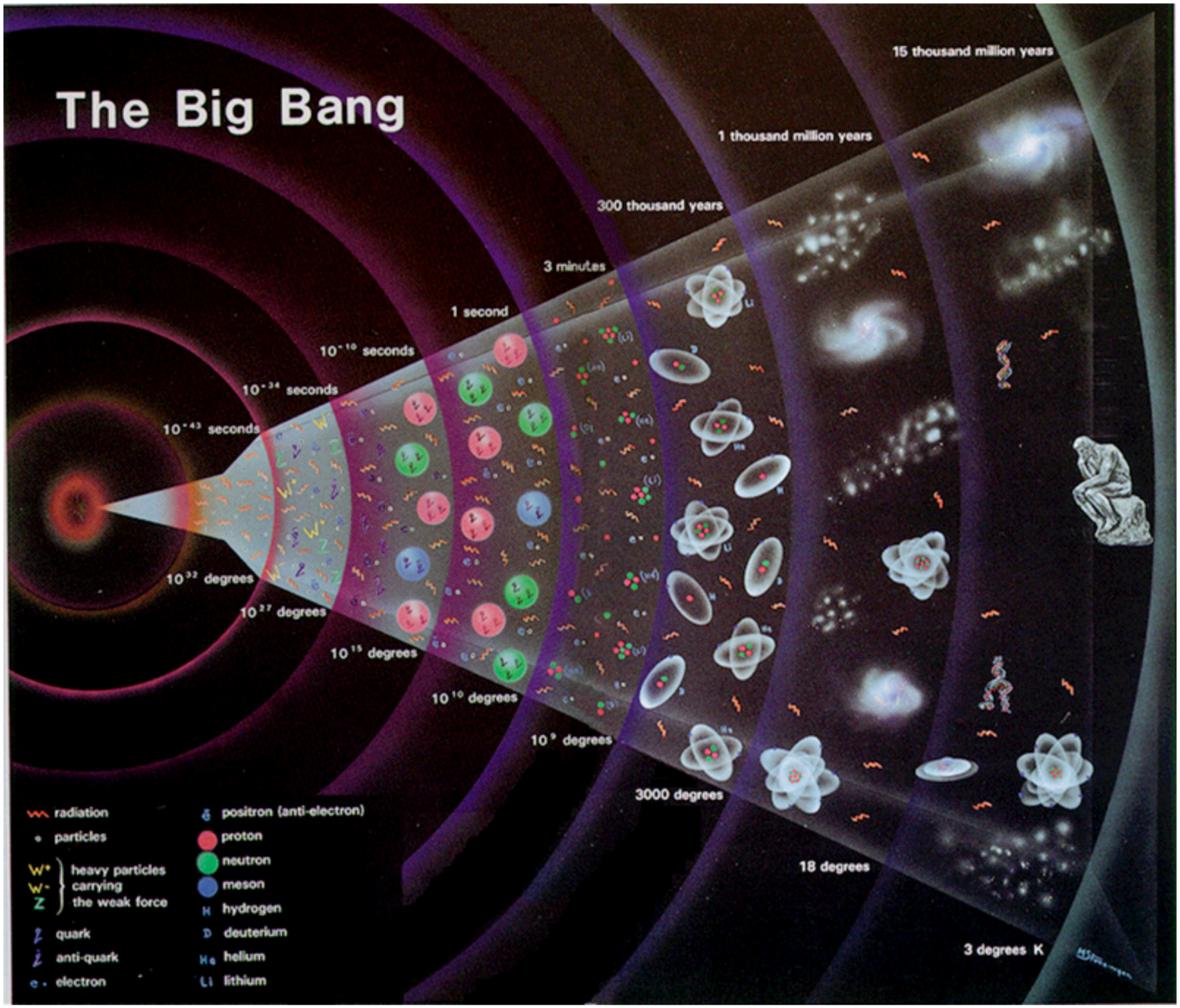
Chapter 18: Cosmology



In this chapter, we're going to cover many of the fundamental questions in astronomy.

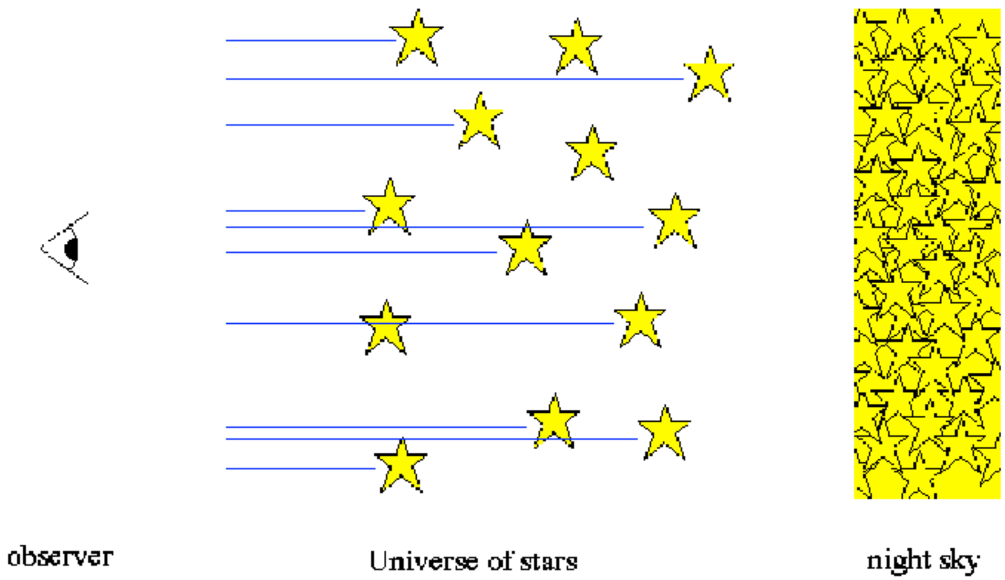
- How did the universe begin?
- What is the size, shape and geometry of the universe?
- What is the fate of the universe?

We're going to see how we can answer these big questions with a few simple observations and a liberal sprinkling of scientific logic.

First of all, let us ask ourselves why the sky is dark at night…

Olber's Paradox

The posit of Olber's paradox states 'if the universe is infinite, then every line of sight towards the sky should end in a star'. This means that the sky at night should shine as brightly as the sun!



We can resolve this paradox if the universe has a finite age. Therefore, light from the farthest stars has not yet reached us.

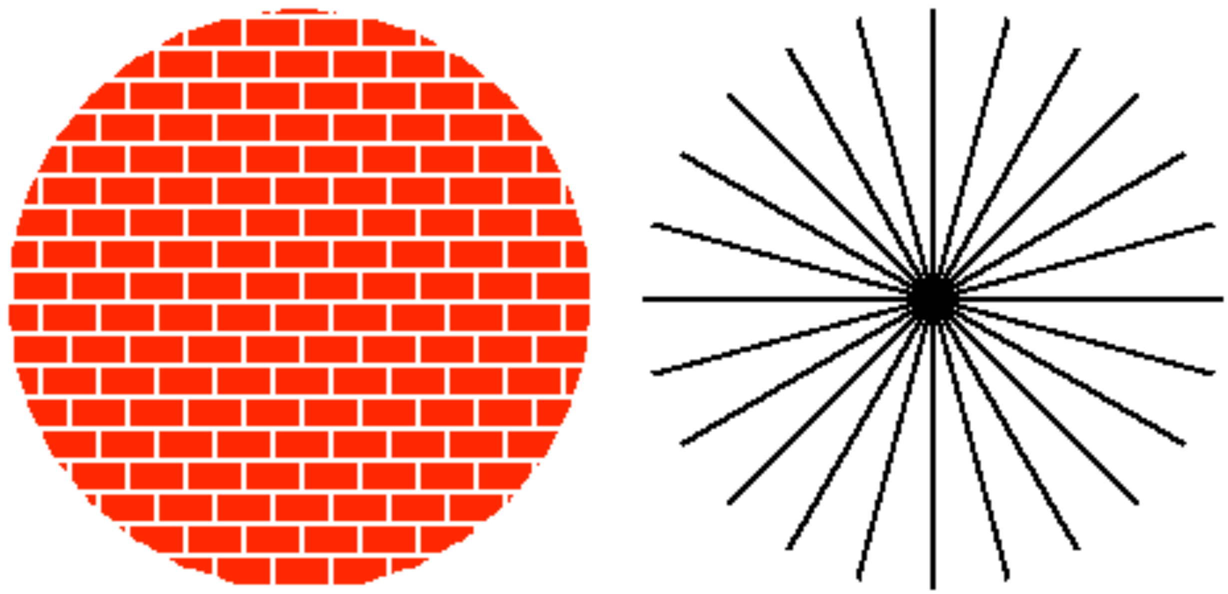
The Cosmological Principle

Olber's paradox highlights the importance of the assumptions we make about the universe. We are going to make 3 basic assumptions that will apply to all our models.

I. Homogeneity. This means that each chunk of space has a similar mass distribution.
II. Isotropy. This means the universe looks the same in every direction.
III. Universality. This means that out laws of physics apply everywhere equally, e.g. the laws of physics don't change with time.

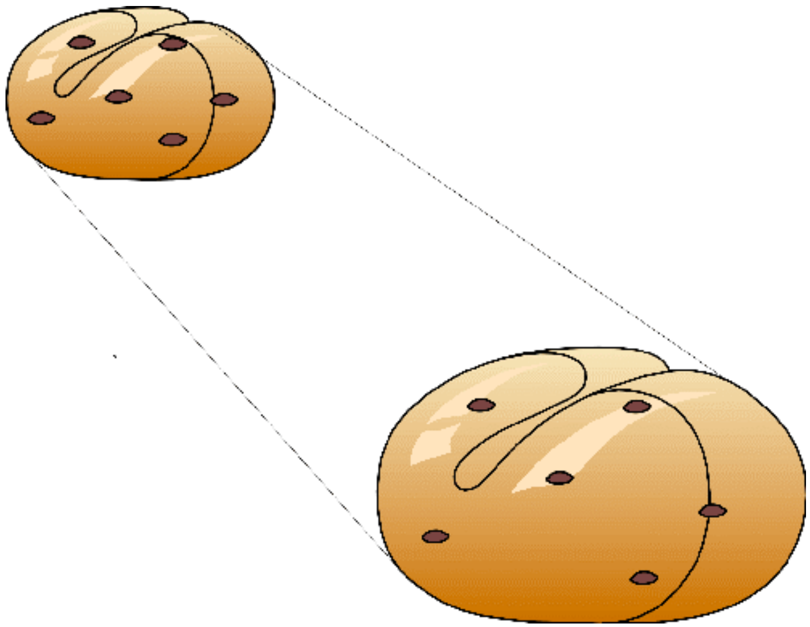
The assumptions of homogeneity and isotropy are so fundamental that we call this the cosmological principle. It states that an observer in another galaxy would see the universe to have the same properties as we do.

Note that there is a difference between a homogeneous universe and an isotropic one. In the figure below, the pattern on the left is homogeneous but not isotropic and the figure on the right is isotropic but not homogeneous.

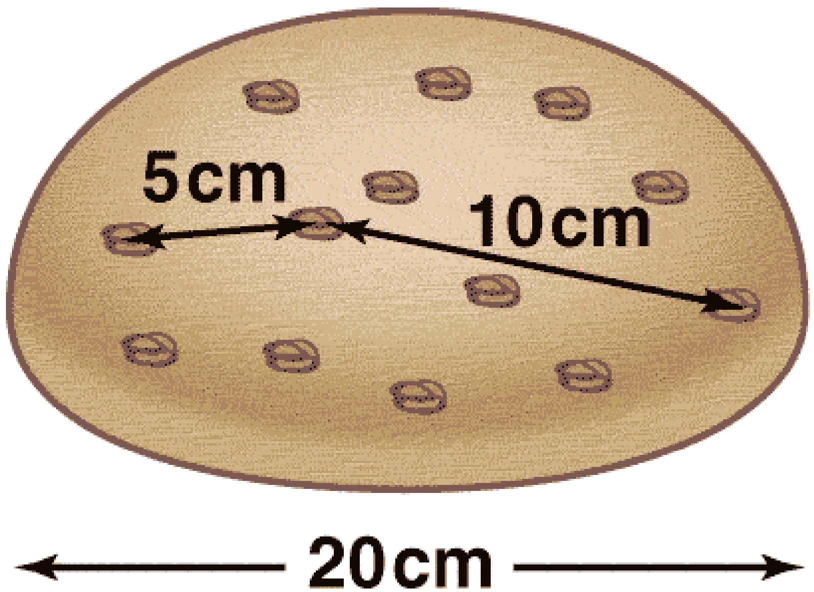


Now that we have made our assumptions, we can start to use our observations to understand the nature of the universe. A very important clue comes from the fact that, as we have already seen, all galaxies appear to be receding from us.

The observation that galaxies are receding is nicely explained if the entire universe is expanding.



Consider raisins in a loaf of bread. As the bread rises, all the raisins move apart from all the other raisins because the bread (which represents the universe in our analogy) itself is expanding. If the loaf doubles in size, all the raisin distances double too. This means that more distant raisins travel faster!



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If the universe is expanding and carrying the galaxies with it, we can extrapolate back in time and infer that the universe was a lot smaller in the past. Furthermore, it implies that the universe had a beginning - the Big Bang.

The term ‘big bang’ was first coined in scorn by Fred Hoyle. It seemed unbelievable to him (and many astronomers in the 1940s and 1950s) that the universe was not steady state. That is, had always been as we see it now.

Predictions of the Big Bang

Like all good scientific theories, the Big Bang made predictions that could be tested by observational astronomers:

I. Galaxies should recede from us with a speed proportional to their distance
II. The chemistry of the early universe should be very simple: it should contain only 75% H and 25% He.
III. We should be able to observe the 'echo' of the Big Bang in every direction we look in the universe.

Note that most of the He was therefore produced in the BB.

We have already seen how the first of these predictions is born out by observations. In order to understand the latter two predictions, we have to understand a little better how the Big Bang happened.

A few tricky concepts to start with:

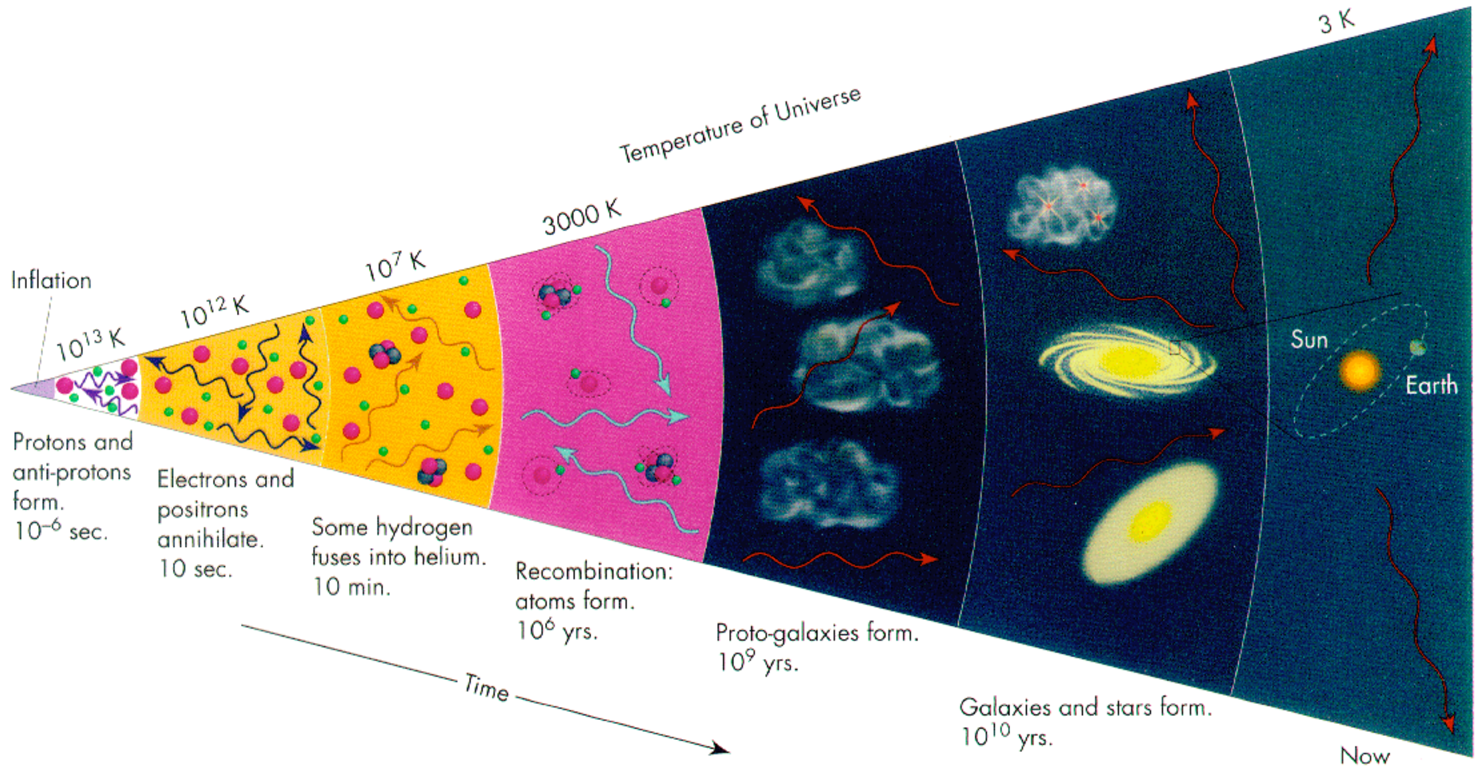
1) The Big Bang occurred everywhere! The Big Bang created space, it did not happen at a point in our existing universe.
2) The Big Bang also marked the dawn of time, so there was no 'before the Big Bang'.

Because energy is conserved, if the universe was once very small, it must also have been very hot. For this reason, we can't predict what the universe was like at the time of its creation, because we don't know how physics works under such extreme conditions.

What we do know is that temperature was more than a trillion, trillion degrees and the density was very high - because all the matter and energy of the universe was in a very small volume.

The Universe Has a Temperature

This brings us to an important point - the universe has a characteristic temperature. As the universe gets older and expands, it cools down.



As the universe cools, atomic nuclei can form (at high temperatures the high energy photons break them apart).

The Big Bang in a Nutshell

- At time=10^{-35} s, the universe expands rapidly in a phase of inflation. The universe is filled with high energy gamma ray photons.

- High energy photons can decay into a particle and an anti-particle, if they have enough energy ($E=mc^2$) again. Protons and neutrons (and their anti-particles) are made until t=0.0001 second, electrons until t=4s.

- Most of these particles annihilate themselves, but a slight imbalance means some matter is left over. This is where all the basic particles in the universe came from.

- After about 100s, the universe cools to 1 billion degrees, enough to form light elements like deuterium (hydrogen with an extra neutron). These then form helium.

The formation of elements has to go one step at a time. That is, the nuclei have to build up mass one unit at a time (where a unit comes from either a proton or a neutron).

Mass = 1: A hydrogen nucleus has 1 proton
Mass = 2: Deuterium is an isotope of hydrogen, it has 1 proton and 1 neutron.
Mass = 3: There is an isotope of helium which has 2 protons and 1 neutron.
Mass = 4: Normal helium has 2 protons and 2 neutrons.

There is no stable nucleus with a mass of 5, so reactions pretty much stopped here. This all happened in the first 30 minutes of the universe, after that the temperature was too low to fuse nuclei.

In this way, the Big Bang model predicts exactly the initial composition of the universe. Indeed, this is what we see when we study very old stars and galaxies.

Eras of Radiation and Matter Domination

Early on, the universe is dominated by radiation: the photons easily outnumber the matter particles. Photons are continually interacting with matter, so they have the same temperature (think of the universe being well mixed).

In this radiation dominated era, electrons are not bound to nuclei. Photons were locked together with matter because they kept bouncing (scattering) off electrons. This means that galaxies and stars can not yet form.

After about 300,000 years, the temperature of the universe drops to 3000 K, cool enough for the electrons to be bound into atoms. This is called recombination and we enter the matter dominated era. Matter is now free to act under gravity and form structures.

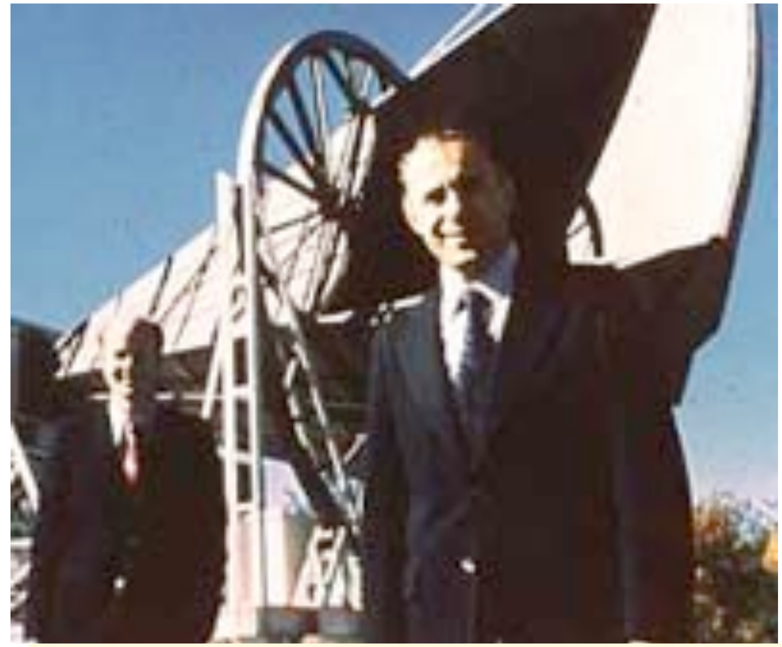
The Cosmic Microwave Background

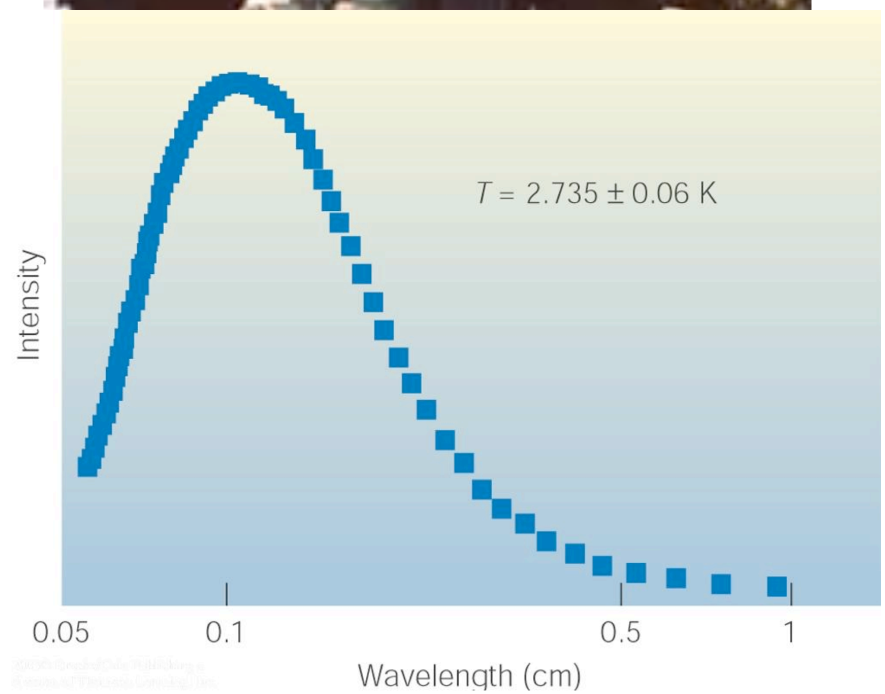
When radiation and matter decouple at the epoch of recombination, the temperature of the universe is 3000 K. This means that photons that were emitted when the universe was only 300,000 years old had an energy (or wavelength) associated with this characteristic temperature.

We can observe photons coming from this epoch, but they have undergone huge redshifts, so that the temperature we now observe some 13 billion years later is only 3K.

This is the final prediction of the Big Bang theory: everywhere we look in the sky, we should see a background signal corresponding the 3 degrees above absolute zero - the echo of the Big Bang. We call this the cosmic microwave background (CMB).

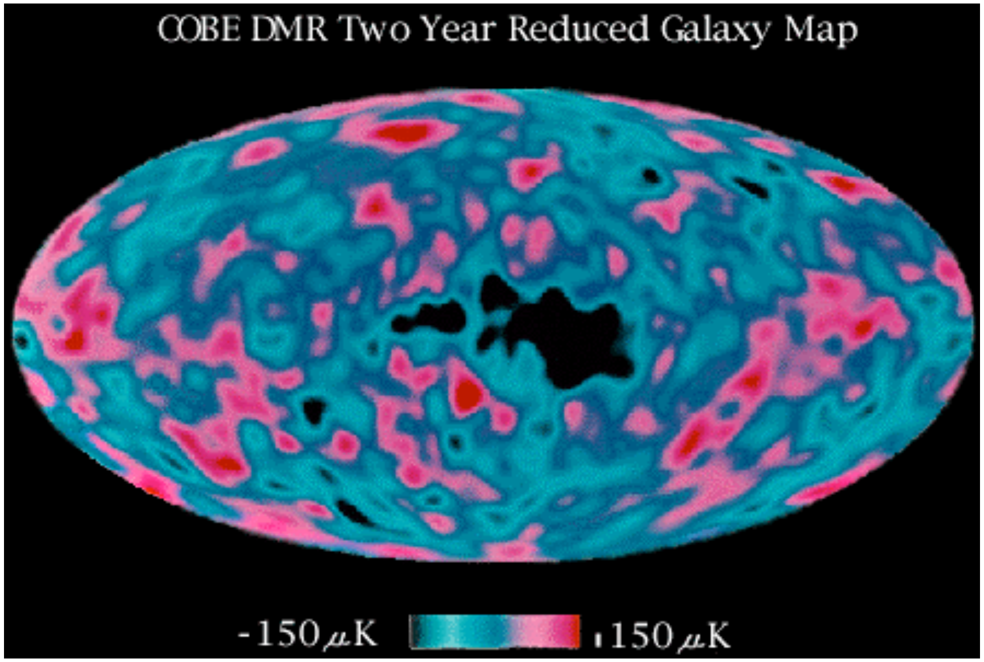
In the 1960s, two engineers, Penzias and Wilson, were working at the Bell telephone labs with an antenna to measure radio signals. They found a persistent noise all over the sky. They didn't realise that this was predicted by the Big Bang, but their discovery of the 3K background eventually won them the Nobel prize in 1978. Since then, there have been many experiments that have confirmed this result: we see a perfect blackbody curve with a temperature of 3K.





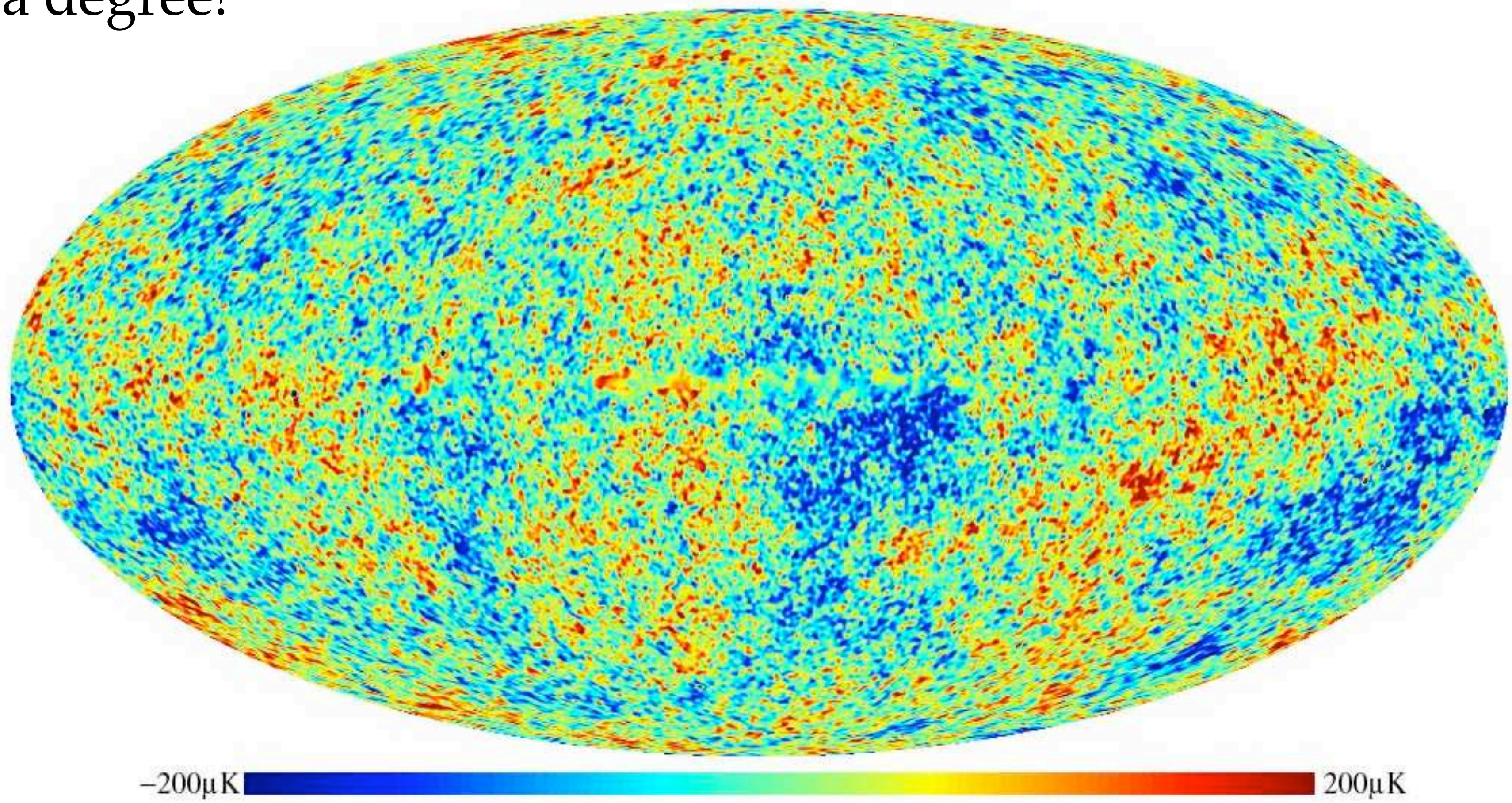
Structure Formation in the Universe

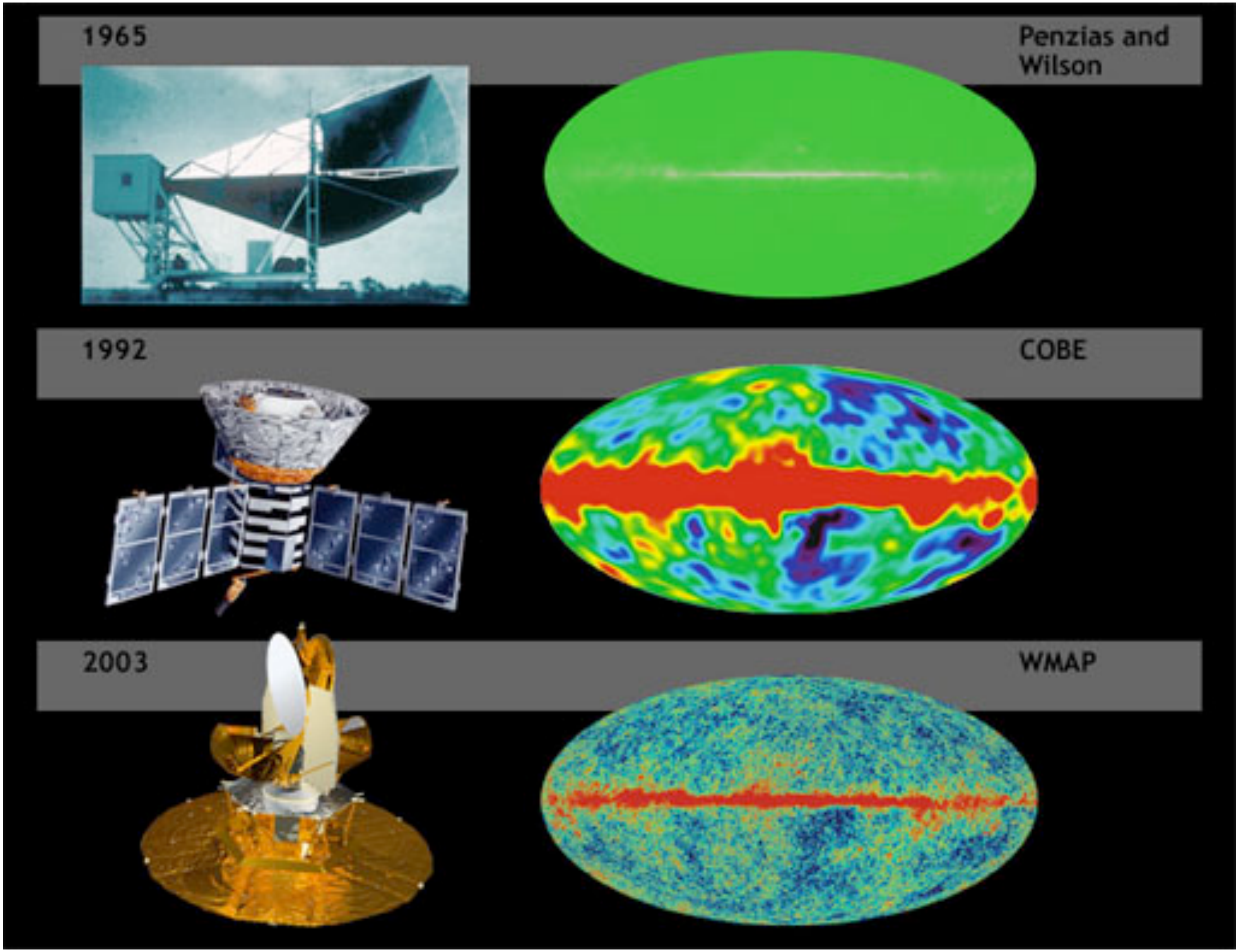
Actually, the temperature of the CMB isn't *exactly* 3K everywhere. In some areas it is slightly hotter and in other areas slightly cooler. This is because matter was not evenly distributed; fluctuations in temperature tell us that there were also fluctuations in the matter distribution. This is very important because it is these matter fluctuations that seed galaxy formation



The first telescope to detect these fluctuations was a satellite called the Cosmic Background Explorer (COBE) in 1989.

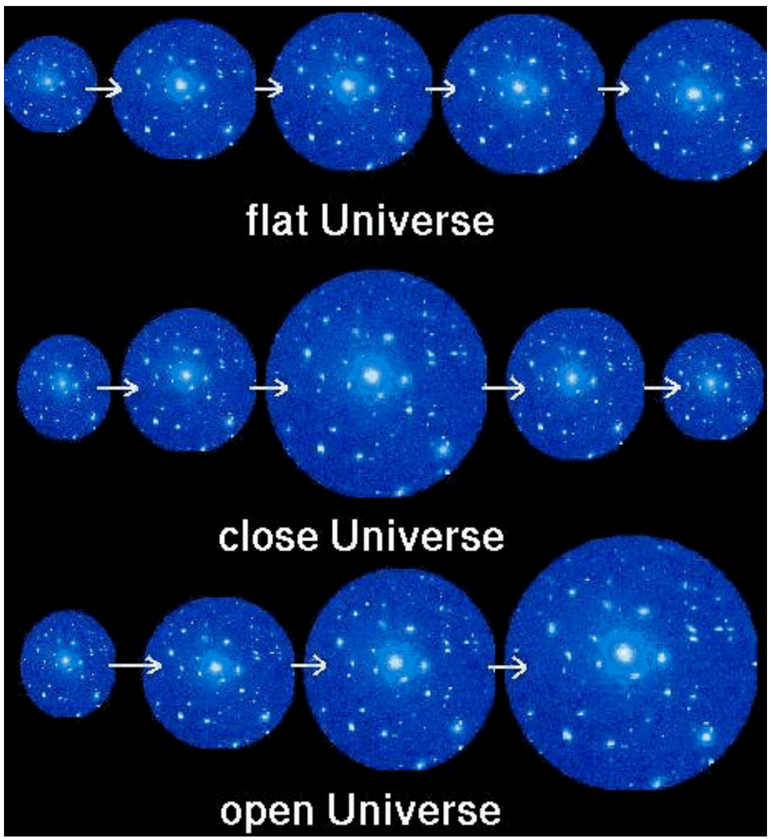
In 2003, a new satellite called WMAP made the most detailed map ever of the CMB, thanks to its fine resolution. It shows incredible detail of the structure imprinted in the early universe that would later form galaxies. The variations between “hot” and “cold” patches on the sky are only 1/10000 of a degree!




1965
Penzias and Wilson
1992
COBE
2003
WMAP

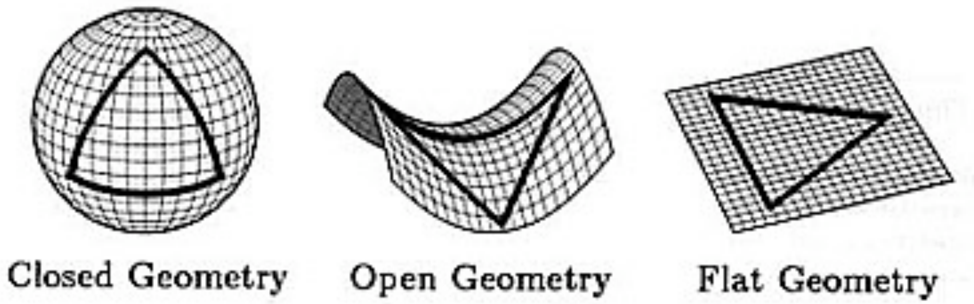
The Geometry of the Universe

We can learn other important things about the universe by studying the structure of the CMB. For example, depending on how much matter there is in the universe dictates how the universe will end. In the following, we assume a universe of matter.



There is a critical density that the universe must be less than if it is to go on expanding forever. If the density of the universe is greater than this, it will eventually start to collapse again. If the universe has exactly the critical density will it exist forever, but its expansion grinds to a halt after an infinite time.

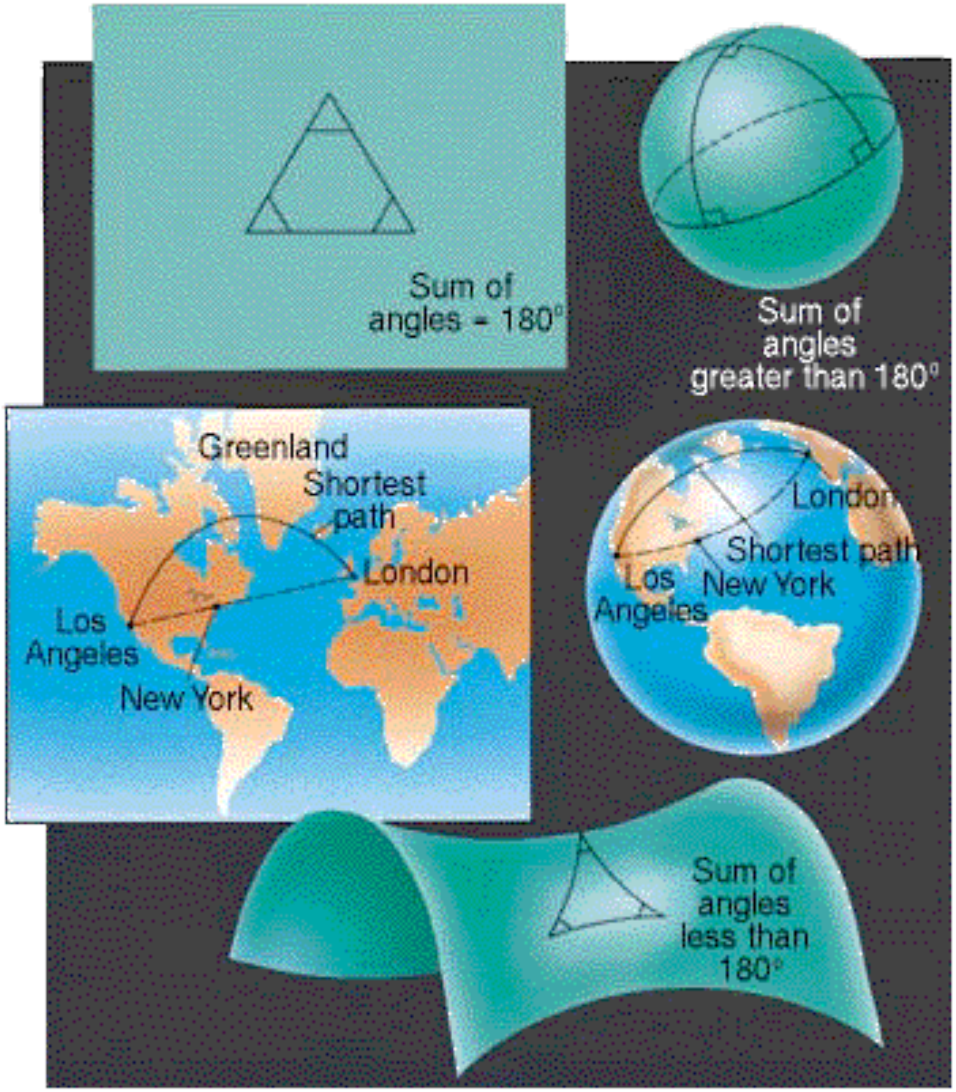
The geometry of space depends on the density of the universe.



Density > critical value.
Universe is positively curved.
Universe is finite in time.
Eventually the universe will collapse again.

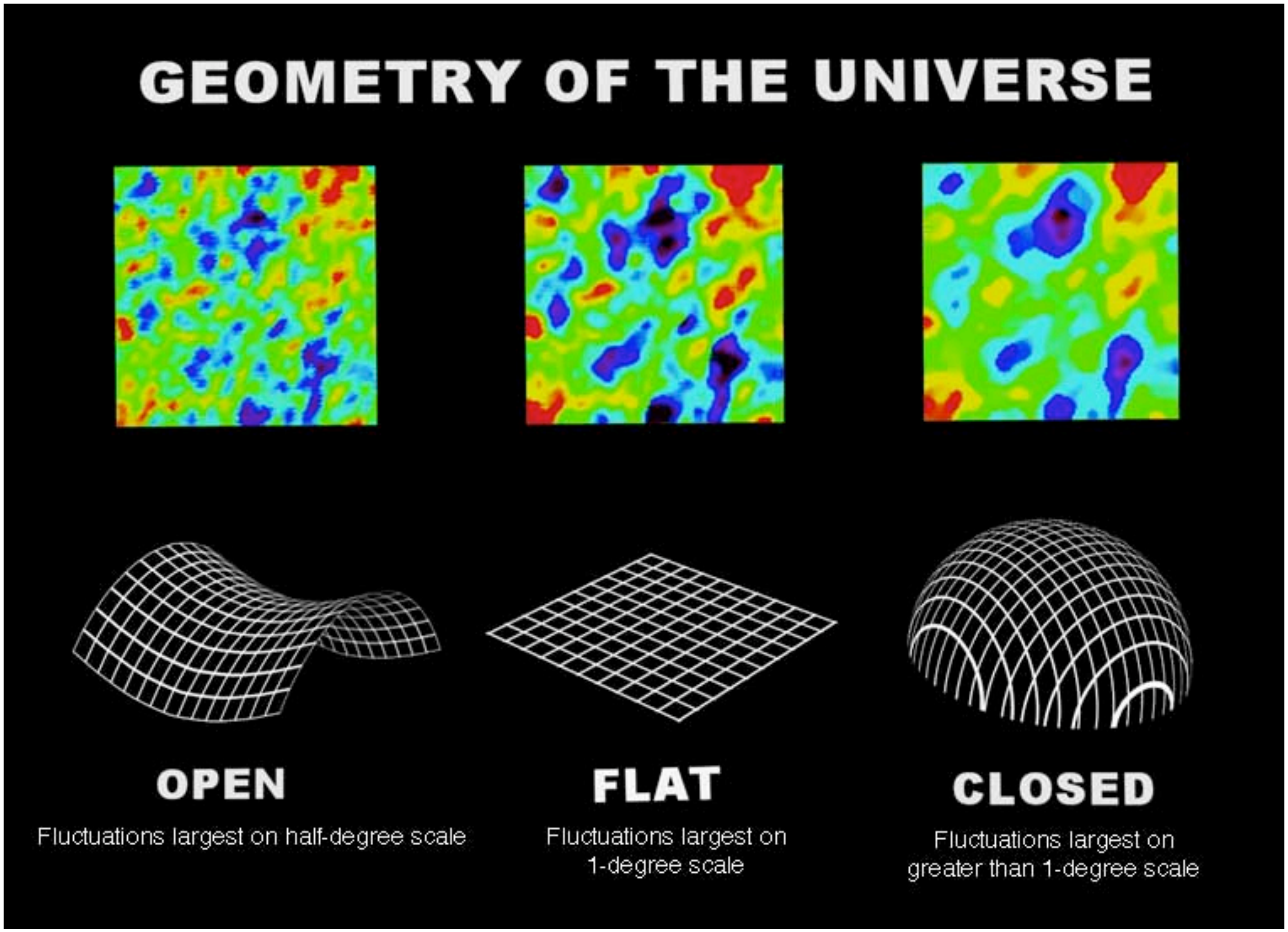
Density < critical value.
Universe is negatively curved.
Universe is infinite in time.
Universe will expand forever

Density = critical value.
Universe is flat (not curved).
Universe is infinite in time.
Universe will continue to expand but slow to a halt after an infinite time.

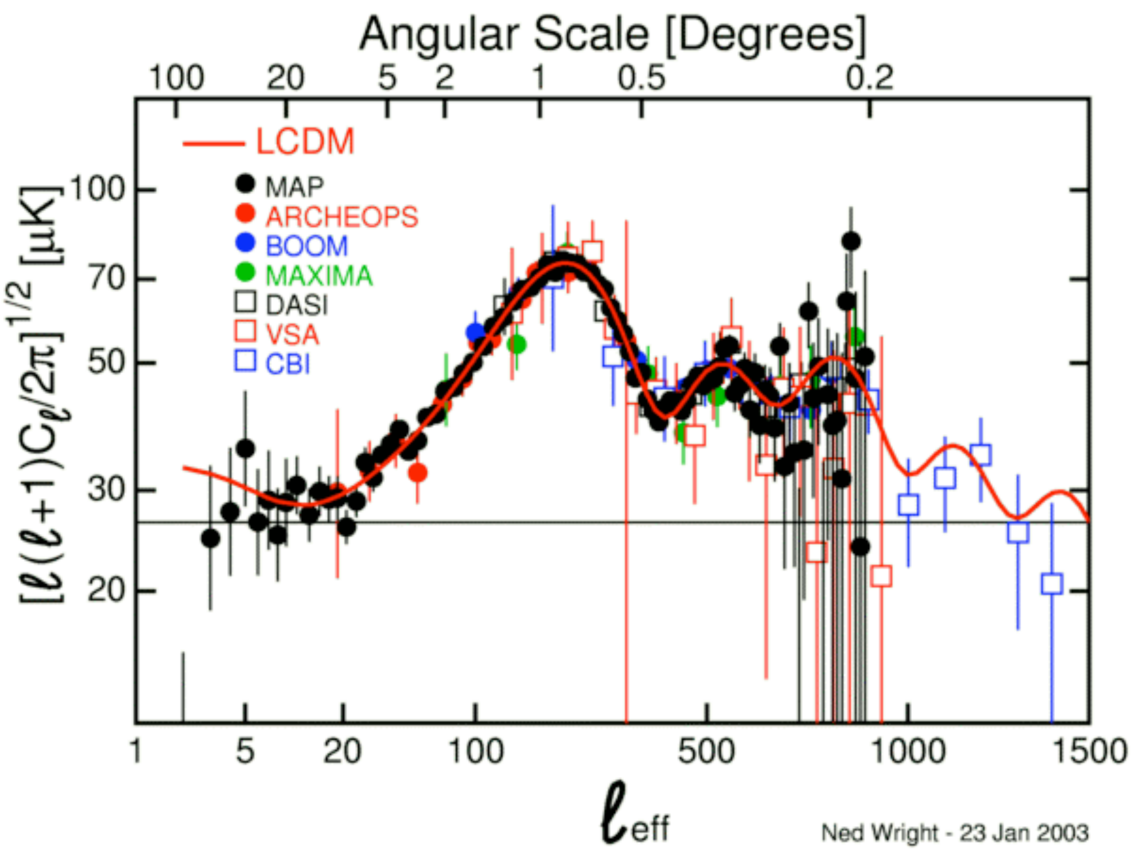


We can understand the effect of curvature by considering how a triangle looks on different surfaces. On a flat surface, all its angles add up to 180 degrees. On a positively curved surface they add up to more than this and on a negatively curved surface they add up to less than 180.

The size of the fluctuations seen by the WMAP satellite tells us what the geometry of the universe is. Large patches in the temperature fluctuations imply a closed universe and vice versa.



We can measure the number of patches in the CMB of a given angular size and find that 1 degree is the most common. This tells us our universe is flat.



Inflation

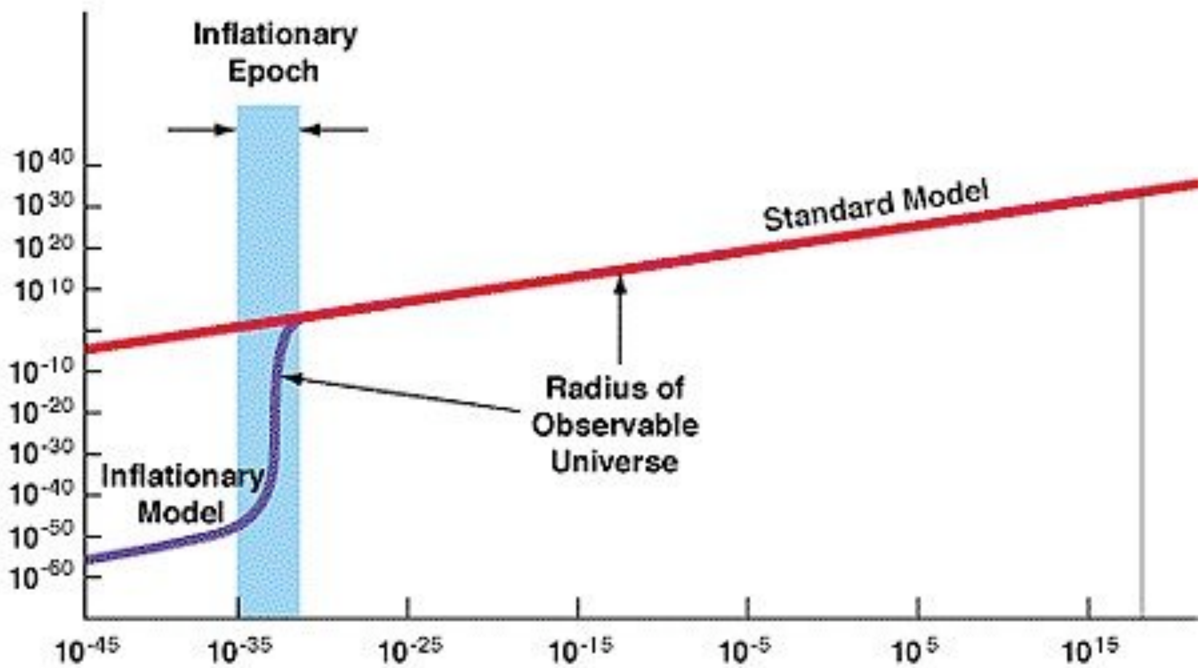
Two problems in cosmology are: why is the density of the universe so close to the critical density (the flatness problem) and why is the CMB so uniform (the horizon problem).

Flatness is more of a coincidence than a problem - we could live in a universe with a density from zero to infinity, so why so close to the magic critical value?

The horizon problem arises because the temperature of the CMB is very uniform, even though 2 parts of the sky have never been in causal contact (unless they are less than 1 degree apart).

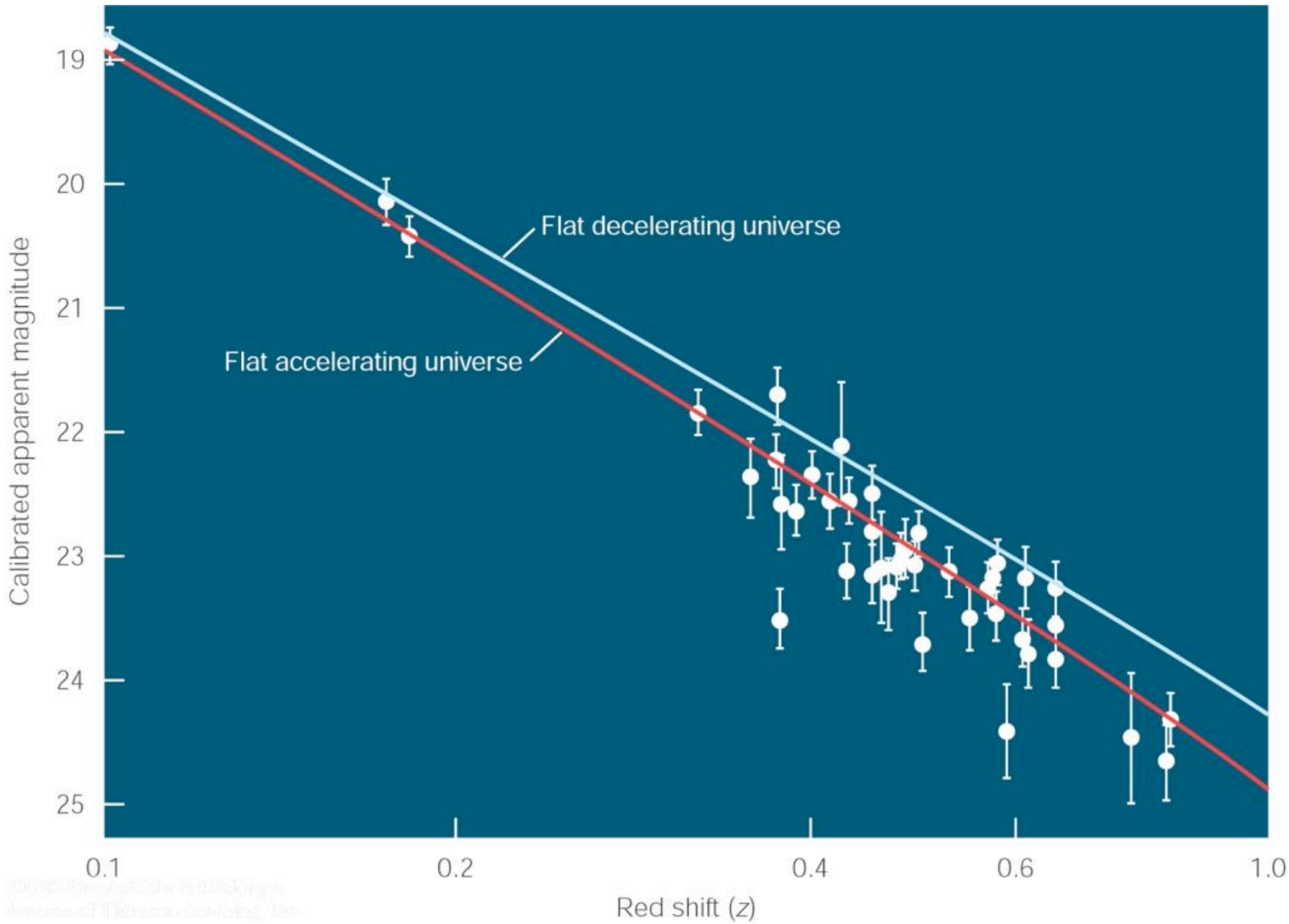
These problems are solved by inflation theory. This says that the 4 forces of nature (electromagnetic, gravity and the strong and weak nuclear forces) came into being when the universe was 10^{-35} s old. This released a lot of energy and caused rapid growth by $x10^{20}$.

Inflation predicts a rapid expansion in the earliest moments of the universe, then the expansion rate settles down to the standard big bang rate.



Dark Energy

Our discussions about geometry have so far assumed that the universe contains only matter. However, results from supernova indicate that this might not be the case…



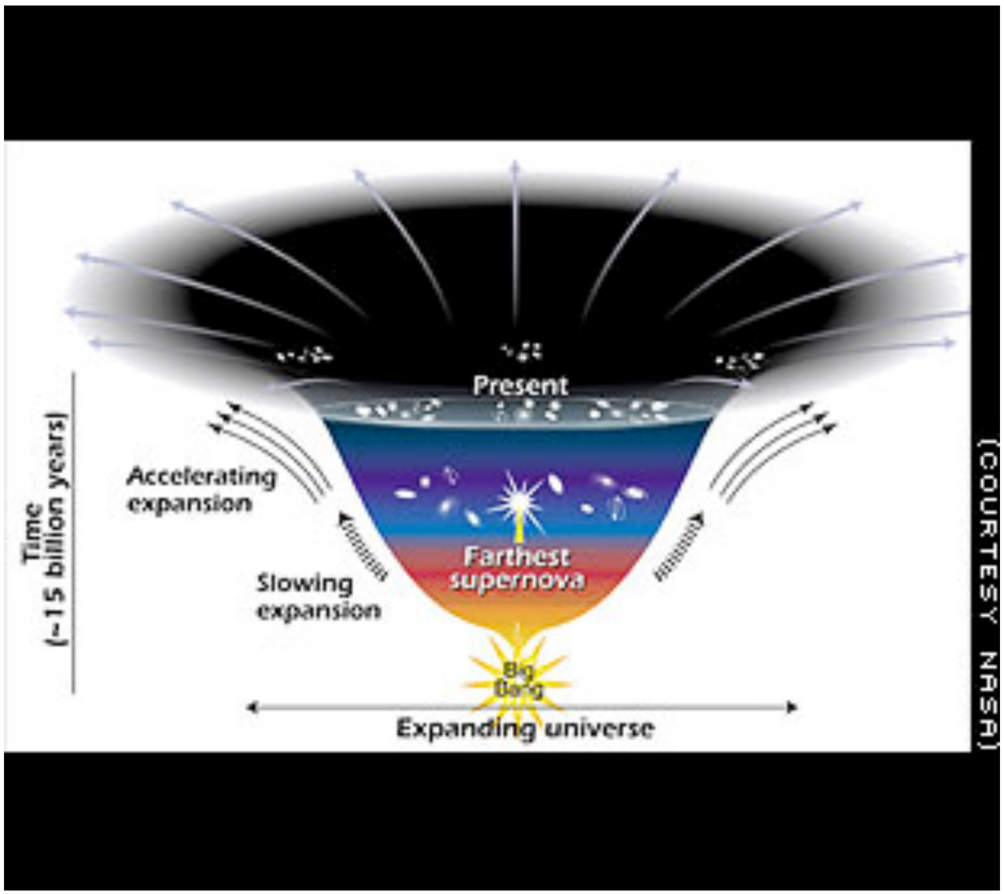
The results from supernovae indicate that they are fainter than they should be for a flat, matter filled universe. This can be explained if the universe is *accelerating*.

We saw that a flat universe should be slowing down, so how do we explain this? The answer is that only about 30% of the universe is matter. The rest is made up of a mysterious dark energy. Dark energy has an effect opposite to gravity.

Einstein actually introduced this concept as early as 1916. His theories of relativity implied that space must be expanding. At that time, the concept of the Big Bang had not been invented and people believed in a steady state universe. Einstein therefore introduced a cosmological constant into his equations as a force to balance gravity.

When Hubble, in 1929, showed that galaxies were receding, Einstein referred to his constant as his 'biggest blunder'.

So, it turns out that Einstein was right again! There is a cosmological constant, but it actually dominates over matter, causing the universe's expansion to accelerate. But this wasn't always the case. The universe was dominated by gravity (and expanded slowly) at early times.



Because of dark energy, the 'flatness' of the universe only tells us about its geometry, not its final fate.

There is still a lot we don't know about what the universe contains! Major challenges now include understanding what dark energy is and what the dark matter is made of.