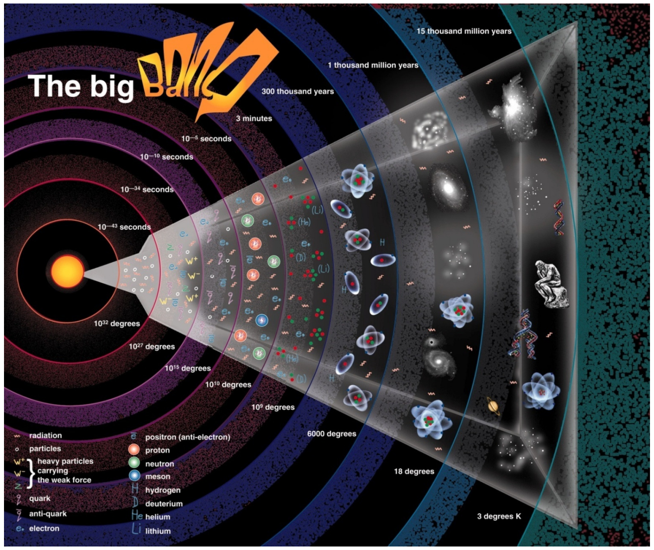
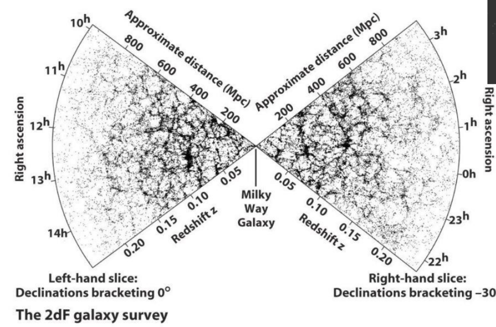
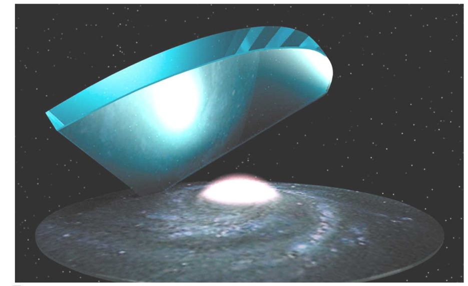
Cosmology and the Early Universe
Ch 25, 26.1, 26.4, 26.6



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



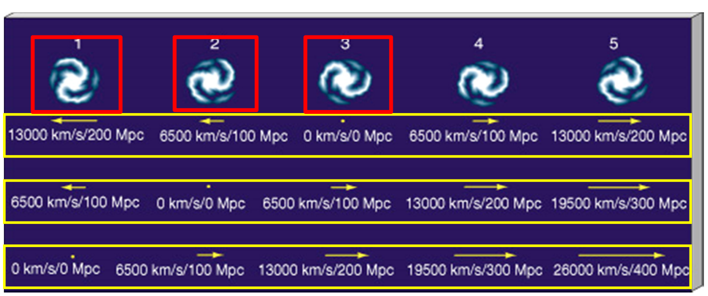


Given no evidence of further structure, assume:

The Cosmological Principle

On the largest scales, the universe is roughly <u>homogeneous</u> (same at all places) and <u>isotropic</u> (same in all directions). Laws of physics same. Hard to prove but can be <u>disproved</u>.

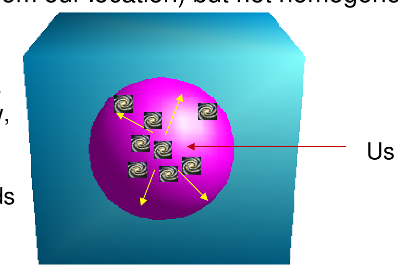
Hubble's Law might suggest that everything is expanding away from us, putting us at center of expansion. Is this necessarily true?



(assumes H_0 = 65 km/sec/Mpc)

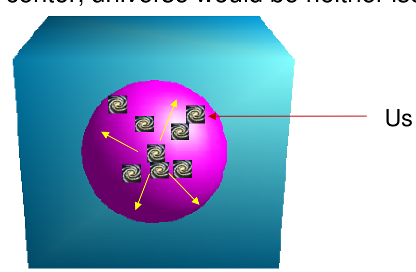
So we may not be the center. But is there one? If there is a center, there must be a boundary to define it. If we were at center, universe would be isotropic (but only from our location) but not homogeneous:

Volume of galaxies expanding away from us. If it obeyed Hubble's Law, would have large mass concentration at center, with lower density towards edge, surrounded by empty space.



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

This situation wouldn't even obey Hubble's Law from our vantage point.



So if the CP is correct, there can be no center, and no edge to the Universe! Does not necessarily mean it's infinitely large, although it might be (see later).

Why should you believe the CP? Best evidence comes from Cosmic Microwave Background Radiation (later).

The Big Bang

All galaxies moving away from each other at speed proportional to separation (Hubble's Law). So, reversing the Hubble expansion, separations must approach zero at some time in past. How long ago?

H_0 gives rate of expansion. Assume H_0 = 75 km / sec / Mpc. So galaxy at 100 Mpc from us moves away at 7500 km/sec. How long did it take to move 100 Mpc from us at that speed?

$$t = \frac{d}{v} = \frac{100 \text{ Mpc}}{7500 \text{ km/s}} = 13 \text{ Gyr}$$

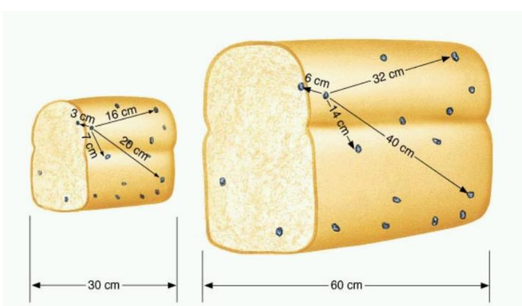
(Note this is just $\frac{1}{H_0}$, also called the "Hubble time"). This assumes constant speed, which means H_0 assumed not constant with time, but shows that the greater H_0, the shorter the time to get to the present separation. Current result from Planck satellite: age=13.80 +/- 0.02 Gyr.

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

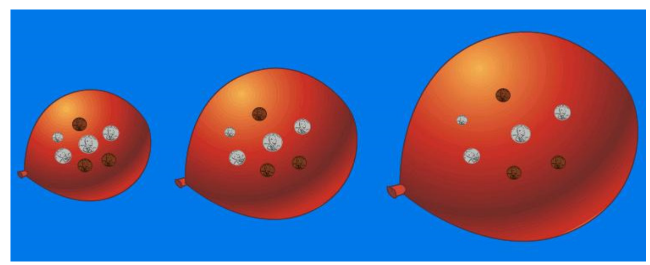
But this is not galaxies expanding through a pre-existing, static space. That would be an explosion with a center and an expanding edge, violating CP.

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

A raisin bread analogy provides some insight:



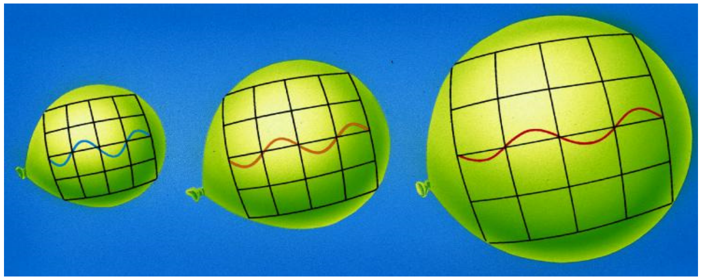
But the bread has a center and edge. Easier to imagine having no center or edge by analogy of universe as a 2-d expanding balloon surface (just one possible analogy for our universe's geometry). All points on surface expand from each other with no center on the surface:



Now take this analogy "up one dimension". All points in space expand from each other. The Big Bang occurred everywhere at once, but "everywhere" was very close together. (This does not mean we are expanding into a real 4th dimension).

(To understand what it would be like in a 2-d universe, read Flatland by Edwin Abbott: www.ofcn.org/cyber.serv/resource/bookshelf/flat10)

If all distances increase, so do wavelengths of photons as they travel.



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

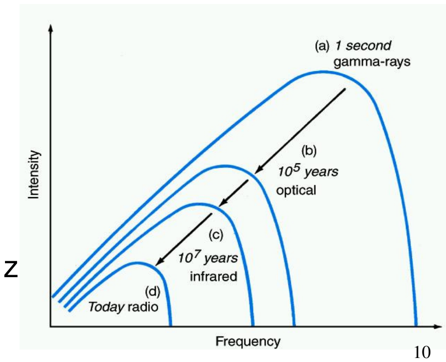
Ratio $\lambda/\lambda_0 = 1 + z$ measures amount of stretching. For z=1, lengths have expanded by a factor of 2 since light was emitted.

The Cosmic Microwave Background Radiation (CMBR)

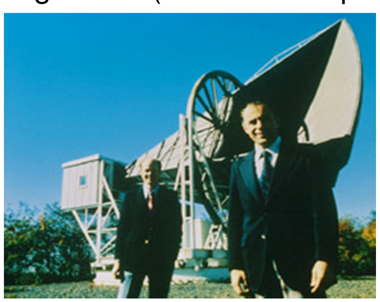
A prediction of Big Bang theory in 1940's. "Leftover" radiation from early, hot, dense universe, uniformly filling space (i.e. obeying CP). Hot, dense objects have a black-body spectrum.

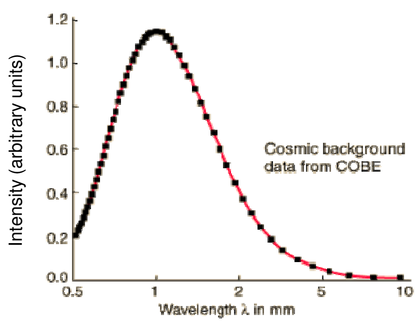
Photons stretched as they travel and universe expands, but spectrum always black-body. Wien's Law: temperature decreases as wavelength of brightest emission increases => was predicted to be ~ 3 K now.

Since λ_{max} α 1/T, and $\lambda/\lambda_0 = 1 + z$ for any λ, then $T/T_0 = 1/(1 + z)$

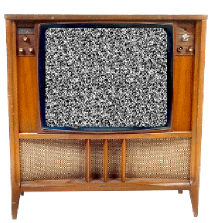


Found in 1964 by Penzias and Wilson. Perfect black-body spectrum at T = 2.718 K (best current value). Uniform brightness (and thus temperature) in every direction.





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



Points are data on the spectrum of the CMBR from the COBE satellite (1989). Curve is a black-body spectrum at T=2.73 K.

How far back are we looking? "Era of recombination"

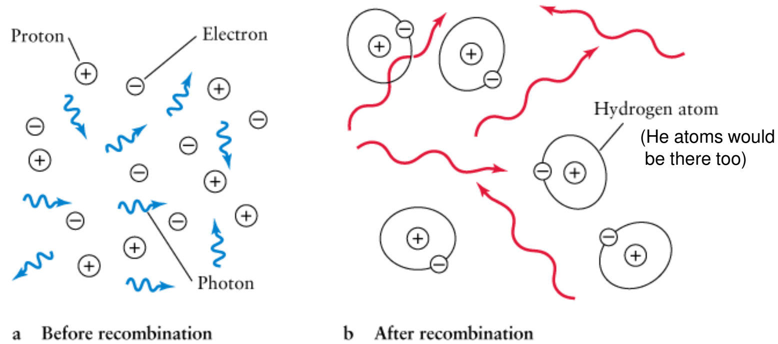
Photons in the early universe had so much energy that all gas was kept ionized. Density very high. A photon could travel tiny distance before scattering off electron.

At z~1,100 (~380,000 years after Big Bang), the universe had cooled off to T~3,000K. Neutral atoms (H, He only elements then) formed, and remained since low-energy photons could not ionize them.

Almost all photons now had wrong λ's to be absorbed, so traveled freely. Space became *transparent*. We now see these photons as the CMBR.

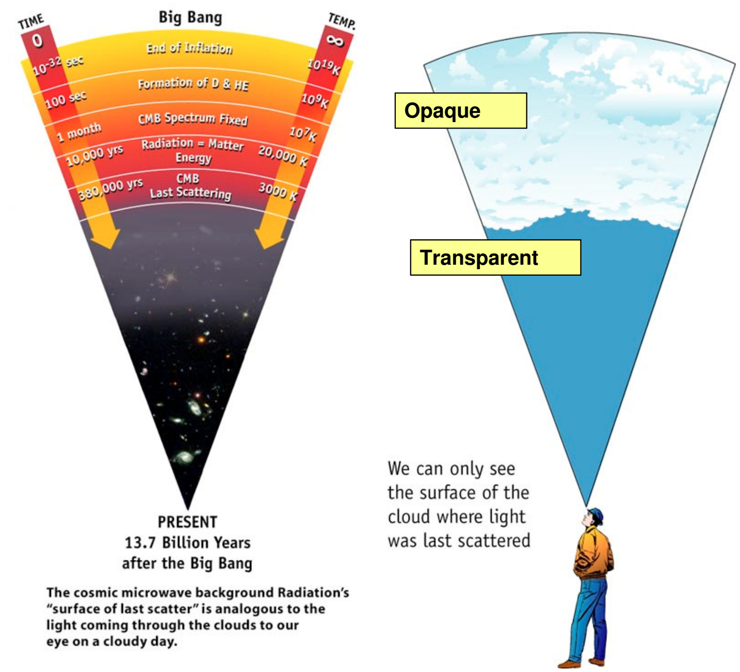
Free nuclei, protons and electrons, bathing in blackbody radiation. (He nuclei not shown). Photons travel short distance before scattering off particles.

At 3000K, recombination made scattering much less effective, absorption also very unlikely, and photons can travel undisturbed.

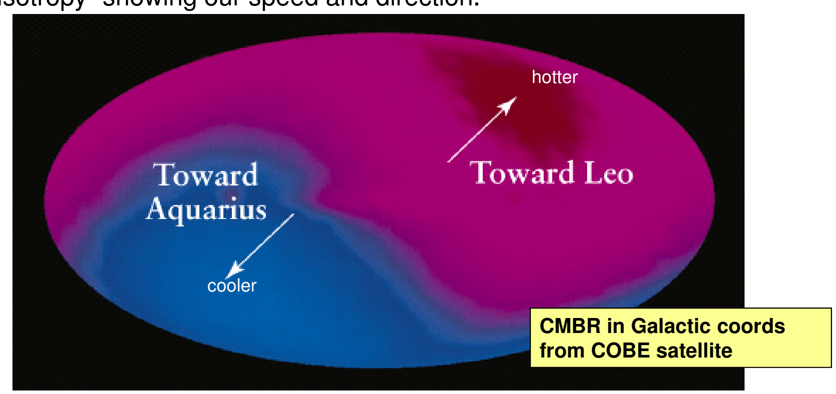


Analogous to Solar interior

Analogous to Solar photosphere

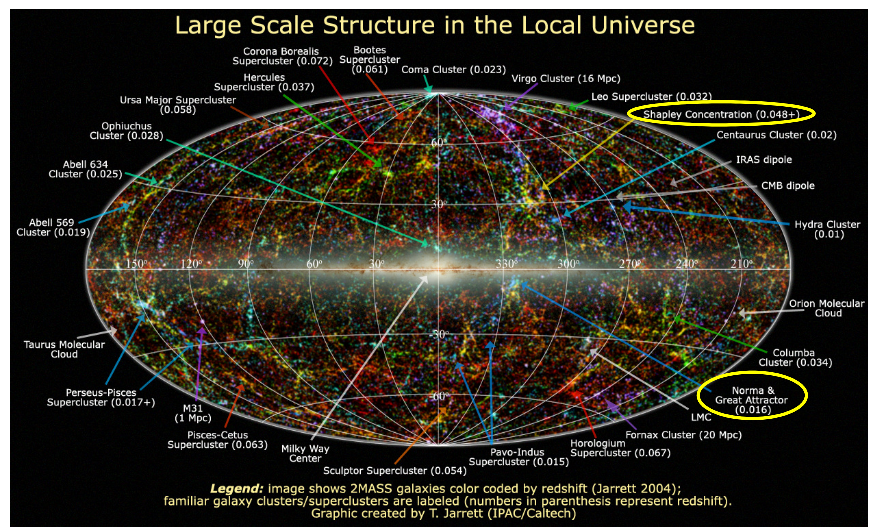


T is not quite constant for a few reasons. Largest effect: we are not at rest with respect to CMBR because we are being tugged by various masses (as we saw via deviations from Hubble's Law). Leads to "dipole anisotropy" showing our speed and direction.



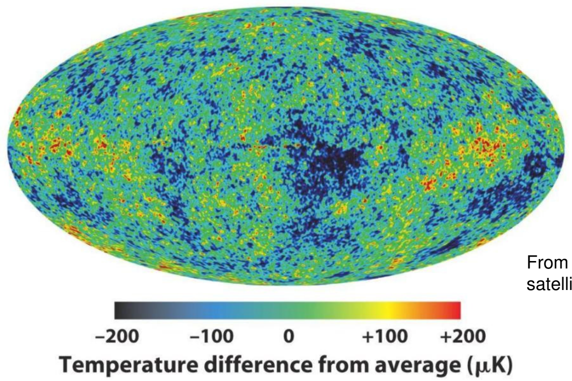
Can show: $\Delta T/T = -\Delta\lambda_{max}/\lambda_{max} = v/c$. $\Delta T = 0.00337$ K => v = 371 km/s.

After removing our motion in MW, MW motion in Local Group, LG pull due to Virgo, find we are pulled by some larger mass(es). These are the "Great Attractor" at 60 Mpc and possibly "Shapley Supercluster" at 200 Mpc away.



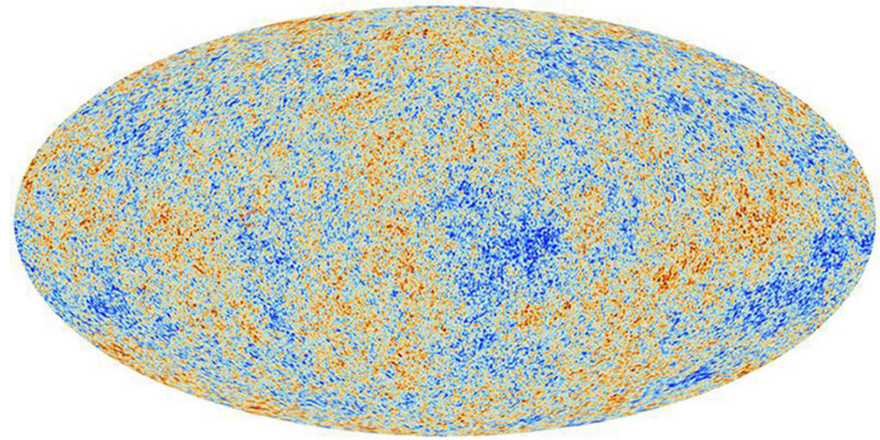
Mass of Great Attractor not well known but estimates are about 3 x 10^{16} M$_\odot$ Shapley Supercluster is probably larger. Possibly a void on opposite side of sky contributes as well.

Removing dipole anisotropy, and MW emission, allows fluctuations in T to be searched for. T constant to one part in 10^5 ! For blackbody radiation, this means intensity is very constant too (Stefan's law). Again, supports CP.



From WMAP
satellite (30' resolution)

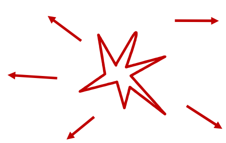
Deviations are an imprint of early density fluctuations that led to current structure in universe.

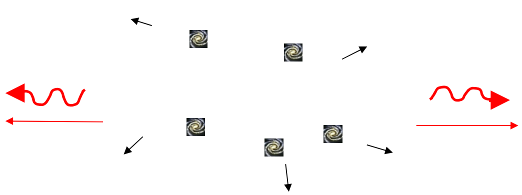


From Planck
satellite (5' resolution)

That the CMBR comes to us from every direction is best evidence that Big Bang happened everywhere. That T 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 (after era of recombination) at speed of light! Wouldn't see it now.