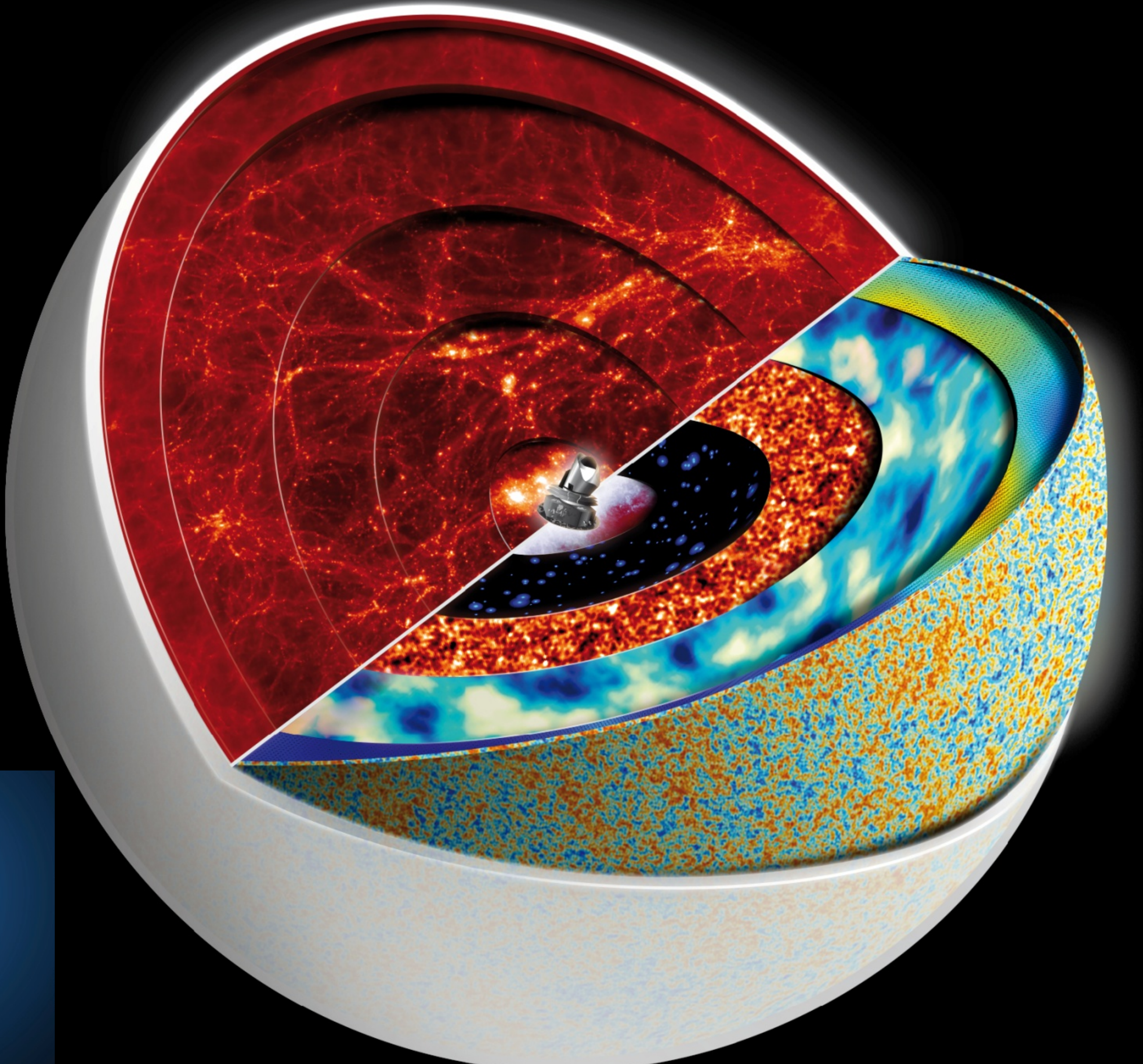
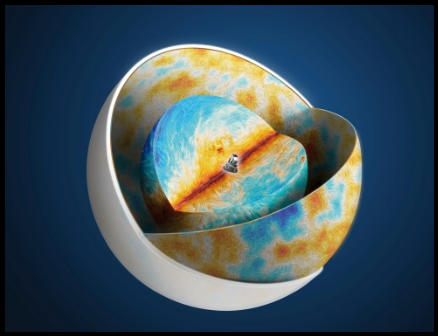
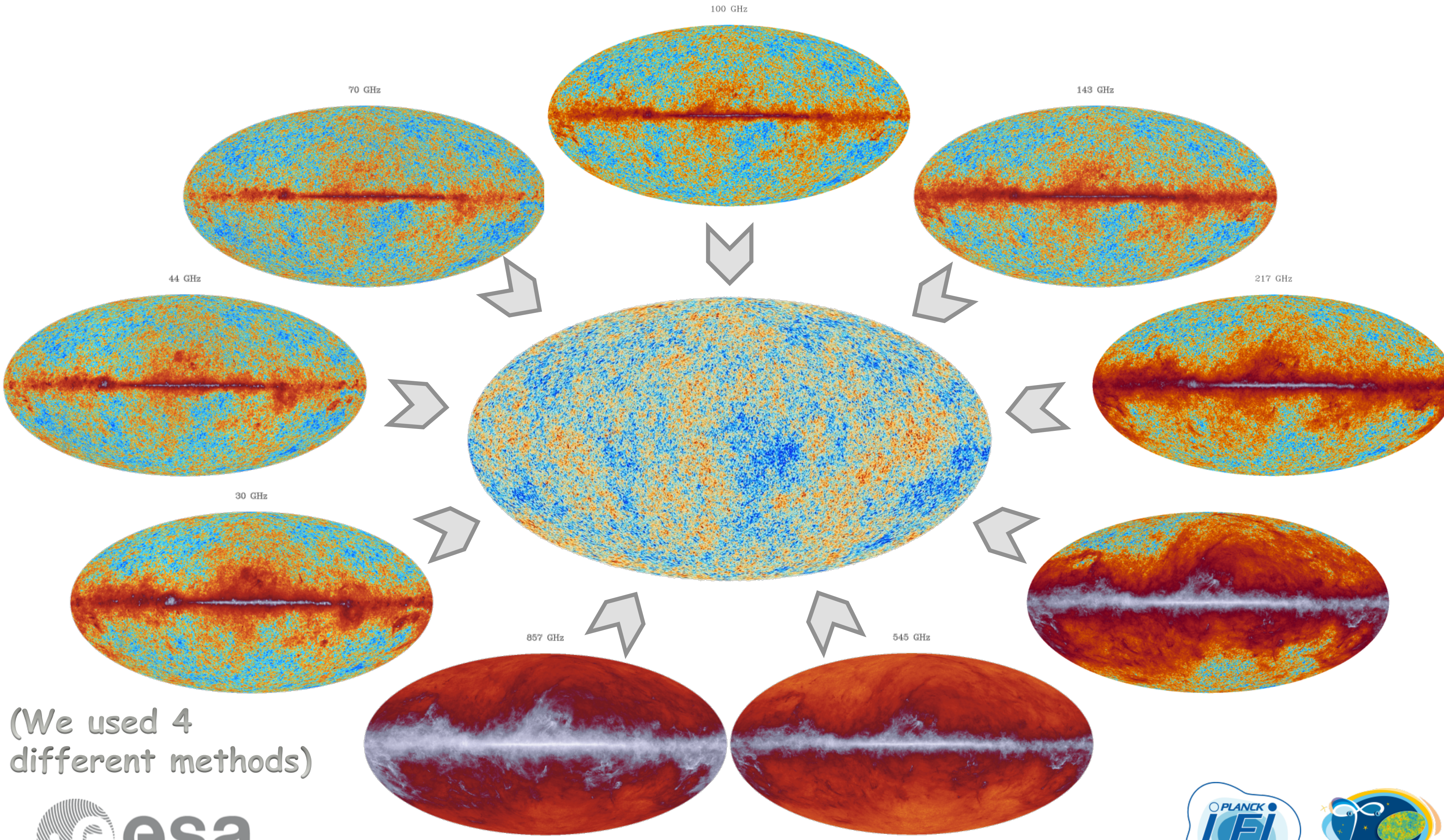
Planck CMB cosmology





François R. Bouchet, on behalf of the Planck Collaboration

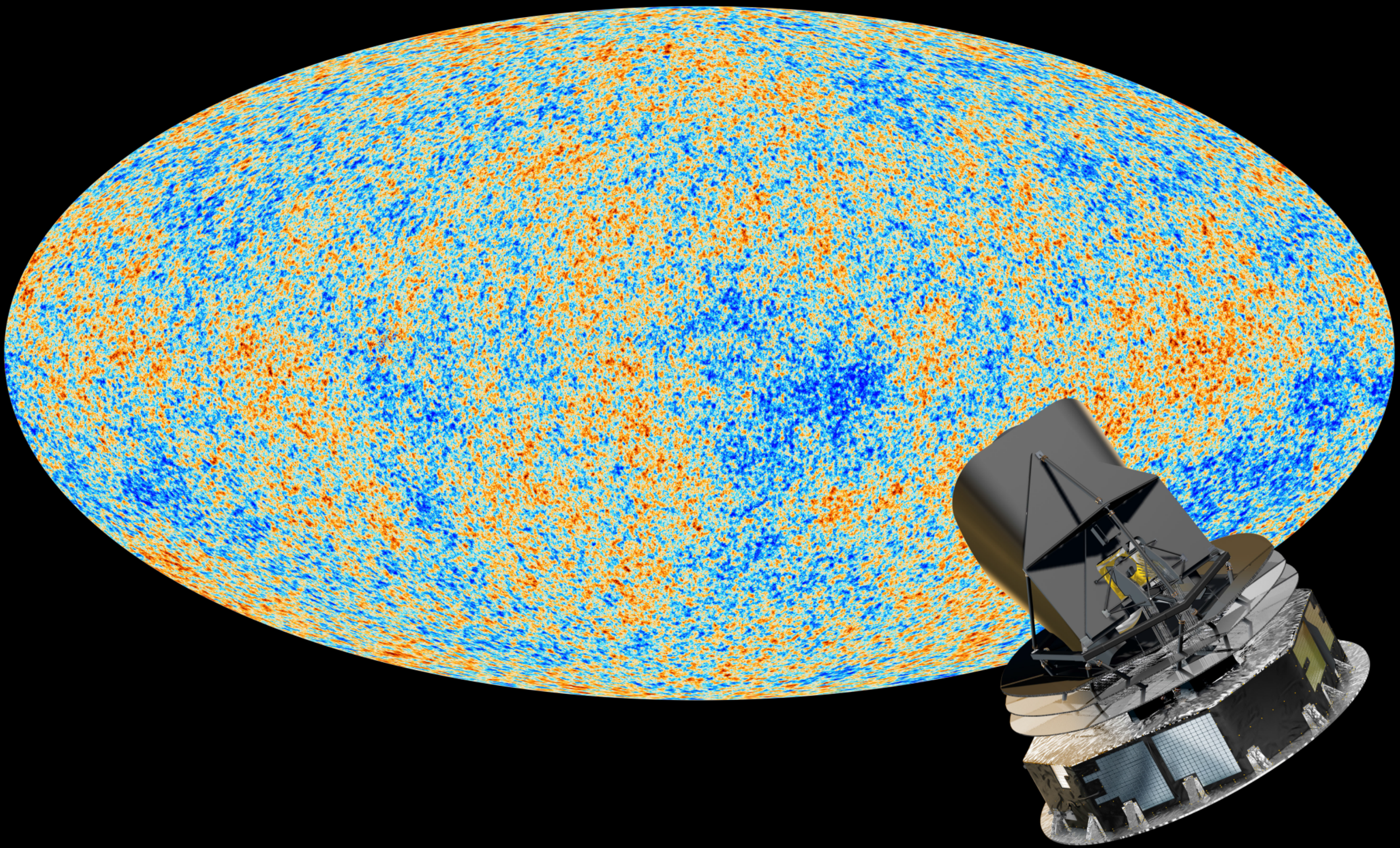
Cleaning the background from its 7 veils



(We used 4 different methods)

3% of the CMB sky replaced by a Gaussian Random realisation

Planck’s exhaustive temperature anistropies map



A theories-measurements contact

The harmonic modes

$$a_{lm} = \int d^2\hat{n}\, T(\hat{n})\, Y^*_{lm}(\hat{n}) \quad ,$$

obey, for a statistically isotropic field,

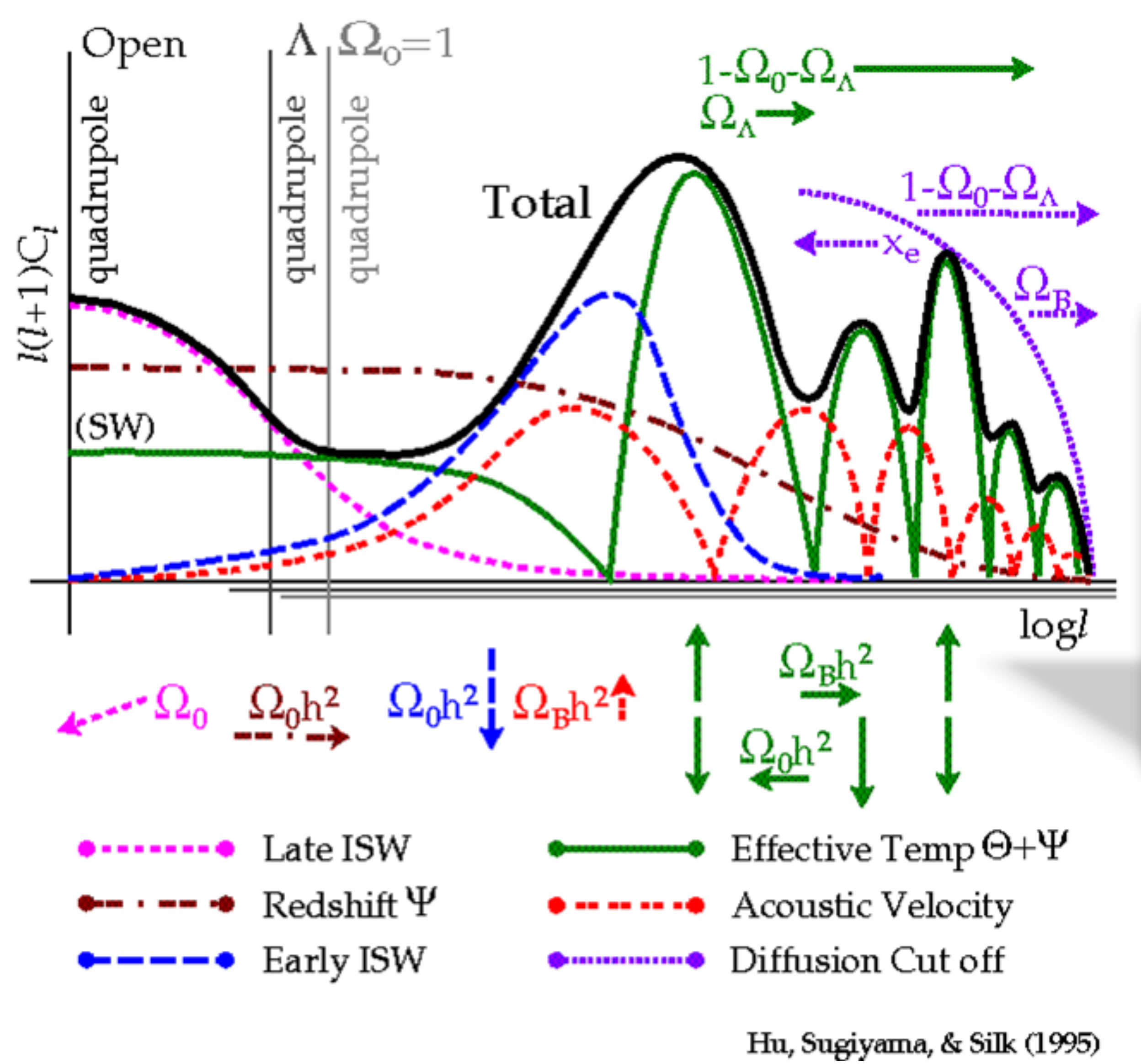
$$< a_{\ell m}\, a_{\ell' m'} > = C_\ell\, \delta_{\ell\ell'}\, \delta_{mm'}$$

The temperature angular **power spectrum** is estimated in practice by

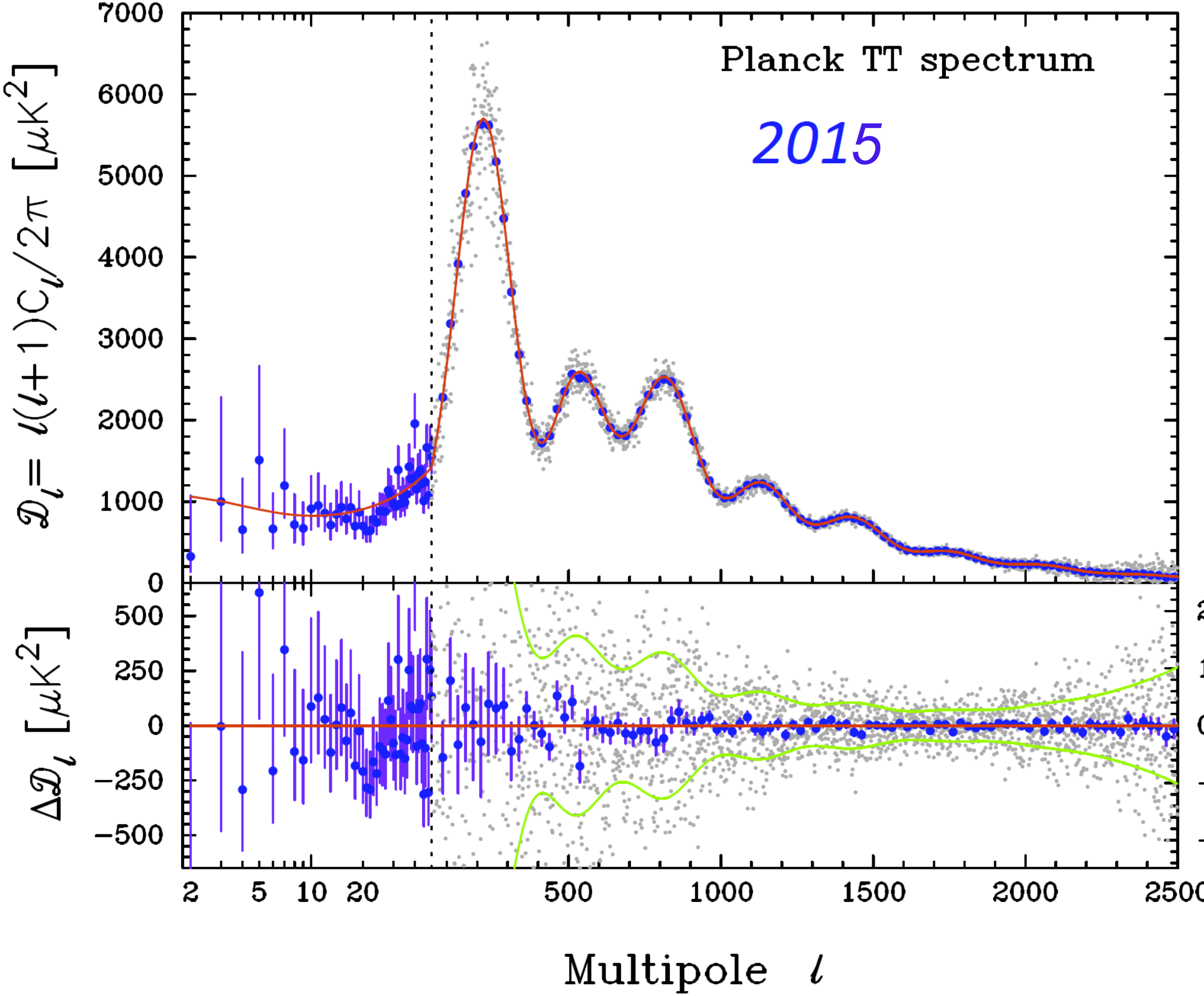
$$\widehat{C_\ell} = \sum_m \frac{|a_{\ell m}|^2}{2\ell + 1}$$

The bi- and tri-spectra may be used to test for NG, NB: biposh coeff.

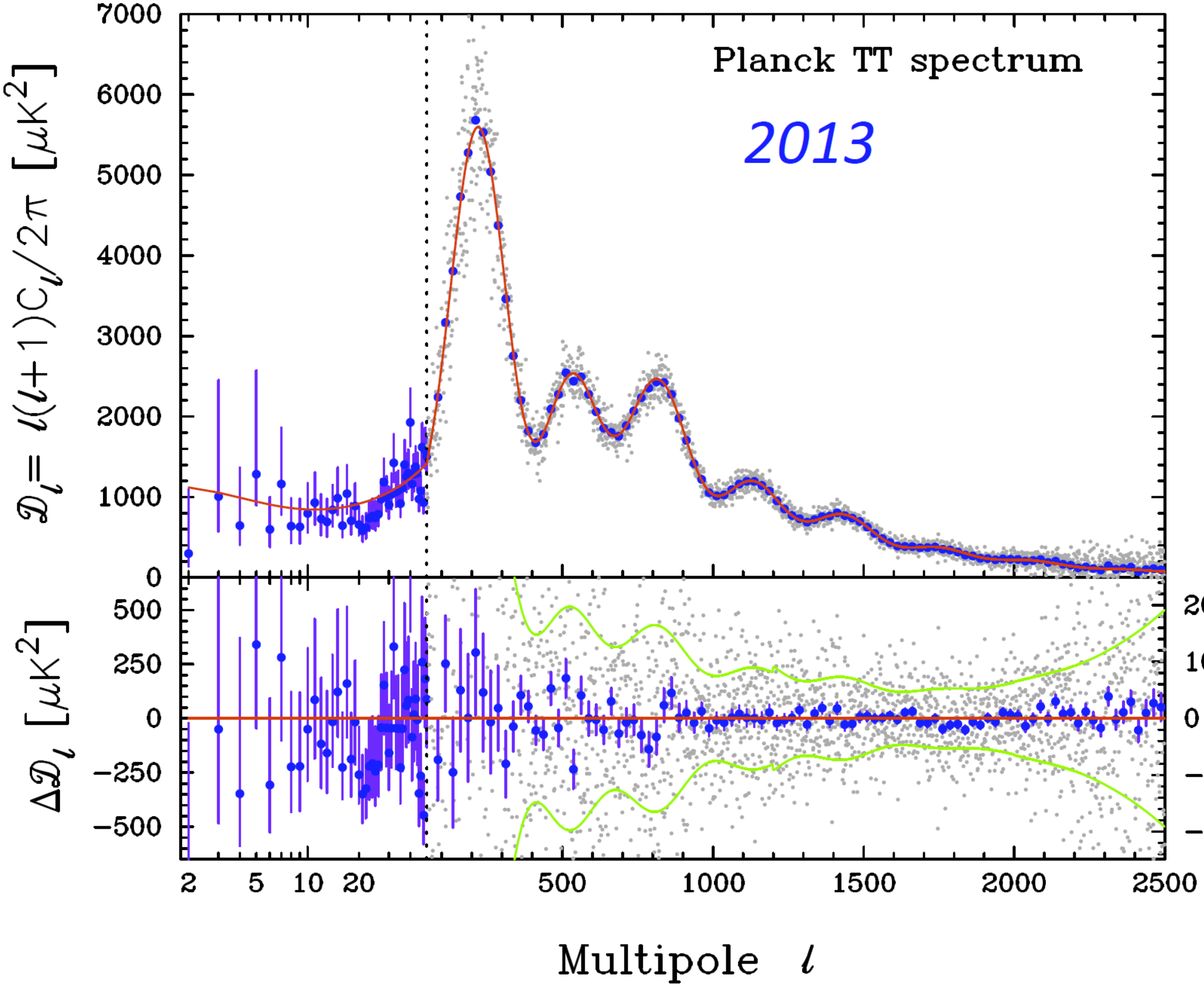
Power spectrum shape & cosmological parameters



A uniquely direct access to the Universe content
and seeds of its large scale structures

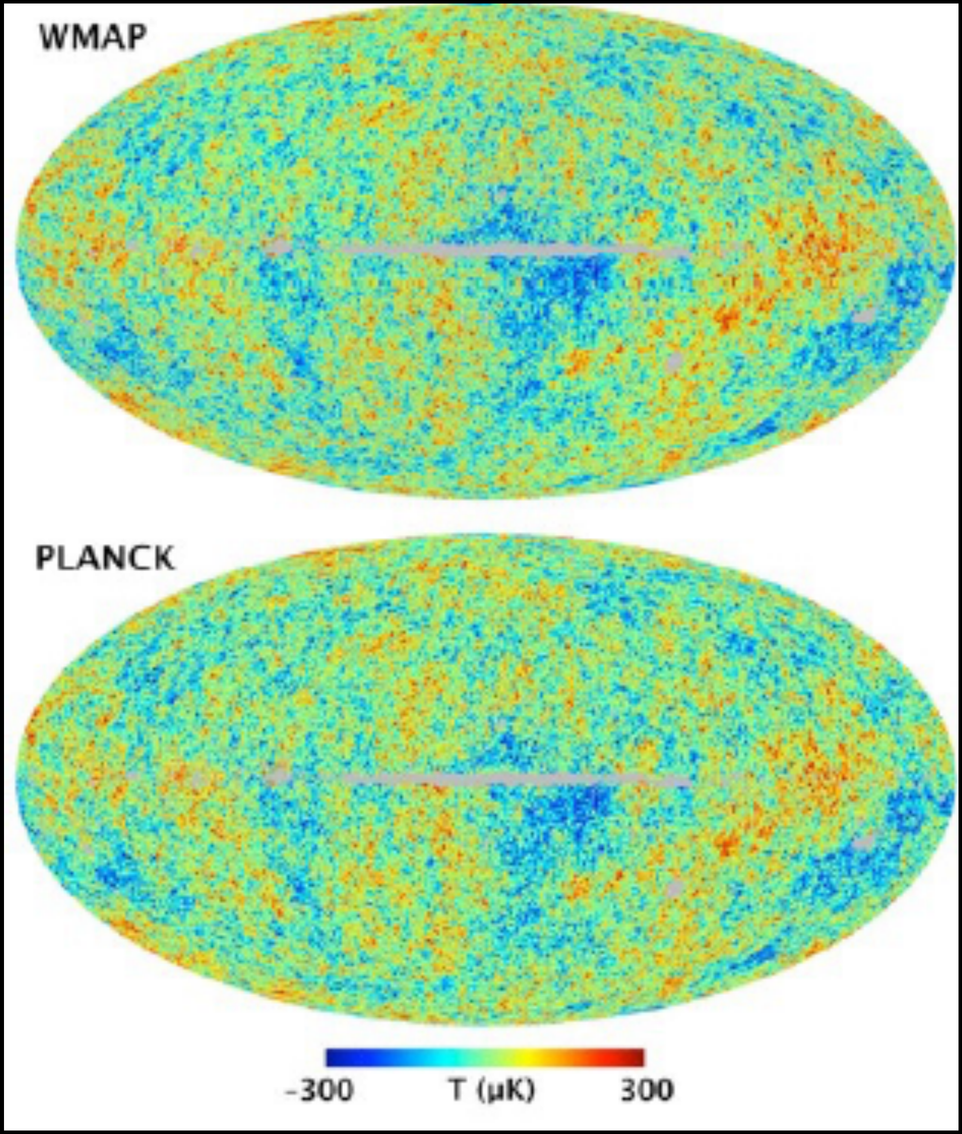


Planck TT spectrum
2015
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
$\Delta\mathcal{D}_\ell\ [\mu K^2]$
Multipole ℓ
7000
6000
5000
4000
3000
2000
1000
0
500
250
0
−250
−500
200
100
0
−100
−200
2
5
10
20
500
1000
1500
2000
2500



Planck TT spectrum
2013
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi$ [μK^2]
$\Delta\mathcal{D}_\ell$ [μK^2]
Multipole ℓ
7000
6000
5000
4000
3000
2000
1000
0
500
250
0
−250
−500
200
100
0
−100
−200
2
5
10
20
500
1000
1500
2000
2500

Planck and WMAP "see" the same sky

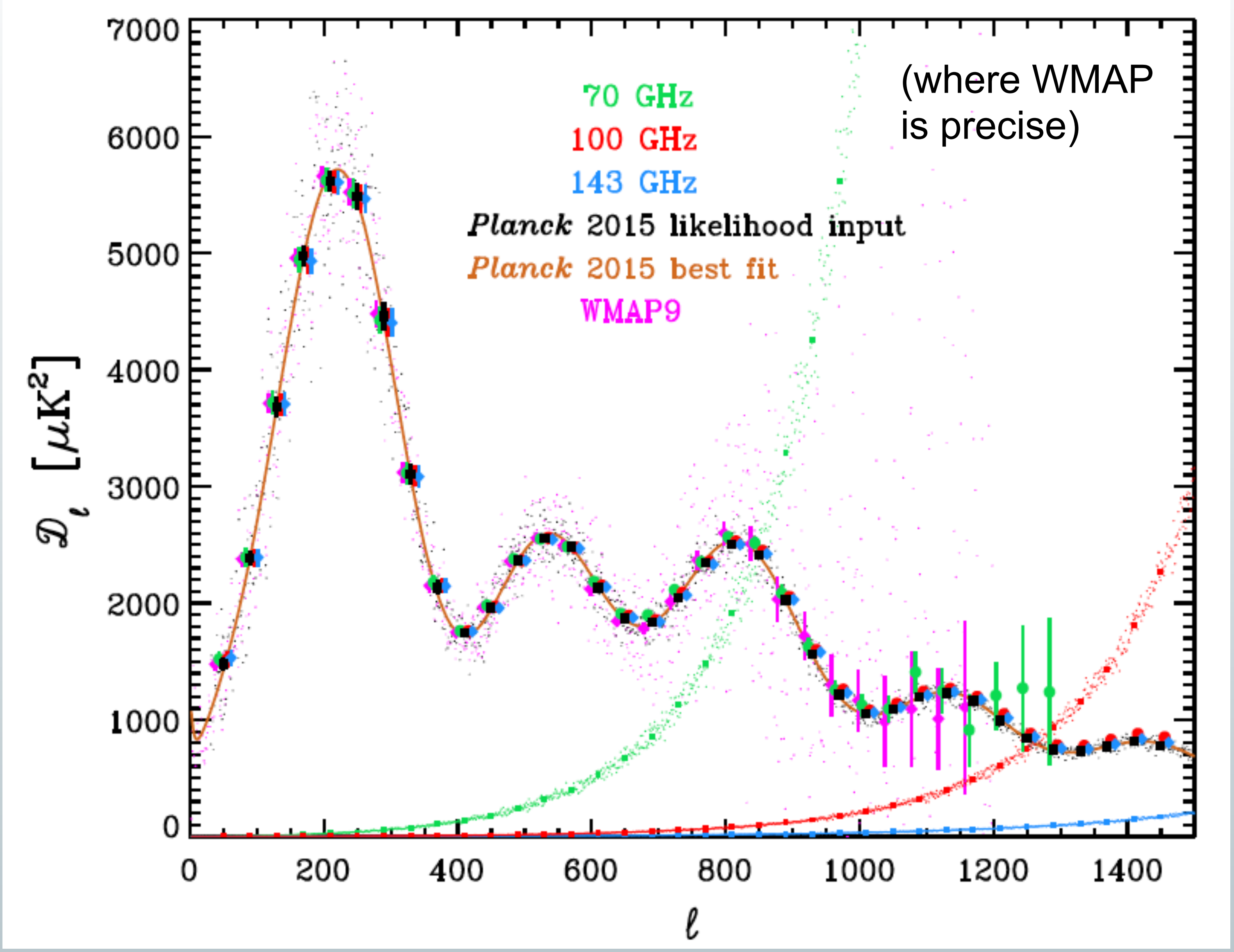


After …

1) correcting the original WMAP map from residual dust emission, only traced by Planck/HFI, and

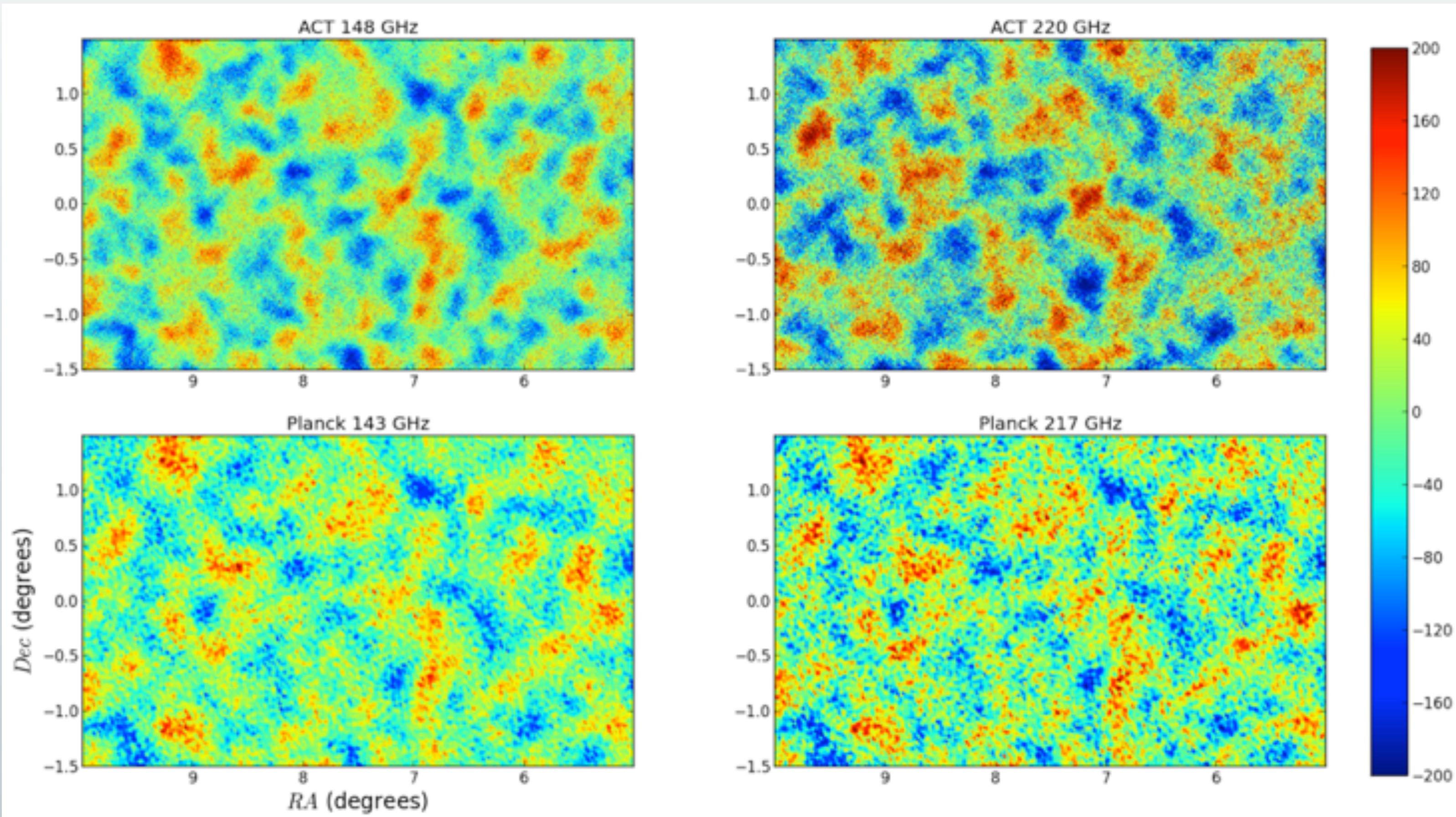
2) Downgrading Planck to WMAP resolution (de facto throwing out the majority of Planck measured modes)

Excellent consistency at l ~< 800

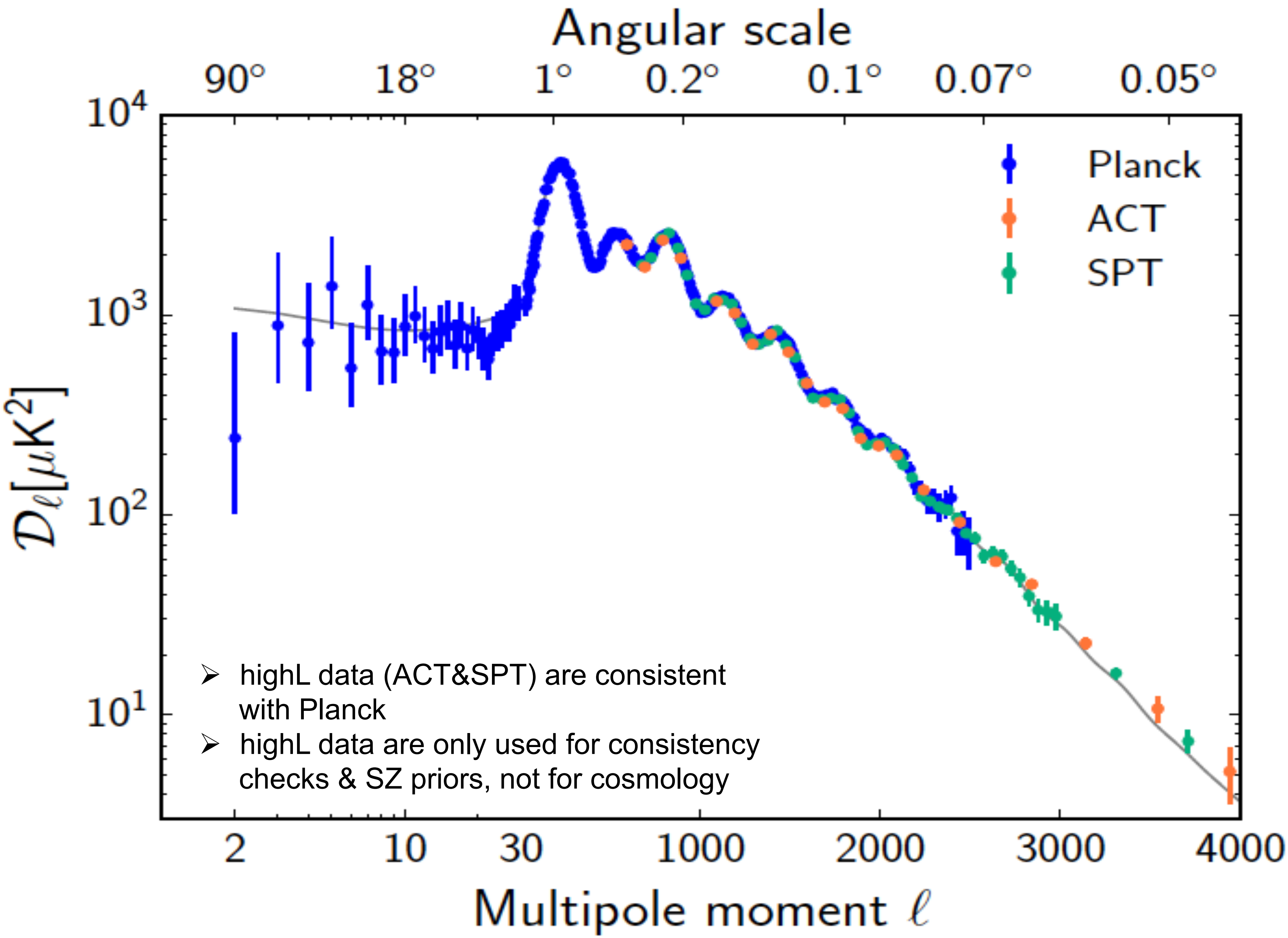


Planck & high-resolution experiments

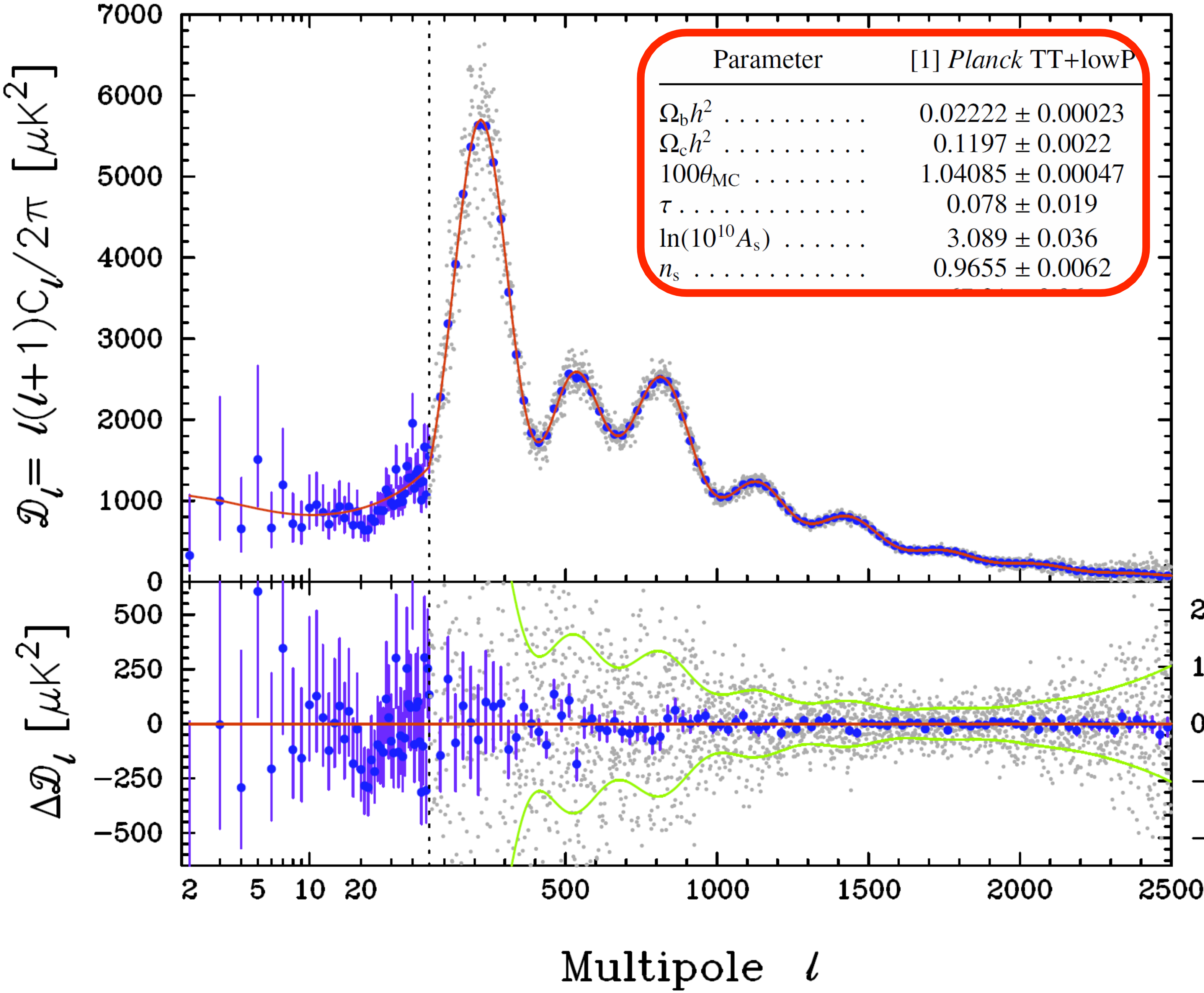
also see the same sky



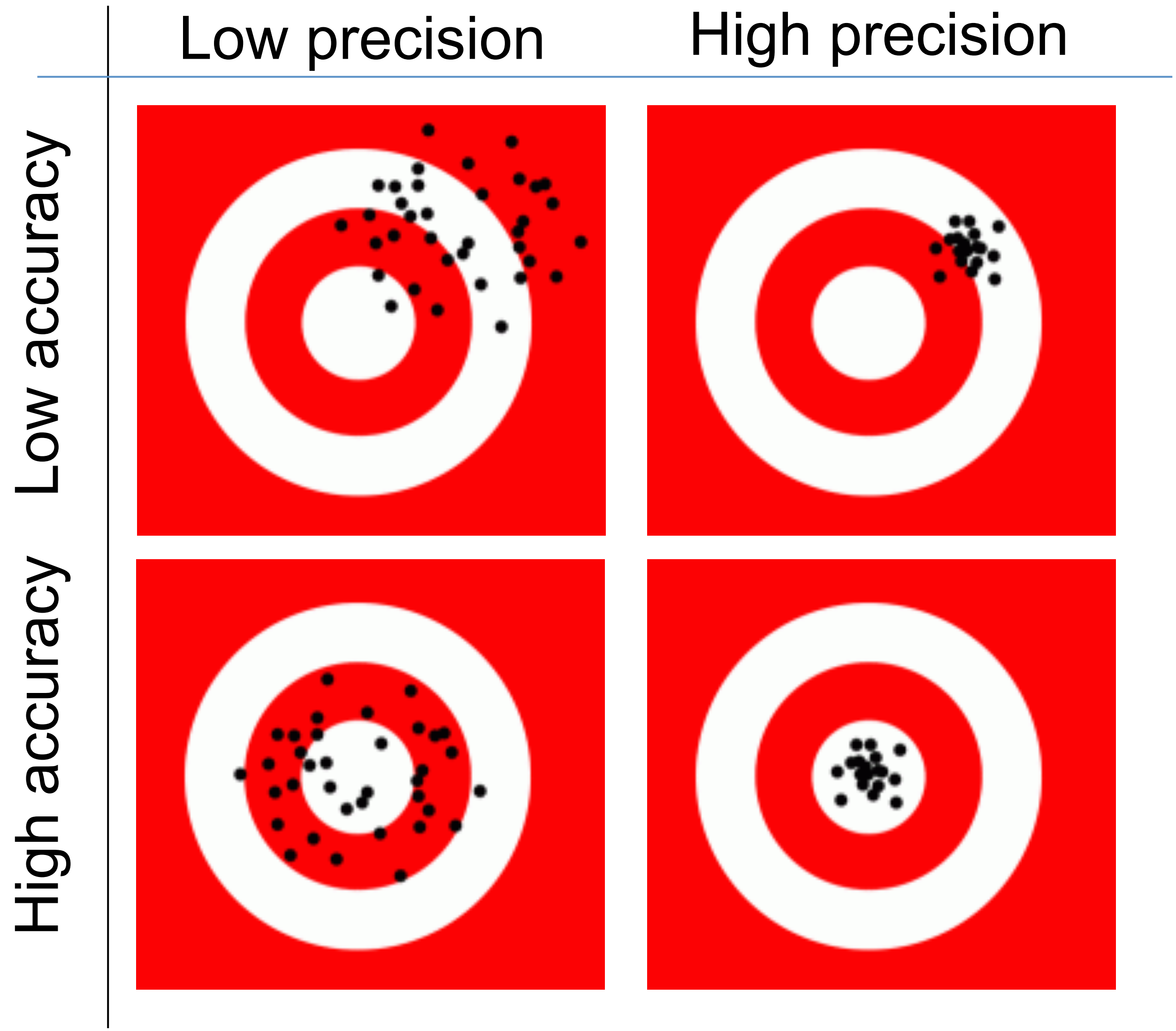
In the bands accessible from the ground. NB: Planck 2013 data

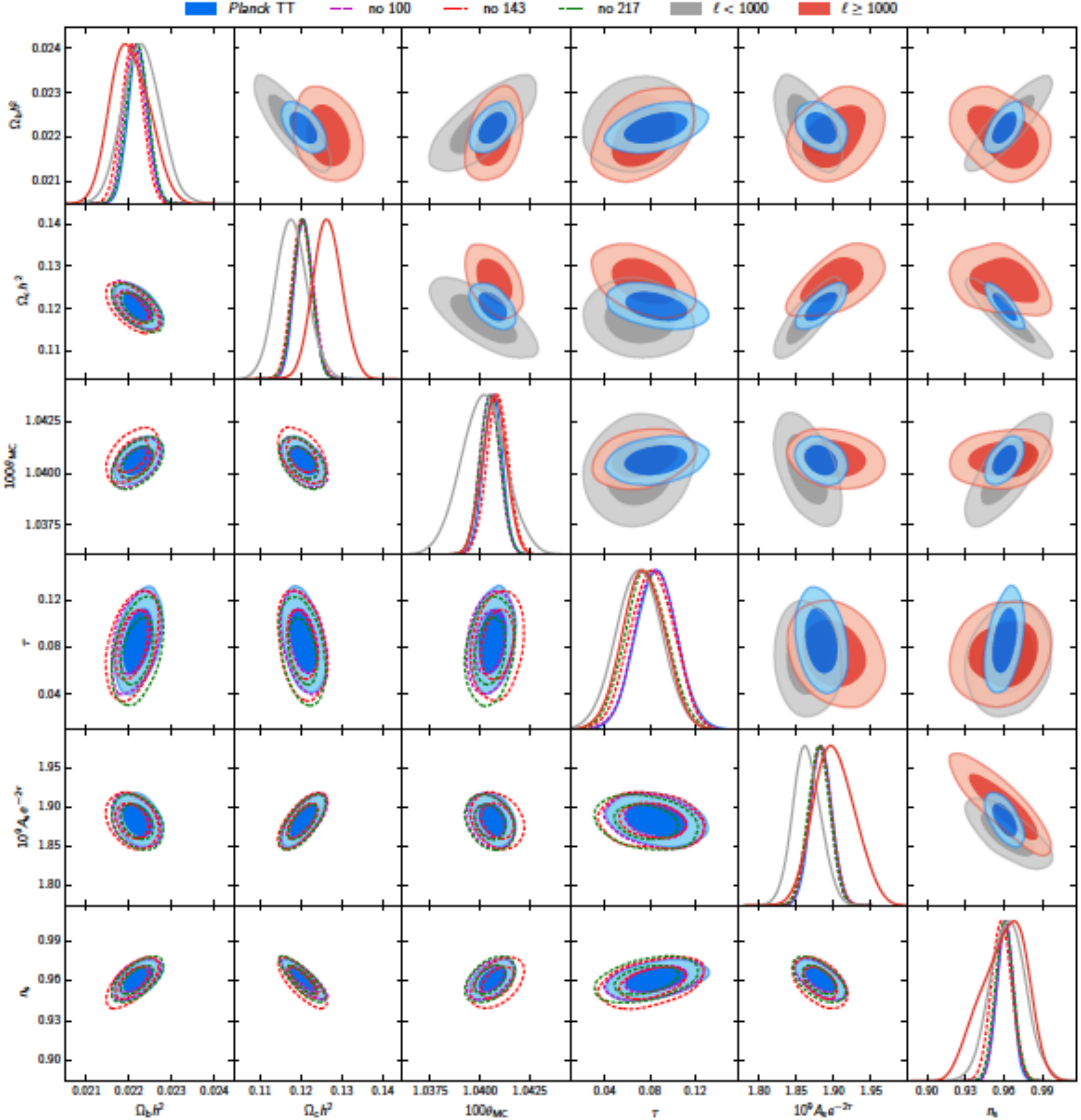


- highL data (ACT&SPT) are consistent with Planck
- highL data are only used for consistency checks & SZ priors, not for cosmology


Parameter
[1] Planck TT+lowP
$\Omega_b h^2$ . . . . 0.02222 ± 0.00023
$\Omega_c h^2$ . . . . 0.1197 ± 0.0022
$100\theta_{MC}$ . . . . 1.04085 ± 0.00047
τ . . . . 0.078 ± 0.019
$\ln(10^{10} A_s)$ . . . . . . 3.089 ± 0.036
n_s . . . . 0.9655 ± 0.0062
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi$ [μK^2]
$\Delta\mathcal{D}_\ell$ [μK^2]
Multipole ℓ
7000
6000
5000
4000
3000
2000
1000
0
500
250
0
−250
−500
200
100
0
−100
−200
2
5
10
20
500
1000
1500
2000
2500

Precision is not accuracy…

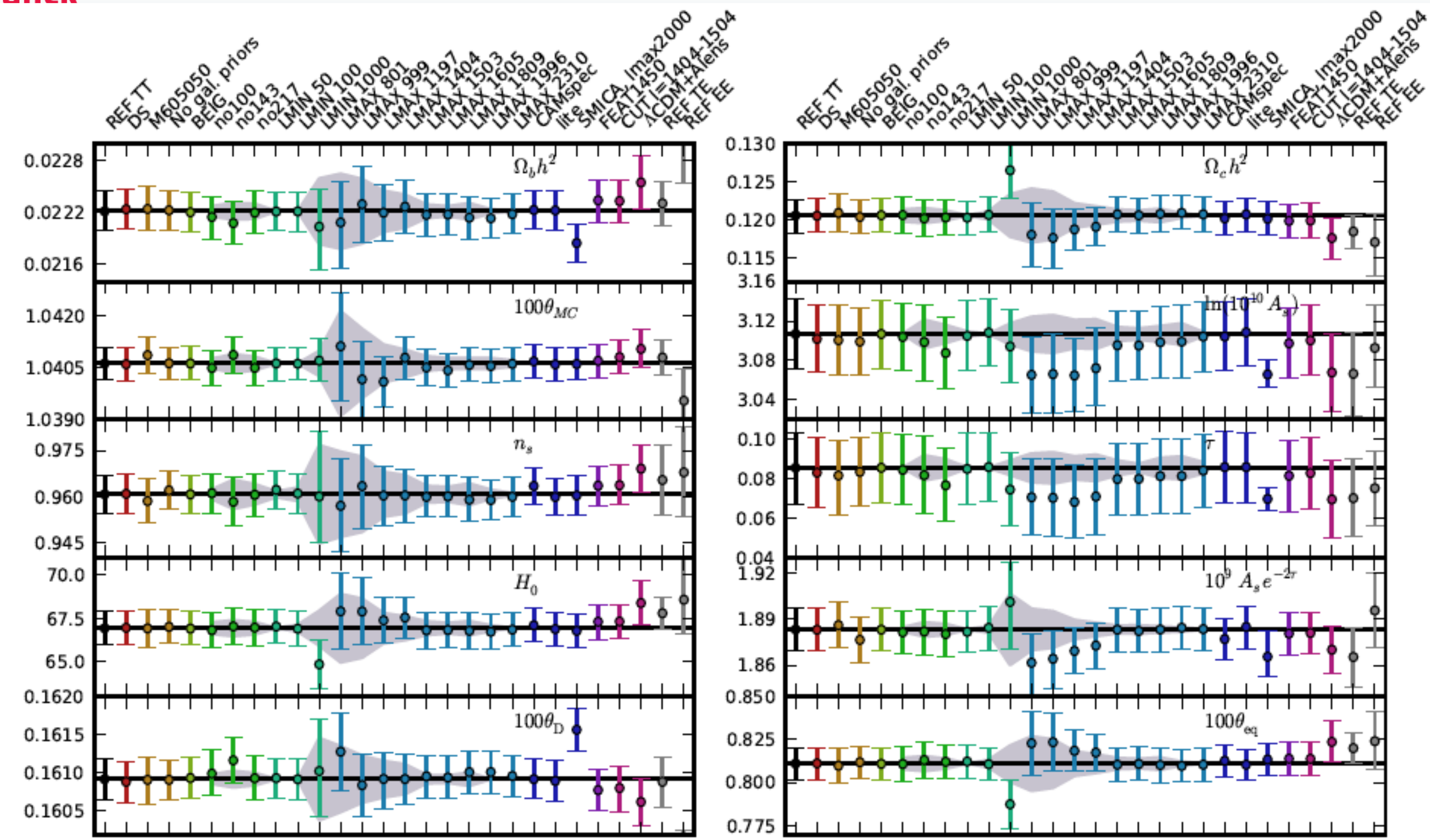




Apart from τ, 5 base LCDM parameters are determined with % level precision.

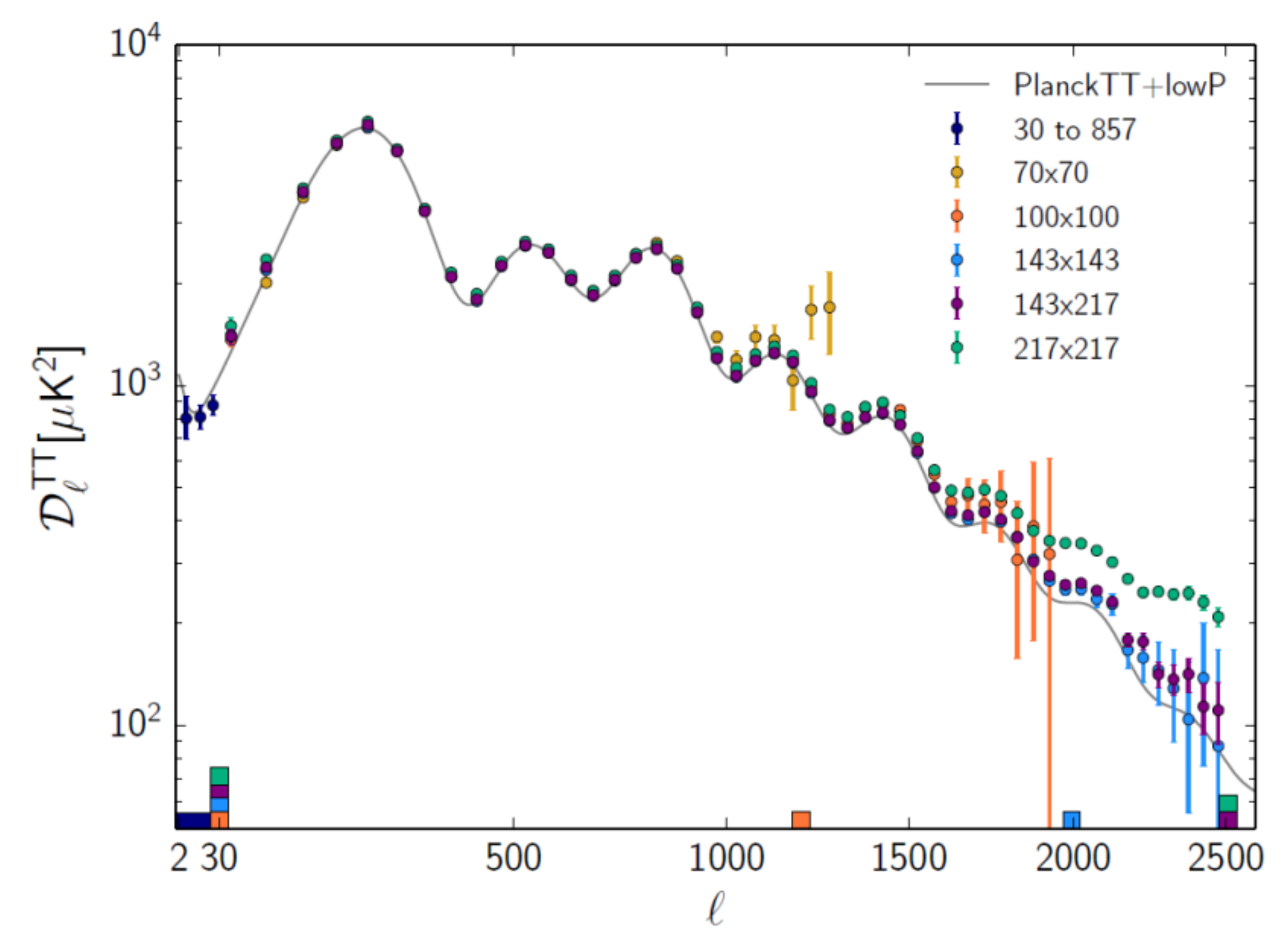
And are robust w.r.t. jack-knife tests like removing channels or even l-range (e.g., all the range probed by WMAP).

And many, many other tests…

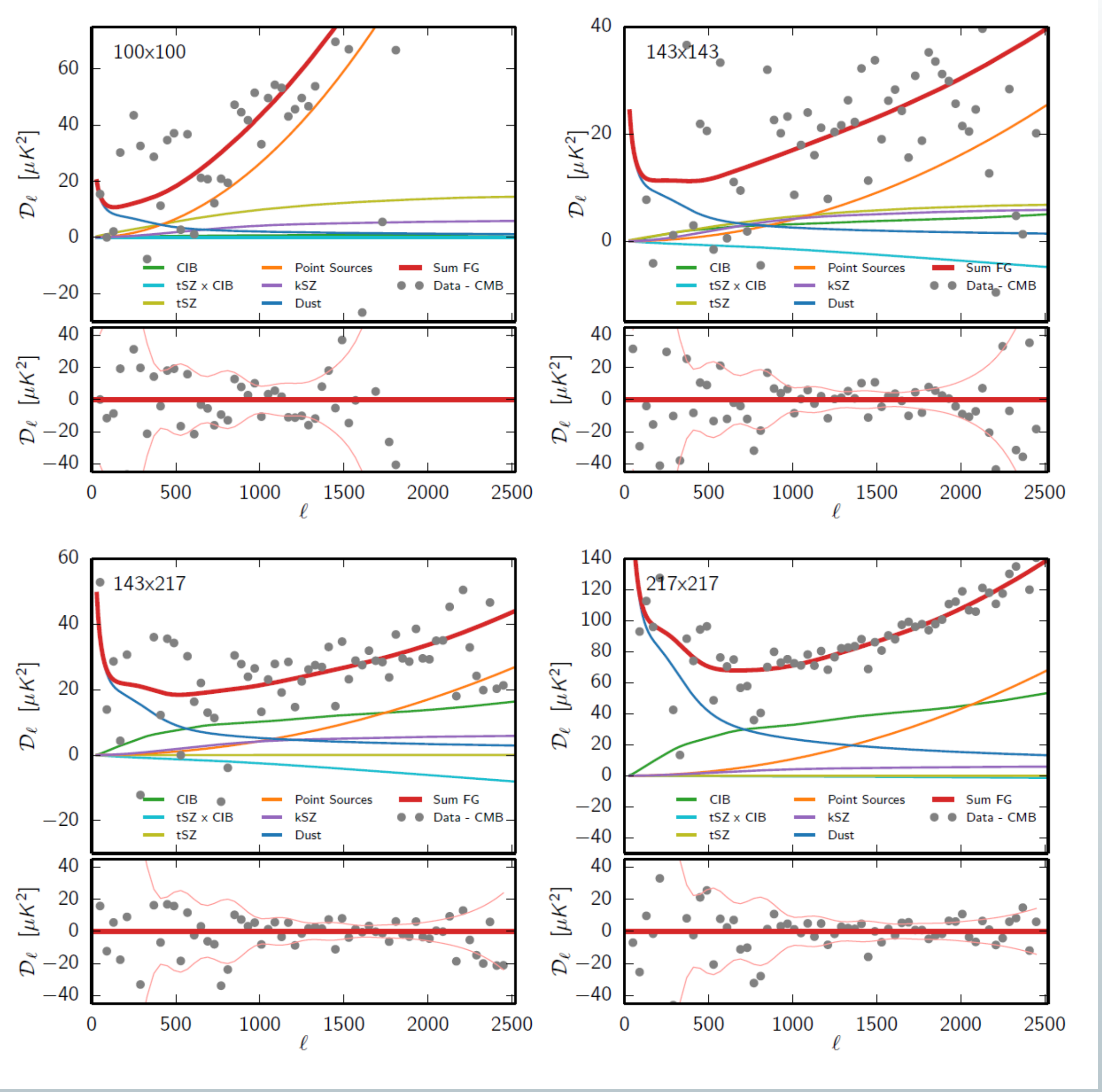


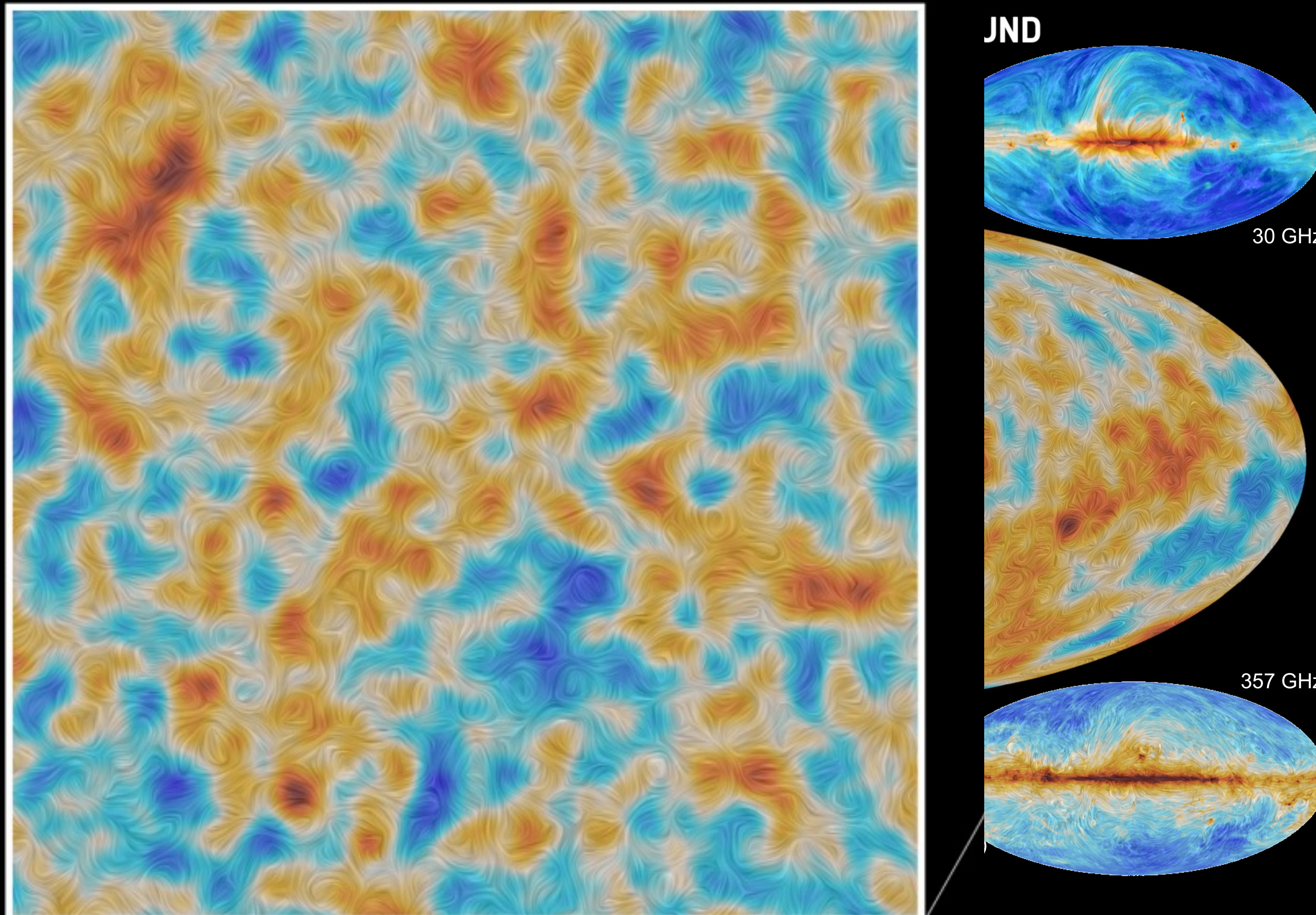
(also performed on 1-parameter extensions to LCDM, eg Neff)

Foregrounds and masks, l-range retained



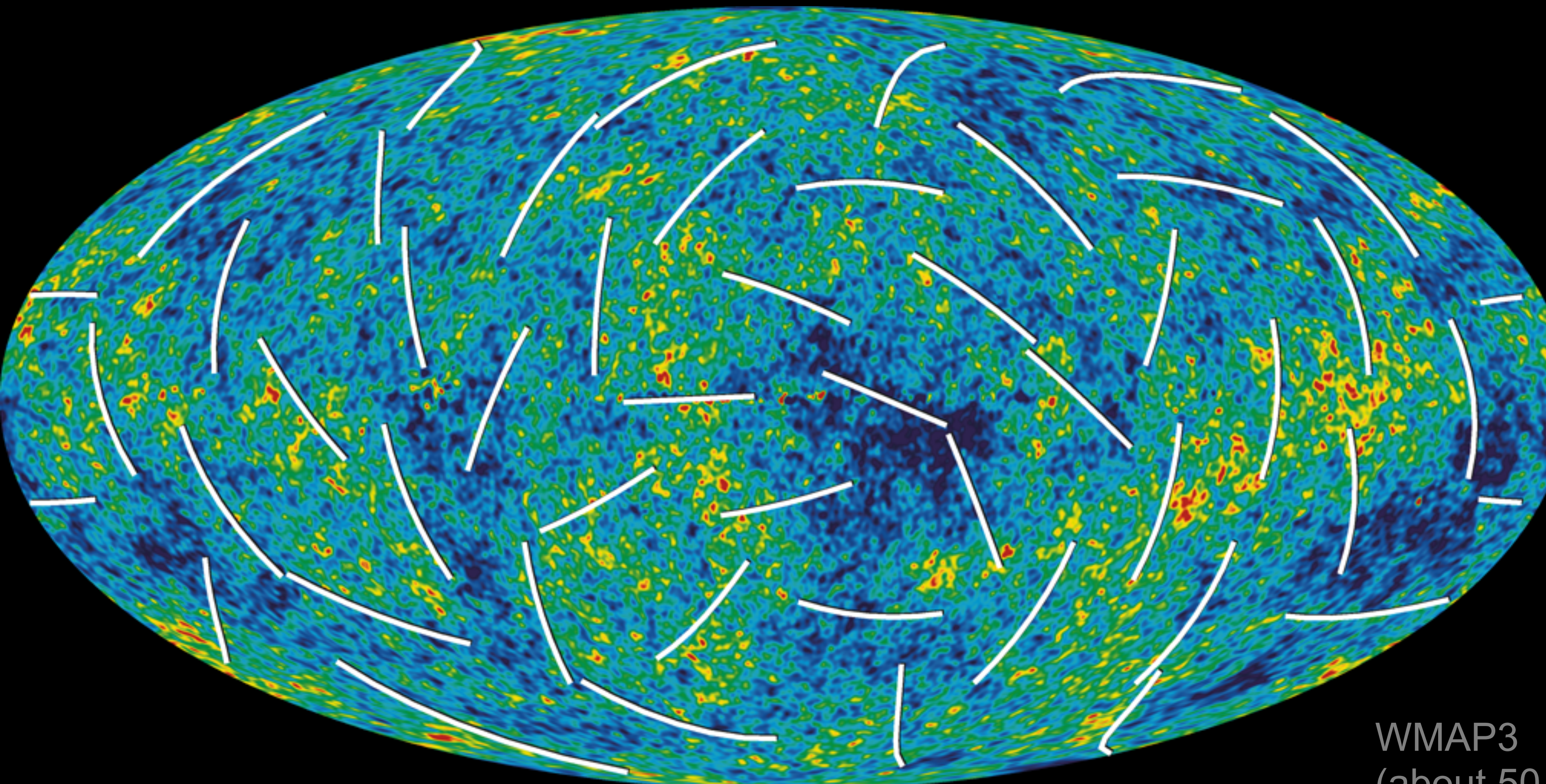
Foregrounds modelling & residuals





Filtered at 20 arcminutes

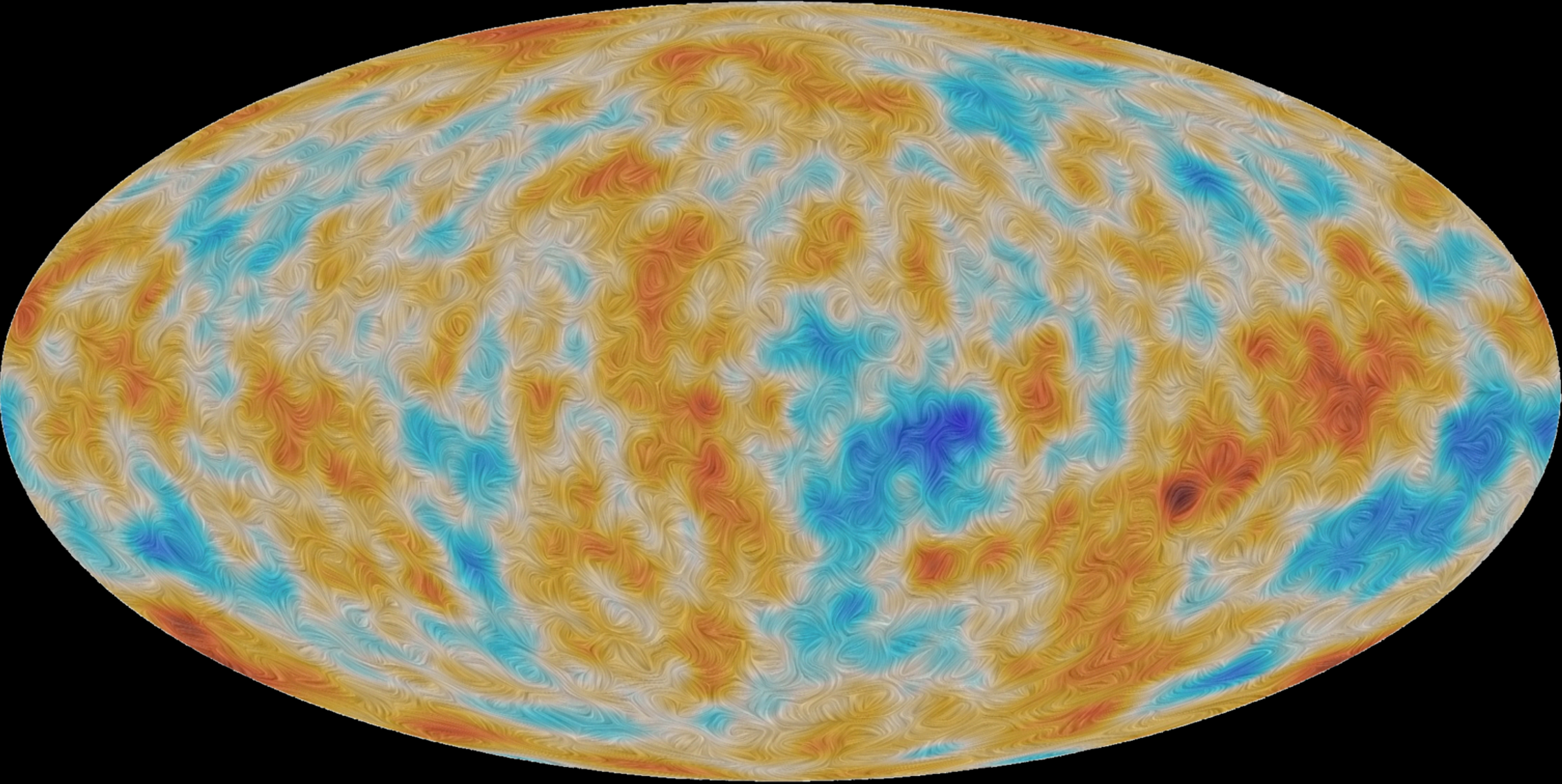
What we already knew



WMAP3
(about 50
locations)

The Planck 2015 CMB polarisation sky

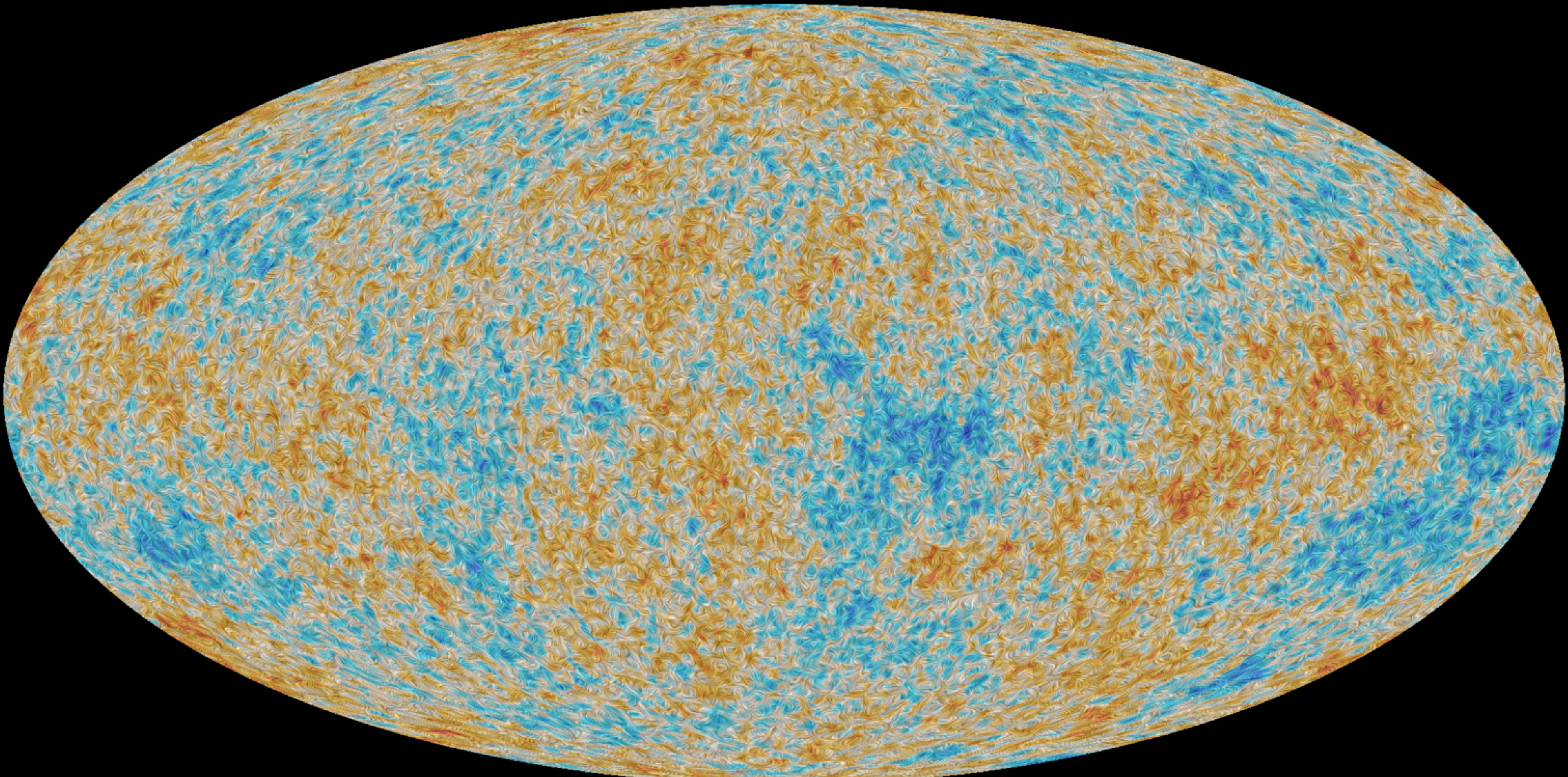
at 5 degree resolution



François R. Bouchet, "Planck CMB Cosmology"

The Planck 2015 CMB polarisation sky

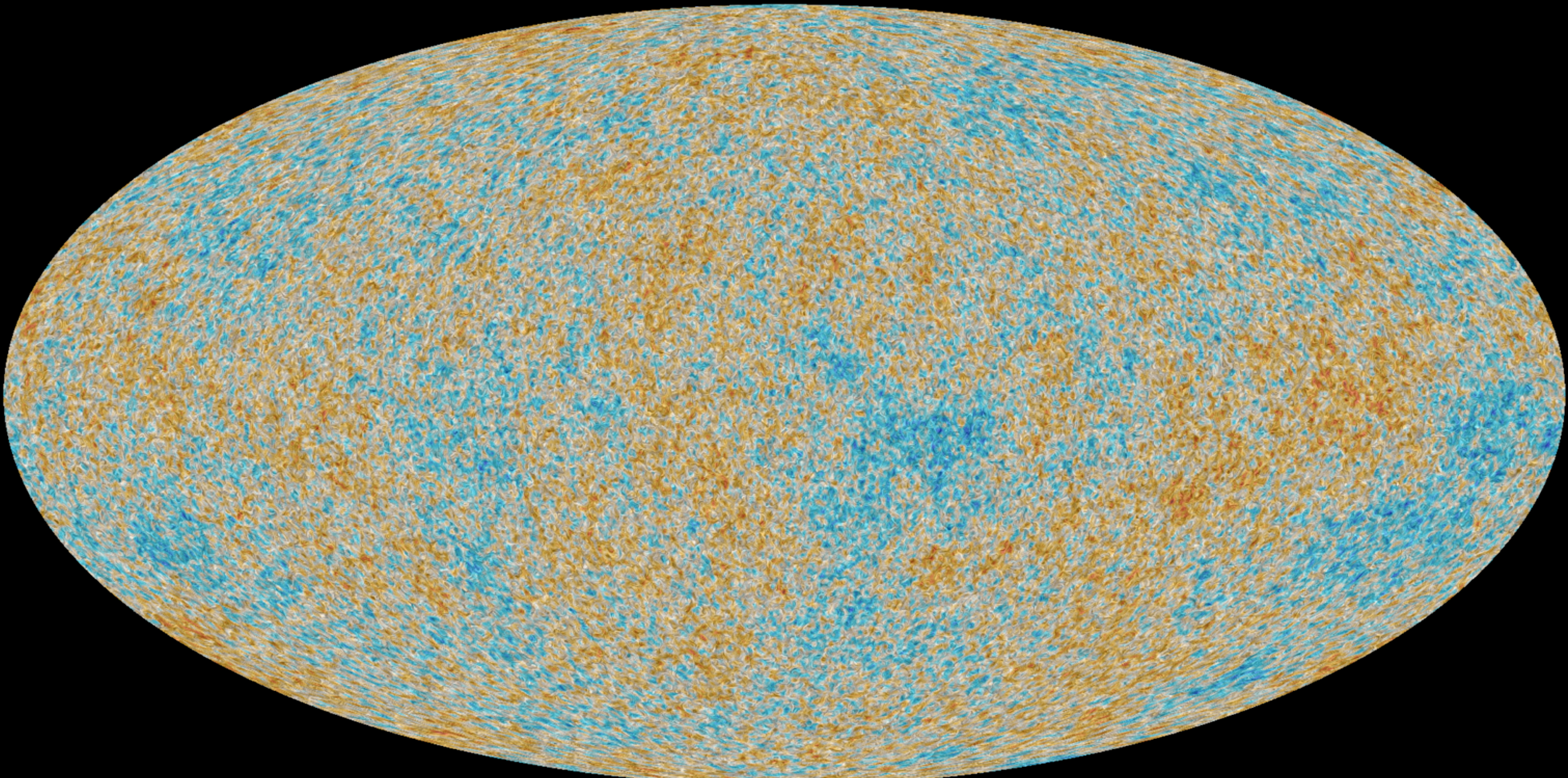
at 1 degree resolution

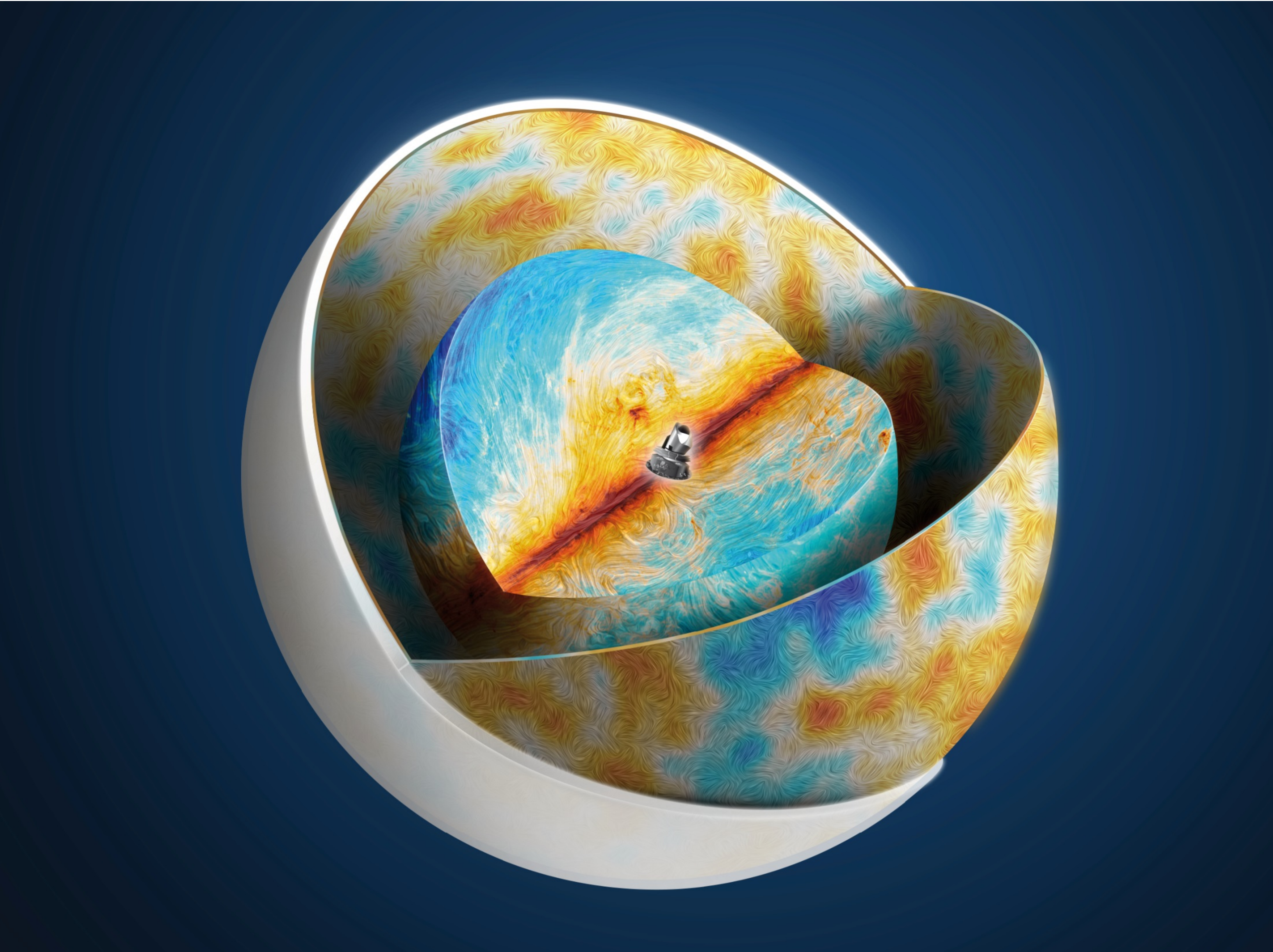


François R. Bouchet, "Planck CMB Cosmology"

The Planck 2015 CMB polarisation sky

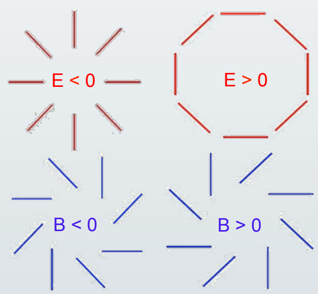
at 5 arc minute resolution



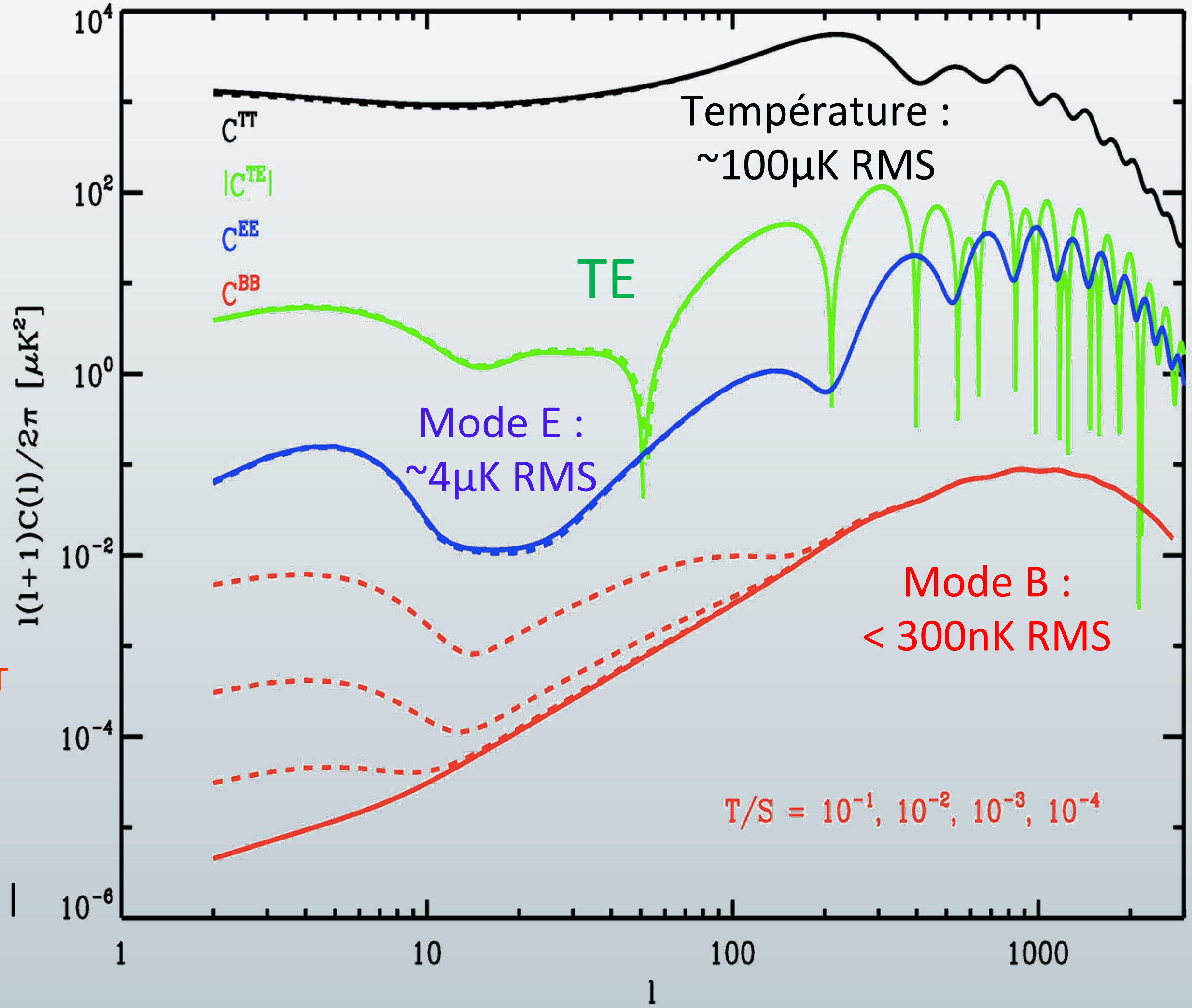


CMB angular power spectra

- 3 observables : T, E, B



- B Modes:
  - **Not** generated by scalar modes
  - “Smoking gun” of tensorial perturbations
  - At best 300 times weaker than T fluctuations
  - case T/S = r = 0.1 (cf. fig),
  - E_{inf}=2 x 10^{16} GeV (GUT).
- B mode Spectrum peaks at l < 200, i.e. θ > 1 deg

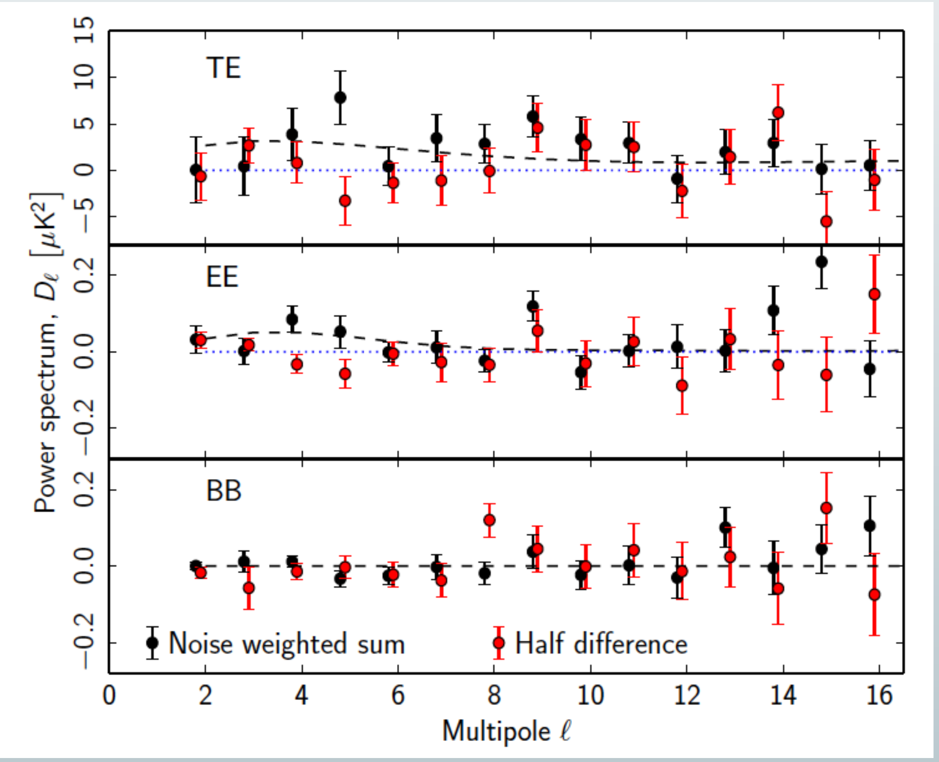


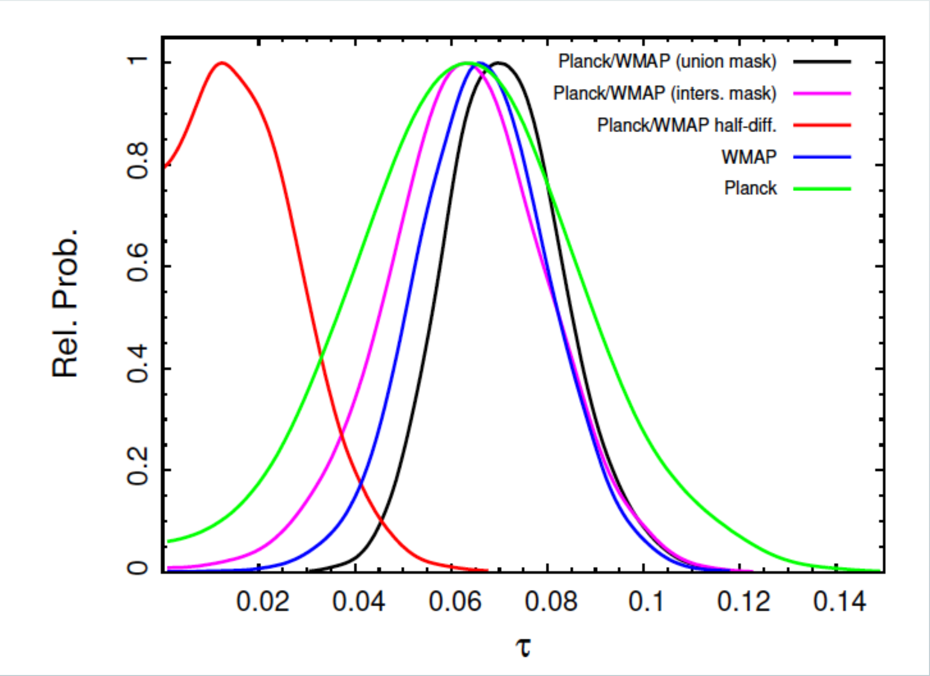
(θ ≈ 180 / l)

Low-ell (2<l<30) polarisation anisotropies

HFI 353 GHz polarisation data was used
to clean both WMAP and LFI 70GHz polarisation data.

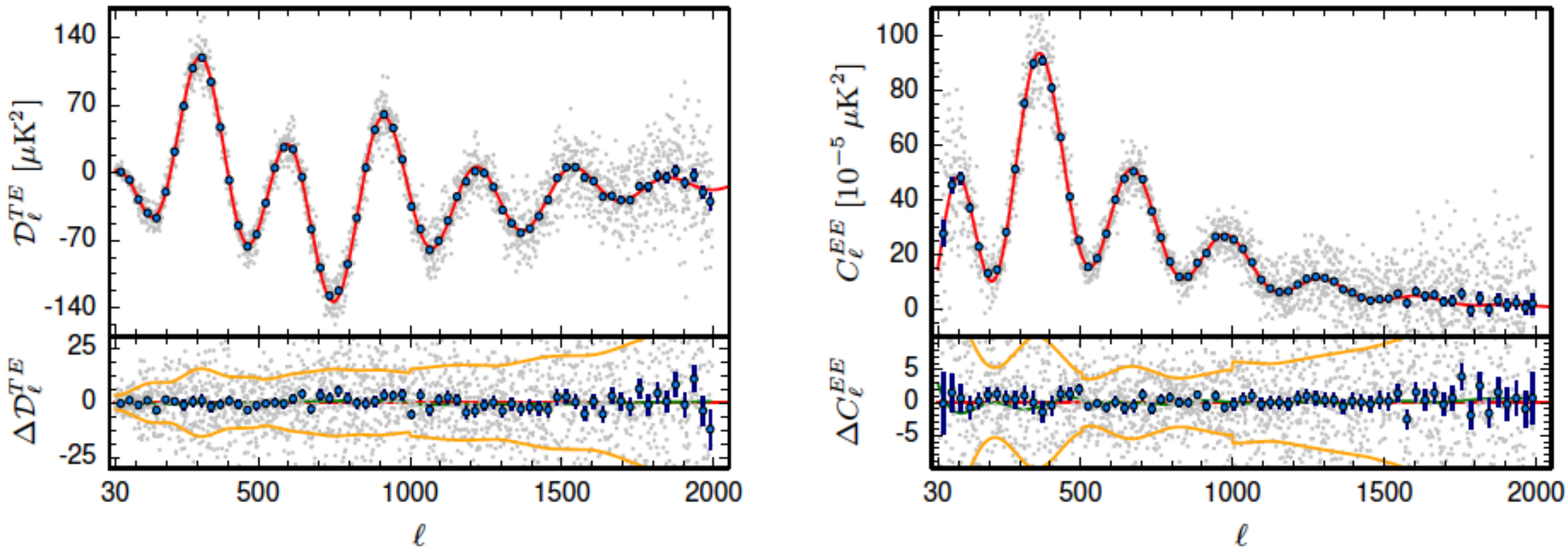
Results are compatible, and it shifts the optical depth
to reionization, τ, to lower values than previously thought.





This plot is for low ell <30 only,
i.e. it is ***not*** the final, full likelihood, outcome

Planck 2015 - TE & EE power spectra



Frequency averaged spectrum reduced chi^2 = 1.04 *Frequency averaged spectrum reduced chi^2 = 1.01*

- Red curve is the prediction based on the best fit TT in base ΛCDM
- Albeit quite precise already, 2015 polarisation data and results are not final yet because all systematic and foreground uncertainties have not been *exhaustively* characterised at O(1μK^2).

Spectra conditionned on TT

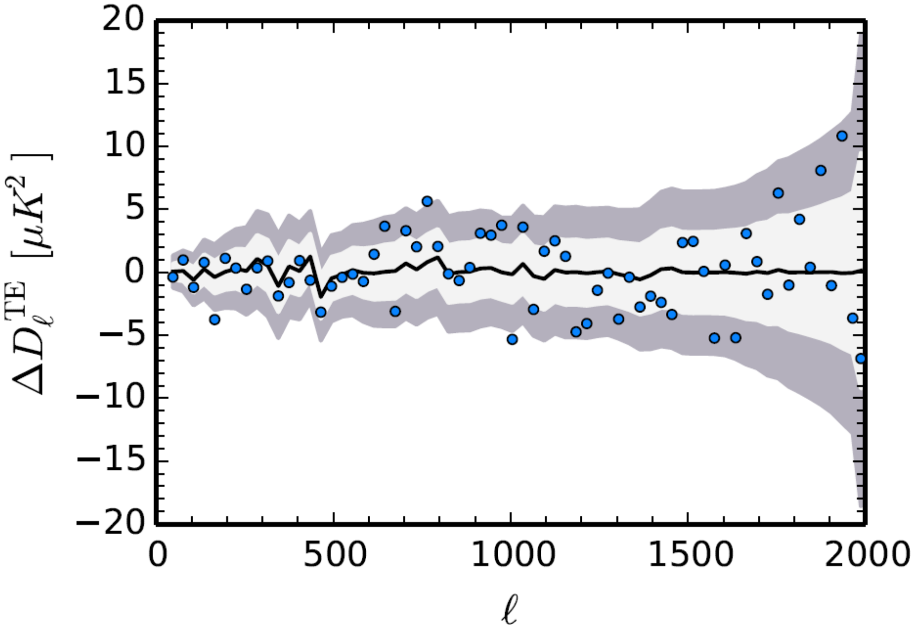
Conditional spectra and covariances

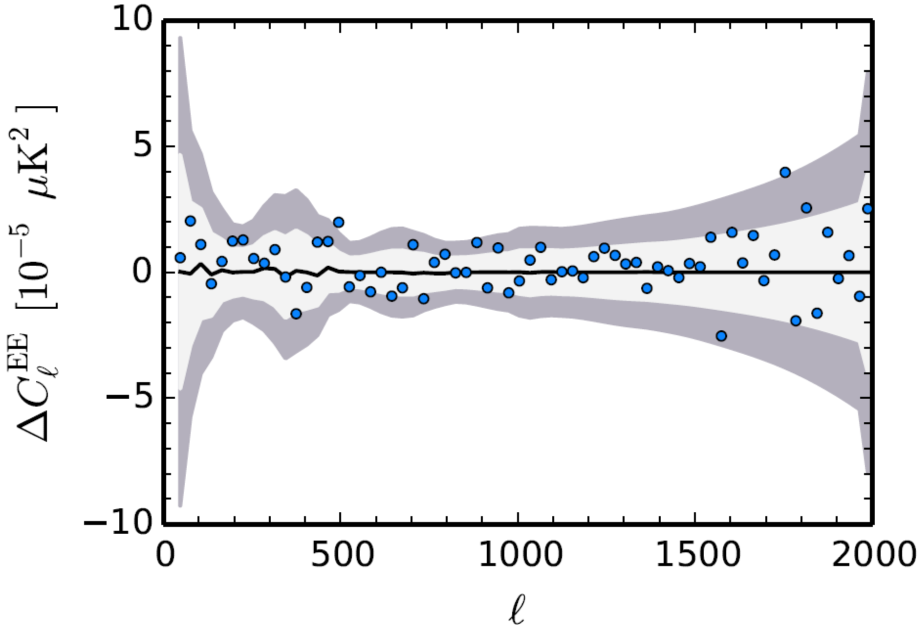
$$C_\ell^{PP}|_{C_\ell^{TT}} = \langle C_\ell^{PP}\rangle + \mathbf{C}_{PP,TT}\mathbf{C}_{TT,TT}^{-1}(C_\ell^{TT} - \langle C_\ell^{TT}\rangle)$$

$$\mathbf{C}_{PP,PP}|_{C_\ell^{TT}} = \mathbf{C}_{PP,PP}\mathbf{C}_{PP,TT}\mathbf{C}_{TT,TT}^{-1}\mathbf{C}_{TT,PP}$$

TE

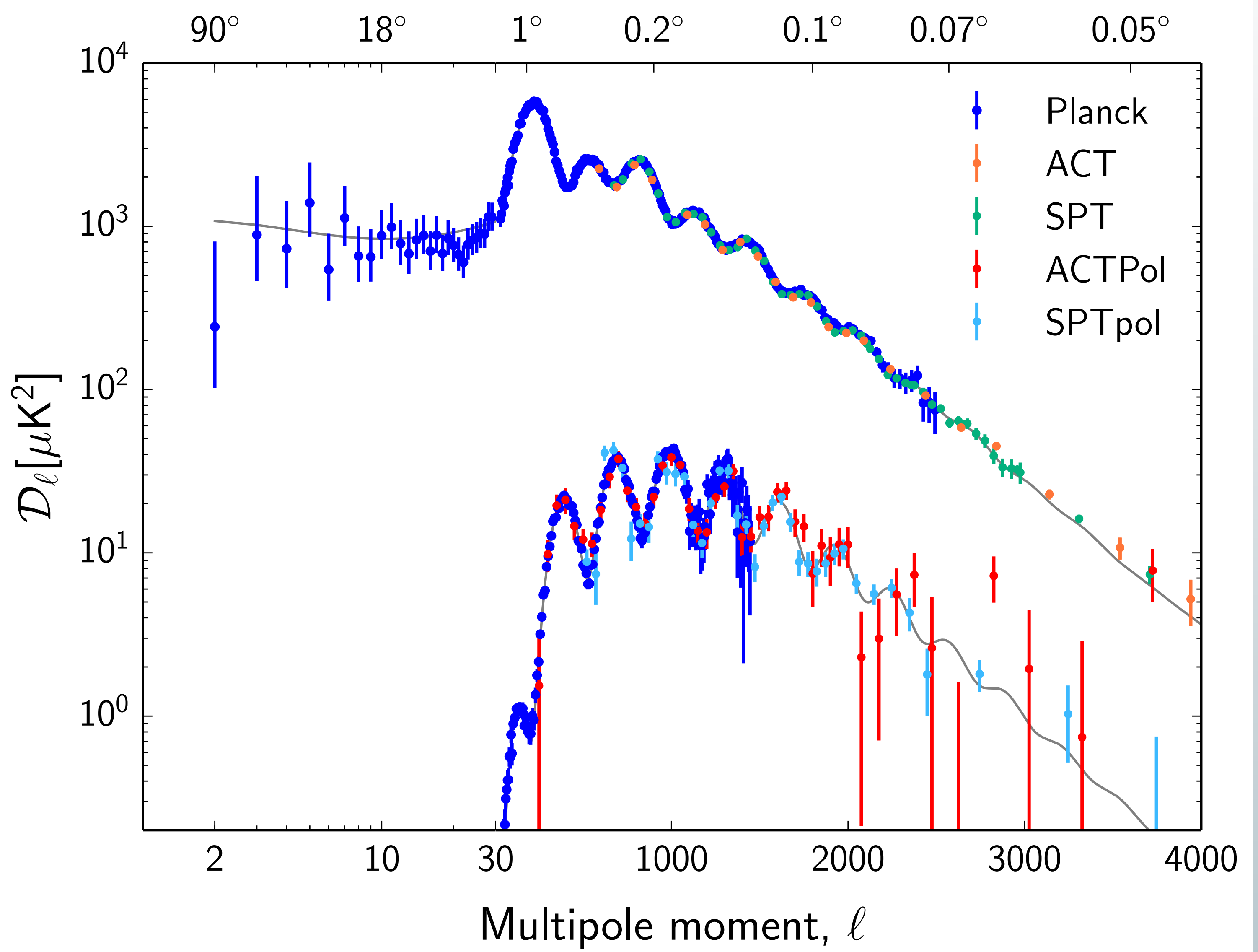
EE



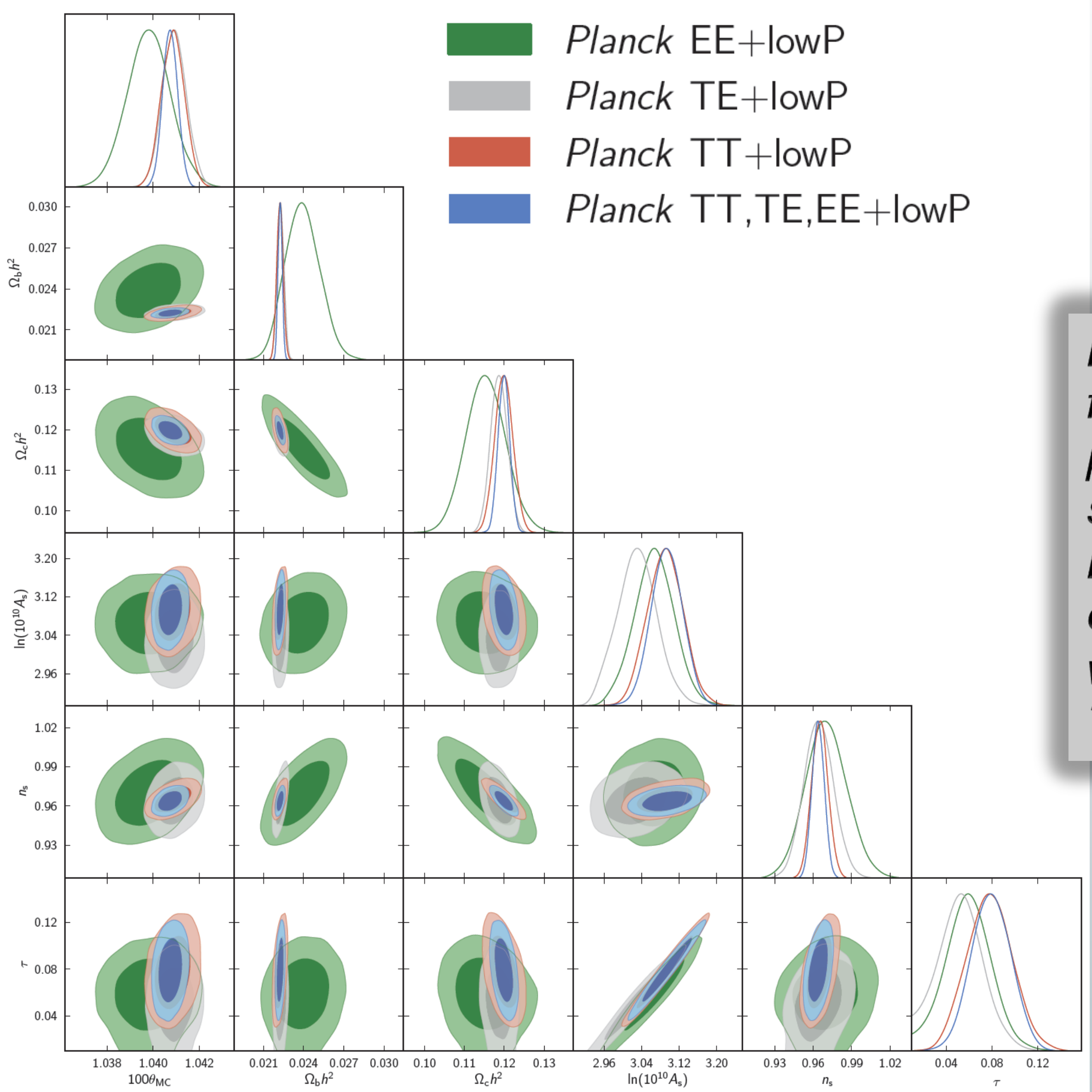


***Within LCDM**, Polarisation spectra are **highly consistent** with TT spectra.*

TT & EE spectra – mid 2015 status



T & E – LCDM parameters



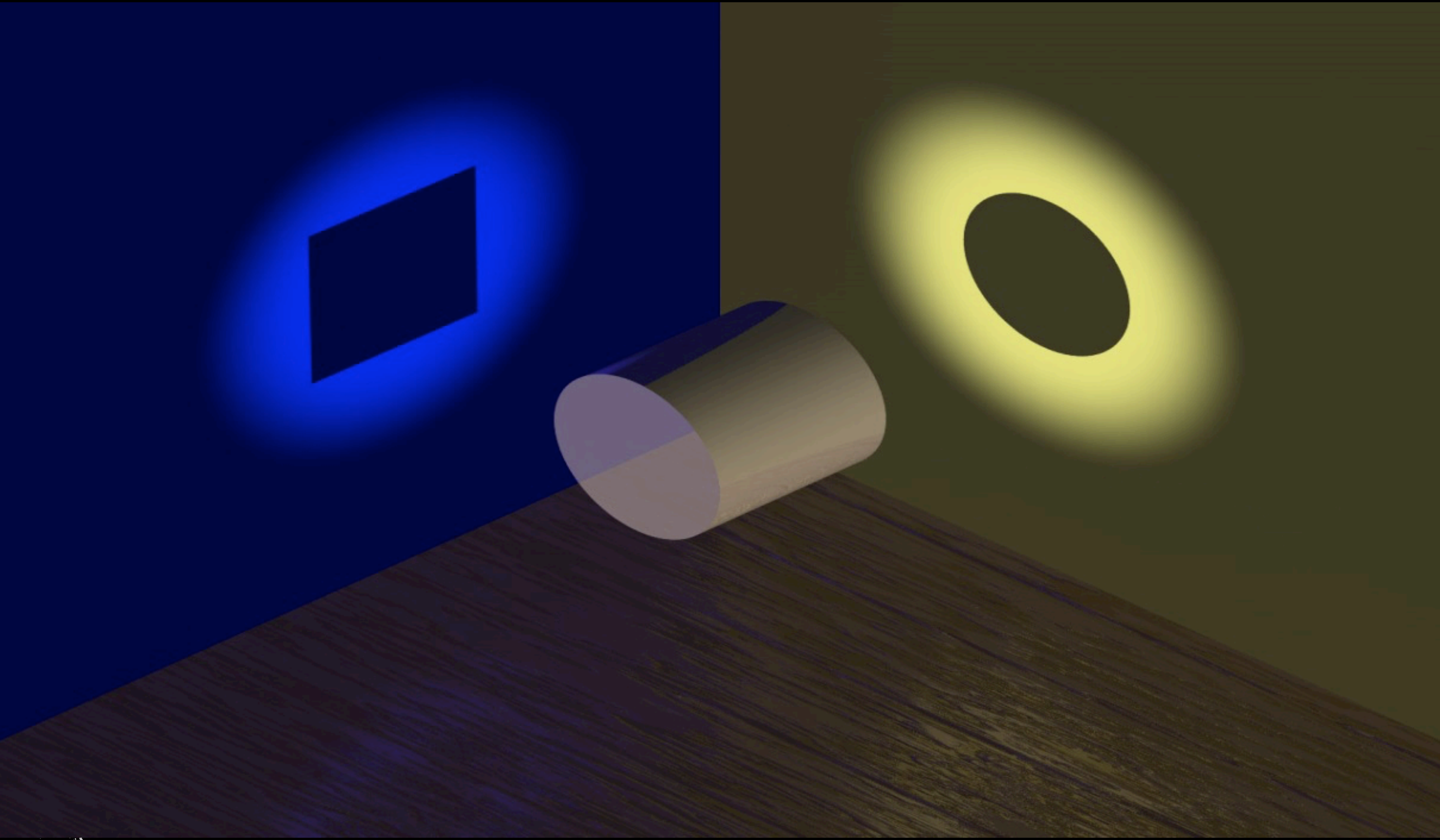
Parameters from polarisation spectra are ***highly consistent*** *with those from TT spectra.*

Base ΛCDM model

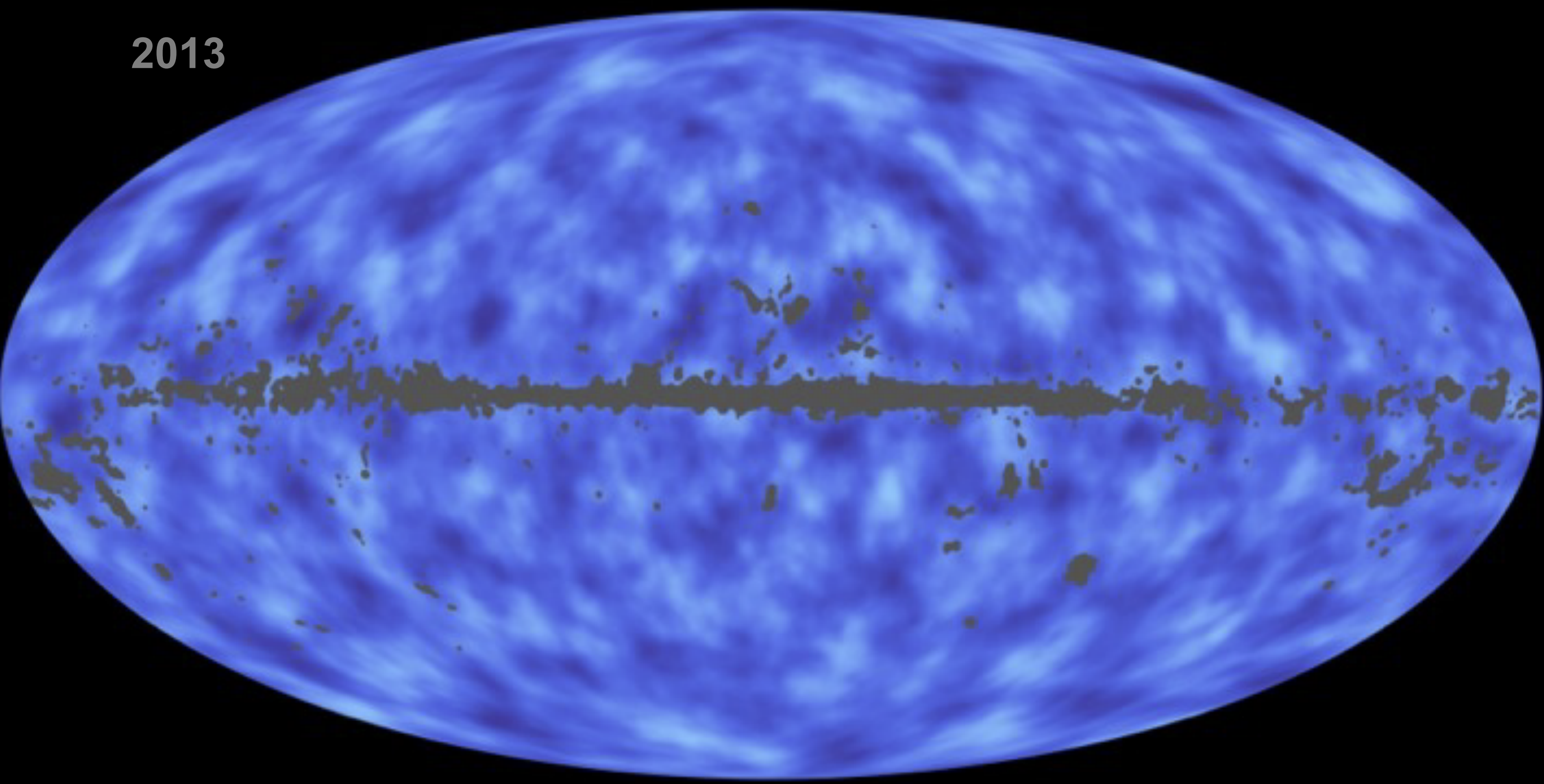
Parameter	[1] *Planck* TT+lowP	[2] *Planck* TE+lowP
$\Omega_b h^2$	0.02222 ± 0.00023	0.02228 ± 0.00025
$\Omega_c h^2$	0.1197 ± 0.0022	0.1187 ± 0.0021
$100\theta_{MC}$	1.04085 ± 0.00047	1.04094 ± 0.00051
τ	0.078 ± 0.019	0.053 ± 0.019
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.031 ± 0.041
n_s	0.9655 ± 0.0062	0.965 ± 0.012
H_0	67.31 ± 0.96	67.73 ± 0.92
Ω_m	0.315 ± 0.013	0.300 ± 0.012
σ_8	0.829 ± 0.014	0.802 ± 0.018
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014	1.865 ± 0.019

TT & TE have quite similar uncertainties (apart from n_s where l-range/noise counts most) but beware that they are still some low level systematics in the polarisation data

This was not granted…



Projected mass map

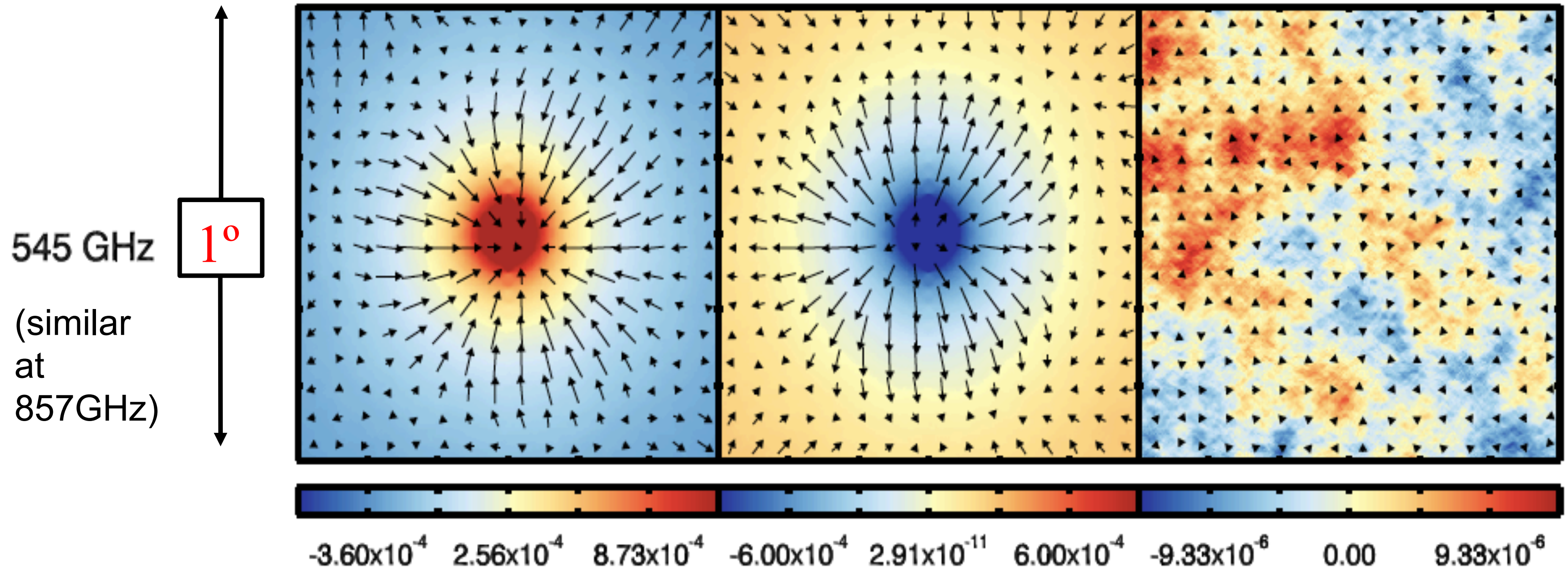


The (grey) masked area is where foregrounds are too strong to allow an accurate reconstruction

European Space Agency

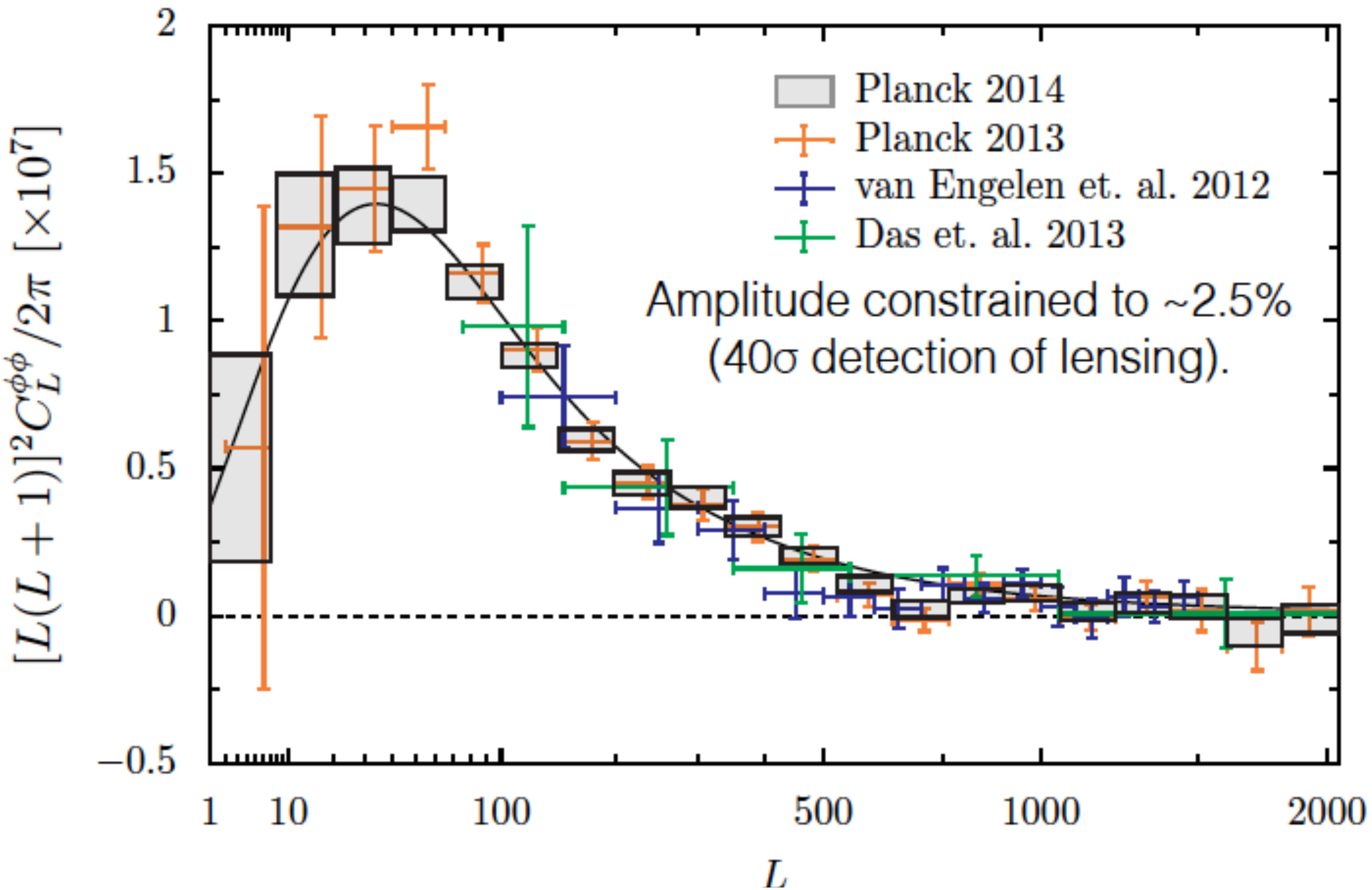
CIB PEAKS CORRESPOND TO MASS PEAKS

Stacking the Planck mass maps at the positions of peaks and troughs of Cosmic Infrared Background leads to a strong detection of the mass associated with these distant star forming galaxies.



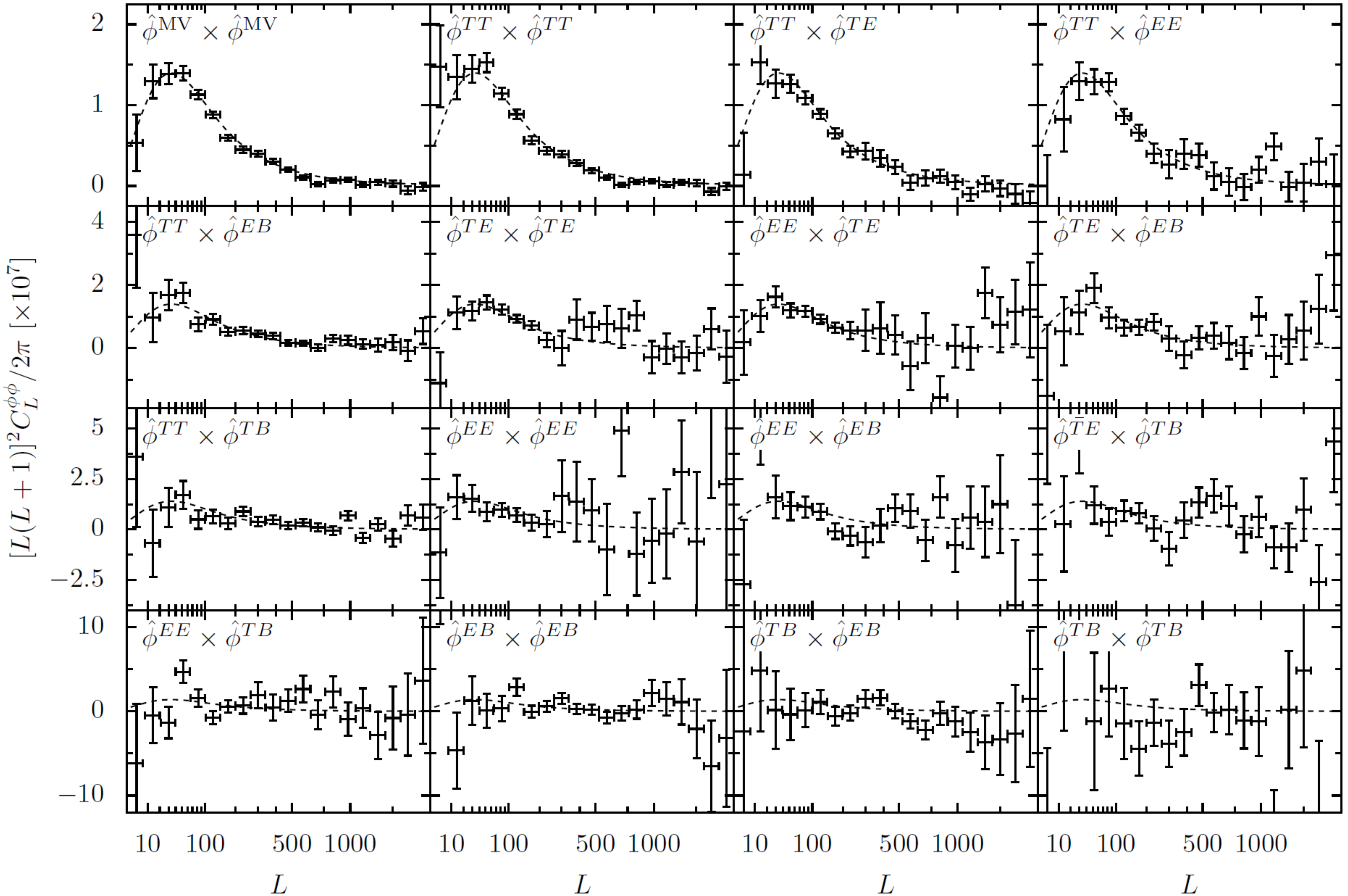
[Planck Collaboration XVIII 2013]

Lensing power spectrum



Planck for the first time measured the lensing power spectrum with higher accuracy than it is predicted by the base CDM model that fits the temperature data

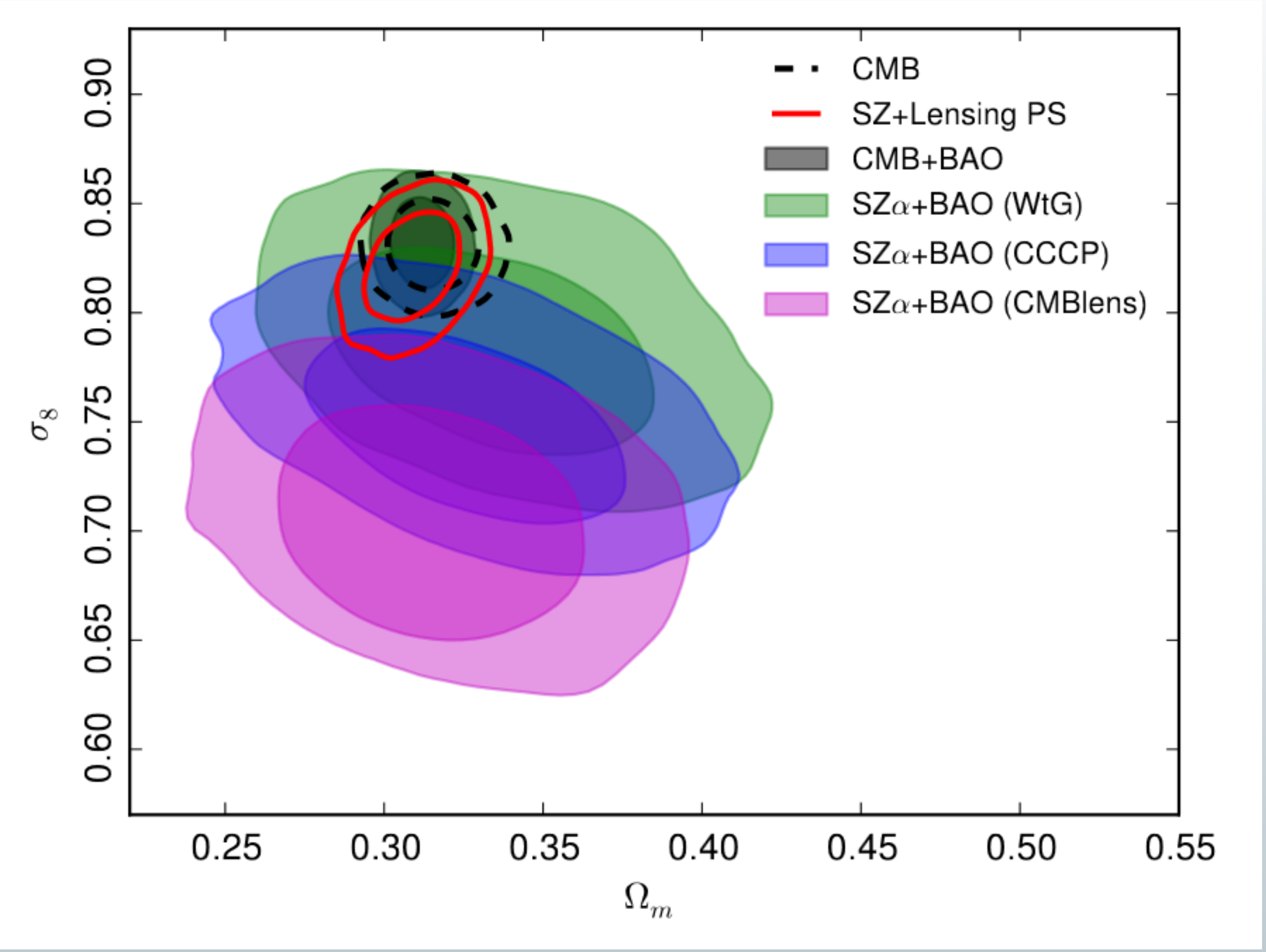
Individual lensing cross-spectra



Standard cosmological model - LCDM

- The CMB TT, TE, EE, Φ-Φ, as well as BBN (but Li7), the BAO and SN1a measurements are all consistent, among themselves and across experiments, despite the per cent level precision of the tests now performed.
- This consistency allows <u>many</u> different checks of the robustness of base LCDM and some of its extensions. e.g., so far base LCDM parameters and derived parameters (including τ constrained two-ways thanks to CMB lensing), flatness at 5 x 10^{-3} level, neutrinos masses and number, DM annihilation, recombination history ($A_{2s\rightarrow1}$, T_0, and also fundamental constants variation, w, or any energy input).

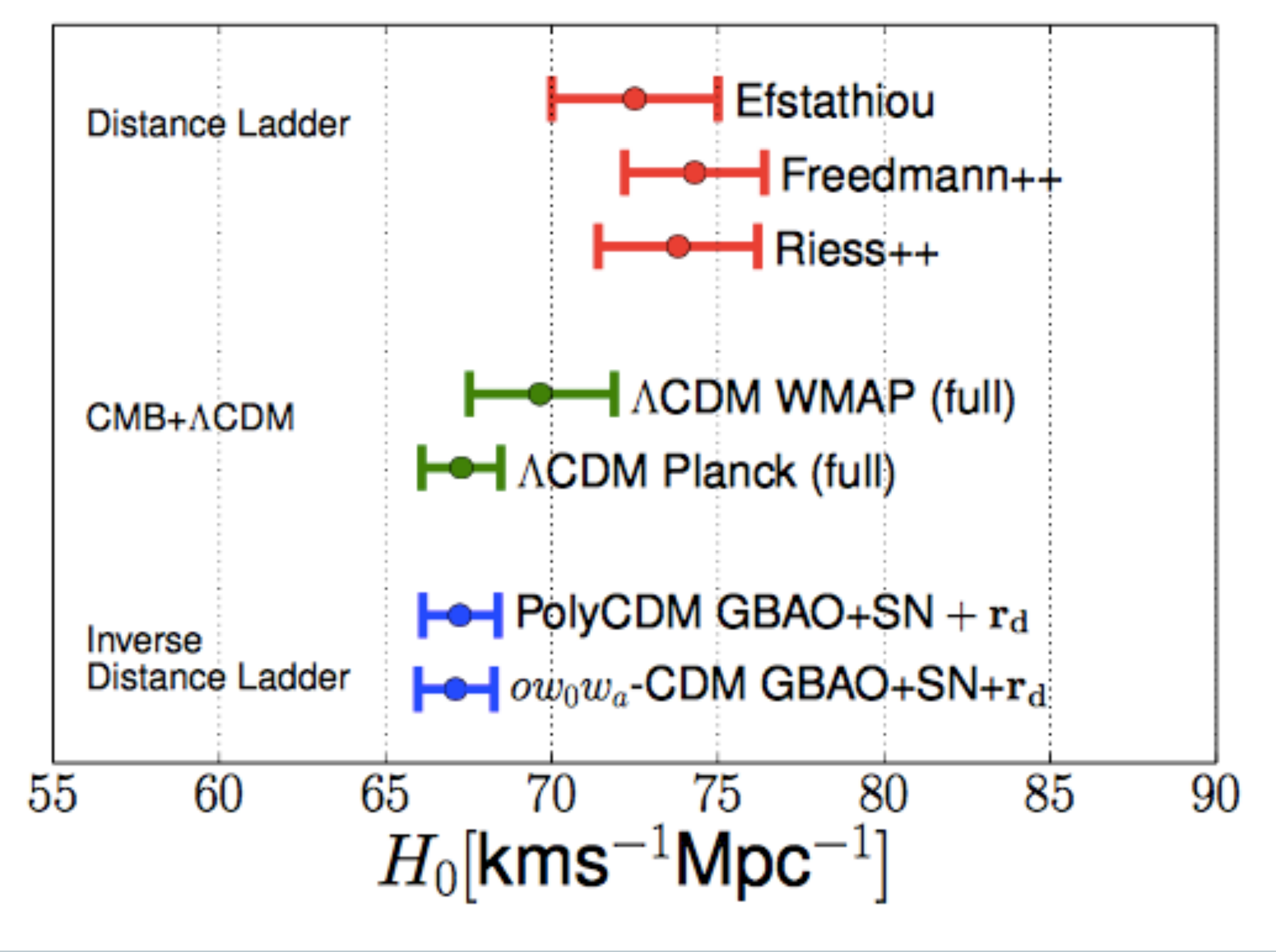
Number counts of SZ clusters



2013 tension only remains with **some** mass proxy calibration

Comparison of H_0

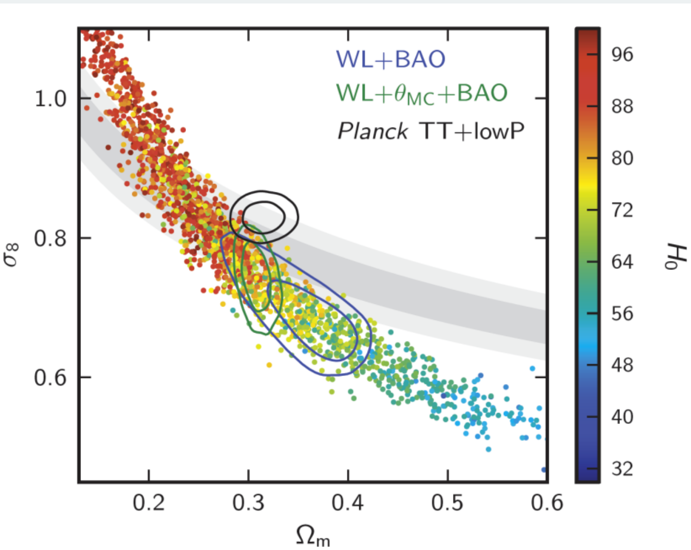
- Inverse distance ladder is In perfect agreement with Planck CMB (use BAO's absolute calibration to calibrate SN1a in the overlapping region at z=0.57 to bring it down to z=0.)
- Some discrepancy with direct distance ladder



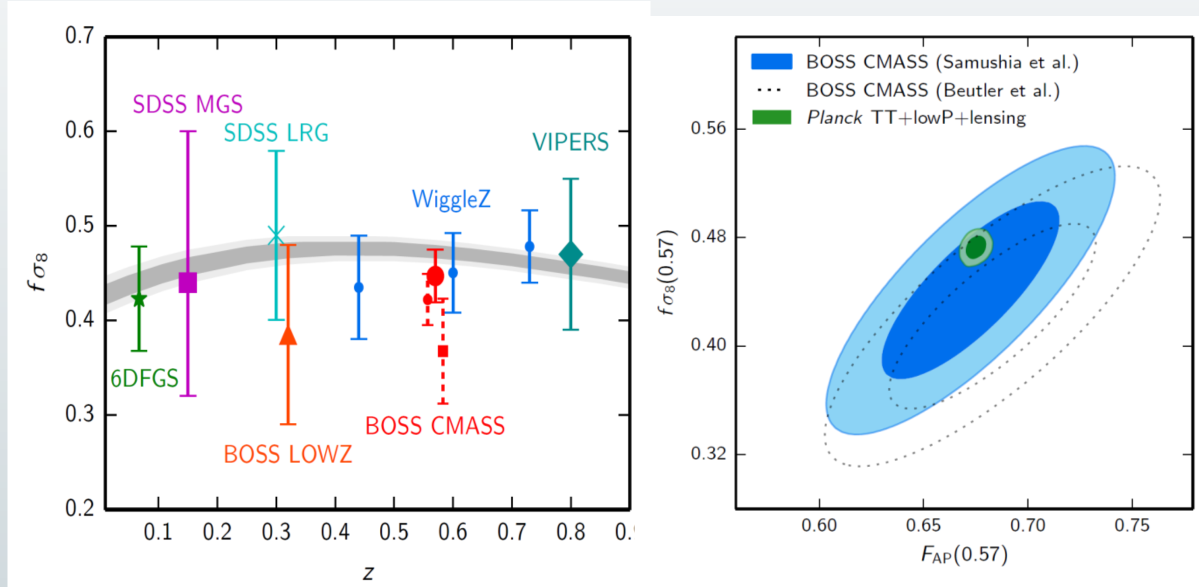
arXiv:1411.1074v2

Some tensions

Weak Lensing from CFHTLens



Growth rate of fluctuations from redshift space distortions

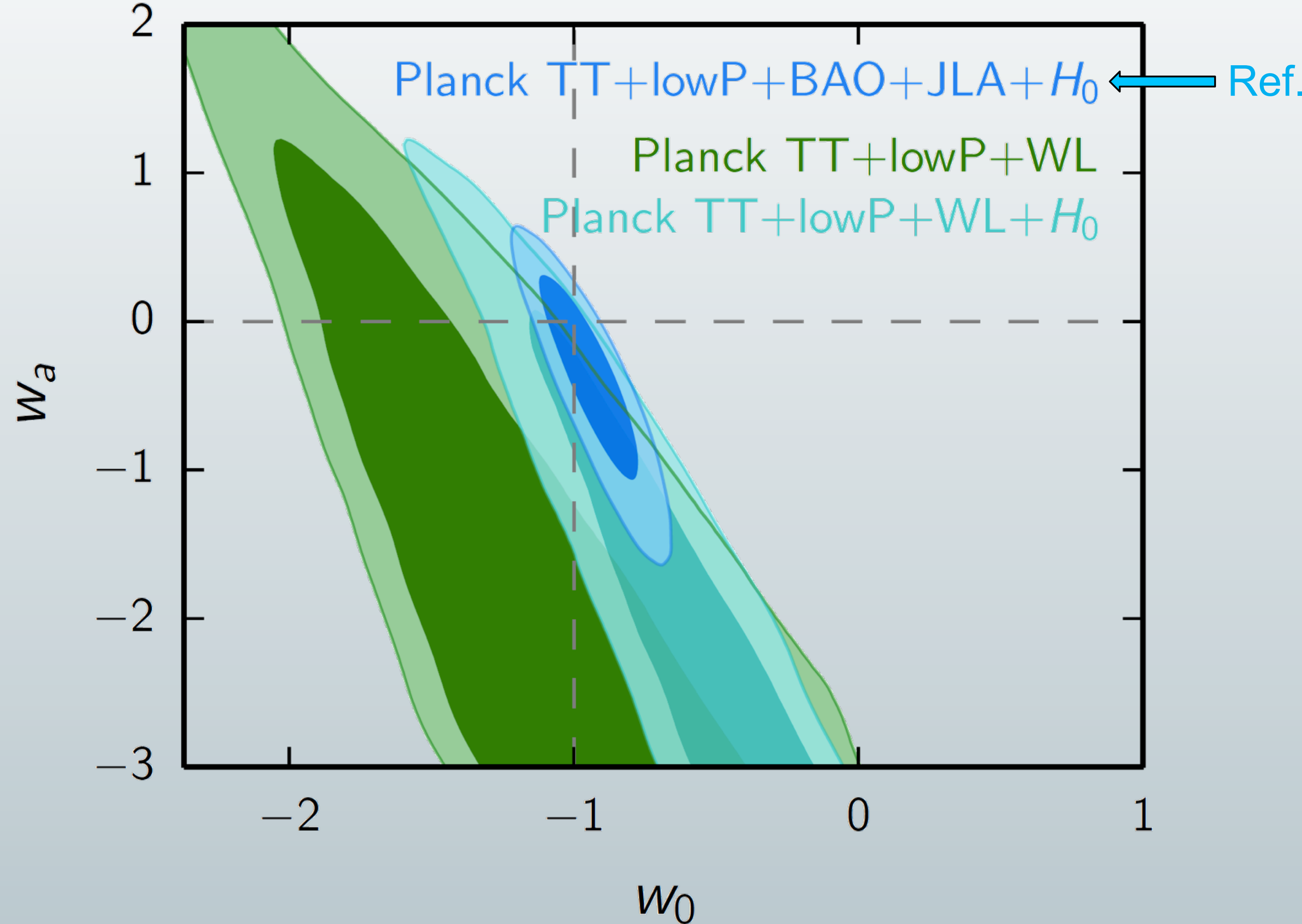


i.e. some tensions with astrophysical measurements of the amplitude of matter fluctuations at low z.

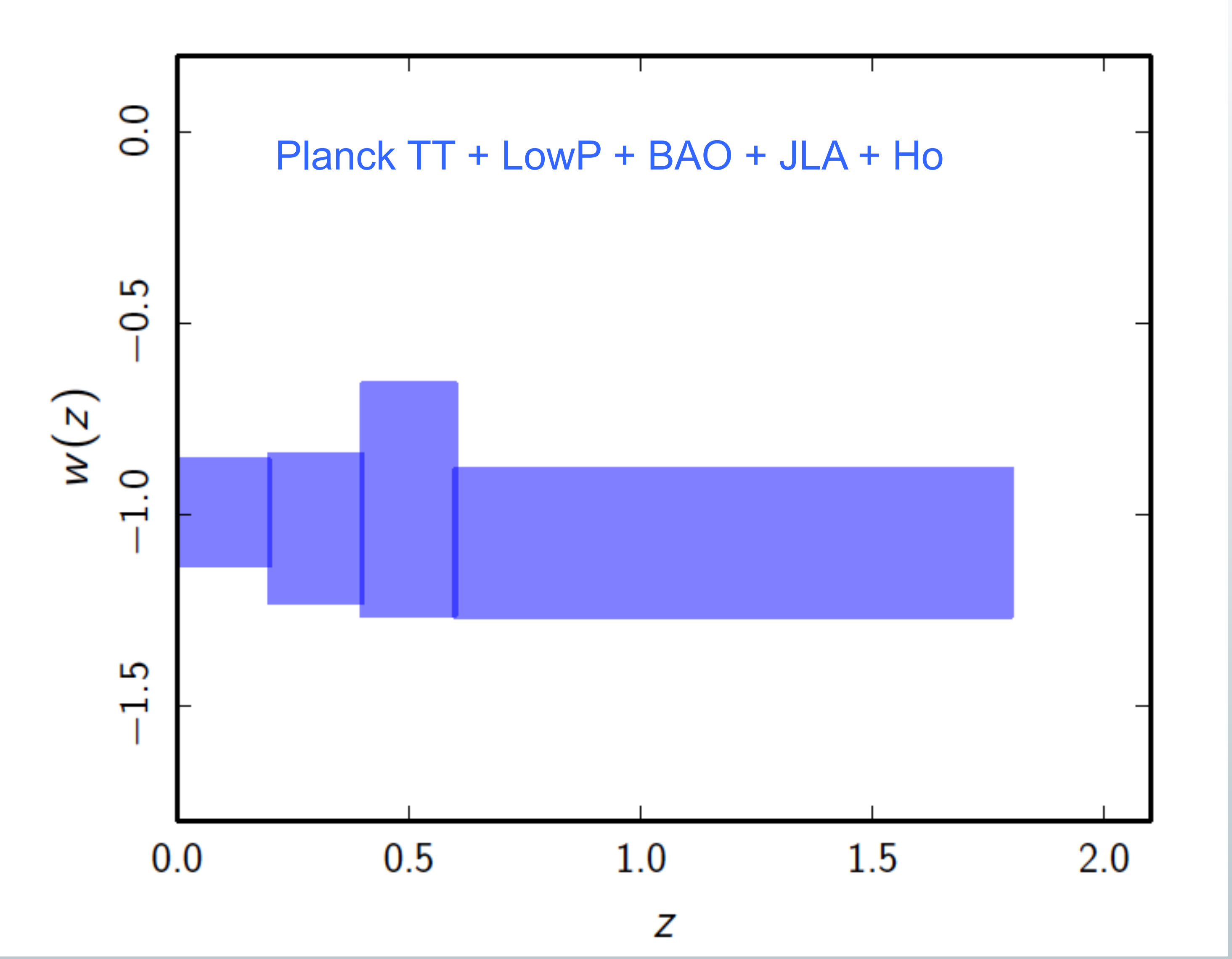
NB: Ly BAO measurements at high redshift are discrepant at 2.7sig, and it is quite difficult to find physical explanation not disrupting BAO consistency elsewhere, see eg Aubourg etal. 2015

What these tensions can do…

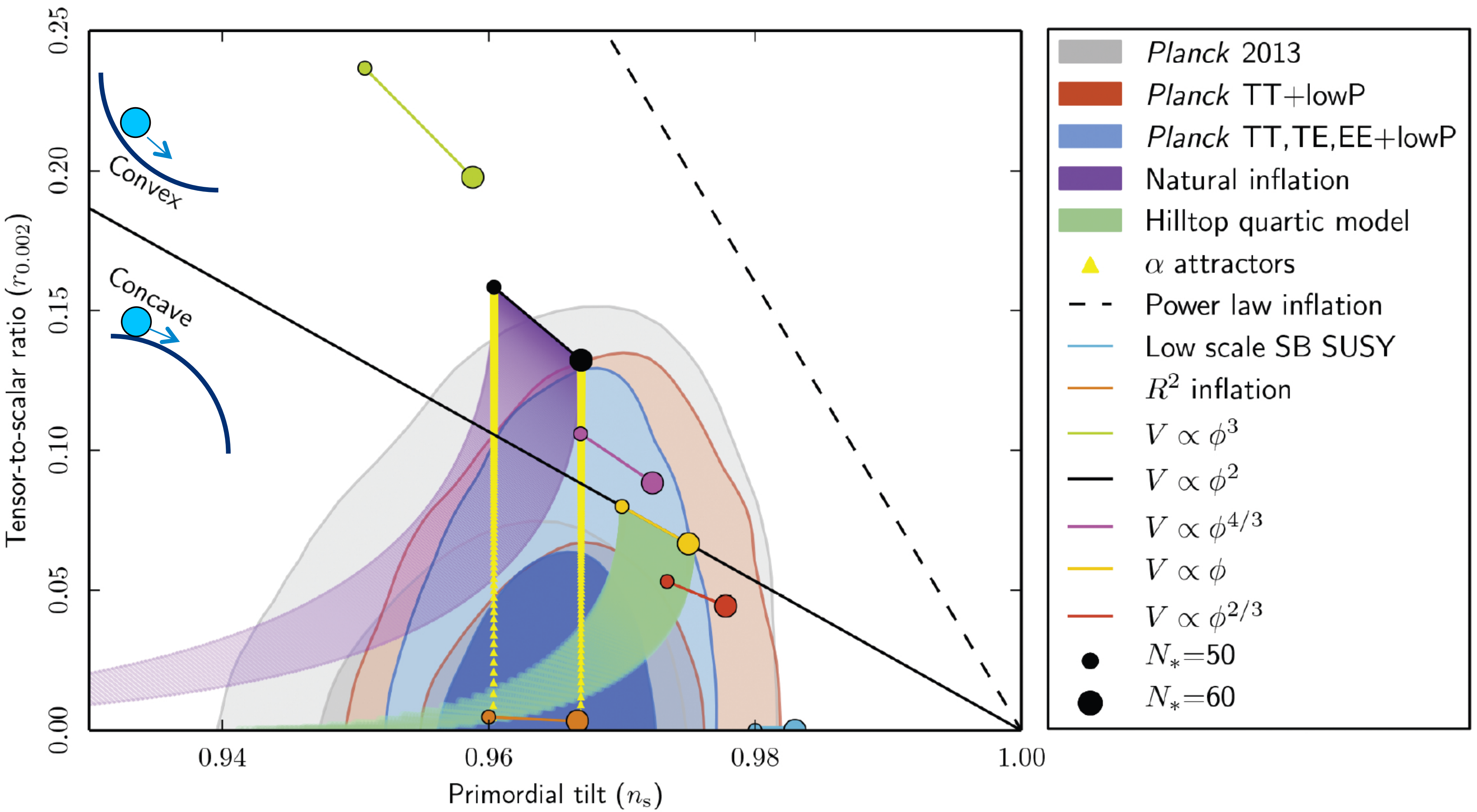
$$W(a) = w_0 + (1-a)\, w_a$$



PCA of w(z)



Planck 2015: n_s vs r



Only weakly tighter (indirect) r constraint than with 2013 release ($r_{0.002} < 0.10$ @ 95% CL vs 0.11)

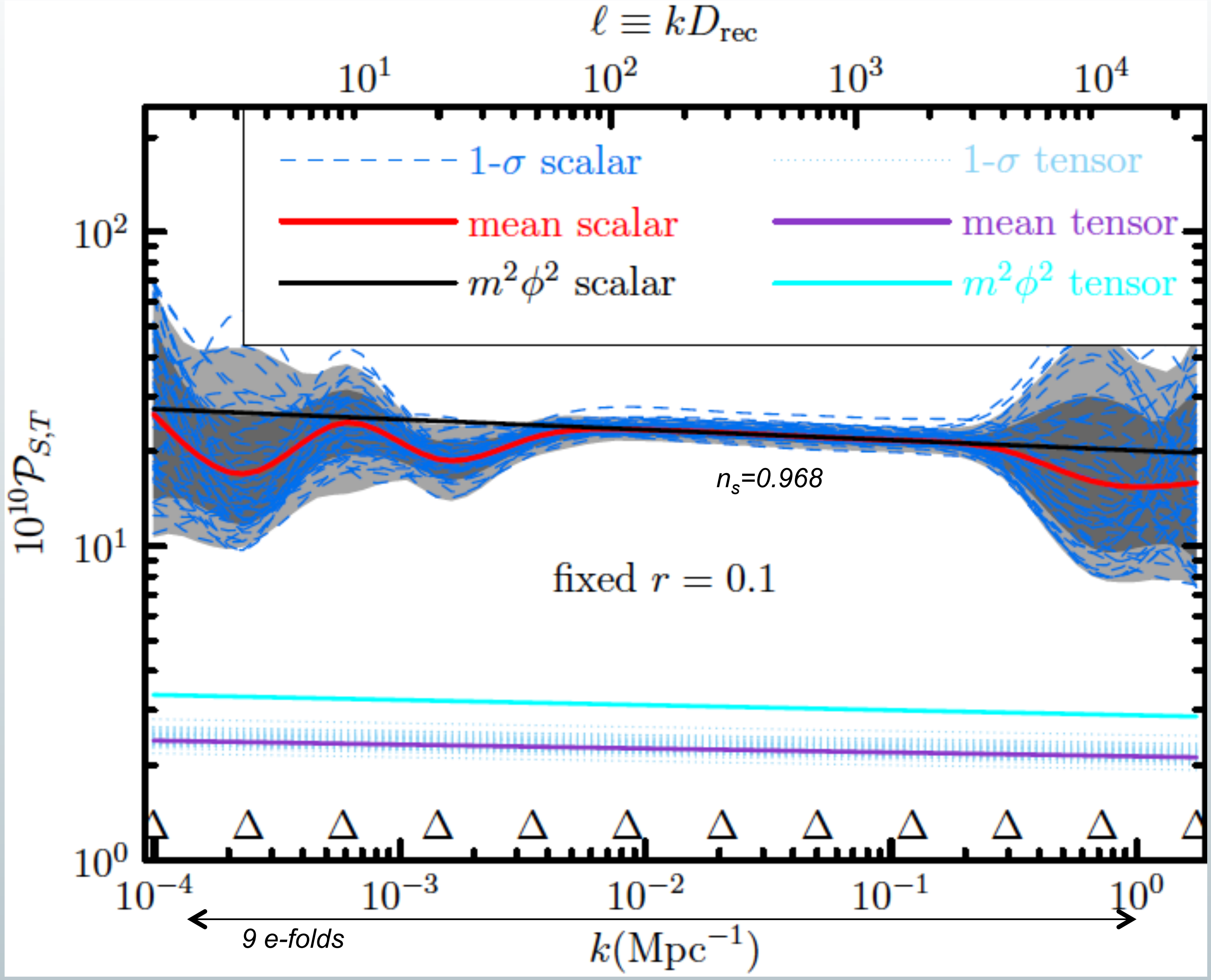
Power spectra reconstruction

2015

TT+lowP

+BAO+JLA

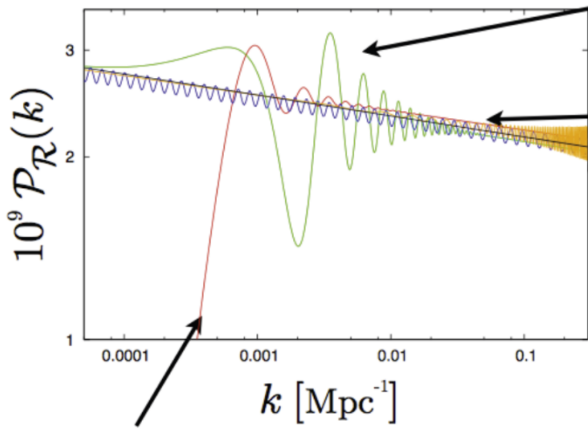
+Hlow



12-knots power spectra

(actually used 3 different methods, all with similar results)

(Unsuccessful) Search for features



Feature in the potential:

$$V(\phi) = \frac{m^2}{2}\phi^2\left[1 + c\tanh\left(\frac{\phi-\phi_c}{d}\right)\right]$$

Non vacuum initial conditions/instanton effects in axion monodromy

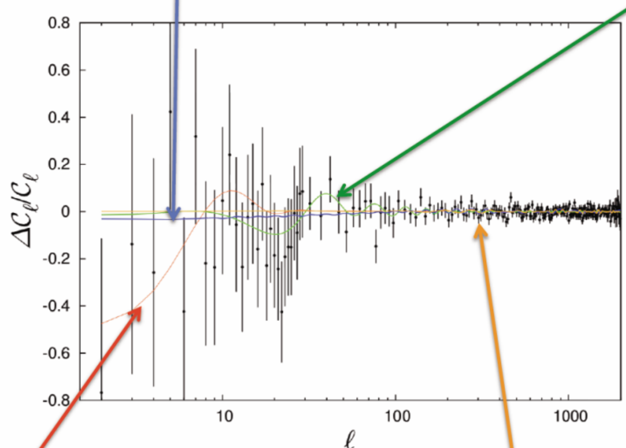
$$V(\phi) = \mu^3\phi + \Lambda^4\cos\left(\frac{\phi}{f}\right)$$

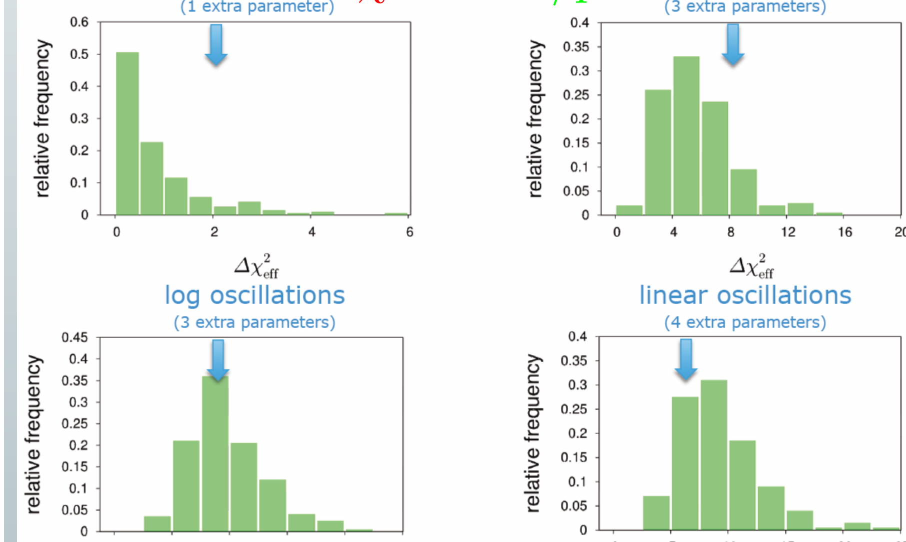
$$\mathcal{P}_\mathcal{R}^{\log}(k) = \mathcal{P}_\mathcal{R}^0(k)\left[1 + \mathcal{A}_{\log}\cos\left(\omega_{\log}\ln\left(\frac{k}{k_*}\right) + \varphi_{\log}\right)\right].$$

Linear oscillations as from Boundary EFT

$$\mathcal{P}_\mathcal{R}^{\rm lin}(k) = \mathcal{P}_\mathcal{R}^0(k)\left[1 + \mathcal{A}_{\rm lin}\left(\frac{k}{k_*}\right)^{n_{\rm lin}}\cos\left(\omega_{\rm lin}\frac{k}{k_*} + \varphi_{\rm lin}\right)\right]$$

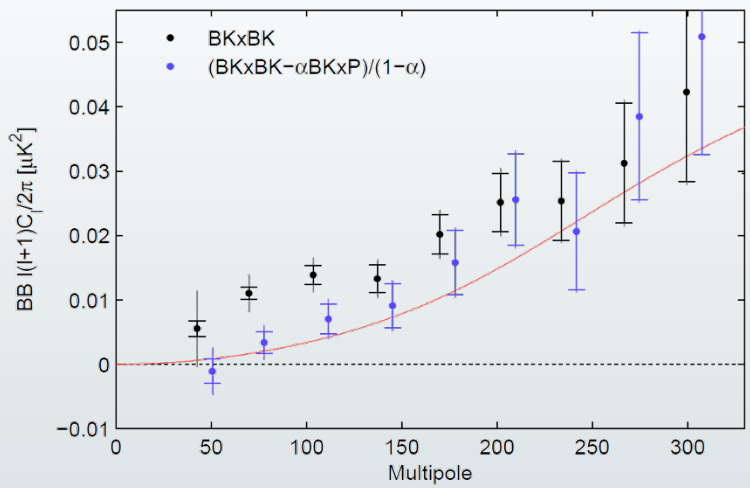
Just enough e-folds, i.e. inflation preceded by a kinetic stage



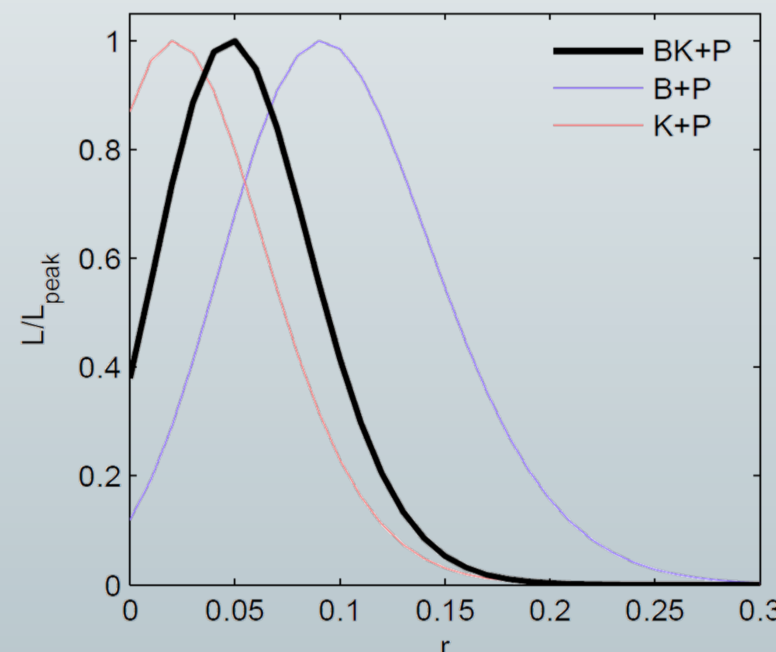


Planck X (Bicep2 & Keck) Ξ BKP

- Since January 30th 2015, the **direct** constraints on r (Planck X Bicep2 & Keck) have reached the level of the previous best **indirect constraints** (from Planck alone T), i.e.



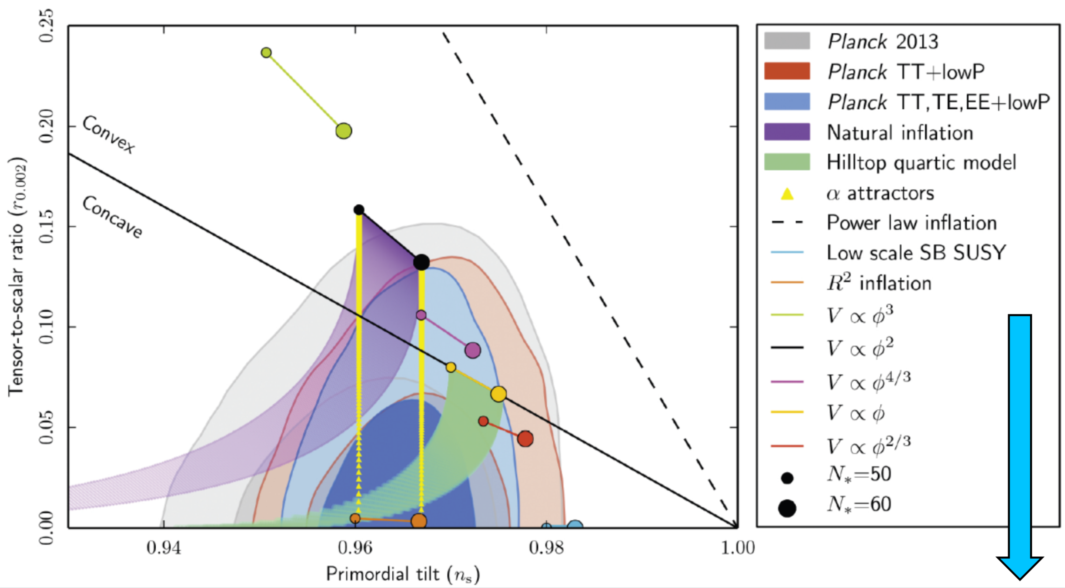
- r < 0.11 @ 95%CL
  (r =A_s/A_T at, e.g., k=0.05Mpc^{-1})

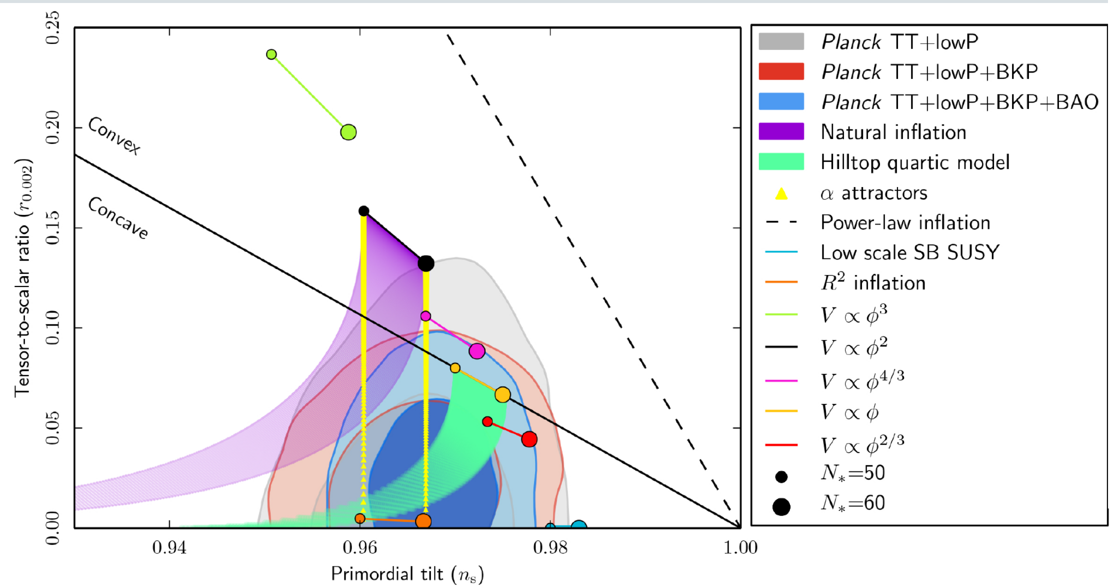


- A great measurement of B modes from lensing

- A new era began…

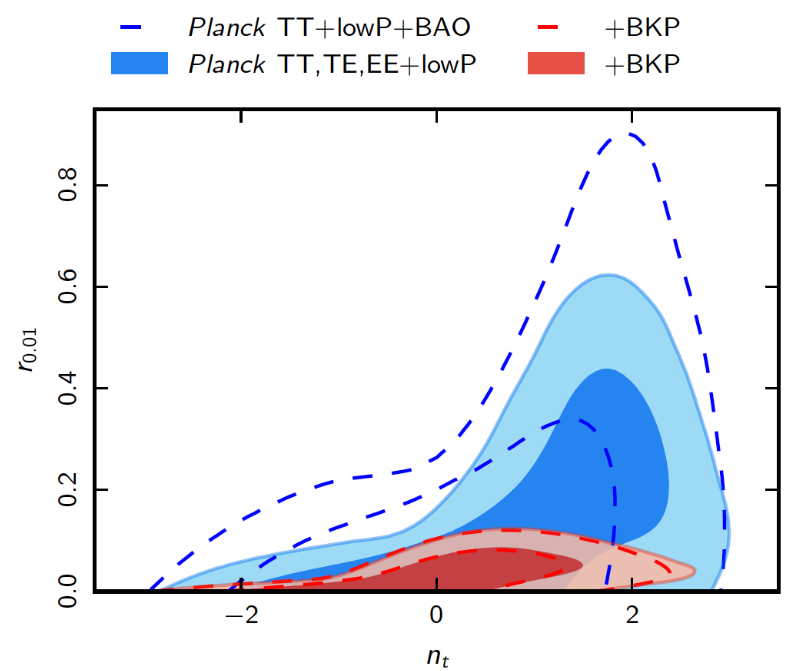
Planck + BK X Planck





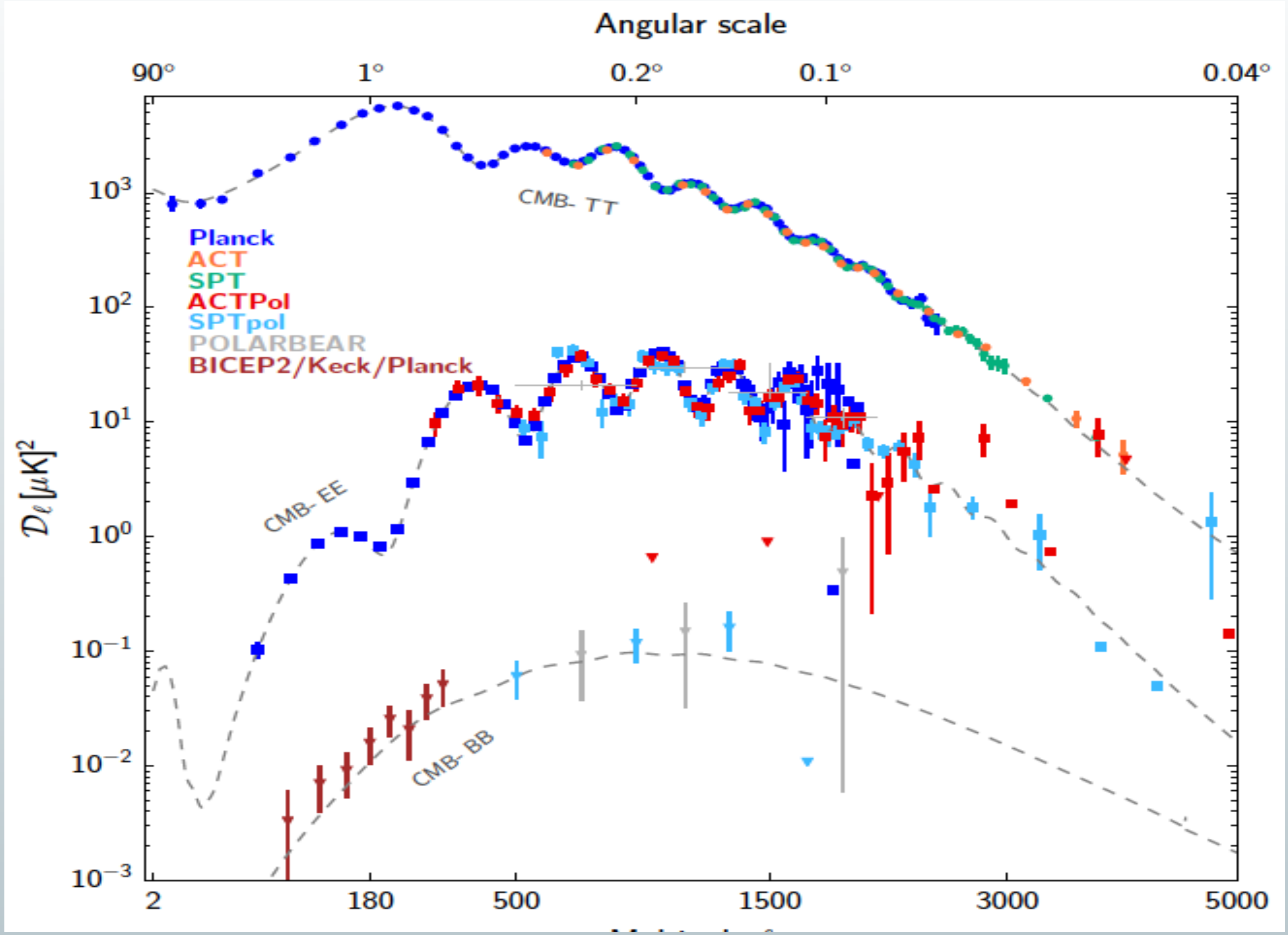
Planck 2013: $r_{0.002}$ < 0.11 @95%cl
Planck 2015: $r_{0.002}$ < 0.10 @95%cl
BKP : $r_{0.002}$ < 0.12 @95%cl

Planck+BKP: $r_{0.002}$ < 0.08 @95%cl

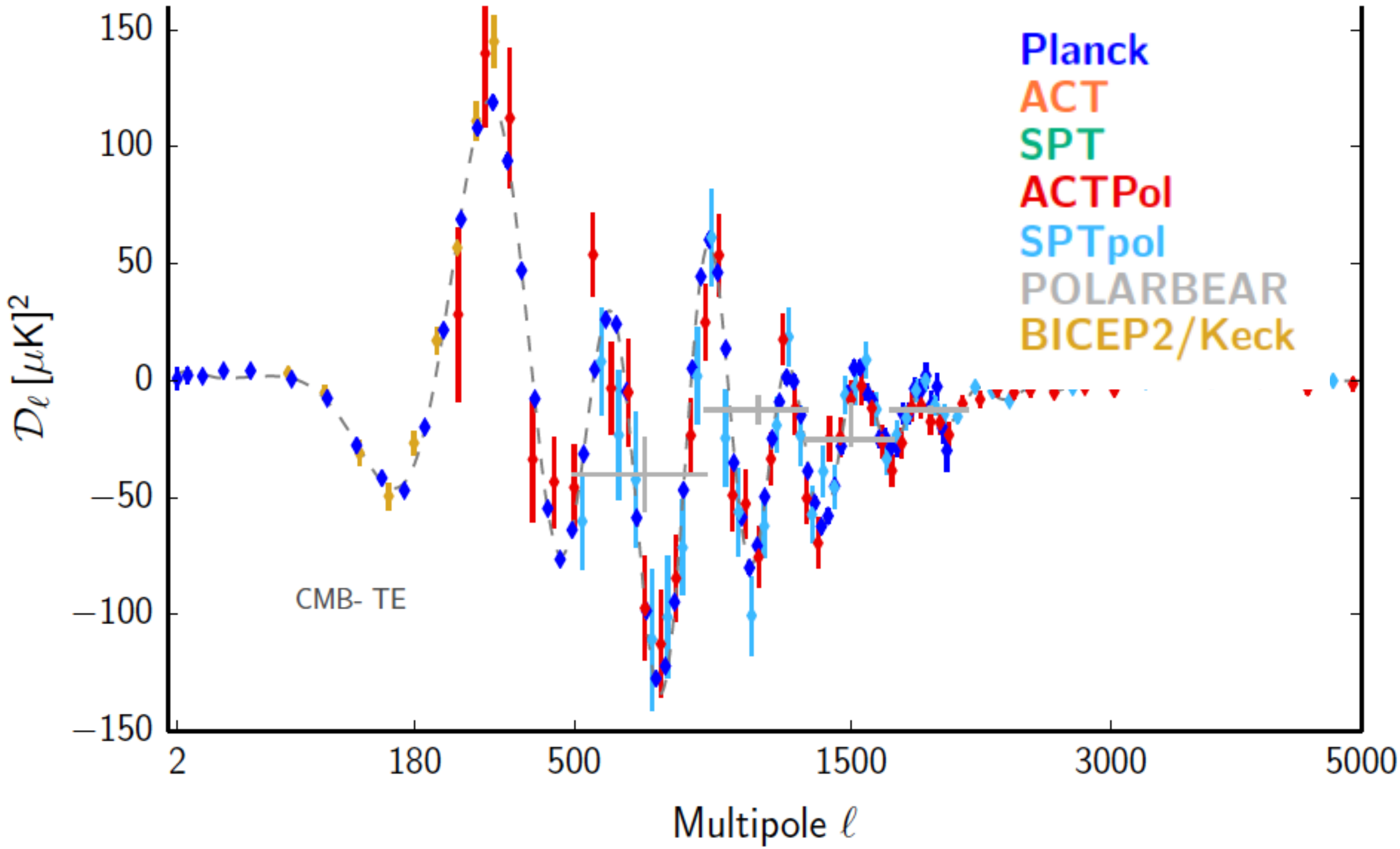


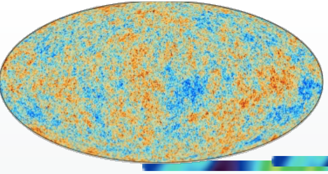
(using n_T and $r_{0.002}$ as primary parameters)

TT, EE, BB – mid 2015 status

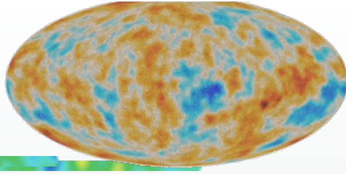


Not forgetting TE

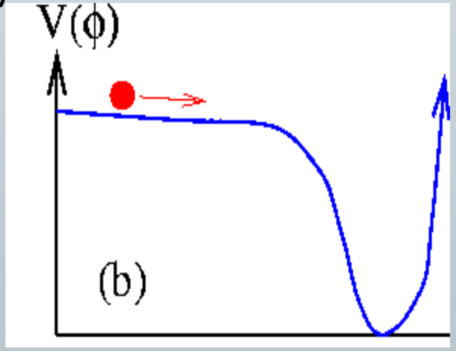




Summary: Basic ΛCDM fits



- Primordial fluctuations are, to a very good approximation:
  - *Isotropic*
  - *Gaussian*
  - *Adiabatic* — *(fluctuations in pressure α to the density)*
  - *Coherent* — *(fluctuations start @same time, harm. osc)*
  - *Close to Scale invariant*
  - *but not exactly* — *(n_s =1 is excluded at more than 5σ)*
- With minimal cosmological content,
  - *Flat spatial geometry* — *(is a very good approximation)*
  - *Matter is mostly dark* — *(and cold)*
  - *"Dark energy" consistent with Λ* — *(w=-1)*
  - *Small fraction of baryon, consistent with BBN*
- No gravitational waves — (10 percent level)
- Large scale power, with TT versus TE anti-correlation ($5^o > \vartheta > 1^o$):
  - *This Signature of « super-horizon » fluctuations at decoupling and adiabaticity of primordial fluctuations (phases TT/TE) provides an indication of apparently a-causal physics, calling for a period of accelerated expansion (Spergel & Zaldariaga 97)*



→ I.e. all consistent with generic inflationary framework

In the Planck Legacy archive…

- Low TEB
- high-l
  - *TT (baseline), TE, EE, TTTEEE,*
  - *High-ell: Binned, or unbinned (l by l, slower, for features searches)*
  - *A detset based one (instead of cross-half-mission)*
  - *A faster version marginalised over the nuisance parameters*
- The lensing likelihood (baseline + aggressive)
- Masks used (and possibility of different l_{Hyb})
- …
- See
  http://wiki.cosmos.esa.int/planckpla2015/index.php/CMB_spectrum_%26_Likelihood_Code#Data_sets_-_Extended_data
- (or g planck likelihood ☺)

- Chains for a large grid of data sets/models…

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.