Cosmic Microwave Background

Phys 313:Cosmology part Lecture 3

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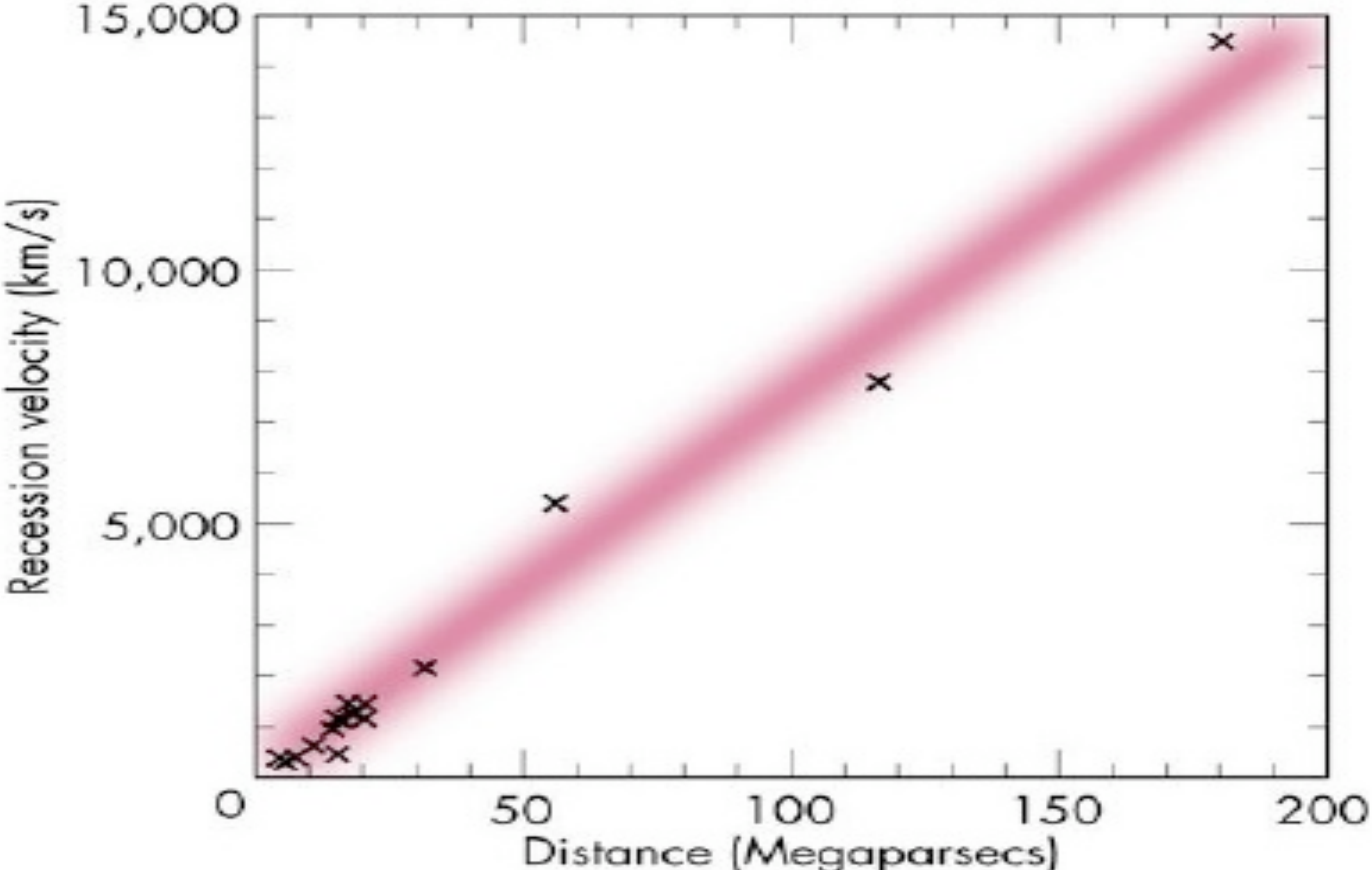
Expectations and discovery of CMB

The work done by pressure in expanding fluid uses heat energy drawn from the fluid.

The Universe is expanding, therefore we expect it was hotter and denser in the past.

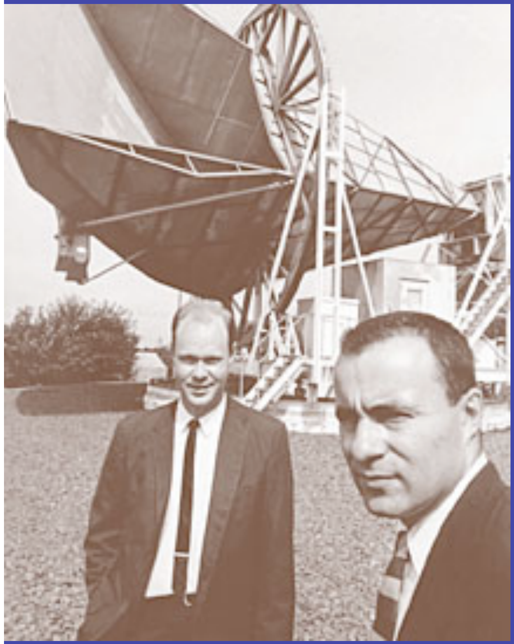
Big Bang model



At sufficiently early times the rapid collision of photons with free electrons would have kept radiation in thermal equilibrium with hot dense matter

As time passed, the matter became cooler and less dense. The radiation began a free expansion, but its spectrum kept the same form

$$n(\nu, t)d\nu = \frac{8\pi\nu^2 d\nu}{exp(h\nu/k_B T(t)) - 1}$$

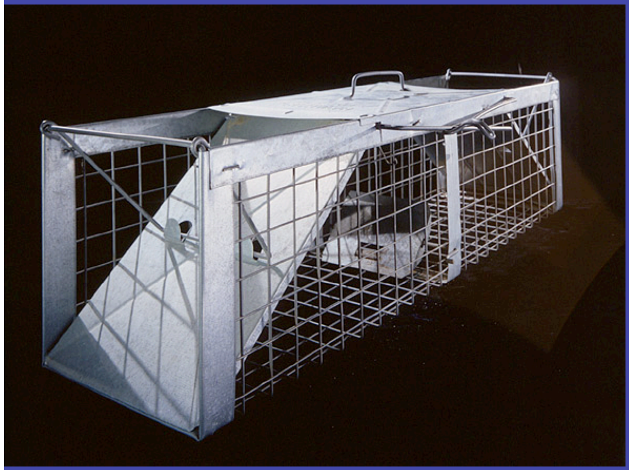


In the early 1960s, two astronomers, Wilson & Penzias, were working with a microwave antenna at Bell Labs.

(Microwaves are electromagnetic waves with wavelengths from 1 millimeter to 10 centimeters.)

Wilson & Penzias were plagued with static.

Wilson & Penzias did everything they could to eliminate "noise" in their antenna.



…including trapping pigeons that had left "a white dielectric material" on the antenna.

Conclusion: "static" or "noise" actually came from outer space.

Microwave radiation picked up by Wilson & Penzias was nearly isotropic.

(That is, it doesn't come from a single source, like the Sun.)

Because they come from everywhere, the microwaves from space are called the **Cosmic** Microwave Background.

Penzias & Wilson won the Nobel Prize.

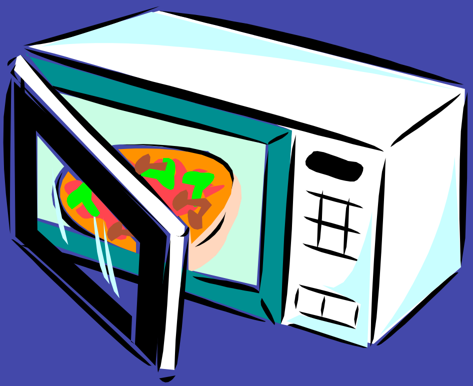
Physicists and astronomers thought that discovering the CMB was really important!

WHY?

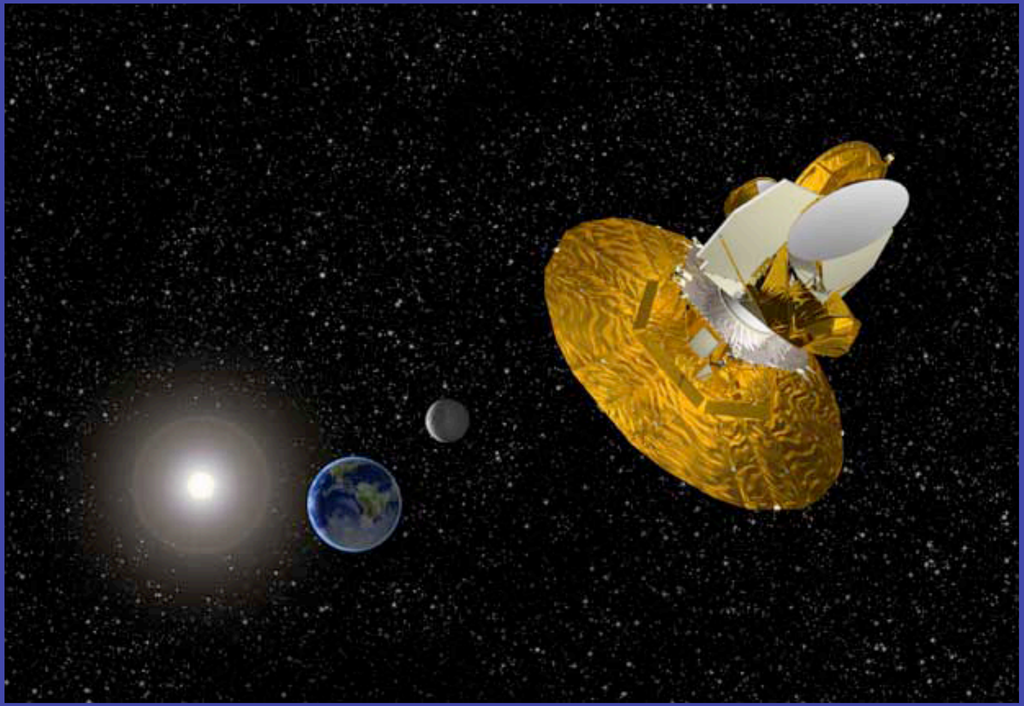
Consider the spectrum of the CMB.

Measuring the CMB spectrum is hard to do from the Earth's surface.

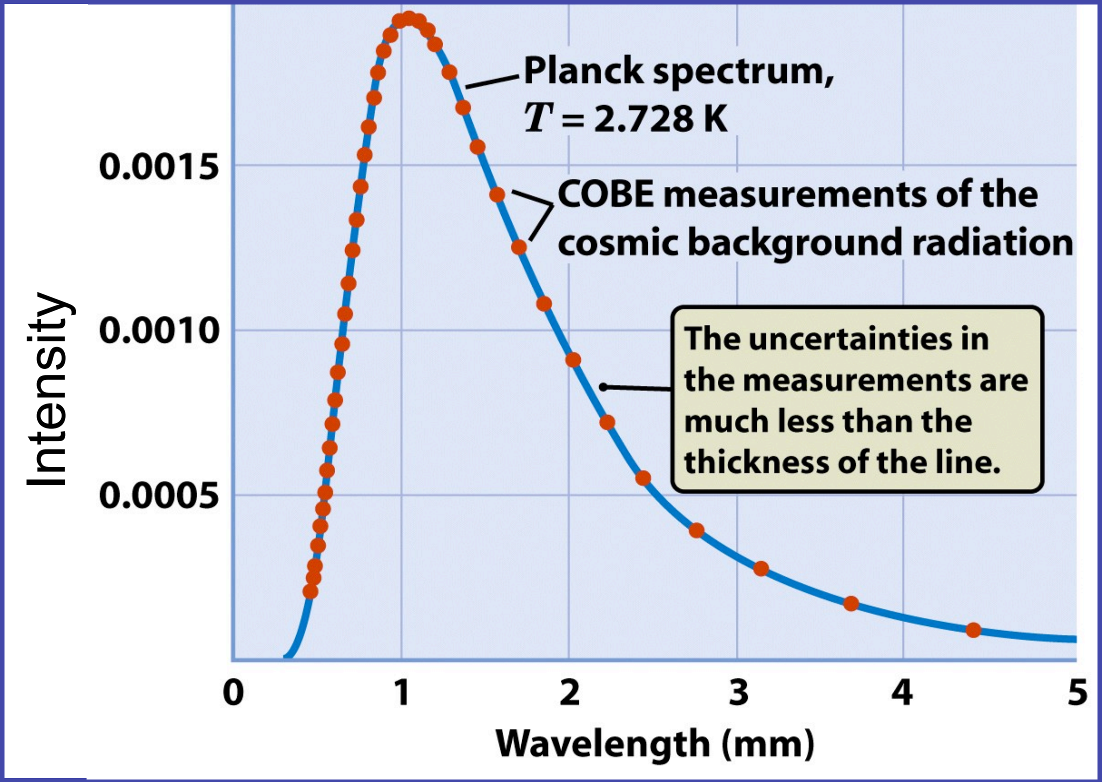
Water is very good at absorbing microwaves.



Astronomers observe the CMB from above the Earth's damp atmosphere with artificial satellites.

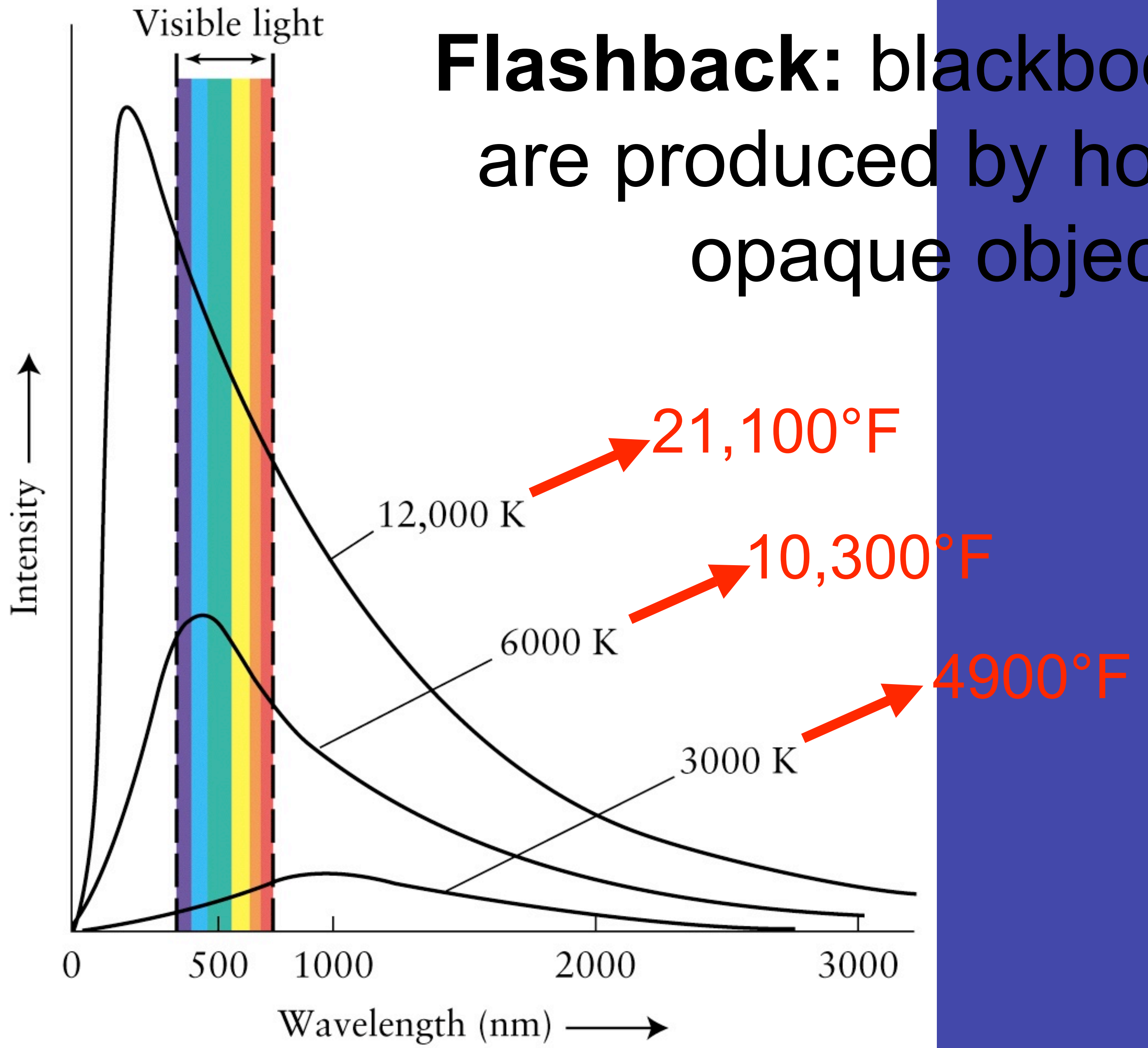


What do these orbiting satellites find?

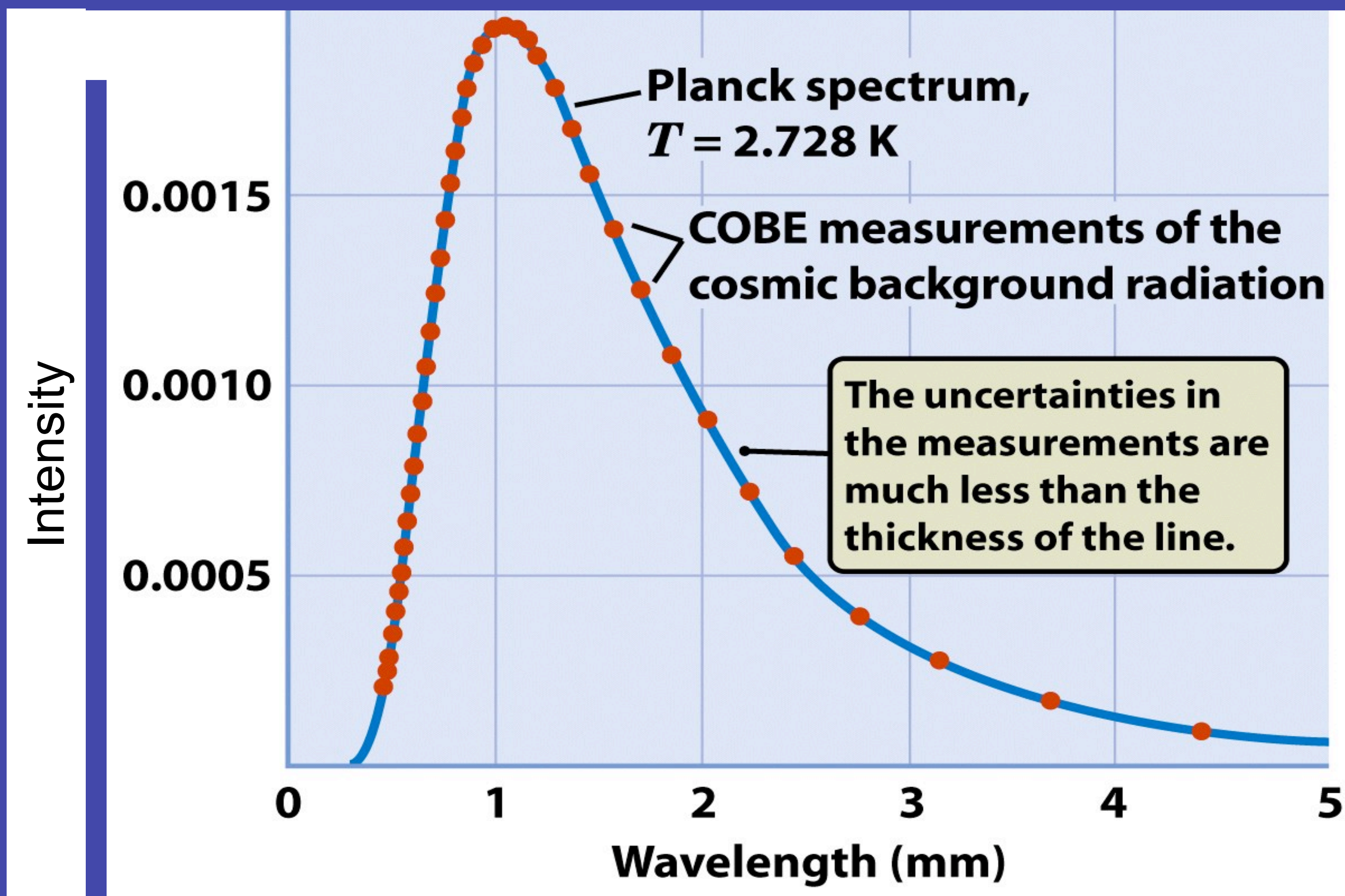


The Cosmic Microwave Background has a **blackbody** spectrum.

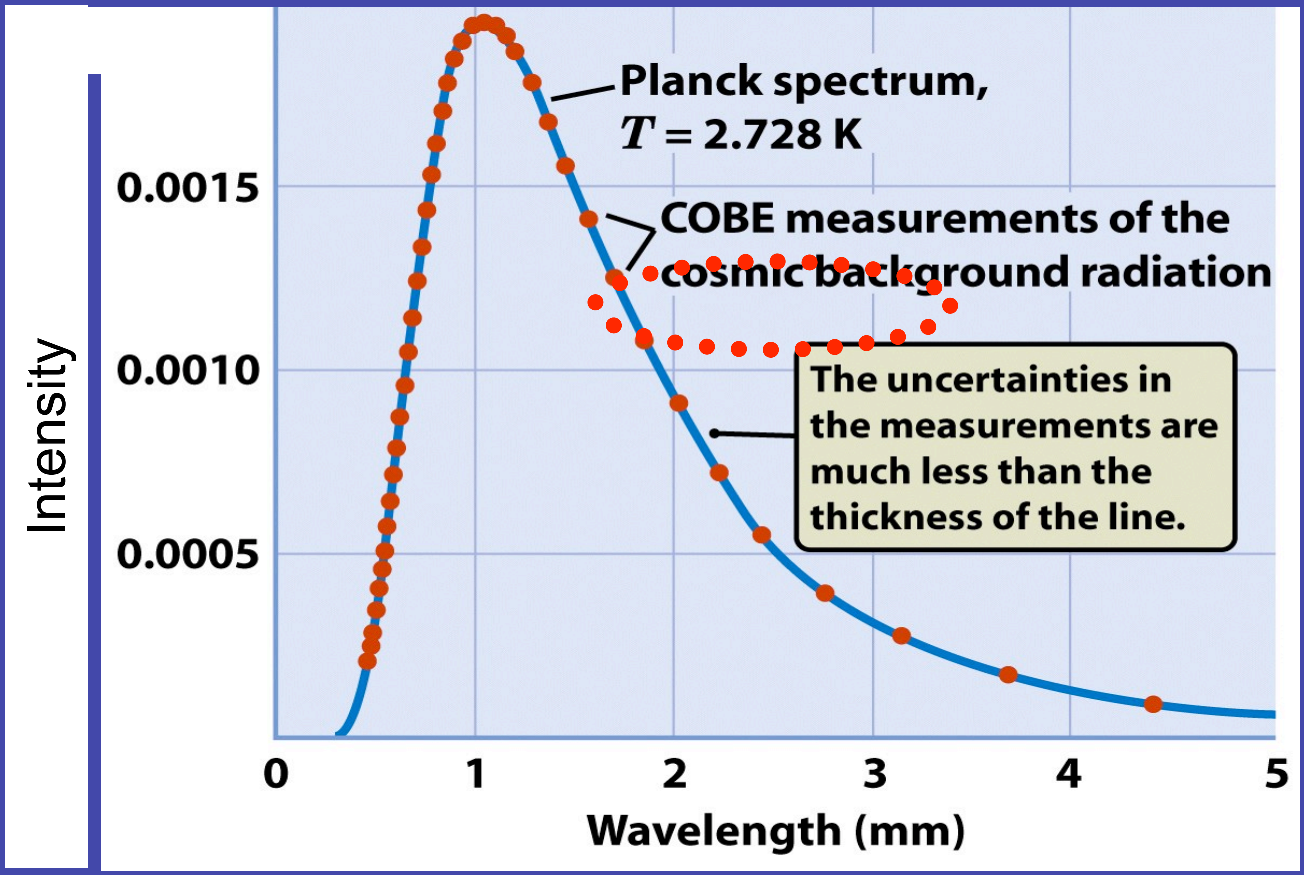
Flashback: blackbody spectra are produced by hot, dense, opaque objects.



The universe (mostly transparent) is filled with nearly isotropic blackbody radiation (characteristic of opaque objects) !



And the temperature of the isotropic blackbody radiation is only **2.7 Kelvin**.



very very cold !

Key questions:

Why is the universe full of isotropic blackbody radiation (the CMB)?

Why is the temperature of the CMB so low?

Why is the universe full of isotropic blackbody radiation (the CMB)?

Let's suppose that the universe was **very hot** as well as **very dense** when it started expanding.

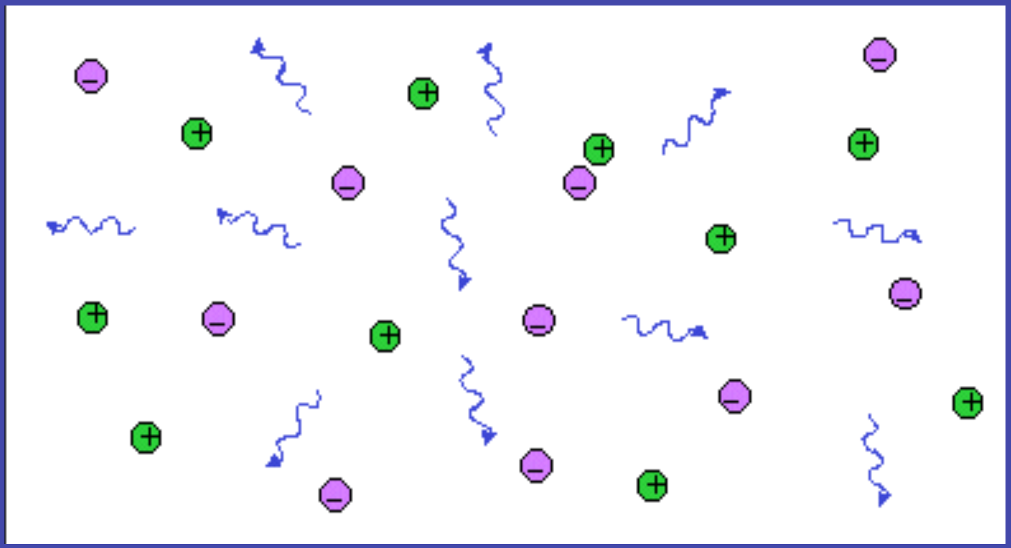
This hypothesis (hot, dense beginning) is called the **Hot Big Bang** model.

If the temperature of the early universe had been T > 3000 K, then hydrogen would have been ionized.

Why does this matter?

Dense ionized gases are opaque. (You can't see through the Sun!)

Ionized gases are opaque because they contain free electrons that scatter photons of any energy.



Photons (blue squiggles) don’t move freely through space, because they collide with electrons (purple dots).

Why does it matter whether the early universe was opaque?

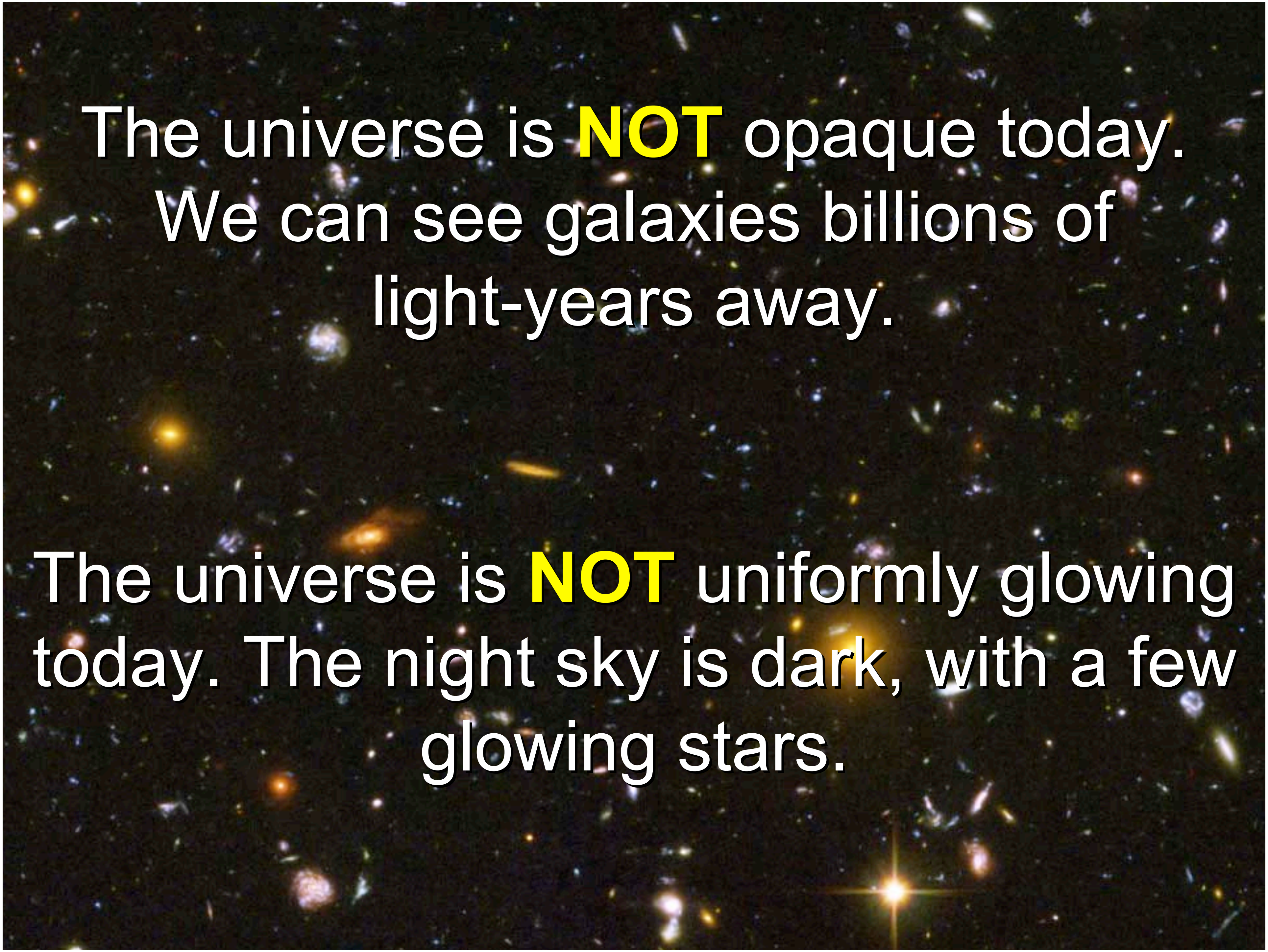
Hot, dense, opaque objects emit light!

Today, we call hot, dense, opaque objects that emit light "**stars**".

Soon after the Big Bang, the **entire universe** was glowing.

Imagine yourself **inside** a star, surrounded by a luminous, opaque “fog”, equally bright in all directions.

Early universe was like that – sort of monotonous, really…


The universe is **NOT** opaque today.
We can see galaxies billions of light-years away.
The universe is **NOT** uniformly glowing today. The night sky is dark, with a few glowing stars.

As the hot, dense, ionized hydrogen expanded, it cooled.

When its temperature dropped below 3000 K, protons & electrons combined to form neutral H atoms.

The universe became transparent.

The universe became transparent at a temperature T ≈ 3000 K.

But…objects at T ≈ 3000 K produce **visible & infrared** light (think “lightbulb filament”), not **microwave** light.

Why is the temperature of the CMB so low?

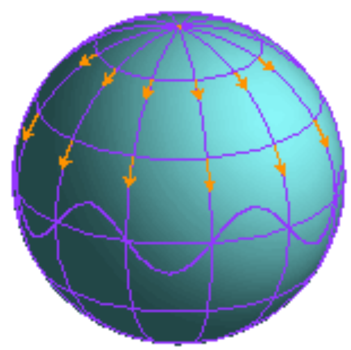
How did its temperature drop from **3000 K** to **3 K**?

How did the cosmic background change from **visible & infrared** light ($\lambda \approx 0.001$ mm) to **microwave** light ($\lambda \approx 1$ mm)?

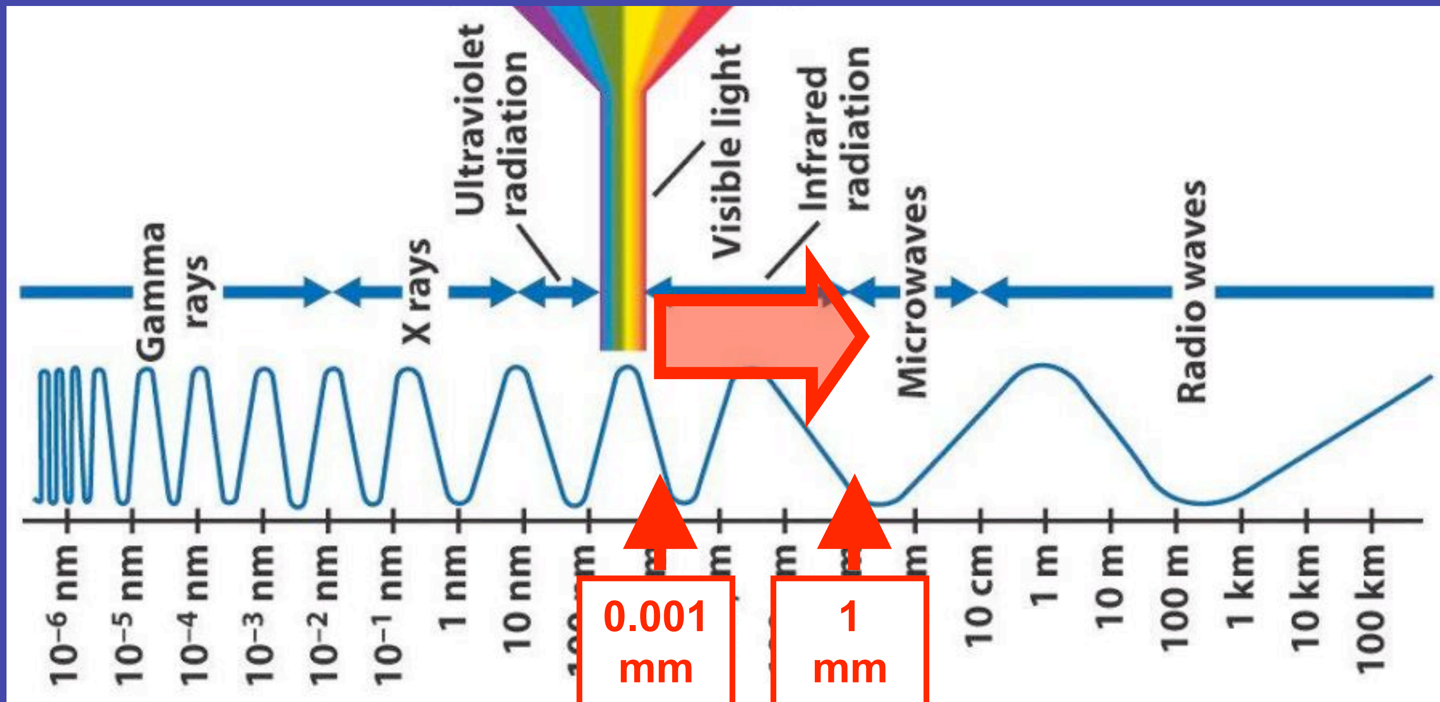
The universe is expanding.

Distance between galaxies increases.

Wavelength of light (distance between wave crests) increases.

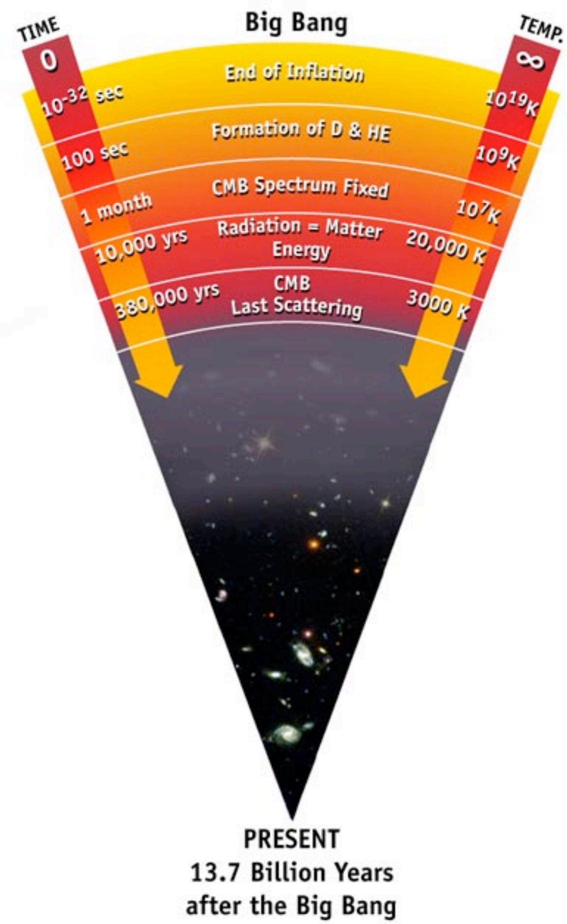


Wavelength of cosmic background light has increased by a factor of 1000.

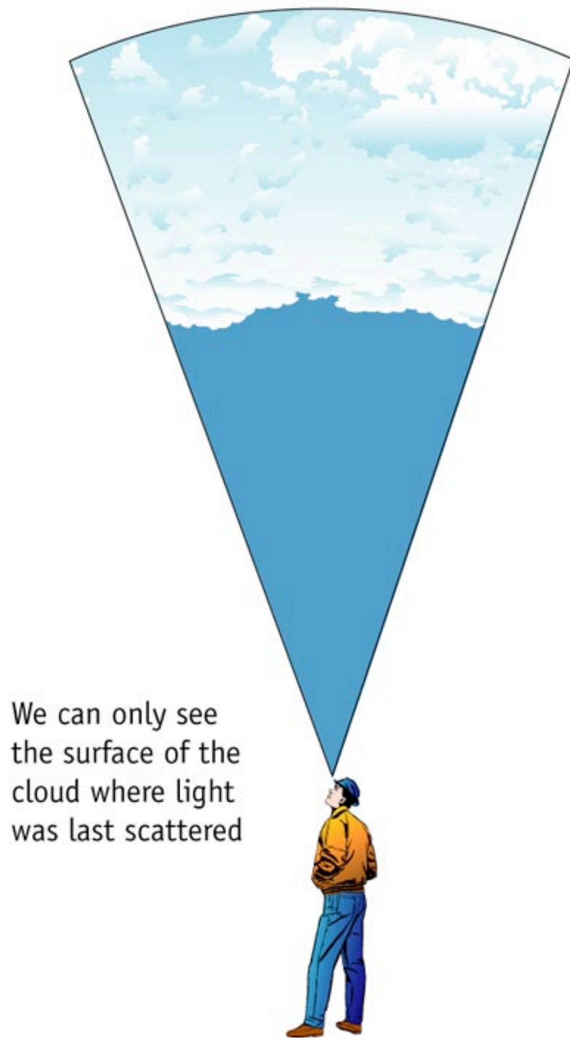


Why? Because the universe has expanded by a factor of 1000 since the time it became transparent.

The CMB has highest redshift of **anything** we can see (z = 1000).



The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.



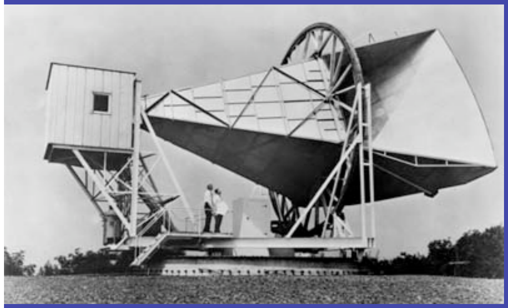
When we look at the CMB, we look at the surface of the glowing "fog" that filled the early universe!

Evidence in favor of the **Hot Big Bang** model.

1) The night sky is **dark**.

2) Galaxies show a **redshift** proportional to their distance.

3) The universe is filled with a **Cosmic Microwave Background (CMB)**.



CMB = light left over from early, hot, dense, opaque universe.

Universe became transparent when scale factor was $a \approx 1/1000$, time was $t \approx 400{,}000$ years.

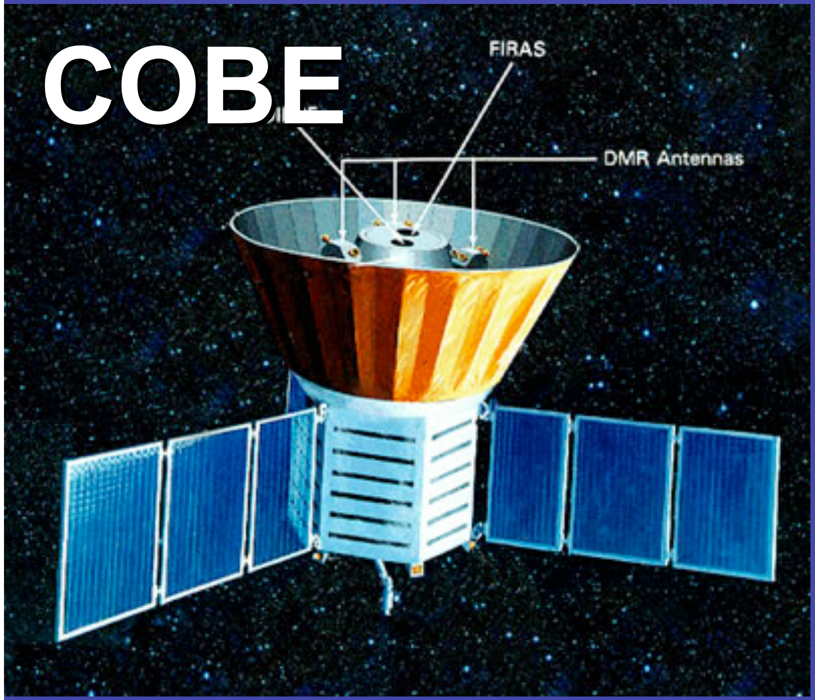
From then until now ($t \approx 14$ billion years), CMB photons have been freely moving through space.

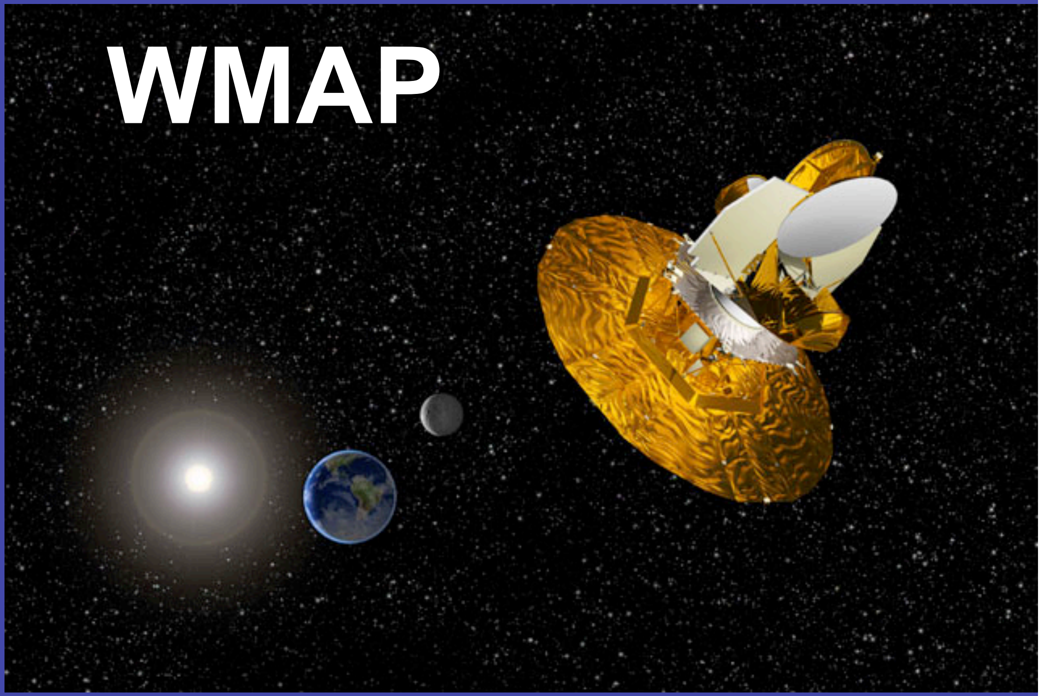
When we observe the CMB, we see a message direct from the early universe.

What is this message telling us?

Messages are often (1) hard to read & (2) hard to interpret.

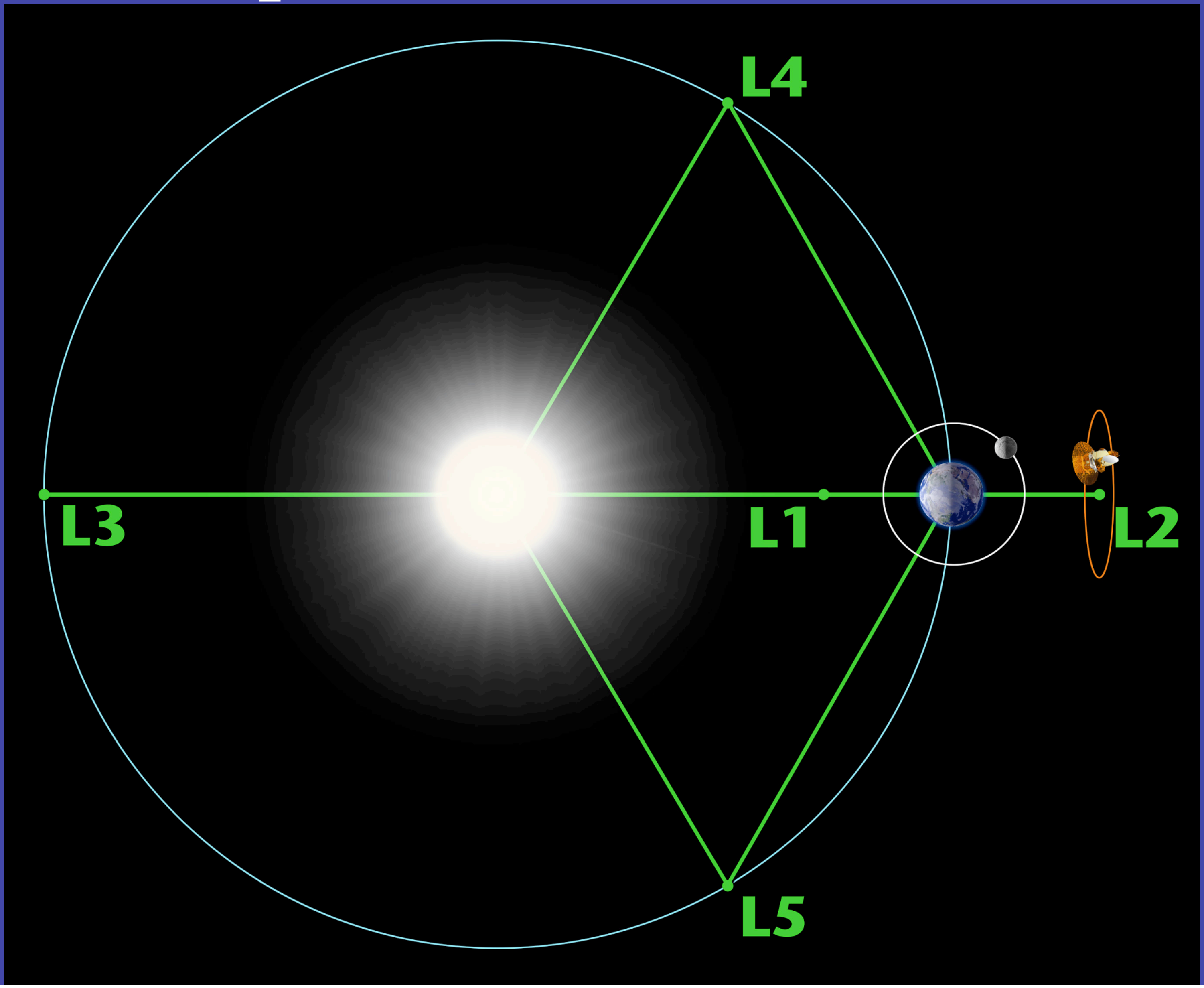
Observing the CMB





Water vapor in Earth's atmosphere absorbs microwaves: go **above** the atmosphere!

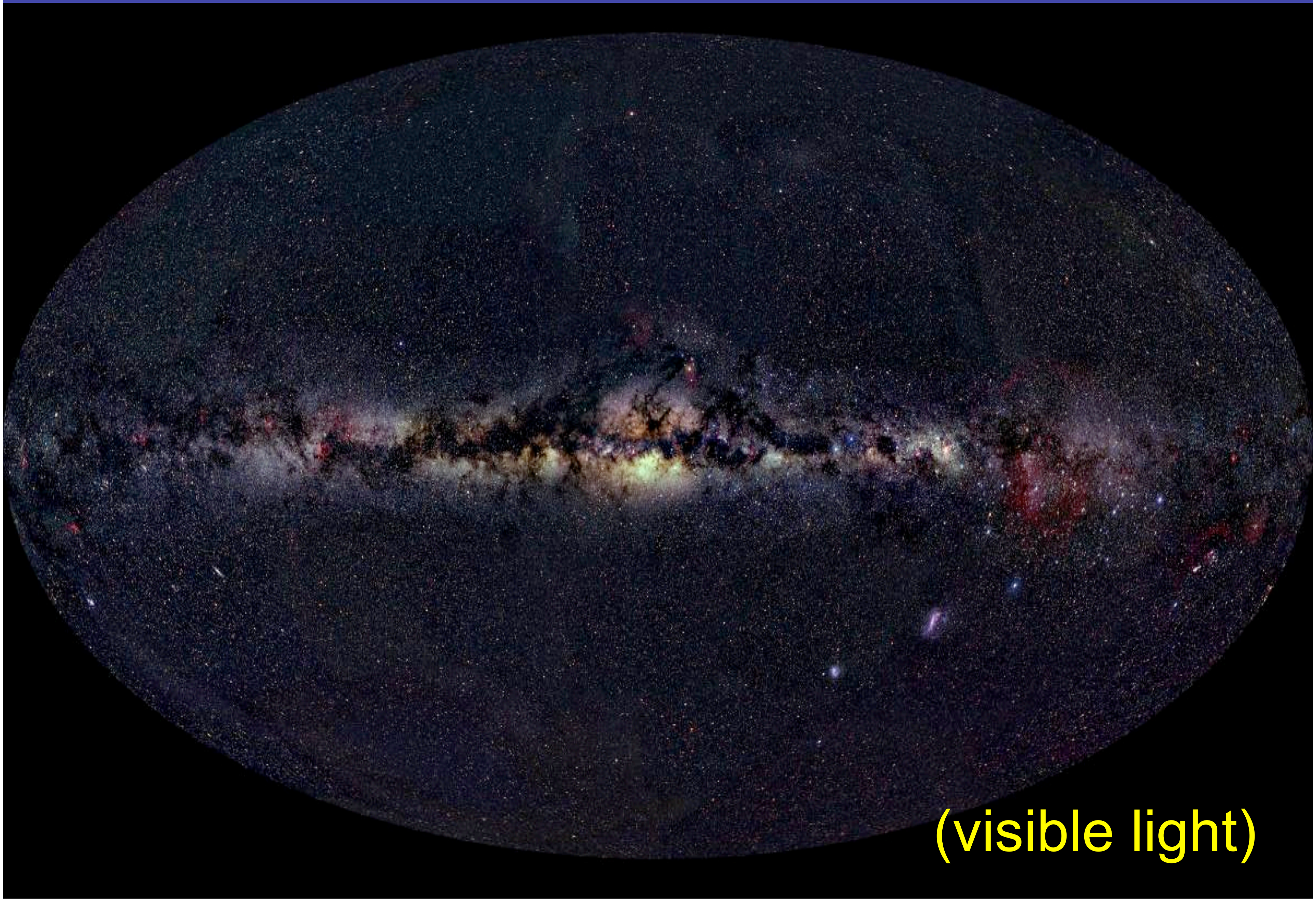
WMAP (Wilkinson Microwave Anisotropy Probe) is at the L_2 point, beyond the Moon's orbit.



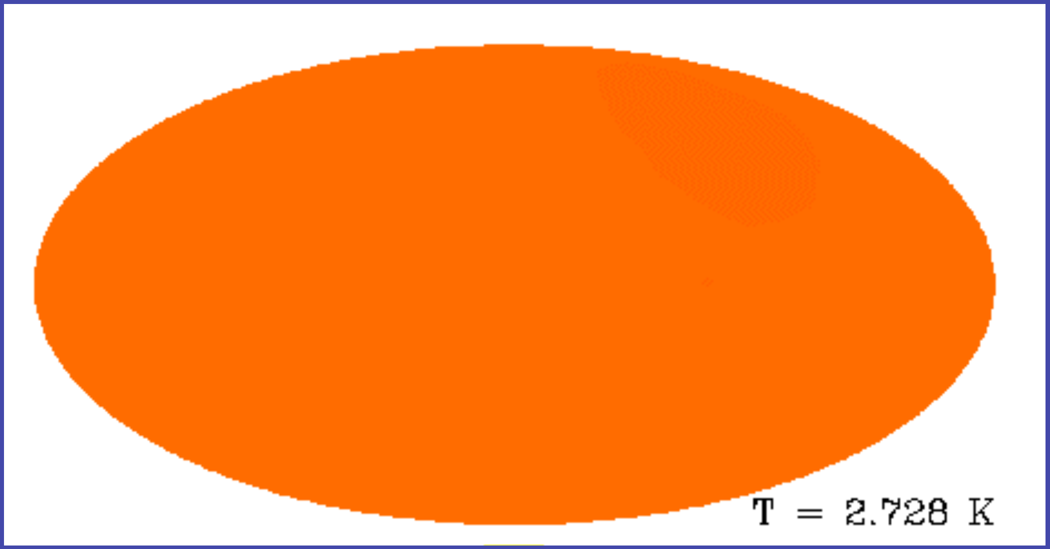
We've looked at the spectrum of the CMB (it's a blackbody), now let's look at a map.

Spherical Earth can be projected onto a flat map:

So can the celestial sphere:

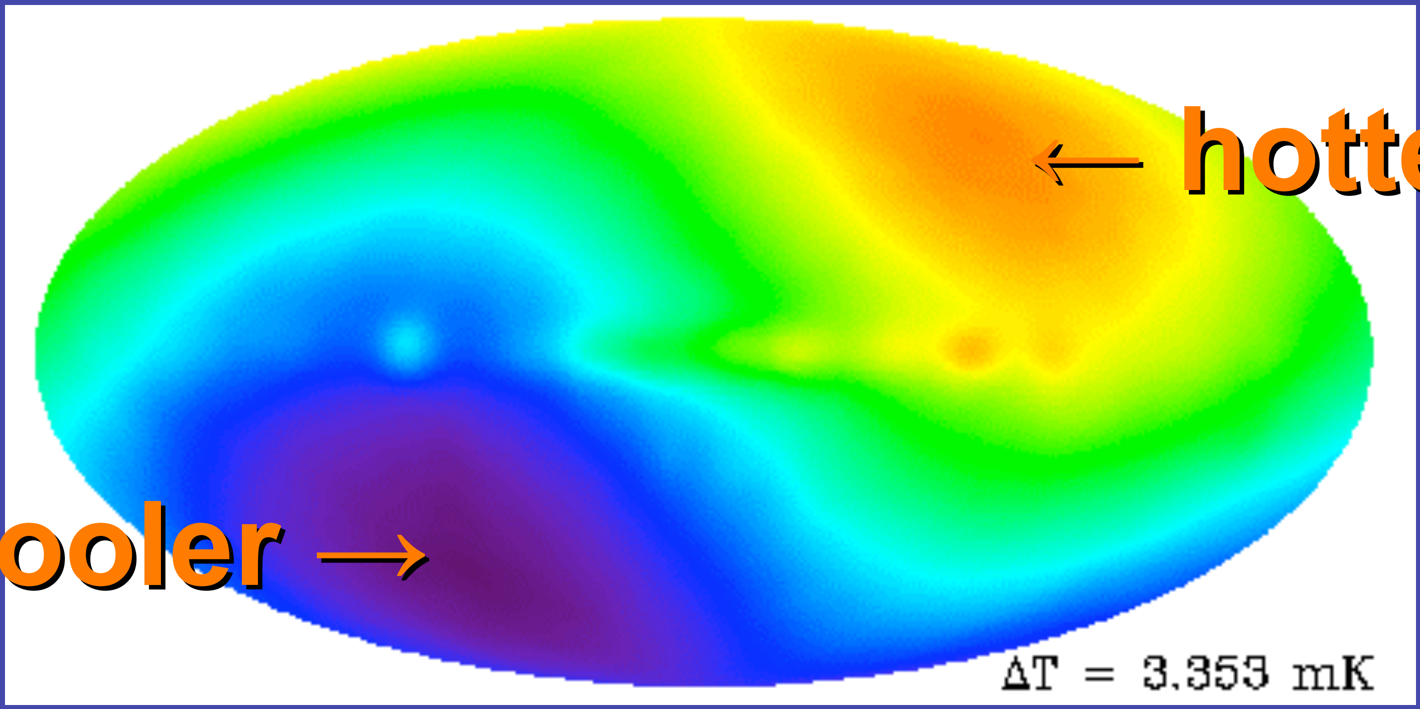


Mapping the CMB (color = temperature)



Observation: Temperature of CMB is nearly **isotropic** (the same in all directions).

Interpretation: early universe was nearly **homogeneous** (the same in all locations).



Observation: Temperature of CMB is slightly **hotter** toward Leo, **cooler** toward Aquarius (on opposite side of sky).

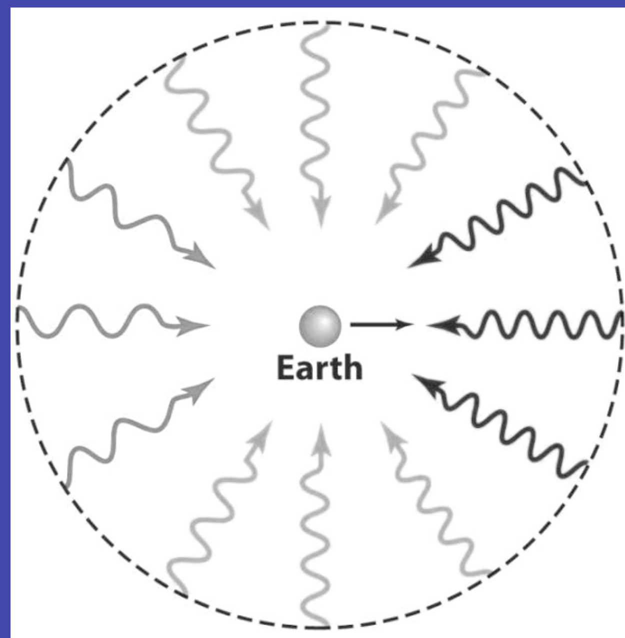
Temperature fluctuation = 1 part per 1000.

Interpretation: difference in temperature results from a **Doppler shift**.

Earth orbits Sun
(v = 30 km/sec)
Sun orbits center of the Galaxy
(v = 220 km/sec)
Galaxy falls toward Andromeda Galaxy
(v ≈ 50 km/sec)
Local Group falls toward Virgo Cluster
(v ≈ 200 km/sec)

Net motion: toward Leo, with a speed v ≈ 300 km/sec ≈ 0.001 c.

redshifted (Aquarius)



blueshifted (Leo)

Cosmic light from direction of Leo is slightly **blueshifted** (shorter wavelength, higher temperature).

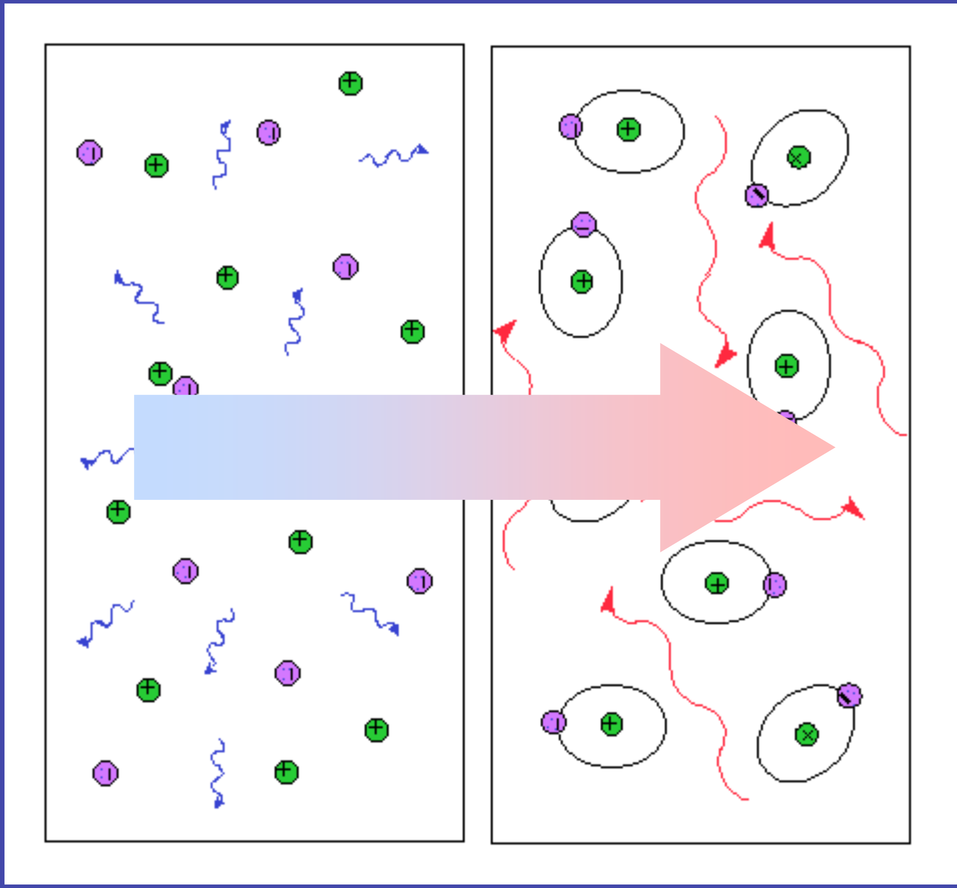
The CMB is slightly hotter toward Leo because of our motion **through** space.

Earth tugged by Sun,
Sun tugged by Galaxy,
Galaxy tugged by Andromeda,
Local Group tugged by Virgo Cluster.

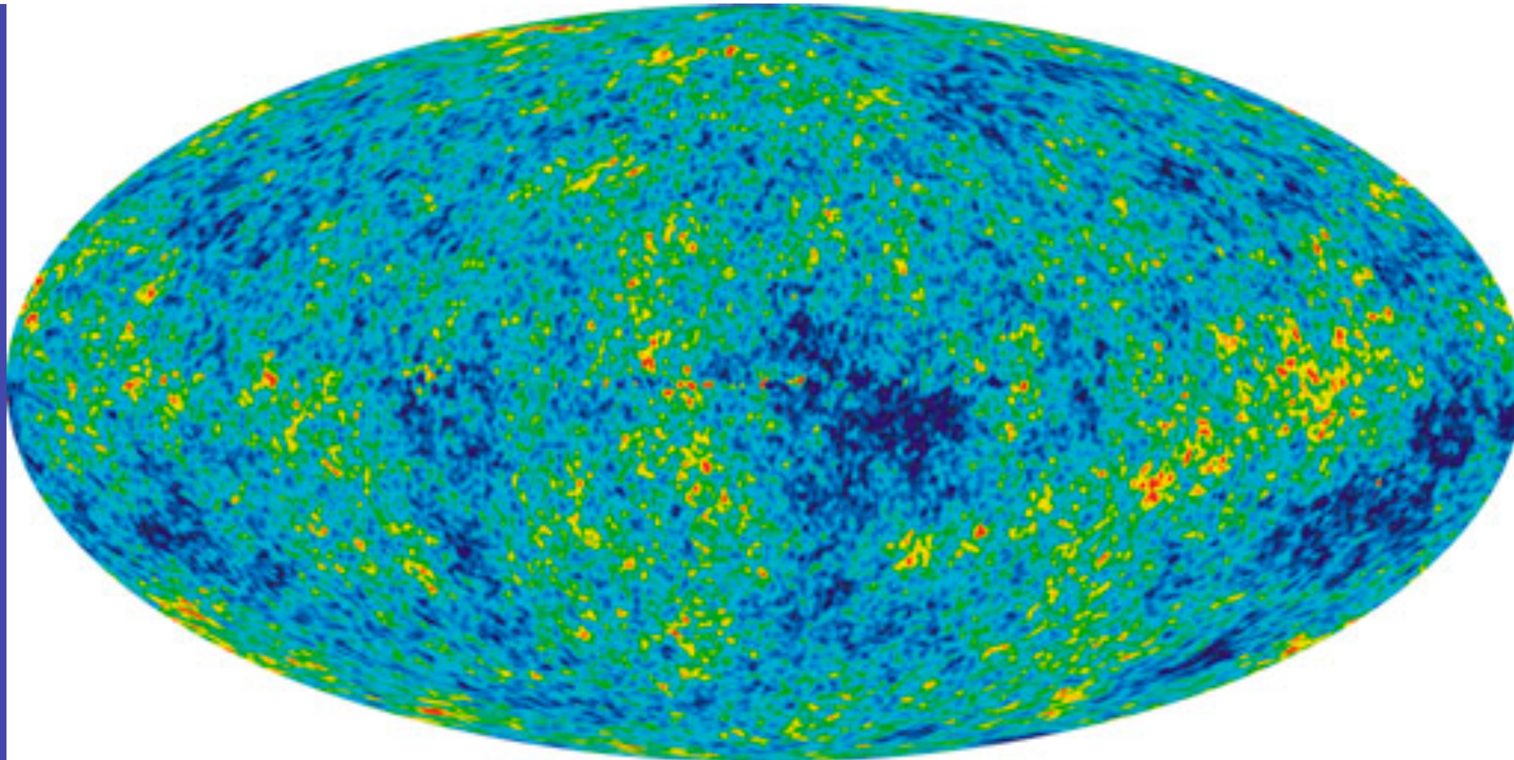
All this is happening locally, **right now**.

What can the CMB tell us about the early universe, at the time everything became transparent?

hot
dense
ionized
opaque



cool
tenuous
neutral
transparent



Observation: After subtracting the effect of our motion through space, CMB still shows hot & cold spots, about 1 degree across.

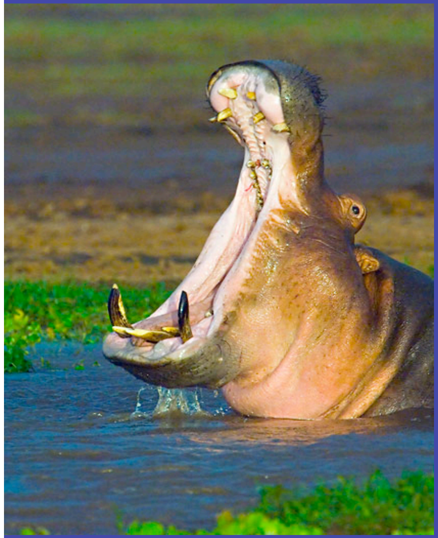
Temperature fluctuation = 1 part per 100,000

Interpretation: observed temperature fluctuations result from **density** fluctuations in the early universe.

Regions that were compressed had higher **density**, but also higher **temperature** (gases heat up as they are compressed).

Hot spots in the CMB are higher in temperature than **cold** spots by only 1 part per 100,000.

Implication: the **density fluctuations** in the early universe were also small (about 1 part per 100,000).



Why do we care about such tiny density fluctuations?

(If the Earth were smooth to within 1 part per 100,000, highest mountains would be just 70 yards above the deepest valleys.)

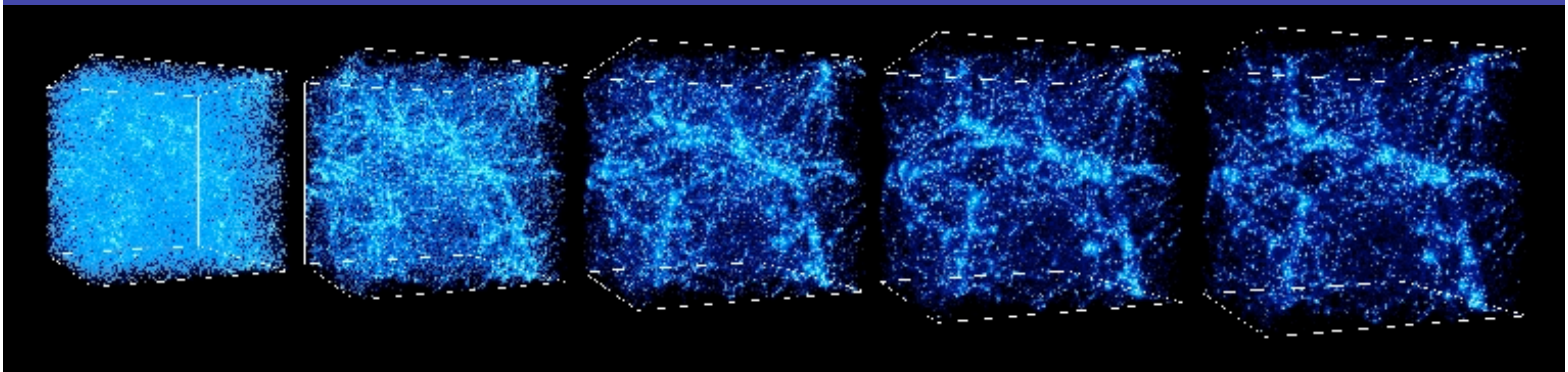
A region that was **slightly** denser than average will eventually become **much** denser than average; it's compressed by its own gravity.

A dense region that initially has a **small** mass will become **more massive** with time; its gravity attracts surrounding matter.

It’s possible (with a big computer) to simulate the growth of density fluctuations.

- Make a large (imaginary) box.
- Fill it with (simulated) massive particles.
- Make sure particles are packed a little closer together in some places than others.

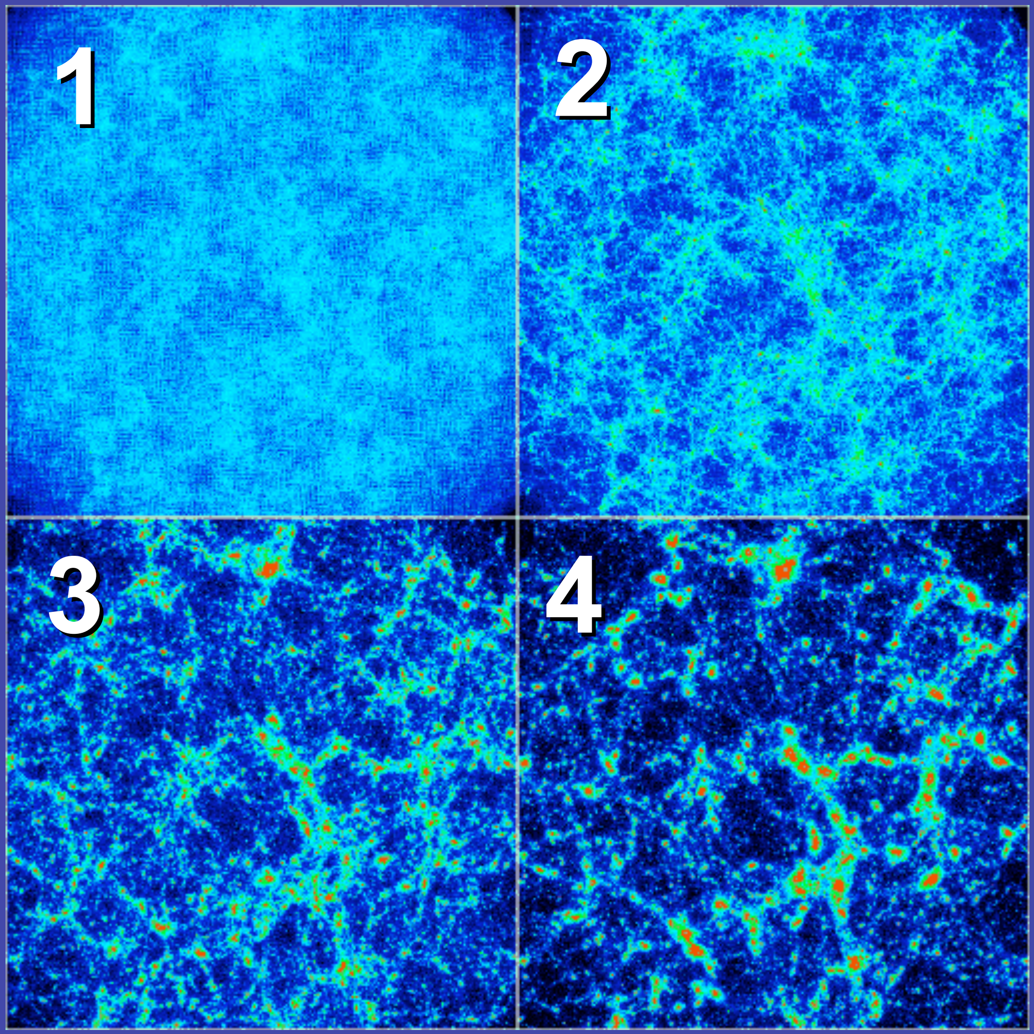
then → now



redshift 29 → redshift 0

(The size of the box grows from 1.5 Mpc to 43 Mpc.)

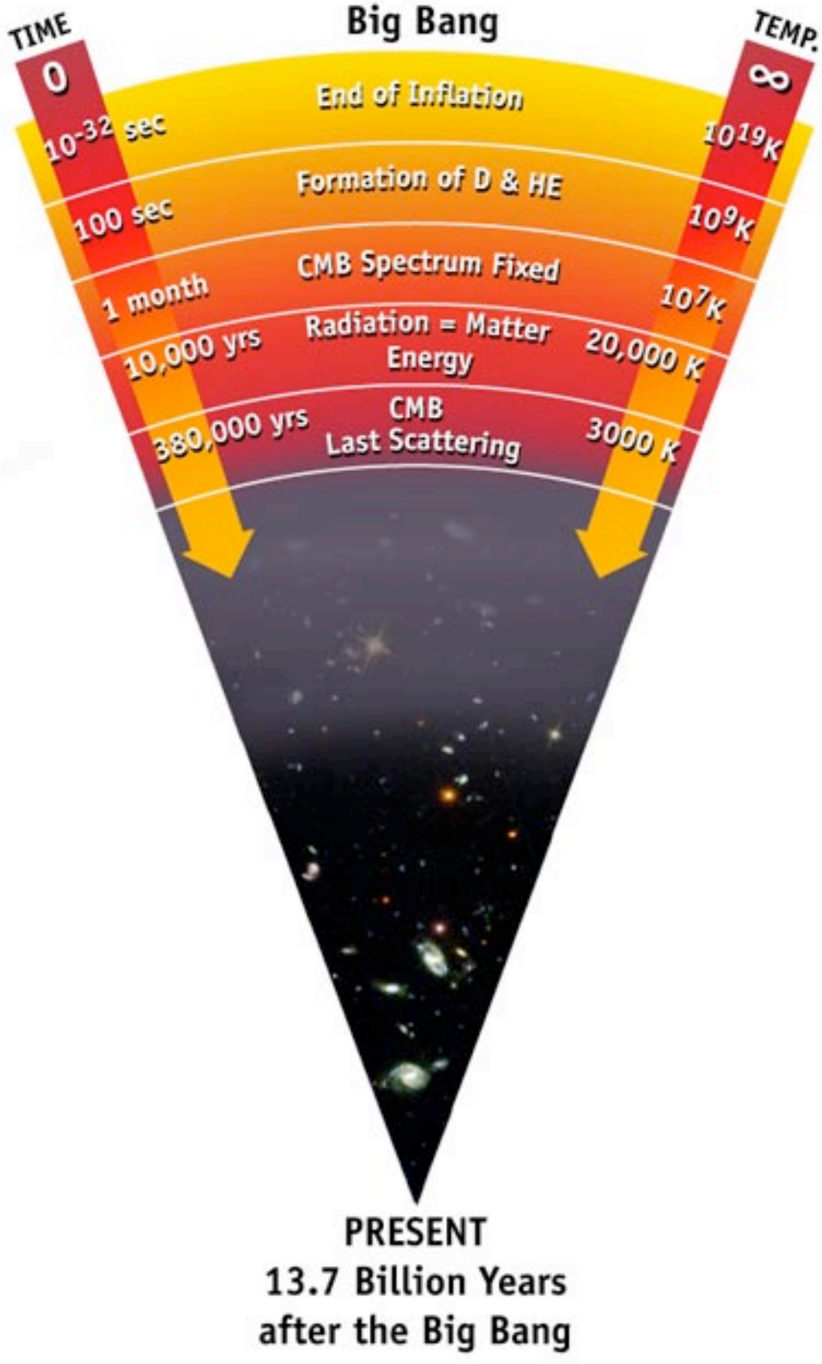
Generic result: matter distribution goes from smooth to lumpy.



"The past is a foreign country; they do things differently there." – L. P. Hartley

The past ($t \approx 400{,}000$ years):
Hot, dense, opaque, nearly homogeneous.

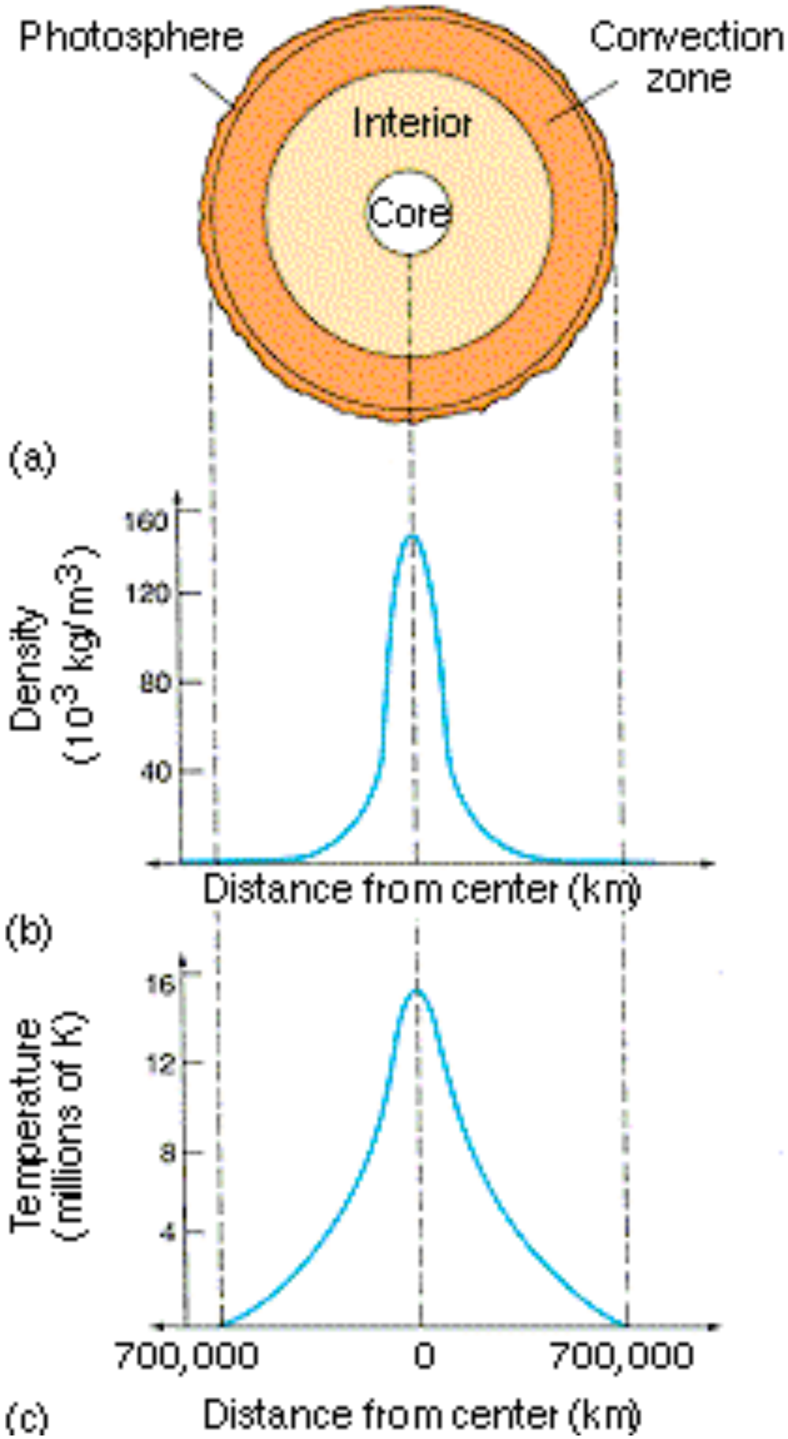
Now ($t \approx 14$ billion years):
Cold background radiation, low average density, mostly transparent, very lumpy



What lies beyond the surface of the "fog"?

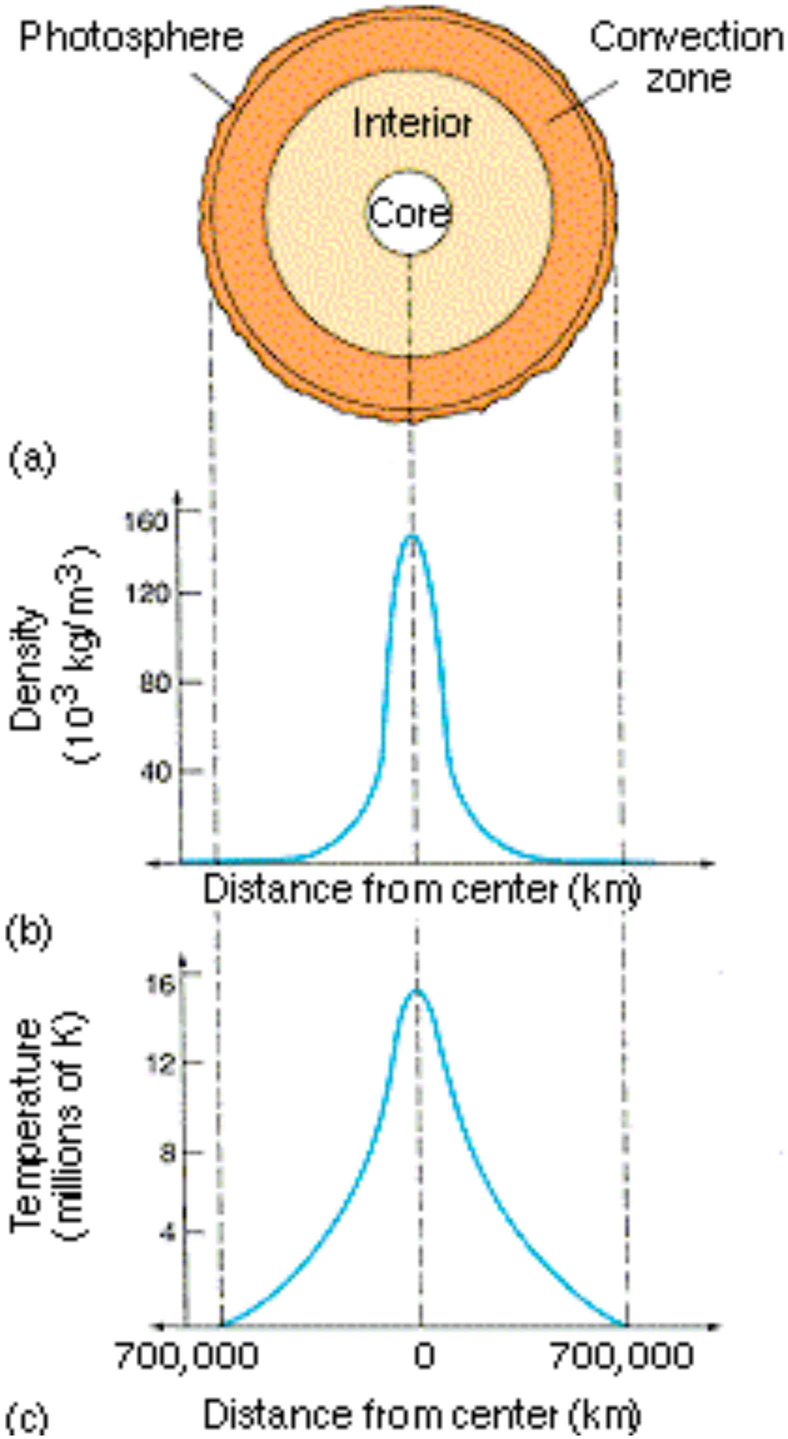
Since the very early universe was opaque, we can't see it directly.

Can we deduce **indirectly** what the universe was like then?



There is hope!

The Sun is opaque, but from our knowledge of physics, we can deduce what it’s like inside.



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