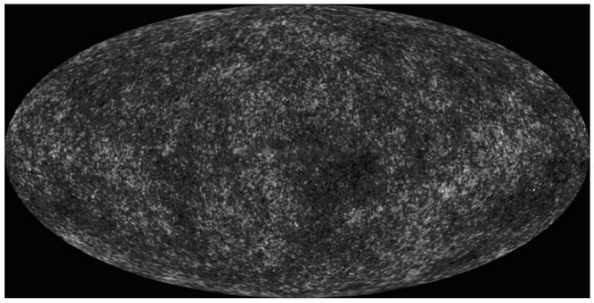
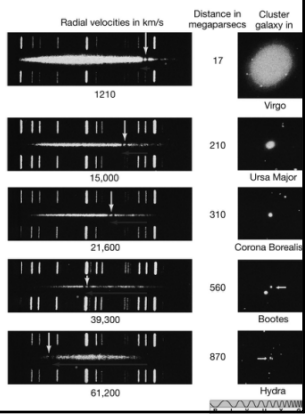
Chapter 21
Evidence of the Big Bang



Hubble's Law

Universal recession: Slipher (1912) and Hubble found that all galaxies seem to be moving away from us: the greater the distance, the higher the redshift



Hubble's Law

The relationship is set by Hubble's constant H_0:

$$\text{recessional velocity} = H_0 \times \text{distance}$$

The current value for Hubble's constant is

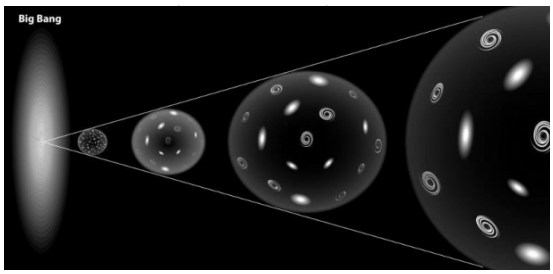
$$H_0 = 70 \text{ km/s/Mpc}$$

Expansion of the Universe

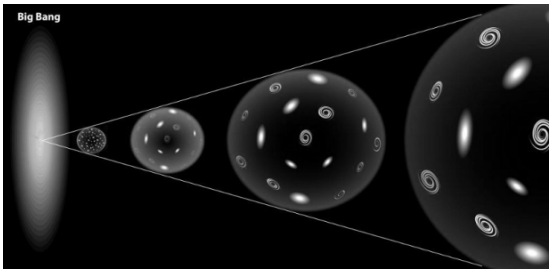
- Motion of galaxies not unique to Milky Way: all galaxies see all others moving away from them
- Whole universe is in state of expansion
- Current expansion implies whole universe much more compact in past
- Hubble Law gives idea of time since universe began: Big Bang theory

Age of the Universe

- Time since any galaxy left origin is d/v (distance/velocity)
- Velocity is given by Hubble's law, v=Hd
- Age = d/v = d/ (Hd) = 1/ H
- H = 70 km/s / Mpc (1 Mpc = 10^6 pc) = 70 km/s / (3.1×10^{19} km) = 2.3×10^{-18} /s
- Age = 1/H = 4.4×10^{17} s = 14×10^9 years (compare to age of Earth 4.5×10^9 years)

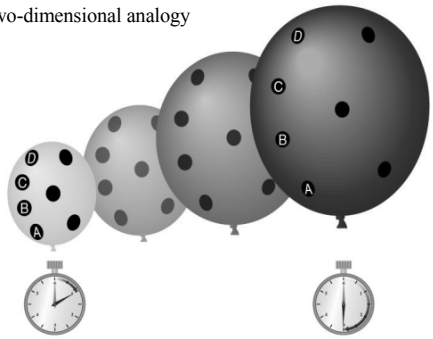


The universe began as a hot, dense singularity that has expanded and cooled over time.



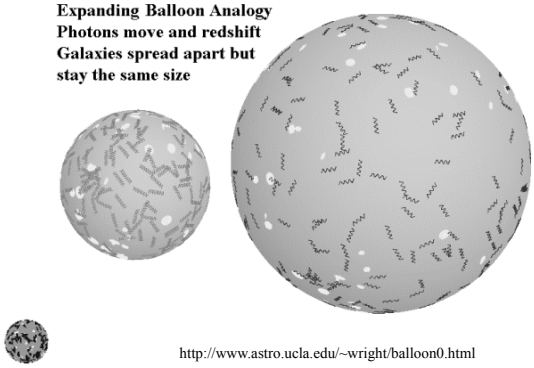
In an expanding universe, every galaxy sees all other galaxies moving away from them. The "center of the universe" perspective is an illusion.

Two-dimensional analogy



Example of something that expands but has no center or edge is the surface of a balloon

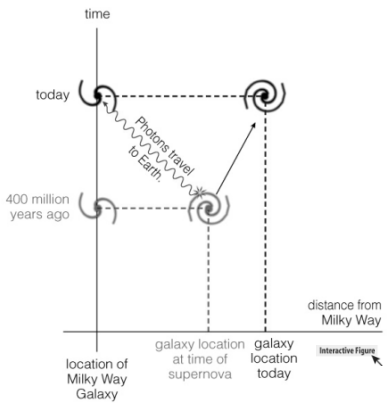
Expanding Balloon Analogy
Photons move and redshift
Galaxies spread apart but stay the same size



http://www.astro.ucla.edu/~wright/balloon0.html

Expansion of the Universe means:

- The Big Bang was *not* an explosion that occurred within the universe.
  - There is no extra space that the universe is expanding into.
  - The Big Bang did not occur at any one location in the universe – rather, it occurred at *all* locations.
  - Rather, space itself is expanding.
- Big Bang also marked the beginning of time.
- Age limits how far back we see or the size of the observable universe (14 billion lightyears).



Distances between faraway galaxies change while light travels

lookback time

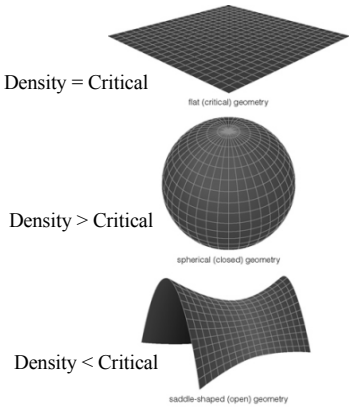
Big Bang Theory

- Einstein's *general relativity theory* applied to the universe as a whole
- John Wheeler: "Matter tells space how to curve, and space tells matter how to move."
- Assumption about the uniformity of the universe in space: *cosmological principle*

The Cosmological Principle

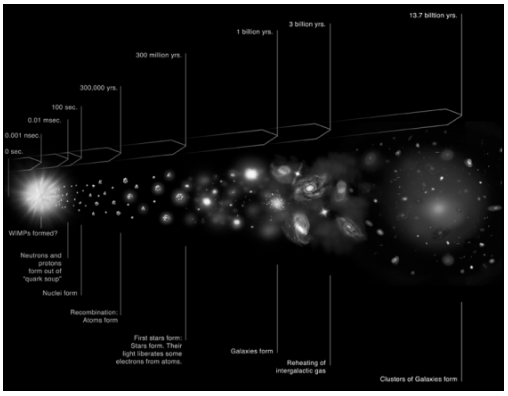
The physical laws that apply to one part of the universe apply throughout the universe.

- The universe is *homogeneous*: it is made of the same materials and has the same composition everywhere (no center; no edges).
- The universe is *isotropic*: the universe has the same general distribution of matter in <u>all</u> directions (expansion looks the same).



Solution: Overall expansion and (spacetime) geometry of the universe is closely related to total density of matter and energy in the universe

Critical density: 6 hydrogen atoms per cubic meter

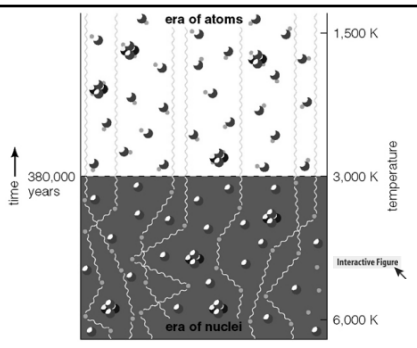


Expansion of Universe implies dense, hot start: **Big Bang**

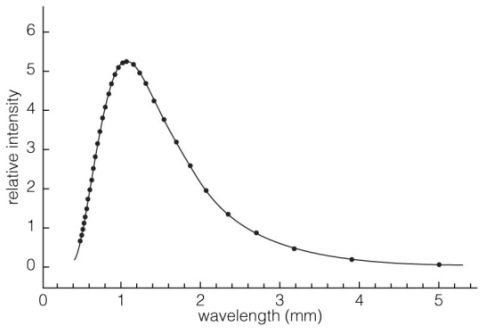
Primary Evidence

1) Expansion of the Universe (Hubble's Law).
2) Detection of the radiation from the Big Bang.
3) Abundances of helium and light elements.
4) Structure in the Universe.

The ***cosmic microwave background*** – the radiation left over from the Big Bang – was detected by Penzias & Wilson in 1965

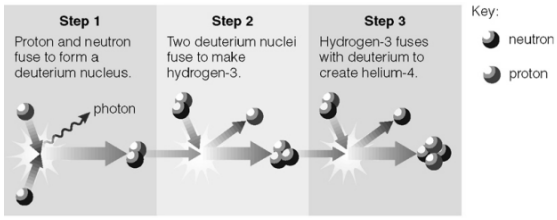


Background radiation from Big Bang has been freely streaming across universe since atoms formed at temperature ~ 3,000 K: *visible/IR*

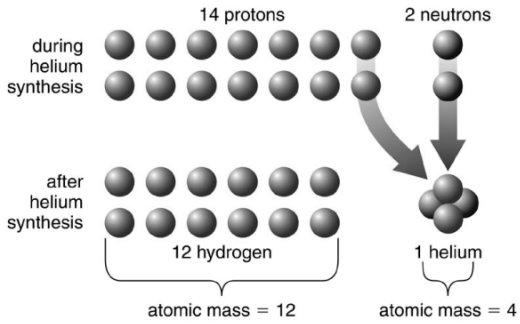


Expansion of universe has redshifted thermal radiation from that time to ~1000 times longer wavelength: *microwaves*

Big Bang Nucleosynthesis



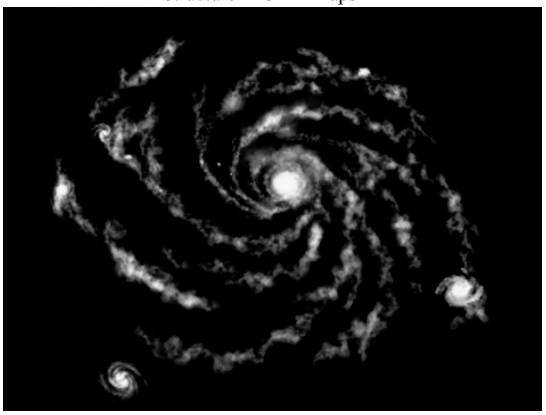
Protons and neutrons combined to make long-lasting helium nuclei when universe was hot and ~ 3 minutes old.
Heavier elements *not* made because universe cooled quickly.



Big Bang theory prediction: 75% H, 25% He (by mass)

Matches observations of nearly primordial gases

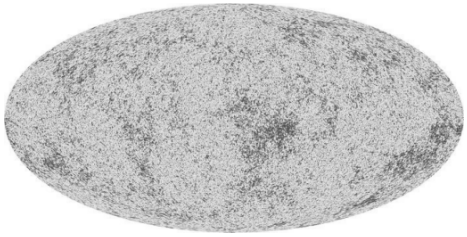
Structure in CMB Maps



Structure in the Universe

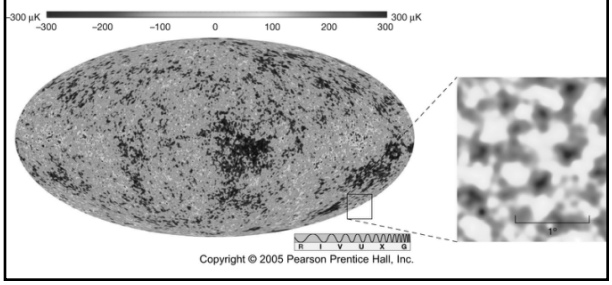
Tiny ripples in cosmic background radiation (after removal of part from Milky Way) found by NASA Wilkinson Microwave Anisotropy Probe (map.gsfc.nasa.gov) and the ESA Planck Space Telescope: https://www.youtube.com/watch?v=p4KX_qMUjLQ

These structures provide the seeds for later development of galaxies and clusters of galaxies.

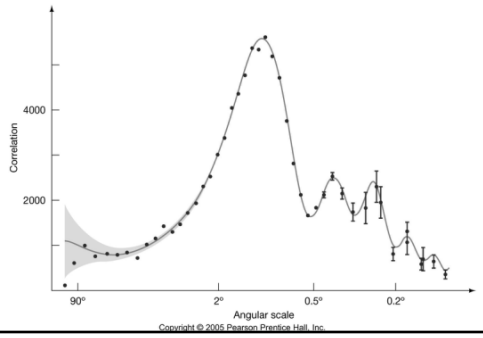


Ancient Structures in the Universe

WMAP ripples of +/- 0.01% (25 arcmin resolution).
Inset: Cosmic Background Imager (9 arcmin resolution).
Structures seen with size of about 1 degree.



Observed and predicted angular scale clumping for critical density (flat Universe) are excellent match.



Summary of WMAP Results

- **Universe is 13.7 billion years old**
- **First stars appeared 200 million years after Big Bang**
- **CMB is from 379,000 years after Big Bang**
- **Universe contains**
  4% Atoms, 23% Cold Dark Matter, 73% Dark Energy
- **Universe will probably expand forever, but …**
  The nature of the dark energy is still a mystery, so results could change.

The Universe As An 80-year-old Person ...

Time Since the Big Bang	The Universe	Human Equivalent
379,000 years	Time when the pattern of CMB light was set. Universe was cool enough for atoms to form.	Baby just 19 hours old.
200 million years	The matter in the Universe has condensed by gravity sufficiently to make the first stars.	Baby of 13 months (first steps).
1 billion years	The first galaxies began to form.	Child just under six years old.
9.1 billion years	Sun and Earth form.	Adult at 53.
13.7 billion years	The present day Universe of stars and galaxies.	Adult at 80.