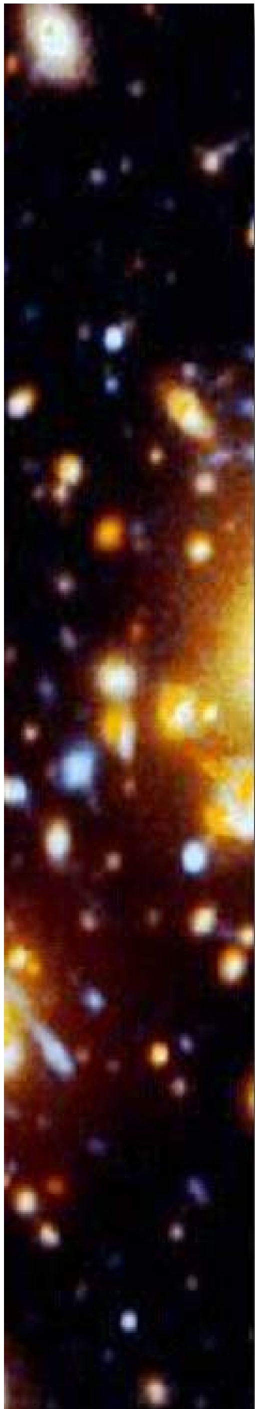
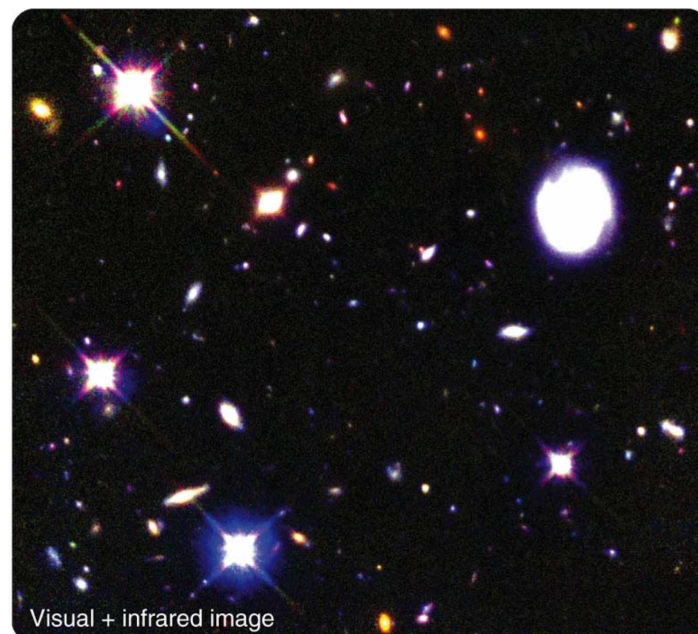
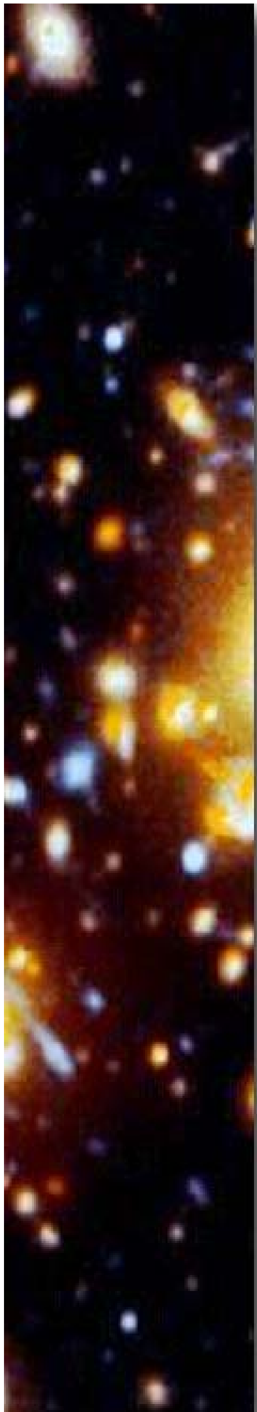


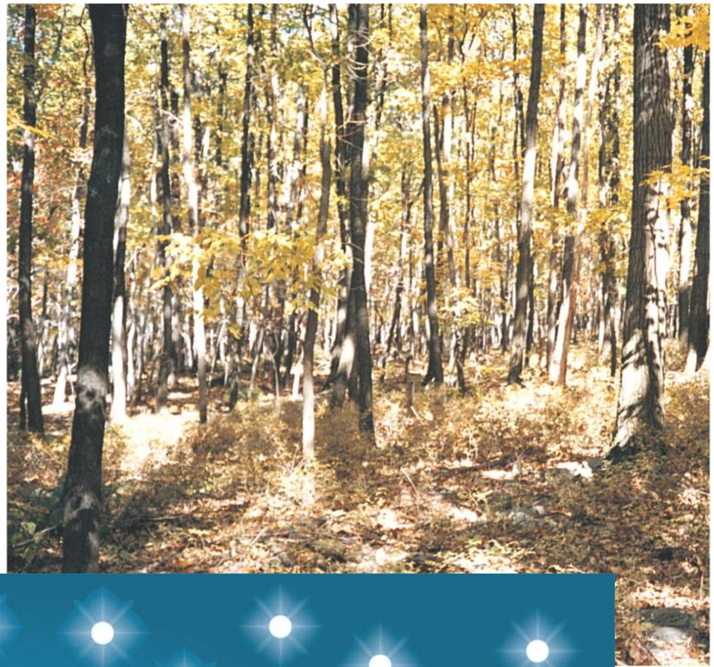
Outline (continued)

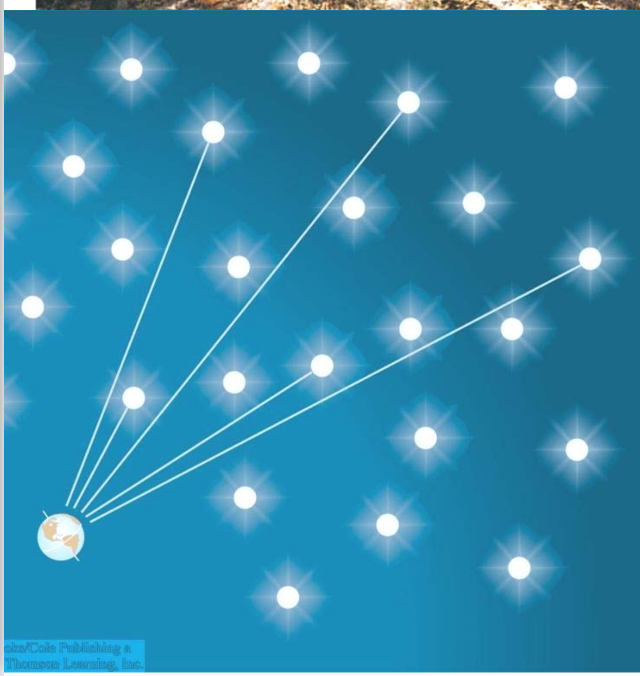
III. 21st-Century Cosmology
- A. Inflation
- B. The Acceleration of the Universe
- C. Dark Energy and Acceleration
- D. The Age and Fate of the Universe
- E. The Origin of Structure and the Curvature of the Universe



Olbers's Paradox







Why is the sky dark at night?

If the universe is infinite, then every line of sight should end on the surface of a star at some point.

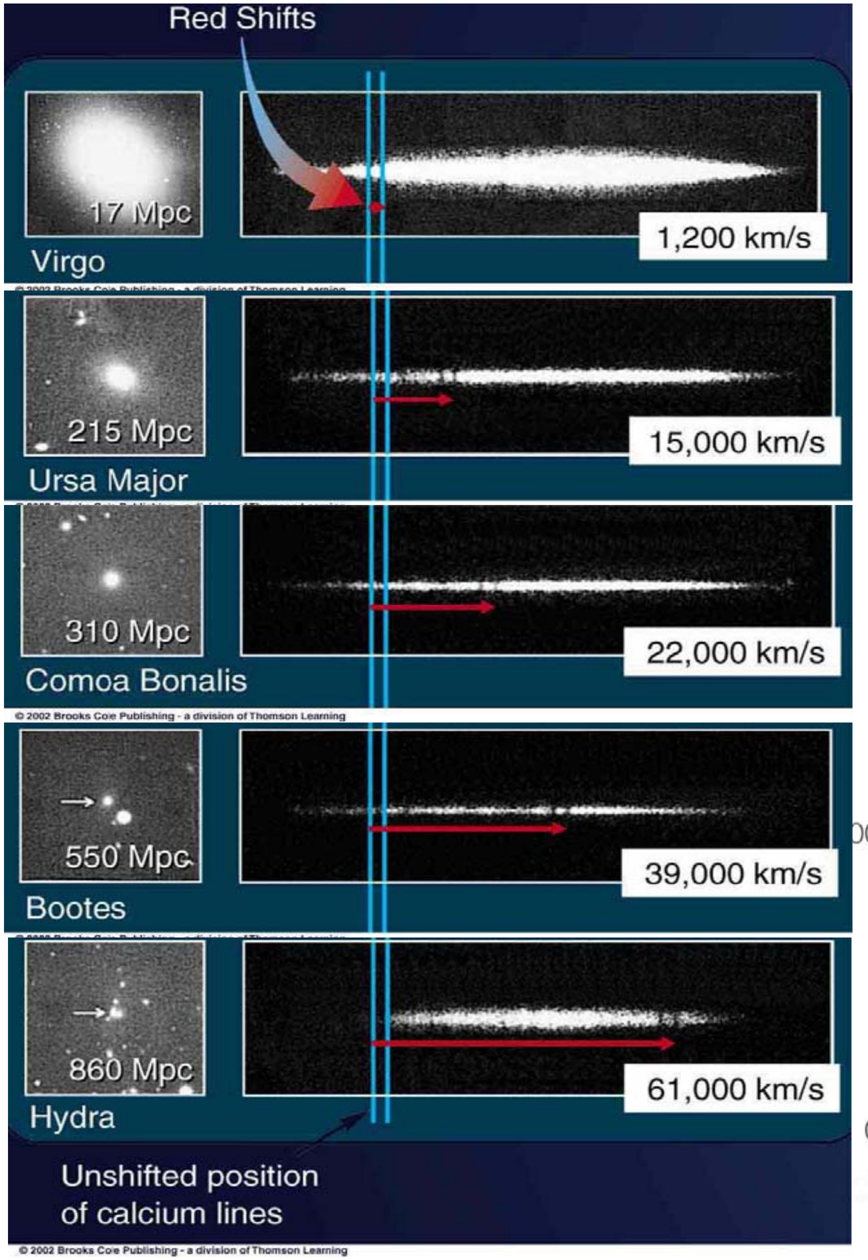
• The night sky should be as bright as the surface of stars!

Solution to Olbers's Paradox:

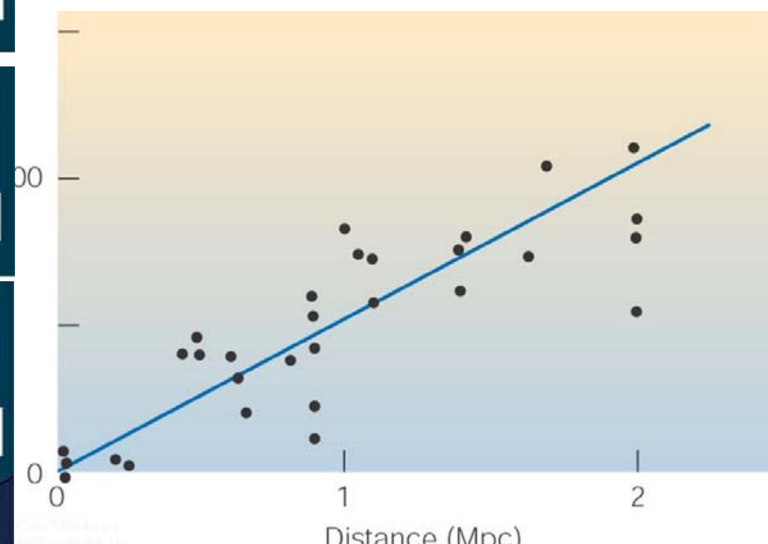
If the universe had a beginning, then we can only see light from galaxies that has had time to travel to us since the beginning of the universe.

• The visible universe is finite!

Hubble's Law



Distant galaxies are receding from us with a speed proportional to distance

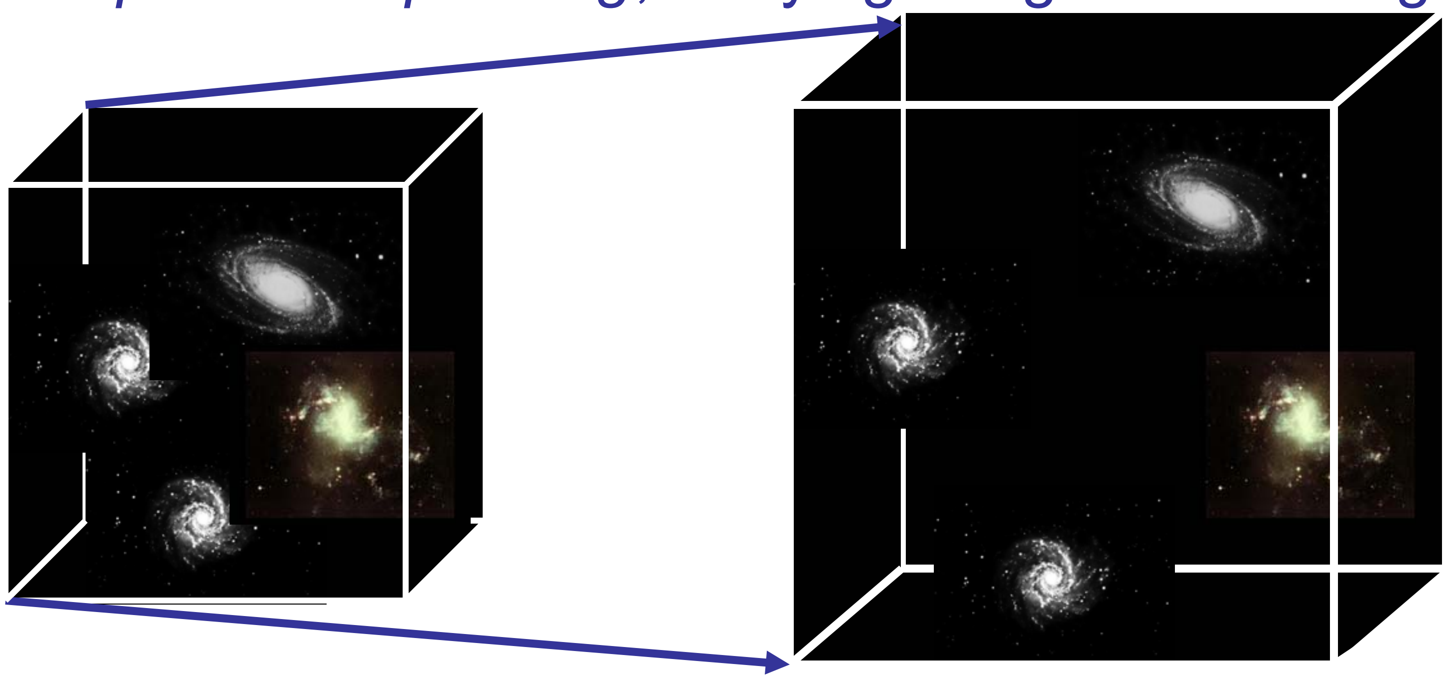


The Expanding Universe

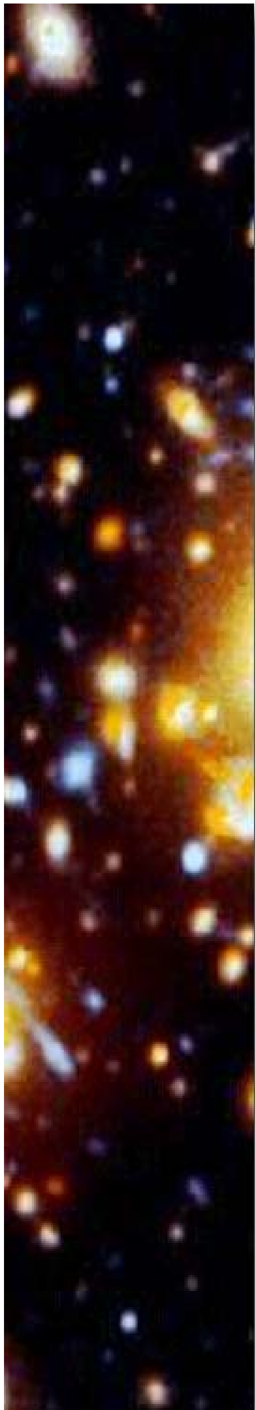
On large scales, galaxies are moving apart, with velocity proportional to distance.

It's not galaxies moving through space.

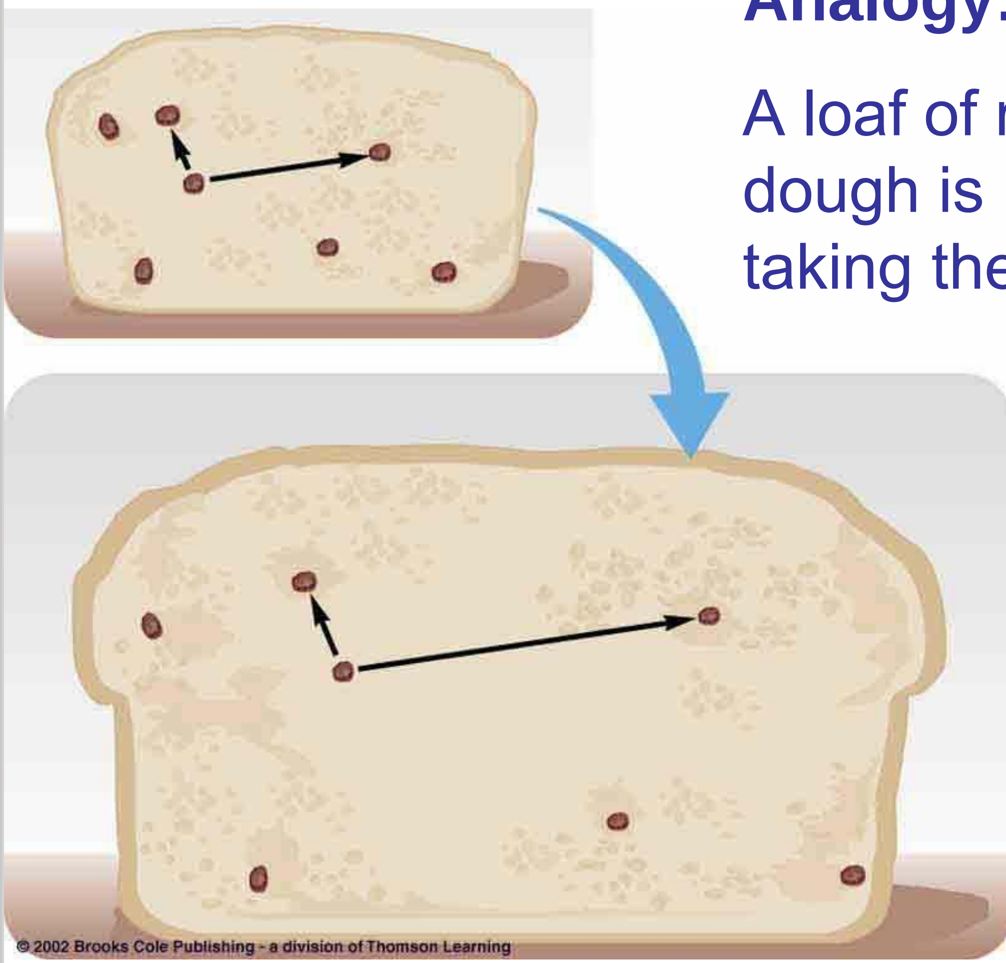
Space is expanding, carrying the galaxies along!



The galaxies themselves are not expanding!



Expanding Space

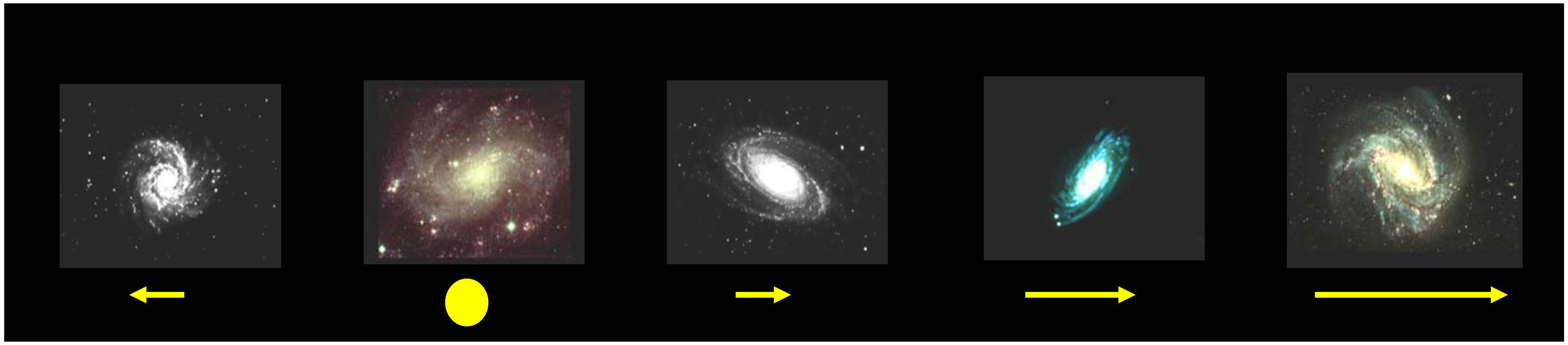


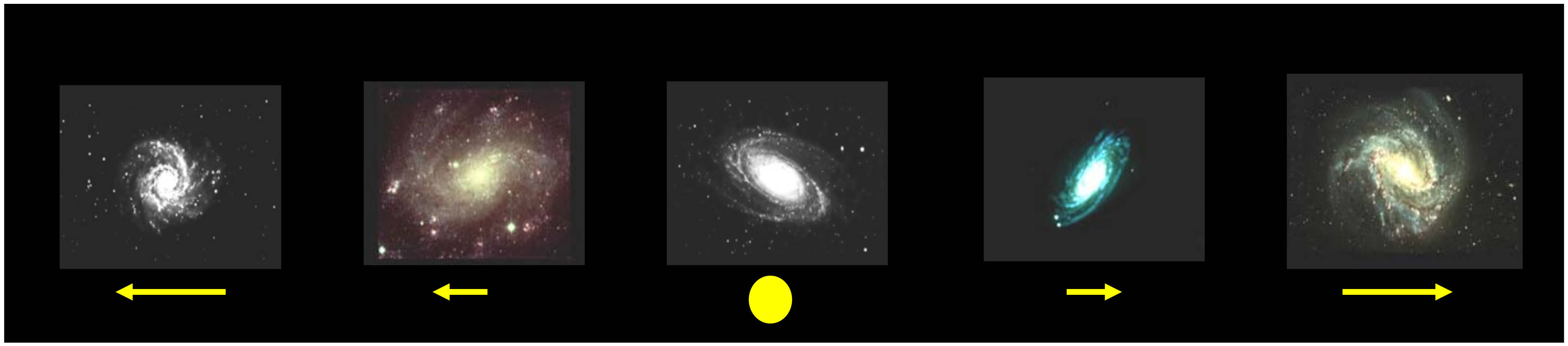
Analogy:

A loaf of raisin bread where the dough is rising and expanding, taking the raisins with it.

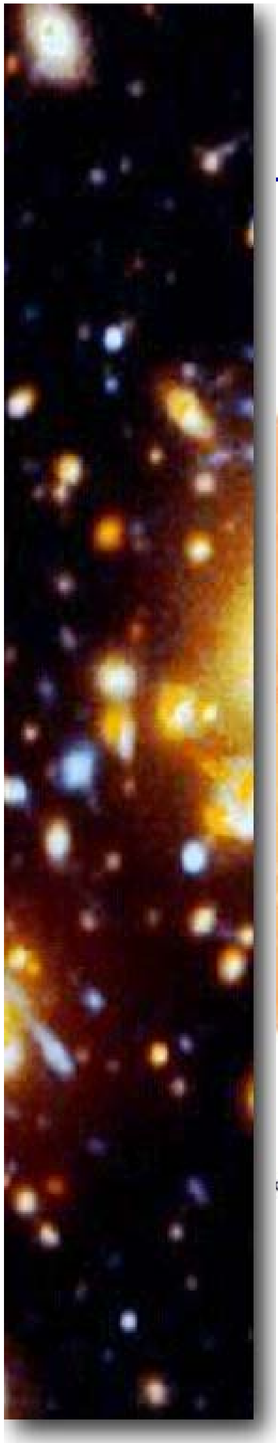
The Expanding Universe (2)

This does not mean that we are at the center of the universe!

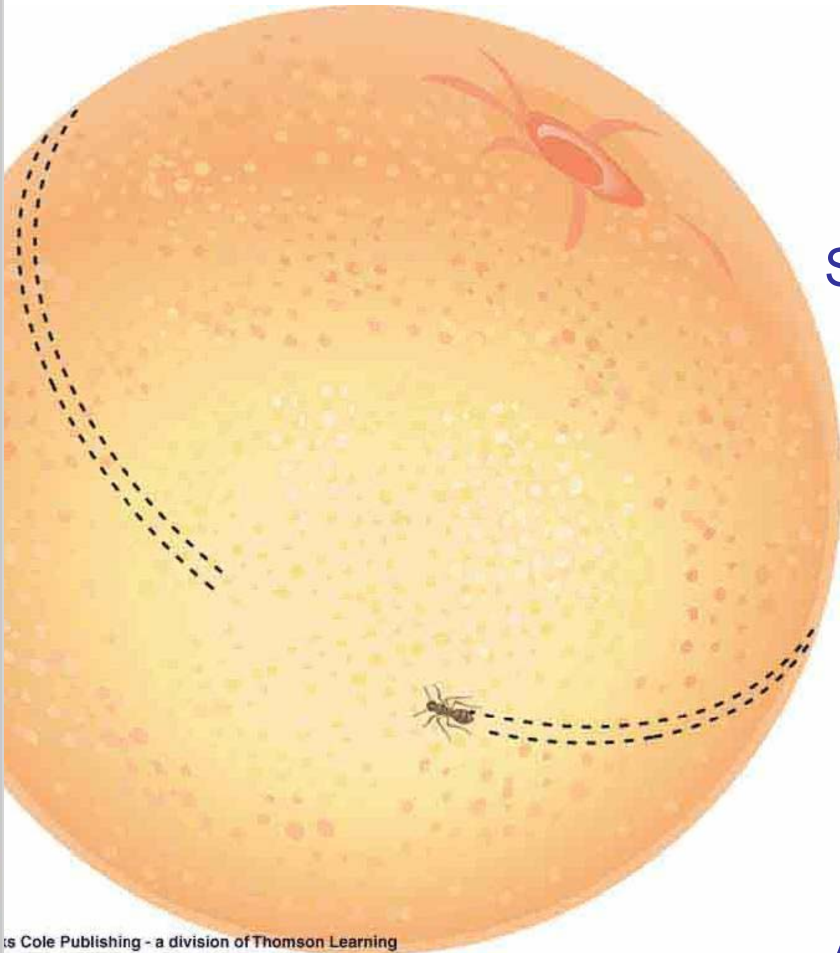




You have the same impression from any other galaxy as well.



Finite, But Without Edge?



<u>2-dimensional analogy:</u>
<u>Surface of a sphere:</u>

Surface is finite, but has no edge.

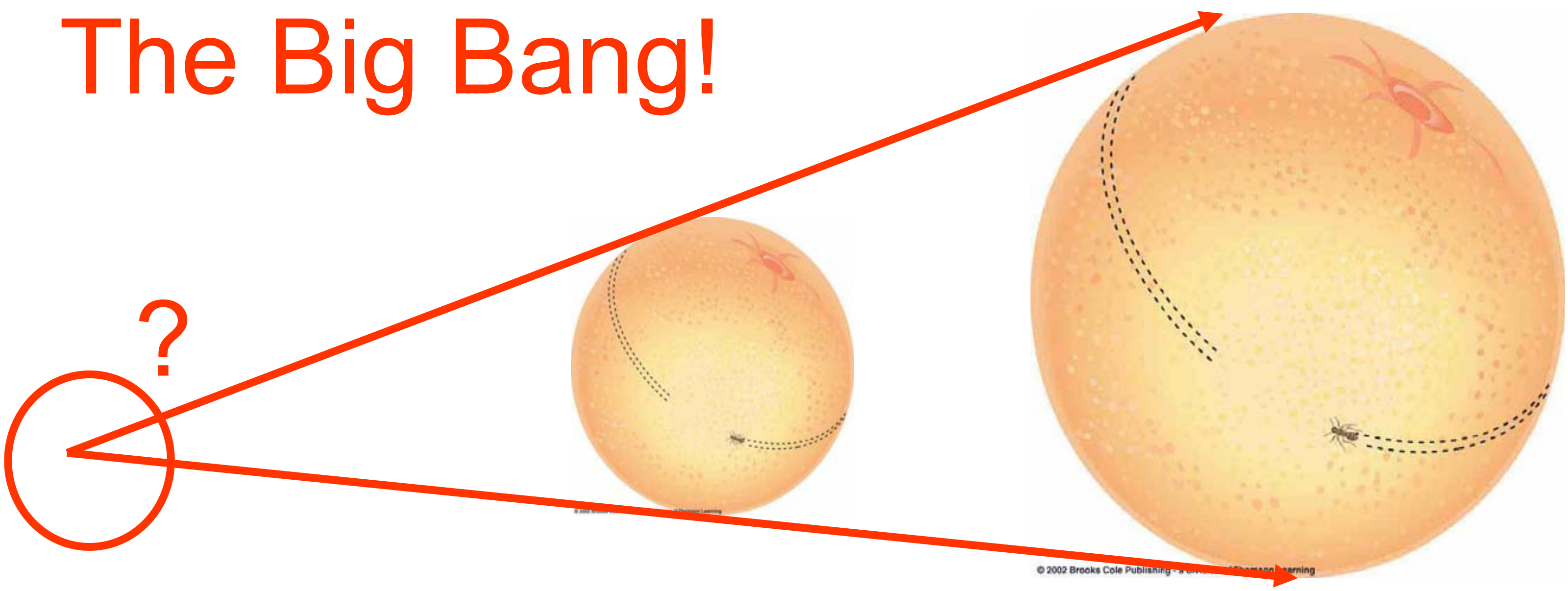
For a creature living on the sphere, having no sense of the third dimension, there's no center (on the sphere!): All points are equal.

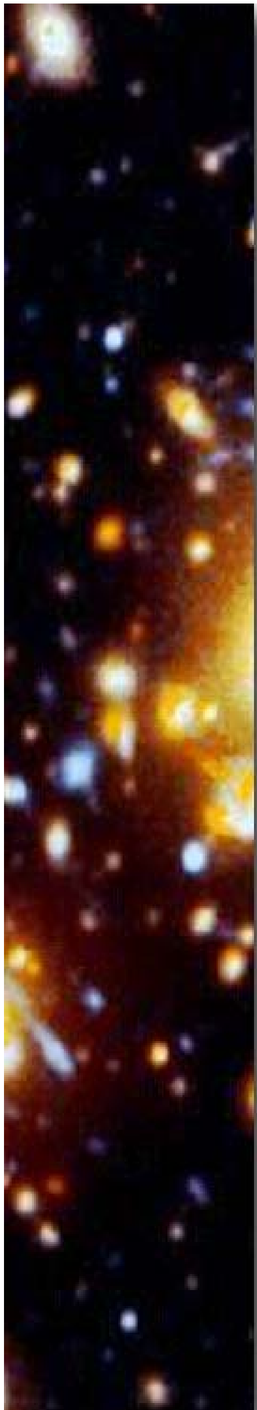
Alternative: Any point on the surface can be defined as the center of a coordinate system.

The Necessity of a Big Bang

If galaxies are moving away from each other with a speed proportional to distance, there must have been a beginning, when everything was concentrated in one single point:

The Big Bang!





The Age of the Universe

Knowing the current rate of expansion of the universe, we can estimate the time it took for galaxies to move as far apart as they are today:

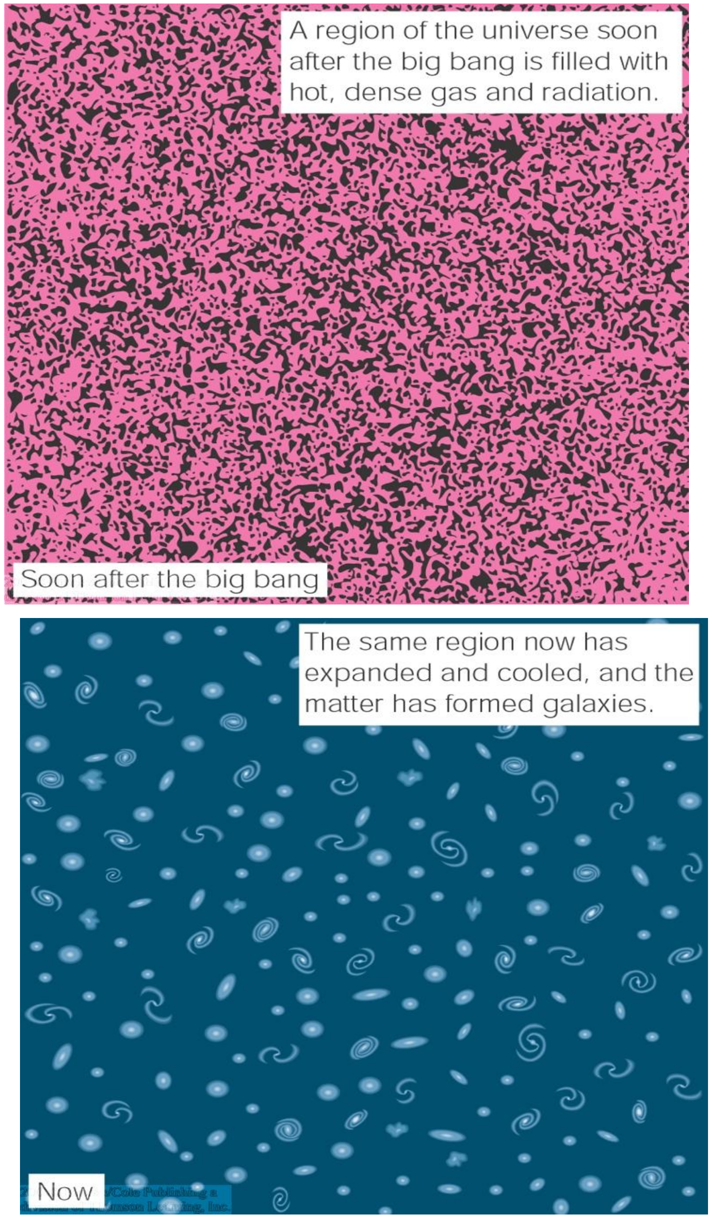
Time = distance / velocity

velocity = (Hubble constant) * distance

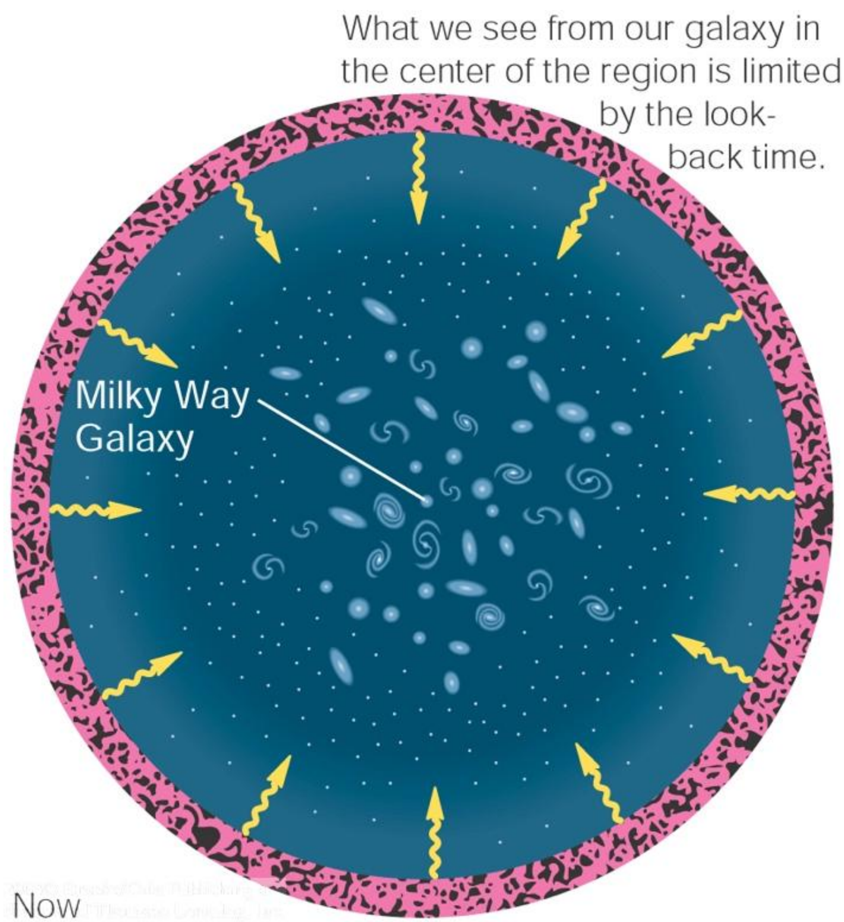
T ≈ d/v = 1/H ~ 14 billion years

The most distant galaxies known are seen as they were only about 1 billion years after the Big Bang.

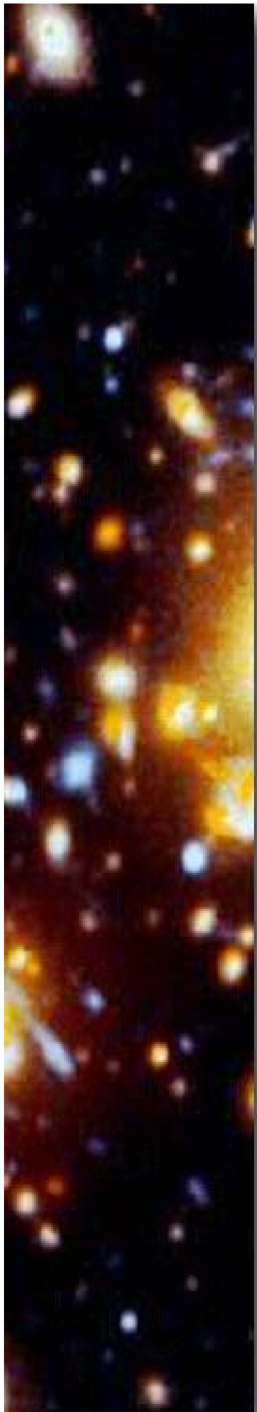
Looking Back Towards the Early Universe



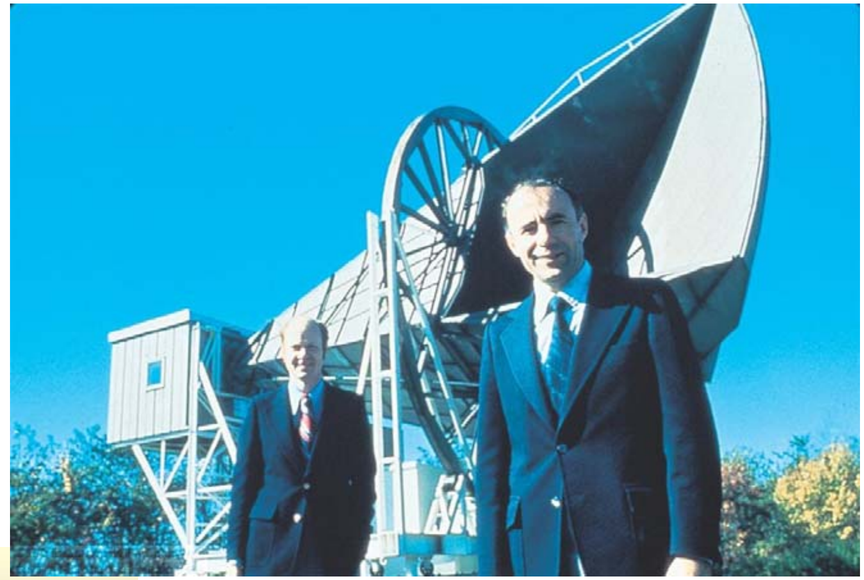
The more distant the objects we observe, the further back into the past of the universe we are looking.



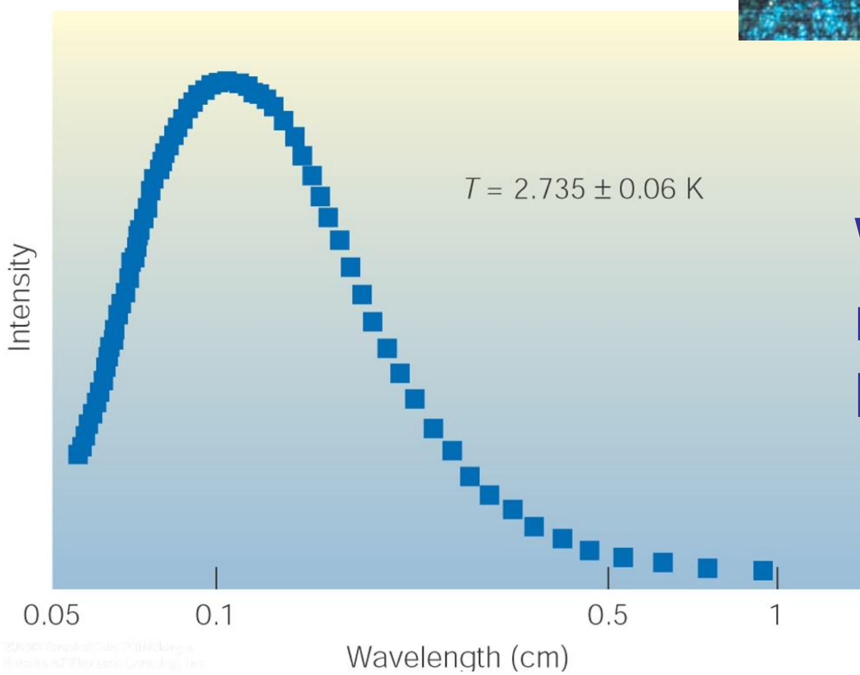
The Cosmic Background Radiation



The radiation from the very early phase of the universe should still be detectable today

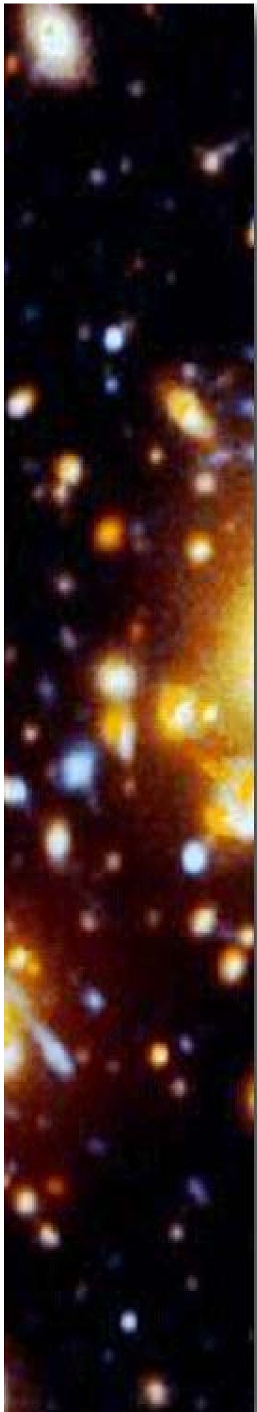


R. Wilson & A. Penzias

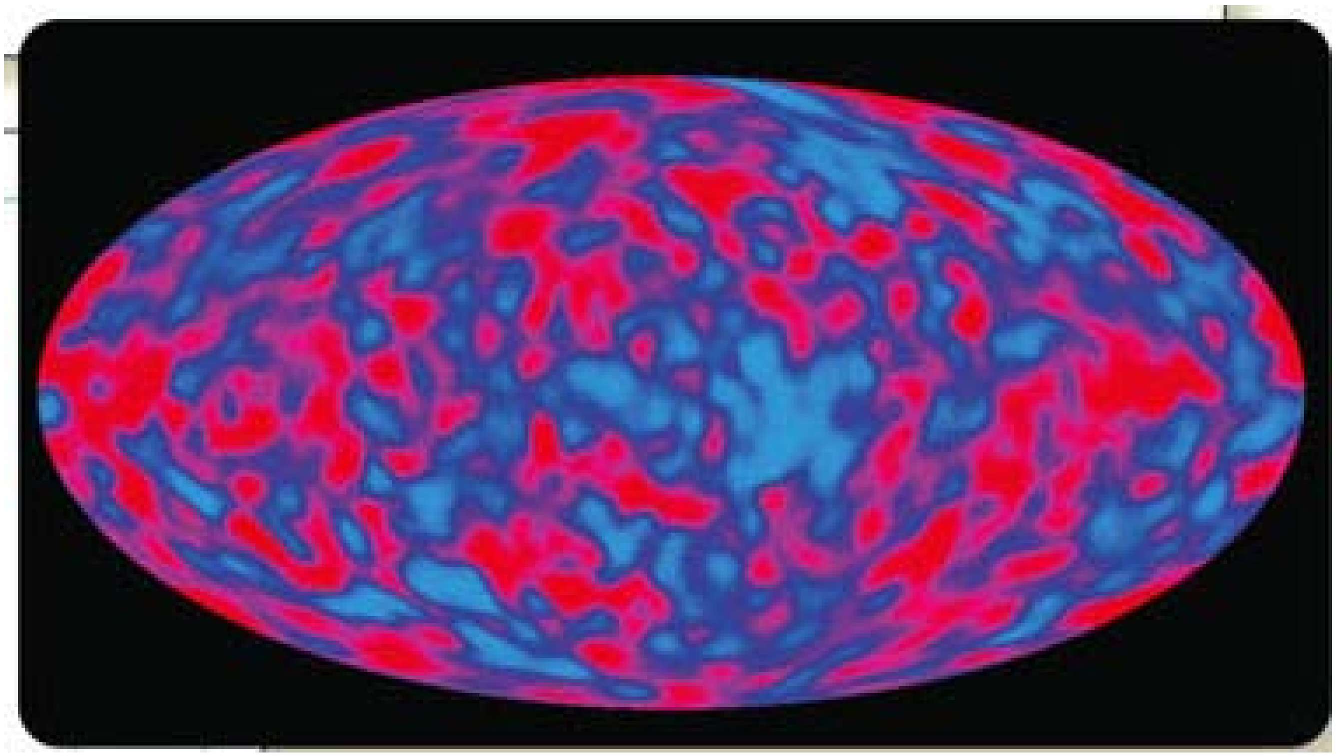


Was, in fact, discovered in mid-1960s as the **Cosmic Microwave Background:**

Blackbody radiation with a temperature of T = 2.73 K



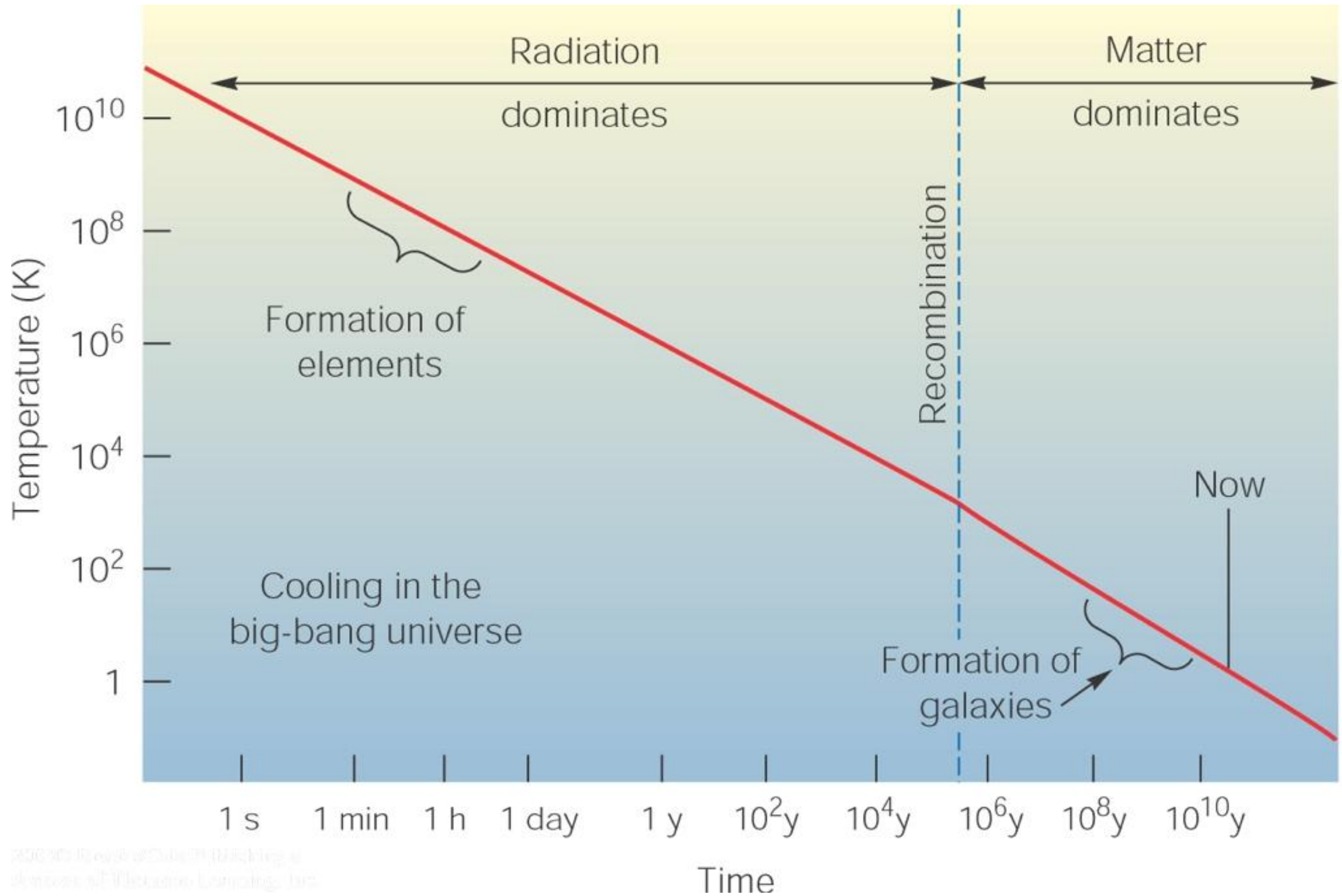
The Cosmic Background Radiation



The COBE satellite mapped the all-sky structure of the Cosmic Background Radiation.

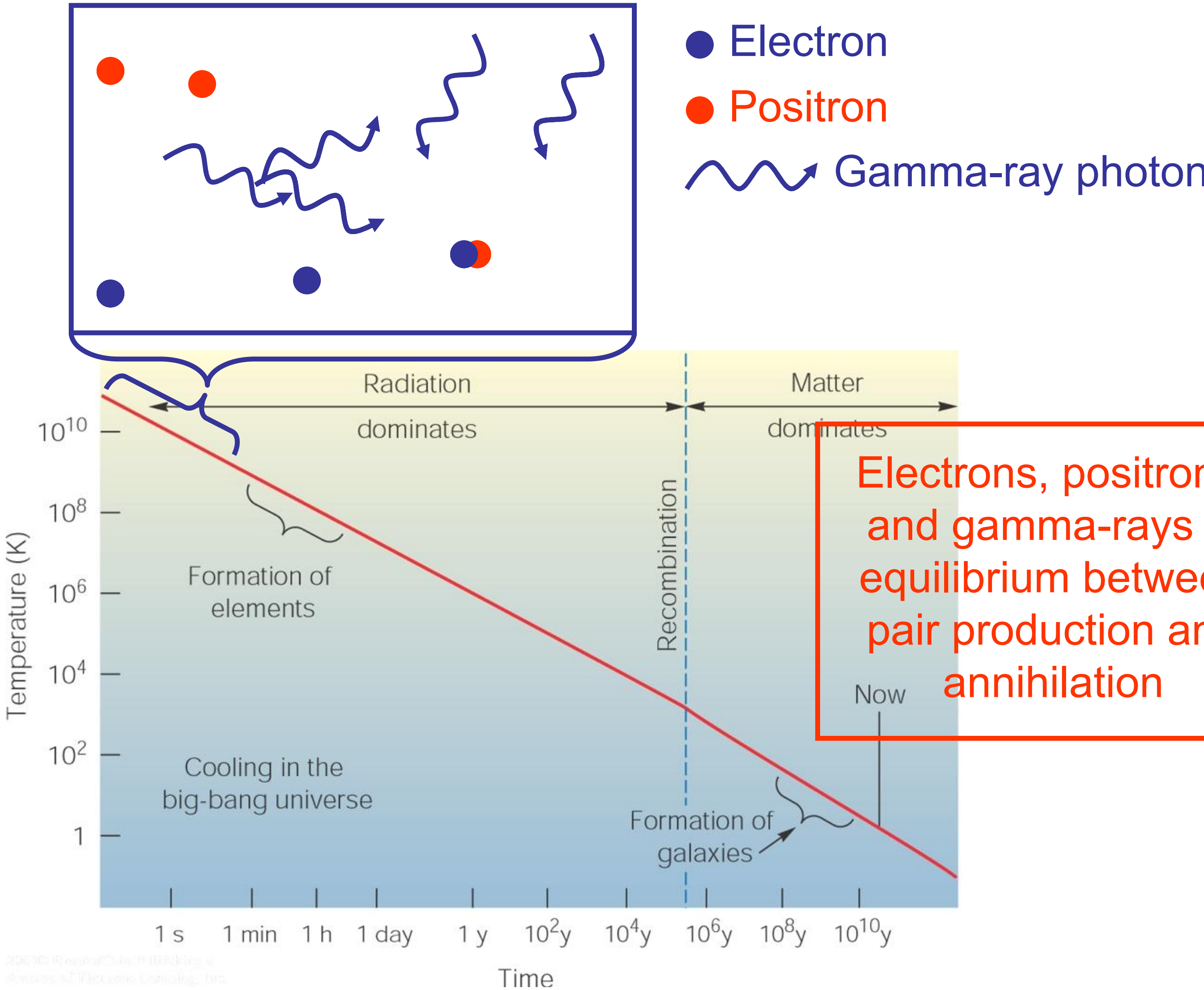
The History of the Universe

Universe cools down as time passes



Universe expands as time passes

The Early History of the Universe

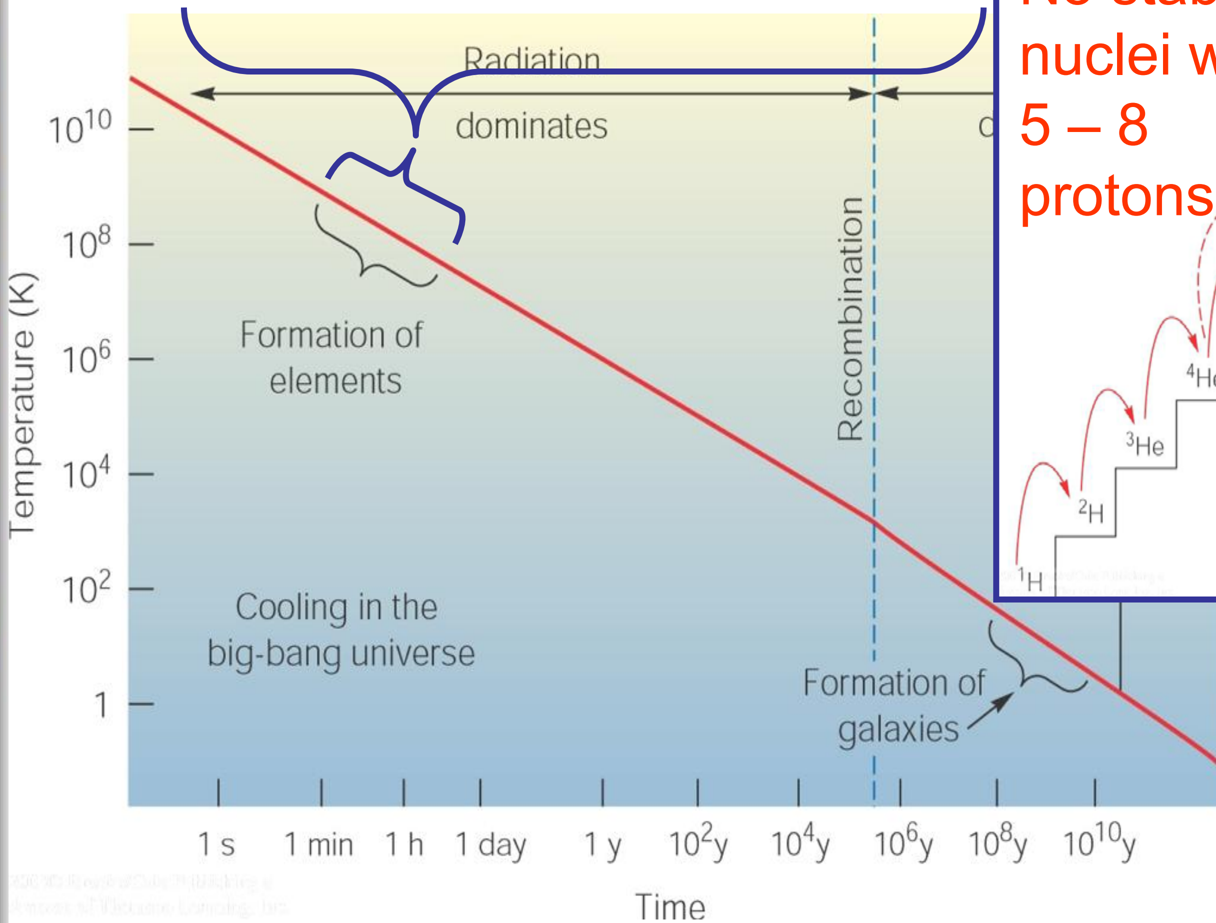


Electrons, positrons, and gamma-rays in equilibrium between pair production and annihilation

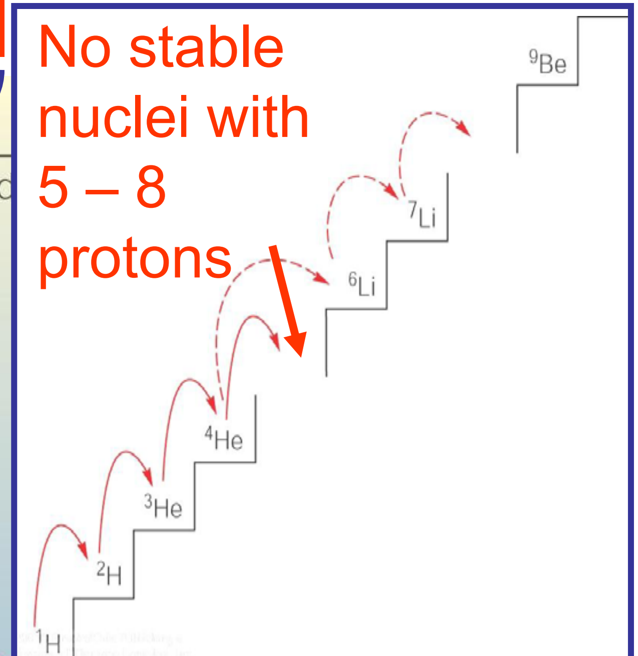
The Early History of the Universe (2)

Protons and neutrons form a few helium nuclei; the rest of protons remain as hydrogen nuclei

25% of mass in helium
75% in hydrogen



No stable nuclei with 5 – 8 protons

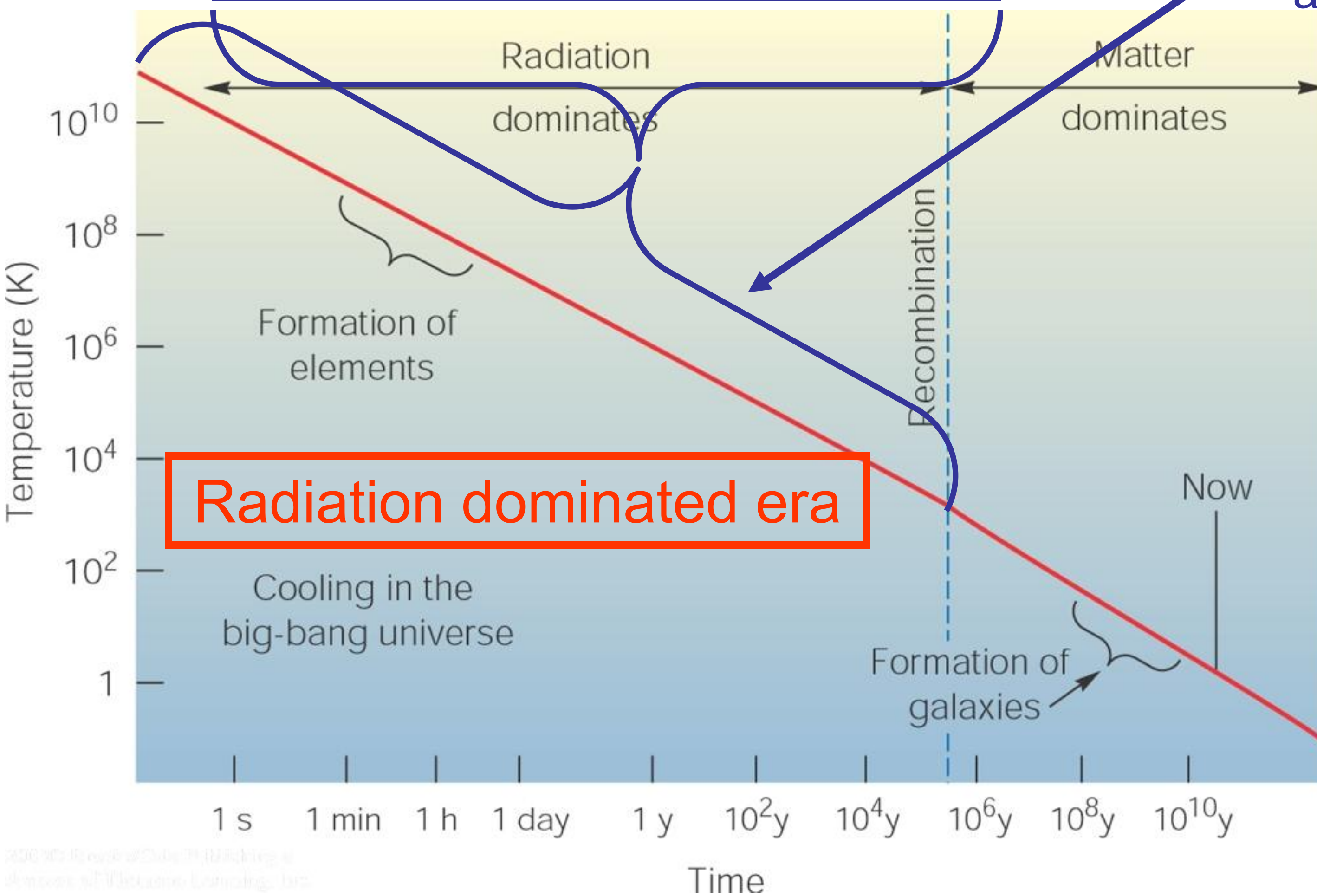


→ Almost no elements heavier than helium are produced.

The Early History of the Universe (3)

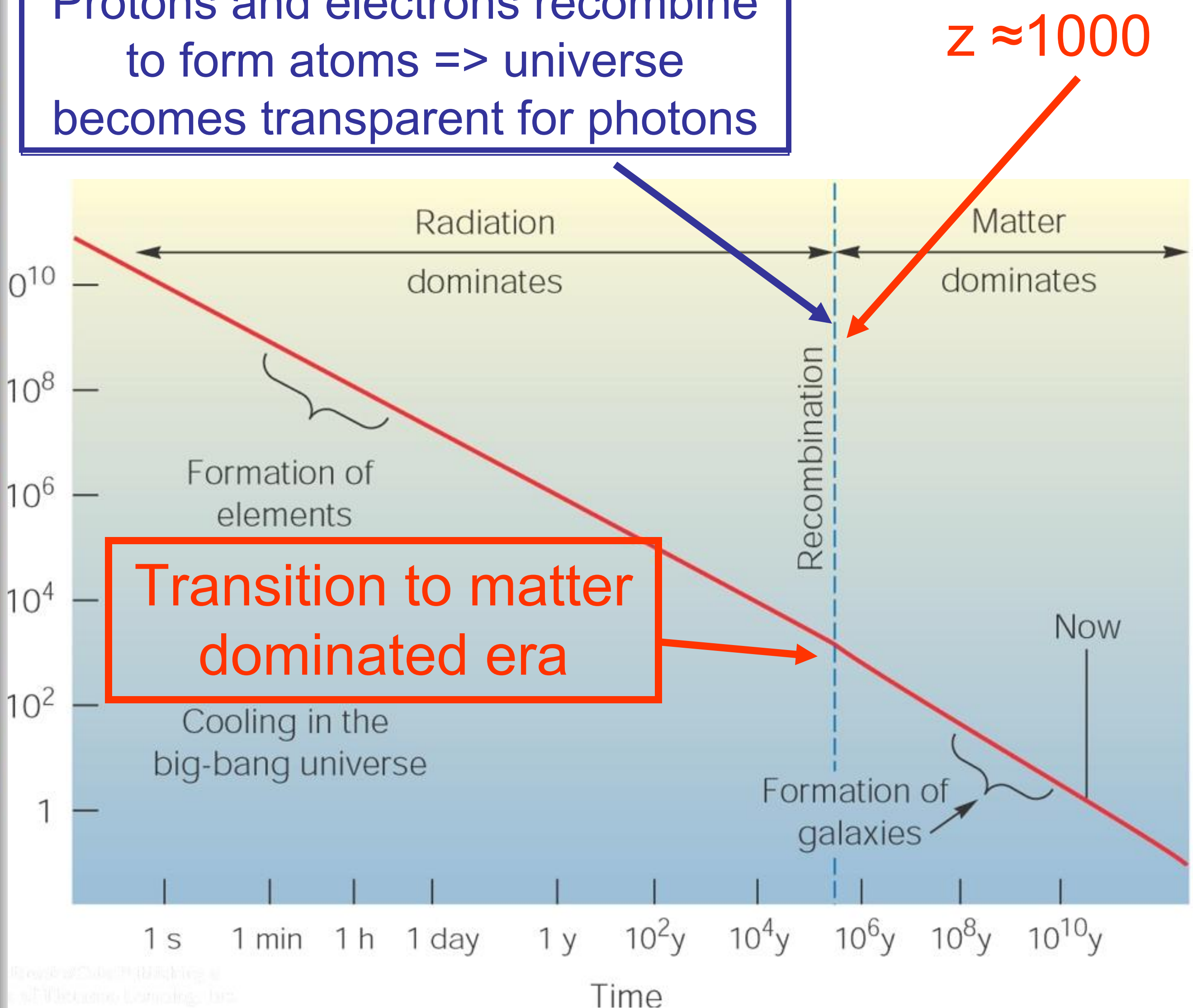
Photons are incessantly scattered by free electrons; photons are in equilibrium with matter

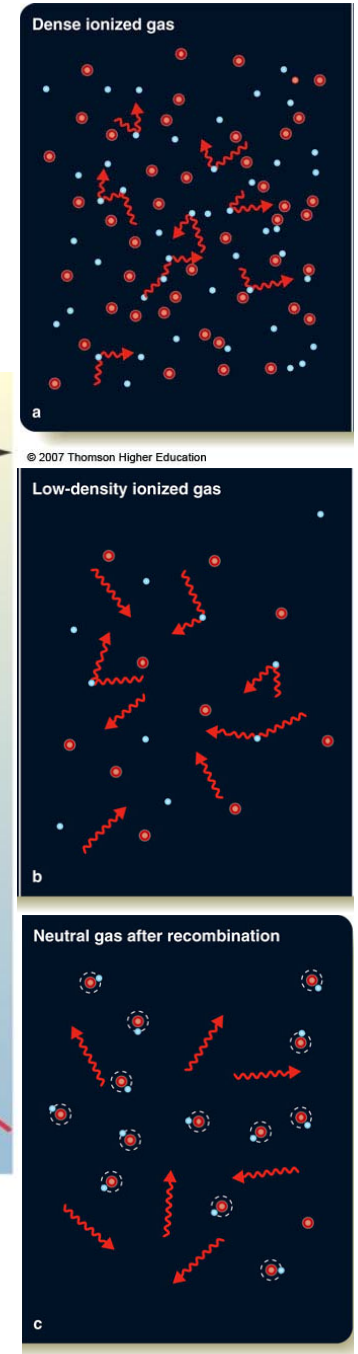
Photons have a blackbody spectrum at the same temperature as matter.



Recombination

Protons and electrons recombine to form atoms => universe becomes transparent for photons

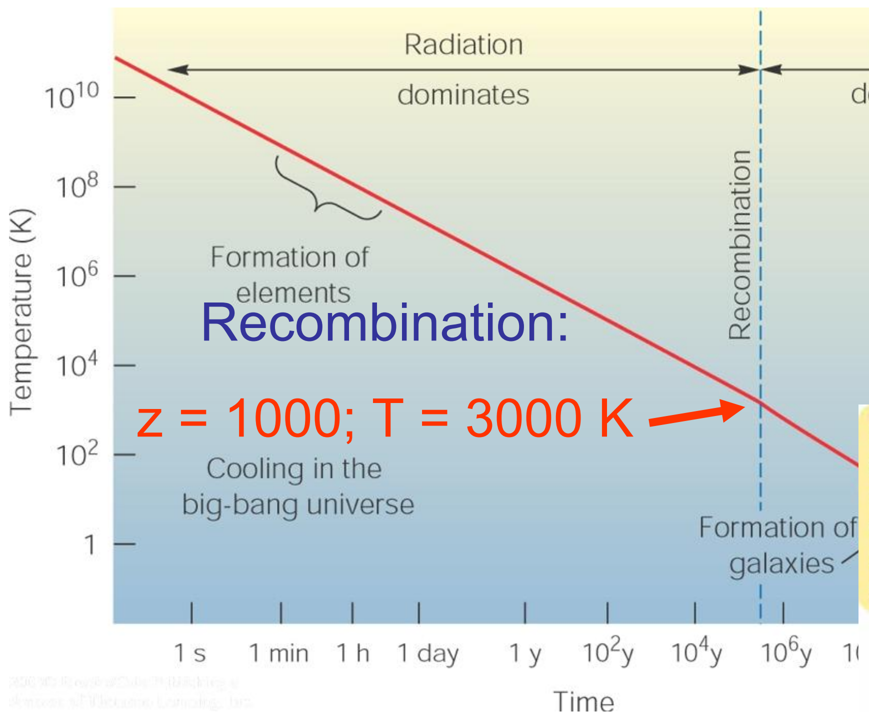




The Cosmic Background Radiation (2)

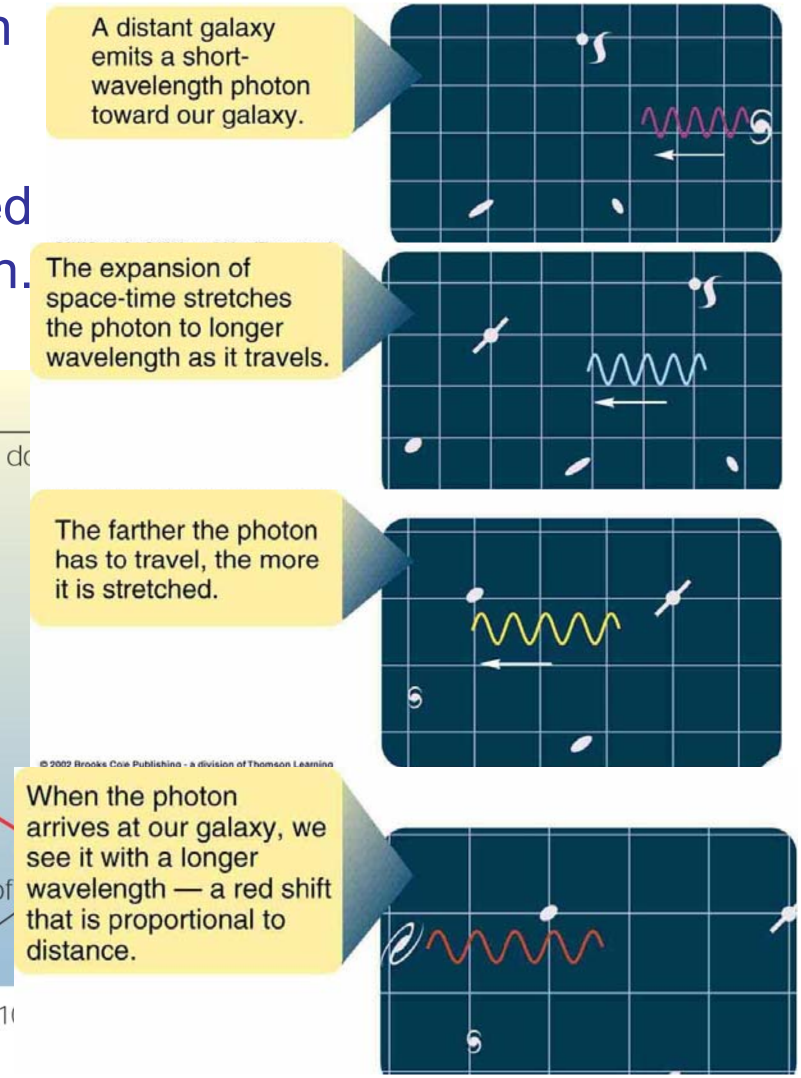
After recombination, photons can travel freely through space.

Their wavelength is only stretched (red shifted) by cosmic expansion.



Recombination:

z = 1000; T = 3000 K

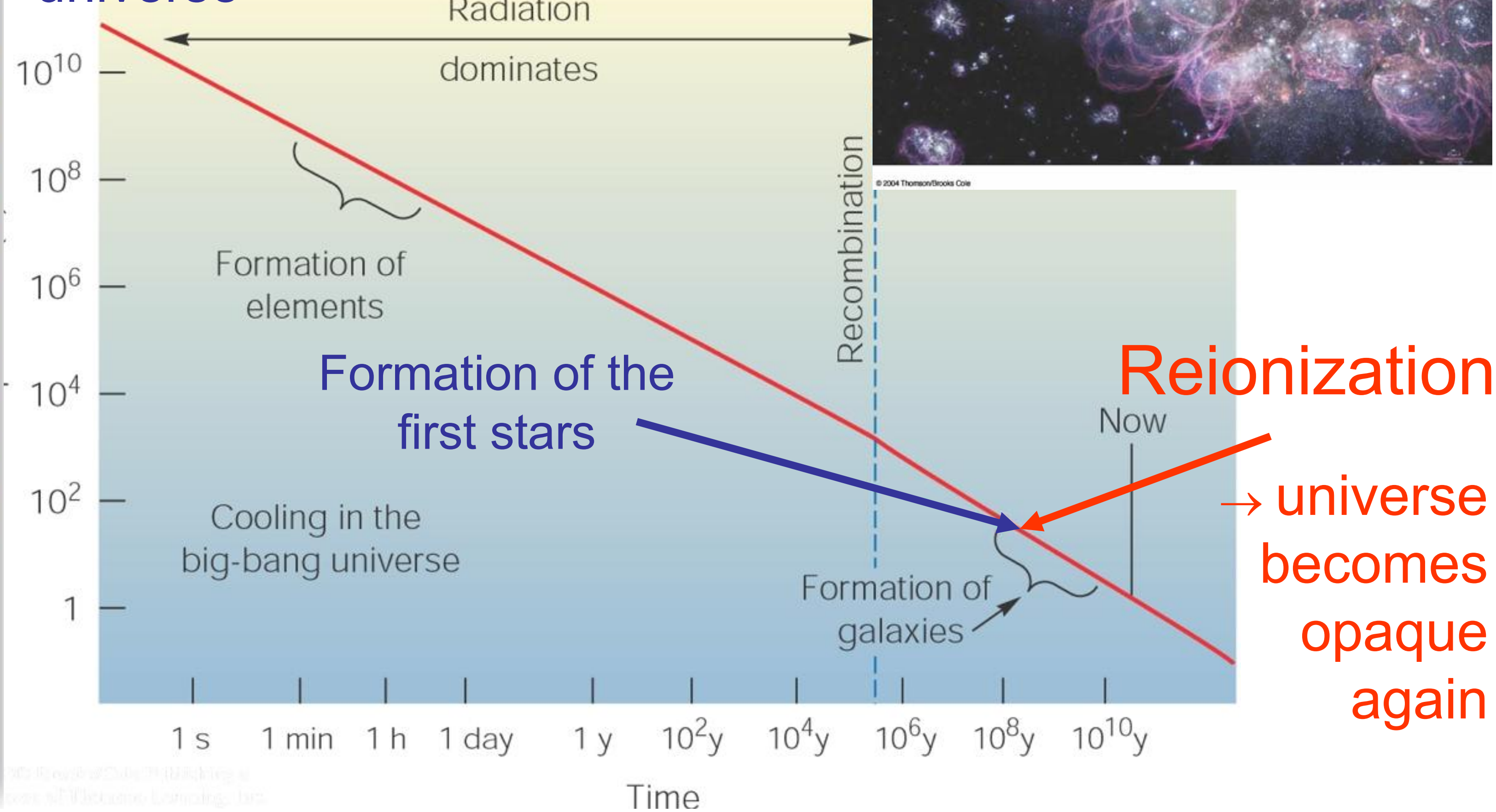


This is what we can observe today as the *cosmic background radiation*!

Reionization

After less than ~ 1 billion years, the first stars form.

Ultraviolet radiation from the first stars re-ionizes gas in the early universe

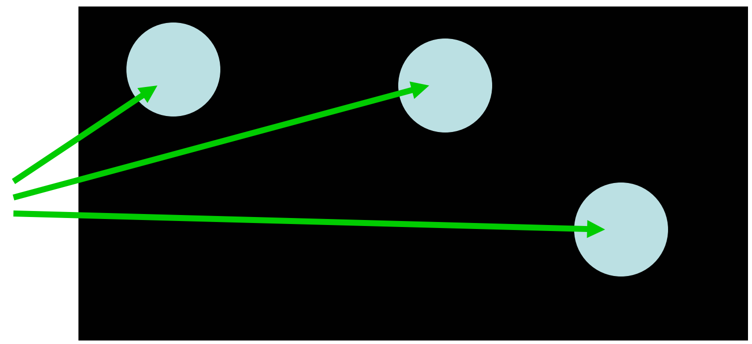


The Cosmological Principle

Considering the largest scales in the universe, we make the following fundamental assumptions:

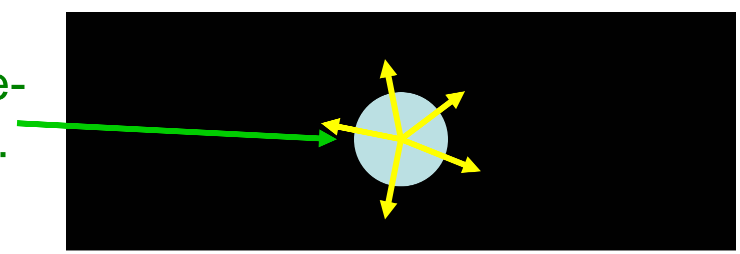
1) Homogeneity: On the largest scales, the local universe has the same physical properties throughout the universe.

Every region has the same physical properties (mass density, expansion rate, visible vs. dark matter, etc.)



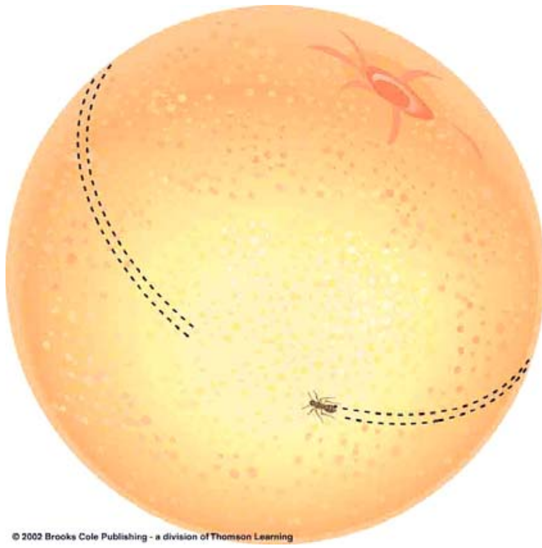
2) Isotropy: On the largest scales, the local universe looks the same in any direction that one observes.

You should see the same large-scale structure in any direction.



3) Universality: The laws of physics are the same everywhere in the universe.

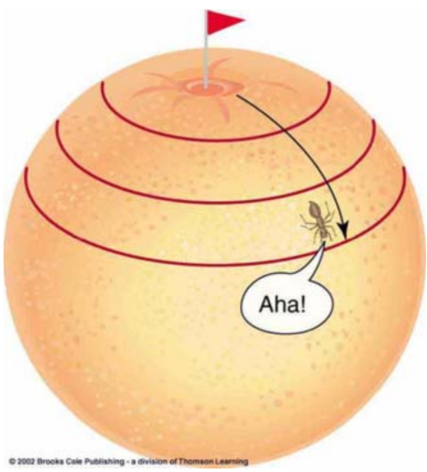
Shape and Geometry of the Universe

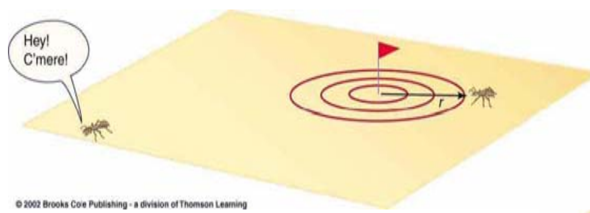


Back to our 2-dimensional analogy:

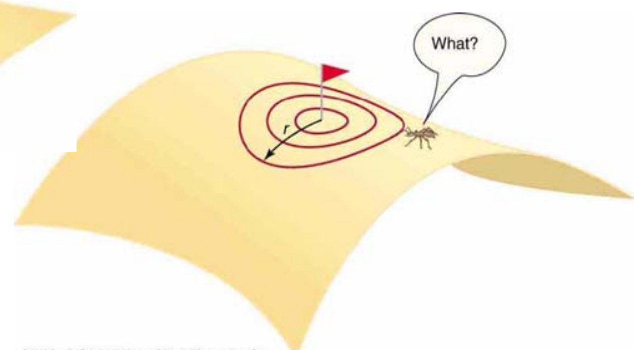
How can a 2-D creature investigate the geometry of the sphere?

Measure curvature of its space!





Flat surface (zero curvature)



Closed surface (positive curvature)

Open surface (negative curvature)

Cosmology and General Relativity

According to the theory of general relativity, gravity is caused by

the curvature of space-time.

The effects of gravity on the largest cosmological scales should be related to the curvature of space-time!

The curvature of space-time, in turn, is determined by the distribution of mass and energy in the universe.

Space-time tells matter how to move;

matter tells space-time how to curve.

Deceleration of the Universe

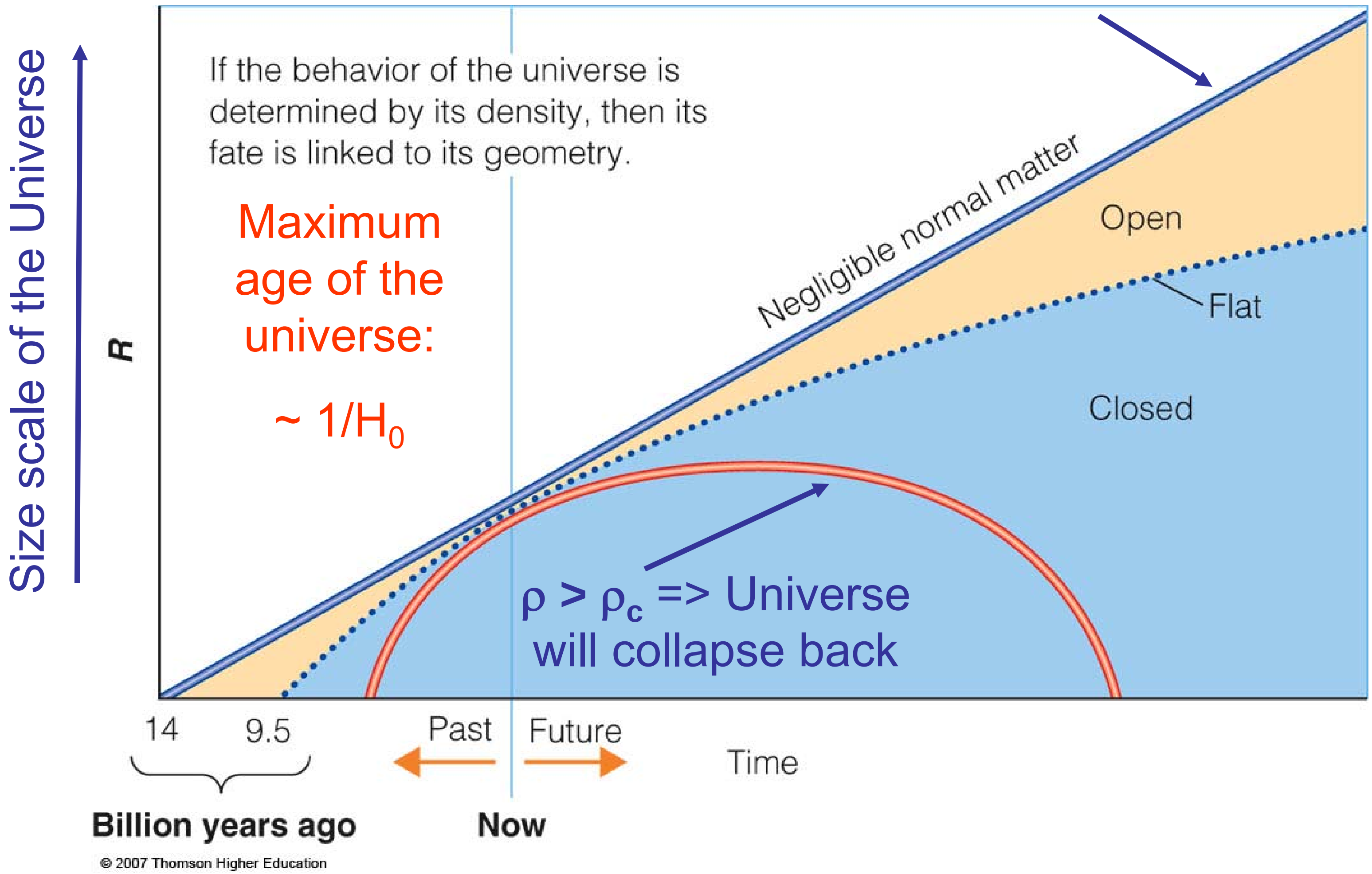
- Expansion of the universe should be slowed down by mutual gravitational attraction of the galaxies.

- Fate of the universe depends on the matter density in the universe.

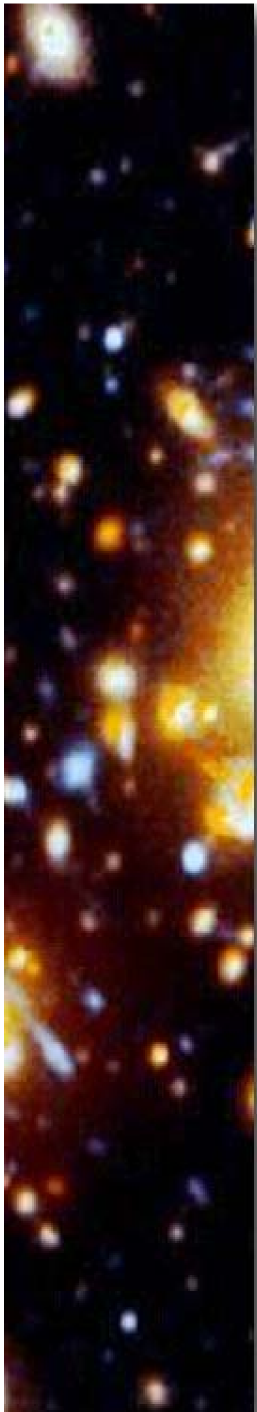
- Define “critical density”, ρ_c, which is just enough to slow the cosmic expansion to a halt at infinity.

Model Universes

$\rho < \rho_c$ => universe will expand forever



If the density of matter equaled the critical density, then the curvature of space-time by the matter would be just sufficient to make the geometry of the universe flat!



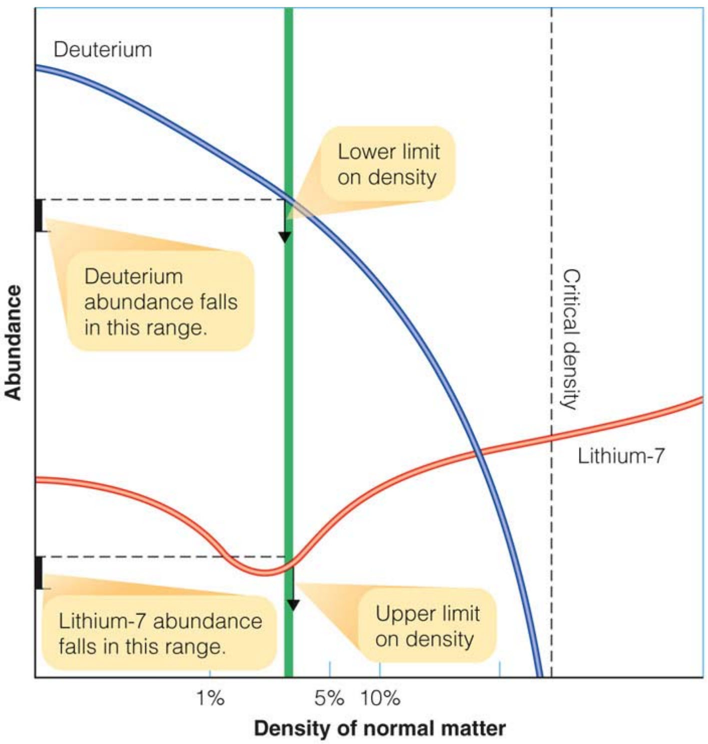
Dark Matter

• Combined mass of all "visible" matter (i.e. emitting any kind of radiation) in the universe adds up to much less than the critical density.

• Gravitational lensing shows that some clusters contain 10 times as much mass as is directly visible.

The Nature of Dark Matter

Can dark matter be composed of *normal matter?*

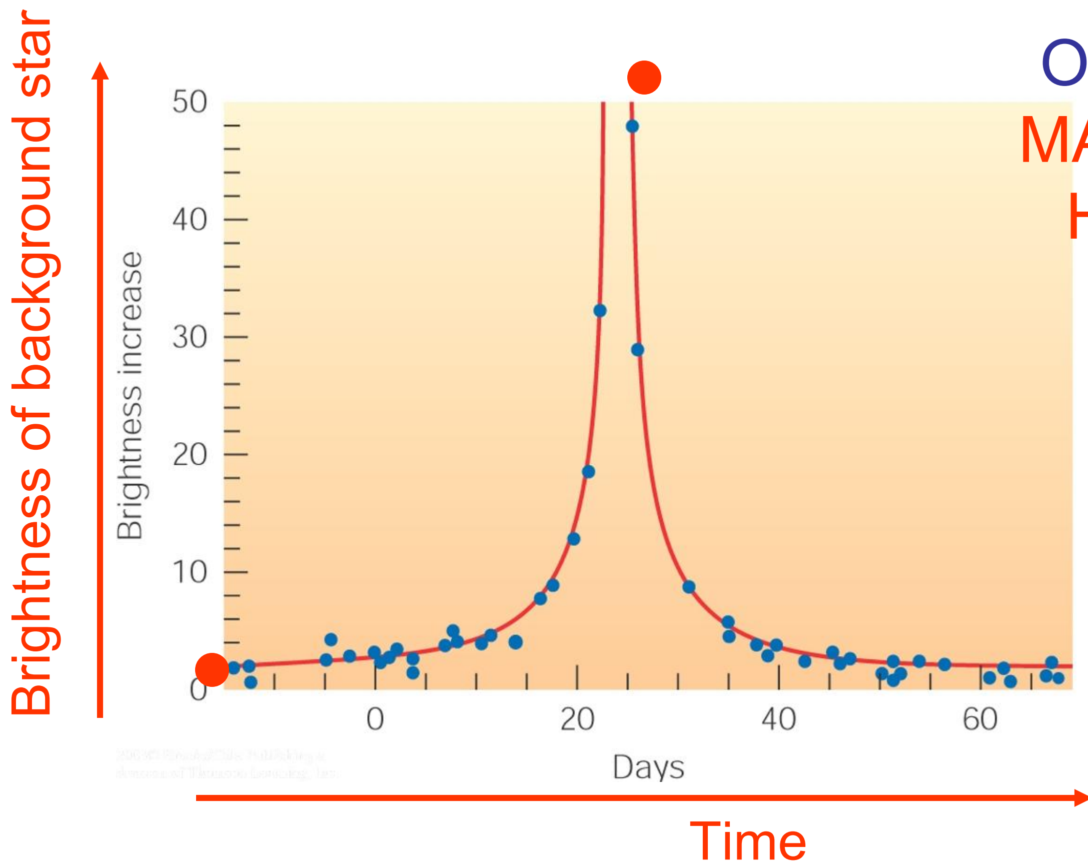


- If so, then its mass would mostly come from protons and neutrons = baryons
- The density of baryons right after the big bang leaves a unique imprint in the abundances of deuterium and lithium.
- Density of baryonic matter is only ~ 4 % of critical density.

- Most dark matter must be non-baryonic!

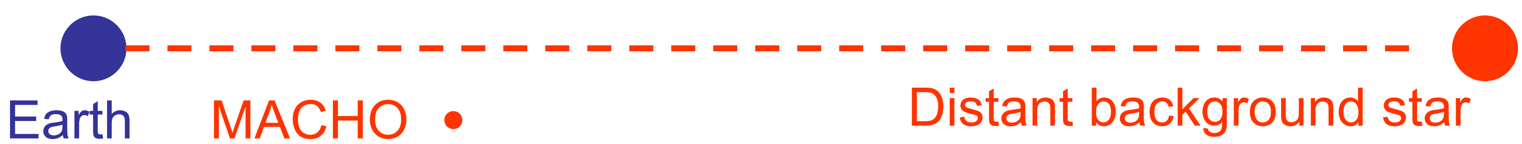
Baryonic Dark Matter

Nature of baryonic dark matter still very uncertain and speculative.



One component: MAssive Compact Halo Objects = "MACHOs":

Small compact objects (e.g., brown dwarfs, small black holes) acting as gravitational lenses.



Problems with the Classical, Decelerating Universe

1) The flatness problem:

The universe seems to be nearly flat.

Even a tiny deviation from perfect flatness at the time of the big bang should have been amplified to a huge deviation today.

=> *Extreme fine tuning required!*

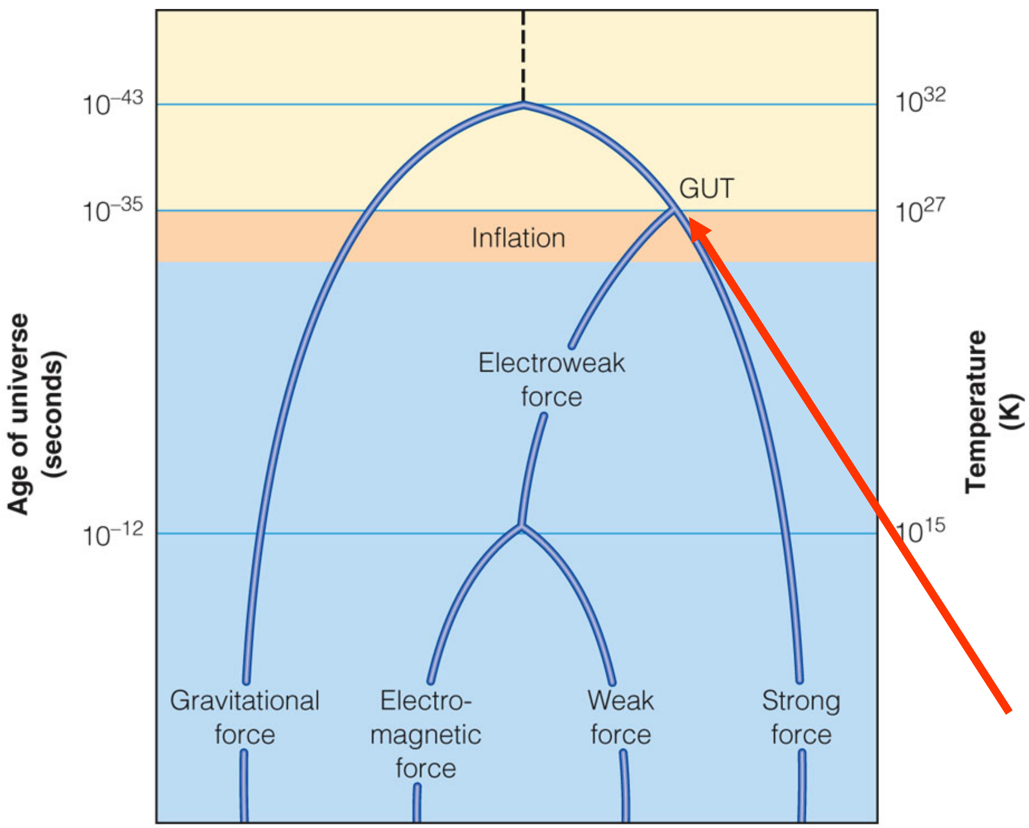
2) The isotropy of the cosmic background:

If information can only travel through the universe at the speed of light, then structure in the cosmic background should not be correlated over large angular scales!

$\Rightarrow$ Contradiction to almost perfect isotropy of the cosmic background!

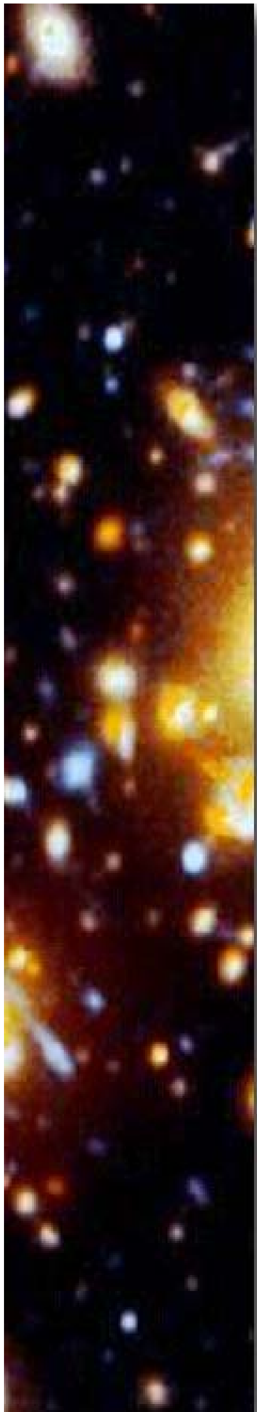
21st Century Cosmology

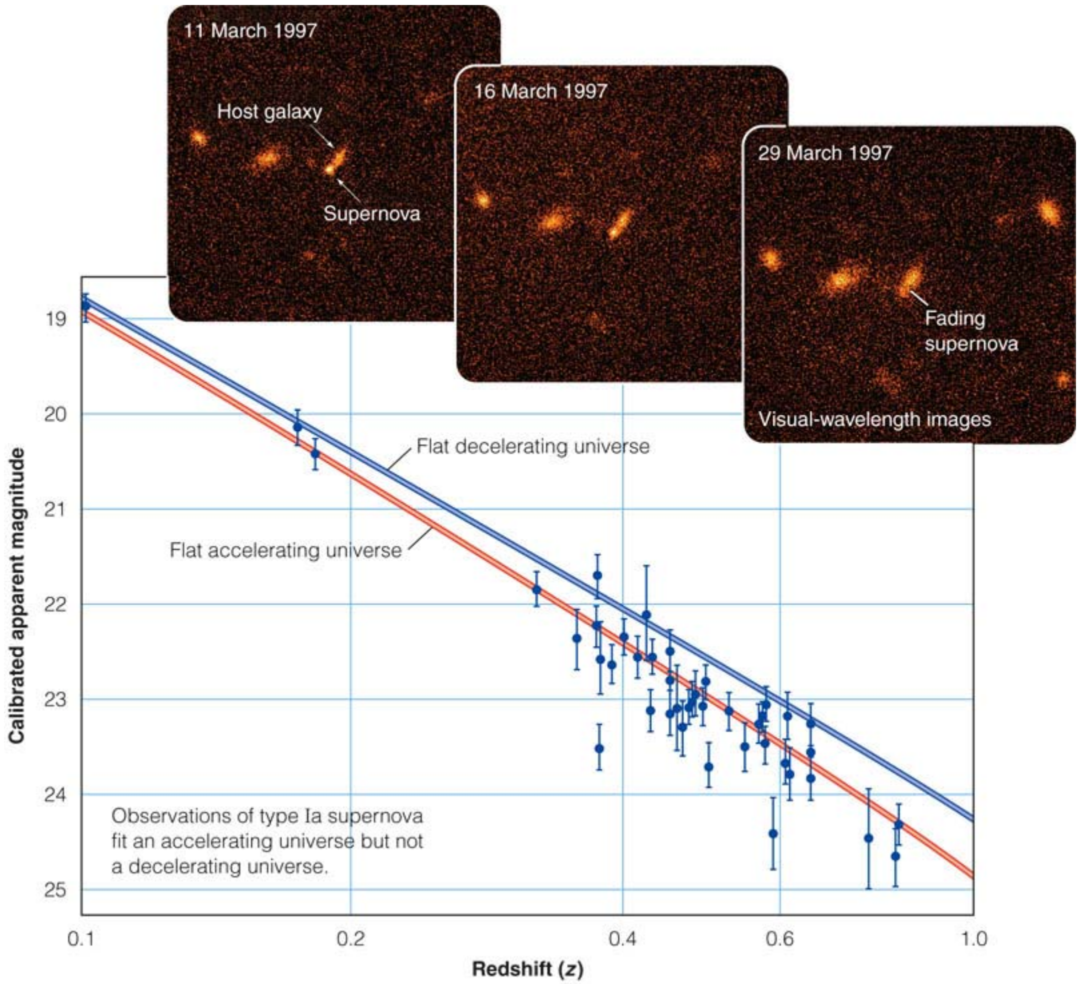
The solution: **Inflation!**



- Inflation: period of sudden expansion during the very early evolution of the universe
- Triggered by the sudden energy release from the decoupling of the strong and electroweak forces

Measuring the Deceleration of the Universe





By observing type Ia supernovae, astronomers can measure the Hubble relation at large distances

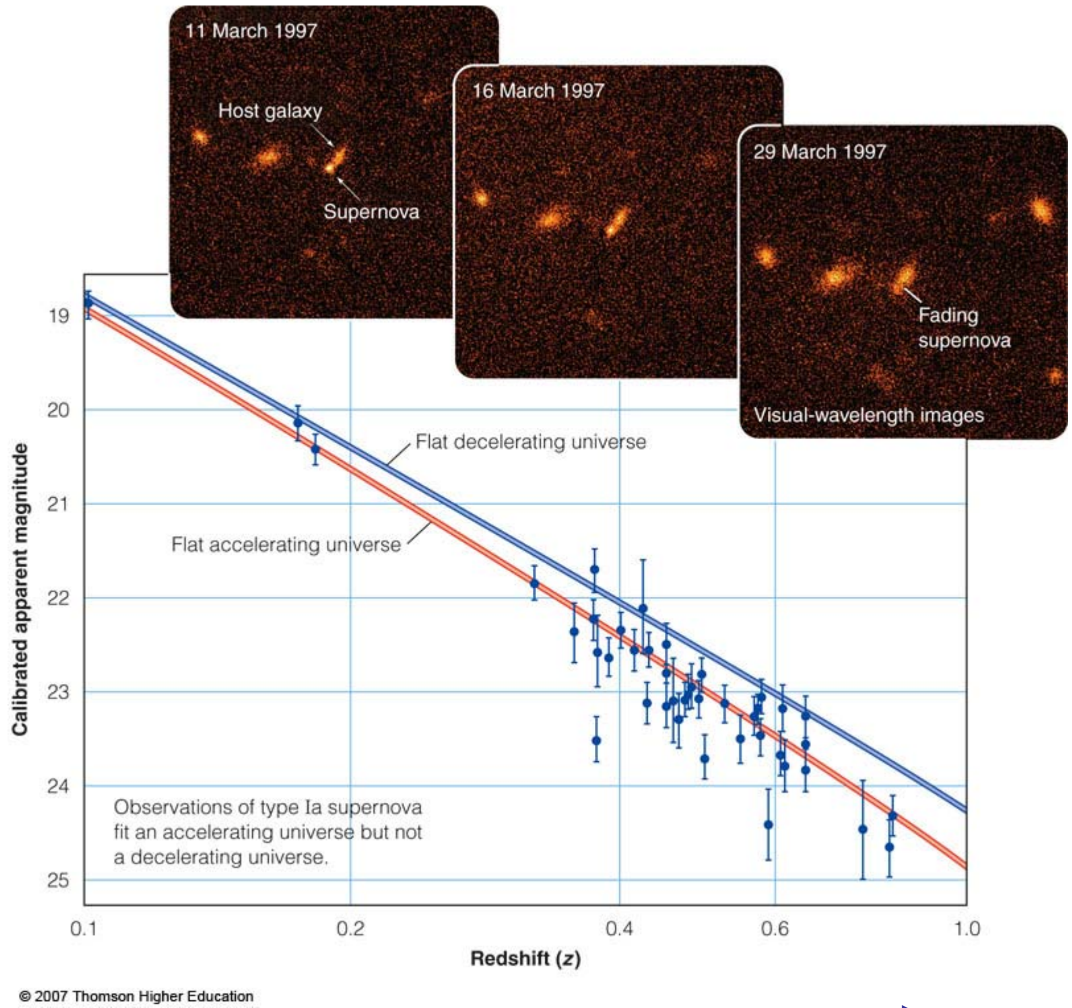
Distance ← recession speed

Size scale of the universe ← rate of expansion

It was expected that this would measure the deceleration of the universe, but …

The Accelerating Universe

Apparent Magnitude of Type Ia Supernovae

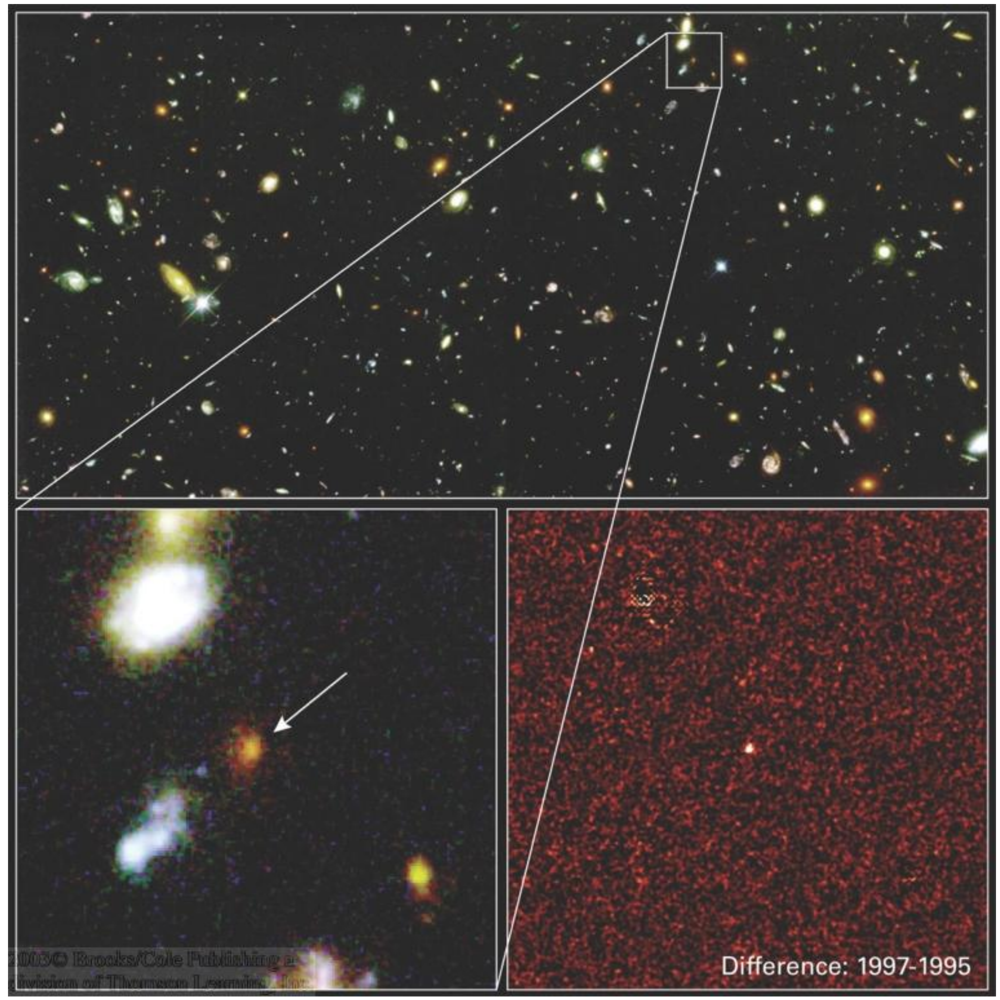


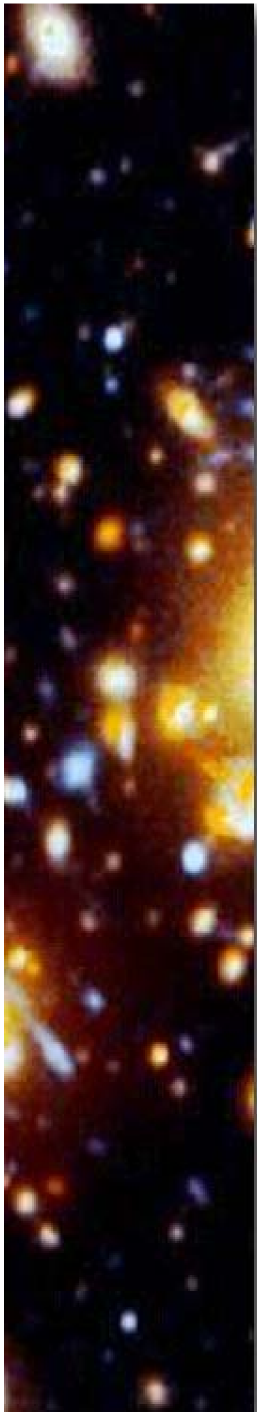
Red Shift z

In fact, SN Ia measurements showed that the universe is accelerating!

Confirmation of the Acceleration

Observation of the high-red-shift (z = 1.7) SN Ia SN1997ff seems to confirm the acceleration of the universe.





The Cosmological Constant

- Cosmic acceleration can be explained with the "Cosmological Constant", Λ (upper-case lambda)

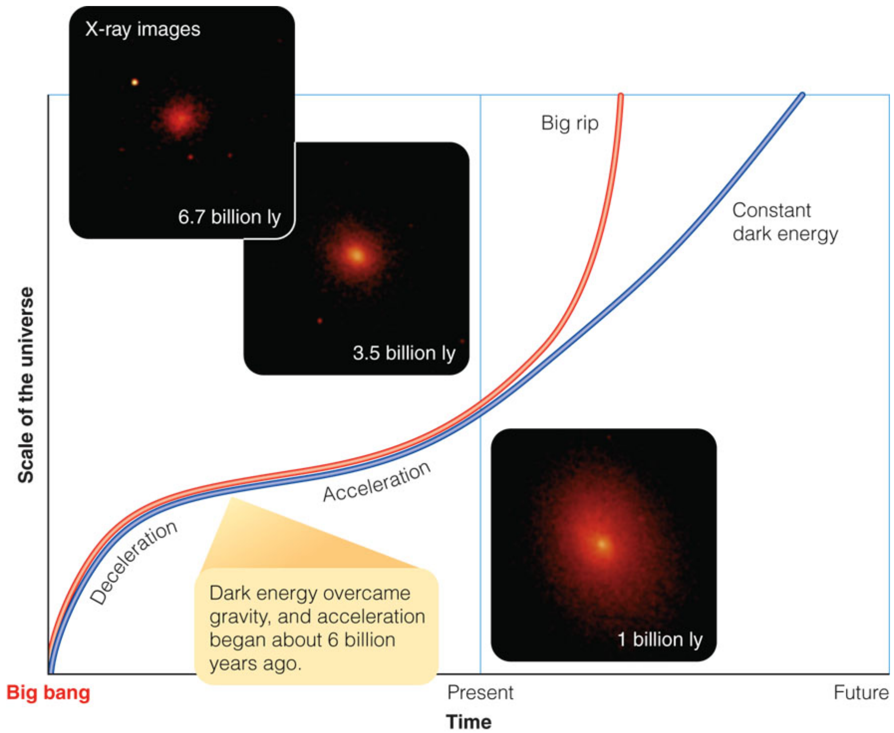
- Λ is a free parameter in Einstein's fundamental equation of general relativity; previously believed to be 0.

- Energy corresponding to Λ can account for the missing mass/energy ($E = m^*c^2$) needed to produce a flat space-time.

$\rightarrow$"Dark Energy"

The Fate of the Universe

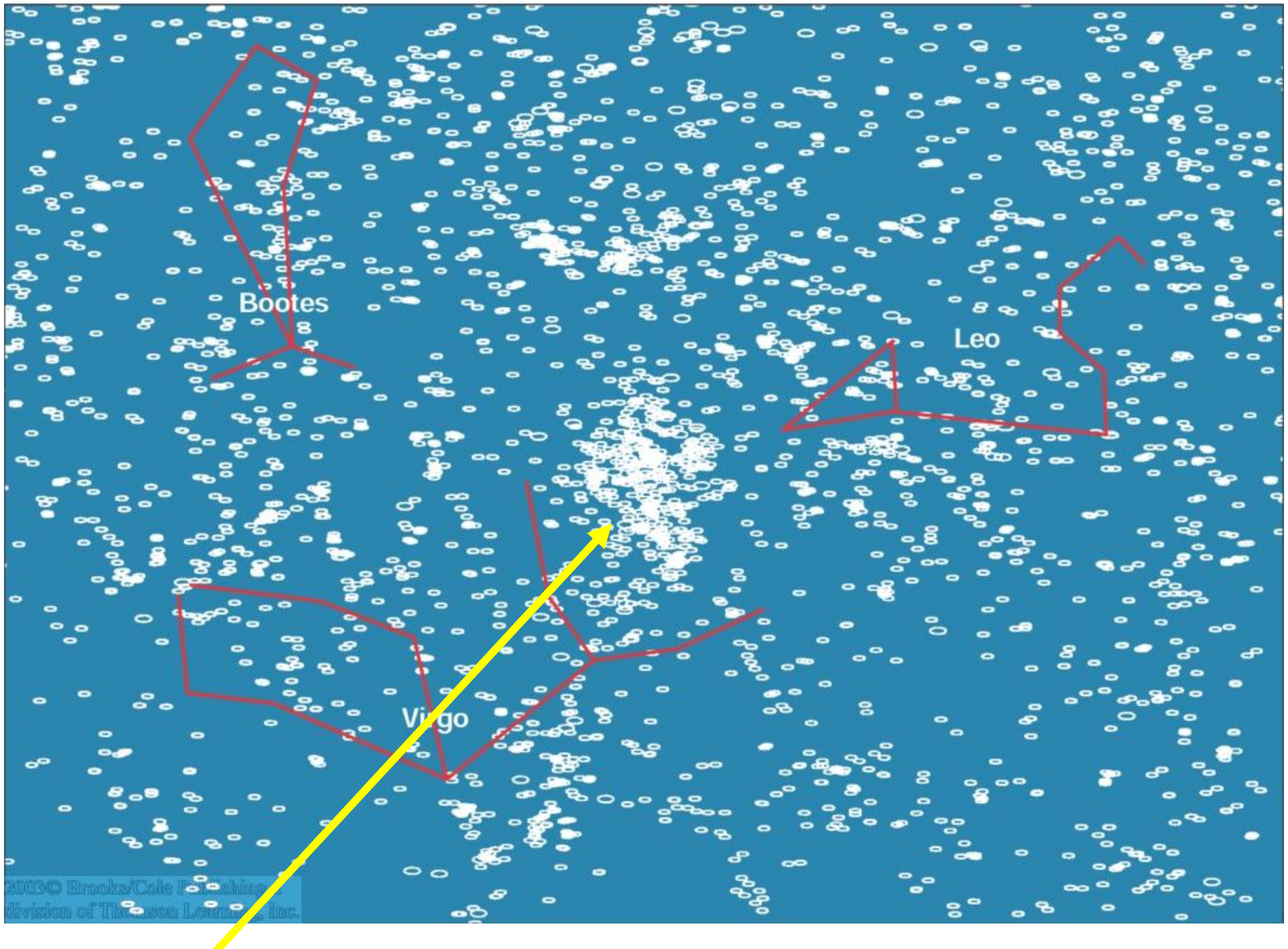
Due to the effect of Dark Energy, the Universe will keep expanding faster and faster …



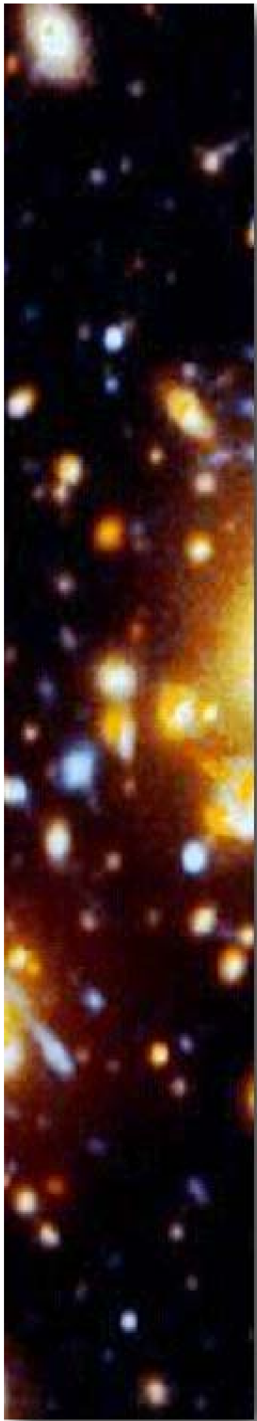
We don’t know the nature of Dark Energy, and we don’t know how it will evolve in the future.

The Universe may keep expanding in a regular manner, or be disrupted in a “big rip”.

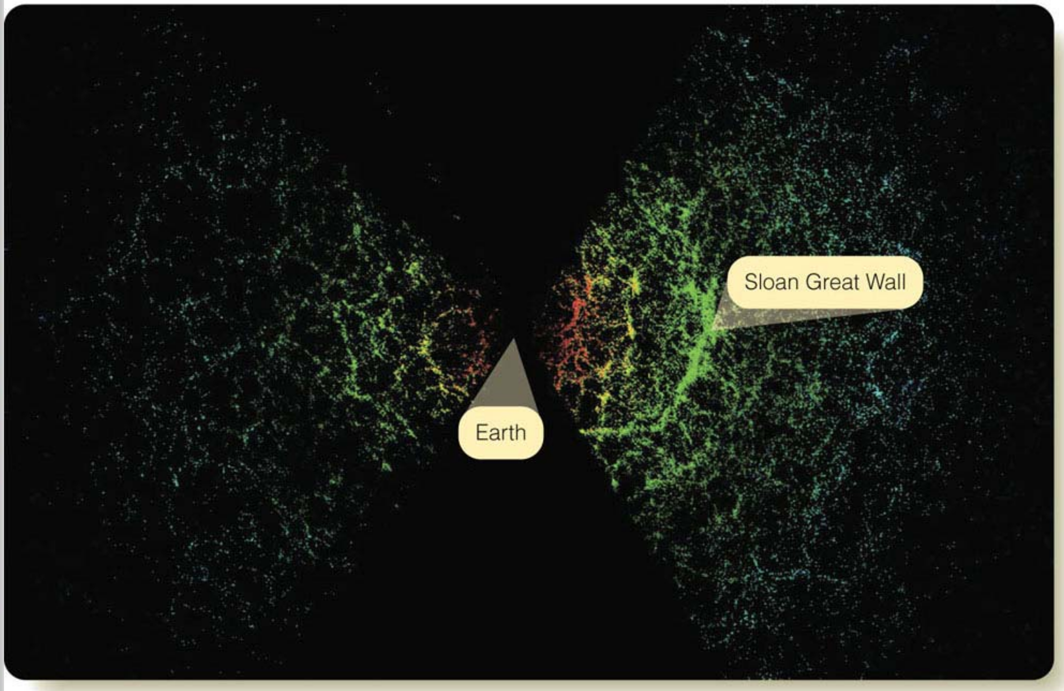
Large Scale Structure



Distribution of bright galaxies in the Virgo region indicates the Virgo cluster and presence of more distant, larger scale structure

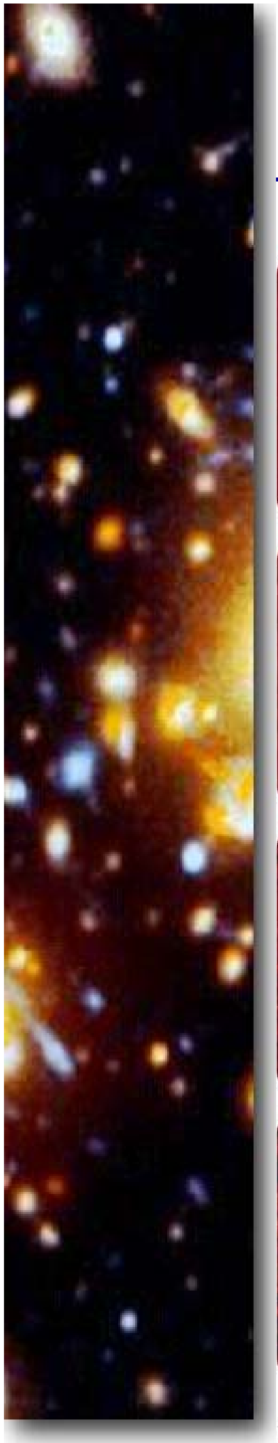


Large Scale Structure (2)

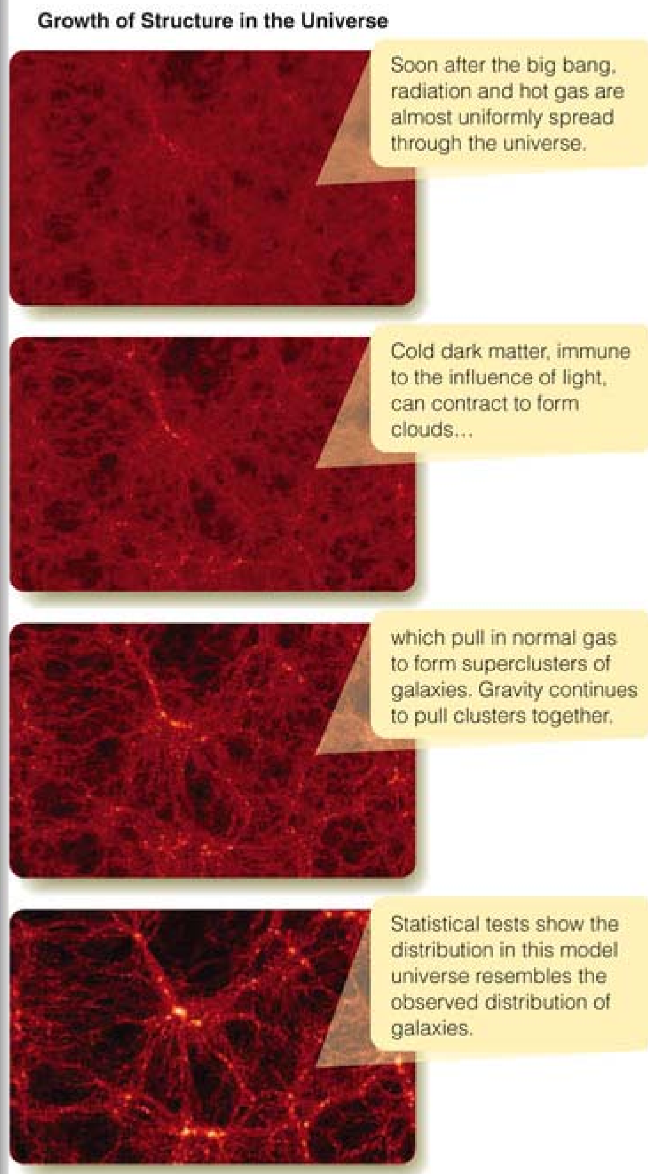


A large survey of distant galaxies shows the largest structures in the universe:

Filaments and *walls* of galaxy superclusters, and *voids*, basically empty space.



The Growth of Structures

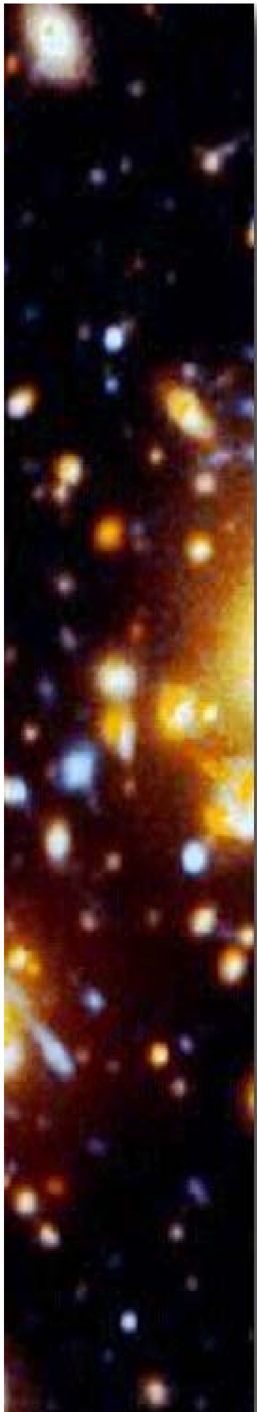


Structures in the Universe could have developed in two fundamentally different ways:

a) Small structures (galaxies) could have developed first, then clustering into larger and larger structures

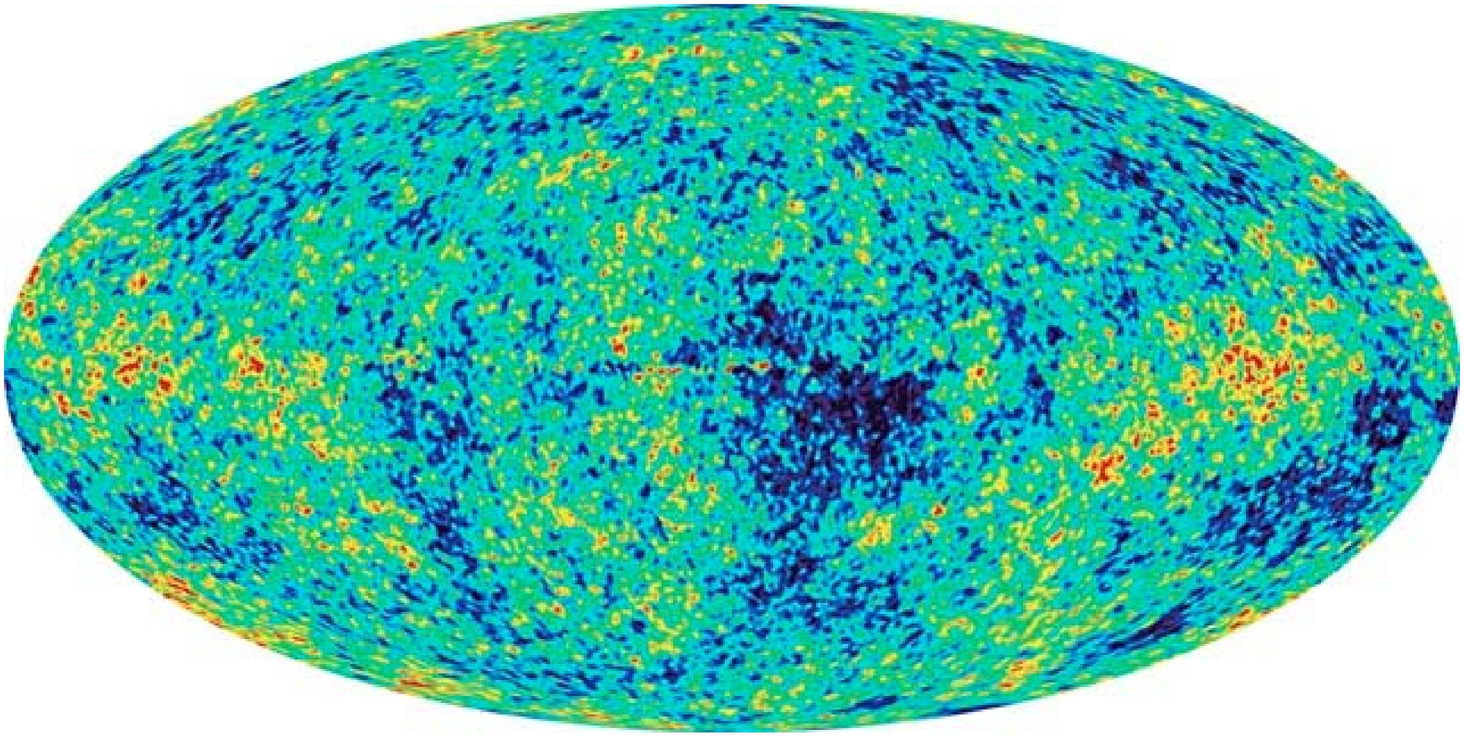
b) The largest structures (superclusters, voids) could have developed first, then breaking up into smaller and smaller units.

The latter scenario seems to be favored by observational evidence.

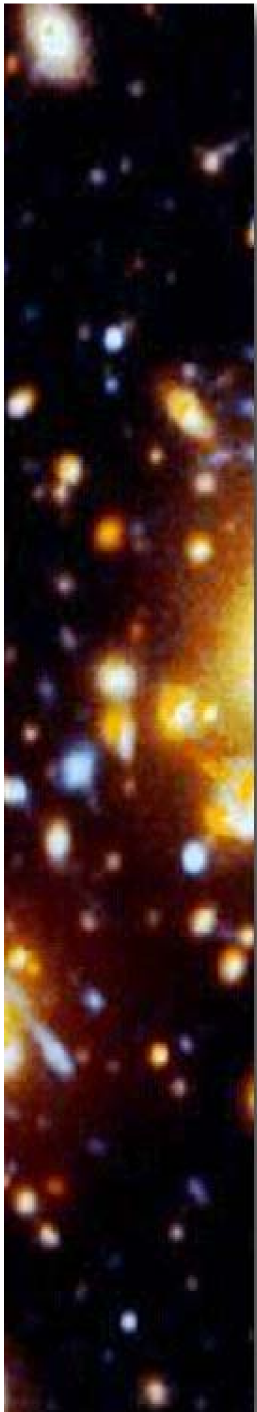


Cosmology with the Cosmic Microwave Background

If the universe were perfectly homogeneous on all scales at the time of reionization (z = 1000), then the CMB should be perfectly isotropic over the sky.



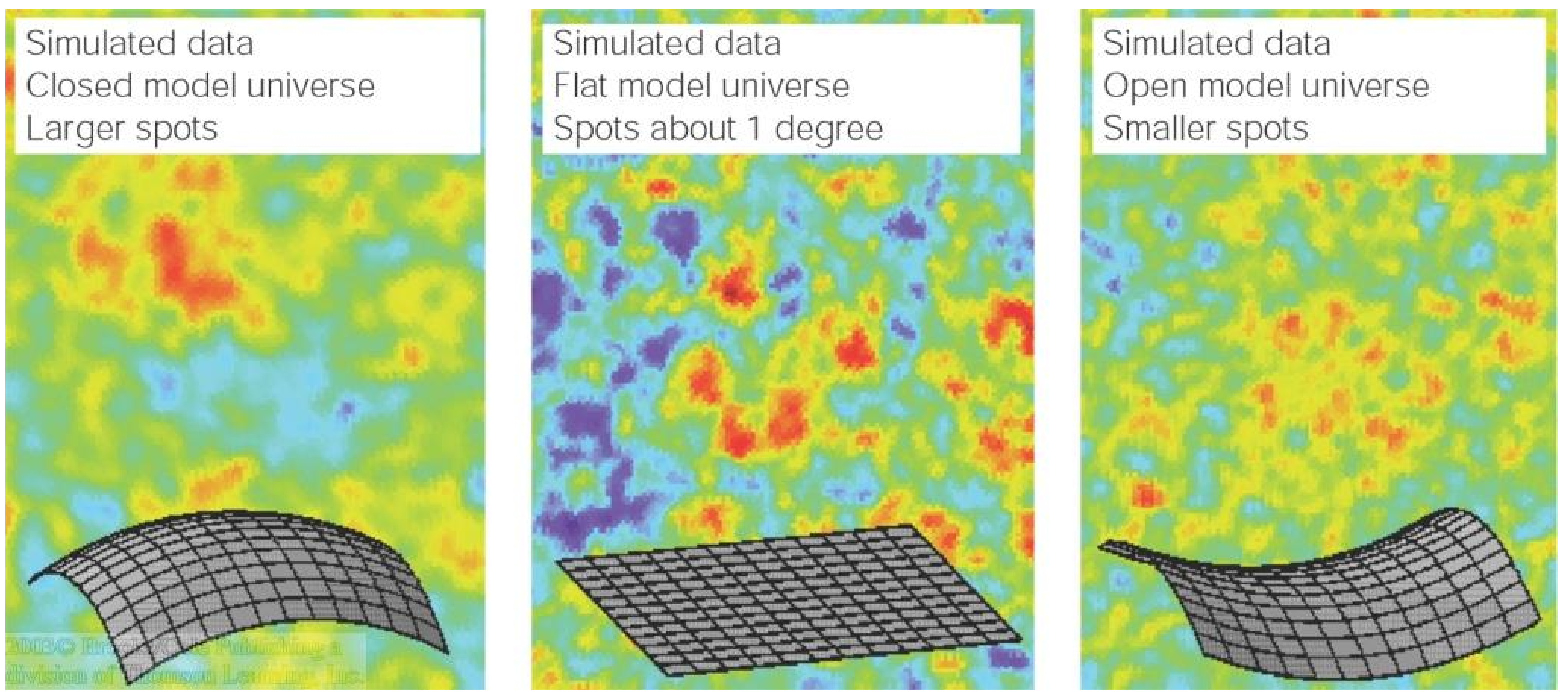
Instead, it shows small-scale fluctuations:



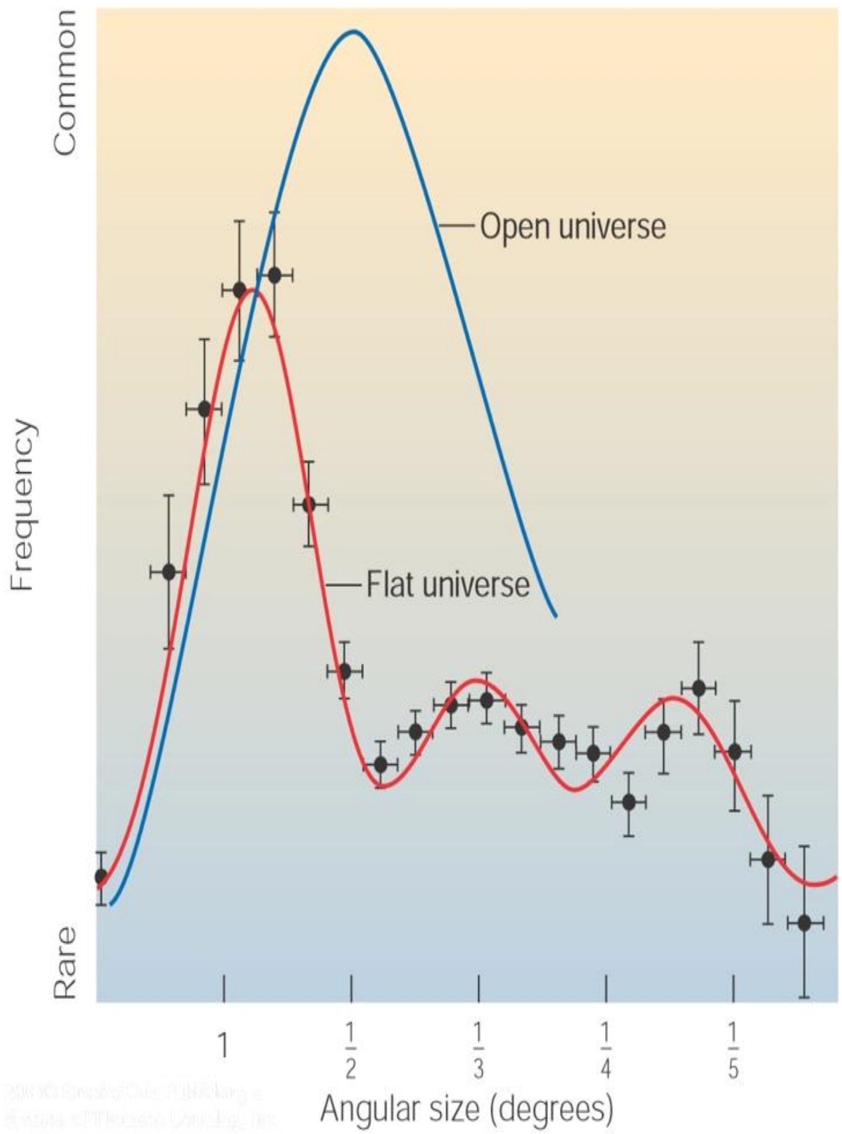
Fluctuations in the Cosmic Microwave Background

The angular size of the CMB fluctuations allows us to probe the geometry of space-time!

CMB fluctuations have a characteristic size of 1 degree.



Analysis of the Cosmic Background Fluctuations



Analyze frequency of occurrence of fluctuations on a particular angular scale

→ Universe has a flat geometry