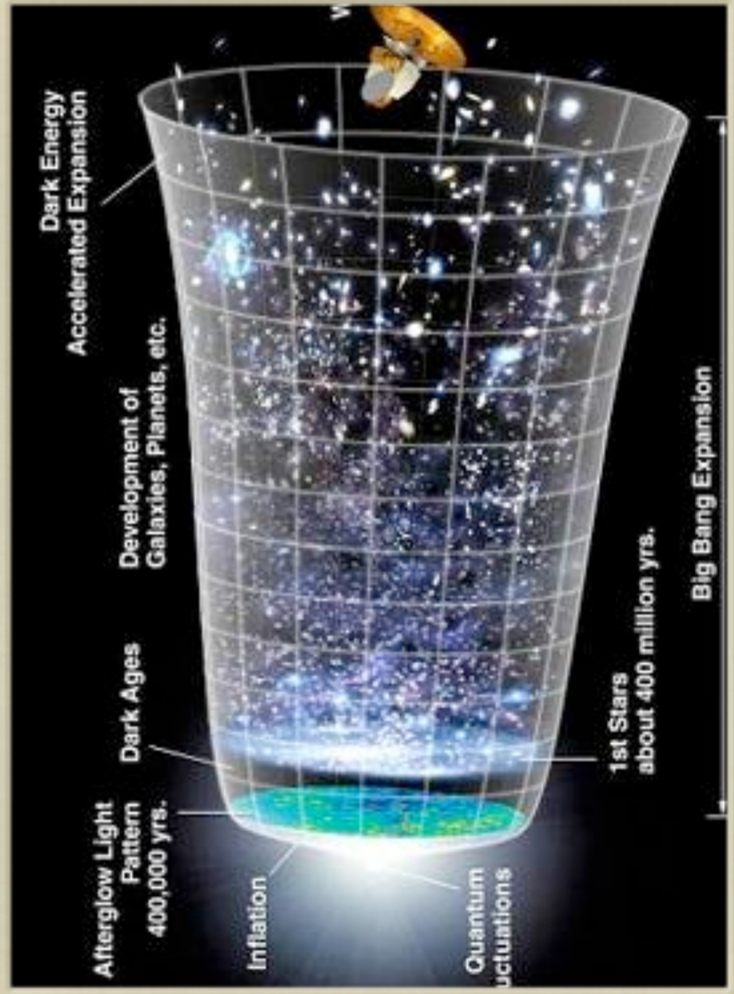
Today

- Modern Cosmology
  - The Hot Big Bang
    - Age & Fate
    - Density and Geometry
    - Microwave Background



Course Evaluations Open

Cosmology

- The study of the universe as a physical system

Historically, people have always asked the big questions - and made up lots of answers.

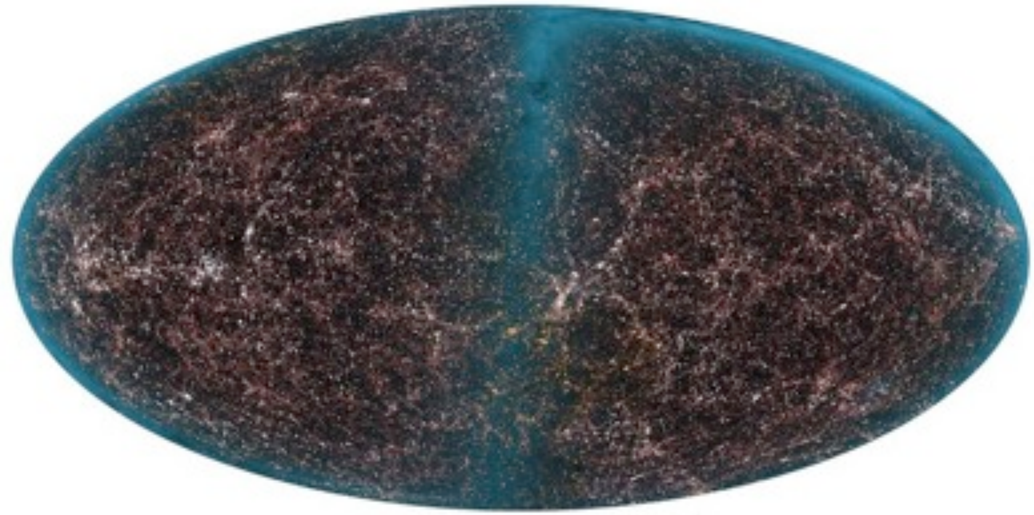
Ancient Cosmology: A Flat Earth

Here there be dragons!

World Map of Hecataeus of Miletus (c. 500 BC)

The Cosmological Principle

- The Universe is
  - Homogeneous
  - Isotropic

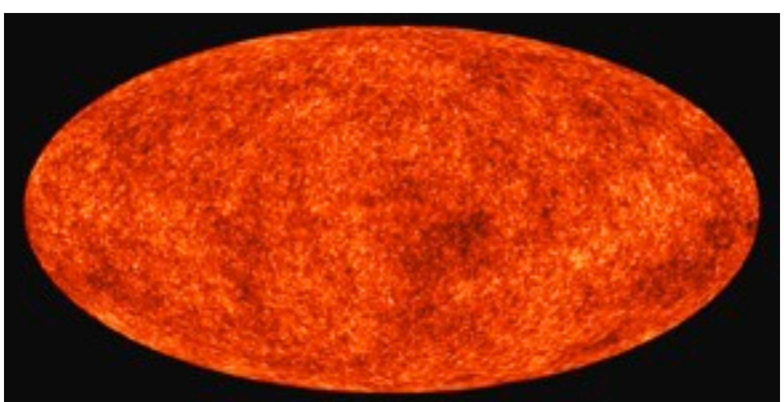


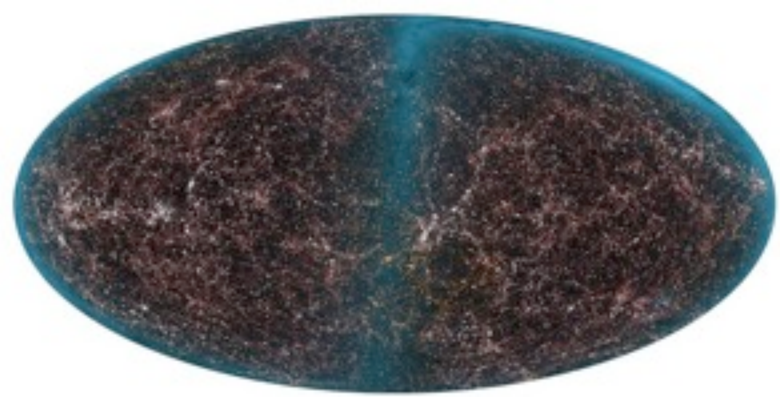
A philosophical assertion that there should be nothing special about where we are, so the universe should look much the same to an distant alien observer as to us.

The Perfect Cosmological Principle

- The universe looks the same from everywhere at all times.

This is a logical extension of the Cosmological Principle in time as well as space. Trouble is, it is **not true**.





Elements of Modern Cosmology

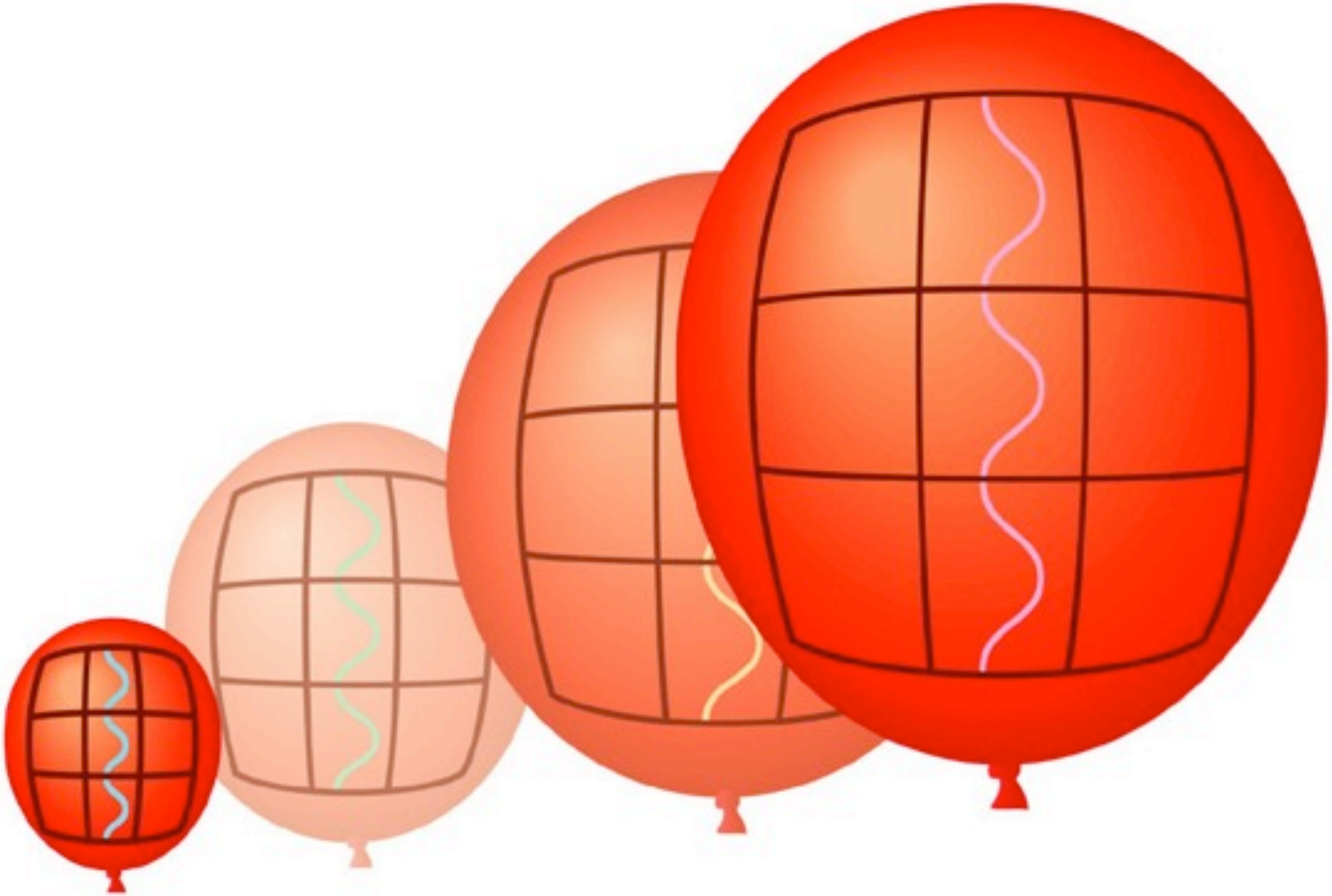
1. Expanding Universe ✓
2. Finite Age ✓
3. Density & Geometry ✓
4. Thermal History ✓
5. Big Bang Nucleosynthesis ✓
6. Dark Matter ?
7. Dark Energy ?

1. Expanding Universe

- Hubble Law

$$V = H_0 d$$

Naturally explained by expansion of space.
The more distant a galaxy, the faster it appears to recede.
The fabric of the intervening space gets stretched with time.



Expansion stretches photon wavelengths causing the ***cosmological redshift***: stretching of space, *not* explosion.

$$V = H_0 d$$

Expansion Age

$$\text{Age} \approx \frac{1}{H_0} \approx 13 \times 10^9 \text{ years}$$

13 billion years is a very long time
- but not forever

Consistent with

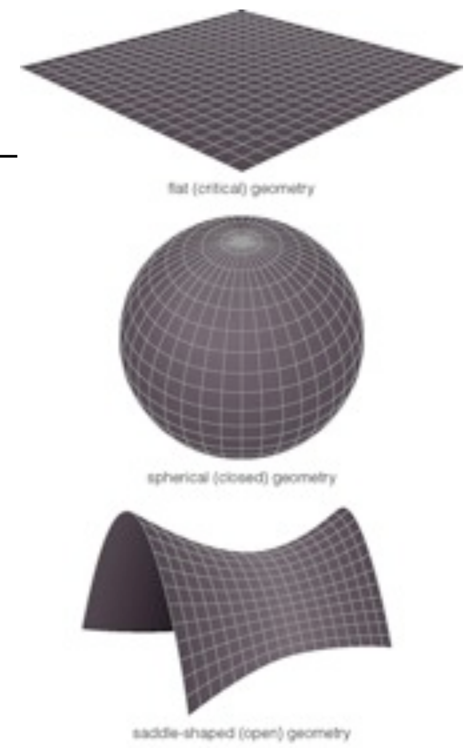
- ✦ Globular Cluster ages
- ✦ White Dwarf cooling times
- ✦ Radioactive decay
- ✦ Dust grain isotopic compositions

} All give about the same age

3. Mass, geometry, and fate

- Gravity dominates the cosmos:
- Density — Ω
- Geometry ———————————
- Fate

expand forever
or recollapse?

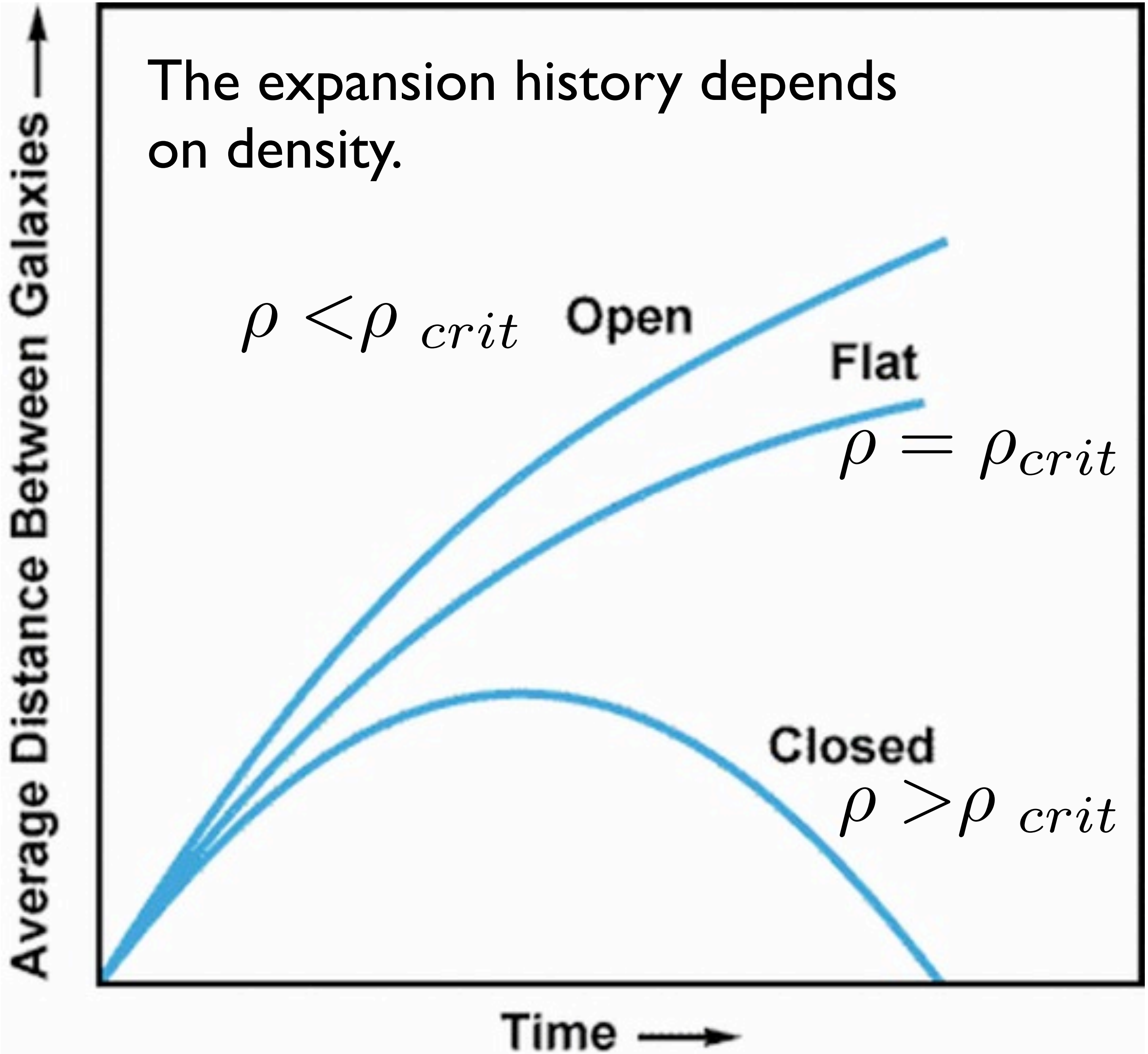


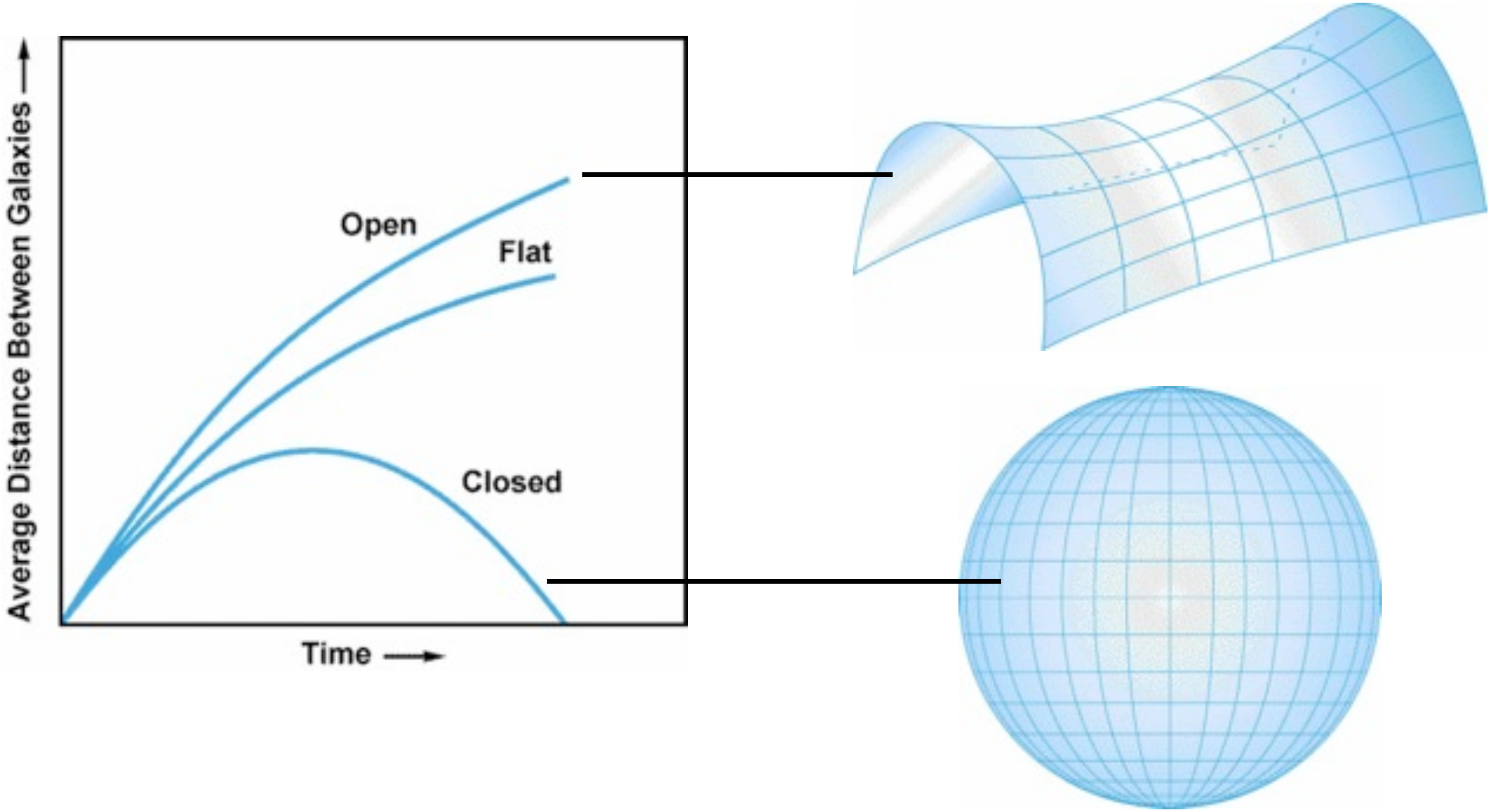
The expansion started by the Big Bang
is resisted by the attraction of gravity.

The more dense the universe, the more gravity...
a balance is reached at a critical density:

IF	the universe is
$\rho < \rho_{crit}$	OPEN: expands forever
$\rho = \rho_{crit}$	FLAT
$\rho > \rho_{crit}$	CLOSED: eventually recollapses

The expansion history depends on density.

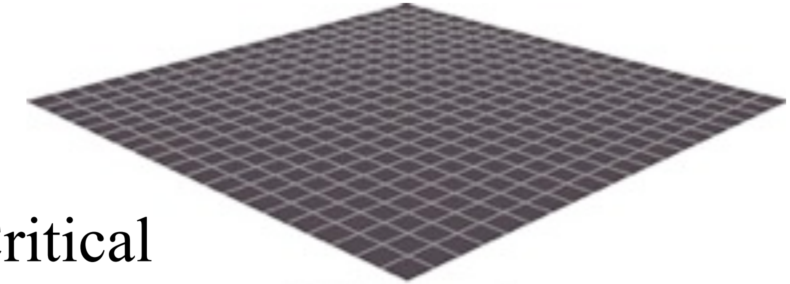




The expansion history and the geometry of the universe are both related to the density. Space can be "curved."

FLAT

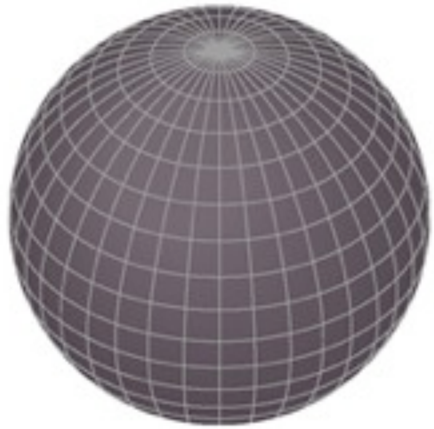
Density = Critical



flat (critical) geometry

CLOSED

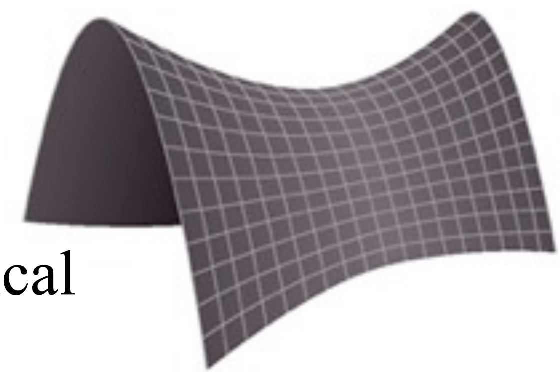
Density > Critical



spherical (closed) geometry

OPEN

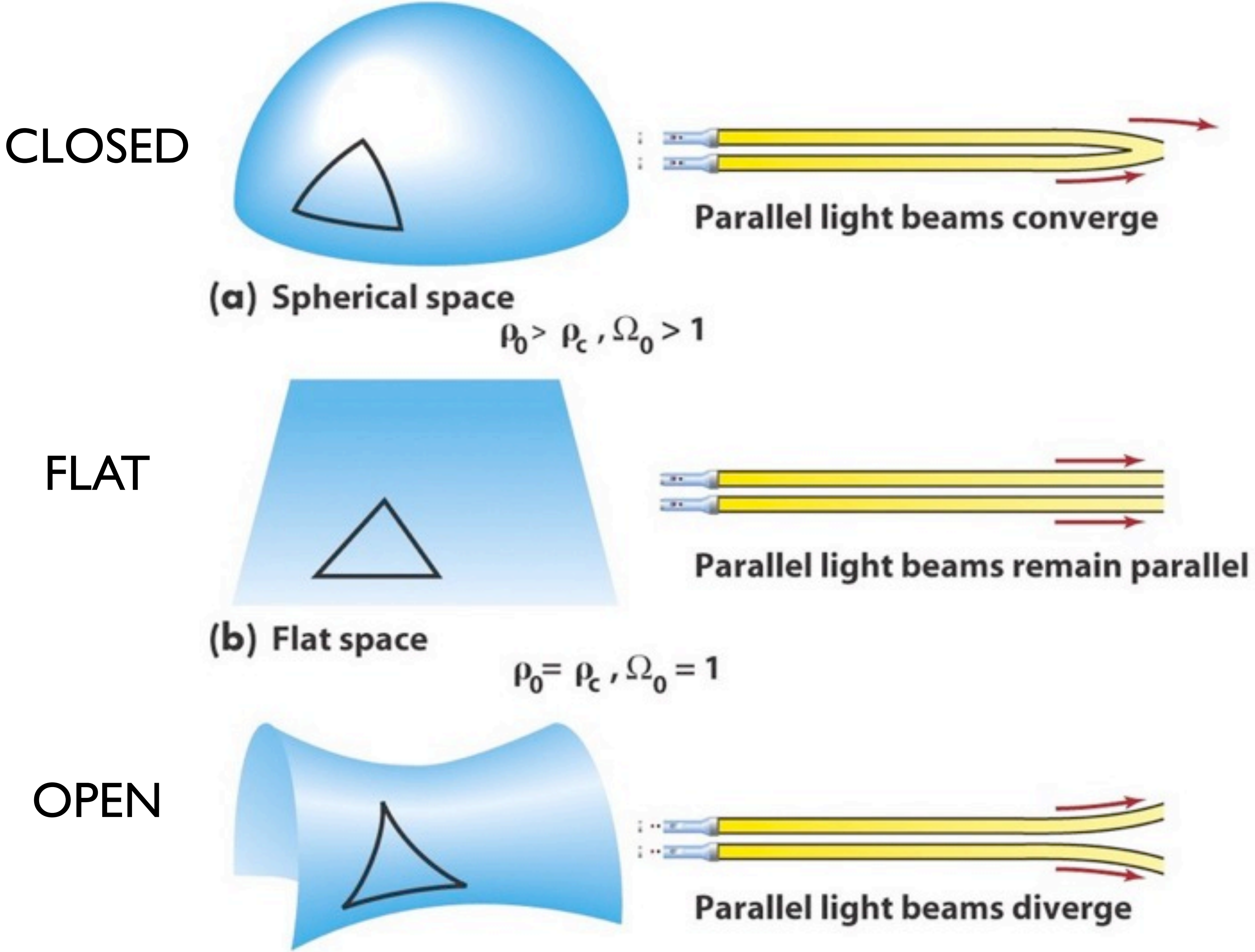
Density < Critical



saddle-shaped (open) geometry

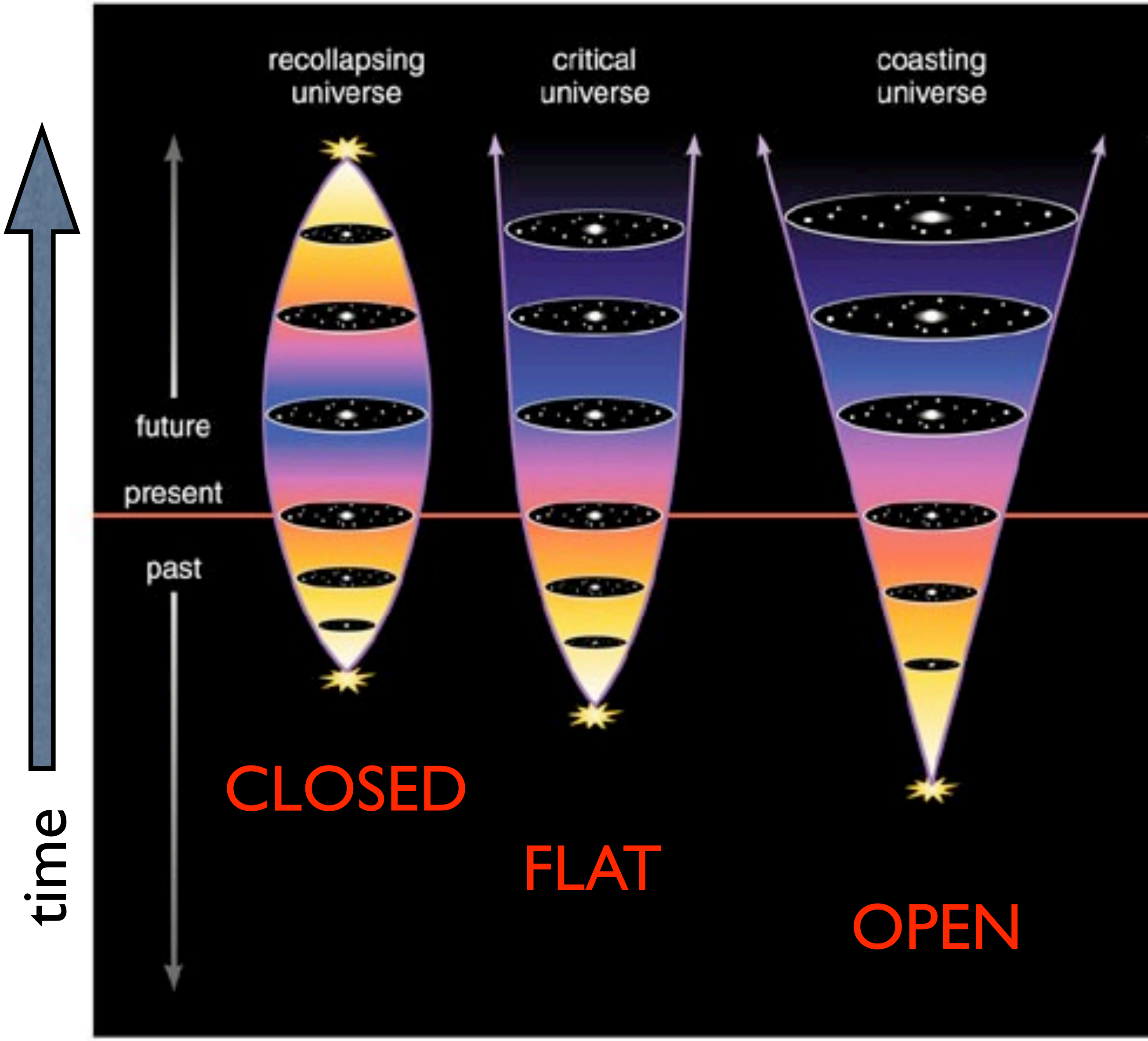
Space can be curved.

The overall geometry of the universe is determined by the total density of matter and energy.


CLOSED
Parallel light beams converge
(a) Spherical space
$\rho_0 > \rho_c$, $\Omega_0 > 1$
FLAT
Parallel light beams remain parallel
(b) Flat space
$\rho_0 = \rho_c$, $\Omega_0 = 1$
OPEN
Parallel light beams diverge

Density is destiny

It determines the age, geometry, and ultimate fate of the universe

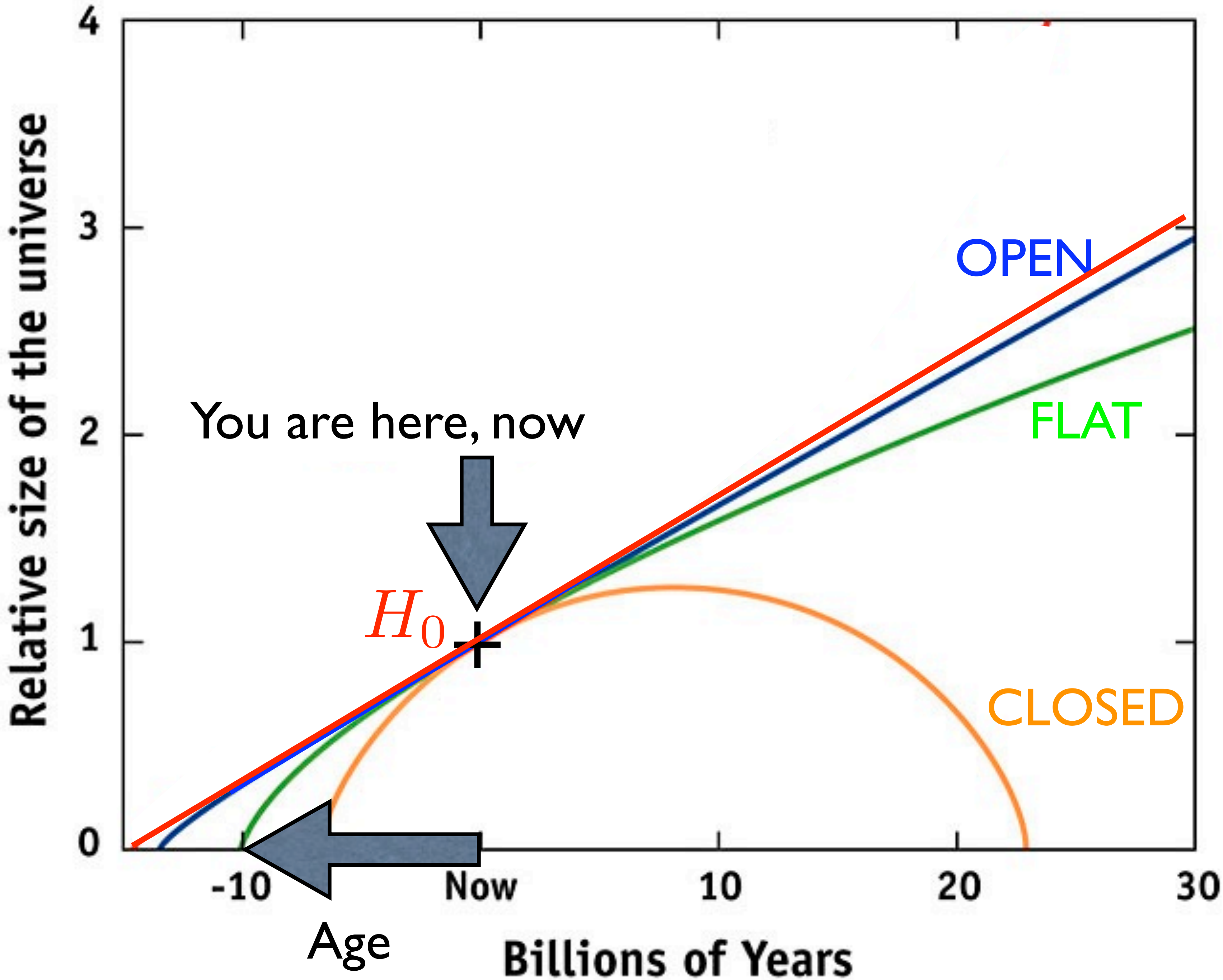


Cosmology often phrases the density in terms of the critical value - the density parameter, "Omega"

$$\rho_{crit} = \frac{3H_0^2}{8\pi G}$$

$$\Omega = \frac{\rho}{\rho_{crit}}$$

$\Omega < 1$	OPEN	eternal expansion
$\Omega = 1$	FLAT	
$\Omega > 1$	CLOSED	eventual recollapse



Relative size of the universe
4
3
2
1
0
-10
Now
10
20
30
Billions of Years
OPEN
FLAT
CLOSED
You are here, now
H_0
Age

Age Problem ?

- If $\Omega \approx 0$ $\text{Age} = \dfrac{1}{H_0}$

- If $\Omega = 1$ $\text{Age} = \dfrac{2}{3H_0}$

The modern value of the Hubble constant, as measured by the Hubble Space Telescope, is

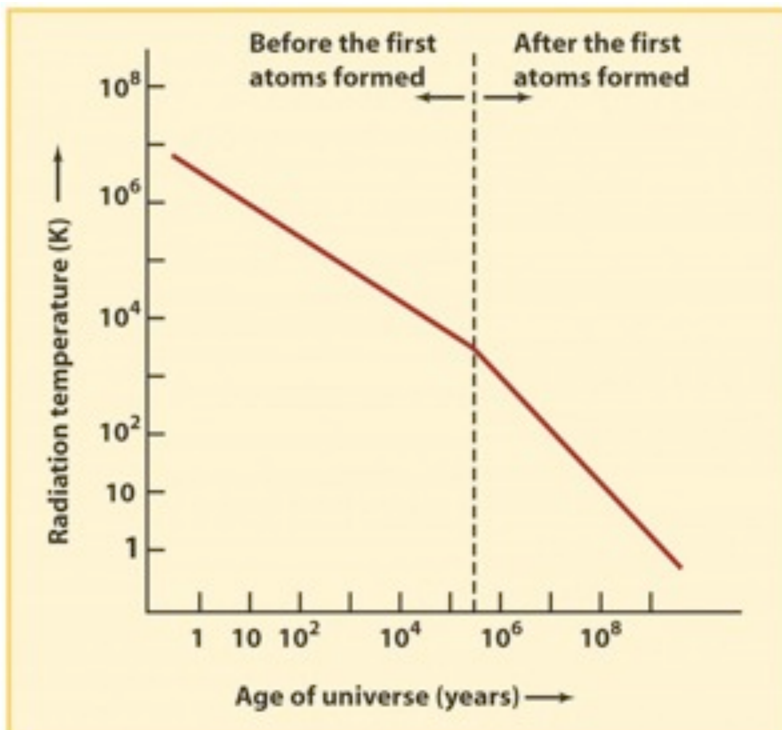
$$H_0 = 72\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$$

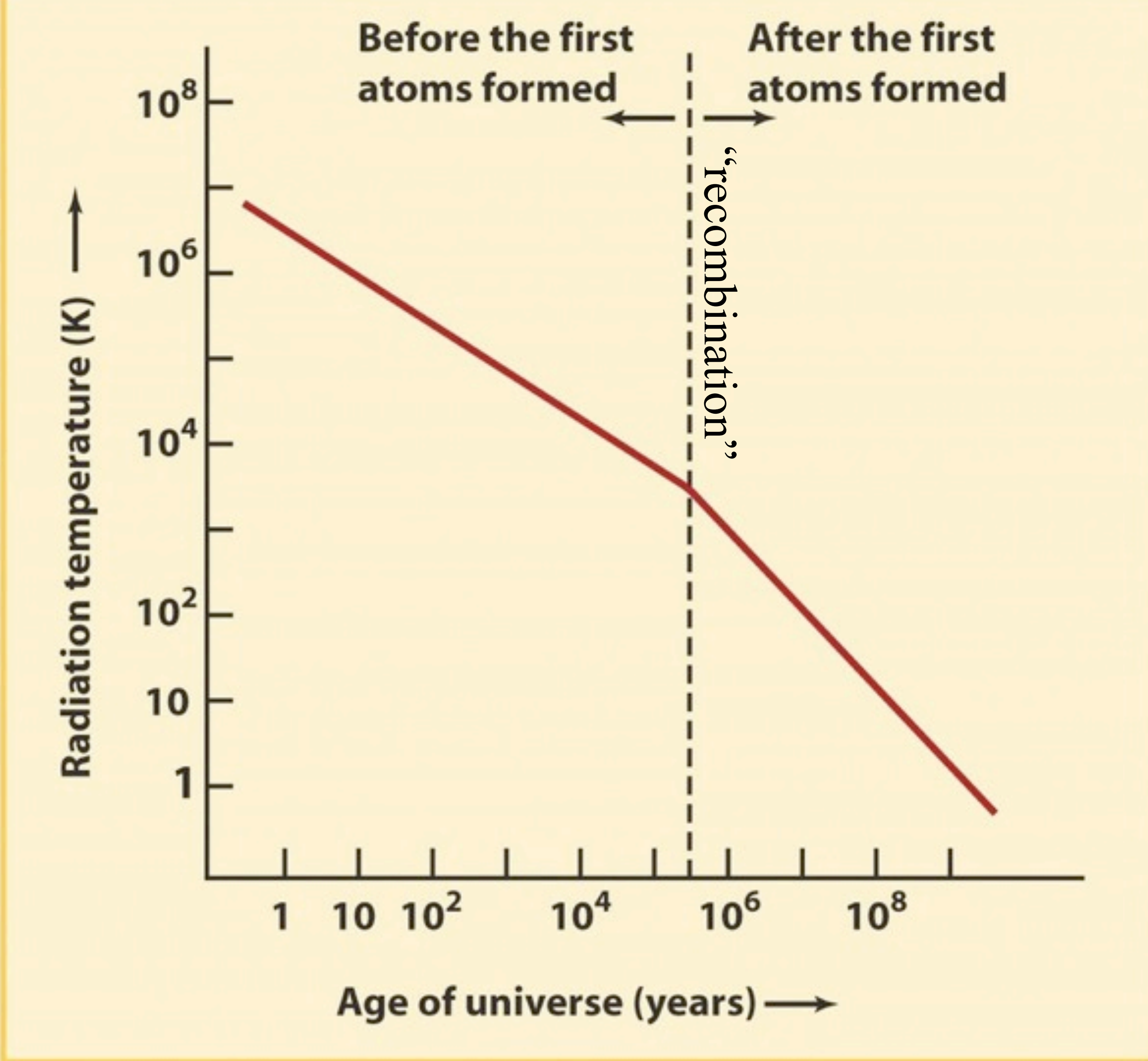
Ω	Age
0	13.5 Gyr
1	9 Gyr

Oldest stars about 13 Gyr

4. Thermal History

- The universe started off very hot (hence the "hot big bang") and cools as it expands

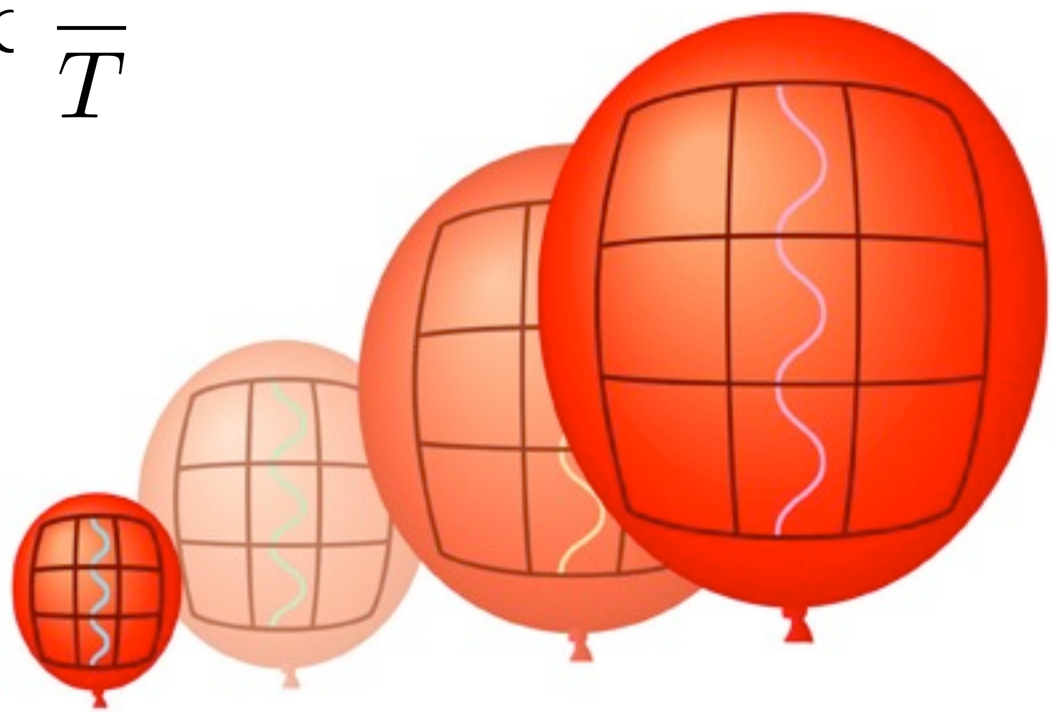



Before the first atoms formed
After the first atoms formed
"recombination"
Radiation temperature (K)
10^8
10^6
10^4
10^2
10
1
1
10
10^2
10^4
10^6
10^8
Age of universe (years)

Cooling is a consequence of expansion.

The wavelengths of photons get stretched as the universe expands. Longer wavelengths mean lower temperature (Wien's Law).

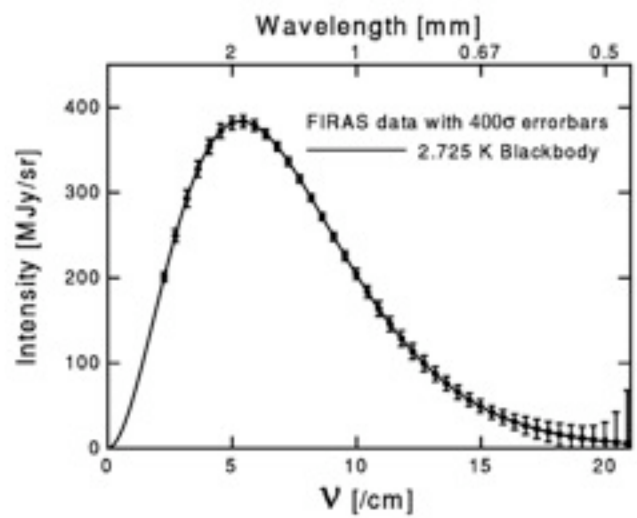
$$\lambda \propto \frac{1}{T}$$



The universe is pervaded by the residual glow of the hot big bang.

We observe this as the
cosmic microwave background.

This radiation is seen in all directions on the sky with a nearly perfect thermal spectrum. The expansion of the universe has cooled it to a mere **2.7 K**.



Relic Radiation Field:

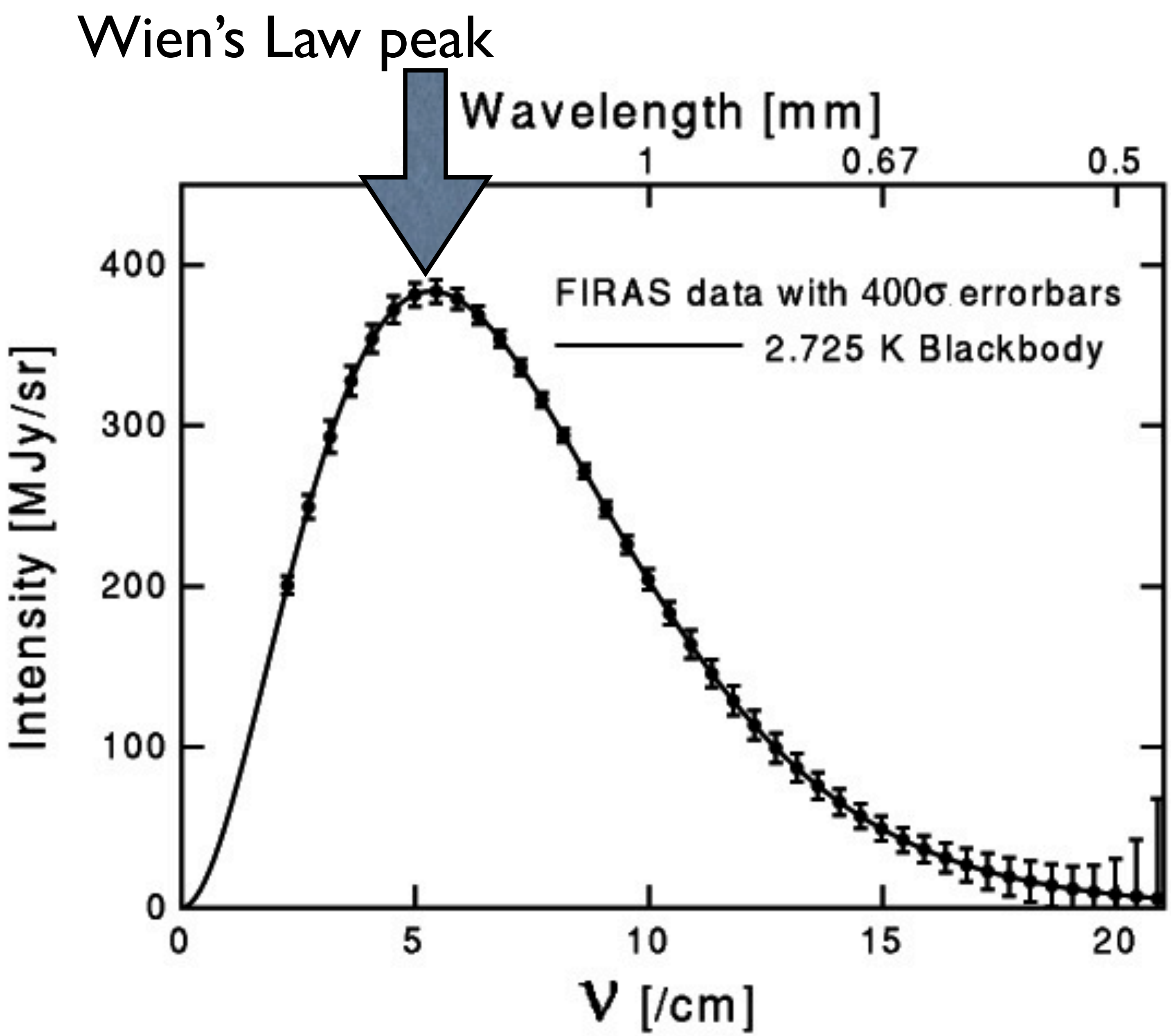
The residual heat of the Big Bang should leave an echo - a relic glow of the cosmic fireball.

This was discovered in 1963; now called the Cosmic Microwave Background (CMB)

Wilson Penzias

Nobel Prize

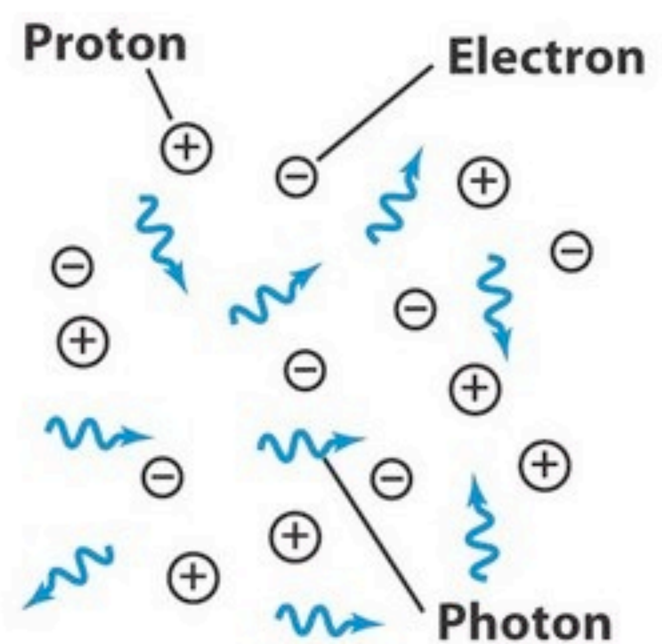
Weren't specifically looking for the CMB; just trying to make a clean, pigeon-free microwave receiver



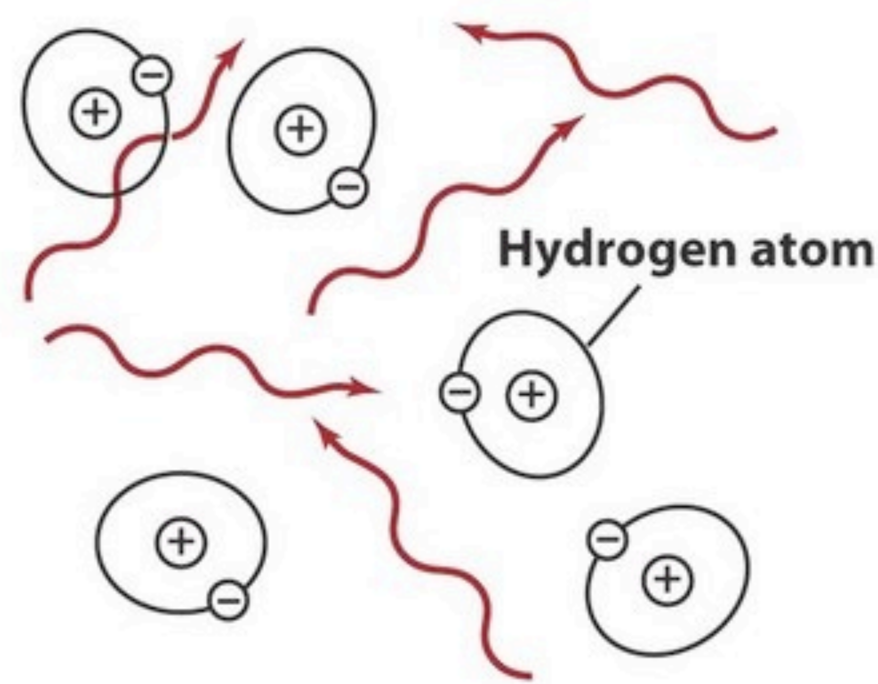
Near perfect thermal spectrum

The universe was hotter in the past.
When it was about 300,000 years old, the temperature was high enough to ionize hydrogen. This time is called **recombination**.

BEFORE



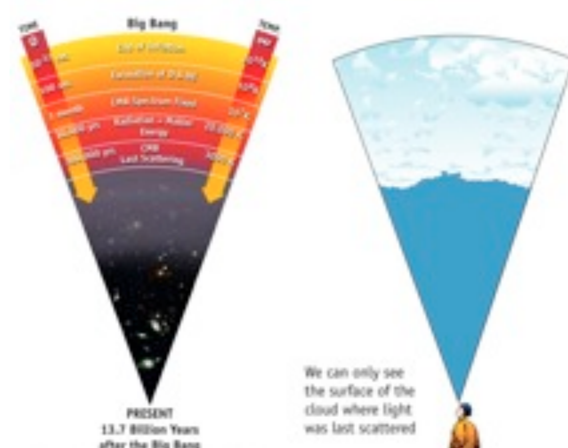
AFTER

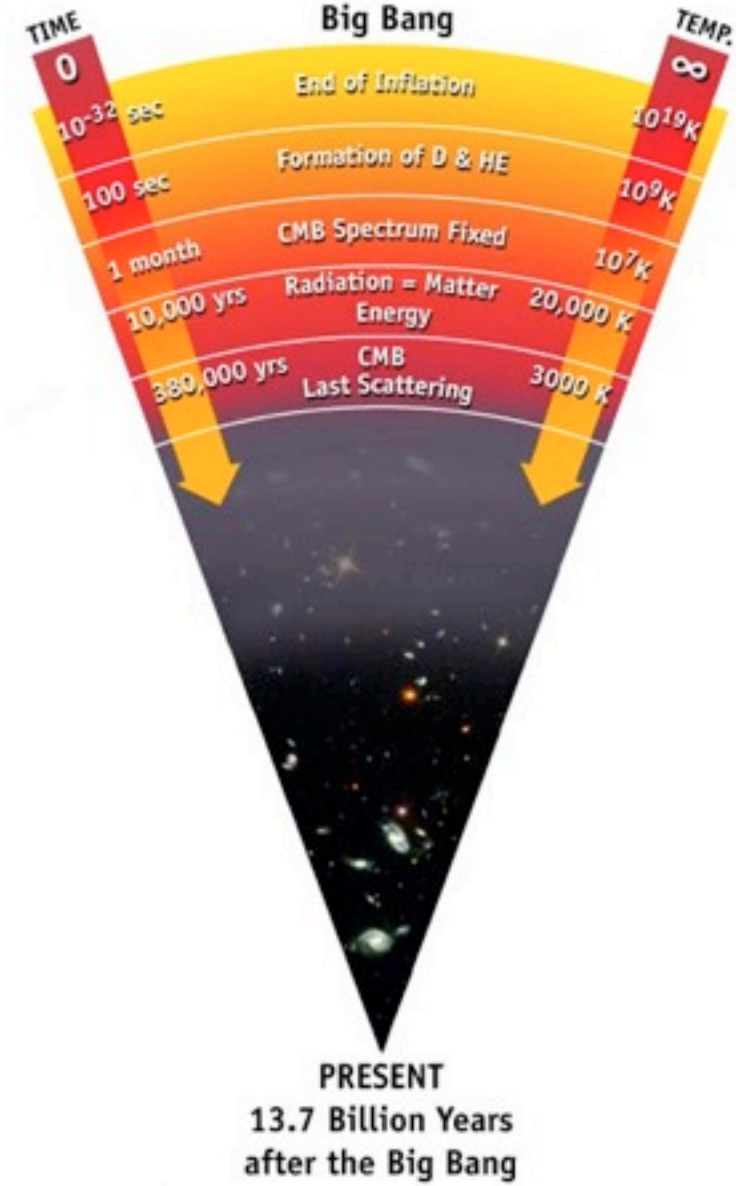


There is a big difference in the opacity of neutral and ionized hydrogen.

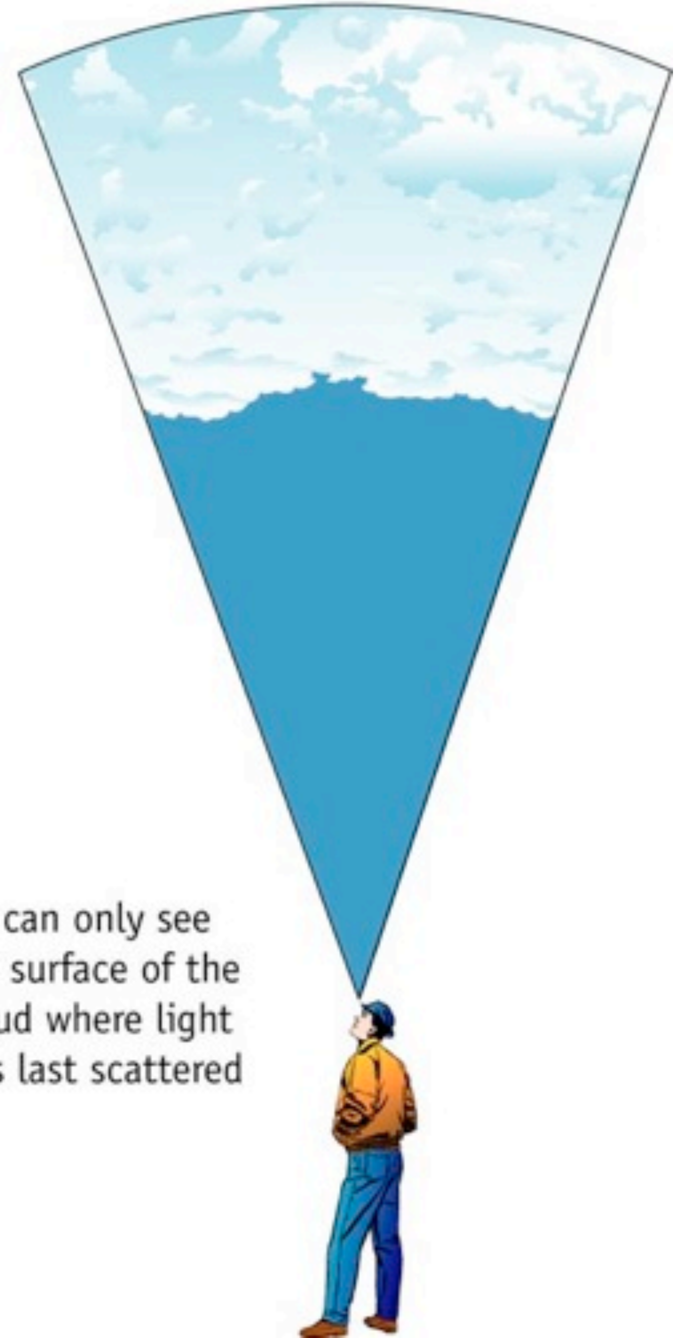
Before recombination, the universe was like a dense fog - the light was trapped.

After recombination, the thermal radiation was free to traverse the universe. The **microwave background** is in effect a snapshot of the universe at the time of **recombination**, when it was only 300,000 years old.



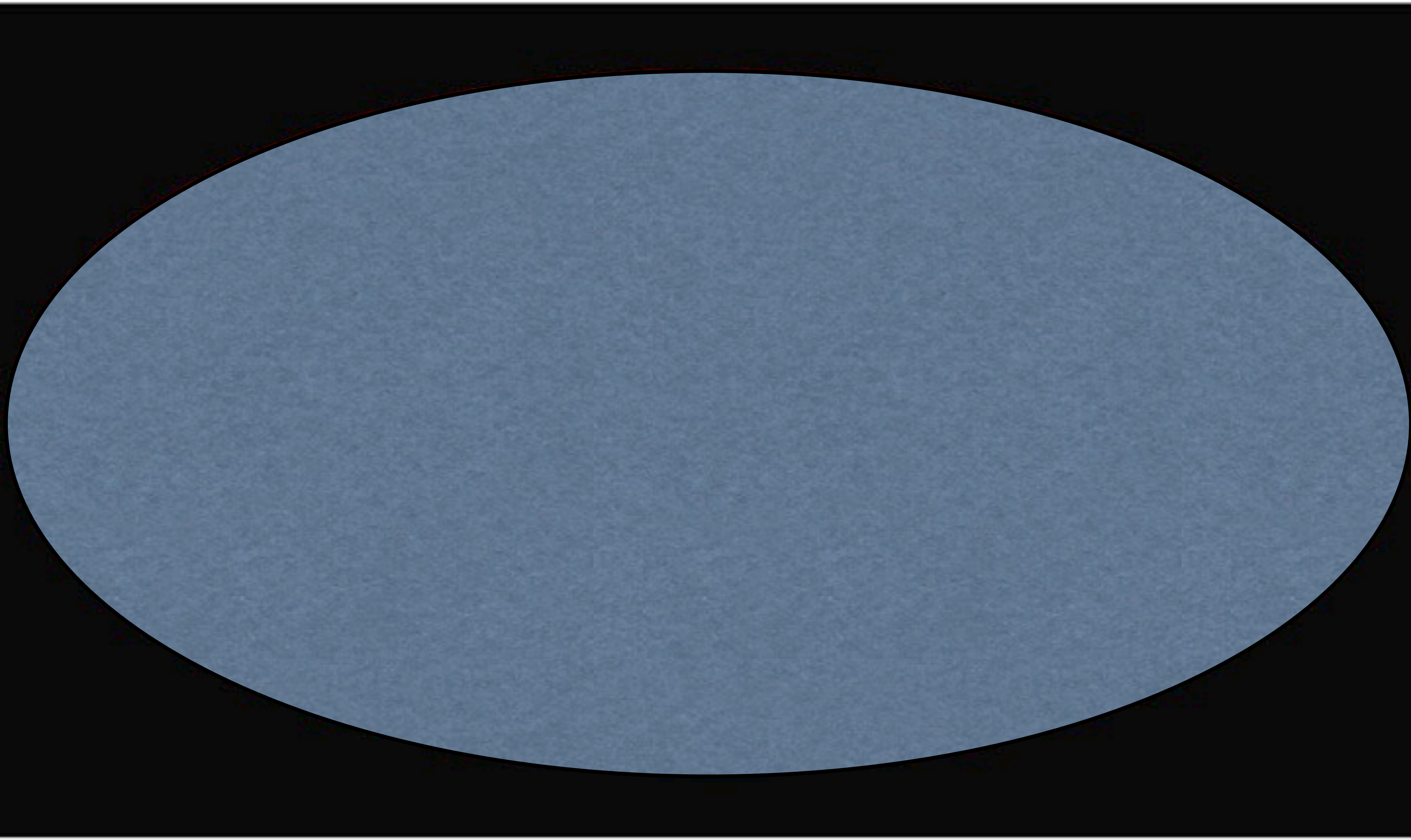


The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.



We can only see the surface of the cloud where light was last scattered

Baby picture of the universe (300,000 years old)

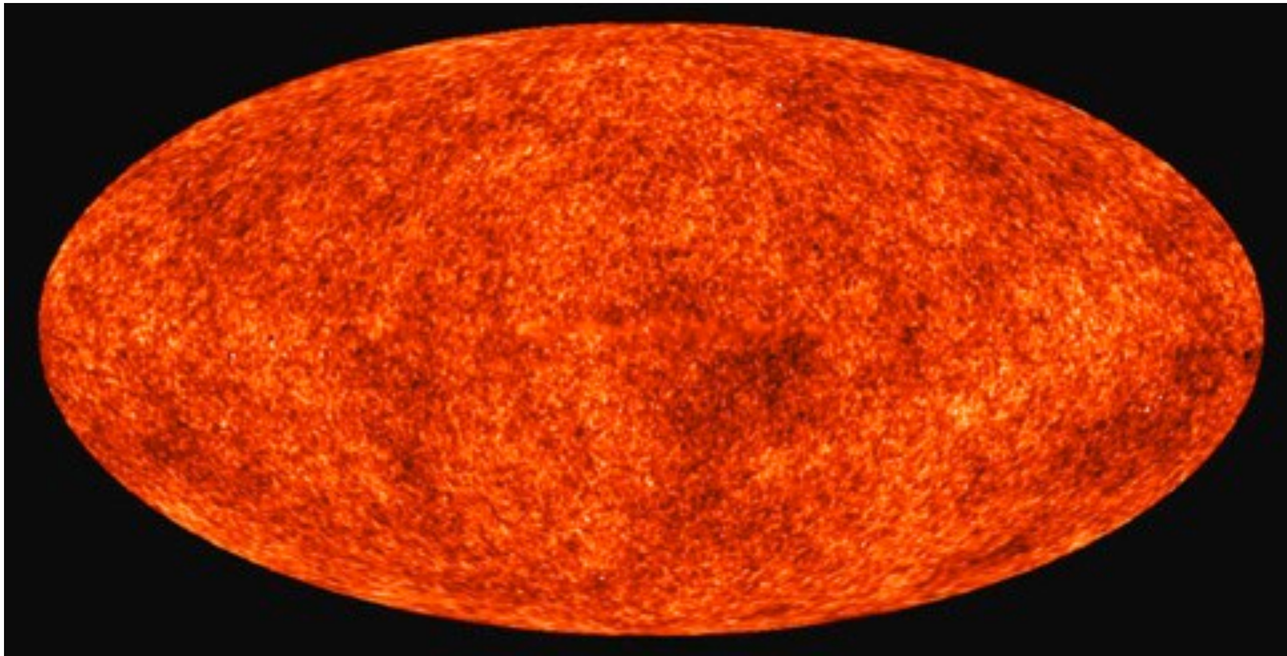


Universe very uniform at z = 1000 (300,000 years old)

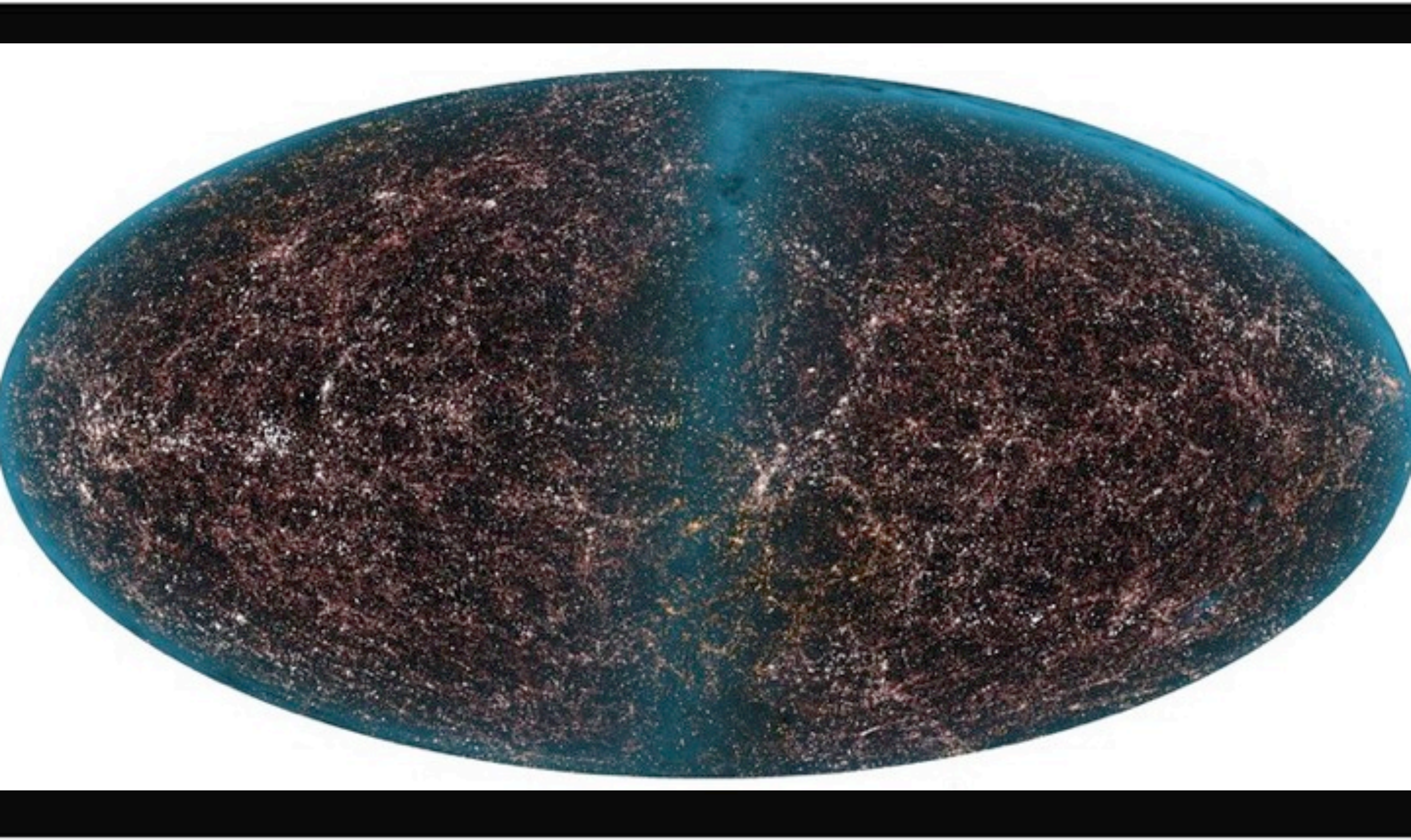
The cosmic microwave background is uniform to one part in 100,000. The early universe obeyed the cosmological principle.

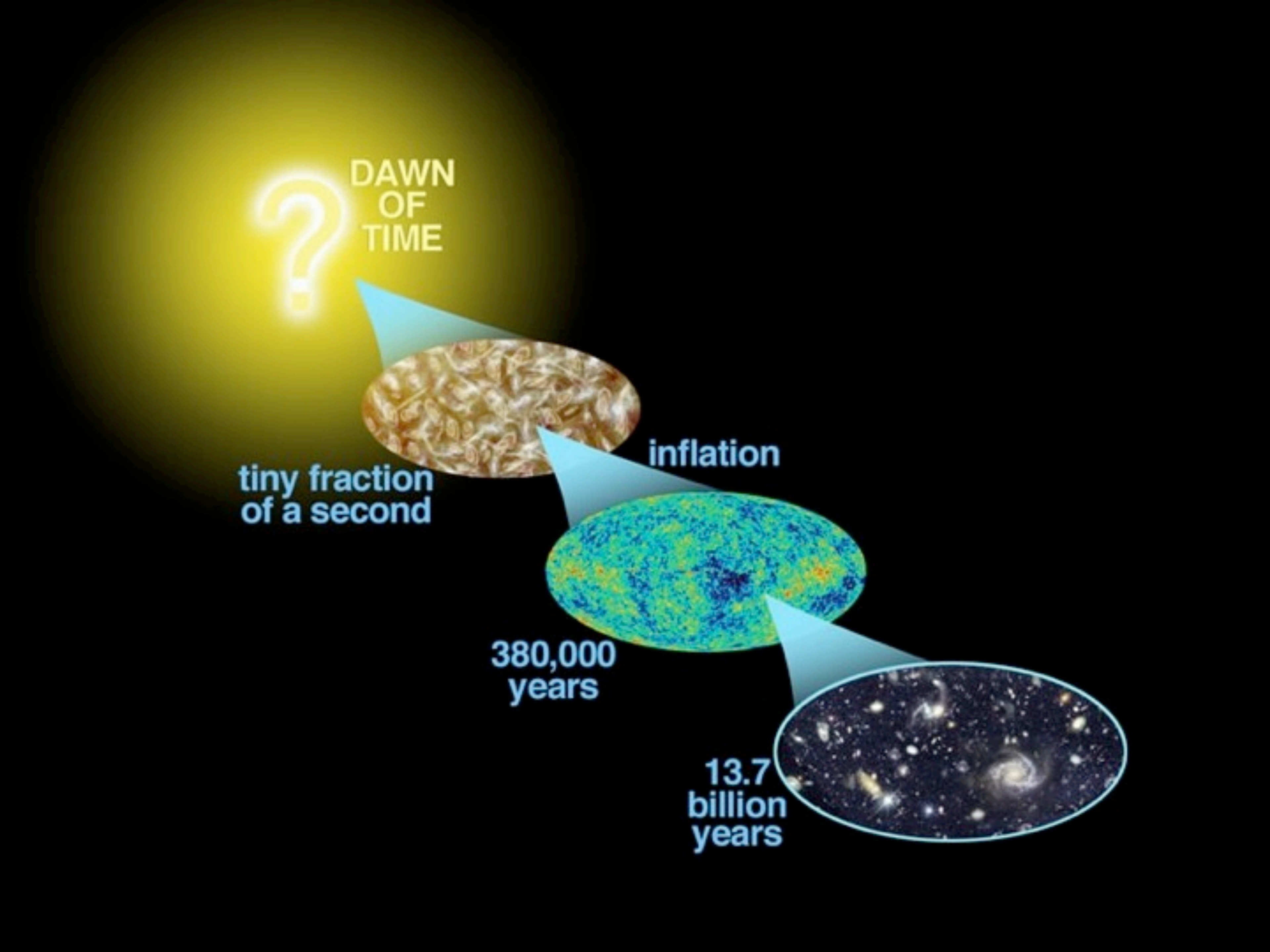
The tiny variations in temperature correspond to tiny variations in density. These slowly grow to become galaxies and other structures.

WMAP



Large scale structure




DAWN OF TIME
tiny fraction of a second
inflation
380,000 years
13.7 billion years