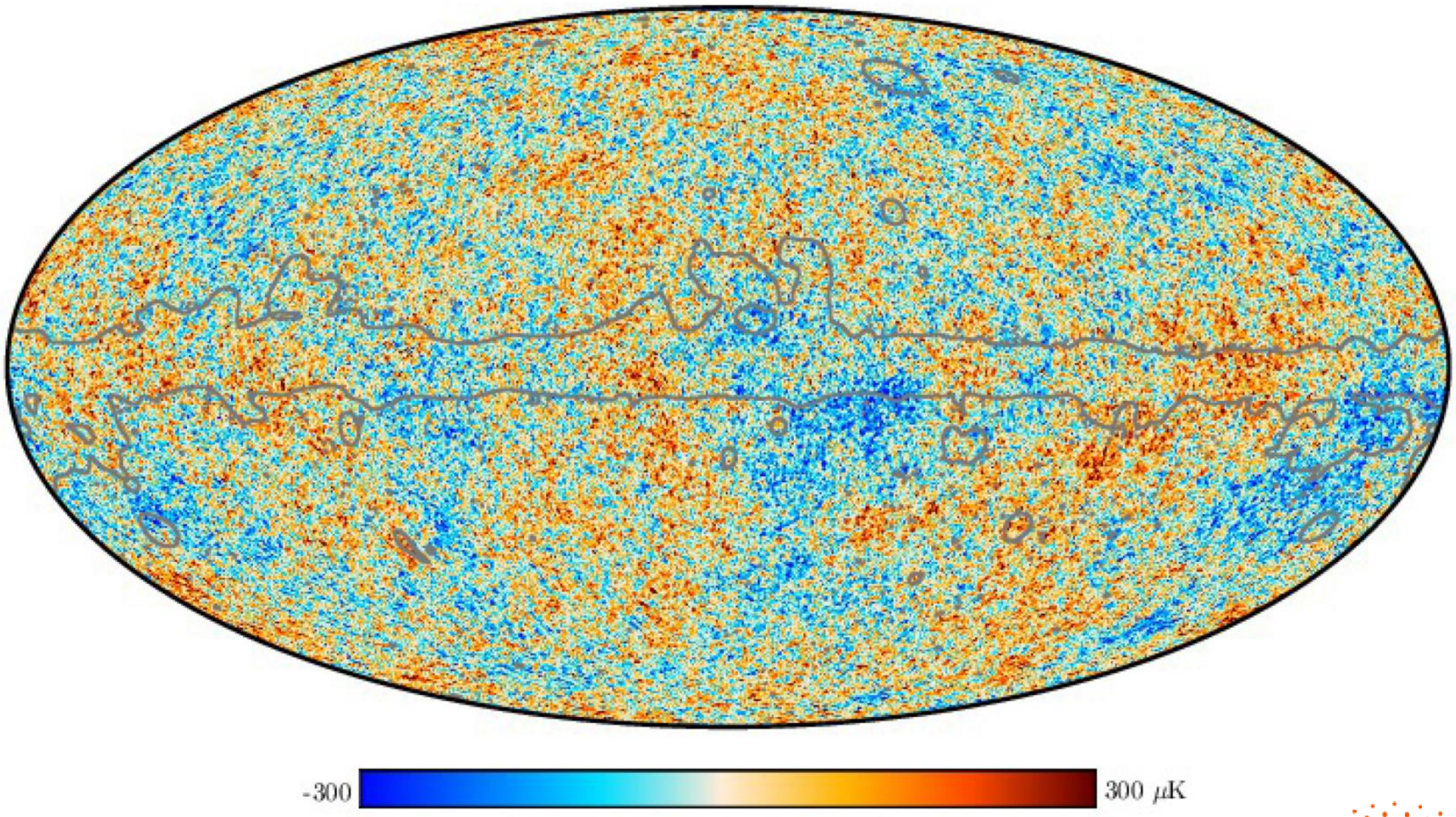
Open questions after Planck



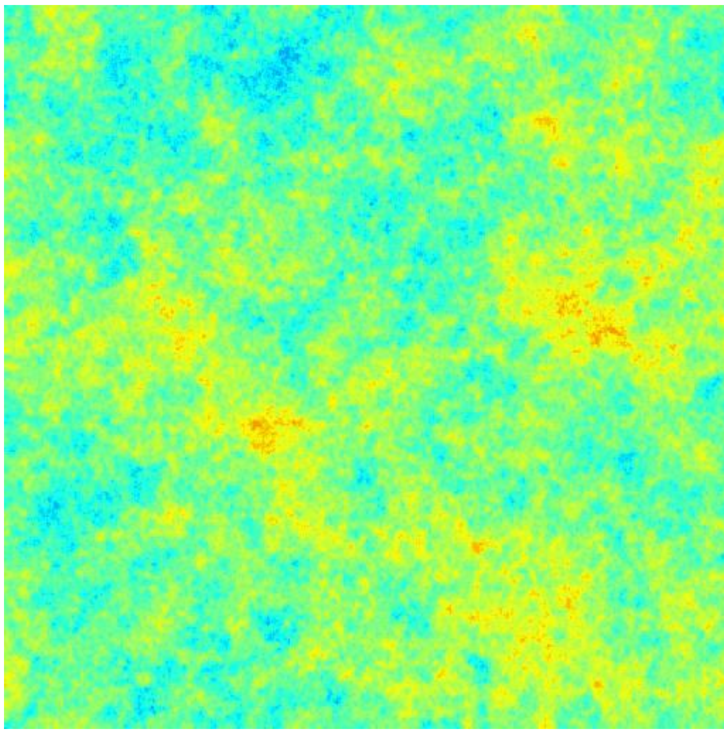
Antony Lewis
http://cosmologist.info/

UNIVERSITY OF SUSSEX

European Research Council
Established by the European Commission

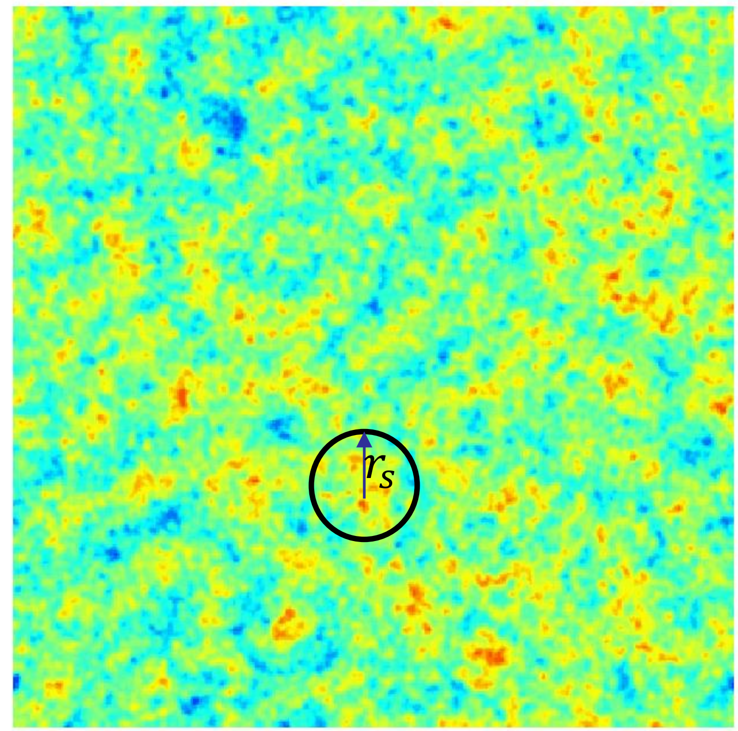
Perturbation evolution

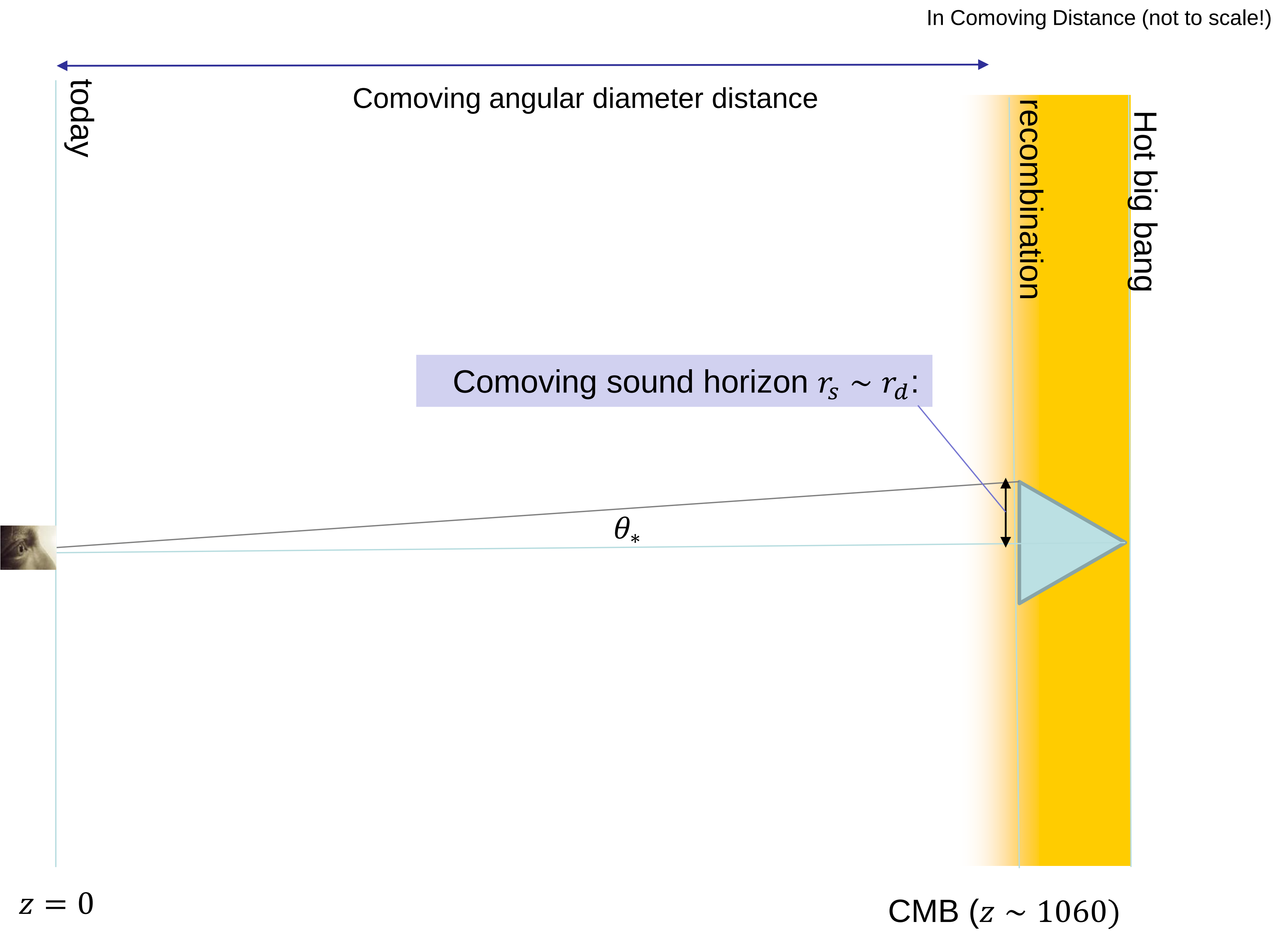
Perturbations: End of inflation



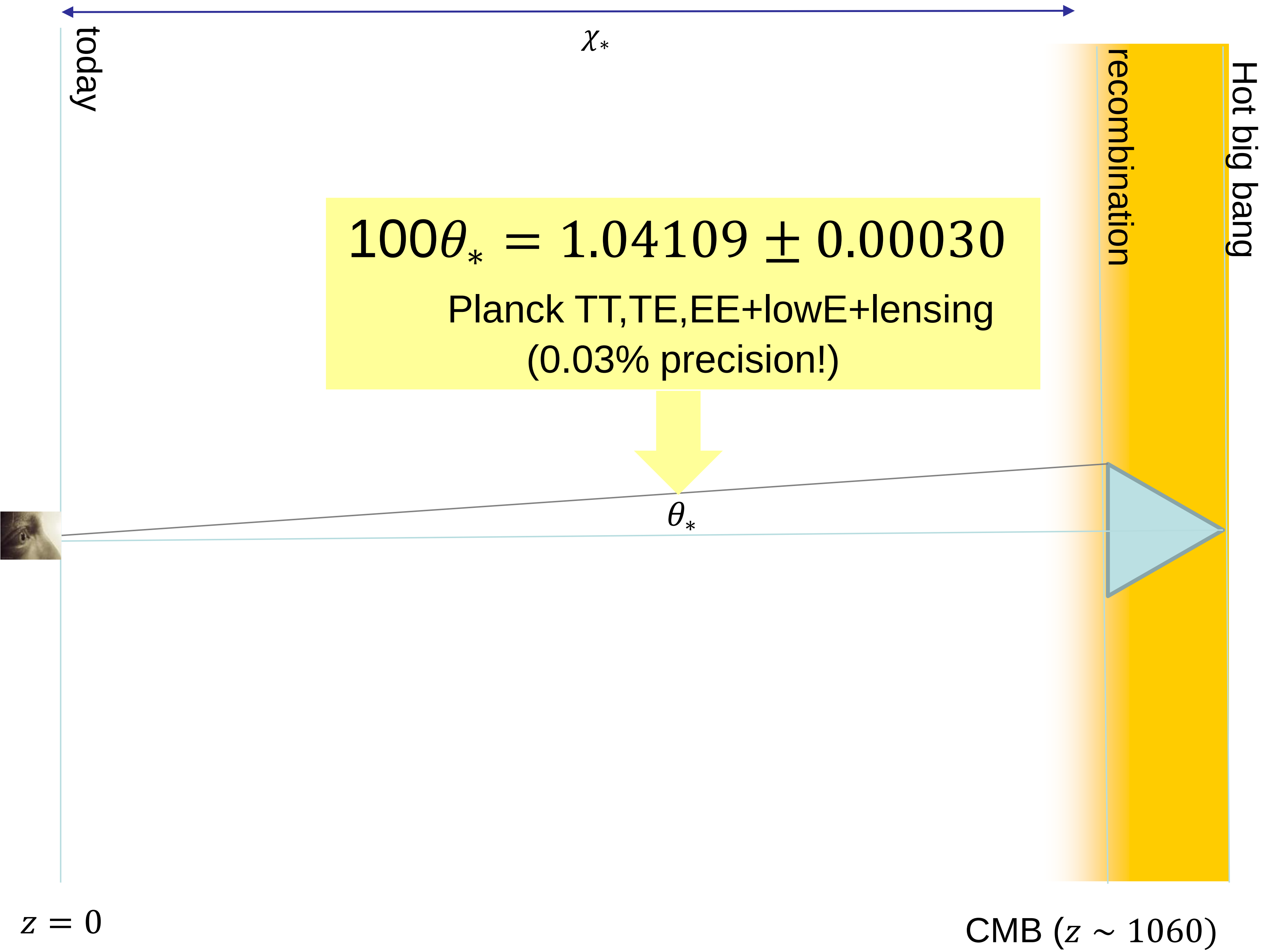
gravity+
pressure+
diffusion

Perturbations: Last scattering surface





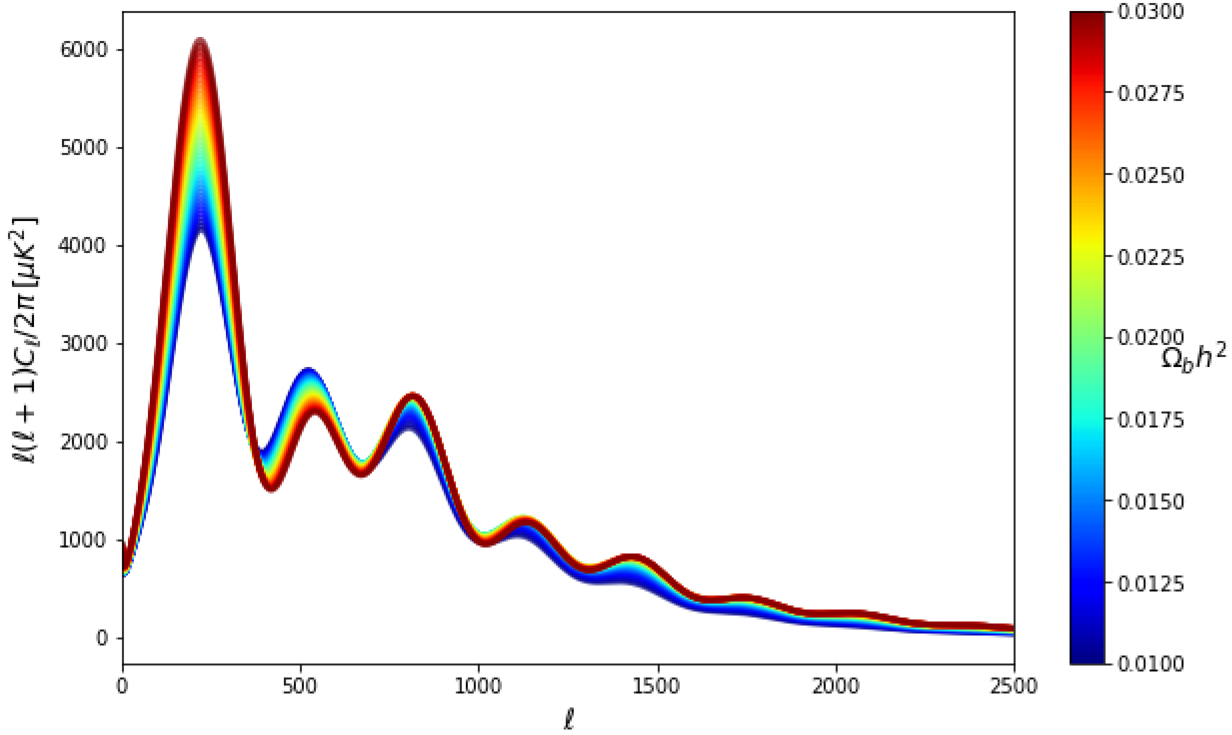
In Comoving Distance (not to scale!)
Comoving angular diameter distance
today
recombination
Hot big bang
Comoving sound horizon $r_s \sim r_d$:
θ_*
$z = 0$
CMB ($z \sim 1060$)



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)



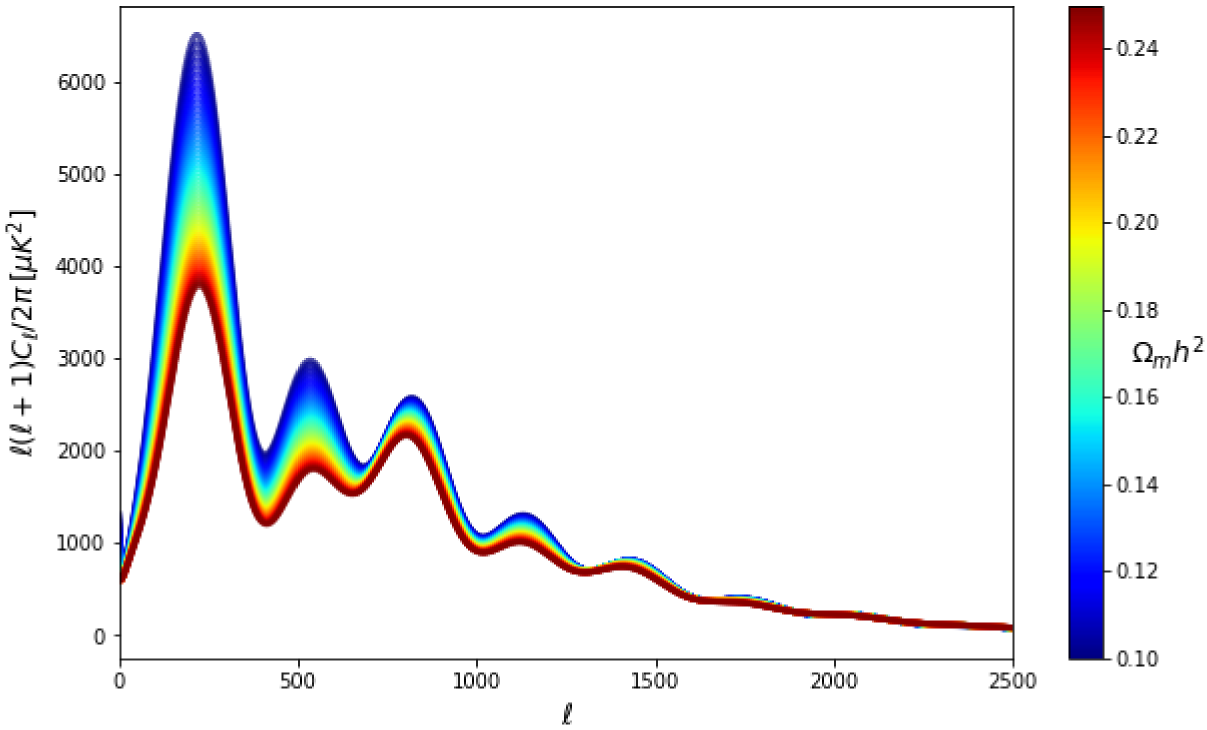
Odd/even height ratio distinctive and quite robust:

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

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

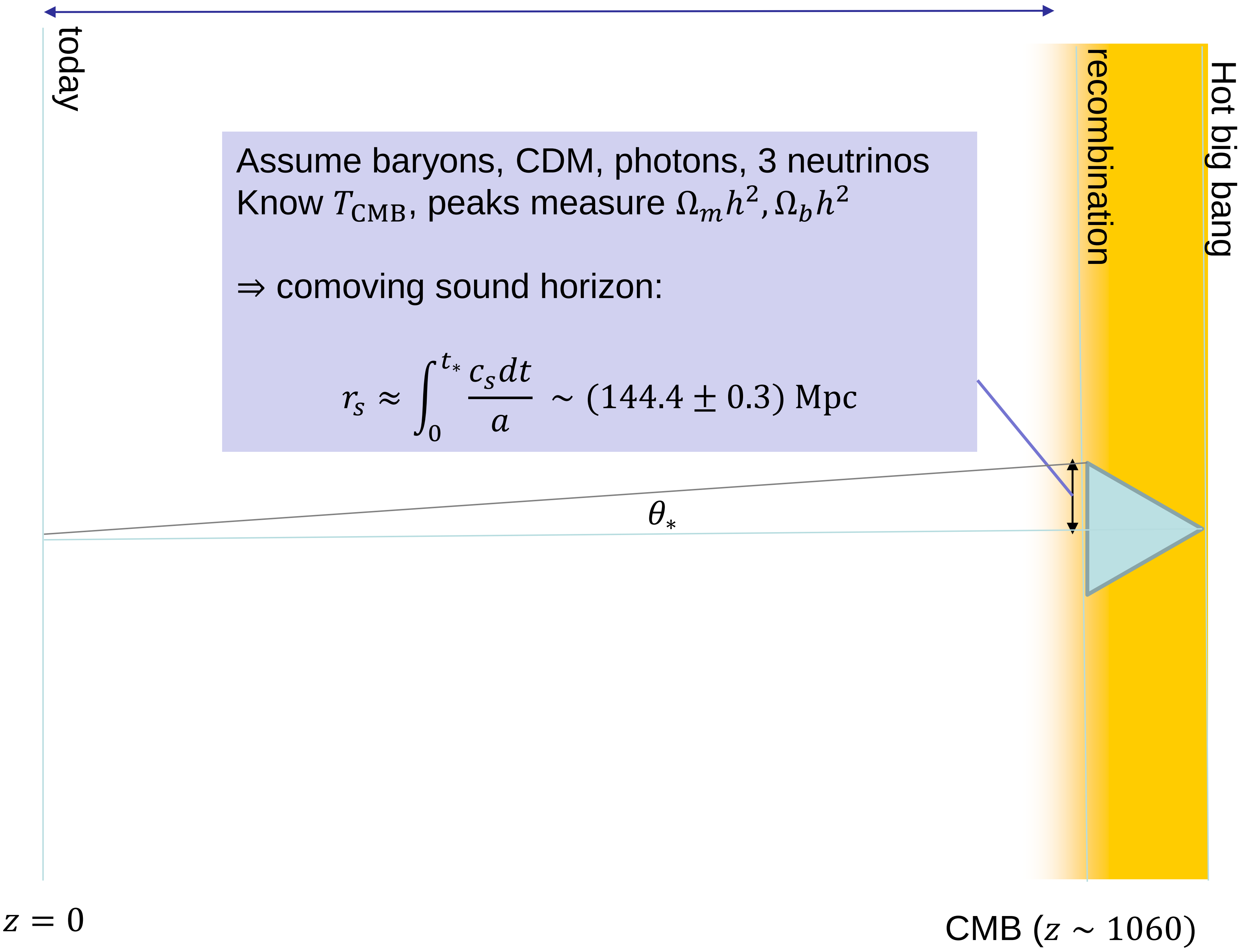
ΛCDM matter density at fixed θ_*, $\Omega_b h^2$

(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

today

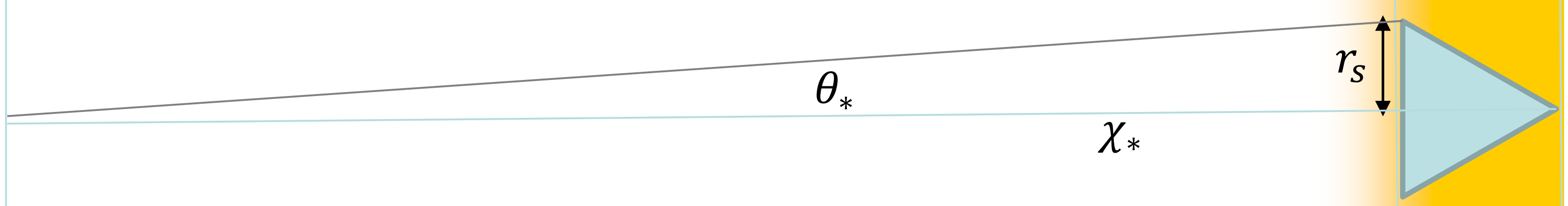
$r_s, \theta_* \Rightarrow$ Comoving radial distance $\chi_* \sim (13.87 \pm 0.03)\ \mathrm{Gpc}$

recombination

Hot big bang

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

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

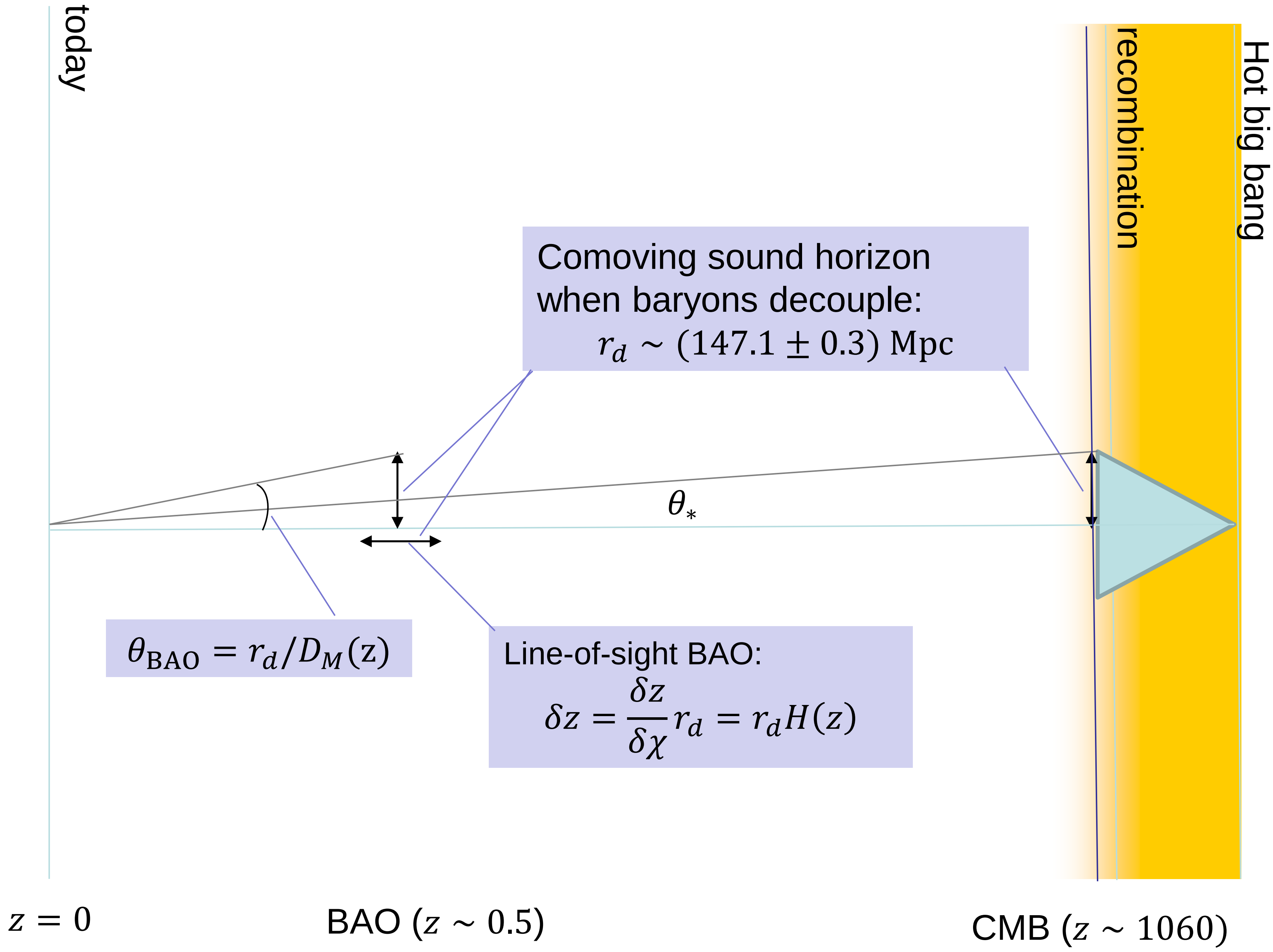


$$\Rightarrow H_0 = (67.3 \pm 0.6)\ \mathrm{km\ s^{-1} Mpc^{-1}}$$

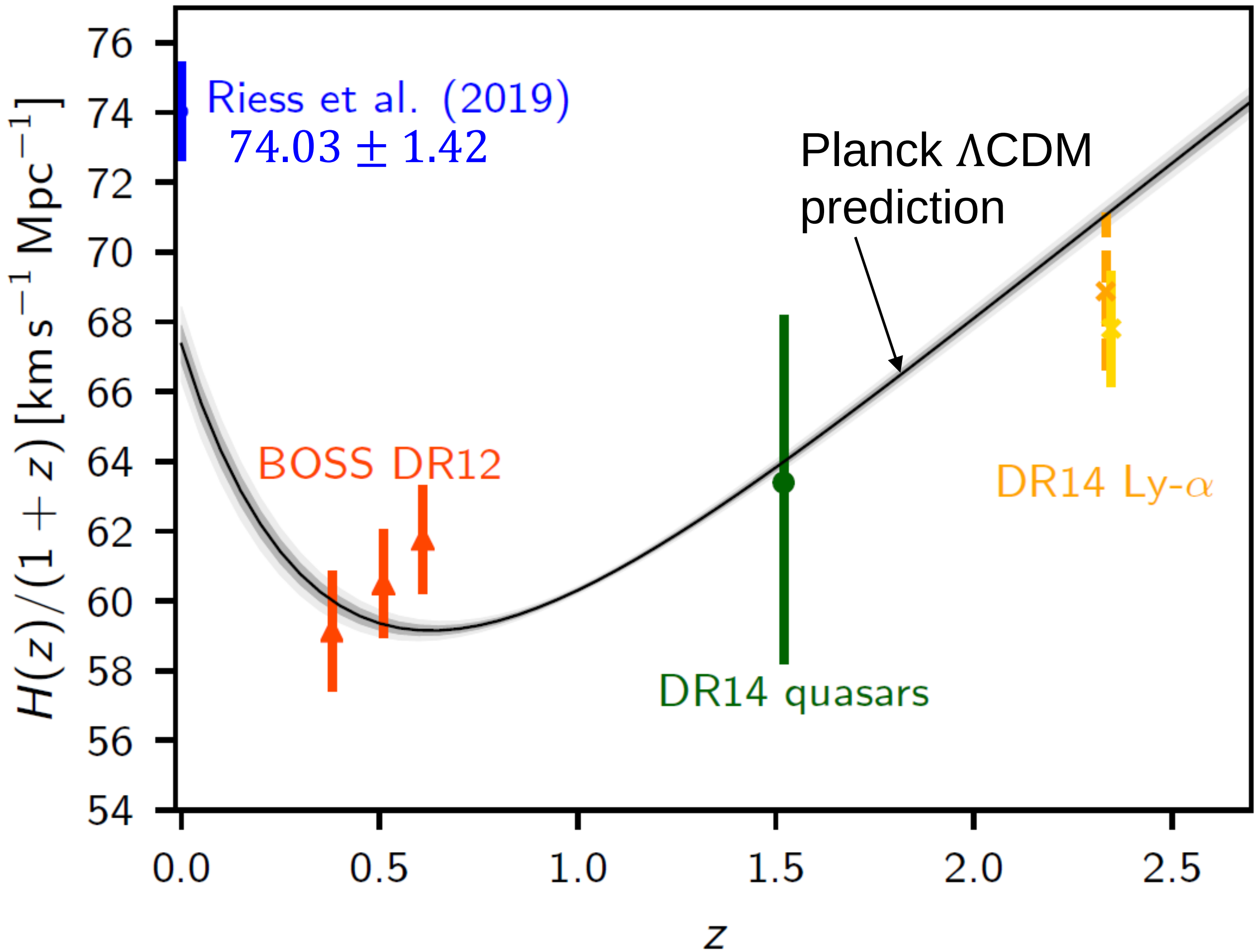
$z = 0$

CMB ($z \sim 1060$)

CMB and BAO consistency in ΛCDM



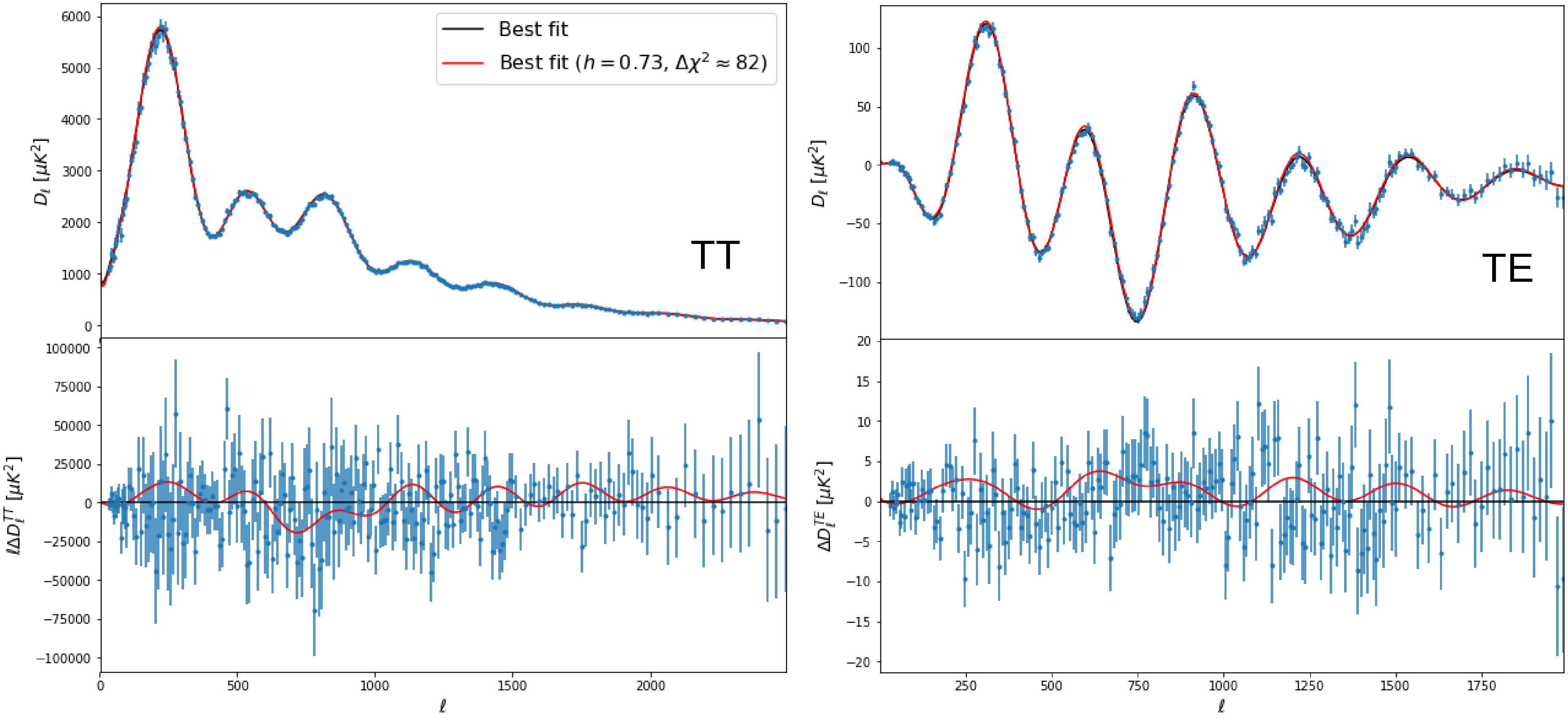
The Hubble discrepancy assuming ΛCDM and Planck sound horizon r_d



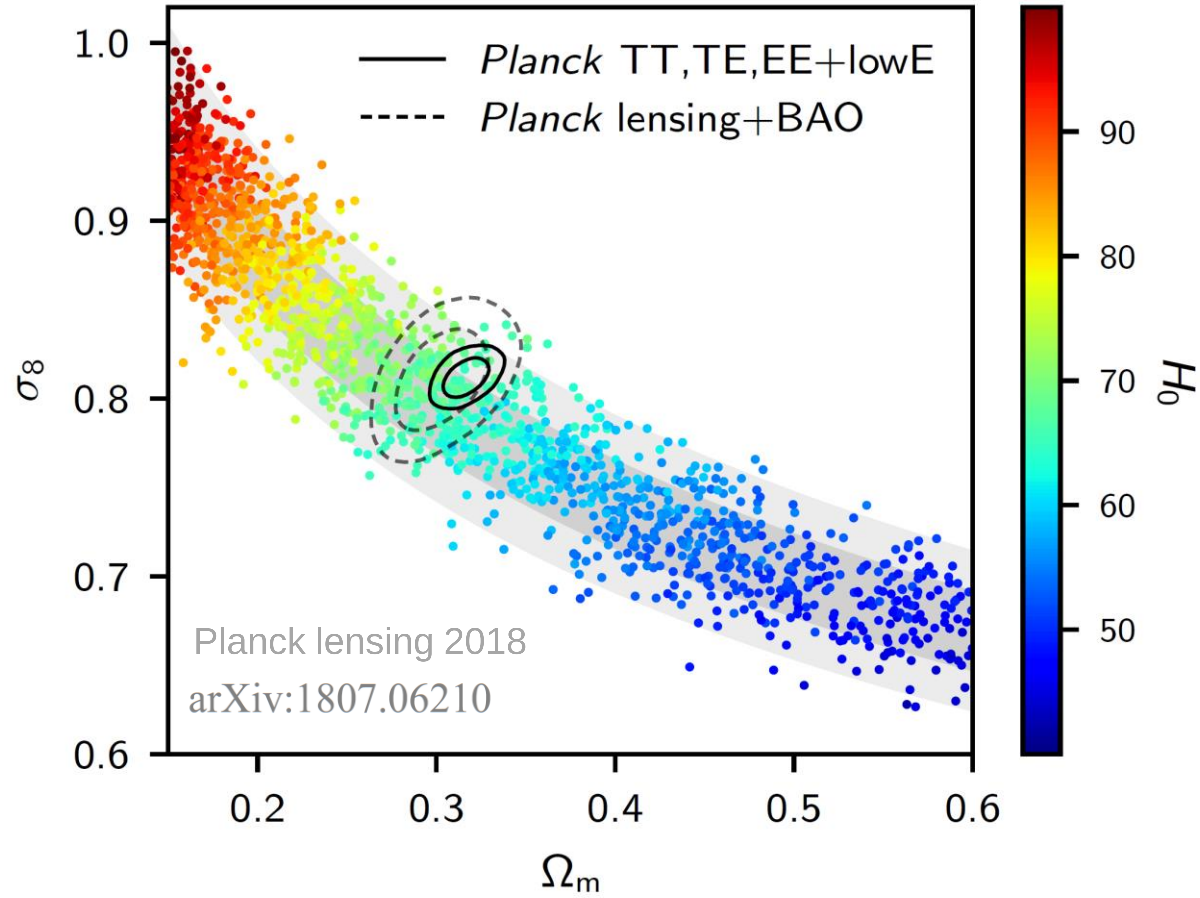
c.f. H0LiCOW (strong lensing): $H_0 = 72.5^{+2.1}_{-2.3}\ \mathrm{km\ s^{-1} Mpc^{-1}}$

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 $H_0 = 73.0$ ($n_s = 0.995$, $\Omega_m = 0.25, \Omega_m h^2 = 0.132$)



Planck CMB lensing ΛCDM parameters



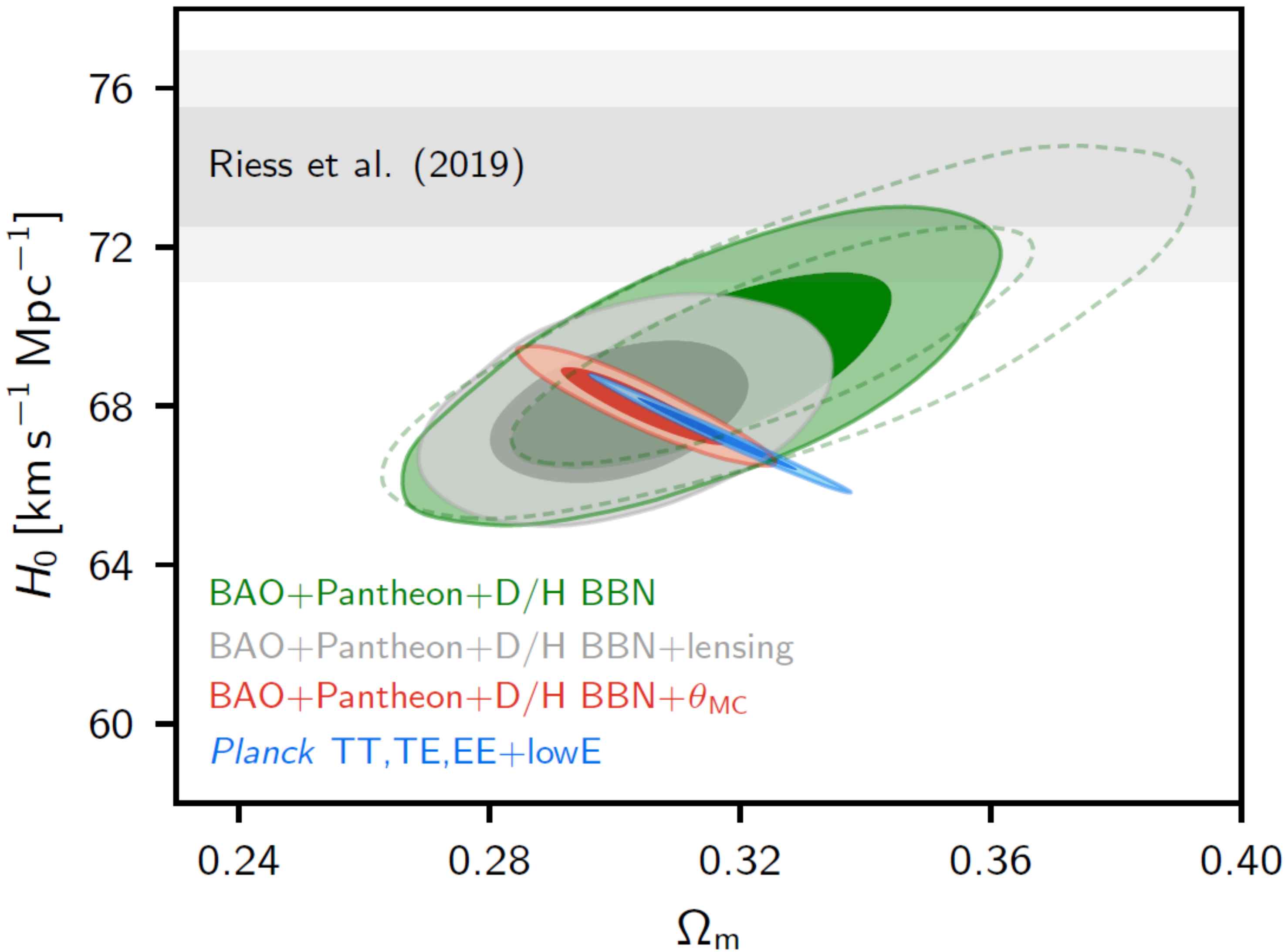
$$\left.\begin{aligned} H_0 &= 67.9^{+1.2}_{-1.3}\ \mathrm{km\ s^{-1}Mpc^{-1}}, \\ \sigma_8 &= 0.811 \pm 0.019, \\ \Omega_\mathrm{m} &= 0.303^{+0.016}_{-0.018}, \end{aligned}\right\} \quad 68\,\%,\ \text{lensing+BAO}$$

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 is consistent with Planck



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

Open Question – Why is H_0 in 4.4σ tension assuming ΛCDM?

- Got *very* unlucky with large statistical fluctuation?

- Something wrong with the local H_0 measurements or their error model? (+ fluctuation/mild systematics in strong lensing)

- Could *both* Planck and BAO be wrong??

- Is $\Lambda\mathrm{CDM}$ wrong?

Possible solutions:

New physics prior to recombination:
- decrease sound horizon r_d, BAO and Planck H_0 both shift proportionately

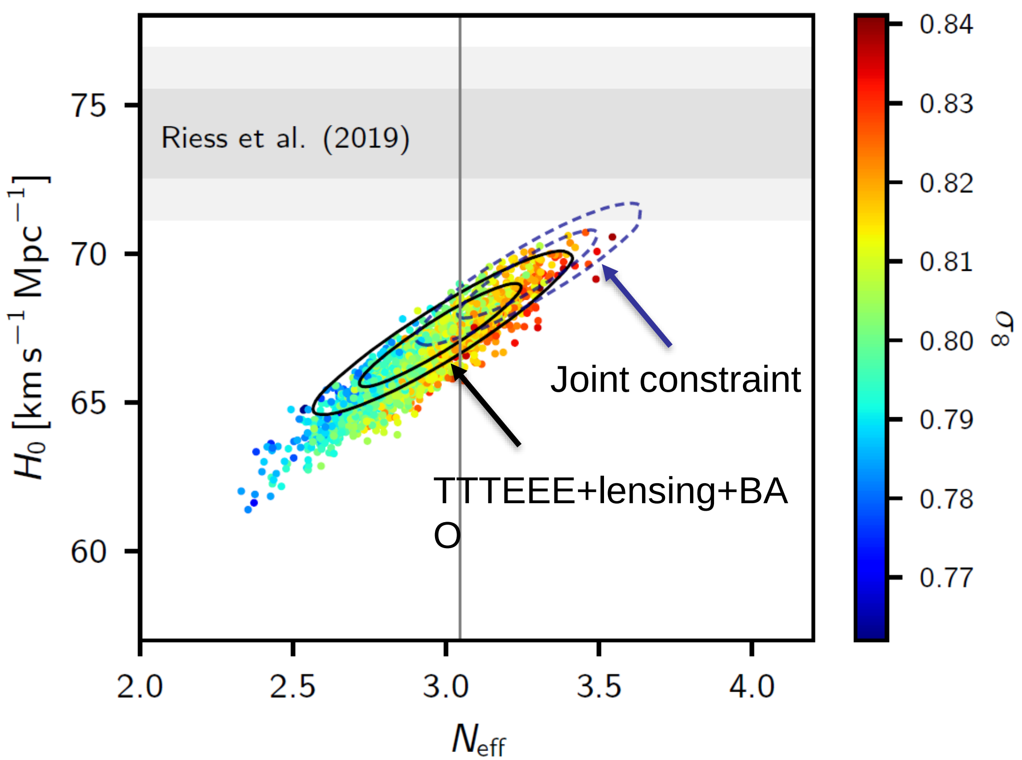
New physics at lower redshift/dark energy/modified gravity
- $w > -1$ only makes H_0 from Planck *lower*
- have to fit BAO and $H(z)/H_0$ from supernovae (or find problem with supernovae)

New physics/very unusual conditions in our local neighbourhood

Some contrived combination of the above

What new physics?

e.g. extra relativistic degrees of freedom ($N_{\rm eff} \neq 3.046$)



This and other simple extensions disfavoured by Planck alone

(+ may run into conflict with reactor/neutrino oscillation experiments/BBN)

More complicated (multi-parameter) extensions

- New species with interactions; new couplings between existing species, …. (many refs…).

Note: Interpretation of observed peak angular scales in terms of θ_* can shift if phasing of acoustic peaks changes (e.g. Kreish et al. 1902.00534)

- Early dark energy (e.g. Poulin et al, Agrawal et al, Lin et al.):
  must have $\frac{\rho_{DE}}{\rho} \sim 0.08$ near matter-radiation equality, then $\rho_{DE} \to \Lambda$.

- ???

Planck TT a precision cosmic-variance measurement and looks a lot like $\Lambda\mathrm{CDM}$

Planck TE/EE also look like $\Lambda\mathrm{CDM}$, but not yet a cosmic-variance measurement

Any model must fit Planck TT almost as well as or better than $\Lambda\mathrm{CDM}$

e.g. trade changes from new physics with changes in $\Omega_c h^2, \Omega_b h^2, A_s, n_s,$ ...

⇒ If new physics is the solution, current $\Lambda\mathrm{CDM}$ measurements of parameters likely to be significantly wrong, e.g. significant implications for inflation n_s.

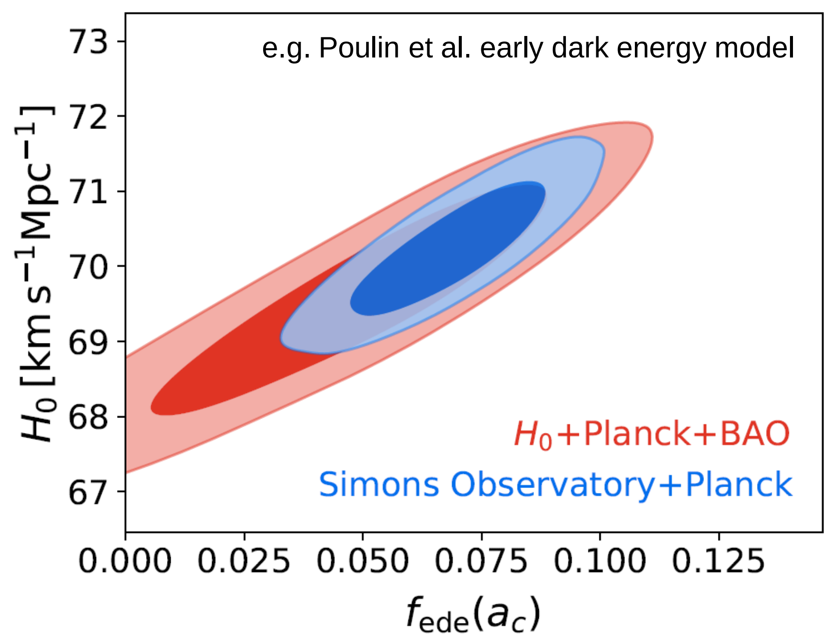
⇒ Almost impossible to *also* fit $\Lambda\mathrm{CDM}$ polarization to cosmic variance

⇒ new "easily" detectable EE/TE signal that does not fit $\Lambda\mathrm{CDM}$

High resolution/sensitivity polarization:

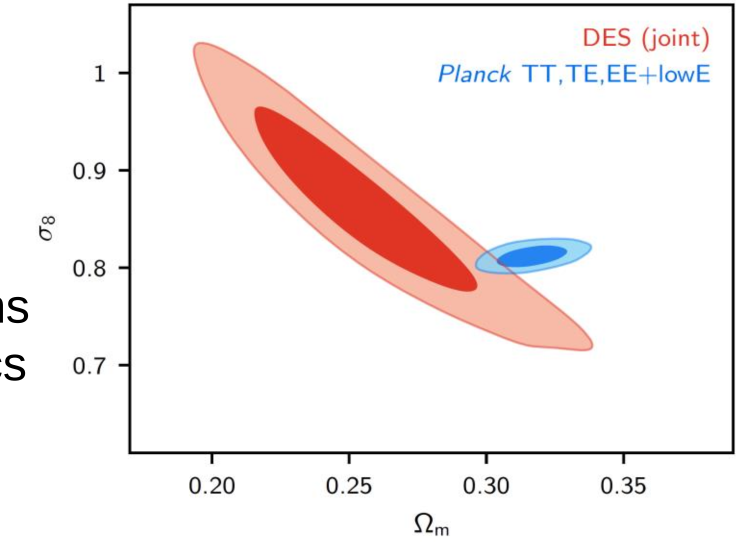
precision small-scale EE, TE, TT power spectrum

If $H_0 > 71\,\mathrm{km\,s^{-1}Mpc^{-1}}$,
new pre-recombination physics
likely detectable at $> 5\sigma$ soon



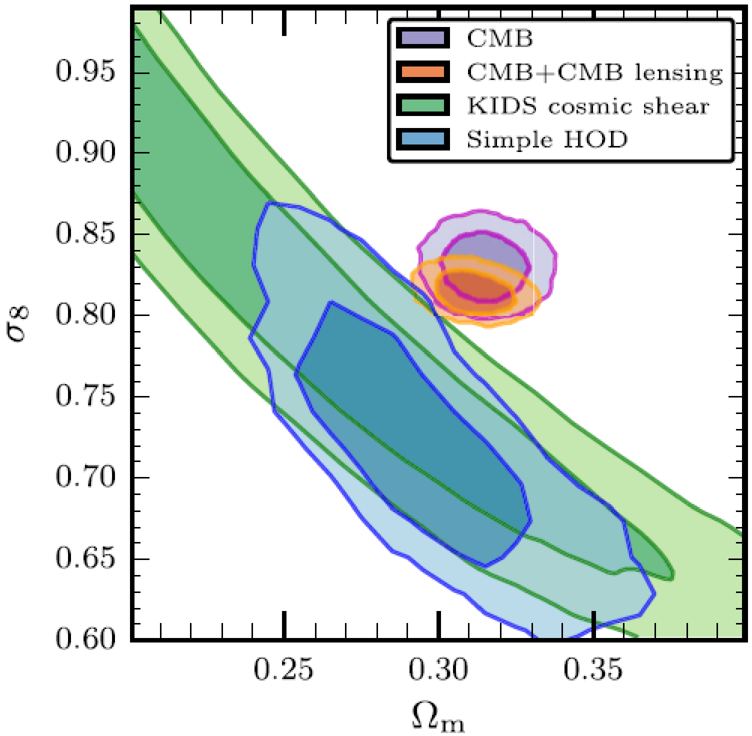
Are there hints of new physics elsewhere?

E.g. Galaxy clustering
Galaxy-galaxy lensing (galaxies x lensing)

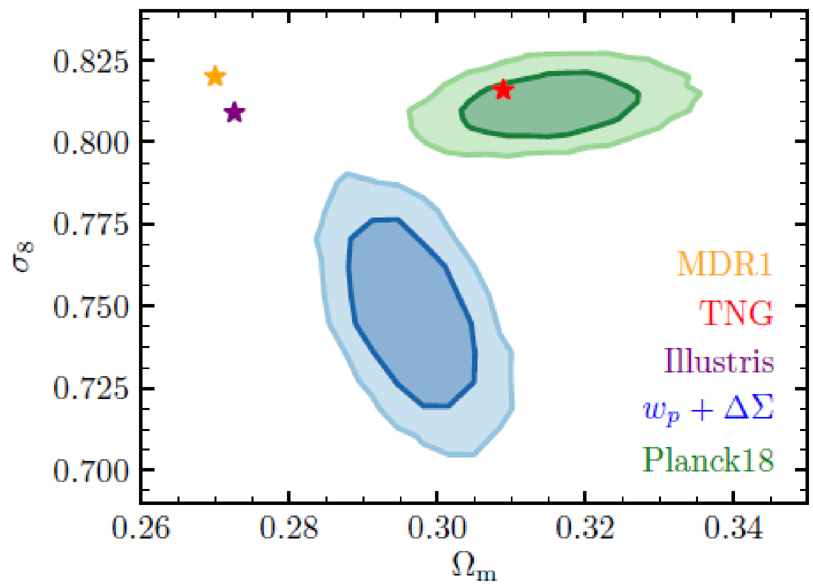


BUT: not inconsistent or complex observations not modellable with simple understood physics

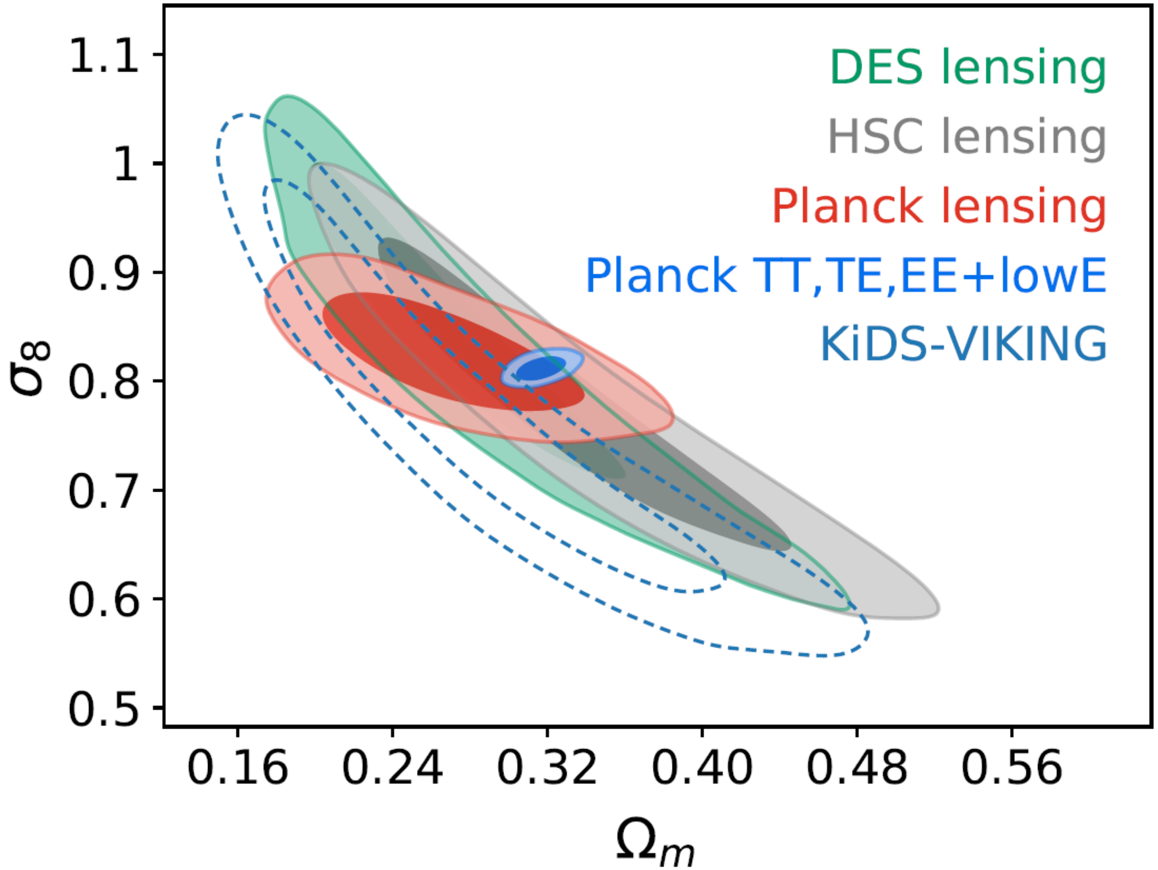
Lethaud et al. 1611.08606



BOSS (Lange et al. 1906.08680)



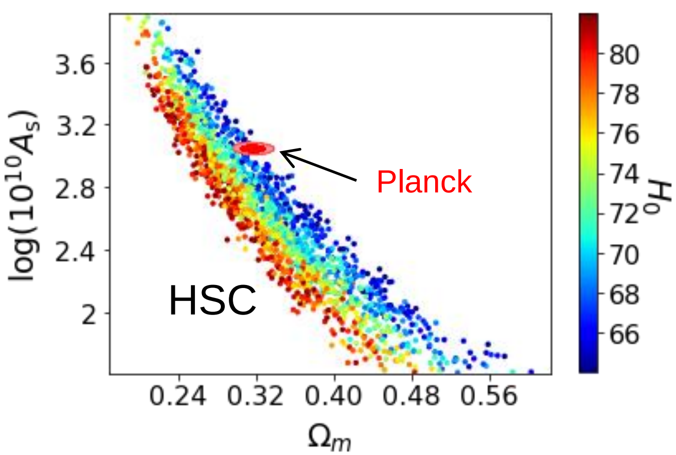
Weak lensing



Troxel et al. 1708.01538

Hamana et al. 1906.06041

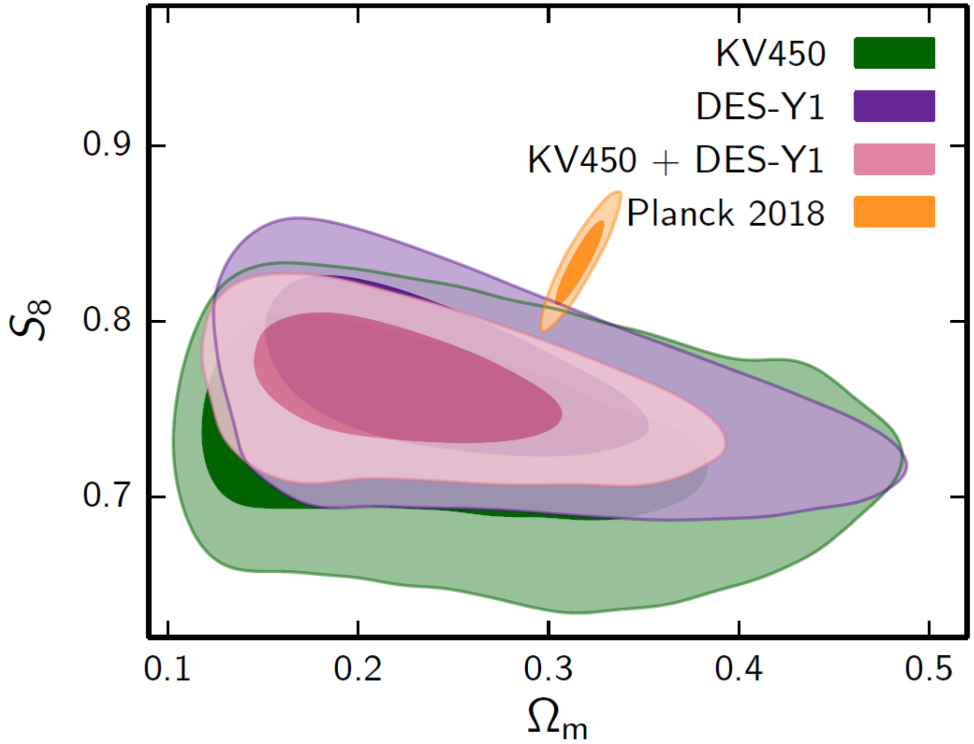
Hildebrandt et al. 1812.06076



(Nearly-consistent priors $1.609 < \log\left(10^{10}A_s\right) < 3.912$; $0.64 < h < 0.82$)

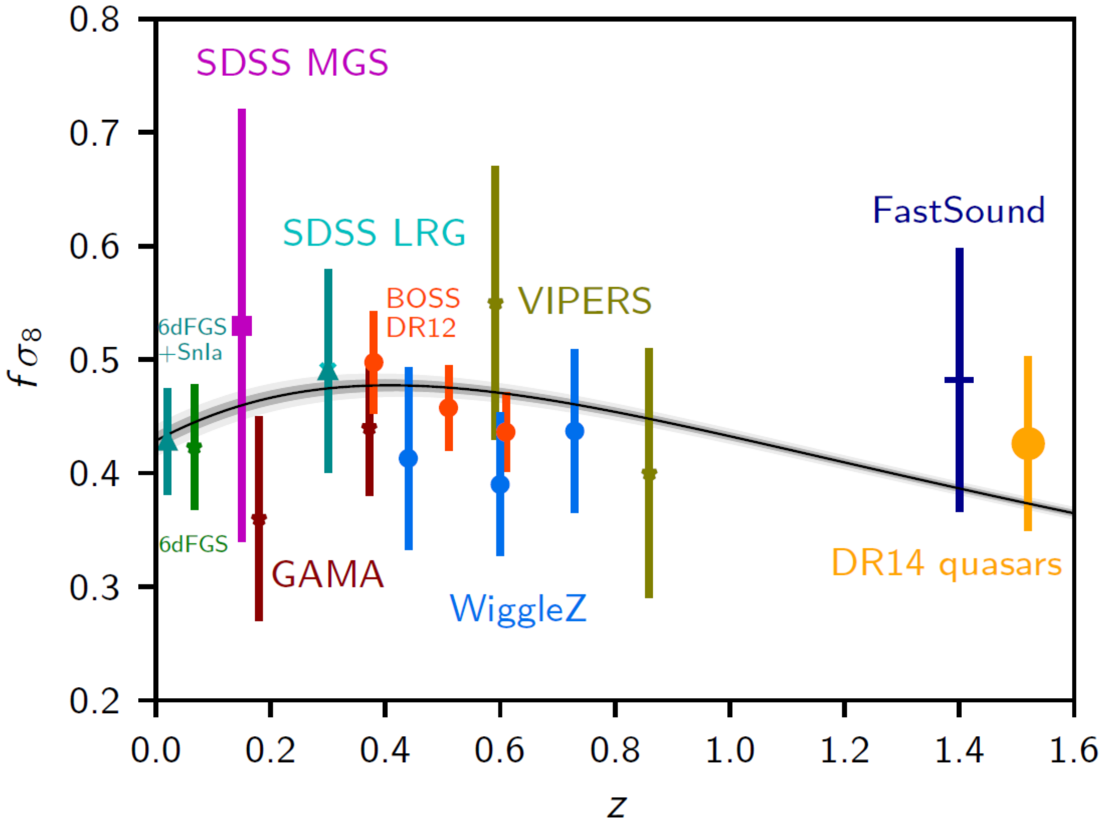
KiDS + DES lensing Y1 (spectroscopic recalibration of redshifts)

Joudaki et al **1906.09262**



2.5σ tension with Planck (without Planck lensing)

Redshift Distortions

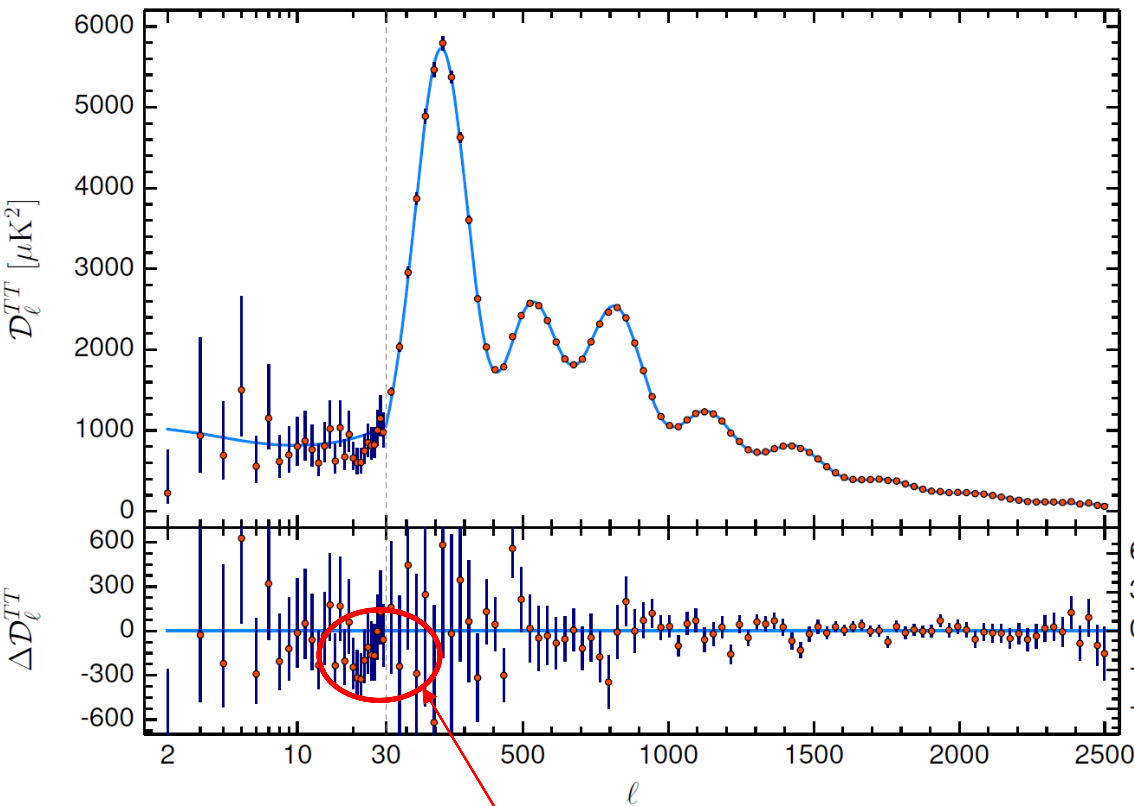


Currently no compelling evidence for deviations from Planck ΛCDM in LSS observations.

Are the $\Lambda\mathrm{CDM}$ "curiosities" in Planck hints of new physics?

Seem consistent with moderate statistical fluctuations from Planck alone.

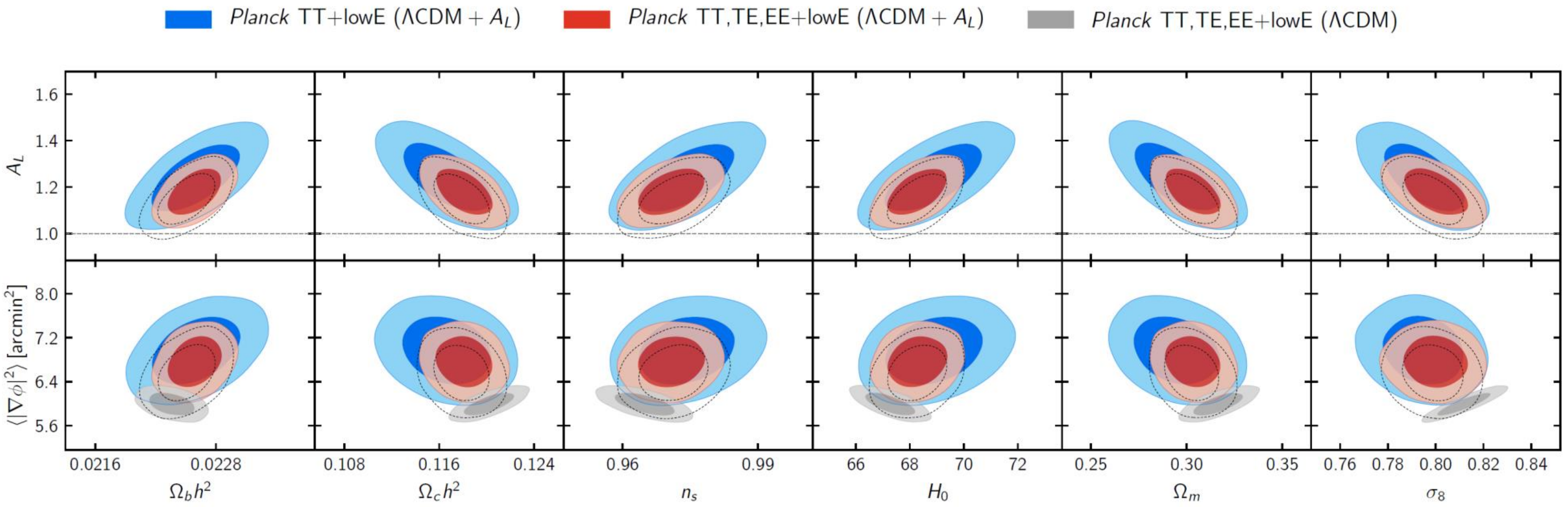
BUT: if new non-$\Lambda\mathrm{CDM}$ physical models could improve fit, would be interesting…



$\ell \sim 27$ dip

$2-3\sigma$ preference for more "lensing" smoothing in TT spectrum

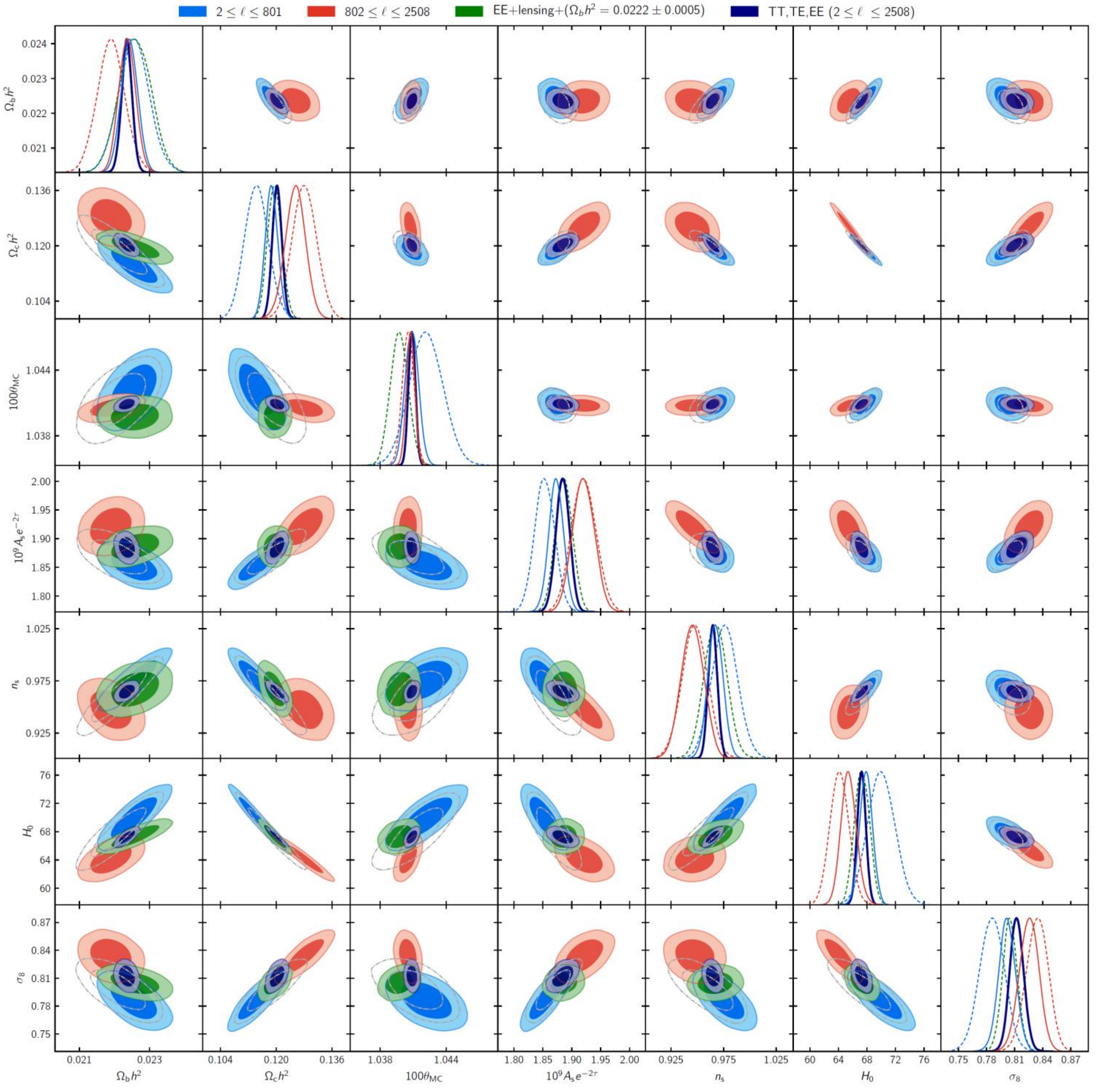
Introducing A_L parameter TT favours cosmological parameters which predict less lensing, but having $A_L > 1$ at $2-3\sigma$



(it is probably *nothing* to do with actual lensing; lensing reconstruction gives $A_L \approx 1$)

$2 - 3\,\sigma$ "tension" between parameters from $\ell < 800$ and $\ell \geq 800$

Looks consistent with fluctuation:
.. but *could* also be hint of new physics.



Conclusions

H_0 discrepancy nearing 5σ. Why?

Is $\Lambda\mathrm{CDM}$ correct/observationally indistinguishable from correct?

- No, new pre-recombination physics

  If $h > 0.71$ likely to be independently detectable at $> 5\sigma$ with CMB polarization soon.

  Other Planck $\Lambda\mathrm{CDM}$ parameter measurements likely to be significantly wrong.

  No models currently attempted are compelling or great fits.
  - what is it, and why does it look in so many ways just like $\Lambda\mathrm{CDM}$?

- No, new late-time physics.

  Looks contrived (must fit SN/BAO), can LSS observations detect?

- Yes.

  - What's wrong with local H_0 or Planck+BAO?

  - What is Λ and what is CDM?