Reading: OpenStax, Chapter 29, Sections 29.1-29.6 (for this lecture + next 2)

Previously: **Dark Matter and Large Scale Structure**

- Galaxies are mostly found in groups and clusters
- Clusters are further organized into superclusters
- Dark matter is needed to hold clusters together
- The large-scale structure of the visible Universe shows large voids threaded by filamentary superclusters

Today: **Cosmology I - The Age of the Universe and the Big Bang**

- Cosmology - answering questions about the origin of the Universe and answering them using observations
- Independent measurements all yield an age of the Universe of about 13.5 billion years
- Time began with a hot Big Bang - expansion and cooling until today
- The Big Bang makes several predictions that can be tested

Cosmology

- **The study of the overall structure and history of the Universe**
- **What caused the Large Scale Structure**
  - **How did the first galaxies form?**
  - **When did the first galaxy clusters form?**
  - **What happened before there were galaxies?**
- **We live in an expanding universe**
  - **How long has it been expanding?**
  - **What caused the expansion?**
  - **Will it expand forever?**
- **The Universe is VERY big**
  - **Is it truly infinite or is there an “edge”?**
  - **Are there other universes?**

Cosmology

- **The study of the overall structure and history of the Universe**
- **What caused the Large Scale Structure**
  - **How did the first galaxies form?**
  - **When did the first galaxy clusters form?**
  - **What happened before there were galaxies?**

Addressed (most of) this last time!

- **We live in an expanding universe**
  - **How long has it been expanding?**
  - **What caused the expansion?**
  - **Will it expand forever?**
- **The Universe is VERY big**
  - **Is it truly infinite or is there an “edge”?**
  - **Are there other universes?**

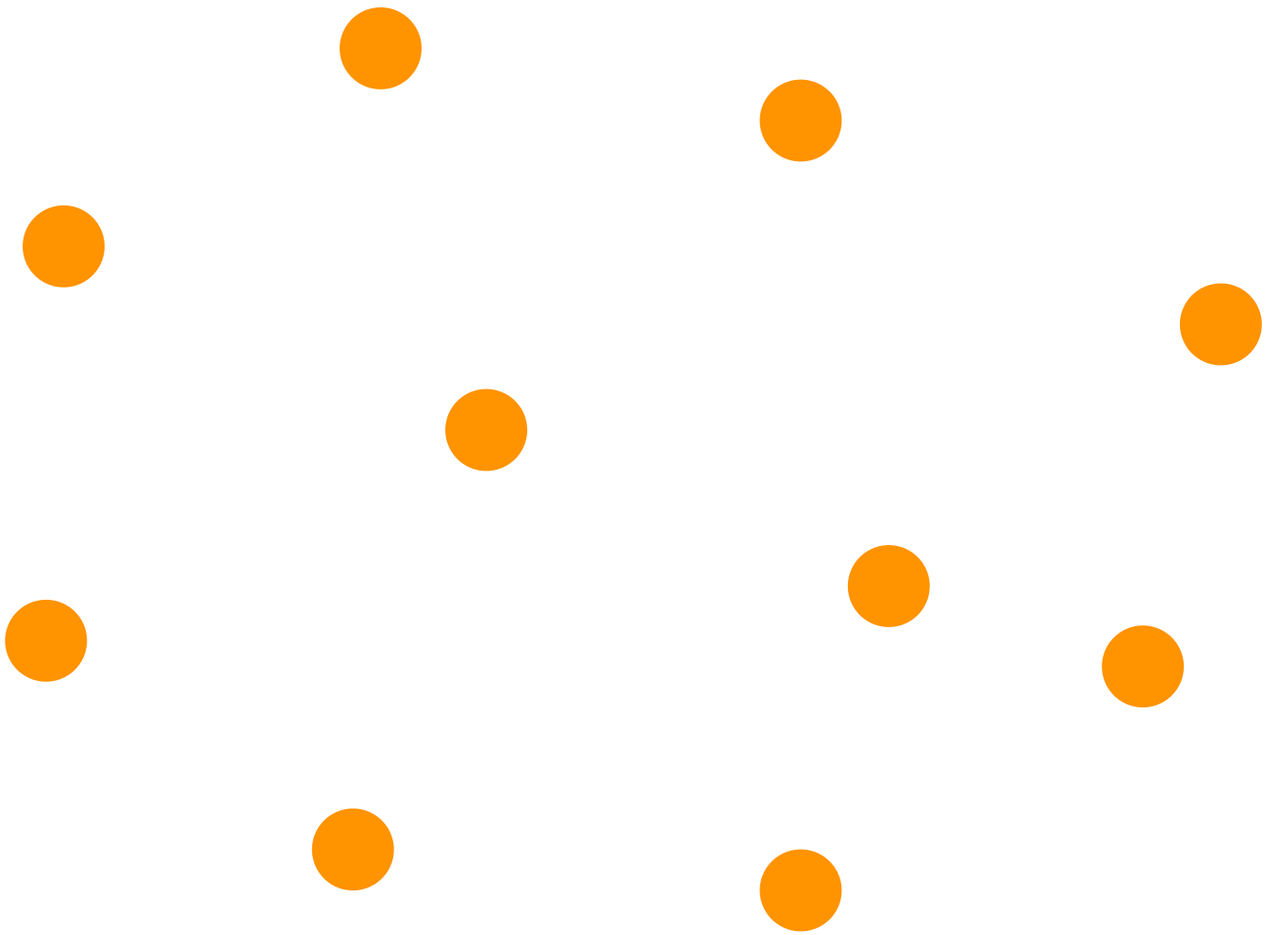
Gravity is the key to explaining large scale structure

Benedikt Diemer

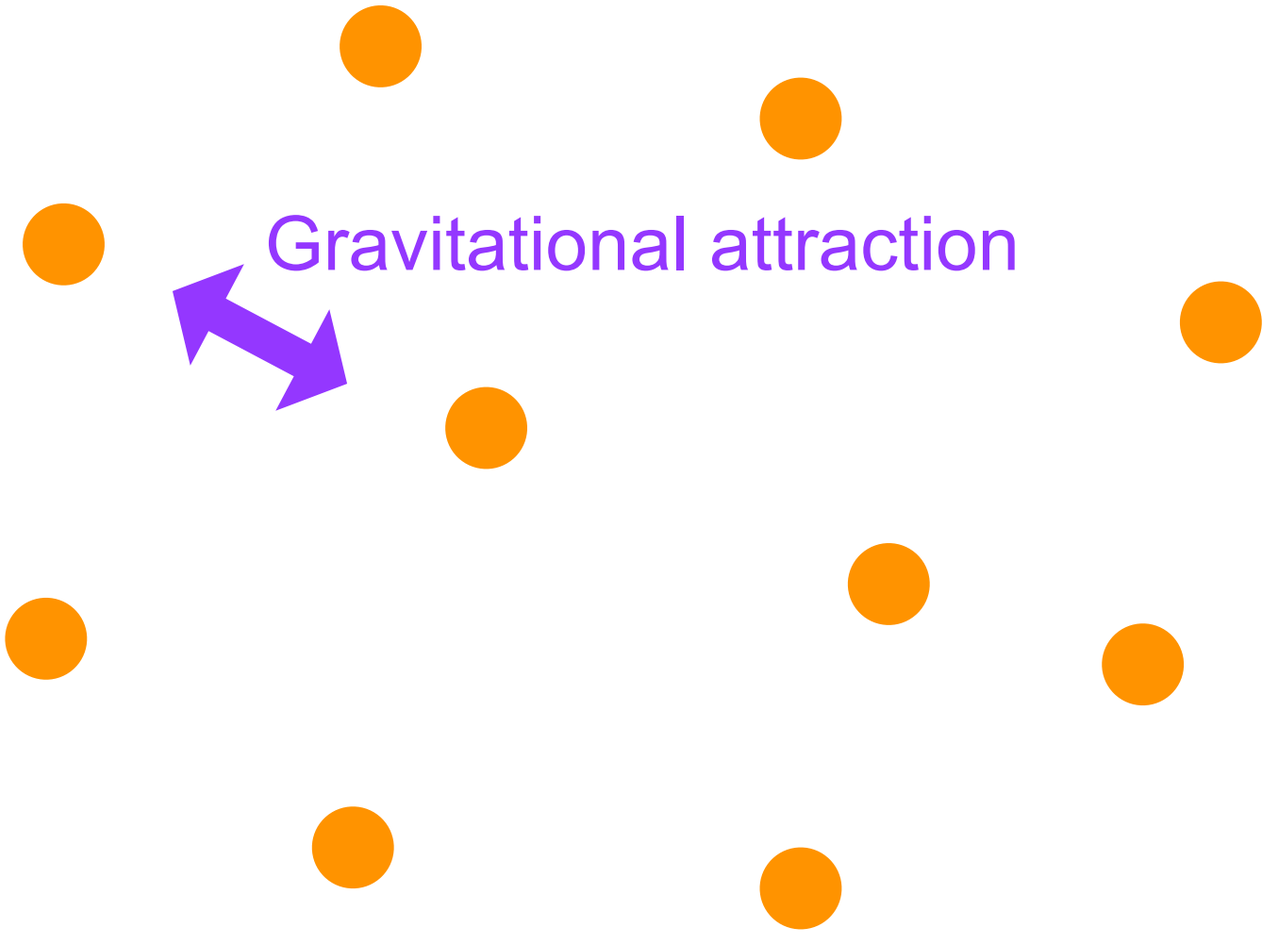
Cosmology

- **The study of the overall structure and history of the Universe**
- **What caused the Large Scale Structure**
  - **How did the first galaxies form?**
  - **When did the first galaxy clusters form?**
  - **What happened before there were galaxies?**
- **We live in an expanding universe**
  - **How long has it been expanding?**
  - **What caused the expansion?**
  - **Will it expand forever?**
- **The Universe is VERY big**
  - **Is it truly infinite or is there an "edge"?**
  - **Are there other universes?**

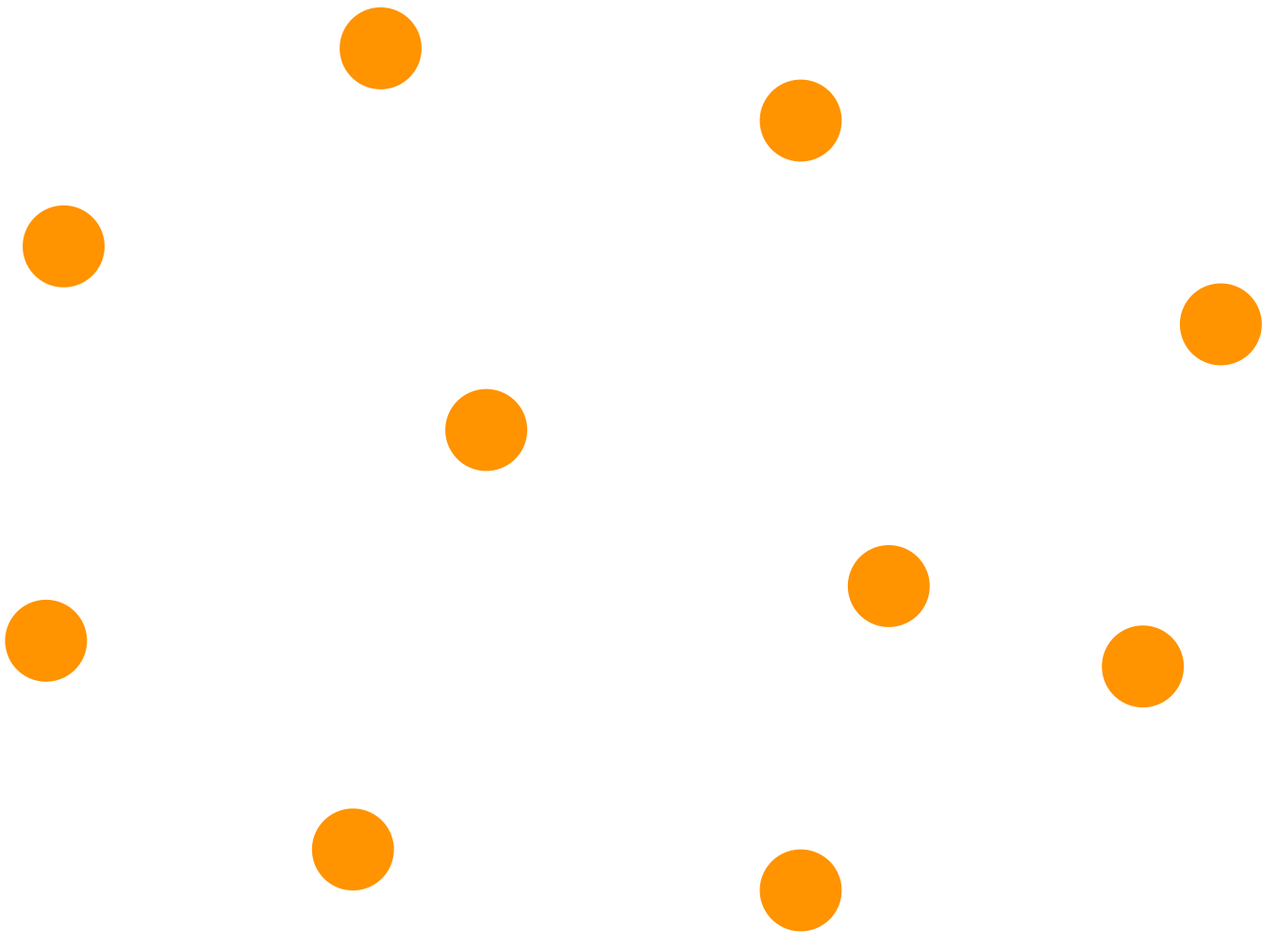
Gravity says that the Universe should collapse in on itself!



Gravity says that the Universe should collapse in on itself!

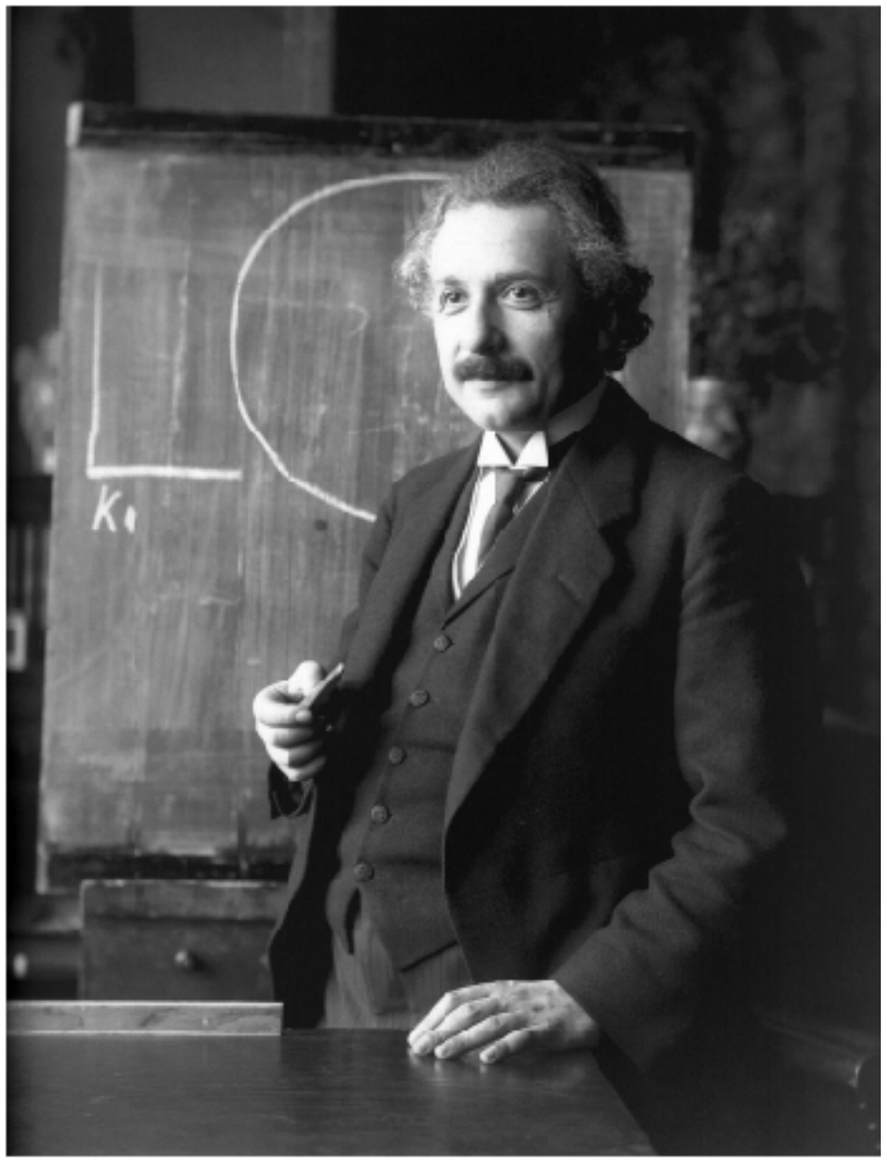


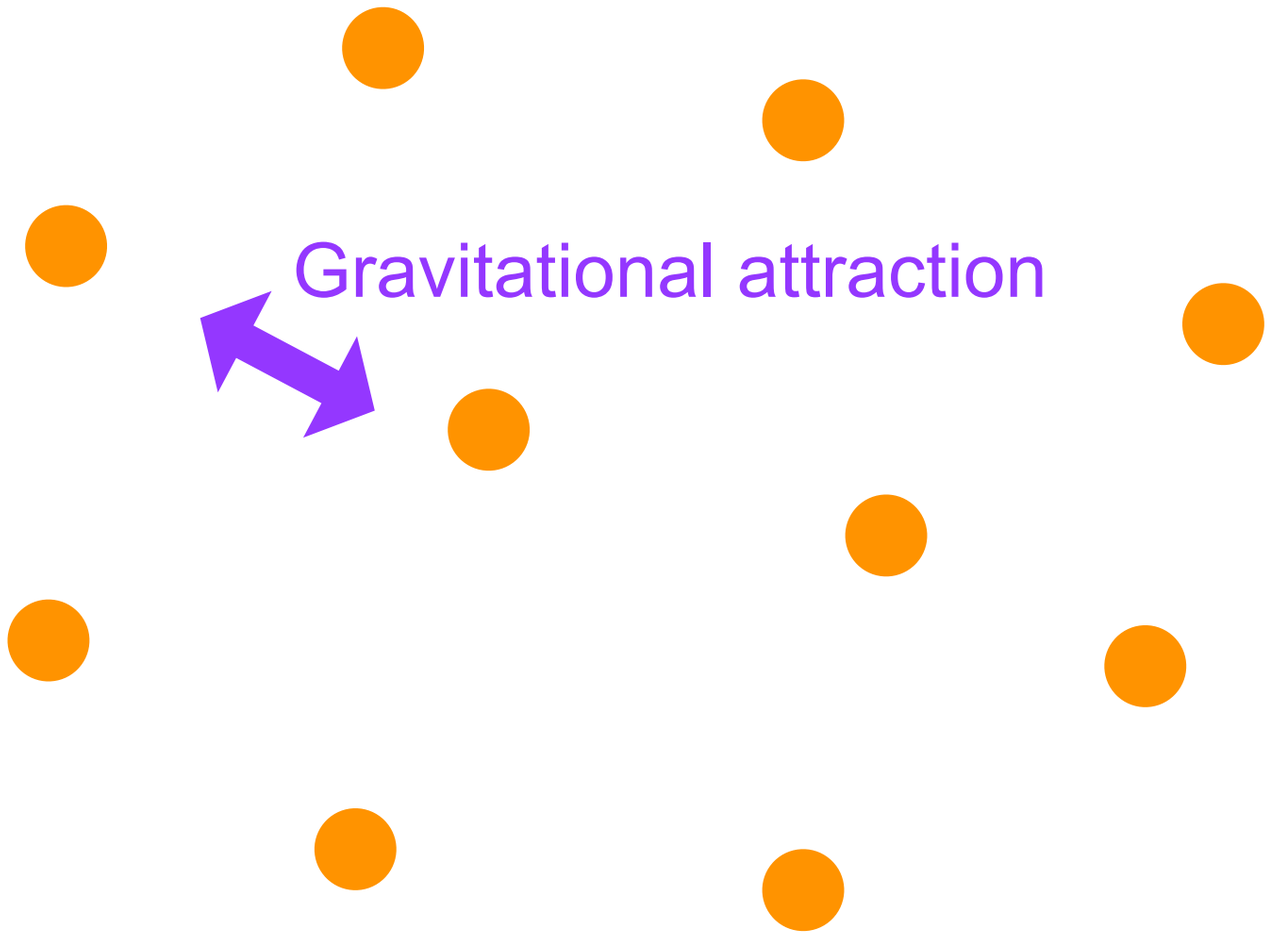
Gravity says that the Universe should collapse in on itself!



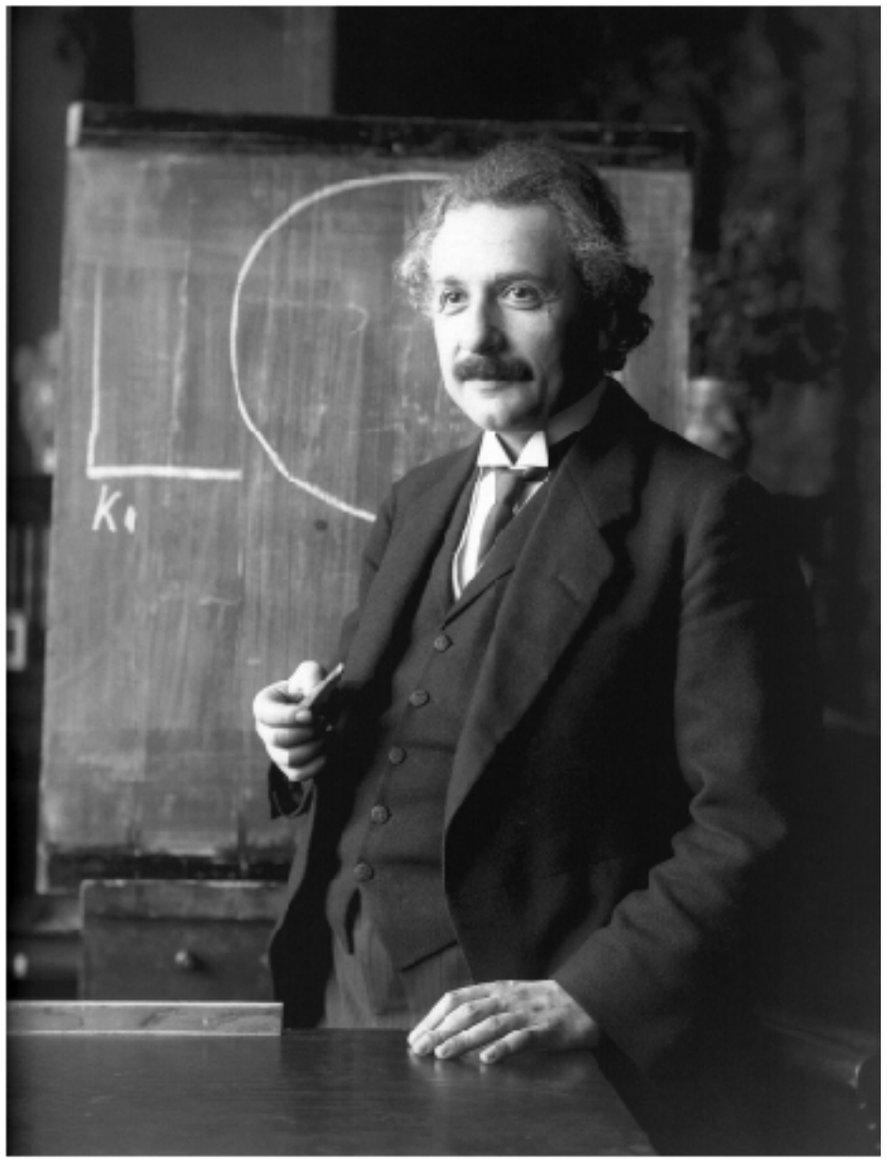
Gravity says that the Universe should collapse in on itself!

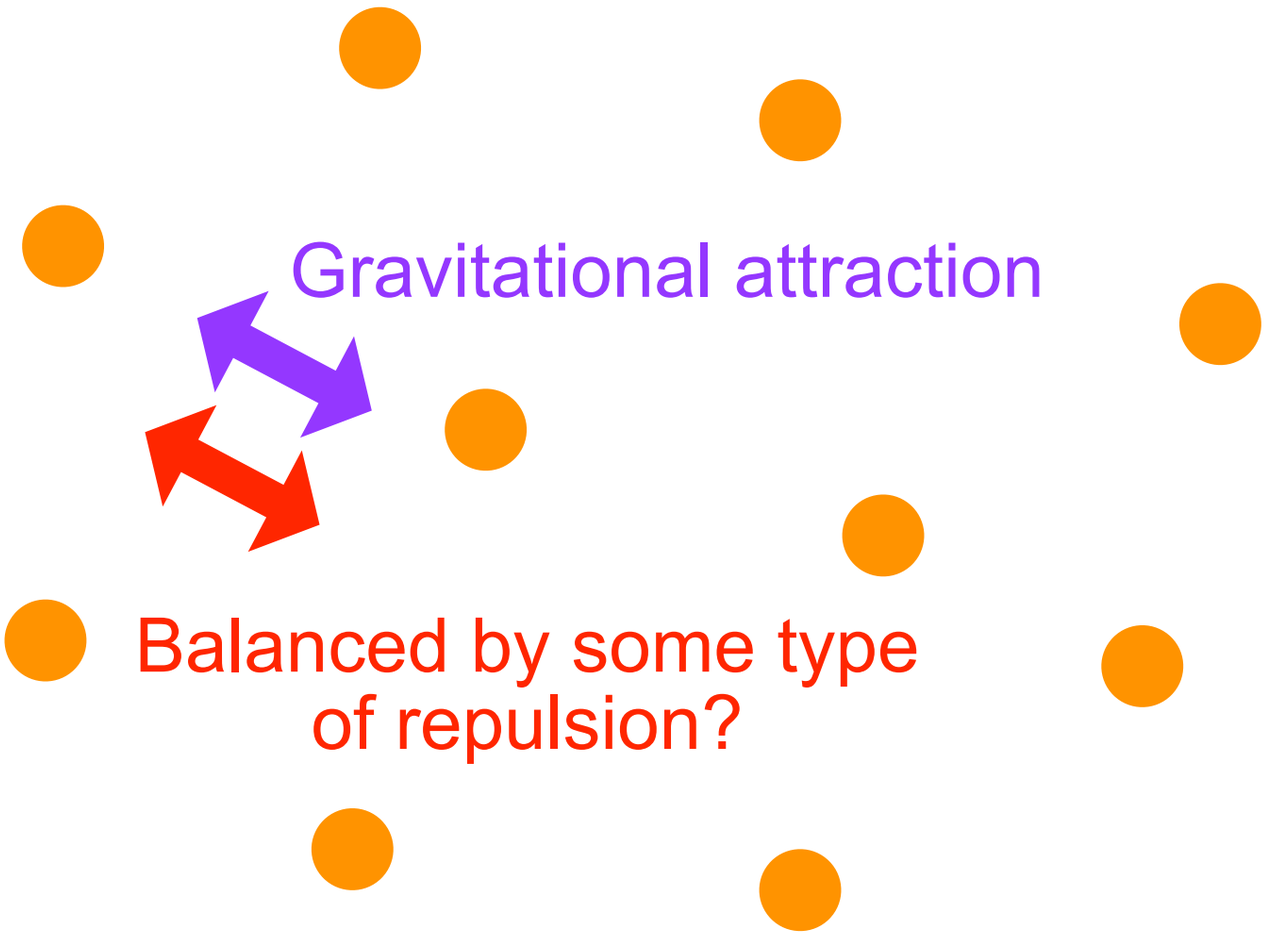
Einstein did not like this and proposed a “cosmological constant”





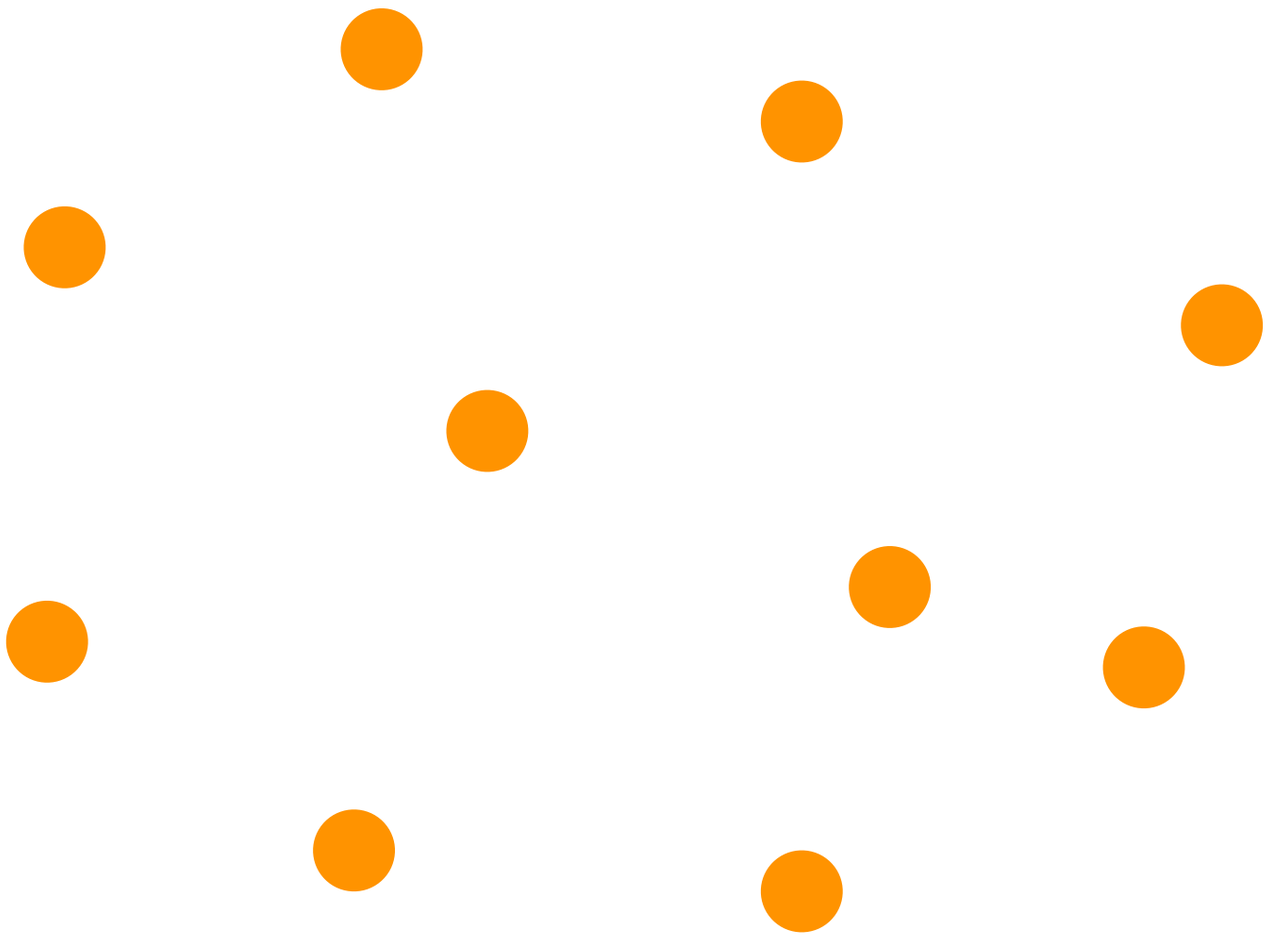
Einstein did not like this and proposed a “cosmological constant”





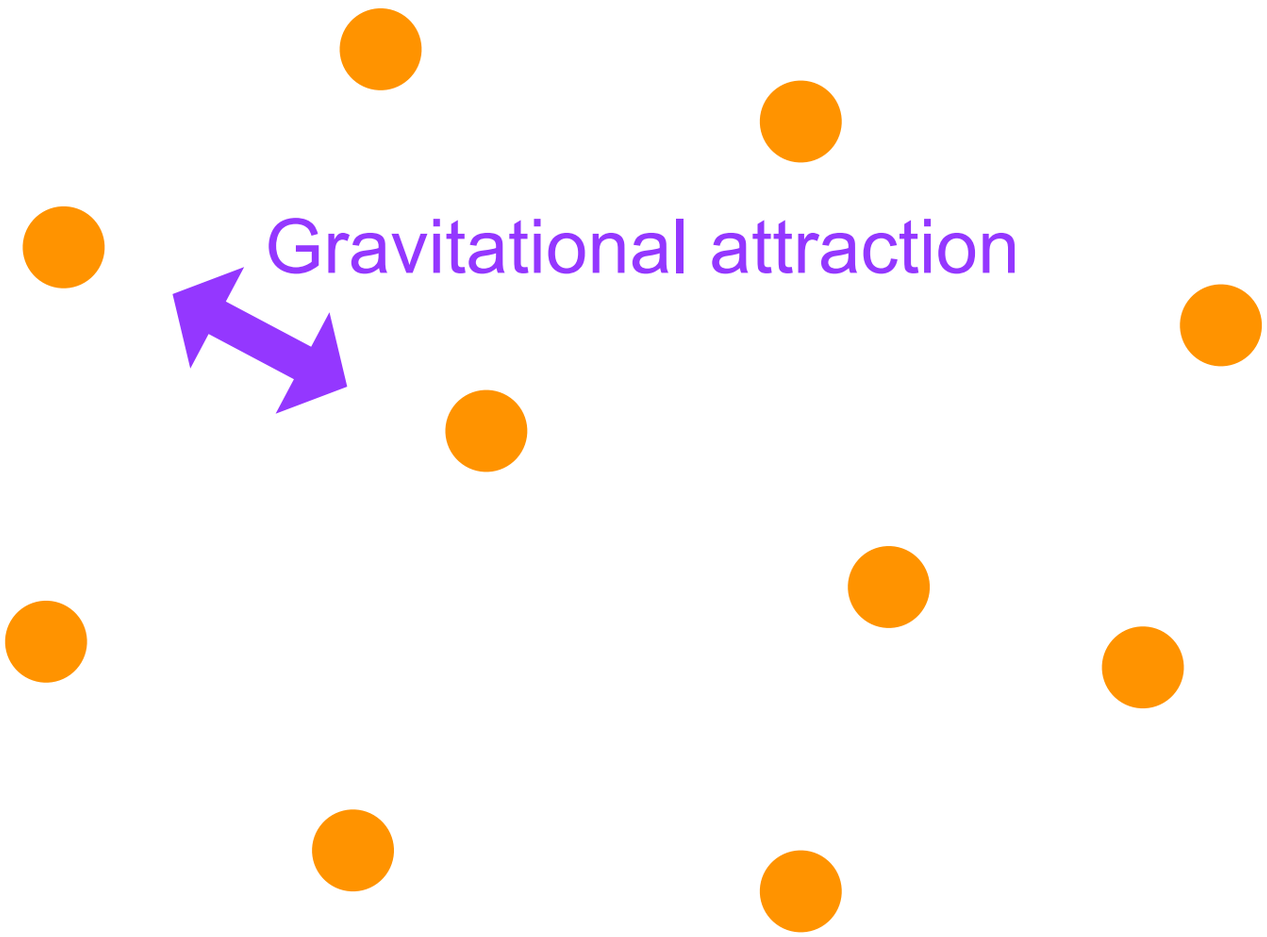
Instead, expansion is overpowering gravity

- When it was discovered that the Universe is expanding, Einstein was forced to concede his notion
- An example of how science works!



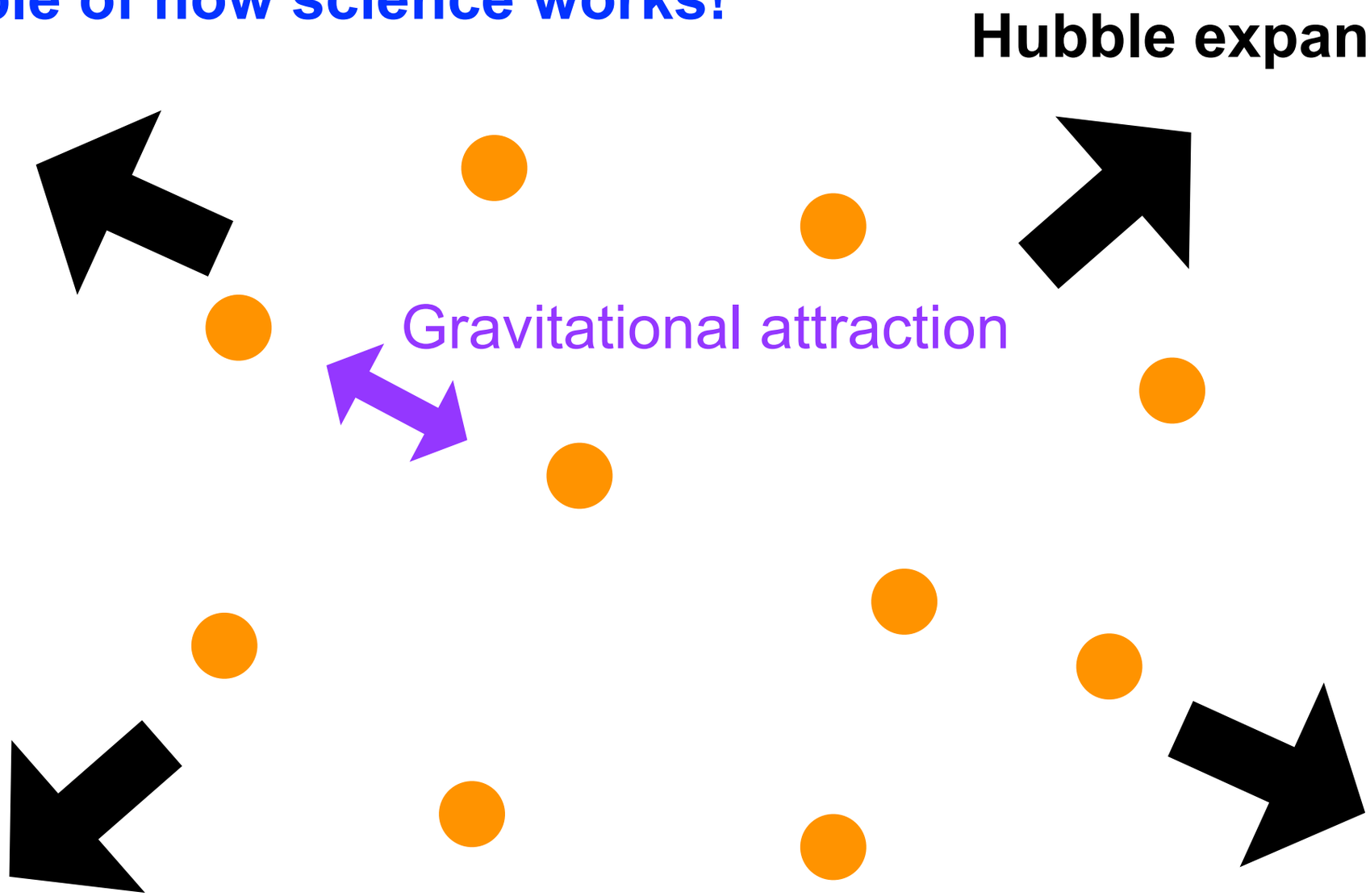
Instead, expansion is overpowering gravity

- When it was discovered that the Universe is expanding, Einstein was forced to concede his notion
- An example of how science works!



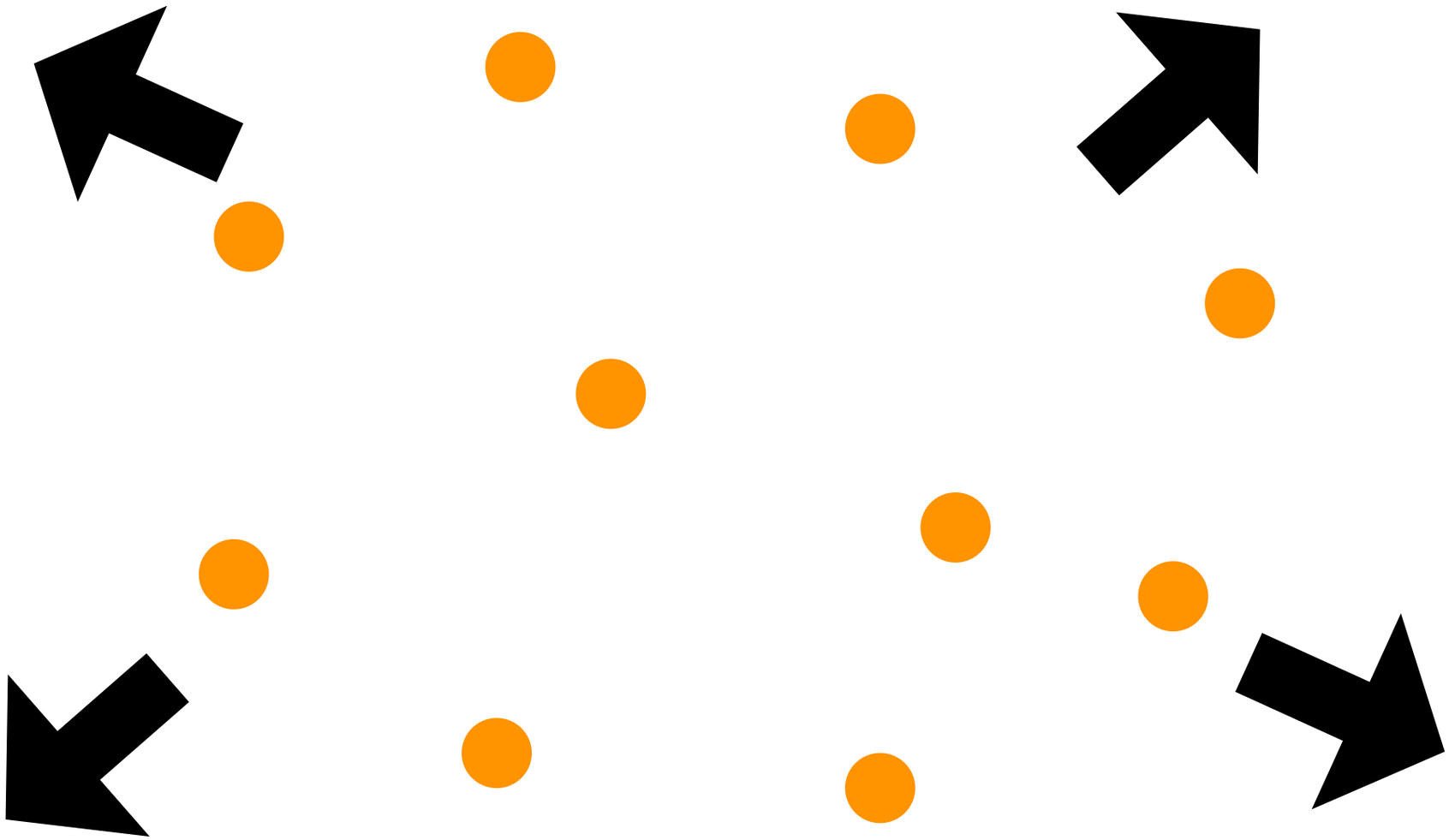
Instead, expansion is overpowering gravity

- When it was discovered that the Universe is expanding, Einstein was forced to concede his notion
- An example of how science works!



Instead, expansion is overpowering gravity

- When it was discovered that the Universe is expanding, Einstein was forced to concede his notion
- An example of how science works!

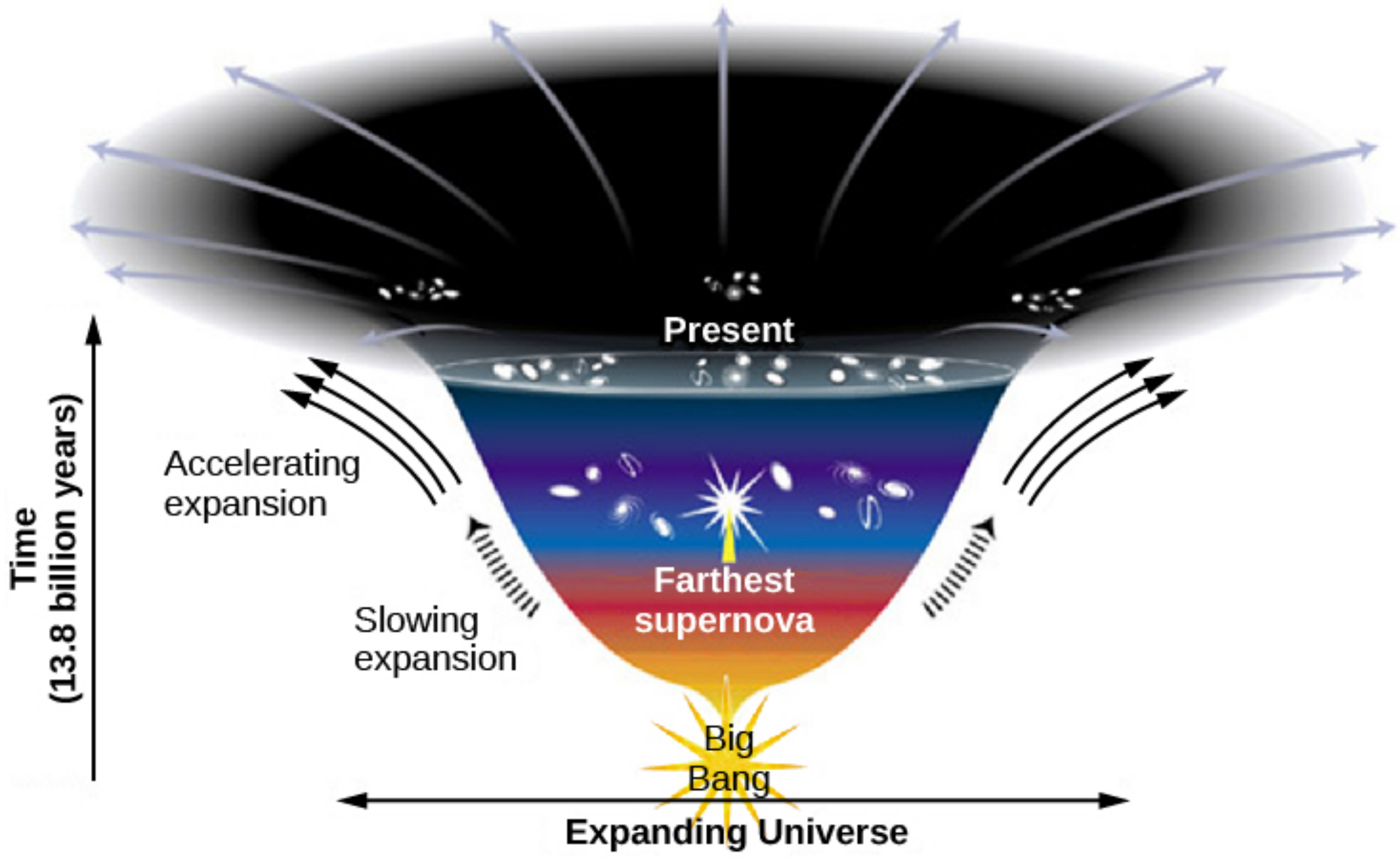


Instead, expansion is overpowering gravity

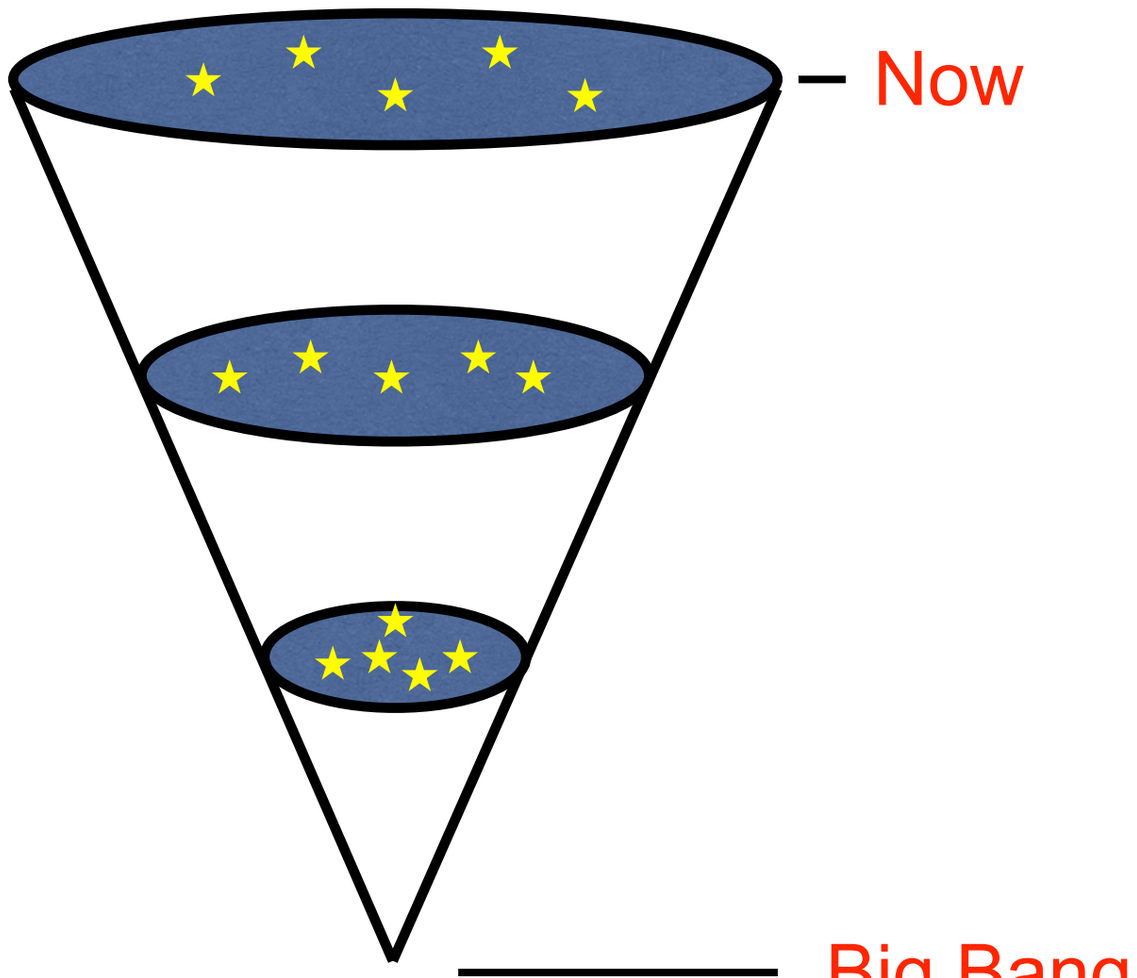
- When it was discovered that the Universe is expanding, Einstein was forced to concede his notion
- An example of how science works!

Hubble expansion

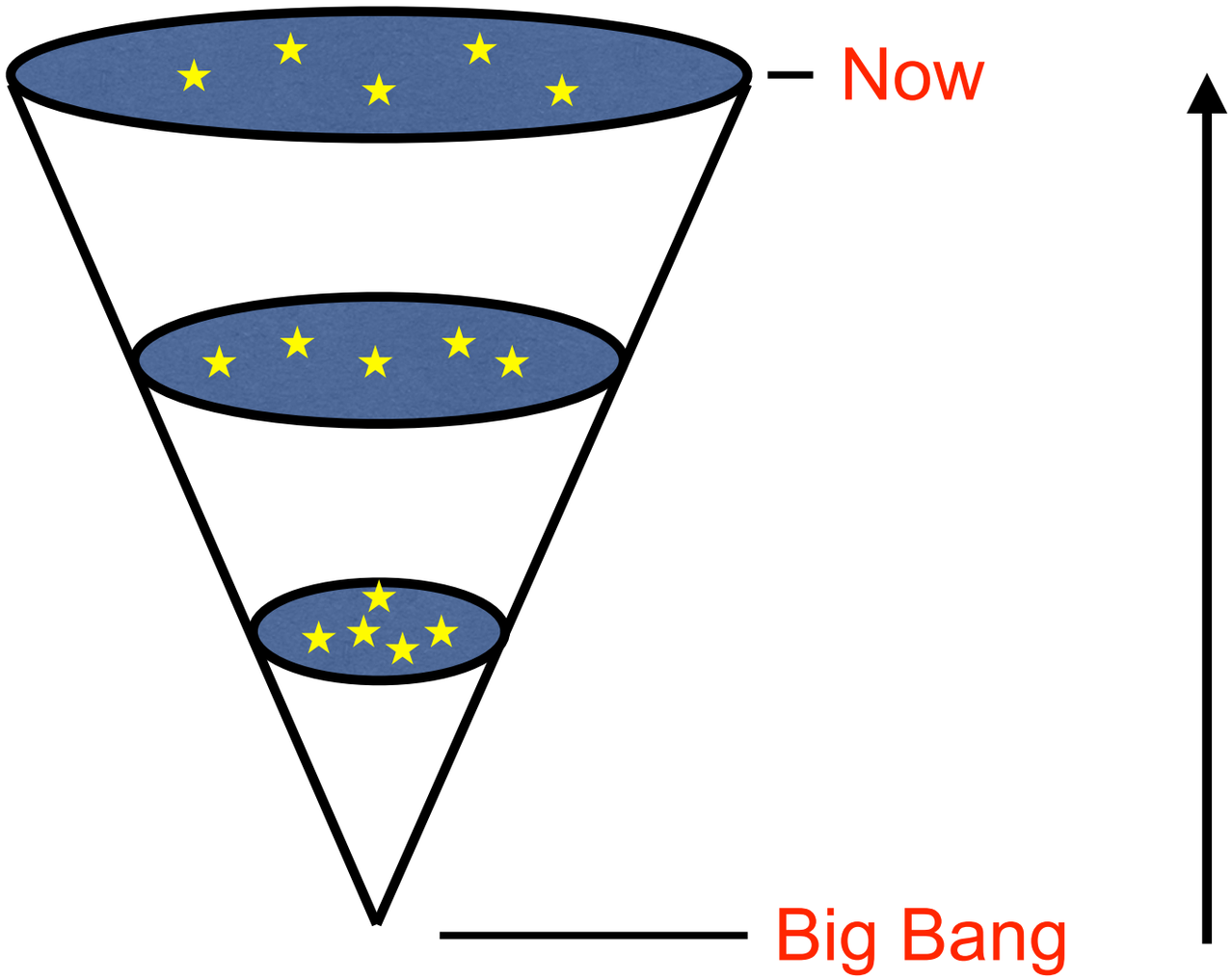
But *why* is the Universe expanding?



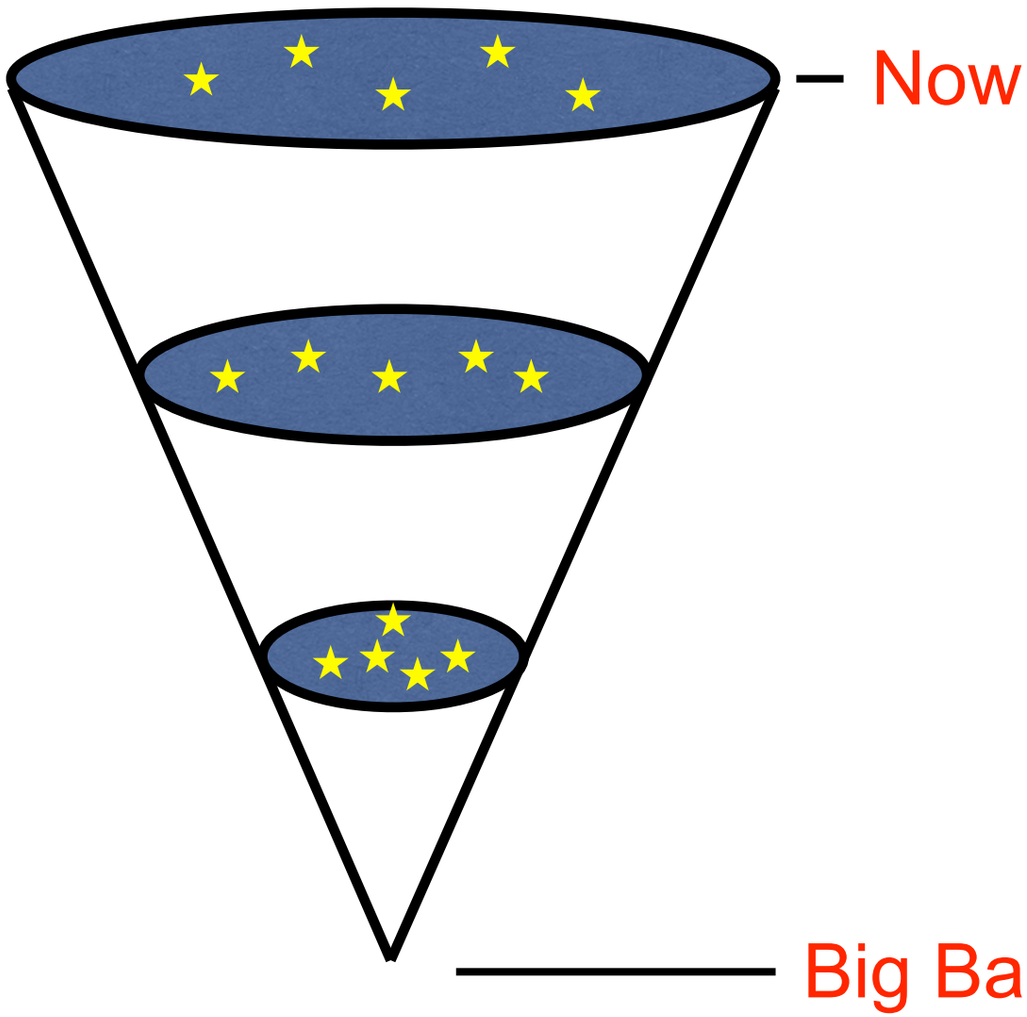
A simpler picture of the Big Bang (for now)



How long did it take for the Universe to expand to its current size?



How long did it take for the Universe to expand to its current size?

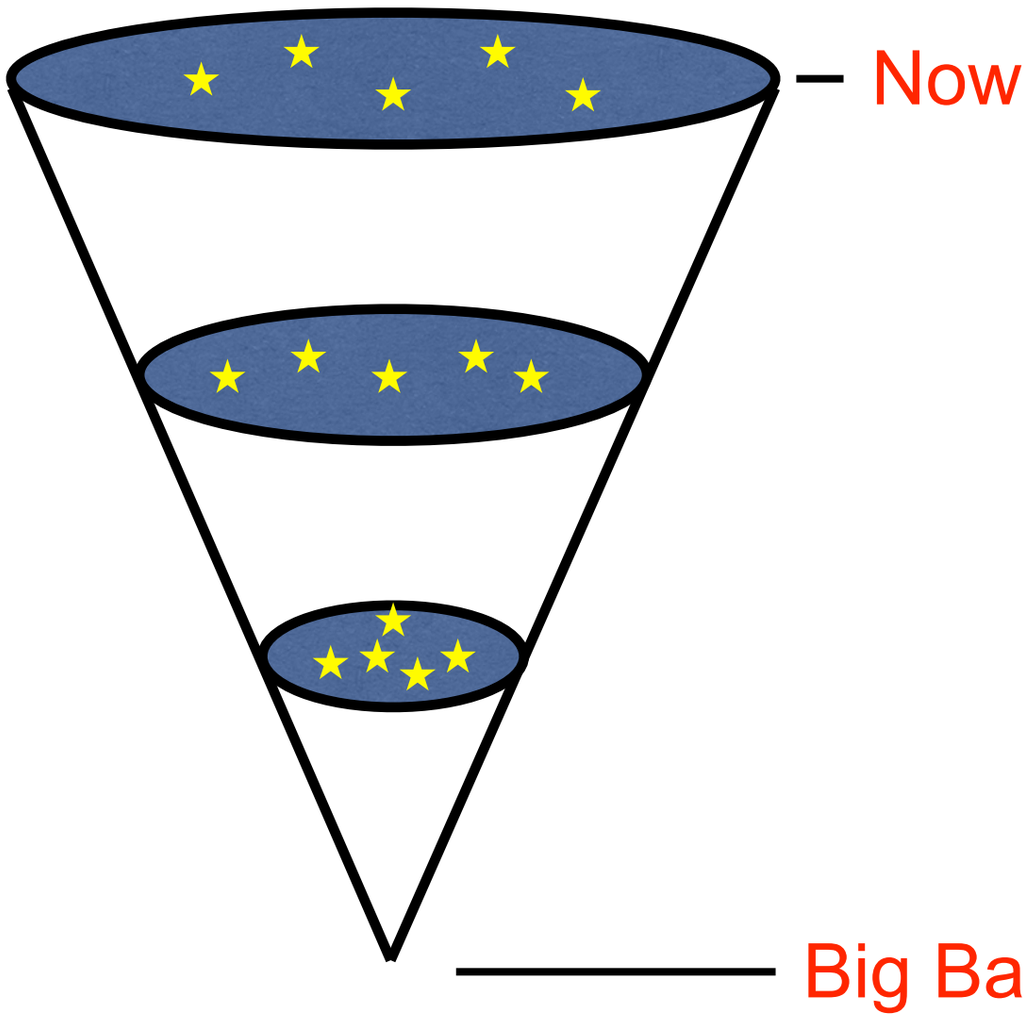


$$t = \frac{d}{v}$$

d is the distance to a galaxy

v is the velocity of expansion

How long did it take for the Universe to expand to its current size?

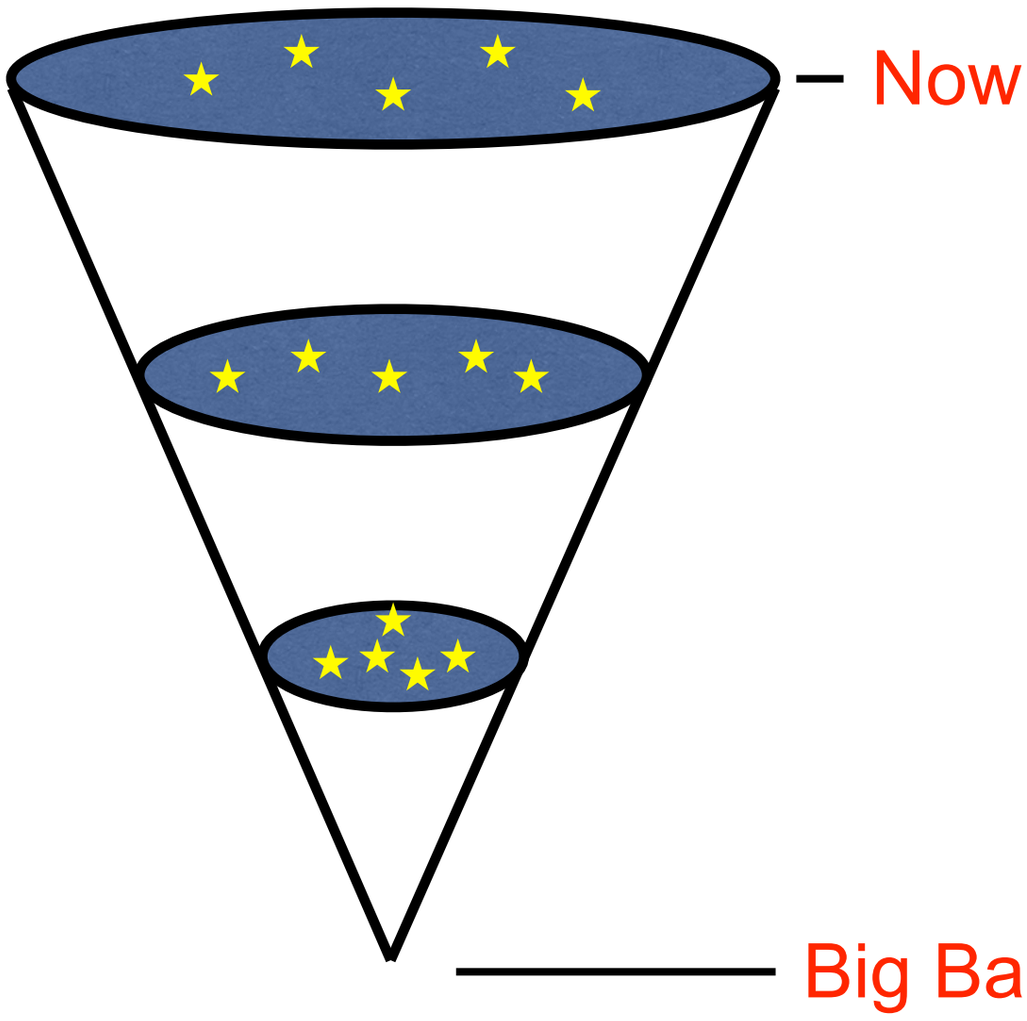


$$t = \frac{d}{v}$$

$$v = H \times d$$

H is the Hubble constant
(this is just the Hubble expansion)

How long did it take for the Universe to expand to its current size?

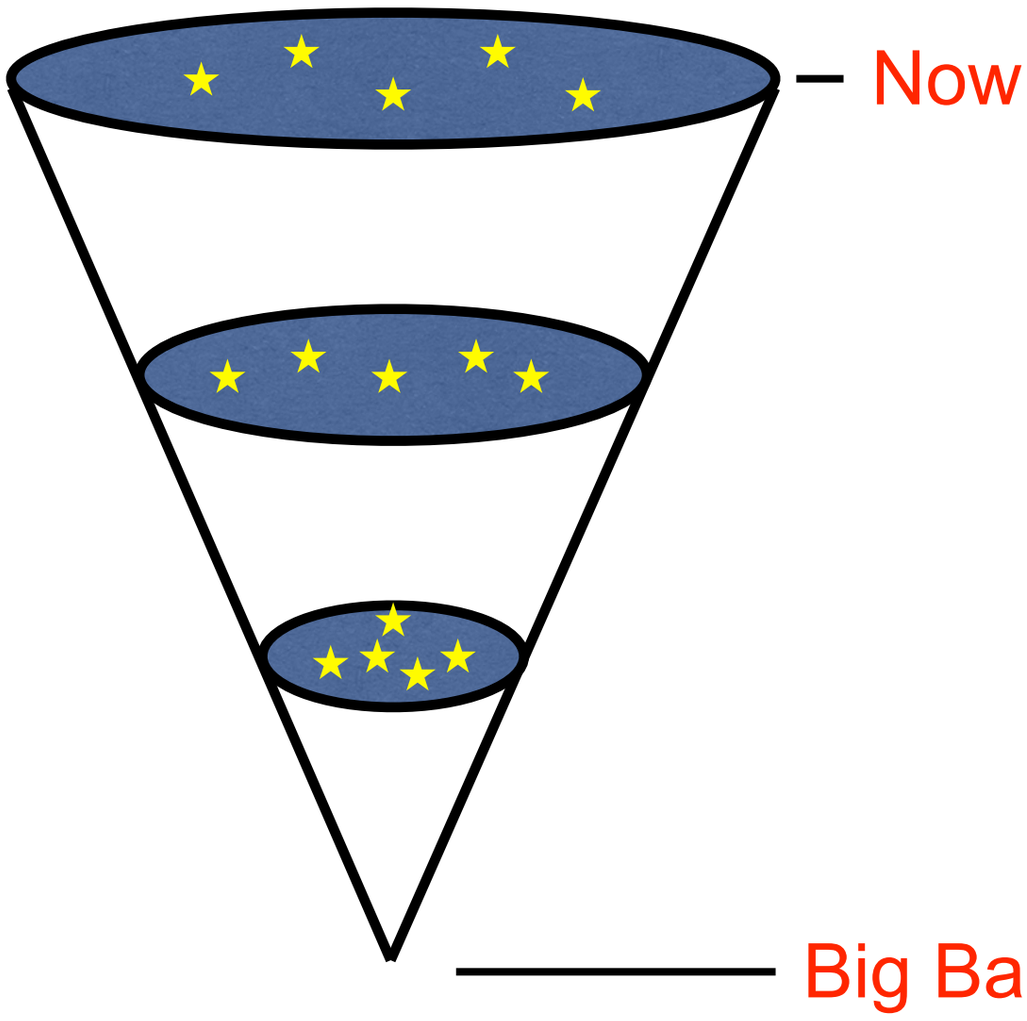


$$t = \frac{d}{v}$$

$$v = H \times d$$

$$t = \frac{d}{H \times d}$$

How long did it take for the Universe to expand to its current size?

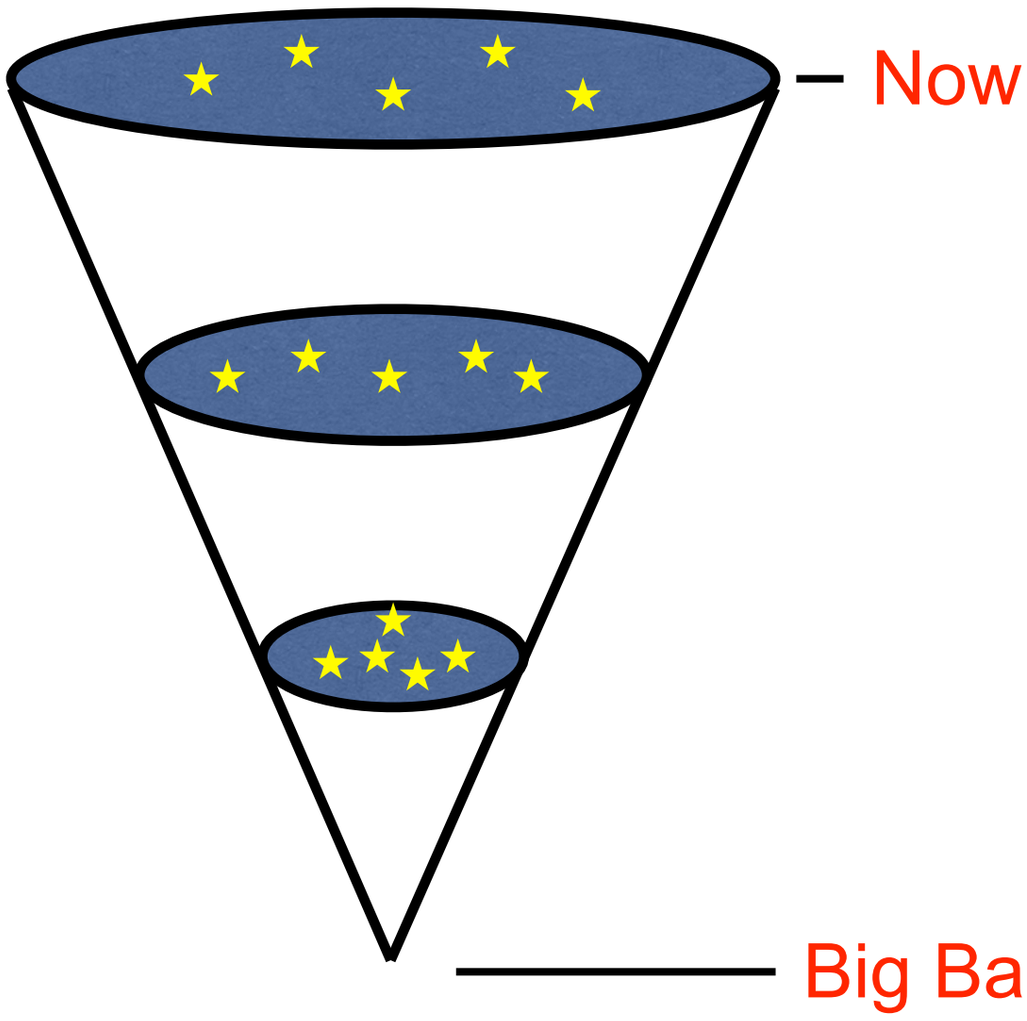


$$t = \frac{d}{v}$$

$$v = H \times d$$

$$t = \frac{\cancel{d}}{H \times \cancel{d}}$$

How long did it take for the Universe to expand to its current size?

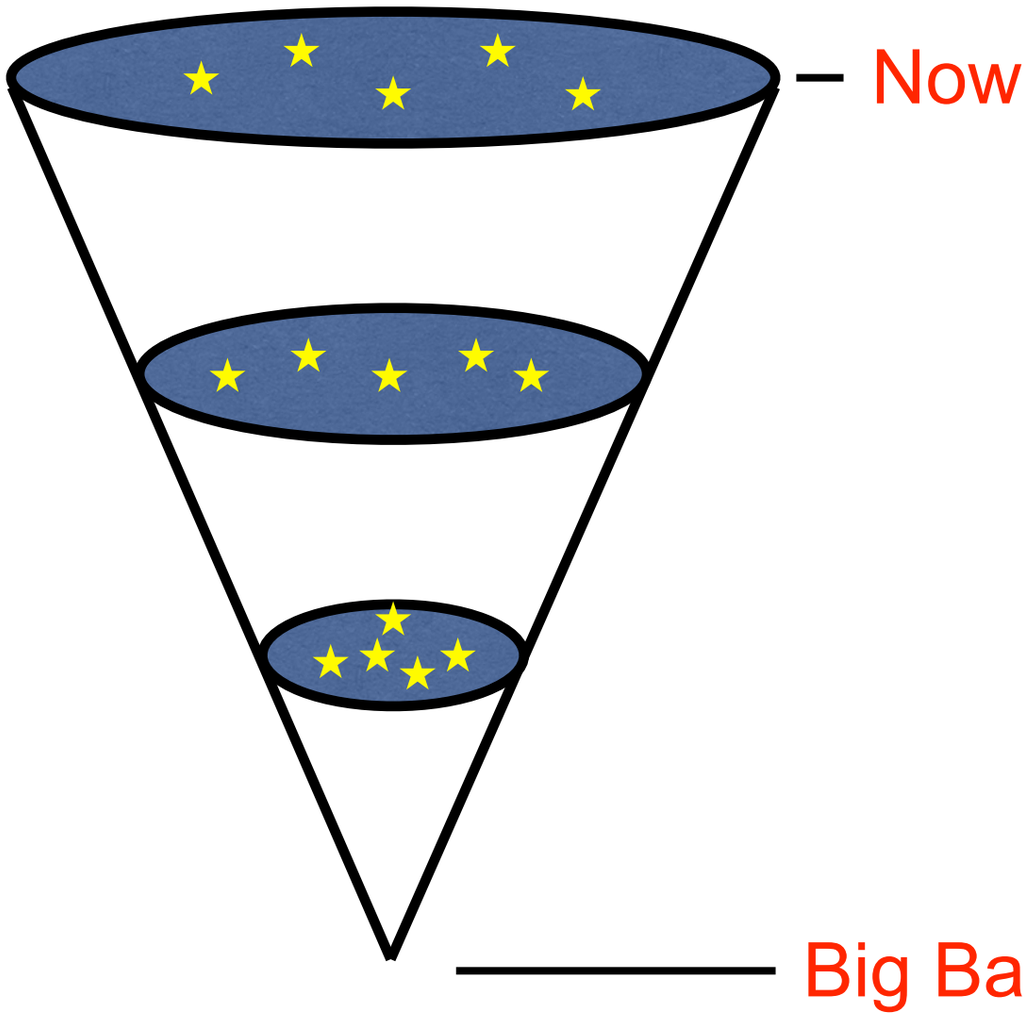


$$t = \frac{d}{v}$$

$$v = H \times d$$

$$t = \frac{\cancel{d}}{H \times \cancel{d}} = \frac{1}{H}$$

The age of the Universe (aka the Hubble time)

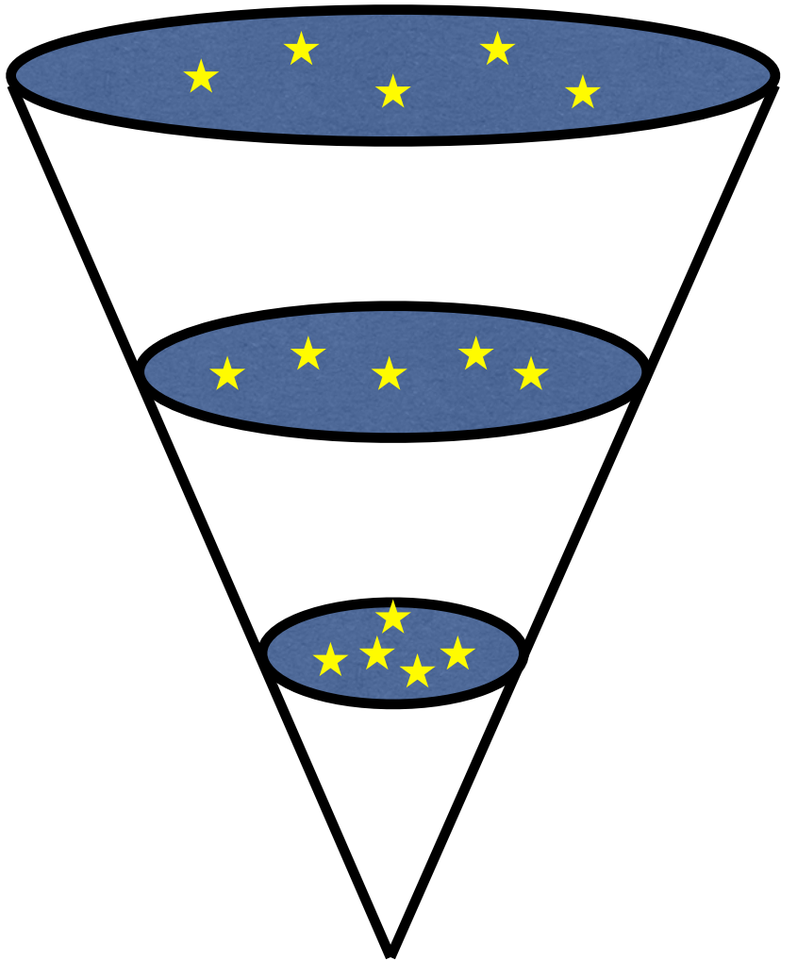


$$t = \frac{1}{H}$$ **The Hubble Time**

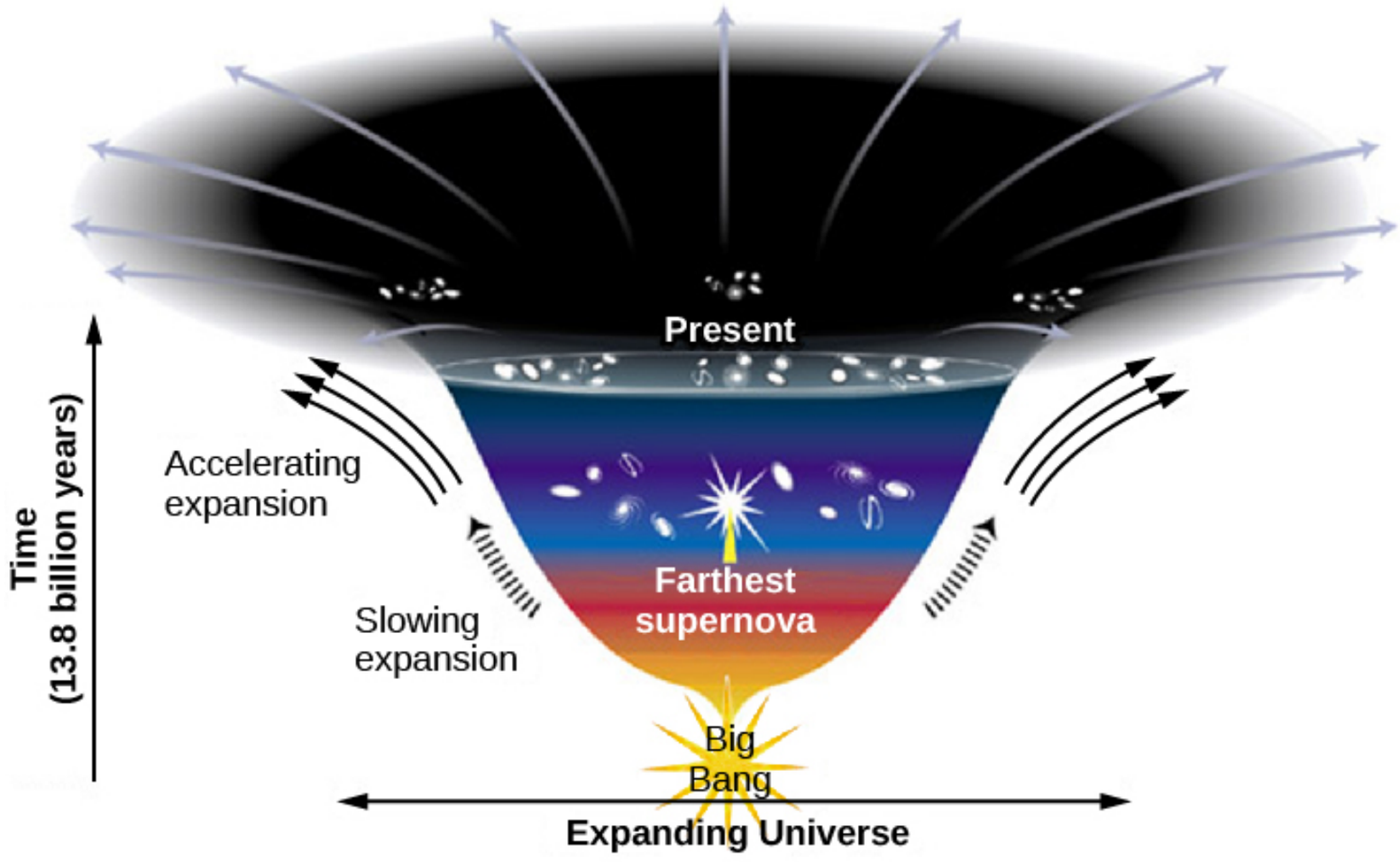
H = 70 km/s/Mpc

$t \approx$ 13 billion years!

But this only applies for a *constant* rate of expansion



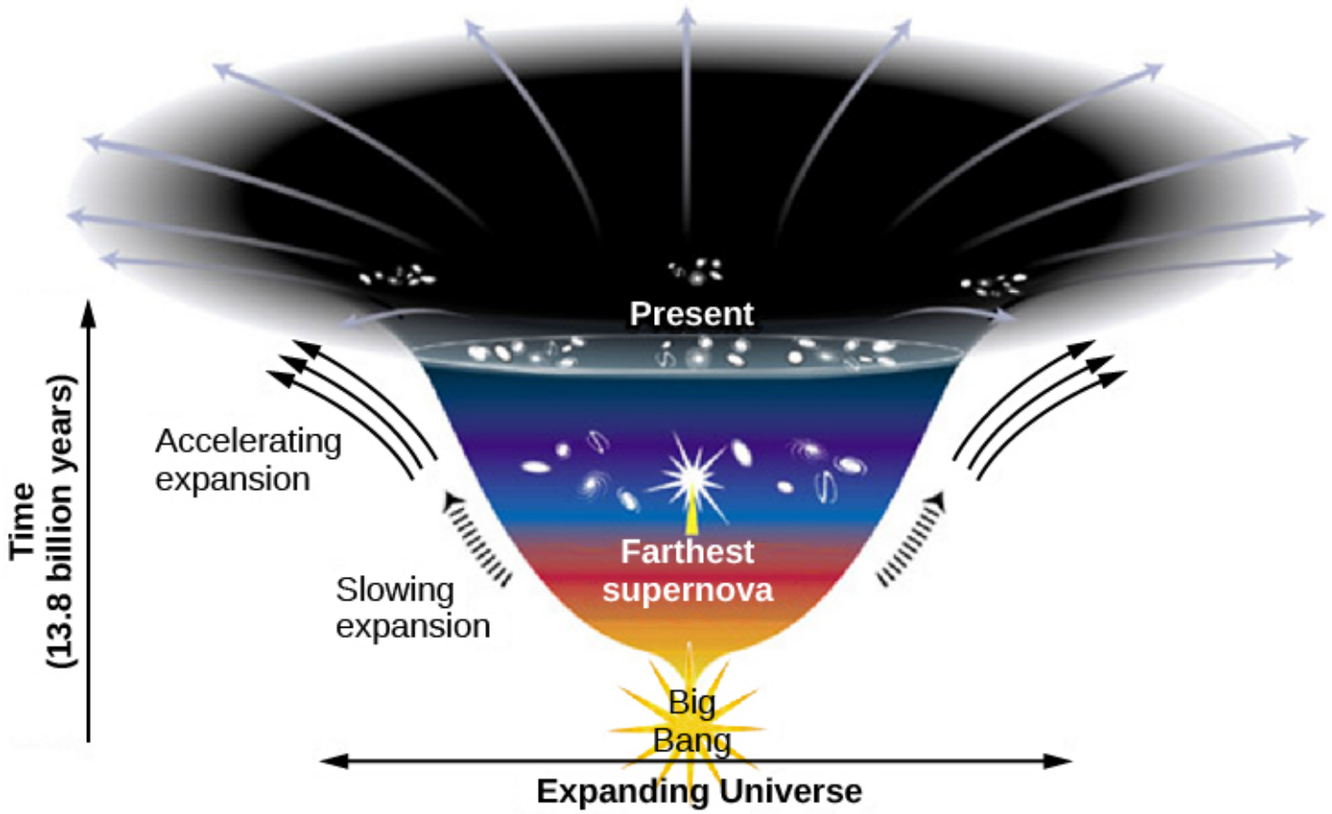
Simple model



More realistic model

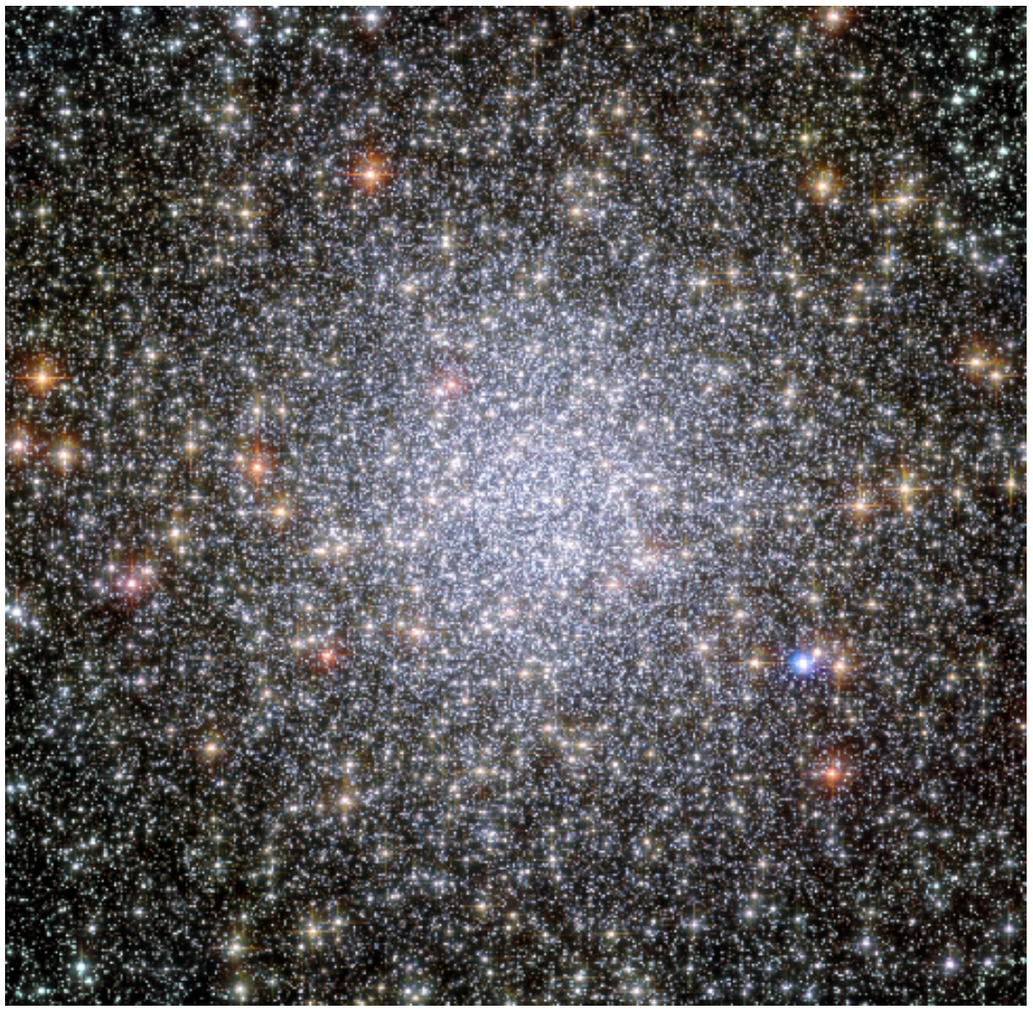
Universe's expansion is actually ***accelerating!!!***

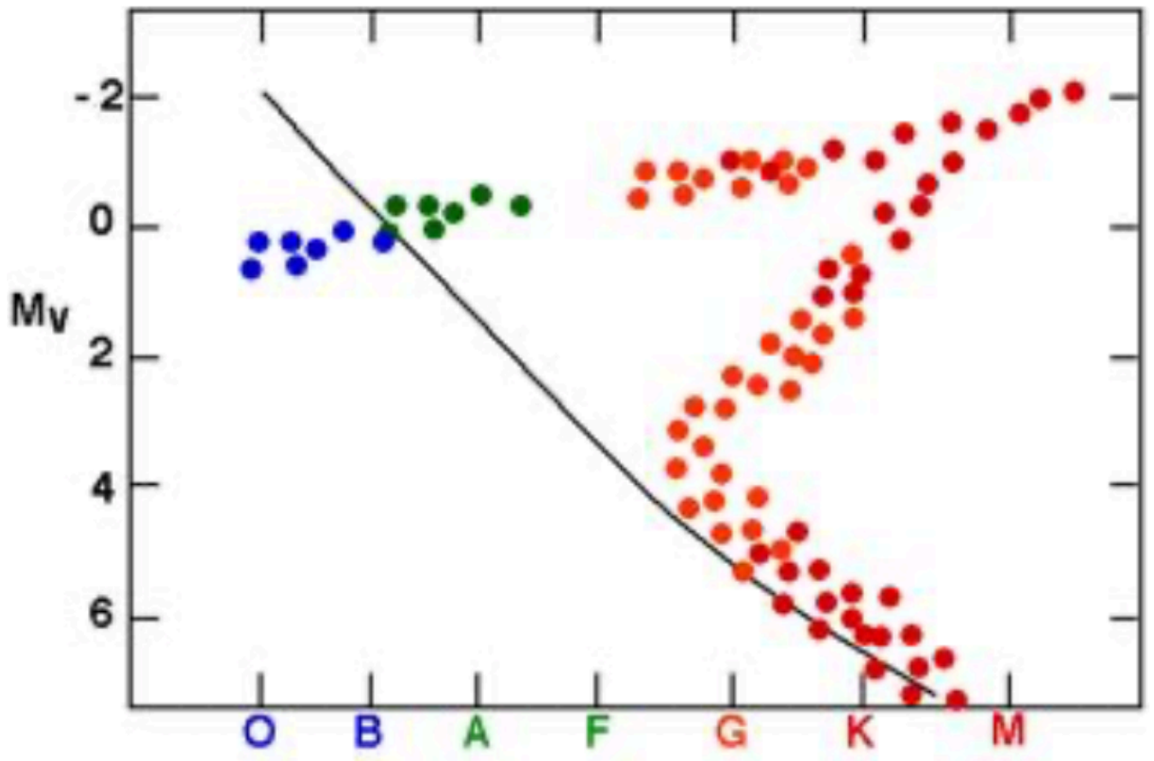
(more on this in Lecture 26)



- **Expansion started to slow down**
- **But "dark energy" eventually starts speeding things up**
- **As a happy coincidence, these factors sort of cancel**
- **Age of the Universe is 13.8 billion years**

The age of the Universe (by looking at the oldest objects)

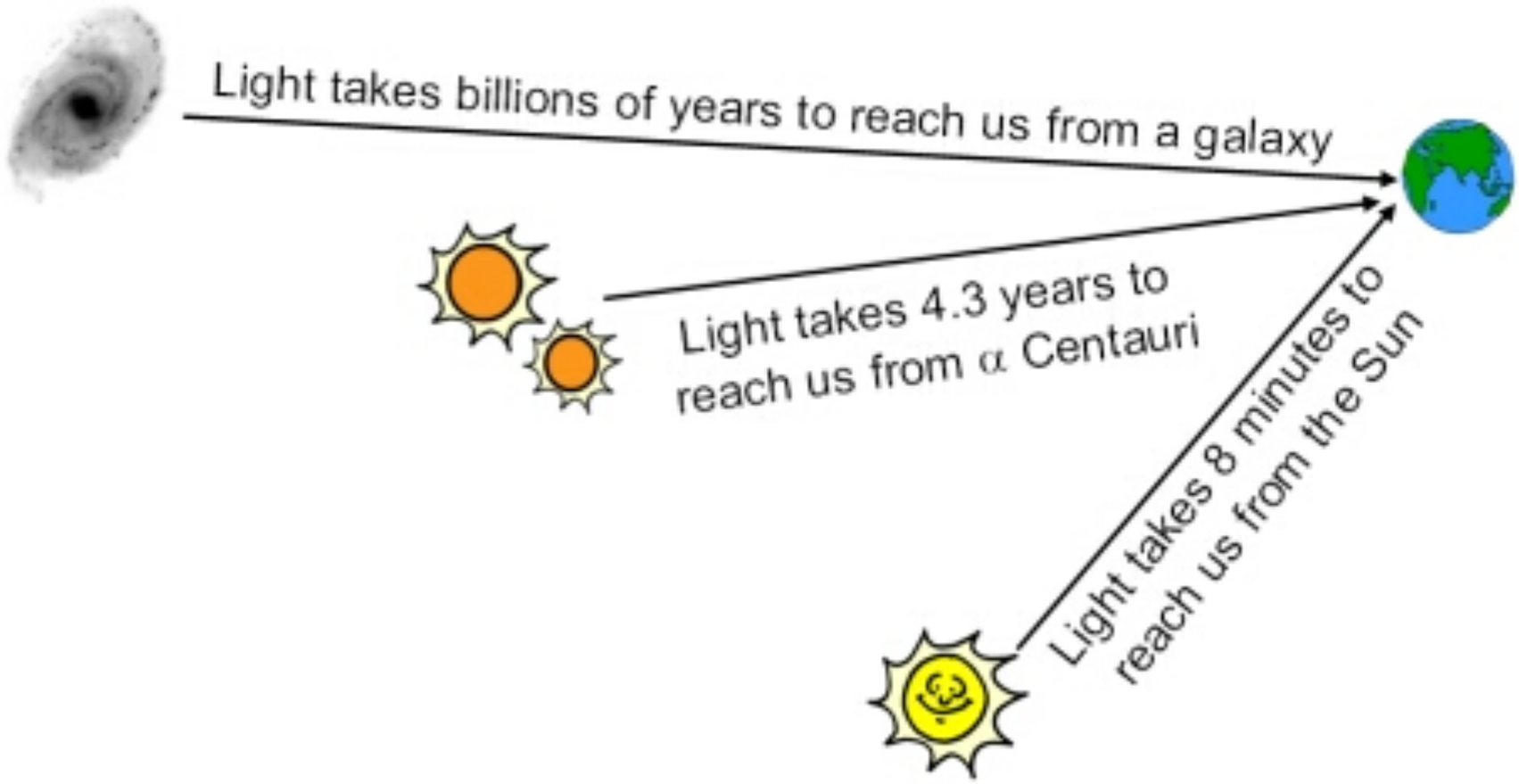




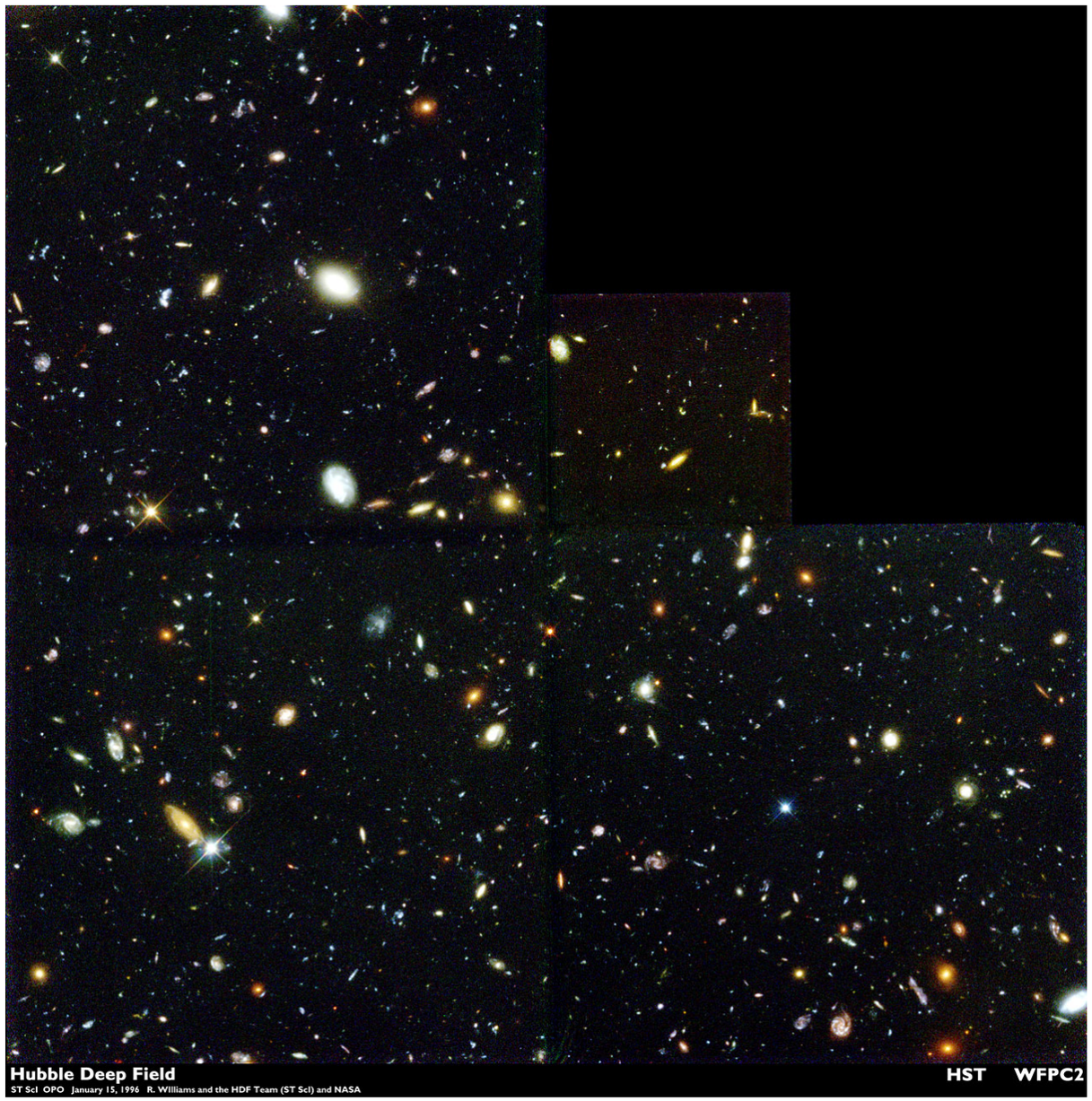
Age of globular clusters: ~13 billion years — consistent!

Looking for hints of the Big Bang (and a review of look back time)

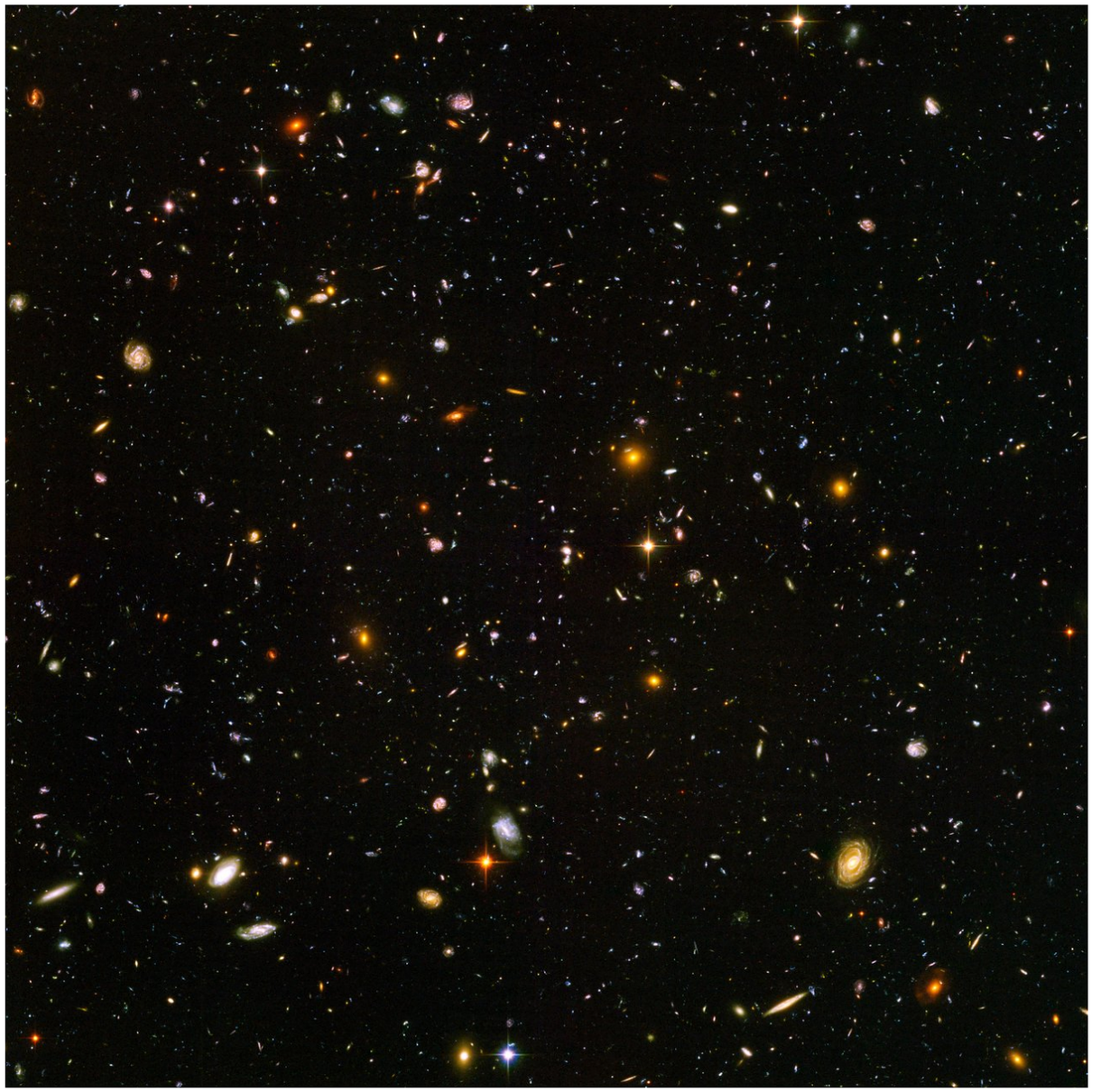
- **More distant galaxies - longer time for light to reach us**
- **We see distant galaxies as they *were* when light left them**



Hubble Deep Fields

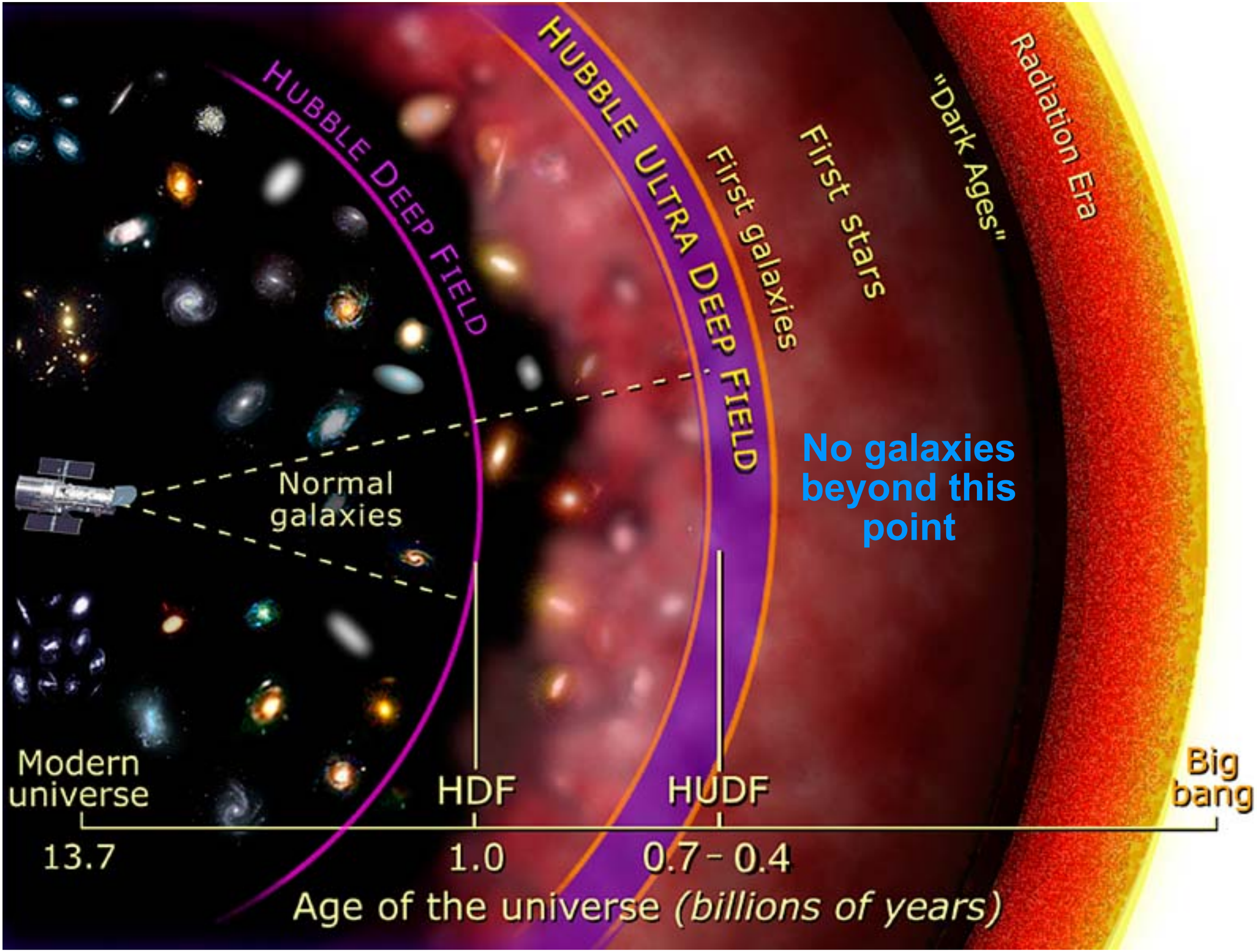


Hubble Deep Field
(500 million years after the Big Bang)

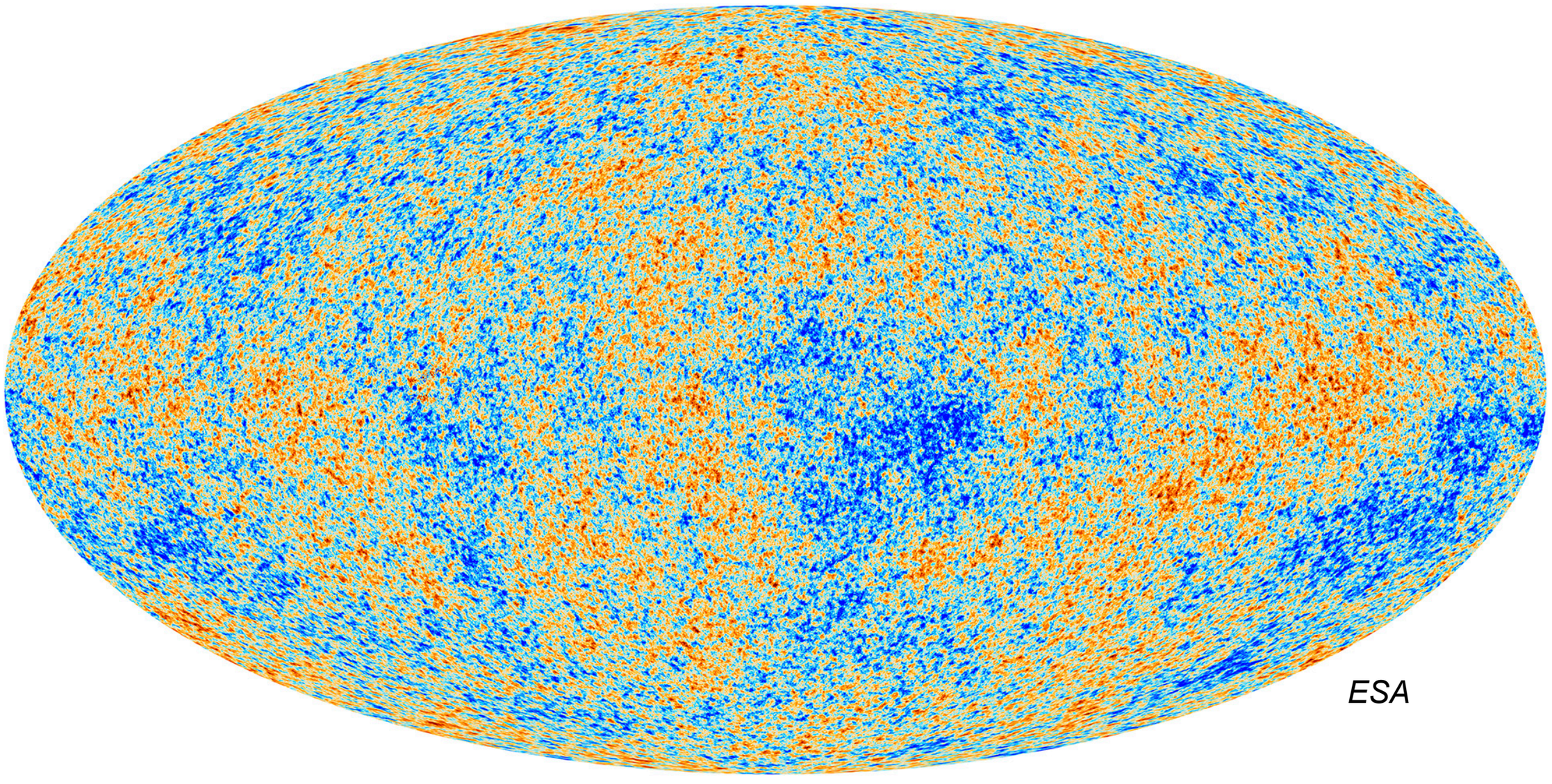


Hubble Ultra Deep Field
The furthest one can see in visible light

Hubble Ultra Deep Field in the IR


HUBBLE DEEP FIELD
HUBBLE ULTRA DEEP FIELD
First galaxies
First stars
"Dark Ages"
Radiation Era
Normal galaxies
No galaxies beyond this point
Modern universe
HDF
HUDF
Big bang
13.7
1.0
0.7 - 0.4
Age of the universe (billions of years)

We can't see all of the way back to the Big Bang, but we can get close!



ESA

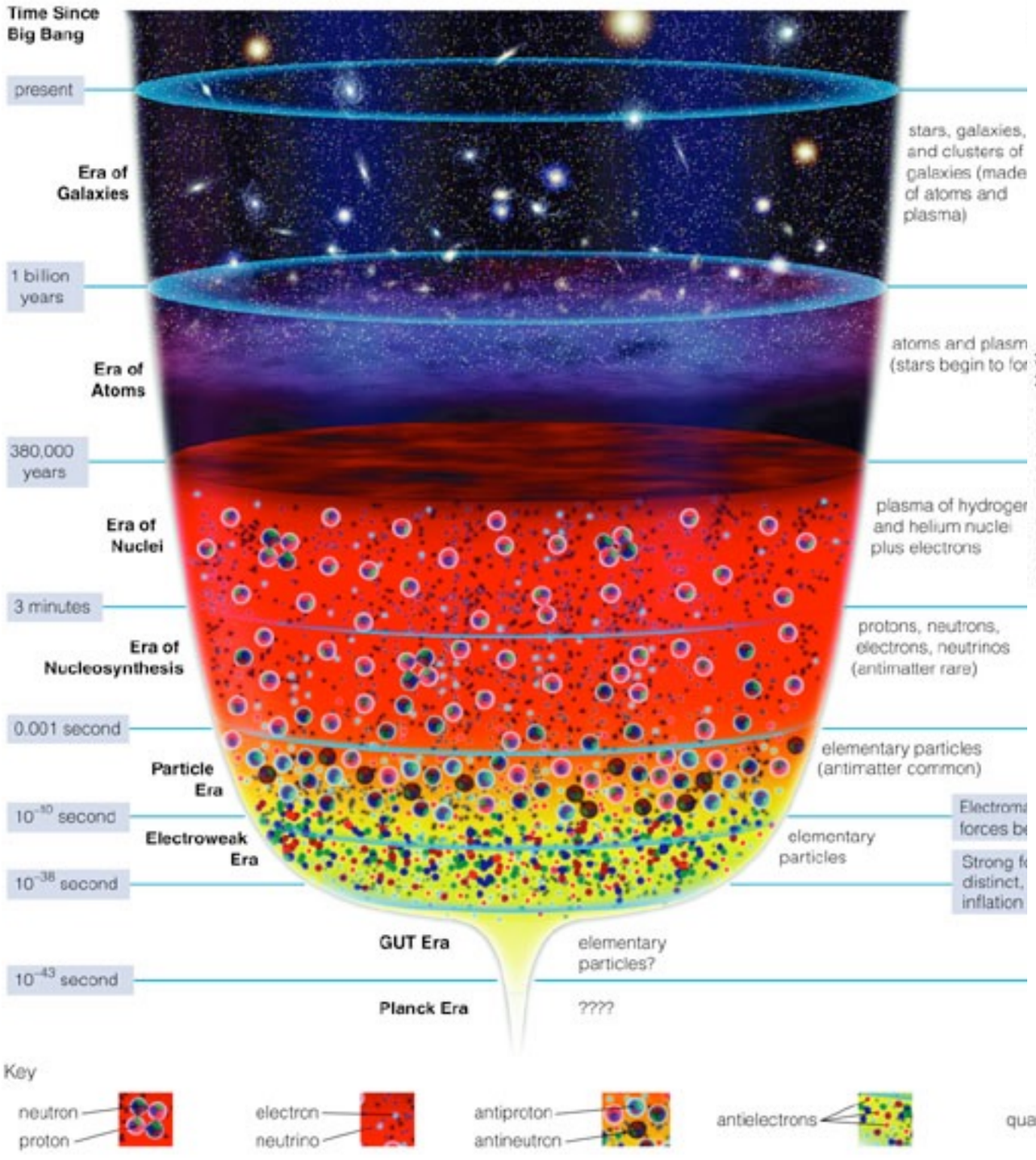
- The universe is only 380,000 years old (a baby!)
- Redshifted into the microwave part of the spectrum by expansion
- Called Cosmic Microwave Background (CMB)

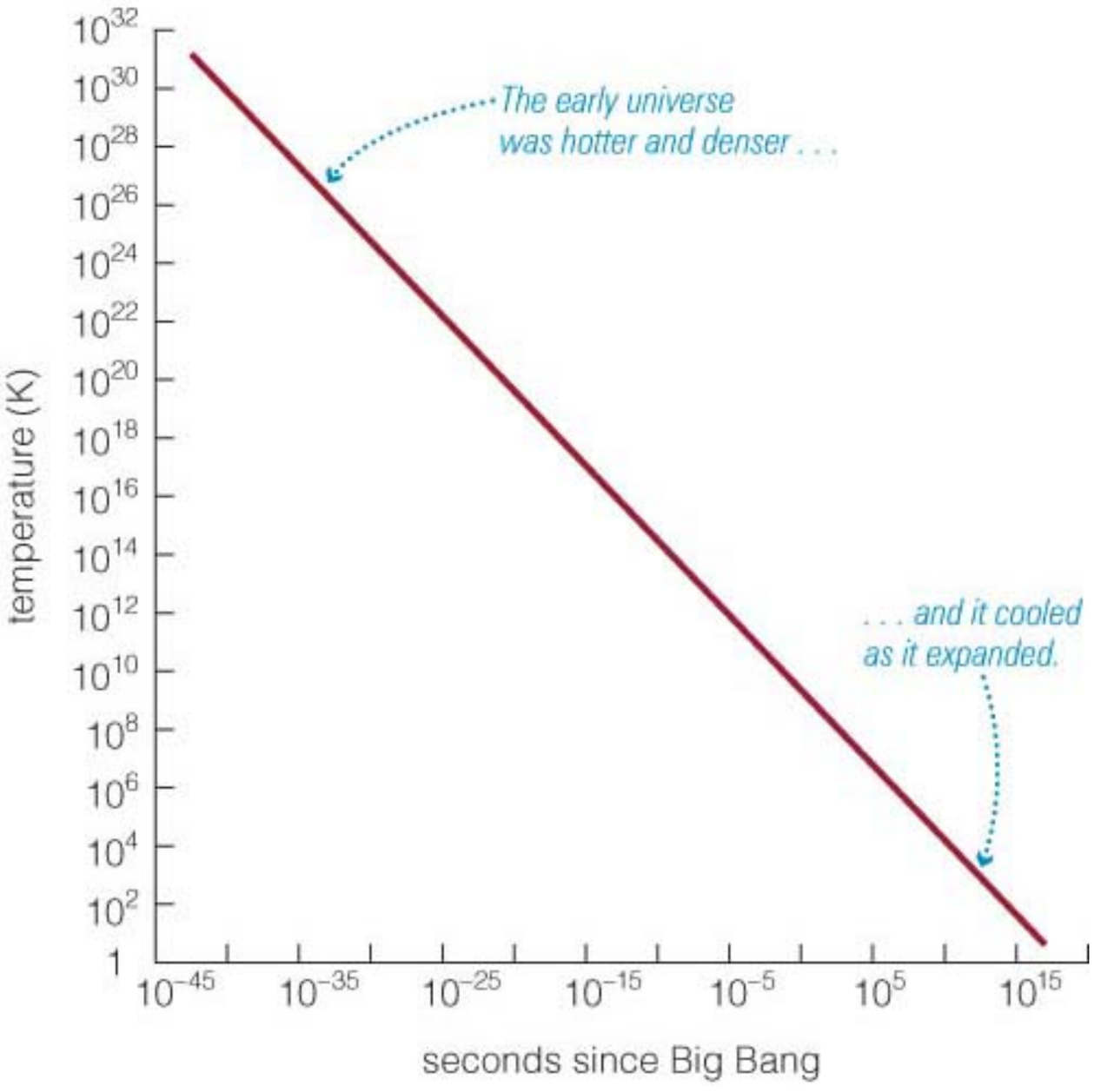
Is there an "edge" to the Universe?

- **Olbers' Paradox**
  - assume: infinite Universe
  - assume: uniform distribution of matter (on large scales)
  - consequence: all lines of sight end on a star
  - consequence: whole sky should be as bright as the Sun
  - Dark night sky ——> Universe has an "edge"

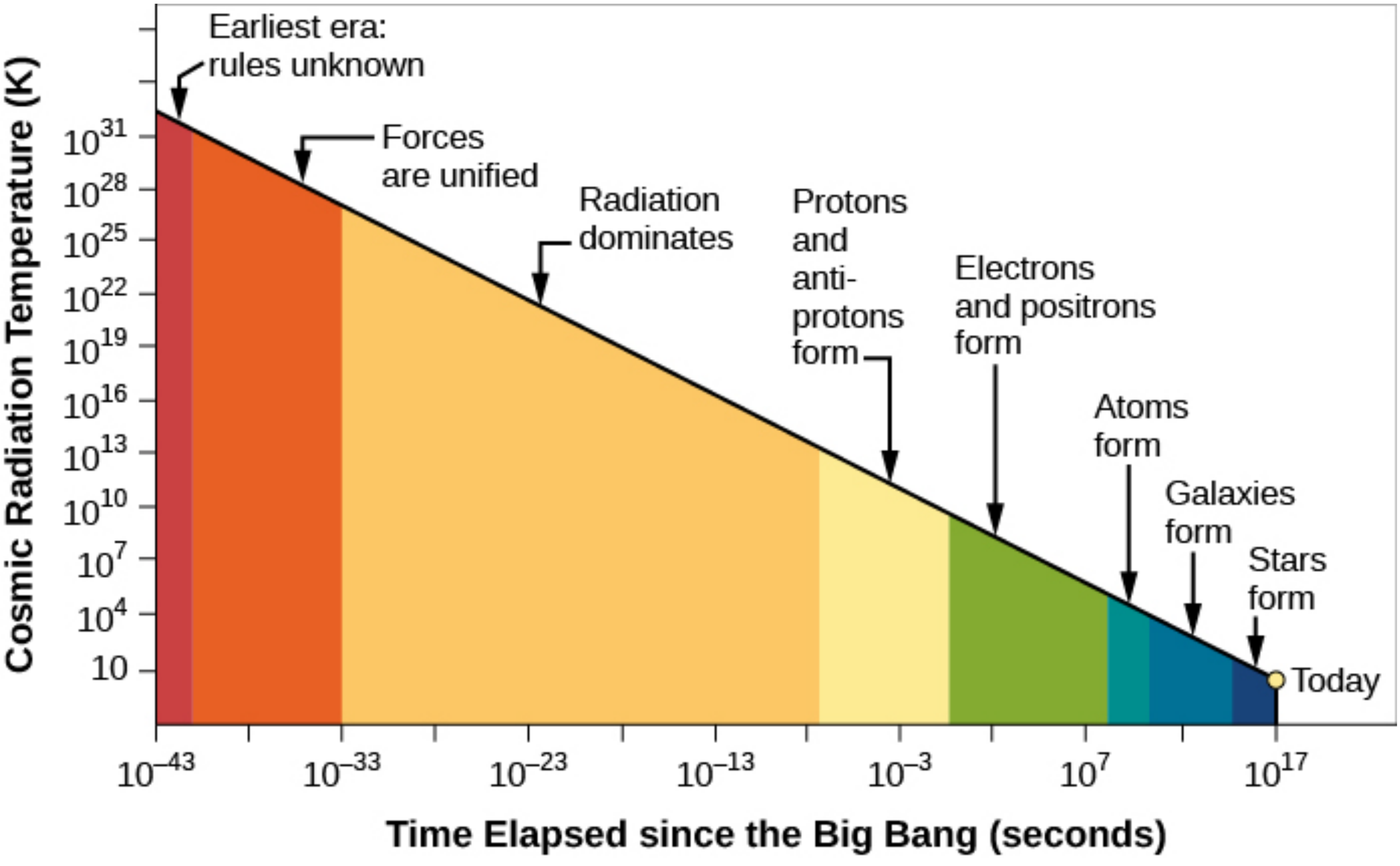
- **The Edge (or Horizon)**
  - back in space = back in time
  - beyond ~14 billion light years → no stars
  - is this a physical edge? No
  - viewed from anywhere, R_{univ} = 14 billion ly

The Universe was hotter in the past

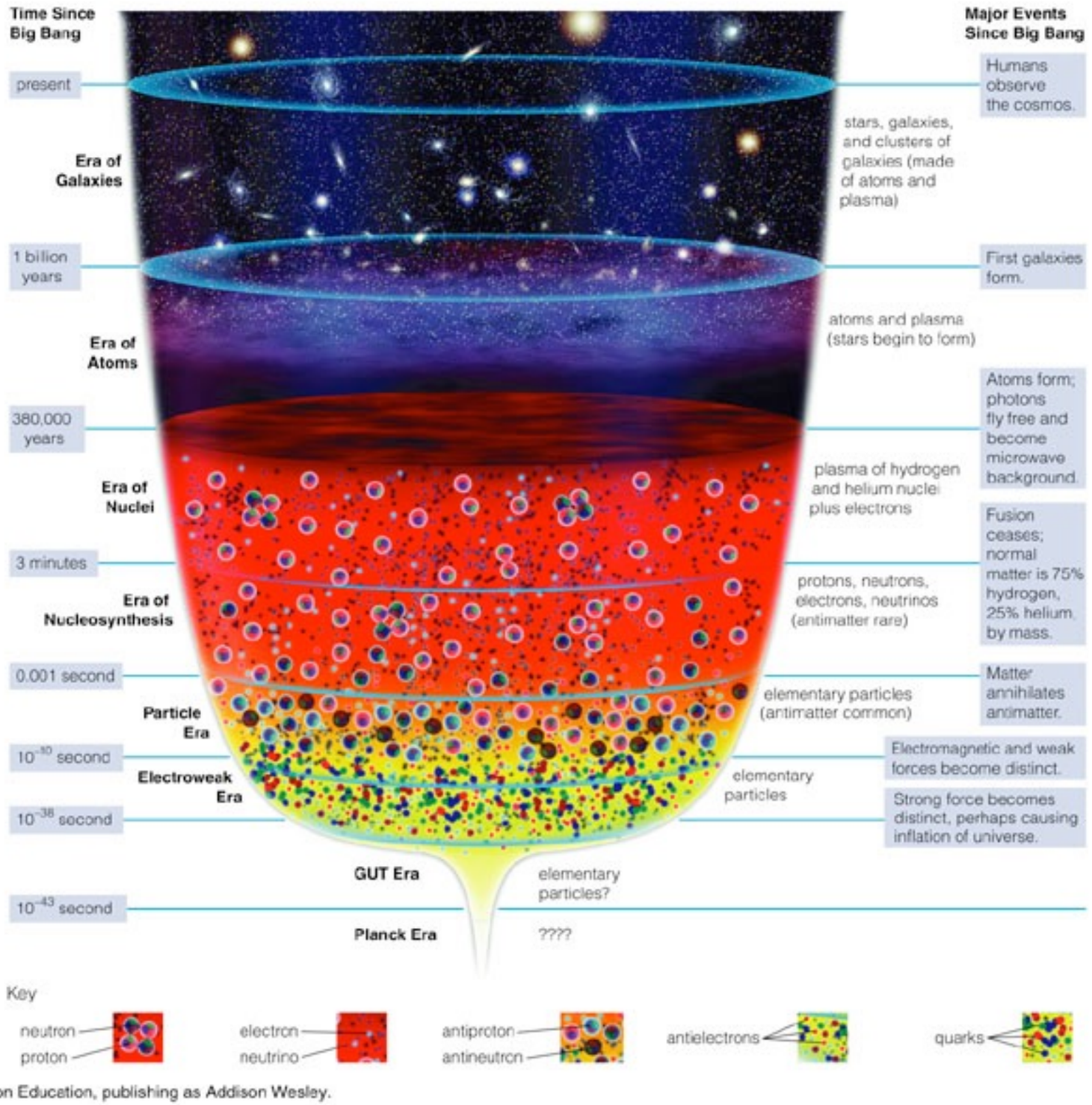


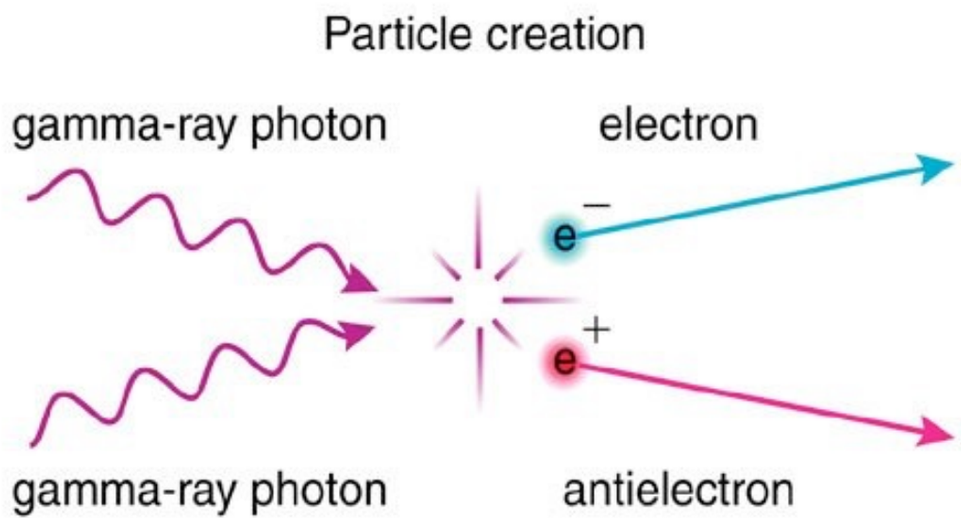


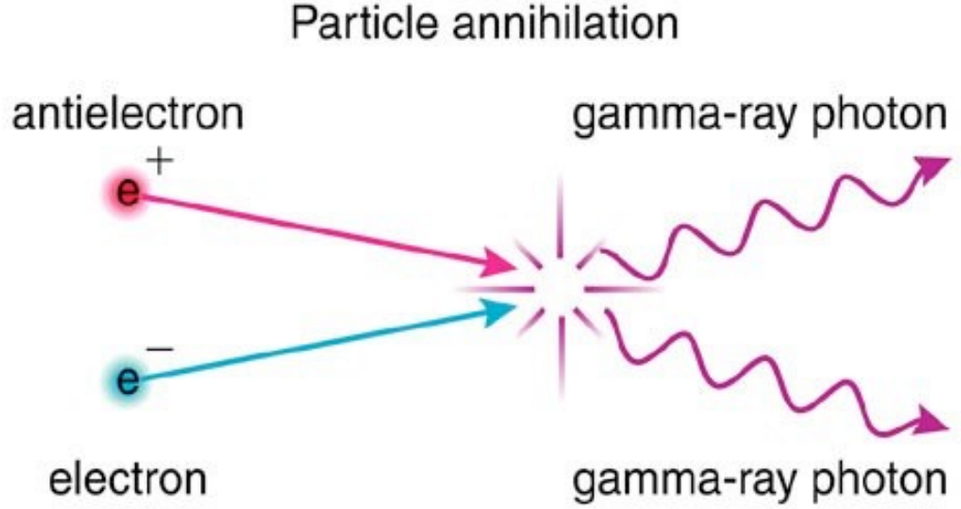
The Universe was hotter in the past



The very hot very early Universe







Energy (radiation) and mass were in equilibrium

Testing the Big Bang Idea

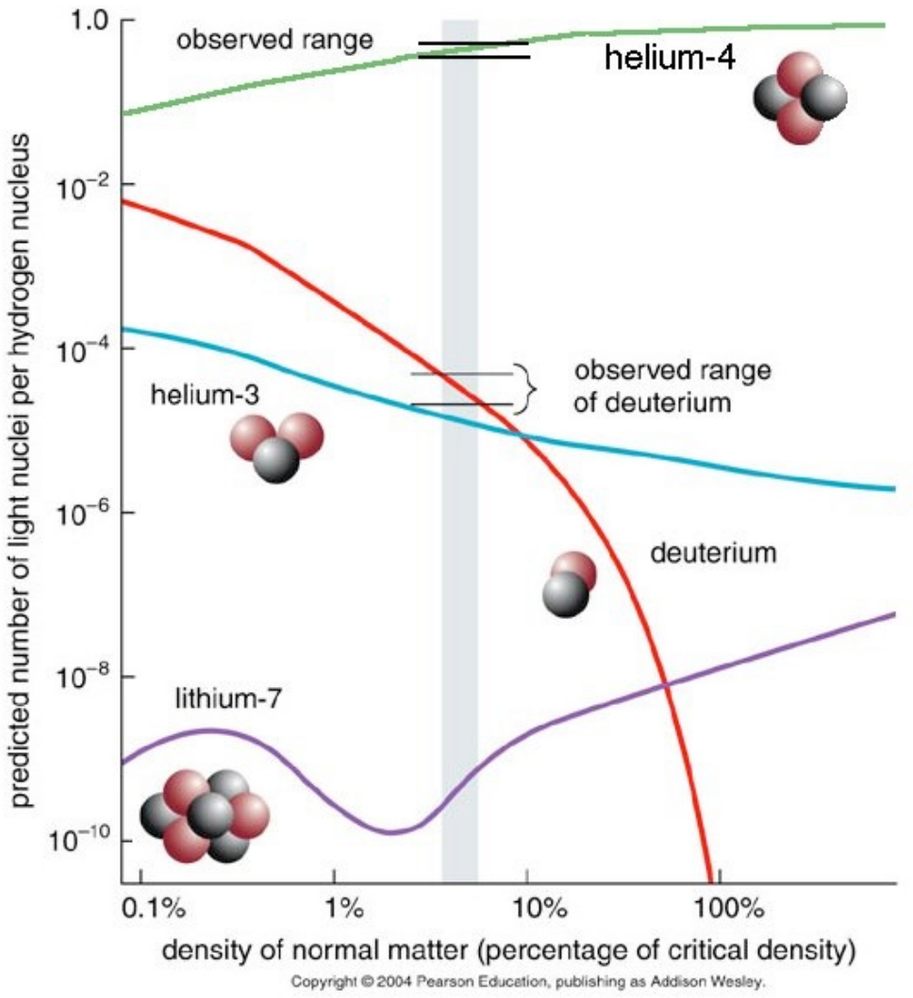
- **Big Bang Nucleosynthesis**
  - production of light elements in the early Universe

- **Remnant radiation from primeval fireball**
  - universal background radiation

- **Origin of Cosmic Structures**
  - formation of galaxies and huge superclusters in an expanding Universe

Big Bang Nucleosynthesis

- **Earliest minutes**
  - H, deuterium
  - He^3, He^4
- **Expansion and cooling**
  - halts further fusion
- **net Big Bang production**
  - ~ 75% Hydrogen
  - ~ 25% Helium
  - < 0.1% lithium, beryllium, etc.
- **Matches composition of the oldest stars!**



Testing the Big Bang Idea

☑ Big Bang Nucleosynthesis

- production of light elements in the early Universe

• Remnant radiation from primeval fireball

- universal background radiation

• Origin of Cosmic Structures

- formation of galaxies and huge superclusters in an expanding Universe