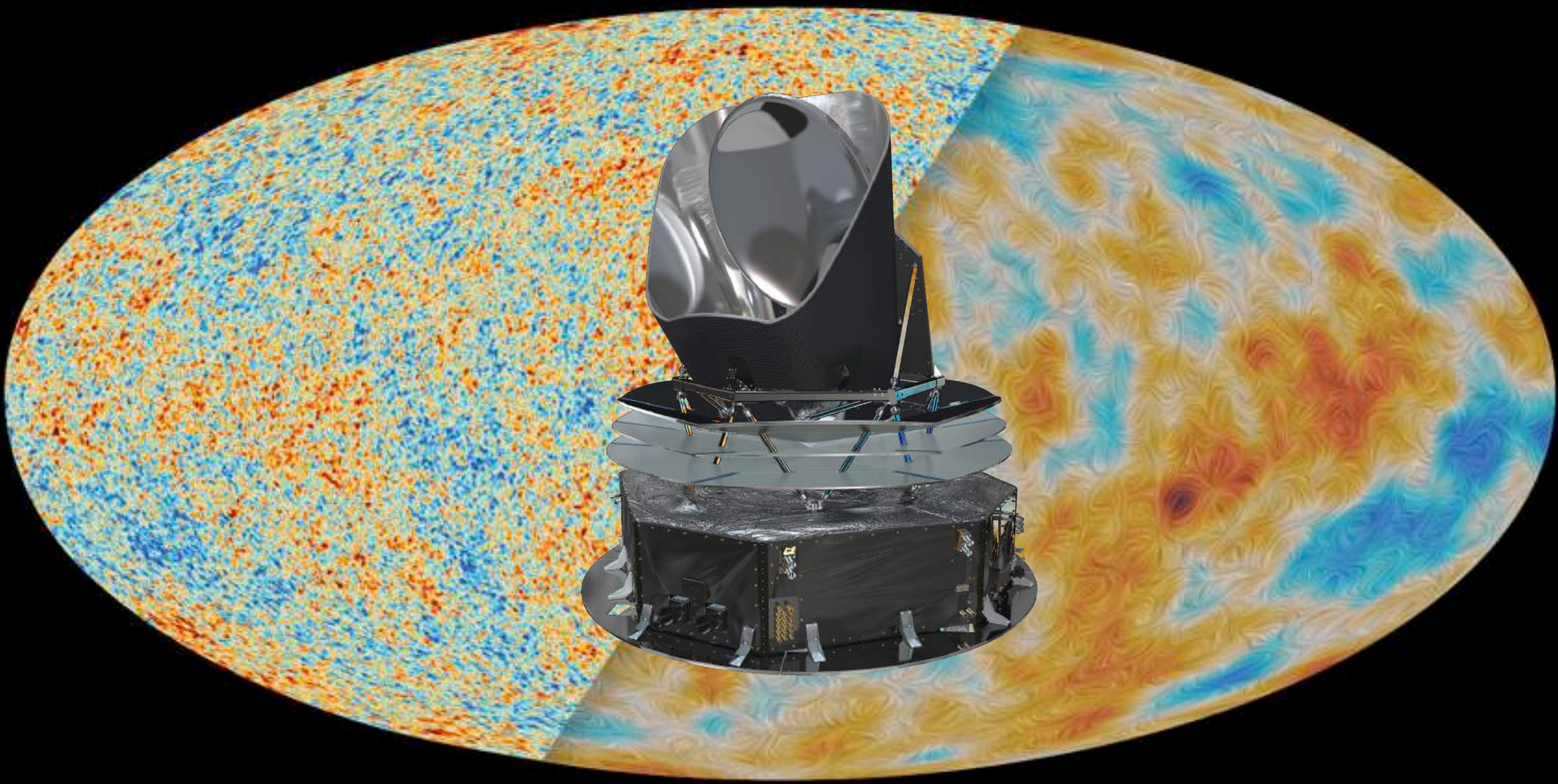
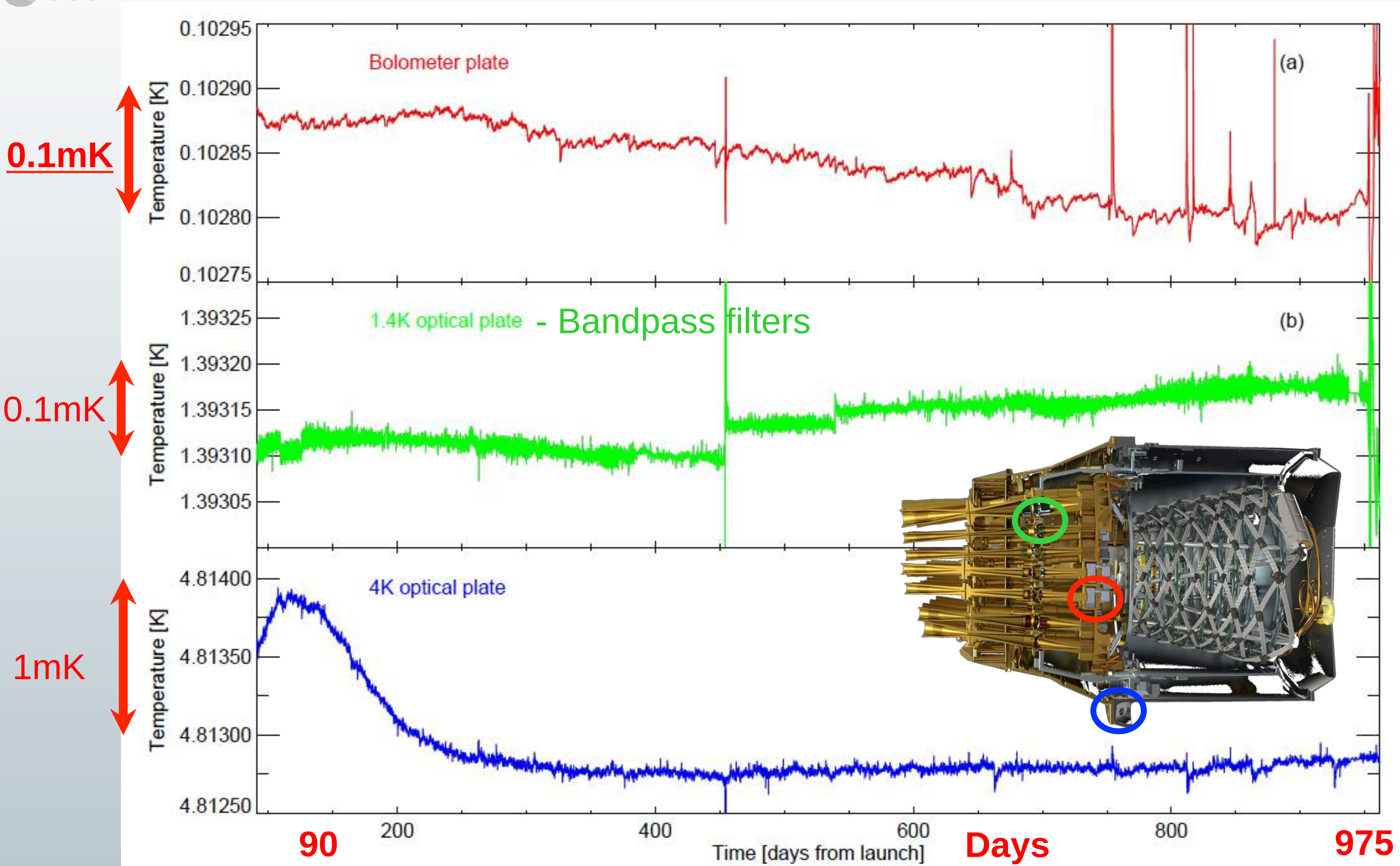
PLANCK 2015 COSMOLOGY

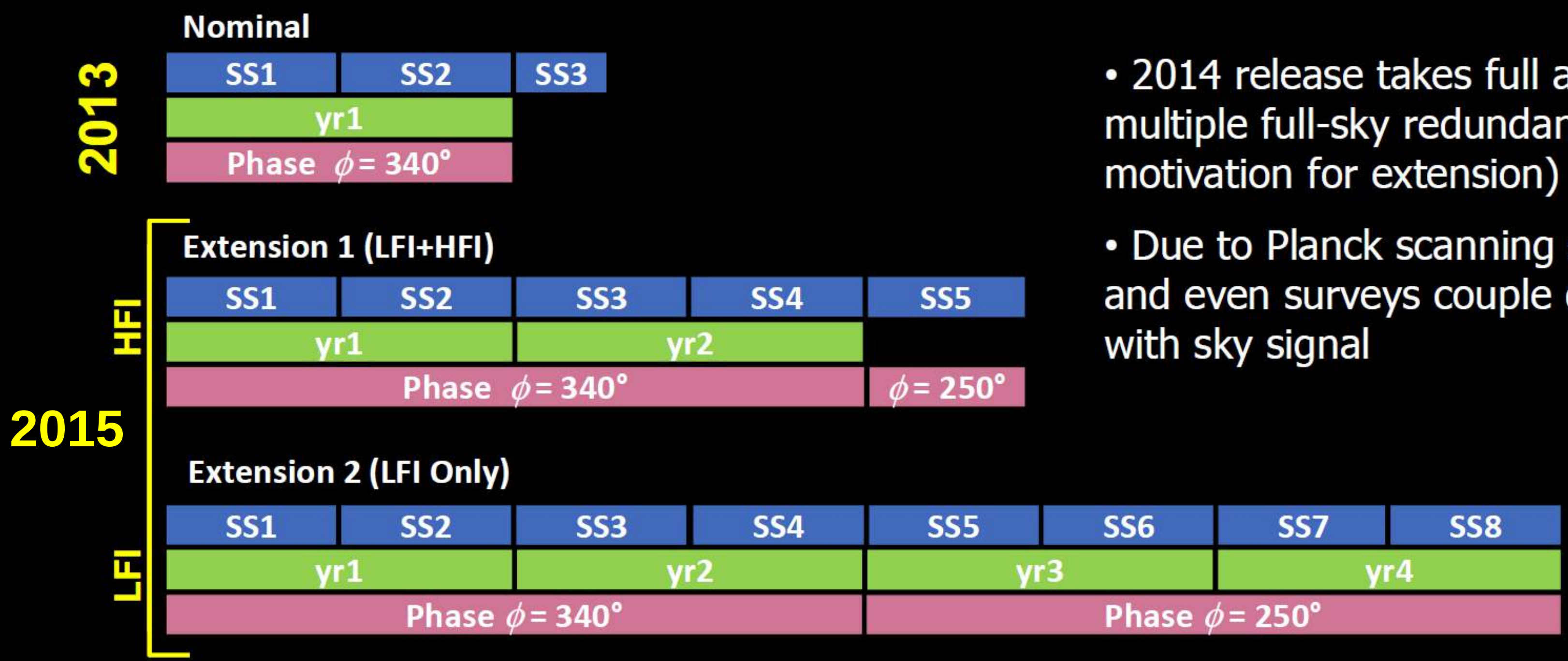


François R. Bouchet on behalf of the Planck Collaboration

Quietly cool...



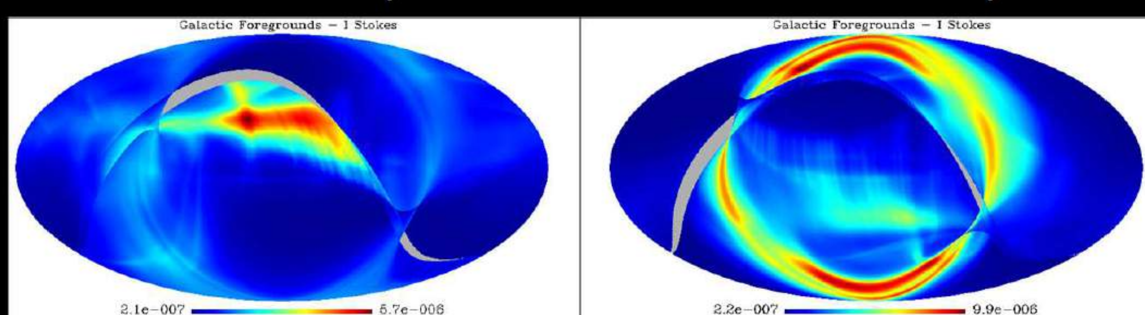
2015 release: Planck full mission data



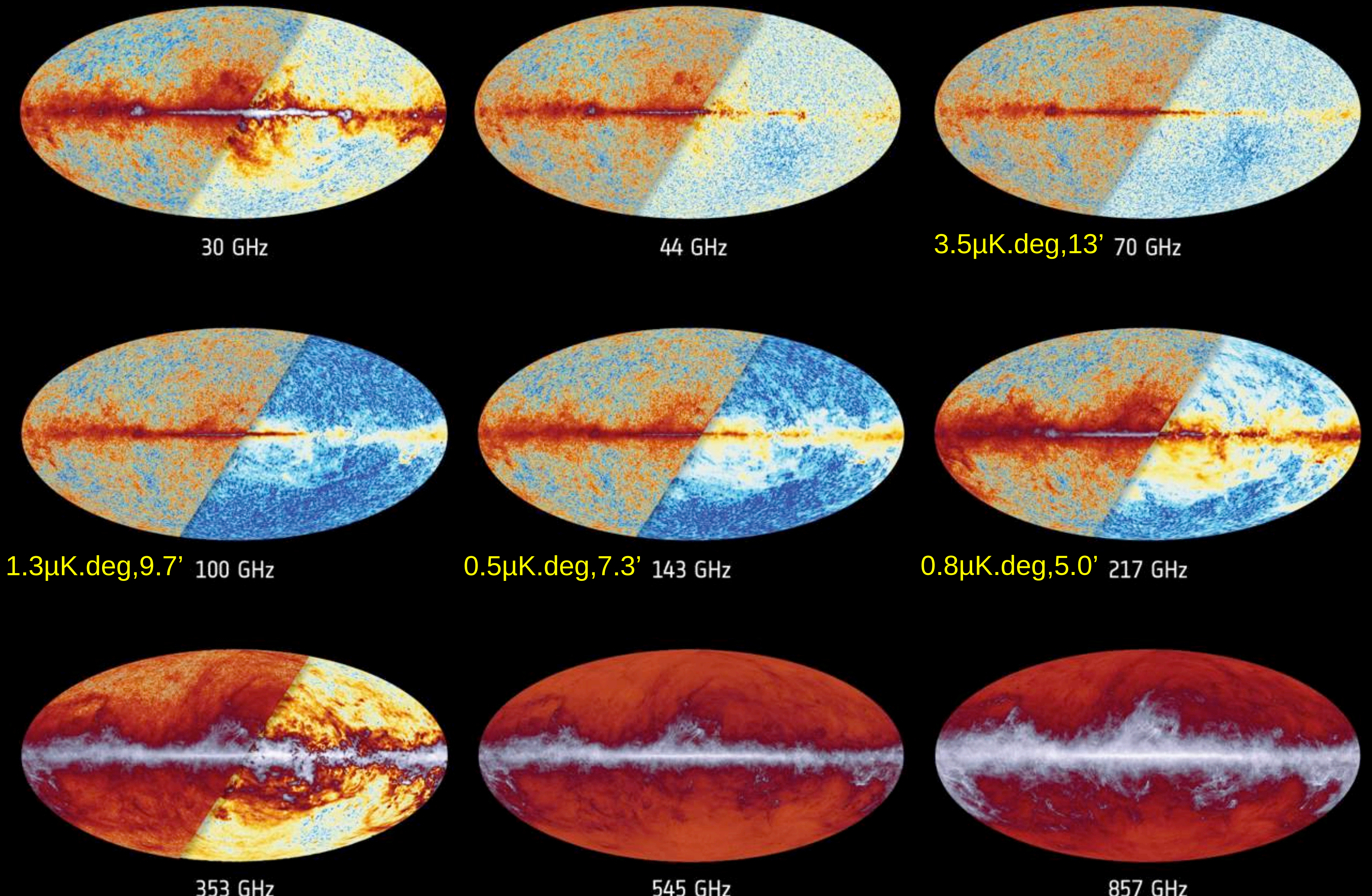
- 2014 release takes full advantage of multiple full-sky redundancies (main motivation for extension)
- Due to Planck scanning strategy, odd and even surveys couple differently with sky signal

Galactic straylight (simulation)

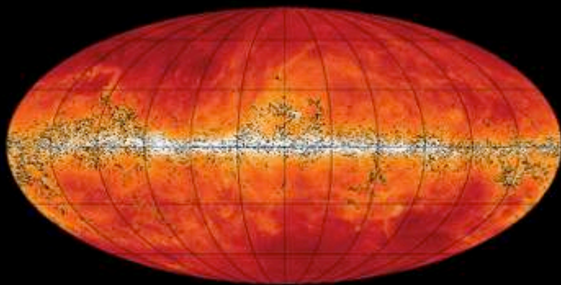
Odd survey | Even survey



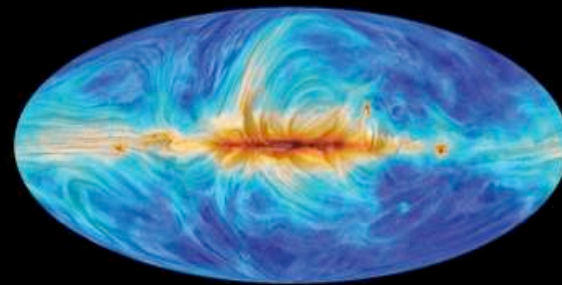
Now available in a store near you



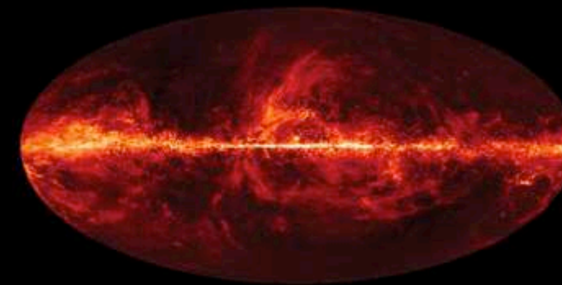
And a lot more…



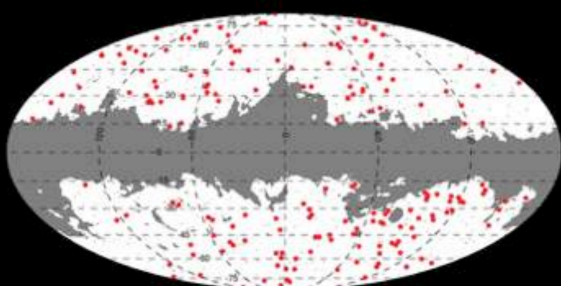
Galactic cold clumps



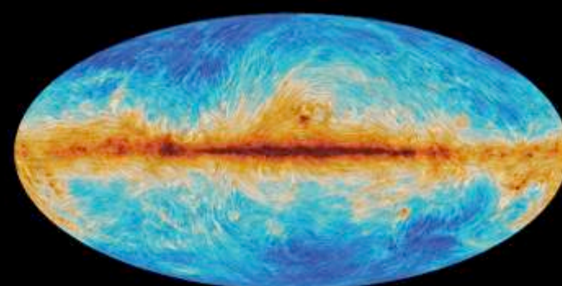
Magnetic field lines traced
by synchrotron radiation at 30 GHz



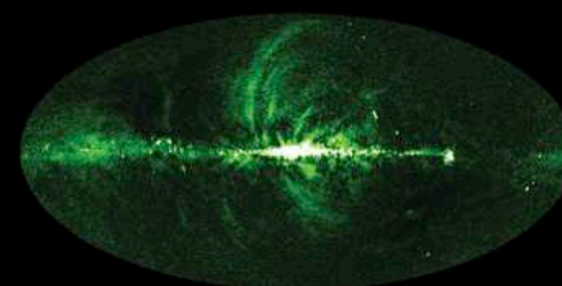
Polarised dust emission



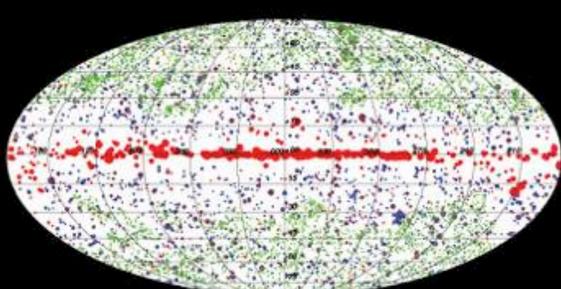
Galaxy clusters detected by
the Sunyaev-Zeldovich effect



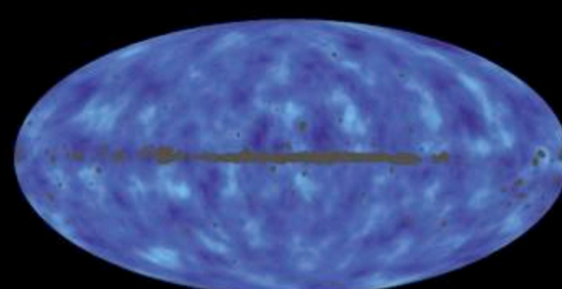
Magnetic field lines traced
by dust emission at 353 GHz



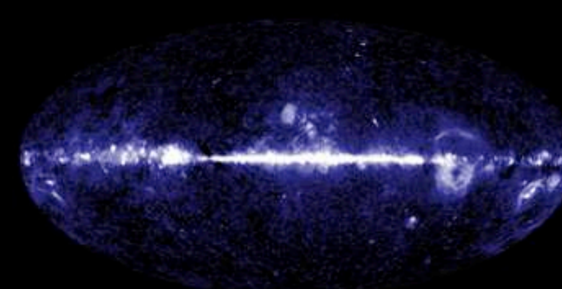
Polarised synchrotron emission



Compact sources



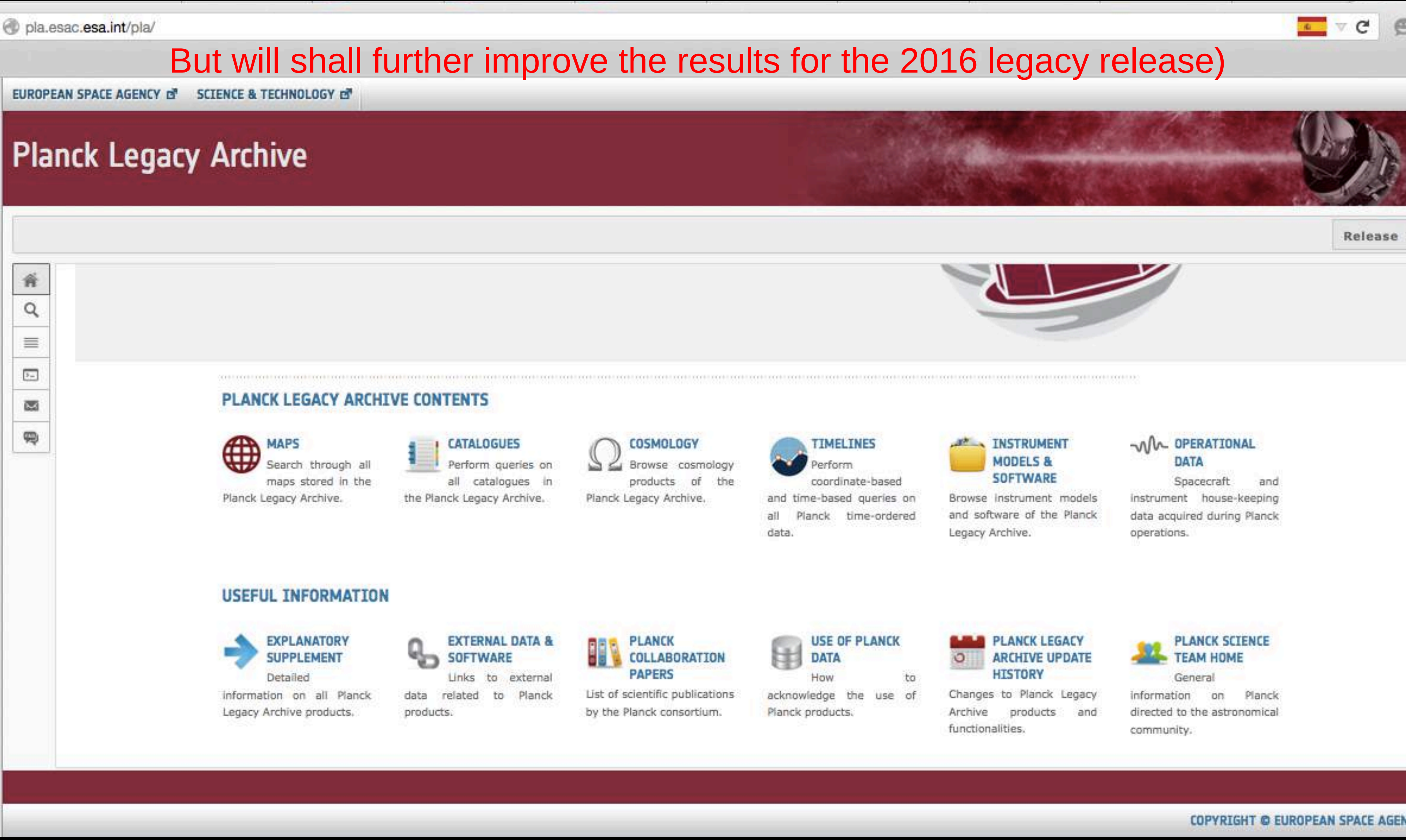
Gravitational-lensing potential —
a tracer of dark matter structures



Line radiation from carbon monoxide gas

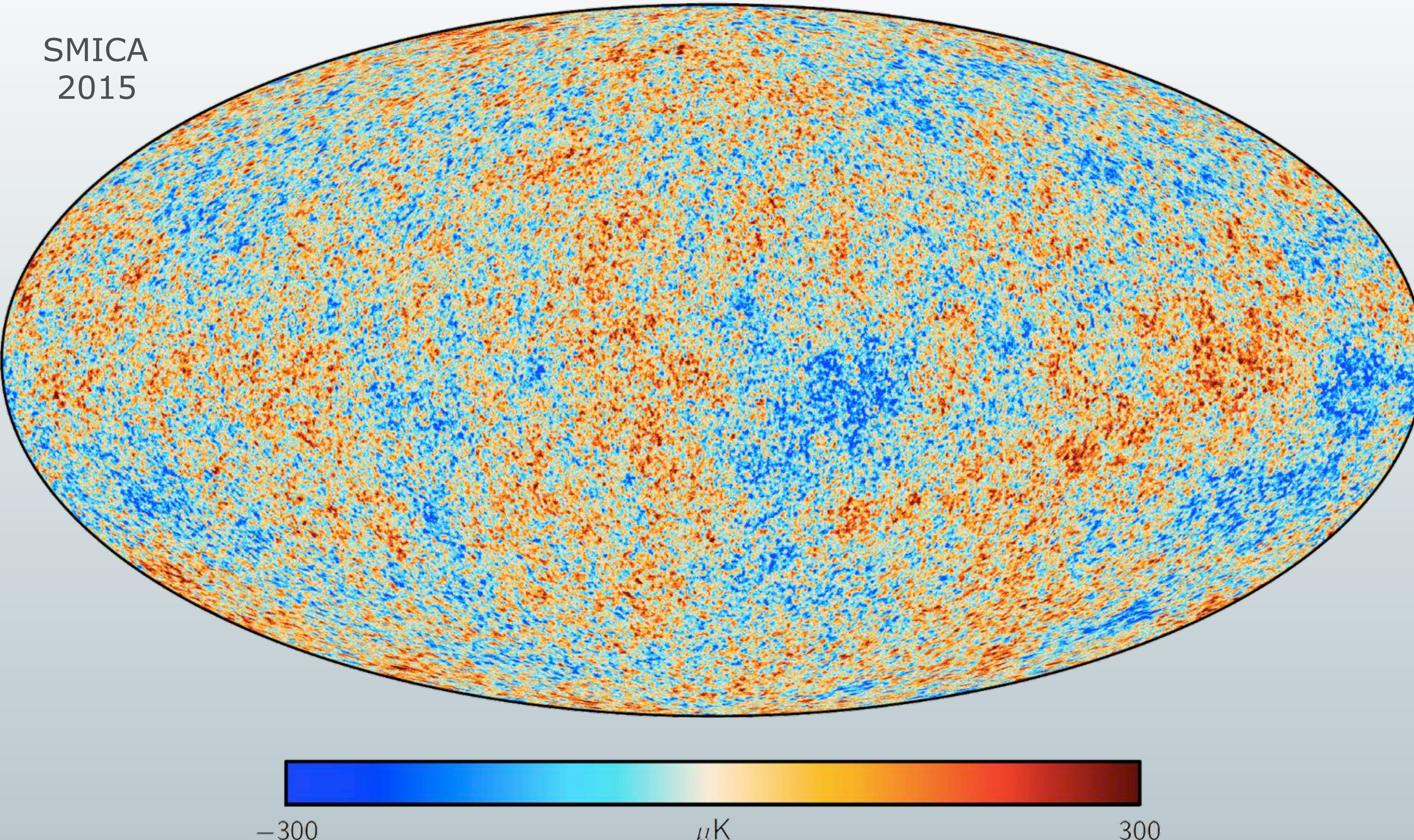
Mission accomplished!

But will shall further improve the results for the 2016 legacy release)



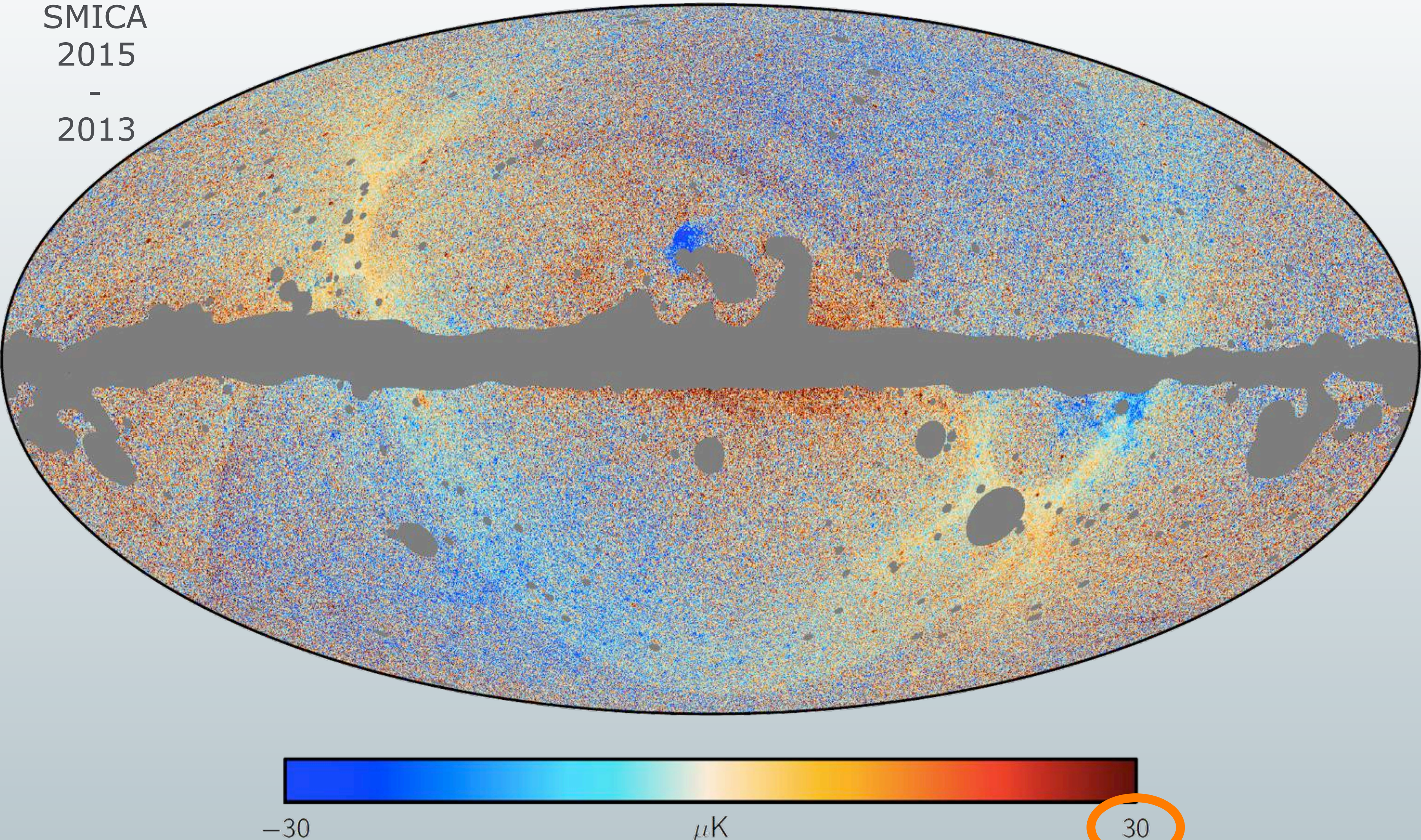
Planck 2015 T anisotropies map

SMICA
2015

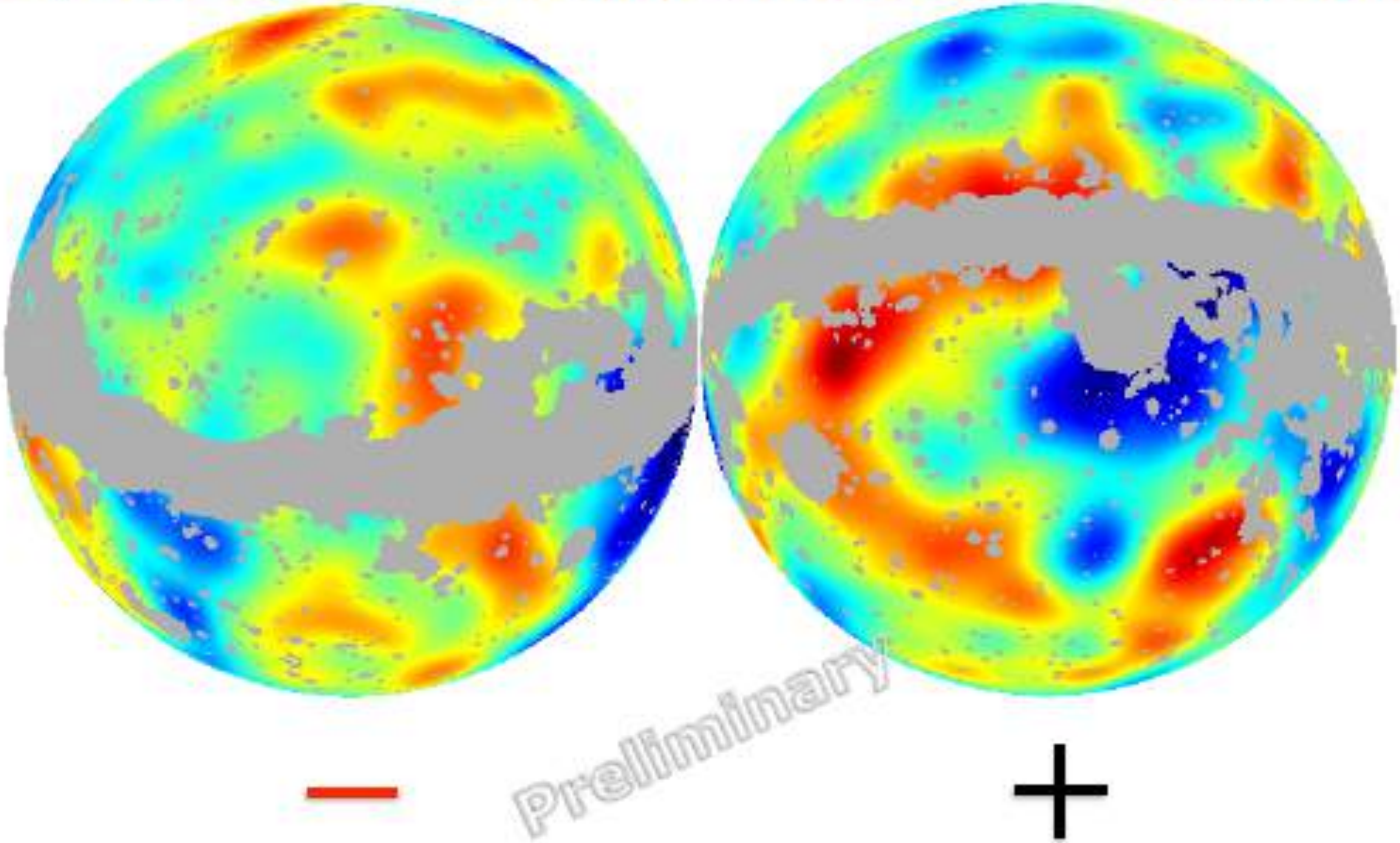


2015 vs 2013 temperature map

SMICA
2015
-
2013



Power asymmetry in *Planck* 2014 full mission data



Features on 2014 full mission data are very similar to 2013 nominal mission data.

Power Spectrum estimation

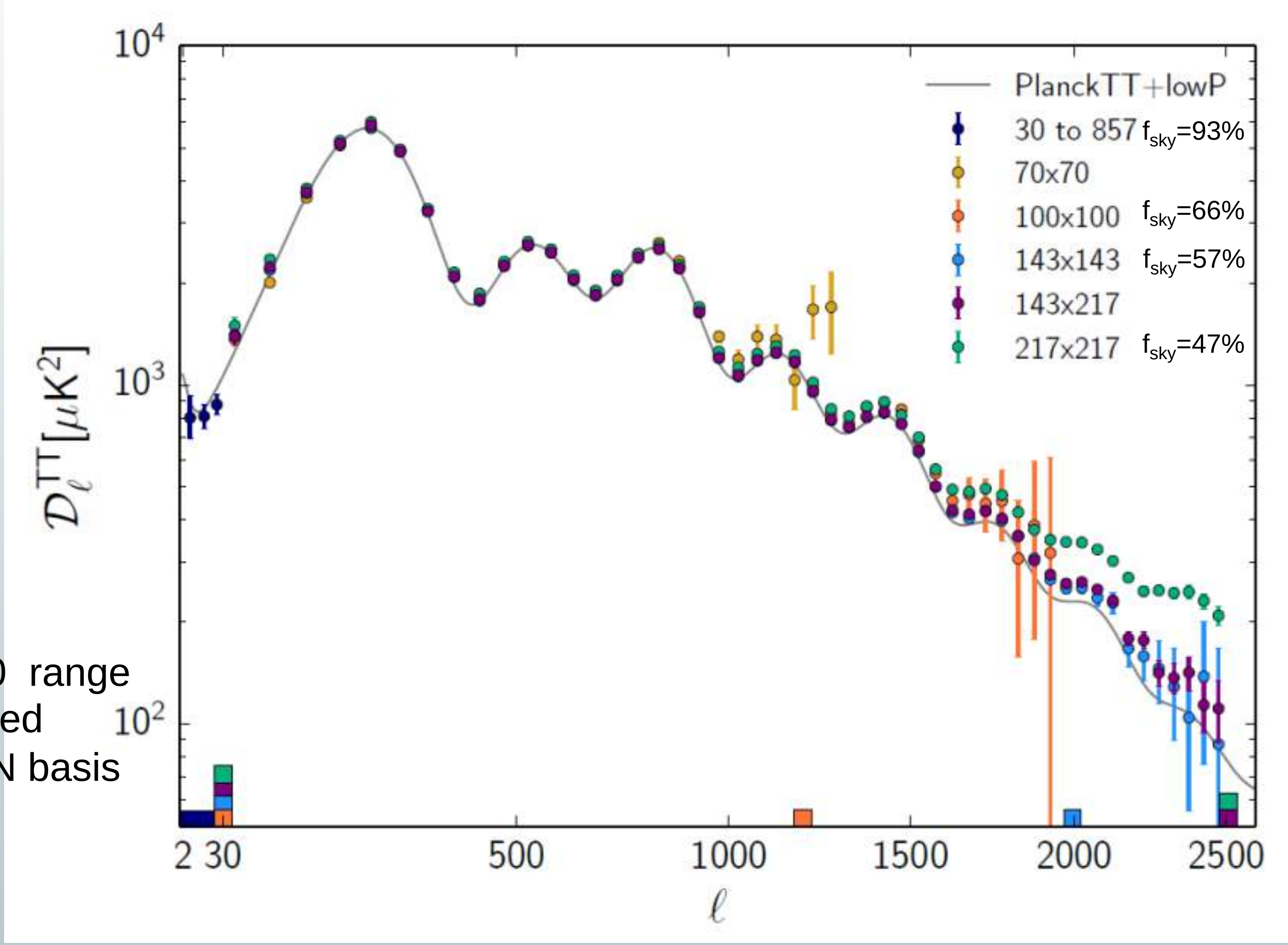
Same hybrid methodology than in 2013. What's new:

- More data: 48/29 months of LFI/HFI observations respectively (instead of 15m), enabling further checks.
- Improved data processing
  - *systematics removal, calibration, beam reconstruction*
- Improved foreground modelling
  → *Larger sky-fraction used for analysis at high ell*
- The 2015 analysis allows using polarization.

- Ell < 30: T from Commander (f_{sky}=93%), *polarisation from 70GHz* (-S2 & S4, f_{sky}=47%), *cleaned with 30 &* ***353GHz***.
- Ell>30: Plik on 100-217GHz data (f_{sky}=70-40%).
  - *More robust to systematics, by being based on half-mission cross power spectra*

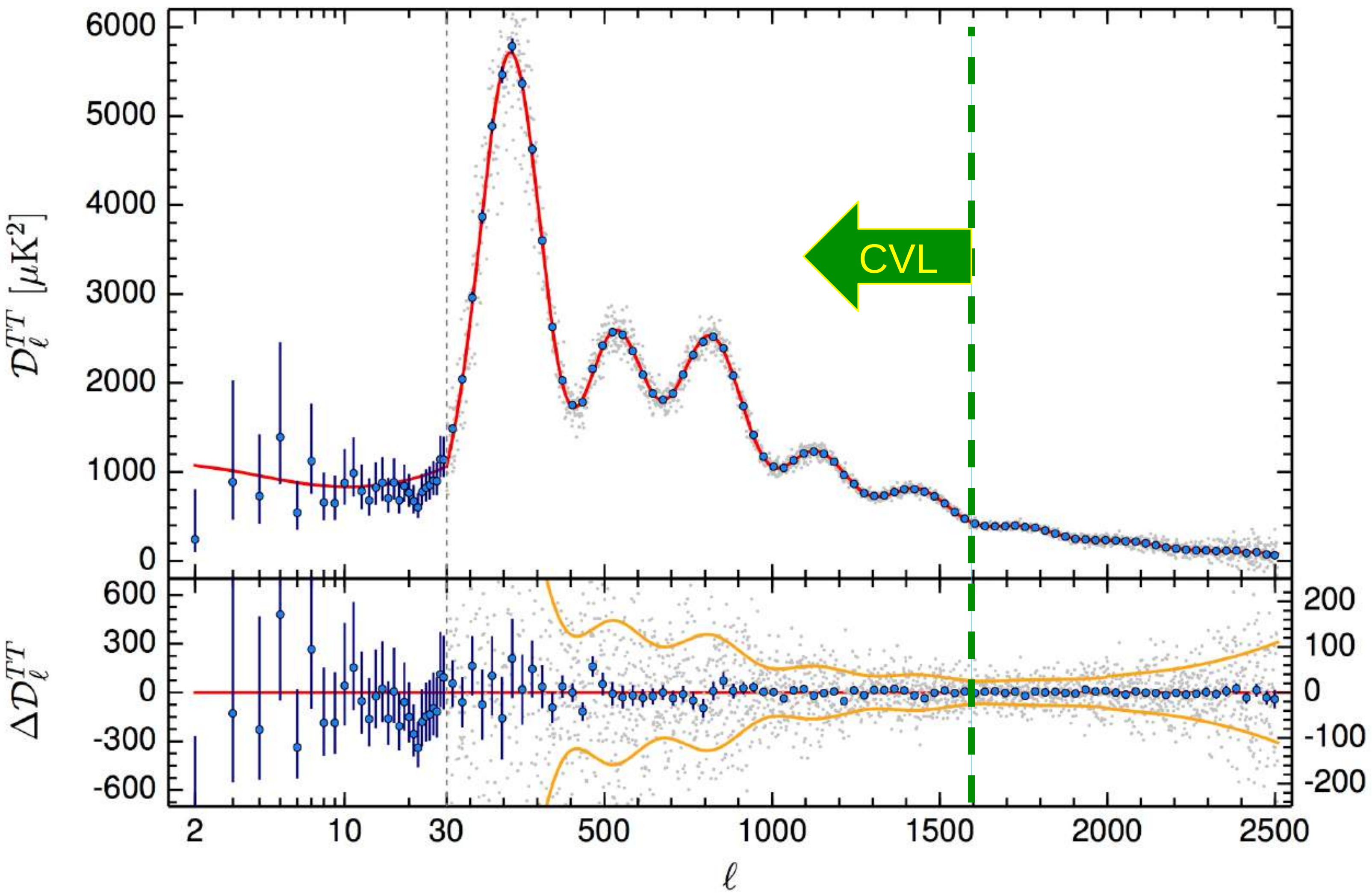
NB: Plik was cross-checked with 4 additional methods, camspec, mspec, hillipop (+Xfaster)

Foregrounds and masks, l-range retained



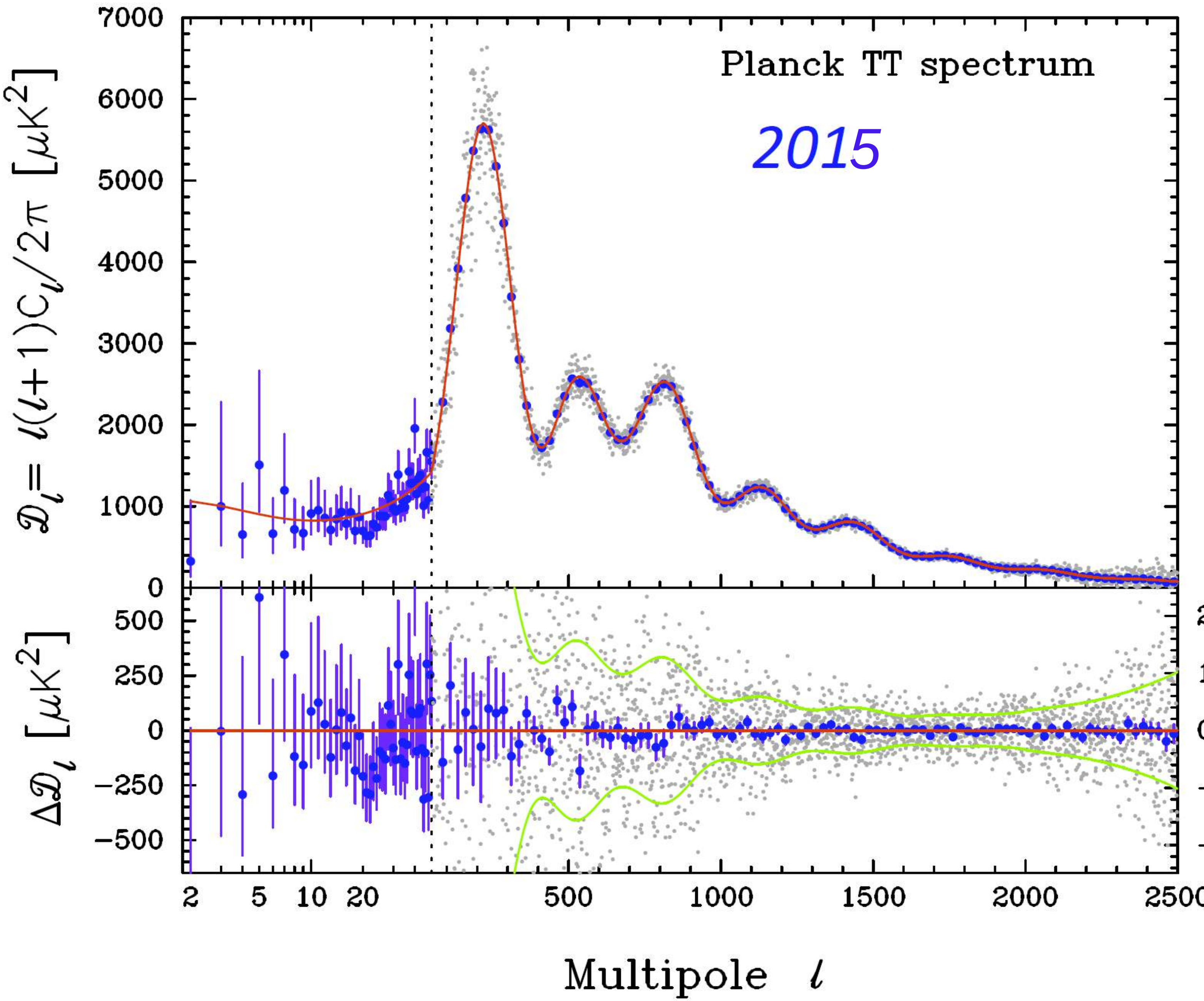
Ell>30 range selected on S/N basis

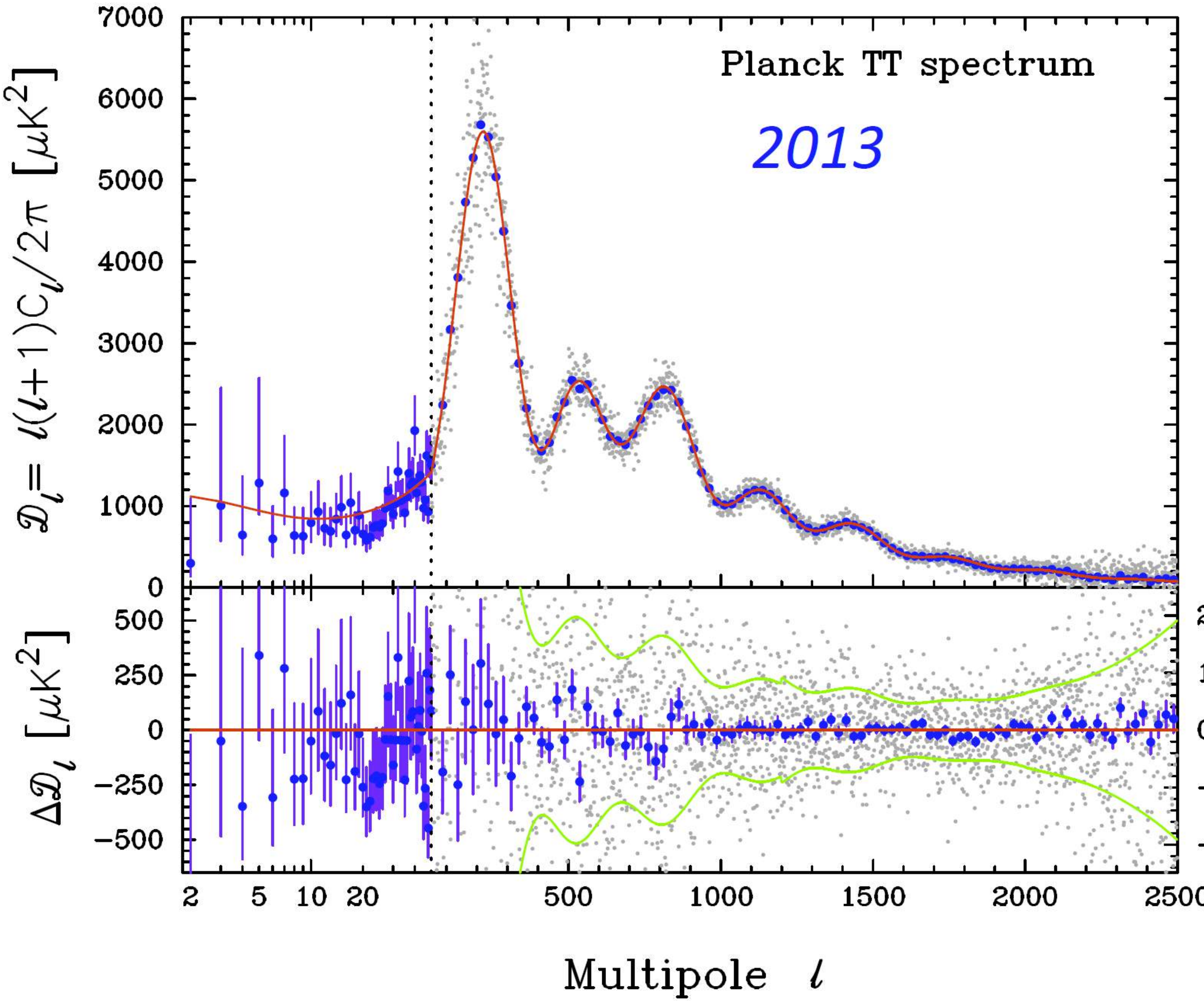
Planck 2015 TT spectrum



8 acoustic peaks well detected

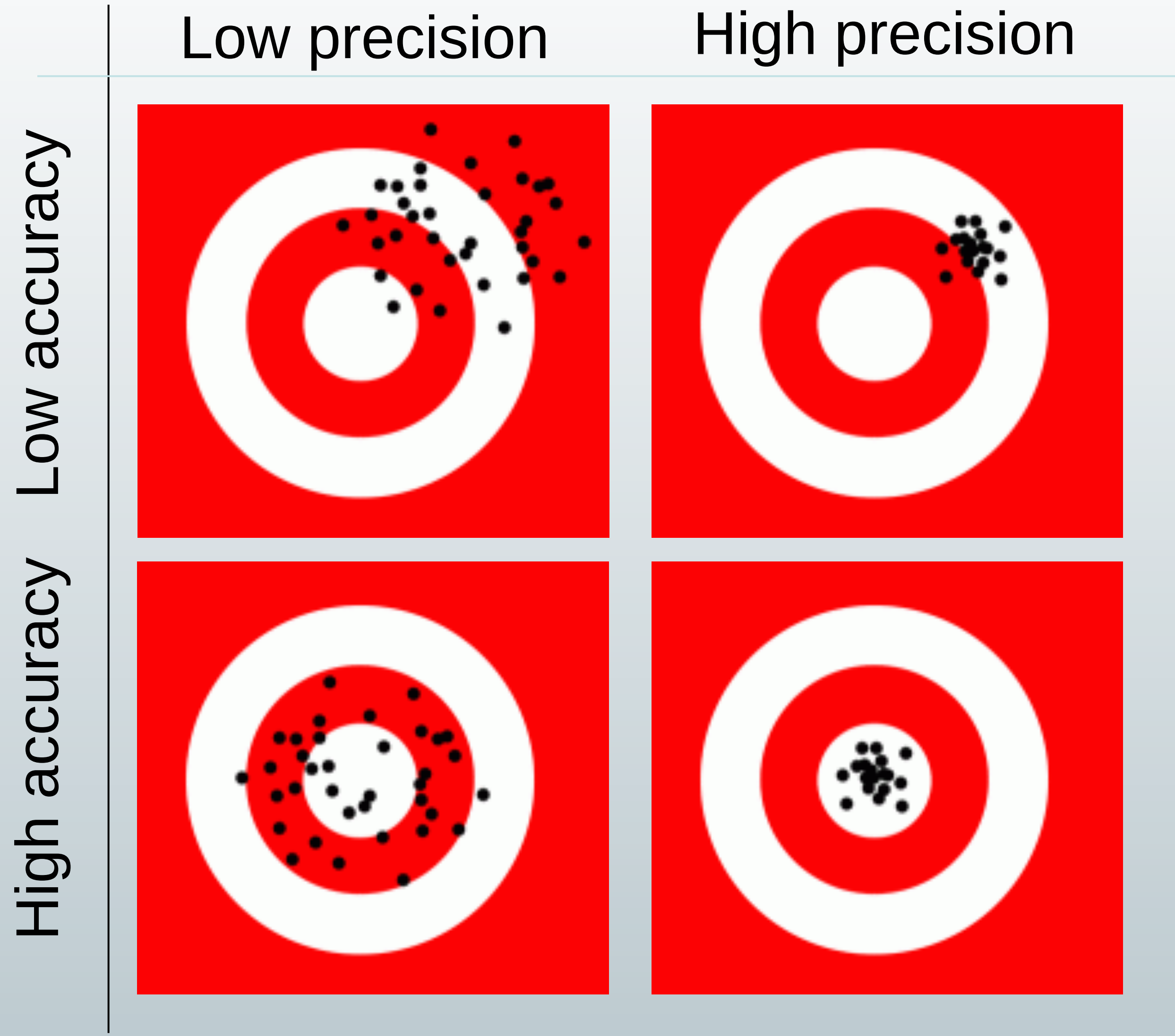
CVL till l~1600 on 40-70% of the sky

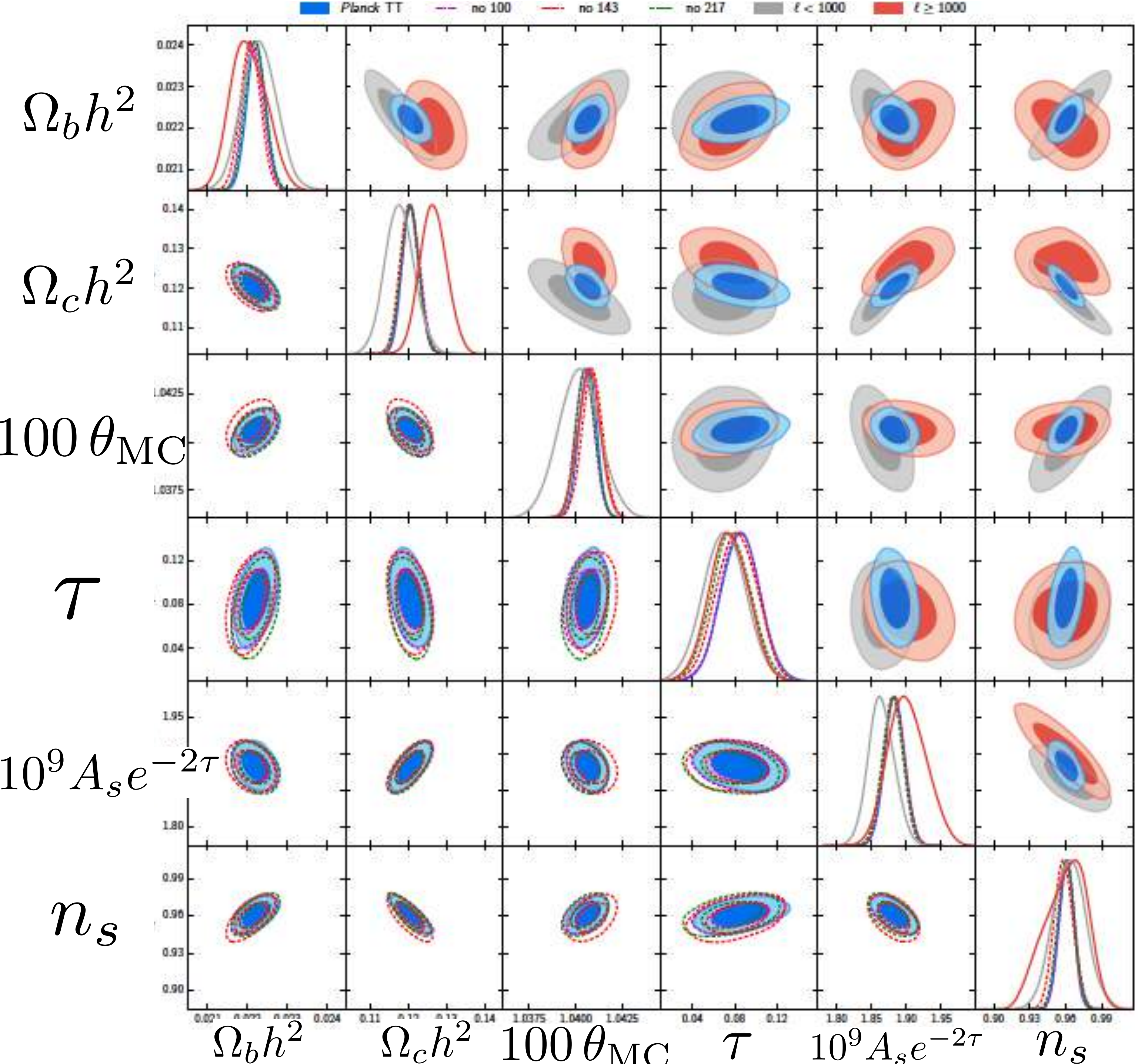

Planck TT spectrum
2015
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi$ [μK^2]
$\Delta\mathcal{D}_\ell$ [μK^2]
Multipole ℓ
7000
6000
5000
4000
3000
2000
1000
0
500
250
0
−250
−500
200
100
0
−100
−200
2
5
10
20
500
1000
1500
2000
2500



Planck TT spectrum
2013
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
$\Delta\mathcal{D}_\ell\ [\mu K^2]$
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

Precision versus accuracy





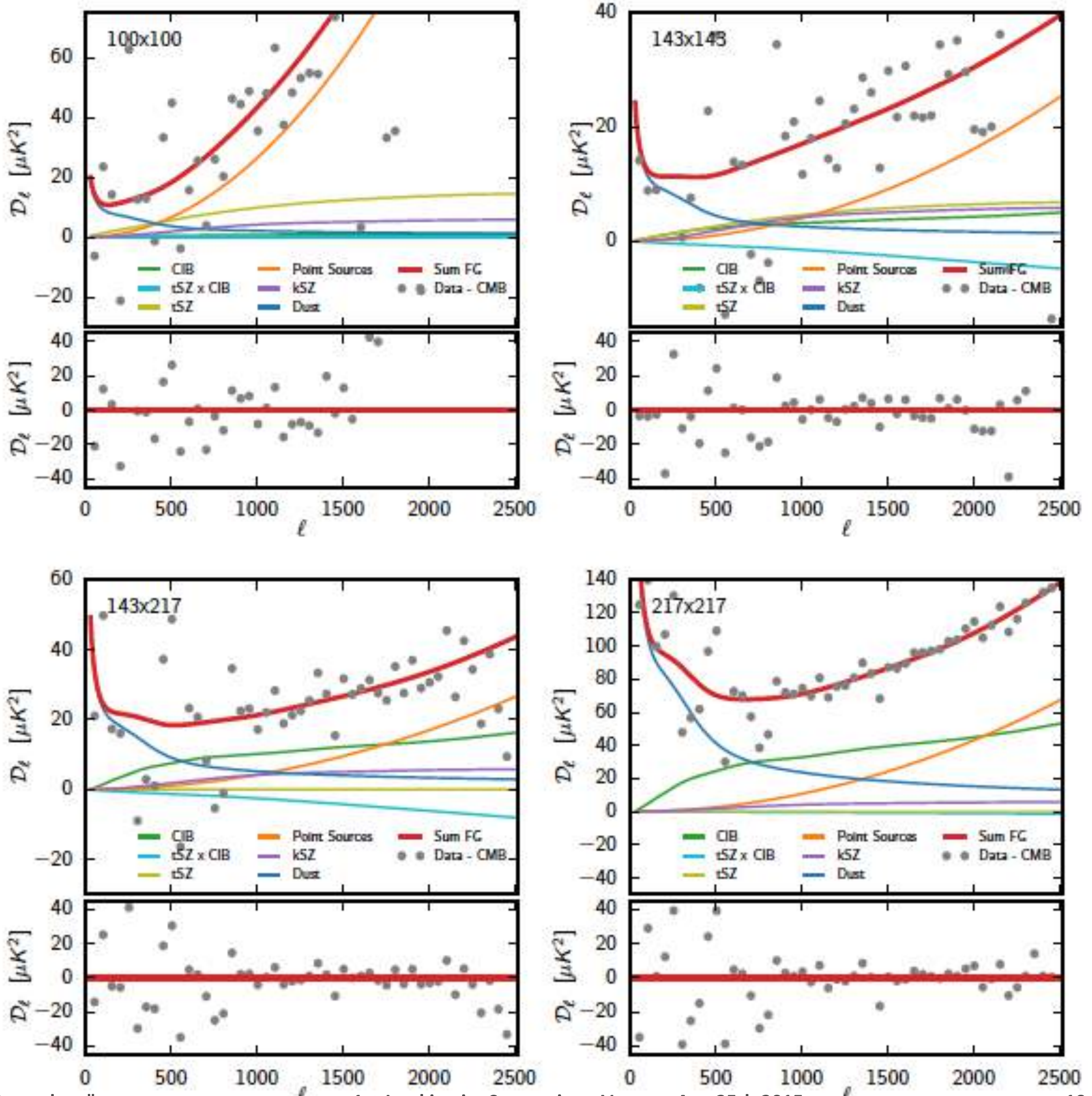
Parameters are stable in jack-knife tests (removing complete frequency channels or even l-range, above or below 1000)

Foregrounds

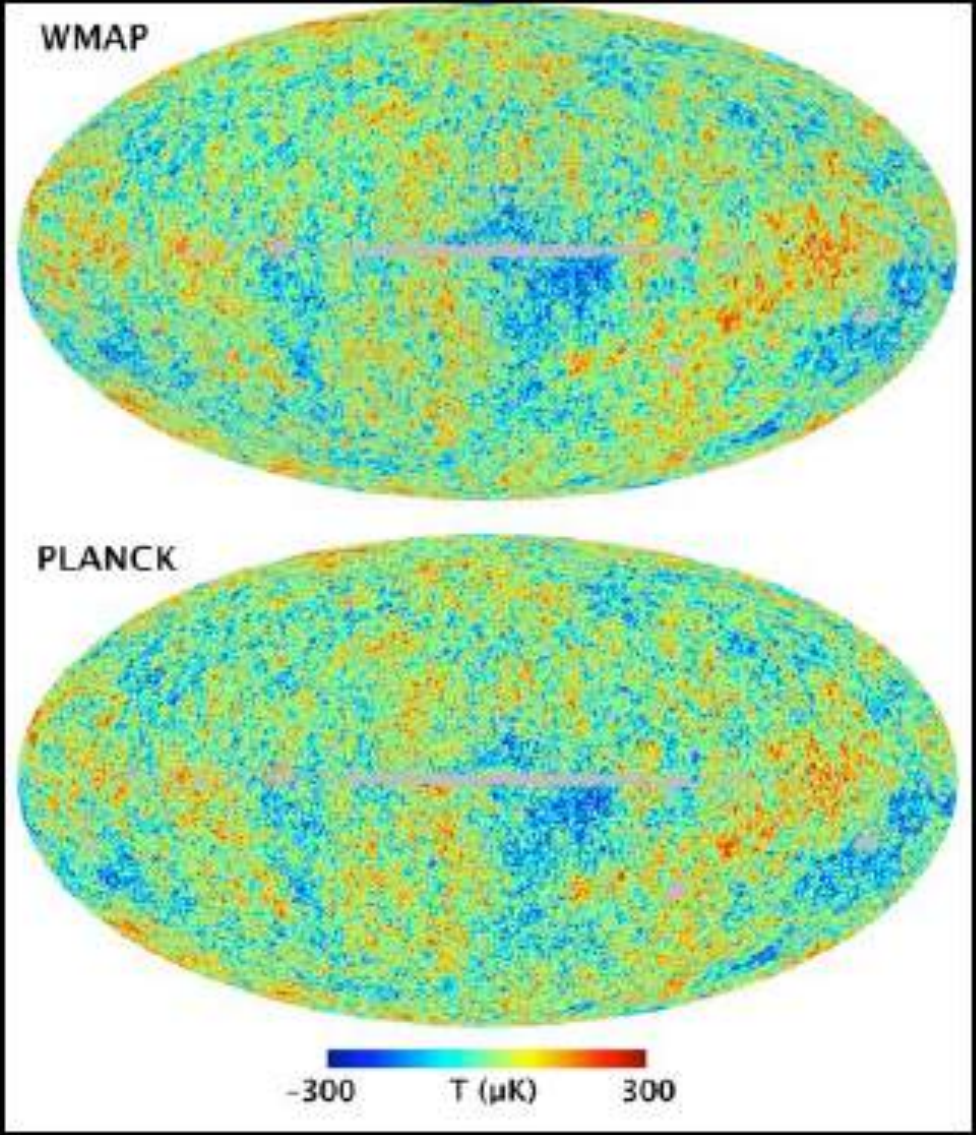
Dust+CIB+PS+SZ

These are spectra
- per frequency pairs
- CMB cleaned with common BF model
- compared with our foregrounds decomposition

NB: the dust template was learnt from correlations with 545 GHz, on varying sky fraction (universal residual but for an amplitude)



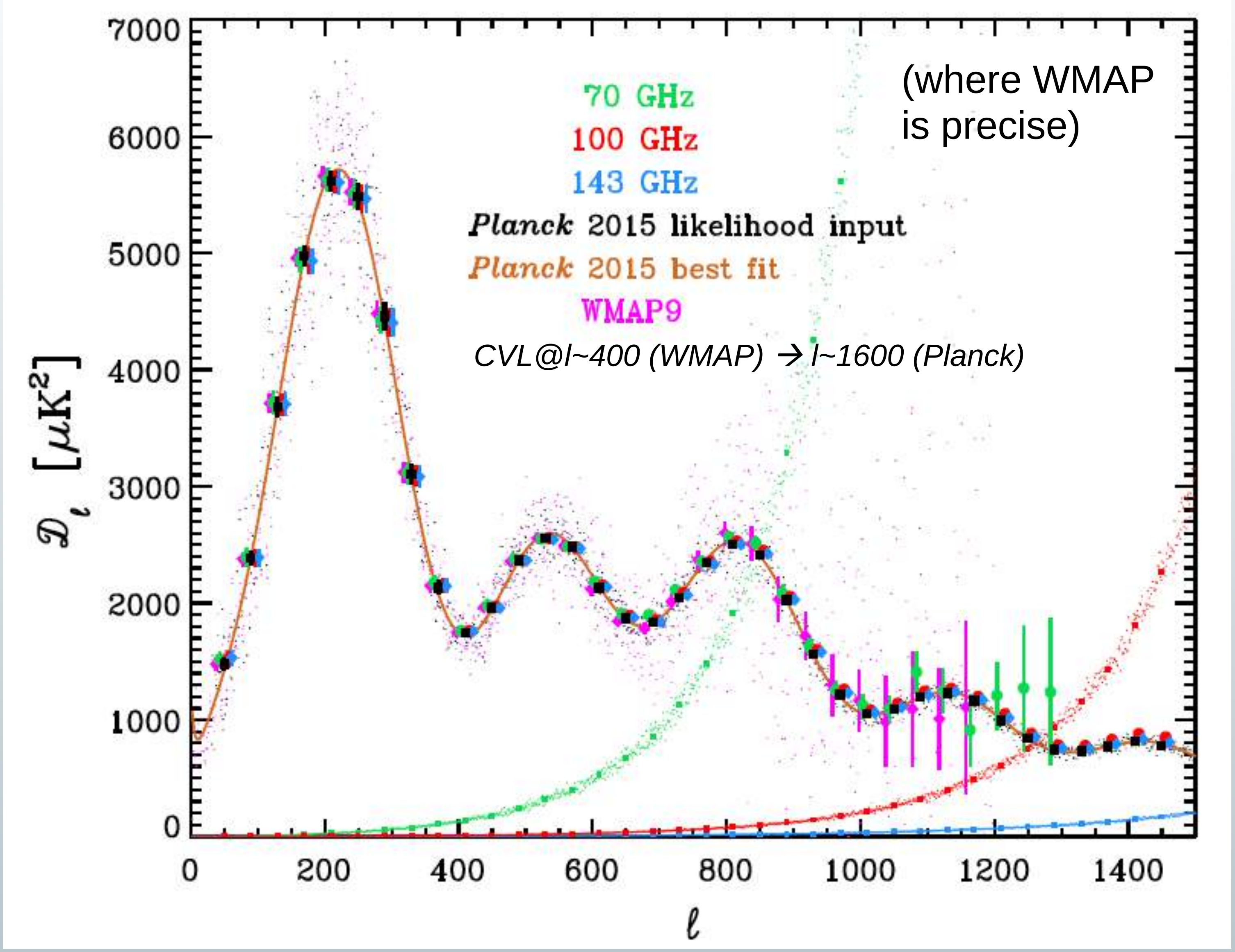
Planck and WMAP see the same sky



After
1) correcting the original WMAP map from some residual dust emission only traced by Planck/ HFI, and
2) Downgrading Planck to WMAP resolution (de facto throwing out ~90% of Planck measured modes)

5

Excellent consistency at l ~< 800

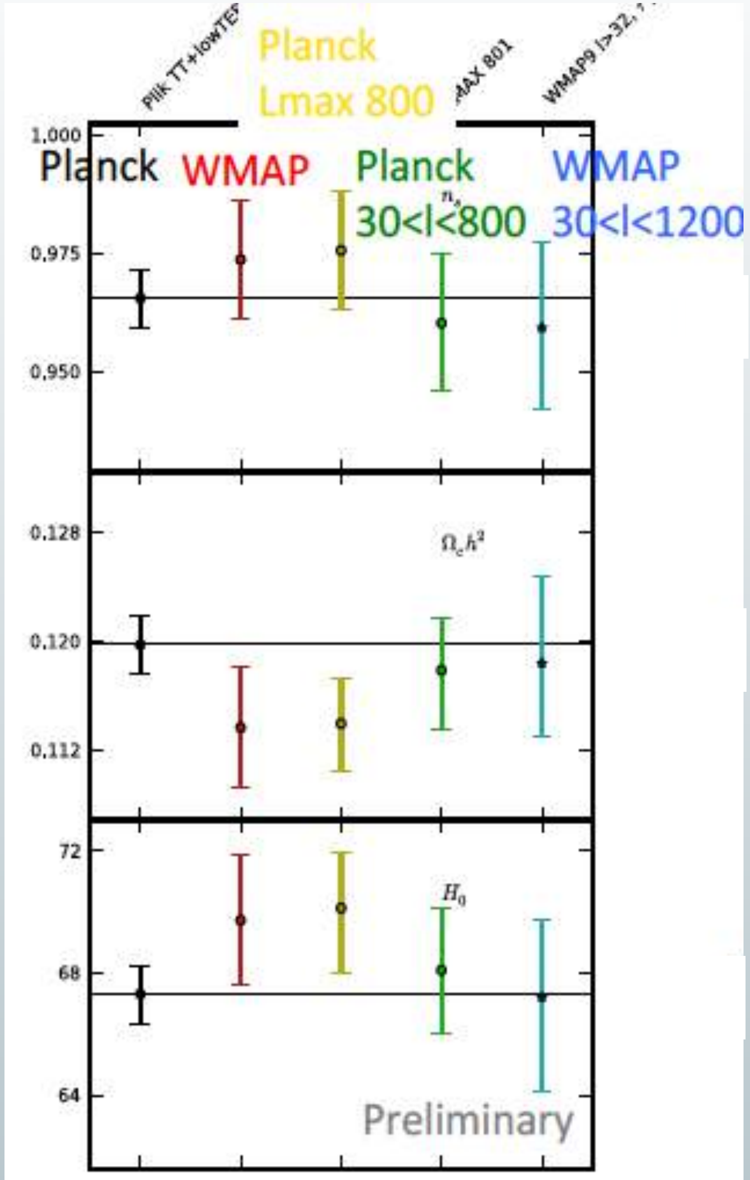


Planck, WMAP, and l~20 deficit

Planck restricted to lmax=800 is quite consistent with WMAP.

Cutting the TT l<30, one recovers the full Planck Cosmology both with Planck lmax=800 and with WMAP!

Planck is less affected than WMAP by the l~20 deficit, however it still has some impact on some parameters (e.g. N_{eff}, A_{lens})



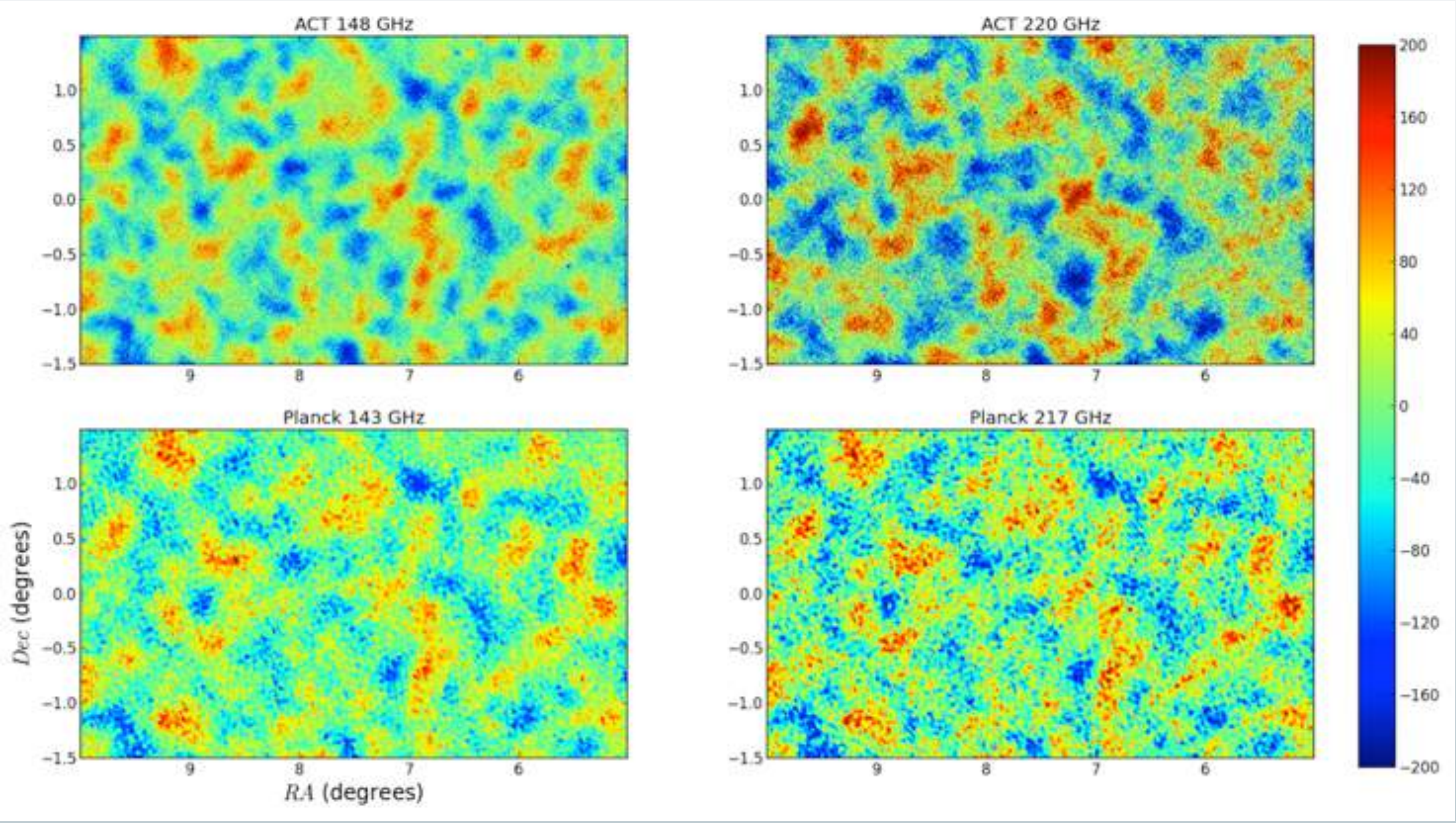
NB: with a relatively restricted number of modes, parameter degeneracies may be large.

n_s may then increase to reduce the low-ell power; but this also reduces the height of the first peak, which can be compensated by decreasing $O_c h^2$, requiring a larger H_0 to keep the position of the peak!

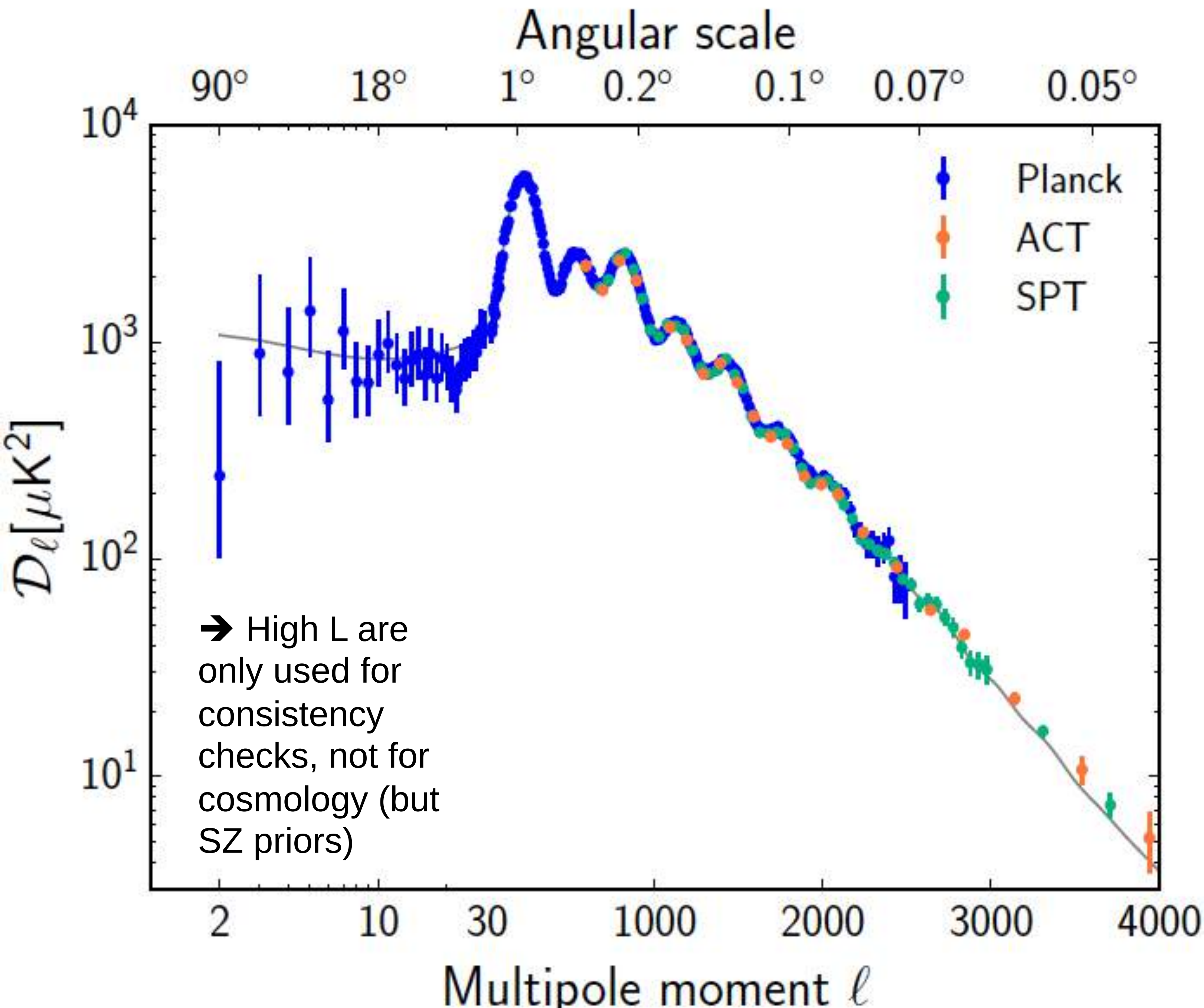
(we cut here both the TT and Pol data at low-l. We use a prior on tau to break degeneracies)

Planck & high-resolution experiments

also see the same sky



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

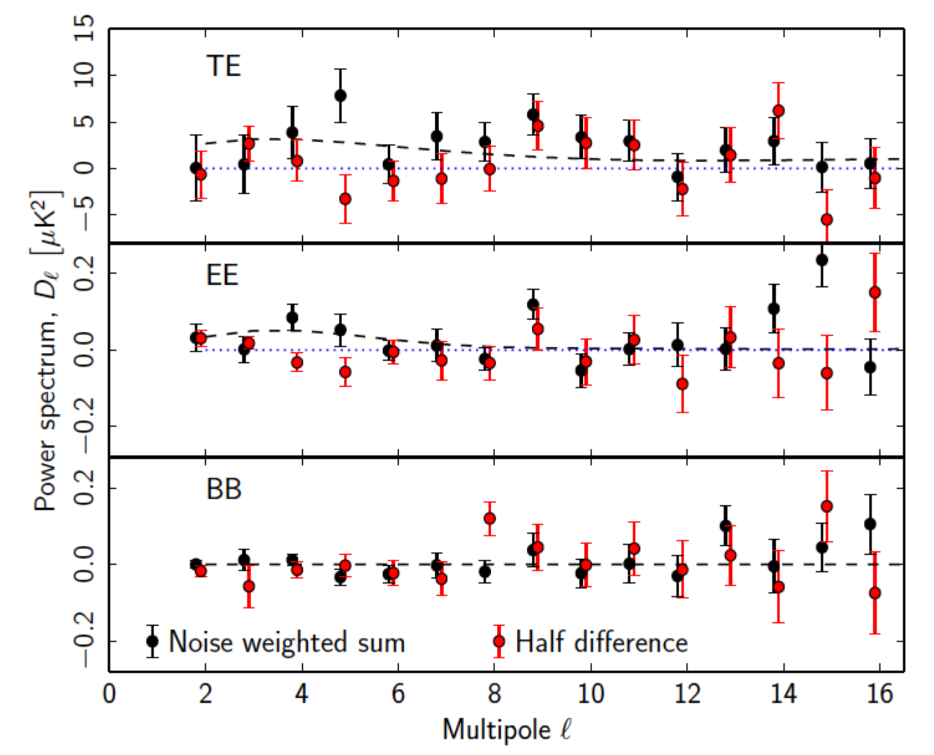


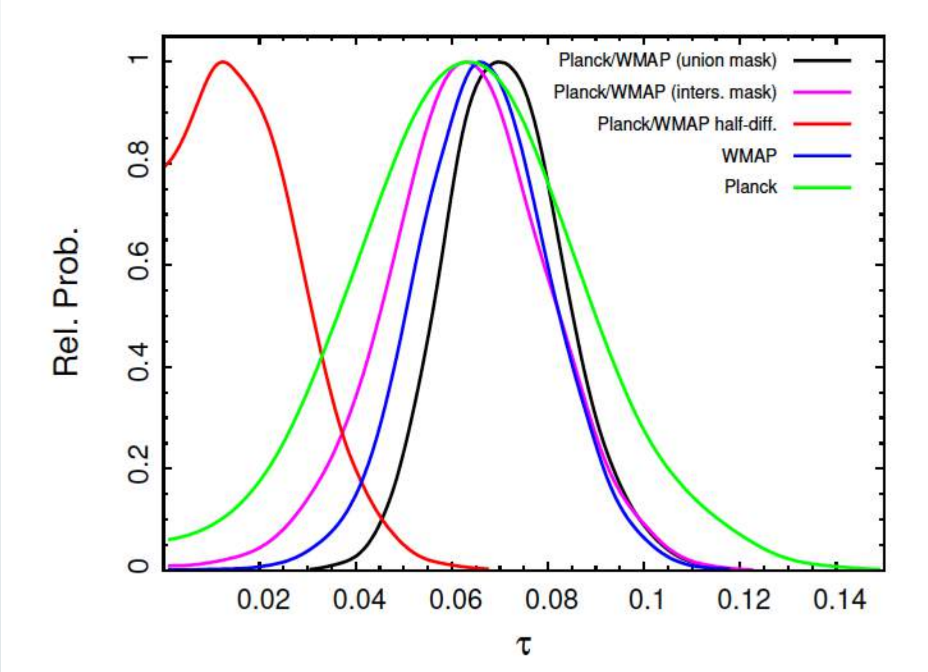
➔ High L are only used for consistency checks, not for cosmology (but SZ priors)

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

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

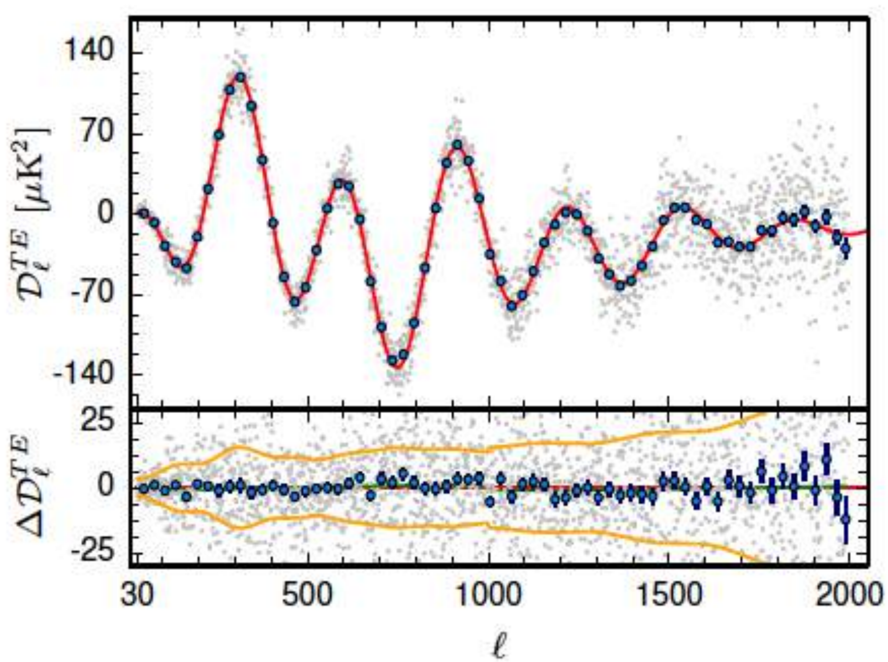
Results are compatible, and it shifts the optical depth
to reionization, τ, to lower values than previously thought.



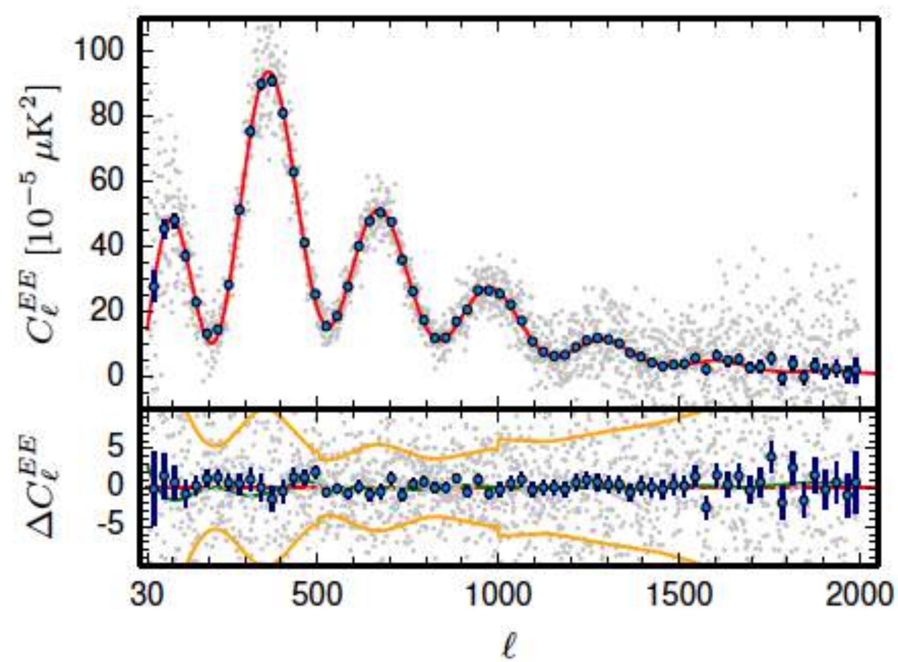


This plot is for low ell <30 only,
i.e. it is ***not*** the final, full likelihood, outcome

Planck 2015 - TE & EE spectra



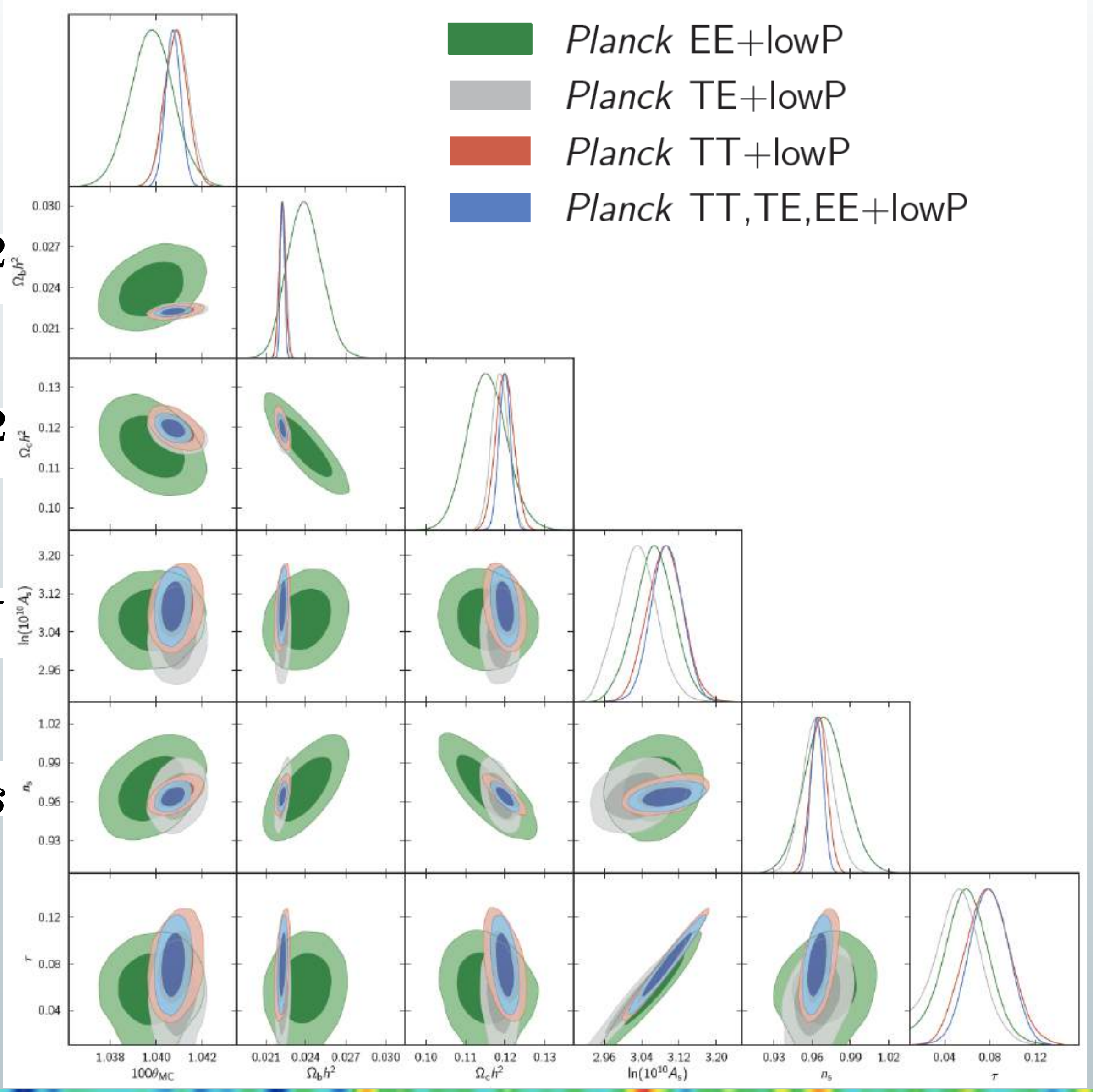
Frequency averaged spectrum reduced ^{2} = 1.04



Frequency averaged spectrum reduced ^{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).

T & E on LCDM parameters



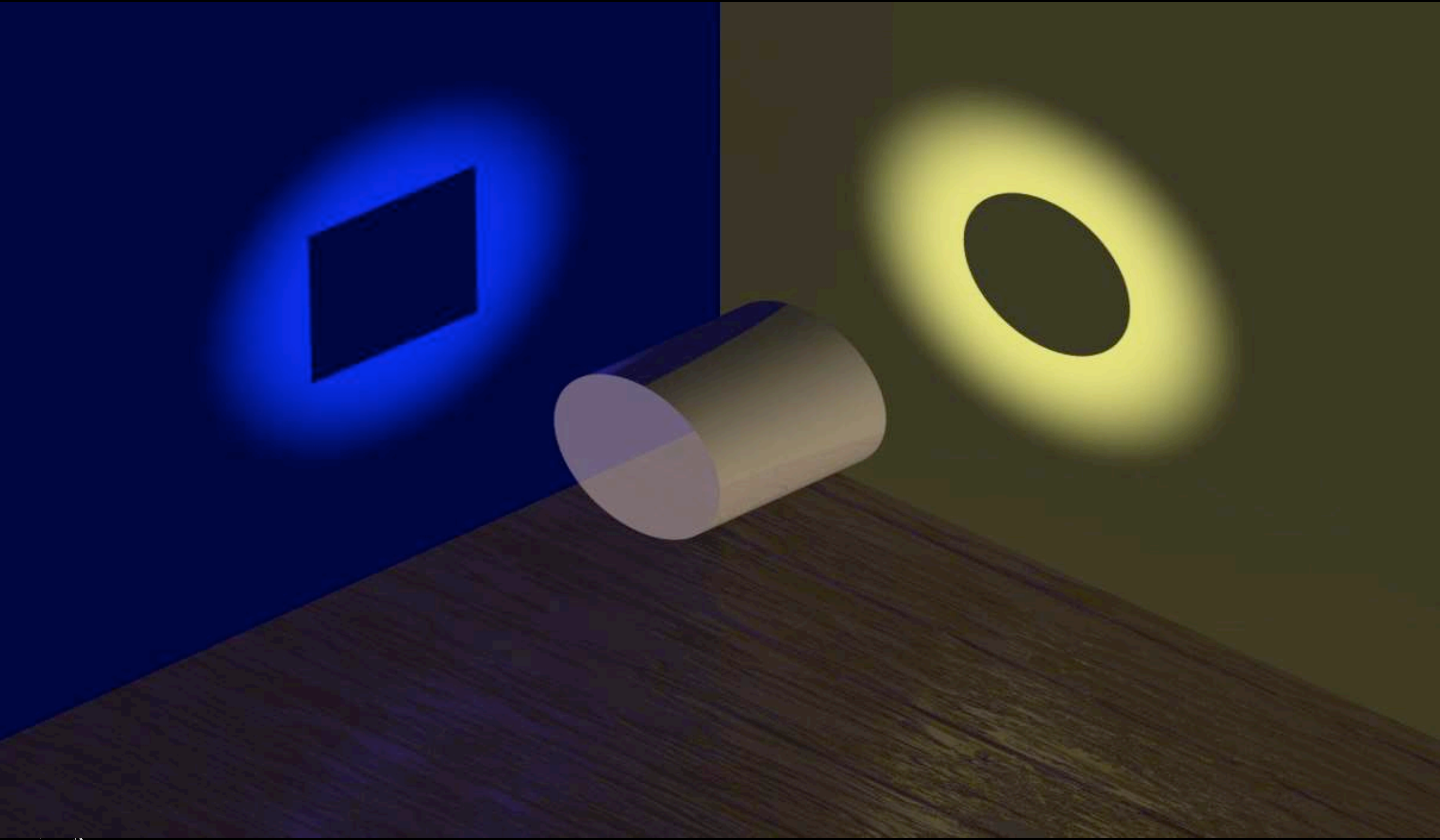
*Parameters from polarisation spectra are **highly consistent** with those from TT spectra.*

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

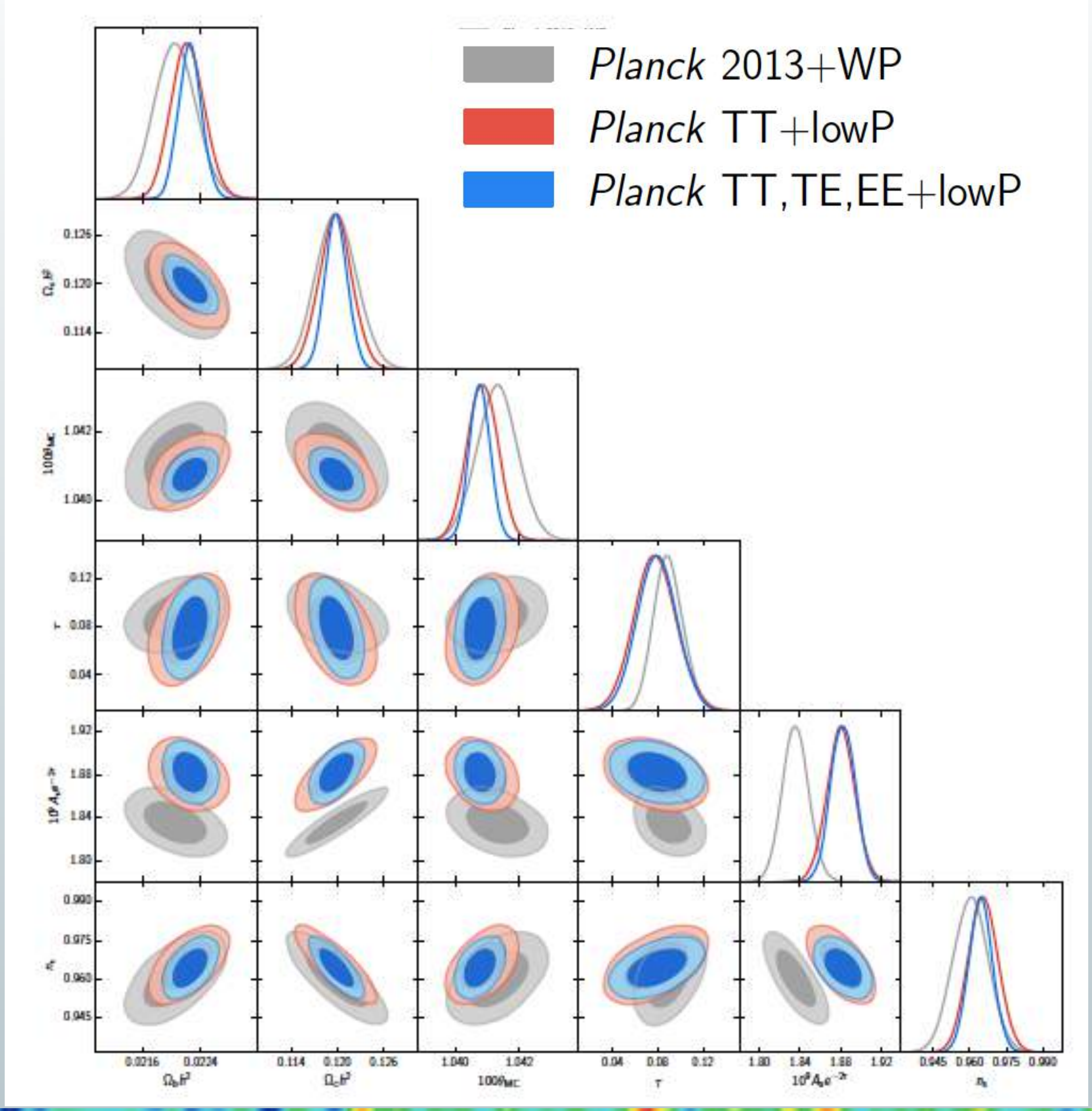
TT & TE have quite similar uncertainties (but for n_s),
but beware that they are still some low level systematics in the polarisation data

This was not granted…



And it further constrains deviations from the base tilted LCDM model

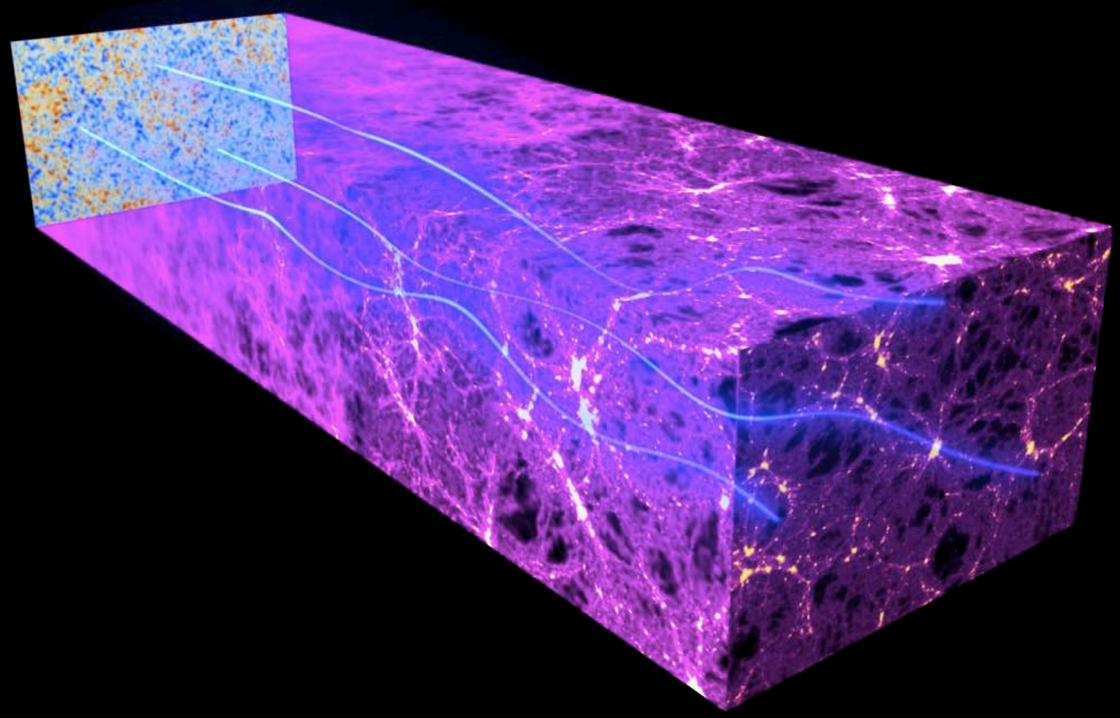
T & E – LCDM parameters



A series of increased precision, but for the overall recalibration (which now sets the standard for mm sky studies -- absolute and accurate).

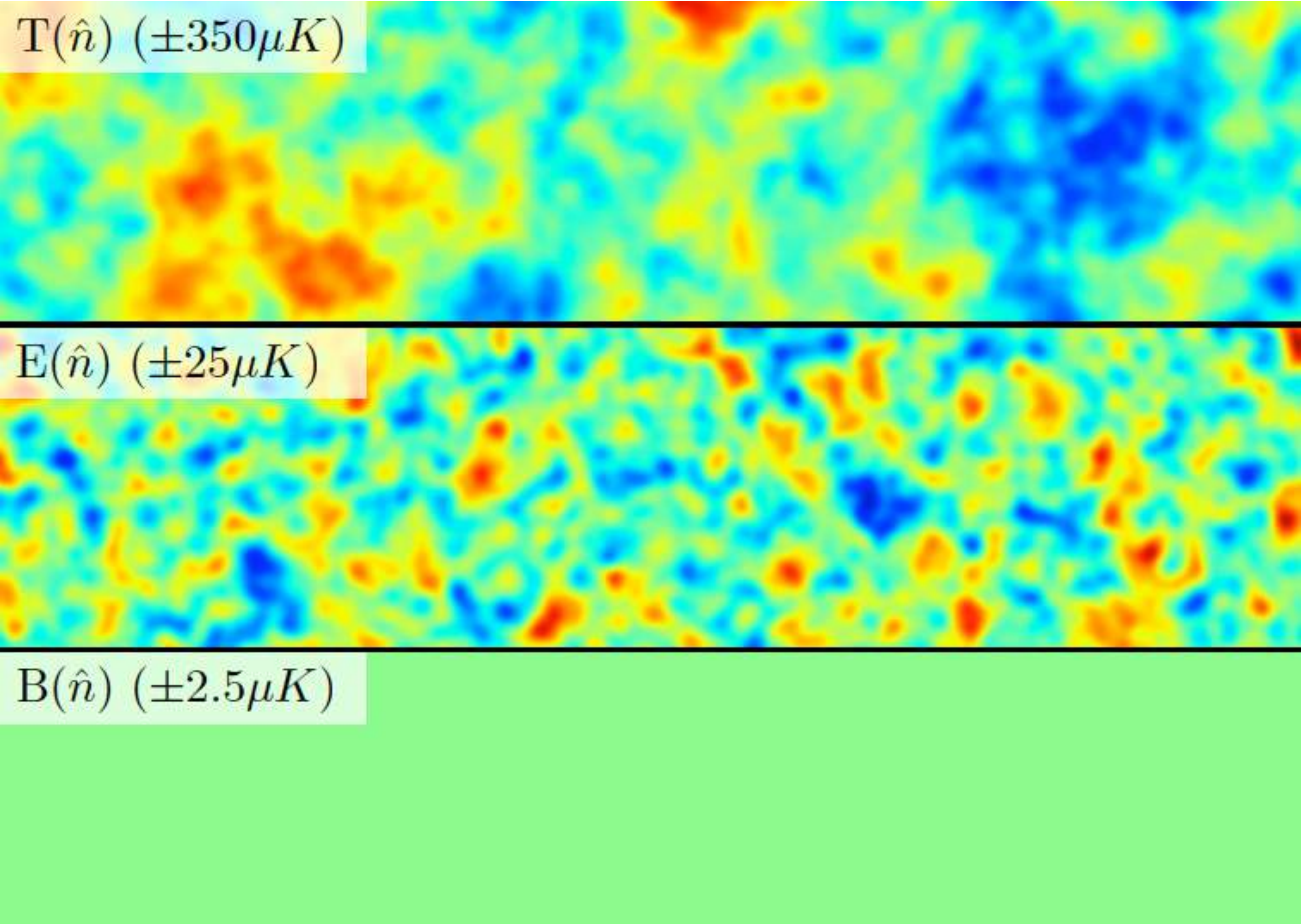
GRAVITATIONAL LENSING DISTORTS IMAGES

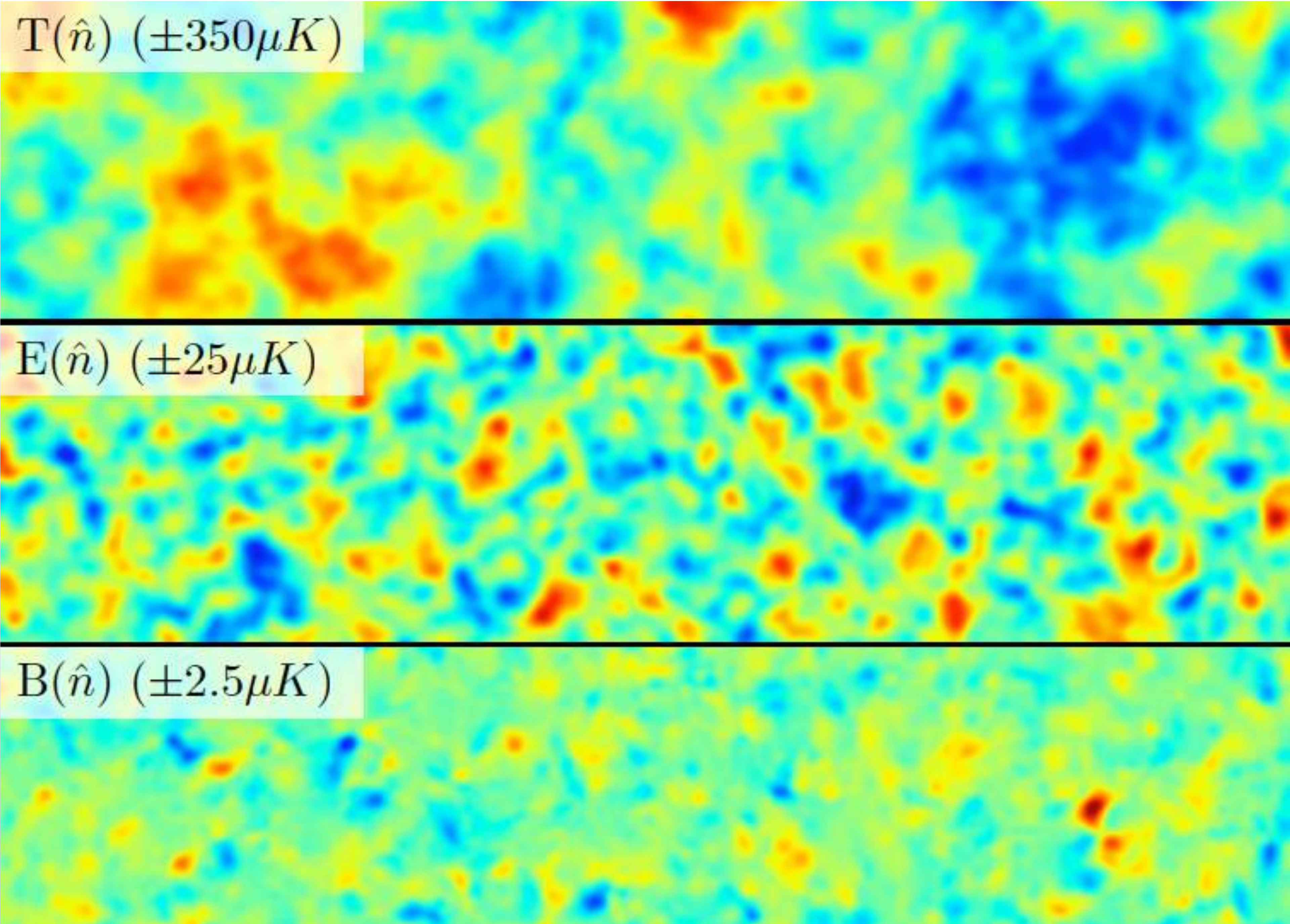
The gravitational effects of intervening matter bend the path of CMB light on its way from the early universe to the Planck telescope. This "gravitational lensing" distorts our image of the CMB (smoothing on the power spectrum, and correlations between scales)



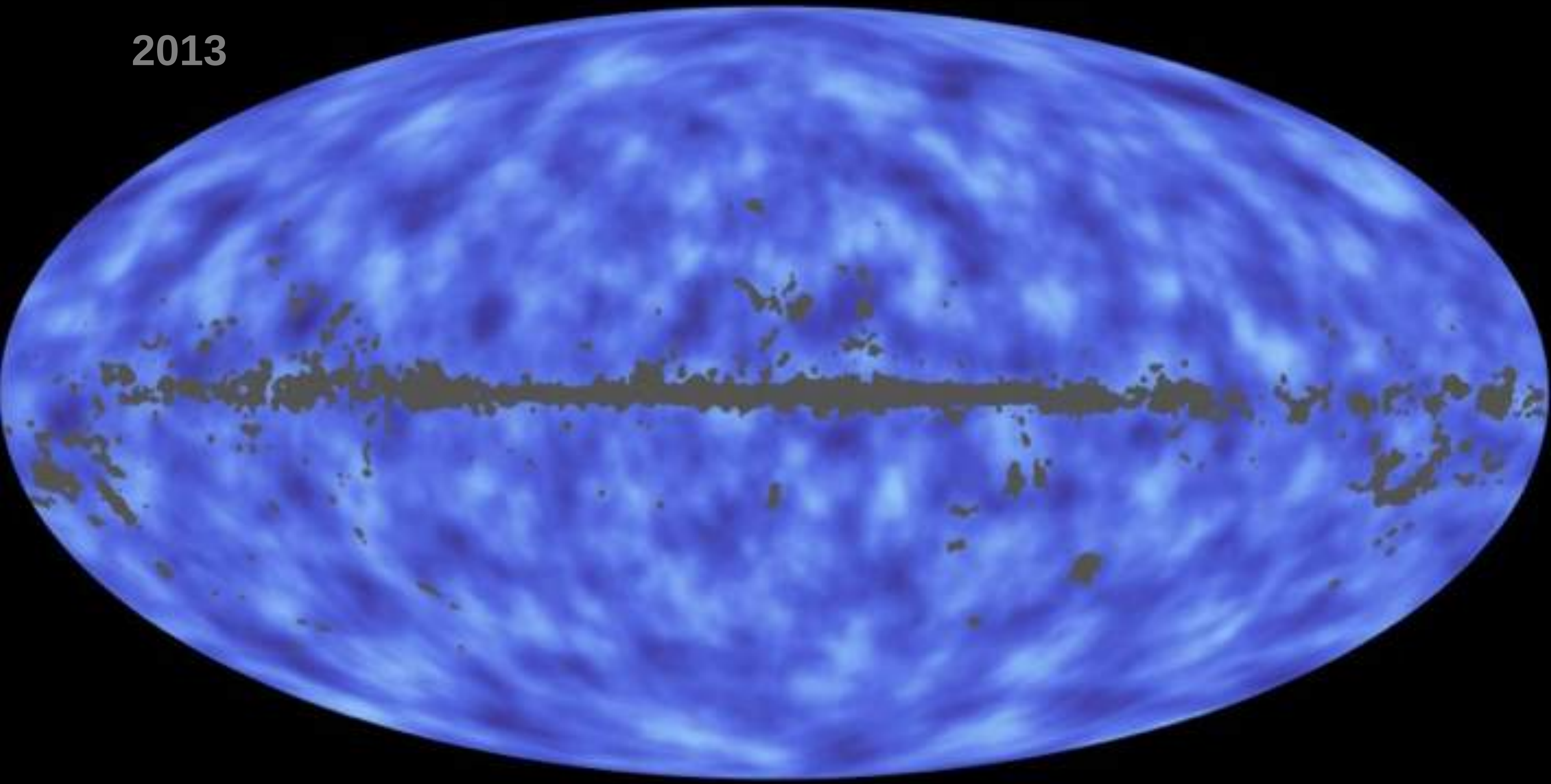
$$\hat{T}(\vec{\theta}) = T(\vec{\theta} + \vec{\nabla}\phi) \approx T(\vec{\theta}) + \vec{\nabla}\phi \cdot \vec{\nabla}T(\vec{\theta}) + ...$$

$$\bar{\phi} = \Delta^{-1}\vec{\nabla} \cdot [C^{-1}T\, \vec{\nabla}(C^{-1}T)]$$


$T(\hat{n})$ $(\pm 350\mu K)$
$E(\hat{n})$ $(\pm 25\mu K)$
$B(\hat{n})$ $(\pm 2.5\mu K)$

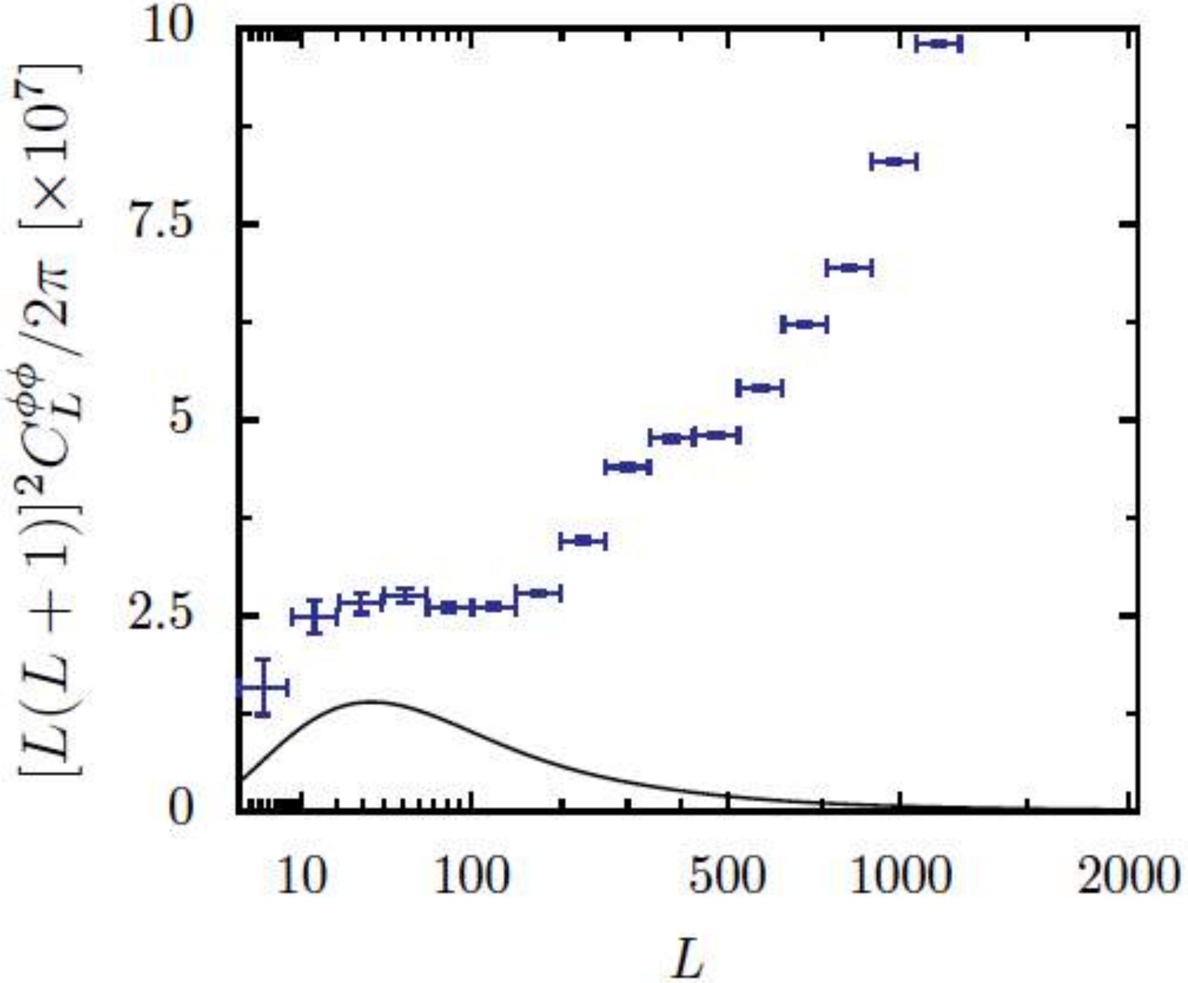

$T(\hat{n})$ ($\pm 350\mu K$)
$E(\hat{n})$ ($\pm 25\mu K$)
$B(\hat{n})$ ($\pm 2.5\mu K$)

Projected mass map



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

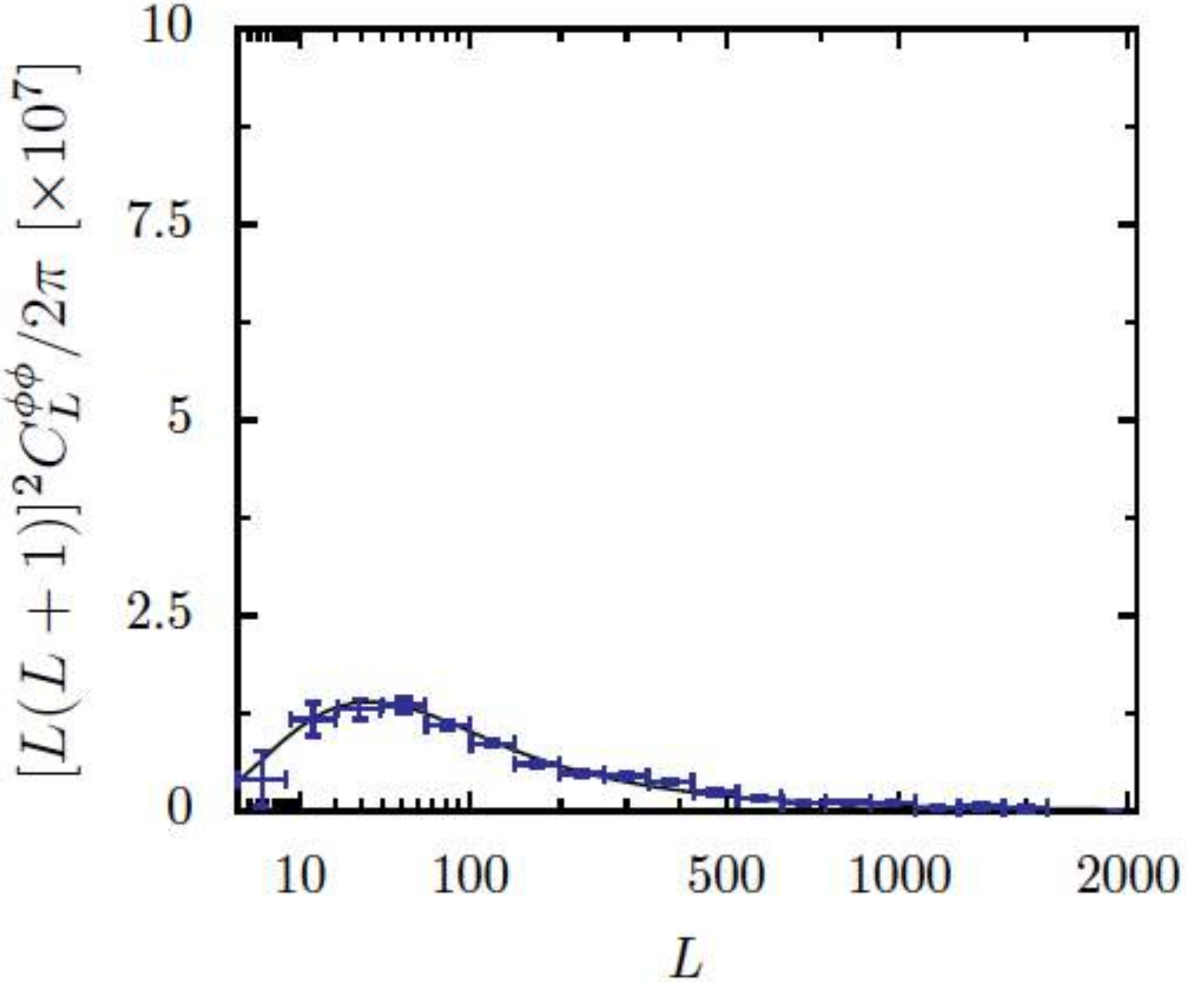
Power spectrum estimation



1) Raw power spectrum of quadratic estimates.

Preliminary

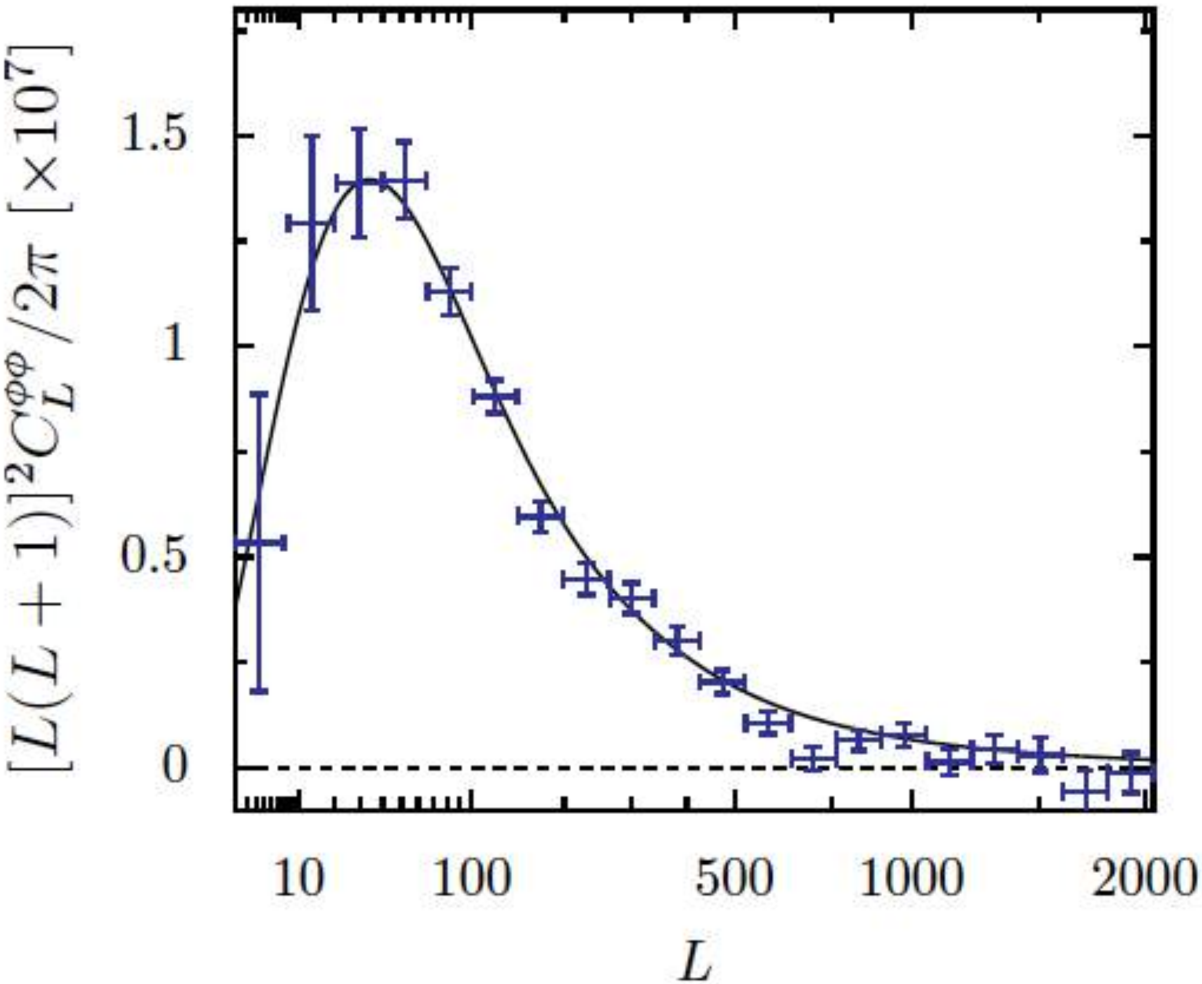
Power spectrum estimation



2) Correct for noise bias estimated from sims.

Preliminary

Power spectrum estimation

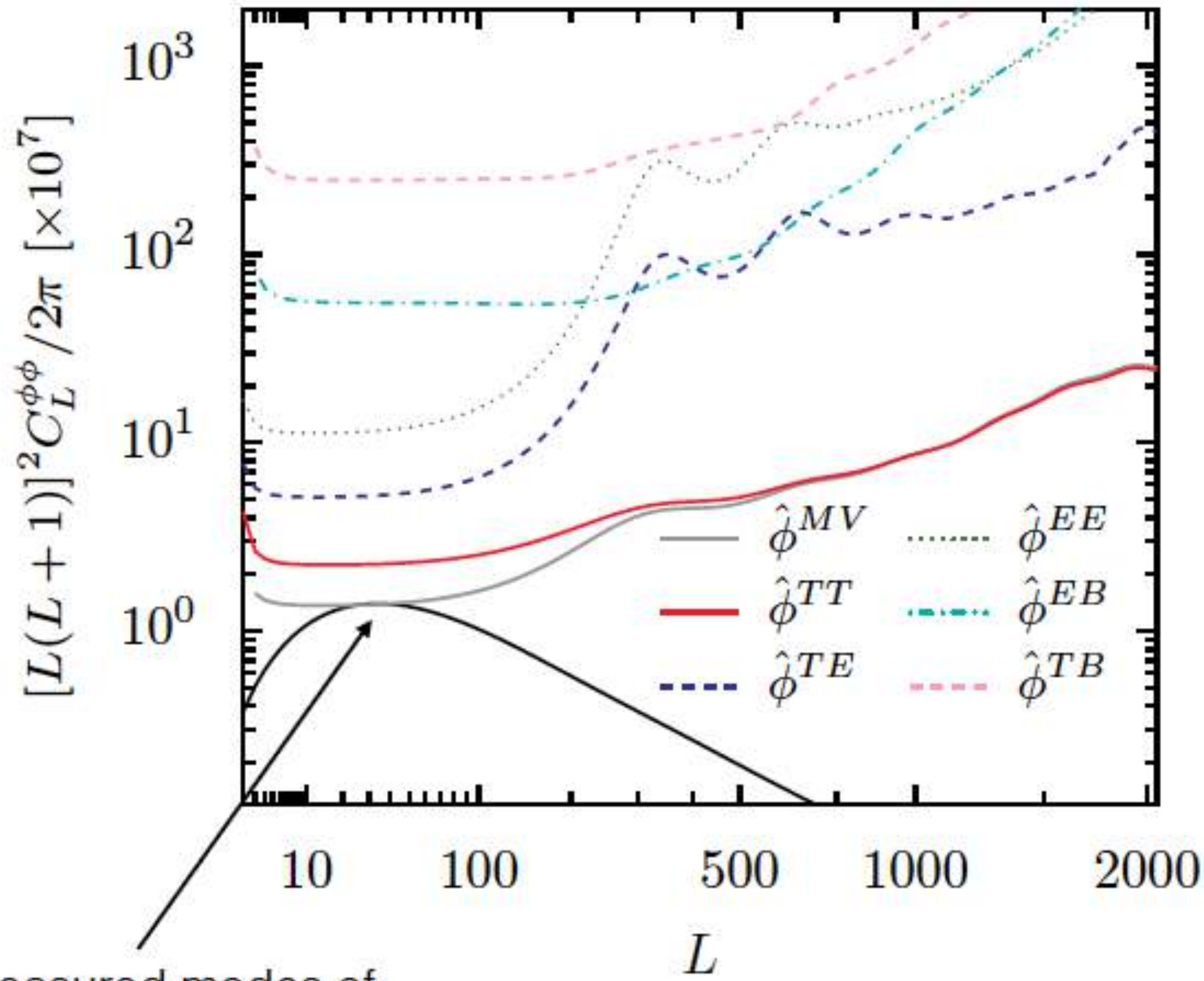


6) Correct for "PS" bias.

Done!

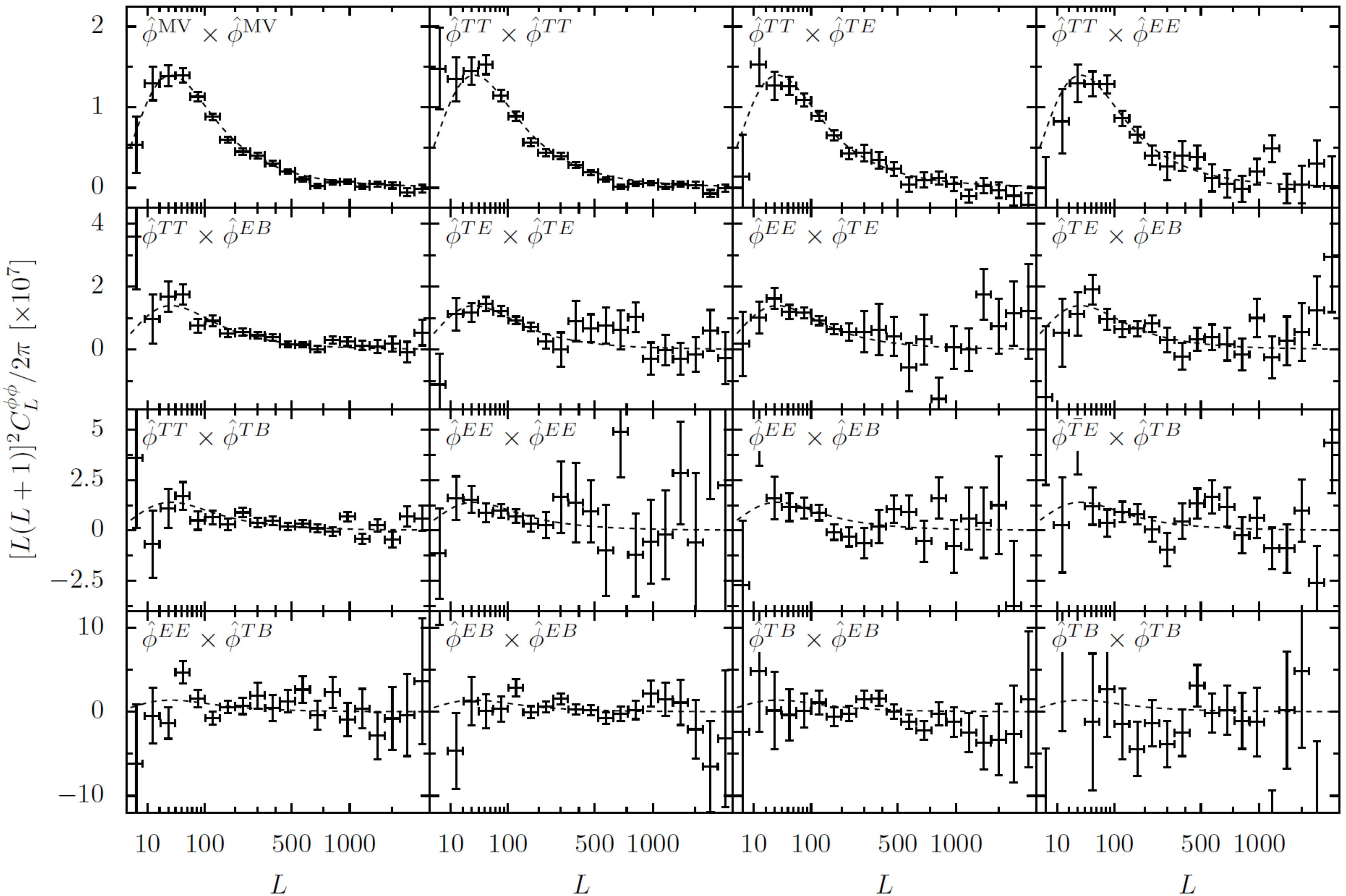
Preliminary

Noise power spectra for lensing estimators

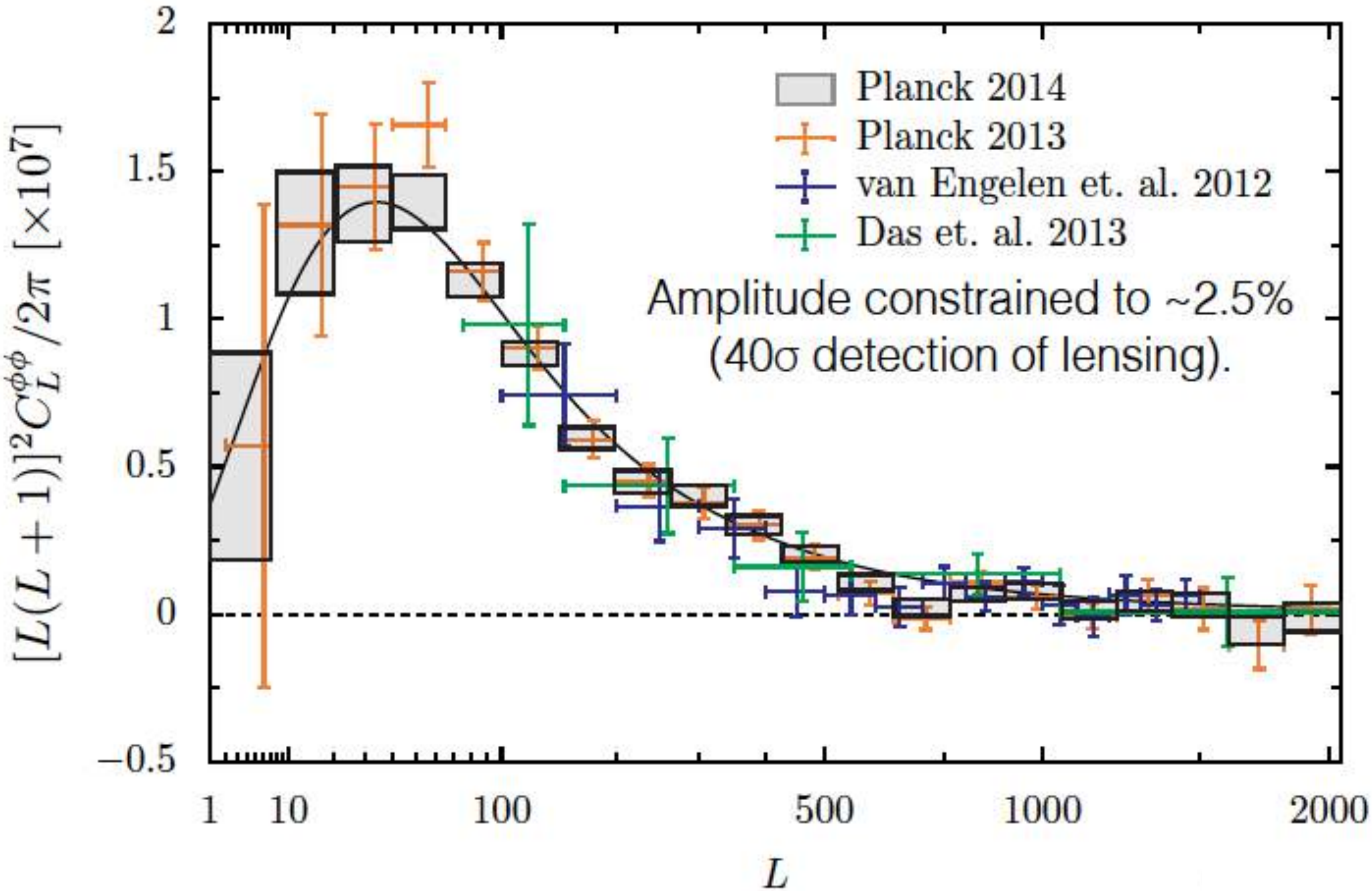


Best measured modes of
MV estimator have S/N=1.

Individual lensing cross-spectra

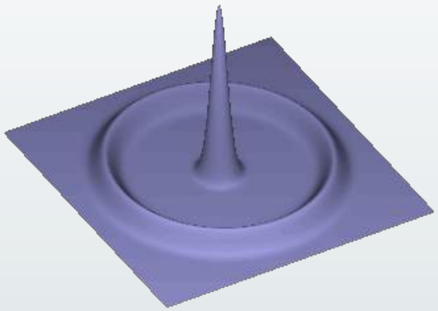


Lensing power spectrum

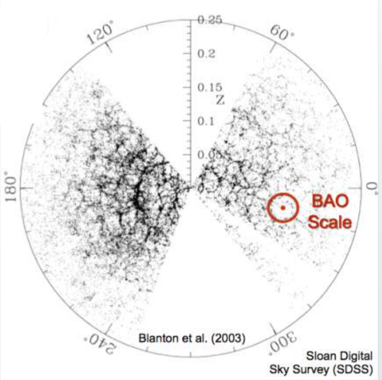


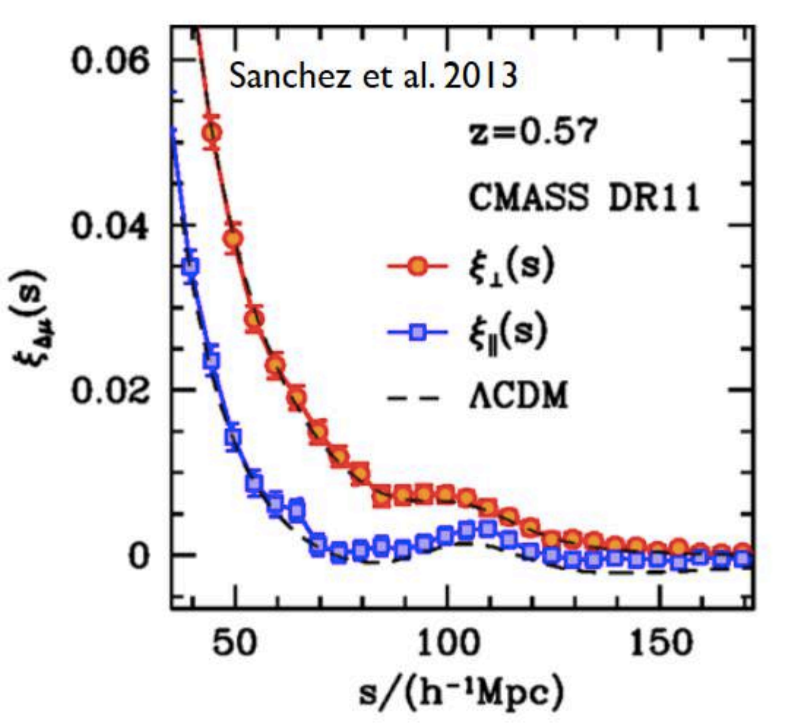
Planck for the first time measured the lensing power spectrum with higher accuracy than it is predicted by the base CDM model that fits the temperature data

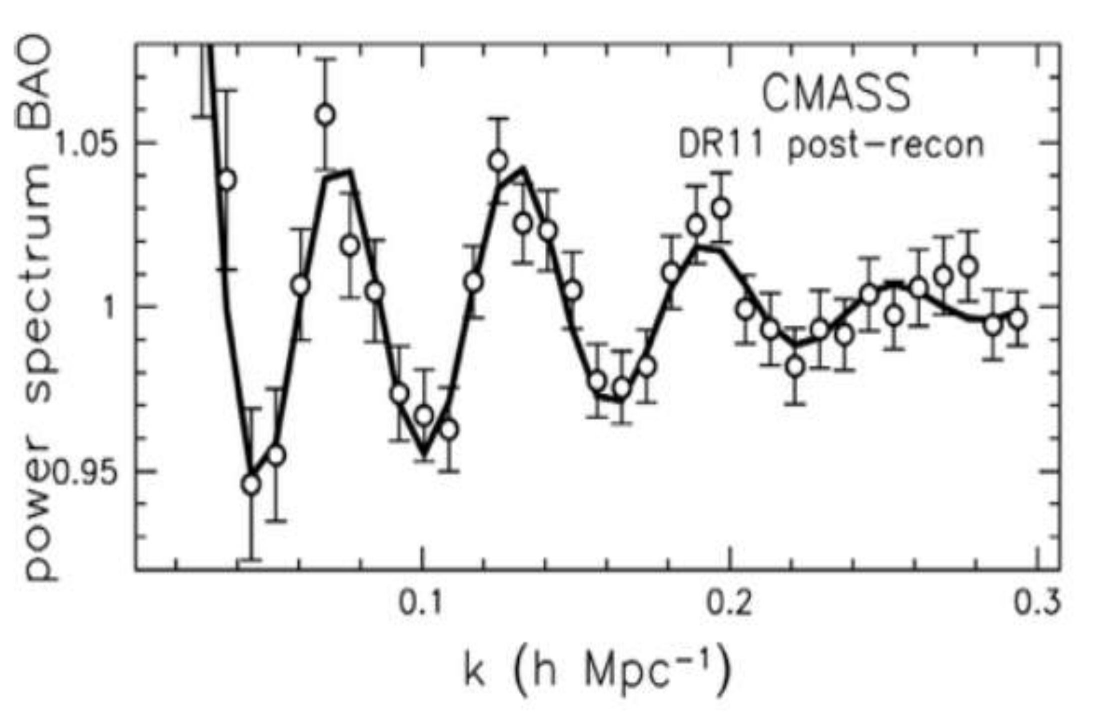
BAO: correlation function & power spectrum



The spherical sound wave from an initial overpressure stalls after decoupling at a distance estimated by Planck of 147.5 ± 0.6 Mpc

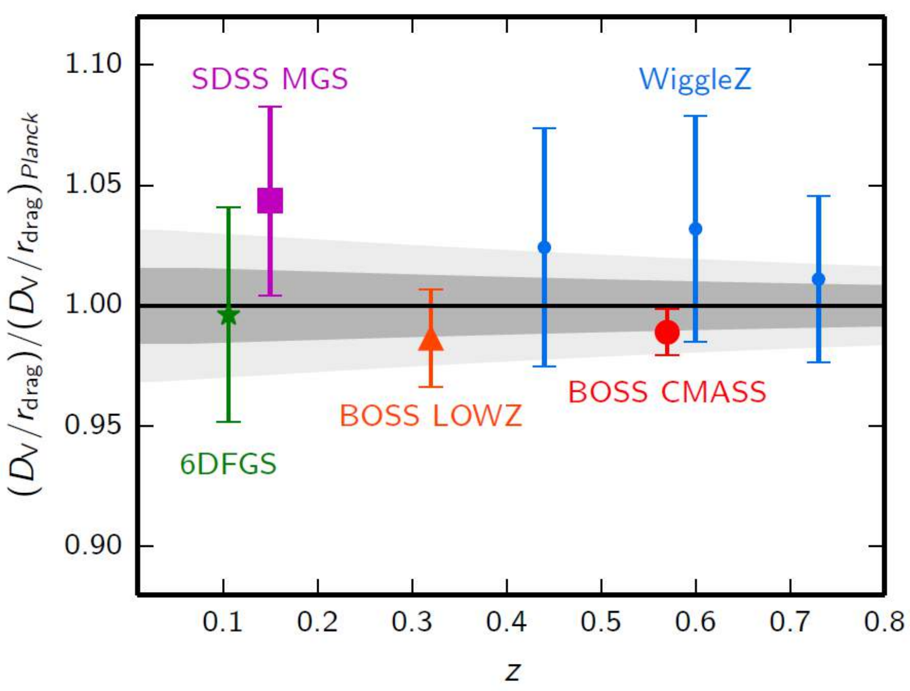


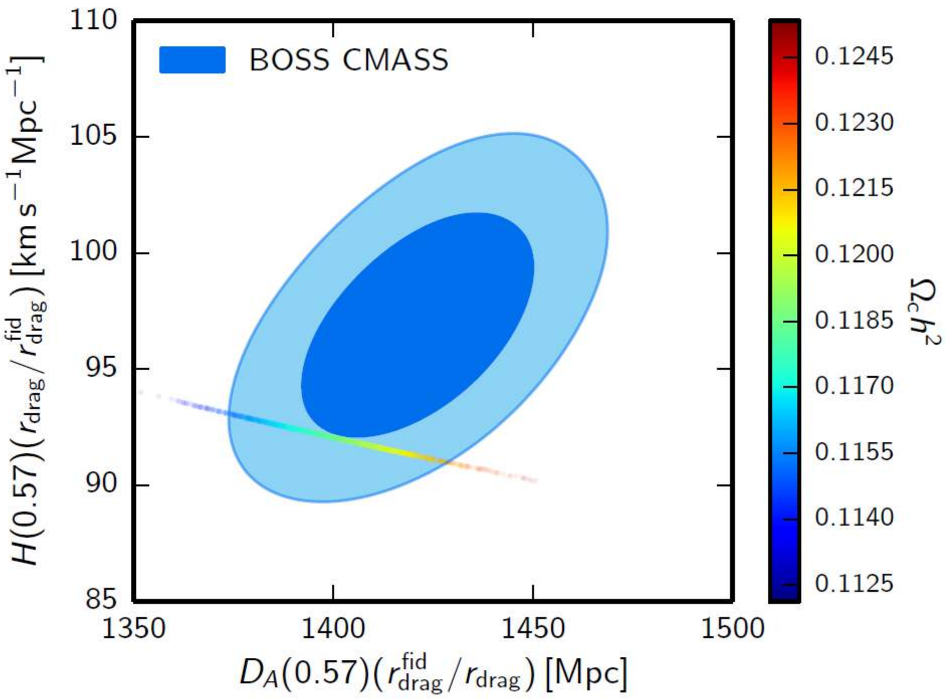




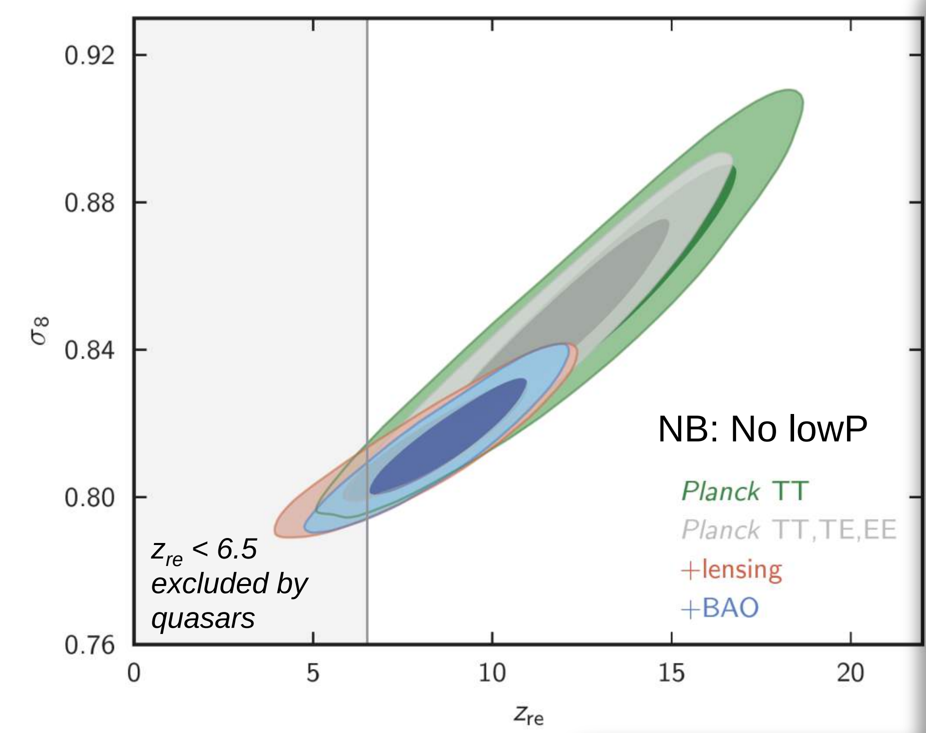
BAO

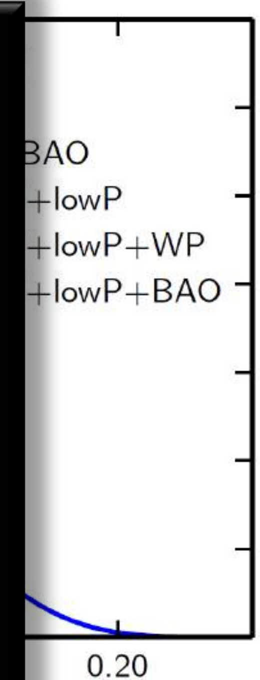
Grey band is Planck TT+LowP 1(2) sigma range





Optical depth constraints





Dark ages therefore ended around 550 million years after the BB – more than 100 million years later than previously thought (note though That the sizeable uncertainties remain similar for now).

There is now little need for exotic/contrived sources of energy to explain the history of reionization.

i.e. a tension between CMB and galaxy formation is now fading away.

A new, independe

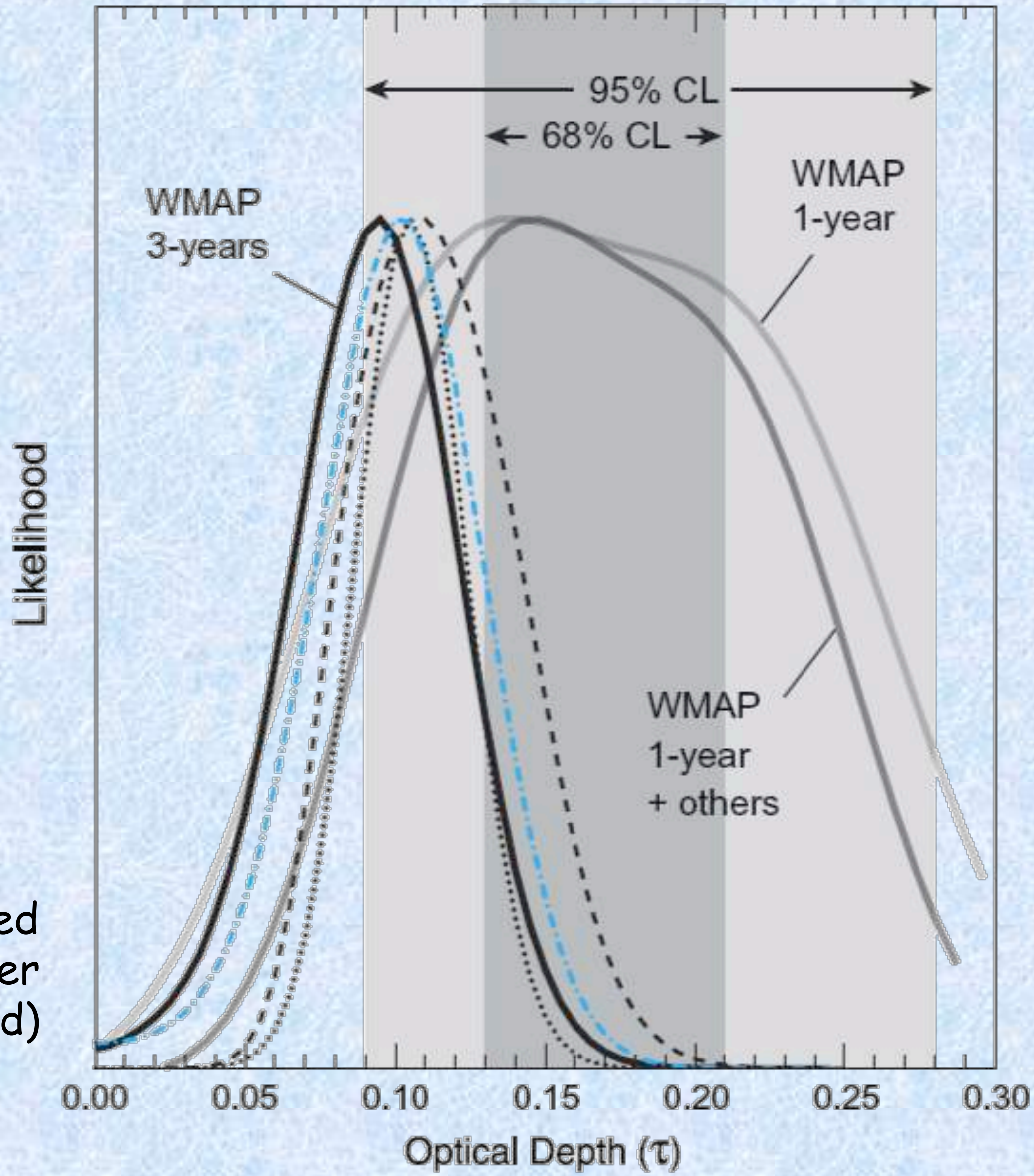
→Consistency of lensing ... τ

Pointing to lower τ values than earlier WMAP(1-9) based ones

OPTICAL DEPTH

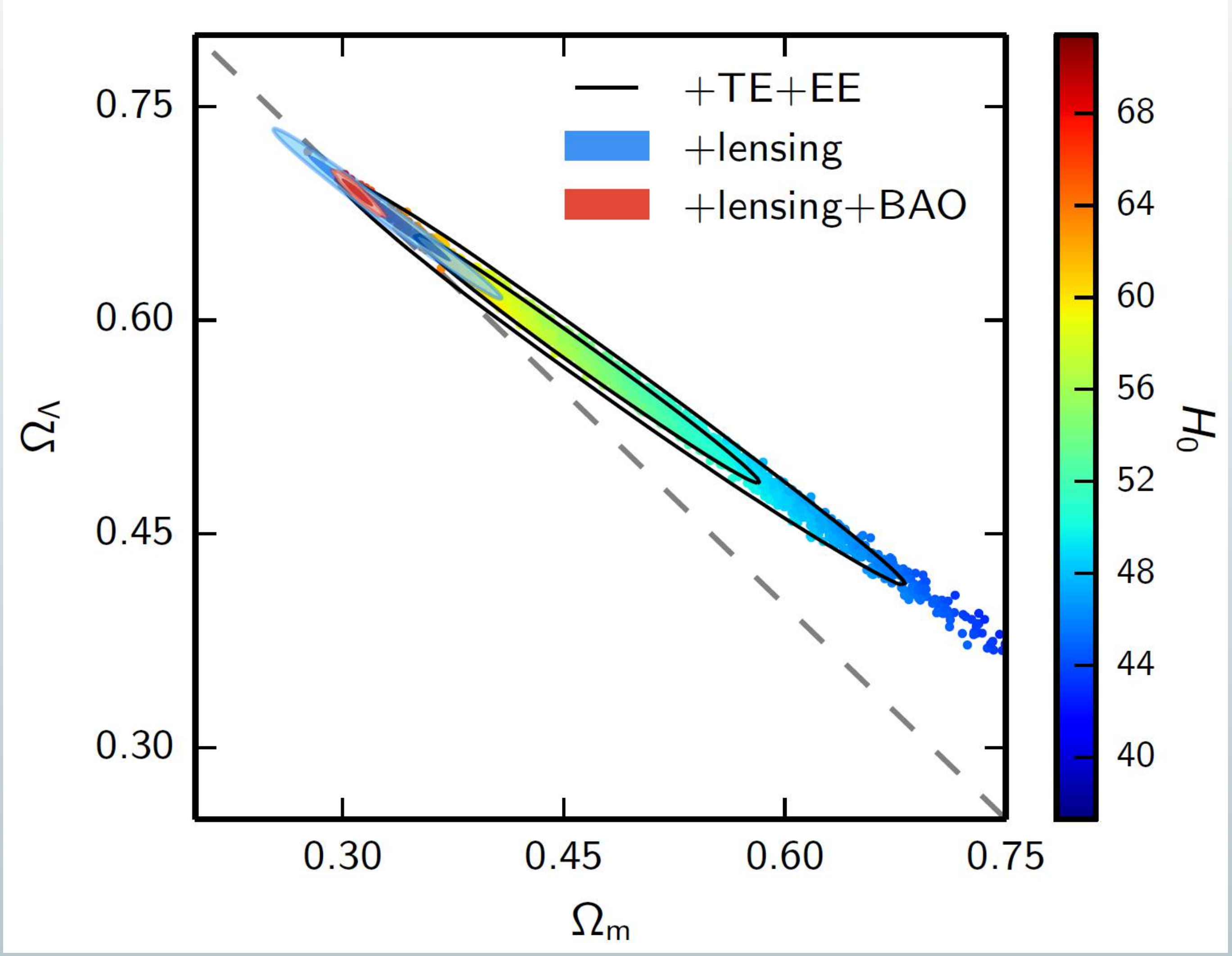
- TE-3 years contributes very little
- Alone would be an upper limit on tau
- New noise estimation (see Fisher) is the reason
- tau-1yr was based on TE
- tau from (EE-) 3yr is compatible at 2σ level with 1 yr data

(likelihood plotted keeping all other parameters fixed)

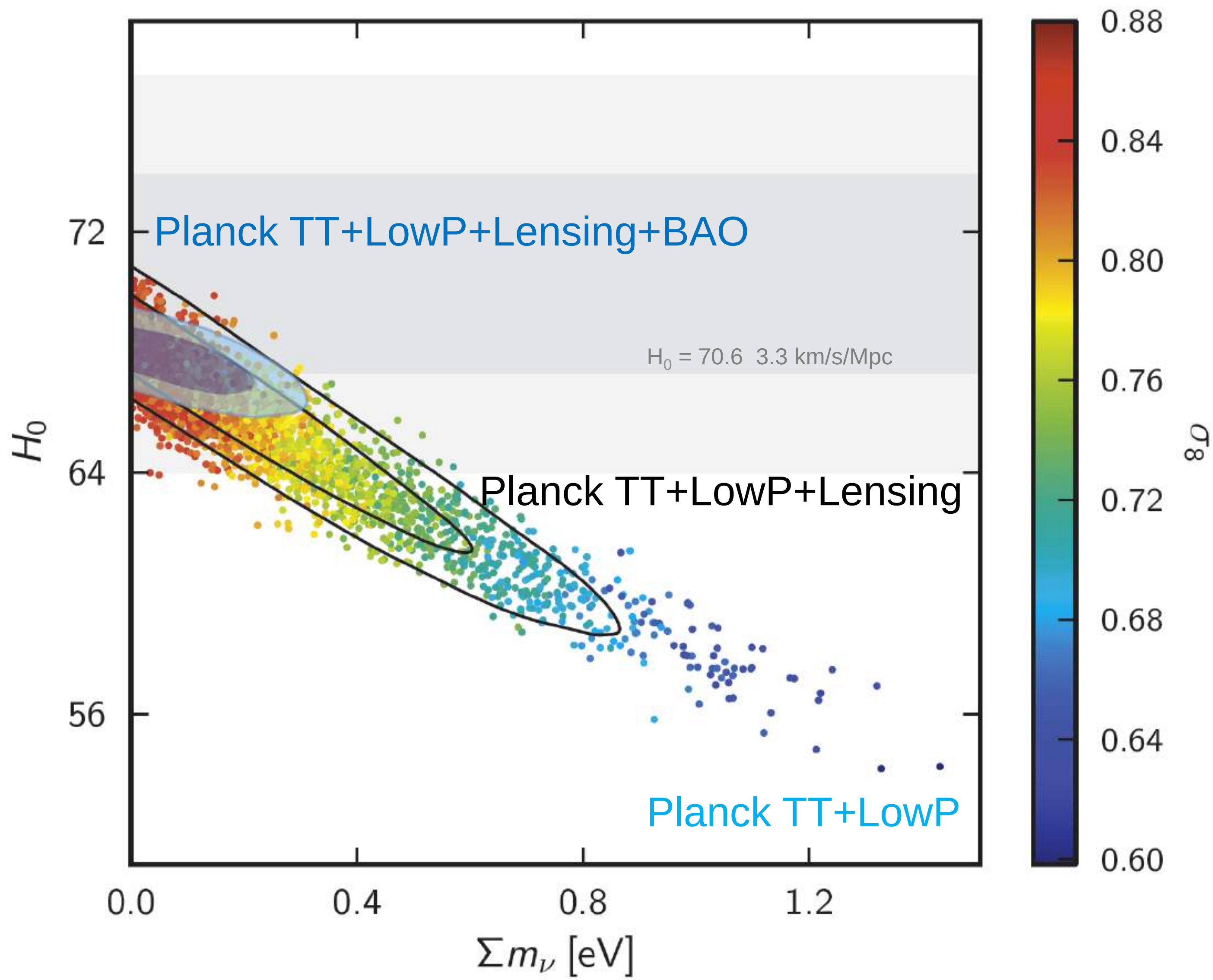


Spatial curvature constraint

$$\Omega_k = 0.000 \pm 0.005 \ (95\% \ \text{CL})$$



Neutrino masses $\sum \mathbf{m}_\nu < \mathbf{0.23}\,\mathrm{eV}$ (95%CL)



assuming three species of degenerate massive neutrinos

0.23 eV comes from TT+lowP +lensing +ext (BAO +JLA +H_0)

$\Omega_\nu h^2 < 0.0025$

With slight tightening with TE & EE

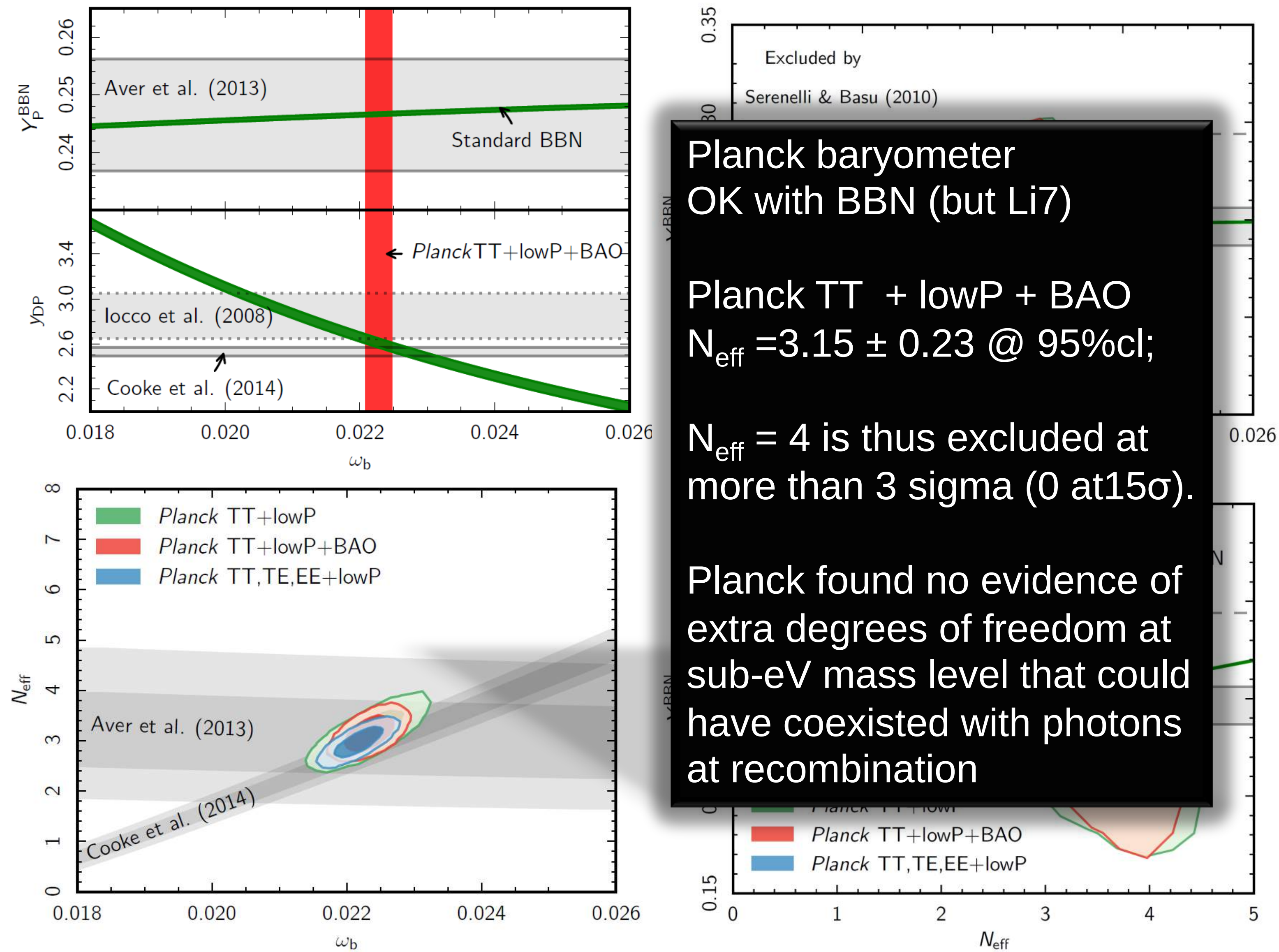
Neutrino masses constraints

Σm_ν(95% CL) [eV]	2013	2015	2015 +TE,EE
PlanckTT+lowP	<0.93	<0.72 (23%)	<0.49 (48%)
PlanckTT+lowP +lensing	<1.1	<0.70 (36%)	<0.58 (47%)
PlanckTT+lowP +lensing+ Ext		**<0.23**	<0.19

For 2013, lowP is WMAP polarization

Assumption: 3 degenerate massive neutrinos

BBN – N_{eff}, Y_p



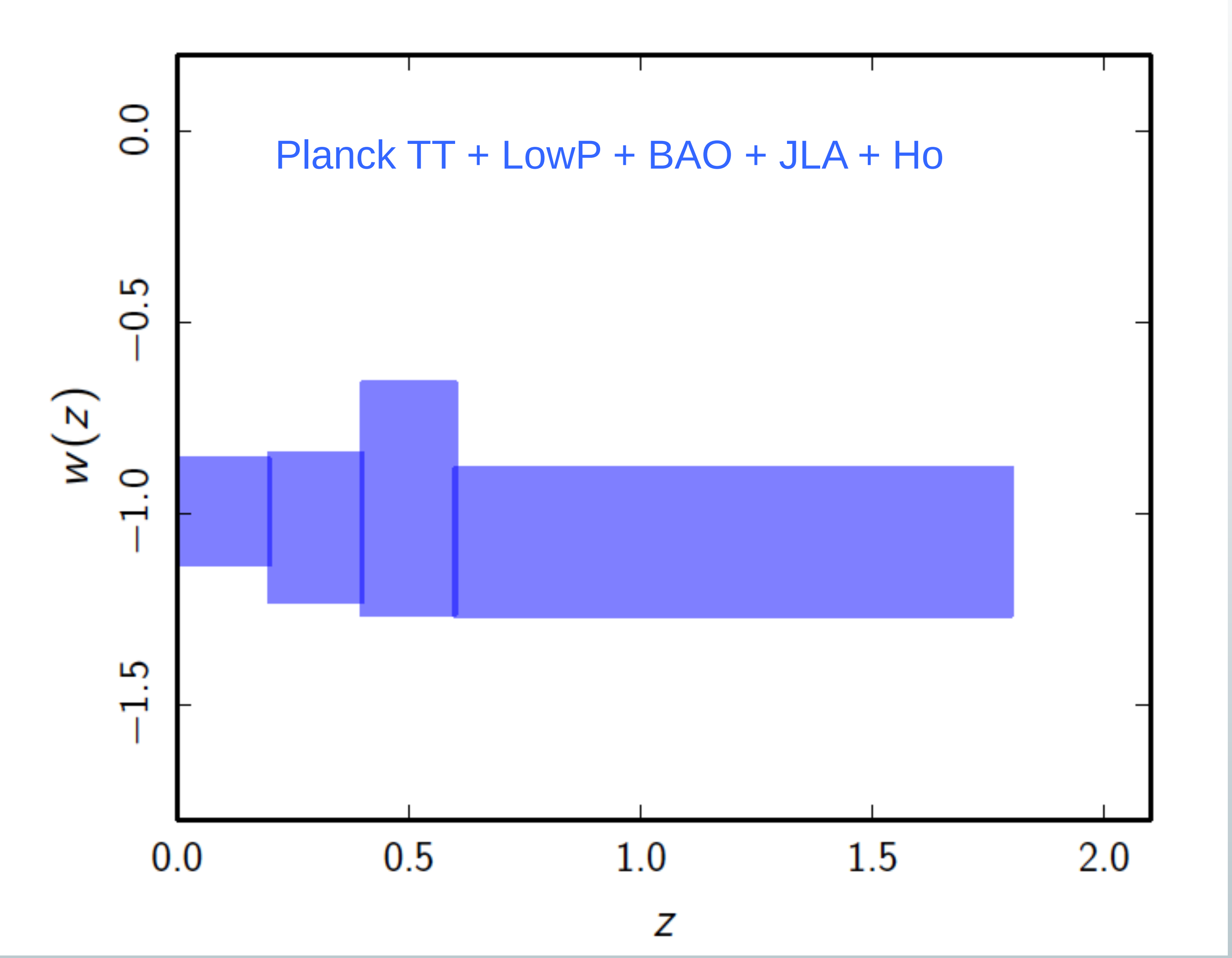
Planck baryometer
OK with BBN (but Li7)

Planck TT + lowP + BAO
N_{eff} =3.15 ± 0.23 @ 95%cl;

N_{eff} = 4 is thus excluded at more than 3 sigma (0 at15σ).

Planck found no evidence of extra degrees of freedom at sub-eV mass level that could have coexisted with photons at recombination

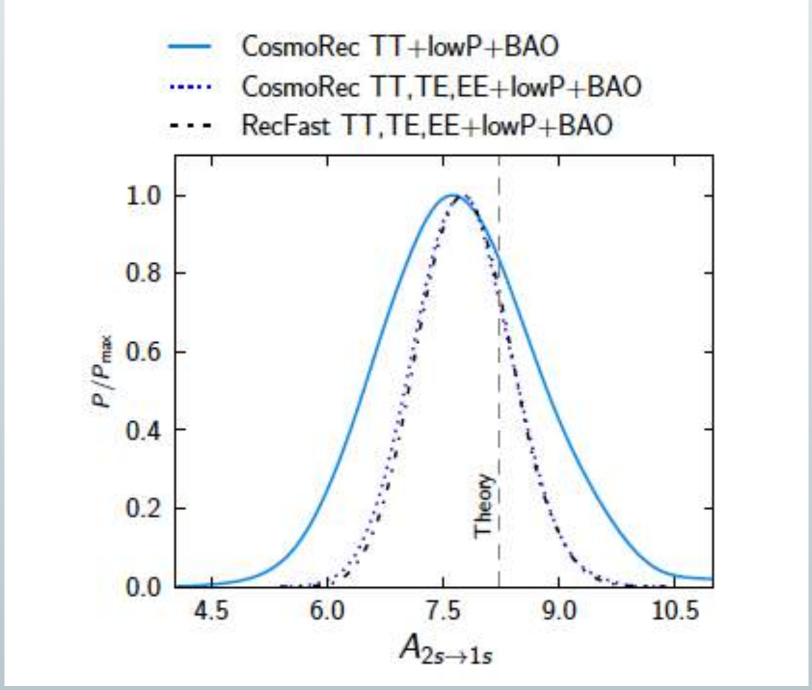
PCA of w(z)

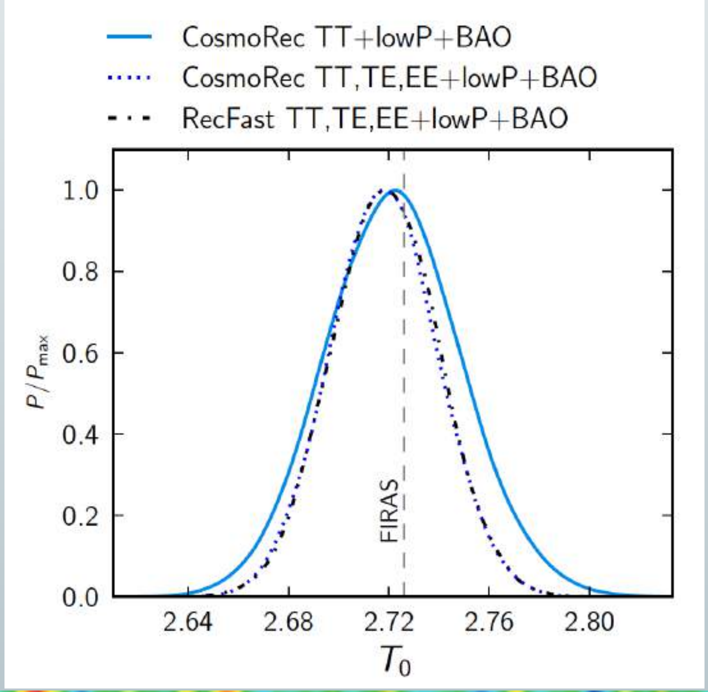


Recombination history

Planck is impressively sensitive to details of the recombination history… and is therefore sensitive to

- Variation of the fundamental constants
- The value of the 2 ϒ decay rate, or the recombination Temperature…, or any non-std history!

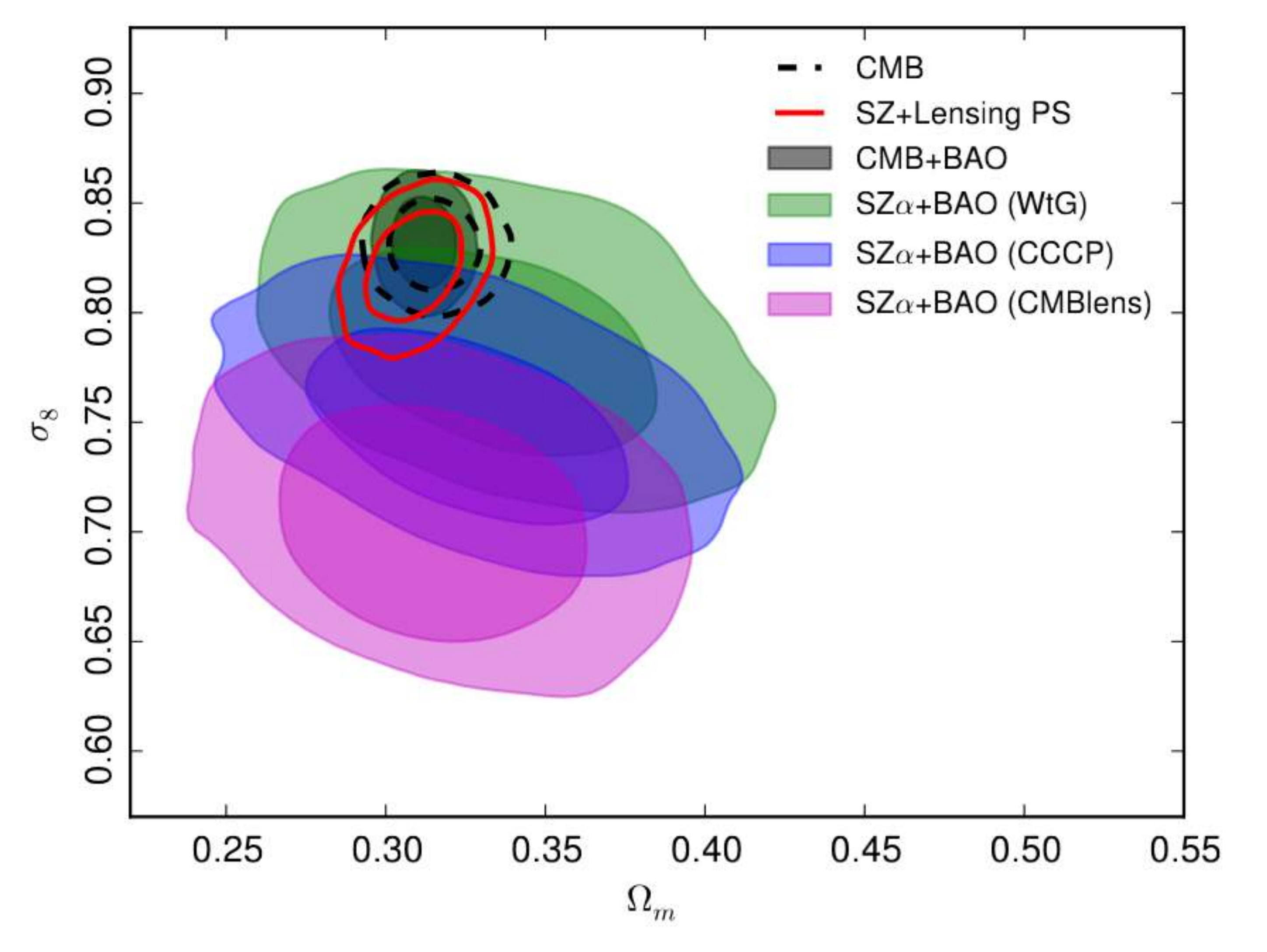




Standard cosmological model - LCDM

- Thus the CMB TT, TE, EE, Φ-Φ, as well as BBN (but Li7), BAO and SN1a measurements are all consistent, among themselves and across experiments, within LCDM.
- This network of tests is done with per cent level precision.
- The consistency allows many different checks of the robustness of this base LCDM model and some of its extensions, including τ constrained two-ways thanks to CMB lensing, flatness at 5 x 10^{-3} level, neutrinos masses and number, DM annihilation limits, w(z), details of the recombination history ($A_{2s\rightarrow 1}$, T_0, and also fundamental constants variation, or any energy input).

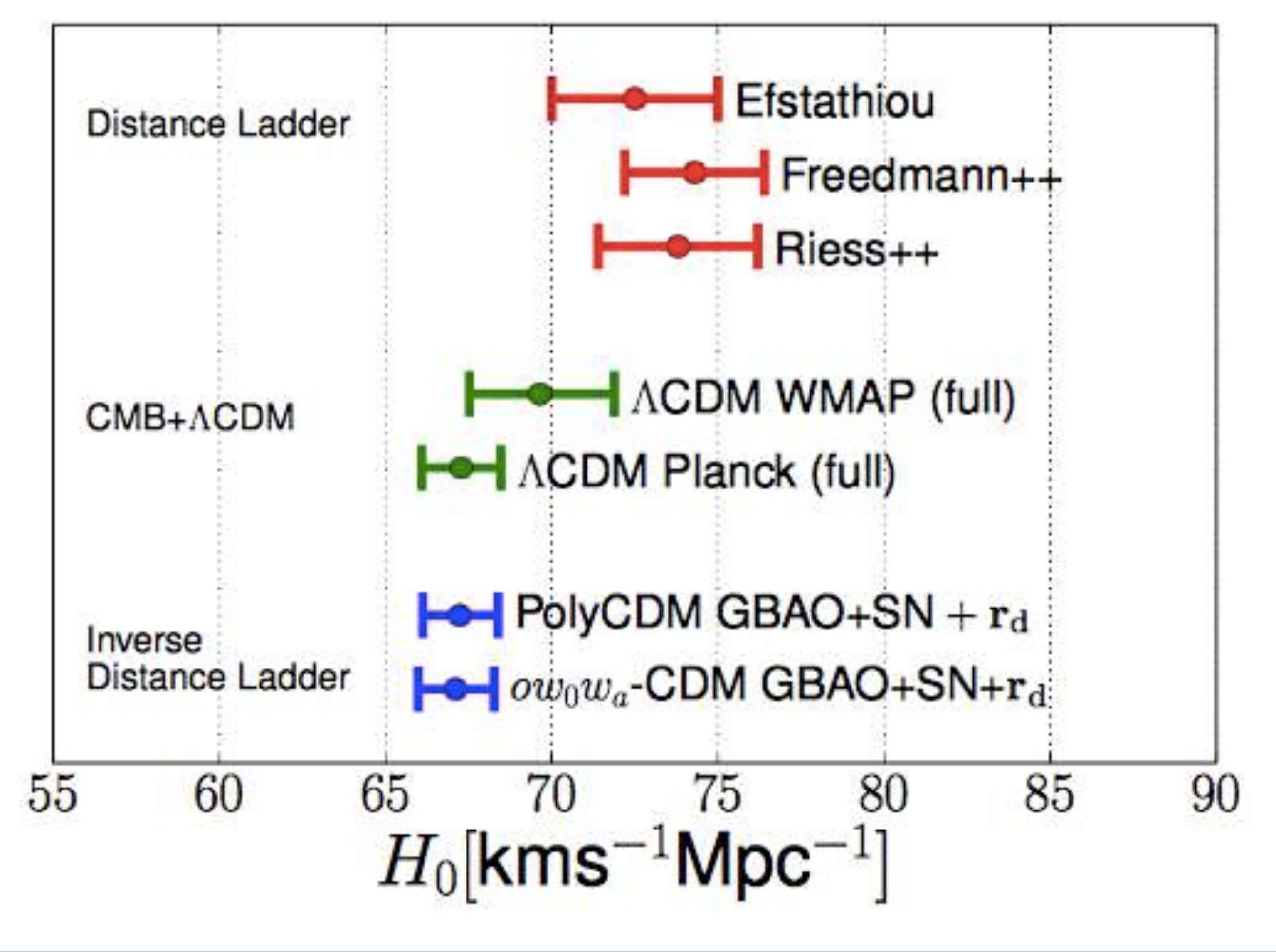
Number counts of SZ clusters



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

Comparison of H_0

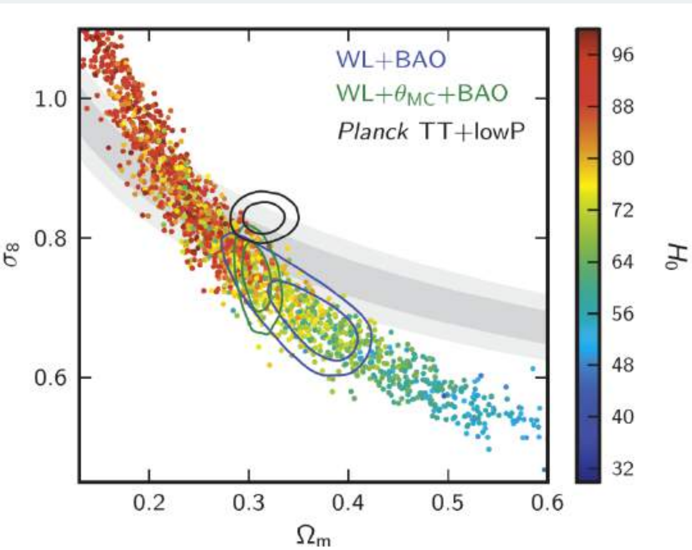
- Inverse distance ladder is in perfect agreement with Planck CMB (this uses the absolute calibration from BAO to calibrate SN1a in the overlapping region at z=0.57 to bring it down to z=0.)
- Some discrepancy with direct distance ladder



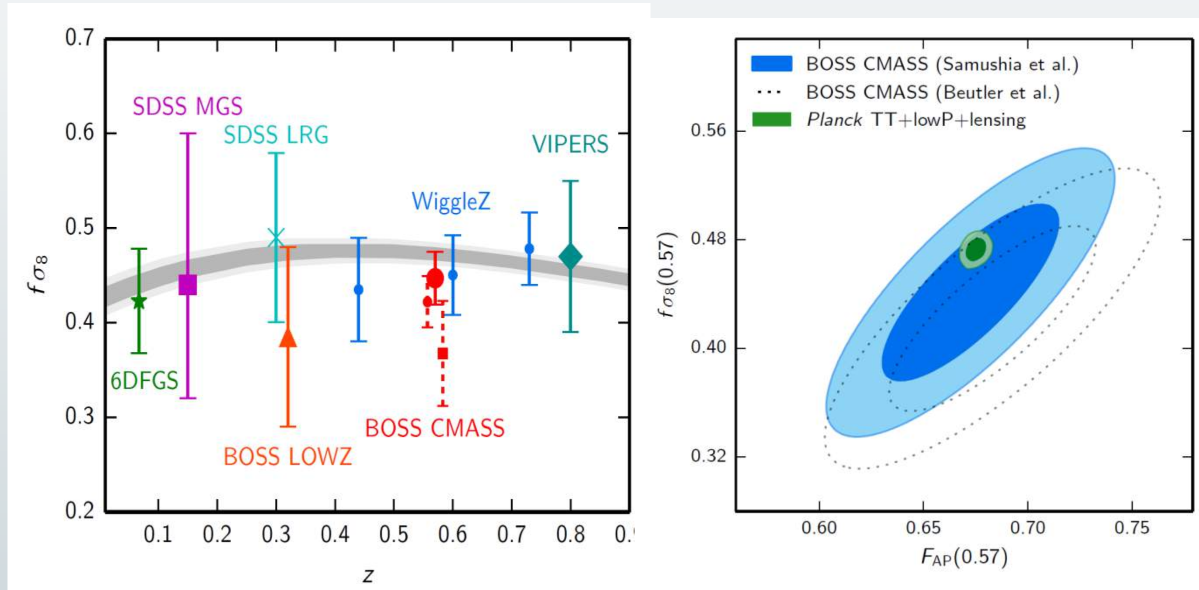
arXiv:1411.1074v2

Some tensions

Weak Lensing from CFHTLens



Growth rate of fluctuations from redshift space distortions

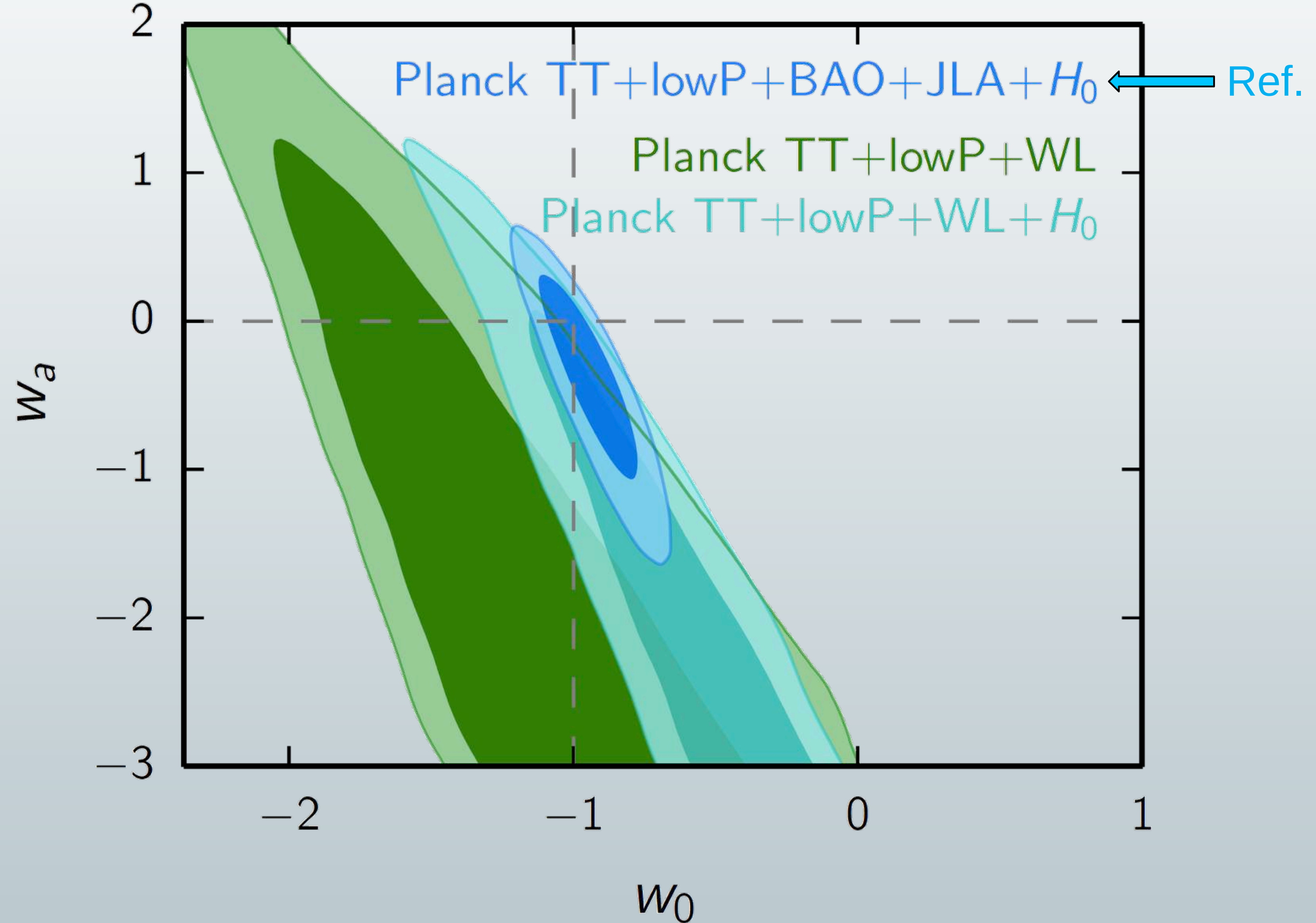


i.e. some tensions with astrophysical measurements of the amplitude of matter fluctuations at low z.

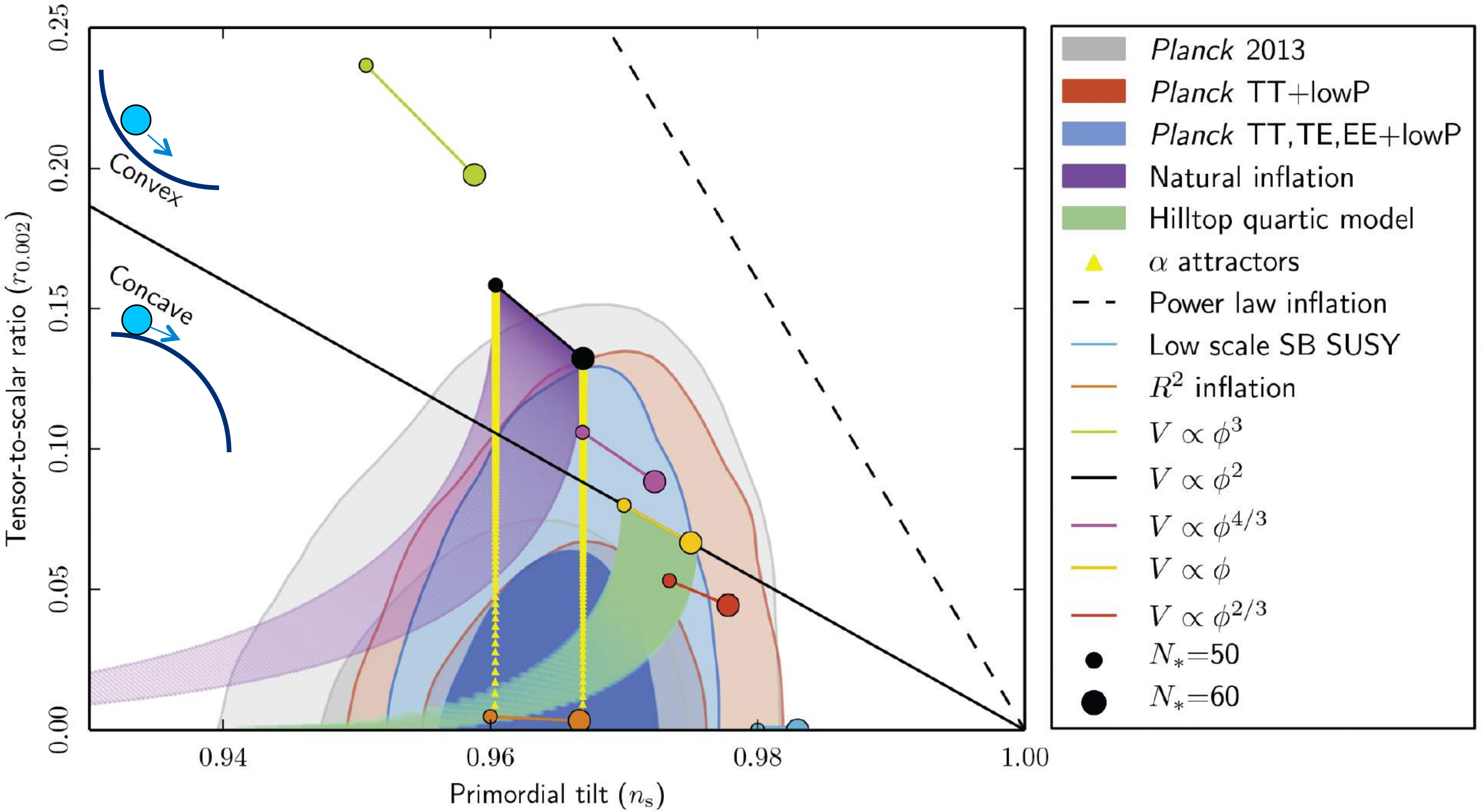
NB: Ly BAO measurements at high redshift are discrepant at 2.7sig, and it is quite difficult to find physical explanation not disrupting BAO consistency elsewhere, see eg Aubourg etal. 2015

What these tensions can do…

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

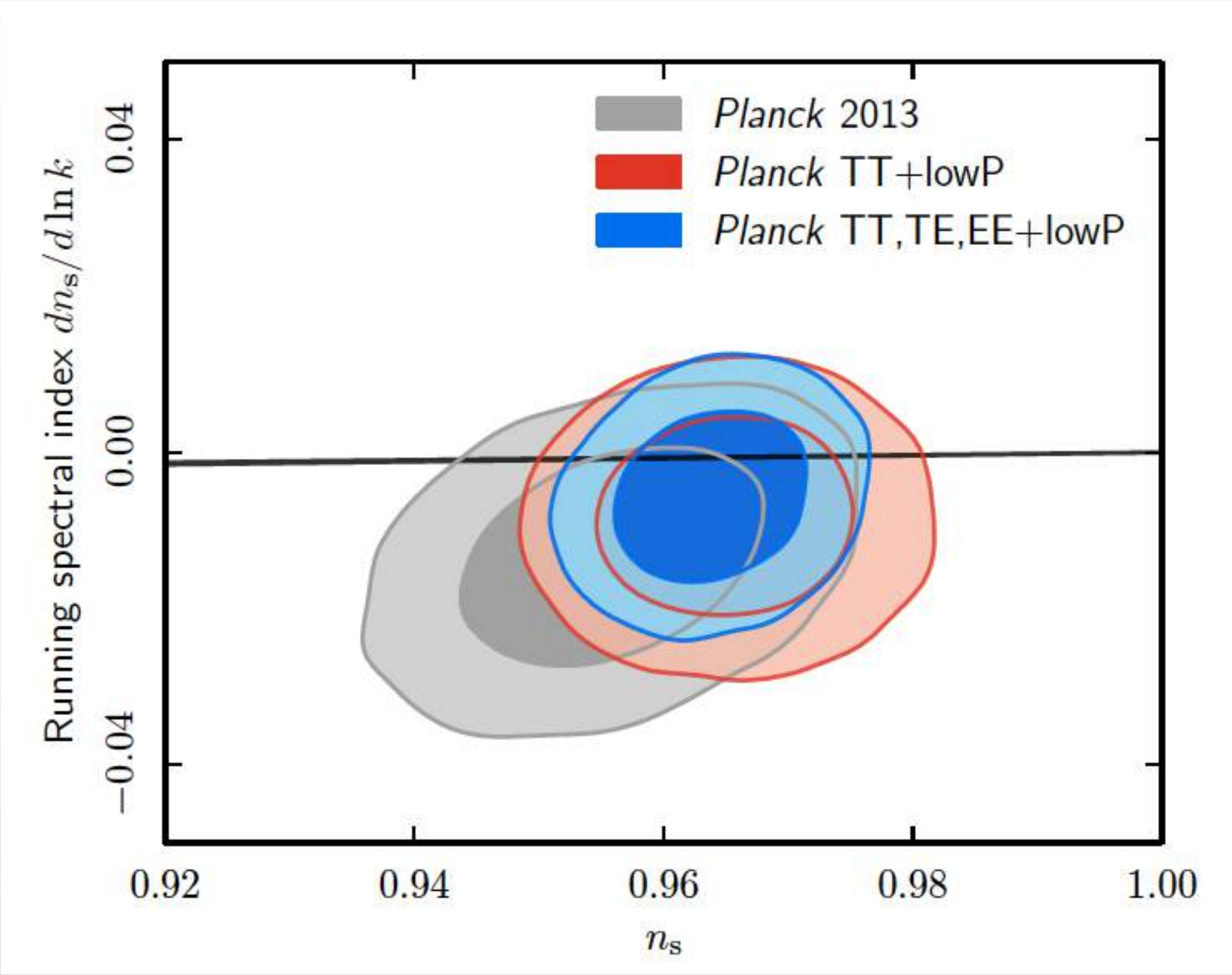


Planck 2015: n_s vs r



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

Planck 2015 on running



The thin black stripe shows the prediction for single-field monomial chaotic inflationary models with 50 < N < 60 .

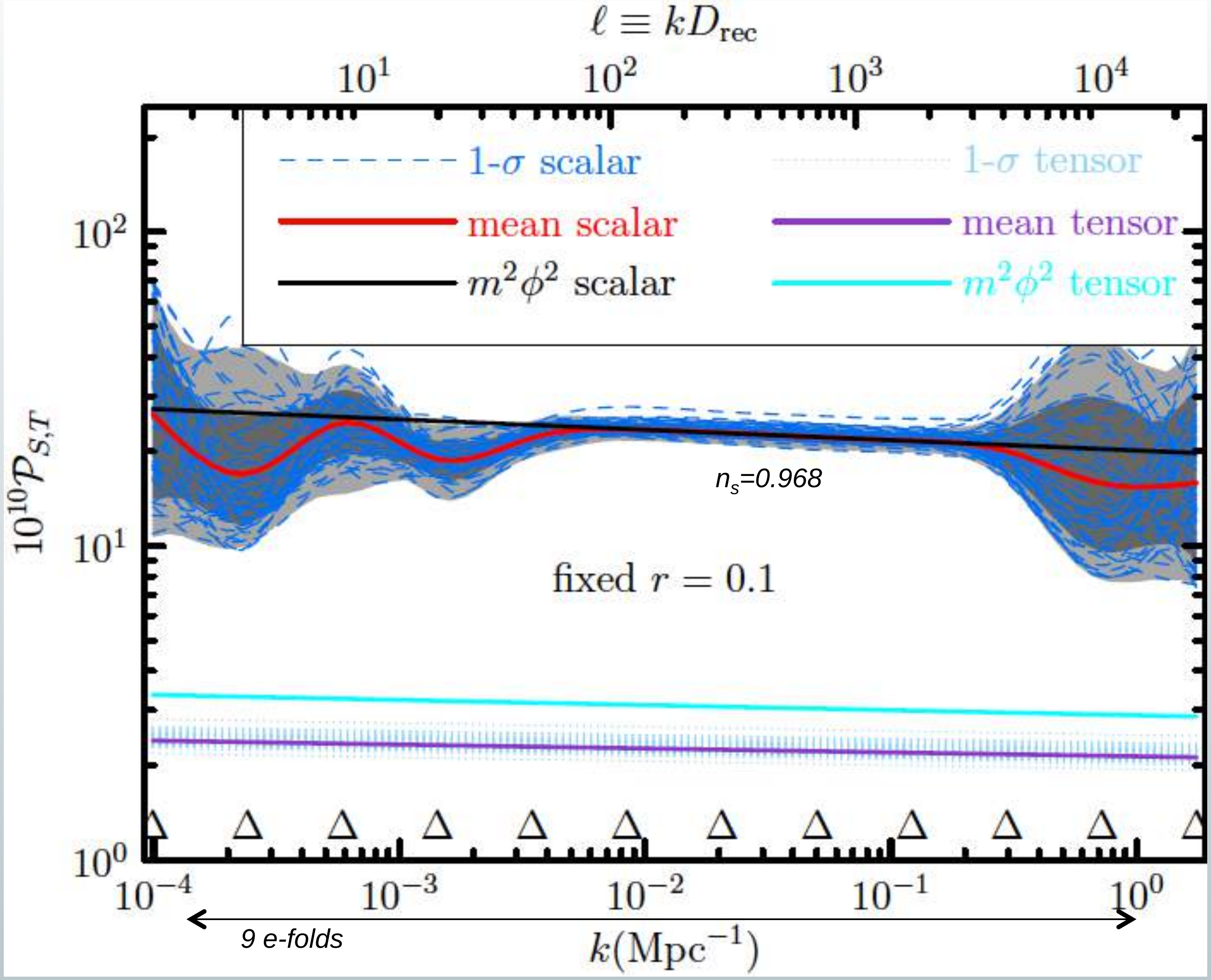
Power spectra reconstruction

2015

TT+lowP

+BAO+JLA

+Hlow

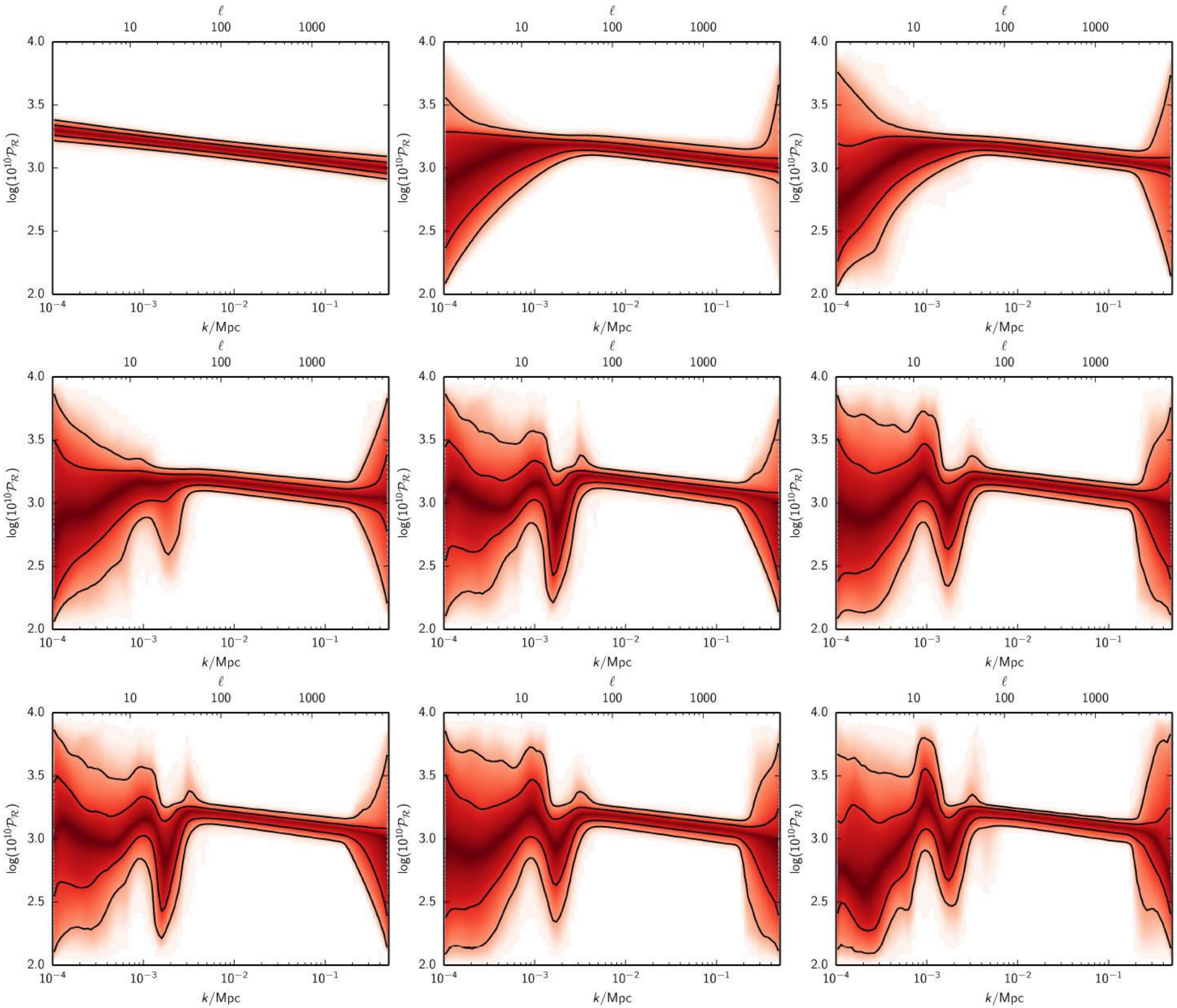


12-knots power spectra

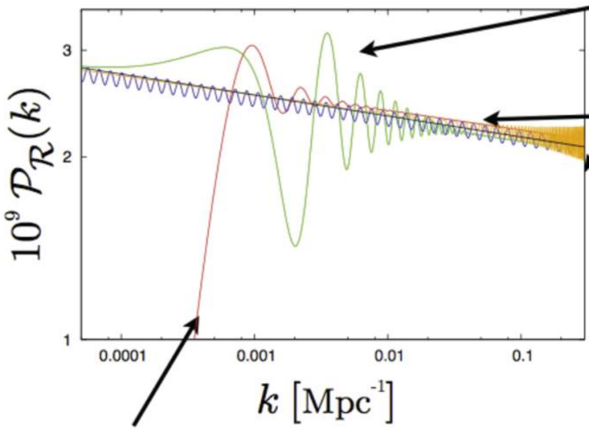
(actually used 3 different methods, all with similar results)

Bayesian moveable knot reconstruction

0 to 8 knots allowed



(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

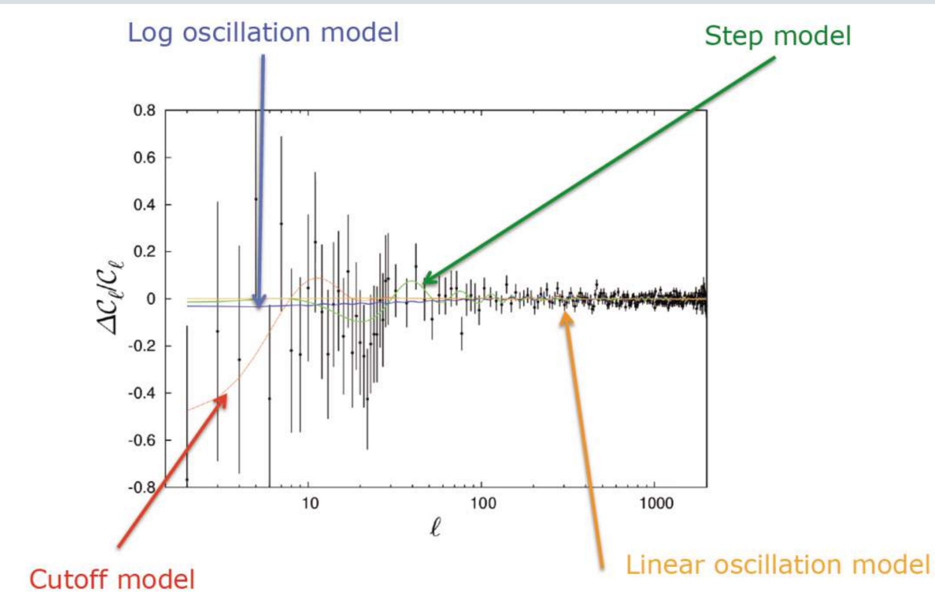
$$V(\phi) = \mu^3\phi + \Lambda^4\cos\left(\frac{\phi}{f}\right)$$

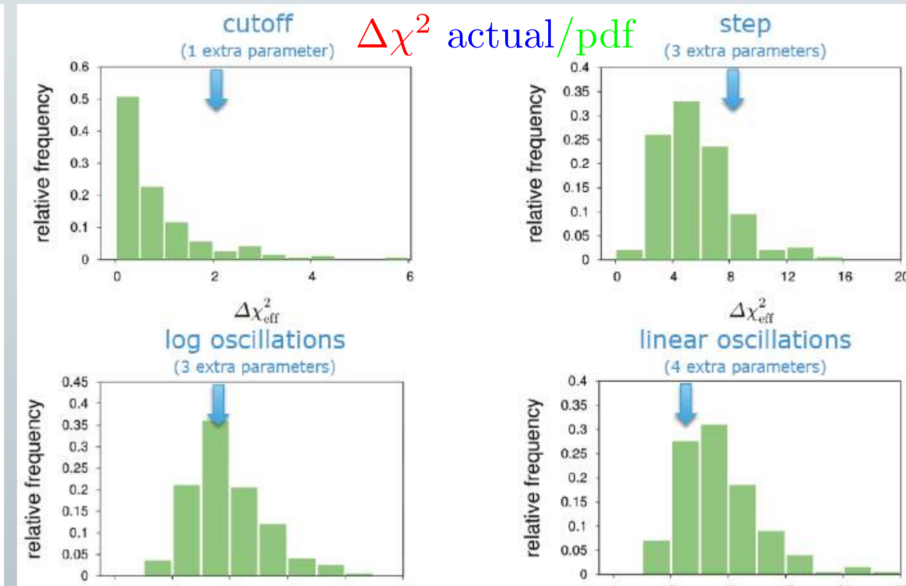
$$\mathcal{P}_\mathcal{R}^{\log}(k) = \mathcal{P}_\mathcal{R}^0(k)\left[1 + \mathcal{A}_{\log}\cos\left(\omega_{\log}\ln\left(\frac{k}{k_*}\right)+\varphi_{\log}\right)\right].$$

Linear oscillations as from Boundary EFT

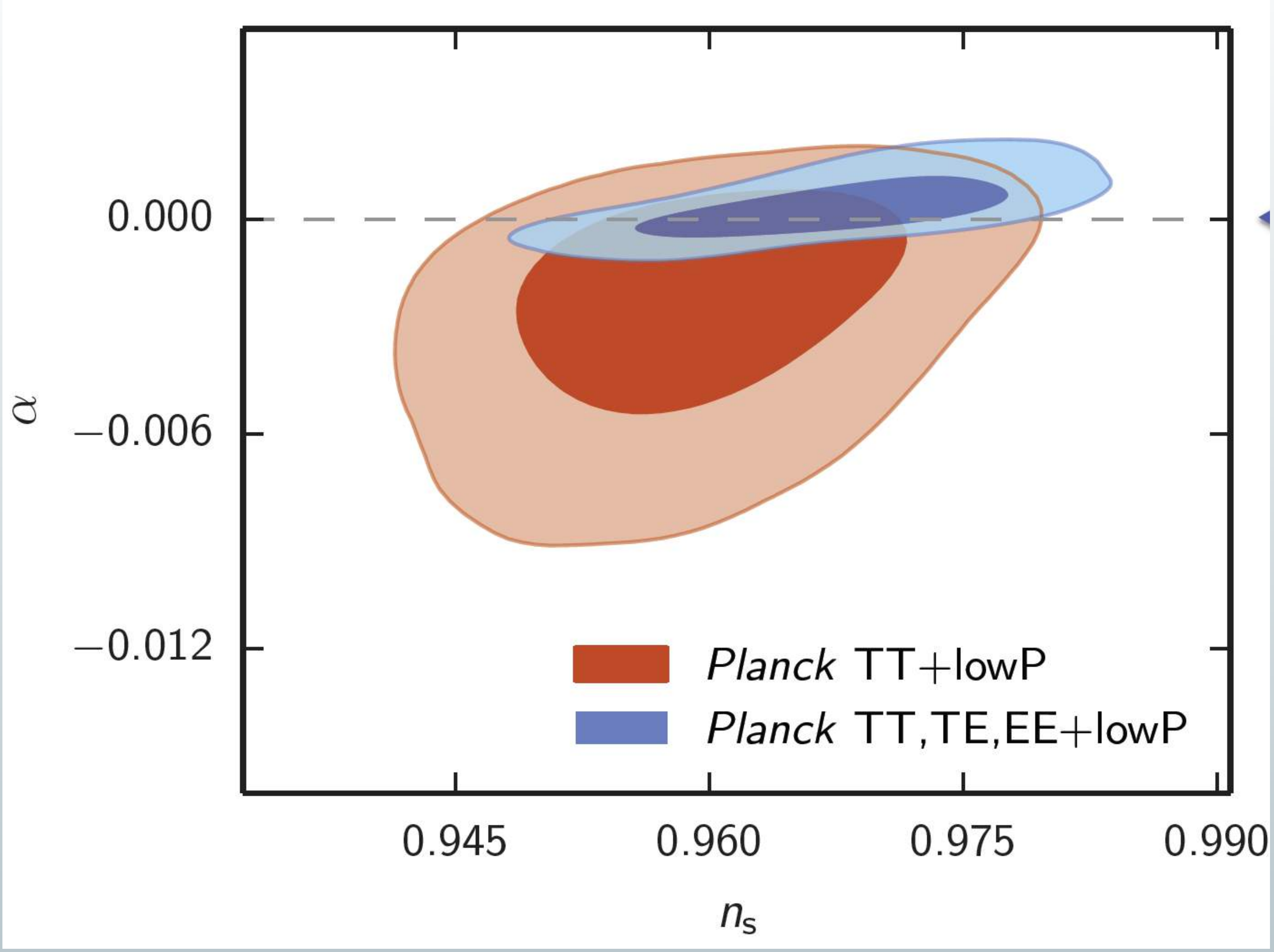
$$\mathcal{P}_\mathcal{R}^{\mathrm{lin}}(k) = \mathcal{P}_\mathcal{R}^0(k)\left[1 + \mathcal{A}_{\mathrm{lin}}\left(\frac{k}{k_*}\right)^{n_{\mathrm{lin}}}\cos\left(\omega_{\mathrm{lin}}\frac{k}{k_*}+\varphi_{\mathrm{lin}}\right)\right]$$

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





Isocurvature modes fraction



Bispectrum constraints w. full mission data

Planck 2015

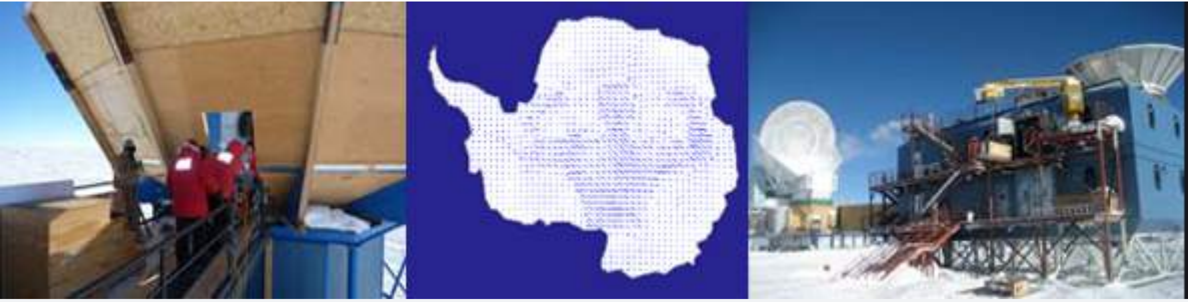
Shape and method	f_{NL}(KSW) Independent	ISW-lensing subtracted
SMICA (T)		
Local	9.5 ± 5.6	**1.8 ± 5.6**
Equilateral	−10 ± 69	**−9.2 ± 69**
Orthogonal	−43 ± 33	**−20 ± 33**
SMICA (T+E)		
Local	6.5 ± 5.1	
Equilateral	−8.9 ± 44	
Orthogonal	−35 ± 22	

$f^{local}_{NL} = 0.8 \pm 5.0$
$f^{equil}_{NL} = -4 \pm 43$
$f^{ortho}_{NL} = -26 \pm 21$

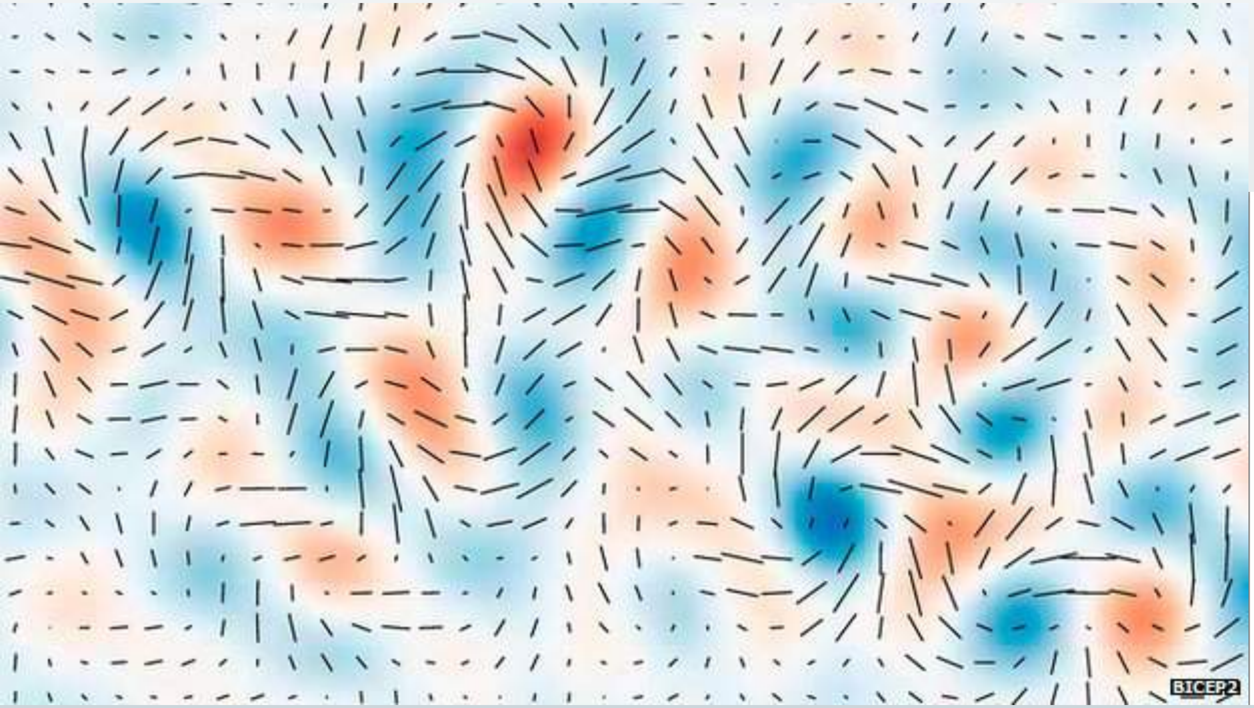
Planck 2013

ISW-lensing subtracted KSW	Binned	Modal
2.7 ± 5.8	2.2 ± 5.9	1.6 ± 6.0
−42 ± 75	−25 ± 73	−20 ± 77
−25 ± 39	−17 ± 41	−14 ± 42

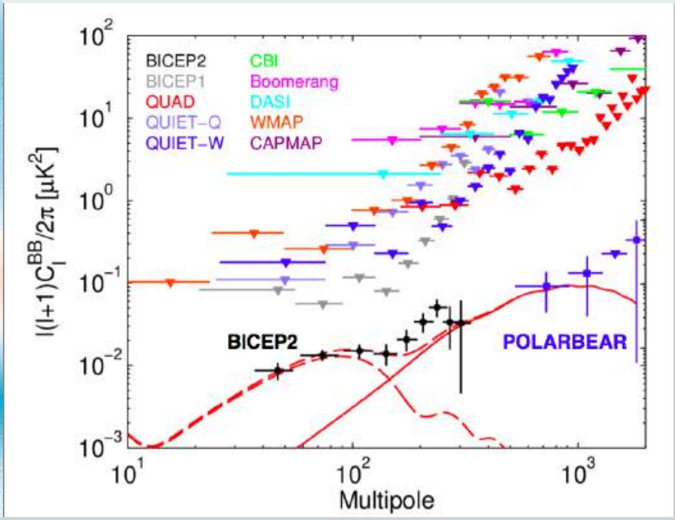
Constraint volume in LEO space shrunk by factor of 3.



BICEP2



March 17^{th} 2014



The world of physics is taken aback by an extraordinary result from a beautiful experiment:

The search for primordial gravitationnal waves is over.

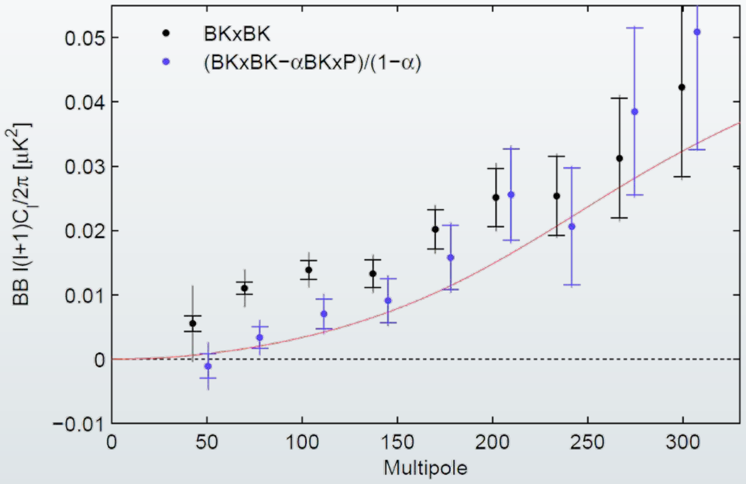
It is r=0.2 and it is 5 sigma!

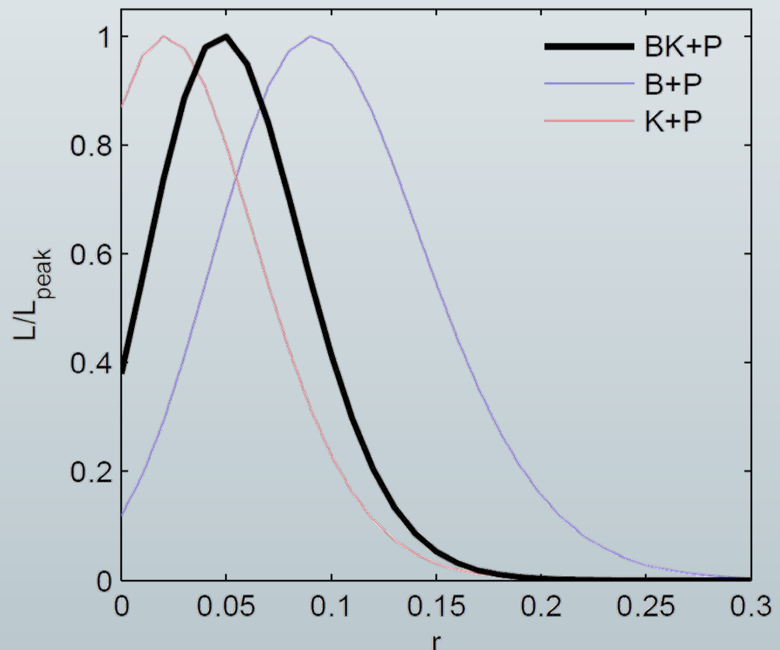
Planck X (Bicep2 & Keck)

- 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.

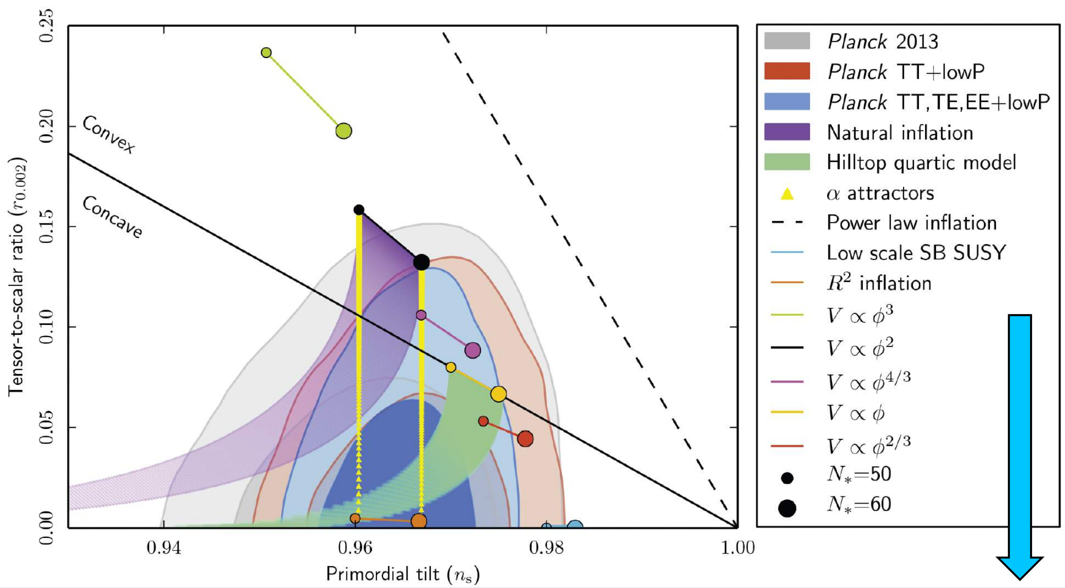
- r < 0.11 @ 95%CL
  (r =A_s/A_T à, e.g., k=0.05Mpc^{-1})

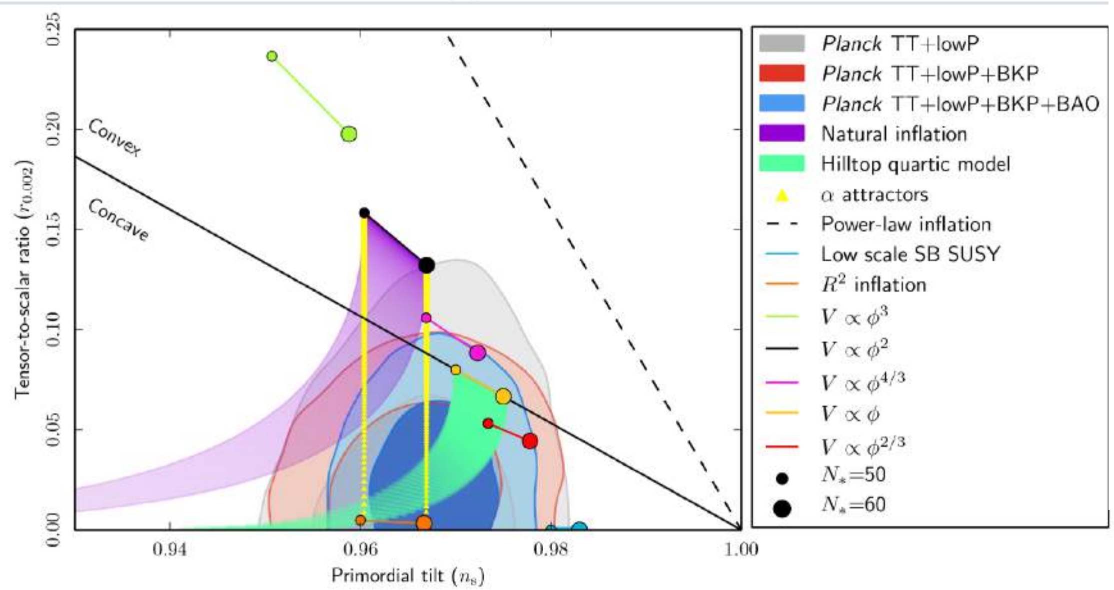
- A new era began…





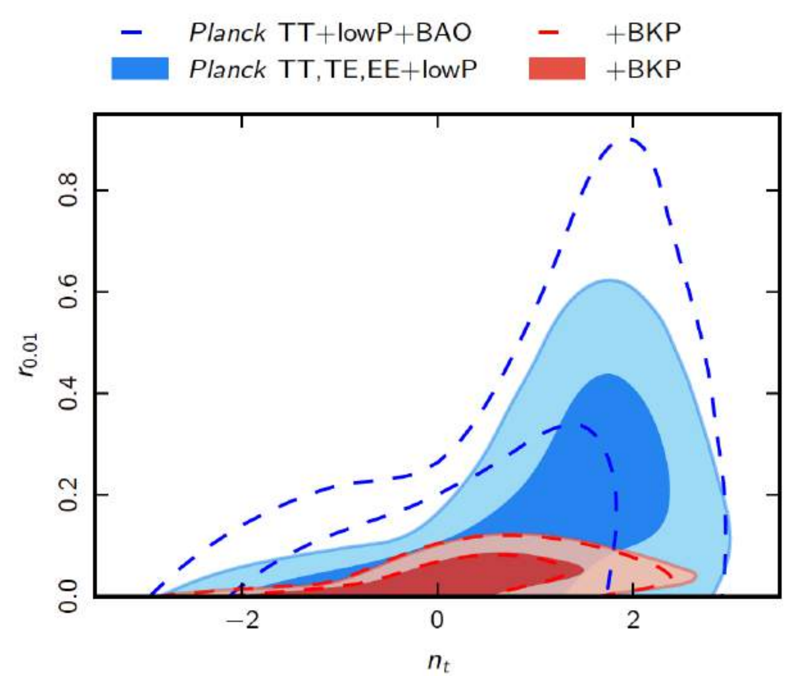
Planck + BK X Planck





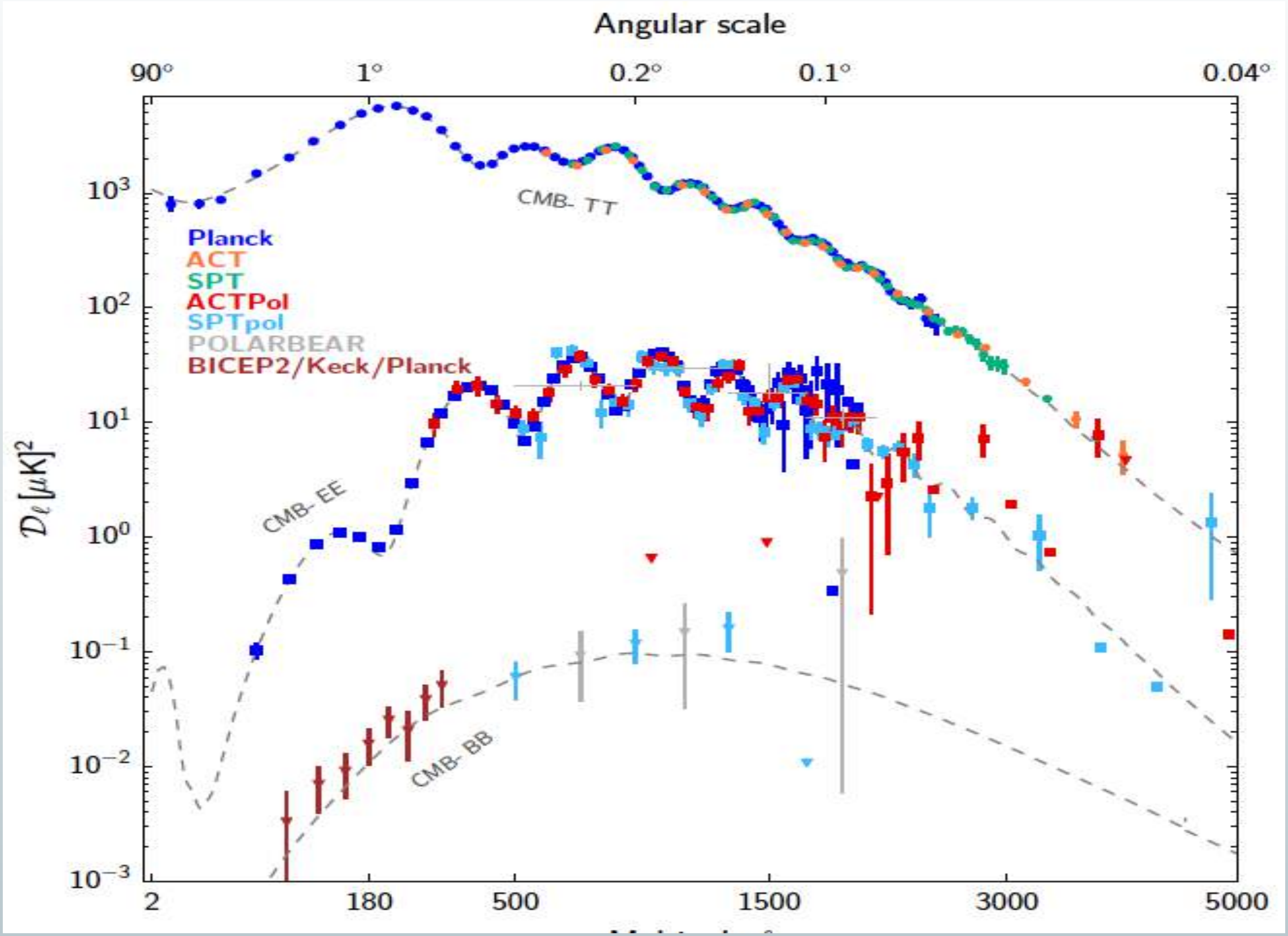
Planck 2013: $r_{0.002}$ < 0.11 @95%cl
Planck 2015: $r_{0.002}$ < 0.10 @95%cl
BKP : $r_{0.002}$ < 0.12 @95%cl

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



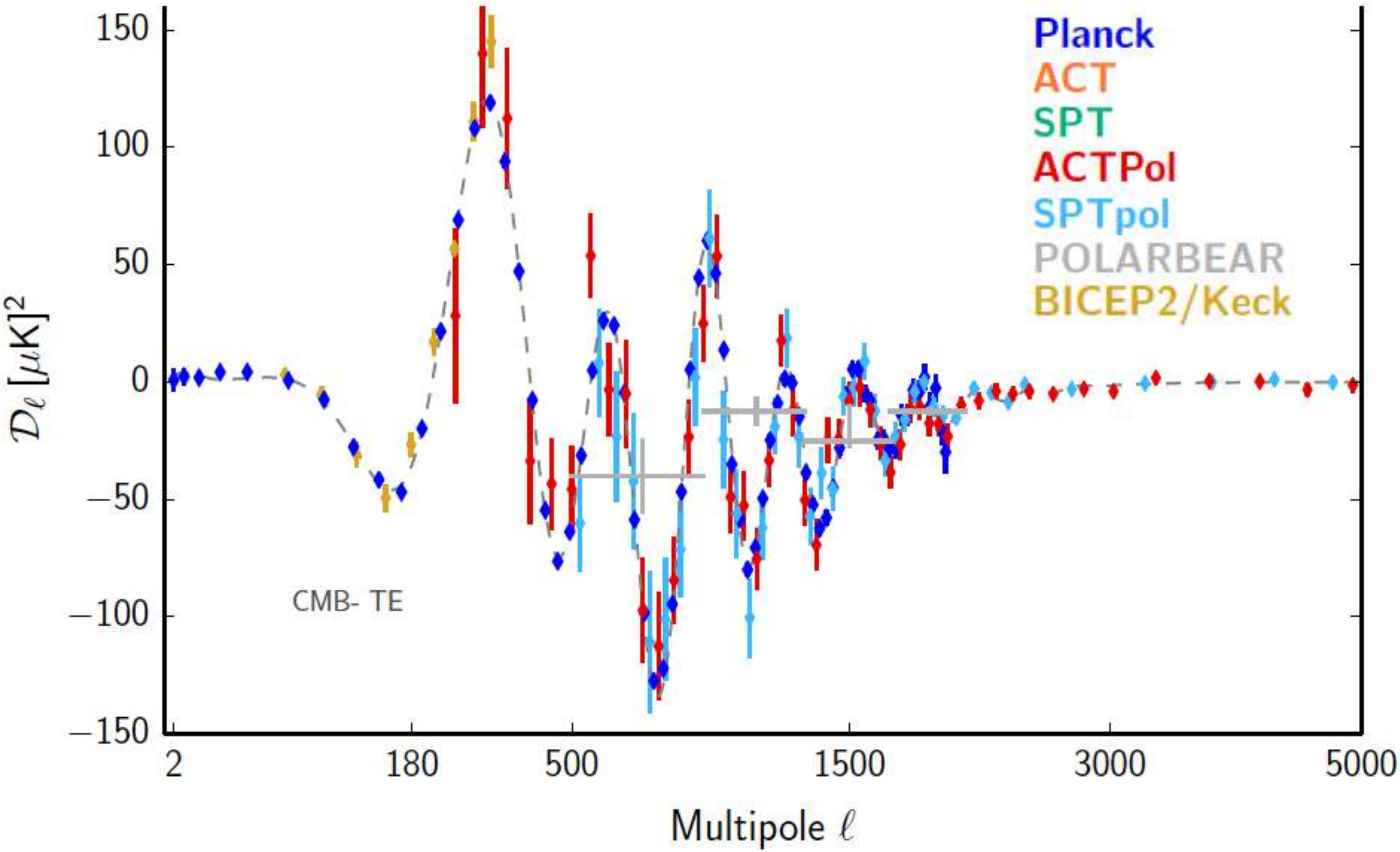
(using n_T and $r_{0.002}$ as primary parameters)

TT, EE, BB – mid 2015 status



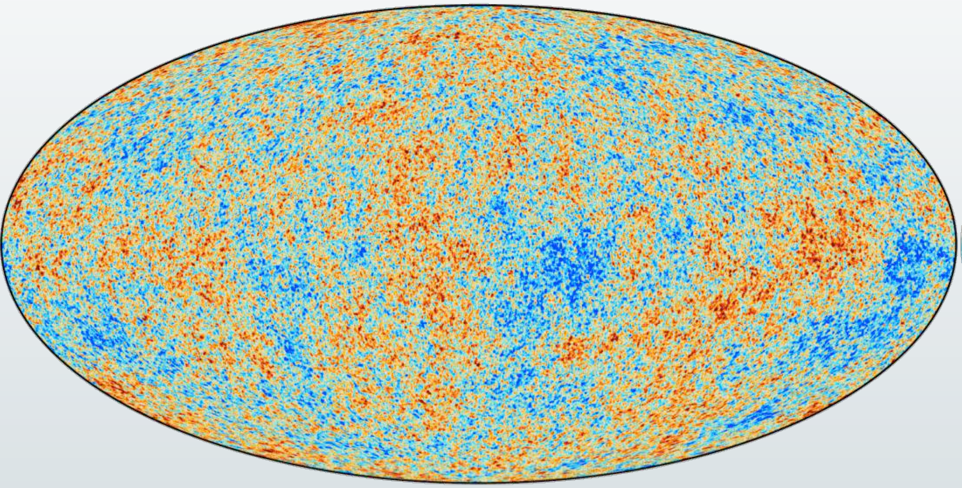
Only keeping points w. sufficiently small error bars

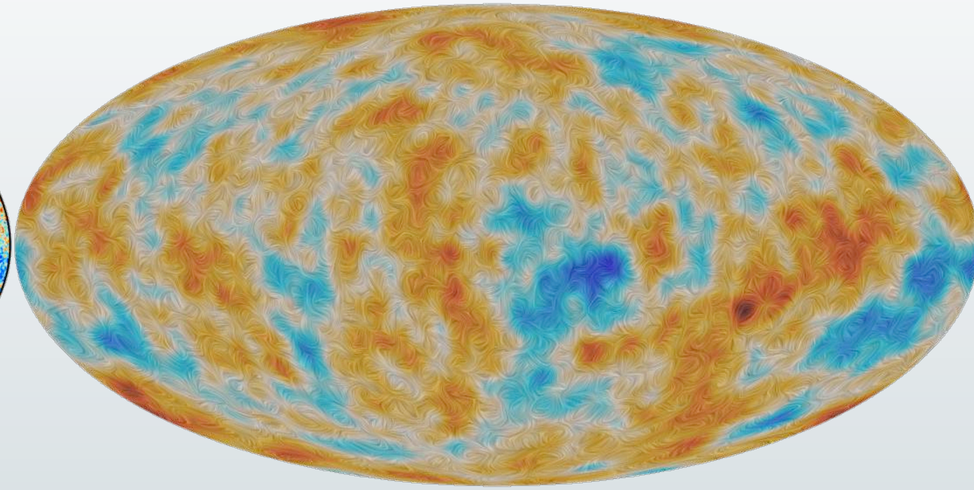
Not forgetting mighty TE !



Conclusions

➔ base ΛCDM continues to be a good fit to the Planck data, *including polarisation*.

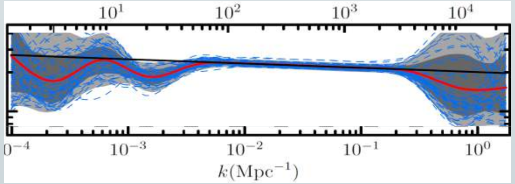


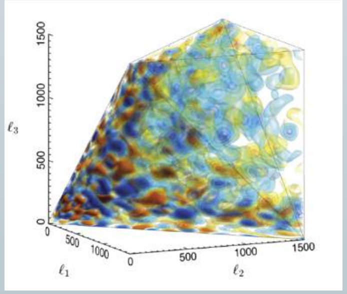


➔powerful evidence in favour of simple inflationary models, that match Planck data to very high precision.

Parameter	*Planck* TT,TE,EE+lowP
$\Omega_b h^2$	0.02225 ± 0.00016
$\Omega_c h^2$	0.1198 ± 0.0015
$100\theta_{MC}$	1.04077 ± 0.00032
τ	0.079 ± 0.017
$\ln(10^{10} A_s)$	3.094 ± 0.034
n_s	0.9645 ± 0.0049
H_0	67.27 ± 0.66
Ω_m	0.3156 ± 0.0091
σ_8	0.831 ± 0.013
$10^9 A_s e^{-2\tau}$	1.882 ± 0.012

@95%cl





Parameter	TT, TE, EE+lensing+ext
Ω_K	$0.0008^{+0.0040}_{-0.0039}$
Σm_ν [eV] . .	< 0.194
$N_{\rm eff}$	$3.04^{+0.33}_{-0.33}$
Y_P	$0.249^{+0.025}_{-0.026}$
$dn_s/d\ln k$ . .	$-0.002^{+0.013}_{-0.013}$
$r_{0.002}$	< 0.113
w	$-1.019^{+0.075}_{-0.080}$

$f^{local}_{NL} = 0.8 \pm 5.0$
$f^{equil}_{NL} = -4 \pm 43$
$f^{ortho}_{NL} = -26 \pm 21$

α_{iso}
P_{ann}
...

Defect	$G\mu/c^2$
NG . .	$< 1.3 \times 10^{-7}$
AH . .	$< 2.4 \times 10^{-7}$
SL . .	$< 8.5 \times 10^{-7}$
TX . .	$< 8.6 \times 10^{-7}$

➔If there is new physics beyond base ΛCDM, its observational signatures in the CMB are weak & difficult to detect.

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.