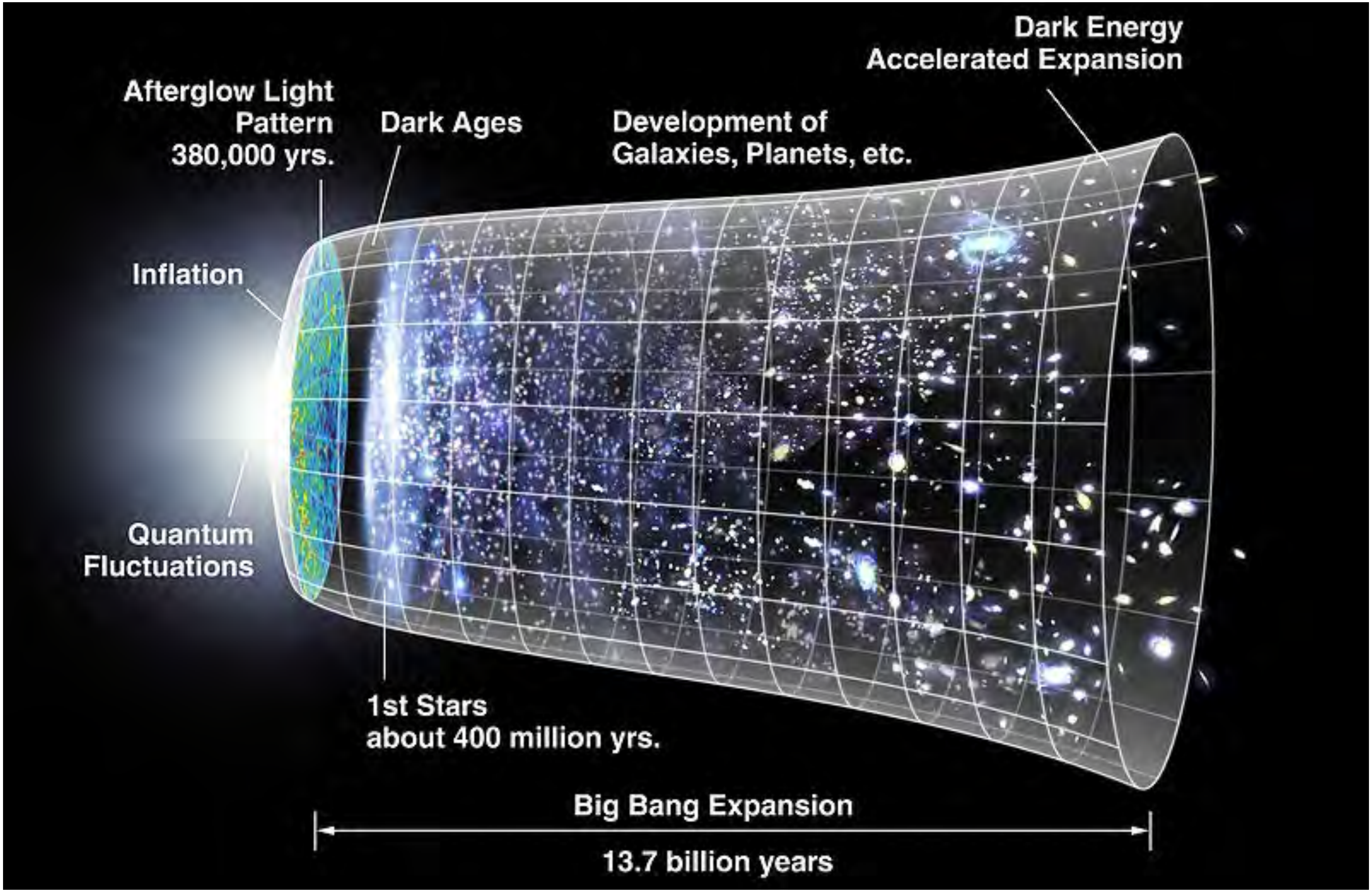
How Far Back Can We See?



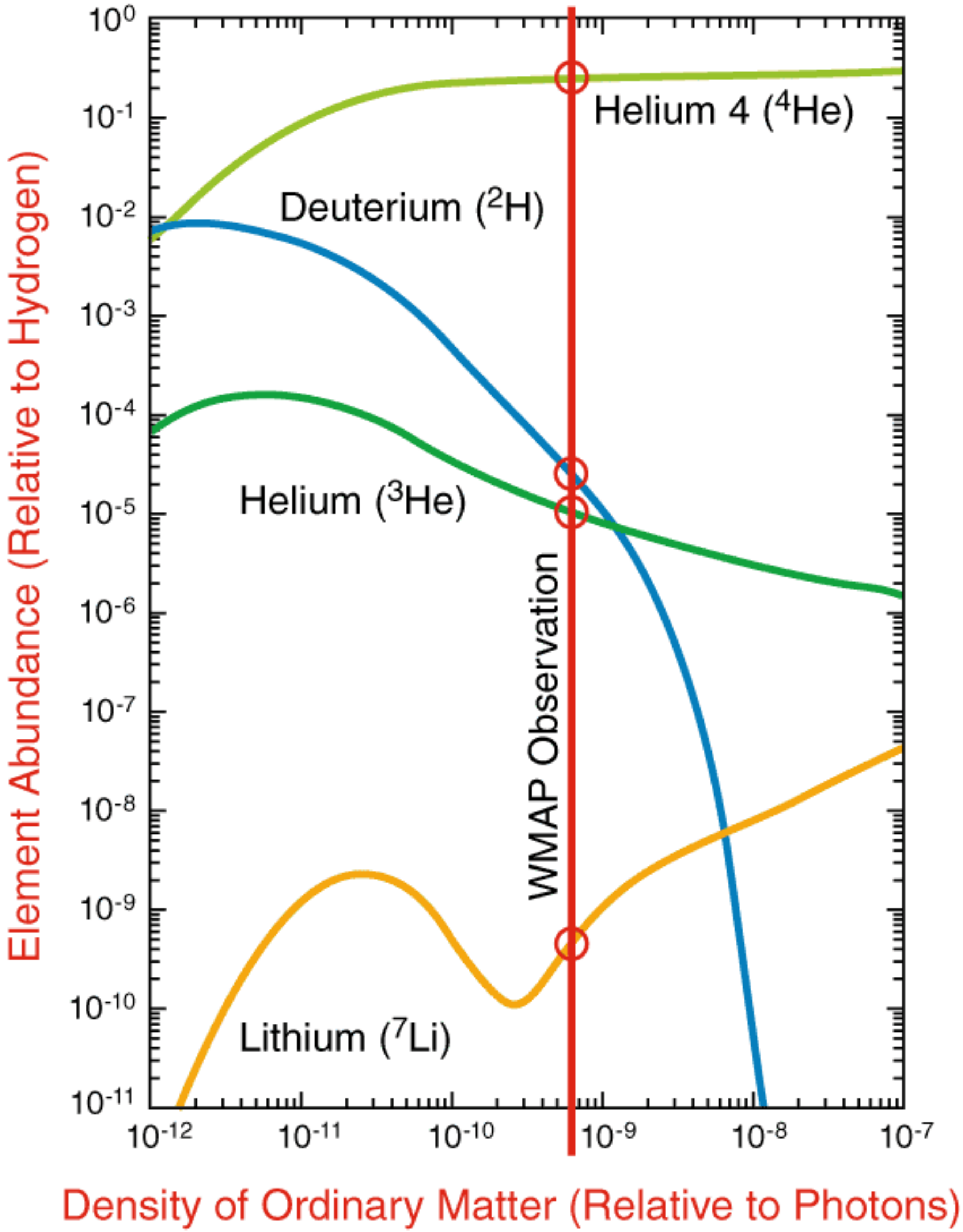
Hubble Deep Field



Evolution of the Universe



Abundance of Light Nuclei



To Learn More

Cornell Messenger Lectures

Nima Arkani-Hamed

Lenny Susskind