Planck Data and its Consistency and Inconsistency with Other Experiments

Ken Ganga
KEN.GANGA@APC.UNIV-PARIS-DIDEROT.FR

Planck & BICEP2
Planck & Polarbear (& SPT)
Planck & WMAP & Others

Planck Temperature Power Spectra

Planck collaboration: CMB power spectra & likelihood

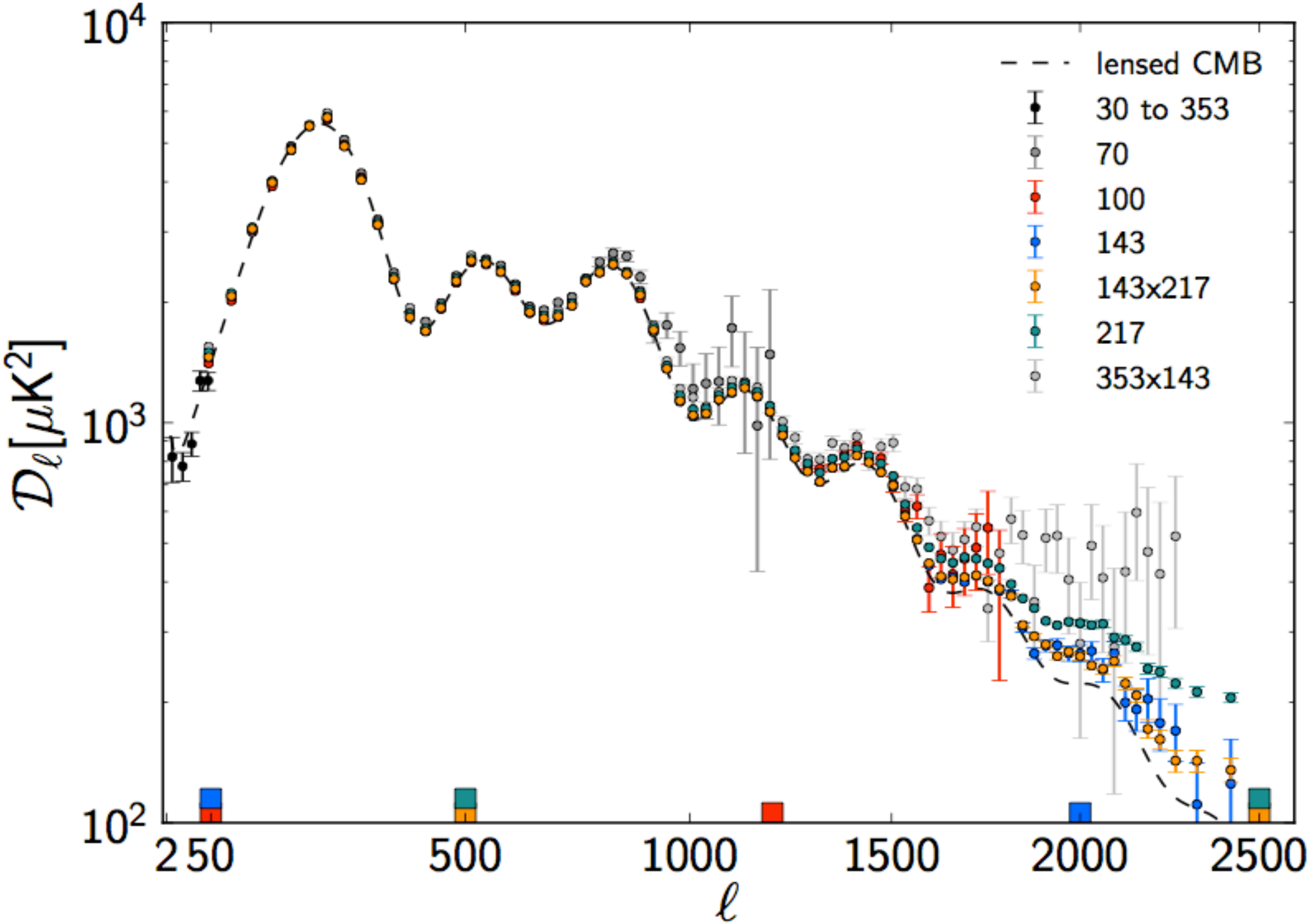
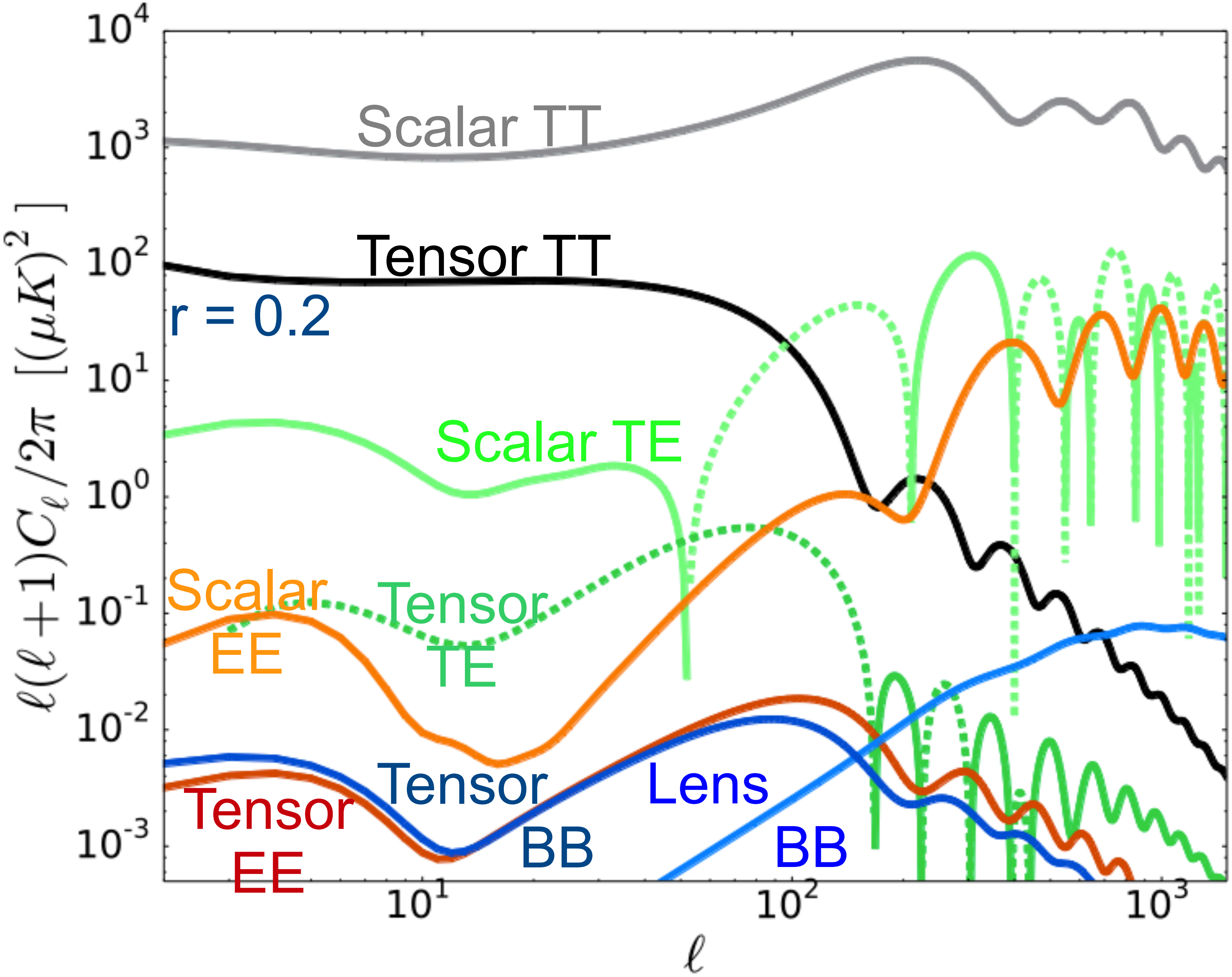


Figure 11. *Planck* power spectra and data selection. The coloured tick marks indicate the ℓ-range of the four cross-spectra included in CamSpec (and computed with the same mask, see Table 4). Although not used, the 70 GHz and 143 x 353 GHz spectra demonstrate the consistency of the data. The dashed line indicates the best-fit *Planck* spectrum.

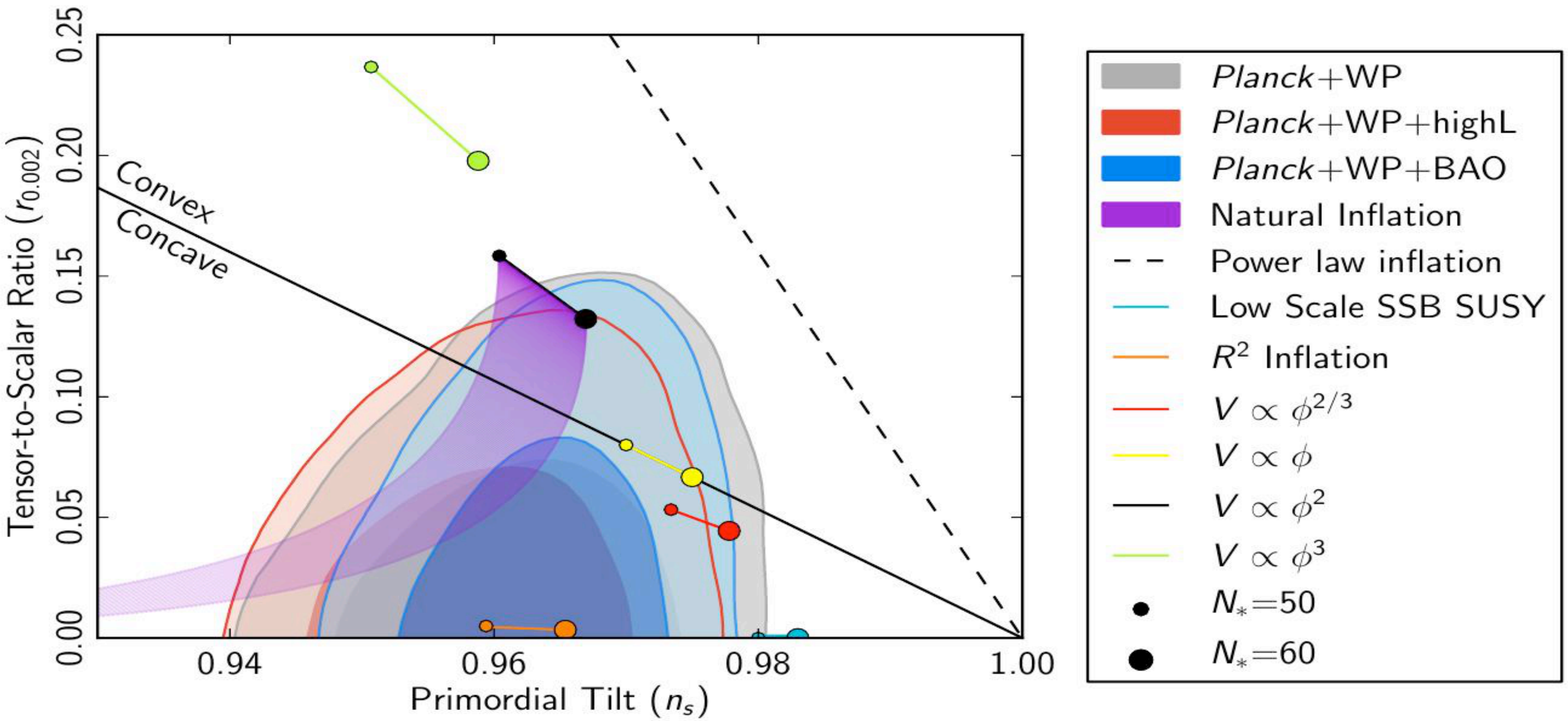
Spectra Zoo

Scalar & Tensor TT, TE, EE & BB Spectra

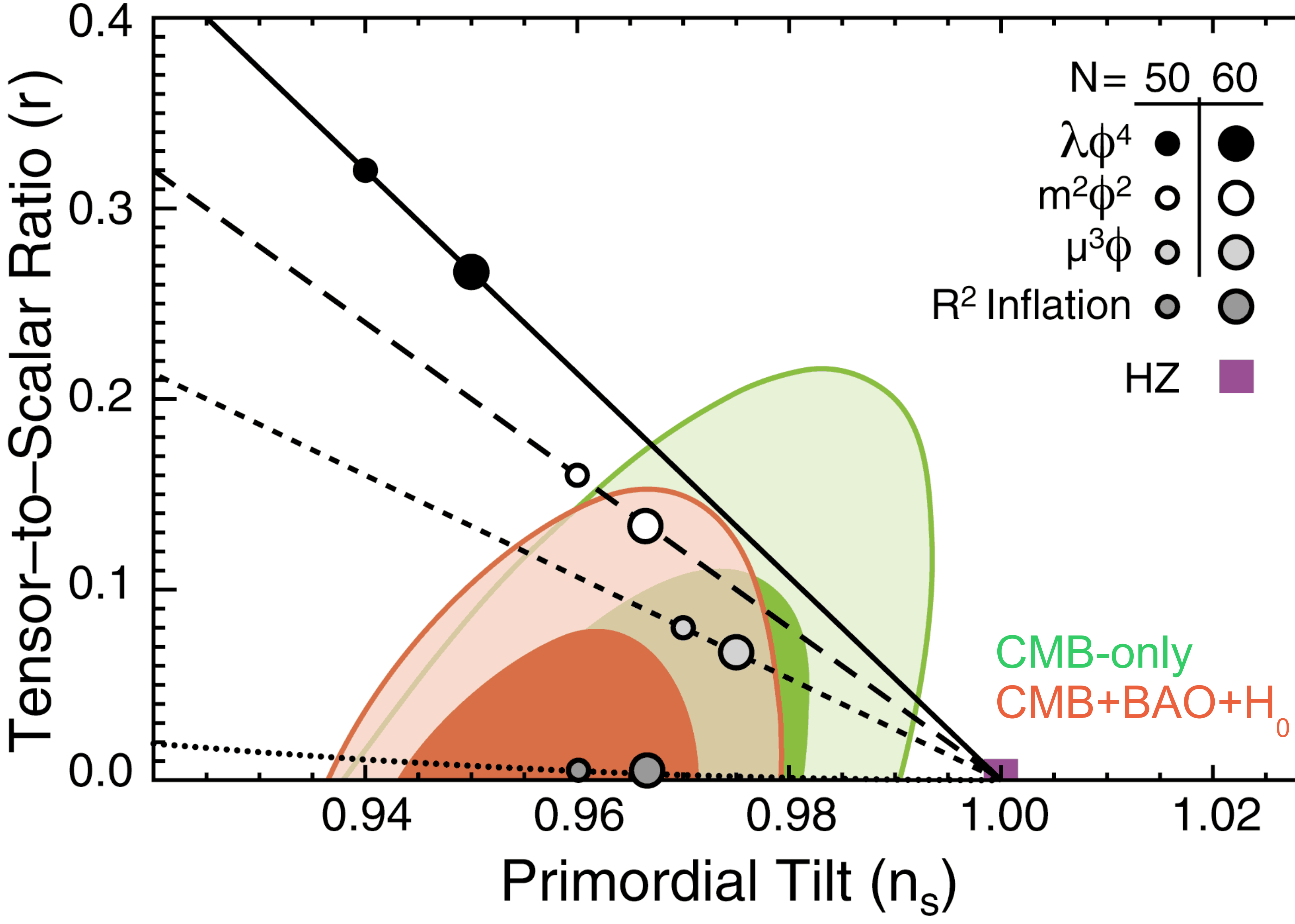
'r' quantifies the fraction of power in tensors versus scalars



1-Year Planck and Inflation



9-Year WMAP and Inflation



BICEP Sees r ~ 0.2

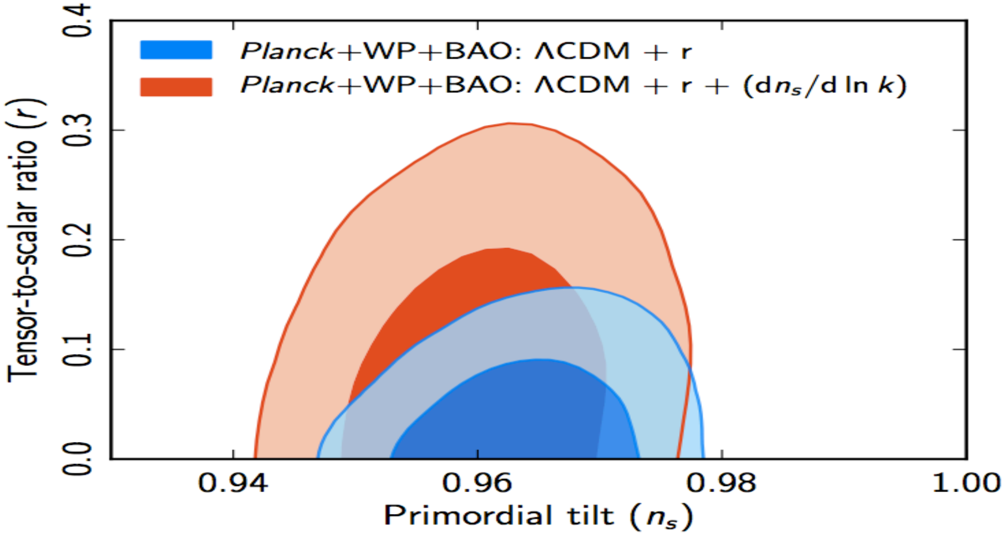
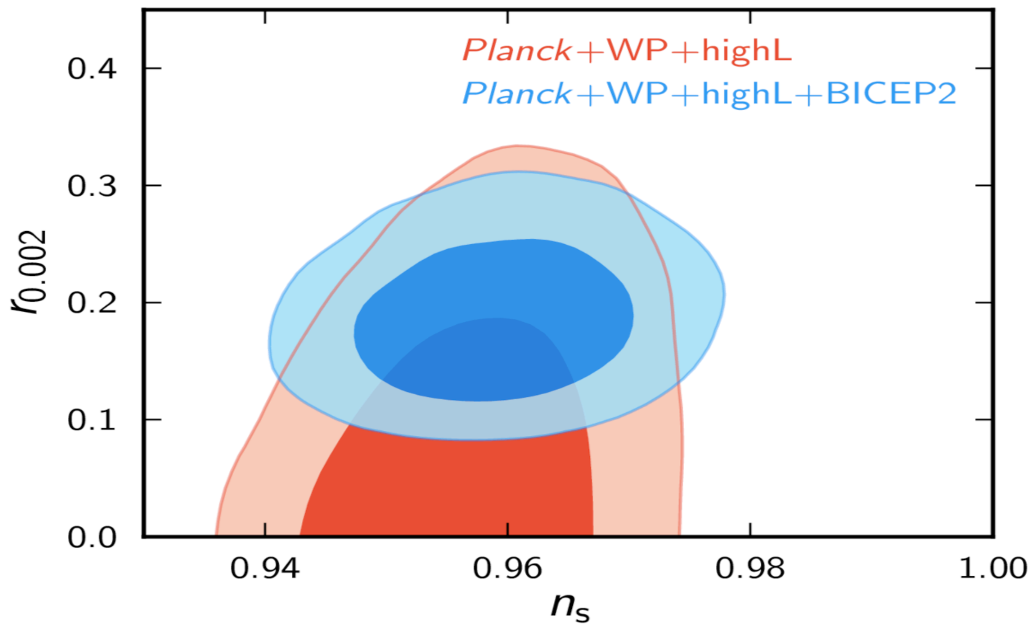


Fig. 4. Marginalized joint 68% and 95% CL regions for (r, n_s), using *Planck*+WP+BAO with and without a running spectral index.



- "... the fractional contribution of tensor modes is limited to r < 0.13 (95% CL)" -- *Nine-year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Cosmological Parameter Results (2012)*
- "Planck establishes an upper bound on the tensor-to-scalar ratio of r < 0.11 (95% CL)." -- *Planck 2013 results. XXII. Constraints on inflation*.
- "The observed B-mode power spectrum is well-fit by a lensed-LCDM + tensor theoretical model with tensor/scalar ratio $r=0.20^{+0.07}_{-0.05}$." -- *BICEP2 I: Detection of B-mode Polarization at Degree Angular Scales (2014)*
- We were looking for a needle in a haystack, but instead we found a crowbar. -- *Clem Pryke*

Exacerbated 'r' Deficit

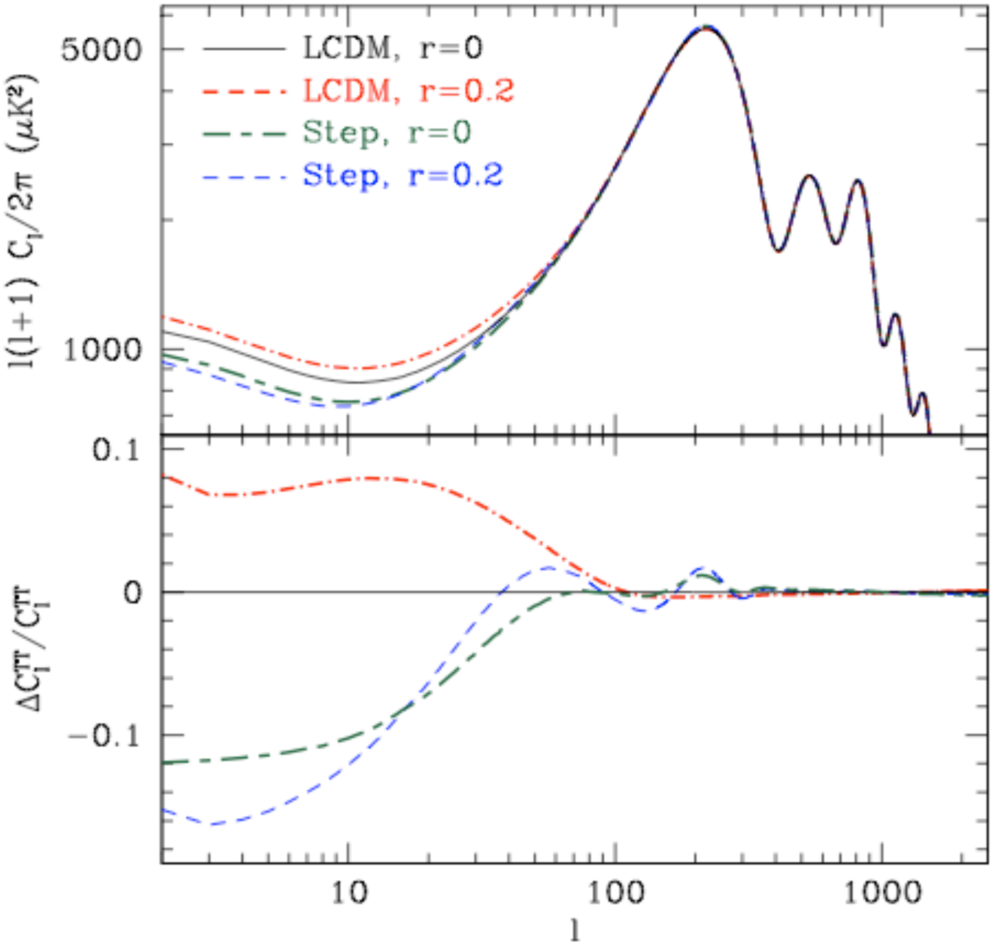
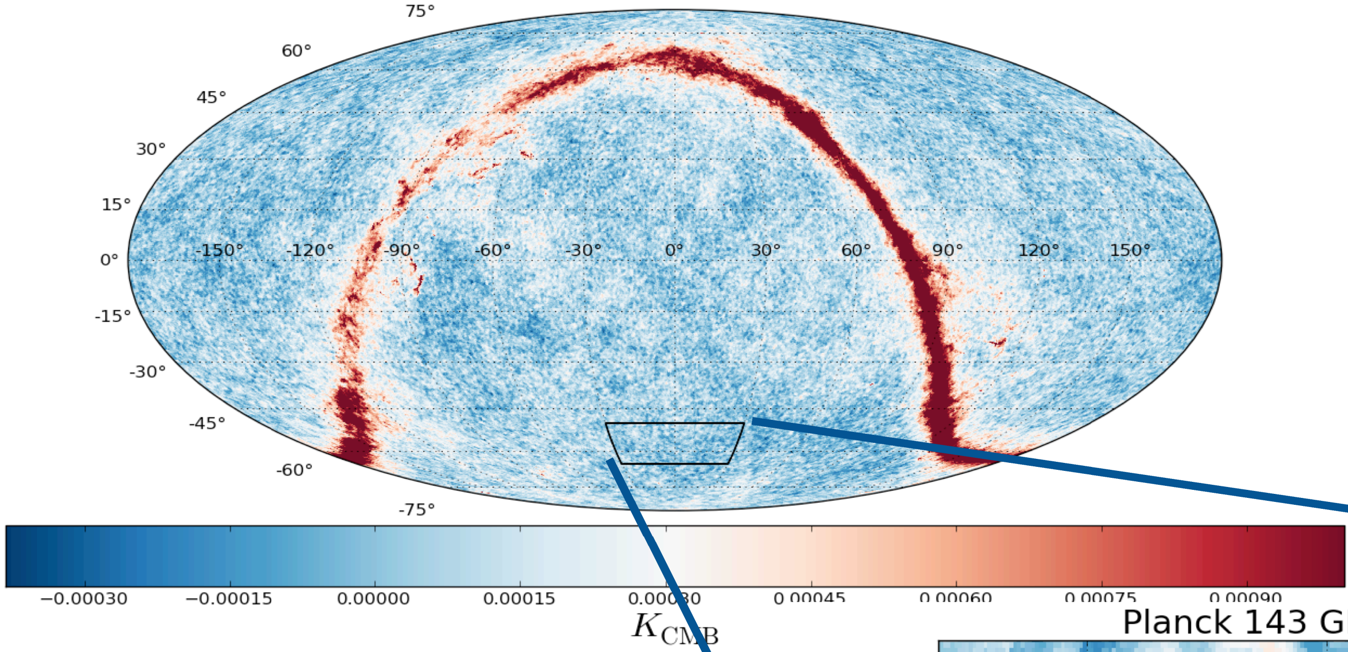


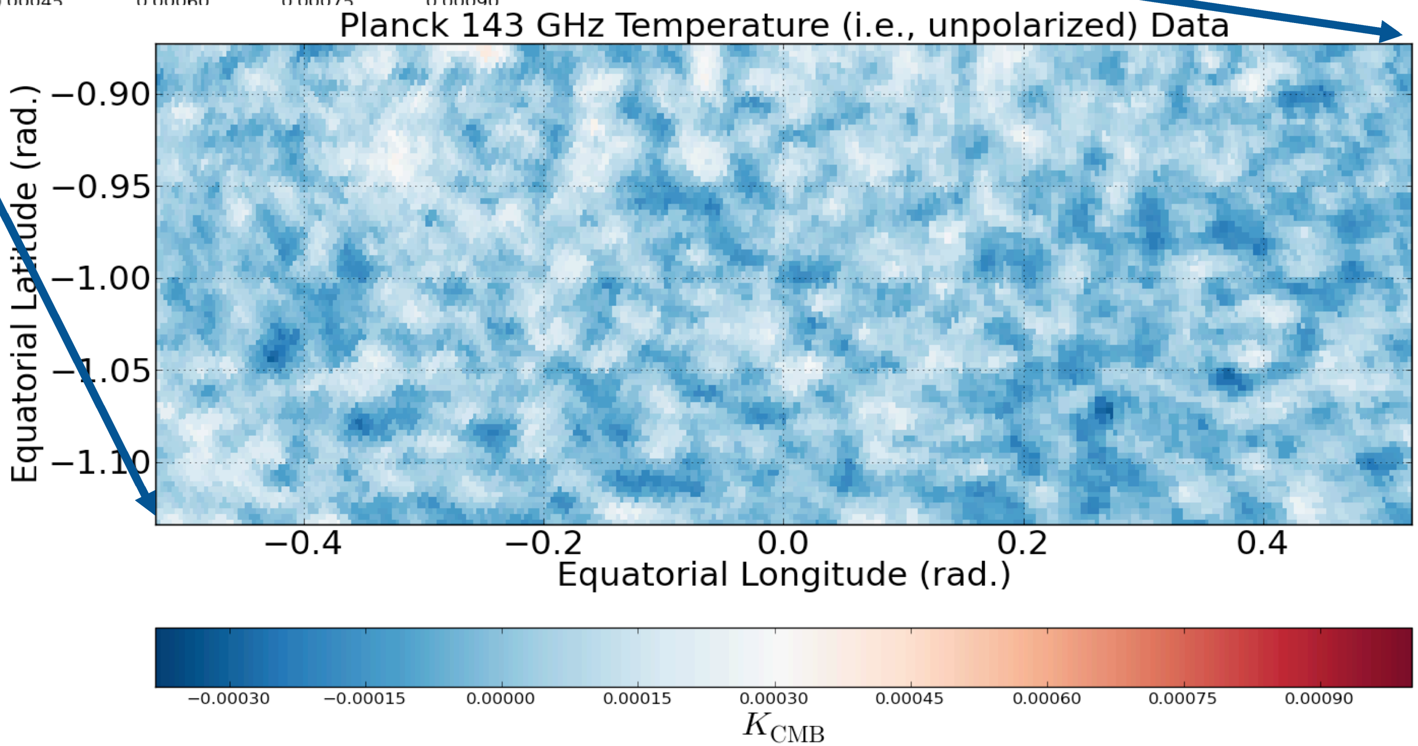
FIG. 1. Total temperature power spectra showing the unobserved excess produced by adding tensors of $r = 0.2$ to the best fit 6 parameter ΛCDM model and its removal by adding a step in the tensor-scalar parameter $\epsilon_H c_s$. Planck data in fact favor removing more power than the tensor excess, preferring a step even if $r = 0$. Step model parameters are given in Tab. I.

- Spectra fits are usually dominated by the smaller angular scales
- This has led to a small “deficit” at smaller angular scales
- The BICEP2 “r” detection exacerbates this.

Miranda *et al.*; arXiv:1403.5231v2 [astro-ph.CO] 9 May 2014

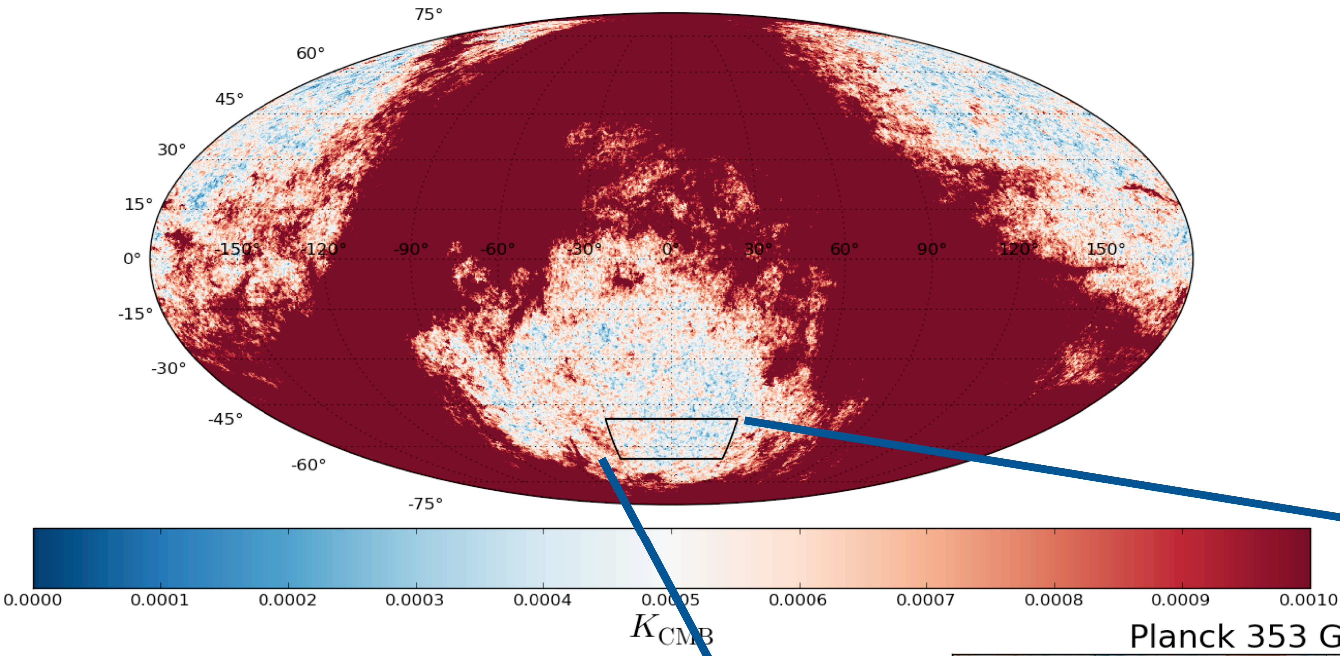
Planck 143 GHz Temperature Map



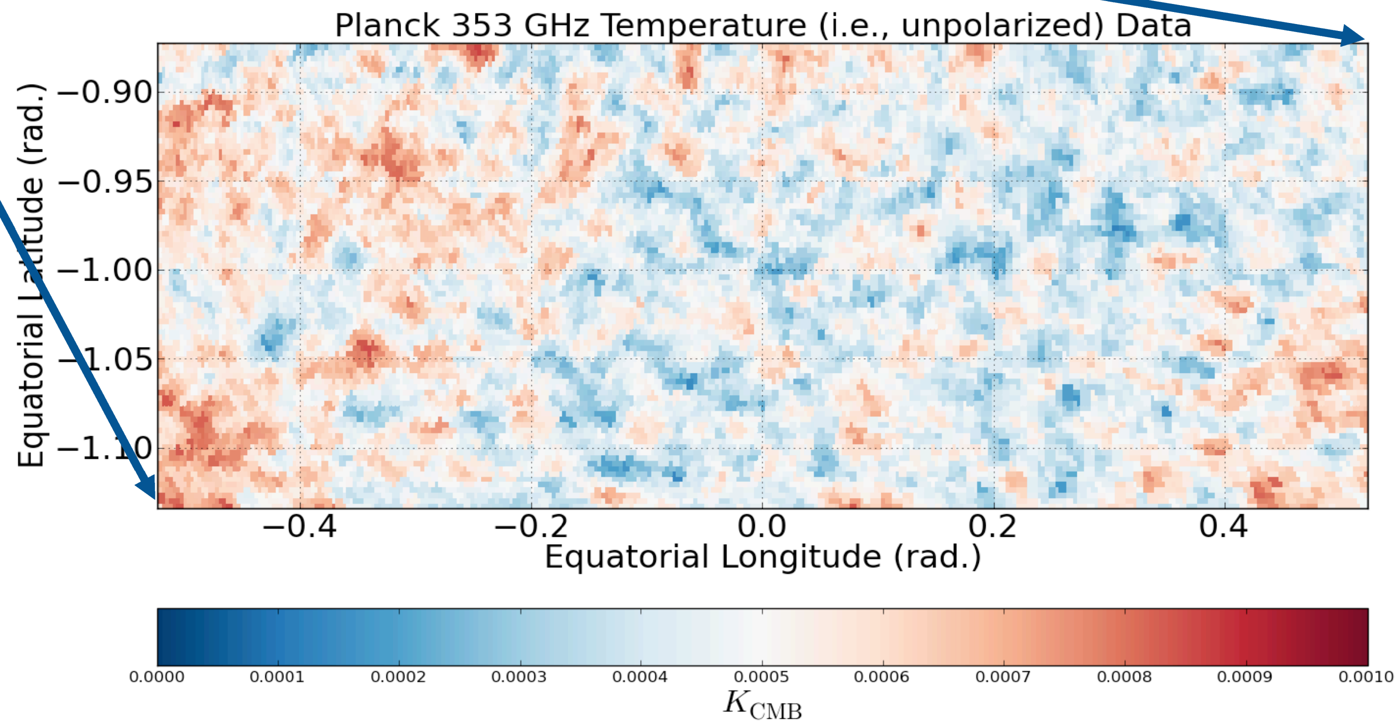


This is a *temperature* map. The analysis for *polarization* is ongoing.

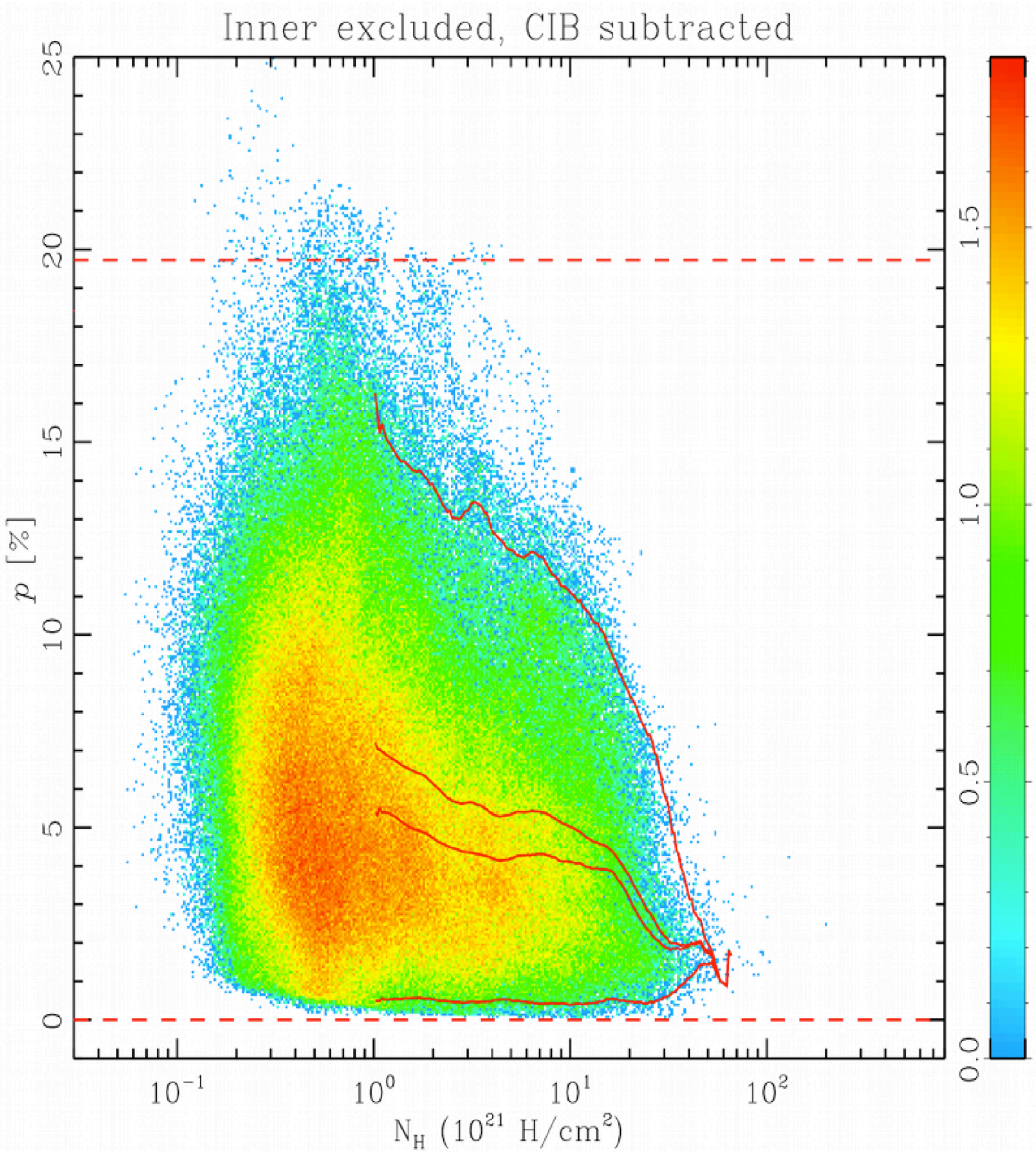
Planck 353 GHz Temperature Map



This is a *temperature* map. The analysis for *polarization* is ongoing.



Polarization vs. Optical Depth



arXiv:1405.0871v1 5 May 2014

- Historically, the CMB world has used a canonical 5% polarization figure for dust
- These are based on the only regions we could measure – bright regions
- Lower column-depth regions are less complicated, have less depolarization and so seem have higher polarization fraction

What Planck is Working on Now

Stokes Q & U at 353 GHz from Planck

Planck collaboration: The *Planck* dust polarization sky

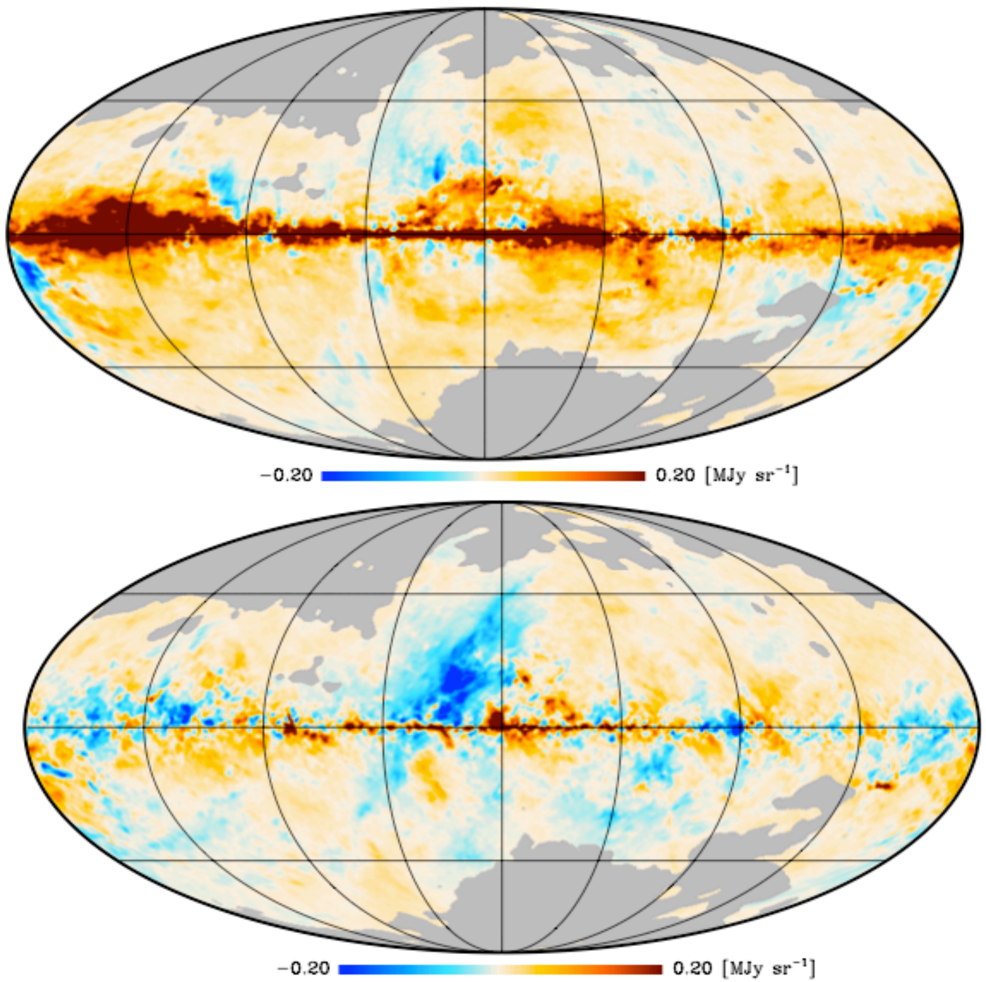
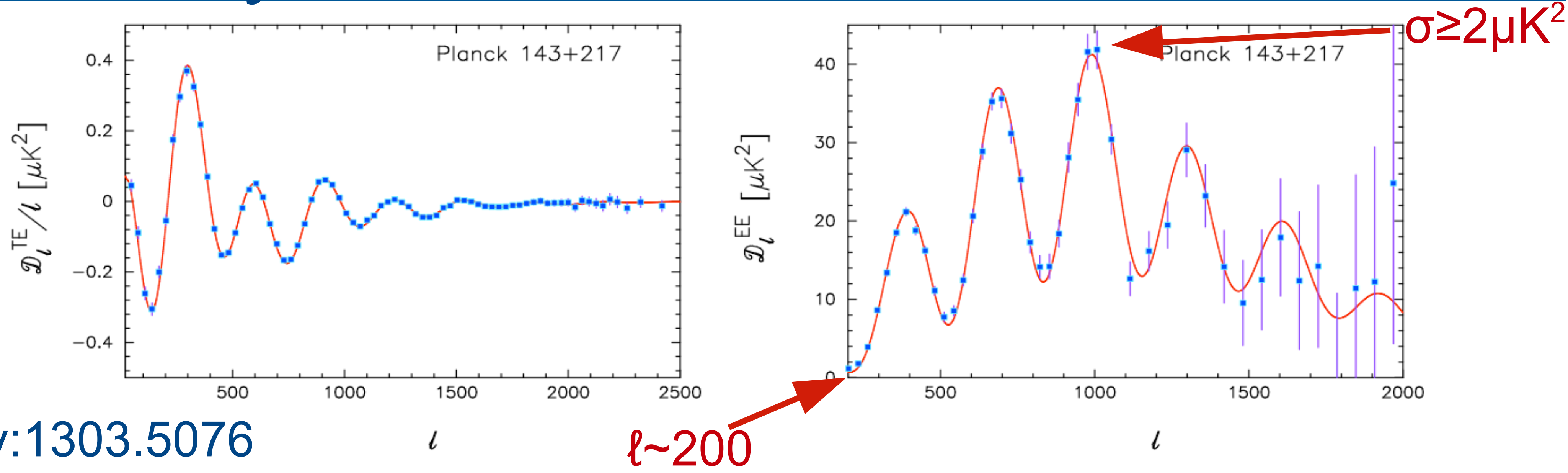


Fig. 1. *Planck* 353 GHz polarization maps at 1° resolution. *Upper*: *Q* Stokes parameter map. *Lower*: *U* Stokes parameter map. The maps are shown with the same colour scale. High values are saturated to enhance mid-latitude structures. The values shown have been bias corrected as described in Sect. 2.3. These maps, as well as those in following figures, are shown in Galactic coordinates with the galactic center in the middle and longitude increasing to the left. The data is masked as described in Sect. 2.4.

arXiv:1405.0871v1 5 May 2014

- Planck is finding that low column density regions tend to sometimes have higher polarization fractions
- BICEP has more sensitivity than Planck in their field at 150 GHz
- BUT, Galactic dust is MUCH brighter at 353 GHz than at 150 GHz
- Planck should be able to say much about polarized dust contamination over the full sky, and over the BICEP2 field

Early Planck Polarization Teases

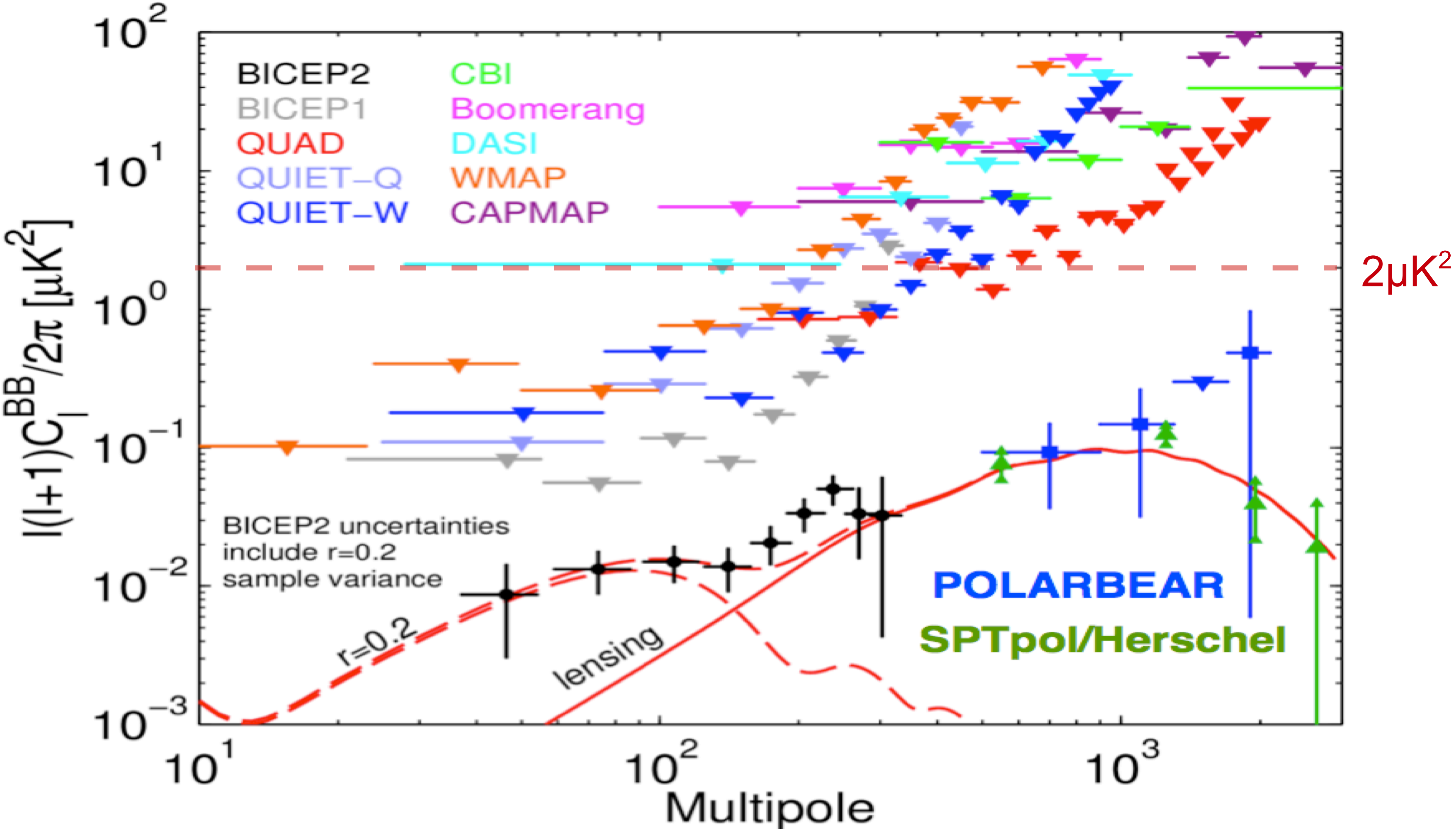


arXiv:1303.5076

Fig. 11. *Planck TE* (left) and *EE* spectra (right) computed as described in the text. The red lines show the polarization spectra from the base ΛCDM *Planck*+WP+highL model, *which is fitted to the TT data only.*

- Planck has shown "teaser" polarization spectra in the 2013 result papers
- The largest angular scales (and perhaps the most interesting!) are not visible
- At these angular scales, things will improve some in 2014, with more data and improved treatment

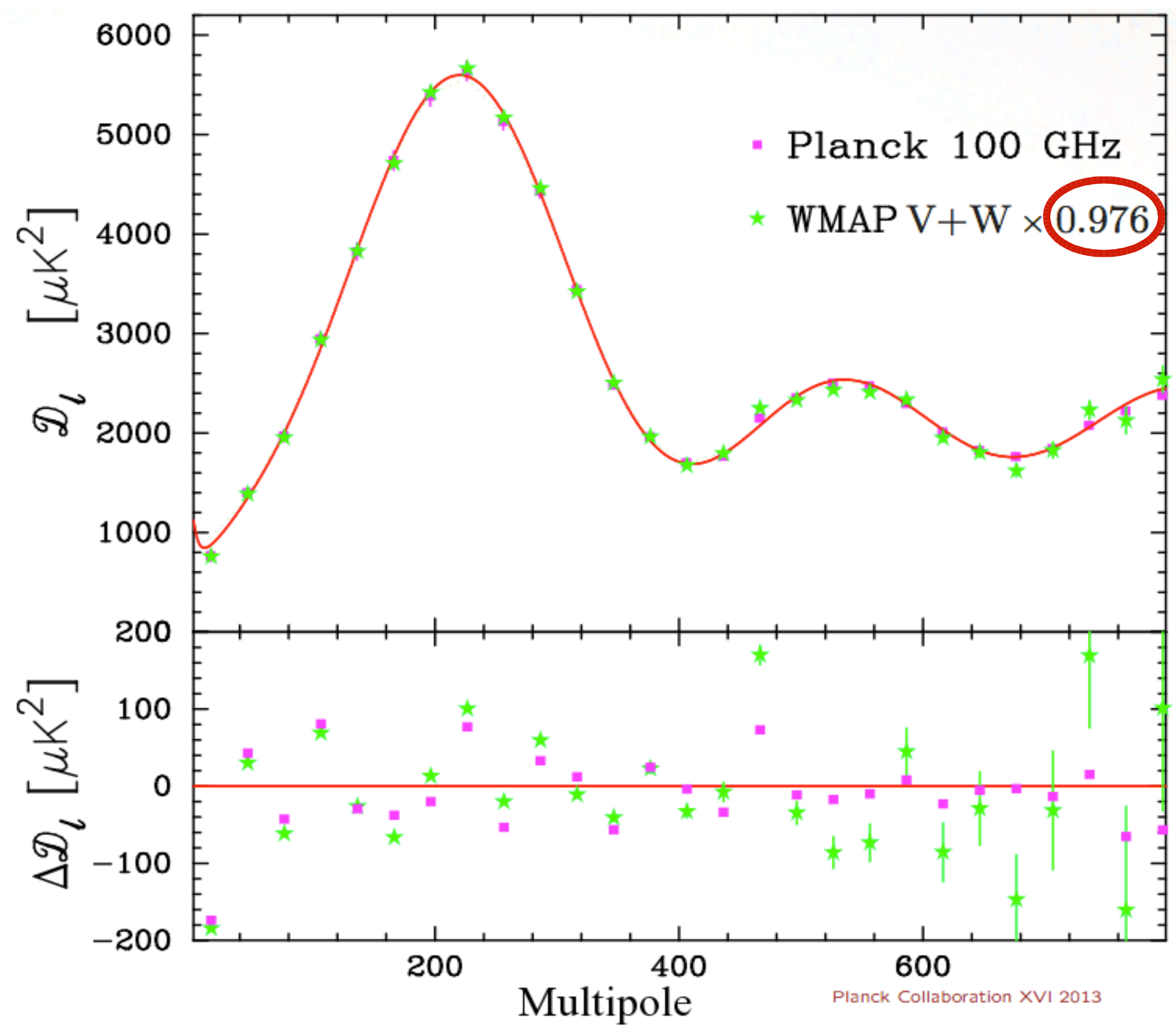
B-Mode Measurements



Stolen from Jeff Filippini; see https://indico.cern.ch/event/296546/session/1/contribution/5

Initial Calibration Difference

- 2.4% in power is 1.2% in the maps
  - And Planck used the WMAP dipole as a calibrator!
    - As well as the WMAP polarization to break degeneracies with τ



Differences with WMAP+SPT

- The accepted version of the Planck 2013 Cosmological Parameters has extended the discussion of comparisons with WMAP+SPT
- In particular, the discussion of relative calibration is now more nuanced

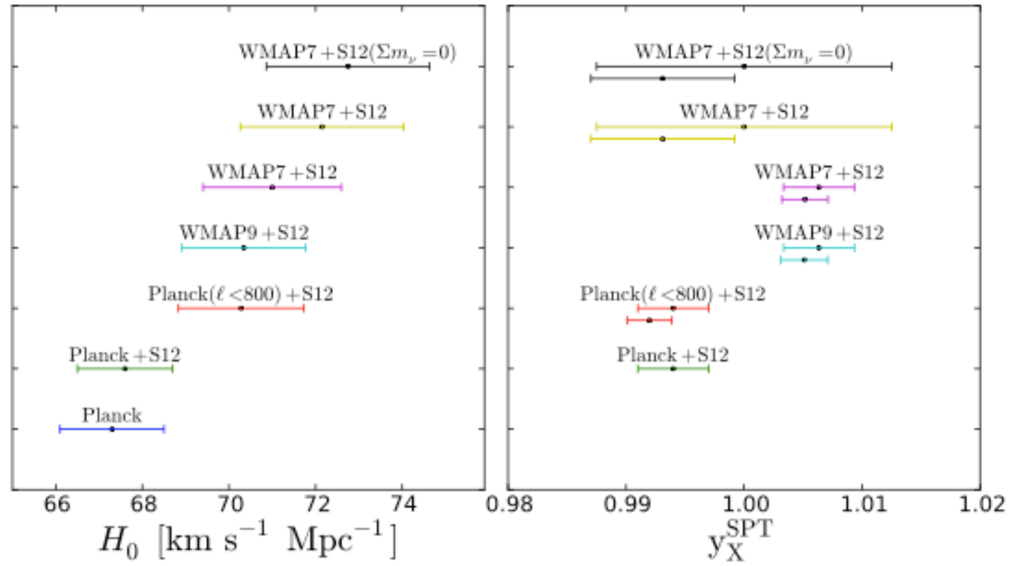


Fig. B.3. A number of separate effects contribute to the difference in H_0 inferred from *WMAP*-7+S12 (top of left panel) and H_0 inferred from *Planck*+WP (bottom of left panel), all going in the same direction. These include assumptions about neutrino masses, calibration procedures, differences between *WMAP*-7 and *WMAP*-9, and differences in the relative calibrations between SPT and *WMAP* (as explained in the text). The right panel shows calibration parameter priors (top lines of each pair) and posteriors (bottom lines of each pair). The tighter of the priors shown for *WMAP*-7+S12, and that shown for *WMAP*-9+S12, come from using *Planck* to provide the relative calibration between *WMAP* and S12. We plot only the posterior for the Planck+S12 relative calibration. Note that the relative-calibration parameter y_X^{SPT} is between S12 and the other indicated data set (i.e., *WMAP* or *Planck*).

“Features” in the Spectra

26 Planck Collaboration: Constraints on inflation

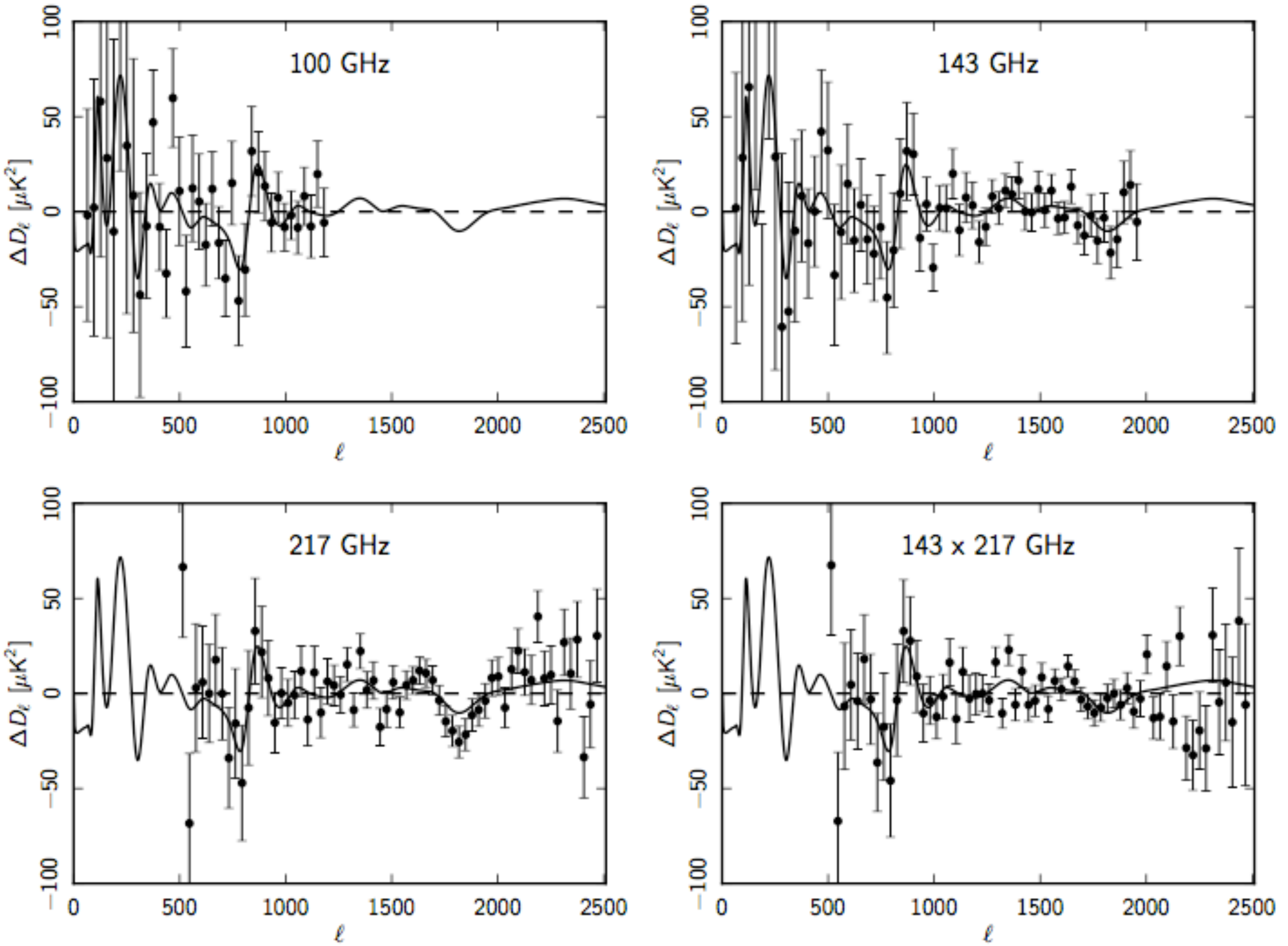


Fig. 16. CMB multipole spectrum residuals for best fit primordial power spectrum reconstruction with smoothing parameter $\lambda = 10^3$. The panels show the C_ℓ spectrum residuals (compared to the best fit power law fiducial model represented by the horizontal straight dashed line) for the four auto- and cross-spectra included in the high-ℓ likelihood. Here $D_\ell = \ell(\ell+1)C_\ell/(2\pi)$. The data points have been binned with $\Delta\ell = 31$ and foregrounds subtracted according to the best fit foreground parameters. The solid black line shows the CMB spectrum residual for the maximum likelihood primordial power spectrum reconstruction with $\lambda = 10^3$.

In work done after submission of this paper, this feature was shown to be associated with imperfectly subtracted electromagnetic interference generated by the drive electronics of the 4 K cooler and picked up by the detector readout electronics.

Vague Differences with WMAP and Others

Some differences are to be expected, as the Planck data delivered to the public is not the same as that used internally.

In addition, different choices inevitably lead to different values.

$\Omega_b h^2 = 0.02197 \pm 0.00027$
$\Omega_c h^2 = 0.1169 \pm 0.0025$
$\tau = 0.089 \pm 0.013$
$N_s = 0.9671 \pm 0.0069$
$\ln(10^{10} A_s) = 3.080 \pm 0.025$
$H_0 = 68.0 \pm 1.1\ \mathrm{kms^{-1}Mpc^{-1}}$

	Planck+WP	
Parameter	Best fit	68% limits
$\Omega_b h^2$	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04119	1.04131 ± 0.00063
τ	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.0980	$3.089^{+0.024}_{-0.027}$
Ω_Λ	0.6817	$0.685^{+0.018}_{-0.016}$
Ω_m	0.3183	$0.315^{+0.016}_{-0.018}$
σ_8	0.8347	0.829 ± 0.012
z_{re}	11.37	11.1 ± 1.1
H_0	67.04	67.3 ± 1.2
$10^9 A_s$	2.215	$2.196^{+0.051}_{-0.060}$
$\Omega_m h^2$	0.14305	0.1426 ± 0.0025
$\Omega_m h^3$	0.09591	0.09589 ± 0.00057
Y_P	0.247695	0.24770 ± 0.00012
Age/Gyr	13.8242	13.817 ± 0.048
z_*	1090.48	1090.43 ± 0.54
r_*	144.58	144.71 ± 0.60
$100\theta_*$	1.04136	1.04147 ± 0.00062

Official- versus Re-Analyses

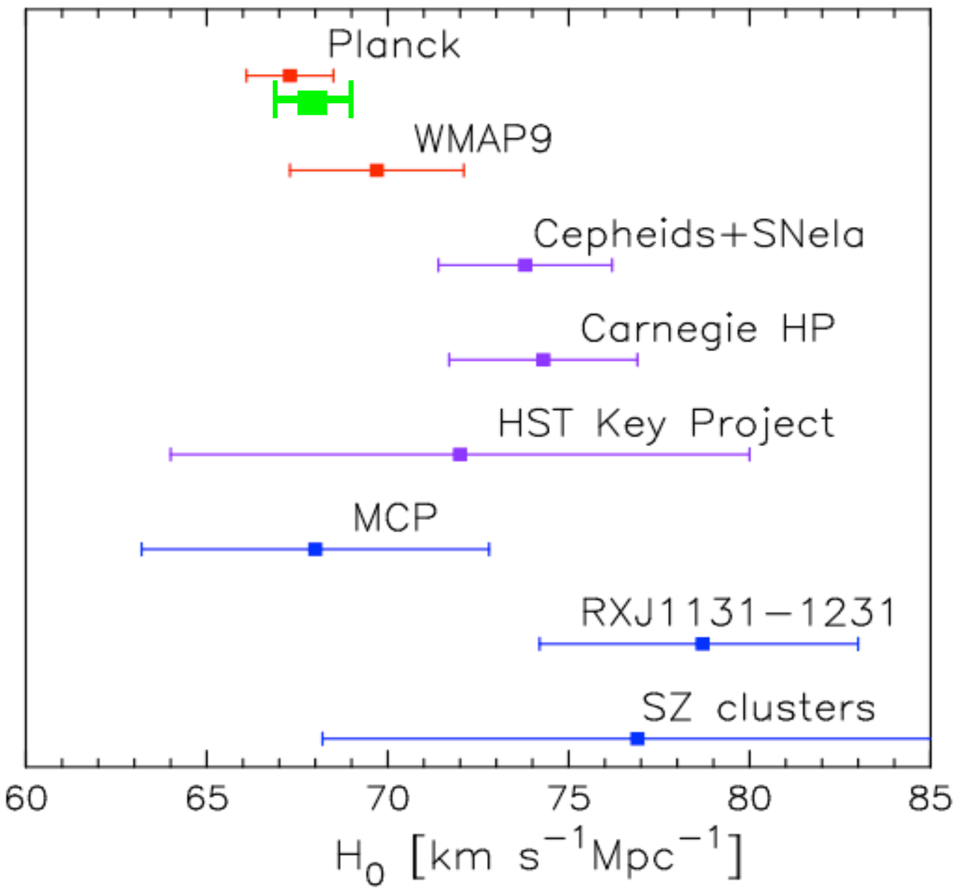


Fig. 16. Comparison of H_0 measurements, with estimates of $\pm 1\,\sigma$ errors, from a number of techniques (see text for details). These are compared with the spatially-flat ΛCDM model constraints from *Planck* and *WMAP*-9.

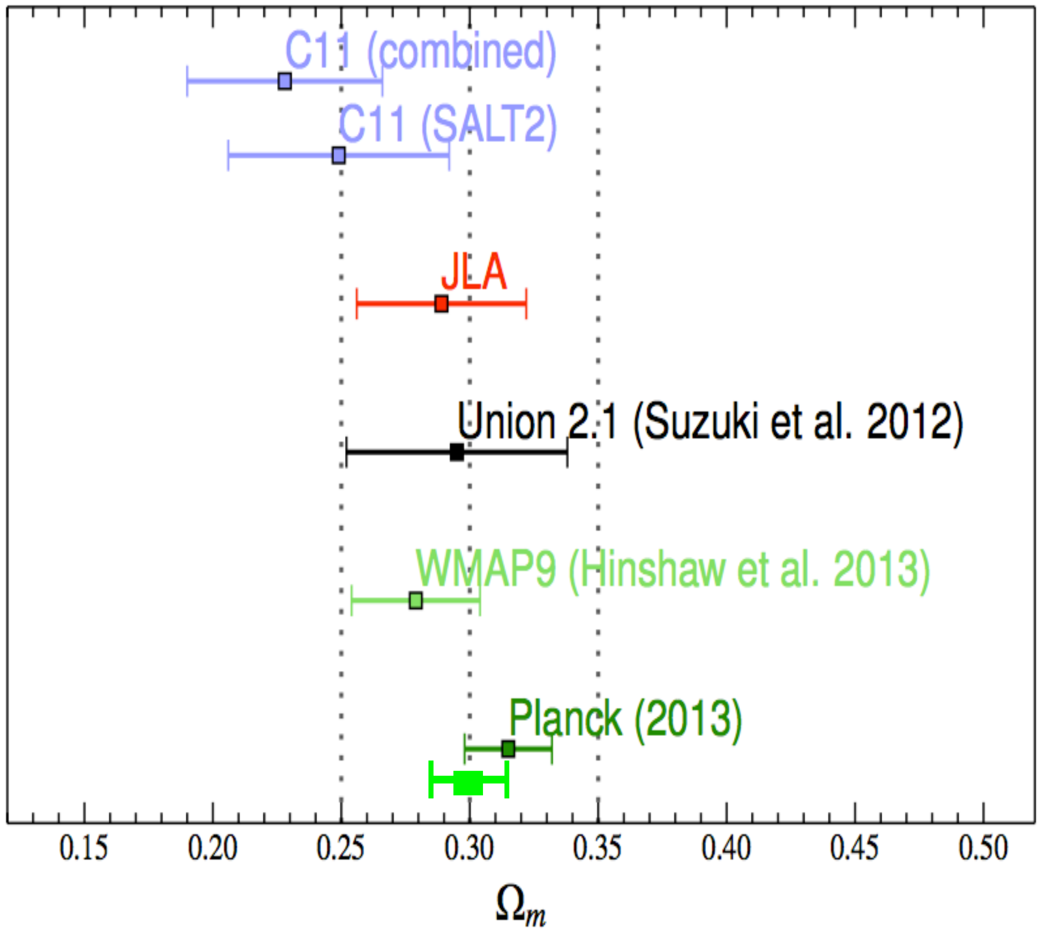


Fig. 13. Comparison of various measurements of Ω_m for a ΛCDM cosmology. Betoule *et al.*: arXiv:1401.4064

Changes noted by SFH may be real, though sub-σ, but are certainly sub-dominant to other considerations.

Degeneracies

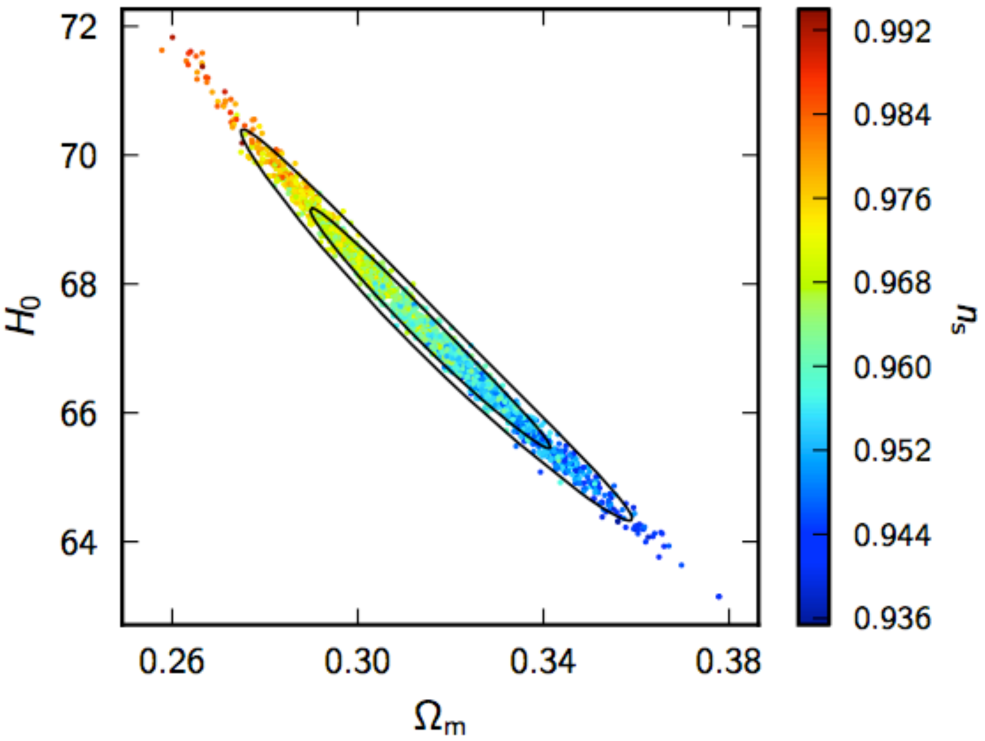


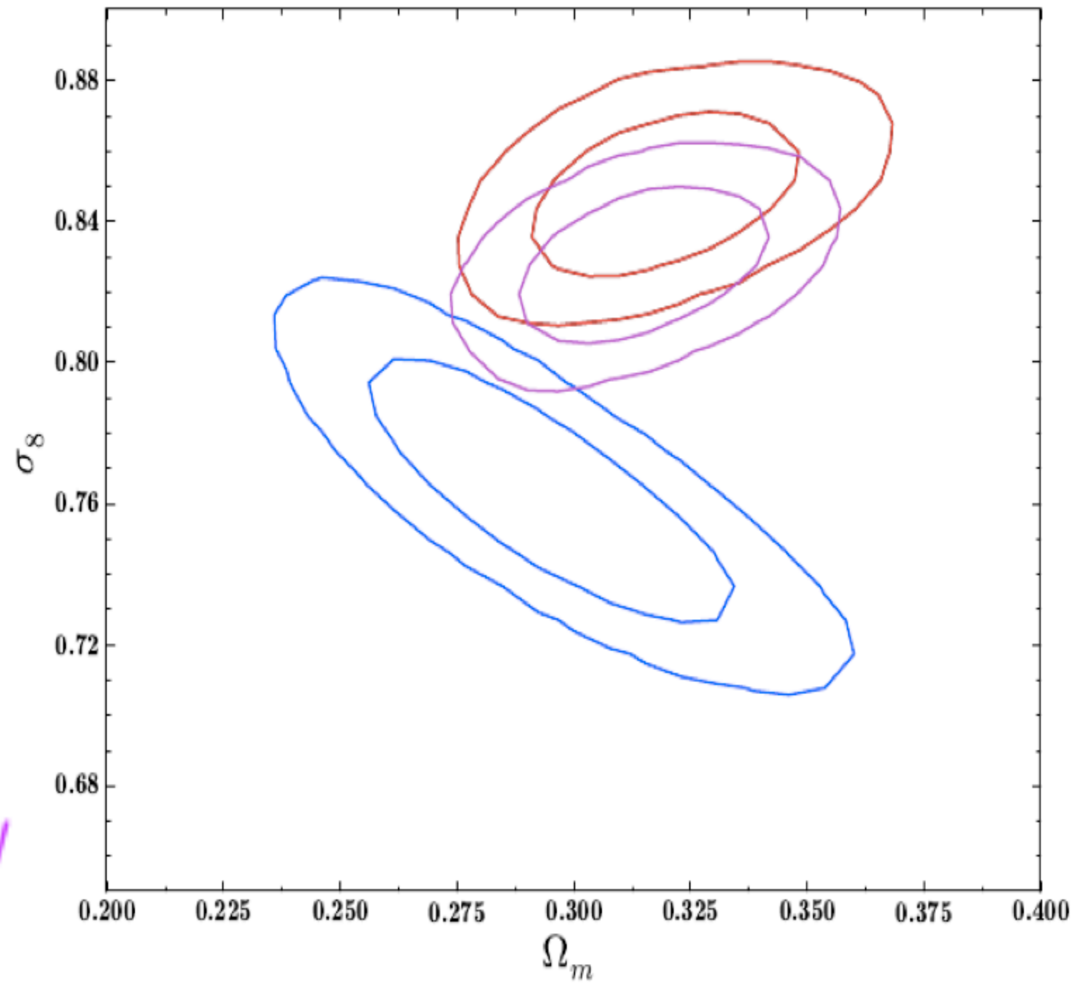
Fig. 3. Constraints in the Ω_m–H_0 plane. Points show samples from the *Planck*-only posterior, coloured by the corresponding value of the spectral index n_s. The contours (68% and 95%) show the improved constraint from *Planck*+lensing+WP. The degeneracy direction is significantly shortened by including WP, but the well-constrained direction of constant $\Omega_m h^3$ (set by the acoustic scale), is determined almost equally accurately from *Planck* alone.

- Omega_m & H_0 are degenerate, so an increase in the latter evokes a decrease in the former.
- The scalar spectral index is also affected.
- Many of the "differences" may have a single "root cause"

Planck Tension with ... Planck

- If 1-b=0.8, the primary CMB results imply twice the number of clusters actually detected.
  - 0.6 would be in agreement.
- These can be reconciled if Σm_ν~0.6
- Or if we still don't quite understand cluster physics perfectly...

σ_8-Ω_m constraints from primary CMB anisotropies and cluster number counts

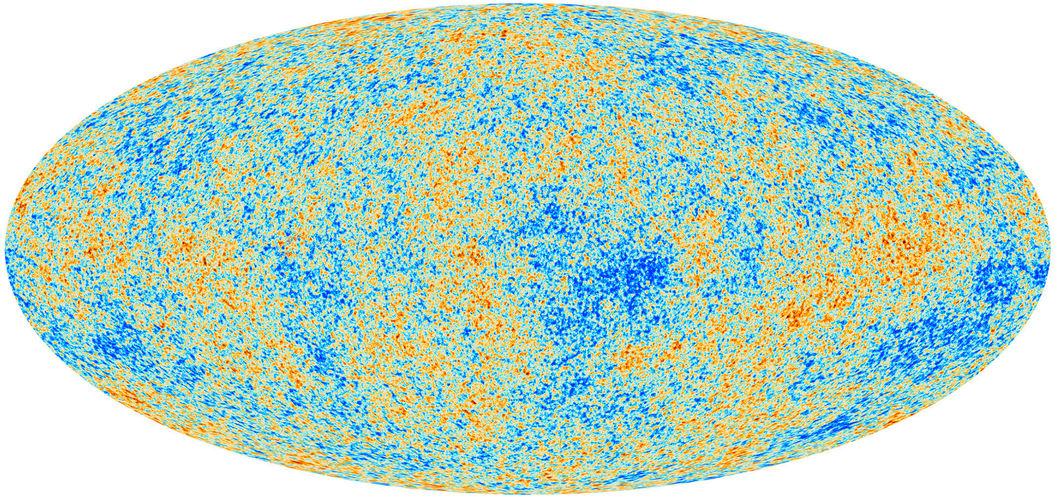


Planck CMB + Σm_ν=0 eV

Planck CMB + Σm_ν=0.06 eV

Planck cluster counts

Anomalies



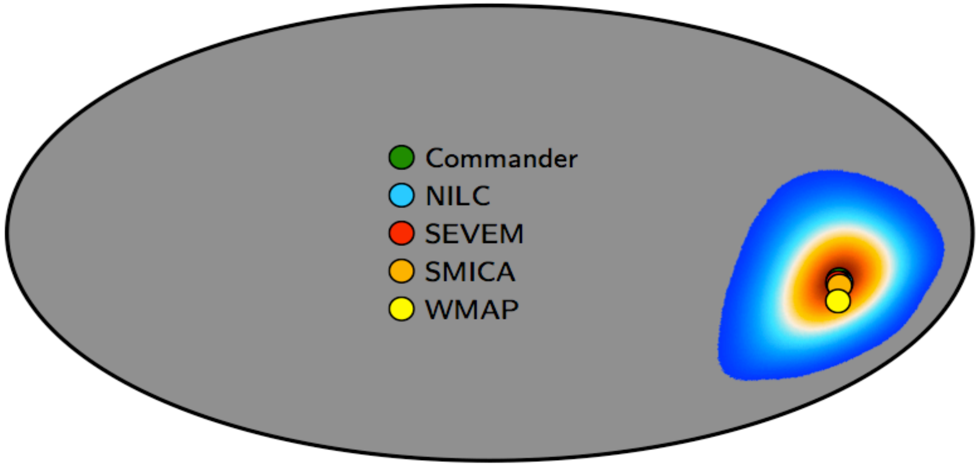
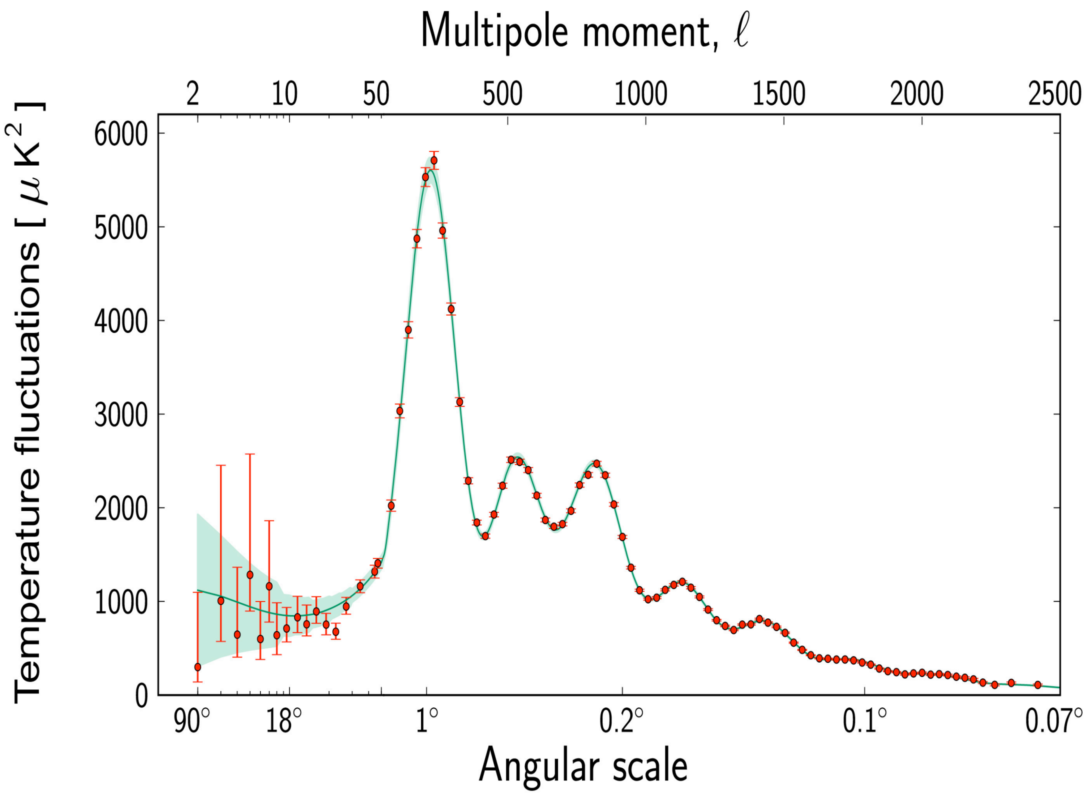


Fig. 32. Consistency between component separation algorithms as measured by the dipole modulation likelihood. The top panel shows the marginal power spectrum amplitude for the 5° smoothing scale, the middle panel shows the dipole modulation amplitude, and the bottom panel shows the preferred dipole directions. The coloured area indicates the 95% confidence region for the `Commander` solution, while the dots shows the maximum-posterior directions for the other maps.



- There are a few ~2-sigma "features" in the CMB maps from COBE, WMAP and now Planck that have intrigued people

Planck's Schedule

2011-today: Planck Early & Intermediate Papers

2013-03: Science papers; Data release 1 (15 months of data; no timelines; no polarization)

2013-14: More papers, including Galactic polarization

2014-10: Polarization Cosmology papers; Data release 2 (full mission, with timelines and polarization; but ***maybe*** something this summer...)

NEW! 2015 Release (at least some funding has been approved for a number of countries)

Archive/Legacy phase