Planck 2018

Cosmology & Parameters

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http://cosmologist.info/

on behalf of the Planck Collaboration.

First batch

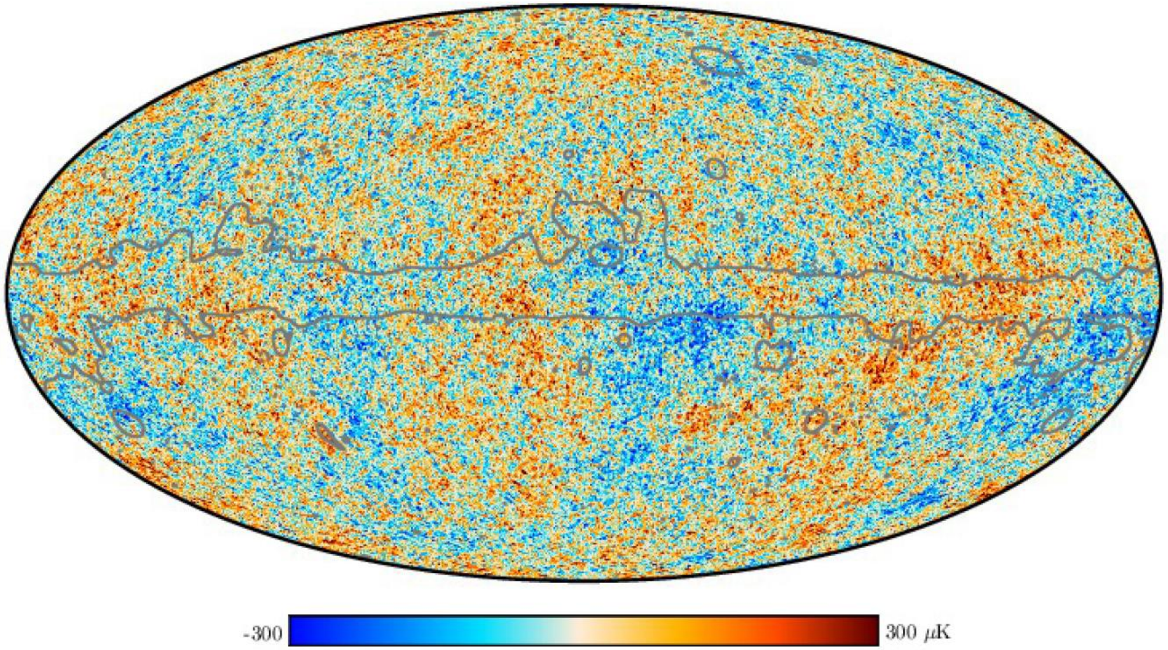
http://www.cosmos.esa.int/web/planck/publications

- Planck 2018 results. I. Overview, and the cosmological legacy of Planck
- Planck 2018 results. II. Low Frequency Instrument data processing
- Planck 2018 results. III. High Frequency Instrument data processing
- Planck 2018 results. IV. CMB and foreground extraction
- Planck 2018 results. VI. Cosmological parameters
- Planck 2018 results. VIII. Gravitational lensing
- Planck 2018 results. X. Constraints on inflation
- Planck 2018 results. XI. Polarized dust foregrounds (submitted)
- Planck 2018 results. XII. Galactic astrophysics using polarized dust emission

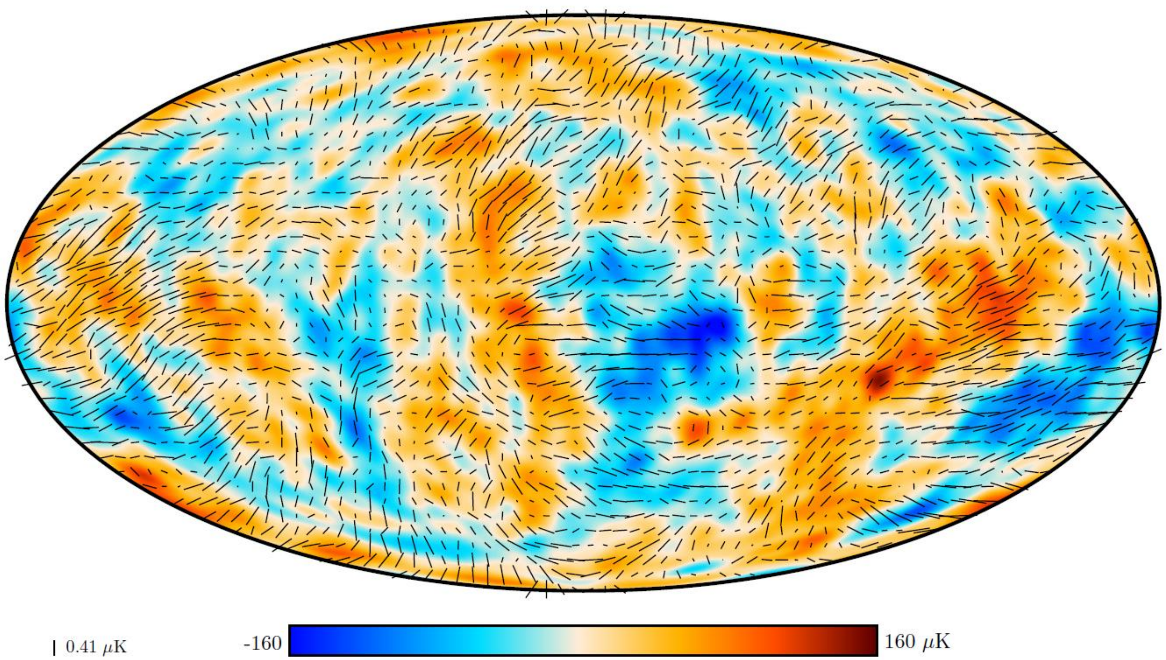
Coming later

Planck 2018 results. V. Legacy Power Spectra and Likelihoods
Planck 2018 results. VII. Isotropy and statistics
Planck 2018 results. IX. Constraints on primordial non-Gaussianity

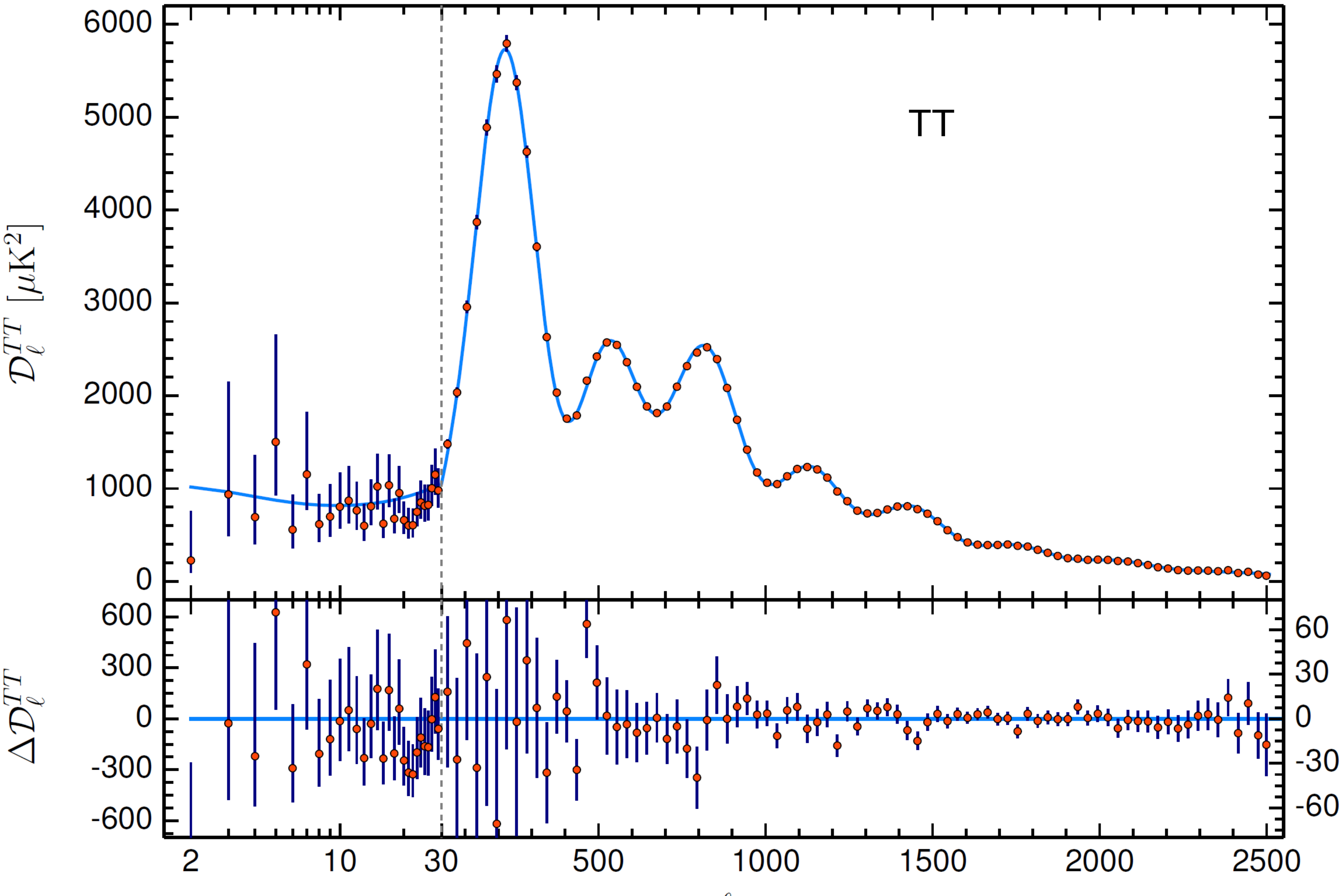
⇒ Only lensing likelihoods released today. CMB likelihoods with likelihood paper.



Temperature

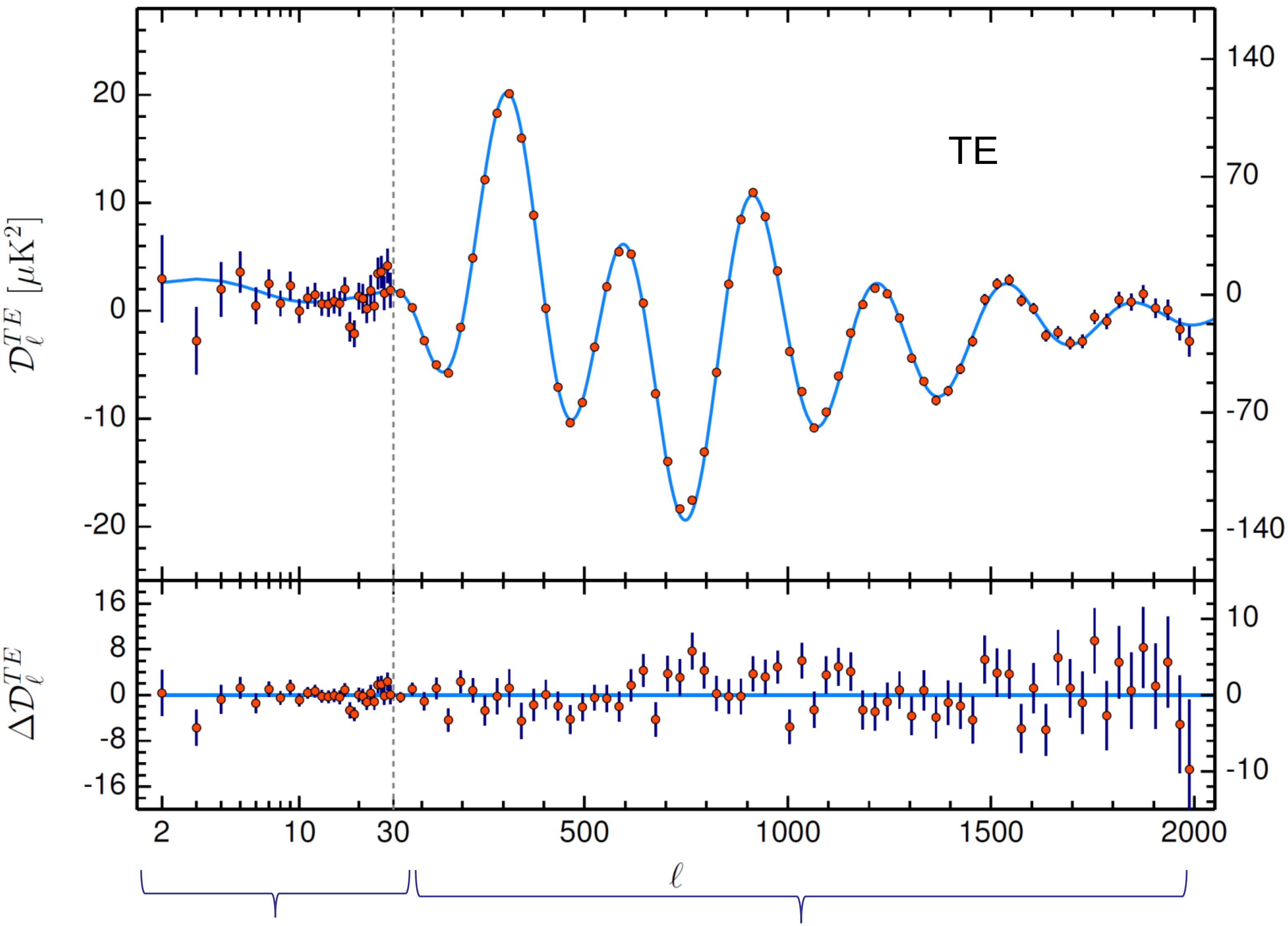


Smoothed T
+ polarization



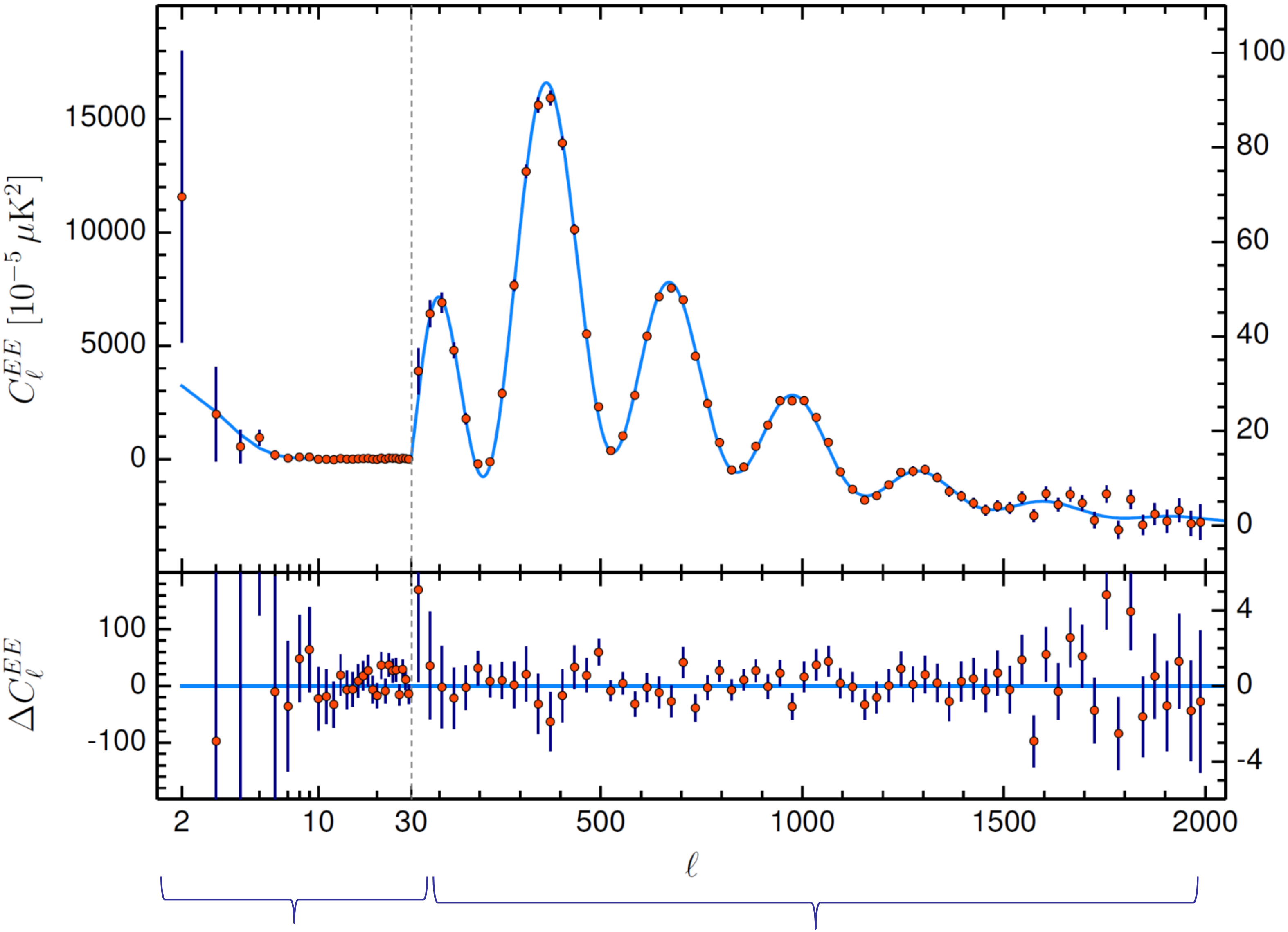
$2 \leq \ell \leq 29$:
"Commander"
Gibbs likelihood

$\ell \geq 30$: "plik" HM C_ℓ likelihood



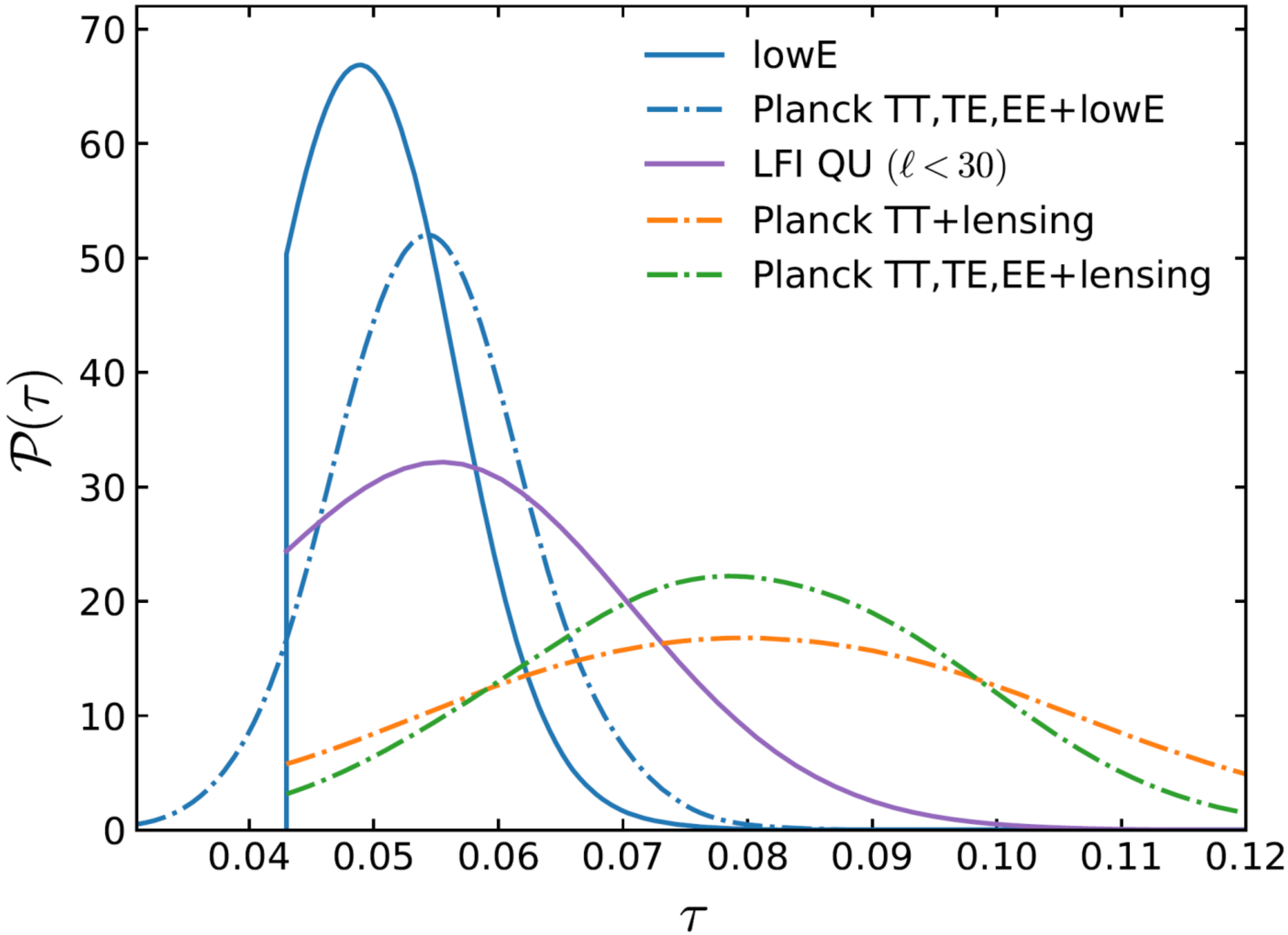
$2 \leq \ell \leq 29$
NOT USED

$\ell \geq 30$: “plik” HM C_ℓ likelihood



$2 \leq \ell \leq 29$
lowE “SimAll” likelihood

$\ell \geq 30$: “plik” HM C_ℓ likelihood

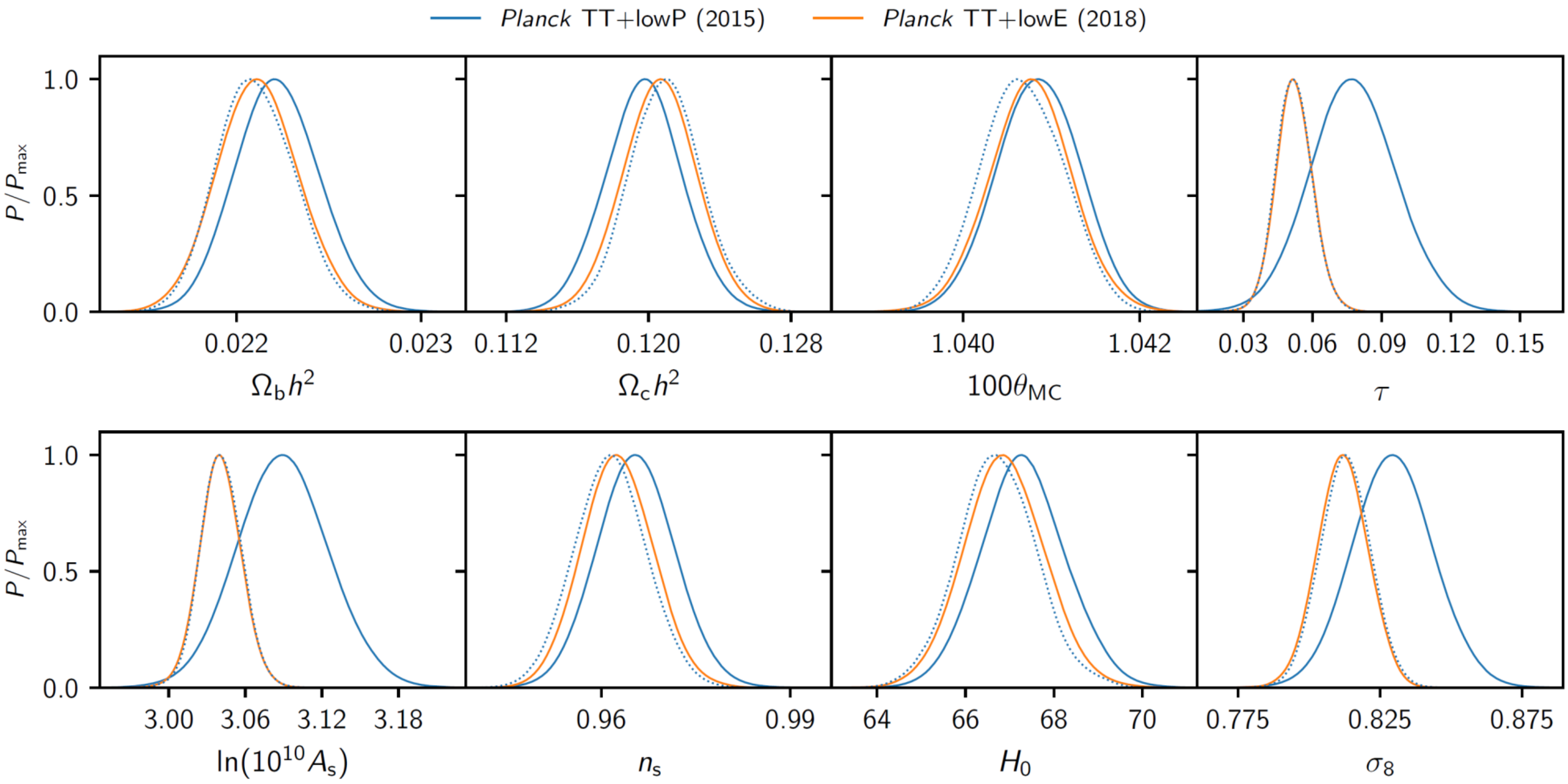


2018: $\tau = 0.0506 \pm 0.0086 \quad (68\,\%,\ \mathrm{lowE})$

2015: $\tau = 0.067 \pm 0.022$

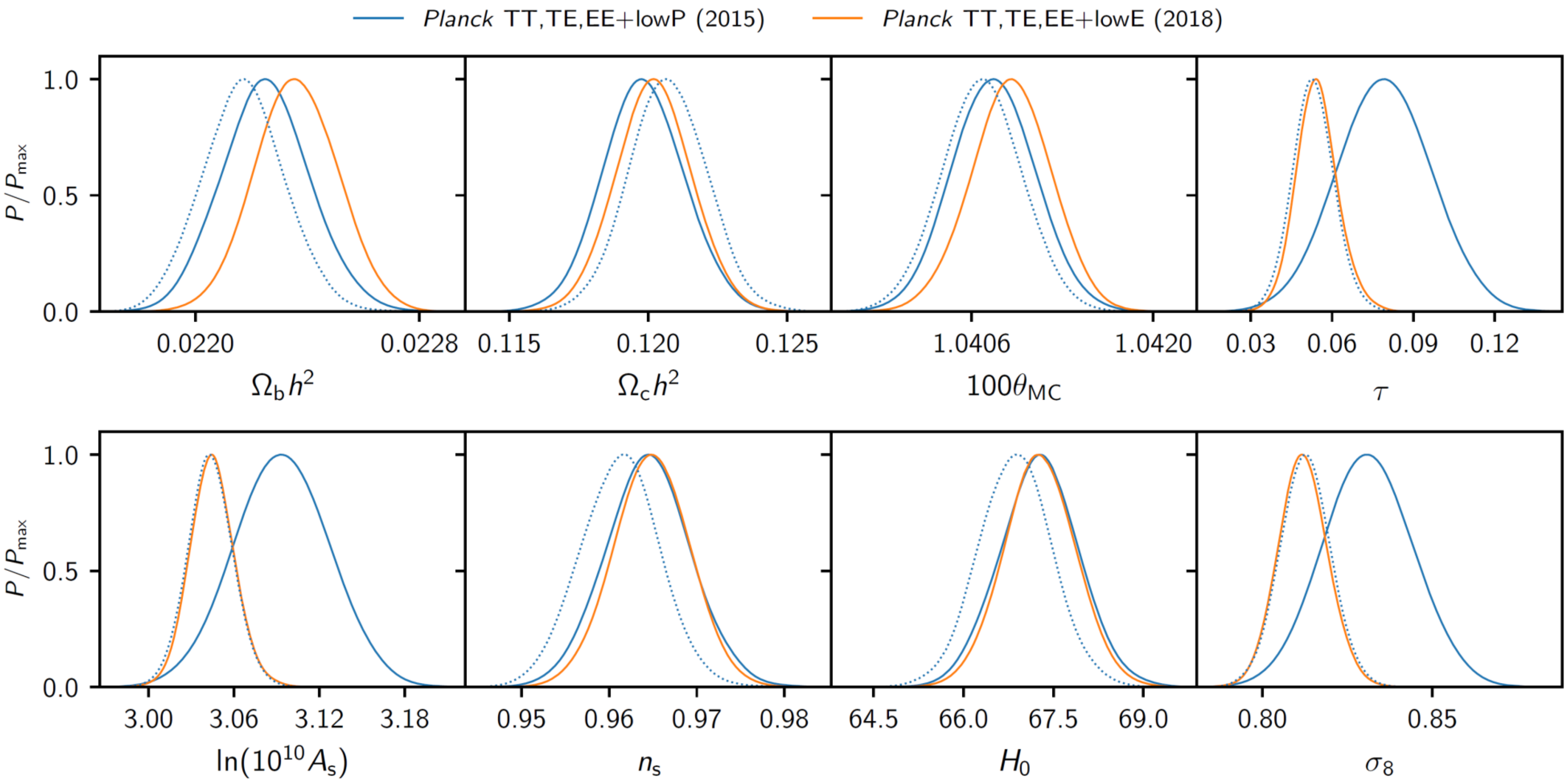
2016: $\tau = 0.055 \pm 0.009$

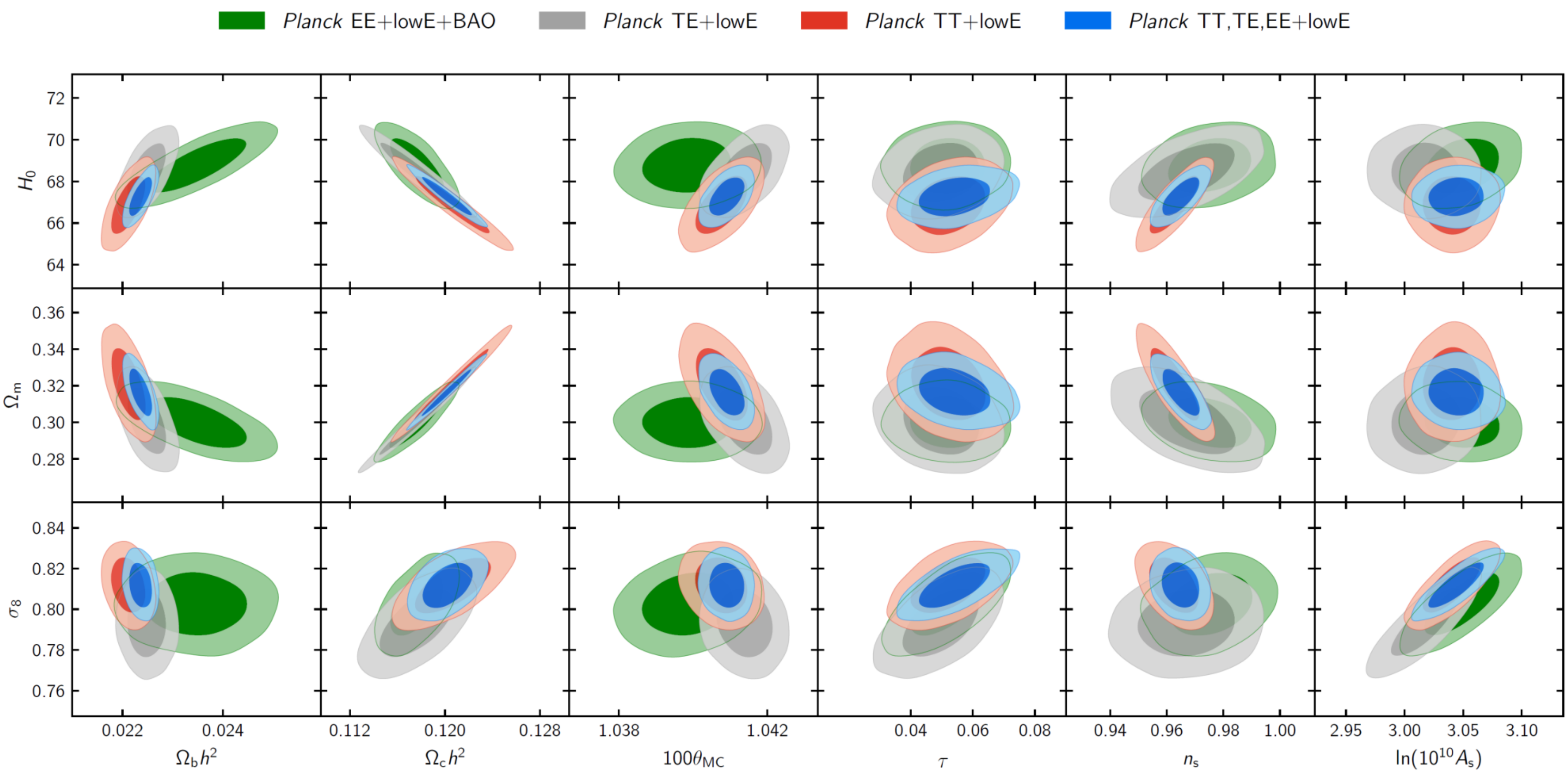
LCDM* parameters: temperature + low-ℓ polarization



* Flat, power-law scalar adiabatic perturbations, 3 active neutrinos, $m_\nu = 0.06$ eV

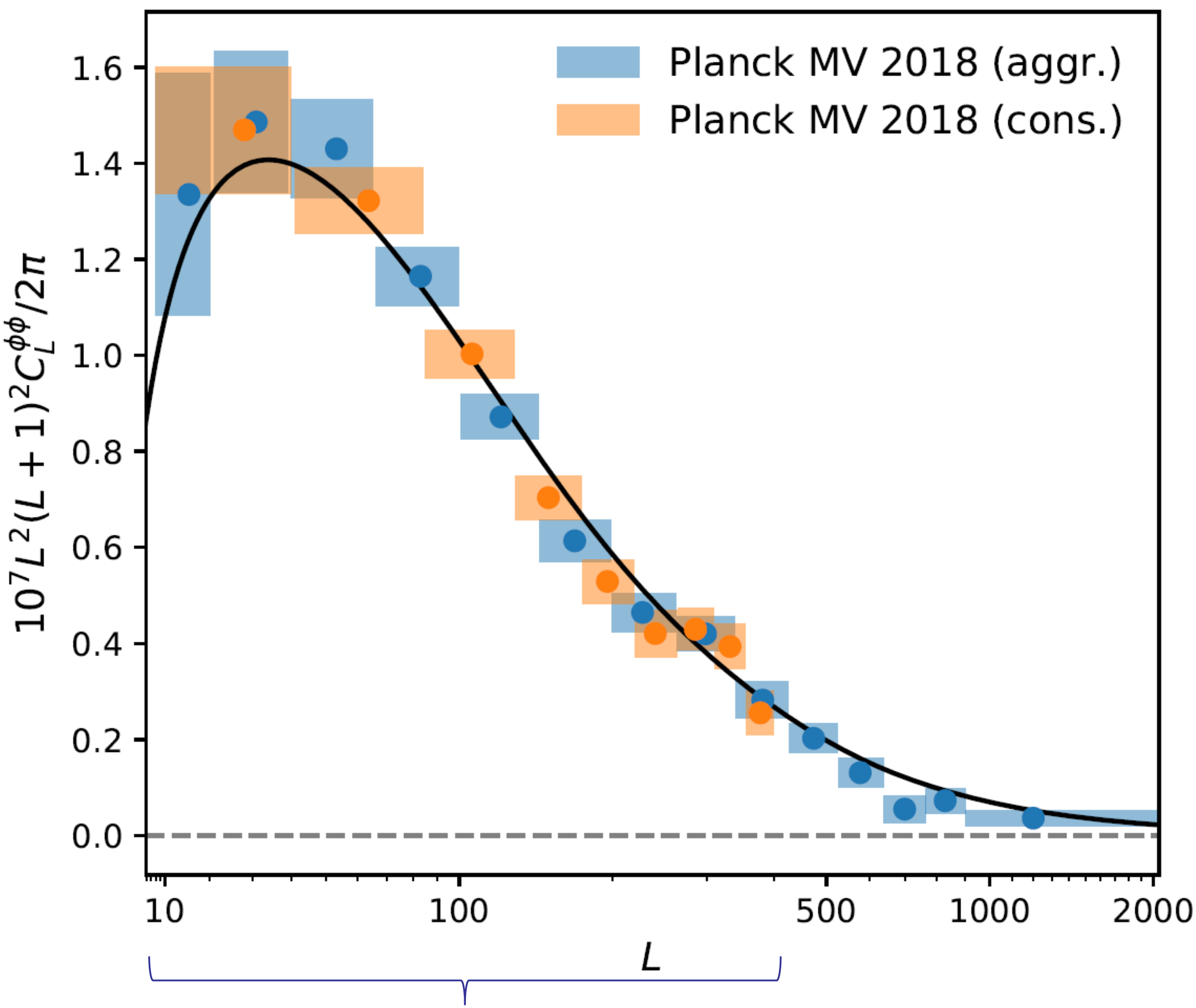
LCDM parameters: all temperature + polarization





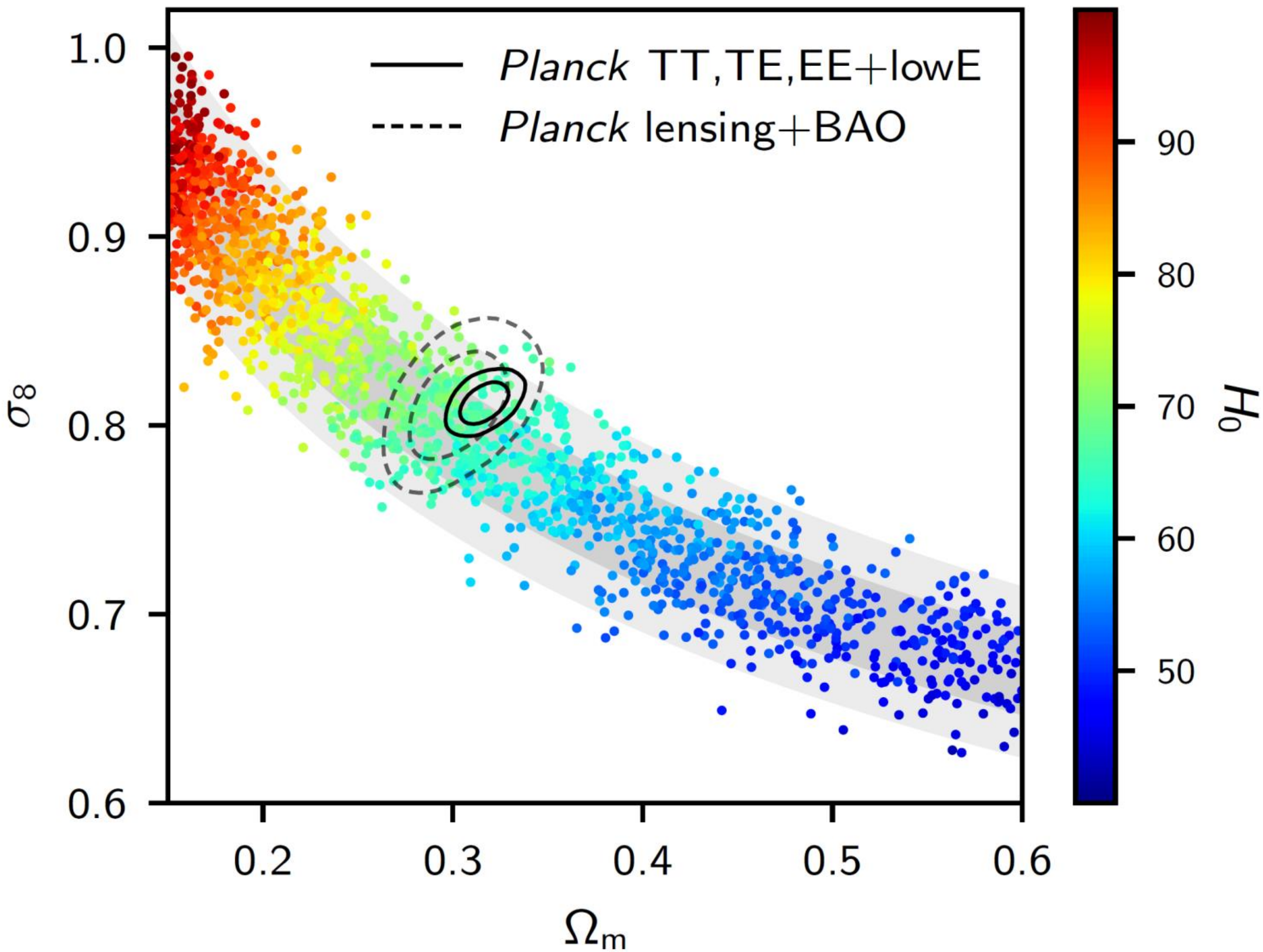
Planck EE+lowE+BAO
Planck TE+lowE
Planck TT+lowE
Planck TT,TE,EE+lowE
H_0
Ω_m
σ_8
$\Omega_b h^2$
$\Omega_c h^2$
$100\theta_{MC}$
τ
n_s
$\ln(10^{10} A_s)$

CMB lensing reconstruction



$8 \leq L \leq 400$:
"Conservative" lensing likelihood

CMB lensing best measures ~ $\sigma_8\Omega_m^{0.25}$ = 0.589 $\pm$ 0.020.



Baseline TT,TE,EE+lowE+lensing LCDM parameters

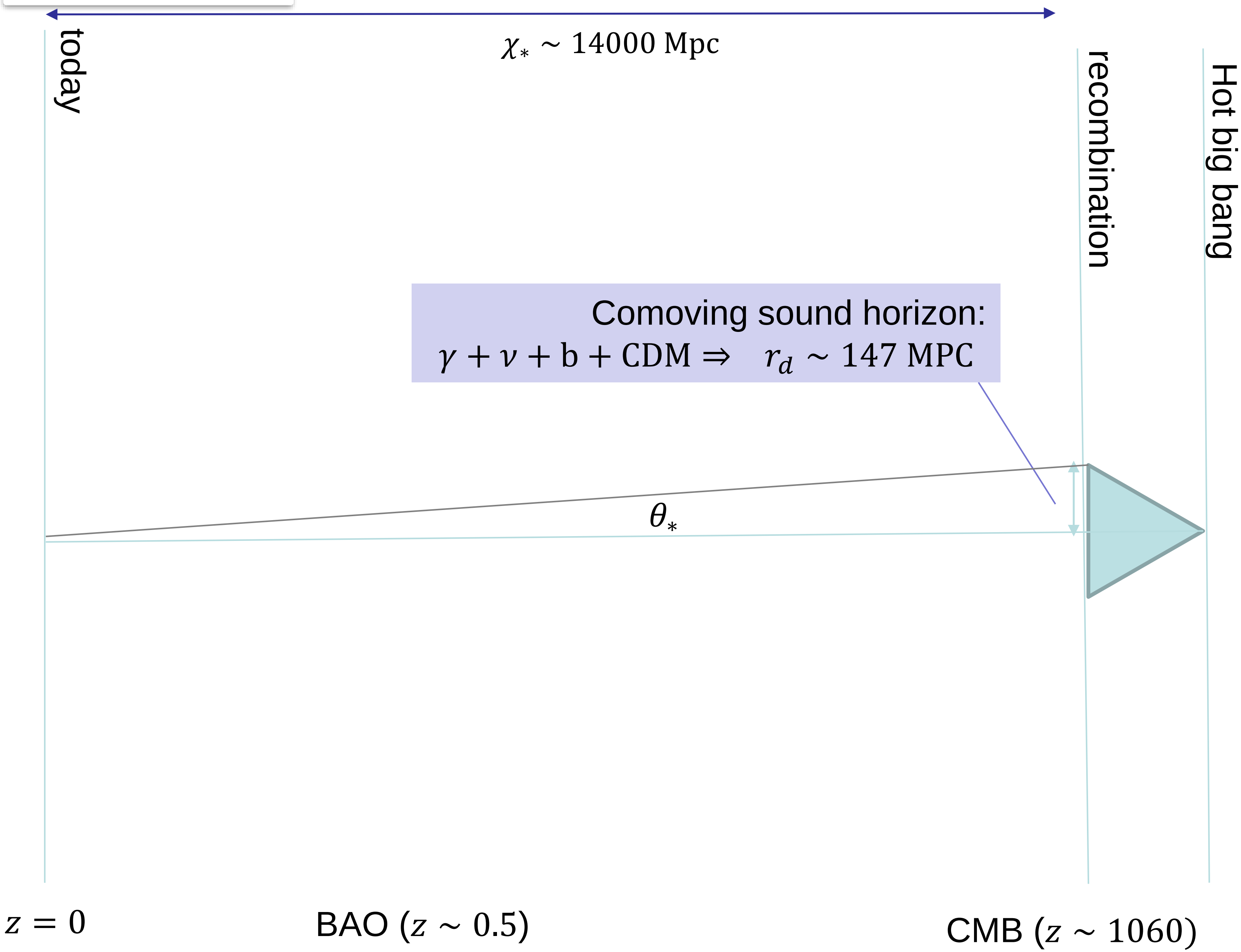
Parameter	Plik best fit	Plik [1]	CamSpec [2]	$([2]-[1])/\sigma_1$	Combined
$\Omega_b h^2$	0.022383	0.02237 ± 0.00015	0.02229 ± 0.00015	-0.5	0.02233 ± 0.00015
$\Omega_c h^2$	0.12011	0.1200 ± 0.0012	0.1197 ± 0.0012	-0.3	0.1198 ± 0.0012
$100\theta_{MC}$	1.040909	1.04092 ± 0.00031	1.04087 ± 0.00031	-0.2	1.04089 ± 0.00031
τ	0.0543	0.0544 ± 0.0073	$0.0536^{+0.0069}_{-0.0077}$	-0.1	0.0540 ± 0.0074
$\ln(10^{10} A_s)$	3.0448	3.044 ± 0.014	3.041 ± 0.015	-0.3	3.043 ± 0.014
n_s	0.96605	0.9649 ± 0.0042	0.9656 ± 0.0042	$+0.2$	0.9652 ± 0.0042
$\Omega_m h^2$	0.14314	0.1430 ± 0.0011	0.1426 ± 0.0011	-0.3	0.1428 ± 0.0011
H_0 [km s^{-1}Mpc^{-1}]	67.32	67.36 ± 0.54	67.39 ± 0.54	$+0.1$	67.37 ± 0.54
Ω_m	0.3158	0.3153 ± 0.0073	0.3142 ± 0.0074	-0.2	0.3147 ± 0.0074
Age [Gyr]	13.7971	13.797 ± 0.023	13.805 ± 0.023	$+0.4$	13.801 ± 0.024
σ_8	0.8120	0.8111 ± 0.0060	0.8091 ± 0.0060	-0.3	0.8101 ± 0.0061
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$	0.8331	0.832 ± 0.013	0.828 ± 0.013	-0.3	0.830 ± 0.013
z_{re}	7.68	7.67 ± 0.73	7.61 ± 0.75	-0.1	7.64 ± 0.74
$100\theta_*$	1.041085	1.04110 ± 0.00031	1.04106 ± 0.00031	-0.1	1.04108 ± 0.00031
r_{drag} [Mpc]	147.049	147.09 ± 0.26	147.26 ± 0.28	$+0.6$	147.18 ± 0.29

Baseline likelihood — Alternative likelihood

LCDM results robust to $\sim 0.5\sigma$ (where σ is small)

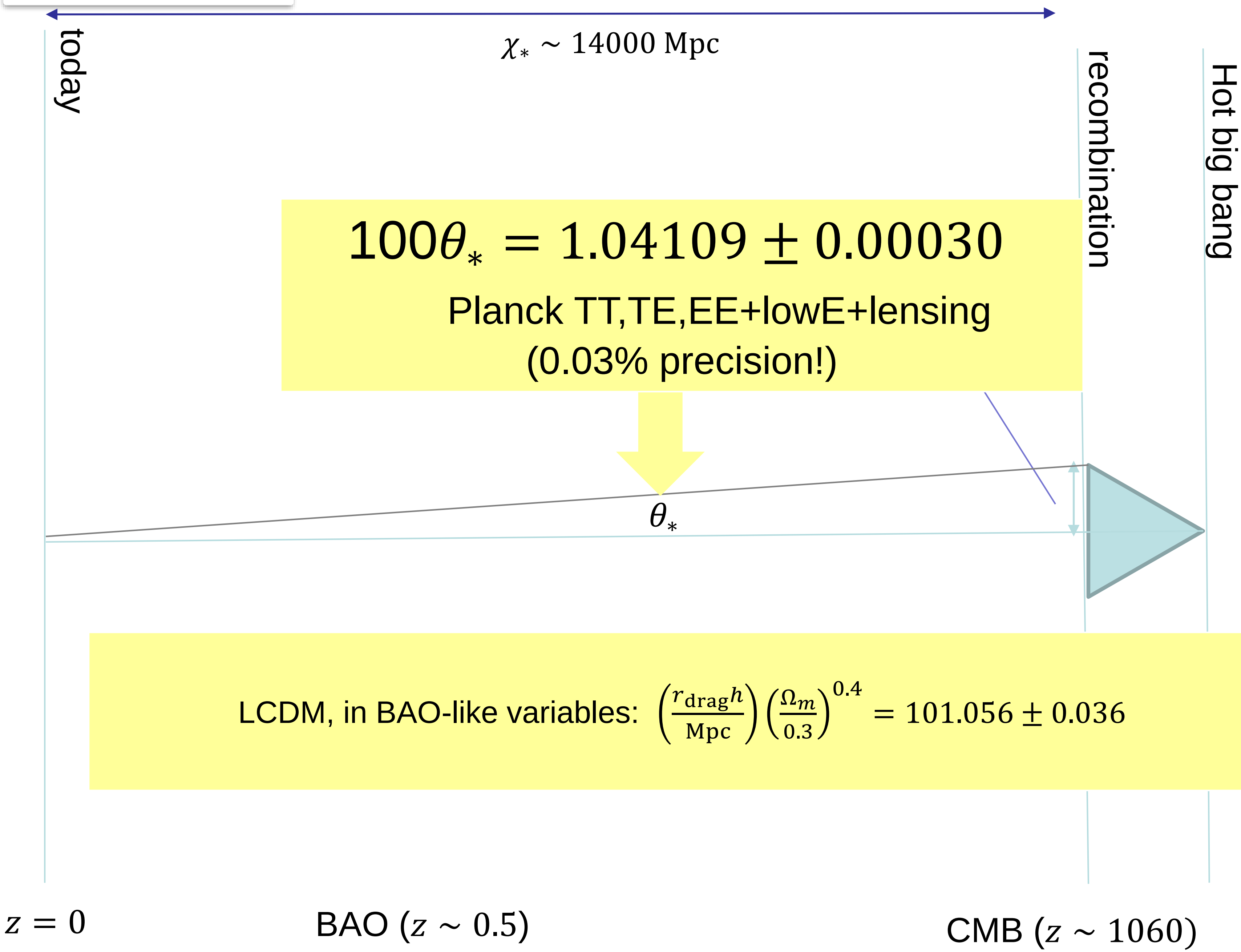
Is Planck+LCDM consistent with other astrophysical data?

CMB and BAO



$\chi_* \sim 14000$ Mpc
today
recombination
Hot big bang
Comoving sound horizon:
$\gamma + \nu + \mathrm{b} + \mathrm{CDM} \Rightarrow \quad r_d \sim 147$ MPC
θ_*
$z = 0$
BAO ($z \sim 0.5$)
CMB ($z \sim 1060$)

CMB and BAO

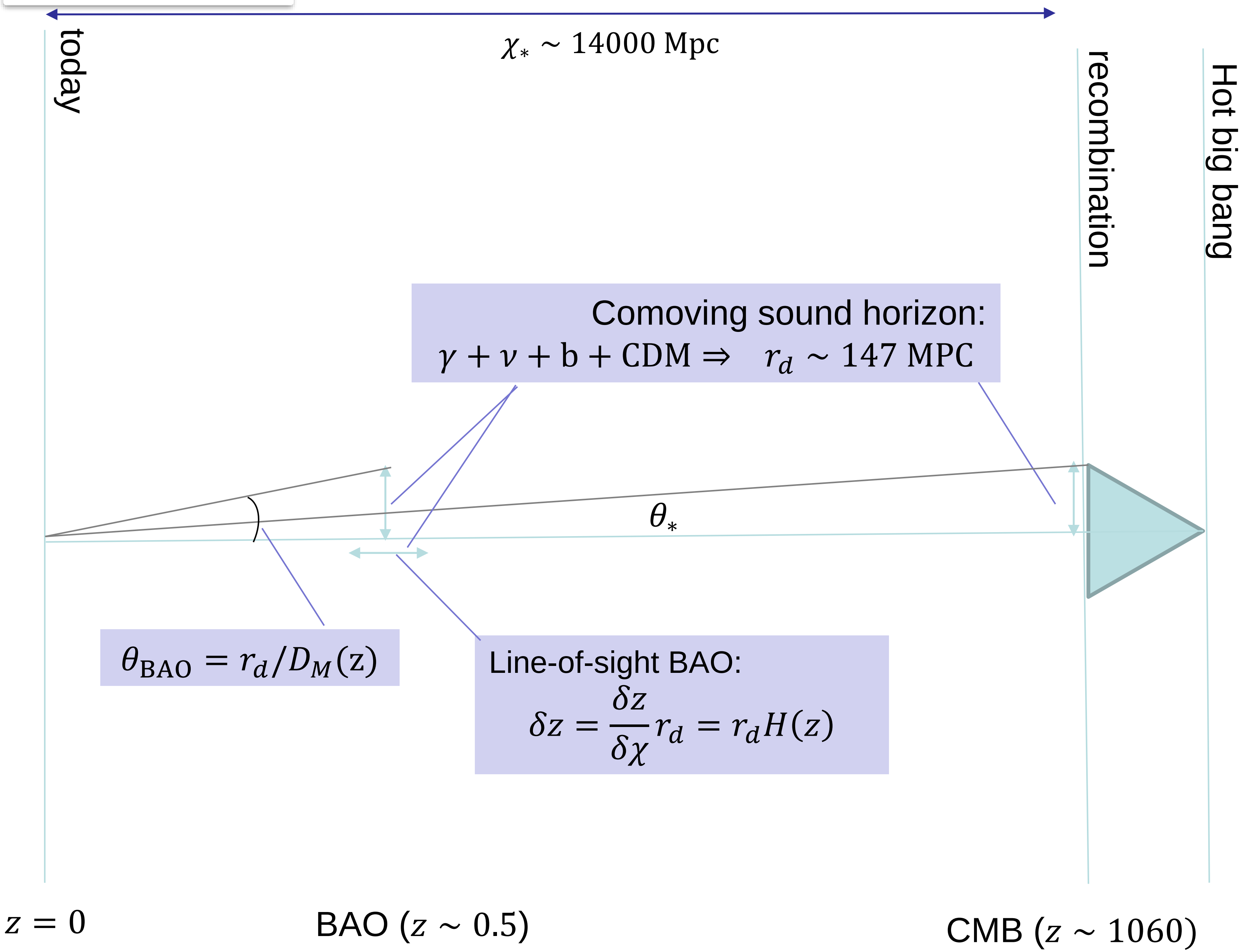


$$100\theta_* = 1.04109 \pm 0.00030$$

Planck TT,TE,EE+lowE+lensing
(0.03% precision!)

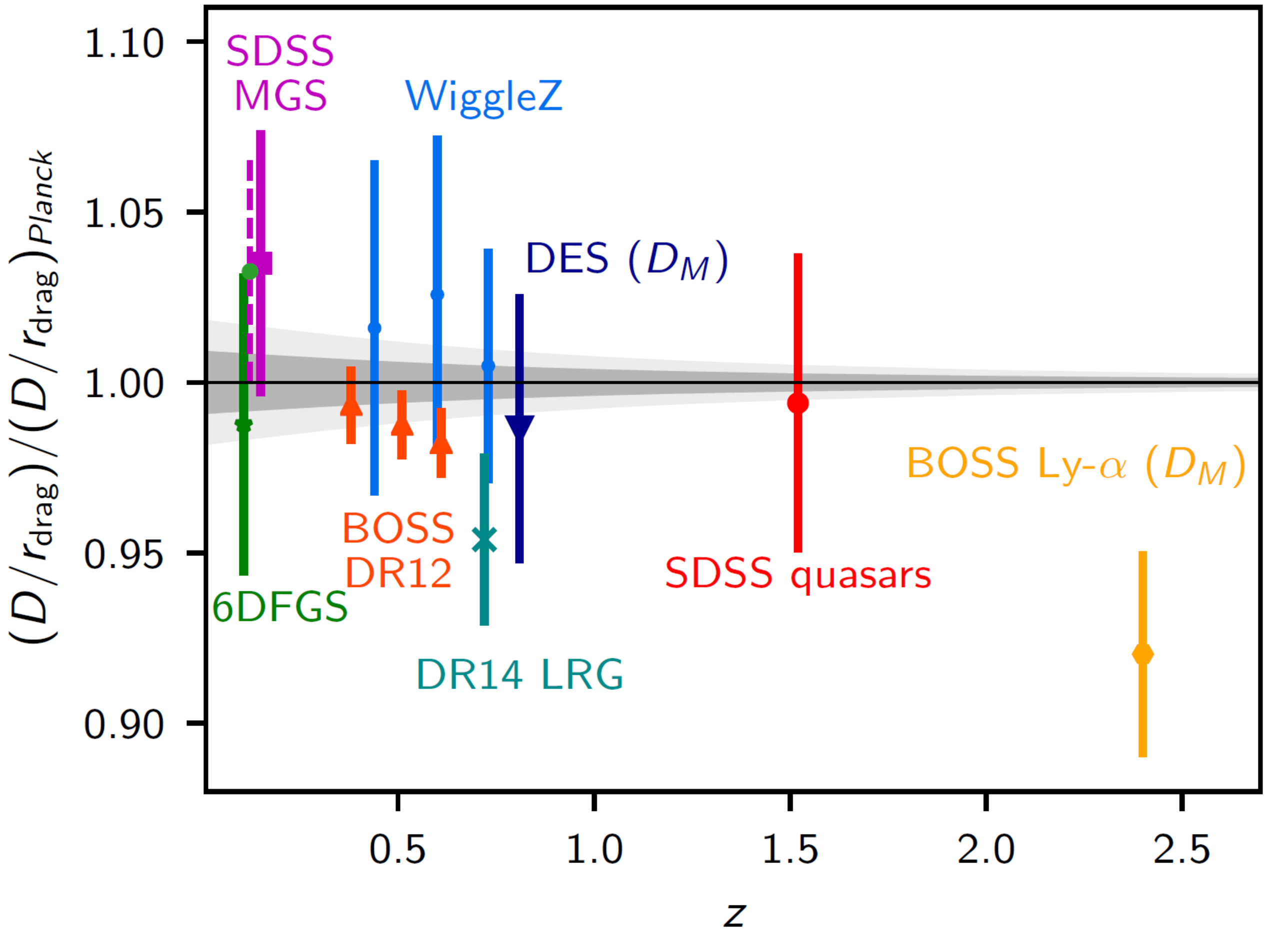
LCDM, in BAO-like variables: $\left(\frac{r_{\rm drag}h}{\rm Mpc}\right)\left(\frac{\Omega_m}{0.3}\right)^{0.4} = 101.056 \pm 0.036$

CMB and BAO



$\chi_* \sim 14000$ Mpc
today
recombination
Hot big bang
Comoving sound horizon:
$\gamma + \nu + \mathrm{b} + \mathrm{CDM} \Rightarrow \quad r_d \sim 147$ MPC
θ_*
$\theta_{\mathrm{BAO}} = r_d / D_M(\mathrm{z})$
Line-of-sight BAO:
$\delta z = \frac{\delta z}{\delta \chi} r_d = r_d H(z)$
$z = 0$
BAO ($z \sim 0.5$)
CMB ($z \sim 1060$)

Transverse and averaged BAO



Use BAO ≡ DR12+MGS+6DFGS (adding others would make little difference)

Supernovae

- Observe redshift and flux for different redshifts: $S(\mathrm{z}) = \frac{L_{\mathrm{SN}}}{4\pi d_L^2(z)}$

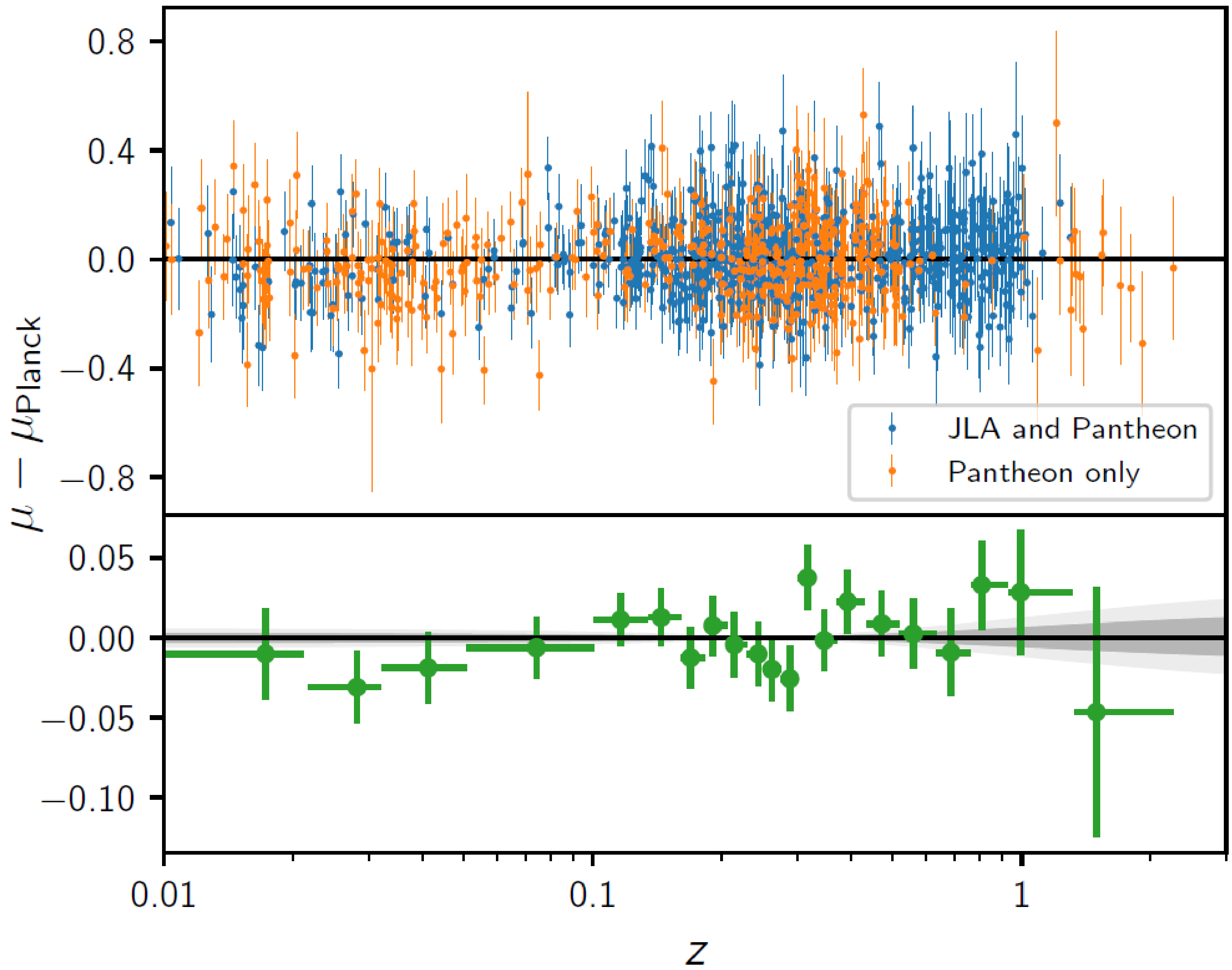
- Luminosity distance $d_L = (1+z)^2 D_A = (1+z) D_M$

- $D_M = \int \left(\frac{cdt}{a}\right) = \int \left(\frac{da}{a^2 H}\right) \approx \frac{1}{H_0} \int \frac{da}{\sqrt{a\Omega_{\mathrm{m}} + a^4(1-\Omega_{\mathrm{m}})}}$ [late-time LCDM]

⇒ can measure H_0 only if you know L_{SN},

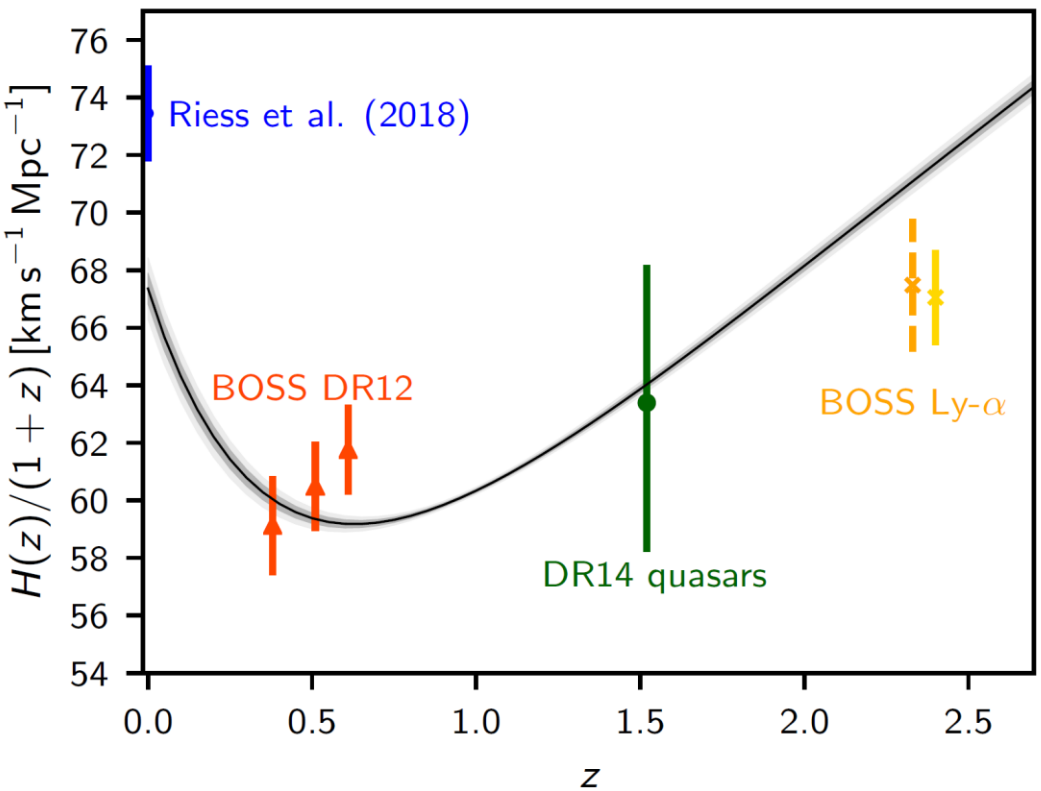
⇒ can measure Ω_m (+w, w_a) without knowing H_0 or L_{SN} (if assumed constant)

Supernovae: Pantheon (Scolnic et al) fits LCDM well (limits room for w_0, w_a)



Hubble Parameter

Forward ladder measurement (SH0ES, Riess et al.);
radial BAO with Planck LCDM r_{drag}

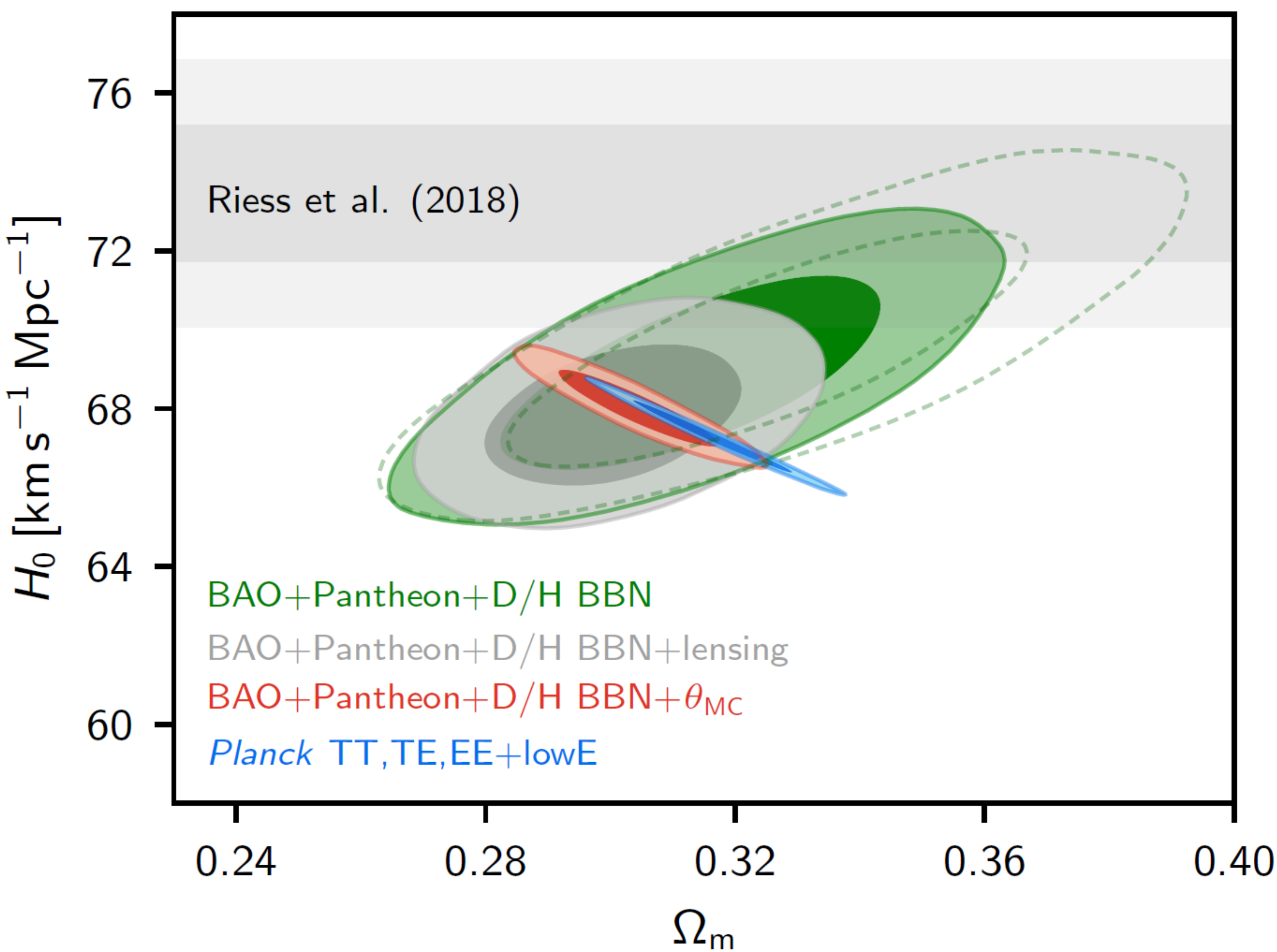


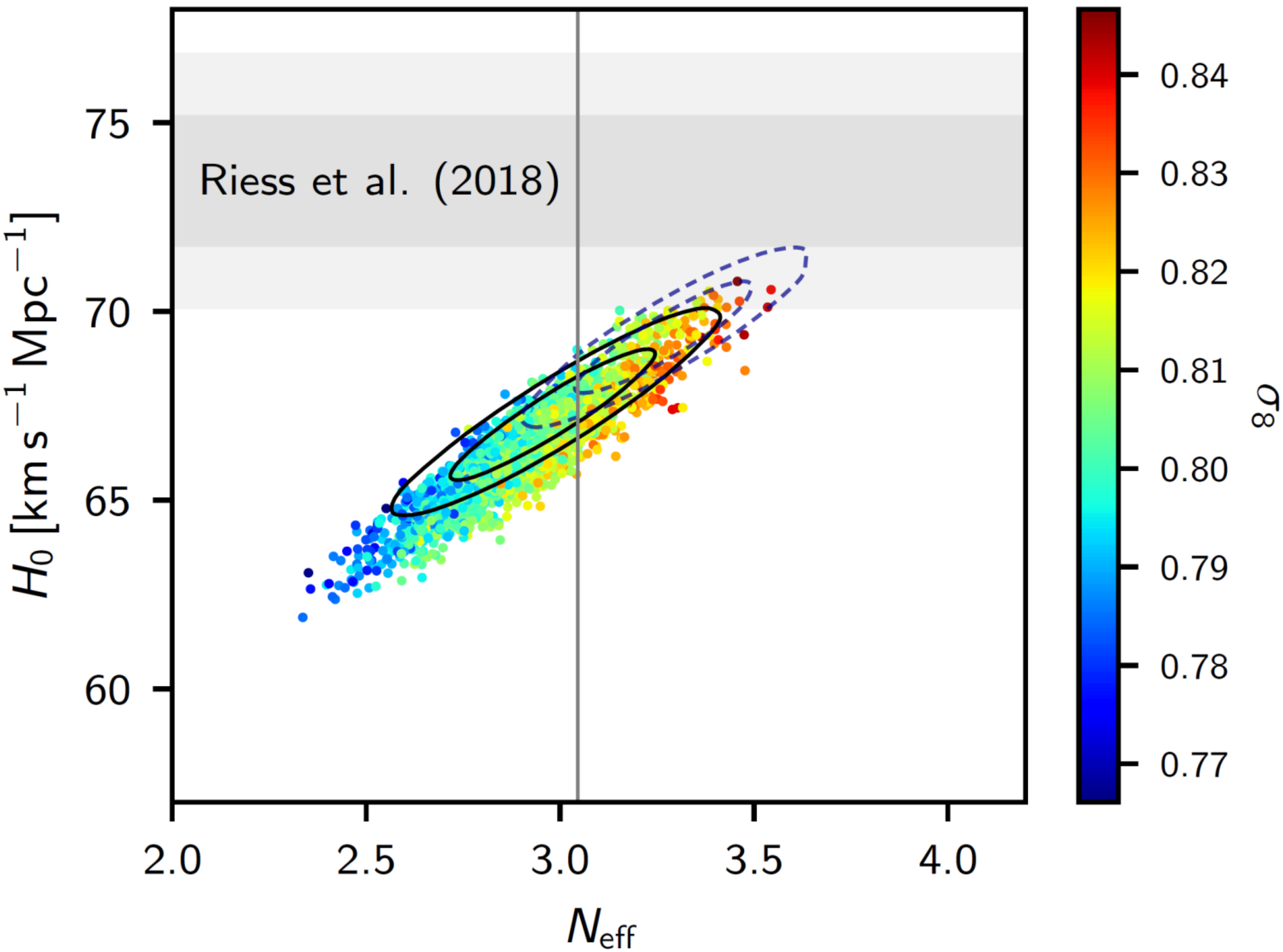
Planck LCDM: $H_0 = (67.36 \pm 0.54)$ km/s/Mpc

Riess et al 2018b: $H_0 = (73.52 \pm 1.62)$ km/s/Mpc

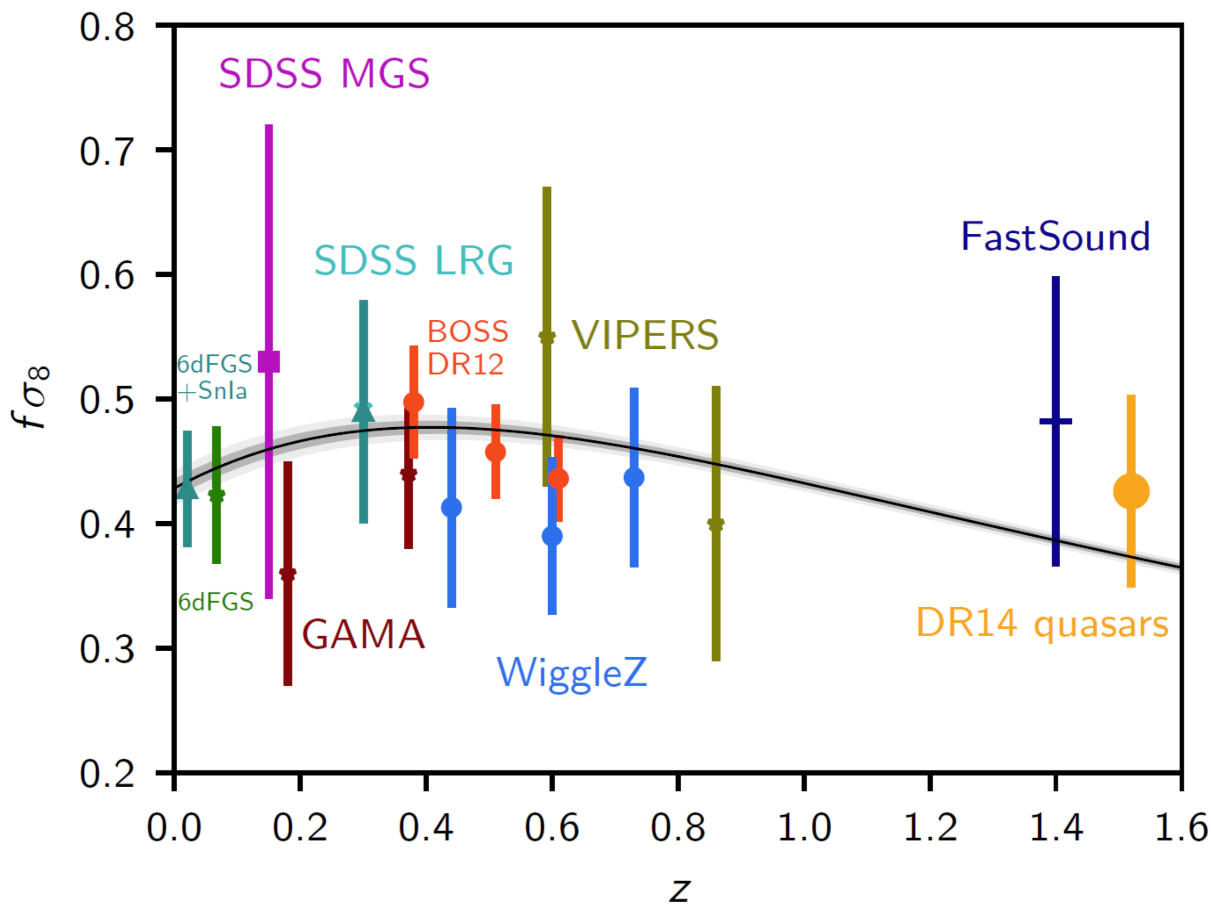
$\Rightarrow 3.6\,\sigma$ tenson

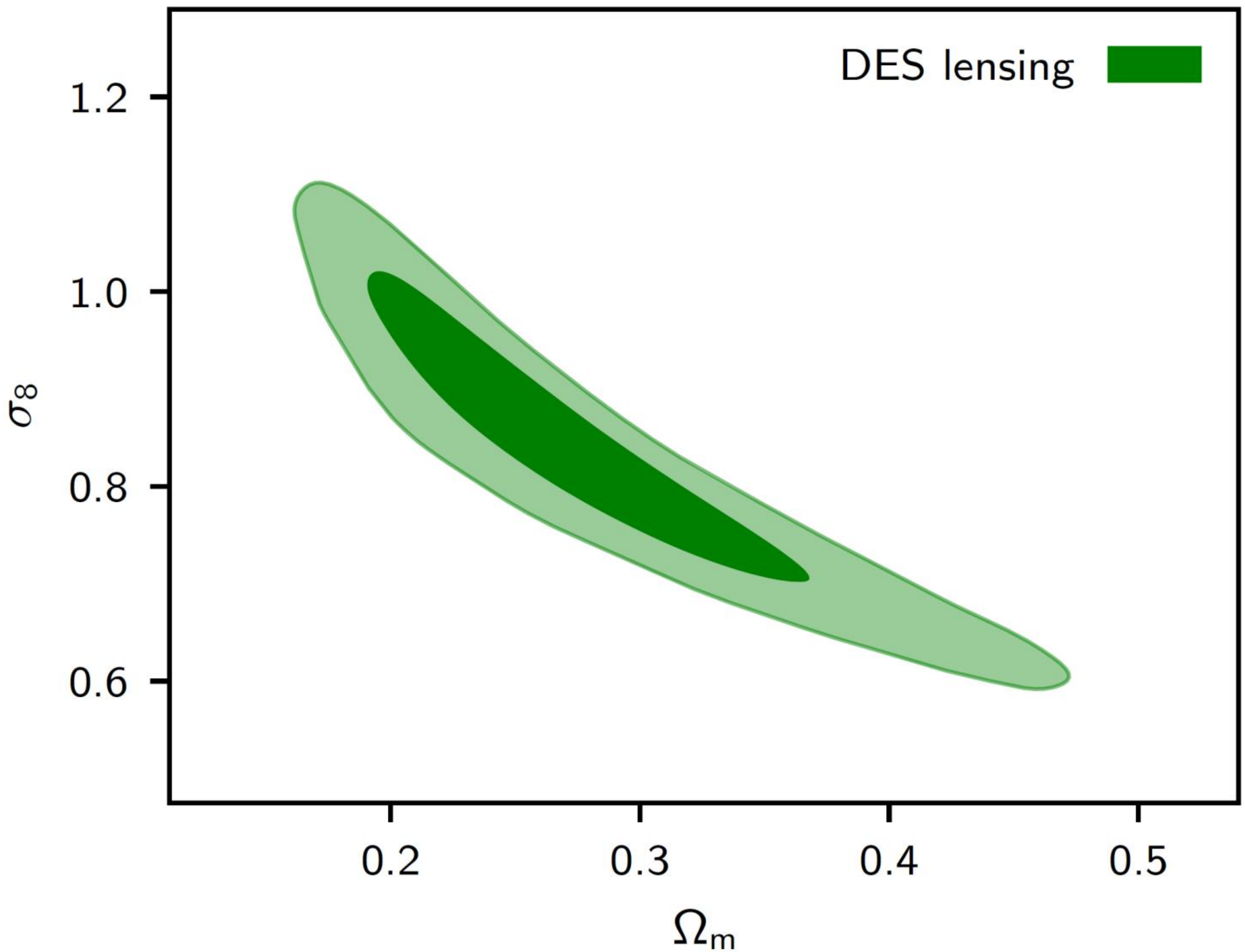
“Inverse distance ladder”

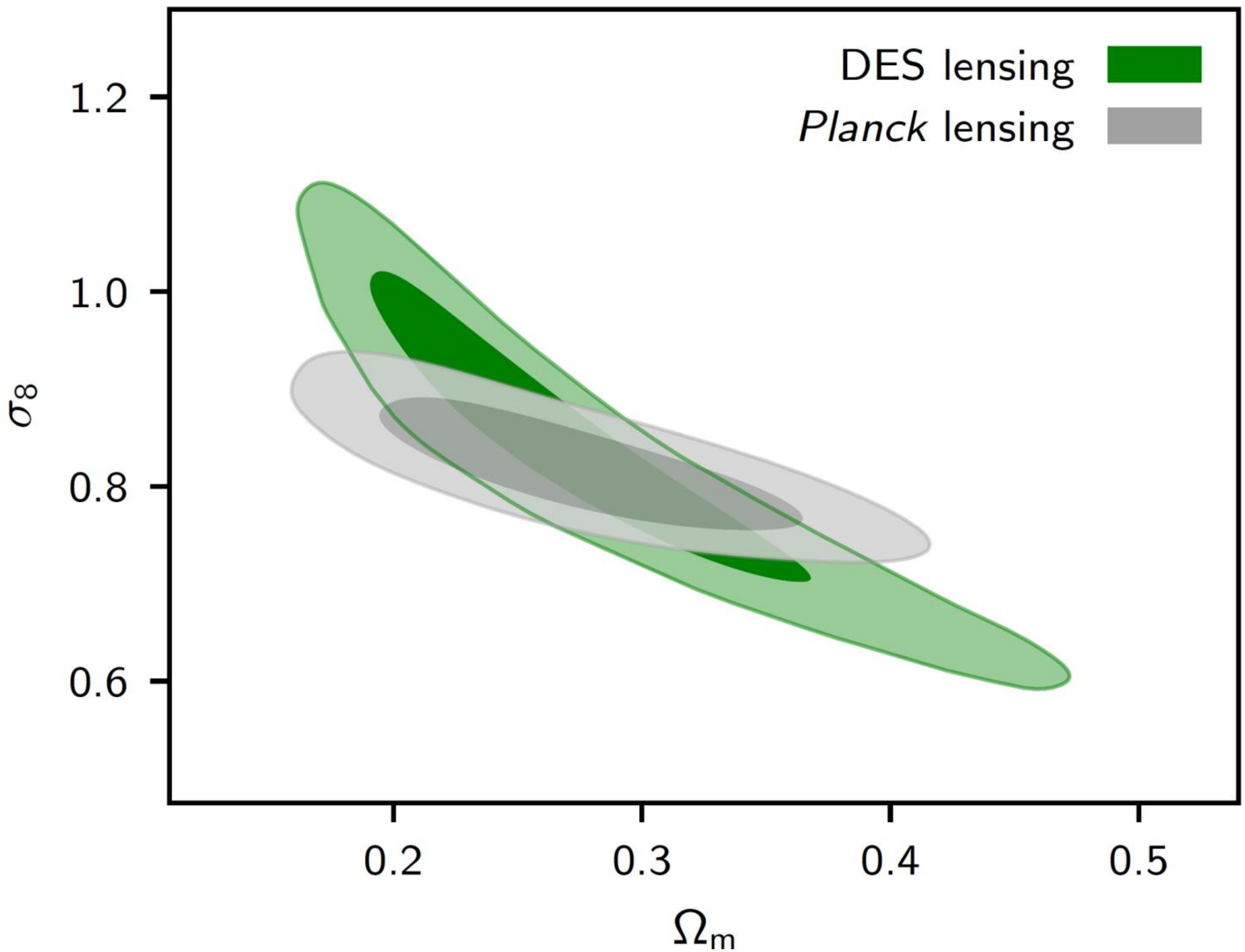


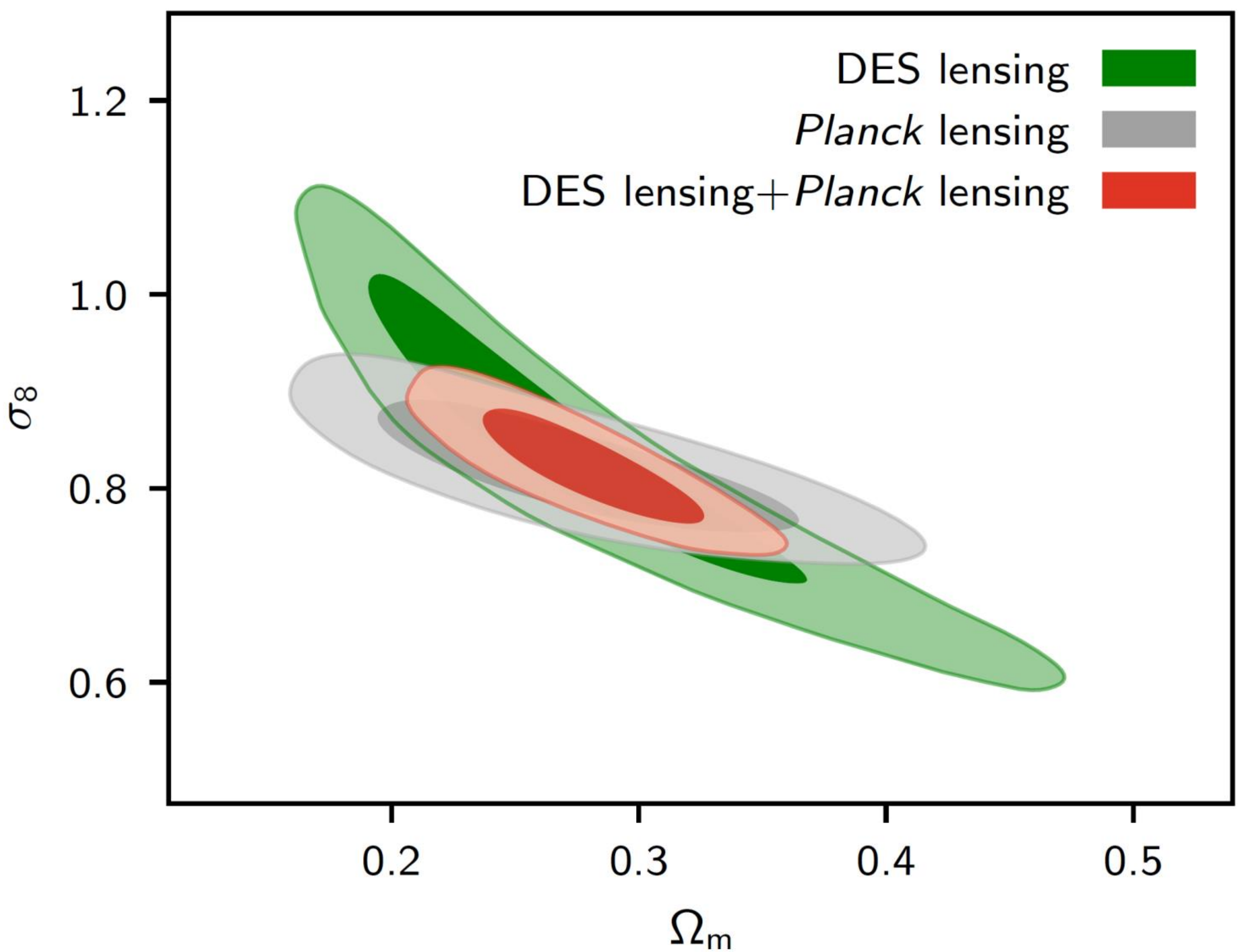

Riess et al. (2018)
H_0 [km s^{-1} Mpc^{-1}]
75
70
65
60
2.0
2.5
3.0
3.5
4.0
$N_{\rm eff}$
σ_8
0.84
0.83
0.82
0.81
0.80
0.79
0.78
0.77

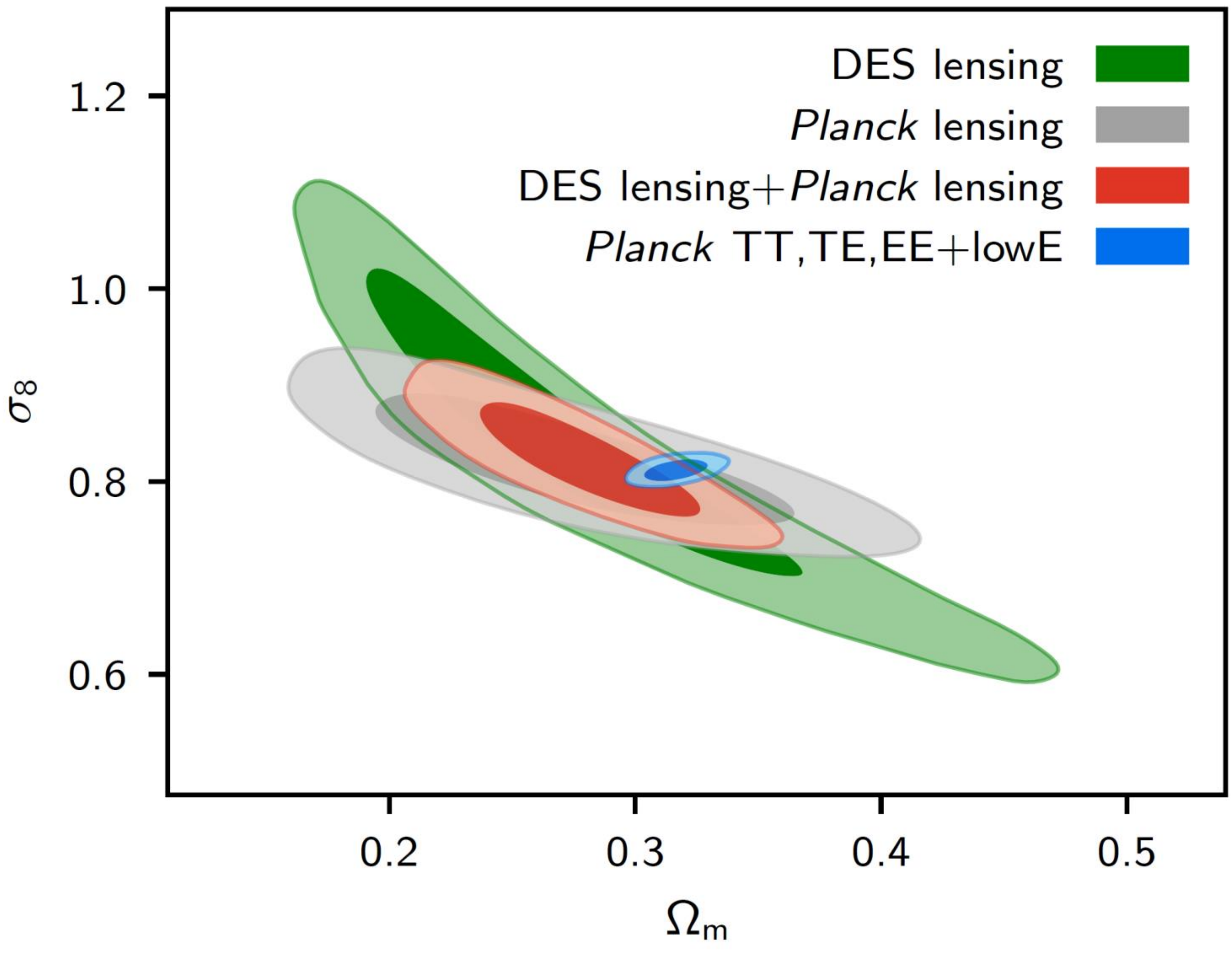
Redshift Distortions measure growth × σ_8



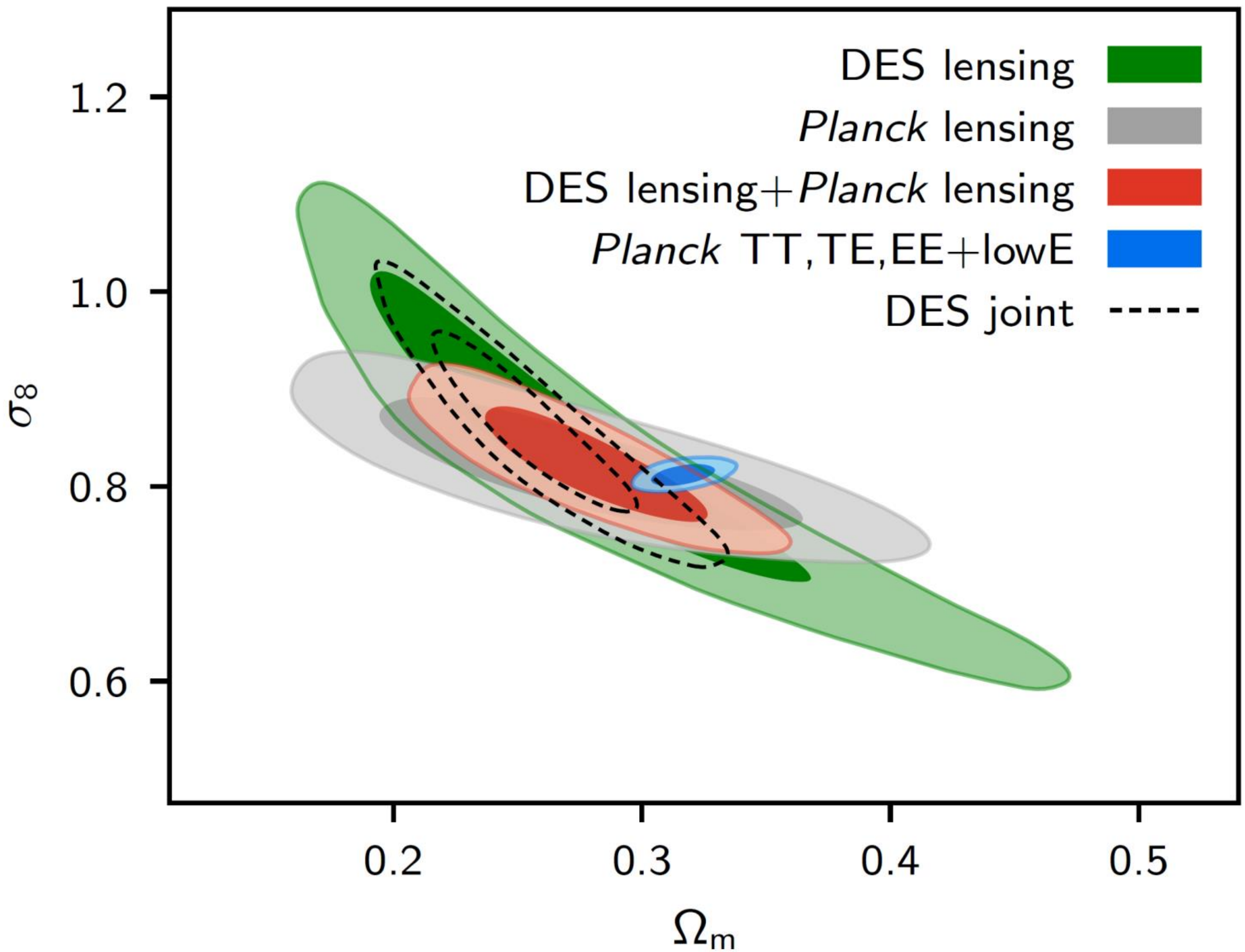

DES lensing
1.2
1.0
0.8
0.6
σ_8
0.2
0.3
0.4
0.5
Ω_m


DES lensing
Planck lensing
1.2
1.0
0.8
0.6
σ_8
0.2
0.3
0.4
0.5
Ω_m

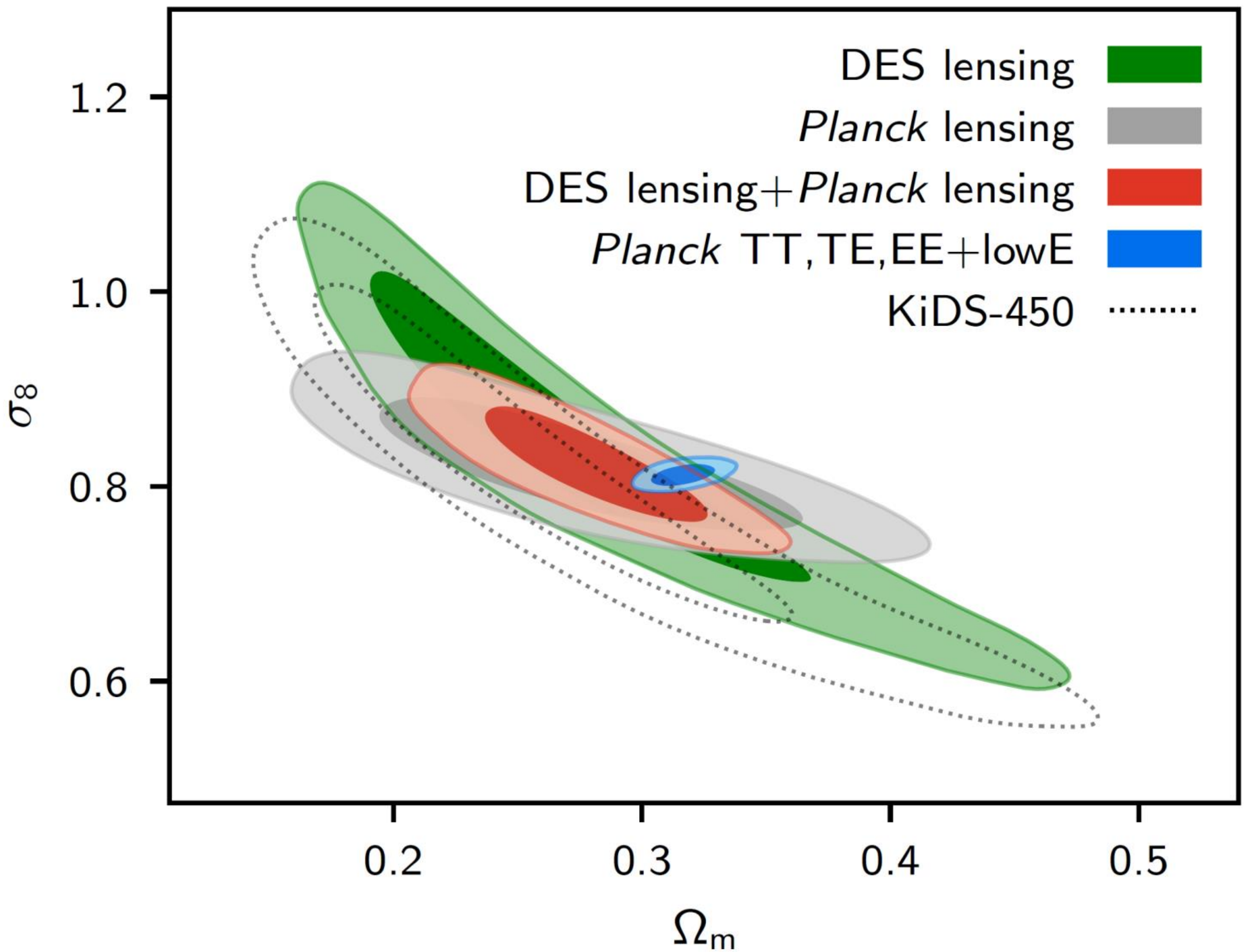

DES lensing
Planck lensing
DES lensing+Planck lensing
1.2
1.0
0.8
0.6
σ_8
0.2
0.3
0.4
0.5
Ω_m



DES lensing
Planck lensing
DES lensing+Planck lensing
Planck TT,TE,EE+lowE
1.2
1.0
0.8
0.6
σ_8
0.2
0.3
0.4
0.5
Ω_m

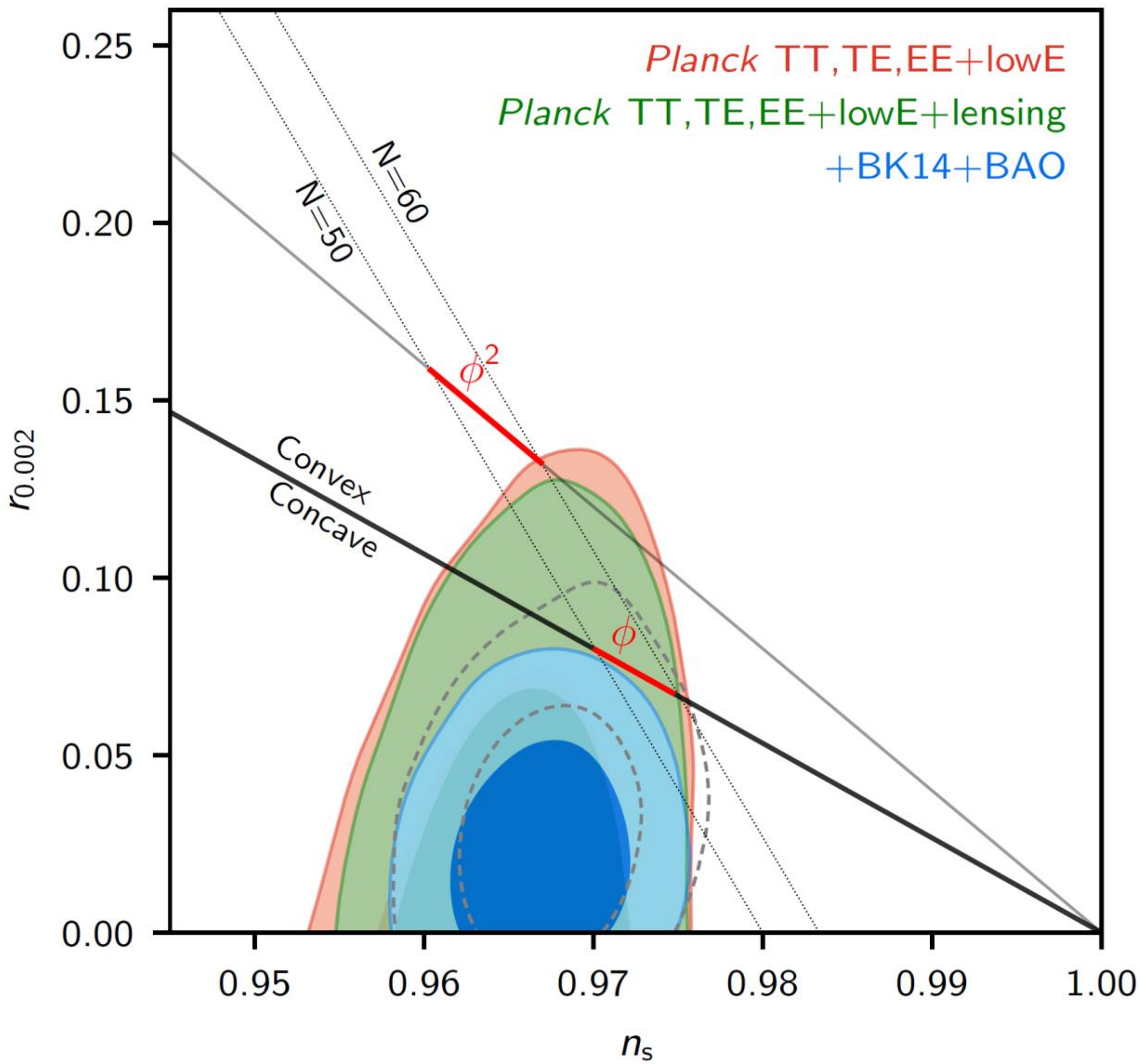


DES lensing
Planck lensing
DES lensing+Planck lensing
Planck TT,TE,EE+lowE
DES joint
1.2
1.0
0.8
0.6
σ_8
0.2
0.3
0.4
0.5
Ω_m



DES lensing
Planck lensing
DES lensing+Planck lensing
Planck TT,TE,EE+lowE
KiDS-450
1.2
1.0
0.8
0.6
σ8
0.2
0.3
0.4
0.5
Ωm

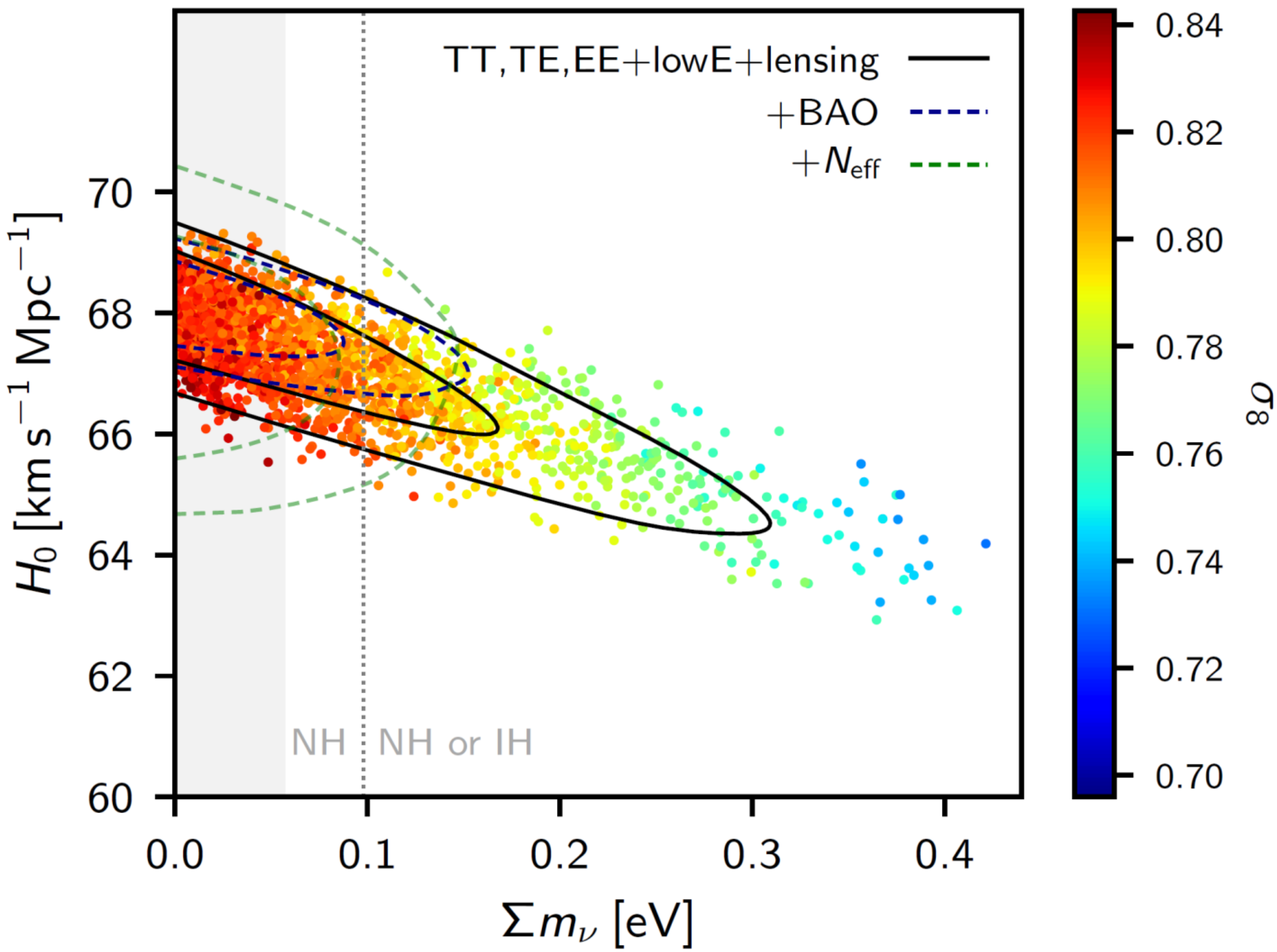
Extensions to LCDM



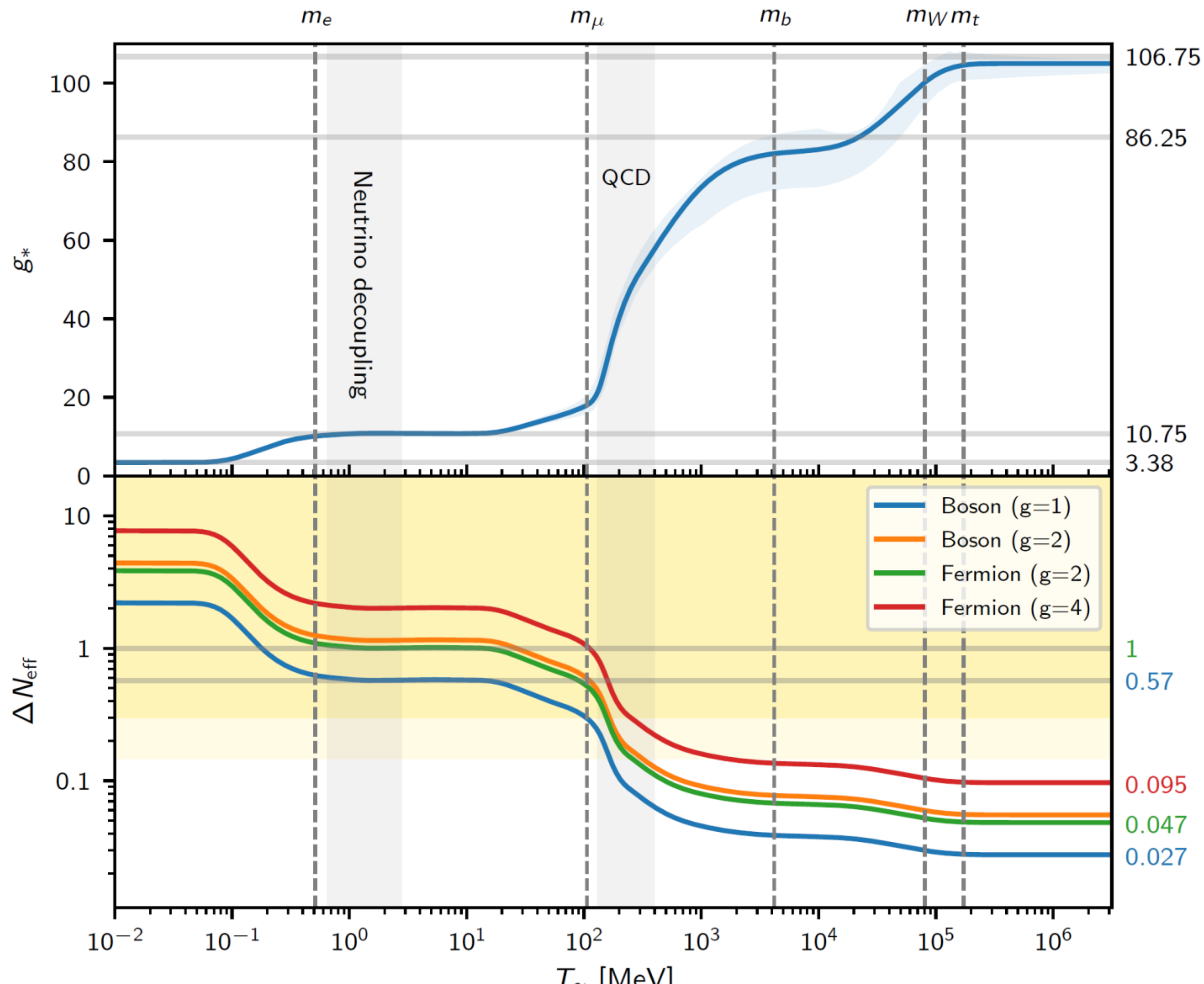
$r_{0.002} < 0.065$ (95 %, TT,TE,EE+lowE+lensing +BK14+BAO),

$n_s = 0.9670 \pm 0.0037$ at $1\,\sigma$.

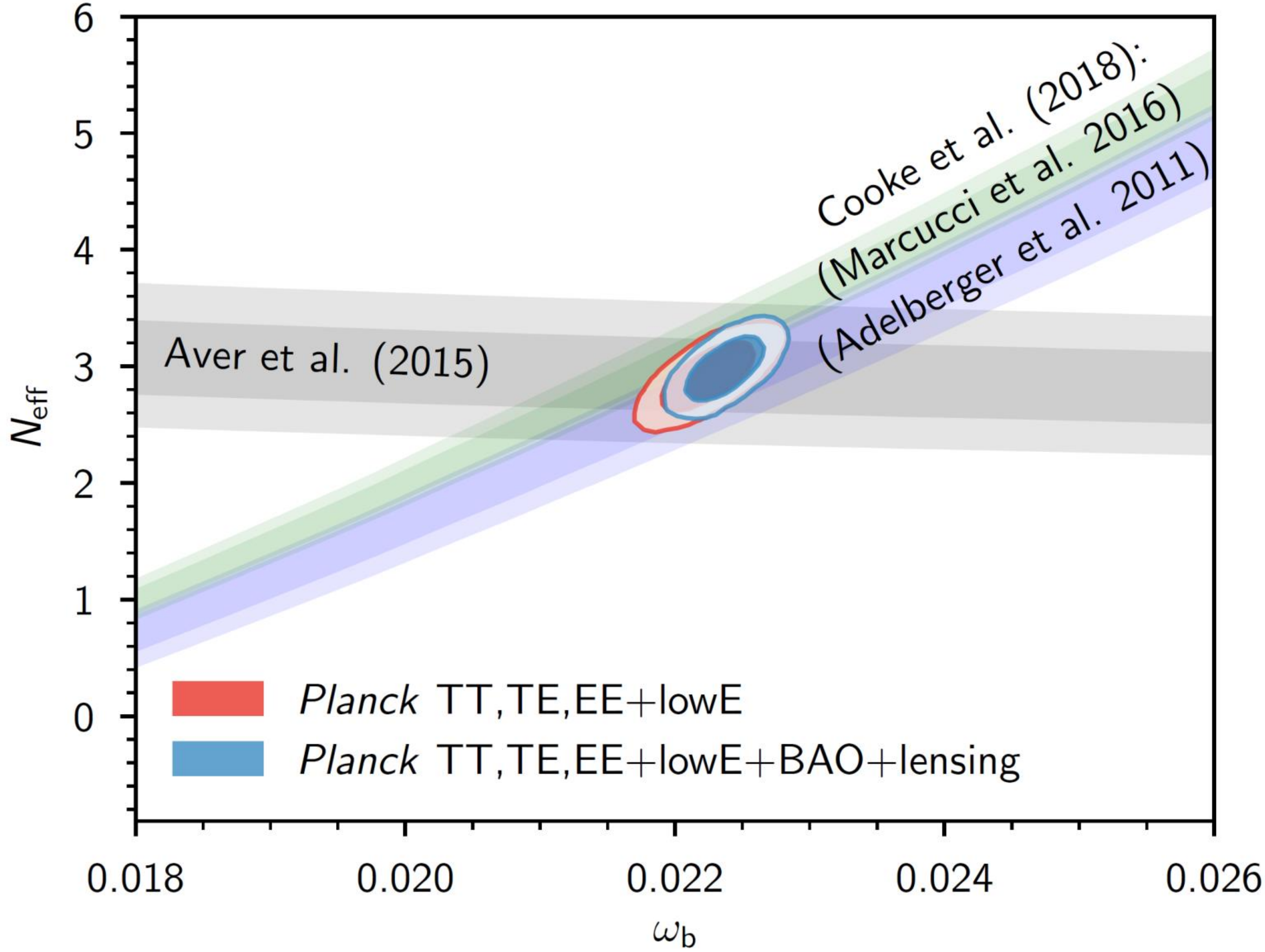
$$\sum m_\nu < 0.12 \text{ eV} \quad \text{(95 \%, \textit{Planck} TT,TE,EE+lowE +lensing+BAO).}$$

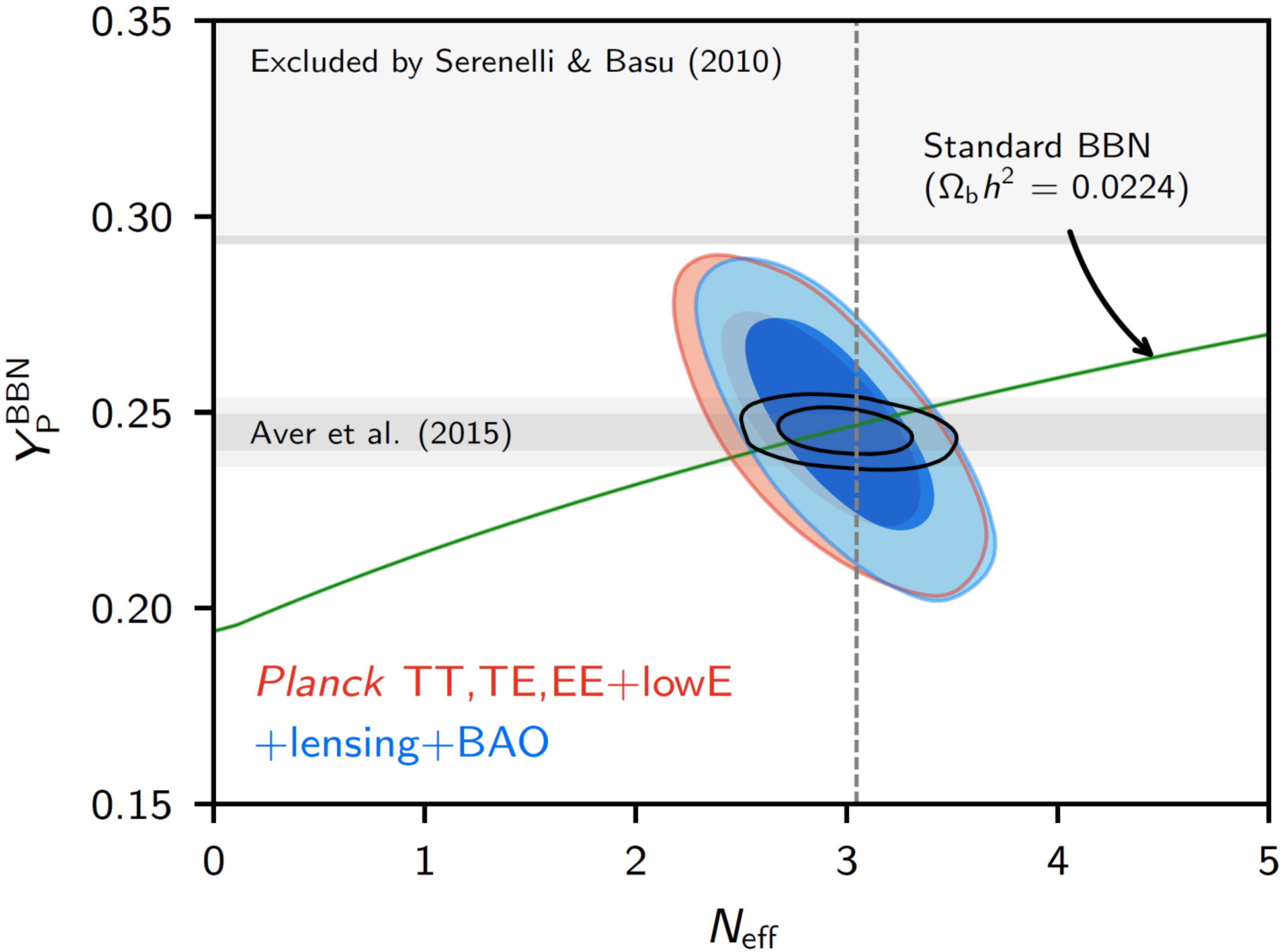


$$N_{\rm eff} = 2.99^{+0.34}_{-0.33} \quad (95\,\%,\ \ \text{TT,TE,EE+lowE+lensing} \\ \text{+BAO}).$$



Consistency with element abundance observations





0.35
0.30
0.25
0.20
0.15
Y_P^{BBN}
0
1
2
3
4
5
N_{eff}
Excluded by Serenelli & Basu (2010)
Standard BBN
($\Omega_b h^2 = 0.0224$)
Aver et al. (2015)
Planck TT,TE,EE+lowE
+lensing+BAO

Table 4. Constraints on 1-parameter extensions to the base-ΛCDM model for combinations of *Planck* power spectra, *Planck* lensing, and BAO (equivalent results using the `CamSpec` likelihood are given in Table A.2). Note that we quote 95 % limits here.

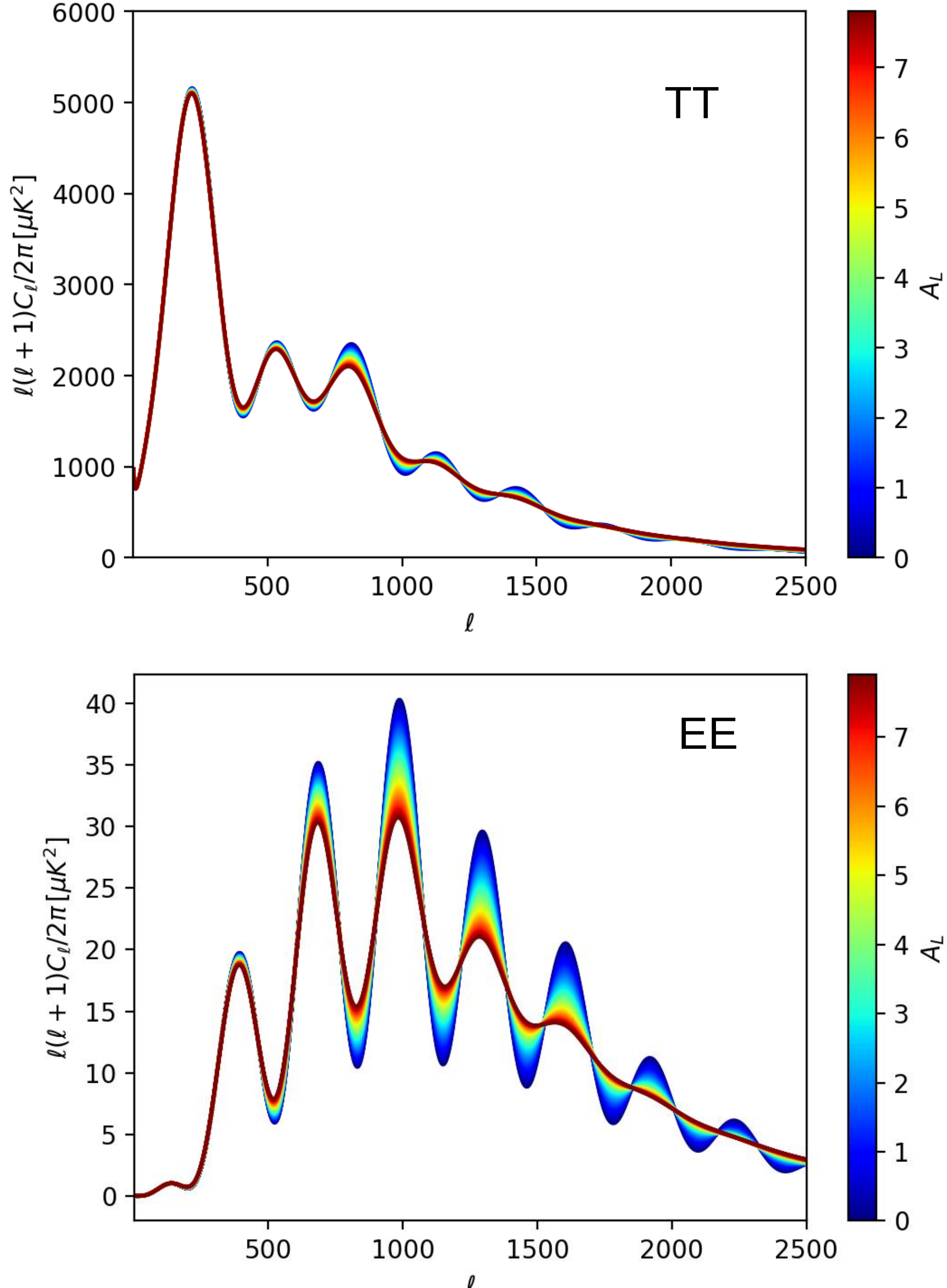
Parameter	TT+lowE	TT, TE, EE+lowE	TT, TE, EE+lowE+lensing	TT, TE, EE+lowE+lensing+BAO
Ω_K	$-0.056^{+0.044}_{-0.050}$	$-0.044^{+0.033}_{-0.034}$	$-0.011^{+0.013}_{-0.012}$	$0.0007^{+0.0037}_{-0.0037}$
Σm_ν [eV]	< 0.537	< 0.257	< 0.241	< 0.120
$N_{\rm eff}$	$3.00^{+0.57}_{-0.53}$	$2.92^{+0.36}_{-0.37}$	$2.89^{+0.36}_{-0.38}$	$2.99^{+0.34}_{-0.33}$
$Y_{\rm P}$	$0.246^{+0.039}_{-0.041}$	$0.240^{+0.024}_{-0.025}$	$0.239^{+0.024}_{-0.025}$	$0.242^{+0.023}_{-0.024}$
$dn_s/d\ln k$	$-0.004^{+0.015}_{-0.015}$	$-0.006^{+0.013}_{-0.013}$	$-0.005^{+0.013}_{-0.013}$	$-0.004^{+0.013}_{-0.013}$
$r_{0.002}$	< 0.102	< 0.107	< 0.101	< 0.106
w_0	$-1.56^{+0.60}_{-0.48}$	$-1.58^{+0.52}_{-0.41}$	$-1.57^{+0.50}_{-0.40}$	$-1.04^{+0.10}_{-0.10}$

Table 5. Constraints on standard cosmological parameters from *Planck* TT,TE,EE+lowE+lensing when the base-ΛCDM model is extended by varying additional parameters. The constraint on τ is also stable but not shown for brevity; however, we include H_0 (in km s^{-1}Mpc^{-1}) as a derived parameter (which is very poorly constrained from *Planck* alone in the ΛCDM+w_0 extension). Here α_{-1} is a matter isocurvature amplitude parameter, following PCP15. All limits are 68 % in this table. The results assume standard BBN except when varying $Y_{\rm P}$ independently (which requires non-standard BBN). Varying $A_{\rm L}$ is not a physical model (see Sect. 6.2).

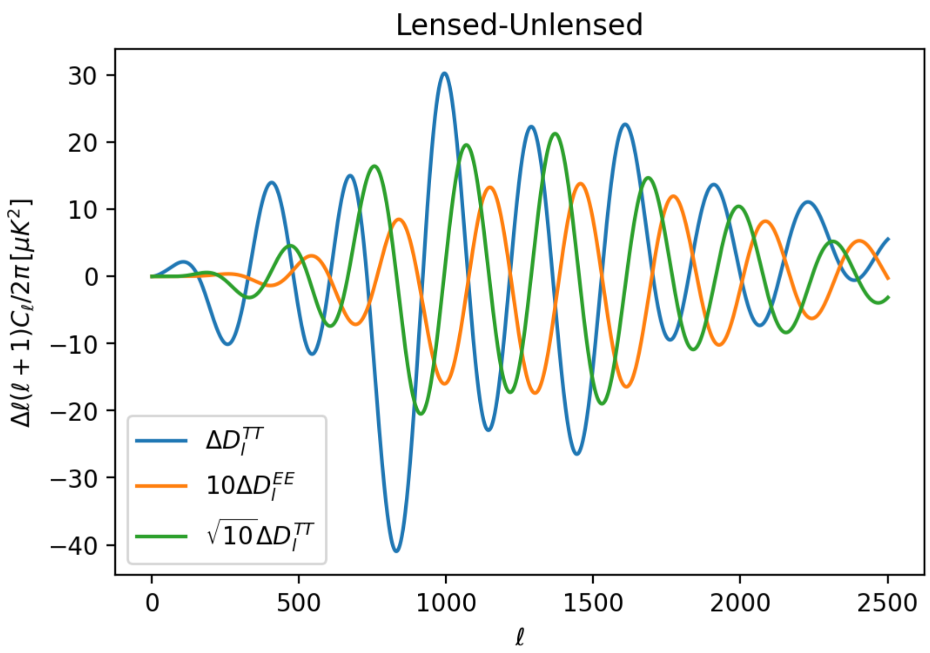
Parameter(s)	$\Omega_b h^2$	$\Omega_c h^2$	$100\theta_{\rm MC}$	H_0	n_s	$\ln(10^{10}A_s)$
Base ΛCDM	0.02237 ± 0.00015	0.1200 ± 0.0012	1.04092 ± 0.00031	67.36 ± 0.54	0.9649 ± 0.0042	3.044 ± 0.014
r	0.02237 ± 0.00014	0.1199 ± 0.0012	1.04092 ± 0.00031	67.40 ± 0.54	0.9659 ± 0.0041	3.044 ± 0.014
$dn_s/d\ln k$	0.02240 ± 0.00015	0.1200 ± 0.0012	1.04092 ± 0.00031	67.36 ± 0.53	0.9641 ± 0.0044	3.047 ± 0.015
$dn_s/d\ln k, r$	0.02243 ± 0.00015	0.1199 ± 0.0012	1.04093 ± 0.00030	67.44 ± 0.54	0.9647 ± 0.0044	3.049 ± 0.015
$d^2n_s/d\ln k^2, dn_s/d\ln k$	0.02237 ± 0.00016	0.1202 ± 0.0012	1.04090 ± 0.00030	67.28 ± 0.56	0.9625 ± 0.0048	3.049 ± 0.015
$N_{\rm eff}$	0.02224 ± 0.00022	0.1179 ± 0.0028	1.04116 ± 0.00043	66.3 ± 1.4	0.9589 ± 0.0084	3.036 ± 0.017
$N_{\rm eff}, dn_s/d\ln k$	0.02216 ± 0.00022	0.1157 ± 0.0032	1.04144 ± 0.00048	65.2 ± 1.6	0.950 ± 0.011	3.034 ± 0.017
Σm_ν	0.02236 ± 0.00015	0.1201 ± 0.0013	1.04088 ± 0.00032	$67.1^{+1.2}_{-0.67}$	0.9647 ± 0.0043	3.046 ± 0.015
$\Sigma m_\nu, N_{\rm eff}$	0.02223 ± 0.00023	0.1180 ± 0.0029	1.04113 ± 0.00044	$66.0^{+1.8}_{-1.6}$	0.9587 ± 0.0086	3.038 ± 0.017
$m^{\rm eff}_{\nu,\,\rm sterile}, N_{\rm eff}$	$0.02242^{+0.00014}_{-0.00016}$	$0.1200^{+0.0032}_{-0.0020}$	$1.04074^{+0.00033}_{-0.00029}$	$67.11^{+0.63}_{-0.79}$	$0.9652^{+0.0045}_{-0.0056}$	$3.050^{+0.014}_{-0.016}$
α_{-1}	0.02238 ± 0.00015	0.1201 ± 0.0015	1.04087 ± 0.00043	67.30 ± 0.67	0.9645 ± 0.0061	3.045 ± 0.014
w_0	0.02243 ± 0.00015	0.1193 ± 0.0012	1.04099 ± 0.00031	...	0.9666 ± 0.0041	3.038 ± 0.014
Ω_K	0.02249 ± 0.00016	0.1185 ± 0.0015	1.04107 ± 0.00032	$63.6^{+2.1}_{-2.3}$	0.9688 ± 0.0047	$3.030^{+0.017}_{-0.015}$
$Y_{\rm P}$	0.02230 ± 0.00020	0.1201 ± 0.0012	1.04067 ± 0.00055	67.19 ± 0.63	0.9621 ± 0.0070	3.042 ± 0.016
$Y_{\rm P}, N_{\rm eff}$	0.02224 ± 0.00022	$0.1171^{+0.0042}_{-0.0049}$	1.0415 ± 0.0012	$66.0^{+1.7}_{-1.9}$	0.9589 ± 0.0085	3.036 ± 0.018
$A_{\rm L}$	0.02251 ± 0.00017	0.1182 ± 0.0015	1.04110 ± 0.00032	68.16 ± 0.70	0.9696 ± 0.0048	$3.029^{+0.018}_{-0.016}$

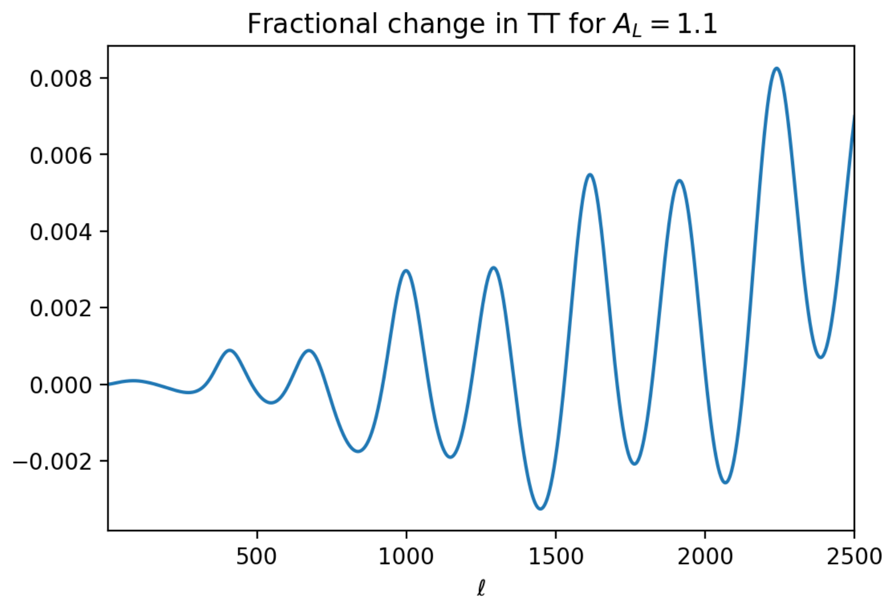
Curiosities

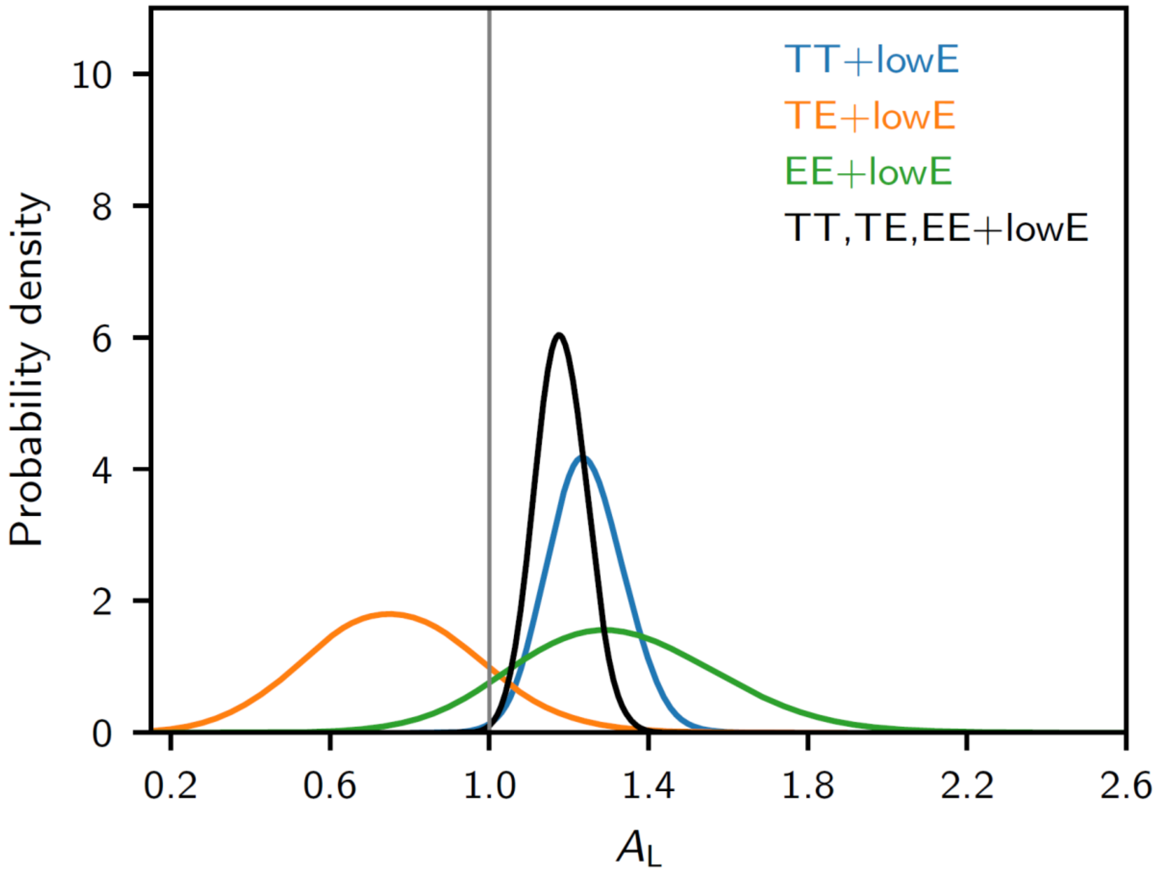
A_L



TT
EE
$\ell(\ell+1)C_\ell/2\pi\,[\mu K^2]$
ℓ
A_L
0
1
2
3
4
5
6
7
500
1000
1500
2000
2500
1000
2000
3000
4000
5000
6000
5
10
15
20
25
30
35
40


Lensed-Unlensed
$\Delta\ell(\ell+1)C_\ell/2\pi\,[\mu K^2]$
ℓ
ΔD_l^{TT}
$10\Delta D_l^{EE}$
$\sqrt{10}\Delta D_l^{TT}$
30
20
10
0
−10
−20
−30
−40
0
500
1000
1500
2000
2500

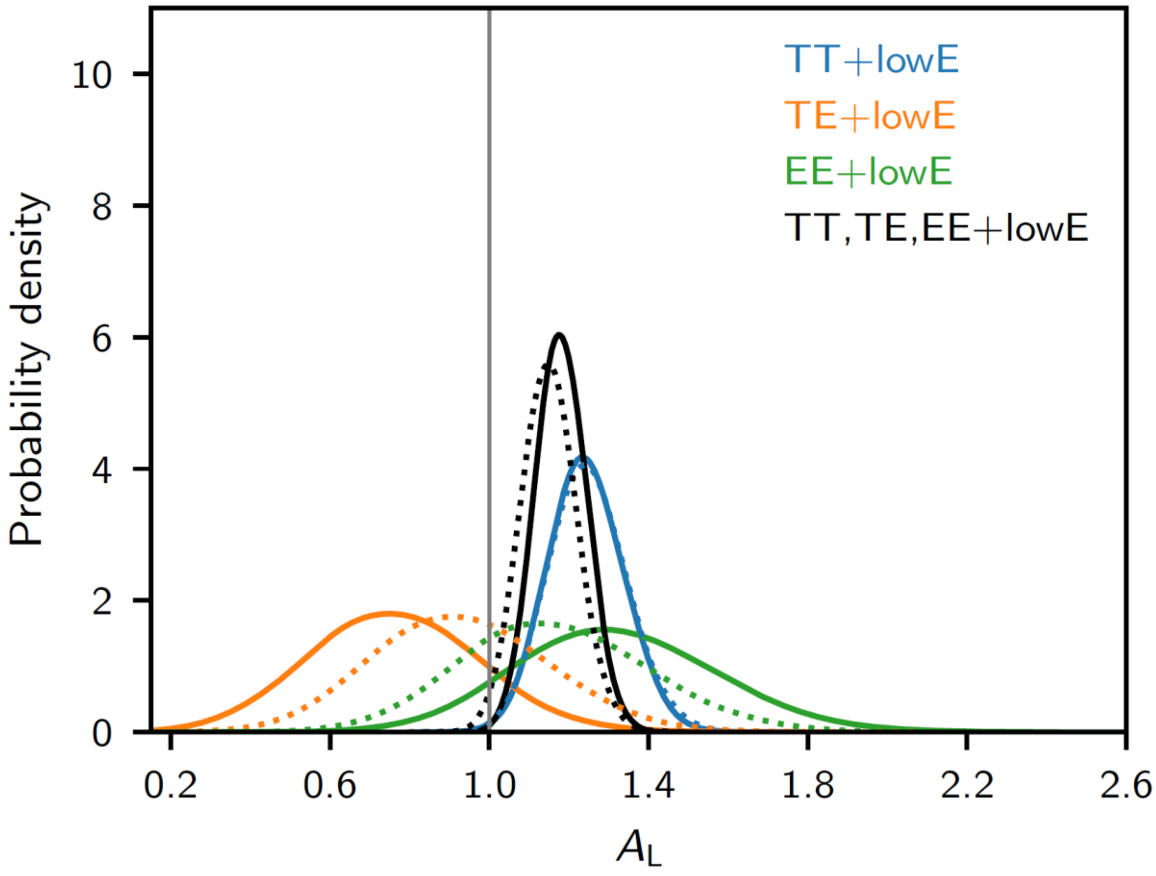

Fractional change in TT for $A_L = 1.1$
ℓ
0.008
0.006
0.004
0.002
0.000
−0.002
500
1000
1500
2000
2500



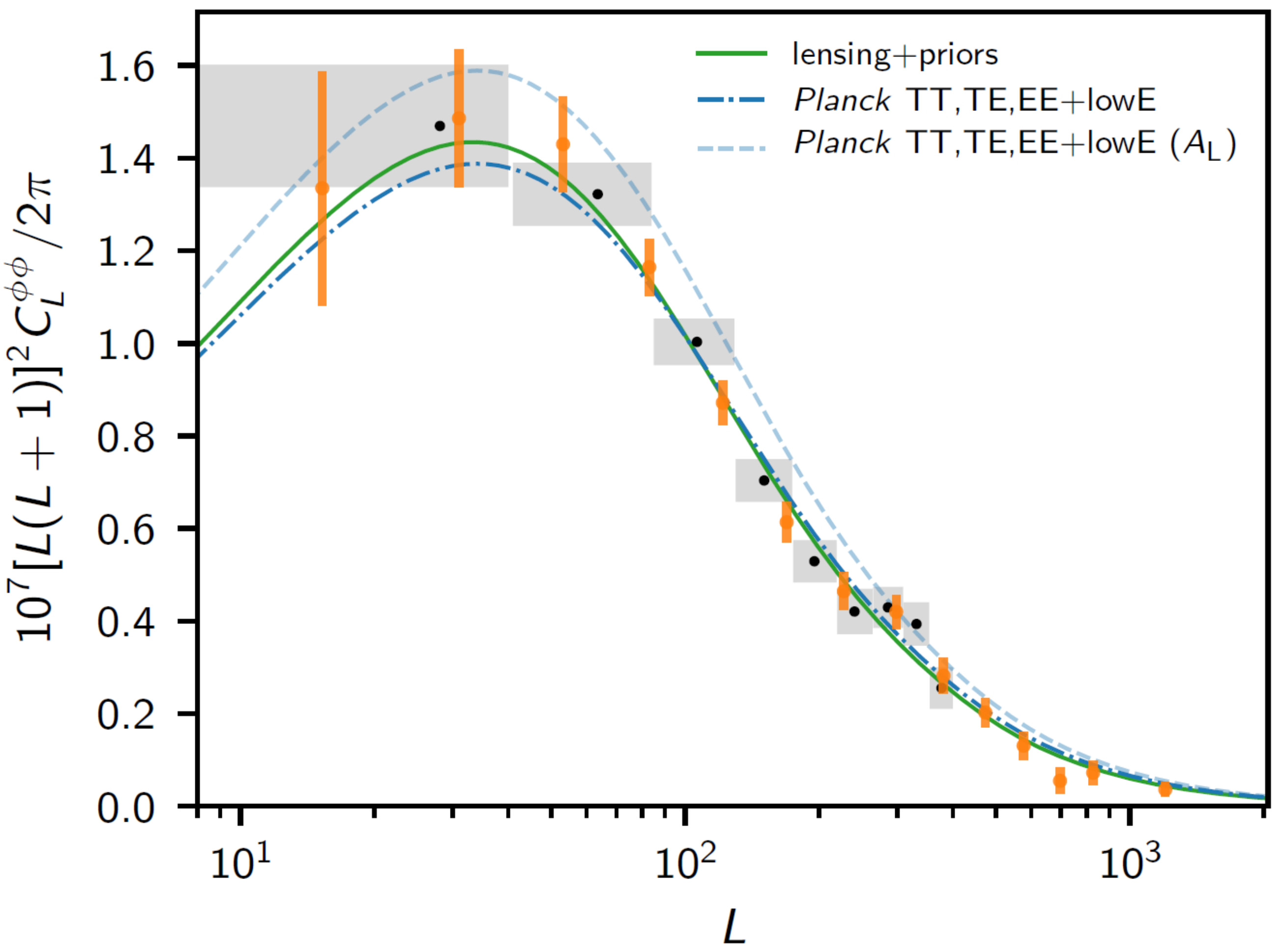
$$A_L = 1.243 \pm 0.096 \quad (68\,\%,\ \textit{Planck}\ \text{TT+lowE}),$$

$$A_L = 1.180 \pm 0.065 \quad (68\,\%,\ \textit{Planck}\ \text{TT,TE,EE+lowE}),$$

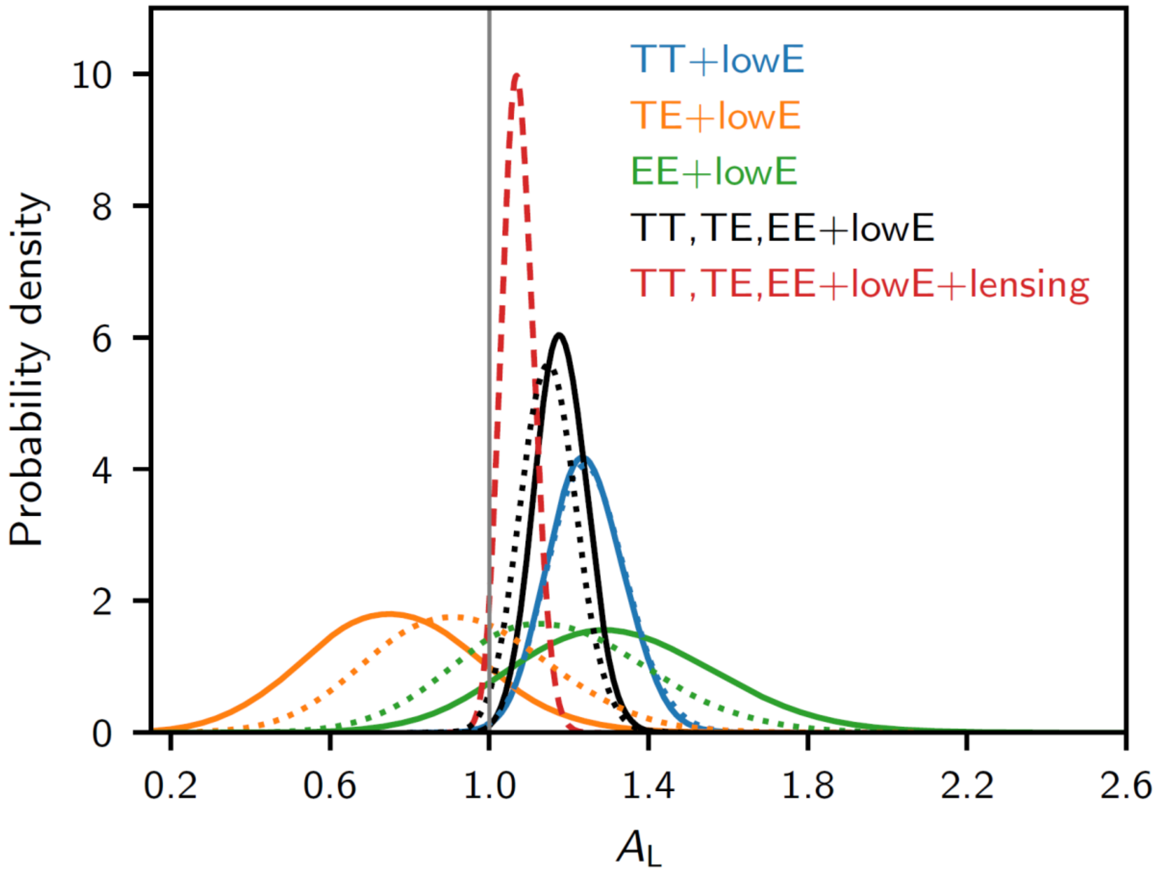
$$\Delta\chi^2 = -9.7$$



(Polarization unstable because of systematics/modelling uncertainties in polarization: only just above 2σ with CamSpec)



Physical models that give more lensing are probably not the answer.

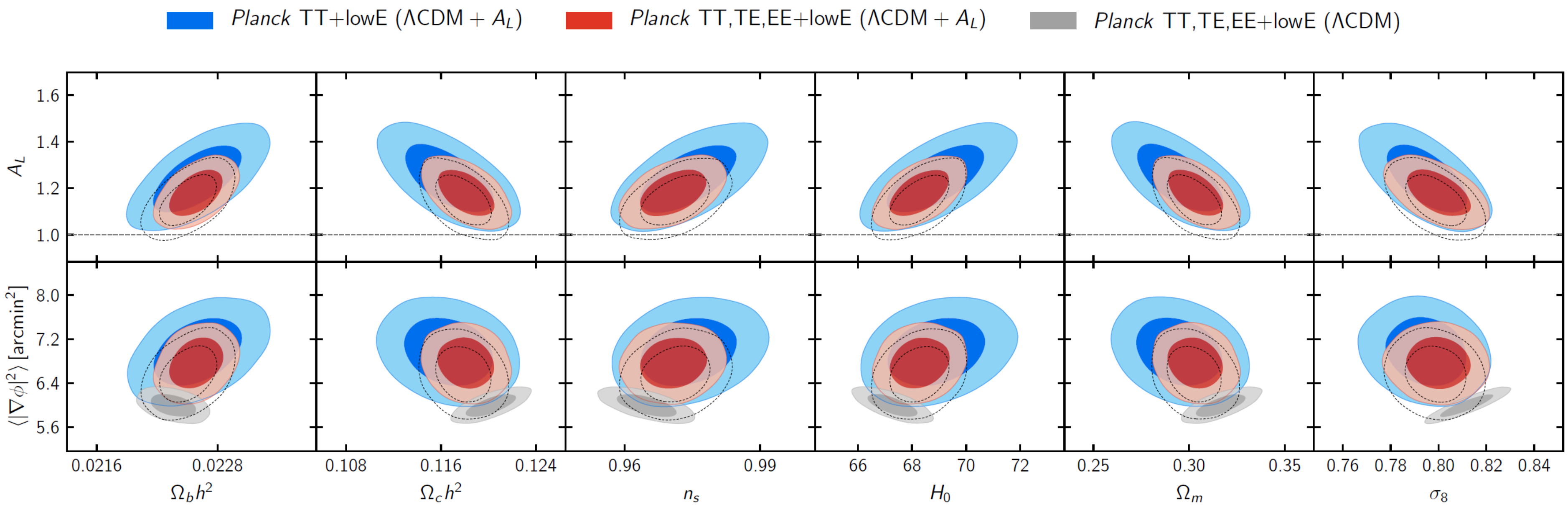


TT+lowE
TE+lowE
EE+lowE
TT,TE,EE+lowE
TT,TE,EE+lowE+lensing
Probability density
0
2
4
6
8
10
0.2
0.6
1.0
1.4
1.8
2.2
2.6
A_L

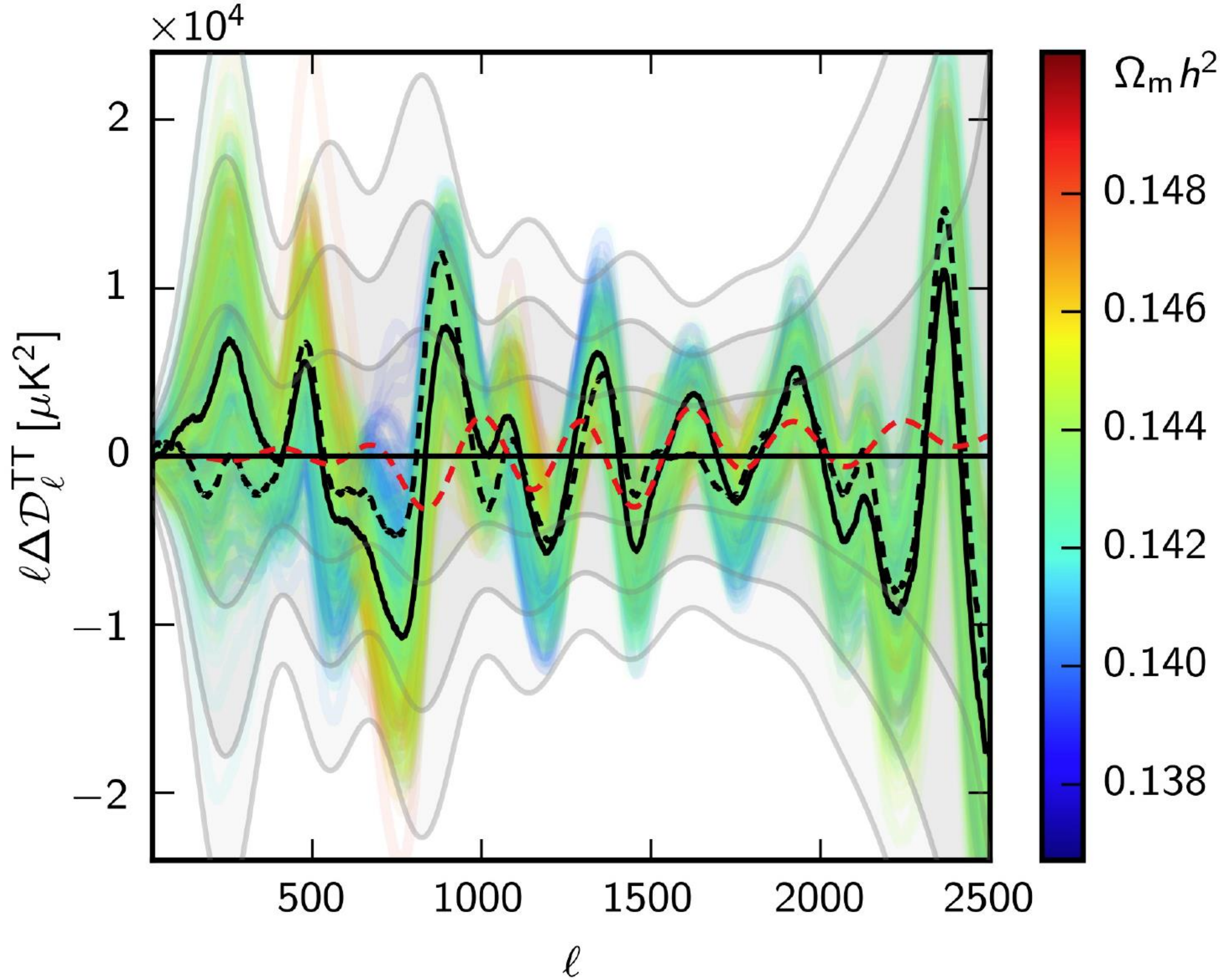
A_L degeneracies

More lensing ⇒ lower third+ peak ⇒ higher n_s
⇒ lower large-scale power ⇒ better fit to low-ℓ data
(plus offer effects)

$A_L \sim 1.1$ preference from smoothing effect
$A_L > 1.1$ preference driven by degeneracies

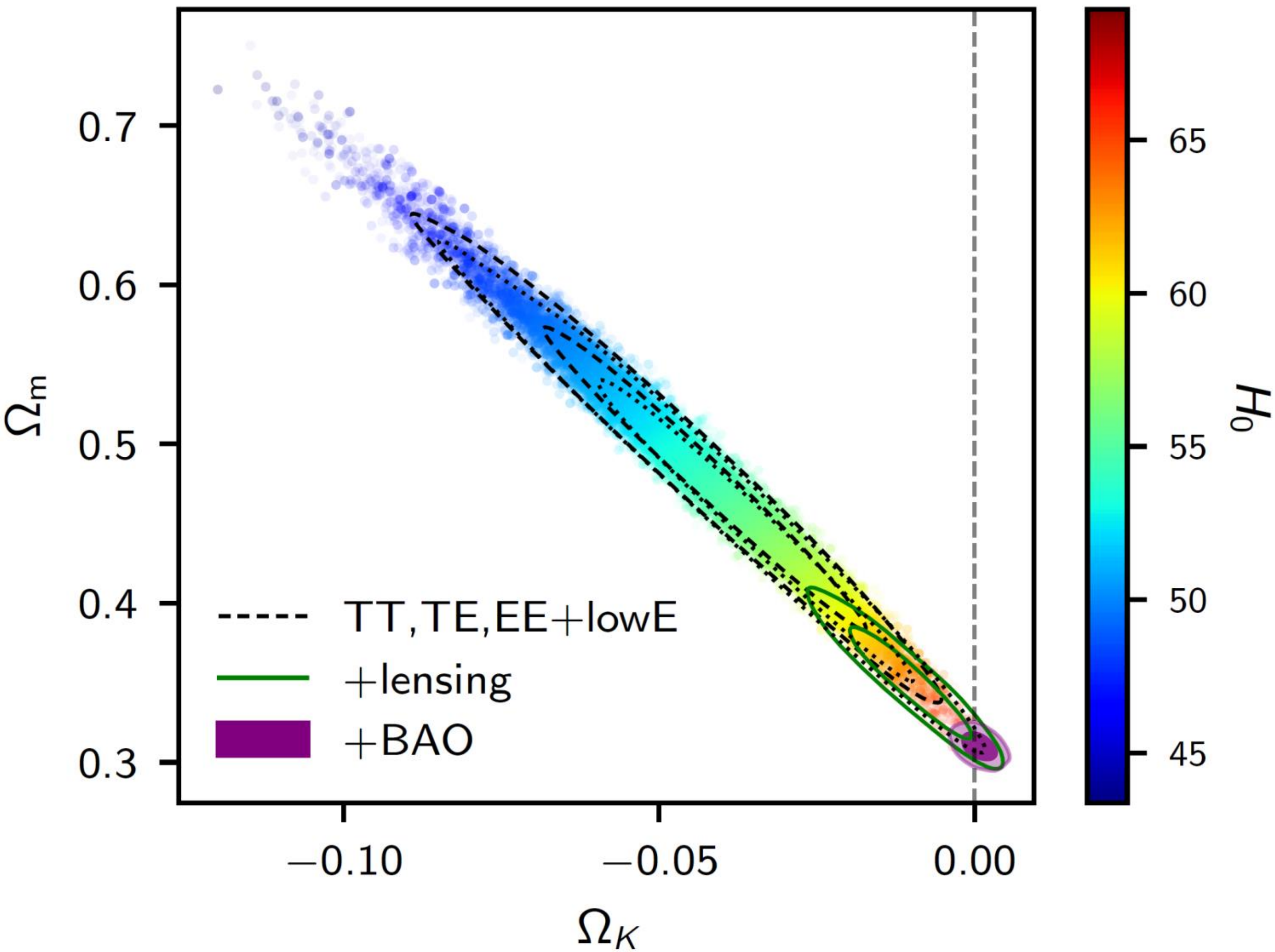


$\mathrm{Var}(d)/\mathrm{Var}(\mathrm{d_{LCDM}}) \sim 1.12$



×10^4
2
1
0
−1
−2
ℓΔD_ℓ^TT [μK^2]
500
1000
1500
2000
2500
ℓ
Ω_m h^2
0.148
0.146
0.144
0.142
0.140
0.138

Spatial Curvature



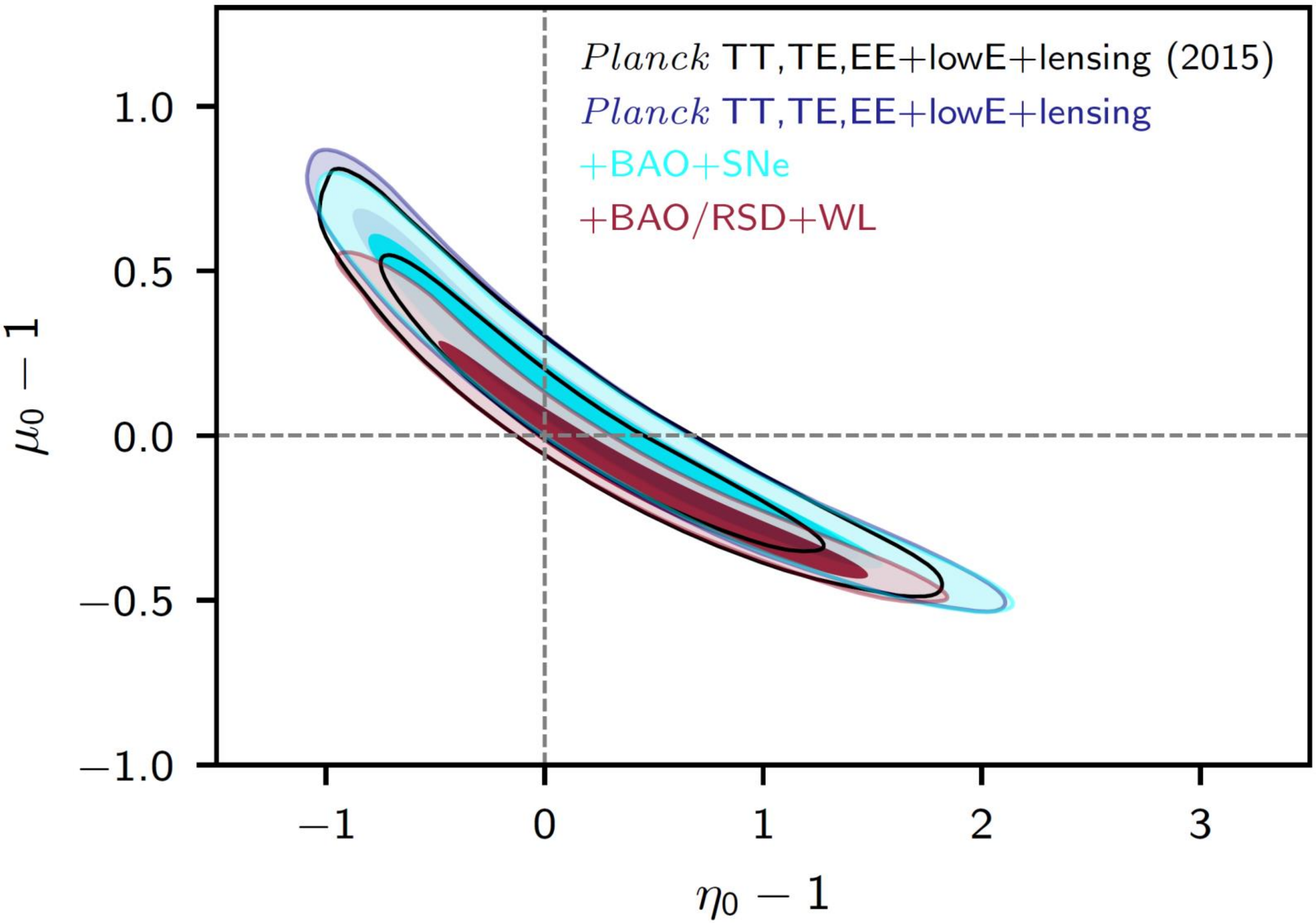
Ad hoc modified gravity

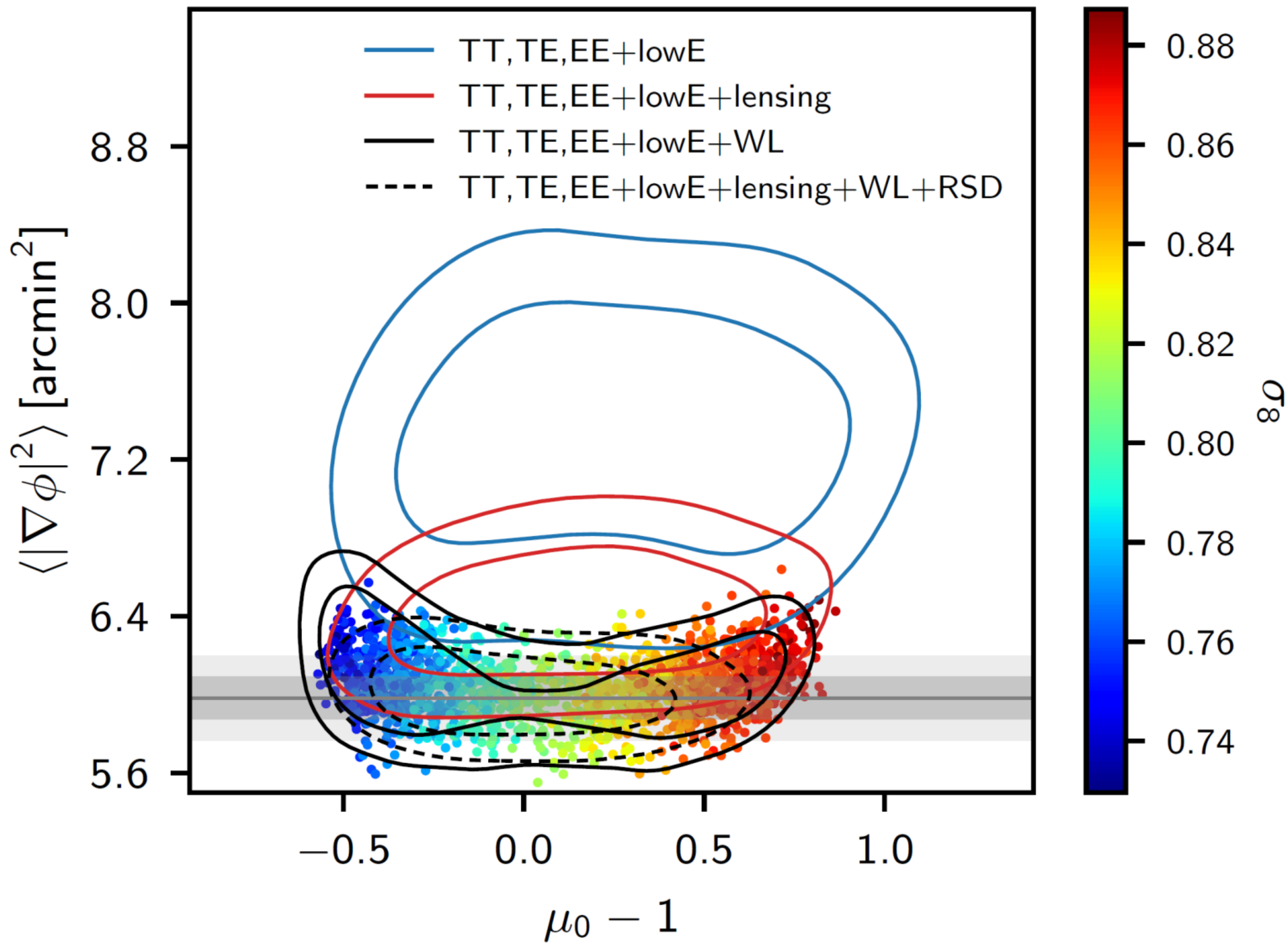
$$k^2\Psi = -\mu(a,k)\,4\pi G a^2\left[\rho\Delta + 3(\rho+P)\sigma\right]$$

$$\mu(z) = 1 + E_{11}\Omega_{\rm DE}(z);$$

$$k^2\left[\Phi - \eta(a,k)\Psi\right] = \mu(a,k)\,12\pi G a^2(\rho+P)\sigma$$

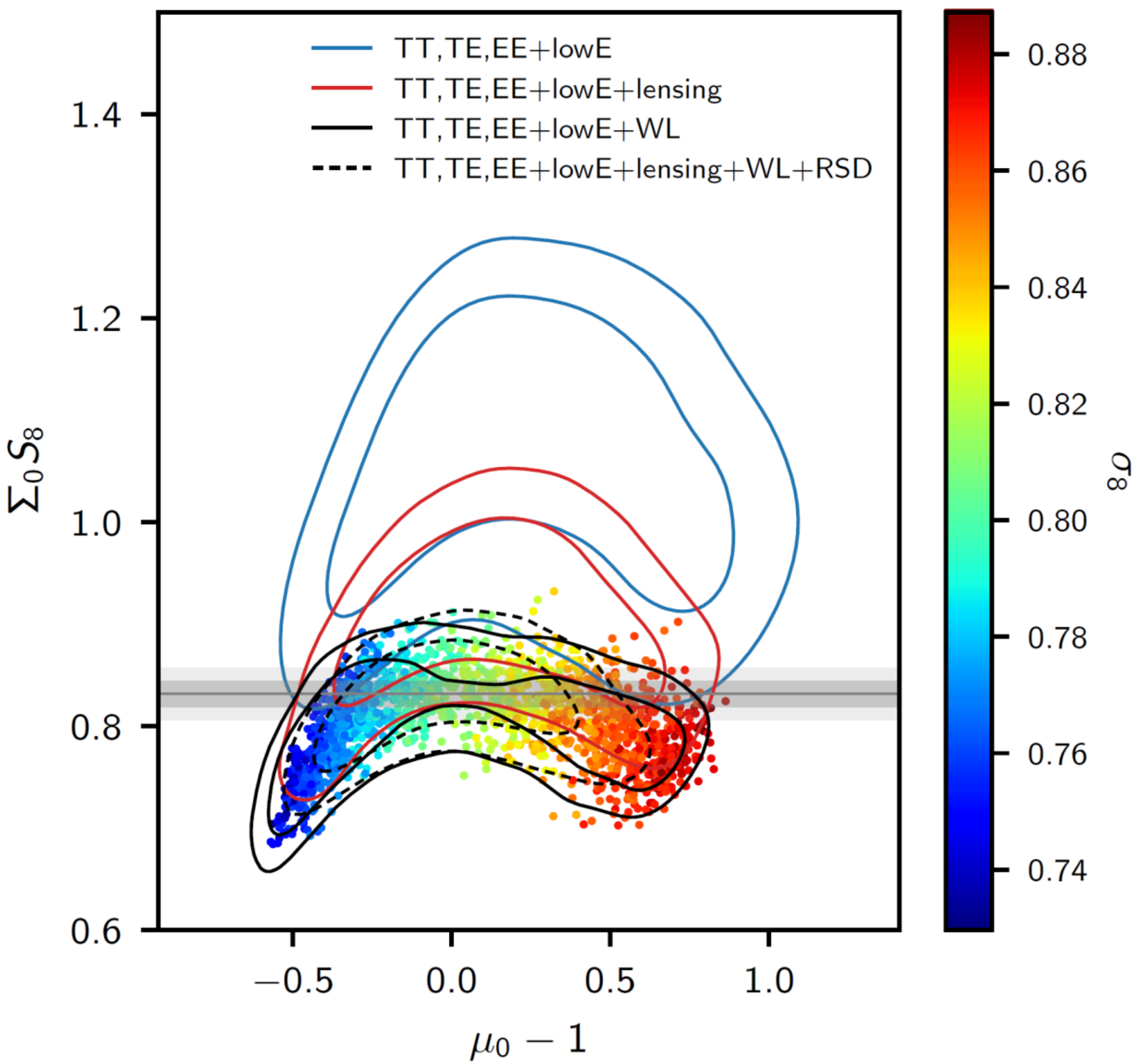
$$\eta(z) = 1 + E_{21}\Omega_{\rm DE}(z).$$



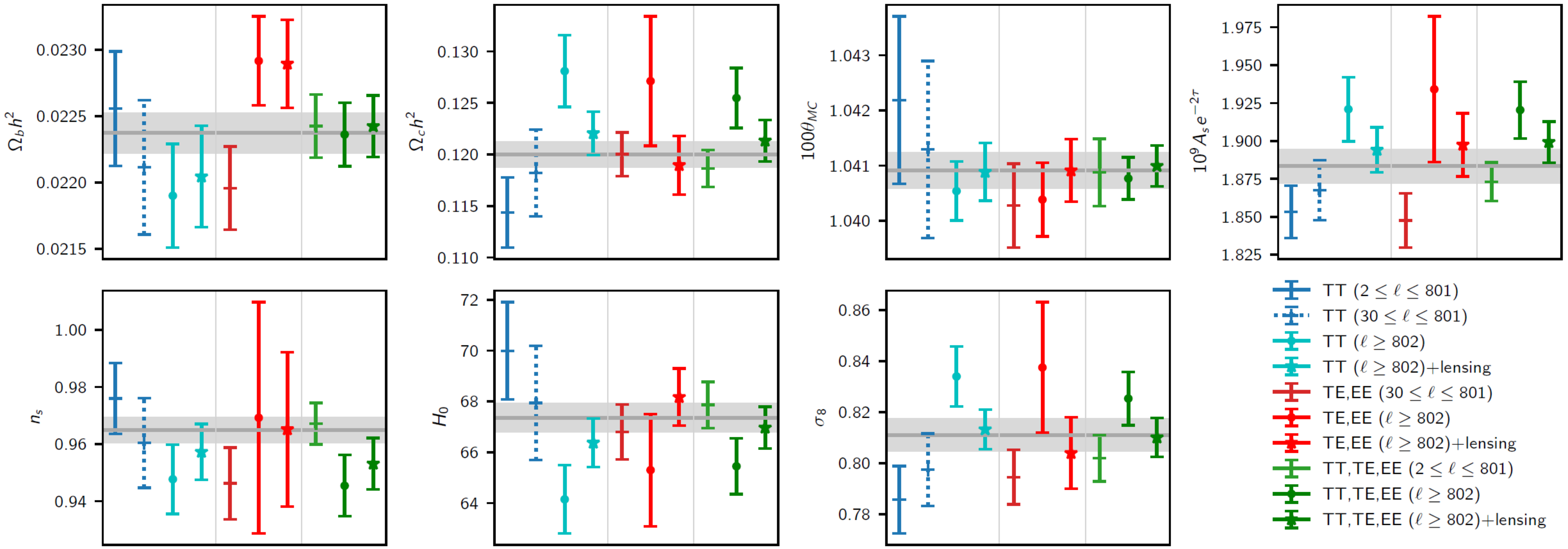


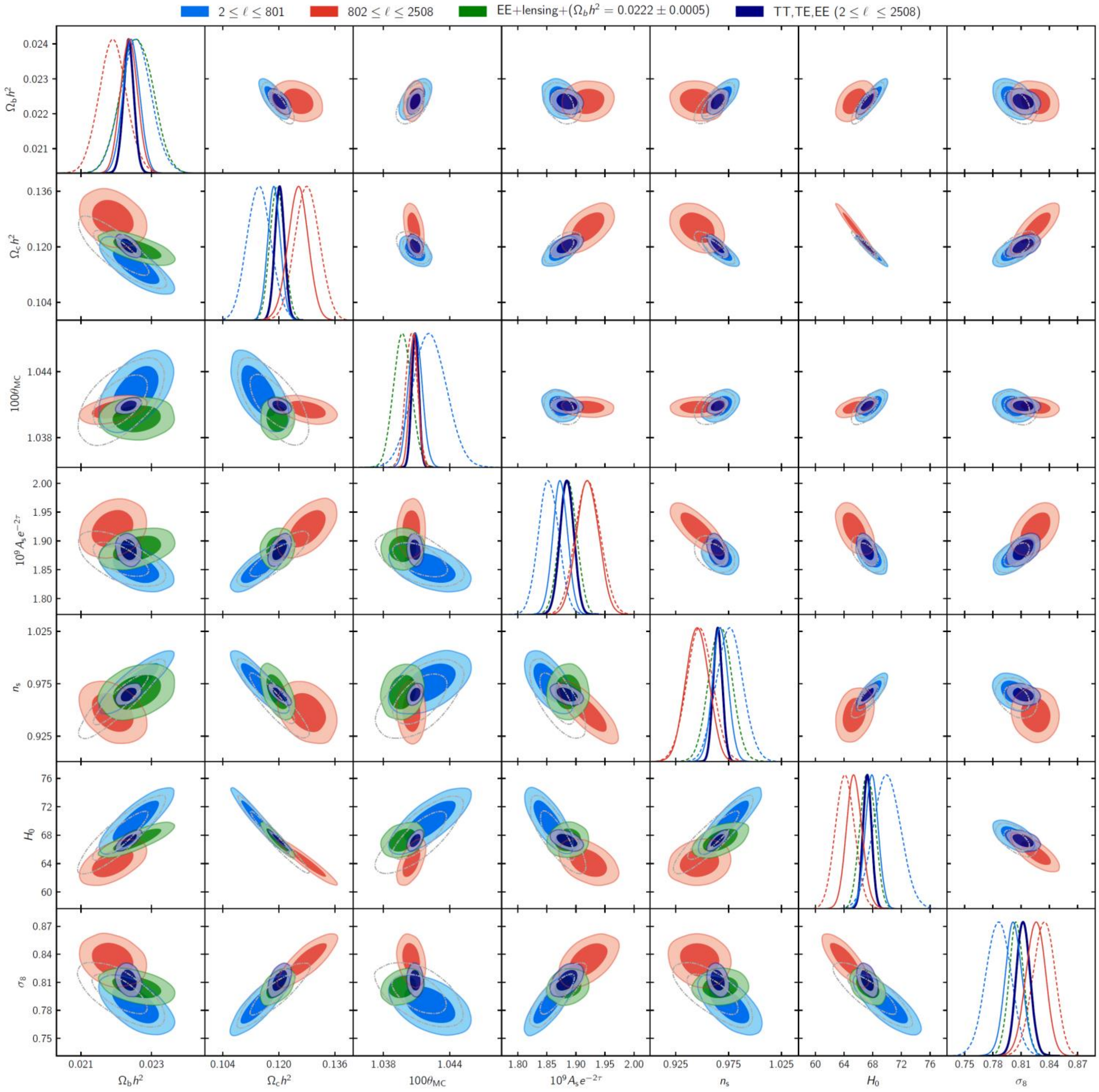
TT,TE,EE+lowE
TT,TE,EE+lowE+lensing
TT,TE,EE+lowE+WL
TT,TE,EE+lowE+lensing+WL+RSD
8.8
8.0
7.2
6.4
5.6
$\langle|\nabla\phi|^2\rangle$ [arcmin^2]
−0.5
0.0
0.5
1.0
$\mu_0 - 1$
0.88
0.86
0.84
0.82
0.80
0.78
0.76
0.74
σ_8

$$k^2 [\Phi + \Psi] = -\Sigma(a, k) 4\pi G a^2 [2\rho\Delta - 3(\rho + P)\sigma]$$



Low-ℓ vs high-ℓ in LCDM





$2 \leq \ell \leq 801$
$802 \leq \ell \leq 2508$
EE+lensing+($\Omega_b h^2 = 0.0222 \pm 0.0005$)
TT,TE,EE ($2 \leq \ell \leq 2508$)
$\Omega_b h^2$
$\Omega_c h^2$
$100\theta_{MC}$
$10^9 A_s e^{-2\tau}$
n_s
H_0
σ_8

Conclusions

- Planck parameters reliable, no major change since 2015
- Polarization now better understood (but not perfect; $\sim 0.5\sigma$ systematic uncertainty)
- Planck alone fits LCDM well: T, P + lensing all consistent
- Planck+LCDM consistent with BAO, SN, RSD, DES lensing
- Planck+LCDM moderate tension with DES joint probes
- Planck+LCDM in strong 3.6σ tension with H_0 from SH0ES
  Cannot just be problem with Planck (BAO+D/H+SN agree with Planck).
- Some curiosities (A_L, low-high features), but not more than $2\sigma - 3\ \sigma$
- If new physics is the solution to tensions, new physics does not have large signal in CMB

https://wiki.cosmos.esa.int/planck-legacy-archive/index.php/Cosmological_Parameters

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.