# 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

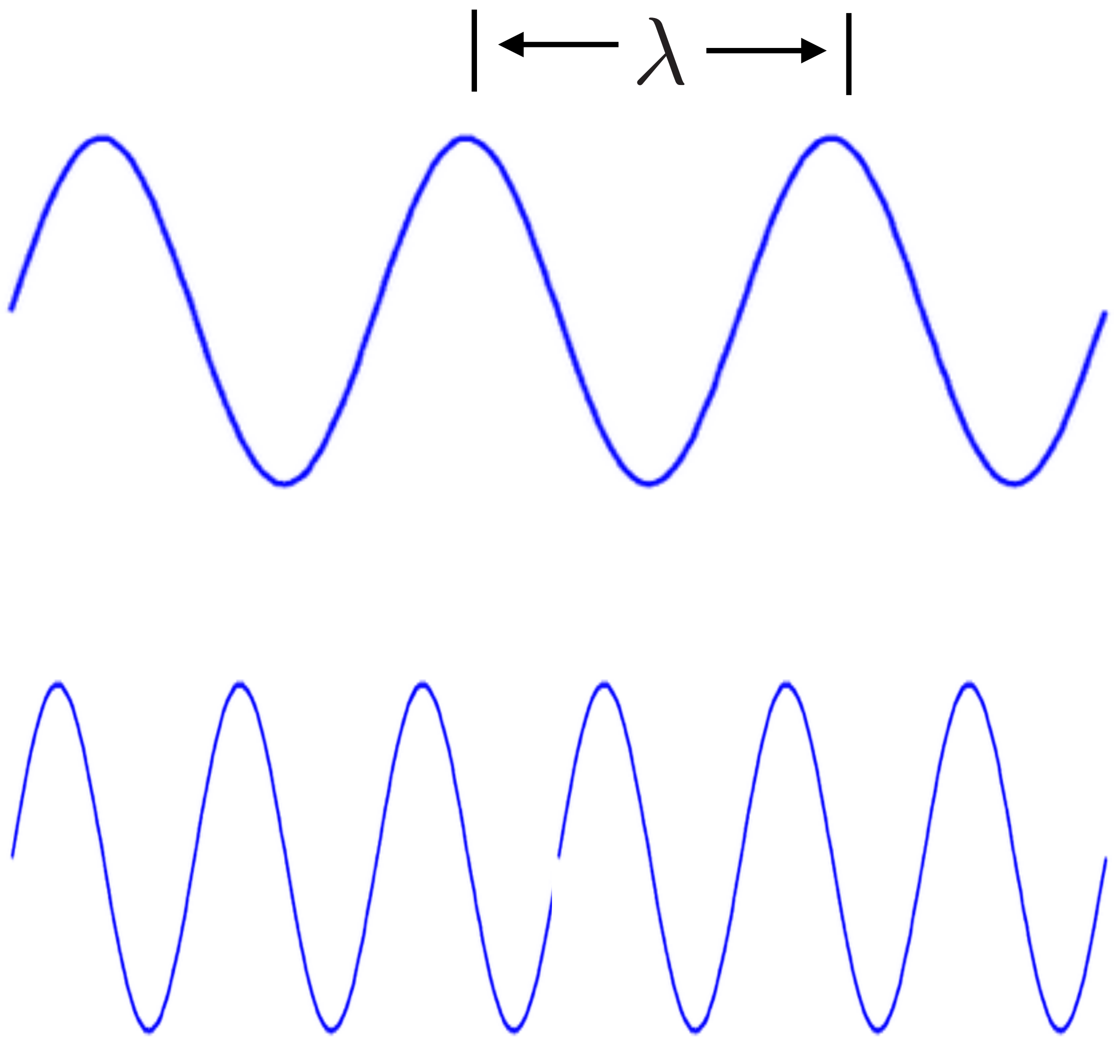
## Study of the small scale structure of the universe

- 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**

$$10^3 \text{ GeV}$$

**Distance scale**

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

**Temperature**

$$10^{16} \text{ K}$$

# 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 $\longrightarrow$ $10^{-12}$ 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

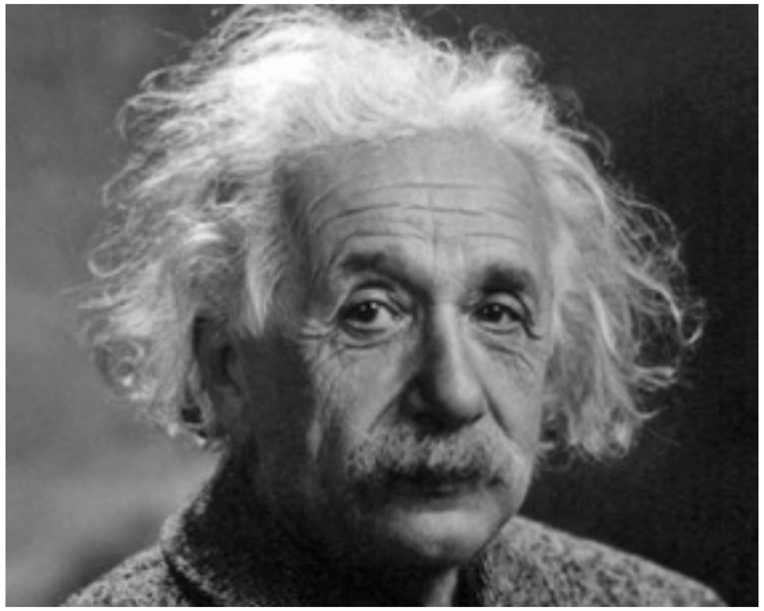
## Pre 20th century

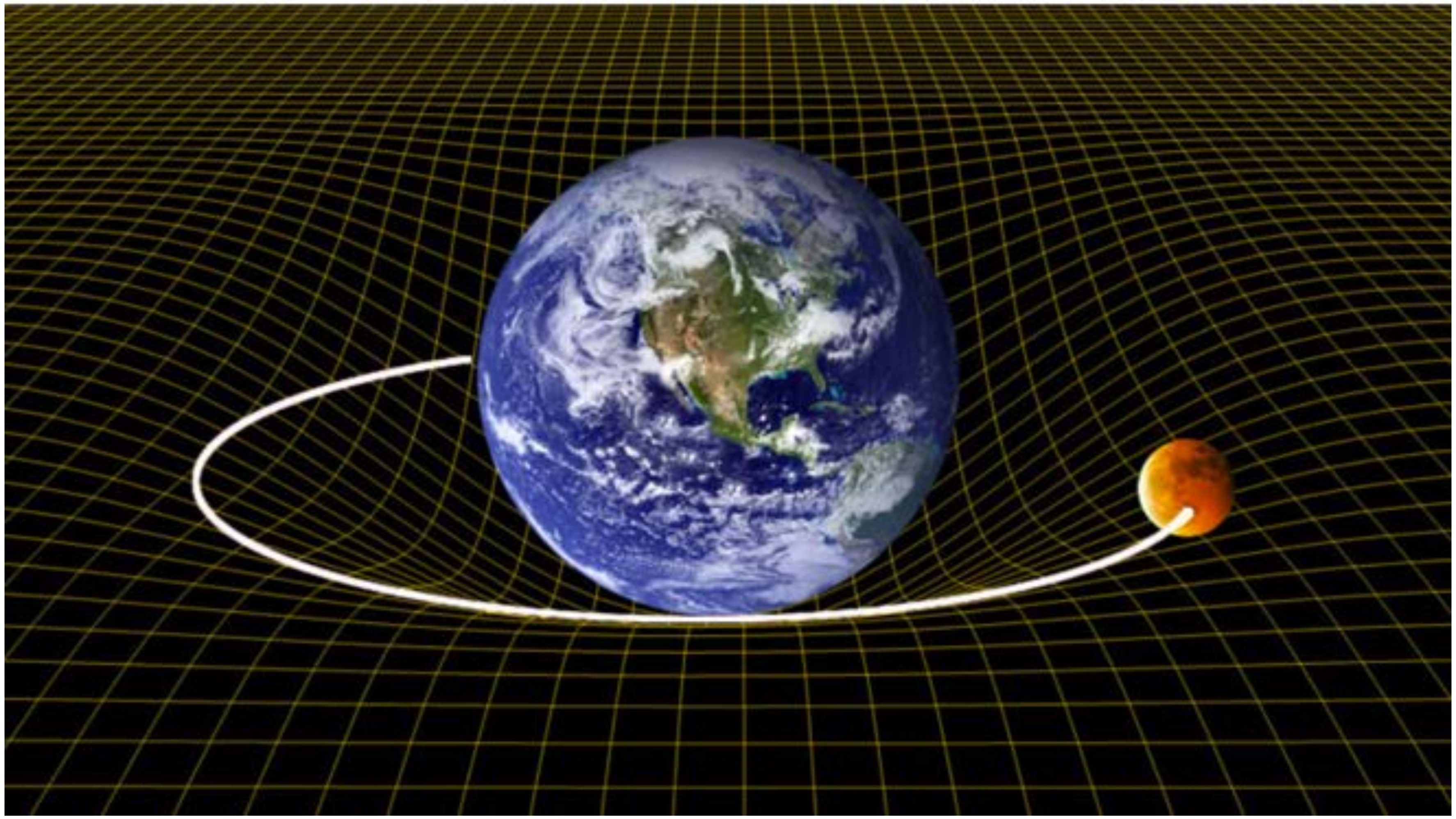
- Stars fixed points in space
- Universe unchanging

# General Relativity

Eistein 1915

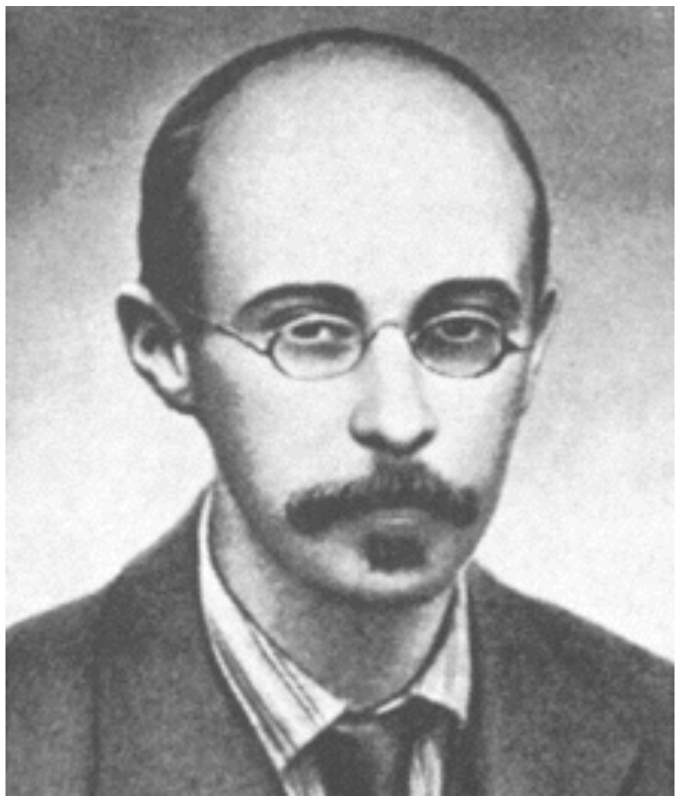
- Gravity due to curvature of space-time





# 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

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

# Cosmological Constant

fudge factor

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

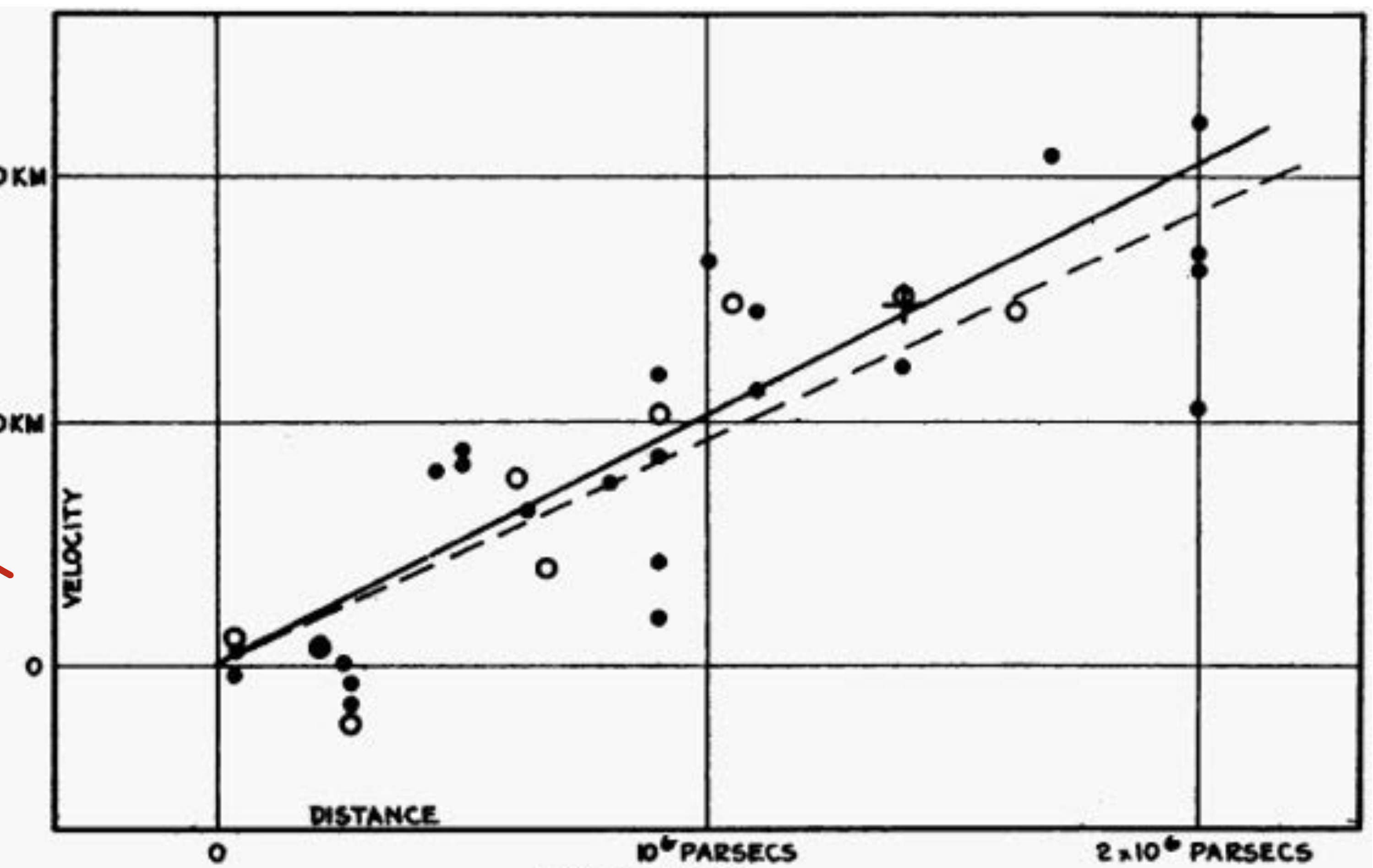
matter energy density

Prevents the universe from expanding (or contracting)

# Hubble Expansion

Hubble 1927

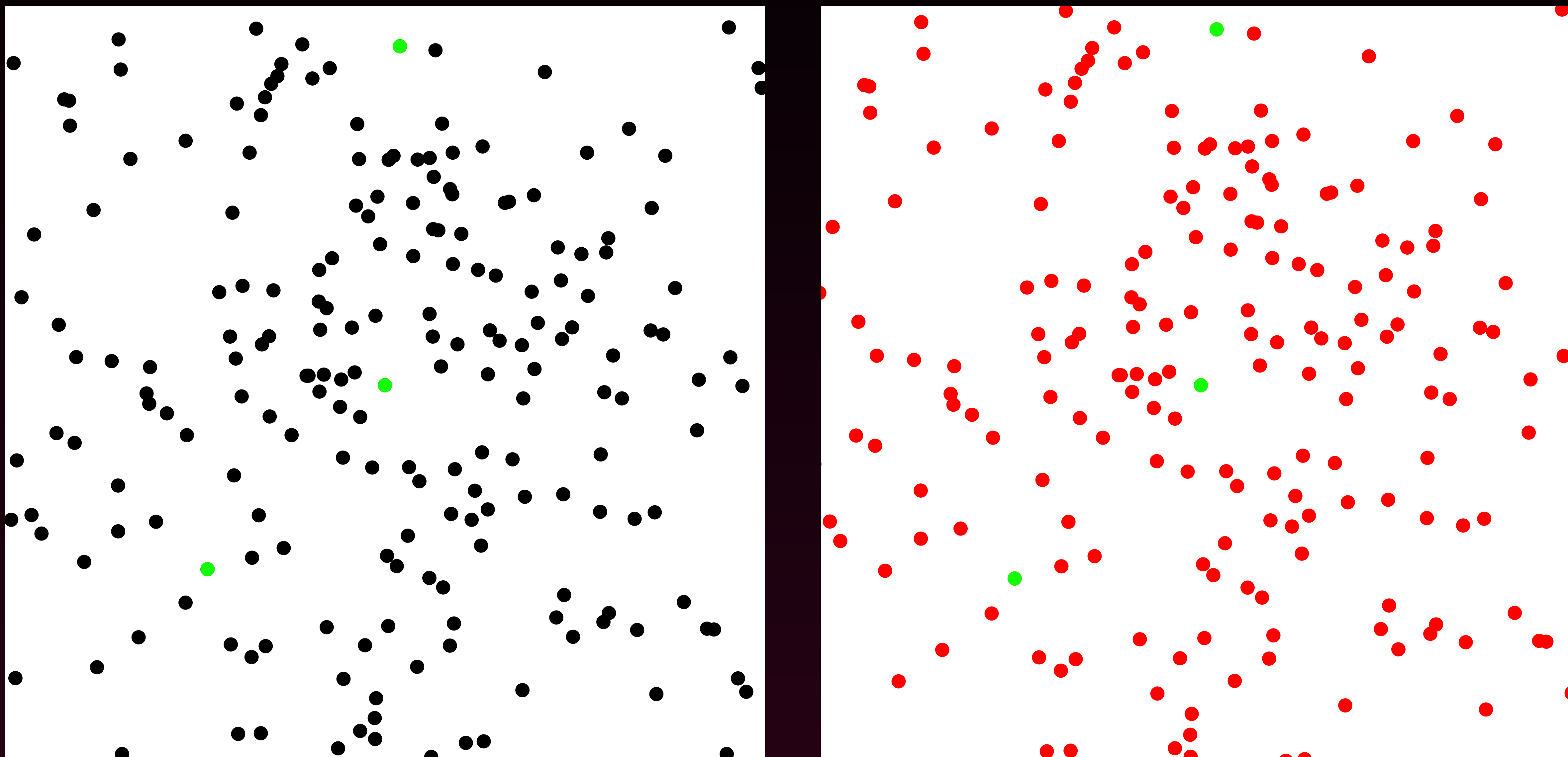
The universe is expanding




velocity

distance

# An Expanding Universe

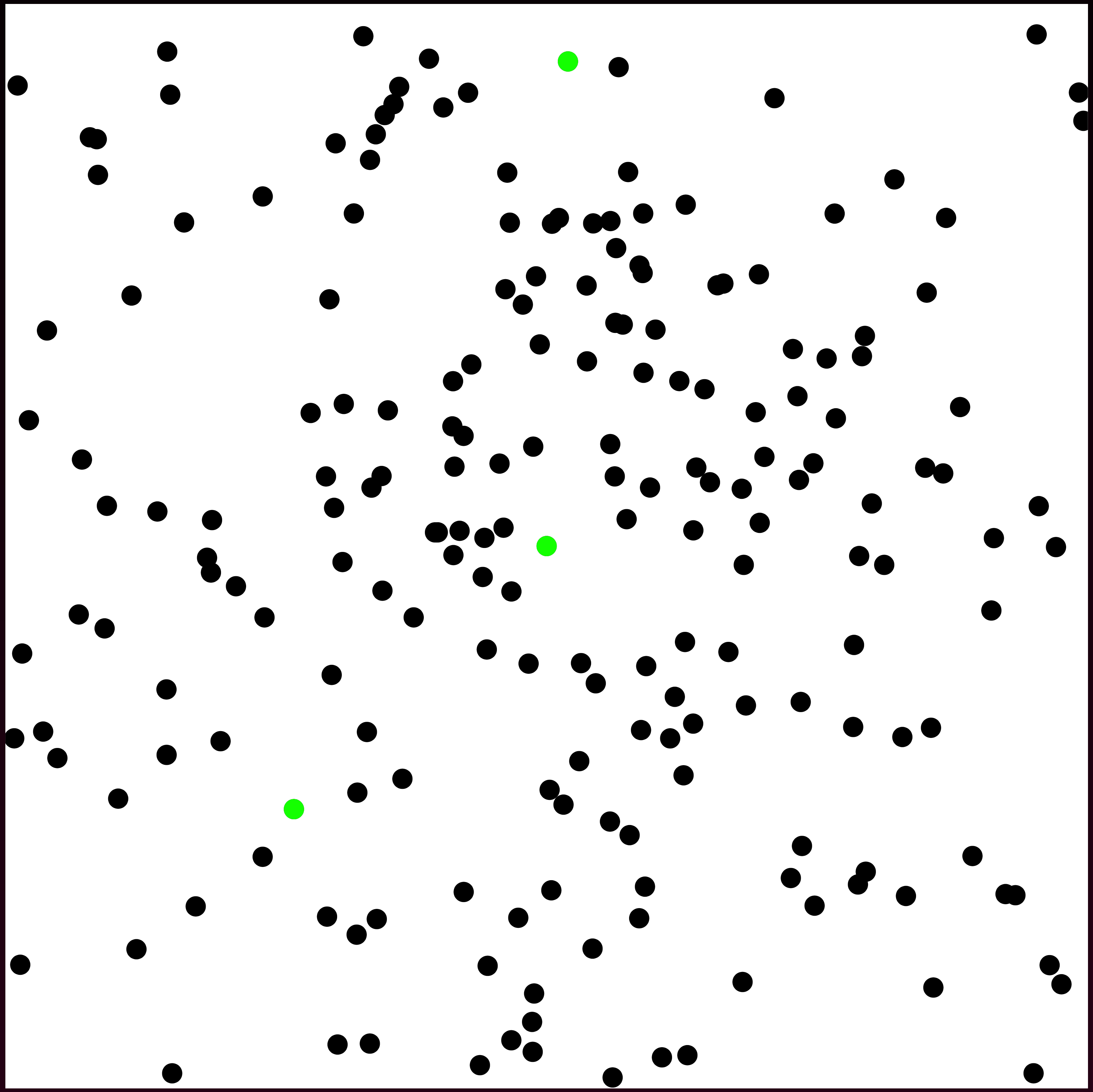


original

expanded by 5%

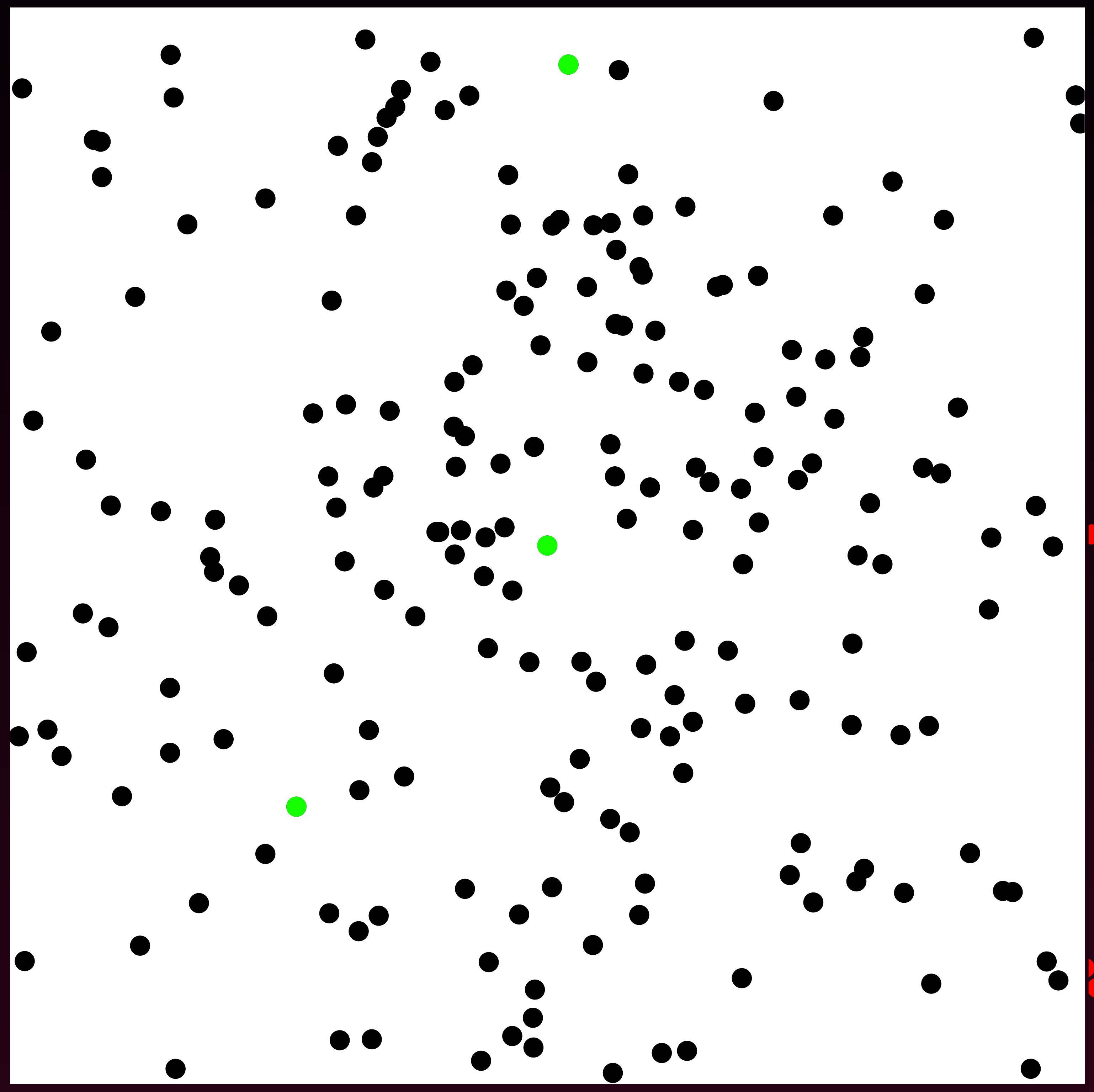
each dot represents a galaxy in the Universe

# An Expanding Universe



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

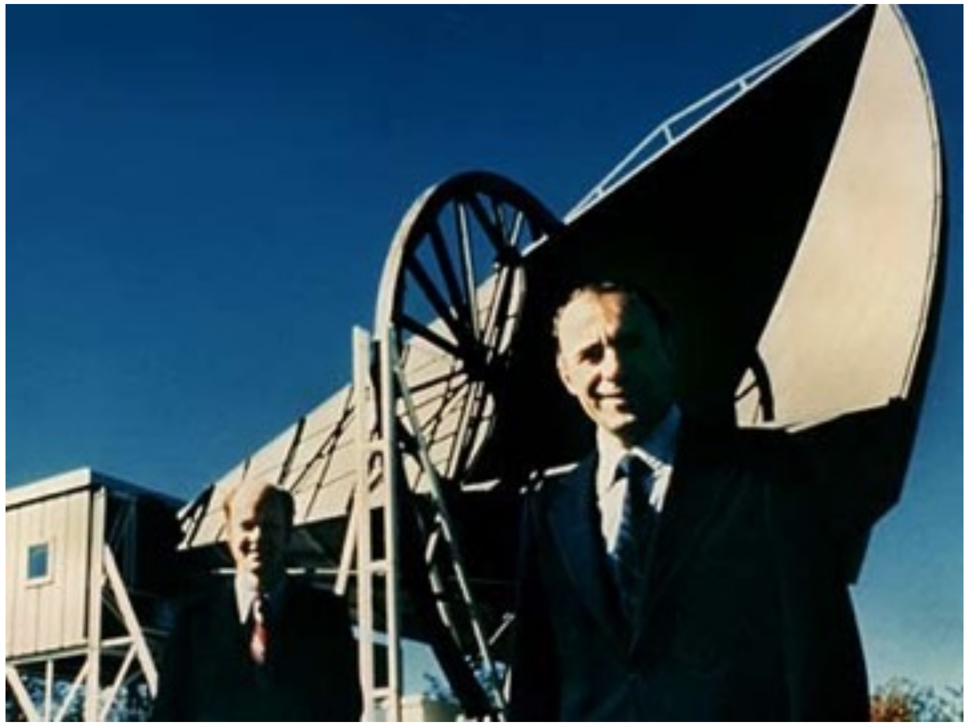
# An Expanding Universe



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

# Cosmic Microwave Background Radiation

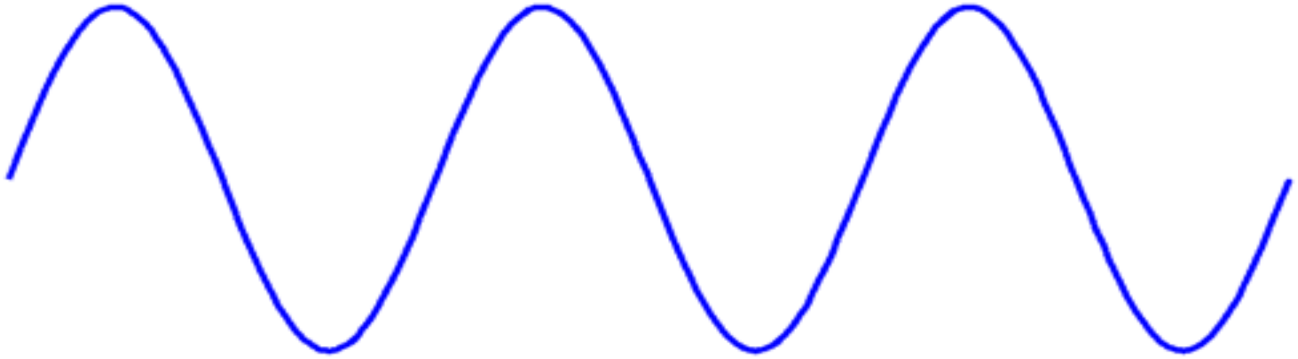
Penzias and Wilson 1965



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

Cooled from 3000 K to 2.7 K

Why?



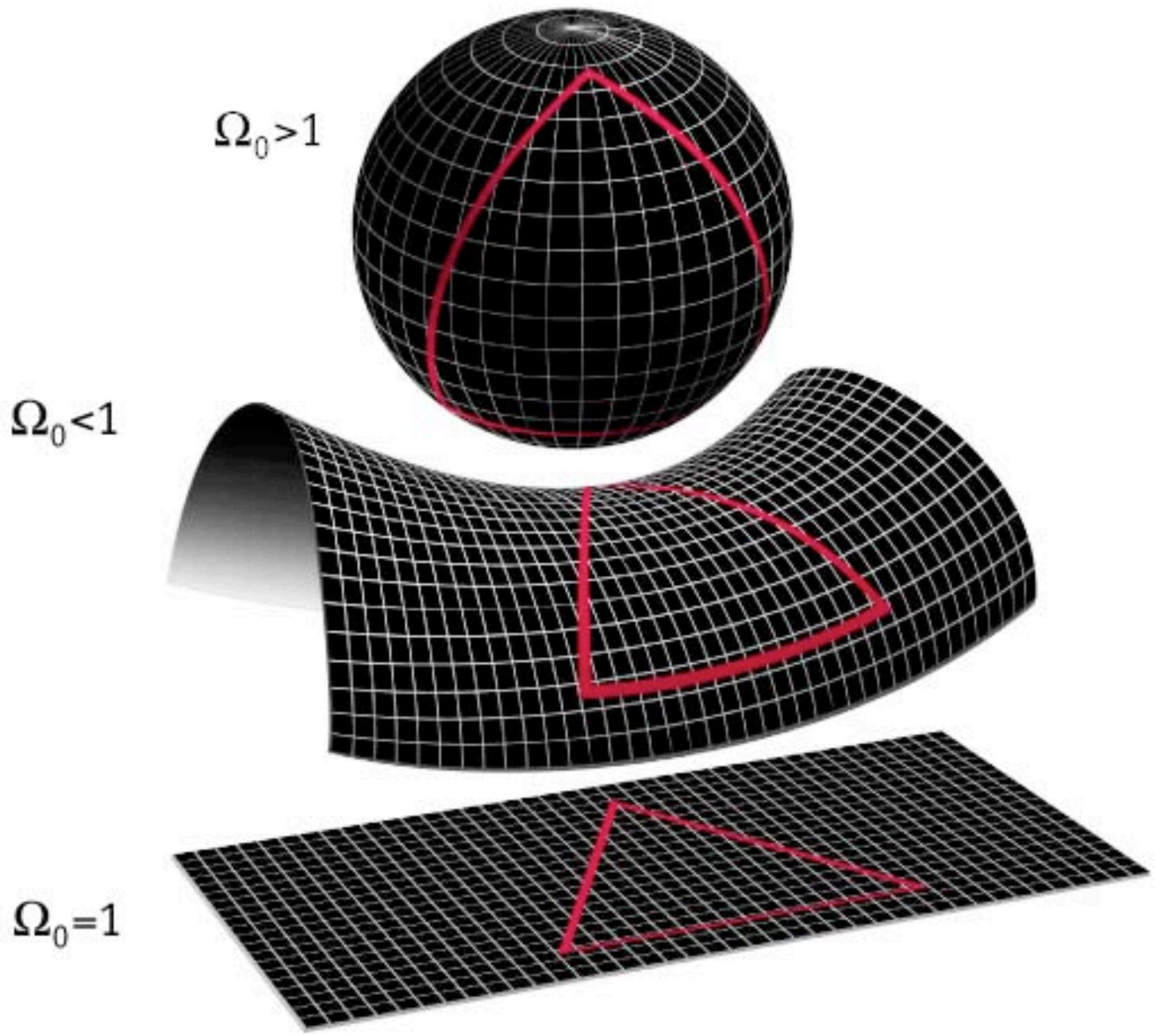
# Something Wrong

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

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

$$\Omega_m \;=\; 0.05$$

# Curvature




positive curvature

negative curvature

zero curvature (flat)

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

# Cosmology in 1970

$$1 = \Omega_m + \Omega_K$$

$0.05$ $\quad$ $0.95$

- Expansion dominated by negative curvature
- Relatively small R

This is wrong

Dark Matter

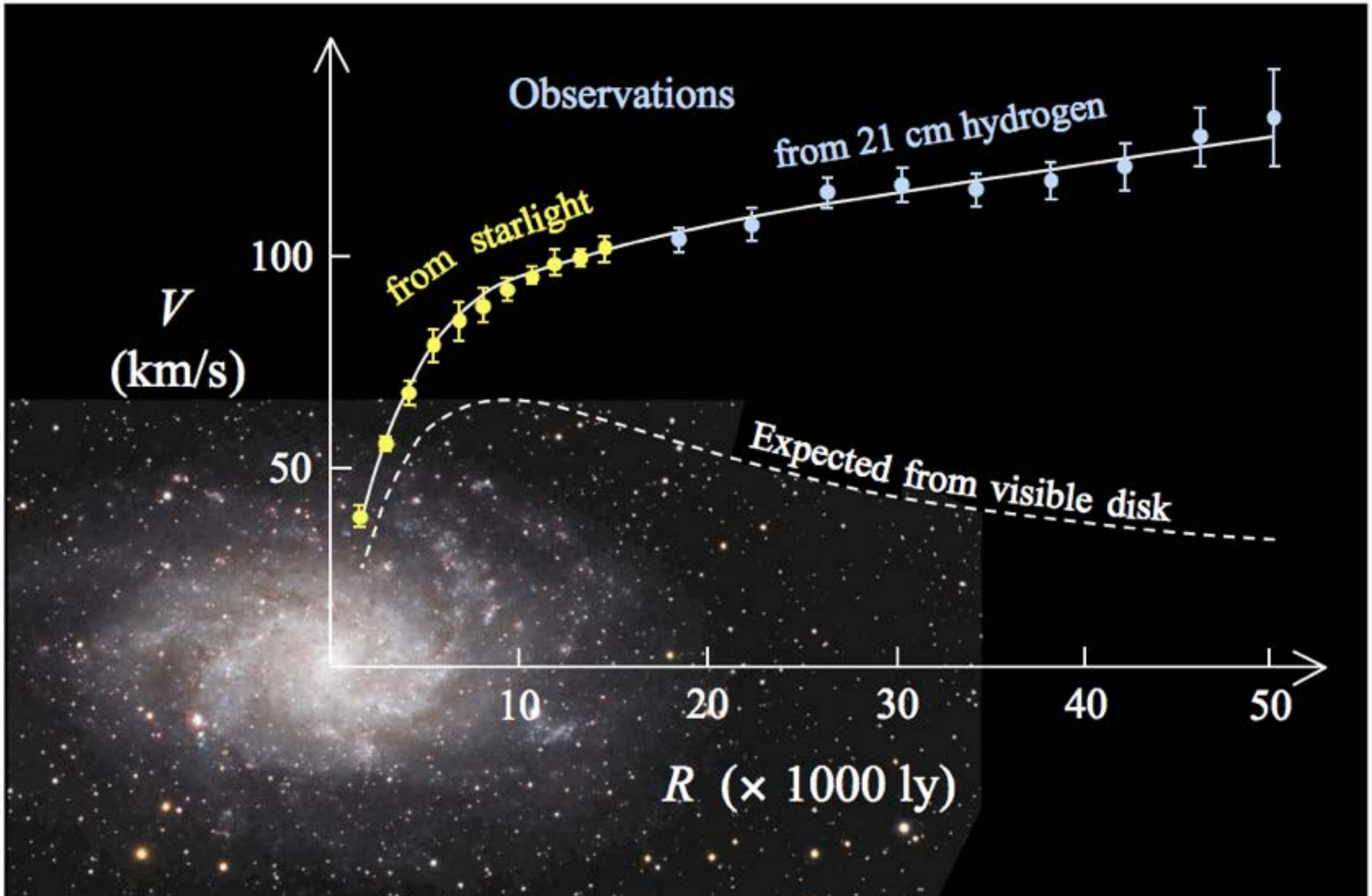
Dark Energy

# Dark Matter

About 80% of the matter
in the universe is dark

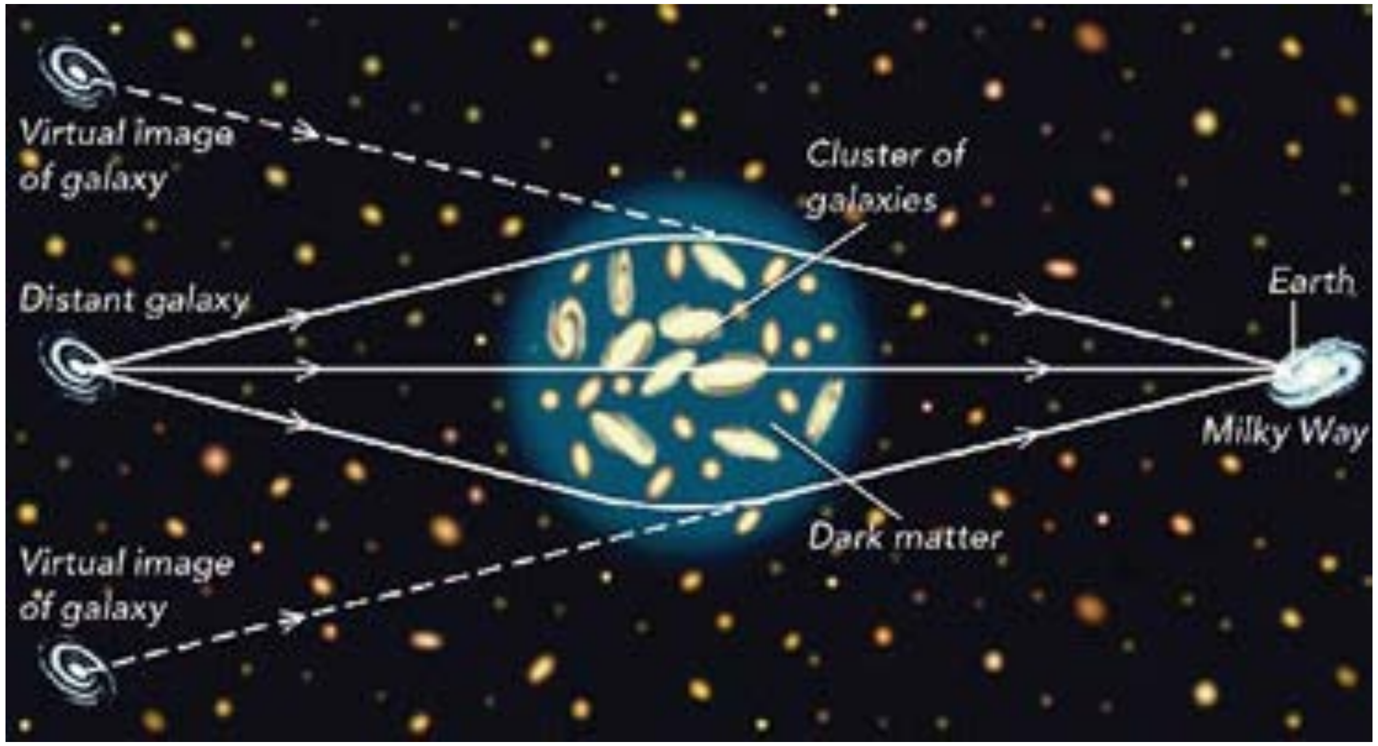
# Evidence for Dark Matter (1)

## Rotational curve of galaxy



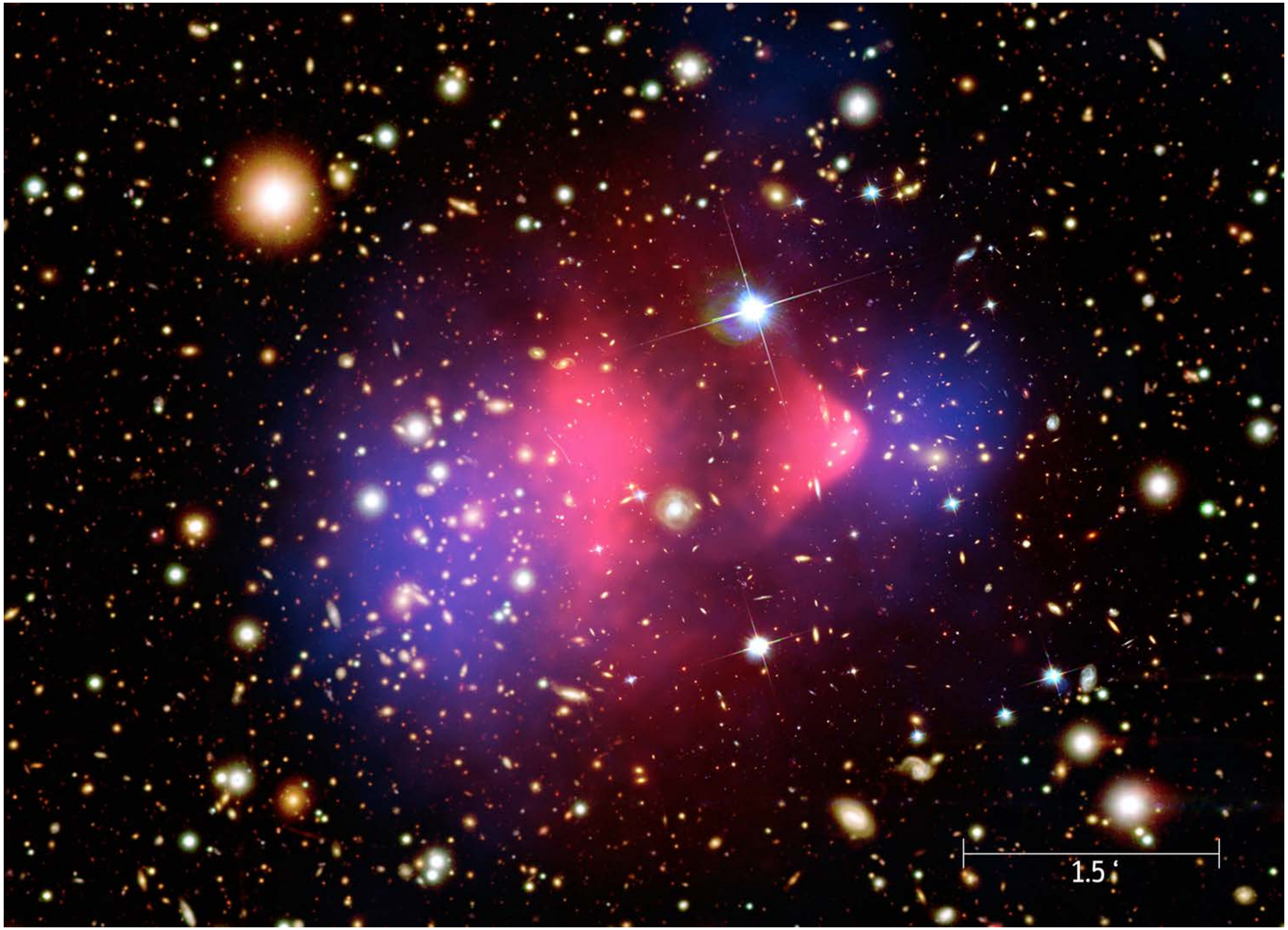
# Evidence for Dark Matter (2)

## Gravitational lensing

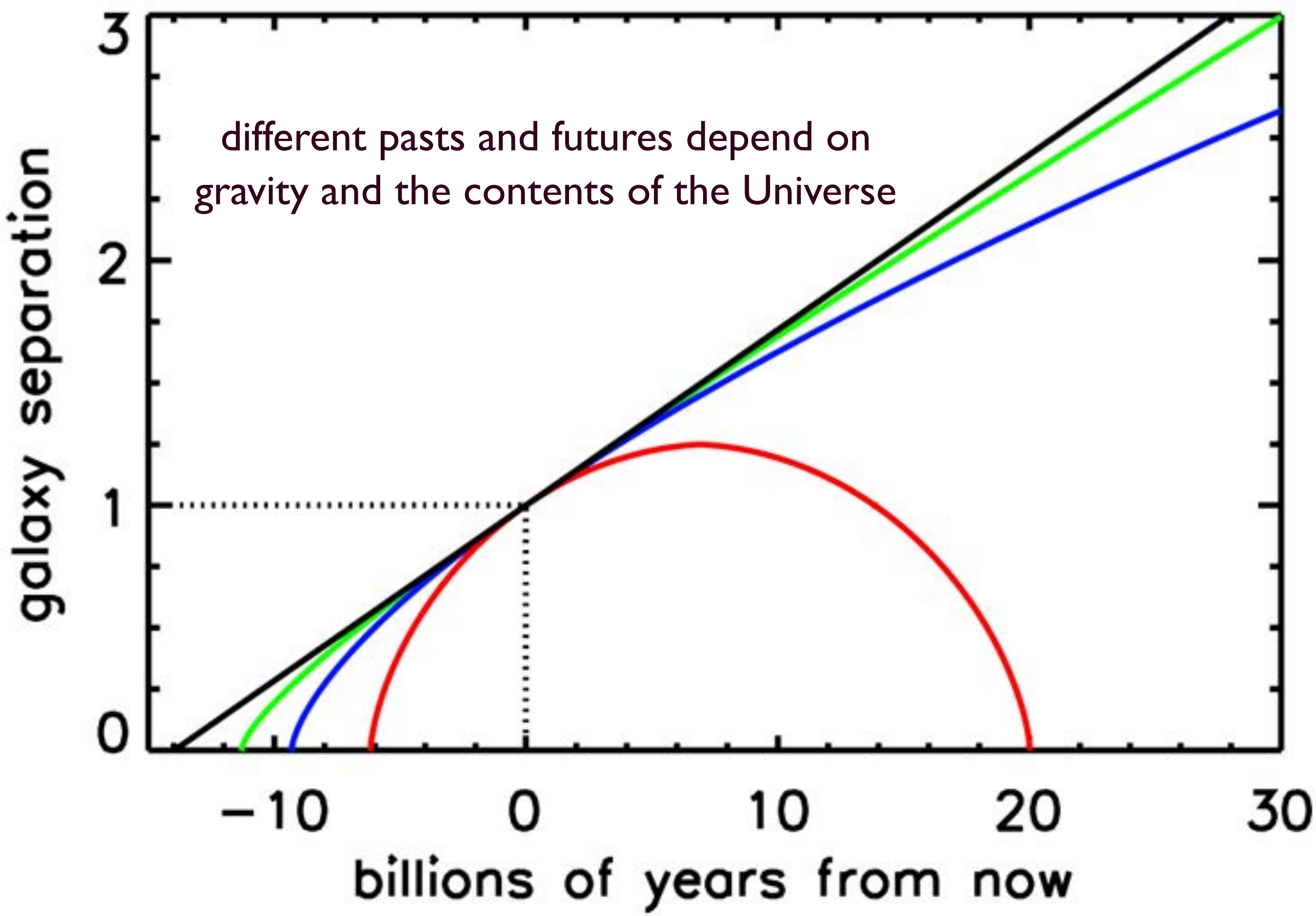



# Evidence for Dark Matter (3)

## Bullet Cluster

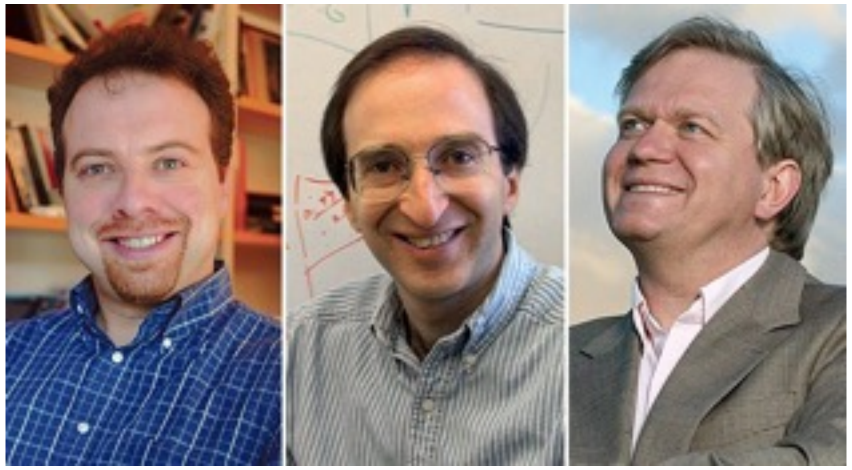


# Evolution of the Universe

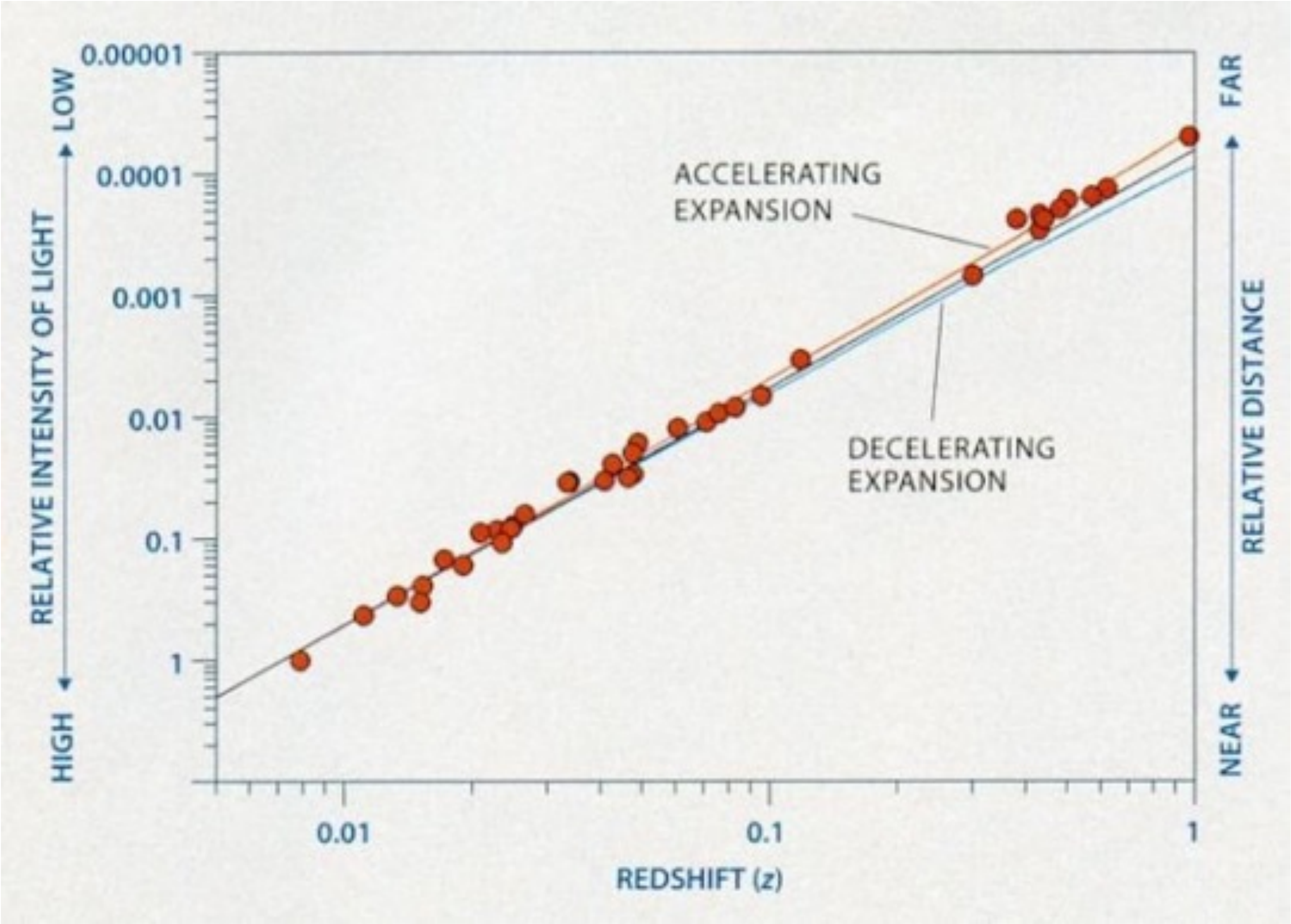


# Dark Energy

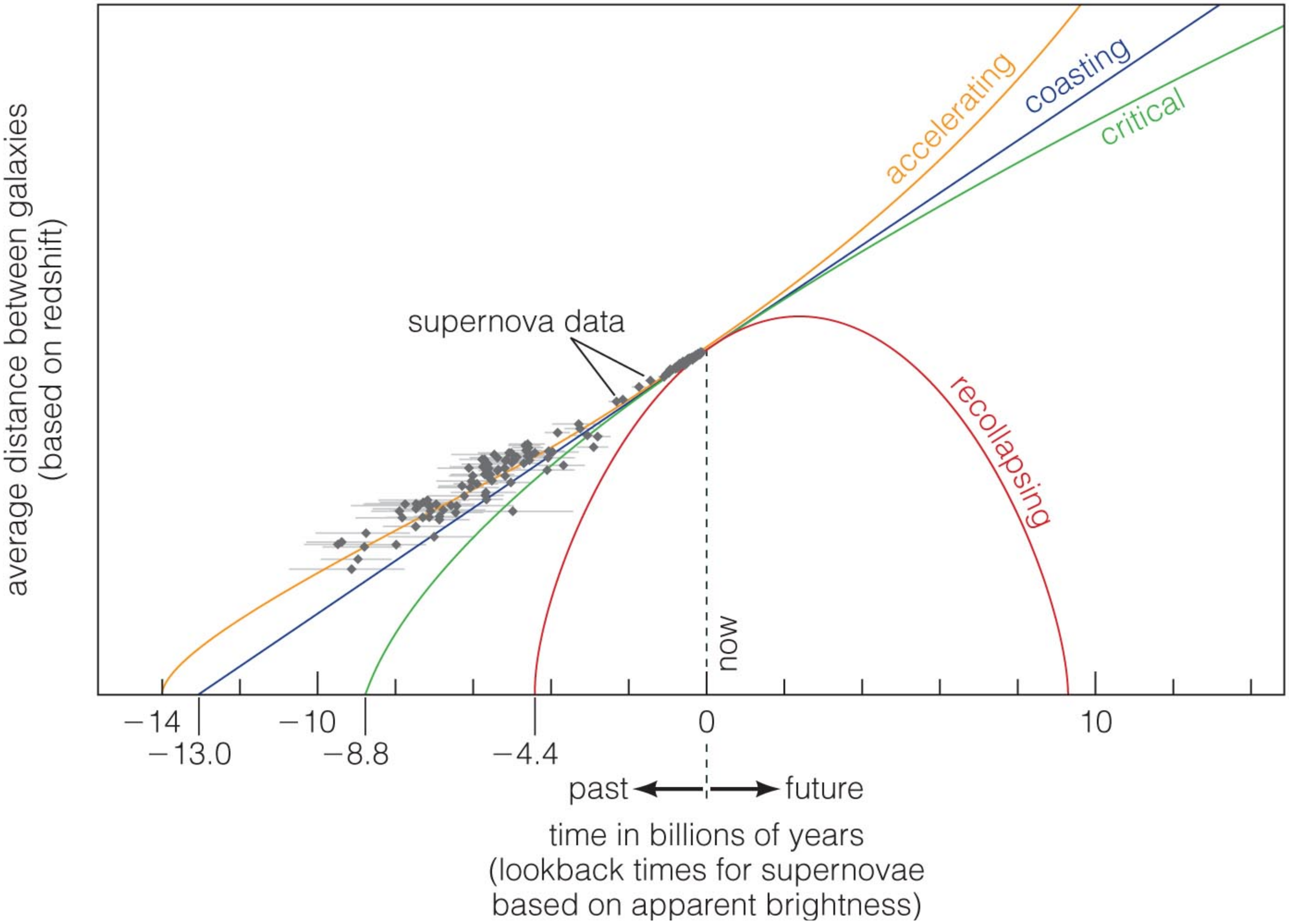
Riess, Perlmutter, Schmidt 1998



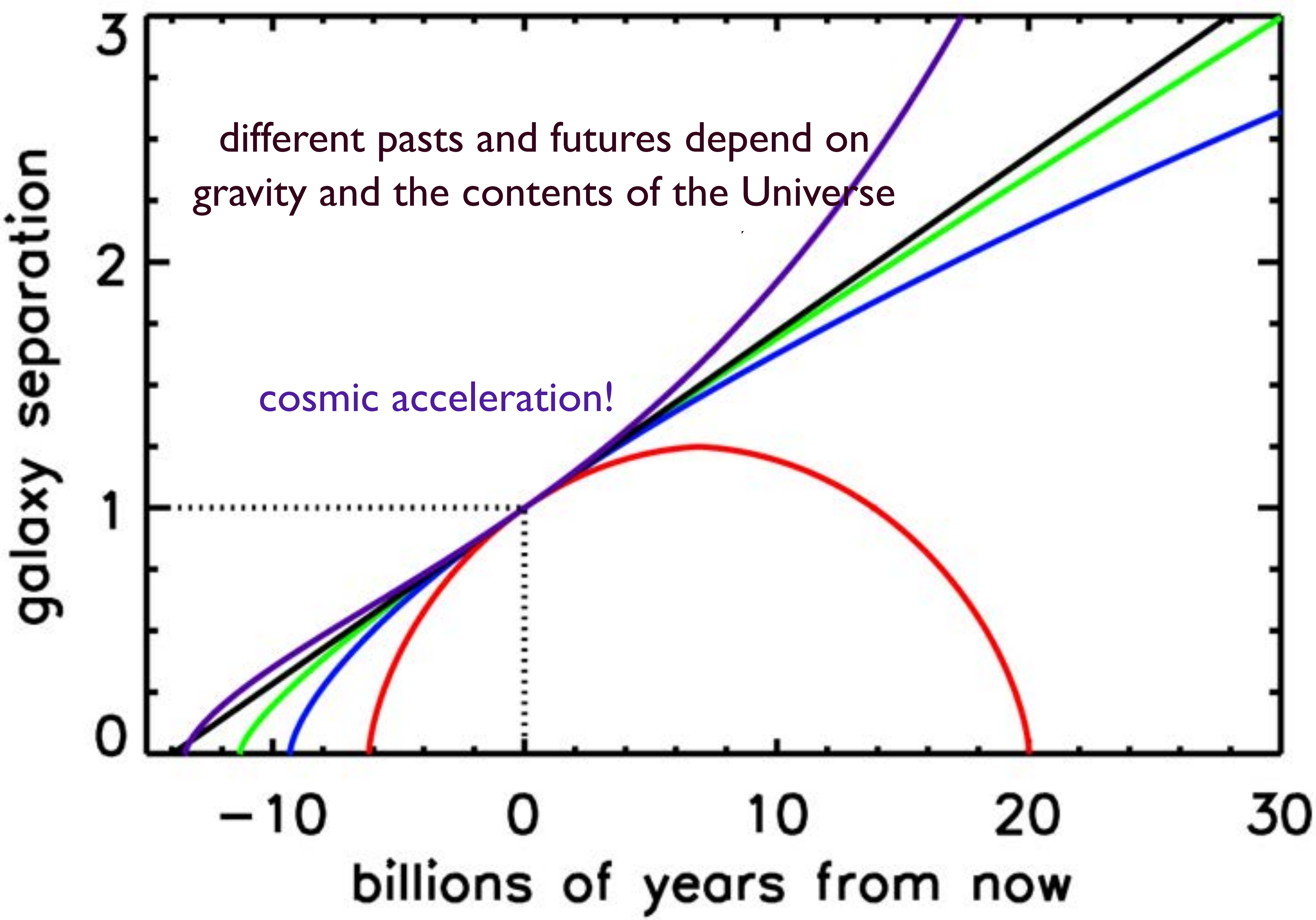
Type Ia supernova




# 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

$\Omega_\Lambda$ 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

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

$\approx 0$    $0.01$    $0.99$    $\approx 0$

Expansion completely dominated by Dark Energy

# Exponential Expansion

Far in the future

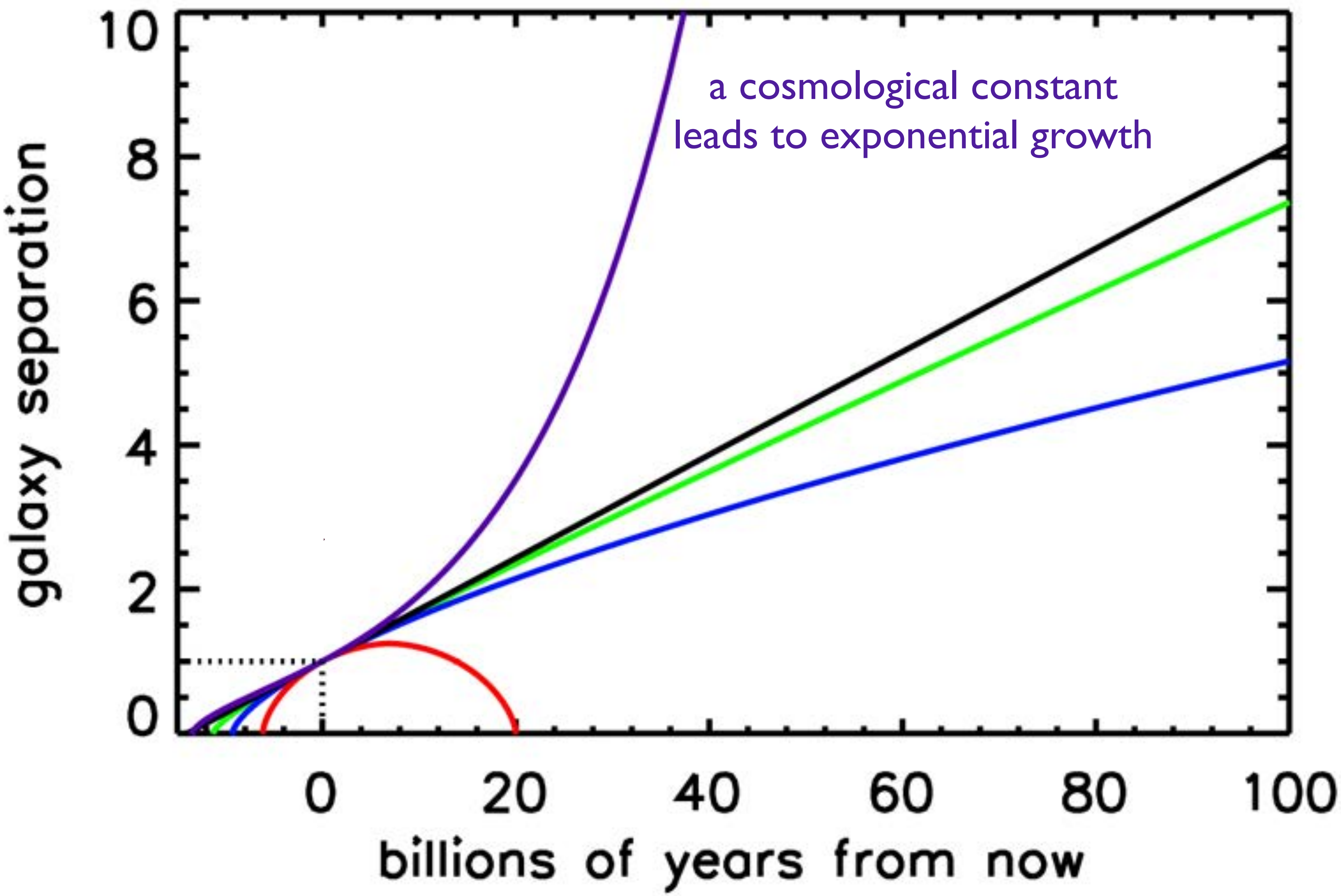
$$\Omega_{dm} = \Omega_m = 0 \qquad \Omega_\Lambda = 1$$

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

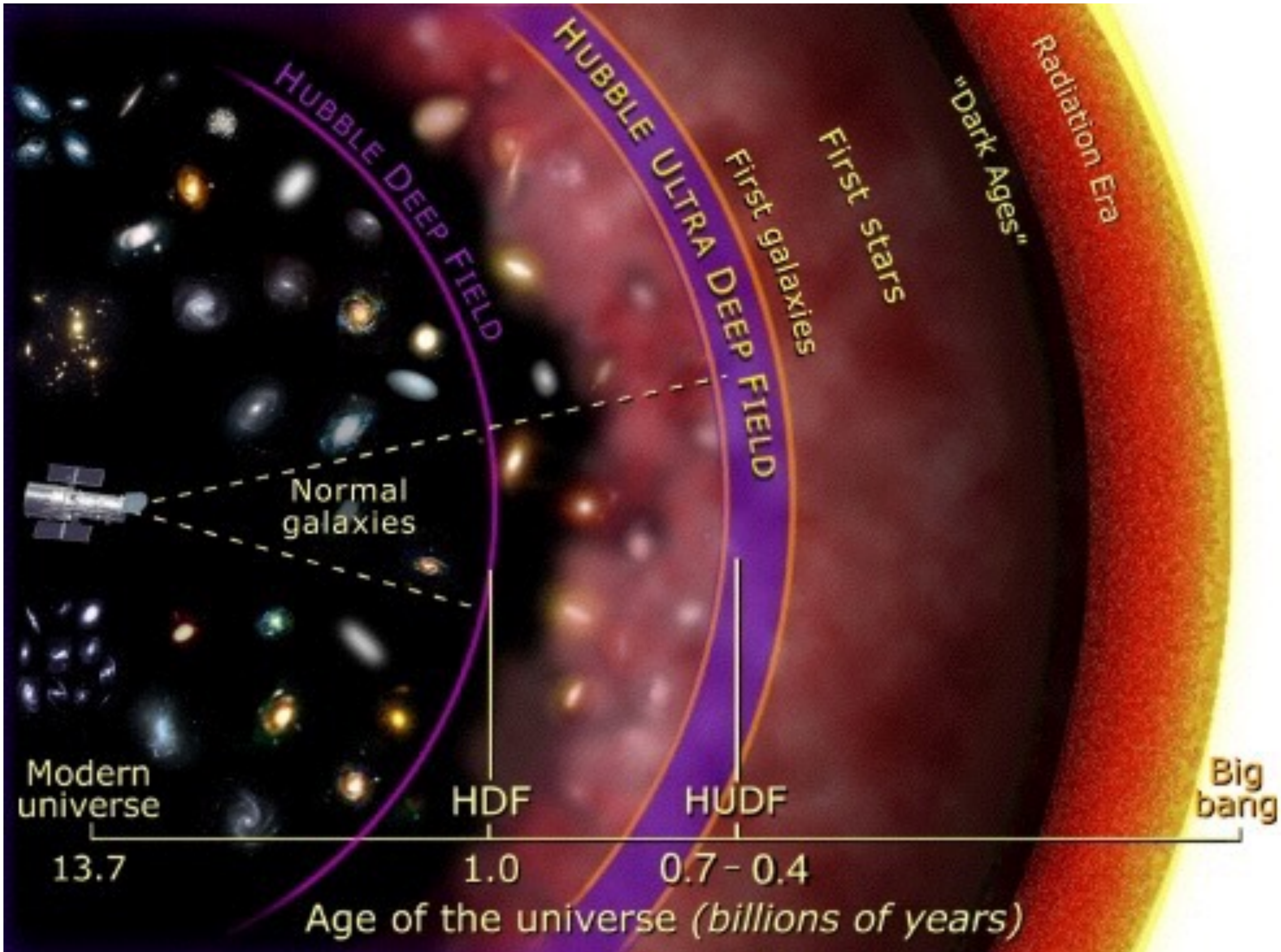
$$\left(\frac{v}{r}\right) = \sqrt{\Lambda} \qquad v = \frac{dr}{dt} = \sqrt{\Lambda}\, r$$

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

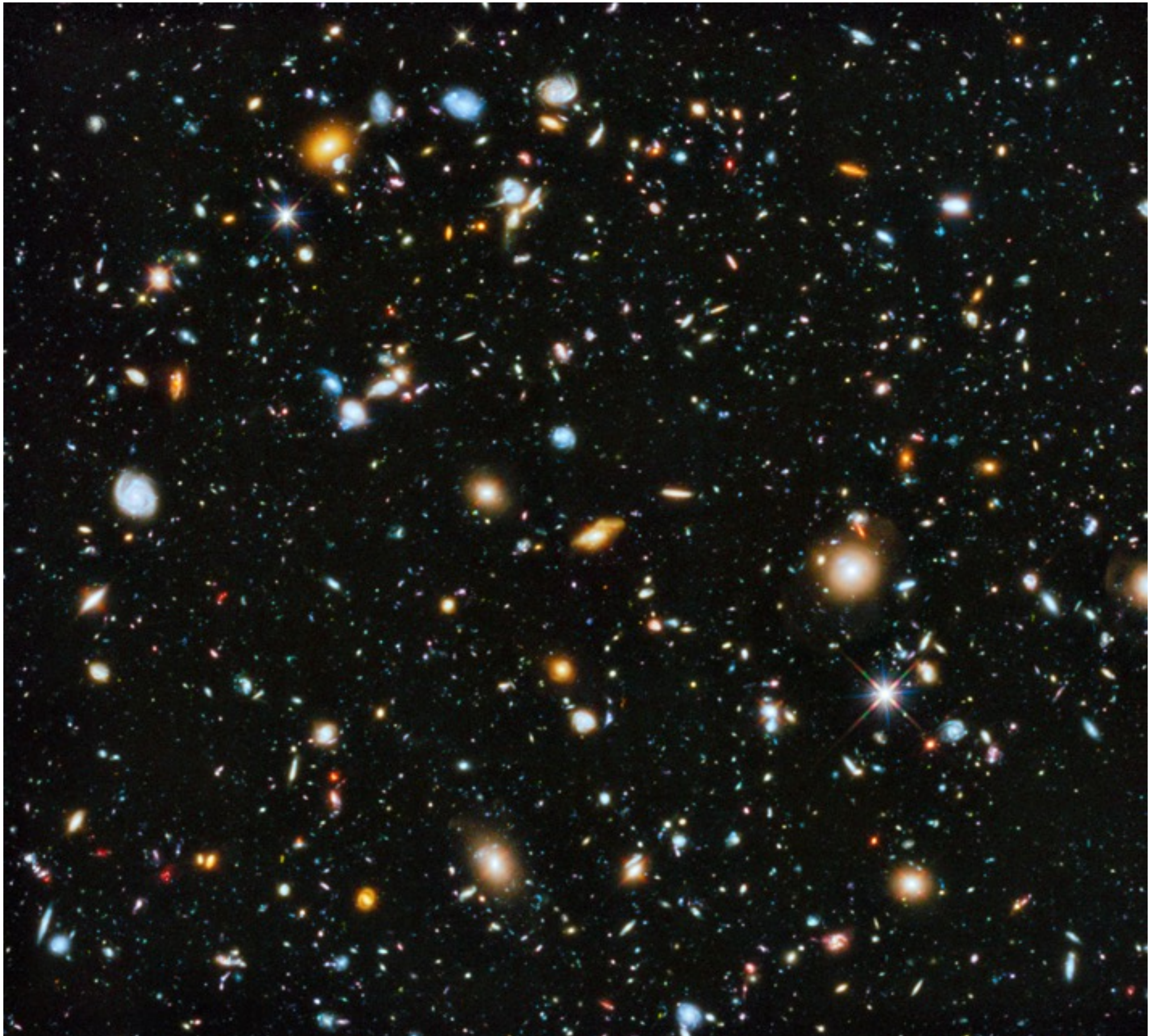
# The Future of the Universe



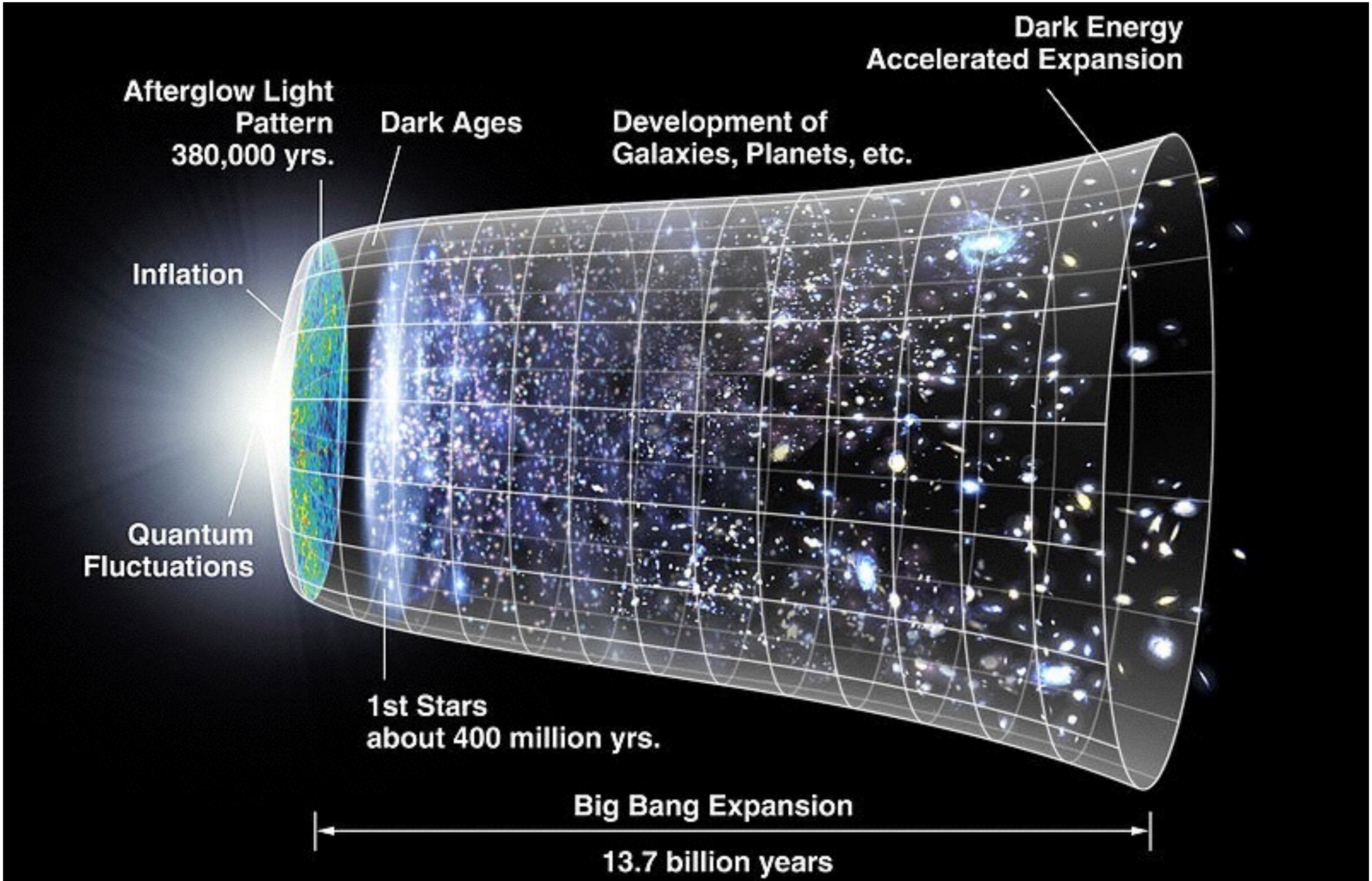
# How Far Back Can We See?



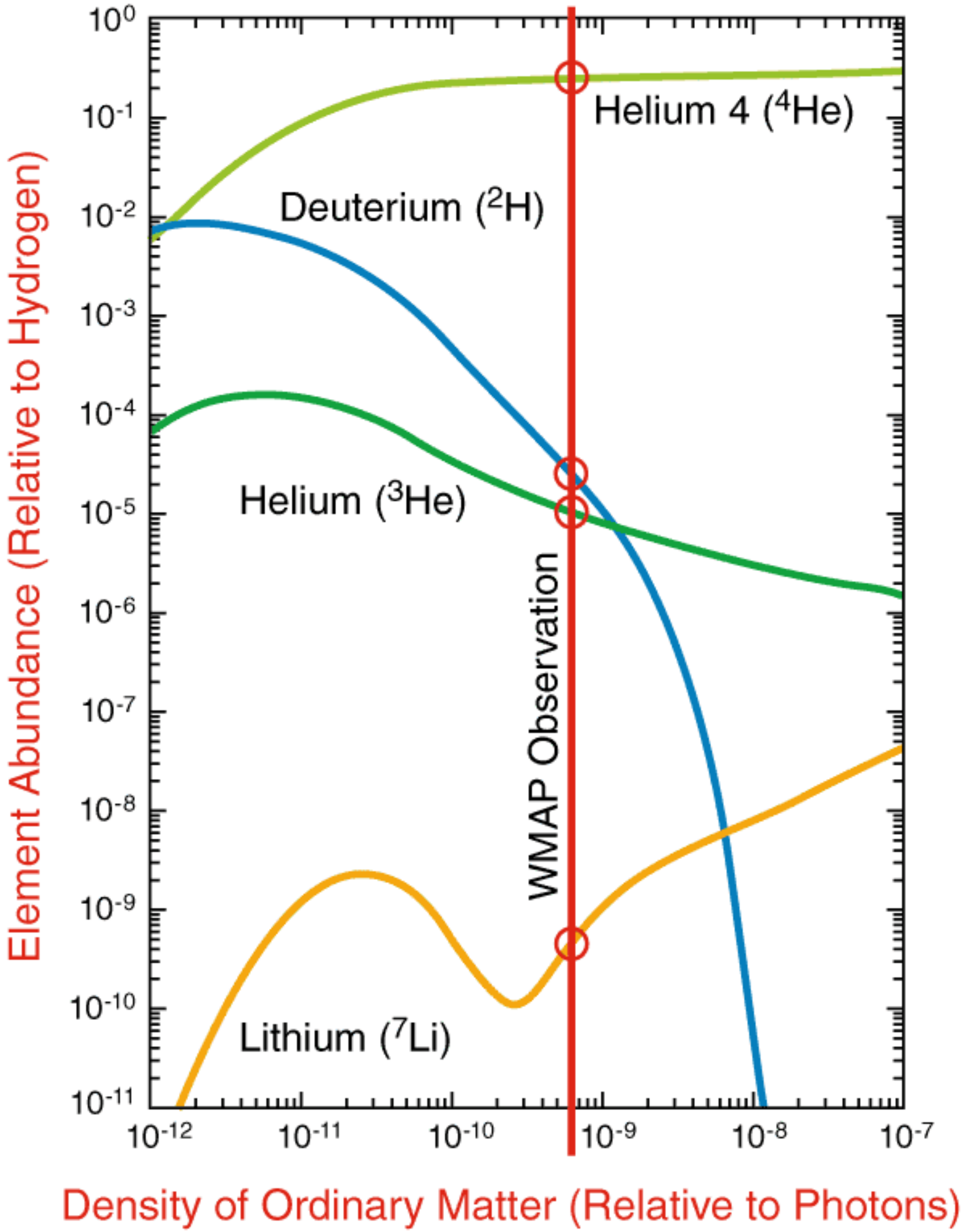
# Hubble Deep Field



# Evolution of the Universe



# Abundance of Light Nuclei



# What Happened Before Recombination

| | | |
|---|---|---|
| $10^{-12}$ s | $10^{16}$ K | limit of our knowledge of physics |
| $10^{-6}$ s | $10^{12}$ K | protons and neutrons form |
| 1 s | $10^{10}$ K | matter anti-matter annihilate |
| 10 s | $10^{10}$ K | photon dominance ($e^+e-$ annihilation) |
| 3 min | $10^{9}$ K | nucleosynthesis |
| $4 \times 10^{5}$ y | 3000 K | atoms form (CMB from this era) |

What happened before $10^{-12}$ s?

# Problems with Simple Big Bang Theory

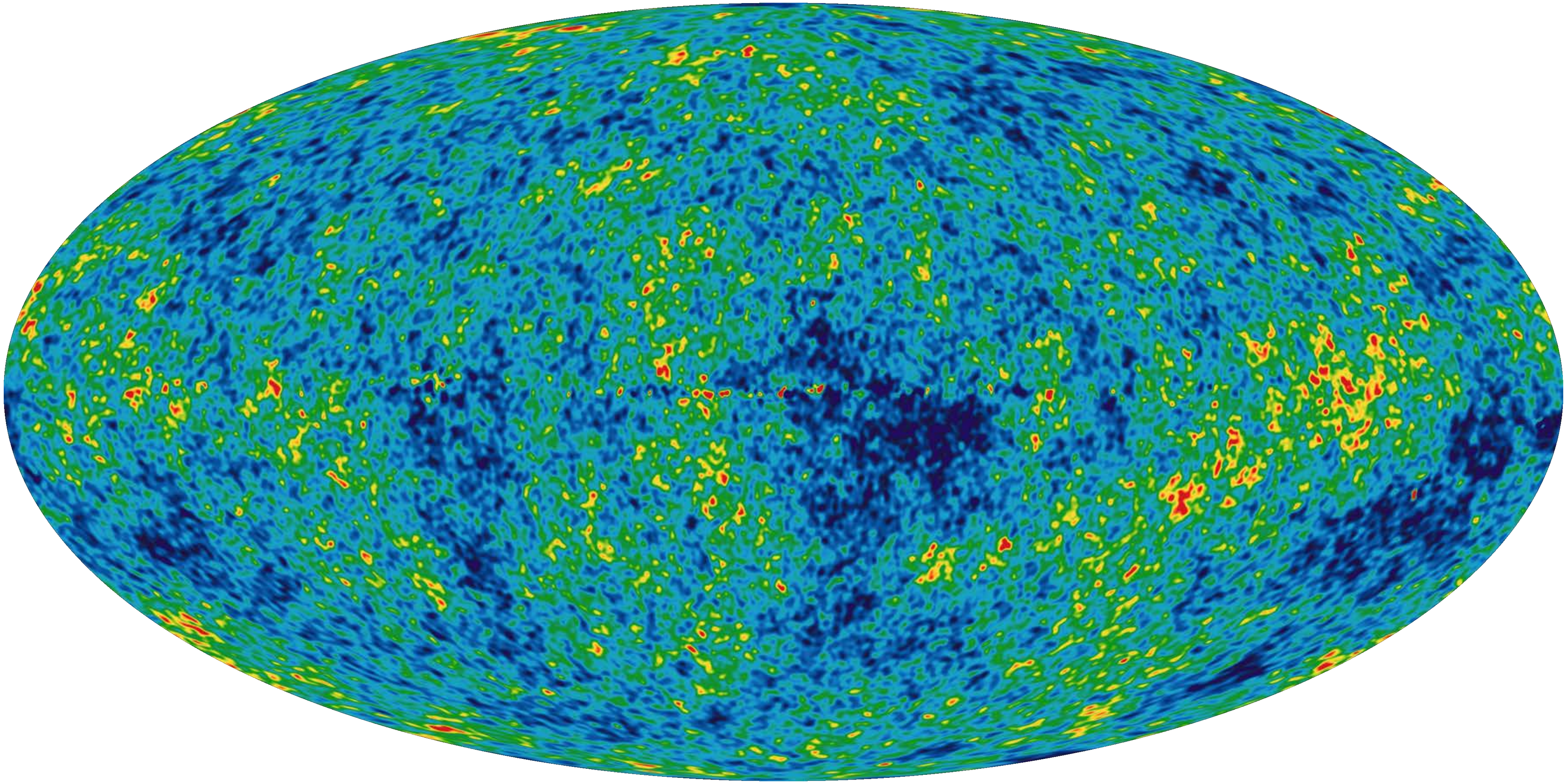
1) Where are magnetic monopoles?

2) Why is the universe so flat?

3) Why are distant parts of the universe in thermal equilibrium? The horizon problem?

# CMB

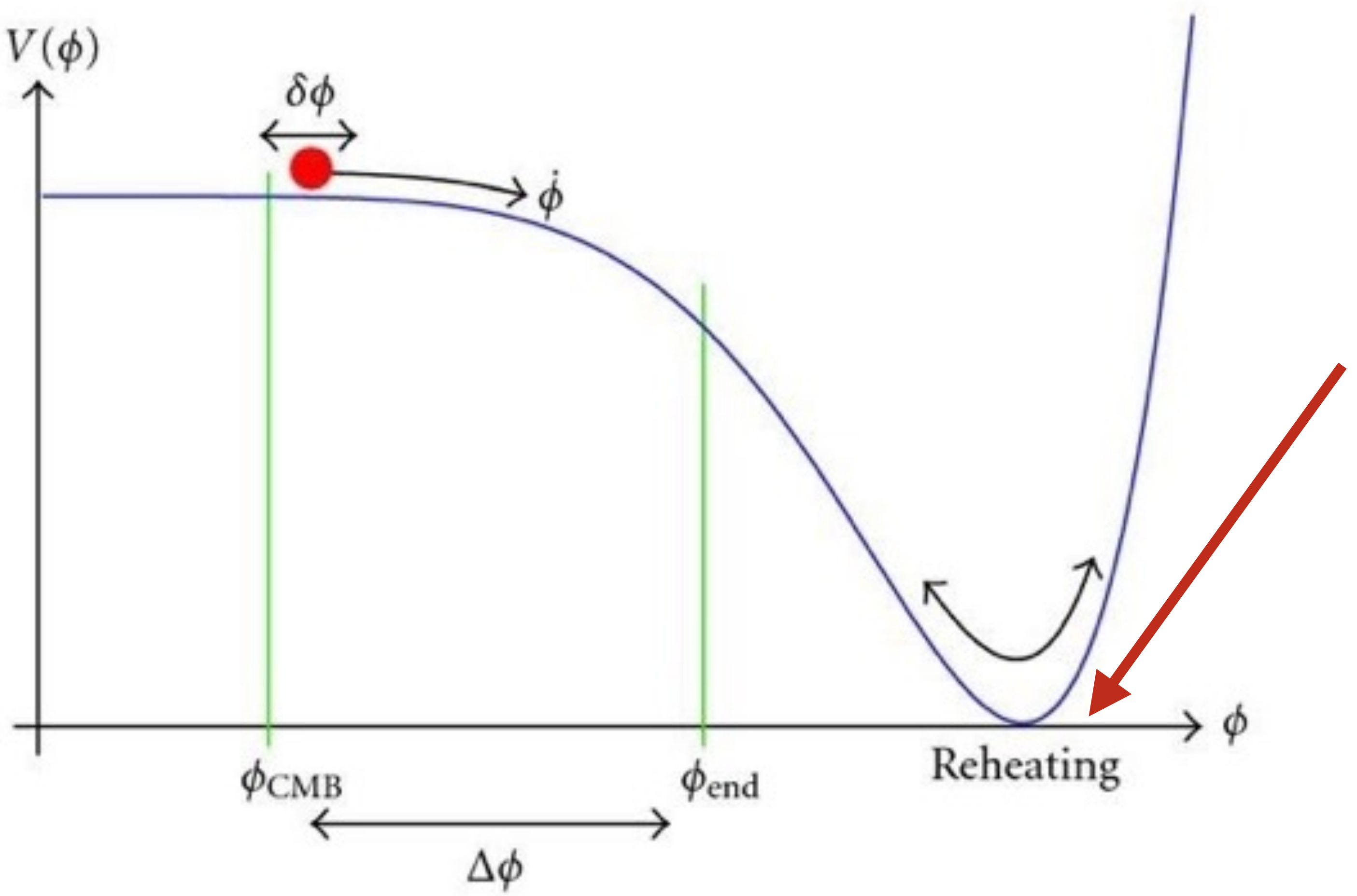
2.7 K microwave photons streaming to us from there
recombination era 380,000 years after the Big Bang



non-uniformities 1 part in $10^5$

# Inflation

- Around $10^{-32}$ s universe increased in size by more than $10^{26}$
- Doubling time $10^{-34}$ s




not exactly zero

Current doubling time $10^{10}$ years

What was driving the exponential expansion?

Vacuum energy

Cosmological constant

# Planck Scale

Planck's constant (quantum mechanics): $\hbar$

Speed of light (special relativity): $c$

Universal gravitation constant: $G$

$$m_{Pl} = \sqrt{\frac{\hbar c}{G}} = 0.02 \text{ mg}$$

$$E_{Pl} = m_{Pl} c^2 = \sqrt{\frac{\hbar c^5}{G}} = 10^{19} \text{ GeV}$$

$$l_{Pl} = \frac{\hbar}{m_{pl} c} = \sqrt{\frac{\hbar c}{G}} = 10^{-35} \text{ m}$$

$$t_{Pl} = \frac{l_{Pl}}{c} = \sqrt{\frac{G\hbar}{c^5}} = 10^{-43} \text{ s}$$

# Cosmological Constant Problem

Natural value for $\Lambda$:

Planck energy in Planck cube

$$\frac{10^{19}\ \mathrm{GeV}}{(10^{-35}\ \mathrm{m})^3} = 10^{124}\ \mathrm{GeV/m^3}$$

Measured value for $\Lambda$: $1\ \mathrm{GeV/m^3}$

Off by 124 orders of magnitude!!!

Biggest mistake in all of ~~physics~~! science

# Limit of Cosmological Constant

Steven Weiberg 1987

- Calculated the upper limit of cosmological constant that would allow for us to be here.

- Larger values would cause the universe to expand to quickly for galaxies, stars, planets, life to evolve.

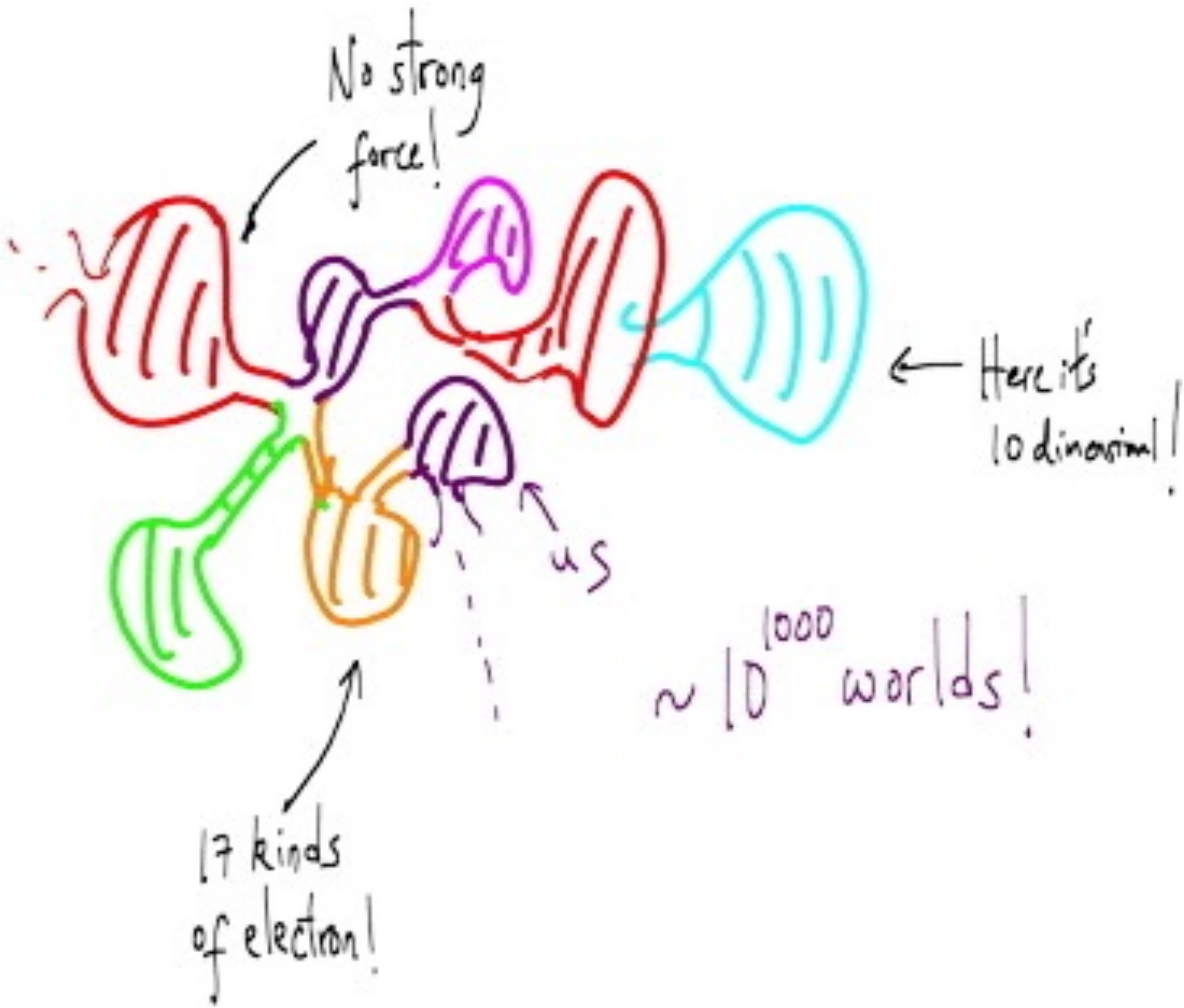
Calculated value in excellent agreement with the value measured in 1998

# Anthropic Principle

- The universe is the way it is because we are here
  - Gives the appearance that the laws of physics are fine tuned for our existence.

- We live in a Goldilocks universe. One of a huge number of universes in which we couldn't exist

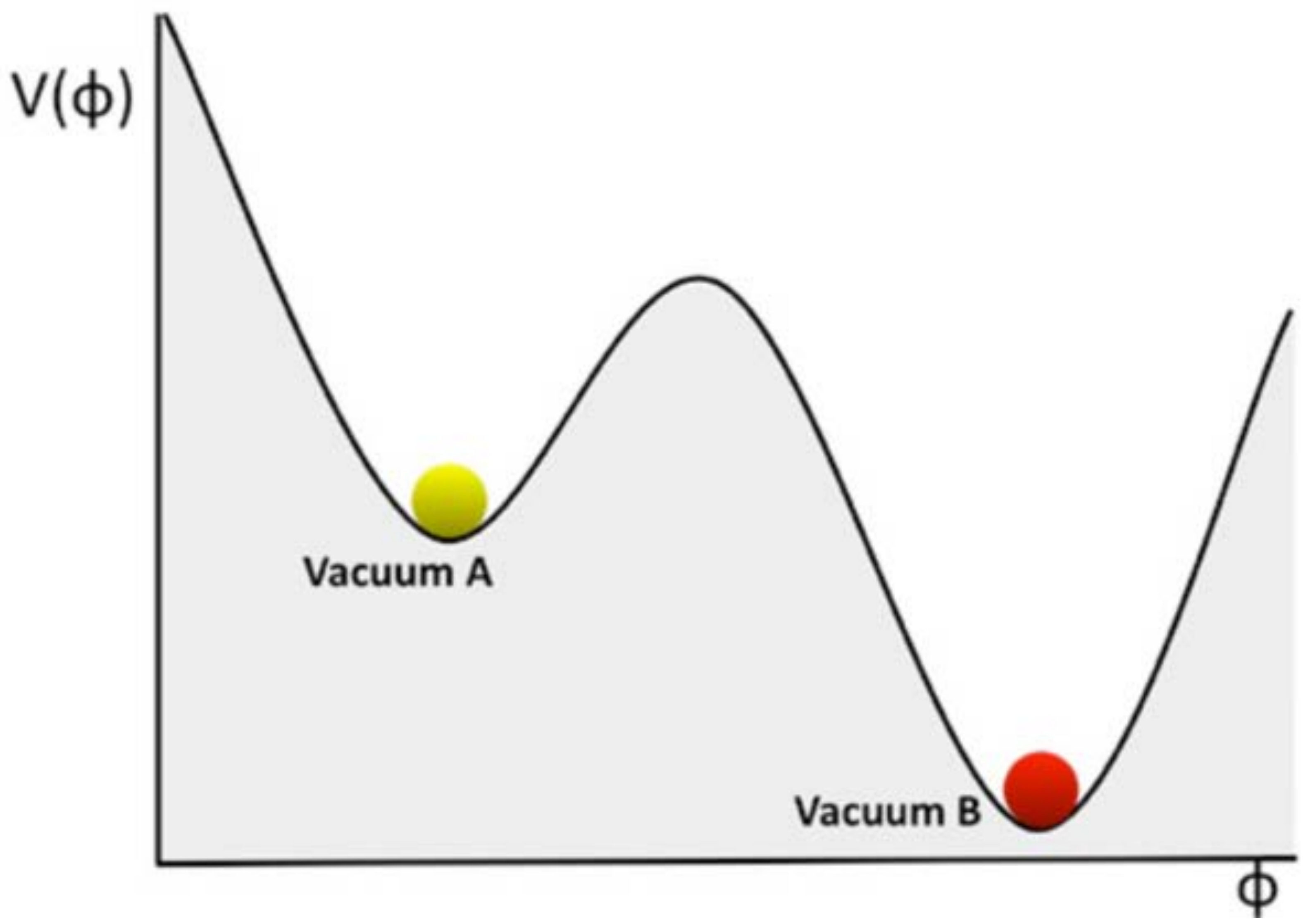
# Multiverse



No strong force!
Here it's 10 dimensional!
us
~ $10^{1000}$ worlds!
17 kinds of electron!

# Multiverse

Vacuum energy different
in different universes



# Outstanding Problems

- Why is the vacuum energy so small?
- What is the physics at $10^{-35}$ m?
- What is the quantum gravity?
- Is there any new physics between $10^{-19}$ m and $10^{-35}$ m?
- Why are the parameters of the universe so finely tuned?
- Why is there an excess of matter over antimatter?
- Are space and time fundamental?

# To Learn More

## Cornell Messenger Lectures

Nima Arkani-Hamed

Lenny Susskind