Cosmological parameters derived from Planck

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IAP

on behalf of the Planck Collaboration

X, COSPAR 2018, July 2018

3 important points

1. Improvements in the understanding and correction of systematics in polarization.

   2018 Planck baseline results
   TT,TE,EE+low EE (l<30)+CMB lensing(L=8-400)

   (2015 was TT+lowP [+CMB lensing])

   Puget's, Benabed's talks today, Carron's talk tomorrow

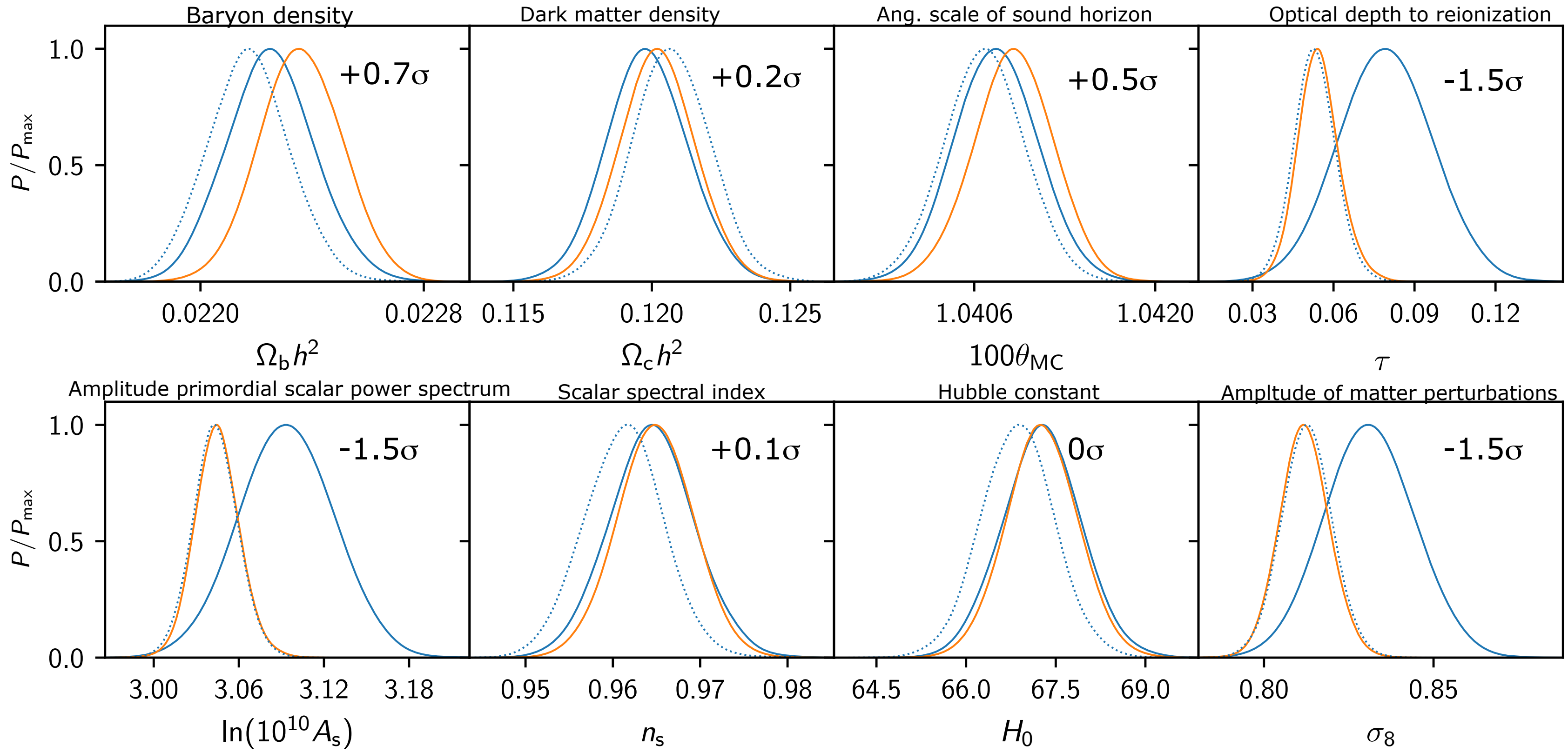
2. Stability of our scientific conclusions across the releases, confirmed by the 2018 legacy release.

3. Limitations and issues to be understood:
   a. Small remaining uncertainties of systematics in polarization (quantified with alternative likelihood at high-l which uses different choices).
   b. Some 2σ "curiosities" (A_L) in the internal consistency tests.
   c. Comparison with a few external datasets have mild/strong tension.

1. Results on ΛCDM
2. Comparison with external datasets
3. « Curiosities »
4. Results on extensions of ΛCDM

ΛCDM results: 2018 (DR3) vs 2015 (DR2)

TT,TE,EE+lowE 2018 **TT,TE,EE+lowP 2015**



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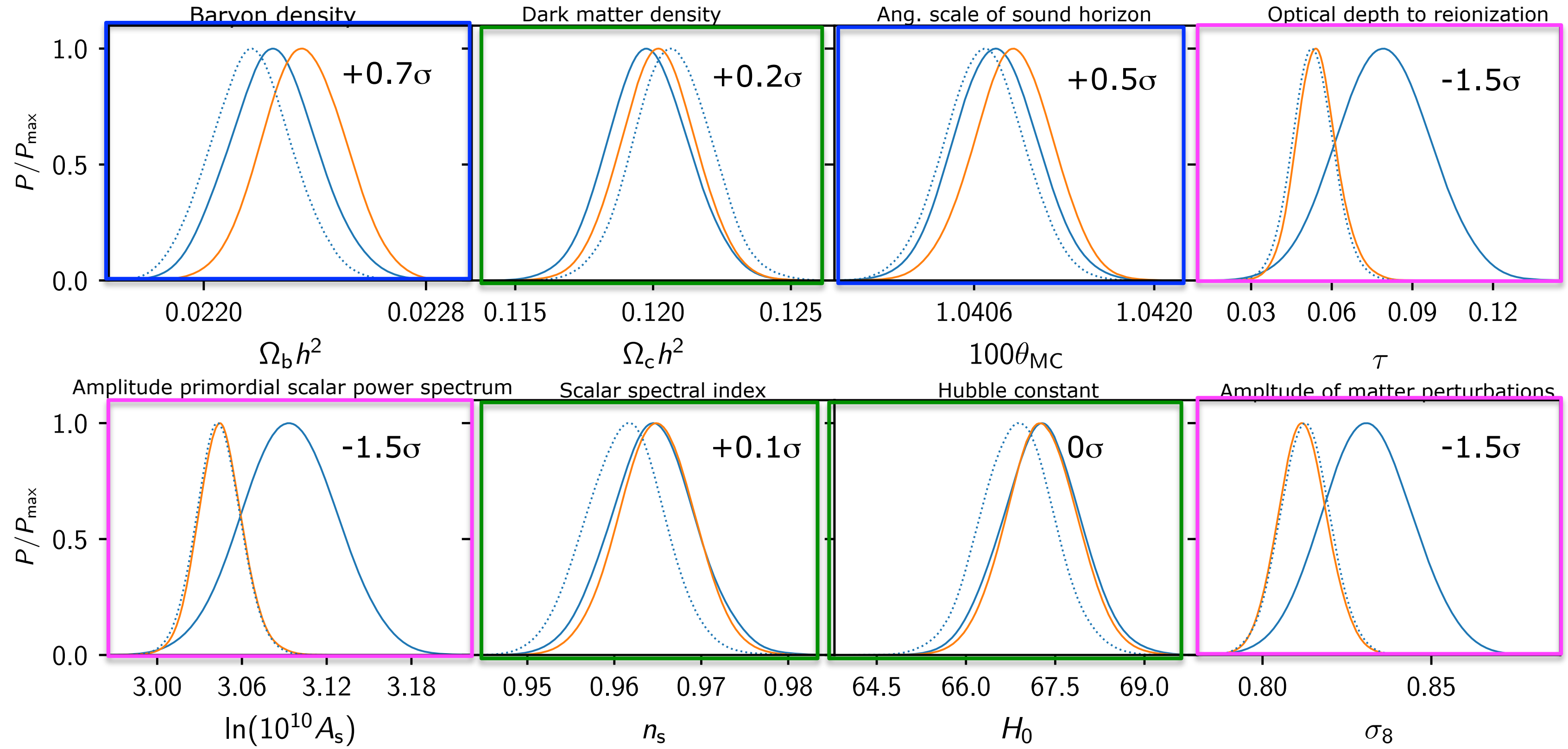

- Due to change in large scale polarization (optical depth to reionization).
- Due to beam leakage correction (in high-l TE).
- Due to opposite effect of beam leakage correction and change in optical depth, which almost cancel out.

Baseline ΛCDM results 2018

(Temperature+polarization+CMB lensing)

	Mean	σ	[%]
$\Omega_b h^2$ Baryon density	0.02237	0.00015	0.7
$\Omega_c h^2$ DM density	0.1200	0.0012	1
100θ Acoustic scale	1.04092	0.00031	0.03
τ Reion. Optical depth	0.0544	0.0073	13
$\ln(A_s 10^{10})$ Power Spectrum amplitude	3.044	0.014	0.7
n_s Scalar spectral index	0.9649	0.0042	0.4
H_0 Hubble	67.36	0.54	0.8
Ω_m Matter density	0.3153	0.0073	2.3
σ_8 Matter perturbation amplitude	0.8111	0.0060	0.7

- Most of parameters determined at (sub-) percent level!
- Best determined parameter is the angular scale of sound horizon θ to 0.03%.
- n_s is 8σ away from scale invariance (even in extended models, always >3σ)
- Best (indirect) **0.8%** determination of the Hubble constant to date.

Robust against changes of likelihood, <0.5σ (and *σ* is small!)

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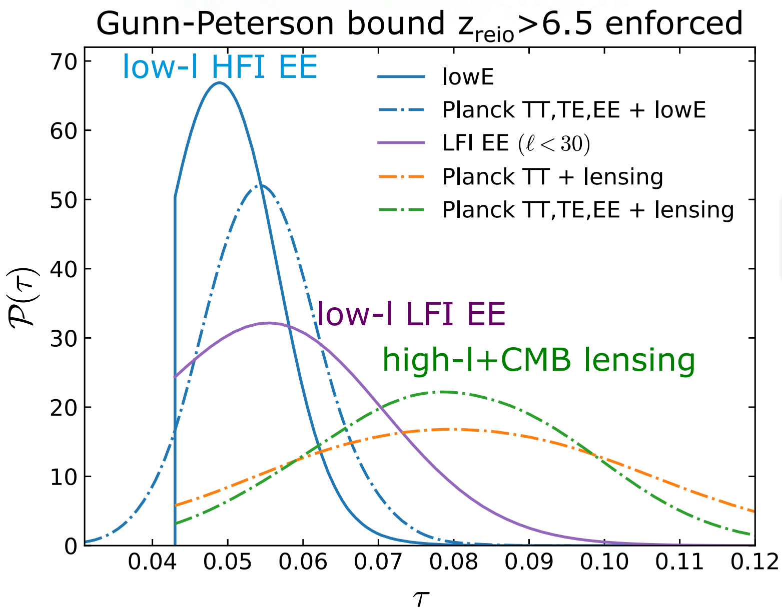
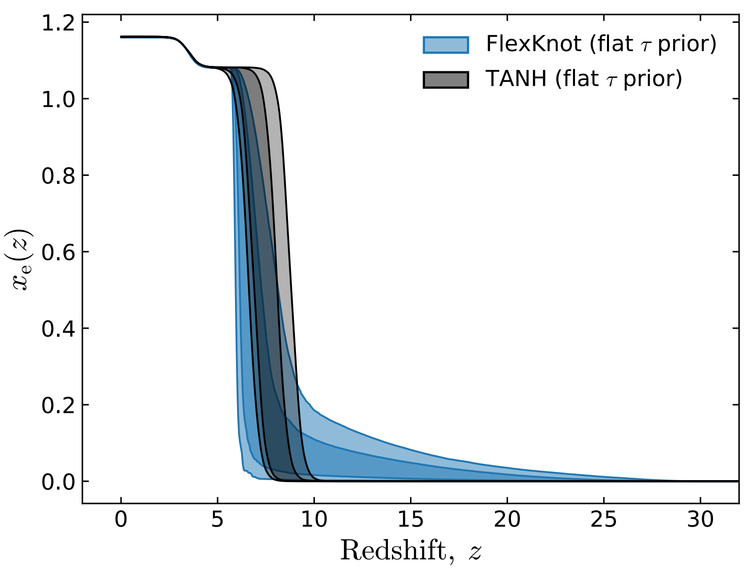
Optical depth to reionization





- Value of optical depth low-l alone (fixing $A_s \exp^{-2\tau}$ to high-l best fit, TANH model):

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

2015: $\tau = 0.067 \pm 0.022$ (LFI, TT,TE,TE)

2016: $\tau = 0.055 \pm 0.009$ (HFI, EE)

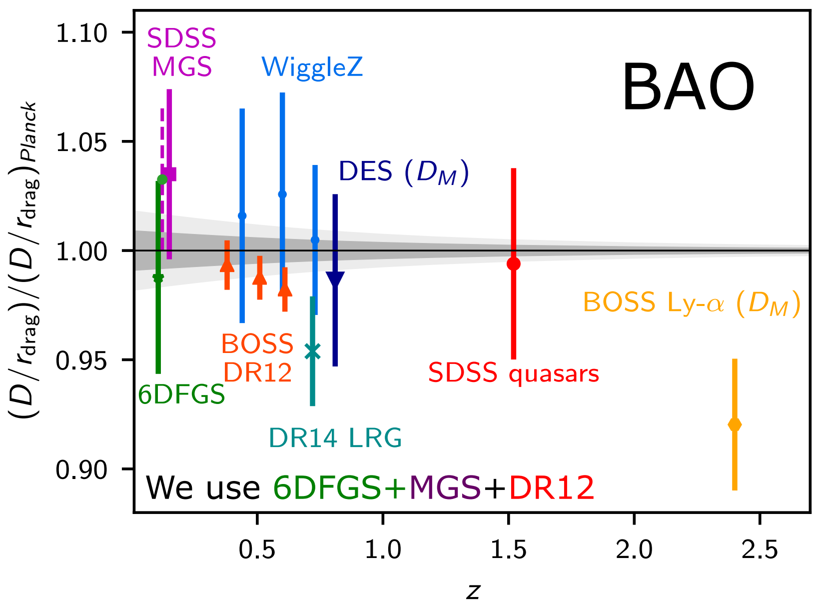
- τ measurement robust against model-independent reconstruction of reionization history. No evidence of deviation from baseline smooth transition TANH reionization model.

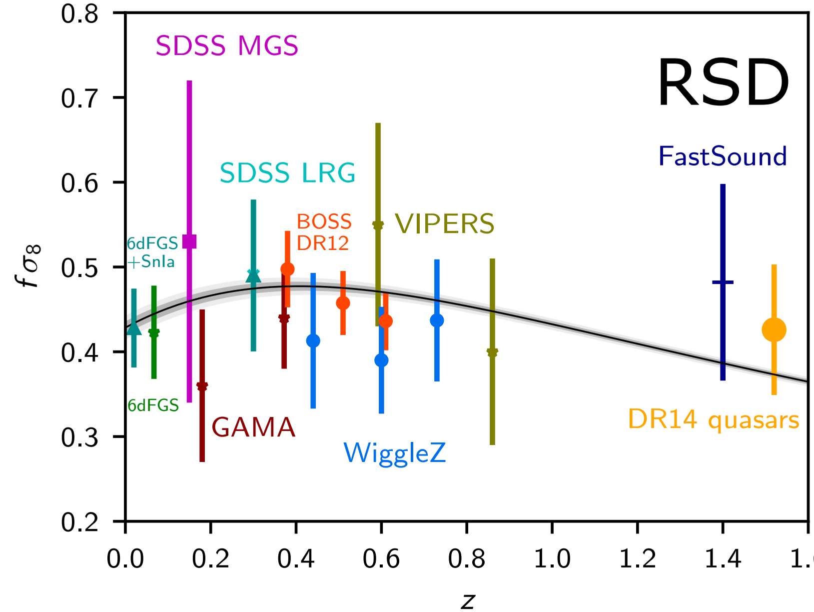
- No evidence for reionization a z>15:

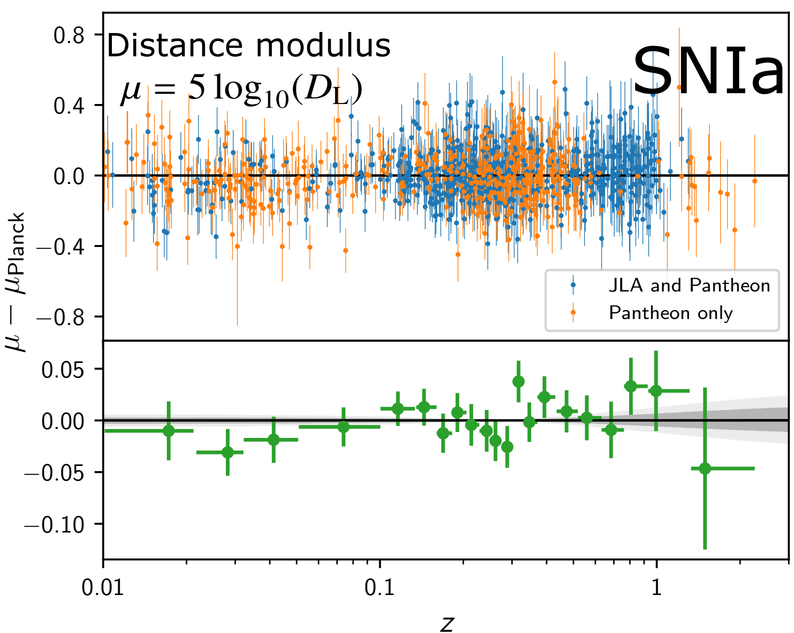
$$\tau(15,30) < 0.006 \quad (\mathrm{lowE; flat}\ \tau(15,30); \mathrm{FlexKnot}).$$

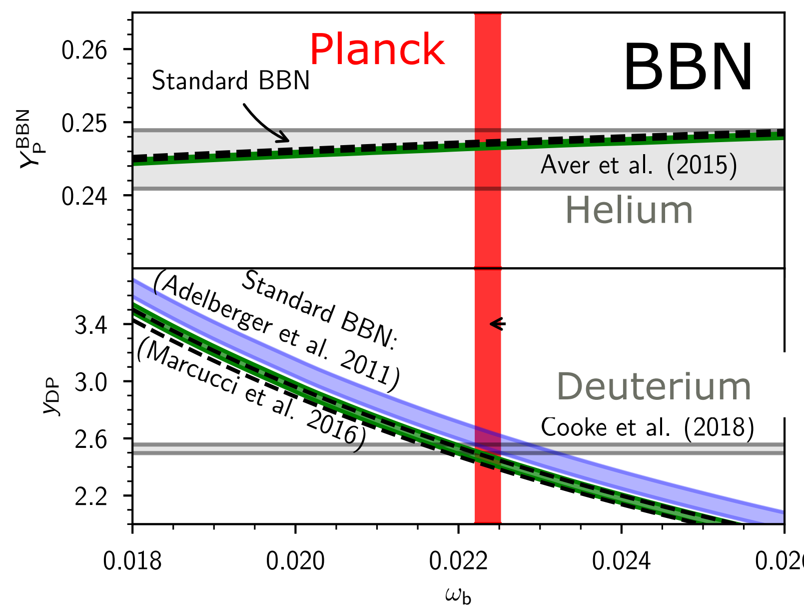
1. Results on ΛCDM
2. **Comparison with external datasets**
3. « Curiosities »
4. Results on extensions of ΛCDM

Good consistency with BAO, RSD, SnIa, BBN









Mild tension with joint DES yr1 results

- Good agreement with DES lensing alone, mild tension with joint DES lensing+galaxy-galaxy lensing +clustering results.
- DES joint (DES priors)

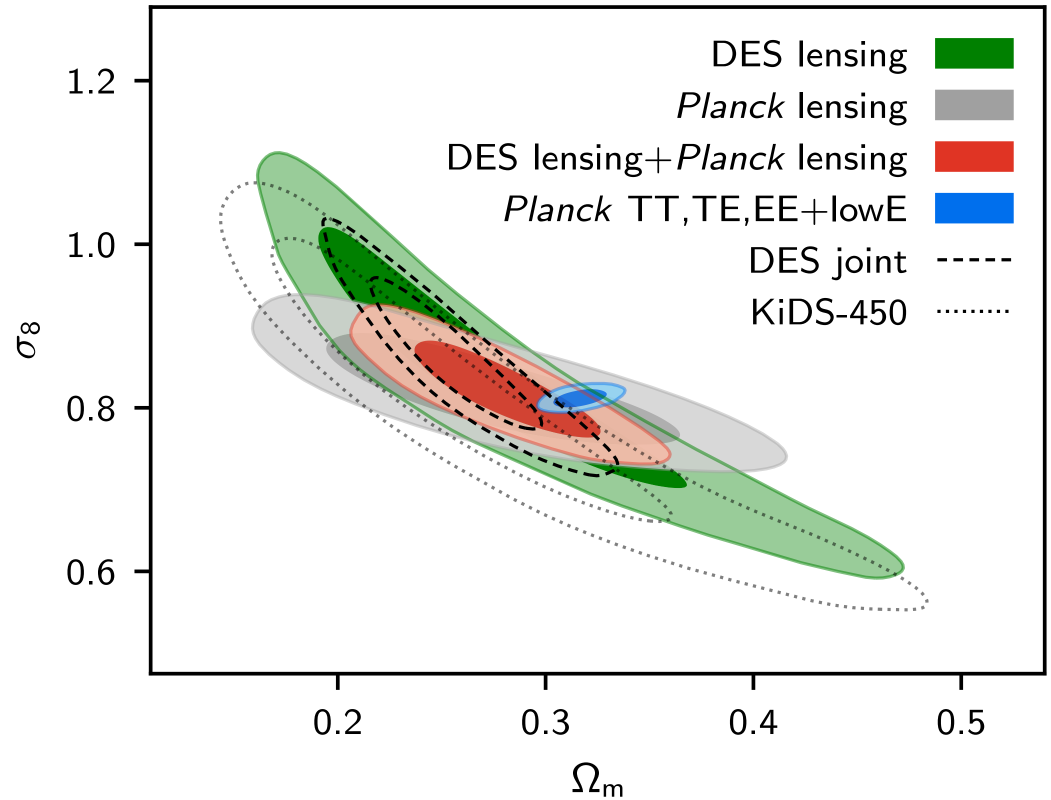
$$S_8 \equiv 0.792 \pm 0.024$$
$$\Omega_m = 0.257^{+0.023}_{-0.031}$$

-
- Planck TT,TE,EE+lowE+lensing

$$S_8 = 0.832 \pm 0.013$$
$$\Omega_m = 0.315 \pm 0.007.$$

- DES: $\Delta\chi^2$=10 for 457 deg with respect to Planck best fit.

$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$



Fixed Σm_ν=0.06

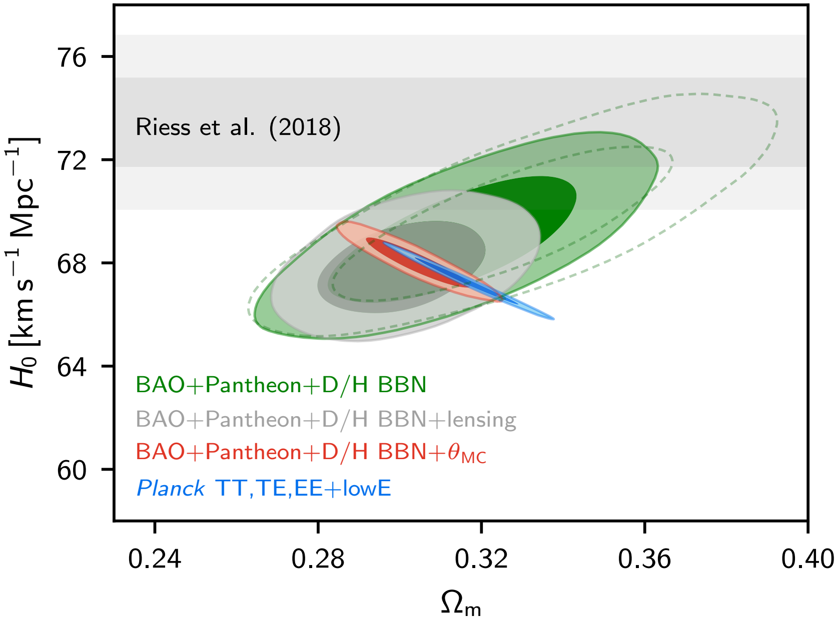
Strong tension with direct measurements. Agreement with inverse distance ladder.

H_0= 67.36±0.54 km/s/Mpc Planck ΛCDM
H_0= 73.5 ±1.6 km/s/Mpc SH0ES (Riess+ 18)

3.6σ tension

Inverse distance ladder:
H_0= 67.9 ± 1.3 km/s/Mpc BAO+D/H+CMB lensing

- Tension with direct measurement (SnIa +cepheids+ancors)
- H_0 can be measured independently from CMB (but indirectly) by using inverse distance ladder.
- BAO galaxy+CMB lensing (or BAO Ly-alpha or DES)+baryon density from (BBN +deuterium measurements) gives low H_0.



(see also Aubourg+15, Addison+ 17, DES collaboration+ 17).

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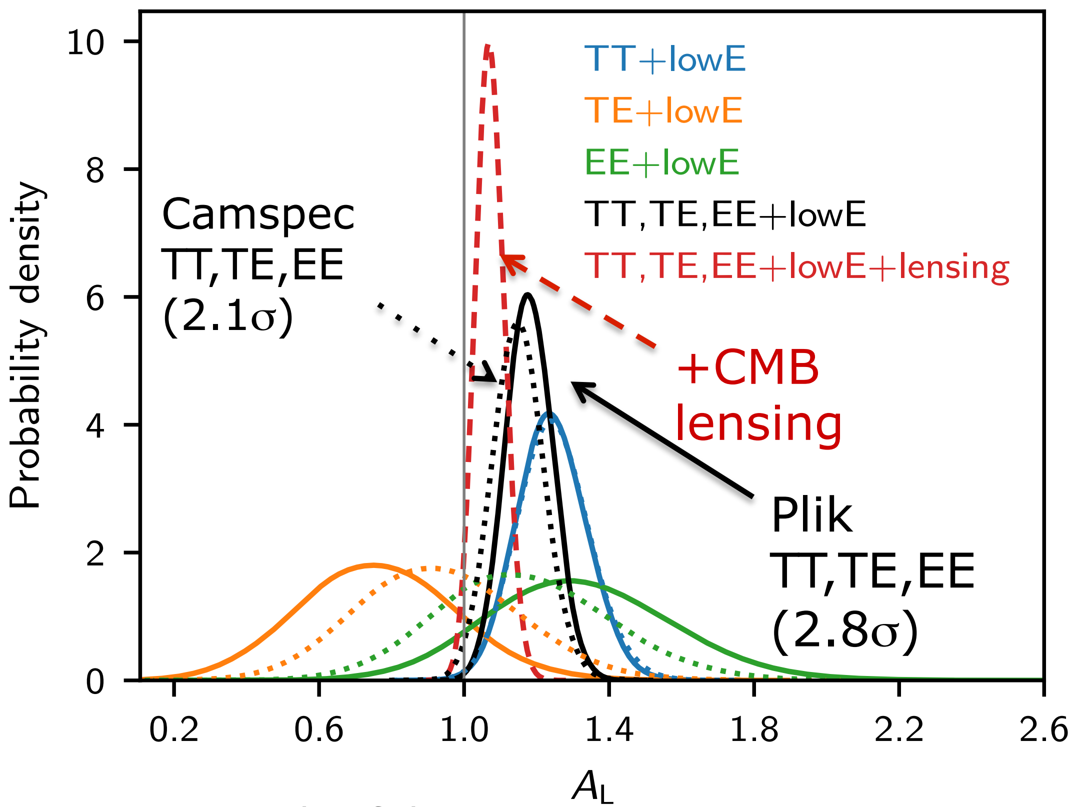
Peak smoothing in the power spectra

- Preference for high A_l from Planck since 2013.
- Unphysical parameter used for consistency check.
- Driven by TT spectrum(2.4σ).
- Not really lensing, not preferred by CMB lensing reconstruction.
- Preference for higher lensing projects into small deviations in extensions which have analogous effect on lensing (Ω_k, w, Σm_ν).
- Adding polarization, A_L degenerate with systematics corrections and thus likelihood used.
- It could be a statistical fluctuation/new physics/ systematics (but no evidence so far)



Amplitude of the lensing potential power spectrum. In ΛCDM=1

Different treatment of systematics in polarization (as done in our two likelihoods) can impact extensions of ΛCDM at ~0.5σ level.

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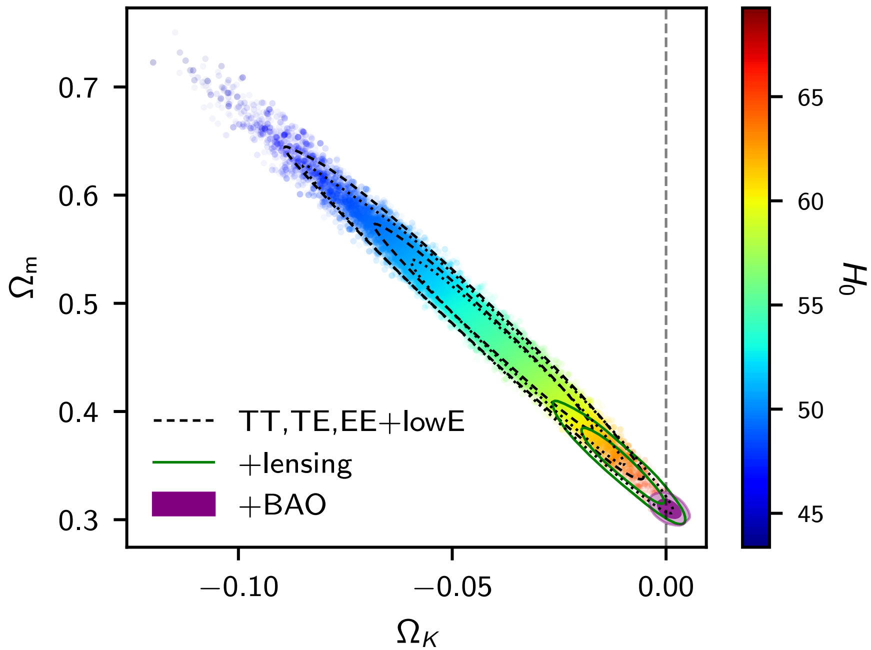
Curvature and Dark Energy

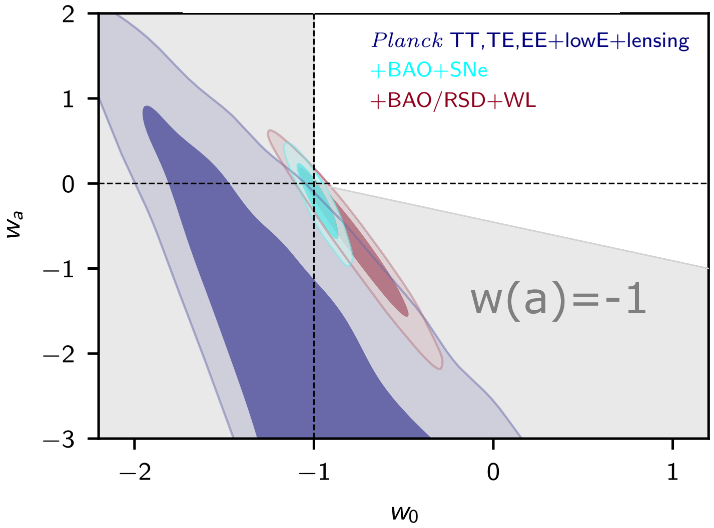
- Both curvature $\Omega_k<1$ and phantom dark energy w<-1 can provide larger lensing amplitude, thus preferred by TTTEEE
- Results from CAMspec differ at **~<0.5σ level.**
- When adding CMB lensing reconstruction, less preference for deviations, further tightened by BAO.



Curvature

$$\Omega_K = 0.0007 \pm 0.0019 \quad \text{(68 %, TT,TE,EE+lowE +lensing+BAO).}$$

$$w(a) = w_0 + (1 - a)w_a$$



Dark energy equation of state

$$w_a = 0,$$

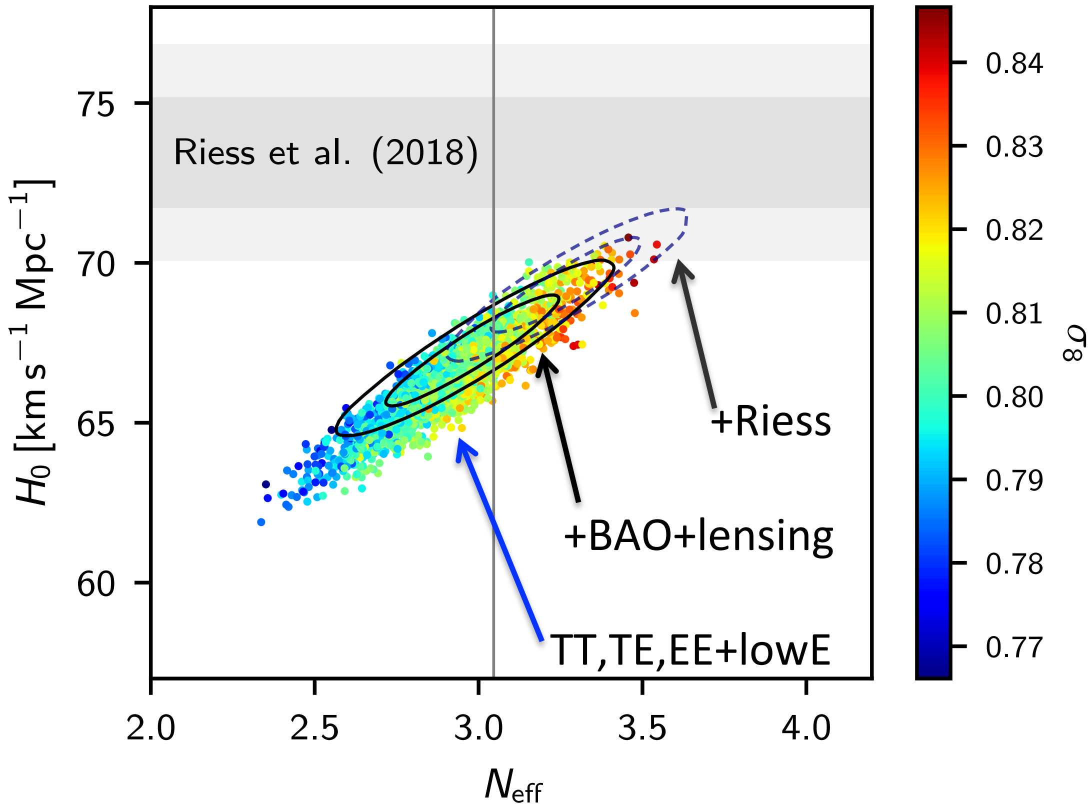
$$w_0 = -1.028 \pm 0.032 \quad \text{(68 %, } \textit{Planck} \text{ TT,TE,EE+lowE +lensing+SNe+BAO),}$$

Number of relativistic species

- CMB is sensitive to radiation density. N_{eff} is radiation density other than photon. N_{eff}=3.046 (standard).

$$\rho_{\rm rad} = N_{\rm eff}\,\frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\rho_\gamma .$$

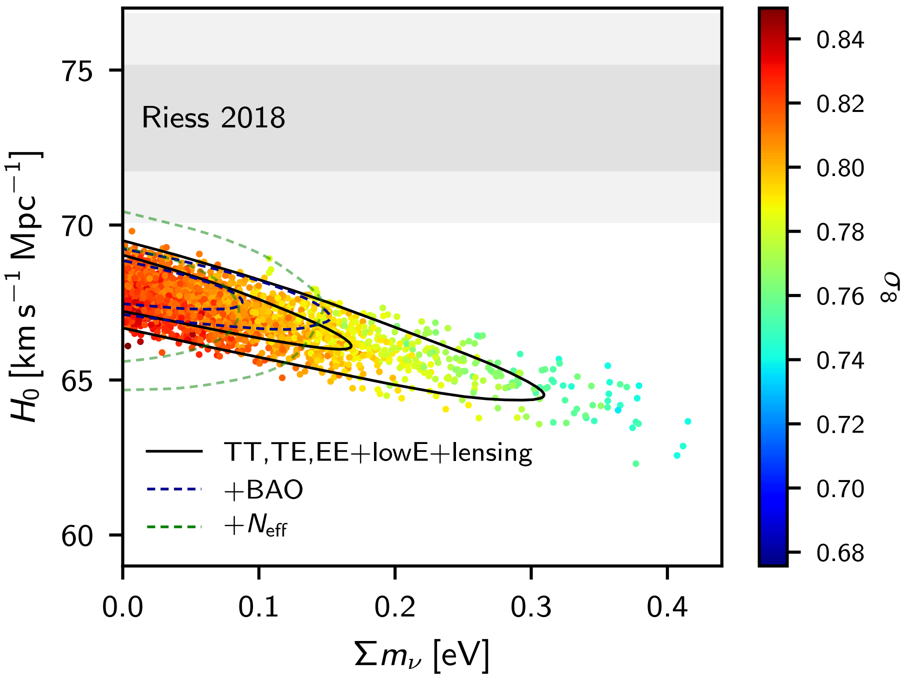
- Non-standard could be radiation (sterile neutrino, light relics) or non-standard thermal history.
- Planck 2018 constraint consistent to standard value (and same results with CAMspec).
- Proposed as possible solution to H_0 tension (N_{eff}-H_0degeneracy)
- Tension remains still at **3.2σ**



Planck TT,TE,EE+lowE+lensing+BAO

$$N_{\rm eff} = 2.99 \pm 0.17$$
$$H_0 = (67.3 \pm 1.1)\ {\rm km\,s^{-1}Mpc^{-1}}$$

Neutrino masses



- Non-relativistic at late times.
  At large scales: changes early and late ISW.
  At small scales: larger Σm_ν suppresses lensing. High lensing preference of high-l forces constraint on Σm_ν to be tighter.

- Constraint from 2015 improved by about 30% (TT)-50%(TTTEEE) due to lower and tighter τ and change in polarization systematics.

- TTTEEE constraint differ in CAMspec by **15%**. Reduced when adding BAO.

$$\sum m_\nu < 0.26\ \text{eV} \quad (95\,\%,\ \textit{Planck}\ \text{TT,TE,EE+lowE}).$$ [<0.492 (2015 TTTEEE+lowP)]

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

Close to disantangle inverted/ normal hierarchy

Conclusions

1. Planck results stable across releases
2. Polarization now better understood (but not perfect; ~0.5σ systematic uncertainty)
3. Consistency with BAO, SN, RSD, DES lensing (in ΛCDM)
4. Moderate tension with DES joint probes
5. Strong 3.6σ tension with H_0 from SH0ES
   Planck value in agreement with inverse distance ladder independent of CMB *(BAO+D/H+CMB lensing).*
6. Some curiosities (A_L ,low-high features), but not more than 2σ – 3σ , no evidence for extensions of ΛCDM

« What we have learned, and the legacy from Planck, is that any signatures of new physics in the CMB must be small. »

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.