

Part 3: Galaxies and the Universe

- Tuesday, March 22 Reading: Chapter 12.1 — 12.3
– Our Galaxy = The Milky Way
- Thursday, March 24 Reading: Chapter 13.1 — 13.2
– Galaxies: types, properties, clusters of galaxies, dark matter
- Tuesday, March 29 Reading: Chapters 13.3, 15
– Galaxies: formation, evolution; distance scales; expansion of the Universe
- Thursday, March 31 Reading: Chapter 12.4, 14
– Galaxies: active galaxies and quasars; supermassive black holes
- Monday, April 4 TA's help session for HW3: 3 to 5 PM in WCH 1.120
- Tuesday, April 5 Reading: Chapter 15; HW 3 due
– Cosmology: Big Bang ➔ background radiation; formation of structure
- Wednesday, April 6 Help session: 4 to 6 PM in Welch 2.224
- Thursday, April 7 Exam 4

Cosmology: The History of the Universe

The Universe originated in an explosion called the “Big Bang”. Everything started out 13.7 billion years ago with “zero” size and “infinite” temperature.

Since then, it has been expanding and cooling. Now its temperature is 2.735 K.

While the temperature was still high enough — at age 2 to 30 minutes — protons and neutrons fused to form light elements. As a result, the Universe contained 75 % hydrogen, 25 % helium, and traces of lithium and beryllium before the first stars formed.

When the Universe was 380,000 years old, protons and electrons combined to make hydrogen atoms. The Universe became transparent.

This is the farthest back that we can see.

Tiny fluctuations in density grew by gravitational clustering into galaxies and stars.

The expansion of the Universe is still going on today. That’s how we measure its age.

**It is astonishing that,
by careful observation and analysis,
we can deduce so much about the history of the Universe.**

The Expansion of the Universe

Hubble's Law

Most galaxies are moving away from us.

Hubble* discovered that the Universe is expanding: the recession velocity V of a galaxy is proportional to its distance D ,

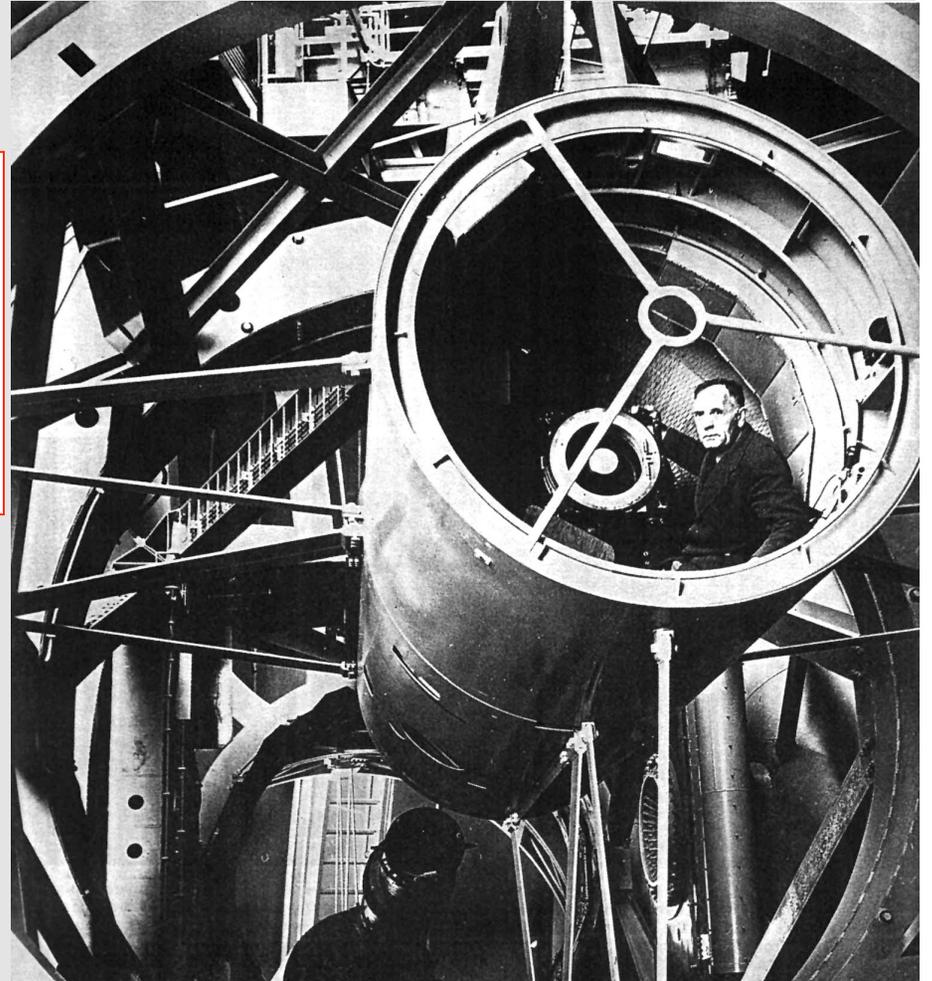
$$V = H_0 D,$$

where H_0 is the Hubble “constant”.

Observations: $H_0 \approx 70 \pm 1$ km/sec/Mpc now.

Note: The self-gravity of the matter in the Universe gradually slows the expansion, so H_0 gets smaller as the Universe gets older. That is, H_0 is not really a constant.

*Georges Lemaître discovered this first.



The Cosmological Principle

Examining the Universe on the largest scales results in **three fundamental observations**:

Homogeneity

Matter is uniformly spread through space. This is obviously not true on the “small” scales of stars and galaxies and clusters of galaxies, but it becomes more and more true as the volume that we look at gets bigger.

Isotropy

The Universe looks the same in every direction. Again, this is true only on large scales.

Universality of Physical Laws

The physical laws are the same everywhere in the Universe. They may depend on time.

The Cosmological Principle

Apart from evolutionary changes, the Universe looks the same to any observer in it.

Note: From the observations it may seem as if the Universe is expanding away from us, but observers in other galaxies will see the same pattern of expansion that we do. There is nothing special about any observer's position. **The expanding Universe has no center.**

The Universe Has No Center

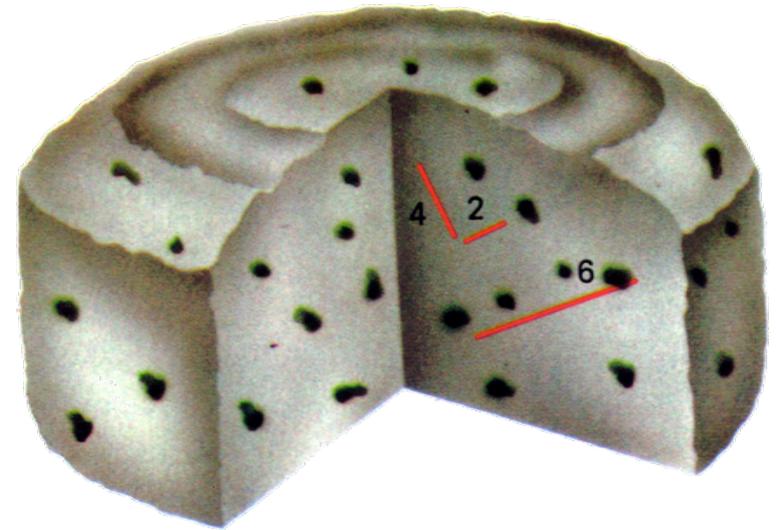
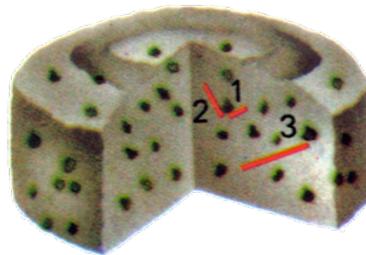
Analogy — the Universe as raisin cake: As a cake expands (“rises”) in an oven, every raisin moves away from every other raisin with an expansion velocity V that is proportional to the separation D of the raisins:

$$V = H_0 D,$$

where

$H_0 \sim 2 \times 10^{16}$ km/s/Mpc for a raisin cake, or

$H_0 = 70$ km/s/Mpc for the Universe

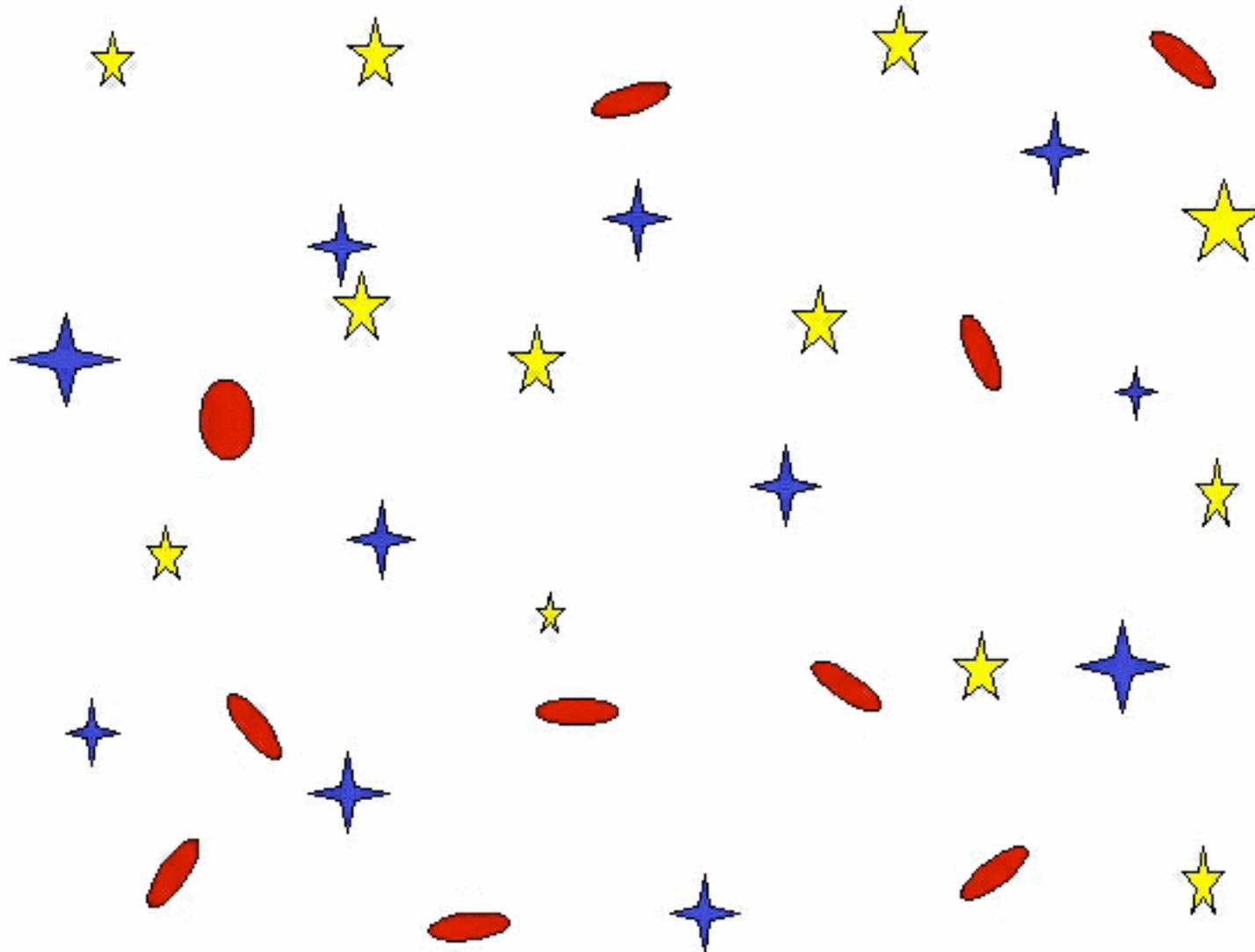


A raisin cake expands much more quickly than the Universe. I assumed that it grows by 3 inches per hour for a 3 inch cake.

Note that the expansion looks the same from every raisin, as long as you can't see the surface of the cake. But the Universe cannot have a surface.

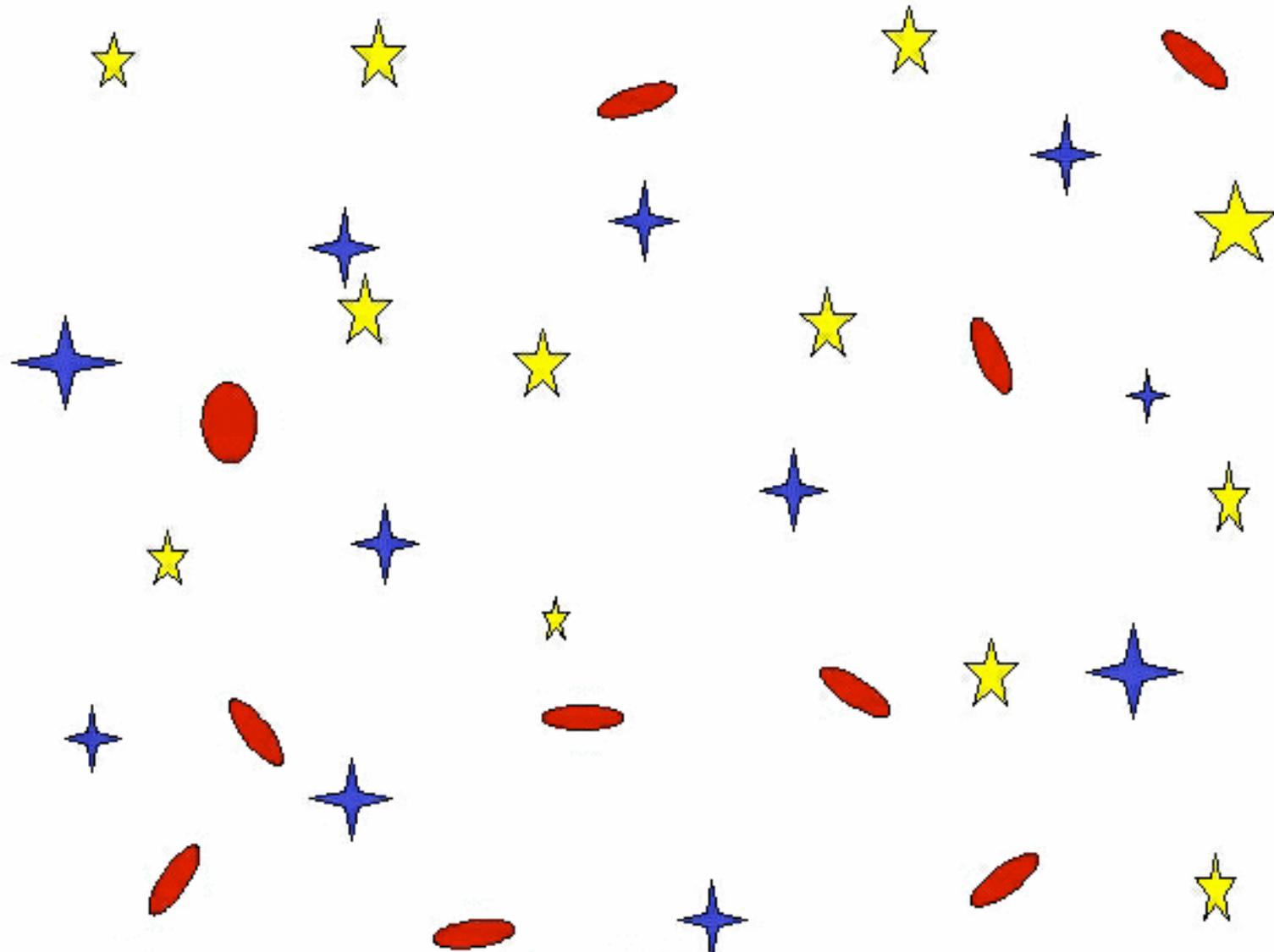
Therefore the expansion of the Universe cannot have a center.

The Universe Has No Center



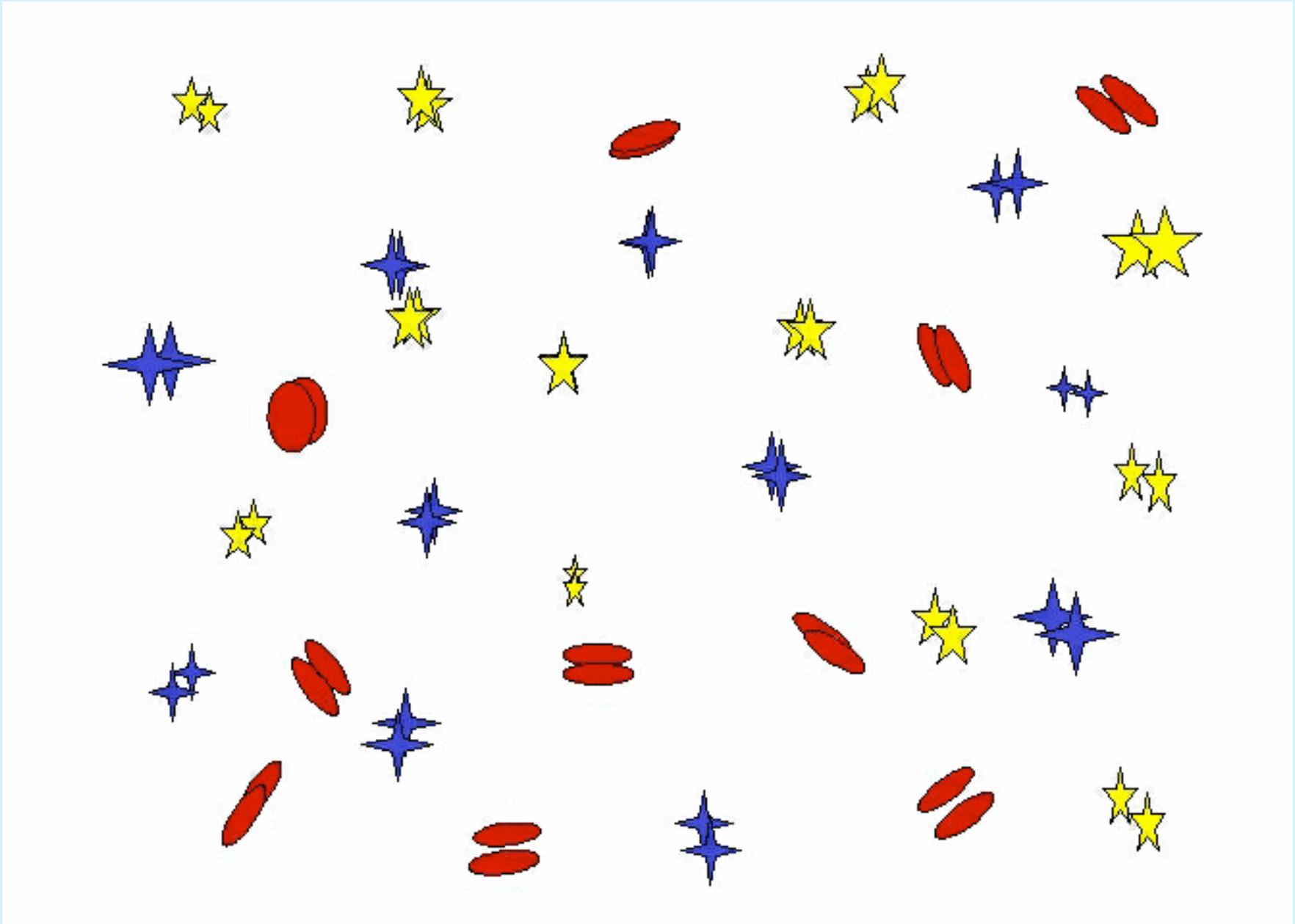
A Toy Universe

The Universe Has No Center

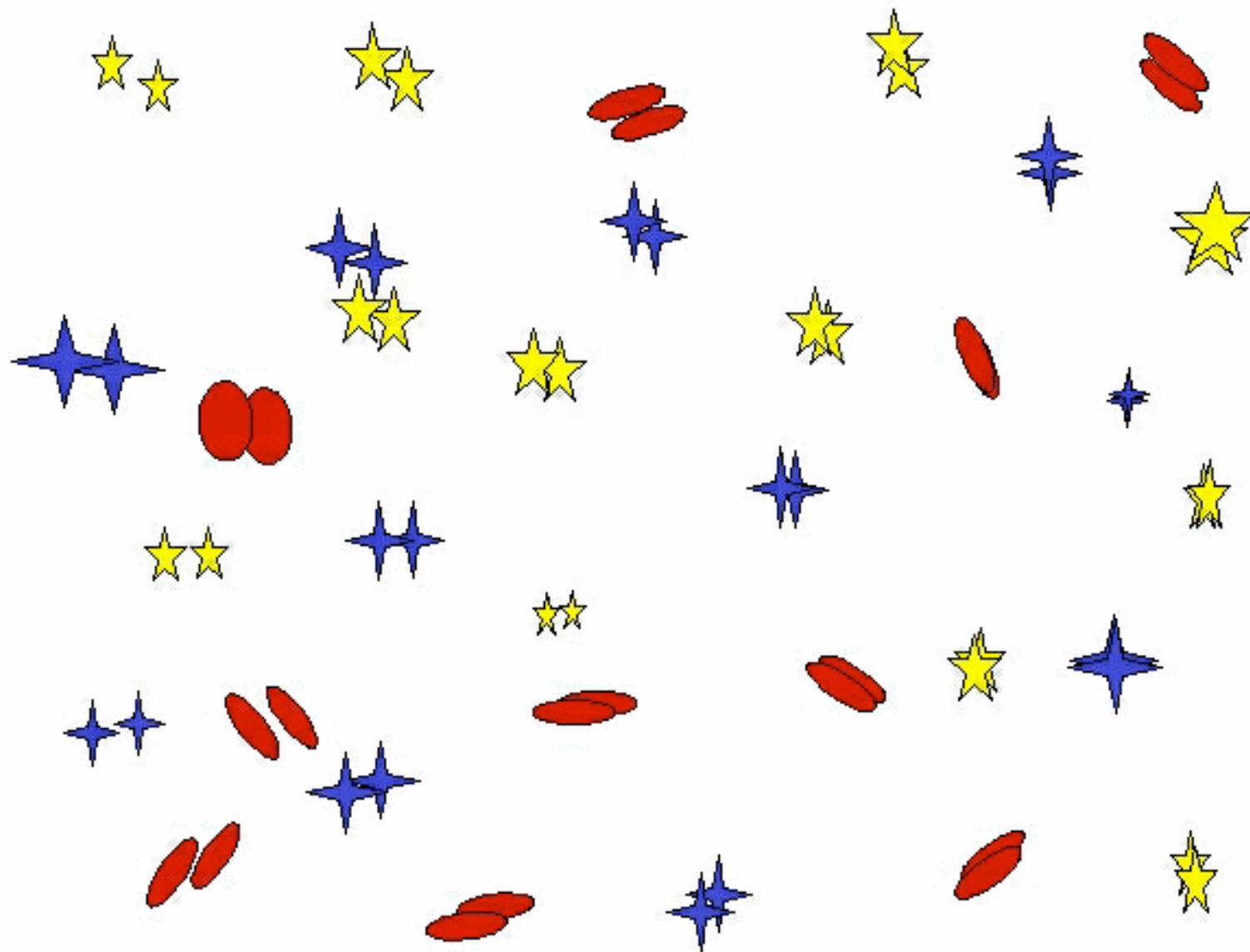


Expanded by 5%

Viewed from **star**, more distant objects moved farther.

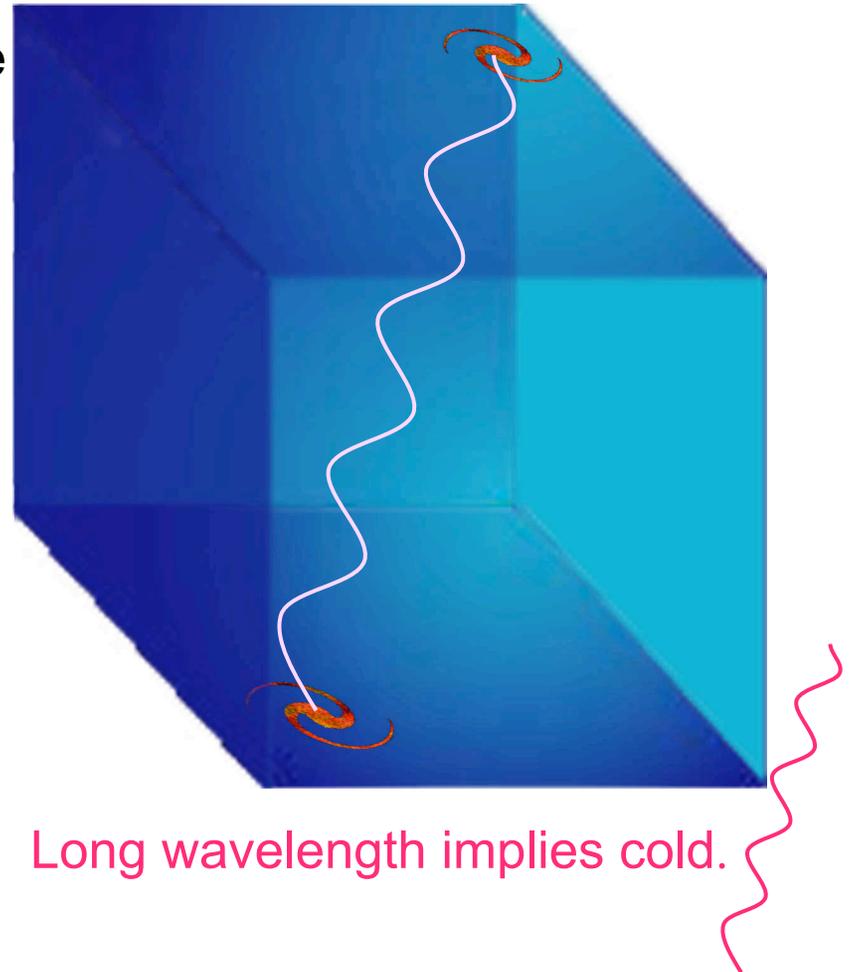
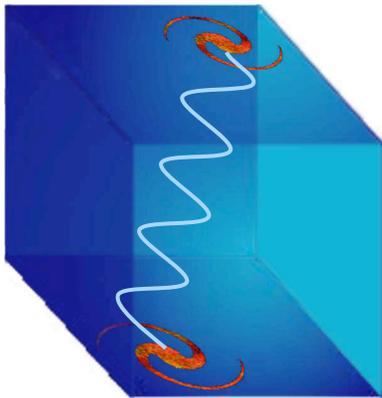


The expansion looks the same to every observer.



Photons Expand with the Universe

As space expands, light waves that move through it expand, too, increasing their wavelength (**blue → red**). Note how remarkable this is – nothing else except space expands as the Universe expands. E.g., atoms do not expand.



Short wavelength implies hot. 

Long wavelength implies cold. 

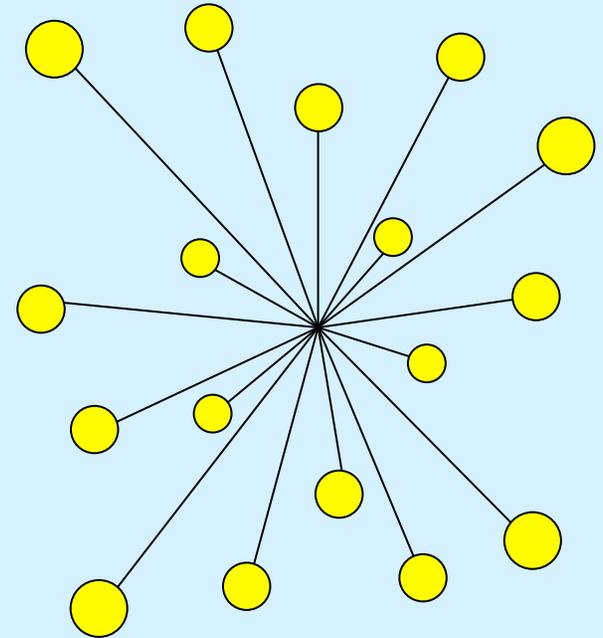
Cosmology: The Most Important Observations

1 – The night sky is dark.

- **Olber's Paradox: Surface brightness is independent of distance. So, if the Universe were infinite in size and age, every line of sight would eventually reach the surface of a star. The sky would everywhere be as bright as the surface of an average star.**

Why is the night sky dark?

- **Solution: (1) The Universe is expanding: light from far away is redshifted. (2) The age of the Universe is finite: light from objects that are farther away than about 14 billion light years has not yet had time to reach us. (3) The Universe is evolving: before its age was a few hundred million years, there were no stars.**



Cosmology: The Most Important Observations

2 – The Universe is expanding.

- The expansion rate implies that everything was at one place 13.7 billion years ago. The Universe began in an explosion called the “Big Bang.”

3 – The Universe is homogeneous and isotropic on large scales. This is surprising, because the most distant objects on opposite sides of the sky are so far apart that light has not had time to travel between them. They have never been “in causal contact”. How does the Universe in opposite directions know to have the same properties?

Solution: We believe that the Universe underwent a sudden period of very rapid “inflation” that started about 10^{-35} seconds after the Big Bang. The entire Universe that we see grew from smaller than the size of a proton to the size of a beach ball and then continued expanding more slowly, as it does now. If this is correct, then the entire Universe that we can see was in causal contact early on.

This sounds like wild speculation. But another period of accelerating expansion is now under way (see “dark energy”, below).

Inflation

During inflation, the whole Universe expanded much faster than the speed of light.

(Actually, the Universe is expanding faster than the speed of light far away from us now, too.)

Cosmology: The Most Important Observations

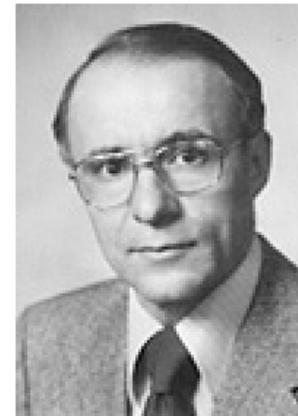
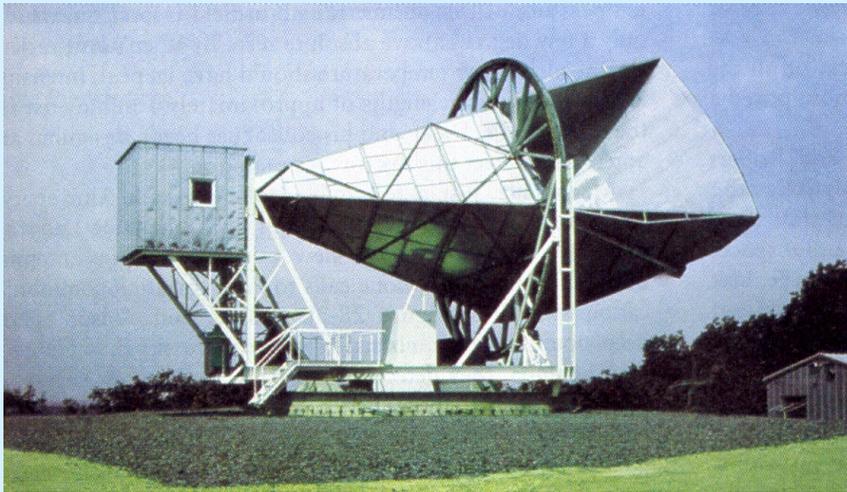
- 4 – The Universe is filled with black-body radiation at a temperature of $T = 2.735 \text{ K}$. This is the “microwave background radiation”.
 - This radiation is the redshifted and cooled relic of the Big Bang fireball. Its discovery is regarded as definitive proof that the Big Bang happened.
 - In the past, the Universe was hotter: $T \propto 1 + z$.
 - When the Universe was about 380,000 years old and had a temperature of about 4000 K, the electrons in the cooling fireball combined with protons to make neutral atoms.

The Universe became transparent.

This is the farthest back that we can see.

Discovery of the Microwave Background Radiation

- 4 – The Universe is filled with black-body radiation at a temperature of $T = 2.735 \text{ K}$. This is the “microwave background radiation”.



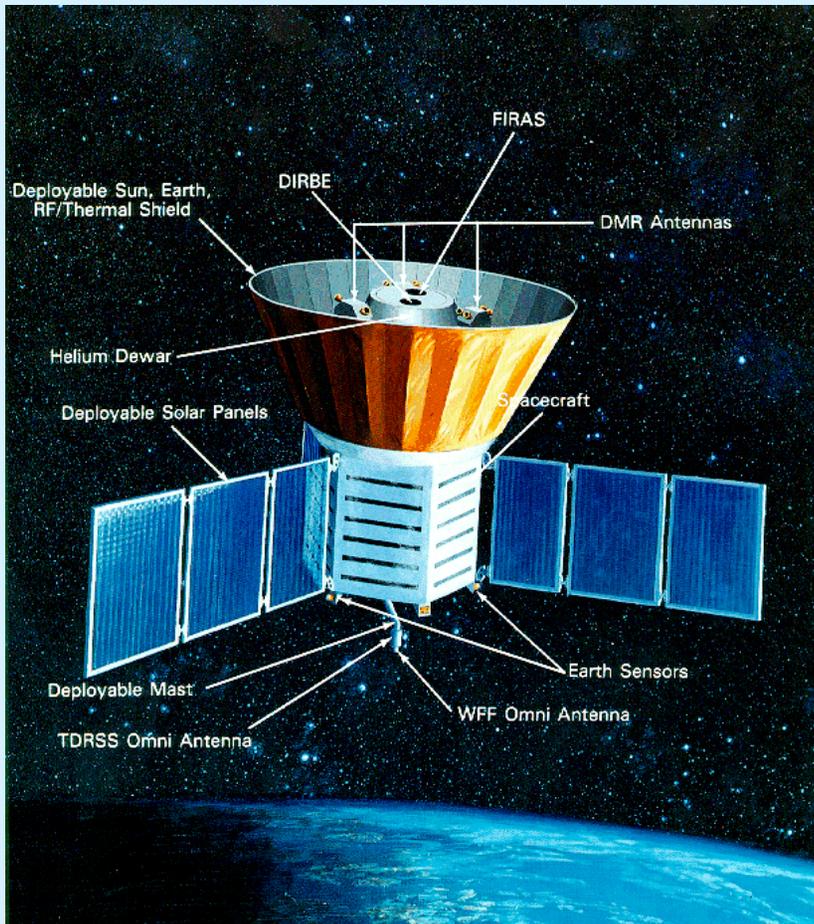
Arno Allan Penzias



Robert Woodrow Wilson

Arno Penzias and Robert Wilson discovered the microwave background radiation with this antenna in Holmdell, NJ, in 1964. They were trying to get rid of sources of noise in satellite communications and found a background “hiss” that they could not eliminate. It turned out to be the radiation left over from the formation of the Universe. For this discovery, they got the 1978 Nobel Prize in Physics.

Microwave Background Radiation



Cosmic Background Explorer

The COBE satellite measured the microwave background radiation exceedingly accurately and found:

it is precisely black-body
with $T = 2.735 \pm 0.06$ K;

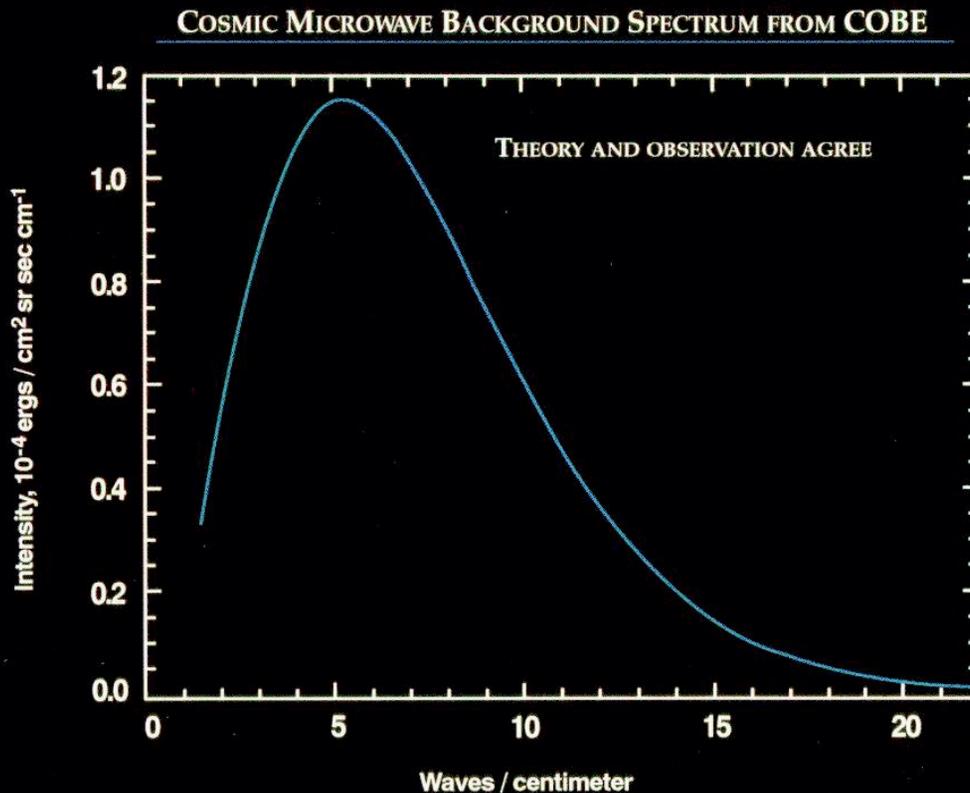
it shows the motion of our Galaxy
with respect to the background radiation;

it shows tiny fluctuations in temperature
that are the origin of all structure
in the Universe.

Microwave Background Radiation

Cosmic Background Explorer

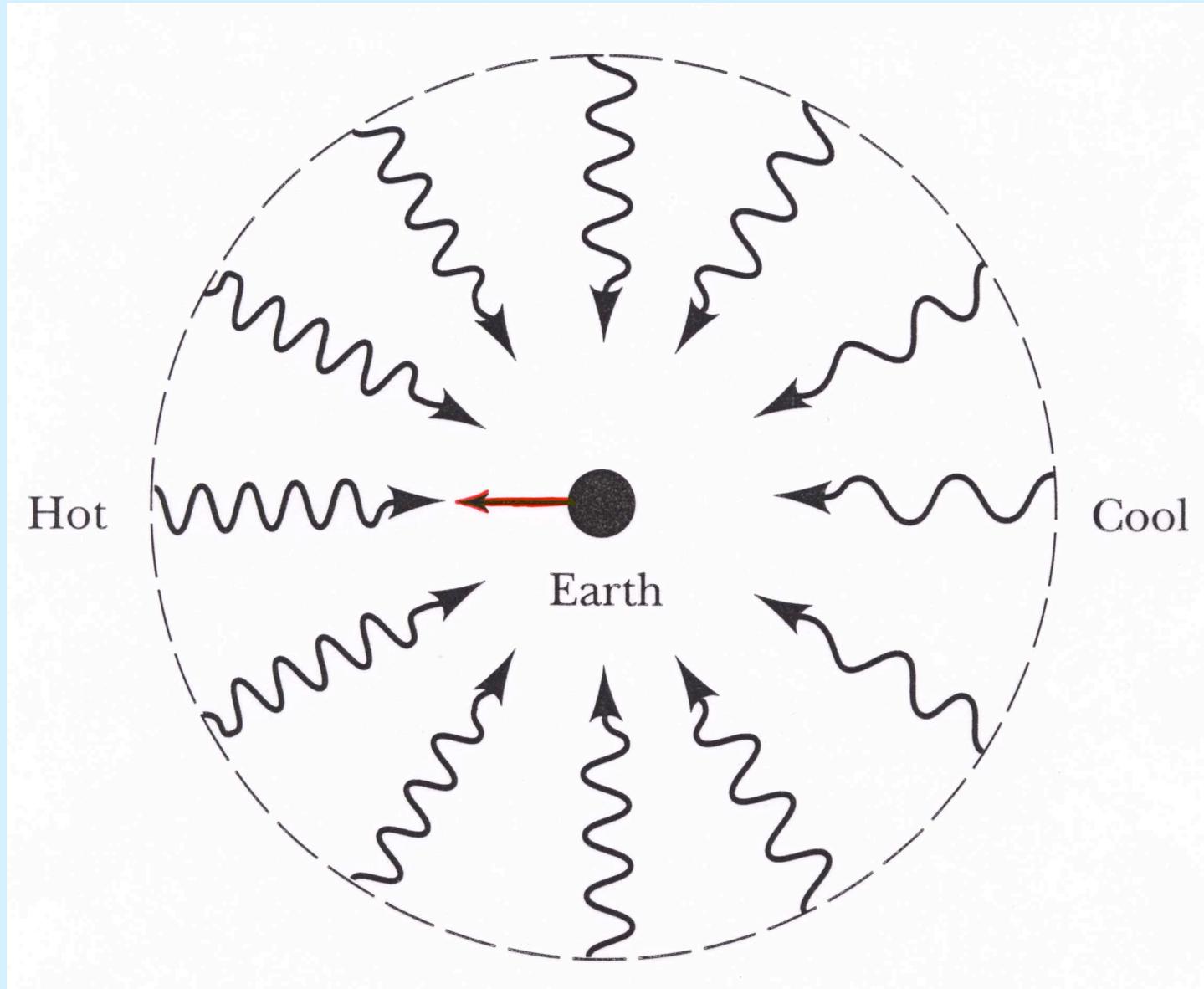
The COBE satellite measured the microwave background radiation exceedingly accurately and found:

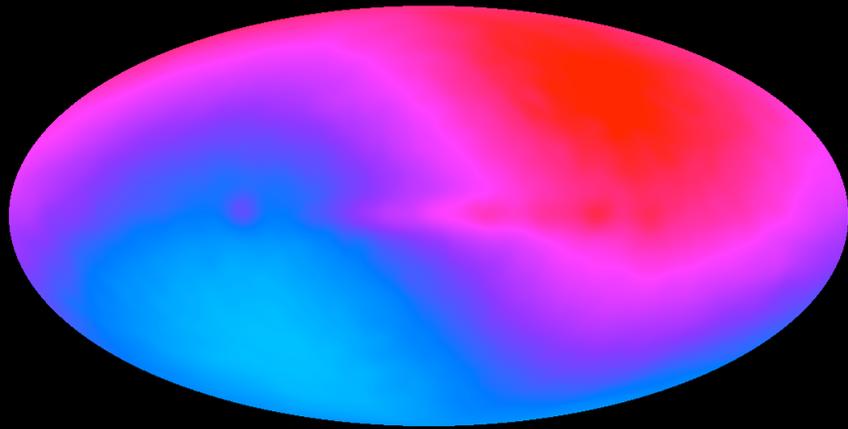


it is precisely black-body
with $T = 2.735 \pm 0.06$ K.

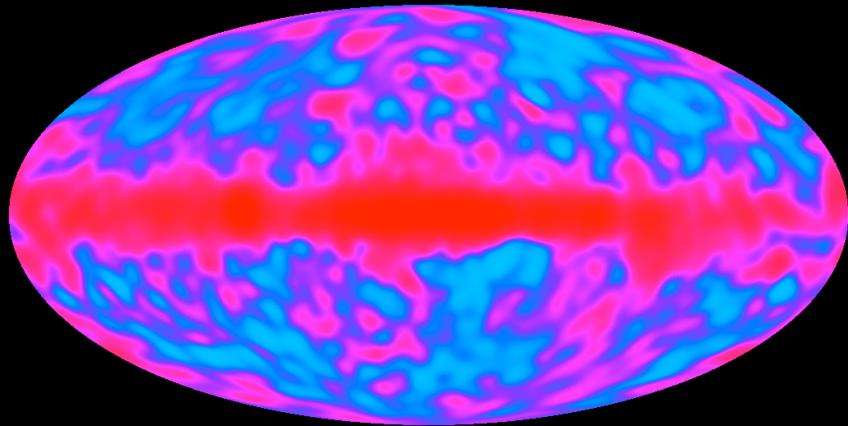
John Mather got the 2006
Nobel Prize in Physics for this work.

The Sun is moving at 620 km/s relative to the microwave background radiation.

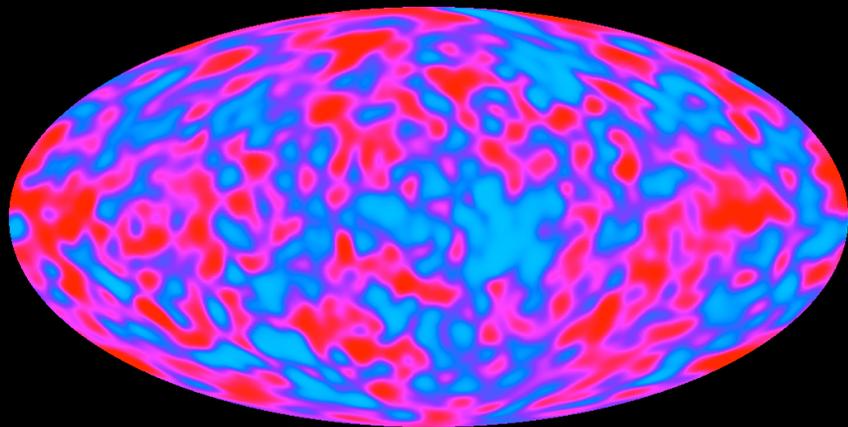




These variations of ± 0.003 K show that our Sun is moving at 620 km/s relative to the microwave background radiation toward the constellation Leo.



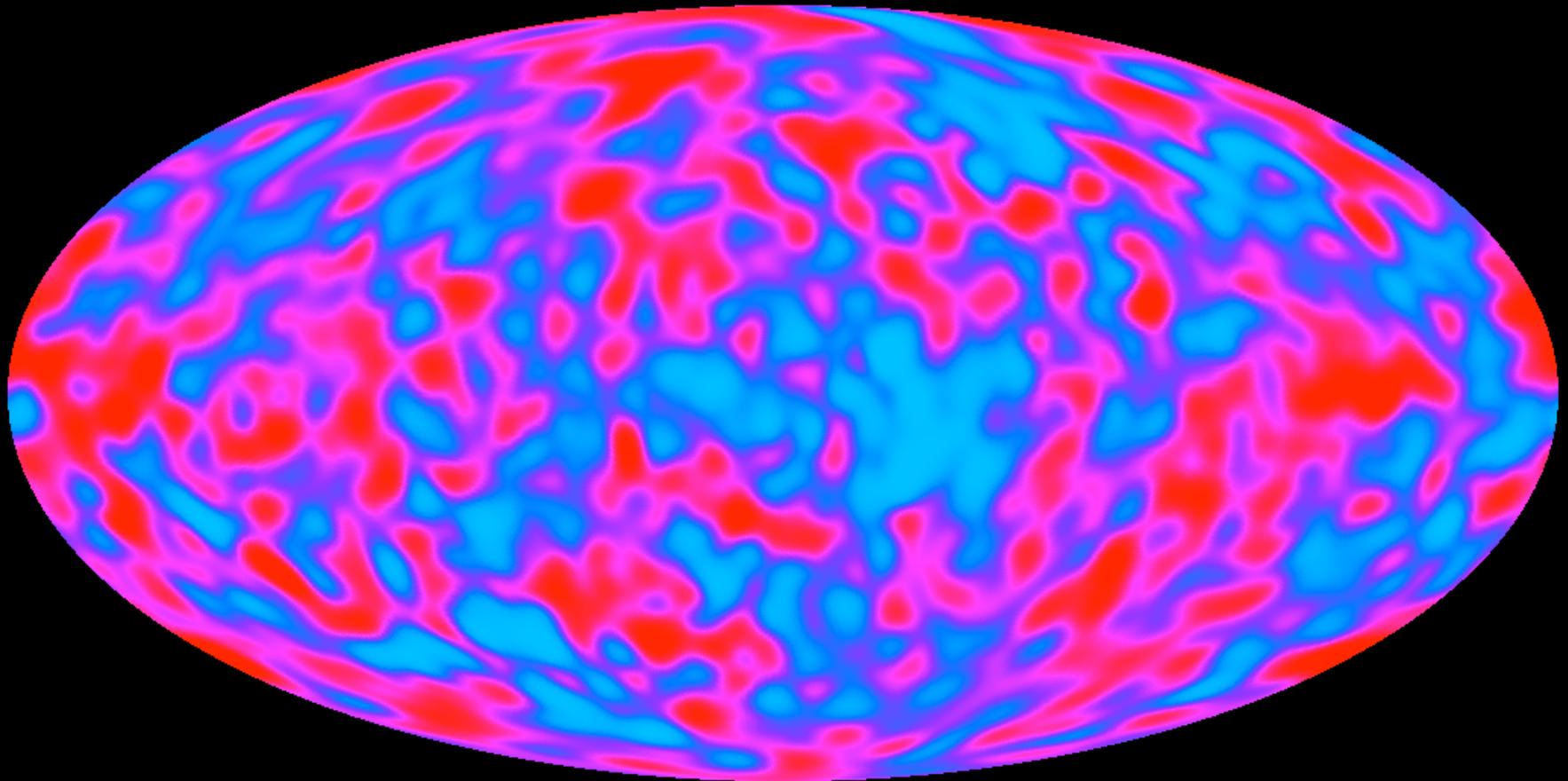
Subtract the Sun's motion. Then we see emission from our Galactic disk superposed on fluctuations in the microwave background radiation.



Subtract the Milky Way. Then we see fluctuations of ± 0.000017 K in the temperature of the background radiation. These are caused by the tiny density fluctuations that were present when the Universe was 380,000 years old.

Cosmology: The Most Important Observations

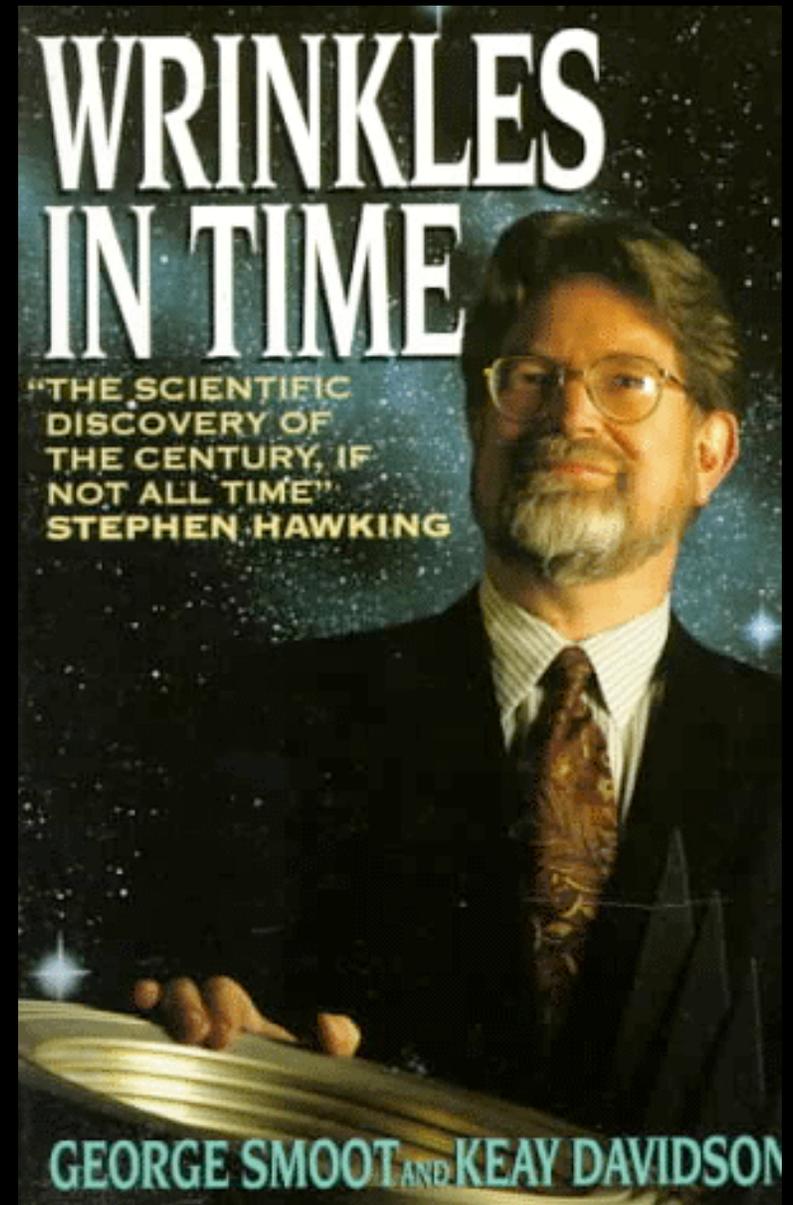
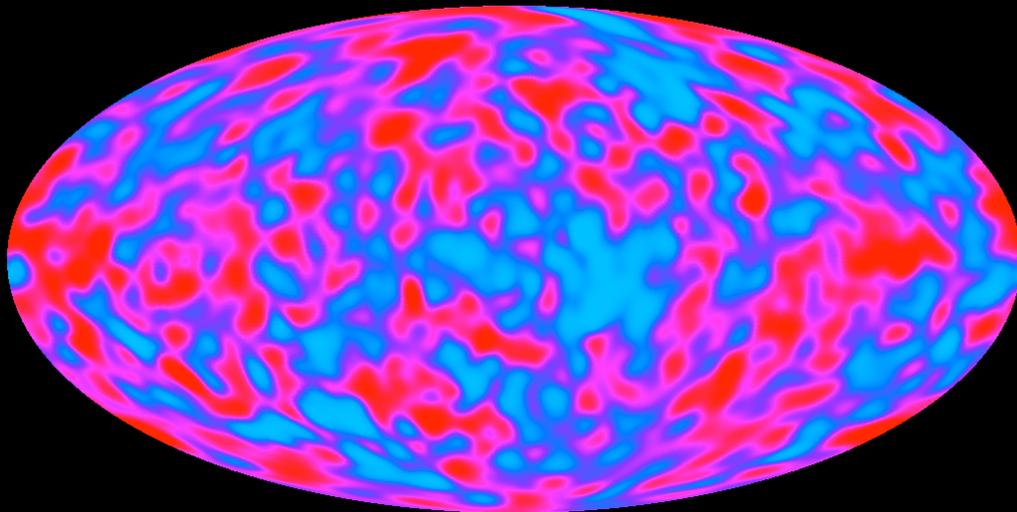
- 5 – **COBE** observed 0.0006 % fluctuations in the temperature of the microwave background. They are the origin of all structure in the Universe, including superclusters of galaxies, clusters of galaxies, and galaxies.



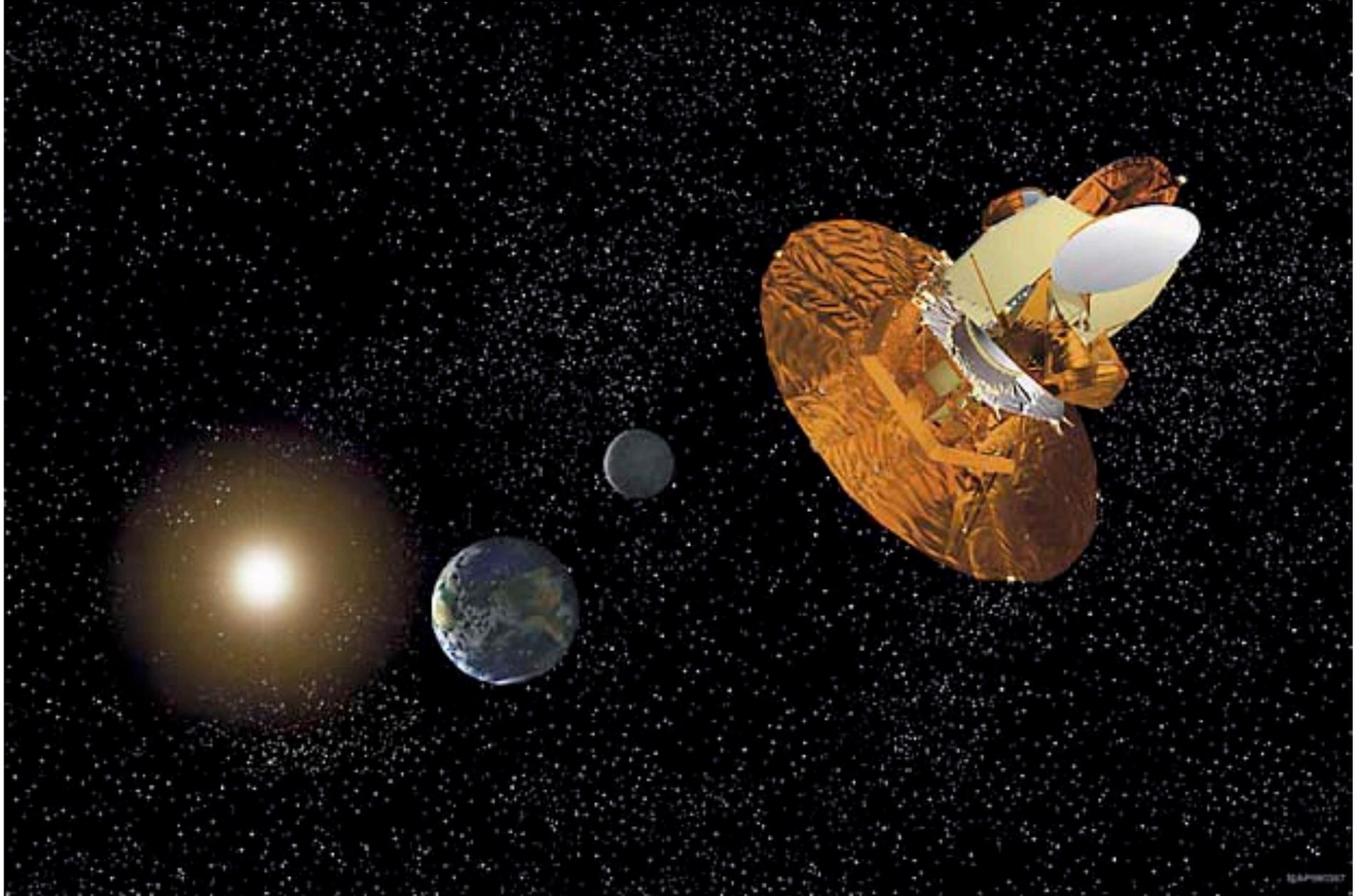
Cosmology: The Most Important Observations

The discovery of fluctuations in the microwave background radiation is one of the most important astronomical results of the 1990s.

George Smoot was co-recipient of the Nobel Prize for Physics in 2006.

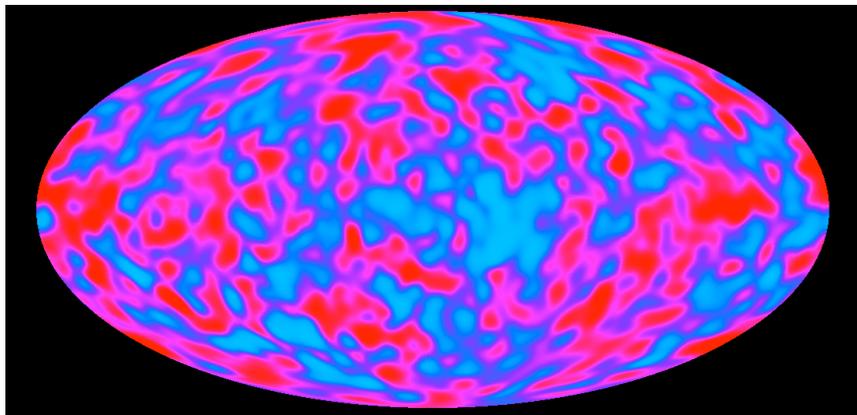
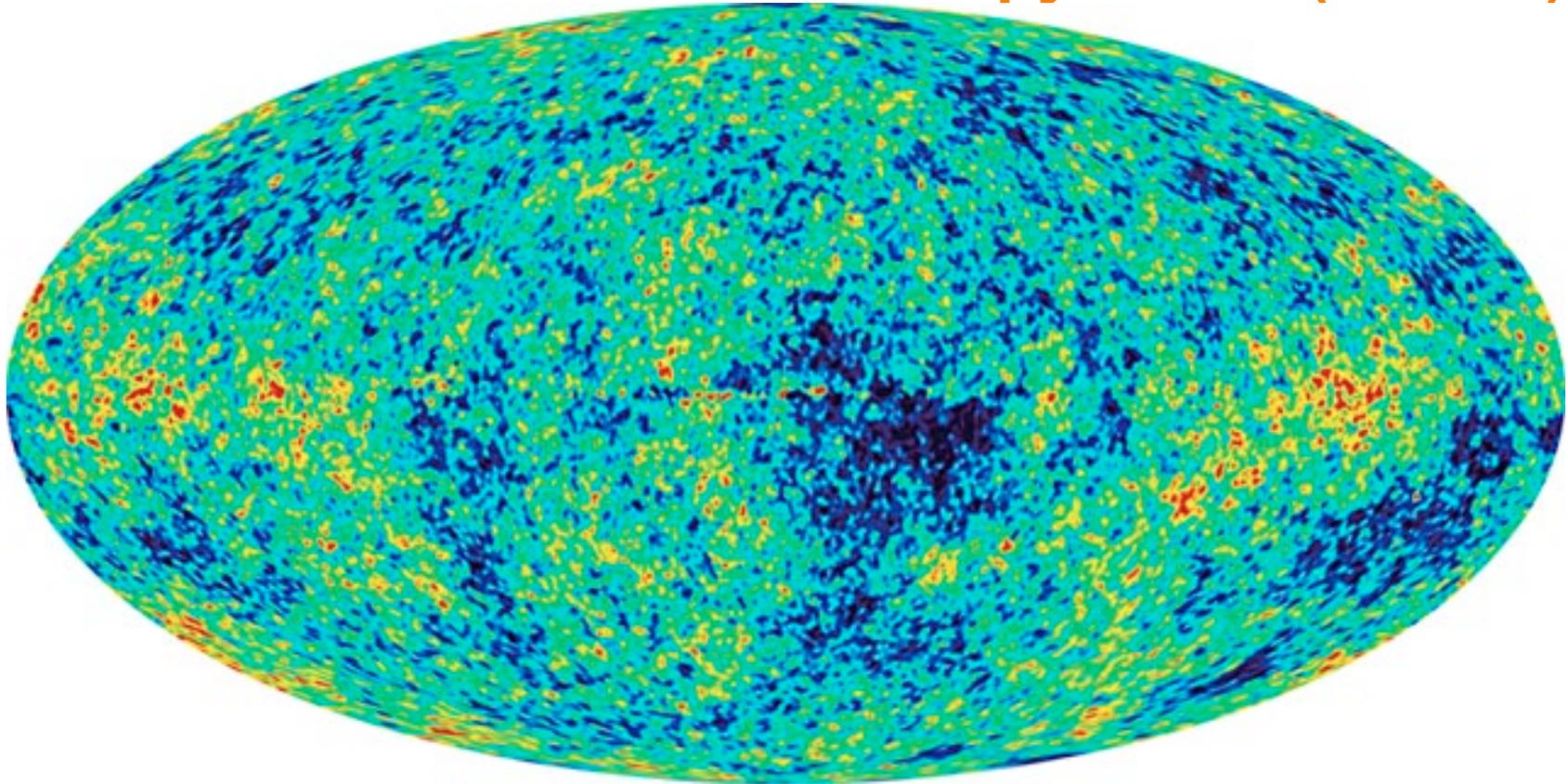


Wilkinson Microwave Anisotropy Probe (WMAP)



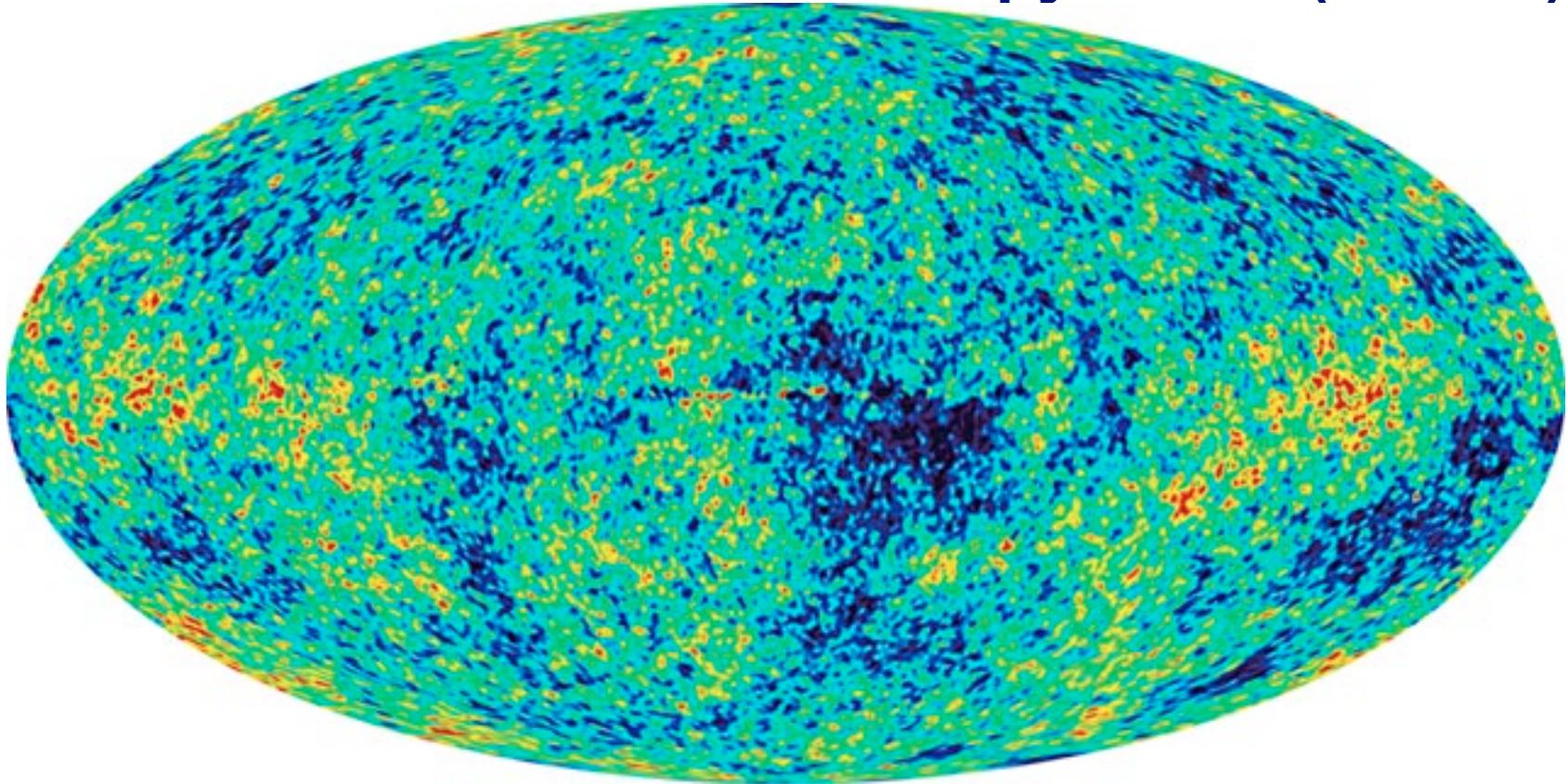


Wilkinson Microwave Anisotropy Probe (WMAP)



WMAP measured the temperature fluctuations in the microwave background with much better spatial resolution and sensitivity than COBE.

Wilkinson Microwave Anisotropy Probe (WMAP)



Conclusions

The Universe is 13.77 billion years old with a margin of error of 0.4 %.

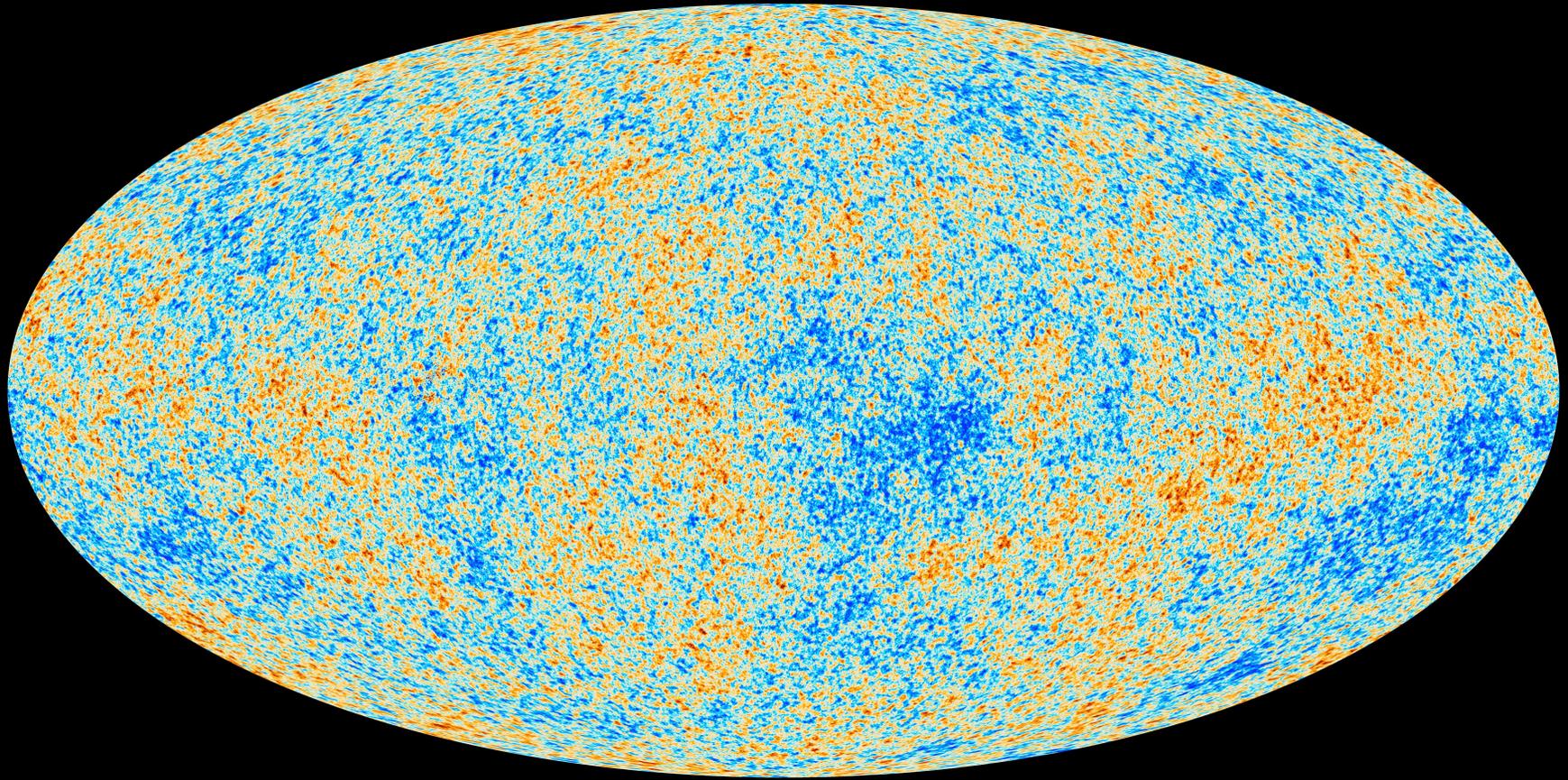
The WMAP picture shows the Universe as it was 380,000 years after the Big Bang.

Content of the Universe: 4.6 % atoms, 24 % cold dark matter, 71 % dark energy.

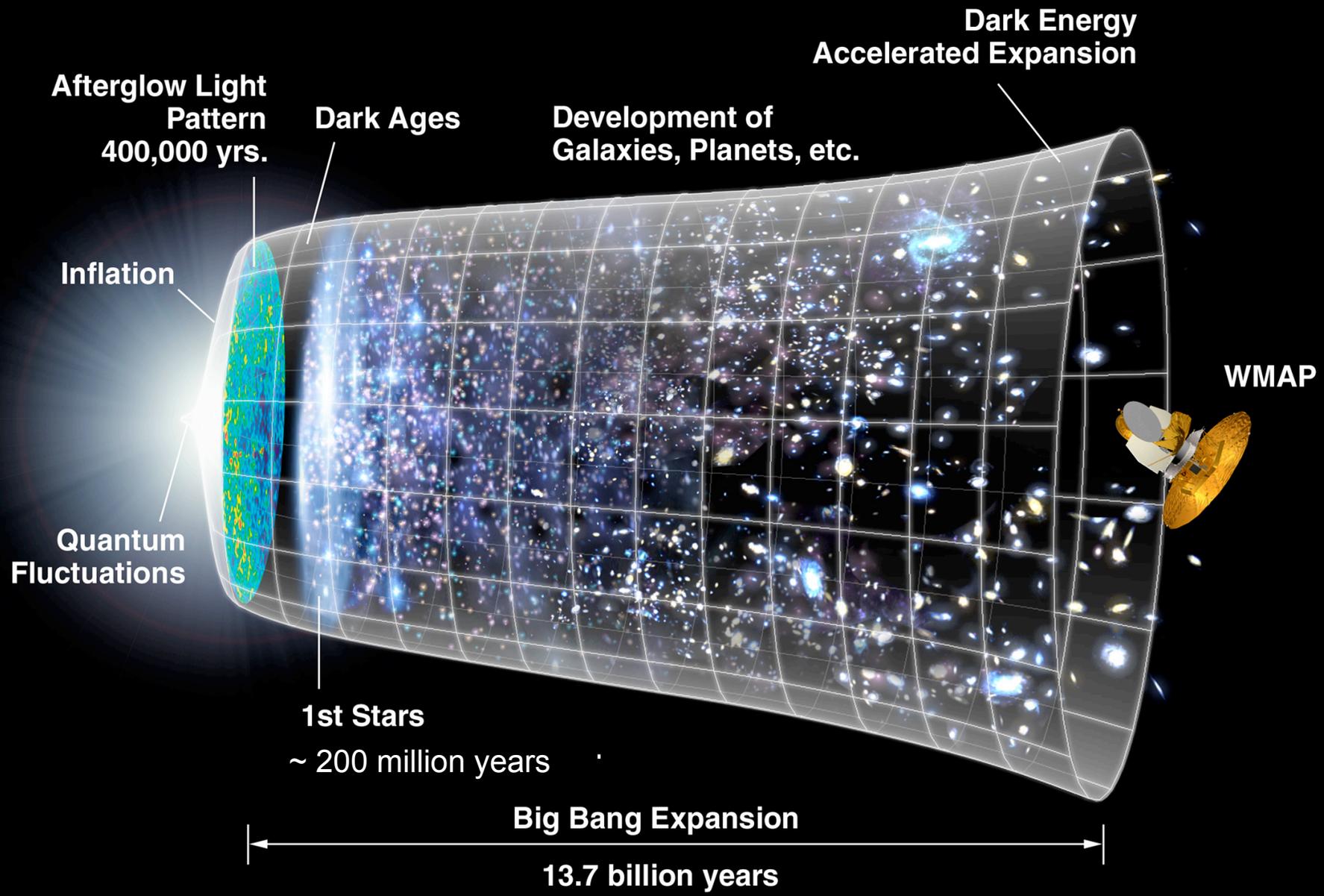
The first stars ignited ~ 200 million years after the Big Bang.

The Hubble constant is 69.3 km/sec/Mpc with a margin of error of about 1 %.

For the simplest theory that fits the above data, the Universe will expand forever.



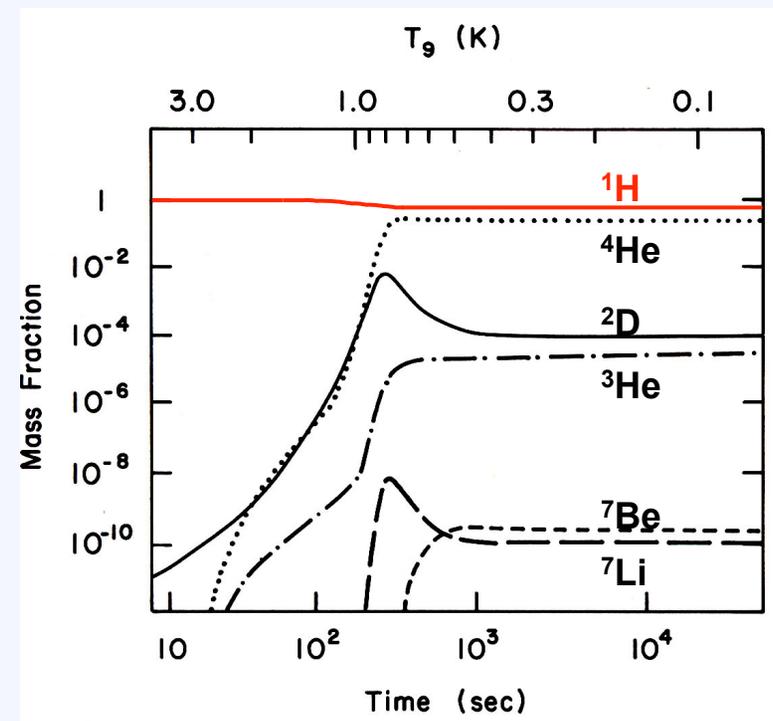
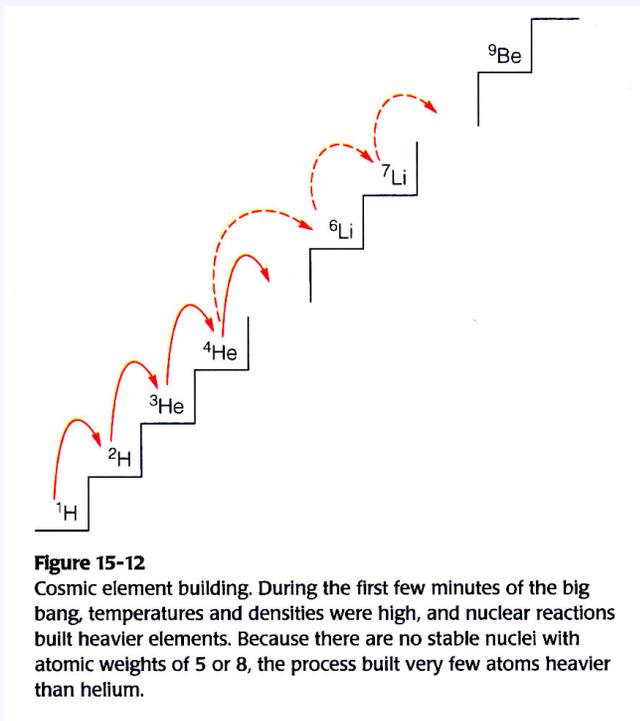
Observations from a new satellite – “Planck” – are now being collected and analyzed.



Cosmology: The Most Important Observations

6 – The abundances of light elements relative to hydrogen:

When the Universe was 2 minutes old, it had cooled to a billion K. Protons and neutrons began to combine to make deuterium = heavy hydrogen, helium, and traces of lithium and beryllium. By the time the Universe was 30 minutes old, it had cooled too much for nuclear reactions. The abundances “froze out”. These abundances can be predicted from first principles. Excellent agreement with observed abundances is one of the triumphs and cornerstones of cosmology.



Cosmology: The Most Important Observations

7 – The Universe is made of matter, not — we think — antimatter.

Before age 10^{-12} s, the temperature $\approx 10^{15}$ K was so high that there were equal numbers of quarks and antiquarks, the particles that make up protons and neutrons. The Universe was a dynamical soup of energy flickering back and forth between photons and particles according to $E = mc^2$.

After this time, particles and antiparticles collided, annihilated, & turned into photons. The nature of the weak nuclear force resulted in a tiny preference of quarks over antiquarks. So a small amount of matter (1 part in a billion) survived. Therefore, the Universe is now made of matter, not antimatter.

At age $\sim 10^{-6}$ s (temperature $\approx 10^{13}$ K), the surviving quarks combined in groups of 3 to produce protons – that is, hydrogen nuclei – and neutrons.

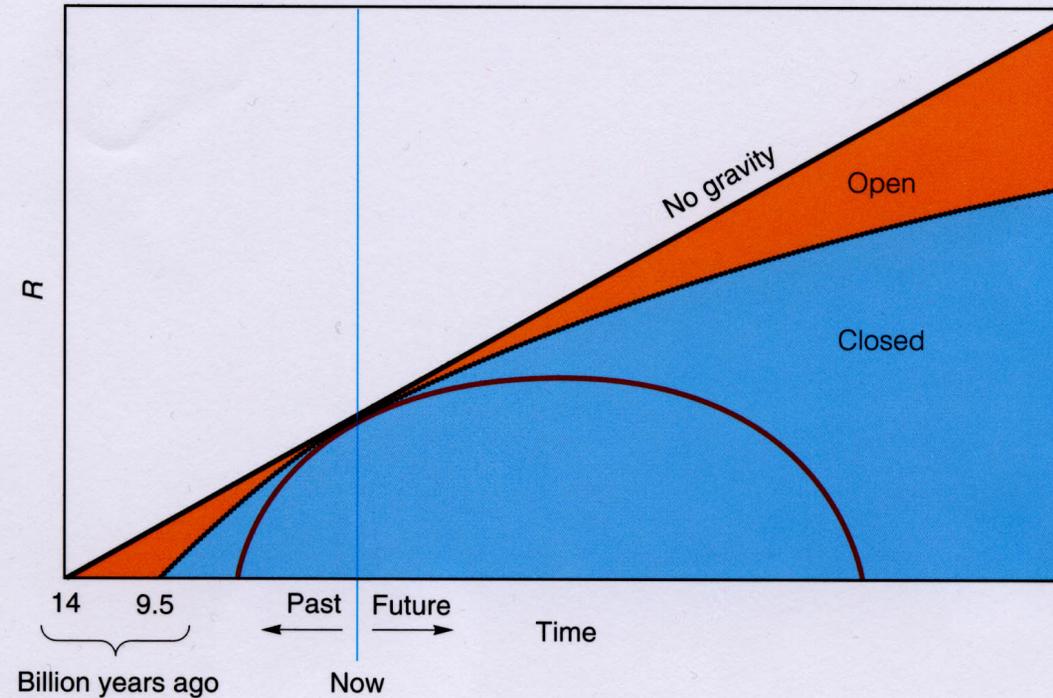
The Fate of the Universe

The fate of the Universe depends on the density of mass-energy in it.

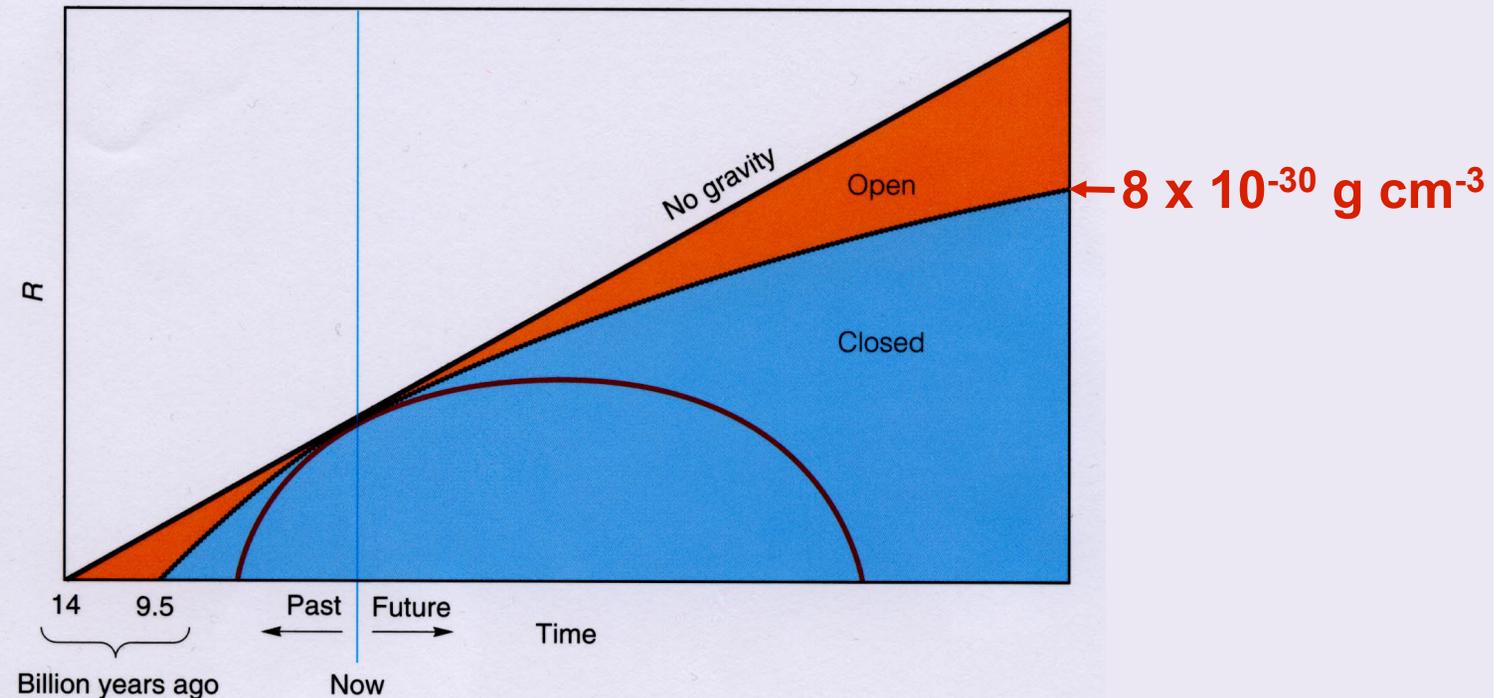
If the density were zero, the universe would expand forever at a uniform rate (“no gravity”). But we know that the density is not zero.

If the density is low, then the Universe will expand forever, although the expansion will slow down with time.

If the density is high, then the Universe will eventually recollapse.



The Geometry of Space-Time Depends of Density



If the density is exactly the critical value, $8 \times 10^{-30} \text{ g cm}^{-3} \approx 5$ atoms per cubic meter of space, then the geometry of space-time is flat. Then the **Universe may be infinite and unbounded**. We do not know its behavior far outside the volume that we can observe.

If the density is lower than the critical density, then the Universe has negative curvature (“Open”). Again, it may be infinite and unbounded.

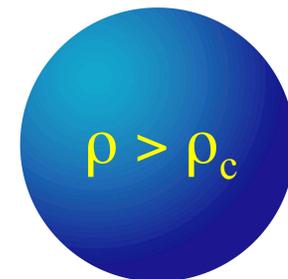
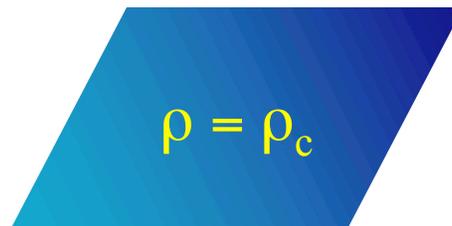
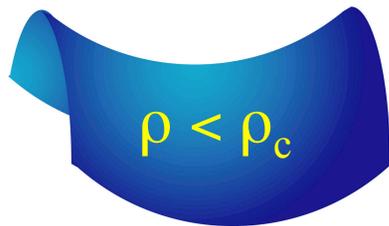
If the density is higher than the critical density, then the Universe has positive curvature (“Closed”). It is probably finite and unbounded.

The Shape of Space-Time

We assume that the Universe is

1. Homogeneous – the same in all places, and
2. Isotropic – the same in all directions.

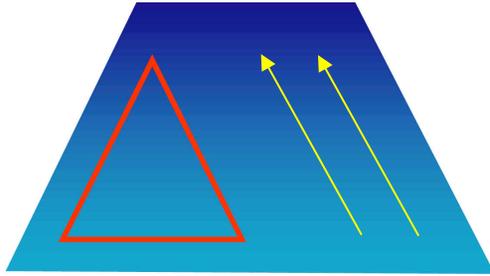
Then General Relativity tells us that there are three possible forms that the Universe can have: open, flat, or closed.



Open and flat Universes are infinite and expand forever. A closed Universe is finite. It first expands and then contracts. **If geometry is the same everywhere.**

Which is correct depends on the average mass density of the Universe compared to the critical density ρ_c . This is something that we cannot predict. It must be observed. Also: **We do not know that the Universe behaves the way that we observe it to behave even outside our light-travel-time horizon.**

The Shape of Space-Time

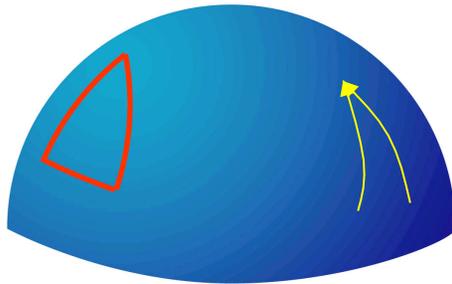


Flat space:

Zero curvature

Universe expands forever

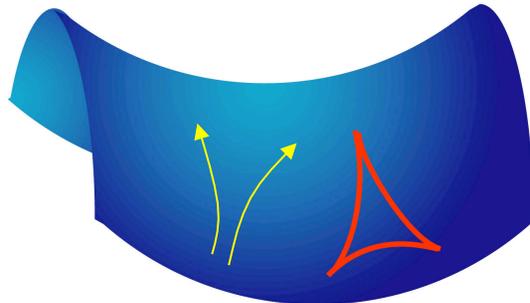
The WMAP and Planck results now show that the Universe is flat.



Spherical space:

Positive curvature

Universe is closed and will recollapse



Hyperbolic space:

Negative curvature

Universe expands forever

New Techniques: High-Redshift Type I Supernovae

Type I supernovae happen when white dwarf stars in binary systems are driven over the Chandrasekhar limit by gas added from evolving companions.

The Chandrasekhar limit does not depend on distance.

This suggests that Type I supernovae are excellent standard candles.

Teams led by Brian Schmidt (Australia) and Saul Perlmutter (USA) observed Type I supernovae at large distances to measure the deceleration of the expansion of the Universe. The goal was to determine the geometry and fate of the Universe. The results are very exciting:

The expansion of the Universe is accelerating.

Team leaders Saul Perlmutter, Brian Schmidt, and Adam Riess won the 2011 Nobel Prize in Physics for this discovery.

The Cosmological Constant Λ

The expansion of the Universe is accelerating.

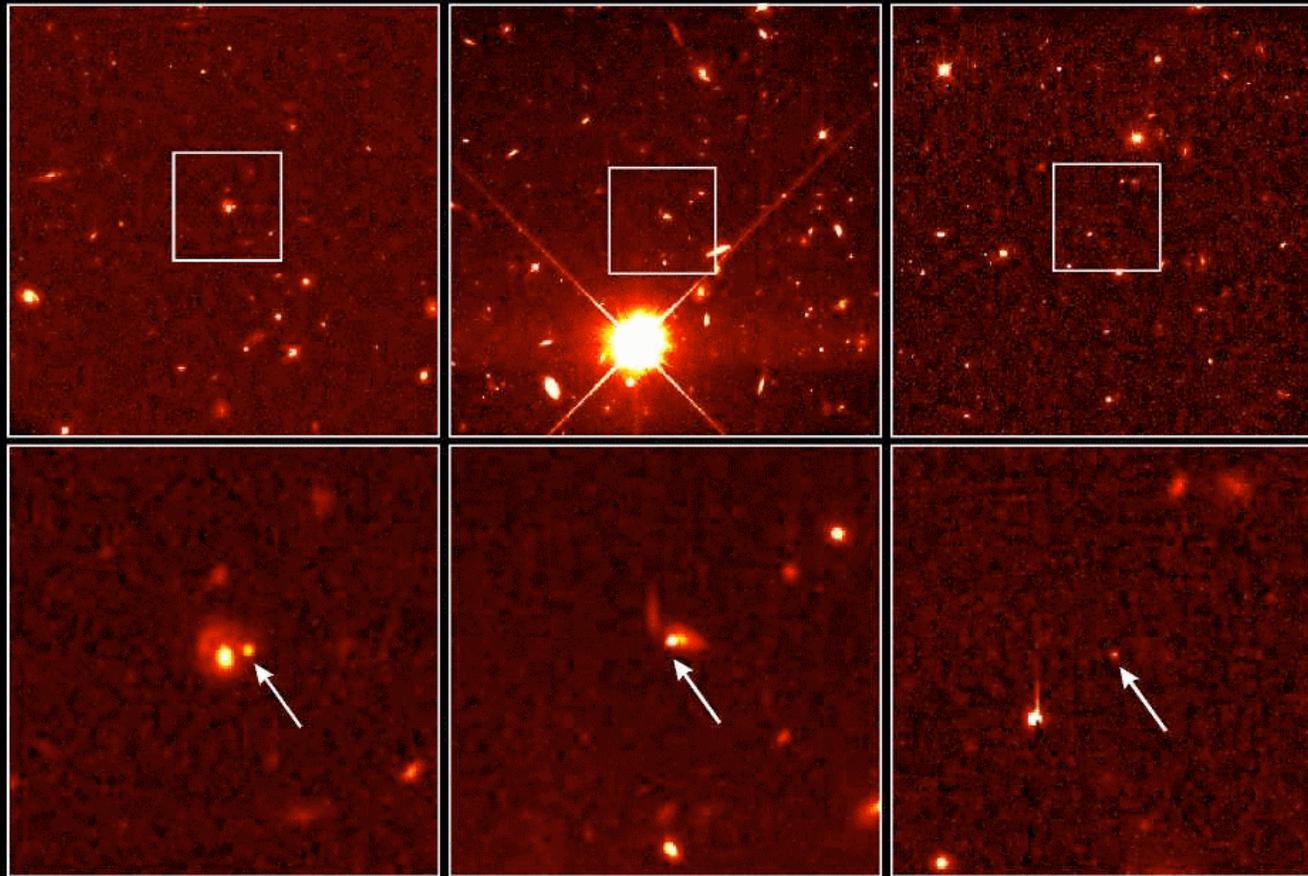
Why? When Einstein applied his theory of General Relativity to the Universe, he found that it should expand or contract. This was before the expansion was discovered. He thought the Universe is static. So he invented a new term called Λ in his equations to provide a repulsion to balance the self-gravity of the Universe and keep it static. Later, when the expansion of the Universe was discovered, he discarded Λ and regarded it as the biggest mistake of his career.

Now, Nature has surprised us again. If the Universe is accelerating, then $\Lambda > 0$ by enough to overcome the mutual attraction of the stuff in the Universe. Empty space contains tremendous “dark energy”.

Is this enough to make the Universe flat?

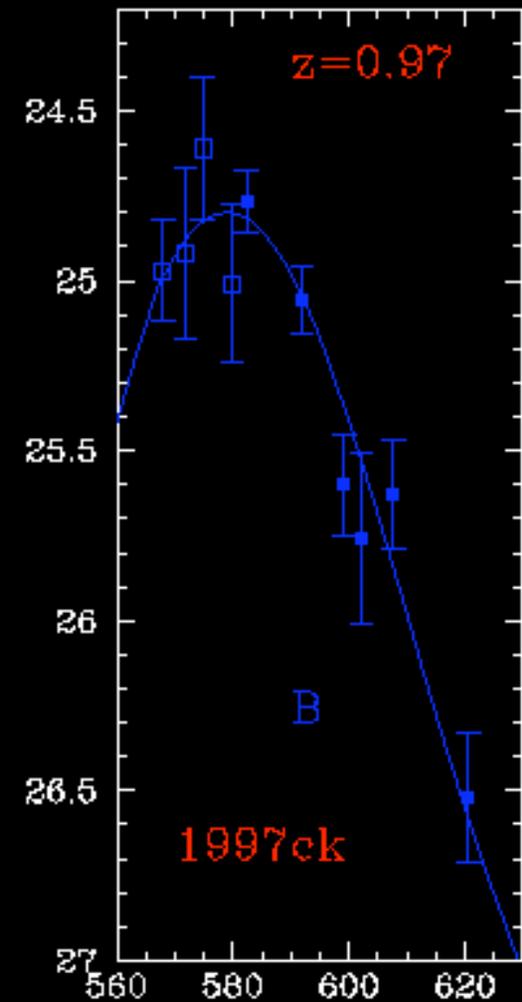
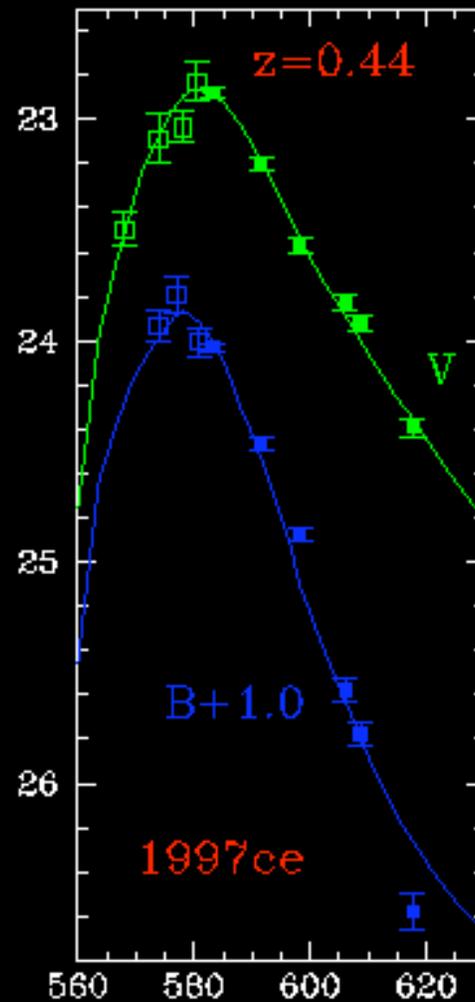
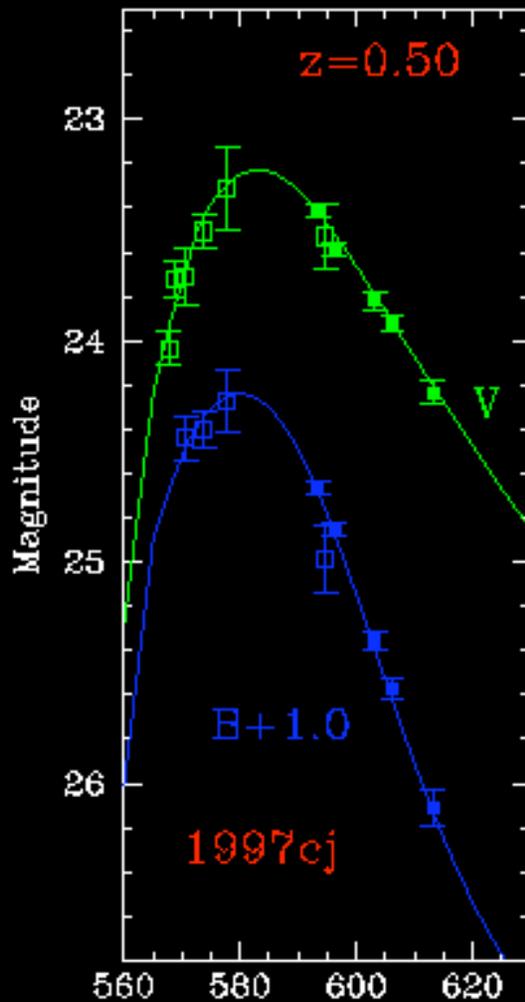
High-Redshift Type I Supernovae

1 — Find supernovae via ground-based searches and then observe them with HST.



Distant Supernovae
Hubble Space Telescope • Wide Field Planetary Camera 2

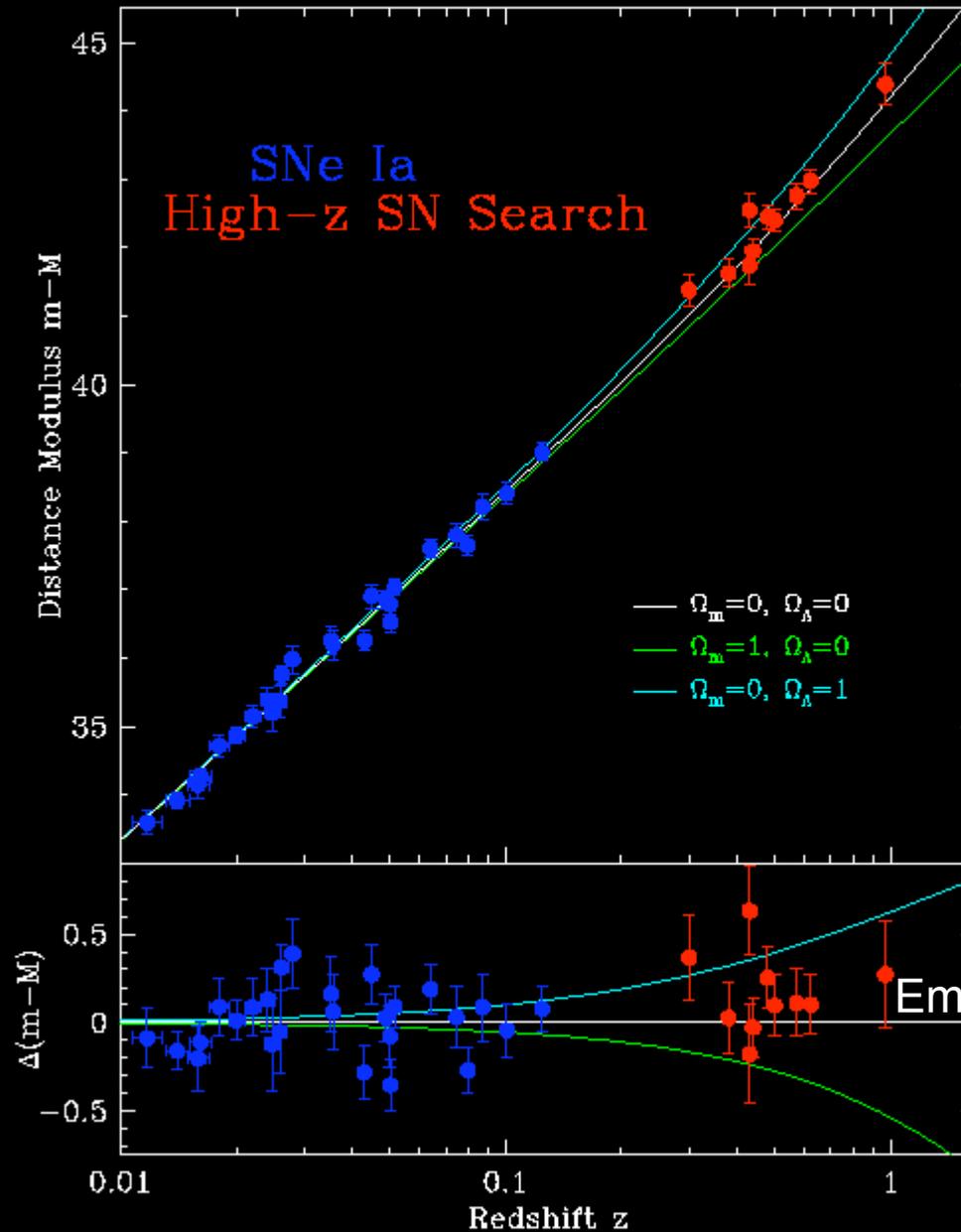
2. Measure their light curves using HST.



Julian Day (+2450000)

3. Make a Hubble Diagram

Definition:
 $\Omega = \rho / \rho_{\text{crit}}$



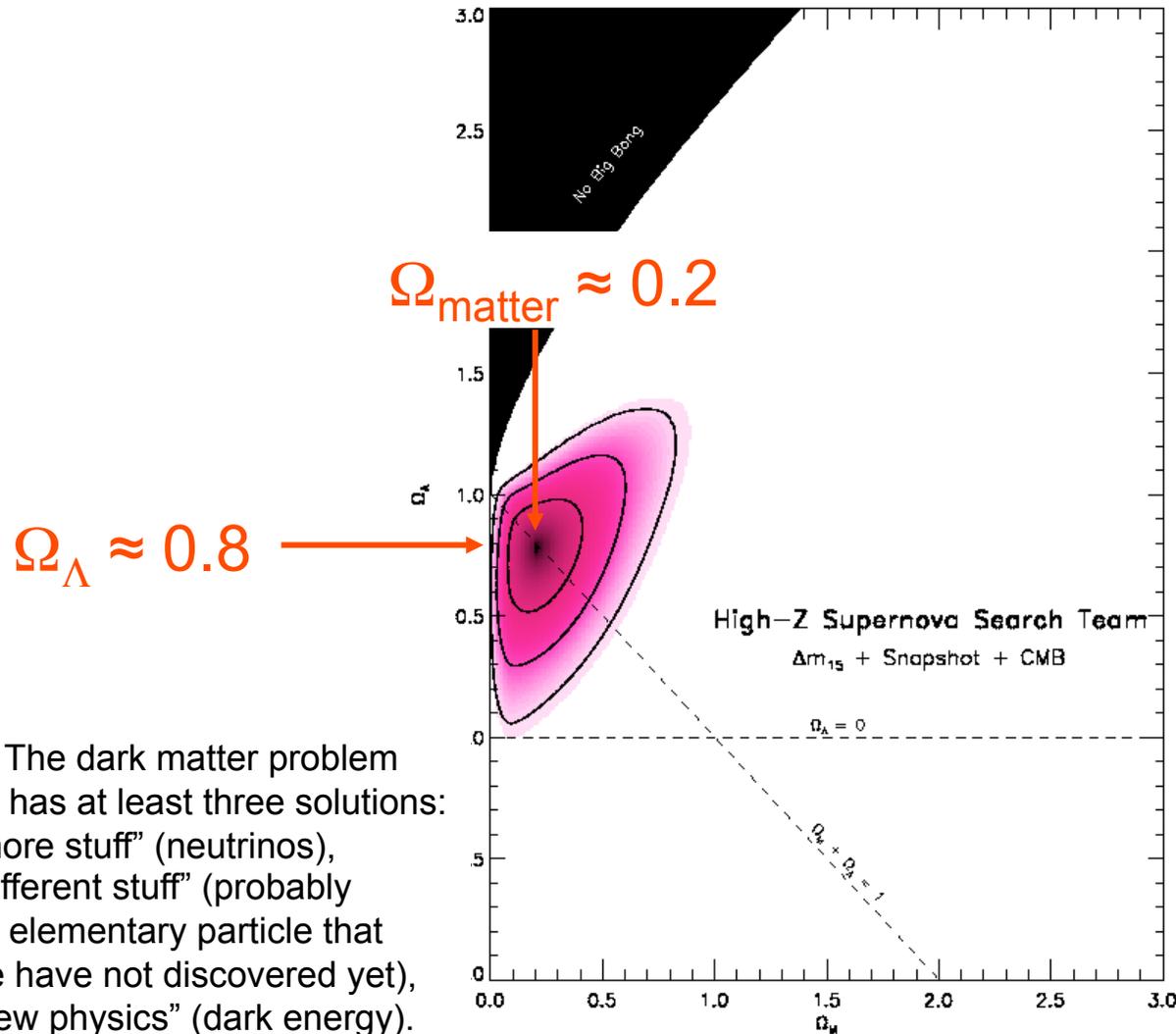
Best fit (not illustrated) is a Universe with some matter ($\Omega_m > 0$) and also a cosmological constant ($\Omega_\Lambda > 0$).

A Universe with only a cosmological constant is excluded.

Empty Universe is excluded

Flat Universe with no cosmological constant is excluded.

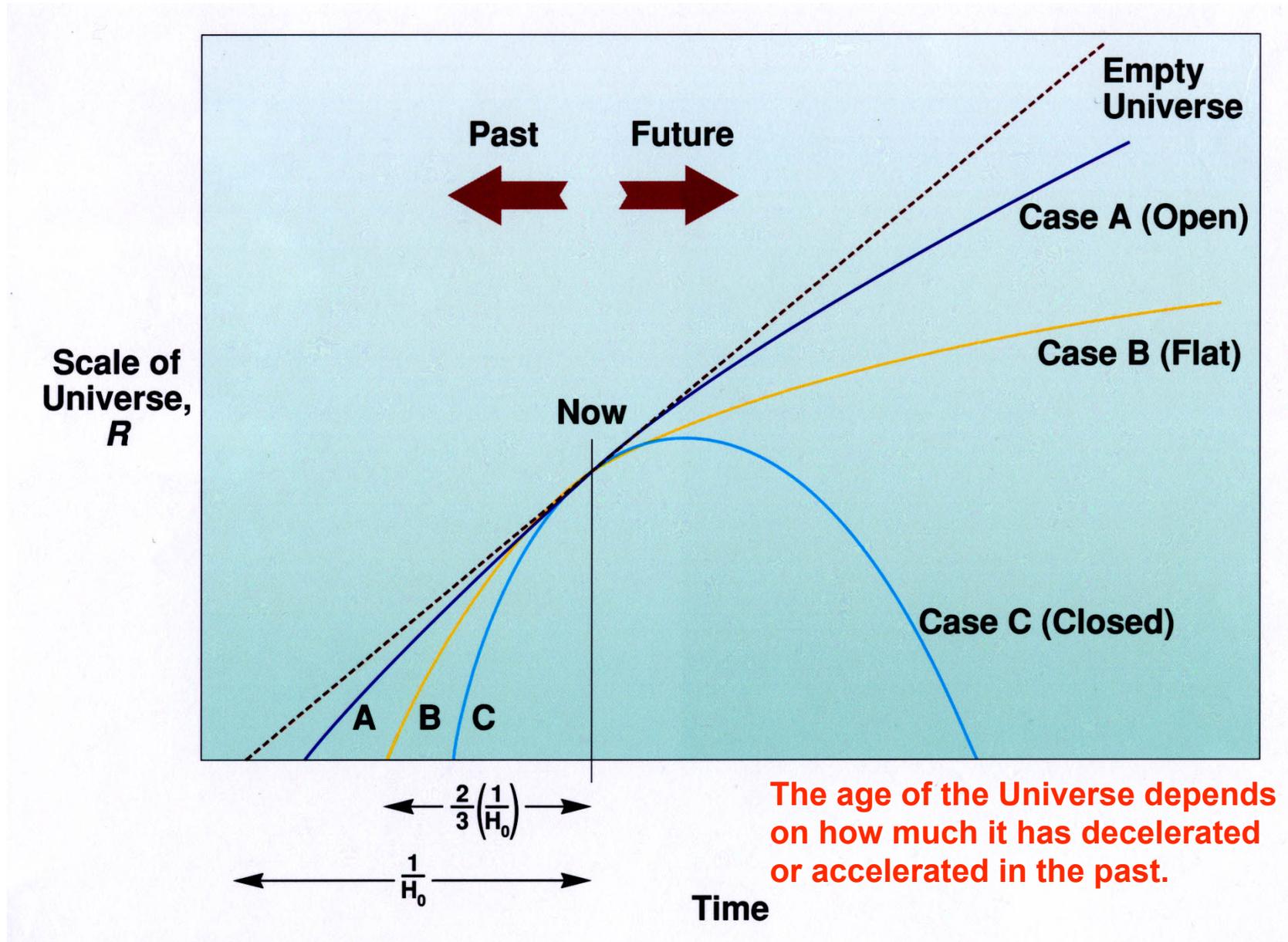
4. Conclusion From Supernovae and Microwave Background Results



$\Omega_{\Lambda} + \Omega_m = 1$
The Universe is flat!

Note: The dark matter problem has at least three solutions:
1 - “more stuff” (neutrinos),
2 - “different stuff” (probably an elementary particle that we have not discovered yet),
3 - “new physics” (dark energy).

Age of the Universe = 13.7 Billion Years



The Future of Cosmology

All of these research programs continue.

**Exploring the history of the Universe
is one of our most remarkable
intellectual adventures.**