Power Spectra and the Likelihood

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On behalf of the Planck collaboration

Mining the Cosmic Frontier, UCDavis, 20th May 2013

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)

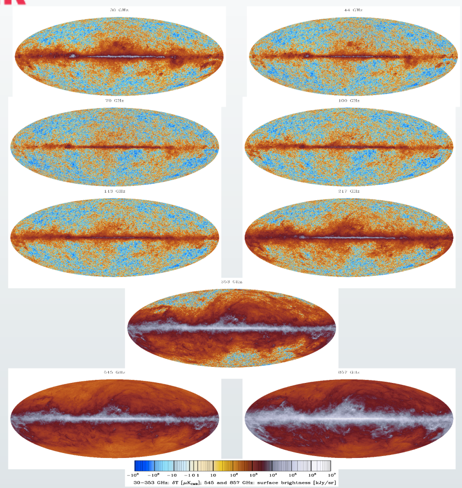
- Maps at nine frequencies

- 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

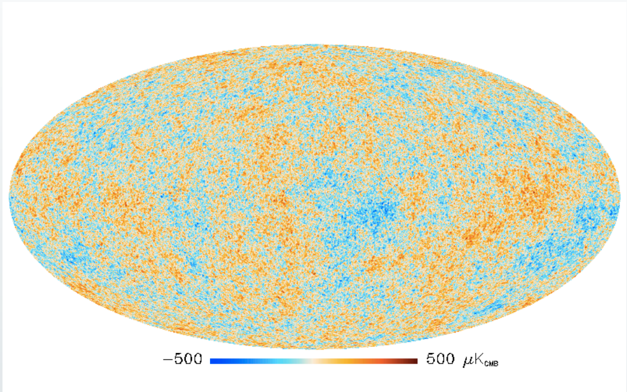
$$L(C_\ell) = P(D \mid C_\ell)$$

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



Frequency maps

Component Separation

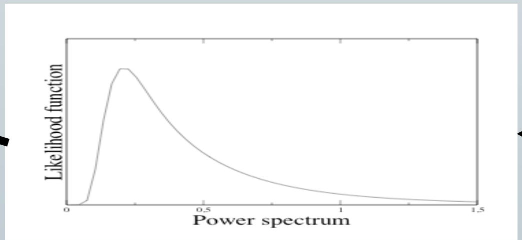


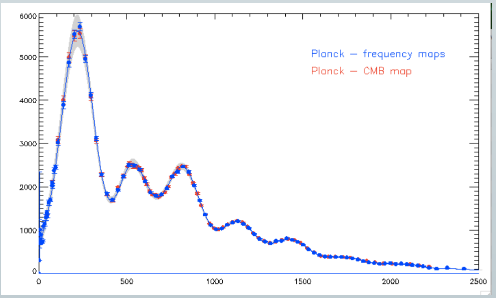
Cleaned CMB map

directly from sky maps
to the likelihood

n_s Ω_b σ_8 Ω_0 H_0 τ

MCMC





Cosmological parameters

Likelihood

Angular Power spectrum

Hybrid Likelihood

- Low-l
  - **Commander** – Gibbs sampling
- High-l
  - Spectra-based:
    - **CamSpec –** Baseline
    - **PLIK**
  - Map-based:
    - **XFcmb**

Planck High-l Likelihoods
CamSpec

- Estimate pseudo-Cls

$$\tilde{C}^{ij}_\ell = \frac{1}{2\ell+1}\sum_m \tilde{T}^i_{\ell m}\tilde{T}^{j\dagger}_{\ell m},$$

only cross-spectra is used

- Estimate the deconvolved spectra:

$$\hat{C}^{T_{ij}} = M^{TT}_{ij}\tilde{C}^{T_{ij}}.$$

$$\hat{\mathcal{M}} = (\tilde{\mathbf{X}} - \langle\tilde{\mathbf{X}}\rangle)(\tilde{\mathbf{X}} - \langle\tilde{\mathbf{X}}\rangle)^T.$$

with

$$\tilde{\mathbf{X}} = \mathrm{Vec}(\tilde{\mathbf{C}})$$

- The deconvolved spectra is efficiently combined within a frequency pair after a small recalibration factor, taking into account respective beam transfer functions and noise levels; the Covariance matrix is computed for a fiducial model

- Estimate Likelihood as a Gaussian: $p = \mathrm{e}^{-S}$ with $S = \frac{1}{2}\left(\hat{\mathbf{X}} - \mathbf{X}\right)^T \hat{\mathcal{M}}^{-1}\left(\hat{\mathbf{X}} - \mathbf{X}\right).$

$$\hat{\mathbf{X}} = (\hat{C}^{100\times100}_\ell, \hat{C}^{143\times143}_\ell, \hat{C}^{217\times217}_\ell, \hat{C}^{143\times217}_\ell),$$

coupled to a parametric model of the CMB and FG power spectra

- Calibration, beam uncertainties and instrumental noise

$$B^{ij}(\ell) = B^{ij}_{\mathrm{mean}}(\ell)\exp\left(\sum_{k=1}^{n_{\mathrm{modes}}} g^{ij}_k E^{ij}_k(\ell)\right),$$

construct a Gaussian posterior dist. of beam eigenmodes from the associated Covariance

- Noise pseudo spectra estimated from half-ring difference maps + noise rms /pixel

Planck High-l Likelihoods
PLIK

Start from the full-sky exact likelihood for a Gaussian signal, which for $\mathbf{N}_{map}$ detector maps is given by:

$$p(\text{maps}|\theta) \propto \exp -\{\sum_{\ell}(2\ell+1)\mathcal{K}(\hat{\mathbf{C}}_{\ell}, \mathbf{C}_{\ell}(\theta))\},$$

K(**A**,**B**) - Kullback divergence between two **n**-variate zero-mean Gaussian distributions with covariance matrices **A** and **B**.

$$\mathcal{K}(\mathbf{A}, \mathbf{B}) = \frac{1}{2}\left[\text{tr}(\mathbf{A}\mathbf{B}^{-1}) - \log\det(\mathbf{A}\mathbf{B}^{-1}) - n\right].$$

Bin the power spectra in such a way that off-diagonal terms of the covariance due to sky cuts are negligible

$$p(\text{maps}|\theta) \propto \exp -\mathcal{L}(\theta), \quad \text{with} \quad \mathcal{L}(\theta) = \sum_{q=1}^{Q} n_q \mathcal{K}(\hat{\mathbf{C}}_q, \mathbf{C}_q),$$

The Plik bin width is $\Delta l = 9$ from $l = 100$ to $l = 1503$; $\Delta l = 17$ to $l = 2013$; $\Delta l = 33$ to $l_{max} = 2508$. This ensures that correlations between any two bins are smaller than 10 %.

Binned Likelihood approximation - Computational speed, and it agrees well with the primary likelihood - well suited for performing an extensive suite of robustness tests + instrumental effects can be investigated quickly - assess the agreement between pairs of detectors within a frequency channel, such as individual detector calibrations and beam errors.

Jointly estimate the noise together with all other parameters using both auto and cross-spectra – then fix the noise estimates, and use the fiducial Gaussian approximation to explore the remaining free parameters excluding the autospectra, optionally including only specific data combinations

Planck High-l Likelihoods
XFcmb

Band powers estimated with XFaster for each of the CMB maps generated by

SMICA, Commander-Ruler, NILC, SEVEM

XFaster: an approximation to the iterative, Maximum likelihood, quadratic band power estimator based on a diagonal approximation to the quadratic Fisher matrix estimator

$$\tilde{C}_\ell = \sum_b q_b \tilde{C}^S_{b\ell} = \sum_b \left(\frac{1}{2} \sum_{b'} \mathcal{F}^{-1}_{bb'} \sum_\ell (2\ell+1) g_\ell \frac{\tilde{C}^S_{b'\ell}}{(\tilde{C}_\ell + \langle \tilde{N}_\ell \rangle)^2})(\tilde{C}^{obs}_\ell - \langle \tilde{N}_\ell \rangle) \right) \tilde{C}^S_{b\ell}$$

$$\mathcal{F}_{bb'} = \frac{1}{2} \sum_\ell (2\ell+1) g_\ell \frac{\tilde{C}^S_{b\ell} \tilde{C}^S_{\ell b'}}{(\tilde{C}_\ell + \langle \tilde{N}_\ell \rangle)^2}$$

The iterative scheme starts from a flat spectrum model - the result is a band power spectrum and the associated Fisher matrix (hence uncertainty of the band powers)

Use a Gaussian Correlated likelihood and a MCMC sampler and PICO for $70<l<2000$

- 6 cosmological parameters
- A_{ps} - the amplitude of a Poisson component , $C_l=A_{ps}$=constant
- Acl - the amplitude of a clustered component with shape:

  D_l at l = 3000 in units of μK^2

$$D_\ell = \ell(\ell+1)C_\ell / 2\pi \propto \ell^{0.8}$$

Planck Low-l Likelihood Commander

For l ≤ 50 - we adopt Gibbs sampling approach as implemented in **Commander**

Data model - > multi-frequency obs + set of foreground signal:

$$\mathbf{d}_\nu = \mathbf{s} + \sum_i \mathbf{f}^i_\nu + \mathbf{n}_\nu.$$

CMB field - Gaussian random field with power spectrum $\mathbf{C_l}$,

Noise - Gaussian with covariance $\mathbf{N_\nu}$

- Model: single low-frequency foreground comp (sum of synchrotron, anomalous microwave emission, and free-free emission), a carbon monoxide (CO)comp, and thermal dust component, in addition to unknown monopole and dipole comp at each frequency.
- Map out the full posterior distribution, **P** (**s**; **f**^{i} ;**C**$_l$|**d**), using a Gibbs sampling (MC sampling) . Directly drawing samples from **P** (**s**; **f**^{i} ;**C**$_l$|**d**) is computationally prohibitive, but this algorithm achieves the same by iteratively sampling from each corresponding **conditional** distribution:

$$\mathbf{s} \leftarrow P(\mathbf{s}|\mathbf{f}, C_\ell, \mathbf{d})$$

Multivariate Gaussian distribution

$$\mathbf{f} \leftarrow P(\mathbf{f}|\mathbf{s}, C_\ell, \mathbf{d})$$

does not have a closed analytic form, but can be mapped out numerically

$$C_\ell \leftarrow P(C_\ell|\mathbf{s}, \mathbf{f}^i, \mathbf{d}).$$

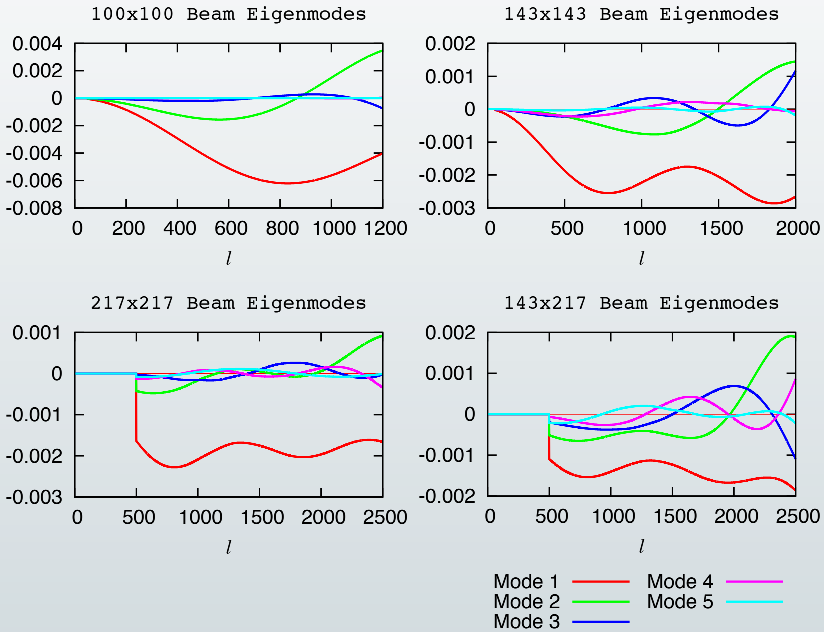
Inverse Gamma distribution

- For CMB Likelihood Ensemble of CMB sky samples , s^k

$$\mathcal{L}^k(C_\ell) \propto \frac{\sigma_{\ell,k}^{\frac{2\ell-1}{2}}}{C_\ell^{\frac{2\ell+1}{2}}} e^{-\frac{2\ell+1}{2}\frac{\sigma_{\ell,k}}{C_\ell}}. \quad \rightarrow \quad \mathcal{L}(C_\ell) \propto \sum_{k=1}^{N_{\mathrm{samp}}} \mathcal{L}^k(C_\ell).$$

BR

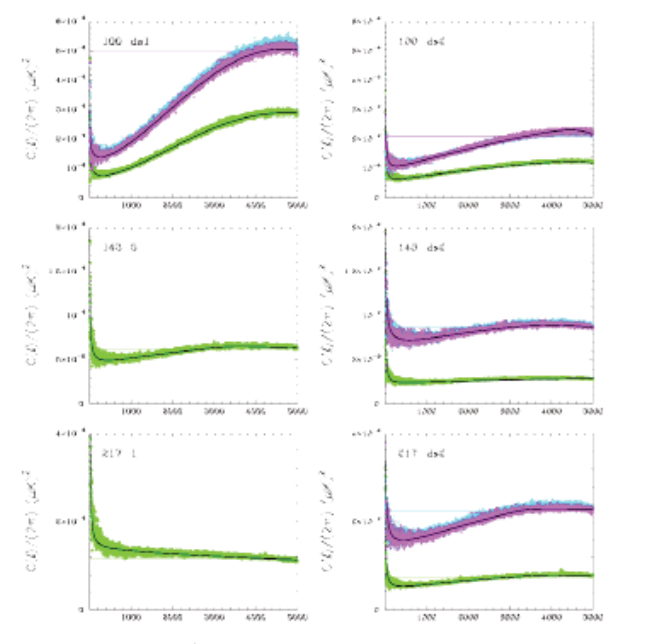
Planck baseline high-l Likelihood: CamSpec
Beam uncertainties, Noise



Map	Mask	$\bar{N}^T$
100-ds1	3	2.717×10^{-4}
100-ds2	3	1.144×10^{-4}
143-5	1	6.165×10^{-5}
143-6	1	6.881×10^{-5}
143-7	1	5.089×10^{-5}
143-ds1	1	2.824×10^{-5}
143-ds2	1	2.720×10^{-5}
217-1	1	1.159×10^{-4}
217-2	1	1.249×10^{-4}
217-3	1	1.056×10^{-4}
217-4	1	9.604×10^{-5}
217-ds1	1	6.485×10^{-5}
217-ds2	1	7.420×10^{-5}

$$B^{ij}(\ell) = B^{ij}_{\rm mean}(\ell)\exp\left(\sum_{k=1}^{n_{\rm modes}} g^{ij}_k E^{ij}_k(\ell)\right),$$

Gaussian posterior distribution of beam Eigenmodes from the associated covariance



$$\bar{N}^{\rm fit}_\ell = A\left(\frac{100}{\ell}\right)^\alpha + \frac{B(\ell/1000)^\beta}{(1+(\ell/\ell_c)^\gamma)^\delta},$$

Planck baseline high-l Likelihood: CamSpec FG model and Sky Masks

Mask	Sky fraction [%]	Sky area [deg²]
CL31	30.71	12 668
CL39	39.32	16 223
CL49	48.77	20 121

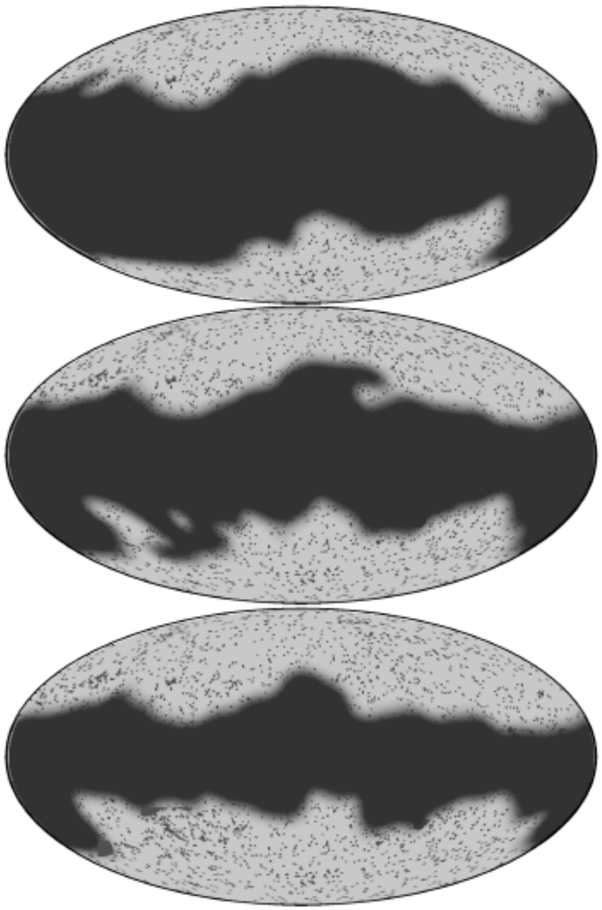
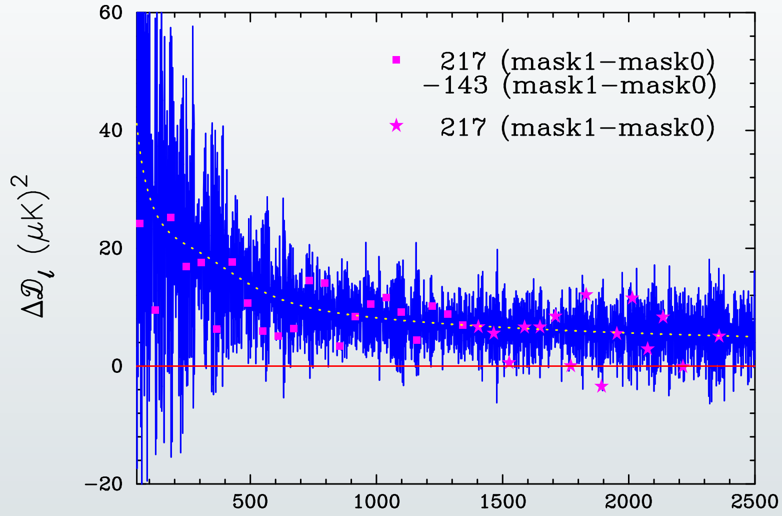
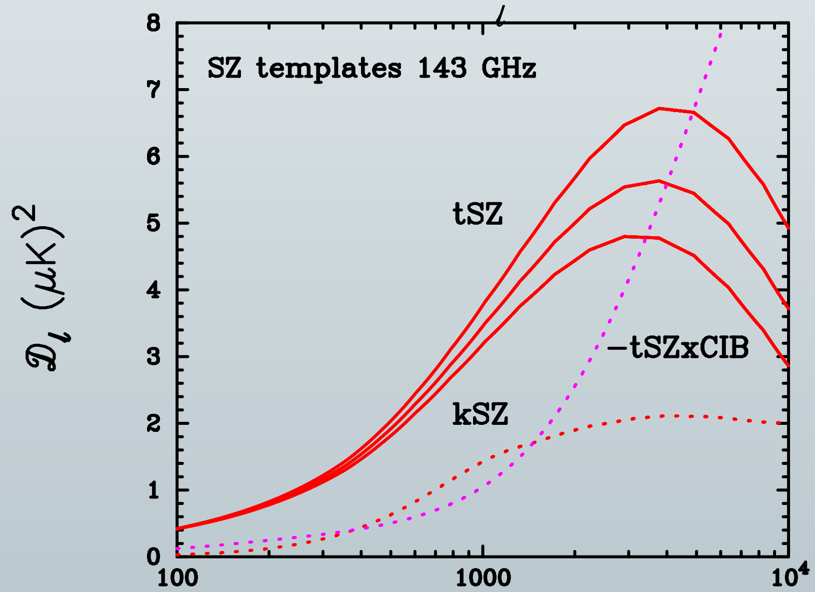
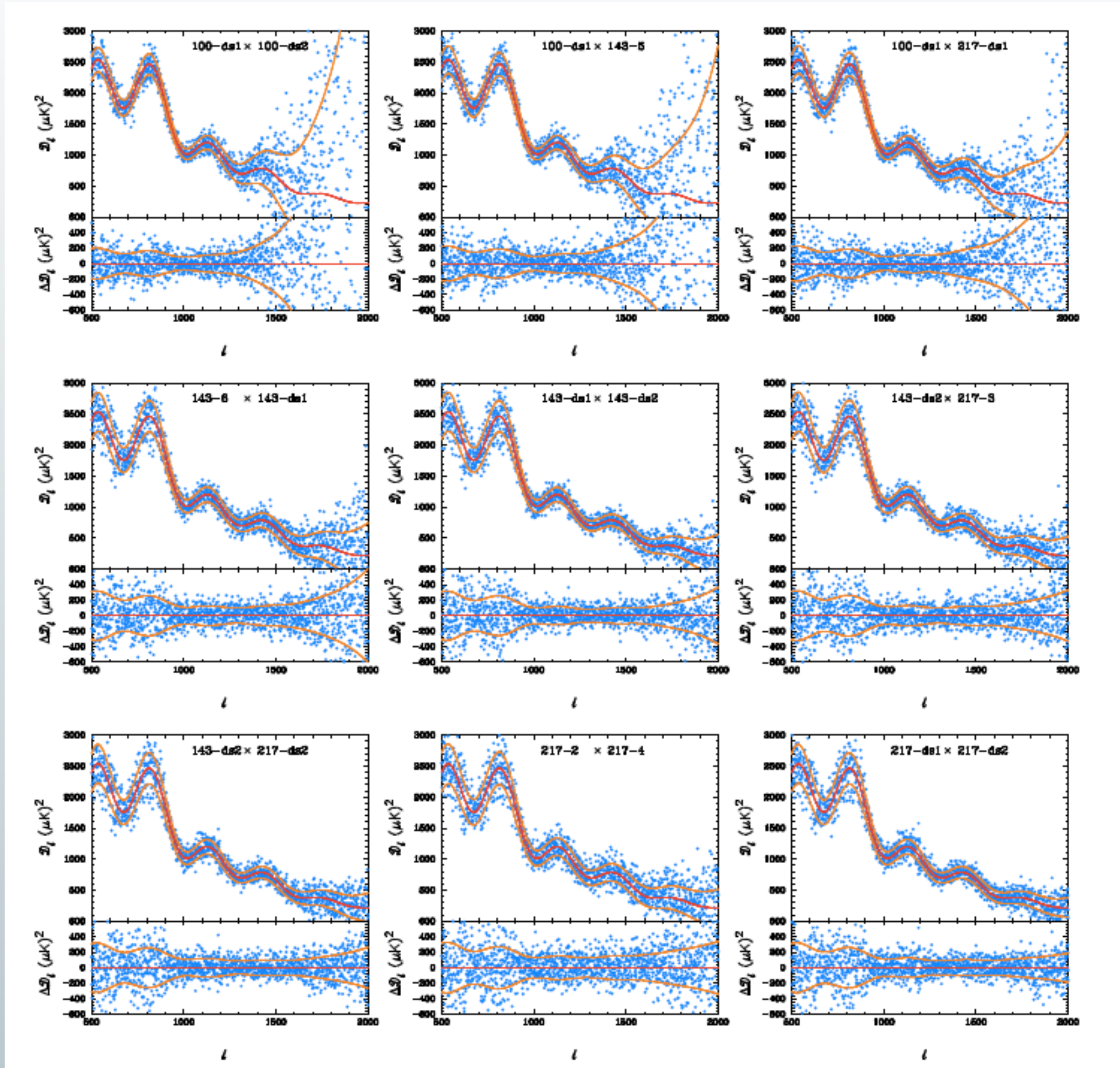


Figure 2. The set of masks (CL31, CL39, CL49) used for the likelihood analyses.





A selection of Cross-Spectra



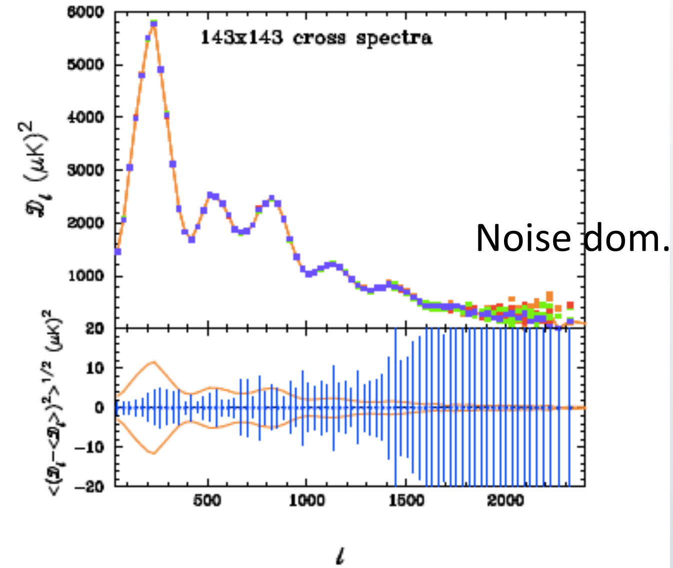
Cross-spectra;
analytic covariance matrices;
Best Fit Model (bfm)

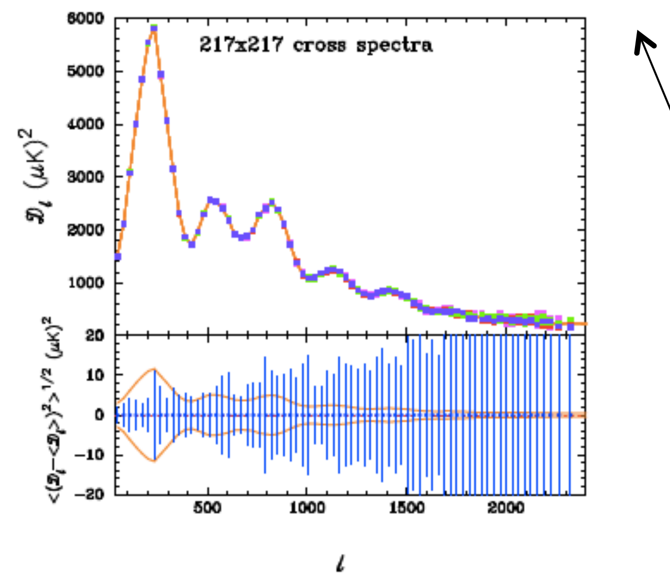
After subtraction of the best fit Foreground (FG) model

Scatter varies with cross-spectra
Due to differences in the instrumental noise + effective resolution of different detector combinations

The error model has been modified by the non-white noise correction

Combined Cross-Spectra
Intra-frequency residuals





Solve for multiplicative Effective calibration coefficients y_i that minimize:

$$\chi^2 = \sum_{\ell} \sum_{ij,j>i} (y_i y_j \hat{C}_\ell^{ij} - \langle \hat{C}_\ell \rangle)^2,$$

where

$$\langle \hat{C}_\ell \rangle = \frac{1}{N_{\rm spec}} \sum_{ij,j>i} y_i y_j \hat{C}_\ell^{ij},$$

Spectra corrected for W_l
Subject to constraints: y_i=1 -> 143-5 and 217-1 detectors
For 5 ≤l ≤ 500 -> signal dom.
minimize impact of beam errors and noise

For mask CL31: calibration factors~ 0.2% -> same order of statistical errors of the calibration on dipole:

map	y_i	map	y_i
143-5	1.0000	217-1	1.0000
143-6	0.9988	217-2	0.9992
143-7	0.9980	217-3	0.9981
-	-	217-4	0.9985
143-ds1	0.9990	217-ds1	0.9982
143-ds2	0.9994	217-ds2	0.9975

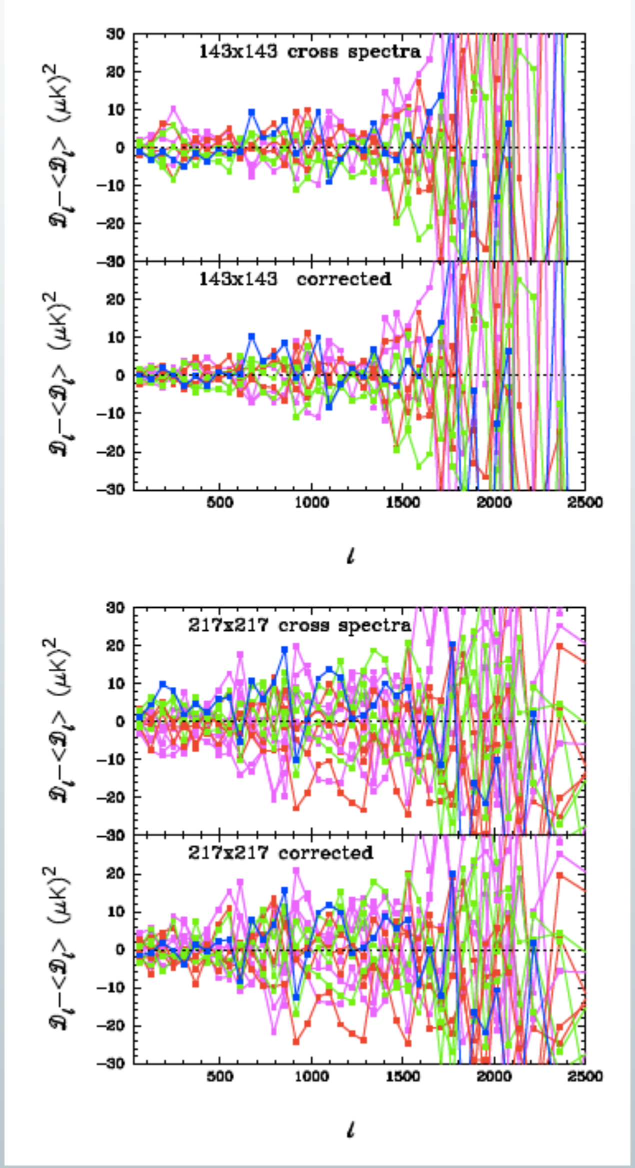
PS corrected for beam and eff. calibration and mean PS.;
Error bar- 0.2% cal. Error

Consistency of power spectra at each freq.to 0.1-0.2% -> test consistency of TTFs and W_l

Combined Cross-Spectra
Intra-frequency residuals

143GHz

217GHz



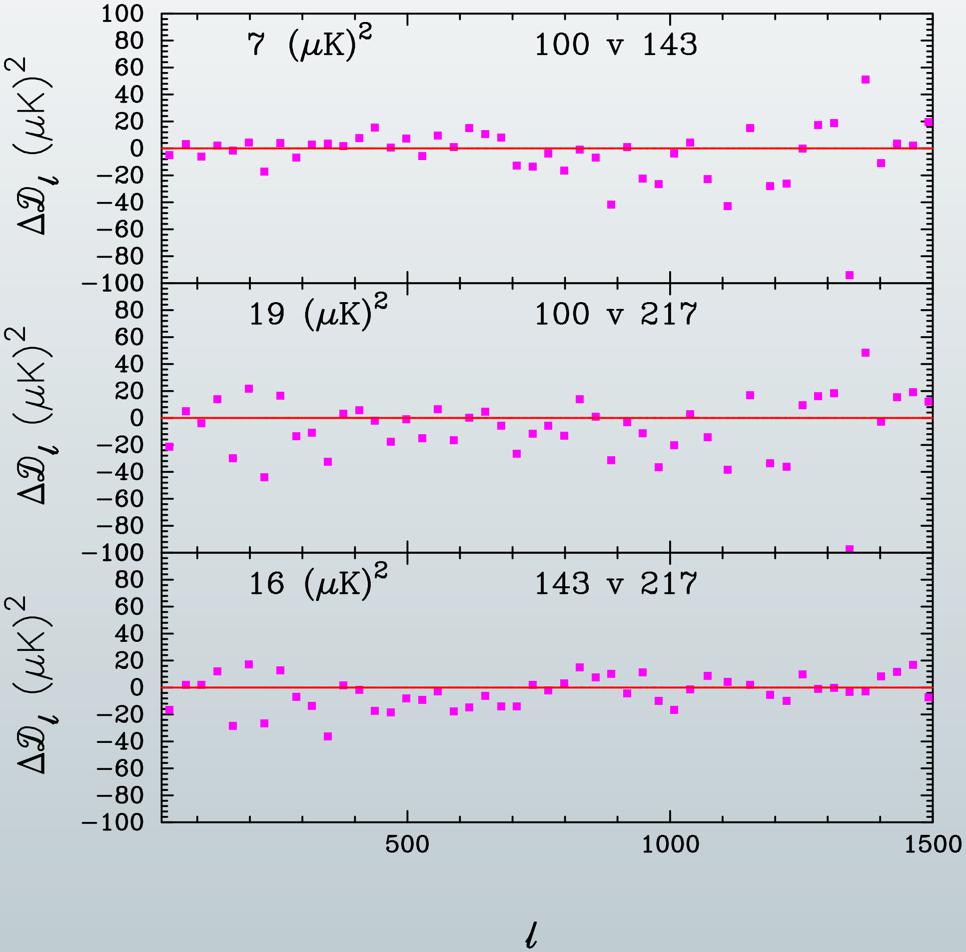
Above – before correction for multiplicative Intra-frequency calibration
Below – after correction

Reduction of scatter for l< 500
Residual scatter consistent with noise and beam errors
At 217GHz beam errors dominate over noise at l<1000

No evidence that the excess scatter is caused by a small number of 'anomalous' detectors

The intra-freq. spectra is consistent to within a few μK^2 at l< 1000

Combined Cross-Spectra
Inter-frequency residuals



Small-scale residuals at $l \leq 800$ larger than expected from instrumental noise:

This excess scatter arises from chance CMB–foreground cross-correlations

The observed scatter can be predicted quantitatively

The high l residuals arise from instrument noise, beam errors, and errors in foreground modelling

A complete analysis of inter-frequency residuals requires the full likelihood machinery and MCMC analysis to determine foreground, beam and calibration parameters

$800 \leq l \leq 1500$

Planck baseline high-l Likelihood: CamSpec Set-up

Set name	Frequency [GHz]	Type	Detectors	FWHM[a] [arcmin]
100-ds0	100	PSB	All 8 detectors	9.65
100-ds1	100	PSB	1a+1b + 4a+4b	
100-ds2	100	PSB	2a+2b + 3a+3b	
143-ds0	143	MIX	11 detectors	7.25
143-ds1	143	PSB	1a+1b + 3a+3b	
143-ds2	143	PSB	2a+2b + 4a+4b	
143-ds3	143	SWB	143-5	
143-ds4	143	SWB	143-6	
143-ds5	143	SWB	143-7	
217-ds0	217	MIX	12 detectors	4.99
217-ds1	217	PSB	5a+5b + 7a+7b	
217-ds2	217	PSB	6a+6b + 8a+8b	
217-ds3	217	SWB	217-1	
217-ds4	217	SWB	217-2	
217-ds5	217	SWB	217-3	
217-ds6	217	SWB	217-4	

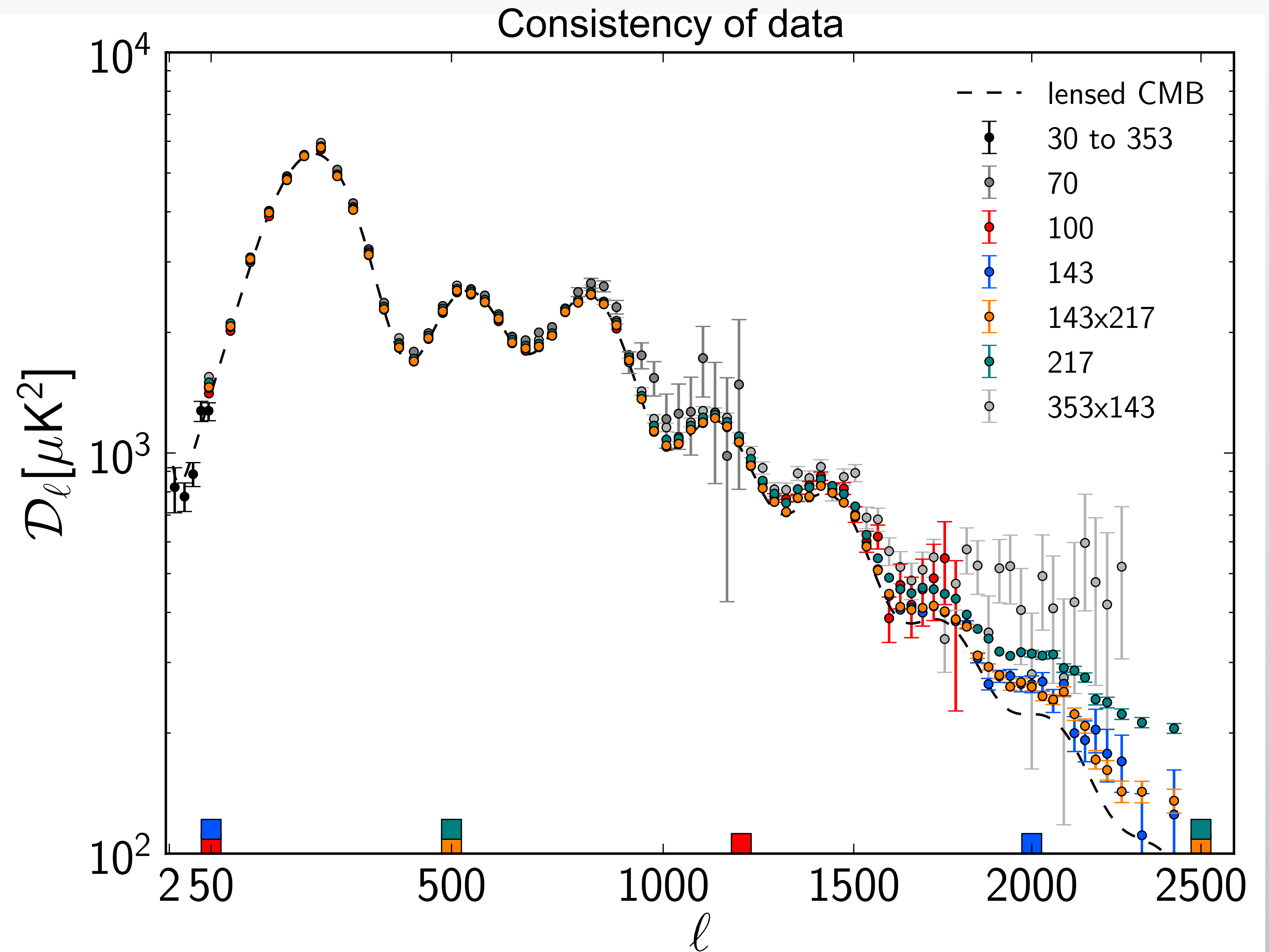
$$\tilde{M} = \left(\begin{array}{c|c|c|c} (100\times100)\times(100\times100) & (100\times100)\times(143\times143) & (100\times100)\times(217\times217) & (100\times100)\times(143\times217) \\ \hline (143\times143)\times(100\times100) & (143\times143)\times(143\times143) & (143\times143)\times(217\times217) & (143\times143)\times(143\times217) \\ \hline (217\times217)\times(100\times100) & (217\times217)\times(143\times143) & (217\times217)\times(217\times217) & (217\times217)\times(143\times217) \\ \hline (143\times217)\times(100\times100) & (143\times217)\times(143\times143) & (143\times217)\times(217\times217) & (143\times217)\times(143\times217) \end{array}\right).$$

Spectrum	Multipole range	Mask	$\chi^2_{\Lambda\mathrm{CDM}}/\nu_{\mathrm{dof}}$	PTE
100×100	50 – 1200	CL49	1.01	0.40
143×143	50 – 2000	CL31	0.96	0.84
143×217	500 – 2500	CL31	1.04	0.10
217×217	500 – 2500	CL31	0.96	0.90
Combined	50 – 2500	CL31/49	1.04	0.08

Gaussian prior on τ (WMAP7) , 0.088±0.015 instead of the low-l likelihood at l<50
Estimate angular power spectrum and covariance matrices and combine

Estimate 6 ΛCDM cosmological parameters + 14 nuissance parameters:
11 foreground par; 2 relative calibration par; 1 beam error par;
Apart from the beam eigenmode amplitude and calibration factors we adopt uniform priors

Planck baseline high-l Likelihood: CamSpec
Planck Power Spectra and data selection



Planck baseline high-l Likelihood: CamSpec Marginal distributions

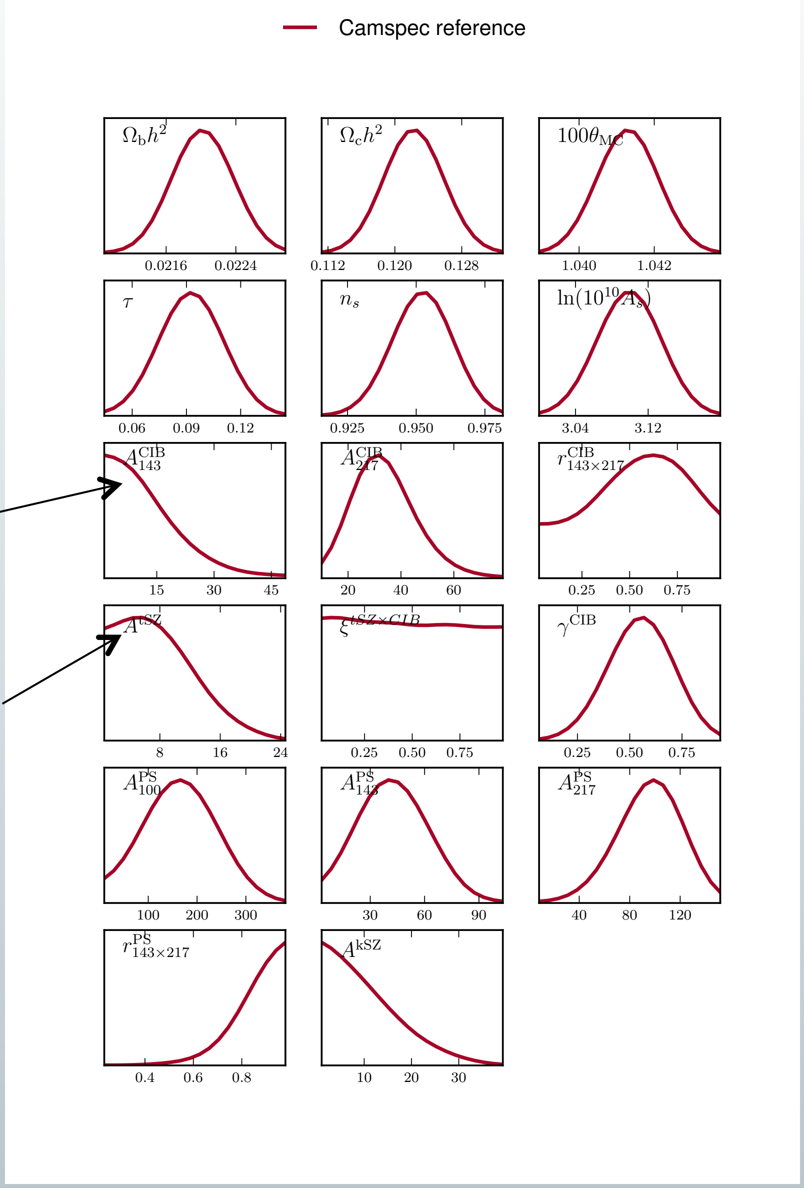
Strong constraining power of Planck data

BUT

A Planck-alone analysis has deficiencies:

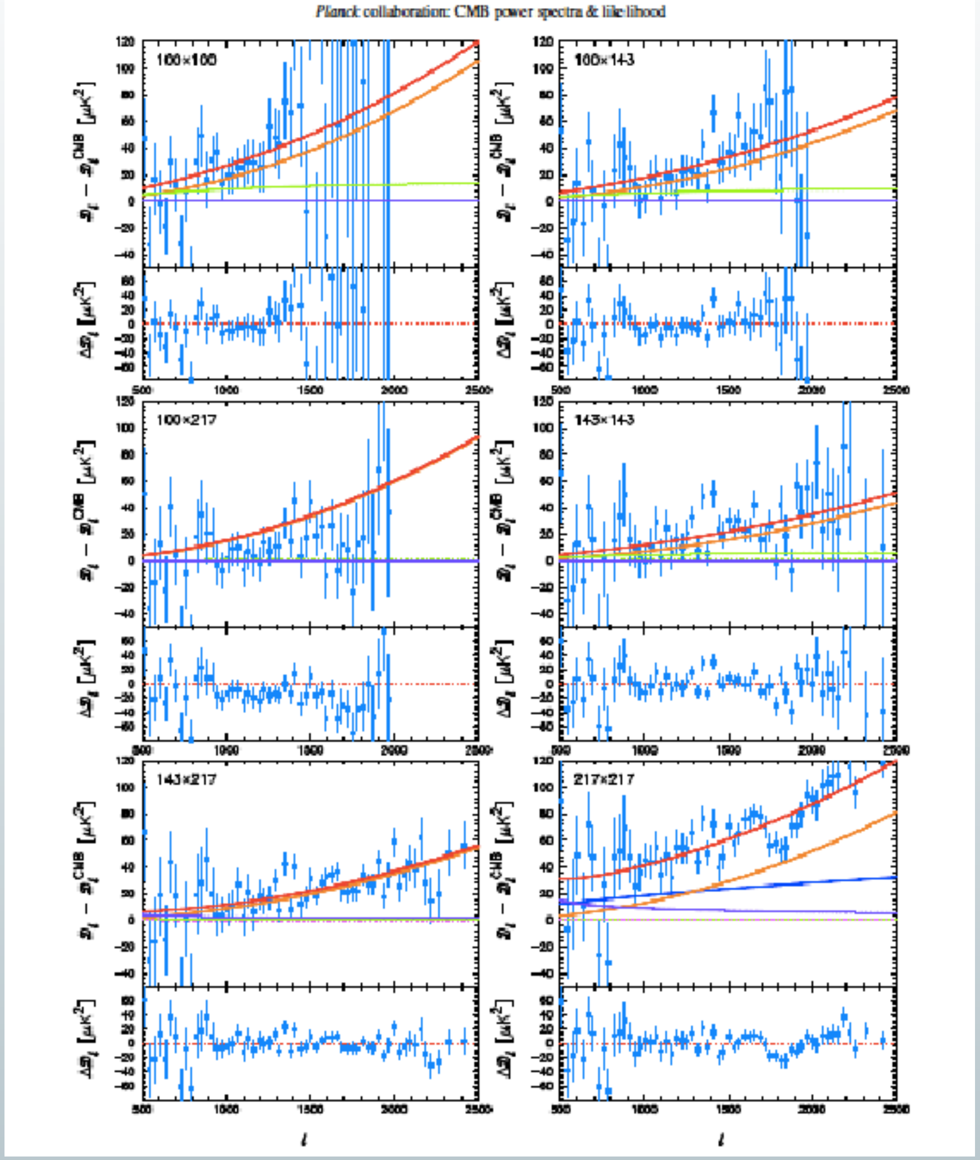
Upper bound weaker than ACT and SPT

Excluded by ACT and SPT



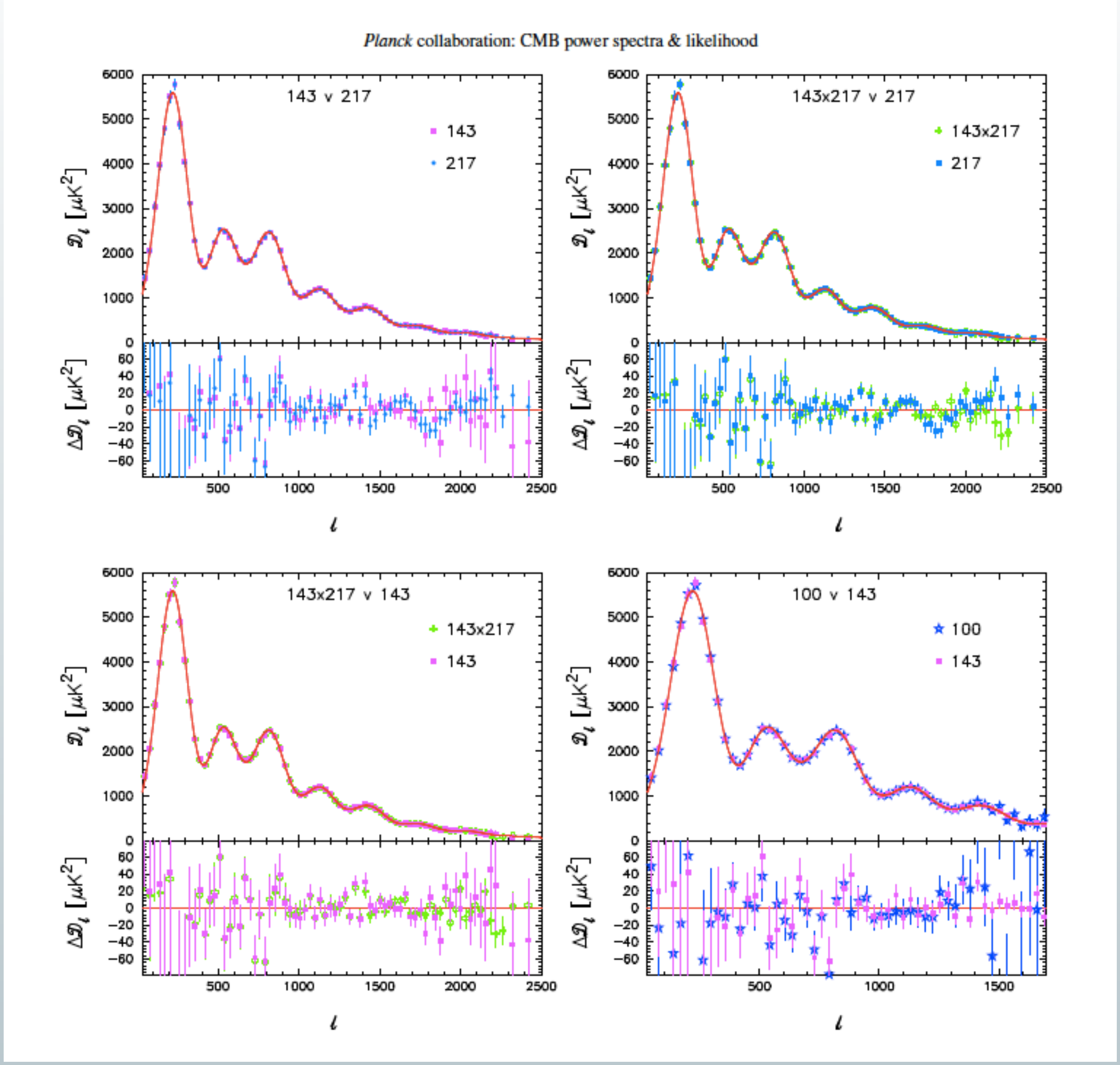
This is why the final Fiducial model and FG param. are derived from a joint Planck+ACT+SPT

Planck baseline high-l Likelihood: CamSpec FG residuals



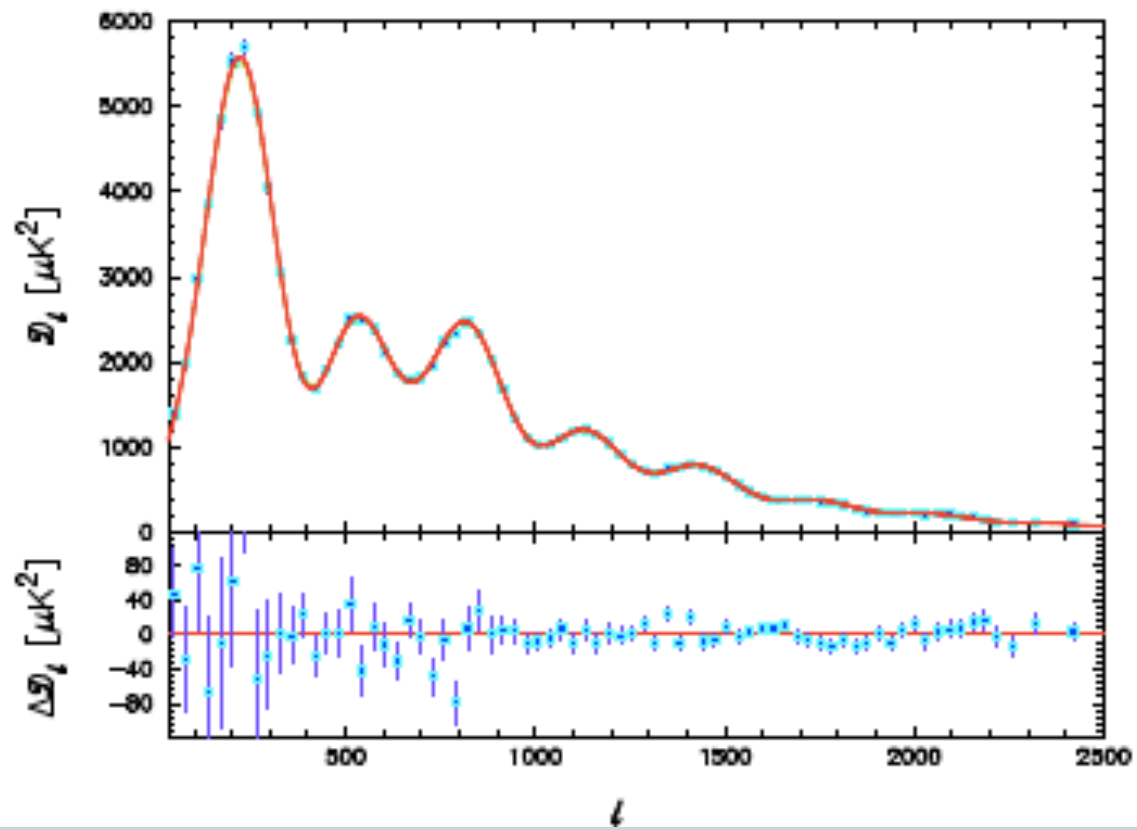
limited ability to disentagle FG

Planck baseline high-l Likelihood: CamSpec Residuals vs bfm



Consistency of residuals wrt best-fit theoretical model bfm.

Planck baseline high-l Likelihood: CamSpec
Planck ML Power Spectrum vs bfm

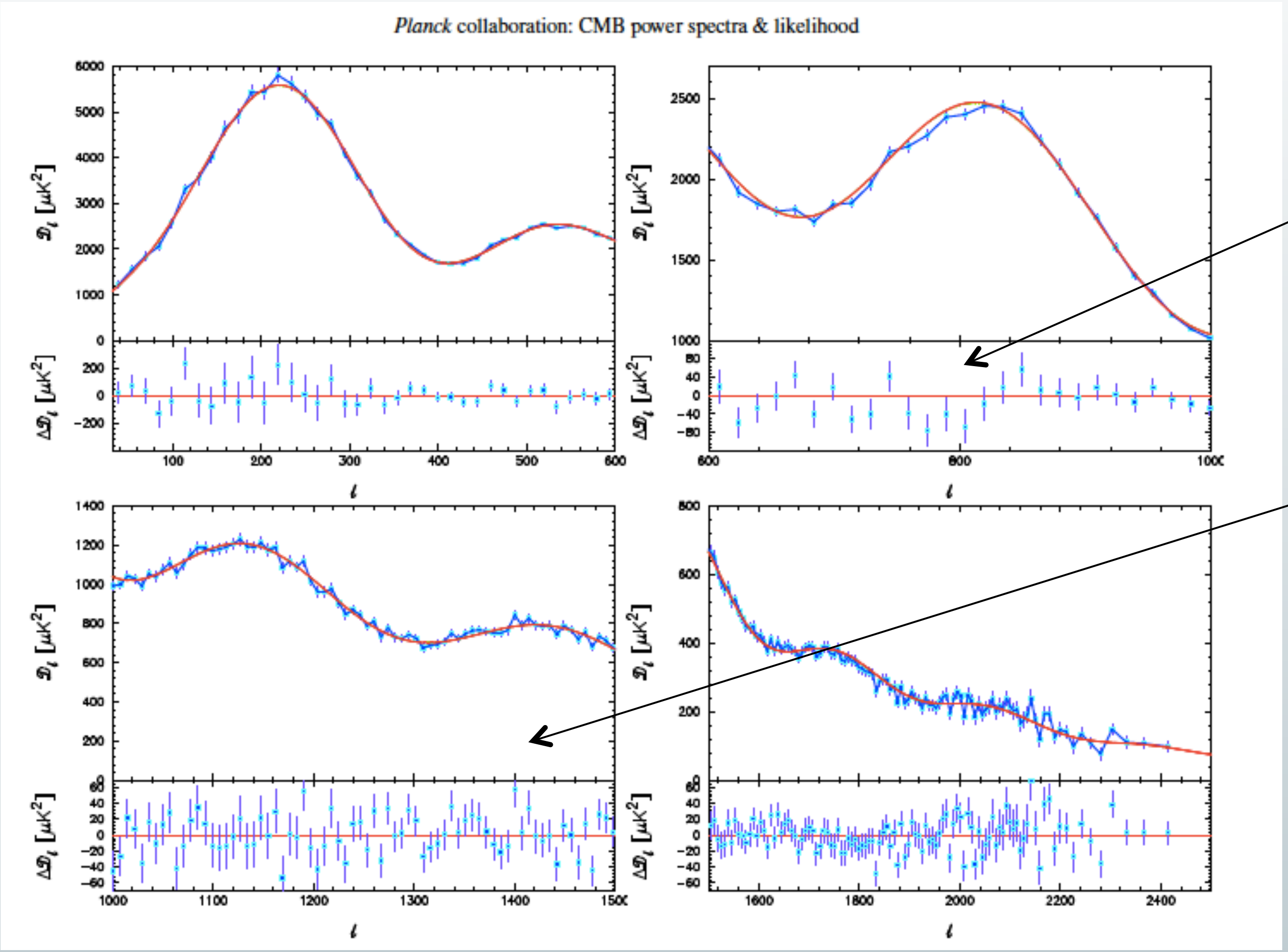


If we fix the foreground model C^{Fk} for each spectrum k , together with the calibration coefficients and beam parameters - we can minimize the likelihood with respect to a 'best-fit' primary CMB spectrum:

$$\sum_{kk'\ell'} (\hat{\mathcal{M}}^{-1}_{\ell\ell'})^{kk'} \hat{C}^{\rm CMB}_{\ell'} = \sum_{kk'\ell'} (\hat{\mathcal{M}}^{-1}_{\ell\ell'})^{kk'} (c^{k'} \hat{C}^{k'}_{\ell'} - \hat{C}^{Fk'}_{\ell'}),$$

$$\langle \Delta\hat{C}^{\rm CMB}_{\ell} \Delta\hat{C}^{\rm CMB}_{\ell'} \rangle = \left(\sum_{kk'} (\hat{\mathcal{M}}^{-1}_{\ell\ell'})^{kk'} \right)^{-1}.$$

Planck baseline high-l Likelihood: CamSpec zoom with a finer grid



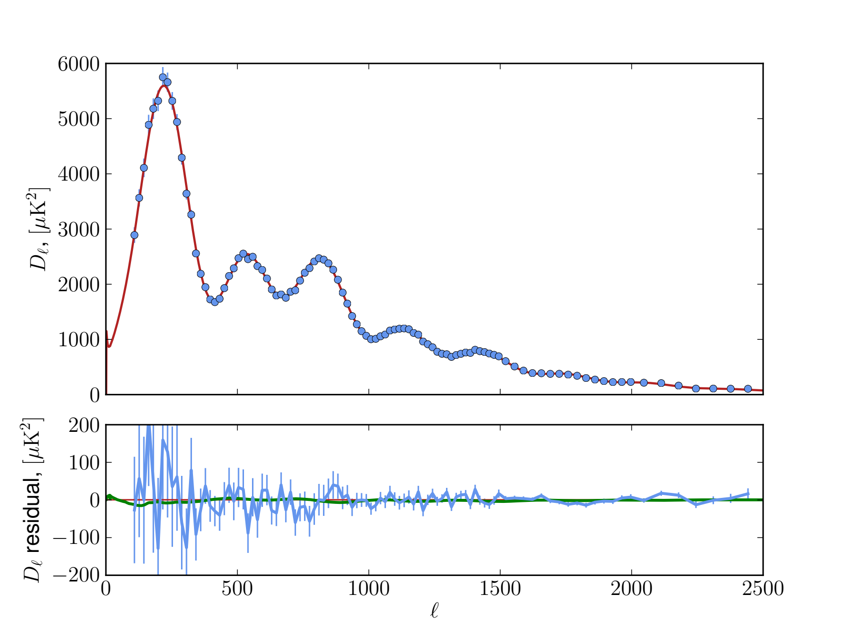
- the ‘bite’ missing from the third peak at l ~ 800

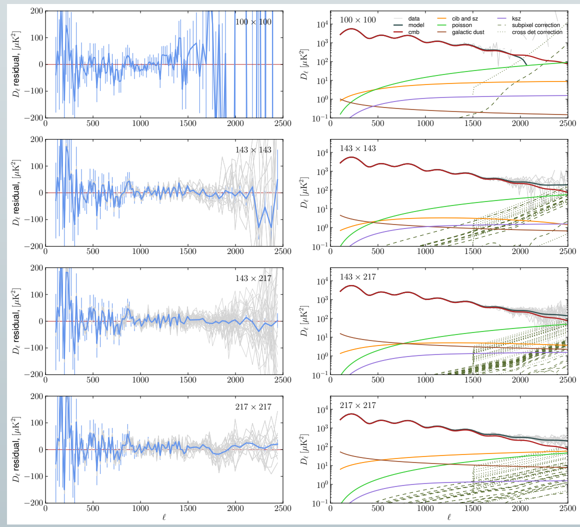
  and

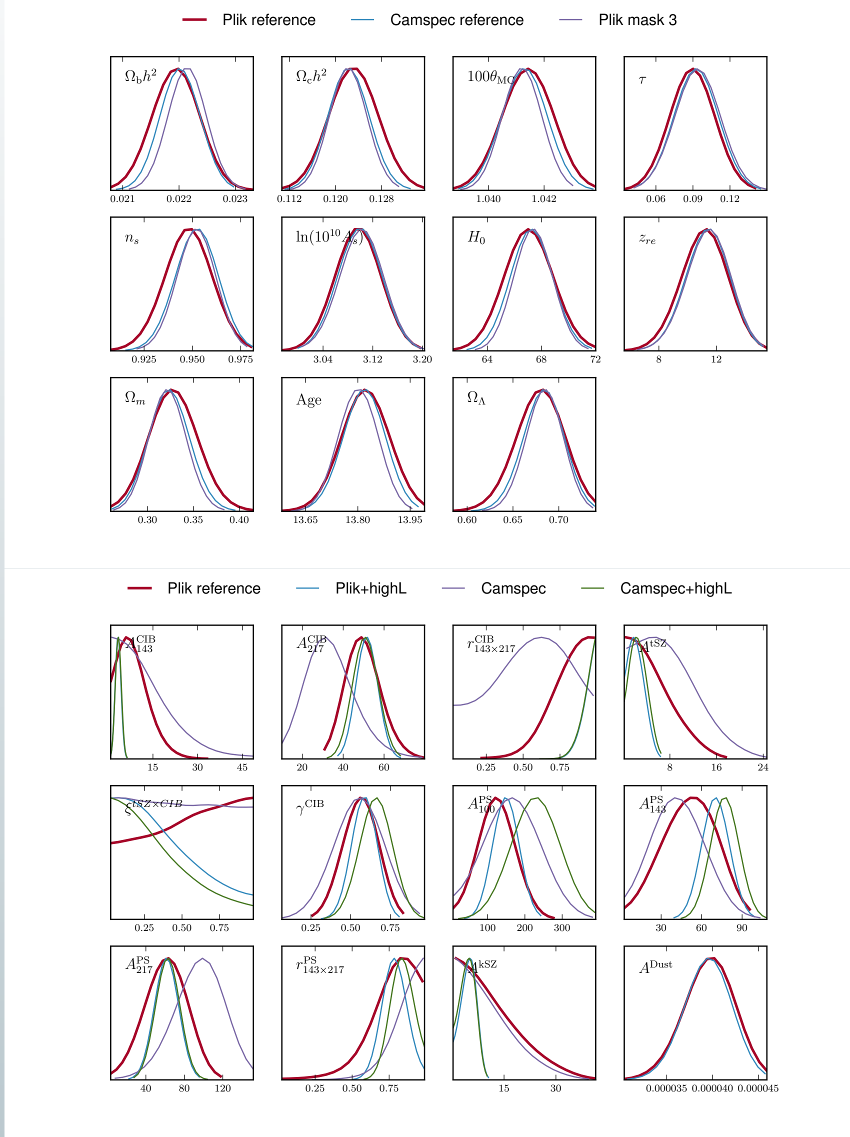
- the oscillatory features in 1300<l<1500

are in agreement with what we expect from covariance matrices and from simulations

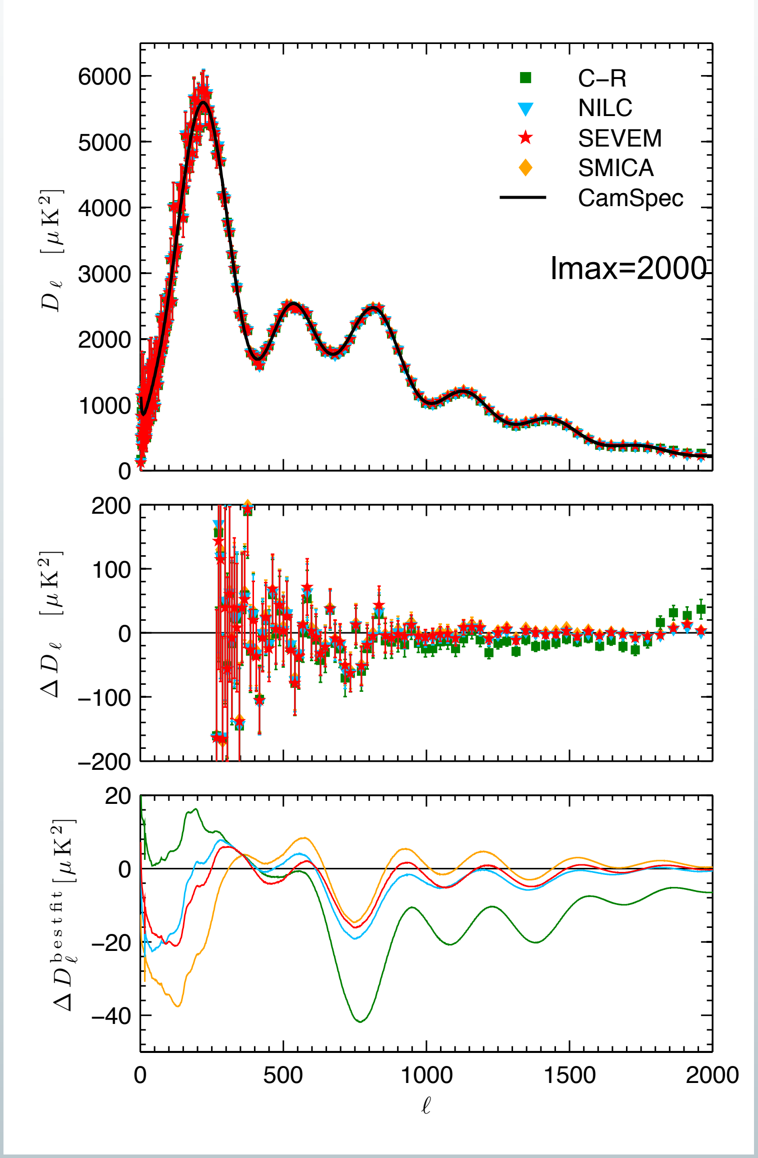
Planck baseline high-l Likelihood: validation CamSpec vs PLIK

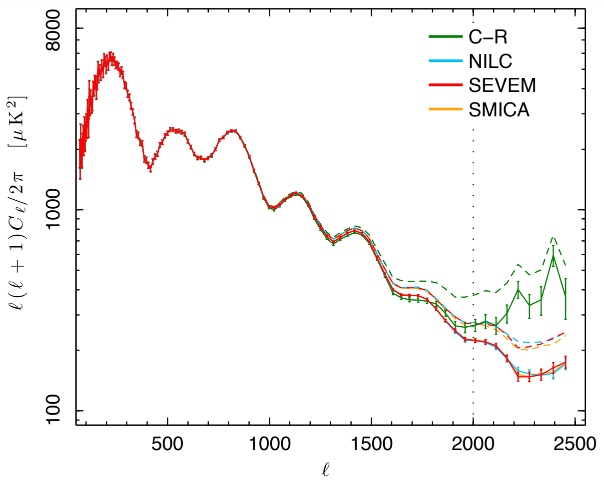


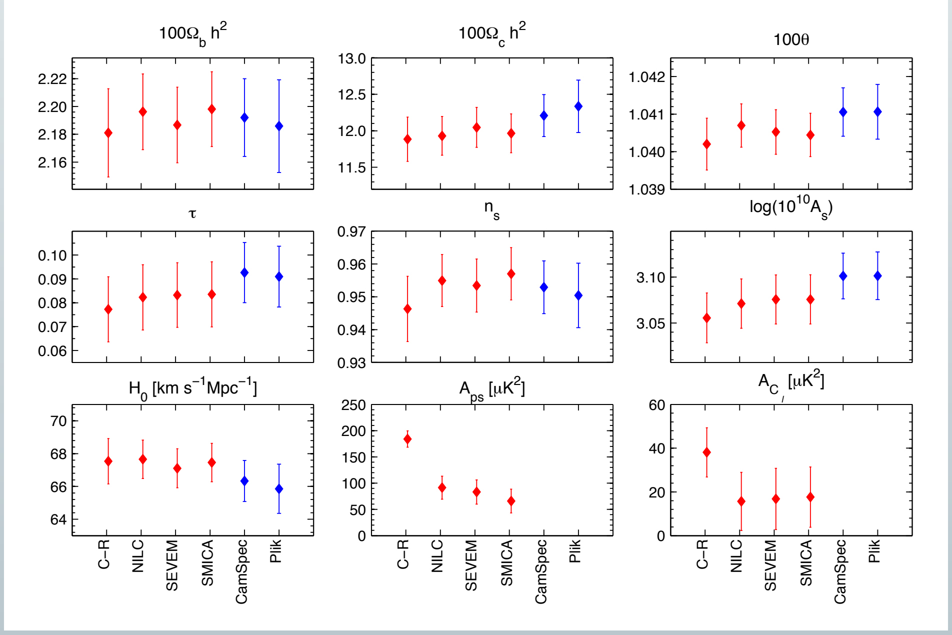




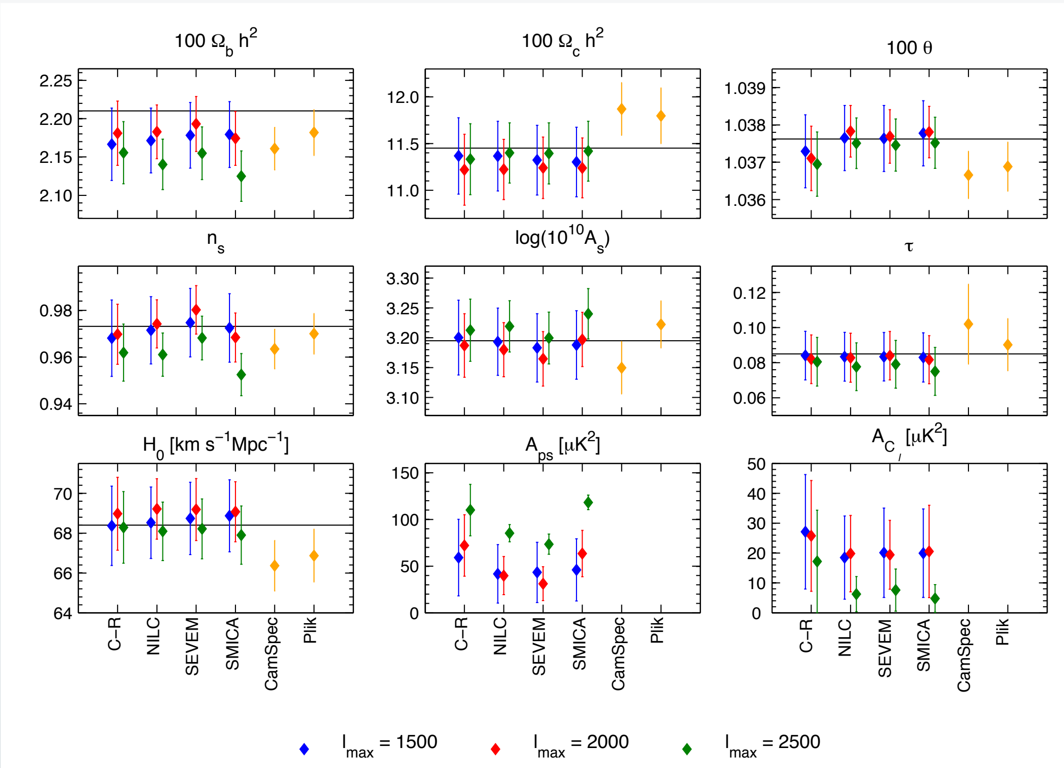
Planck baseline high-l Likelihood: validation spectra-based vs map-based

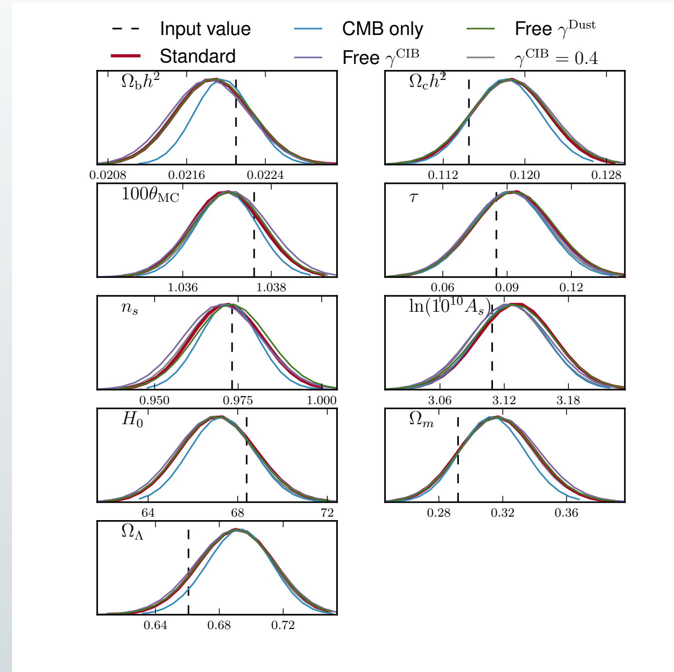


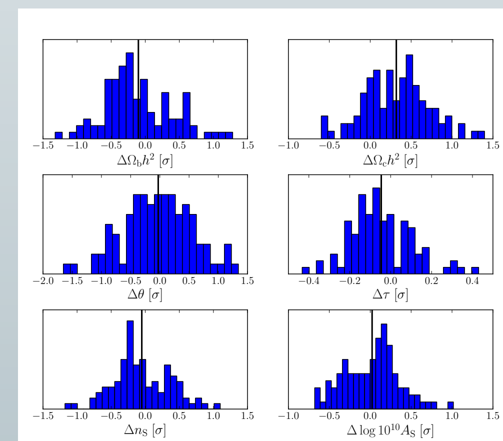




Validation of high-l Likelihood Simulations

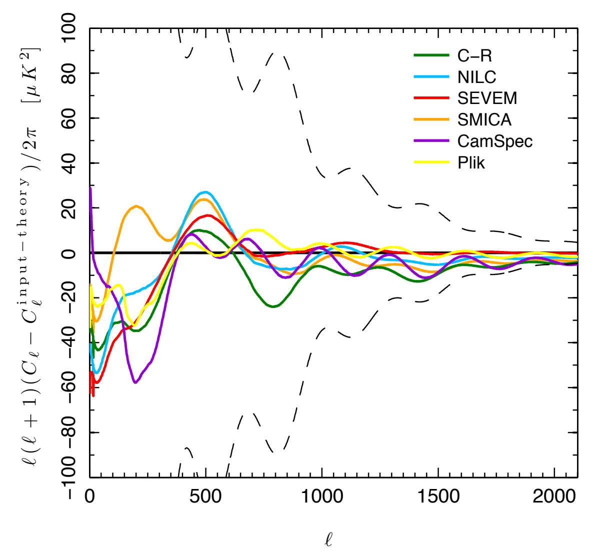


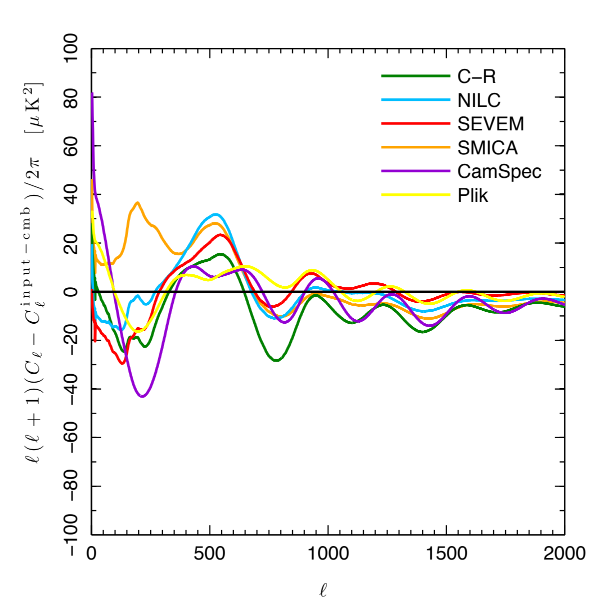




K_{pivot}=0.002
CamSpec: K_{pivot}=0.05

Validation of high-l Likelihood
FFP6 simulations





Best Fit models: CMB maps, multi-frequency, and inputs

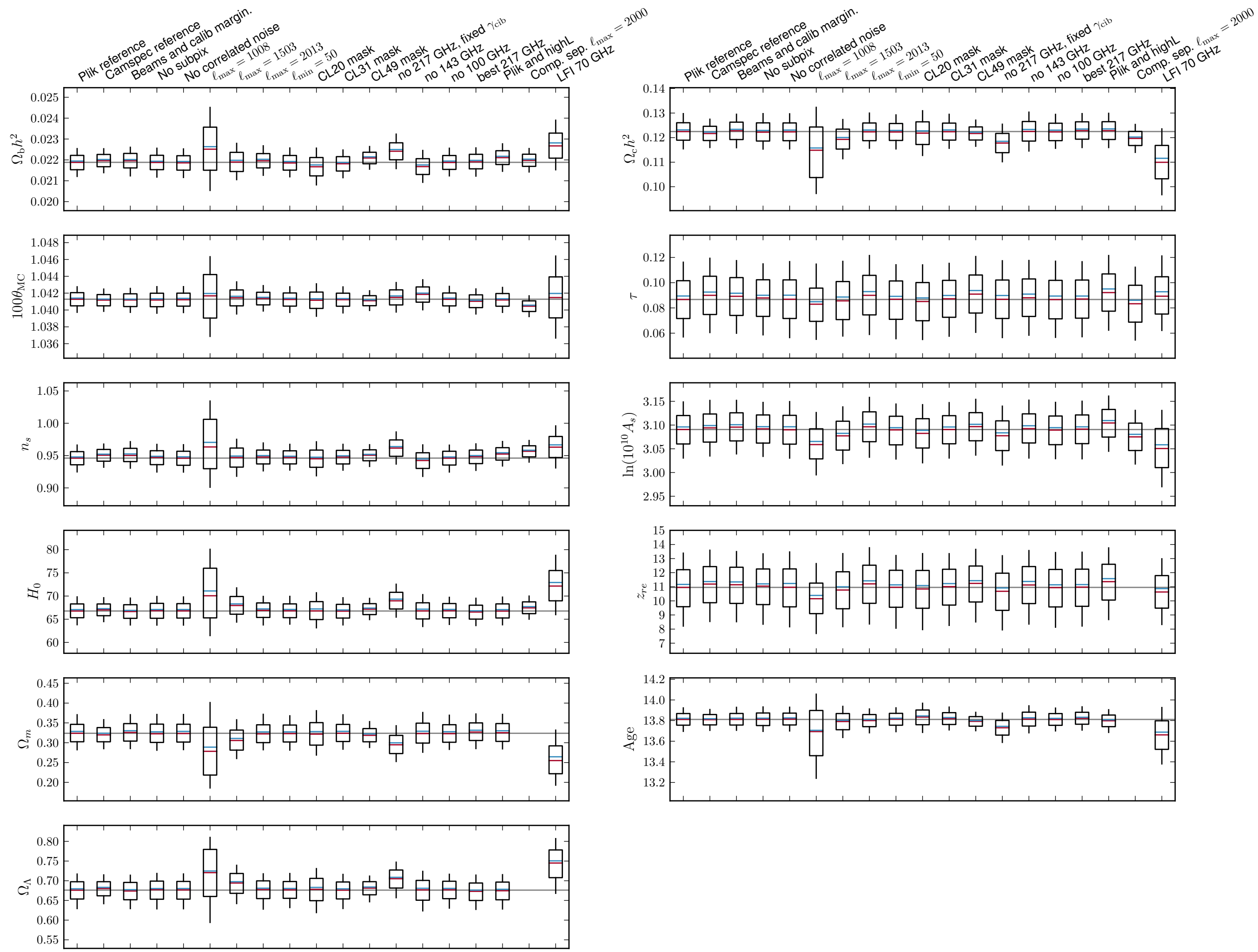
Residuals of map-based and spectrum-based best-fit models relative to the FFP6 simulation input CDM spectrum

Cosmic variance is shown as the black dashed line.

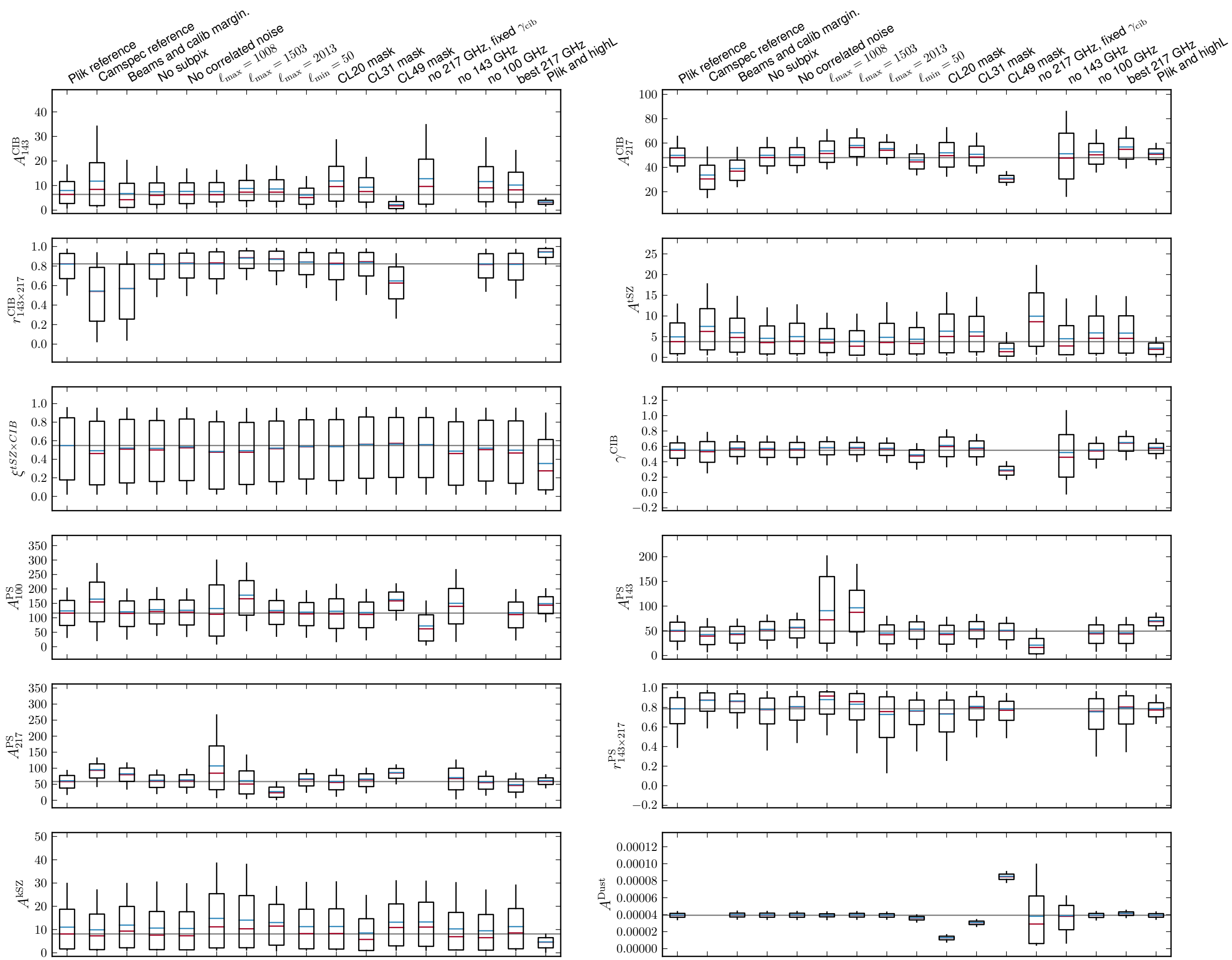
Residuals of CMB map based and spectrum-based best fit models relative to the best fit model of the CMB input realization

$\ell_{\max} = 2000$

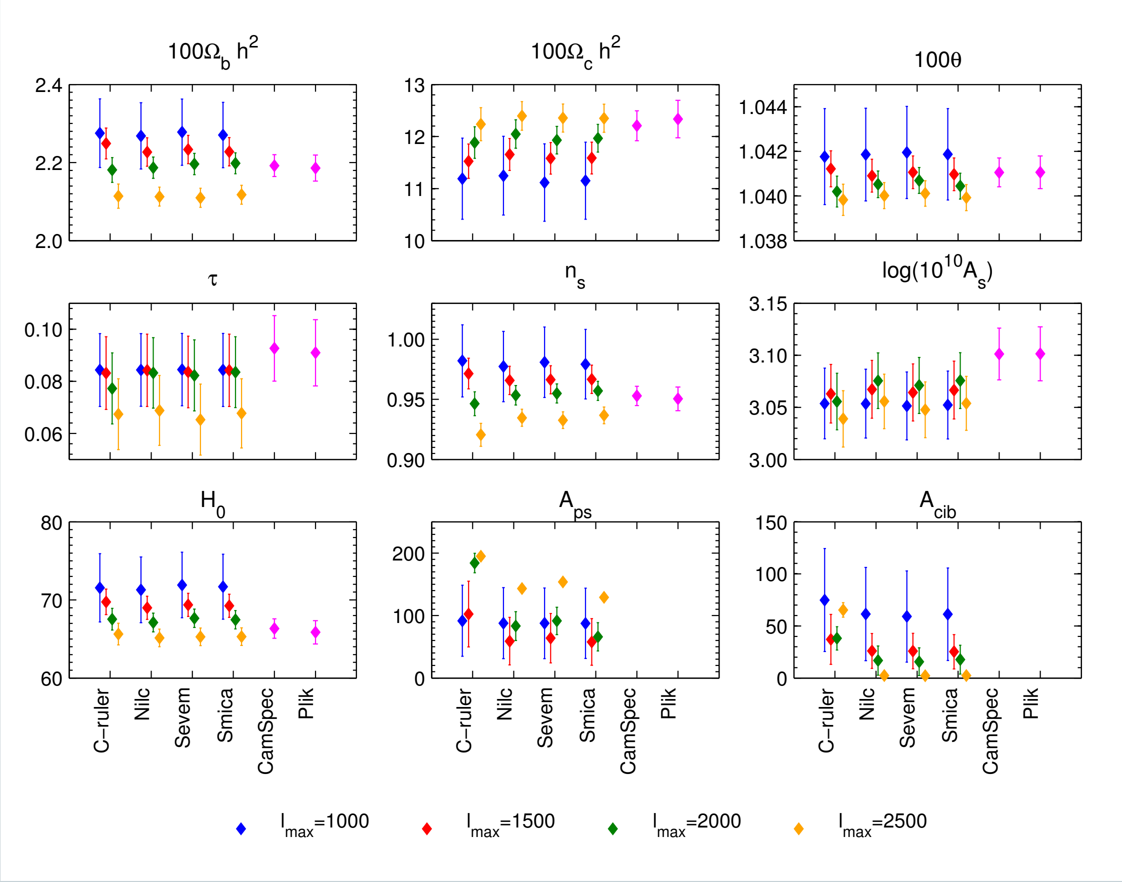
Validation test cases
Cosmological parameters



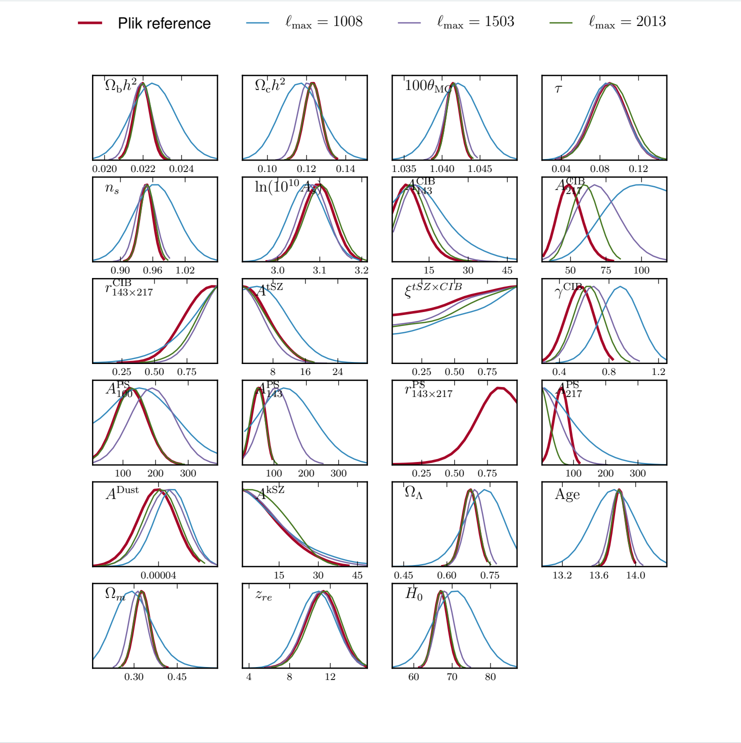
Validation test cases
FG model parameters



Validation test cases
Varying l_{max}

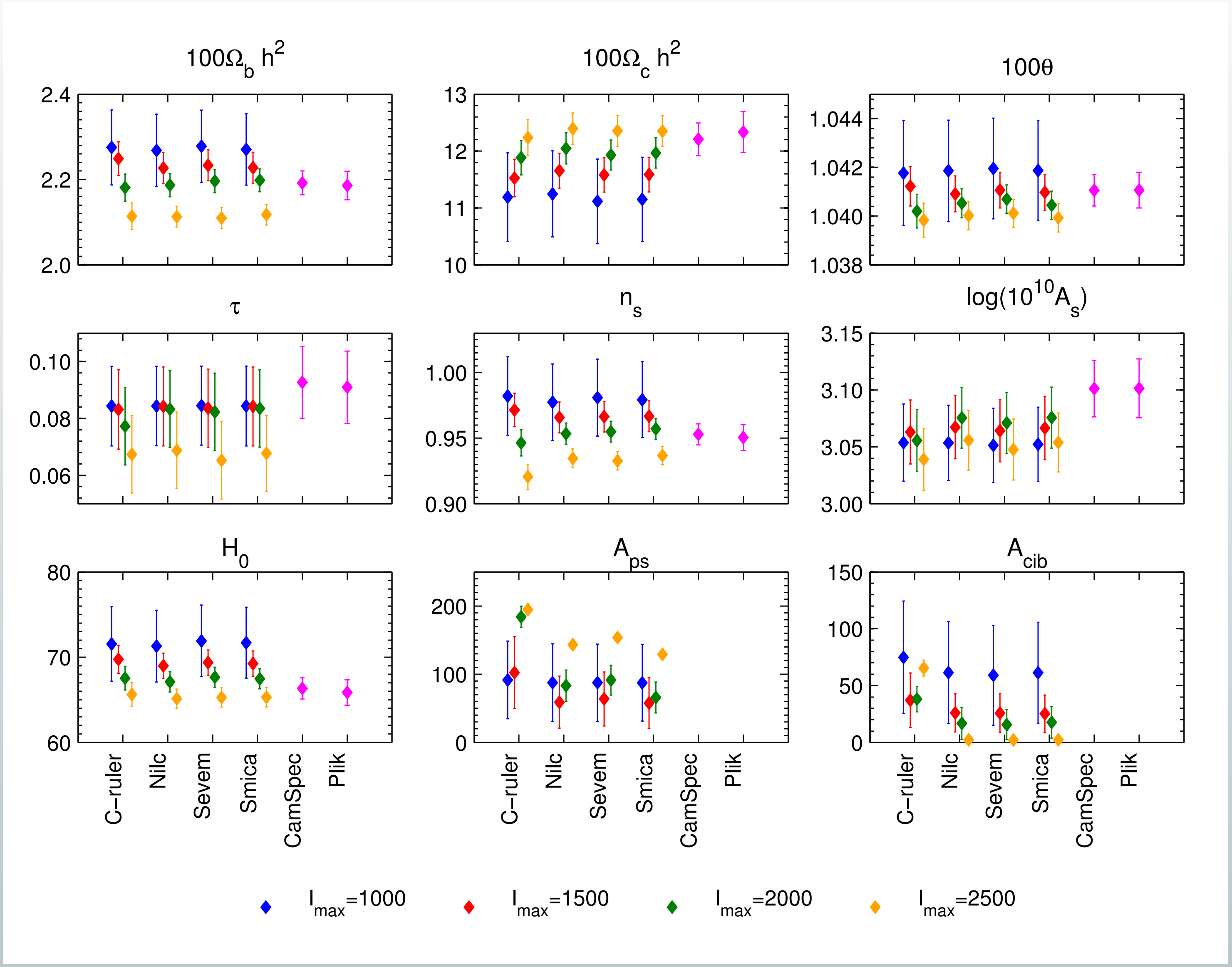


XFcmb



PLIK

Parameters from CMB maps



l_{max} ↑

H_0 ↓

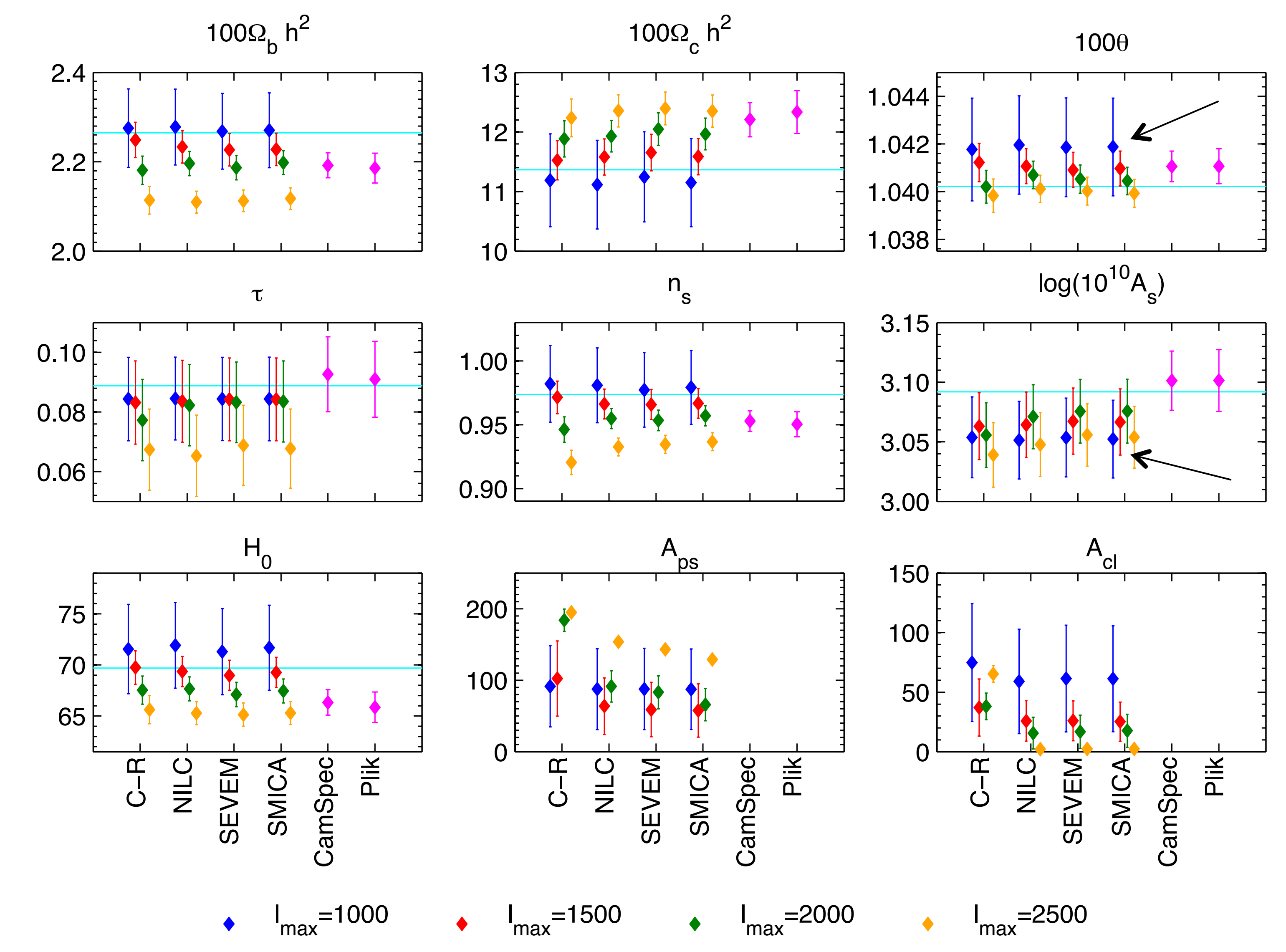
$\Omega_c h^2$ ↑

$\Omega_b h^2$ ↓

n_s ↓

Error bars ↓

Parameters from CMB maps



l_{max} ↑

H_0 ↓

$\Omega_c h^2$ ↑

$\Omega_b h^2$ ↓

n_s ↓

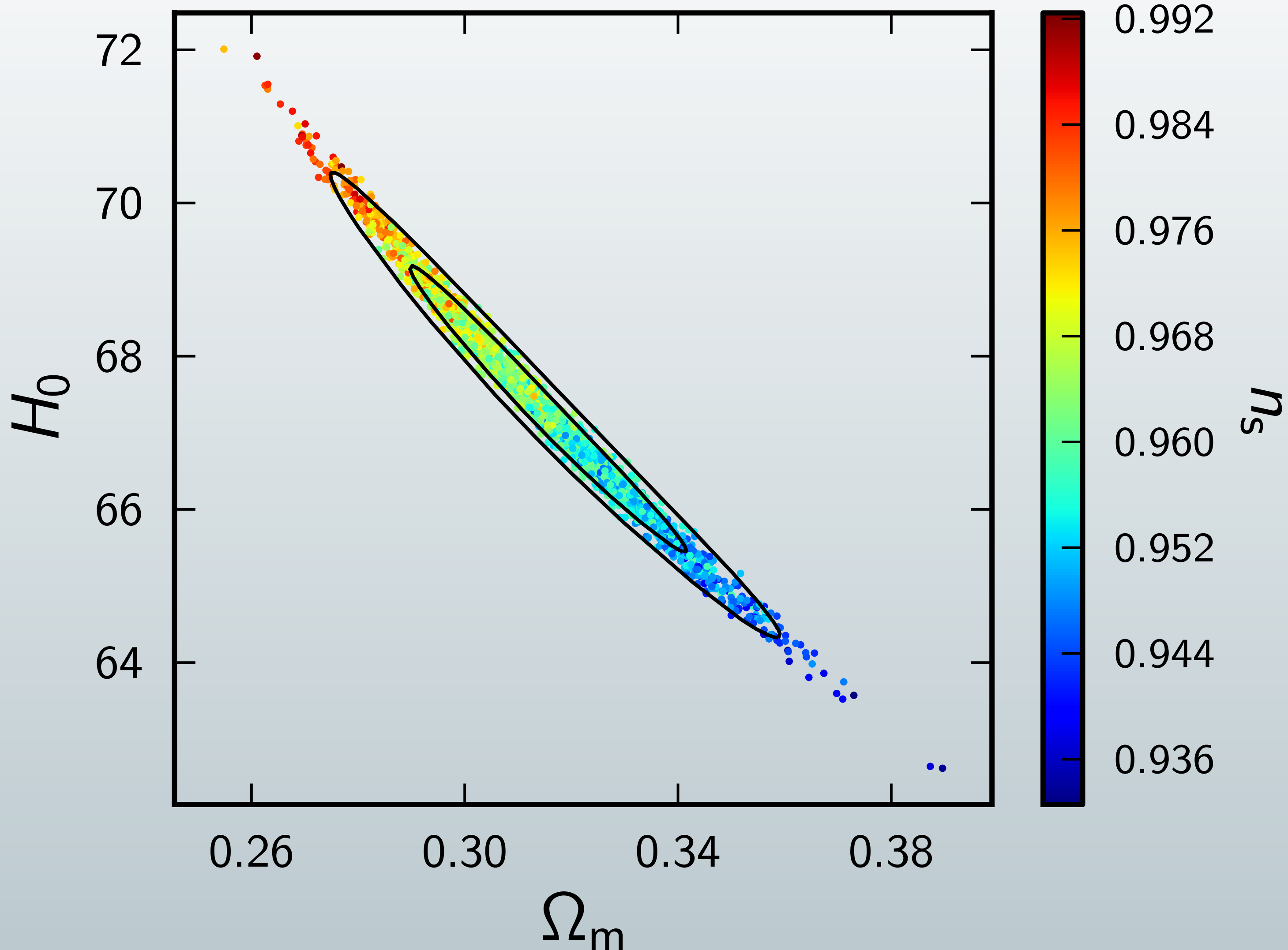
Error bars ↓

Validation test cases
Cosmological parameters

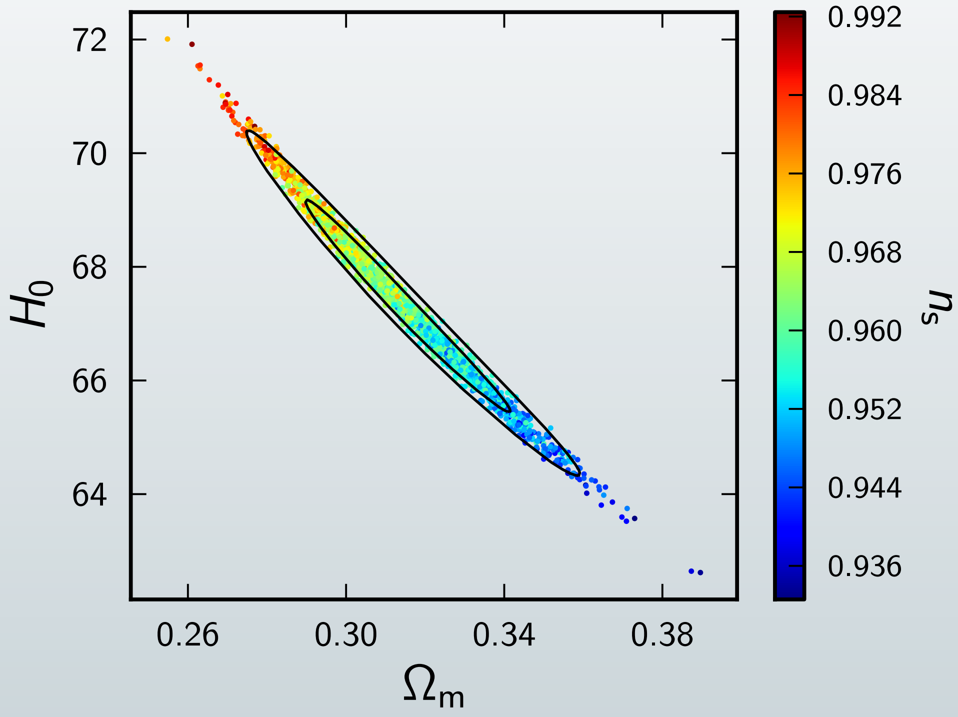
l_{max} ↑ H_0 ↓ Ω_m ↑ n_s ↓

Ω_Λ ↓

Parameters from CMB maps



ΛCDM model parameters



- 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

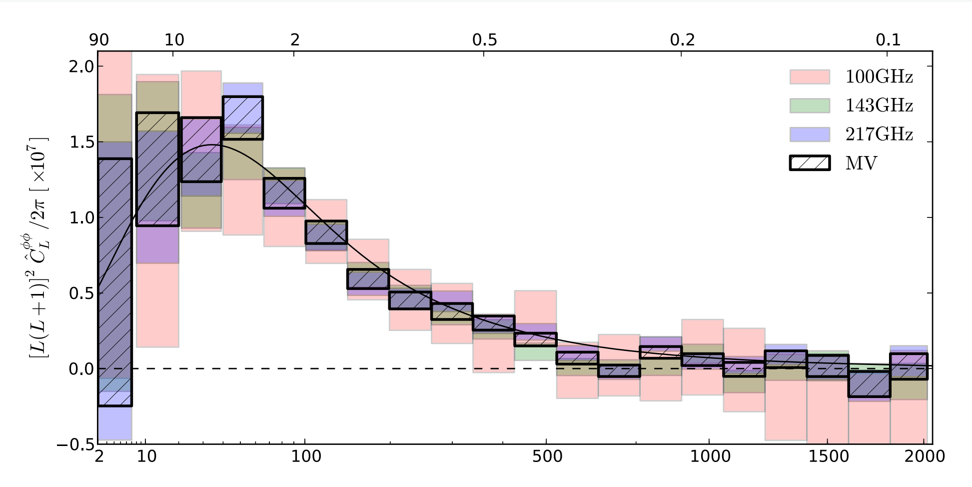
- parameter combinations can be constrained as well – 3d Ω_m- h - $\Omega_b h^2$, PCA -> ~ $\Omega_m h^3$

- 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

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

ΛCDM model parameters



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)

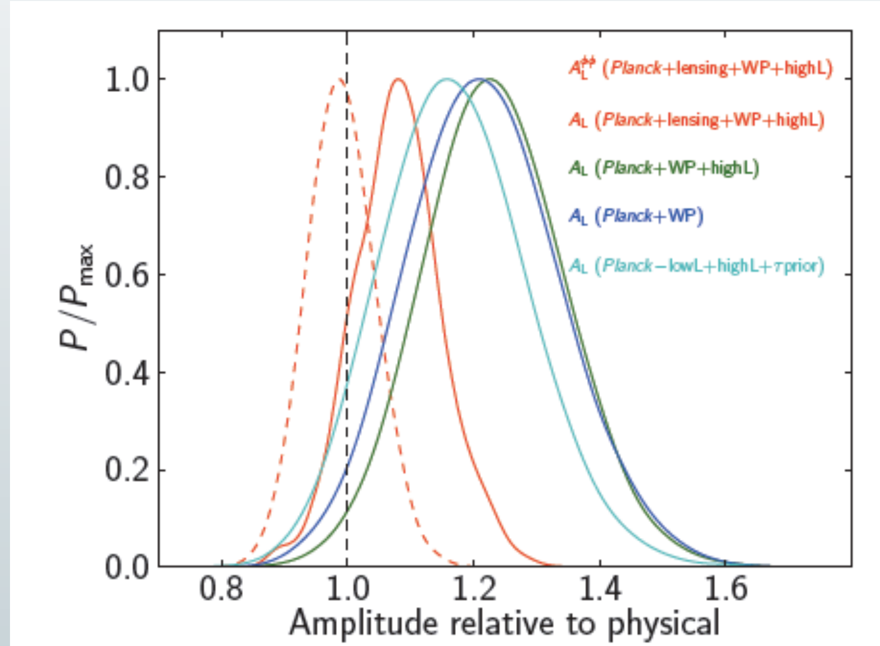
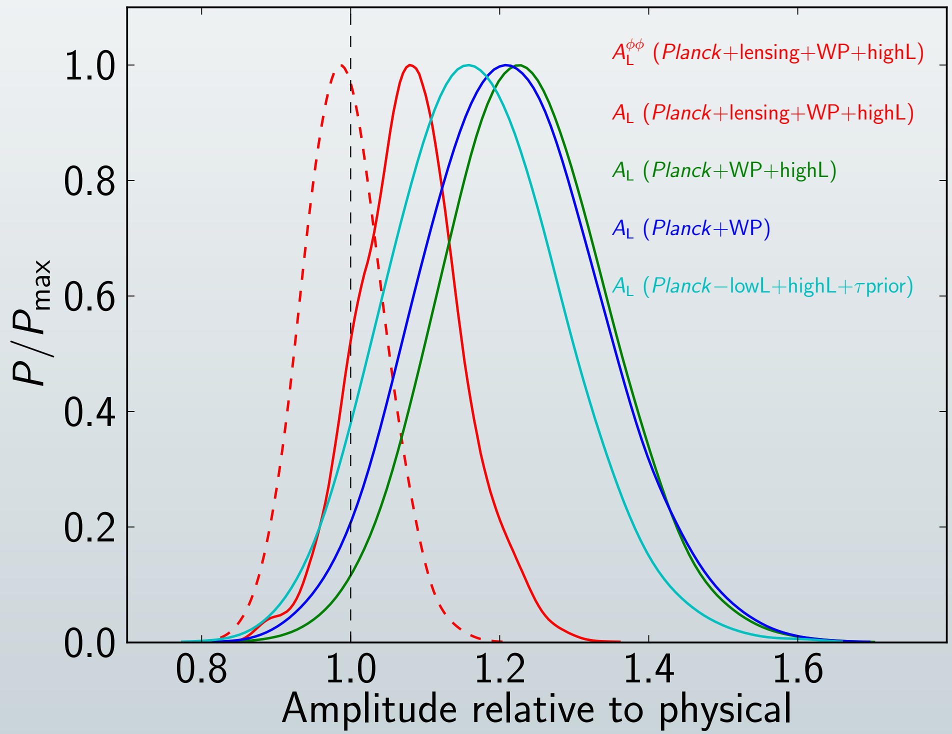
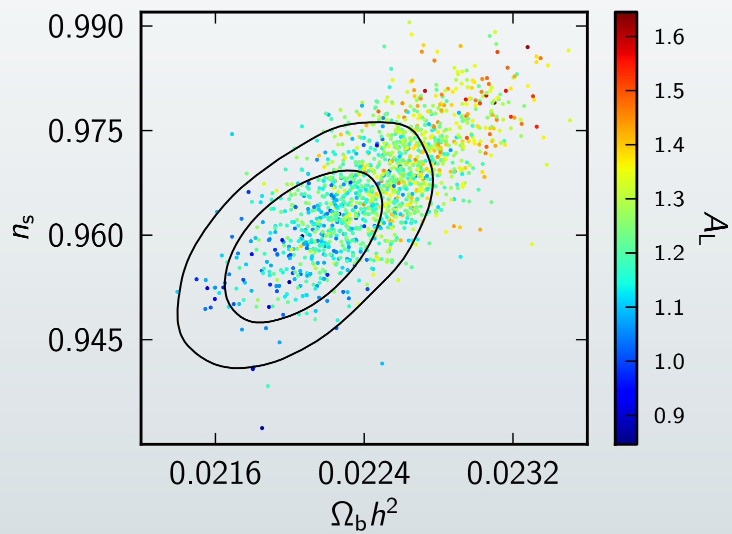


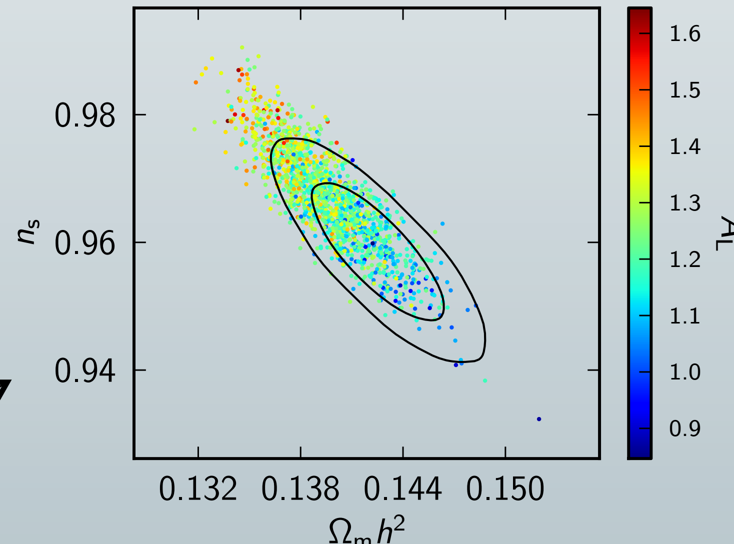
Fig. 13. Marginalized posterior distributions for $A_L^{\phi\phi}$ (dashed) and A_L (solid). For $A_L^{\phi\phi}$ we use the data combination *Planck*+lensing+WP+highL. For A_L we consider *Planck*+lensing+WP+highL (red), *Planck*+WP+highL (green), *Planck*+WP (blue) and *Planck*−lowL+highL+τprior (cyan; see text).

ΛCDM model parameters





$A_L > 1$



Parameter degeneracies

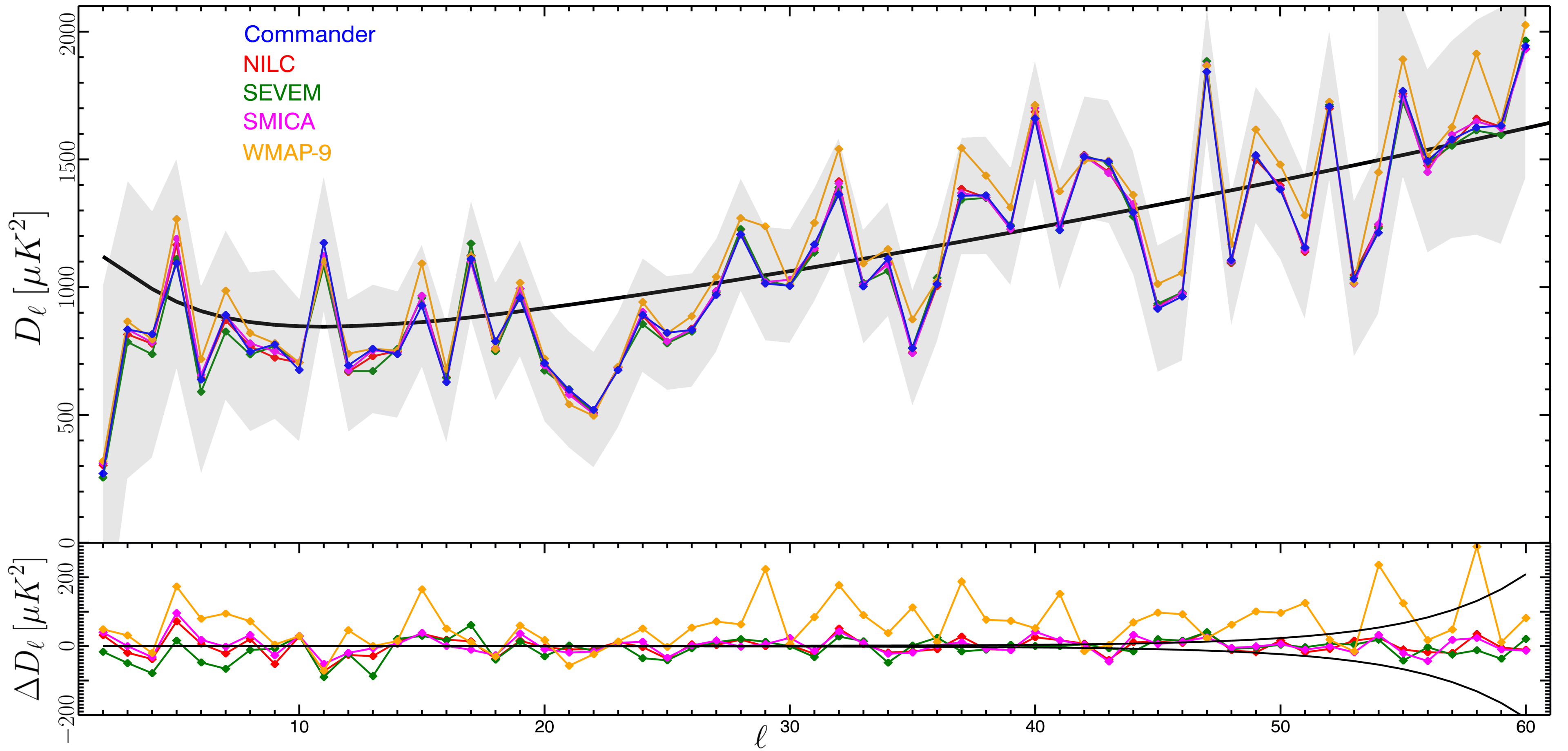
Planck baseline low-l Likelihood: Commander Set-up

Separate the Temperature and Polarization parts of the Likelihood

- Low-l Temperature Likelihood:
  - Consider frequencies between 30GHz to 353GHz
  - Each frequency map is downgraded to a common resolution of 40' , and projected onto an N_{side} = 256 HEALPix grid
  - Uncorrelated Gaussian regularization noise is added to each frequency map, (with an RMS proportional to the spatial mean of the instrumental noise of the corresponding channel, $<\sigma_v>$, conserving relative signal-to-noise between channels. The resulting signal-to-noise is unity at l= 400, and the additional uncertainty due to the regularization noise is less than 0.2 μK^2 below l= 50,and less than 1μK^2 below l= 100)
  - Mask: 87.5% sky coverage (mask B)

- Low-l Polarization Likelihood:
  - 9-year WMAP polarisation likelihood derived from the WMAP polarisation maps at 33, 41, and 61 GHz (Ka, Q, and V bands)
  - Introduce one modification to this pixel-based likelihood code - replace a^T_{lm} with those derived from the Planck temperature map derived by Commander, for which the Galactic plane has been replaced with a Gaussian constrained realization

Planck baseline low-l Likelihood: validation CMB maps



Top: Temperature power spectra estimated with Commander , NILC , SEVEM , or SMICA , and the 9-year WMAP ILC map, using the **Bolpol** quadratic estimator; Grey band - 1σ Fisher errors. Solid line is Planck best-fit ΛCDM model.

Bottom: Differences w.r.t. Commander . Black lines - expected 1σ uncertainty due to (regularization)noise

Planck Likelihood
Hybridization of low-l and high-l Like

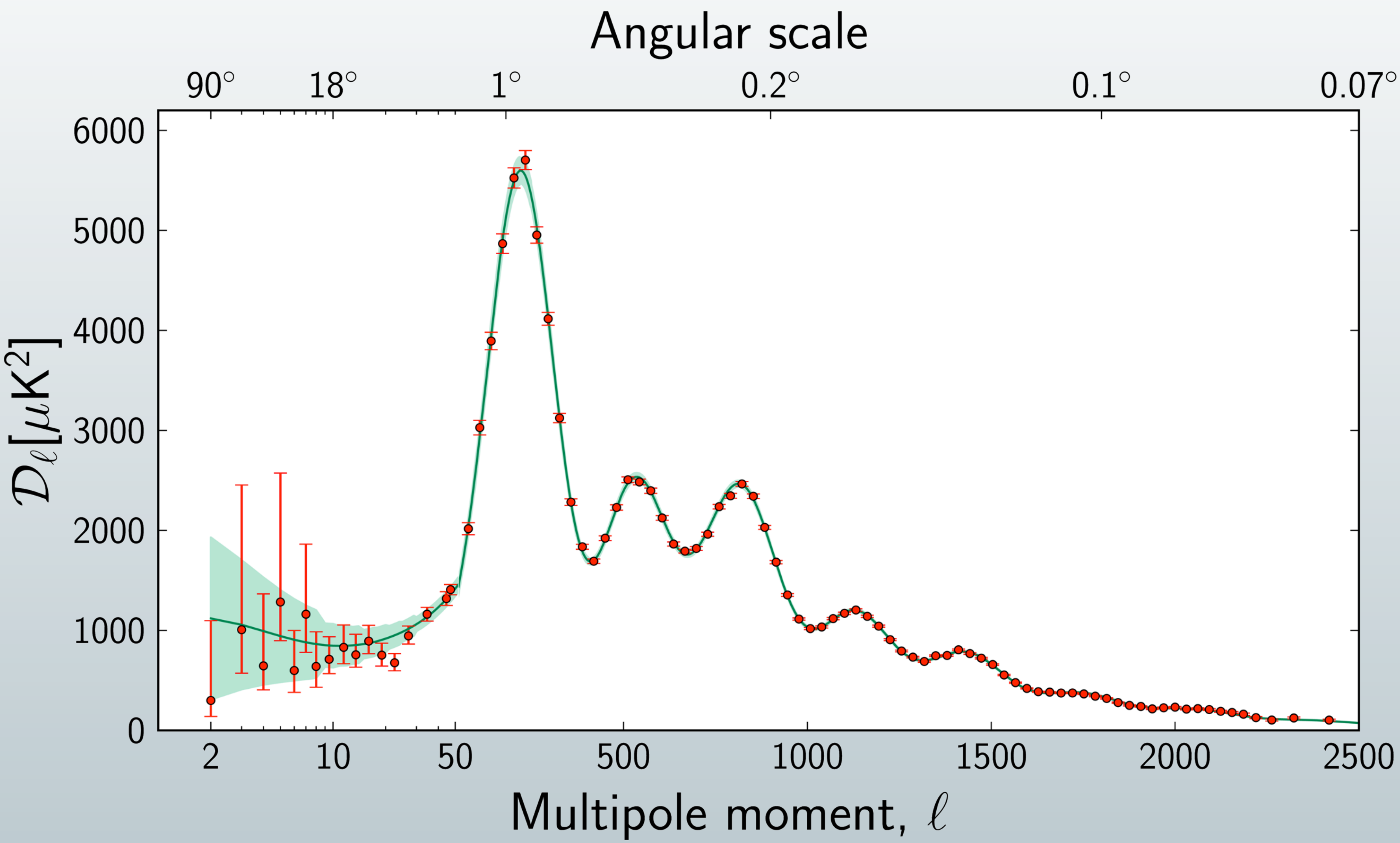
l_{trans}=50 -> a compromise between obtaining robust convergence properties for the low-l likelihood, and ensuring that the Gaussian approximation holds for the high-l likelihood

To combine the likelihoods, we must account for the weak correlations between the low-l and high-l components, 3 options:

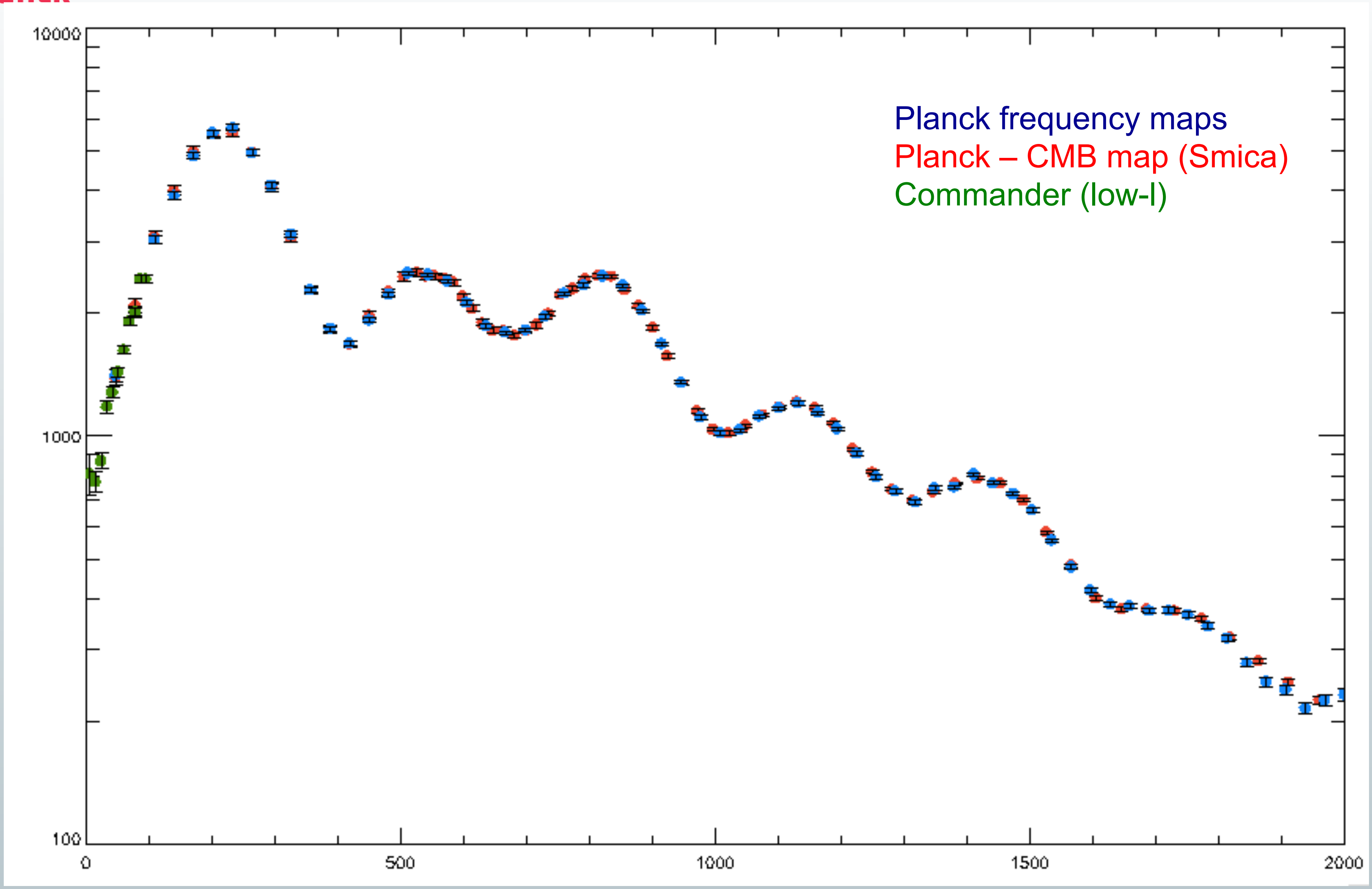
1. Sharp transition: low-l l_{max}=39; high-l l_{min}=50
2. Gap: low-l l_{max}=32; high-l l_{min}=50
3. Ovelap with correction: low-l l_{max}=70; high-l l_{min}=50; the double counting of the overlap region is accounted for by subtracting from the log-likelihood a contribution only including 50 ≤l≤ 70 as evaluated by the Commander estimator

- Posterior means of cosmological parameters vary by 0.1σ (mostly from case2); case 1 and 3 are indistinguishable – we adopt a Sharp transition

CMB angular power spectrum from Planck measurement vs models

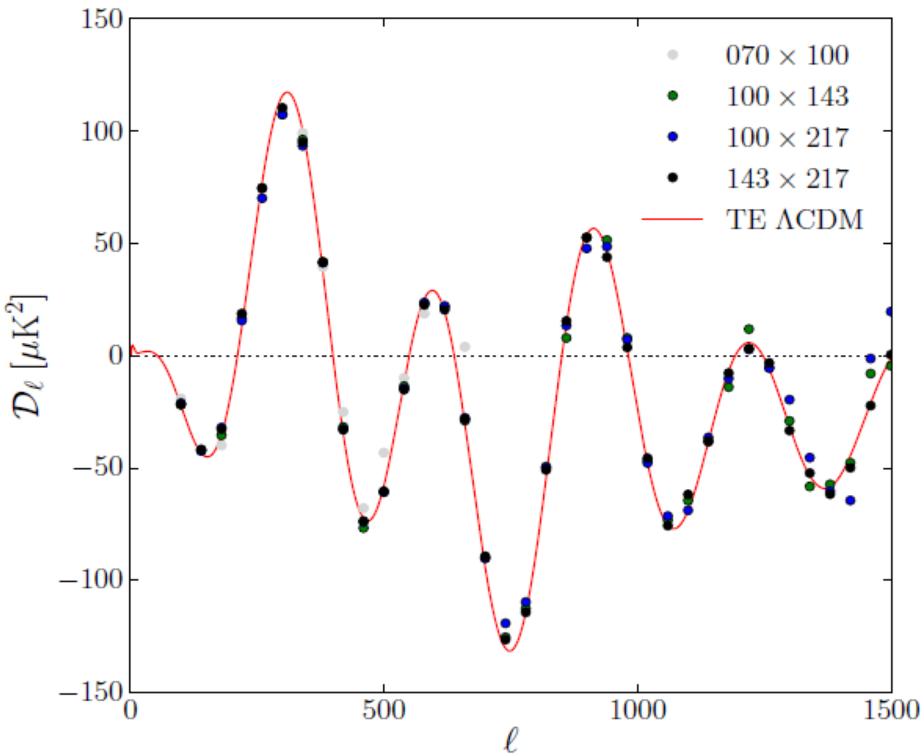


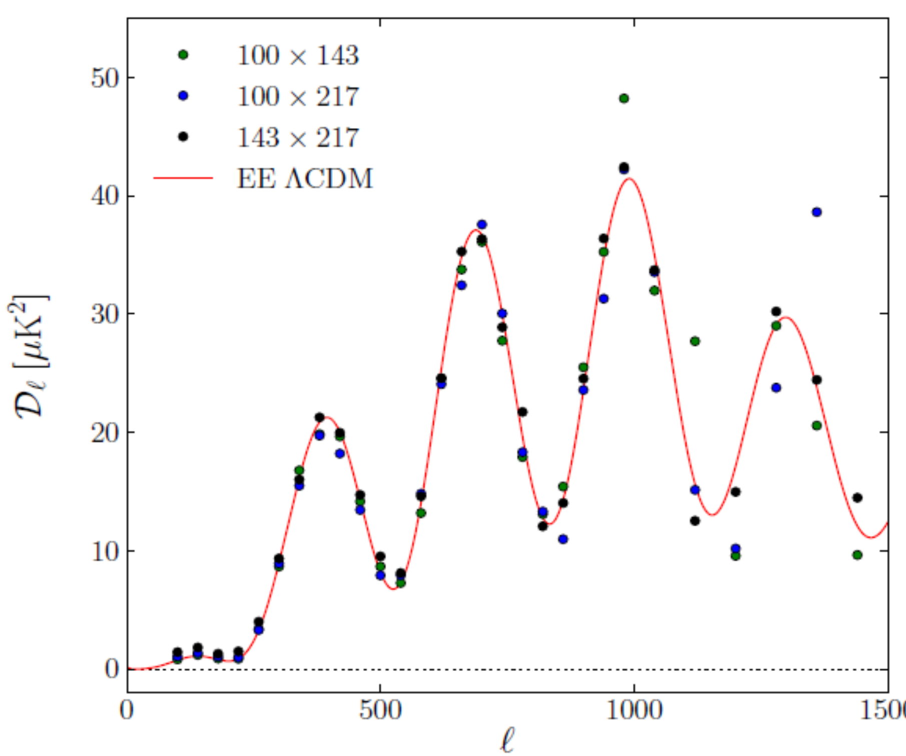
Planck Power Spectrum



Polarization

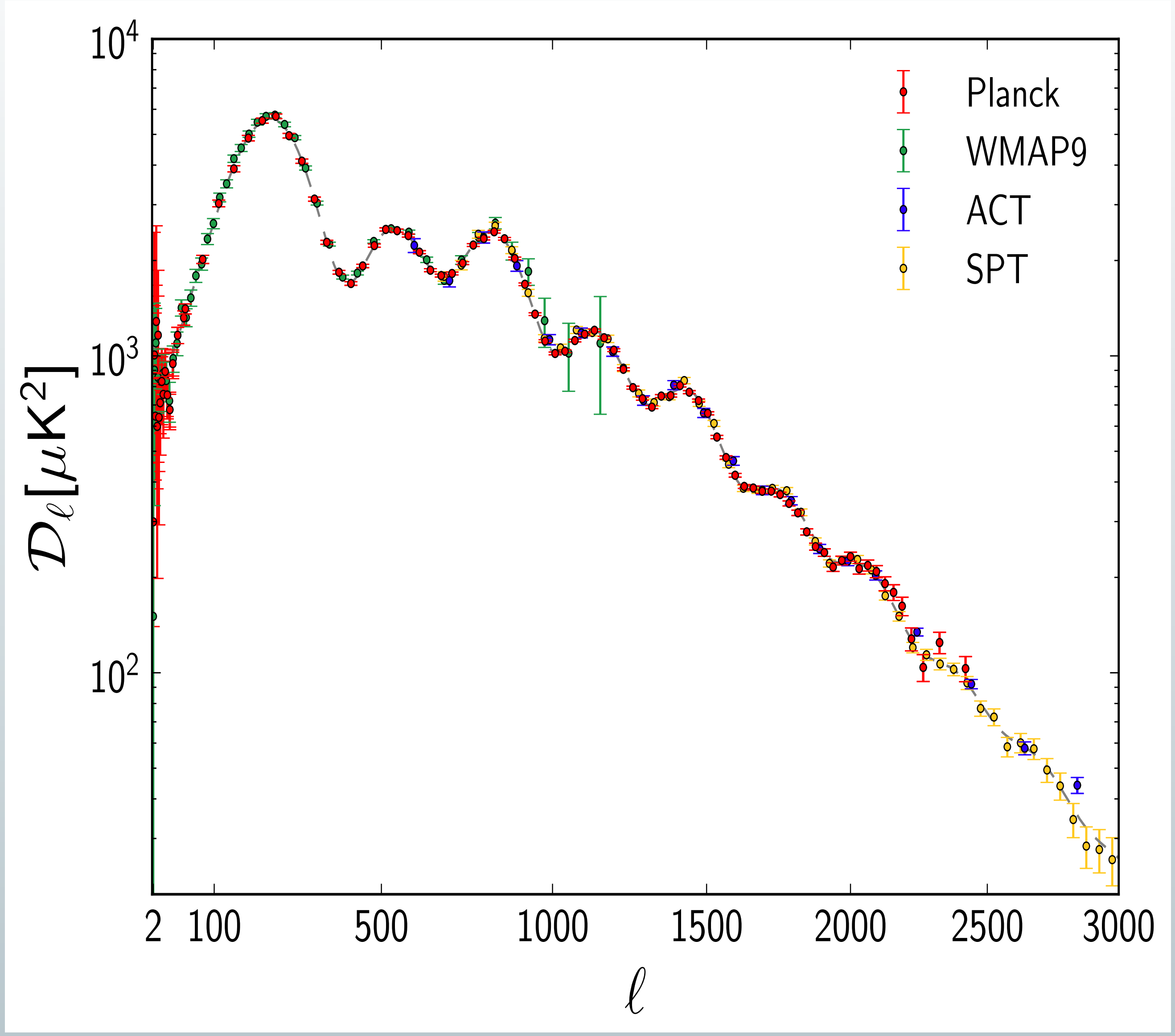
TE and EE Power Spectra (preliminary!) - red line is not a fit to the polarized spectra – it is the TT best fit model



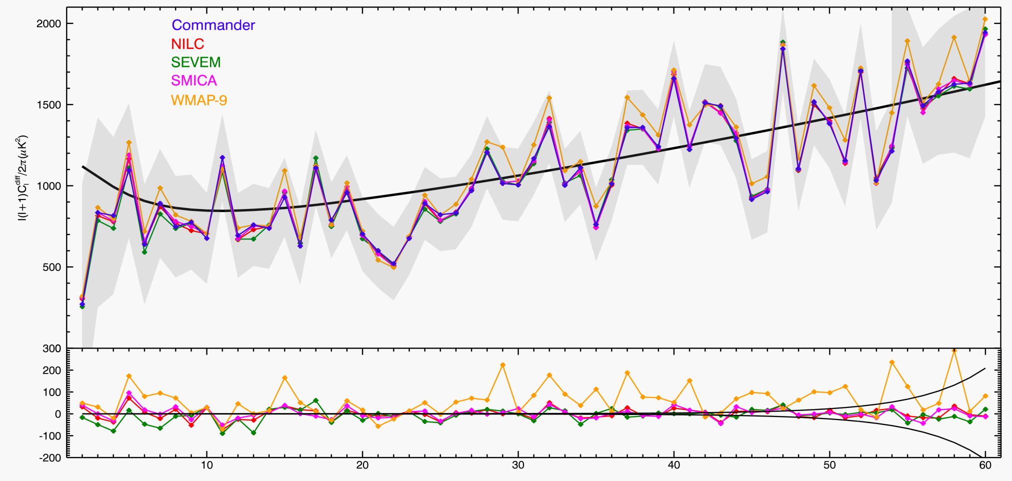


Excellent quality of the data
Foregounds and systematics are not dominant

CMB angular power spectrum
Planck, WMAP9, SPT,ACT



What Have We Learned ?
"Tensions" WMAP



Low-l

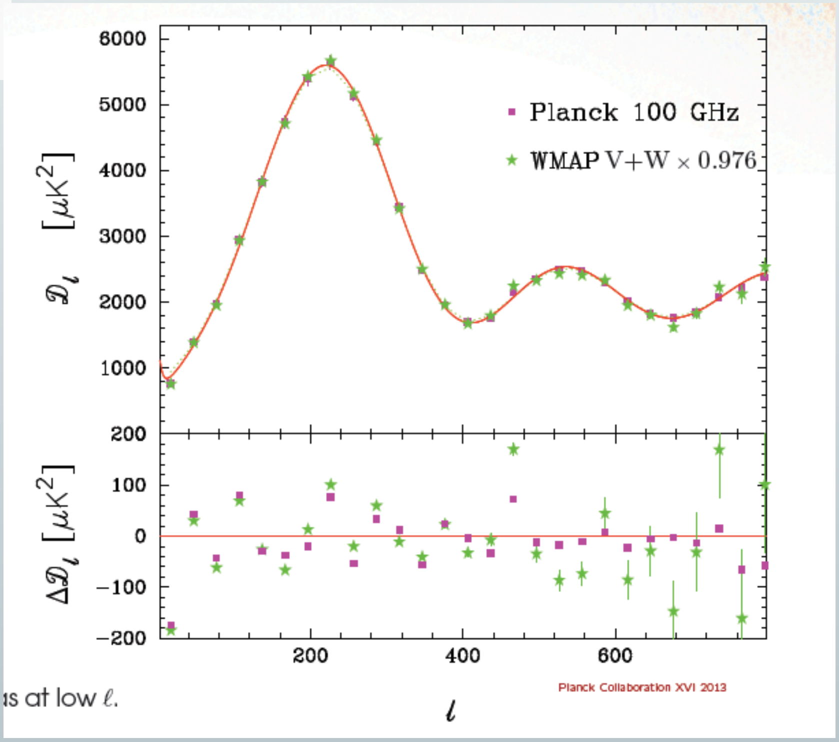
WMAP is consistently higher than Planck by about 2.5%

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

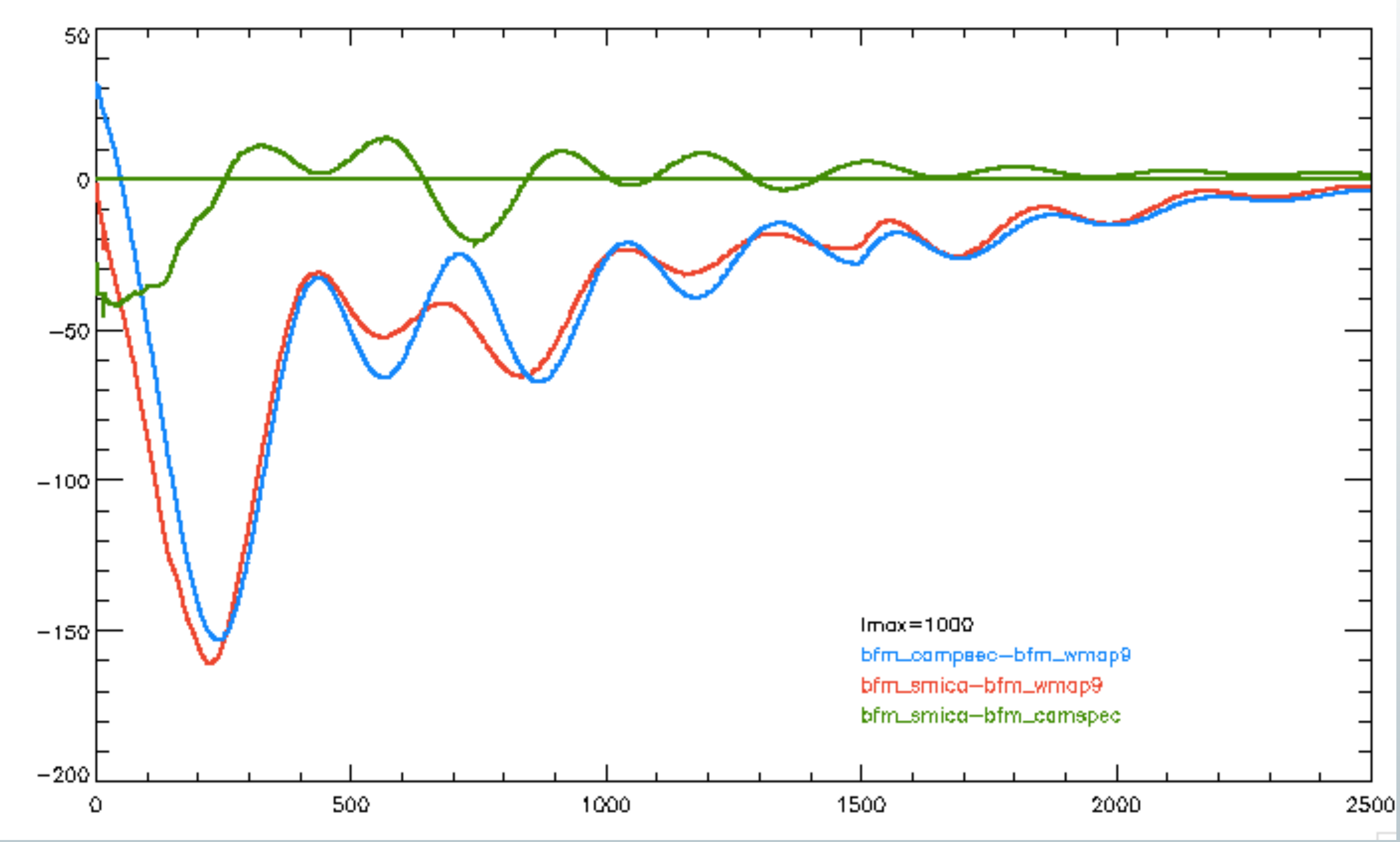
- Planck 100x100GHz spectrum
- WMAP9 V+W spectrum scaled by 0.976.
- Red line is the best-fit Planck+WP + highL ΛCDM model.

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

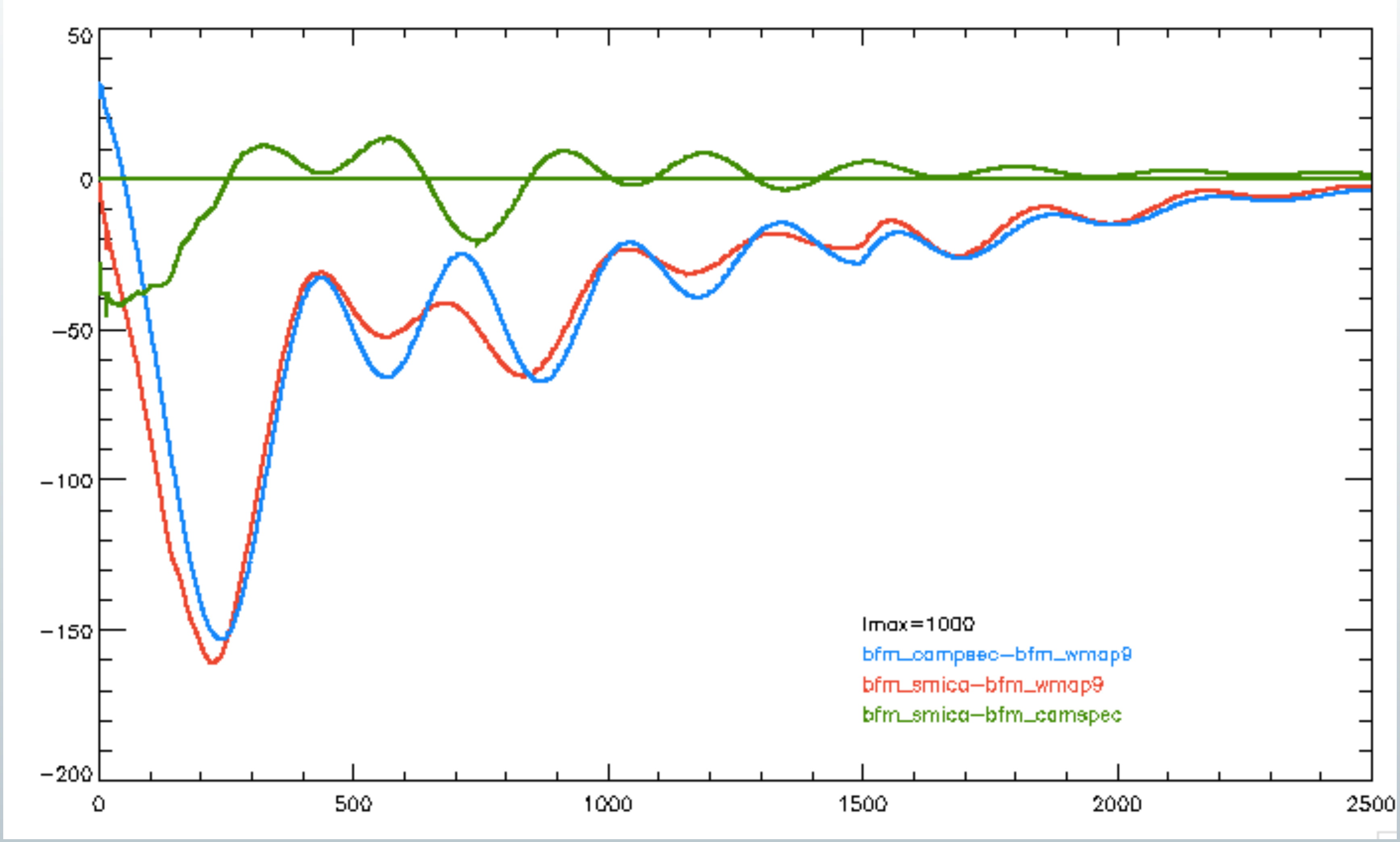
High-l



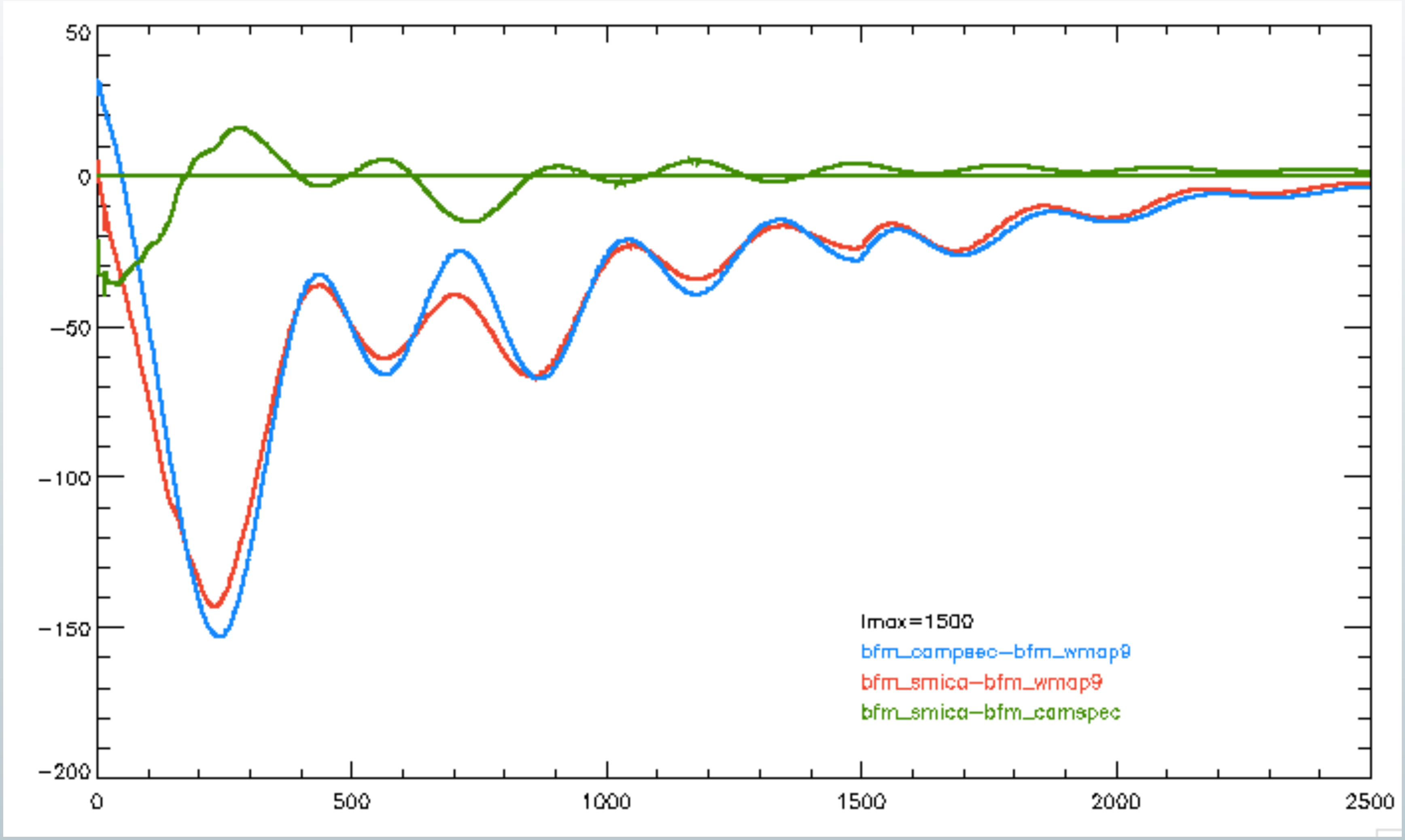
Planck vs WMAP9
lmax=1000



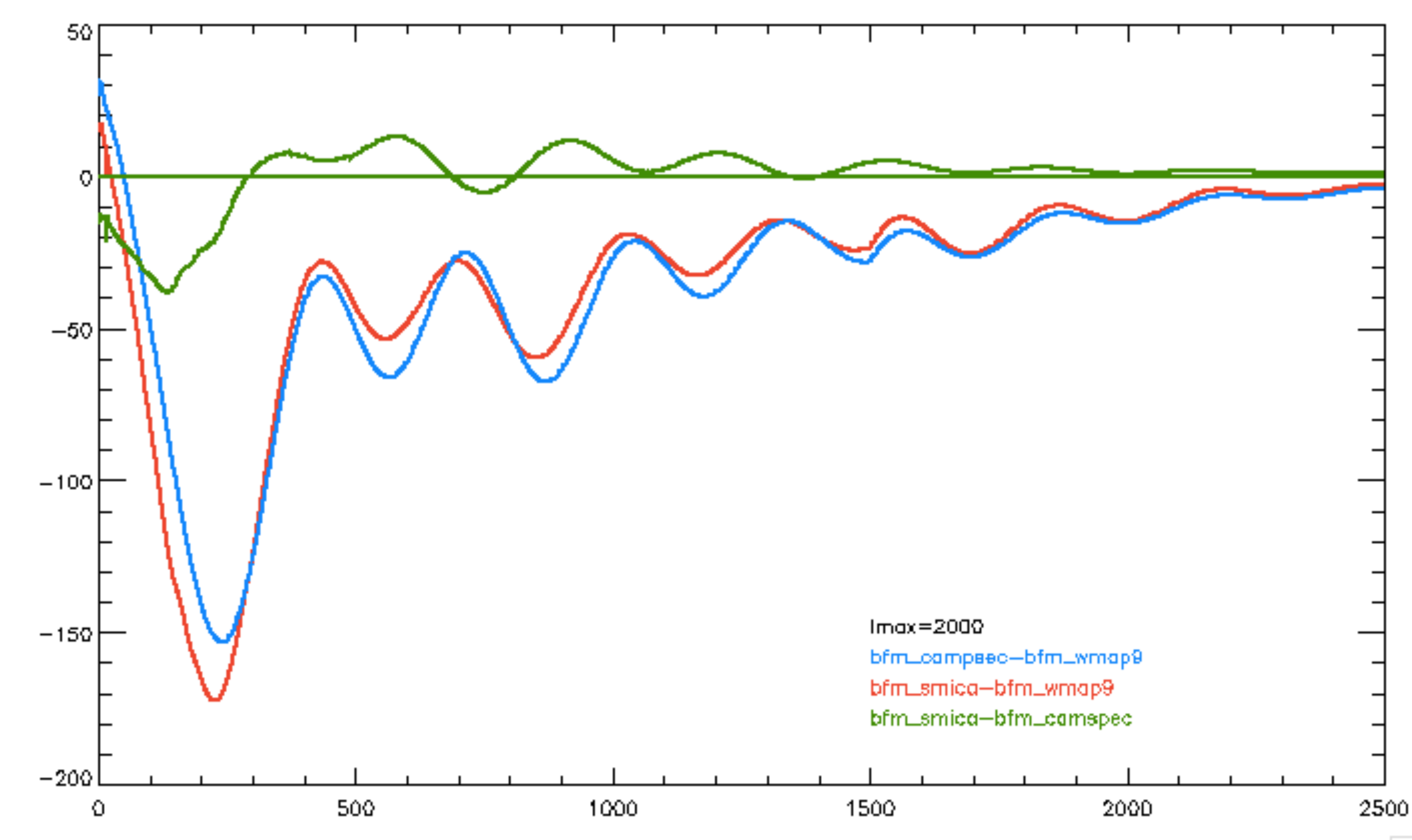
Planck vs WMAP9
lmax=1000



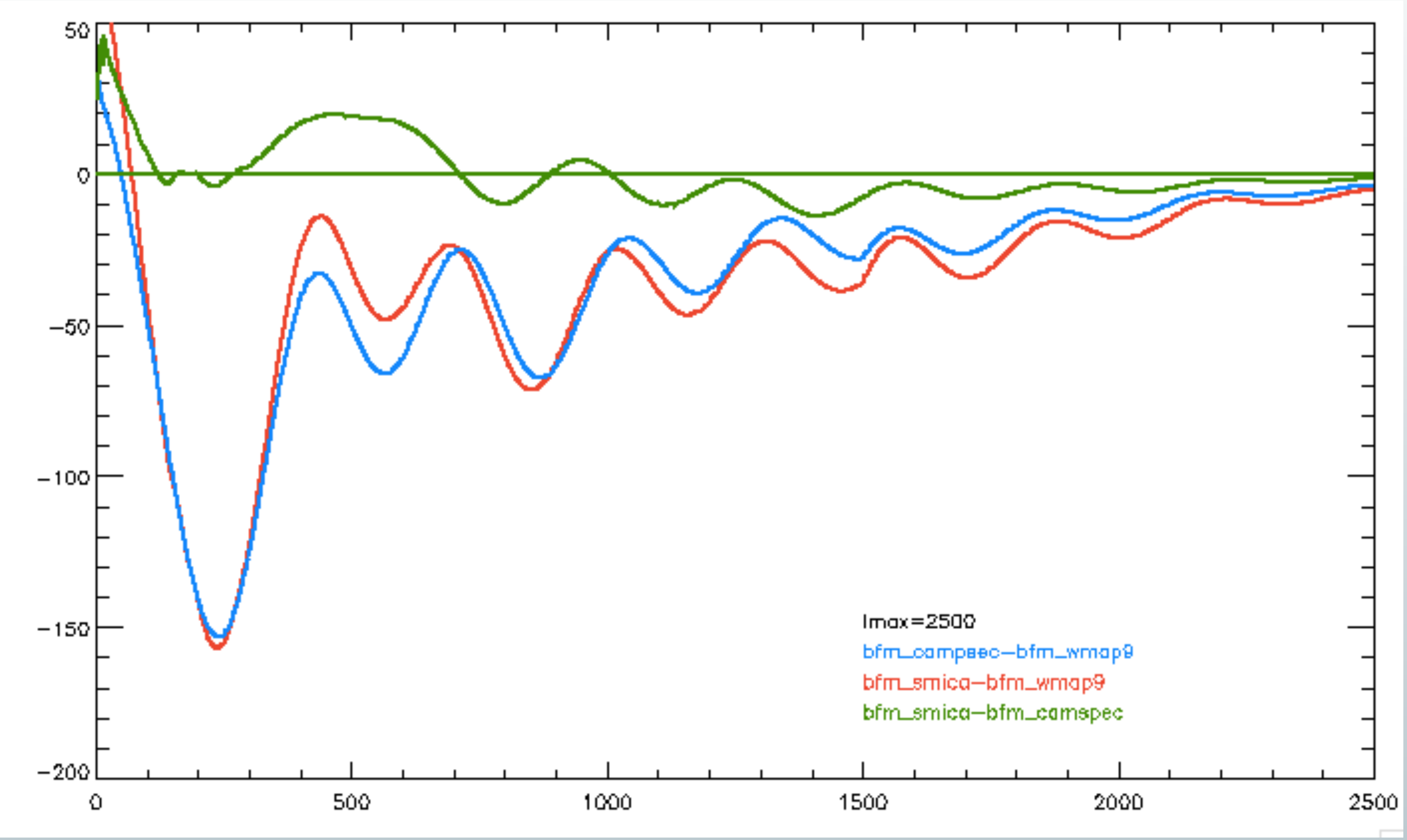
Planck vs WMAP9
lmax=1500



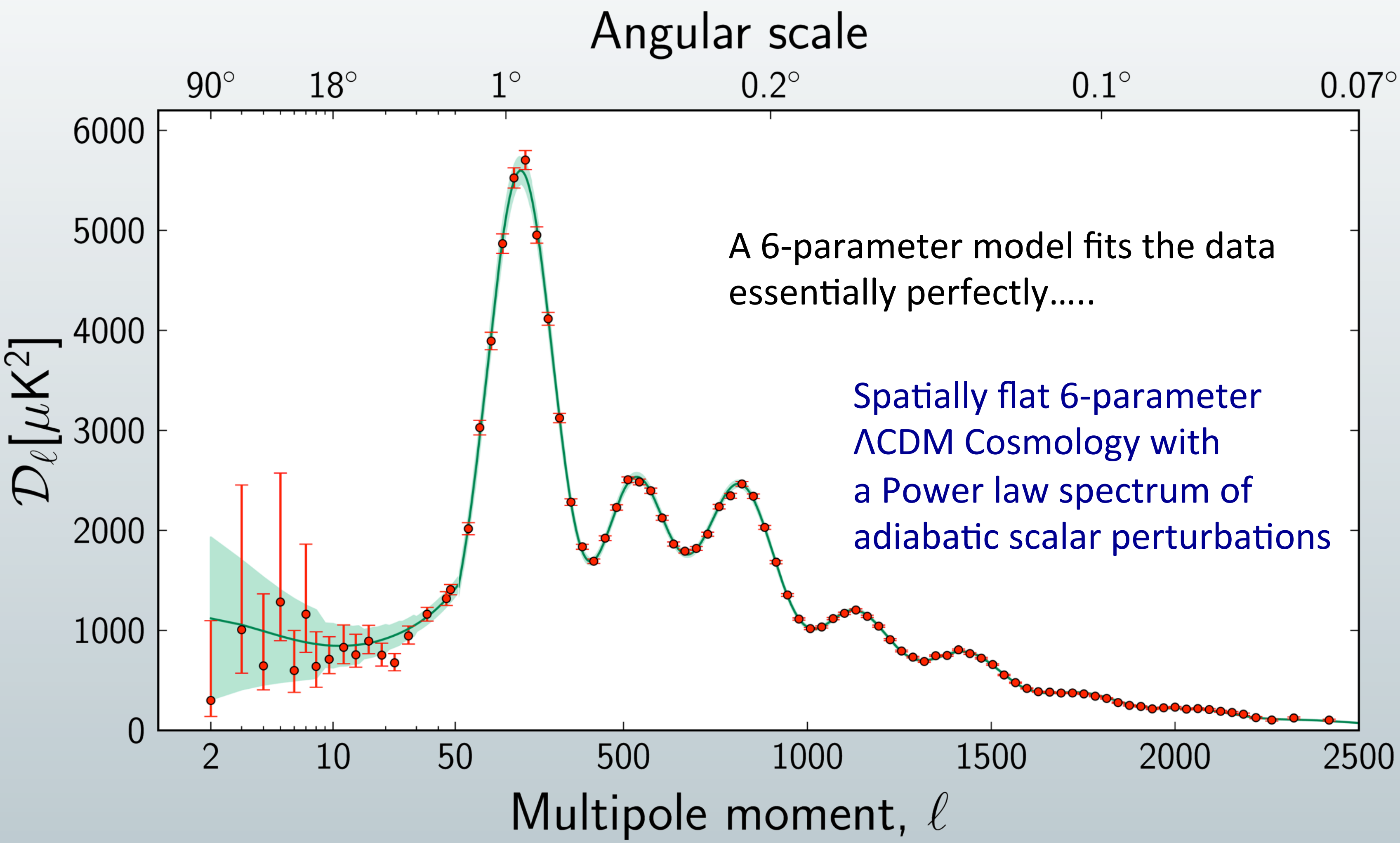
Planck vs WMAP9
lmax=2000



Planck vs WMAP9
lmax=2500



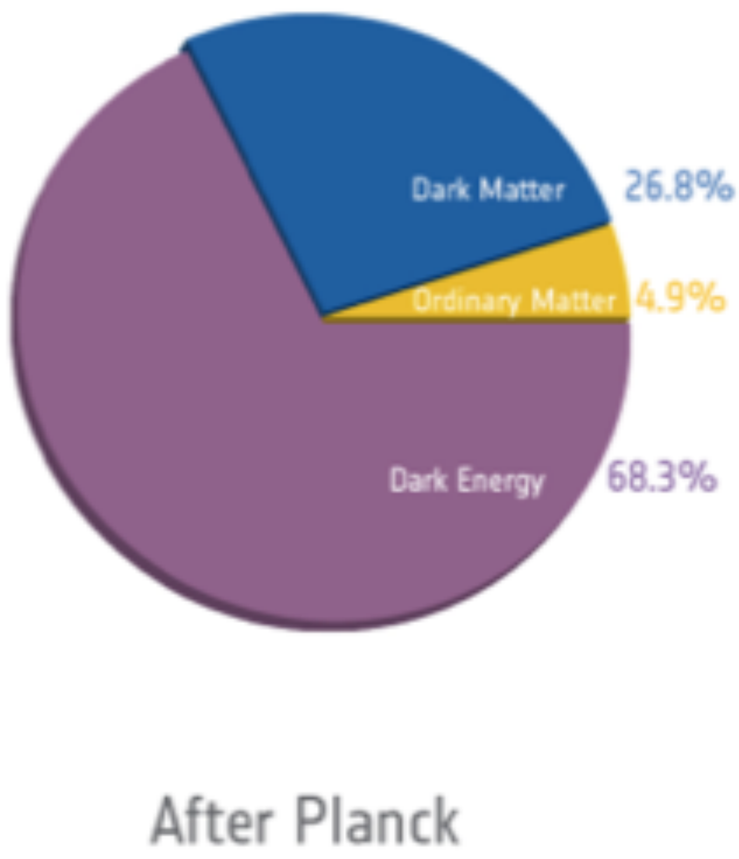
CMB angular power spectrum from Planck measurement vs models



ΛCDM model parameters from Planck

The Universe

Has more matter and less dark energy



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

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

$$n_s = 0.9603 \pm 0.0073$$

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

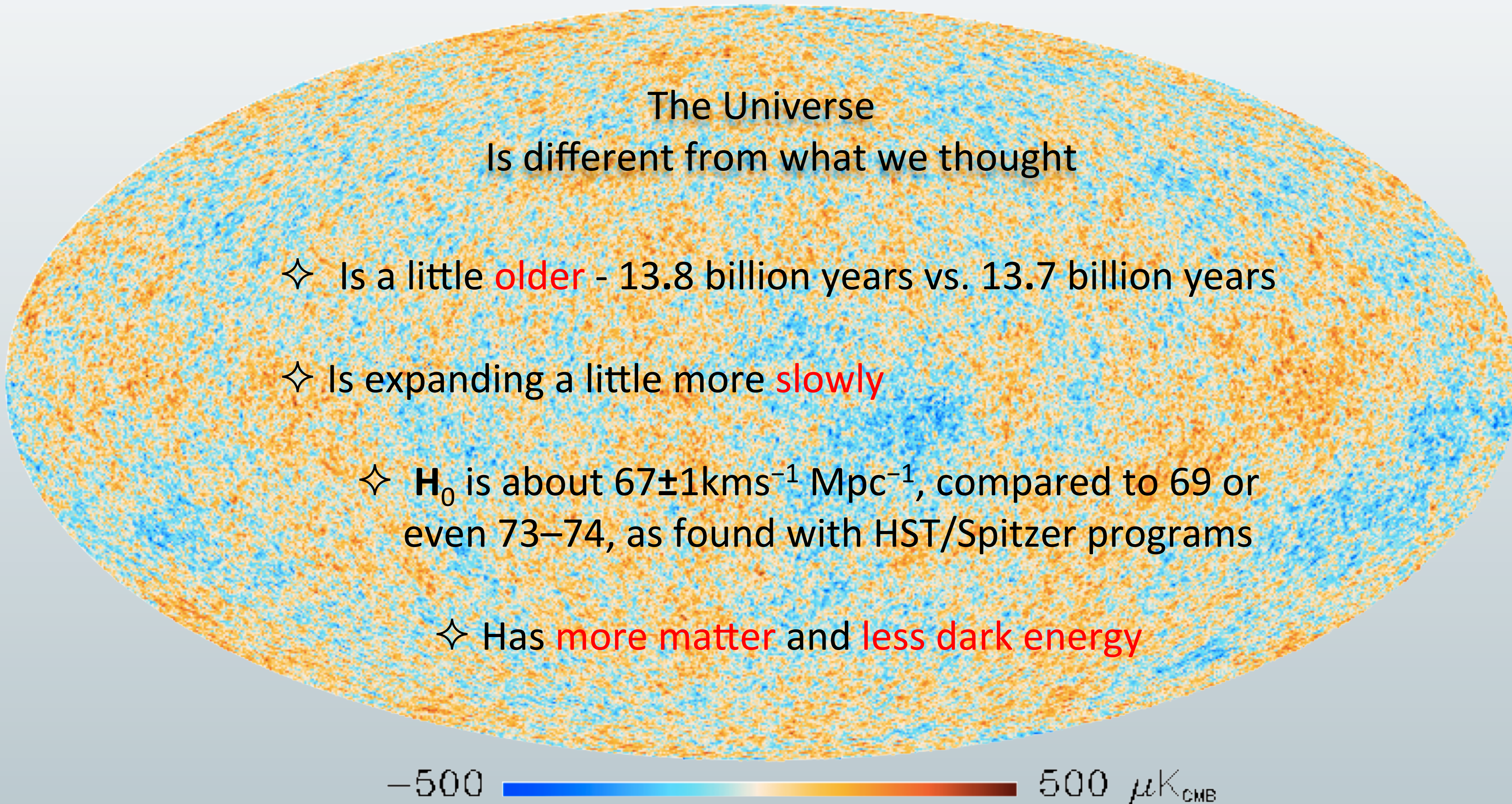
$$100\theta = 1.04131 \pm 0.00063$$

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

Age = 13.81± 0.05 billion years

Consistent with spatial flatness to % level

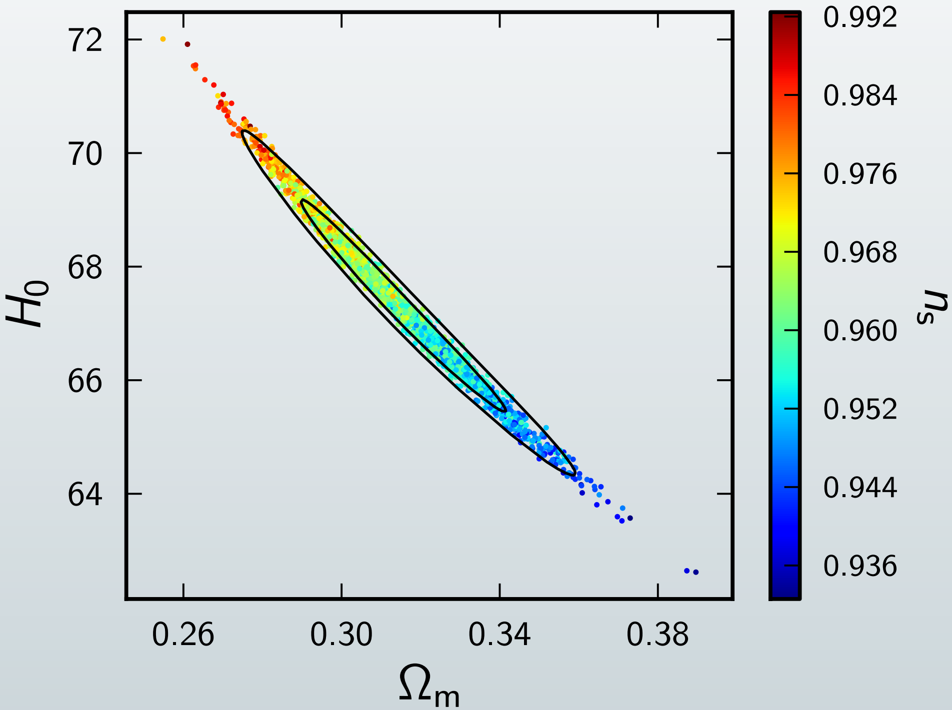
What Have We Learned ?
In words



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 -> ~ $\Omega_m h^3$

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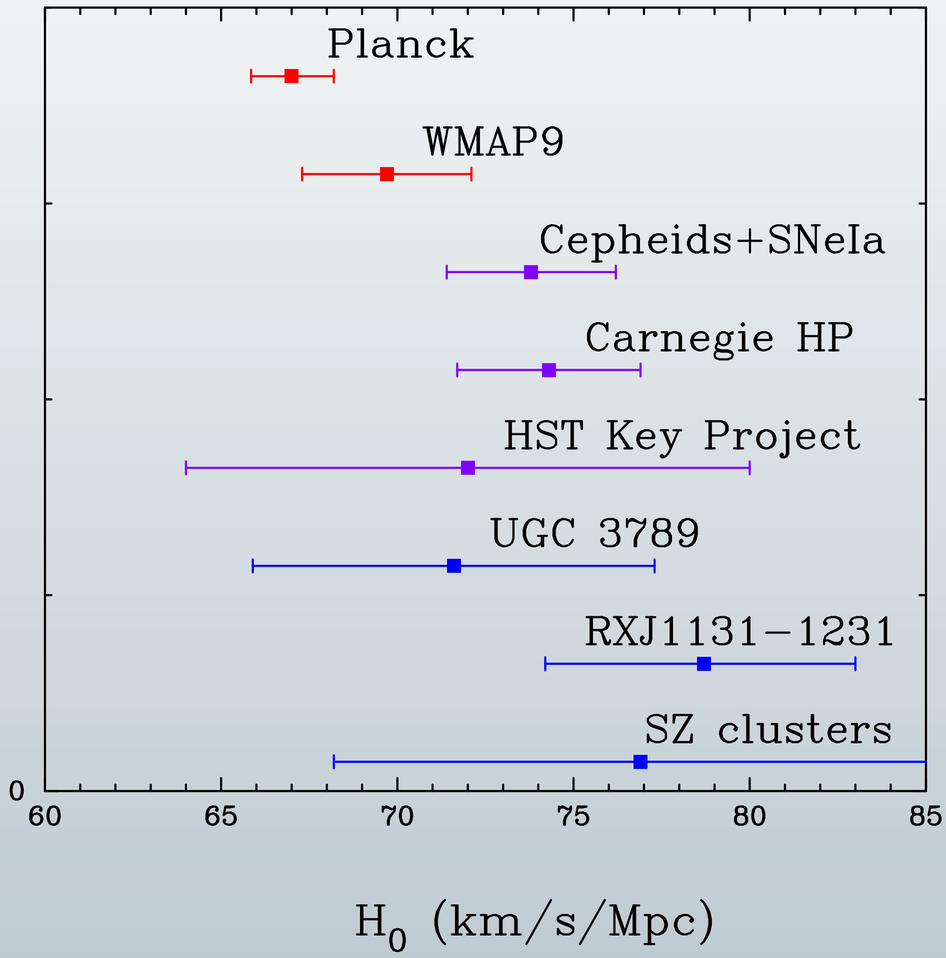
The projection of the constant elipse onto the axes yields useful marginalised constraints on H_0 and Ω_m (or equivalently Ω_Λ) separately

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

What Have We Learned ?
"Tensions" – H_0

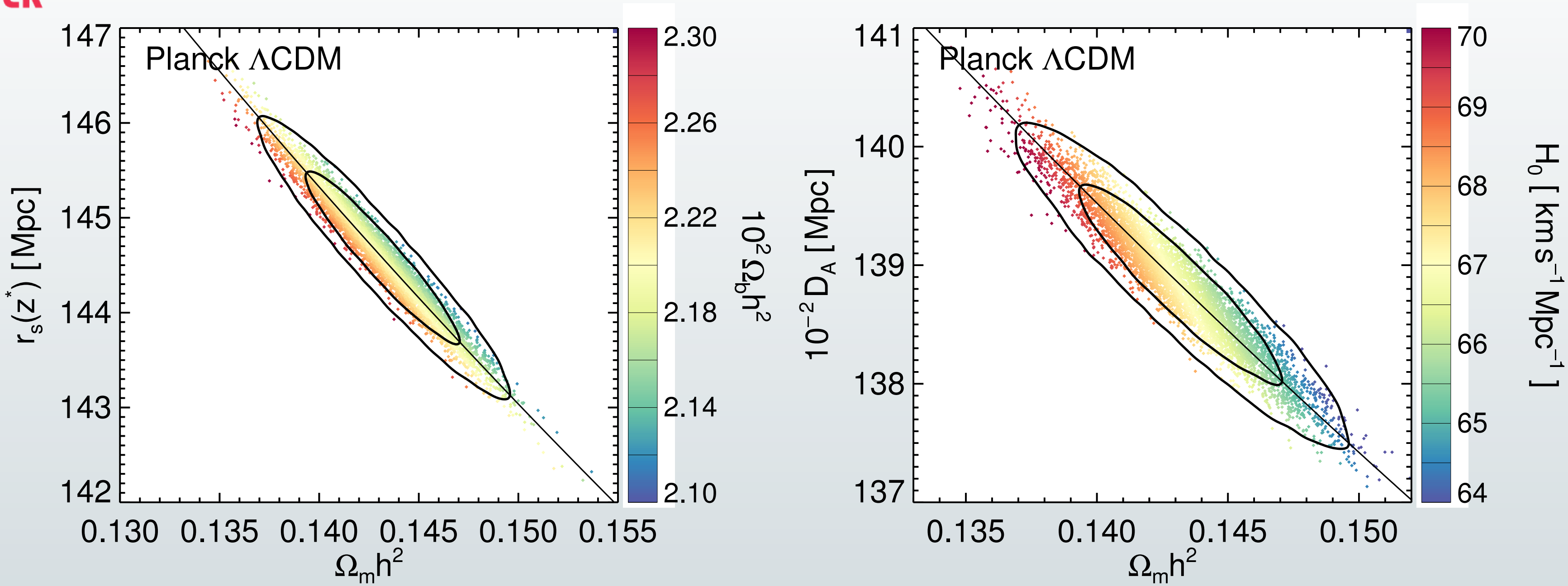


Independent local cosmological probes:

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($\Omega_m h^2$, $\Omega_b h^2$)

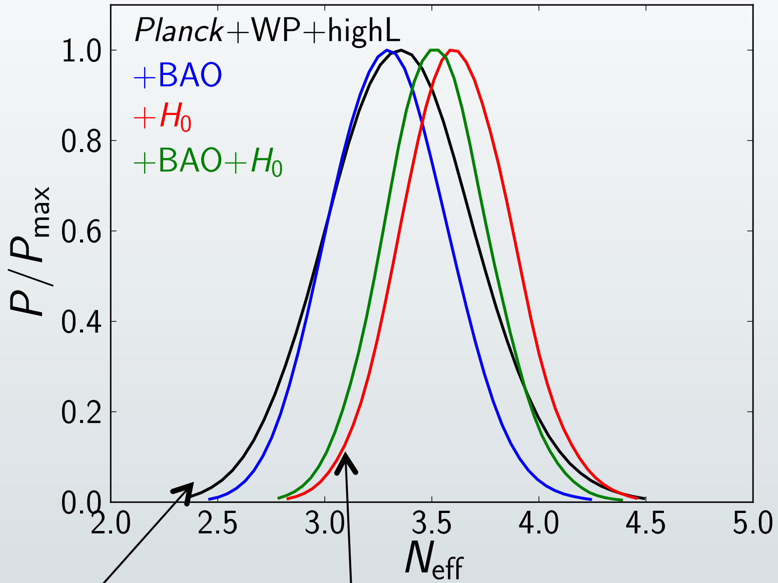
$D_A(z)$ =f(H_0, $\Omega_m h^2$)

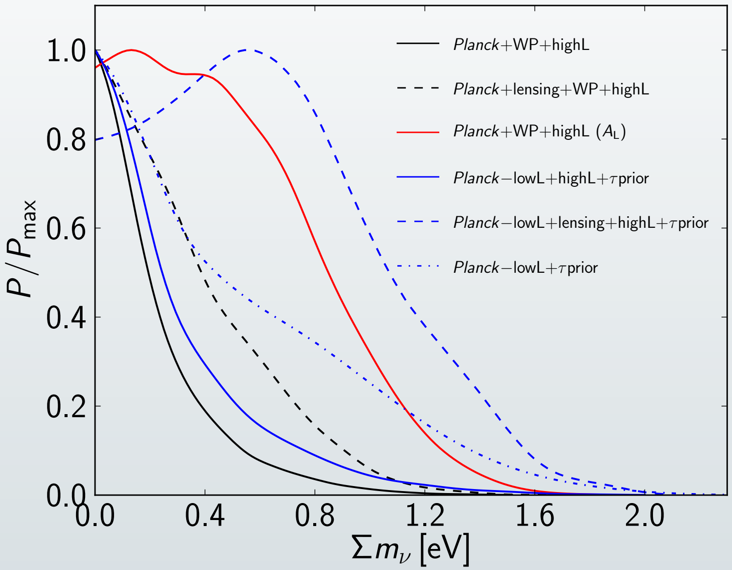
Θ_* tightly constrained by CMB power spectrum

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}

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

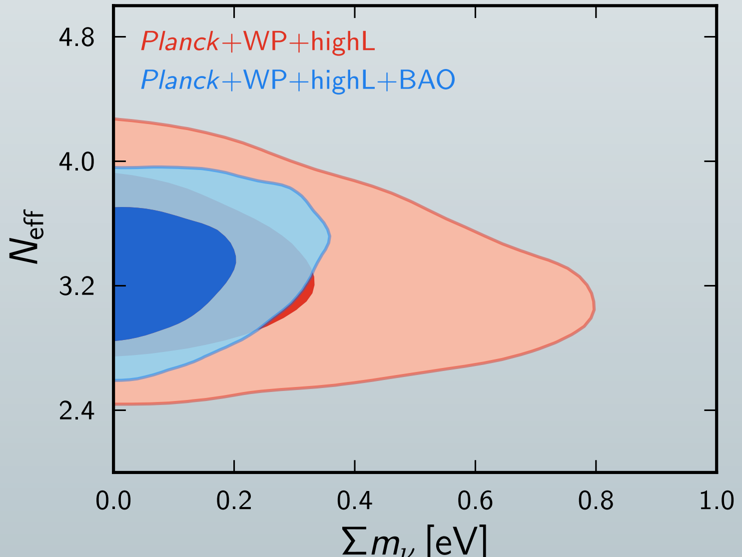
Extensions to ΛCDM model
Neutrino Physics: Number of neutrino species: Neff
neutrino mass m_ν





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

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



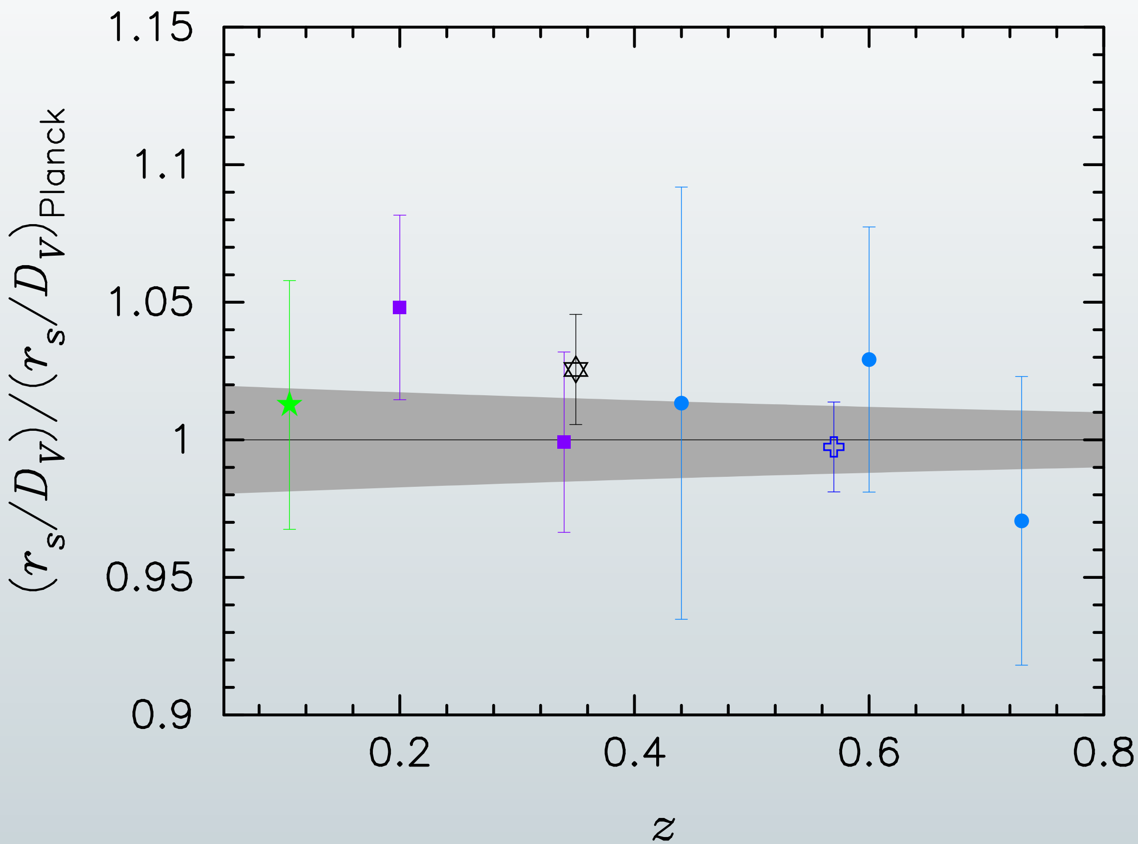
1 solution For H_0 tension:

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

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

Planck and BAO

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

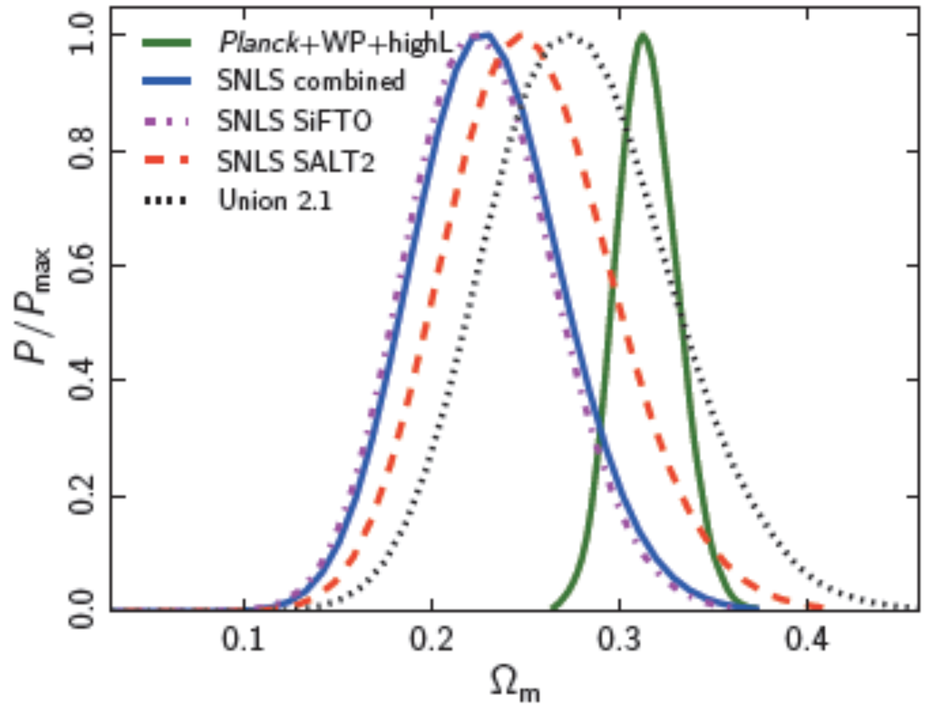


Fig. 19. Posterior distributions for Ω_m (assuming a flat cosmology) for the SNe compilations described in the text. The posterior distribution for Ω_m from the *Planck*+WP+highL fits to the base ΛCDM model is shown by the solid green line.

There is some tension between Planck and SNLS combined

ΛCDM model parameters
“Tensions” σ_8

Cosmology from Planck SZ clusters

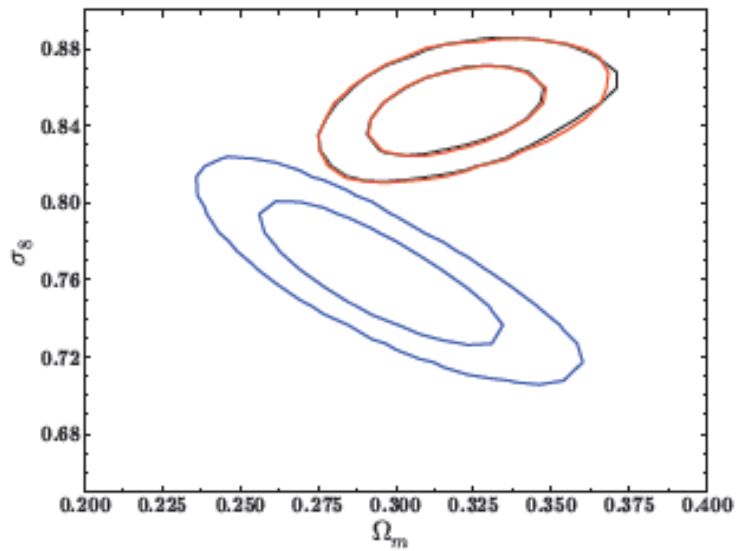


Fig. 11. 2D Ω_m–σ_8 likelihood contours for the analysis with *Planck* CMB only (red); *Planck* SZ + BAO + BBN (blue); and the combined *Planck* CMB + SZ analysis where the bias $(1 - b)$ is a free parameter (black).

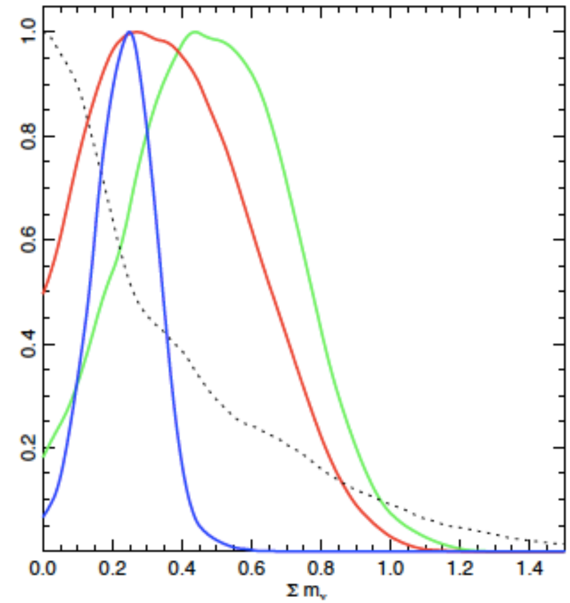


Fig. 12. Cosmological constraints when including neutrino masses $\sum m_\nu$ from: *Planck* CMB data alone (black dotted line); *Planck* CMB + SZ with $1 - b$ in [0.7, 1] (red); *Planck* CMB + SZ + BAO with $1 - b$ in [0.7, 1] (blue); and *Planck* CMB + SZ with $1 - b = 0.8$ (green).

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

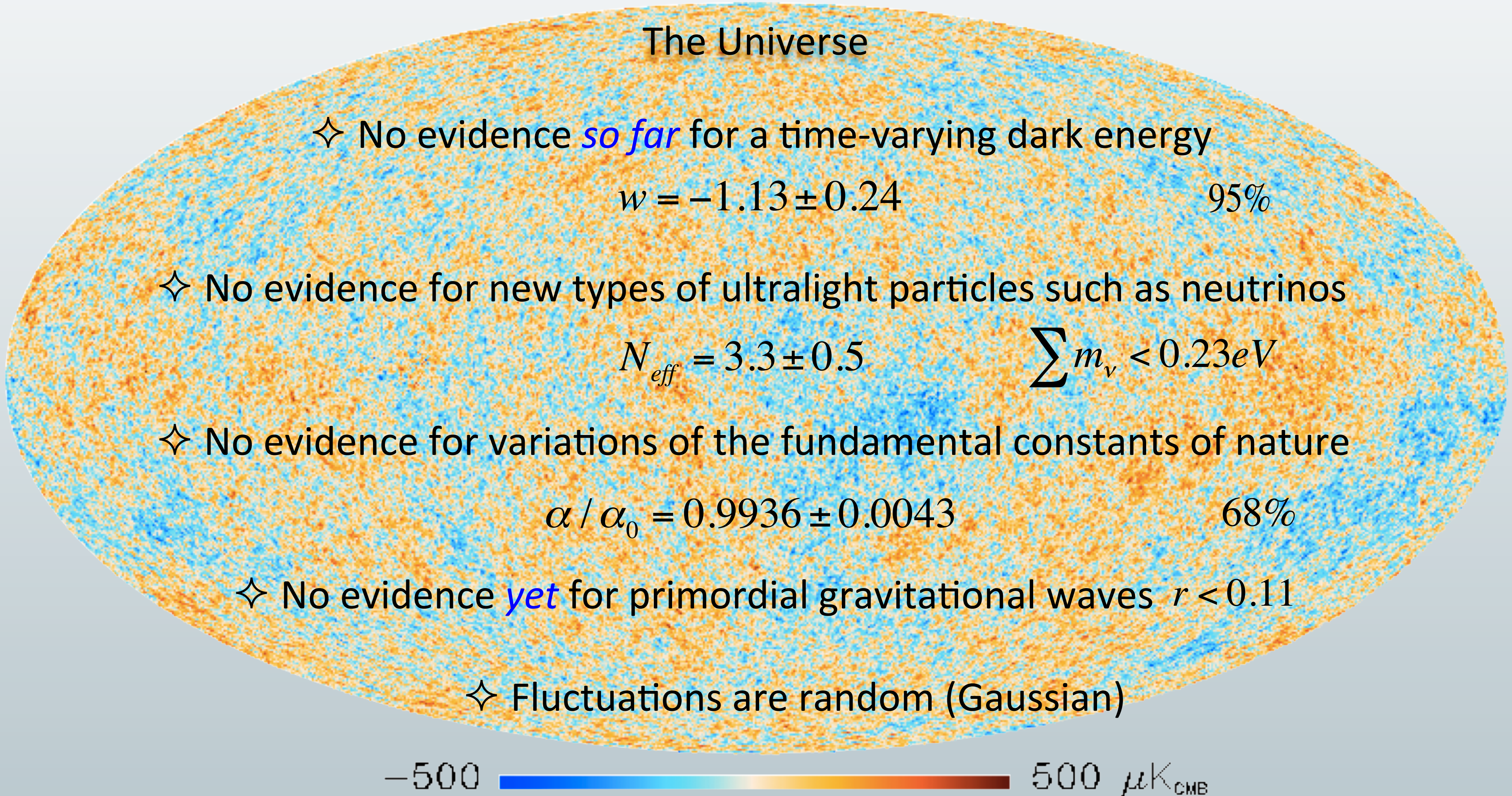
$$\sigma_8(\Omega_m/0.27)^{0.3} = 0.79 \pm 0.01$$ SZ

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

CMB+SZ+BAO

Extensions to ΛCDM model

Potential new physics ?



The Universe

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

  $w = -1.13 \pm 0.24$ 95%

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

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

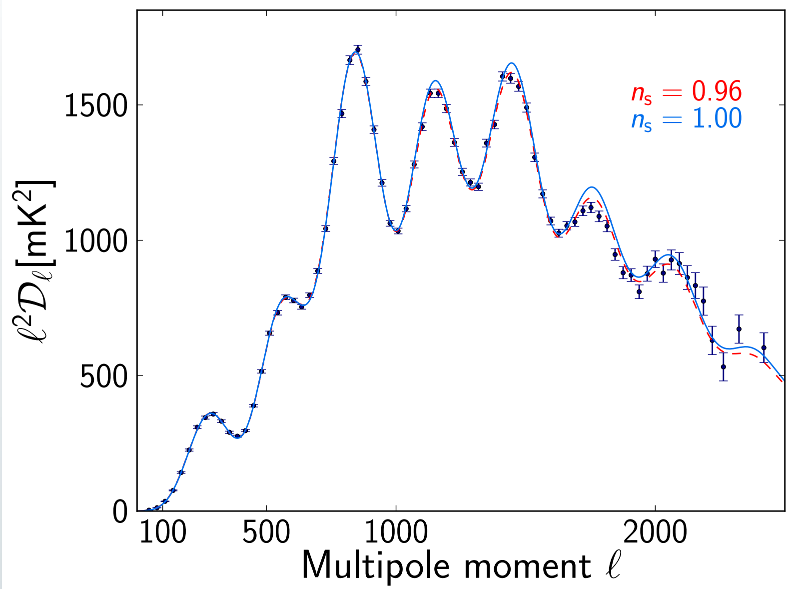
- ✧ No evidence for variations of the fundamental constants of nature

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

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

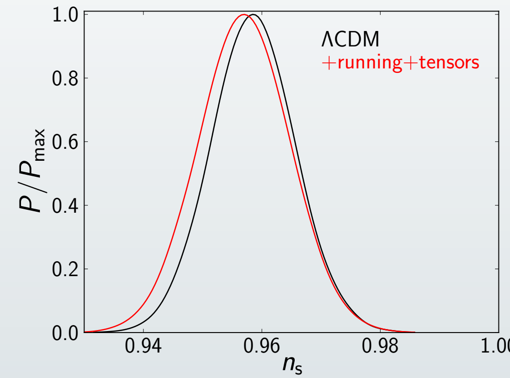
- ✧ Fluctuations are random (Gaussian)

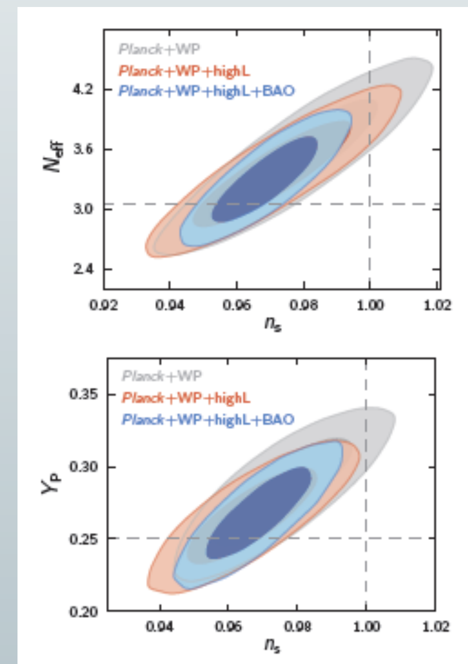
Extensions to ΛCDM model
Early-Universe physics: ns, dn_s/dk and r



6σ departure from scale invariance

$$n_s = 0.9603 \pm 0.0073$$





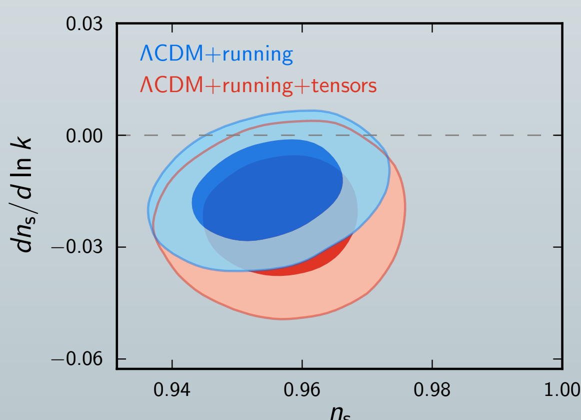
3σ

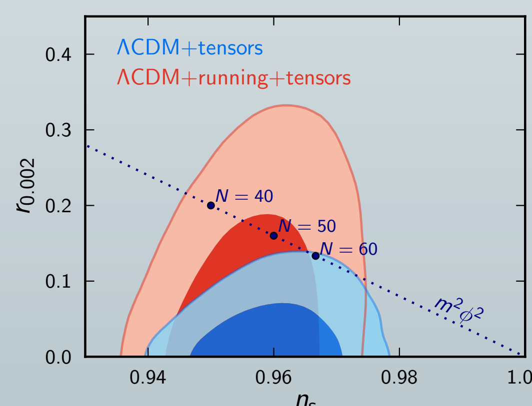
l<50

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

$$r < 0.11 \qquad V_*$$

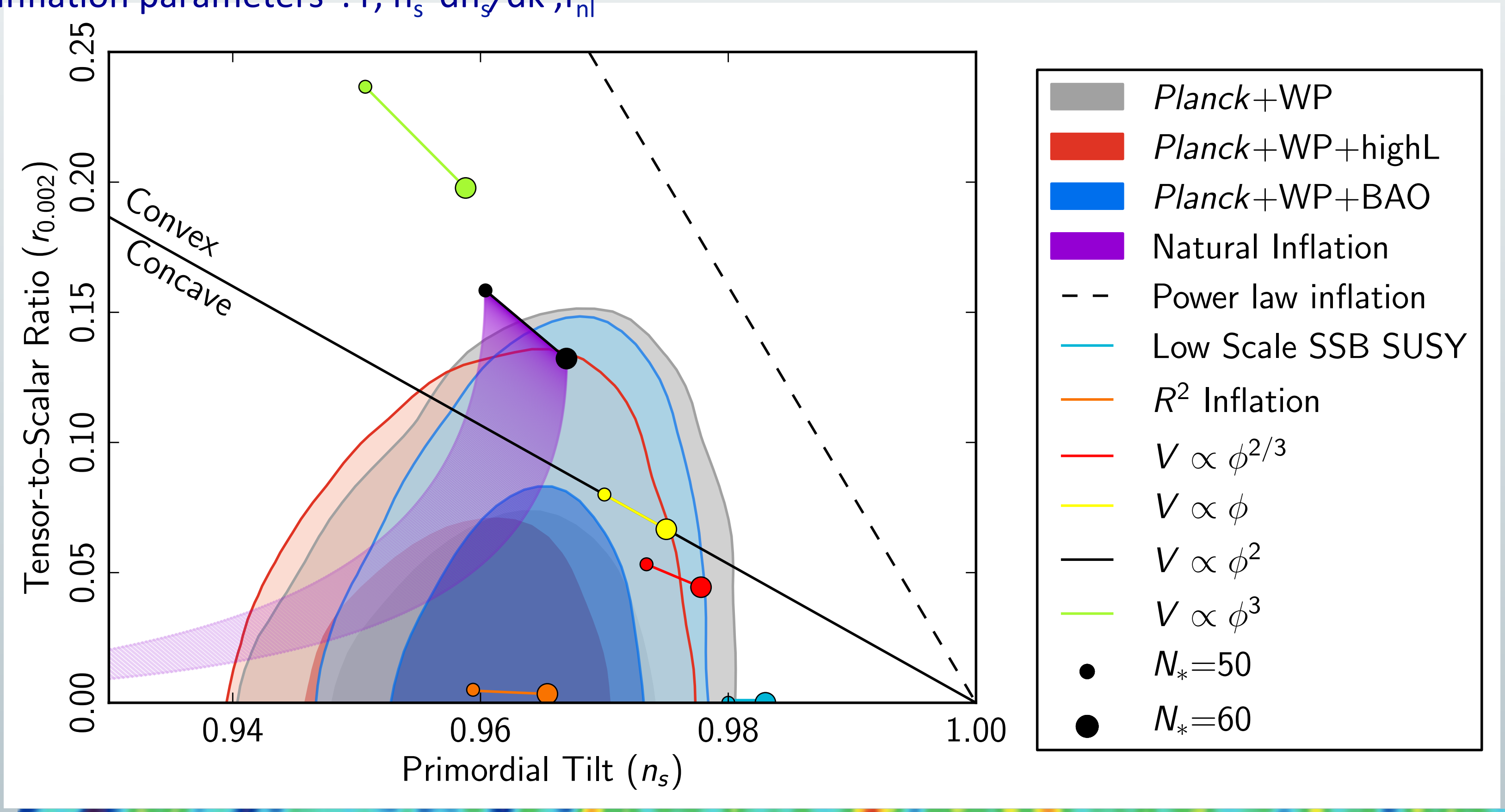
$$V = (1.94 \times 10^{16} GeV)^4 (r_{0.02} / 0.12)$$



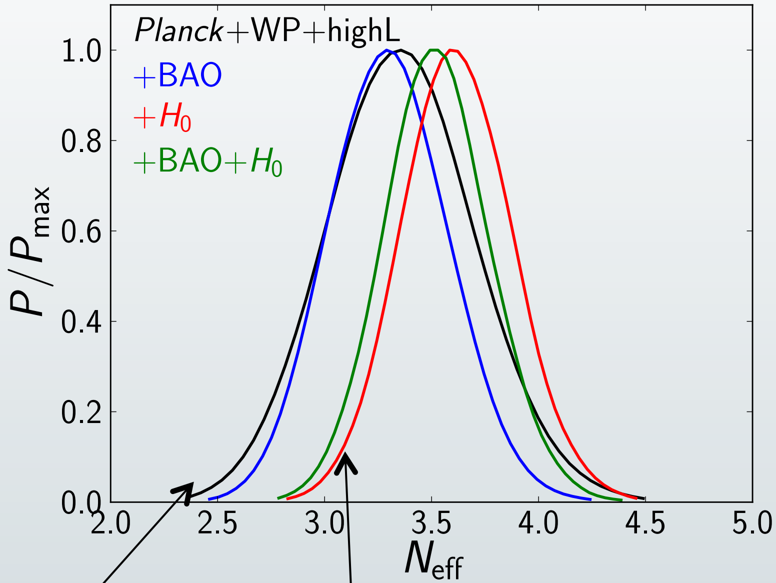


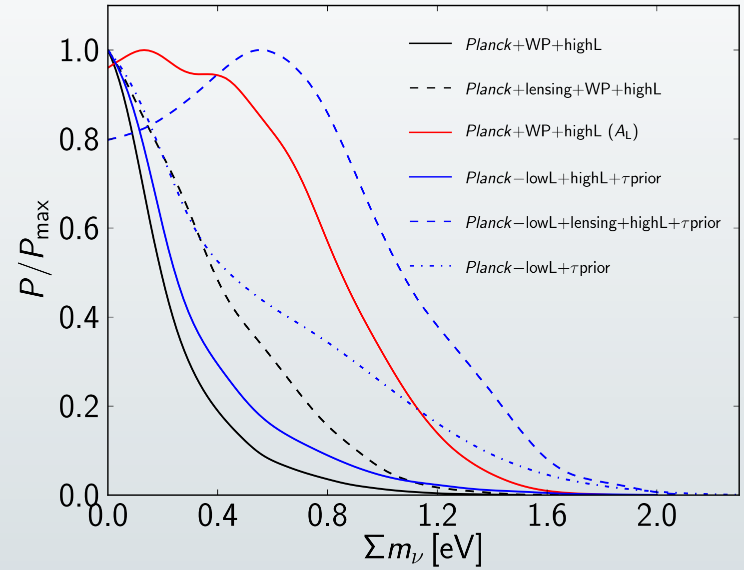
Inflationary Scenarios
Constraints on slow-roll inflationary models

- 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}



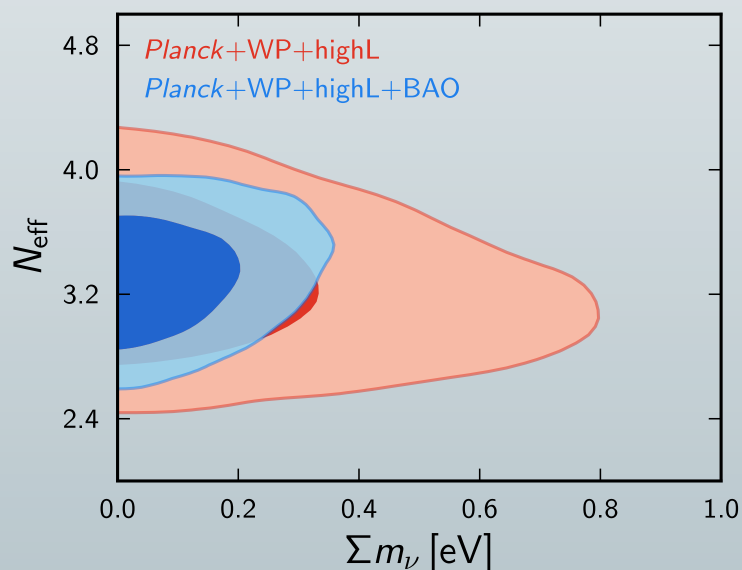
Extensions to ΛCDM model
Neutrino Physics: Number of neutrino species: Neff
neutrino mass m_ν





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

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



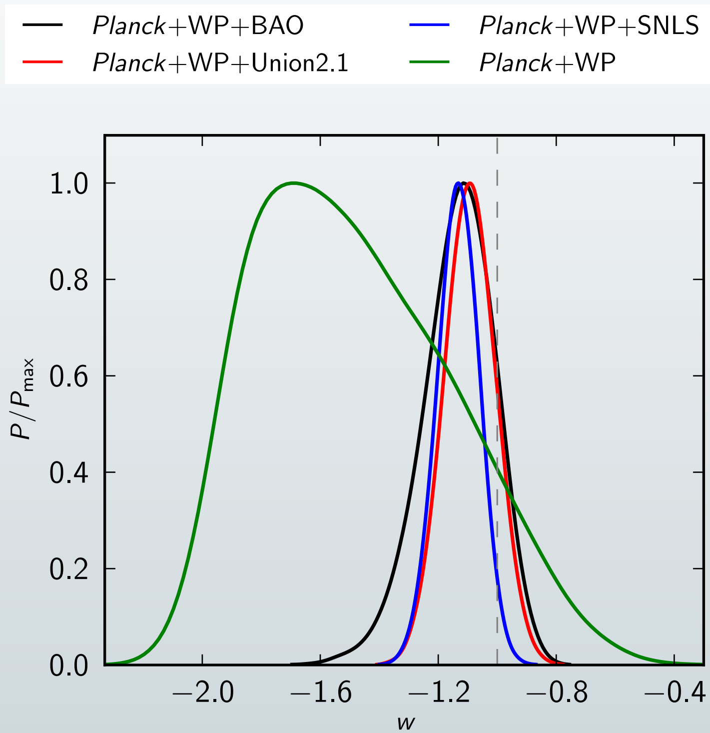
1 solution For H_0 tension:

$N_{eff} = 3.6 \pm 0.5$

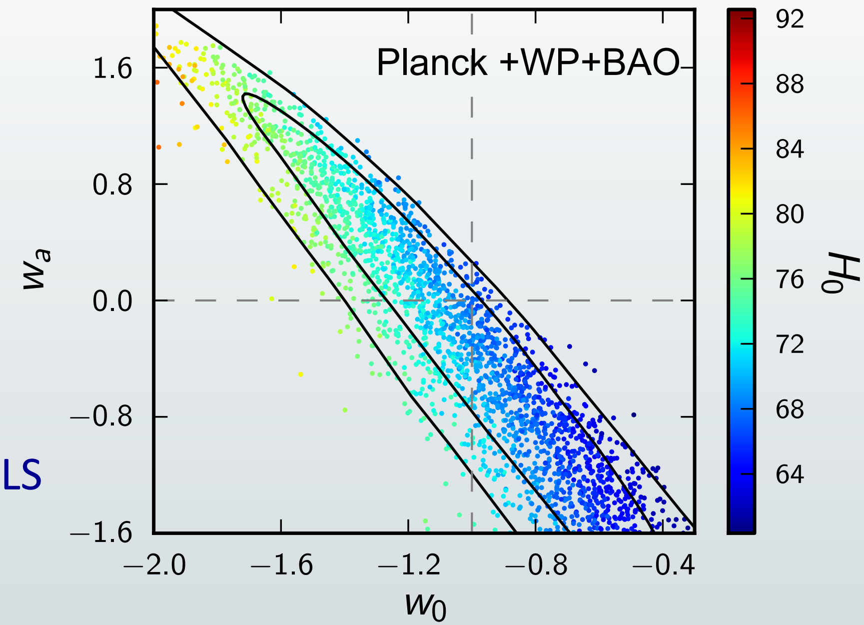
$\sum m_\nu < 0.23 eV$

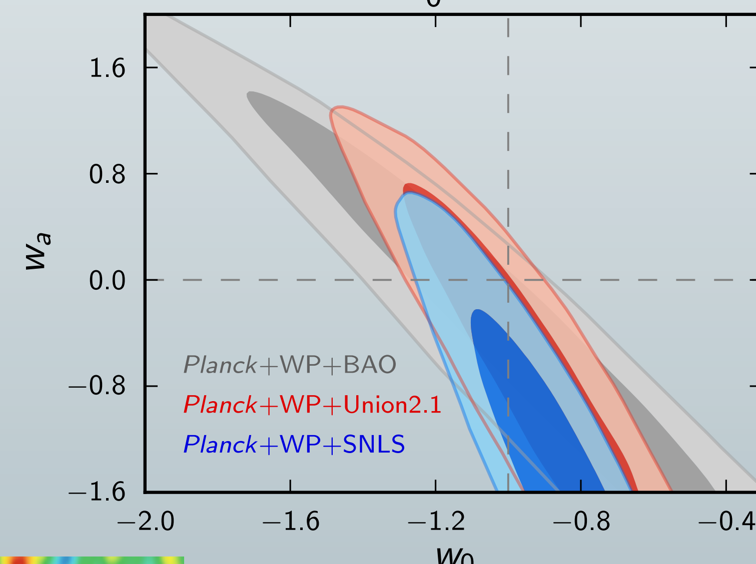
Planck and BAO

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

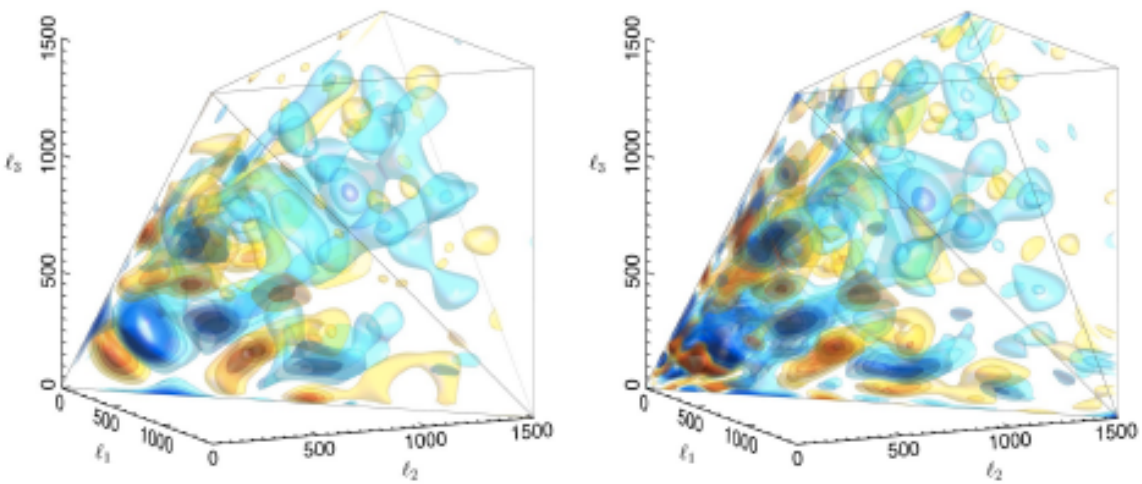


Fig. 7. *Planck* CMB bispectrum detail in the signal-dominated regime showing a comparison between full 3D reconstruction using hybrid Fourier modes (left) and hybrid polynomials (right). Note the consistency of the main bispectrum properties which include an apparently 'oscillatory' central feature 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.

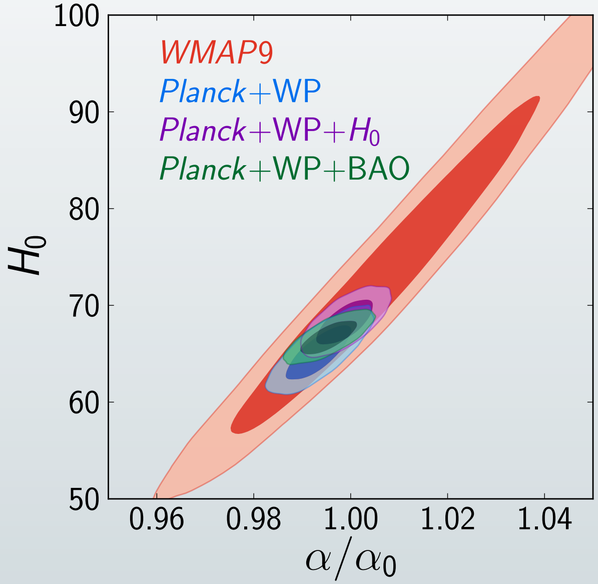
Detection of ISW-lensing bispectrum at 2 to 3σ

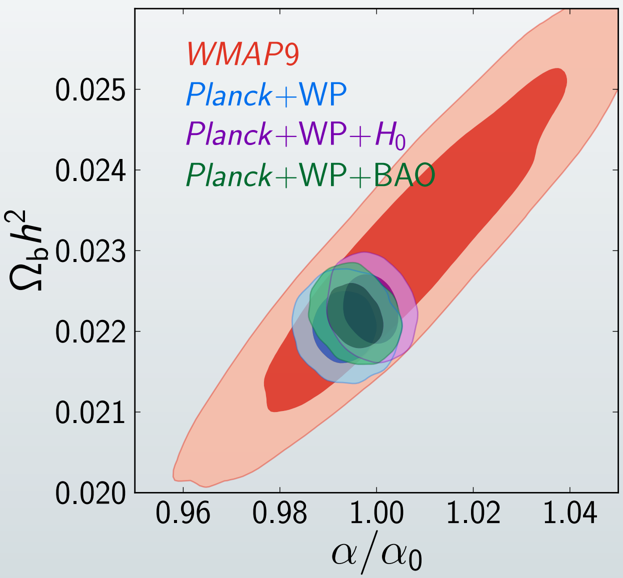
Periodic CMB ISW-lensing signal in the squeezed limit along the edges of the tetrapyd

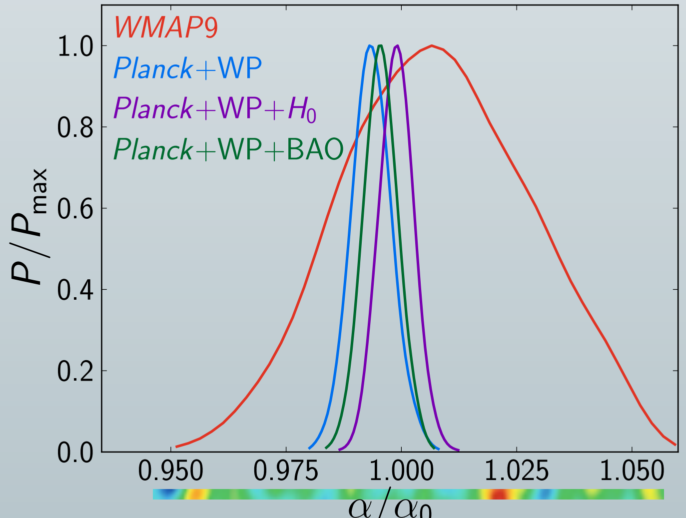
Extensions to ΛCDM model
Varying fundamental constants

Varying Fine Structure Constant

68%





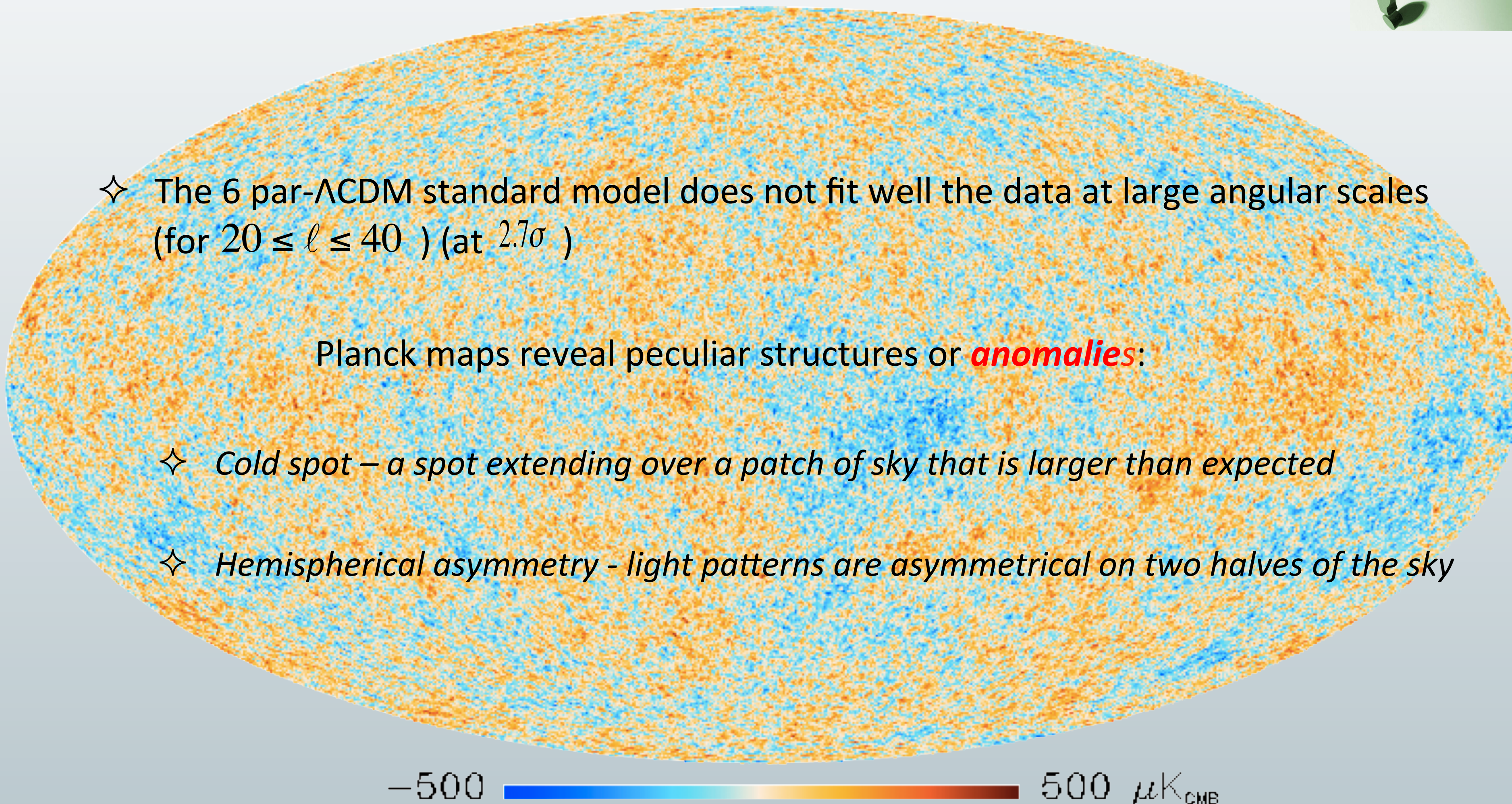


$$\alpha / \alpha_0 = 0.9936 \pm 0.0043$$

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?



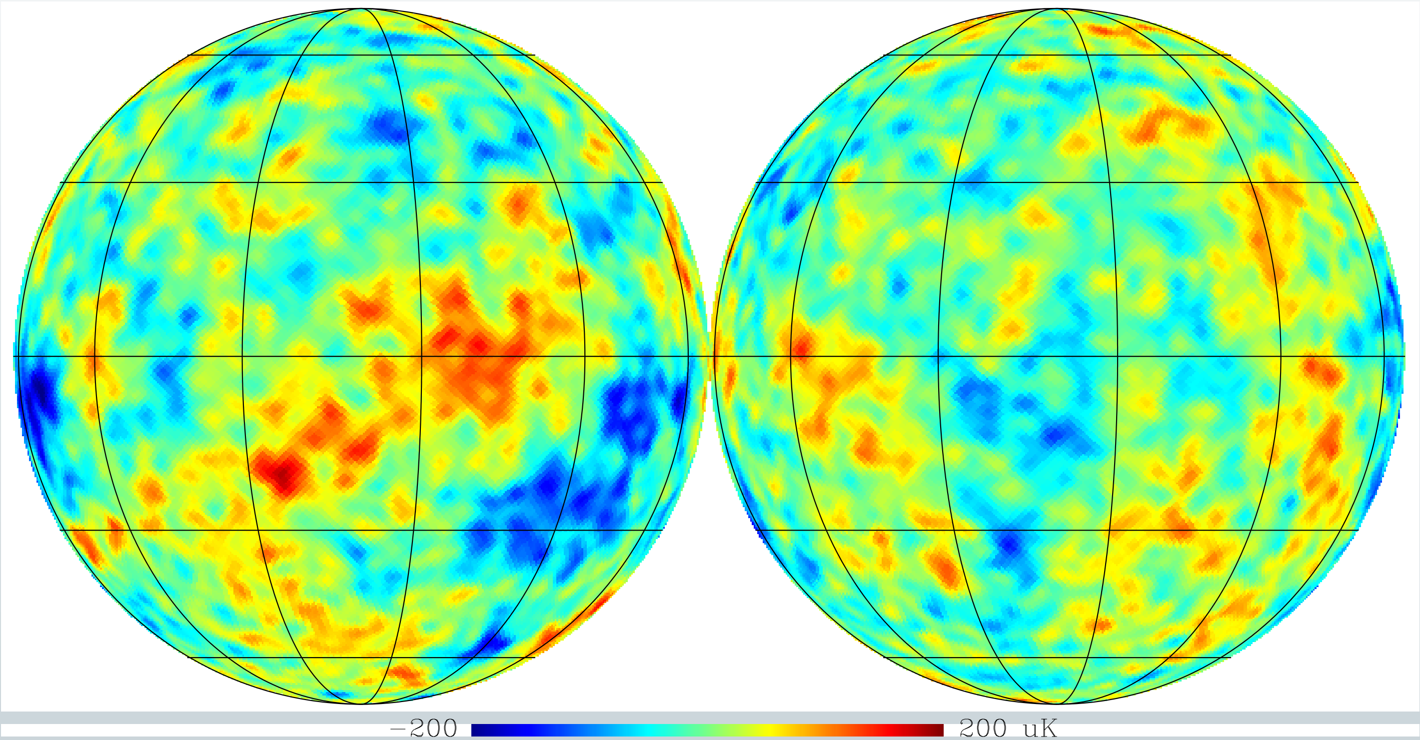
- The 6 par-ΛCDM standard model does not fit well the data at large angular scales (for $20 \leq \ell \leq 40$) (at 2.7σ)

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*

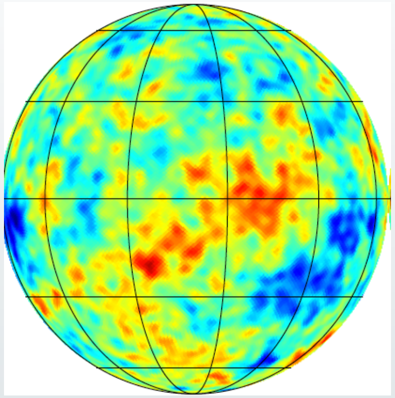
Planck sees peculiar features (anomalies) in the patterns of the relic light

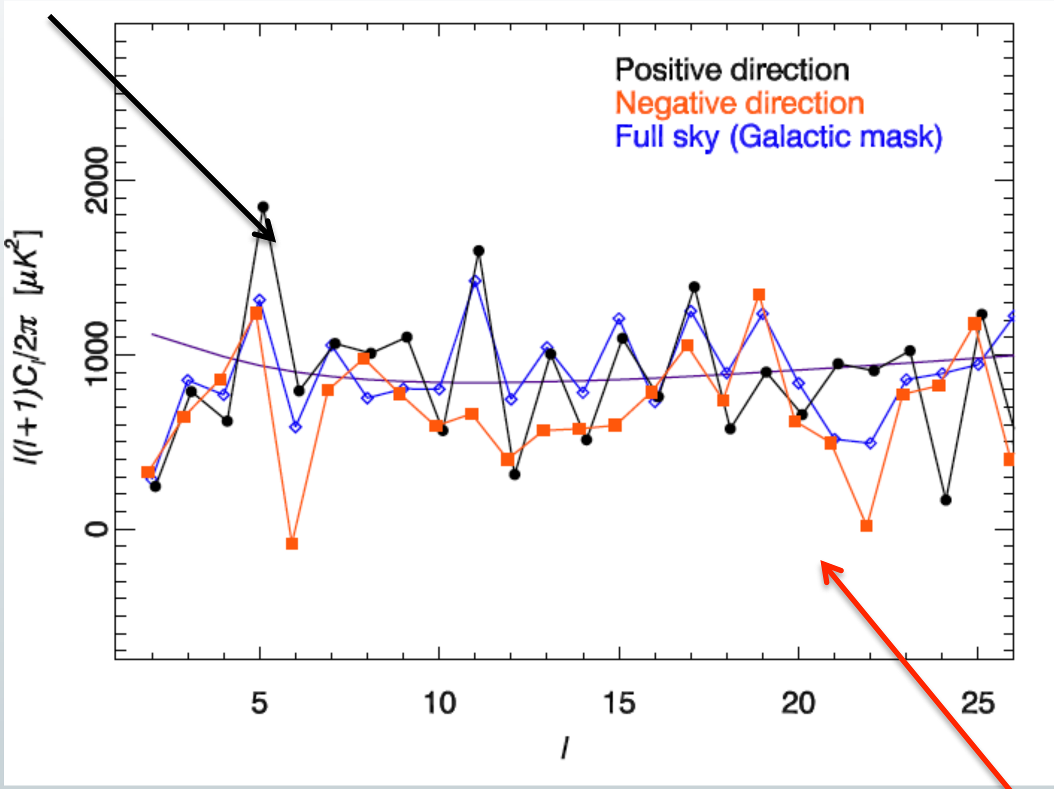
The two halves of the sky that we see look different

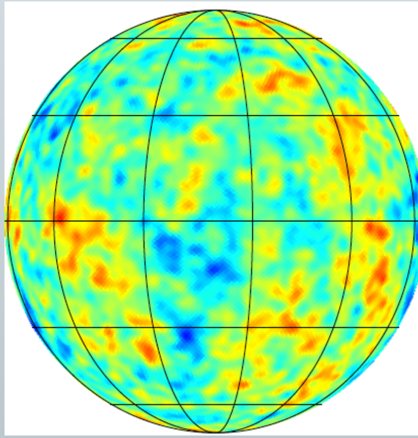


A feature noticed before and considered controversial
is now proven real by Planck
Does this call for new physics?
These are large scale (super-horizon) features.
They give a pristine image of the very very early Universe.

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?

Summary

- Consistency tests of the Planck baseline Power Spectrum and Likelihood via comparisons with alternative methodologies show its robustness
- Validation tests of the baseline setup demonstrates its adequacy
- We have validated our results through an extensive suite of consistency and robustness analyses, propagating both instrumental and astrophysical uncertainties to final parameter estimation; further we have studied the degeneracies between foregrounds and cosmological parameters at high-l with Planck observations and shown that they have a weak impact on cosmological conclusions
- 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

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.