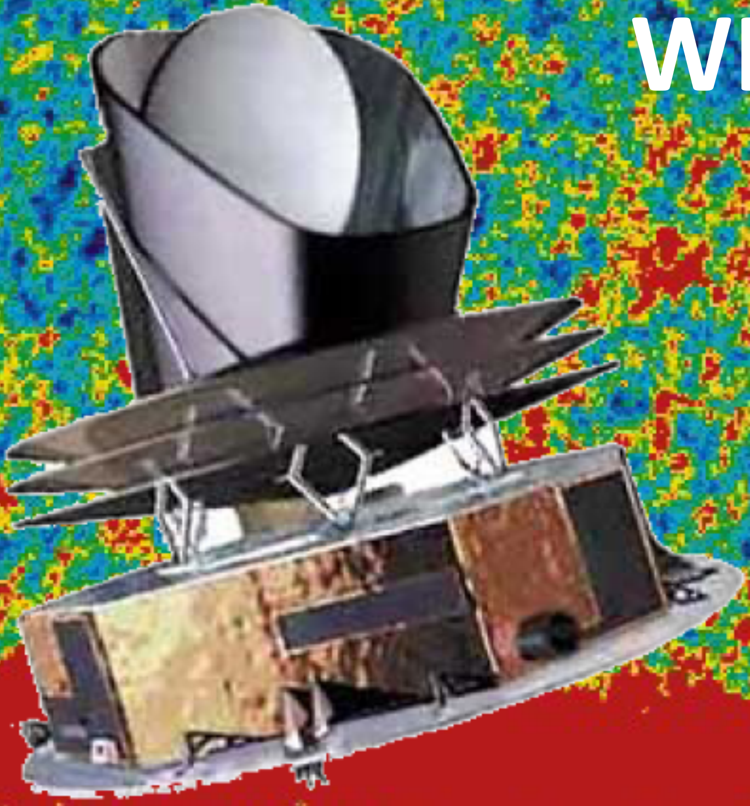
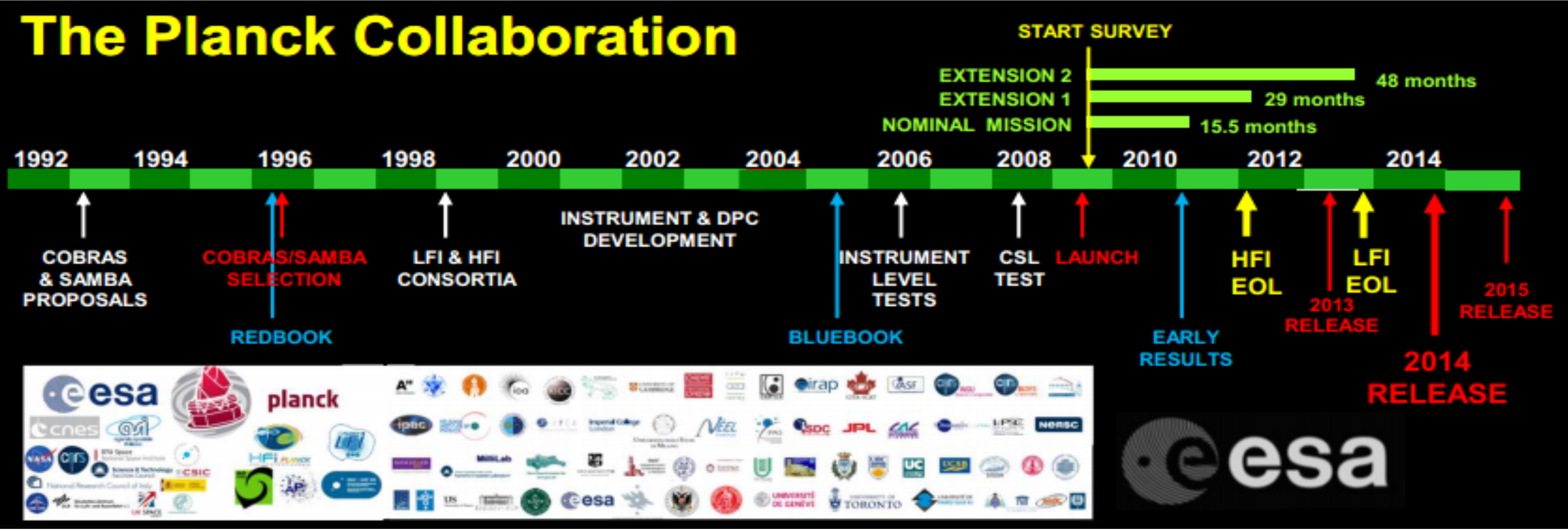
COSMOLOGICAL PARAMETERS WITH PLANCK



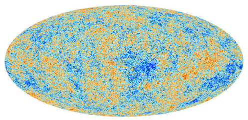
Planck 2015 results. XIII
Planck 2015 results. XI

Marina Migliaccio
for the Planck Collaboration

Cosmo Cruise – 5th September 2015

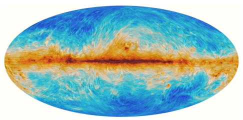


May 2009: Launched from Kourou



Mar 2013: Data Release and Cosmology Results
Nominal Mission Temperature data

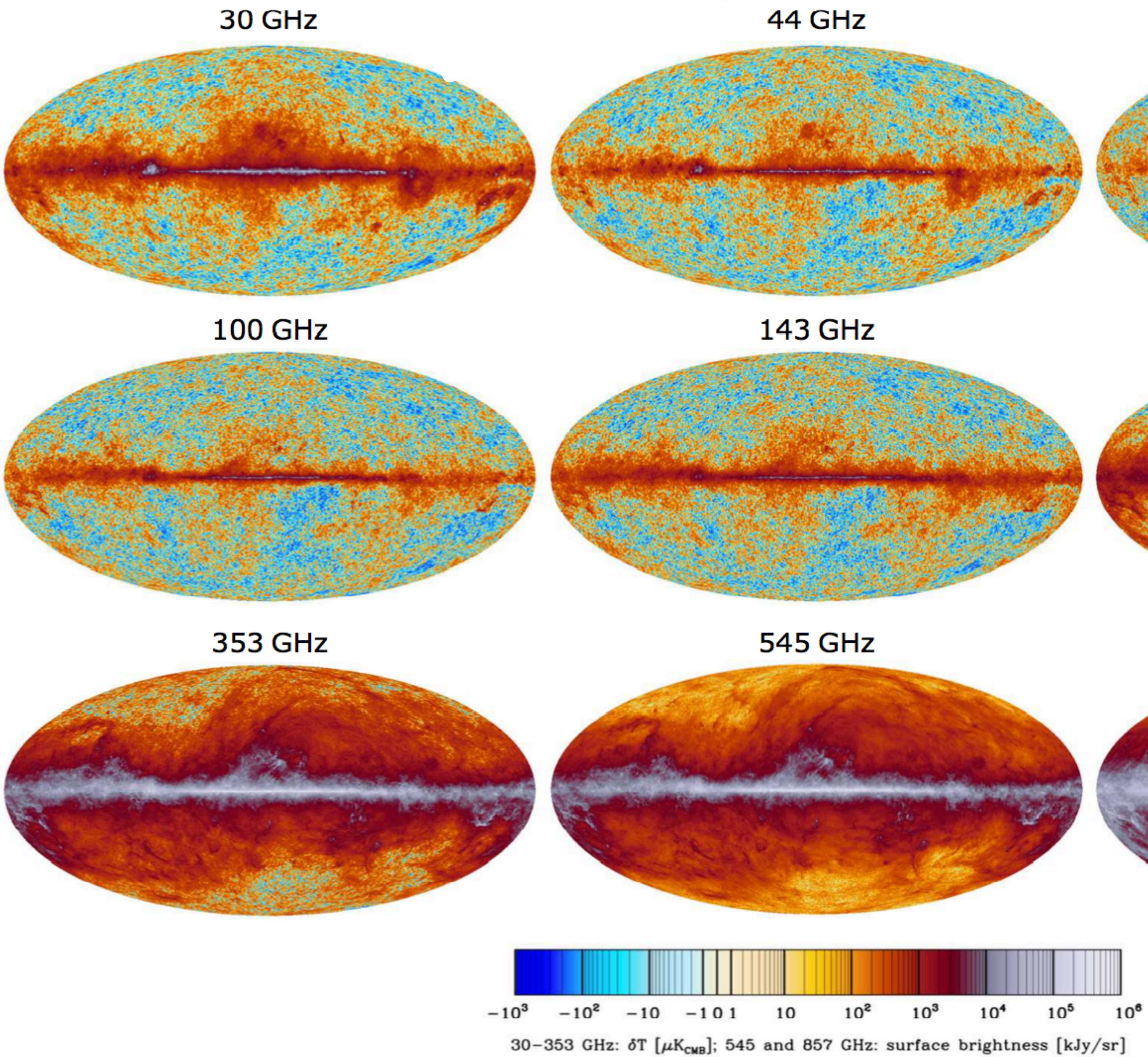
Oct 2013: Planck 'Shut Down'



Feb 2015: Data Release and Cosmology Results
Full Mission Temperature and (preliminary) Polarization data

2016: Legacy Data & Paper Release

TEMPERATURE



Planck Likelihood

EUROPEAN SPACE AGENCY | SCIENCE & TECHNOLOGY | SIGN IN

Planck Legacy Archive

esa

Release: PR2 - 2015

RESULTS | Close All | << | < | PR2 Cosmology #1 | >

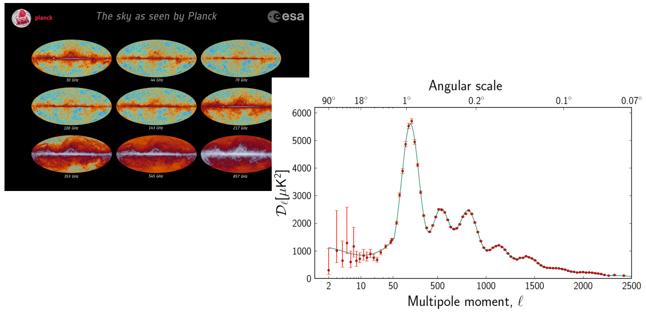
Cosmology products (7)

0 selected items

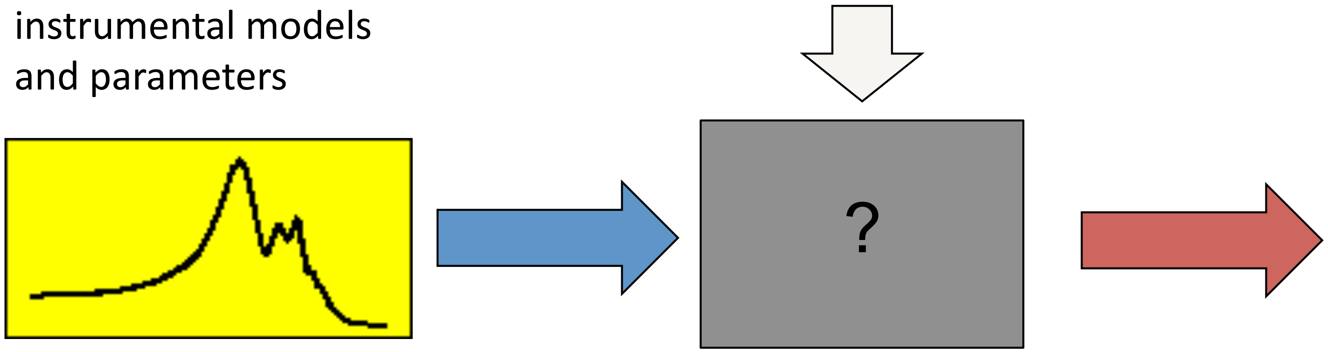
File name	Size	Product type	Release
COM_Likelihood_Code-v2.0_R2.00.tar.bz2	1.5 MB	Likelihood	PR2
COM_Likelihood_Data-baseline_R2.00.tar.gz	299.6 MB	Likelihood	PR2
COM_Likelihood_Data-extra-lensing-ext_R2.00.tar.gz	1.2 MB	Likelihood	PR2
COM_Likelihood_Data-extra-plik-DS_R2.00.tar.gz	55.1 MB	Likelihood	PR2
COM_Likelihood_Data-extra-plik-HM-ext_R2.00.tar.gz	46.3 MB	Likelihood	PR2
COM_Likelihood_Data-extra-plik-unbinned_R2.00.tar.gz	4.2 GB	Likelihood	PR2
COM_Likelihood_Masks_R2.00.tar.gz	274.6 MB	Likelihood	PR2

Planck Likelihood

$$P(\text{model} \mid \text{data}) \propto P(\text{data} \mid \text{model})\, P(\text{model})$$



CMB, foregrounds,
instrumental models
and parameters



a number

CAMB to compute theoretical CMB power spectra
COSMOMC to sample the parameter space

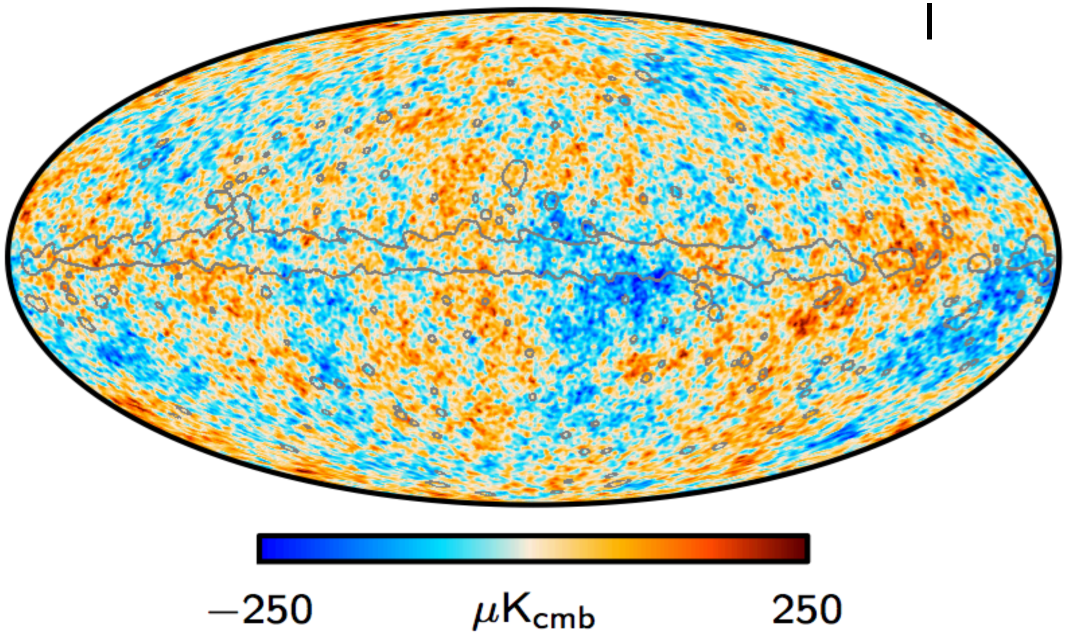
Hybrid approach

- Low-ℓ likelihood at large angular scales ($\ell < 30$)
- High-ℓ likelihood at small angular scales ($\ell \geq 30$)

Low-ℓ Likelihood

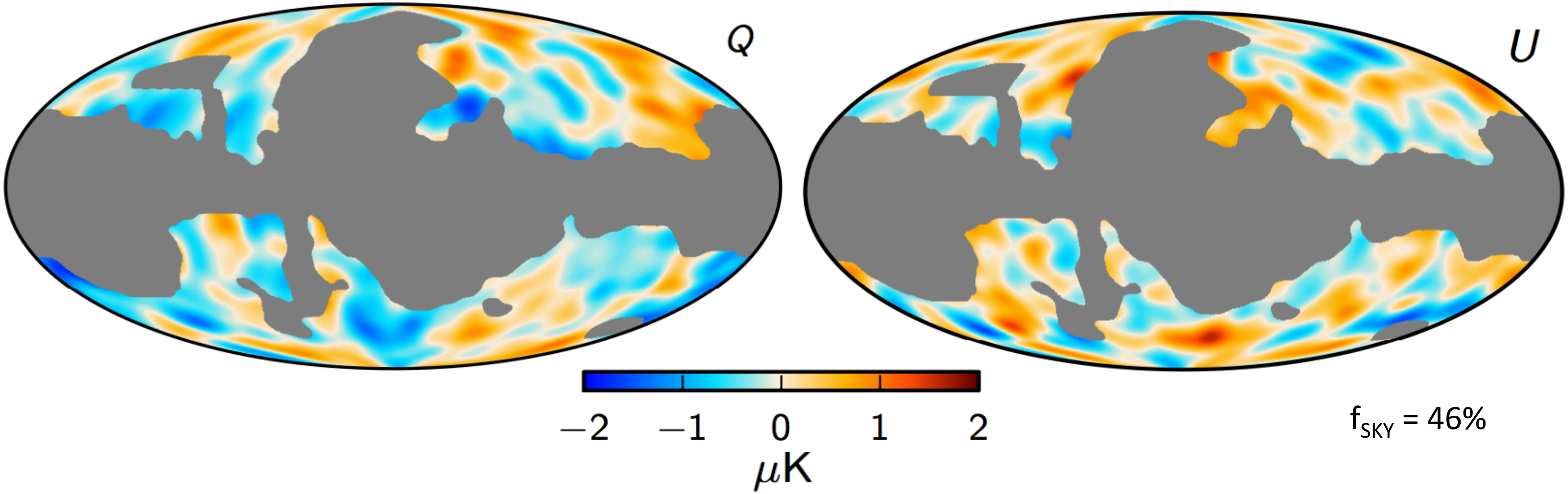
Commander map from Planck, WMAP9 and 408 MHz (Haslam et al.)

f_{SKY} = 93%



Foreground cleaned 70 GHz

Using 30 GHz for synchrotron and 353 GHz for dust



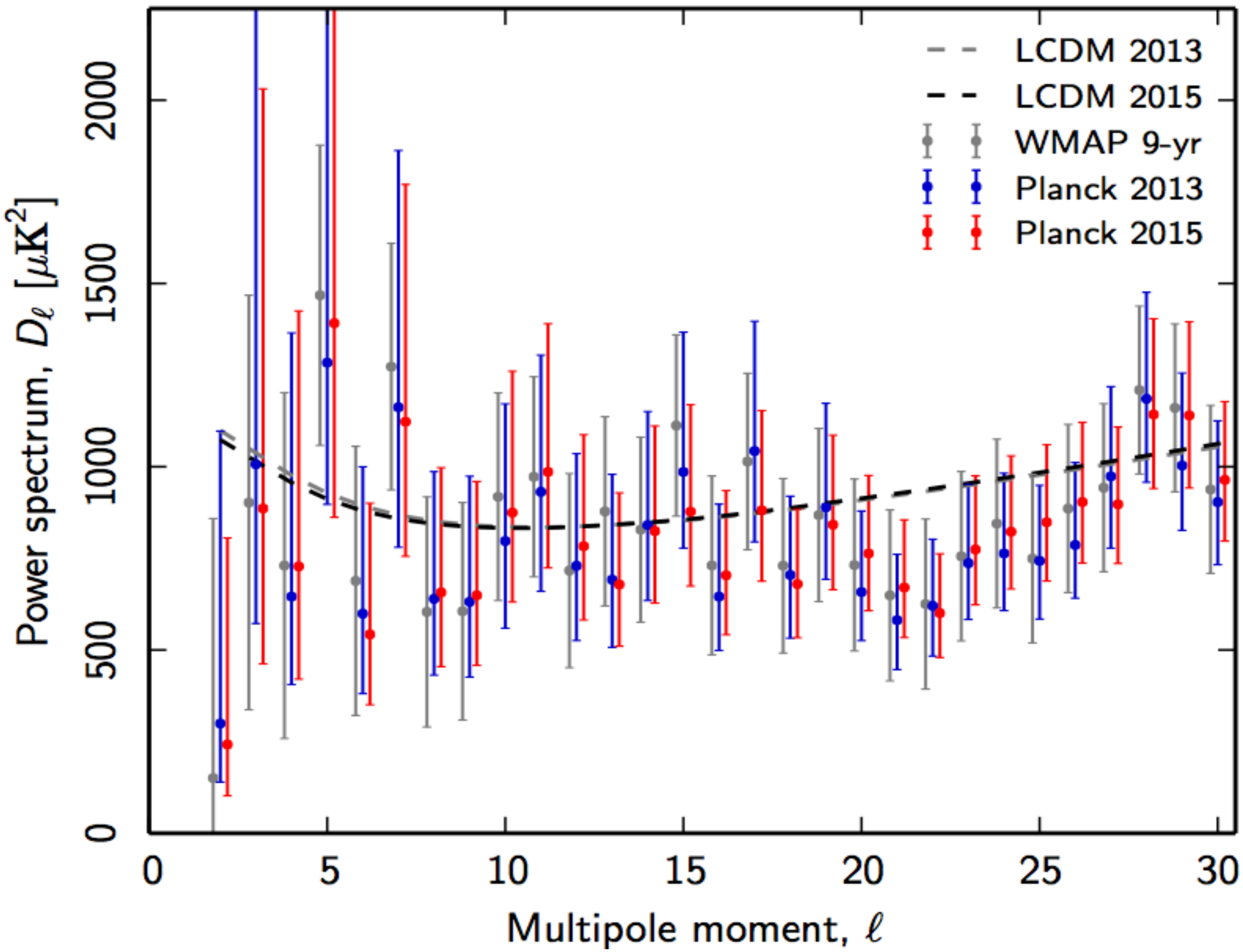
f_{SKY} = 46%

FULL PIXEL BASED GAUSSIAN LIKELIHOOD

$$\mathcal{L}(C_\ell) = \mathcal{P}(\boldsymbol{m}|C_\ell) = \frac{1}{2\pi|\mathsf{M}|^{1/2}} \exp\left(-\frac{1}{2}\boldsymbol{m}^\mathsf{T}\,\mathsf{M}^{-1}\boldsymbol{m}\right)$$

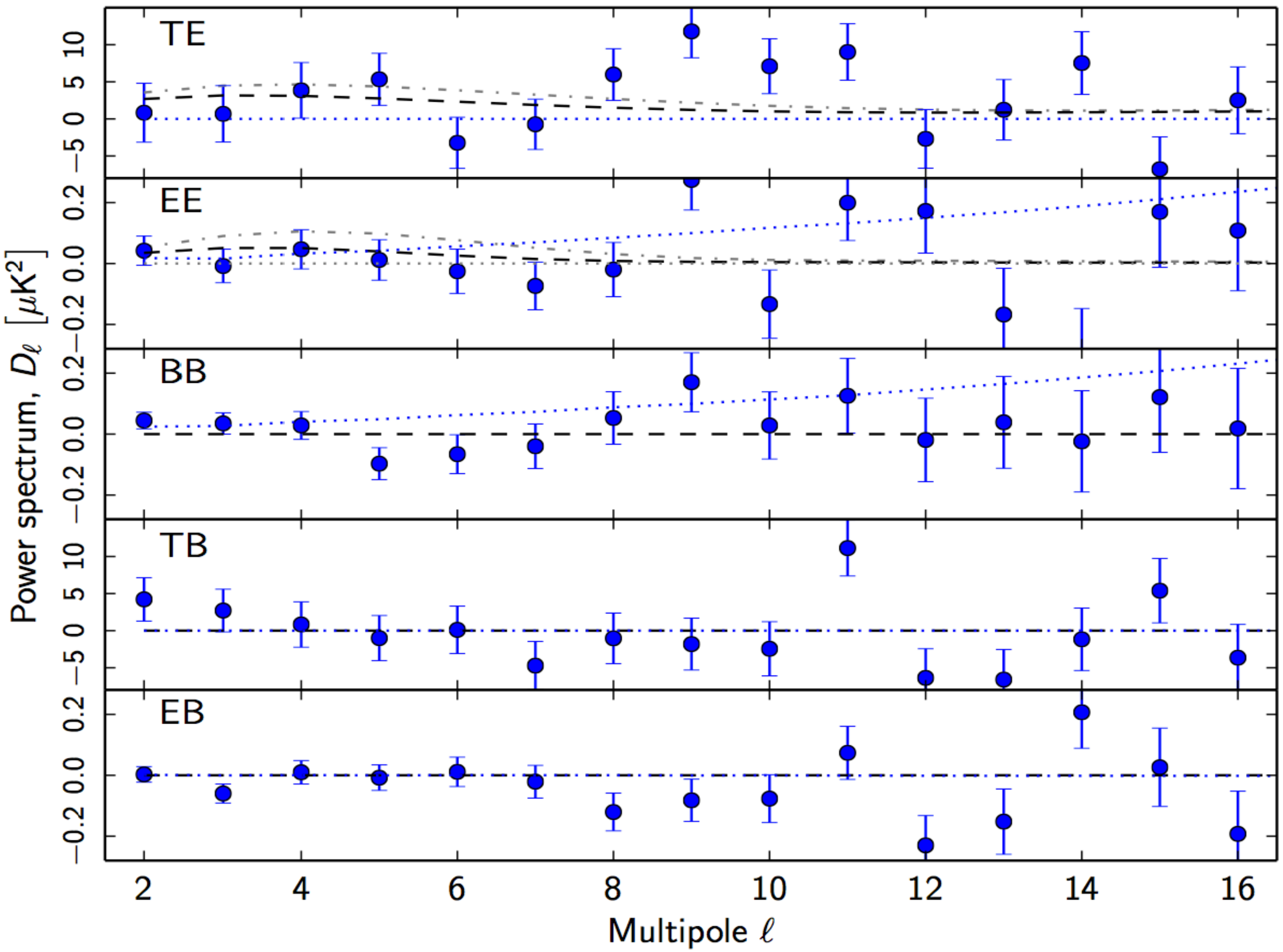
Full pixel based Gaussian Likelihood

$$\mathcal{L}(C_\ell) = \mathcal{P}(\boldsymbol{m}|C_\ell) = \frac{1}{2\pi|\mathsf{M}|^{1/2}} \exp\left(-\frac{1}{2}\boldsymbol{m}^{\mathsf{T}}\,\mathsf{M}^{-1}\boldsymbol{m}\right)$$



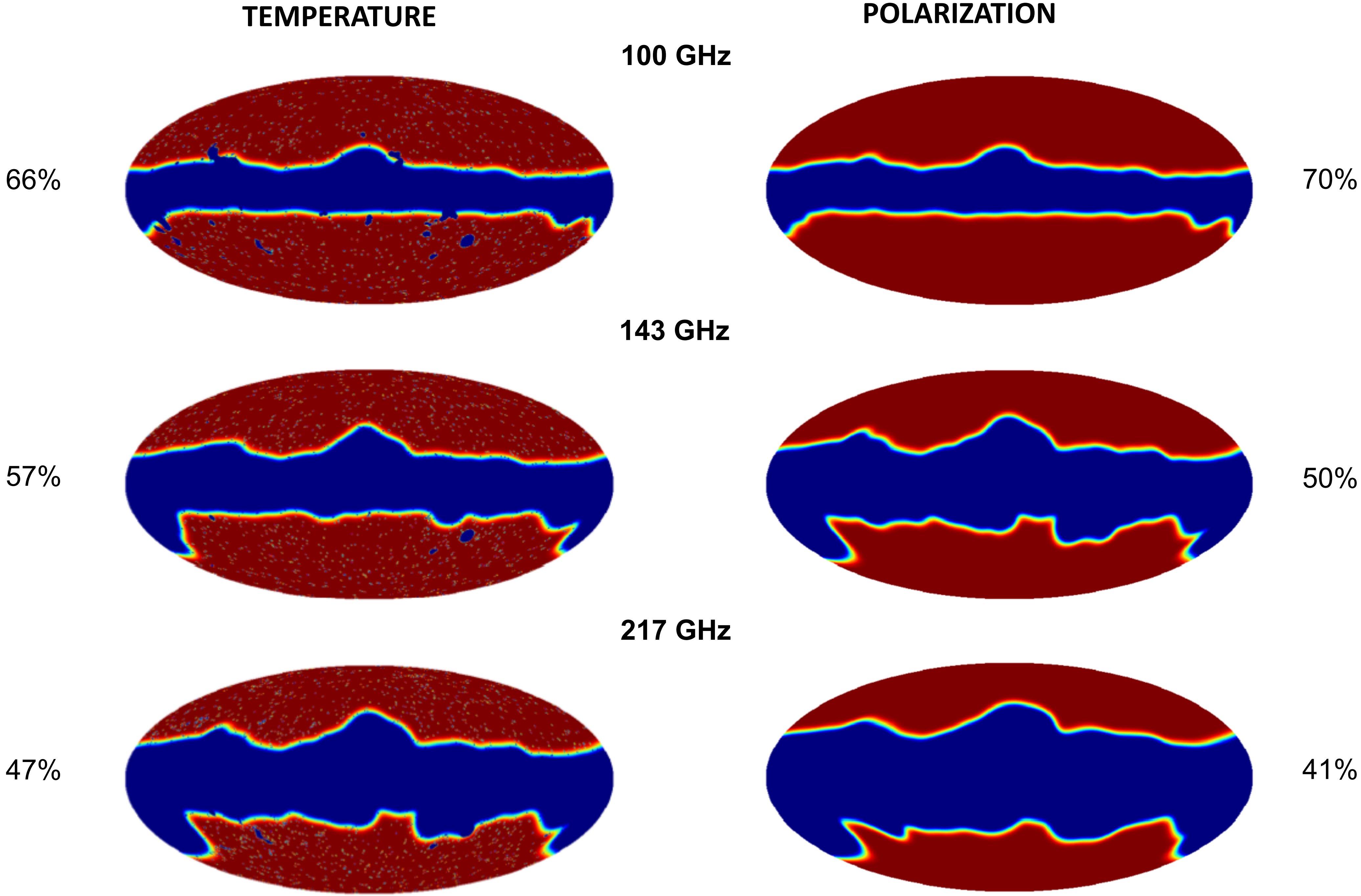
FULL PIXEL BASED GAUSSIAN LIKELIHOOD

$$\mathcal{L}(C_\ell) = \mathcal{P}(\boldsymbol{m}|C_\ell) = \frac{1}{2\pi|\mathsf{M}|^{1/2}} \exp\left(-\frac{1}{2}\boldsymbol{m}^{\mathsf{T}}\,\mathsf{M}^{-1}\boldsymbol{m}\right)$$

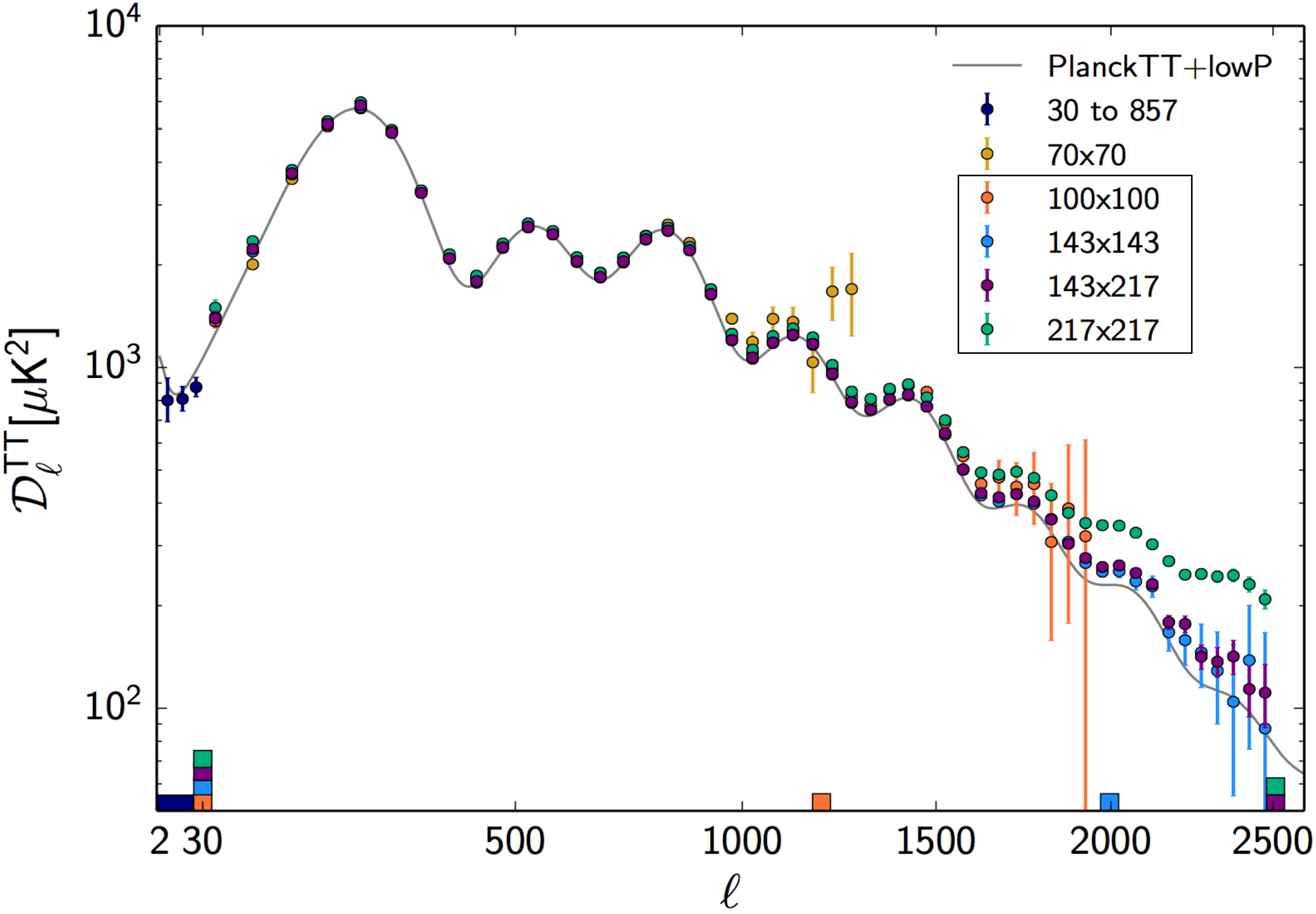


HIGH-ℓ LIKELIHOOD

MASKS

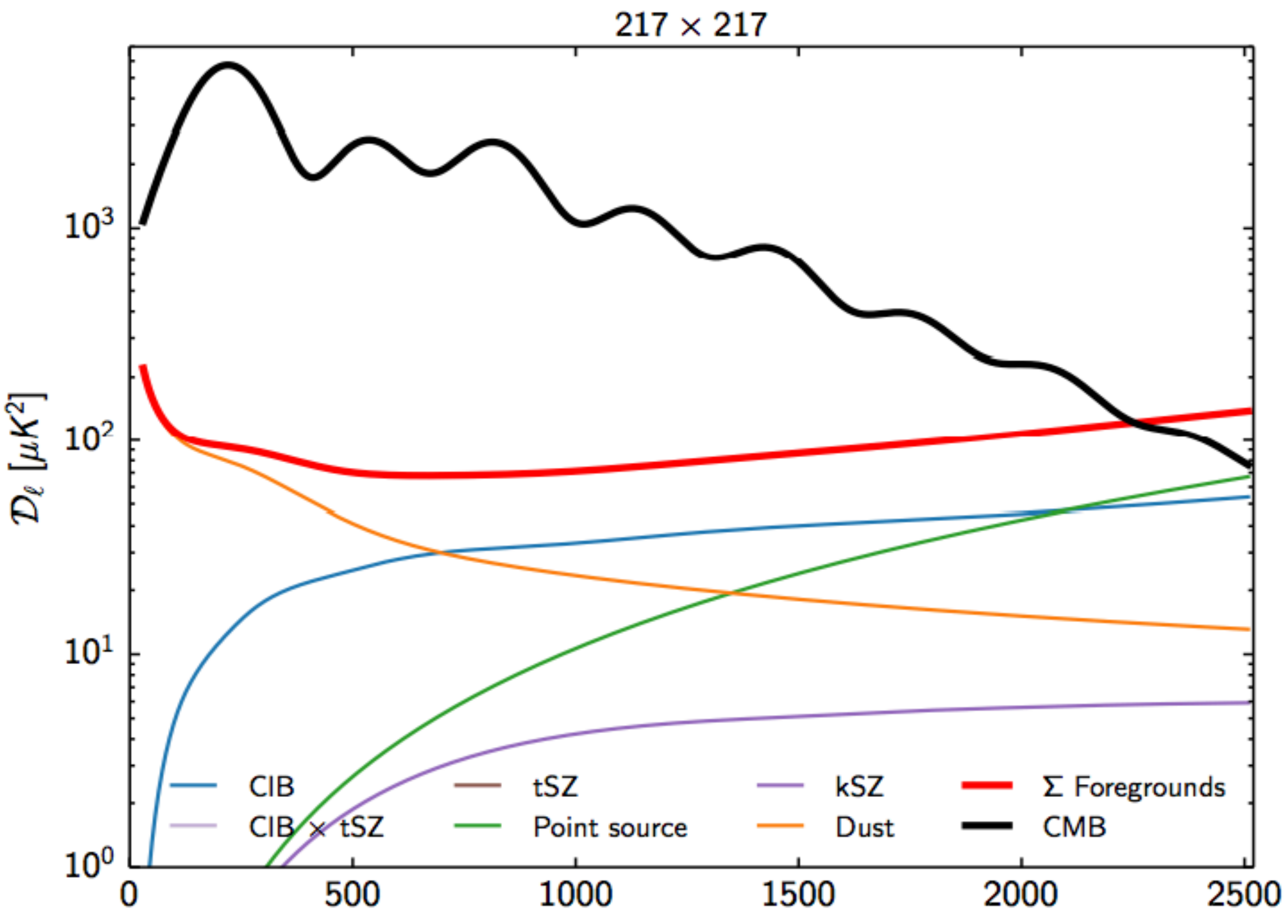

TEMPERATURE
POLARIZATION
100 GHz
66%
70%
143 GHz
57%
50%
217 GHz
47%
41%

Temperature Frequency Power Spectra



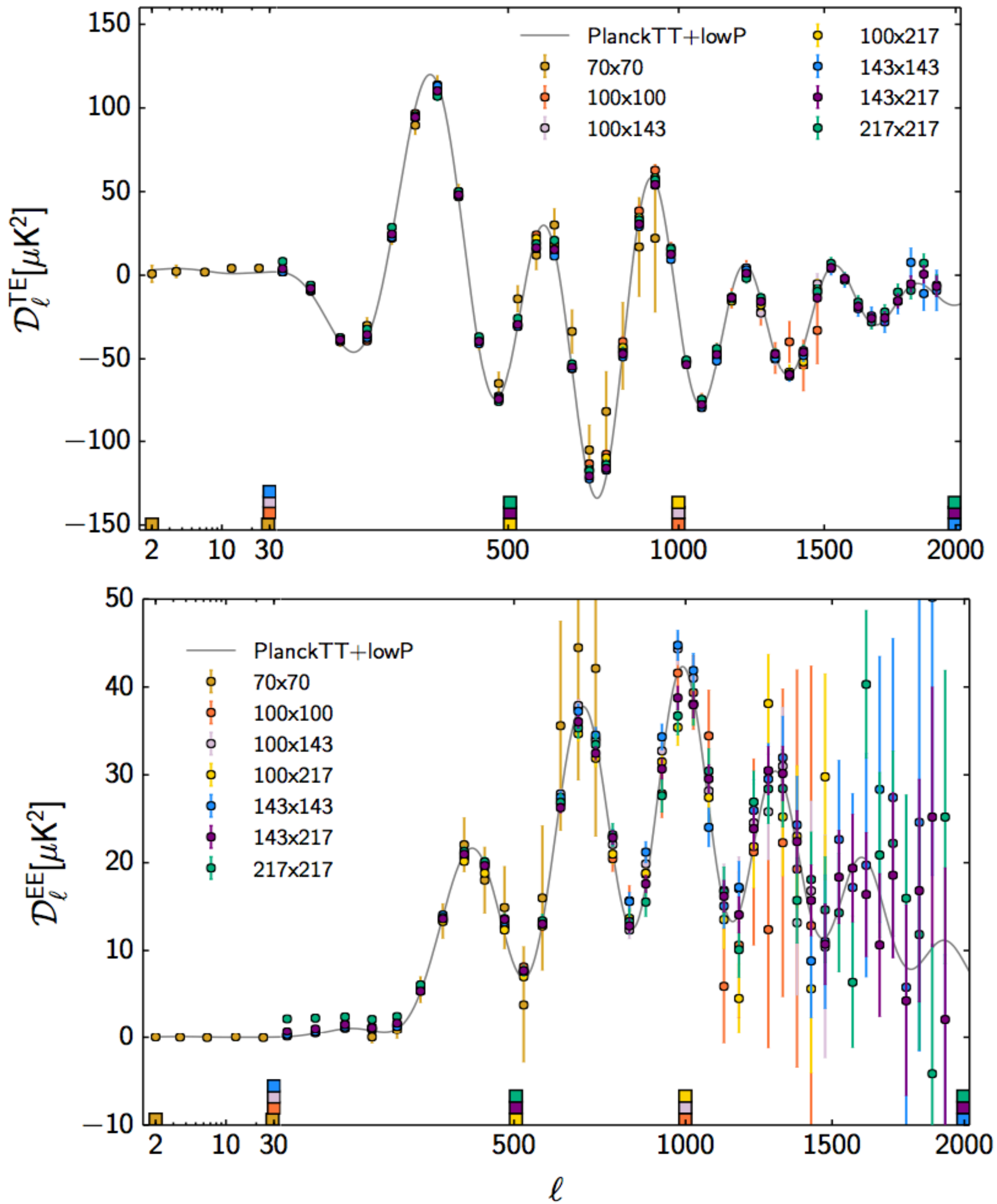
PARAMETRIC FOREGROUND MODEL

TEMPERATURE



12 foreground parameters in total for all the channels

Polarization Frequency Power Spectra



Extragalactic foregrounds are negligible (c.f. also SPT and ACT). Dust is the only component of the foreground model in polarization

$$C_\ell^{\mathrm{dust}} \propto \ell^{-2.4}$$

12 foreground parameters in total for all the channels

HIGH-ℓ LIKELIHOOD

- Compress data by computing the power spectra
- Analytical approximations to compute power spectrum covariance matrices
  - fiducial model spectra at each frequency (CMB + FGs)
  - model of noise
  - correction for point source leakage effect
  - beam error marginalization
- Construct a fiducial Gaussian likelihood

$$-\ln \mathcal{L}(\hat{\boldsymbol{C}}|\boldsymbol{C}(\theta)) = \frac{1}{2}\left[\hat{\boldsymbol{C}} - \boldsymbol{C}(\theta)\right]^{\mathrm{T}} \mathrm{C}^{-1}\left[\hat{\boldsymbol{C}} - \boldsymbol{C}(\theta)\right] + \text{const}$$

- θ = {Cosmological parameters, parametric foreground model to marginalize over (24 parameters), and calibration parameters (3 parameters)}

High-ℓ Likelihood

Large number of robustness checks:

- ✓ Different likelihood code implementations (Plik, CamSpec, Hillipop, Mspec, Xfaster)
- ✓ Different multipole range choices
- ✓ Removal of single frequencies
- ✓ Change the analysis masks
- ✓ Different foreground modeling: parametric vs map-based
- ✓ Validation on realistic Monte Carlo simulations

Base ΛCDM

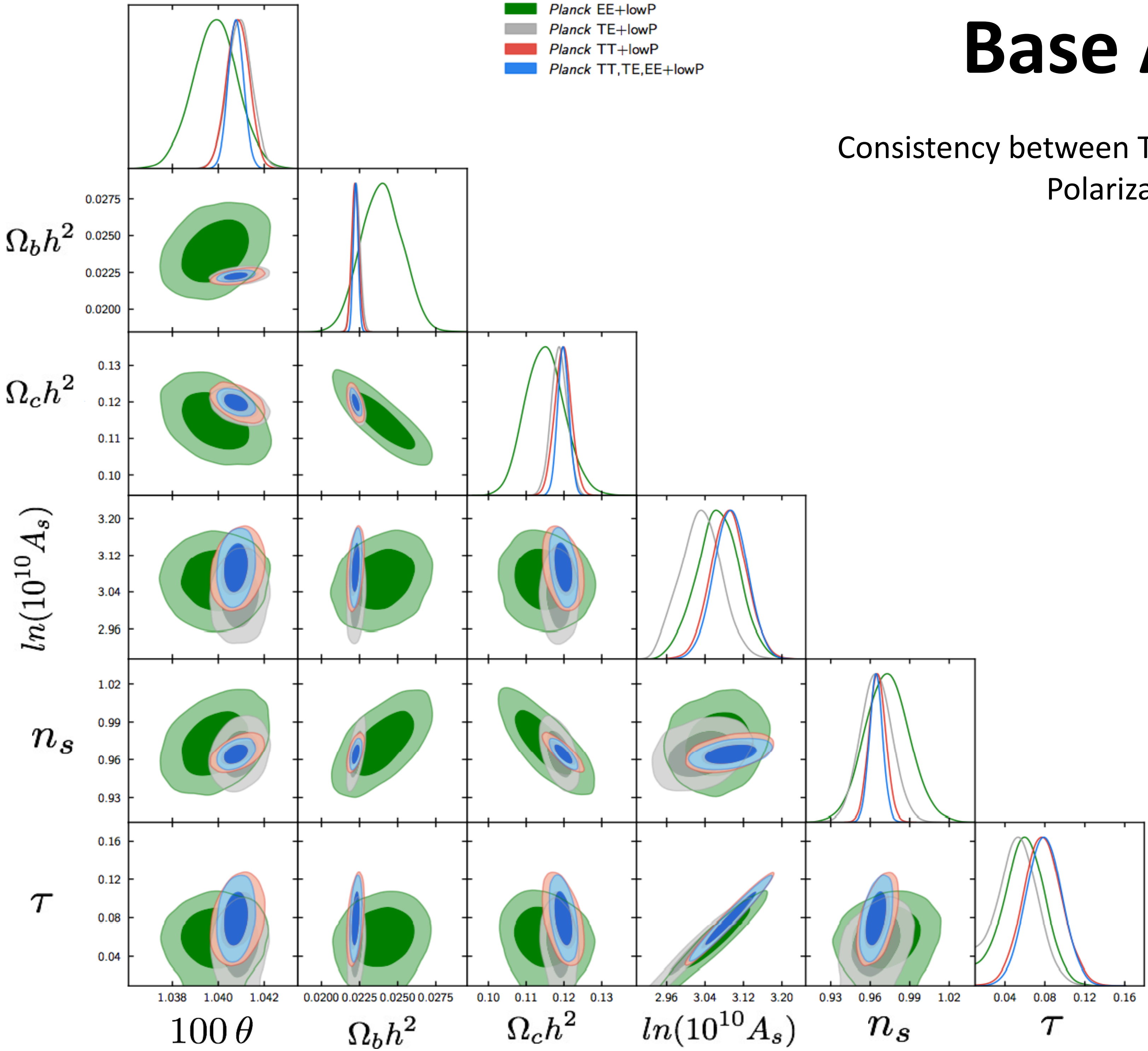
Good fit to the data
High precision parameter estimates even better than 1%

Parameter	[1] *Planck* TT+lowP	[2] *Planck* TE+lowP	[3] *Planck* EE+lowP	[4] *Planck* TT,TE,EE+lowP
$\Omega_b h^2$	0.02222 ± 0.00023	0.02228 ± 0.00025	0.0240 ± 0.0013	0.02225 ± 0.00016
$\Omega_c h^2$	0.1197 ± 0.0022	0.1187 ± 0.0021	$0.1150^{+0.0048}_{-0.0055}$	0.1198 ± 0.0015
$100\theta_{MC}$	1.04085 ± 0.00047	1.04094 ± 0.00051	1.03988 ± 0.00094	1.04077 ± 0.00032
τ	0.078 ± 0.019	0.053 ± 0.019	$0.059^{+0.022}_{-0.019}$	0.079 ± 0.017
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.031 ± 0.041	$3.066^{+0.046}_{-0.041}$	3.094 ± 0.034
n_s	0.9655 ± 0.0062	0.965 ± 0.012	0.973 ± 0.016	0.9645 ± 0.0049
H_0	67.31 ± 0.96	67.73 ± 0.92	70.2 ± 3.0	67.27 ± 0.66
Ω_m	0.315 ± 0.013	0.300 ± 0.012	$0.286^{+0.027}_{-0.038}$	0.3156 ± 0.0091
σ_8	0.829 ± 0.014	0.802 ± 0.018	0.796 ± 0.024	0.831 ± 0.013
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014	1.865 ± 0.019	1.907 ± 0.027	1.882 ± 0.012

Almost independent determinations from polarized spectra - **good consistency**
TT → EE at most 1σ shifts
TT → TE at most 0.5σ shifts
TE results are already almost as powerful as TT

Base ΛCDM

Consistency between Temperature and Polarization parameters

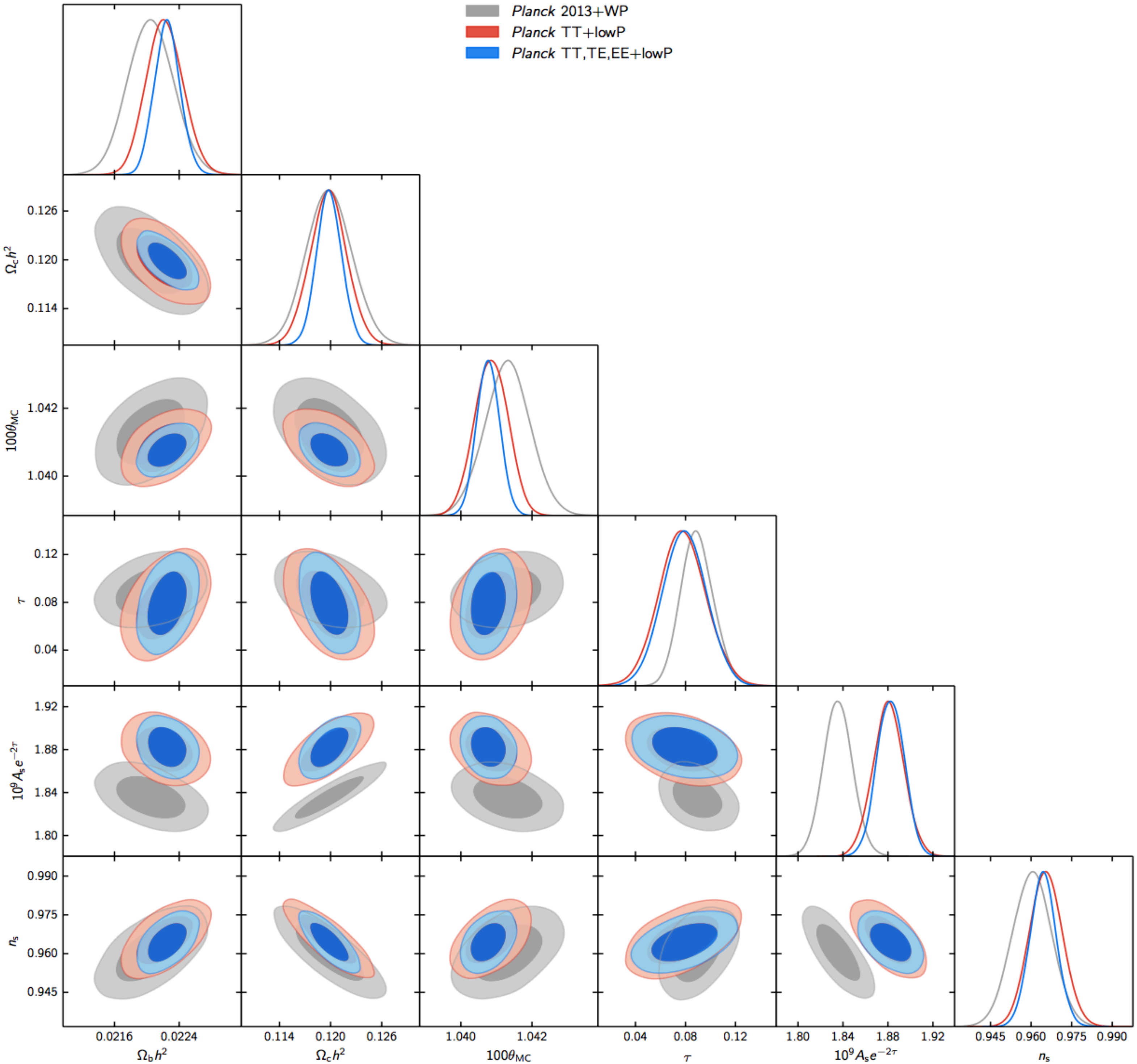


GOING FROM 2013 TO 2015

TEMPERATURE

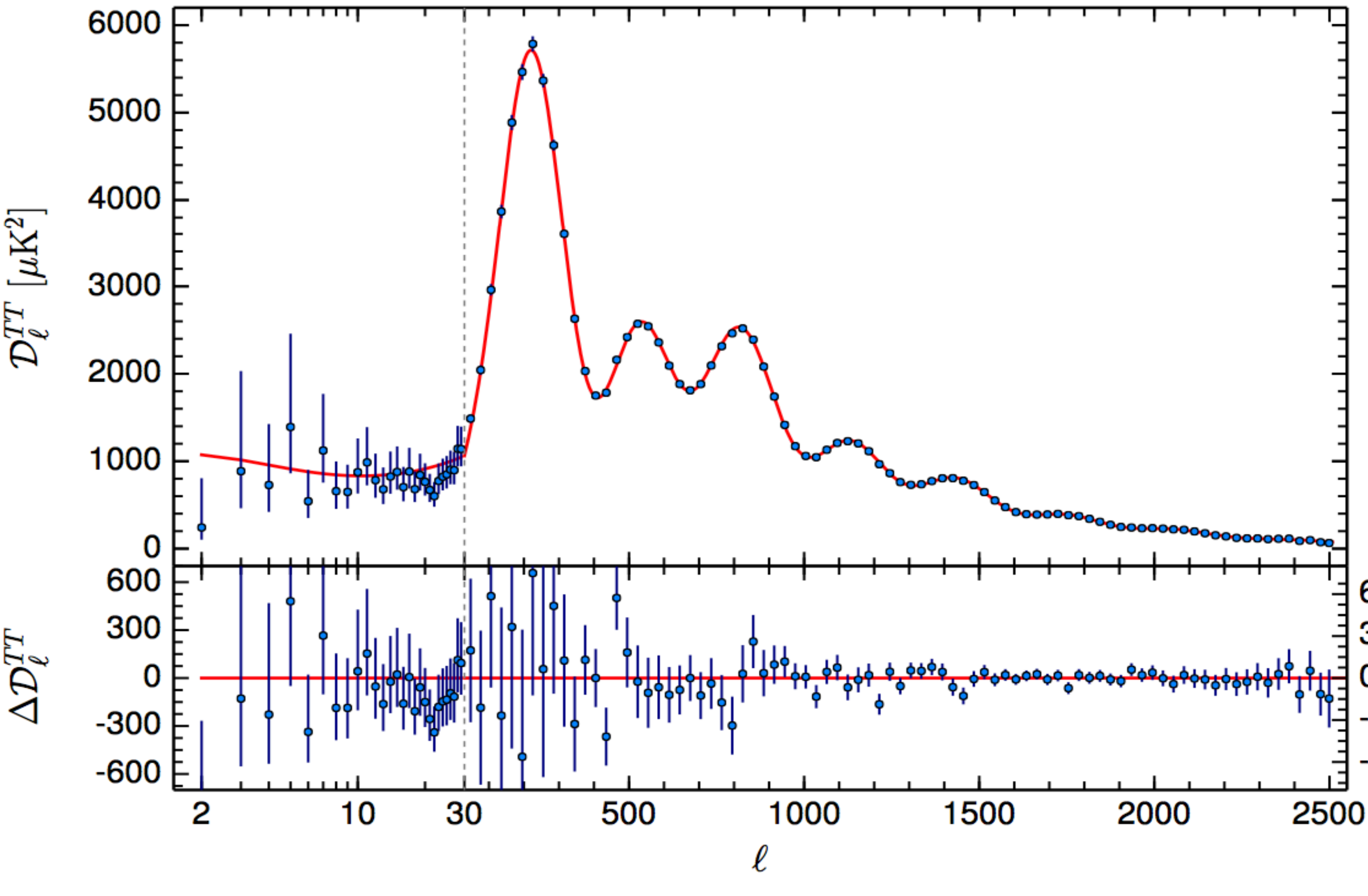
[1] Parameter	[2] 2013N(DS)	[6] 2015F(CHM) (Plik)	$([2]-[6])/\sigma_{[6]}$
$100\theta_{MC}$	1.04131 ± 0.00063	1.04086 ± 0.00048	0.71
$\Omega_b h^2$	0.02205 ± 0.00028	0.02222 ± 0.00023	−0.61
$\Omega_c h^2$	0.1199 ± 0.0027	0.1199 ± 0.0022	0.00
H_0	67.3 ± 1.2	67.26 ± 0.98	0.03
n_s	0.9603 ± 0.0073	0.9652 ± 0.0062	−0.67
Ω_m	0.315 ± 0.017	0.316 ± 0.014	−0.06
σ_8	0.829 ± 0.012	0.830 ± 0.015	−0.08
τ	0.089 ± 0.013	0.078 ± 0.019	0.85
$10^9 A_s e^{-2\tau}$	1.836 ± 0.013	1.881 ± 0.014	−3.46

- Improved TOI processing
- Improved calibration and beam description
- Better handling of 4K lines systematics
- Full Mission Data
- Increase in sky area
- Correction of low level correlated noise between detectors (cross half-mission maps)
- Refined foreground treatment (dust at all frequencies, new CIB model, …)
- Alternate Likelihood code
- New Planck low-ell likelihood

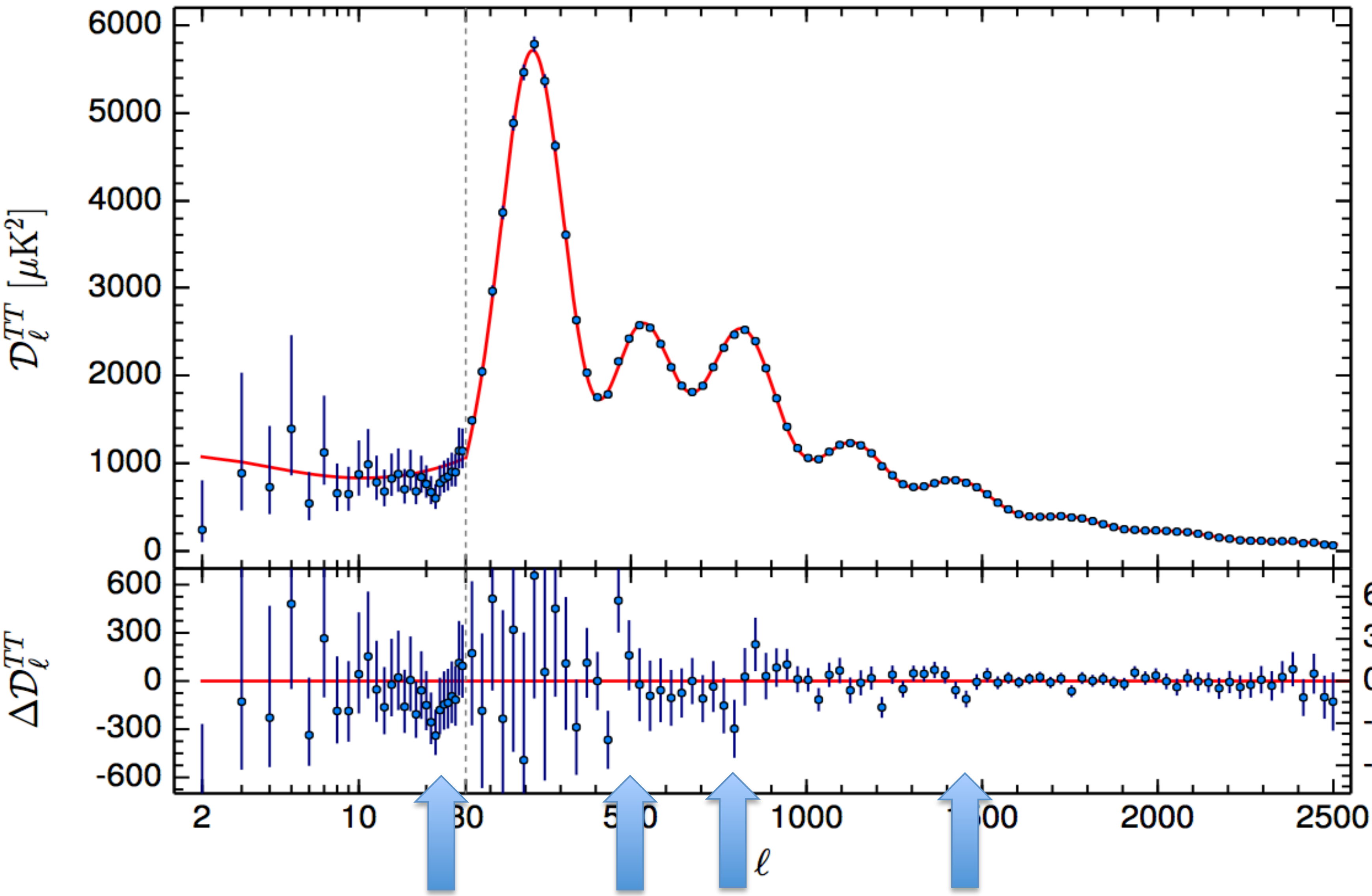


Planck 2013+WP
Planck TT+lowP
Planck TT,TE,EE+lowP
$\Omega_c h^2$
$100\theta_{MC}$
τ
$10^9 A_s e^{-2\tau}$
n_s
$\Omega_b h^2$
0.0216 0.0224
0.114 0.120 0.126
1.040 1.042
0.04 0.08 0.12
1.80 1.84 1.88 1.92
0.945 0.960 0.975 0.990

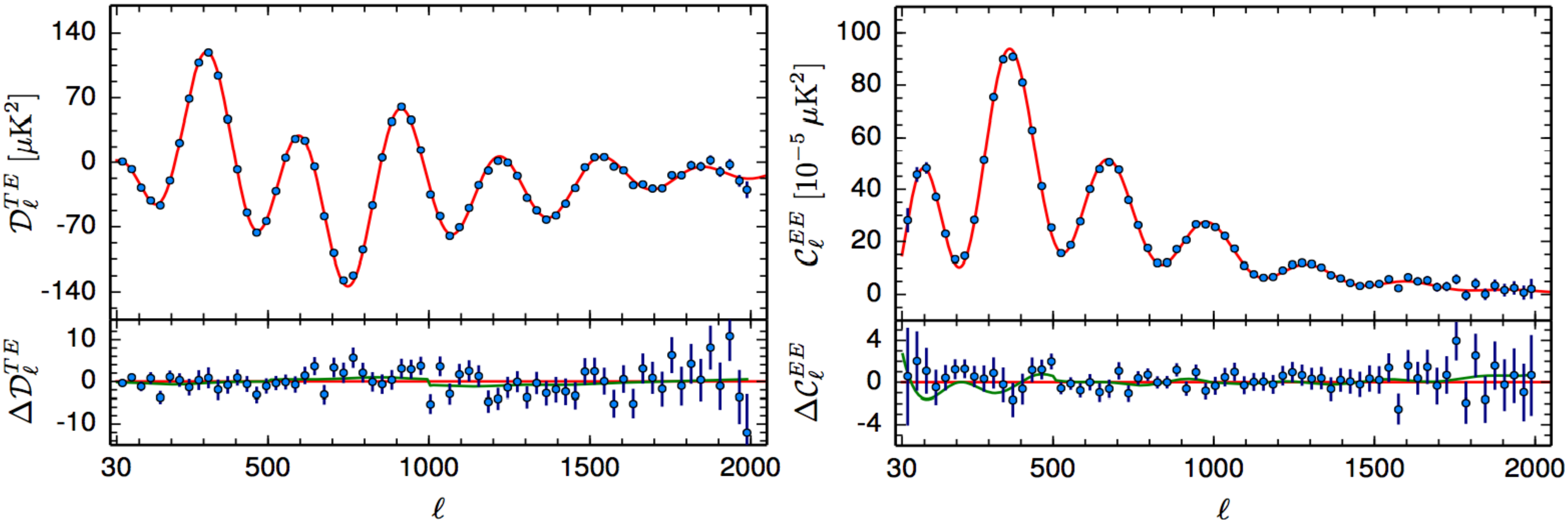
TEMPERATURE BEST FIT POWER SPECTRUM



TEMPERATURE BEST FIT POWER SPECTRUM



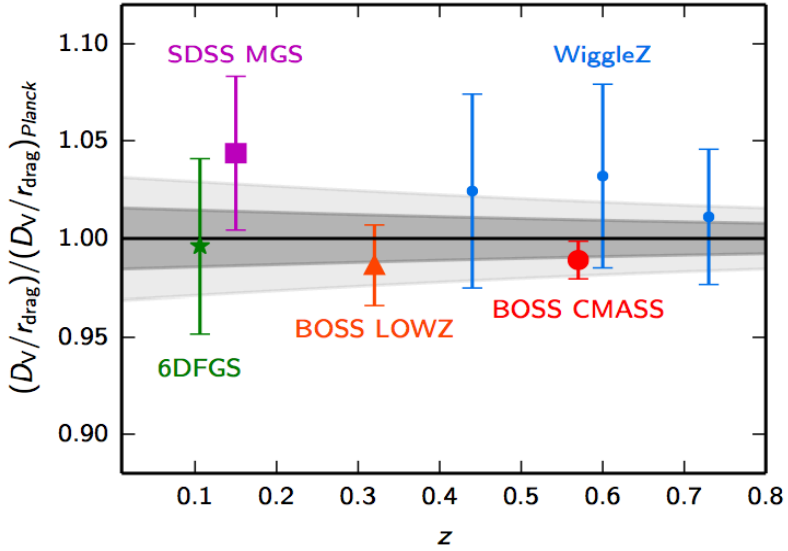
POLARIZATION BEST FIT POWER SPECTRA



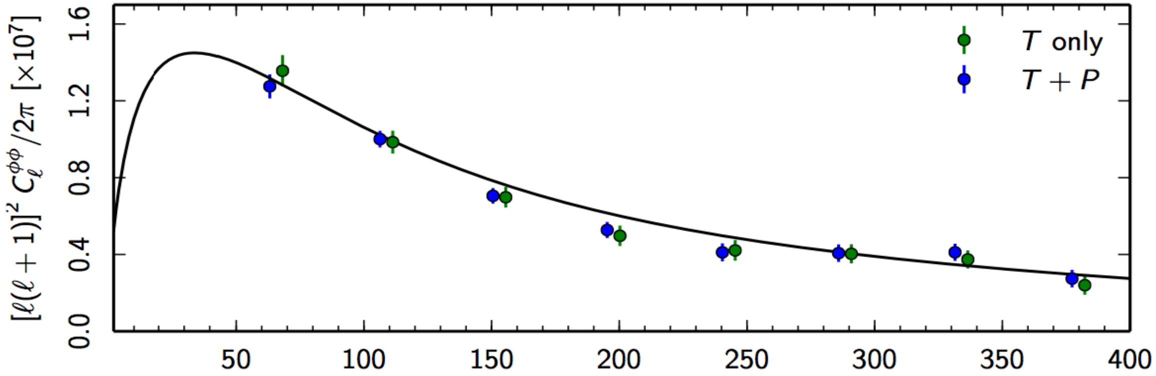
Residual low level systematics are still present (e.g., T → P leakage,…)

Other datasets

BAO



Lensing



H_0 prior (70.6±3.3) km s^{-1} Mpc^{-1} (Efstathiou 2014, reanalysis of Reiss et al 2011)

JLA Type Ia SuperNova (SNLS + SDSS + low-z SNe)

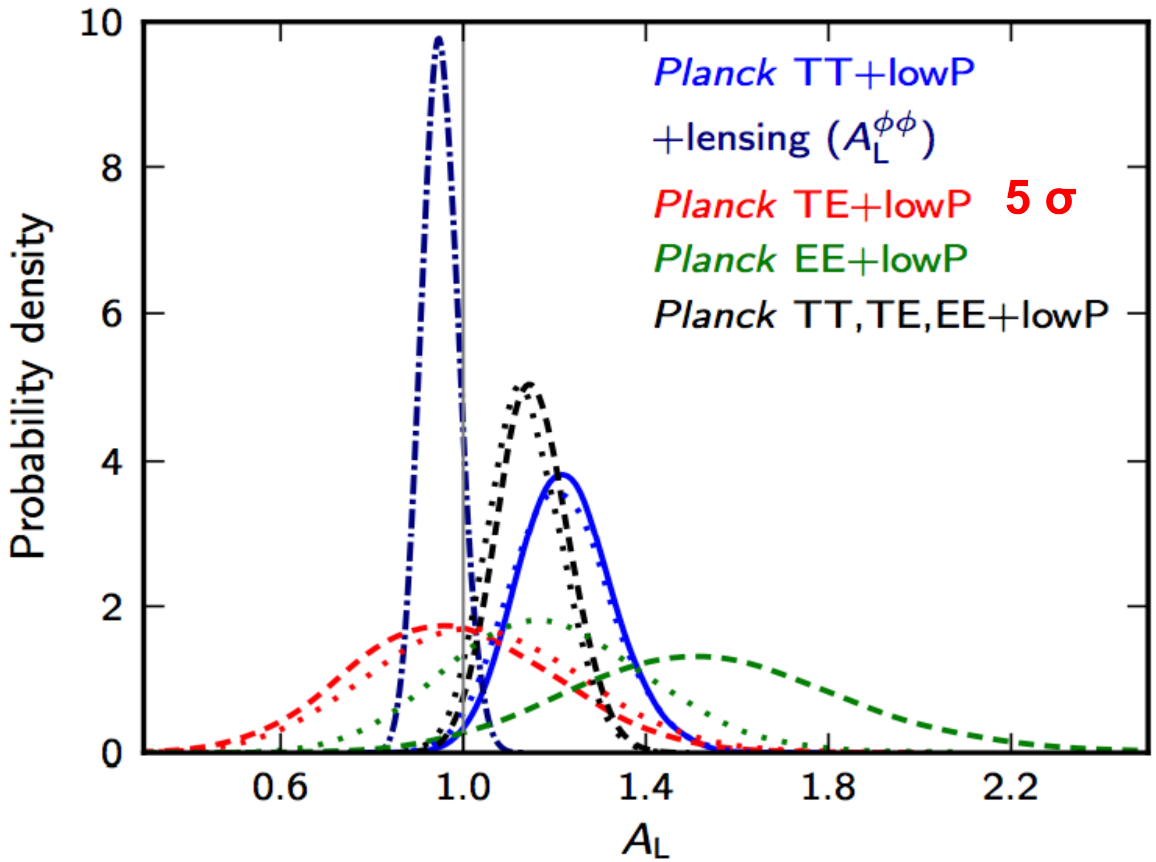
Provide sensitivity to parameters affecting the late-time expansion, geometry, and matter clustering
→ they break degeneracies in the CMB alone analysis

a lensing conundrum

$$A_L = 1.22 \pm 0.10$$
$$A_L^{\phi\phi} = 0.95 \pm 0.04$$

A larger amount of lensing helps to fit the spectra at $\ell \sim 1300 - 1500$. Opening up A_L the CMB solution tries to fit the power deficit in the TT power spectrum at low multipoles and around the second peak.

First detection of lensing in polarization spectra



Dotted curves from Camspec

Planck EE results still not completely robust

POLARIZATION AND REIONIZATION

In 2015 new low-ℓ likelihood entirely based on Planck polarization data

Planck TT + lowP + lensing + BAO

$$\tau = 0.066 \pm 0.013$$

$$z_{\rm re} = 8.8^{+1.3}_{-1.2}$$

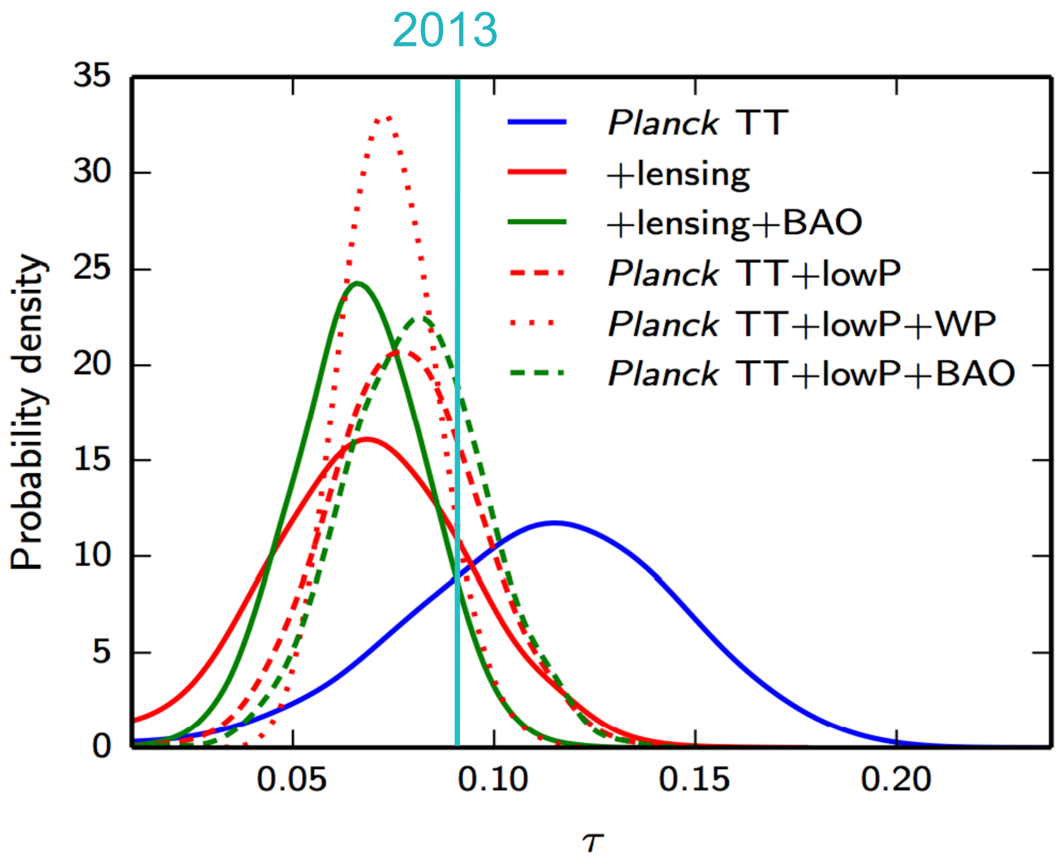
Optical depth and reionization redshift lower than with WMAP's polarization

(2013)

$$z_{\rm re} = 11.1 \pm 1.1$$

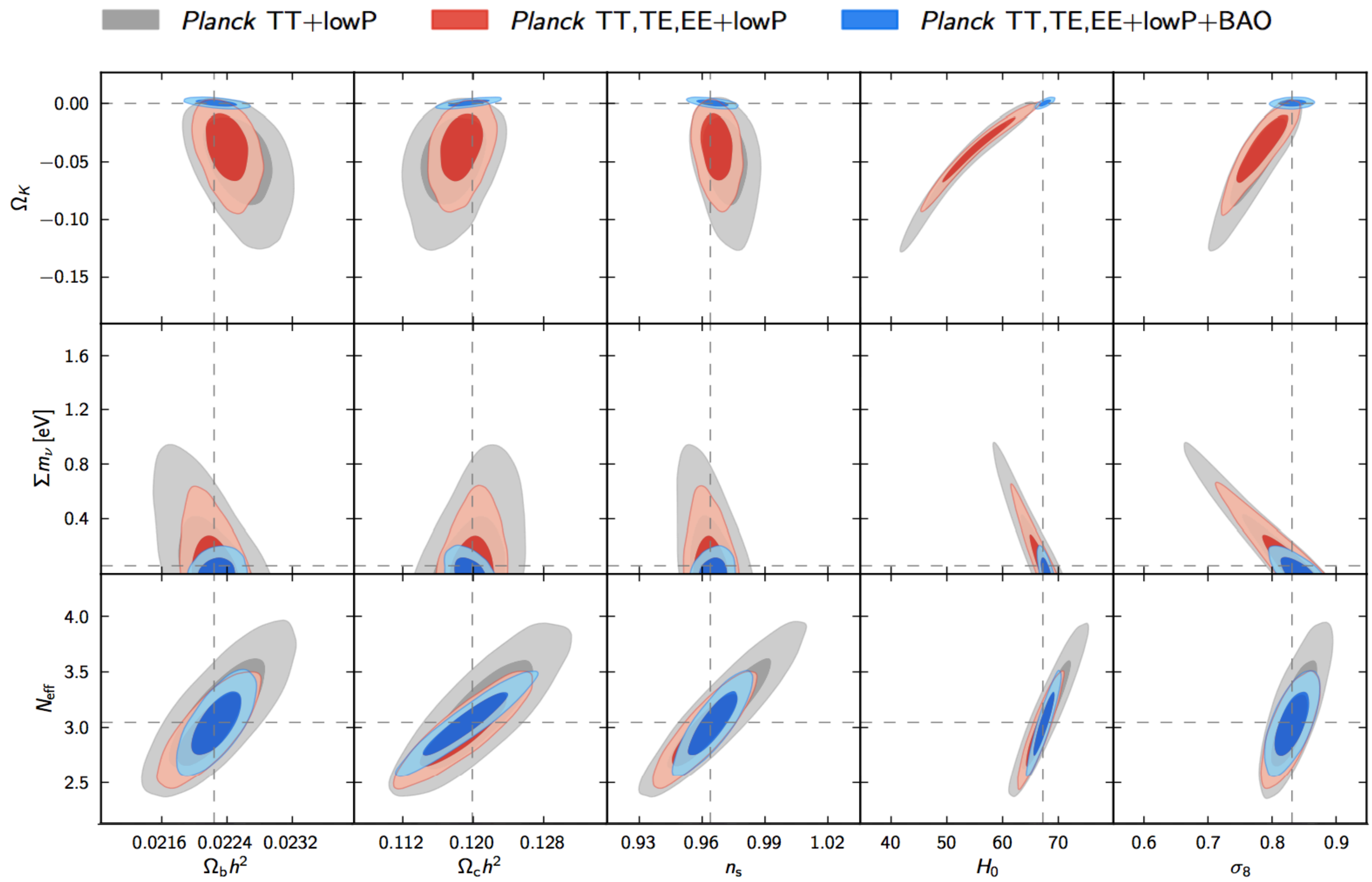
agreement with astrophysical observations and models of galaxy formation

Note: when we clean the dust in WMAP with 353 GHz we get a lower tau value compatible with Planck



Coming soon : tau from HFI polarization data!!

EXTENSIONS TO BASE ΛCDM



Neutrinos

Σm_ν [eV] (95% CL)	2013	2015	2015 + TE, EE
PlanckTT+lowP	< 0.933	< 0.715 (23%)	< 0.492 (46%)
PlanckTT+lowP+lensing	< 1.110	< 0.675 (38%)	< 0.589 (46%)
PlanckTT+lowP+BAO	< 0.247	< 0.214 (16%)	< 0.168 (32%)
PlanckTT+lowP+ext		< 0.197	< 0.153
PlanckTT+lowP +lensing+ext		<0.234	<0.194

In 2015 higher S/N spectra at high-ell plus polarization data → better constraints on lensing.

A_L problem: the mild tension between lensing from CMB spectra and lensing reconstruction limits the improvement in neutrino mass from CMB+lensing

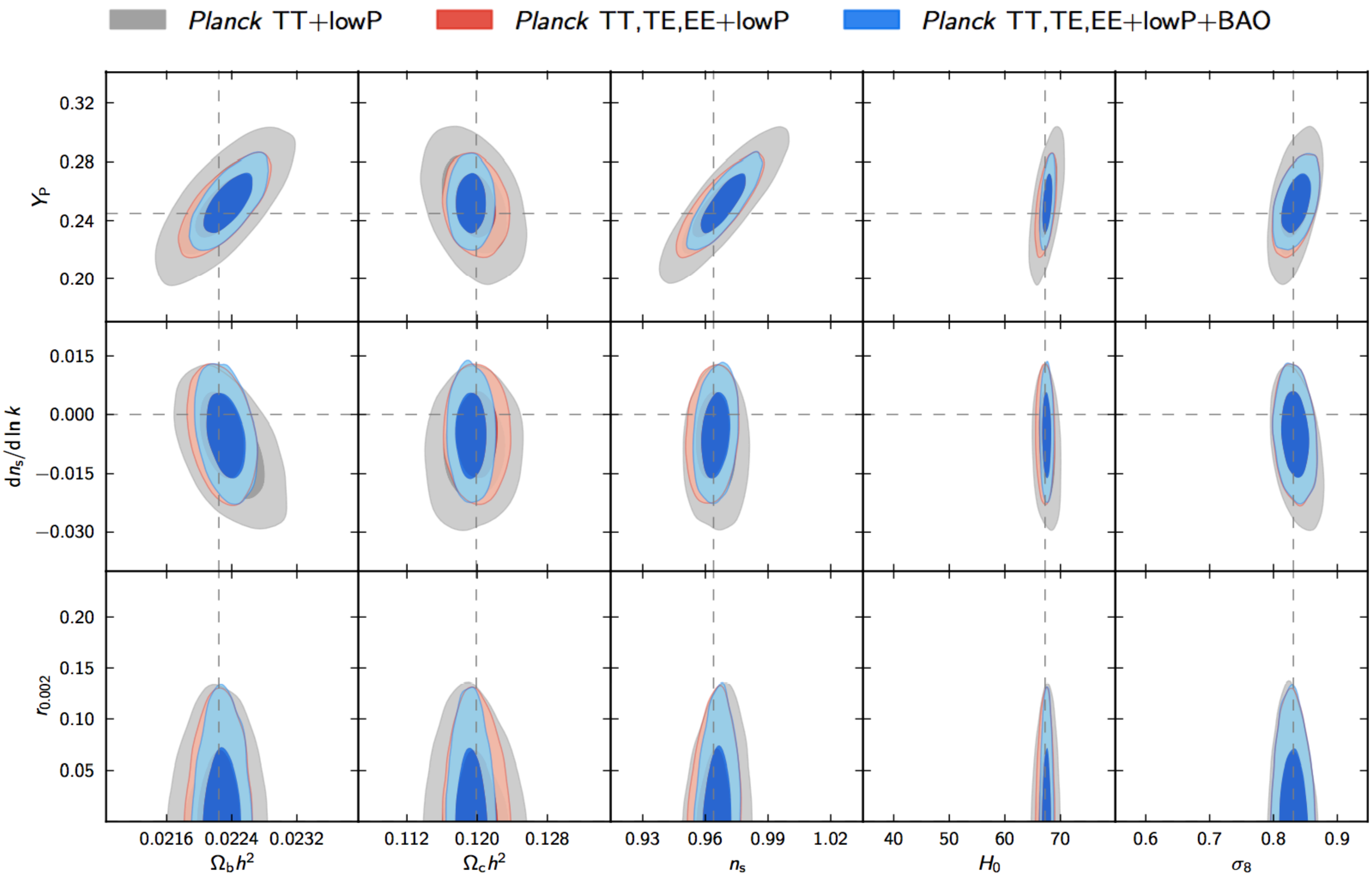
However, constraints are already better than the expected sensitivity by the KATRIN experiment (~ 0.2 eV)

Planck measures **N_{eff}** in perfect agreement with the standard value

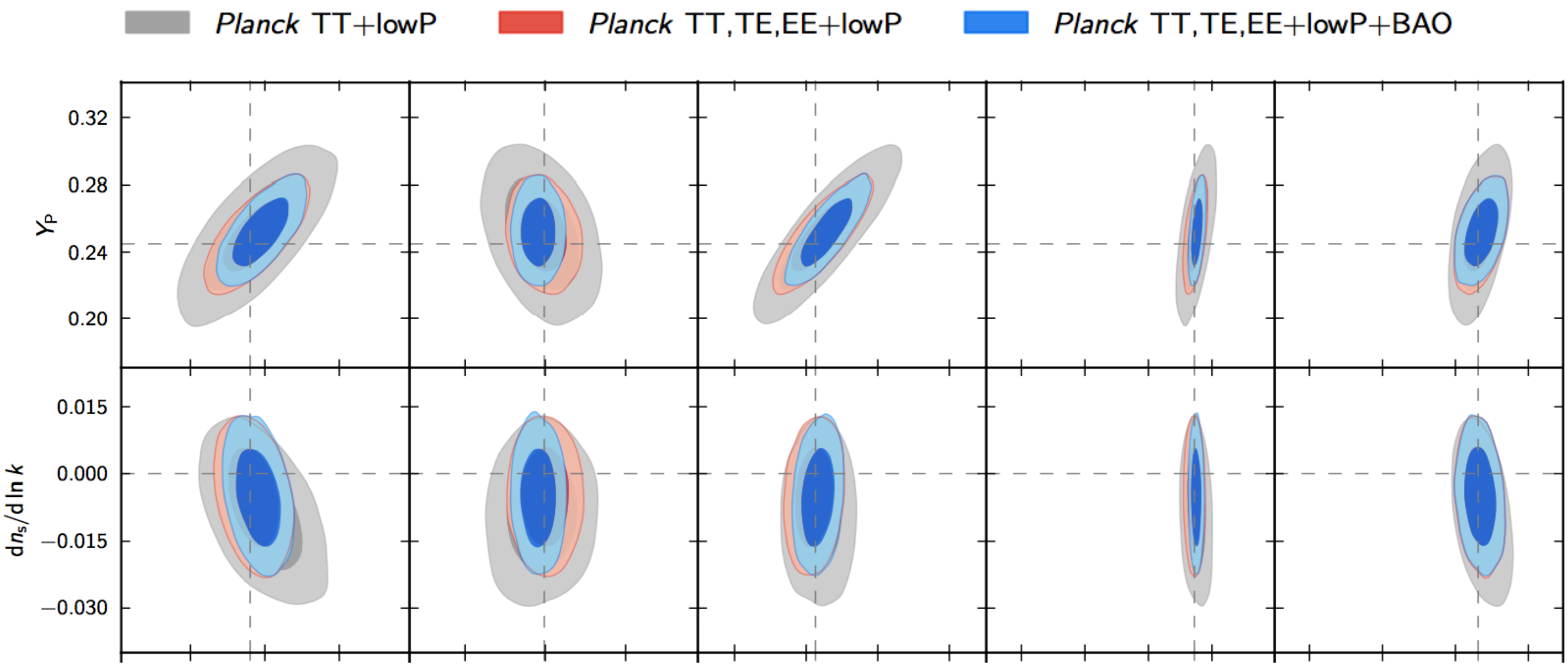
$N_{eff} > 0$ confirmed at ~ 15σ

$N_{eff} = 4$ excluded at ~ 3σ

Extensions to base ΛCDM



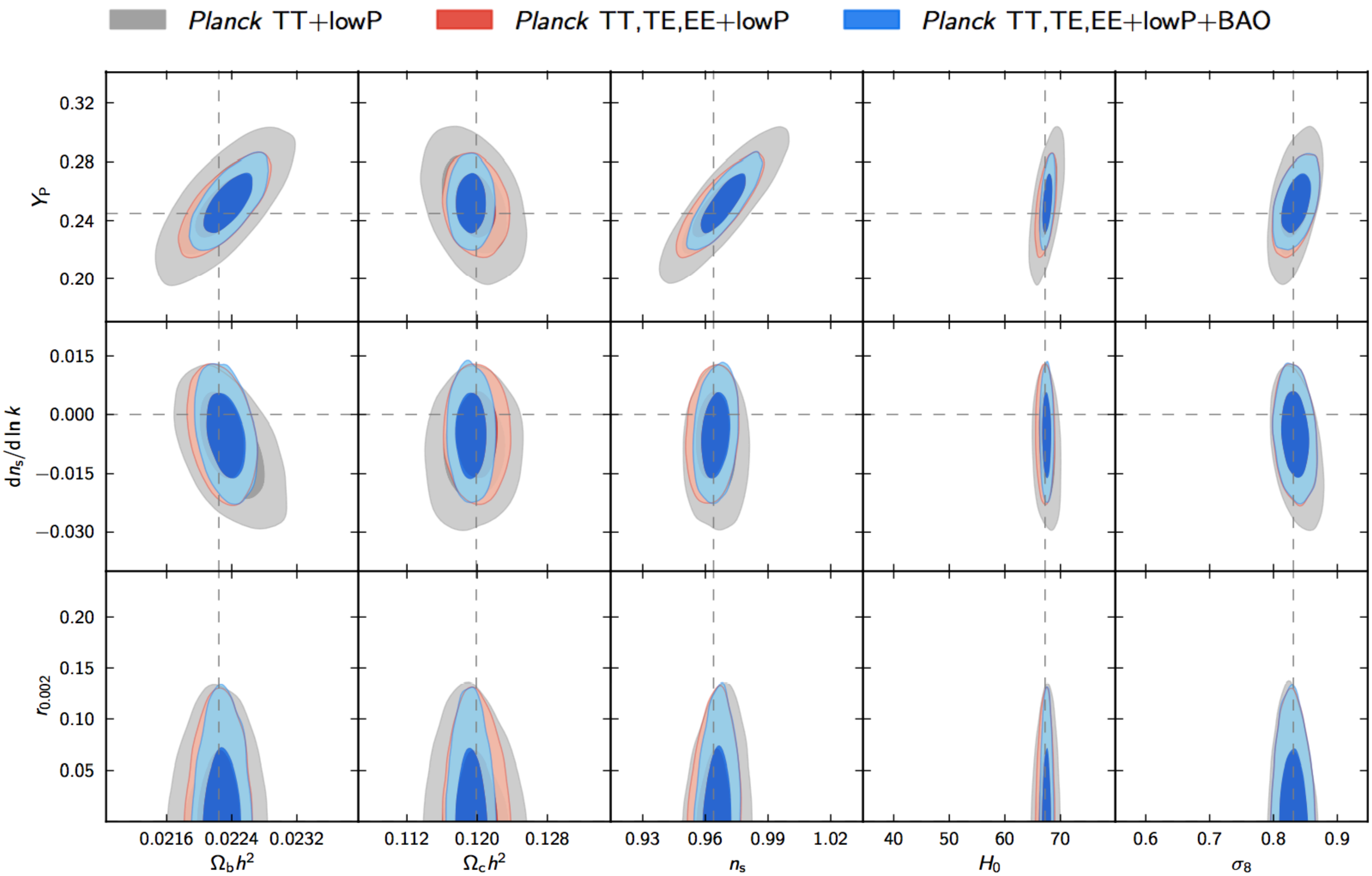
Extensions to base ΛCDM



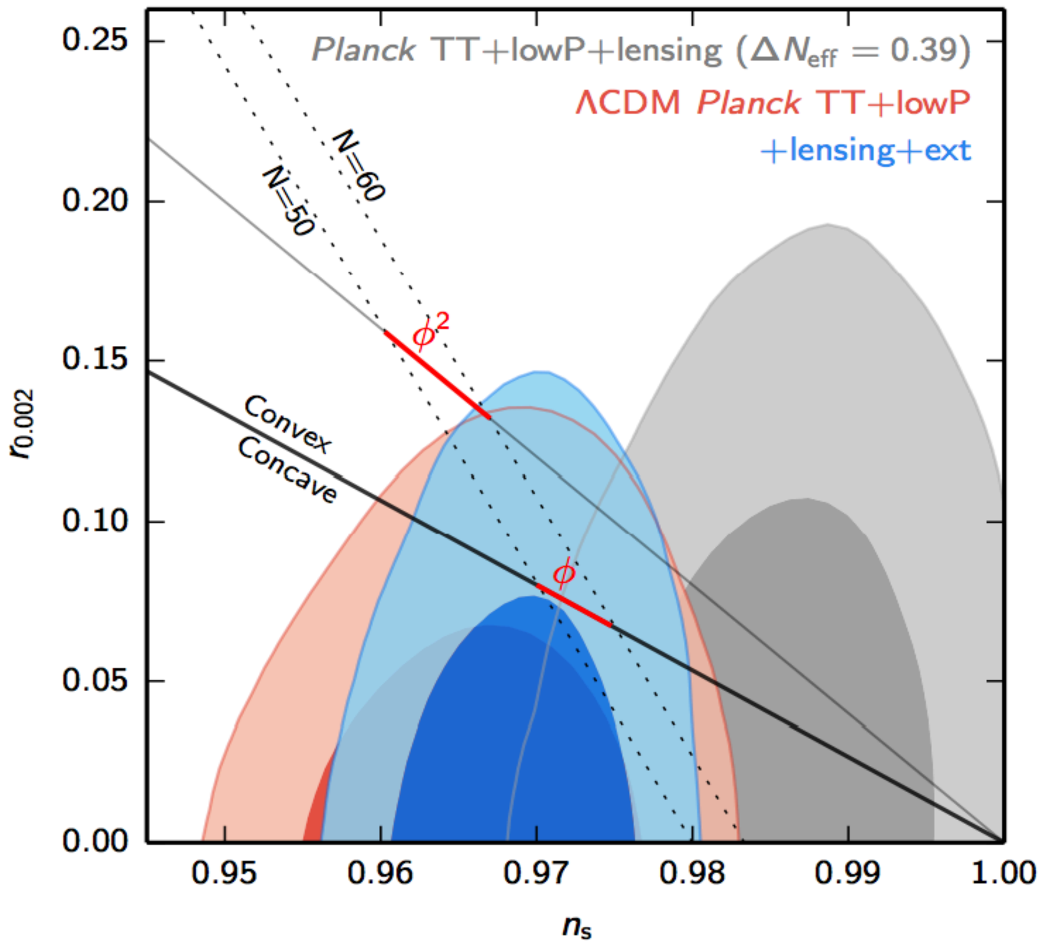
Planck data allow for value an order of magnitude higher than expected in single field models of inflation, where the running of the spectra index is of second order in inflationary slow-roll parameters

$$\left|\frac{dn_s}{dlnk}\right| \approx (n_s - 1)^2 \approx 10^{-3}$$

EXTENSIONS TO BASE ΛCDM



Upper limits on primordial tensor modes. The constraints from Planck are already cosmic variance limited. They are also model dependent. To improve we need direct detection of primordial B-modes. Quite a number of sub-orbital experiments are ongoing or planned in the coming years, there is potential for breakthroughs



Dark Energy?

$$w = w_0 + (1 - a)w_a.$$

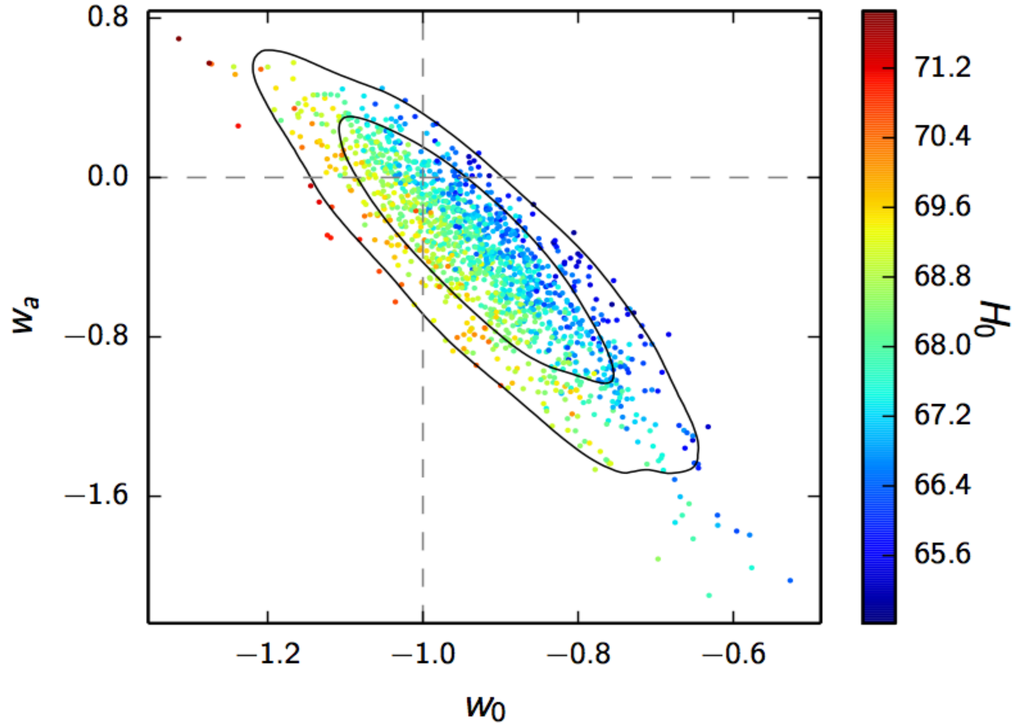
$$w = -1.54^{+0.62}_{-0.50} \quad (95\%, \textit{Planck}\ \mathrm{TT{+}lowP})$$

Planck alone is about 2σ away from the standard result

- Strong geometrical degeneracy
- Partially a parameter volume effect
- Partially same pull as for A_L

$$\Delta\chi^2 \approx 2$$

But if we add external datasets, we get a
good agreement with the cosmological constant scenario



Cf. Planck 2015 results. XIV.

Conclusions

- ✓ Planck data are more precise than those from any previous CMB experiment
- ✓ Cosmological parameters at unprecedented (sub-%) precision from the 2015 analysis
- ✓ First results from polarization in agreement with temperature
- ✓ Some low level systematics in polarization that will be better characterized in the next release, including also a low-ℓ analysis of HFI
- ✓ Yet we find no compelling evidence for new physics beyond the base inflationary ΛCDM model of Cosmology

  –> if there are deviations they ought to be small and challenging to detect
- ✓ There are, however, some anomalies (A_L, Ω_k, $dn_s/d\ln k$, power deficit at large angular scales)
- ✓ And some tension with astrophysical datasets on σ_8 (but see also Alexandre's talk)

Acknowledgements: the scientific results presented here are a product of the Planck Collaboration, including individuals from more than 100 institutes in Europe, the USA and Canada.

THANK YOU