Since density scales as R^{-3}, we can estimate the scale factor of the Universe when this happened (if we have an estimate of the current baryonic density). Since

$$\rho_0 = \rho R^3$$

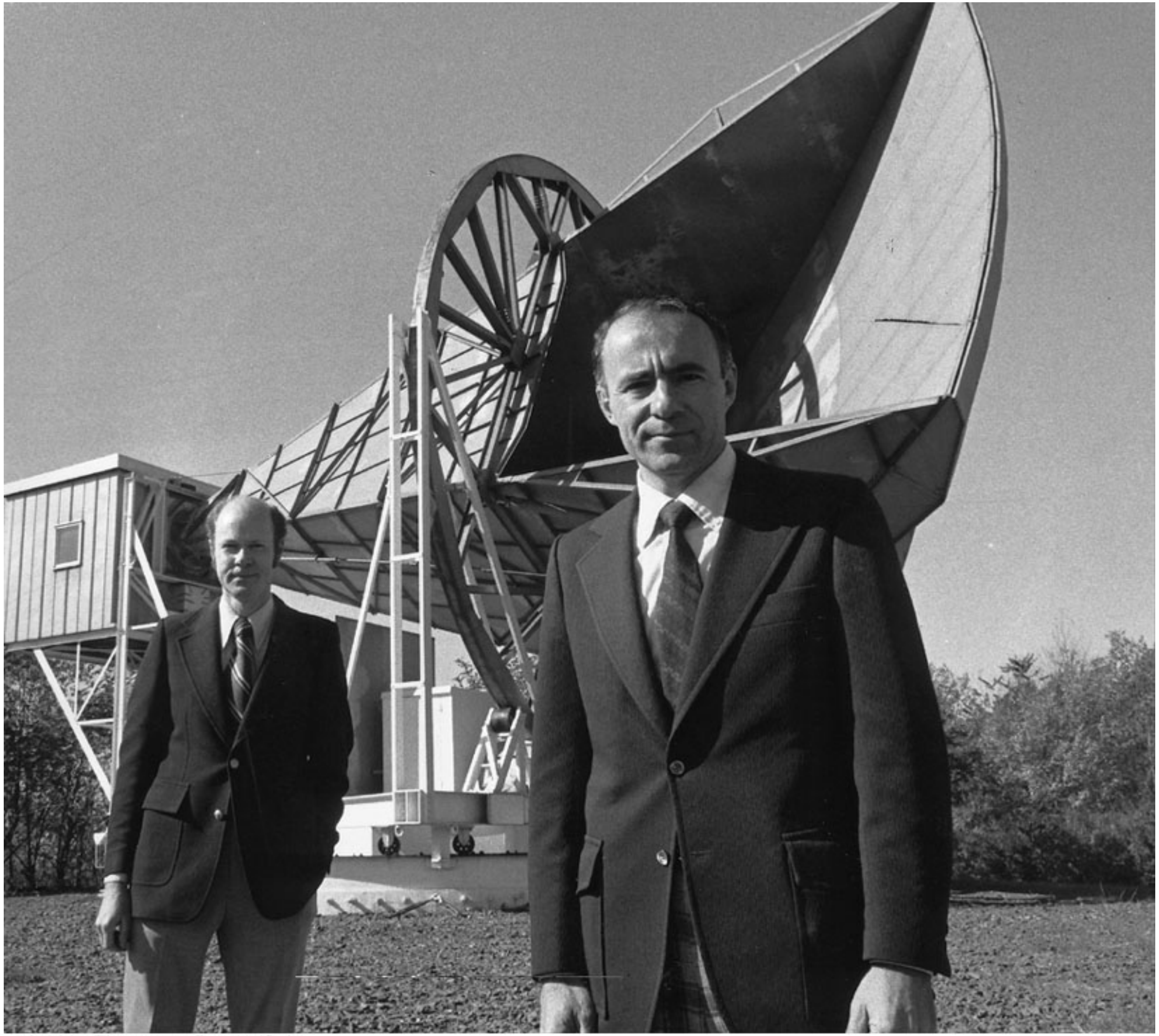
We have $R \sim (\rho_0/\rho)^{1/3} \sim 3 \times 10^{-9}$

Since this happened at $T=10^9$, and the radiation cools like 1/R, we should have radiation running around the universe with a characteristic temperature of

$$T_0 = RT = (3 \times 10^{-9})(10^9) = 3 \text{ Kelvin}$$

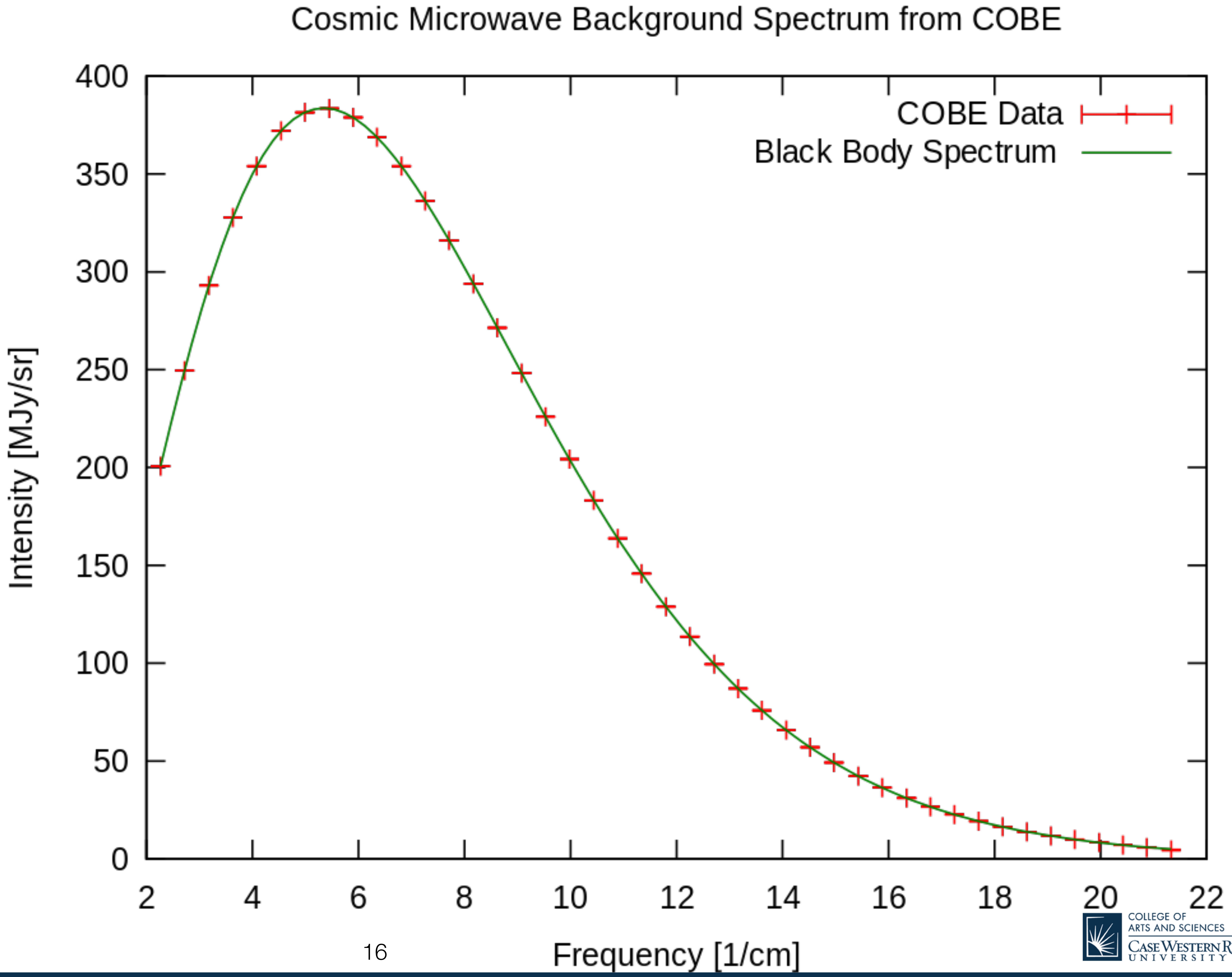
This peaks in the microwave portion of the spectrum.

Gamov and Herman predicted the Universe should be glowing in microwaves

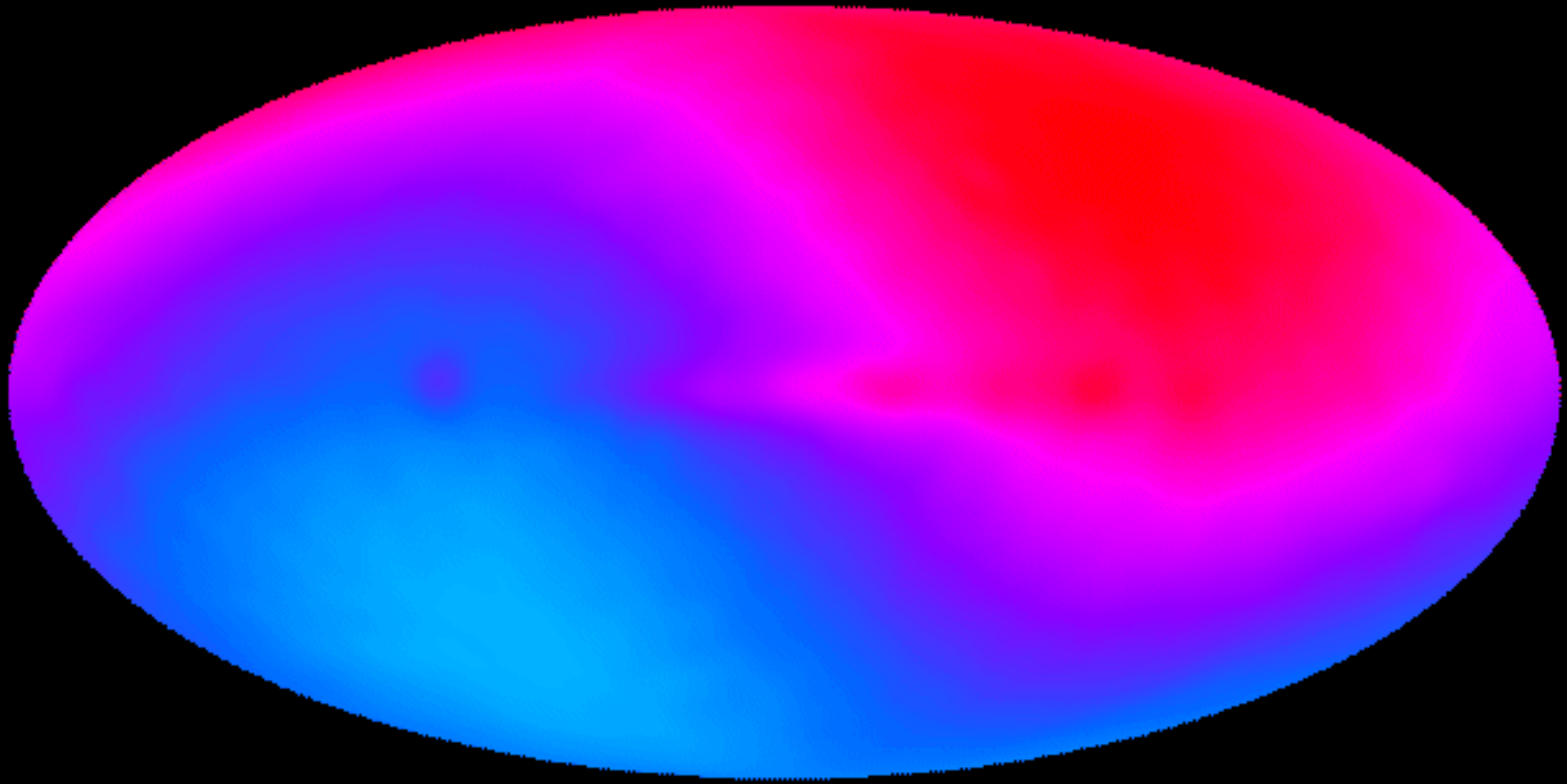


Sixteen years later, in 1964, unaware of the cosmological predictions, Penzias and Wilson discovered a persistent "hiss" in their radio antennae used to communicate with the Telstar satellite. *The cosmic microwave background radiation (CMB) had been detected!*

It's a perfect blackbody,
with temperature 2.726 K

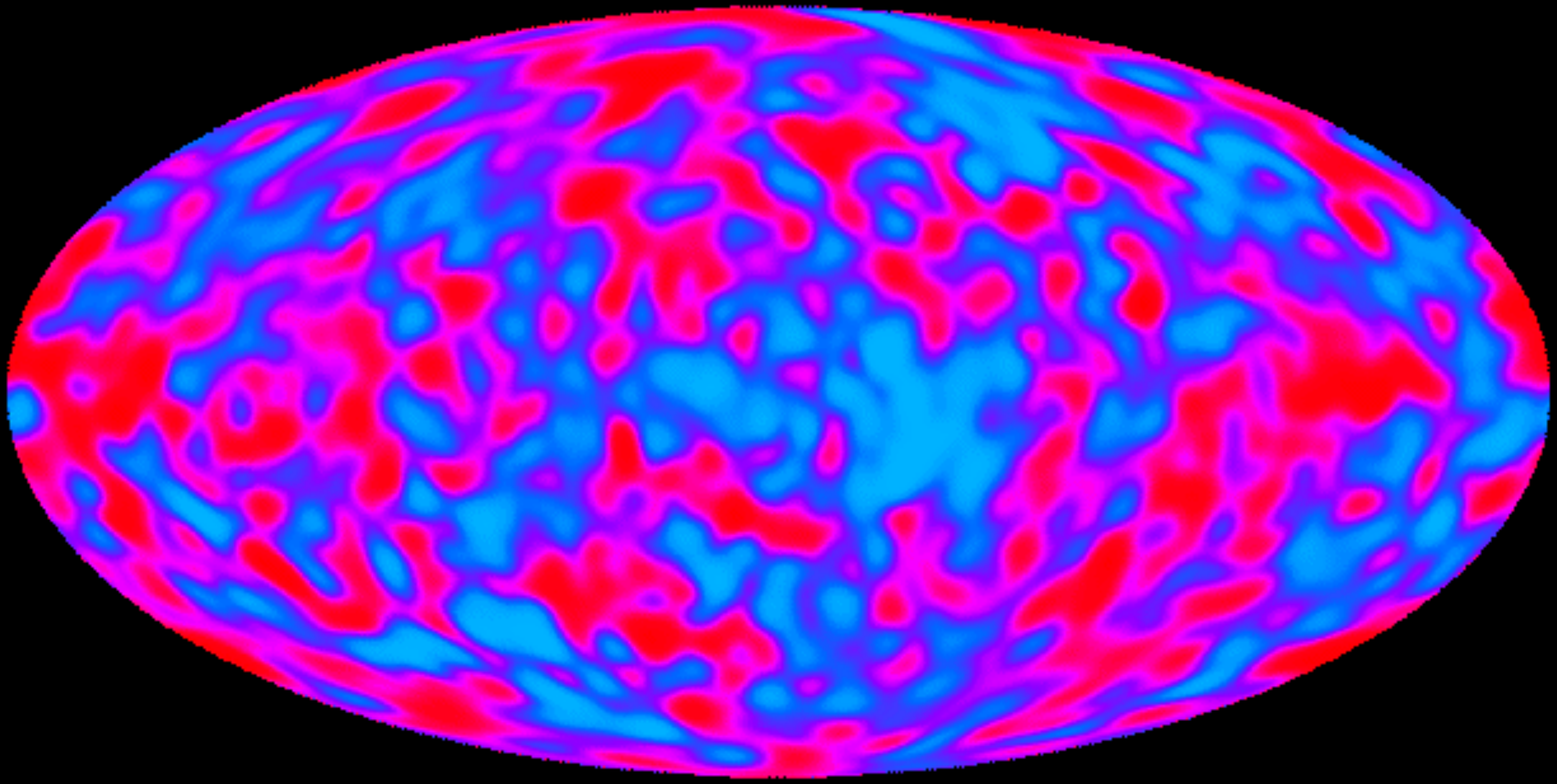


It's **extremely uniform in temperature**:

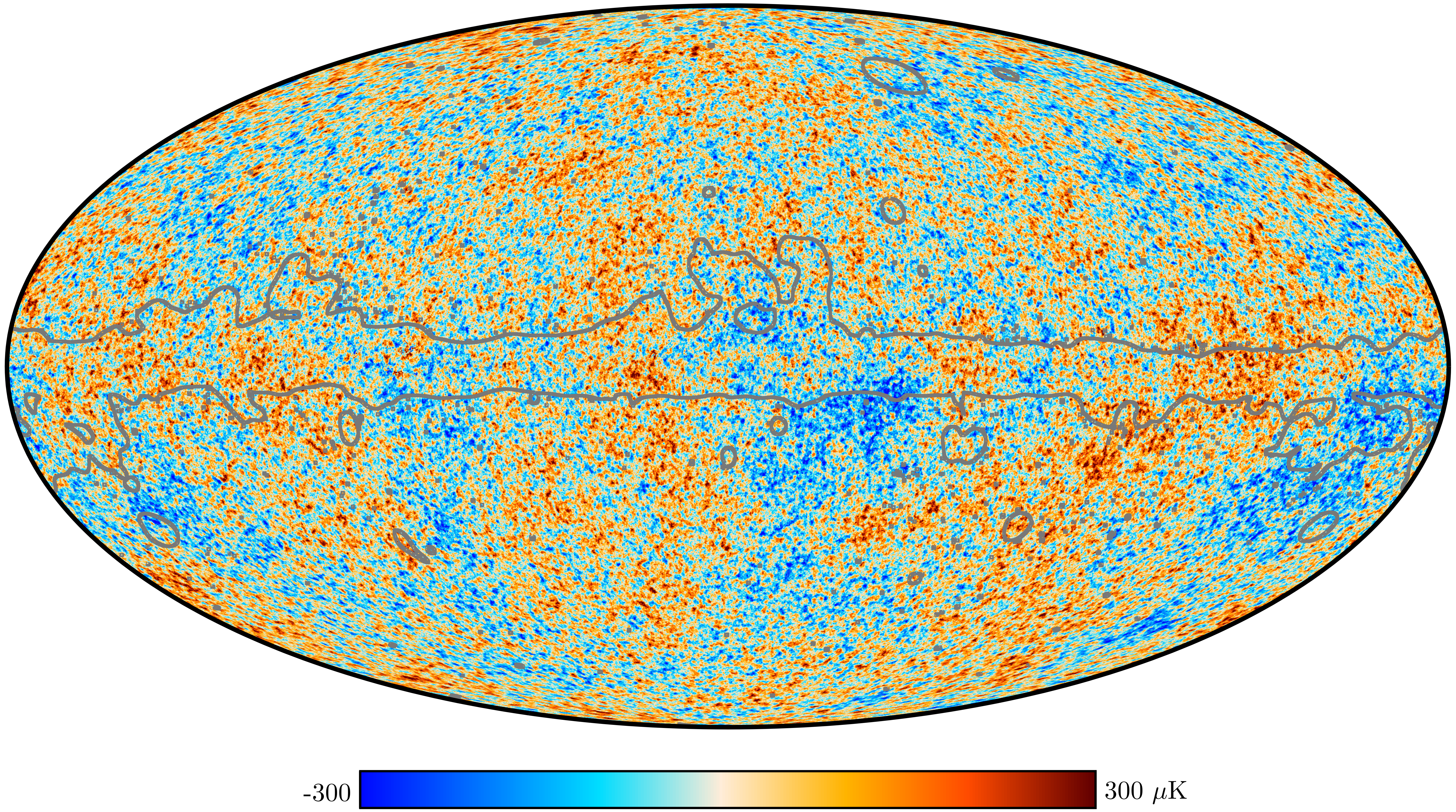


COBE temperature map (+/- 0.001 K)

But it does have temperature fluctuations -- extremely small ones ($dT/T \sim$ few x 10^{-5})



COBE temperature map (+/- 0.00001 K)


-300
300 μK

What are we seeing?

We are seeing light from the Universe when it was very old. Remember, in the hot, dense Universe, the mean free path of photons was small -- they couldn't travel very far. The reason is that they were scattering of free electrons (Thomson scattering). As soon as there were no free electrons, the photons could travel and we could "see" -- the Universe became transparent . This happens when the Universe was cool enough that protons and electrons could combine, and we call this point in history "recombination".

When we look at the CMB, we are seeing the Universe as it was at recombination, when all those photons could travel freely so that we can detect them.

When did this happen? At a temperature of ~ 4000 K, which is a redshift of ~ 1000, or a time of ~ few hundred thousand years after the Big Bang.

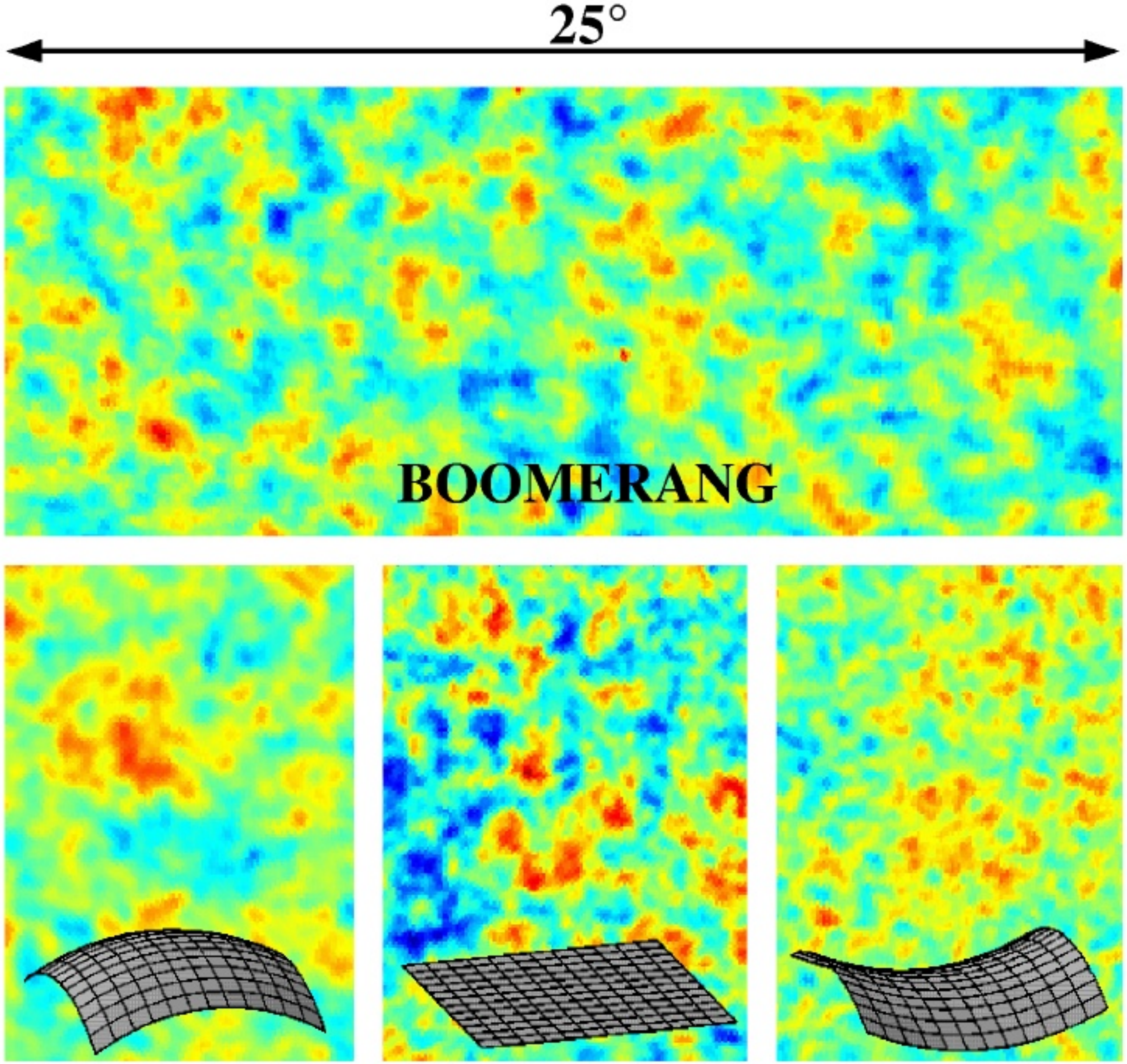
The fluctuations we see in temperature are related to the fluctuations in mass. These fluctuations will grow with time to form the galaxies and galaxy clusters that we see and live in today!

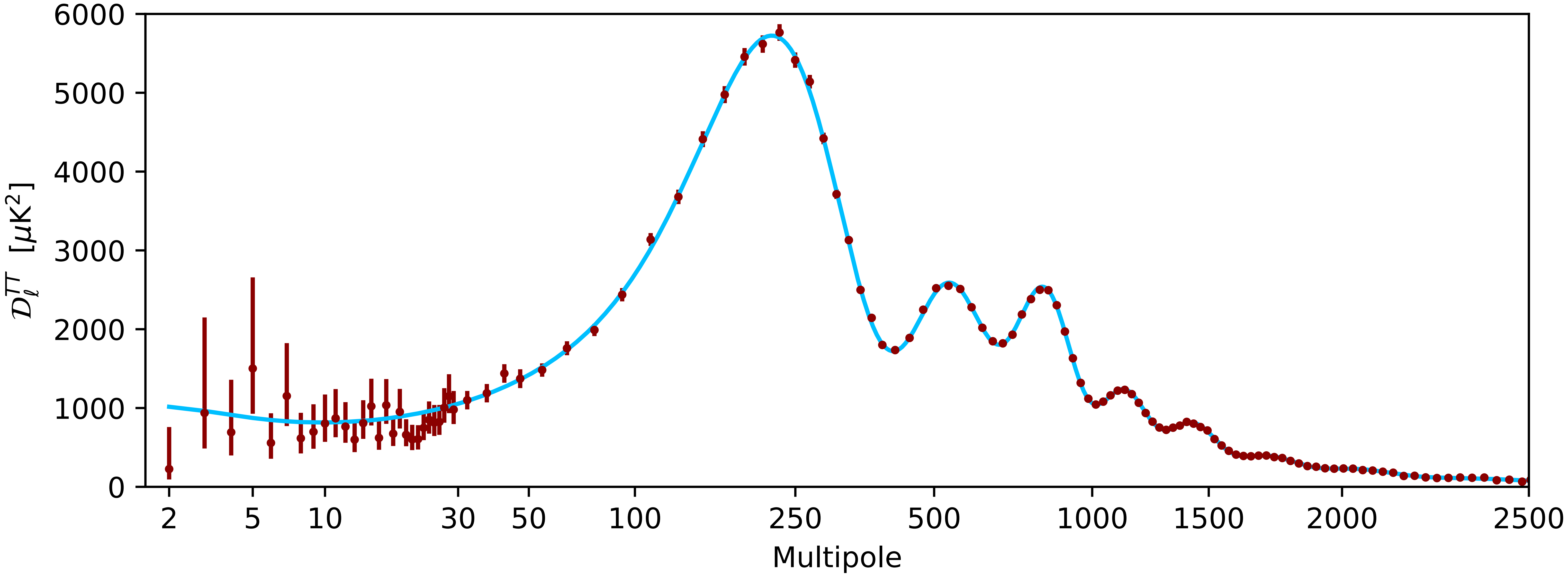
Shape of Space

What we are seeing is fluctuations in the ionized gas temperature that trace the underlying mass distribution.

The biggest possible size for a fluctuation is given by the "sound horizon": d = cs x t, where cs is the sound speed, and t is the age of the universe at that time.

This turns out to be about 65 Mpc (comoving). This is essentially a standard rod we can use to measure the shape of space.



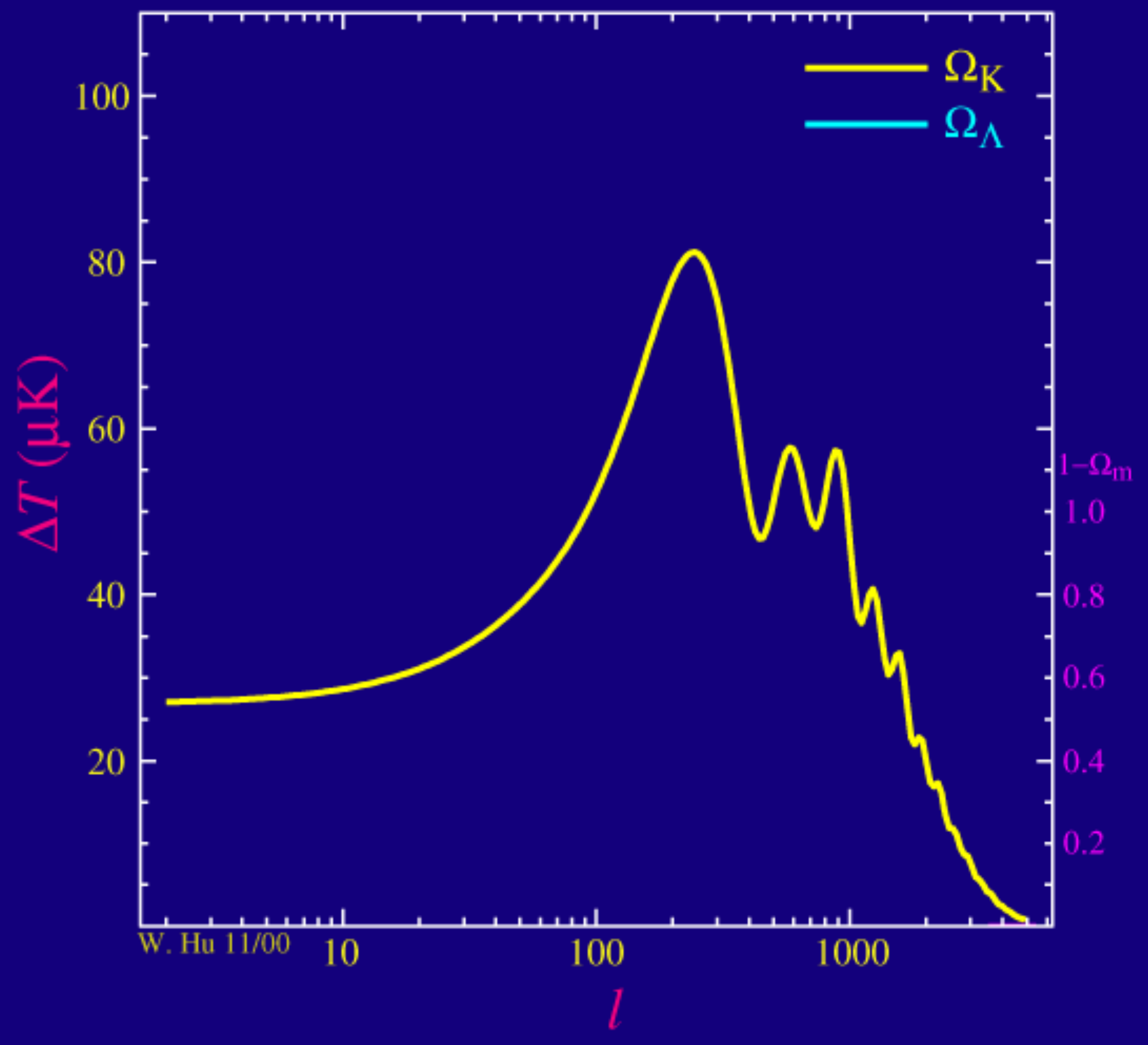


Parameters from the CMB (Planck 2015 results)

Parameter	Value
H_0	67.8 km/s/Mpc
Ω_M	0.308
Ω	1.000
Ω_b	0.0484
t_0	13.8 Gyr

(Since Ω_M=0.308 and Ω=1, this implies Ω_Λ=0.692)

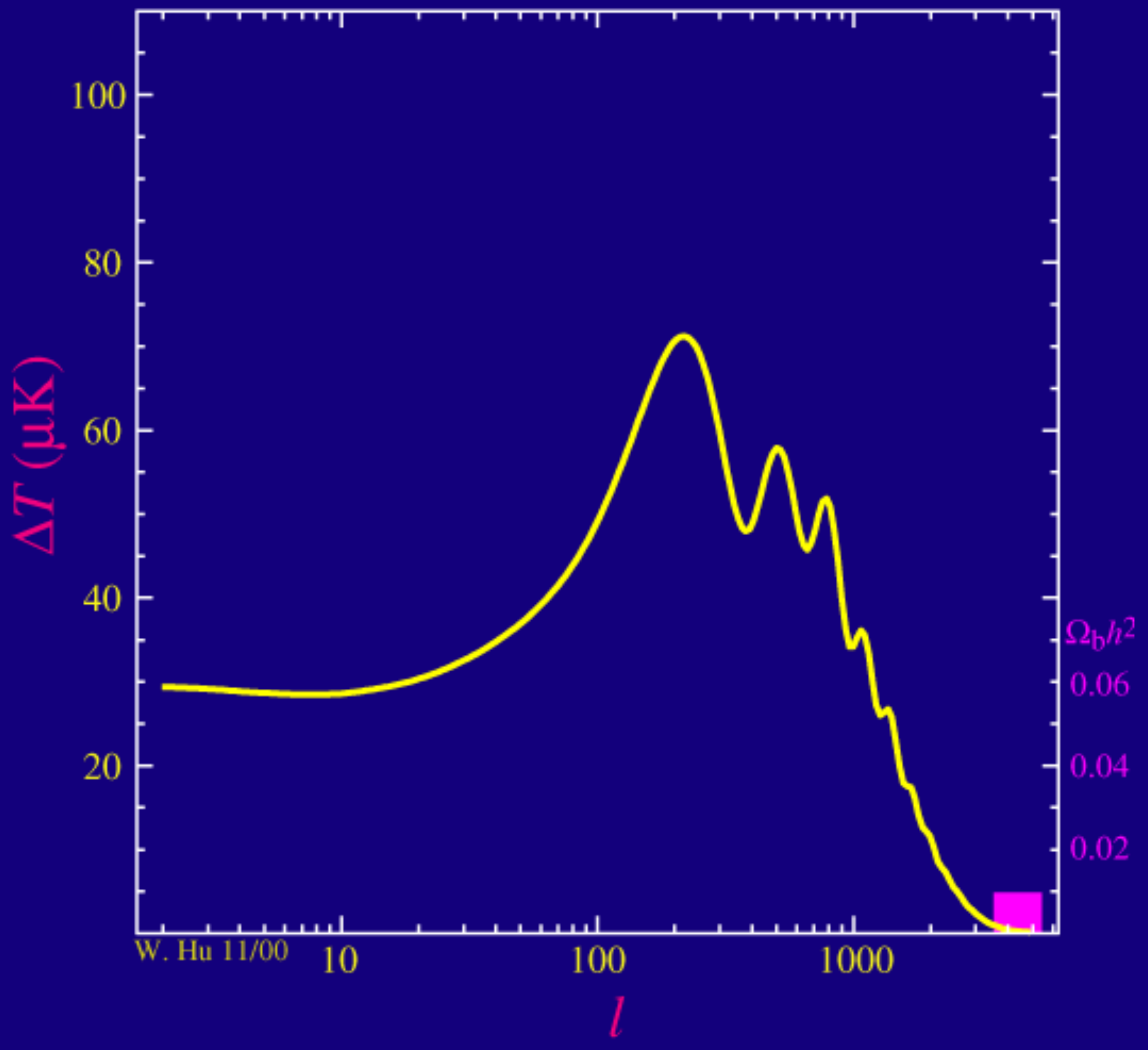
the structure in the CMB is acoustic oscillations — gravity/radiation pressure cause random fluctuations in density to oscillate like a sound wave — the power spectrum tells us about the underlying conditions



first peak

=

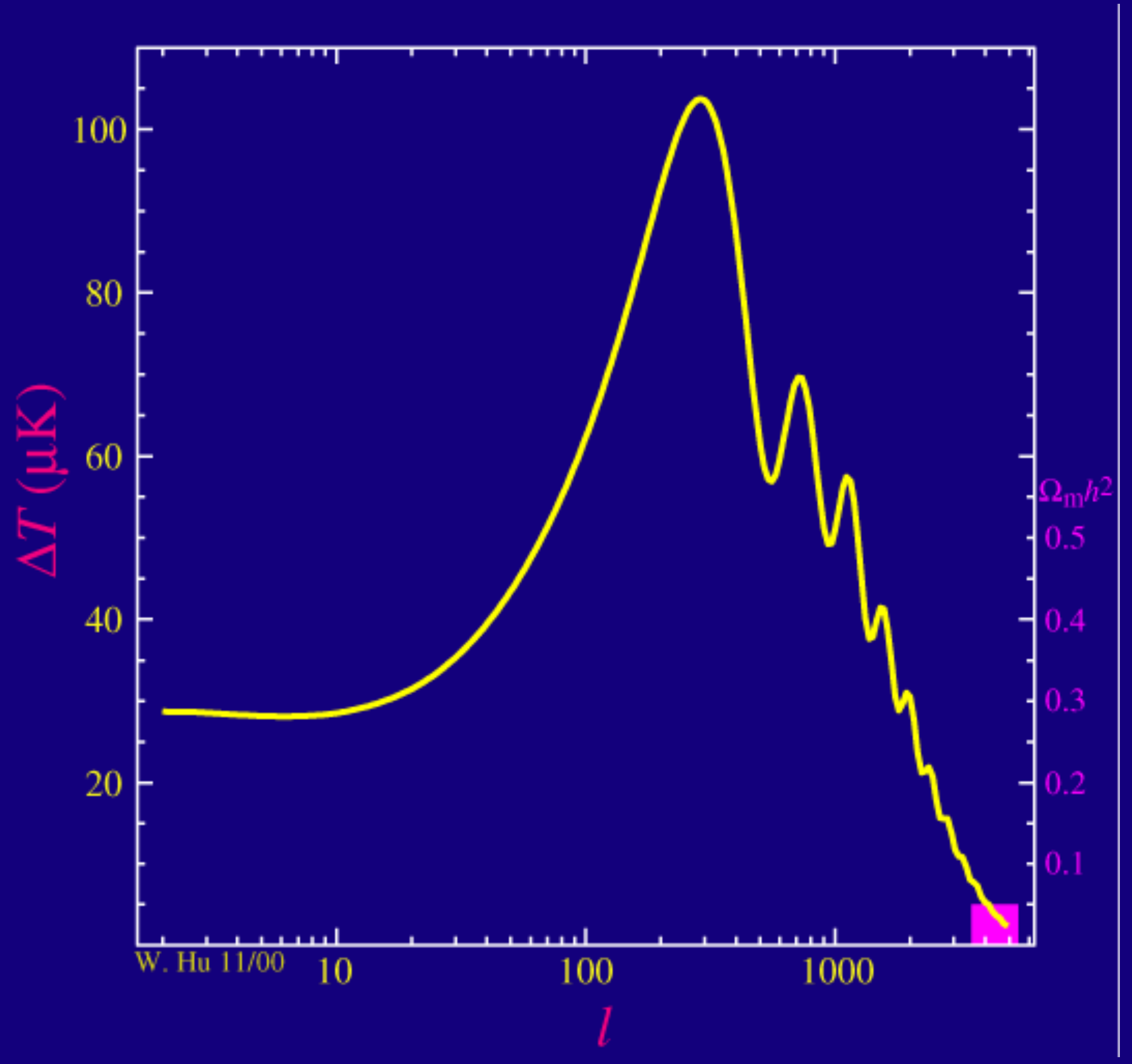
total Ω / curvature



second peak

=

baryon density



third peak

=

dark matter density