Announcements

- First to last quiz due tonight :-)
- Start working on problem sets if you haven't done so yet!
  → Due by end of semester, worth 10% of final grade
- Stargazing Blitz Week this week, Dec. 1-4: stargazing every night this week, 8-9 pm on 5th floor of Physics building
  → 1% bonus on final grade

Plan for Rest of Semester

Only 5 classes left before final!

- Today: Large Scale structure, age of universe
- Wednesday: Big Bang, Cosmology
- Friday: Life in the Universe
- Monday next week: ??? → Ideas?
  Behind the scenes of an observing run / More review / Other topics → Let me know
- Wednesday next week: Review for Final

Finding the age of the Universe

Three independent ways of finding the age of the universe and of its oldest stars and galaxies:

- Dating the oldest globular clusters by using their H-R diagrams to see what stars have evolved off the main sequence: Today's best estimate: 11-13 billion years since first stars formed in globular clusters
- Using Hubble's law to deduce when the galaxies were all at a single point - when the Big Bang occurred: 14 billion years
- Finding the most distant objects and finding that they are about 13 billion light years away.

The Big Bang

From their redshifts, we know how fast the galaxies are moving apart — how fast the universe is expanding. But this means that 14 billion years ago, every point in the universe was just concentrated in one point – one really, hot dense point.

We don’t know the physics of an infinitely dense point, but we will allow this point to expand a little bit – for a few microseconds – and we can then reconstruct the history of the universe.

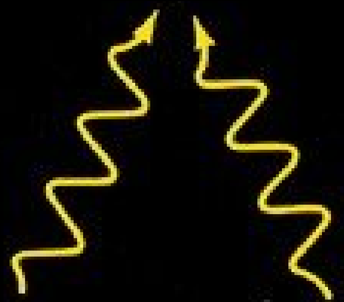
The first 3 minutes of the universe

A large part of the way the universe is today is the result of its history during the first few minutes after the Big Bang. Here is a short description of that history.

For a small fraction of a second, the temperature was above 1 trillion K (10^{12} K).

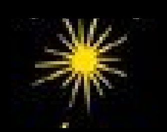
At these hottest temperatures, light is energetic enough to create pairs of particles and antiparticles – protons and antiprotons, electrons and positrons, for example; and there are equal numbers of each.

Particles and antiparticles forming and annihilating each other



(a) Pair production

Particles and antiparticles forming and annihilating each other



(a) Pair production

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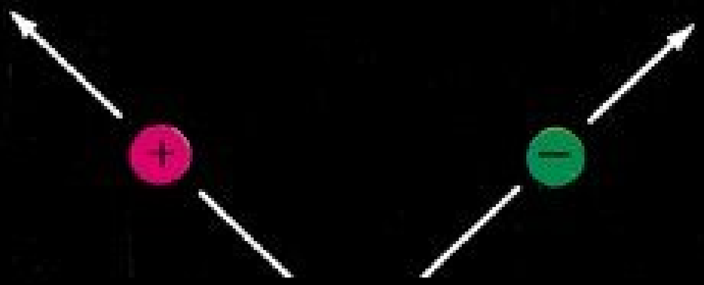

(a) Pair production

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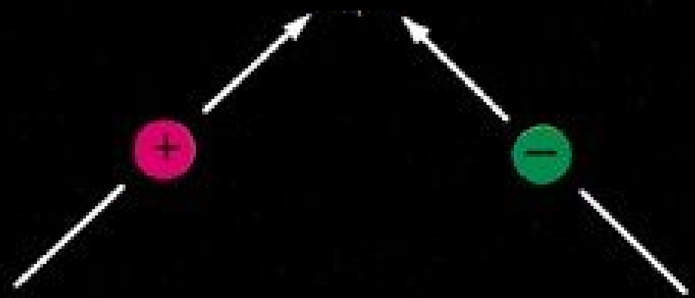

(b) Annihilation

Particles and antiparticles forming and annihilating each other

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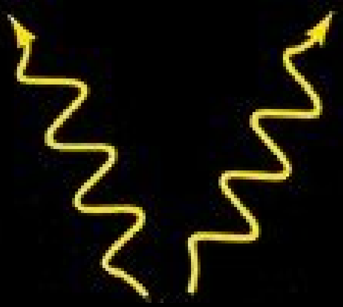
Particles and antiparticles forming and annihilating each other



(b) Annihilation

The creation of matter

The universe should have created equal amounts of matter and antimatter, but we and everything else we know about are made of matter

Because of a tiny, tiny imperfection in the amount of matter created versus antimatter, the universe ended up with more matter than antimatter

Why this occurred is still a mystery, but fortunately for us it did

Big Bang Nucleosynthesis

From about 2 minutes to 30 minutes from the beginning, protons and neutrons start to fuse in the same process as in the Sun.

Protons fuse to become helium and (a very little bit of) other stuff.

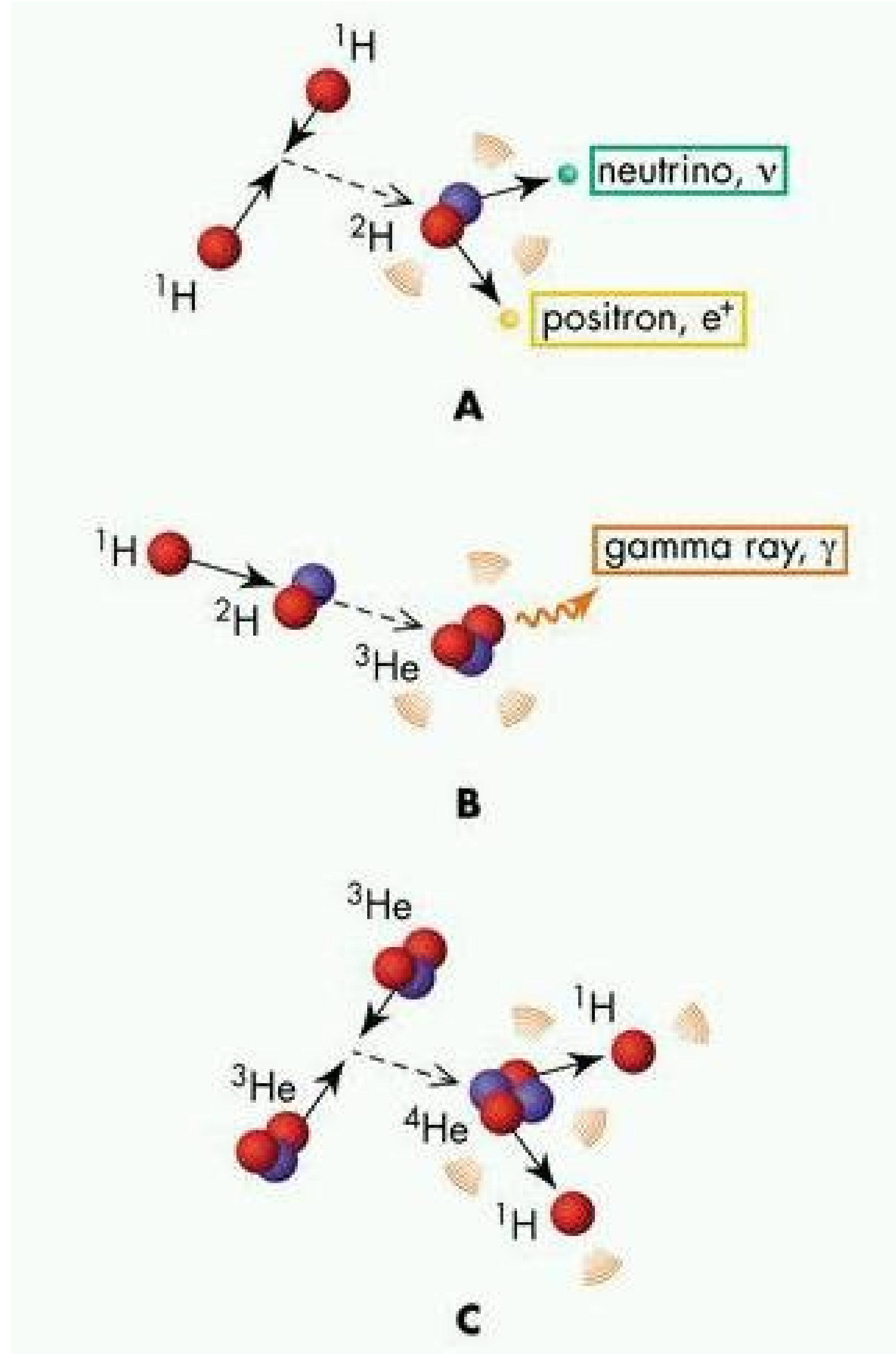
After 30 minutes, the temperature and density are too low to allow any more fusion: 25% of the hydrogen has fused to helium, and the universe is 25% helium, 75% hydrogen, very close to its composition today.

This process is called **big bang nucleosynthesis.**

Big Bang Nucleosynthesis

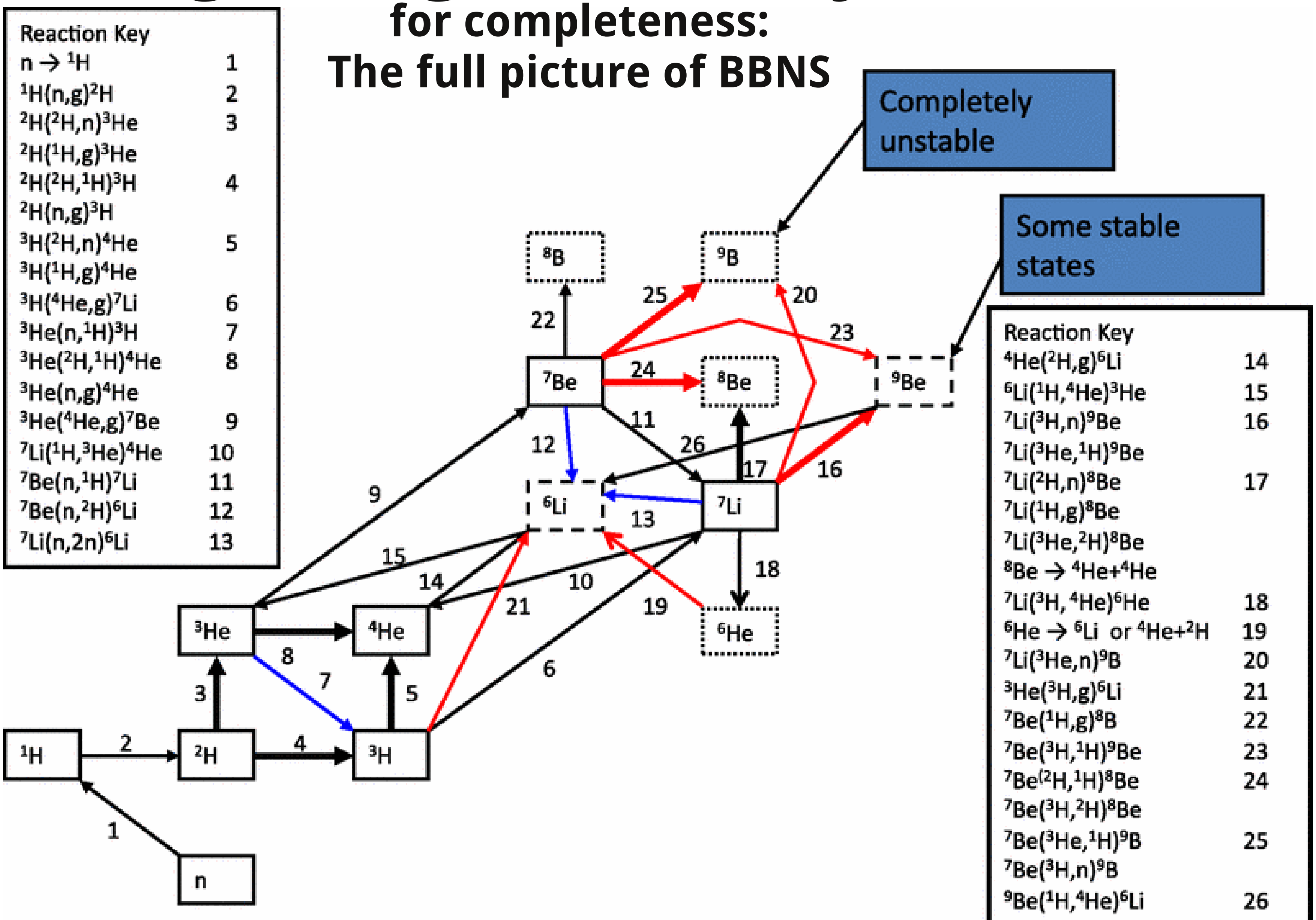
Shortly after the Big Bang densities were similar to those in the core of stars (i.e. dense & hot)

→ Fusion of Hydrogen to mostly Helium and little else



Big Bang Nucleosynthesis

for completeness:
The full picture of BBNS



Source: http://journals.aps.org/prd/article/10.1103/PhysRevD.82.105005

Big Bang Nucleosynthesis

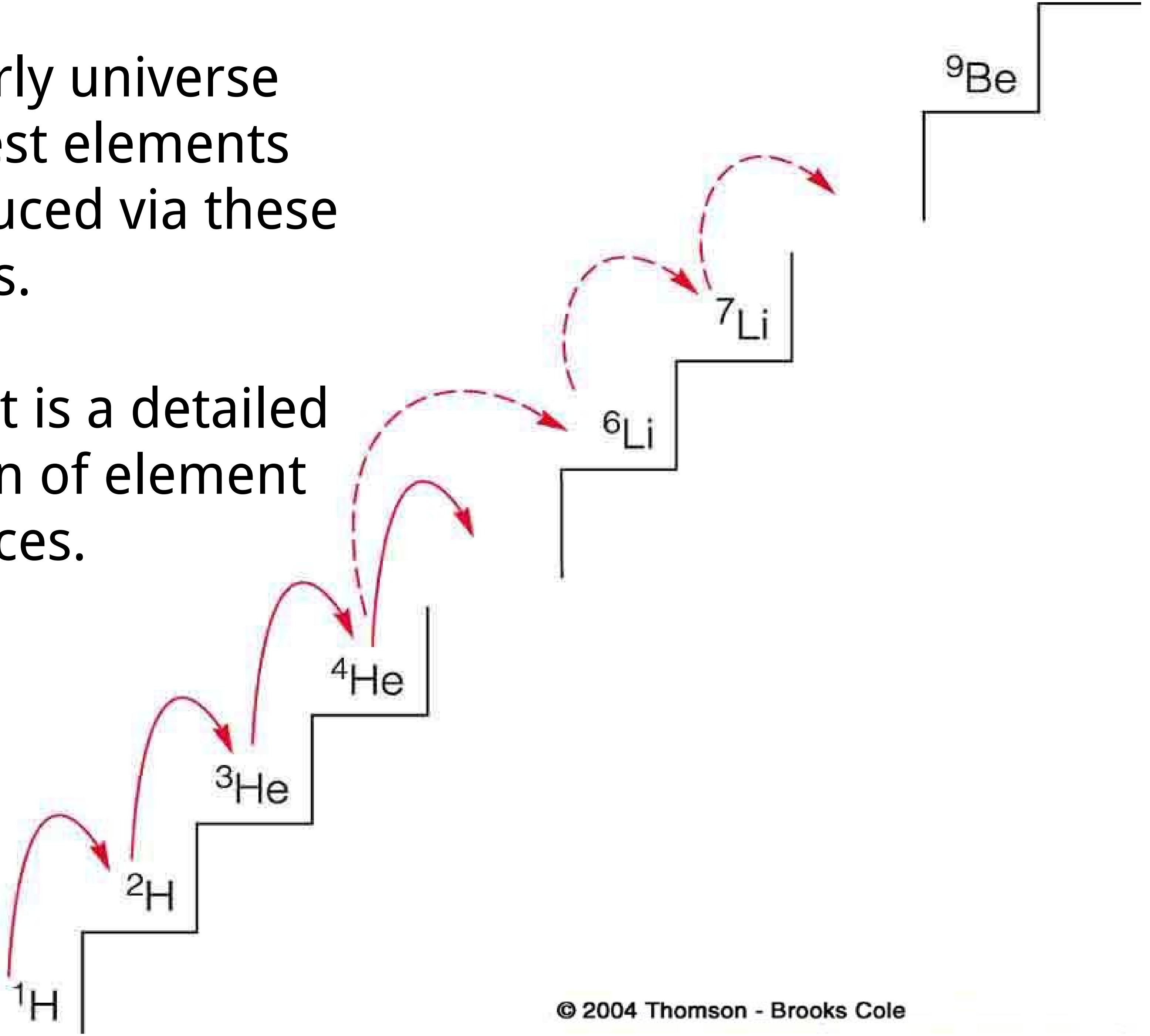
Trace amounts of deuterium and of lithium (from collisions of deuterium with helium) remain, accounting for the abundances of these light elements we see today.

Most of the universe's helium was formed in the Big Bang

As the universe continues to expand, the light and matter that fill it continue to cool. The hot light that filled the universe during the Big Bang still fills the universe, but its temperature is now only 3 K. It is called the cosmic microwave background radiation – more on that later.

In the early universe the lightest elements are produced via these processes.

The result is a detailed prediction of element abundances.

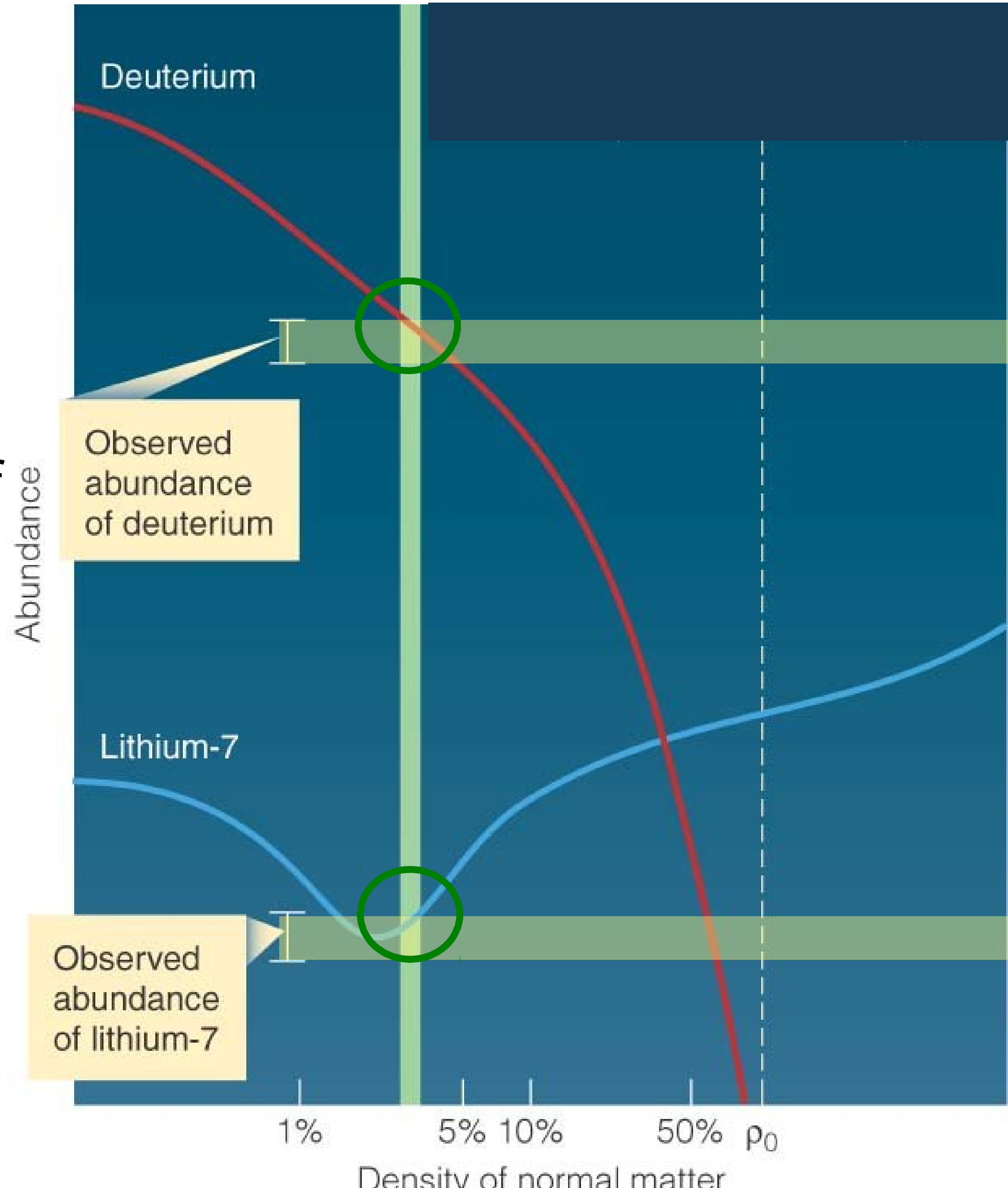


Primordial Nucleosynthesis: Helium and Deuterium abundances

Most of the helium and nearly all of the next two lightest nuclei now in the universe were created in the Big Bang. These are lithium and deuterium – hydrogen with an extra neutron. Elements heavier than this were made in stars, with elements heavier than iron made primarily in supernovae.

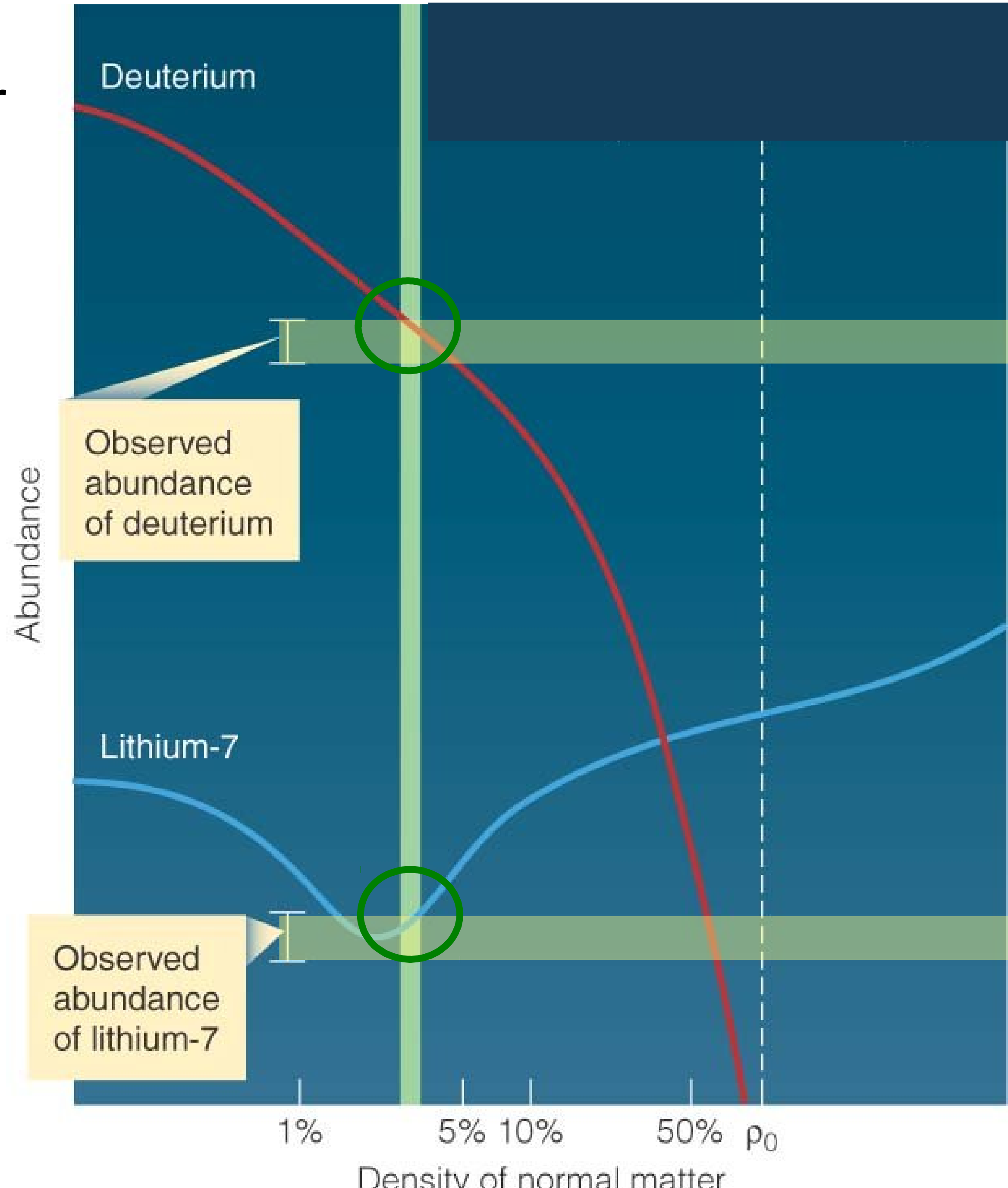
The abundance of helium and deuterium predicted in the Big Bang agree with the observed helium in the universe, as long as the density of ordinary matter is not much larger than what we see. **That means that most of the missing matter cannot be ordinary matter.**

The abundances of deuterium, lithium and helium in the universe agree with predictions from the big bang. This is true if the amount of amount of ordinary matter is about equal to the amount we see (green vertical line showing less than 5% of the total mass of the universe).



But, if the dark matter were ordinary matter, there would be far too much matter to agree with the observed abundances of Deuterium, Li, & He.

So the abundances of the light elements are even more evidence of dark matter!



The Early Universe: Recap

At 1 s after the big bang, all the protons and neutron were made in the universe during a process called **baryongenesis**.

At about 2 – 30 minutes after the Big Bang, helium, deuterium and lithium were formed via **big bang nucleosynthesis**

The universe at this point contains protons and electrons (ionized hydrogen) and helium – the universe is a plasma.

History of the Universe

The photons bounce off the free electrons: **the universe is opaque to light.**

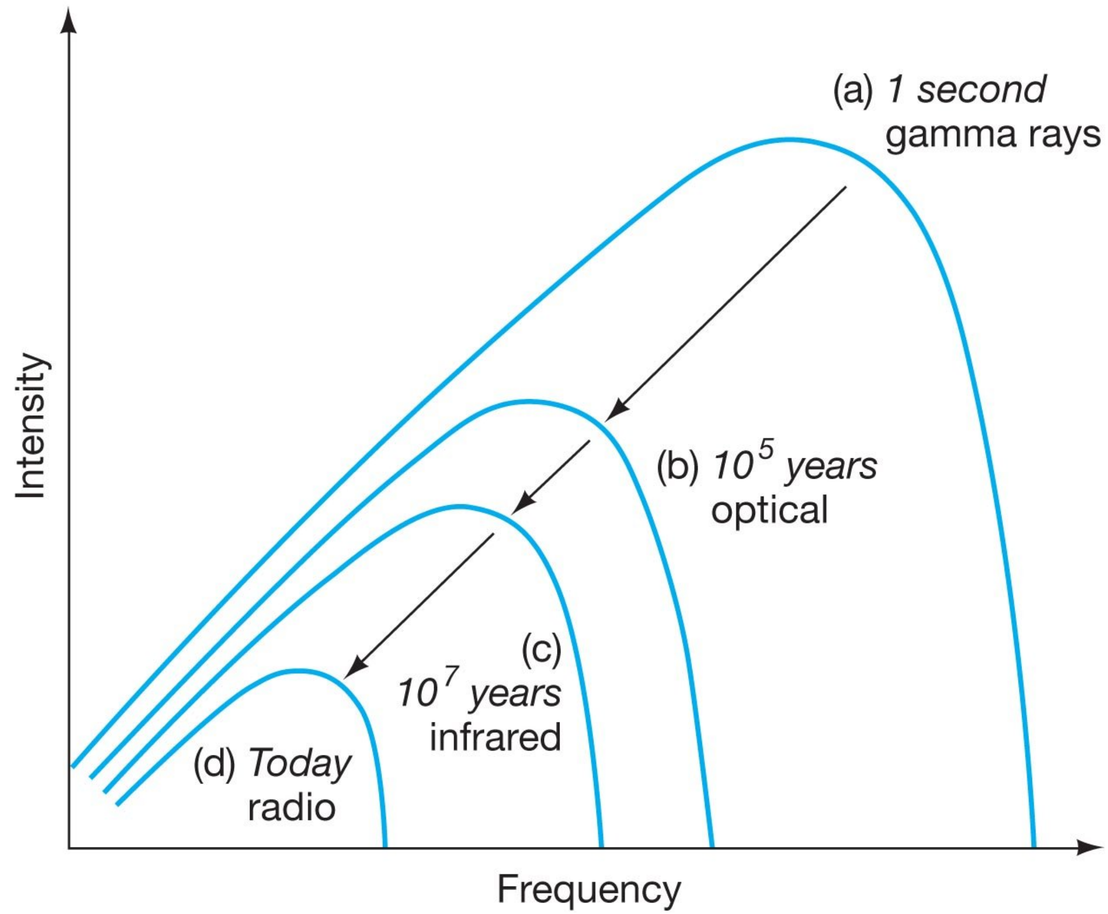
As the universe continues to expand, it cools.

At ~ 400,000 years after the big bang, electrons and protons combine to make neutral hydrogen atoms – suddenly the photons don't have free electrons to scatter them, so the universe is transparent to photons and they stream in all directions. This is called **recombination**.

Cosmic Microwave Background

At this time the temperature of the universe is about 4,000 K. This light gets redshifted as the universe expands until today when the temperature of the radiation is 3 K.

So the universe is not absolutely cold, but has a temperature of ~3 K.



Cosmic Microwave Background

At 3 K, the radiation is in the microwave regime, so this radiation is called the **cosmic microwave background**.

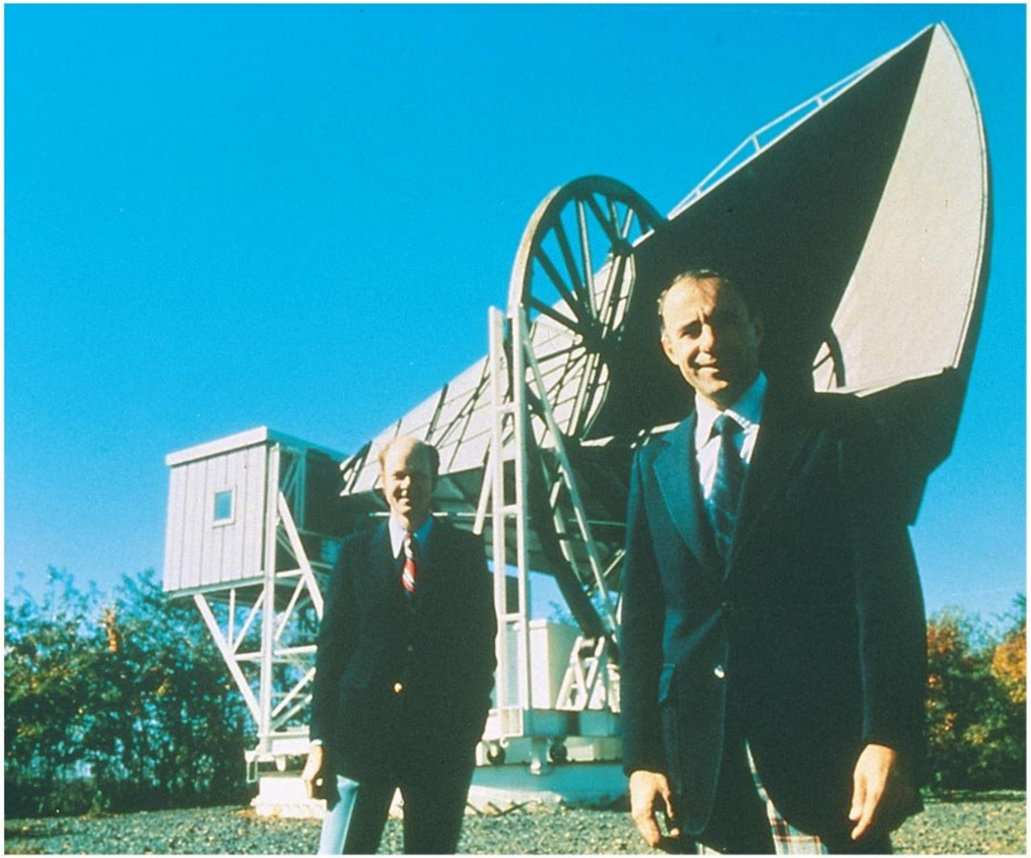
The cosmic background radiation was predicted by Gamow in 1948 as a natural consequence of the big bang theory.

But there was no attempt to measure it (or realization that it could be measured) until the early 60's.

Cosmic Microwave Background

When it was discovered in 1965, the discovery was accidental, made by Penzias and Wilson at a Bell Labs telescope in Holmdel, New Jersey.

They were looking for sources of radio noise on Earth and stumbled across the radiation that pervades the universe, photons left over from the Big Bang.

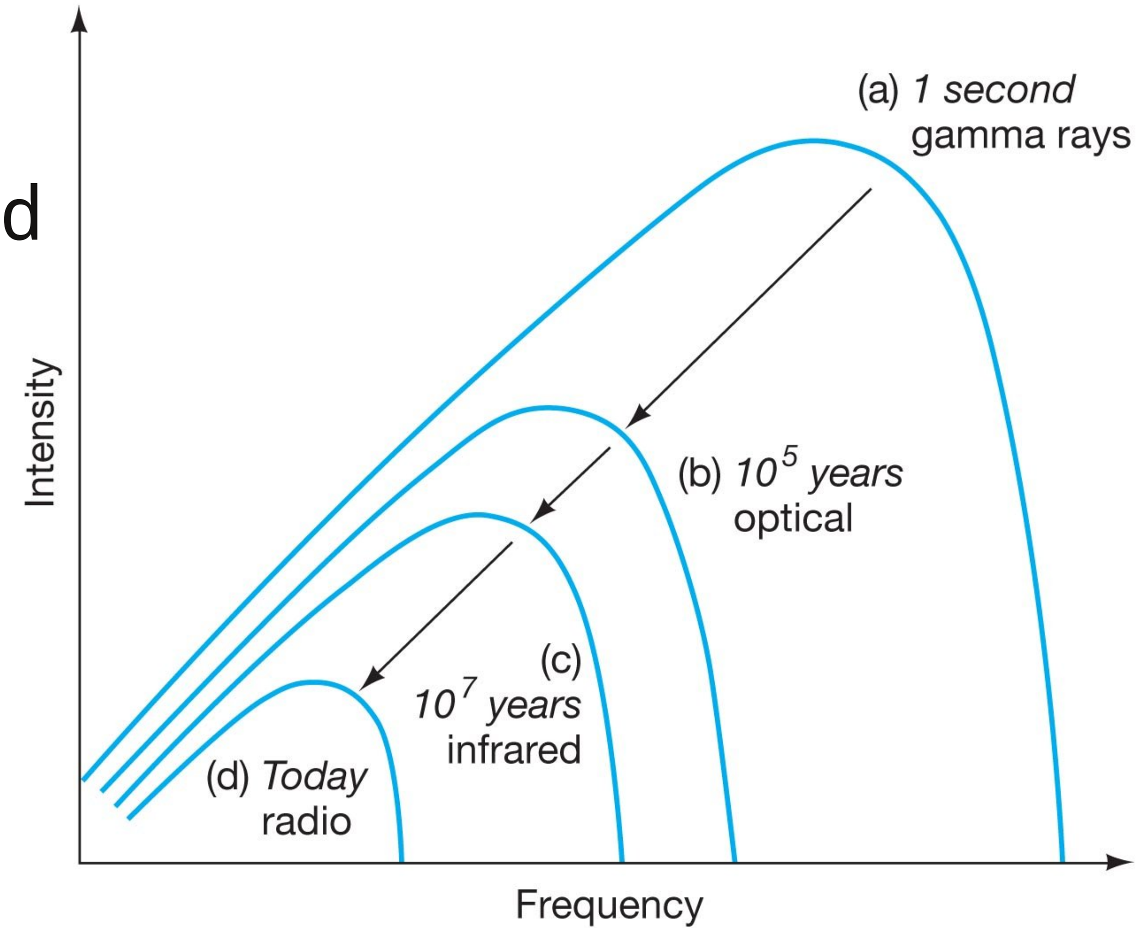


The radio antenna at Holmdel, New Jersey, whose noise turned out to be light from the Big Bang.

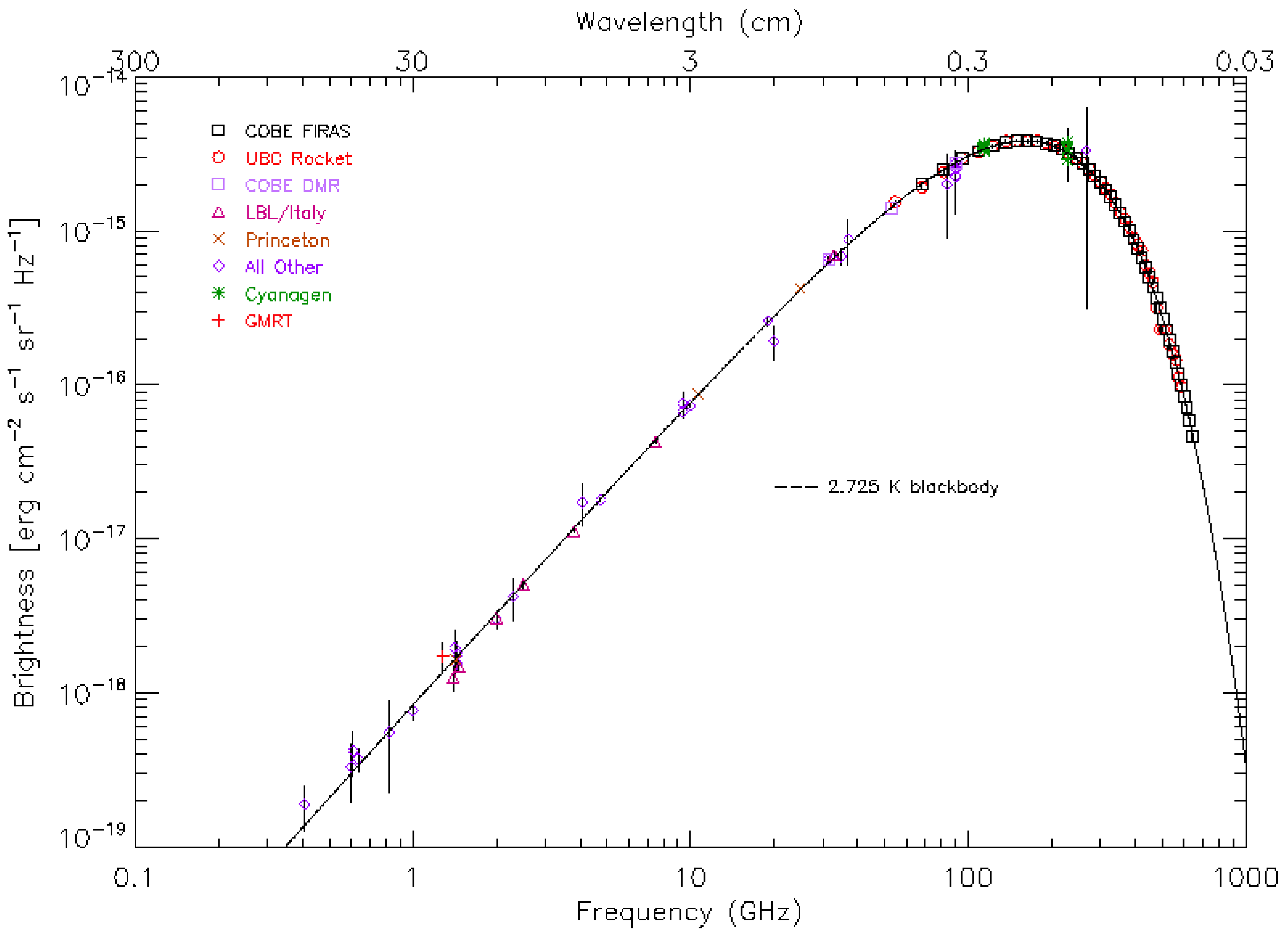
Cosmic Microwave Background

When these photons were created, it was only one second after the Big Bang, and they were very highly energetic.

The expansion of the universe has redshifted their wavelengths so that now they are in the radio spectrum, with a blackbody curve corresponding to about 3 K.



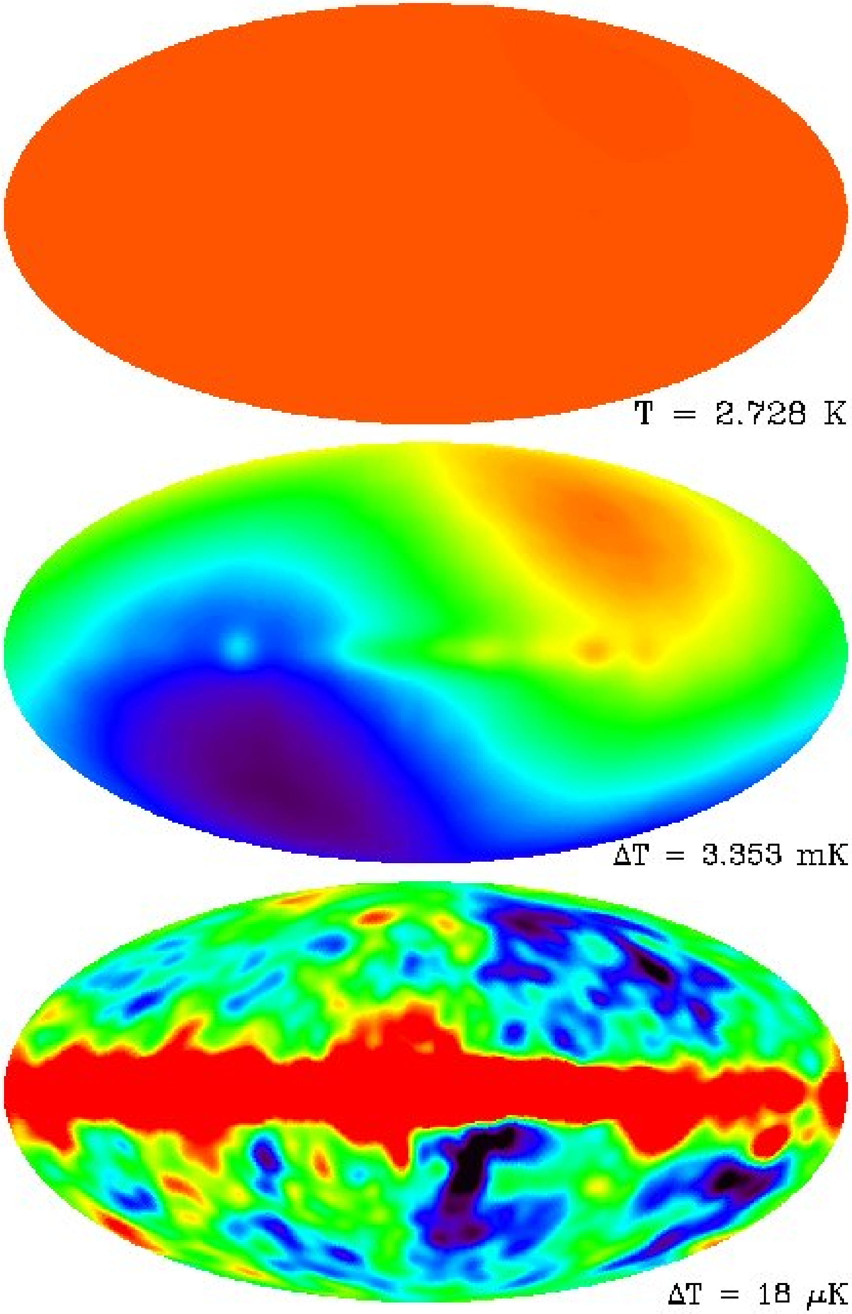
As predicted, the cosmic microwave background has a nearly perfect blackbody spectrum with a temperature about 3 K.



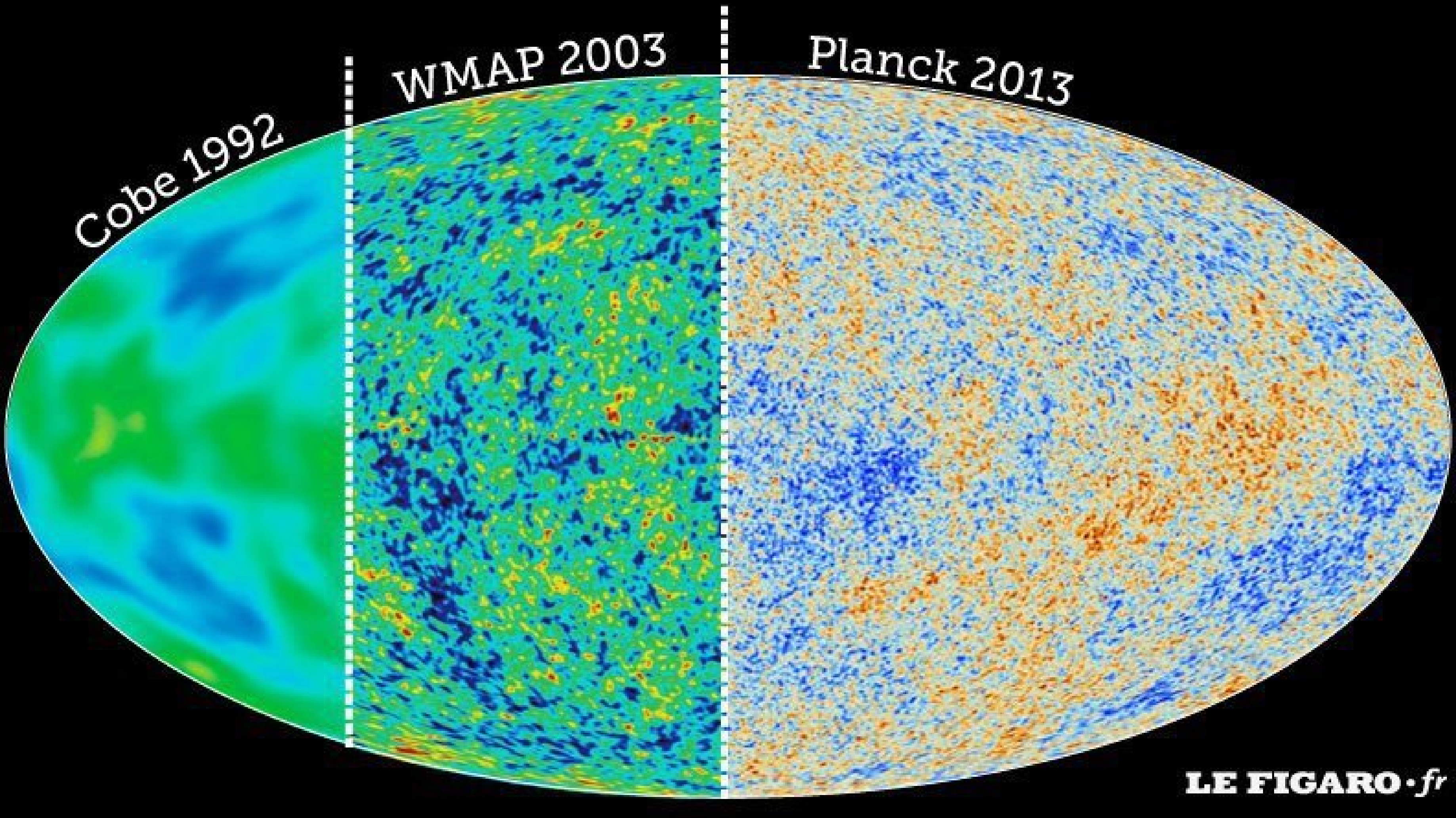
CMB map

The CMB can be used to study the temperature of the universe. This was done since ~20 years ago using satellites.

To reveal small fine structure, we first need to subtract the constant, global temperature and the dipole moment (caused by doppler shift of the signal as the sun moves relative to the CMB).



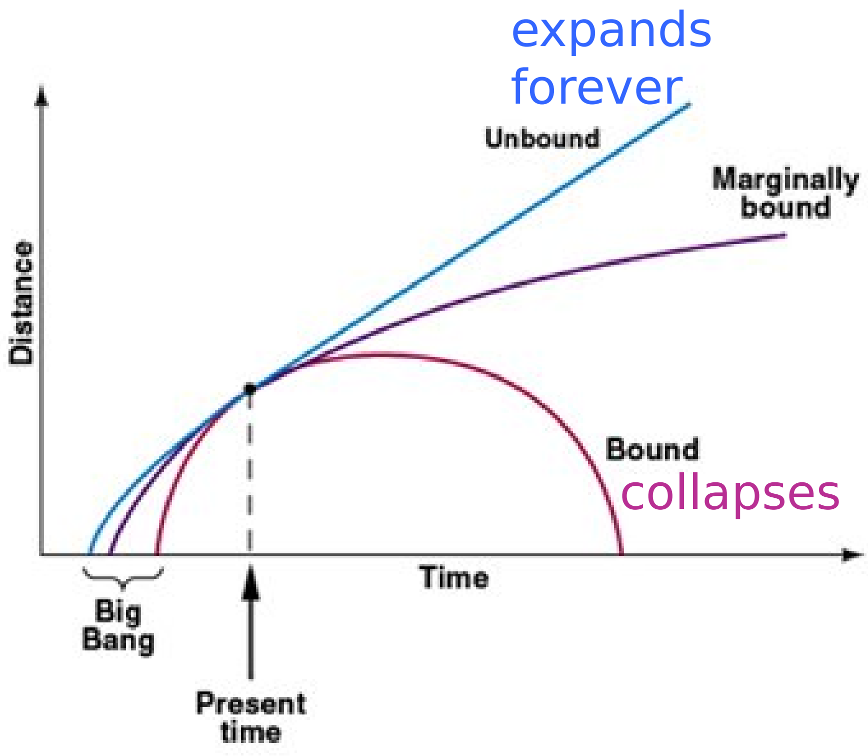
CMB temperature maps



The Fate of the Cosmos

There are two possibilities for the universe in the far future:

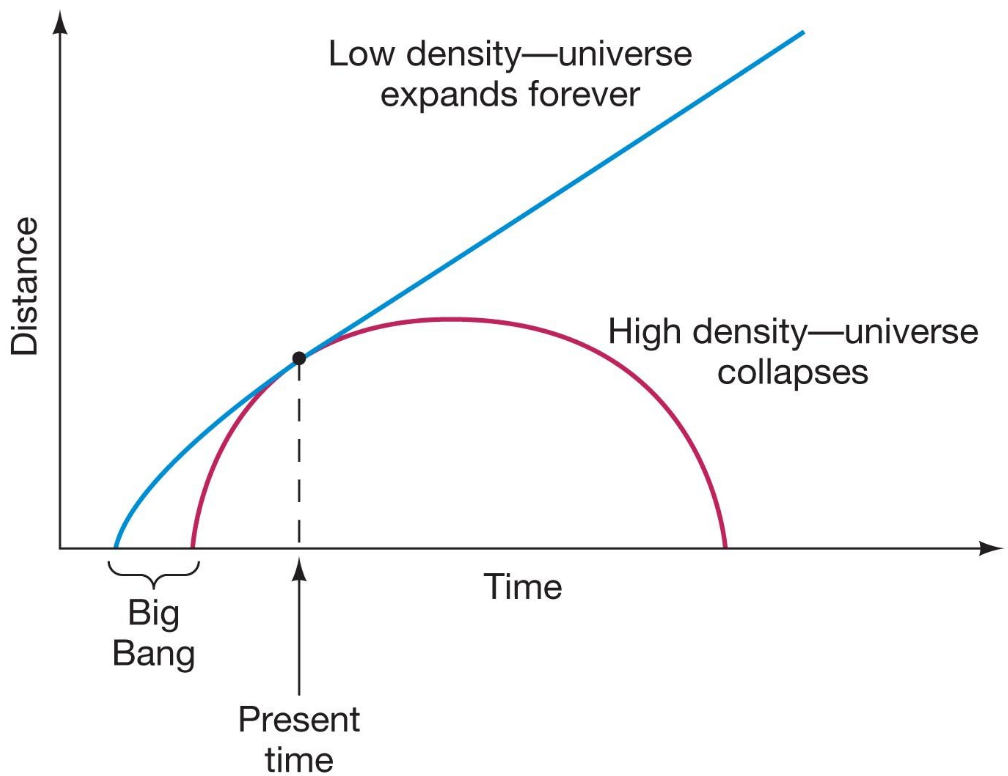
1. Keep expanding forever.
2. Collapse.



Assuming that the only relevant force is gravity, which way the universe goes depends on its density: how much matter there is.

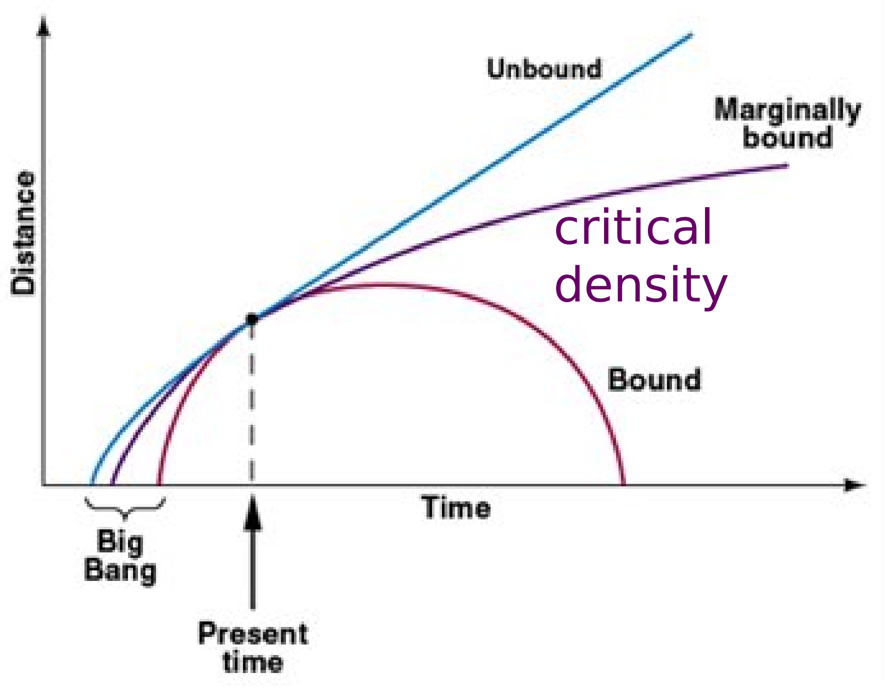
The Fate of the Cosmos

If the density is low, the universe will expand forever. If it is high, the universe will ultimately collapse. This is just a battle between the initial energy of expansion from the Big Bang and gravity.



The Fate of the Cosmos

If the density is low, the universe will expand forever. If it is high, the universe will ultimately collapse. The density that separates these two possibilities is the **critical density**.



What is the critical density?

About 9 x 10^{-27} kg/m^3: five hydrogen atoms per cubic meter, or 0.1 Milky Way galaxies per cubic megaparsec.

Cosmic Dynamics and the Geometry of Space

These possibilities for the future of the universe are related to the **curvature of space**. According to general relativity, space is curved, and the curvature is determined by the **total density** of the universe.

Note that total density includes everything: both matter (including dark matter) and energy, which are related by $E=mc^2$.

Cosmic Dynamics and the Geometry of Space

There are three ways that space can be curved, and they are related to the ultimate fate of the universe:

- Closed – this is the geometry that leads to ultimate collapse
- Flat – this corresponds to the critical density: exactly the right amount of matter and energy to make the universe flat
- Open – expands forever

Cosmic Dynamics and the Geometry of Space

How can we figure out what kind of universe we live in?

Try to measure how much matter and energy there is, and see how it compares to the critical density.

Measure the curvature! The apparent brightness and apparent sizes of distant objects will be different for different geometries.

The Fate of the Cosmos

The ultimate fate of the universe depends on its actual density of matter and energy.

Measurements of luminous matter suggest that the actual density is only a few percent of the critical density.

But – we know there must be large amounts of dark matter. However, the best estimates for the amount of dark matter needed to bind galaxies in clusters, and to explain gravitational lensing, still only bring the observed density up to about 0.3 times the critical density, and it seems very unlikely that there could be enough dark matter to make the density critical.

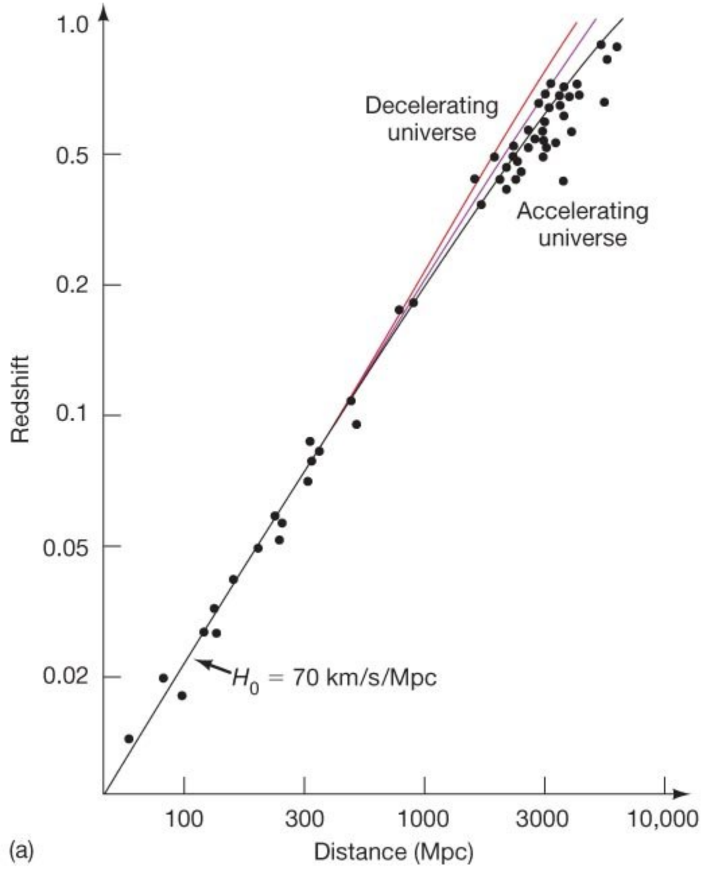
The Fate of the Cosmos

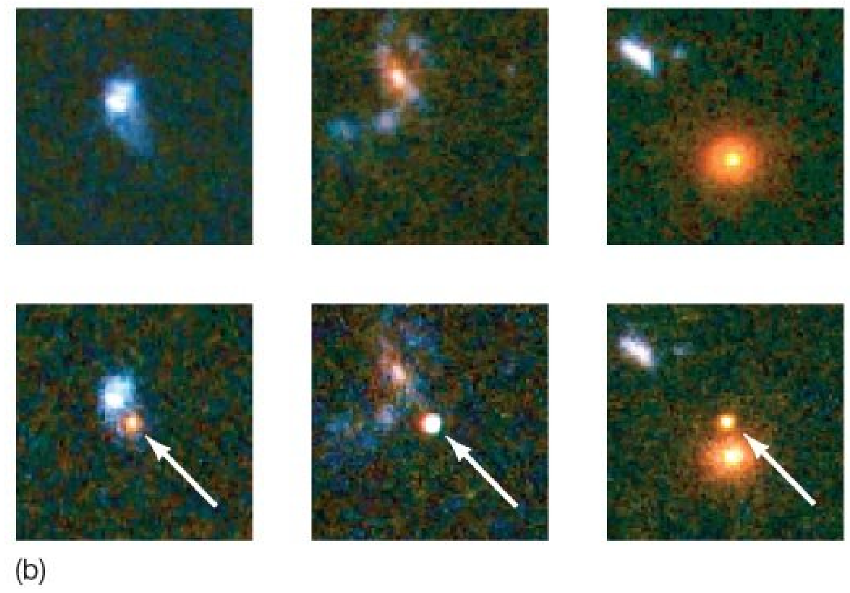
So measurements of the **matter density** suggest that the universe is open, with less than the critical density. But this is not the full story...

Type I supernovae can be used to measure the behavior of distant galaxies.

If the expansion of the universe is decelerating, as it would be if gravity were the only force acting, the farthest galaxies had a more rapid recessional speed in the past, and will appear as though they were receding faster than Hubble’s law would predict.

The Fate of the Cosmos

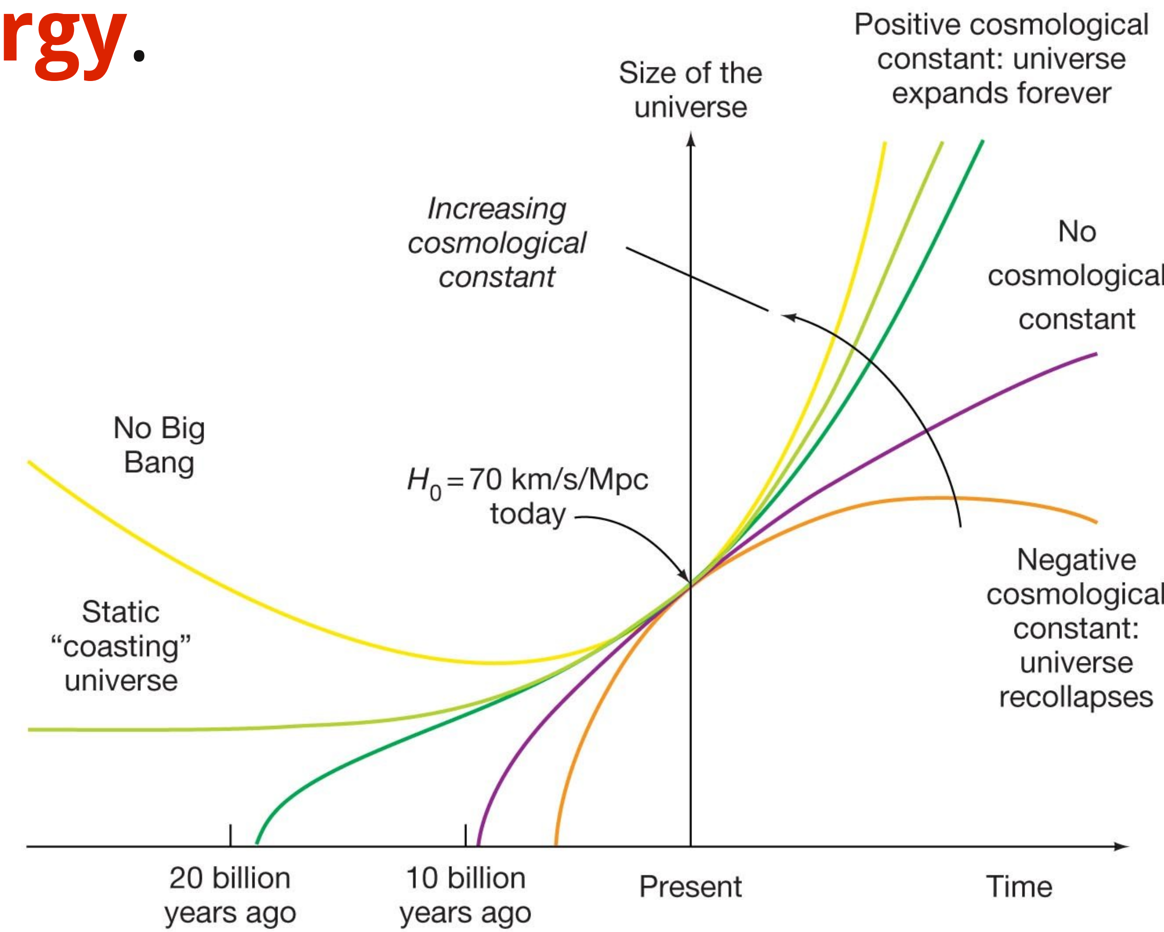




However, when we look at the data, we see that it corresponds not to a decelerating universe, but to an accelerating one!

The Fate of the Cosmos

Possible explanation for the acceleration: Vacuum pressure (cosmological constant), also called **dark energy**.



The Nobel Prize in Physics 2011
Saul Perlmutter, Brian P. Schmidt, Adam G. Riess

Photo: Roy Kaltschmidt. Courtesy: Lawrence Berkeley National Laboratory

Saul Perlmutter

Photo: Belinda Pratten, Australian National University

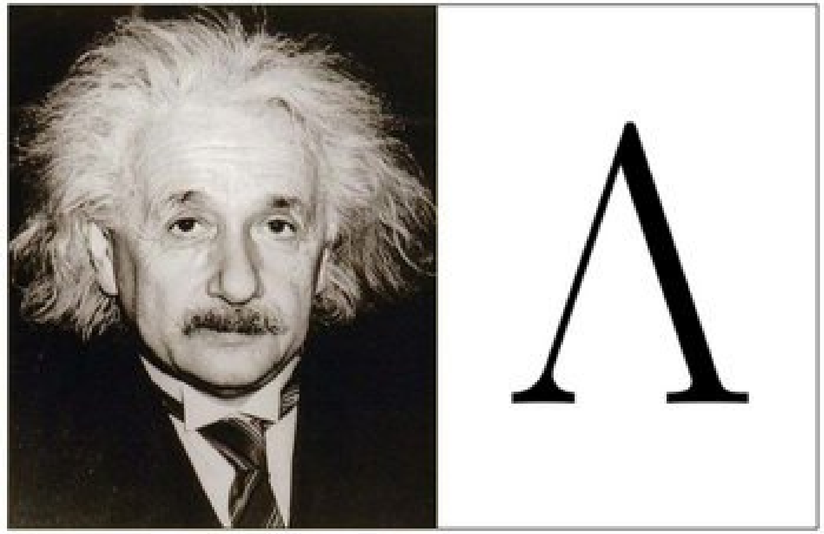
Brian P. Schmidt

Photo: Homewood Photography

Adam G. Riess

The Nobel Prize in Physics 2011 was divided, one half awarded to Saul Perlmutter, the other half jointly to Brian P. Schmidt and Adam G. Riess *"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"*.

Einstein and the Cosmological Constant



The cosmological constant is symbolized with the capital Greek letter lambda.

1915: Einstein's general theory of relativity predicts expanding universe…

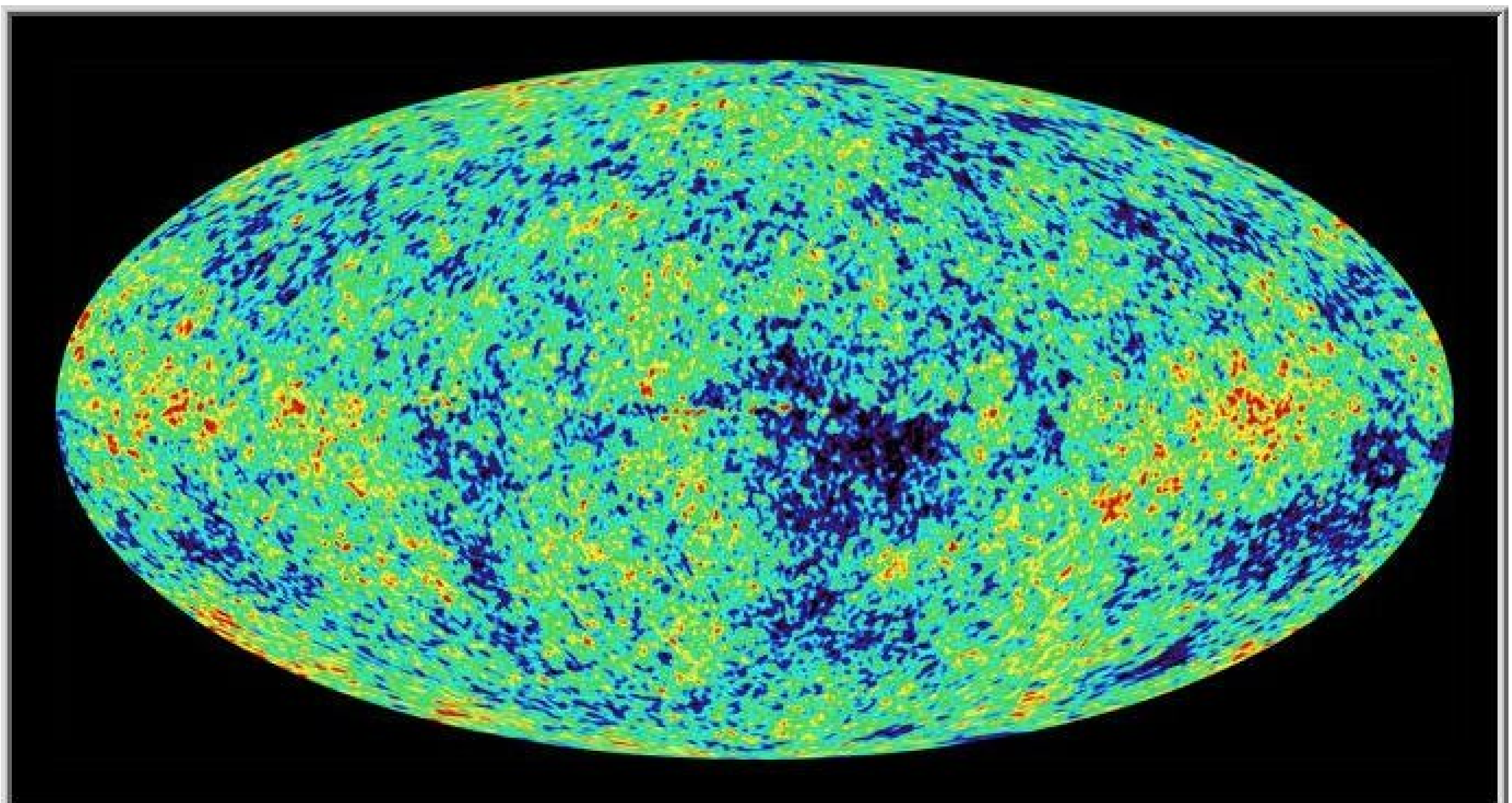
…but Einstein doesn't believe it, adds "cosmological constant" to make universe static

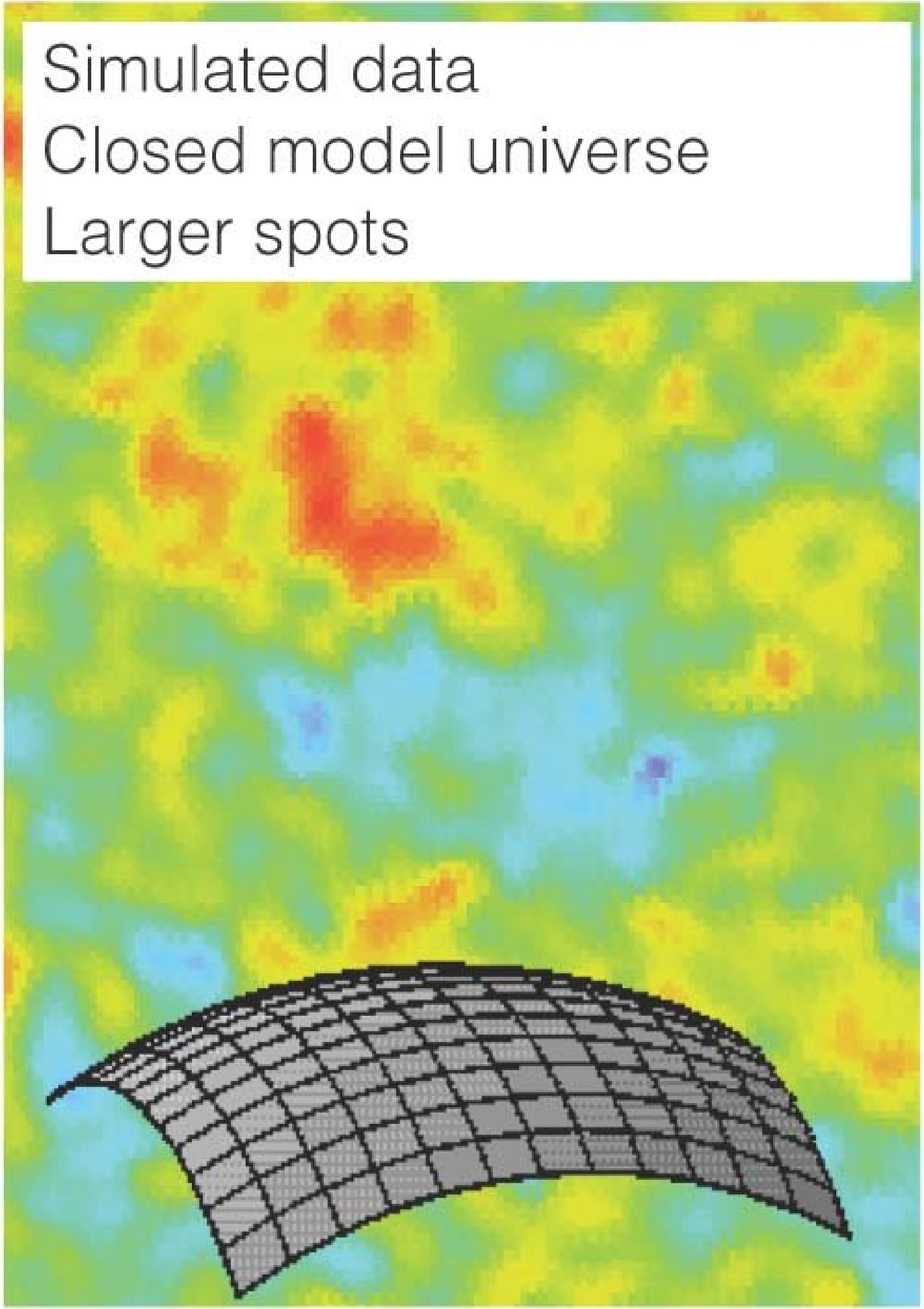
"Einstein's biggest blunder"

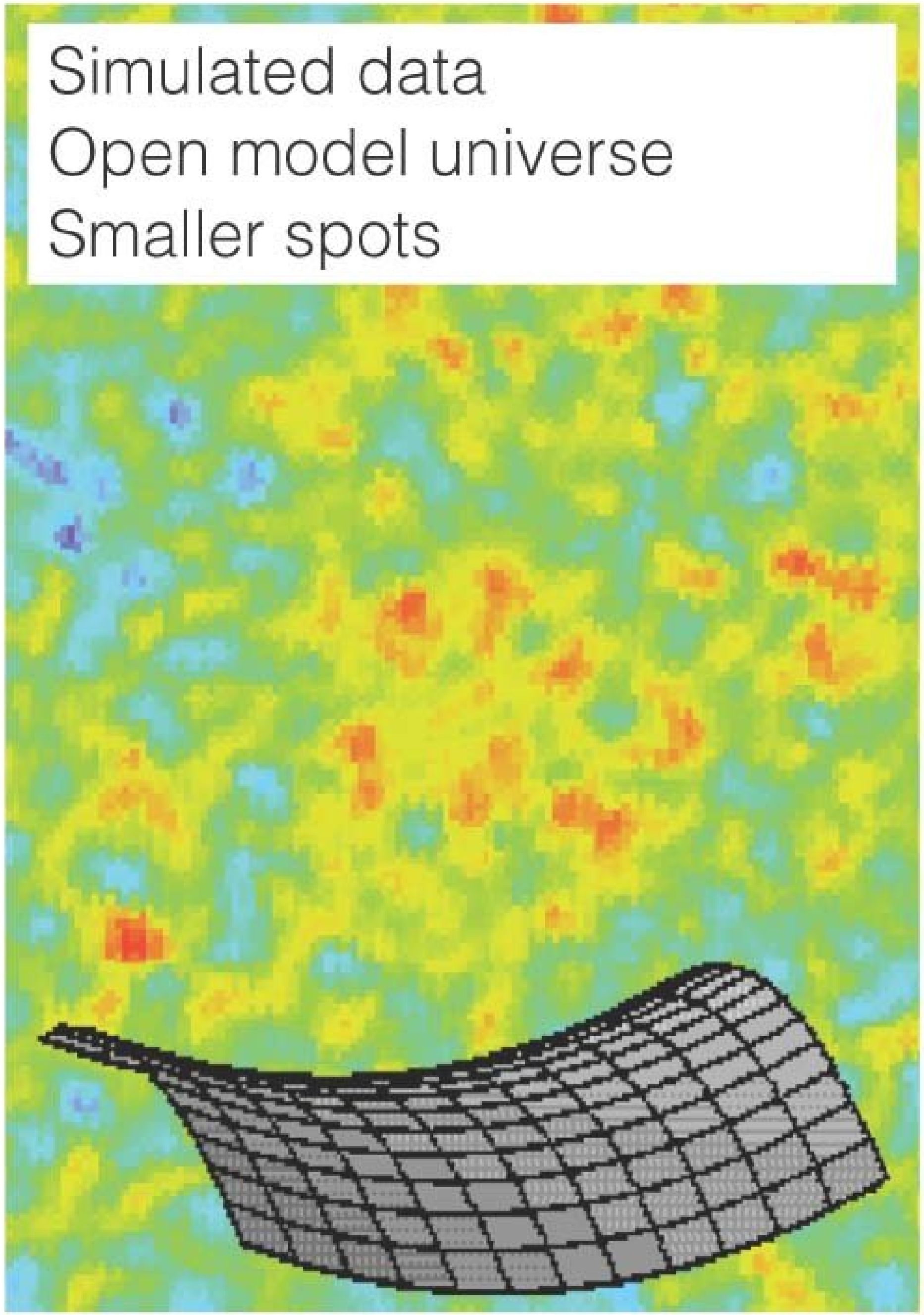
But it seems we need it after all!

CMB and space curvature

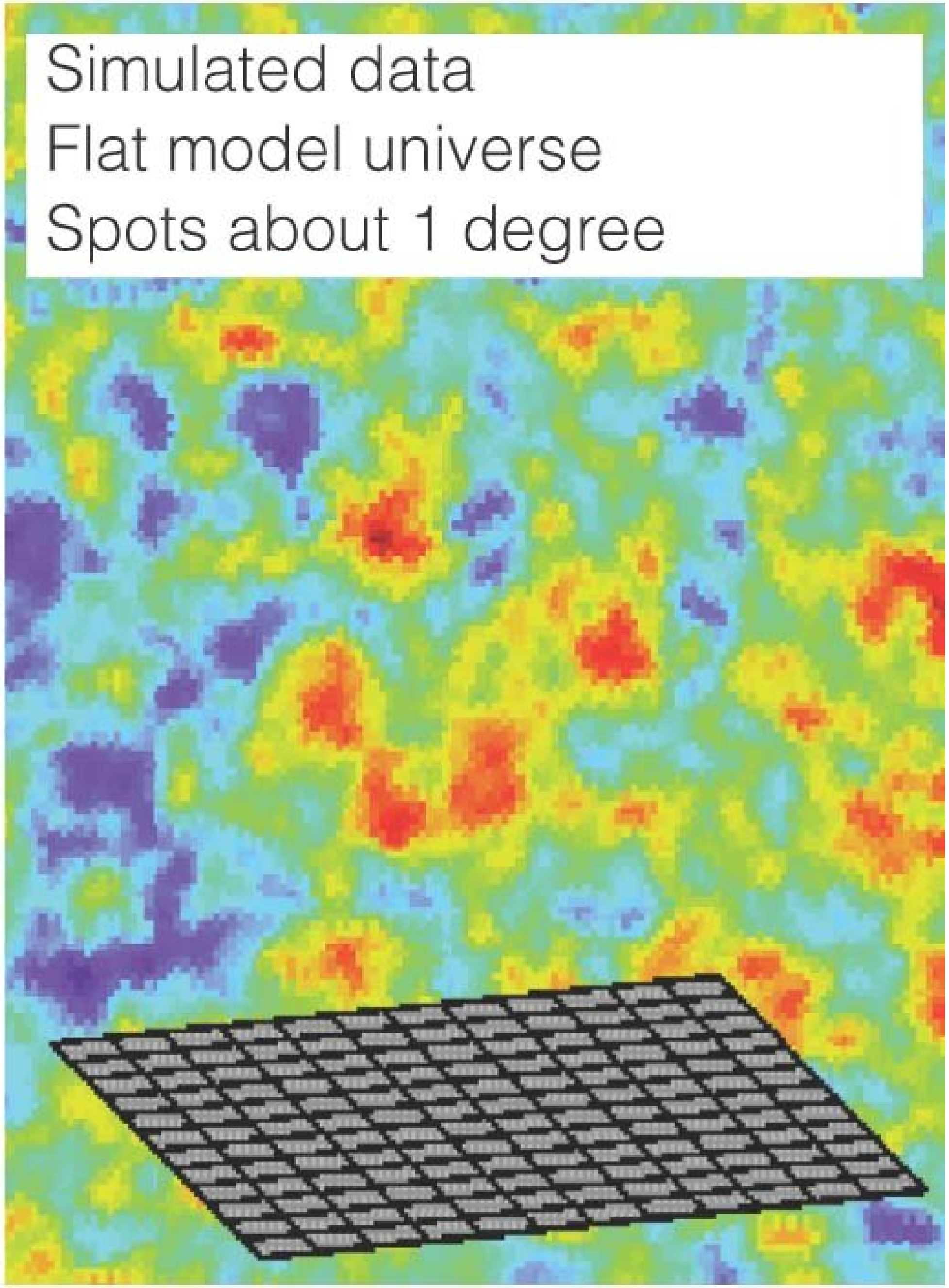
The size of the hotter and cooler spots depends on the geometry of the universe.




Simulated data
Closed model universe
Larger spots


Simulated data
Open model universe
Smaller spots

Our observations match the flat model universe – the universe is flat!

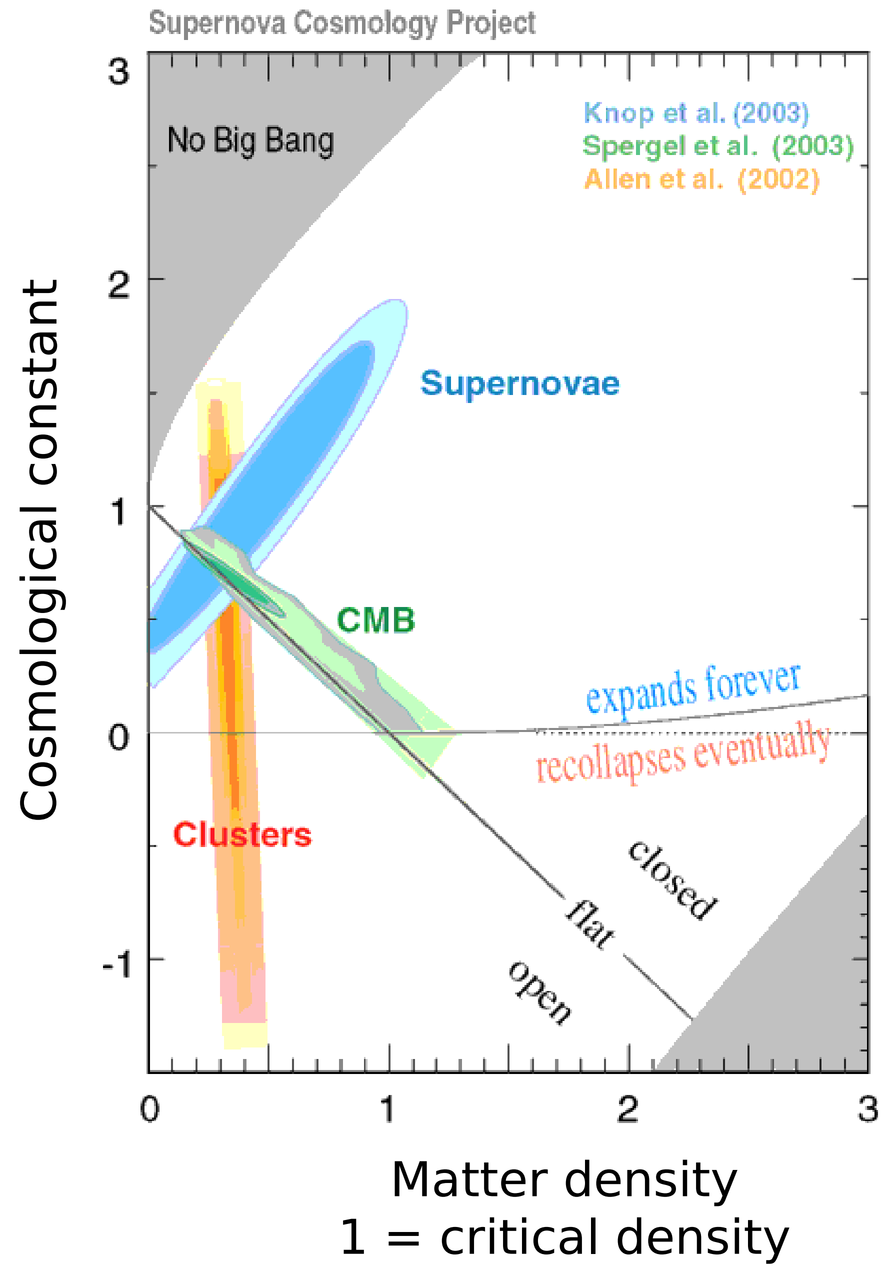


The Contents of the Universe

Observations of the cosmic microwave background tell us that the universe is flat: the total density is equal to the critical density.

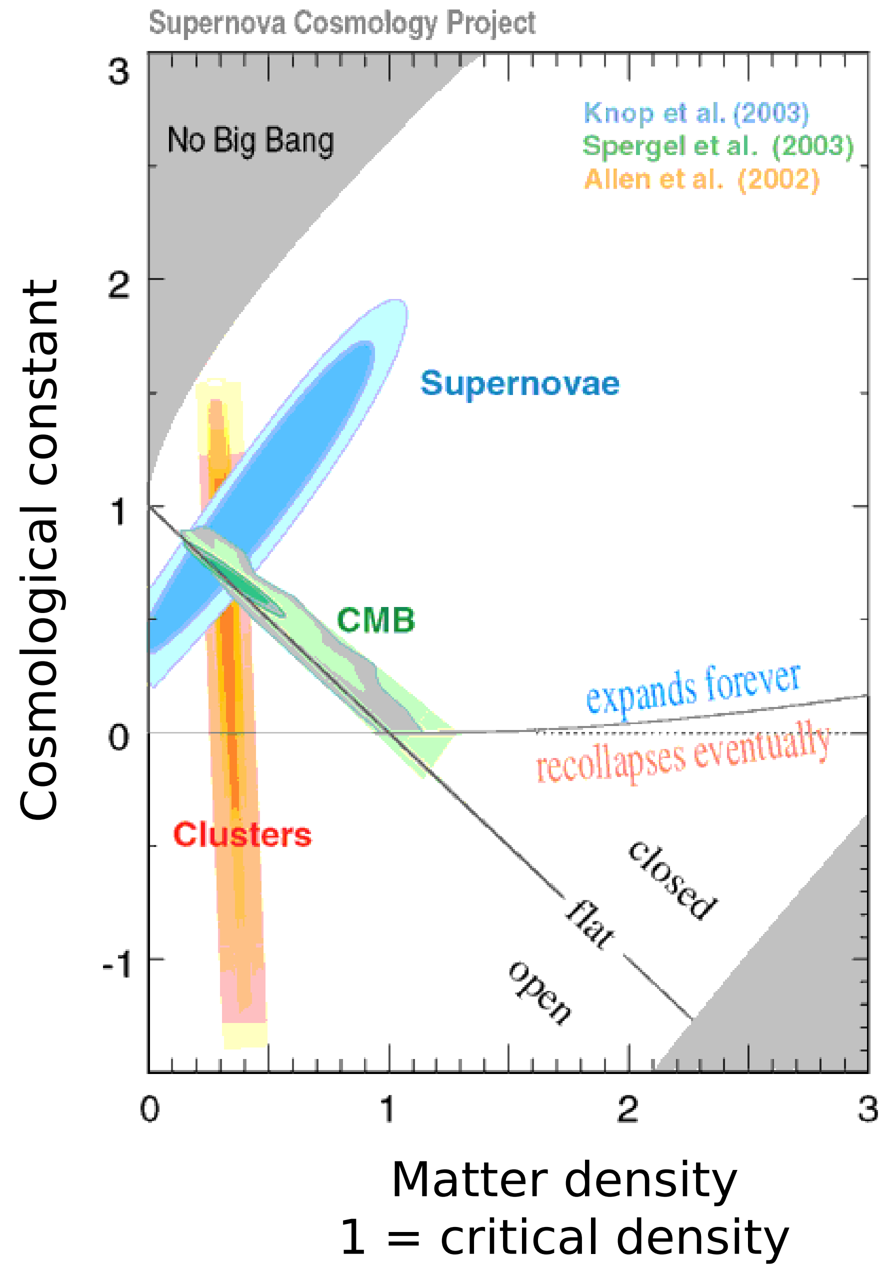
Type Ia supernovae tell us that there is a cosmological constant and the universe is accelerating.

Counting galaxy clusters tells us that the total matter density is low, about 30% of the critical density.



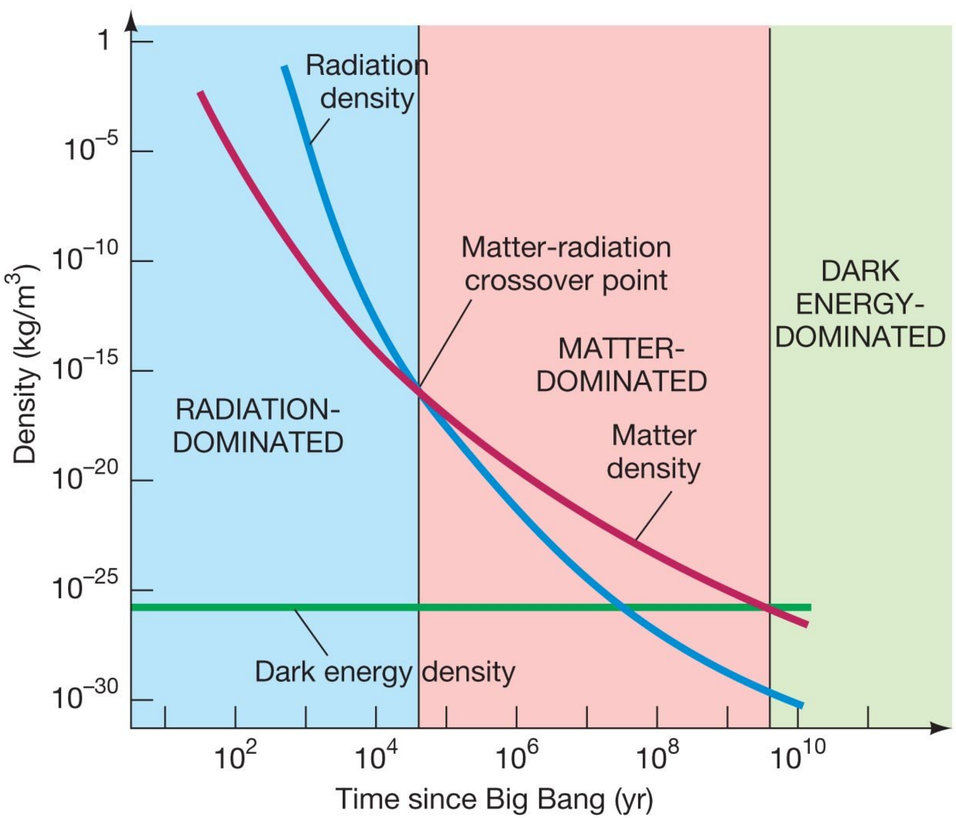
The Contents of the Universe

Combining all these measurements, we find that the universe is flat with density equal to the critical density. About 70% of the energy in the universe is dark energy, and about 30% is matter. Most of the matter is dark.



The Content of the Universe and the Fate of the Cosmos

What does this mean for the ultimate fate of the universe?



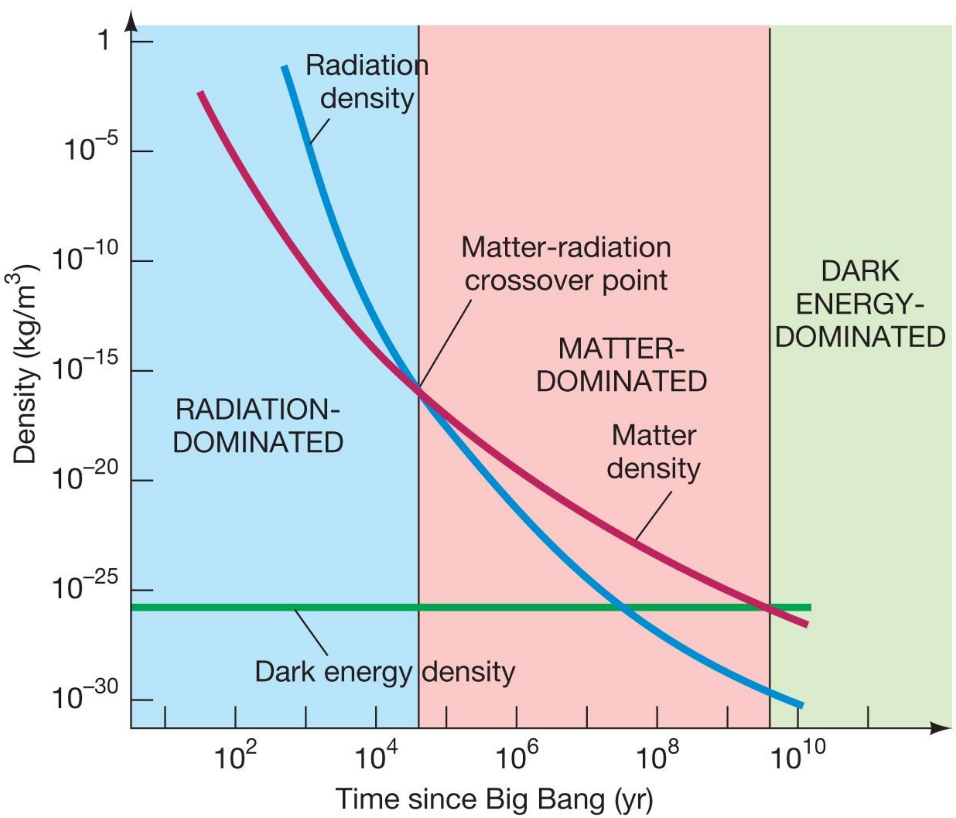
The total energy of the universe consists of matter, radiation, and dark energy.

At early times, radiation dominated, then matter took over.

The matter density decreases as the universe expands, but the density of dark energy is constant.

The Content of the Universe and the Fate of the Cosmos

What does this mean for the ultimate fate of the universe?

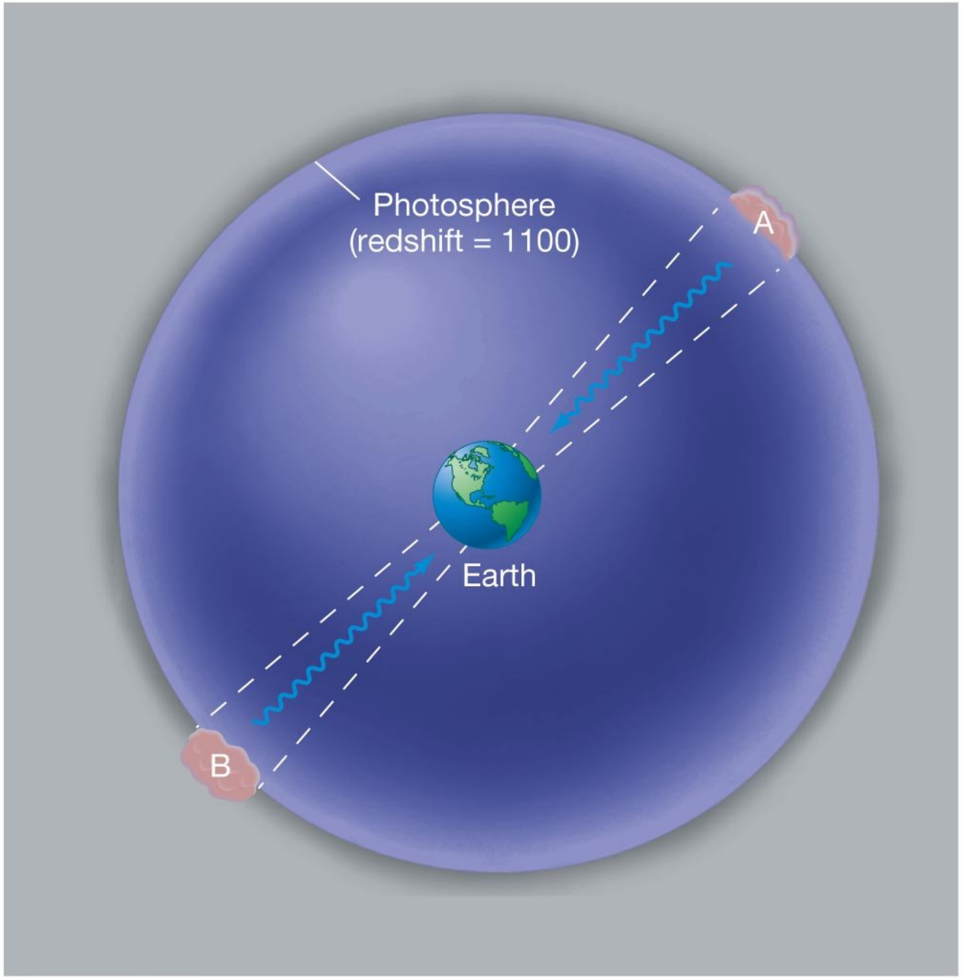


Since the density of dark energy is constant while the matter density decreases, dark energy will eventually take over.

This has already happened.

The universe is dominated by dark energy and will expand forever.

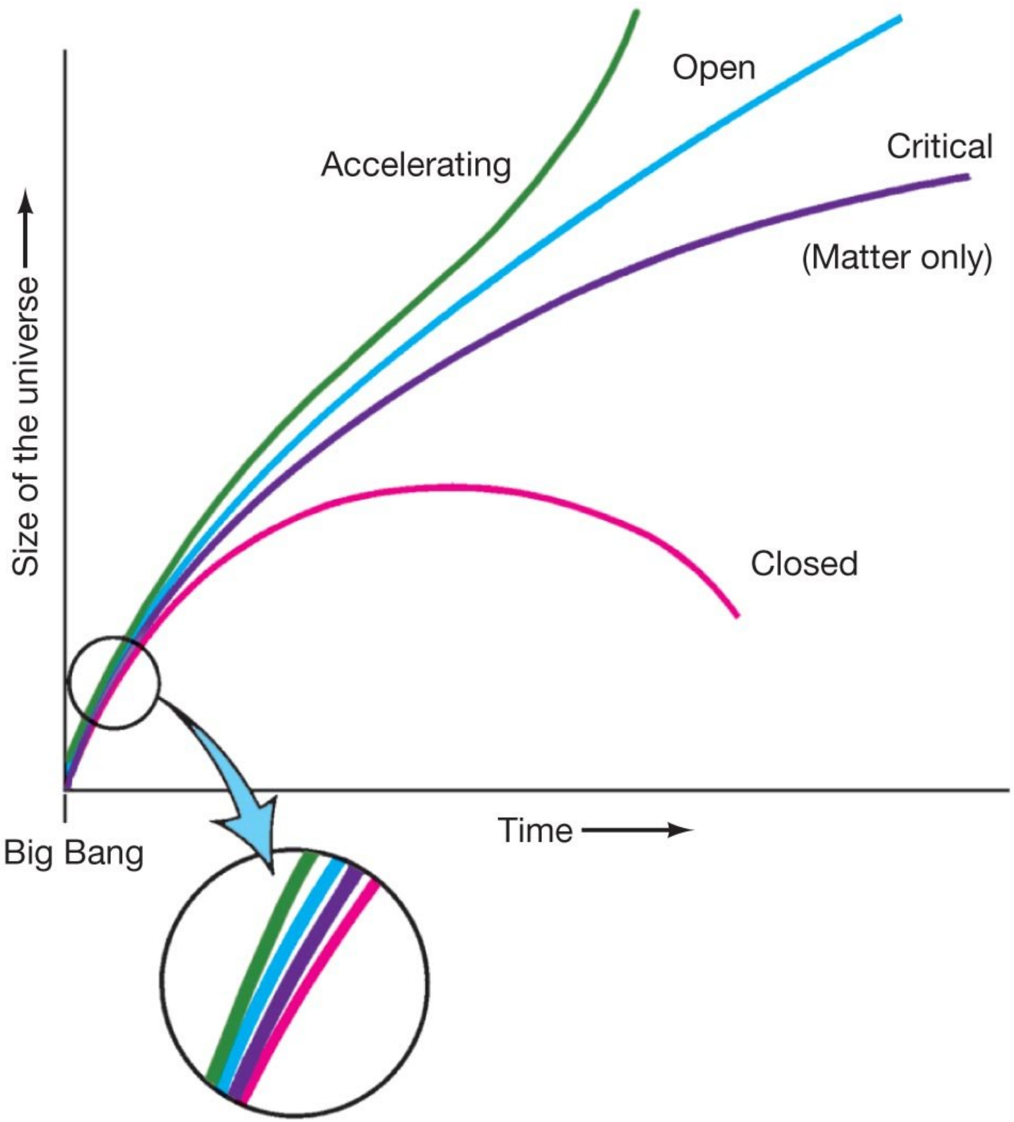
Problems with the Standard Model



We can see both A and B, but A and B can't see each other because light hasn't had time to travel from A to B. A and B are not in **causal contact**.

The horizon problem: Cosmic background radiation appears the same in diametrically opposite directions from Earth, even though there hasn't been enough time since the Big Bang for these regions to be in thermal contact.

Problems with the Standard Model

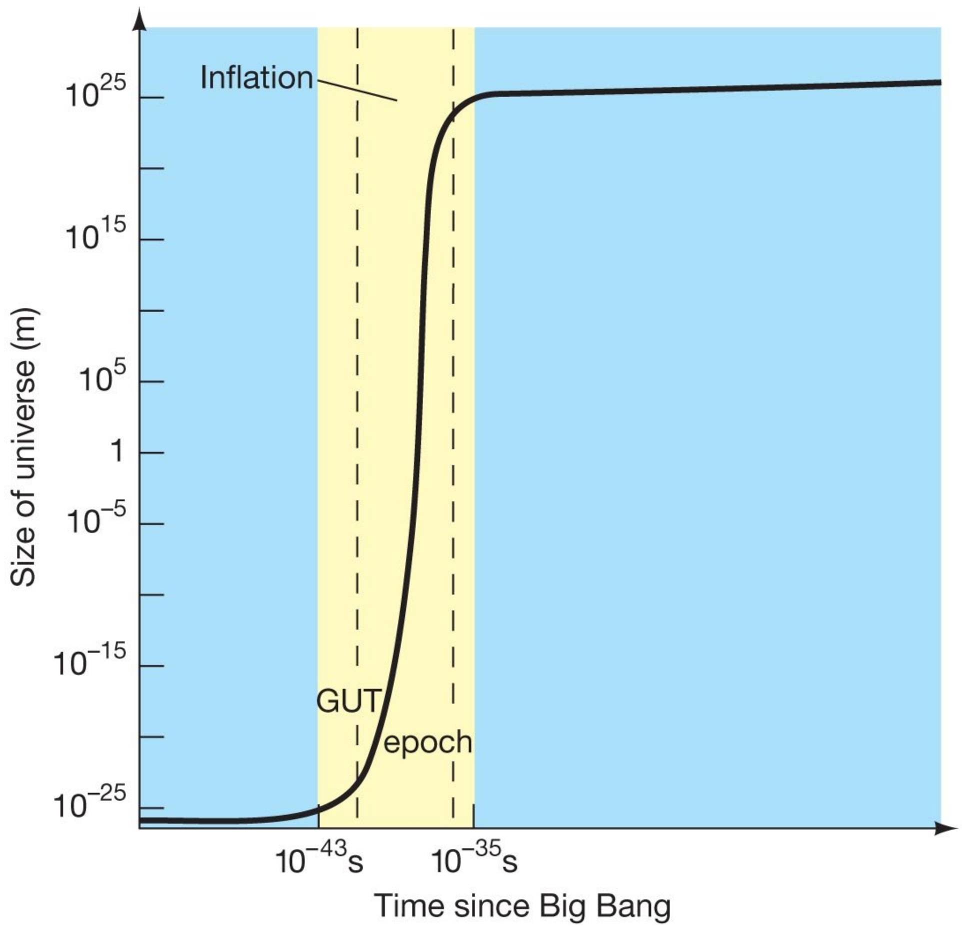


The flatness problem:

In order for the universe to have survived this long, its density in the early stages must have differed from the critical density by no more than 1 part in 10^{15}.

Why?

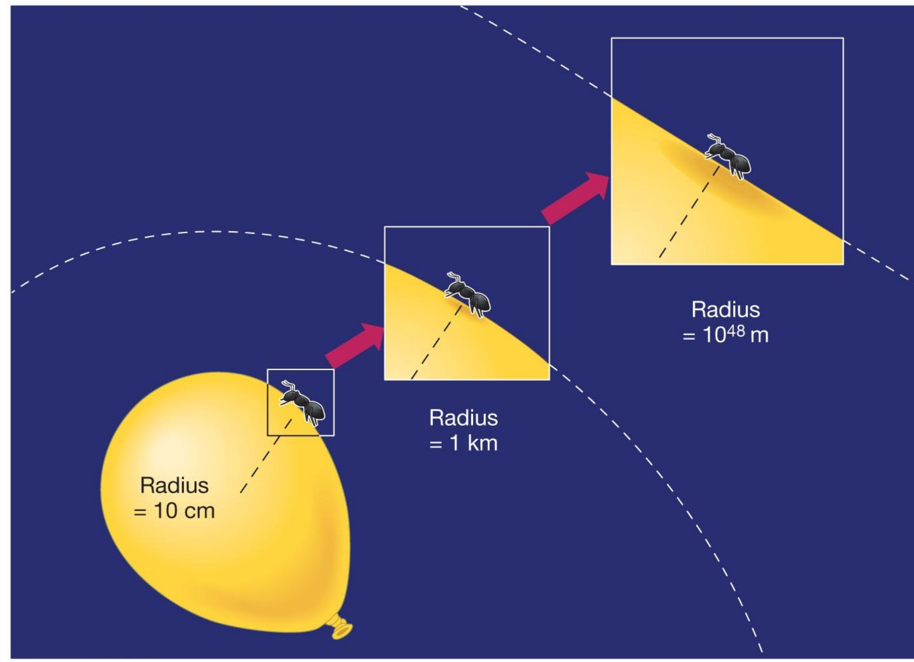
Possible Solution: Cosmic Inflation



Between 10^{-35} s and 10^{-32} s after the Big Bang, some parts of the universe may have found themselves in an extreme period of inflation, as shown on the graph. Between 10^{-35} s and 10^{-32} s, the size of this part of the universe expanded by a factor of 10^{50}!

Solutions to the Horizon and Flatness Problems

Solution to the horizon problem: before inflation, the part of the universe that inflated was small enough to be in causal contact and so was all at the same temperature.



Solution to the flatness problem: Inflation flattens space

Recap: The Standard Model

The universe began with the Big Bang: a point of infinite density and temperature, which then expanded and cooled.

Evidence: the observed expansion of the universe, the leftover light from the Big Bang (the cosmic microwave background), the agreement between independent measurements of the age of the universe.

The universe is flat, containing radiation, (mostly dark) matter, and dark energy. Evidence from the size of the temperature fluctuations in the cosmic microwave background, from Type Ia supernovae, and from counting galaxy clusters.