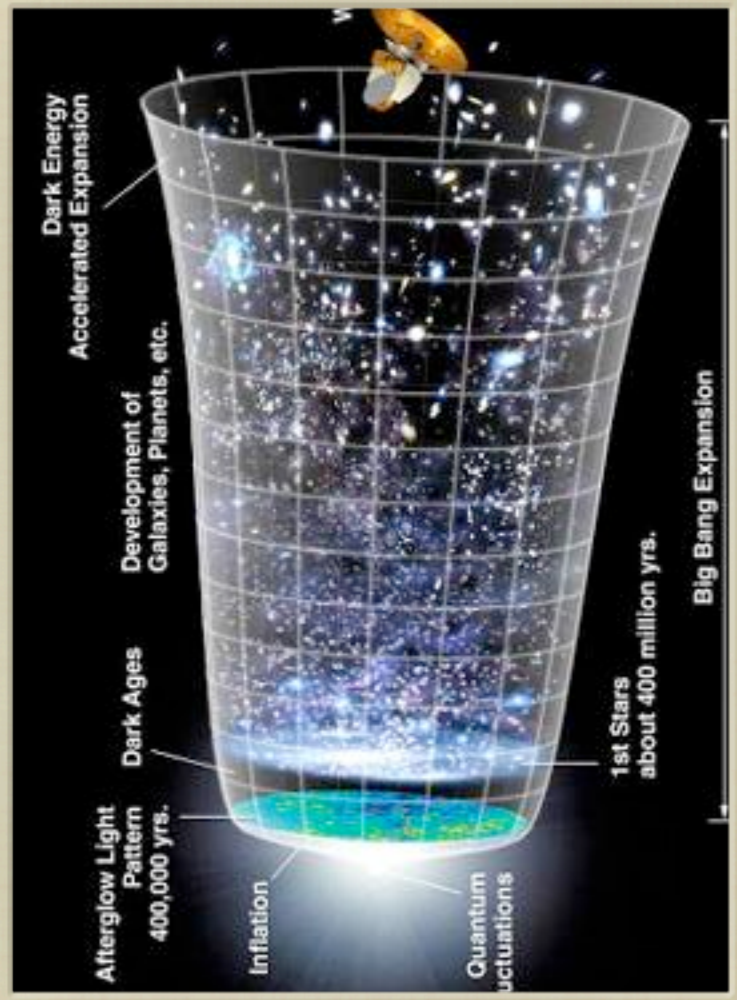
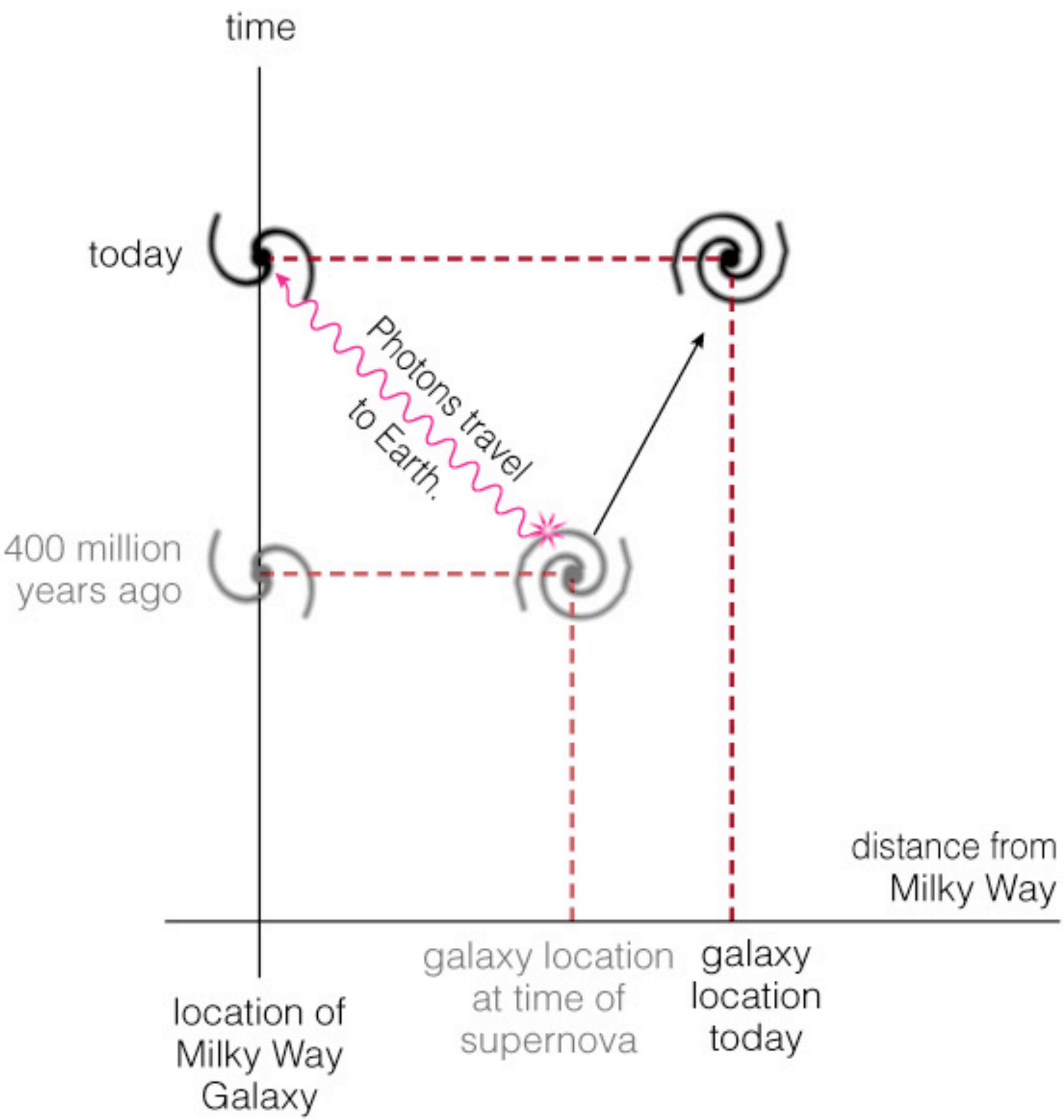
Today

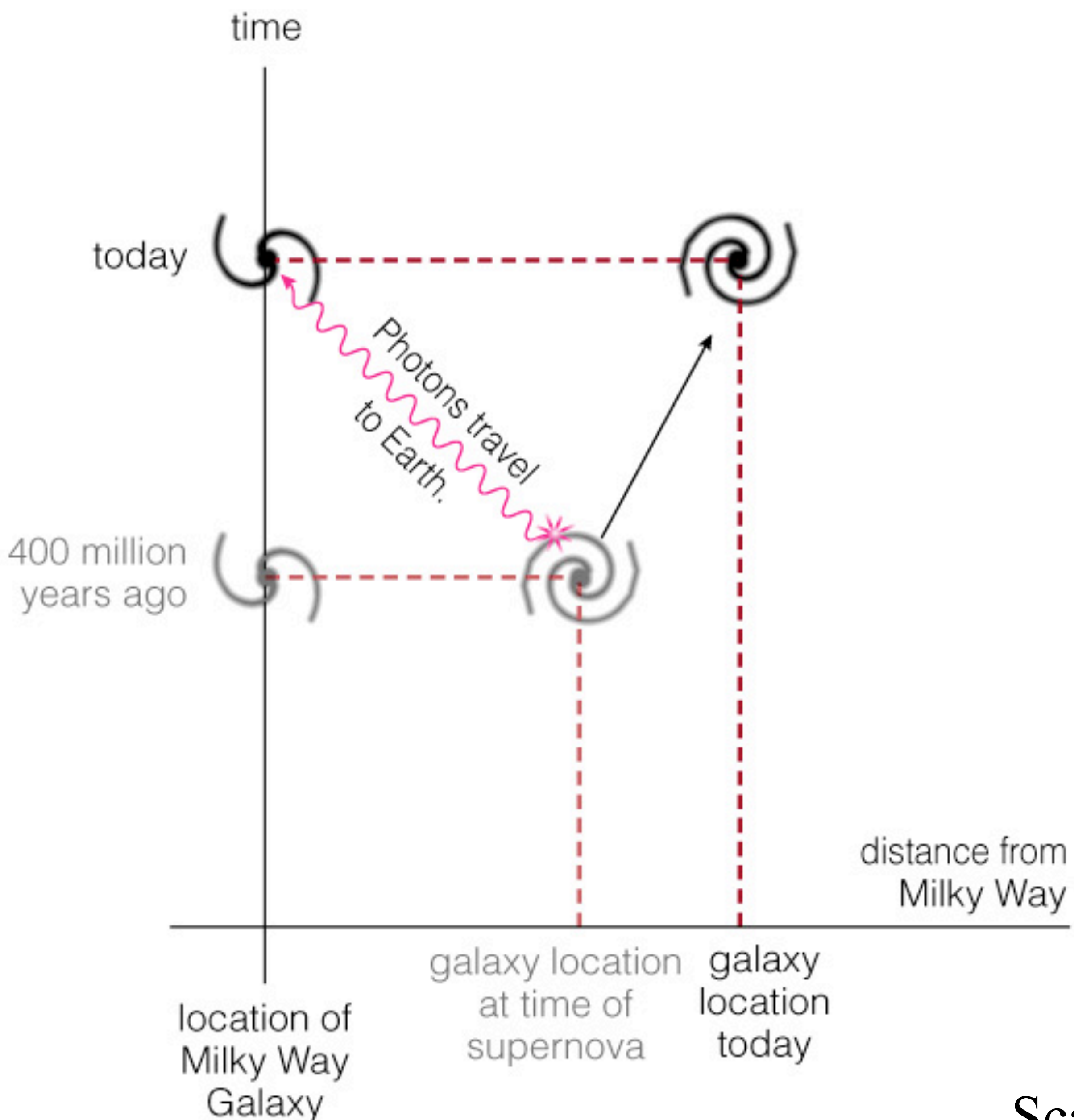
- Modern Cosmology
  - The Hot Big Bang
    - Age & Fate
    - Density and Geometry
    - Microwave Background



Course Evaluations Open



Distances between faraway galaxies change while light travels.



Distances between faraway galaxies change while light travels.

Looking further away is equivalent to looking back in time.

Scales

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!

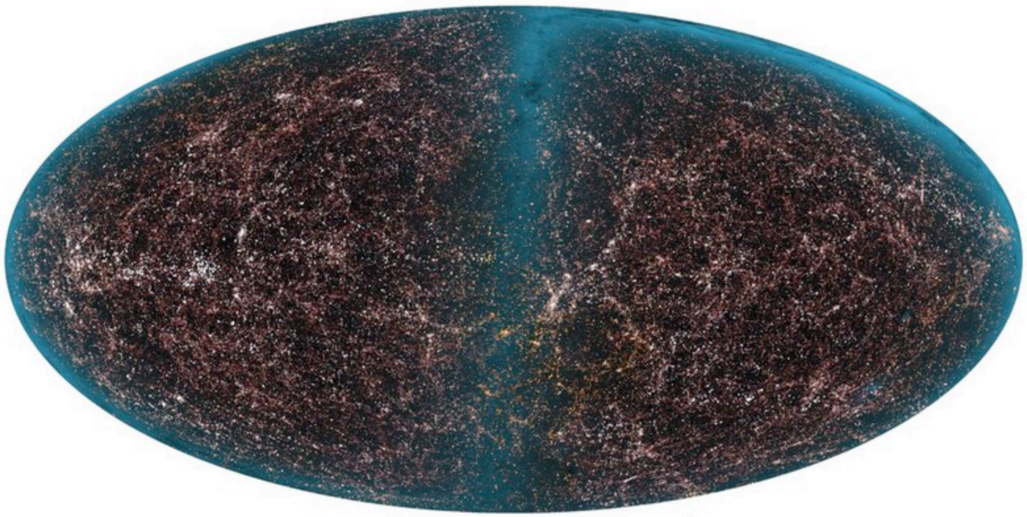
d Map of Hecataeus of Miletus (c. 500 BC)

Modern Cosmology

- We live in an expanding universe
  - The expansion of space causes the wavelengths of photons to stretch
  - more distant objects have larger redshift (Hubble's Law: $V = H_0 d$)
- The universe may be spatially infinite
- The universe has a finite age
  - about 13 or 14 Billion years

The Cosmological Principle

- The Universe is
  - Homogeneous
  - Isotropic

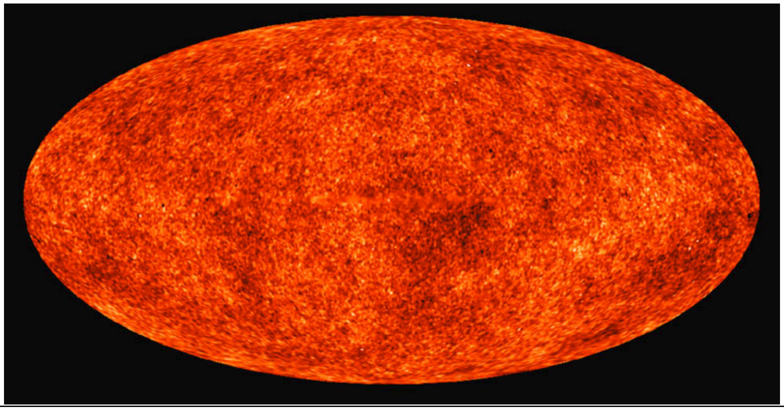


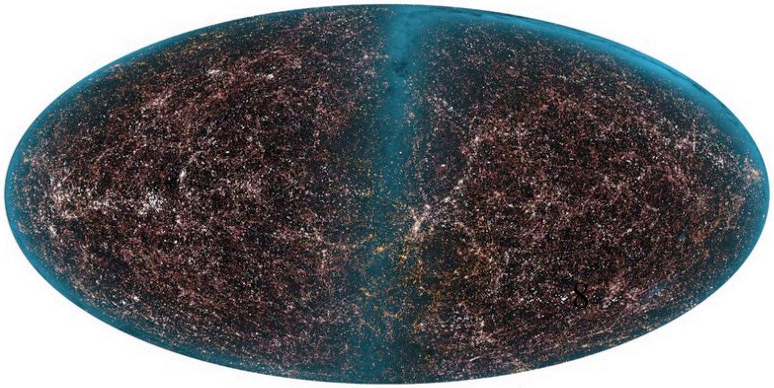
A philosophical assertion that there should be nothing special about where we are, so the universe should look much the same to an distant alien observer as to us.

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**.





Three key indicators that the universe was once much hotter and denser (hot Big Bang)

- Expansion of the universe
  Run the film backwards; hotter, denser
- Primordial glow
  Called the Cosmic Microwave Background
  Required if universe was hotter, denser
- Big Bang Nucleosynthesis
  Universe has much more helium than could have been produced just in stars
  Early hot, dense phase: some H->He

Elements of Modern Cosmology

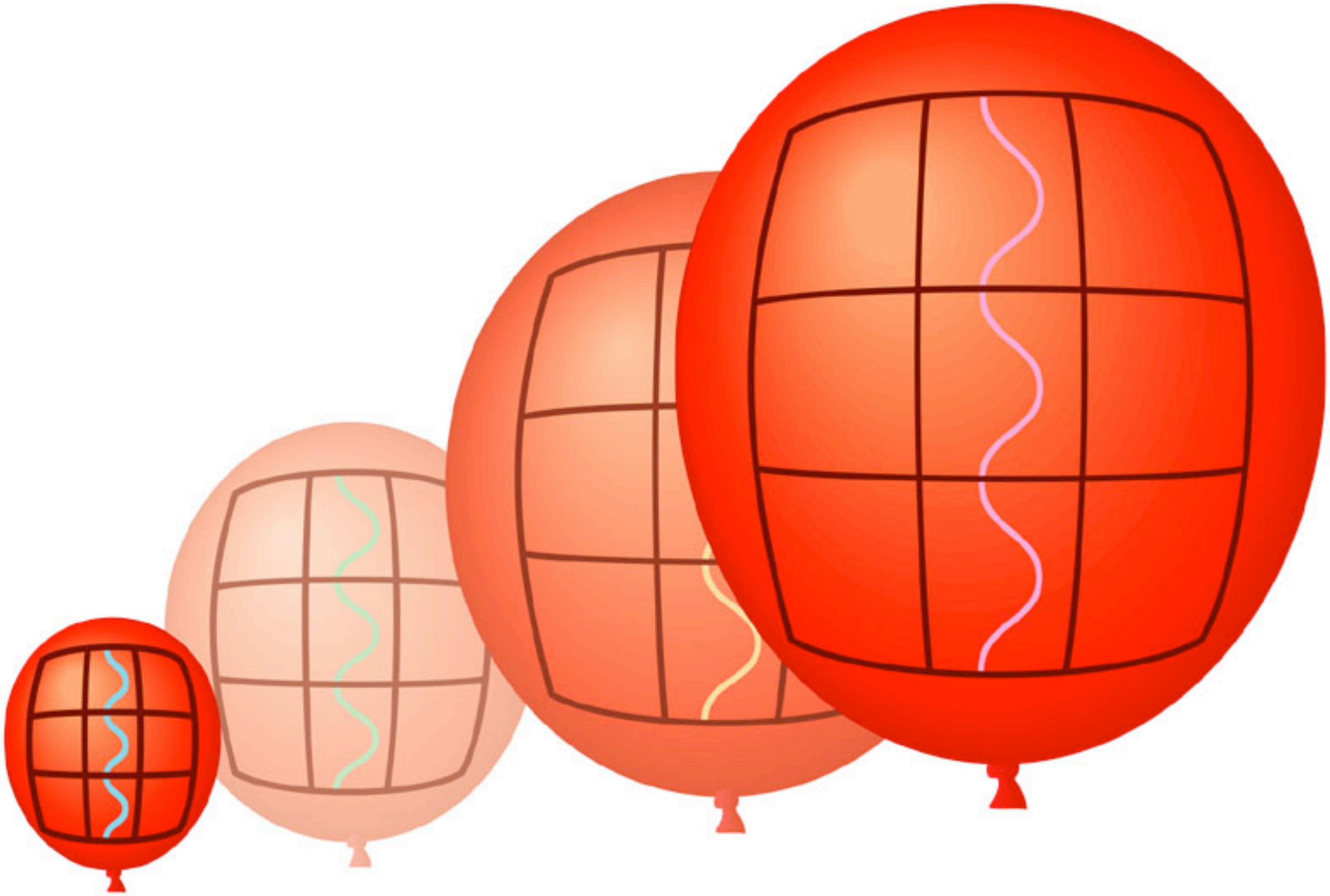
1. Expanding Universe ✓
2. Finite Age ✓
3. Density & Geometry ✓
4. Thermal History ✓
5. Big Bang Nucleosynthesis ✓
6. Dark Matter ?
7. Dark Energy ?

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.

$$V = H_0 d$$


WHAT WOULD YOU CALL THE CREATION OF THE UNIVERSE?
"THE HORRENDOUS SPACE KABLOOIE!"

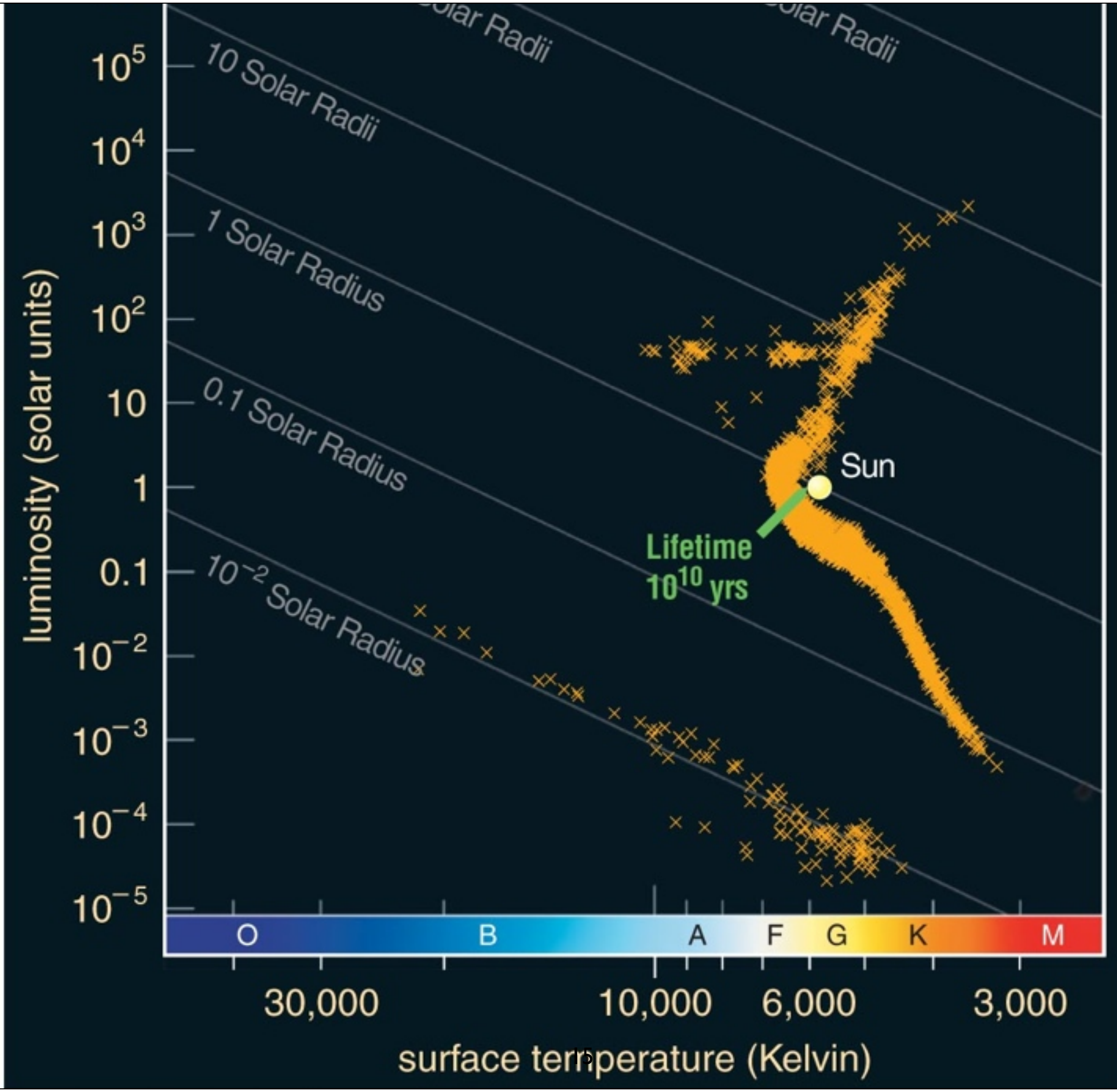
Expansion Age

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

Consistent with

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

} All give about the same age

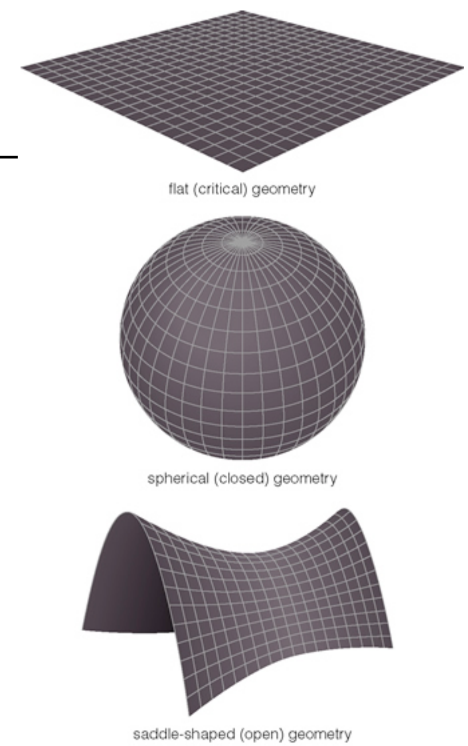


Solar Radii
Solar Radii
10 Solar Radii
1 Solar Radius
0.1 Solar Radius
10^{-2} Solar Radius
10^5
10^4
10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
luminosity (solar units)
Sun
Lifetime
10^{10} yrs
O
B
A
F
G
K
M
30,000
10,000
6,000
3,000
surface temperature (Kelvin)

3. Mass, geometry, and fate

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

expand forever
or recollapse?



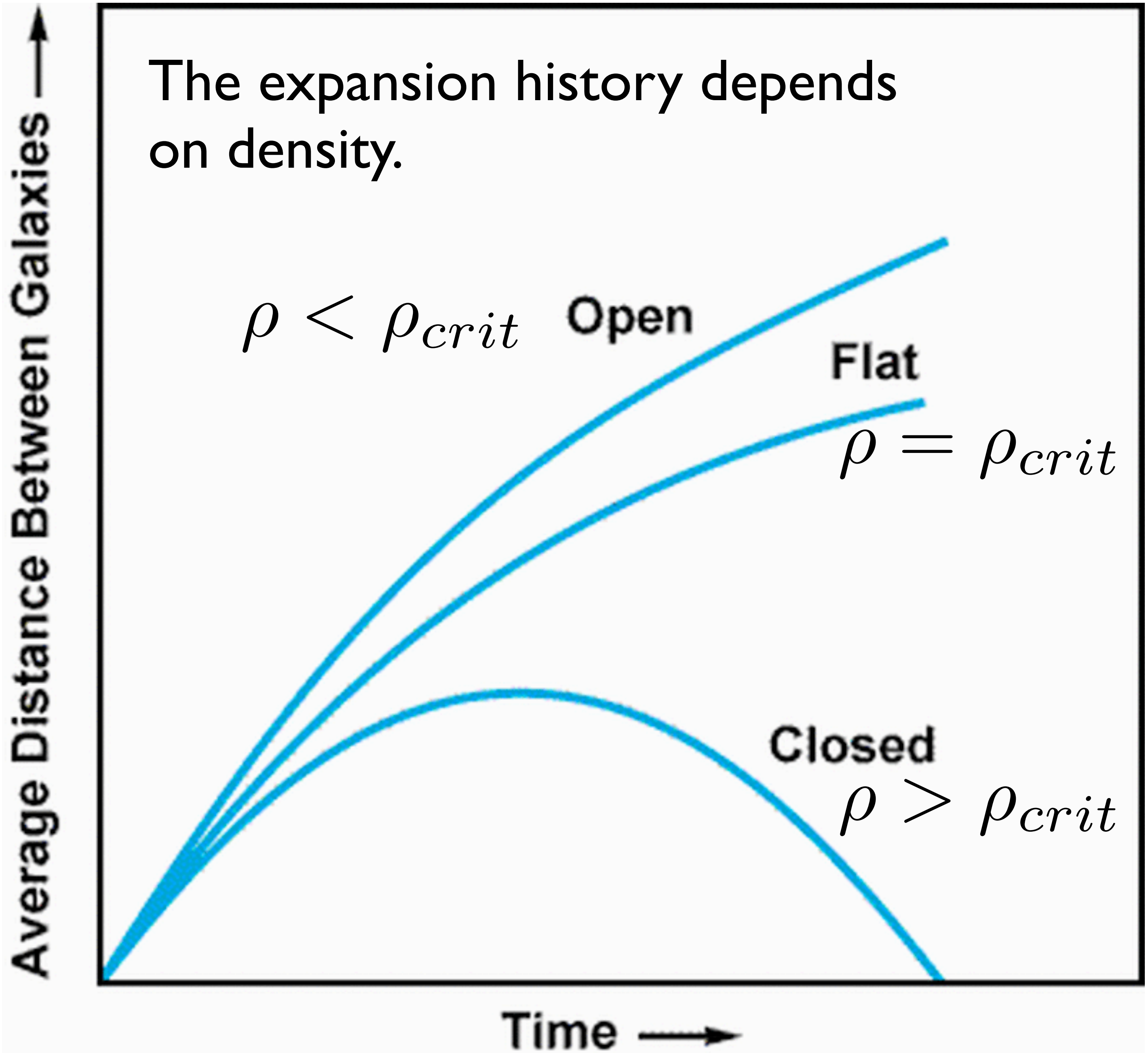
The expansion started by the Big Bang
is resisted by the attraction of gravity.

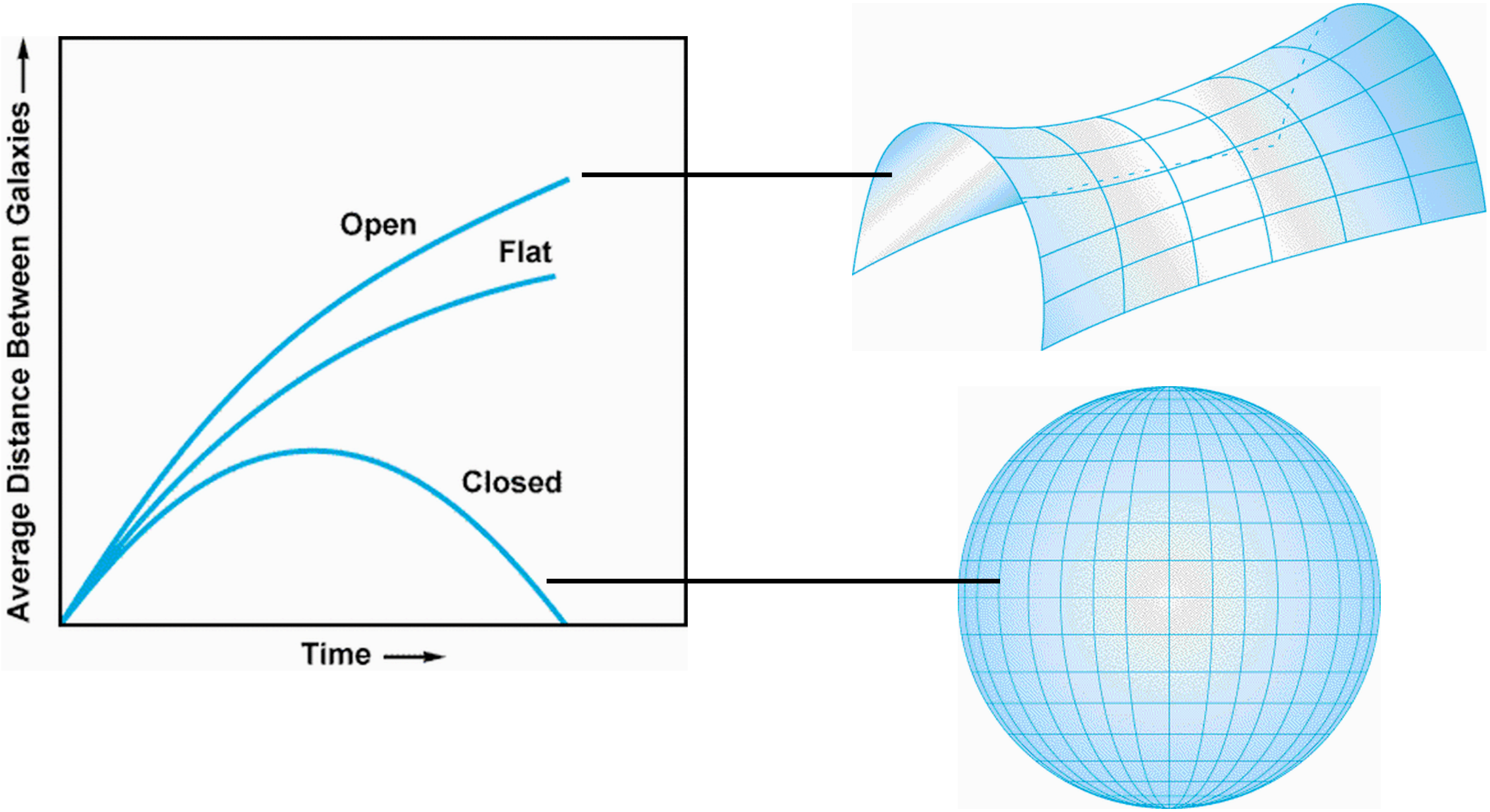
The more dense the universe, the more gravity...
a balance is reached at a critical density:

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

Cosmos

The expansion history depends on density.

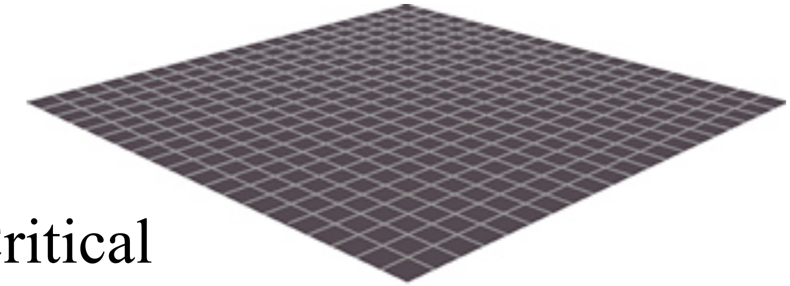




The expansion history and the geometry of the universe are both related to the density. Space can be "curved."

FLAT

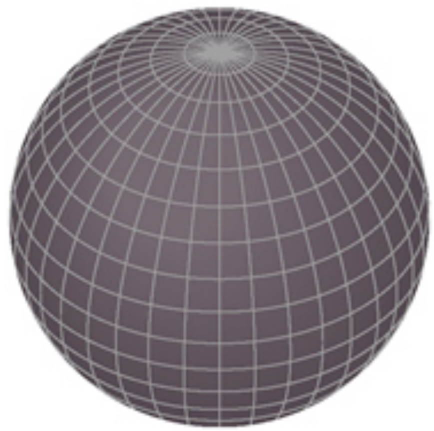
Density = Critical



flat (critical) geometry

CLOSED

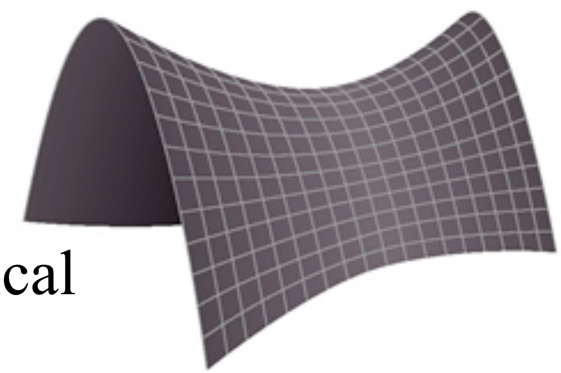
Density > Critical



spherical (closed) geometry

OPEN

Density < Critical



saddle-shaped (open) geometry

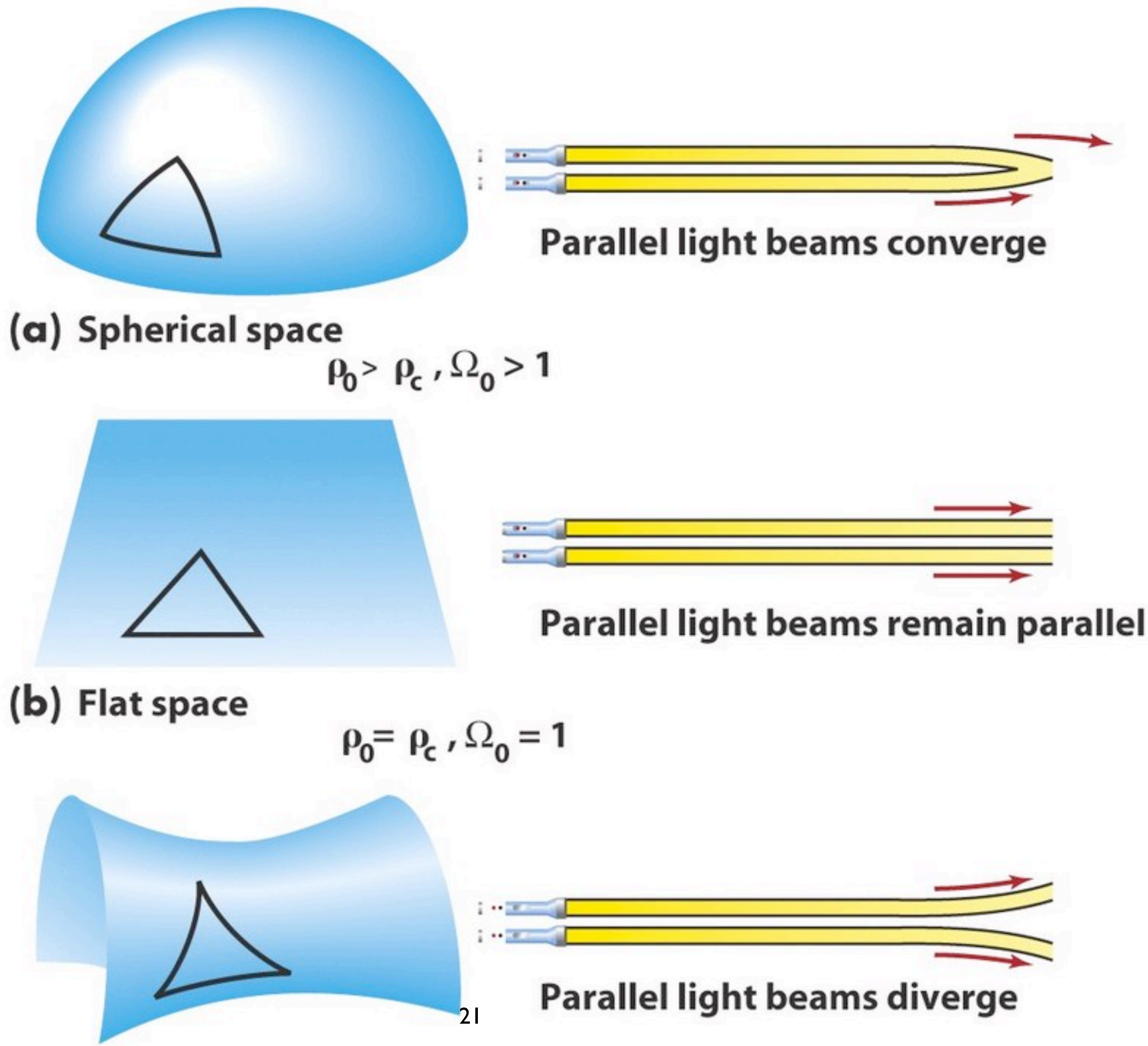
Space can be curved.

The overall geometry of the universe is closely related to total density of matter and energy.

CLOSED

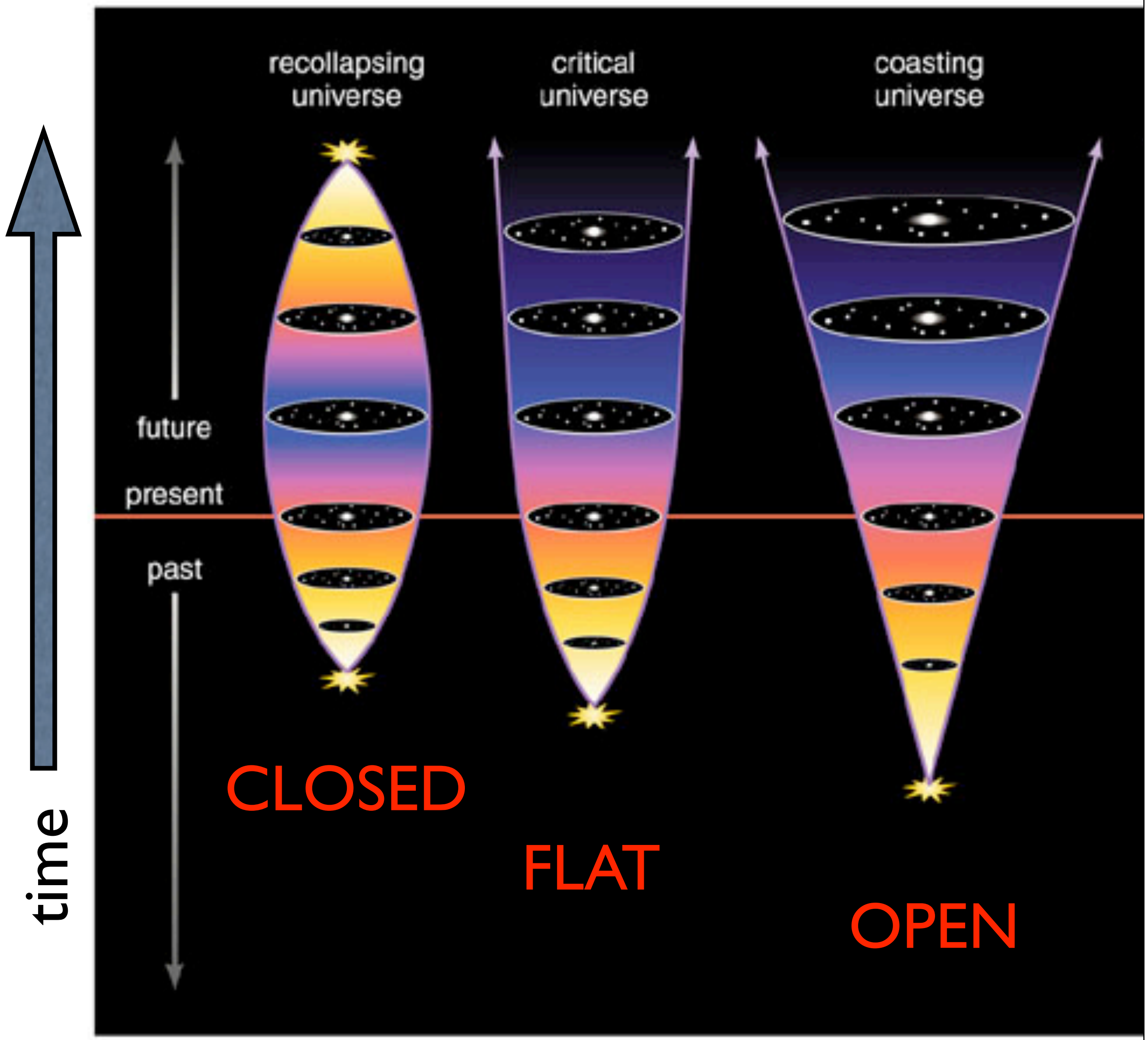
FLAT

OPEN



Density is destiny

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

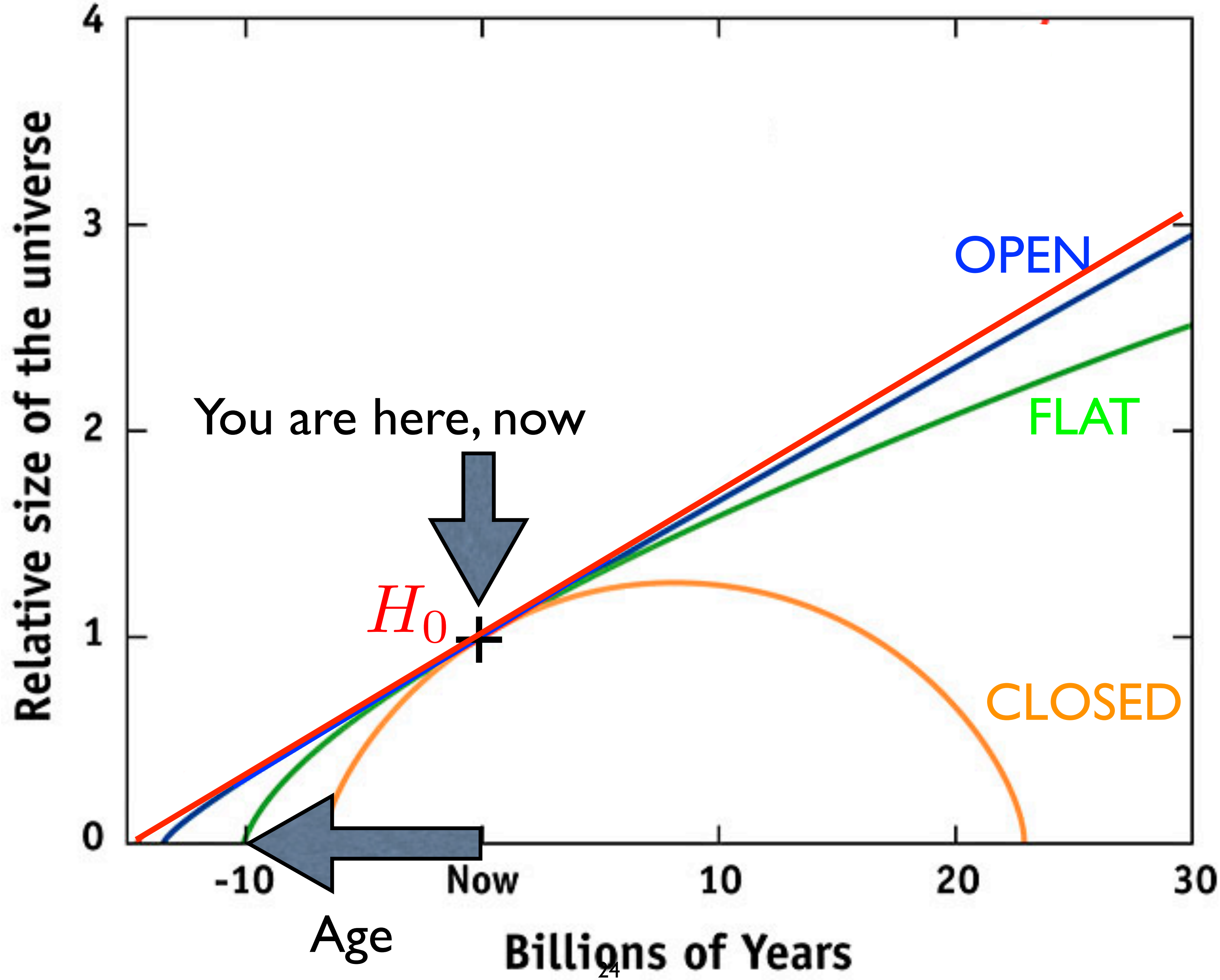


Cosmology often phrases the density in terms of the critical value - the density parameter, "Omega"

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

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

$\Omega < 1$	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

Messengers from the Past?

If the universe was much hotter and denser in the past, what would we expect to see from that phase?

A. Nothing; radiation couldn't reach us

B. Absorption lines from that phase

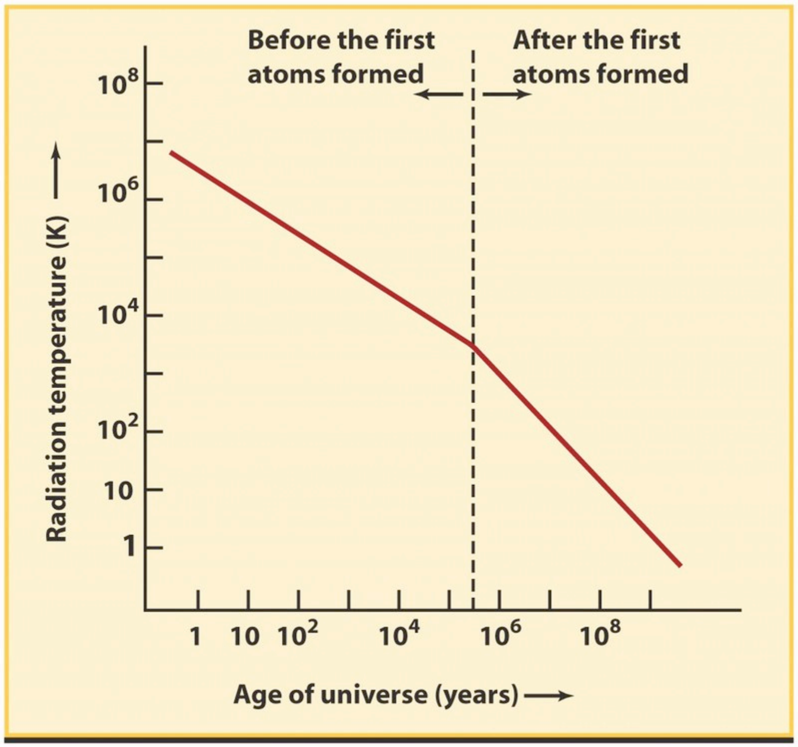
C. Radiation as hot as when it was emitted

D. Radiation, but cooled by the redshift due to the expansion of the universe

E. I don't know

4. Thermal History

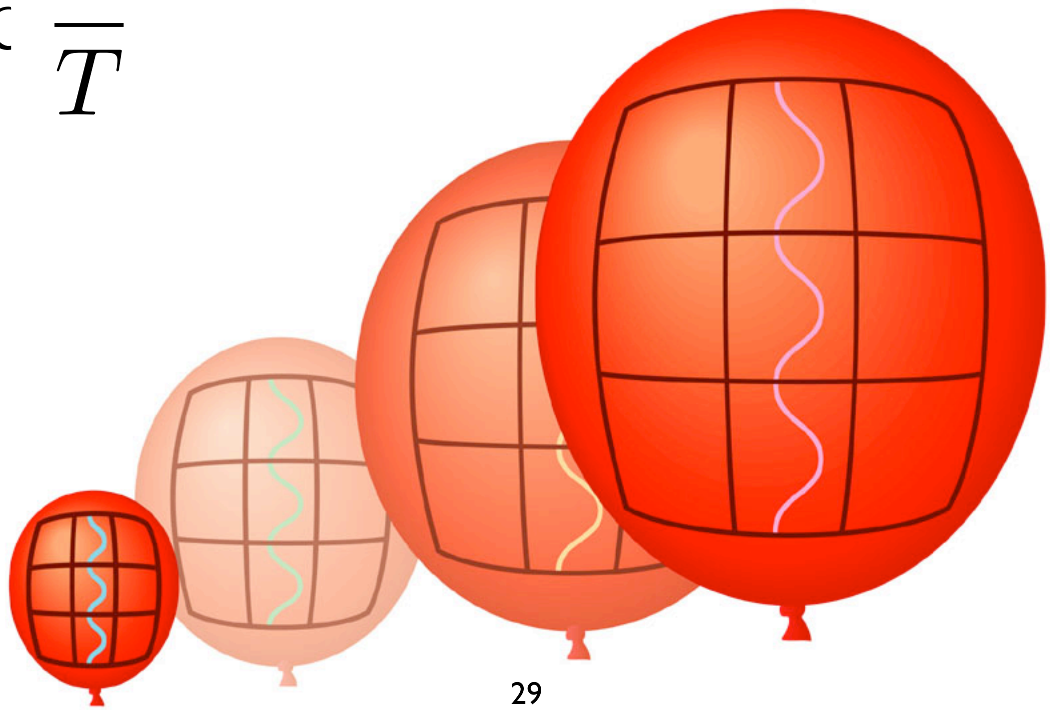
- The universe started off very hot (hence the "hot big bang") and cools as it expands



Cooling is a consequence of expansion.

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

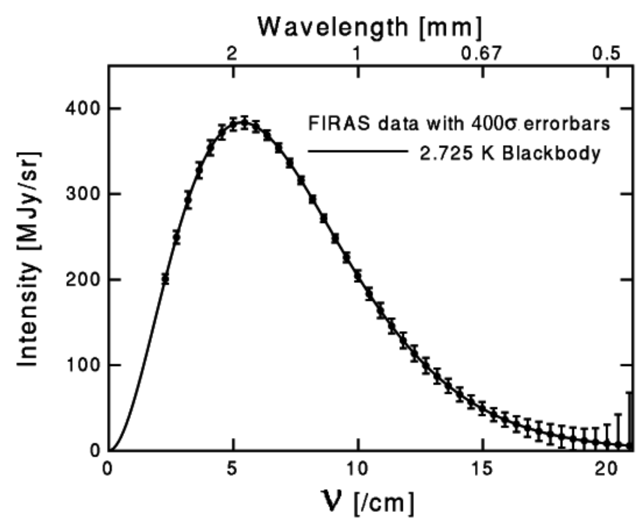
$$\lambda \propto \frac{1}{T}$$



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.

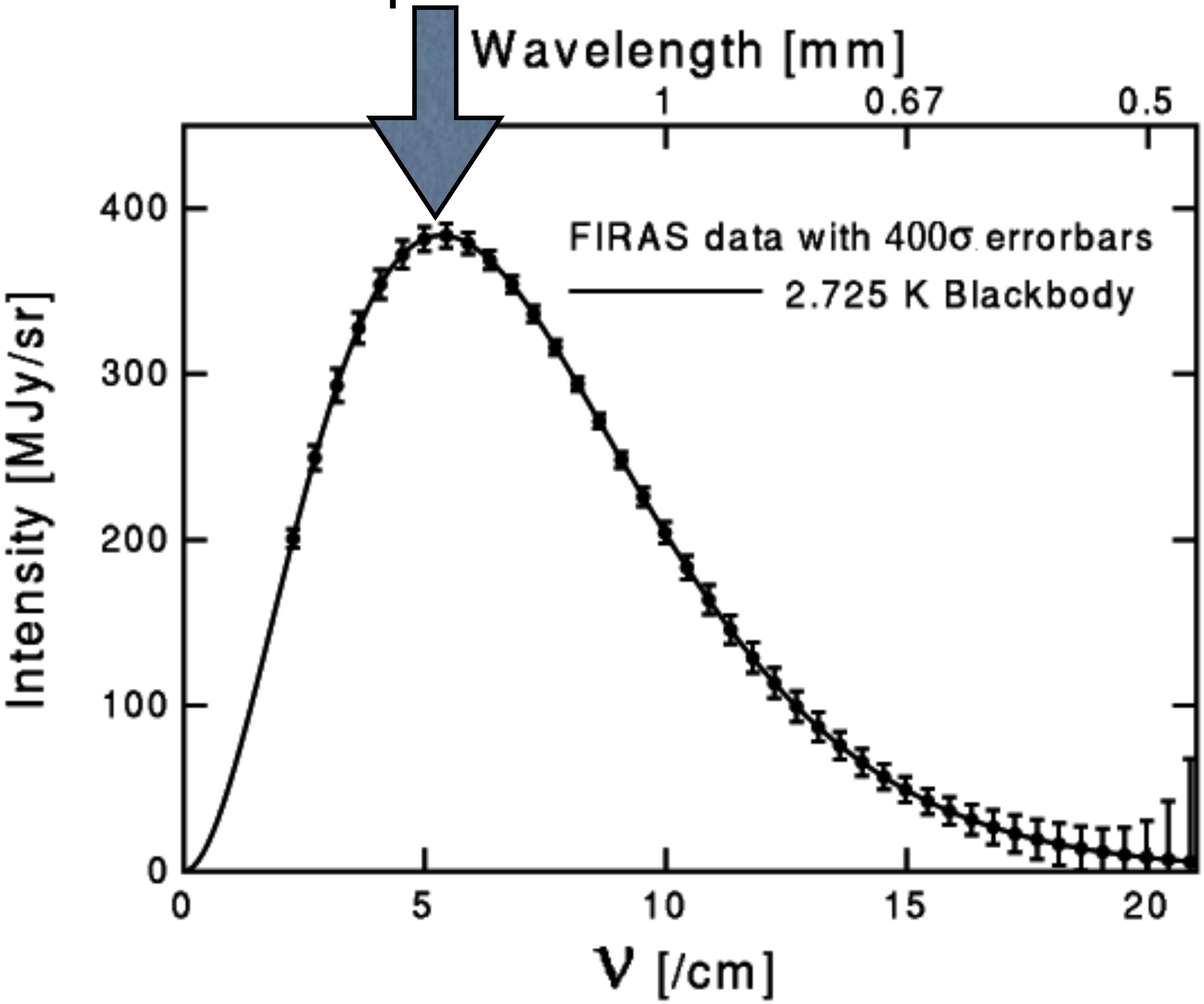
This was discovered in 1965; now called the Cosmic Microwave Background (CMB)

Wilson Penzias

Nobel Prize

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

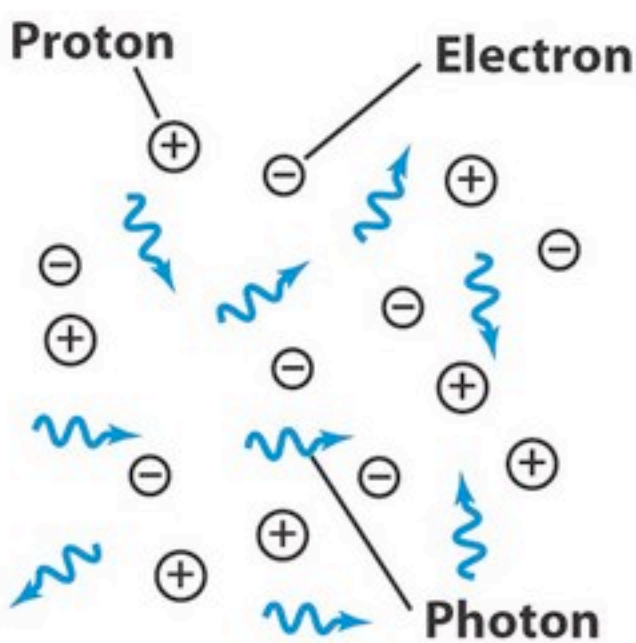
Wien's Law peak



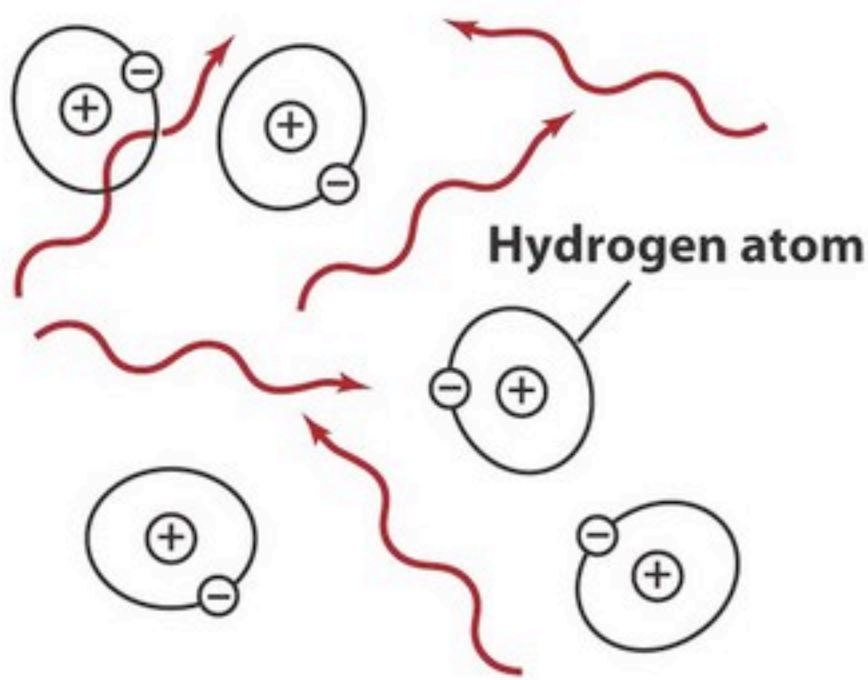
Near perfect thermal spectrum

The universe was hotter in the past.
Prior to when it was about 380,000 years old, hydrogen was ionized. Afterwards, electrons and protons came together to make hydrogen atoms. This time is called **recombination**.

BEFORE



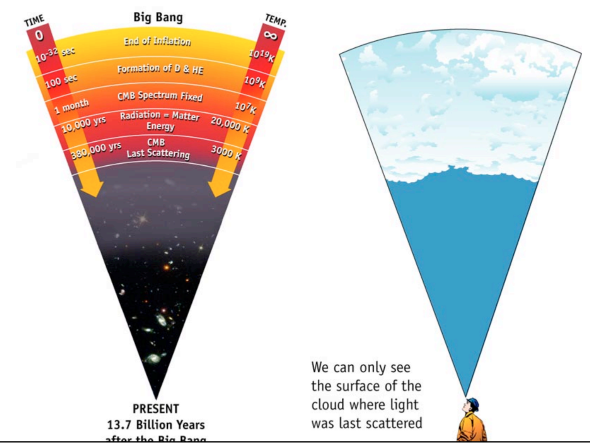
AFTER

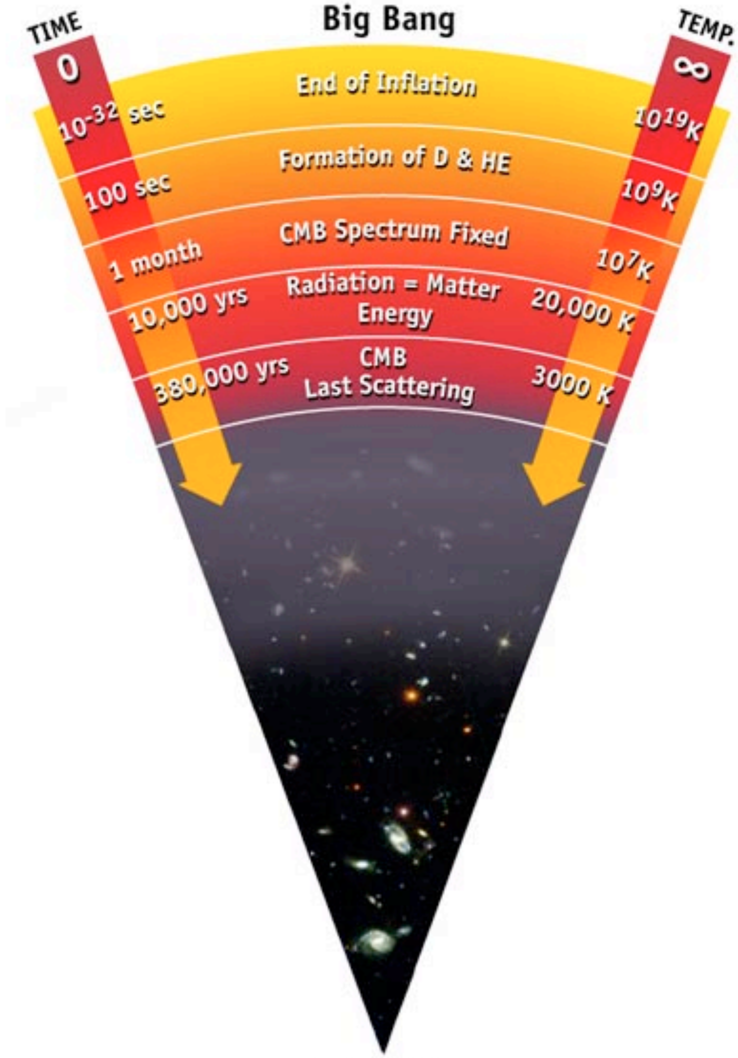


There is a big difference in the opacity of neutral and ionized hydrogen.

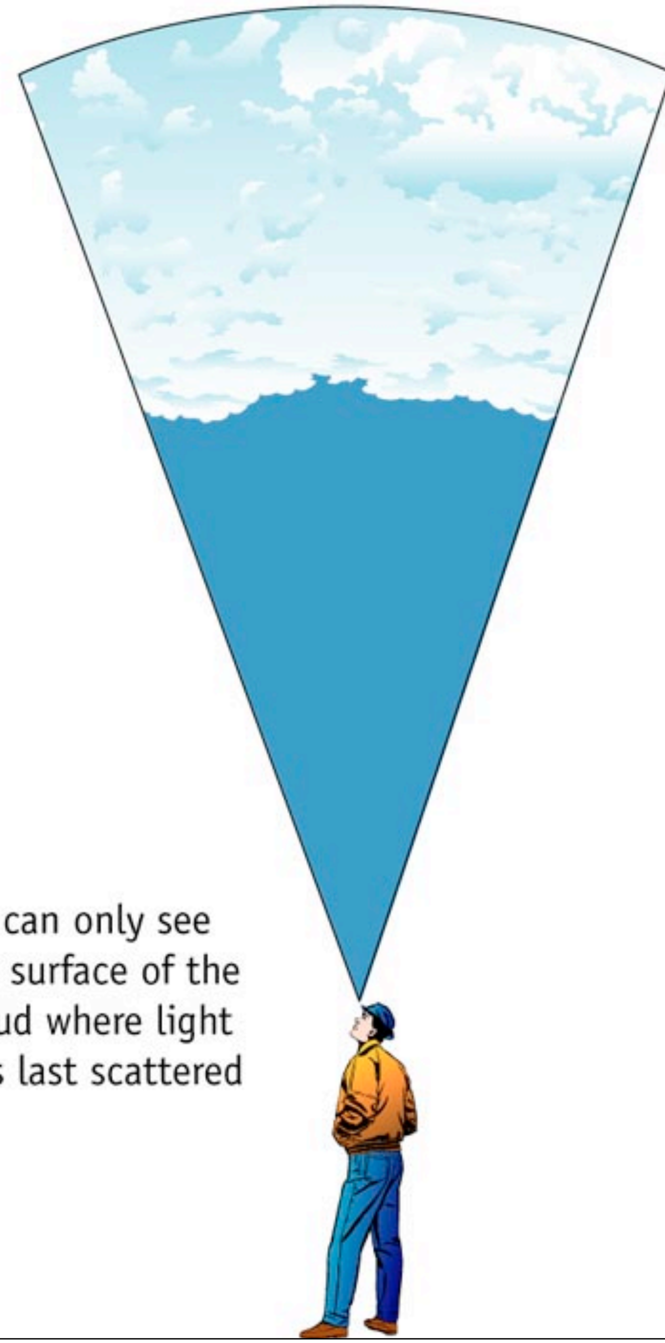
Before recombination, the universe was like a dense fog - the light was trapped.

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 380,000 years old.



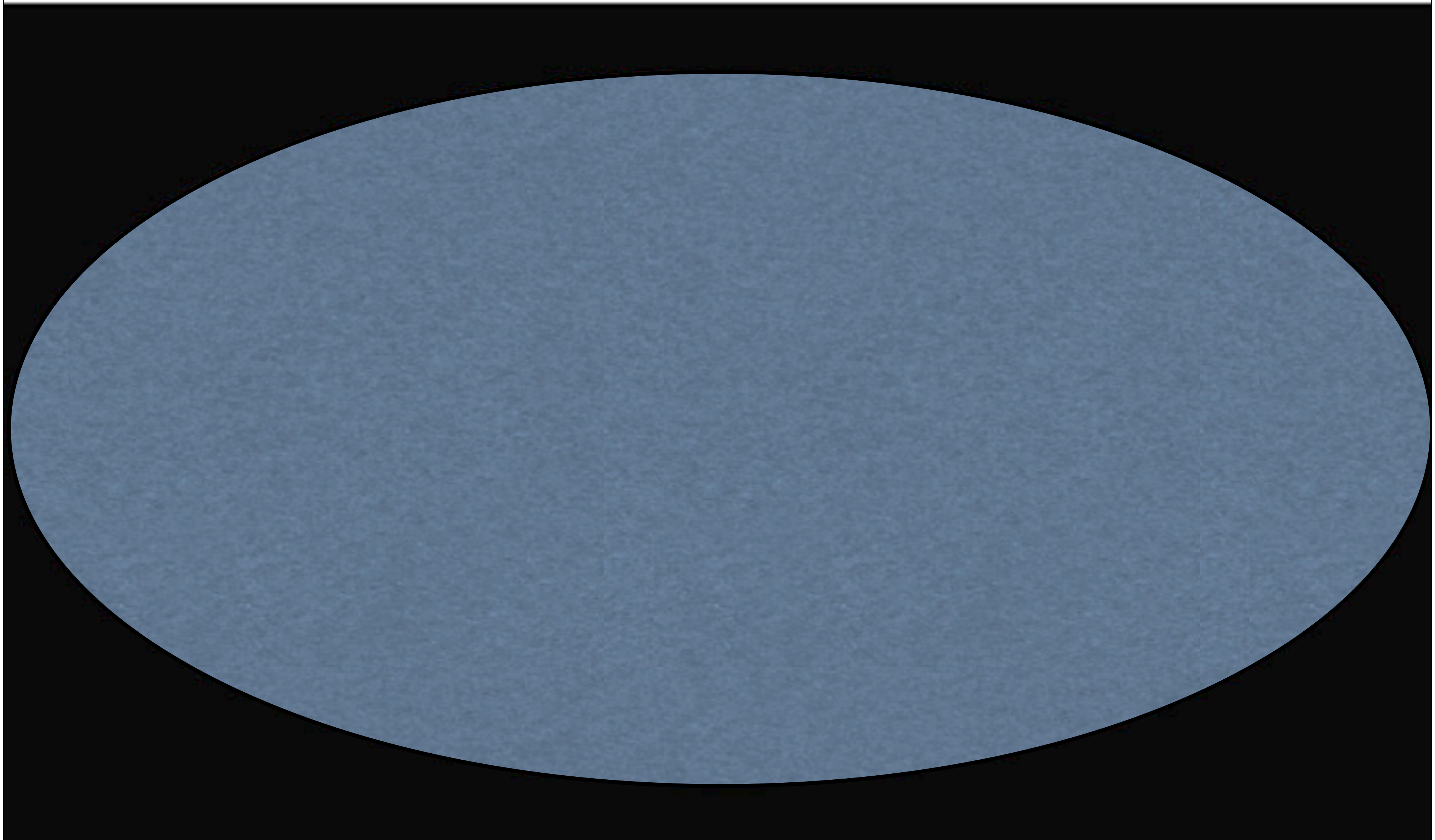


PRESENT
13.7 Billion Years
after the Big Bang



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.

Baby picture of the universe (380,000 years old)

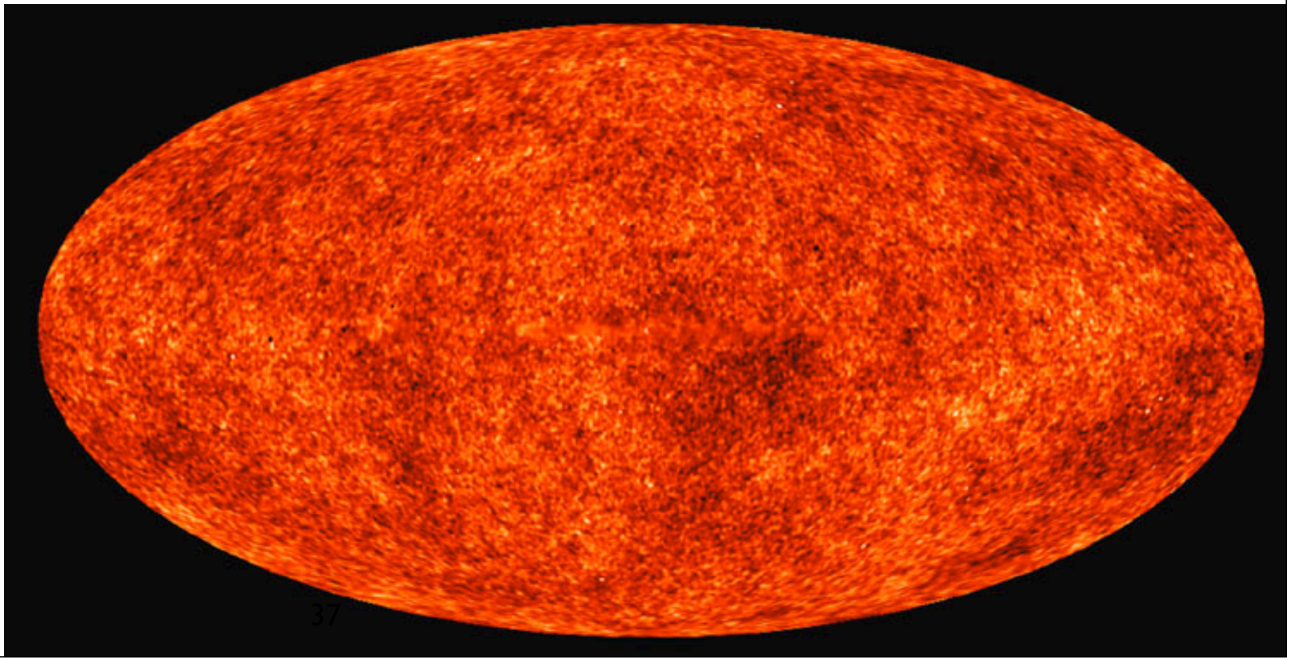


Universe very uniform at $z = 1090$ (380,000 years old)

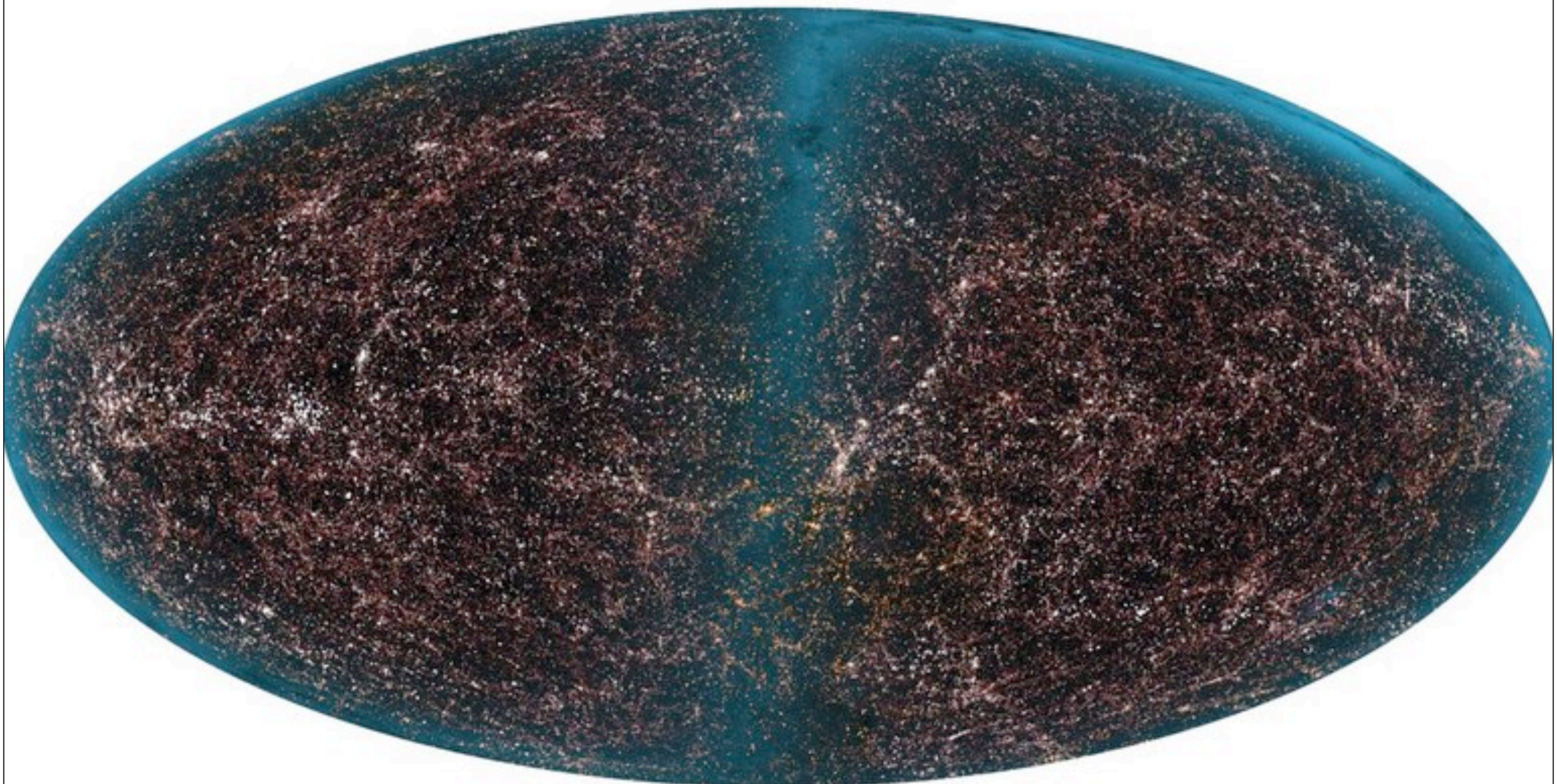
The cosmic microwave background is uniform to one part in 100,000. The early universe obeyed the cosmological principle.

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

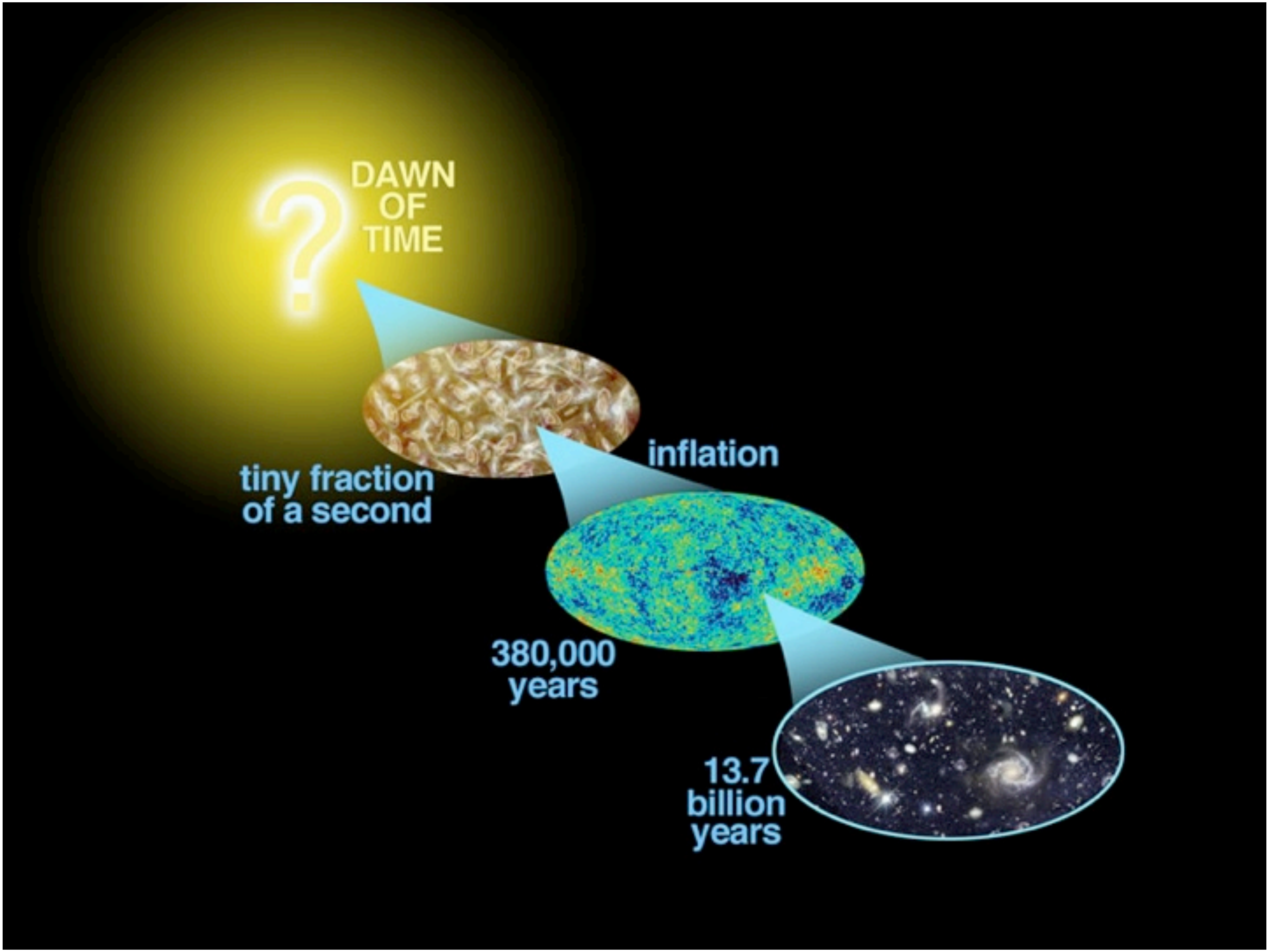
WMAP



Large scale structure



MIB


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