Announcements

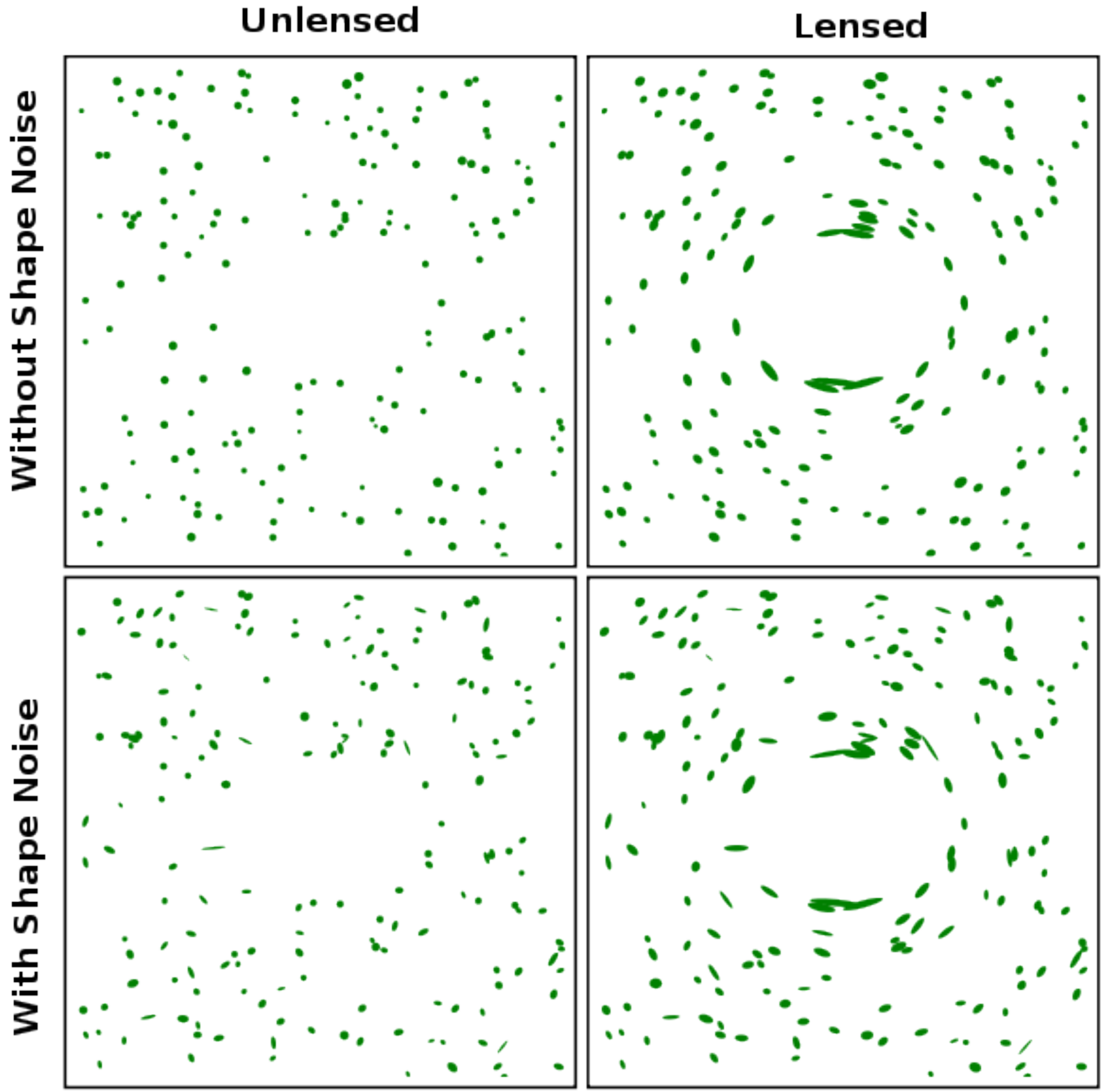
- **Quiz 12** on Chapter 16 due tonight
- Quiz 13 on Chapter 17 due next Monday, last regular quiz
- Midterm grades by Wednesday
- Today: Finish Chapter 16, start Chapter 17: Cosmology

Gravitational Lensing

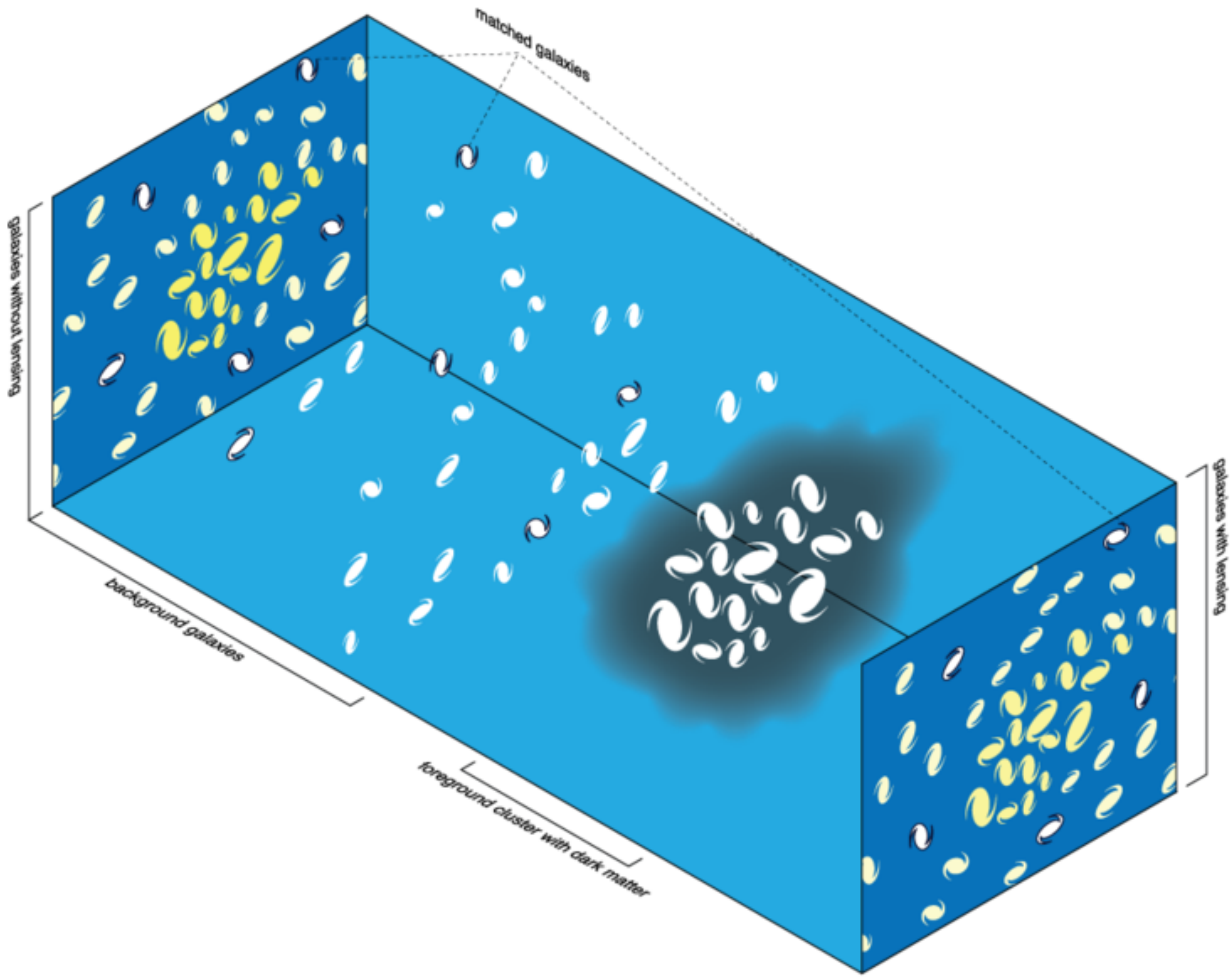
- Last week we discussed **strong gravitational lensing** – strong because it is quite obvious, with multiple and/or strongly distorted images of background objects
- However, most galaxies are not lensed so strongly – instead they are only slightly distorted by matter (particularly dark matter) in the foreground
- If we can measure this very slight distortion, we can map the dark matter
- This slight distortion is called **weak lensing**

Weak Gravitational Lensing

- The distortion changes the shape of galaxies, so that they “wrap” around the foreground dark matter
- This picture is exaggerated!



Weak Gravitational Lensing



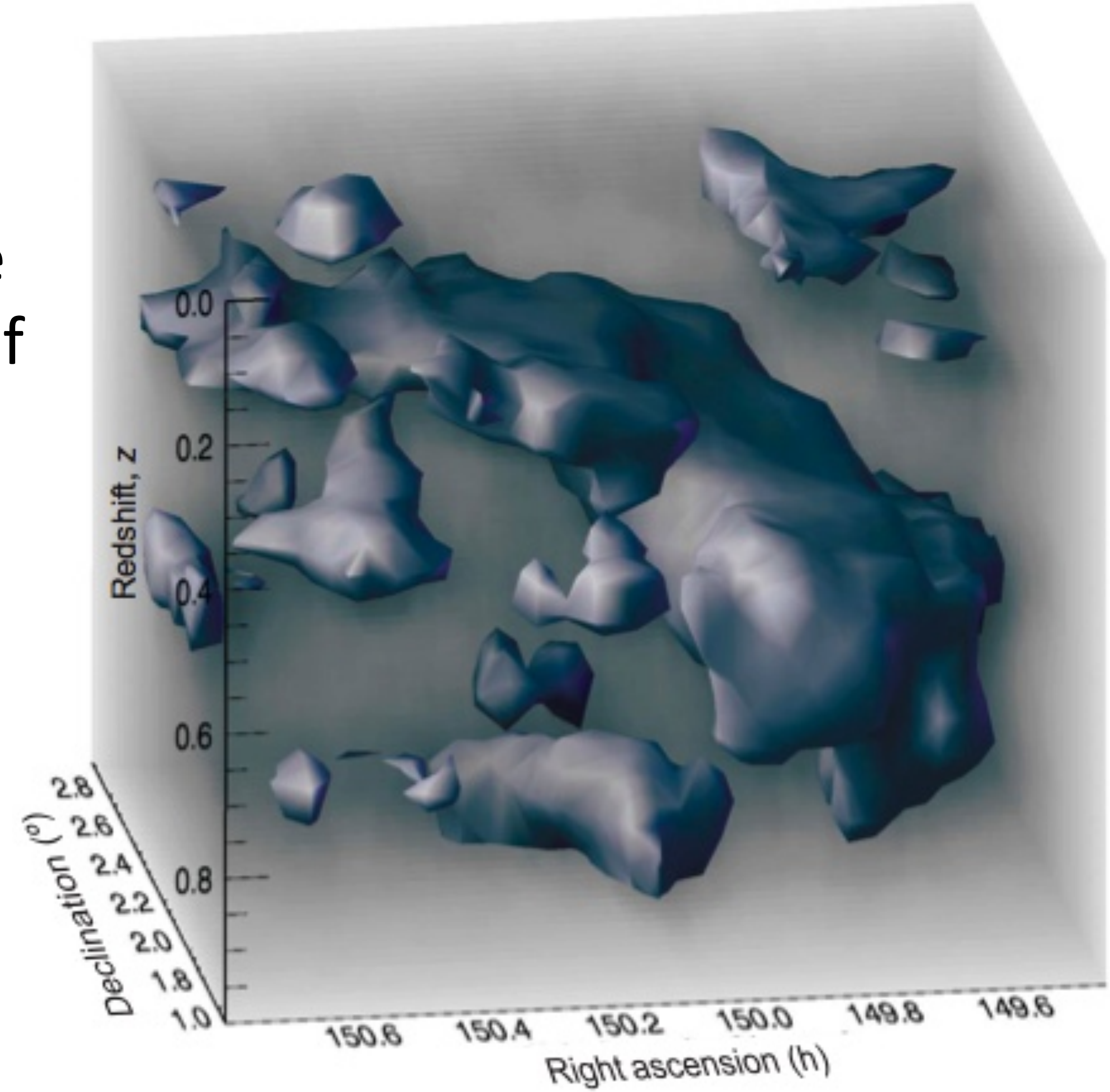
Weak Gravitational Lensing

- Problem: we don't know what shape the galaxies were before they were distorted!
- So, to measure the distortion, we need to measure a lot of galaxies and assume that they are randomly oriented
- This turns out to be extremely hard! Some progress, but still highly uncertain

Weak Gravitational Lensing

By looking at galaxies and their distortion at different redshifts, we can make a 3-d map of the dark matter

Here is one example from the COSMOS survey



Galaxies and Dark Matter: Summary

- Galaxy masses can be determined by rotation curves, and galaxy cluster masses from measuring velocities of galaxies
- All measures show that a large amount of dark matter must exist
- Large galaxies probably formed from the merger of smaller ones
- Collisions are important to the evolution of galaxies
- Merger of spiral galaxies probably results in an elliptical

Galaxies and Dark Matter: Summary

- Quasars, active galaxies, and normal galaxies may represent an evolutionary sequence

- Galaxy clusters are found in larger groups called superclusters

- The universe has structure up to about 200 Mpc; beyond that, there is no sign of it

- Gravitational lensing can be used to map the distribution of dark matter

Astronomy 103

Cosmology

Please read chapter 17

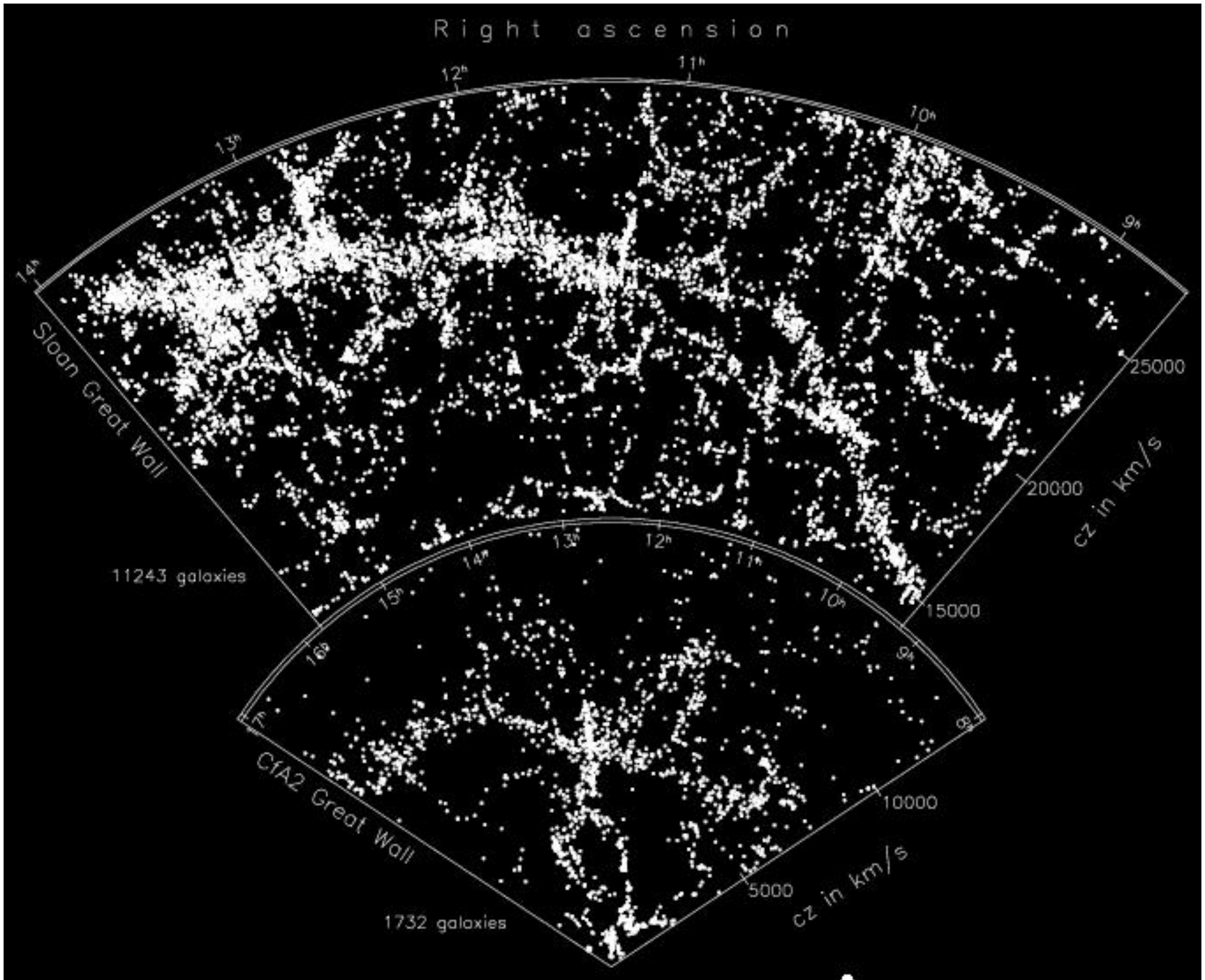
The Universe on Large Scales

- When we look at our local part of the universe, it's clumpy – matter is distributed in stars, galaxies, clusters, superclusters, and filaments, with empty voids between

- But on the largest scales, the universe is more or less uniform – looks about the same everywhere

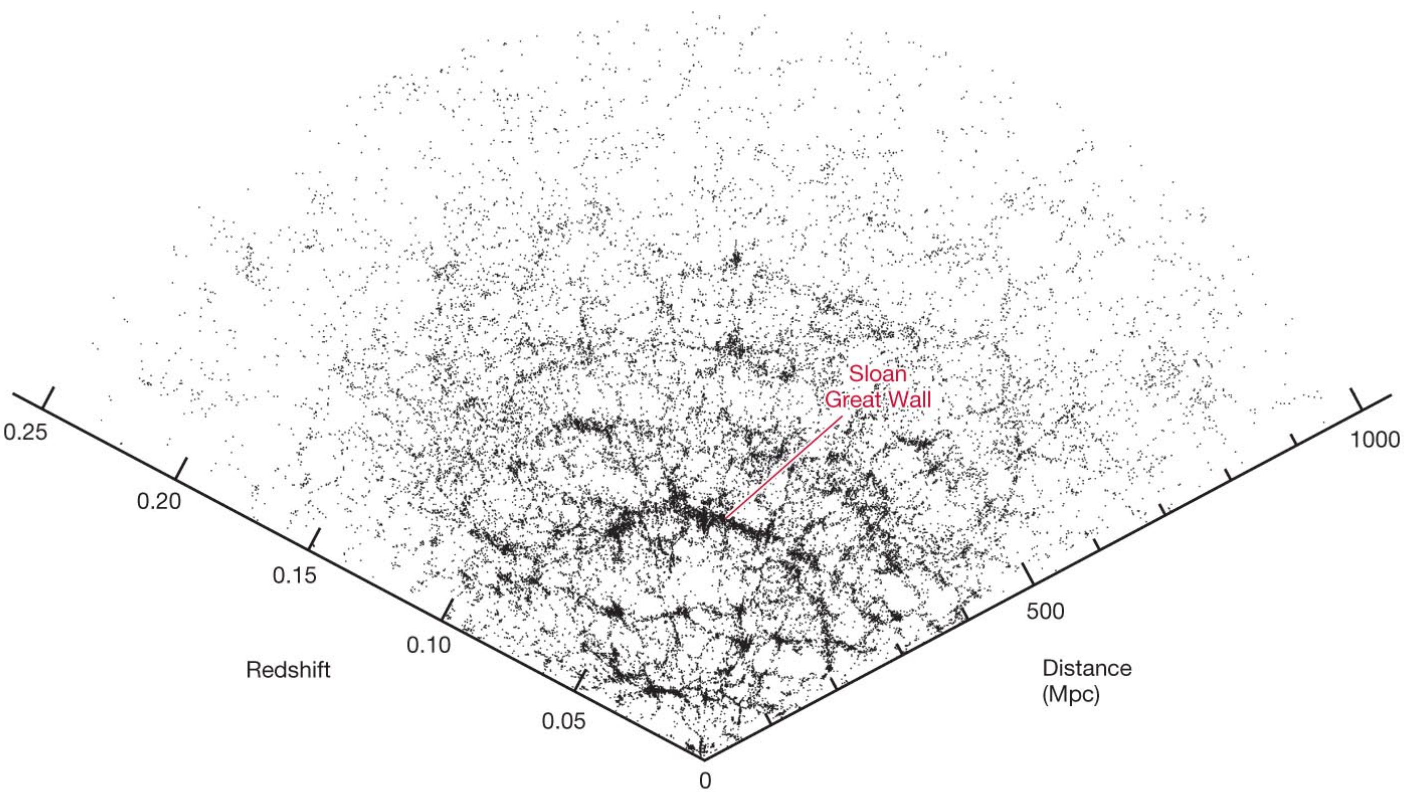
- This happens on a scale around 200 megaparsecs: every 200 Mpc box looks about the same

The Universe on Large Scales



The Universe on the Largest Scales

This galaxy map shows the largest structure known in the universe, the Sloan Great Wall. No structure larger than 300 Mpc is seen.



The Universe on the Largest Scales

Therefore, the Universe is homogenous (any 200-Mpc-square block appears much like any other).

The universe also appears to be isotropic – the same in all directions.

The **cosmological principle** is the assumption that the Universe is isotropic and homogeneous.

Homogeneity means the universe has no edge: It looks the same everywhere

Isotropy means the universe has no center: it looks the same in every direction

The Universe on the Largest Scales

The **cosmological principle** is the assumption that the Universe is isotropic and homogeneous.

Homogeneity means the universe has no edge: it looks the same everywhere

Isotropy means the universe has no center: it looks the same in every direction

The cosmological principle is also called the **Copernican principle** – Copernicus showed that we aren't at the center of the solar system, and the cosmological principle says we aren't at the center of the universe. It has no center.

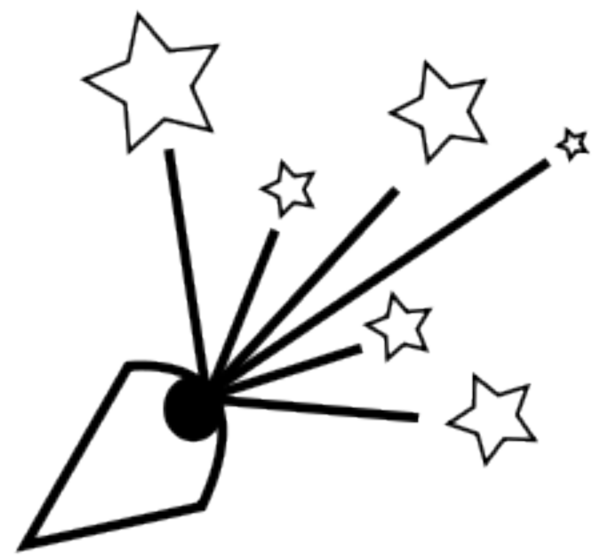
Olber's Paradox

- The main difference between night and day is that it is dark at night – but why?

- If the universe is infinite and eternal, the sky can't be dark at night – **Olber's paradox**

- In every direction we look, we'll eventually see a star

- The sky should be as bright as the surface of a star!



Olber’s Paradox

So why is the sky dark?

Because the universe hasn’t existed forever, and light from the greatest distances hasn’t had time to reach us yet.

Edgar Allen Poe in 1848: “Were the succession of stars endless, then the background of the sky would present us an [sic] uniform density ...since there could be absolutely no point, in all that background, at which would not exist a star. The only mode, therefore, in which, under such a state of affairs, we could comprehend the voids which our telescopes find in innumerable directions, would be by supposing the distance of the invisible background so immense that no ray from it has yet been able to reach us at all.”

Hubble's Law Redux

- Remember that Hubble's law says that galaxies are moving away from us at a speed given by

$$V = H \times d$$

  where H is Hubble's constant.

- So at a very early time in the universe, those galaxies must all have been in the same place

The Expanding Universe

If this expansion is extrapolated backward in time, all galaxies are seen to originate from a single point in an event called the Big Bang.

So, where was the Big Bang?

It was everywhere!

No matter where in the universe we are, we will measure the same relation between recessional velocity and distance, with the same Hubble constant.

The Expanding Universe

One hour later….

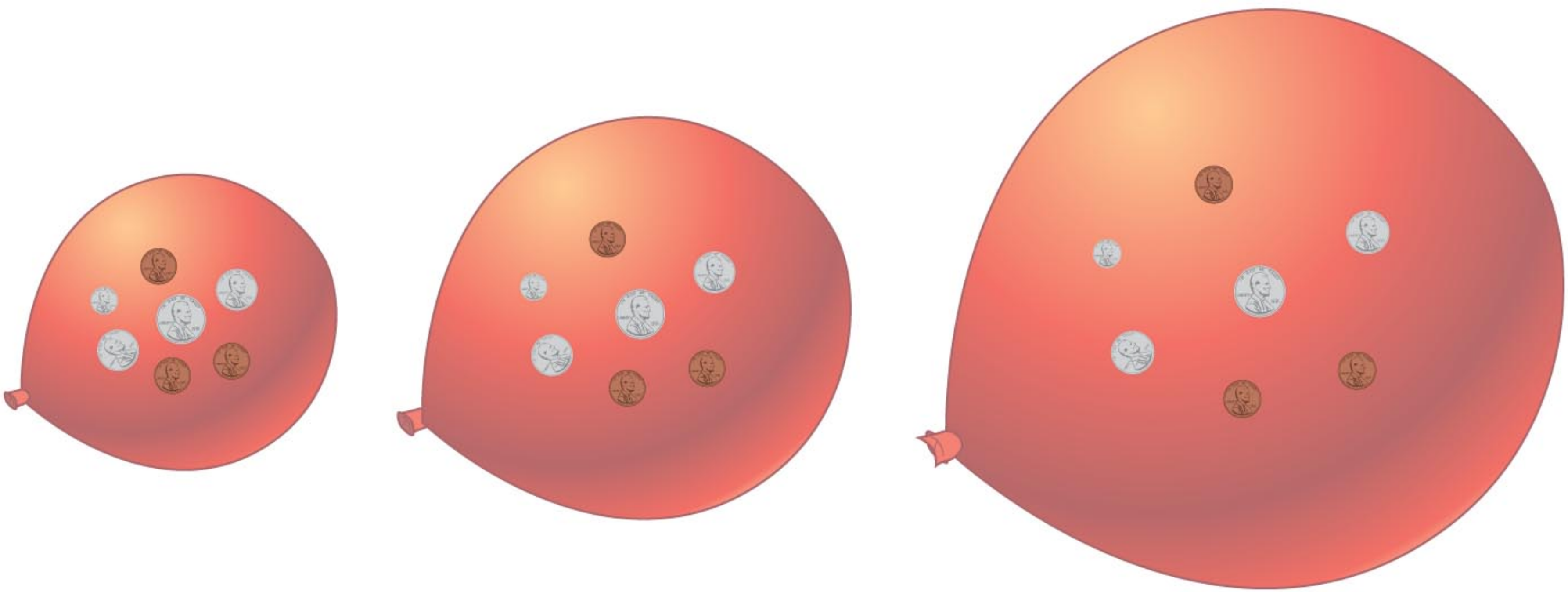
Seattle moves 2000 miles in an hour: recessional velocity is 2000 mph

Atlanta moves 700 miles in an hour: recessional velocity is 700 mph

Each point moves away from every other point, and speed at which it recedes is proportional to its distance. You'll observe this no matter where you are.

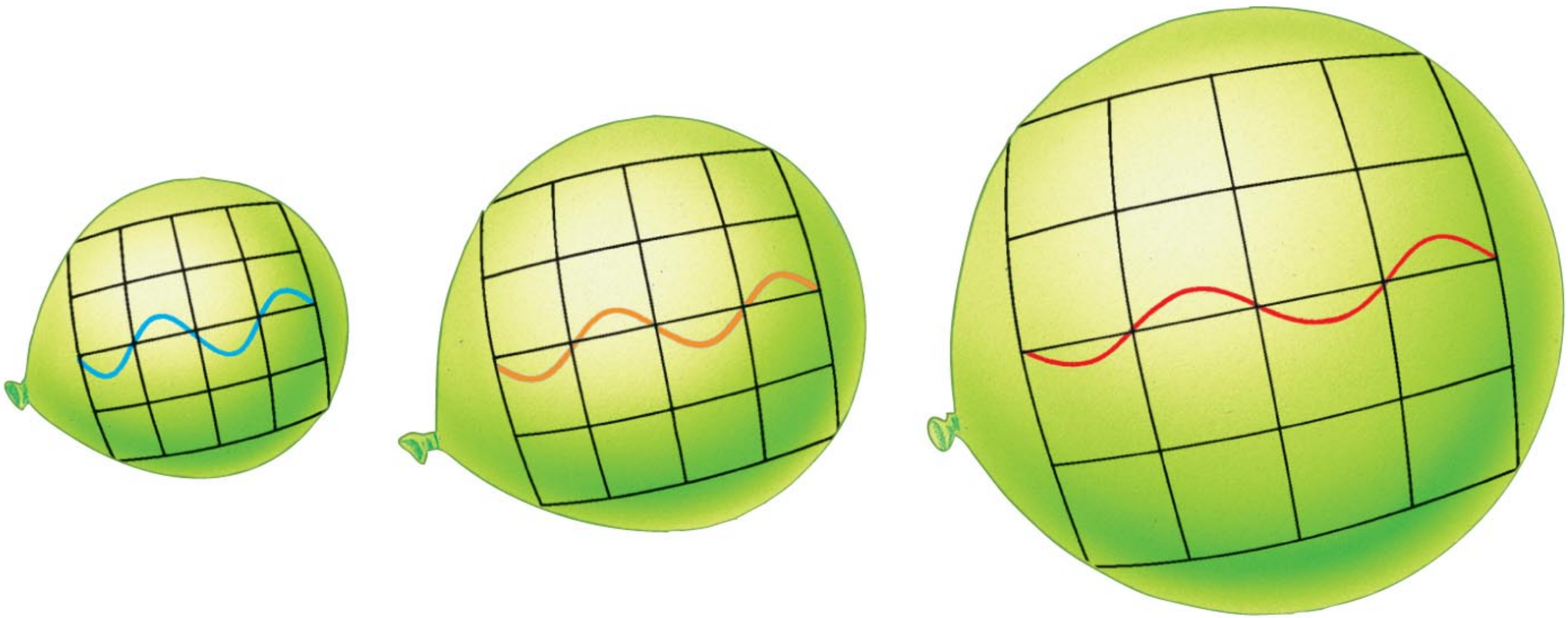
The Expanding Universe

The expanding universe in two dimensions: imagine a balloon with coins stuck to it. As we blow up the balloon, the coins all move farther and farther apart. There is, on the surface of the balloon, no "center" of expansion.



The Expanding Universe

The same analogy can be used to explain the cosmological redshift: the wavelength of light is stretched as the universe expands.



How old is the universe?

There are several ways of determining the time that the universe (at least the part of it we can see) began.

First, by using Hubble's law, we can find the time at which all the galaxies we see were at the same place.

We have already found that galaxies are moving away from us faster the farther away they are:

$$v = H \times d$$

So, how long did it take the galaxies to get to where they are now?

$$\text{time} = \frac{\text{distance}}{\text{velocity}} = \frac{\text{distance}}{H_0 \times \text{distance}} = \frac{1}{H_0}.$$

Using *H* = 70 km/s/Mpc, we find that this time is about 14 billion years.

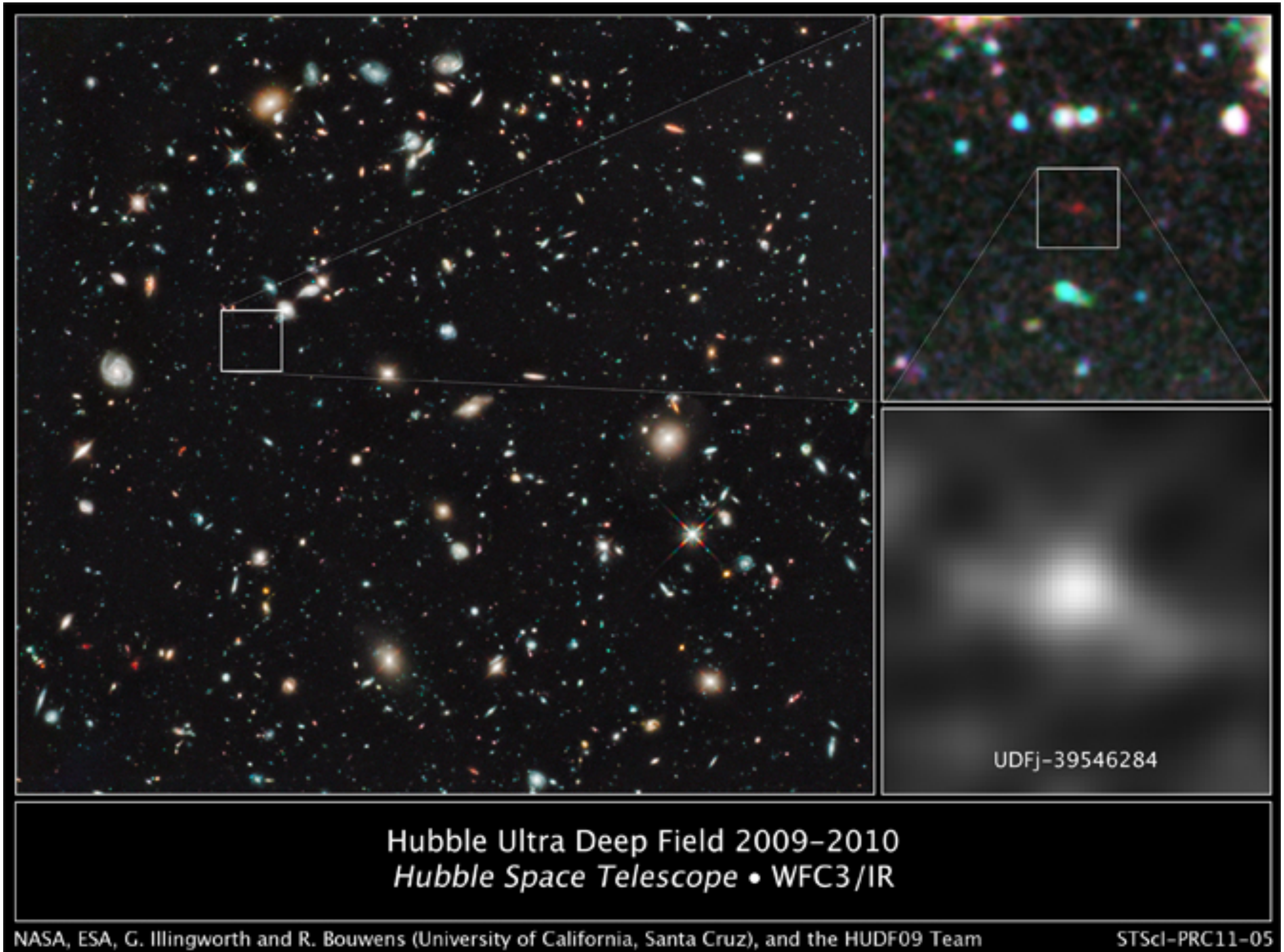
Note that Hubble's law is the same no matter who is making the measurements and where they are made.

Age of the Universe

- So the universe is about 14 billion years old

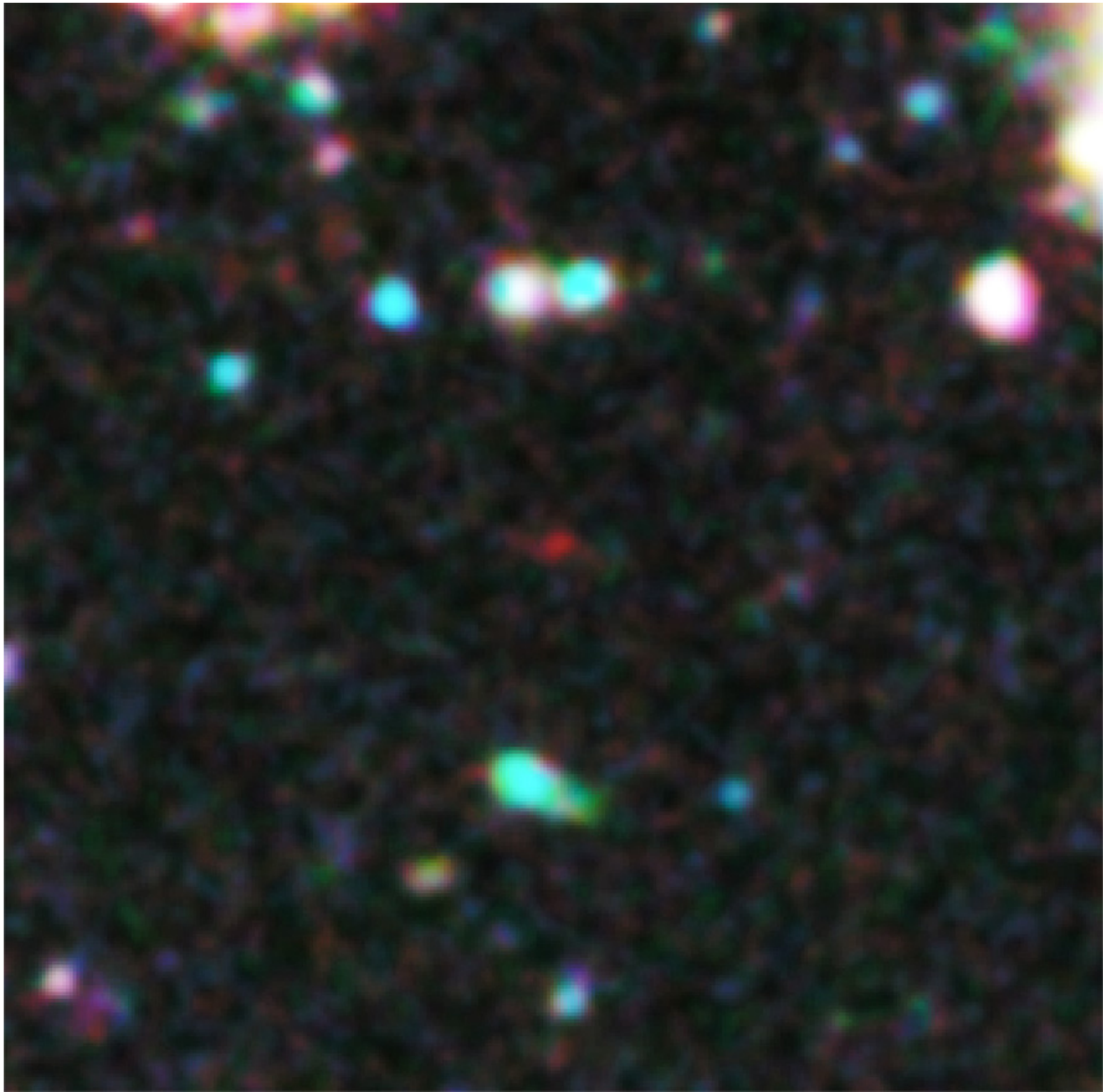
- This agrees with other things we observe:
  - The most distant galaxies we see are around 13 billion light years away
  - The oldest stars we can find live in globular clusters, and are all younger than about 10-13 billion years

One of the most distant galaxies so far detected: A redshift of 8.6 and a distance of about **13 billion light years**



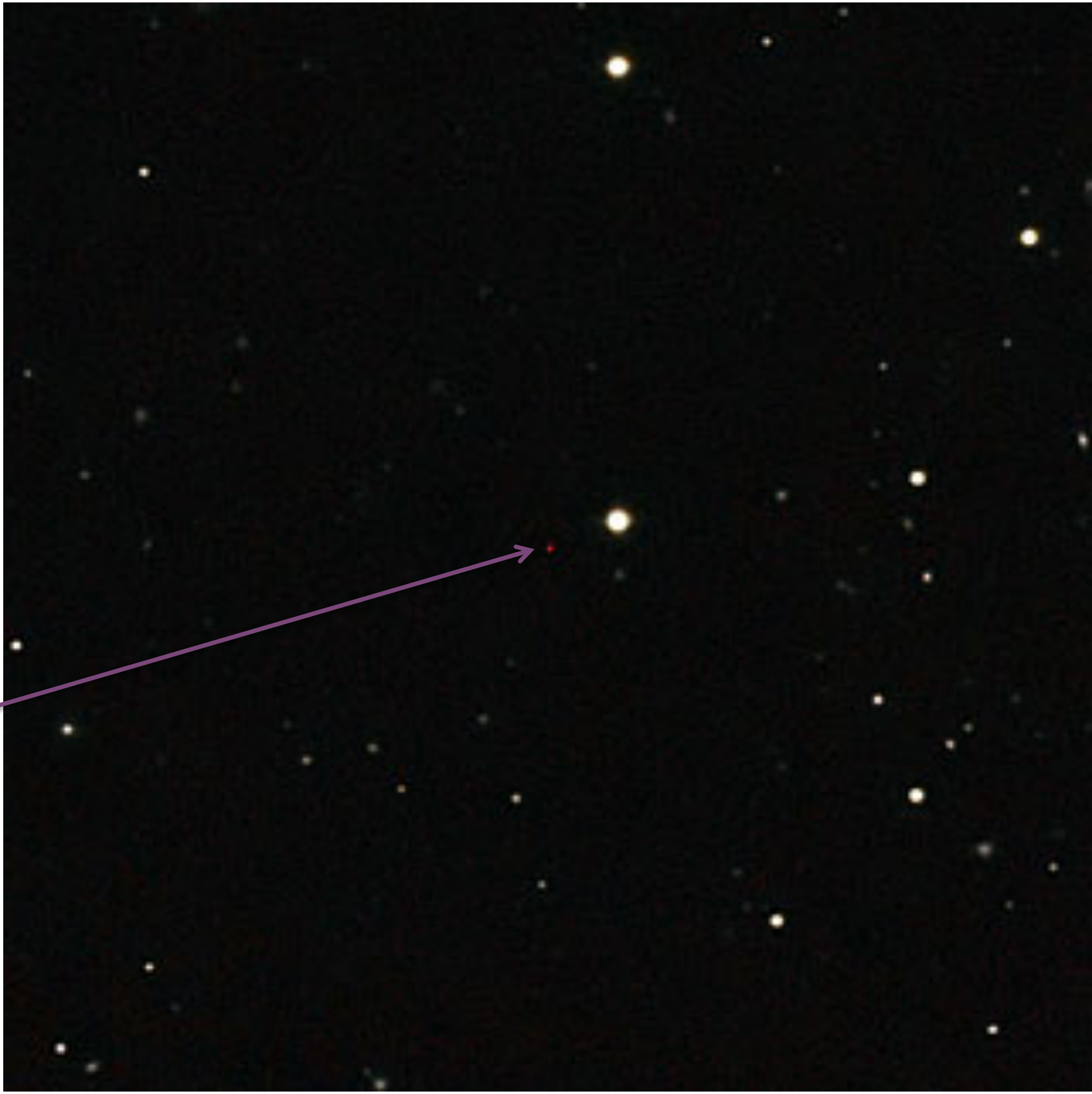
One of the most distant galaxies so far detected: A redshift of 8.6 and a distance of about **13 billion light years**

This picture was taken as part of the Hubble Ultra-deep Field: Hubble Space Telescope stared at a patch of sky for 1000000 seconds or about 11 days.



Another very distant object: A quasar with a redshift of 7.1.

(Observed by the Gemini telescope)



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

(1) 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: 11-12 billion years since first stars formed in globular clusters

(2) Using Hubble's law to deduce when the galaxies were all at a single point - when the Big Bang occurred: 14 billion years

(3) 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

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Particles and antiparticles forming and annihilating each other

(b) Annihilation

Particles and antiparticles forming and annihilating each other

(b) Annihilation

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

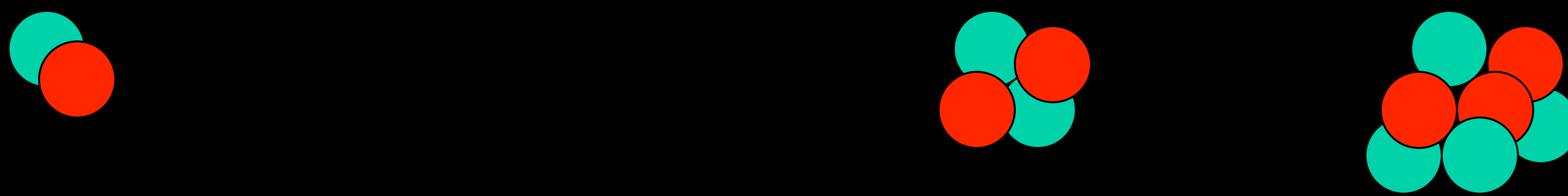
- Because of a tiny, tiny imperfection in the amount of matter created versus antimatter, the universe ended up with more matter than antimatter

- 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**.

Nucleosynthesis:
Formation of the lightest elements, deuterium (heavy hydrogen), helium, lithium



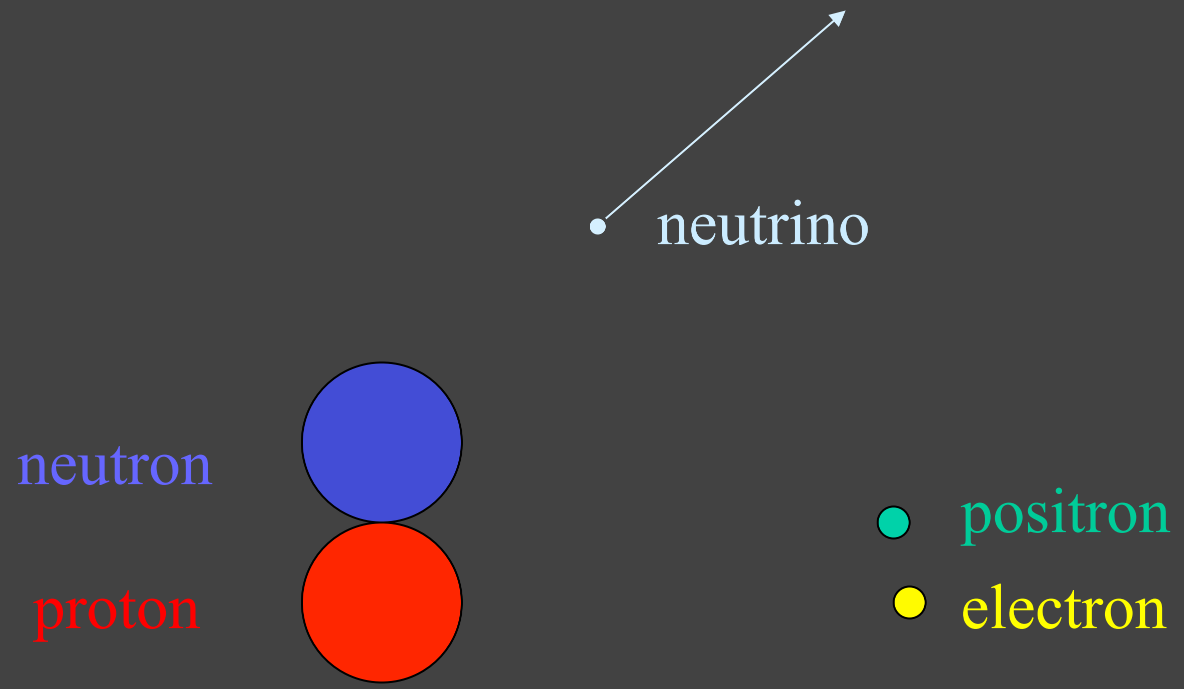
proton

neutron

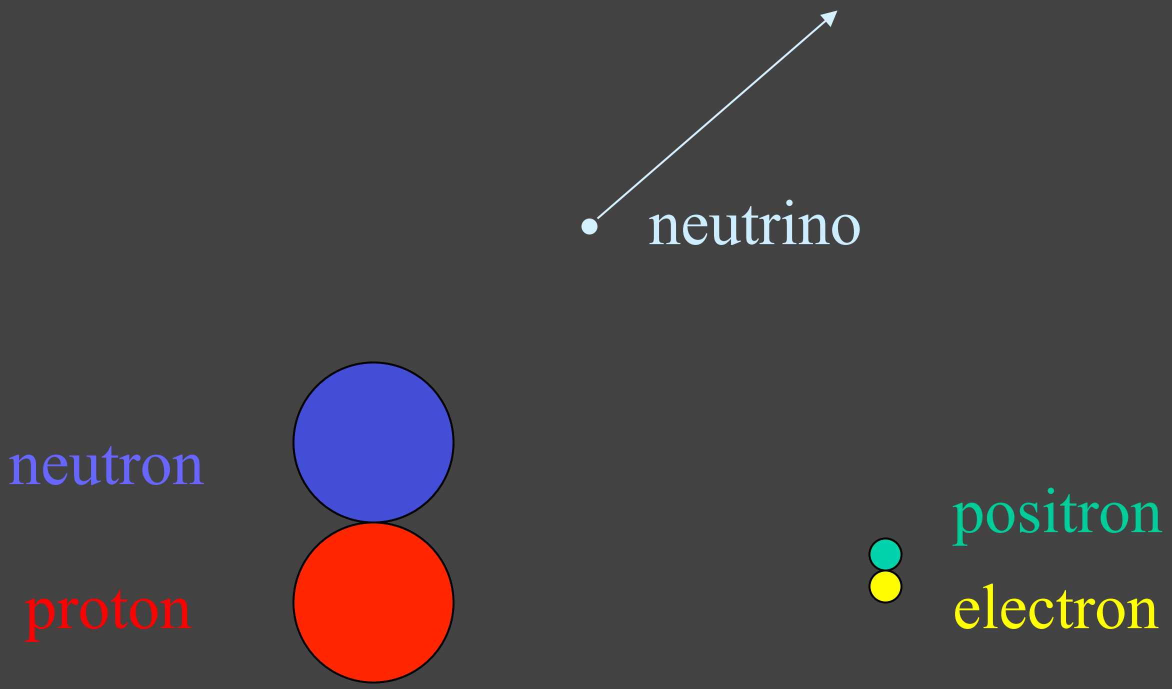
Deuterium production

Deuterium production

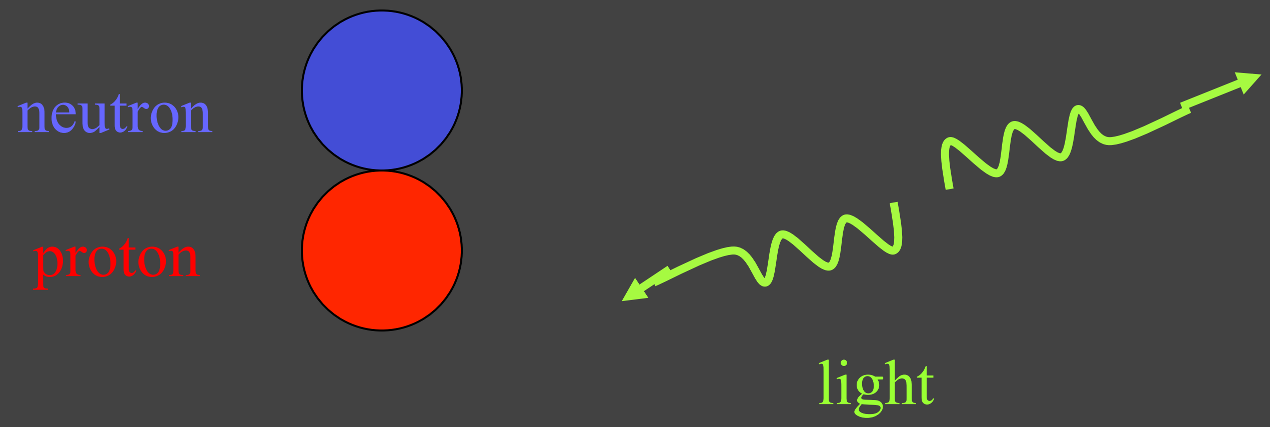
Deuterium production



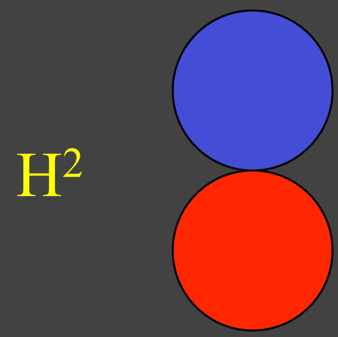
Deuterium production



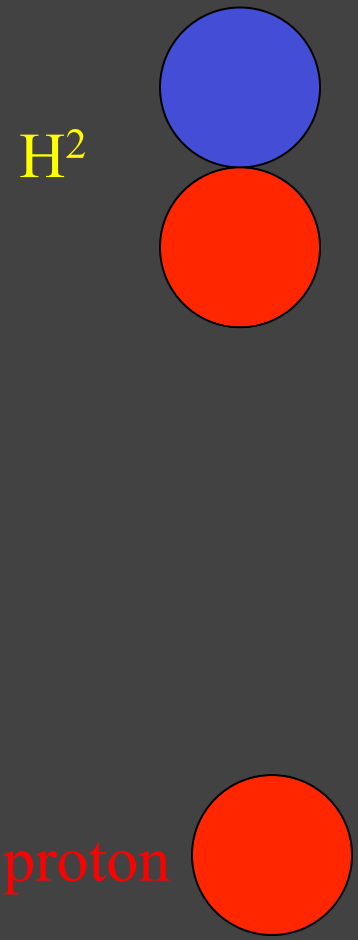
Deuterium production



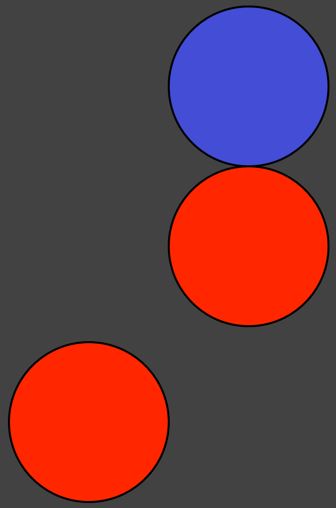
Deuterium production



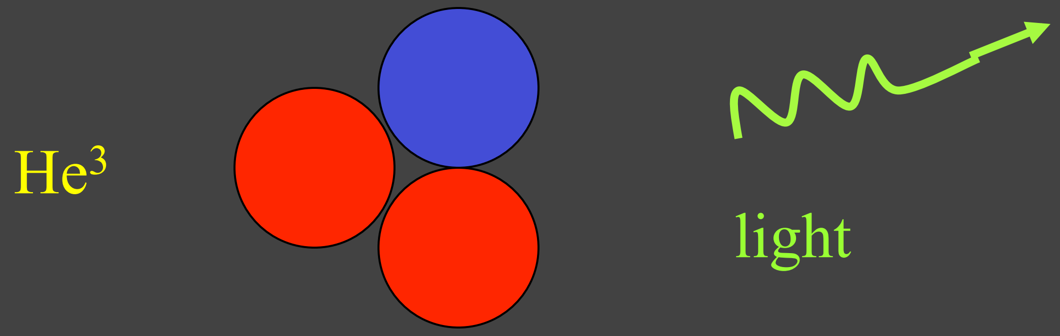
Fusion of d to He



Fusion of d to He

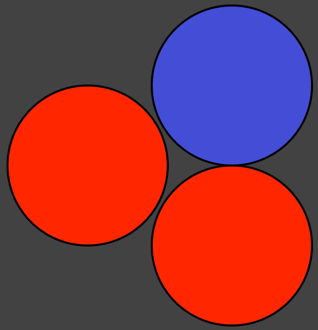


Fusion of d to He

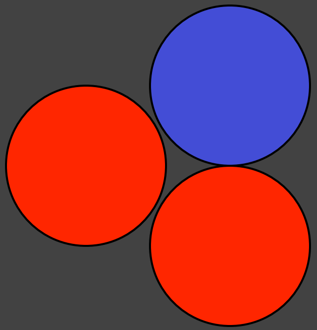


Fusion of d to He

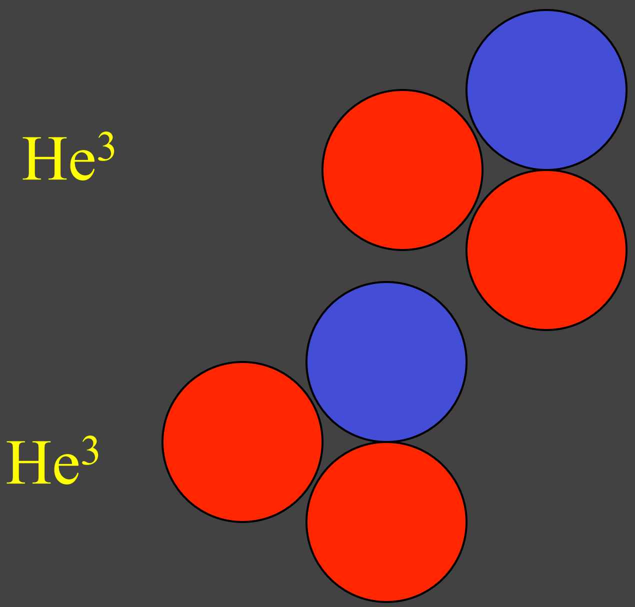
He^3



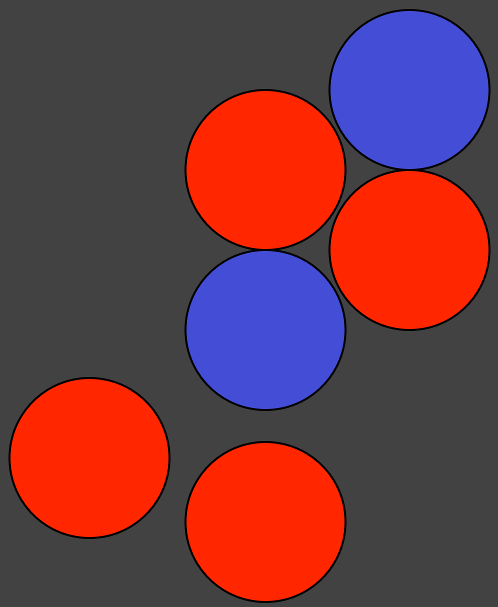
He^3



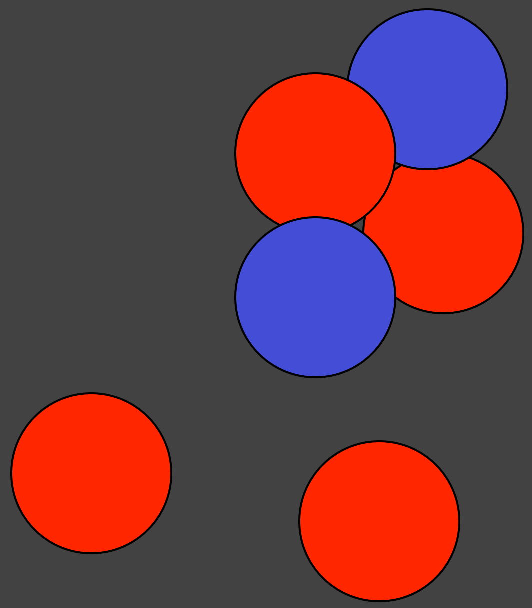
Fusion of d to He



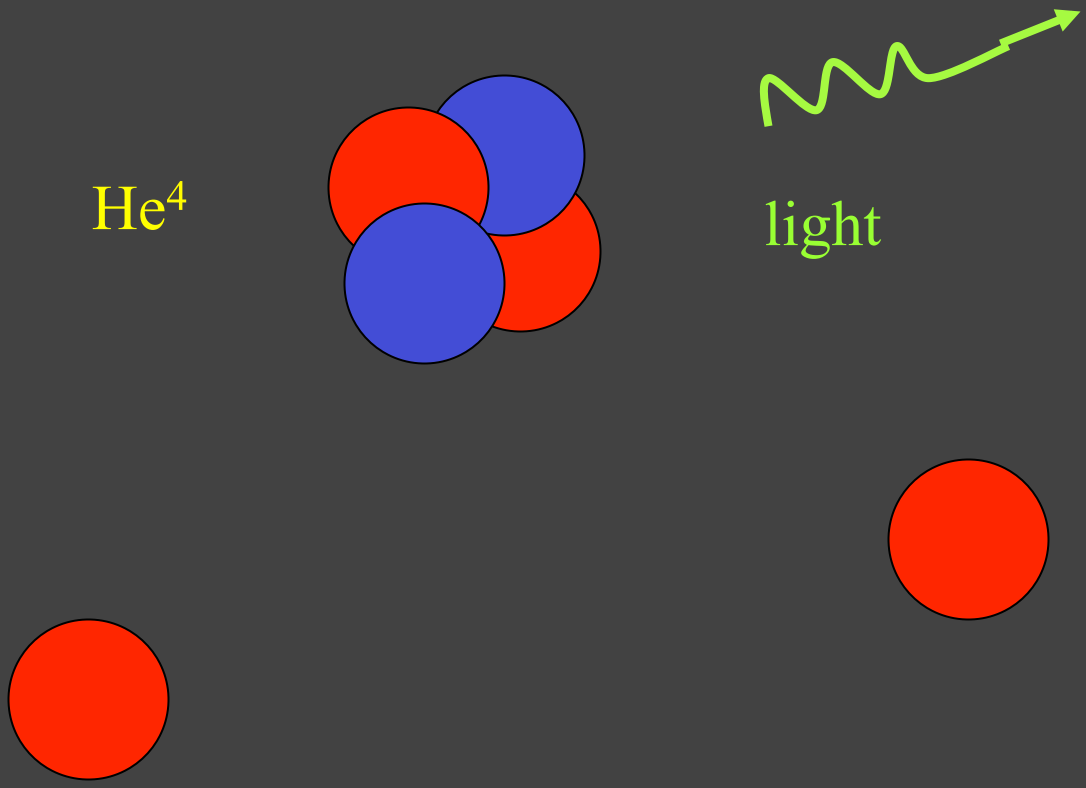
Fusion of d to He



Fusion of d to He



Fusion of d to He



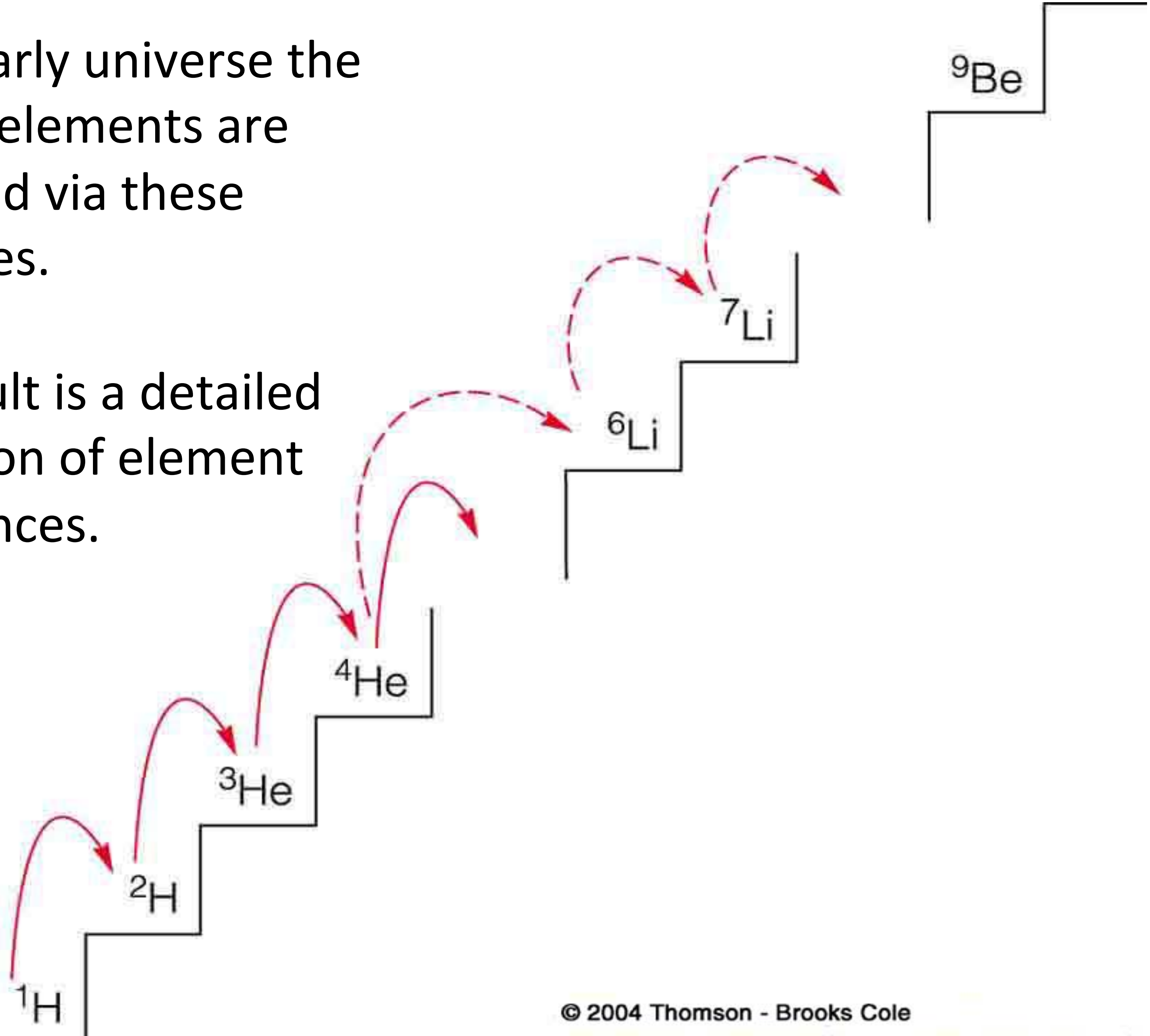
Trace amounts of deuterium and of lithium (from collisions of deuterium with helium) remain, accounting for the abundances of these light elements we see today.

- **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.



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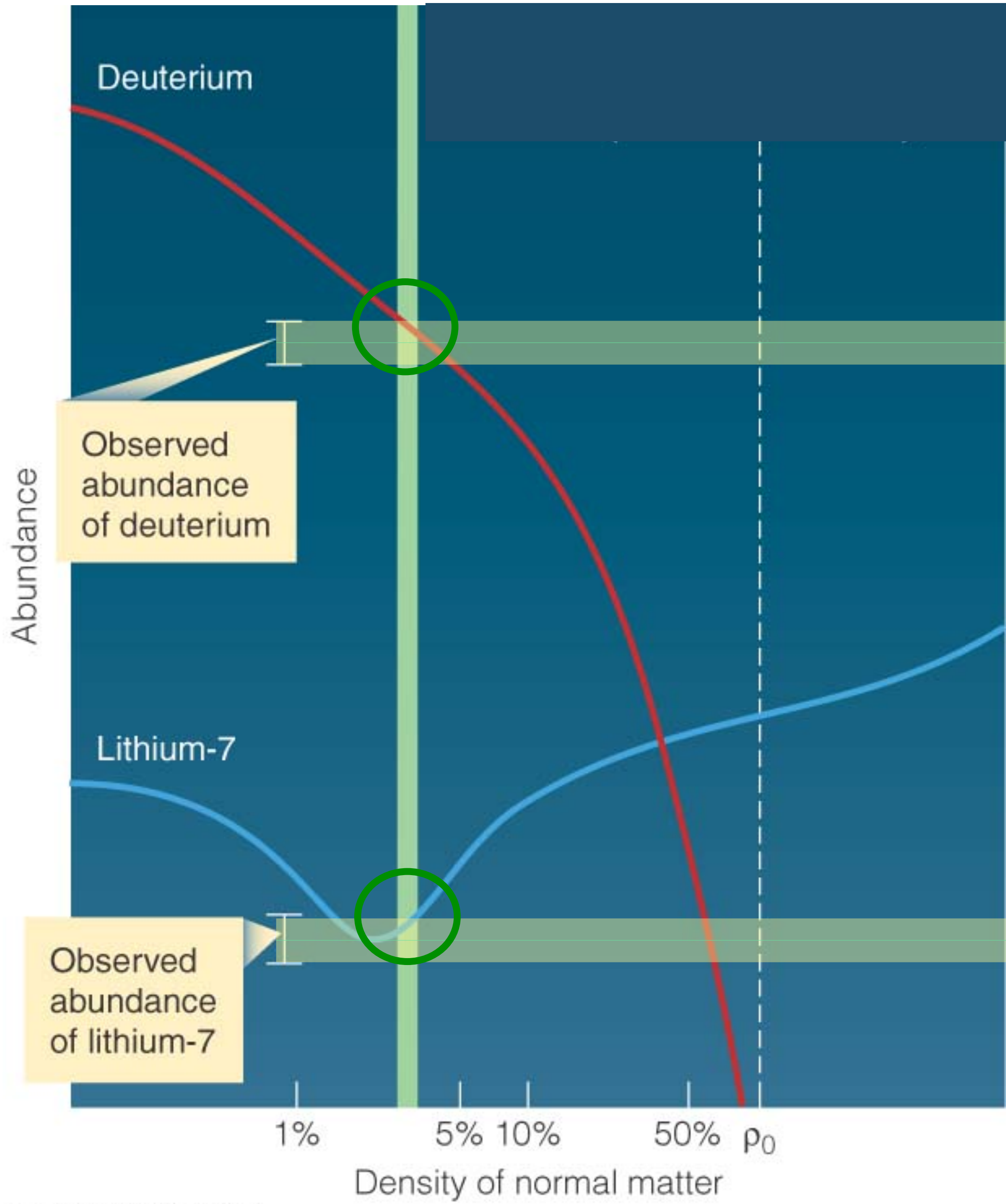
Primordial Nucleosynthesis: Helium and Deuterium abundances

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).



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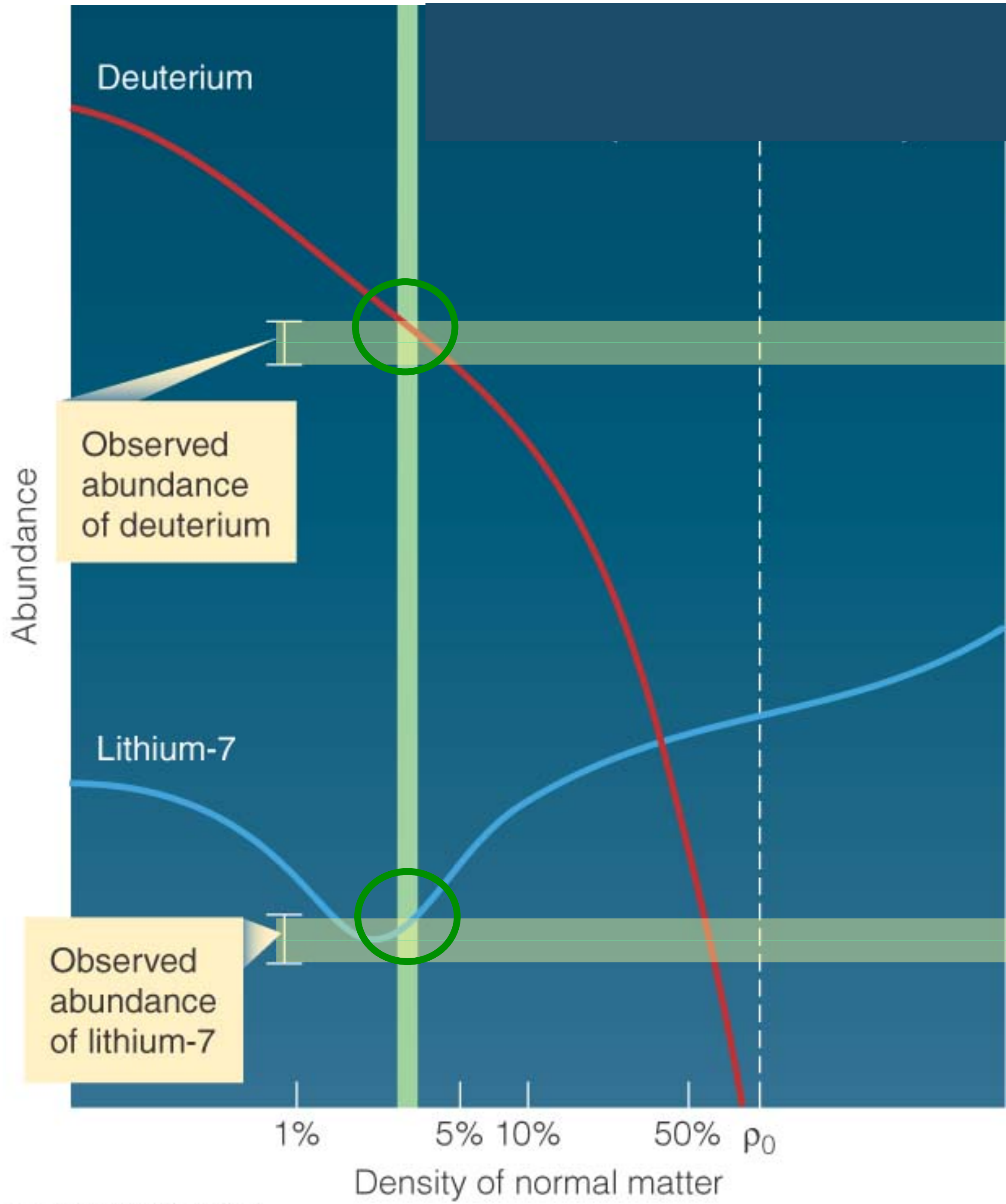
But, if the dark matter were ordinary matter, there would be far too much matter to agree with the observed abundances of Deuterium, Li, & He.

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



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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.

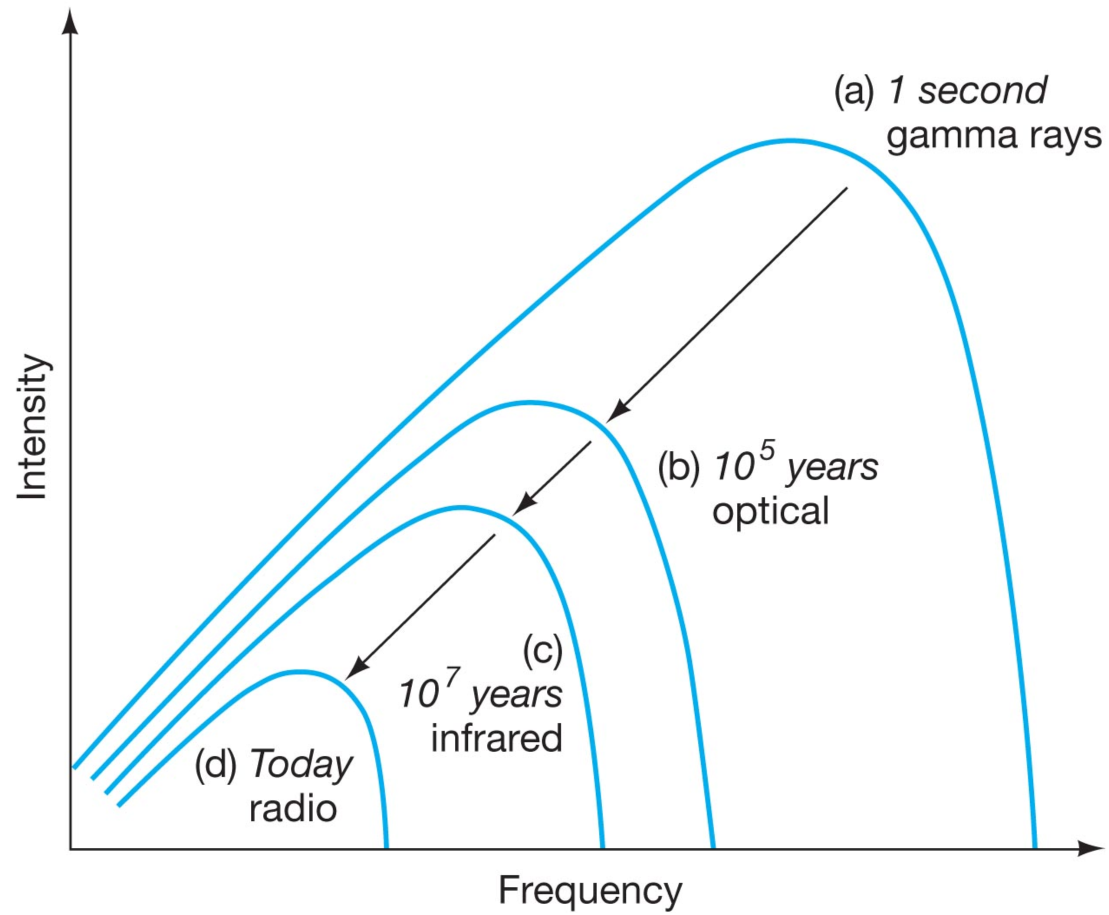
History of the Universe

- 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**.

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.



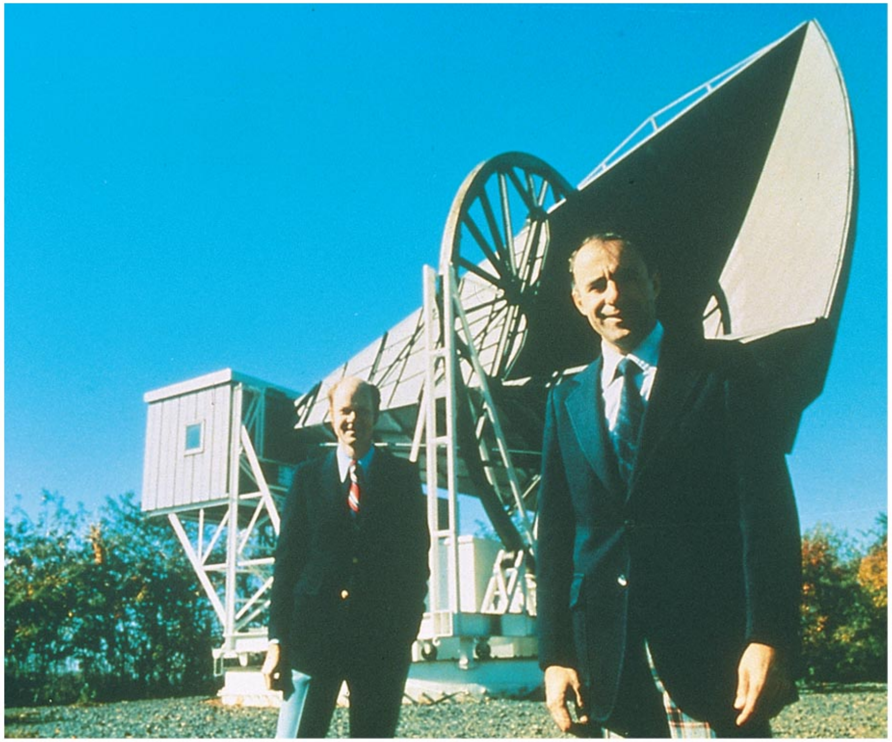
So the universe it not absolutely cold, but has a temperature of 3 K.

Cosmic Microwave Background

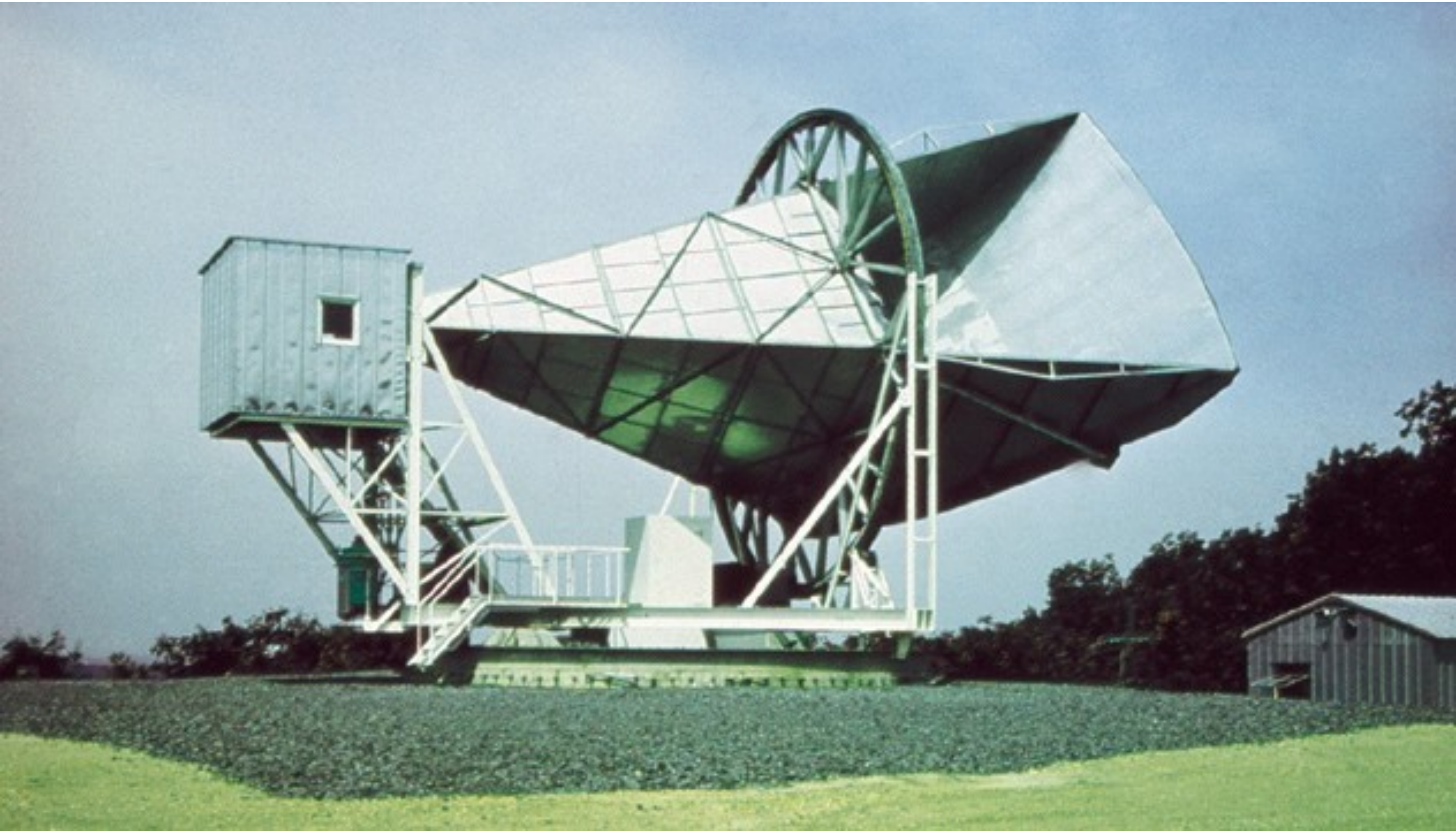
- At 3 K, the radiation is in the microwave regime, so this radiation is called the cosmic microwave background.
- The cosmic background radiation was predicted by Gamow in 1948 as a natural consequence of the big bang theory.
- But there was no attempt to measure it (or realization that it could be measured) until the early 60's.

The 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.

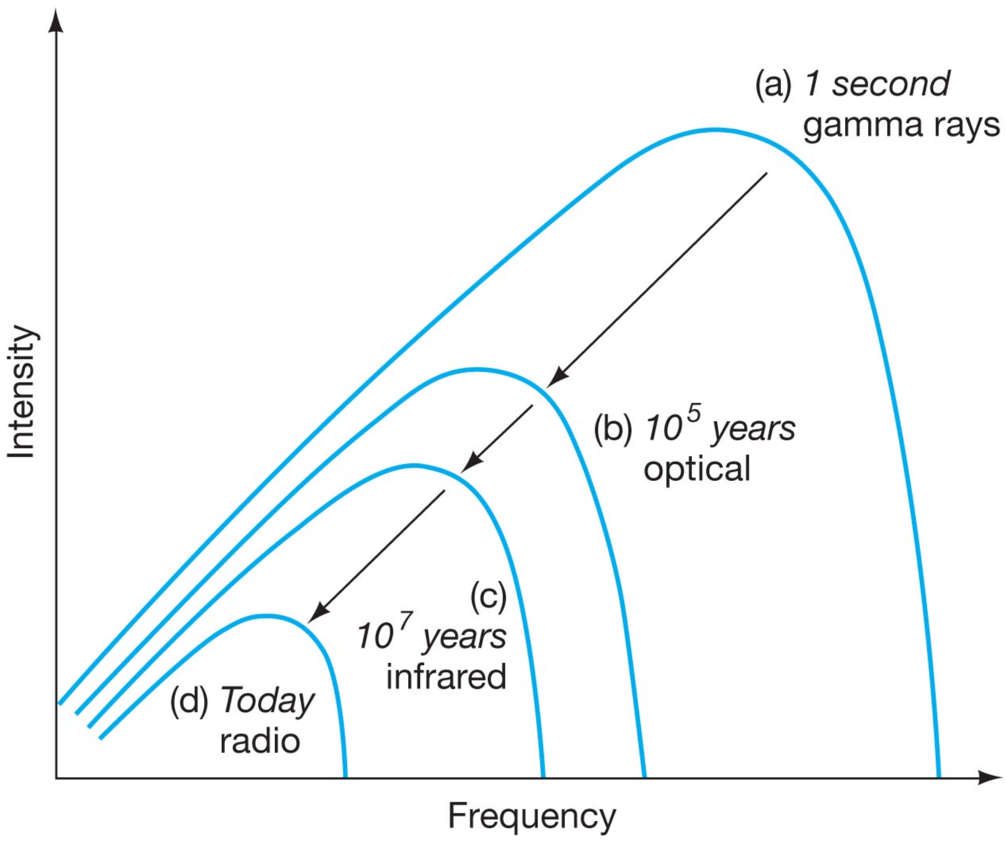


The radio antenna at Holmdel, New Jersey, whose noise turned out to be light from the Big Bang

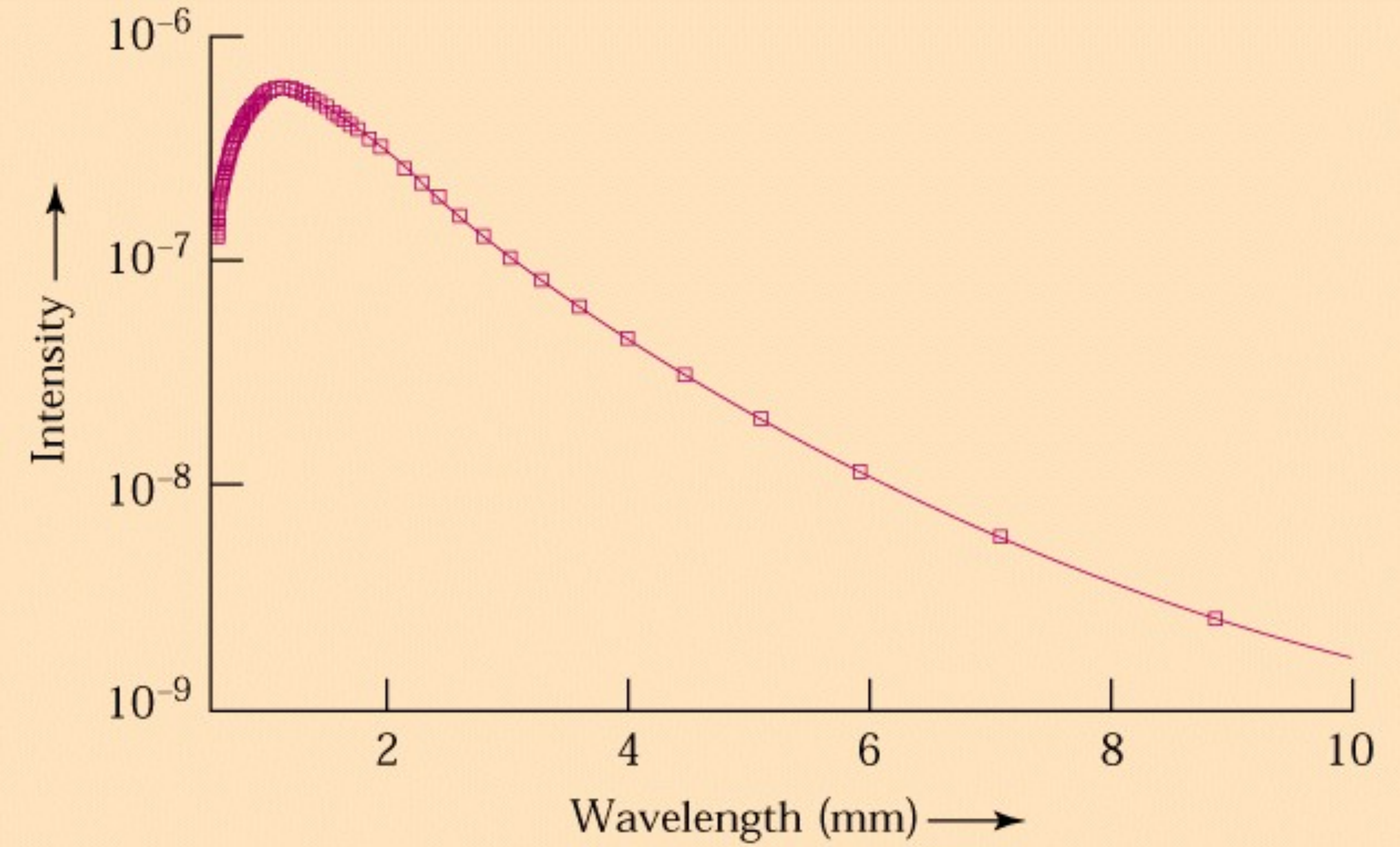


The Cosmic Microwave Background

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.



With wavelength λ measured in nanometers and T in degrees Kelvin, the relation between the average wavelength of light emitted by a hot object and the temperature of the object is

$$\lambda = \frac{3\times 10^{6}}{T}\ \text{nm}$$

To 2 decimal-place accuracy and with λ measured in cm

$$\lambda = \frac{0.29}{T}\ \text{cm}$$

Example: Cosmic microwave background at 3 K

Peak wavelength is 0.1 cm: radio (microwave)