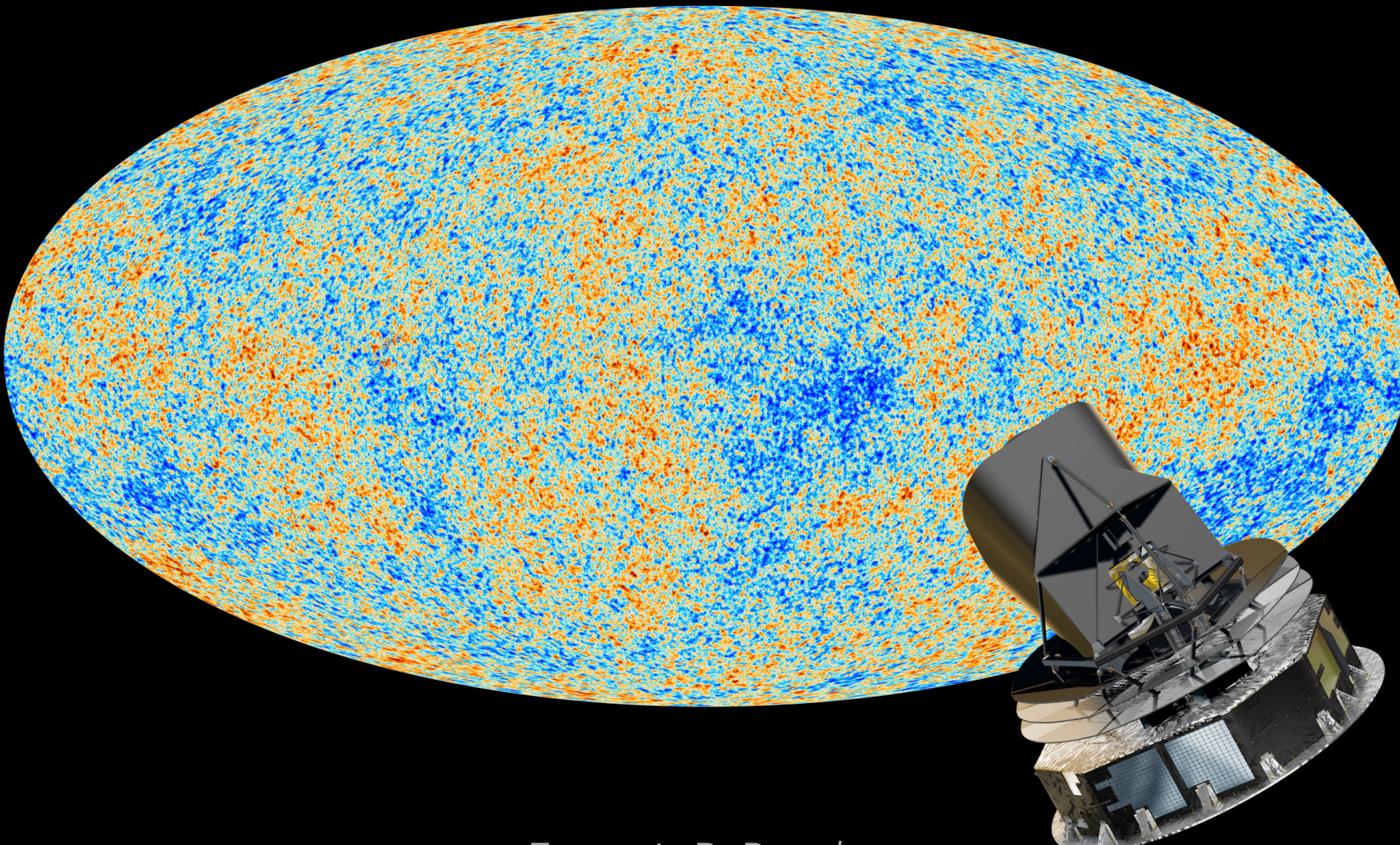
CMB: The Planck experiment status and prospects



François R. Bouchet

Some questions to address

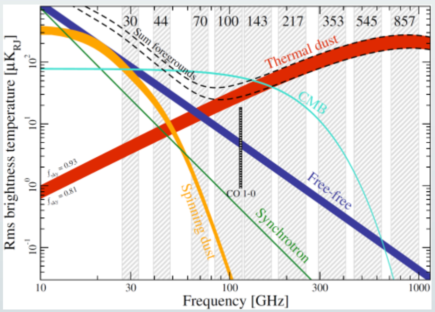
- How serious is the tension between LambdaCDM and cosmological observations ? [A. Riess]
- The Planck analysis assumes sum m_nu = 0.06 eV. How do the results change with the assumption sum m_nu = 0.6 eV? In particular, how do h and the spectral index n change? [B. Hoeneisen]

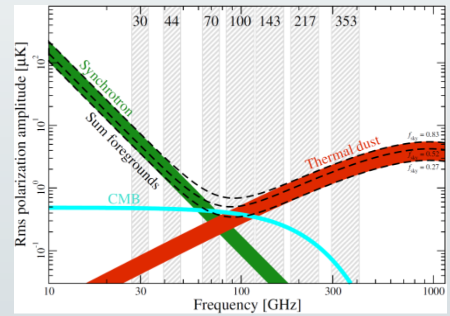
- Menu, based on P15+16+Latest_ext
  - *Quick overview of main cosmological results*
  - *Are the derived results as accurate as they are precise?*
  - *Is there any fly in the ointment?*
  - *What to expect next from Planck?*

Planck in brief

Main goal: *to image the temperature and polarization of the CMB over the whole sky at 5' resolution with a large frequency coverage and a sensitivity limited by cosmic variance and the ability to remove the astrophysical foregrounds*.

- 3rd generation full sky satellite; 2 Instruments, 9 frequencies.
  - ***LFI:*** *22 radiometers at* ***30, 44, 70 Ghz.***
  - ***HFI:*** *• 50 bolometers (32 polarized)* ***at 100, 143, 217, 353, 545, 857 Ghz*** *(30-353 Ghz polarized)*

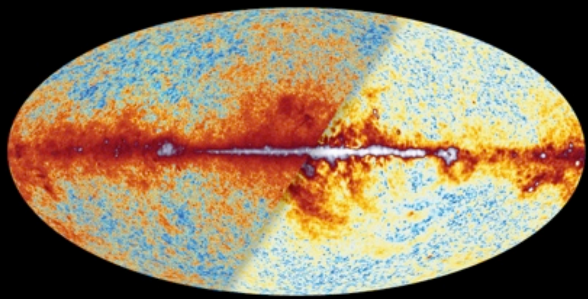




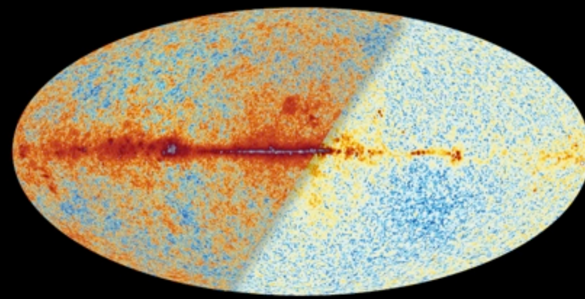
- May 1993 . . . . . ESA Proposals for COBRAS (LFI) and SAMBA (HFI) submitted
- Jul 1996 . . . . . . (Combined) Project selection as M3
- 14 May 2009 . . .Launch
- 27 Nov 2010 . . . End of nominal mission, start of extended mission
- 14 Jan 2012 . . . .End of cryogenic mission, start of warm phase
- 23 Oct 2013 . . . .Last command

- Mar 2010 . . . . . First (of 15) internal data releases
- Mar 2013 . . . . . Nominal Mission data release (temperature, PR1)
- Aug 2015 . . . . . Extended mission data release (PR2)
- Jul 2018 . . . . . . .Legacy data release (PR3)

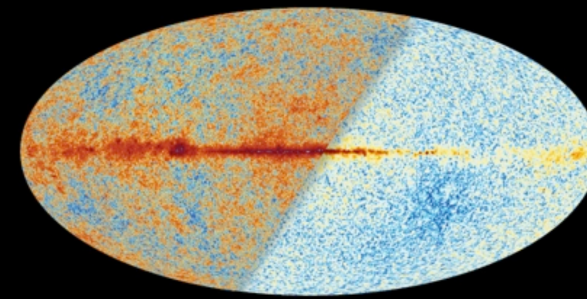
Planck 2015 maps (←pla.esac.esa.int)



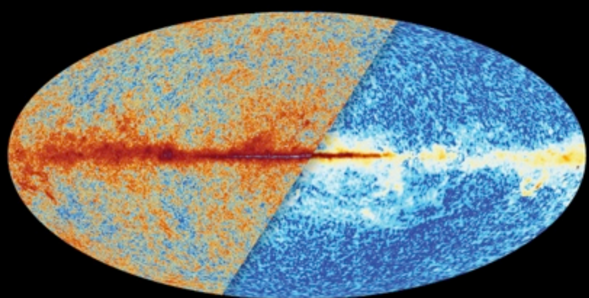
30 GHz



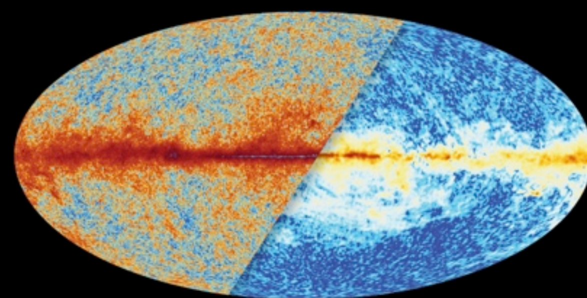
44 GHz



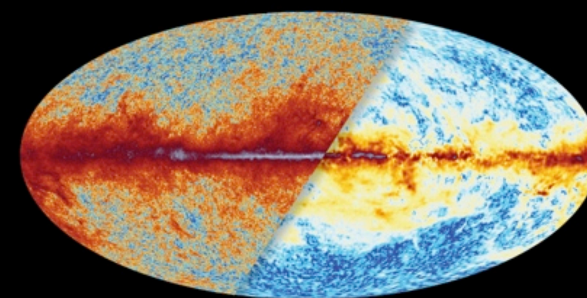
3.5μK.deg,13’ 70 GHz



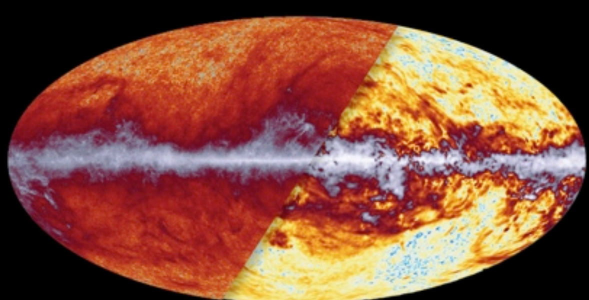
1.3μK.deg,9.7’ 100 GHz



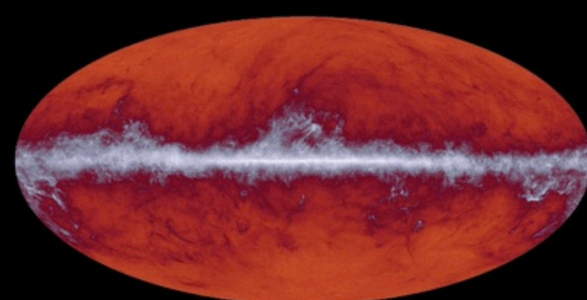
0.5μK.deg,7.3’ 143 GHz



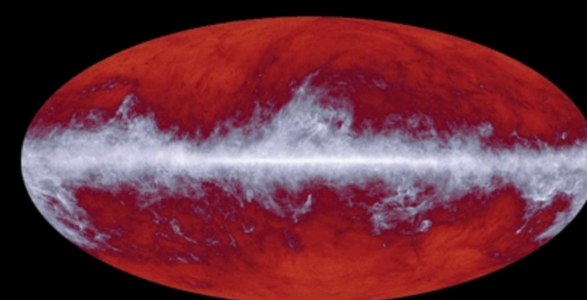
0.8μK.deg,5.0’ 217 GHz



353 GHz

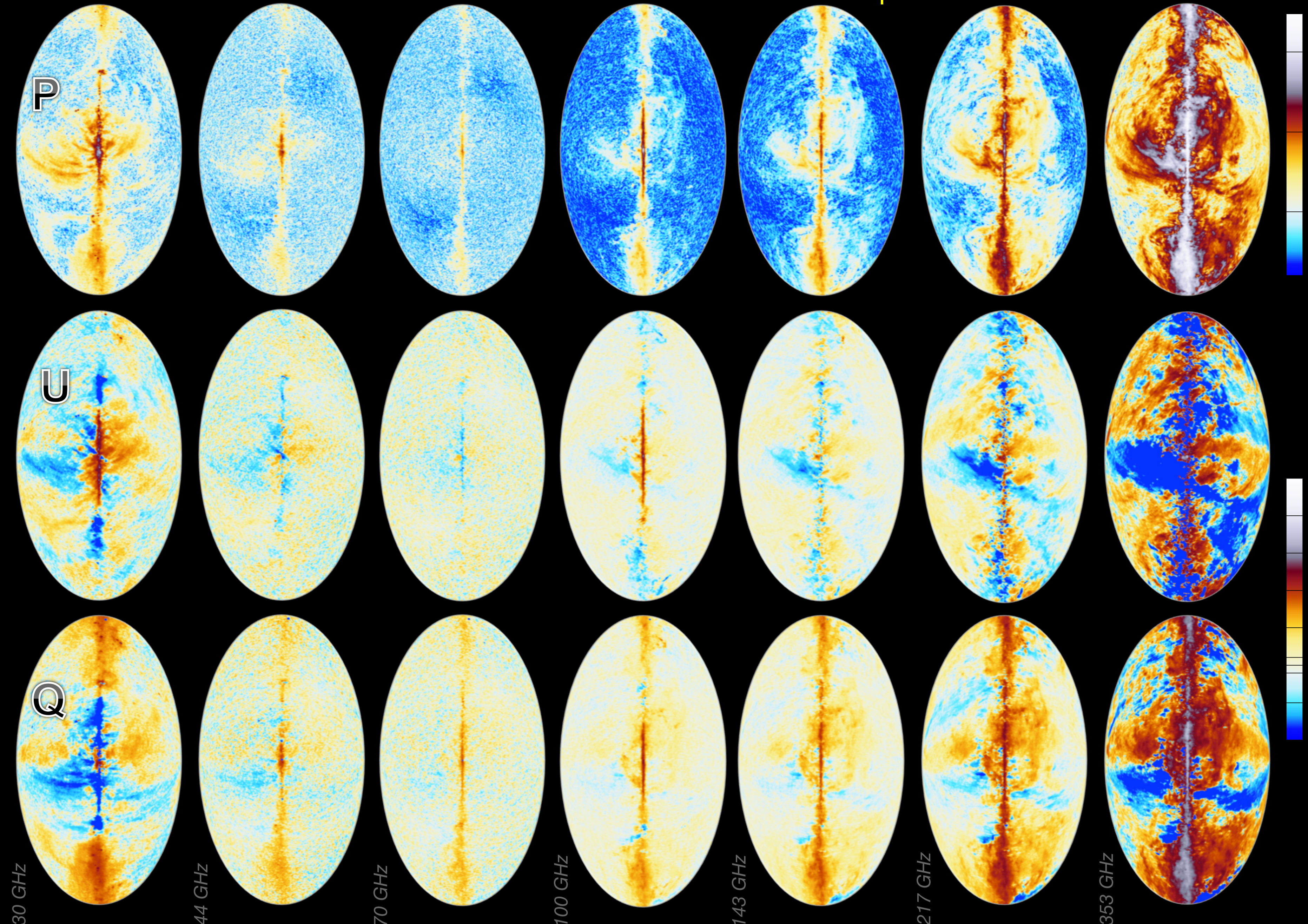


545 GHz

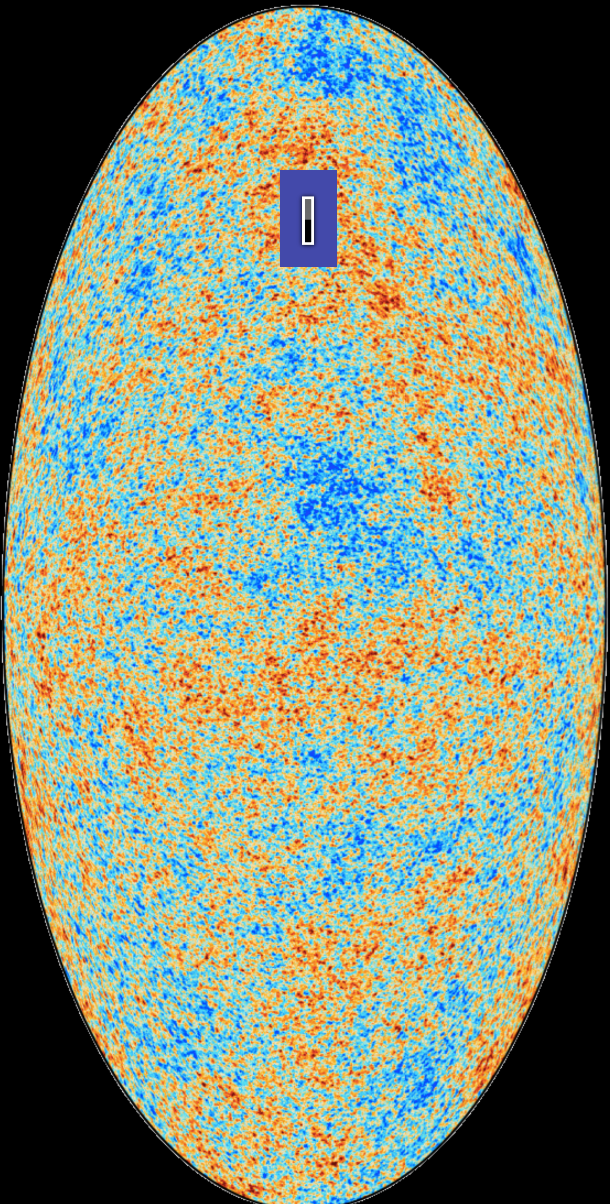


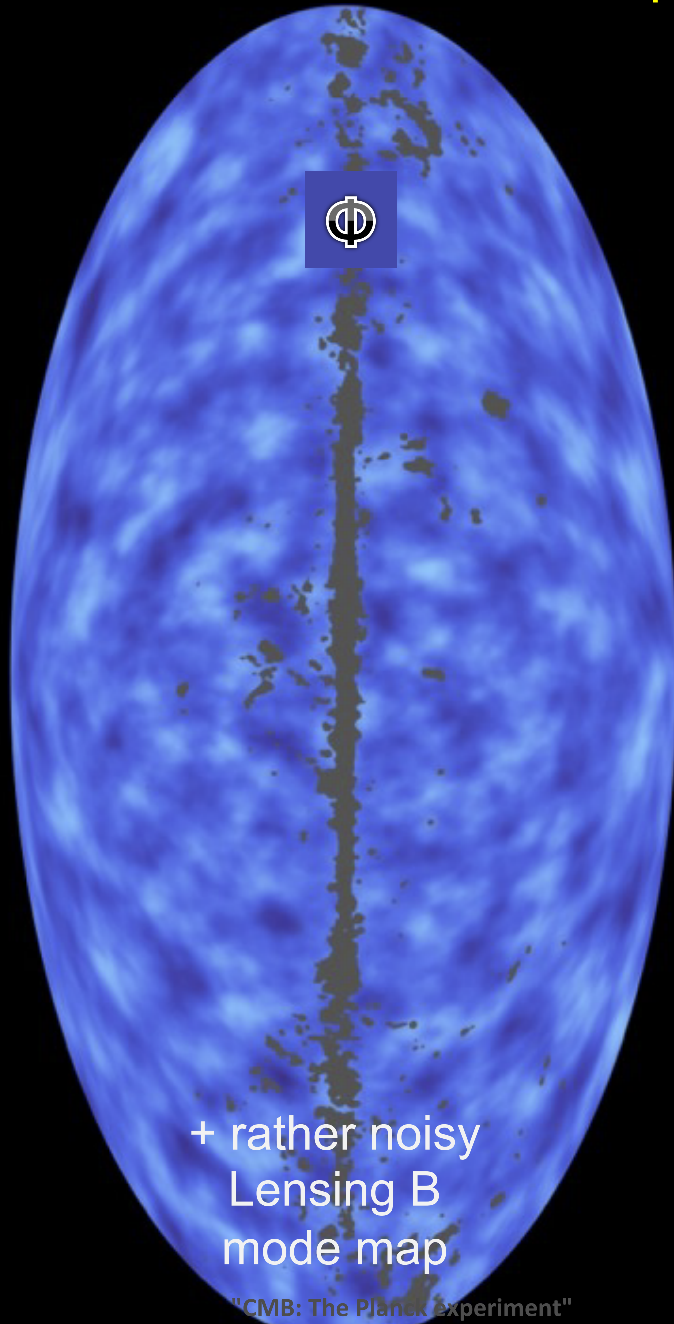
857 GHz

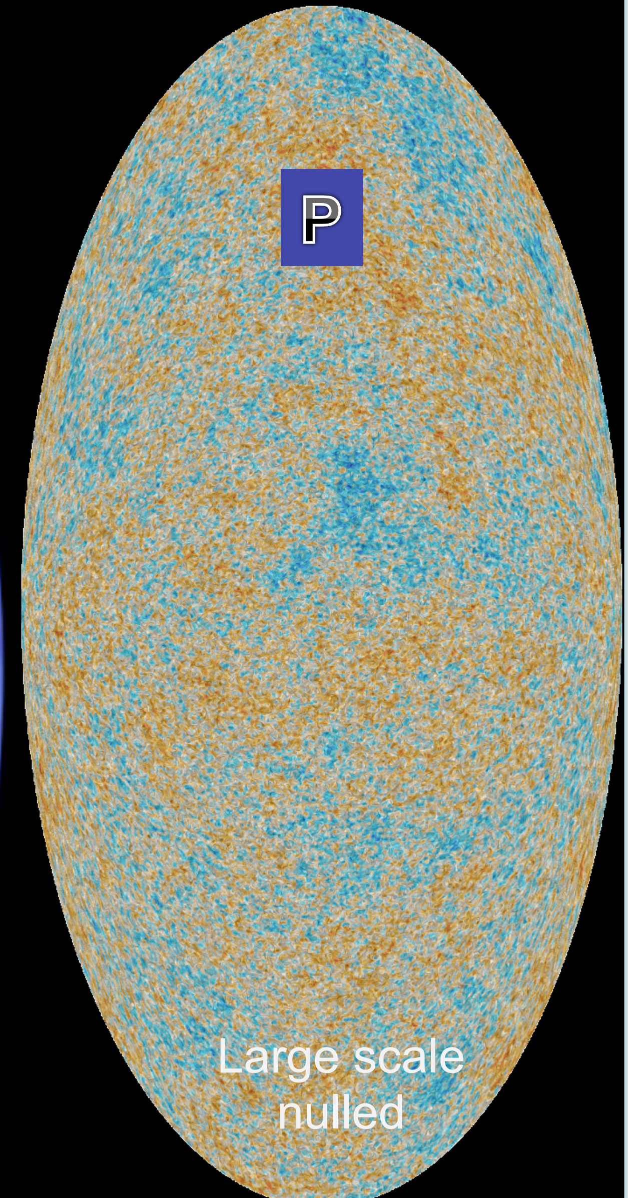
Planck 2015 Polarisation maps



Planck 2015 CMB maps







P15 SIMULATIONS

Roles & Specifications

ROLES

1. Code validation & verification: requires **accurate** fiducial simulation
2. Data uncertainty quantification & debiasing: requires **massive** MC
3. Knowledge transfer

SPECIFICATION

1. Instrument model:
   a. Satellite focal plane, pointing & flags
   b. Detector beams, band-passes & noise
2. Sky model:
   a. Foregrounds
   b. CMB
3. Processing:
   a. Replication of *both* DPC's processing
   b. At massive scale

Improved 10-component model:

1. CO lines
2. Cosmic Infrared Background
3. Free-free
4. Point Sources (Infrared)
5. Point Sources (Radio)
6. Spinning dust
7. Sunyaev-Zel'dovich (Kinetic)
8. Sunyaev-Zel'dovich (Thermal)
9. Synchrotron
10. Thermal dust

esa

FFP8 Fiducial Realization

planck

360 timelines:

1. 3 x CMB
2. 2 x Foreground

16 map flavors:

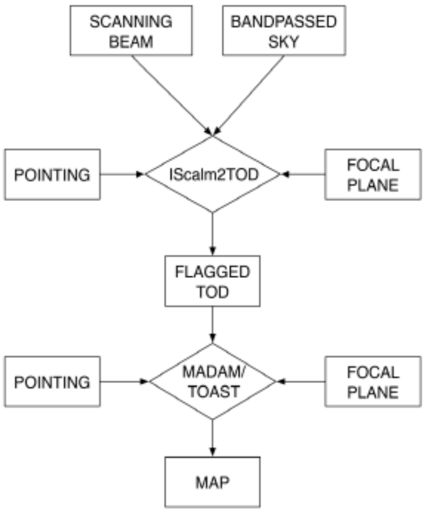
1. 6 x component (CMB, Foreground, Noise)
2. 10 x total: (5 x [r, f_{NL}]) x (2 x FG)

1,134 data combinations:

. Frequency channel & detset
. Mission, half-mission, year & survey
. Full & half-ring

18,144 maps

250K NERSC CPU-hours



esa

LFI HFI PLANCK

CMB Monte Carlos

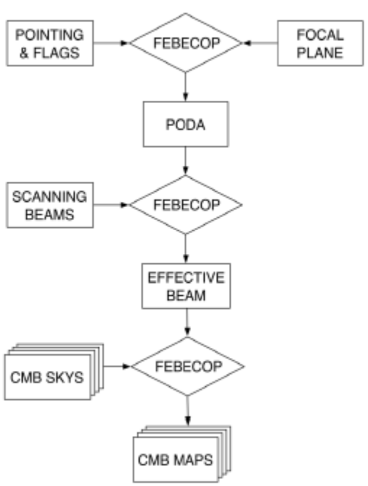
planck

FFP8 contains:

1. 10^4 mission channel full maps
2. 10^4 half-mission channel full maps
3. 10^4 mission (some) detset full maps

460,000 maps

8M NERSC CPU-hours



Noise Monte Carlos

planck

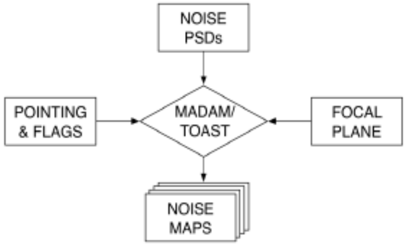
FFP8 contains:

1. 10^4 mission channel full maps
2. 10^3 other full maps
3. 10^2 half-ring maps.

671,400 maps

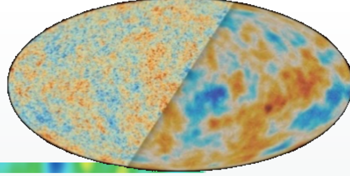
12M NERSC/CSC CPU-hours

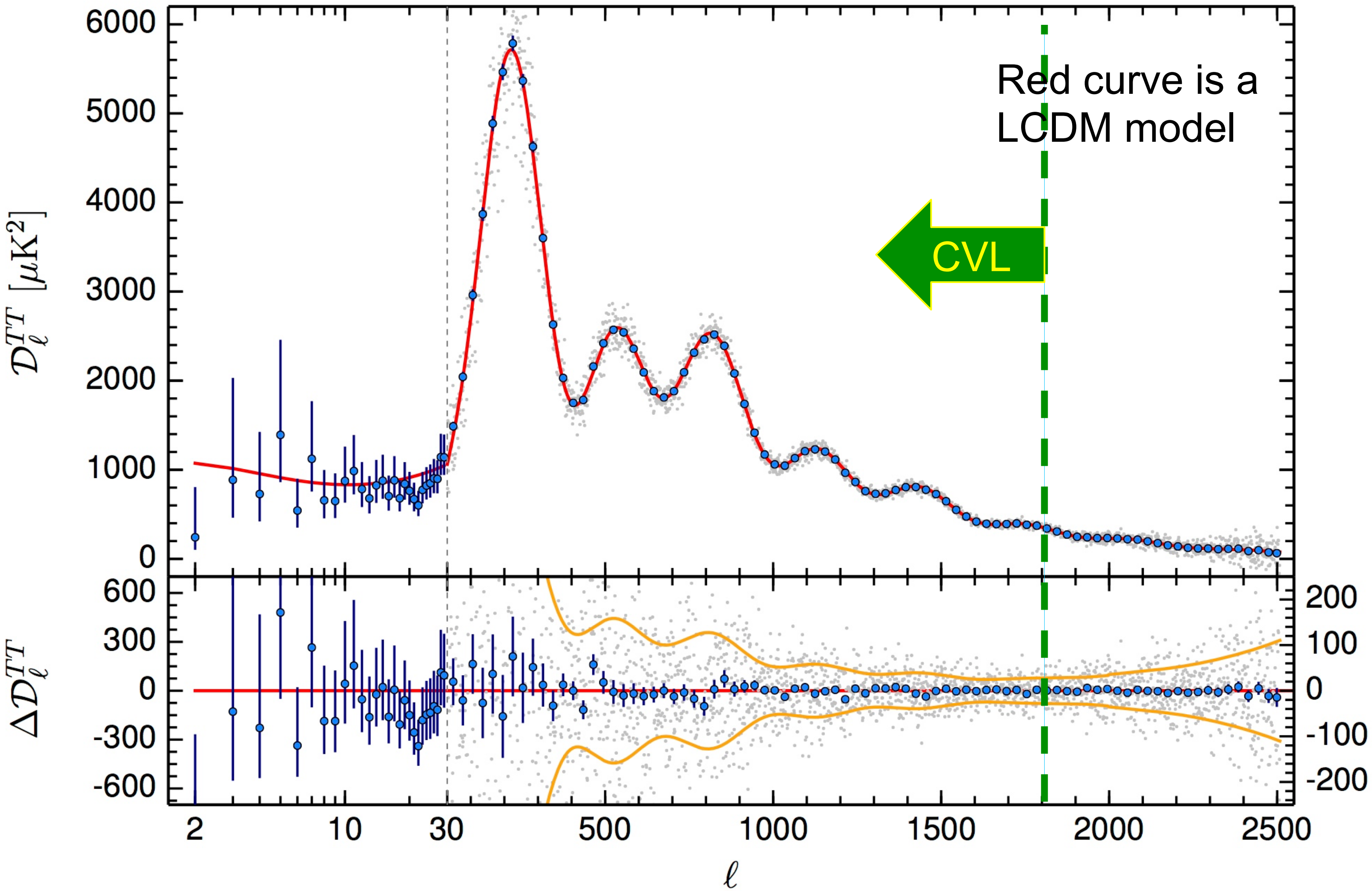
(10K maps/hour)



+ Dedicated ones (of instrumental effects) to determine what to simulate massively

Planck 2015 TT spectrum

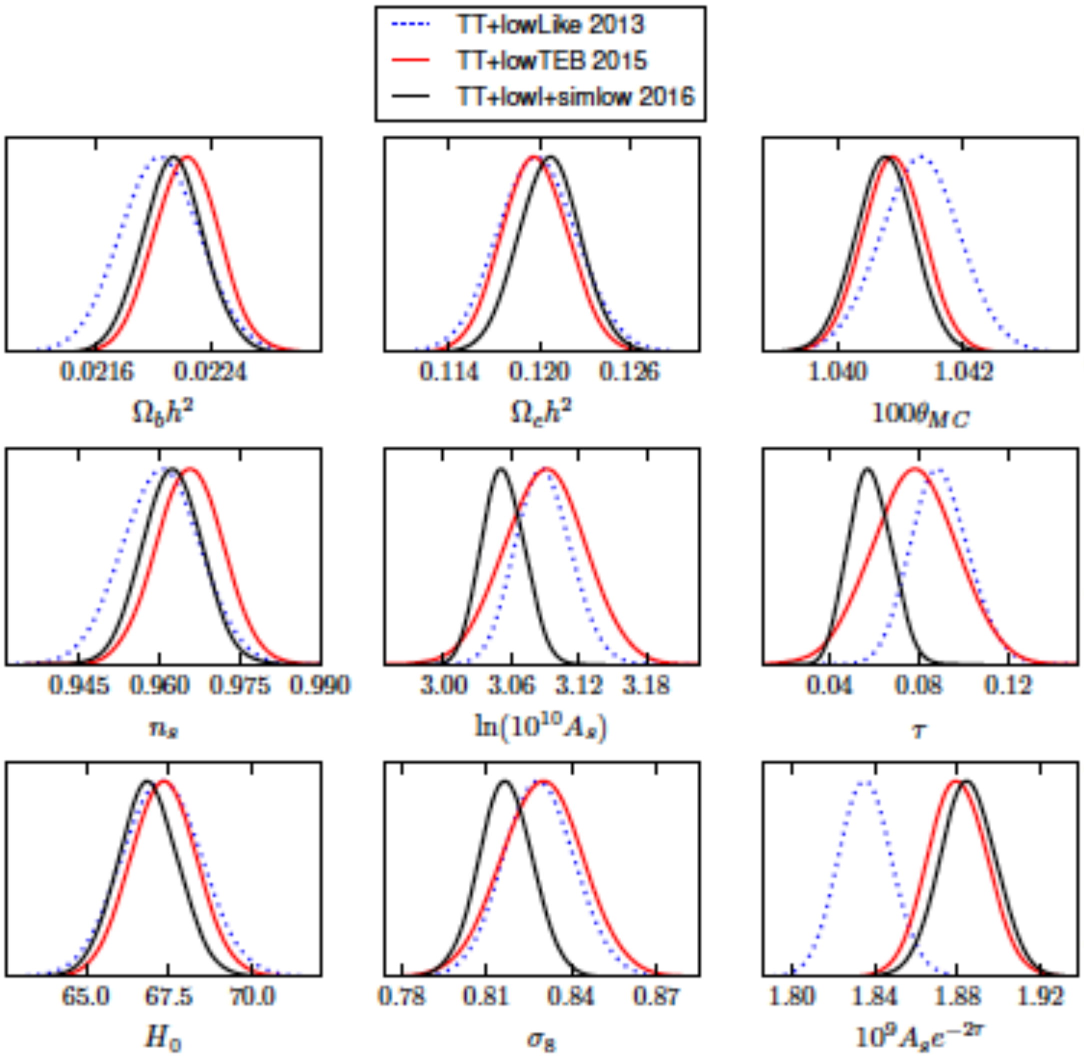




8 acoustic peaks well detected

CVL till l=1800 (l~1600 on 40-70% of the sky)

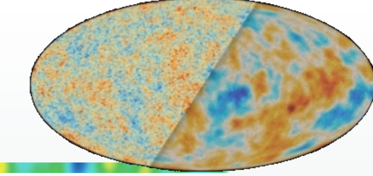
ΛCDM TT results 2013, 2015, 2016



- 2013 -> 2015 from nominal mission (~1yr of data) to full mission (~2yr of data for HFI)
- 2013 -> 2015 1% re-calibration at map level (near sidelobes, VLT, from solar to orbital dipole).
- Optical depth to reionization τ from WMAP->LFI->HFI
- 2015 vs 2016 results: 0.5σ lower H_0: 67.3±0.96 -> **66.8±0.91 Km/s/Mpc**
- 1σ lower σ_8, 30% smaller error bar: 0.829±0.014->**0.8167±0.0095**

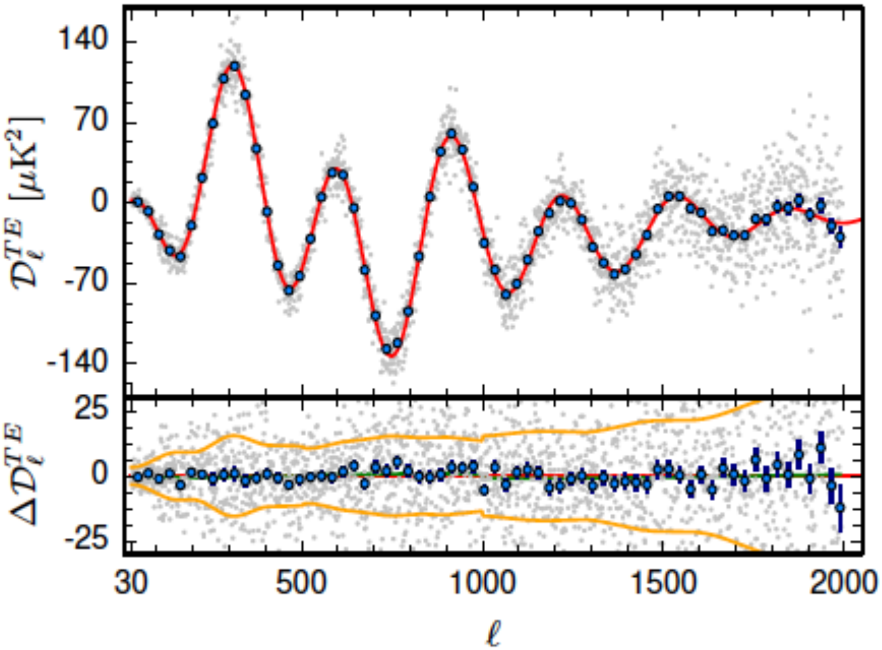
LCDM excellent fit to the data (TT PTE=17%), no significant deviation in extended models, parameters measured at percent and subpercent level

Very stable results across releases, shifts well understood.

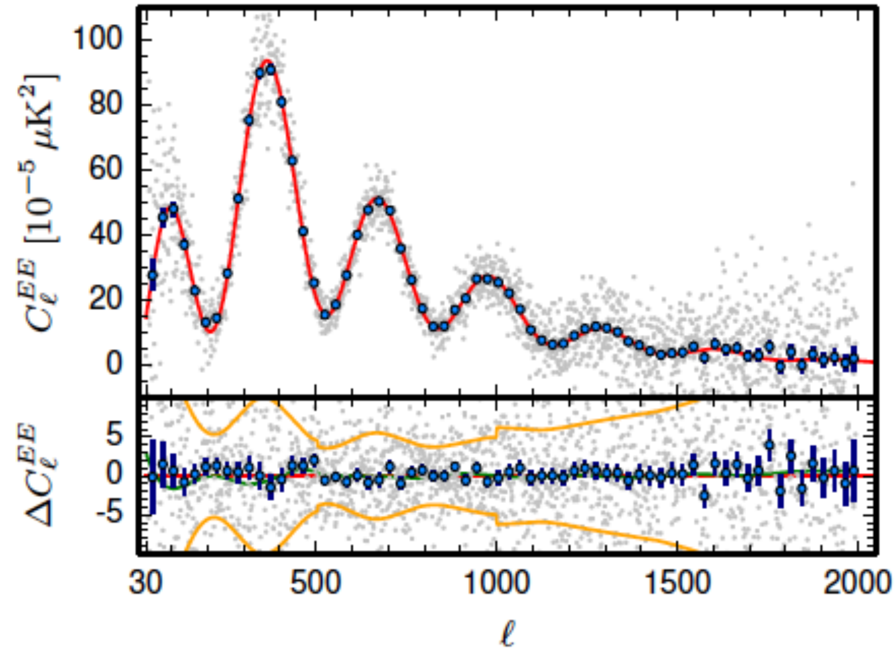


Planck 2015 - TE & EE spectra

(Planck 2015 XIII)



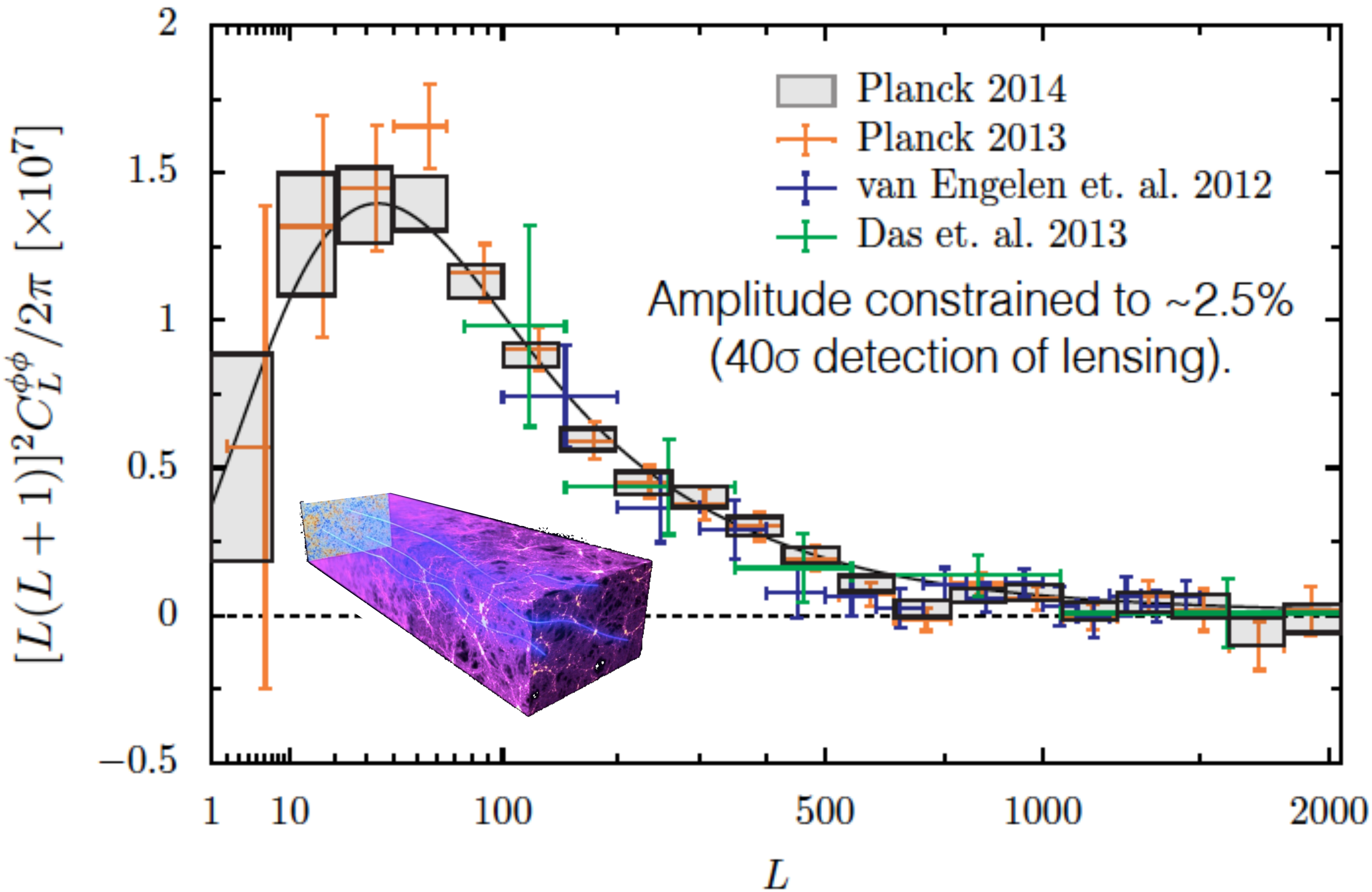
Frequency averaged spectrum reduced ^{2} = 1.04



Frequency averaged spectrum reduced ^{2} = 1.01

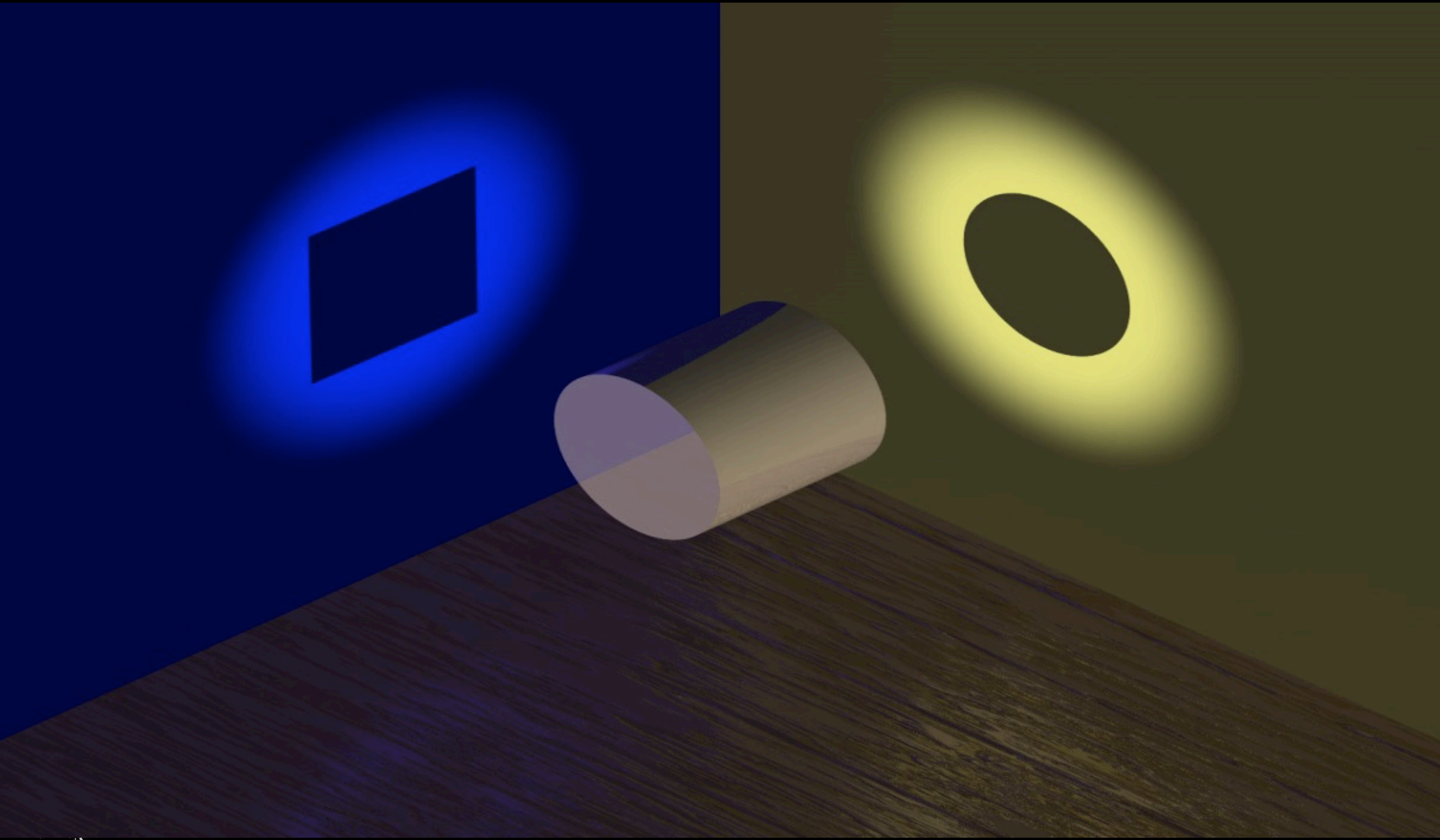
- Red curve is the *prediction* based on the best fit TT in base ΛCDM
- Albeit *magnificent*, 2015 polarisation data and results are *preliminary* because all systematic and foreground uncertainties have not been *exhaustively* characterised at levels below O(1μK^2).

2015 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

I, P, Phi are quite consistent within LCDM.
It could have been otherwise!

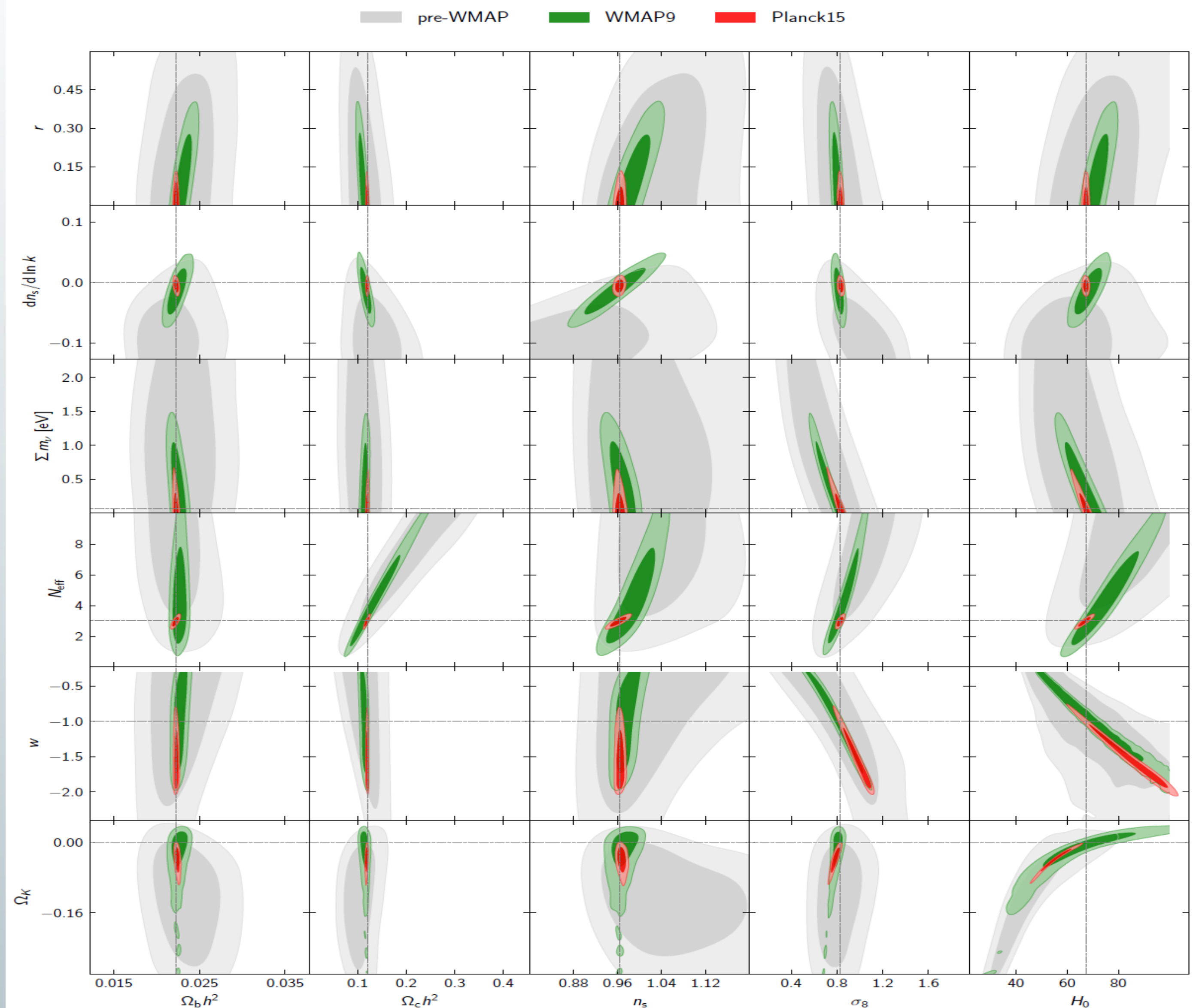


And it further constrains potential deviations from the base tilted LCDM model/physics

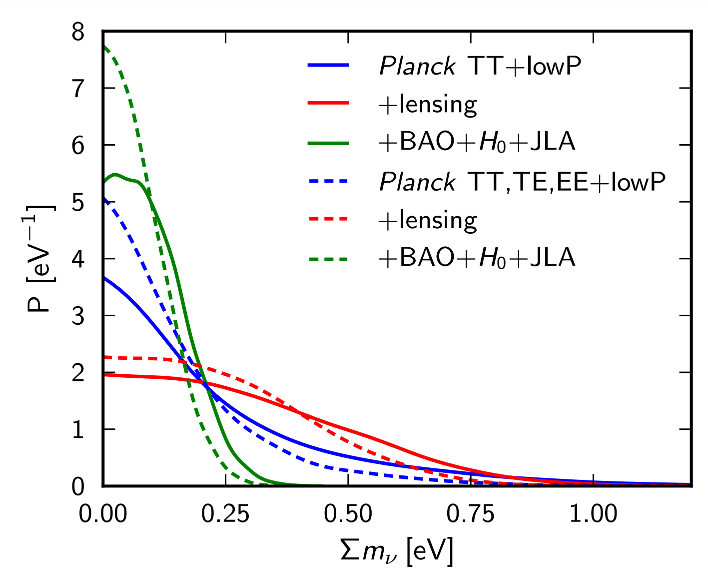
Zooming in LCDM…

- Each row shows the constraints on a specific 1-parameter extension to LCDM (from top: r, dns/dlnk, Σm_ν , w, Ω_K) versus standard LCDM ones (dotted BF).
- Contours at 1 &2σ are from
  - *pre-WMAP (grey),*
  - *WMPA9 (green)*
  - *Planck15 (red)*

  (No extension)

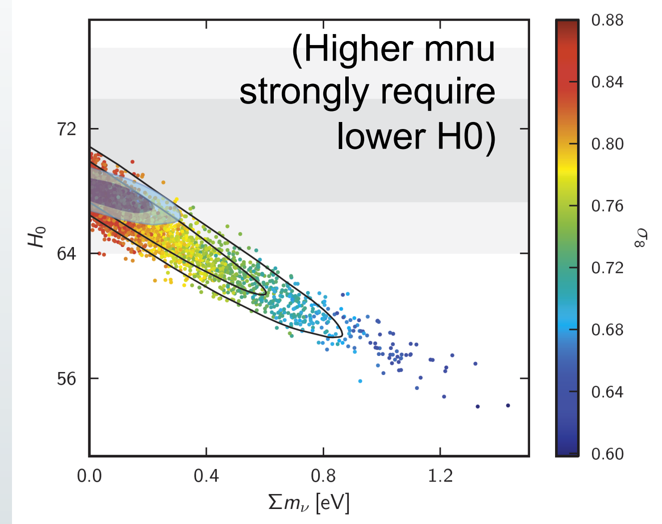


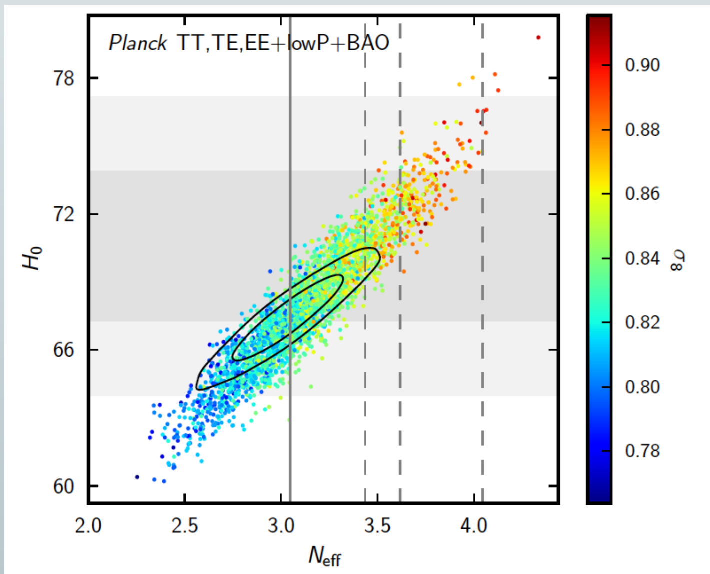
Neutrinos extensions to base LCDM



$\sum m_\nu < 0.23\,\mathrm{eV}$
(95%) is from TT+lowP+lensing +ext *[P15 XIII]*

$\Omega_\nu h^2 < 0.0025$
(slight tightening With TE & EE)





$N_{eff} = 3.15 \pm 0.23$

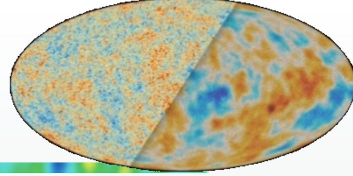
$N_{\rm eff} > 0$ at ~ 15σ
$N_{\rm eff} = 4$ excluded at 3-5 σ (P)

Large $N_{\rm eff}$ would allow larger H_0 & alleviate tension with direct measurement, but would require large σ_8

$c^2_{eff} = c^2_{vis} = 1/3$ to within 2% and 10% resp; Free-streaming particles have (1/3, 1/3), a perfect fluid would have (1/3, 0).

NB: In Planck base LCDM, we assume 3 (quasi-)degenerate neutrinos, imposing Mnu=0.6eV

For Bruce Hoeneisen



By using base_plik_HM_TT_lowTEB_BAO on base LCDM, one finds

H_0	67.65	67.63 ± 0.57
n_s	0.96747	0.9673 ± 0.0045

$\bar{\chi}^2_{\rm eff} = 11286.37;\ R-1 = 0.01395$

i.e., with the standard assumption sum m_nu = 0.06 eV.

If one assumes instead sum m_nu = 0.6 eV, one finds

H_0	65.17 ± 0.55
n_s	0.9797 ± 0.0047

$\bar{\chi}^2_{\rm eff} = 11313.01;\ R-1 = 0.01804$

H_0 goes as expected towards lower values (since anti-correlated), even more than the case in which mnu is a free parameter.
n_s is barely changed.

Summary on primordial non-gaussianity

- Single field slow-roll inflation survived the most stringent test of Gaussianity performed to date; NG constraints severely limit alternatives.

- The new LEO trio: $f_{NL}^{local} = 2.7\pm5.8$, $f_{NL}^{equi} = -42\pm75$, $f_{NL}^{orth} = -25\pm39$

- Model independent 3 dimensional reconstruction (modal&binned) → no new types (/LEO) at low-ell, but interesting hints a higher-l
- Constraints on signatures from key specific scenario, including
  - *General single field, including non-separable shapes*
  - *Excited initial states (Non-BD) – no indication*
  - *Directionally dependent vector model*
  - *Initial scout of scale dependent feature and resonant models*
- Limits on 4 points , $\tau_{NL} < 2800$ (95%CL) (ok / f_{NL}^2)

- Ekpyrotic/cyclic models are not favoured (predict local non-Gaussianity; either ruled out or under pressure)

A perfect (-ly boring) Universe?

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

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

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

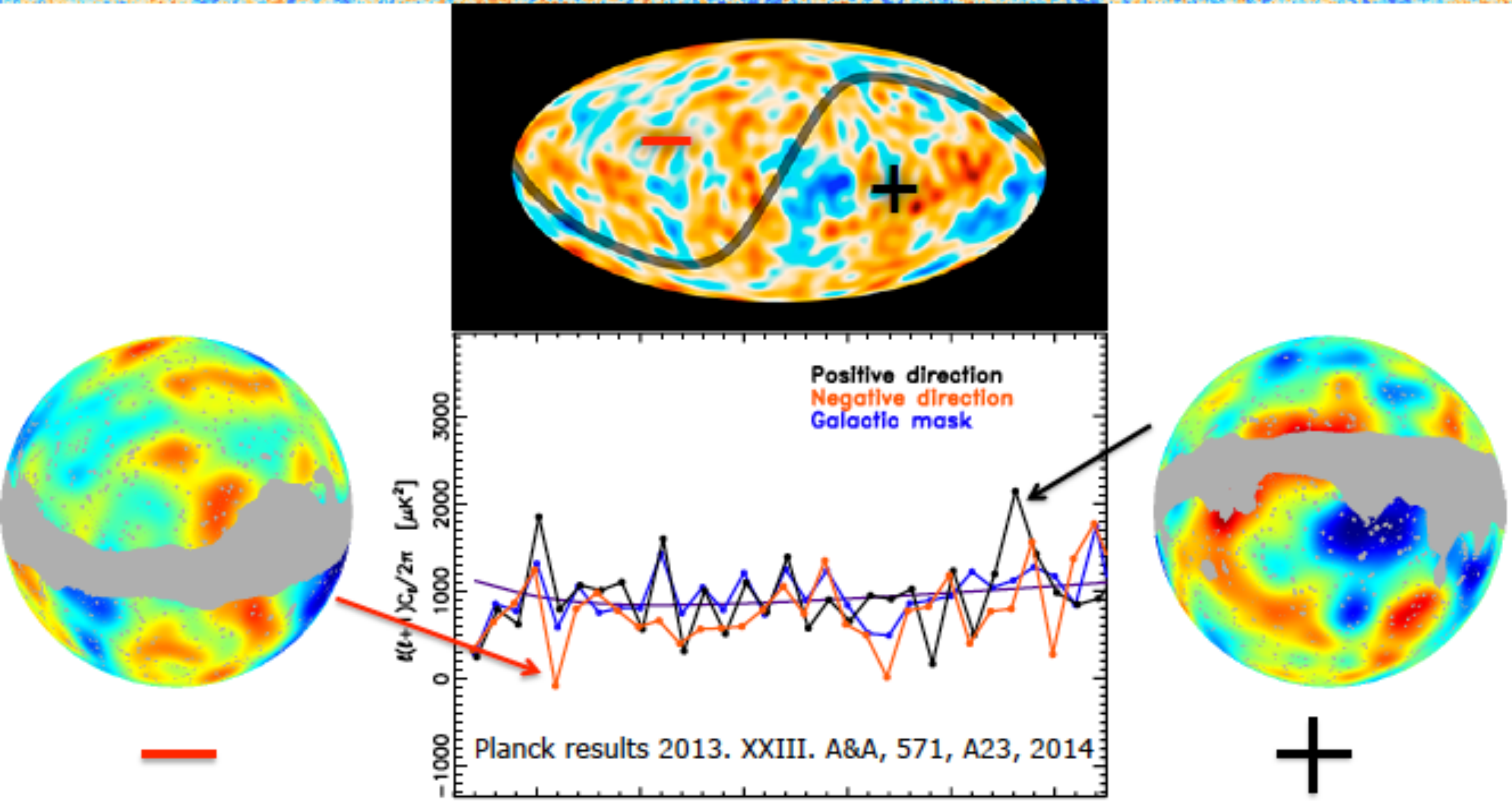
$\alpha_{\rm ISO}$
α (Fine structure constant)
$P_{\rm ann}$
C_s (for MG)
$c^2_{\rm eff} = c^2_{\rm vis} = 1/3$ for nu's
$A_{2s\text{->}1s}$
…

+ all others obtained by the community!
(Specific theories, specific data combinations, new data…)

Anomalies *[Planck 2015 XVI]*

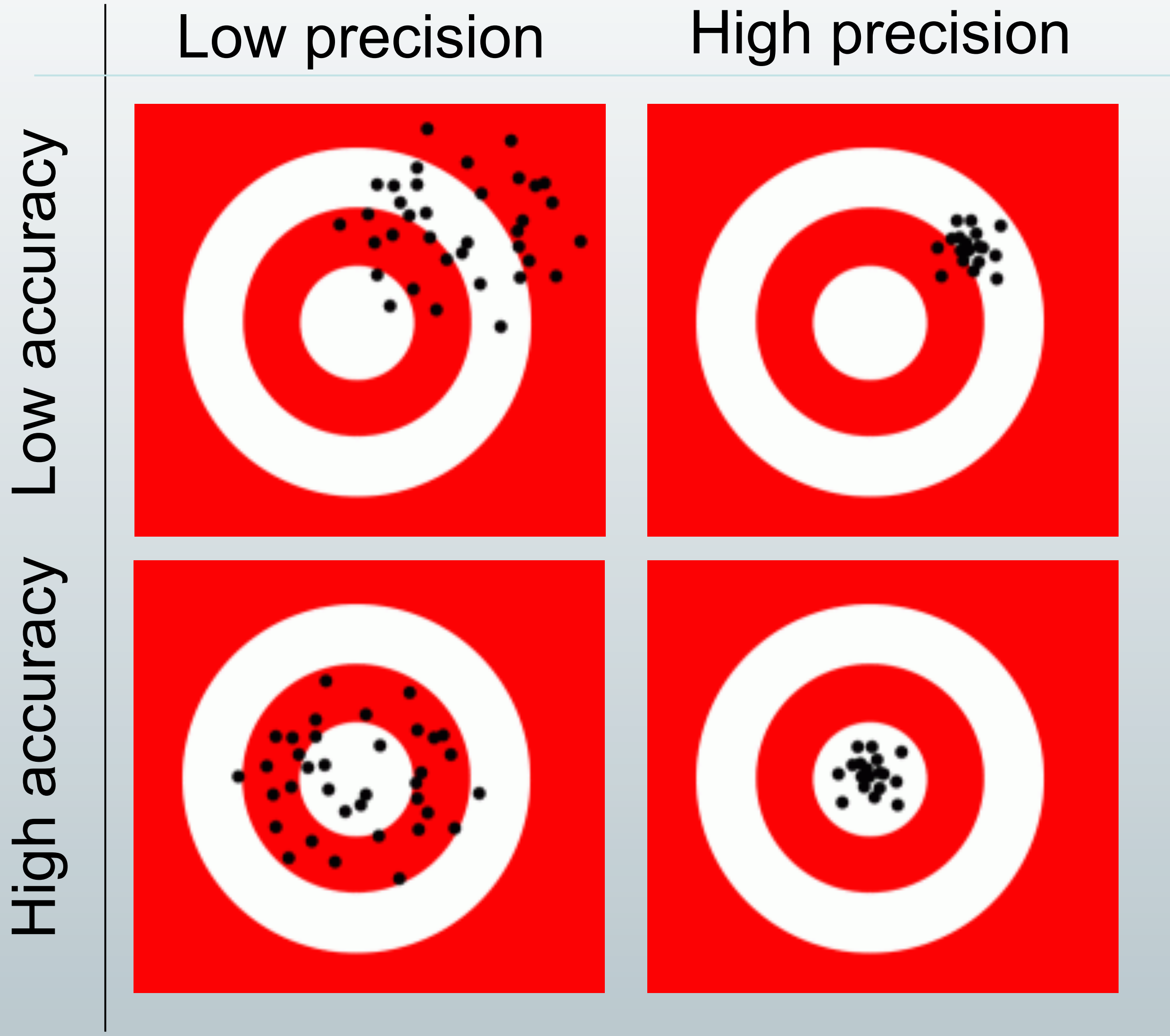
- Some large scale anomalies detected pre-Planck were confirmed and significance often increased (in particular since BF model is better determined)
  - *Power deficit at low-ell*
  - *Power asymmetry between hemisphere*
  - *Low multipoles alignment*
  - *Dipolar modulation*
  - *Low variance*
  - *Cold spot*
  - *Point parity and mirror-parity asymmetry*
- Planck provides high confidence in their existence due to two independent instruments, the quality of data, the unprecedented coverage of Foregrounds…
- No compelling explanation
  - *Statistical fluke in LCDM is quite possible (NB: A_lens)*
  - *Secondary effect apparently too weak*
  - *Foregrounds are well controlled (and systematics essentially ruled out)*
  - *Of course, tantalising possibility of new physics, But CV, a posteriori, etc.*

Power asymmetry in *Planck* 2013 nominal mission data

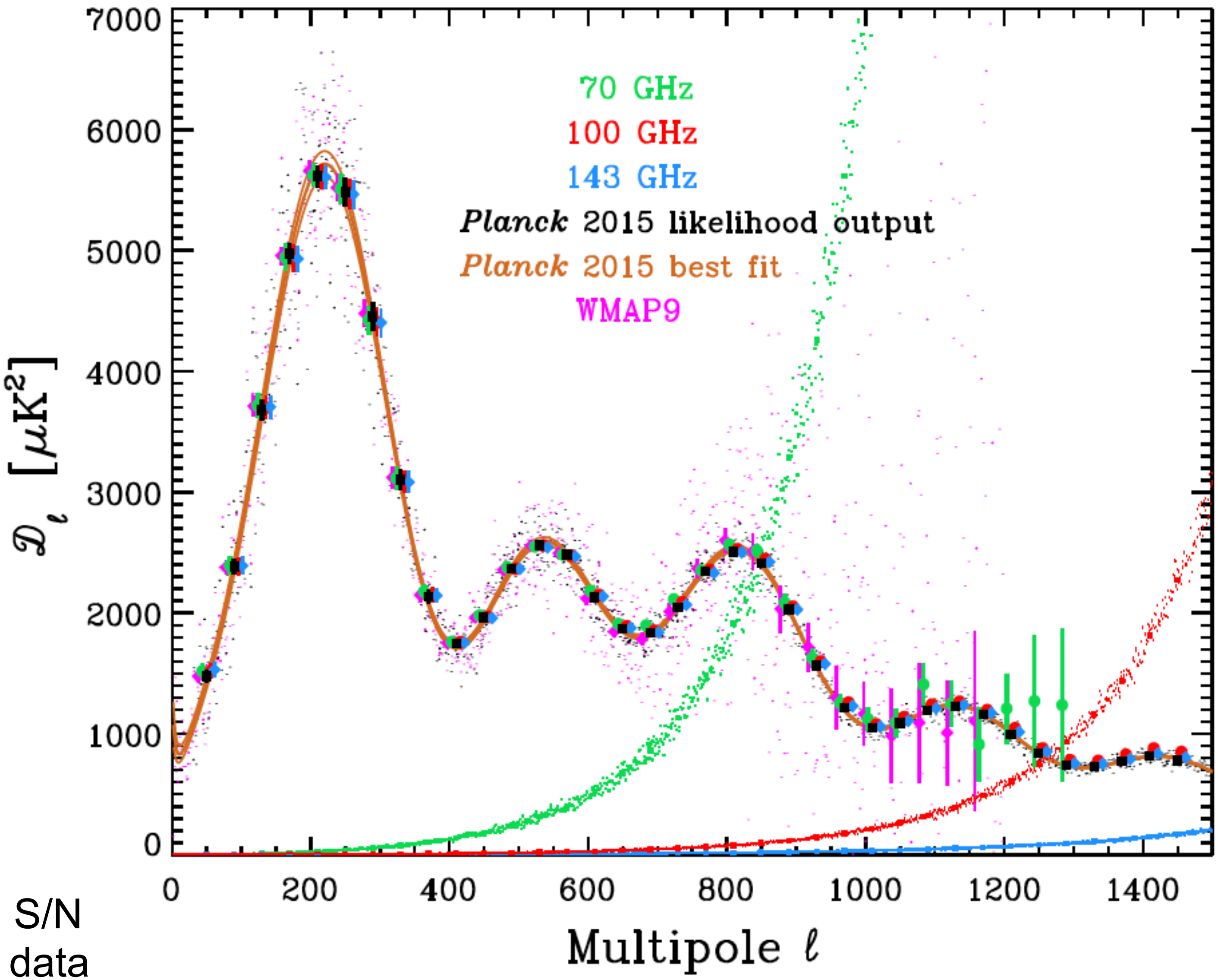


Large scale feature in 2015 full mission data are very similar to those in 2013 nominal mission data

Precision versus accuracy



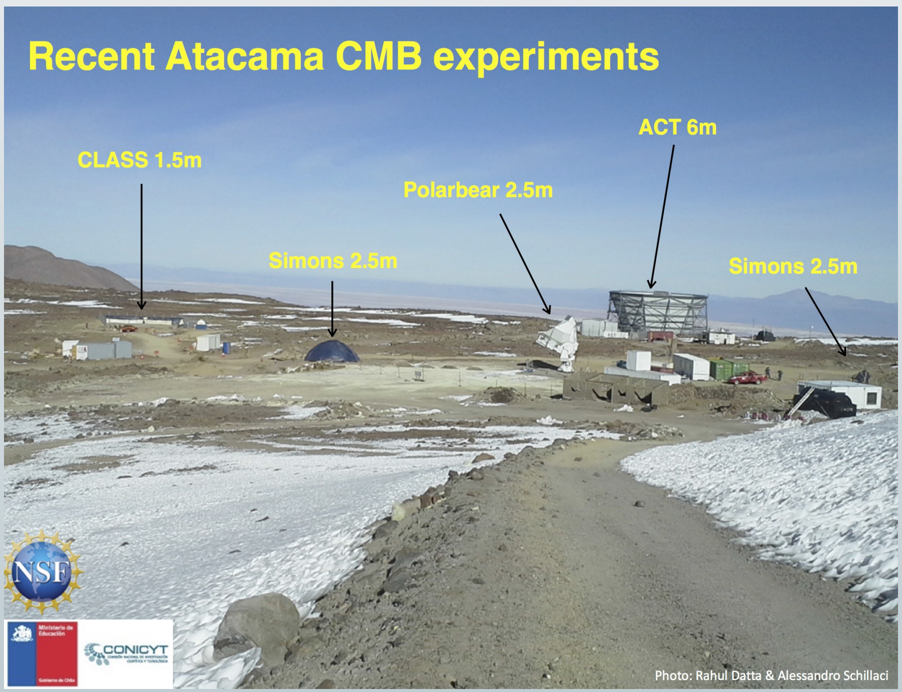
Channels consistency / noise levels

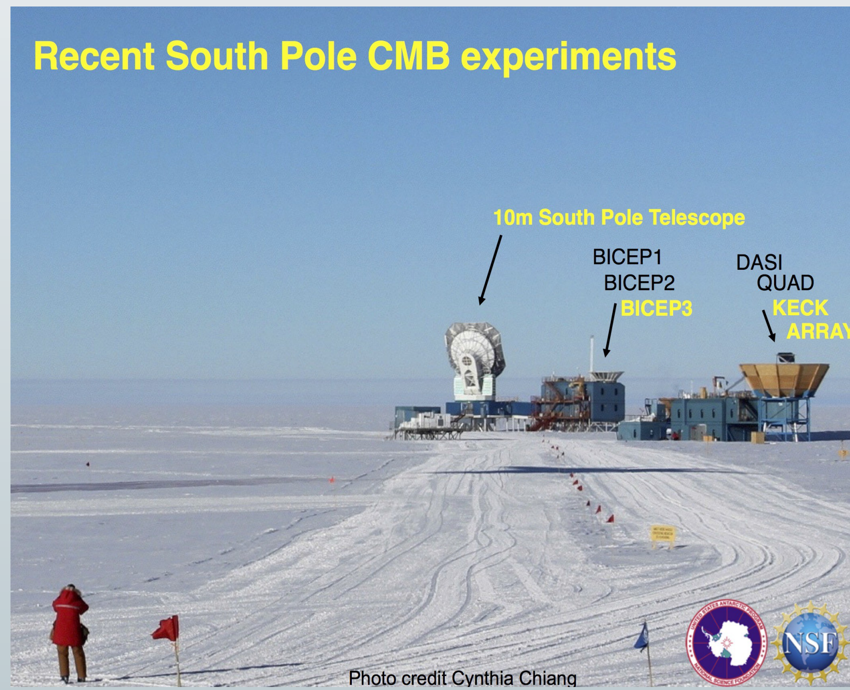


Many high S/N
redundant data

Higher-ell Comparisons

- ACT= Atacama Cosmology Telescope: a 6m telescope in Chile. Had results from TT at 148 and 217GHz on ~500 sq.deg. Recently published polarisation from ACTPOL (*Louis+ arXiv:1610.02360*)
- SPT=South Pole Telescope: a 10m telescope at S.Pole. *Hou+ arXiv: 1704.00884, Aylor+ arXiv:1706.10286, Henning+ arXiv: 1707.09353v3*

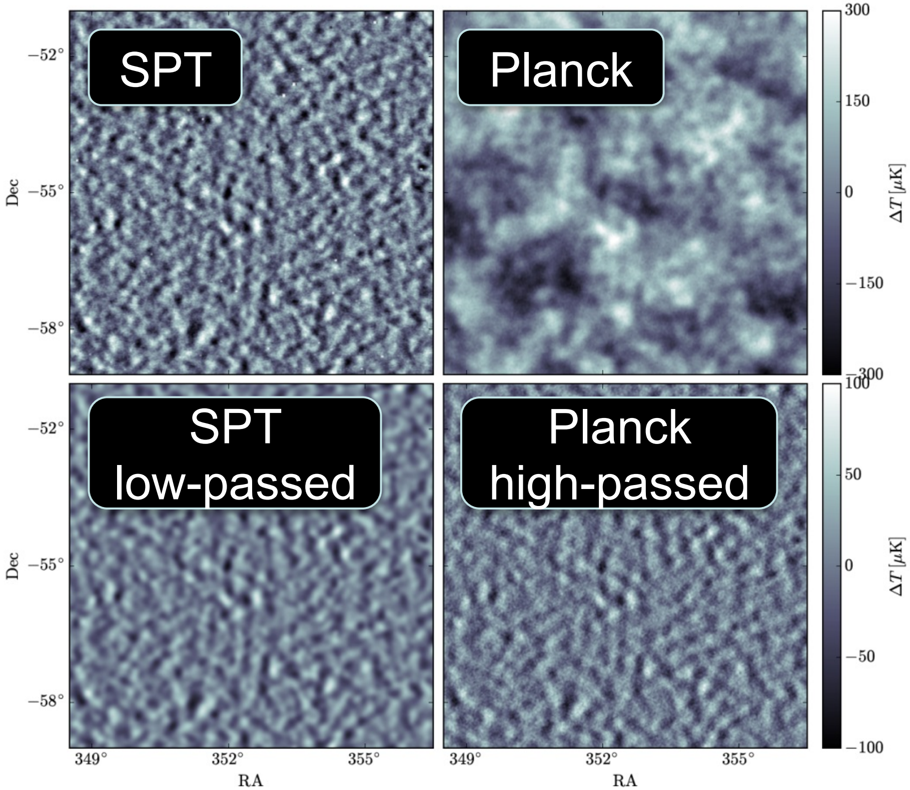




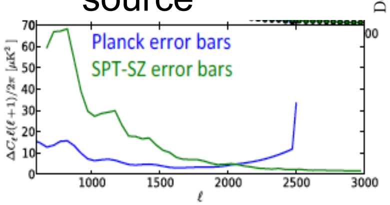
(Also: QUBIC, NIKA from France , QUIJOTE, C-BASS from Europe, GroundBird, AMIBA from Asia, Mustang2 in the US, Ali-Tibet)

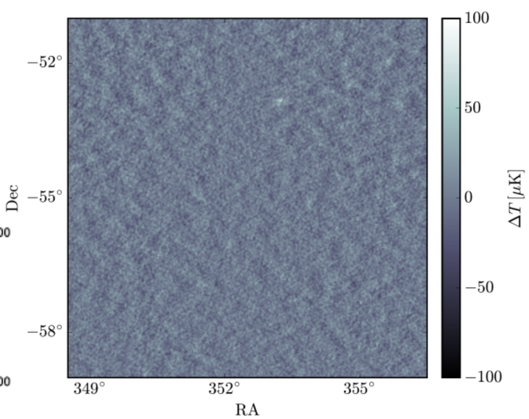
SPT@150GHz vs Planck@143GHz

Hou+ arXiv:1704.00884v1



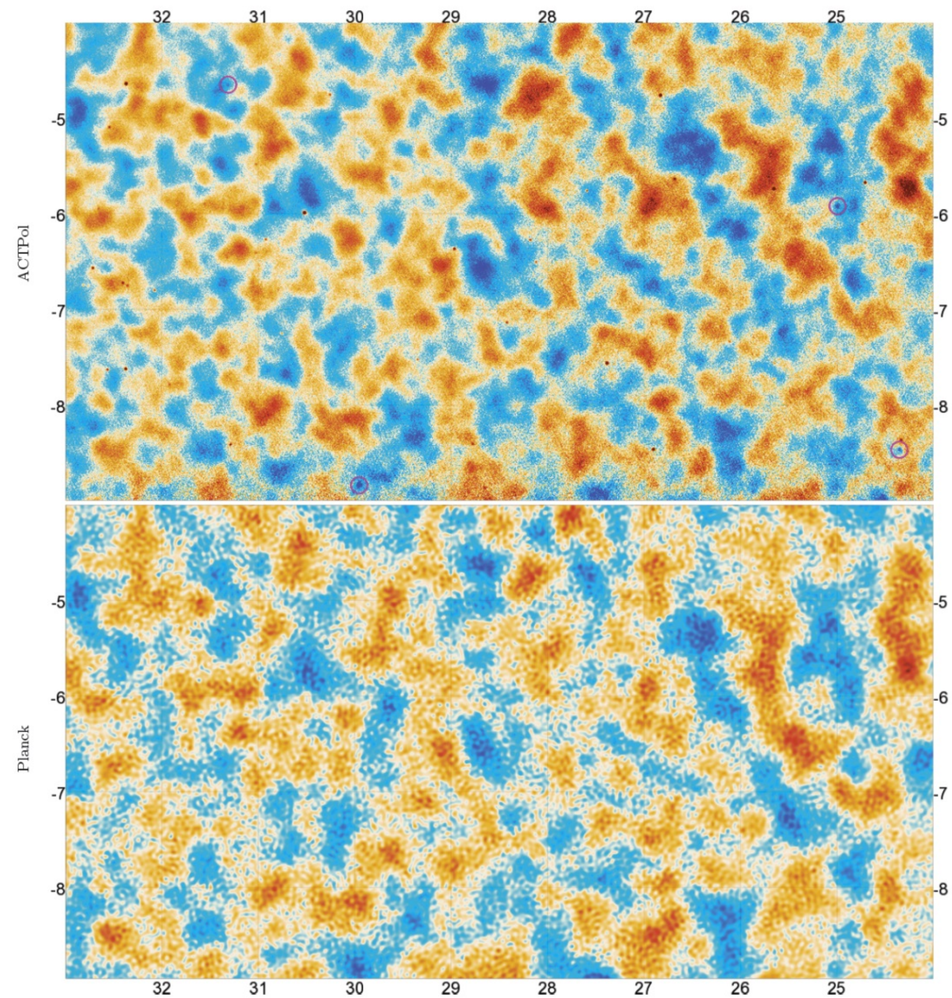
Little residual in SPT-low minus Planck-high, but a variable source





ACT@150GHz vs Planck@143GHz

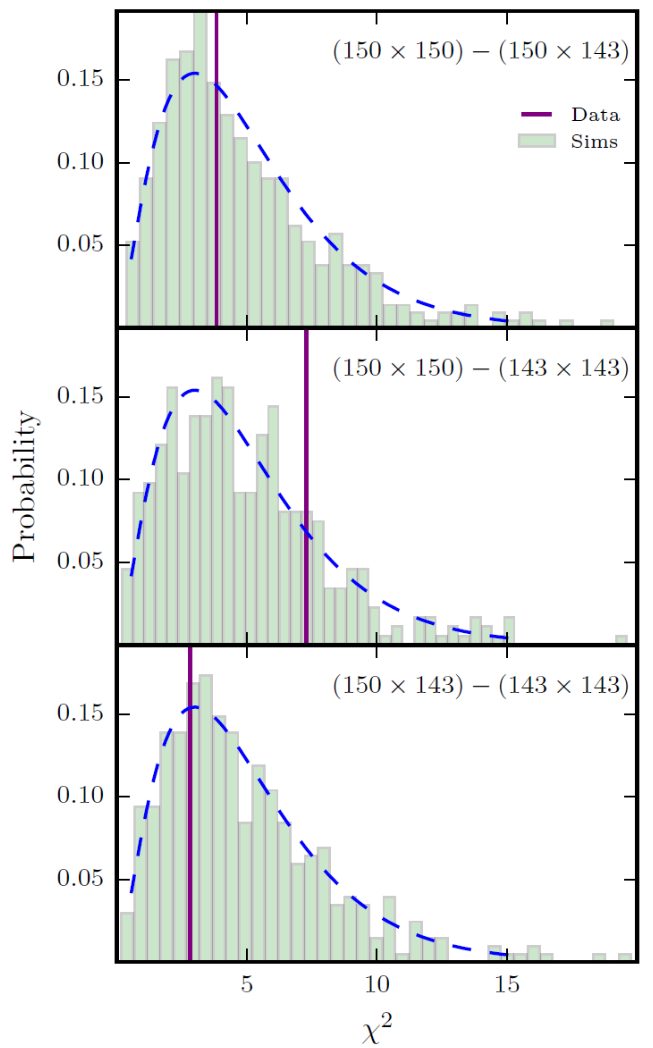
Louis+ arXiv:1610.02360v1



➔ Excellent consistency at map level around 150GHz for Planck vs SPT & ACT

Planck/SPT consistency: LCDM parameters

(Using 2540 deg2 SPT-SZ, Aylor+ arXiv:1706.10286v1



PTEs Between Parameters in SPT Sky Patch.

	ℓ_{max}		
	2000	2500	3000
$150 \times 150 - 150 \times 143$	0.74	0.66	0.57
$150 \times 150 - 143 \times 143$	0.32	0.38	0.20
$150 \times 143 - 143 \times 143$	0.62	0.73	

Planck and SPT LCDM parameters fully consistent WITHIN the SPY sky patch

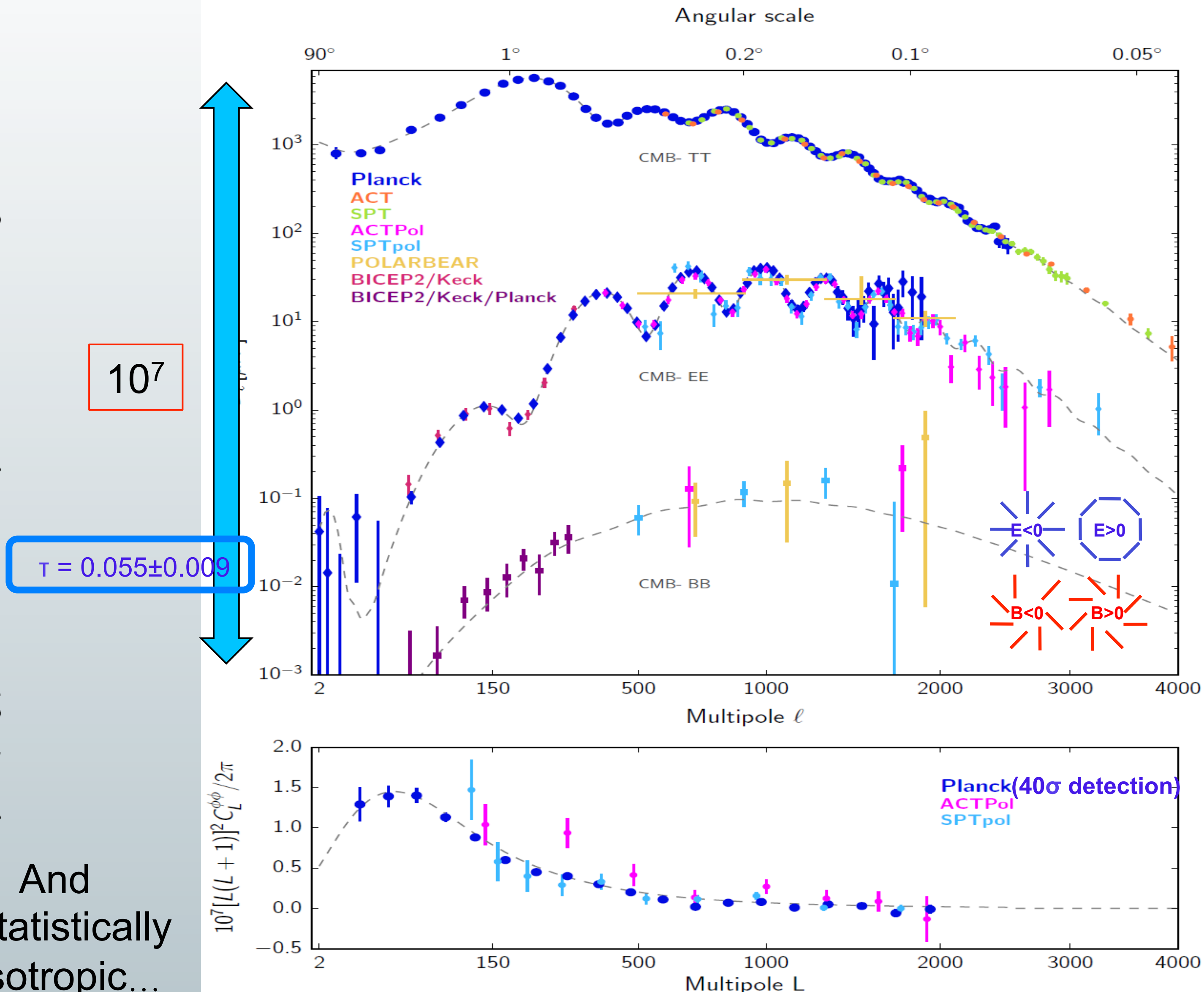
PTEs Between PlanckFS and In-patch Parameters.

	ℓ_{max}		
	2000	2500	3000
150×150	0.24	0.094	0.032
150×143	0.19	0.18	
143×143	0.29	0.31	

PlanckFS (Full sky) is consistent with SPT in-patch at all scale probed well by Planck (lmax =2000). Need to go to lmax_SPT=3000 to find some tension (at 3.2% PTE) [where SPT goes to larger H0 & FGs]

TT, EE, BB, ΦΦ – 2018 status

Only keeping points w. sufficiently small error bars, Fig. E Calabrese



And statistically isotropic…

Planck 15:

1 114 000 Modes measured with TT,

60 000 with TE (not shown)

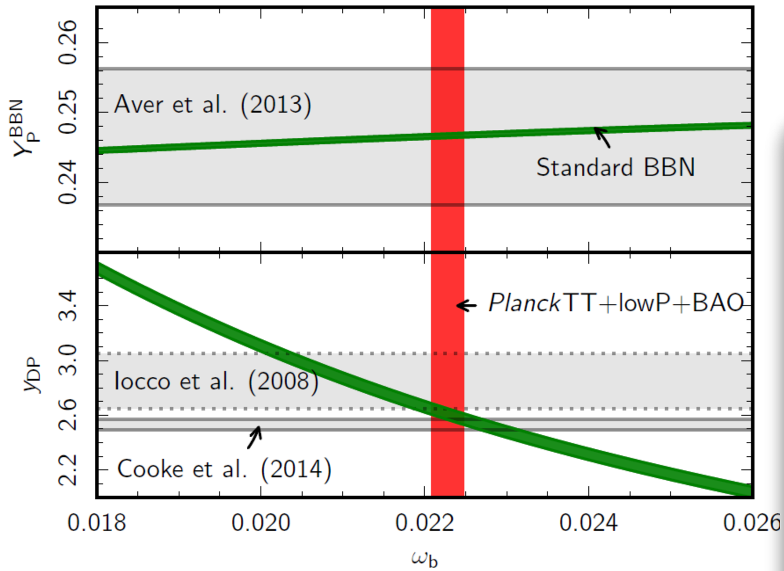
96 000 with EE

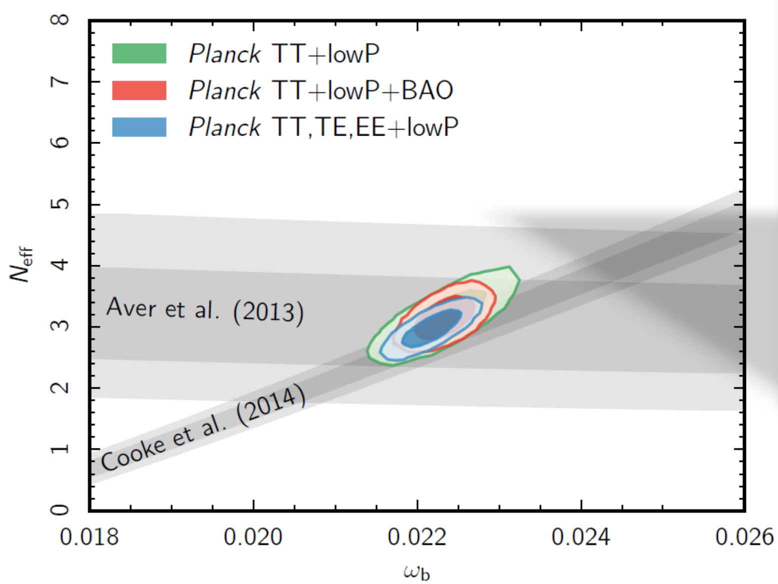
… and 10's in BB and φφ

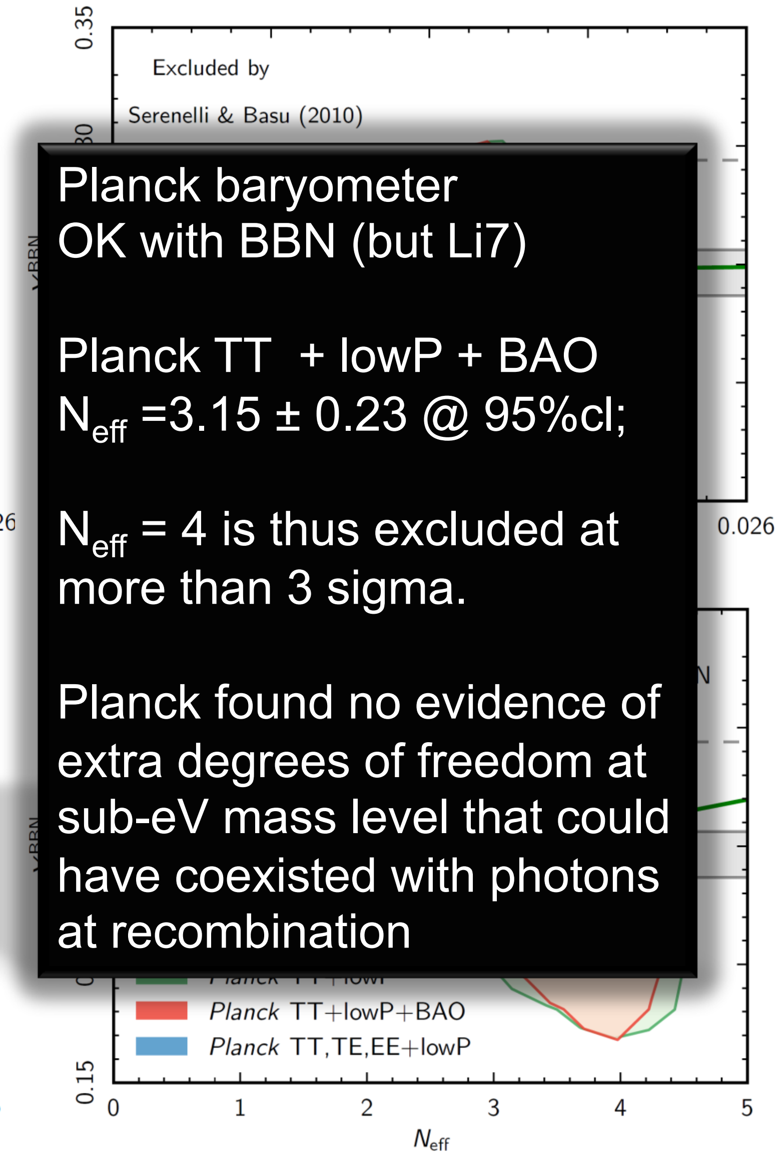
+ weak constraints with TB and EB

CMB VERSUS OTHER PROBES

BBN – N_{eff}, Y_p







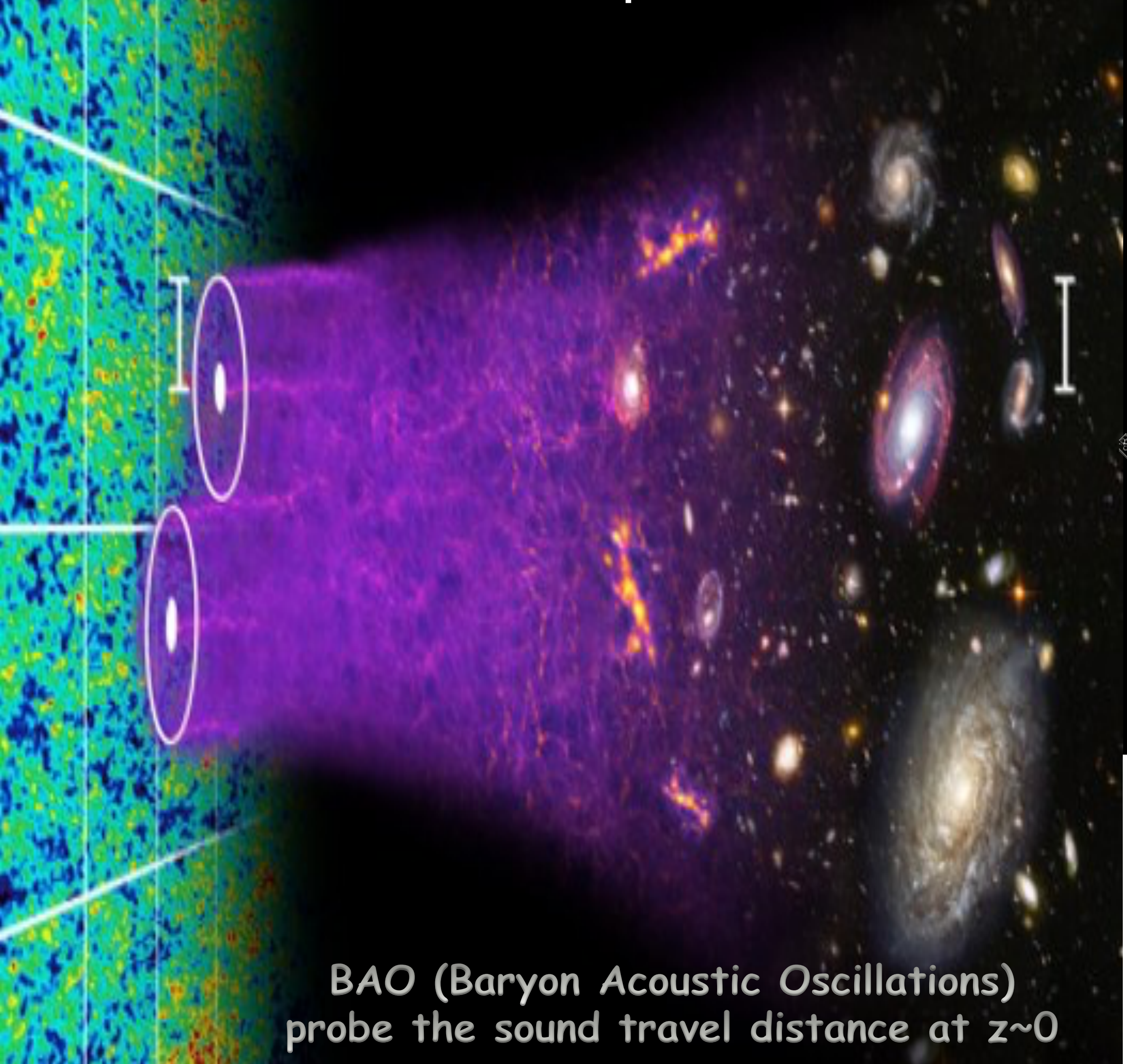
Planck baryometer
OK with BBN (but Li7)

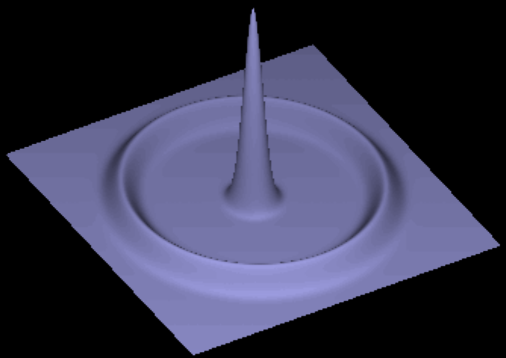
Planck TT + lowP + BAO
N_{eff} =3.15 ± 0.23 @ 95%cl;

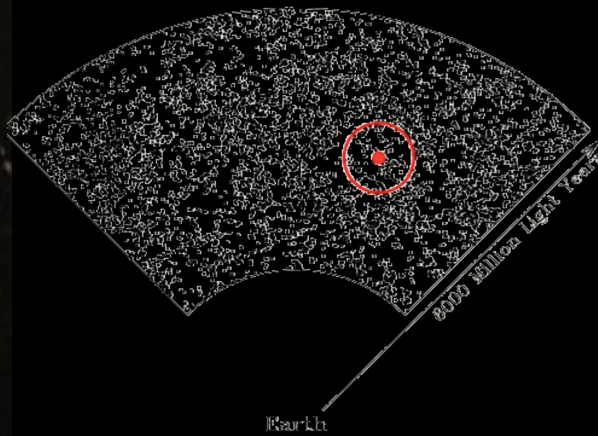
N_{eff} = 4 is thus excluded at more than 3 sigma.

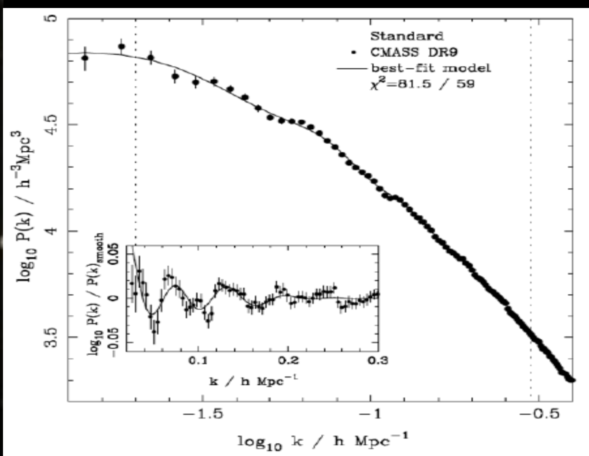
Planck found no evidence of extra degrees of freedom at sub-eV mass level that could have coexisted with photons at recombination

Echoes of the primordial drum…





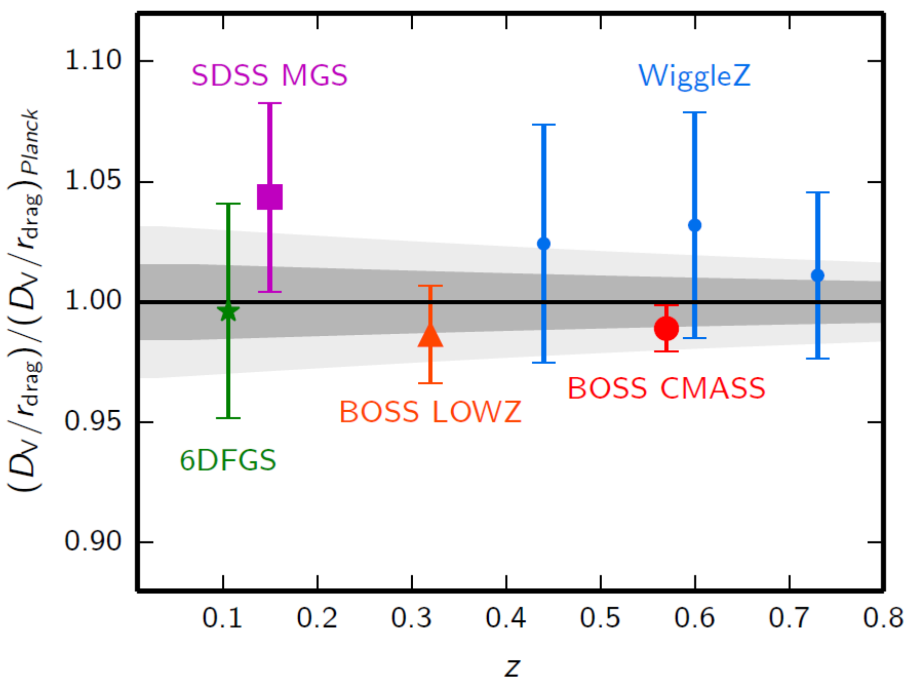


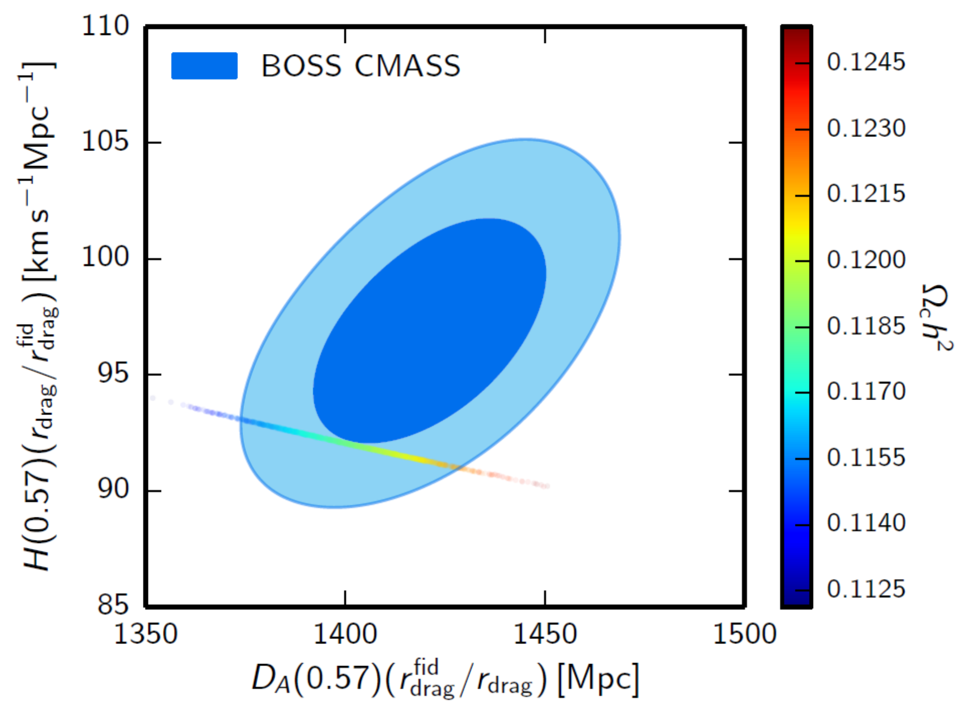


BAO (Baryon Acoustic Oscillations) probe the sound travel distance at z~0

Baryonic Acoustic Oscillations / Planck

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

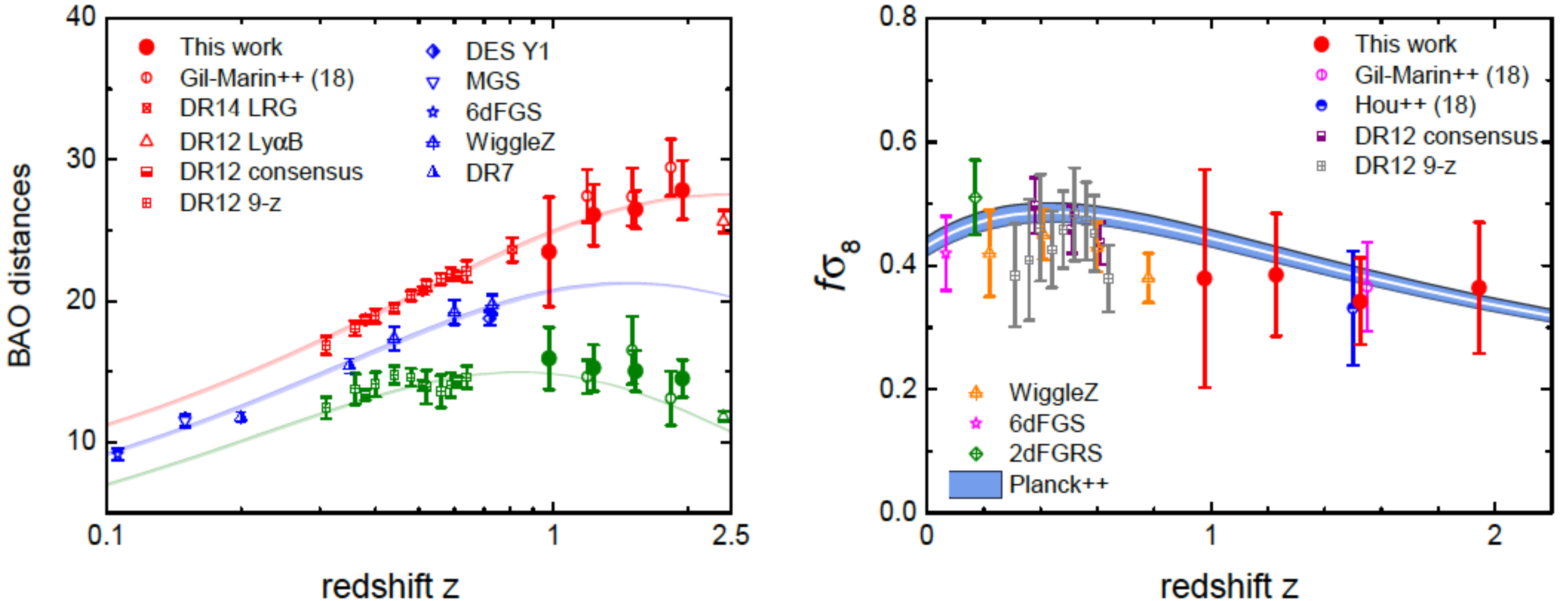




Grey band is Planck TT+LowP 1(2) sigma range [P15 Parameters]

Acoustic-scale distance ratio, $D_V(z)/r_s$, divided by the distance ratio of the Planck TT base model.

Recent BAO data

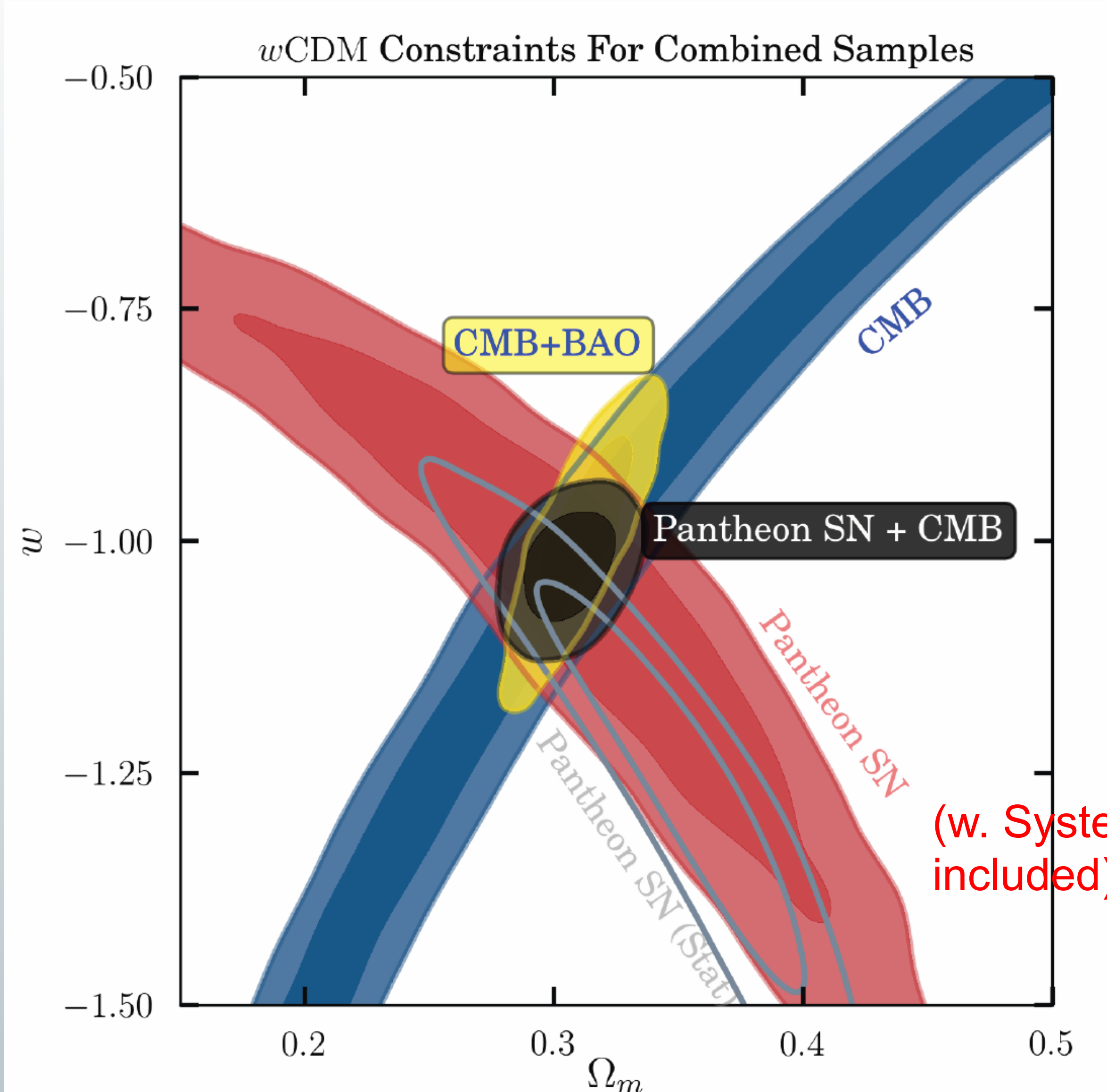


… still agree very well with Planck data prediction within LCDM

Zhao+ arXiv:1801.03043

(See also Zarrouk+ arXiv:1801.03062)

Pantheon (1049 SN Ia from 0.01 <z<2.3)



Scolnic+ arXiv:1710.00845

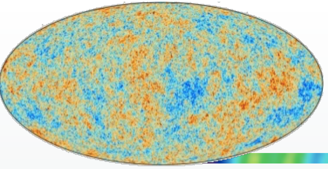
Claim: “The systematic uncertainties on our measurements of dark energy parameters are now smaller than the statistical uncertainties”.

CMB+ BAO was:
Ω_m=0.312+–0.013
w =–0.991+_0.074

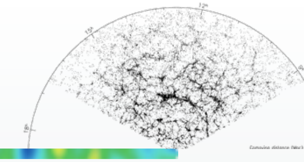
Now SN+CMB:
Ω_m=0.303+–0.012
w =–1.031+_0.040

Twice more data + better Syst. analysis
➔ W≠-1 *gone !*

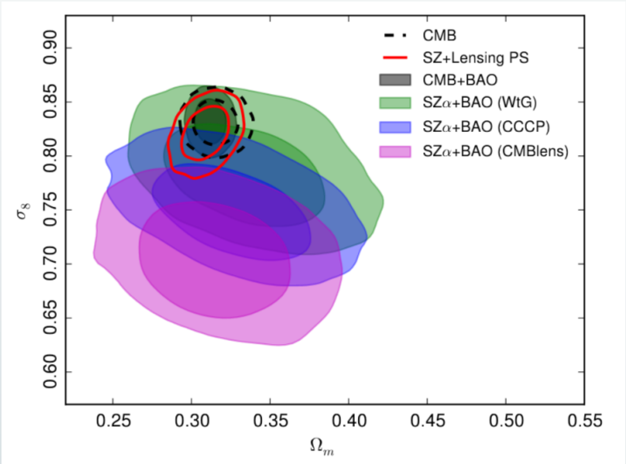
NB: Other data:
- CMB=(Planck TT + lowP)15,
- BAO=SDSS Main Galaxy Sample (Ross et al. 2015)+BOSS and CMASS survey (Anderson et al. 2014).



Some tensions do exist (still)

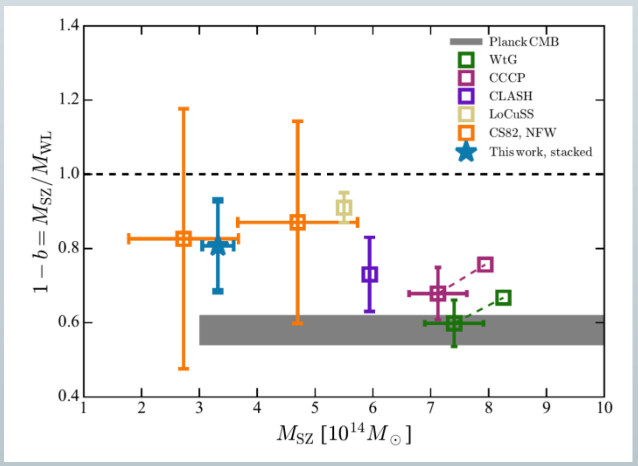


SZ

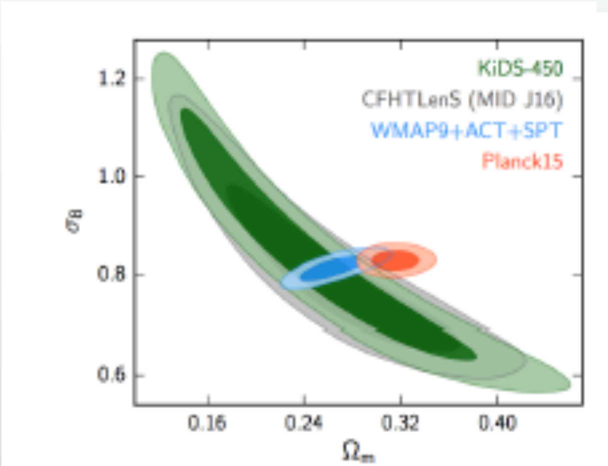


?

Medezinski+ arXiv:1706.00434: a cluster mass dependence of the bias? (HSC new point)



WL



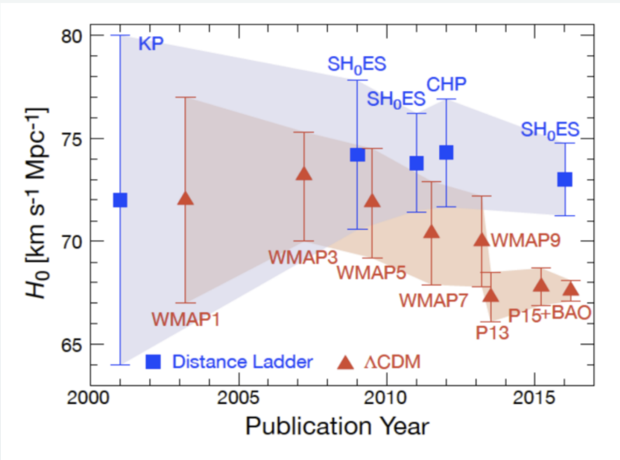
Hildebrandt+ 16 BUT GPE+ arXiv:1707.00483

(And Troxel+, cf below)

Ly BAO measurements at high redshift are discrepant at 2.7sig; it is quite difficult to find a physical explanation not disrupting BAO consistency elsewhere, see, e.g., Aubourg etal. 2015

Dark Matter- Dark Radiation interaction? (Pan+ arXiv: 1801.07348)

H0

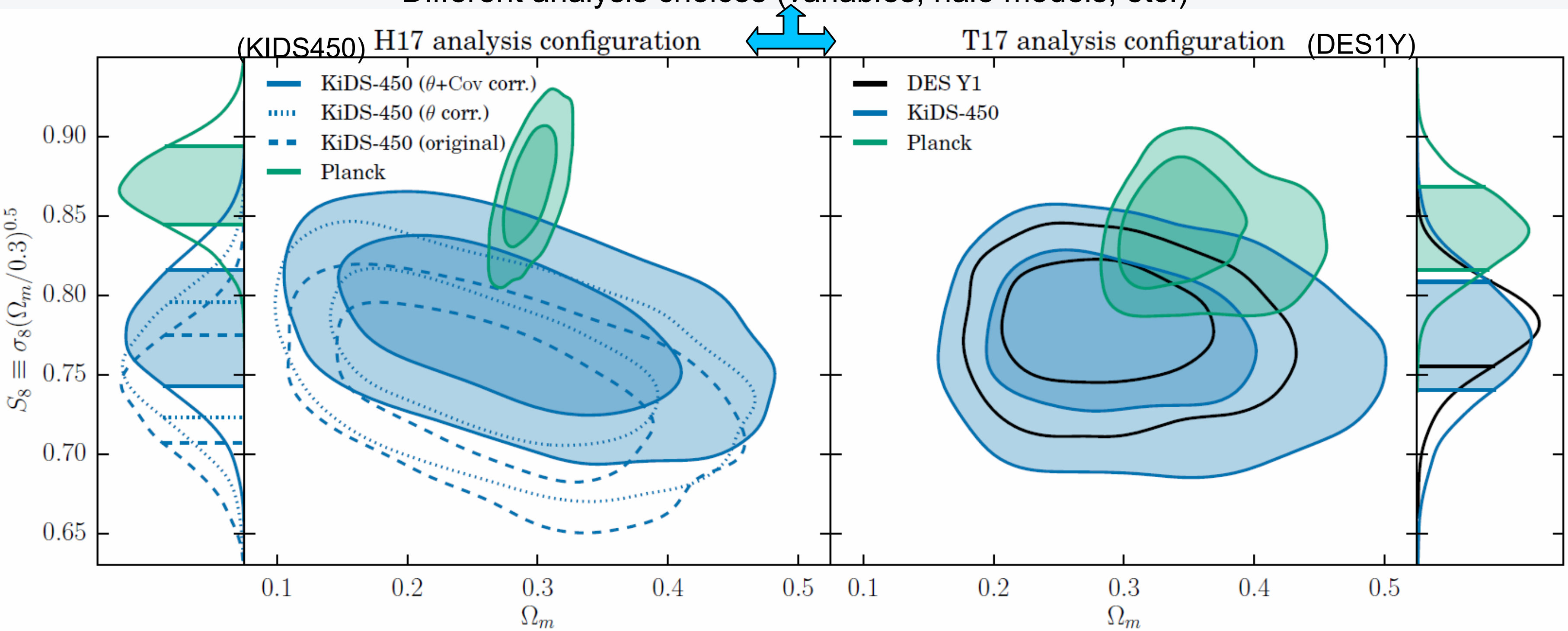


Freedman, arxiv/1706.02739

- Planck consistent with BAO, SN, BBN within LCDM.
- H_0 tension present also in WMAP+BAO+SN.
- WMAP and Planck in very good agreement *if compared at same scales.*
- WMAP+SPT do not have statistical power of Planck.
- Planck low-l & Planck high-l are in good statistical agreement.

KIDS450-DES1Y: Impact of survey geometry

Different analysis choices (variables, halo models, etc.)



Troxel+ arXiv:1804.10663

After correction (weighting the pair separation, Cov. mat improvement), the relatively strong tension of KIDS-450 with Planck essentially evaporates!

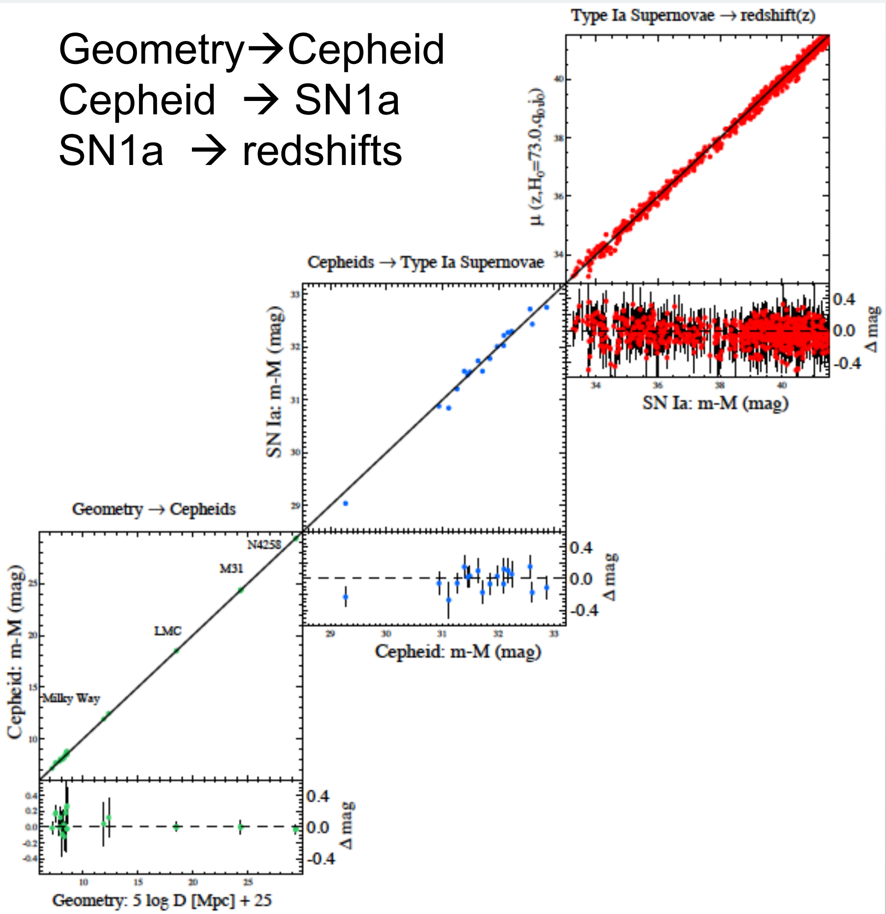
Both analyses (with these corrections) agree very well between themselves, and with Planck

- These correction may also help with the lack of internal consistency pointed out by Lemos & Efstathiou 2018.
- These relatively new analyses are maturing: it may be that other effects currently neglected may re-increase the tensions in the future and lots of new data soon will permit more stringent tests!.

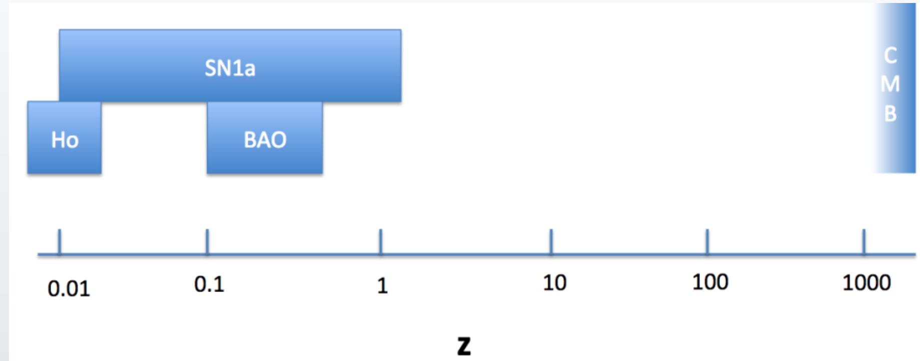
Direct vs Inverse distance ladder

"Direct" H0 measurements
involve 3 steps

Geometry→Cepheid
Cepheid → SN1a
SN1a → redshifts



Riess+ arXiv:1604.01424



Inverse distance ladder: Use rd=sound horizon at radiation drag (~recombination) as a rod. Connect high-z to low-z by using BAO + SN (i.e., rd+BAO normalise the SNs).

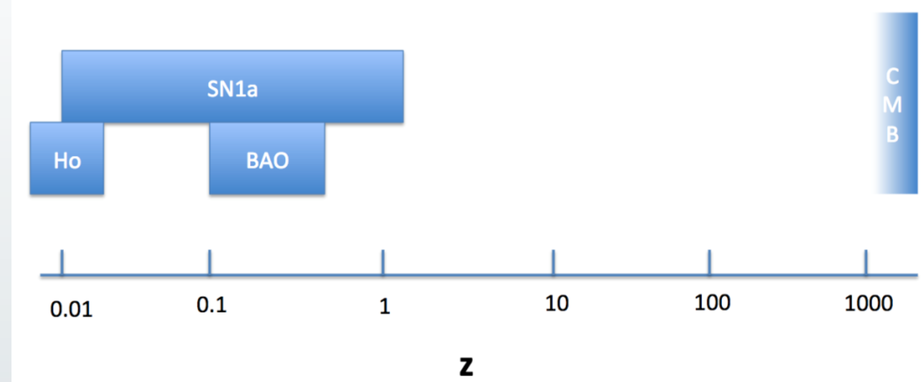
Aubourg+ (1411.1074) and then Cuesta+ (1411.1094) find very good agreement with Planck H_0 value for LCDM.
Recently, Feeney+ (1802.03404v2*)*, Lemos+ *(*1806.06781v1) confirm. As well as Gomez-Valent & Amendola (1802.01505) with essentially all current ways to infer H(z). Others confirm that direct H_0 appears as outlier.

NB: ways to change rd appear contrived to most.

Recent Inverse distance ladder

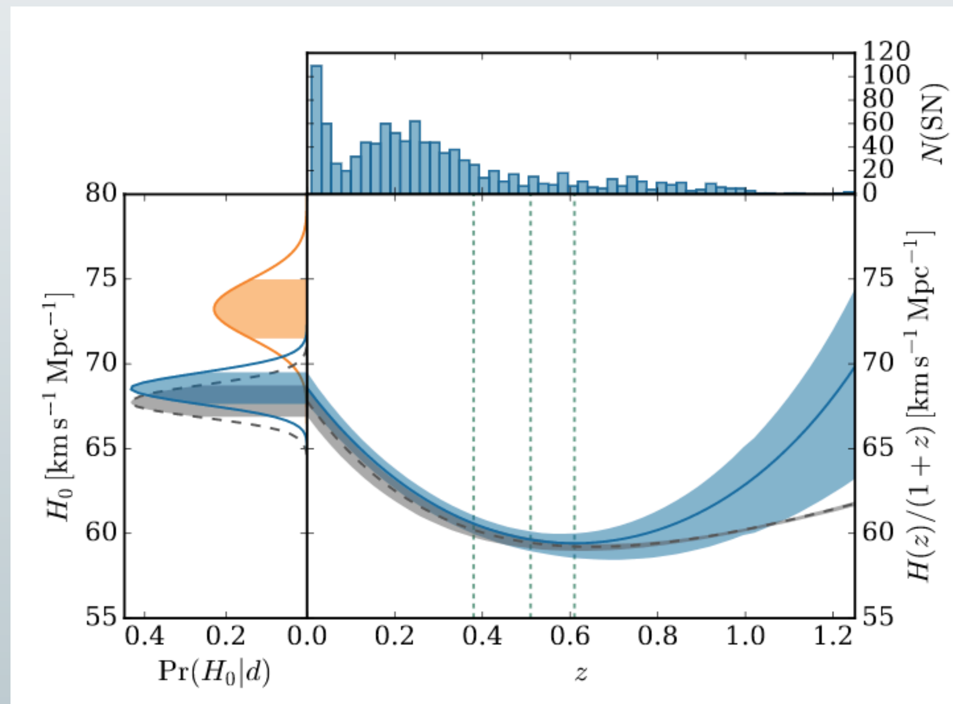
Assume only that the expansion is smooth, adopting the third-order Taylor expansion of the luminosity distance used by SH0ES (q0 and j0 are the deceleration and jerk parameters).

$$d_{\rm L}(z) = \frac{c\,z}{H_0}\left[1 + \frac{z}{2}(1-q_0) - \frac{z^2}{6}\left(1 - q_0 - 3q_0^2 + j_0\right)\right]$$



Derived expansion history for

- BOSS BAO, Pantheon SNe and Planck rd assuming smooth expansion and early-time physics only [rd] (blue),
- Planck assuming LCDM (grey).



BAO redshifts are shown as short-dashed lines. Top panel: redshift distribution of Pantheon SNe.
Left panel: corresponding H0 posteriors and Cepheid distance ladder measurement (orange).

Feeney+ arXiv: 1802.03404v2

Latest Inverse distance ladder

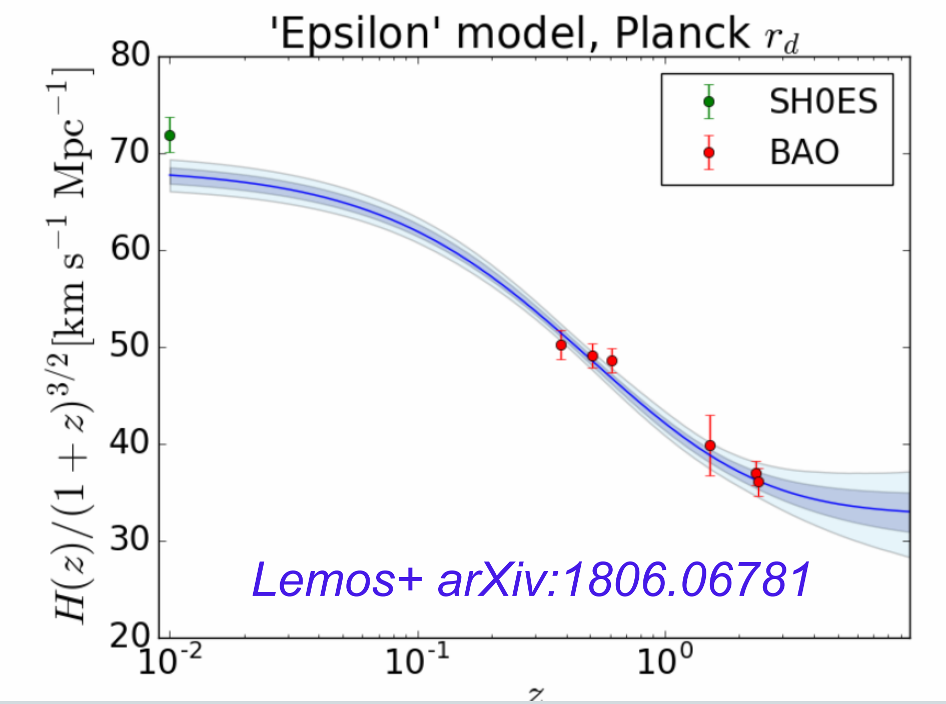
Assume "epsilon"model

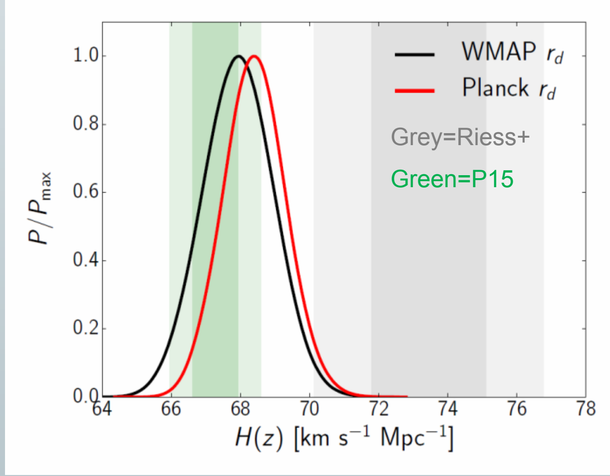
$$H^2(z) = H^2_{\rm fid}\left[A(1+z)^3 + B + Cz + D(1+z)^\epsilon\right]$$

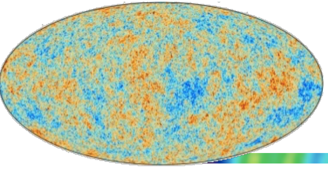
With, for LCDM

$$A = \left(\frac{H_0}{H_{\rm fid}}\right)^2 \Omega_m, \quad B = \left(\frac{H_0}{H_{\rm fid}}\right)^2 (1-\Omega_m),$$
$$C = D = 0, \epsilon \neq 0,$$

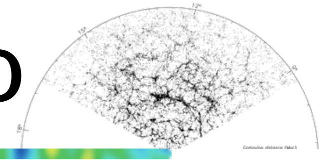
Dataset	$z_{\rm eff}$	Measurement	Constraint
6dFGS	0.106	$r_d/D_V(z_{\rm eff})$	0.336 ± 0.015
BOSS DR12	0.38	$D_M(z_{\rm eff})r_{d,\rm fid}/r_d$	1512 ± 25 Mpc
		$H(z_{\rm eff})r_d/r_{d,\rm fid}$	81.2 ± 2.4 km s^{-1}Mpc^{-1}
	0.51	$D_M(z_{\rm eff})r_{d,\rm fid}/r_d$	1975 ± 30 Mpc
		$H(z_{\rm eff})r_d/r_{d,\rm fid}$	90.9 ± 2.3 km s^{-1}Mpc^{-1}
	0.61	$D_M(z_{\rm eff})r_{d,\rm fid}/r_d$	2307 ± 37 Mpc
		$H(z_{\rm eff})r_d/r_{d,\rm fid}$	99.0 ± 2.5 km s^{-1}Mpc^{-1}
eBOSS DR14 QSO	1.52	$D_A(z_{\rm eff})r_{d,\rm fid}/r_d$	1850^{+90}_{-115} Mpc
		$H(z_{\rm eff})r_d/r_{d,\rm fid}$	159^{+12}_{-13} km s^{-1}Mpc^{-1}
BOSS DR12 Lyα	2.33	$D_M(z_{\rm eff})/r_d$	37.8 ± 2.1
		$c/(H(z_{\rm eff})r_d)$	9.07 ± 0.31
BOSS DR12 QSOxLyα	2.40	$D_M(z_{\rm eff})/r_d$	35.7 ± 1.7
		$c/(H(z_{\rm eff})r_d)$	9.01 ± 0.36



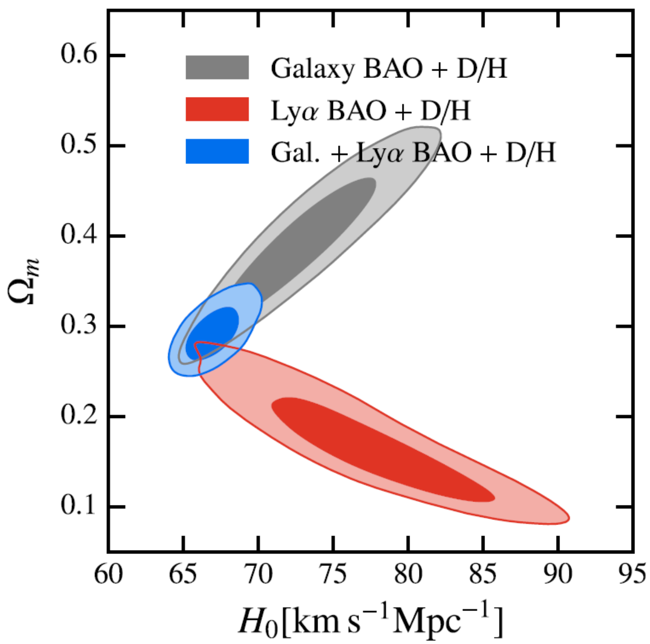




CMB, BAO, SN1A, D/H… and Ho



- Direct H_0 value appears as outlier in many recent studies. But no obvious problem identified with Sh0ES (see A. Riess)
- Ways to change rd through early Universe physics appear contrived to most, in particular given the great consistency of Planck results on $\Omega_b h^2$ with BBN predictions (given the observed abundances by Cooke+ 2018)…
- Addison+ (and DES) used the $\Omega_b h^2$ constraint derived from the same D/H observations (Cooke+2018), in combination with Galaxy BAO and Lyα, to constrain H_0 independently from CMB data:



"These results show that it is not possible to explain the H0 disagreement solely with a systematic error specific to the Planck data."

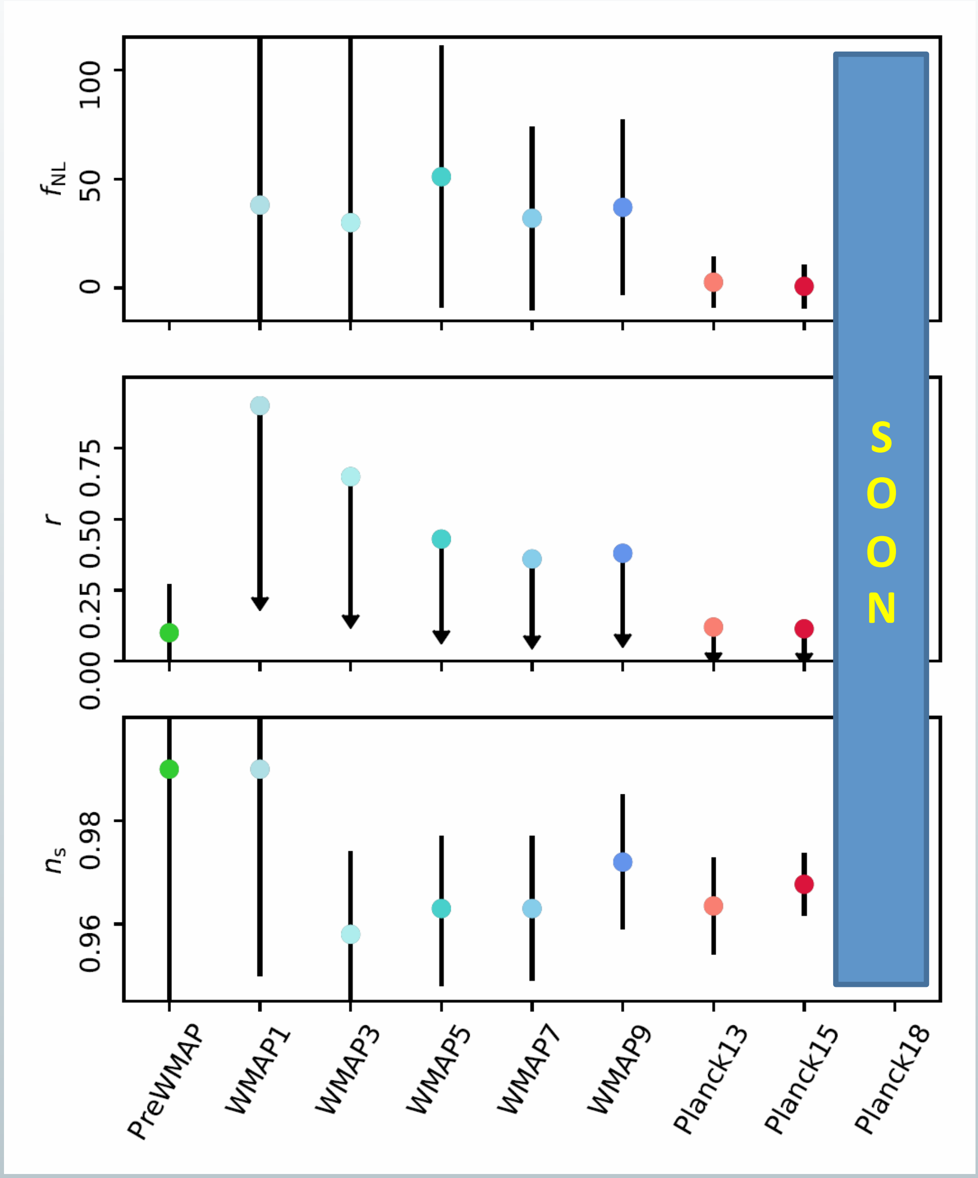
(Addison+ arXiv:1707.06547)

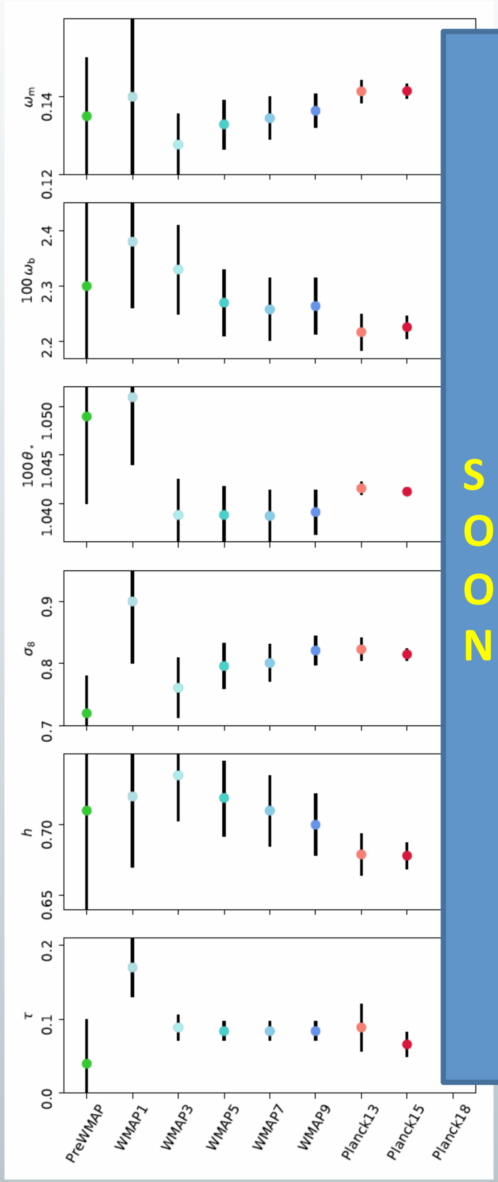
;-)

CMB Anisotropies post-Planck

- The LCDM model fits all CMB data in T, E, B, ϕ (stable across releases).
  - *No need for an extension. A lavish source of constraints /papers…*
  - *Same model parameters, determined at the per cent level (but tau), also fit other data (BAO, and also BBN, SN1a…).*
  - *Some tensions (anomalies, SZ, H0, WL), whose meaning remains unclear as of now.*
- LCDM is a tilted model (n_s <1) and the inflationary phase models check all the generic boxes. Many specific models have been ruled out though.
- Alternatives have either been falsified, or they mostly/only do post-dictions so far. We now want $\sigma_r < 10^{-3}$!
- T anisotropies information essentially exhausted (as we promised to ESA back in 1996), but much still to learn on foregrounds, e.g. from SZ. Polarisation promises a very rich harvest at all angular scales.
- A new field, CMB lensing, has emerged (observationally), with a great scientific potential. It has unique advantages (known source plane, well understood, mostly linear physics at work); but it is a foreground to be removed for improving the detection capability of a Primordial Gravitation wave stochastic background. In any case, it is a great source of problem to solve for astrophysicists.
- Tantalising (?) anomalies (mostly large scale) & tensions…

LCDM parameters vs time





PERSPECTIVE FOR THE FUTURE & GOALS

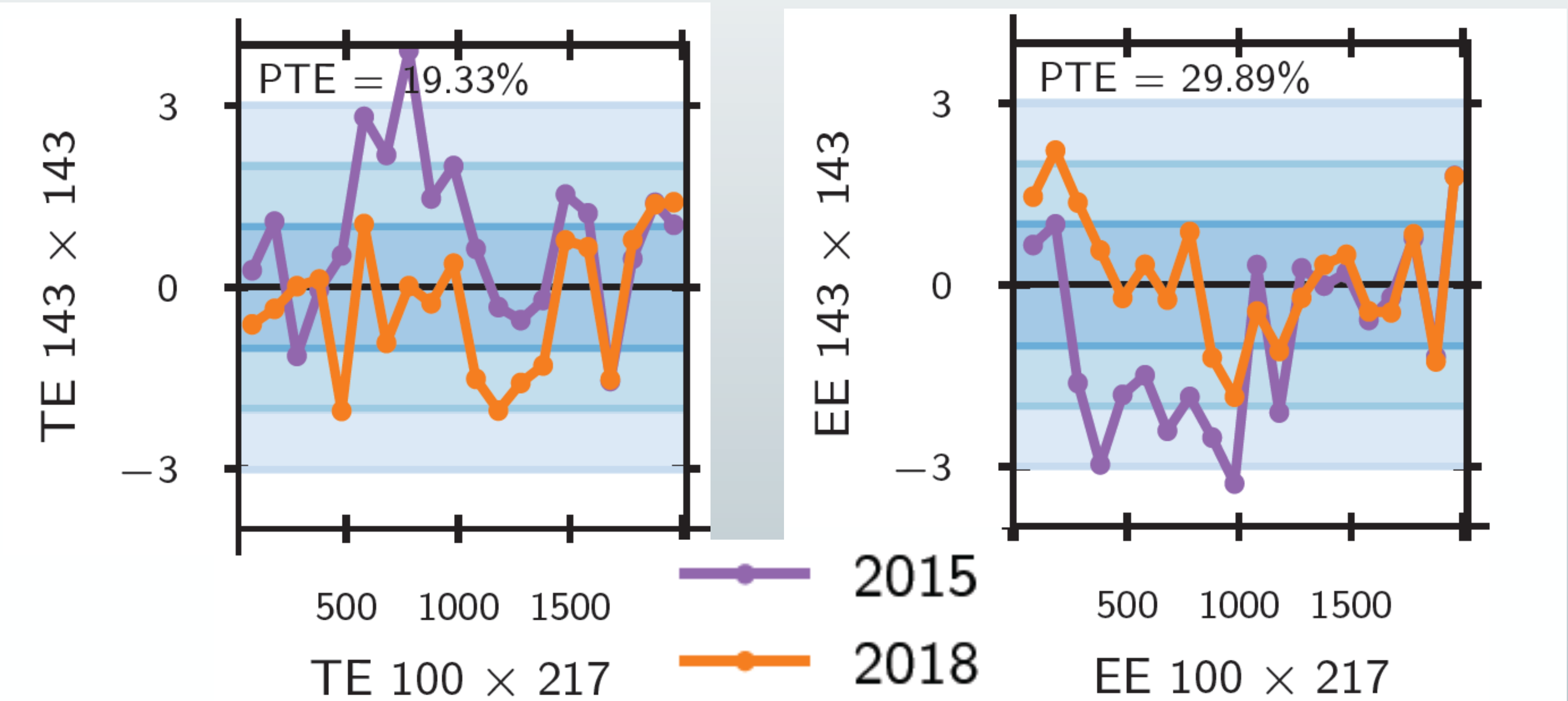
Planck 2018 “Legacy” Release

- To be expected on July 17th…
- New set of maps with notably the processing improvements introduced for the HFI low-ell EE analysis (i.e., same TOIs, different HPR & data model)
- Hivon et al (2017) model accounting for beam leakage effects at PS level for high-ell analyses
- A new set of simulations with fidelity enhanced to describe much smaller effects (for instrumental systematics, e.g., ADC NL, BP leakage, etc.)
- A new round of analyses with updated data model, CMB likelihoods, chains and parameters, component maps, NG analyses, etc.

(˜12papers)

Polarisation at high ell…

- 2015: was declared preliminary, because we could demonstrate in null tests (see below) an incomplete characterisation of polarisation systematics, (even though there were estimated to be at quite low levels ~O(1 mukˆ2)
- 2018: much improved inter frequency consistency in TE and EE



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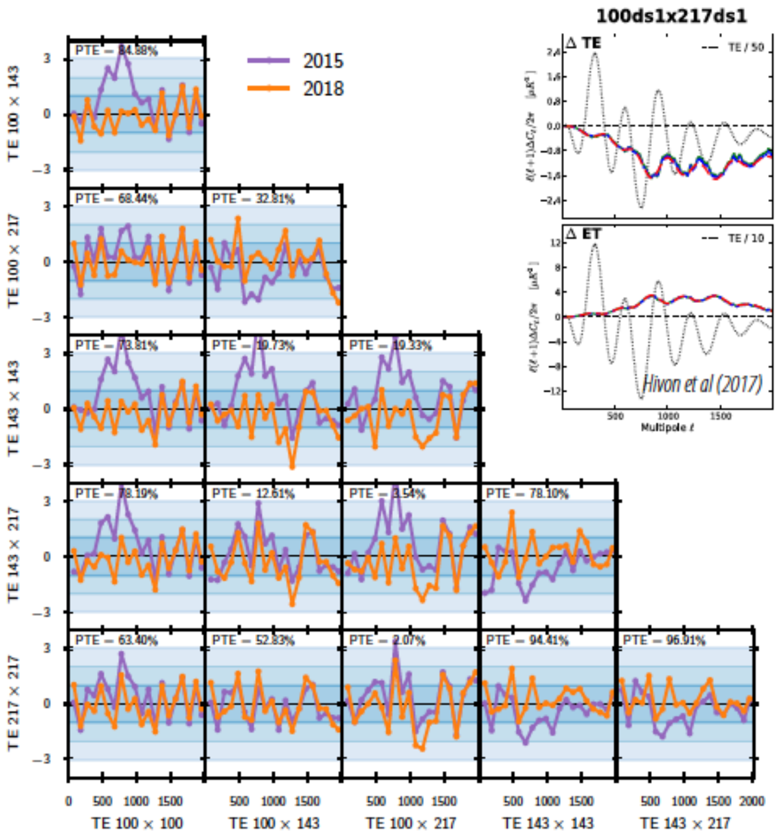
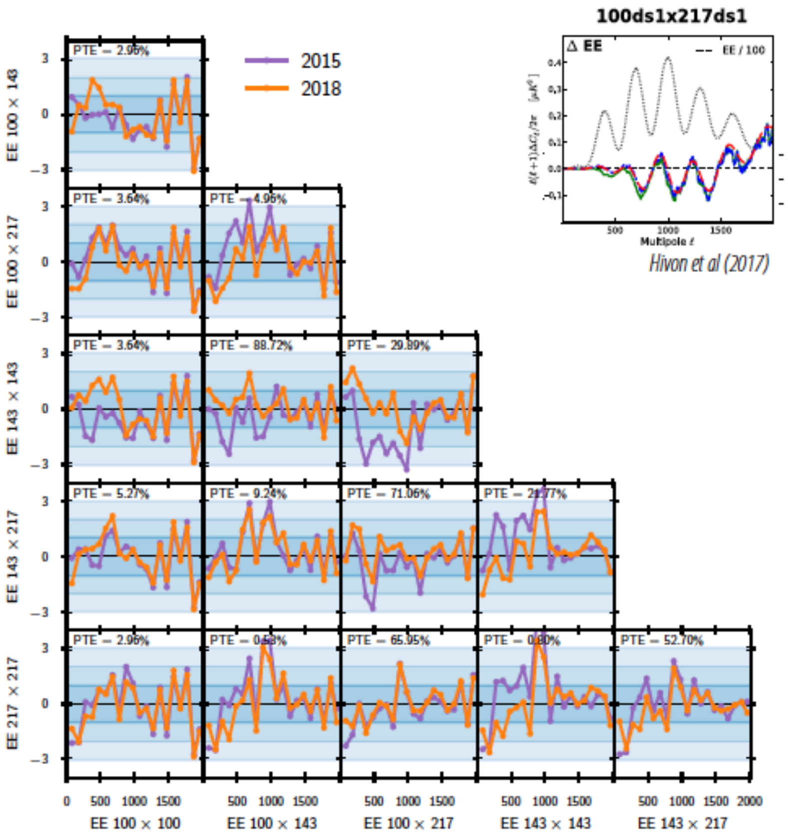




So what?

- Increased robustness, at low-ell, high-ell, lensing…
- Increased number of useful modes

- **Planck Legacy Cosmology is in general agreement with 2015+2016**

- And our paper I will be a "Planck cosmological legacy" paper with (hopefully) nice summary figures for giving talks ☺

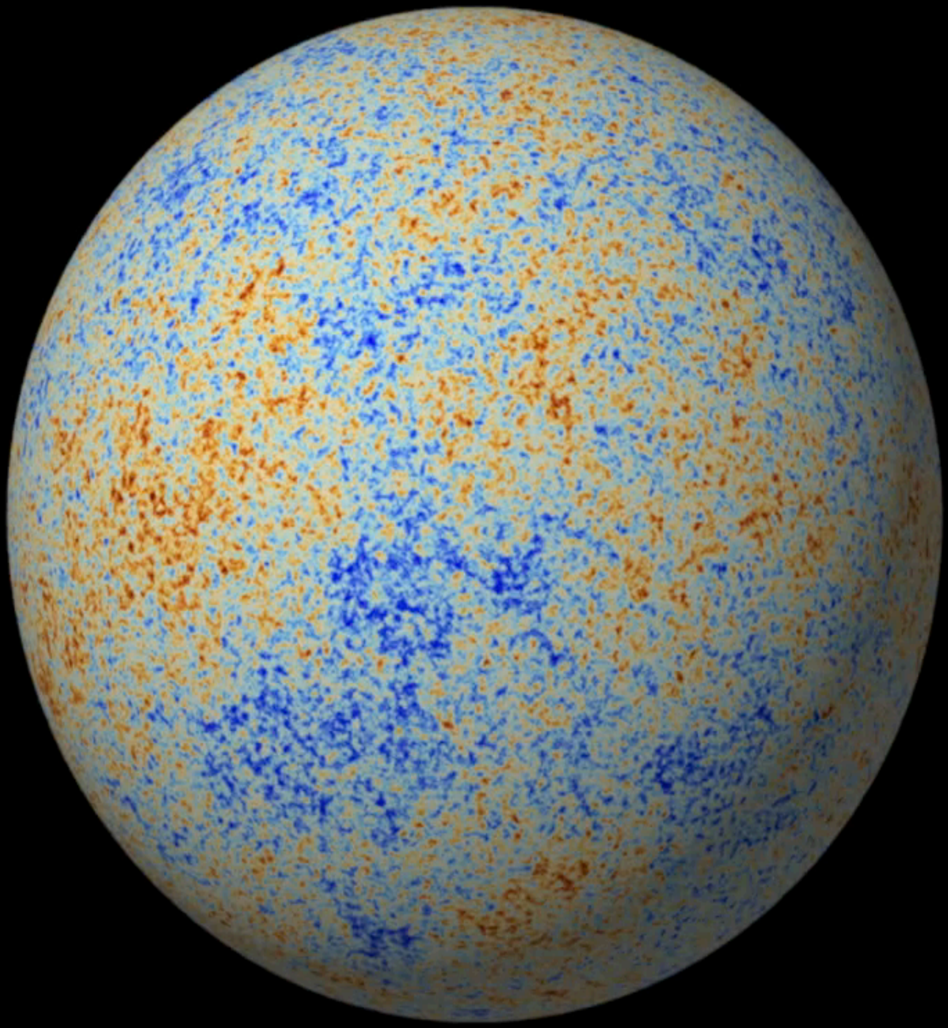
Collaboration

Planck publications and products

2003-2015: Planck technical results	≈ 47 publications describing work performed by the Instrument Teams, DPCs and WGs.
2010: Planck pre-launch papers	13 publications describing the technical capabilities of Planck's instruments
2011: Planck Early papers	26+1 publications coming with the 1st delivered product: The Early Release Compact Source Catalogue
2012-2018: Planck intermediate results	55 publications mainly on galactic and extragalactic astrophysics
2013: Planck 2013 results	32 publications on cosmology science from CMB temperature data (first year data). Maps, C_l's and likelihoods delivered
2015: Planck 2015 results	28 publications mainly on cosmology science from CMB temperature and polarization data (full mission)
2018: Planck 2018 results	12 papers expected. Updated products and legacy results

Planck products can be found at: http://pla.esac.esa.int/pla/

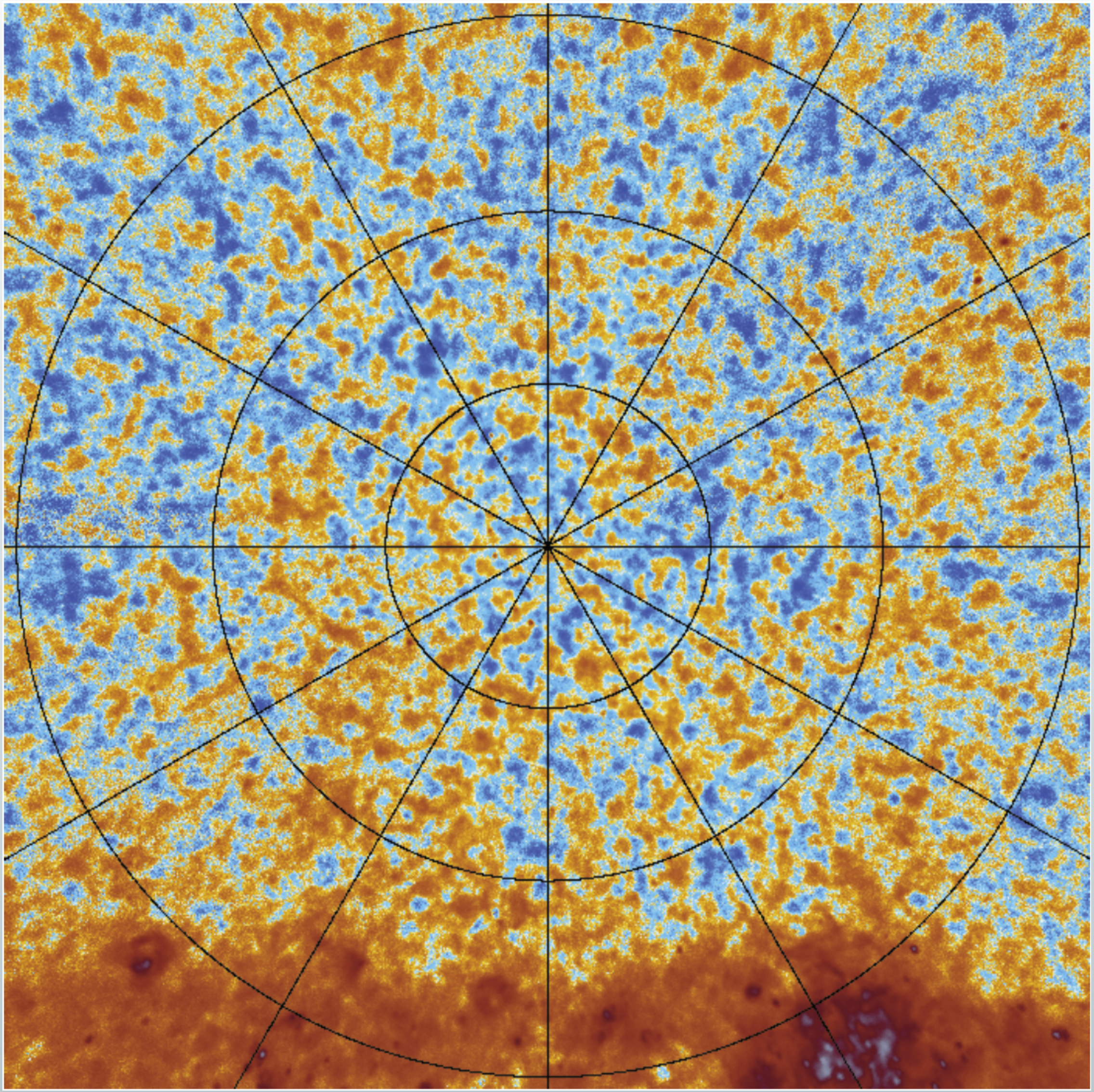
With much more to come!



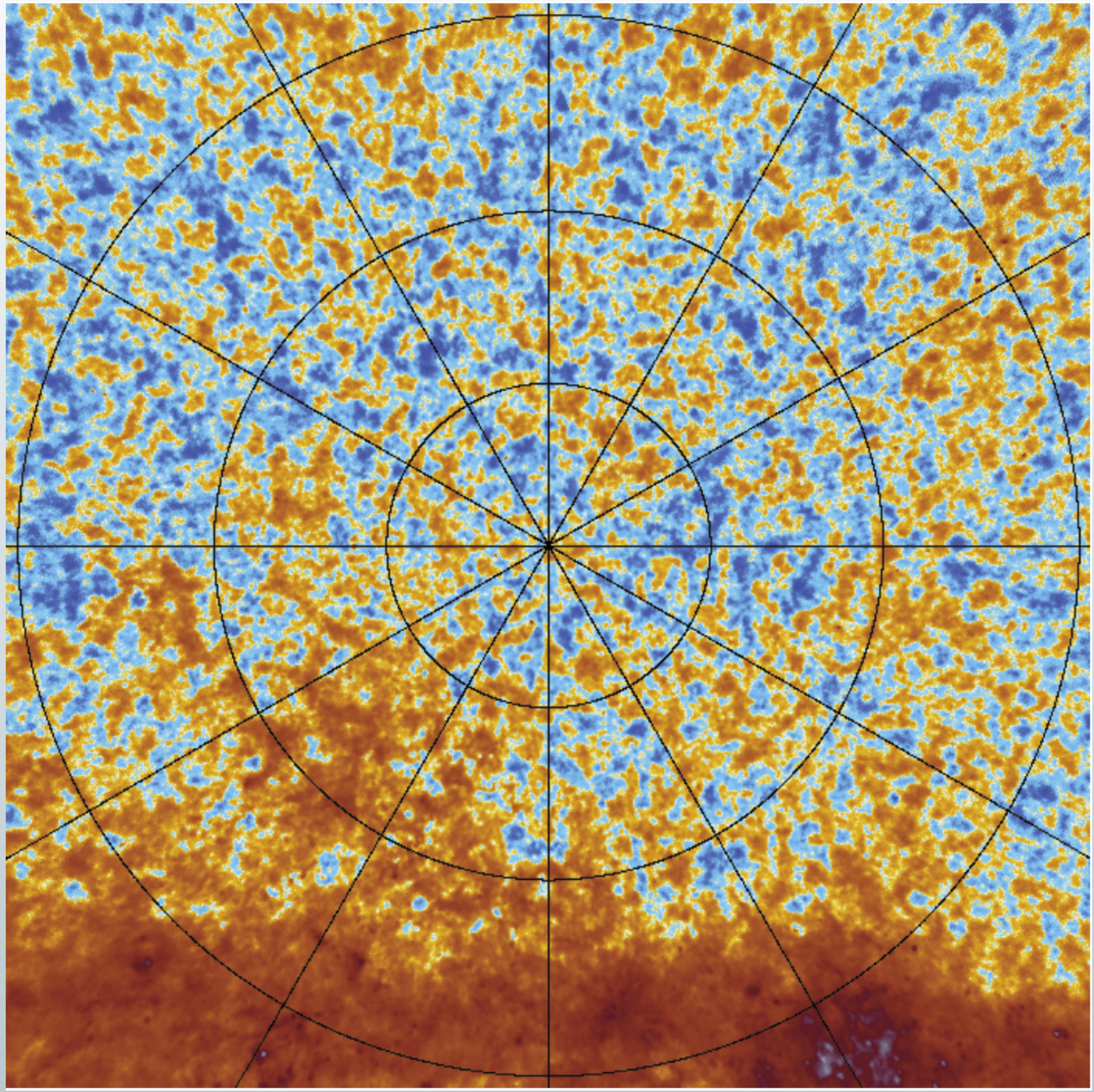
Starting with Planck 2018 “legacy” release!

ROBUSTNESS
CONSISTENCY
PRECISION
AND ACCURACY

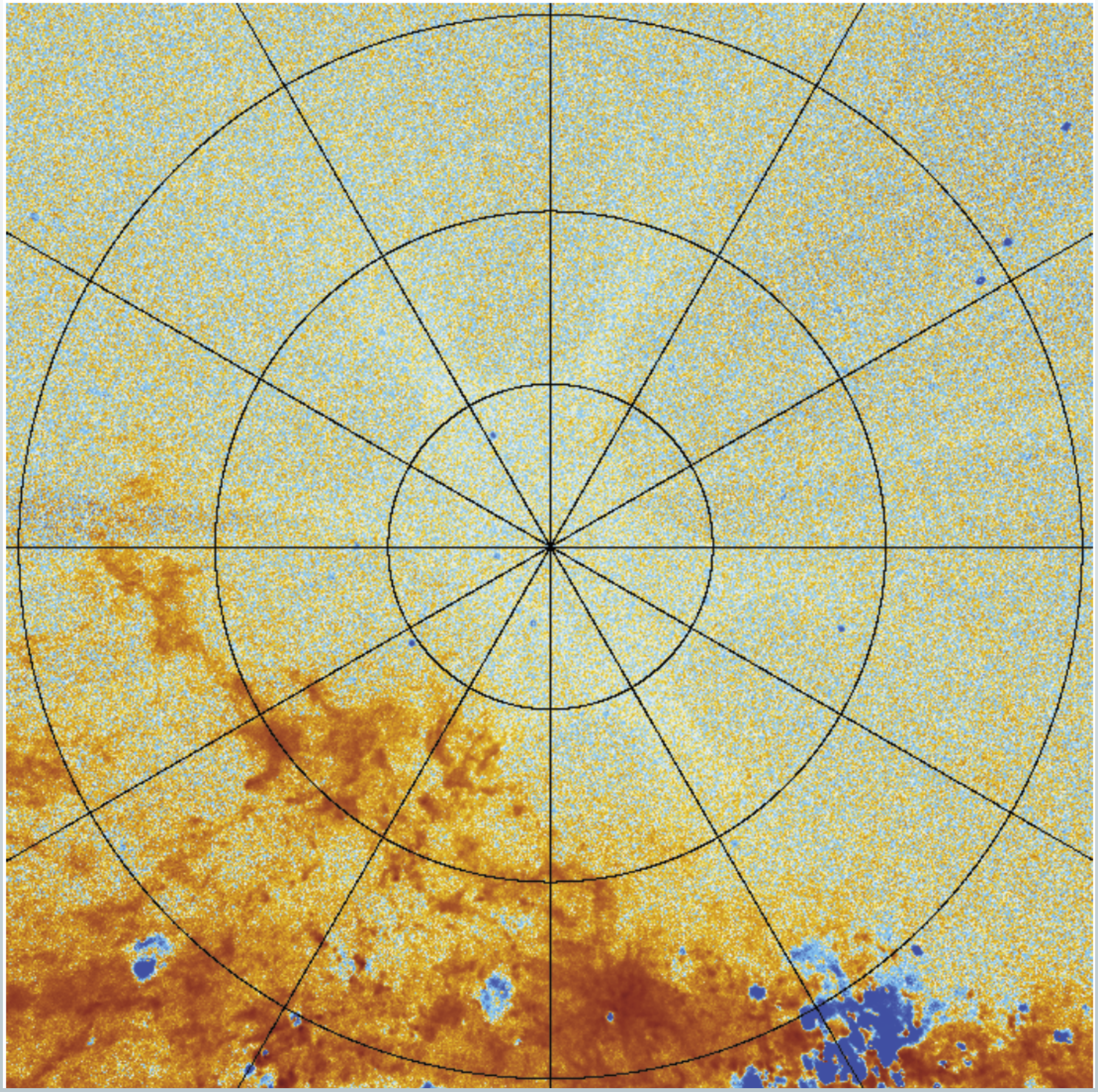
North Ecliptic pole: LFI @ 70 GHz



North Ecliptic pole: HFI @ 100 GHz

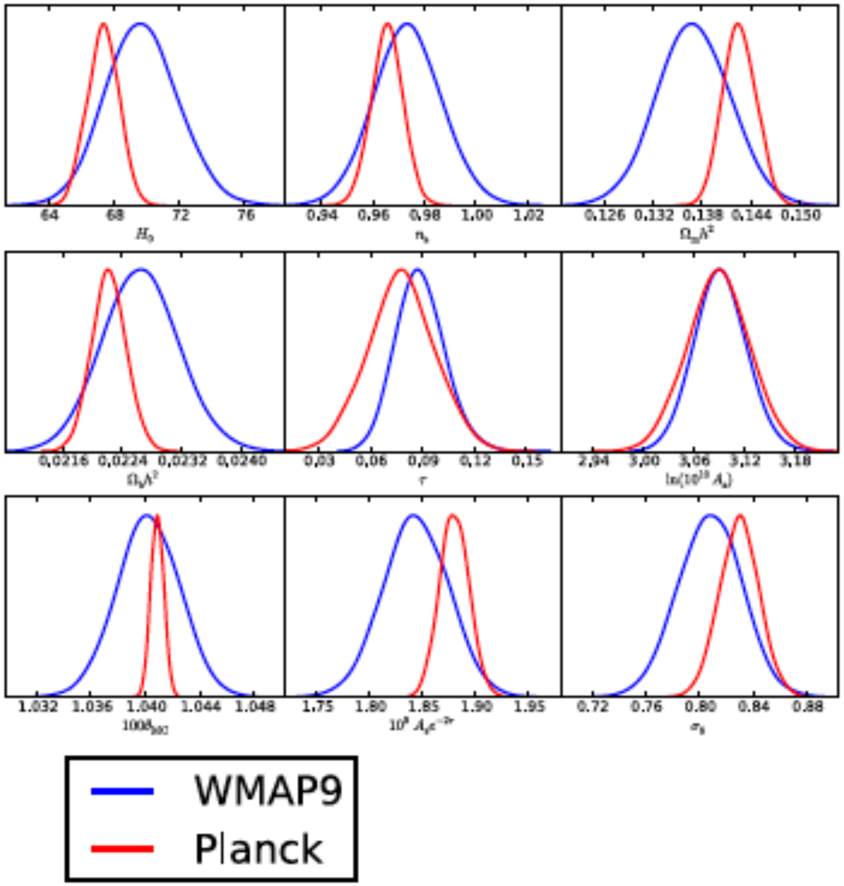


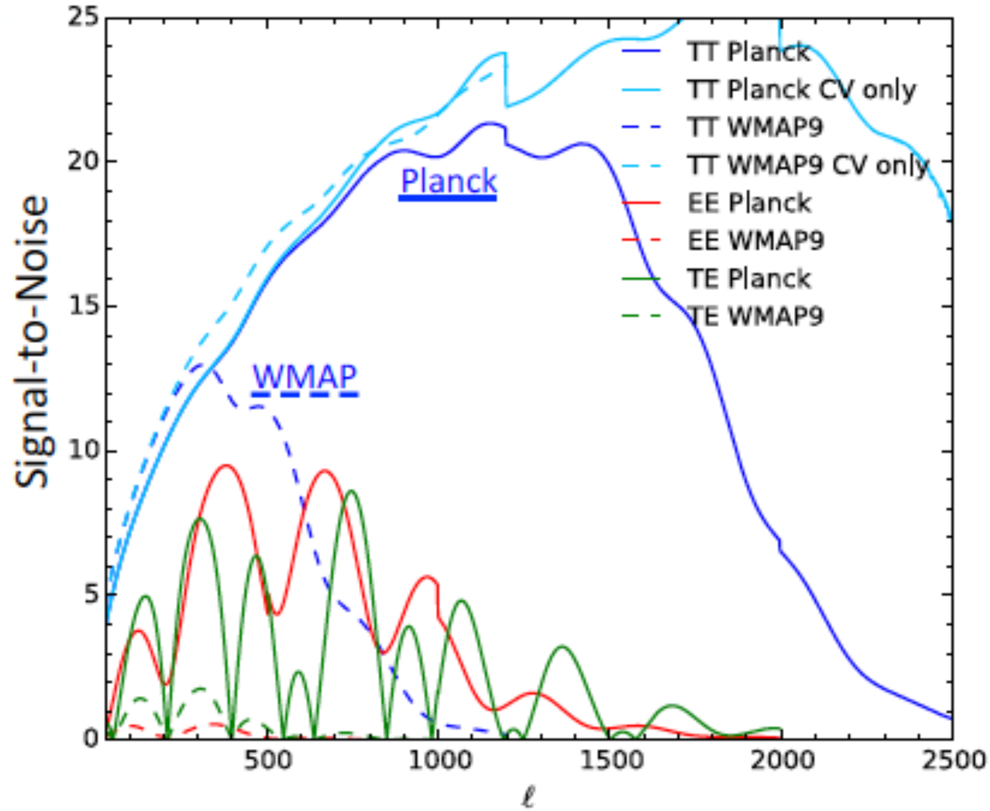
North Ecliptic pole: 100-70 GHz



The two Planck instruments / technologies measure the same CMB anisotropies

Planck and WMAP

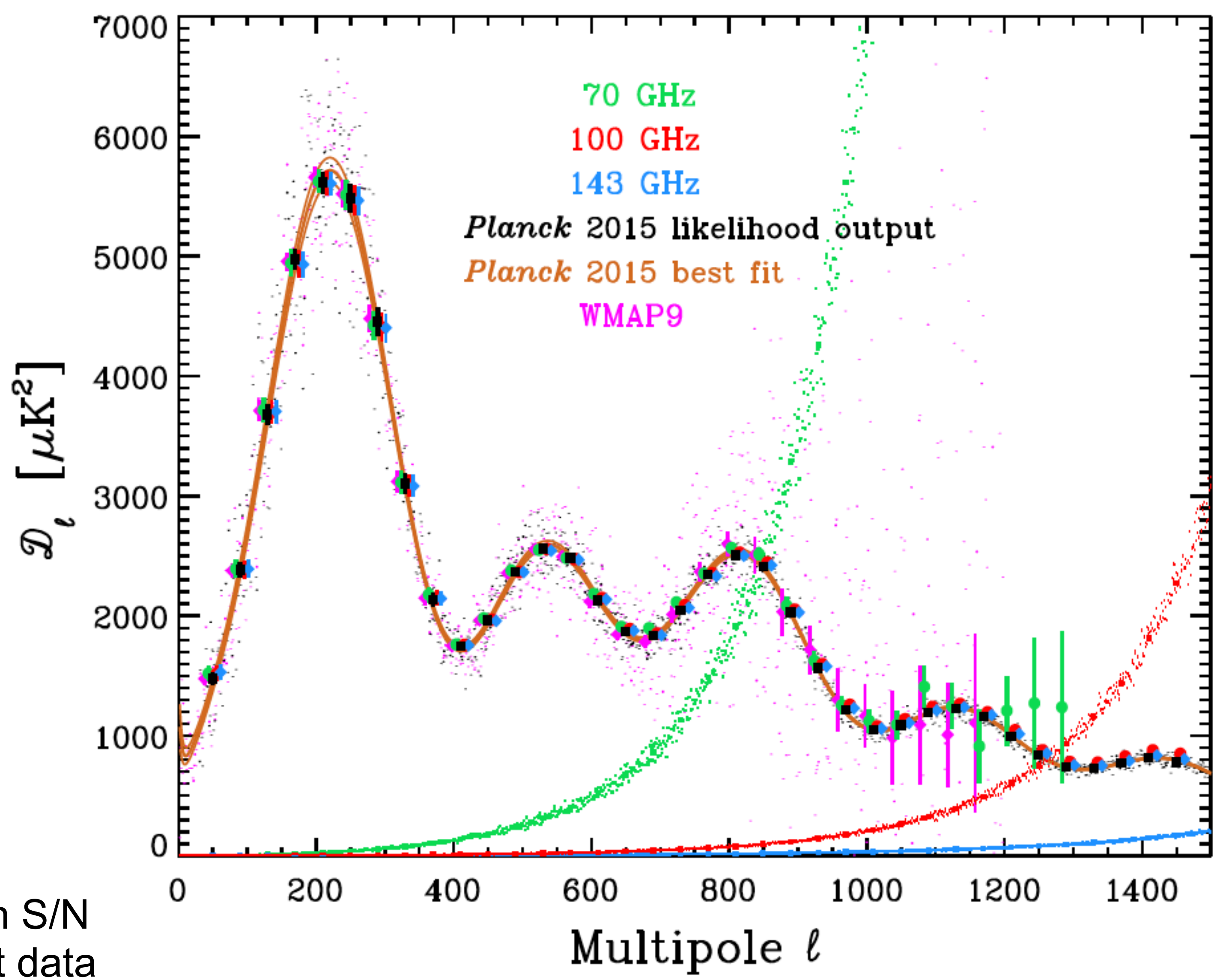




Planck sample variance limited till **l~1600** (data points till ~2500, fsky~40-70%)

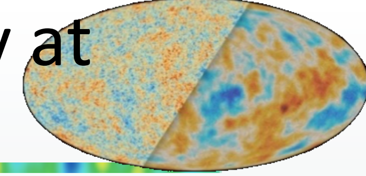
WMAP sample variance limited till **l~600** (data points till l~1200)

Channels consistency / noise levels



Many high S/N
redundant data

We are not the only ones to look critically at Planck data ☺



ASSESSING CONSISTENCY BETWEEN WMAP9 AND Planck15 T POWER SPECTRA
Y. Huang1, G. E. Addison1, J. L. Weiland1, C. L. Bennett1, Draft version April 17, 2018

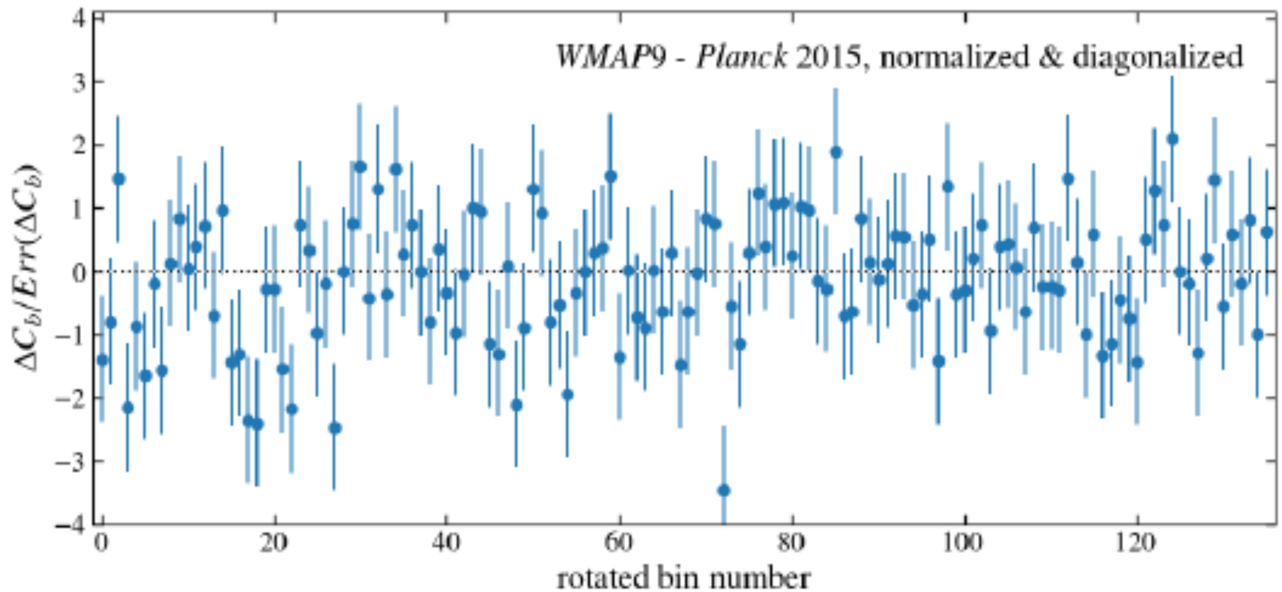


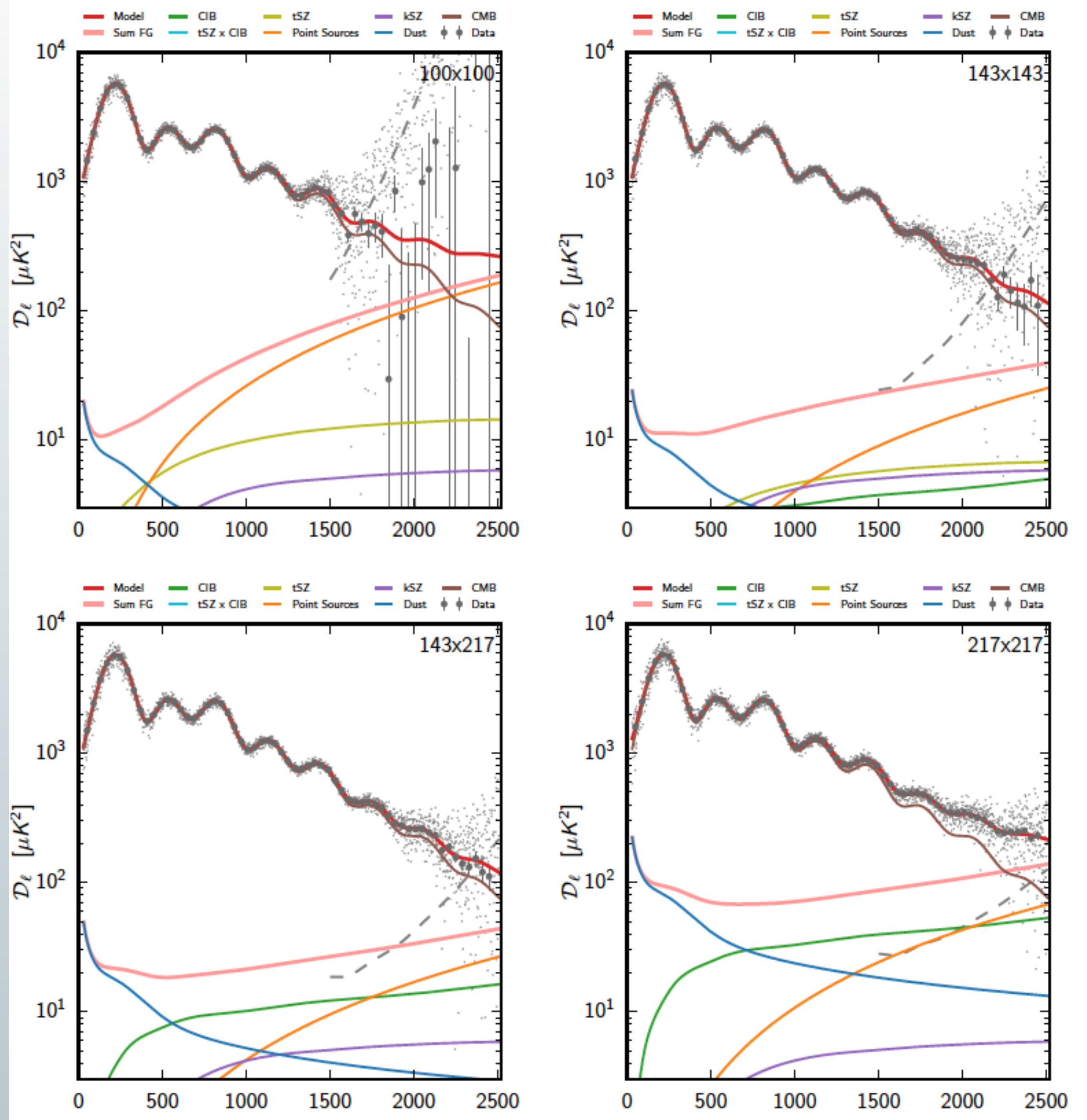
Figure 5. Top: observed binned power spectrum difference between *WMAP9* and *Planck* 2015, normalized by error bars estimated from simulations, which account for the correlated CMB cosmic variance between the two experiments. Most data points are within 2σ from zero. The first 13 bins are anti-correlated at $\sim 13\%$ with their immediate neighbors, while the rest are at $\sim 5\%$. Bottom: the vector of differences is rotated so that its covariance is diagonalized and the bins are uncorrelated. The rotated difference shows no statistically significant deviation from zero, except for the 72nd bin. We do not consider it as a sign of inconsistency, because the probability of at least 1 out of 136 bins deviating more than 3σ from zero is 25%, for 136 independent Gaussian-distributed random variables. We note that similar "clumping" of adjacent points also appears in randomly generated sets of 136 Gaussian numbers.

"Our results indicate that cosmological model differences between Planck and WMAP do not arise from measurement differences, but from the high multipoles not measured by WMAP" (an indirect admission that WMAP did not measure everything in the CMB?)

The high-ell likelihood (l>30)

We construct a Gaussian likelihood, using

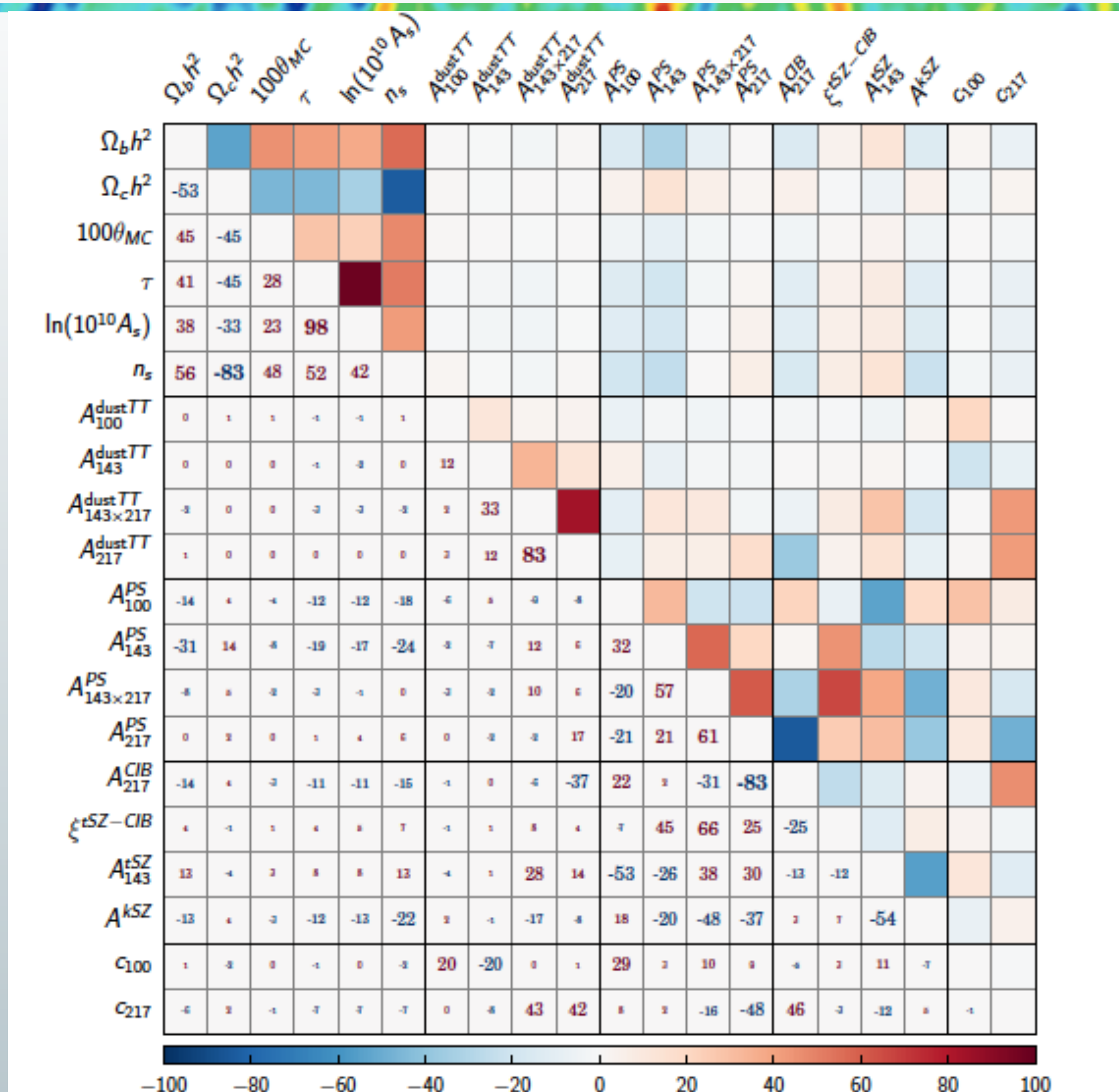
- A parameterised foreground model to, in the end, marginalise over (12 parameters)
- a covariance matrix which includes signal, noise, FG, masks… Full TT, TE, EE reduces to 2300^2 elements when binned instead of 23000^2 (Condition Number~ $O(10^{11})$)
- In practice, many detailed, intertwined choices, e.g., of masks, l-ranges, FG model, cross-spectra combination, etc.
- Test, test, test



About degeneracies…

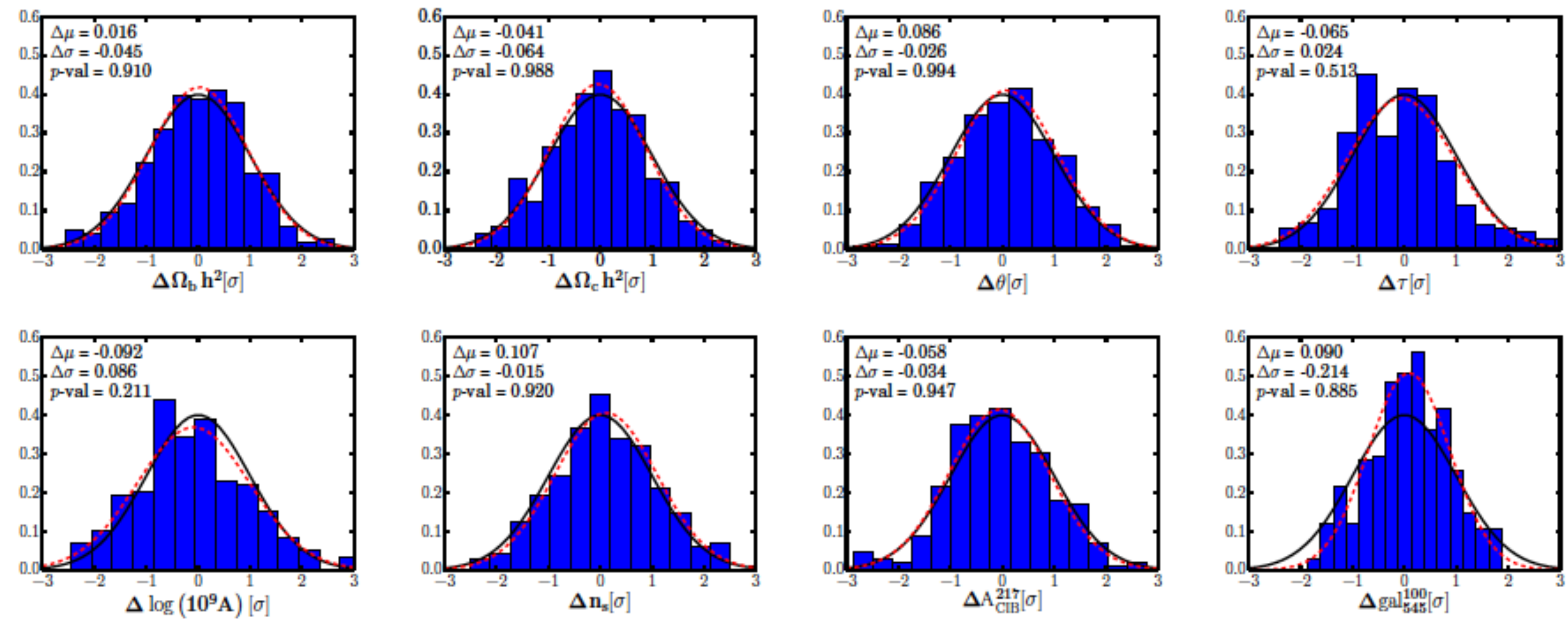
➔ Cosmology & foreground parameters are largely decoupled

(with these masks,ell-cuts, & sensitivities)

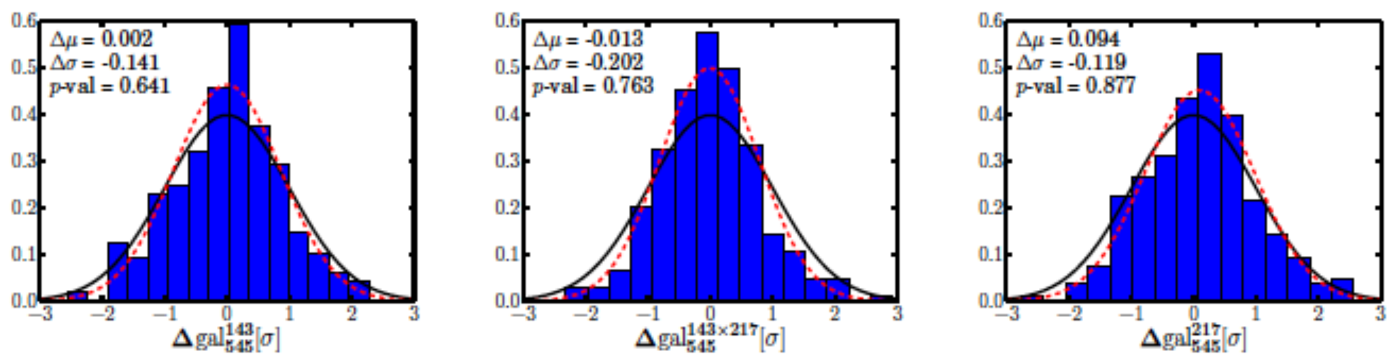


So very robust to inaccuracies in modelling of gastrophysics

Methodological tests on sims, better than 0.1σ



Each sims analysed like real data, from nu maps to parameters



Distribution of deviation of mean posterior vs input sims params, in units of expected rms.

.

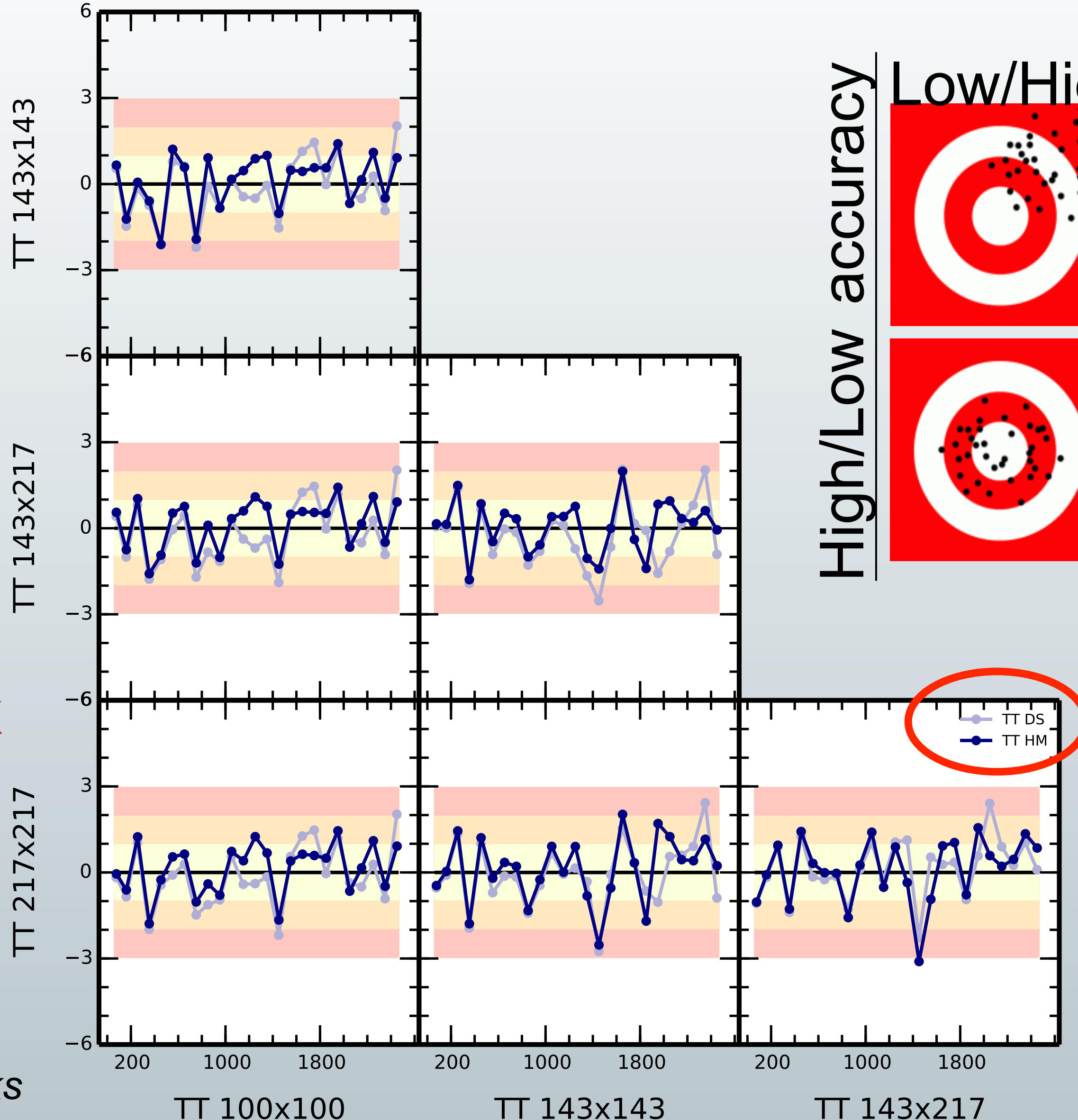
Consistency checks (interfreq., DetSets)

(i.e. blind assessment of data model)

12 different CMB takes are being differenced and expressed in CMB Sigma Units

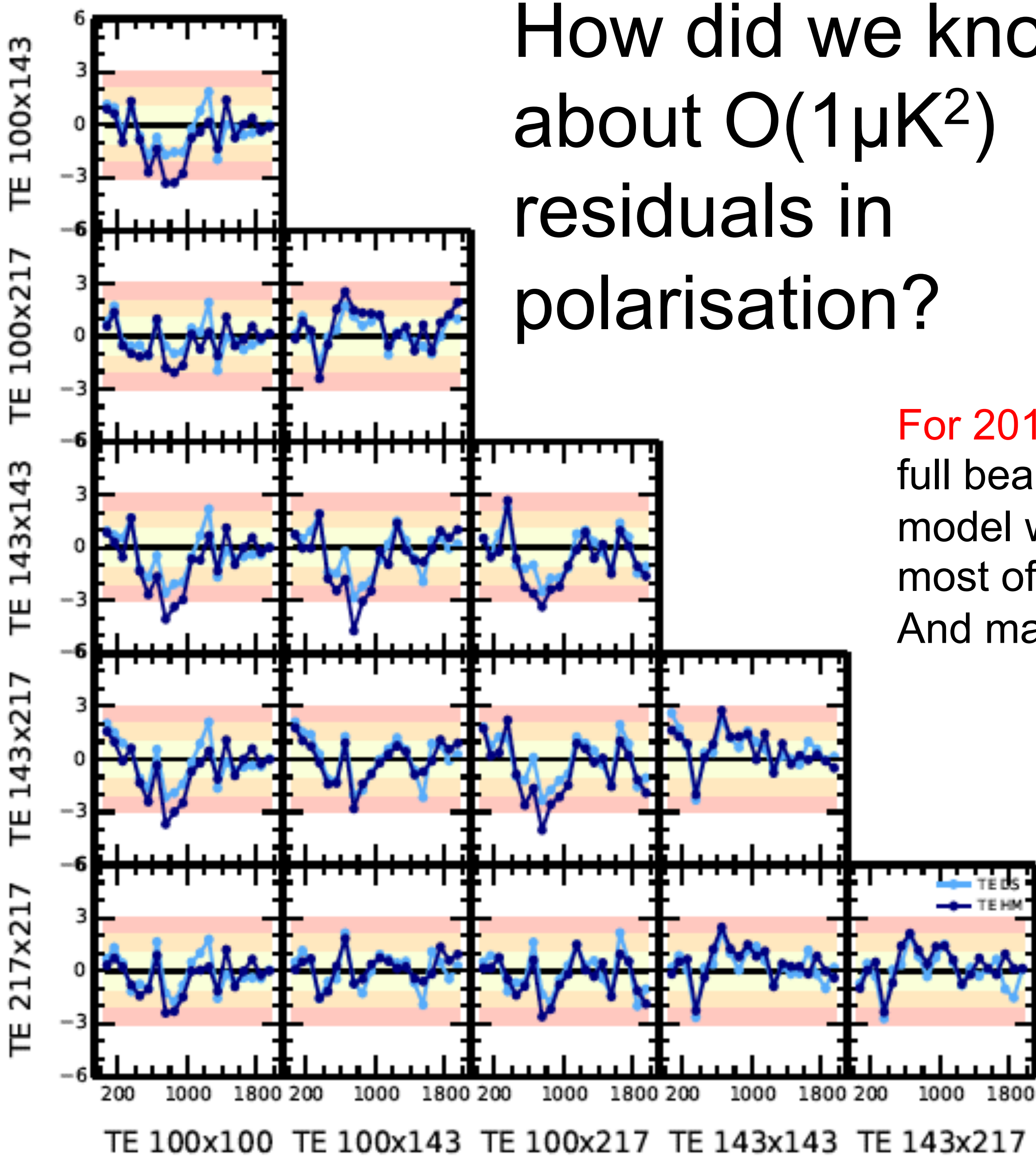
➔ All null tests OK

NB: DS not used but for consistency checks



Worst is dip at 1460
Cut 1400-1500
→parameters shift .5 to 1sig

How did we know about O(1μK^2) residuals in polarisation?



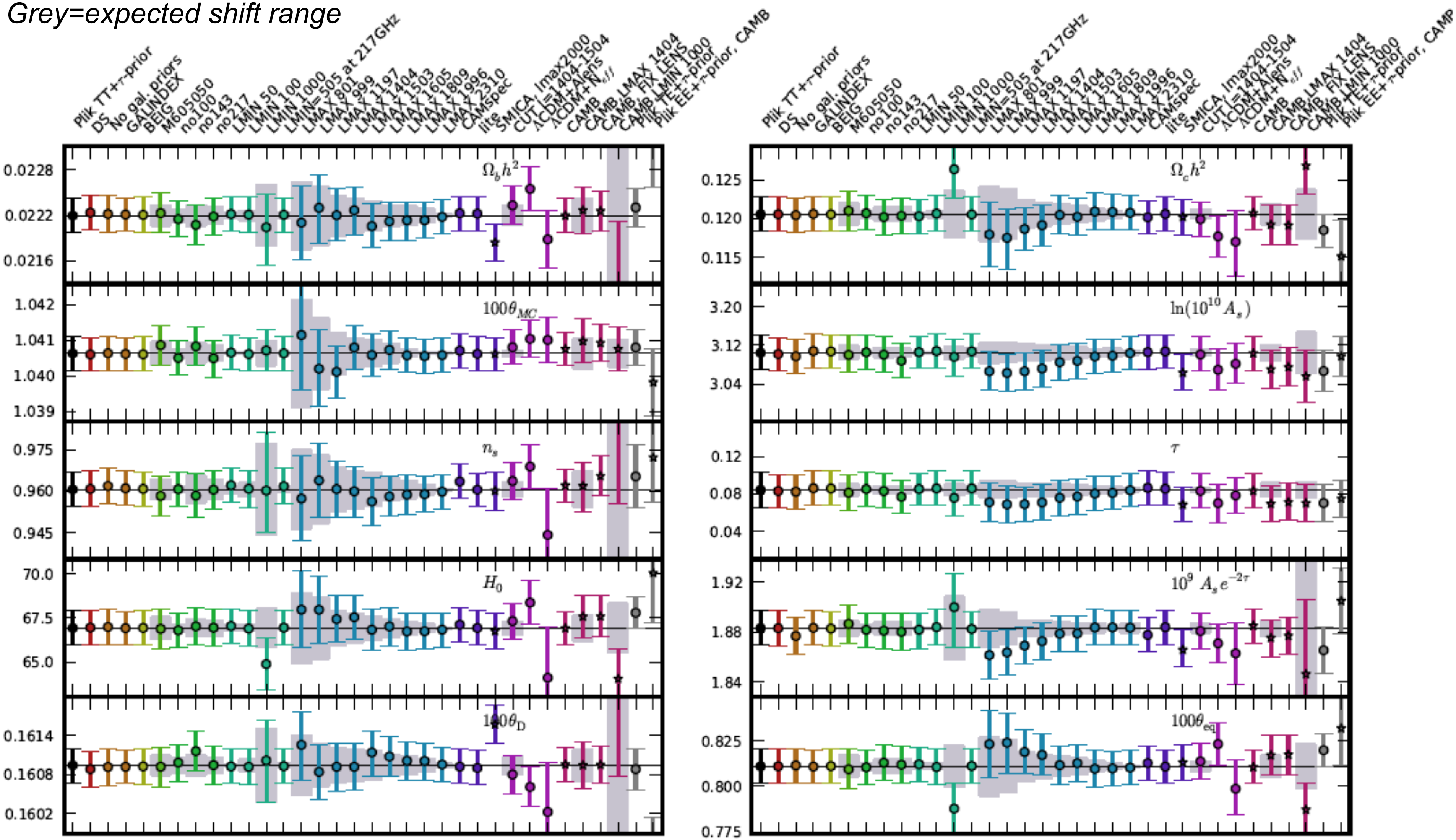
For 2018, we have developed a full beam and leakage physical model which predicts *ab initio* most of these differences…
And many other improvements.

Test, test, test…

- Different data cut (detector sets instead of Half mission maps),
- Foregrounds (no Galactic dust priors from higher frequencies, free CIB power spectrum index),
- Beam eigenvalues parameters,
- Different mask (60%, 50%, 50% instead of 80%, 70%, 60% at 100, 143, 217GHz),
- Eliminate one frequency at the time,
- Different lmax,
- Different likelihood (Camspec),
- Component separated maps (SMICA),
- Cutting a feature at 1400-.-1500,
- Cutting lmin.

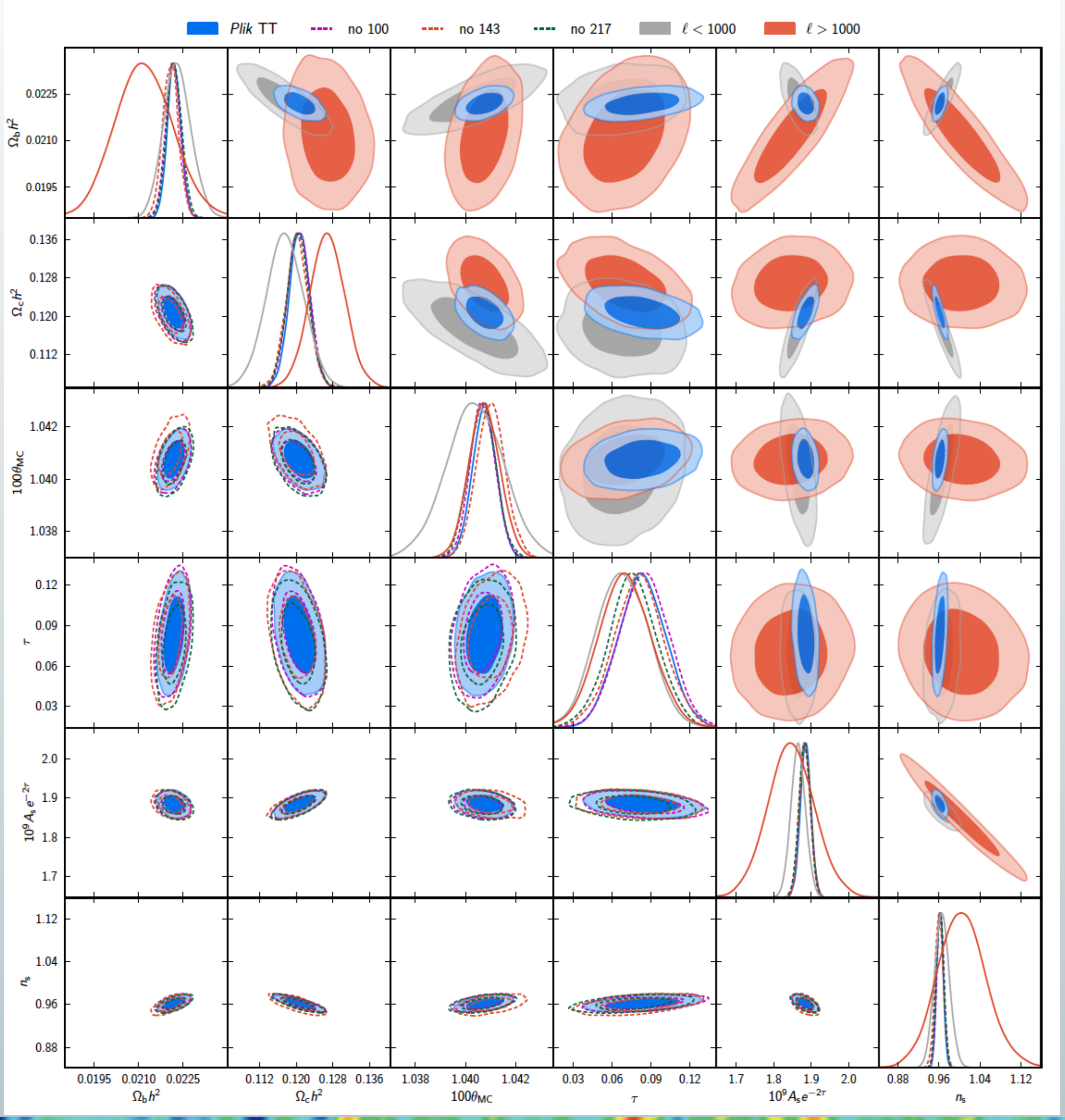
Test, test, test… are OK (in TT)

Grey=expected shift range



Removing entire nu channels, Varying l-range, Using detsets inside of Half-missions, etc.

The high-ell shift (l~1000)



Like15

This attracted the attention of Addison et al. ...

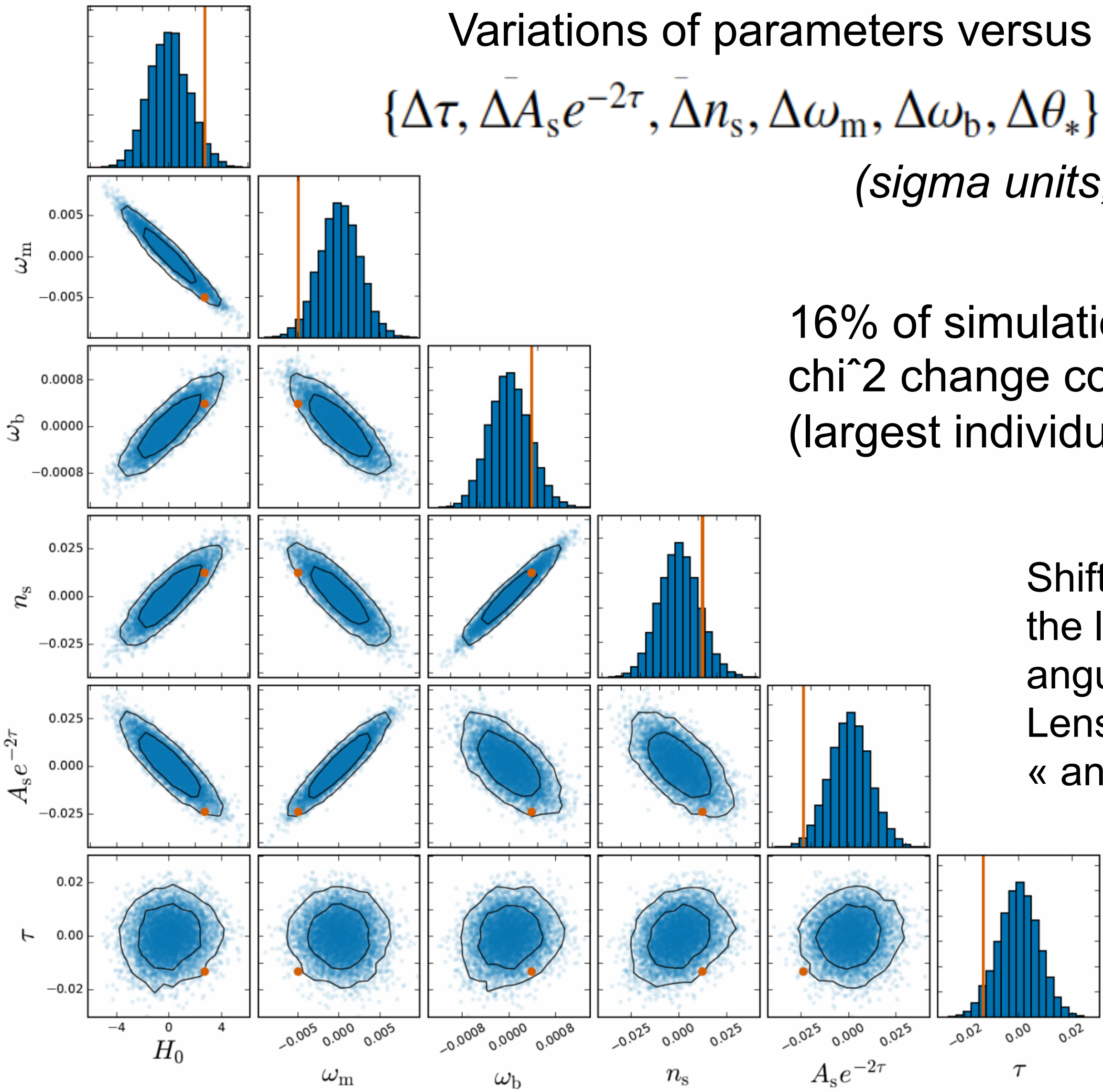
Simulations

- We simulate ~5000 TT power spectra and estimate cosmological parameters from each different l-ranges (e.g. $l<800$ and $l<2500$).

- We only use **TT data** and use a prior on the optical depth $\tau=0.07\pm0.02$ as a proxy of the large scale polarization data (but we also tested the a prior $\tau=0.055\pm0.01$, compatible with the latest HFI results 2016).

"Planck 2016 intermediate results. LI. Features in the cosmic microwave background temperature power spectrum and shifts in cosmological parameters "
arXiv:1608.02487

Cosmological shifts with more information



Variations of parameters versus expectation for l<800 vs l<2500

$$\{\Delta\tau, \Delta A_{\rm s}e^{-2\tau}, \Delta n_{\rm s}, \Delta\omega_{\rm m}, \Delta\omega_{\rm b}, \Delta\theta_*\} = \{-1.8, -2.2, 1.2, -2.0, 1.2, 0.9\}$$

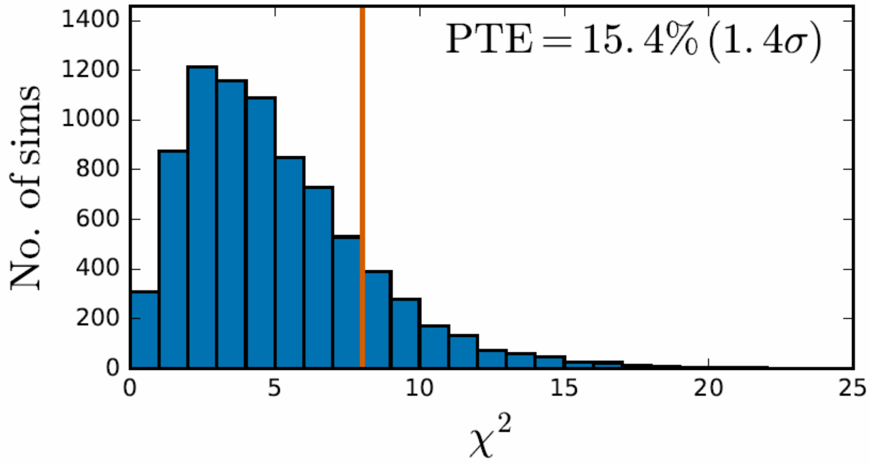
(sigma units, chi^2=8)

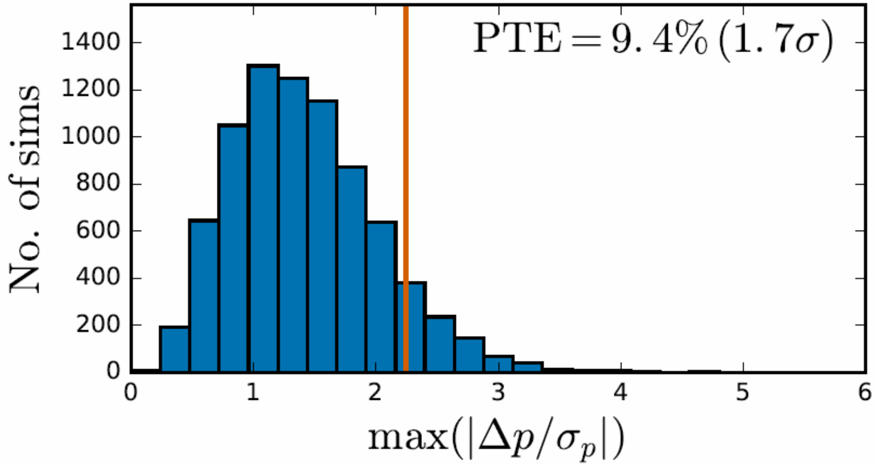
16% of simulations have a global chi^2 change comparable to data (largest individual change is 10%)

Shifts driven by a set of oscillations wrt the l<800 model across a broad range of angular scales, not due mostly to grav. Lensing enhancement. But role of l=20 « anomaly » (tilting ns → Ho) on l<800….

Planck 2016 intermediate results. LI. Features in the CMB temperature Power spectrum and shifts in cosmological parameters", arXiv:1608.02487v1)

Is the shift from WMAP (l<800) to Planck cosmology (l<2500) surprising?





For both statistics (chi^2 and largest deviation), we find that the observed shifts are largely consistent with expectations from simulations. Including for other data splits:

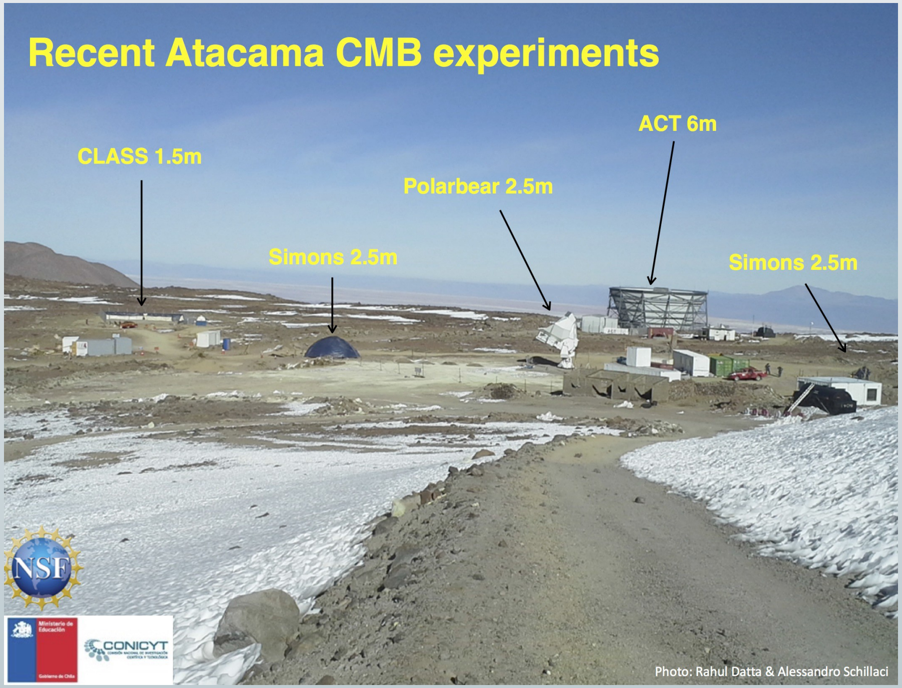
Data set 1	Data set 2	Test: χ^2	Test: max-param
$\ell < 800$	$\ell < 2500$	$1.4\,\sigma^\dagger$	$1.7\,\sigma$ $(A_s e^{-2\tau})$
$\ell < 800$	$\ell > 800$	$1.6\,\sigma$	$2.1\,\sigma$ $(A_s e^{-2\tau})$
$\ell < 1000$	$\ell < 2500$	$1.8\,\sigma^\dagger$	$1.5\,\sigma$ $(A_s e^{-2\tau})$
$\ell < 1000$	$\ell > 1000$	$1.6\,\sigma$	$1.6\,\sigma$ (ω_m)
$30 < \ell < 800$	$\ell > 30$	$1.2\,\sigma^\dagger$	$1.3\,\sigma$ (τ)
$30 < \ell < 800$	$\ell > 800$	$1.2\,\sigma$	$1.2\,\sigma$ $(A_s e^{-2\tau})$
$30 < \ell < 1000$	$\ell > 30$	$1.4\,\sigma^\dagger$	$1.5\,\sigma$ (τ)
$30 < \ell < 1000$	$\ell > 1000$	$1.2\,\sigma$	$0.7\,\sigma$ (ω_m)

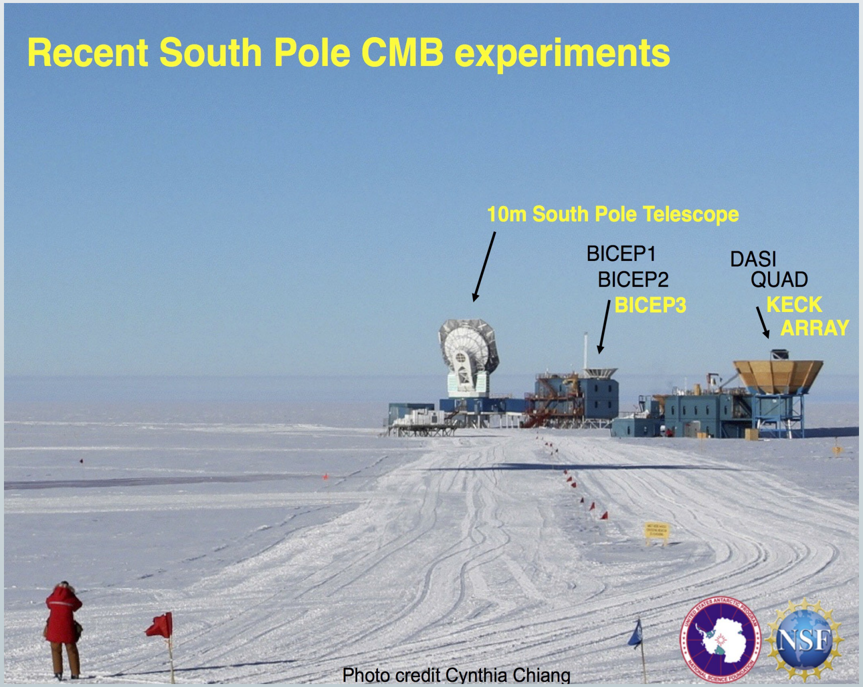
Planck IR-LI, arXiv:1608.02487v1

(NB: Change of [-0.1,0.3] σ when using prior on tau=0.055\pm0.01 instead of 0.07\pm 0.02)

Higher-ell Comparisons

- ACT= Atacama Cosmology Telescope: a 6m telescope in Chile. Had results from TT at 148 and 217GHz on ~500 sq.deg. Recently published polarisation from ACTPOL (*Louis+ arXiv:1610.02360*)
- SPT=South Pole Telescope: a 10m telescope at S.Pole. *Hou+ arXiv:1704.00884, Aylor+ arXiv:1706.10286, Henning+ arXiv:1707.09353v3*

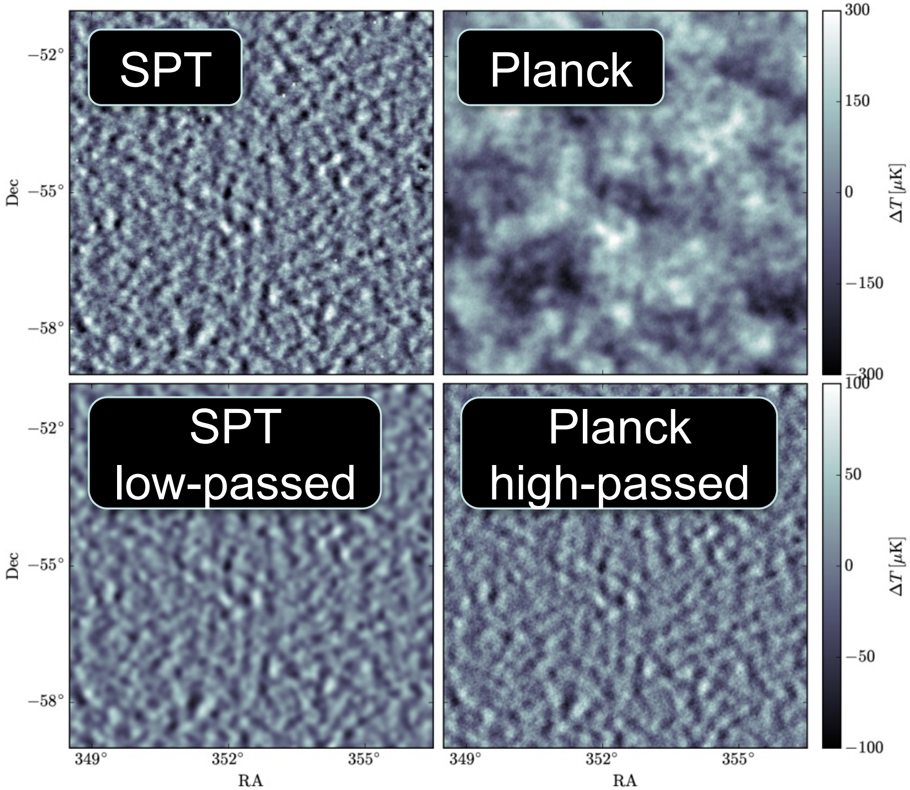




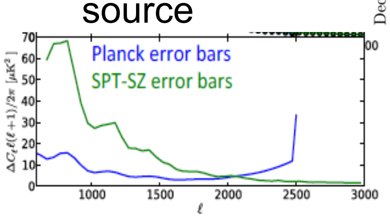
(Also: QUBIC, NIKA from France , QUIJOTE, C-BASS from Europe, GroundBird, AMIBA from Asia, Mustang2 in the US, Ali-Tibet)

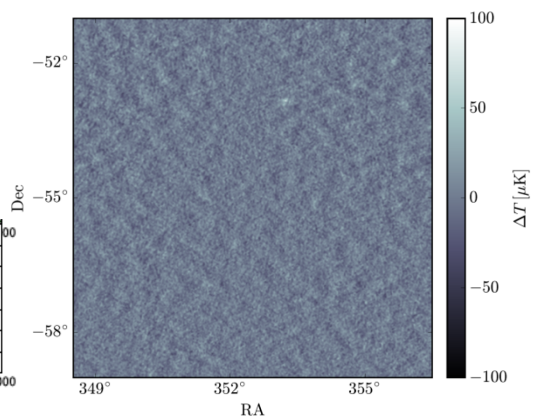
SPT@150GHz vs Planck@143GHz

Hou+ arXiv:1704.00884v1



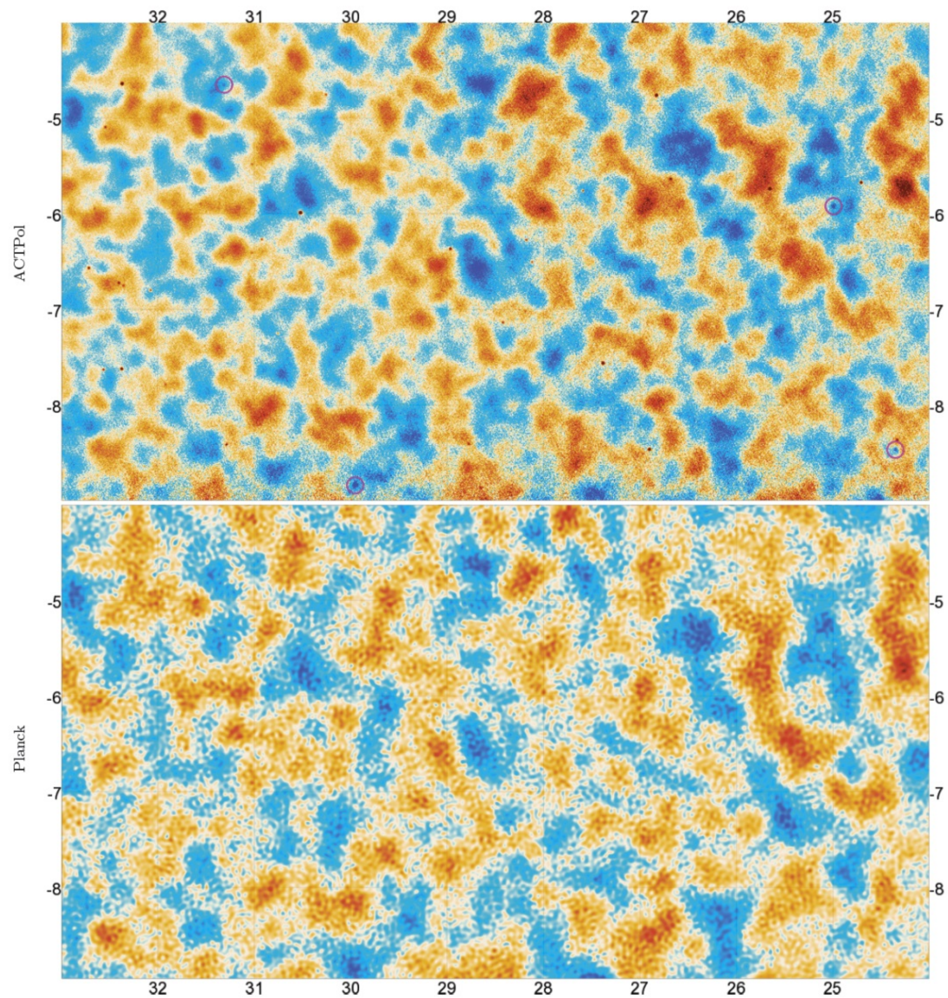
Little residual in SPT-low minus Planck-high, but a variable source





ACT@150GHz vs Planck@143GHz

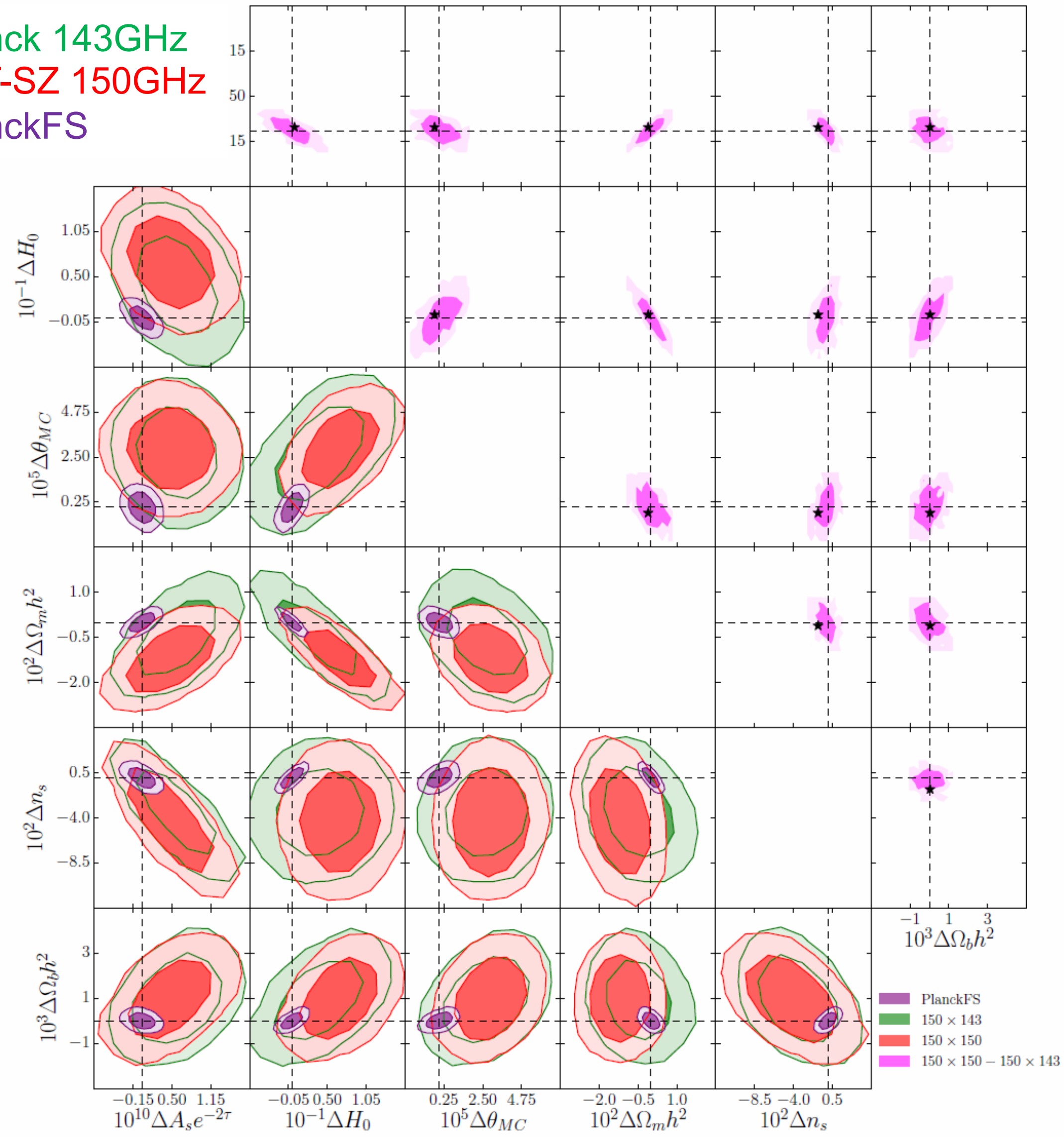
Louis+ arXiv:1610.02360v1



➔ Excellent consistency at map level around 150GHz for Planck vs SPT & ACT

P/SPT in-patch consistency is excellent

Planck 143GHz
SPT-SZ 150GHz
PlanckFS



This plot shows posterior distributions for parameter differences for several different tests. In all cases, contours indicate the 68% and 95% confidence regions. The dashed lines correspond to = 0.

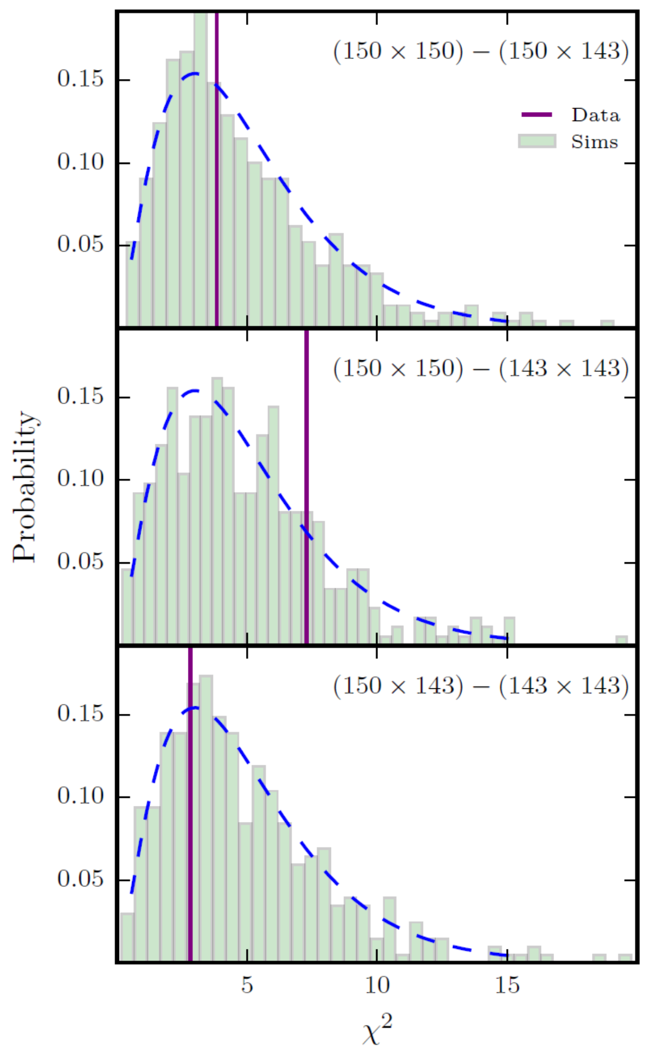
Lower triangle: The posterior distributions for 150 X 150,
150 X 143, both with ell_max = 2000, and PlanckFS. Each distribution has the PlanckFS best-t values subtracted.

Upper triangle:
Contours indicate the posterior distributions from simulations for 150 X 150 - 150 X 143 with ell_max = 2000, and black stars indicate the parameter difference values from the same comparison in the data. It is visually apparent that this comparison constitutes a much more stringent consistency test than comparing to PlanckFS; in fact, this comparison reduces the parameter volume by a factor of 300. **The observed consistency provides strong evidence against a systematic difference in the modes measured in common between the two experiments.**

Aylor+ arXiv:1706.10286v1

Planck/SPT consistency: LCDM parameters

(Using 2540 deg2 SPT-SZ, Aylor+ arXiv:1706.10286v1



PTEs Between Parameters in SPT Sky Patch.

	ℓ_{max}		
	2000	2500	3000
150 × 150 – 150 × 143	0.74	0.66	0.57
150 × 150 – 143 × 143	0.32	0.38	0.20
150 × 143 – 143 × 143	0.62	0.73	

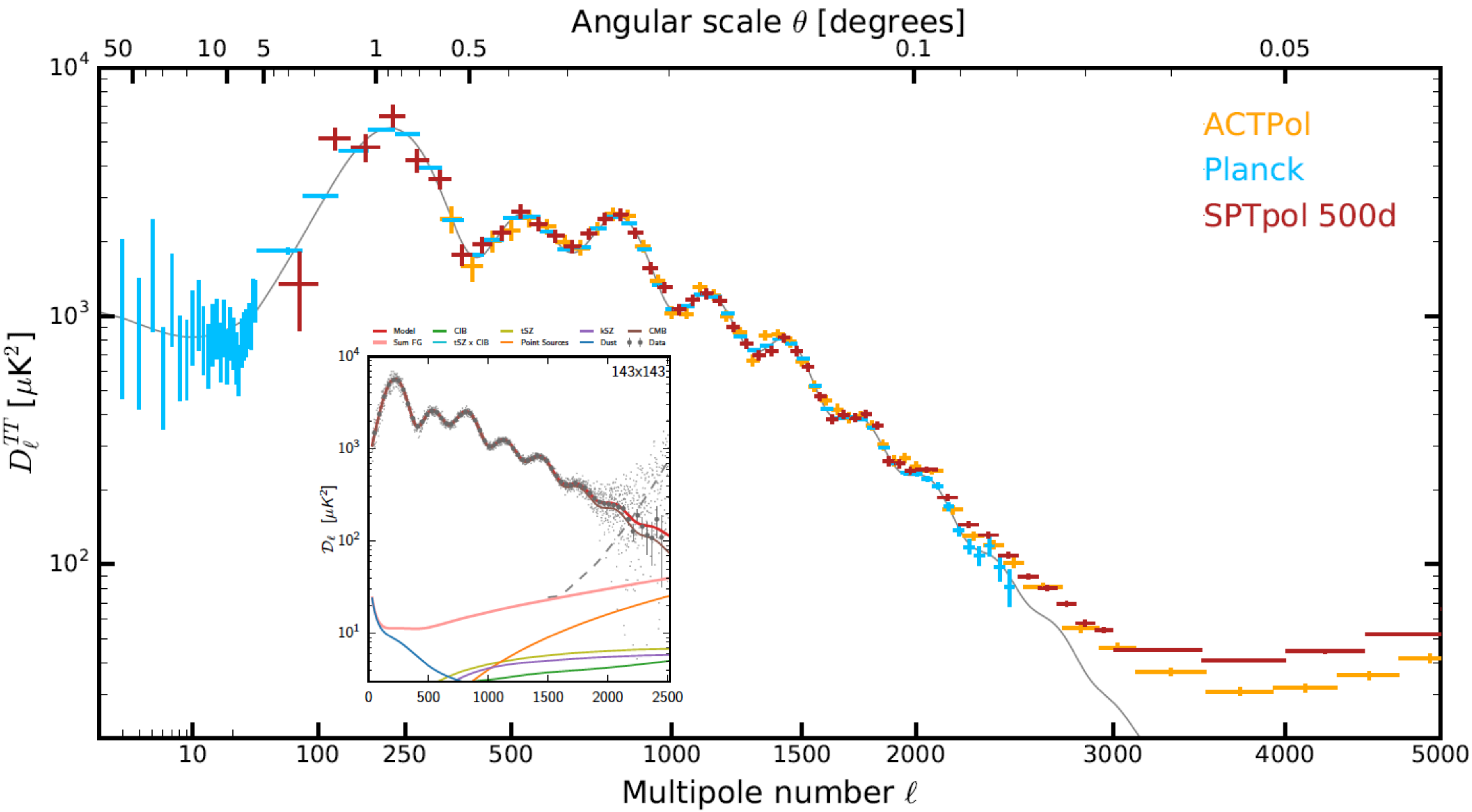
Planck and SPT LCDM parameters fully consistent WITHIN the SPY sky patch

PTEs Between PlanckFS and In-patch Parameters.

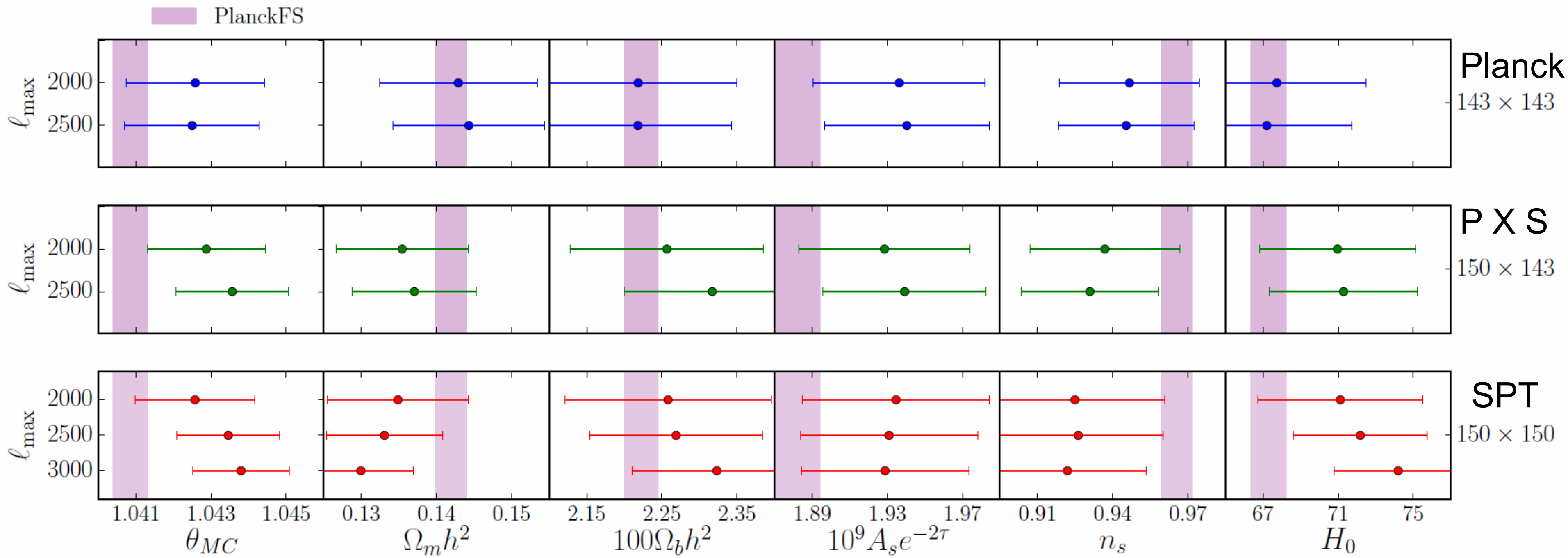
	ℓ_{max}		
	2000	2500	3000
150 × 150	0.24	0.094	0.032
150 × 143	0.19	0.18	
143 × 143	0.29	0.31	

PlanckFS (Full sky) is consistent with SPT in-patch at all scale probed well by Planck (lmax =2000). Need to go to lmax_SPT=3000 to find some tension (at 3.2% PTE) [where SPT goes to larger H0 & FGs]

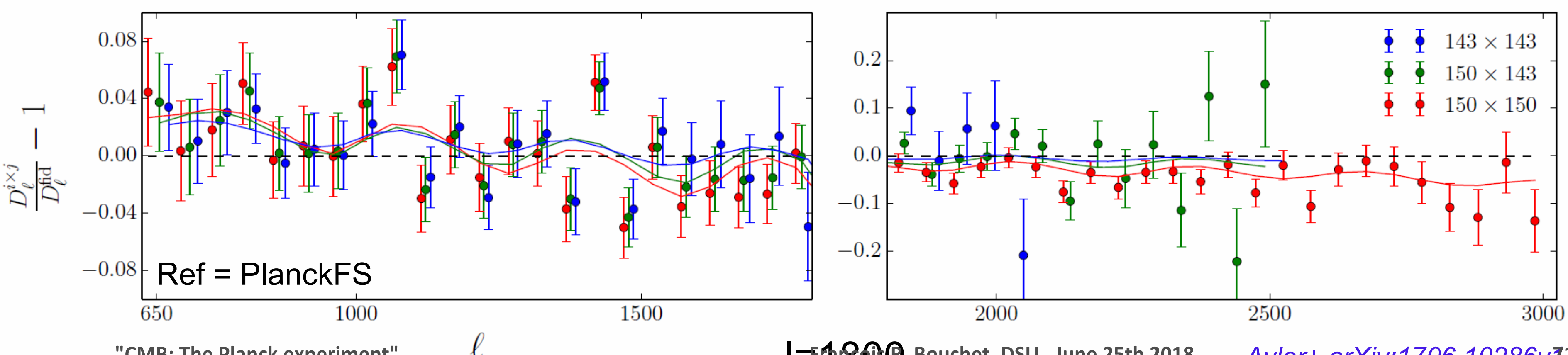
FGs are strong at l>2500 for most of the sky



Parameters PP, PS, SS in-patch at different lmax, versus PlanckFS,



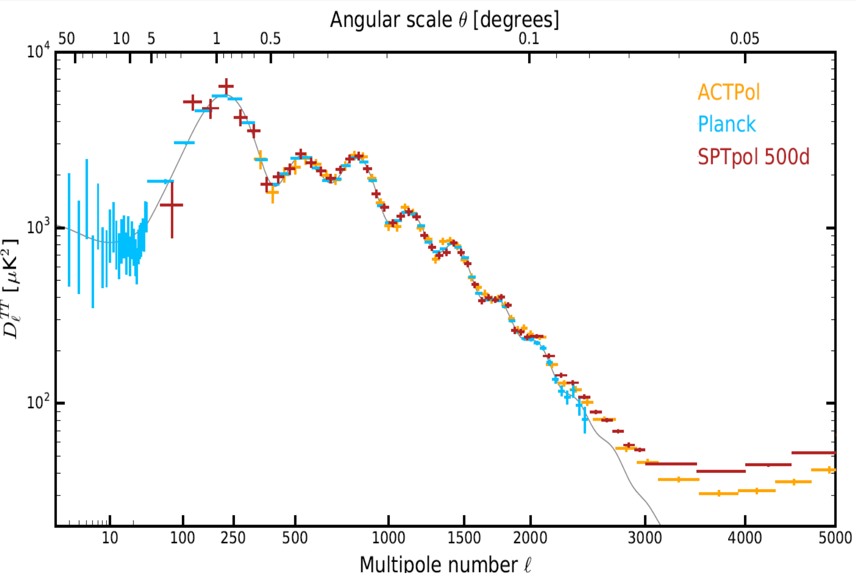
Where it's coming from, at power spectrum level (curves are BF models):

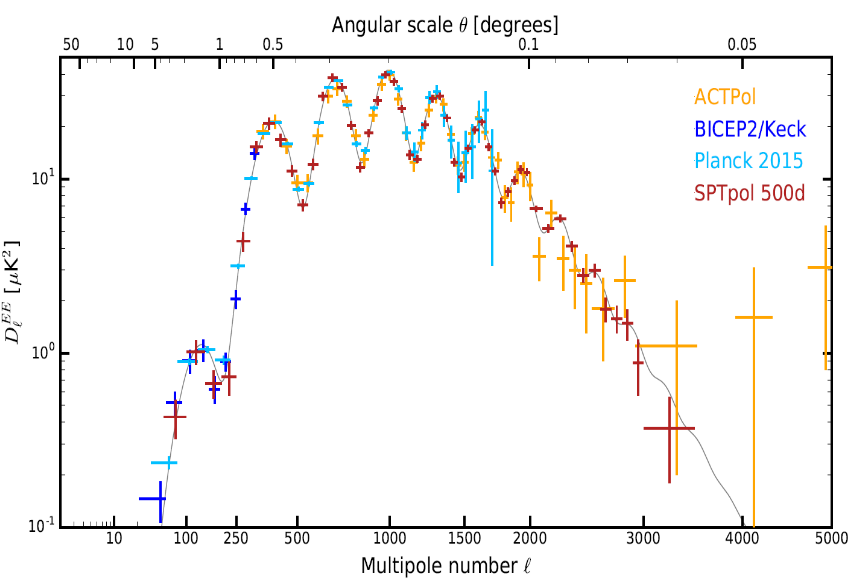


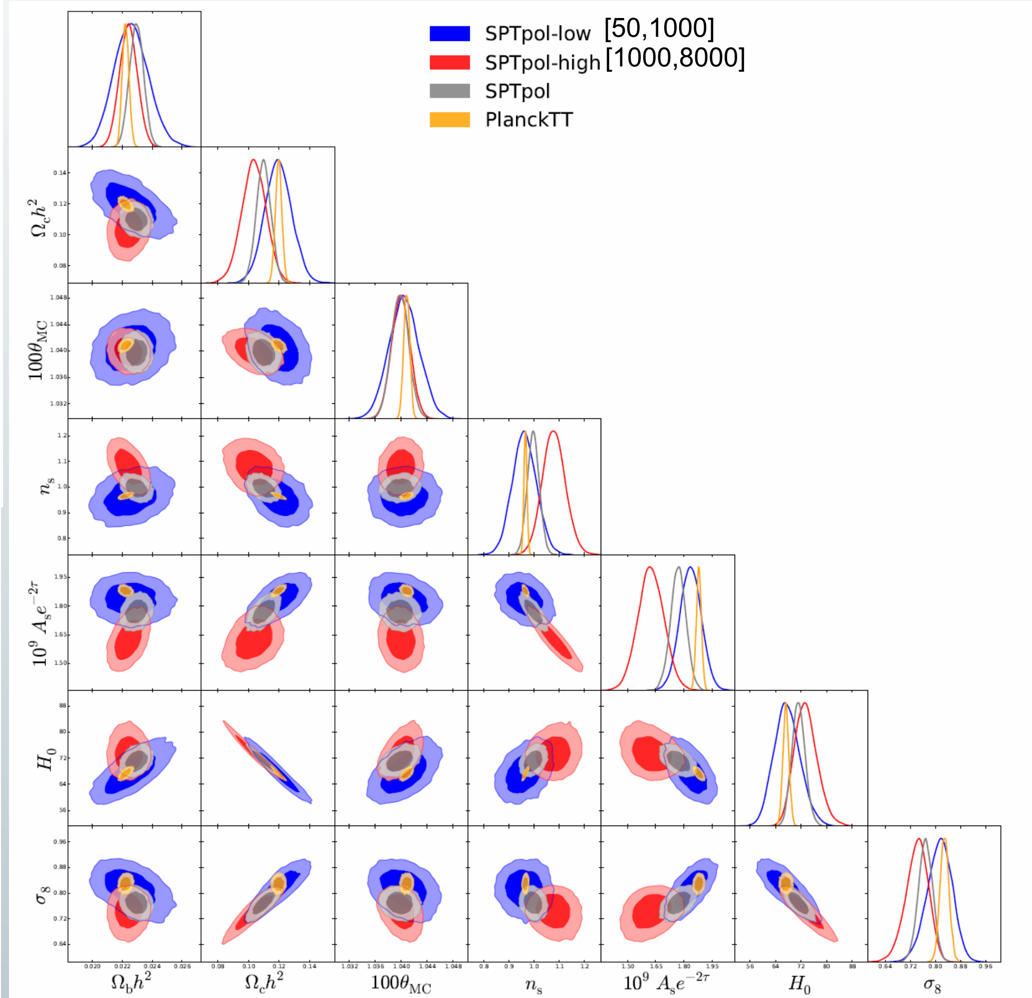
l=1800

Aylor+ arXiv:1706.10286v1

SPTPOL on 500 sq.deg







Henning+, arXiv:1707.09353v3

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 homogeneous and isotropic field,

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

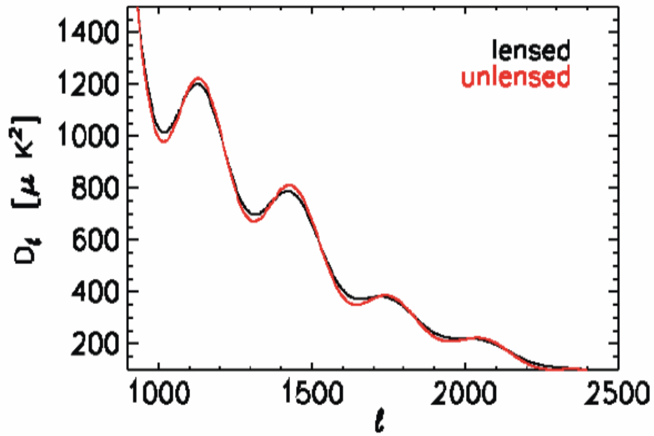
The temperature angular **power spectrum** is estimated in practice by

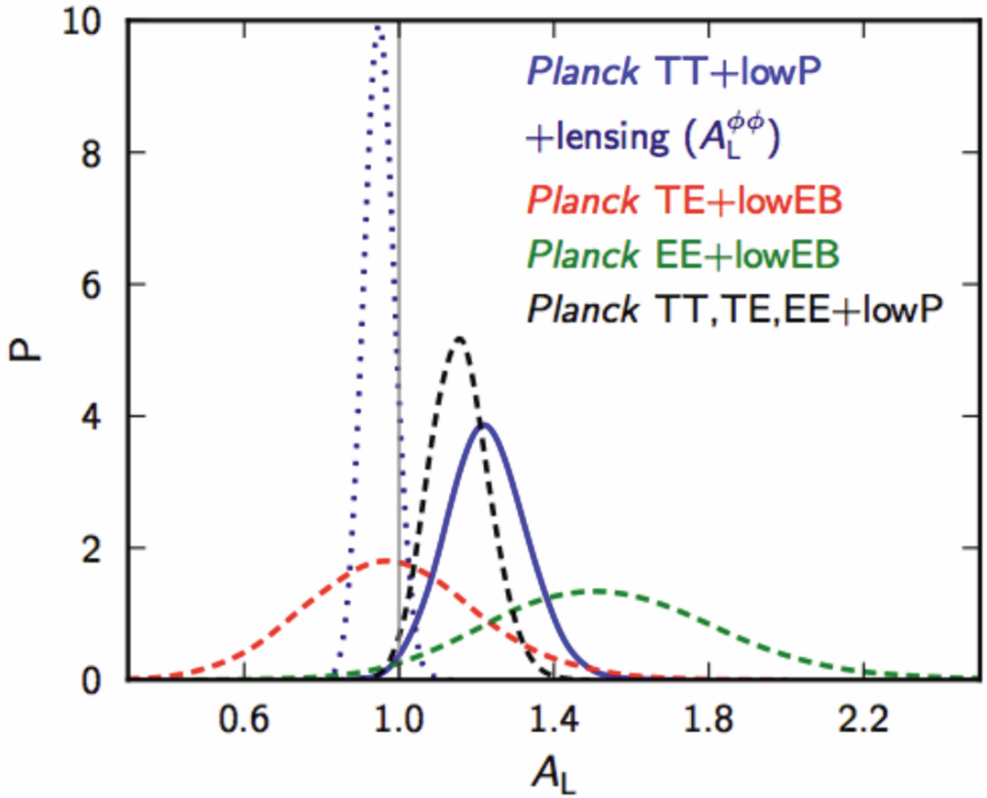
$$\widehat{C_\ell} = \sum_m \frac{|a_{\ell m}|^2}{2\ell + 1}$$

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

Similar expressions for polarisation (on spin2 harmonics)

Related deviations: Alens





- A_L parametrizes amplitude of lensing power spectrum.
- In ΛCDM+A_L model, ~2 sigma deviation :
  Alens= 1.23±0.96 (TT+simall 2016)
- Planck CMB reconstructed lensing potential power spectrum ($\phi\phi$) has a smaller amplitude.
- Discrepancy on $\sigma_8\Omega_m^{0.25}$ (proxy for lensing amplitude) between lensing reconstruction and l>1000 parameters at 2.4 σ.
- Larger lensing can be given by extensions of LCDM (e.g. negative Ω_k or w<1) but deviations disappear when adding CMB lensing reconstruction data or BAO.

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

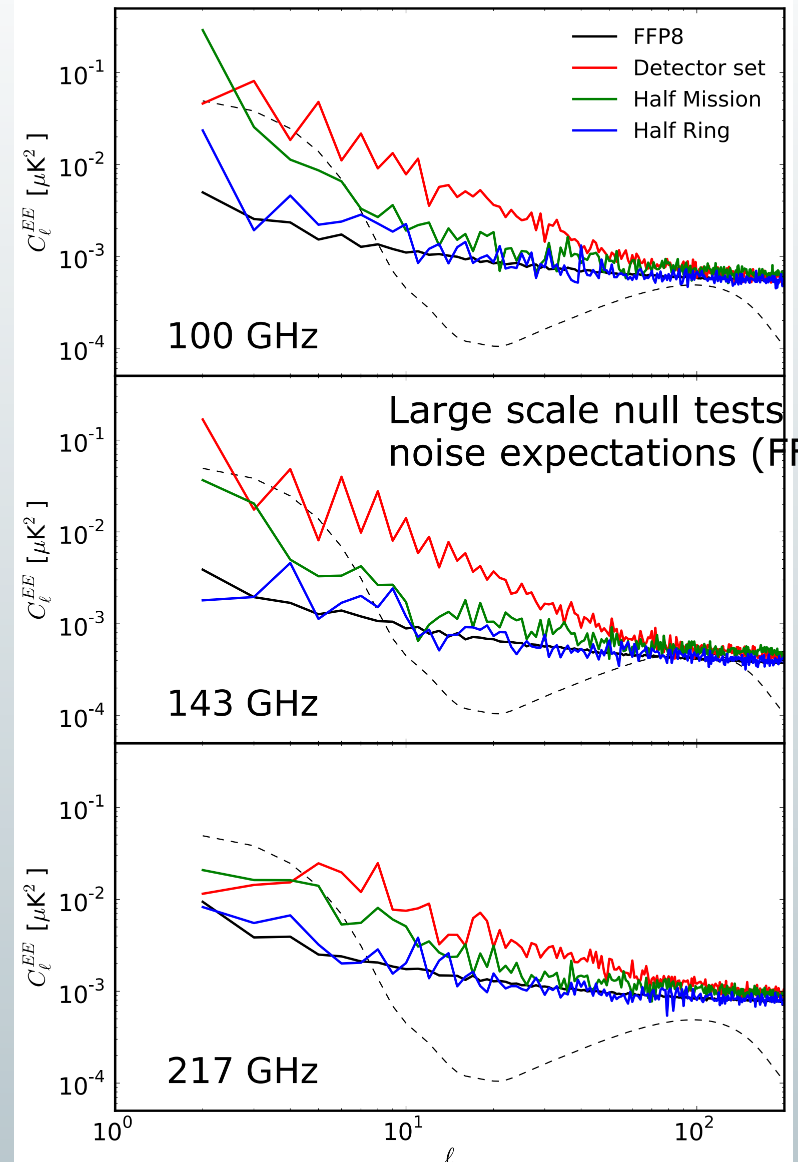
THE LEGACY OF PLANCK

- The most precise picture of the universe: 6-parameters ΛCDM model
- Best characterisation of the isotropy and statistics of the CMB anisotropies
- Inflation physics
- Primordial non-Gaussianity
- Fundamental physics:
  - Modulation and aberration effects
  - Neutrino physics
  - DE and MG
- Map of the lensing potential at $z \approx 2$
- SZ clusters: 1653 detections
- Measure of the ISW effect
- Map of the CIB
- Extragalactic sources: radio (quasars and radio galaxies) and infrared sources (dusty star-forming galaxies)
- Detailed information on the space-frequency distribution of the diffuse Galactic components: synchrotron, free-free, thermal dust, spinning dust emission, magnetic field, …
- Galactic sources (cold cores, HII regions and young star-forming regions)
- Best determination of the Solar Dipole

Large scale polarization

- The 2015 polarized maps of HFI still contain significant excess power at large angular scales
  - *Only the 70 GHz data was deemed safe enough for polarization-based science at large angular scales*
  - *CMB pol-map-based analysis uses high-pass filtering*

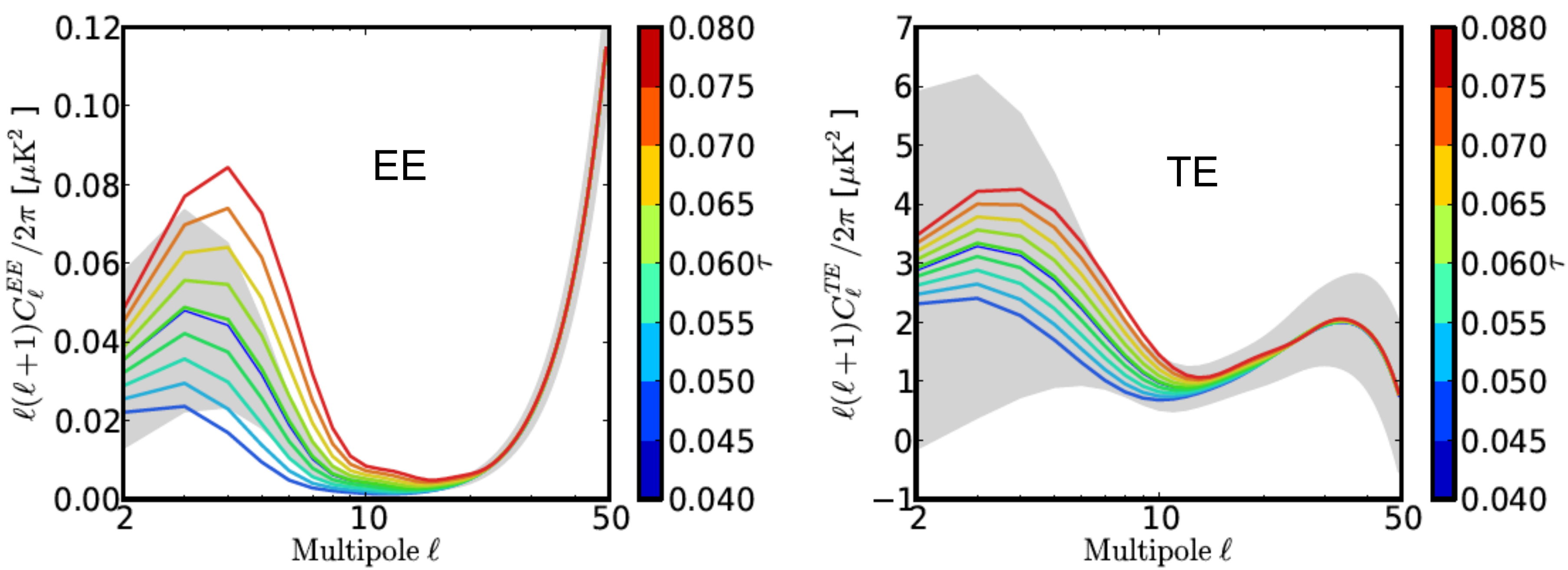
- Large scale polarization is particularly important for two cosmological parameters
  - τ *(optical depth to reionization)*
  - *r (amplitude of primordial gravitational*



Planck Collaboration VIII 2016

Optical depth to reionization, τ

- The scattering of CMB photons when the Universe reionized reduced the amplitudes (TT ~ A_s exp-2τ), but it also generated large scale E-mode at very large angular scales (EE ~ A_s τ^2).
- Note that TT first acoustic peak is ~5600μK^2, while EE signal is a few 10^{-2} μK^2 …



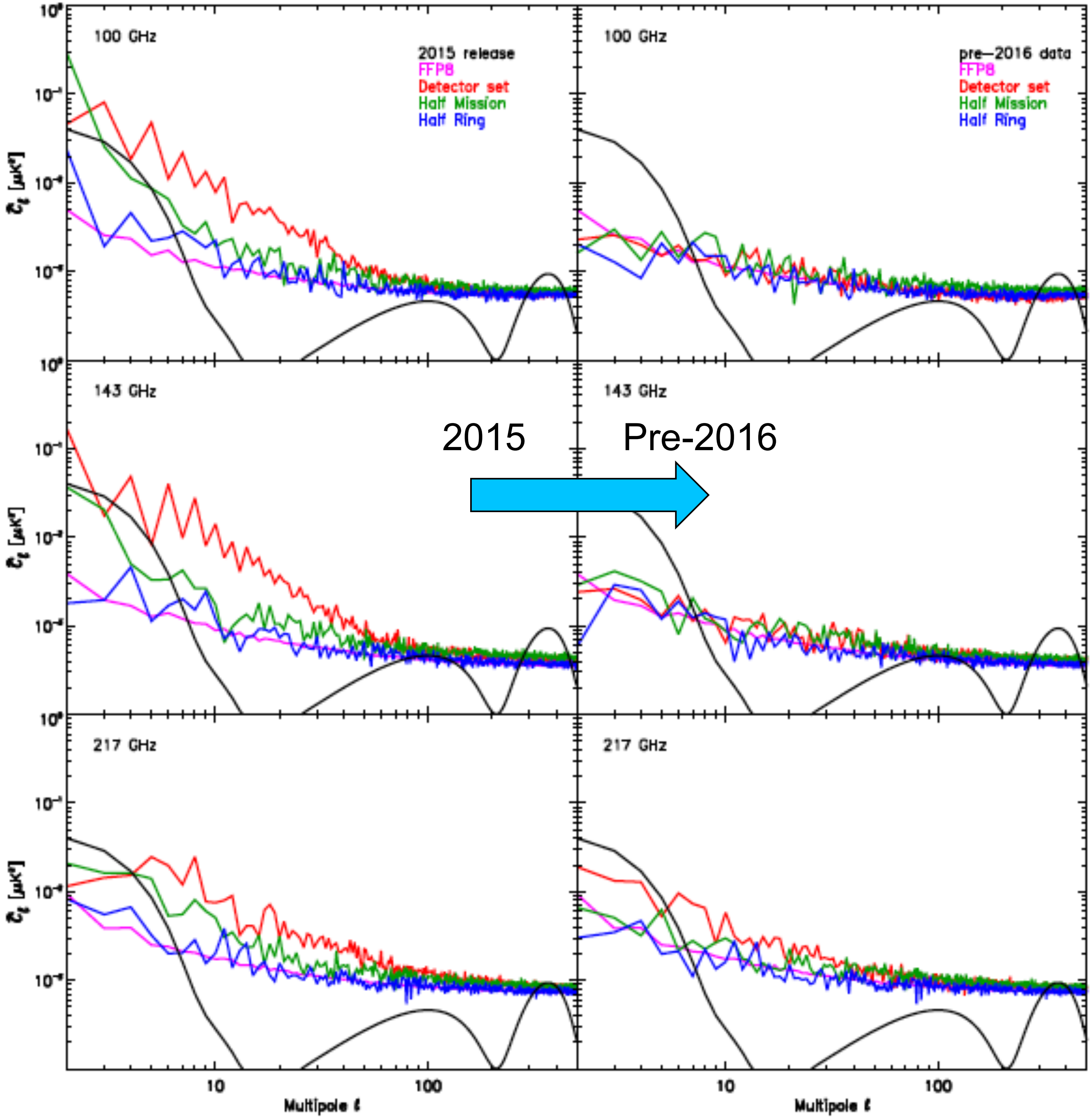
Grey bands = full sky cosmic variance if tau = 0.06

Pre-2016 processing improvement

- We introduced a generalized destriper solution for the map-making from rings, solving simultaneously for band-pass-mismatch leakage, inter-calibration errors, and ADC induced gain variations and dipole distortions (to achieve a nearly complete correction of the ADC nonlinearities).
- This led to much improved maps at low multipoles compared to previous releases.
- At 100, 143, and 217 GHz, we are now close to being noise limited on all angular scales (with small remaining systematic errors due to the empirical ADC corrections at the map making level).

arXiv:1605.02985

EE

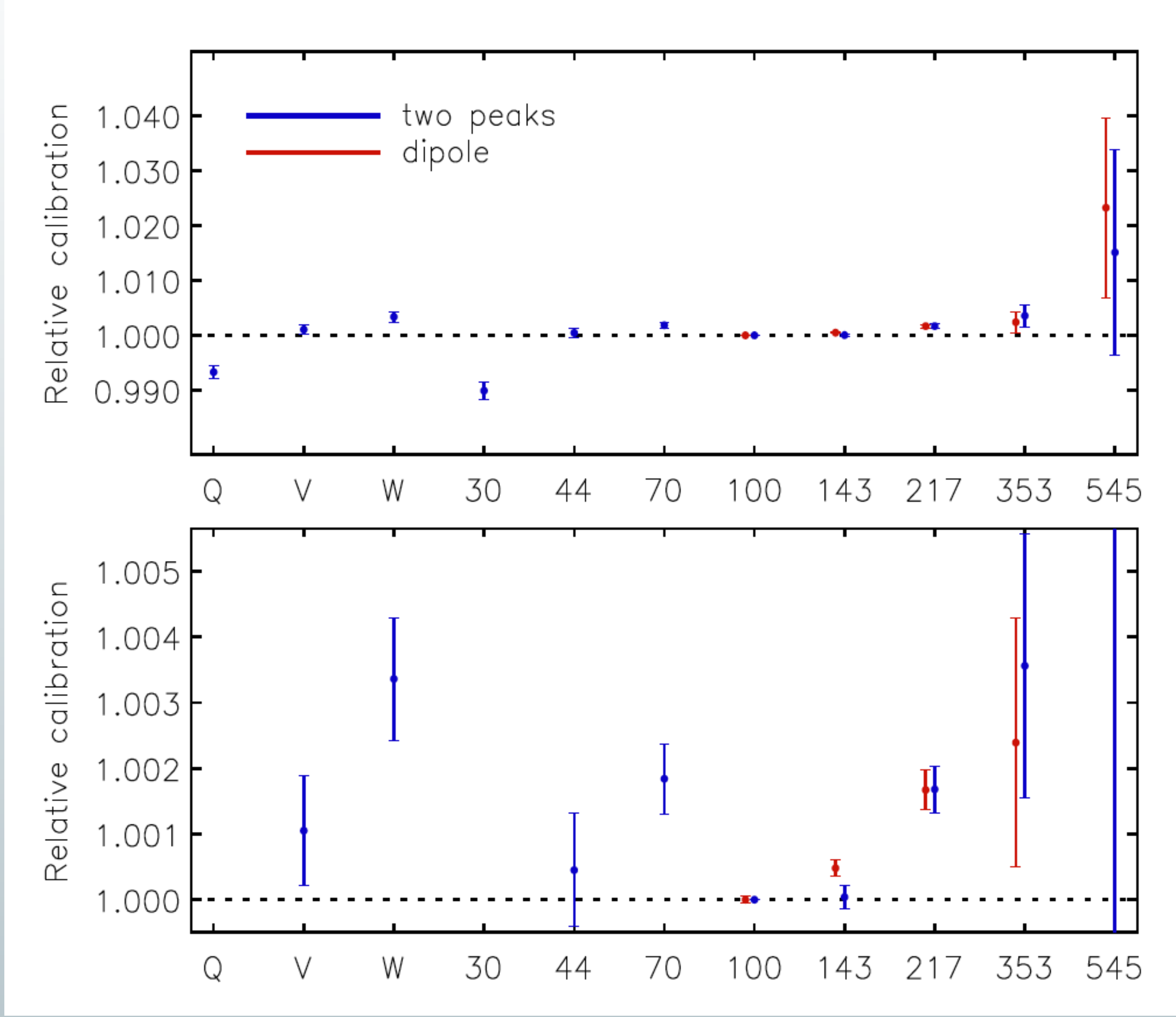


Spectacular reduction of residual systematic effects at large scales (in pre-2016 vs 2015 polarisation maps)

Fiducial model in black, for tau=0.066

arXiv:1605.02985

Frequency Intercalibration

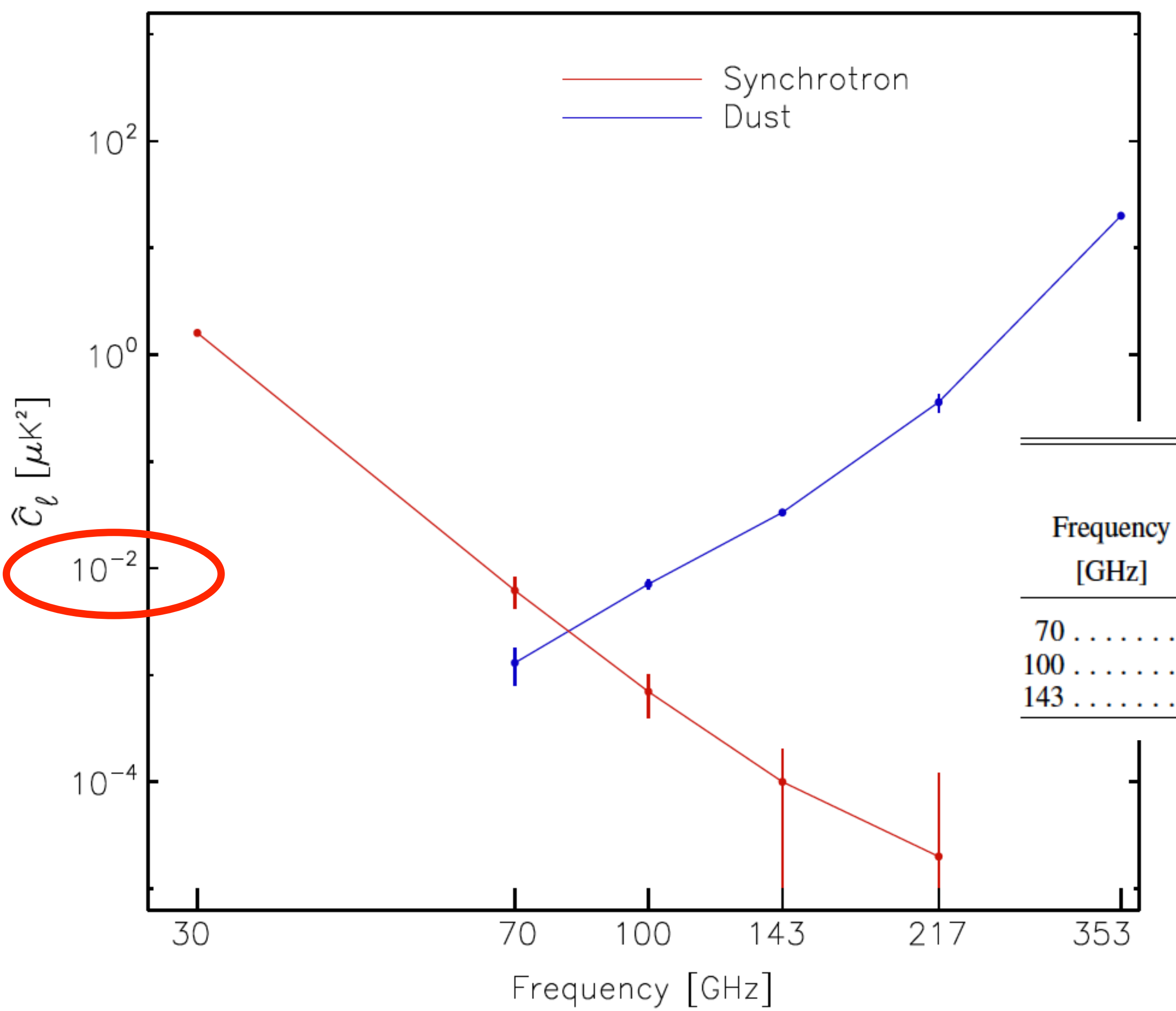


0.1% accuracy achieved over a broad frequency range

~0.01% accuracy at frequencies used for the tau analysis!

Note consistency of solar dipole versus 1st two acoustic peaks calibrations (a direct check on transfer function)

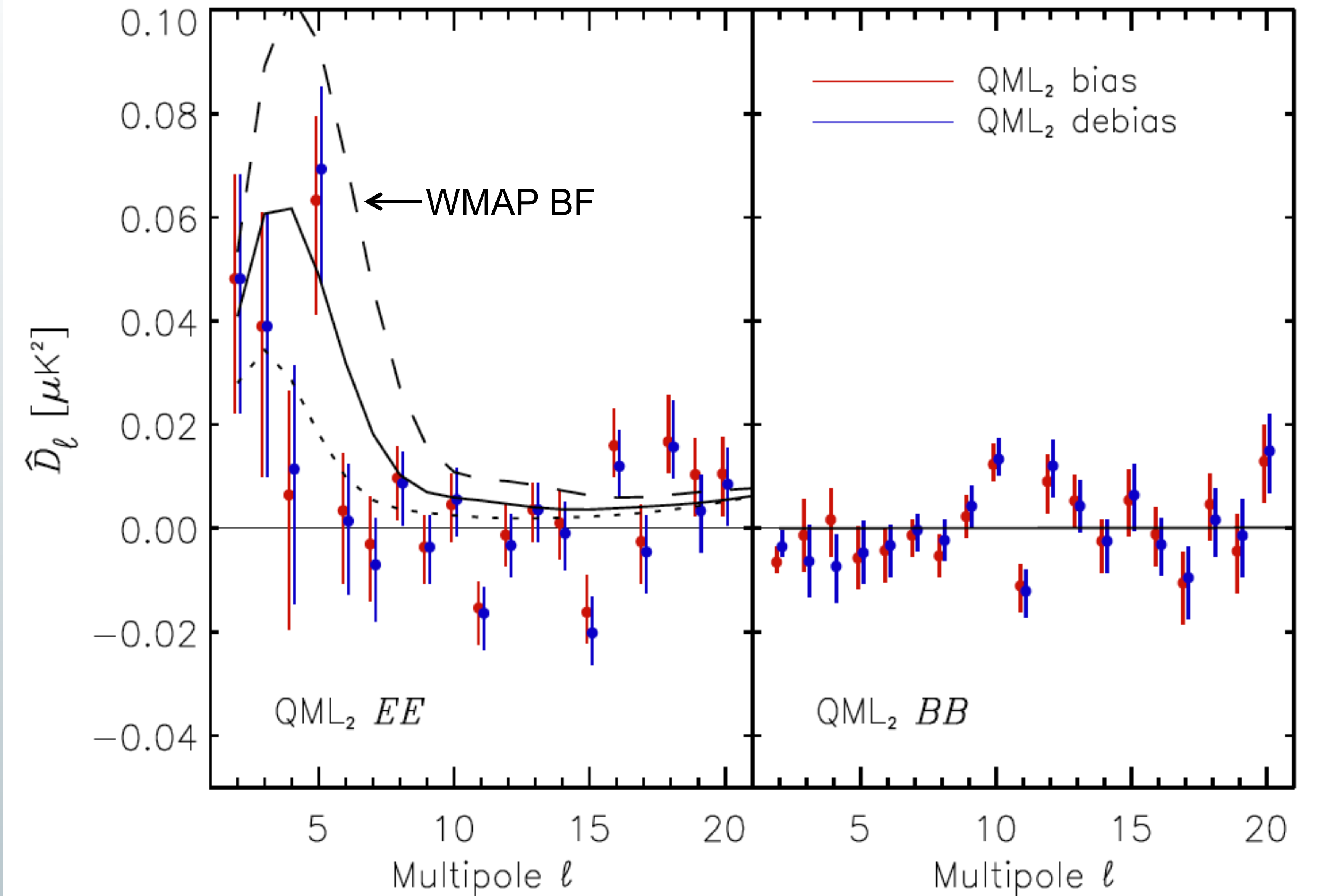
Polarised foregrounds corrections



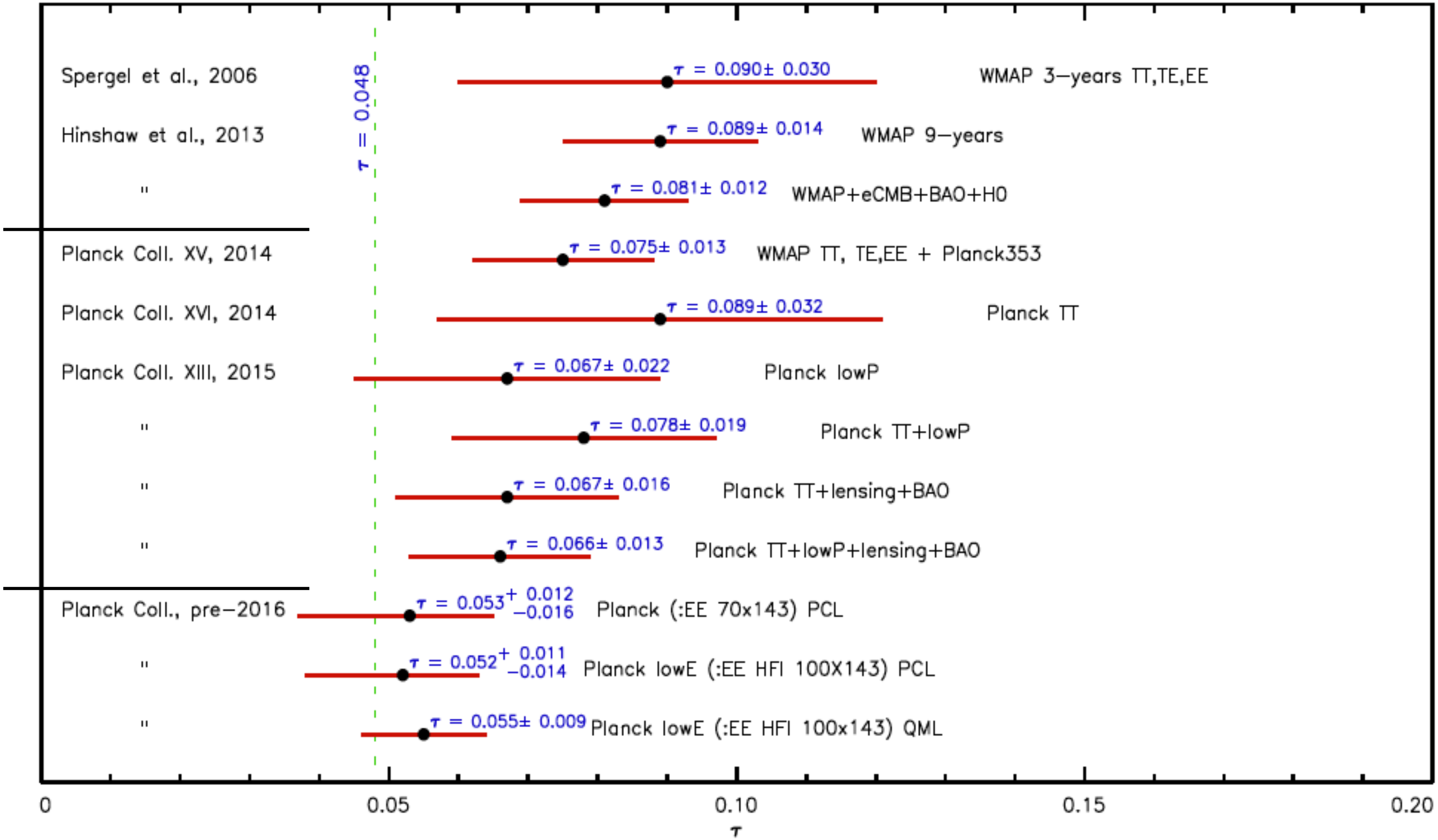
average value of the power spectrum removed
for each foreground at the peak of the EE reionization feature (l=4)

Frequency [GHz]	Dust Mean [μK^2]	Dust Uncertainty [μK^2]	Synchrotron Mean [μK^2]	Synchrotron Uncertainty [μK^2]
70	0.0041	0.0010	0.019	0.005
100	0.0227	0.0020	0.0036	0.0011
143	0.106	0.0052	0.0007	0.0004

Data versus τ_{fid}=0.05, 0.07, 0.09



A short « history » of tau



(w. BAO, and sym hist, z_{re} = 8.5 +-1)

Implications for LCDM

This improvement does not alter any major Planck15 conclusion

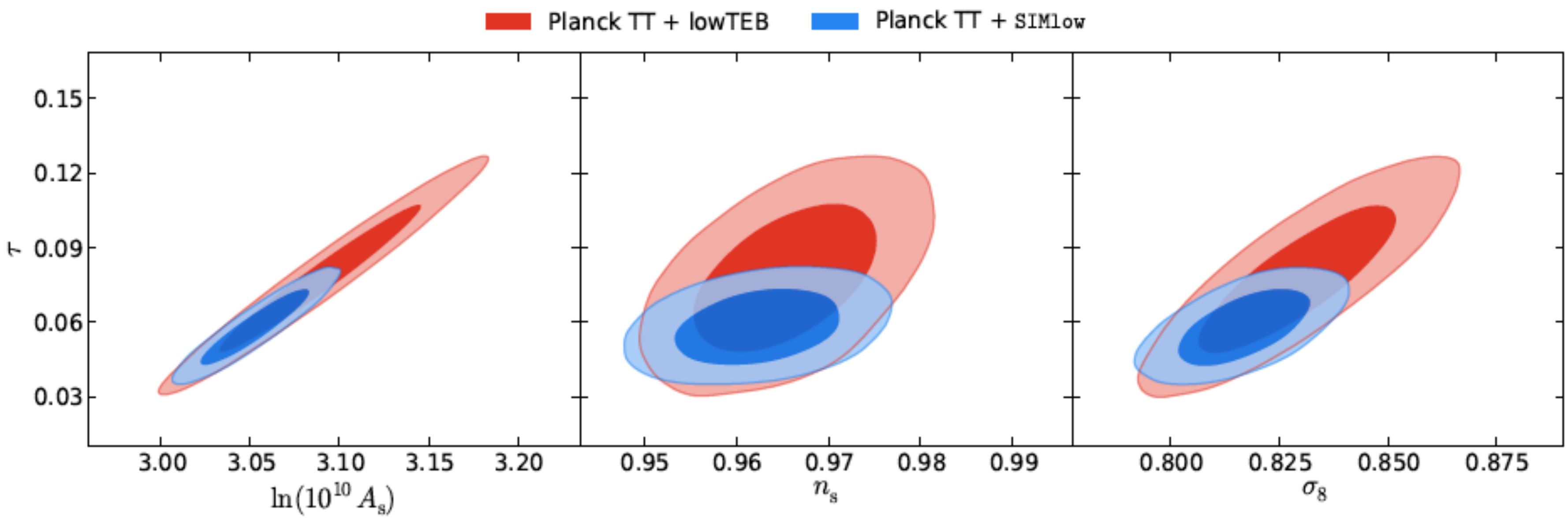
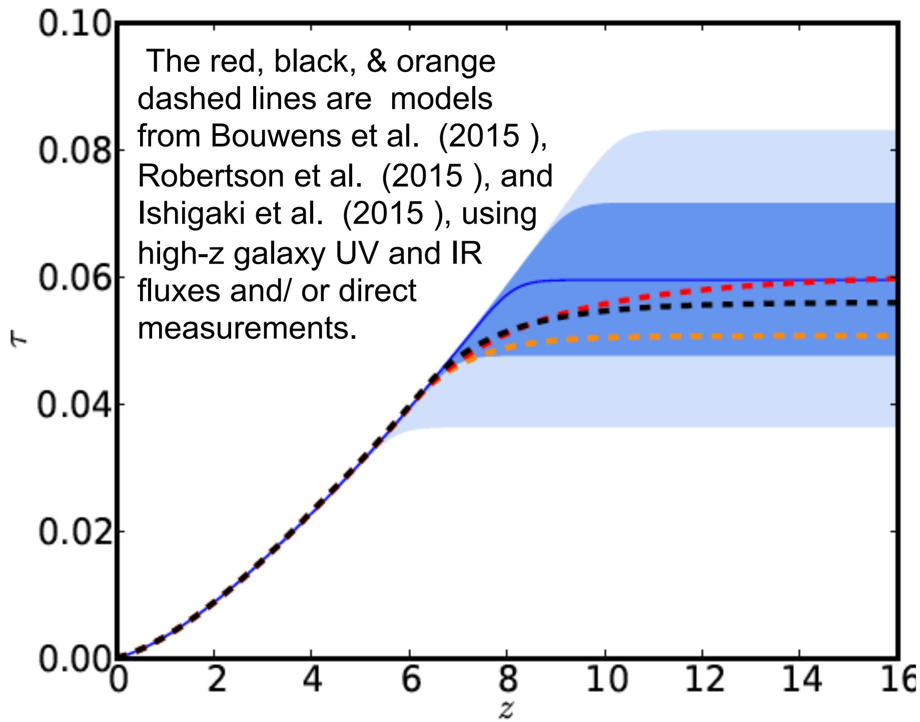
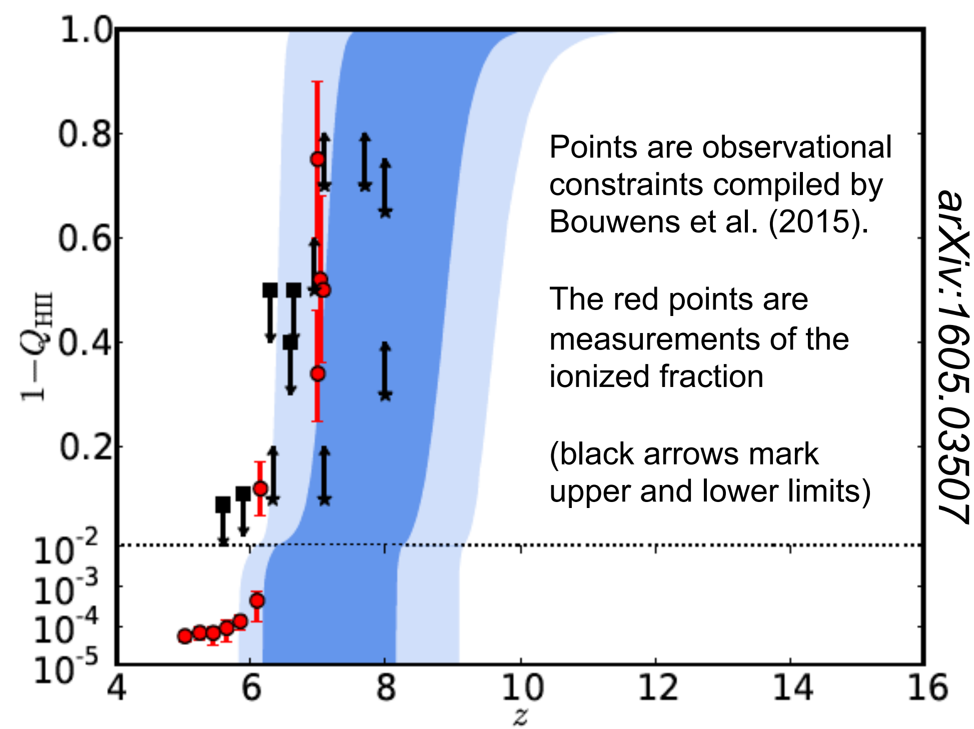


Fig. 42. Parameter constraints for the base ΛCDM cosmology, illustrating the τ–n_s degeneracy and the impact of replacing the LFI-based lowP likelihood used in the 2015 *Planck* papers with the HFI-based `SimLow` likelihood discussed here. The values of τ and σ_8 shift downwards.

Constraints on reionisation

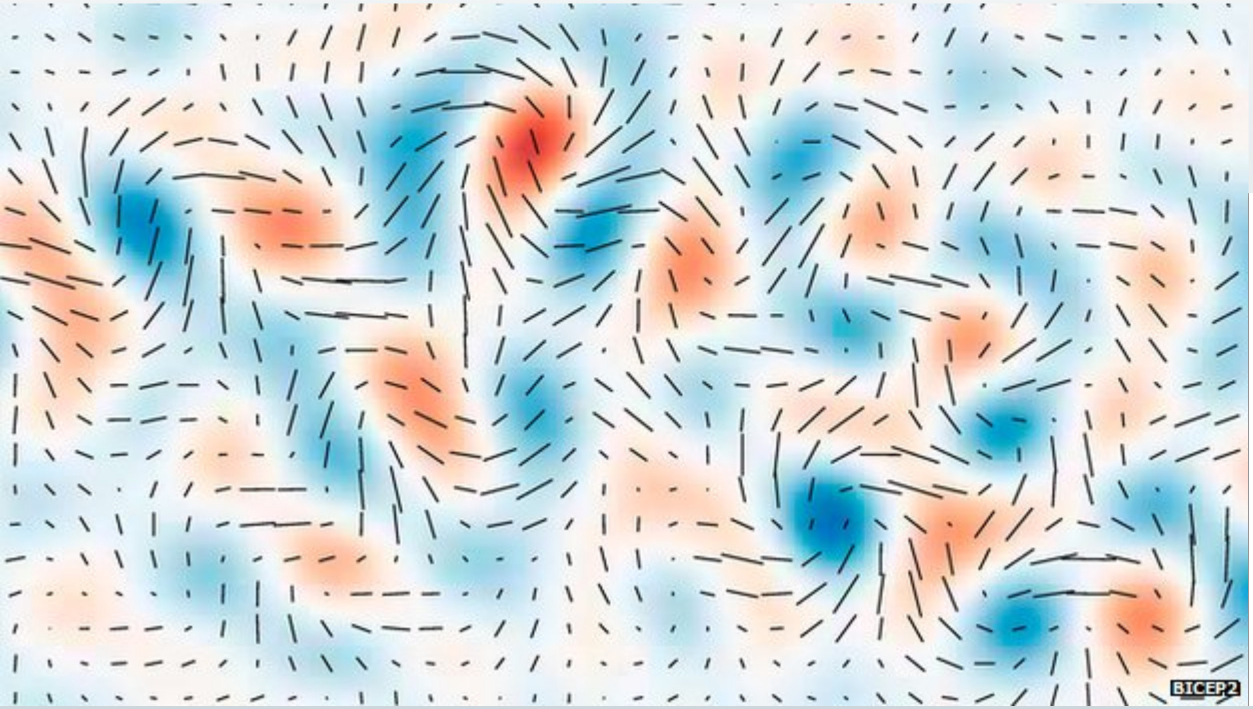
(Using here a redshift-symmetric parameterisation)



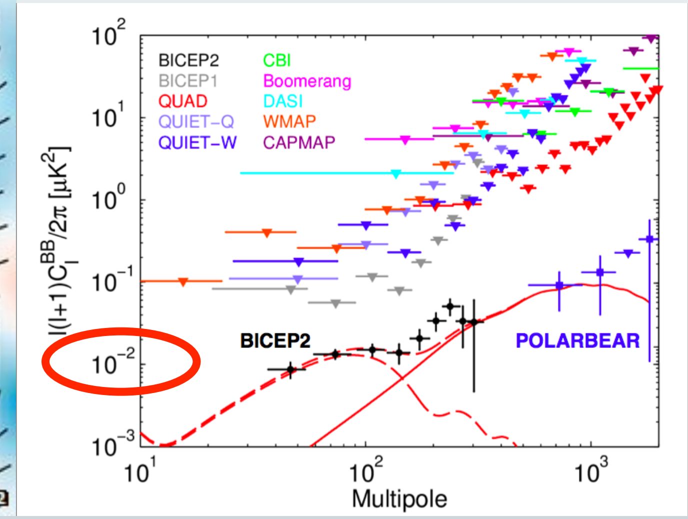


This removes the tension between CMB and models of reionisation based on the formation of first stars and galaxies

BICEP2



March 17th 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 $=A_s/A_T$ at, e.g., k=0.05Mpc^{-1})
  (r <0.07 w. new BK2 data)

- A new era has begun…