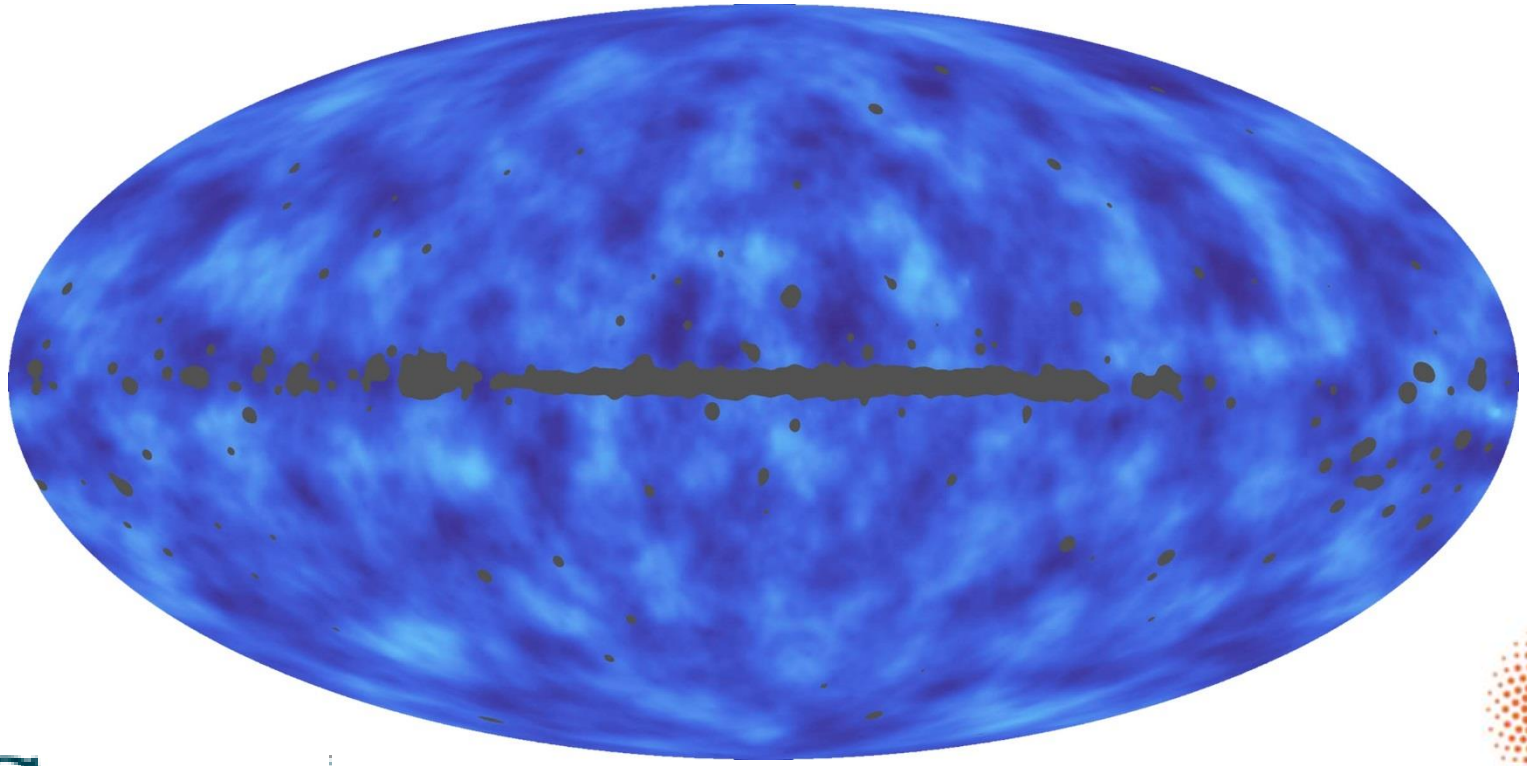
Planck parameter constraints

Antony Lewis
On behalf of the Planck Collaboration
http://cosmologist.info/



Preliminary

University of Sussex

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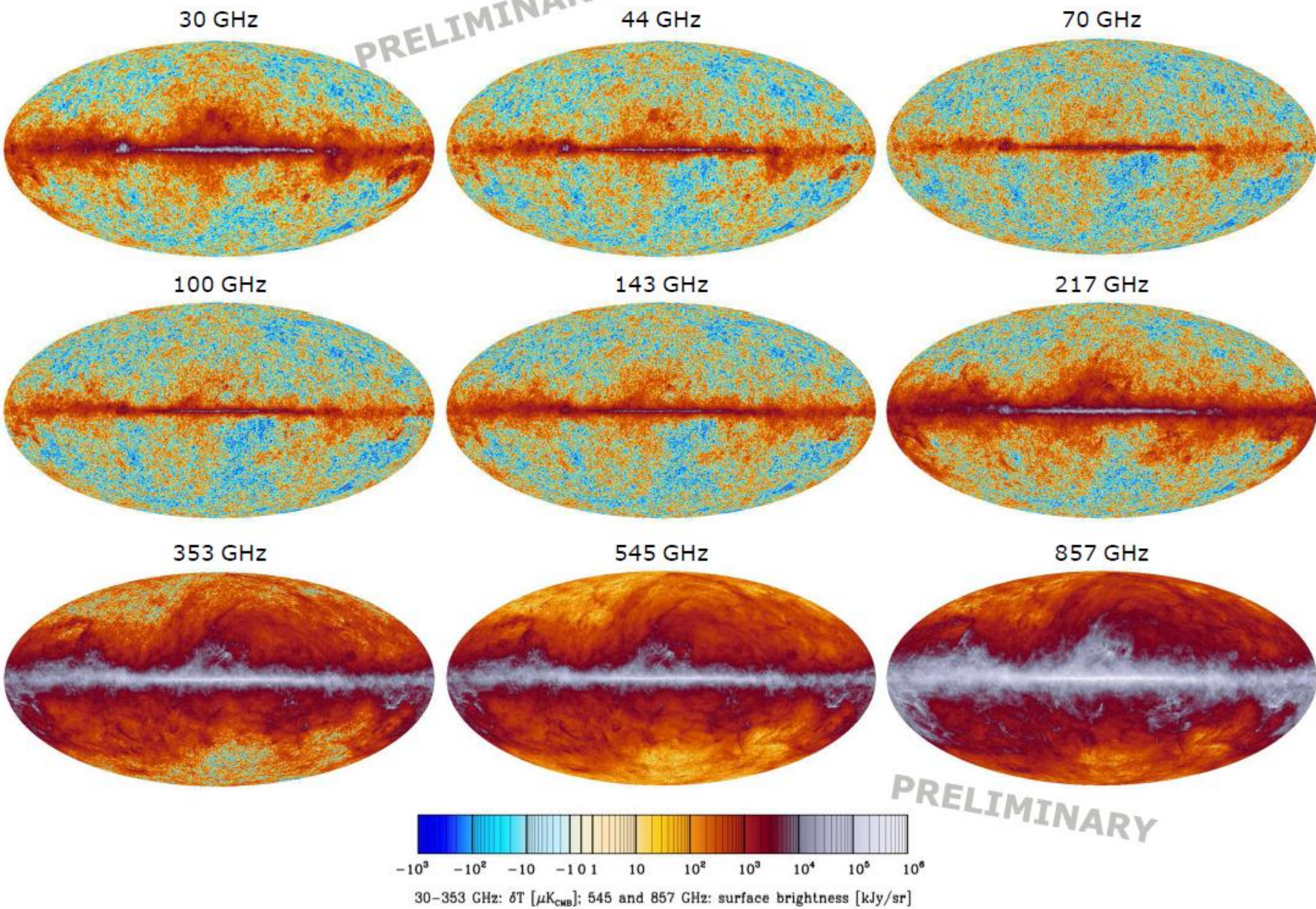
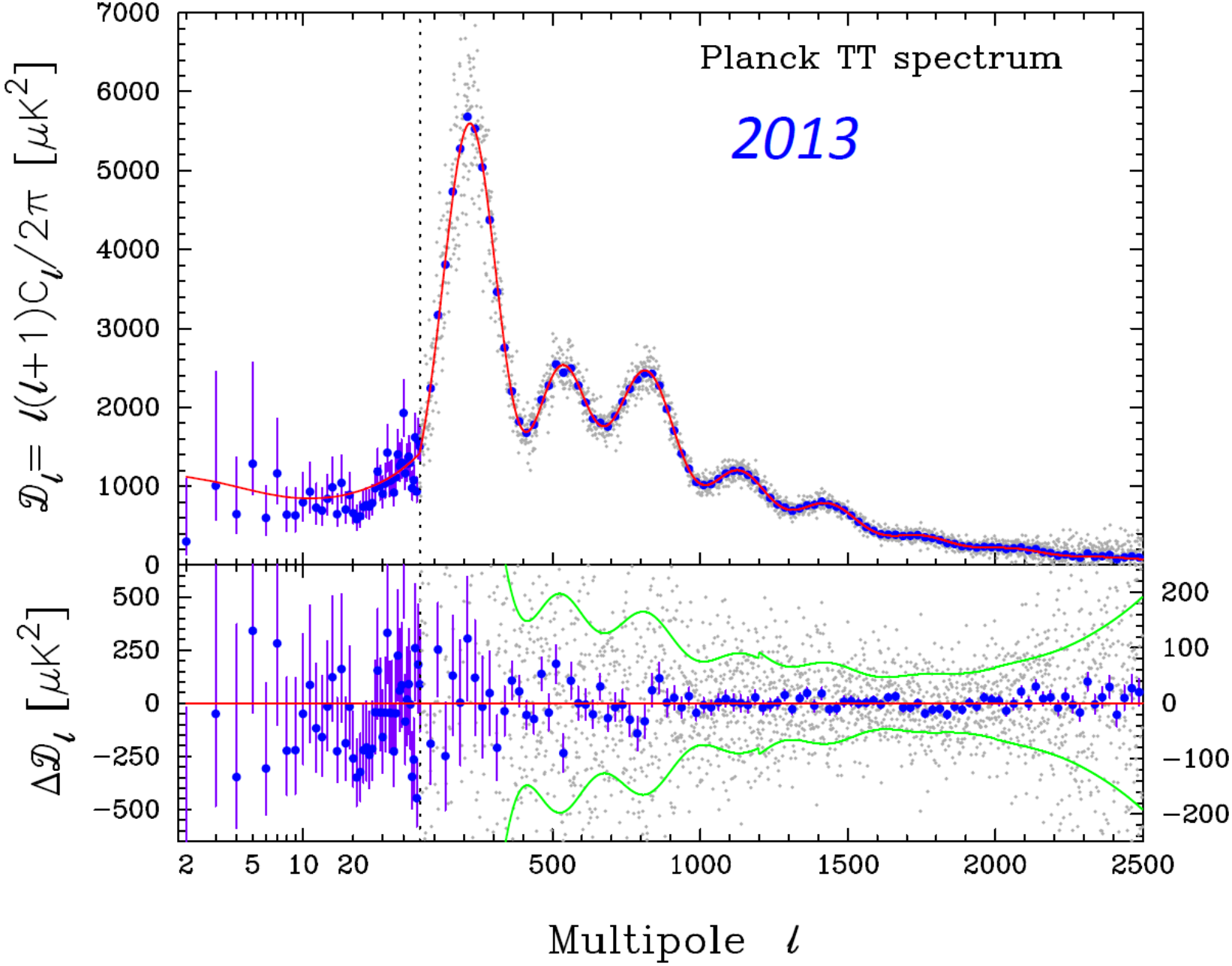
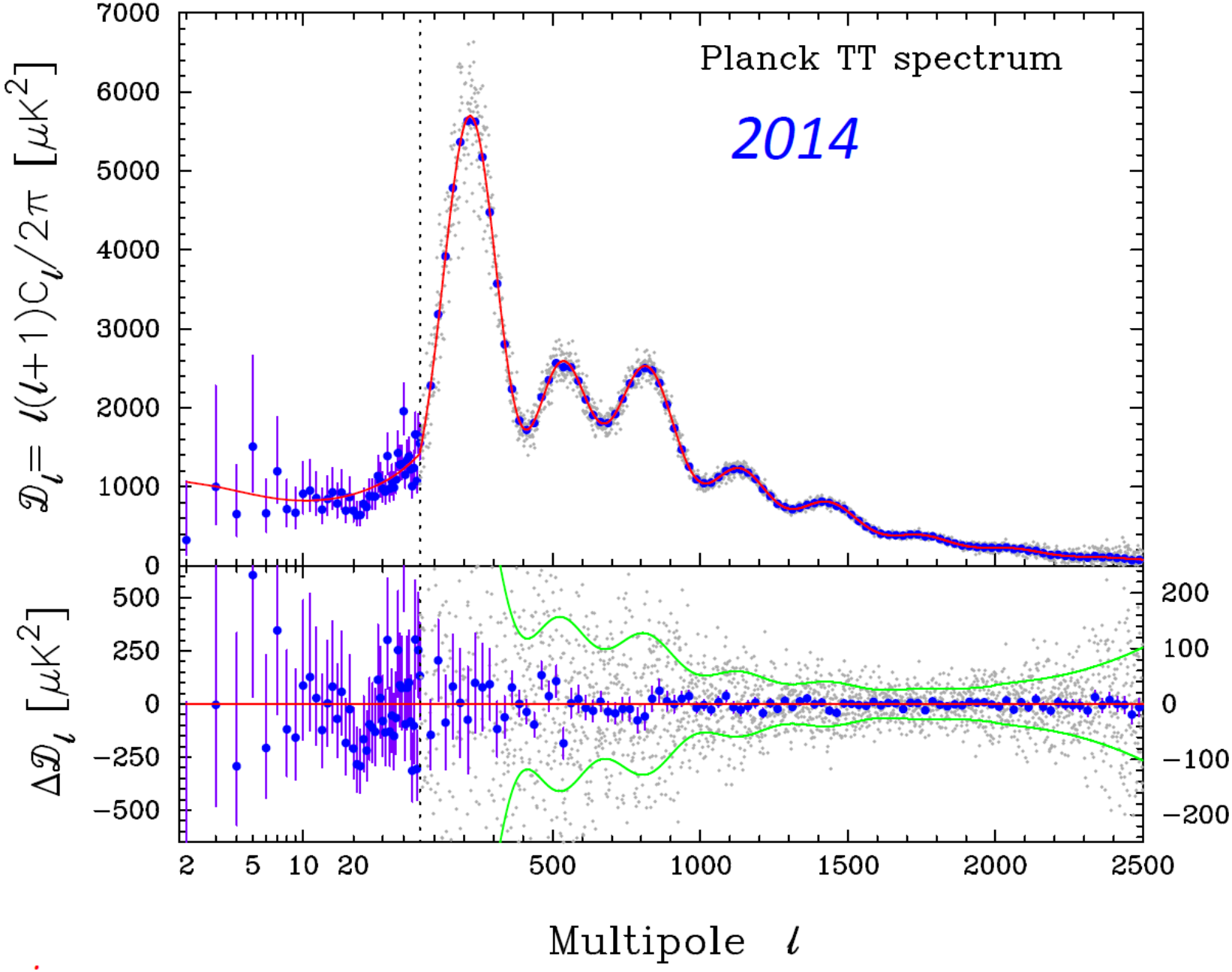
Planck 2014 frequency maps: Temperature




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



preliminary

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
- Binned Plik likelihood rather than unbinned CamSpec
- Many new internal consistency checks

Base LCDM

Preliminary

Nominal (2 sky surveys)

Full mission (5 sky surveys)

2013 maps

2014 maps

[1] Parameter	[2] 2013N(DS)	[3] 2013F(DS)	[4] 2013F(CY)	[5] 2014F(CHM)	[6] 2014F(CHM) (Plik)	$([2]-[6])/\sigma_{[6]}$	$([5]-[6])/\sigma_{[5]}$
	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		
$100\theta_{\rm MC}$	1.04131 ± 0.00063	1.04126 ± 0.00047	1.04126 ± 0.00048	1.04094 ± 0.00048	1.04086 ± 0.00048	0.71	0.17
$\omega_{\rm b}$	0.02205 ± 0.00028	0.02234 ± 0.00023	0.02230 ± 0.00023	0.02225 ± 0.00023	0.02222 ± 0.00023	−0.61	0.13
$\omega_{\rm c}$	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
$n_{\rm s}$	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	0.823 ± 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
$10^9 A_{\rm s} e^{-2\tau}$	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

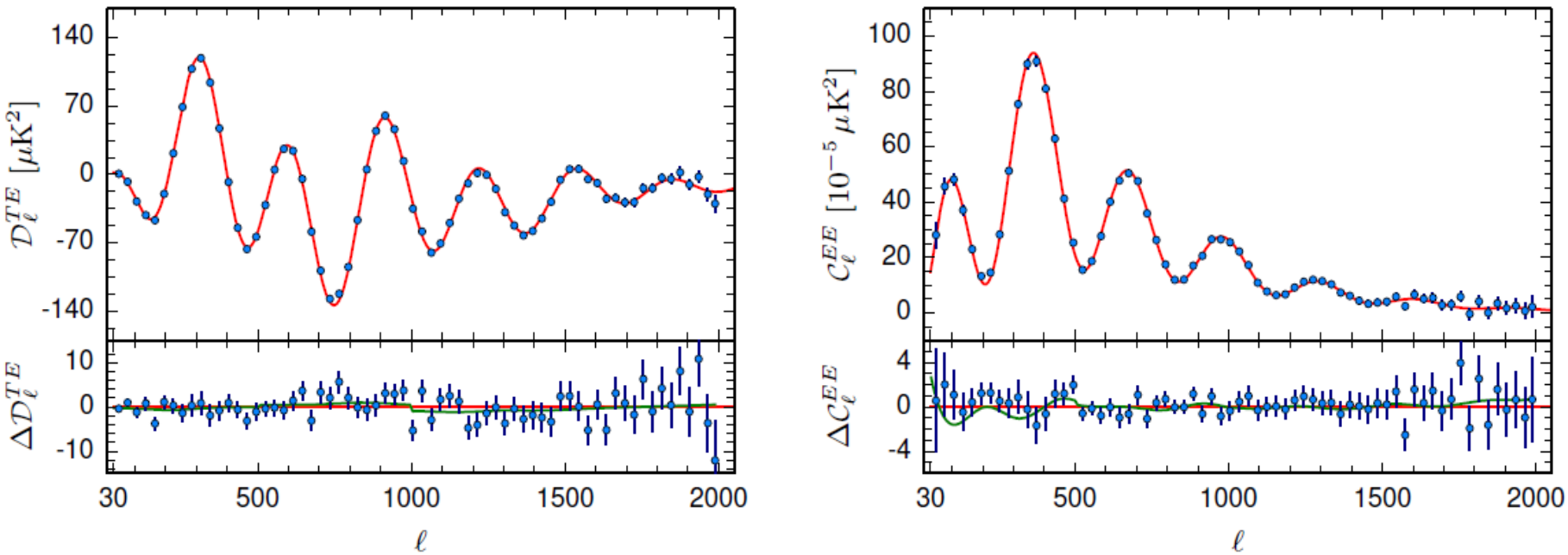
Mainly non-statistical shifts

Note:

* Consistency between likelihoods at 0.5σ level for TT

* 2014 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

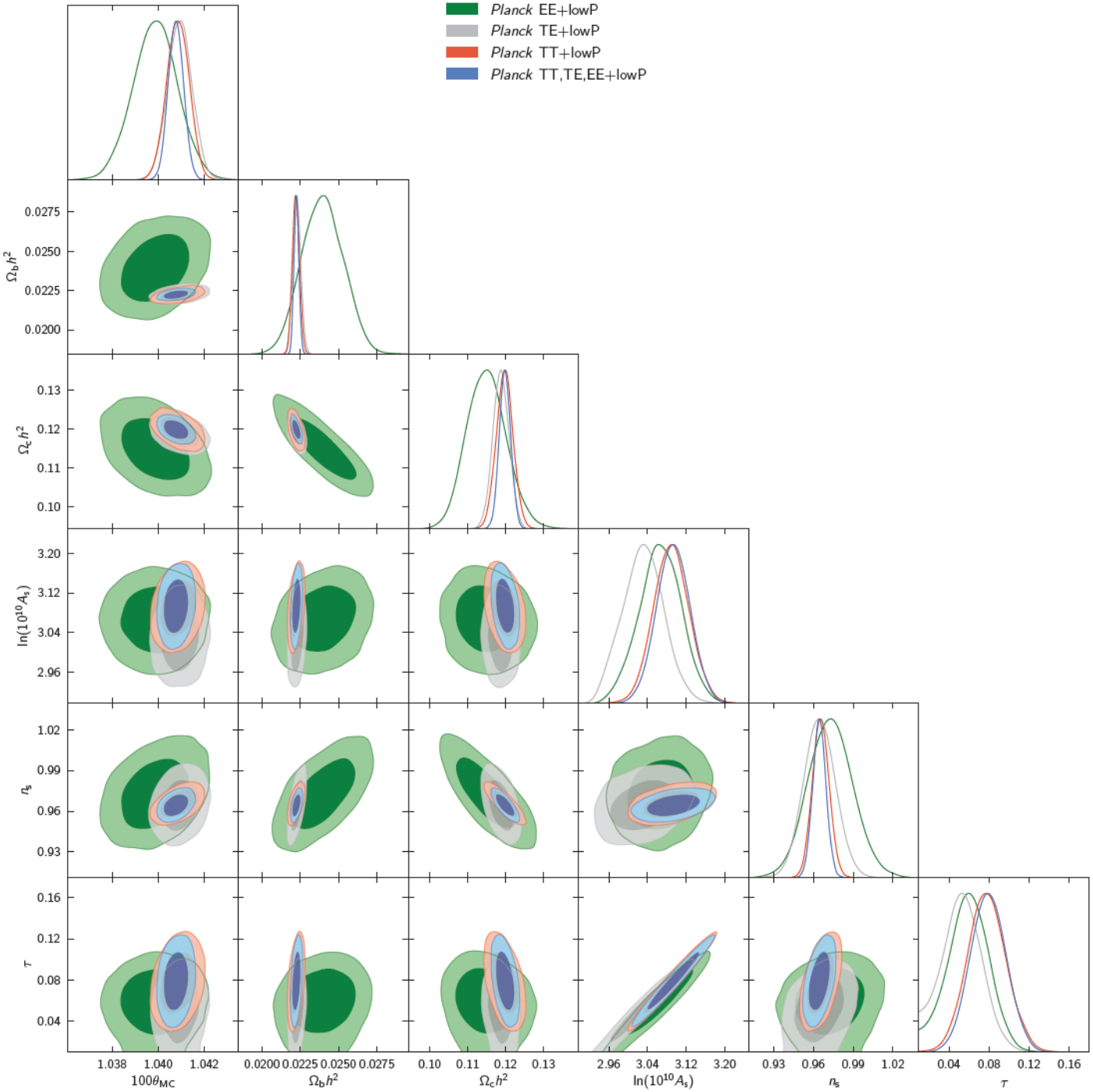
New: E-mode polarization



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

Preliminary

Base LCDM



Preliminary

Base LCDM

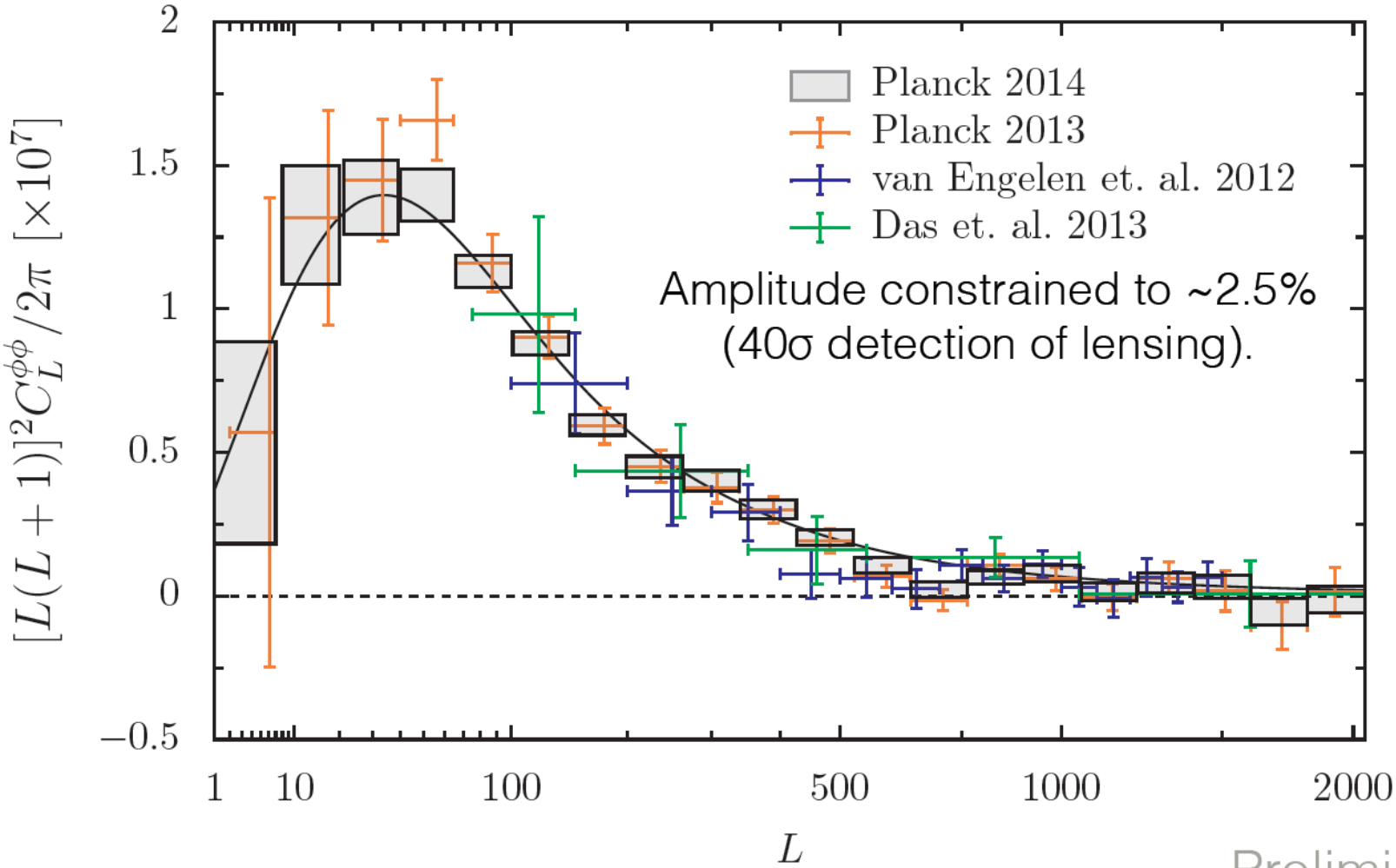
Parameter	[1] *Planck* TT+lowP	[2] *Planck* TE+lowP	[3] *Planck* EE+lowP	[4] *Planck* TT,TE,EE+lowP
$\Omega_b h^2$	0.02222 ± 0.00023	0.02228 ± 0.00025	0.0240 ± 0.0013	0.02225 ± 0.00016
$\Omega_c h^2$	0.1197 ± 0.0022	0.1187 ± 0.0021	$0.1150^{+0.0048}_{-0.0055}$	0.1198 ± 0.0015
$100\theta_{MC}$	1.04085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

…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

Preliminary

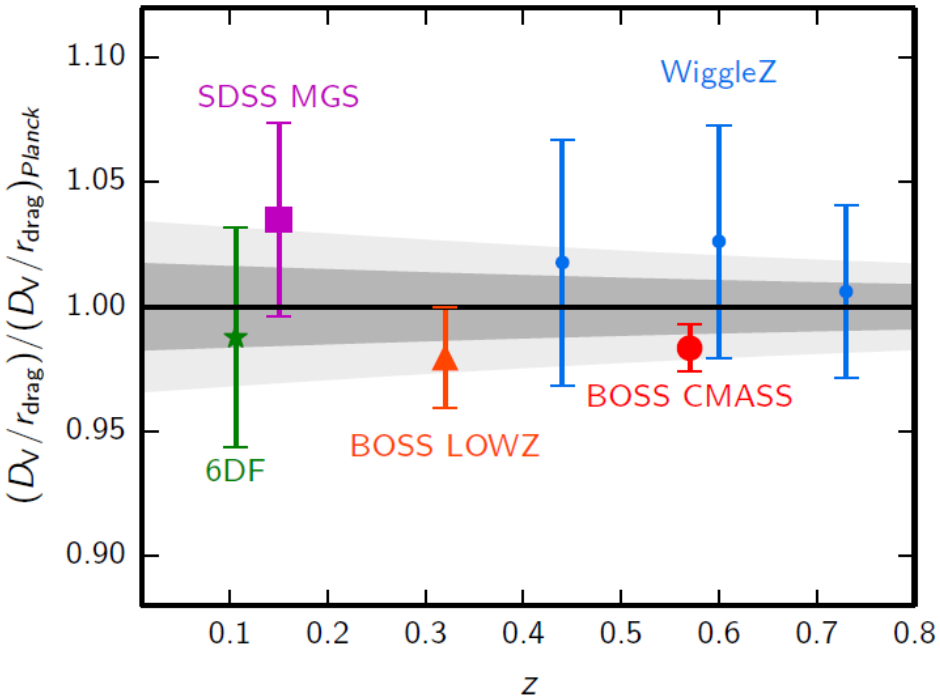
Updated: Planck CMB lensing power spectrum

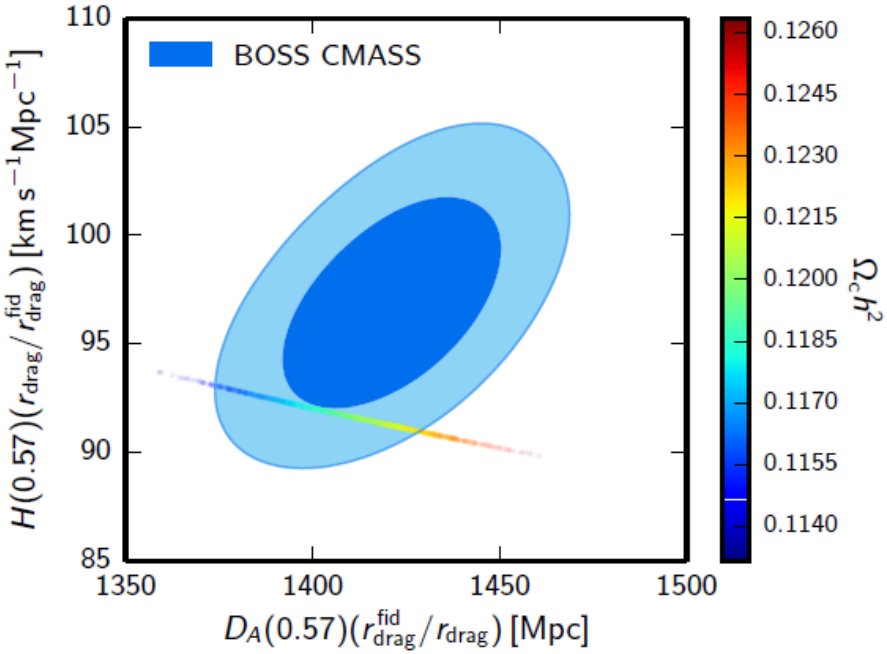


Preliminary

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)

Preliminary

Hubble parameter

Riess et al 2011:

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

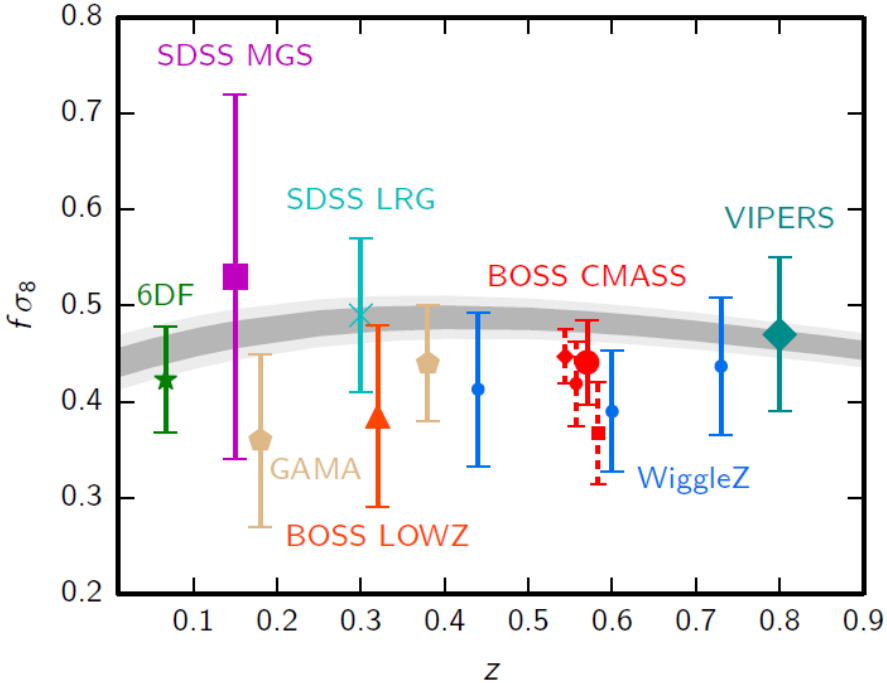
Humphreys et al 2013, Efstathiou 2013

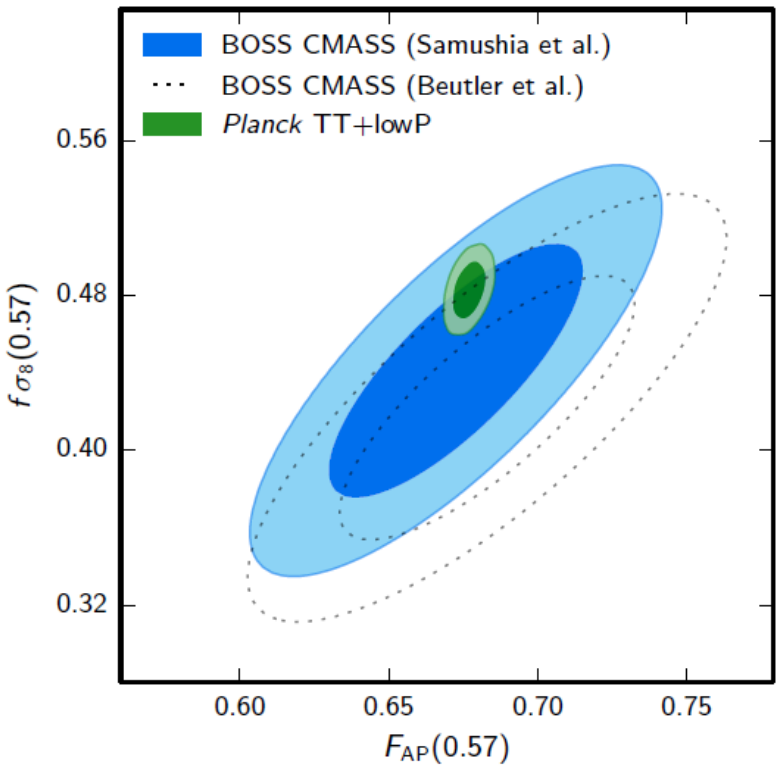
$$H_0 = 70.6 \pm 3.3\ \ \mathrm{km\ s^{-1} Mpc^{-1}}, \qquad \text{NGC 4258,}$$ ✓

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

Preliminary

Redshift distortions/growth



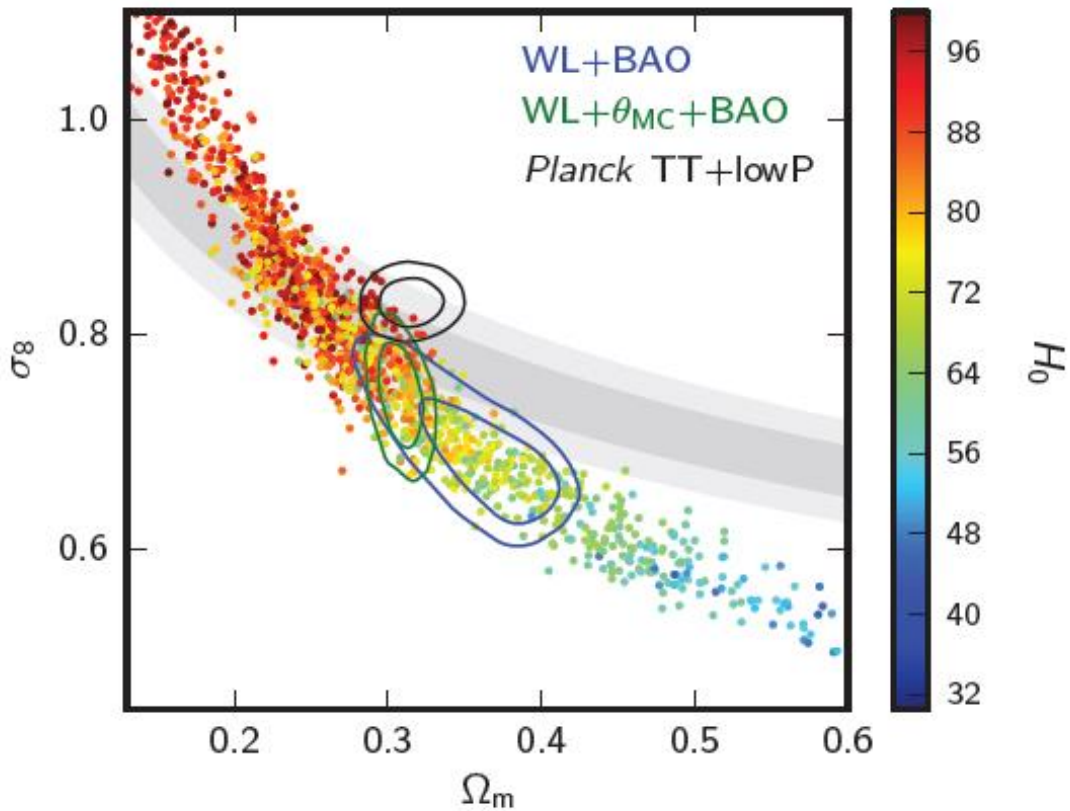


Consistent (or a bit low?)

Preliminary

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

Galaxy weak gravitational lensing



WL prefer higher H_0 or lower σ_8 ✗

WL: Heymans et al. 2013

Preliminary

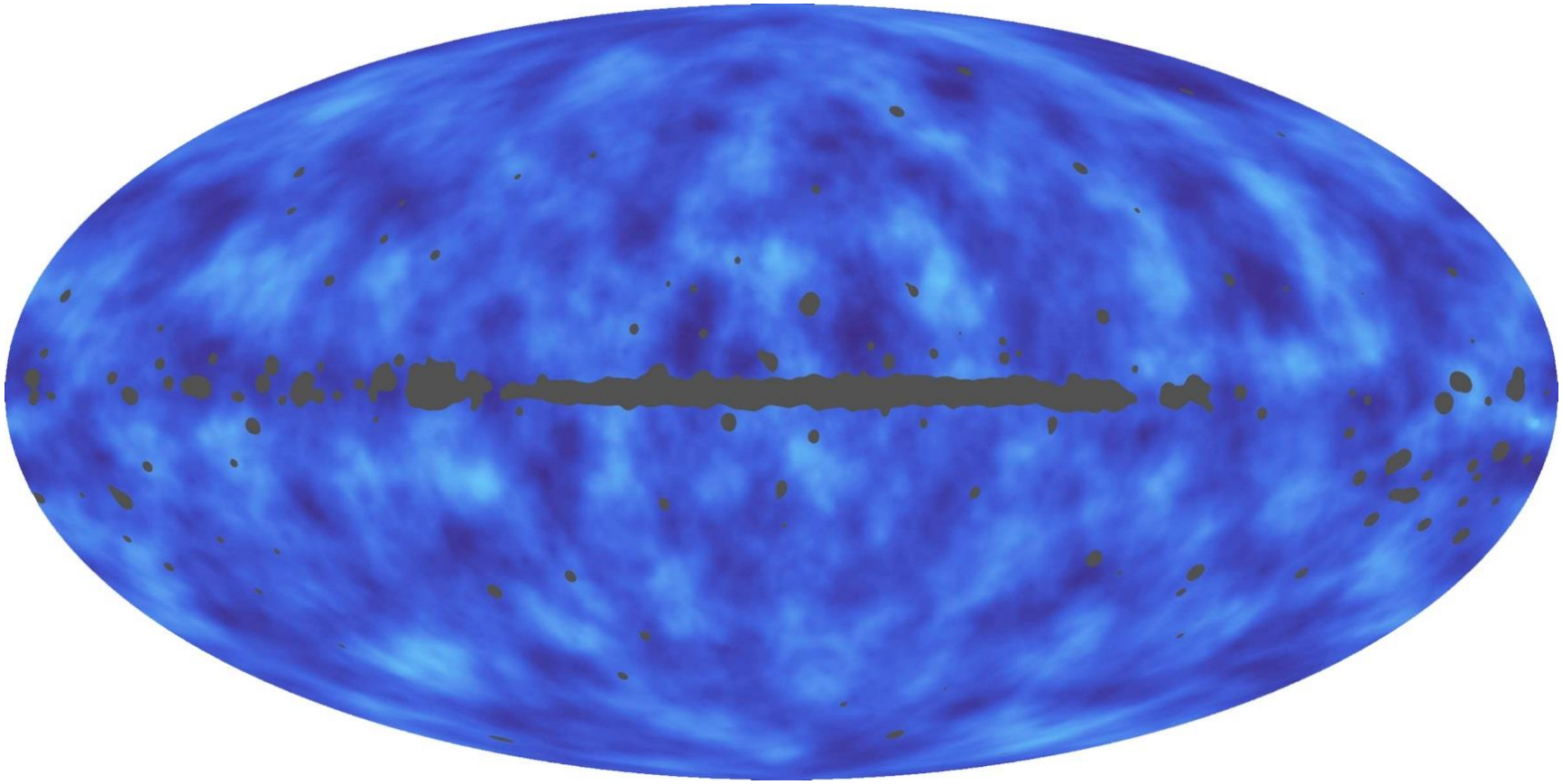
Clusters etc.

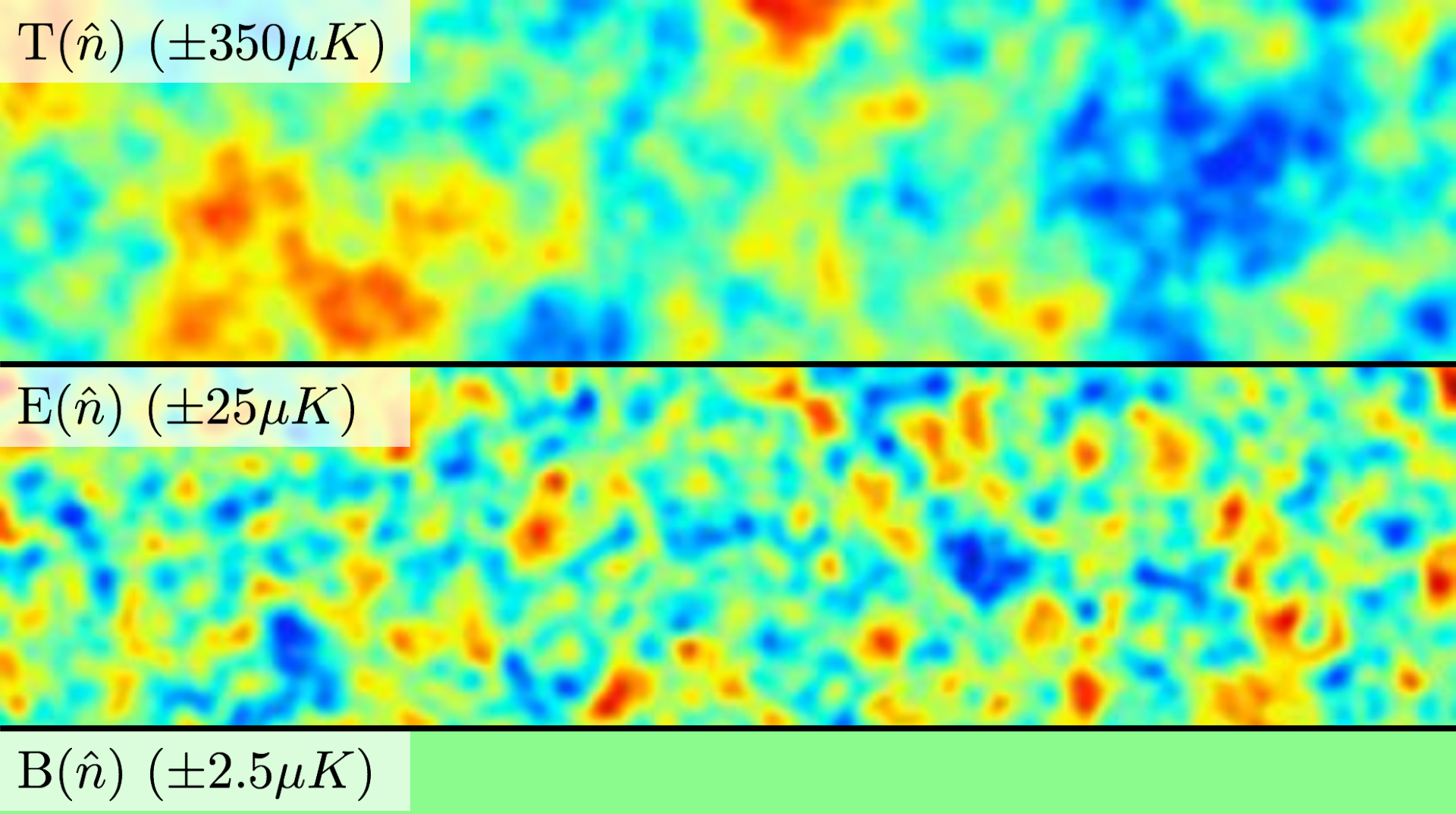
- Complicated physics and selection effects… mass calibration etc.

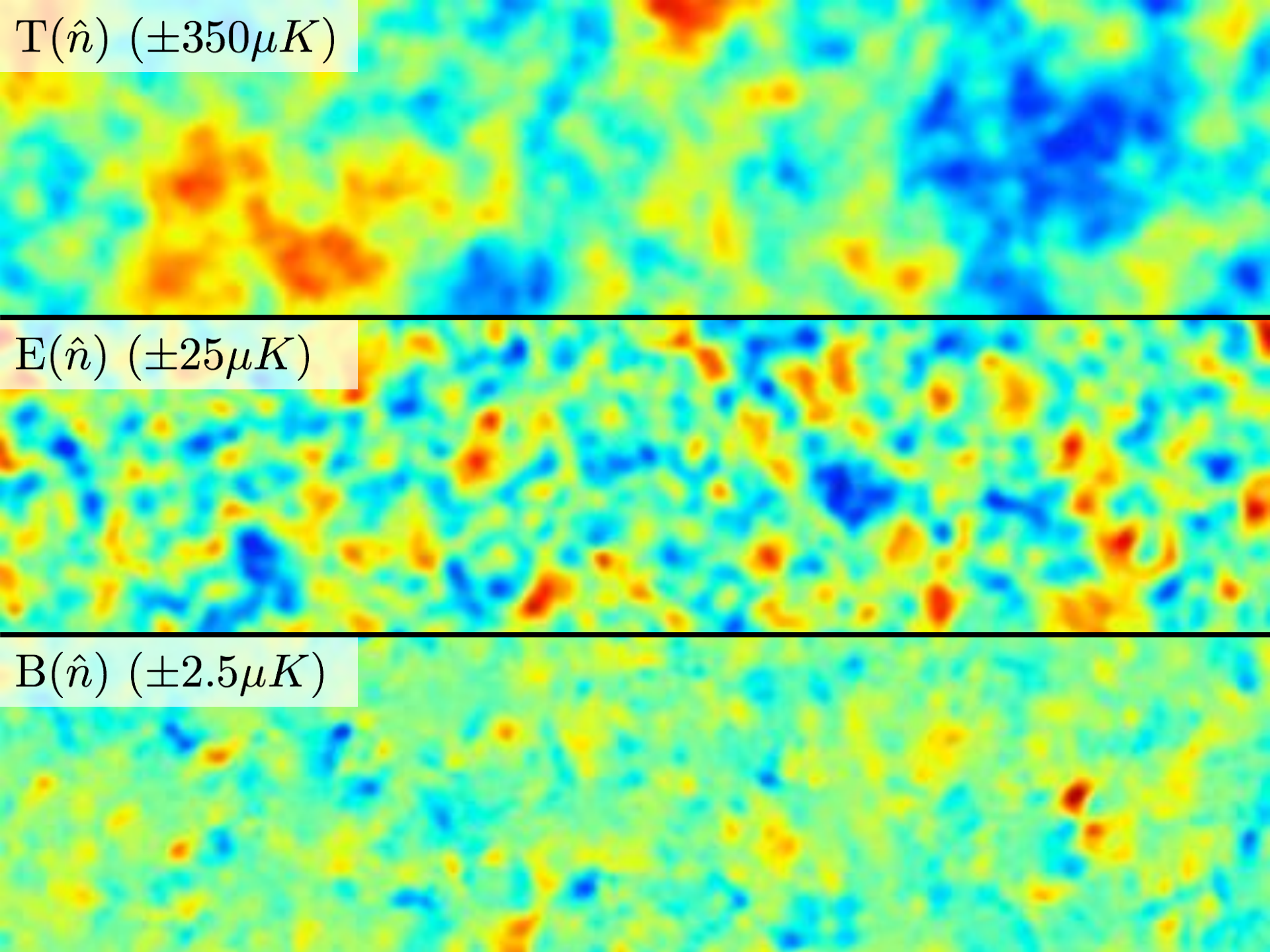
  Some analyses prefer lower σ_8, some OK – needs more work.

Preliminary

Planck CMB Lensing




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


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

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.

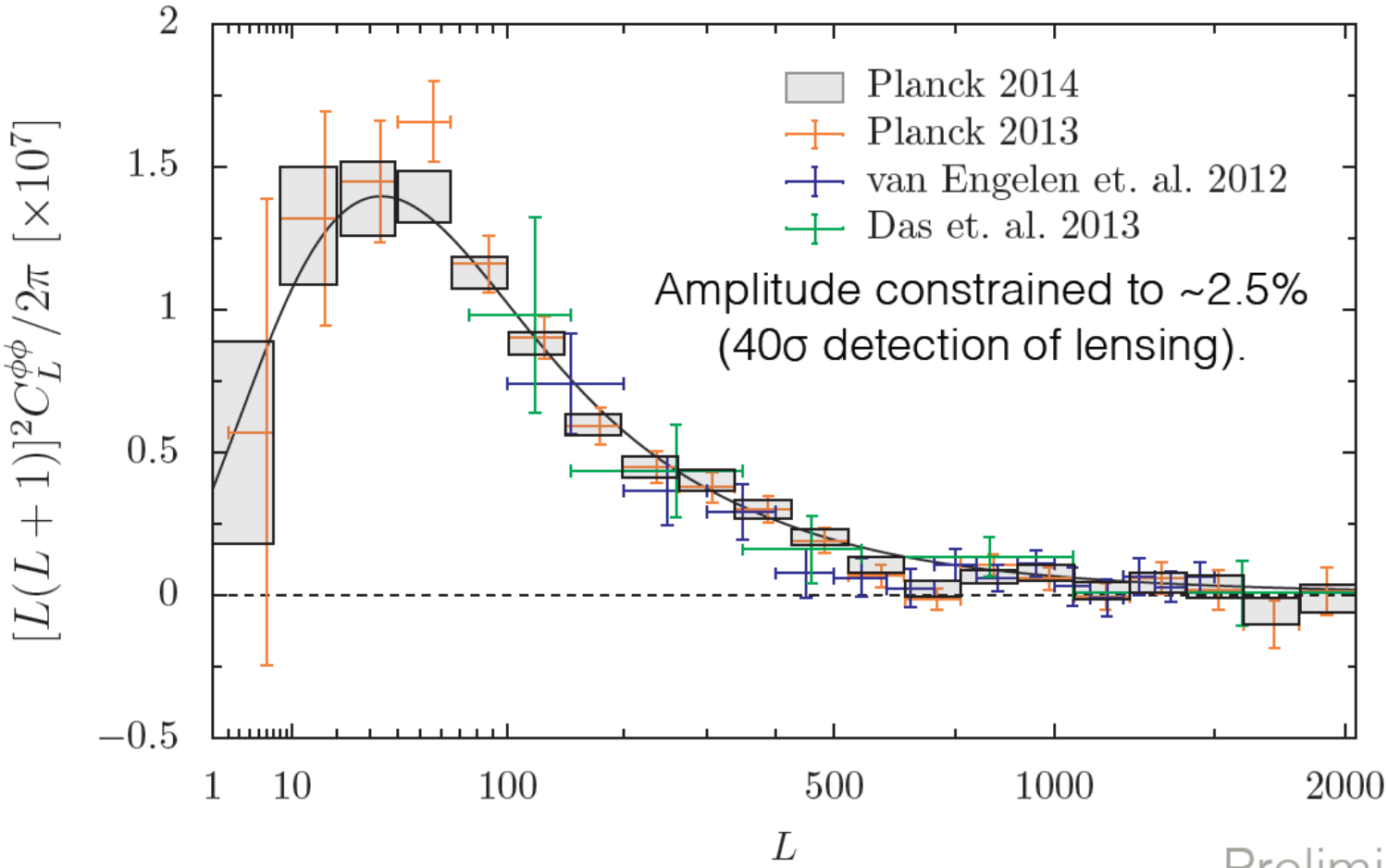
- Improved likelihood ($N^{(1)}$ theory dependence, faster)

- Many new consistency and null tests:

Internal consistency of polarization and temperature estimator pairs.

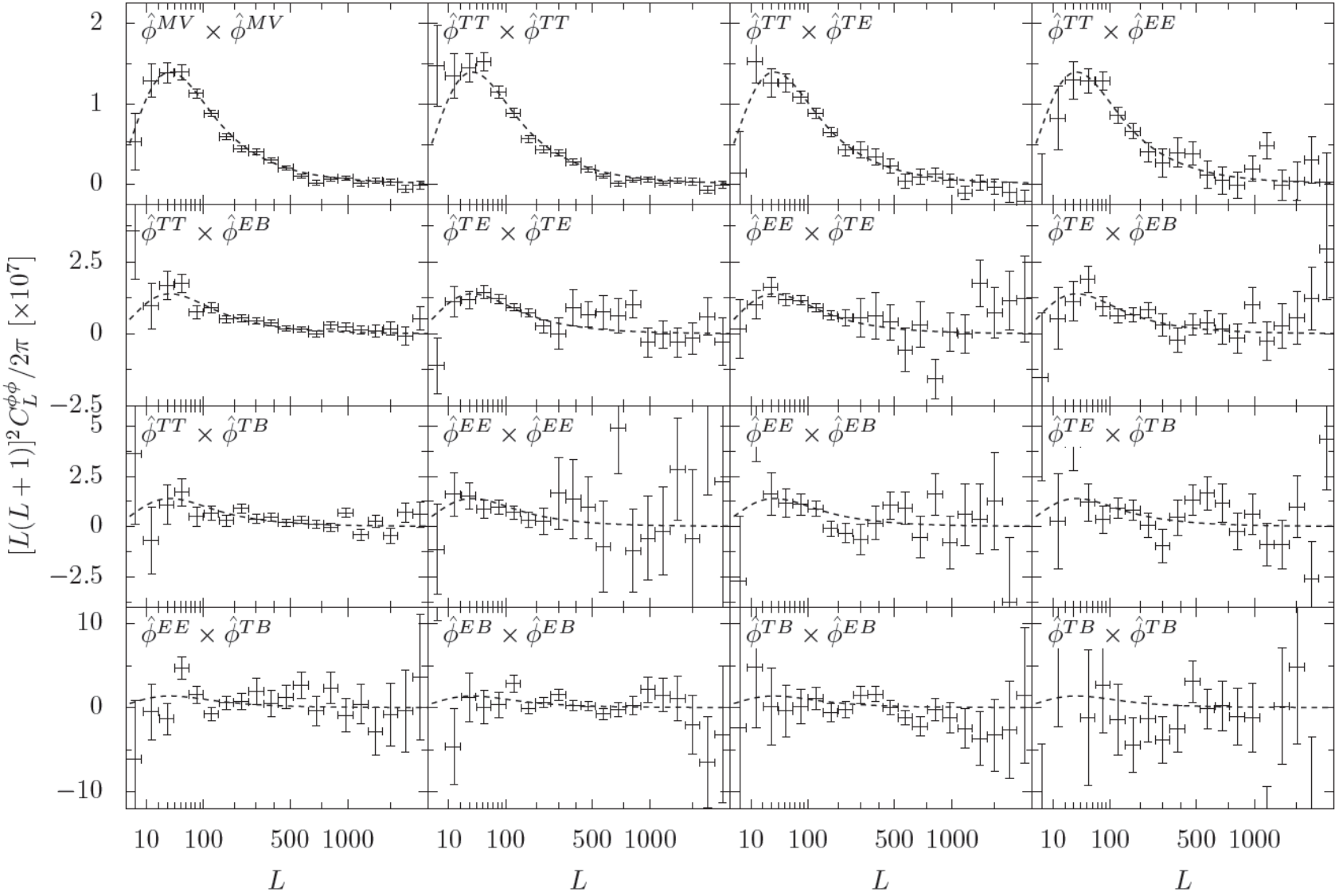
Half-mission nulls and crosses

Lensing Power Spectrum



Preliminary

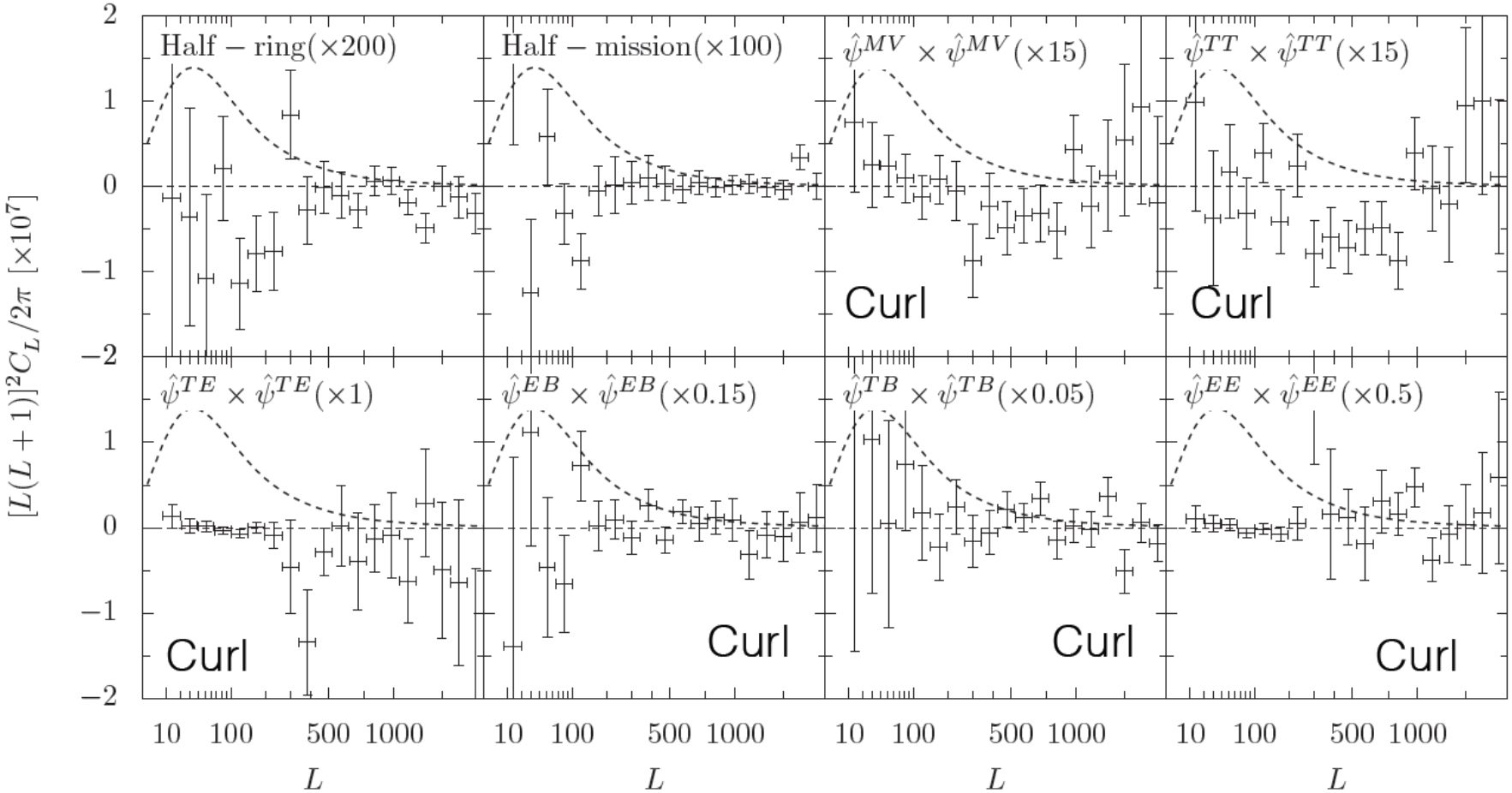
Individual Cross-spectra



Preliminary

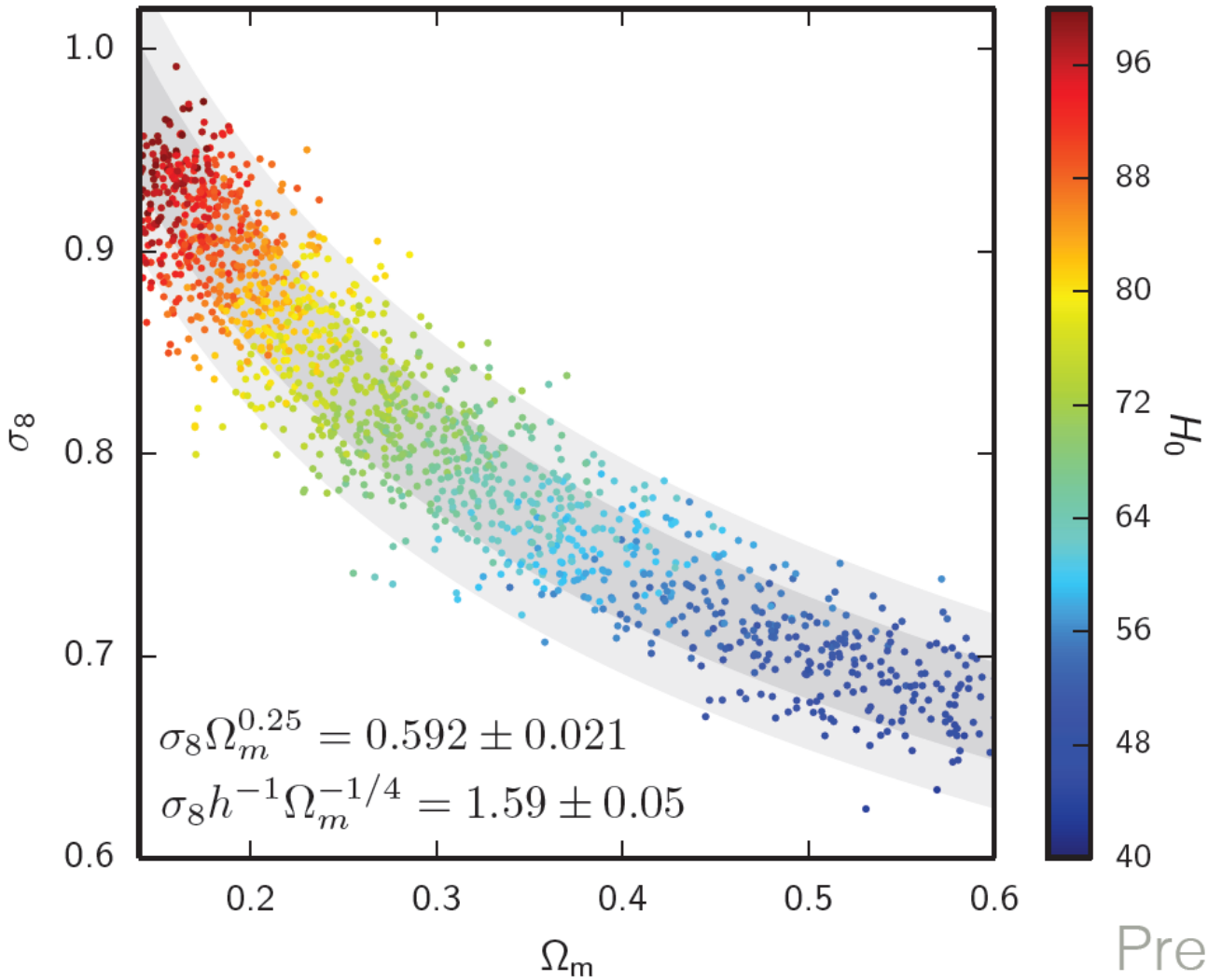
Null Tests

Preliminary



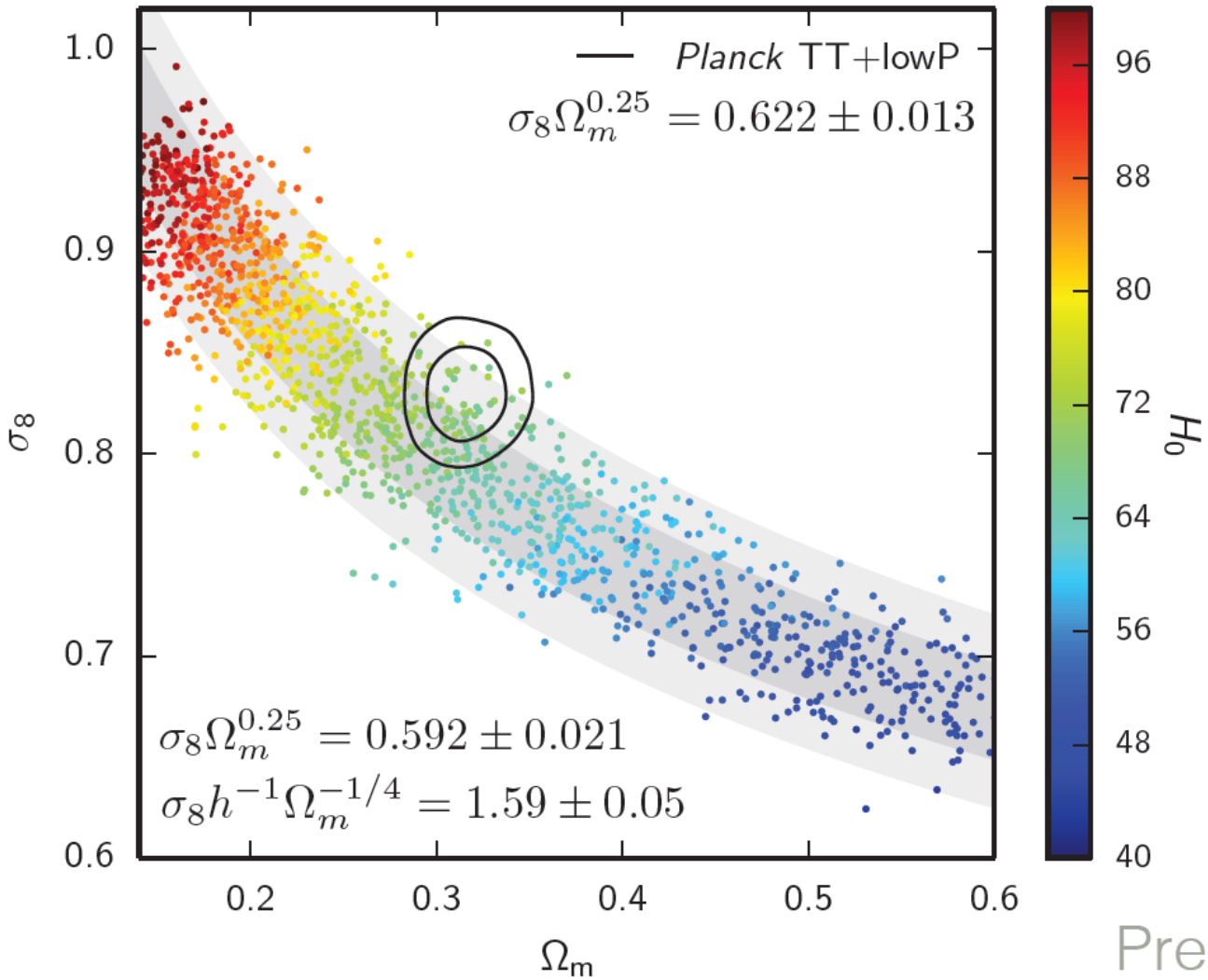
Conservative likelihood uses 40 ≤ L ≤ 400

LCDM Parameter Constraints from CMB Lensing Only



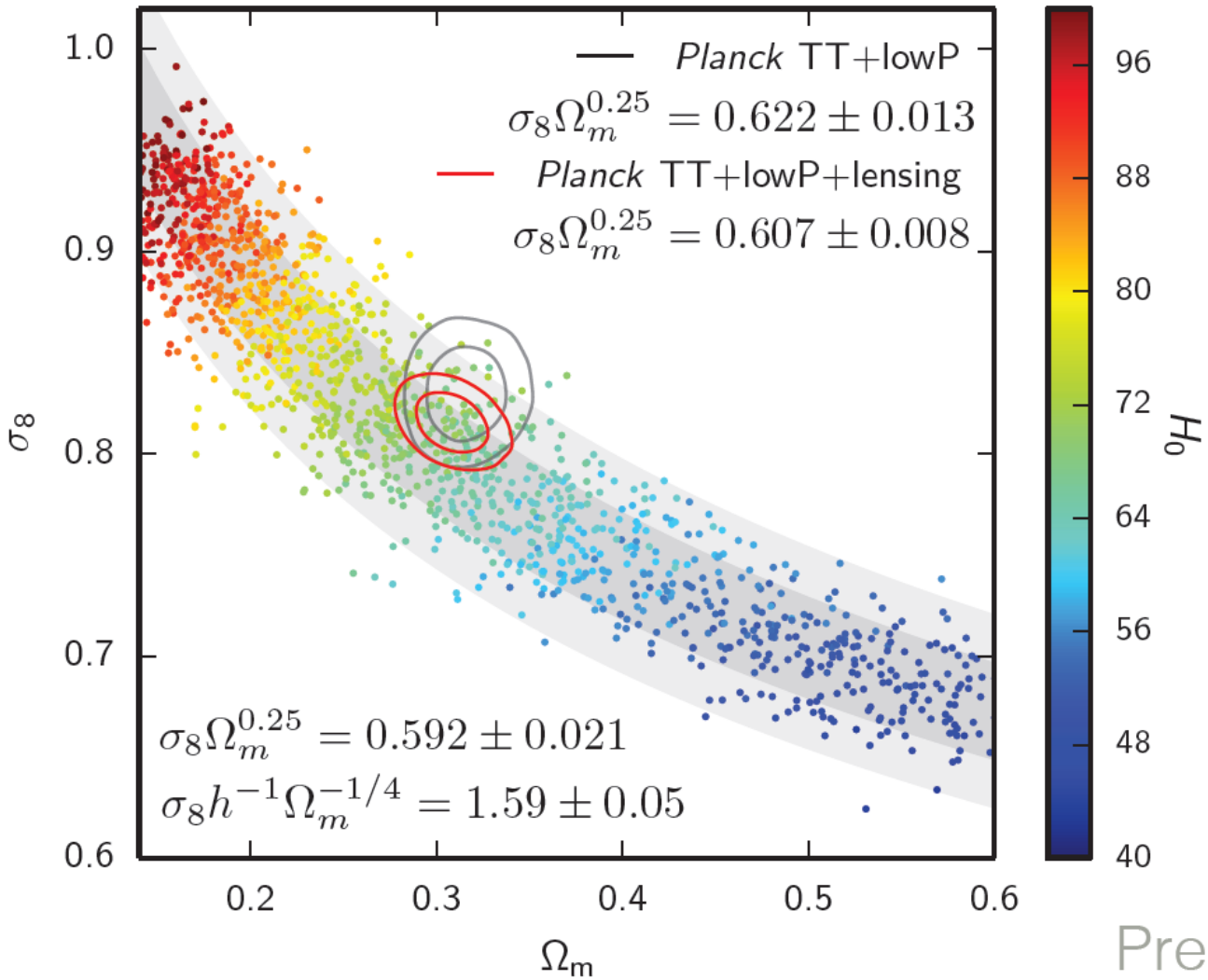
Preliminary

LCDM Parameter Constraints from CMB Lensing Only



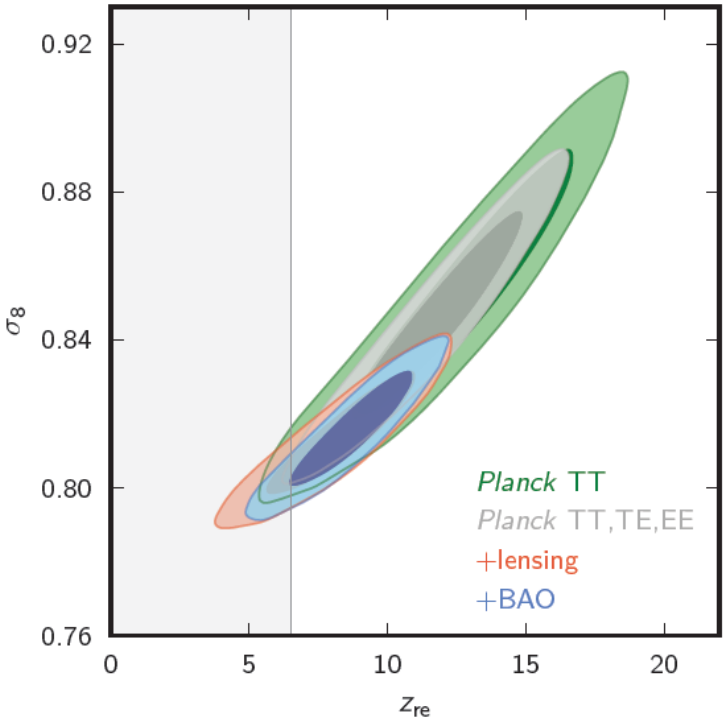
Preliminary

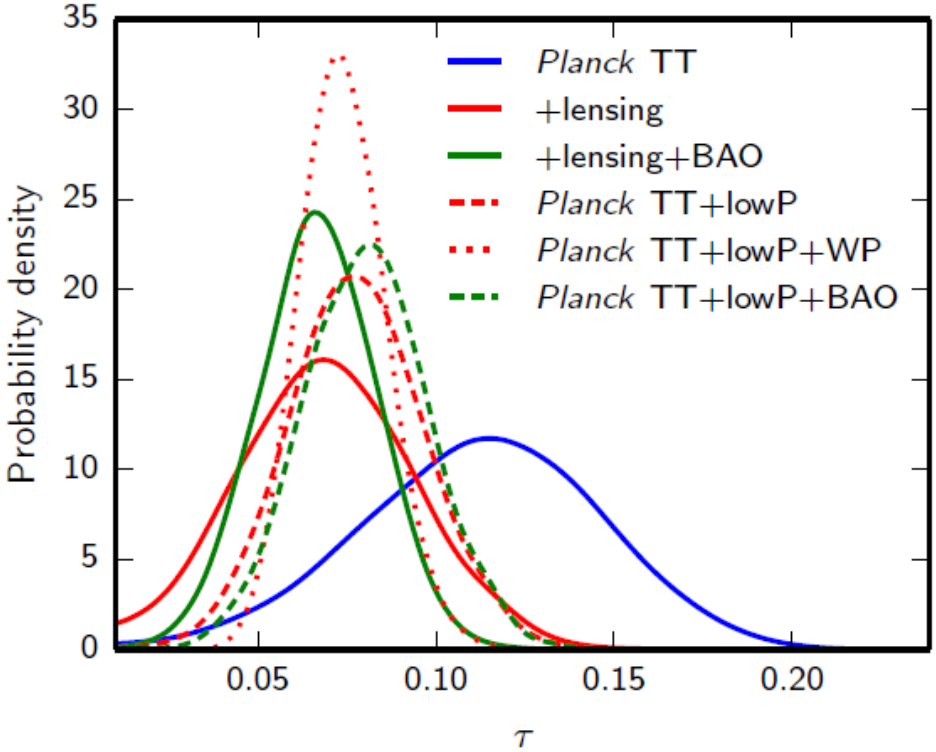
LCDM Parameter Constraints from CMB Lensing Only



Preliminary

Optical Depth Constraints

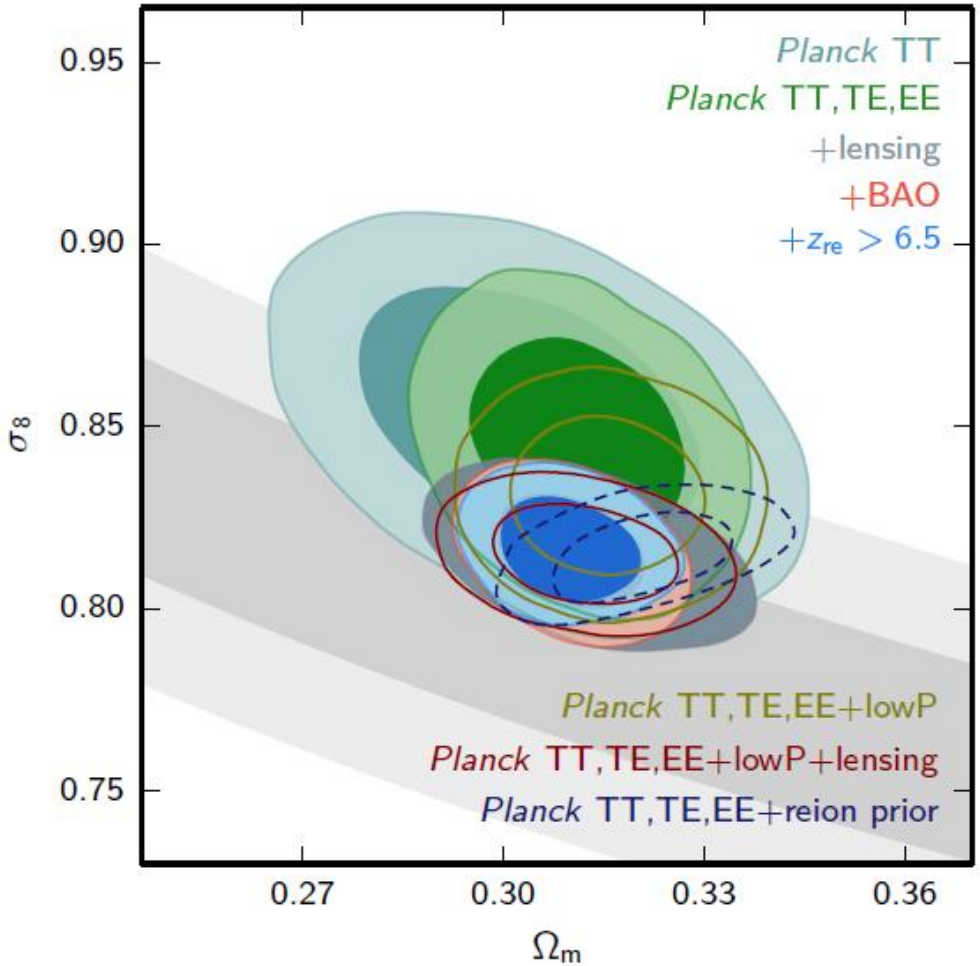




... are consistent with low-L polarization.

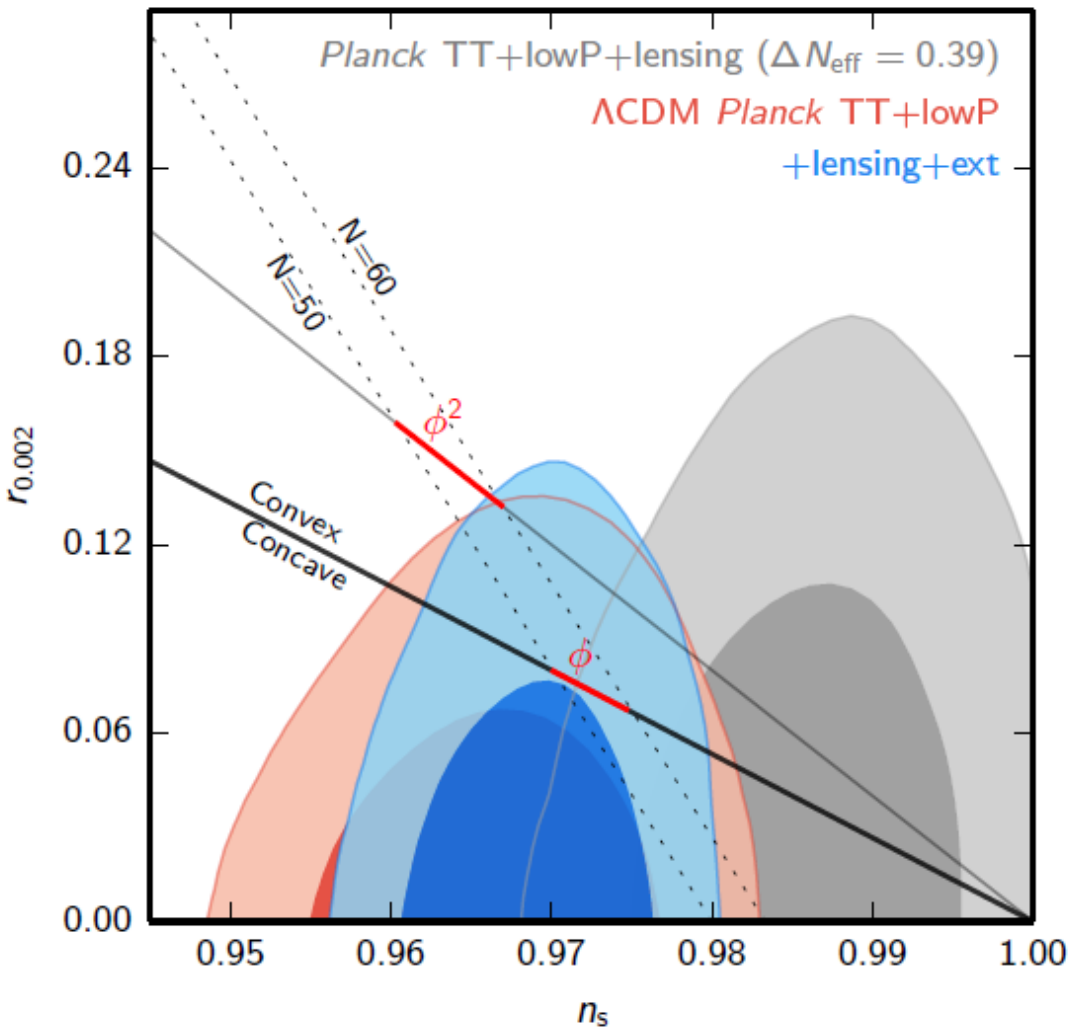
Preliminary

Planck σ_8 in the base LCDM model



Only consistent with $\sigma_8 > 0.8$

Beyond the base LCDM model



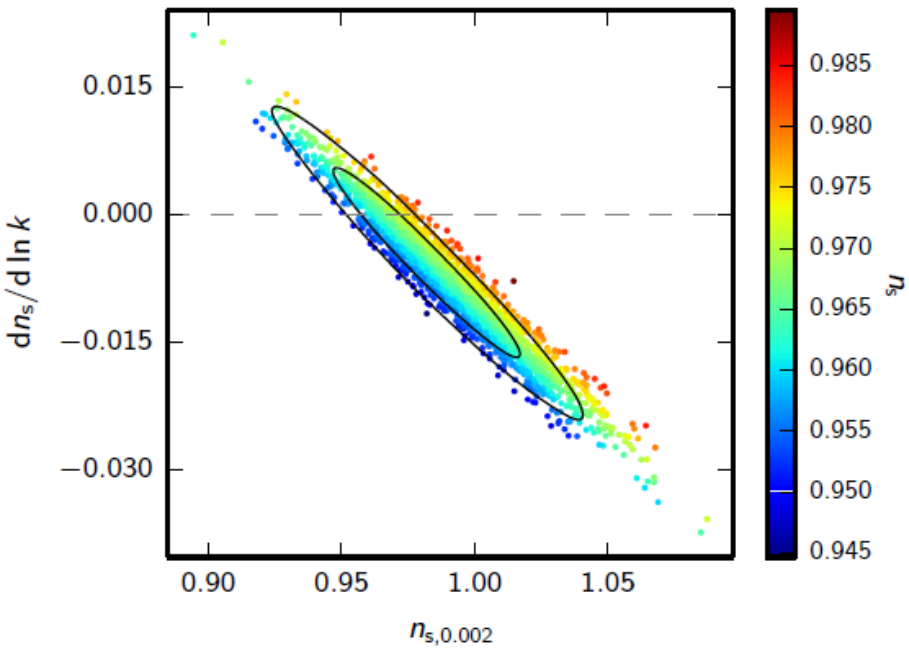
Base LCDM + tensors:

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

$r_{0.002} < 0.12$, *Planck* TT+lowP+lensing+ext

Preliminary

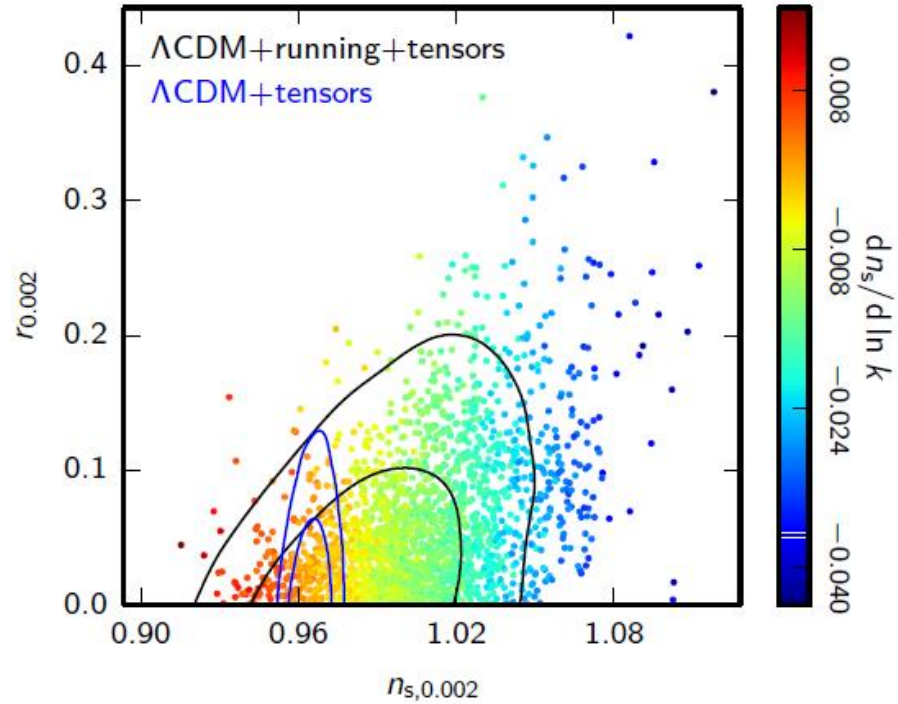
Base LCDM + running



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

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

Base LCDM + running + tensors

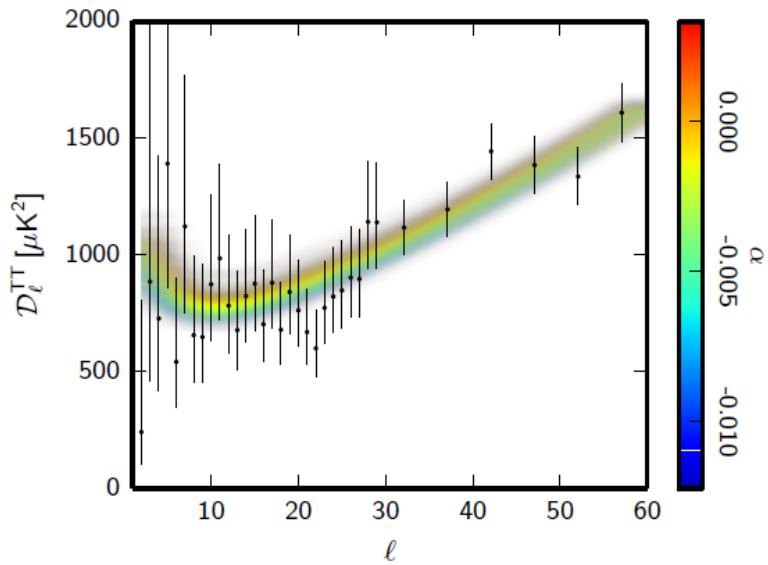


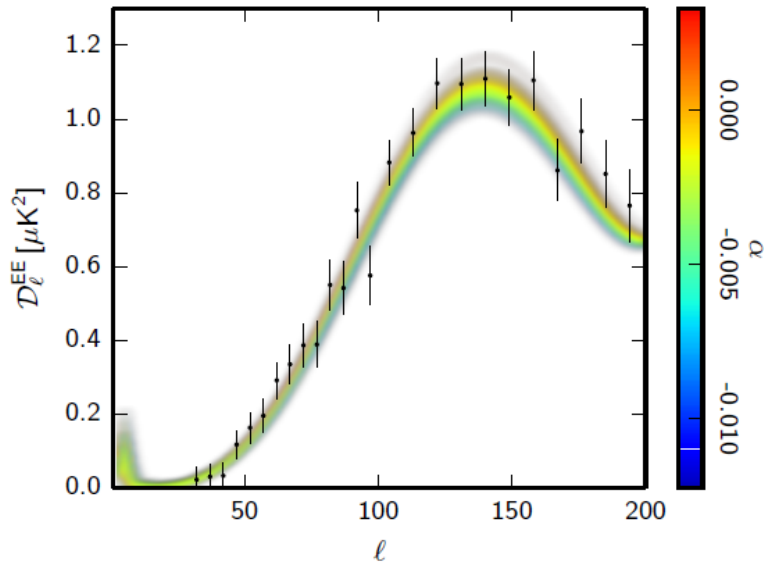
$$\frac{dn_s}{d\ln k} = -0.0126^{+0.0098}_{-0.0087}, \quad \textit{Planck}\ \text{TT+lowP},$$

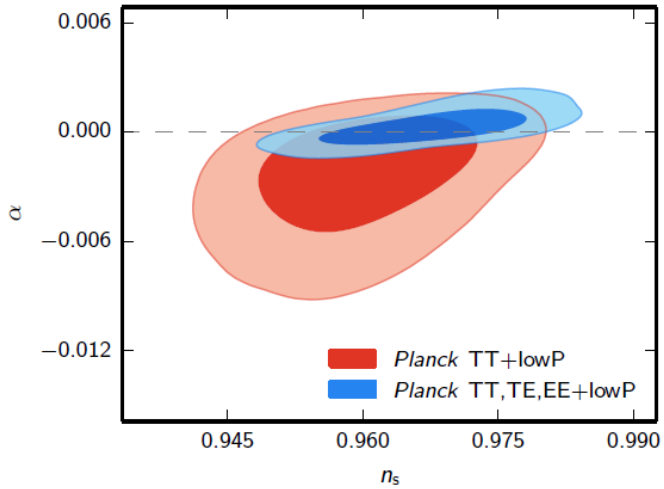
$$\frac{dn_s}{d\ln k} = -0.0085 \pm 0.0076, \quad \textit{Planck}\ \text{TT, TE, EE+lowP}.$$

Preliminary

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





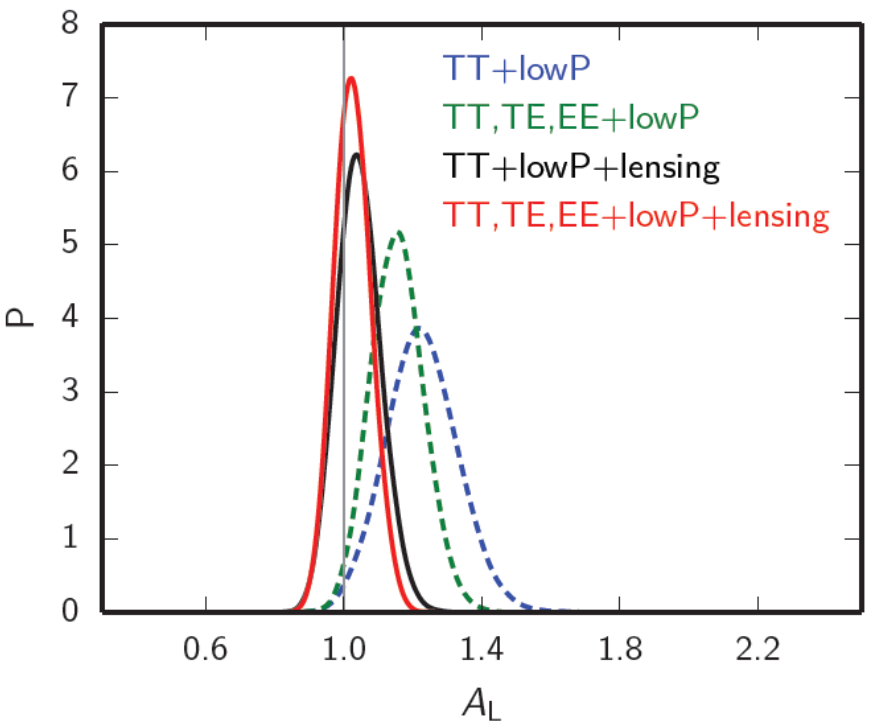


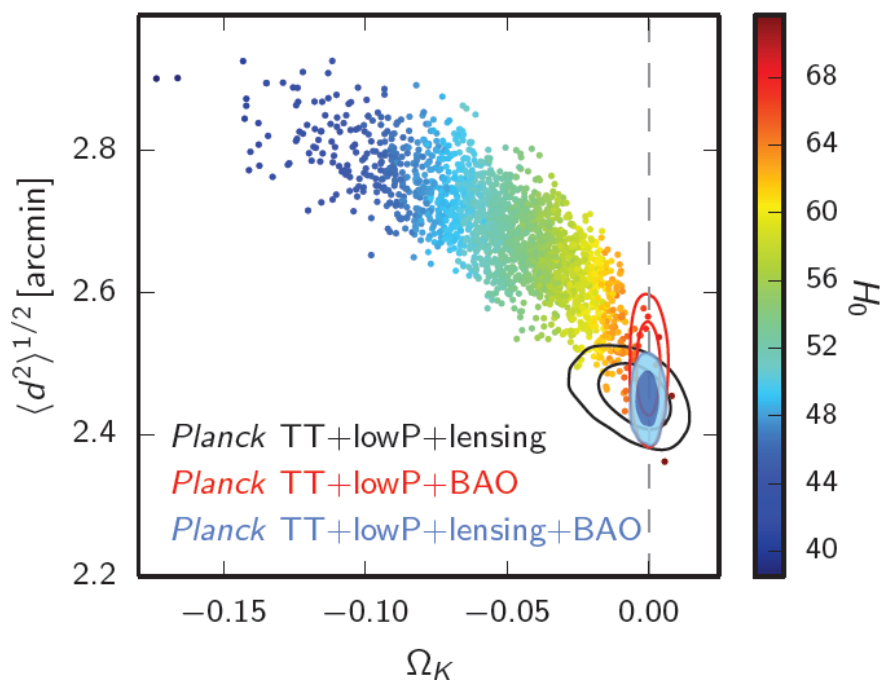
Consistent with adiabatic

Polarization dramatically improves constraint

Preliminary

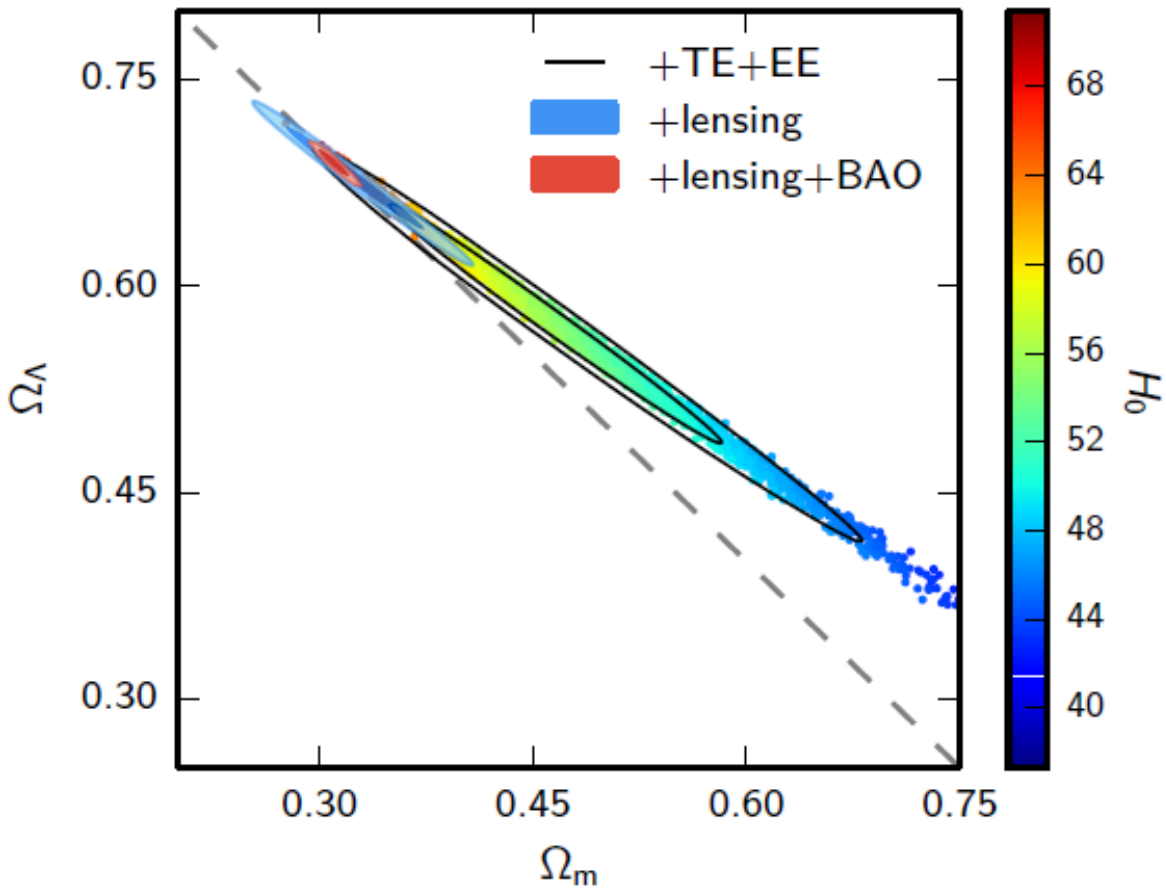
Lensing amplitude and extended parameters





Lensing reduces A_L pulls in CMB power spectrum likelihood.

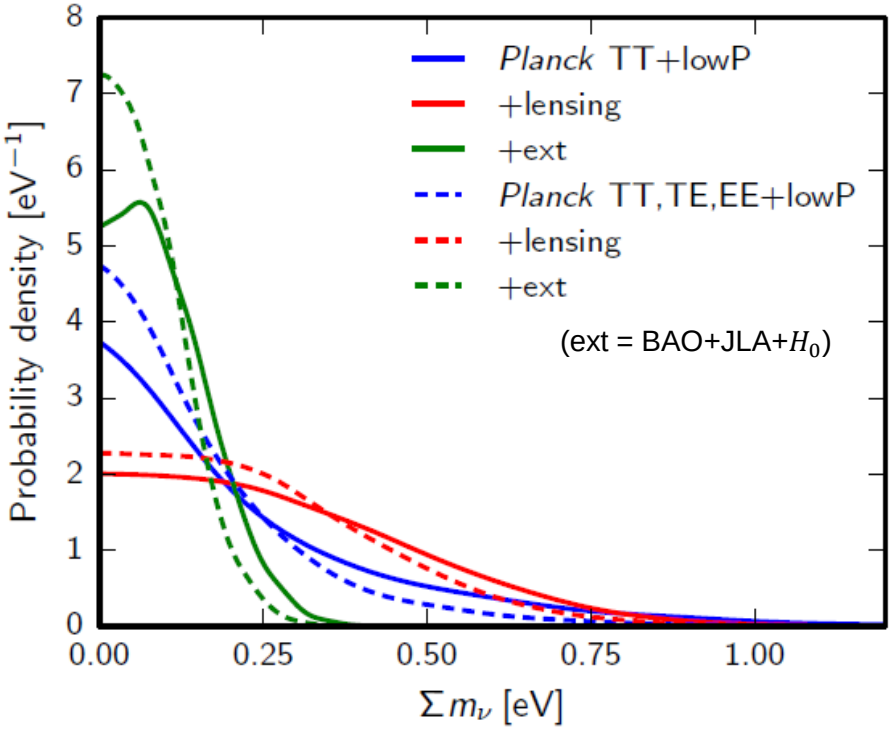
Preliminary

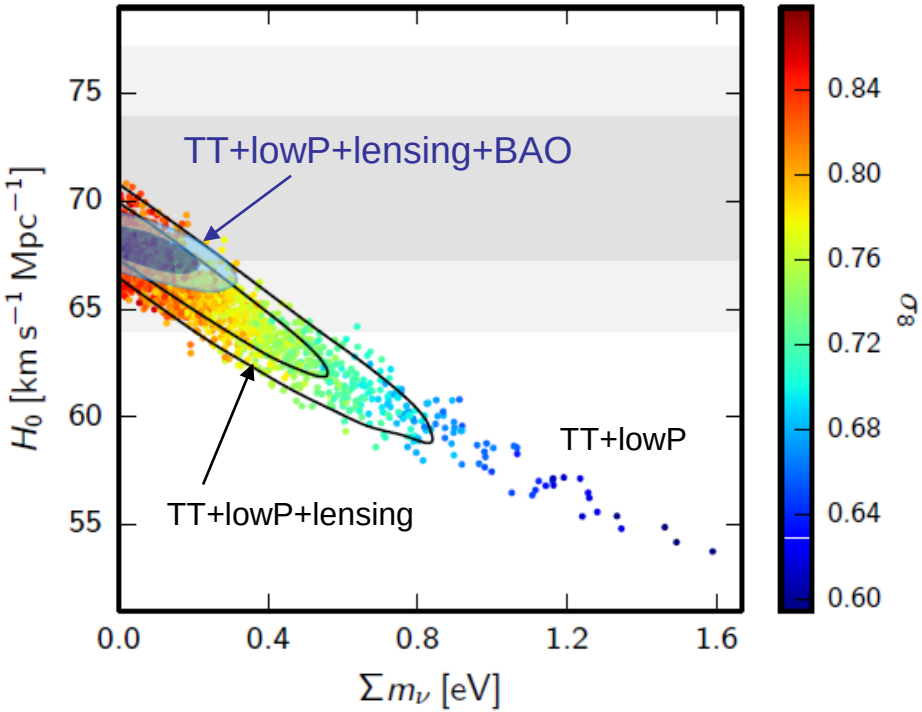


Joint constraints consistent with flat universe

Preliminary

Massive neutrinos





$$\sum m_\nu < 0.72\,\text{eV} \quad \textit{Planck}\ \text{TT+lowP}$$

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

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

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

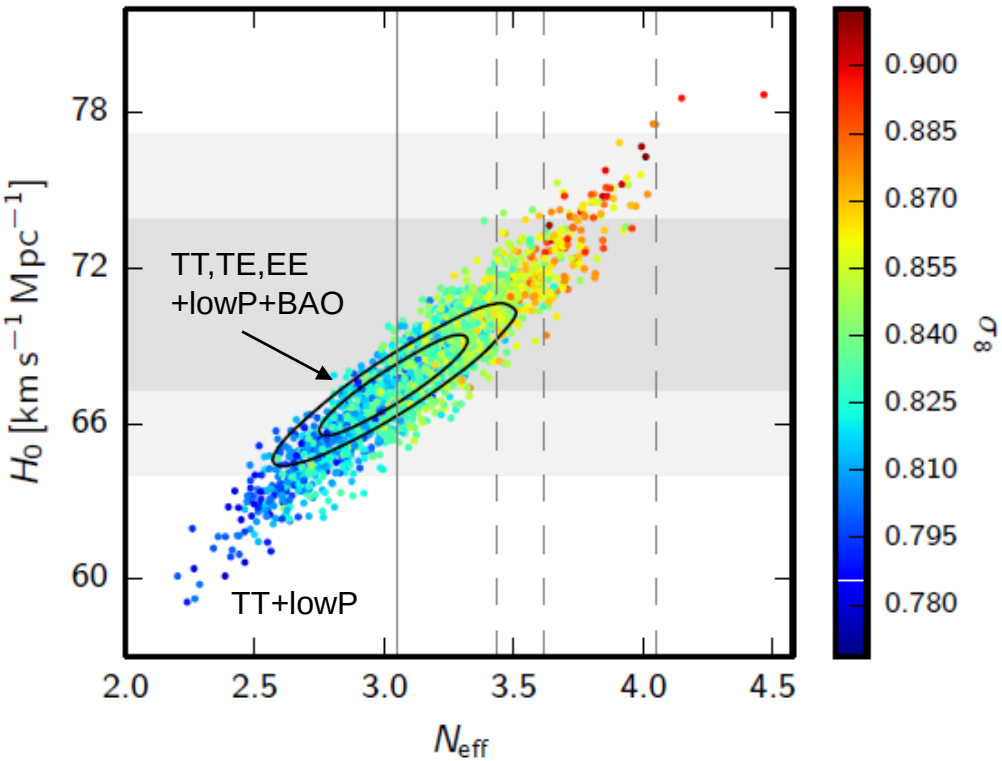
(95% CL)

$$\left.\begin{aligned} H_0 &= 67.7 \pm 0.6 \\ \sigma_8 &= 0.810^{+0.015}_{-0.012} \end{aligned}\right\} \textit{Planck}\ \text{TT+lowP+lensing+ext}$$

(68% CL)

Preliminary

Extra relativistic degrees of freedom



$N_{\rm eff} = 3.13 \pm 0.32$ *Planck* TT+lowP

$N_{\rm eff} = 3.15 \pm 0.23$ *Planck* TT+lowP+BAO

$N_{\rm eff} = 2.99 \pm 0.20$ *Planck* TT, TE, EE+lowP

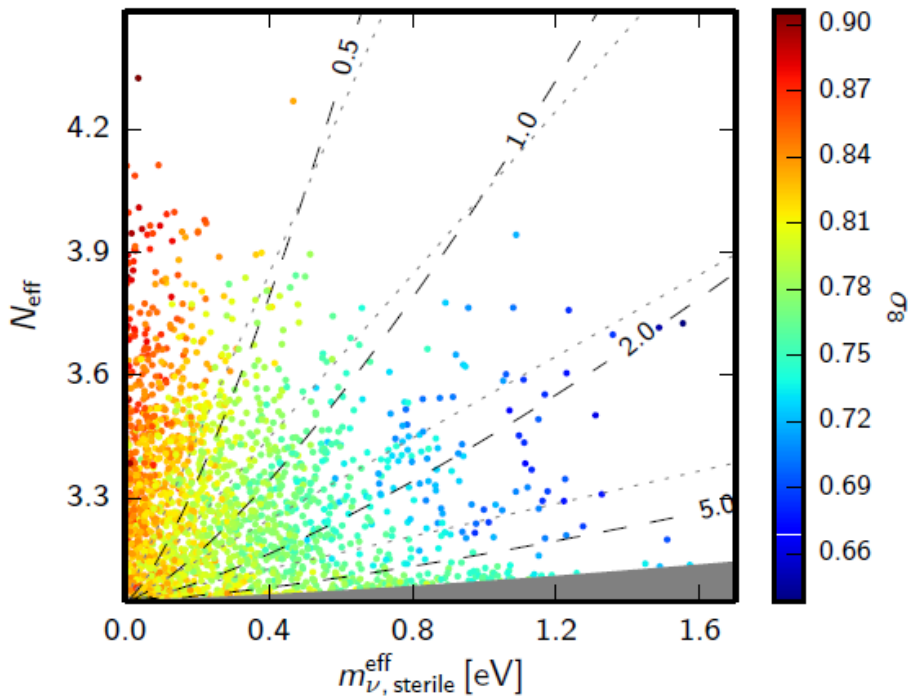
$N_{\rm eff} = 3.04 \pm 0.18$ *Planck* TT, TE, EE+lowP+BAO

(68% CL)

$\Delta N_{\rm eff} < 4$ at over 3σ

Preliminary

Massive sterile neutrinos



Thermalized sterile

$$m^{\rm eff}_{\nu,\,\rm sterile} = (T_s/T_\nu)^3 m^{\rm thermal}_{\rm sterile} = (\Delta N_{\rm eff})^{3/4} m^{\rm thermal}_{\rm sterile}$$

Dodelson-Widrow production by oscillation:

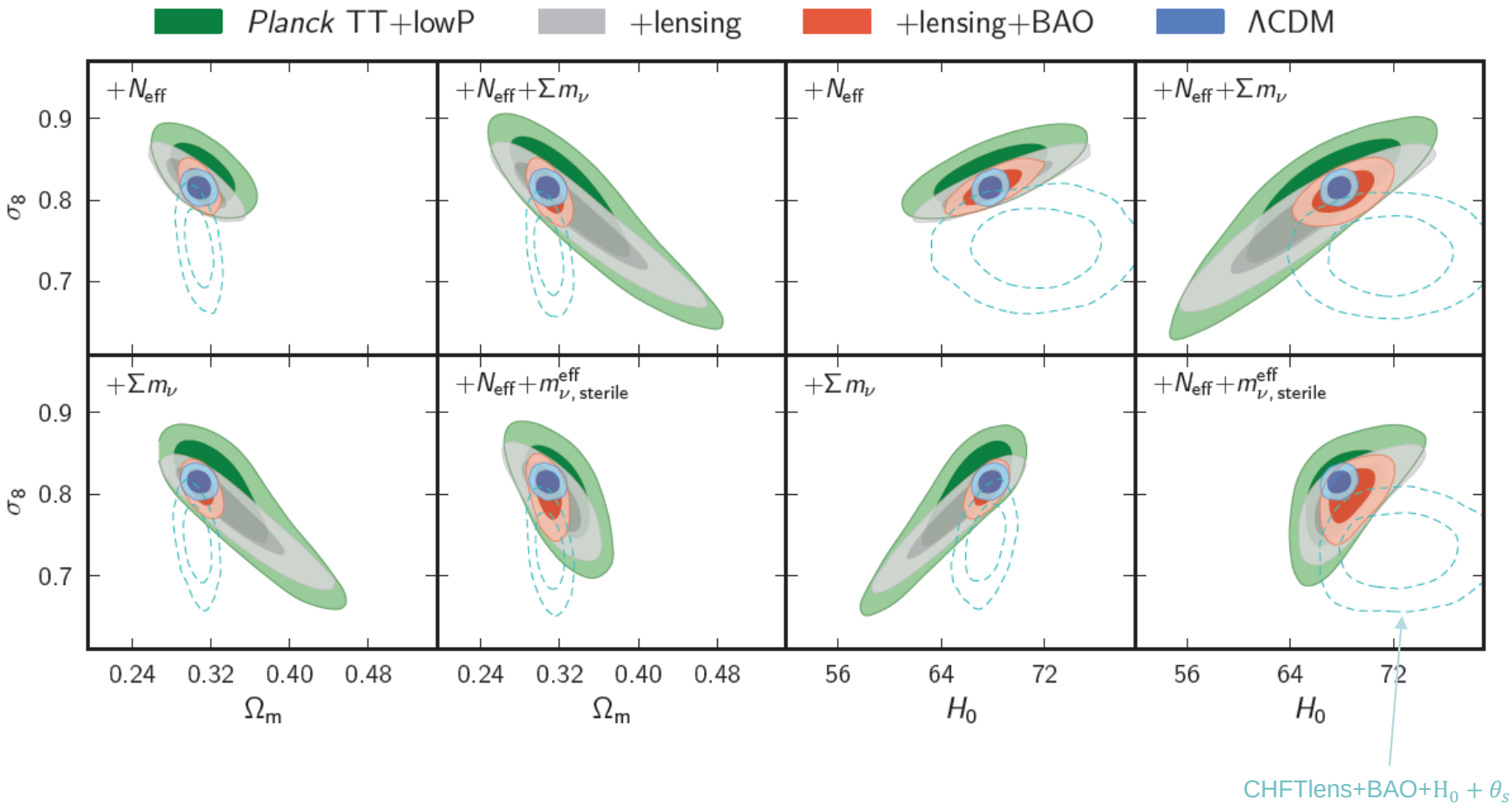
$$m^{\rm eff}_{\nu,\,\rm sterile} = \chi_s m^{\rm DW}_{\rm sterile}$$

$$\left.\begin{array}{r} N_{\rm eff} < 3.7 \\ m^{\rm eff}_{\nu,\,\rm sterile} < 0.38\,{\rm eV} \end{array}\right\} \text{95\%, } \textit{Planck} \text{ TT+lowP+lensing+BAO}$$

(assuming $m_{\rm phys} < 2{\rm eV}$)

Preliminary

Can neutrino models reconcile Planck and lensing/other data?



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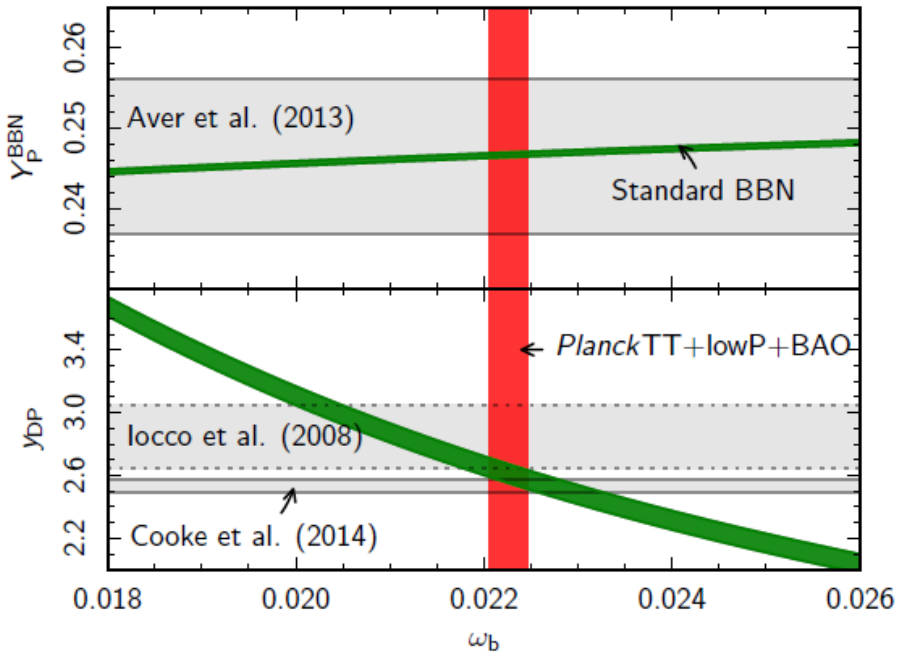
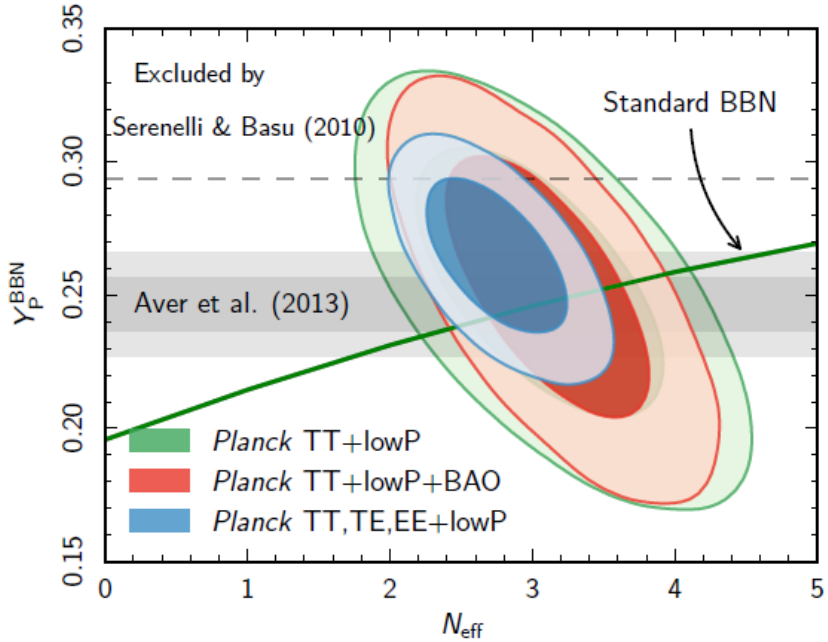
Comparison with BBN predictions and abundance observations





Good consistency with standard BBN and published abundance results

Preliminary

Joint BBN + abundance observation constraints

Aver et al. Helium measurement:

$$N_{\rm eff} = \begin{cases} 3.11^{+0.59}_{-0.57} & \text{heli.} + \textit{Planck}\ \text{TT+lowP}, \\ 3.14^{+0.44}_{-0.43} & \text{heli.} + \textit{Planck}\ \text{TT+lowP+BAO}, \\ 2.99^{+0.39}_{-0.39} & \text{heli.} + \textit{Planck}\ \text{TT,TE,EE+lowP}, \end{cases}$$

(95% CL)

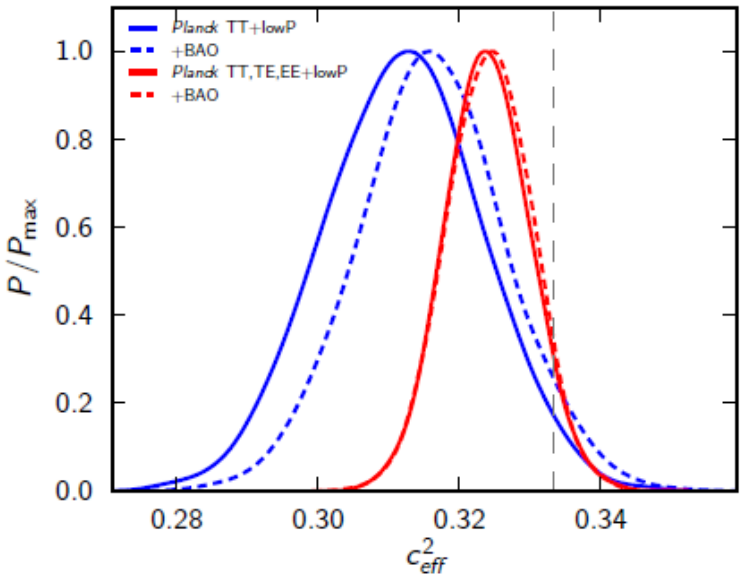
Cooke et al. D/H measurement:

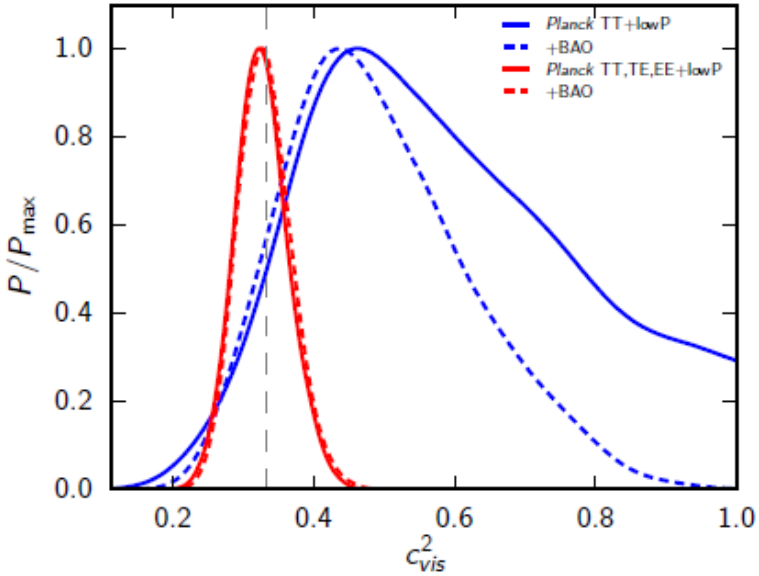
$$N_{\rm eff} = \begin{cases} 2.95^{+0.52}_{-0.52} & \text{deu.} + \textit{Planck}, \text{TT} \\ 3.01^{+0.38}_{-0.37} & \text{deu.} + \textit{Planck}\ \text{TT+lowP+BAO}, \\ 2.91^{+0.37}_{-0.37} & \text{deu.} + \textit{Planck}\ \text{TT,TE,EE+lowP}, \end{cases}$$

(95% CL)

Fully consistent with standard $N_{\rm eff} = 3.046$

Tests for non-standard neutrinos



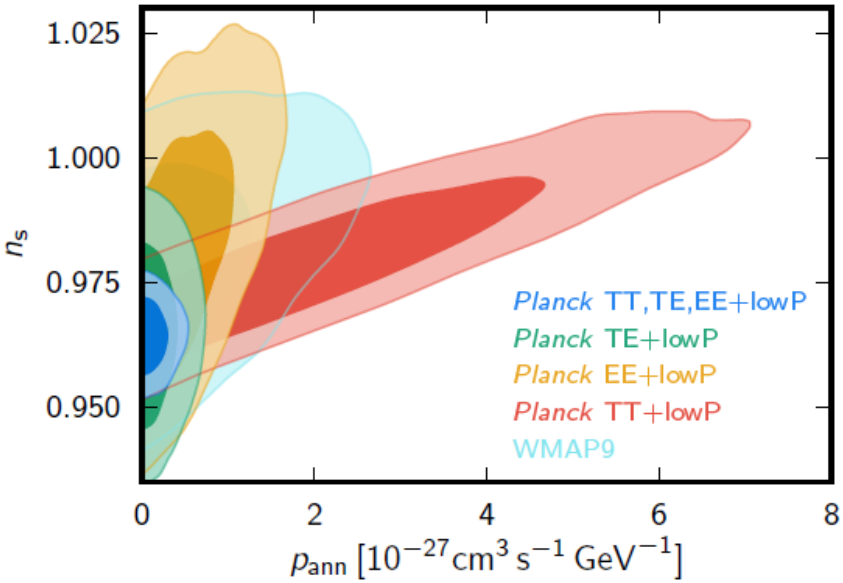


- consistent with free-streaming non-interacting neutrinos: $c^2_{\mathrm{eff}} = c^2_{\mathrm{vis}} = 1/3$
- Polarization greatly strengthens results (sensitive to phase shifts)

Dark matter annihilation

$$\frac{dE}{dtdV}(z) = 2\,g\,\rho_c^2 c^2 \Omega_c^2 (1+z)^6 p_{\rm ann}(z)$$

$$p_{\rm ann}(z) \equiv f(z)\frac{\langle \sigma v \rangle}{m_\chi}$$



Data combinations	$p_{\rm ann}$ (95% upper limits)
TT+lowP	$< 5.7 \times 10^{-27}$
EE+lowP	$< 1.4 \times 10^{-27}$
TE+lowP	$< 5.9 \times 10^{-28}$
TT+lowP+lensing	$< 4.4 \times 10^{-27}$
TT,TE,EE+lowP	$< 4.1 \times 10^{-28}$
TT,TE,EE+lowP+lensing	$< 3.4 \times 10^{-28}$
TT,TE,EE+lowP+ext	$< 3.5 \times 10^{-28}$

Huge gain from polarization!

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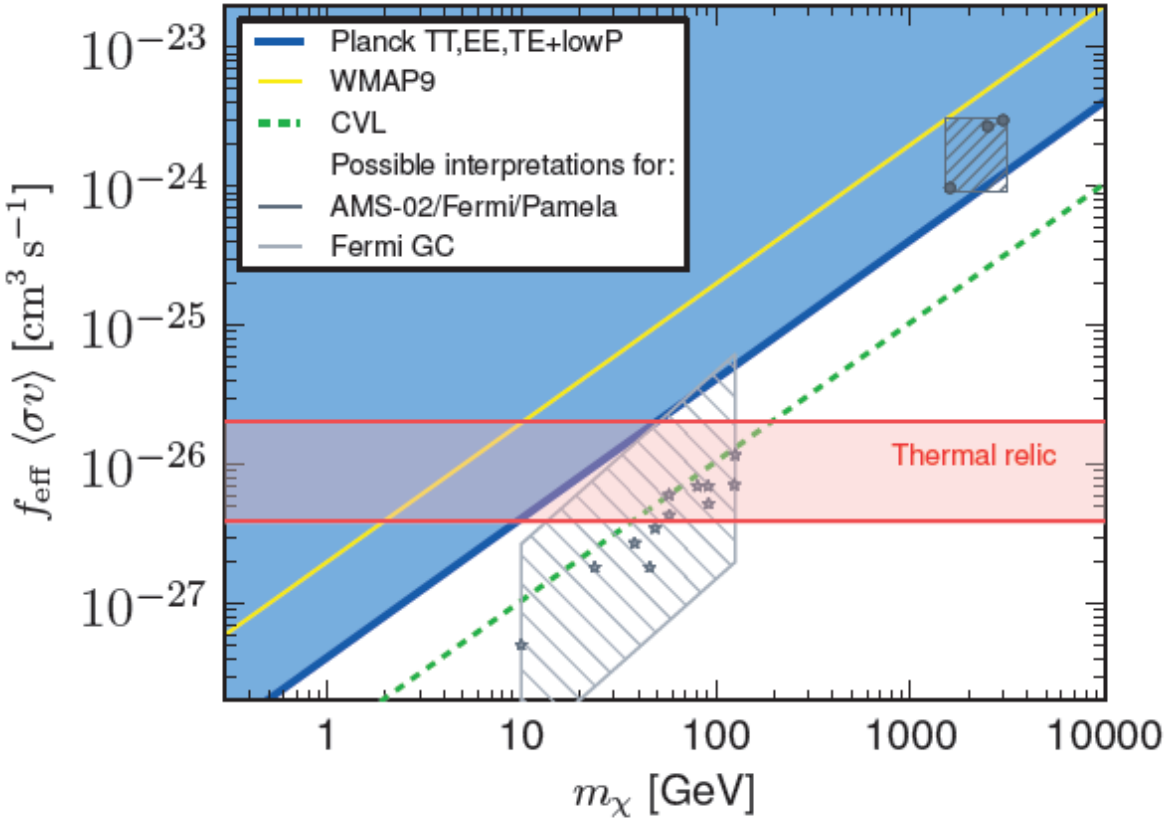


Preliminary

Preliminary conclusions

Main cosmology conclusions of 2013 unchanged, smaller errors

Many analysis improvements/corrections, many more to come
- including low-L HFI polarization

Powerful CMB lensing constraint on the amplitude

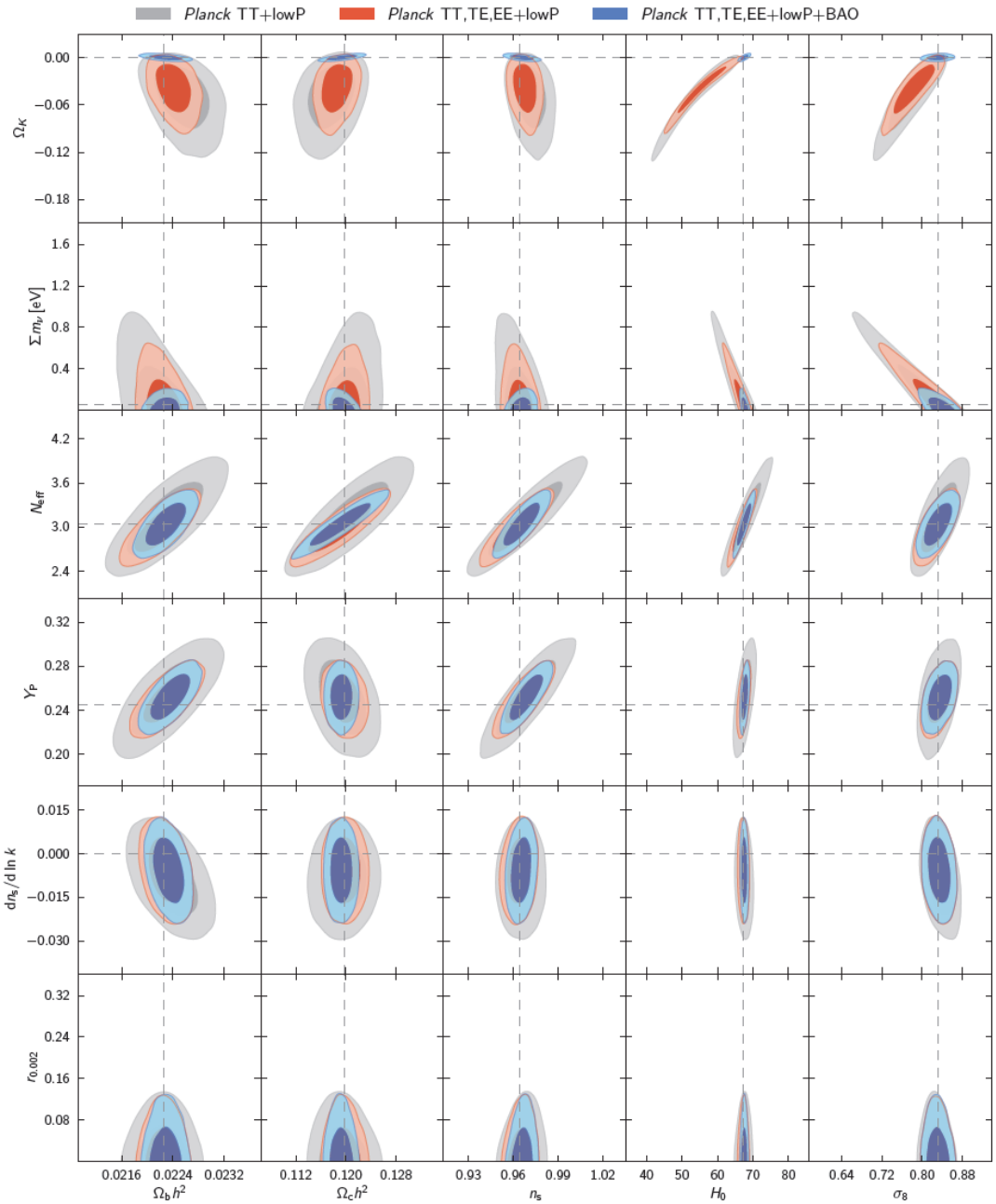
Broadly consistent with LCDM and minimal-mass standard neutrinos
but:
- tensions with external data; no obvious way to reconcile all
- some puzzles like high A_L
- significant variations from base LCDM still allowed
(e.g. $\sum m_\nu \lesssim 0.2\mathrm{eV}$, $\Delta N_{\mathrm{eff}} \lesssim 0.4$)

Polarization can significantly tighten constraints (DM annihilation, isocurvature..)
- work in progress, more robust analysis next year

Coming soon…. Planck+BICEP+Keck B-mode r constraints

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.



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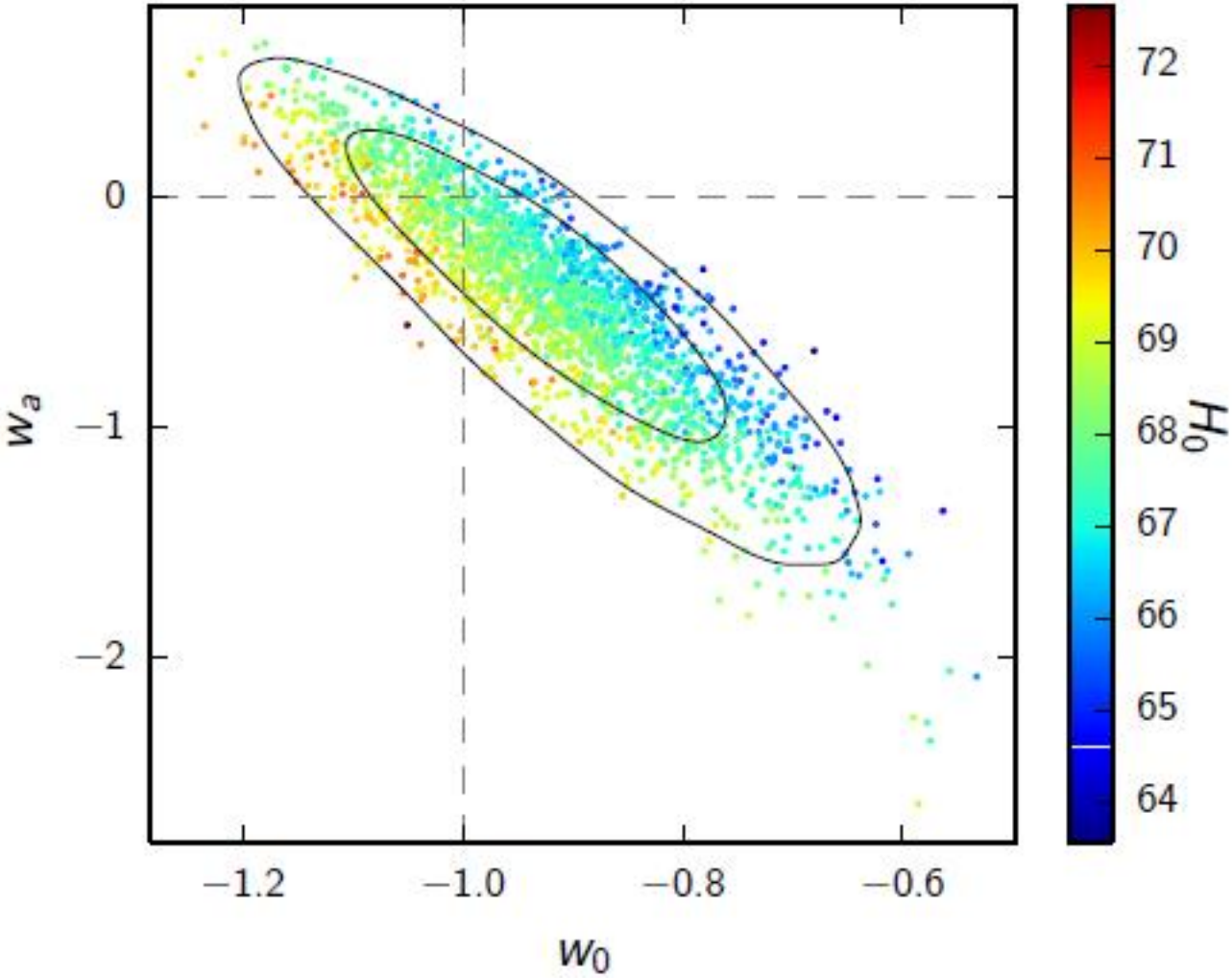

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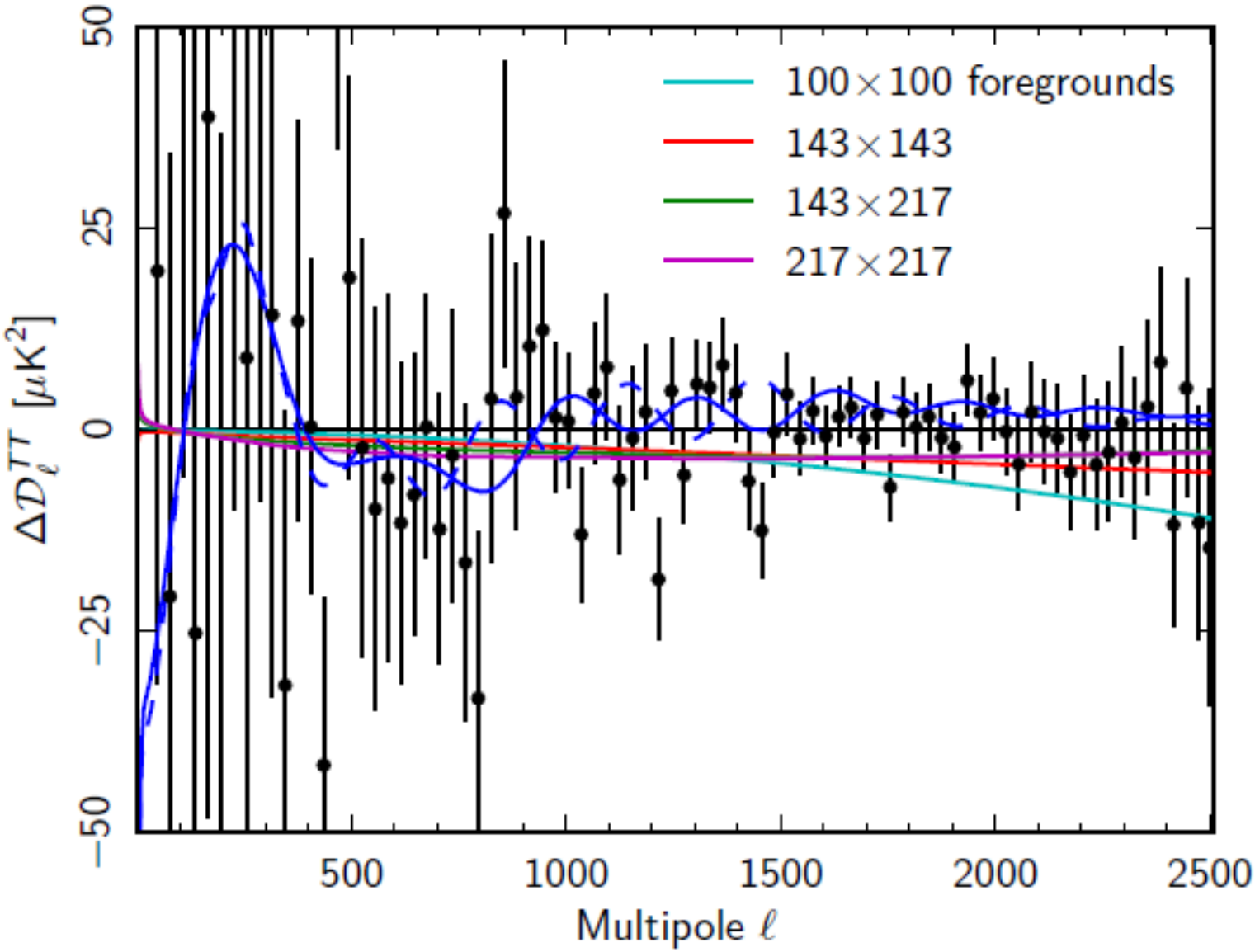

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