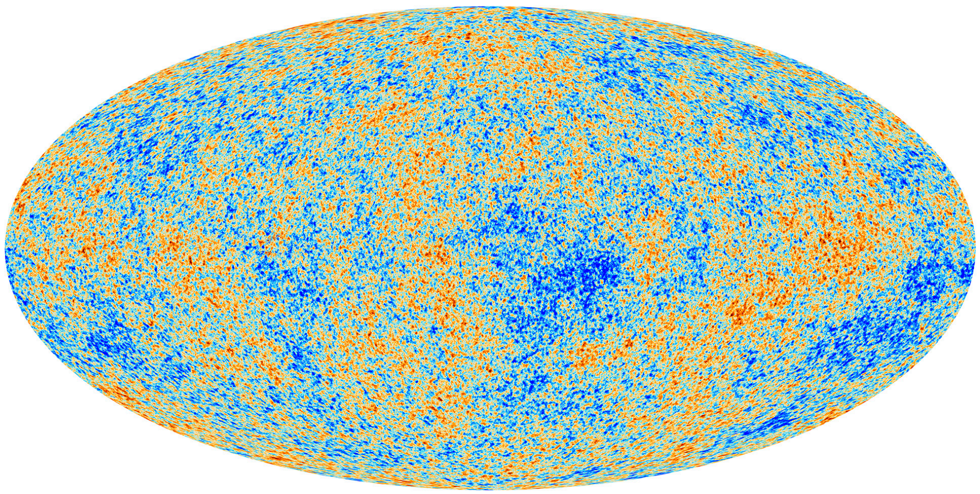
[23] Evidence for the Big Bang (4/26/18)

Upcoming Items

- Homework #6 due May 8.
- Read Ch. 22.3–22.4 by next class and do the self-study quizzes

CMB, from the Planck satellite



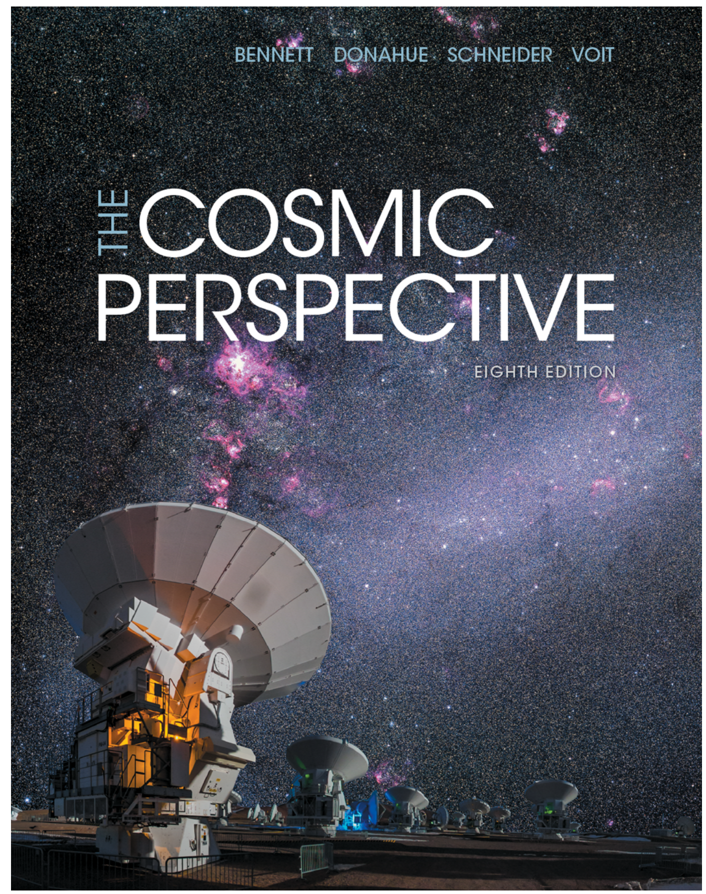
LEARNING GOALS

Chapter 22.2

For this class, you should be able to…

… *explain how the cosmic microwave background informs cosmologists about details regarding the universe's physical structure at an early time;*

… *explain why the Big Bang theory predicts the early universe should have contained 75% hydrogen and 25% helium by mass.*



Any astro questions?

Evidence for the Big Bang

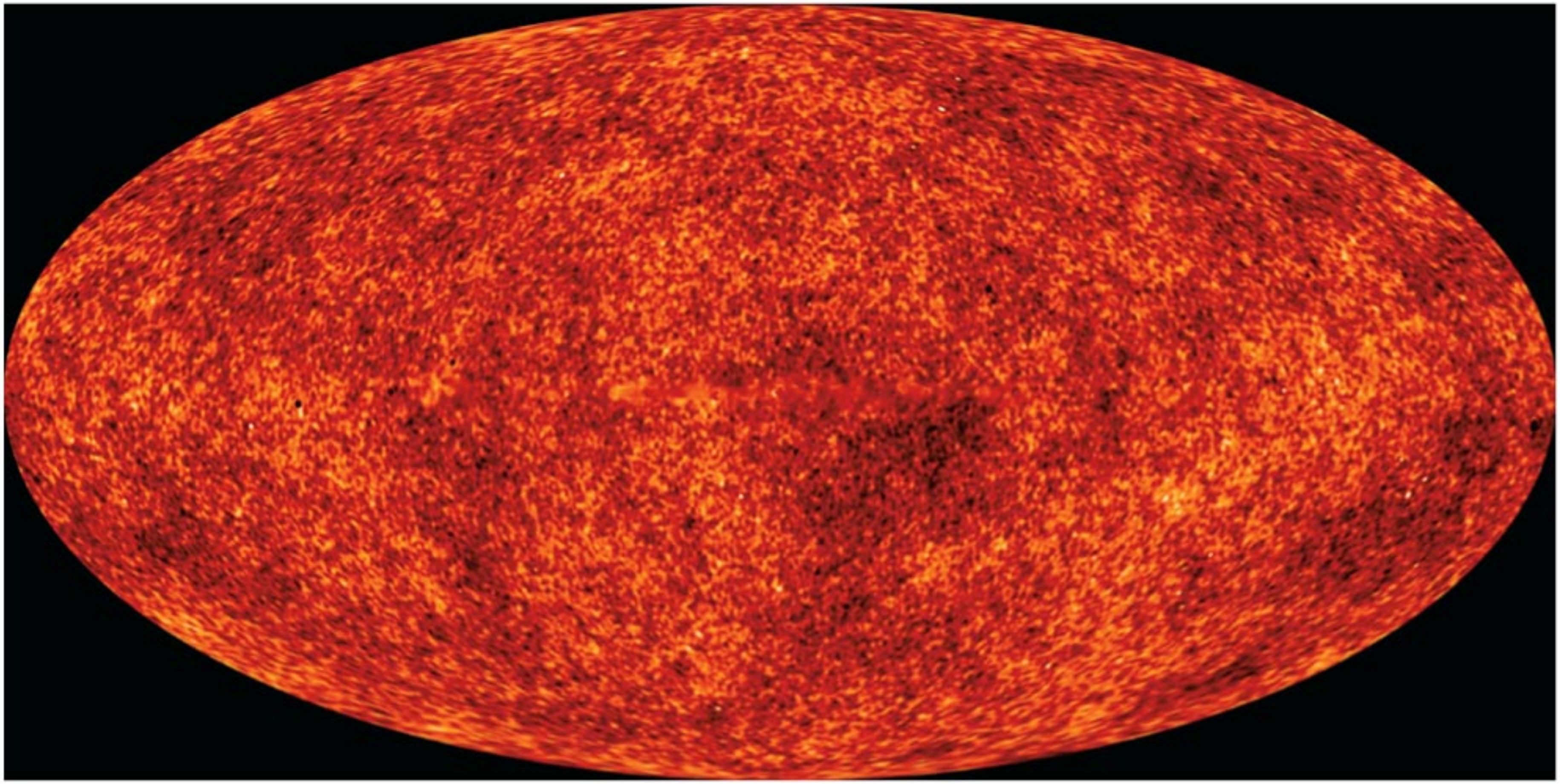
1. Cosmic Microwave Background (CMB).
   - Nearly perfect black body spectrum of temperature 2.275 K.
     - Measured by various missions, including COBE, WMAP, & Planck.
     - Deviations reflect density fluctuations in early universe ("sound waves").
       - Higher density (compression) gives lower relative temperature, & vice versa.
     - Power spectrum of fluctuations reveal geometry of universe and the normal and dark matter densities, among other things.
2. Abundance of helium.
   - Cooling rate and mass difference between proton and neutron determine how much helium is produced by fusion.
   - Expect 7:1 ratio of protons to neutrons, yielding 25% He by mass.
   - Other light-element abundances also strongly constrained.
   - All other elements formed by stars, cosmic rays, or humans!

Primary Evidence

1. We have detected the leftover radiation from the Big Bang.

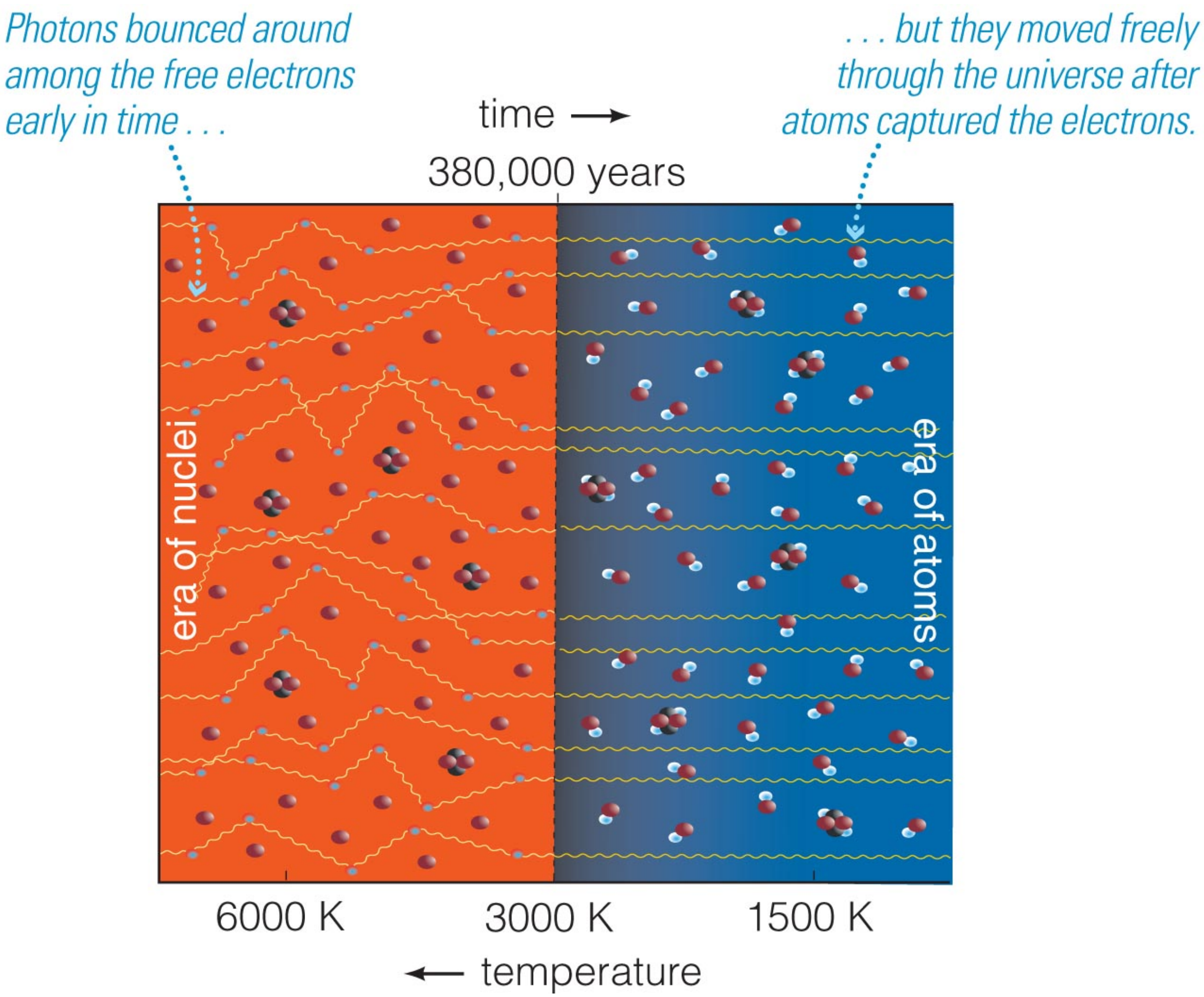
2. The Big Bang theory correctly predicts the abundance of helium and other light elements.

How do we observe the radiation left over from the Big Bang?



The ***cosmic microwave background (CMB)***—the radiation left over from the Big Bang—was detected by Penzias and Wilson in 1965.

Nobel Prize in Physics 1978.



Background radiation from Big Bang has been freely streaming across the universe since atoms formed at temperature ~3,000 K: *visible/IR at that time; microwave now*.

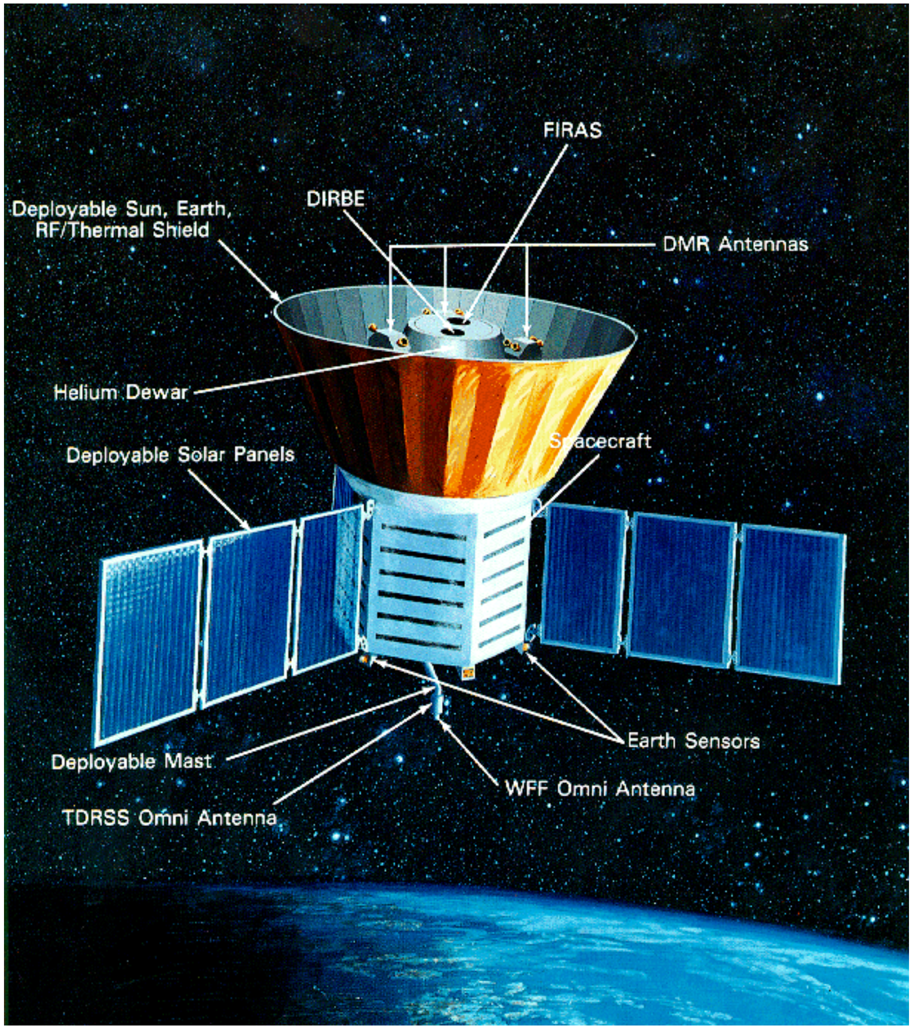
Penzias & Wilson

- These astronomers were attempting to study radio emissions from our galaxy using a sensitive antenna built at Bell Labs.
- Needed to characterize and eliminate all sources of noise.
- They never could get rid of a certain noise source… this noise had a characteristic temperature of about 3 K.
- They figured out that the noise was coming from the sky, and was approximately the same in all directions…
- This constituted crucial evidence that the universe really was hot and dense in the past.

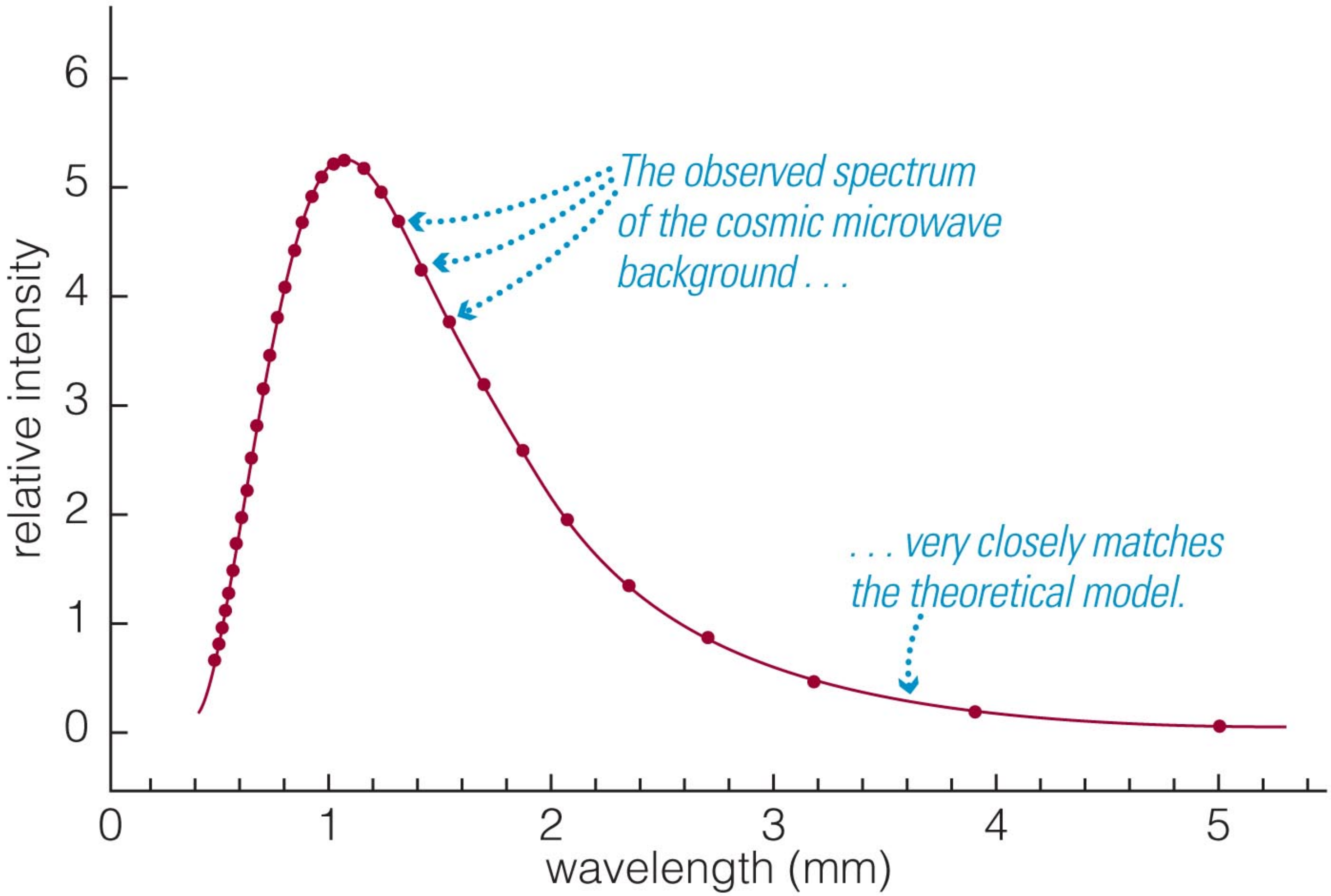
Cool fact: if you tune your TV set between channels, a few percent of the "snow" that you see on your screen is noise caused by the background of microwaves…

The COBE Mission

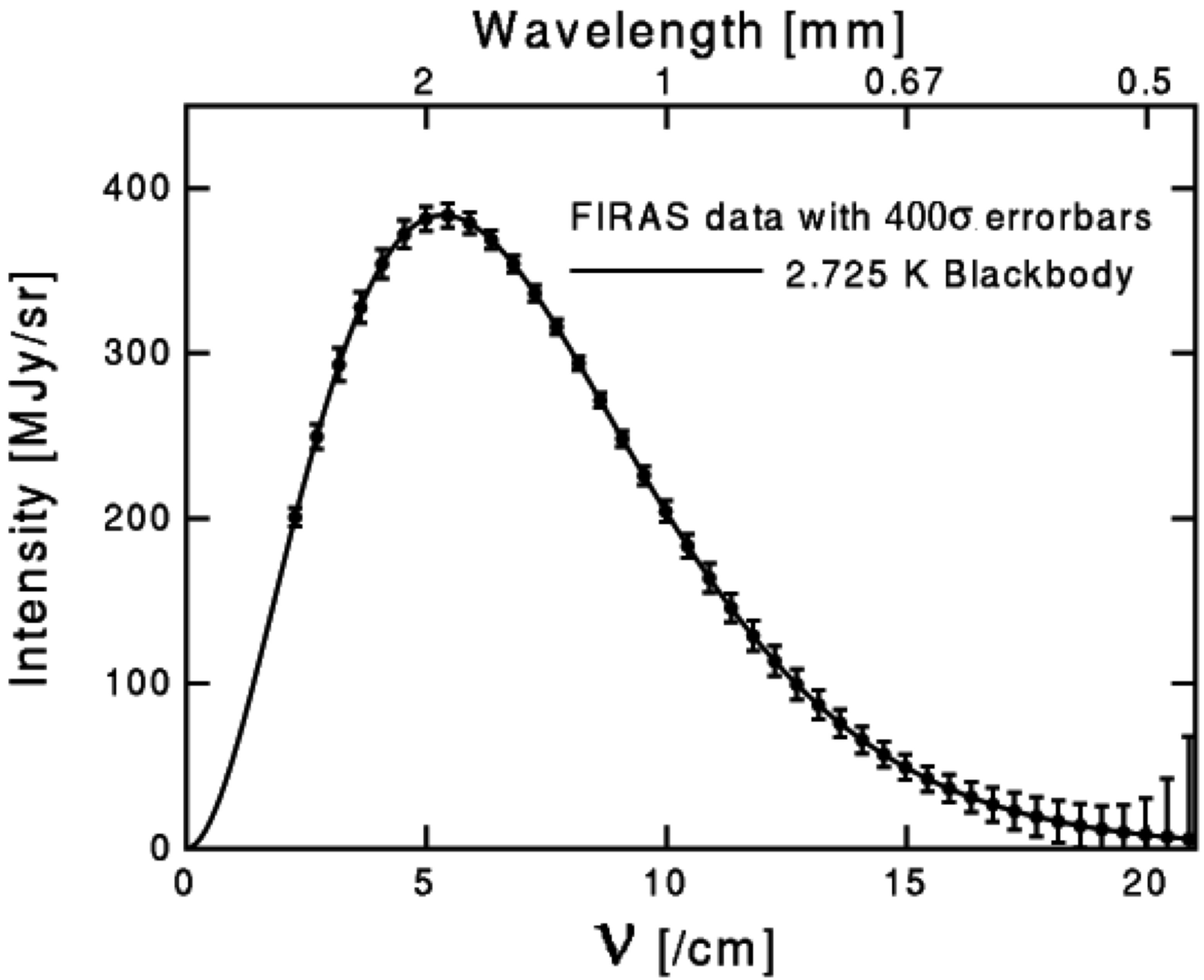
Nobel Prize in Physics 2006.



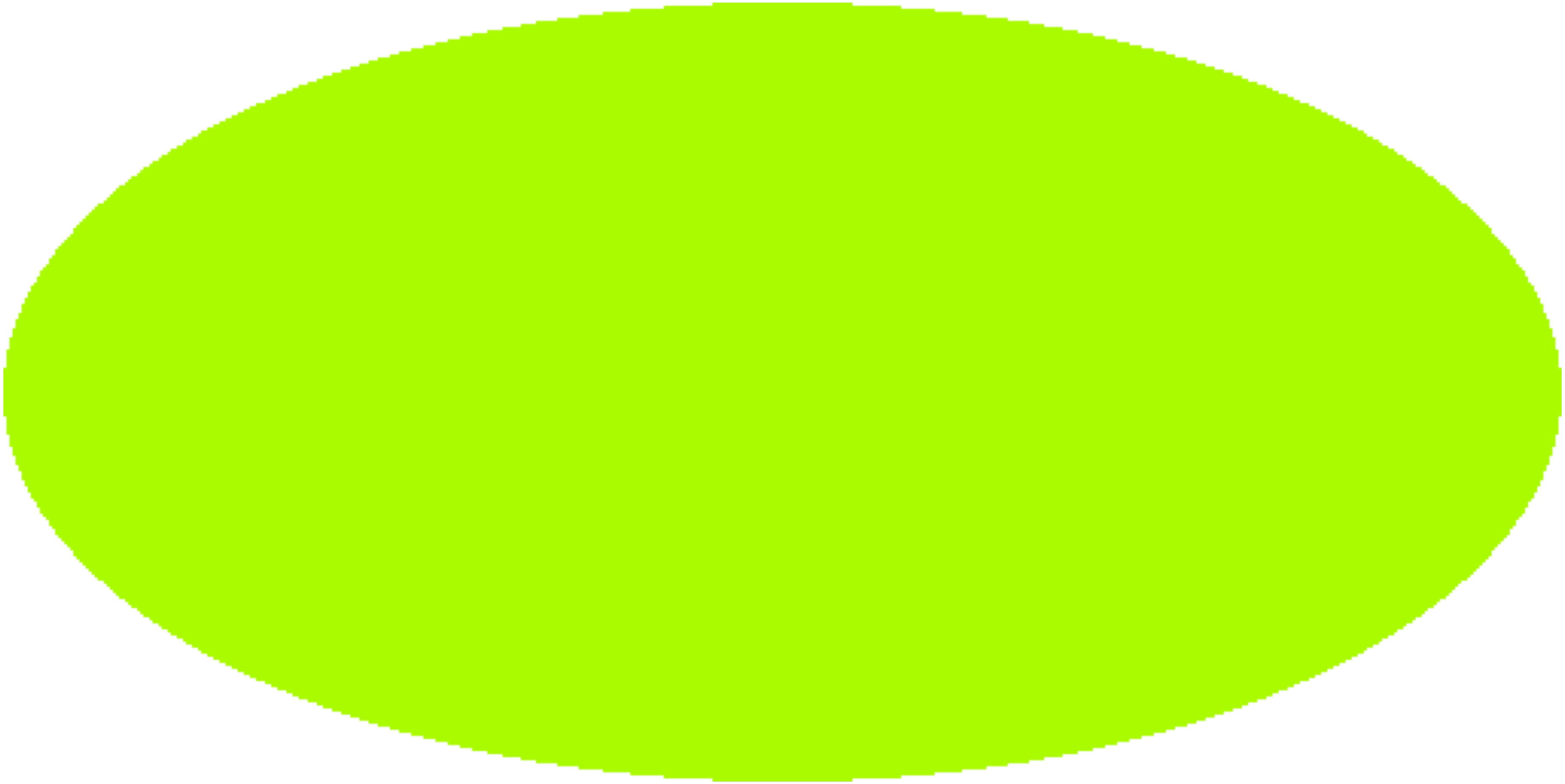
- COsmic Background Explorer.
- Built right next door at NASA Goddard Space Flight Center!
- Launched in November 1989.
- Purpose: survey IR and micro-wave emission across whole sky and characterize the CMB.
- Instruments:
  - FIRAS (Far Infrared Absolute Spectrophotometer): spectrum.
  - DMR (Differential Microwave Radiometer): anisotropy.
  - DIRBE (Diffuse Infrared Background Experiment): dust.



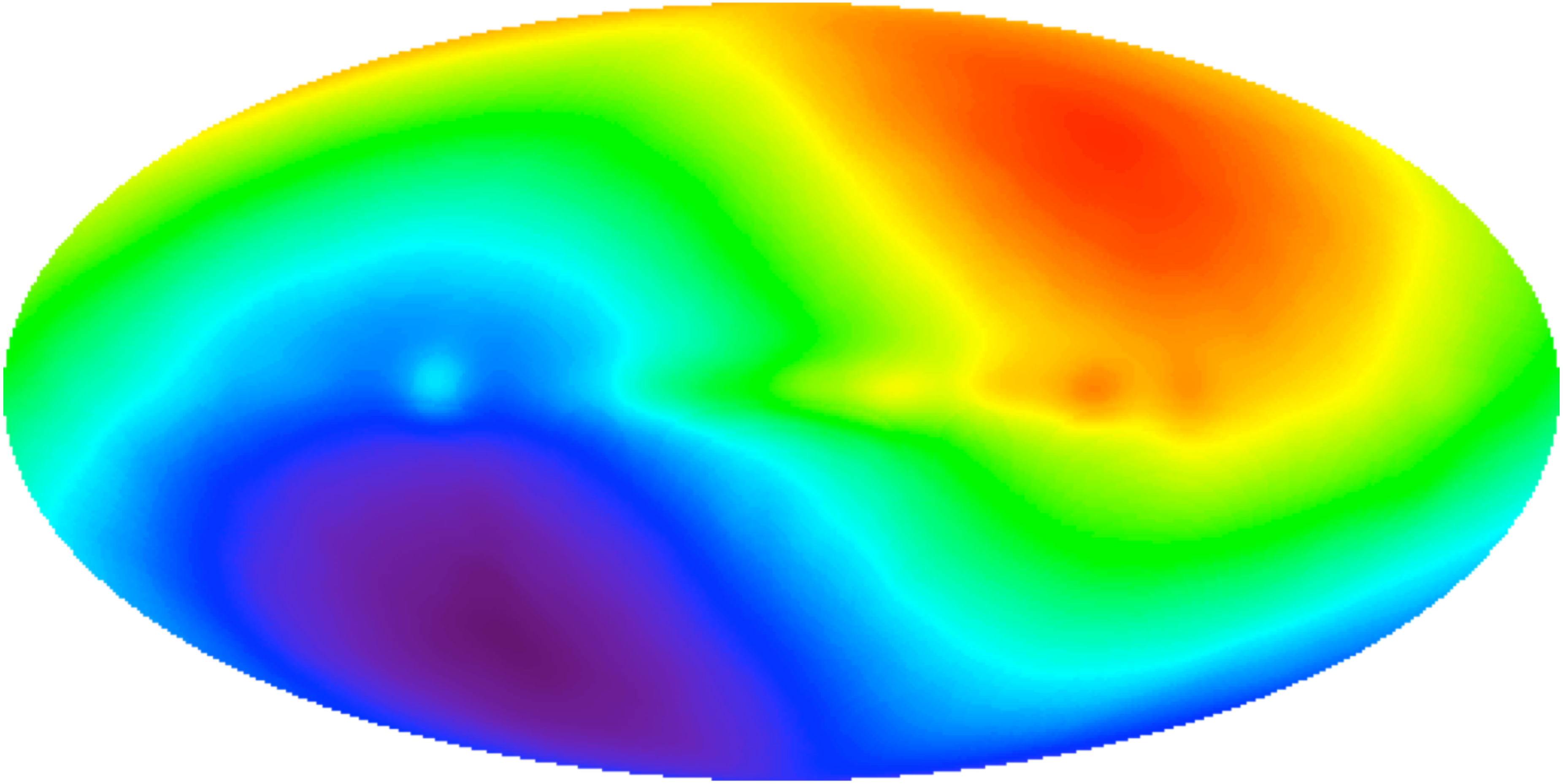
- Background has an almost perfect thermal radiation spectrum at temperature 2.725 K.
- Expansion of universe has redshifted thermal radiation from Big Bang to ~1,000 times longer wavelength: *microwaves*.



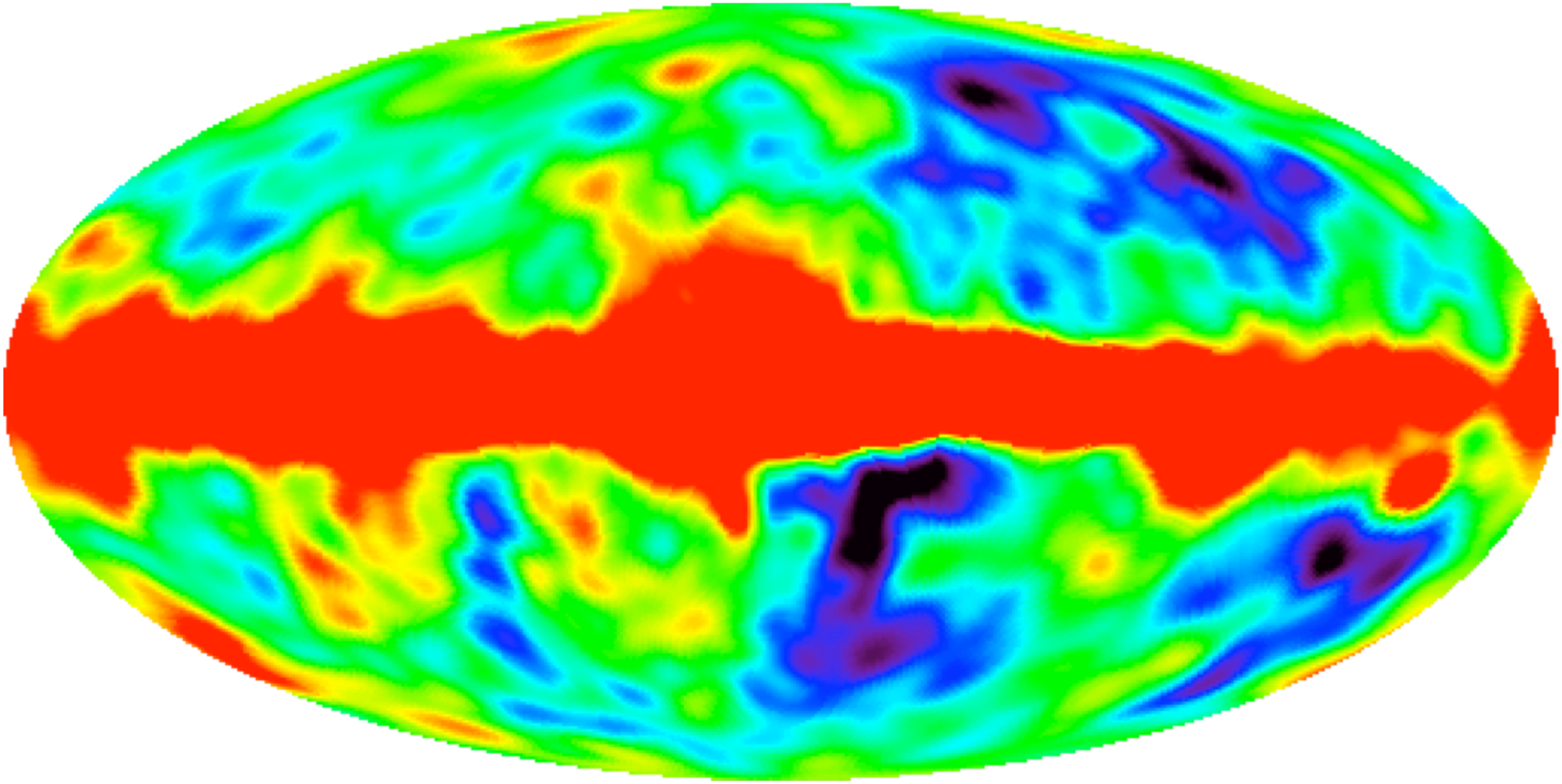
The error bars have been multiplied by a factor of 400!



- Almost uniform intensity of microwaves in all directions (isotropic 2.725 K black-body radiation).
- Here, blue = 0 K, red = 4 K…all green on this scale!

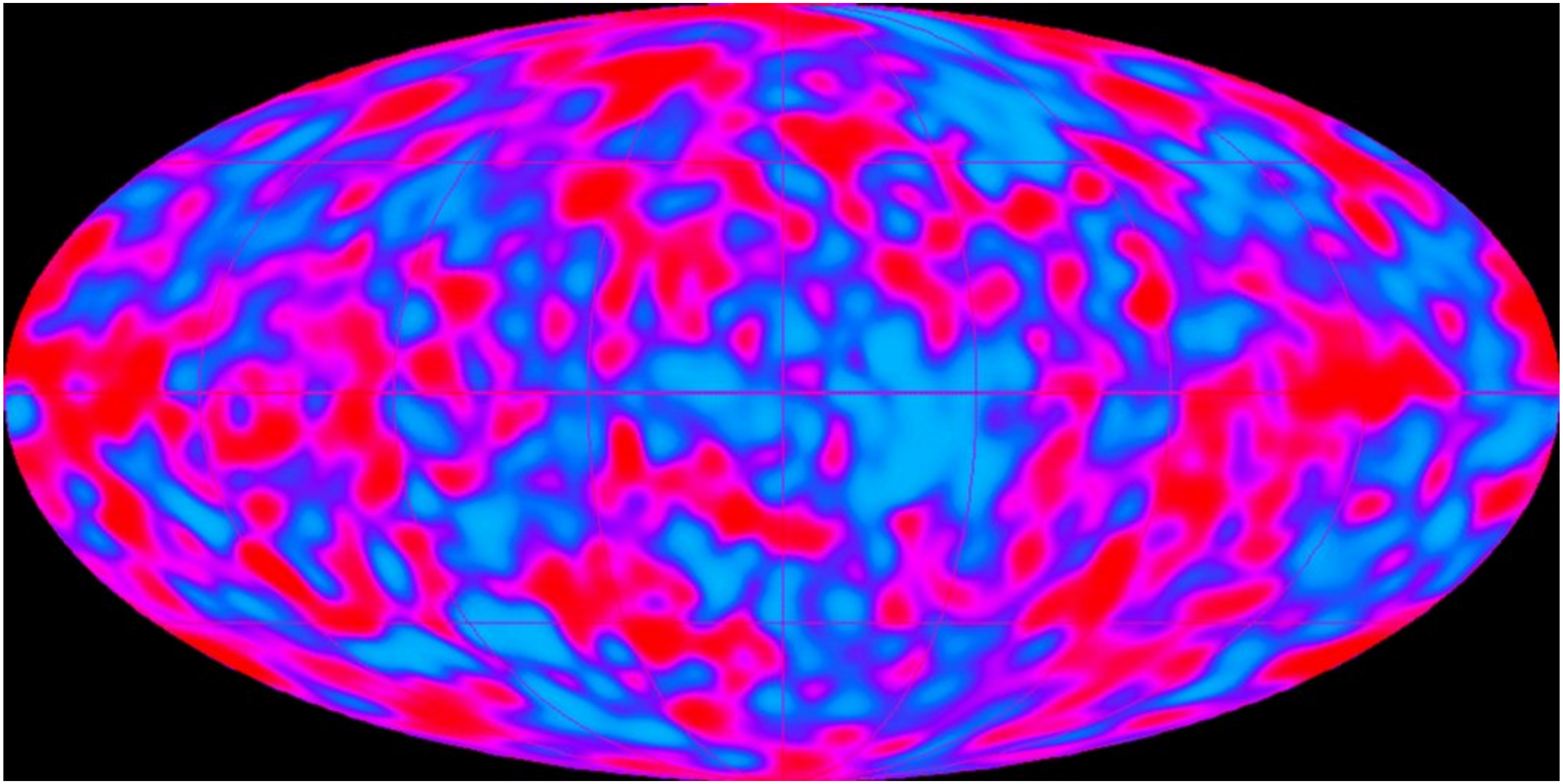


- Zoom in: blue = 2.721 K, red = 2.729 K.
- Find “dipole anisotropy” that results from the motion of the Sun relative to the rest frame of the cosmic microwave background.



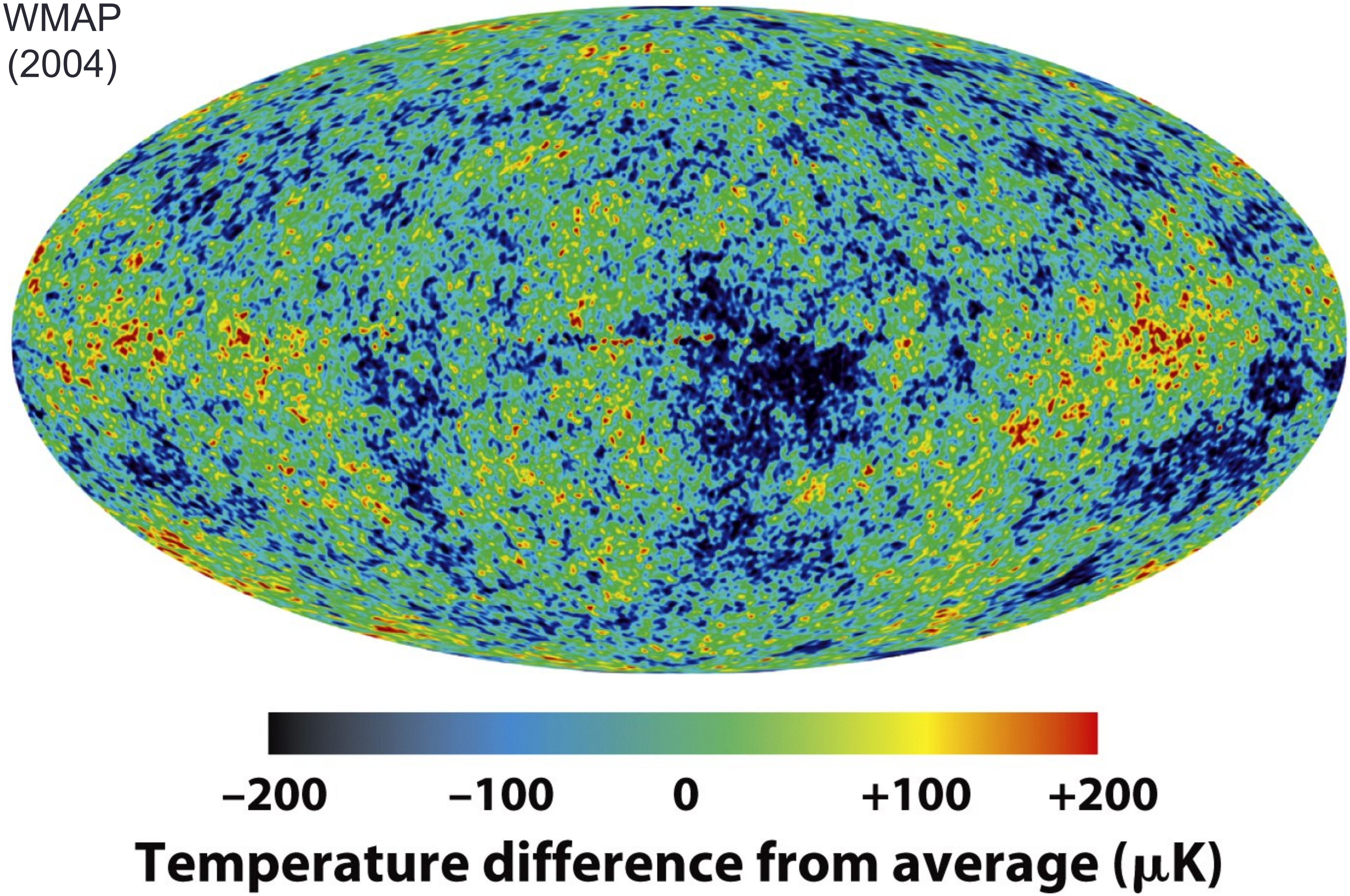
- Removing the dipole and setting the resolution to $\Delta T = 0.0002\ \mathrm{K}$ reveals the Milky Way's emission (what Penzias and Wilson were looking for!).

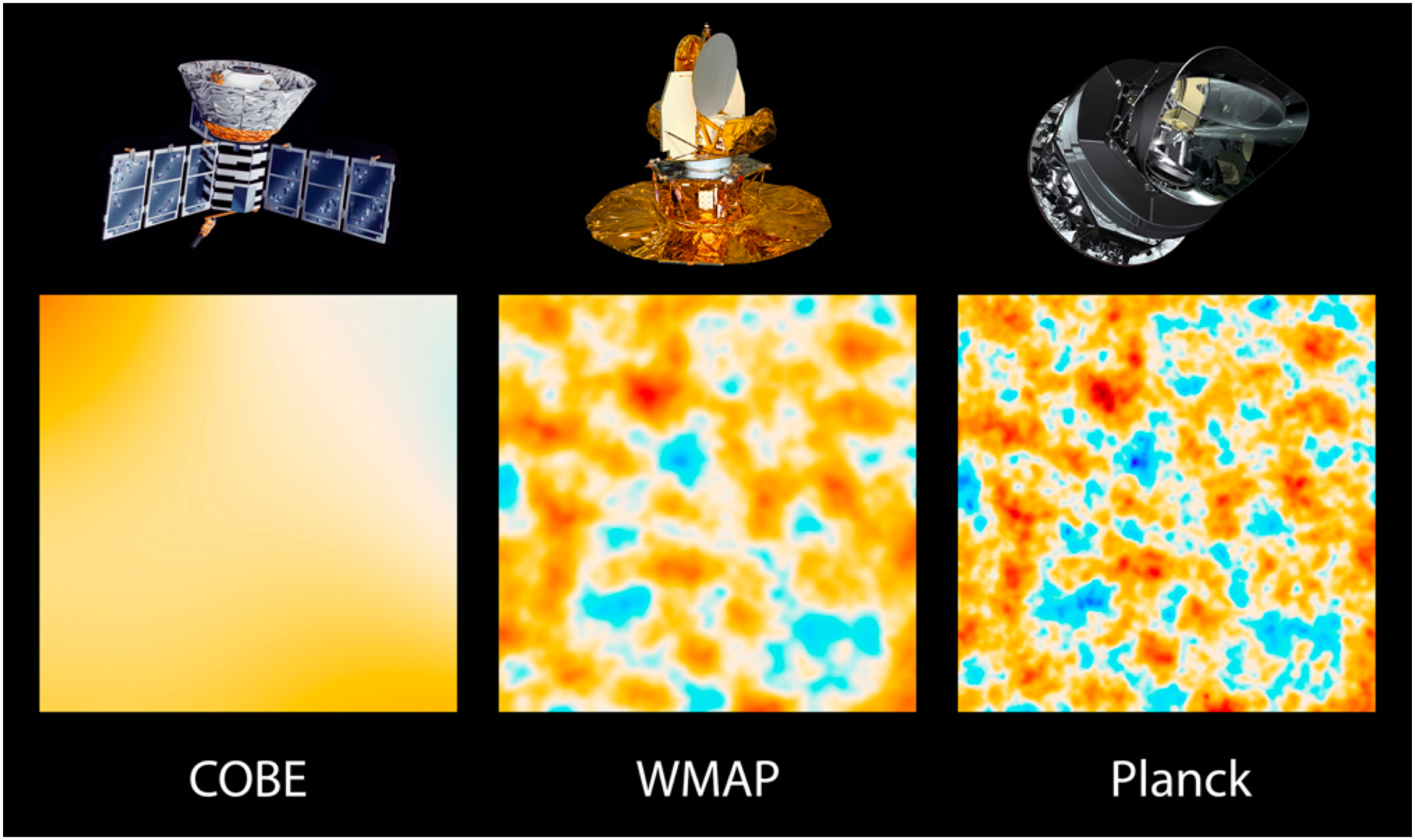
COBE (1992)



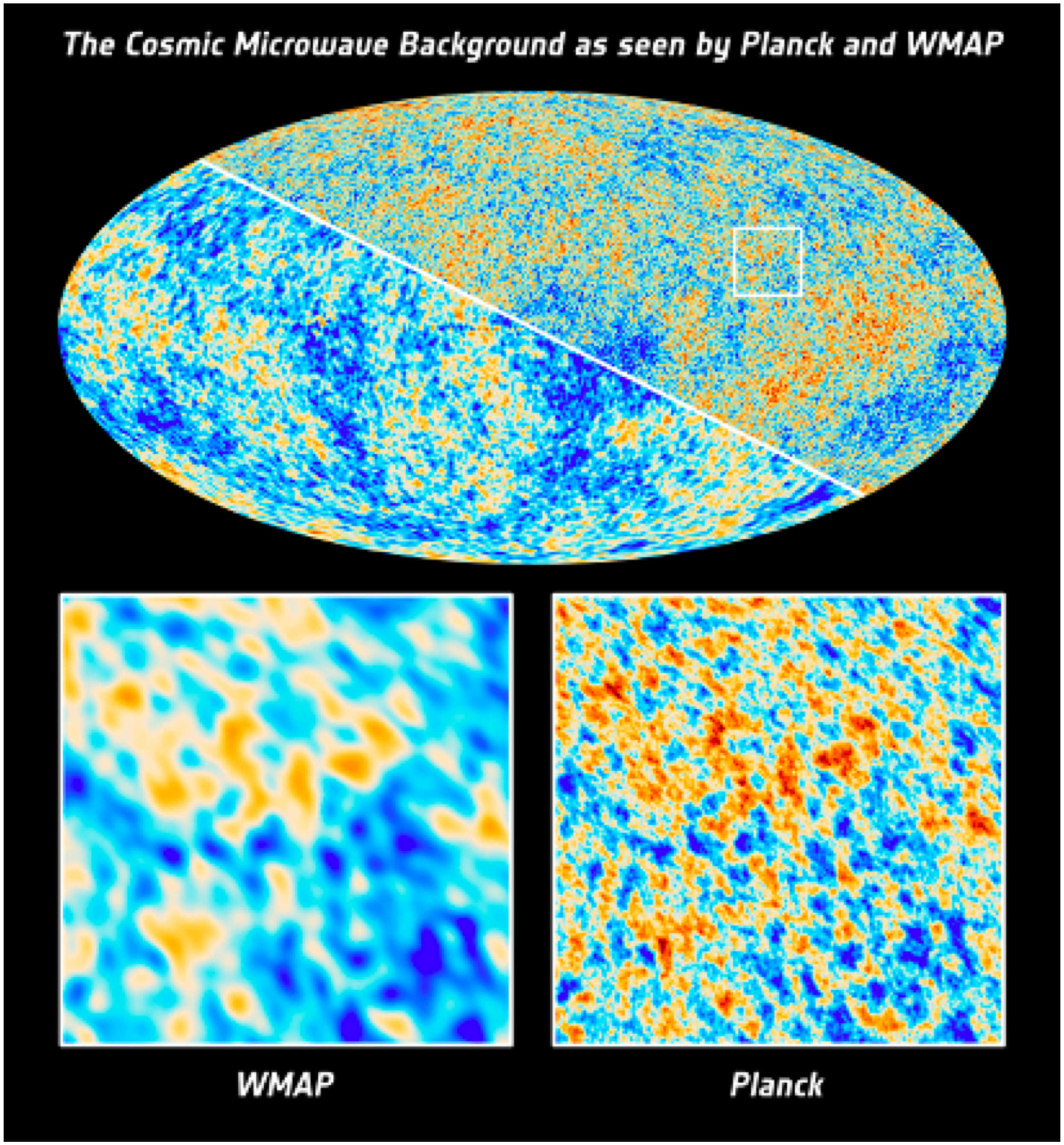
- Subtracting contributions from our galaxy and other sources reveals the intrinsic fluctuations in the CMB.

WMAP
(2004)

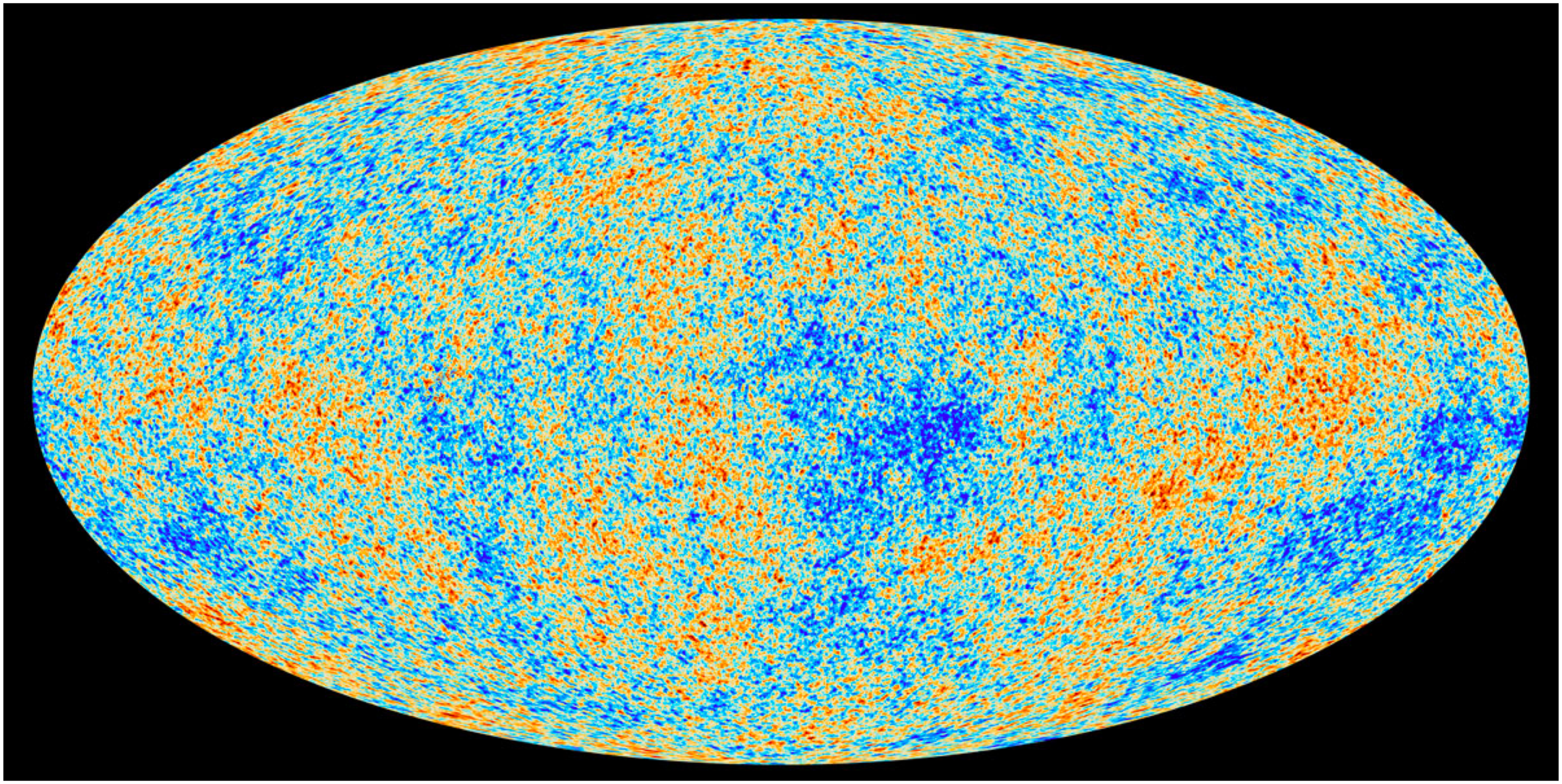




- Our view of the cosmic microwave background radiation is even better with Planck!

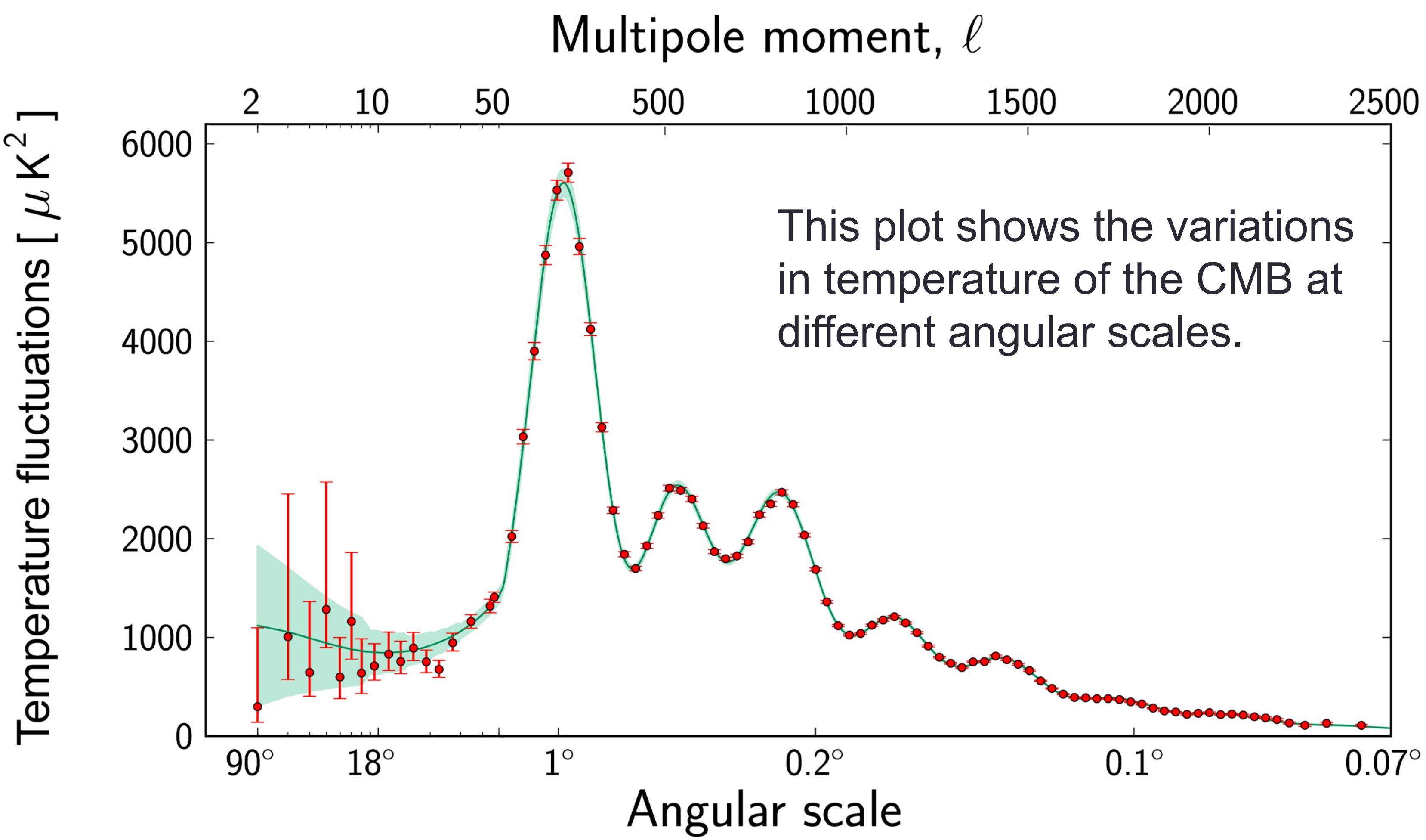

The Cosmic Microwave Background as seen by Planck and WMAP
WMAP
Planck

Planck (2013)



- The temperature fluctuations in the CMB show us the “seeds” of structure in the universe.

The Power Spectrum: Quantifying the CMB fluctuations



What do the fluctuations mean?

- Arise from density oscillations (sound waves) present in the plasma around recombination.
- An "image" of the sound waves was frozen into the CMB at the time that radiation and matter decoupled.
  - Compression ➔ higher density ➔ photons more gravitationally redshifted ➔ colder.
  - Rarefaction ➔ lower density ➔ photons less gravitationally redshifted ➔ warmer.

For a good tutorial, I recommend that you go through http://background.uchicago.edu/~whu/beginners/introduction.html

Power Spectrum of CMB Fluctuations

- Expand using spherical harmonics (surface of sphere):

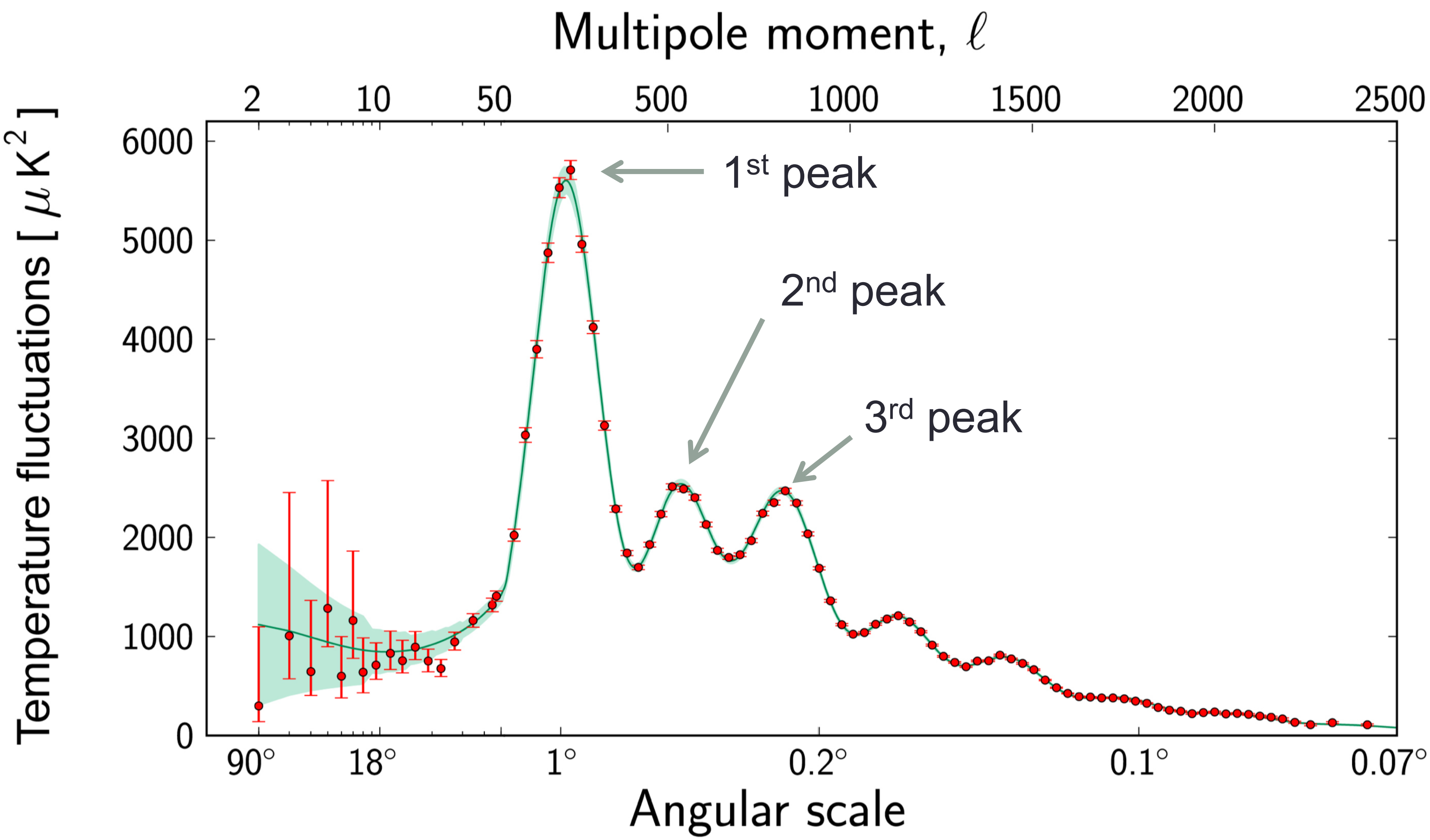
$$F(\theta,\phi) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} A_{l,m} Y_{l,m}(\theta,\phi).$$

Distribution of flux on sky

Amplitudes

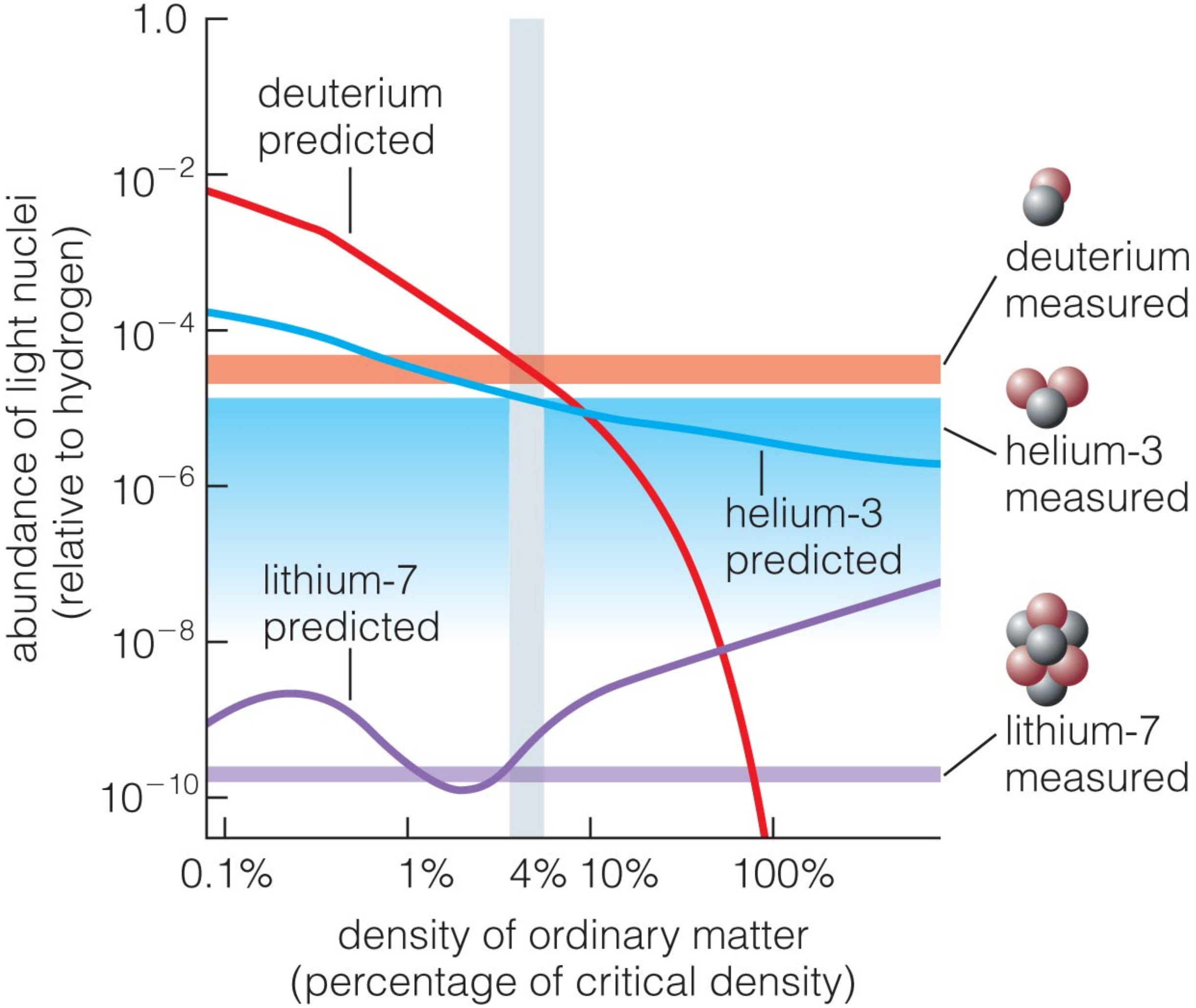
Spherical harmonics

- The amplitudes $A_{l,m}$ (y-axis) tell us how much fluctuation occurs on certain angular scales l (x-axis).
- Higher l corresponds to smaller angular scale.
- The *physical* scale of the peaks in the power spectrum relates to the size of the horizon when the CMB radiation was emitted.



- 1st peak: tells us the universe is spatially flat (next lecture).
- 2nd peak: tells us the baryon-to-photon ratio; implies $\Omega_{b,0} = 0.04$.
- 3rd peak: tells us the dark matter density.

How do the abundances of elements support the Big Bang theory?



The Big Bang theory predicts 7 protons for every neutron

- In the first few seconds, neutrons combine with positrons/neutrinos to make protons and anti-neutrinos/electrons, and vice versa:

$$n + e^{+} \leftrightarrow p^{+} + \overline{\upsilon}_e$$

$$n + \upsilon_e \leftrightarrow p^{+} + e^{-}$$

$$\frac{n_n}{n_p} = \exp\left(-\frac{(m_n - m_p)c^2}{k_B T}\right)$$

Detailed expression for the relative densities.

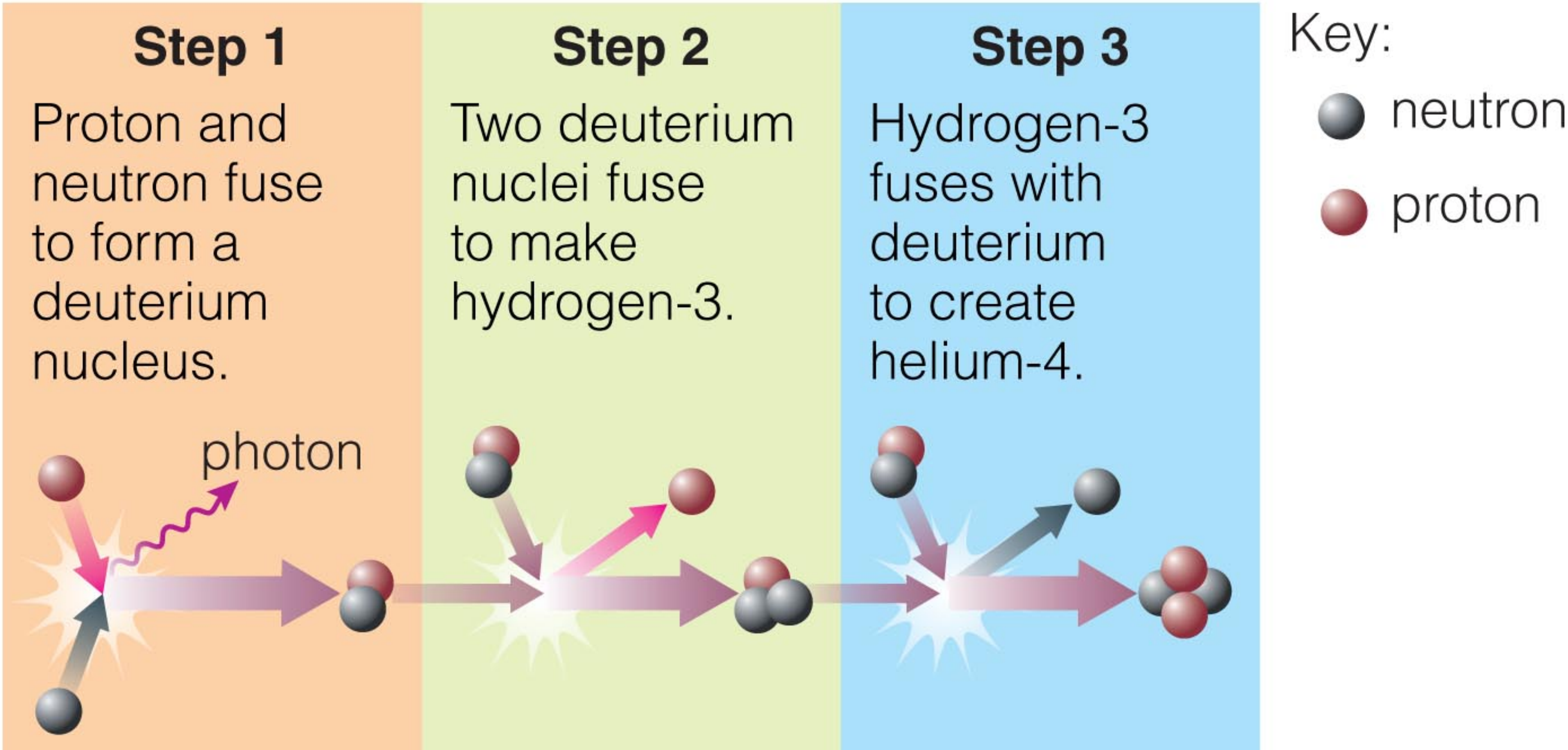
- Initially, $n_n/n_p \sim 1$ because the temperature was very high.
- As the universe cooled, neutrons became relatively less abundant because of their higher mass.
  - $(m_n - m_p)c^2 = 1.2934\ \mathrm{MeV}$ (this corresponds to $T \sim 1.5 \times 10^{10}\ \mathrm{K}$).

The Big Bang theory predicts 7 protons for every neutron

- The process of converting neutrons to protons slowed when the temperature dropped sufficiently.
  - Happened at $k_B T \sim 0.7$ MeV ($T \sim 8 \times 10^9$ K), so expect $n_n/n_p \sim 1/6$.
- Neutrons also decay with a half-life of ~10 minutes,

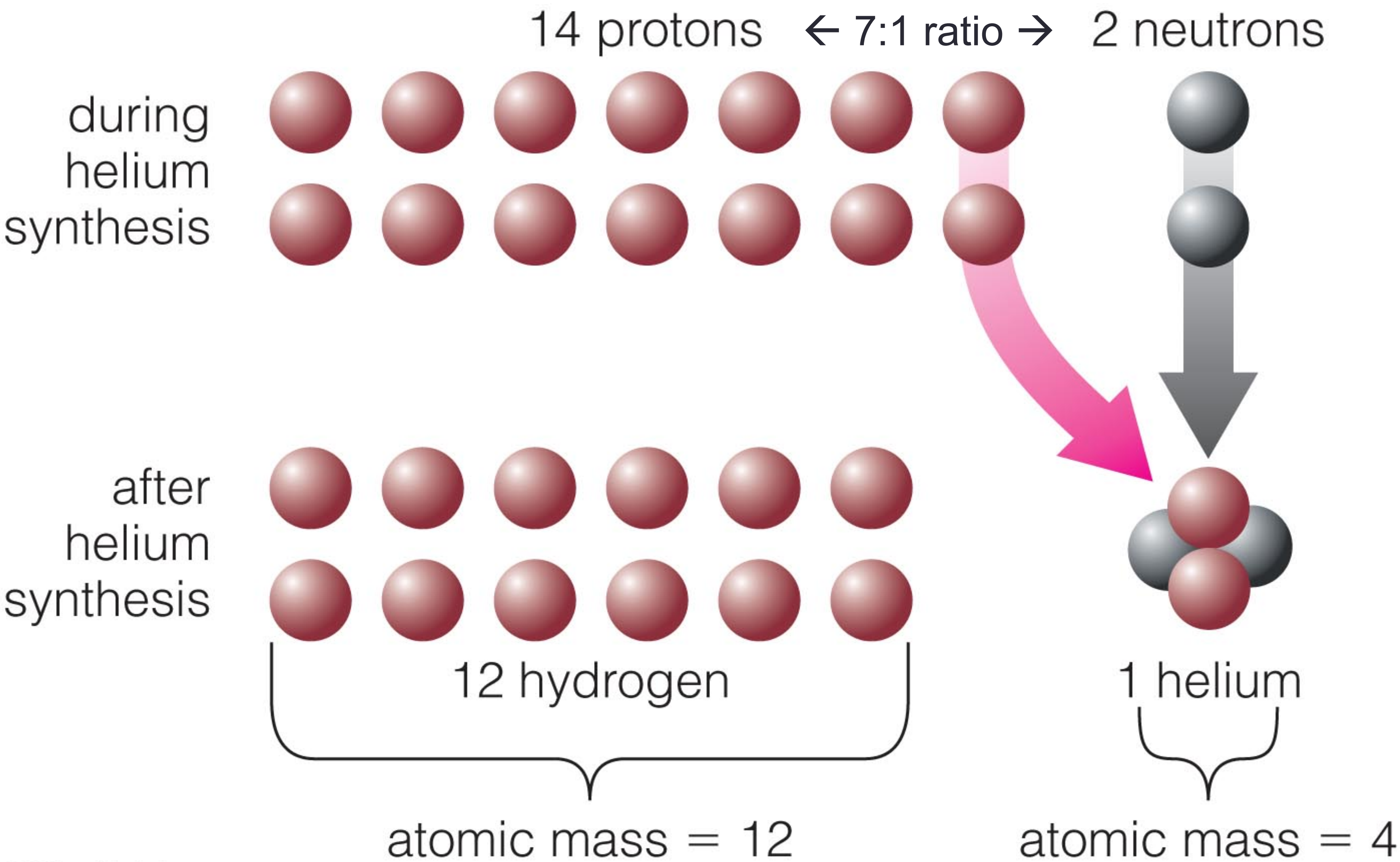
$$n \rightarrow p^+ + e^- + \overline{\nu}_e.$$

- All of this results in an expected 7-to-1 ratio of protons to neutrons at the time of helium nucleosynthesis.



Protons and neutrons combined to make long-lasting helium nuclei when the universe was ~3 minutes old.

(Why doesn't this sequence happen today in stars?)

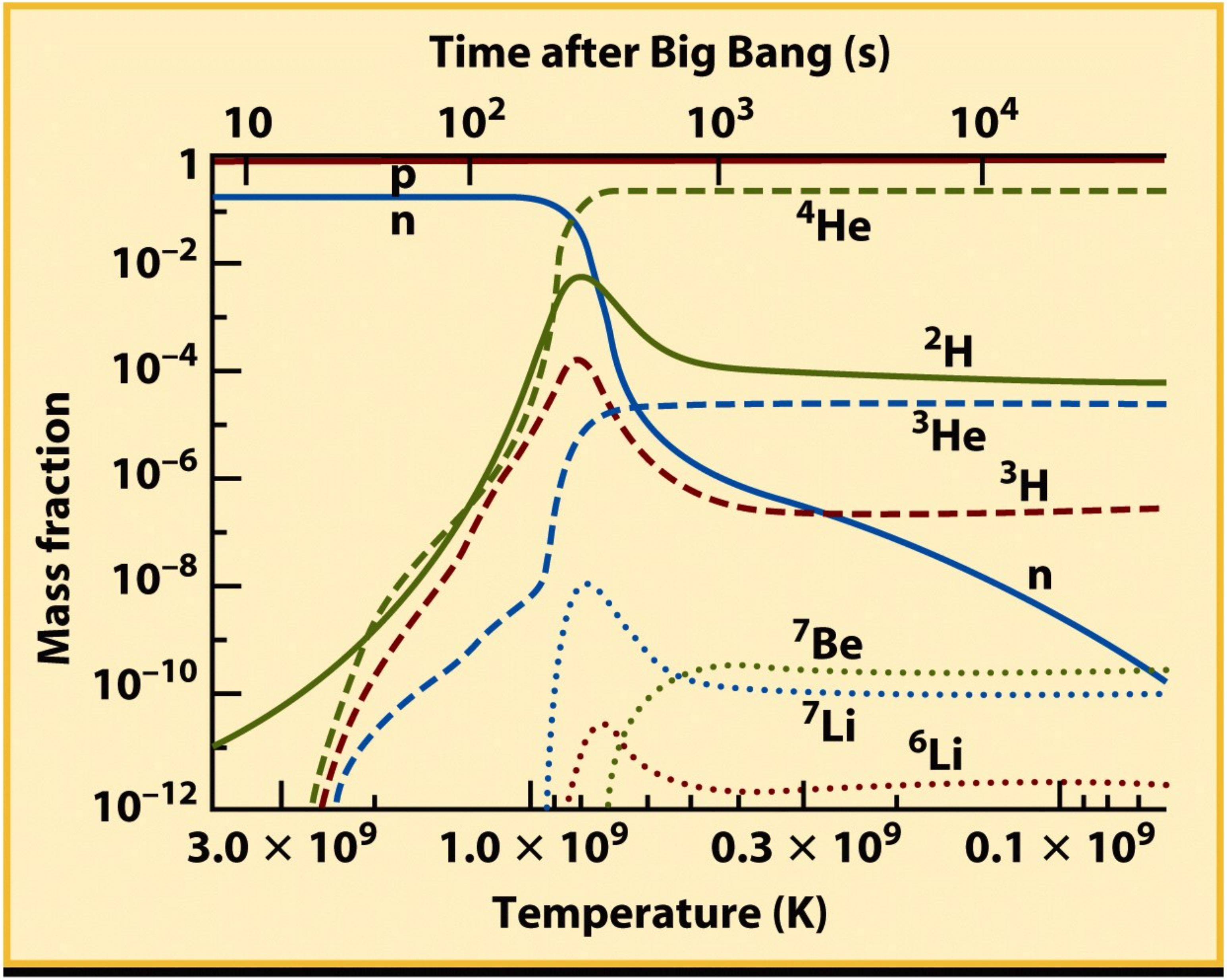


- Big Bang theory prediction: 75% H, 25% He (by mass).
- This prediction matches observations of primordial gases.

What determines the abundance of deuterium?

- Unlike helium, deuterium (heavy hydrogen) can be destroyed easily by energetic photons.
- Helium-4 production must wait for the universe to cool such that deuterium is safe from destruction: the *deuterium bottleneck.*
  - Once deuterium is stable, create helium-4 very rapidly.
- But the universe continues to expand and cool, and soon becomes too cool for fusion.

- *There is only a brief window in time (and temperature) when deuterium can fuse to ultimately make helium-4.*


Time after Big Bang (s)
10
10^2
10^3
10^4
1
p
n
4He
10^-2
2H
10^-4
3He
3H
10^-6
10^-8
n
7Be
10^-10
7Li
6Li
10^-12
Mass fraction
3.0 × 10^9
1.0 × 10^9
0.3 × 10^9
0.1 × 10^9
Temperature (K)