Cosmology

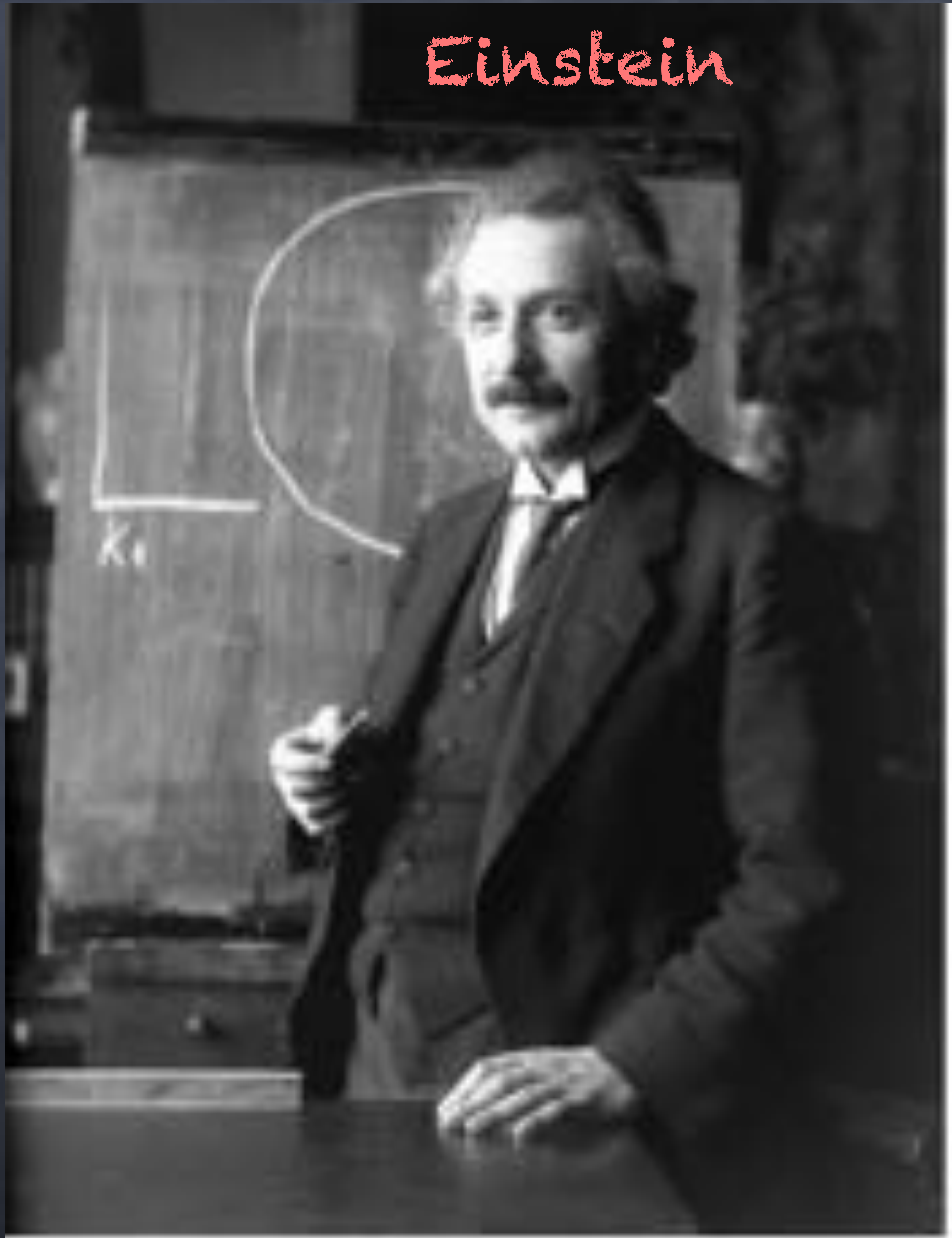
Chapter 29

The Big Bang

- Cosmology is the study of the Universe. Describing it and any changes that may occur over time.
- It used to be the case that there were a few theories about how the Universe worked. One of those theories was mockingly called "The Big Bang" cosmology.
- All the evidence has pointed to that model being correct, so we will only discuss the big bang cosmology which we just call cosmology these days.

A changing Universe

- People used to think that the universe was static. That it had always been there, would always be there and never changed.
- This is actually a bit odd for physicist who know about gravity. Since gravity attracts we expect objects to be drawn together, or if moving away from one another for those velocities to decrease.
- After Einstein formulated general relativity he applied it to cosmology. He found that the Universe must either be expanding contracting. Thinking this was wrong he added a new repulsive force called the cosmological constant to gravity to balance the attraction of gravity.
- When Hubble discovered the expansion of the Universe a decade later he realized this was a mistake.


Einstein


Hubble

The Age of the Universe

- If the Universe is expanding that means it was smaller in the past. If we go far enough in the past we reach the smallest the Universe could be, no size at all. Which means the Universe has only existed for a finite time.
- The craziness of the whole Universe contracting to a point was called the Big Bang, but we actually have a lot of evidence that the universe was very small and dense in the past. How old is the Universe?
- From the Hubble law we can calculate when the Universe was all at a single point if nothing has changed over time.

The Hubble Time

- The Hubble Law is

$$v = H \times d$$

- The time it takes to go somewhere at constant speed is

$$T = d / v$$

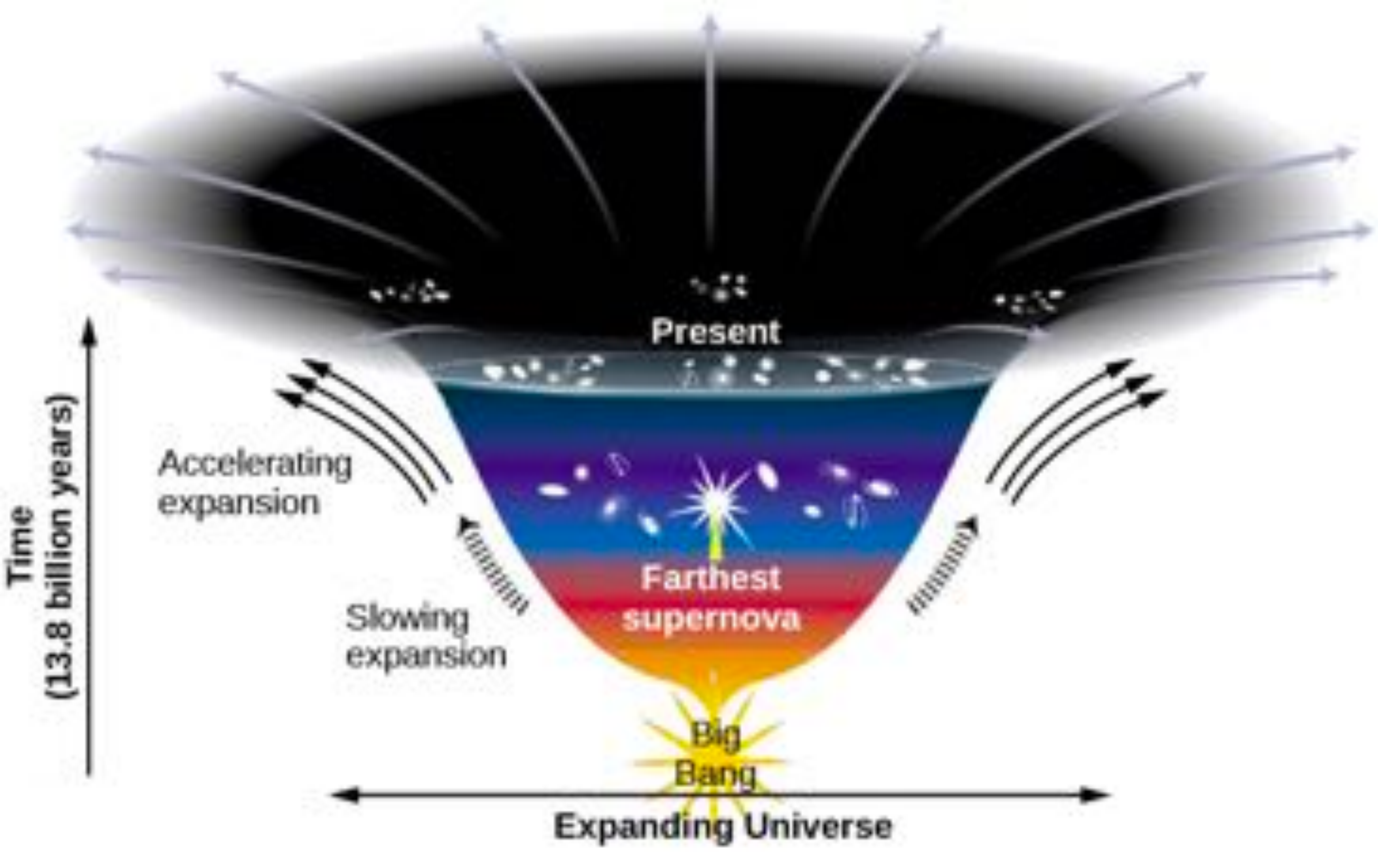
- So if a galaxy has gone a distance d since the birth of the Universe the time that would take is

$$T = d / (H \times d) = 1/H$$

The Hubble Time

- Hubble's first calculation of H got around 500 km/s/Mpc. That gives a Hubble time of 2 billion years. Since we know the Earth has rocks on it older than that, this was problematic.
- Today we know H is close to 70 km/s/Mpc, which makes the Hubble time 14 billion years.
- But the matter in the universe means H should be decreasing, so the actual age would be somewhat less than this. But then we discovered the universe is expanding which counterbalances that and gives at an age of 13.8 billion years.

The expansion was discovered using type Ia supernova. With them we can measure the distances to distance galaxies, and find that the value of H does not stay constant. Instead it was lower in the past.

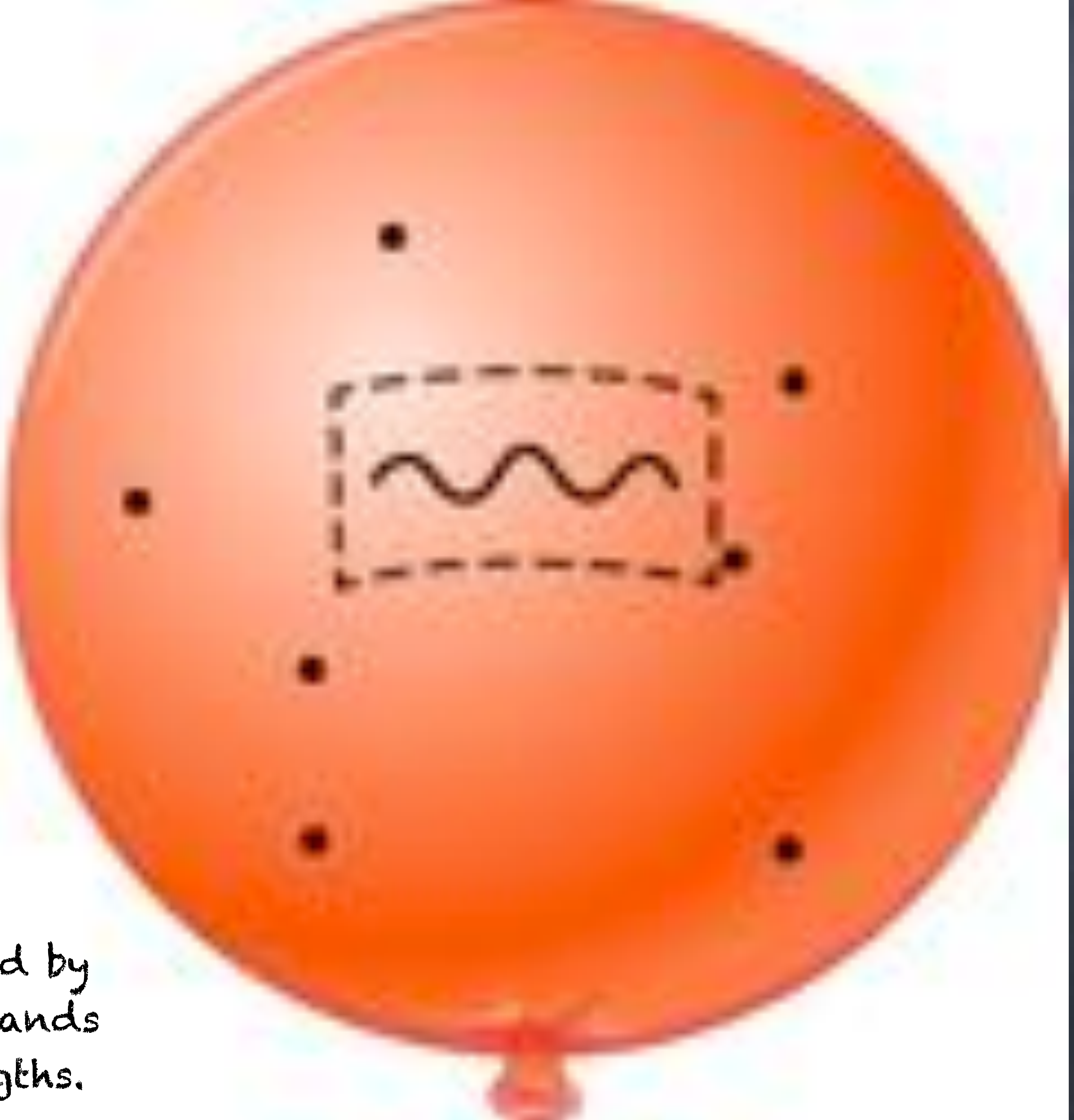

Present
Accelerating expansion
Time (13.8 billion years)
Farthest supernova
Slowing expansion
Big Bang
Expanding Universe

Comparing Ages

- The oldest stars in our galaxy are in globular clusters.
- For awhile it was estimated that the oldest of them where 15 billion years old, holder than the universe.
- Better measurements now suggest they are 12-13 billion years old, very old, almost but not quite as old as the universe.

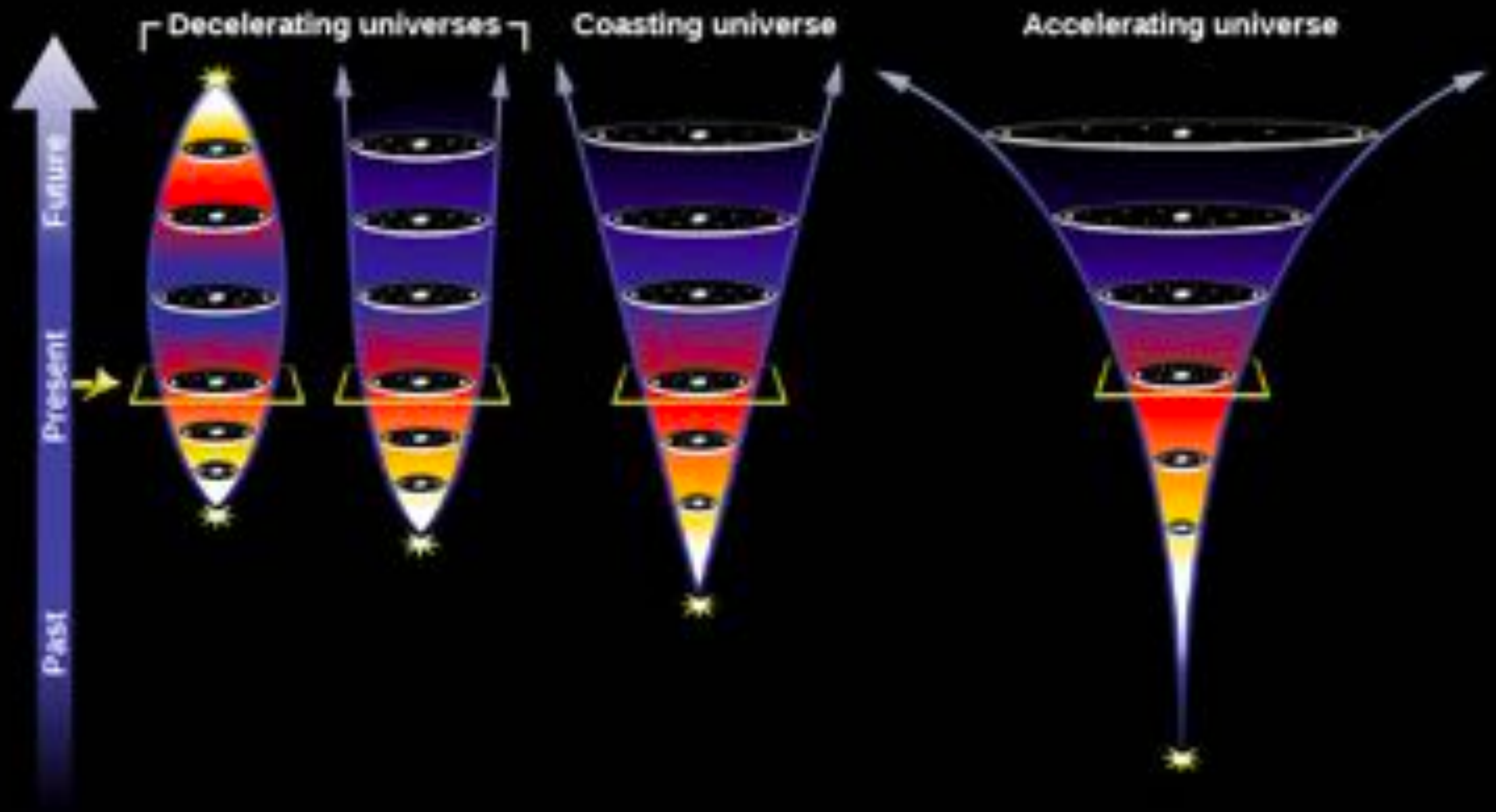
The Expanding Universe

- So far our cosmological model includes the expansion of the universe and the cosmological principle on large scales (it is homogenous and isotropic).
- This means the rate of expansion of the universe is the same everywhere. We should think of the space expanding instead of the galaxies moving, as if we are all living on a ballon that is being inflated.
- The scale of the space we can call R, and then we just say that R increases with time. When R doubles everything is twice as far apart as before, when R triples 3 times as far apart.



Cosmological redshift is actually caused by the expansion of space. As the space expands it stretches the light to longer wavelengths.

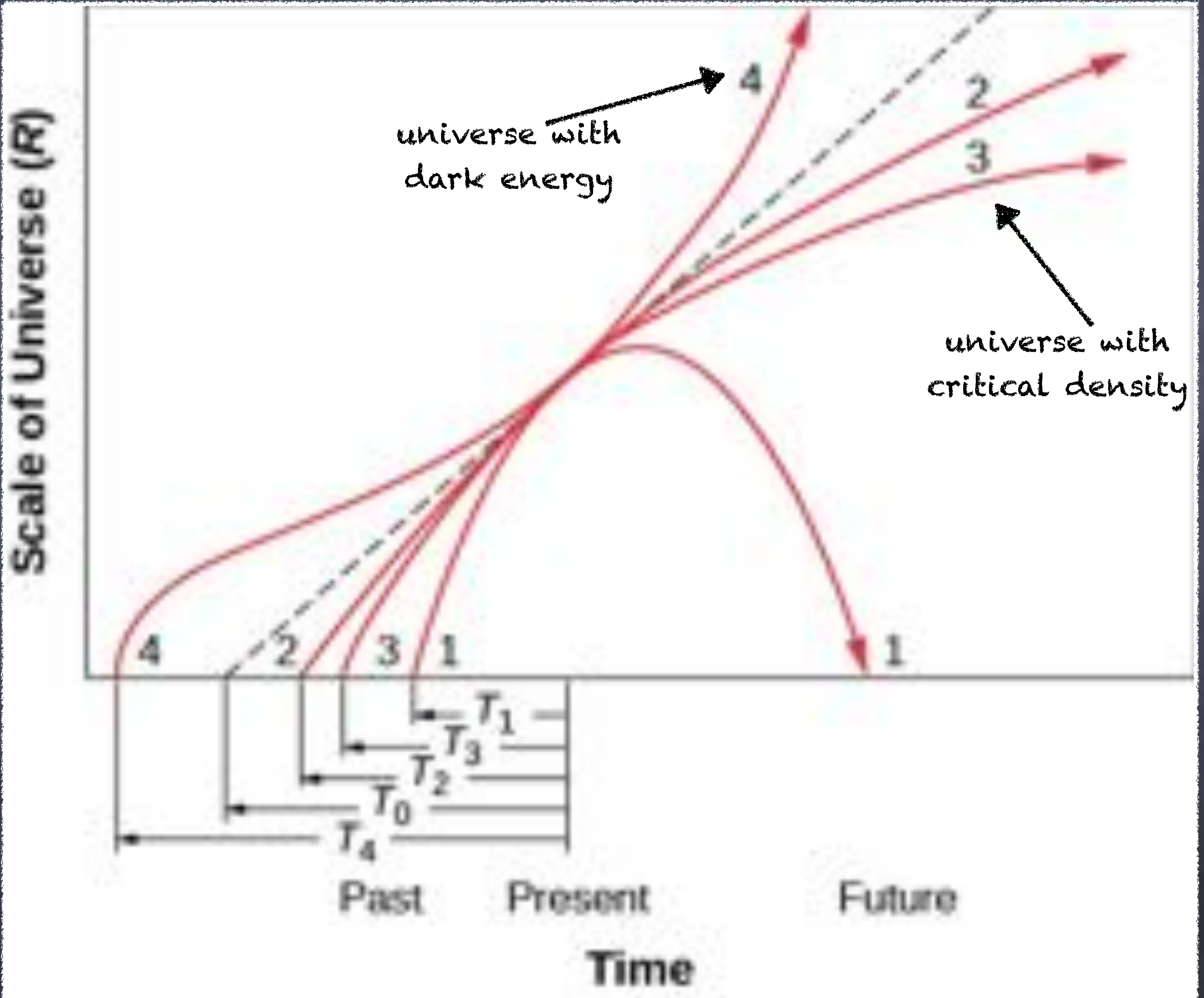
As the scale of the universe changes there are a number of possible futures. Gravity could slow the expansion and eventually collapse the universe back to a point. Or it can slow the expansion but never reverse it. The universe can just continue as it has been with no change, or the expansion could increase in the future. We now know the last choice is us.



Cosmic Tug of War

- The fate of the Universe depends on competition between gravity (density) and dark energy (Einstein's cosmological constant got renamed and expanded).
- There is a critical density, where without dark energy, the gravity is just enough to stop the expansion, but not enough to cause collapse.
- If the density of the universe is greater than this then is will collapse, if less than this value it will expand forever.

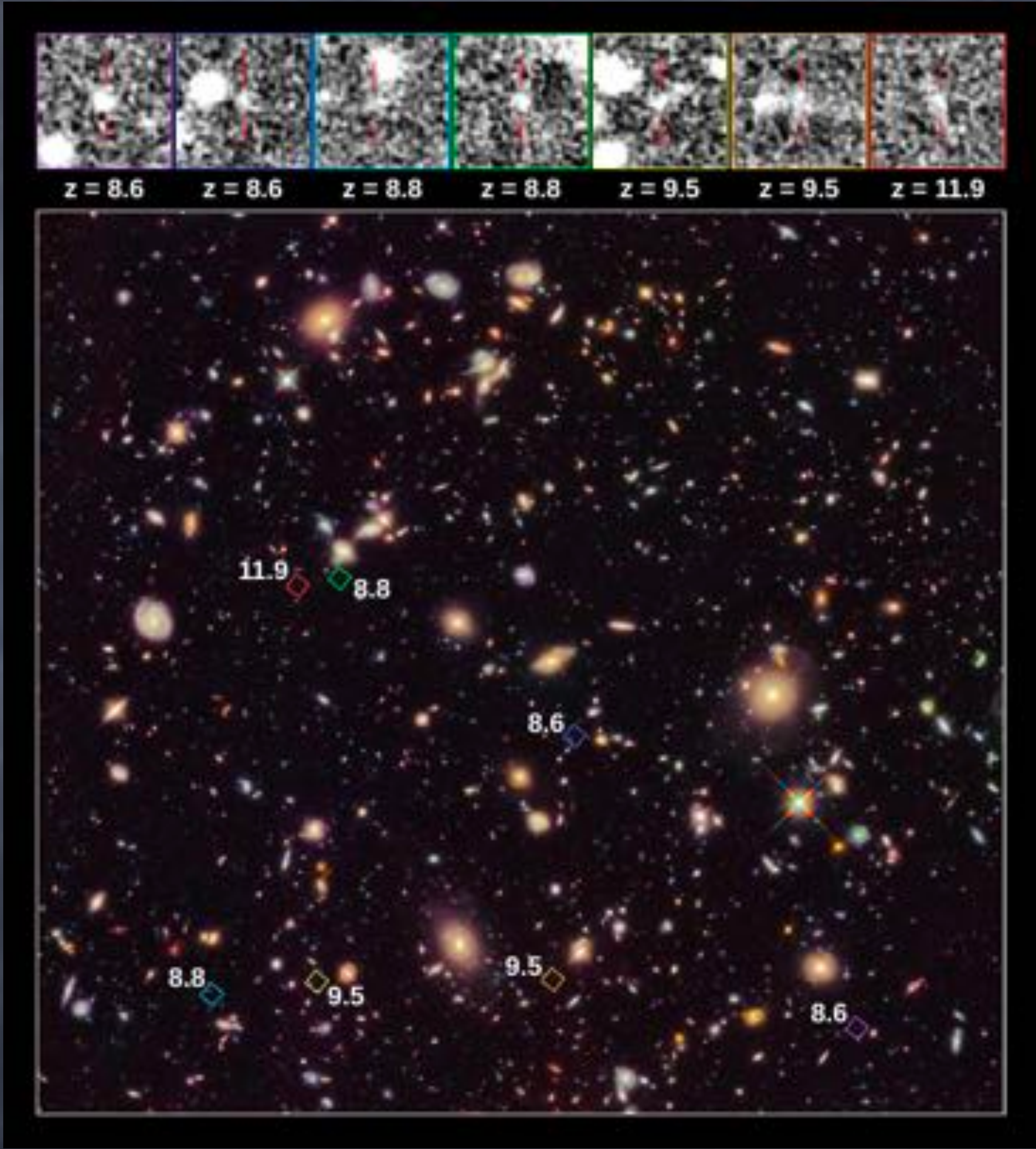
1. A universe with a average density greater than the critical density, it eventually collapses.
2. A universe with less than the critical density, it expands for ever.
3. A universe with the critical density, it expands forever, but always at a slower rate.
4. A universe with dark energy, expands forever and faster as time goes on.



Distances and Ages of Distant Galaxies

- We can use the Hubble law to get distances and thus light travel times to nearby galaxies.
- But when we look at very distant galaxies we need to know the cosmological model to convert a redshift to a distance or time.
- Thus astronomers prefer just keeping things in terms of redshift which we can easily measure instead of distance or time which will change if our cosmological model changes.

Distant galaxies in the Hubble ultra deep field labeled by their redshift. Their actual distances will change depending on the cosmological model. However, we know the 11.9 galaxy is farther away then the 8.8 galaxy and we are looking at it farther back in time.

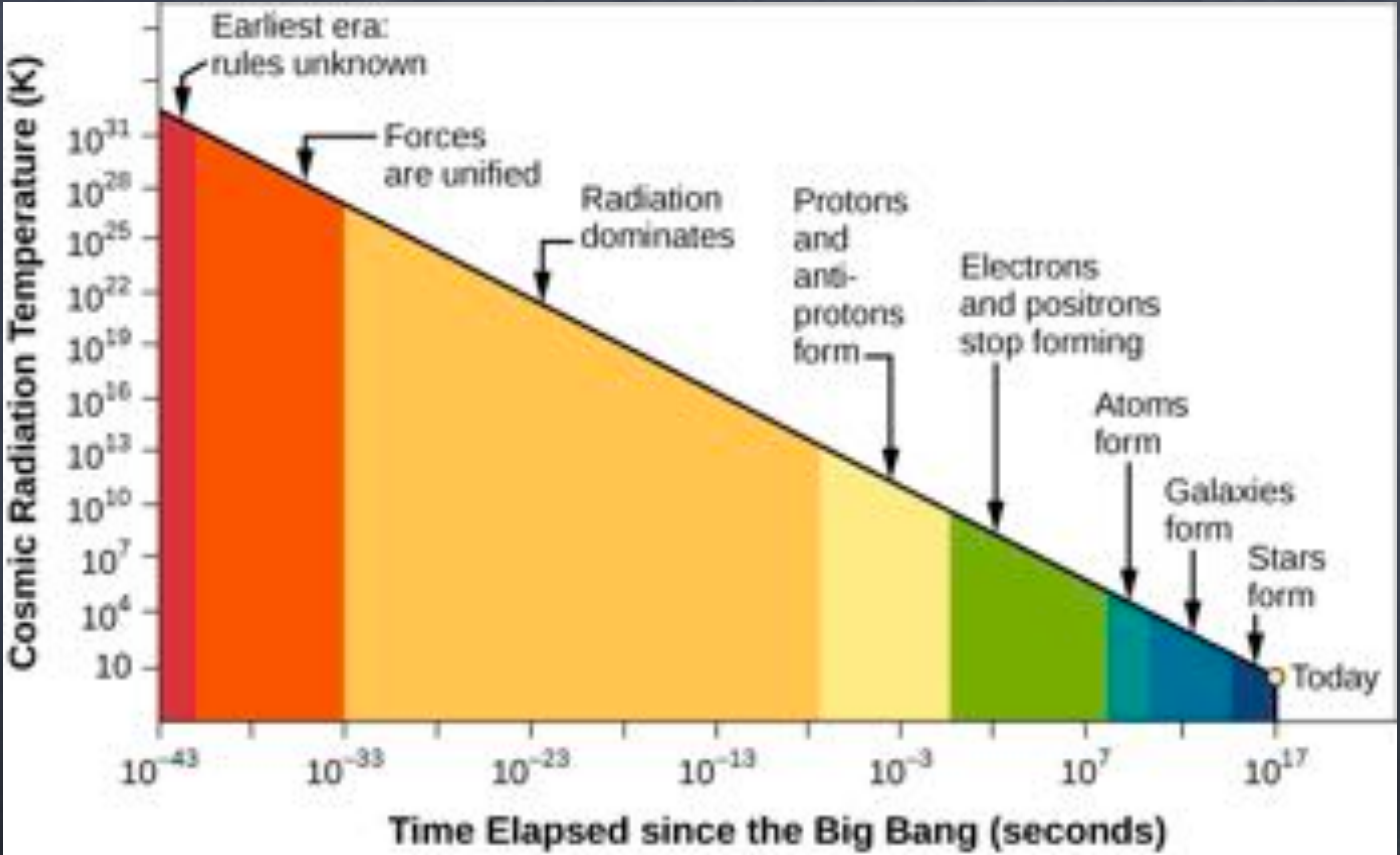


The Big Bang

- Likely the first person to suggest the Universe was expanding was the Belgian priest Lemaitre.
- He suggested the Universe started as one giant atom which fragmented and fragmented until it became all of the atoms in the Universe.
- Our current understanding of atomic nuclei does not support this idea.

The Big Bang

- The physicist Gamow later suggested that the Universe started off with protons and that they fused into heavier elements because the Universe was hot and dense.
- This is called Big Bang Nucleosynthesis and is our current idea for where the original hydrogen and helium come from.



Earliest era: rules unknown
Forces are unified
Radiation dominates
Protons and anti-protons form
Electrons and positrons stop forming
Atoms form
Galaxies form
Stars form
Today
Cosmic Radiation Temperature (K)
10^{31}
10^{28}
10^{25}
10^{22}
10^{19}
10^{16}
10^{13}
10^{10}
10^{7}
10^{4}
10
10^{-43}
10^{-33}
10^{-23}
10^{-13}
10^{-3}
10^{7}
10^{17}
Time Elapsed since the Big Bang (seconds)

Evolution of the Universe

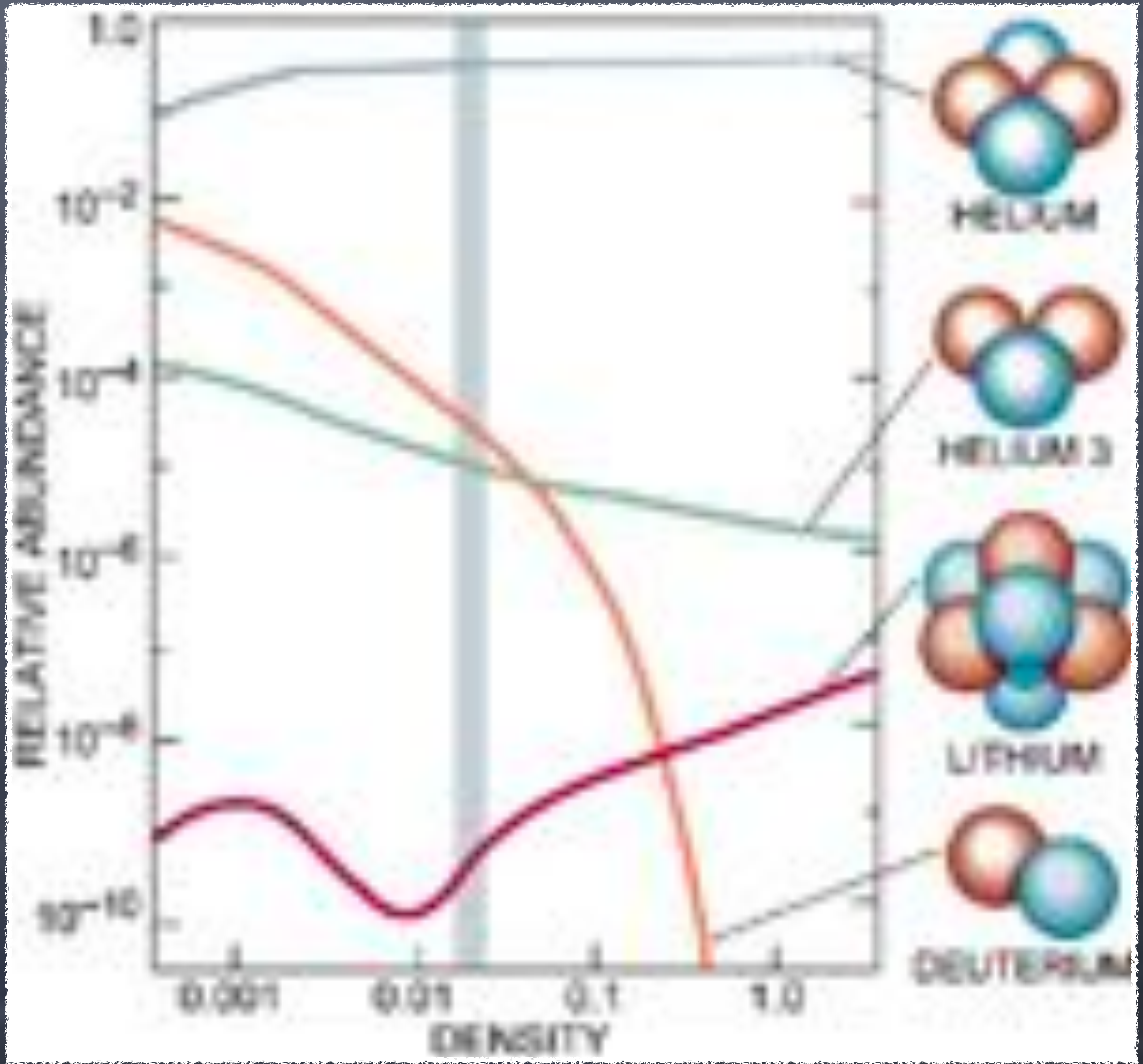
- The very early Universe would be governed by physics we have never seen before. For now let us start at 0.01s and a temperature of 100 billion K.
- At this temperature the universe consists of radiation, protons and neutrons. The radiation collides and produces electrons and positions (positive electrons) which then combine and form gamma-rays.
- Also neutrinos are created and destroyed. It was so dense that even neutrinos quickly ran into something.
- But once the universe is 1s old it's density has dropped so that neutrinos no longer are interacting with the rest of the matter. Since that time they should almost all still not have interacted with everything and be floating around today.

Atomic Nuclei

- When the Universe is about 3 minutes old and 900 million K protons and neutrons can combine to form atoms.
- Now fusion can occur and some of the hydrogen combines to form helium as well as a little bit of lithium.
- This only lasts a minute after which the Universe has cooled down enough that fusion stops happening.
- The amount of helium created at his time is exactly the cosmological abundance we see about 10% of all atoms.

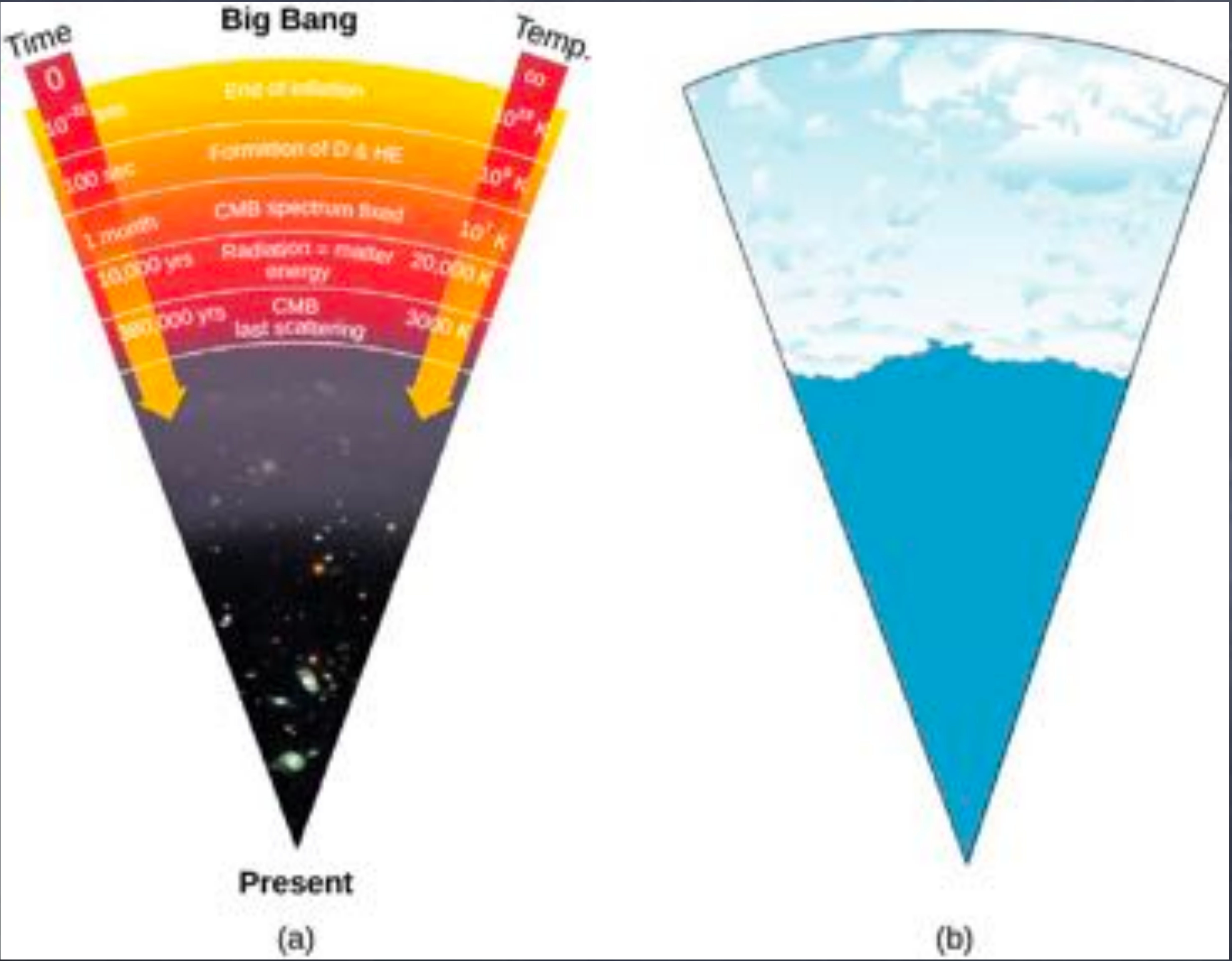
Big Bang Nucleosynthesis

- We can actually test this theory by looking at the abundances of nuclei today.
- It isn't easy and some elements like helium are also created in stars, but deuterium is only destroyed in stars so its abundance reflects what was created when the universe was 3 minutes old.
- Measurements find that the abundances match the predictions.



Cosmic Microwave Background

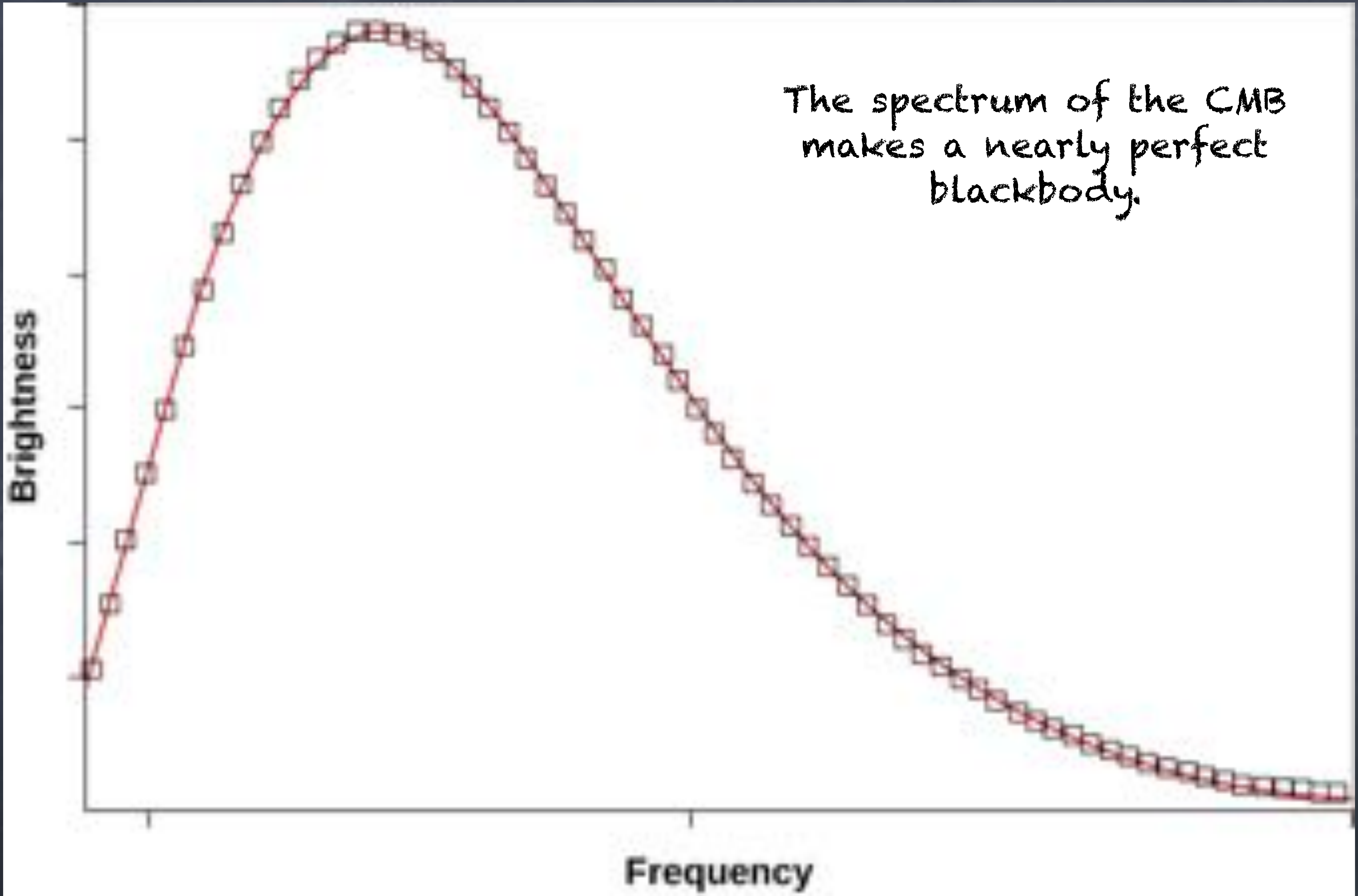
- After the Universe is 4 minutes old it resembles the interior of a star. The atoms are all ionized and radiation bounces around scattering off electrons constantly.
- At about 380,000 years the Universe becomes cool enough (3000K) that the electrons and atomic nuclei can combine and form neutral atoms. When this happens the radiation is suddenly able to escape like it does from the photosphere of a star.
- The radiation is called the cosmic background radiation and it was theorized to exist by Gamow and collaborators. Since that time the universe has expanded by a factor of 1000, so the radiation would be redshifted into the microwave.



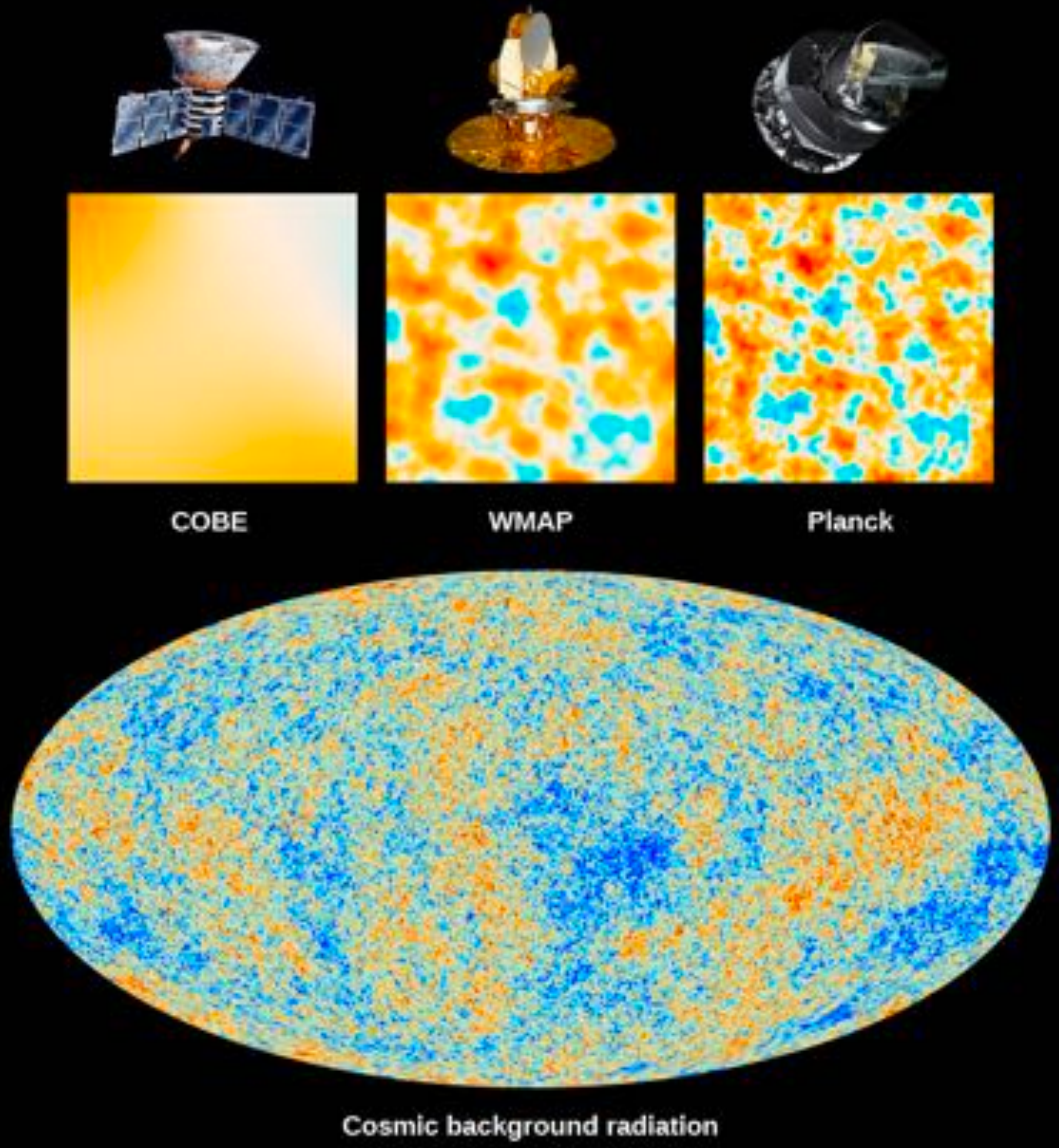
Looking through the Universe to the cosmic microwave background is like looking through the sky to a layer of clouds. Light easily passes through the universe after the atoms become neutral, but before that is like looking into the clouds, you'll only see the surface of the clouds.

Detection of the CMB

- Penzias and Wilson discovered the cosmic microwave background by accident.
- They were testing out a new microwave antenna for Bell Labs and found a signal coming from all directions.
- They tried to get rid of it, but couldnt. Eventually, they met physicist at Princeton who were trying to build a microwave detector to discover the CMB and found out they had just done that.

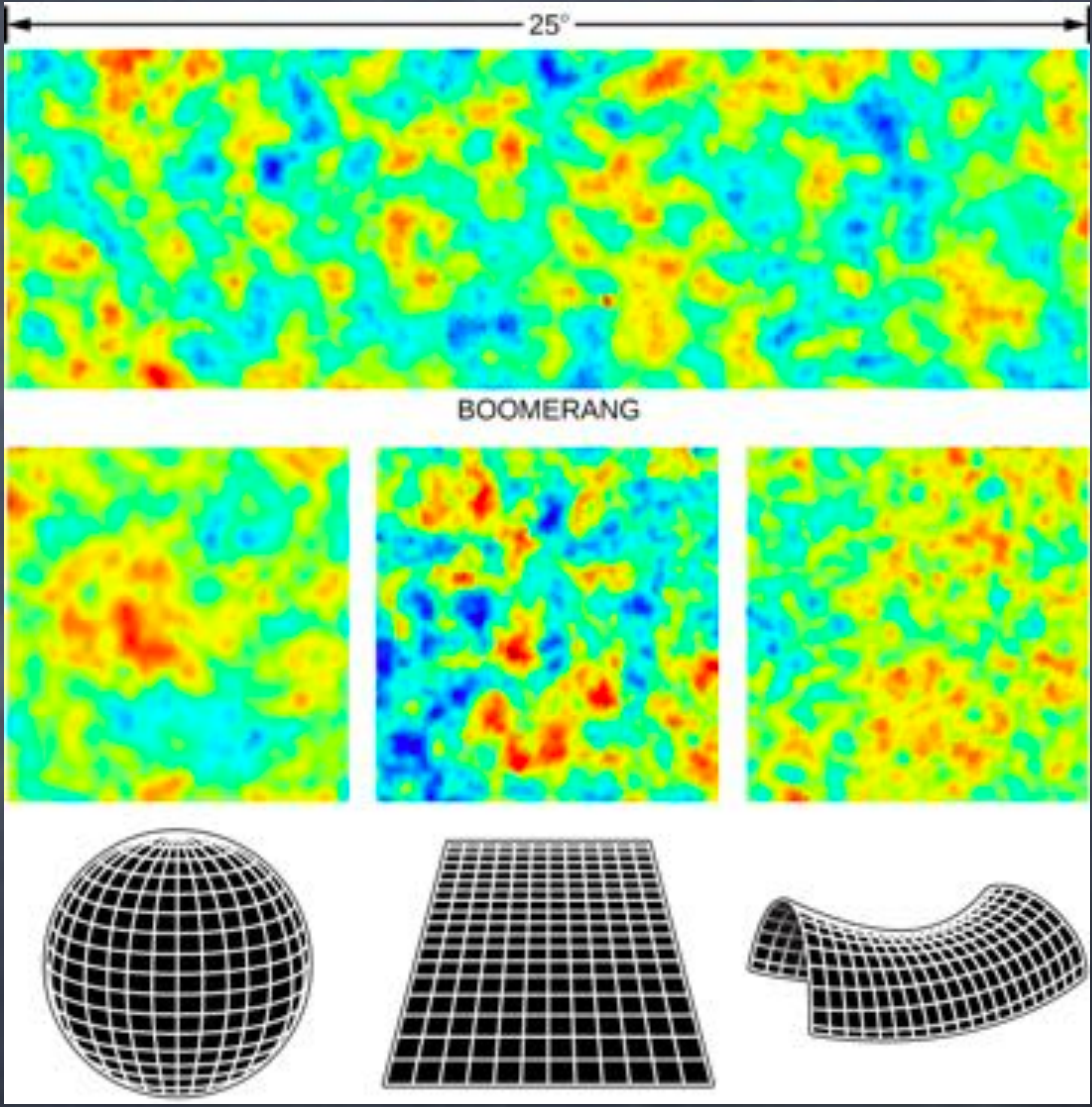

The spectrum of the CMB makes a nearly perfect blackbody.
Brightness
Frequency

However, there are very small differences in the CMB, only varying by 1 in 100,000. Future experiments have worked to map these fluctuations because they can be used to measure cosmological parameters.



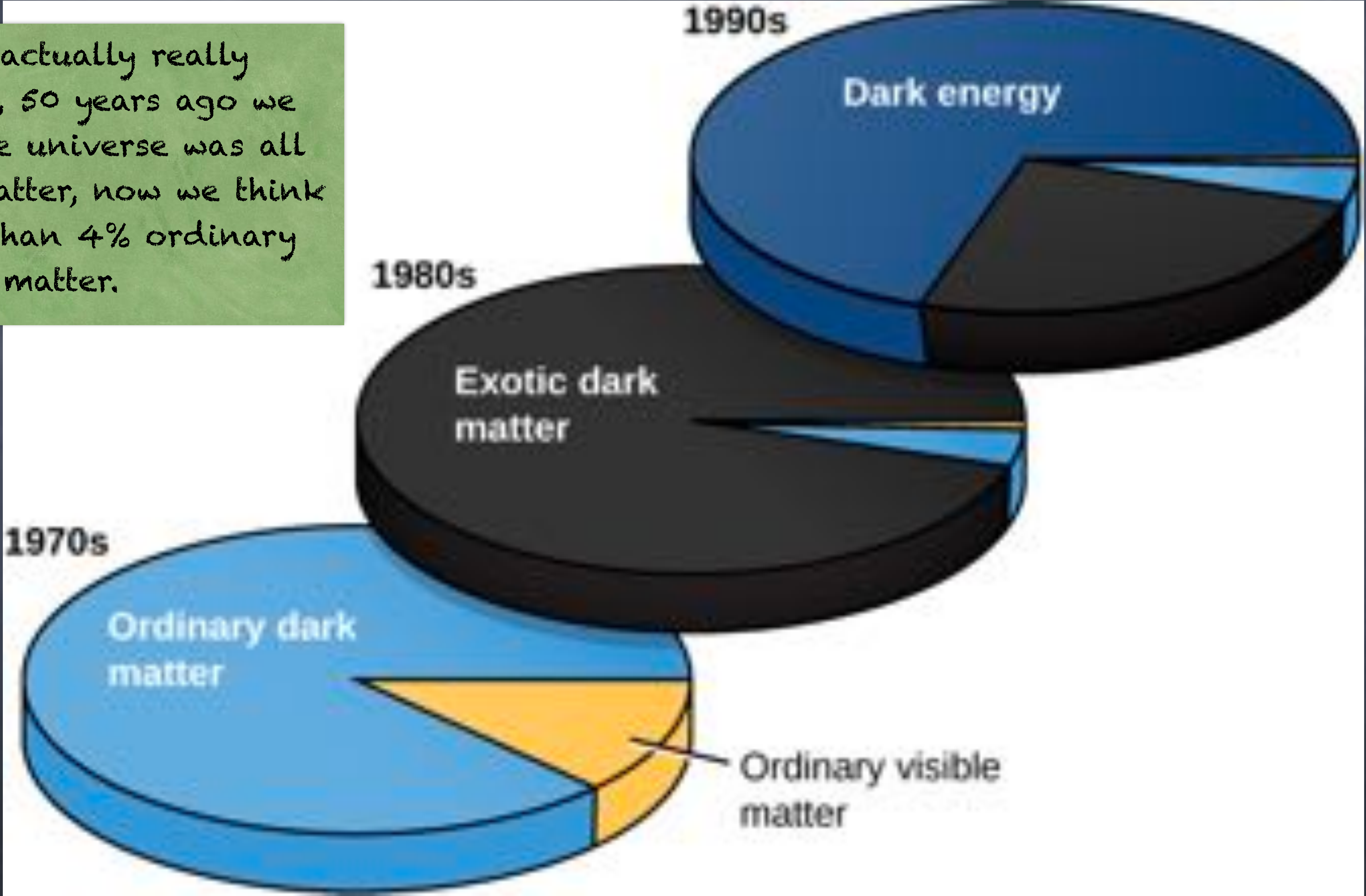
Fluctuations in the CMB can be used to measure the curvature of the Universe. Since the Universe is expanding space-time it is possible that the space-time is curved like a sphere, or flat or negatively curved which cant be visualized.

Measuring the typical size of the fluctuations let us conclude that the Universe is flat.
It also tells us the amount of atoms, dark matter and dark energy in the Universe.



Composition of the Universe

This is actually really surprising, 50 years ago we thought the universe was all ordinary matter, now we think it is less than 4% ordinary matter.



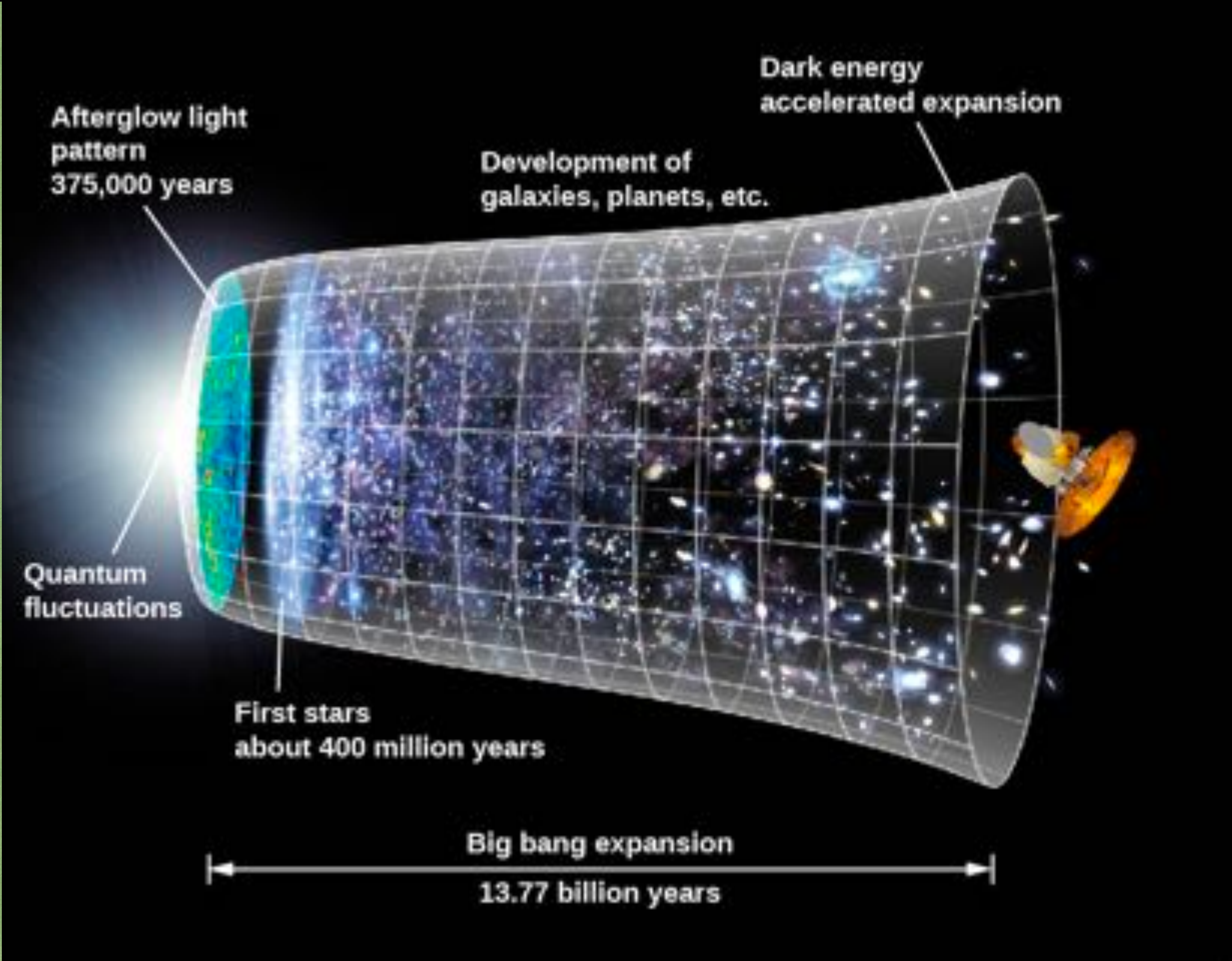
What is Dark Matter?

- The truth is we really dont know. The best though is that like the neutrino you have something that barely interacts with normal matter at all, but unlike the neutrino is fairly massive.
- Suggesting such a thing exists is strange, but no stranger then suggesting the neutrino existed, which ended up being true.
- However, unlike the neutrino we have found no evidence for this new dark matter particle either from experiments designed to look for it, or in the Large Hadron Collider where particles are smashed together to look for new particles.

What is Dark Energy?

- We have even less of an idea about what dark energy might be. It could simply be the cosmological constant Einstein first proposed, but there is no reason for such a thing to exist.
- Most physicist think it is some energy of empty space created by quantum mechanics in some as yet still not understood manner.
- We do have other evidence about dark matter from galaxies, both in their rotation and motion in clusters, their stability to bars and in the timing of the first galaxies. We have no other evidence for dark energy accept for the theory of inflation which proposes a similar repulsive force existed in the very very very early Universe.

A way over used graphic showing the history of the universe, from a very small region to the CMB to the first stars and the formation of galaxies.



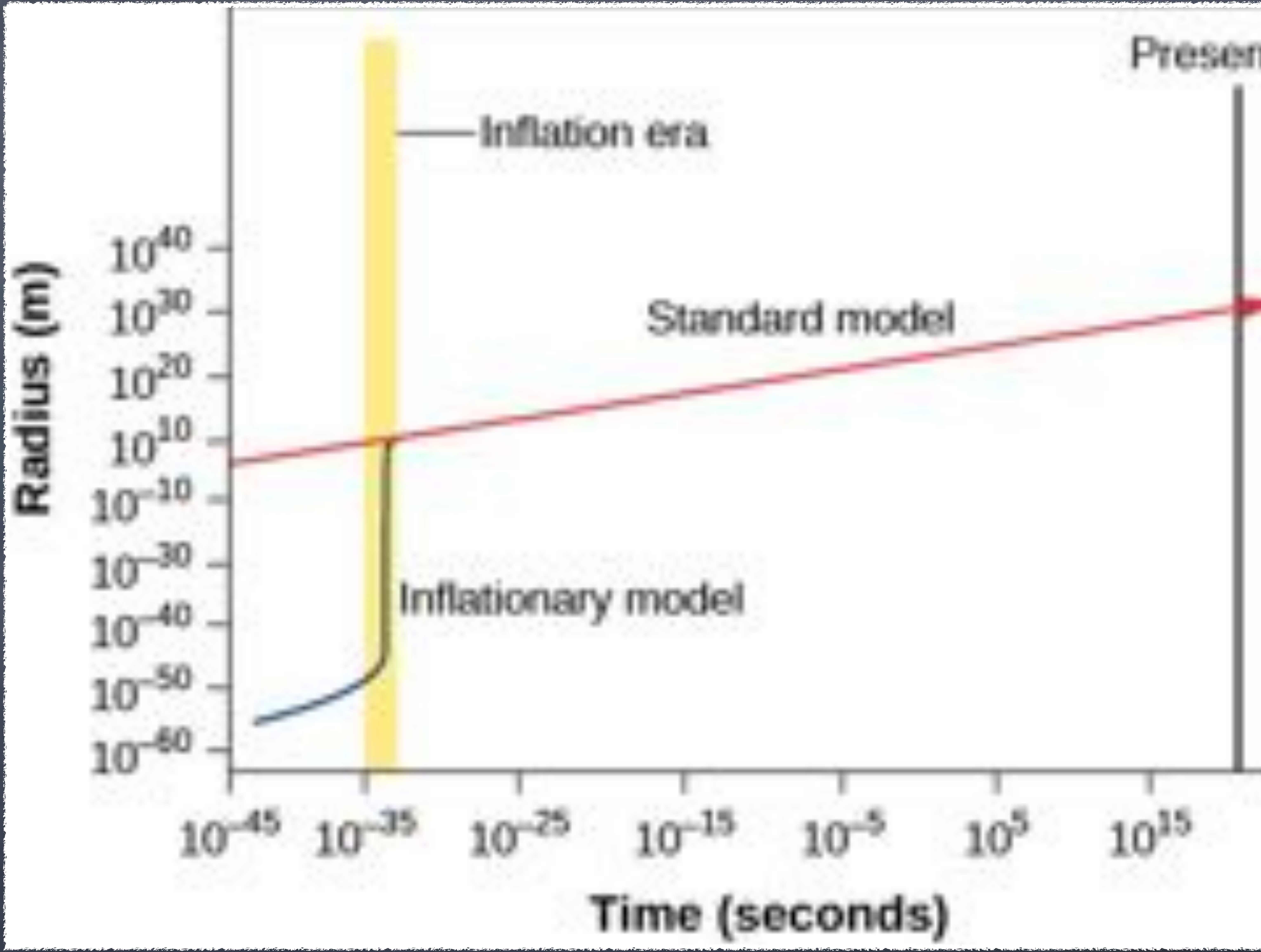
Problems with the Model

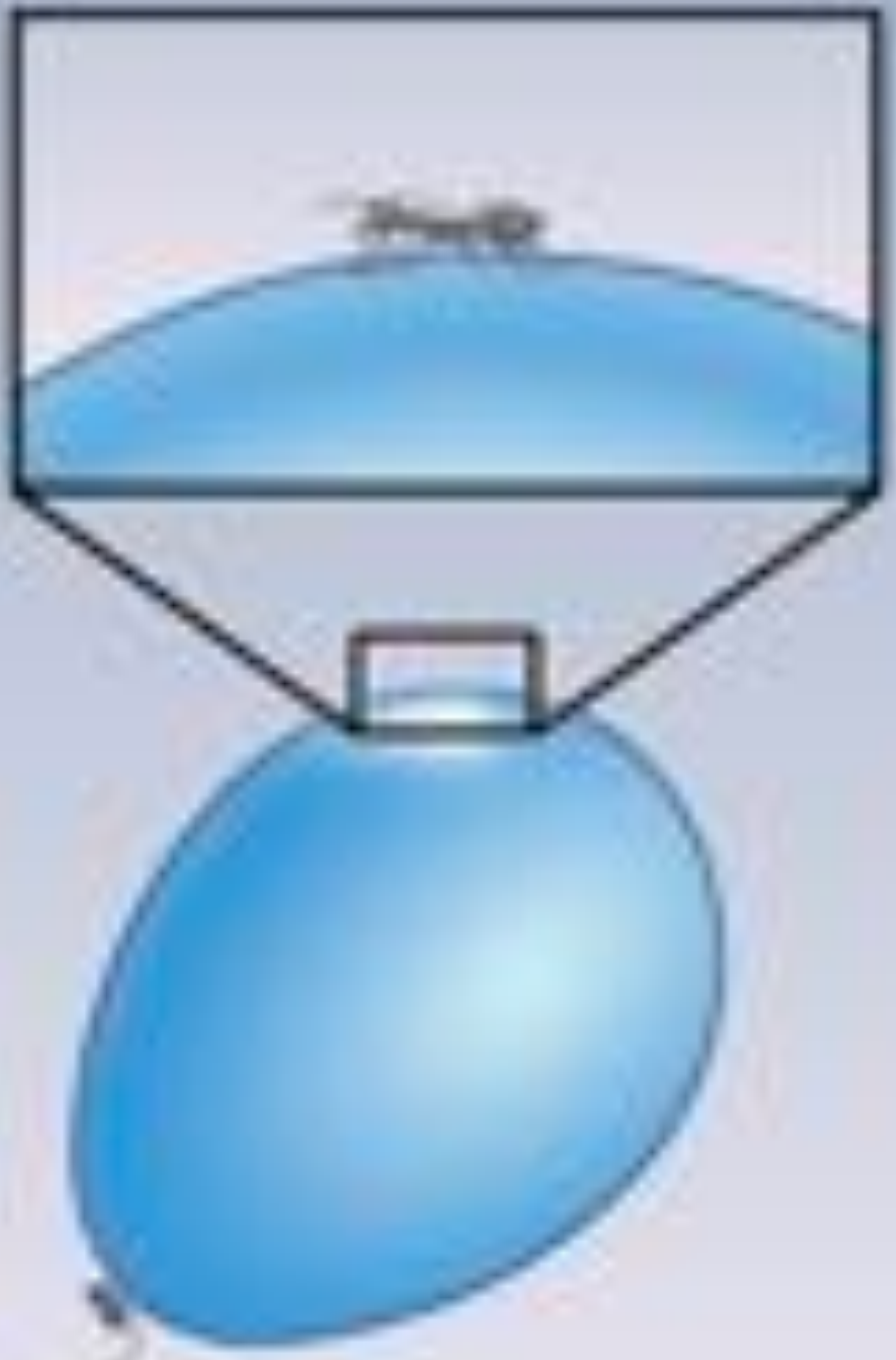
- Though the big bang cosmological model explains all observations we have about the universe, it does have a number of puzzling features.
  - Why is the Universe flat? That is why is the total density very close to the critical density?
  - Why is the Universe so very very uniform? When we look at the CMB in opposite directions we are looking at parts of the Universe which only came in contact today. How did they know to have the same density to 1 in 100,000.
  - What caused the fluctuations we see in the CMB which are responsible for the formation of galaxies and everything in the Universe?

Inflation

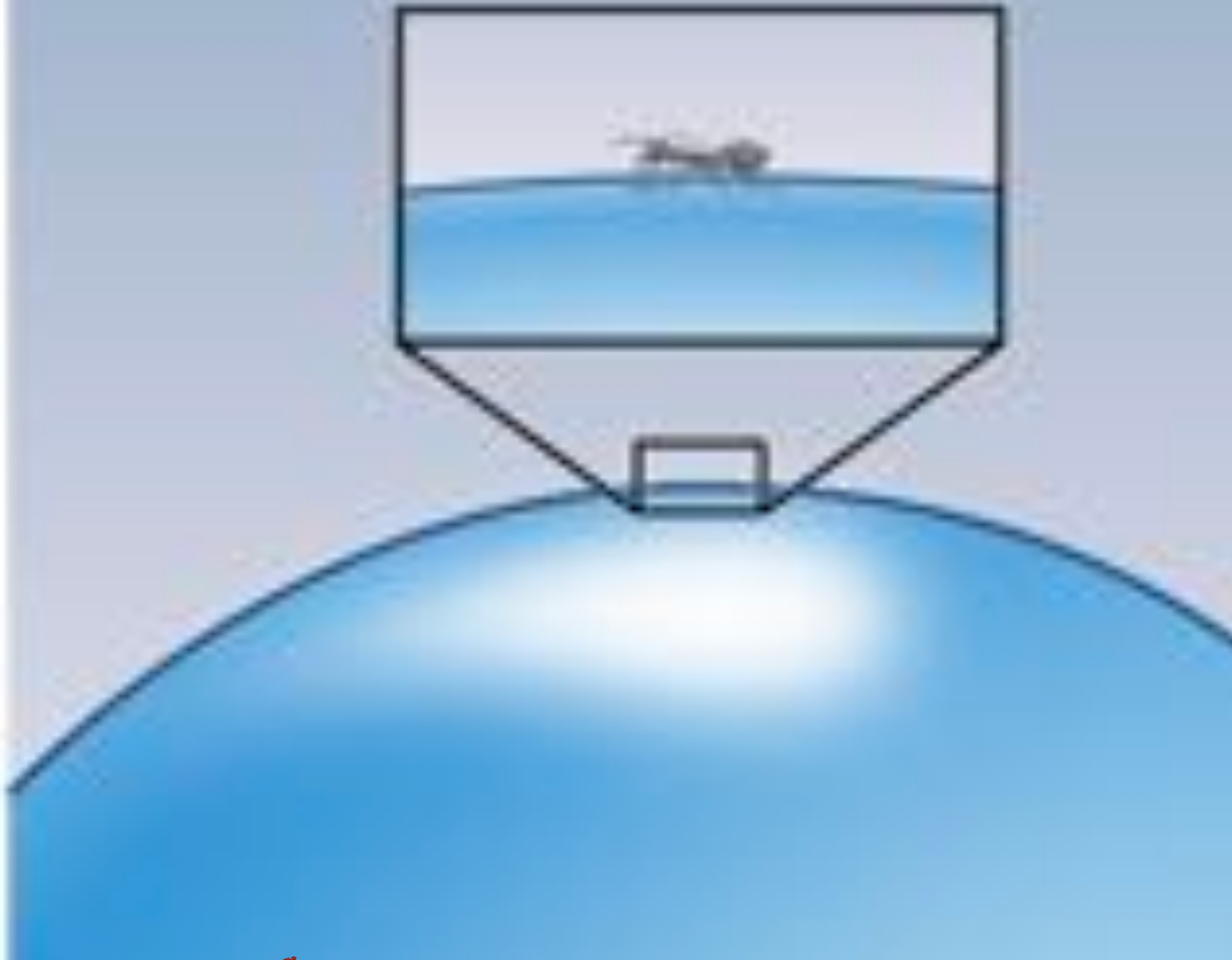
- A proposal to solve these problems is called inflation and it theorizes that at very early times (10^{-30} seconds) the Universe underwent a tremendous inflation, growing in size by 10^{50}.
- This is totally crazy, but remember we really dont know anything about the physics at these times. These are densities and temperatures so much higher than we ever observe that we cant assume anything.

- Inflation proposes an enormous amount of growth in a very short time.
- This allows a volume that is in causal contact at 10^{-35} seconds to grow to the size of the Universe today.
- This would explain why the density is almost uniform throughout the Universe.

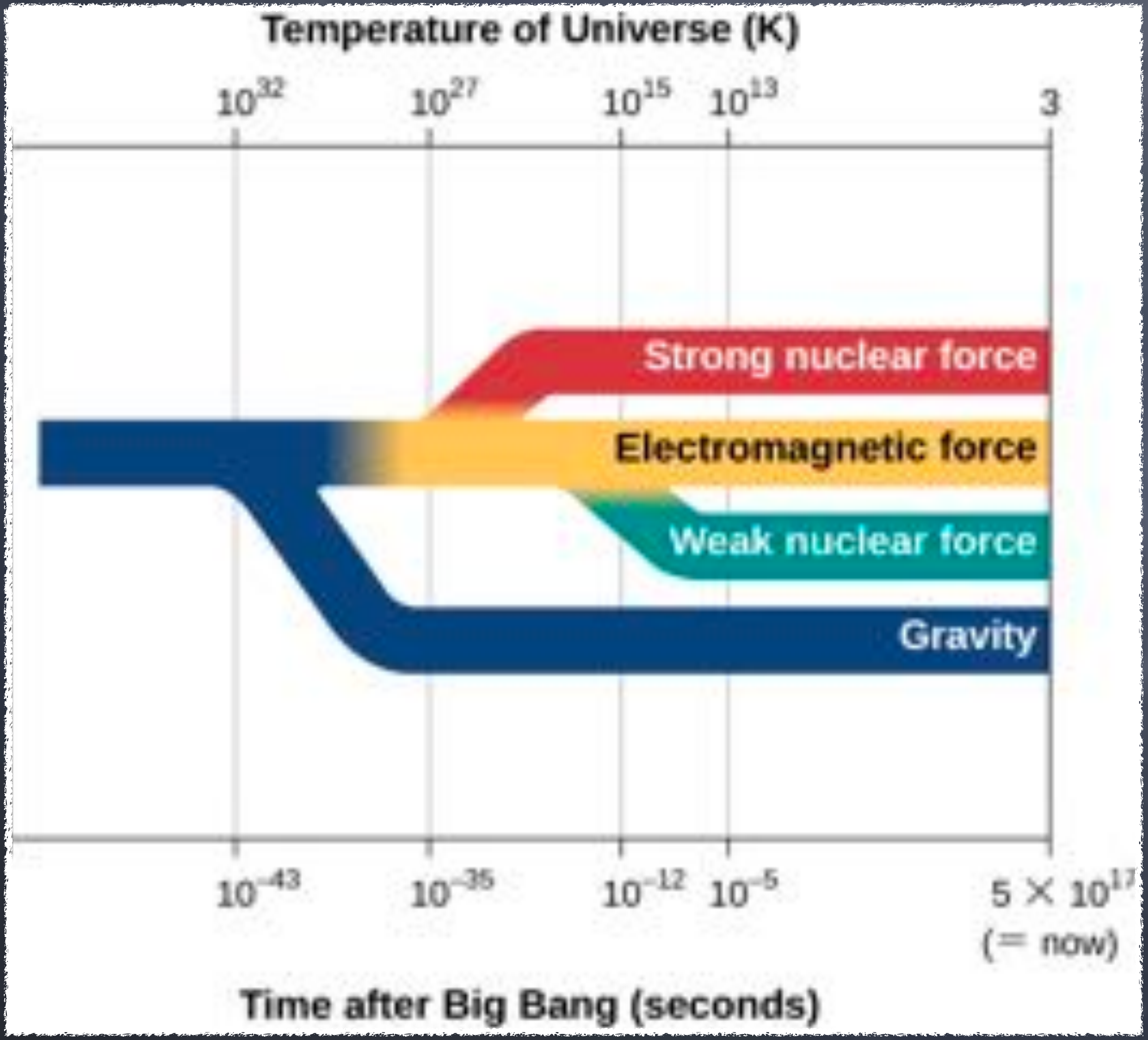




Inflation makes the Universe flat because any curvature is stretched away.



Inflation also creates flections because quantum fluctuations are stretched to the size of the Universe.



- Why would such a thing a happen?
- Many physicist believe the forces were unified at some point.
- When the unification breaks in creates quantum mechanical energy in the space, just like what we need for dark energy.
- This might have caused the inflation at these early times.

Anthropic Principle

- Inflation explains some of the mysteries of big bang cosmology, but creates many of its own. For inflation to work out right seems to require a luck accident.
- One possible solution to this is that there are many universes, not just this one. In each one physics might be slightly different, inflation might last a little longer or less time.
- But only in some universes would galaxies and stars form in such a way that intelligent life (us) might exist and ask these questions in the first place. This is called the anthropic principle.
- So we might have gotten lucky, but only those who get lucky ask why are they so lucky.
- Or maybe there is a deeper reason that things are the way they are that we haven't uncovered yet.