The contribution of Planck to Cosmology

13.8 billion years of the history of the universe unveiled by the satellite mission Planck

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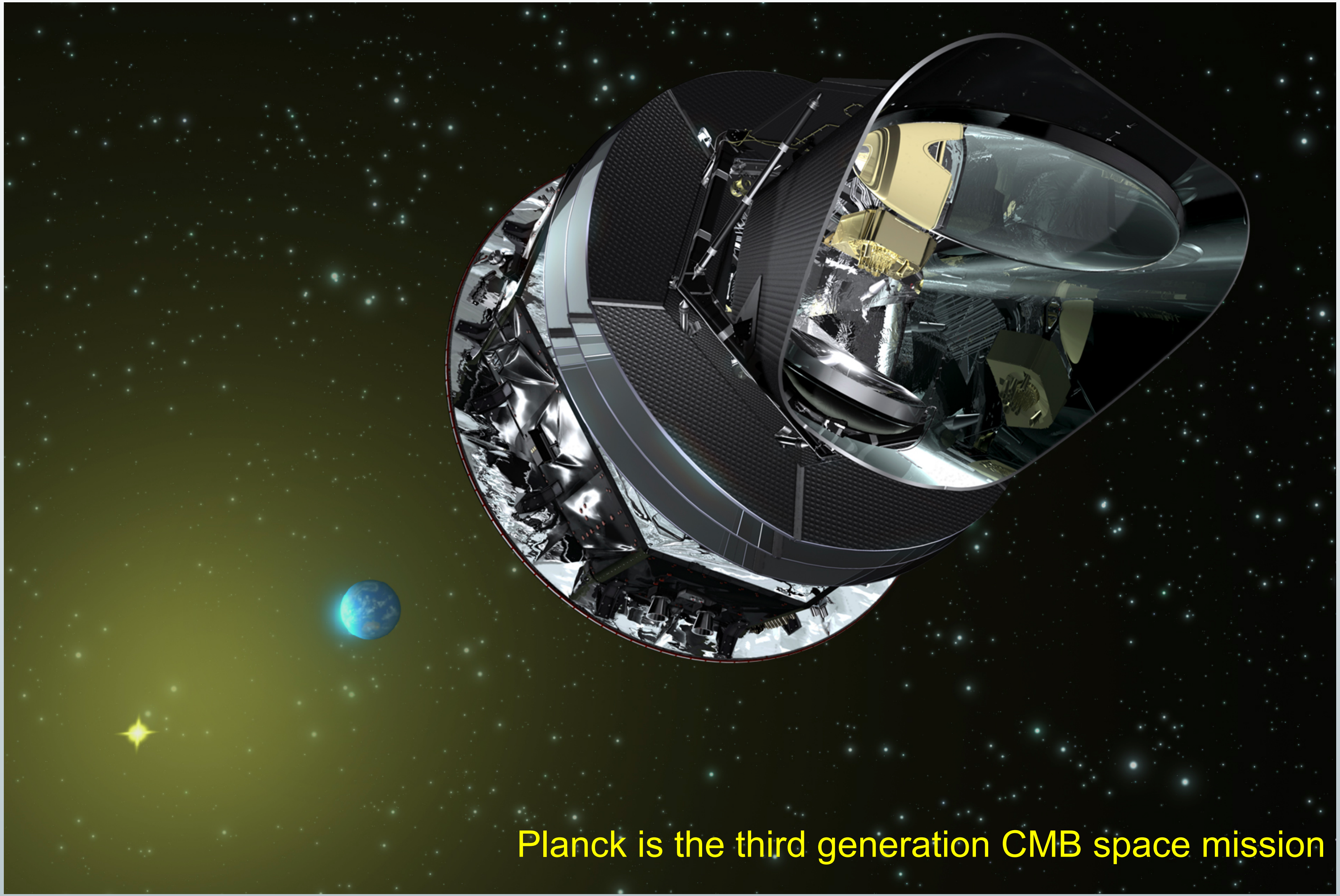
On behalf of the Planck collaboration

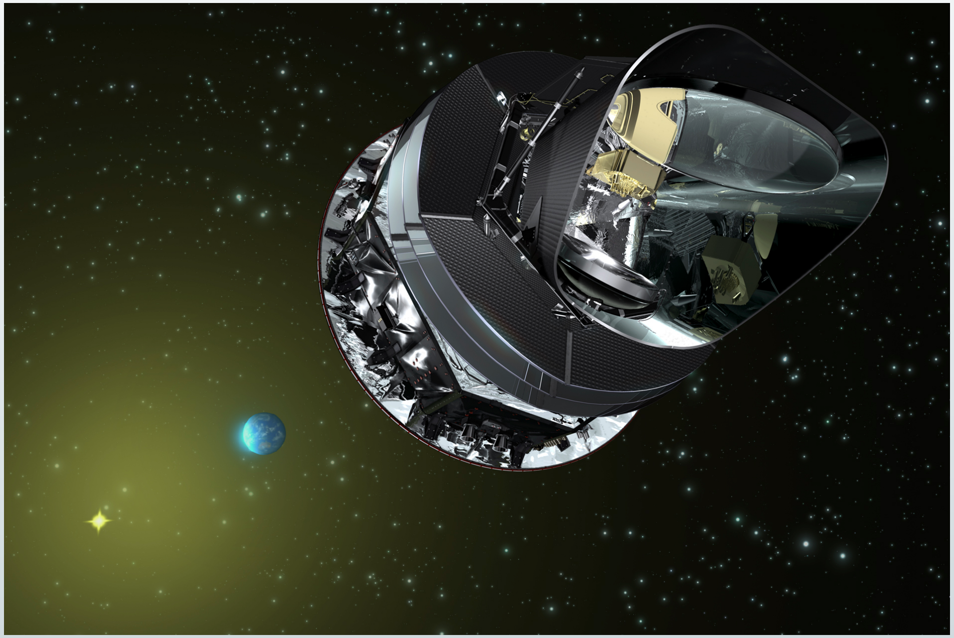
EPI conference, Santander, 26thth June 2013

Planck



Planck

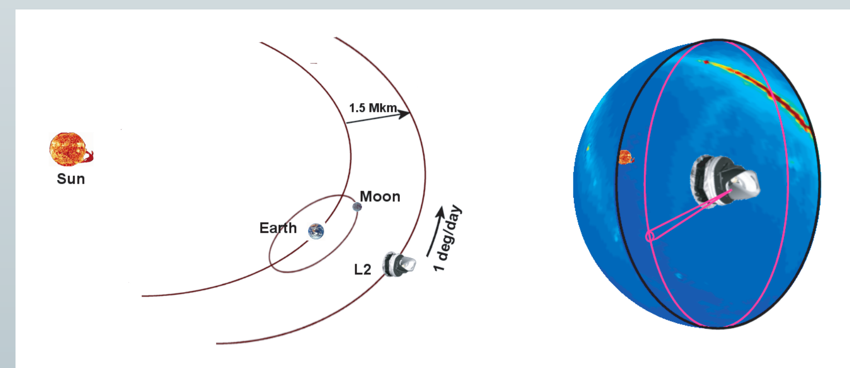
Planck is the third generation CMB space mission



Scientific goal:

Measure the tiny fluctuations
In the temperature of this relic radiation called Cosmic Microwave Background with high accuracy and resolution

Fly at Sun-Earth $\mathbf{L_2}$ point



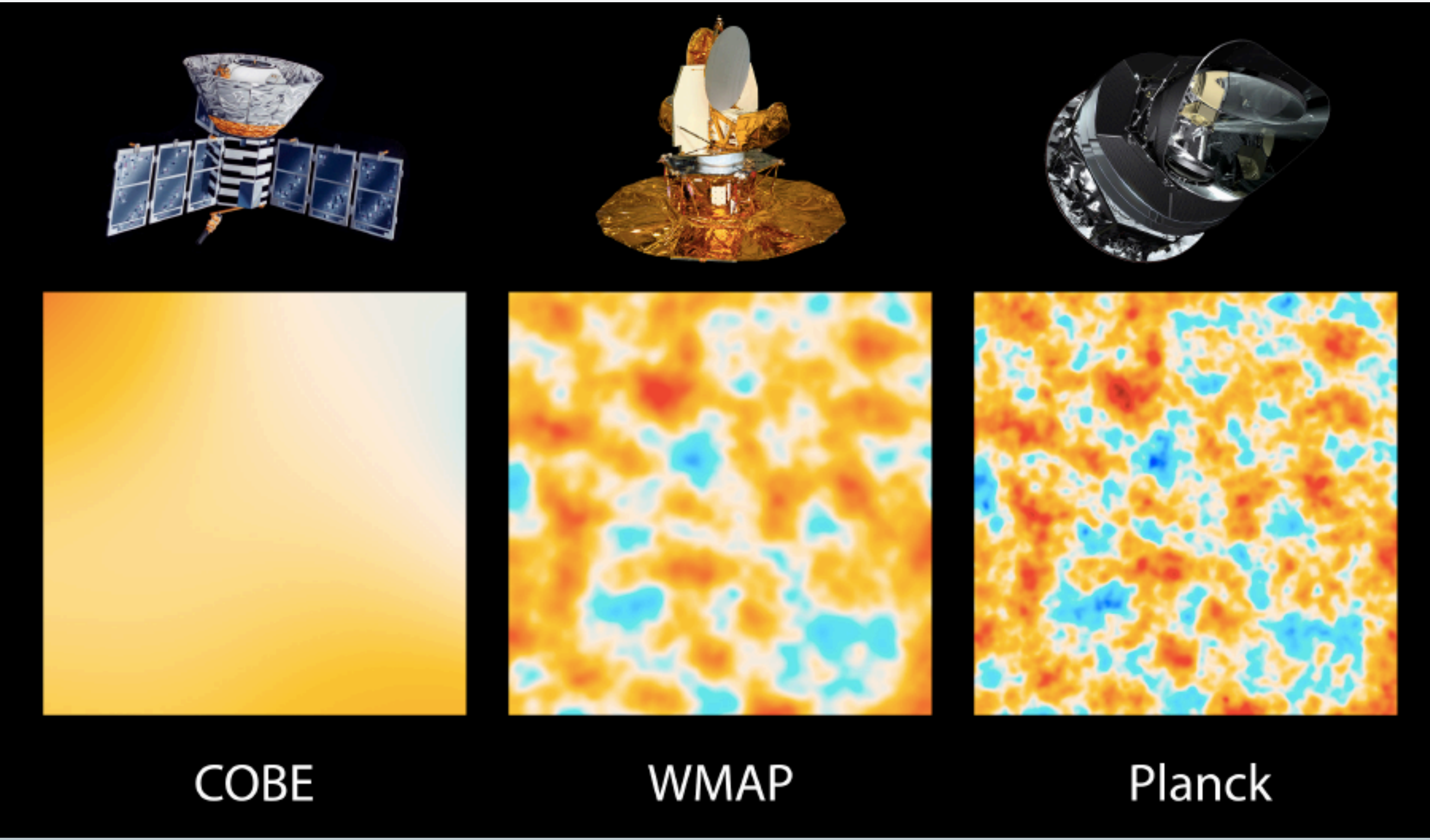
Two instruments:

- Low Frequency Instrument (LFI), 20-K cryogenic amplifiers
- High Frequency Instrument (HFI), 0.1-K bolometers

Covers a large number (9) frequencies:
30, 44, 70, 100, 143, 217, 353, 545, 857 GHz

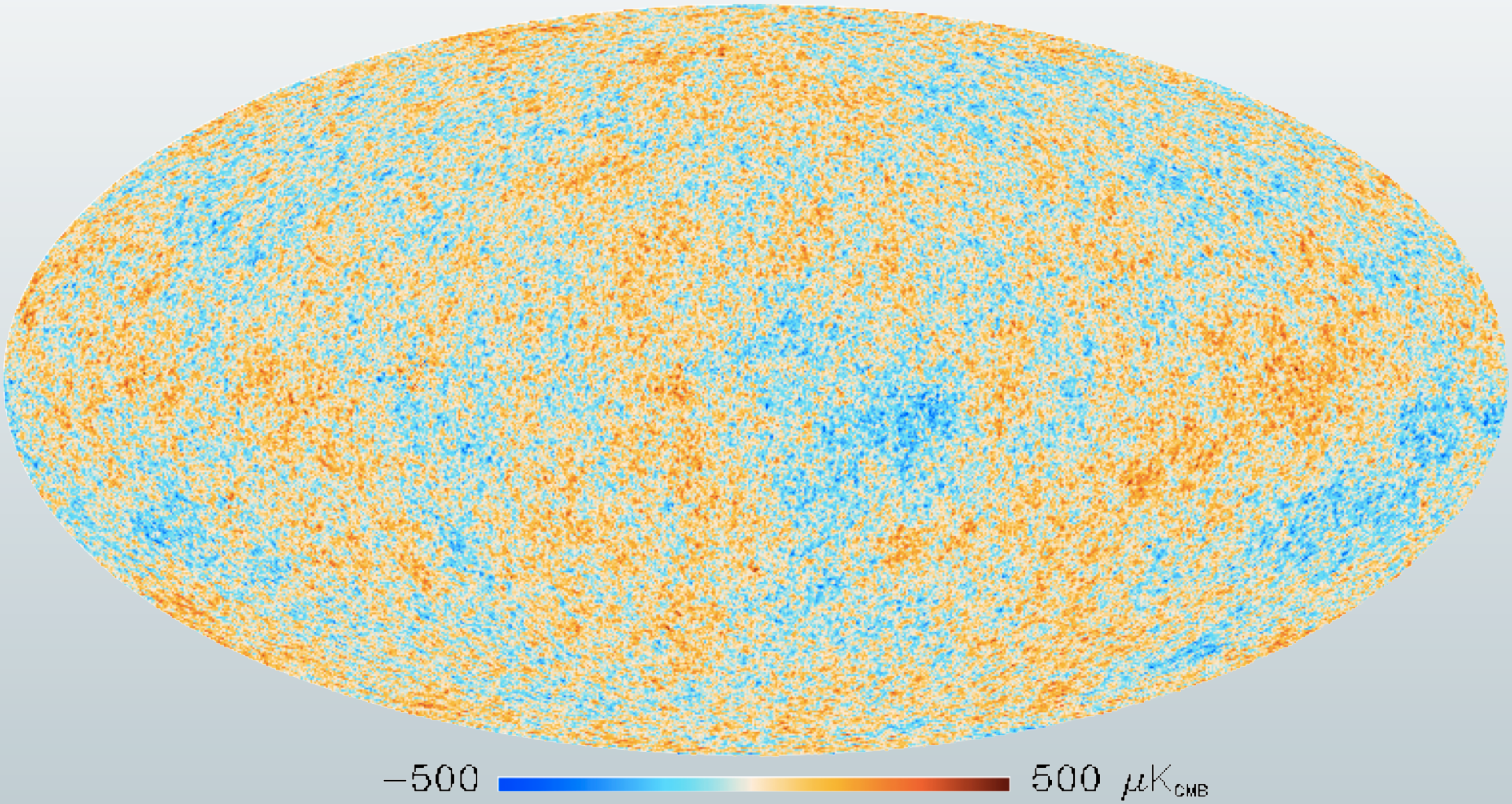
Cosmic Microwave Background Fluctuations

Resolution and Sensitivity



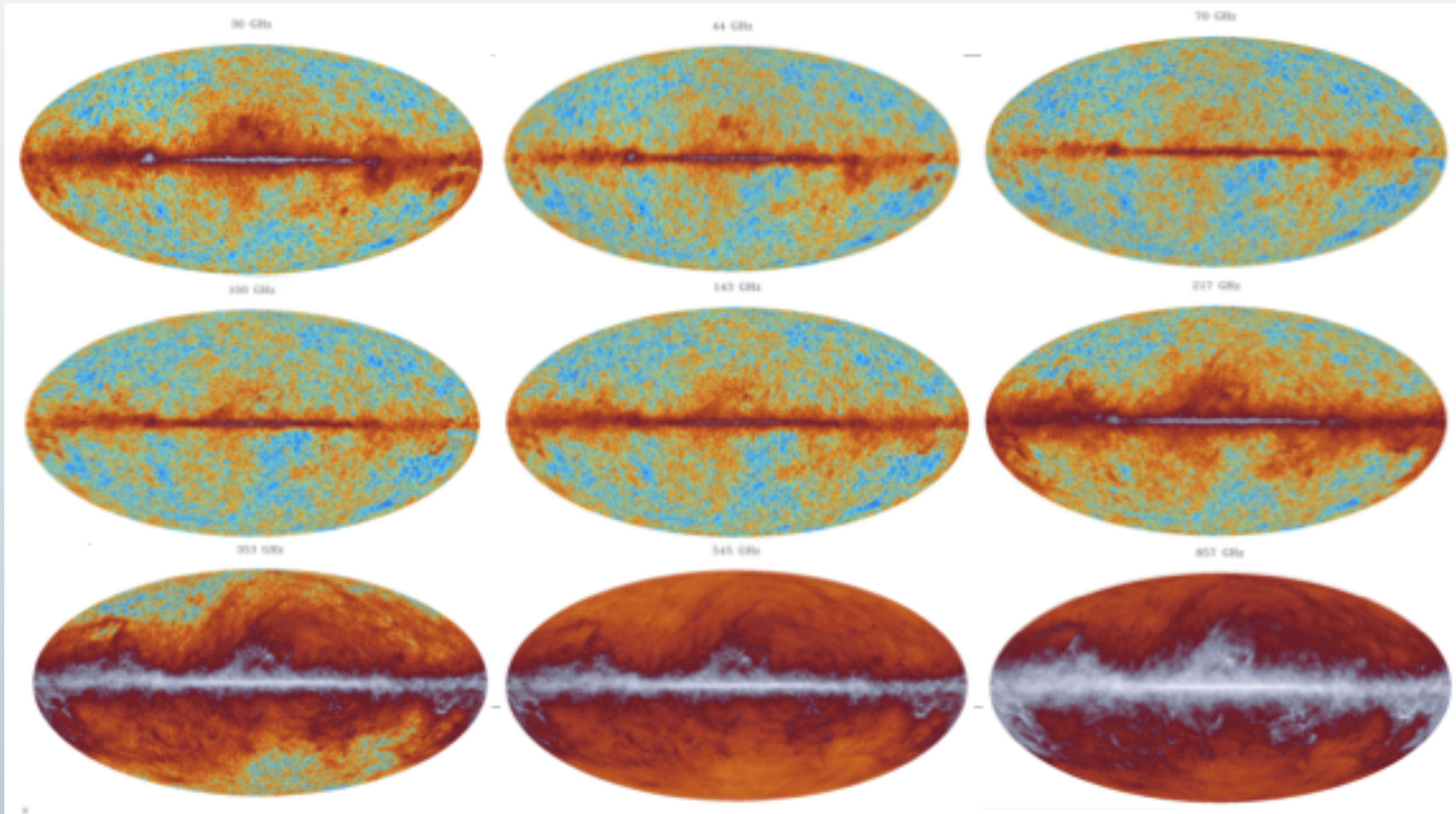
Cosmic Microwave Background Fluctuations

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



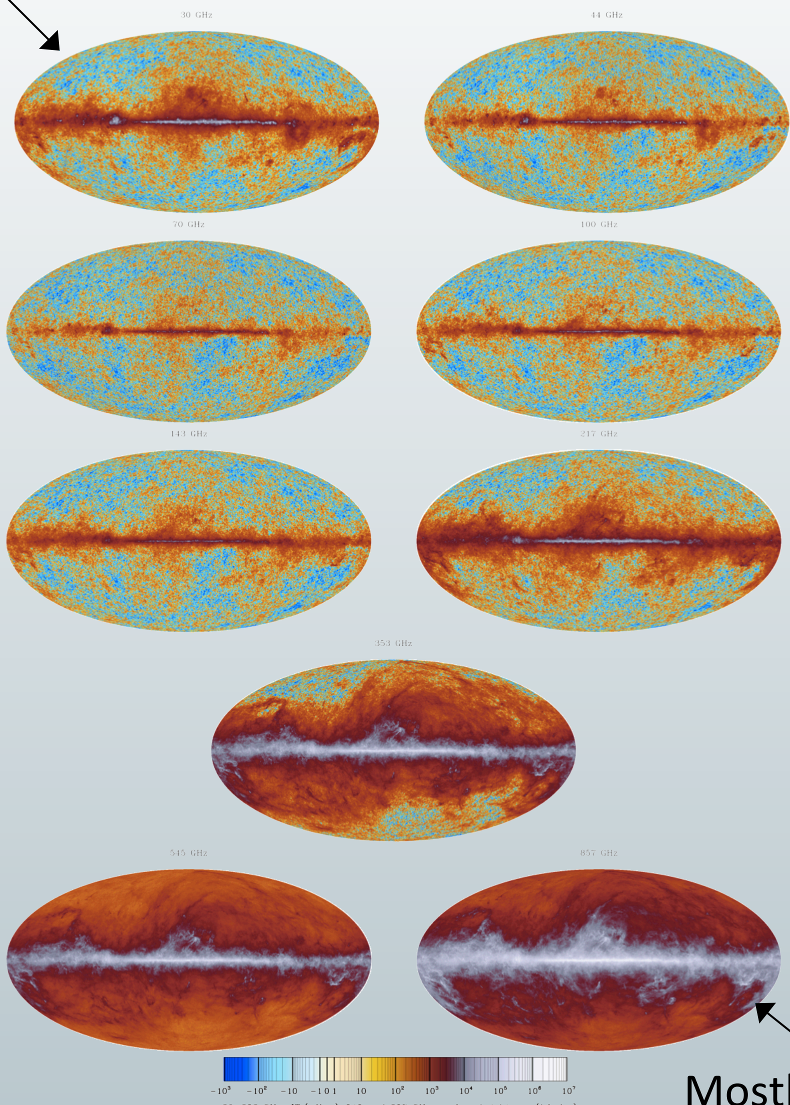
How Planck sees the sky
Planck Frequency Maps

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



How Planck Sees the Sky

Mostly synchrotron



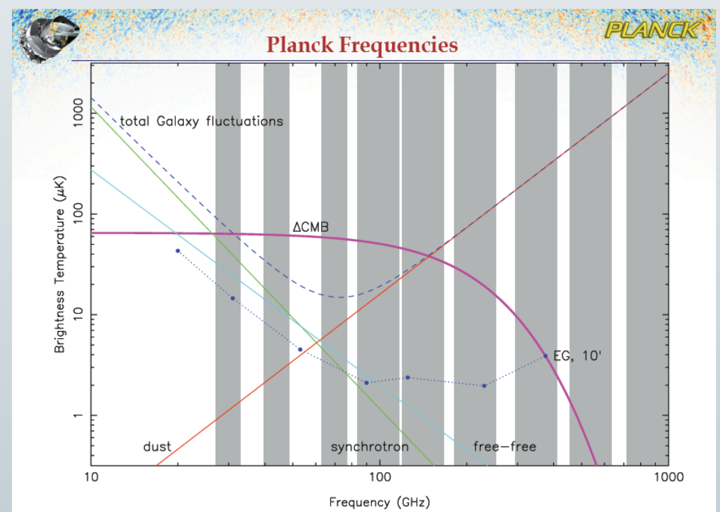
Mostly dust

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

Planck data

- 2013 data release based on the first 15.5 months of data, temperature only.
  - 2014 data release will be based on 29 months HFI, 50 months LFI data, temp + polarization (full mission)

- Maps at nine frequencies

- Maps of separated components:
  - CMB
  - "Low frequency" component: synchrotron + free-free + spinning dust
  - "High frequency" component: dust + cosmic infrared background
  - Carbon monoxide

- Angular power spectrum of the CMB map and the Likelihood function

$$L(C_\ell) = P(D \mid C_\ell)$$

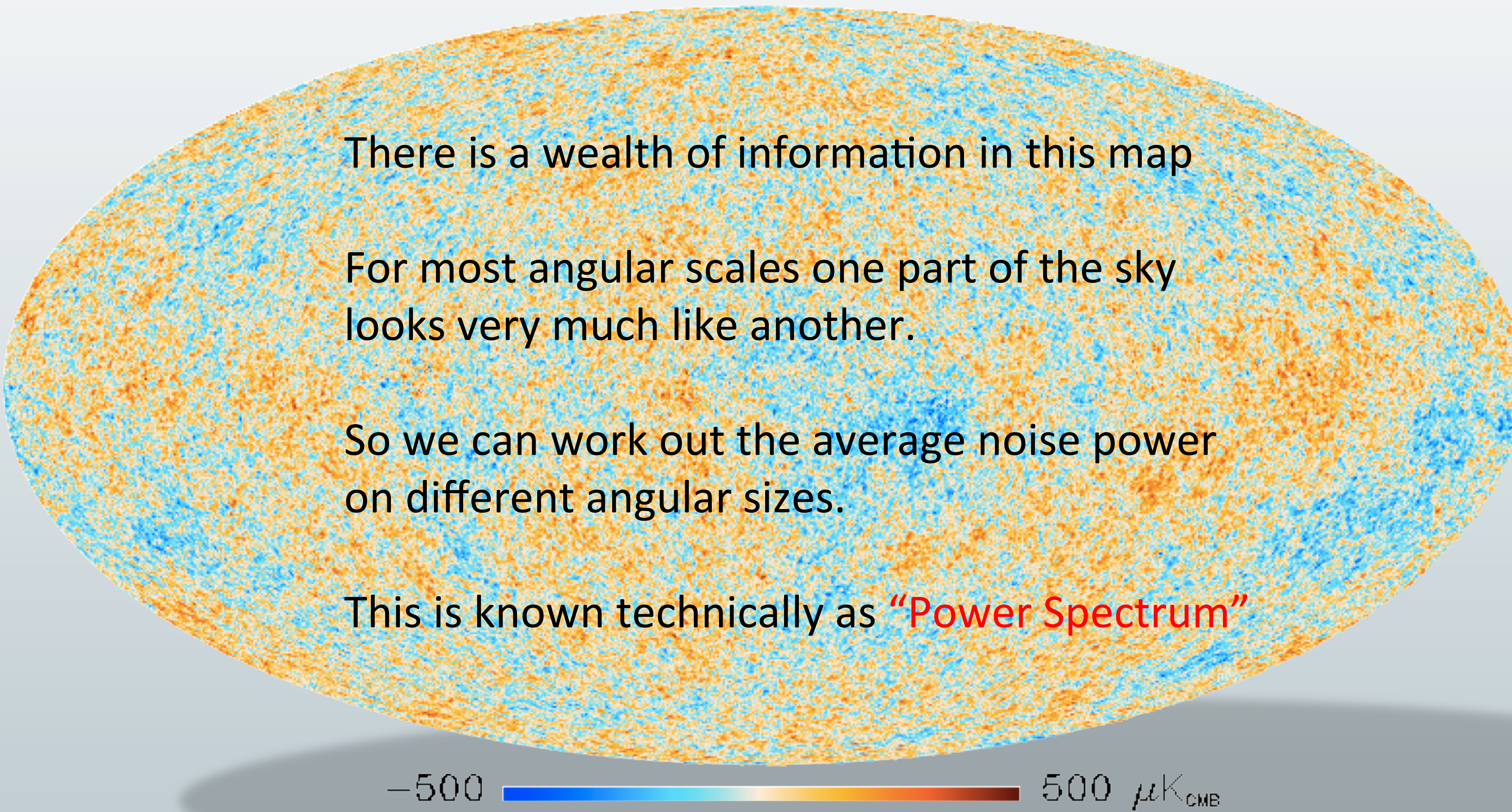
Cosmic Microwave Background some technicalities

There is a wealth of information in this map

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

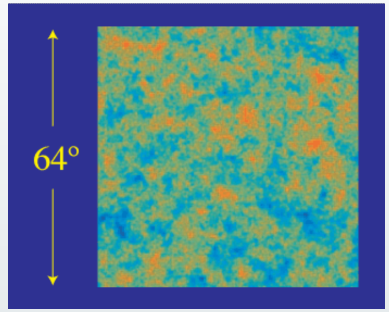
So we can work out the average noise power on different angular sizes.

This is known technically as “Power Spectrum”



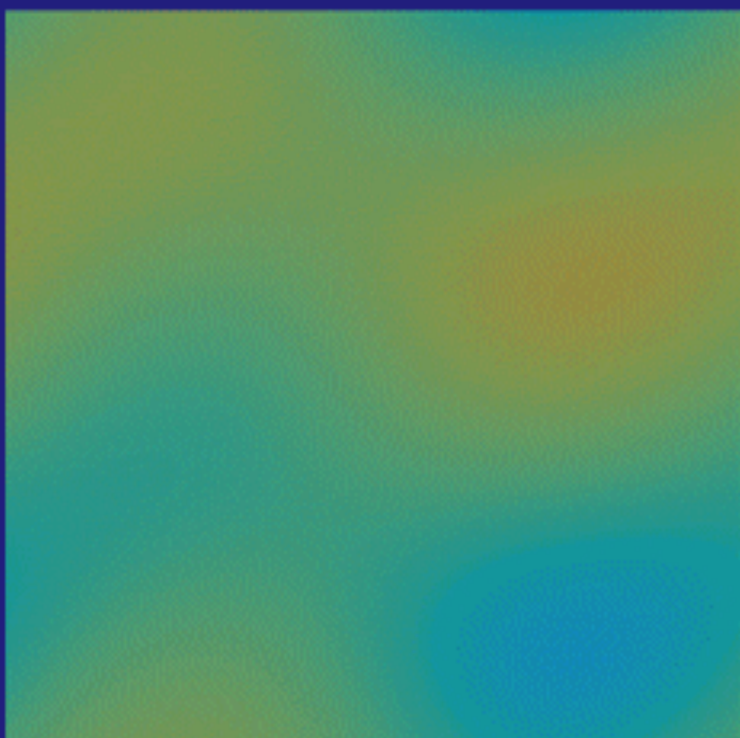
CMB angular power spectrum
how does it work?

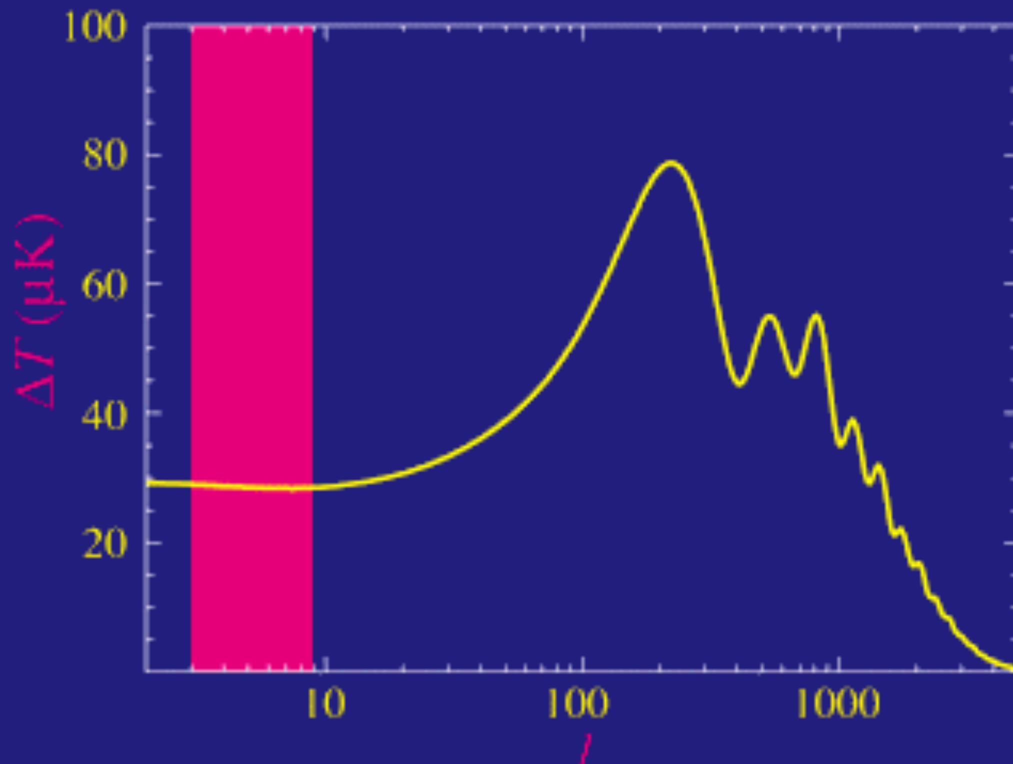
The angular power spectra tell us how the amplitude of the fluctuations vary with size



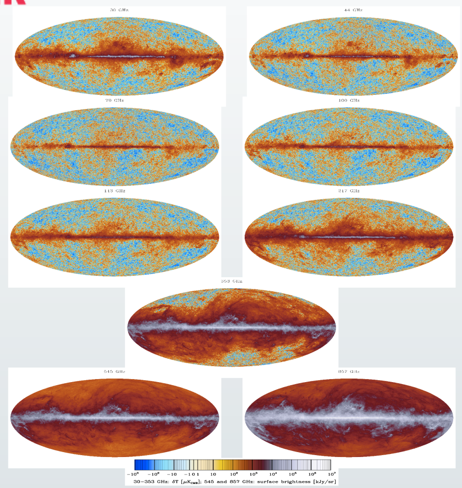
As the pink filter slides from left to right the spots get smaller,
and up to first peak they also get brighter; beyond this point they get smaller and fainter

90° 1° 0.5'



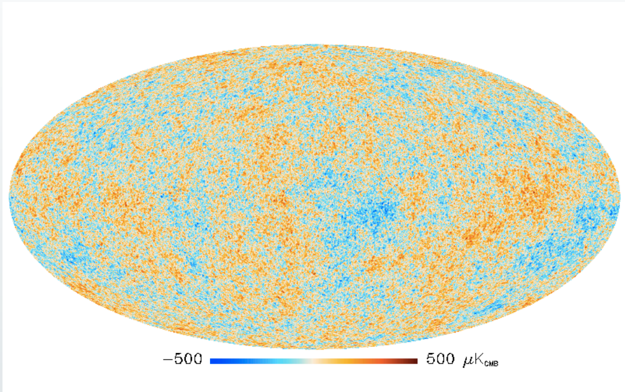


Science Extraction from the Multi-frequency CMB Sky Maps (in a Nutshell)



Frequency maps

Component Separation



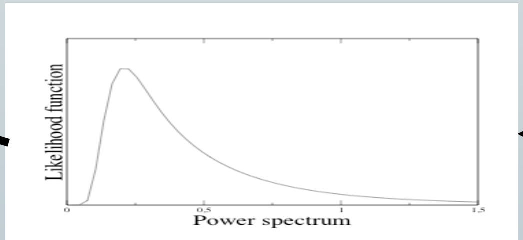
Cleaned CMB map

directly from sky maps to the likelihood

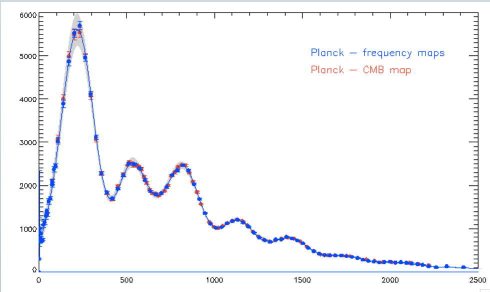
n_s Ω_b σ_8 Ω_0 H_0 τ

Cosmological parameters

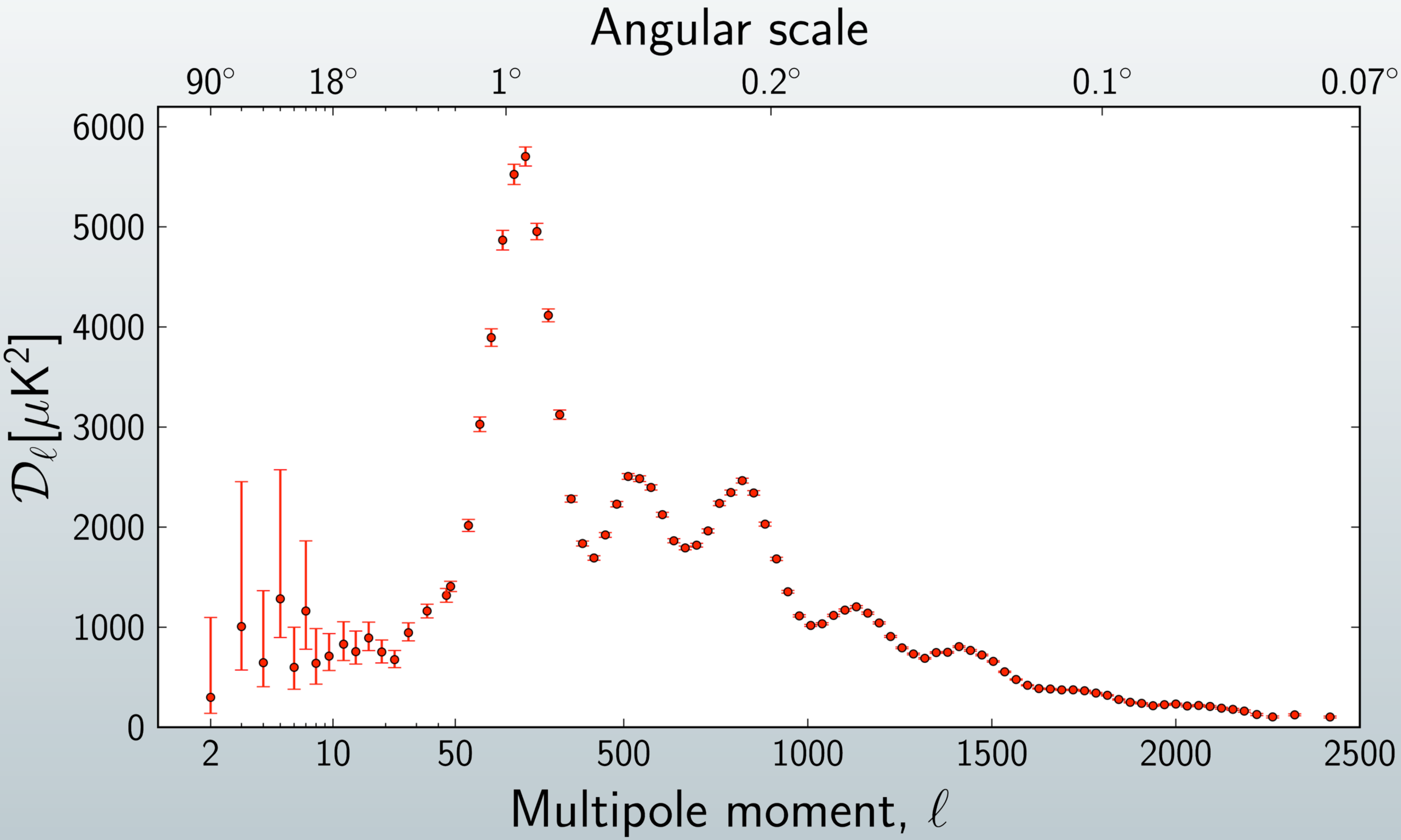
MCMC



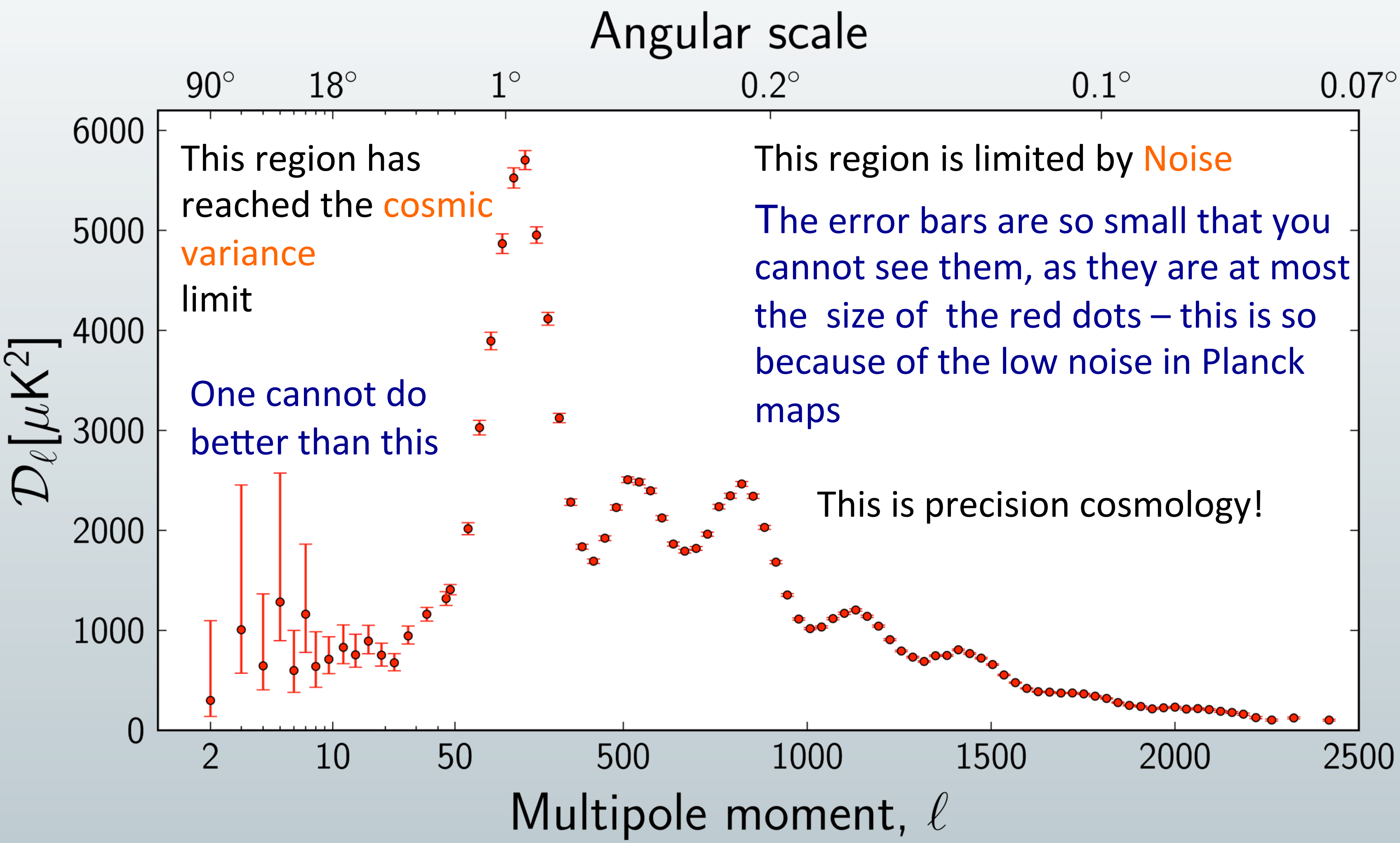
Likelihood



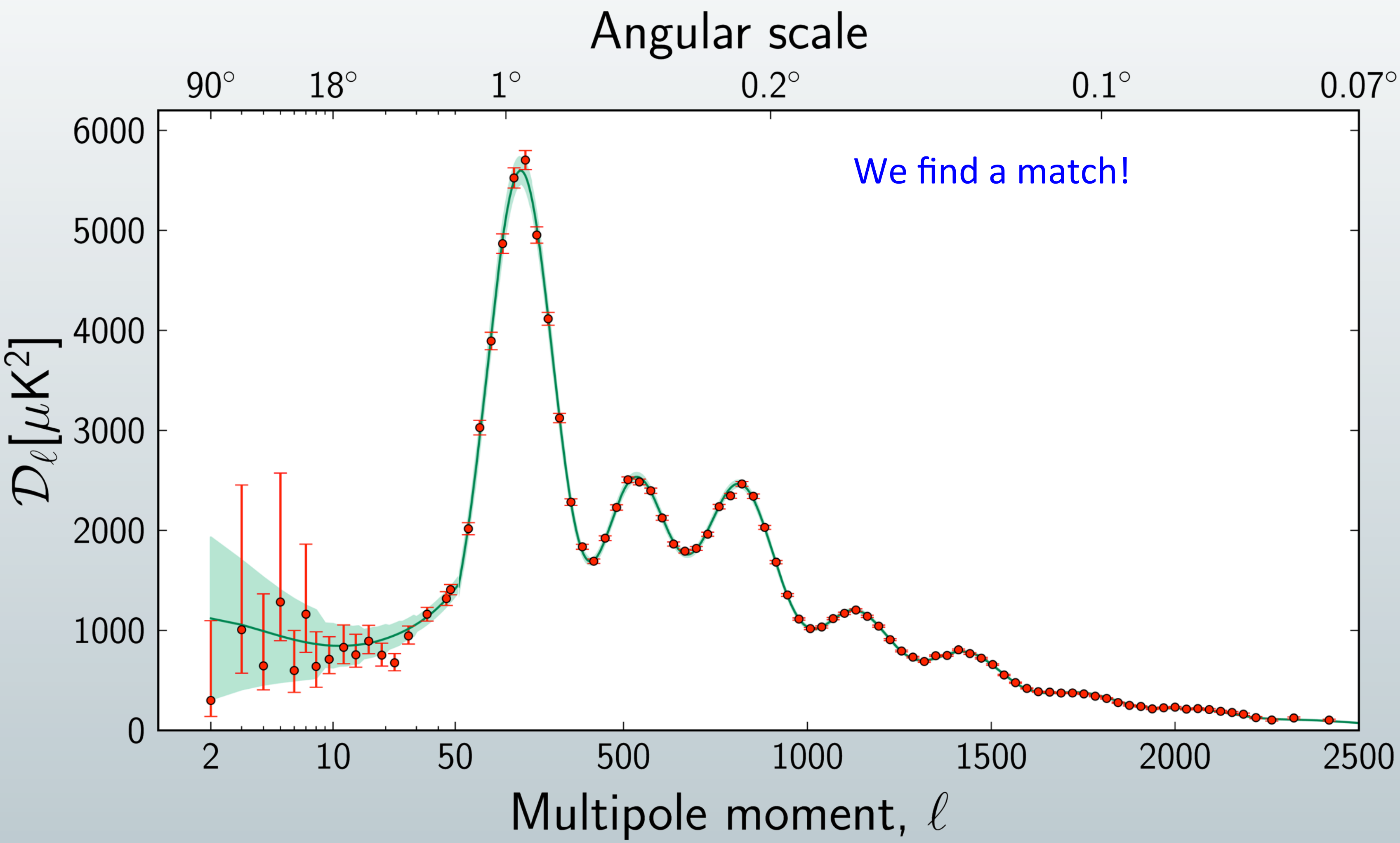
Angular Power spectrum


Angular scale
90°
18°
1°
0.2°
0.1°
0.07°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell [\mu K^2]$
2
10
50
500
1000
1500
2000
2500
Multipole moment, ℓ

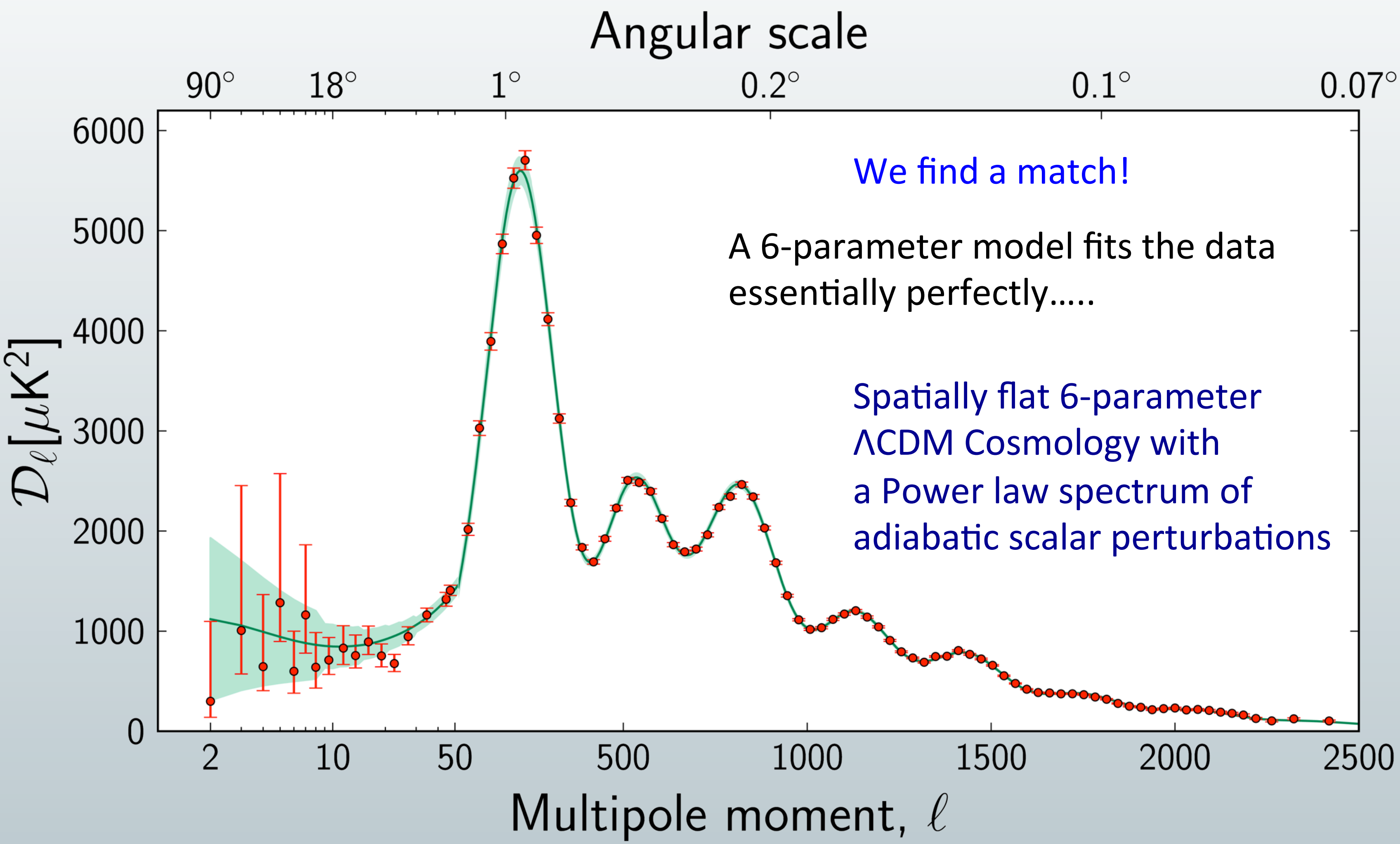
CMB angular power spectrum
what we measure from Planck



CMB angular power spectrum from Planck measurement vs models



CMB angular power spectrum from Planck measurement vs models

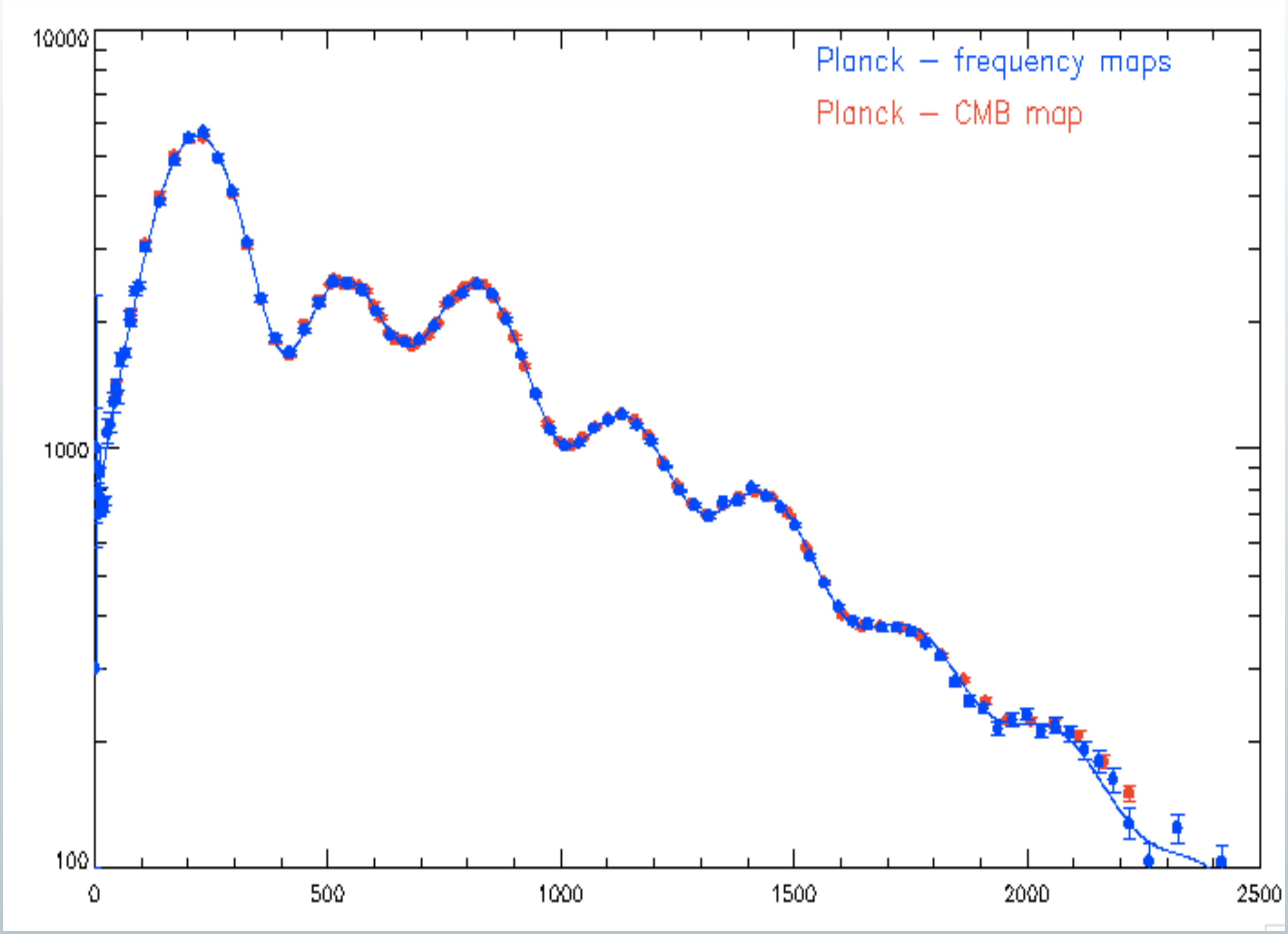


We find a match!

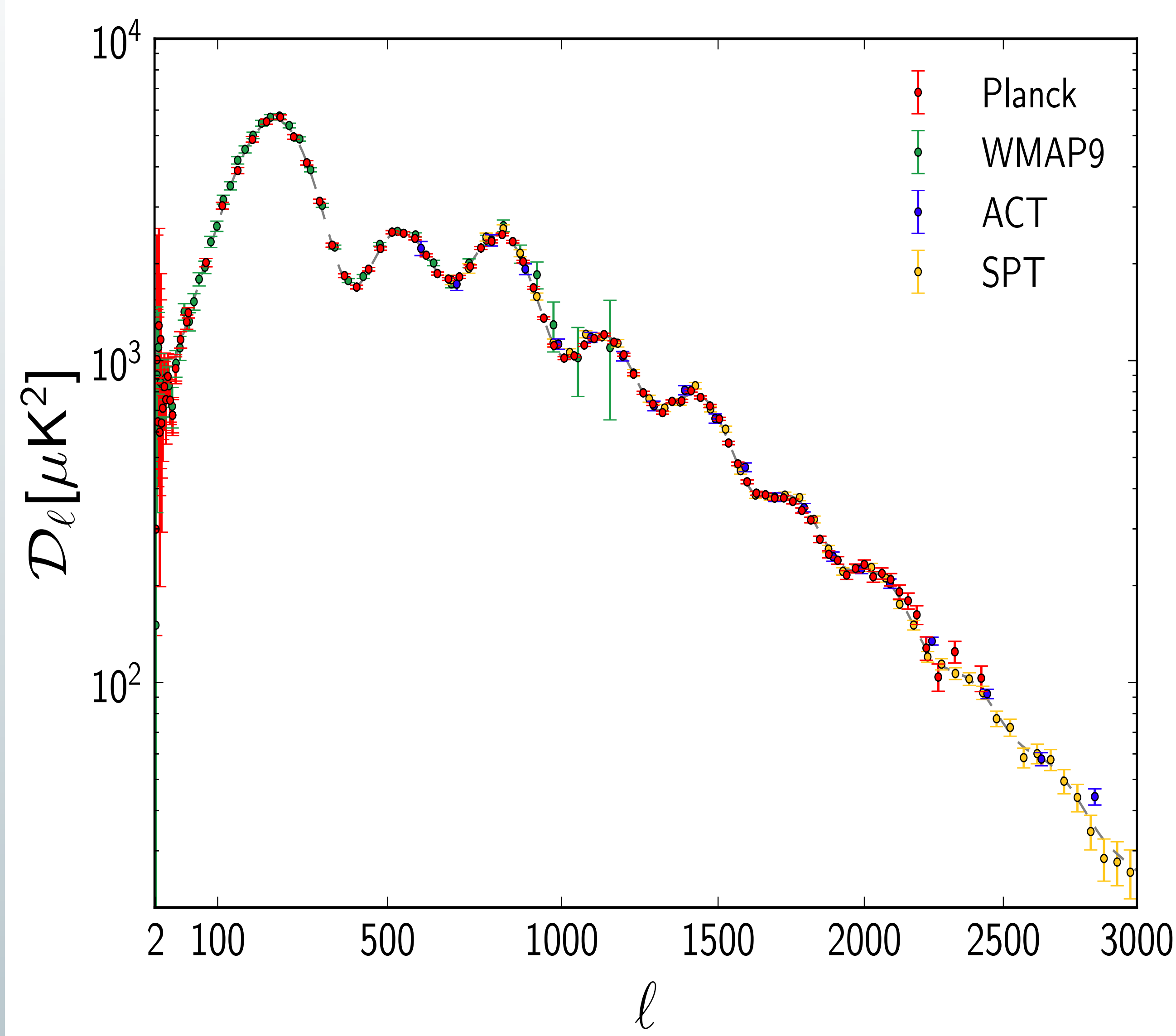
A 6-parameter model fits the data essentially perfectly.....

Spatially flat 6-parameter ΛCDM Cosmology with
a Power law spectrum of
adiabatic scalar perturbations

CMB angular power spectrum from Planck Freqs maps and CMB map



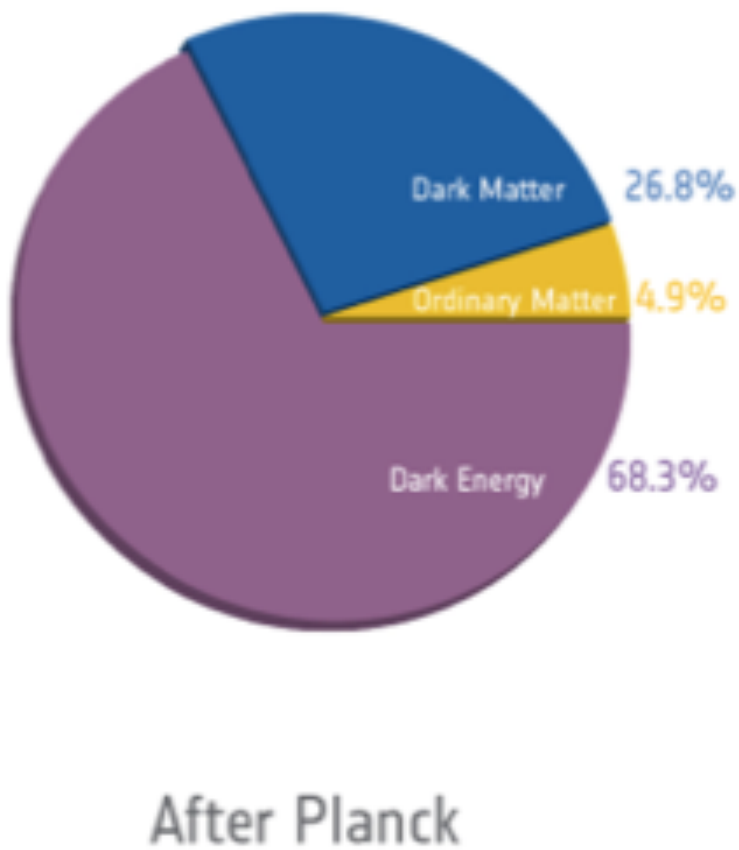
CMB angular power spectrum
Planck, WMAP9, SPT,ACT



ΛCDM model parameters from Planck

The Universe

Has more matter and less dark energy



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

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

$$n_s = 0.9603 \pm 0.0073$$

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

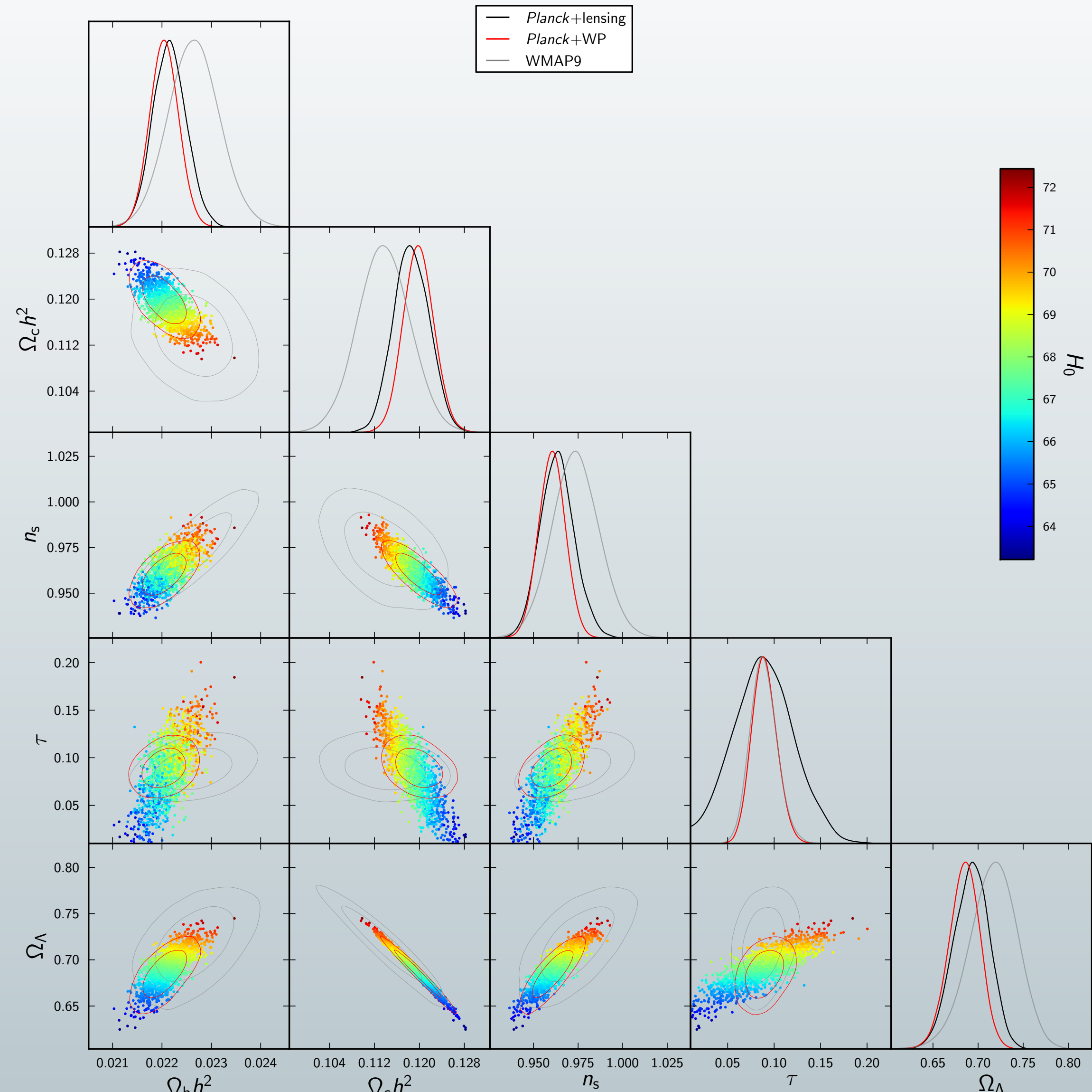
$$100\theta = 1.04131 \pm 0.00063$$

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

Age = 13.81± 0.05 billion years

Consistent with spatial flatness to % level

ΛCDM model parameters from Planck 2d and 1d marginal distributions

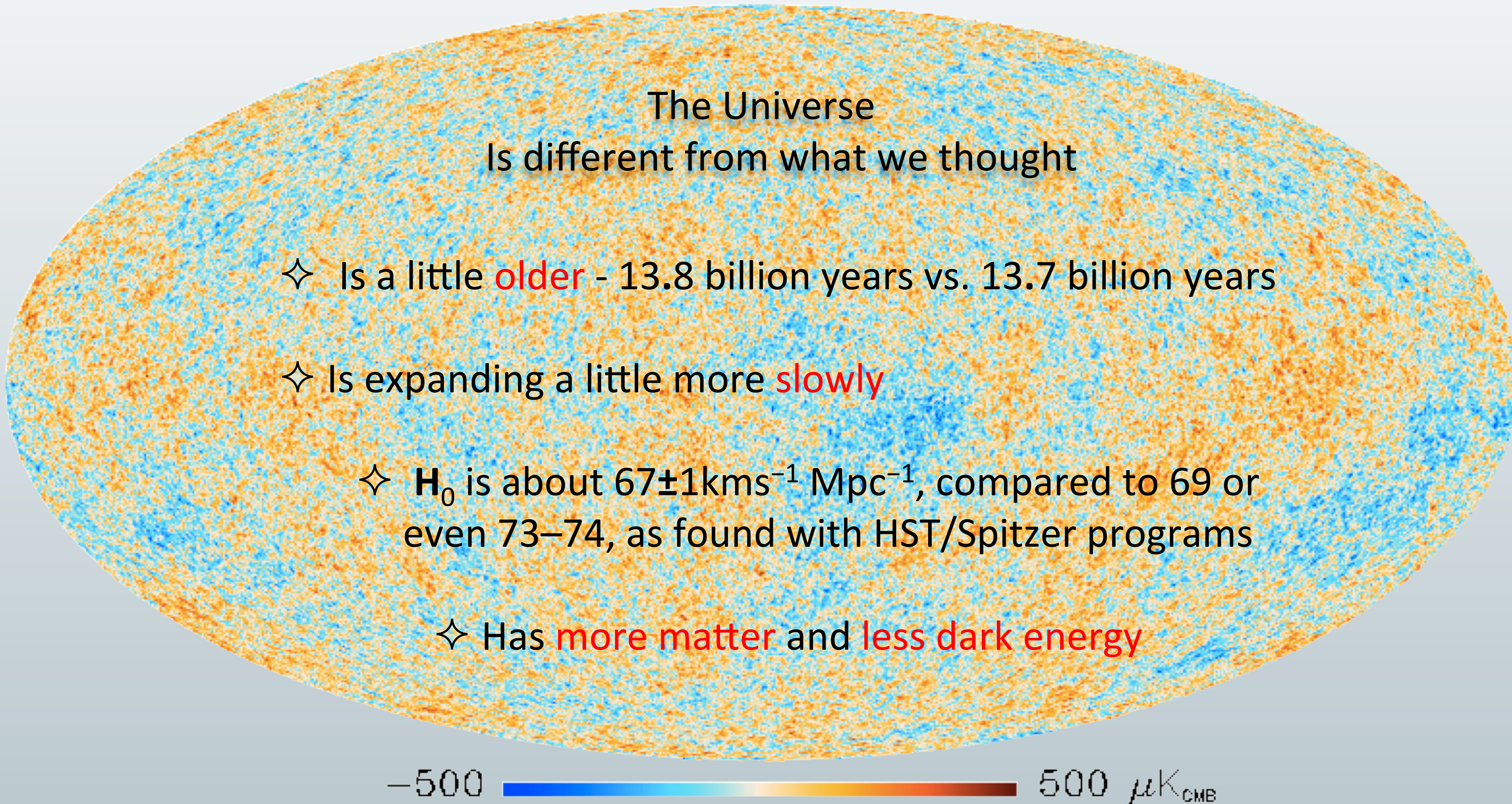


Spatially flat 6-parameter ΛCDM Cosmology with a Power law spectrum of adiabatic scalar perturbations

$$P_R(k) = A_s\left(\frac{k}{k_0}\right)^{n_s}$$

$$P_R(k) = A_s\left(\frac{k}{k_0}\right)^{n_s - 1 + (1/2(dn_s/d\ln k)\ln(k/k_0)}$$

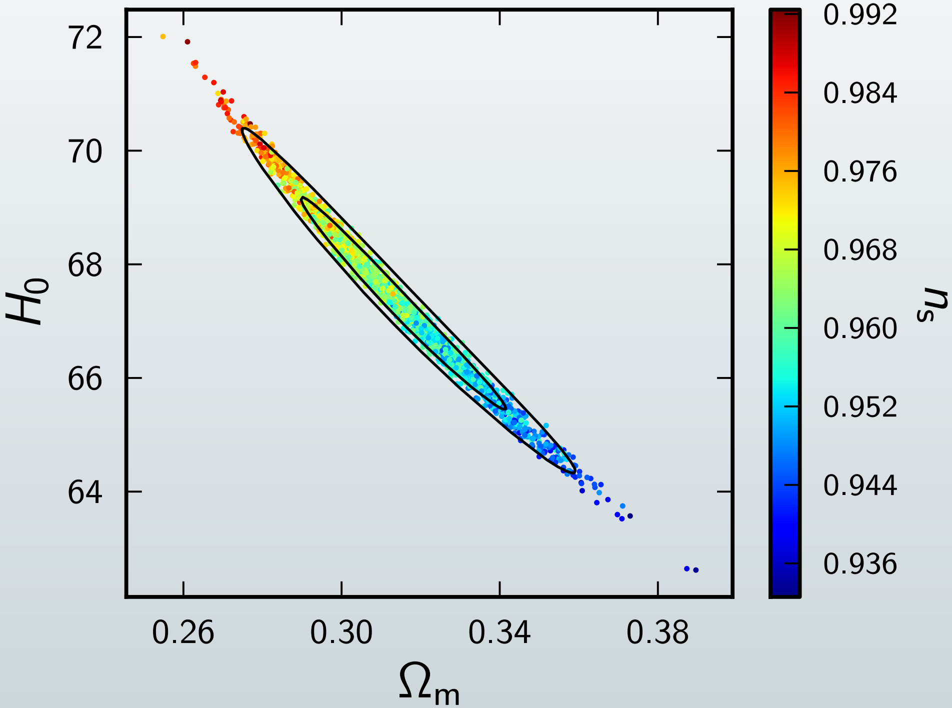
What Have We Learned ?
In words



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
  - ✧ $\mathbf{H_0}$ 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

ΛCDM model parameters H_0



- With accurate measurements of 7 acoustic peaks Planck determines the acoustic scale (angular size of the sound horizon at last scattering surface) better than 0.1% precision at 1σ

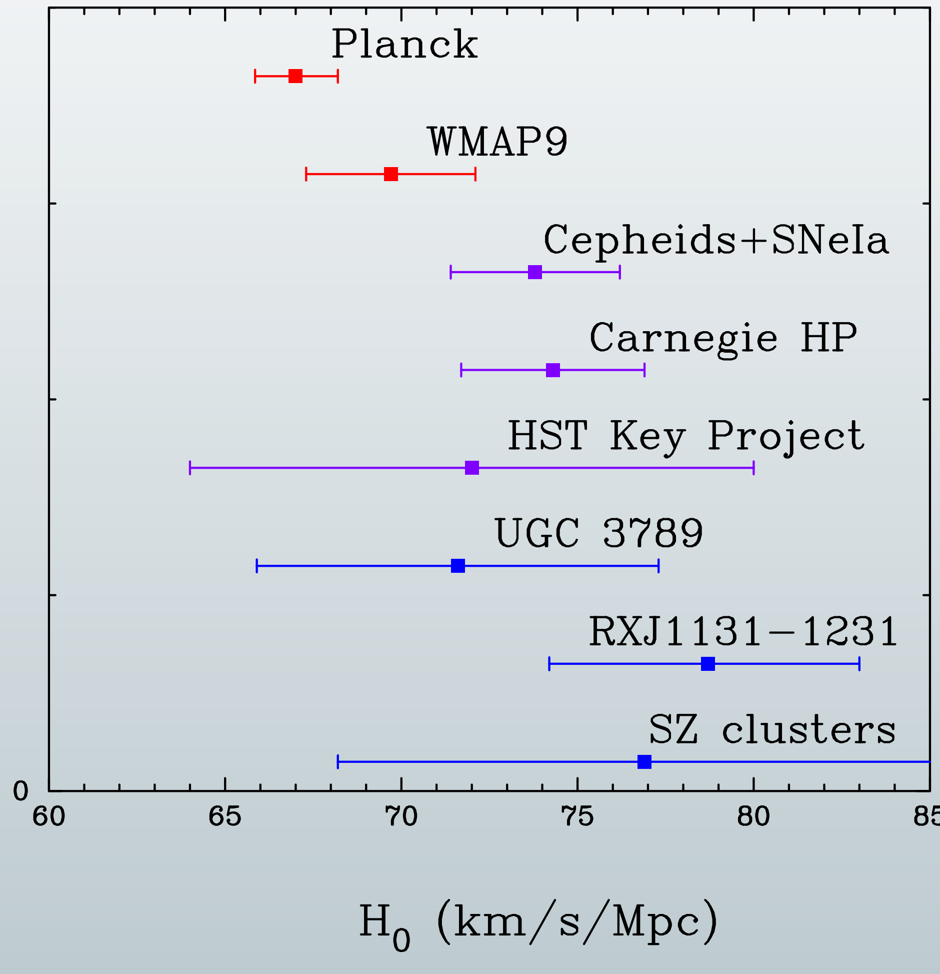
- parameter combinations can be constrained as well – 3d Ω_m- h - $\Omega_b h^2$, PCA -> ~ $\Omega_m h^3$

- H_0, Ω_m are only constrained by $\Omega_m h^3$ degeneracy limited by $\Omega_m h^2$ (rel heights of peaks)

The projection of the constant elipse onto the axes yields useful marginalised constraints on H_0 and Ω_m (or equivalently Ω_Λ) separately

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

What Have We Learned ?
“Tensions” – H_0

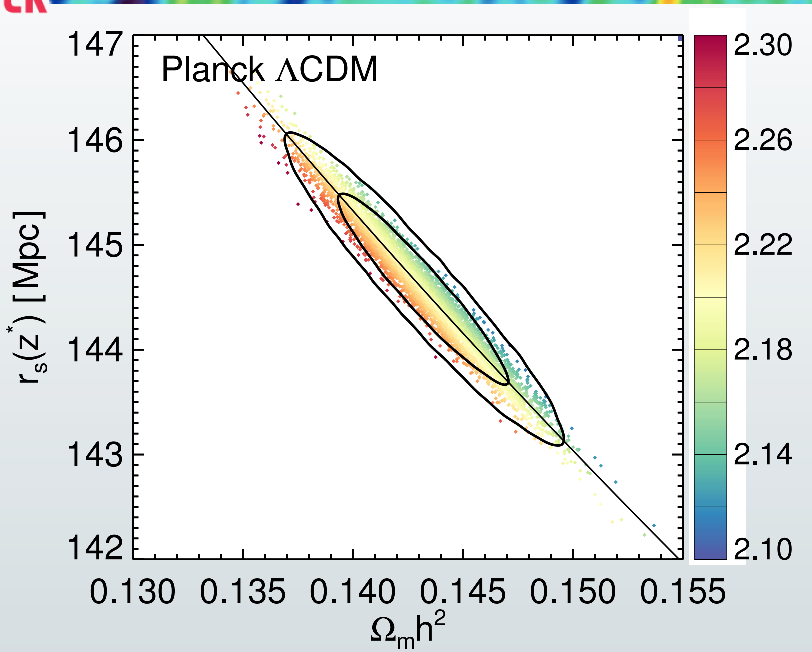


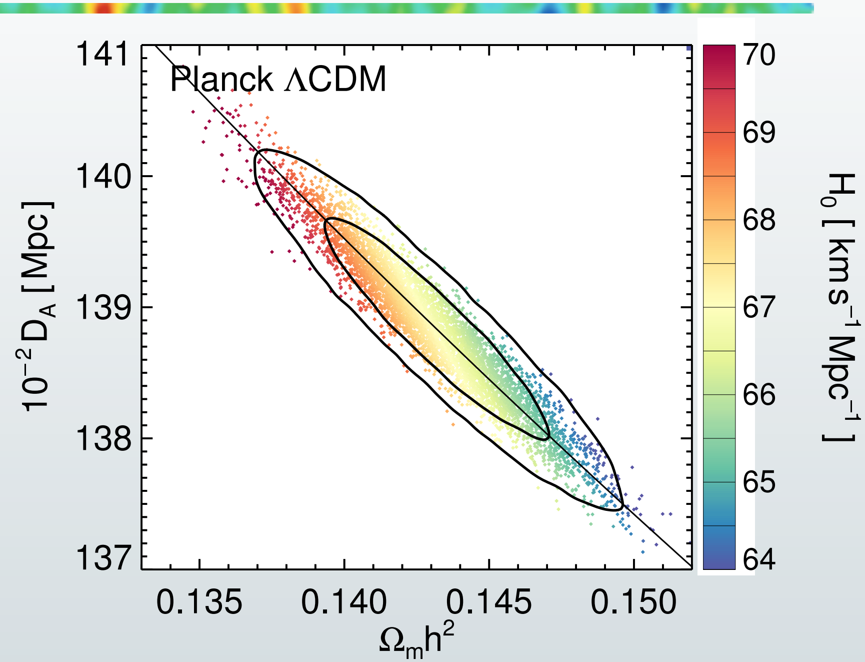
Independent local cosmological probes:

Non-geometric and Geometric determination of H_0 are discordant with Planck value at 2.5σ level

CMB estimation of H_0 is model dependent

What Have We Learned ?
"Tensions" – H_0





Sound horizon = f($\Omega_m h^2$, $\Omega_b h^2$)

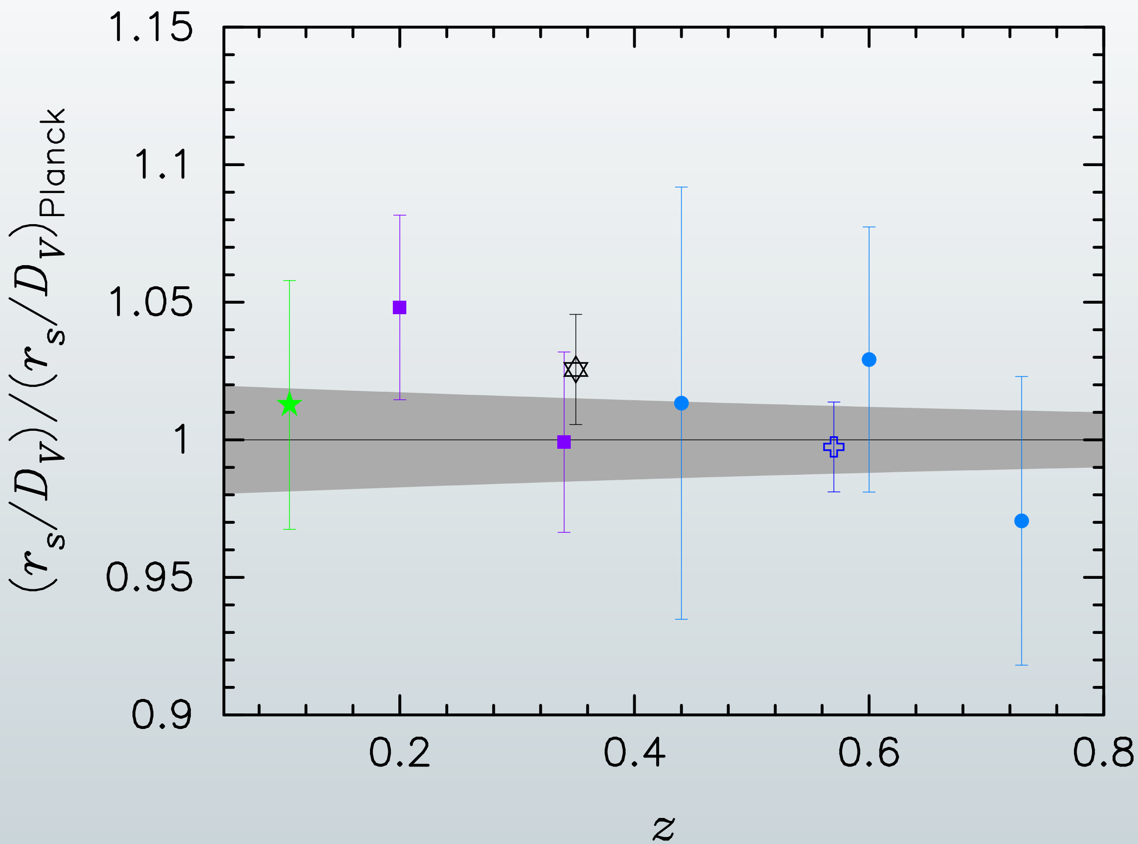
$D_A(z)$ =f(H_0, $\Omega_m h^2$)

Θ_* tightly constrained by CMB power spectrum

Shift in H_0 between Planck and WMAP9 – primarily due to higher $\Omega_m h^2$ from Planck
However a shift around 7Kms^{-1}Mpc^{-1} to match astrophysical measurements would require a even larger $\Omega_m h^2$ which is disfavoured by Planck data – this cannot be easily resolved by varying the parameters of the base ΛCDM model - we need to consider extensions to the model eg N_{eff}

$$N_{eff} = 3.6 \pm 0.5$$

What Have We Learned?
Acoustic-scale distance ratio – BAO vs Planck



BAO -> $d_z = \frac{r_s(z_{drag})}{D_v(z)}$

$D_v(z) = f(D_A(z), H(z))$

6DF (green star) , SDSS-DR7 (purple squares), SDSS-DR7 (P) (black star) , BOSS (blue cross), WiggleZ (blue circles); 1σ range in d_z from Planck+WP+highl cosmoMC chains for base ΛCDM (grey band)

All of the BAO measurements are compatible with the base ΛCDM parameters from Planck

What Have We Learned?
Type Ia SN vs Planck

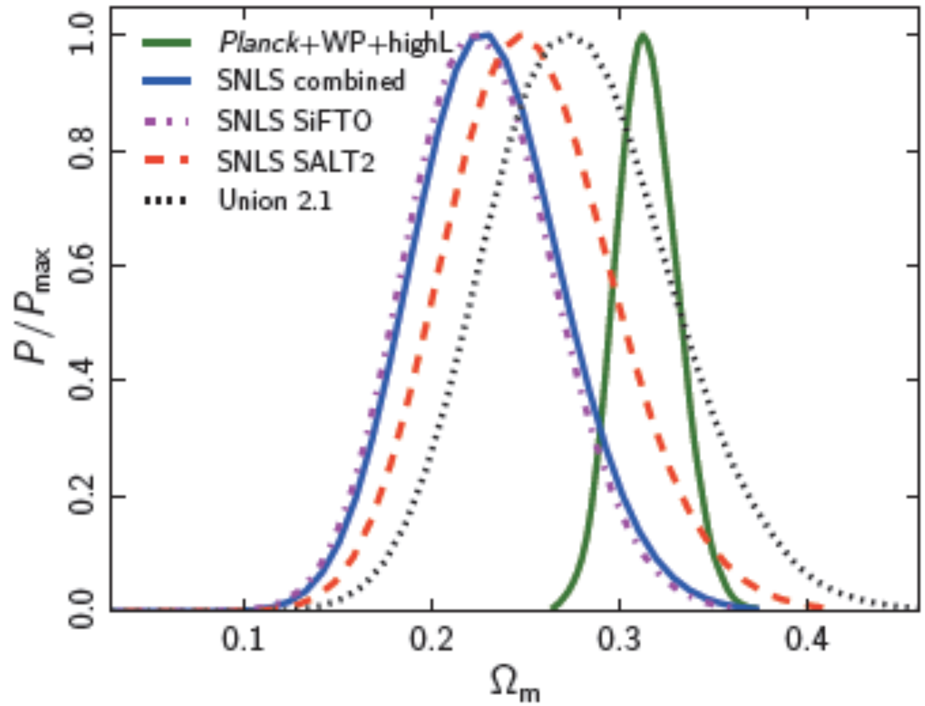


Fig. 19. Posterior distributions for Ω_m (assuming a flat cosmology) for the SNe compilations described in the text. The posterior distribution for Ω_m from the *Planck*+WP+highL fits to the base ΛCDM model is shown by the solid green line.

There is some tension between Planck and SNLS combined

ΛCDM model parameters
"Tensions" σ_8

Cosmology from Planck SZ clusters

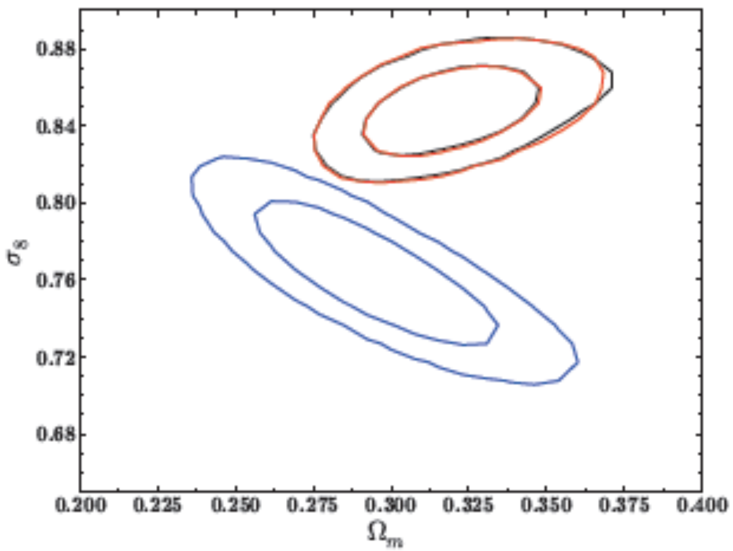


Fig. 11. 2D Ω_m–σ_8 likelihood contours for the analysis with *Planck* CMB only (red); *Planck* SZ + BAO + BBN (blue); and the combined *Planck* CMB + SZ analysis where the bias $(1 - b)$ is a free parameter (black).

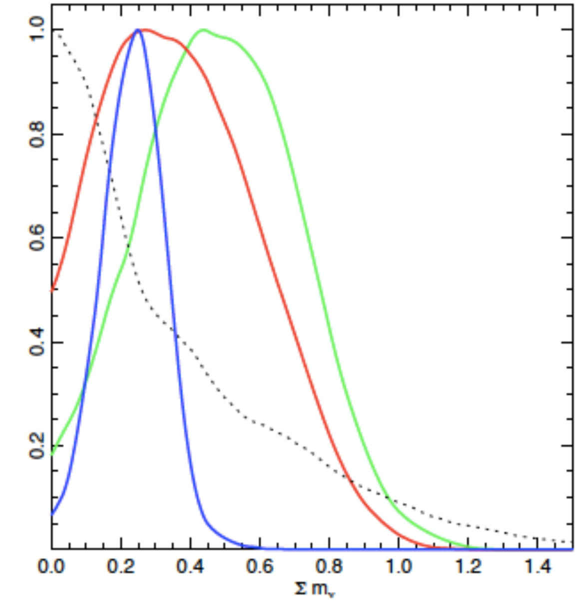


Fig. 12. Cosmological constraints when including neutrino masses $\sum m_\nu$ from: *Planck* CMB data alone (black dotted line); *Planck* CMB + SZ with $1 - b$ in [0.7, 1] (red); *Planck* CMB + SZ + BAO with $1 - b$ in [0.7, 1] (blue); and *Planck* CMB + SZ with $1 - b = 0.8$ (green).

$\sigma_8(\Omega_m/0.27)^{0.3} = 0.87 \pm 0.02$ CMB

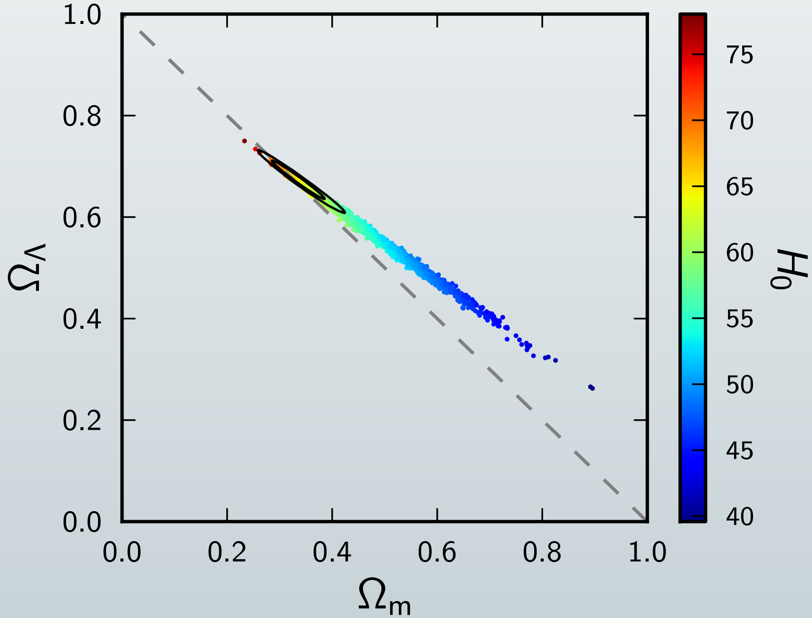
$\sigma_8(\Omega_m/0.27)^{0.3} = 0.79 \pm 0.01$ SZ

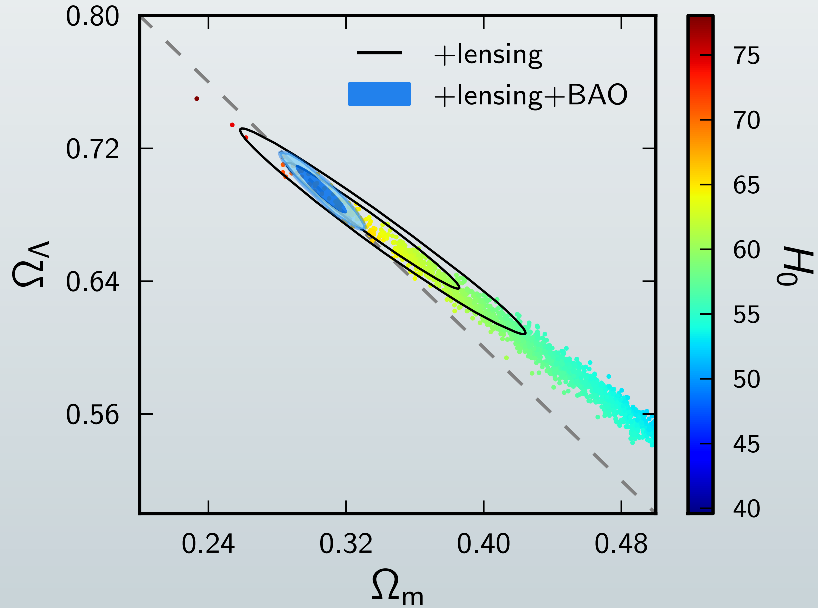
A 3σ level discrepancy – can be reduced by non-zero neutrino masses $\sum m_\nu = 0.22 \pm 0.09 eV$
or a mass bias of 45%

CMB+SZ+BAO

ΛCDM model parameters
Curvature

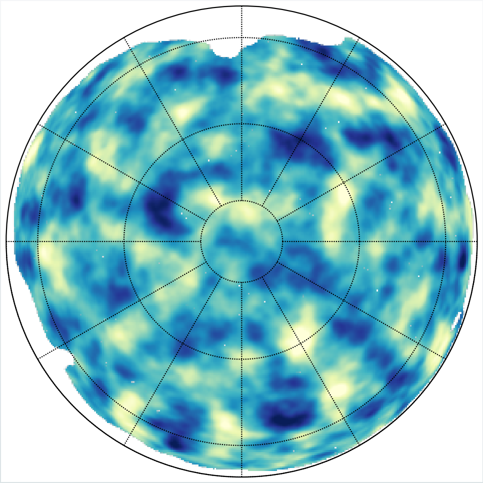
Geometric degeneracy

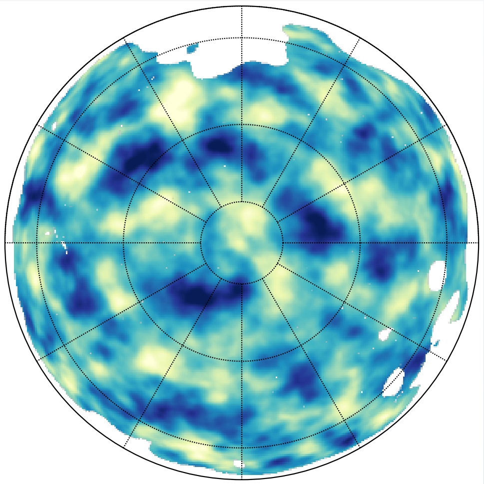




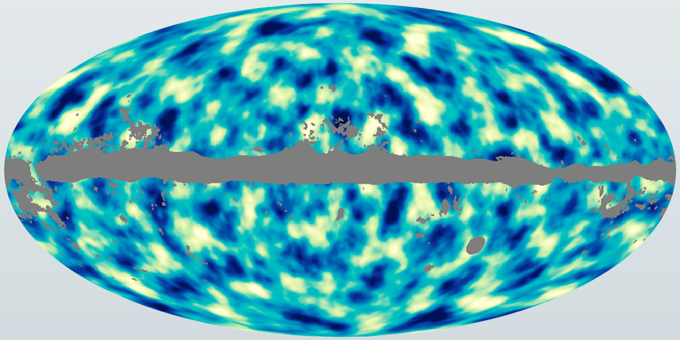
Lensing by large scale structure

Consistent with spatial flatness to % level

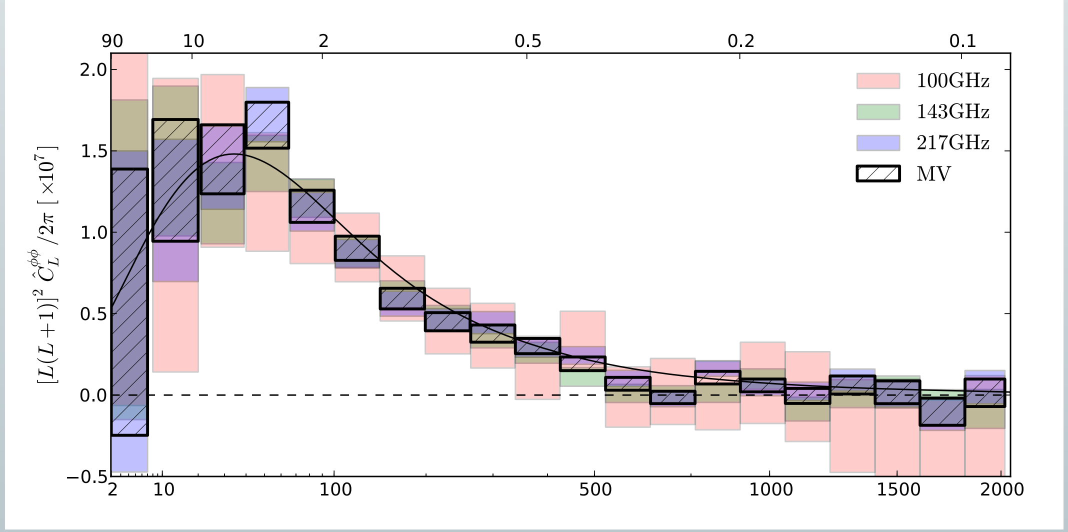




- Wiener-filtered lensing potential estimate reconstruction, in Galactic coordinates using orthographic projection
- The gradient of this map gives the deflection angle



SNR ~ 25σ

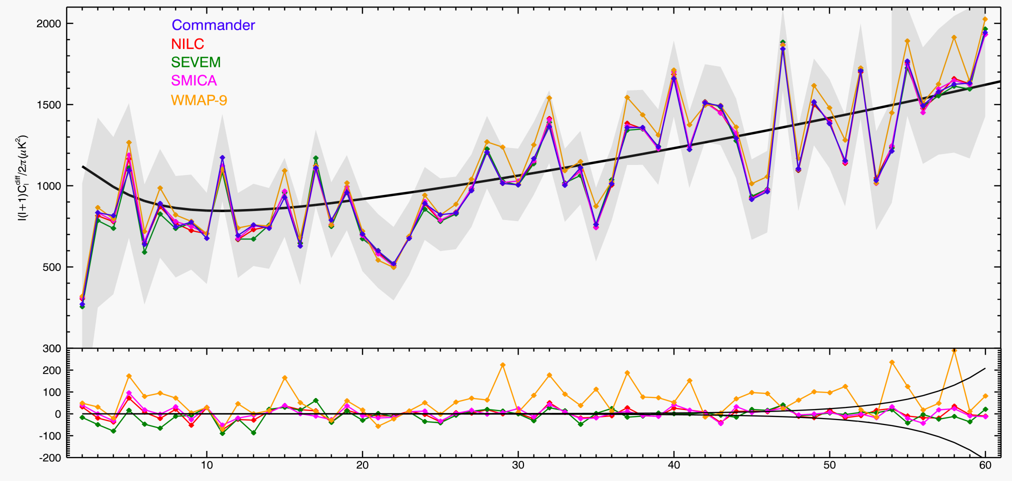


Lensing potential power spectrum
Best fit model ΛCDM model from CMB Temperature power spectrum (black line)

$C_\ell^{\phi\phi}$ Derived from the measured trispectrum (4-point function)

What Have We Learned ?
"Tensions" WMAP

WMAP is consistently higher than Planck by about 2.5%



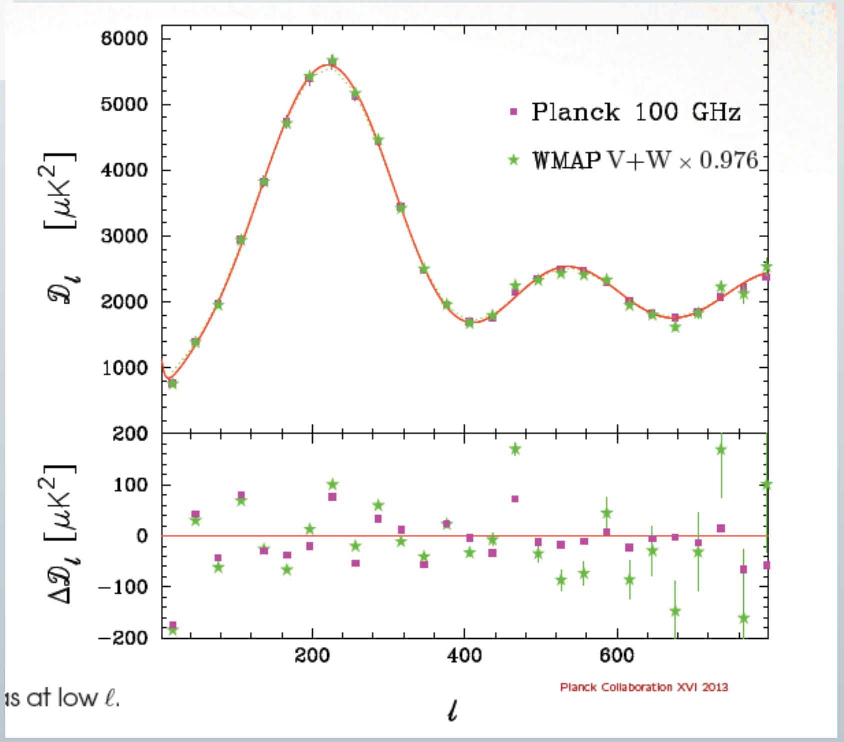
Top: Grey band - 1σ Fisher errors. Solid line is Planck best-fit ΛCDM model.
Bottom: Differences w.r.t. the Commander spectrum. Black lines - expected 1σ uncertainty due to (regularization) noise

Low-l

- Planck 100x100GHz spectrum
- WMAP9 V+W spectrum scaled by 0.976.
- Red line is the best-fit Planck+WP + highL ΛCDM model.

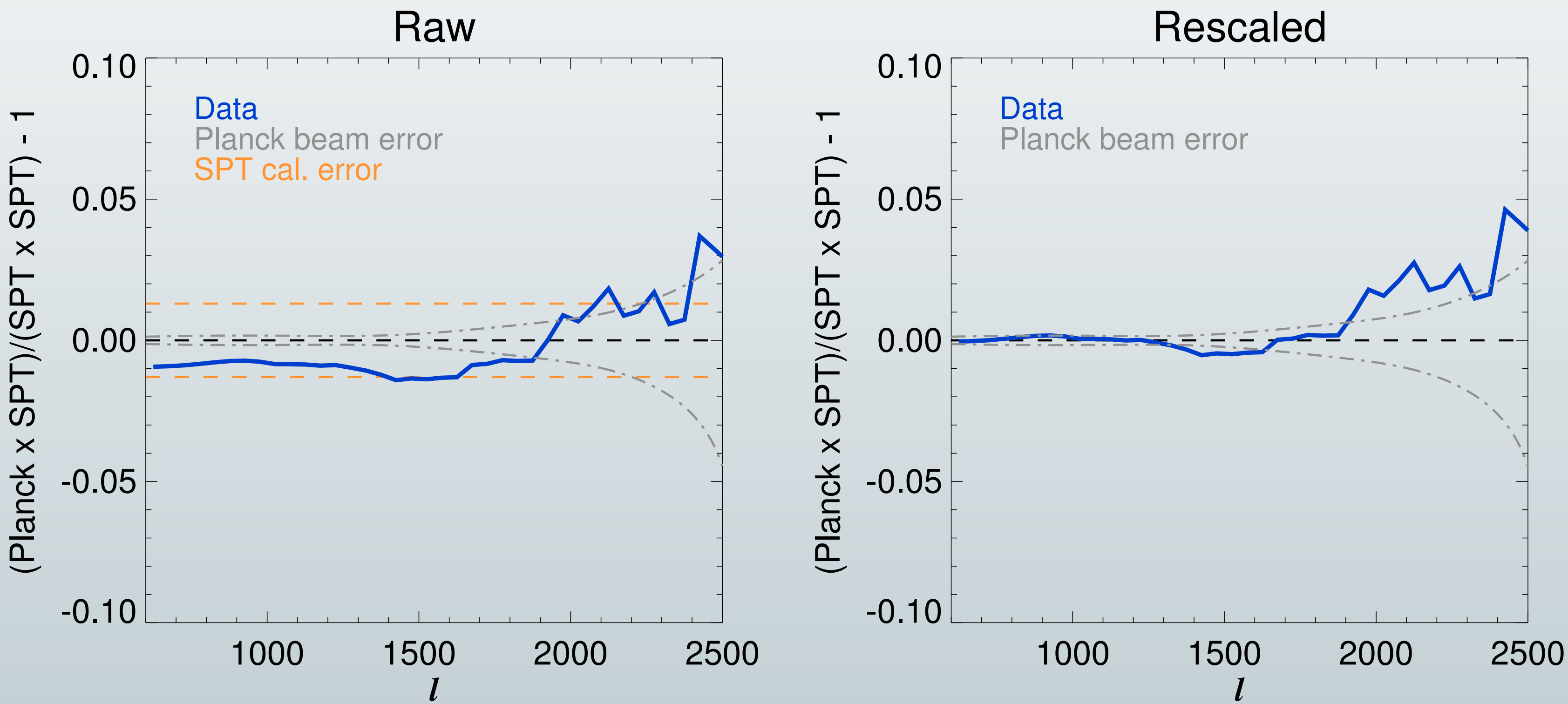
Residuals with respect to the model. The error bars on the WMAP points show errors from instrumental noise alone.

High-l



What Have We Learned ?
"Tensions" SPT

When SPT is calibrated to Planck the agreement is excellent



Courtesy of Planck+SPT team

Extensions to ΛCDM model

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

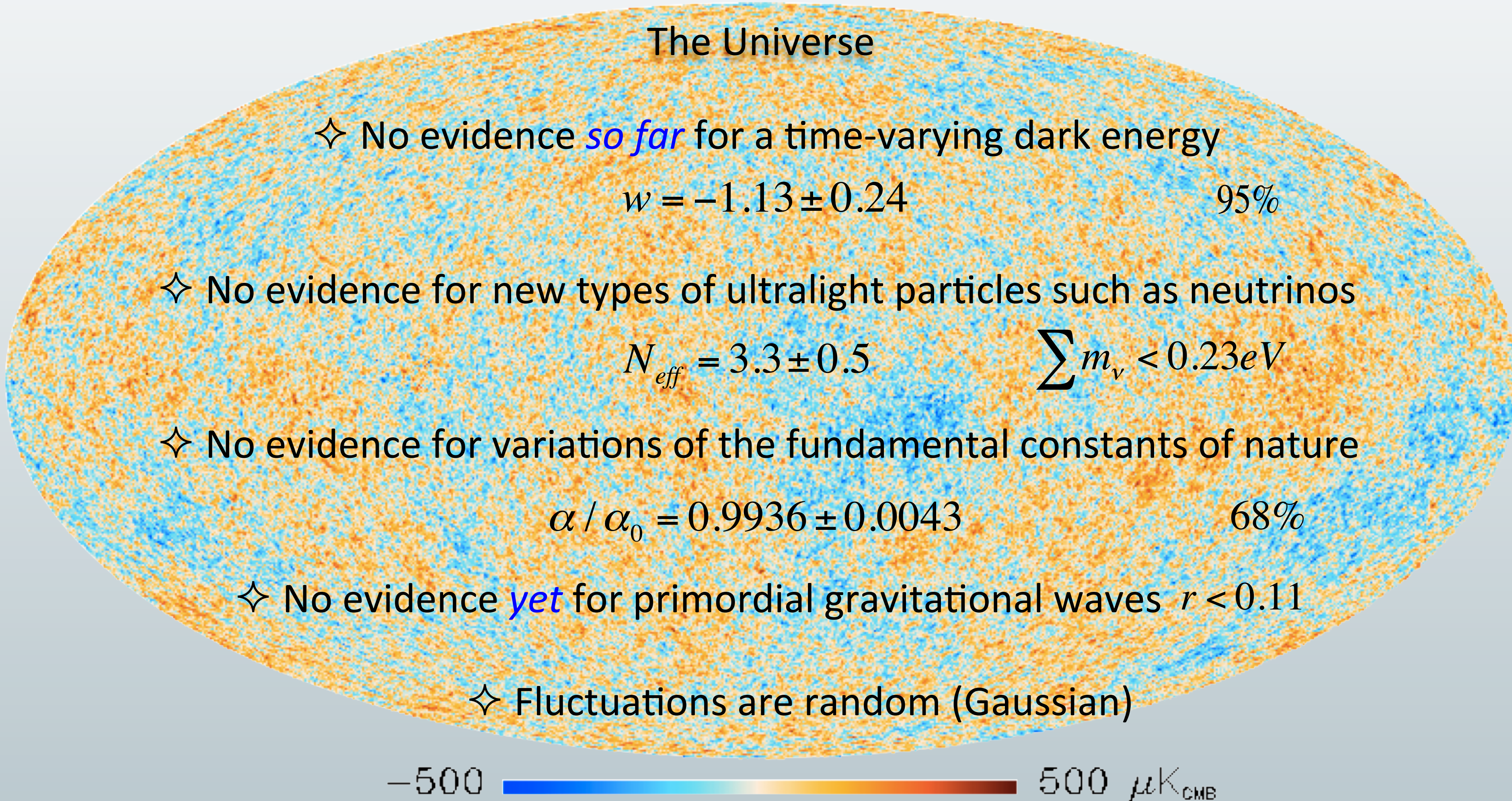
$$N_{eff} = 3.3 \pm 0.5 \qquad \sum m_\nu < 0.23eV$$

✧ No evidence for variations of the fundamental constants of nature

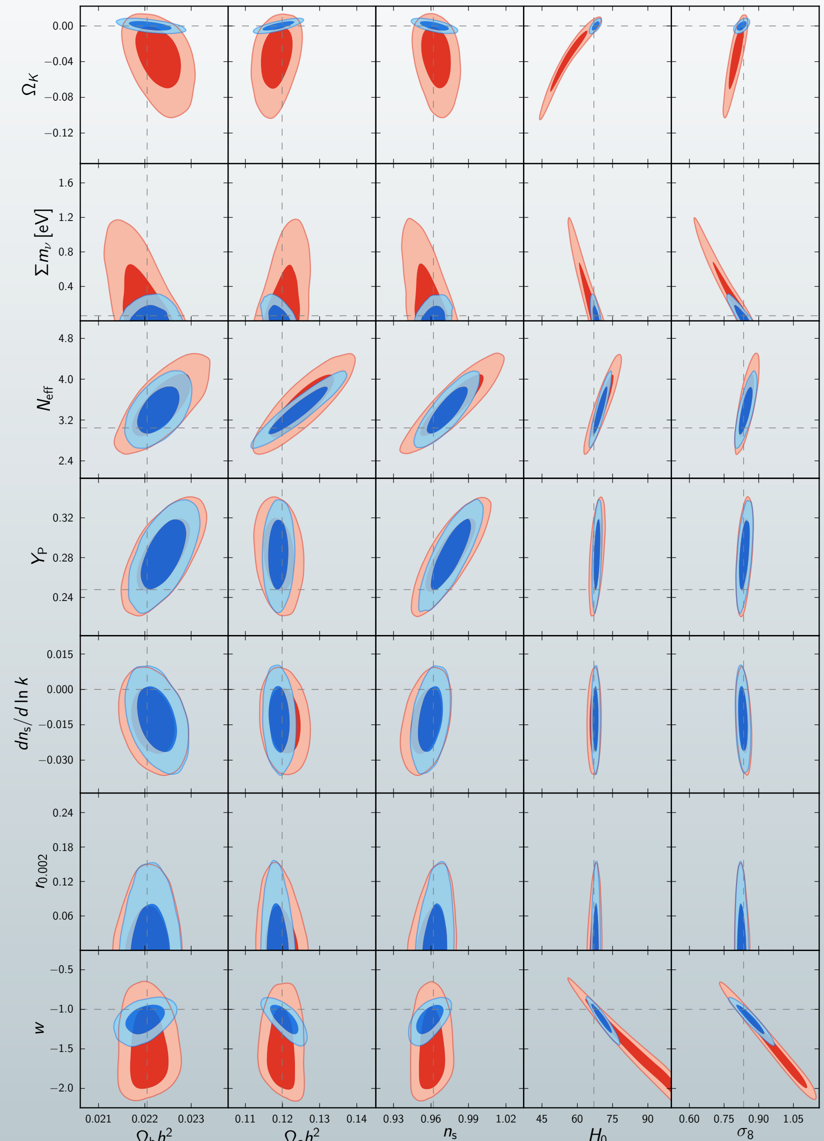
$$\alpha / \alpha_0 = 0.9936 \pm 0.0043 \qquad 68\%$$

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

✧ Fluctuations are random (Gaussian)



Extensions to ΛCDM model



Planck +WP (red)
Planck +WP+BAO (blue)

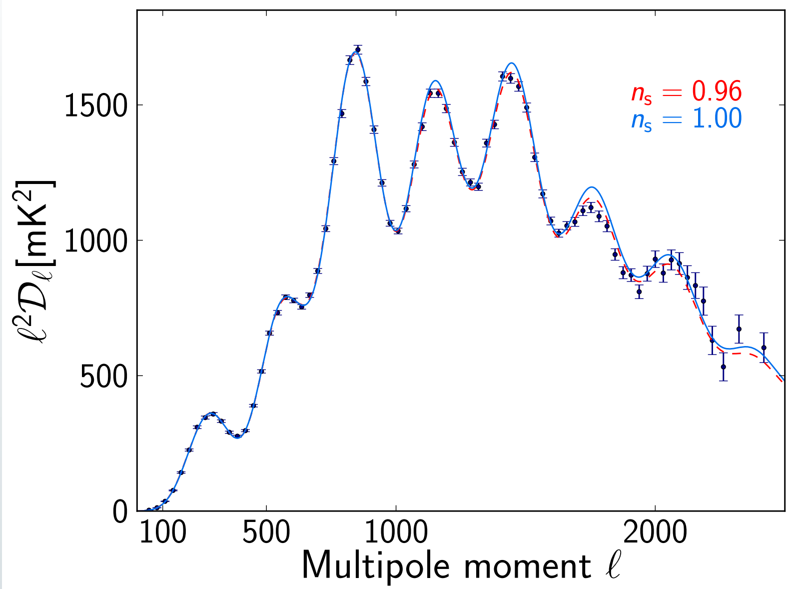
Posteriors of individual extra parameters
Generally overlaps the fiducial model within 1σ

The inclusion of BAO data shrinks further the allowed scope for deviation – the ΛCDM model is relatively robust to inclusion of additional parameters – but the error on some parameters broaden when additional degeneracies open-up

Vertical lines:
Mean posterior value in the base model
For Planck+WP

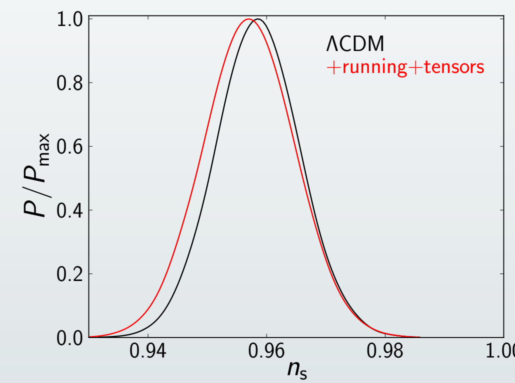
Horizontal lines:
Fixed base model parameter value

Extensions to ΛCDM model
Early-Universe physics: ns, dn_s/dk and r



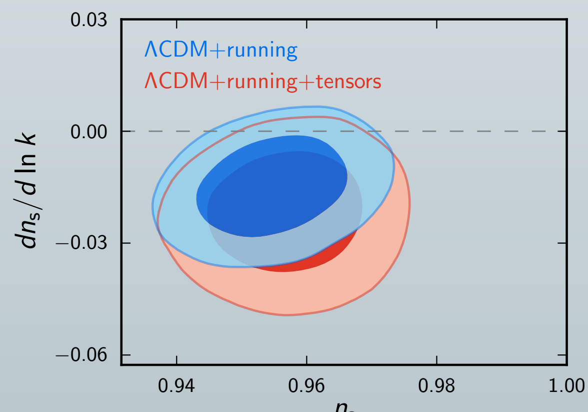
6σ departure from scale invariance

$$n_s = 0.9603 \pm 0.0073$$



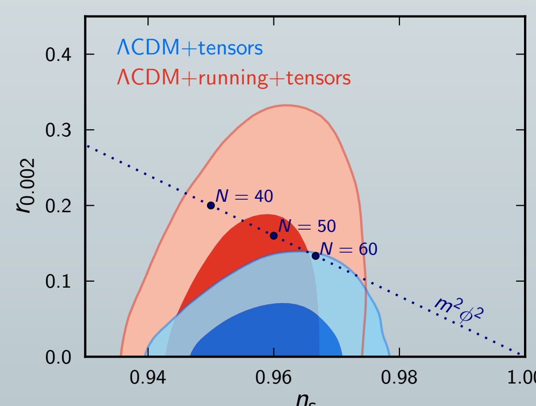
l<50

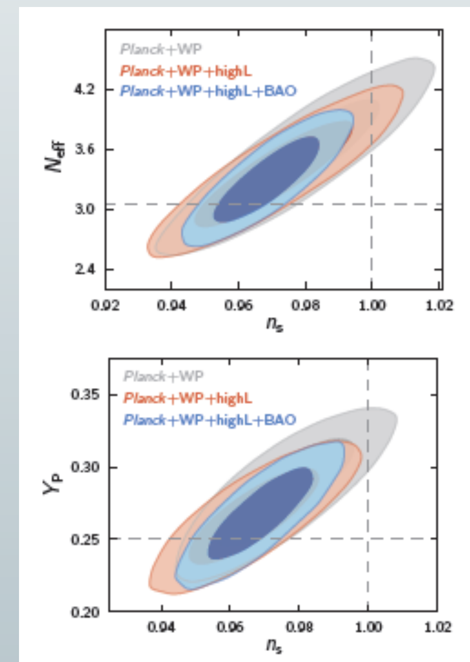
$$dn_s / d\ln k = -0.0134 \pm 0.0090$$



$$r < 0.11 \qquad V_*$$

$$V = (1.94 \times 10^{16}\,GeV)^4 (r_{0.02} / 0.12)$$

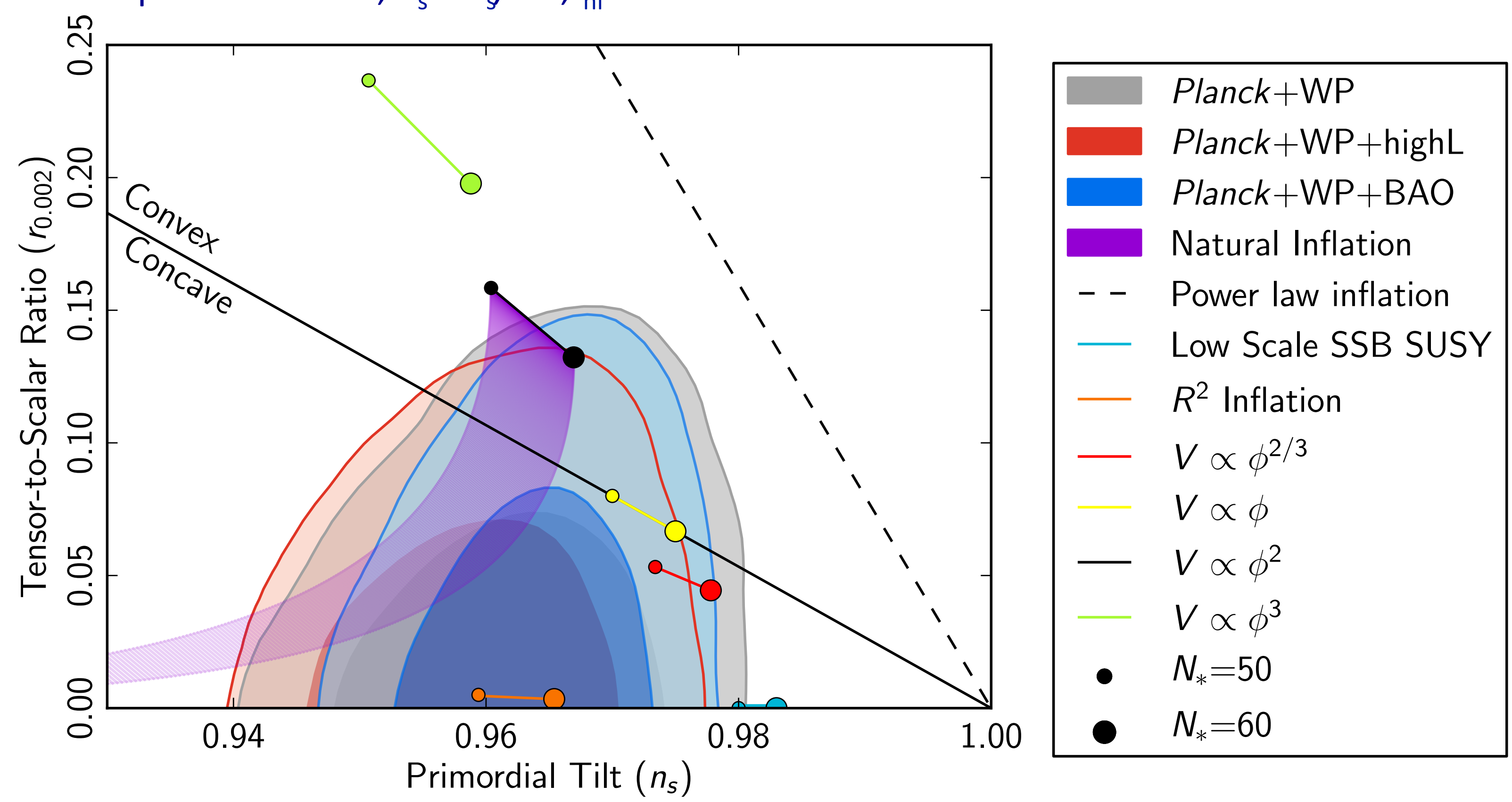




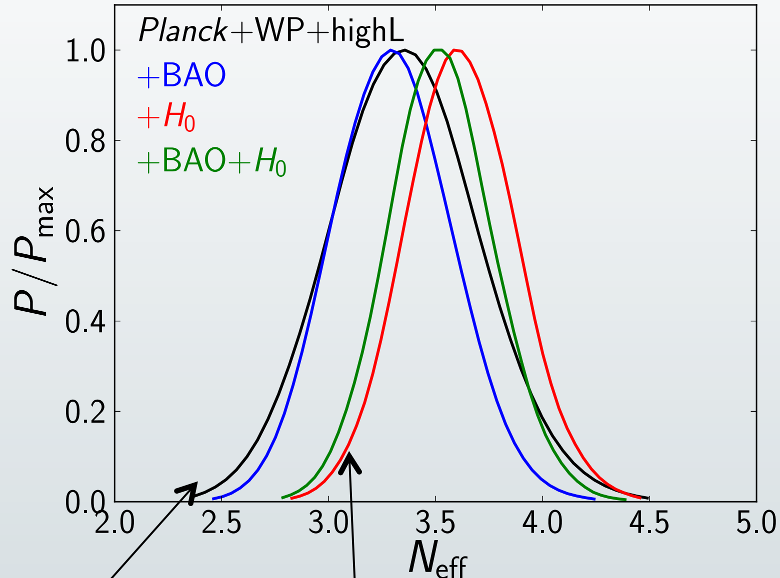
3σ

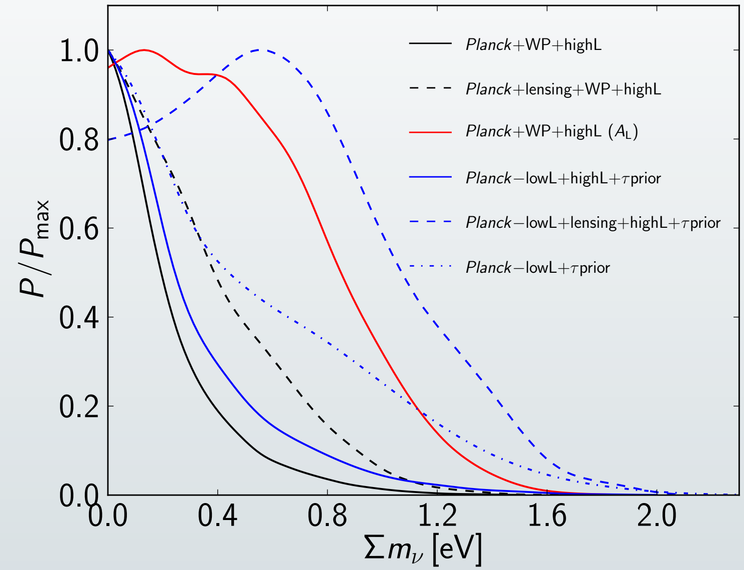
Inflationary Scenarios
Constraints on slow-roll inflationary models

- Best fit to data - a single, weakly coupled, neutral scalar field; models with a canonical kinetic term and a field slowly-rolling a featurelss potential; models with locally concave potentials
- Exponential potential models, the simplest hybrid inflationary models, and monomial potential models of degree n >= 2 do not provide a good fit to the data.
- "Inflation parameters": r, n_s, dn_s/dk, f_{nl}



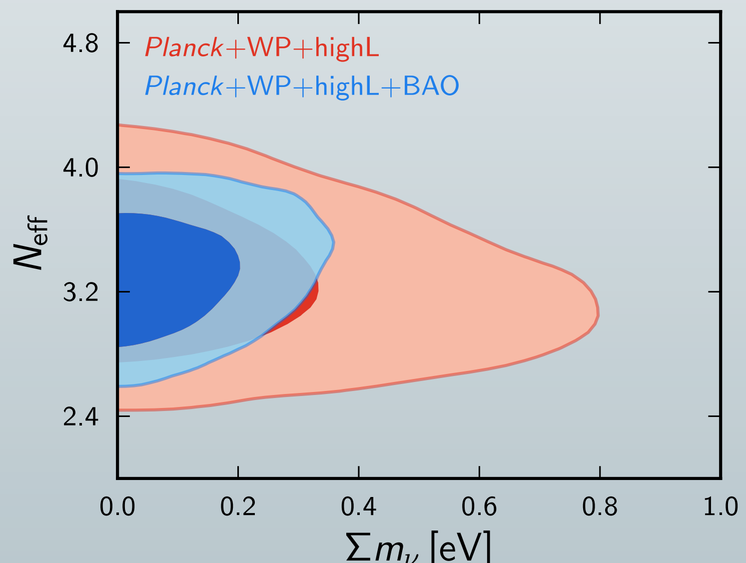
Extensions to ΛCDM model
Neutrino Physics: Number of neutrino species: Neff
neutrino mass m_ν





$$N_{eff} = 3.3 \pm 0.5 \quad 95\%$$

$$\sum m_\nu < 0.66 eV \quad 95\%$$



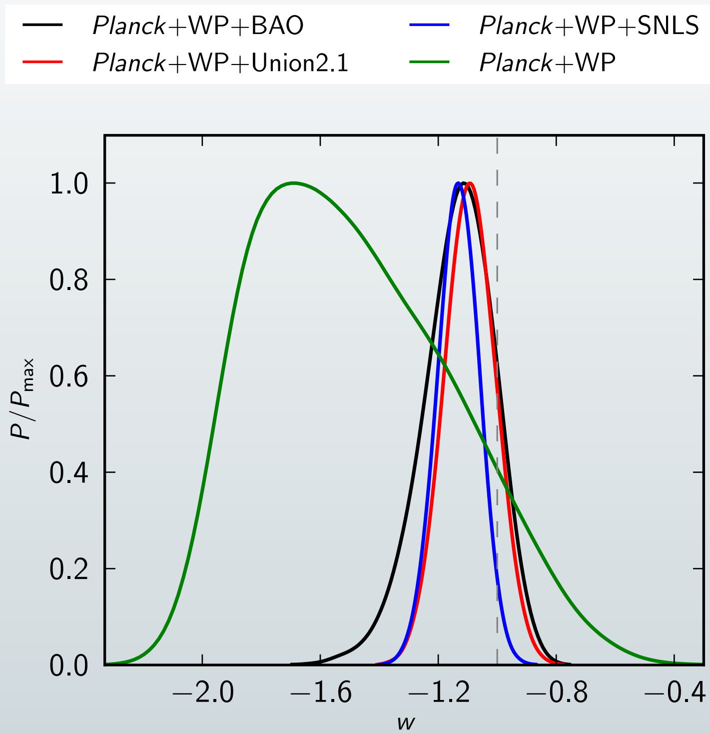
1 solution For H_0 tension:

$$N_{eff} = 3.6 \pm 0.5$$

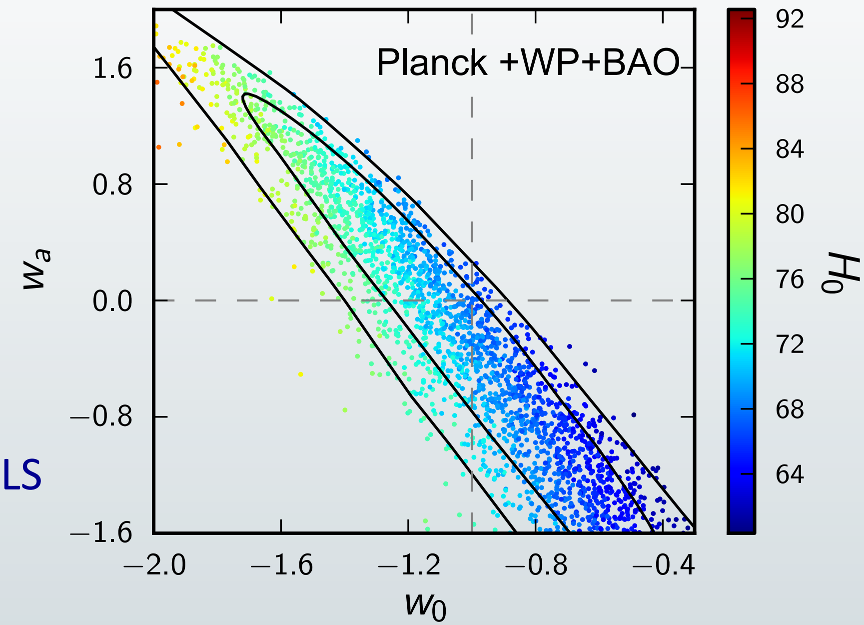
$$\sum m_\nu < 0.23 eV$$

Planck and BAO

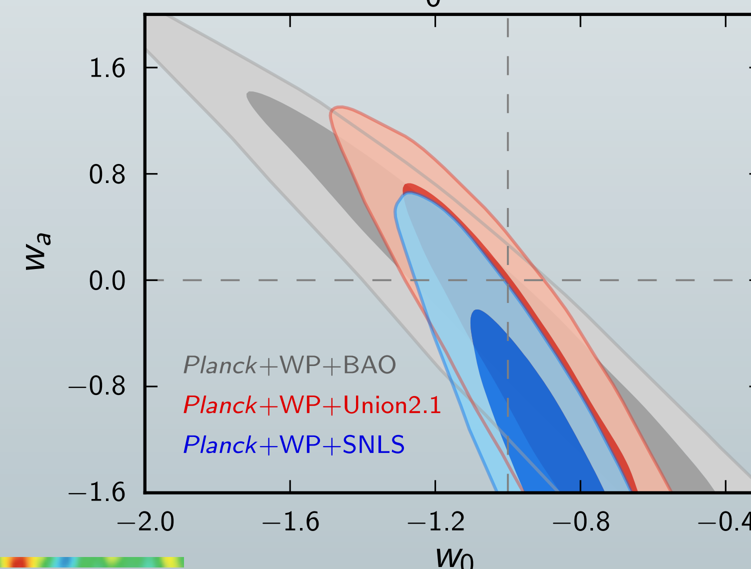
Extensions to ΛCDM model
dark energy: w



Tensions eg Planck and SNLS



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



Cosmological constant has an equation of state:

$$w = p/\rho = -1$$

Dynamical dark energy: $w(a) = w_0 + w_a(1-a)$

Non-Gaussianity

$f_{NL}^{local} = 2.7 \pm 5.8$
$f_{NL}^{equil} = -42 \pm 75$
$f_{NL}^{ortho} = -25 \pm 39$

No detection of primordial NG

$B_{\Phi}(k1, k2, k3) = f_{NL} F(k1, k2, k3)$
B_{Φ} – bispectrum (FT of 3-point function)
f_{NL} - non-linearity parameter

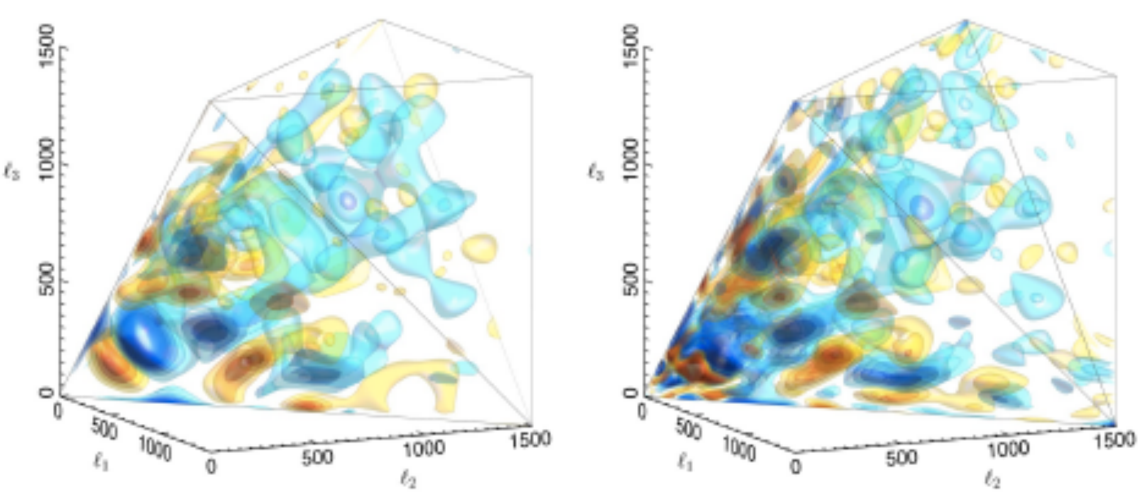


Fig. 7. *Planck* CMB bispectrum detail in the signal-dominated regime showing a comparison between full 3D reconstruction using hybrid Fourier modes (left) and hybrid polynomials (right). Note the consistency of the main bispectrum properties which include an apparently 'oscillatory' central feature for low-ℓ together with a flattened signal beyond to $\ell \lesssim 1400$. Note also the periodic CMB ISW-lensing signal in the squeezed limit along the edges of the tetrapyd.

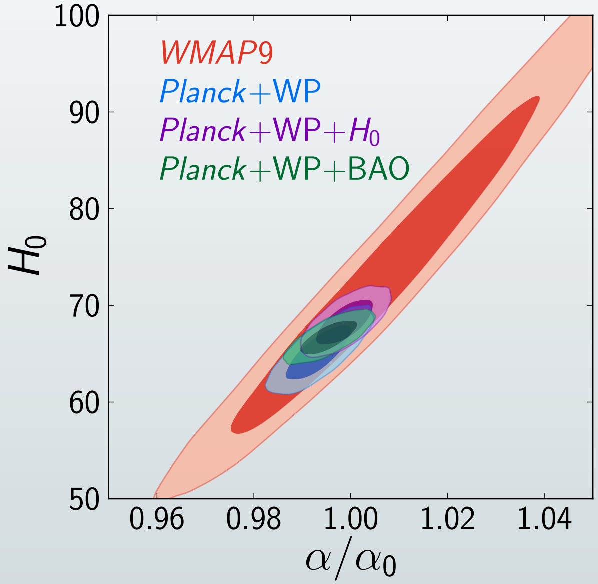
Detection of ISW-lensing bispectrum at 2 to 3σ

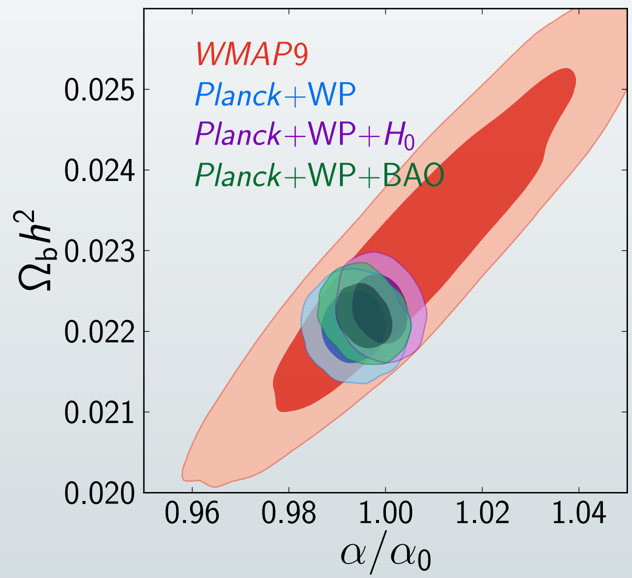
Periodic CMB ISW-lensing signal in the squeezed limit along the edges of the tetrapyd

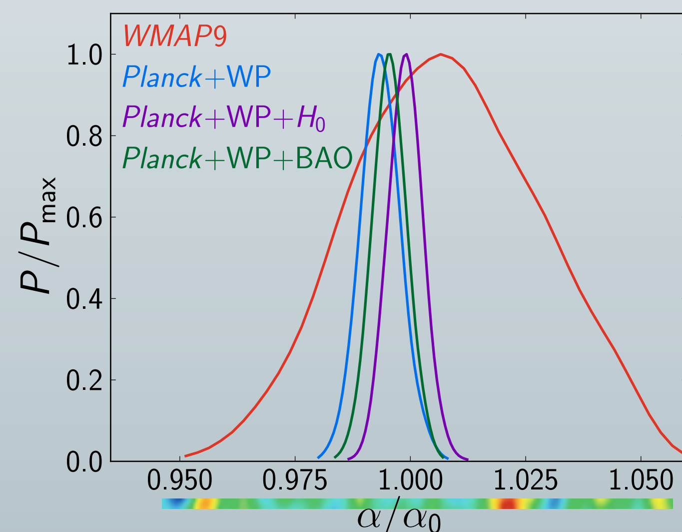
Extensions to ΛCDM model
Varying fundamental constants

Varying Fine Structure Constant

68%





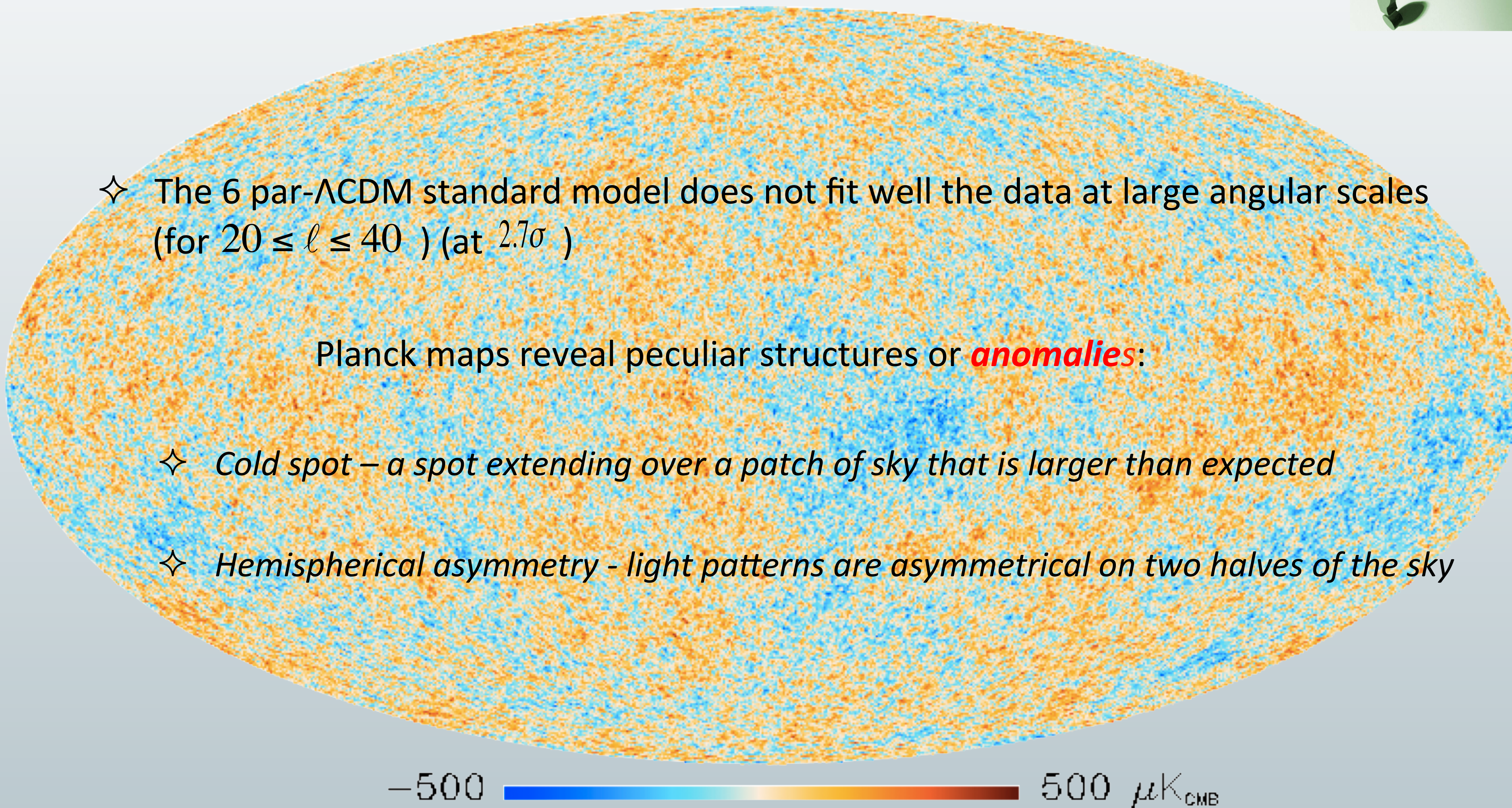


$$\alpha/\alpha_0 = 0.9936 \pm 0.0043$$

A factor of 5 improvement compared to WMAP

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)

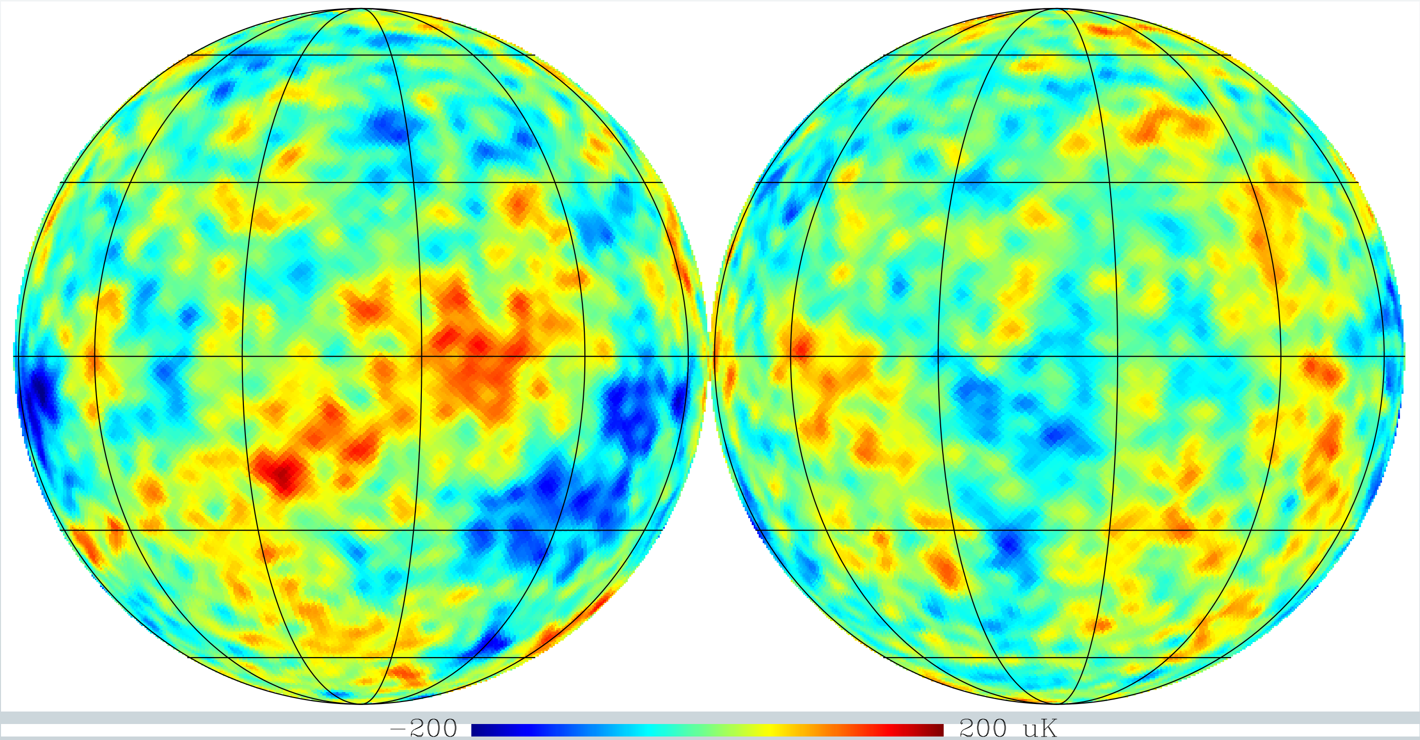
Planck maps reveal peculiar structures or ***anomalies***:

✧ *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*

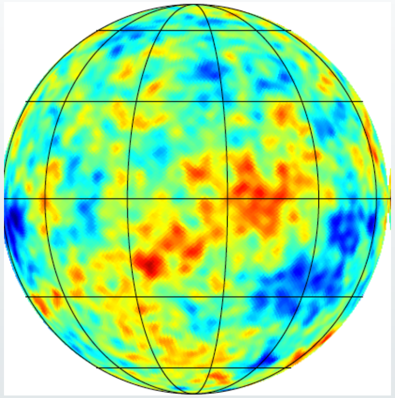
Planck sees peculiar features (anomalies) in the patterns of the relic light

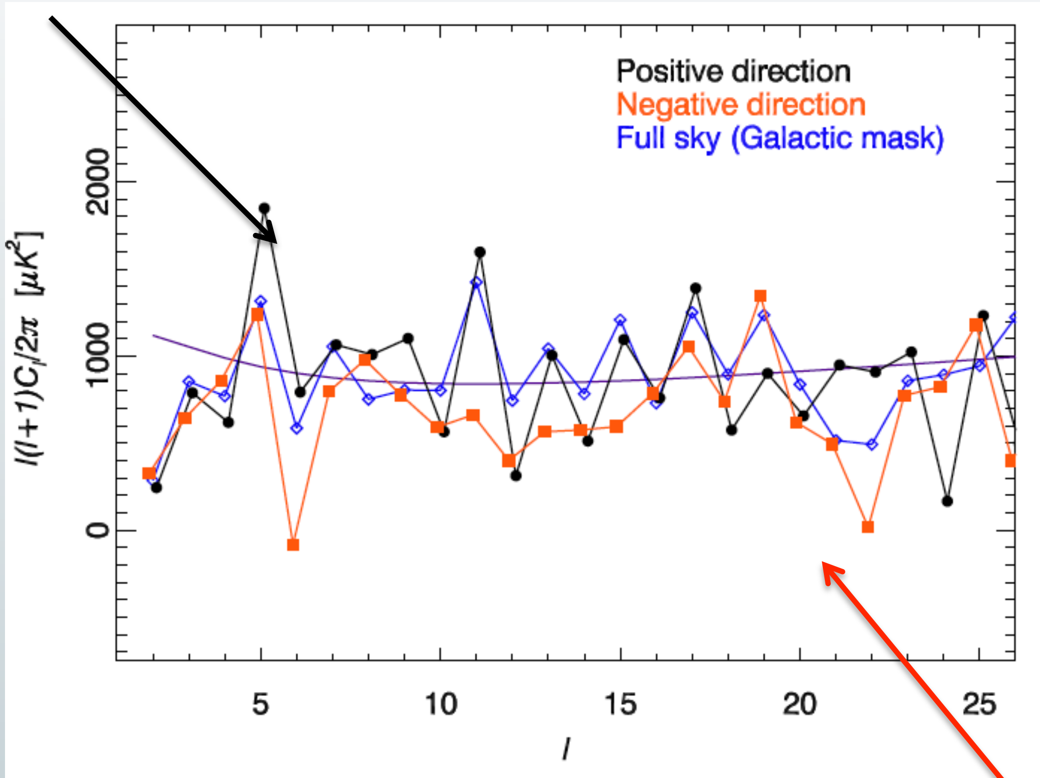
The two halves of the sky that we see look different

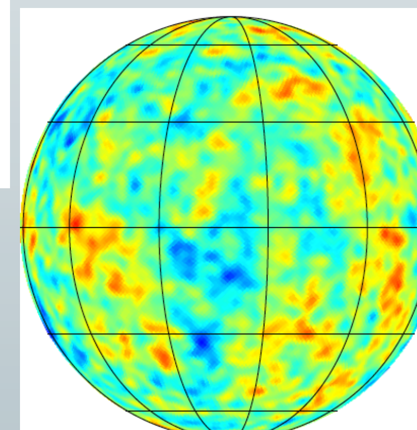


A feature noticed before and considered controversial
is now proven real by Planck
Does this call for new physics?
These are large scale (super-horizon) features.
They give a pristine image of the very very early Universe.

Planck sees peculiar features (anomalies)
Hemispherical asymmetry



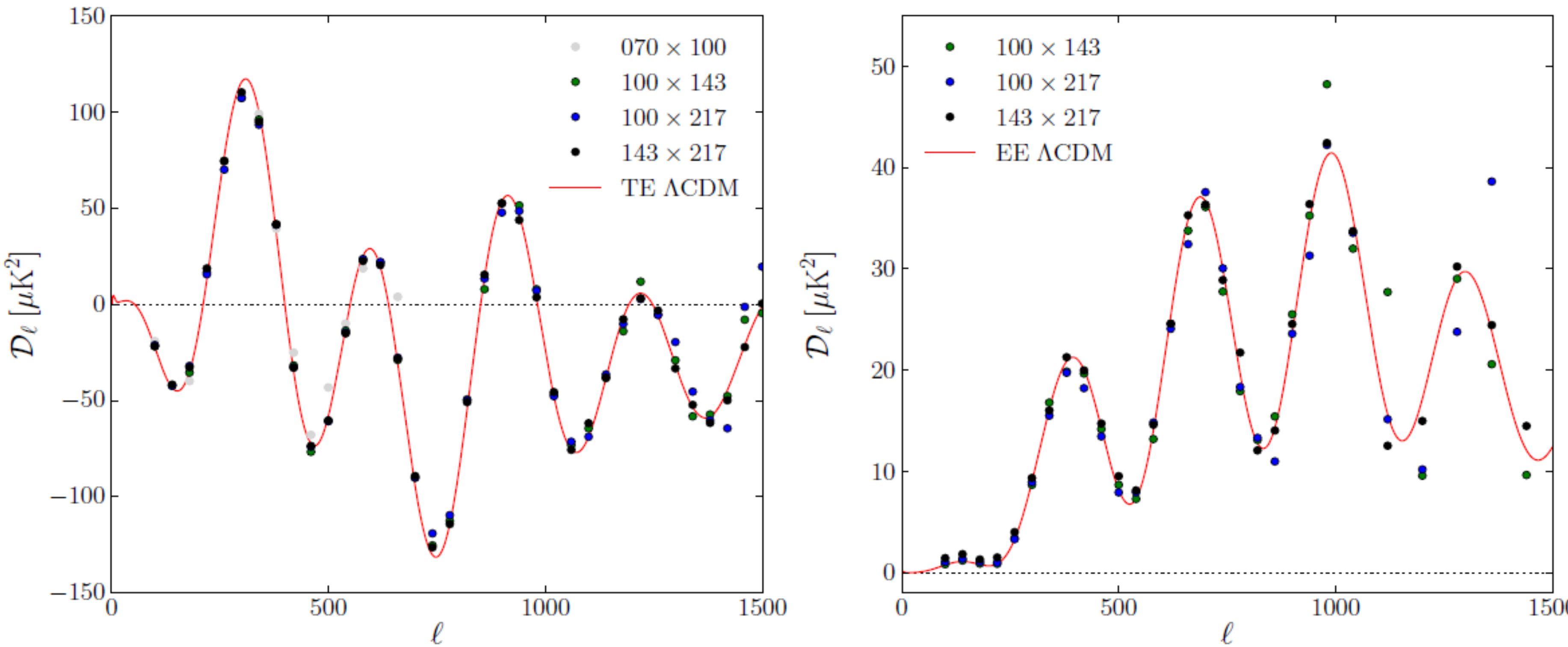




A feature noticed before and considered controversial
is now proven real by Planck
Could this be a fluke? Or does this call for new physics?

Polarization

TE and EE Power Spectra (preliminary!) - red line is not a fit to the polarized spectra – it is the TT best fit model



Excellent quality of the data
Foregounds and systematics are not dominant

Summary

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.

- A standard spatially flat 6-parameter ΛCDM Cosmology with a Power law spectrum of Gaussian adiabatic scalar perturbations fits well Planck data. The Universe is a little older, it is expanding a little bit more slowly, has more matter and less dark energy.
- Planck values of H_0 and Ω_m are in tension with other data sets but in good agreement with BAO data
- None of the extensions to the 6-parameter model is favoured over the standard 6-parameter ΛCDM model; some of this extensions points to new physics but these are mostly driven by data "tensions" that need to be understood
- Anomalies : The 6-parameter ΛCDM standard model does not fit well the data at large angular scales ($20 < l < 40$); Cold spot; Hemispherical asymmetry

What next?

- However there is still a huge amount to learn and do. There is a lot of data to look at and analyse (full mission), including the polarization of this ancient light. *Stay tuned!*

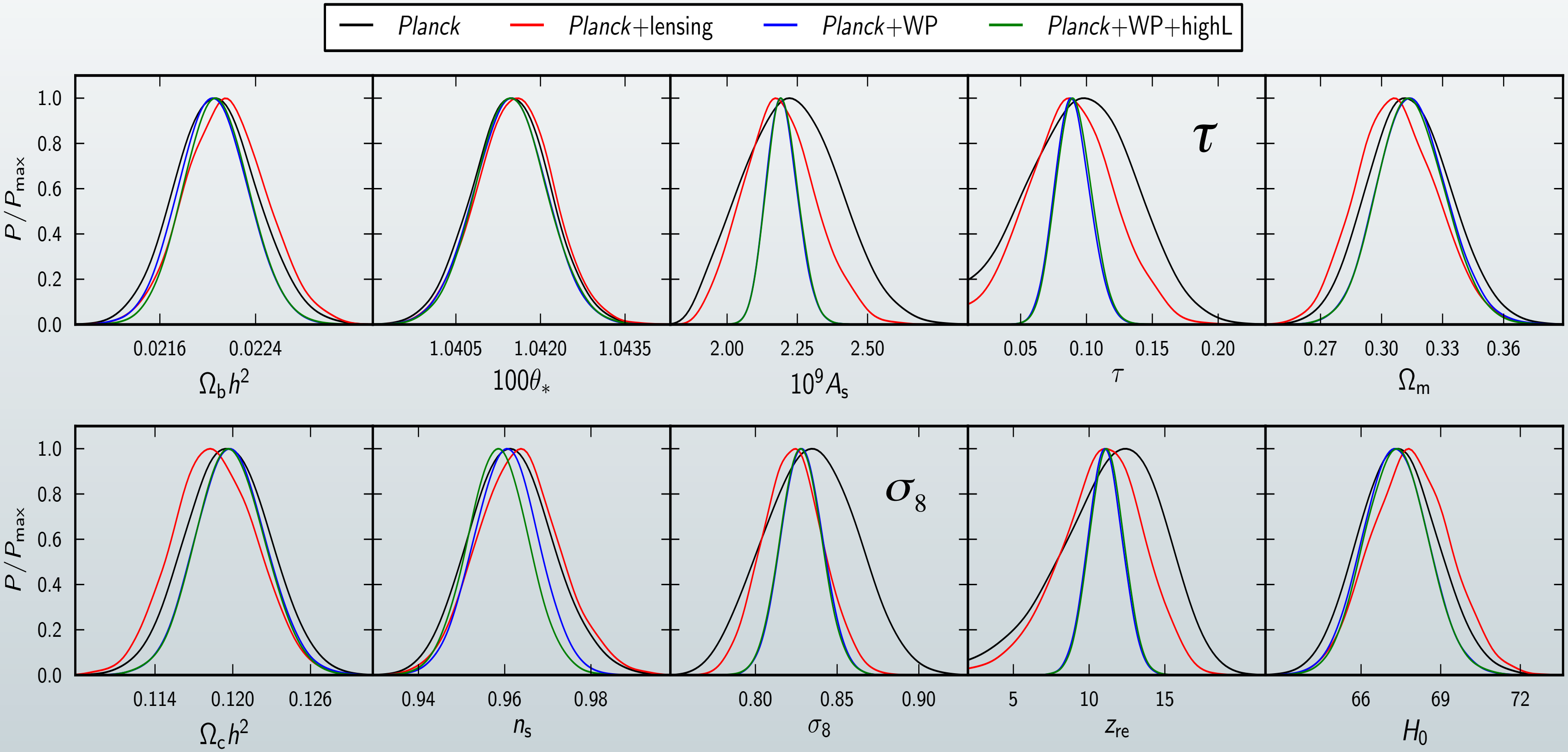
It has taken us 20 years to get to this point. One might ponder what our knowledge of the Universe will look like in 20 years time. It will be interesting to see!

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.

Appendix

ΛCDM model parameters from Planck: 1d marginal distributions



Polarization-free optical depth to reionization (τ) in good agreement with τ from the WMAP9 large-scale polarization

$\tau = 0.089 \pm 0.032$ (Planck+lensing)

$\tau = 0.089 \pm 0.014$ (WMAP9 E-mode polarization)

Planck & WMAP9

ΛCDM Parameters, WMAP & Planck

Parameter	Planck ("CMB+Lens")	WMAP (9-year)	Uncertainty ratio (Planck/WMAP)	Shift (WMAP sigma)	Shift (Planck sigma)
Fit parameters					
$\Omega_b h^2$	0.02217 ± 0.00033	0.02264 ± 0.00050	0.66	-0.9	-1.36
$\Omega_c h^2$	0.1186 ± 0.0031	0.1138 ± 0.0045	0.69	$+1.1$	+1.6
Ω_Λ	0.693 ± 0.019	0.721 ± 0.025	0.76	-1.1	-1.4
n_s	0.9635 ± 0.0094	0.972 ± 0.013	0.72[a]	-0.7	-0.97
τ	0.089 ± 0.032	0.089 ± 0.014	2.28[a]	0	0
$10^9 \Delta^2_{\mathcal{R}}$	...	2.41 ± 0.10 (4.1%)			
$\ln(10^{10} A_s)$	3.085 ± 0.057 (1.8%)	...	0.44[a]		
Derived parameters					
t_0 (Gyr)	13.796 ± 0.058	13.74 ± 0.11	0.53	$+0.5$	+0.94
H_0 (km/s/Mpc)	67.9 ± 1.5	70.0 ± 2.2	0.68	-1.0	-1.5
σ_8	0.823 ± 0.018	0.821 ± 0.023	0.78	$+0.1$	+0.13
$100\,\theta_*$	1.04141 ± 0.00067	1.0390 ± 0.0023	0.29	$+1.0$	+3.4

[a] These parameter uncertainties benefit most from polarization data to constrain τ.

However the shifts in parameters are not independent they talk to the spectra the net result is more significative

Polarization

Stacked maps of the CMB intensity I and polarization Q_r at the position of the temperature extrema, at a common resolution of 30 arcmin