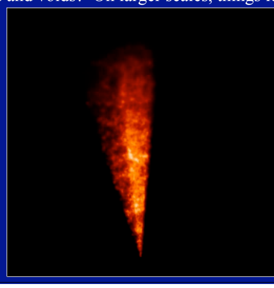
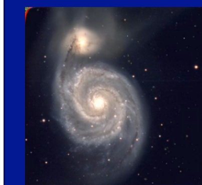
Cosmology
The Study of the Universe as a Whole
Including the beginning of the Universe

What is the largest kind of structure in the universe? The ~100-Mpc filaments, shells and voids? On larger scales, things look more uniform.



600 Mpc

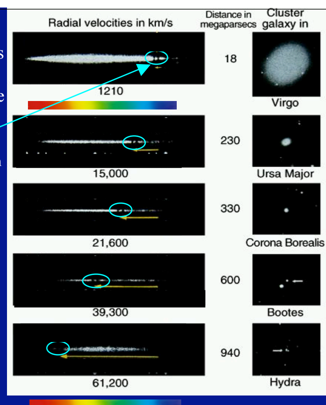
The Variety of Galaxy Morphologies






Spectra of galaxies in clusters of increasing distance

prominent pair of absorption lines



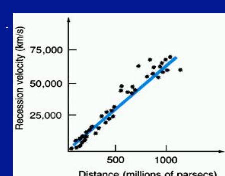
In 1920's, Hubble used Cepheids to find distances to some of these receding galaxies. Showed that redshift or recessional velocity is proportional to distance:

$$V = H_0 \times D \quad \text{(Hubble's Law)}$$

velocity (km / sec)　　Distance (Mpc)

Hubble's Constant (km / sec / Mpc)

Or graphically. . .



Current estimate:

H_0 = 73 +/- 2 km/sec/Mpc

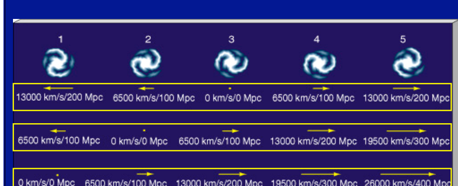
If H_0 = 75 km/sec/Mpc, a galaxy at 1 Mpc moves away from us at 75 km/sec, etc.

Given no evidence of further structure, assume:

The Cosmological Principle

On the largest scales, the universe is roughly homogeneous (same at all places) and isotropic (same in all directions).

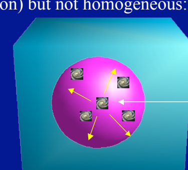
Hubble's Law might suggest that everything is expanding away from us, putting us at center of expansion. Is this necessarily true?



(assumes H_0 = 65 km/sec/Mpc)

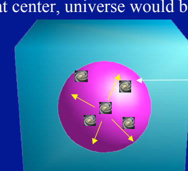
If we were at center of expansion, universe would be isotropic (but only from our location) but not homogeneous:

Galaxies expanding away from us into empty space



Us

But if we were not at center, universe would be neither isotropic nor homogeneous:



Us

So if the CP is correct, there is no center, and no edge to the Universe!

Best evidence for CP comes from Cosmic Microwave Background Radiation (later).

The Big Bang

All galaxies moving away from each other. If twice as far away from us, moving twice as fast (Hubble's Law). So, reversing the Hubble expansion, everything must have been together once. How long ago?

Hubble's Law: $v = H_0 d$ where H_0 gives rate of expansion. Assume H_0 = 75 km / sec / Mpc. So galaxy at 1 Mpc from us moves away at 75 km/sec. How long did it take to move 1 Mpc from us?

$$\text{time} = \frac{\text{distance}}{\text{velocity}} = \frac{1}{H_0}$$

$$= \frac{1\ \text{Mpc}}{75\ \text{km/sec}}$$

$$= 13\ \text{billion years}$$

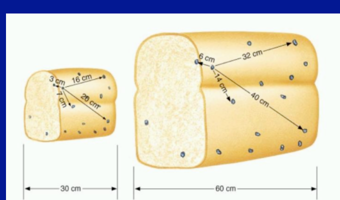
The faster the expansion (the greater H_0), the shorter the time to get to the present separation.

Big Bang: we assume that at time zero, all separations were infinitely small. Universe then expanded in all directions. Galaxies formed as expansion continued.

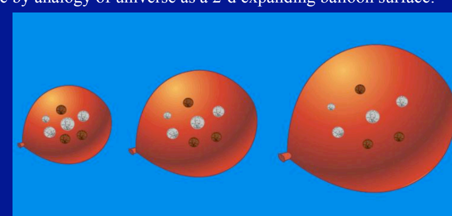
But this is not galaxies expanding through a pre-existing, static space. That would be an explosion with a center and an expanding edge.

If CP is correct, space itself is expanding, and galaxies are taken along for the ride. There is no center or edge, but the distance between any two points is increasing.

A raisin bread analogy provides some insight:



But the cake has a center and edge. Easier to imagine having no center or edge by analogy of universe as a 2-d expanding balloon surface:



To understand what it would be like in a 2-d universe, read Flatland by Edwin Abbott

DEMO - Expansion in 1-D

Now take this analogy "up one dimension". The Big Bang occurred everywhere at once, but "everywhere" was a small place.

If all distances increase, so do wavelengths of photons as they travel and time goes on.

When we record a photon from a distant source, its wavelength will be longer. This is like the Doppler Shift, but it is not due to relative motion of source and receiver. This is correct way to think of redshifts of galaxies.

Clicker Question:

What is the Cosmological Principle?

A: The Universe is isotropic on small scales.

B: The Universe is homogeneous on large scales.

C: The Universe is isotropic and homogenous on small scales.

D: The Universe is isotropic and homogenous on large scales.

Clicker Question:

As photons travel through our expanding Universe over millions (or billions) of years what happens to them?

A: Their wavelength decreases.

B: Their wavelength increases.

C: Their velocity slows down.

D: Their energy increases.

Clicker Question:

The Hubble constant for the expansion of the Universe is 72 km/s/Mpc right now. What was it 7 billion years ago (half the age of the Universe) assuming a flat universe with no acceleration.

A: less than 72 km/s/Mpc

B: 72 km/s/Mpc

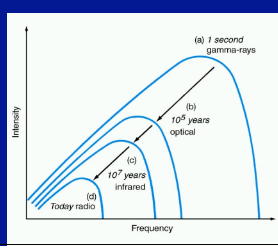
C: more than 72 km/s/Mpc

D: -72 km/s/Mpc

The Cosmic Microwave Background Radiation

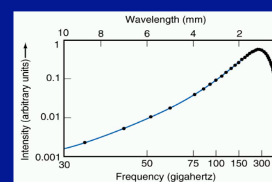
A prediction of Big Bang theory in 1940's. "Leftover" radiation from early, hot universe, uniformly filling space (i.e. isotropic, homogeneous). Predicted to have perfect black-body spectrum.

Photons stretched as they travel and universe expands, but spectrum always black-body. Wien's Law: temperature decreases as wavelength of brightest emission increases => T much lower now.
T ~ 3 K predicted.



Found in 1964 by Penzias and Wilson. Perfect black-body spectrum at T = 2.735 K. Uniform brightness (and thus temperature) in every direction.

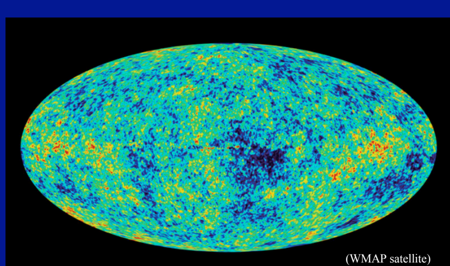
Wilson, Penzias and the antenna used to discover the radiation



The points are data on the spectrum of the microwave background from the COBE satellite (1989). The curve is a black-body spectrum at T=2.735 K.

1% of the "snow" on a blank TV channel is this radiation!

All-sky map of the microwave background temperature, constant everywhere to one part in 10^5 ! For blackbody radiation, this means intensity is very constant too (Stefan's law).

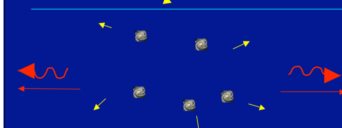


(WMAP satellite)

Deviations are -0.25 milliKelvin (blue) to +0.25 milliKelvin (red) from the average of 2.735 Kelvin.

That the microwave background radiation comes to us from every direction is best evidence that Big Bang happened everywhere in the universe, not one special place. That the temperature is so constant in every direction is best evidence for homogeneity on large scales.

IF the Big Bang happened at one point in 3-d space:



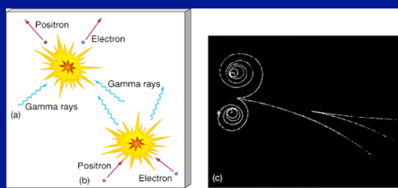
Later, galaxies form and fly apart. But radiation from Big Bang streams freely at speed of light! Wouldn't see it now.

The Early Universe

The First Matter

At an age of 1 microsecond, the universe is thought to have been dominated by high-energy, high-temperature radiation. Only particles are quarks and anti-quarks.

pair production



annihilation

At time ~ 30 microsec, and T > 10^{13} K, gamma rays form proton-antiproton pairs.

At time < 15 sec, and T > 6 x 10^9 K, electron-positron pairs form.

Annihilation occurred at same rate as formation, so particles coming in and out of existence all the time.

As T dropped, pair production ceased, only annihilation. A tiny imbalance (1 in 10^9) of matter over antimatter led to a matter universe (cause of imbalance not clear, but other such imbalances are known to occur).

Primordial Nucleosynthesis

Hot and dense universe => fusion reactions.

At time 100-1000 sec (T = 10^9 - 3 x 10^8 K), helium formed.

Stopped when universe too cool. End result 75% hydrogen, 25% helium. Traces of lithium.

Temperature and density too low to form elements heavier than He

Oldest stars' atmospheres (unaffected by stellar nucleosynthesis) confirm Big Bang prediction of 25% helium.

Successes of the Big Bang Theory

It explains the expansion of the universe.

It predicted the cosmic microwave background radiation, its uniformity, its current temperature, and its black-body spectrum.

It predicted the correct helium abundance (and lack of other primordial elements).

Misconceptions about the Big Bang

1. "The universe was once small." The observable universe, which is finite, was once small. But the universe is infinite (no edge), so it contains an infinite number of volumes which were once small.

2. "The Big Bang happened at some point in space." The microwave background showed that it happened everywhere in the universe.

3. "The universe must be expanding into something." It is not expanding into "empty space". That would imply the Big Bang happened at some location in space. It is a stretching of space itself.

4. "There must have been something before the Big Bang."

The Big Bang was a singularity in space and time (like the center of a black hole). Our laws of physics say the observable universe had infinitesimally small size, and infinite temperature and density.

In these conditions, we don't have a physics theory to describe the nature of space and time before the Big Bang. At the Big Bang, time took on the meaning that we know it to have.

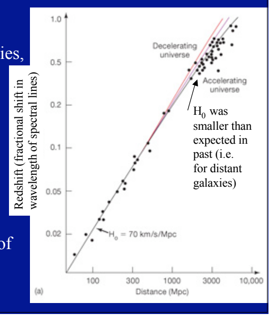
"Before" is only a relevant concept given our everyday understanding of time. We must await a better understanding of the nature of space and time. Such theories are in their infancy.

Shouldn't be surprising that these concepts are hard to grasp. So was the heliocentric Solar System 400 years ago.

The Expansion of the Universe Seems to be Accelerating

The gravity of matter should retard the expansion. But a new distance indicator shows that the expansion rate is speeding up!

Type I supernovae: from ones in nearby galaxies, know luminosity. In distant galaxies, determine apparent brightness. Thus determine distance. Works for more than 3000 Mpc. From redshifts, they are not expanding as quickly from each other as galaxies are now.



Taking this into account, best age estimate of Universe is 13.8 Gyrs.

The Cosmological Constant, Λ

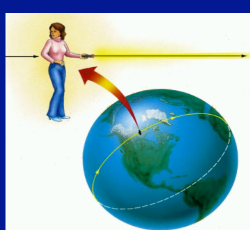
Introduced by Einstein in 1917 to balance gravitational attraction and create static Universe. Can think of Λ as repulsive force that exists even in a vacuum. After Hubble found expanding universe, Einstein called Λ "the greatest blunder of my life". But accelerating universe indicates there is a Λ! Also often called "dark energy". But we have little idea of its physical nature.

From measurement of acceleration, can find the amount of dark energy needed to explain it: the current result is that there is more dark energy than the energy contained in matter.

The Geometry of Curved Space

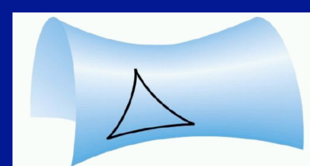
Possibilities:

1) Space curves back on itself (like a sphere). "Positive" curvature.



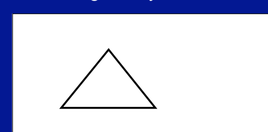
Sum of the Angles > 180

2) More like a saddle than a sphere, with curvature in the opposite sense in different dimensions: "negative" curvature.



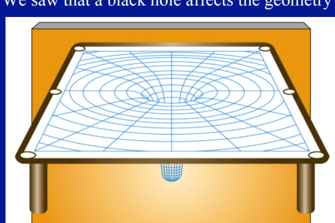
Sum of the Angles < 180

3) A more familiar flat geometry.



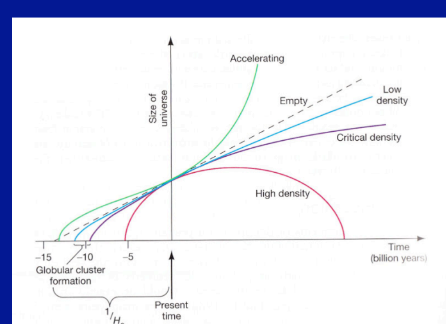
Sum of the Angles = 180

We saw that a black hole affects the geometry of space around it.



Likewise, the geometry of the universe depends on the total mass and energy of the universe (including dark energy). There is a critical amount, which if exceeded, implies positive curvature, and if not met, implies negative curvature. If right at the critical amount, get flat universe. Latest measurements imply flat universe.

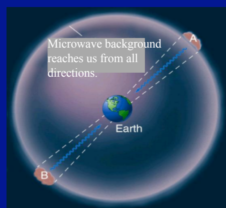
The Geometry of the Universe determines its fate



The Early Universe

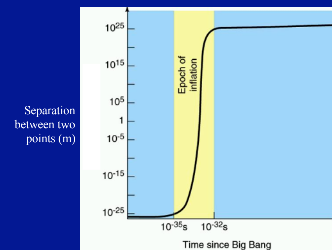
Inflation

A problem with microwave background:



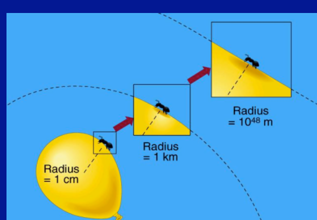
Temperature of background in opposite directions nearly identical. Yet even light hasn't had time to travel from A to B (only A to Earth), so A can know nothing about conditions at B, and vice versa. So why are A and B almost identical? This is "horizon problem".

Solution: Inflation. Theories of the early universe predict that it went through a phase of rapid expansion.



If true, would imply that points that are too far apart now were once much closer, and had time to communicate with each other and equalize their temperatures.

Inflation also predicts universe has flat geometry:



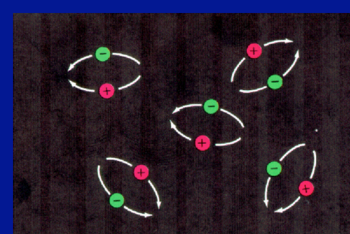
Microwave background observations seem to suggest that this is true.

What drove Inflation?

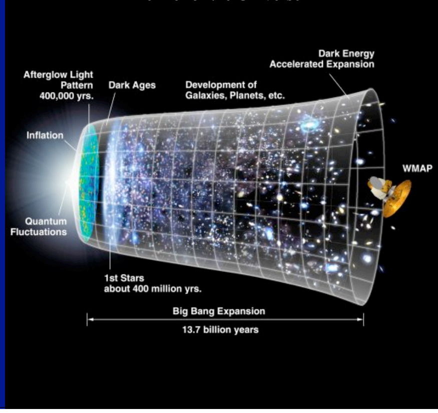
State change of the Vacuum

Vacuum has energy fluctuations, Heisenberg uncertainty principle states:

$dE\, dt > h/2\pi$



Timeline for the Universe



Clicker Question:

What is the geometry of the Universe?

A: closed (sum of angles in a triangle > 180)

B: flat (sum of angles in a triangle = 180)

C: open (sum of angles in a triangle < 180).

D: variable (sum of angles in a triangle changes).

Clicker Question:

The epoch of Inflation occurred when?

A: When the Universe was << 1 second old.

B: When the Universe was ~ 1 second old

C: When the Universe was ~300,000 years old.

D: When the Universe was ~1 billion years old.