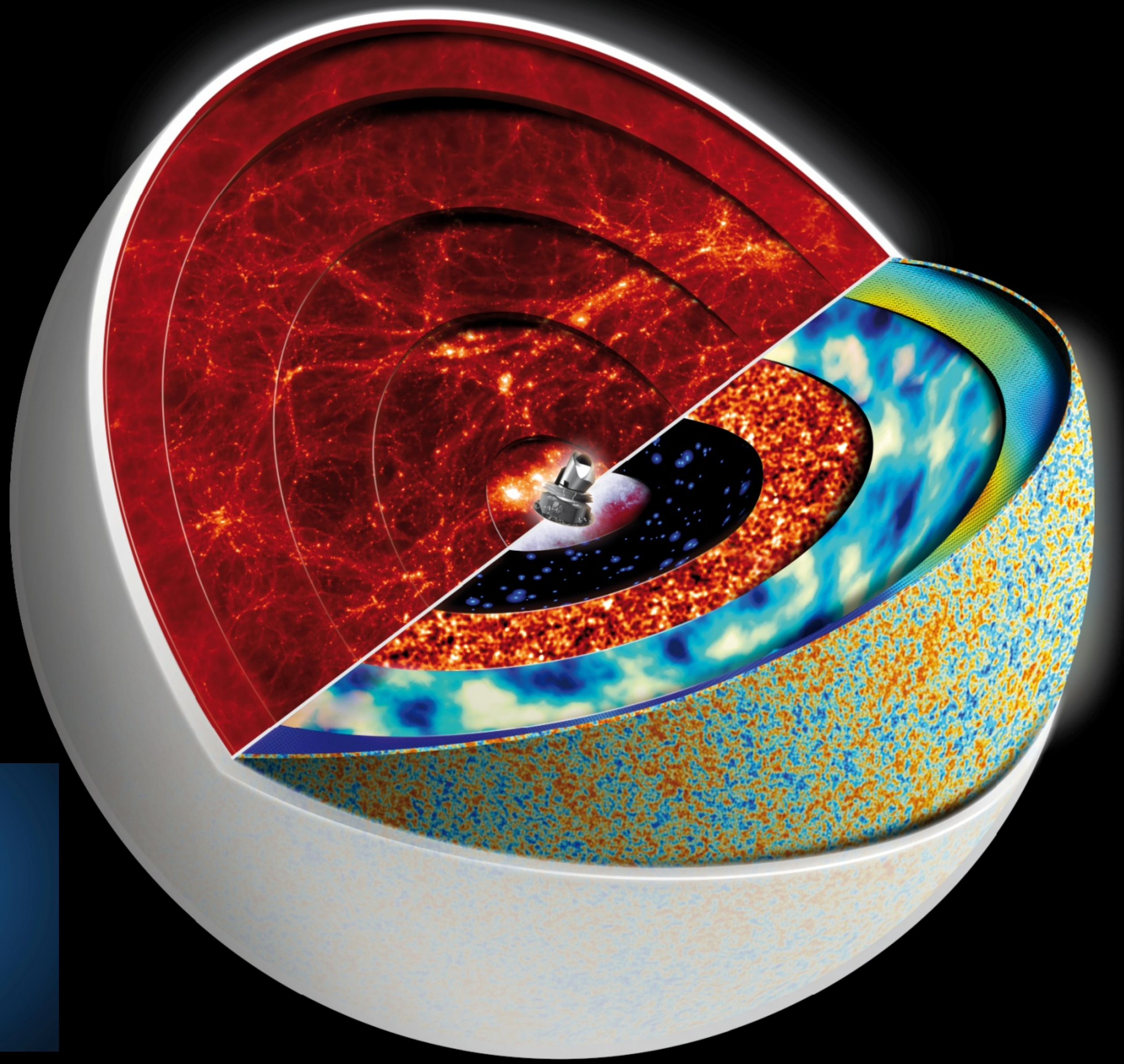
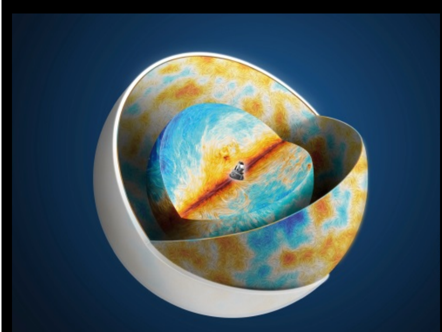
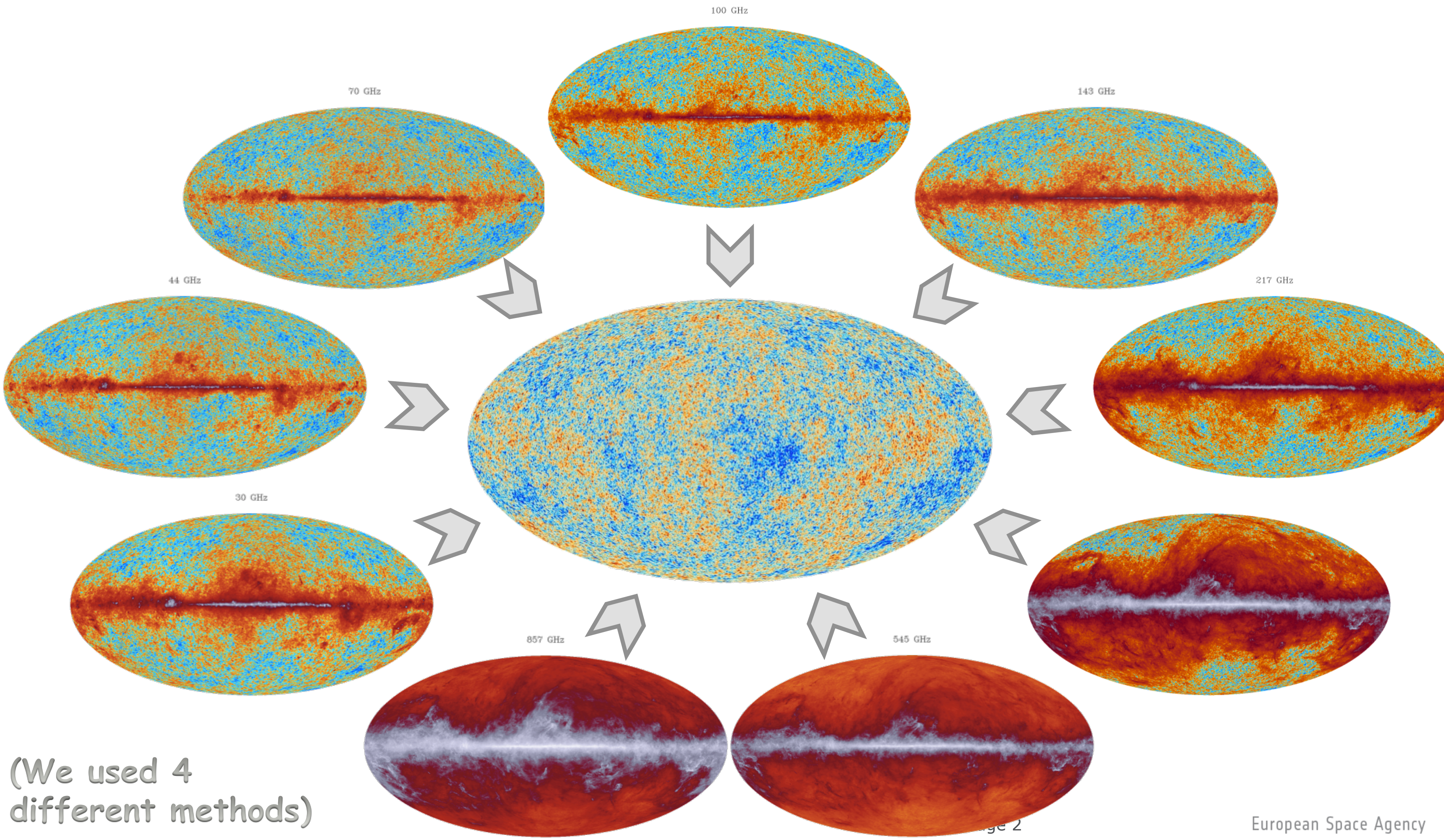
CMB@50: Planck@22, BICEP2, ACT, SPT..





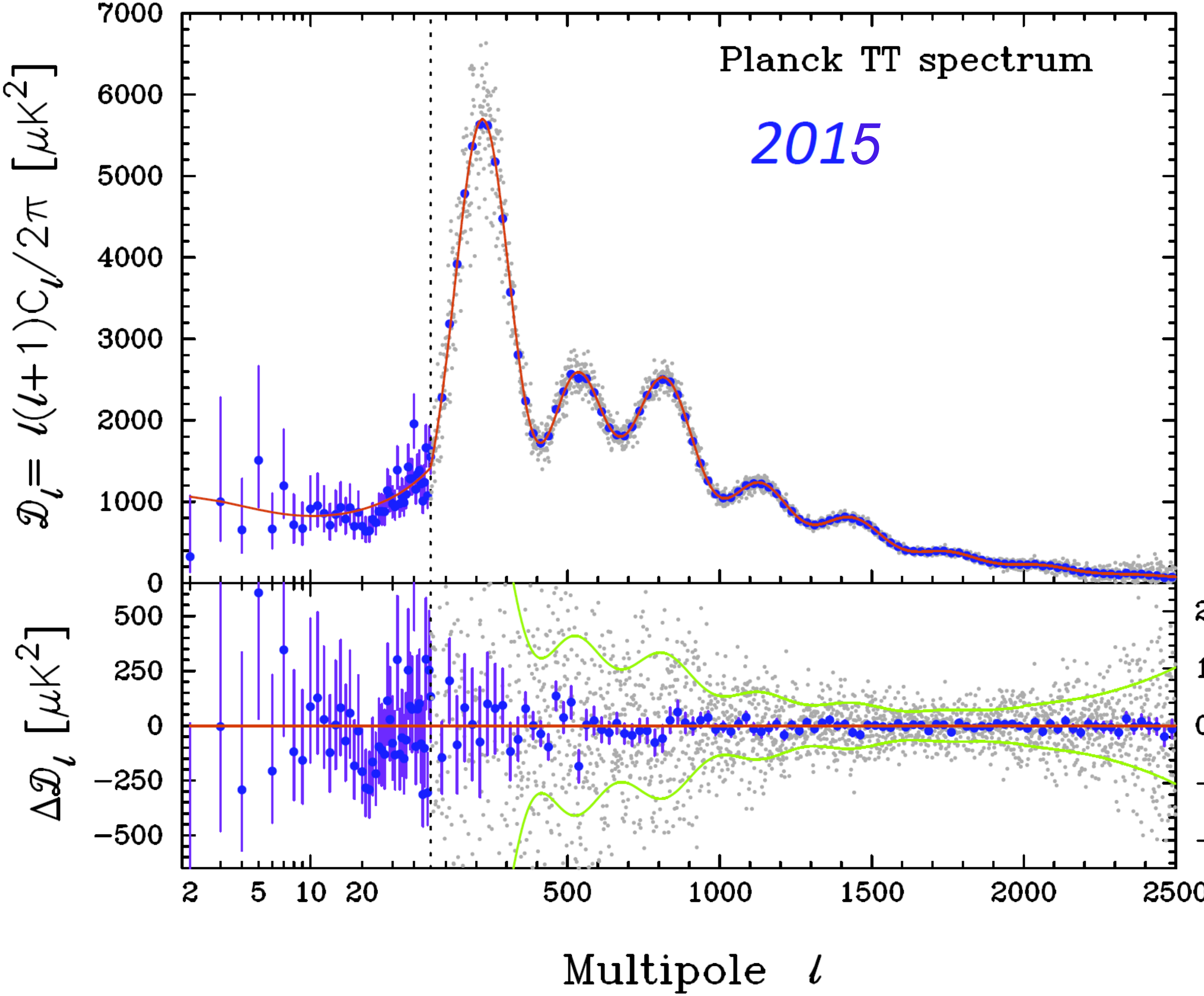
François R. Bouchet, on behalf of the Planck Collaboration for Planck results

Cleaning the background from its 7 veils

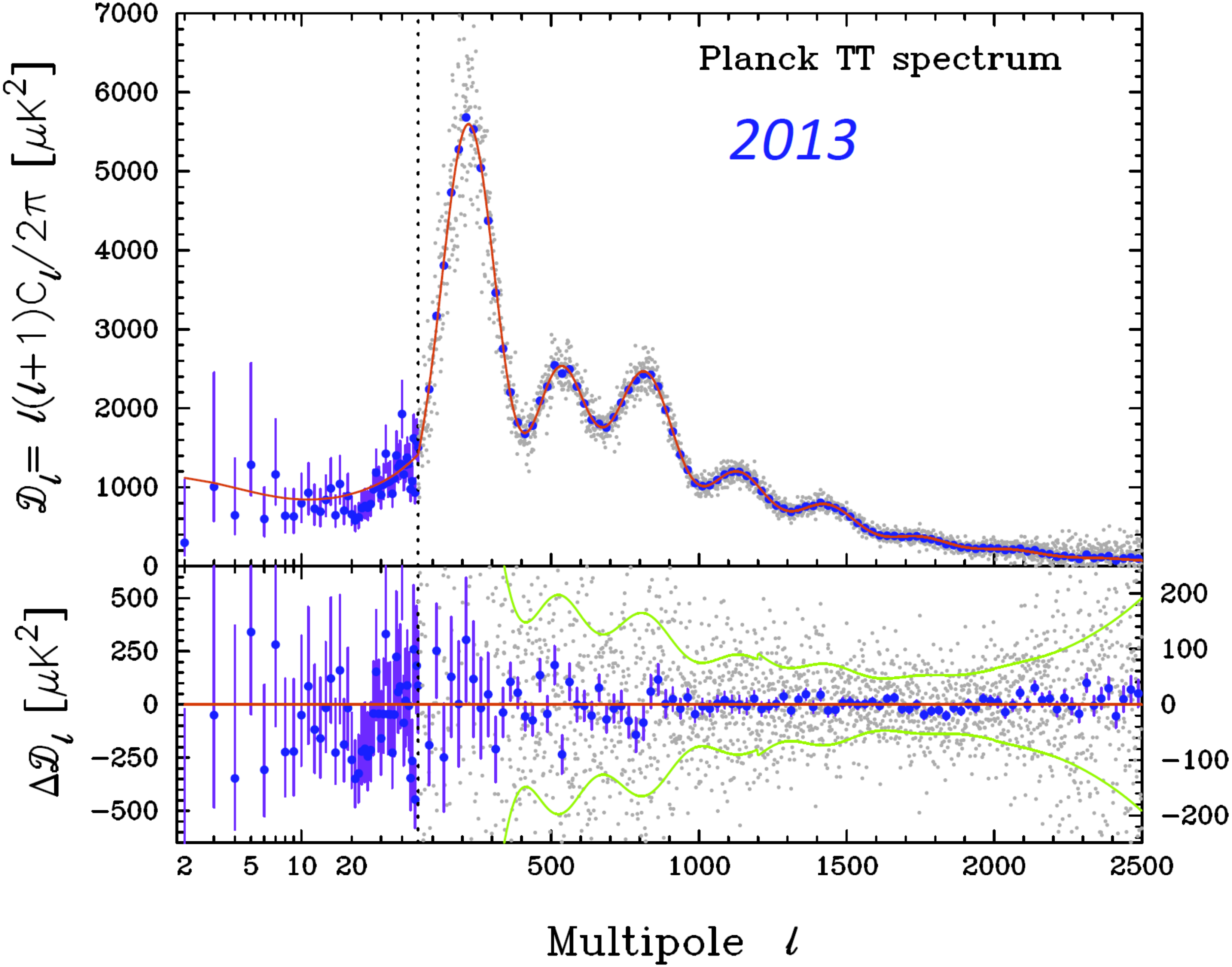


(We used 4 different methods)

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

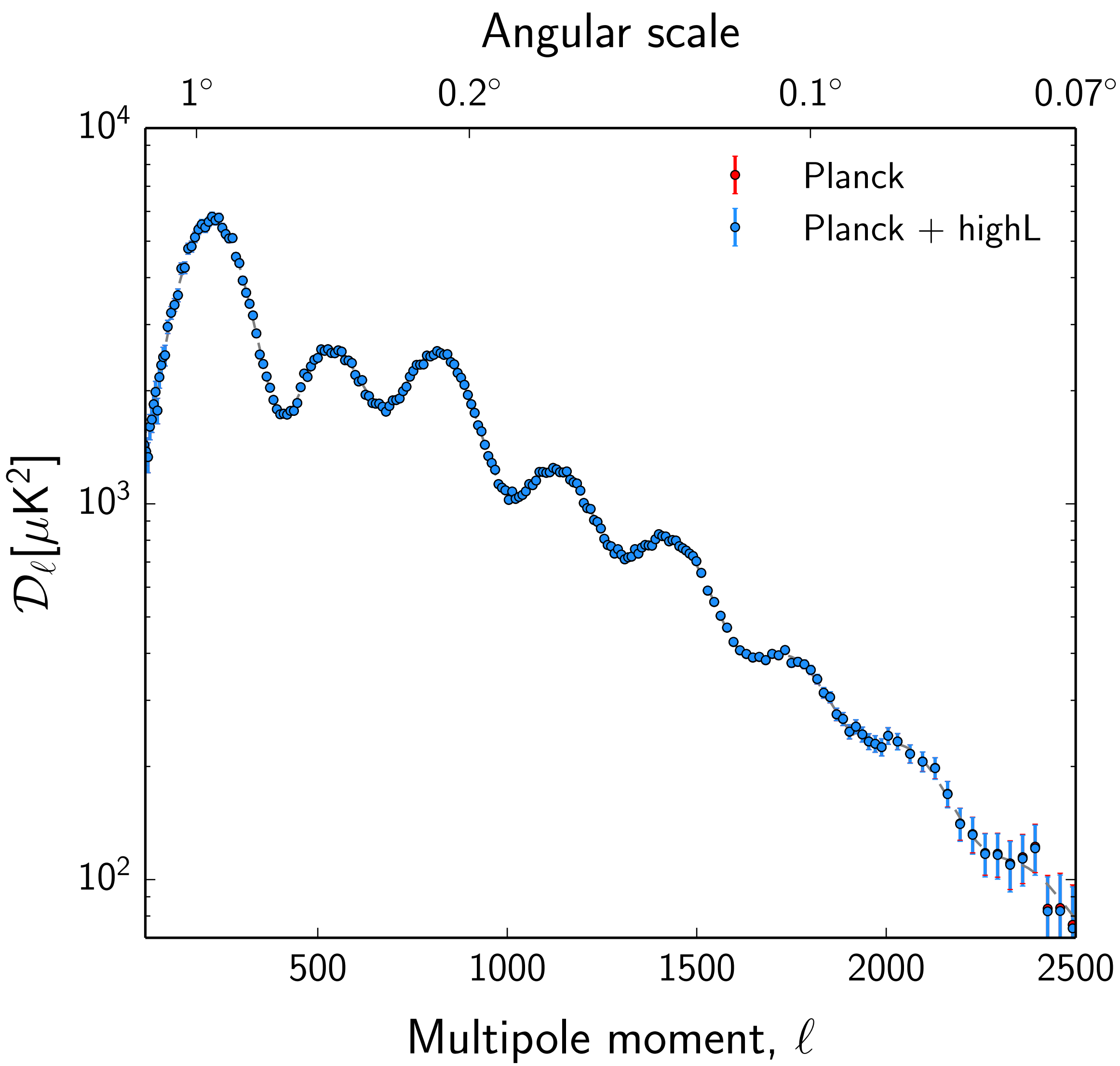


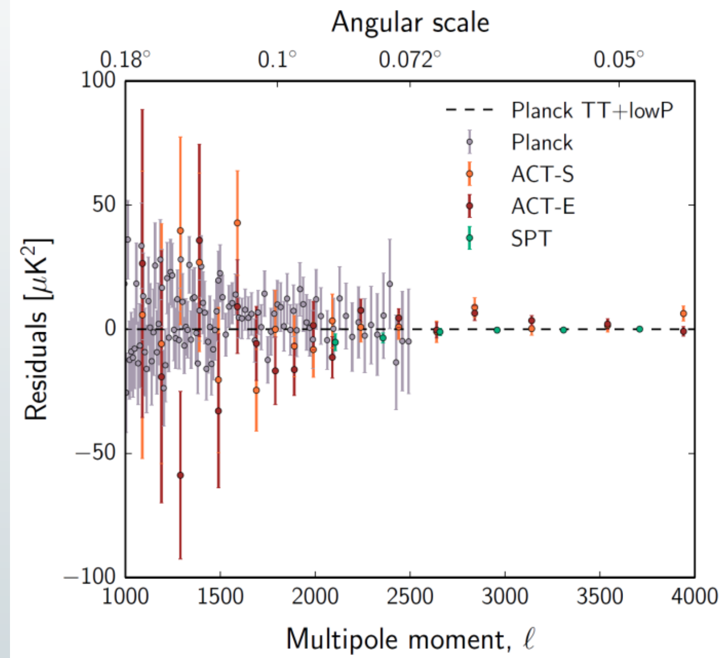
Planck TT spectrum
2015
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi$ [μK^2]
$\Delta\mathcal{D}_\ell$ [μK^2]
Multipole ℓ
7000
6000
5000
4000
3000
2000
1000
0
500
250
0
−250
−500
200
100
0
−100
−200
2
5
10
20
500
1000
1500
2000
2500



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

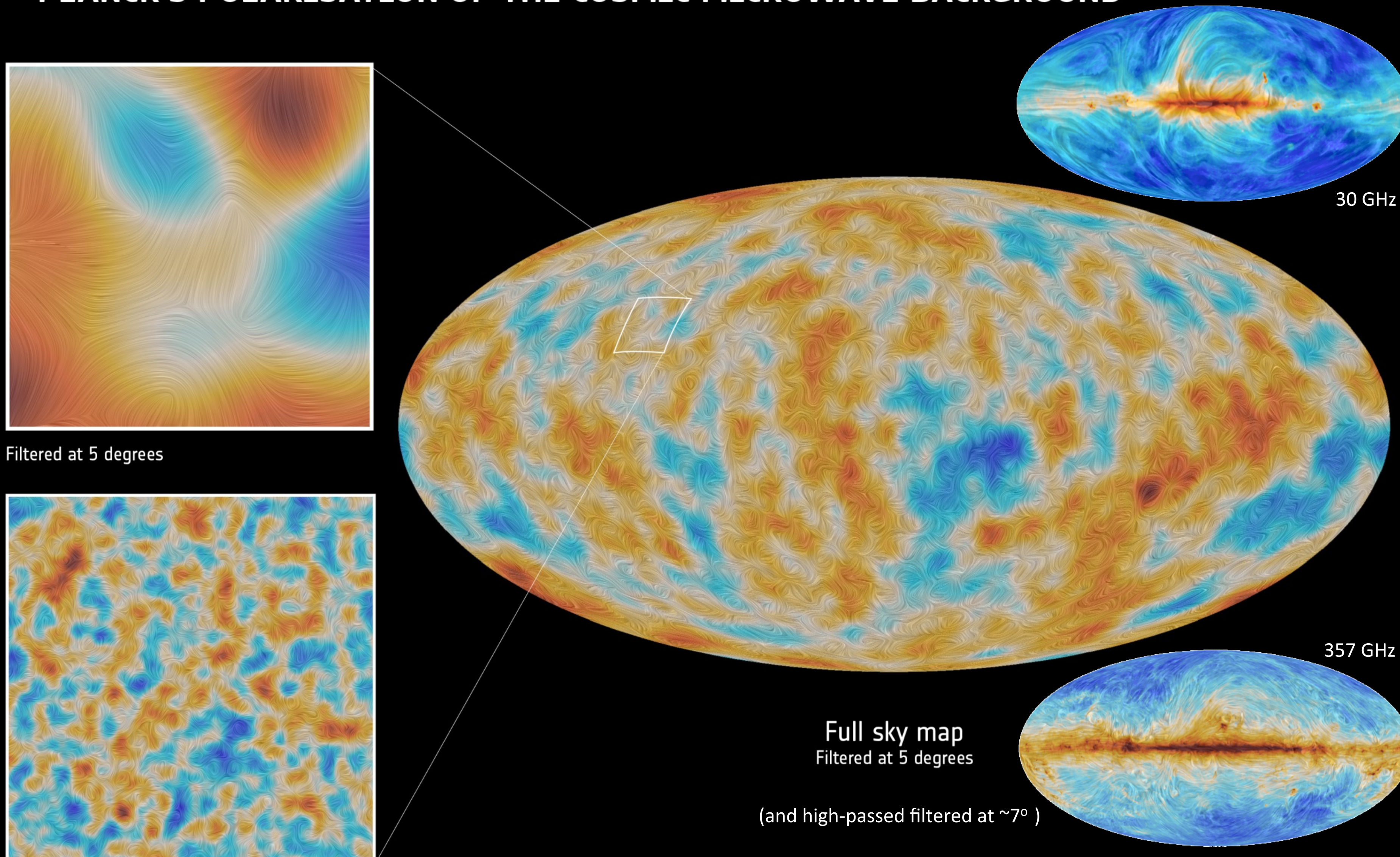
highL data (ACT&SPT) are consistent with Planck





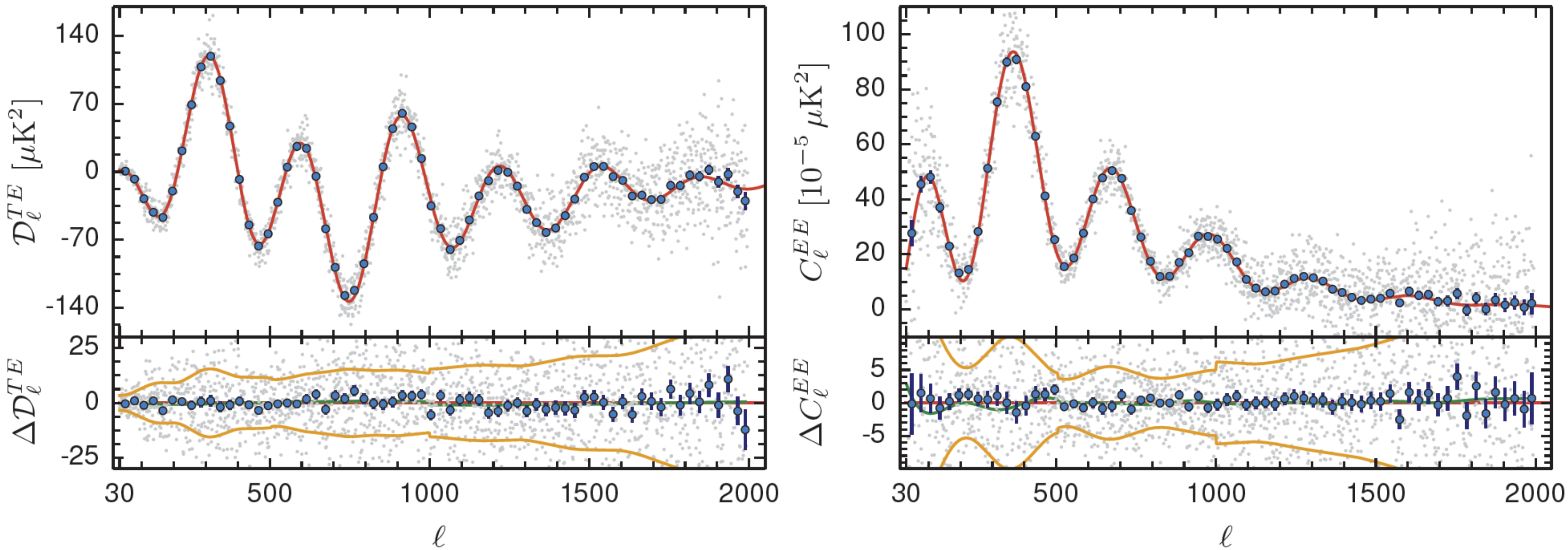
➔ highL data only used for consistency checks, not for cosmology (but for SZ priors)

➔ PLANCK'S POLARISATION OF THE COSMIC MICROWAVE BACKGROUND



Filtered at 20 arcminutes

Planck 2015 - TE & EE spectra



Frequency averaged spectrum reduced ^{2} = 1.04

Frequency averaged spectrum reduced ^{2} = 1.01

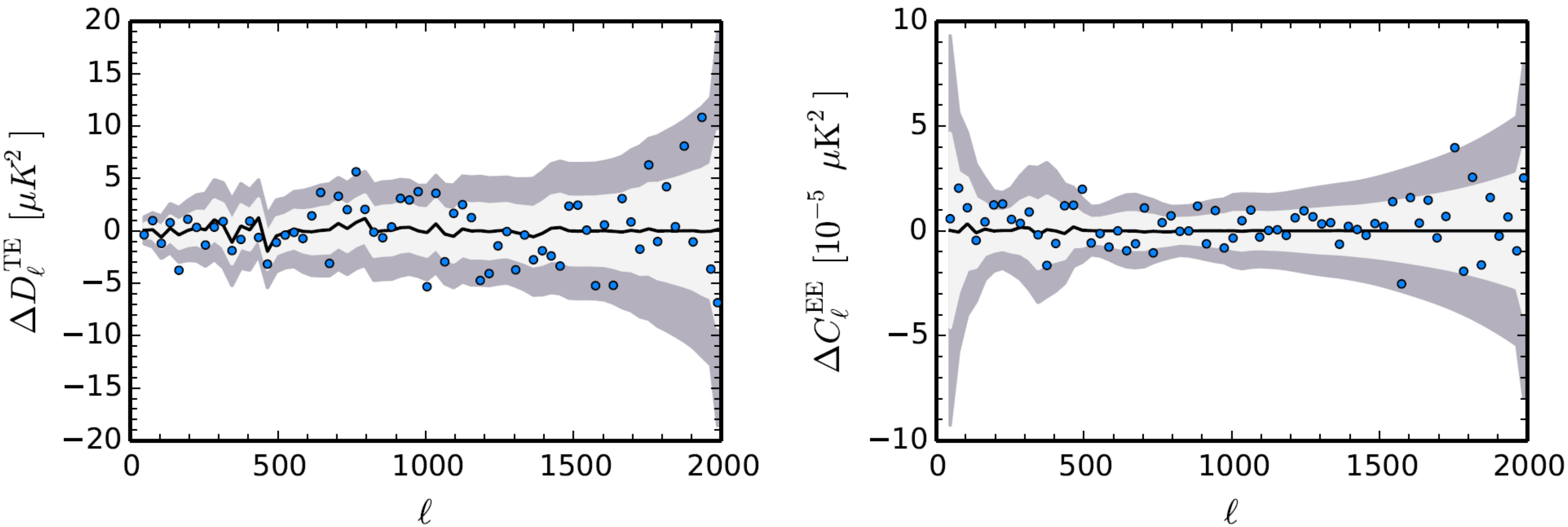
- Red curve is the prediction based on the best fit TT in base LCDM
- 2015 data model is fine in polarisation till ~ O(1) μK^2
  - *There are unmodelled systematics at lower level, i.e., we are limited by the sophistication of the analysis and not yet by the noise of the HFI instrument*
  - *The green line presents an estimate of the (uncorrected) beam mismatch systematic effect, possibly the largest one at high ell.*

Spectra conditionned on TT

Conditional spectra and covariances

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

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



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

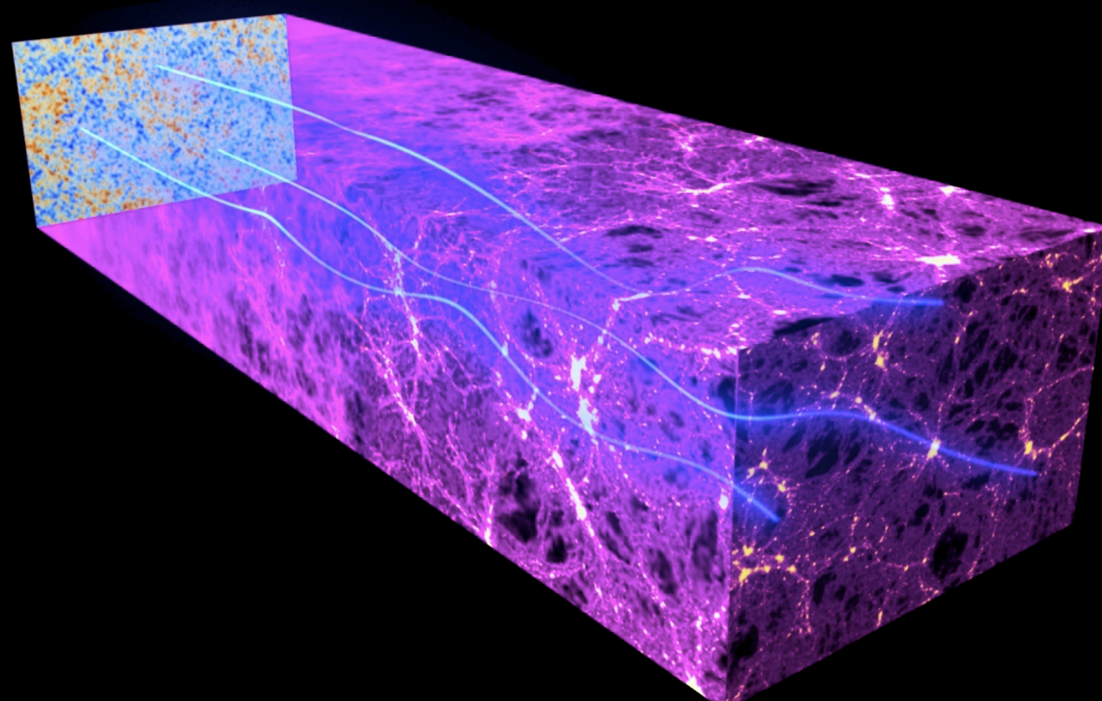
Base ΛCDM model

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

GRAVITATIONAL LENSING DISTORTS IMAGES

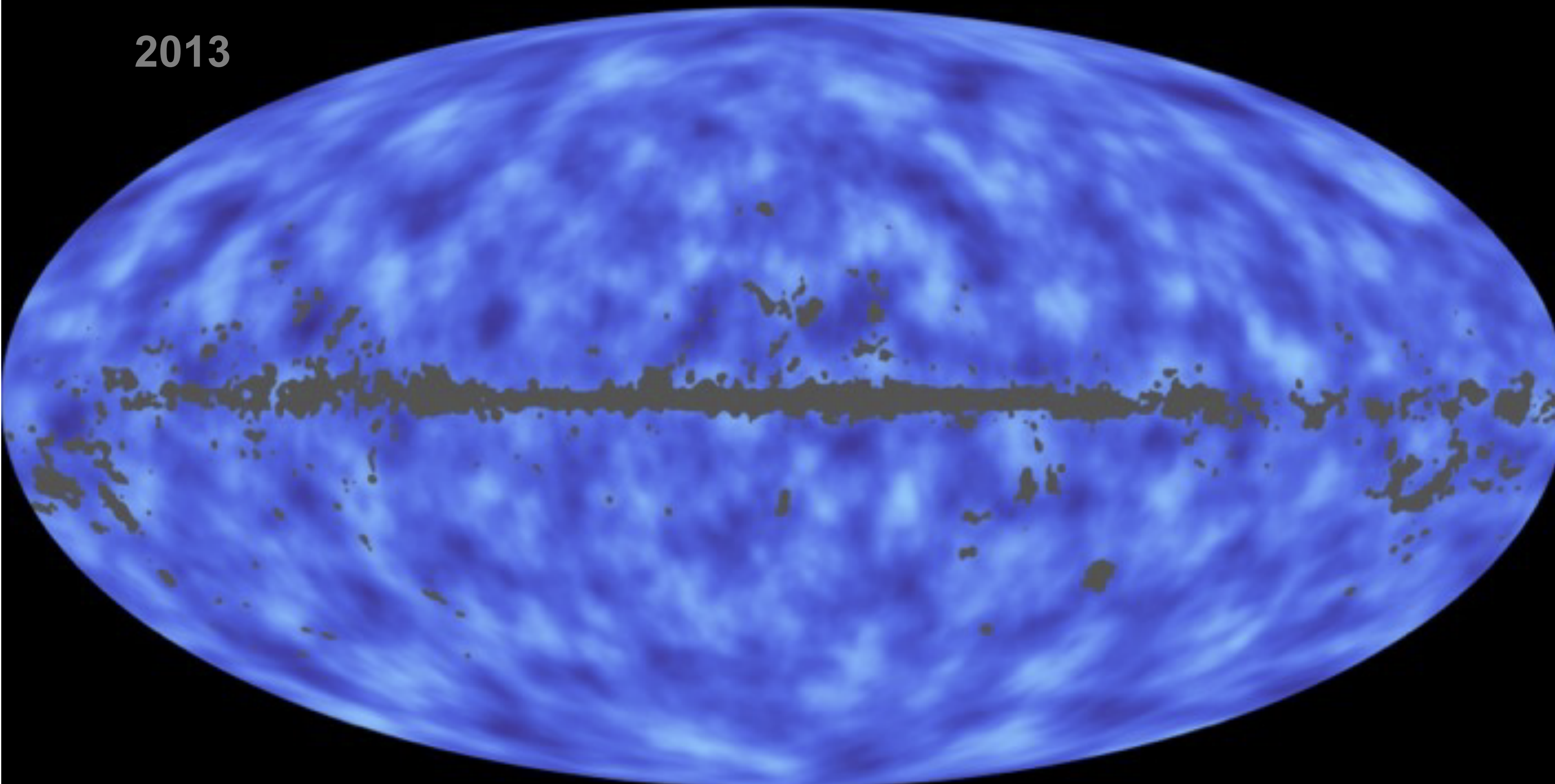
The gravitational effects of intervening matter bend the path of CMB light on its way from the early universe to the Planck telescope. This "gravitational lensing" distorts our image of the CMB (smoothing on the power spectrum, and correlations between scales)



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

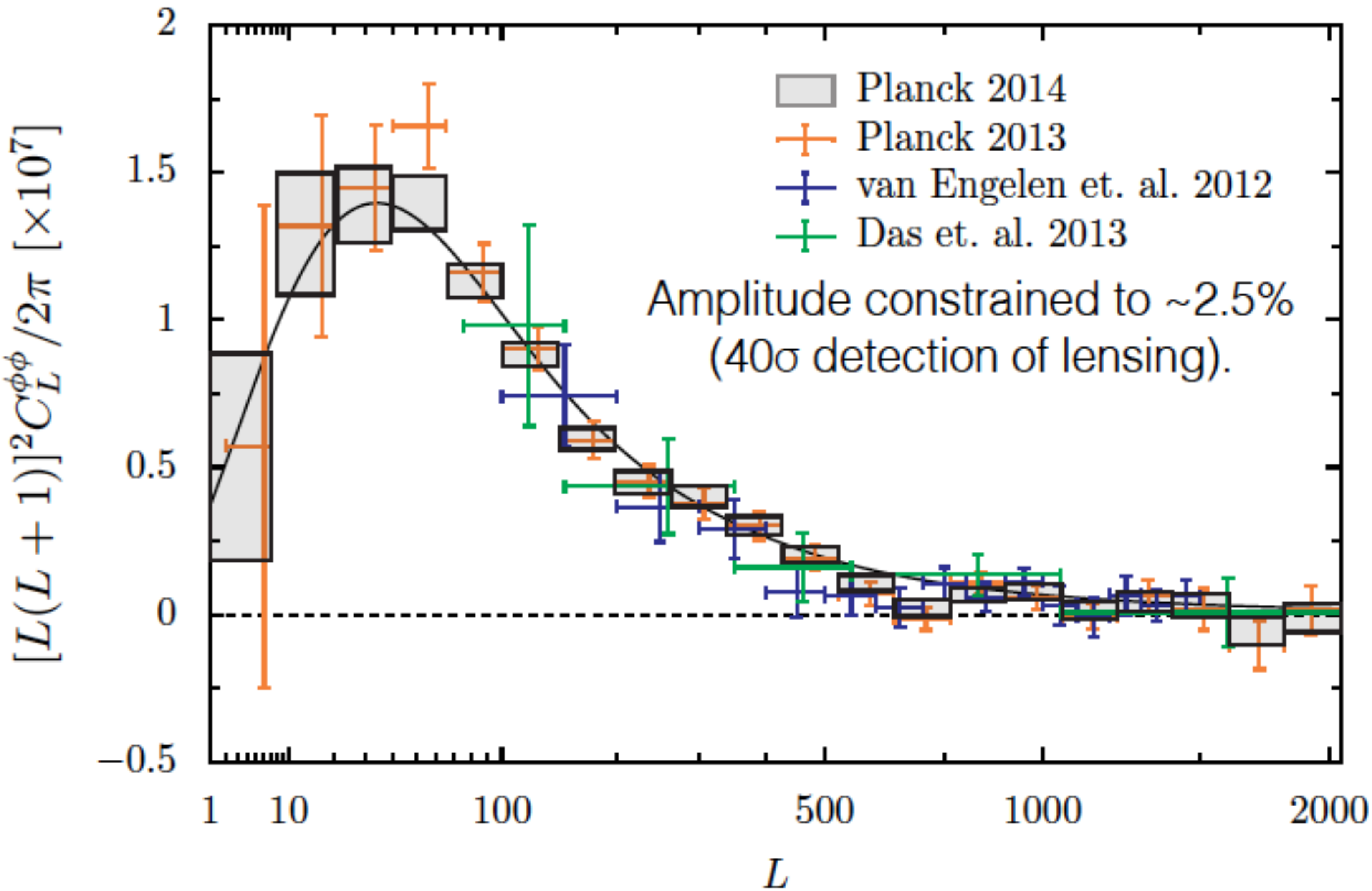
$$\bar{\phi} = \Delta^{-1}\vec{\nabla} \cdot [C^{-1}T\,\vec{\nabla}(C^{-1}T)]$$

Projected mass map



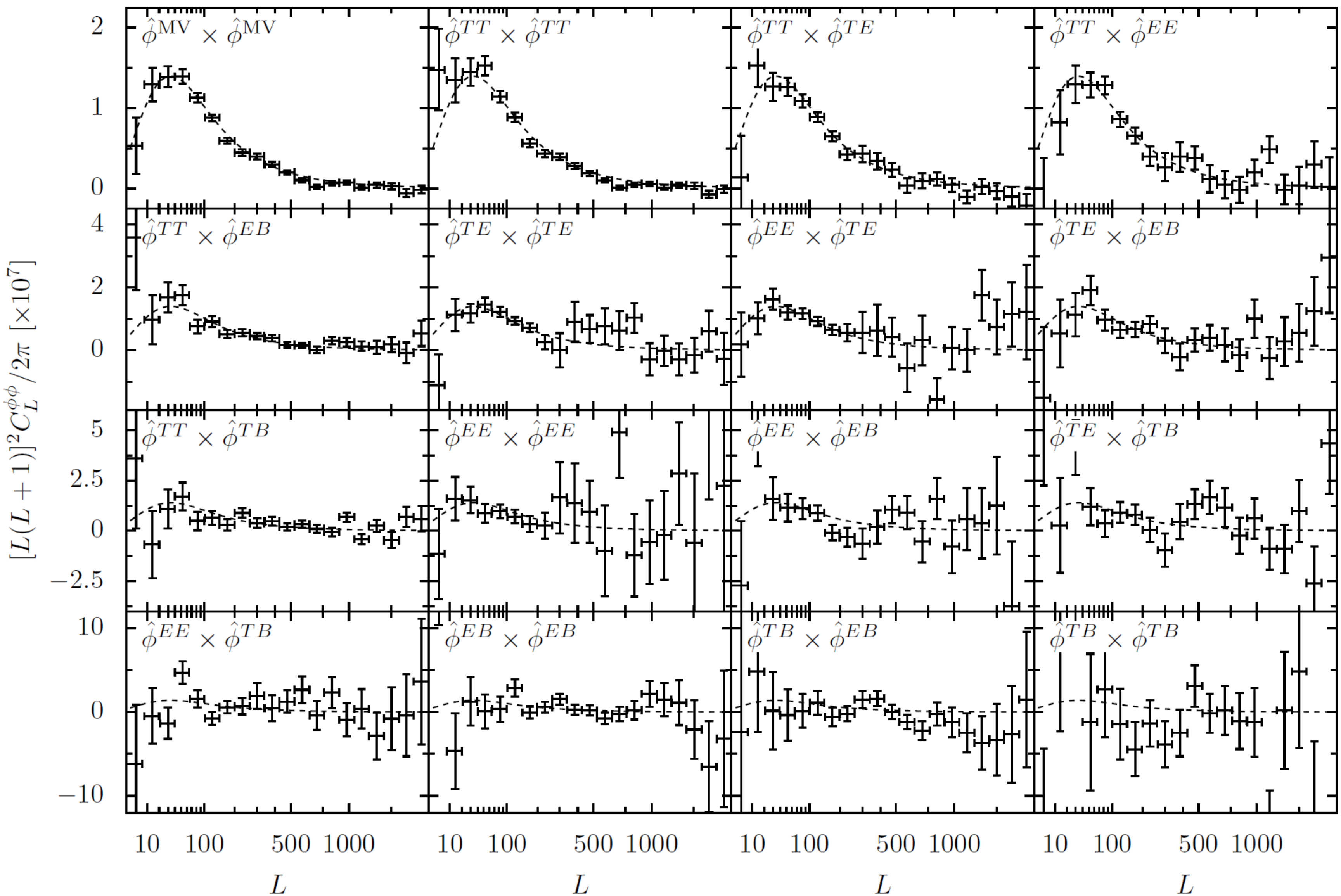
The (grey) masked area is where foregrounds are too strong to allow an accurate reconstruction

Lensing power spectrum

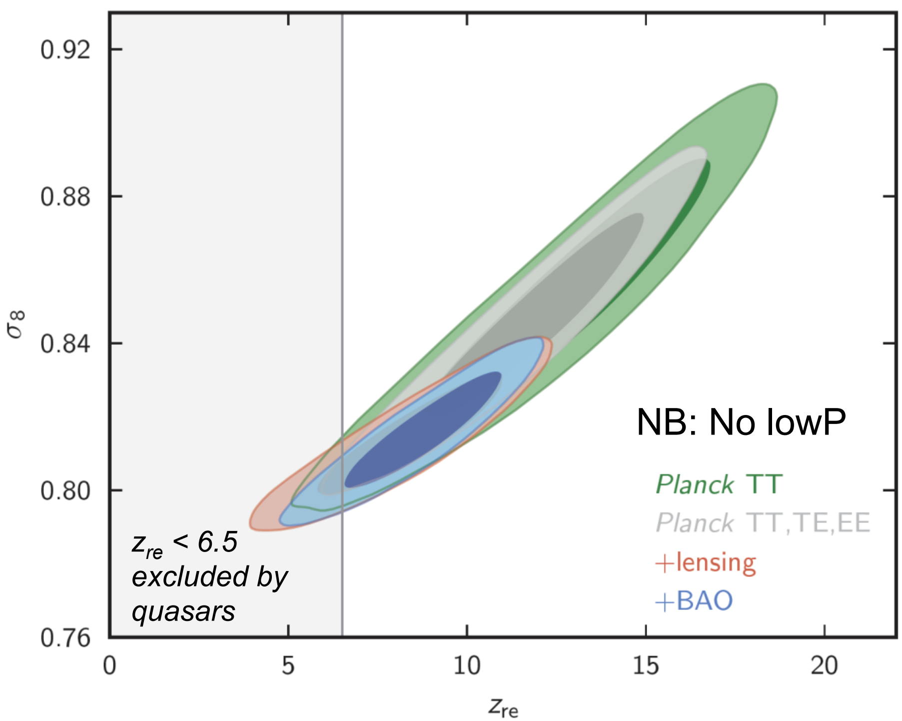


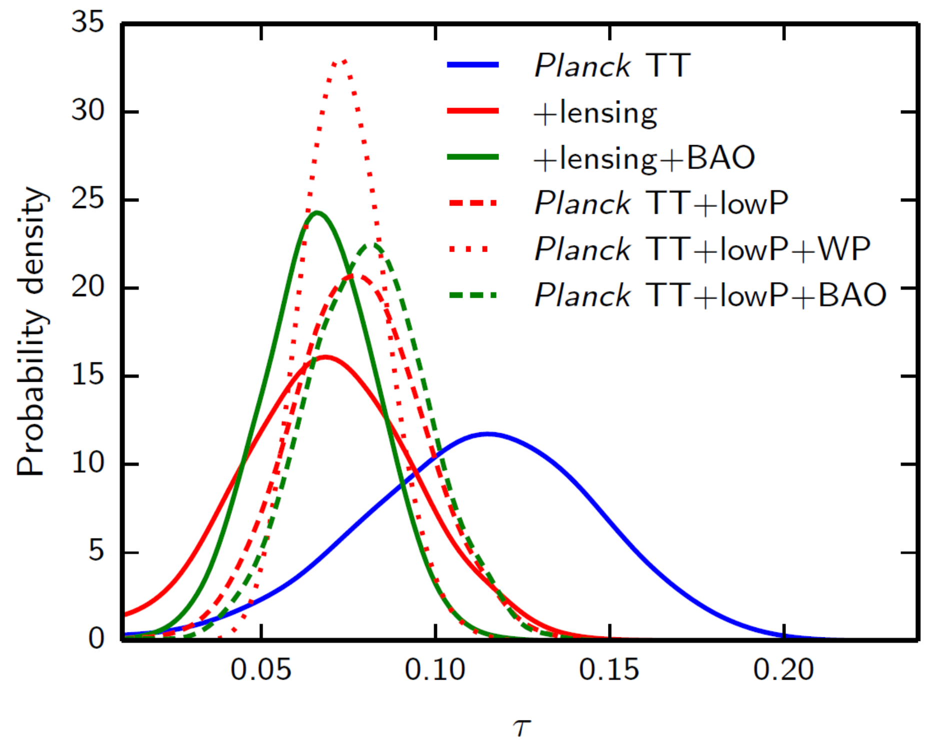
Planck for the first time measured the lensing power spectrum with higher accuracy than it is predicted by the base CDM model that fits the temperature data

Individual lensing cross-spectra



Optical depth constraints





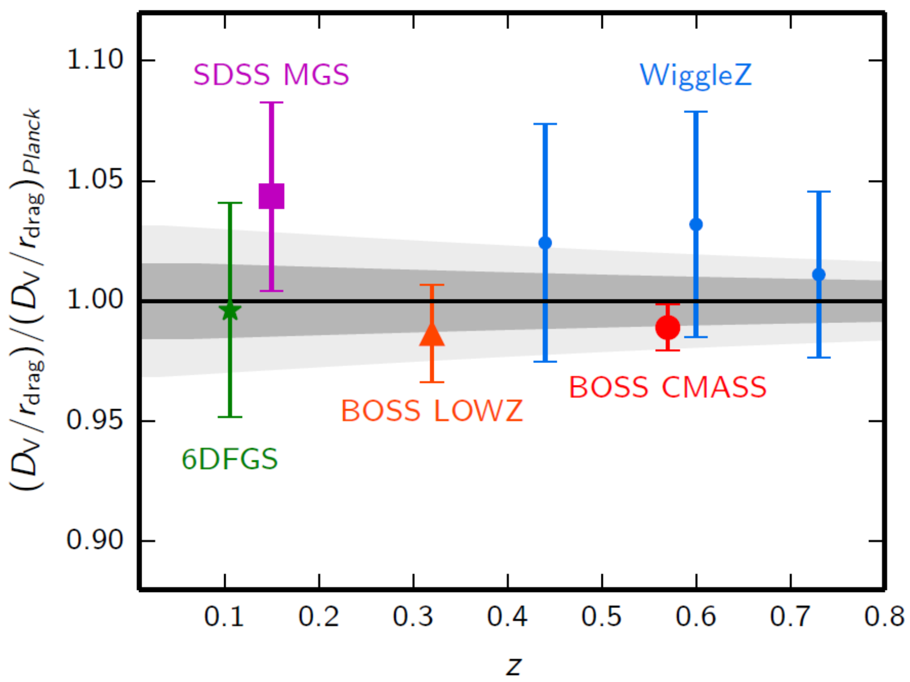
➔Consistency of lensing versus LowP constraints on τ

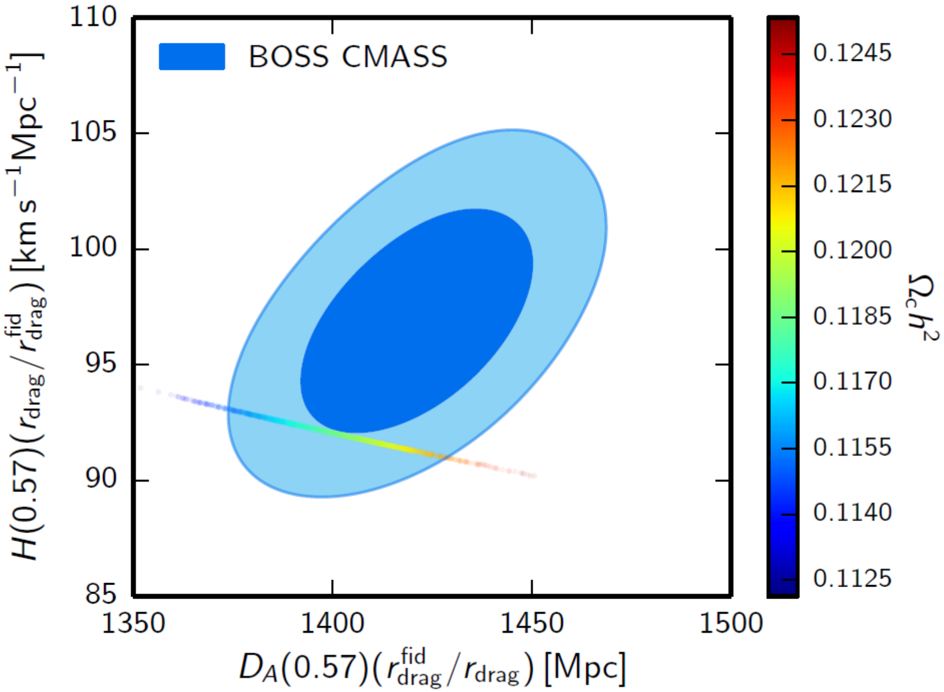
(τ_{lowP} =0.064±0.023, z_{re} =8.5 +2.5-2.0)

➔Next is to bring HFI data to bear on that – real soon now ☺

BAO

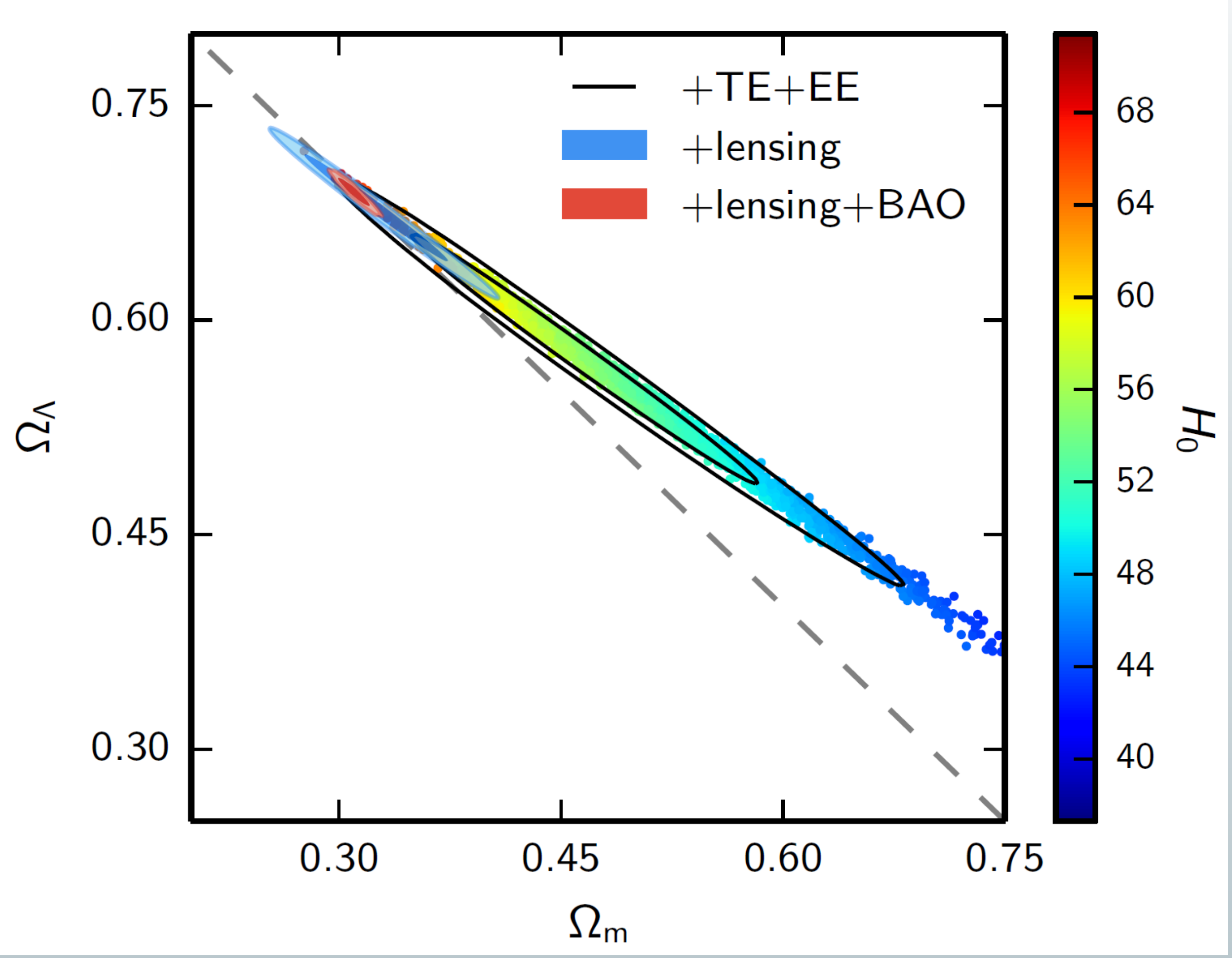
Grey band is Planck TT+LowP 1(2)-sigma range



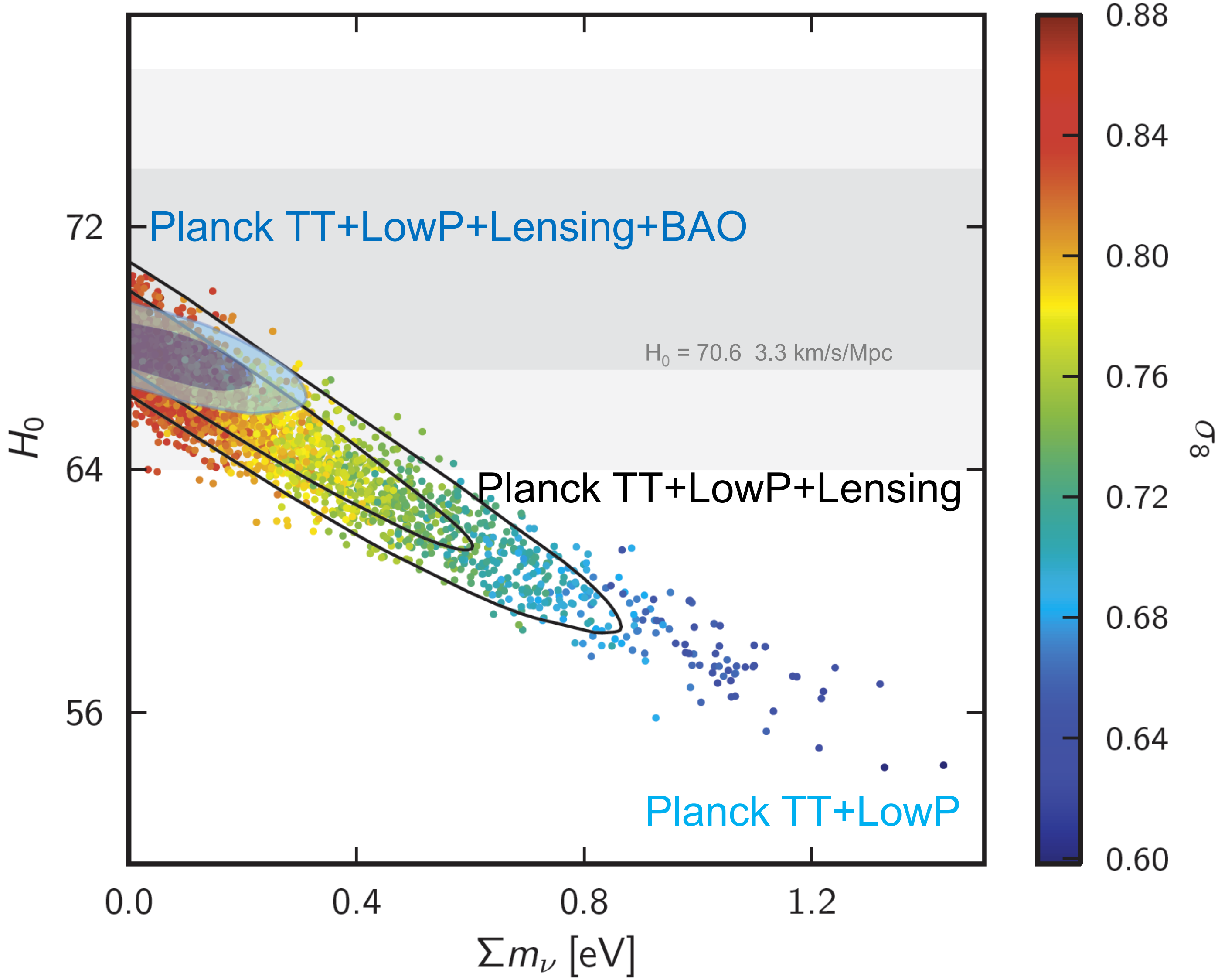


Spatial curvature constraint

Ωk=0.000 ±0.005 (95% CL) !



Neutrinos masses $\sum m\nu < 0.23$ eV (95%)

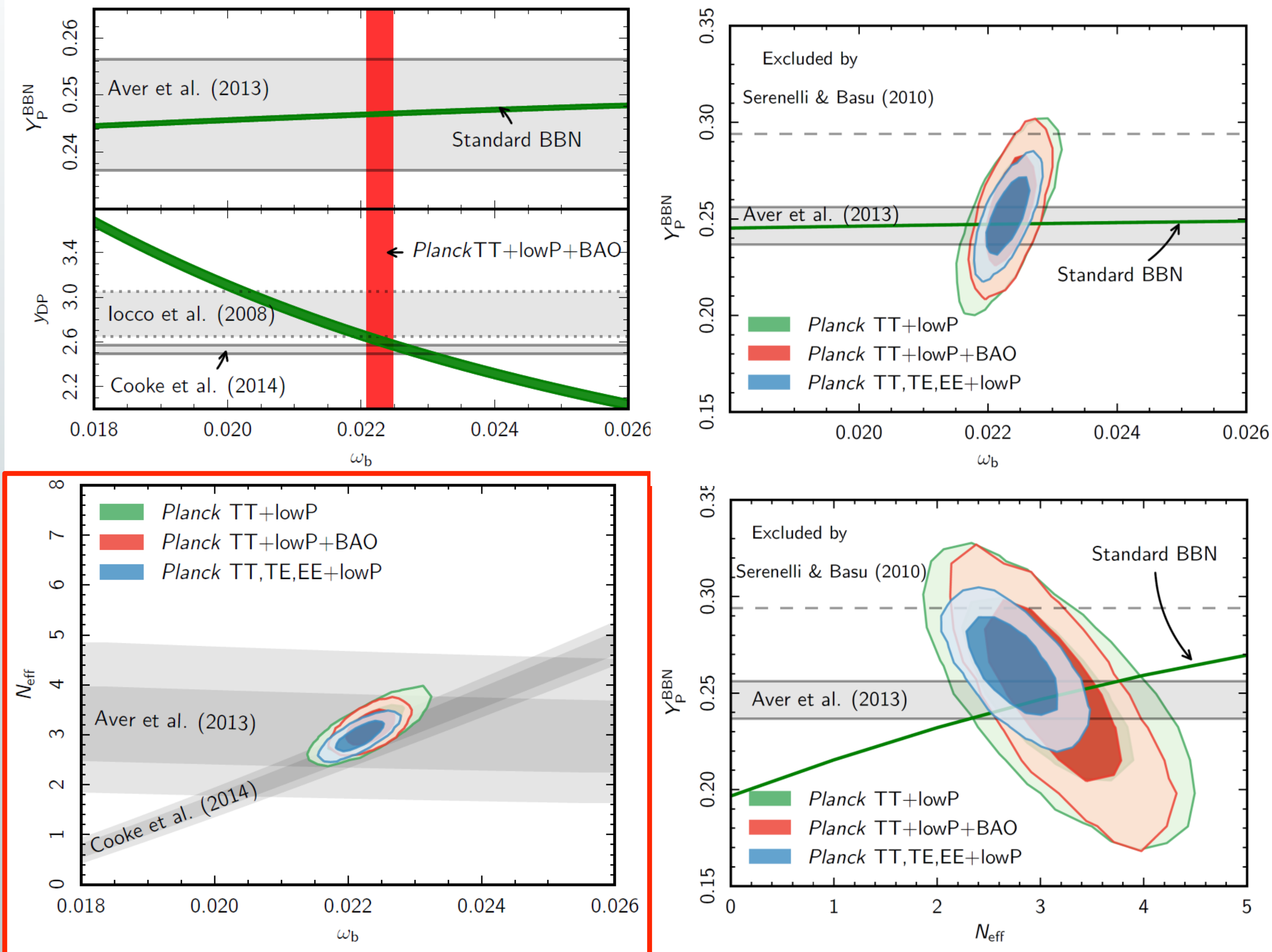


0.23eV is from TT+lowP +lensing +ext

➔ $\Omega\nu h^2 < 0.0025$

(slight tightening with TE & EE)

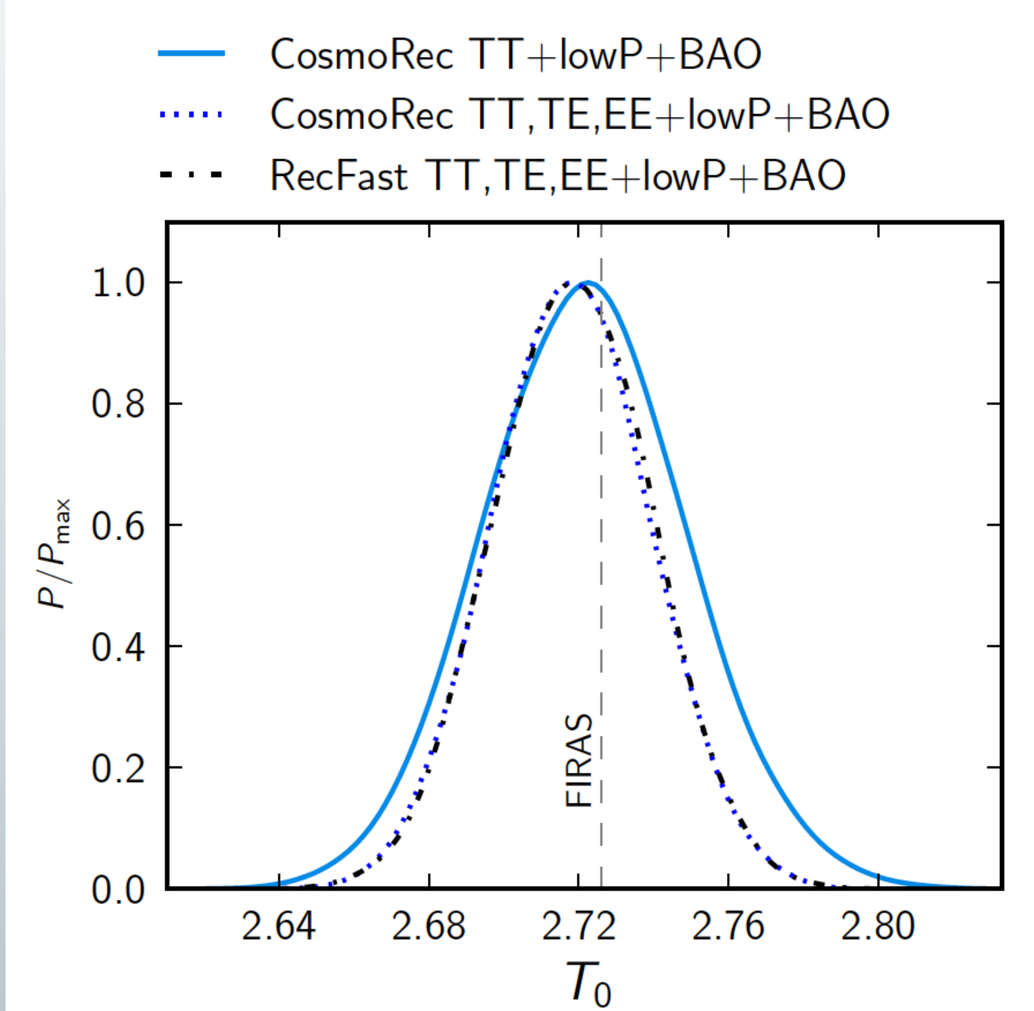
BBN – Neff, Yp



Aver et al. (2013)
Standard BBN
Planck TT+lowP+BAO
Iocco et al. (2008)
Cooke et al. (2014)
0.018 0.020 0.022 0.024 0.026
ω_b
Y_P^{BBN}
y_{DP}
Excluded by
Serenelli & Basu (2010)
Aver et al. (2013)
Standard BBN
Planck TT+lowP
Planck TT+lowP+BAO
Planck TT,TE,EE+lowP
Planck TT+lowP
Planck TT+lowP+BAO
Planck TT,TE,EE+lowP
Aver et al. (2013)
Cooke et al. (2014)
N_{eff}
Excluded by
Serenelli & Basu (2010)
Standard BBN
Aver et al. (2013)
Planck TT+lowP
Planck TT+lowP+BAO
Planck TT,TE,EE+lowP

Measuring T_0 at LSS

- To affects recombination physics…



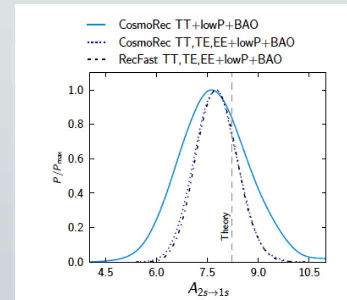
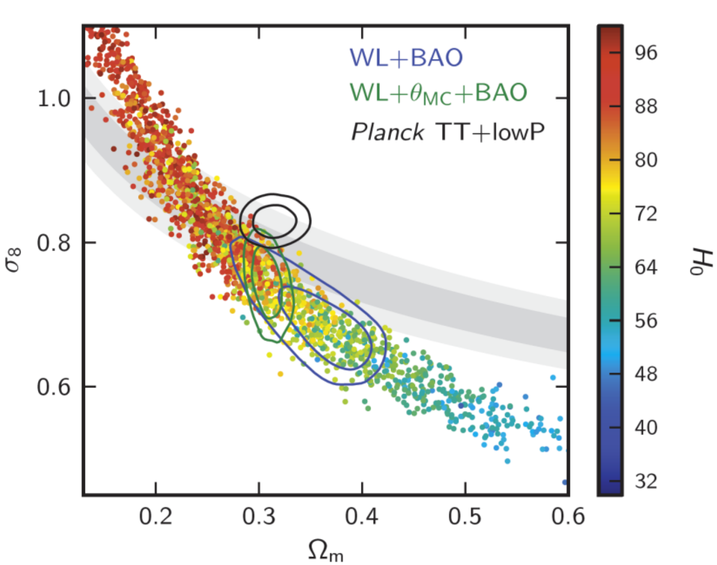


Fig. 42. Marginalized posterior for $A_{2s\to1s}$, obtained using CosmoRec. We find good agreement with the theoretical value of $A_{2s\to1s} = 8.2206\,{\rm s}^{-1}$. For comparison, we also show the result for *Planck* TT,TE,EE+lowP+BAO obtained with `recfast`, emphasizing the consistency of different treatments.

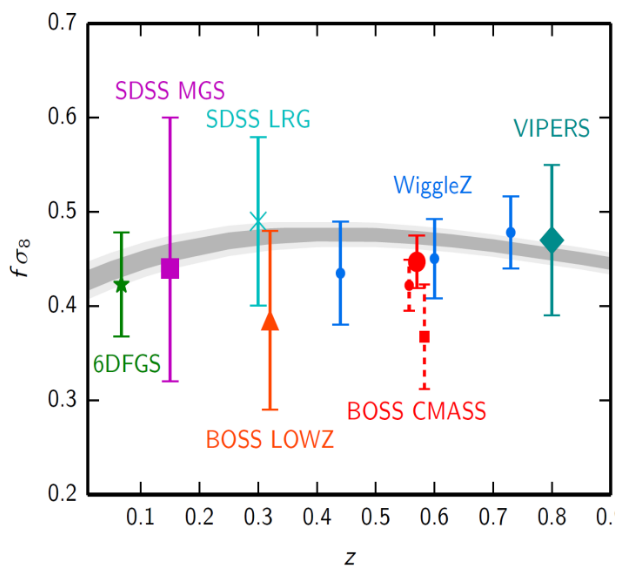
which depends crucially on 2 photons decay rate…

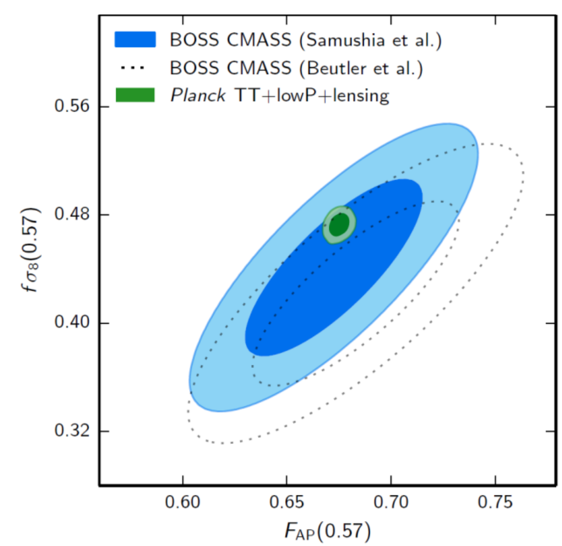
Some tensions

WL from CFHTLens

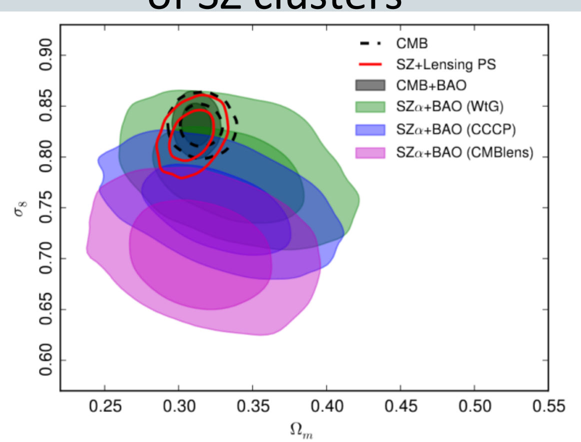


Growth rate of fluctuations from redshift space distortions





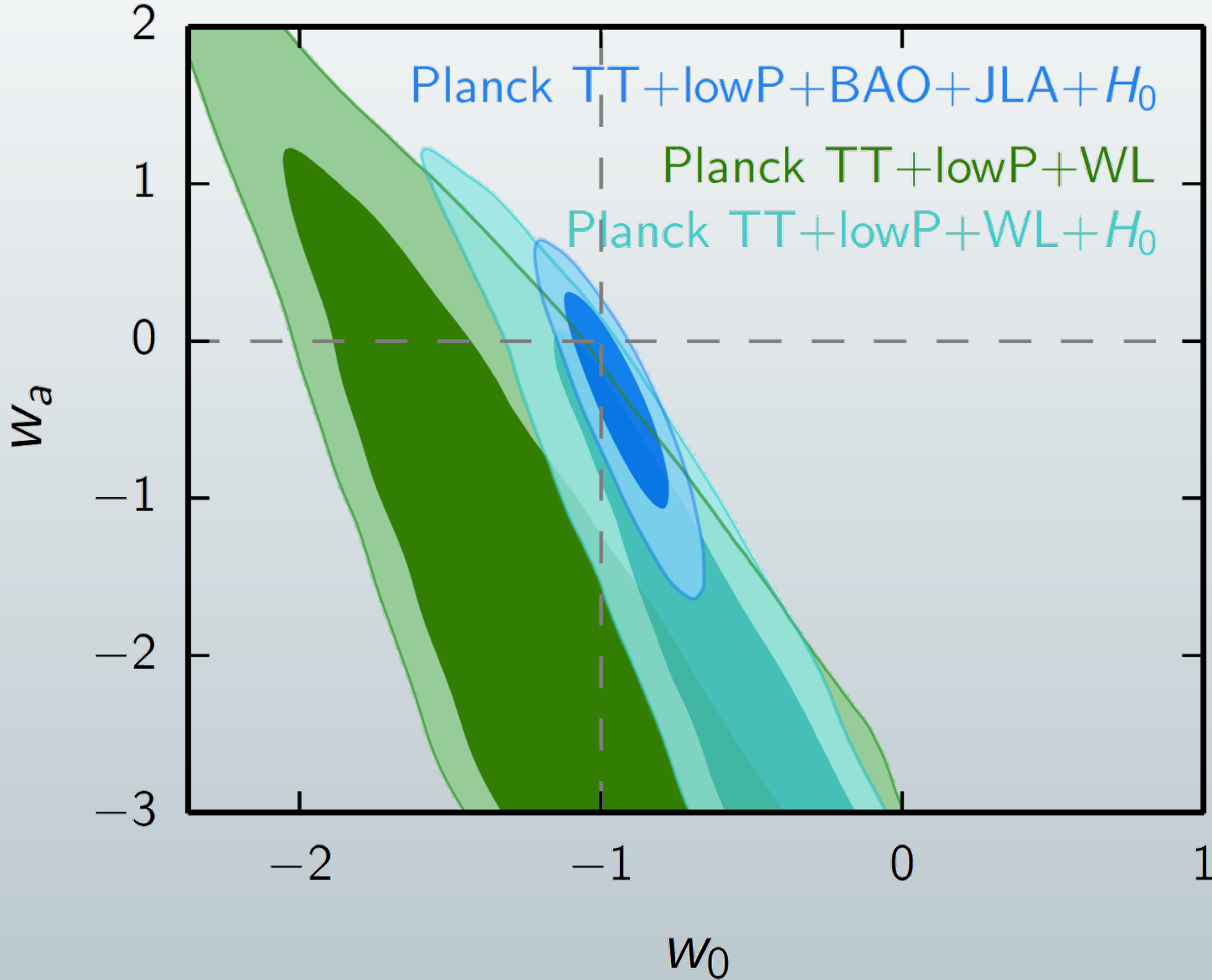
Number counts of SZ clusters



i.e., some tensions with astrophysical measurements of the amplitude of matter fluctuations

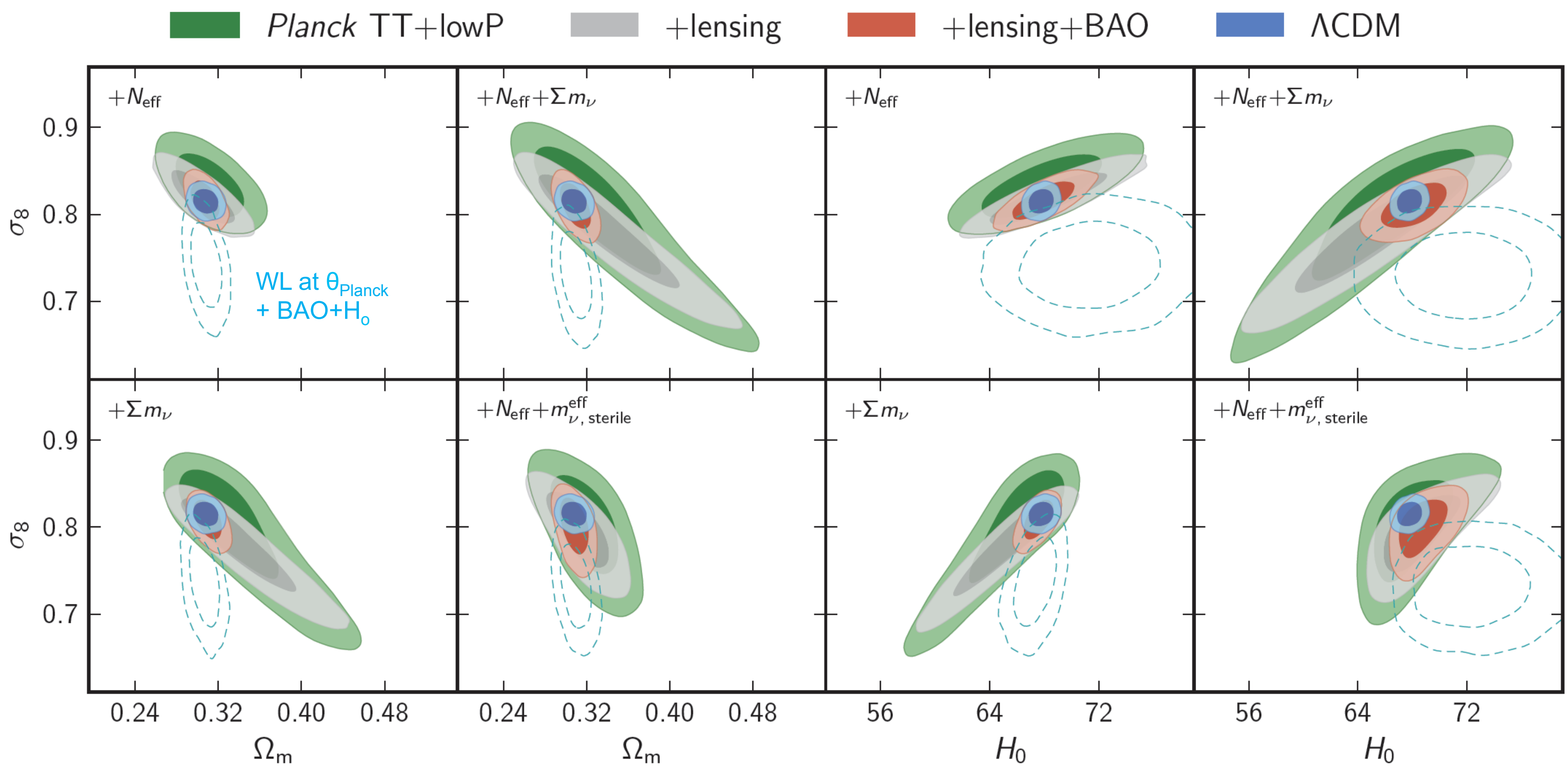
What these tensions can do…

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

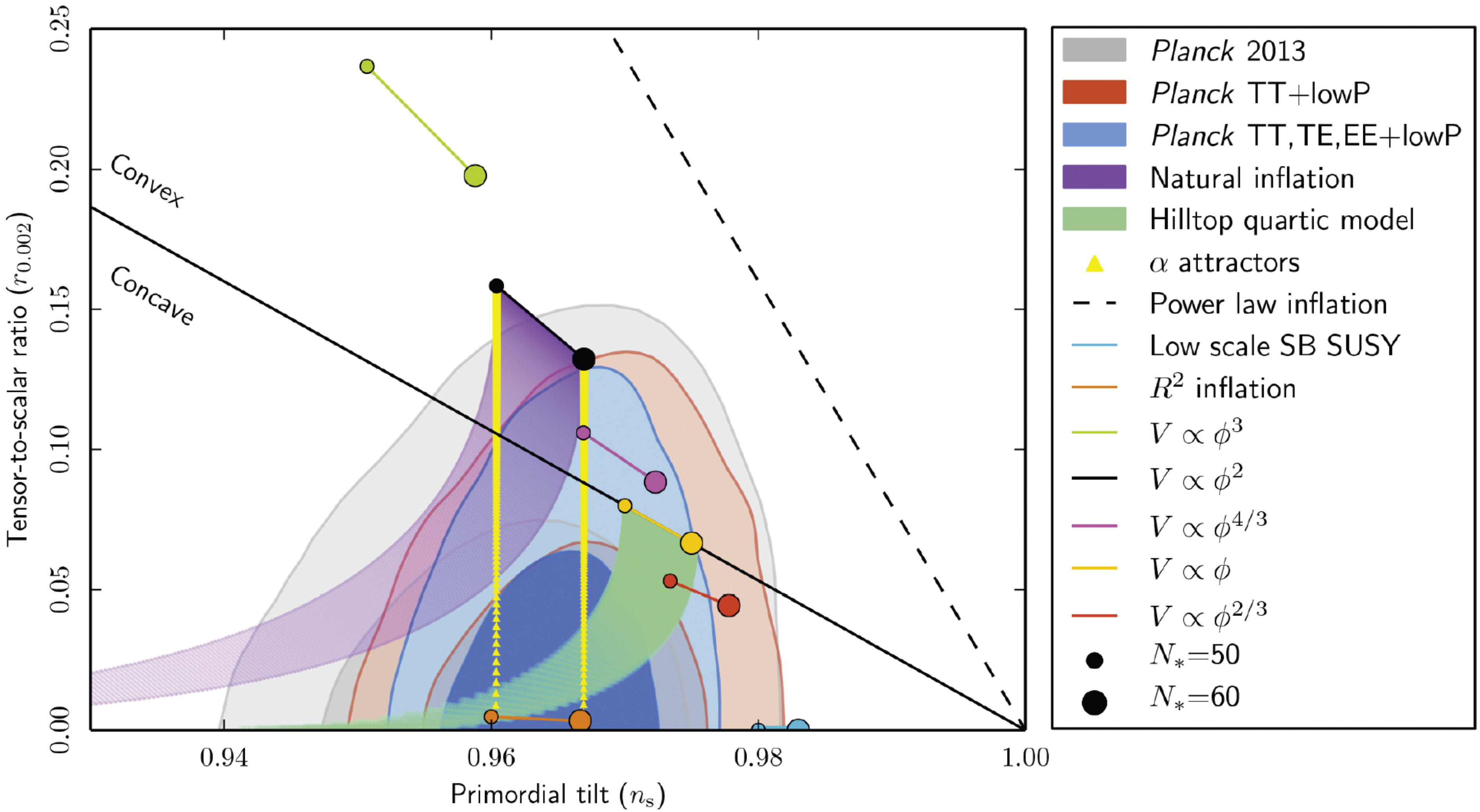


Ref.

Allowing neutrinos extensions

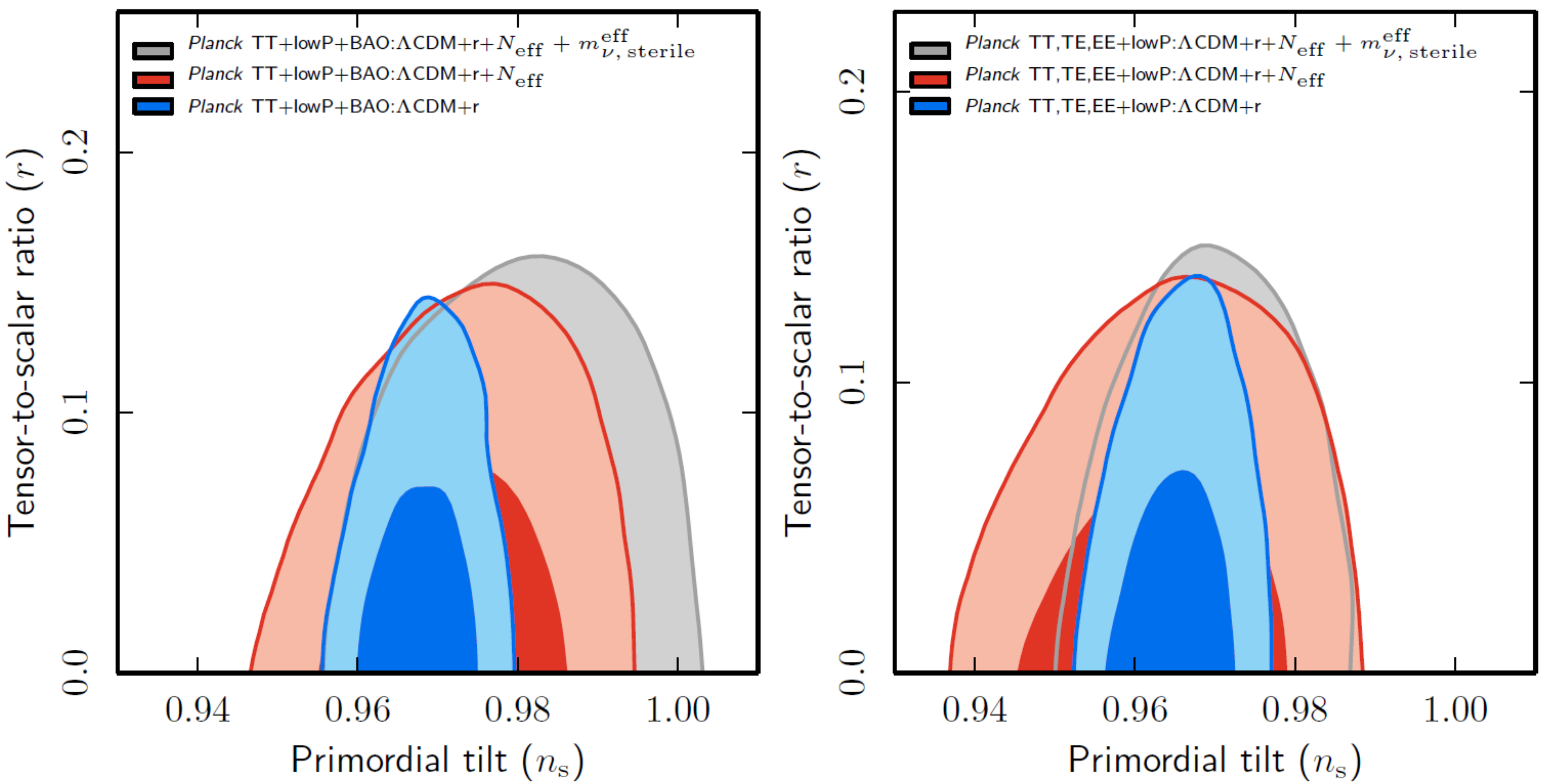


Planck 2015: n_s vs r

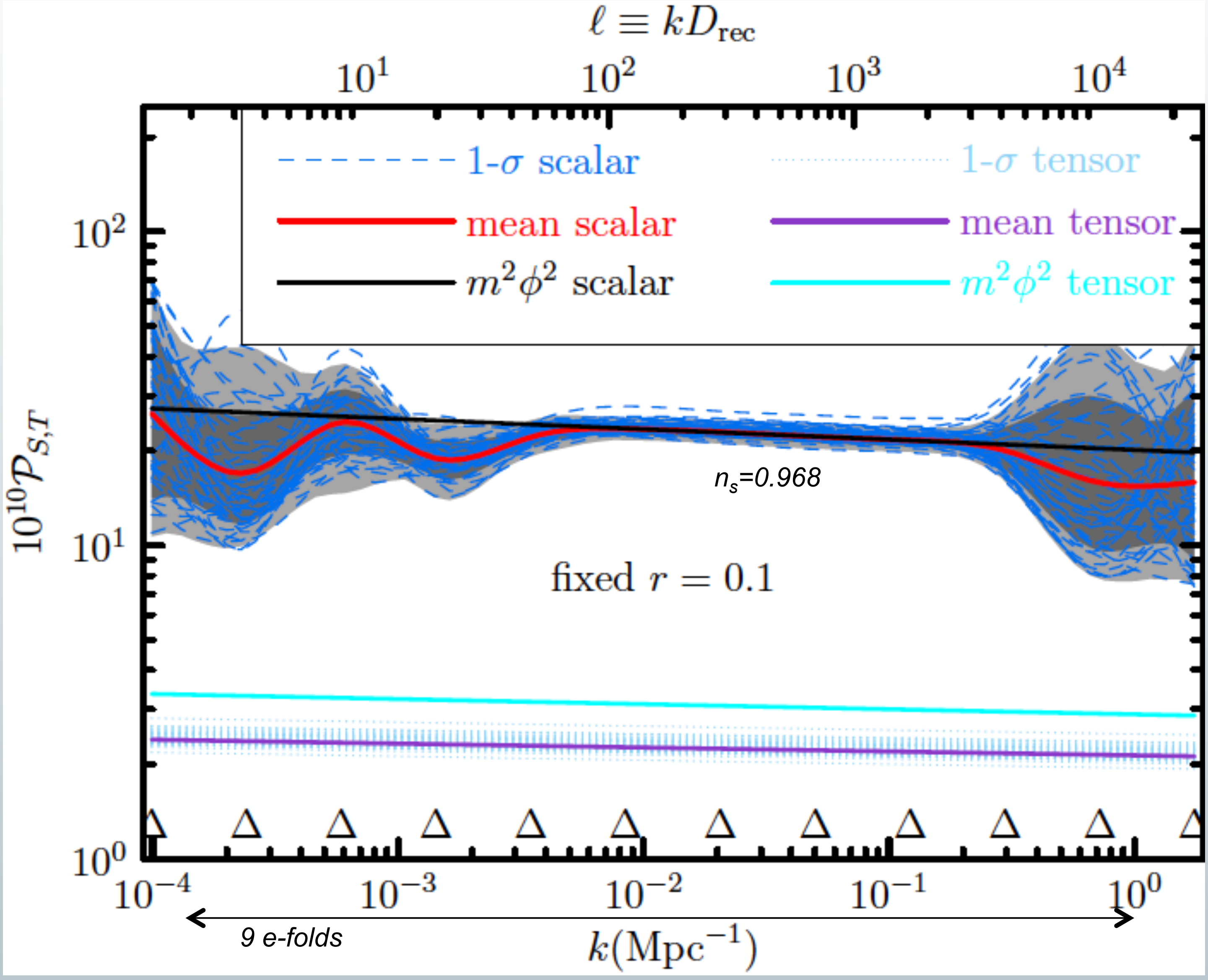


Tightening ns, and (indirect) r constraint wrt the 2013 release
($r_{0.002}$ < 0.10 @ 95% CL instead of 0.11)

With a little help from my friend (polarisation)



Power spectra reconstruction

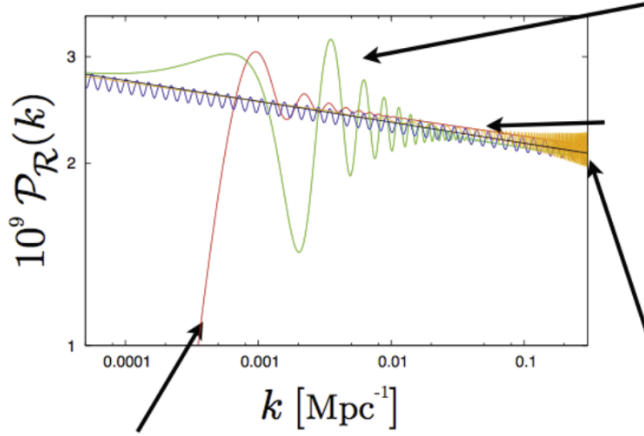


2015
TT+lowP
+BAO+JLA
+Hlow

12-knots power spectra

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

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

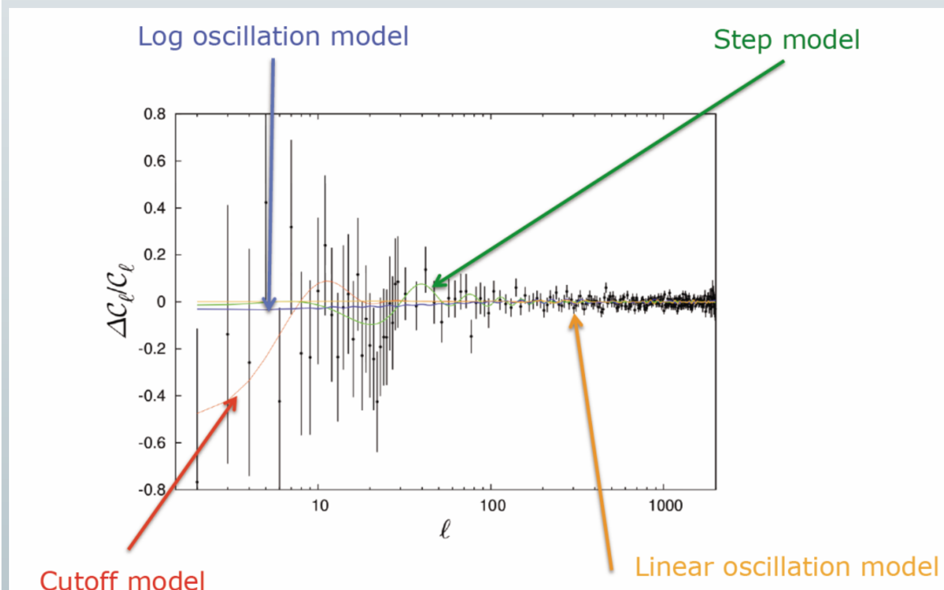
$$V(\phi) = \mu^3\phi + \Lambda^4\cos\left(\frac{\phi}{f}\right)$$

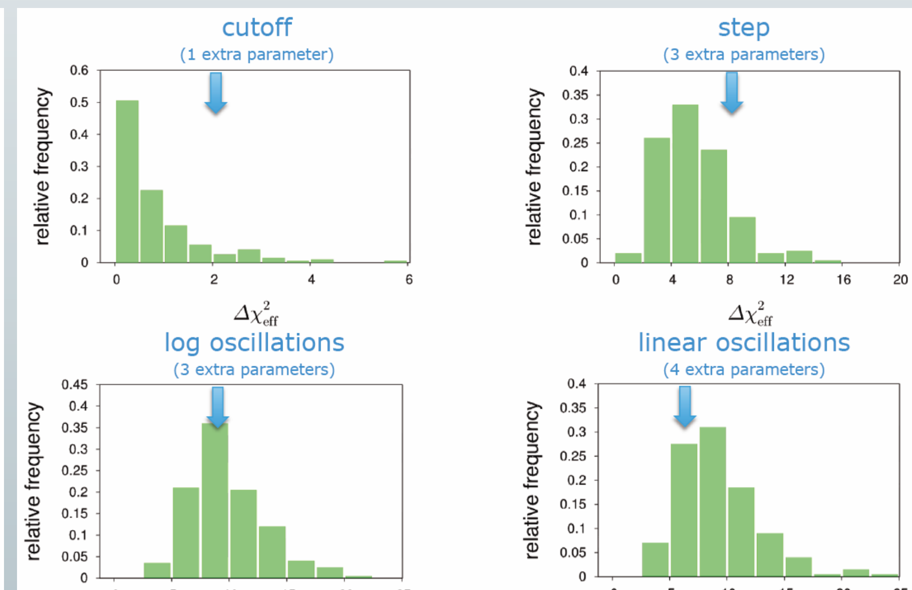
$$\mathcal{P}_{\mathcal{R}}^{\log}(k) = \mathcal{P}_{\mathcal{R}}^{0}(k)\left[1 + \mathcal{A}_{\log}\cos\left(\omega_{\log}\ln\left(\frac{k}{k_*}\right) + \varphi_{\log}\right)\right].$$

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



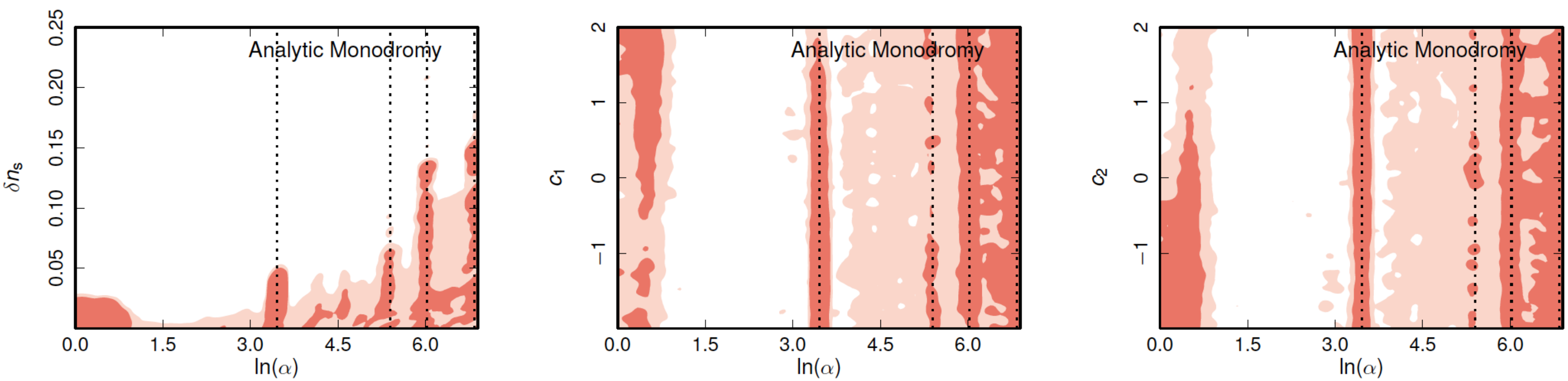


Axion monodromy inflation

Periodic potential, analytical template from Flauger etal.

$$\phi_k = \sqrt{2p\,(N_0 - \ln(k/k_*))}$$

$$\mathcal{P}_\mathcal{R}(k) = \mathcal{P}_\mathcal{R}(k_*)\left(\frac{k}{k_*}\right)^{n_s-1}\left\{1 + \delta n_s \cos\left[\frac{\phi_0}{f}\left(\frac{\phi_k}{\phi_0}\right)^{p_f+1} + \Delta\phi\right]\right\}$$



➔Chi² improvement insufficient. There are expected bispectrum oscillations $f_{NL}^{res} = \frac{\delta n_s}{8}\alpha^2$
Lowest frequency checked already. Others imminent.

Bispectrum constraints w. full mission data

Planck 2015

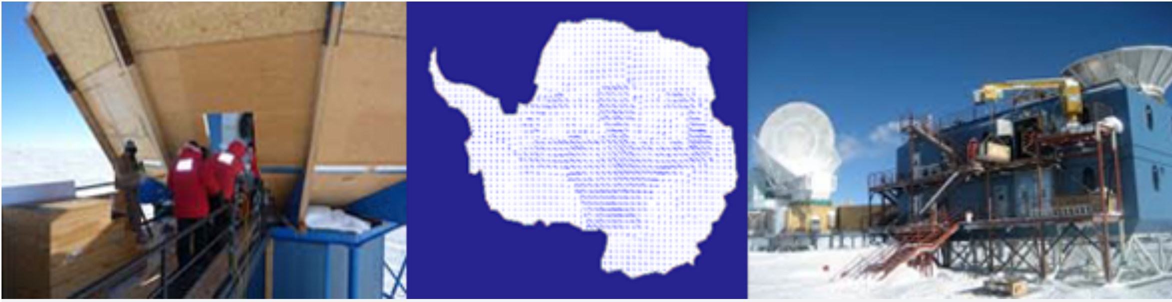
Shape and method	f_{NL}(KSW) Independent	ISW-lensing subtracted
SMICA (T)		
Local	9.5 ± 5.6	**1.8 ± 5.6**
Equilateral	−10 ± 69	**−9.2 ± 69**
Orthogonal	−43 ± 33	**−20 ± 33**
SMICA (T+E)		
Local	6.5 ± 5.1	
Equilateral	−8.9 ± 44	
Orthogonal	−35 ± 22	

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

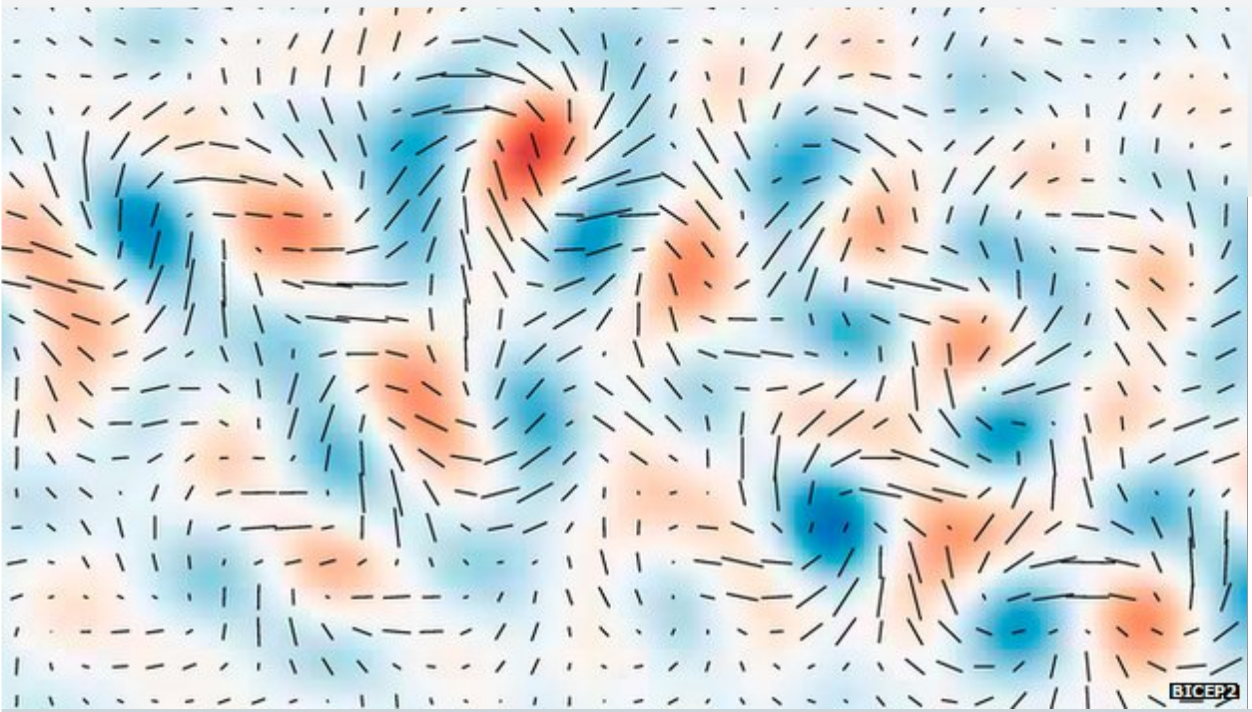
Planck 2013

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

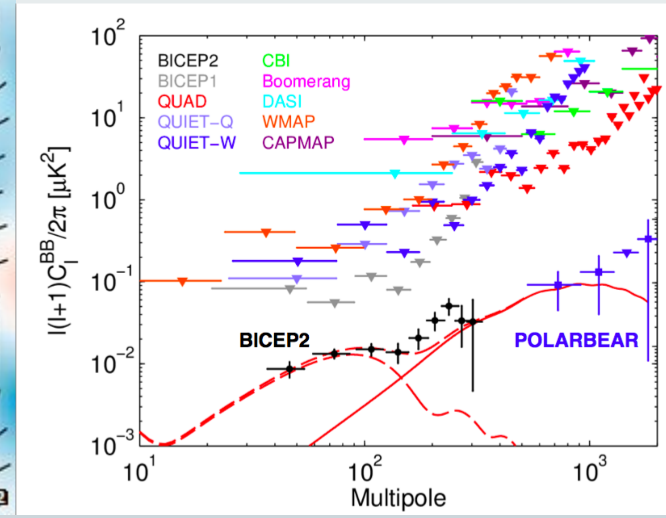
Constraint volume in LEO space shrunk by factor of 3.



BICEP2



March 17th 2014

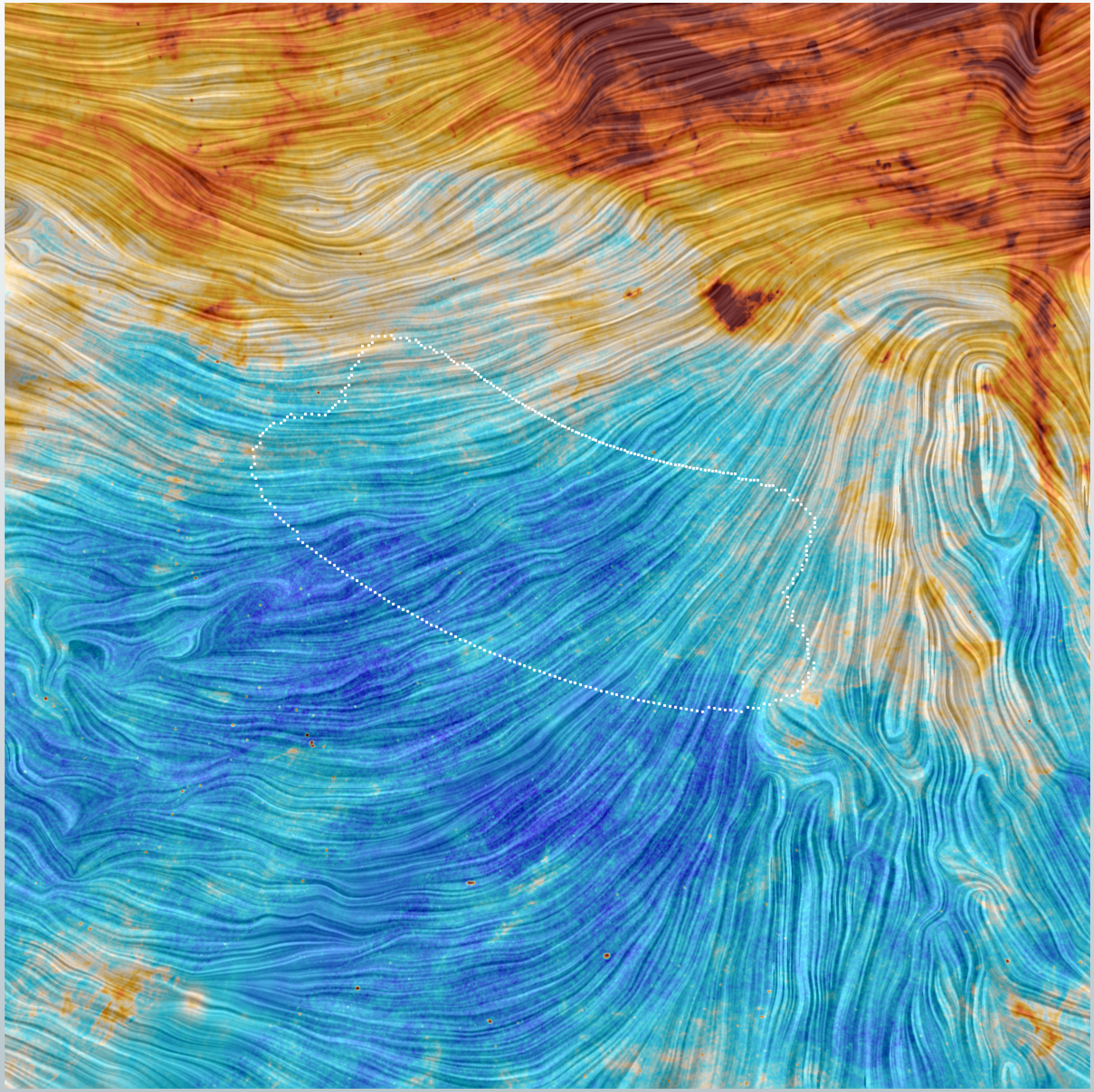


The world of physics is taken aback by an extraordinary result from a beautiful experimen with great sensitivity.

The search for primordial gravitational waves is over.

It is r=0.2 and it is 5 sigma!

Plank I and B-fields in Bicep2 region



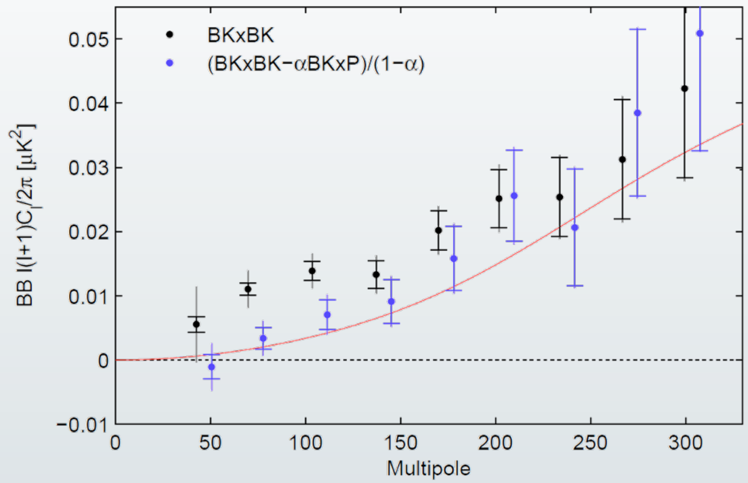
Planck X (Bicep2 & Keck) Ξ BKP

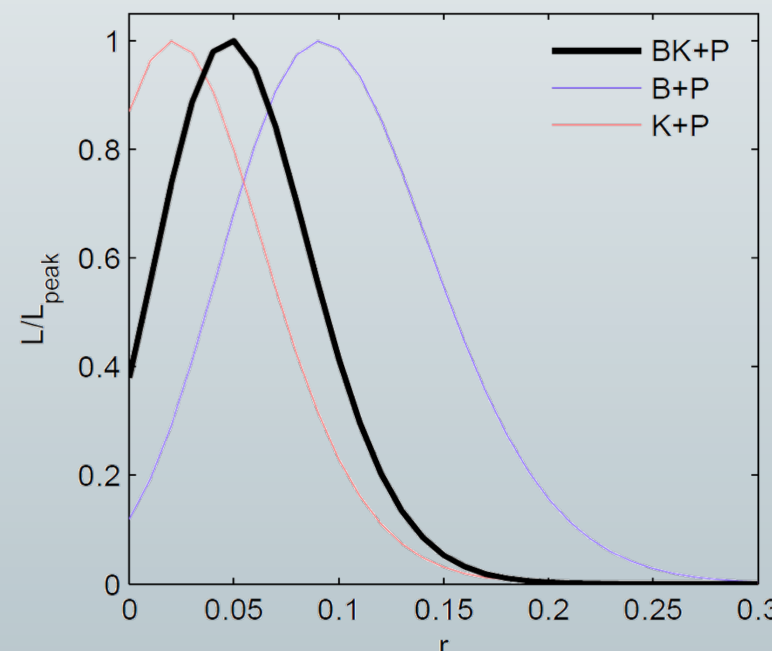
- Since January 30th 2015, the **direct** constraints on r (Planck X Bicep2 & Keck) have reached the level of the previous best **indirect constraints** (from Planck alone T), i.e.

- r < 0.11 @ 95%CL

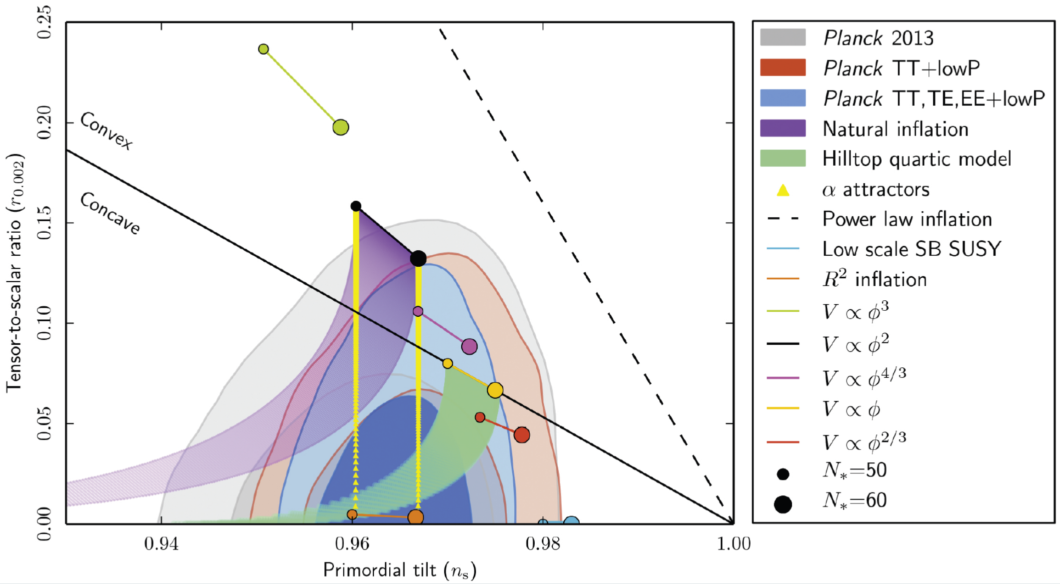
  ($r = A_s/A_T$ at, e.g., $k=0.05 Mpc^{-1}$)

- A new era began…



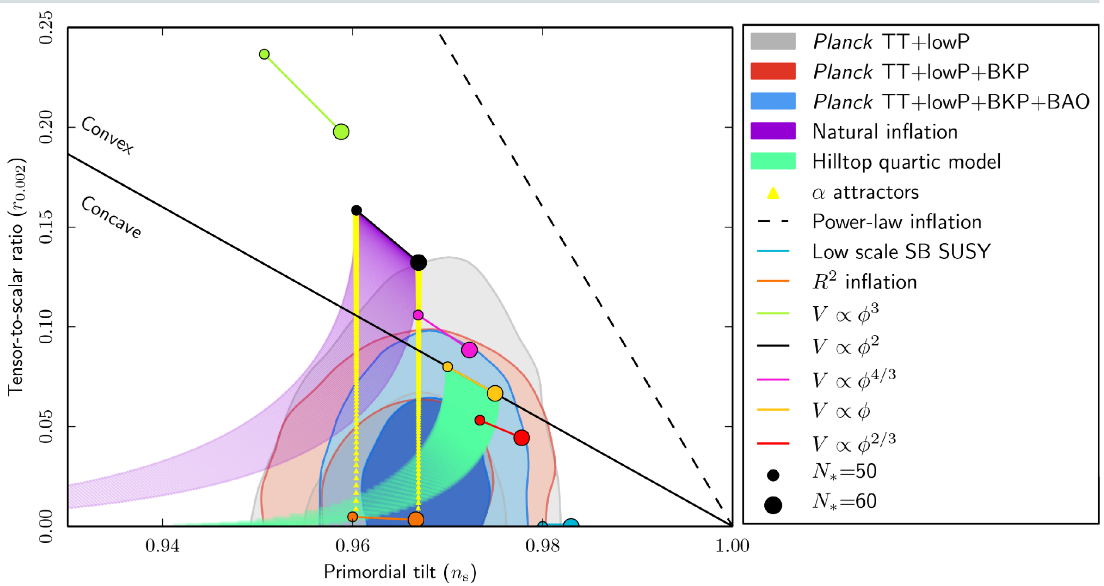


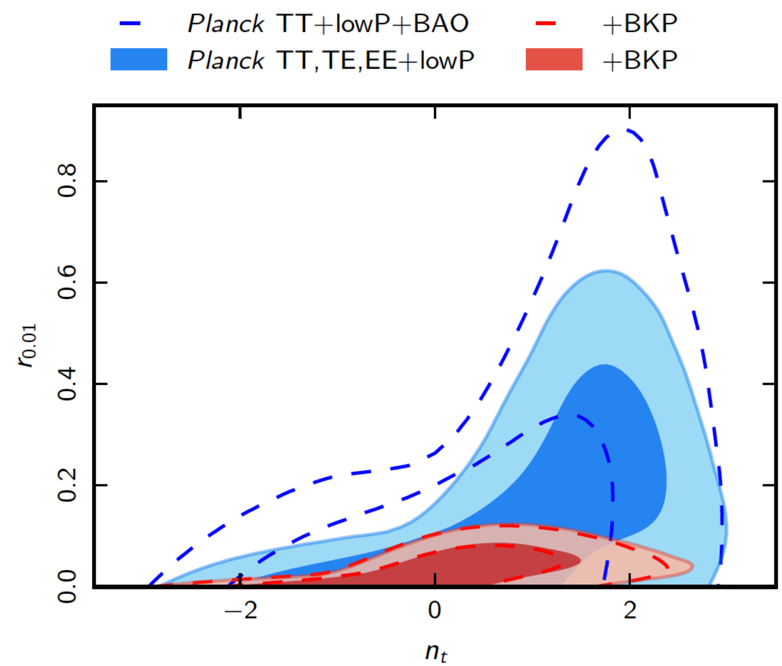
Planck vs Planck + BKP



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

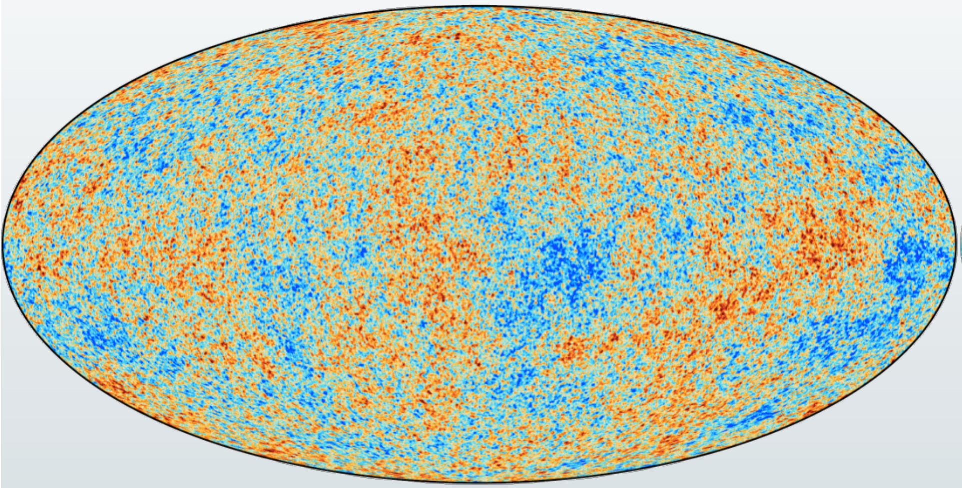


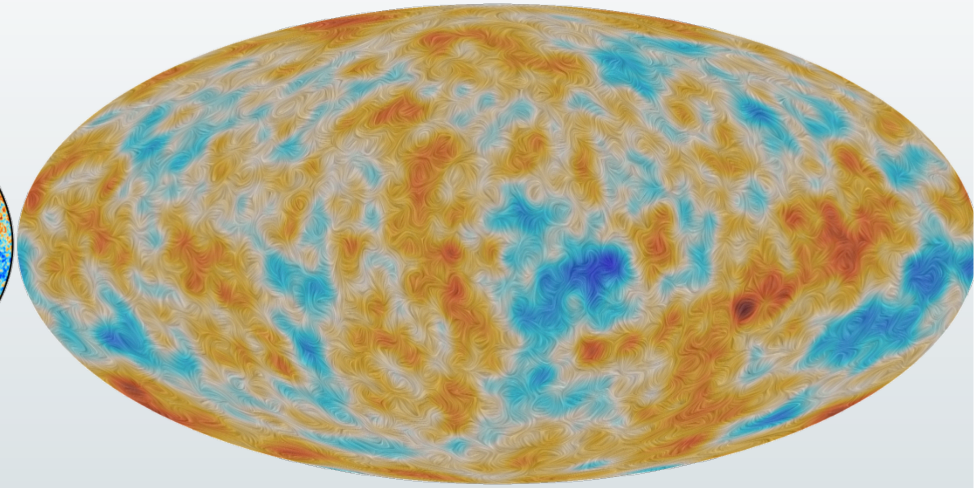


(using n_t and $r_{0.002}$ as primary parameters)

Conclusions

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

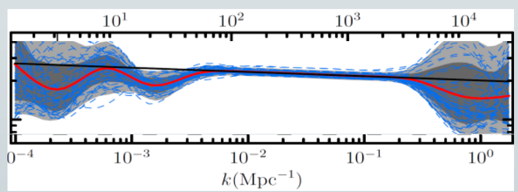


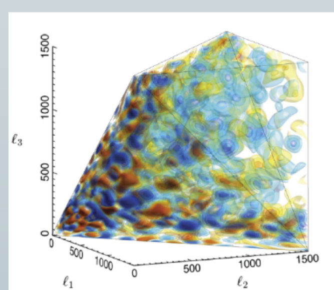


➔powerful evidence in favour of simple inflationary models, that match Planck data to very high precision.

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}

...

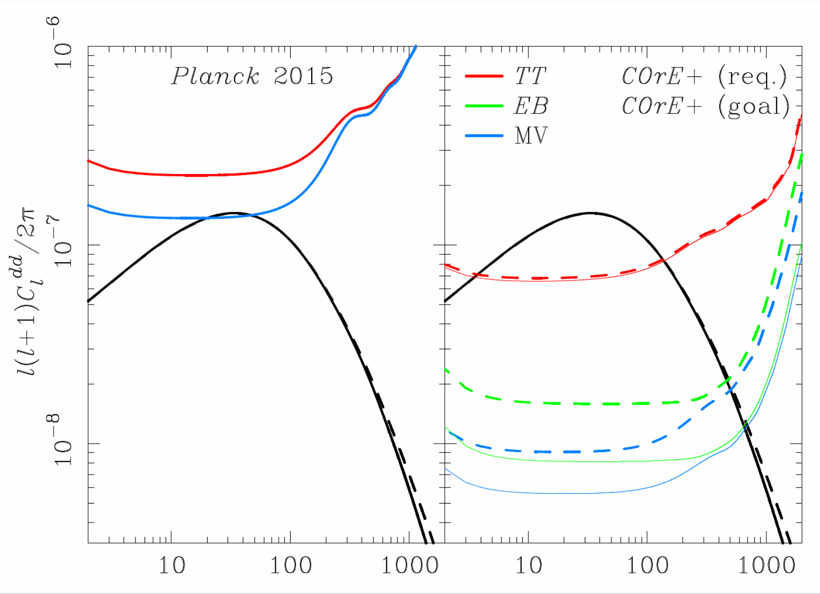
Defect	$G\mu/c^2$
NG . .	$< 1.3 \times 10^{-7}$
AH . .	$< 2.4 \times 10^{-7}$
SL . .	$< 8.5 \times 10^{-7}$
TX . .	$< 8.6 \times 10^{-7}$

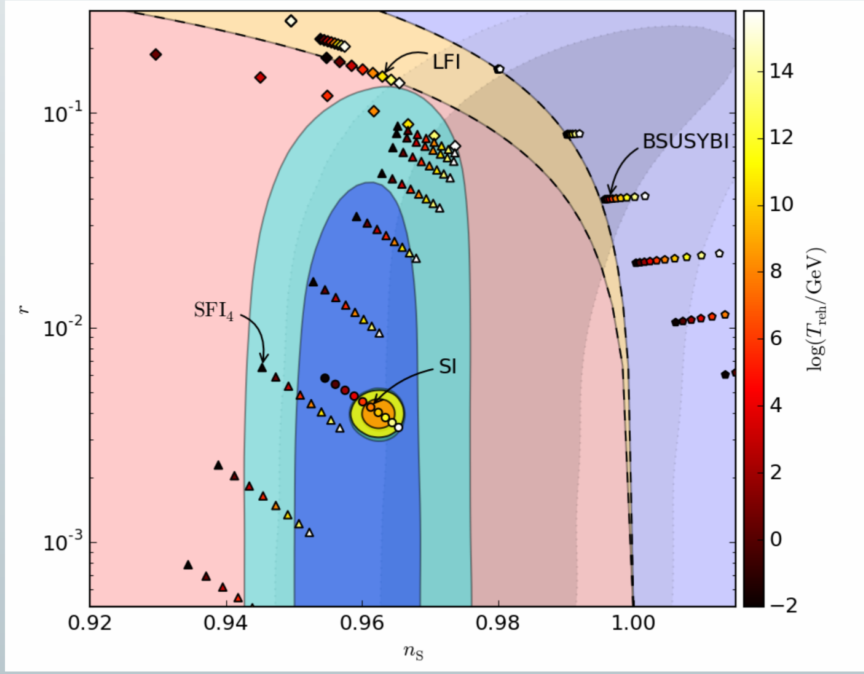
➔If there is new physics beyond base ΛCDM, its observational signatures in the CMB are weak & difficult to detect.

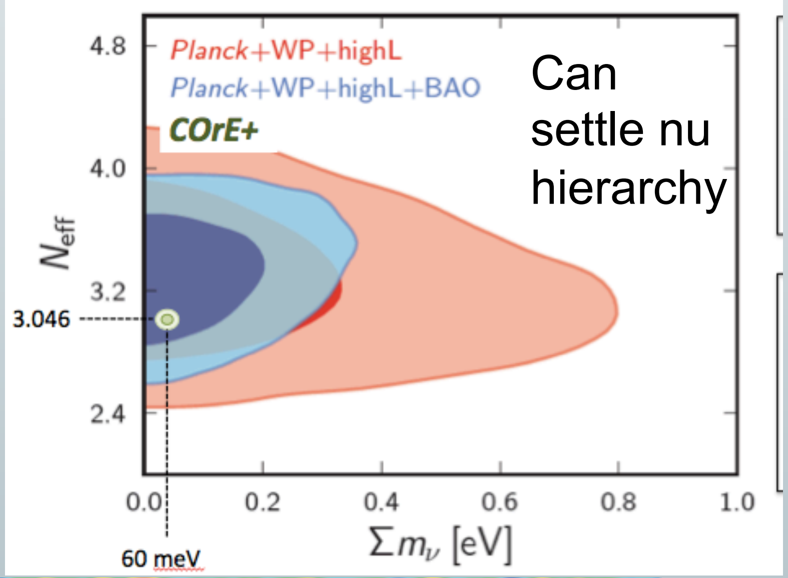
What's coming in CMB

Next Planck release, in 1 year…+lots of steps and opportunities towards

- full sky polarisation mapping, with enough sensitivity to detect unambiguously $r=10^{-3}$, and lots of frequency channels (+SZ, * form)
- + spectroscopy: y, mu, recombination lines…







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.

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