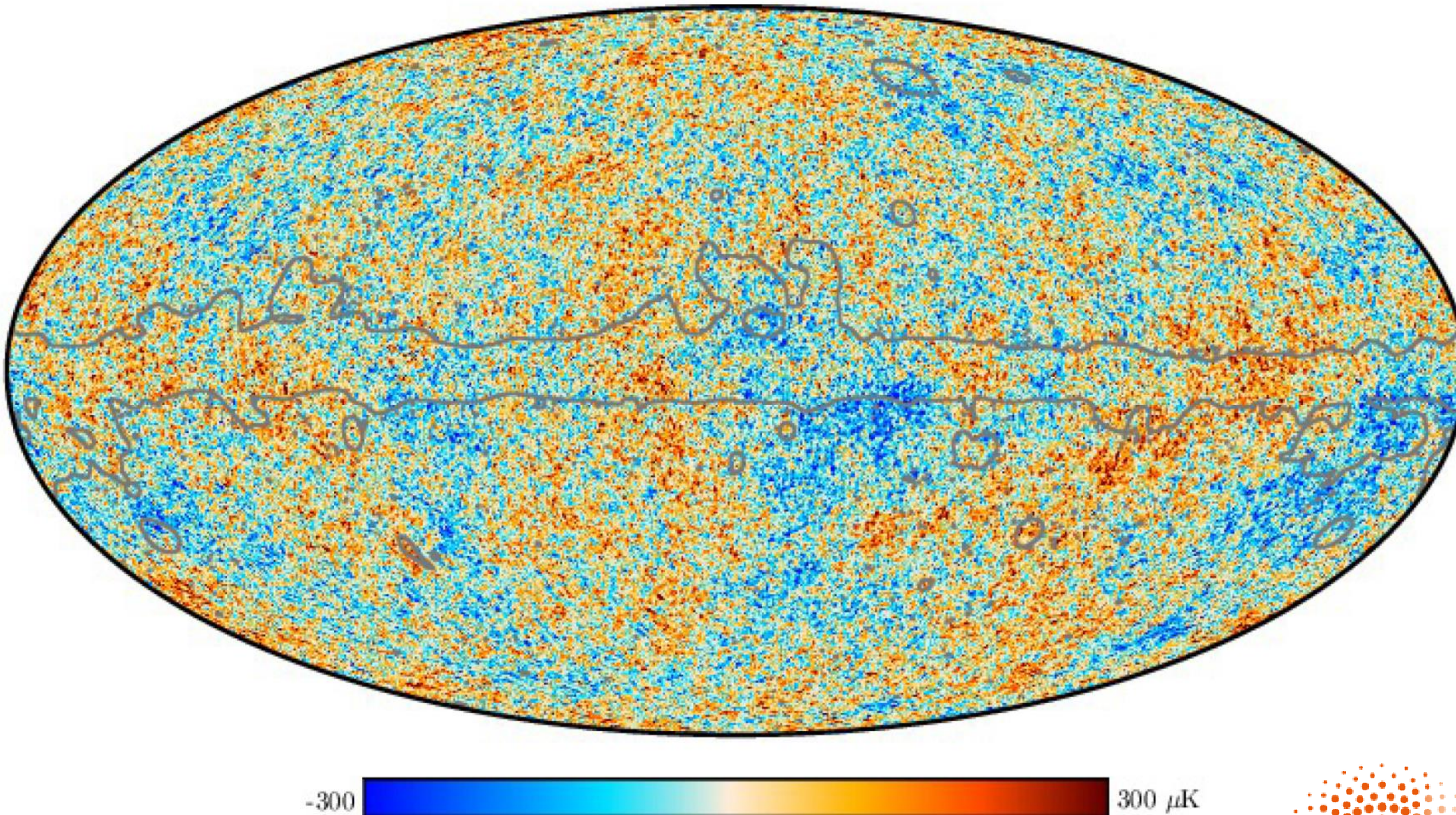
H_0 from CMB and Planck



Antony Lewis
http://cosmologist.info/

UNIVERSITY OF SUSSEX

European Research Council
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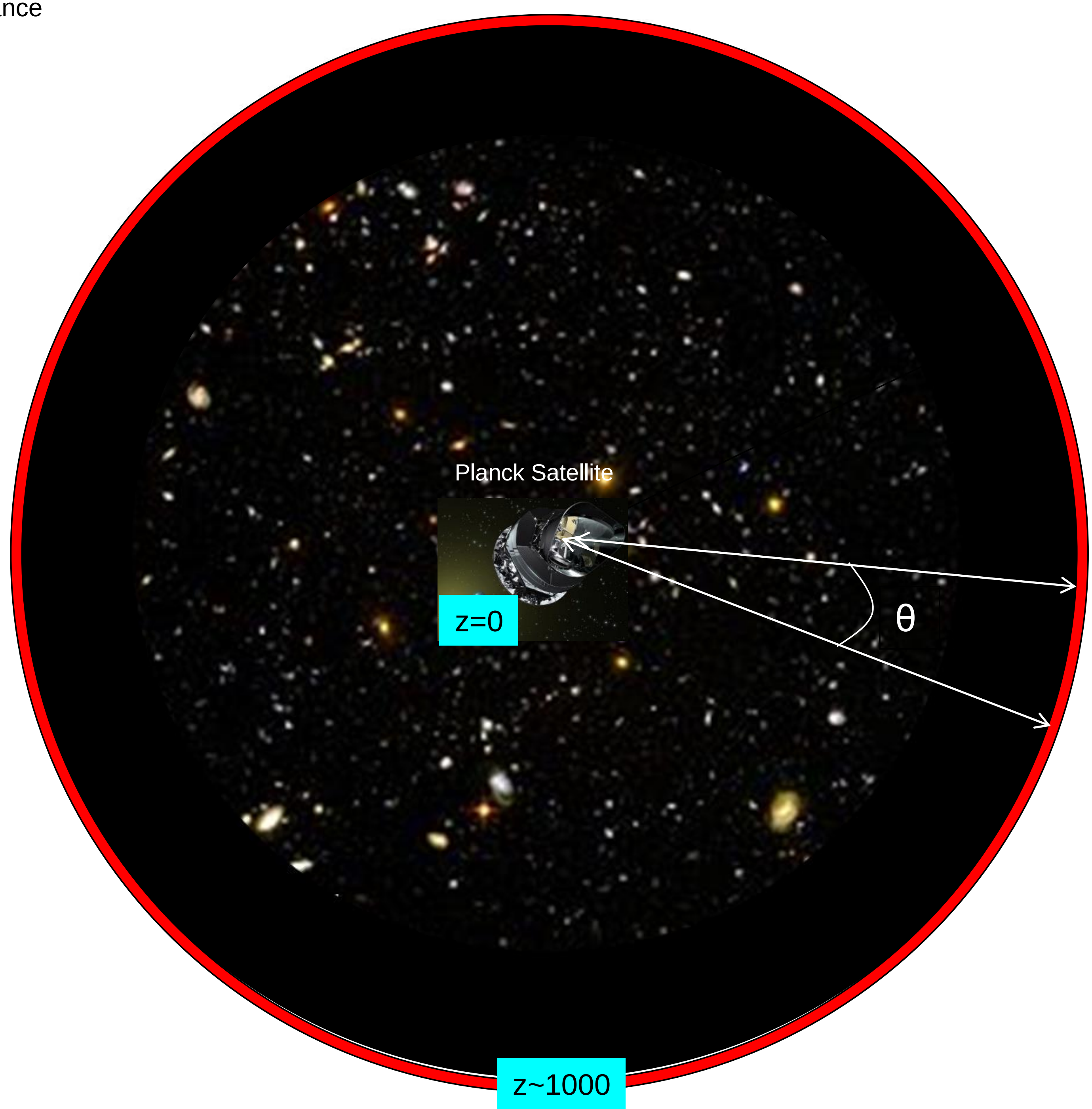
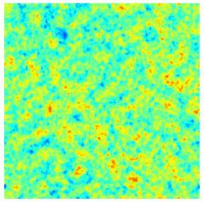
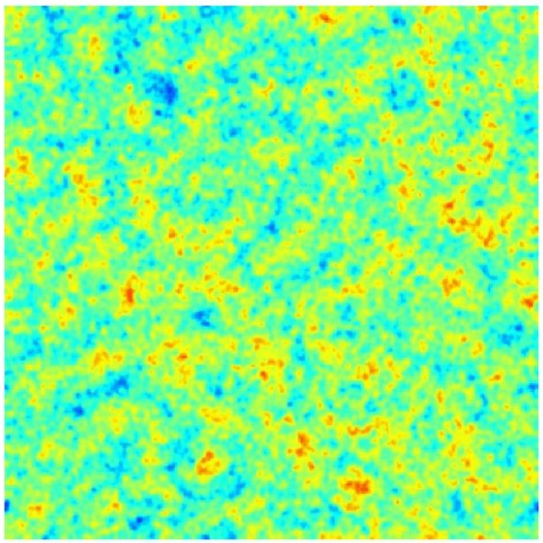
In comoving distance

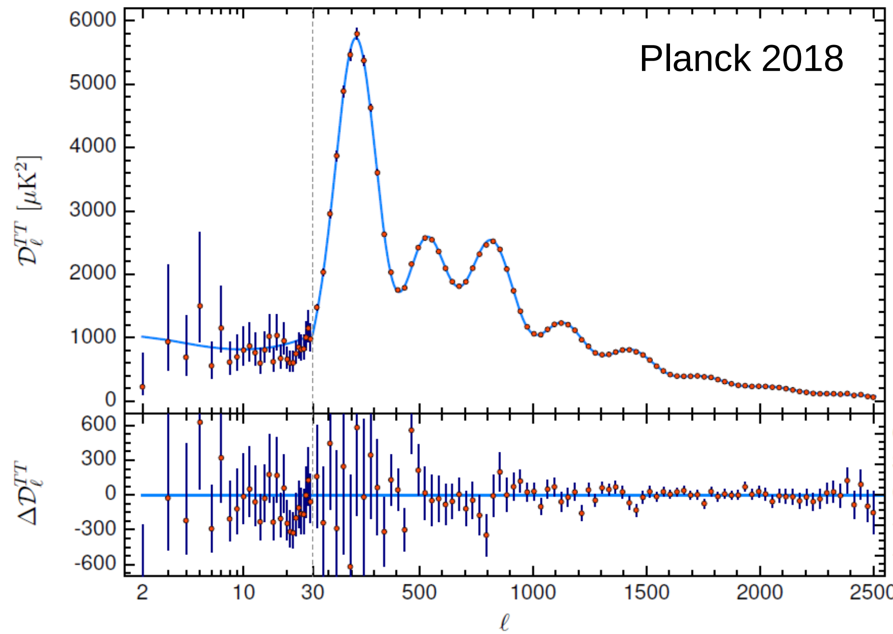




Observed CMB power spectrum



arXiv:1807.06209



Observations

(10^{-5} perturbations)

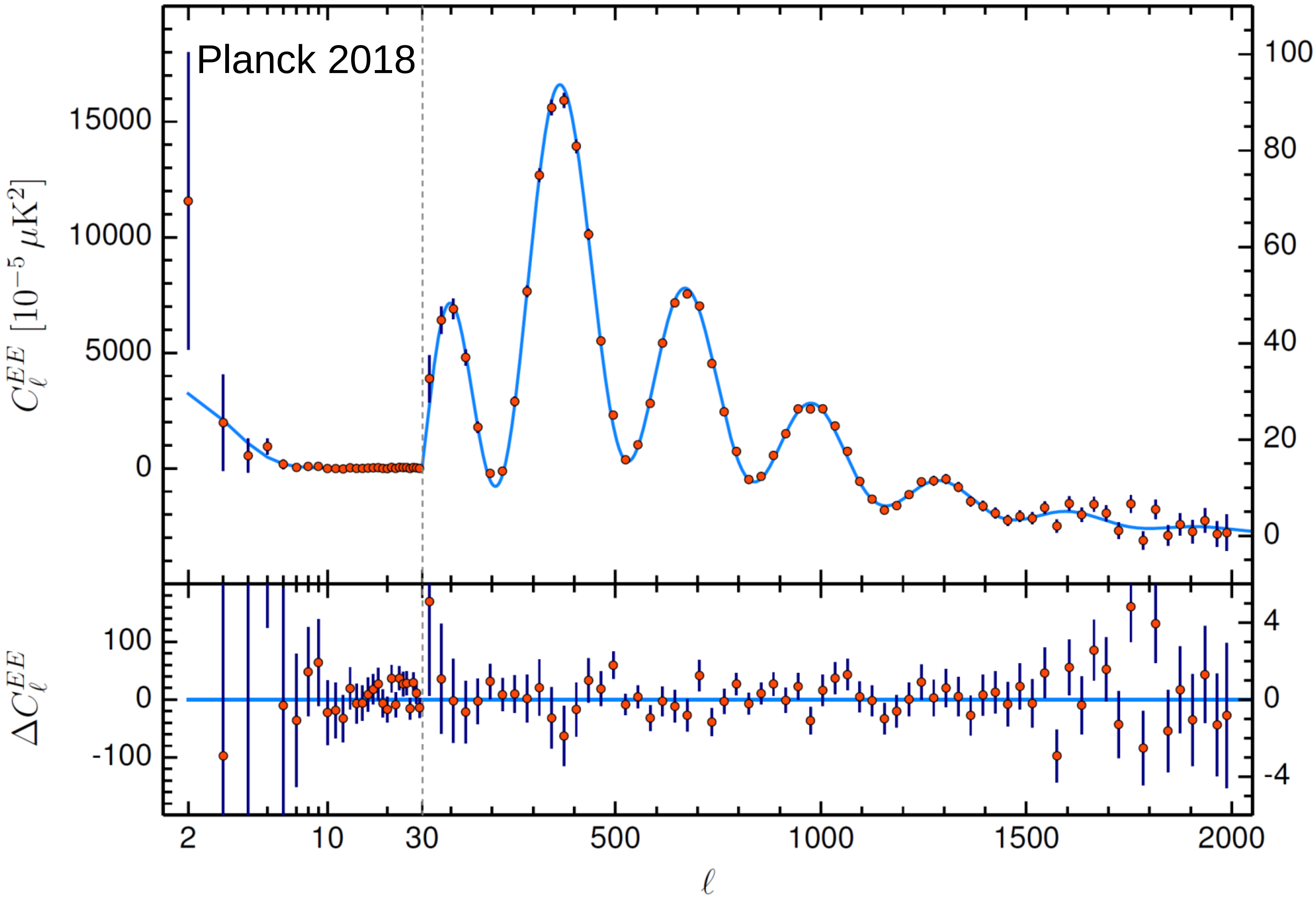
Constrain theory of early universe
+ evolution parameters and geometry

Linear perturbation theory very accurate: given a model, can calculate to high precision

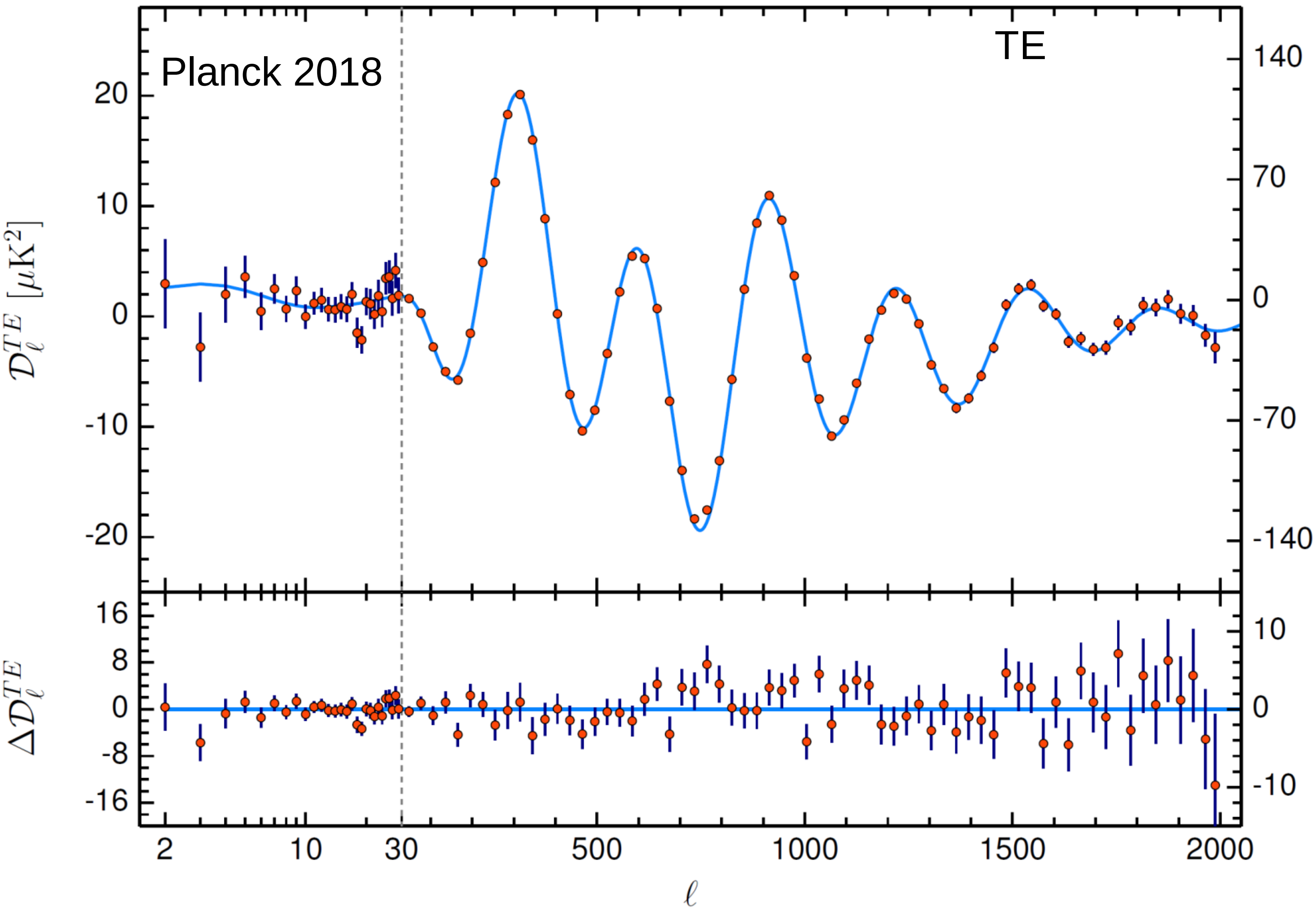
E-mode polarization

2018: polarization now included in main results.

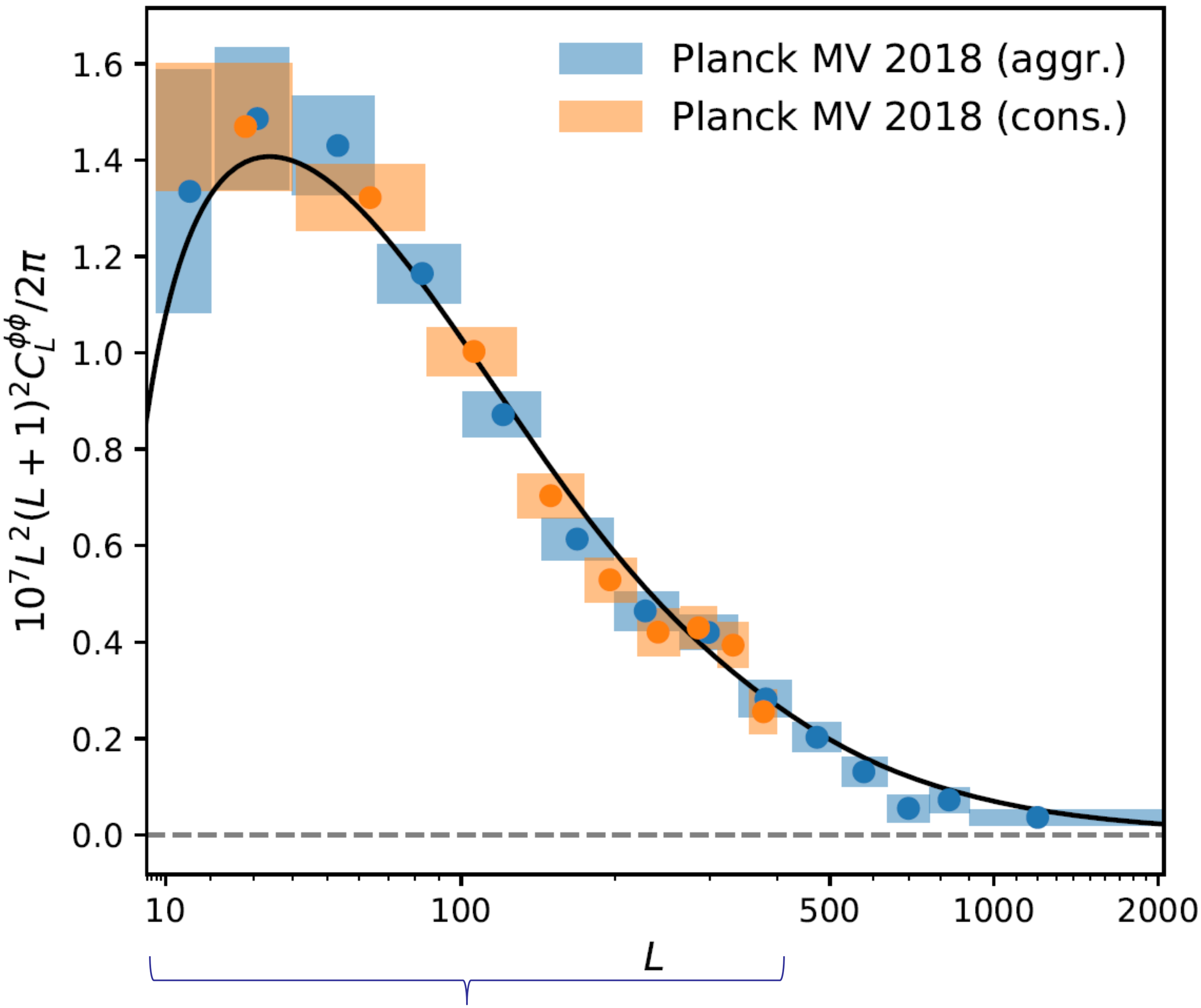
Improved understanding and correction of systematics (e.g. TE leakage), but some unresolved issues (e.g. with polar efficiencies) remain



Cross-correlation with temperature



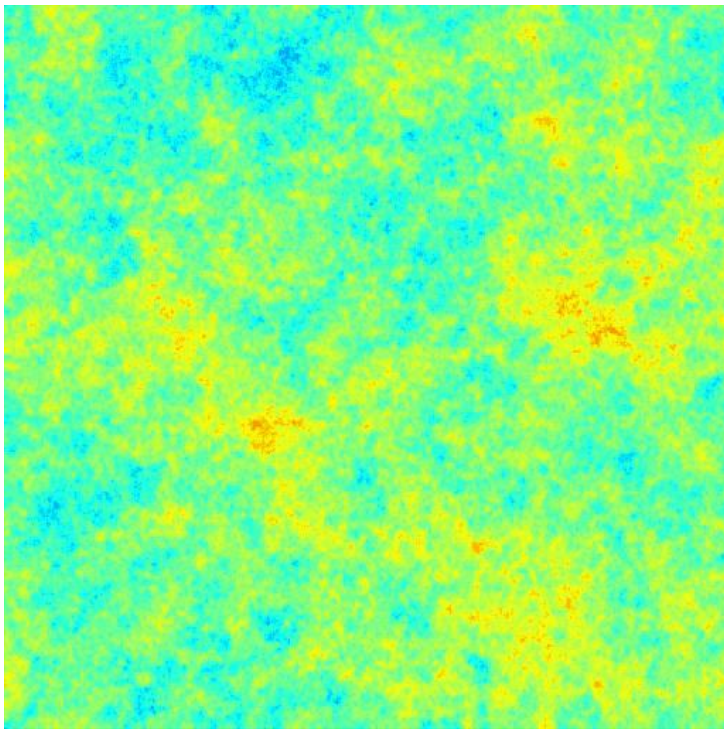
CMB lensing reconstruction



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

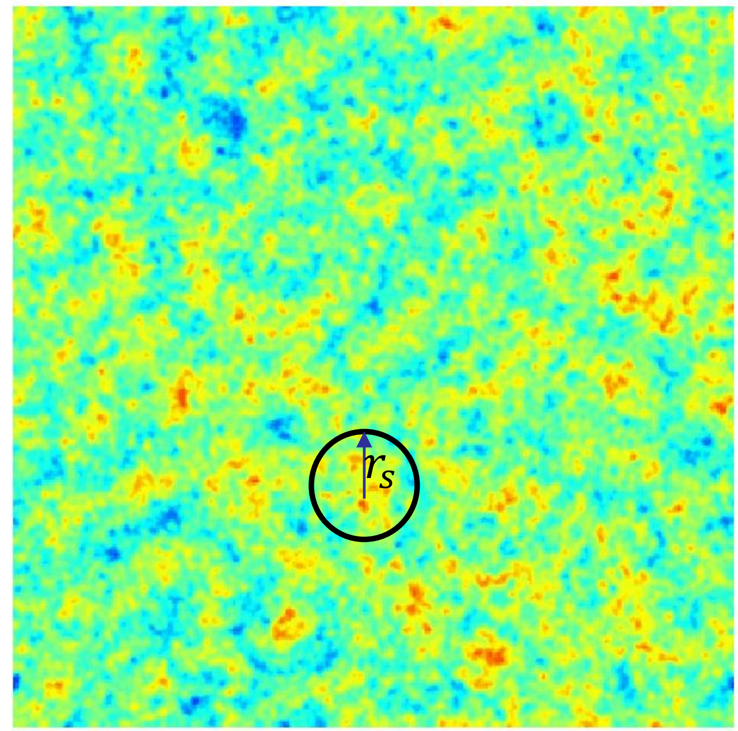
Perturbation evolution

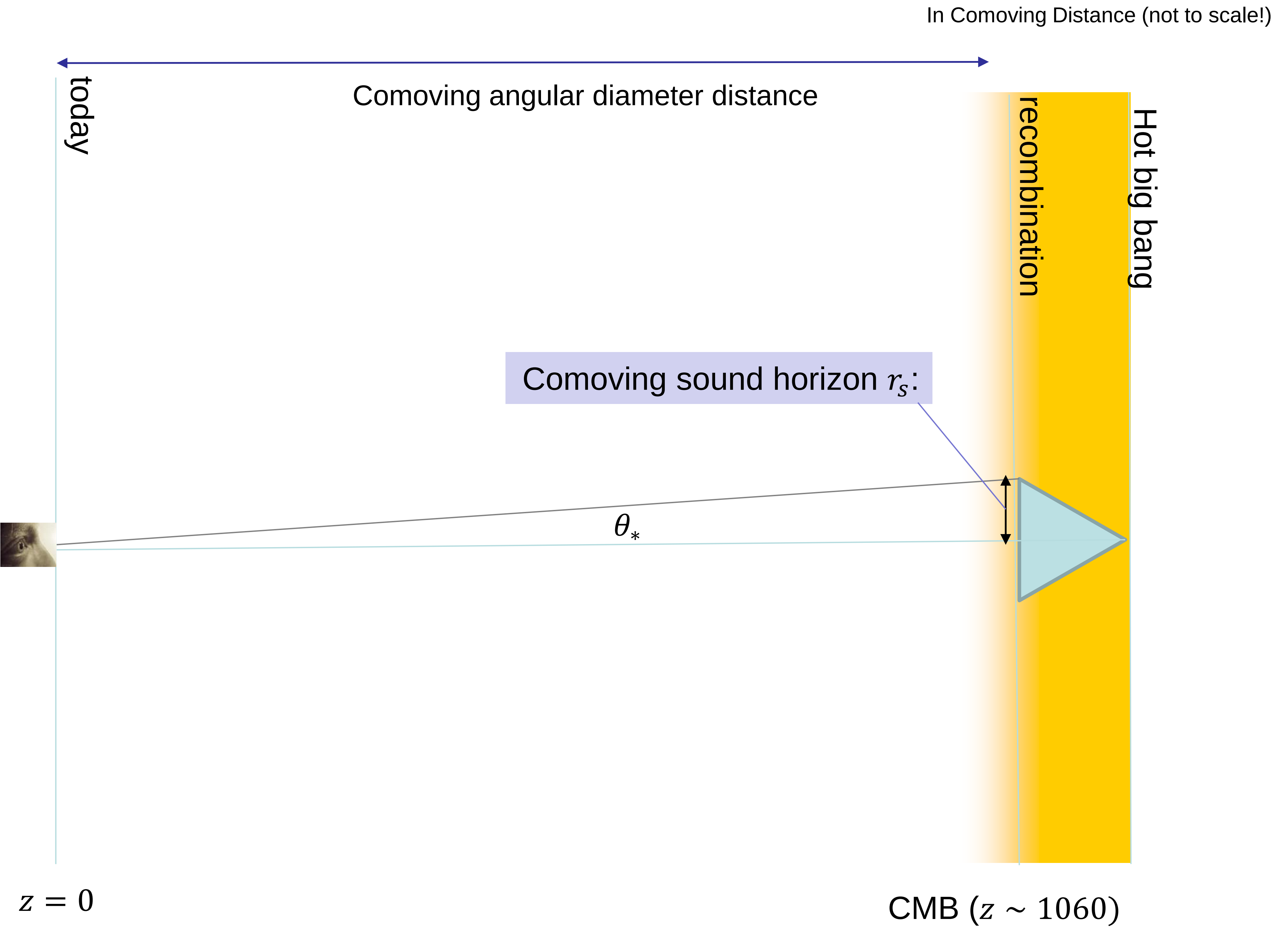
Perturbations: End of inflation

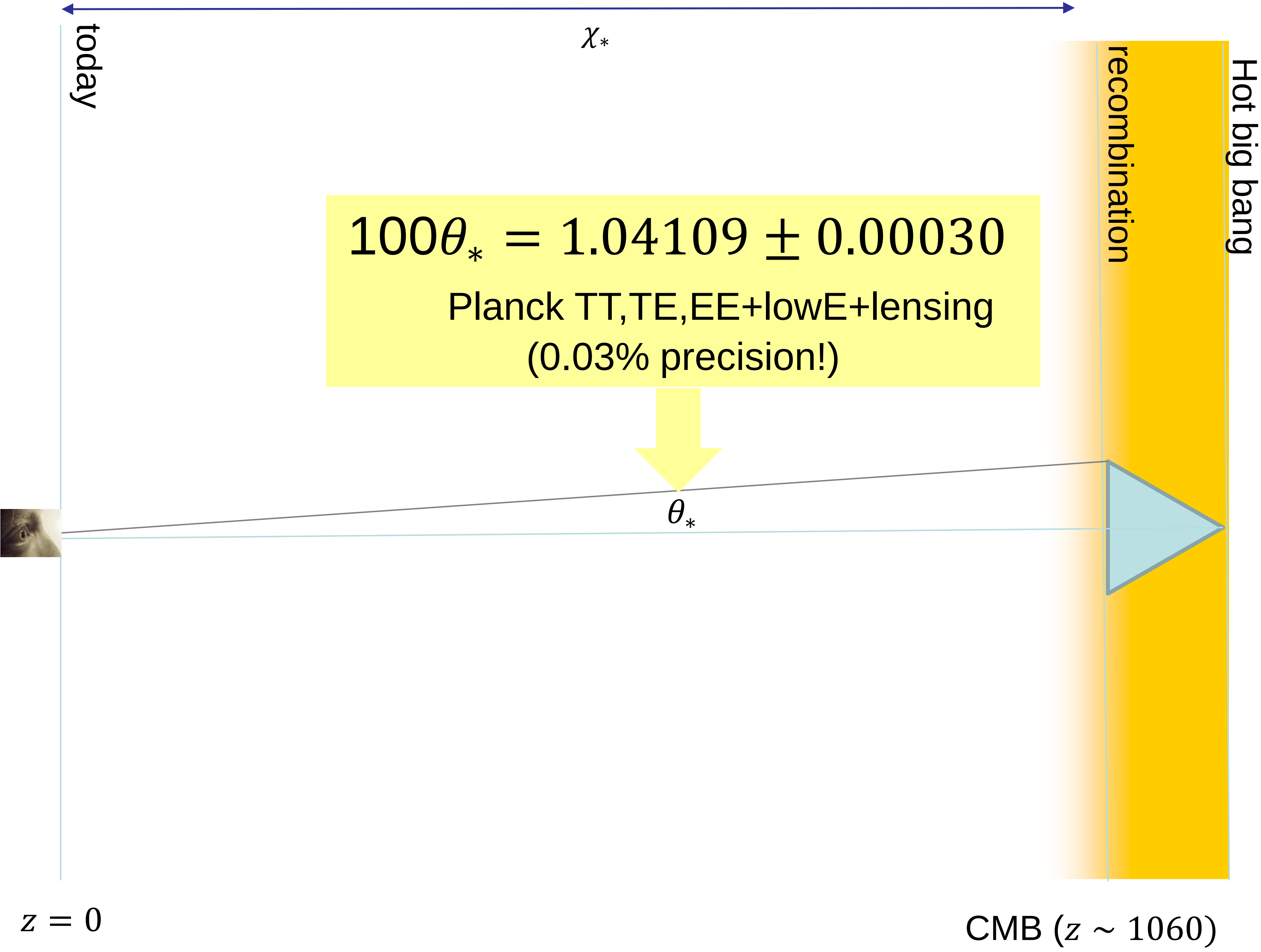


gravity+
pressure+
diffusion

Perturbations: Last scattering surface



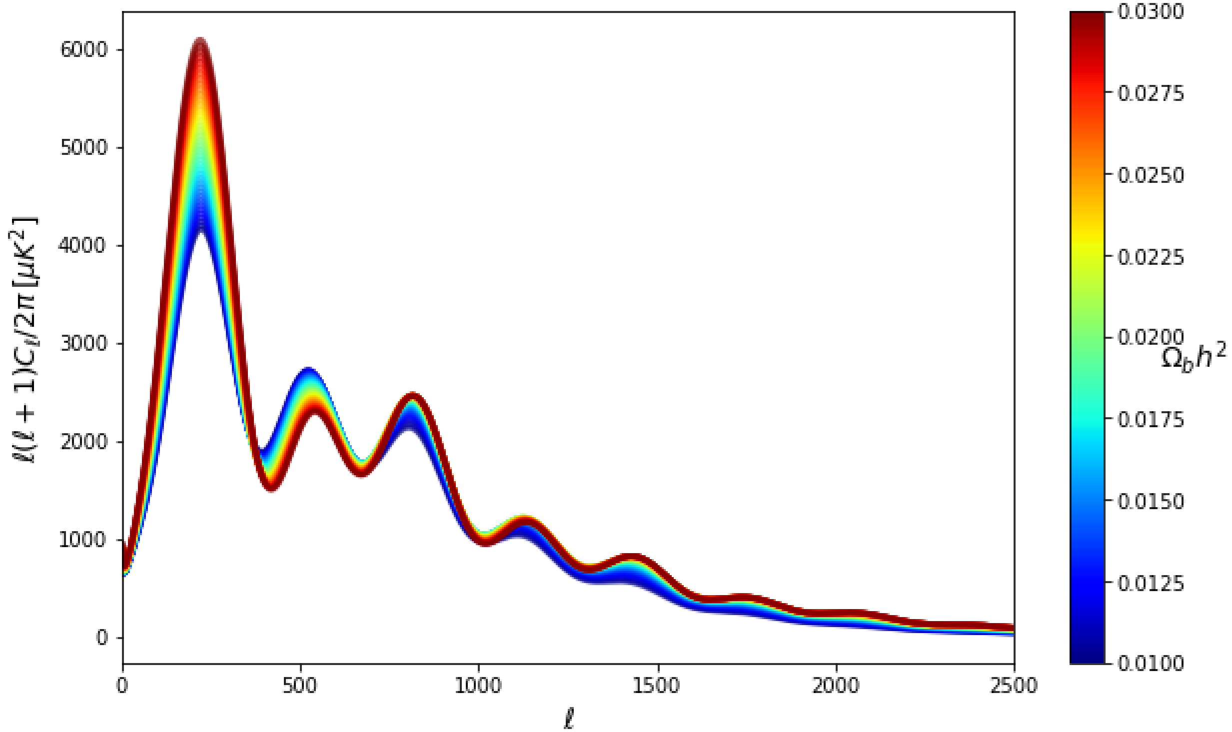

In Comoving Distance (not to scale!)
Comoving angular diameter distance
today
recombination
Hot big bang
Comoving sound horizon r_s:
θ_*
$z = 0$
CMB ($z \sim 1060$)



χ_*
today
recombination
Hot big bang
$100\theta_* = 1.04109 \pm 0.00030$
Planck TT,TE,EE+lowE+lensing
(0.03% precision!)
θ_*
$z = 0$
CMB ($z \sim 1060$)

ΛCDM baryon density at fixed θ_*, $\Omega_m h^2$

(baryons deepen overdensity compressions: enhance odd peaks of spectrum)



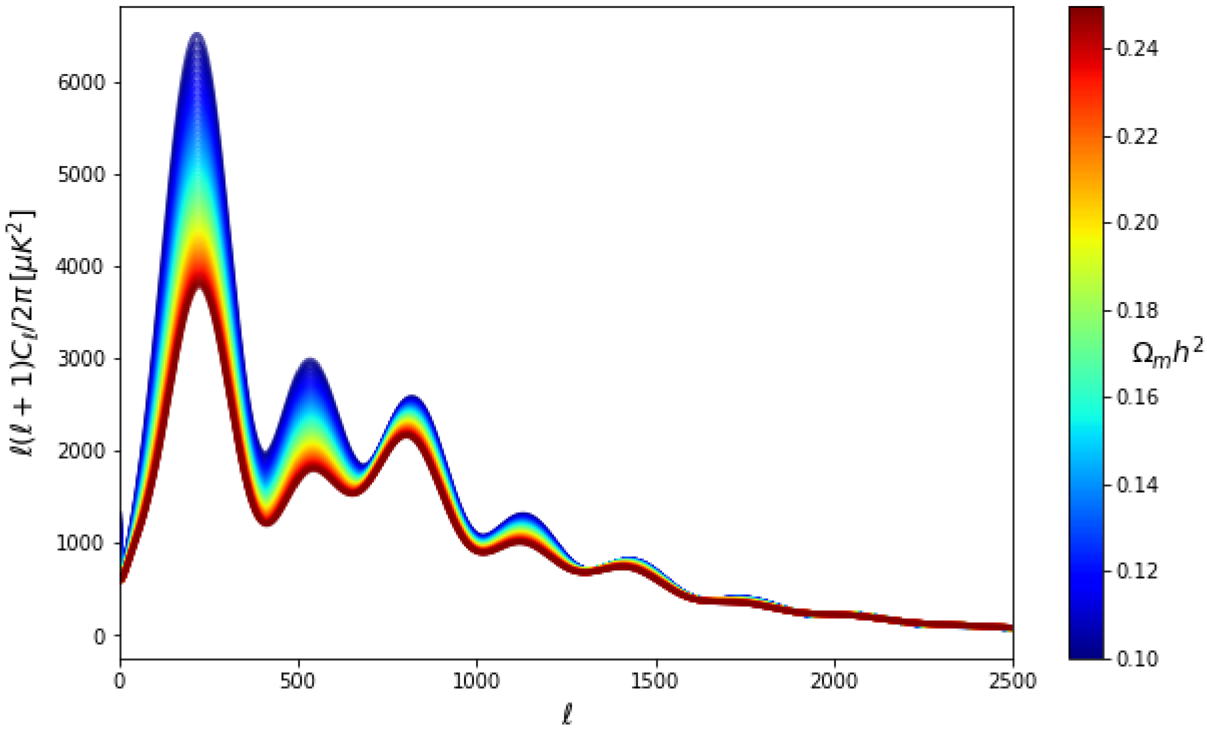
Odd/even height ratio distinctive and quite robust:

$$\Omega_b h^2 = 0.0224 \pm 0.0002$$

(and agrees with BBN prediction based on element abundance observations, Cooke et al.)

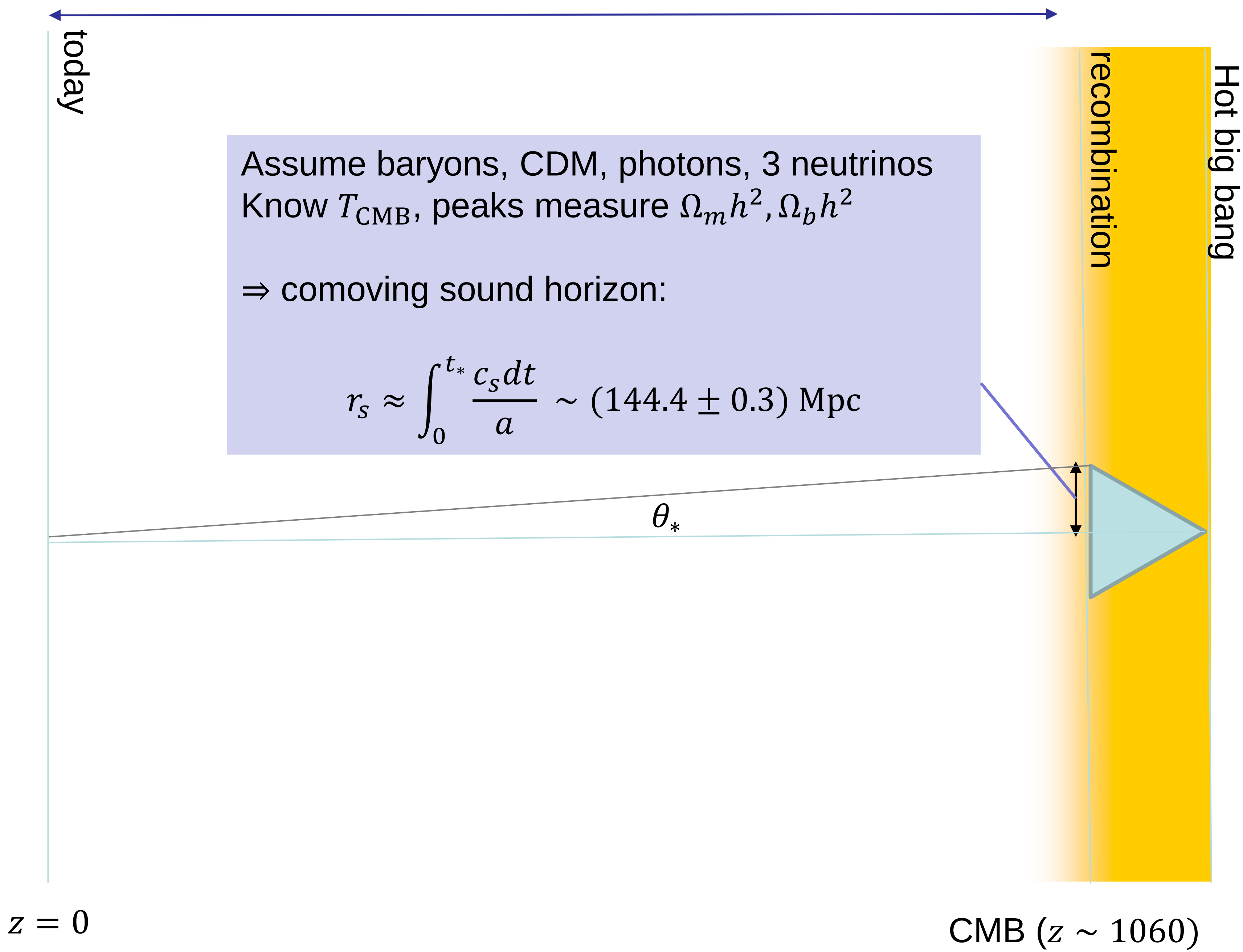
ΛCDM matter density at fixed θ_*, $\Omega_b h^2$

(more matter *lowers* amplitude for modes that enter horizon in matter domination)



Can be partly compensated by changing initial power A_s, n_s and foregrounds.
But detailed shape is still quite distinctive and robust:

$$\Omega_m h^2 = 0.143 \pm 0.001$$


today
recombination
Hot big bang
Assume baryons, CDM, photons, 3 neutrinos
Know T_{CMB}, peaks measure $\Omega_m h^2, \Omega_b h^2$
⇒ comoving sound horizon:
$r_s \approx \int_0^{t_*} \frac{c_s dt}{a} \sim (144.4 \pm 0.3)\ \mathrm{Mpc}$
θ_*
$z = 0$
CMB ($z \sim 1060$)

CMB

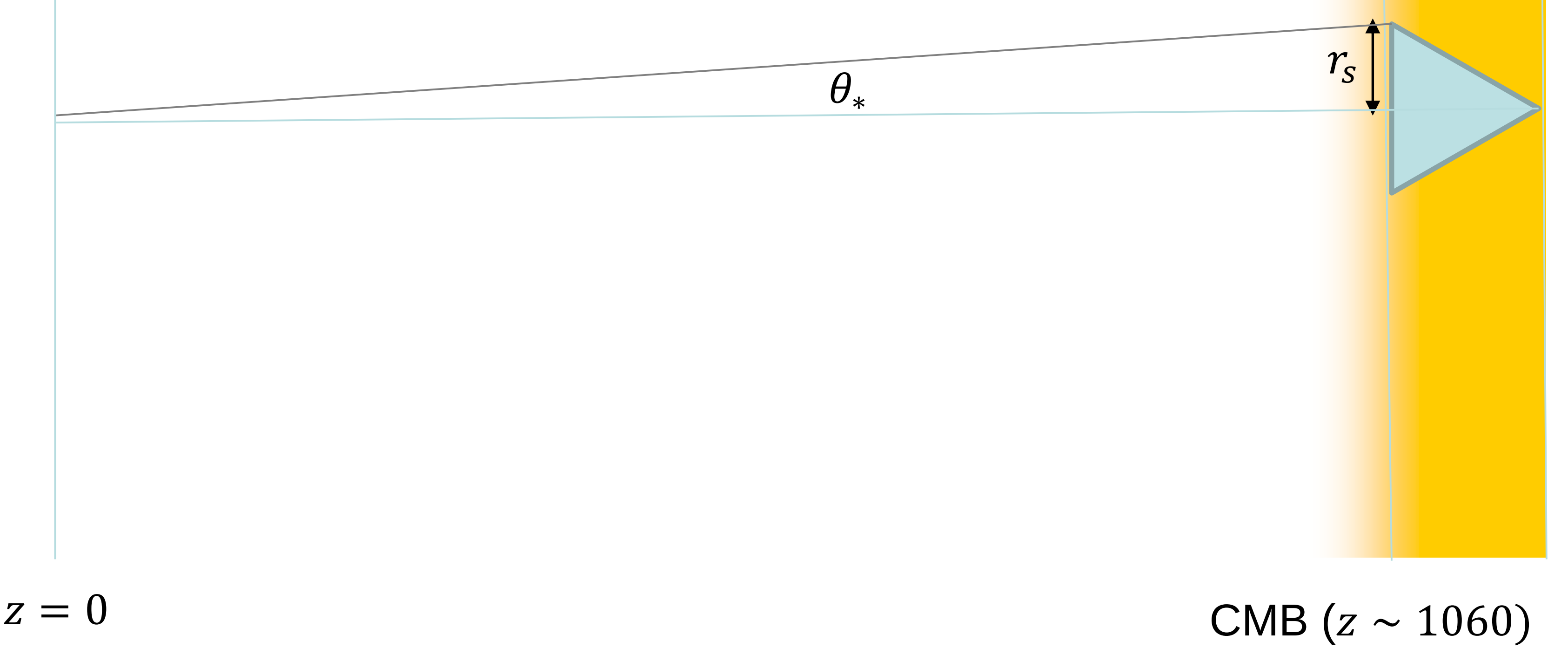
Assuming flat ΛCDM cosmology

$r_s, \theta_* \Rightarrow$ Comoving radial distance $\chi_* \sim (13.87 \pm 0.03)\ \mathrm{Gpc}$

$$\chi_* = \int \left(\frac{c\,dt}{a}\right)$$

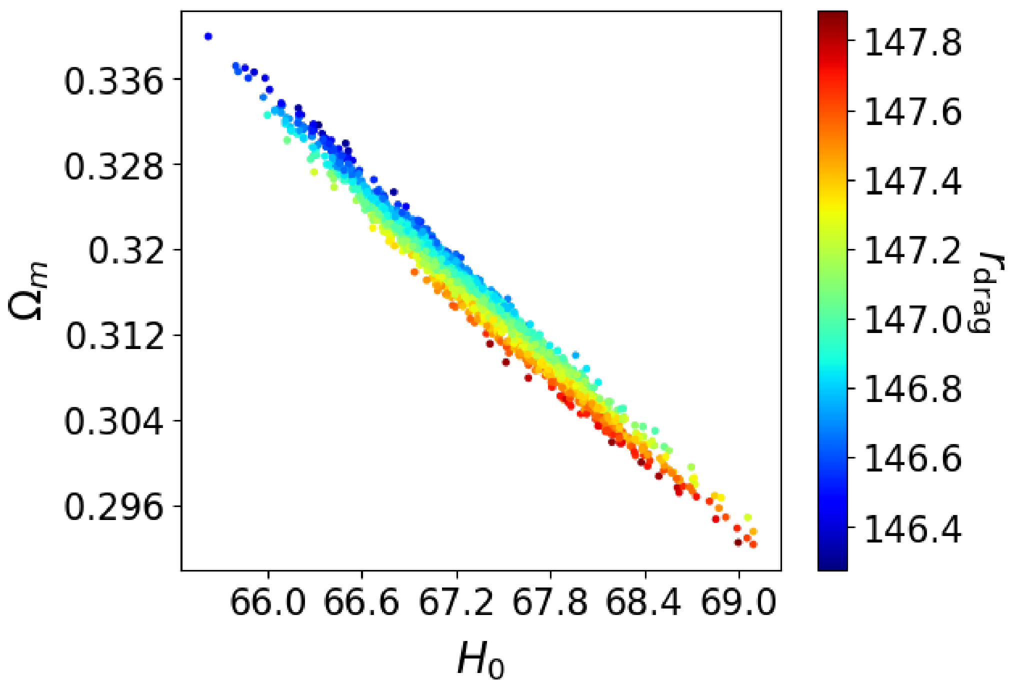
$$= \int \left(\frac{da}{a^2 H}\right) \approx \int \frac{da}{\sqrt{a\Omega_\mathrm{m} H_0^2 + a^4 \Omega_\Lambda H_0^2}}$$

$\Omega_\Lambda H_0^2 = H_0^2 - \Omega_m H_0^2$ and know $\Omega_m h^2 \Rightarrow H_0$



$\Omega_m - H_0$ degeneracy

- θ_* constrained more tightly than anything else
- In ΛCDM $\theta_* \sim$ constant $\Rightarrow$ $\Omega_m h^3 \sim$ const at Planck parameters
- $\Rightarrow \Omega_m$ and H_0 (and $\Omega_m h^2$ and H_0) tightly anti-correlated



Planck 2018 ΛCDM TT,TE,EE+lowE+lensing parameters

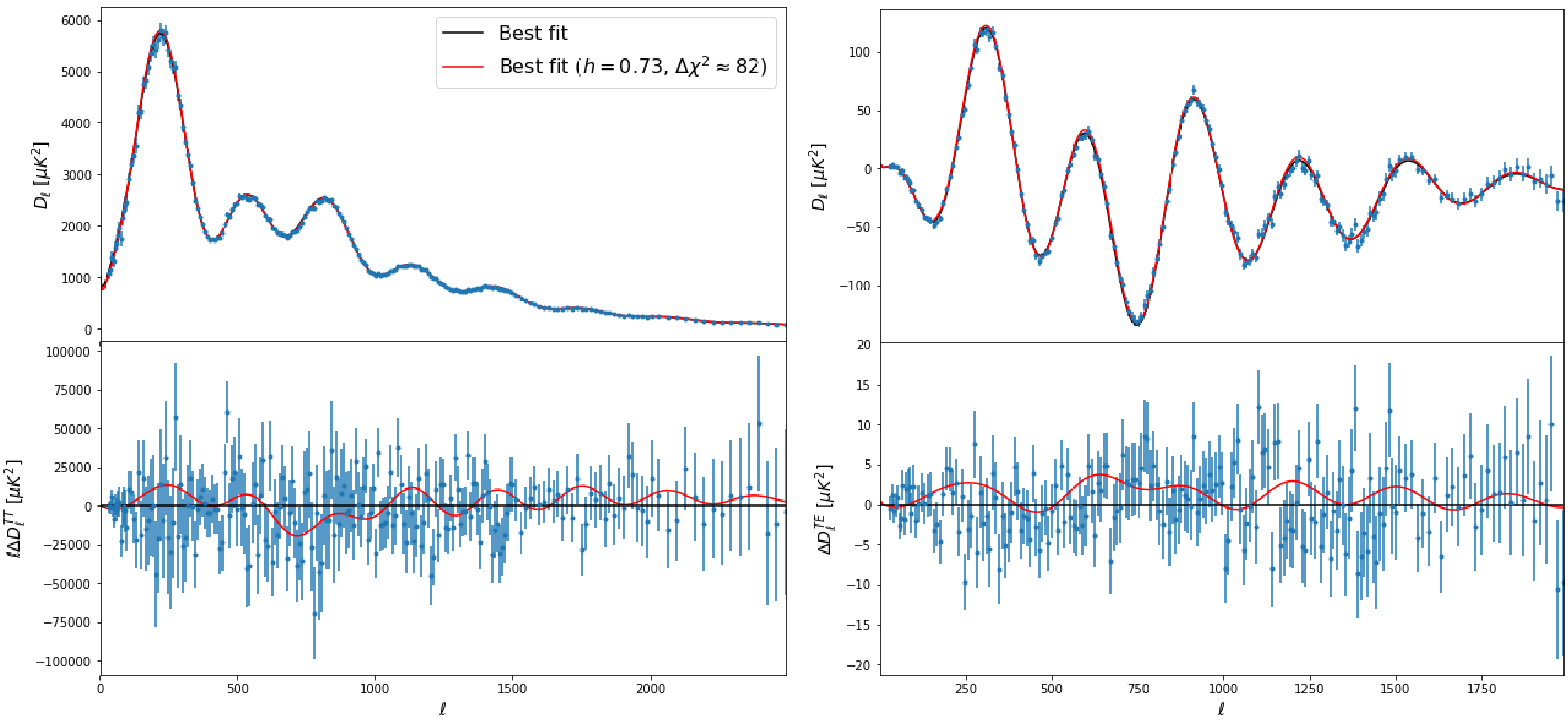
Parameter	Plik best fit	Plik [1]	CamSpec [2]	$([2]-[1])/\sigma_1$	Combined
$\Omega_b h^2$	0.022383	0.02237 ± 0.00015	0.02229 ± 0.00015	-0.5	0.02233 ± 0.00015
$\Omega_c h^2$	0.12011	0.1200 ± 0.0012	0.1197 ± 0.0012	-0.3	0.1198 ± 0.0012
$100\theta_{MC}$	1.040909	1.04092 ± 0.00031	1.04087 ± 0.00031	-0.2	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

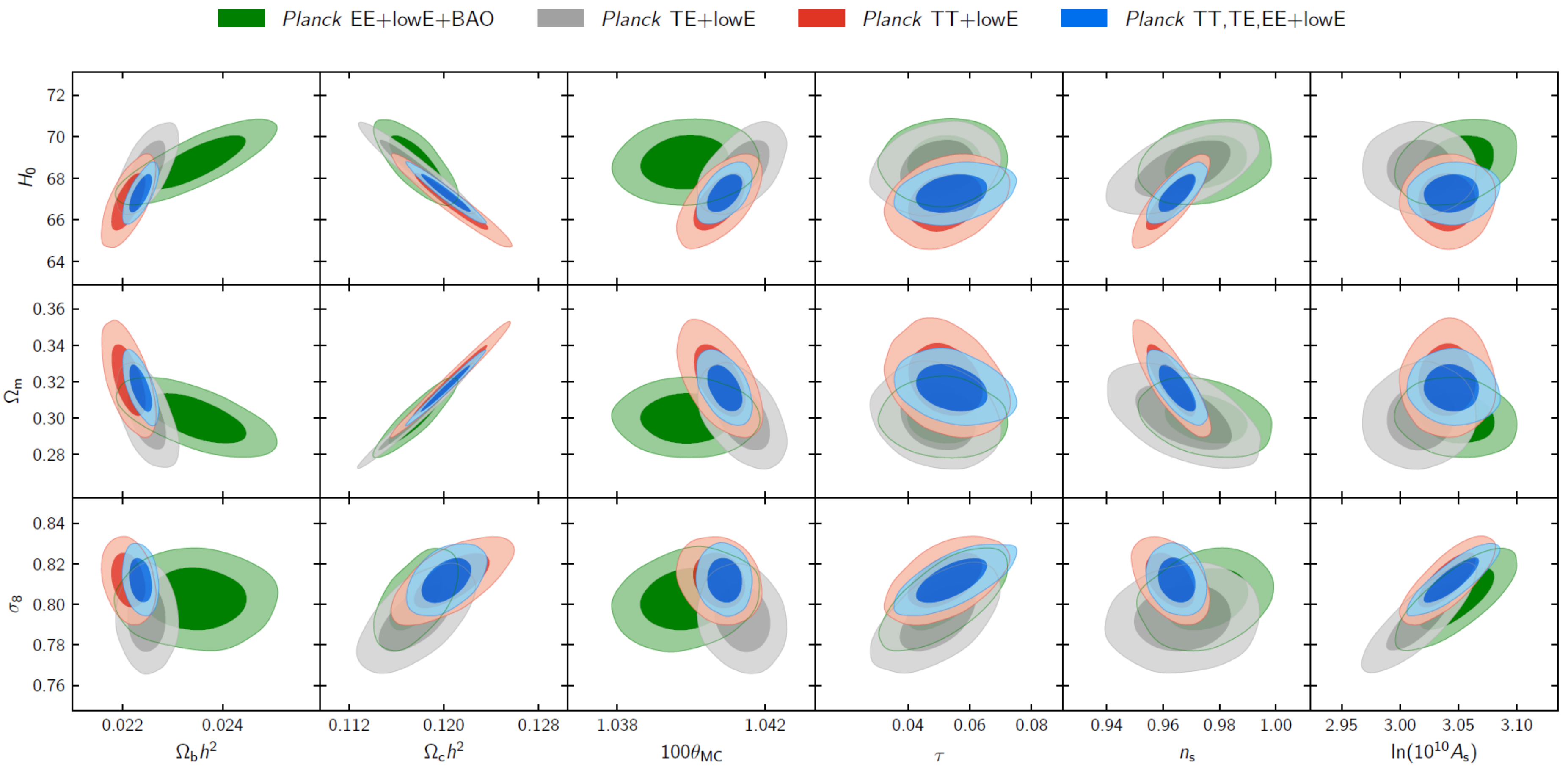
LCDM results robust to $\sim 0.5\sigma$ (where σ is small)

Model fits

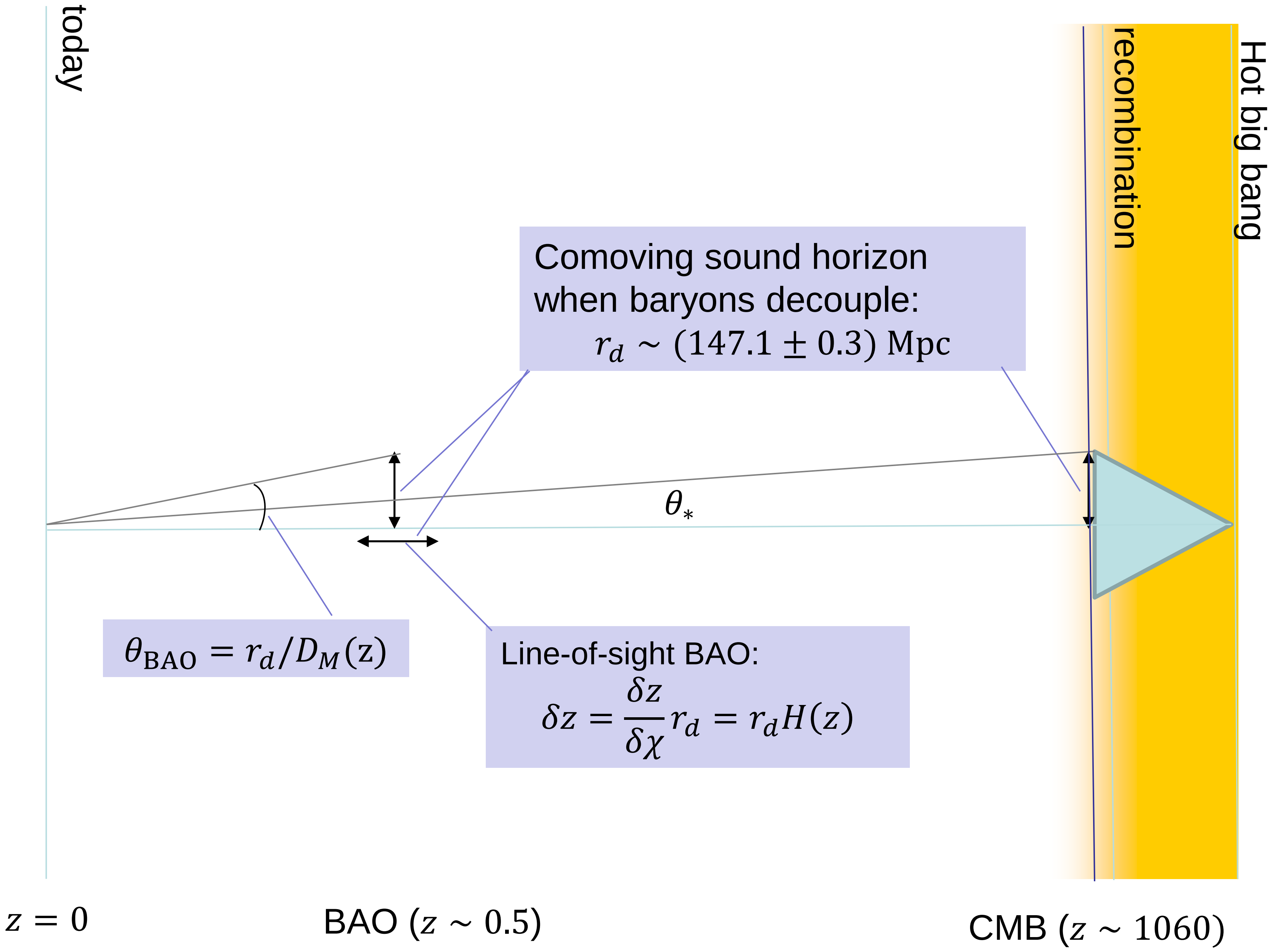
LCDM best-fits: $H_0 = 67.3$ ($n_s = 0.966$, $\Omega_m = 0.32, \Omega_m h^2 = 0.143$)
vs. best fit for $H_0 = 73.0$ ($n_s = 0.995$, $\Omega_m = 0.25, \Omega_m h^2 = 0.132$)



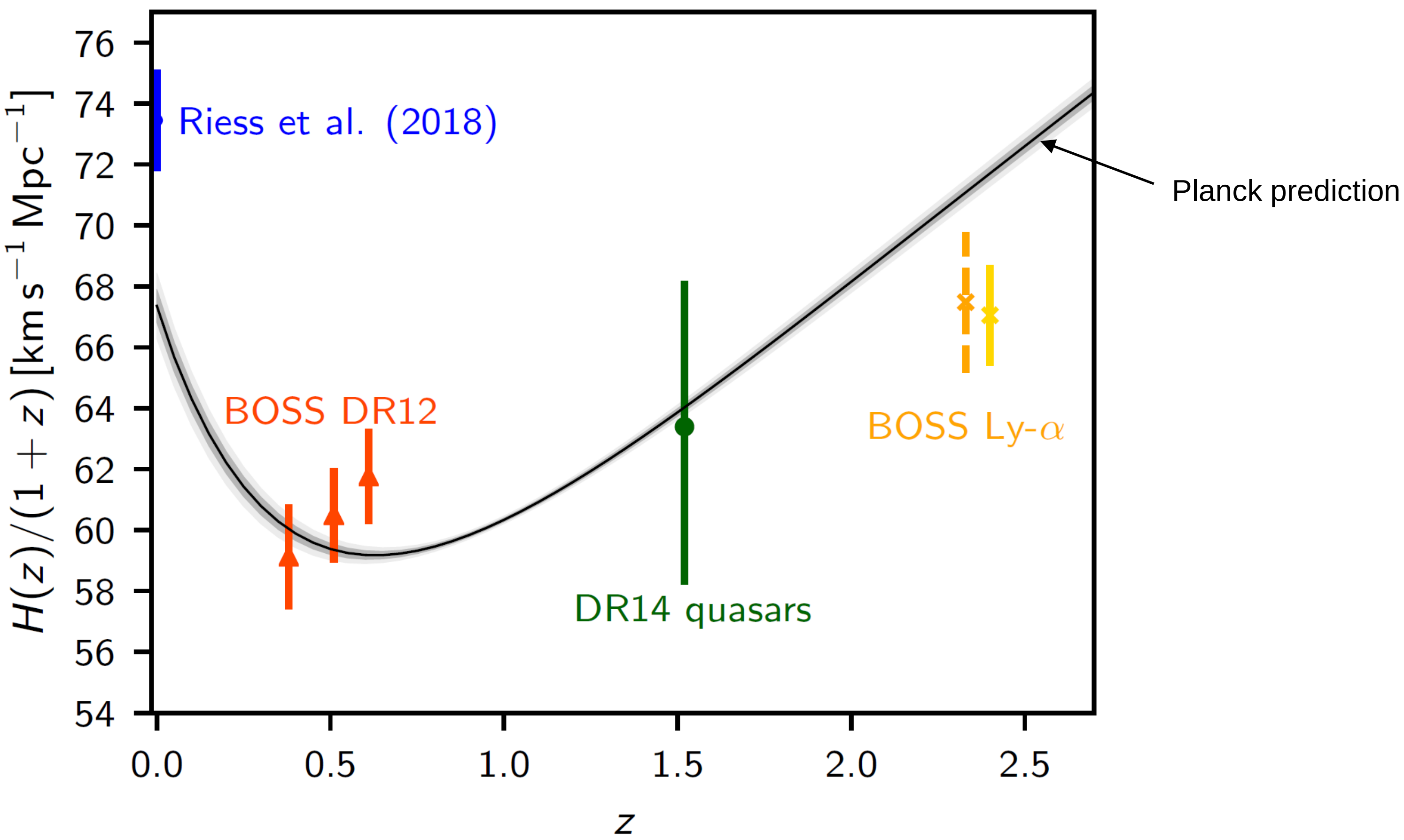
ΛCDM polarization/temperature consistency



CMB and BAO consistency in ΛCDM

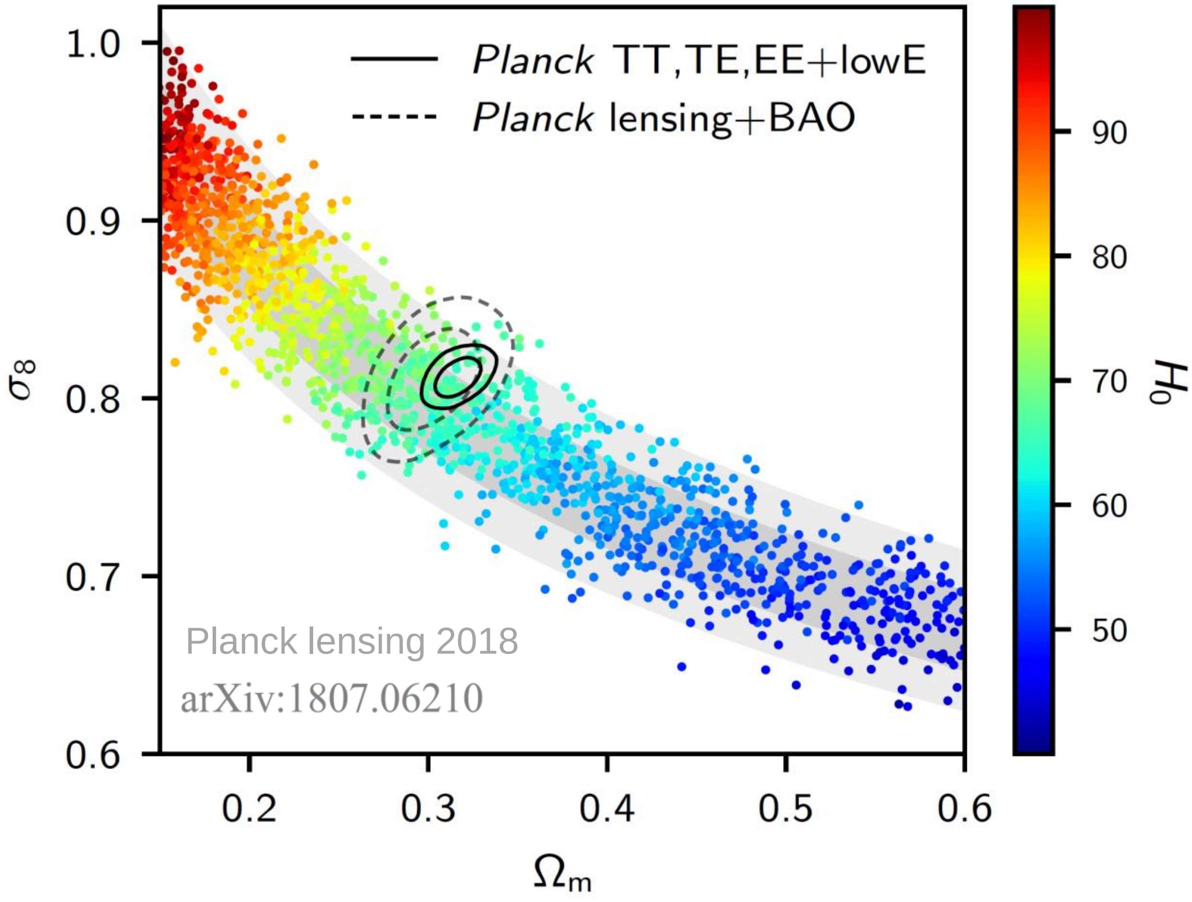


Assuming ΛCDM + Planck sound horizon r_d



(transverse and other BAO also very consistent)

Planck CMB lensing ΛCDM parameters

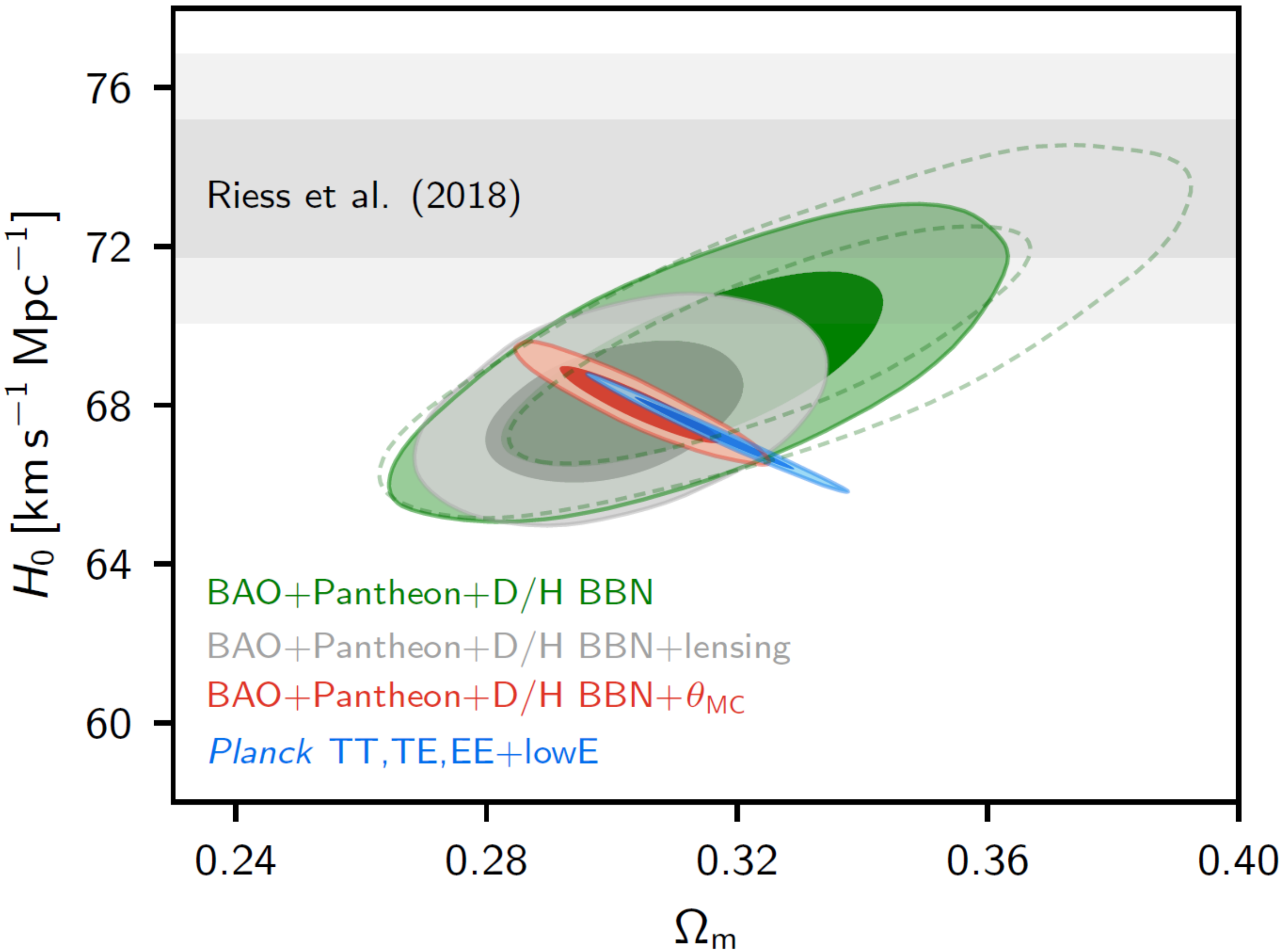


$$\left.\begin{aligned} H_0 &= 67.9^{+1.2}_{-1.3}\ \mathrm{km\ s^{-1}Mpc^{-1}}, \\ \sigma_8 &= 0.811 \pm 0.019, \\ \Omega_\mathrm{m} &= 0.303^{+0.016}_{-0.018}, \end{aligned}\right\} \ 68\,\%,\ \text{lensing+BAO}$$

Also adding robust CMB θ_* constraint:
$H_0 = 68.0 \pm 0.7$ (68 %, lensing+BAO+θ_*)

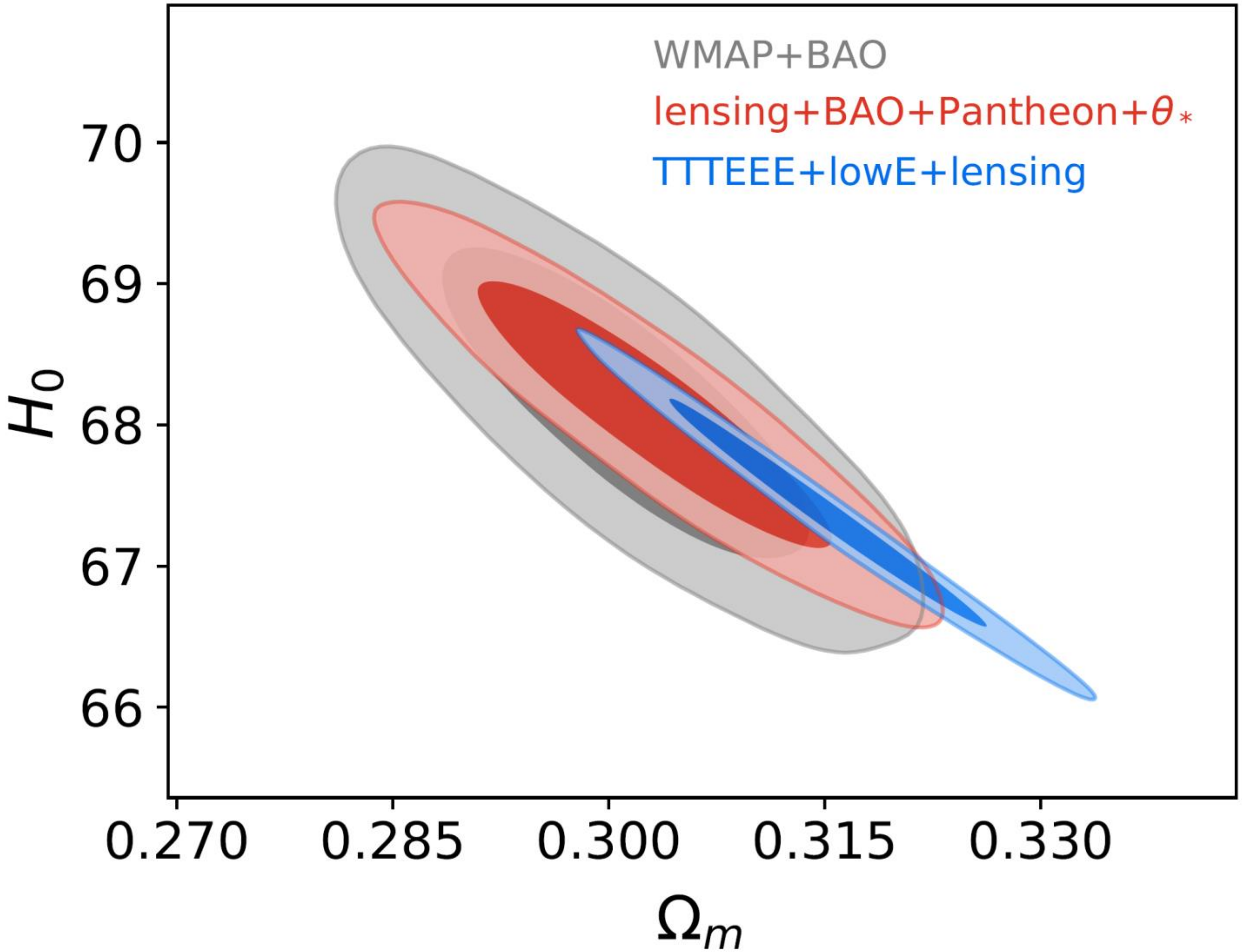
(“Lensing-only” priors: $\Omega_\mathrm{b}\mathrm{h}^2 = 0.0222 \pm 0.0005, n_s = 0.96 \pm 0.02, 0.4 < h < 1$)

ΛCDM inverse distance ladder comparison



Note BAO inverse distance ladder and CMB θ_* degeneracies different
- cannot have big fluctuation along one degeneracy direction

WMAP, Planck and inverse distance ladder $\Lambda\mathrm{CDM}$ constraints agree well
(also ACTpol, SPTpol, BUT *SPTpol find* $H_0 = 71 \pm 2$ *at* $l > 1000$*)*



(c.f. Aubourg, Addison, Cuesta, Heavens, DES collaboration, etc et al.)

H_0 constraint model dependent
…but in practice constraint fairly robust to many model extensions

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_P independently (which requires non-standard BBN). Varying A_L is not a physical model (see Sect. 6.2).

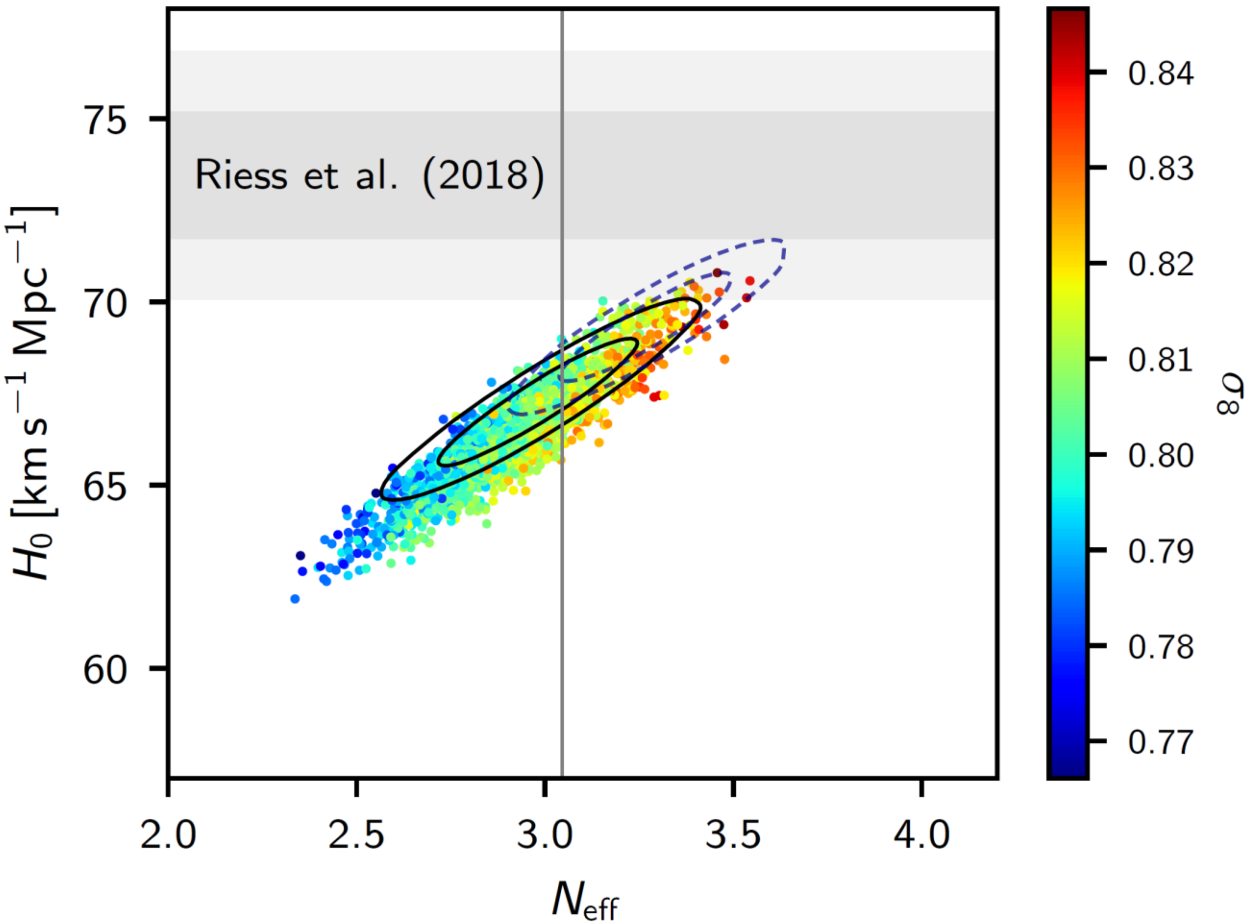
Parameter(s)	$\Omega_b h^2$	$\Omega_c h^2$	$100\theta_{MC}$	H_0	n_s	$\ln(10^{10}A_s)$
Base ΛCDM	0.02237 ± 0.00015	0.1200 ± 0.0012	1.04092 ± 0.00031	67.36 ± 0.54	0.9649 ± 0.0042	3.044 ± 0.014
r	0.02237 ± 0.00014	0.1199 ± 0.0012	1.04092 ± 0.00031	67.40 ± 0.54	0.9659 ± 0.0041	3.044 ± 0.014
$dn_s/d\ln k$	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_{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
$N_{eff}, dn_s/d\ln k$	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
$\Sigma m_\nu, N_{eff}$	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
$m^{eff}_{\nu,\,sterile}, N_{eff}$	$0.02242^{+0.00014}_{-0.00016}$	$0.1200^{+0.0032}_{-0.0020}$	$1.04074^{+0.00033}_{-0.00029}$	$67.11^{+0.63}_{-0.79}$	$0.9652^{+0.0045}_{-0.0056}$	$3.050^{+0.014}_{-0.016}$
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_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_P, N_{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_L	0.02251 ± 0.00017	0.1182 ± 0.0015	1.04110 ± 0.00032	68.16 ± 0.70	0.9696 ± 0.0048	$3.029^{+0.018}_{-0.016}$

Note:

No useful constraint in varying dark energy models, but consistently constrained adding SN/BAO

Higher neutrino mass or dark energy with $w > -1$ only *lower* H_0. Ω_K also pulls towards low H_0.

Extra relativistic degrees of freedom ($N_{\text{eff}} \neq 3.046$)



No preference from *Planck* alone, though errors somewhat increased.

ΛCDM+N_{eff} Planck+BAO: $H_0 = (67.3 \pm 1.1)\ \text{km s}^{-1}\text{Mpc}^{-1}$ (still 3σ from Riess et al.)

Conclusions

Planck 2018 gives high-precision measurements of TT, TE, EE spectra and lensing

Systematic errors/modelling parameter uncertainties thought to be <1σ. *And σ is very small*!

Angular acoustic scale θ_* measured to 0.03%.

Details of acoustic peak amplitudes constrain physical densities to percent precision.

CMB does not measure H_0 directly, but provides tight indirect constraints if a model is assumed.

Planck TT, TE, EE and lensing data consistent with ΛCDM and $H_0 \sim (67.4 \pm 0.5)$ km/s/Mpc.

Other CMB experiments and inverse distance ladder give consistent results.

No simple late-time model extensions substantially change H_0 without conflicting with lensing, SN and/or BAO.

Any change to early-universe physics to change r_s (and $r_{\rm drag}$) and hence inferred H_0 must reproduce observed spectrum shape quite accurately (changing $N_{\rm eff}$ does not)

- Simons Observatory, S4 could detect small differences due to new physics not resolved by Planck/SPT/ACT

There are some other oddities in the Planck data fits - could hint at new physics (peaks slightly too smooth, dip at low ℓ)

- *are there any models which simultaneously change $r_{\rm drag}$, keep broad fit, but resolve oddities ??*

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.