Planck *2018* before the legacy release

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Institut d'Astrophysique de Paris - CNRS/Sorbonne Université

This talk is based mainly on the 2015+2016 (intermediate) papers

Planck Legacy is almost there

- It's been a rough ride
  - *data analysis at this level of precision is hard*
  - *large reduction in resources (money but mainly people and energy)*

- **I cannot present the latest data, but…**
  - I will give a little teaser of what's to come at the end of this talk

Planck (1993-L14/5/2009-23/10/2013)

esa

planck

cnes

asi
agenzia spaziale italiana

NASA

CNRS

DTU Space
National Space Institute

INAF
Istituto Nazionale di Astrofisica

Science & Technology Facilities Council

CSIC
Consejo Superior de Investigaciones Científicas

National Research Council of Italy

Gobierno de España
Ministerio de Ciencia e Innovación

CSA ASC

DLR
Deutsches Zentrum für Luft- und Raumfahrt e.V.

UK SPACE AGENCY

MAX-PLANCK-GESELLSCHAFT

HFI PLANCK
a look back to the birth of Universe

PLANCK LFI

IAS orsay

IAP

INAF - IASF BO
ISTITUTO NAZIONALE DI ASTROFISICA
ISTITUTO DI ASTROFISICA SPAZIALE E FISICA COSMICA DI BOLOGNA

A" Aalto University

APC

California Institute of Technology

ioa

KICC
Kavli Institute for Cosmology Cambridge

Cavendish Astrophysics

University of Cambridge

Cardiff University
Prifysgol Caerdydd

irfu
cea
saclay

CEFCA

CESR

CITA–ICAT

IASF

CNRS INSU
Observer & comprendre

CNRS IN2P3
Les deux infinis

ipac

Helsinki Institute of Physics

Instituto de Astrofísica de Canarias

IFCA
Instituto de Física de Cantabria

Imperial College London

Università degli Studi di Milano

Néel institut

IPAG
Institut de Planétologie et d'Astrophysique de Grenoble

ISDC
Data Centre for Astrophysics

JPL

LAL
Laboratoire de l'Accélérateur Linéaire

l'Observatoire de Paris
LERMA

LPSC
Laboratoire de Physique Subatomique et de Cosmologie
Grenoble

The University of Manchester

MilliLab

Max-Planck-Institut für Astrophysik

NUI Maynooth

INAF
Osservatorio Astronomico di Padova

University of Oxford

Dipartimento di Fisica
Sapienza
Università di Roma

Science & Technology Facilities Council
Rutherford Appleton Laboratory

Università degli Studi di Roma Tor Vergata

Osservatorio Astronomico Trieste

UBC

UC
Universidad de Cantabria

UCSB

SISSA

Leland Stanford Junior University

ALMA

ESO

US
University of Sussex

Haverford

esa

University of Helsinki

Universitas Osloensis

Université de Genève

University of Toronto

Université de Paris-Sud XI

ISTI
Istituto di Scienza e Tecnologie dell'Informazione "A. Faedo"

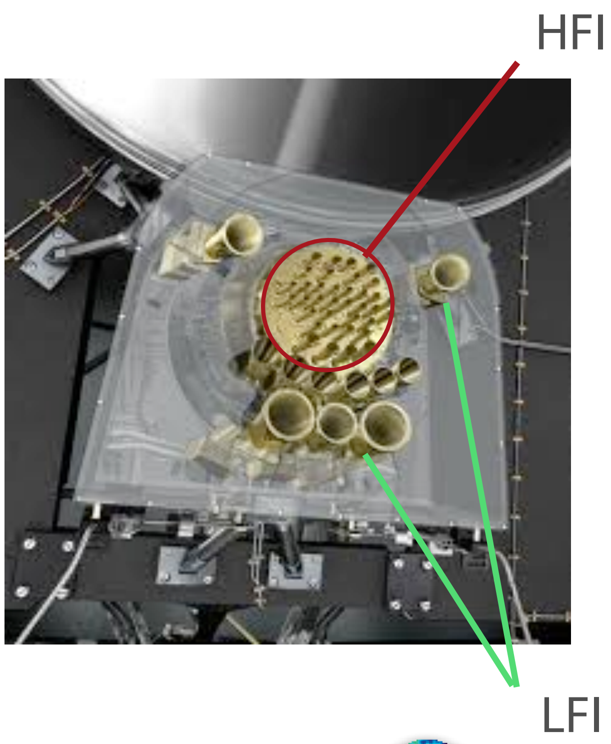
asdc
ASI Science Data Center

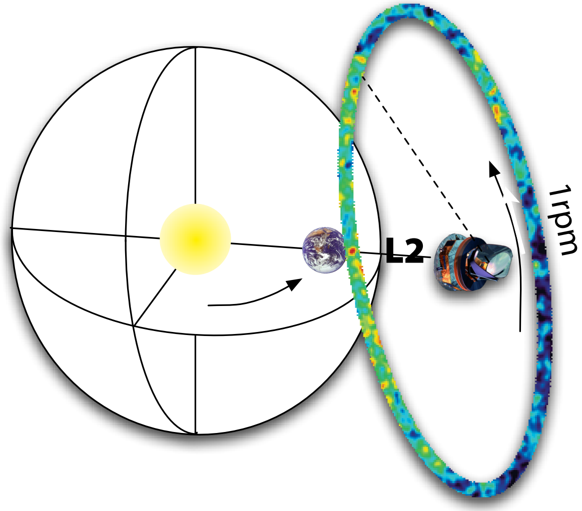
RAS Group Achievement Award 2018

« Planck has been transformative [. . .] and it has ushered a new era of tension cosmology. »

Gruber Price 2018

Planck in numbers

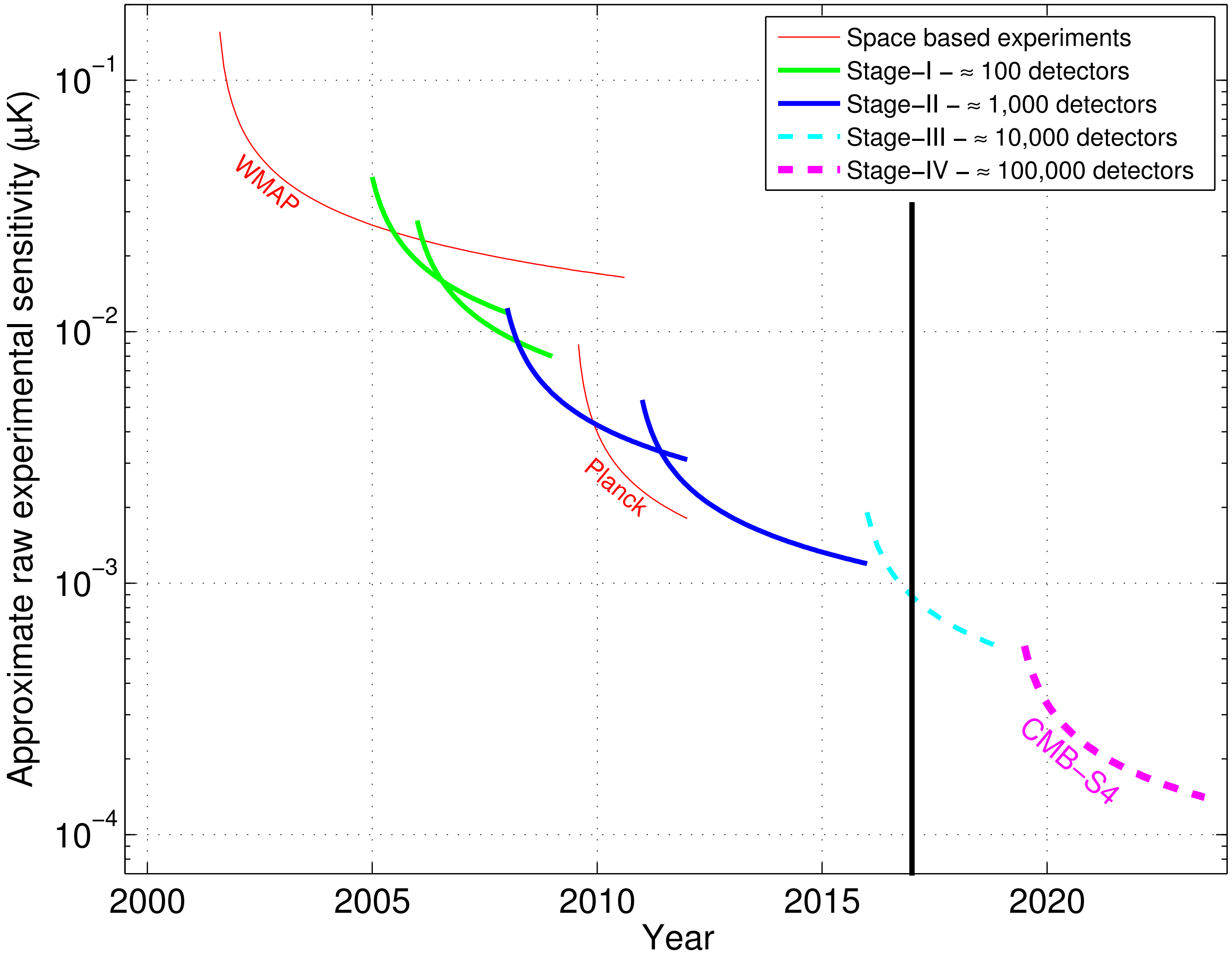




Driving goal

Perform the definitive temperature anisotropies measurement

- Primary 1.5m
- 2 instruments
  - LFI, 3 bands, 22 polarized radiometers
  - HFI, 6 bands, 50 bolometers (32 polarized)
- 4 stage cooler chain, going down to 0.1K
  - *last stage is a He3/He4 dilution cooler*
- Flawless operation !
  - 2yr: 4 sky surveys for HFI (until 01/2012)
  - 4yr: 8 sky surveys for LFI
- Data releases
  - 2013 : 1yr survey
  - **2015 : full mission**
  - *2018 : Legacy release*

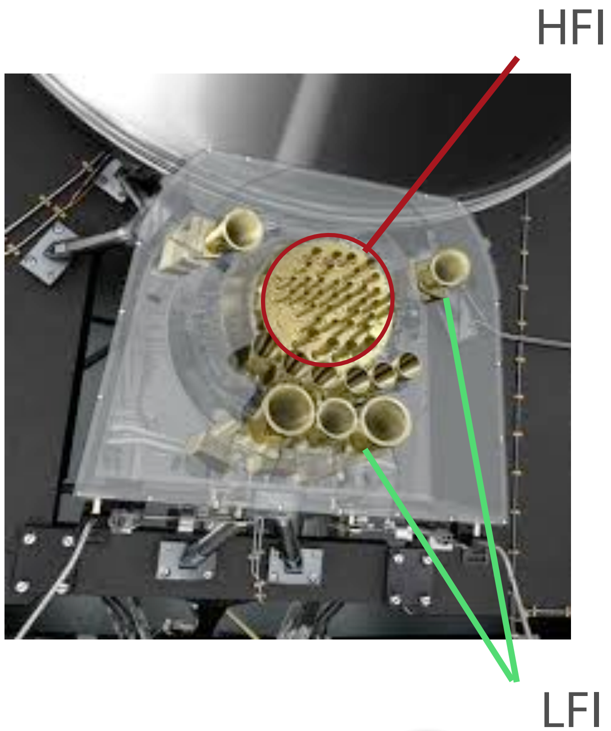


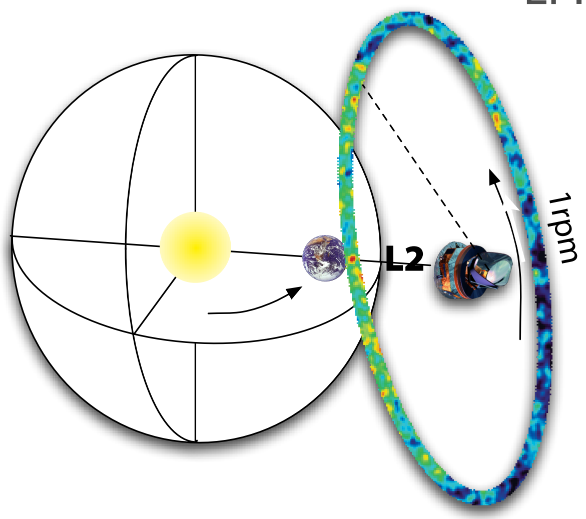
Next stages in CMB experiments.

Entering Stage 3 - entirely ground based

S4 science book

Planck in numbers





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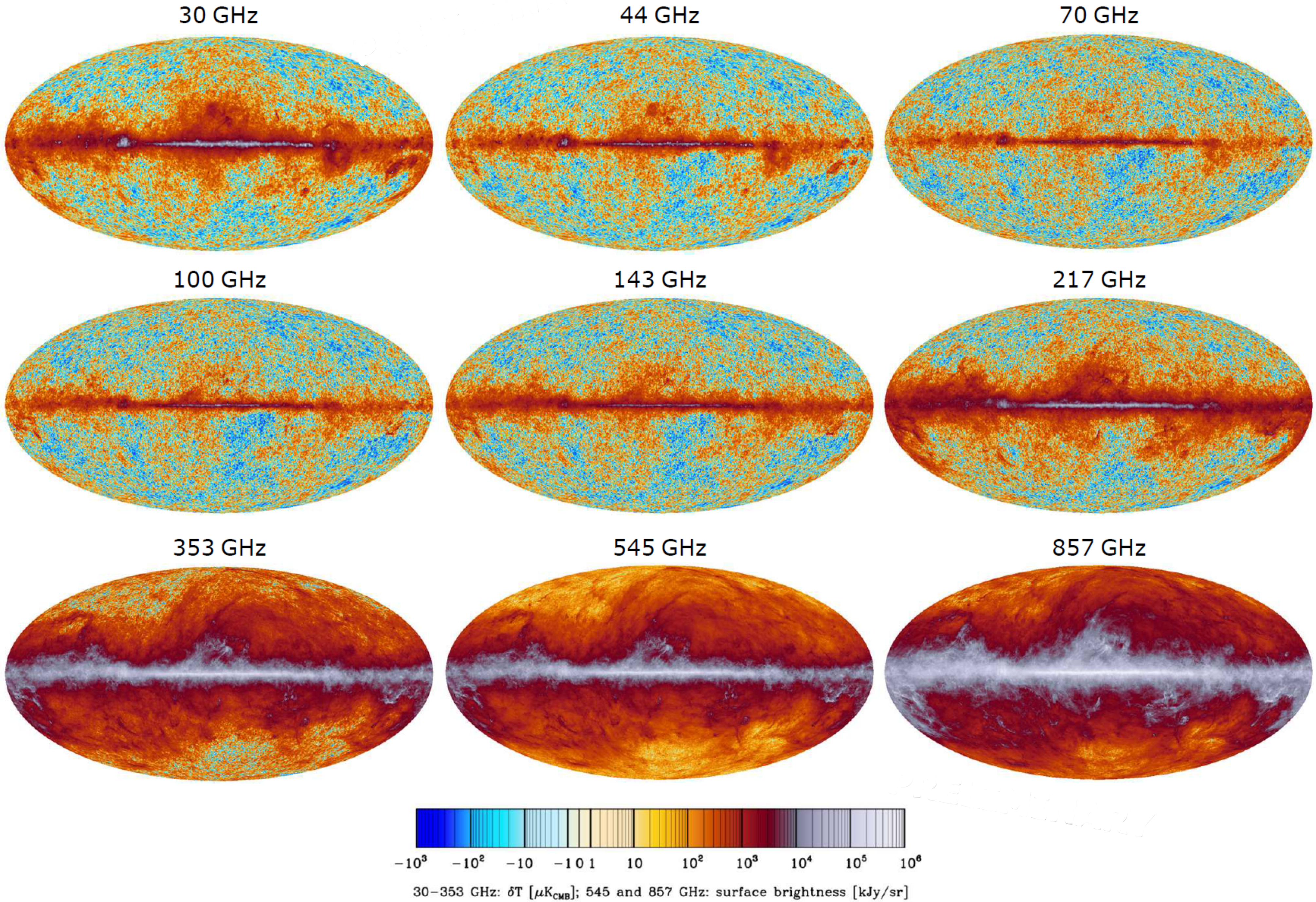
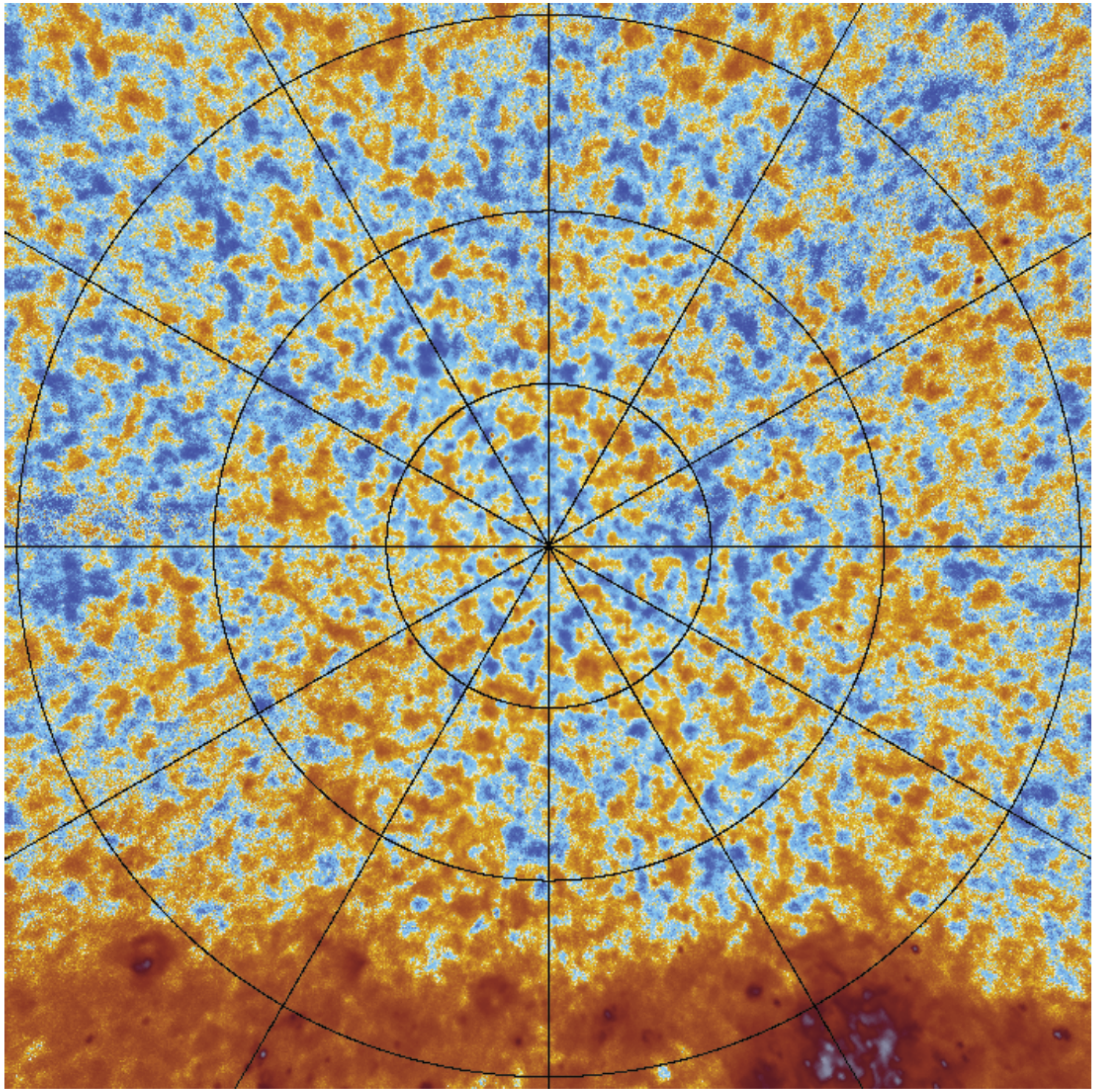
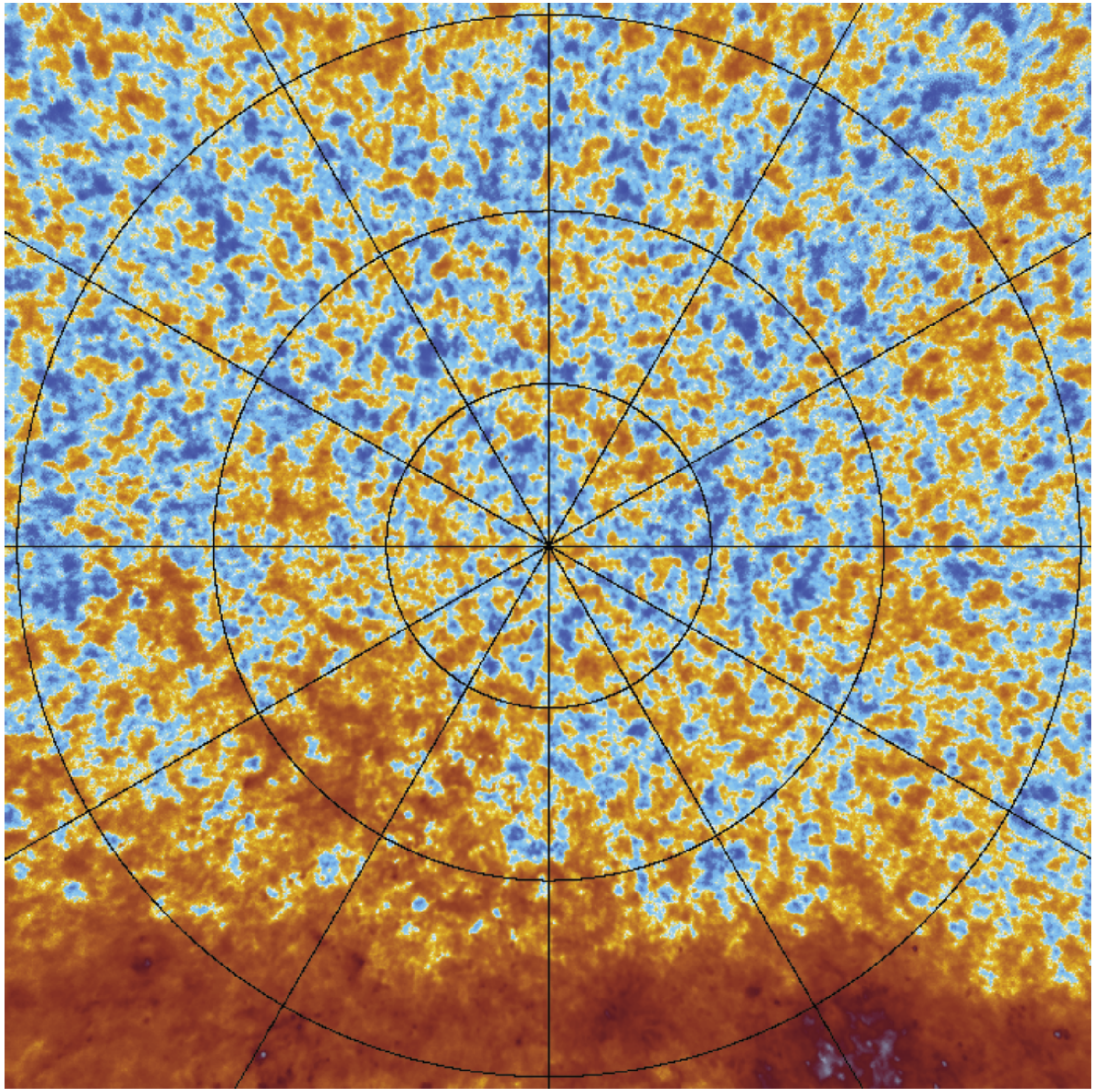


Planck 2015

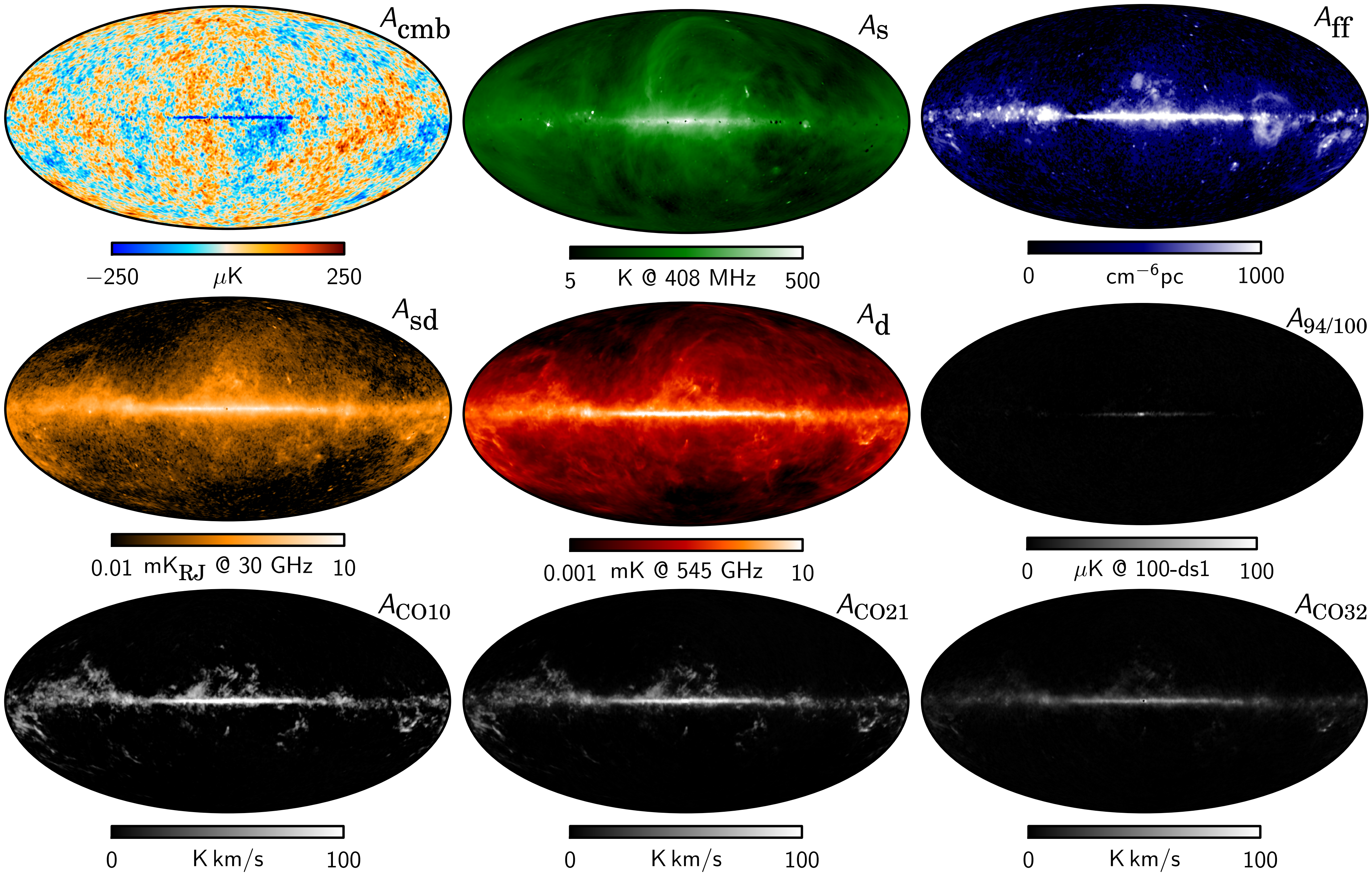
Microwave sky



North ecliptic pole - 70GHz

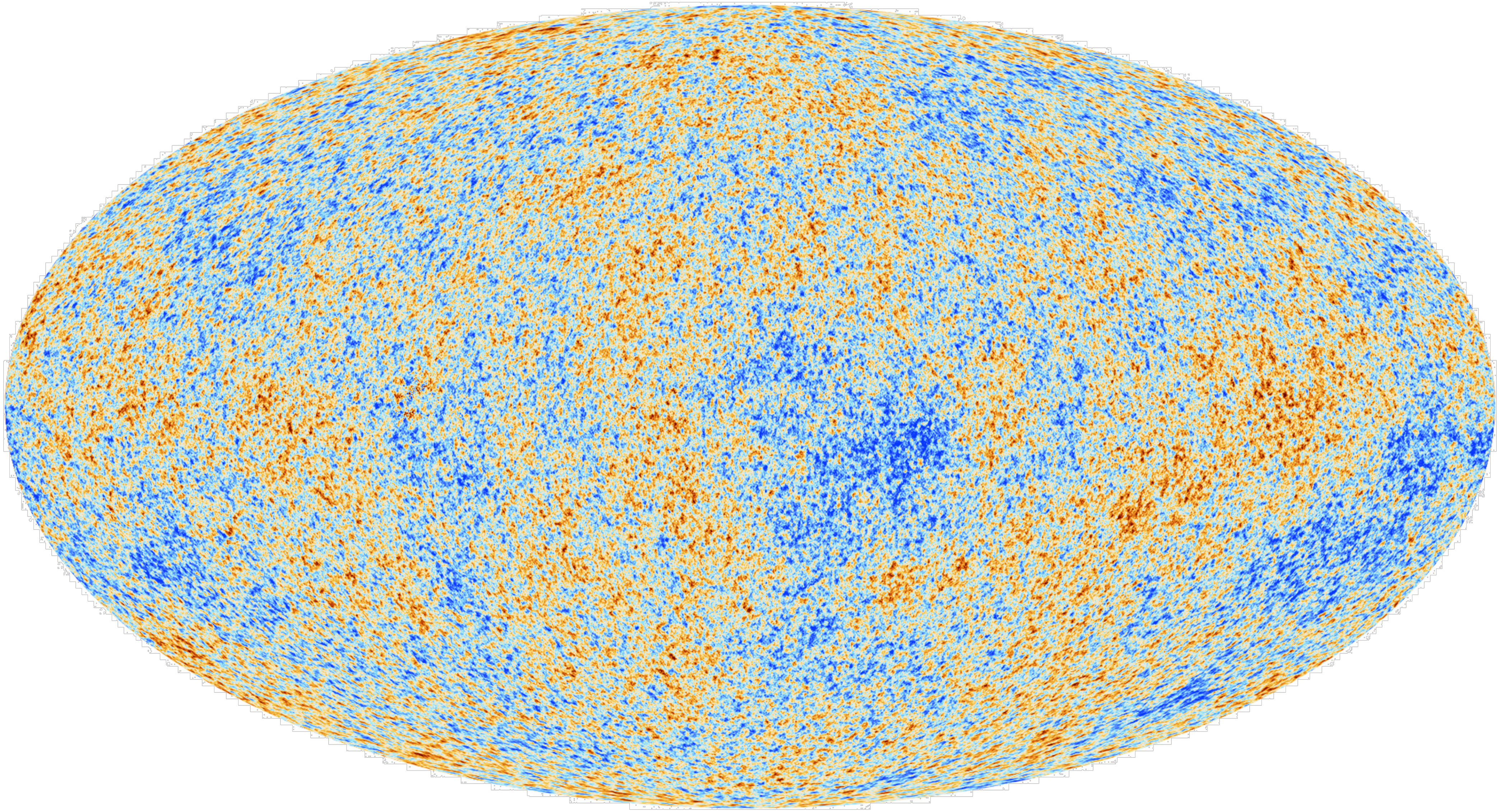


North ecliptic pole - 100GHz

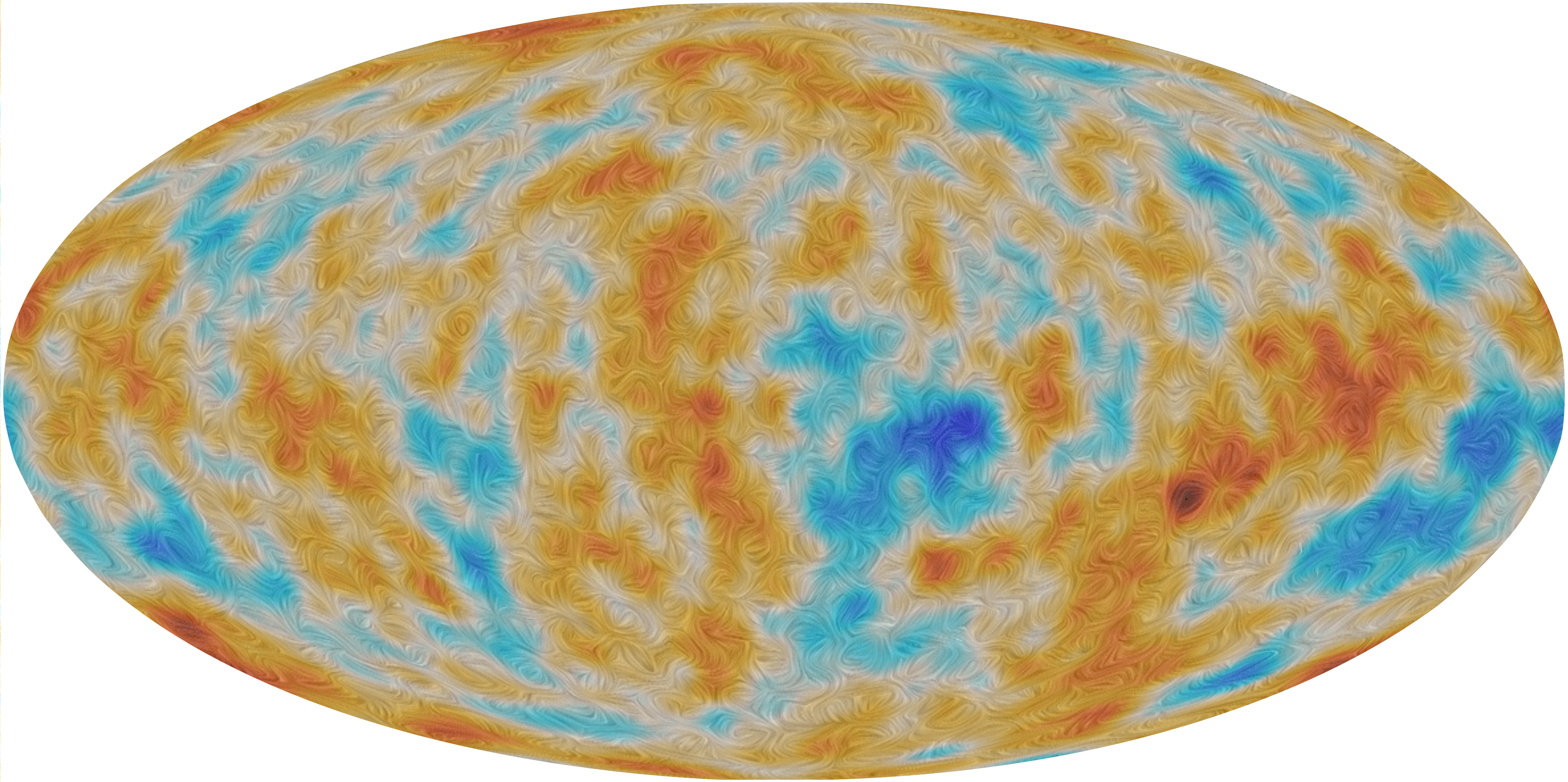


Planck 2015

Components in the microwave sky



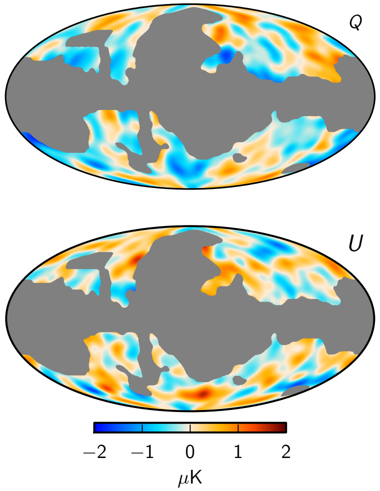
Temperature anisotropies (microK level)



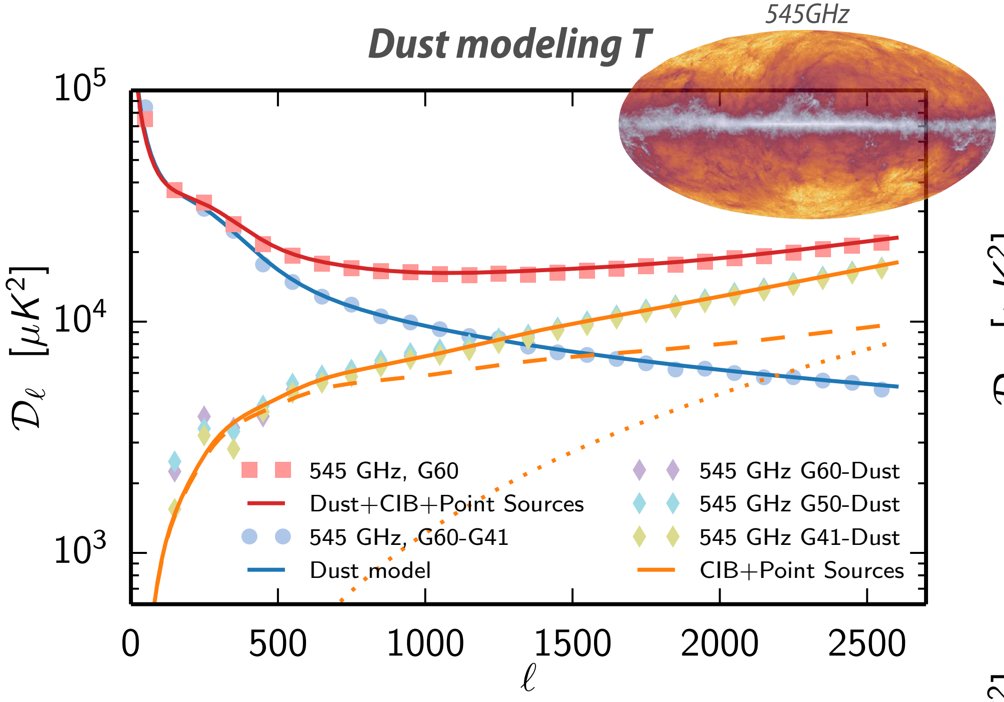
Polarization
(10º scale)

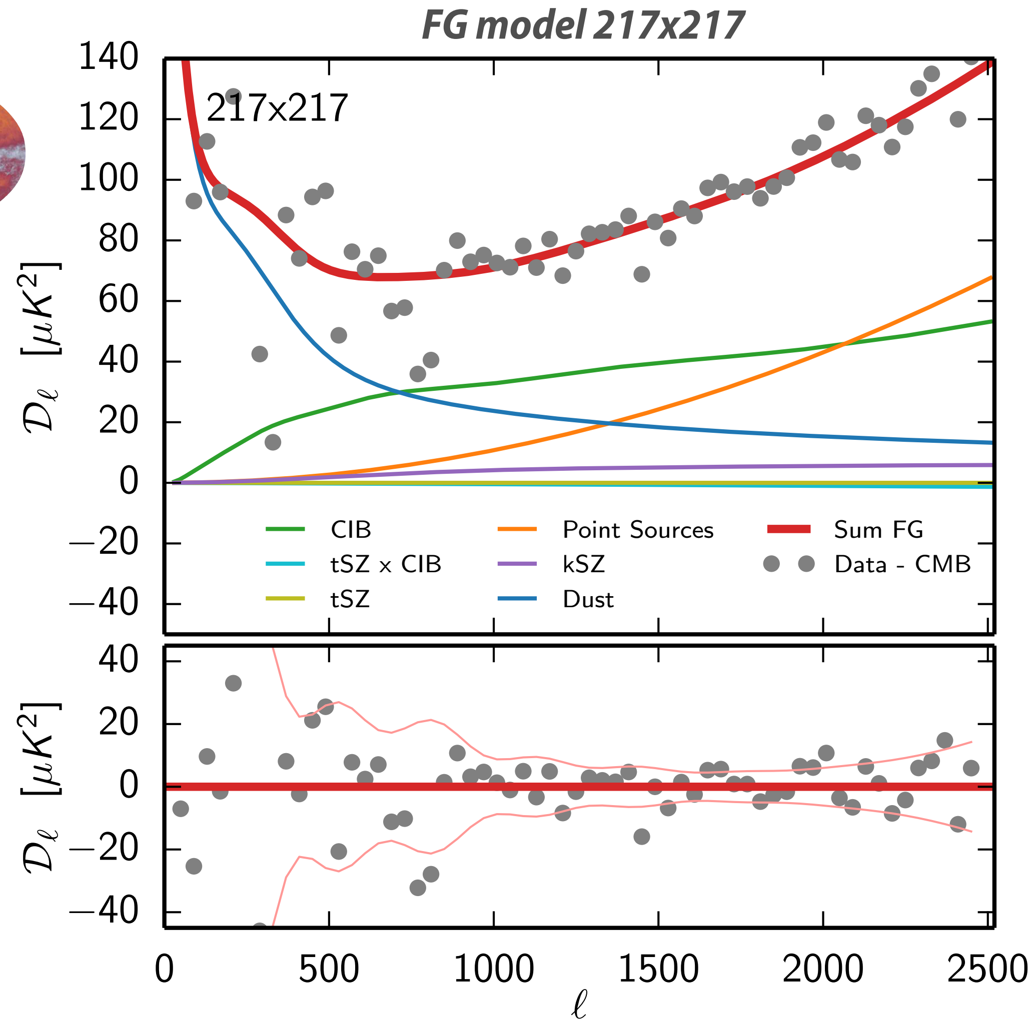
Likelihood & Cosmology products

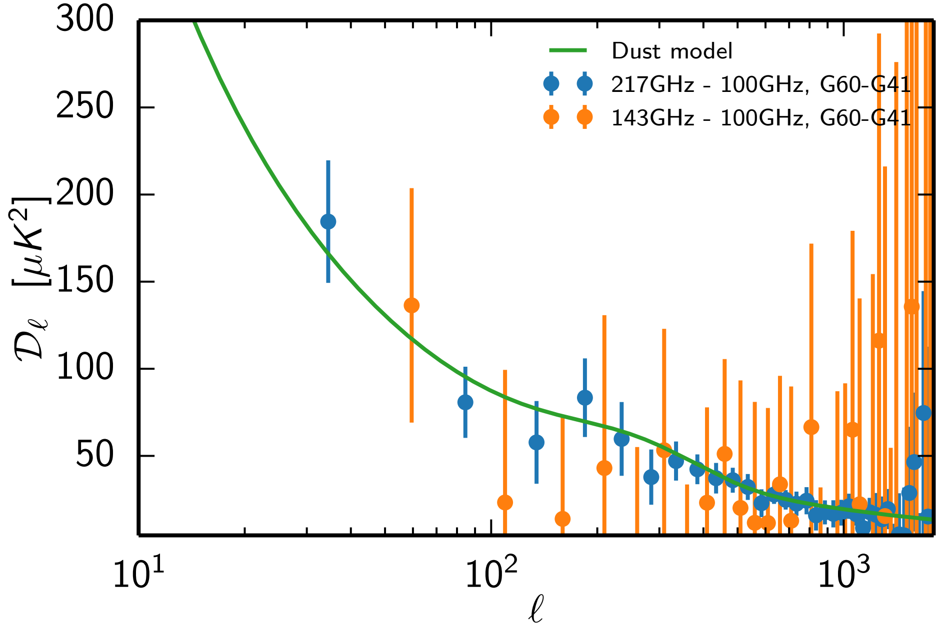
- ***2015*** *(Planck 2015 XI)*
  - Low-ell : l<30 TEB LFI data *(survey 2 and 4)*
    - T from commander (gibbs) comp sep map
    - P cleaned using LFI (30GHz) and HFI (353GHz) data
    - Pixel based approximation
  - High-ell : 30<l<2500 TT *(+TE and EE with residual)* HFI data
    - Power spectrum template based fg cleaning
    - Gaussian approximation
  - Lensing : 40<l<400 T+P HFI data
    - larger coverage limited by null test failure

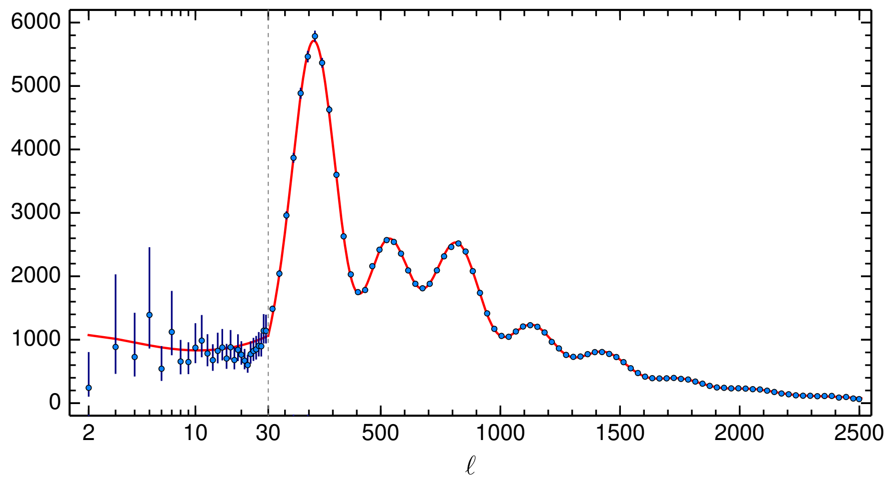


- ***2016 Intermediate*** *(Planck intermediate XLVI)*
  - Low-ell : l<30 EE HFI data
    - Use improved HFI large scale improved analysis
    - 100x143 cross spectra


Dust modeling T
545GHz
545 GHz, G60
Dust+CIB+Point Sources
545 GHz, G60-G41
Dust model
545 GHz G60-Dust
545 GHz G50-Dust
545 GHz G41-Dust
CIB+Point Sources
$\mathcal{D}_\ell \ [\mu K^2]$
ℓ


FG model 217x217
217x217
CIB
tSZ x CIB
tSZ
Point Sources
kSZ
Dust
Sum FG
Data - CMB
$\mathcal{D}_\ell \ [\mu K^2]$
ℓ


Dust model
217GHz - 100GHz, G60-G41
143GHz - 100GHz, G60-G41
$\mathcal{D}_\ell \ [\mu K^2]$
ℓ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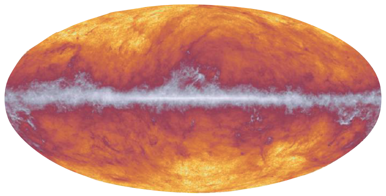
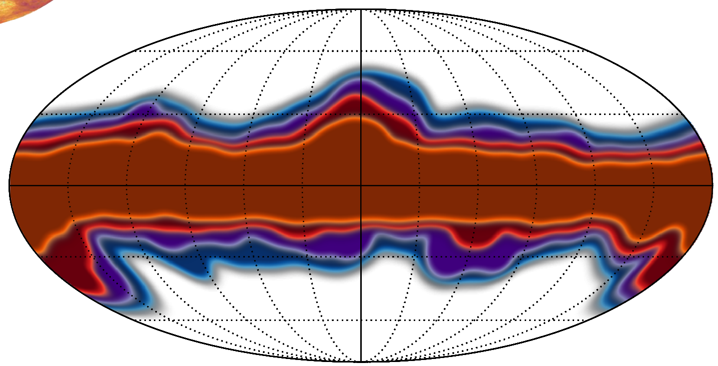
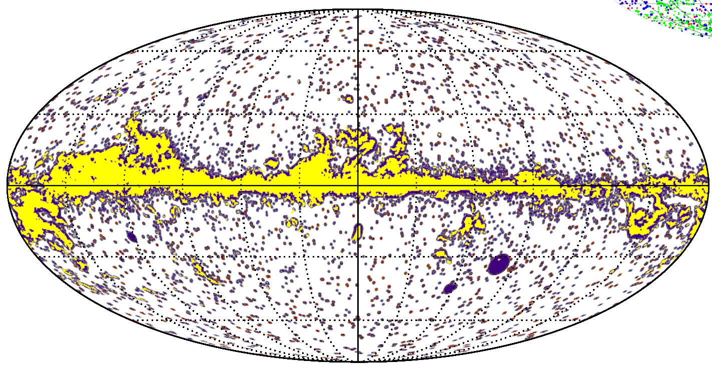
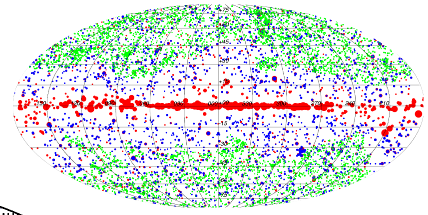
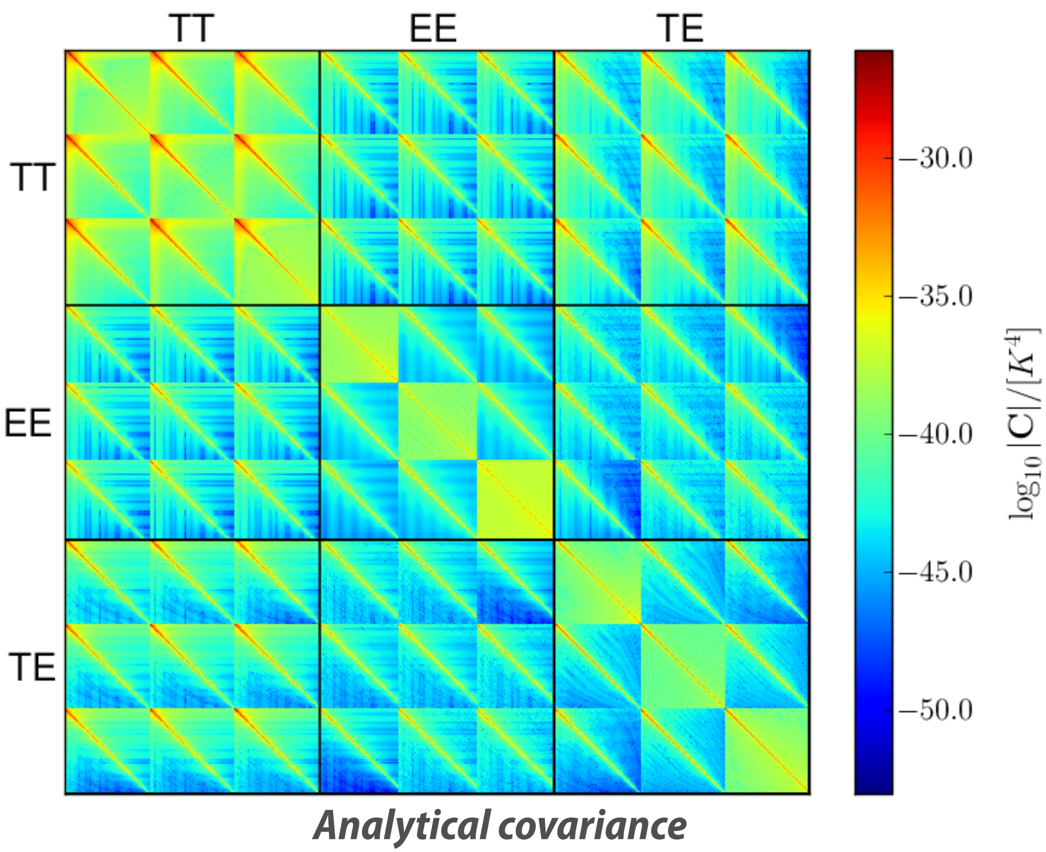
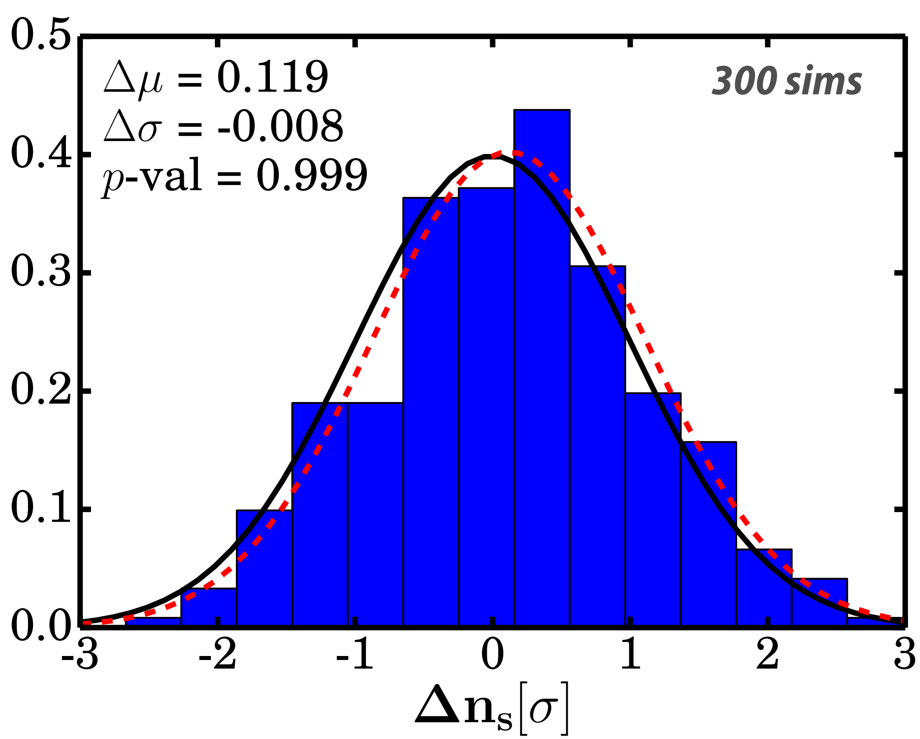


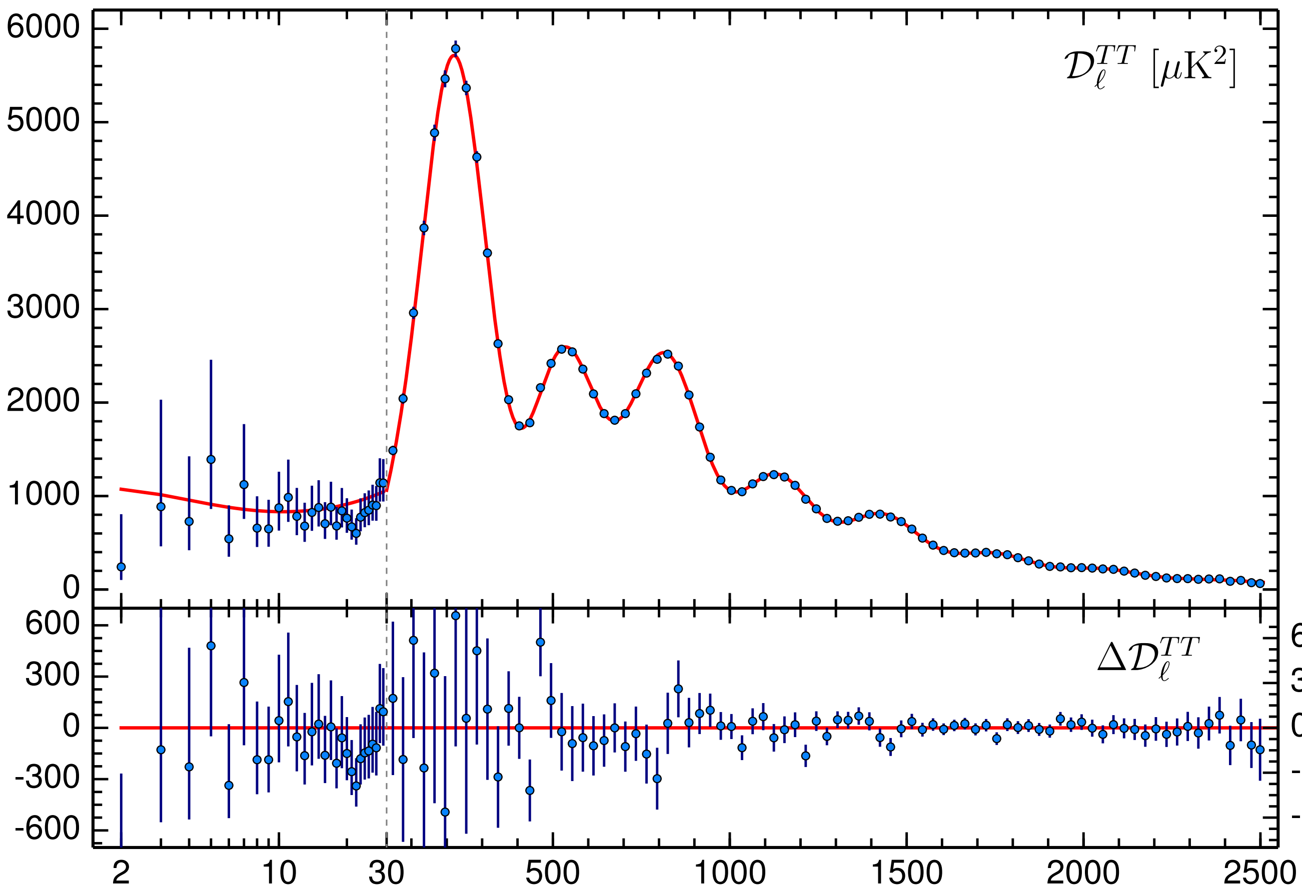


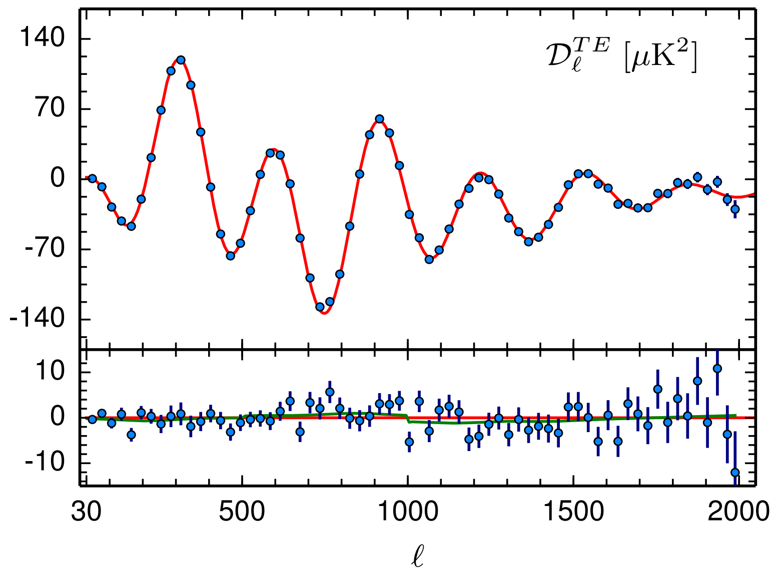


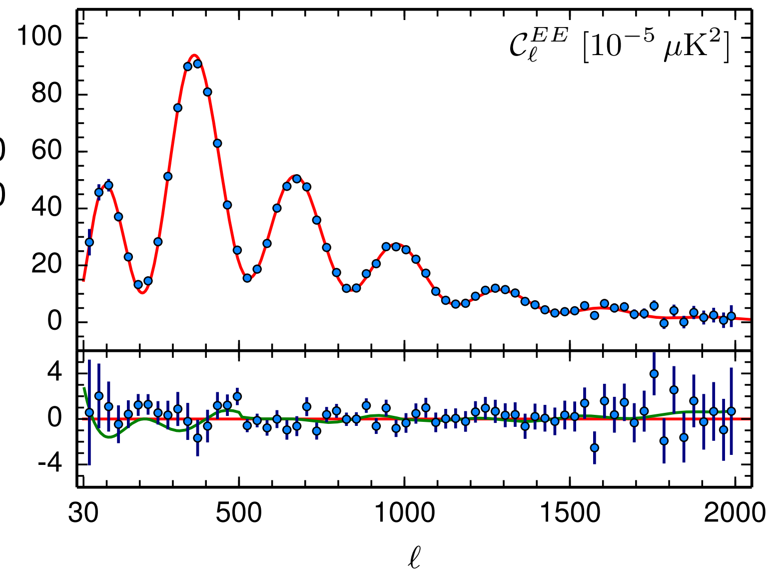



TT
EE
TE
TT
EE
TE
−30.0
−35.0
−40.0
−45.0
−50.0
$\log_{10}|\mathbf{C}|/[K^4]$
Analytical covariance


$\Delta\mu$ = 0.119
$\Delta\sigma$ = -0.008
p-val = 0.999
300 sims
0.5
0.4
0.3
0.2
0.1
0.0
-3
-2
-1
0
1
2
3
$\mathbf{\Delta n_s}[\sigma]$







Best fit ΛCDM model

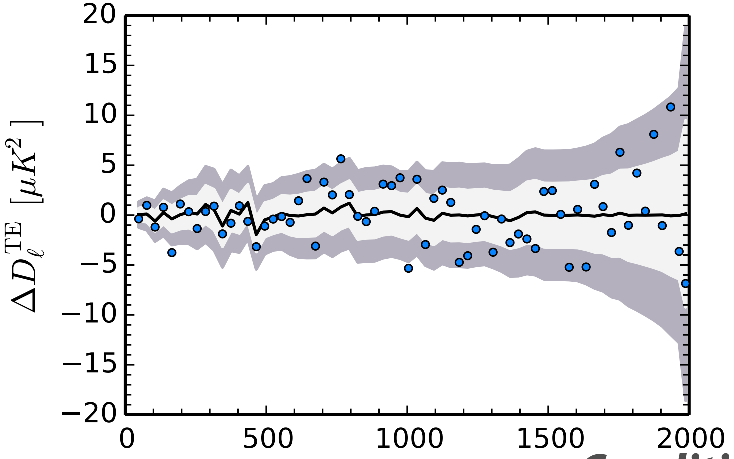
Coadded, foreground cleaned spectrum

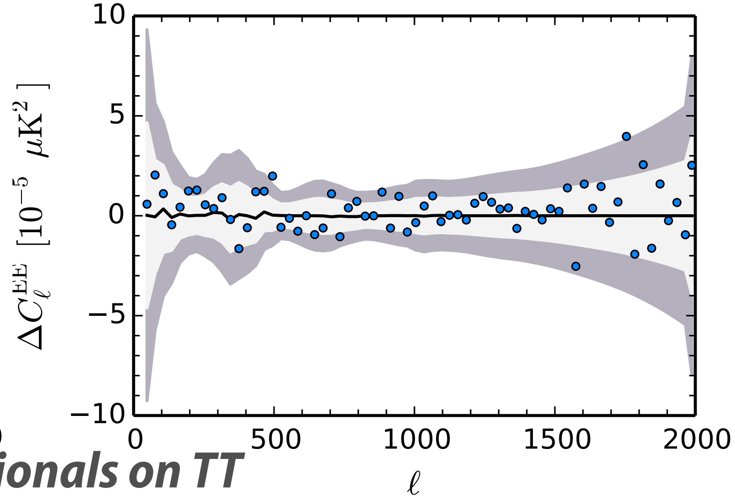
Residual beam mismatch

expected dominant residual contribution at muK² level

(high l) Polarization is NOT USED FOR PLANCK 2015 COSMOLOGY

Planck 2015 XI

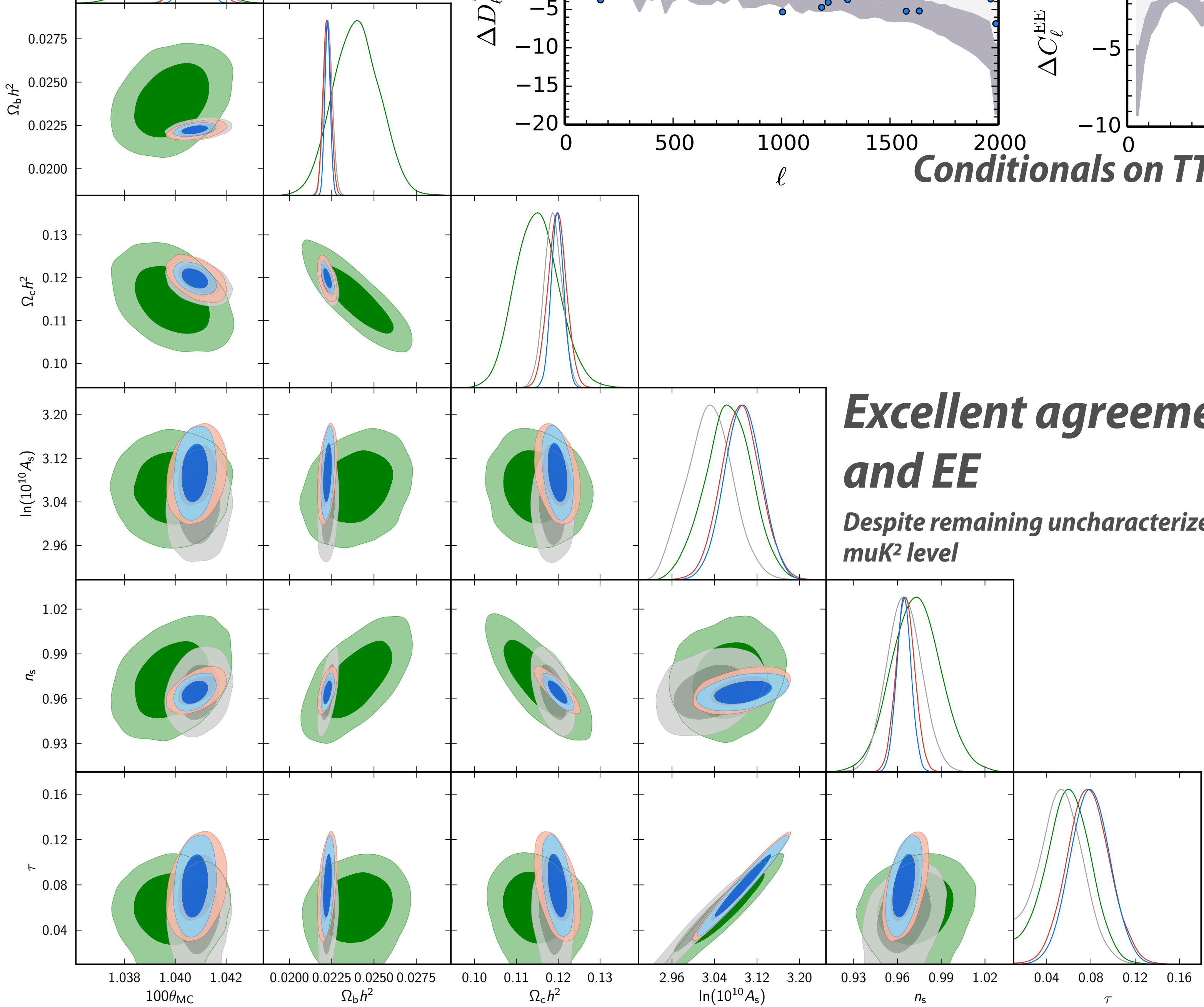




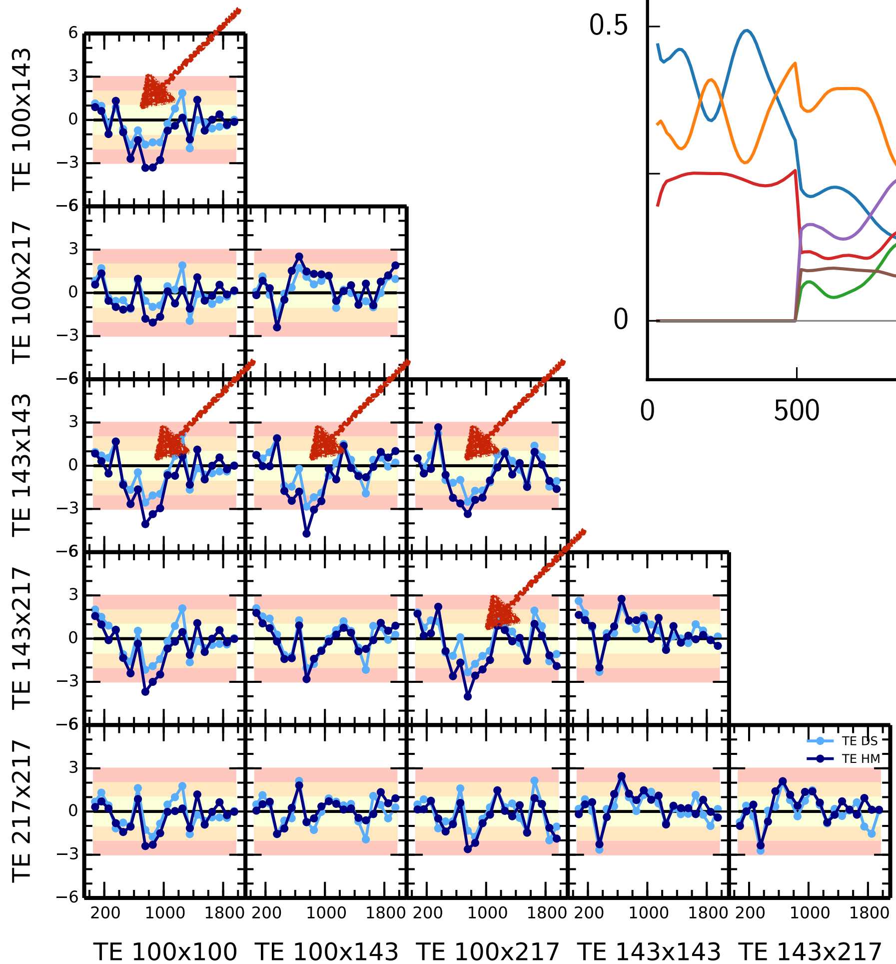
Conditionals on TT

Excellent agreement between TT, TE and EE

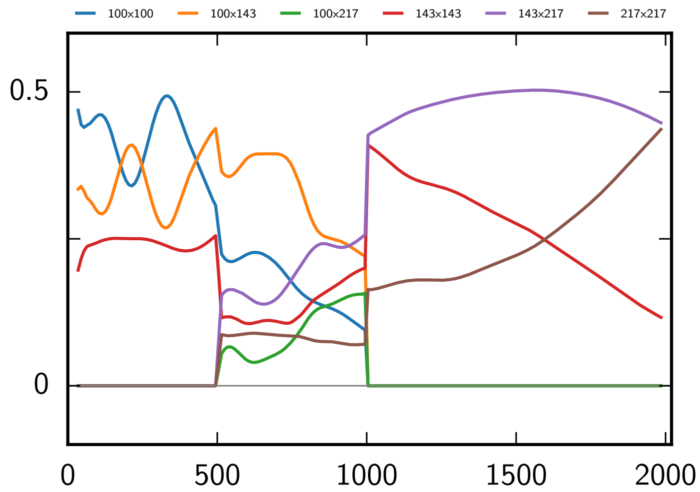
Despite remaining uncharacterized systematics in polarization at muK² level



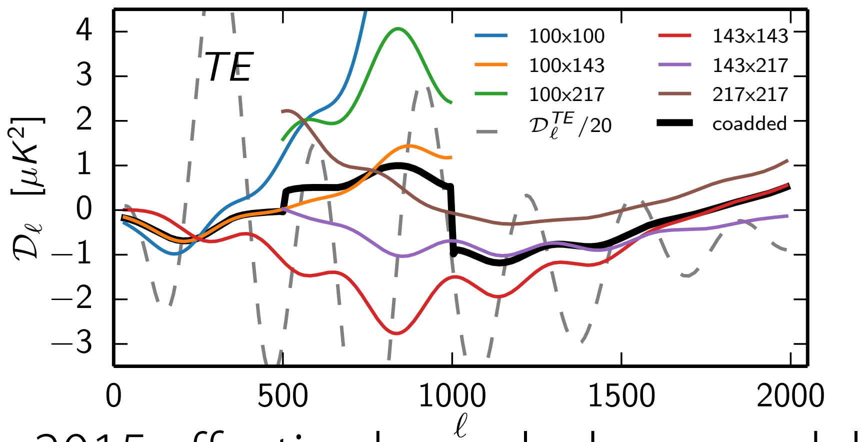
Planck 2015 XI



frequency contribution to TE



Planck 2015 XI

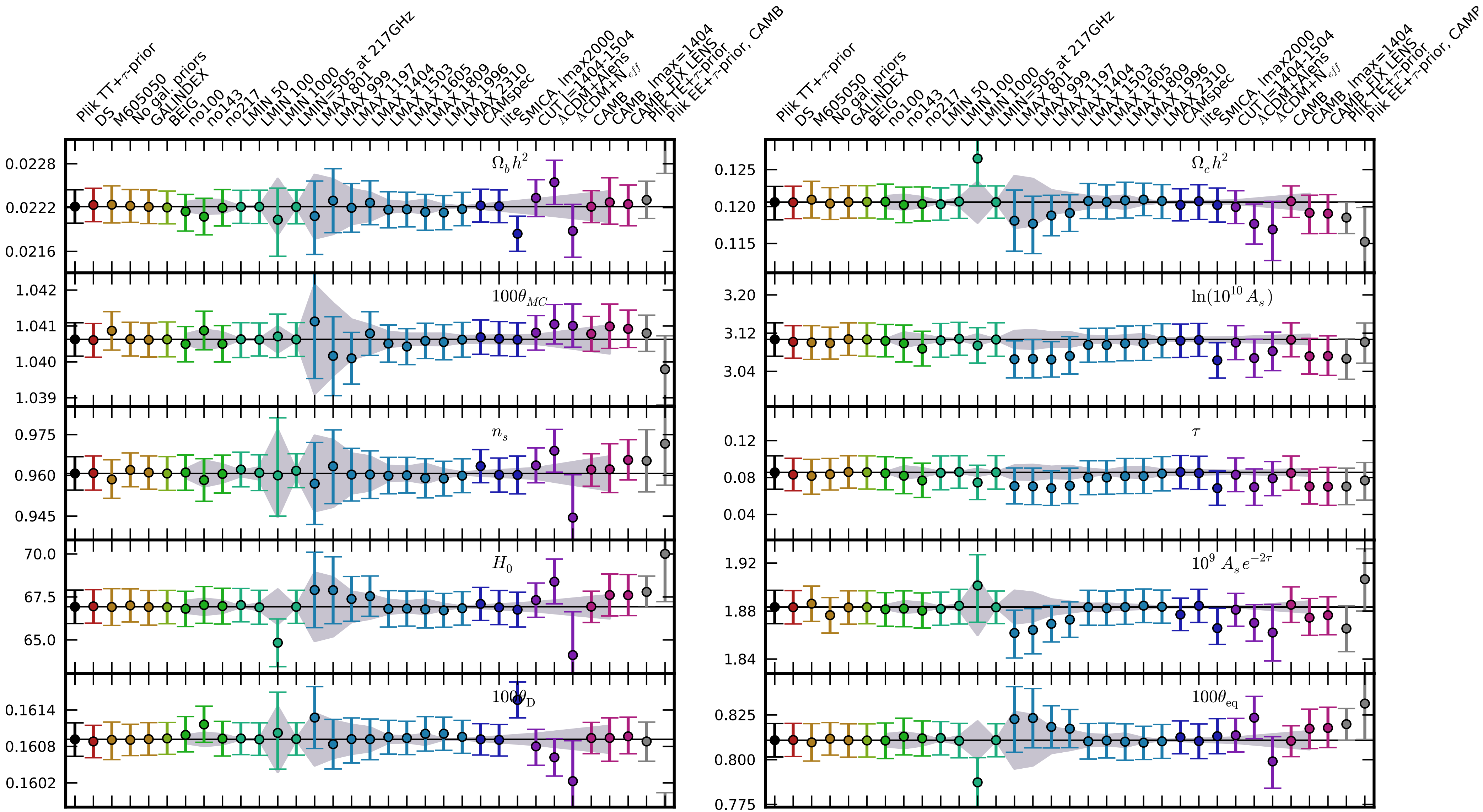


2015 effective beam leakage model (assuming TT result is perfect)

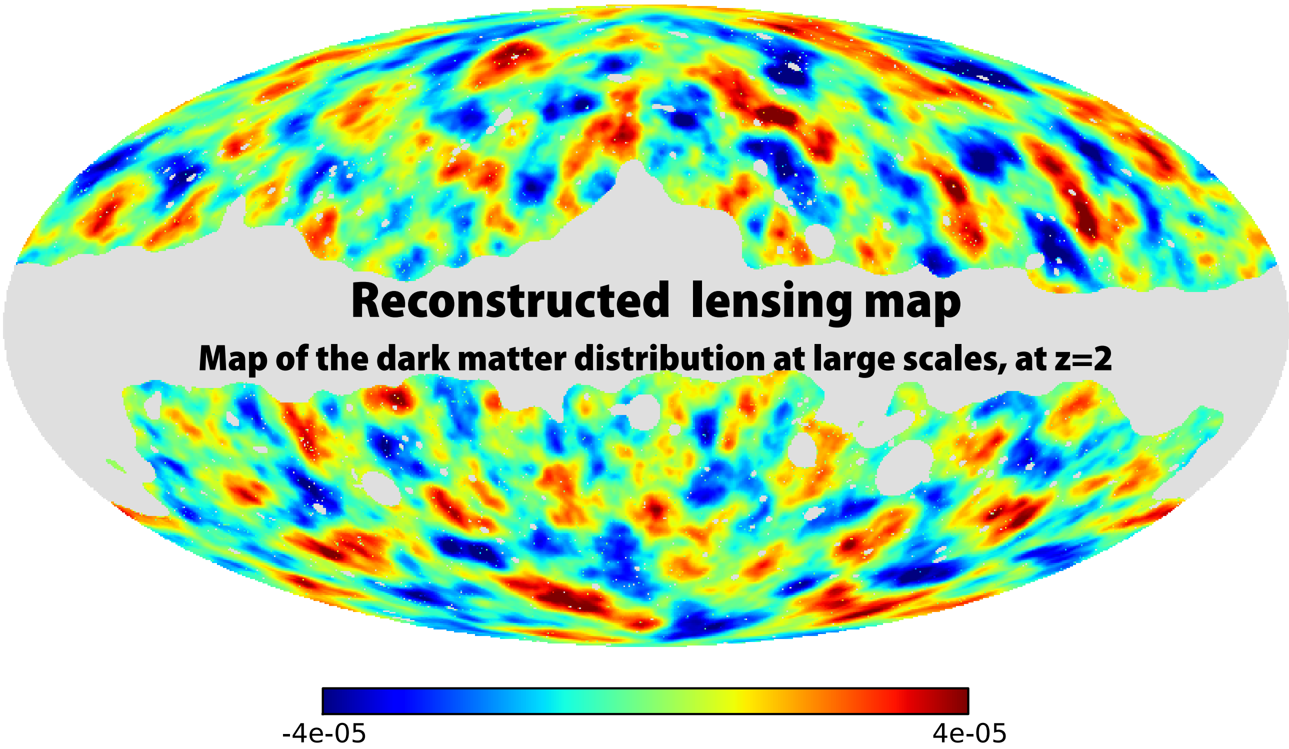
Parameter	[1] *Planck* TT+lowP	[2] *Planck* TE+lowP	[3] *Planck* EE+lowP	[4] *Planck* TT,TE,EE+lowP	$([1]-[4])/\sigma_{[1]}$
$\Omega_b h^2$	0.02222 ± 0.00023	0.02228 ± 0.00025	0.0240 ± 0.0013	0.02225 ± 0.00016	-0.1
$\Omega_c h^2$	0.1197 ± 0.0022	0.1187 ± 0.0021	$0.1150^{+0.0048}_{-0.0055}$	0.1198 ± 0.0015	0.0
$100\theta_{MC}$	1.04085 ± 0.00047	1.04094 ± 0.00051	1.03988 ± 0.00094	1.04077 ± 0.00032	0.2
τ	0.078 ± 0.019	0.053 ± 0.019	$0.059^{+0.022}_{-0.019}$	0.079 ± 0.017	-0.1
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.031 ± 0.041	$3.066^{+0.046}_{-0.041}$	3.094 ± 0.034	-0.1
n_s	0.9655 ± 0.0062	0.965 ± 0.012	0.973 ± 0.016	0.9645 ± 0.0049	0.2
H_0	67.31 ± 0.96	67.73 ± 0.92	70.2 ± 3.0	67.27 ± 0.66	0.0
Ω_m	0.315 ± 0.013	0.300 ± 0.012	$0.286^{+0.027}_{-0.038}$	0.3156 ± 0.0091	0.0
σ_8	0.829 ± 0.014	0.802 ± 0.018	0.796 ± 0.024	0.831 ± 0.013	0.0
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014	1.865 ± 0.019	1.907 ± 0.027	1.882 ± 0.012	-0.1

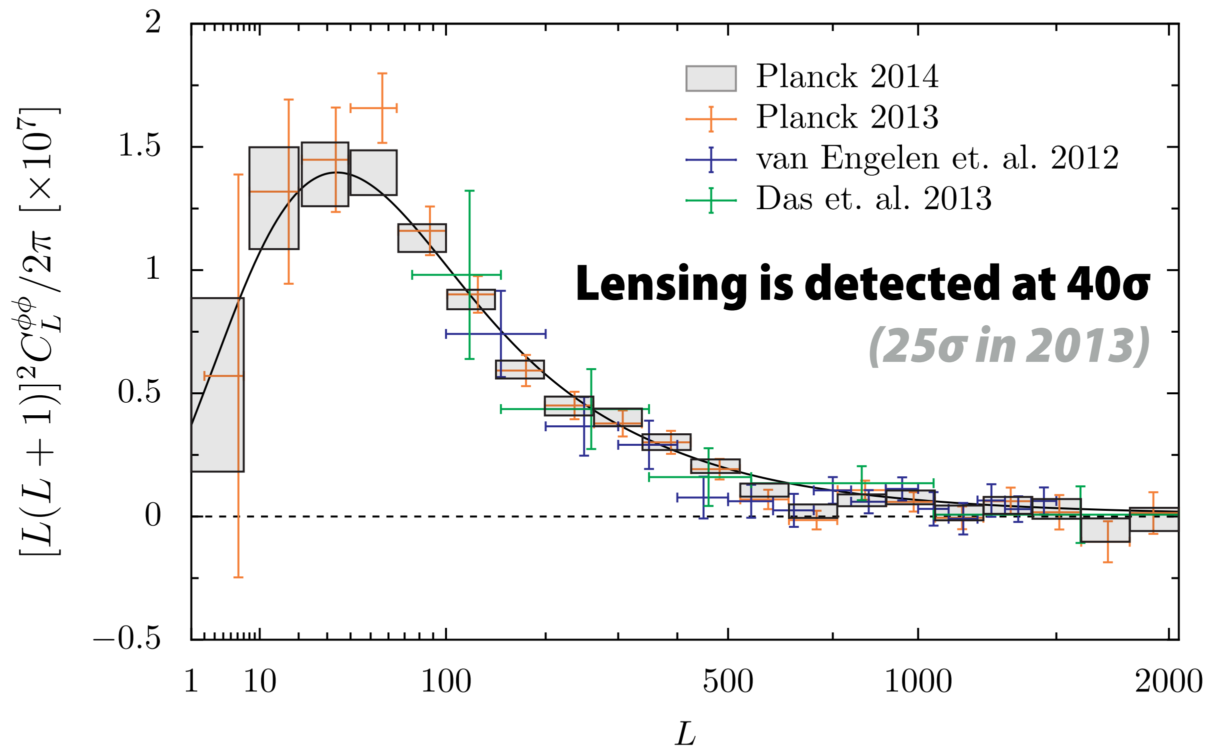
Planck 2015 XI

To summarize, our systematic error budget consists of a $0.1\,\sigma$ methodology bias on n_s for TT, at most a $0.2\,\sigma$ instrumental bias on TT (on ω_b), TE and possibly a slightly greater one on EE. The few-μK^2-level leakage residual in polarization does not appear to project onto biases on the ΛCDM parameters. We conservatively evalute our astrophysical bias to be $0.2\,\sigma$ on n_s. The astrophysical parameters might suffer from instrumental biases.



Robustness under data selection

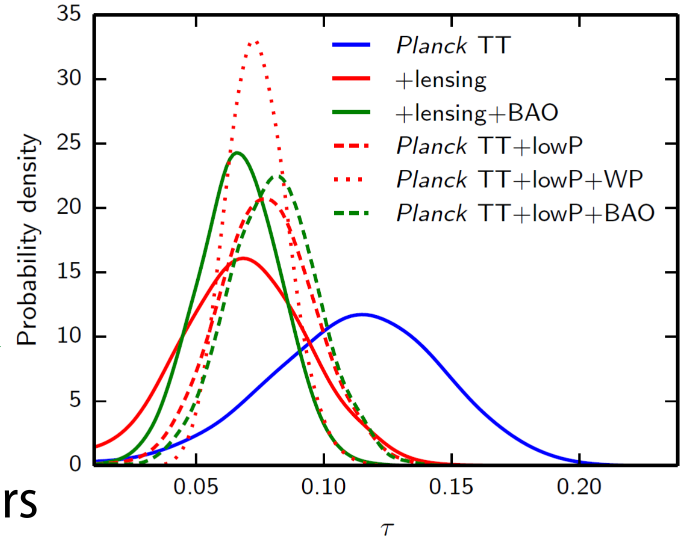




Planck 2015 XV

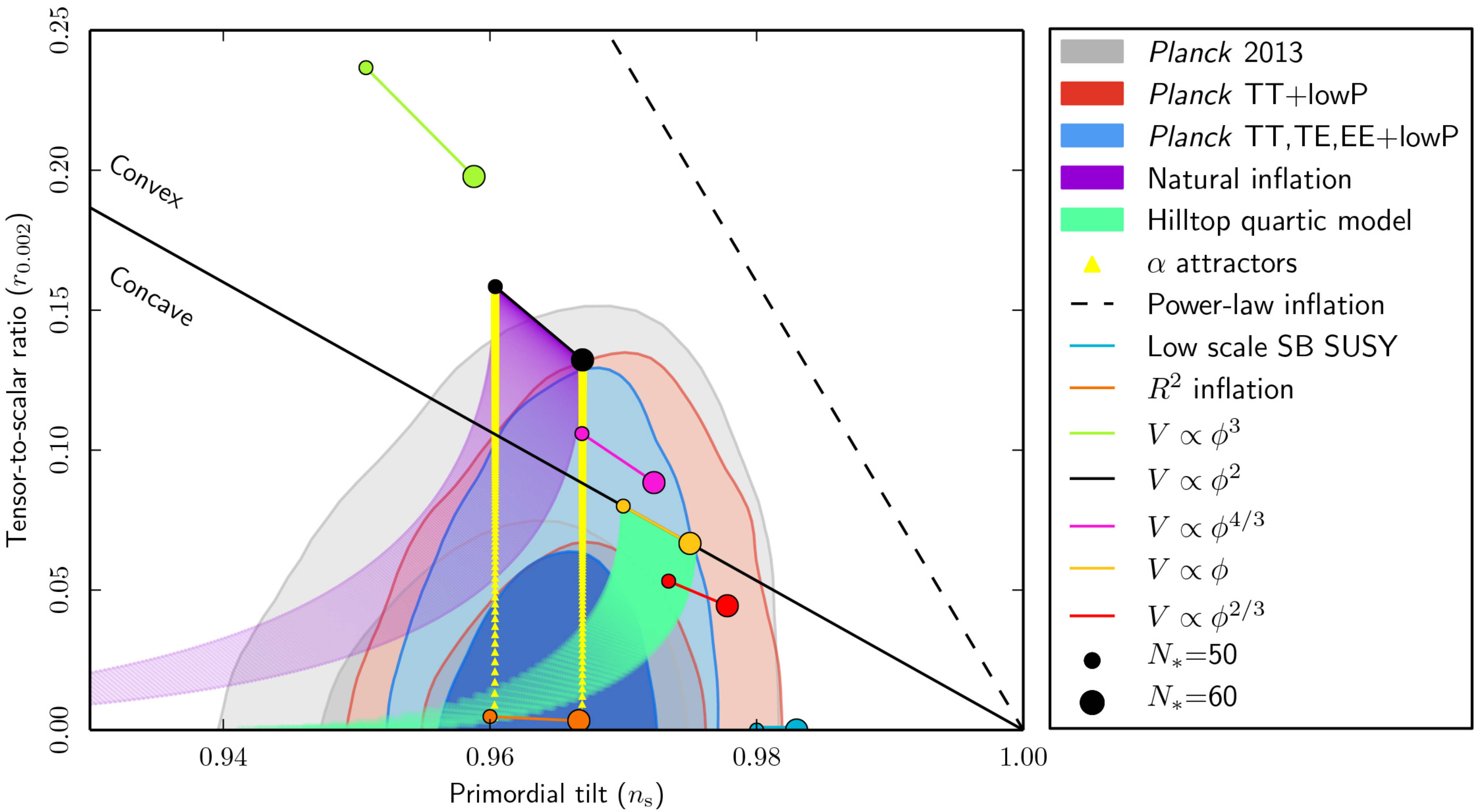
Parameter	TT+lowP 68 % limits	TT+lowP+lensing 68 % limits	TT+lowP+lensing+ext 68 % limits	TT,TE,EE+lowP 68 % limits	TT,TE,EE+lowP+lensing 68 % limits	TT,TE,EE+lowP+lensing+ext 68 % limits
$\Omega_b h^2$	0.02222 ± 0.00023	0.02226 ± 0.00023	0.02227 ± 0.00020	0.02225 ± 0.00016	0.02226 ± 0.00016	0.02230 ± 0.00014
$\Omega_c h^2$	0.1197 ± 0.0022	0.1186 ± 0.0020	0.1184 ± 0.0012	0.1198 ± 0.0015	0.1193 ± 0.0014	0.1188 ± 0.0010
$100\theta_{MC}$	1.04085 ± 0.00047	1.04103 ± 0.00046	1.04106 ± 0.00041	1.04077 ± 0.00032	1.04087 ± 0.00032	1.04093 ± 0.00030
τ	0.078 ± 0.019	0.066 ± 0.016	0.067 ± 0.013	0.079 ± 0.017	0.063 ± 0.014	0.066 ± 0.012
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.062 ± 0.029	3.064 ± 0.024	3.094 ± 0.034	3.059 ± 0.025	3.064 ± 0.023
n_s	0.9655 ± 0.0062	0.9677 ± 0.0060	0.9681 ± 0.0044	0.9645 ± 0.0049	0.9653 ± 0.0048	0.9667 ± 0.0040
H_0	67.31 ± 0.96	67.81 ± 0.92	67.90 ± 0.55	67.27 ± 0.66	67.51 ± 0.64	67.74 ± 0.46

- slope of the fluctuations
- Sound horizon: location of the first peak
- Total matter: Changes the contrast between the peaks
- Baryon density: Changes the ratio between peak heights
- Amplitude of the fluctuation
- Reionization fraction
  - (from low l LFI polar or lensing)
- Ho: indirect measurement from the above parameters



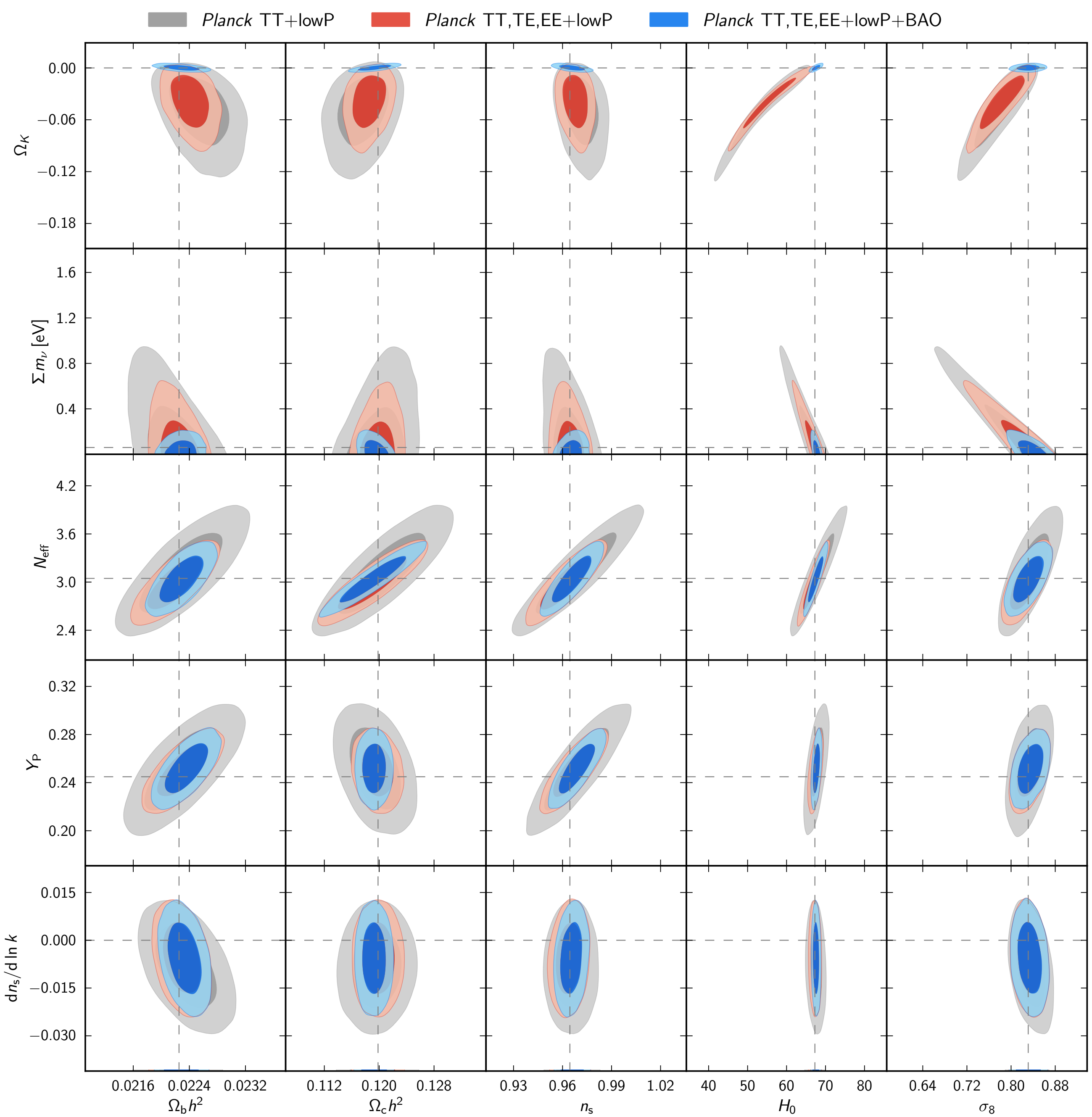
Planck 2015 XIII

Constraints on Inflation



Planck 2015 XX

No deviation from ΛCDM



$$\Omega_K = 0.000 \pm 0.005 \ (95\%)$$

(PlanckTT+lowP+Lensing+BAO)

$$\sum m_\nu < 0.23 \text{ eV}$$

(PlanckTT+lowP+Lensing+ext)

Bound already stronger than what achievable by Katrin (tritium beta decay)

$$N_{\rm eff} = 3.13 \pm 0.32$$

(PlanckTT+lowP)

Compatible with standard predition N_{eff}=3.046 with 3 active neutrinos

$$Y_{\rm P}^{\rm BBN} = 0.253 \pm 0.021$$

(PlanckTT+lowP)

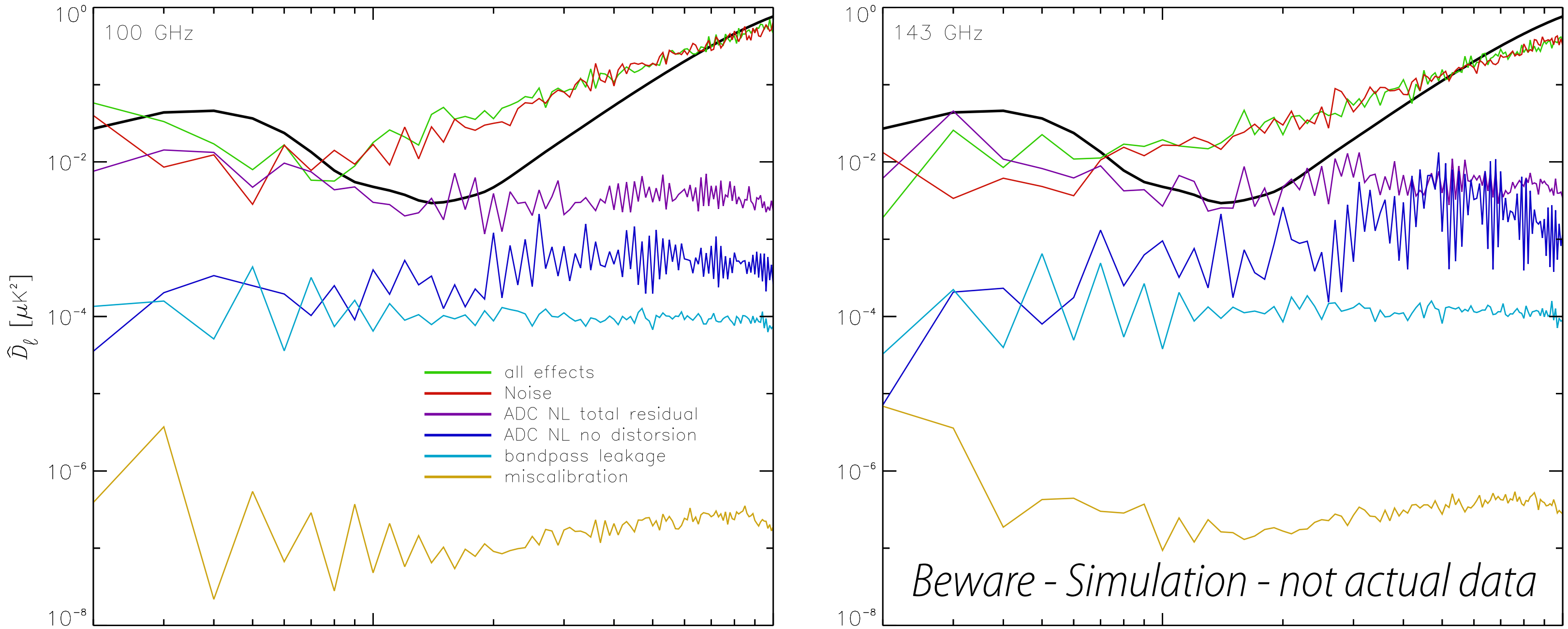
Good agreement with measurements of primordial abundances and BBN predictions

$$\frac{dn_s}{d\ln k} = -0.0084 \pm 0.0082$$

(PlanckTT+lowP)

Planck 2015 XIII

Planck intermediate XLVI



Large improvement in the handling of HFI polarized systematics and T->P leakage

(at the simulation and map-making level)

-> ADC non-linearity

(including dipole distortion using simulations based template)

-> Bandpass leakage

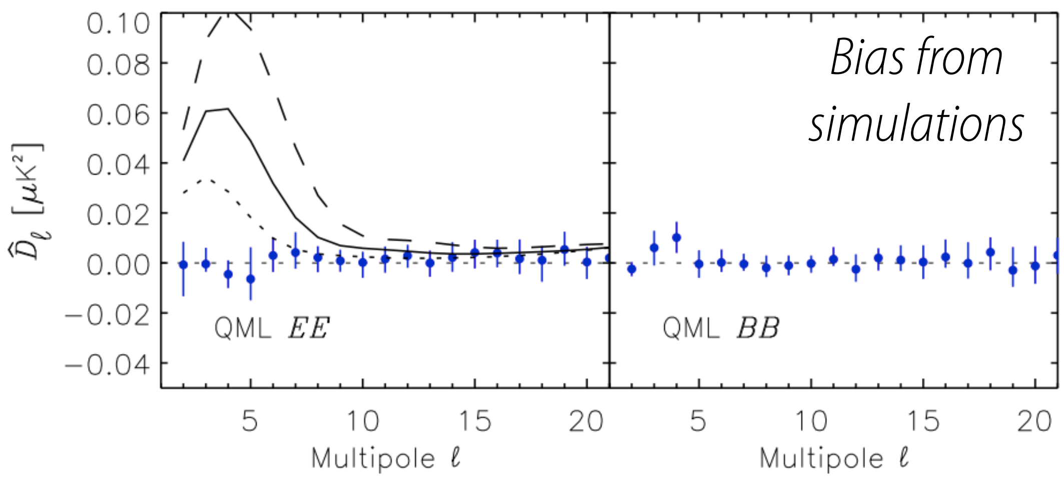
-> better freq inter calibration

2016 Intermediate - low-ell HFI specific data analysis

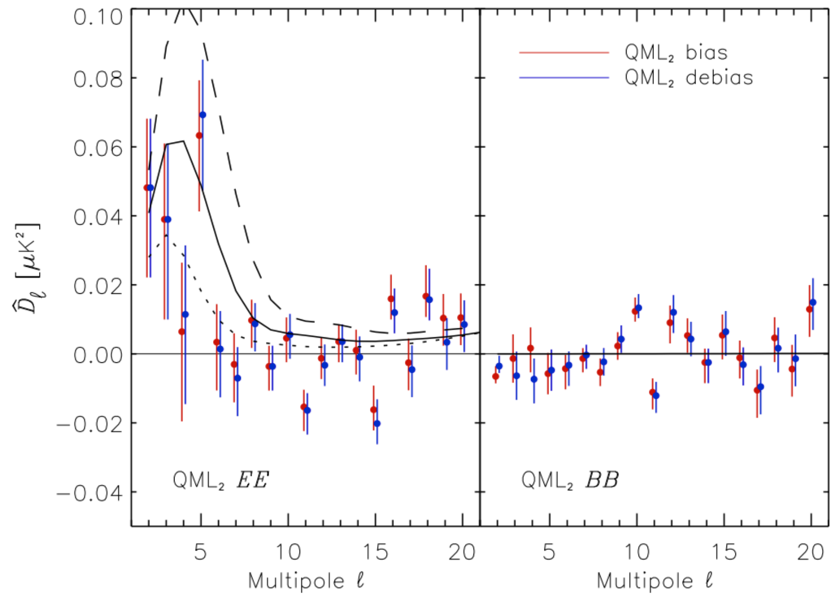
2016 intermediate low-l likelihood

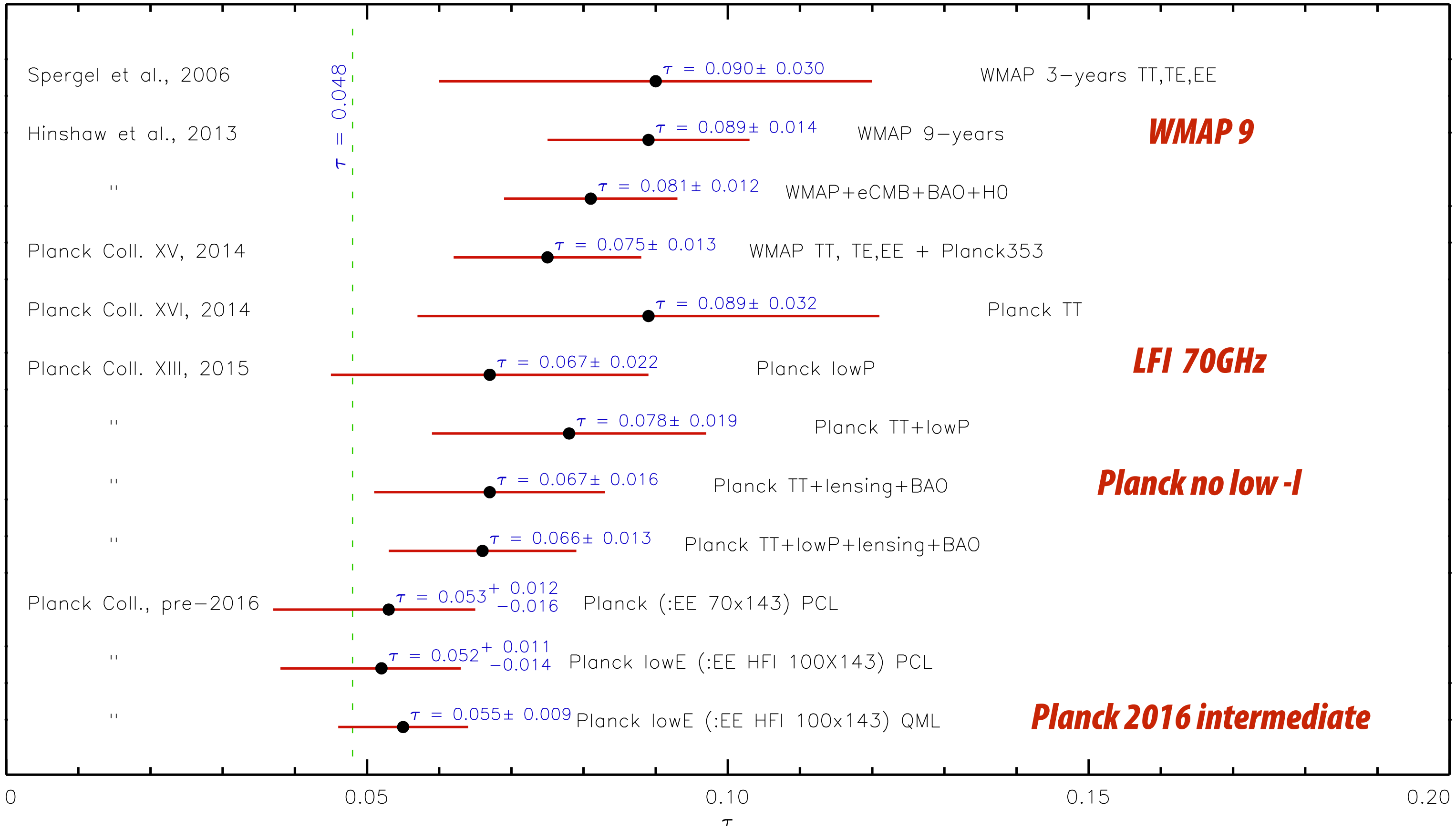
- Cannot use HFI channels for pixel based likelihood
  - Poor description of noise covariance
  - residual systematic biases
- Simulation based likelihood for 100x143 FG cleaned QML
  - FG clean using 30GHz and 353GHz
  - use approximate noise covariance for QML estimates (using E2E sims)
  - Estimate residual systematic biases on E2E sims

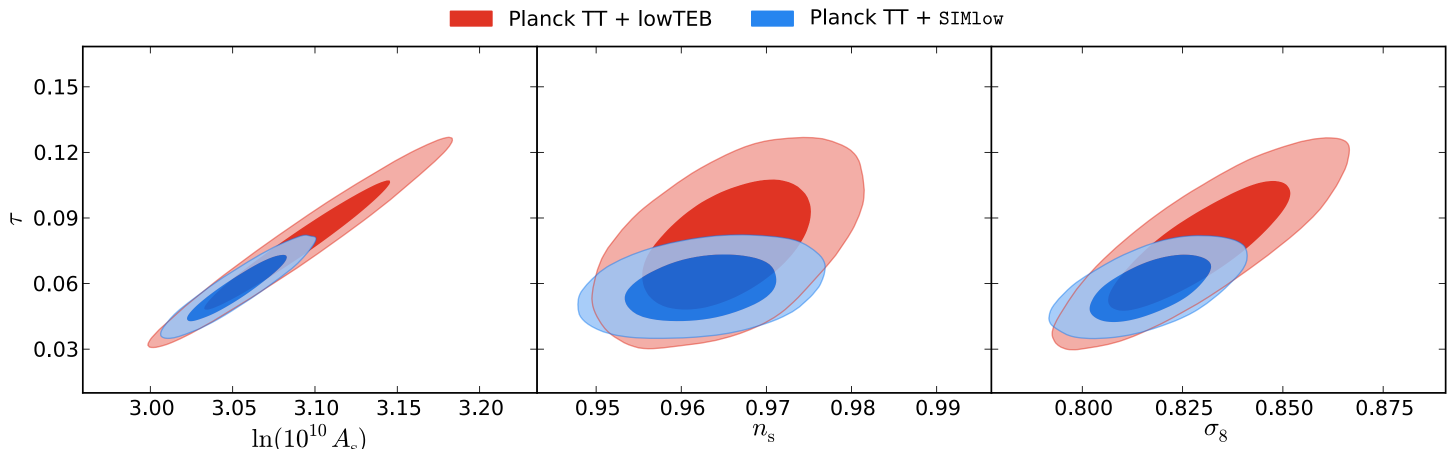
$$\tau = 0.055 \pm 0.009 \ \ \mathrm{SimLow}$$



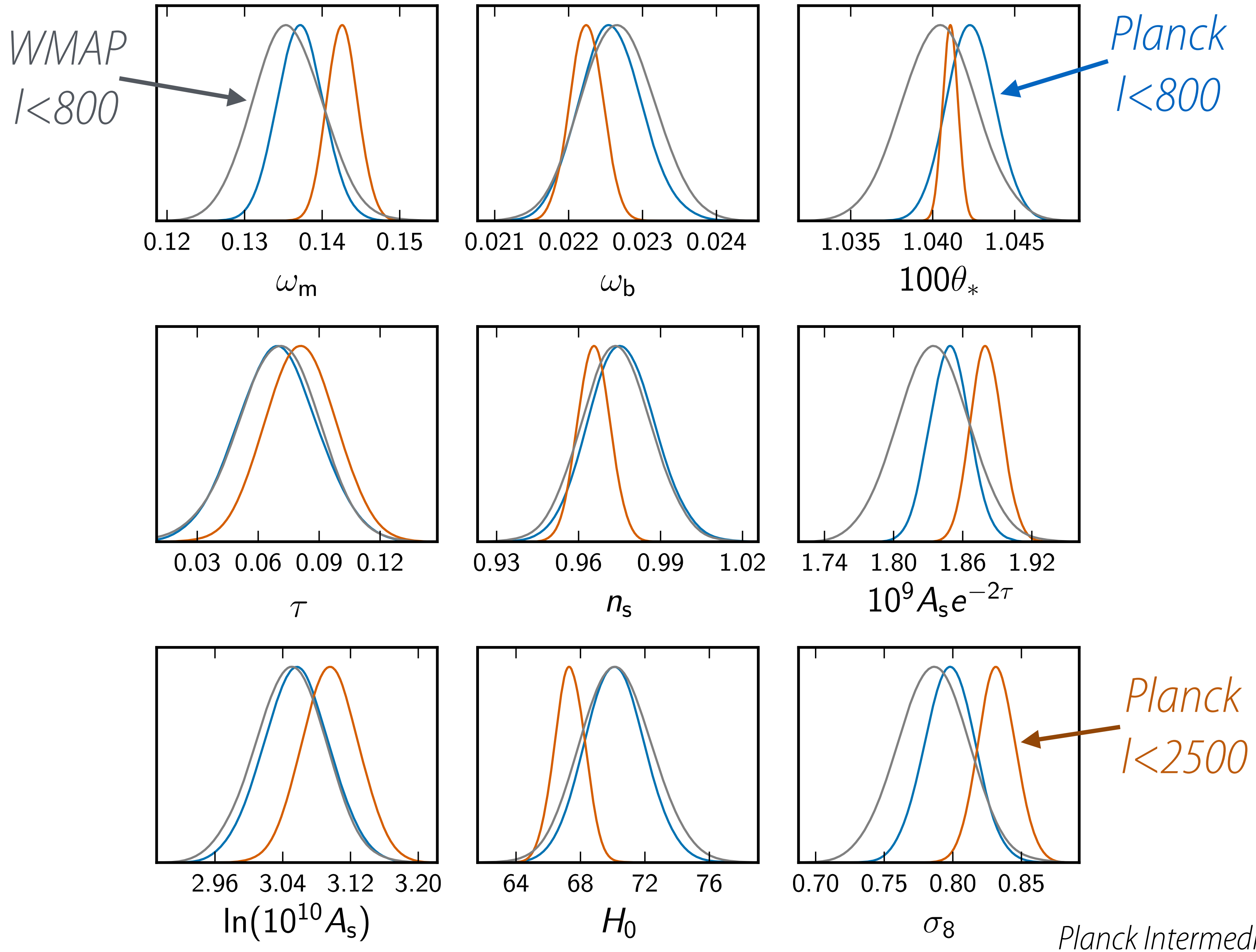
Planck intermediate XLVI





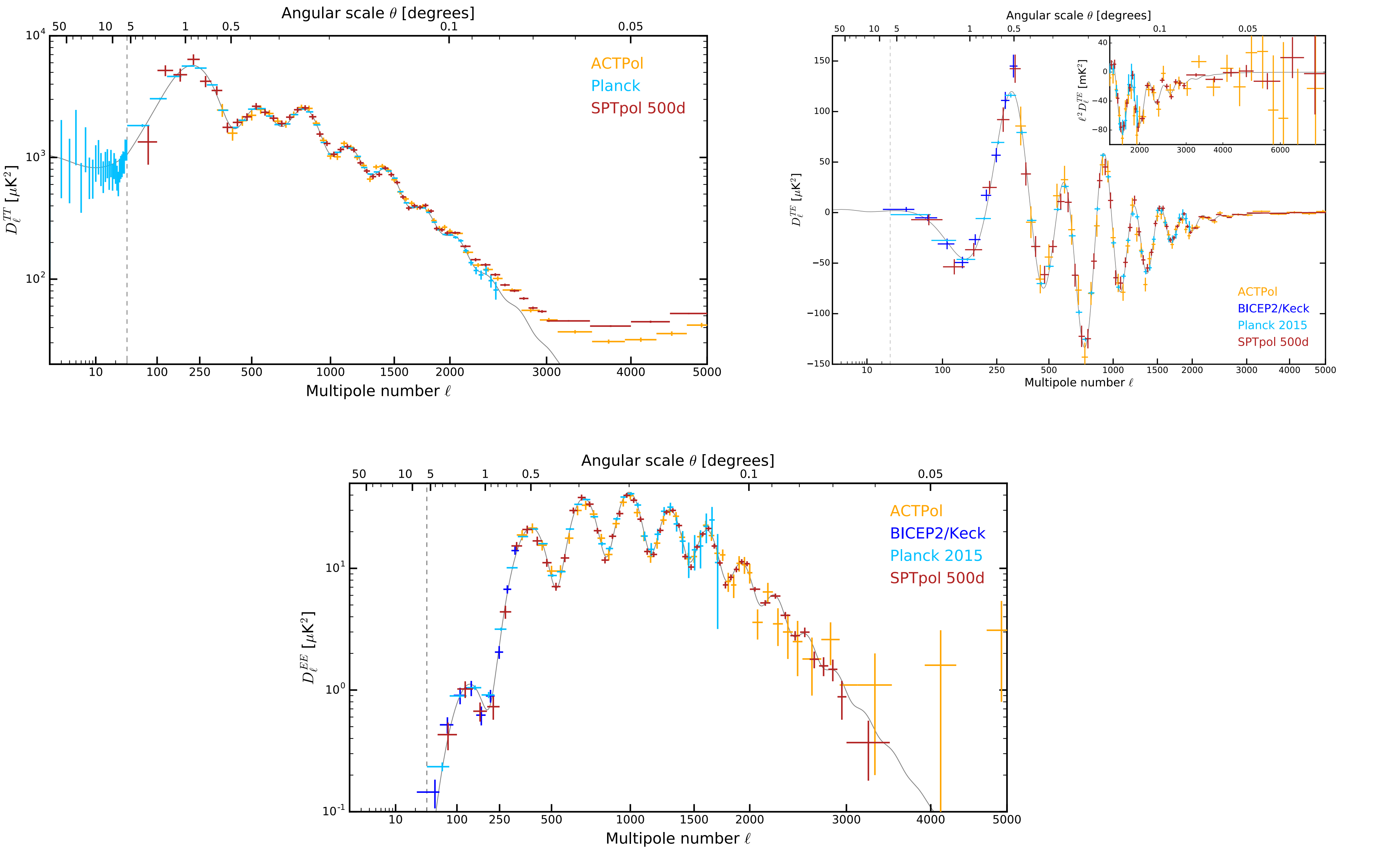


Planck intermediate XLVI



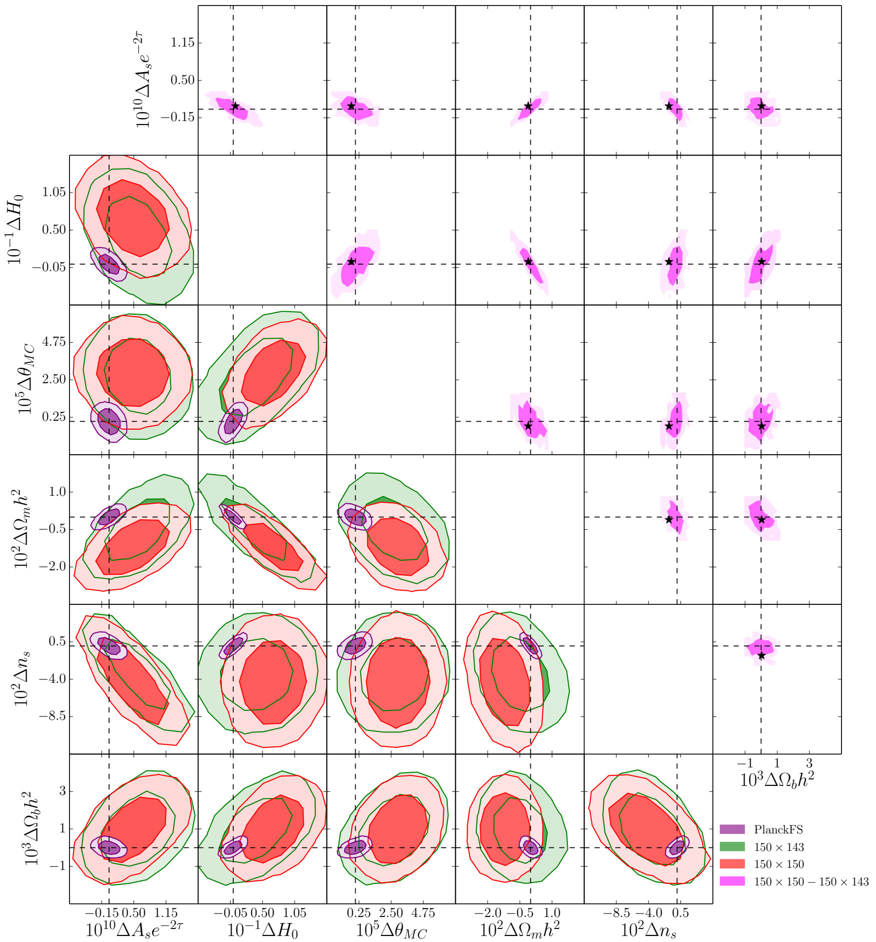
Planck Intermediate LI

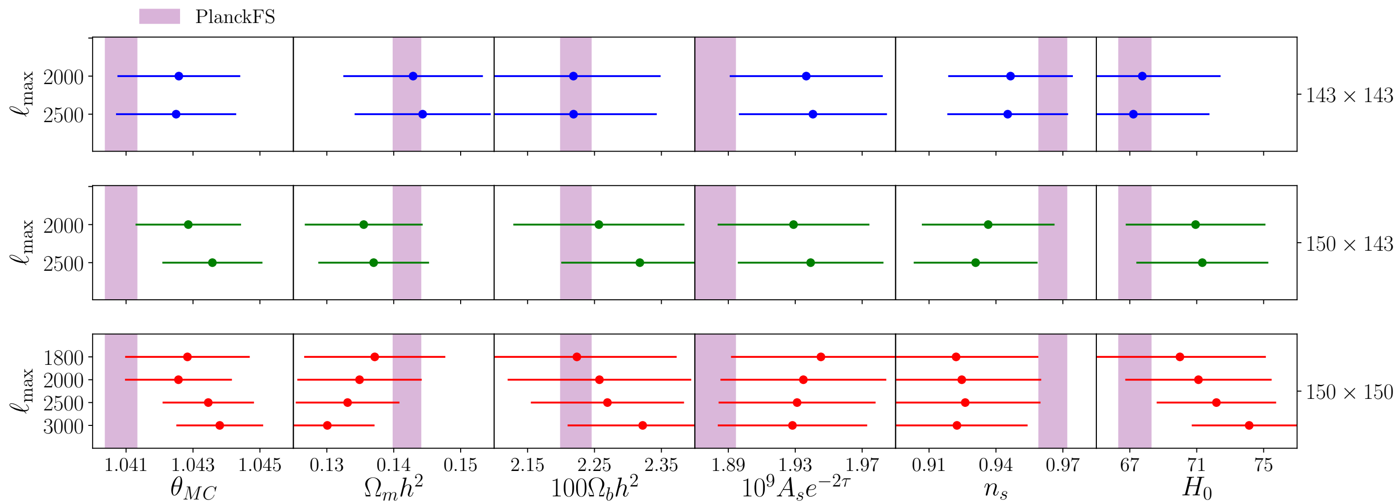
Good Planck/WMAP consistency *(see also Huang et al. 2018)*

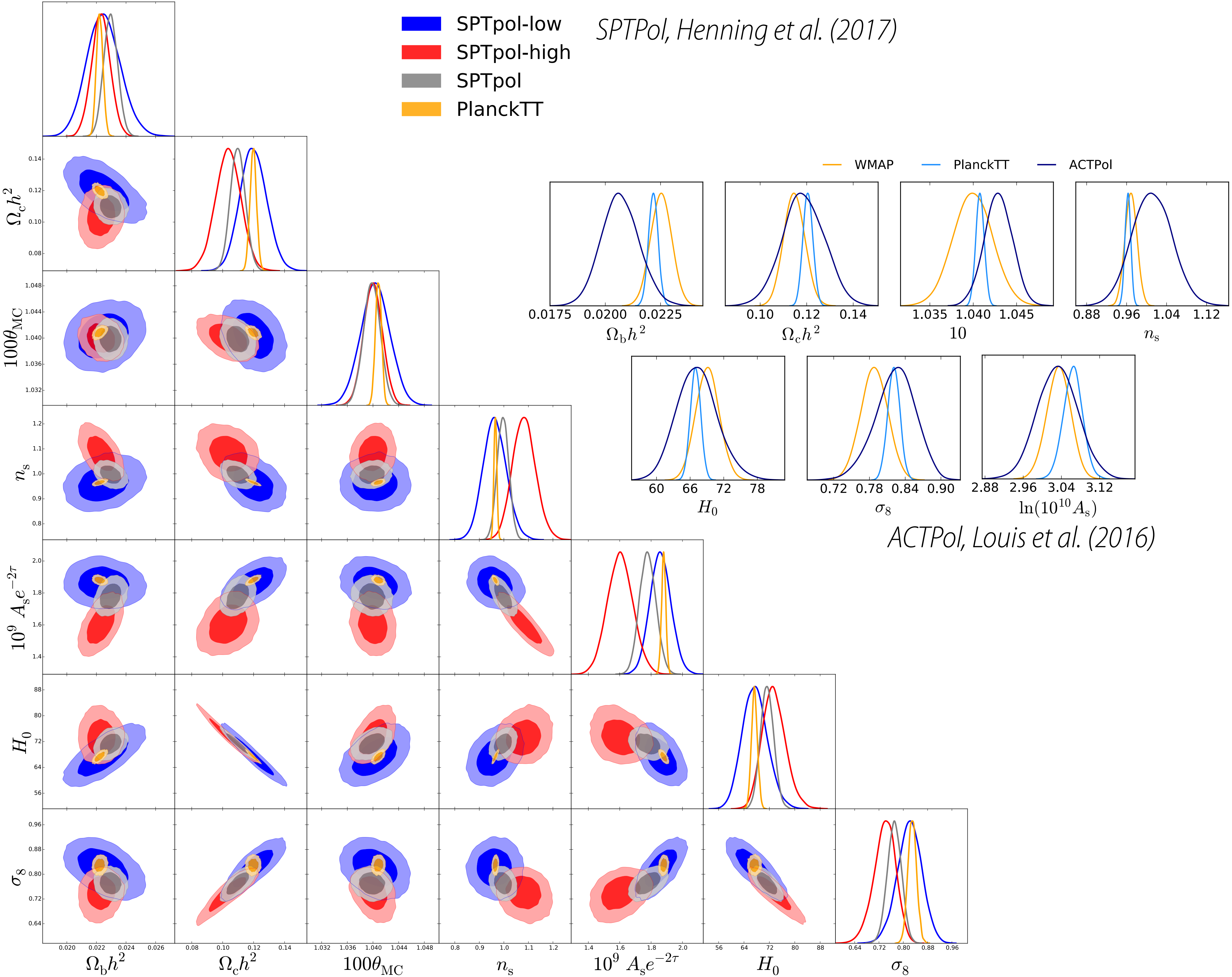


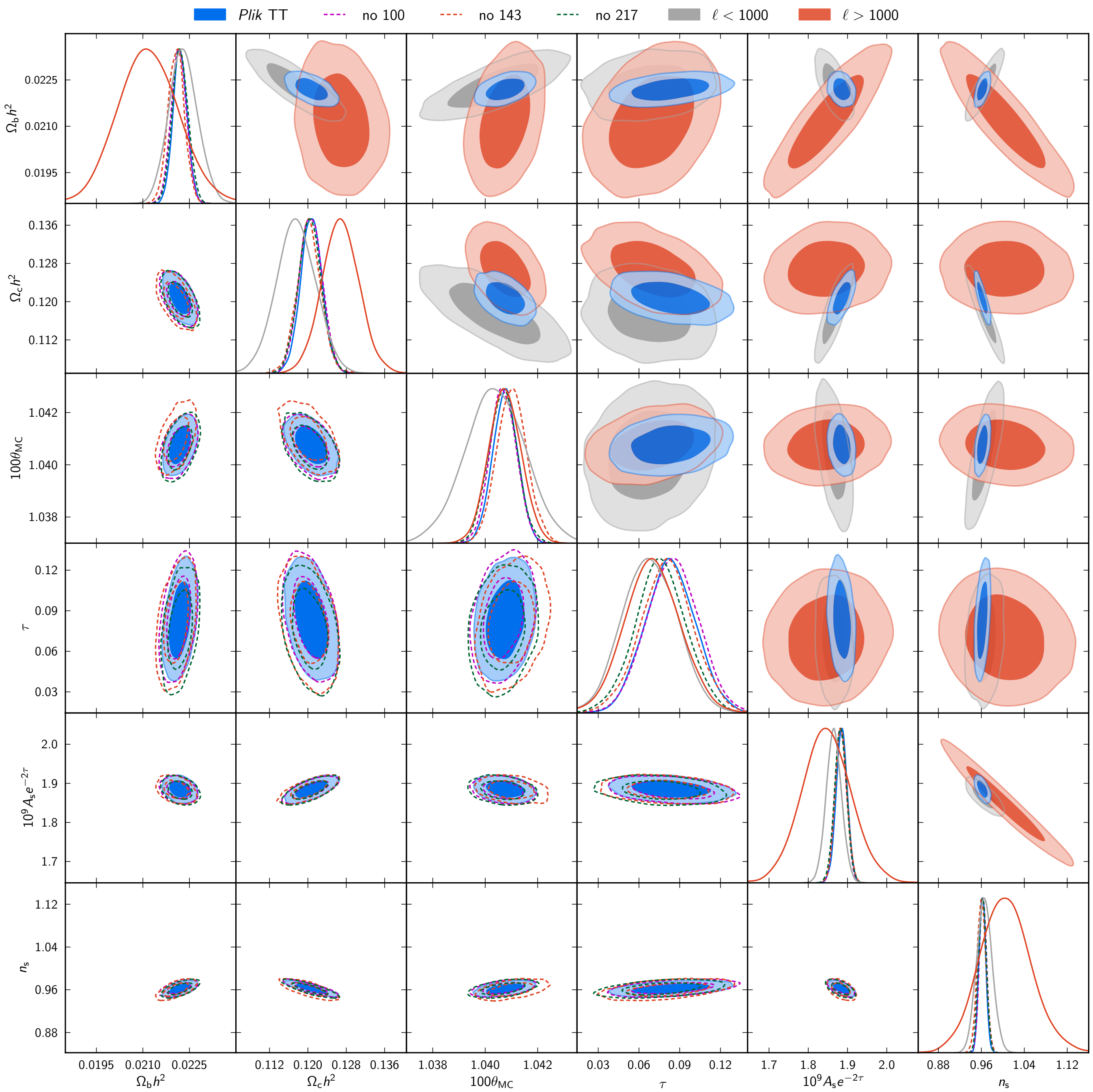
SPTPol, Henning et al. (2017)

SPT, Aylor et al. (2017)



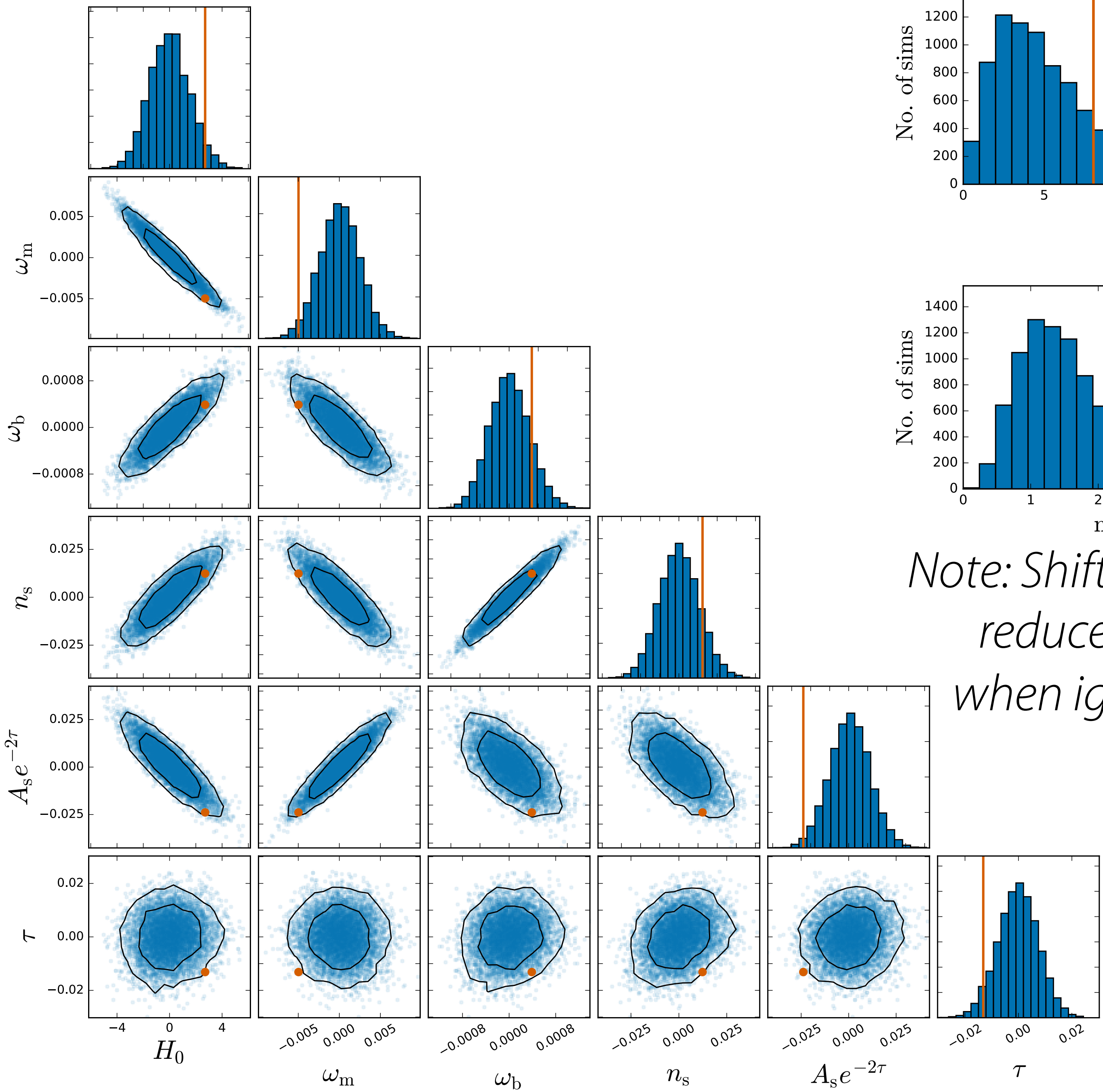


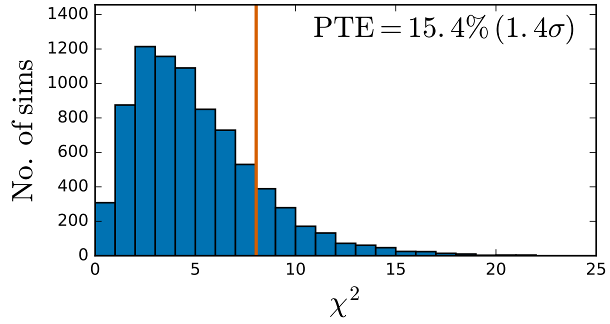

SPTpol-low
SPTpol-high
SPTpol
PlanckTT
SPTPol, Henning et al. (2017)
$\Omega_b h^2$
$\Omega_c h^2$
$100\theta_{MC}$
n_s
$10^9 A_s e^{-2\tau}$
H_0
σ_8
WMAP
PlanckTT
ACTPol
$\ln(10^{10} A_s)$
ACTPol, Louis et al. (2016)

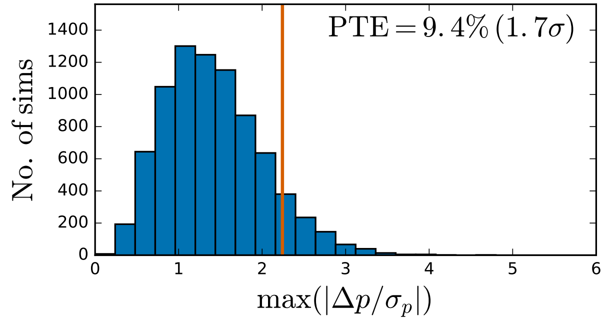


Low-l / high-l tension

Planck 2015 XI



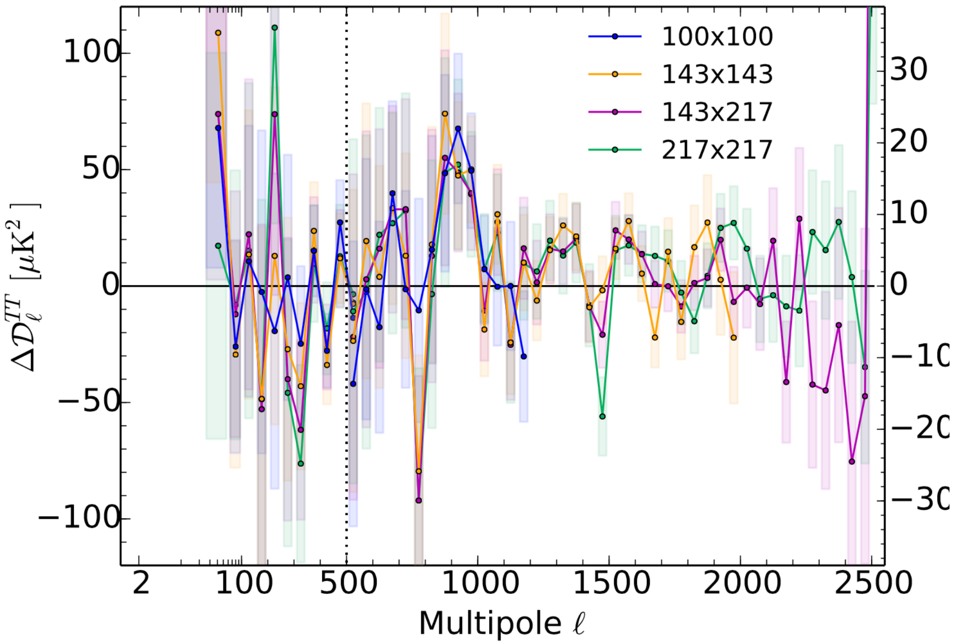




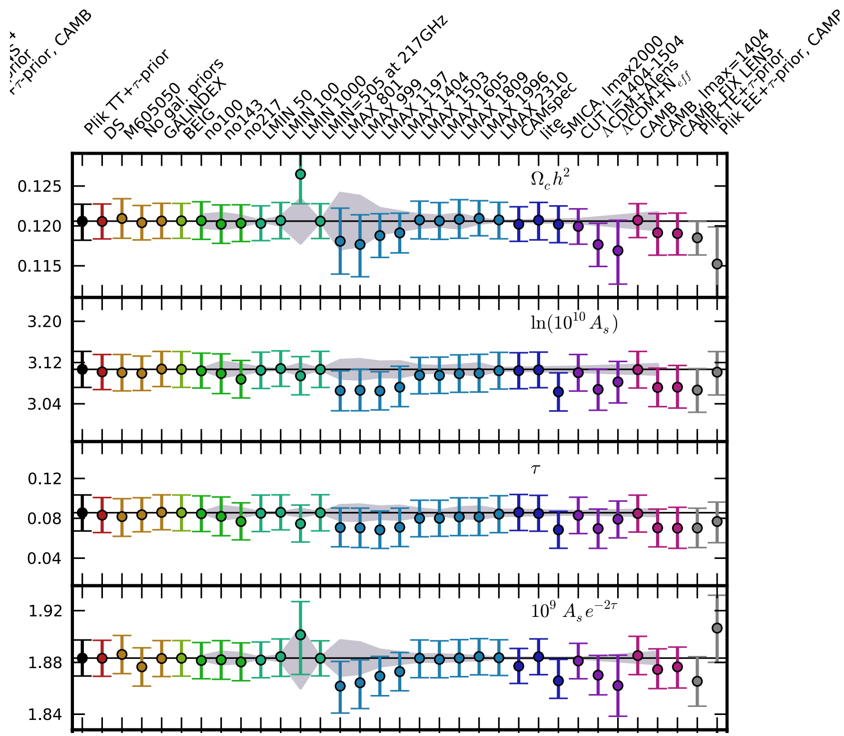
Note: Shifts (per parameter) reduces by 1~sigma when ignoring l<30 TT

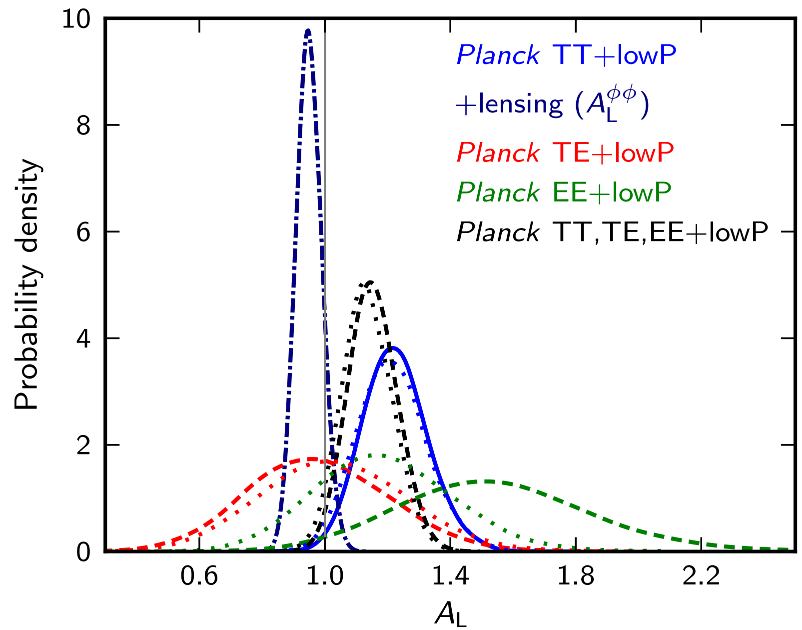
Low-l / high-l tension

Planck 2015 LI

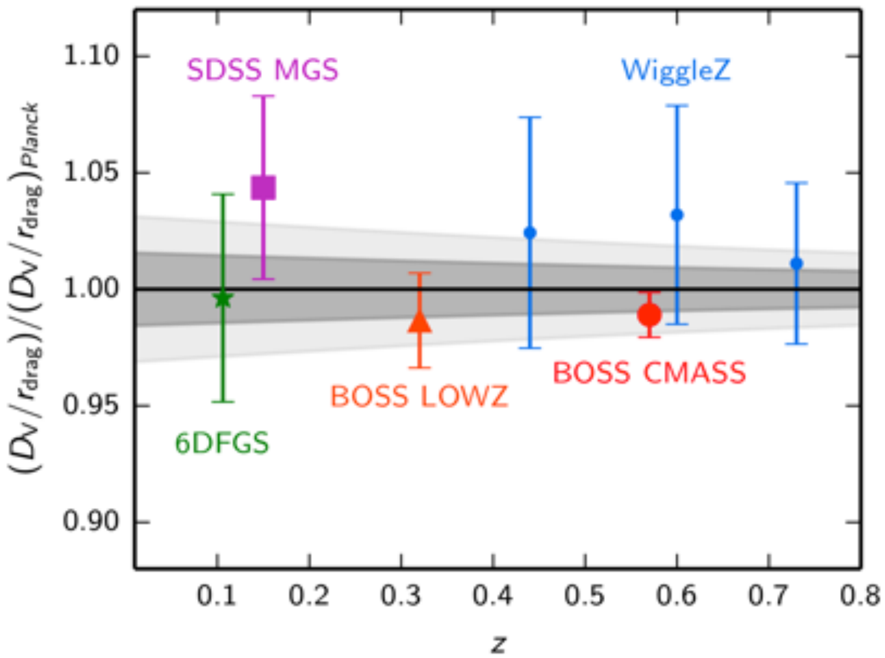


Residuals to l<800 best fit
Small oscillatory in all freqs.
Cause (in part) a 2.4sigma high Alens
Or a tension in tau
Beware: tension reduced by ~1sigma when fixing FG

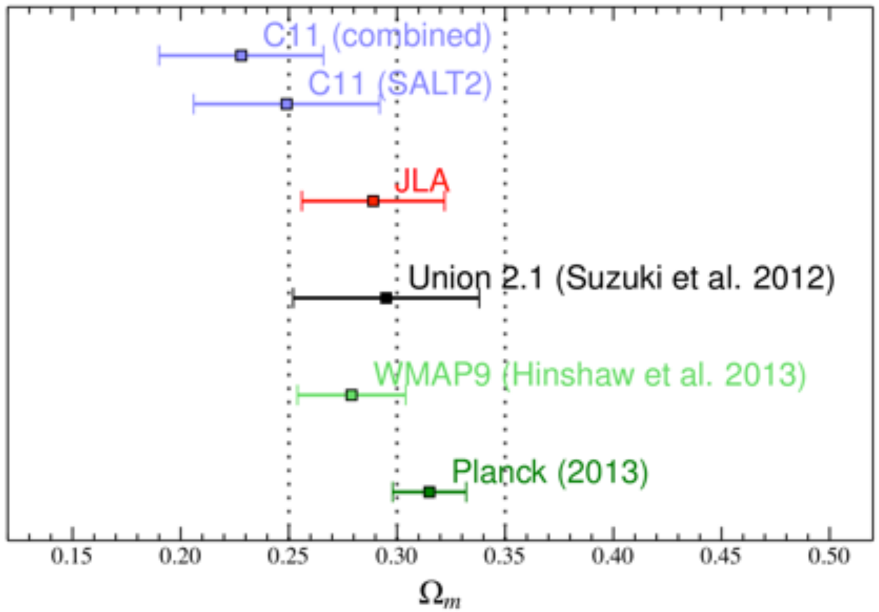




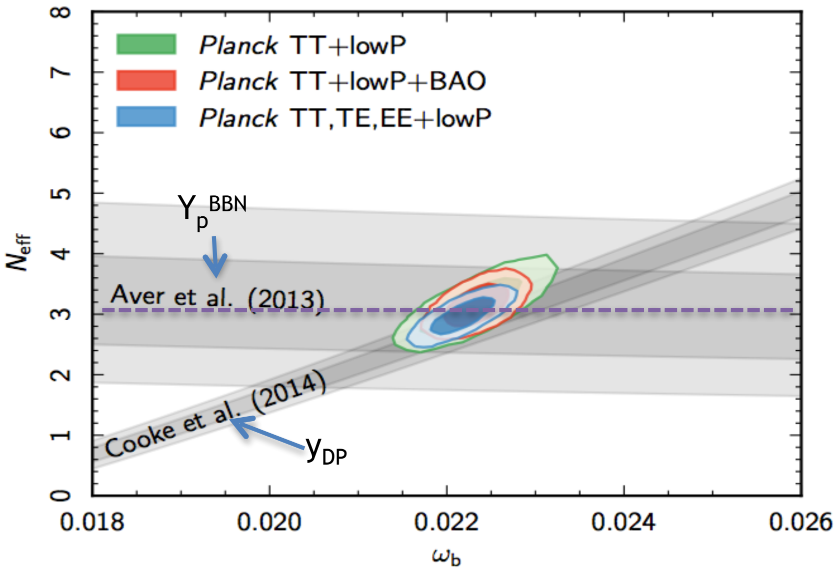
Planck XI,Planck XIII, Planck Intermediate LI



Good agreement with BAO
(acoustic scale/distance @ z=0.1 – 0.9)
Some tension in the highest redshift bin of BOSS RD12



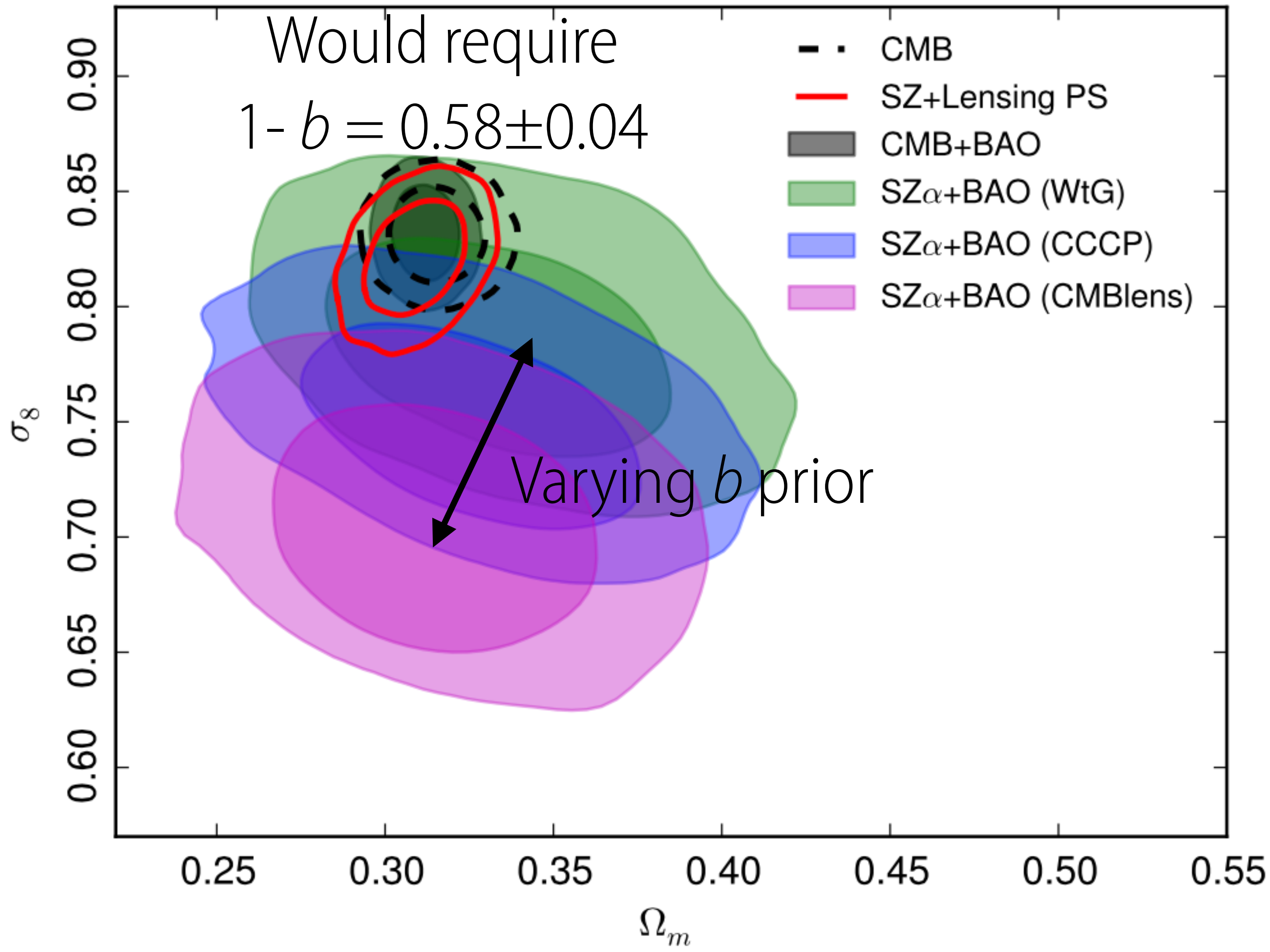
Good agreement with SN
(luminosity distance @ z=0 – 1.4)



Excellent agreement with BBN

Planck 2015 XIII

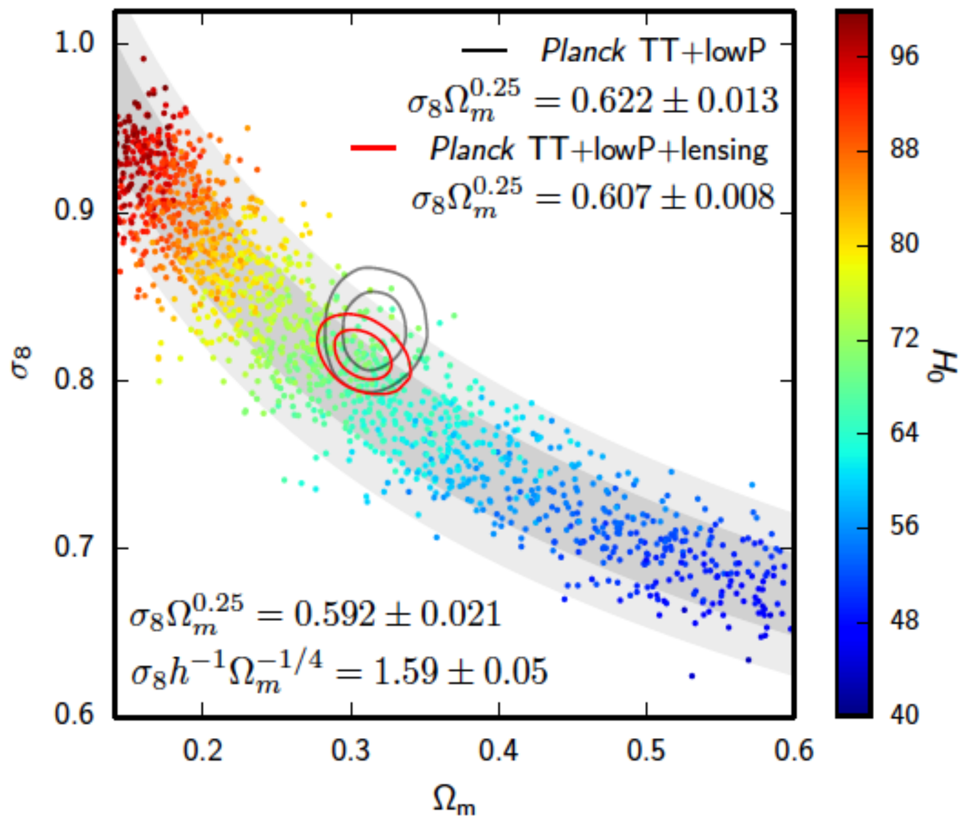
Sigma8 tension (clusters)

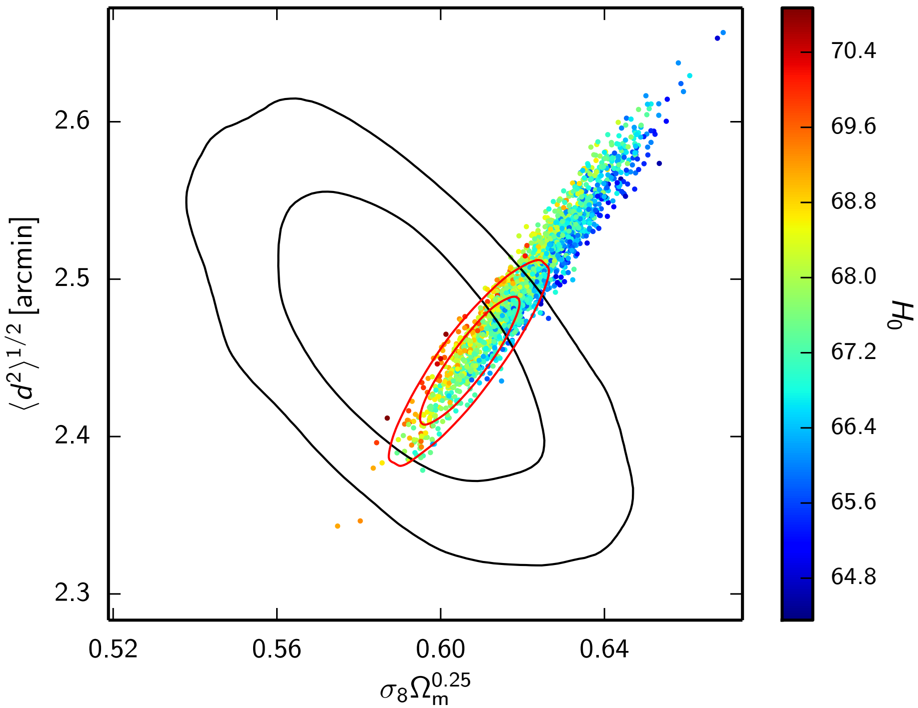


Prior name	Quantity	Value & Gaussian errors
Weighing the Giants (WtG)	$1-b$	0.688 ± 0.072
Canadian Cluster Comparison Project (CCCP)	$1-b$	0.780 ± 0.092
CMB lensing (LENS)	$1/(1-b)$	0.99 ± 0.19

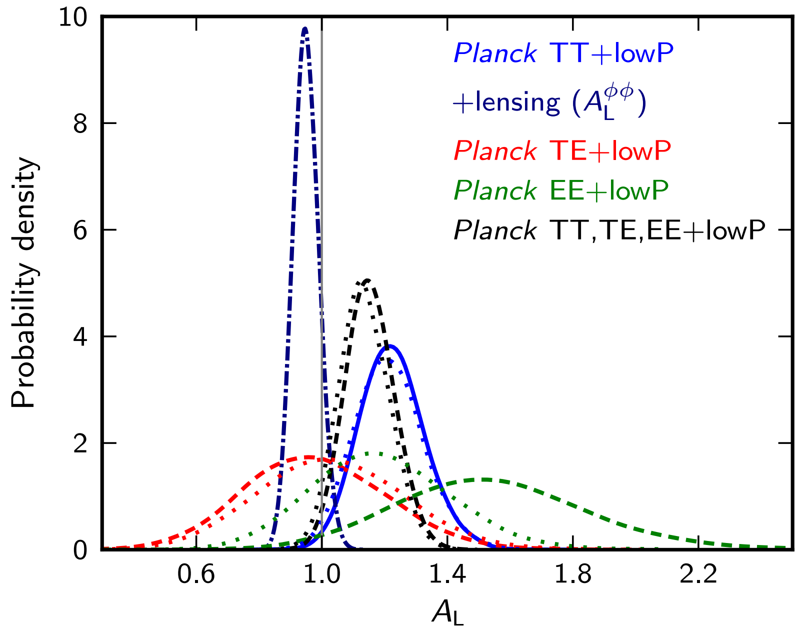
- **Number of clusters** as a function of **z** sensitive to cosmological parameters.
- Clusters can be detected through **Sunyaev-Zeldovitch effect in CMB** surveys (e.g. Planck, ACT, SPT).
- To compare observations to predictions, we need to know the **redshift and the mass** of the observed clusters.
- Relation between SZ observables and mass calibrated on X-ray observations. Mass estimate assume hydrostatic equilibrium and is thus biased.
- mass bias is obtained through lensing observations of some clusters

Planck 2015 XXIV



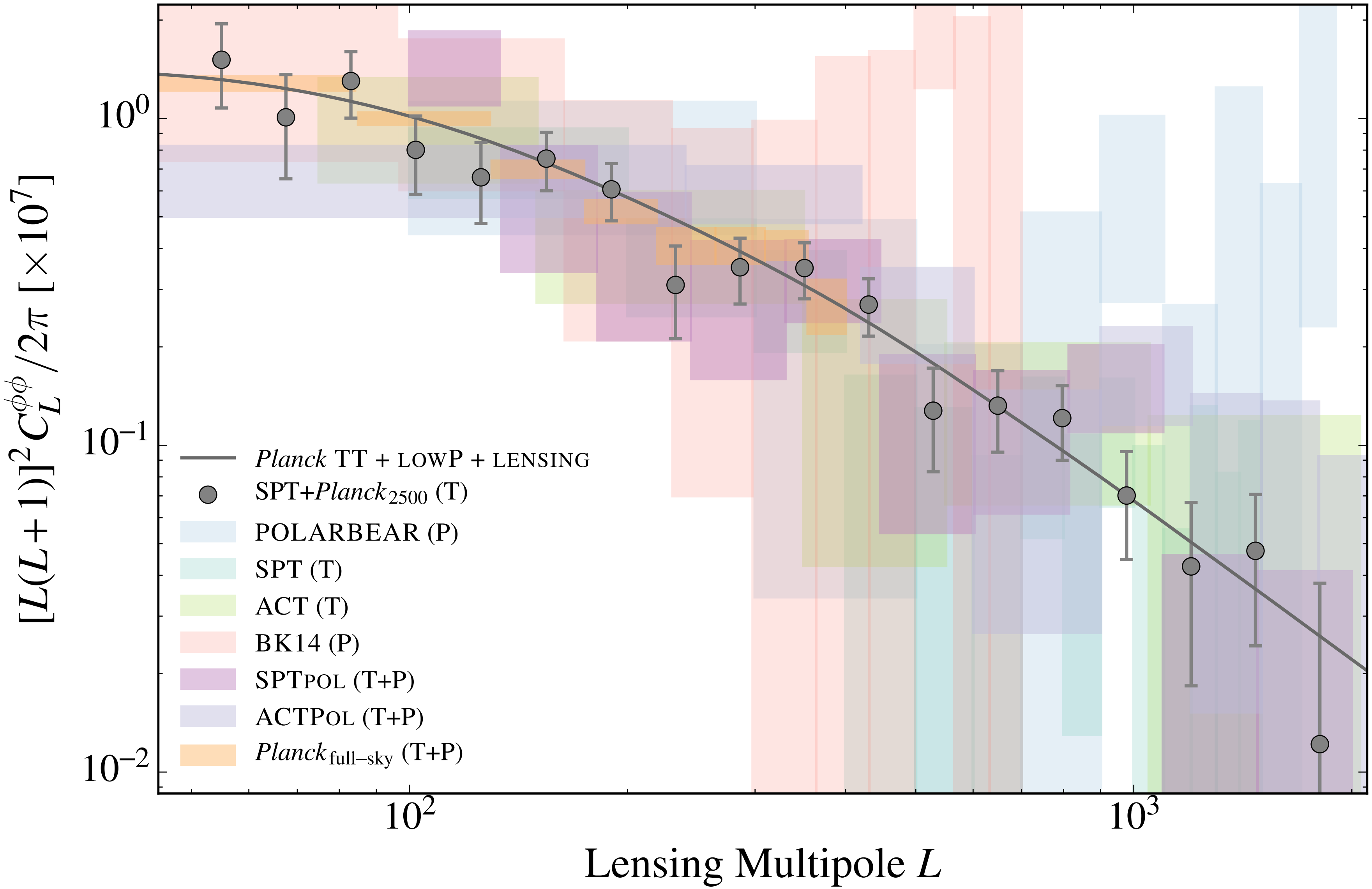


Reasonable agreement between CMB and CMB Lensing.



CMB Lensing wants slightly less deflection than CMB.
Tension is 2.4sigma. At all frequencies.
1Sigma « due » to FG.

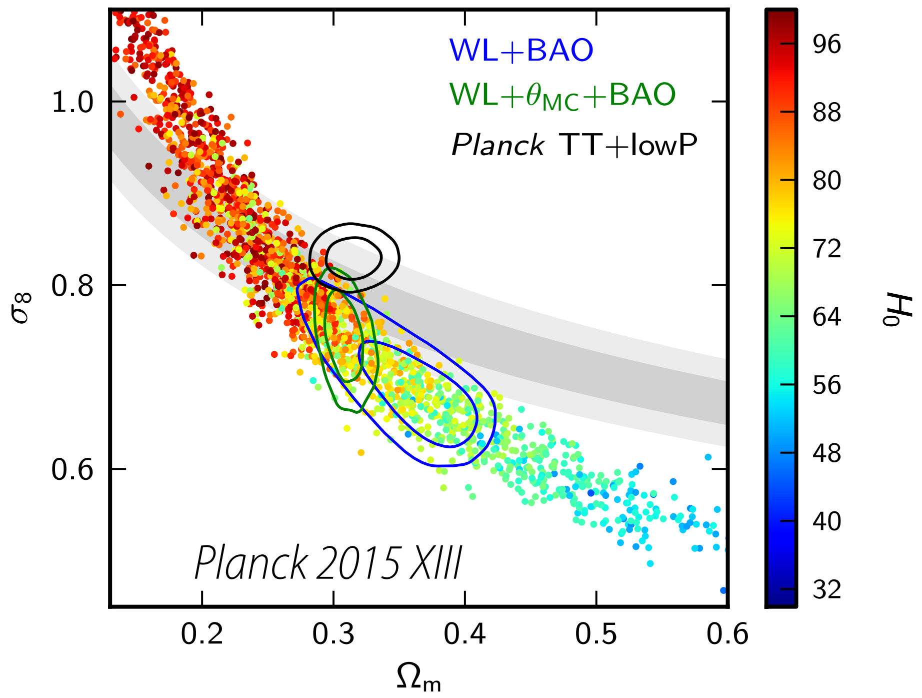
Planck 2015 XIII & XV, Planck Intermediate LI, and also Mortloch & Hu 2018

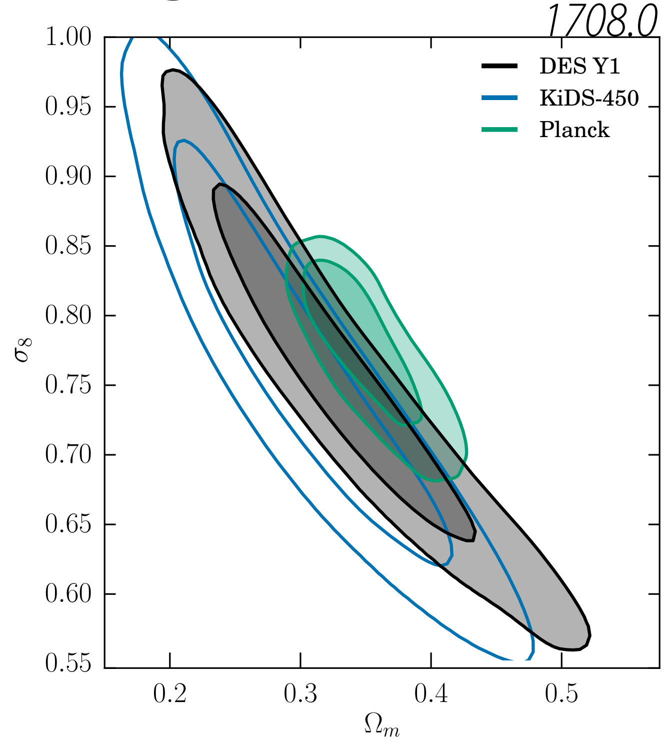


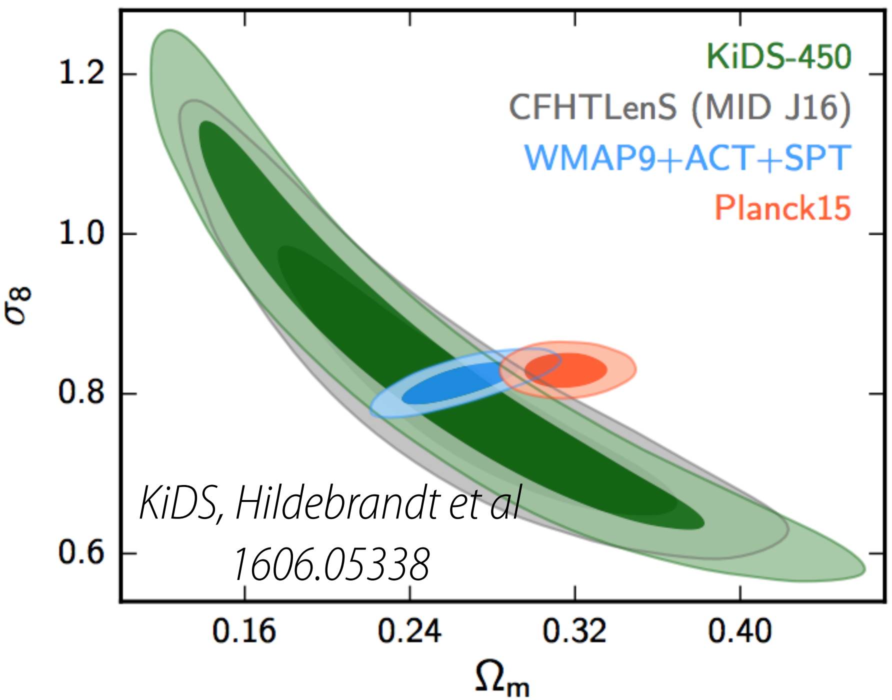
SPT, Simard et al. 2017

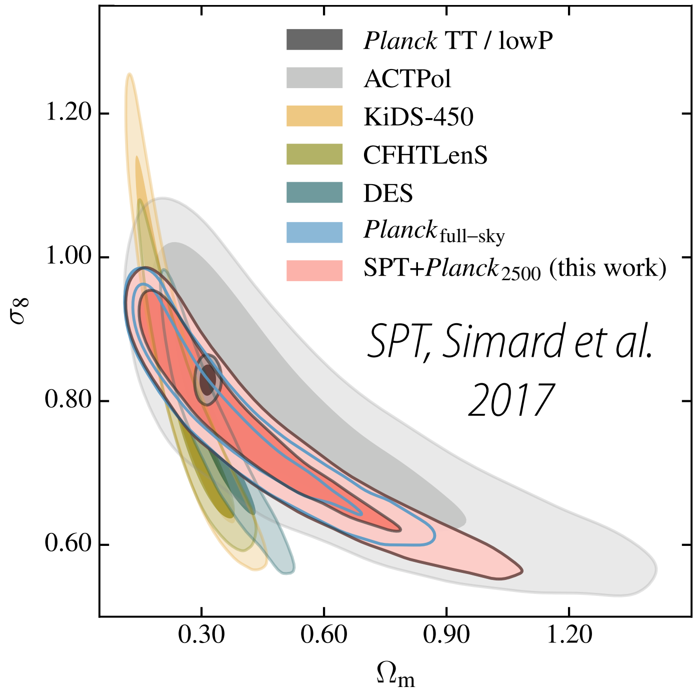
Sigma8 tension (Lensing)

DES 1Yr, Troxel et al 1708.01538

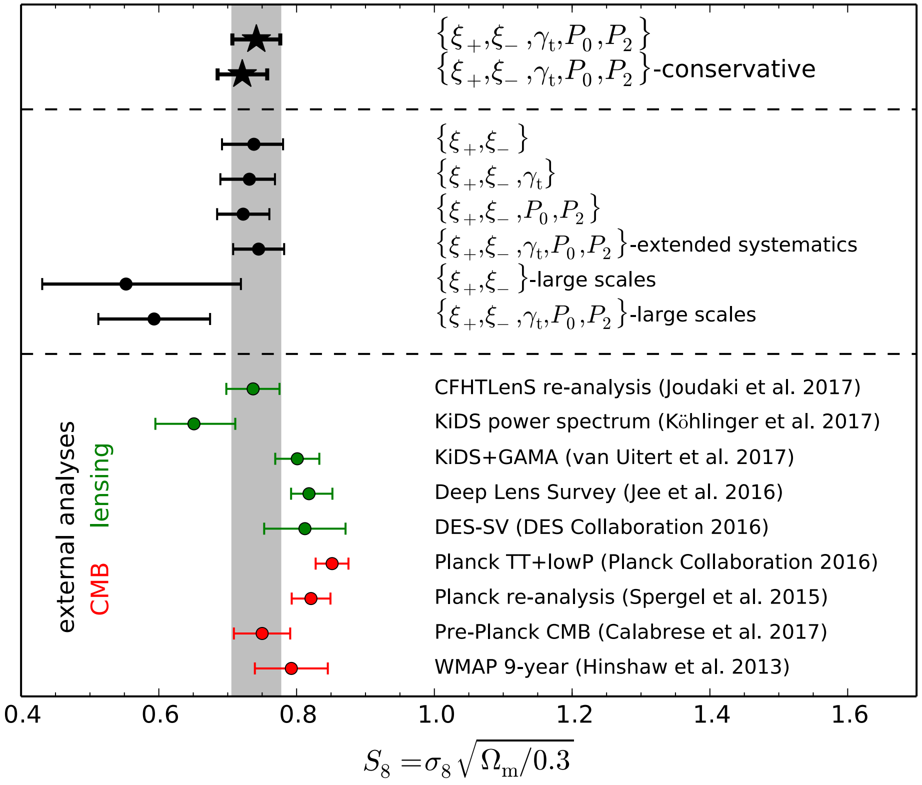




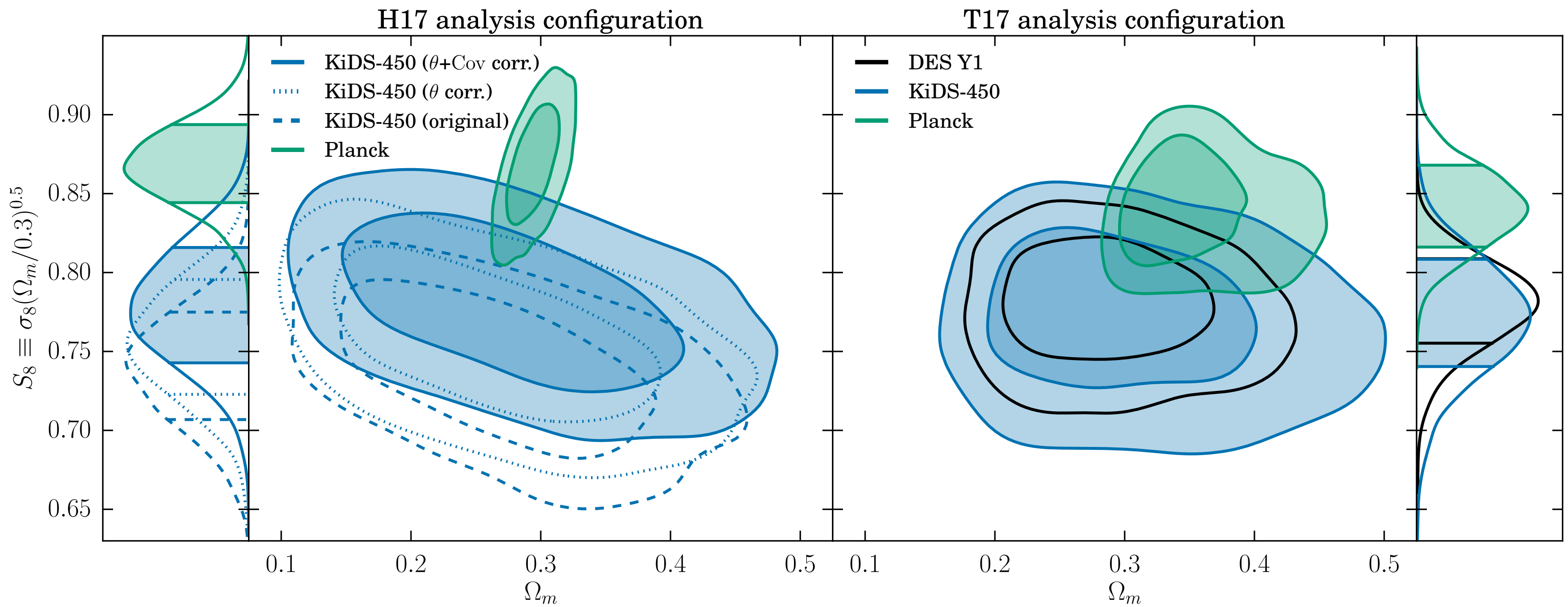




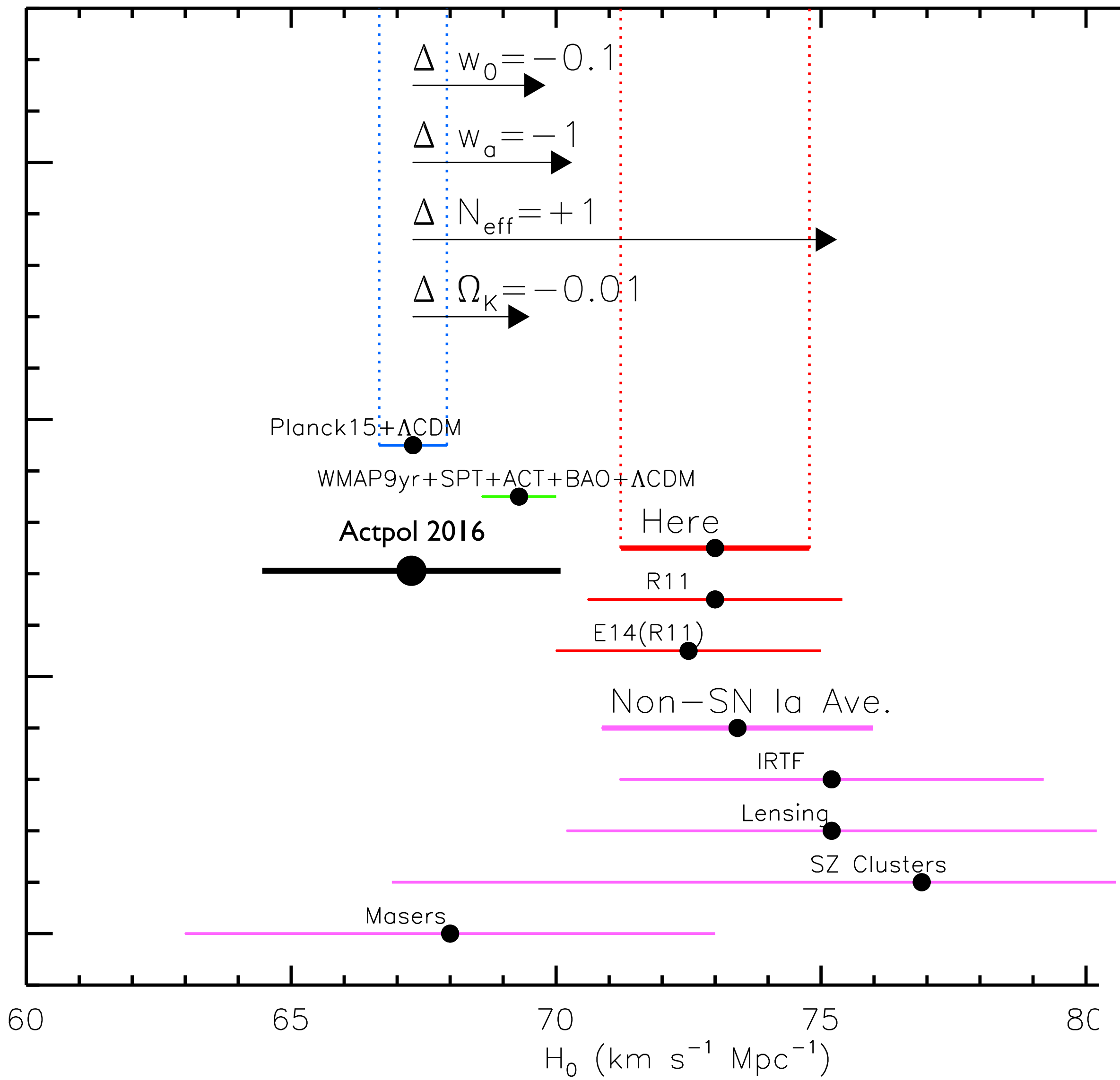
KIDS, Joudaki et al., 2017



DES 1Yr, Troxel et al. 2018



Riess et al. 2016

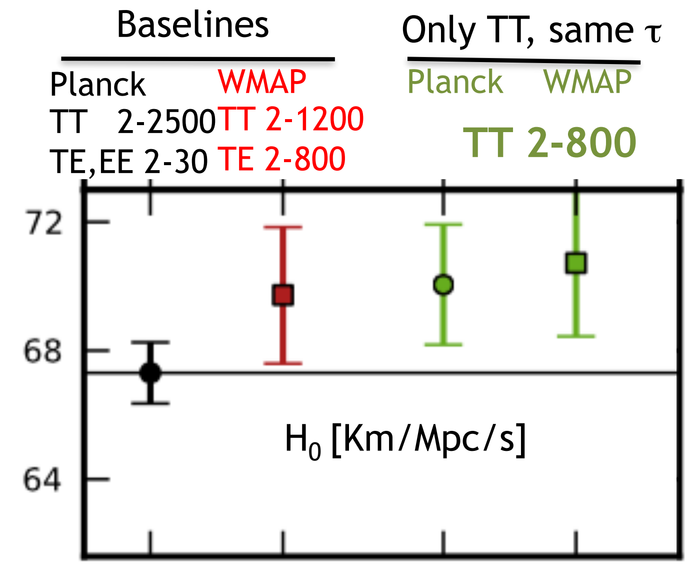


And see also:

DES 1yr (2017)

Addison et al. (2017)

...



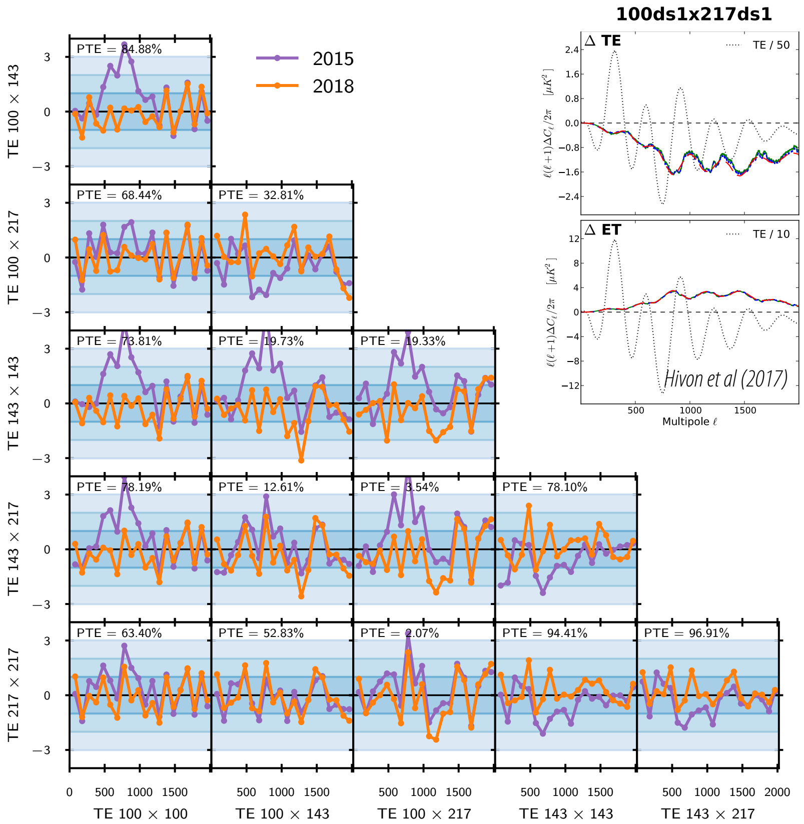
Planck Intermediate LI

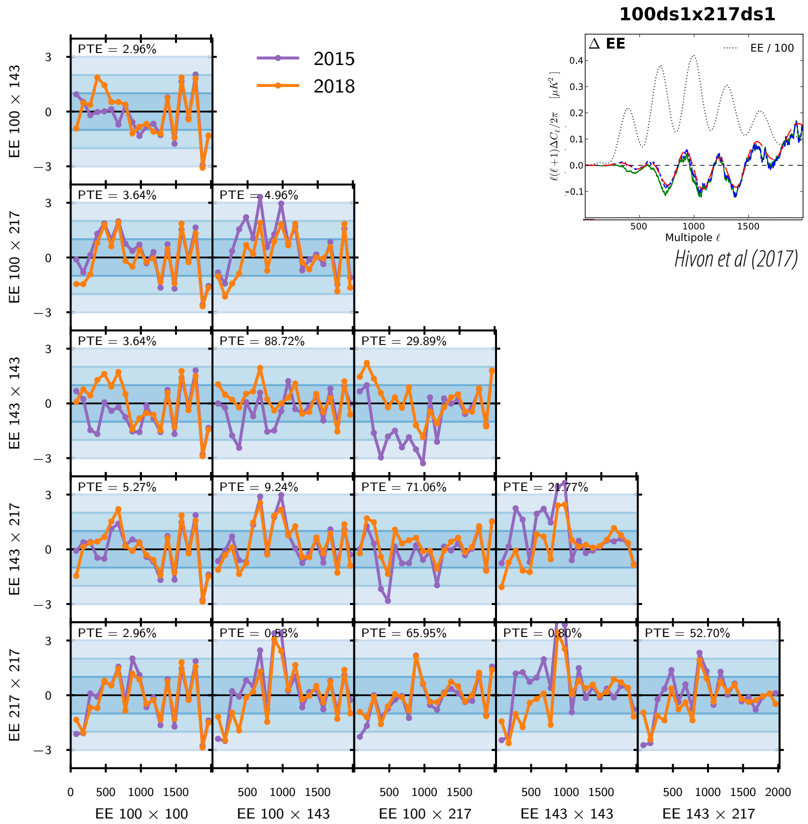
H_0

The road to Planck Legacy

- Main limitation of the 2015 release was the quality of the polarization data model, preventing us from using all of it at large and small scales
  - *2016 intermediate data analysis gave us insight on how to deal with the large scale residuals in HFI and improve tau constraints*
  - *Hivon et al (2017) proposed a model to account for beam leakage effects*
- 2018 release will be mainly about improving the polarisation data model
  - *improved data analysis, better characterisation and modelling of polarisation data, better simulations for LFI & HFI*
  - *Improvements and more robustness at low-ell, high-ell and lensing*

The road to Planck Legacy:
Polarisation at high-ell

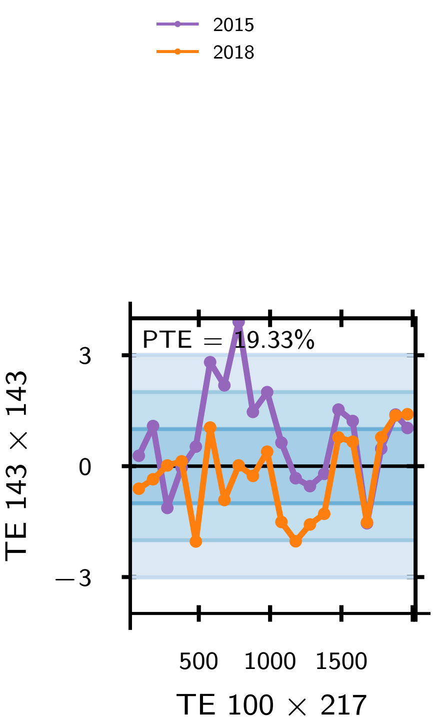


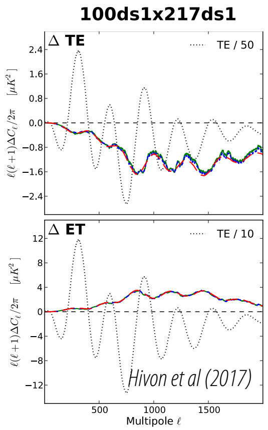


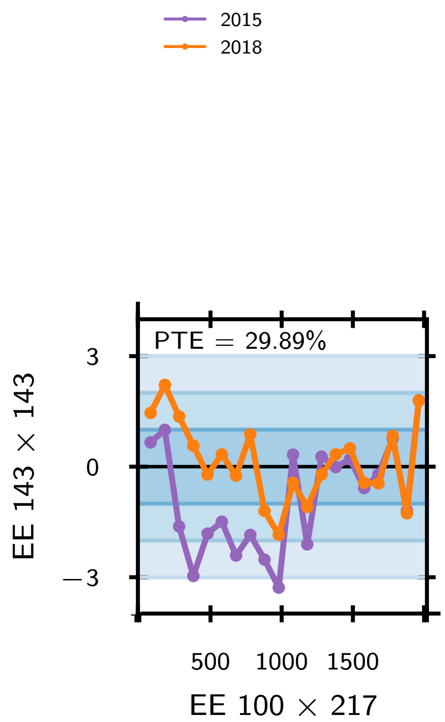
Much improved inter frequency agreement in TE and EE

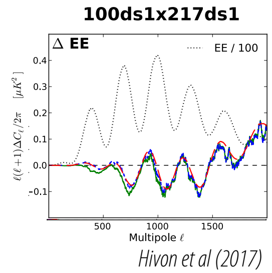
Better characterisation of the new E maps and application of Hivon et al (2017) beam leakage templates

The road to Planck Legacy:
Polarisation at high-ell









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  - *Improvements and more robustness at low-ell, high-ell and lensing*

Planck Legacy Cosmology is in general agreement with 2015+2016

Summary

- 2015 release based mainly on TT (for the cosmological parameters) provides excellent agreement with LambdaCDM
  - Some tension with sigma8/OmegaM (cluster counting, lensing)
  - Some tension between the low-ell and high-ell part of the spectrum (1.8sigma) and feature that project toward extra smoothing of the peaks (2.2sigma)
- Road to Legacy release
  - Improved low-ell HFI polarization (and expand on the LFI data, only 2 survey used for 2015)
  - Improving the high-ell Polarization (beam leakages)