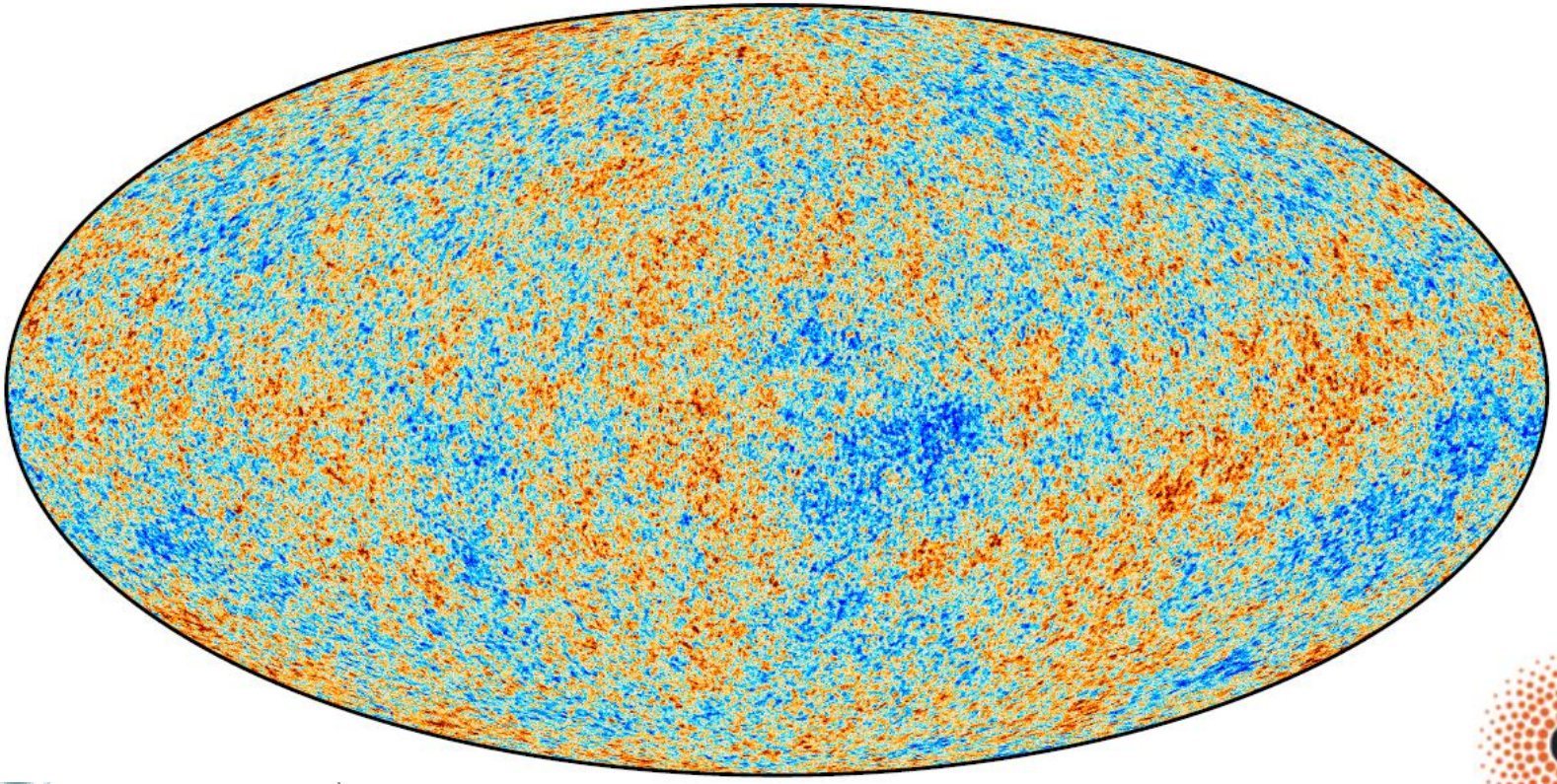
Planck 2015 parameter constraints

Antony Lewis

On behalf of the Planck Collaboration

http://cosmologist.info/



University of Sussex

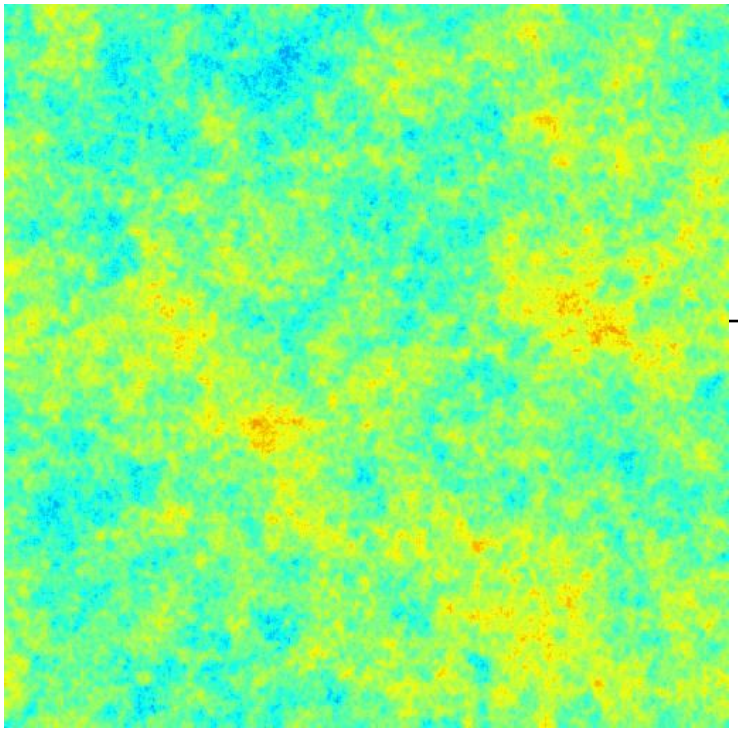
European Research Council

Established by the European Commission

Supporting top researchers from anywhere in the world

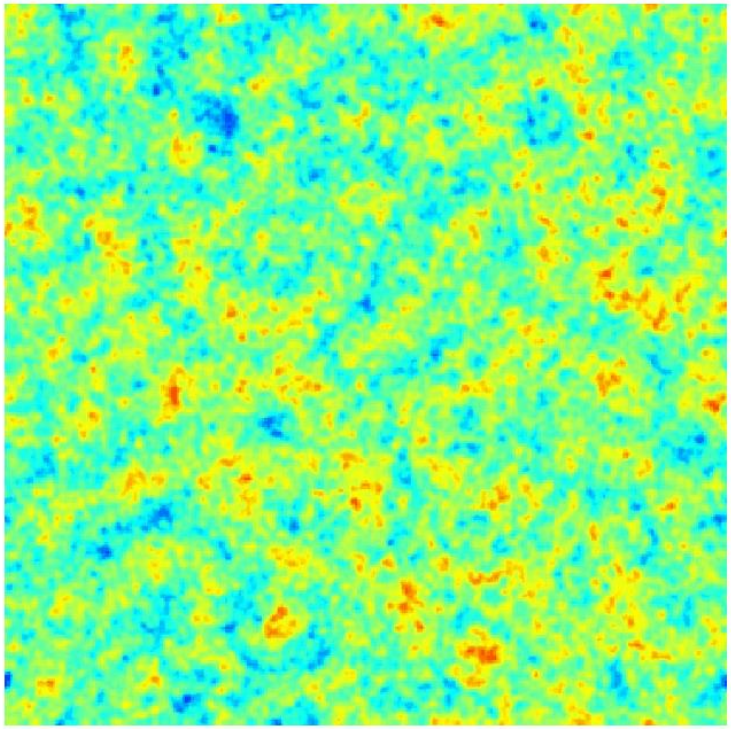
CMB temperature

End of inflation

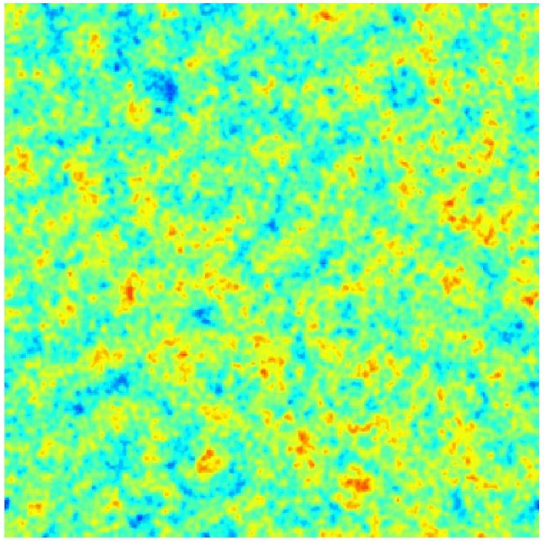


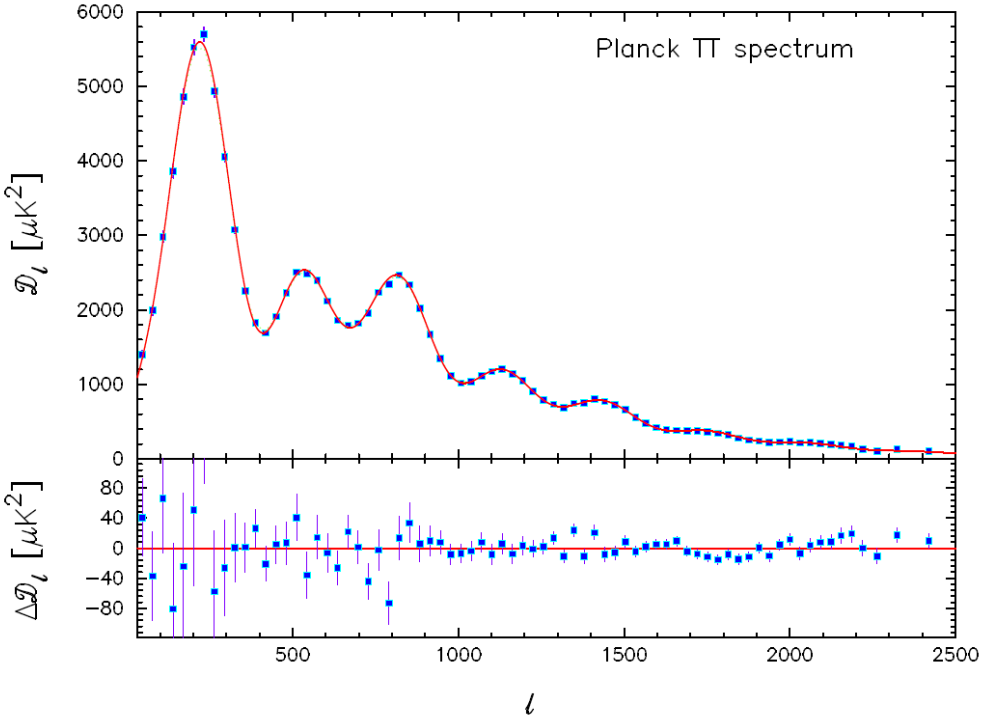
gravity+
pressure+
diffusion

Last scattering surface



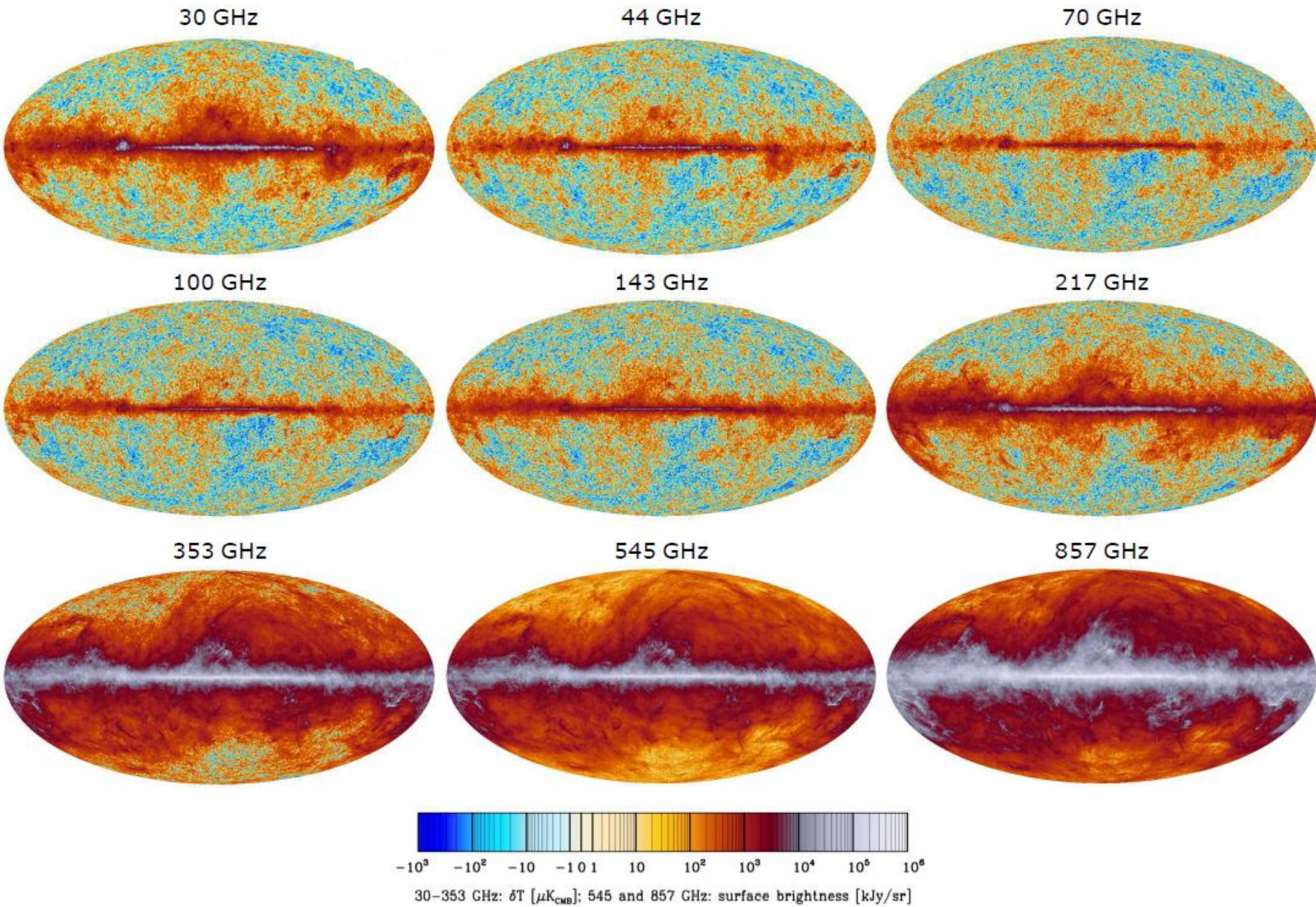
Observed CMB blackbody power spectrum

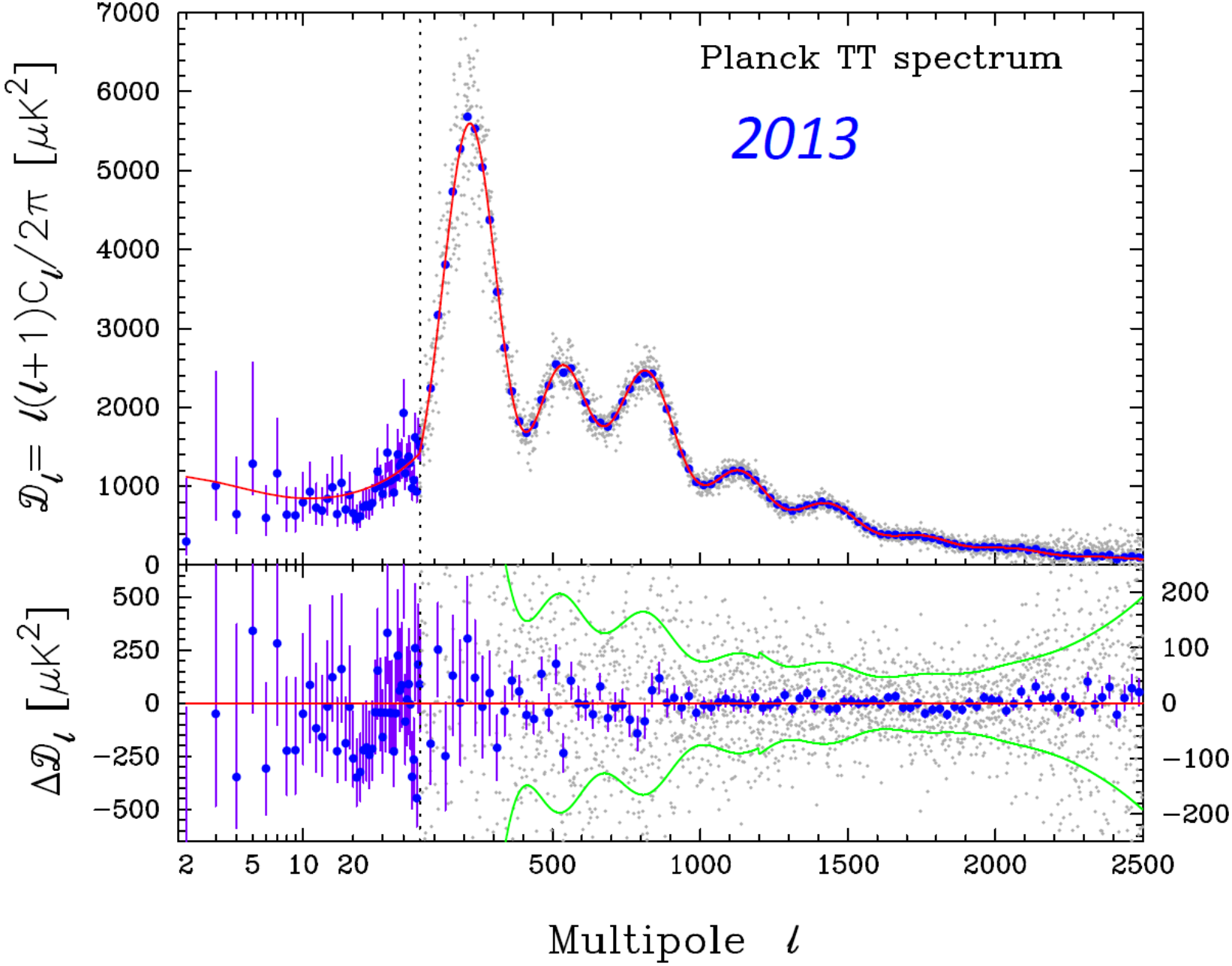


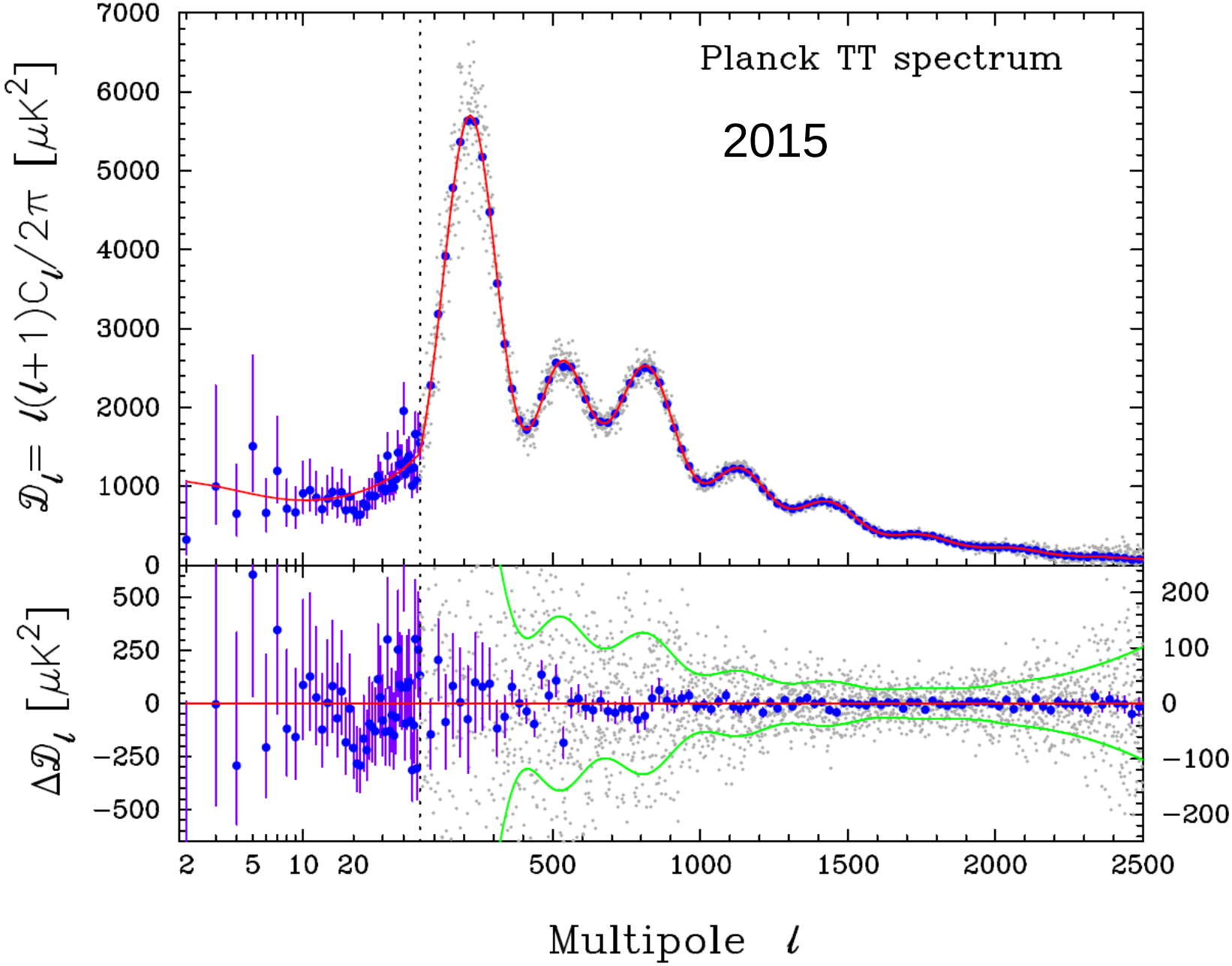


Observations

Constrain theory of early universe
+ evolution parameters and geometry


30 GHz
44 GHz
70 GHz
100 GHz
143 GHz
217 GHz
353 GHz
545 GHz
857 GHz
-10^3 -10^2 -10 -1 0 1 10 10^2 10^3 10^4 10^5 10^6
30–353 GHz: δT [μK_{CMB}]; 545 and 857 GHz: surface brightness [kJy/sr]


Planck TT spectrum
2013
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
$\Delta\mathcal{D}_\ell\ [\mu K^2]$
Multipole ℓ
7000
6000
5000
4000
3000
2000
1000
0
500
250
0
−250
−500
200
100
0
−100
−200
2
5
10
20
500
1000
1500
2000
2500


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

Main changes in TT analysis:

- Full mission data (2 → 5 sky surveys): *lower noise*
- Larger sky fractions (100Ghz 66.3%,143Ghz 57.4%, 217Ghz 47.1%): *lower cosmic variance*
- Cross Half-Mission (CHM) rather than cross detector sets (DS): *avoids correlated noise at high L*
- More detailed dust modelling, weak foreground priors rather than +ACT/SPT
- LFI low-L polarization (lowP) rather than WMAP: *prefers lower optical depth* τ
- Corrected calibration (now agrees with WMAP)
- 4K cooler line systematic (mostly) removed (removes L~1800 feature)
- Bug fixes and numerous analysis changes (new beams, etc.)
- Binned Plik likelihood rather than unbinned CamSpec
- Many new internal consistency checks

Nominal
(2 sky surveys)

Full mission
(5 sky surveys)

2013 maps

2015 maps

2013 TT
+ WP

det. sets
+ larger $f_{\rm sky}$
+ WP

cross-year
+ larger $f_{\rm sky}$
+ WP

cross-HM
+ larger $f_{\rm sky}$
+ lowP

cross-HM
+ larger $f_{\rm sky}$
+ lowP

[1] Parameter	[2] 2013N(DS)	[3] 2013F(DS)	[4] 2013F(CY)	[5] 2015F(CHM)	[6] 2015F(CHM) (Plik)	$([2]-[6])/\sigma_{[6]}$	$([5]-[6])/\sigma_{[5]}$
$100\theta_{\rm MC}$	1.04131 ± 0.00063	1.04126 ± 0.00047	1.04121 ± 0.00048	1.04094 ± 0.00048	1.04086 ± 0.00048	0.71	0.17
$\Omega_b h^2$	0.02205 ± 0.00028	0.02234 ± 0.00023	0.02230 ± 0.00023	0.02225 ± 0.00023	0.02222 ± 0.00023	−0.61	0.13
$\Omega_c h^2$	0.1199 ± 0.0027	0.1189 ± 0.0022	0.1188 ± 0.0022	0.1194 ± 0.0022	0.1199 ± 0.0022	0.00	−0.23
H_0	67.3 ± 1.2	67.8 ± 1.0	67.8 ± 1.0	67.48 ± 0.98	67.26 ± 0.98	0.03	0.22
n_s	0.9603 ± 0.0073	0.9665 ± 0.0062	0.9655 ± 0.0062	0.9682 ± 0.0062	0.9652 ± 0.0062	−0.67	0.48
$\Omega_{\rm m}$	0.315 ± 0.017	0.308 ± 0.013	0.308 ± 0.013	0.313 ± 0.013	0.316 ± 0.014	−0.06	−0.23
σ_8	0.829 ± 0.012	0.831 ± 0.011	0.828 ± 0.012	0.829 ± 0.015	0.830 ± 0.015	−0.08	−0.07
τ	0.089 ± 0.013	0.096 ± 0.013	0.094 ± 0.013	0.079 ± 0.019	0.078 ± 0.019	0.85	0.05
$10^9 A_s e^{-2\tau}$	1.836 ± 0.013	1.833 ± 0.011	1.831 ± 0.011	1.875 ± 0.014	1.881 ± 0.014	−3.46	−0.42

CamSpec

Plik

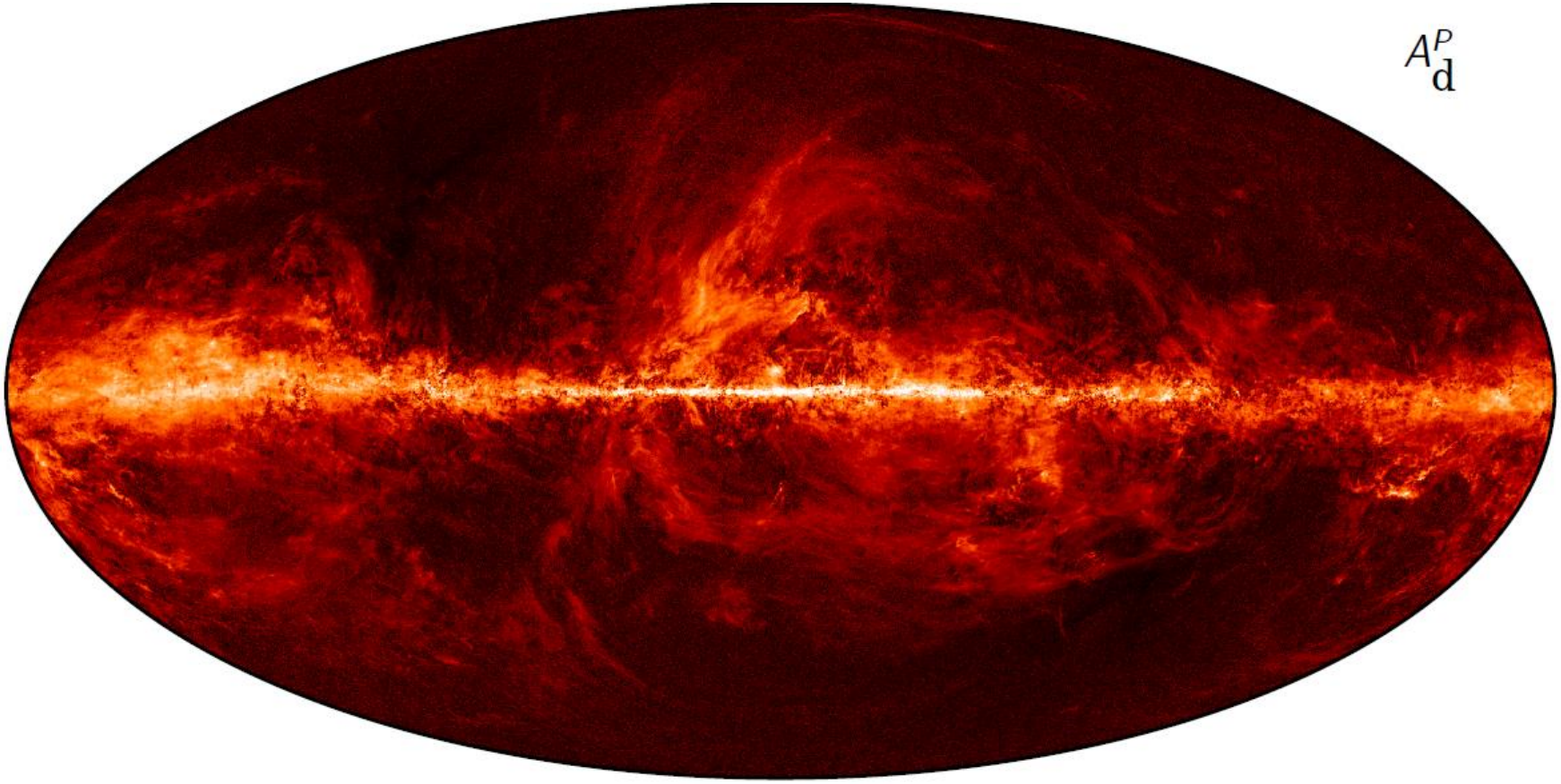
Cosmic-variance/noise
- mainly statistical shift

Mainly non-statistical shifts

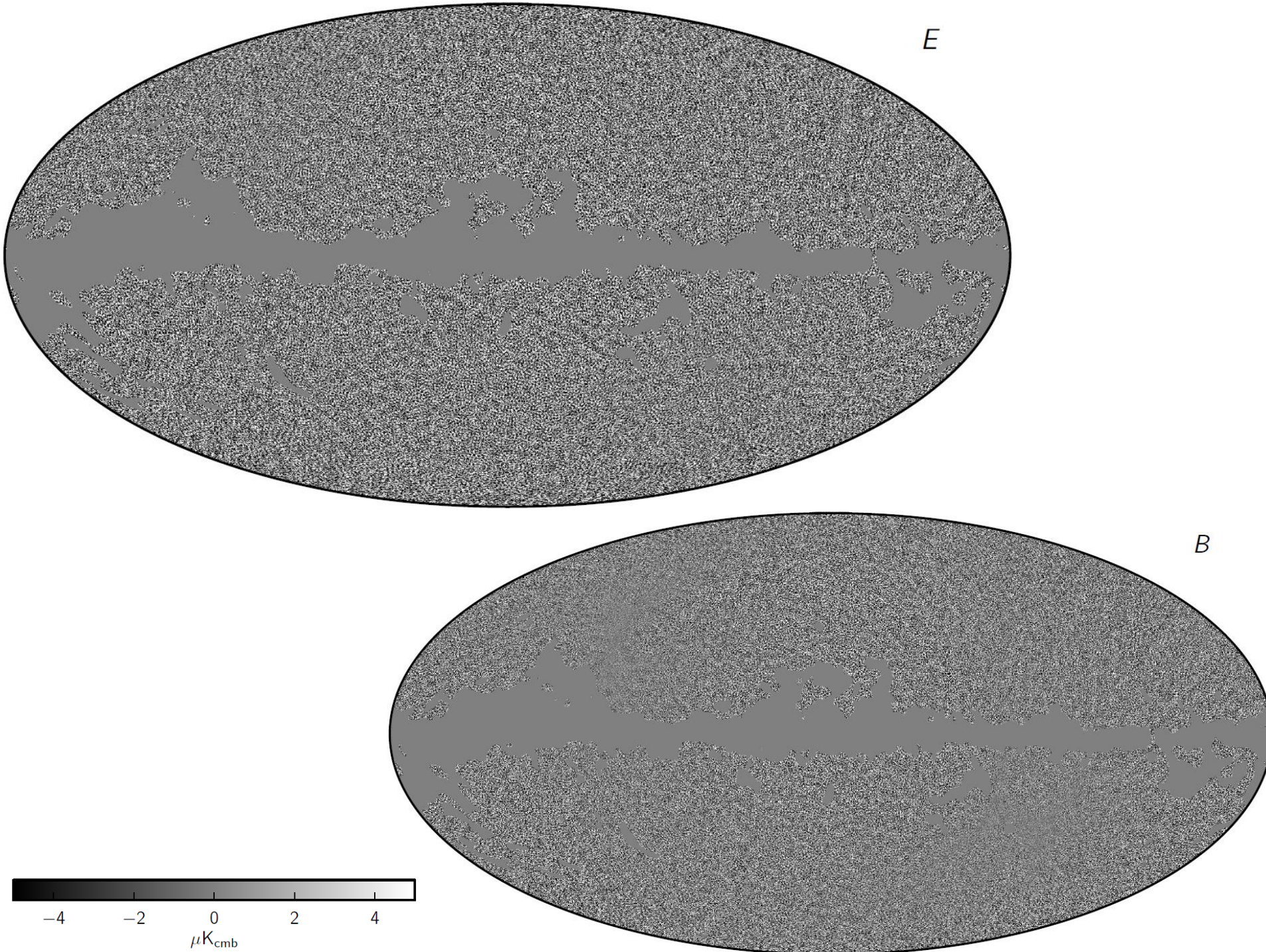
Notes: * Consistency between likelihoods at 0.5σ level for TT

* 2015 calibration change moves C_l (hence also $A_s e^{-2\tau}$) up by $\sim 2\%$
Switching WP to lowP (LFI) shifts τ down by $\sim 10\% \Rightarrow e^{-2\tau}$ shifts up by $\sim 2\%$
$\Rightarrow$ little change to inferred amplitudes A_s and σ_8

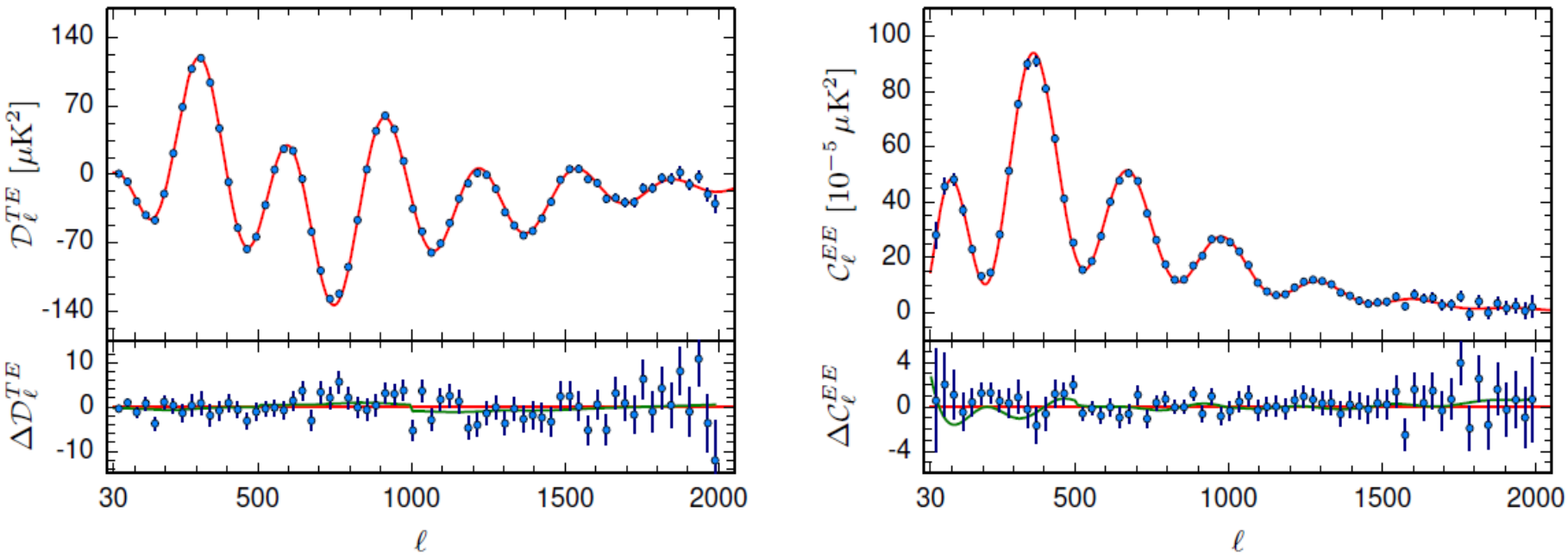
New for 2015: Polarization



Dust polarization amplitude

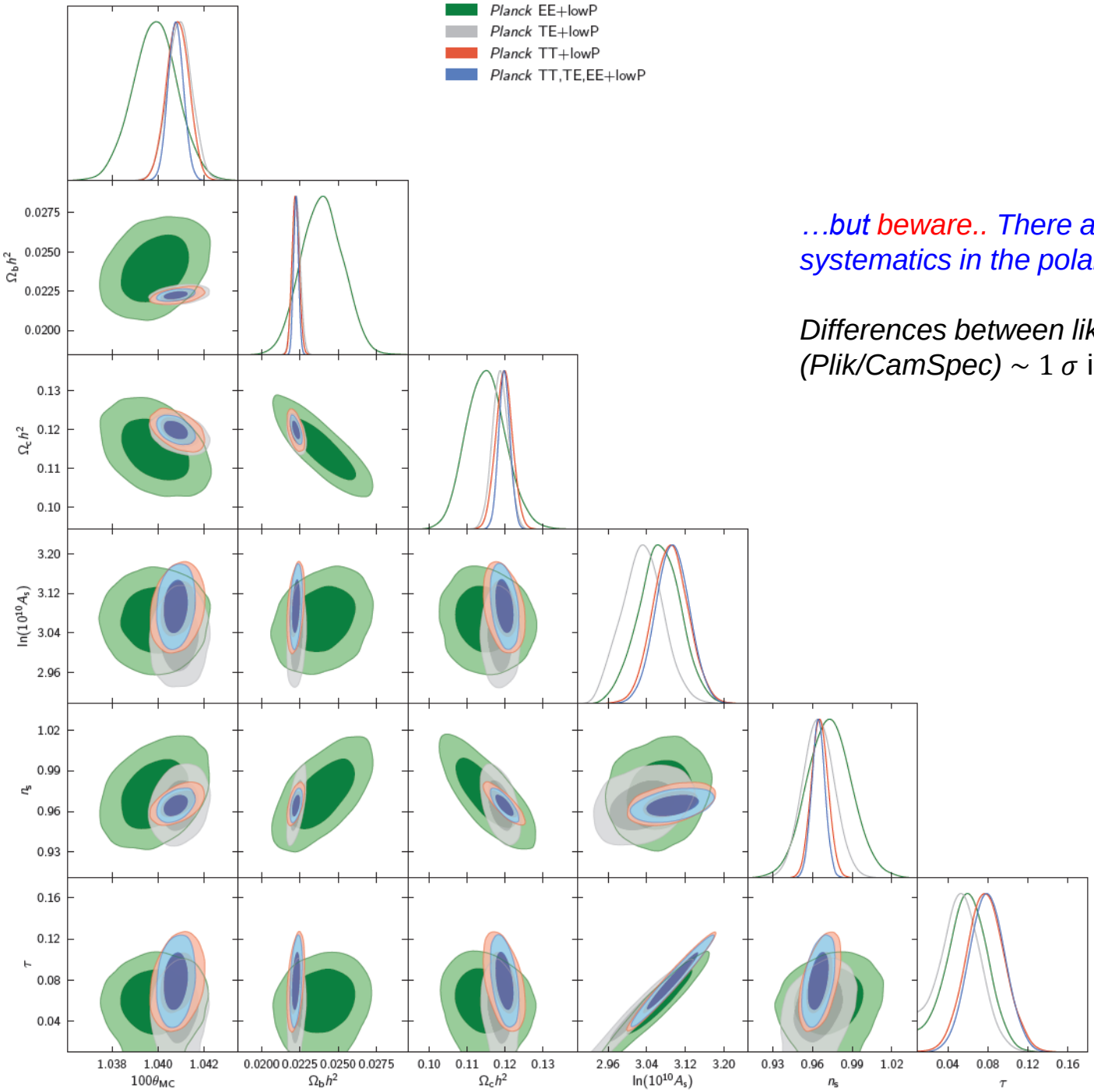

E
B
−4
−2
0
2
4
μK_cmb

CMB E-mode polarization spectra



- Visually very good fit to prediction from TT best fit
- Evidence for small T-E leakage

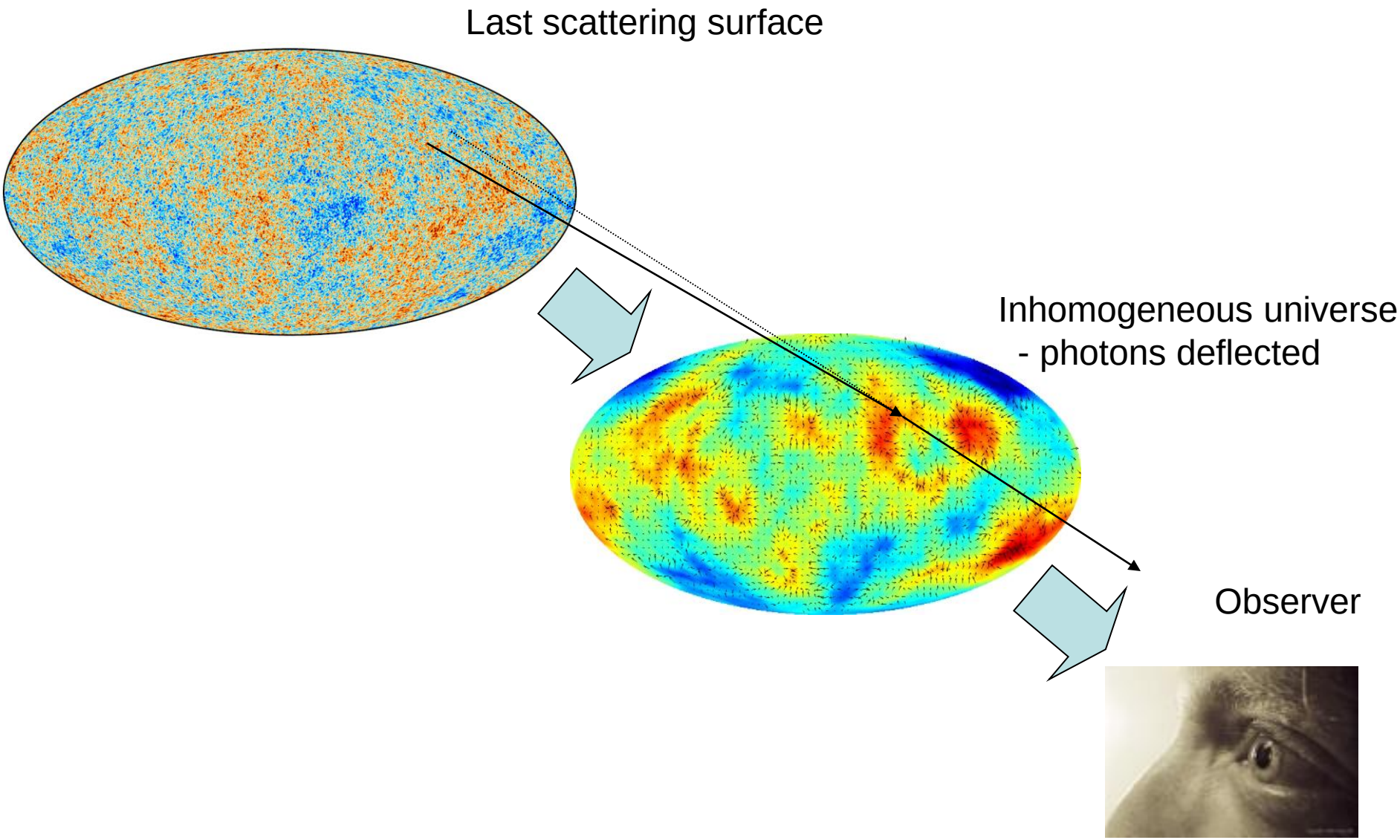
Base LCDM

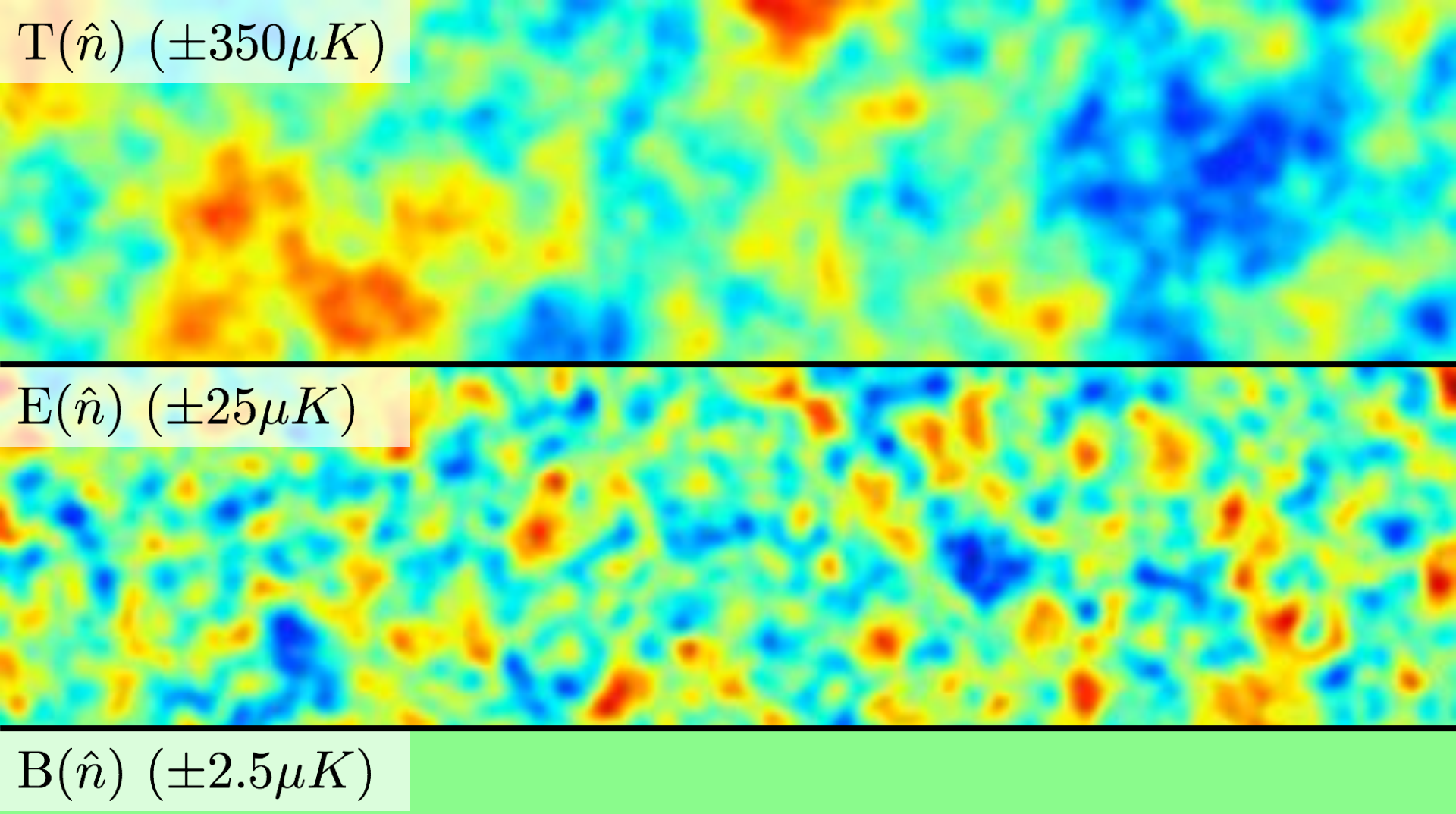


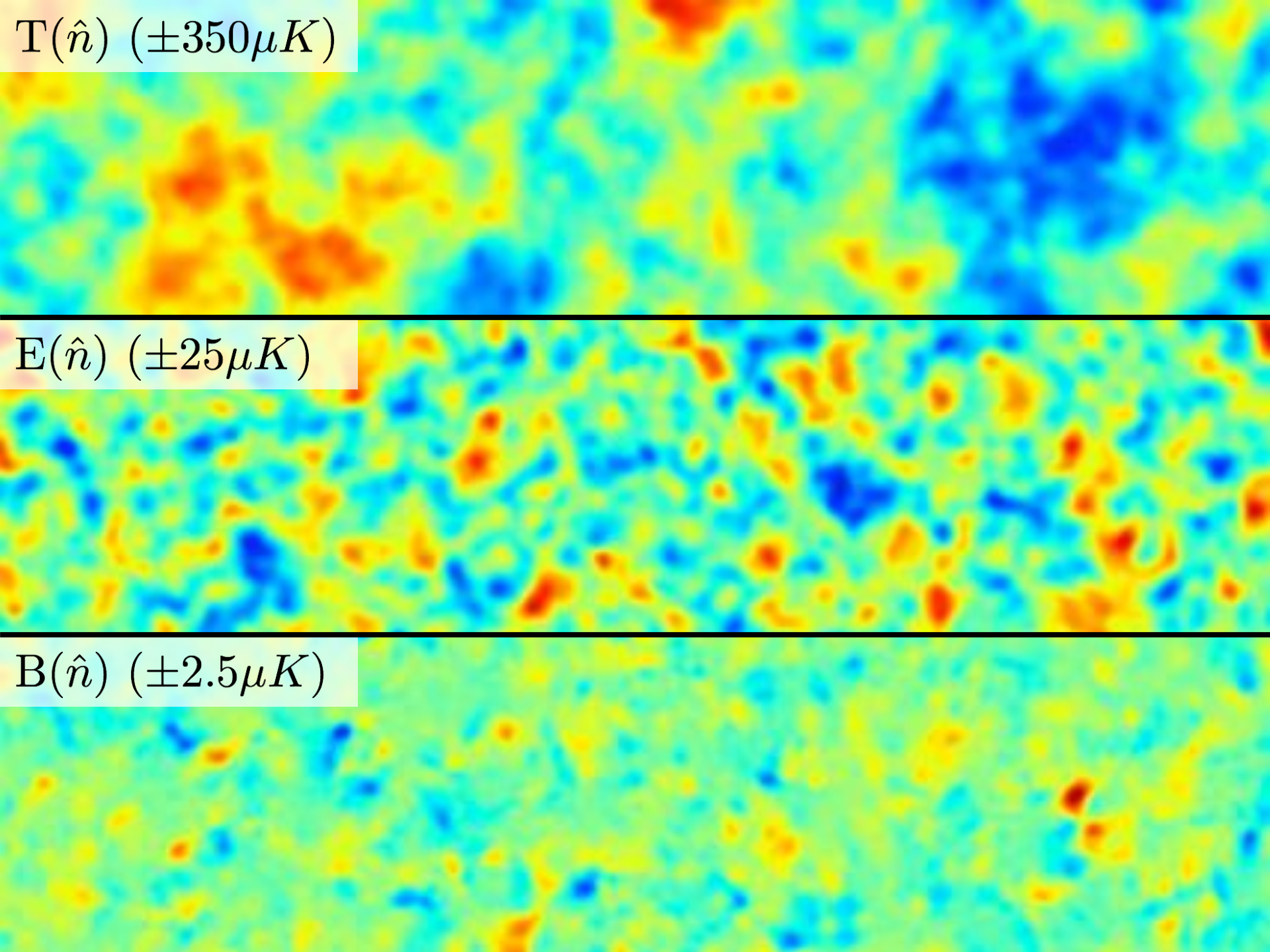
…but beware.. There are still low level systematics in the polarization spectra.

Differences between likelihood implementations (Plik/CamSpec) $\sim 1\,\sigma$ in some extended models

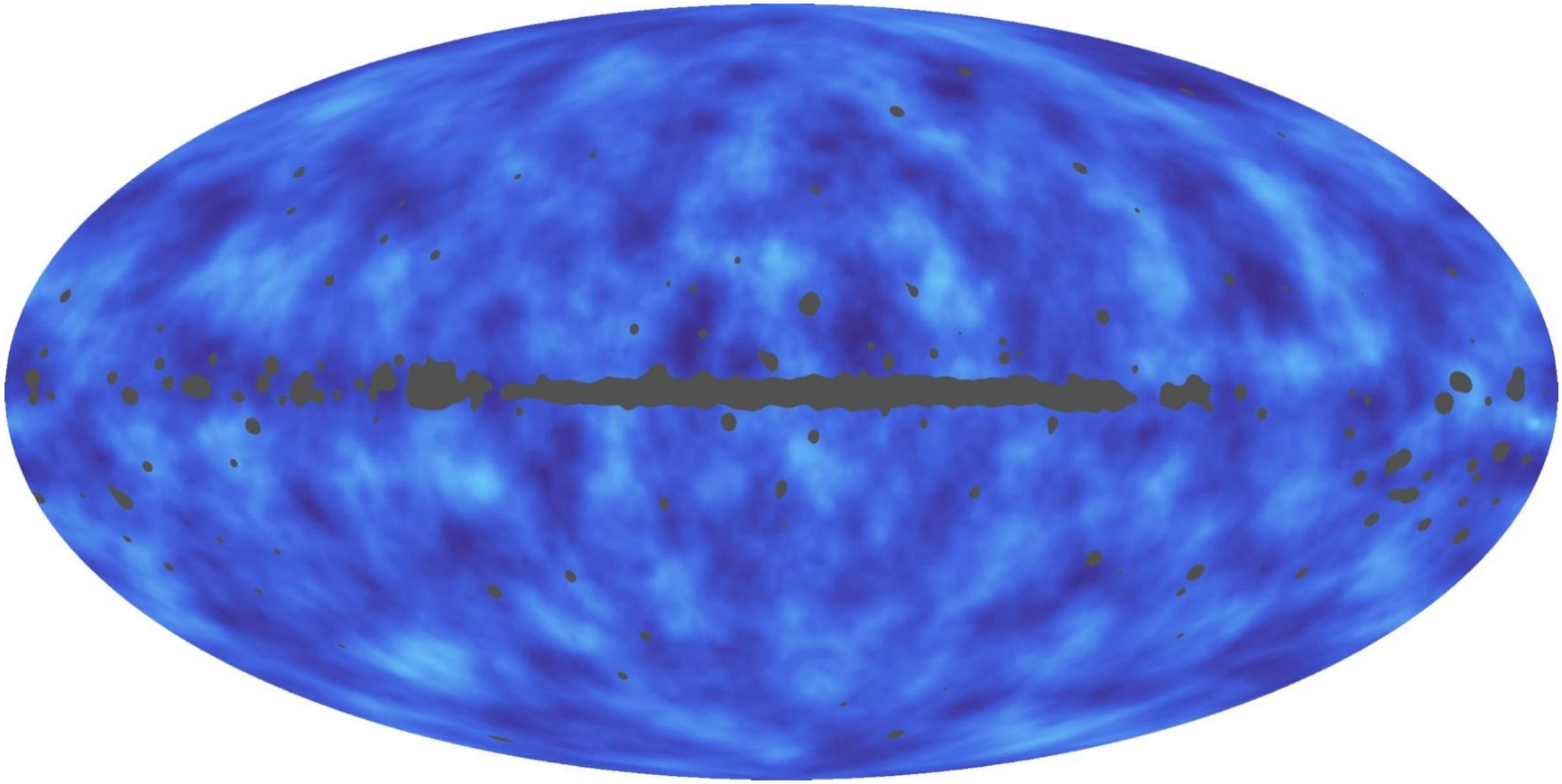
CMB Lensing


Last scattering surface
Inhomogeneous universe
- photons deflected
Observer


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


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

Planck CMB Lensing Reconstruction



Lensing Reconstruction Improvements over 2013

★ Error bars reduced by nearly a factor of 2x.

- Twice as much temperature data + all-new polarization data.

★ Full set of lensing estimators (TT, TE, EE, EB, TB) + All combined (MV)

- Crosses give 15 possible lensing power spectrum estimators.

★ SMICA component-separated maps as baseline, on 67.3% sky.

★ Numerous analysis improvements.

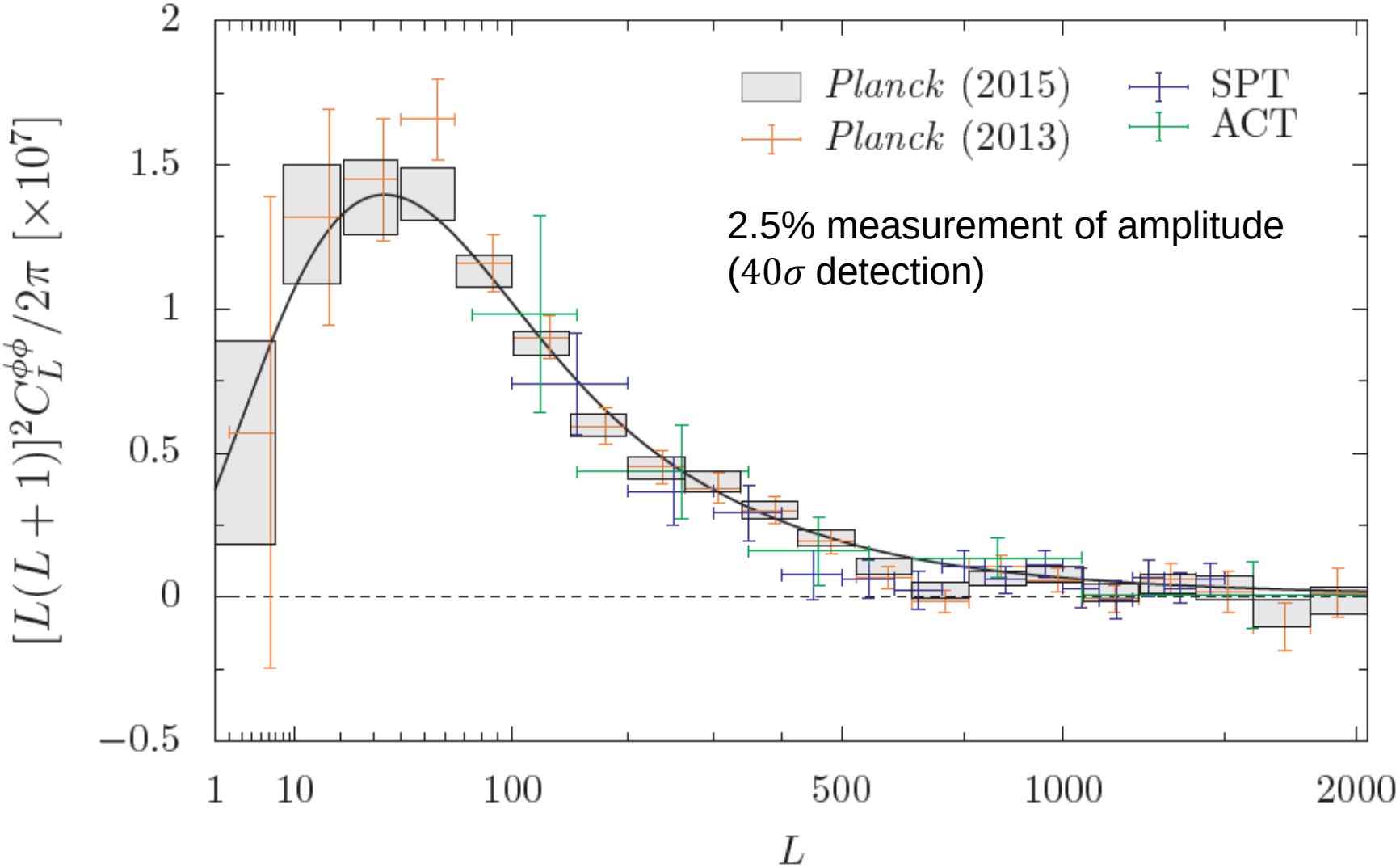
- Improved likelihood ($N^{(1)}$ theory dependence, faster)

- Many new consistency and null tests:

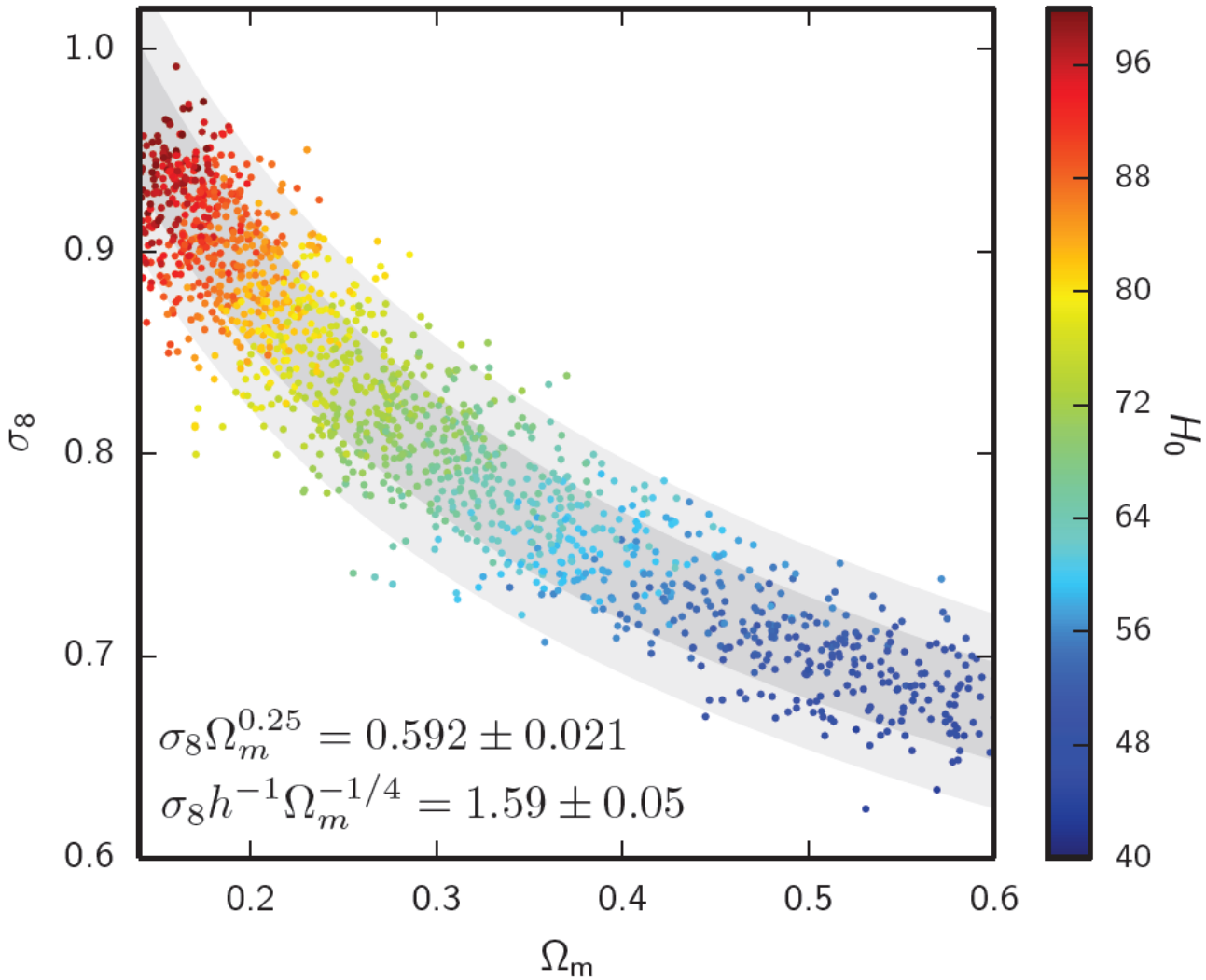
Internal consistency of polarization and temperature estimator pairs.

Half-mission nulls and crosses

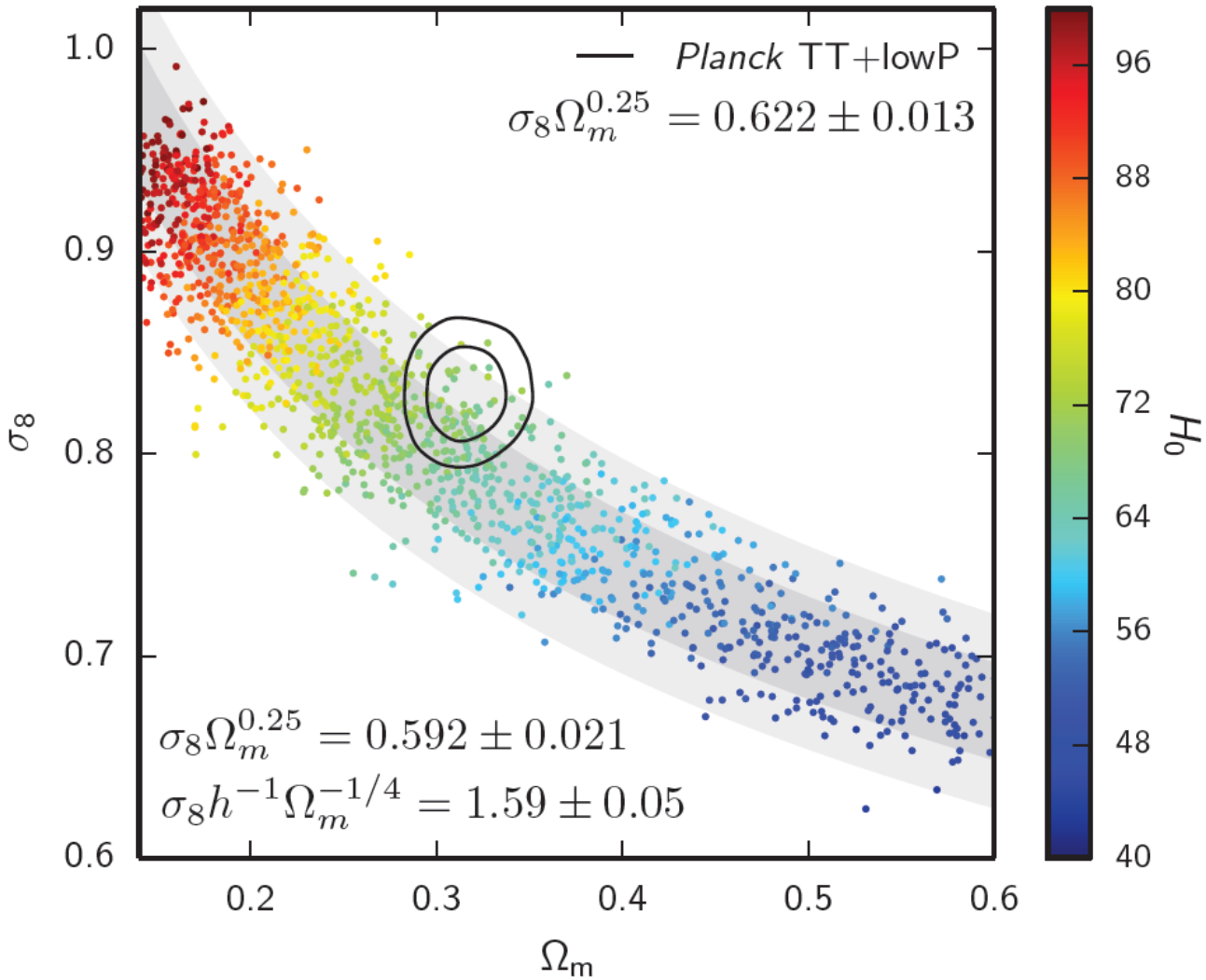
Lensing Power Spectrum



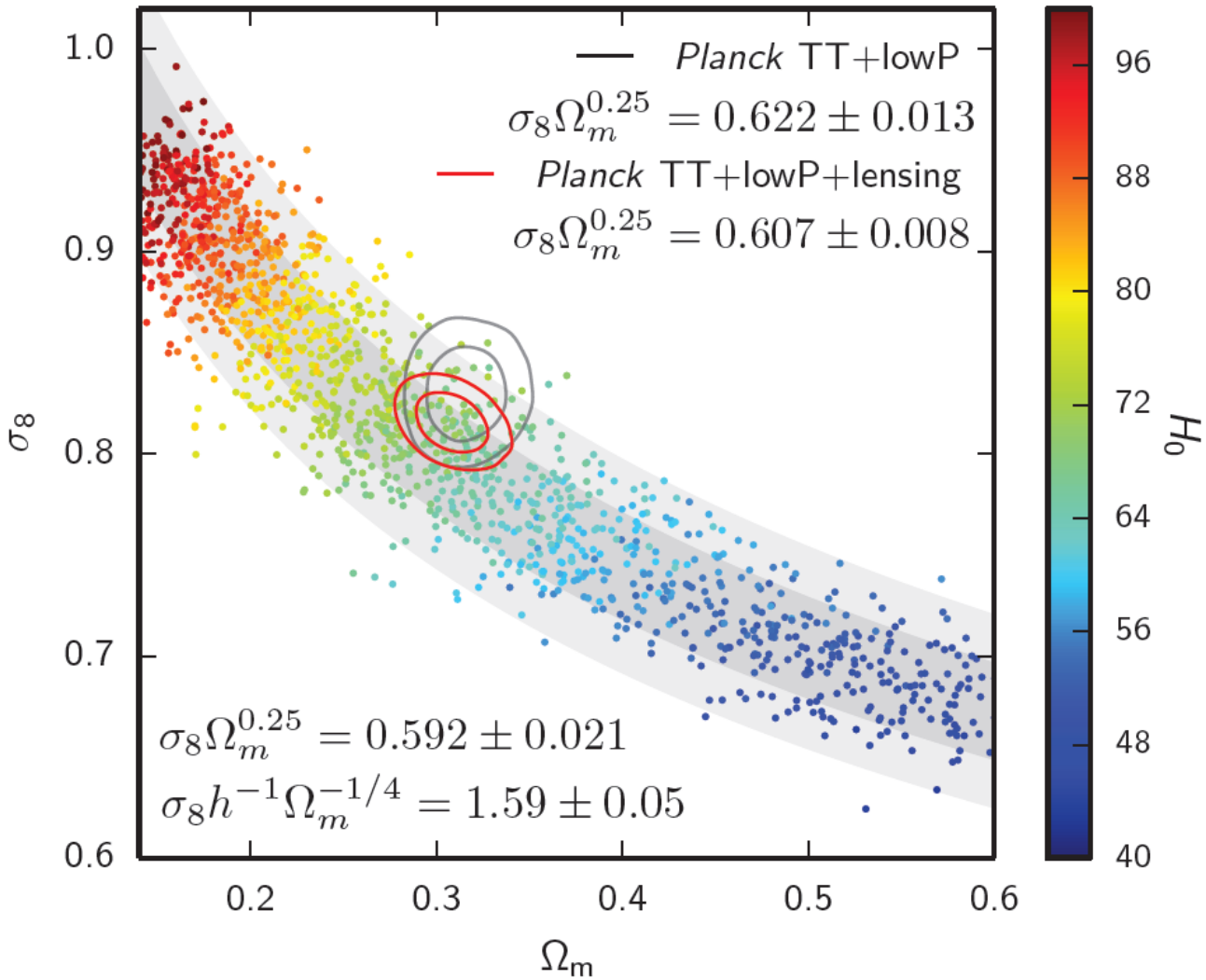
LCDM Parameter Constraints from CMB Lensing Only



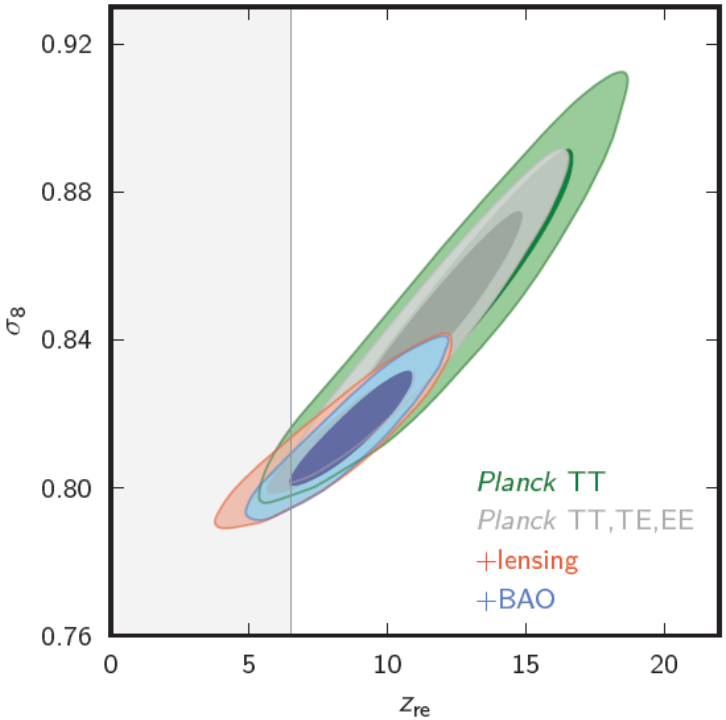
LCDM Parameter Constraints from CMB Lensing Only

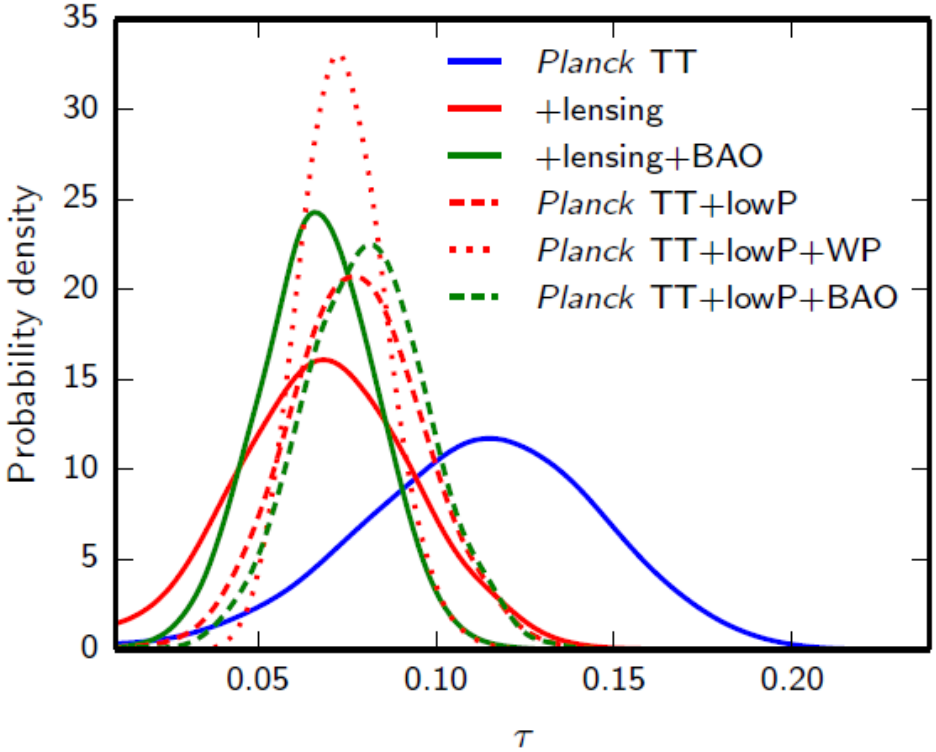


LCDM Parameter Constraints from CMB Lensing Only



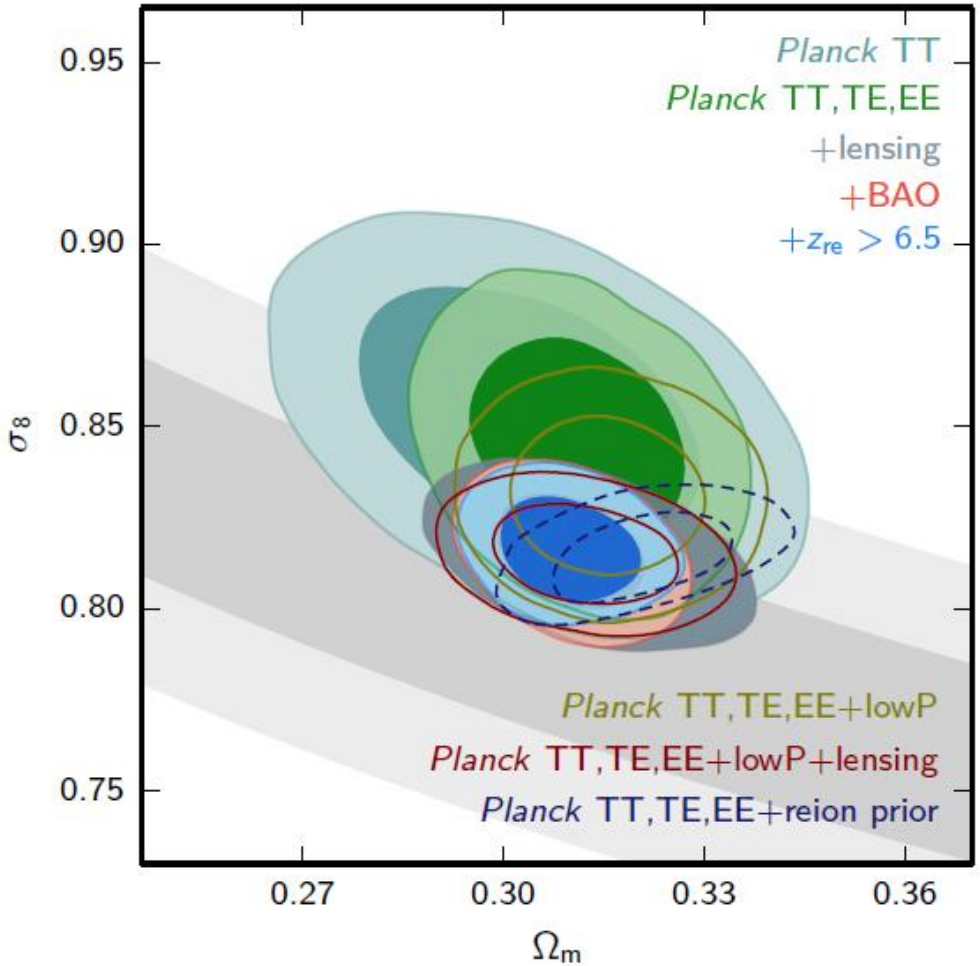
Optical Depth Constraints





... are consistent with low-L polarization.

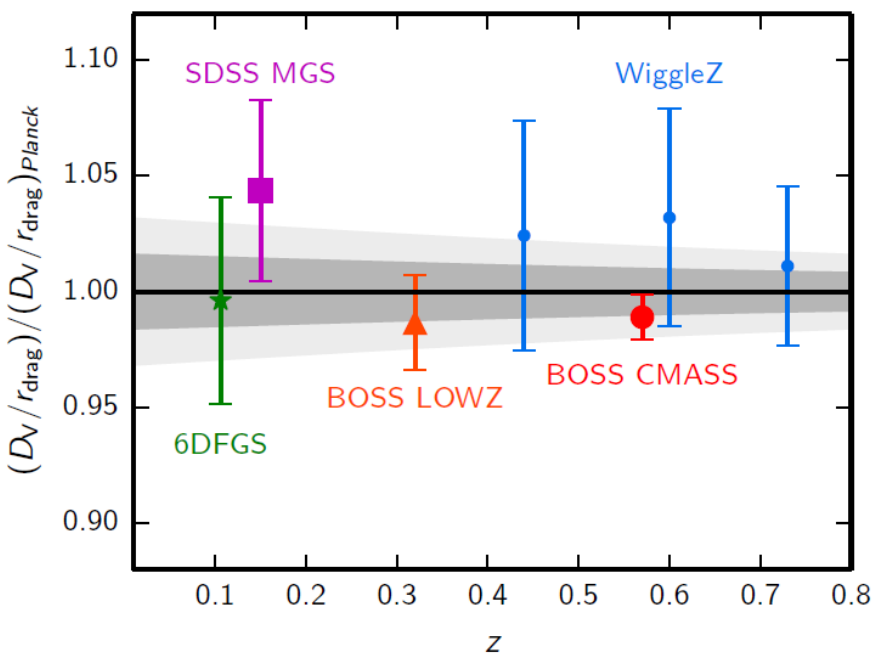
Planck σ_8 in the base LCDM model

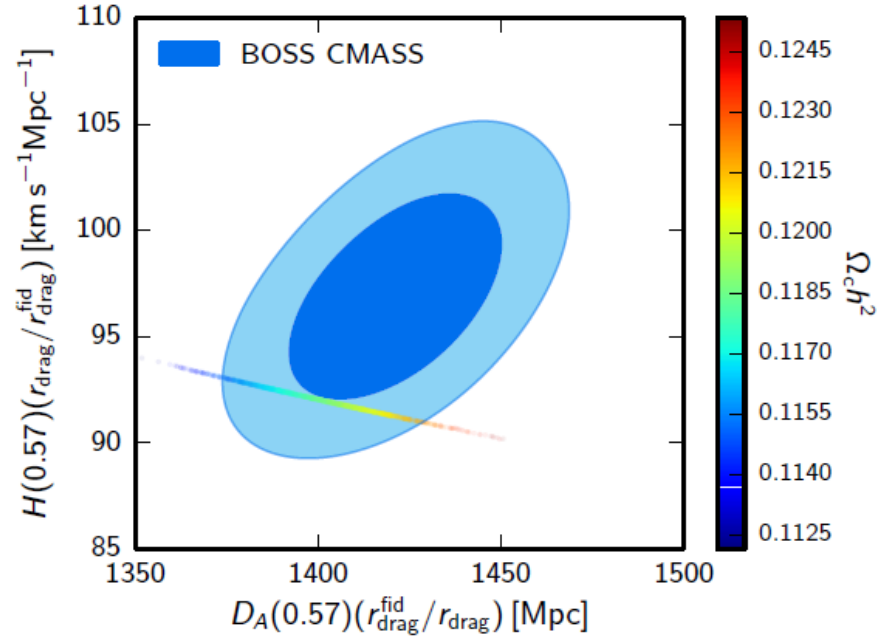


Only consistent with $\sigma_8 > 0.8$

Are Planck power spectrum likelihoods consistent with other data in the base LCDM model?

Baryon Oscillations (BAO)





$z < 1$ BAO consistent in LCDM ✓
(adding BAO improves constraints)

But BOSS $z \sim 2.34$ Ly$-\alpha$ discrepant by $\sim 2.7\,\sigma$ ✗
(Delubac et al, Font-Ribera et al 2014)

Hubble parameter

Planck+lensing: (67.8 ± 0.9)km s^{-1} Mpc^{-1}

Riess et al 2011:

$$H_0 = (73.8 \pm 2.4) \text{ km } s^{-1} \text{ Mpc}^{-1}$$ ✗

Humphreys et al 2013, Efstathiou 2013

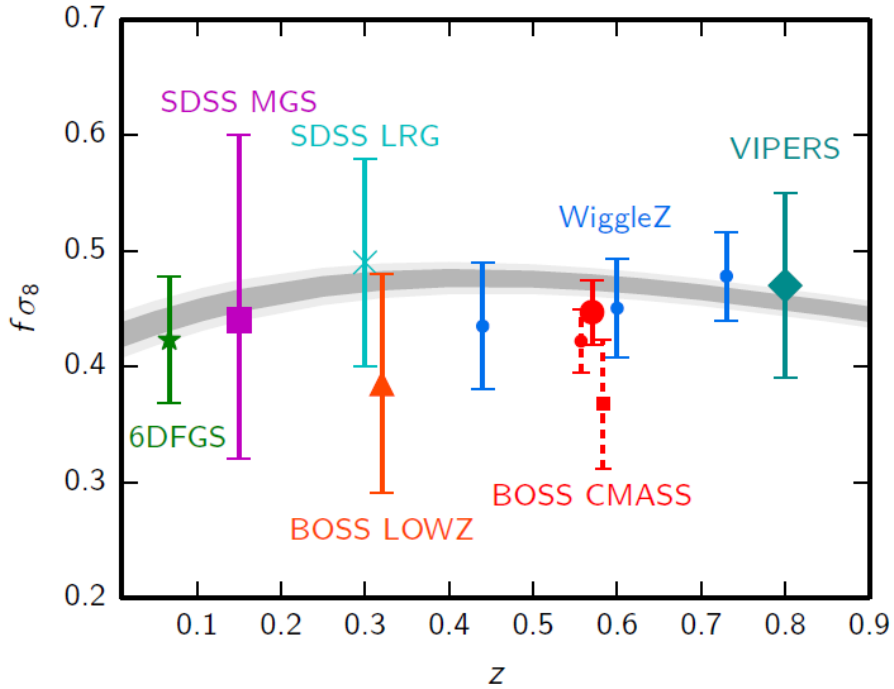
$$H_0 = 70.6 \pm 3.3 \ \text{ km s}^{-1}\text{Mpc}^{-1}, \qquad \text{NGC 4258,}$$ ✓

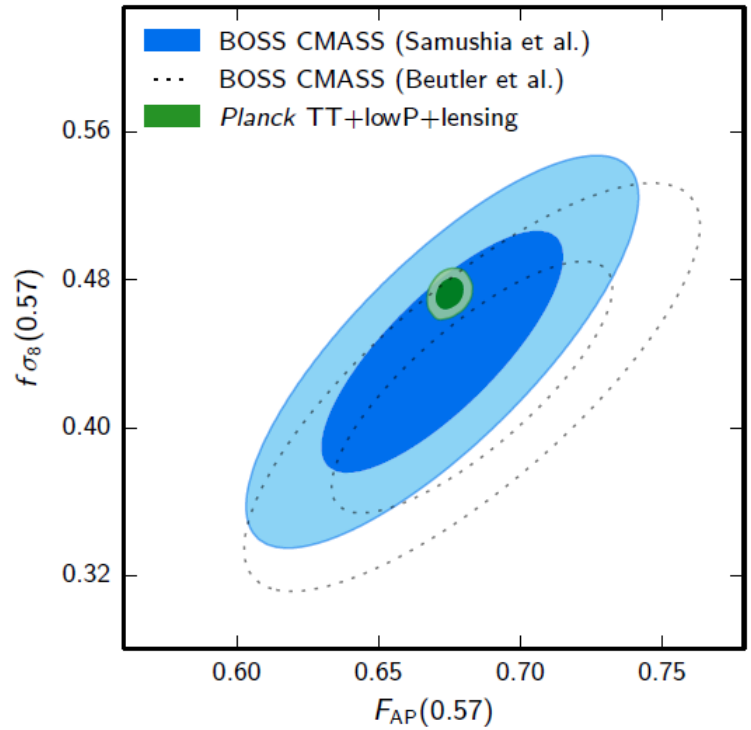
Rigault et al. 2014

$$H_0 = 68.8 \pm 3.3 \text{ km s}^{-1}\text{Mpc}^{-1}$$ ✓

$$H_0 = 69.7 \pm 2.1 \ \text{ km s}^{-1}\text{Mpc}^{-1}, \qquad \text{WMAP9,}$$
$$H_0 = 68.0 \pm 0.7 \ \text{ km s}^{-1}\text{Mpc}^{-1}, \qquad \text{WMAP9+BAO.}$$ ✓

Redshift distortions/growth

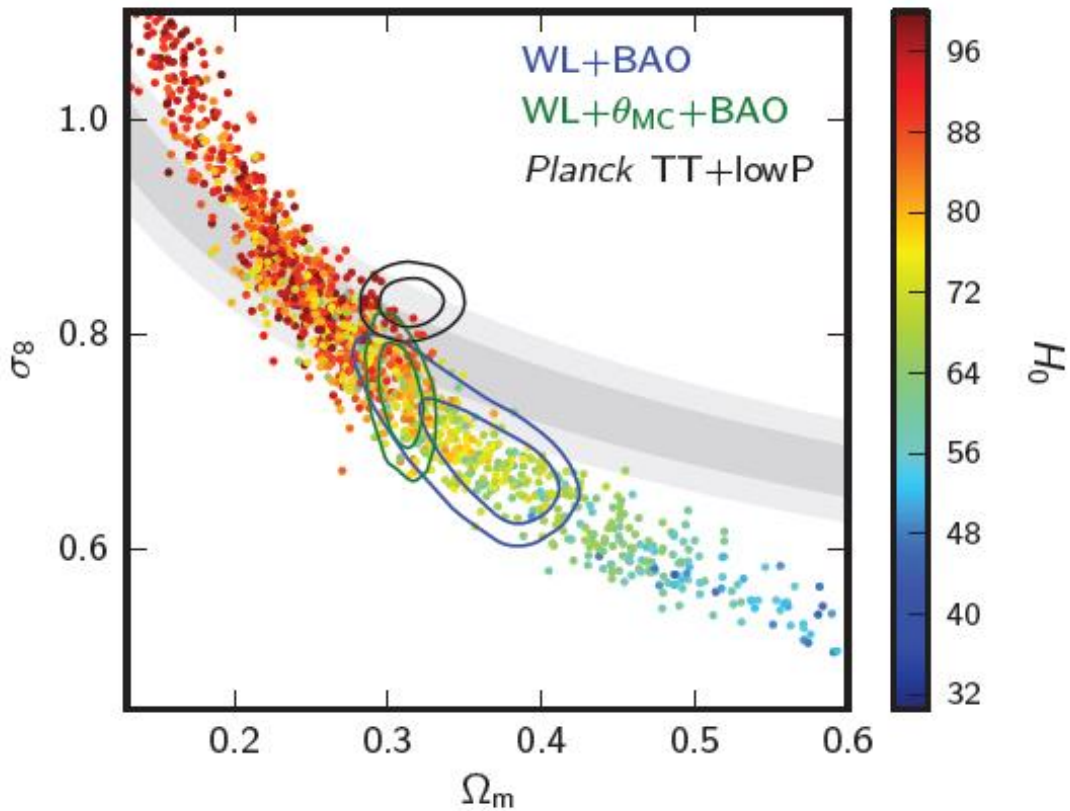




Looks quite consistent? ✓

BOSS variants: solid – Samushia et al; dashed - Chuang, Beutler et al.

Galaxy weak gravitational lensing



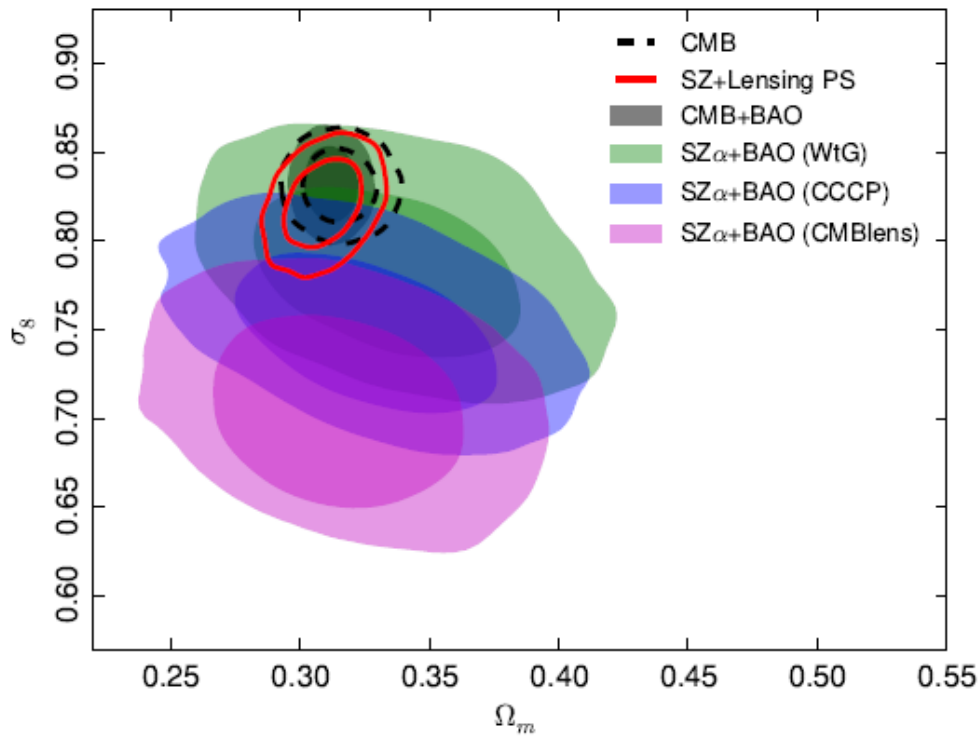
WL prefer higher H_0 or lower σ_8 ✗

WL: Heymans et al. 2013

Clusters etc.

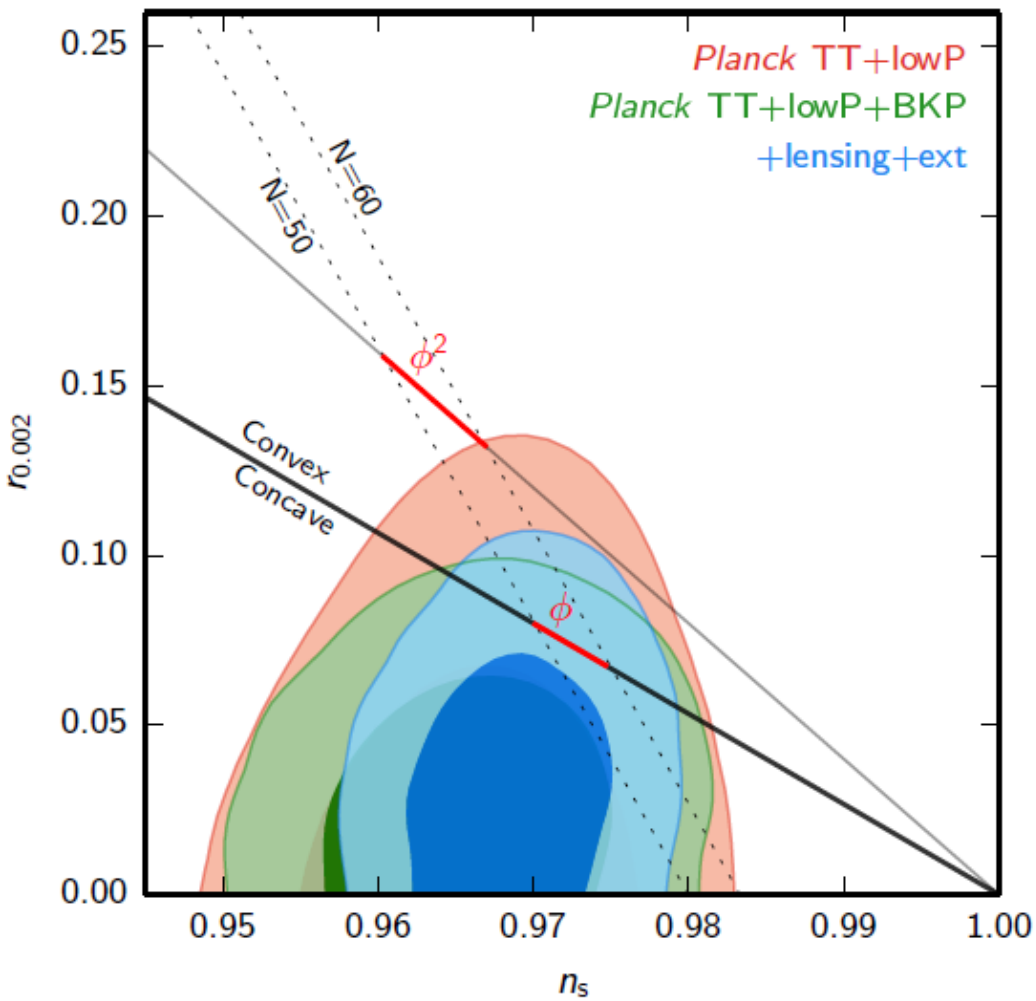
- Complicated physics and selection effects… mass calibration etc.

Some analyses prefer lower σ_8, some OK – needs more work.



?

Beyond the base LCDM model



Base LCDM + tensors:

$r_{0.002} < 0.10$, *Planck* TT+lowP,
$r_{0.002} < 0.11$, *Planck* TT+lowP+lensing+ext,

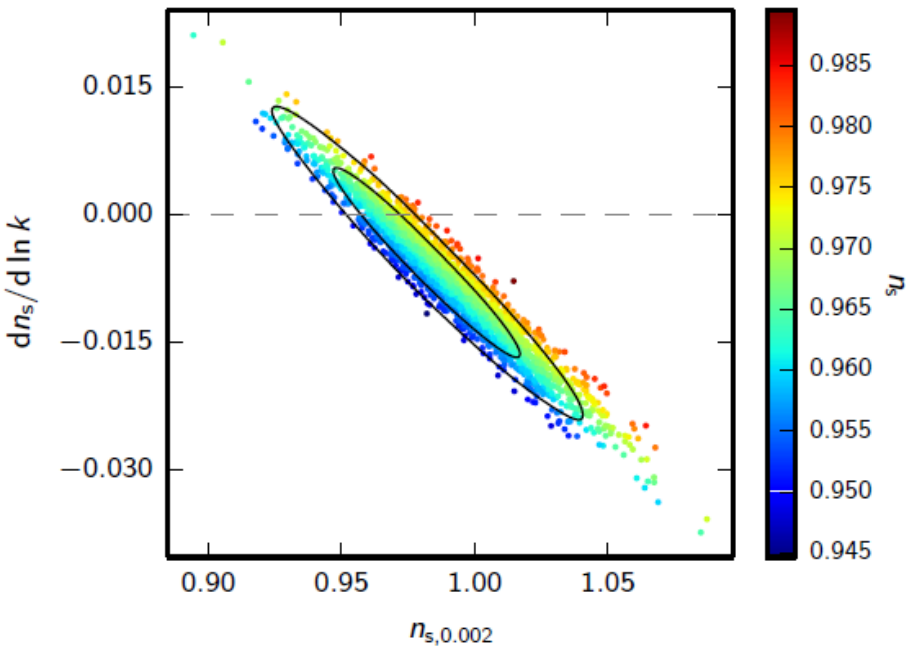
Planck + BICEP2/Keck/Planck (BKP)

$r_{0.002} < 0.08$, *Planck* TT+lowP+BKP,
$r_{0.002} < 0.09$, *Planck* TT+lowP+lensing+ext+BKP

Reminder: result is model dependent

+BKP result also depends on dust model

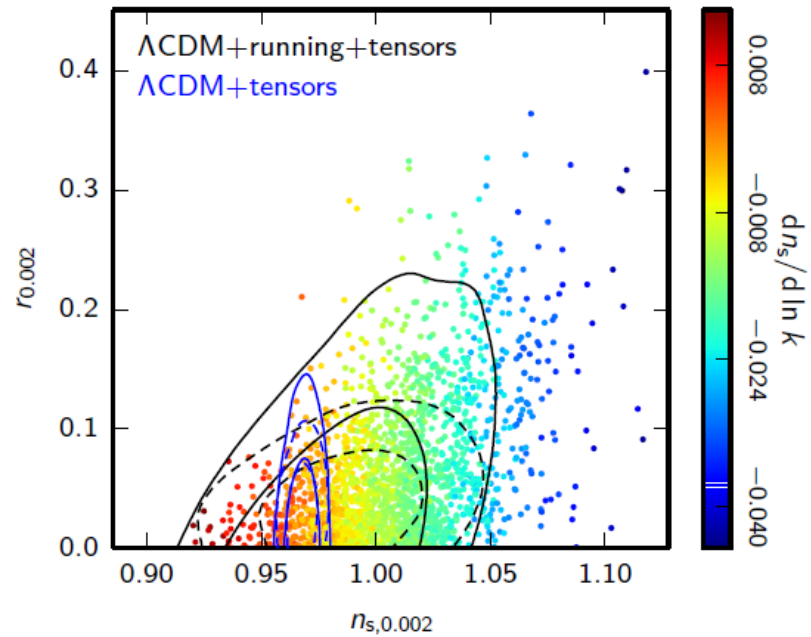
Base LCDM + running



$$\frac{dn_s}{d\ln k} = -0.0084 \pm 0.0082, \quad \textit{Planck}\ \text{TT+lowP},$$

$$\frac{dn_s}{d\ln k} = -0.0057 \pm 0.0071, \quad \textit{Planck}\ \text{TT, TE, EE+lowP}$$

Base LCDM + running + tensors

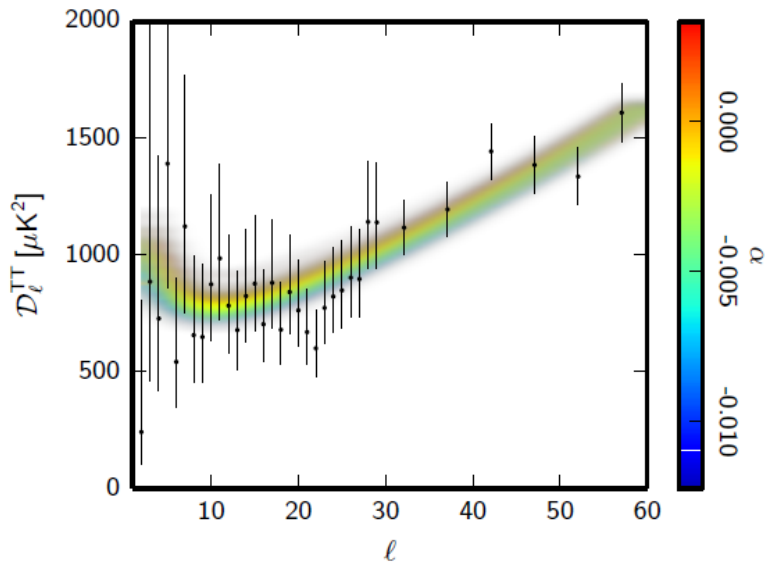


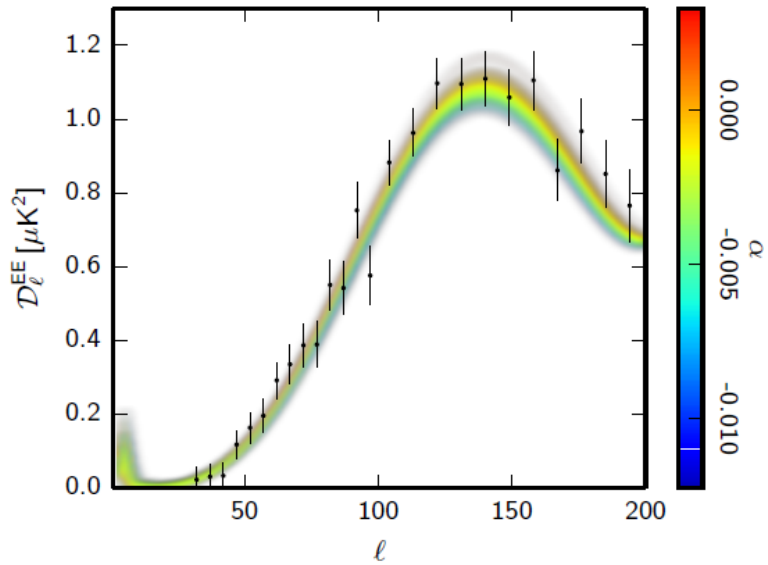
$$\frac{dn_s}{d\ln k} = -0.0126^{+0.0098}_{-0.0087}, \quad \textit{Planck}\ \text{TT+lowP},$$

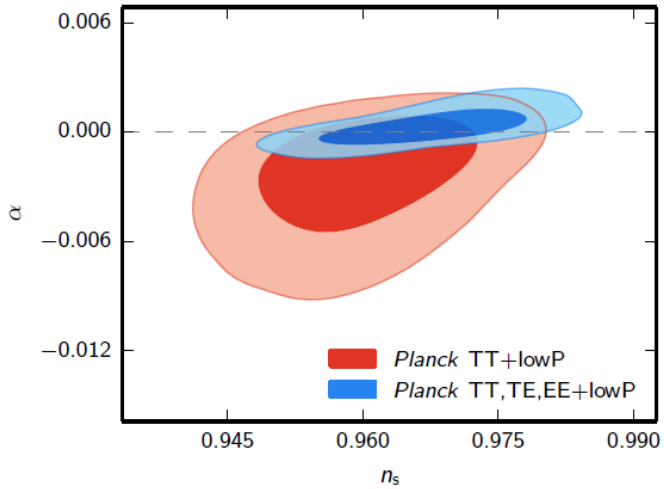
$$\frac{dn_s}{d\ln k} = -0.0085 \pm 0.0076, \quad \textit{Planck}\ \text{TT, TE, EE+lowP},$$

$$\frac{dn_s}{d\ln k} = -0.0065 \pm 0.0076, \quad \textit{Planck}\ \text{TT+lowP+lensing +ext+BKP}.$$

Isocurvature: e.g. (anti-)correlated matter density isocurvature



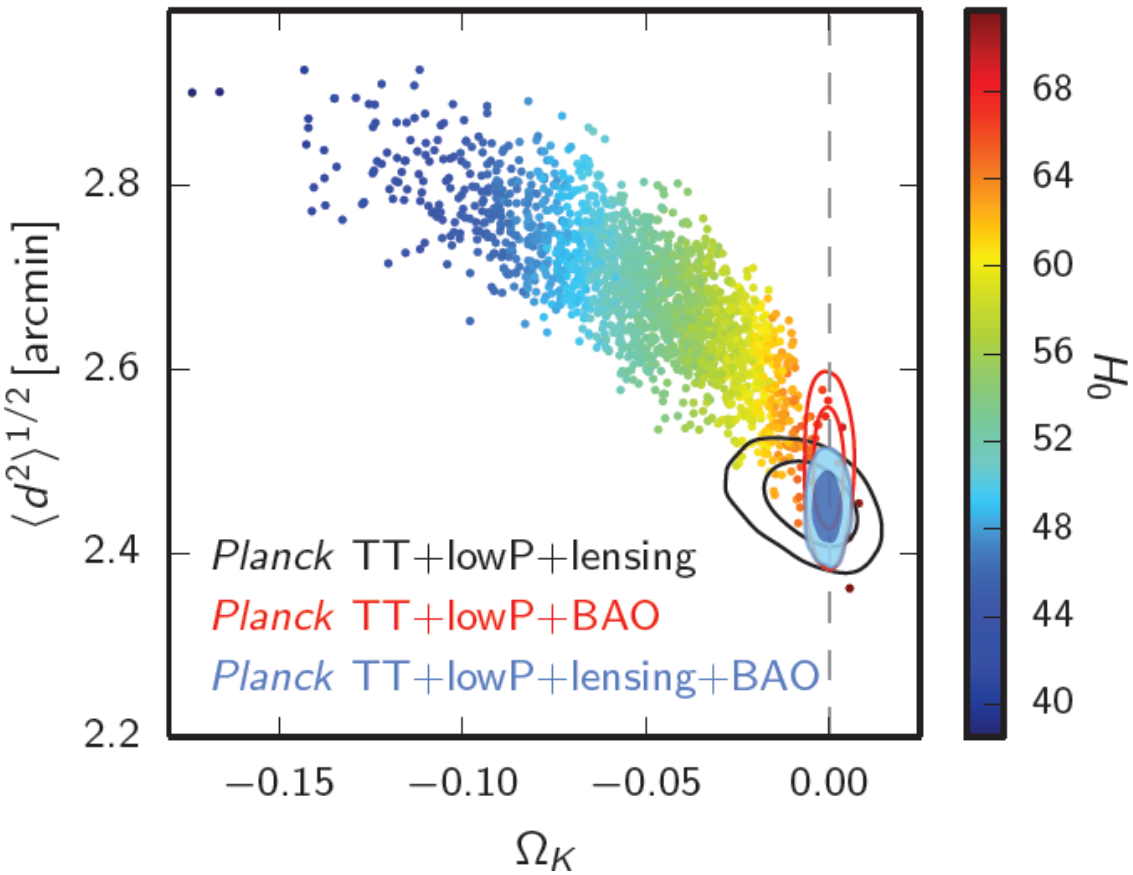


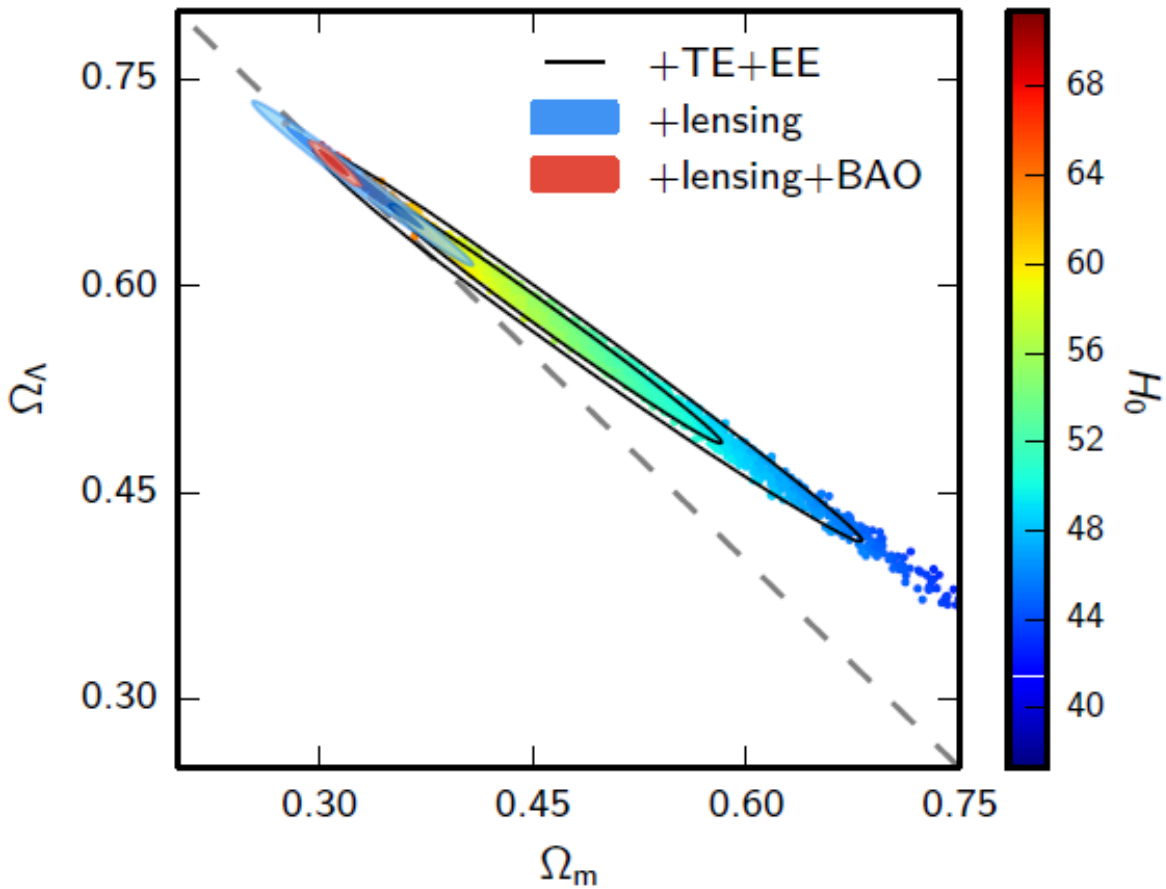


Consistent with adiabatic

Polarization dramatically improves constraint

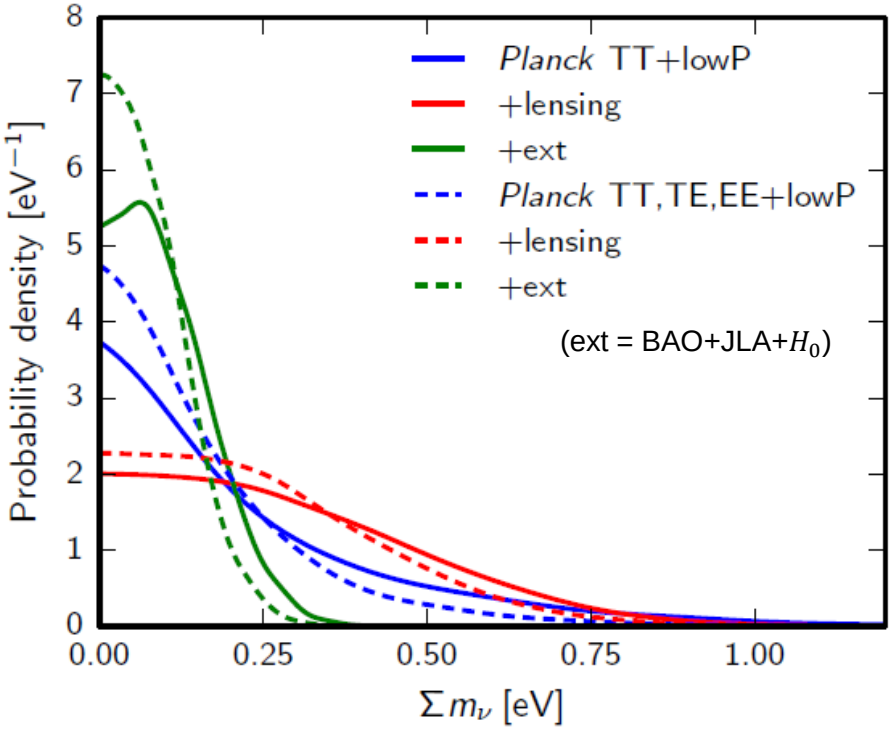
Lensing amplitude and extended parameters

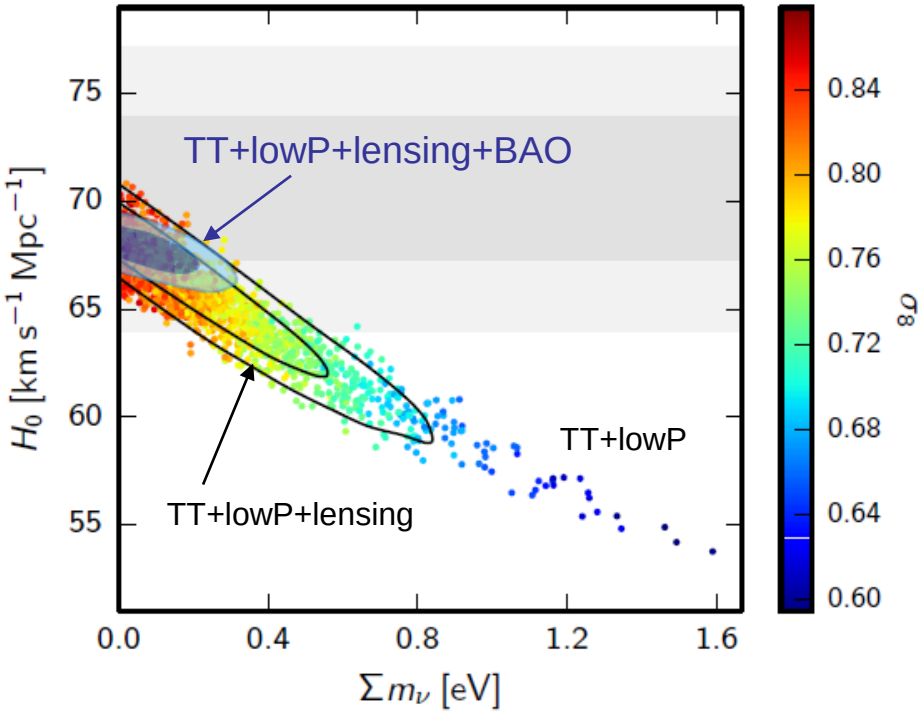




Joint constraints consistent with flat universe

Massive neutrinos





$\sum m_\nu < 0.72\,\text{eV}$ *Planck* TT+lowP (95% CL)

$\sum m_\nu < 0.21\,\text{eV}$ *Planck* TT+lowP+BAO

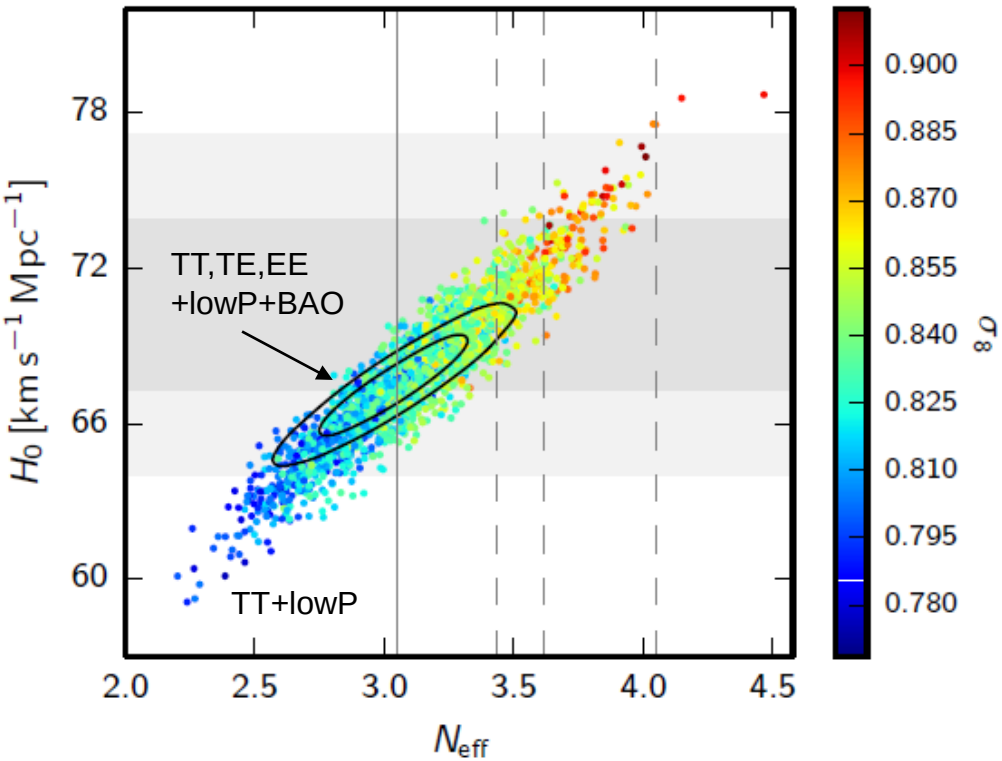
$\sum m_\nu < 0.49\,\text{eV}$ *Planck* TT, TE, EE+lowP

$\sum m_\nu < 0.17\,\text{eV}$ *Planck* TT, TE, EE+lowP+BAO.

$$\left.\begin{array}{l}\sum m_\nu < 0.23\,\text{eV} \\ \Omega_\nu h^2 < 0.0025\end{array}\right\}$$ 95%, *Planck* TT+lowP+lensing+ext

$$\left.\begin{array}{l}H_0 = 67.7 \pm 0.6 \\ \sigma_8 = 0.810^{+0.015}_{-0.012}\end{array}\right\}$$ *Planck* TT+lowP+lensing+ext (68% CL)

Extra relativistic degrees of freedom

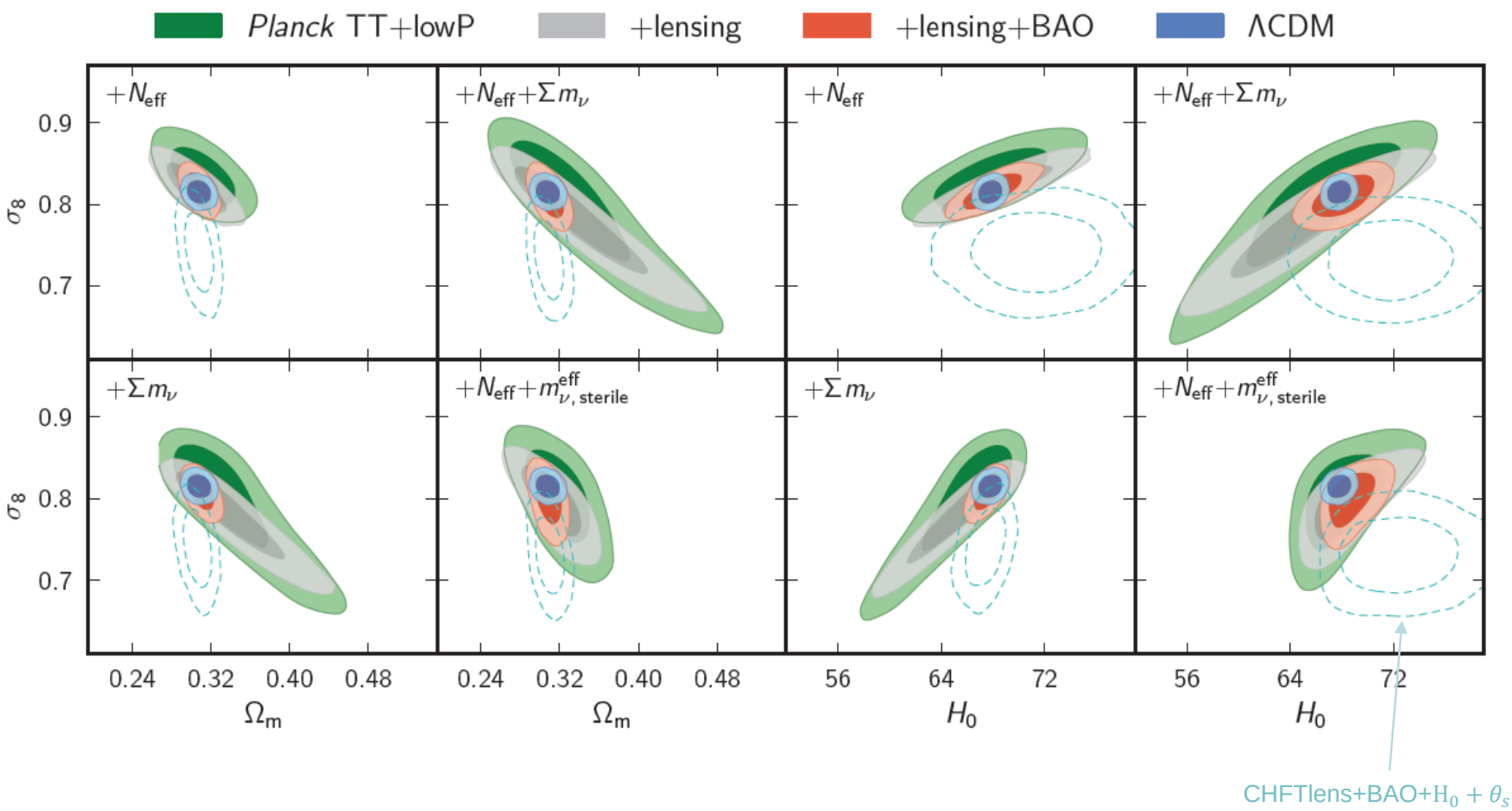


$$N_{\rm eff} = 3.13 \pm 0.32 \quad \textit{Planck}\ \text{TT+lowP}$$
$$N_{\rm eff} = 3.15 \pm 0.23 \quad \textit{Planck}\ \text{TT+lowP+BAO}$$
$$N_{\rm eff} = 2.99 \pm 0.20 \quad \textit{Planck}\ \text{TT, TE, EE+lowP}$$
$$N_{\rm eff} = 3.04 \pm 0.18 \quad \textit{Planck}\ \text{TT, TE, EE+lowP+BAO}$$

(68% CL)

$\Delta N_{\rm eff} < 4$ at over 3σ

Can neutrino models reconcile Planck and lensing/other data?



Conclusions

Main cosmology conclusions of 2013 unchanged, smaller errors

Somewhat lower optical depth than from WMAP $\tau \sim 0.08$

Powerful CMB lensing constraint on the fluctuation amplitude

Planck+BICEP+Keck gives strong upper limit on gravity waves

Broadly consistent with LCDM and minimal-mass standard neutrinos

but:

- tensions with external data; no obvious way to reconcile all
- some puzzles like high A_L
- significant variations from base LCDM still allowed

(e.g. $\sum m_\nu \lesssim 0.2\mathrm{eV}$, $\Delta N_{\mathrm{eff}} \lesssim 0.4$)

Polarization can significantly tighten constraints

- work in progress, more robust analysis next year, + HFI low-ℓ polarization

The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada.

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.