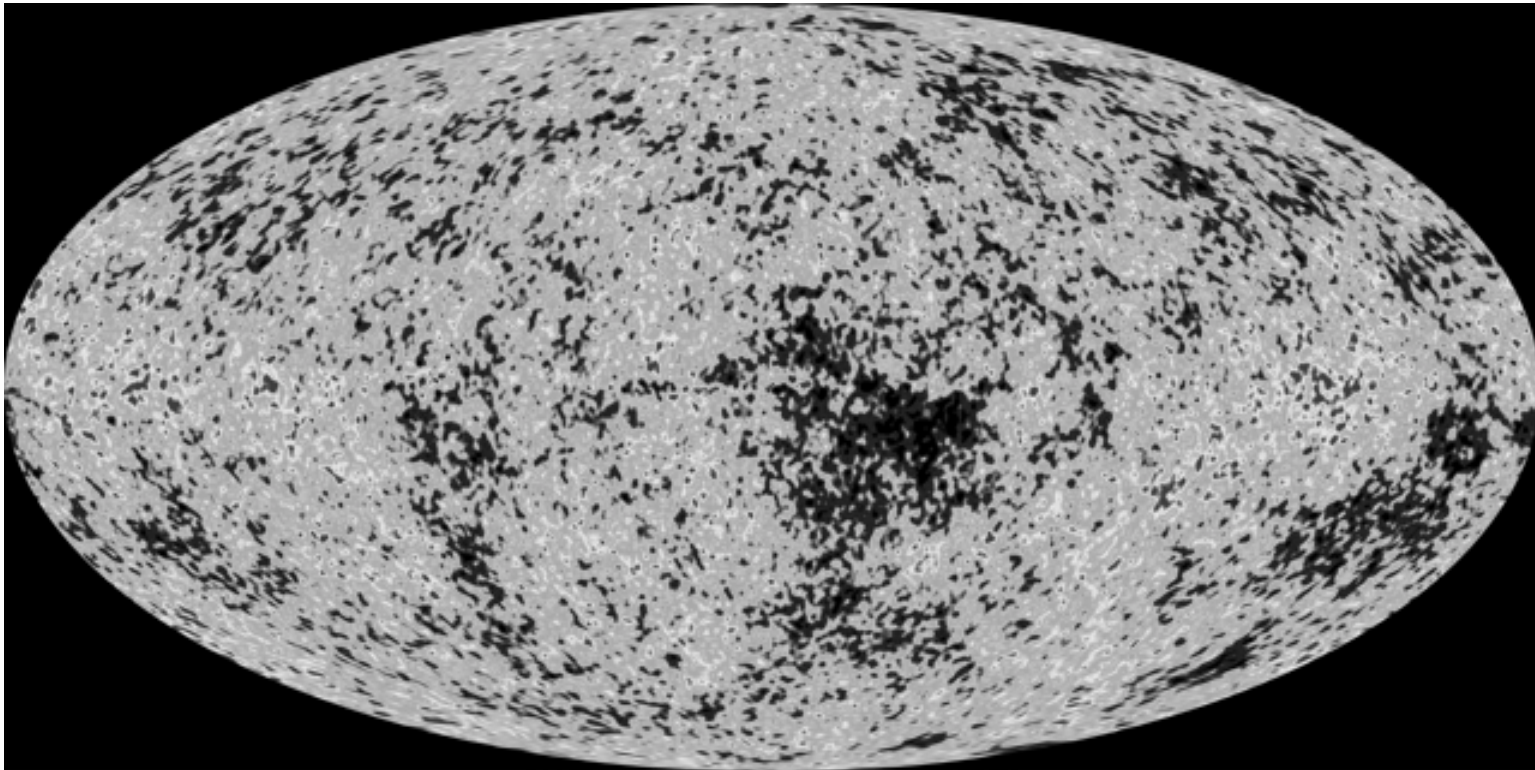


Galaxy A has a redshift of 0.3. Galaxy B has a redshift of 0.6. From this information and the existence of the Hubble Law you can conclude that

- A) Galaxy B is two times further away than Galaxy A.
- B) Galaxy A is two times further away than Galaxy B
- C) Galaxy A is four times further away than Galaxy B.
- D) Galaxy B is four times further away than Galaxy A.
- E) Galaxy A and Galaxy B are at the same distance.

Tests of the Big Bang



WMAP

Astronomy 1101

The Three Pillars of the Big Bang

Expansion of the Universe:

-
-

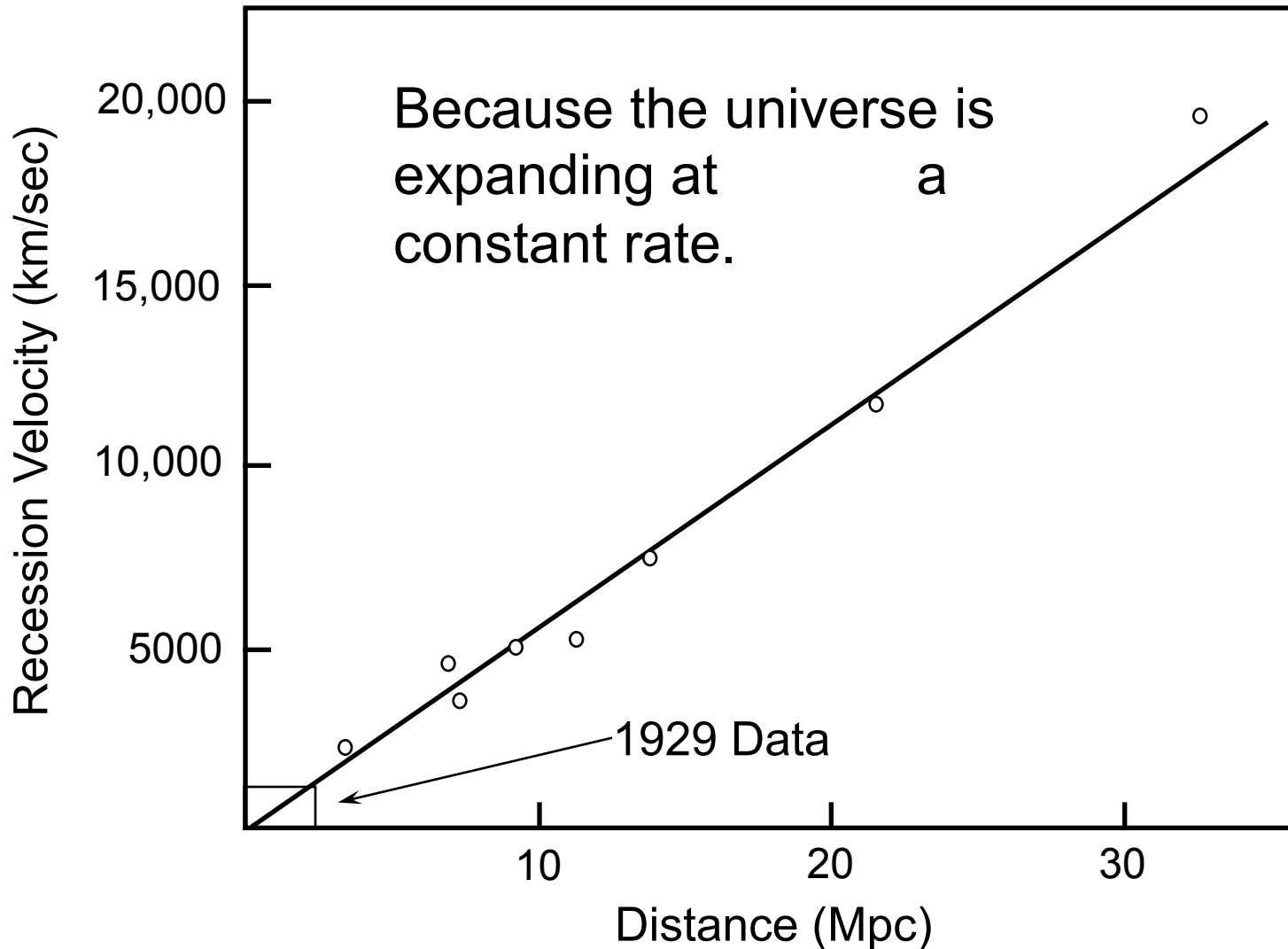
Primordial Nucleosynthesis:

-
- 2

Cosmic Background Radiation:

-

Hubble & Humason (1931)



$$D = V t$$

So

$$V = D/t$$

So, the slope is

$$1/t = H$$

Time since expansion started.

But...

Cosmic expansion is not expected to be constant over all times

If faster in the past:

-
- T_0 *overestimate* the age of the Universe.

If slower in the past:

- accelerated by some agent (e.g., a non-zero cosmological constant Λ)
- T_0 would *underestimate* the age of the Universe.

So, How Old is it Really?

Need two hard-to-measure numbers:

Hubble Parameter, H_0 :

- *now.*

Density Parameter, Ω_0 :

- How the matter & energy density affected the expansion rate in the past.
- Can include another term (Λ) that enhances the expansion rate, accelerates expansion.

These parameters are needed to determine the *expansion history, and thus the history of the universe.*

Best Estimate:

~13.8 Gyr

This number assumes:

- $H = 71$ km/sec/Mpc
- 30% from all forms of matter $\Omega_m \sim 0.3$, 70% (!) from the energy density associated with a non-zero Cosmological Constant, $\Omega \sim 0.7$.
- The universe will expand forever at an ever-increasing rate.

Independent check: This age is consistent with the ages of the oldest stars seen in globular clusters.

The Hot Big Bang

What we see Now:

- The Universe is cold & low density.
- Galaxies (matter) are getting further apart as space expands between them.
- As the Universe expands, it cools further.

In the past:

- Universe was smaller, hotter, & denser

Is there any evidence of this early hot, dense phase in the past?

Yes. The origin of Helium.

Pop I Stars (and the Sun):

- 70% H, 28% He, & ~2% metals
- Pop I metals come from Pop II star supernovae

Metal-poor Pop II Stars:

- 75% H, 25% He, & <0.01% metals
- He/H ~ 0.3

Where did all the He in Pop II stars come from?

- If from the first stars, where are all the metals that would have formed along with it?

Primordial Nucleosynthesis

Run the Universe back in time. Really far.

When the Universe was just 1 second old:

- Density: $\sim 1 \text{ g cm}^{-3}$
- Temperature: 10 Billion K
- Too hot for atomic nuclei to exist
- Only free protons, neutrons, electrons, & photons
- 1 neutron for every 5 protons

Hot, dense soup of sub-atomic particles & photons.

- As it expanded, it cooled off, nuclei could form.

Primordial Deuterium Formation

When the Universe was 2 minutes old:

- Temperature dropped to 1 Billion K

Neutrons & protons fuse into Deuterium (${}^2\text{H}$)

- All of the free neutrons go into making Deuterium nuclei
- Leftover protons stay free as Hydrogen nuclei
- Proportions: about 1 ${}^2\text{H}$ for every 4 protons (H)

Soup of mostly H and ${}^2\text{H}$ along with a mix of photons, electrons & other particles.

Primordial Helium Formation

Most of the ^2H fuses to form ^4He nuclei

- Other reactions make ^3He , Li, Be, and B in very tiny quantities

When the Universe was 4 minutes old:

- Much of the Deuterium turned into ^4He
- Left with tiny traces of Deuterium and other light elements.

The Universe cooled so much that fusion simply stopped. So, how much He & D is produced, and does that jive with observations?

Aftermath

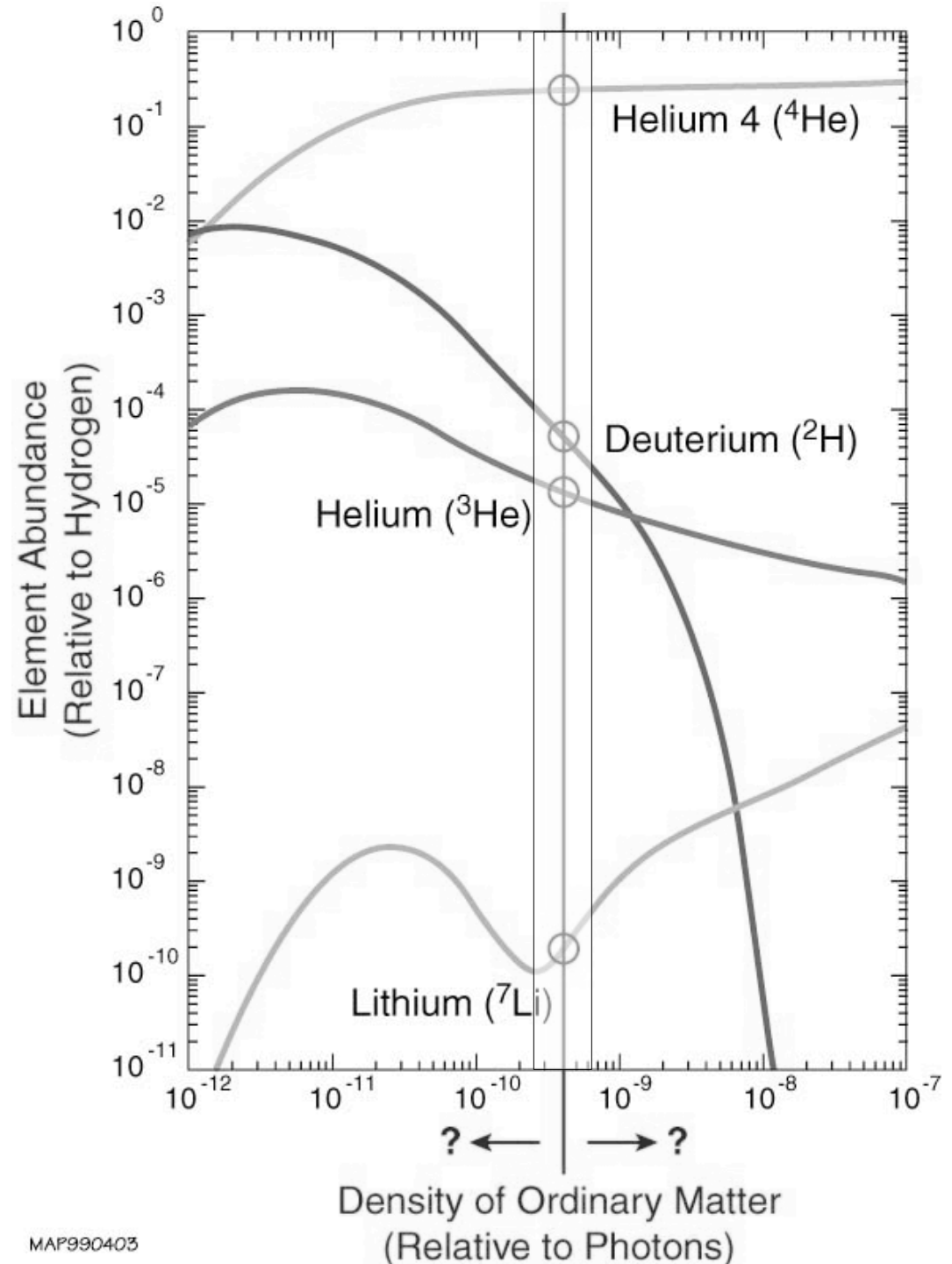
When Primordial Nucleosynthesis stopped:

Predictions:

- ${}^4\text{He}/\text{H} = 0.3$
- $\text{D}/\text{H} = 0.0001\text{--}0.1\%$

Observations:

- ${}^4\text{He}/\text{H} = 0.3$
- $\text{D}/\text{H} = 0.001\text{--}0.02\%$



Current Status

Predictions of Primordial Nucleosynthesis agree well with current observations:

Observations:

- Measurements of D, Li, & other elements are very difficult.

Theory:

- Everything depends on how well you know ratio of n s and p s and what the density is. That, plus fusion physics and particle physics.

The Hot Early Universe

After Nucleosynthesis, the Universe stays hotter than 3000 K for a long time:

- electrons & nuclei cannot combine to form neutral atoms
- Universe remains *fully ionized*
- Free electrons **easily** scatter photons

Universe is opaque to light during this time.

- Filled with a hot ionized fog of ions & free electrons.

Foggy, opaque, hot universe,
filled with ionized gas,
free electrons that easily,
scatter light.

Foggy tree picture

Blackbody Radiation

The Early Universe is filled with a hot, opaque ionized gas:

- Has a perfect blackbody spectrum,
- with a characteristic temperature, T

As the Universe expands, it cools:

- Photons *redshift*
- The peak of the spectrum shifts *redward*
- The blackbody temperature *drops*

Epoch of Recombination

When the Universe is $\sim 300,000$ years old:

Temperature drops below ~ 3000 K:

- electrons & nuclei combine to form atoms
- not enough free electrons to scatter photons

Universe suddenly becomes *transparent* :

- Photons stream through space without scattering.
- What's left: Photon Spectrum: 3000 K Blackbody

Before Recombination:

Foggy, opaque, hot universe, filled with ionized gas, free electrons, that easily scatter light.

Foggy picture

Time $< \sim 300,000$ yrs.
Temperature $> \sim 3000$ K.

After Recombination:

Clear, cool universe, after electrons have combined with protons to make neutral H.

Clear picture

Time $> \sim 300,000$ yrs.
Temperature $< \sim 3000$ K

Cosmic Background Radiation

After Recombination, the Universe is filled with diffuse, relic blackbody radiation.

As the Universe expands further:

- Blackbody photons *redshift*.
- Spectrum peak shifts to *redder wavelengths*, and hence *cooler* temperatures.

By today, the spectrum is redshifted by a factor of ~ 1000 , from 3000K down to T  3K

Discovery

1965: Penzias & Wilson (Bell Labs)

- Mapping sky at microwave wavelengths.
- Found a faint microwave background noise.
- First thought it was equipment problems (noisy amplifiers, pigeons in the antenna).
- Finally determined it was *cosmic* in origin.

Won the Nobel Prize in 1978 for discovering the Cosmic Background Radiation.



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But, is it **Really *Blackbody*** Radiation?

The Big Bang model makes very specific predictions:

- the spectrum is a (nearly) *perfect blackbody*
- characterized by a *single temperature*

Observations:

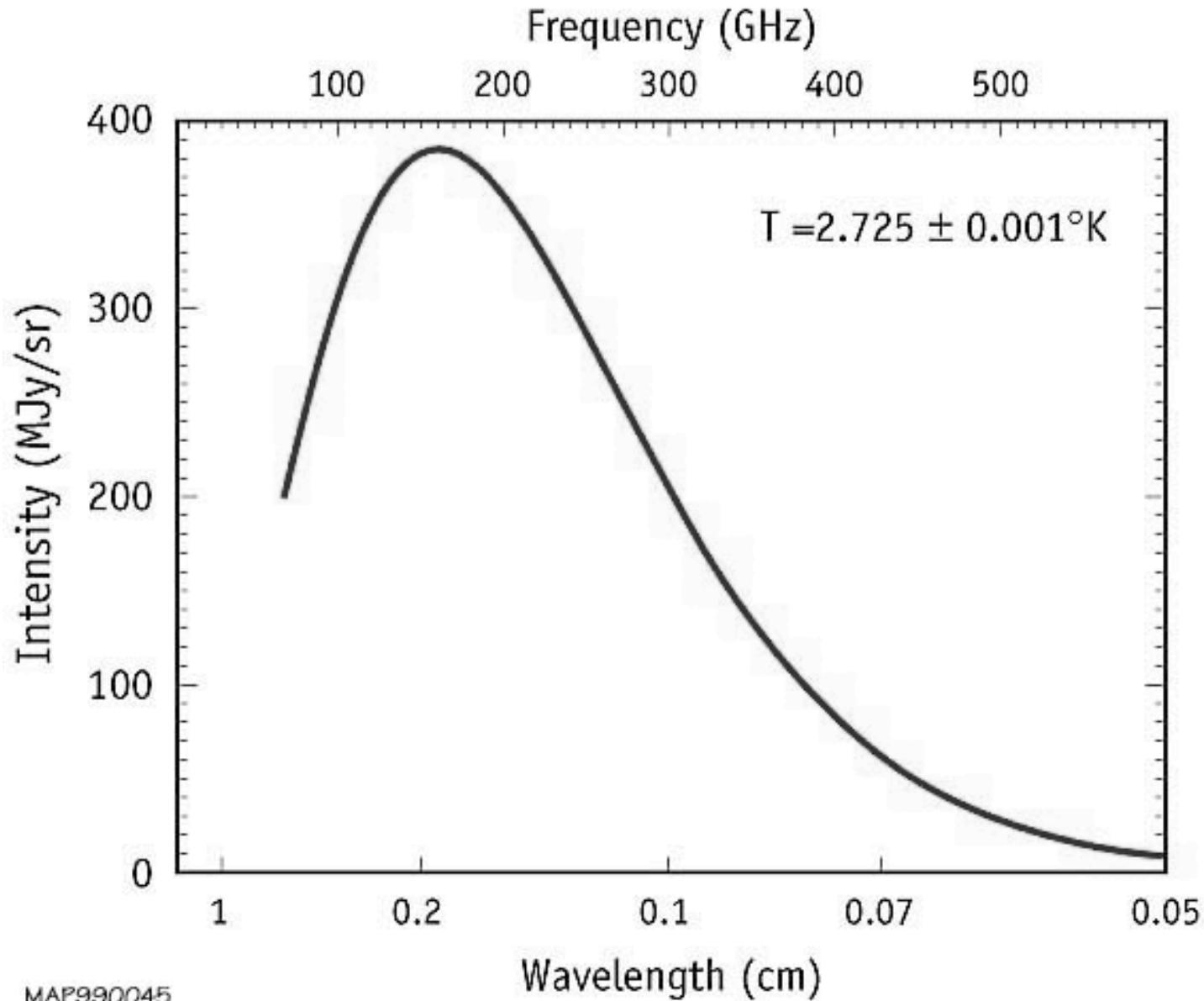
- Best measurements with instruments at the South Pole, high altitude, or in orbit.
Experiments with balloons, rockets, radio antennas, and satellites.

Spectacular Confirmation

Current data all spectacularly confirm the predictions of the Big Bang:

- (nearly) Perfect blackbody spectrum
- A single temperature, $T = 2.725 \pm 0.001$ K
- Uniformly fills the Universe (isotropy, homogeneity)

Cosmic Background Spectrum

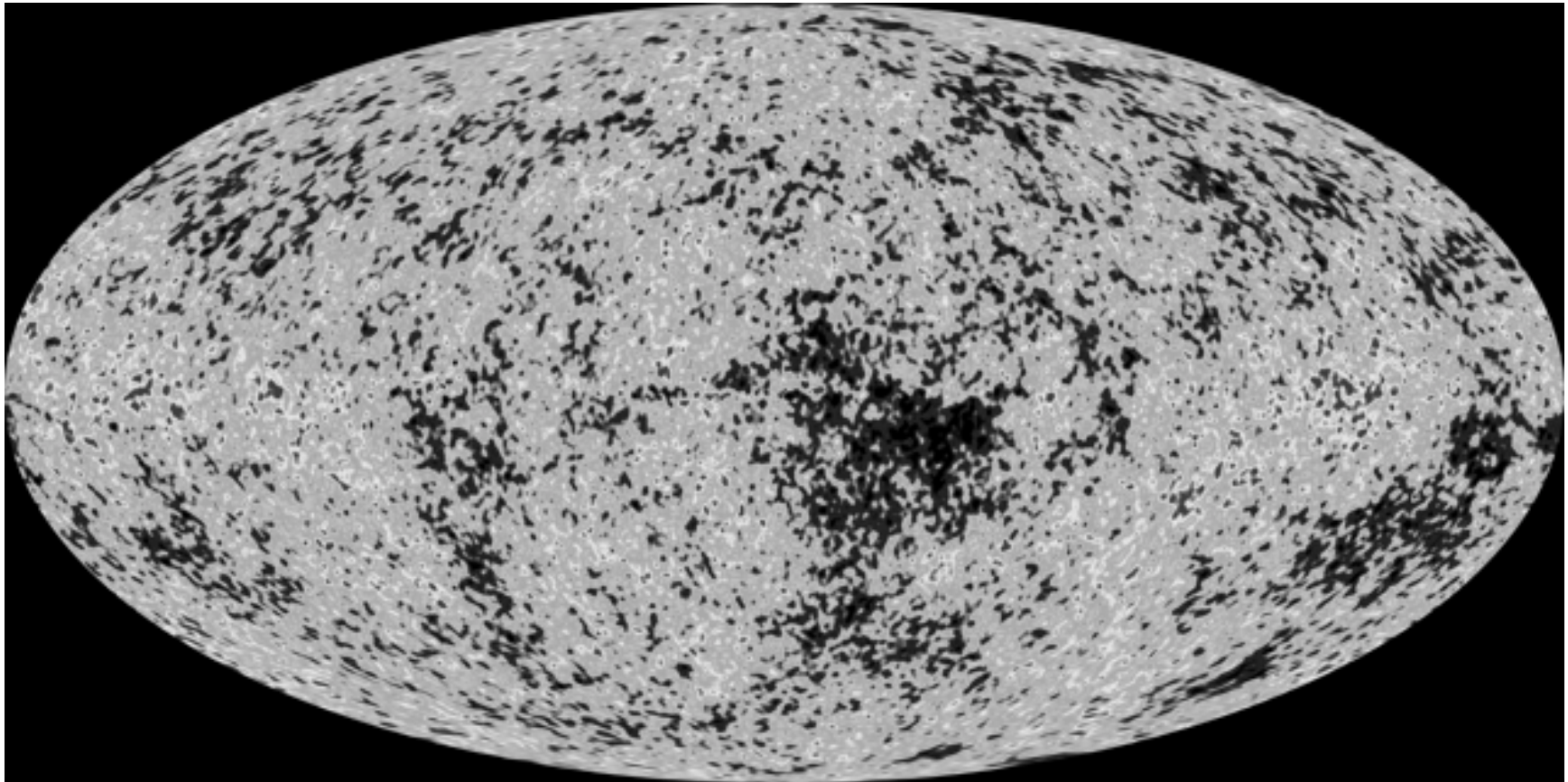


Connection with Structure.

The Cosmic Microwave Background is not **perfectly** smooth:

- Fine structure at part in 10^5 level.
- The physical scale of the hot and cool spots and the hotness and coolness of the spots are related to the large-scale structure we see today in the galaxies.
- These are primordial fluctuations in the fireball. They are the source of structure.
- If the universe had been **perfectly** smooth, structure would not exist.

WMAP Cosmic Microwave Background map



1 part 10^5 roughness

Evidence for the Big Bang

Expansion of the Universe: CONFIRMED

- Hubble's Law
- Age is consistent with the oldest stars

Primordial Nucleosynthesis: CONFIRMED

- Helium & Deuterium in the right amounts

Cosmic Background Radiation: CONFIRMED

- Perfect blackbody with a single temperature

So, How Old is it Really?

Need two hard-to-measure numbers:

Hubble Parameter, H_0 :

- How fast the universe is expanding *now*.

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- The universe will expand forever at an ever-increasing rate.

Independent check: This age is consistent with the ages of the oldest stars seen in globular clusters.

Taken together, our current estimates of the Hubble constant (H_0) and the density parameter (Ω_0) tell us that the age of the Universe is about

- A) 14 billion years old.
- B) 14 trillion years old.
- C) 14,000 years old.
- D) 14 years old.
- E) 14 million years old.