The Contribution of Planck to Cosmology

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On behalf of the Planck collaboration

What have we learned so far

- For almost 50 years the Cosmic Microwave background (CMB) has been one of most important sources of information about the Universe at large.

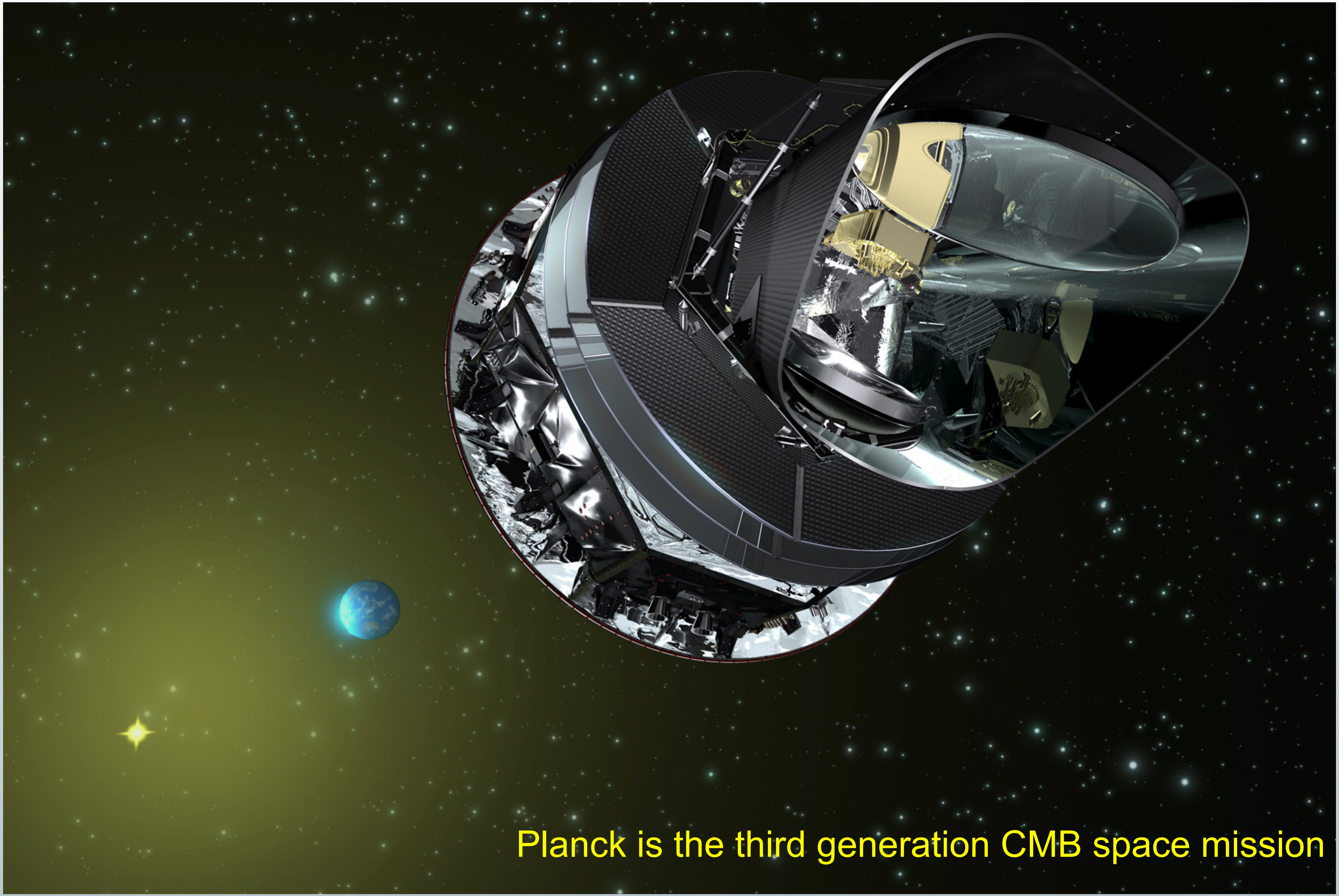
- Let's start by reviewing what we have learned so far:

  - The Universe used to be hot and dense - there's no credible alternative to a "big bang"

  - Very early on, it is plausible that the Universe expanded really fast for a short time - something like "inflation" happened

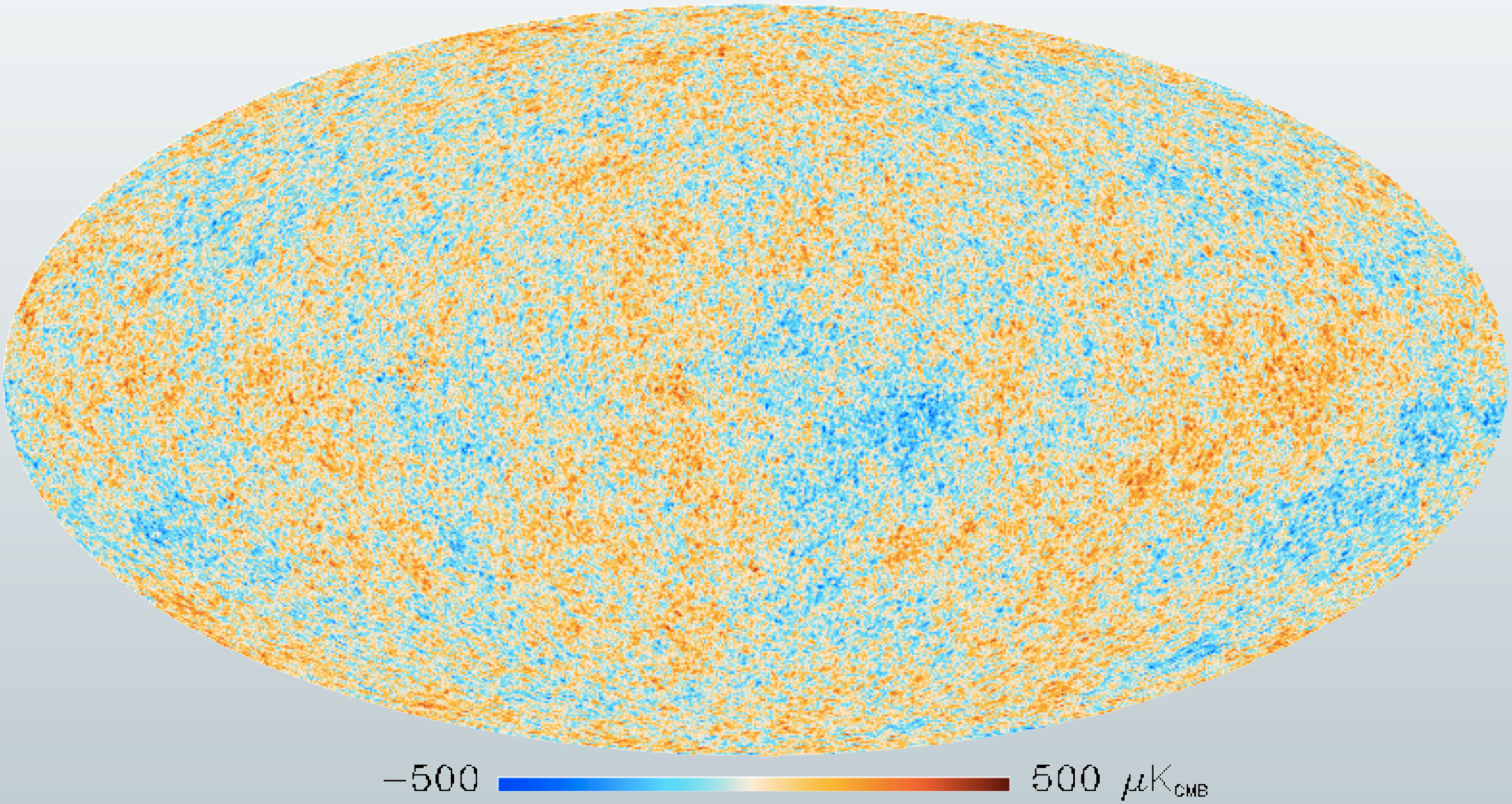
  - There's lots of invisible matter in the Universe - "dark matter"

Planck



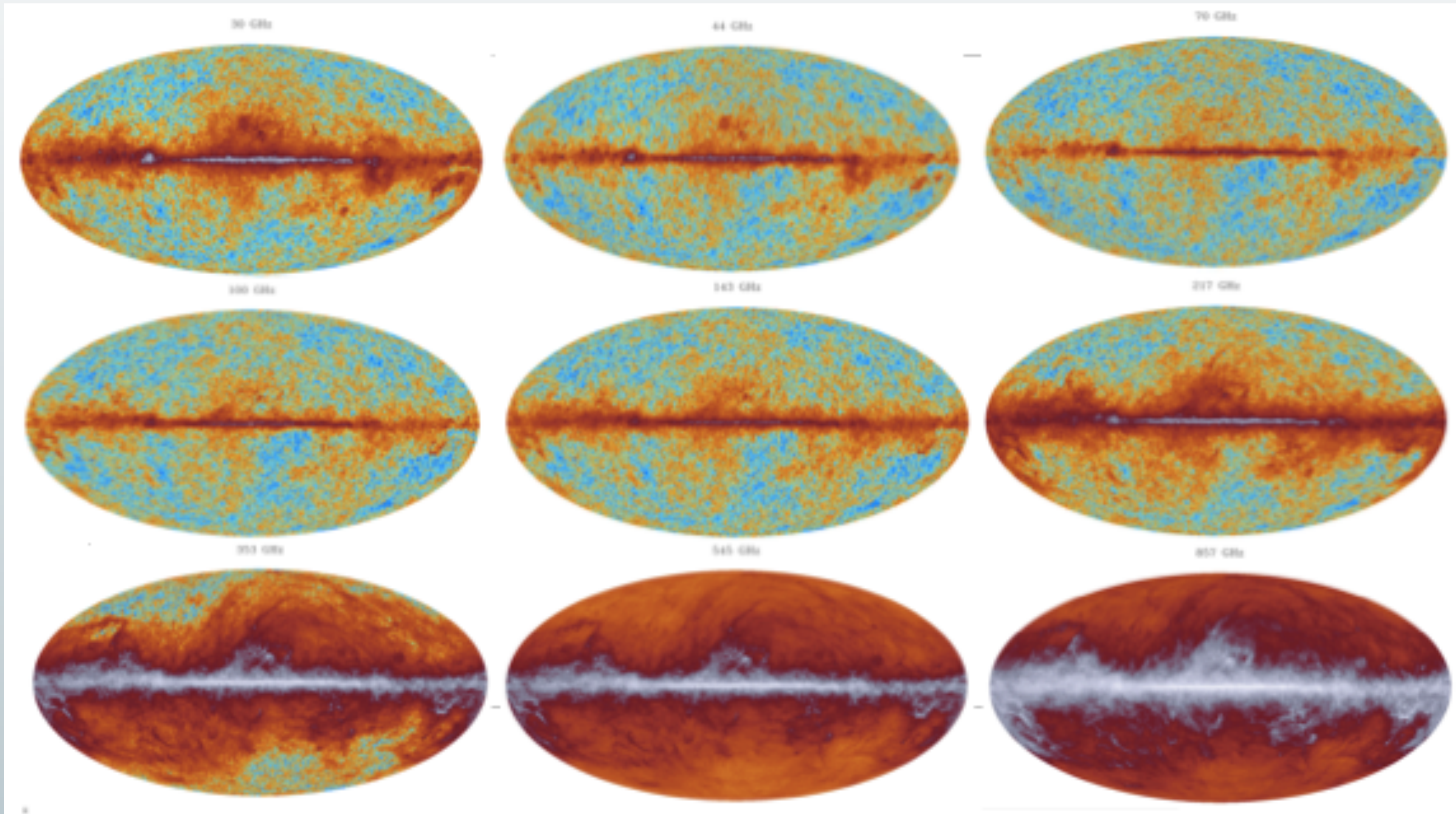
Cosmic Microwave Background Fluctuations

Planck gives us the sharpest and clearest view of this ancient light.



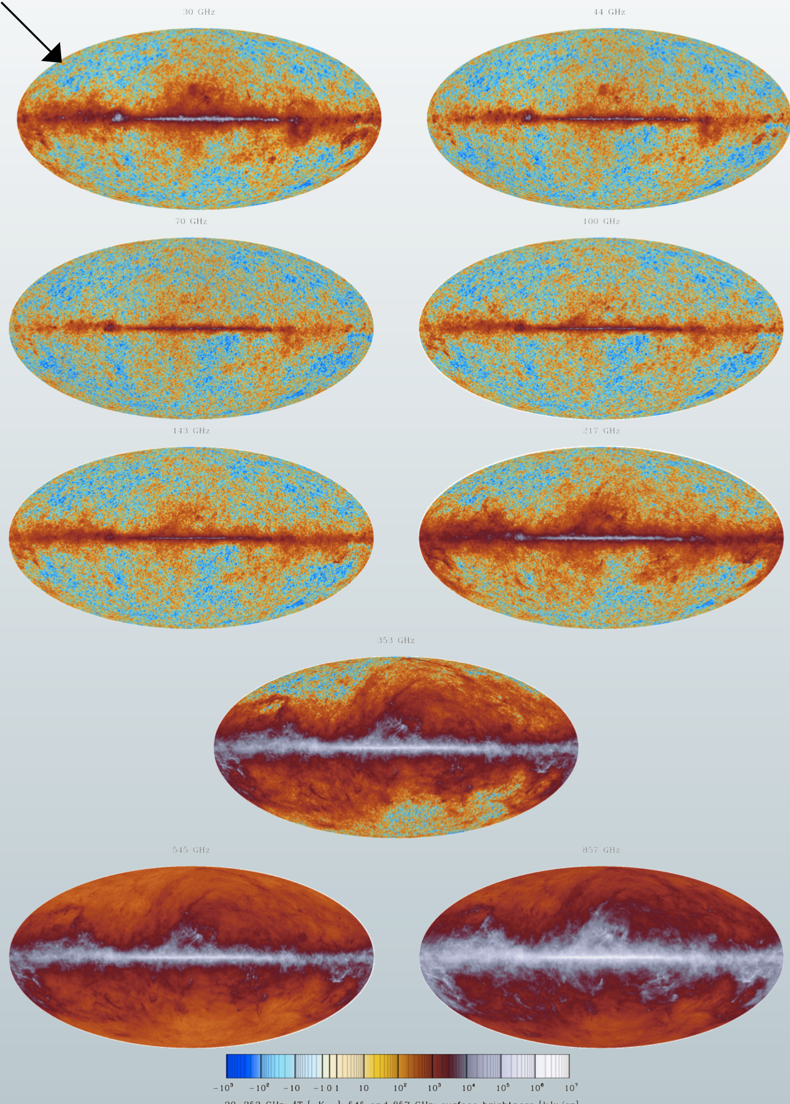
Planck Frequency Maps

These are beautiful maps: they are at independent frequencies and contain contributions of different types of foregrounds



How Planck Sees the Sky

Mostly synchrotron



Making the CMB map is a meticulous process.

All the foreground light from our own galaxy and from other galaxies must be carefully removed to get the primeval light.

How?

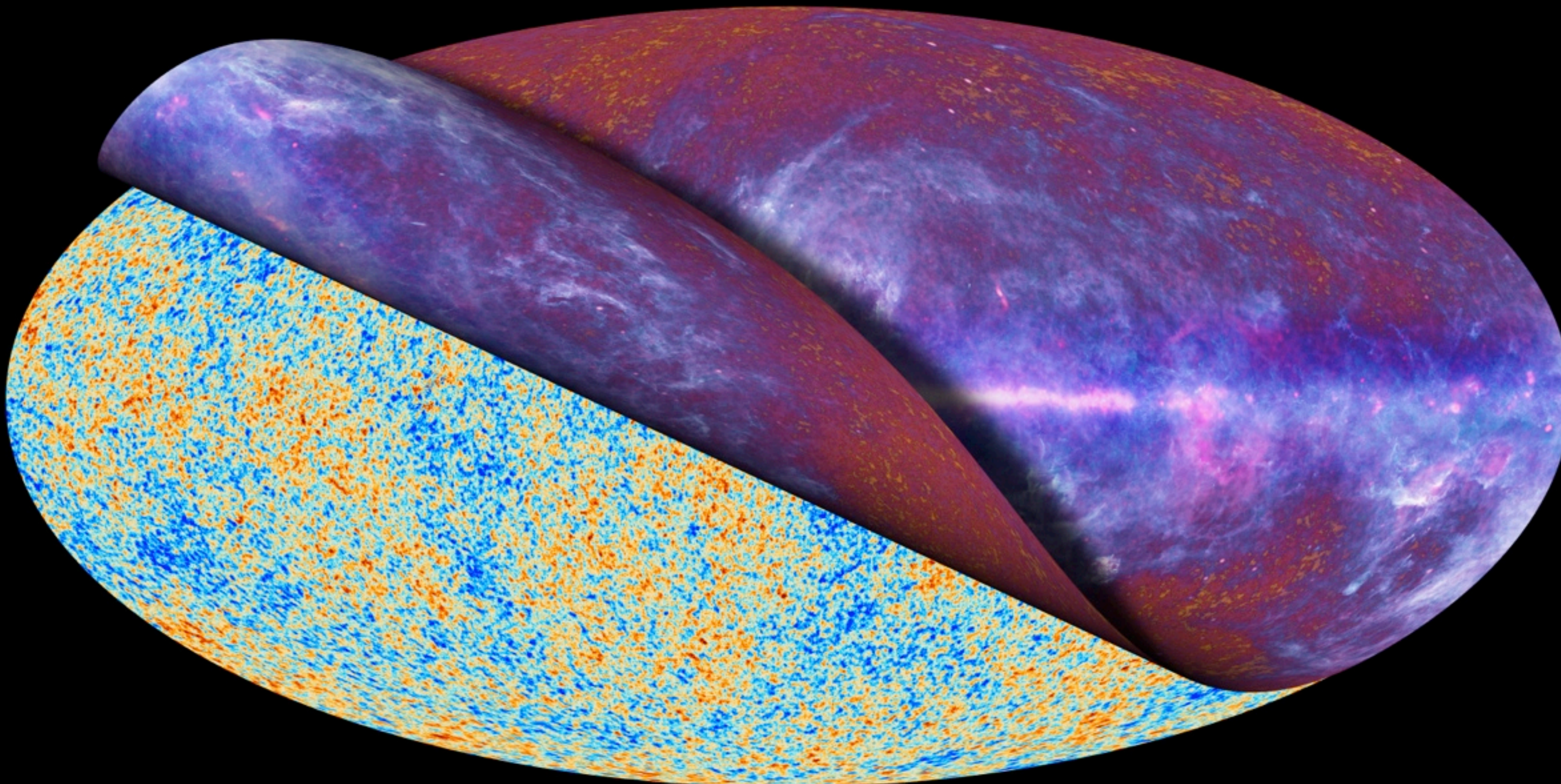
- As the light emitted by our galaxy and the CMB have different spectra (i.e. vary differently from one wavelength to the other) we can separate them.

- As Planck covers a wide range of wavelengths we can separate these emissions extremely well and recover the true CMB light with unprecedented high-quality

Mostly dust

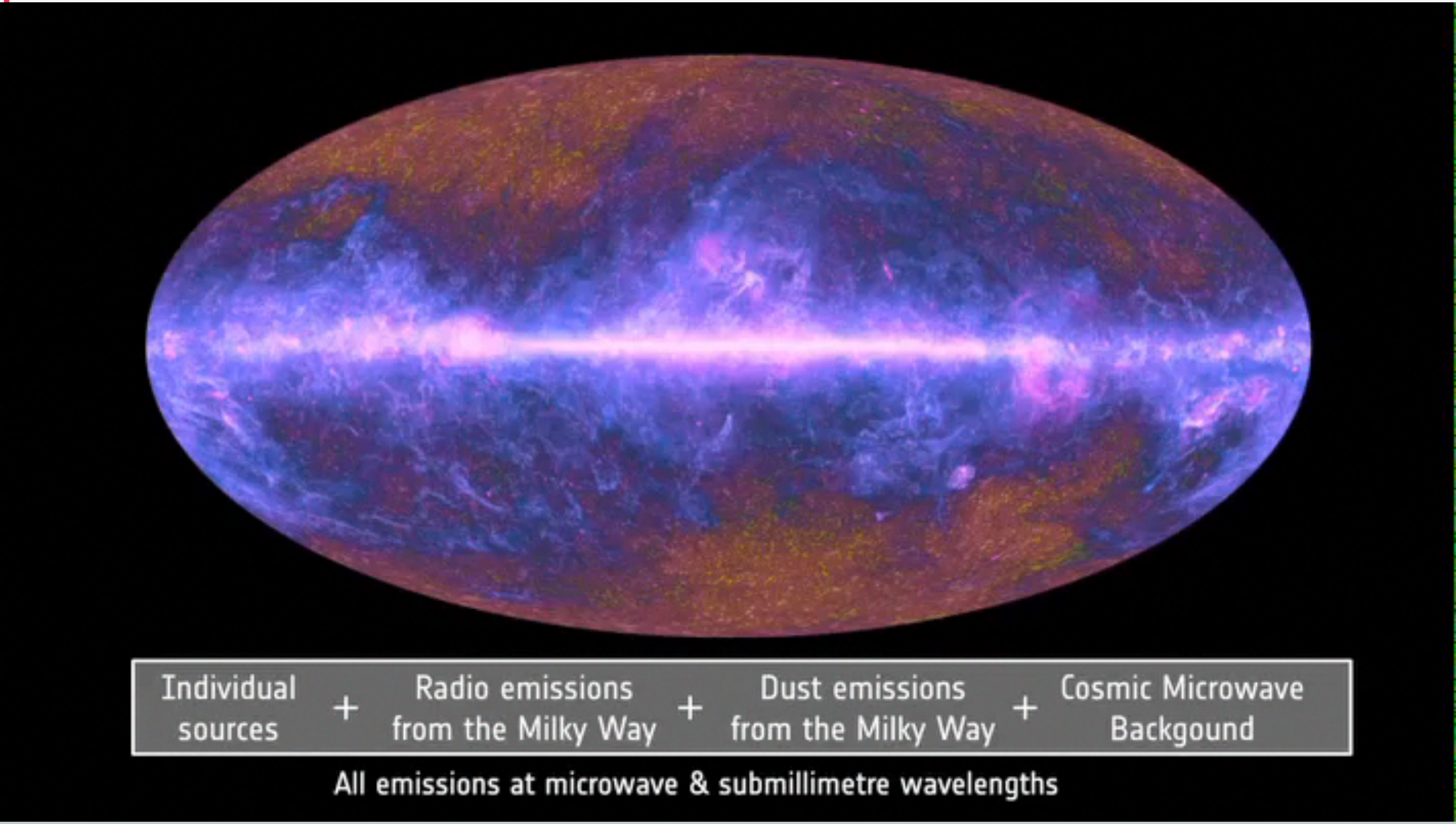
planck

esa

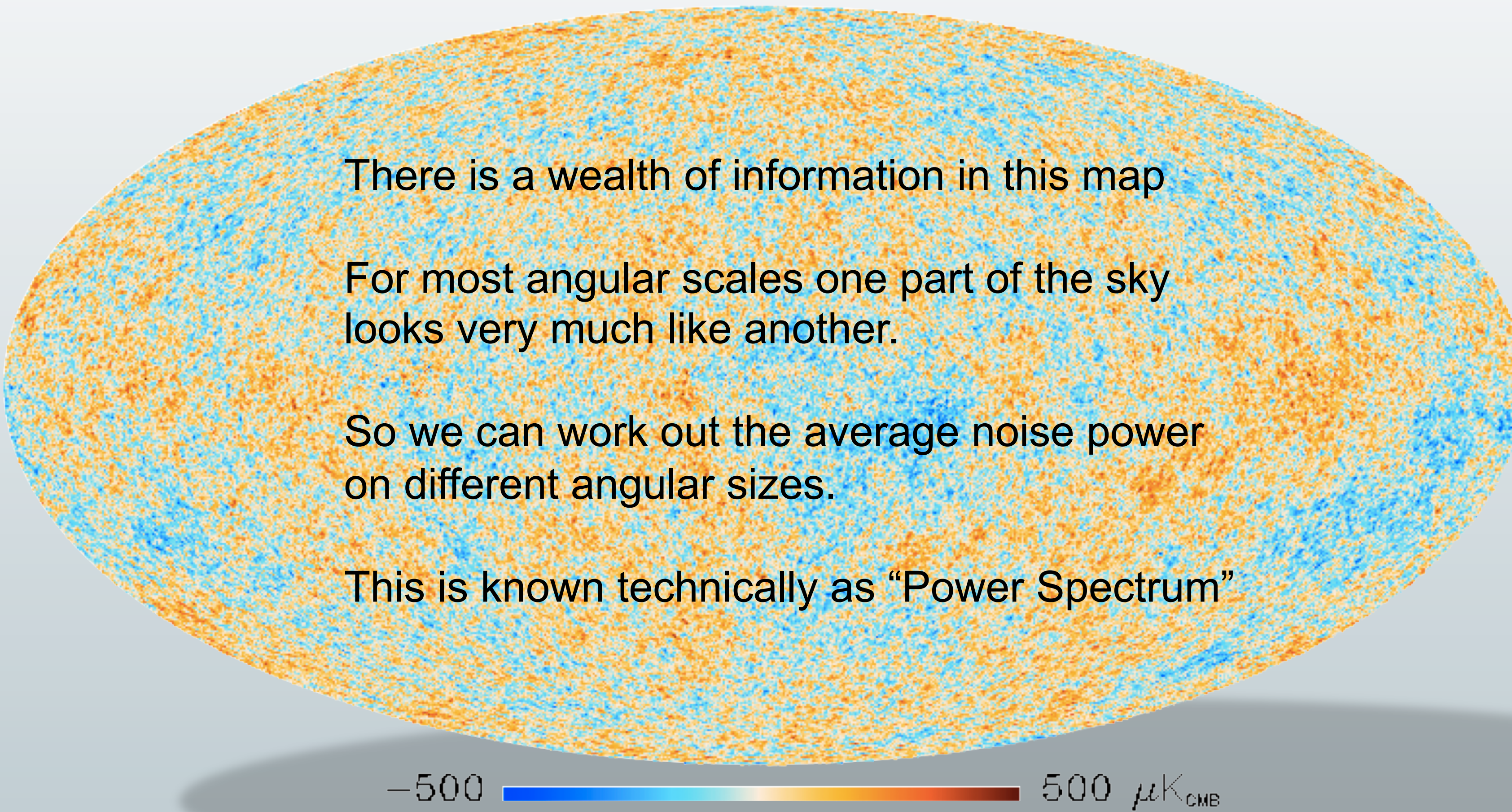


Planck unveils the Cosmic Microwave Background

How Planck Unveils the most Ancient Light



Cosmic Microwave Background some technicalities



There is a wealth of information in this map

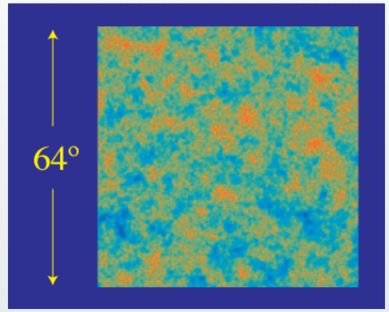
For most angular scales one part of the sky looks very much like another.

So we can work out the average noise power on different angular sizes.

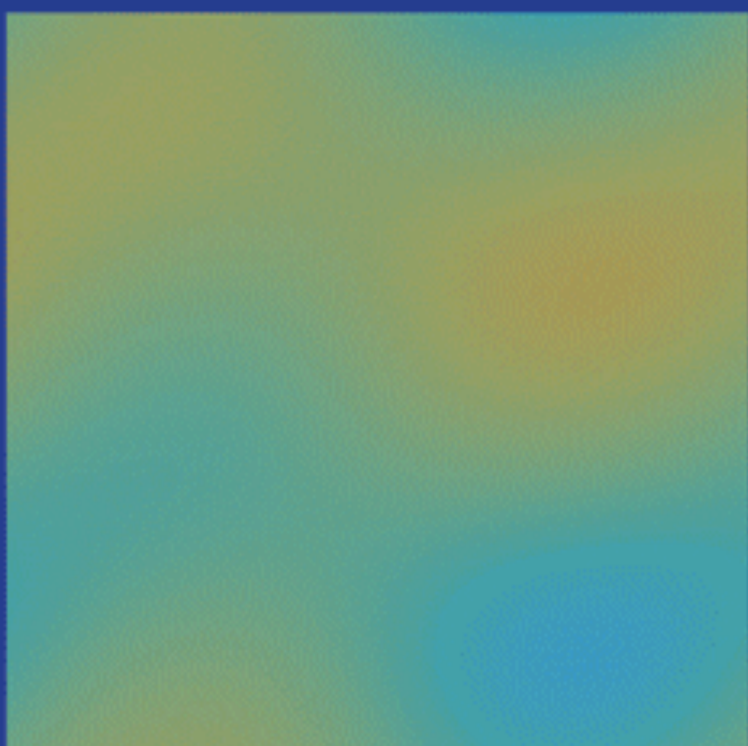
This is known technically as “Power Spectrum”

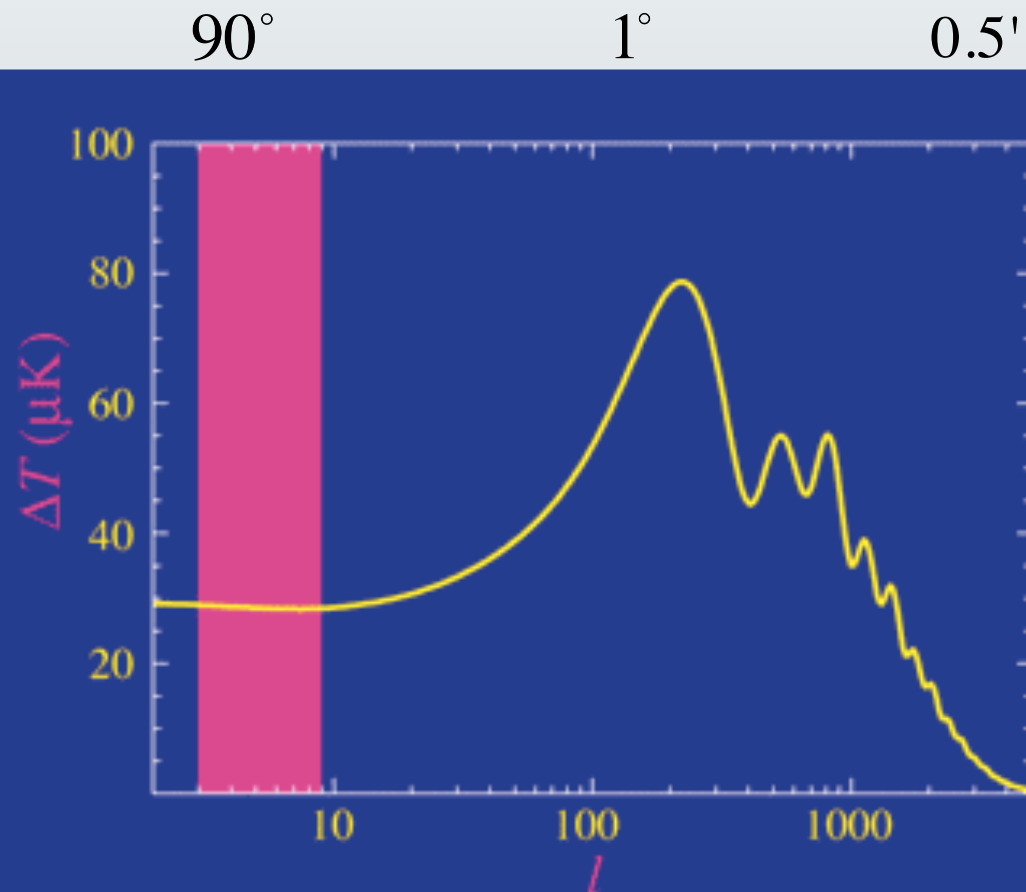
CMB angular power spectrum
how does it work?

The angular power spectra tell us how the amplitude of the fluctuations vary with size



As the pink filter slides from left to right the spots get smaller,
and up to first peak they also get brighter; beyond this point they get smaller and fainter





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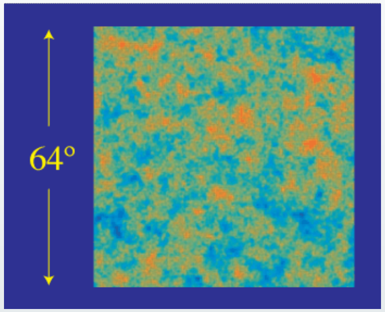

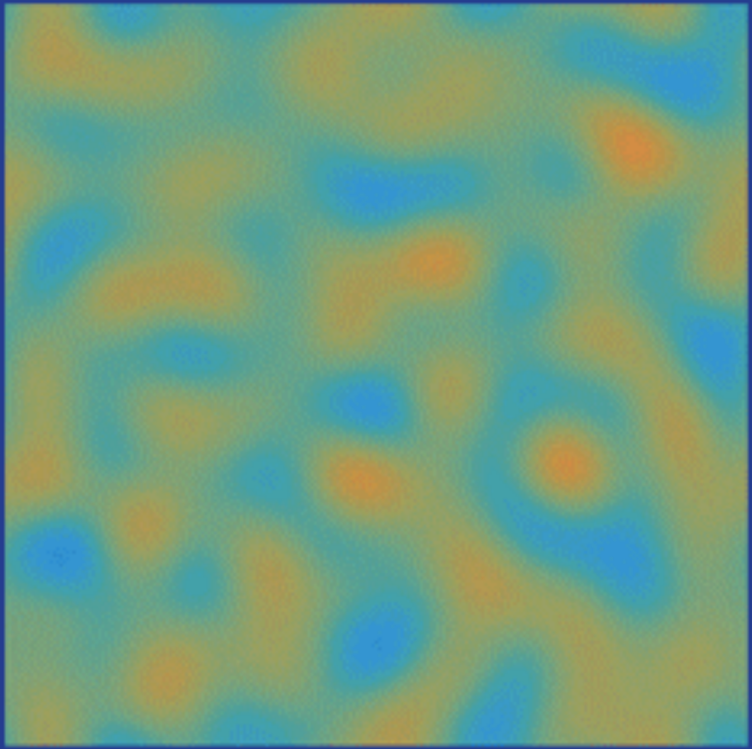

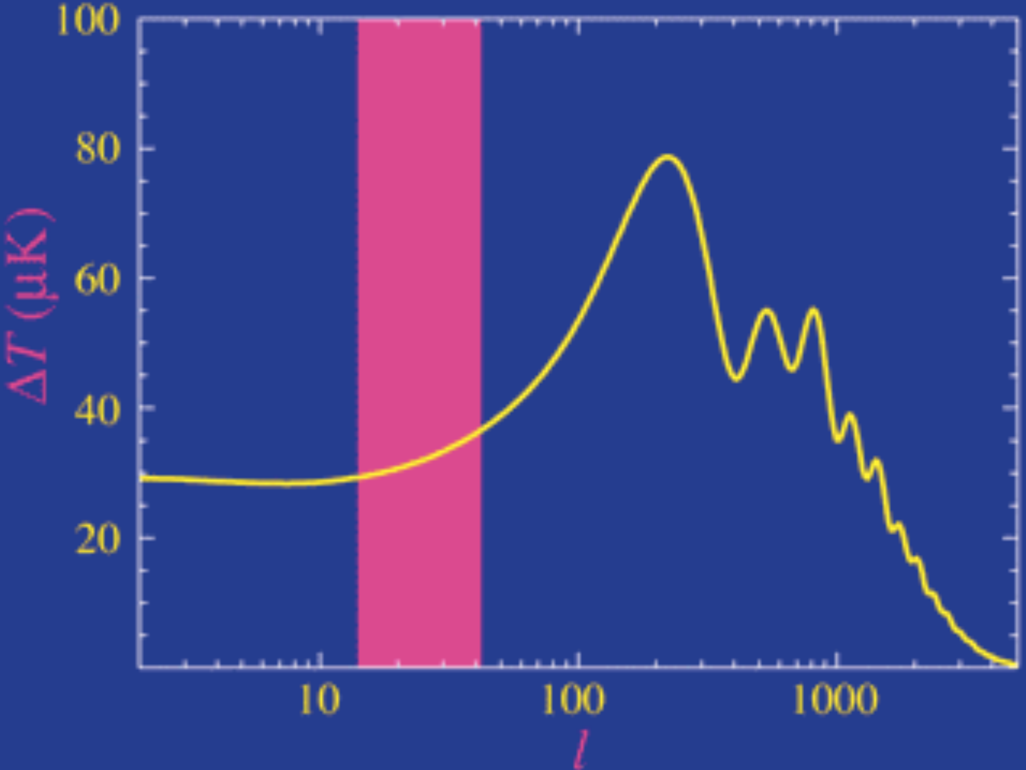

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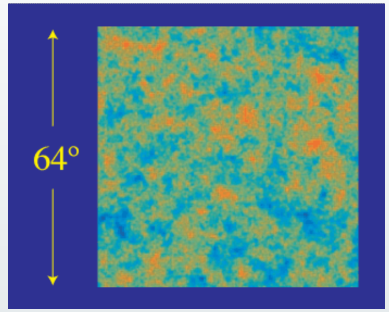

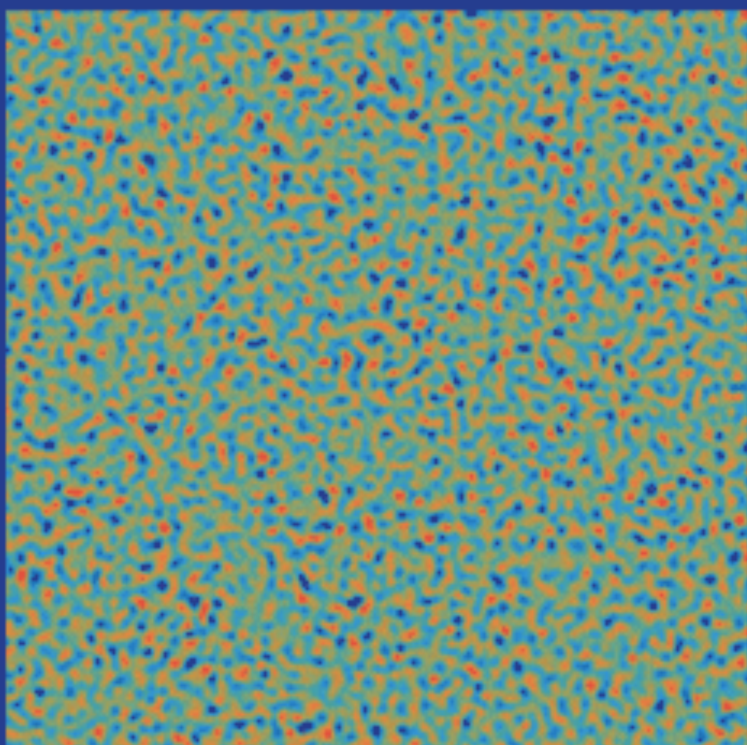

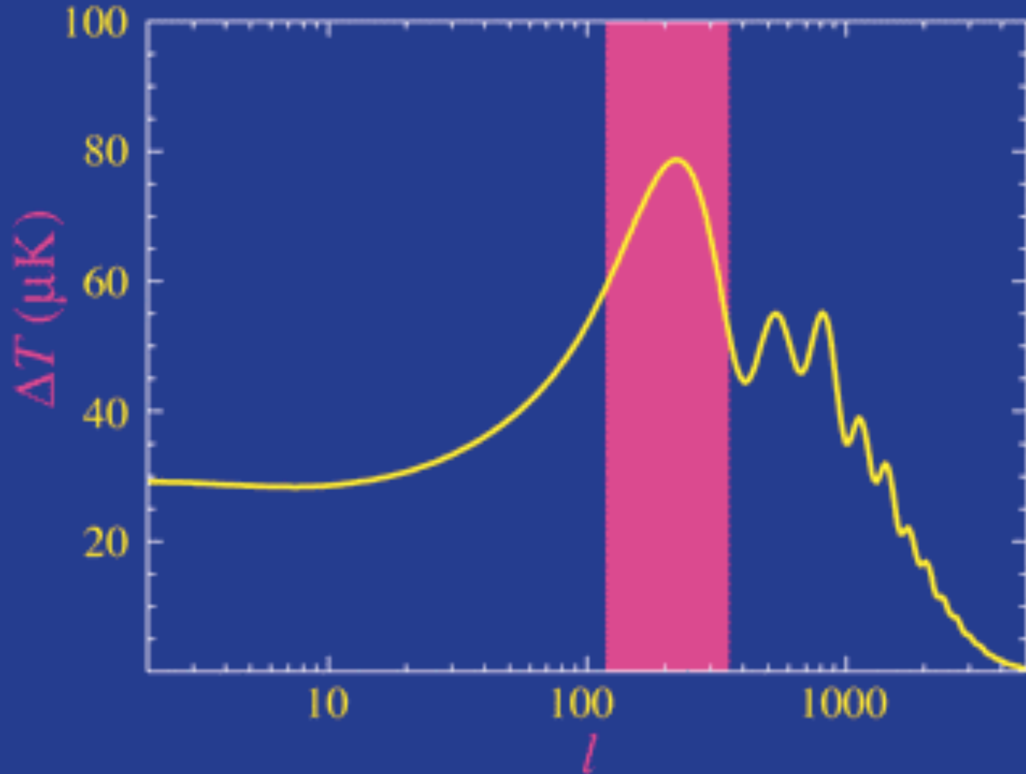

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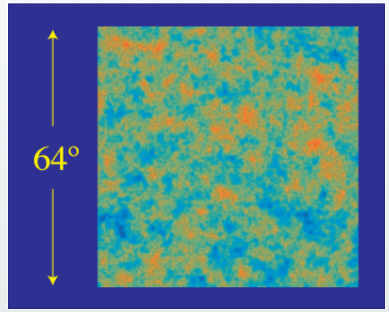
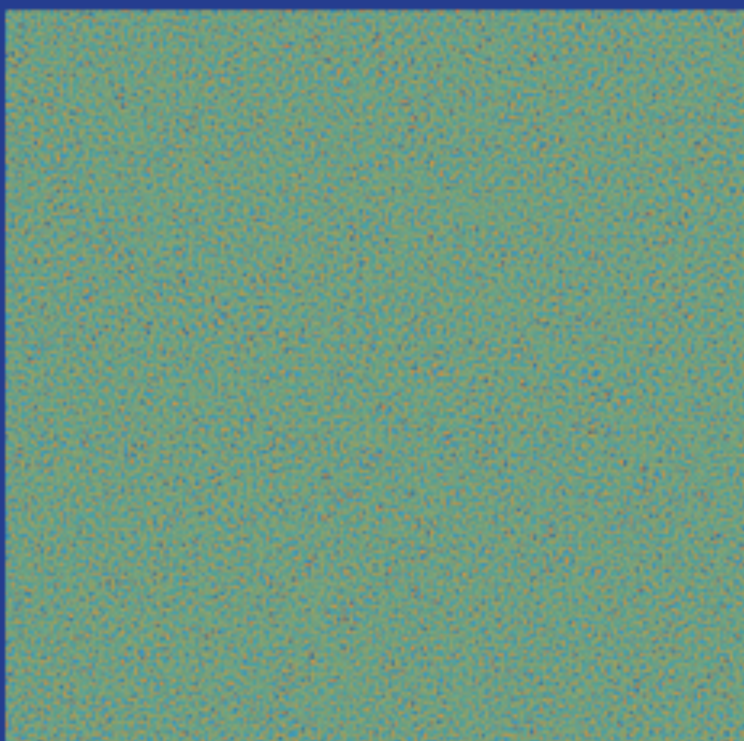
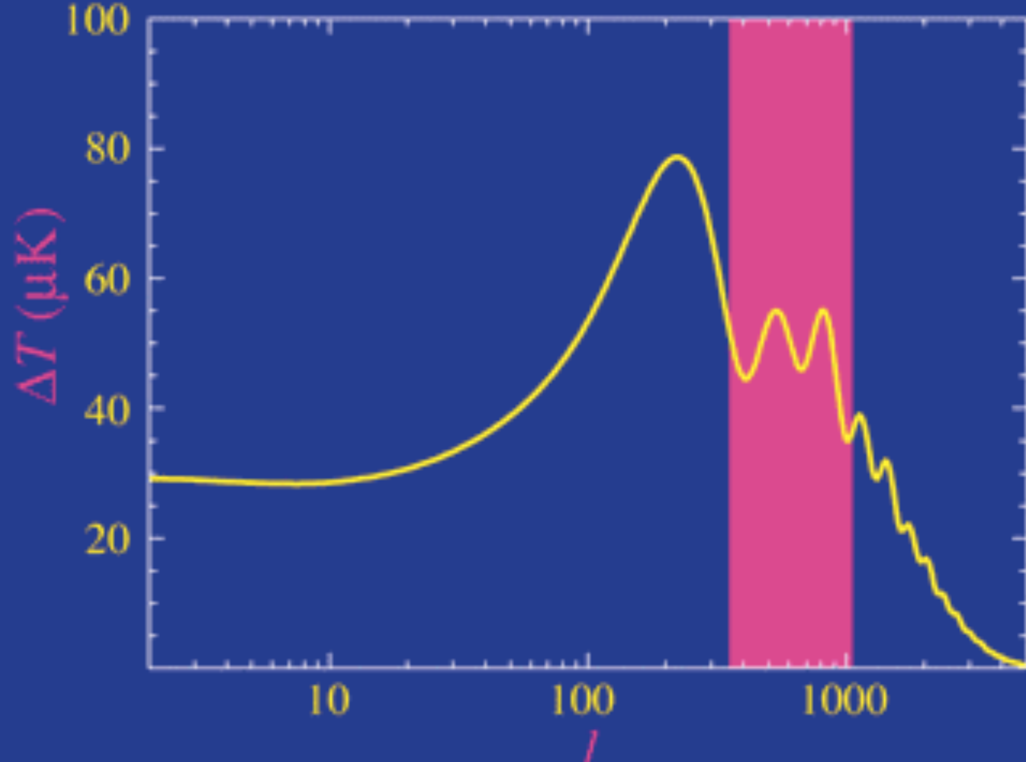
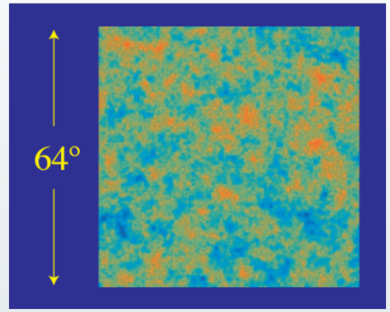


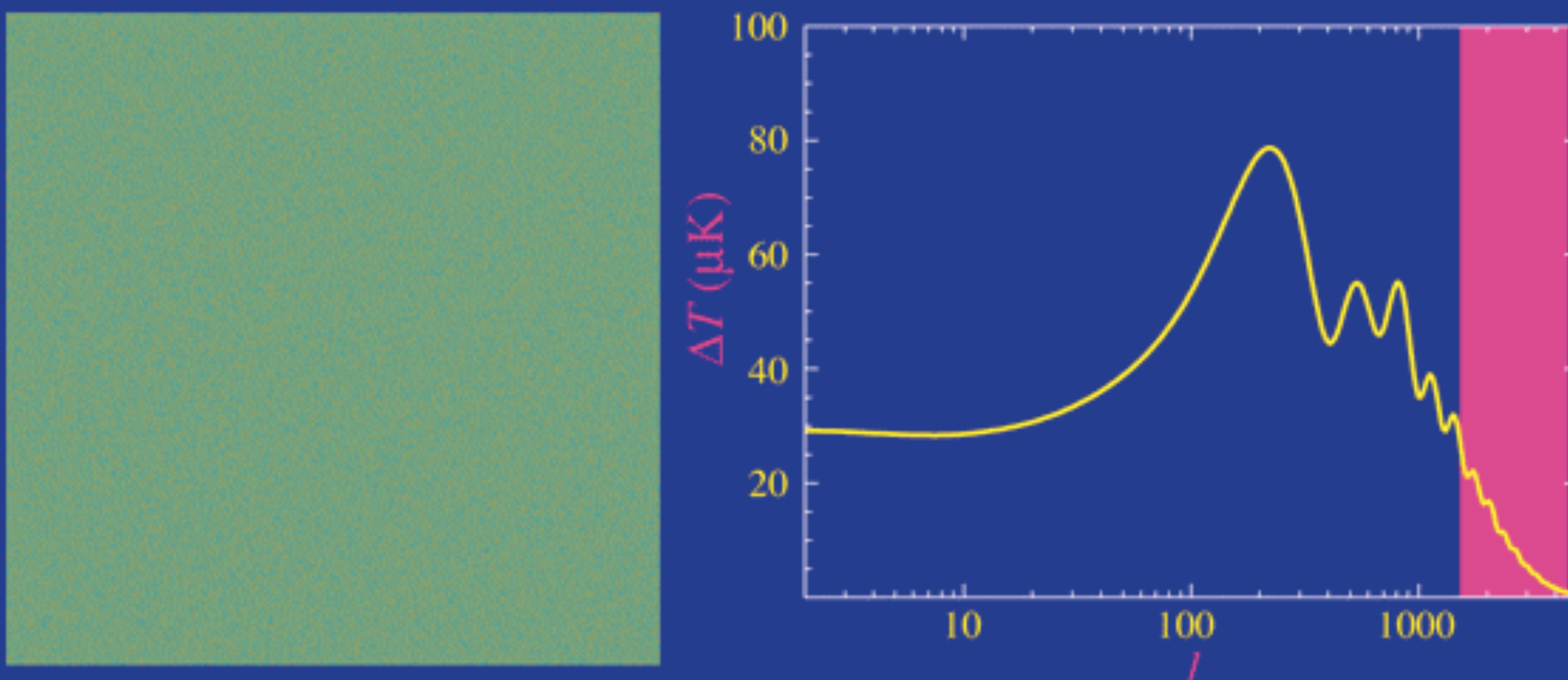




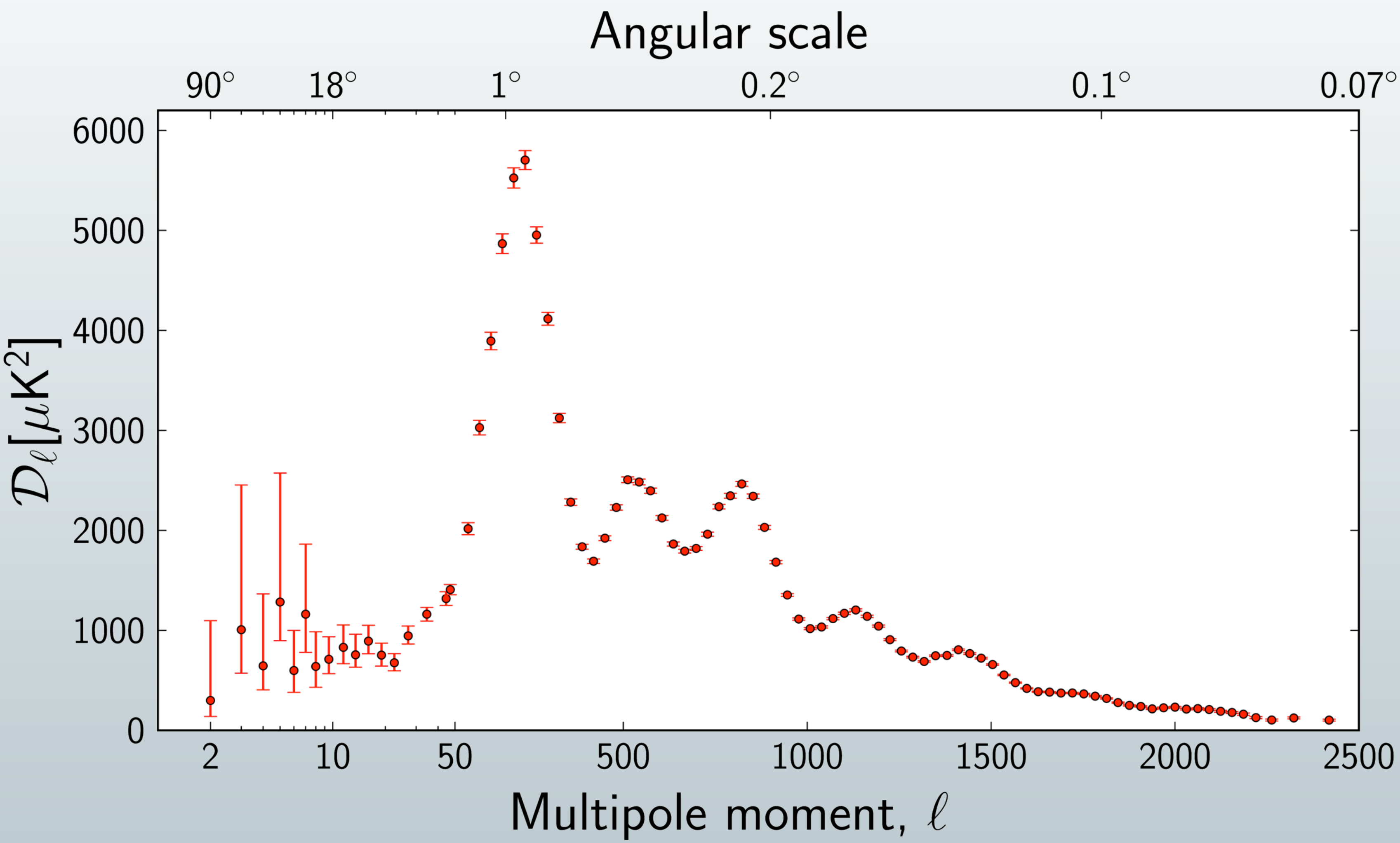
CMB angular power spectrum how does it work?

The angular power spectra tell us how the amplitude of the fluctuations vary with size

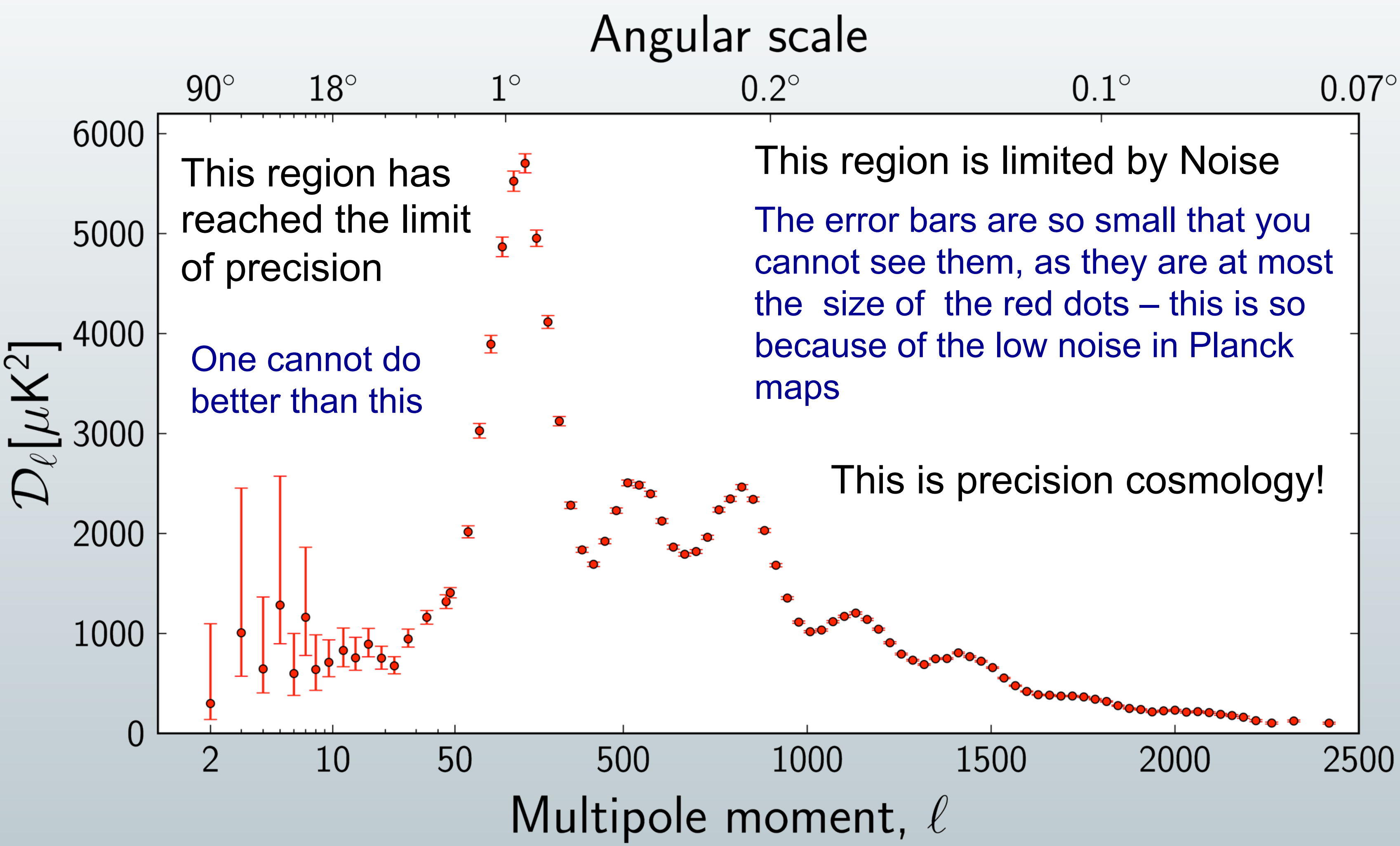




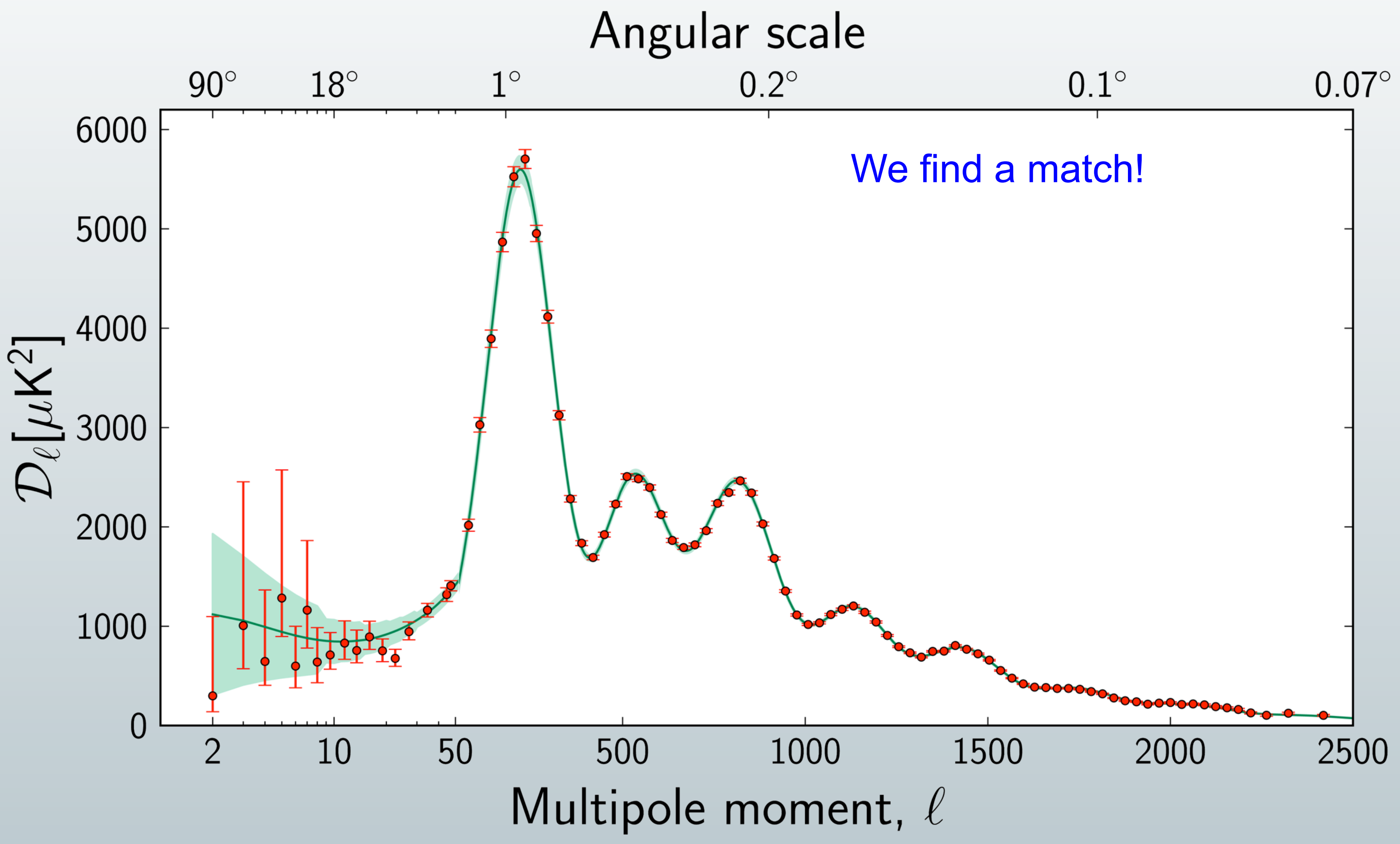
CMB angular power spectrum
what we measure from Planck



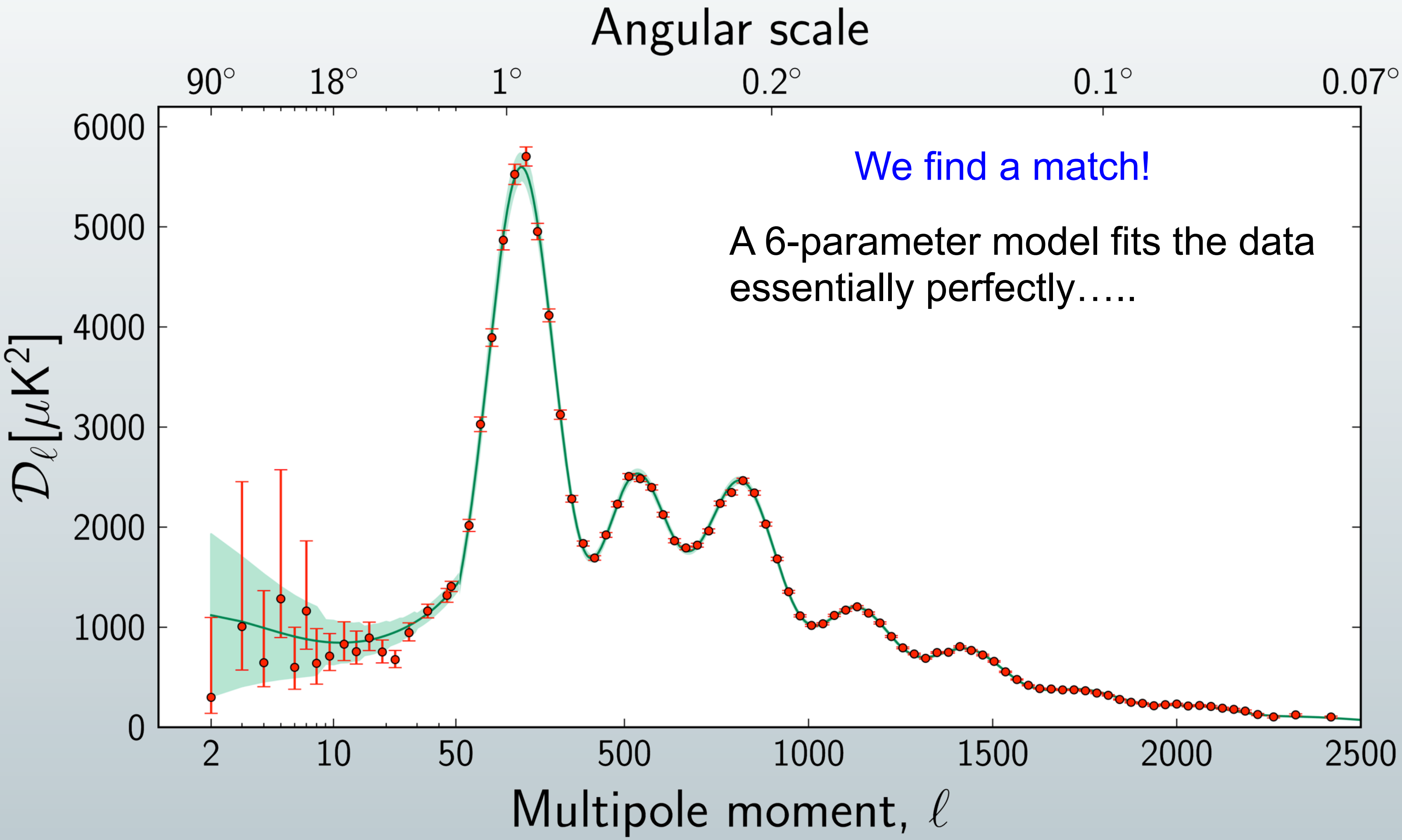
CMB angular power spectrum what we measure from Planck



CMB angular power spectrum from Planck measurement vs models



CMB angular power spectrum from Planck measurement vs models



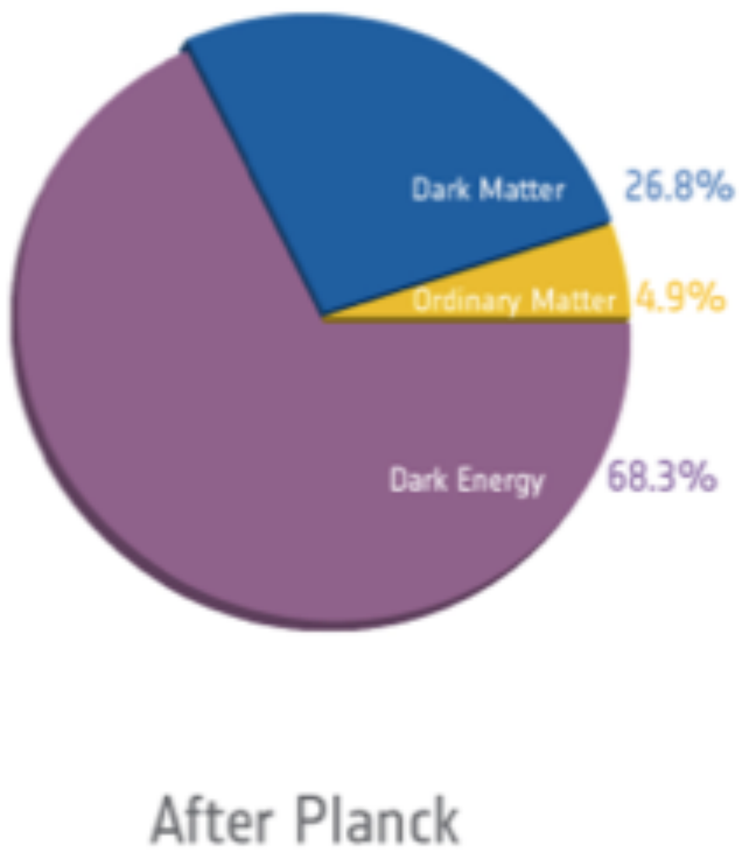
We find a match!

A 6-parameter model fits the data essentially perfectly…..

What Have We Learned ?

The Universe

Has more matter and less dark energy



$$\Omega_b h^2 = 0.02205 \pm 0.00028$$

$$\Omega_c h^2 = 0.1199 \pm 0.0027$$

$$n_s = 0.9603 \pm 0.0073$$

$$\ln(10^{10} A_s) = 3.089 \pm 0.025$$

$$100\theta = 1.04131 \pm 0.00063$$

$$H_0 = 67.3 \pm 1.2 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

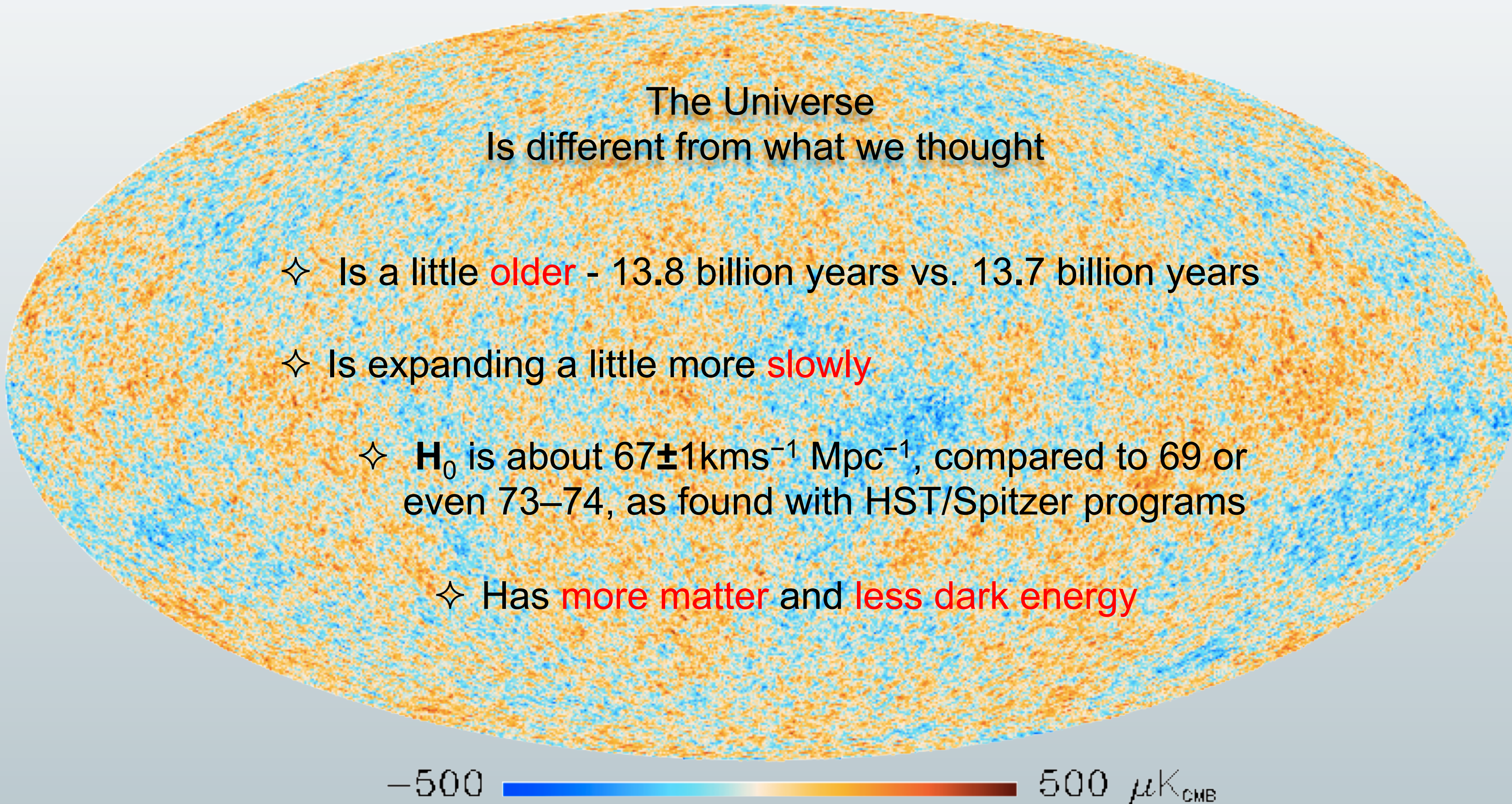
$$\text{Age} = 13.81 \pm 0.05 \text{ billion years}$$

Consistent with spatial flatness to % level

What Have We Learned ?
In words

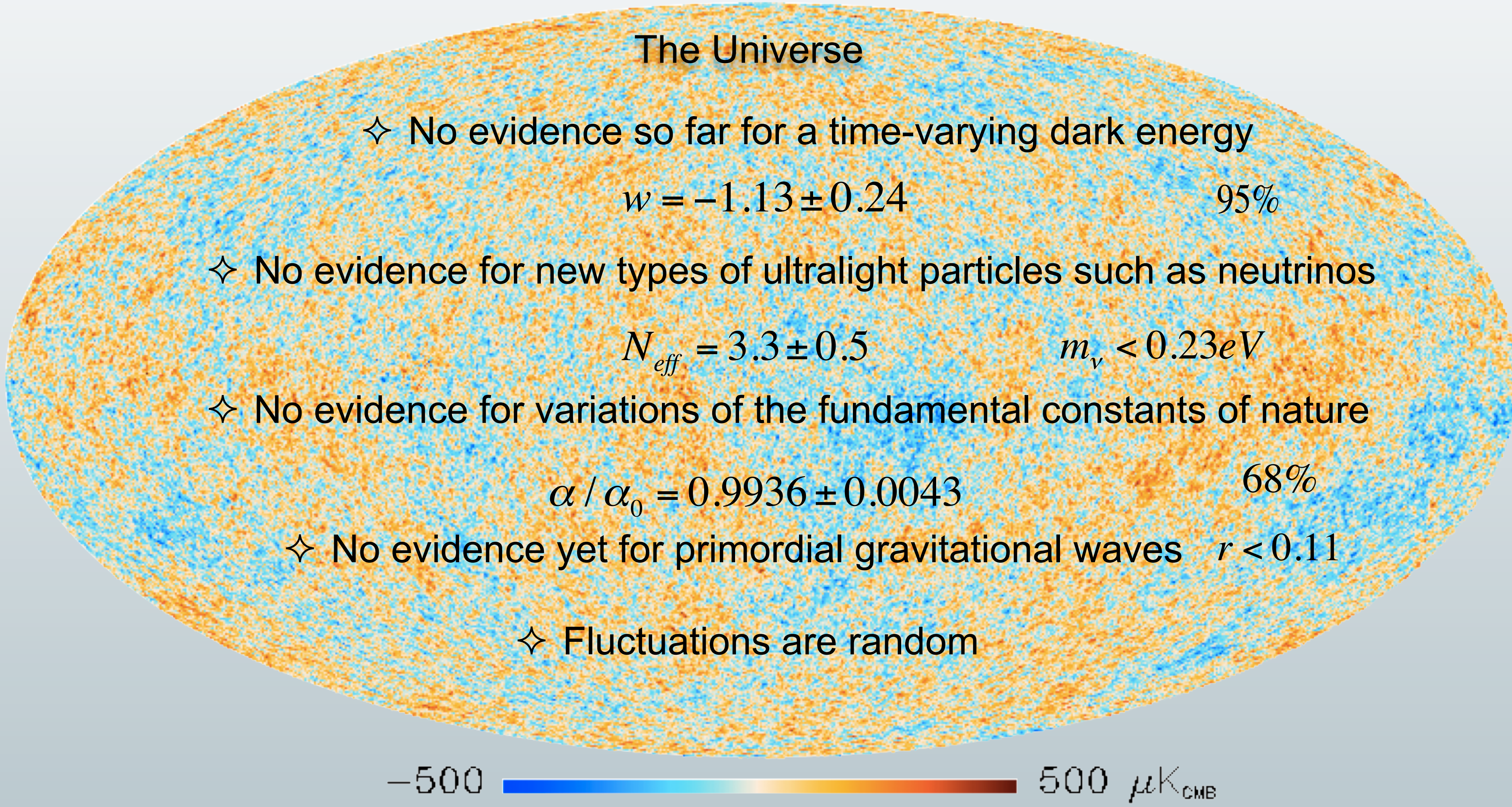
The Universe
Is different from what we thought

- ✧ Is a little older - 13.8 billion years vs. 13.7 billion years
- ✧ Is expanding a little more slowly
  - ✧ H_0 is about 67±1kms^{-1} Mpc^{-1}, compared to 69 or even 73–74, as found with HST/Spitzer programs
- ✧ Has more matter and less dark energy



What Have We Learned ?
Extending beyond 6-parameters

Potential new physics ?



The Universe

✧ No evidence so far for a time-varying dark energy

$$w = -1.13 \pm 0.24 \qquad 95\%$$

✧ No evidence for new types of ultralight particles such as neutrinos

$$N_{eff} = 3.3 \pm 0.5 \qquad m_{\nu} < 0.23 eV$$

✧ No evidence for variations of the fundamental constants of nature

$$\alpha / \alpha_0 = 0.9936 \pm 0.0043 \qquad 68\%$$

✧ No evidence yet for primordial gravitational waves $r < 0.11$

✧ Fluctuations are random

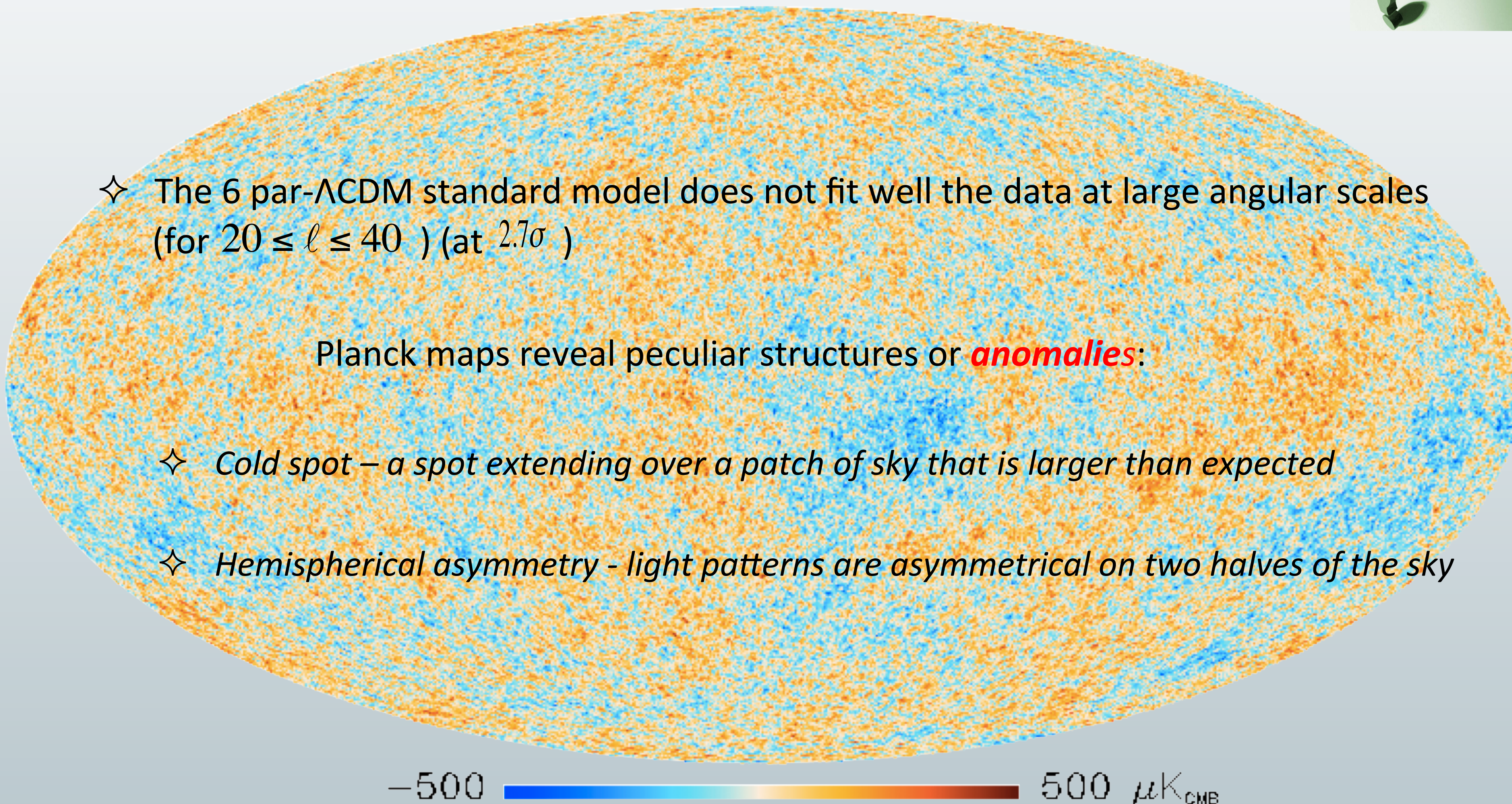
The anomalies

However…..there are small deviations from this picture
Is Planck prompting us to find new ways to explain what we see?

- ✧ The 6 par-ΛCDM standard model does not fit well the data at large angular scales (for $20 \leq \ell \leq 40$) (at 2.7σ)

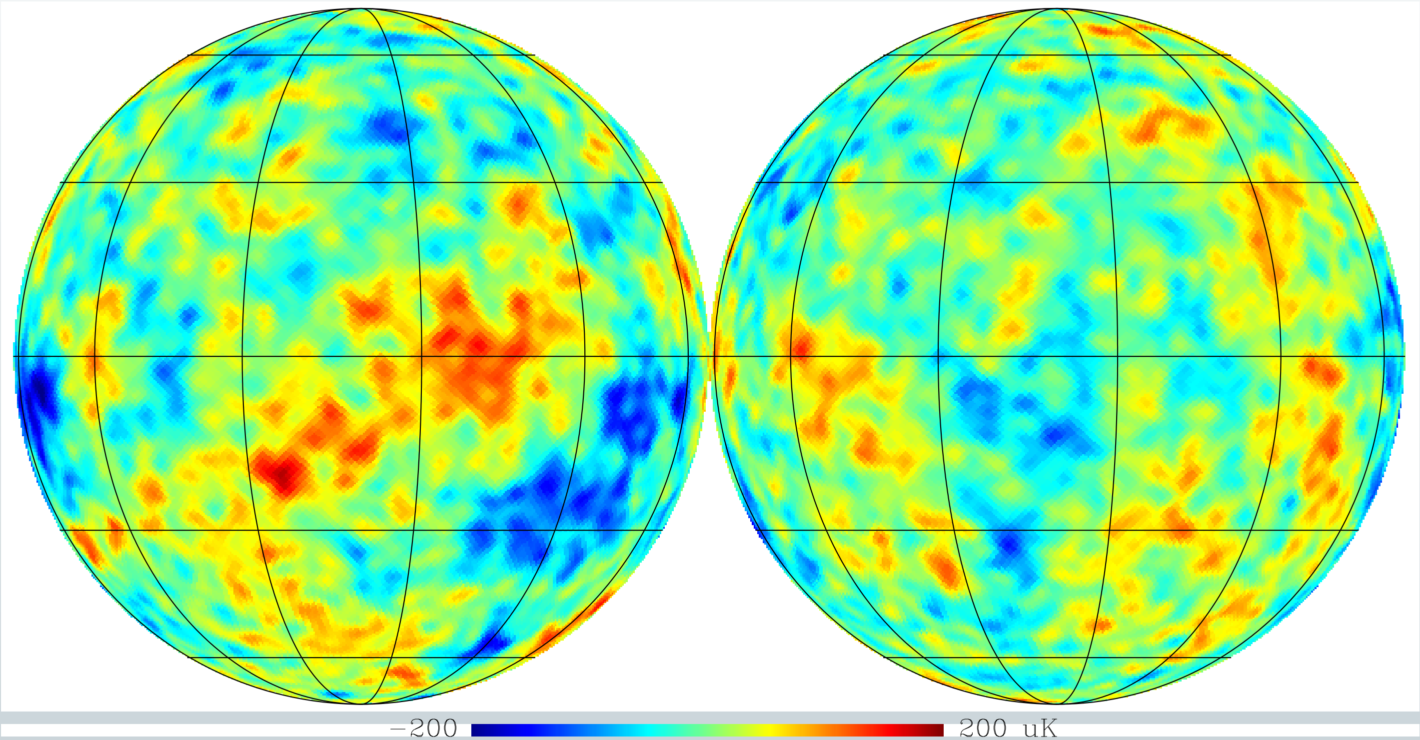
Planck maps reveal peculiar structures or ***anomalies***:

- ✧ *Cold spot – a spot extending over a patch of sky that is larger than expected*
- ✧ *Hemispherical asymmetry - light patterns are asymmetrical on two halves of the sky*



Planck sees peculiar features (anomalies) in the patterns of the relic light

The two halves of the sky that we see look different



A feature noticed before and considered controversial
is now proven real by Planck
Does this call for new physics?
These are large scale features. They give a pristine image of the very very early Universe.

What next?

- Planck data is like a jewel-box filled with treasures.
- We have learnt a great deal about our Universe, even if getting to this point was quite exhausting, as many Planck team members could tell you.
- However there is still a huge amount to learn and do. There is a lot of data to look at and analyse, including the polarization of this ancient light.
- It has taken us 20 years to get to this point. One might ponder what our knowledge of the Universe will look like in 20 years time. It will be interesting to see!

The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.