Cosmology from the Planck satellite

- 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

Not out yet:

- 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 release. CMB likelihoods with likelihood paper.

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

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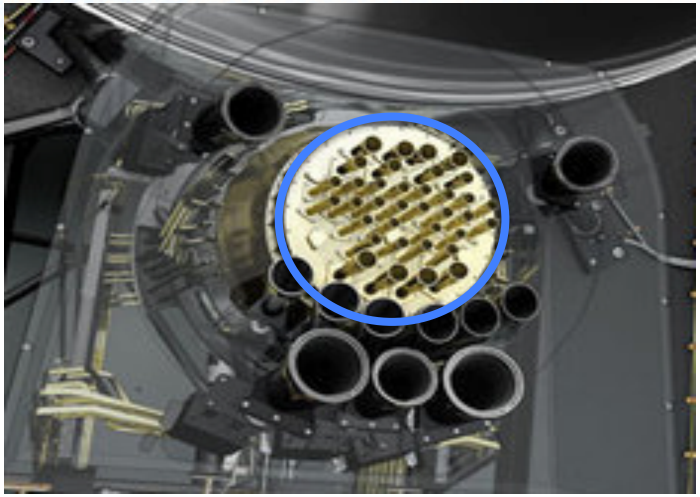
IAP

on behalf of the Planck Collaboration

Tenerife, 15/10/2018

The Planck satellite

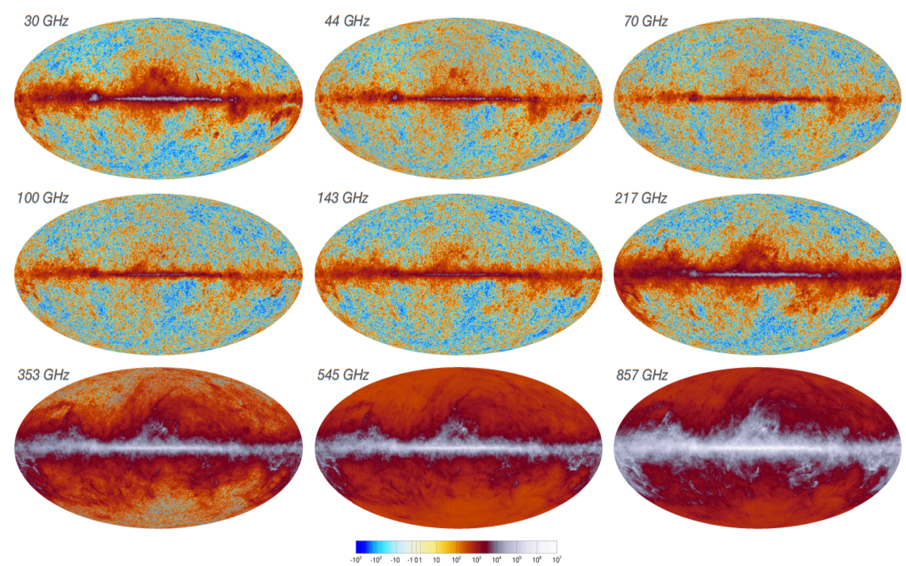


3rd generation full sky satellites (COBE, WMAP)
Launched in 2009, operated till 2013.
2 Instruments, 9 frequencies.

LFI:
- 22 radiometers at **30, 44, 70 Ghz.**

HFI:
- 50 bolometers (32 polarized) at **100, 143, 217, 353, 545, 857 Ghz.**
- **30-353 Ghz polarized.**

- **1st release 2013: Nominal mission**, 15.5 months, Temperature only (large scale polarization from WMAP).
- **2nd release 2015: Full mission**, 29 months for HFI, 48 months for LFI, Temperature + Polarization
  Intermediate results 2016: low-l polarization from HFI
- **3nd release 2018: Full mission, improved polarization, low/high-l from HFI**



Three important features of the Planck legacy release

1. **Understanding and correction of systematics** in polarization (large scales: map-making and sims. Small scales: beam leakage and polarization efficiency corrections). Changes of < 1σ on parameters.

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

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

Beams, calibration — Polar efficiency

$$d(\mathbf{r},\alpha) = B(\mathbf{r})\otimes[T(\mathbf{r}) + \rho(Q(\mathbf{r})\cos 2\alpha + U(\mathbf{r})\sin 2\alpha)]$$

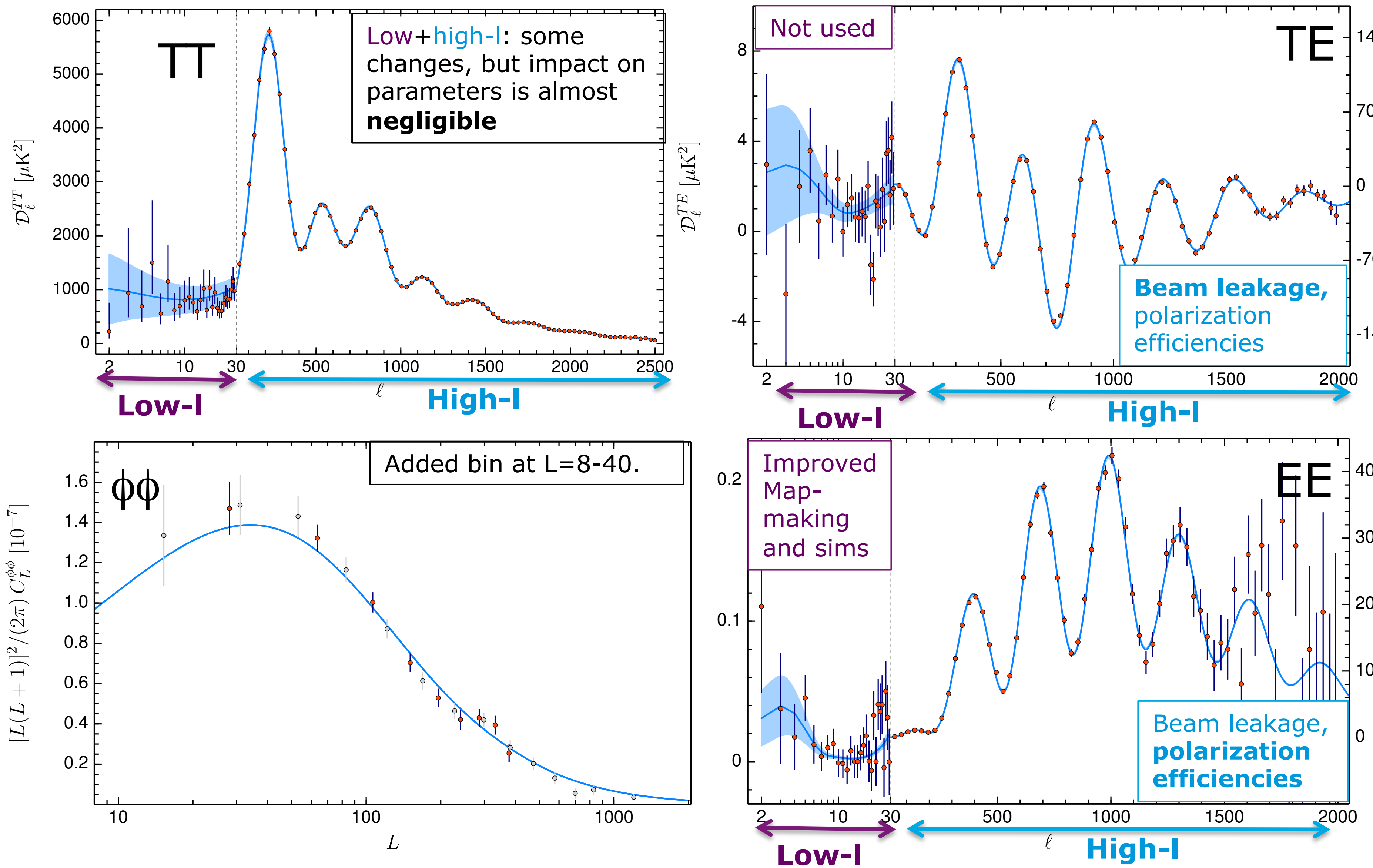
Intensity — Polarization

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(CAMspec) at high-l which uses different choices than baseline (Plik)).
   b. Some 2σ “curiosities” (A_L) in the internal consistency tests.
   c. Comparison with a few external datasets have mild/strong tension.

2018 Power spectra

TT, TE, EE: different likelihoods at low-l (<30) and high-l (>30).

Better systematics modeling in polarization



1. **Results on ΛCDM**
2. Comparison with external datasets
3. Results on extensions of ΛCDM

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
z_{reio}	7.68	0.79	10.2

Robust against changes of likelihood, <0.5σ.

- Most of parameters determined at (sub-) percent level!
- Best determined parameter is the angular scale of sound horizon θ to 0.03%.
- τ lower and tighter due to HFI data at large scales(LFI15: 0.067± 0.022).
- 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.

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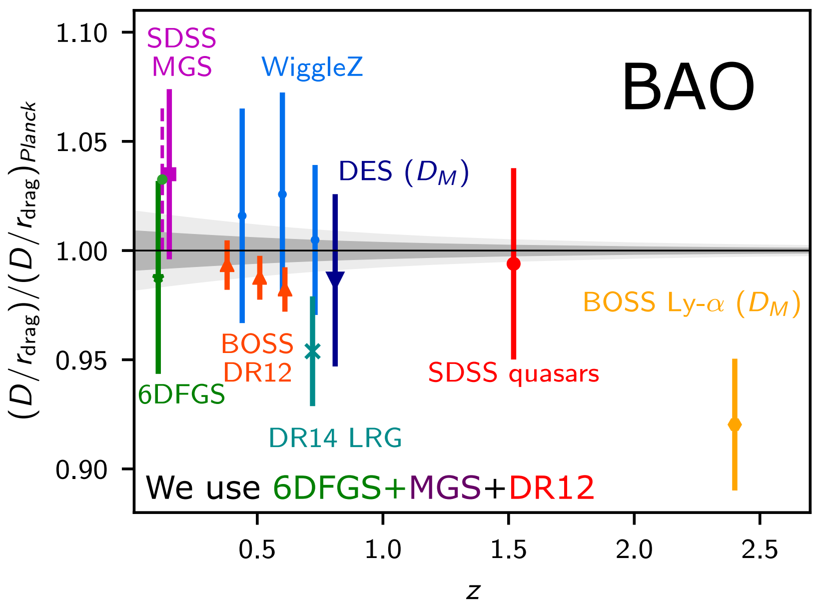
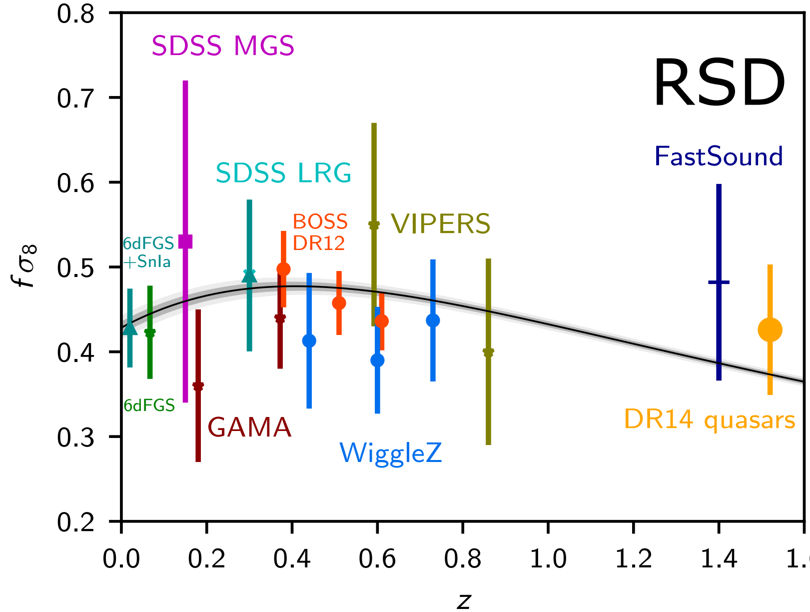
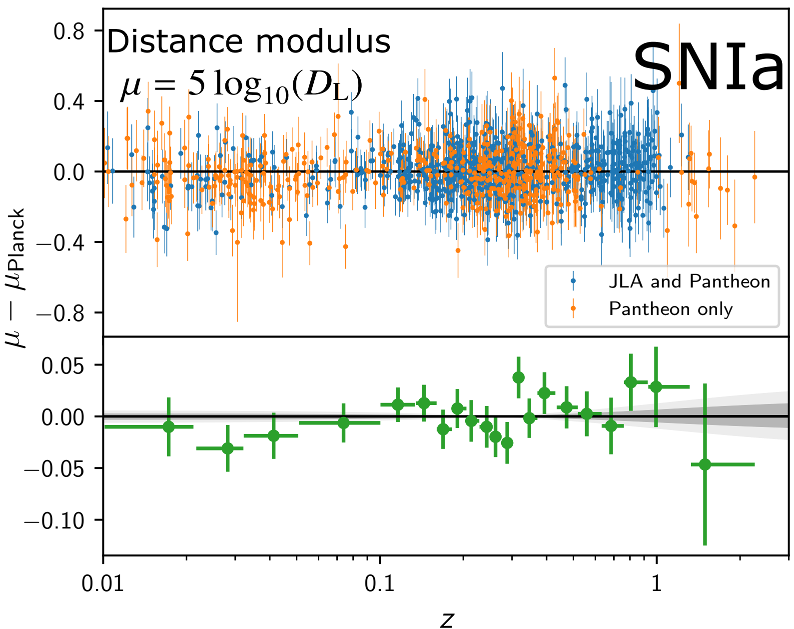
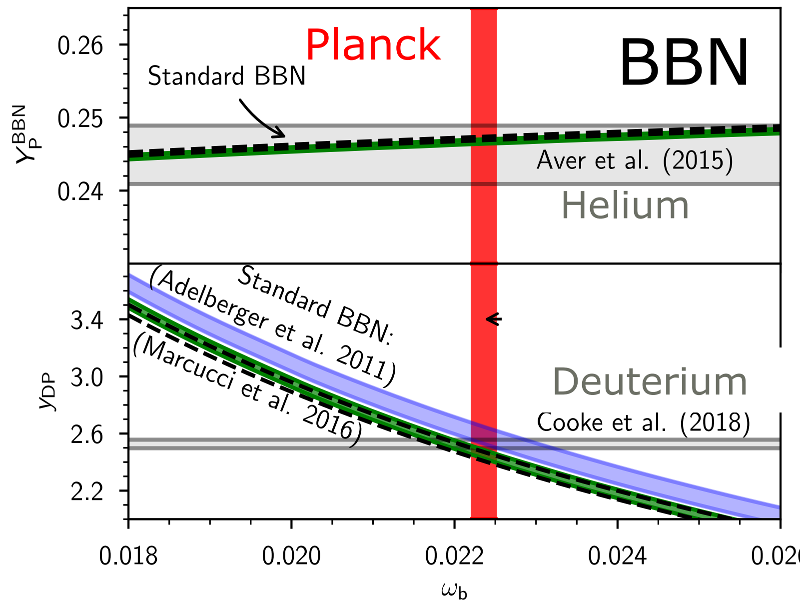
1. Results on ΛCDM
2. **Comparison with external datasets**
3. Results on extensions of ΛCDM

Good consistency with BAO, RSD, SnIa, BBN









Strong tension with direct measurements of the expansion rate of the universe H_0.

- The Hubble constant H_0 directly measured using SNIa CALIBRATED WITH CEPHEIDS to obtain absolute calibration of luminosity-distance relation and thus H_0.

  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

  Other measurements:

  Inverse distance ladder:
  H_0= 67.9 ± 1.3 km/s/Mpc
  galBAO+(BBN+deuterium)+CMB lensing (or LyαBAO or DES lensing)

  Time delay multiply-imaged quasars
  $H_0=72.5^{+2.1}_{-2.3}$ km/s/Mpc H0LiCOW (Birrer+ 2018)

- Both **CMB** and **inverse distance ladder H_0** measurements are **indirect (model dependent) measurements.**
- Maybe this indicates a break in the ΛCDM model!

1. Results on ΛCDM
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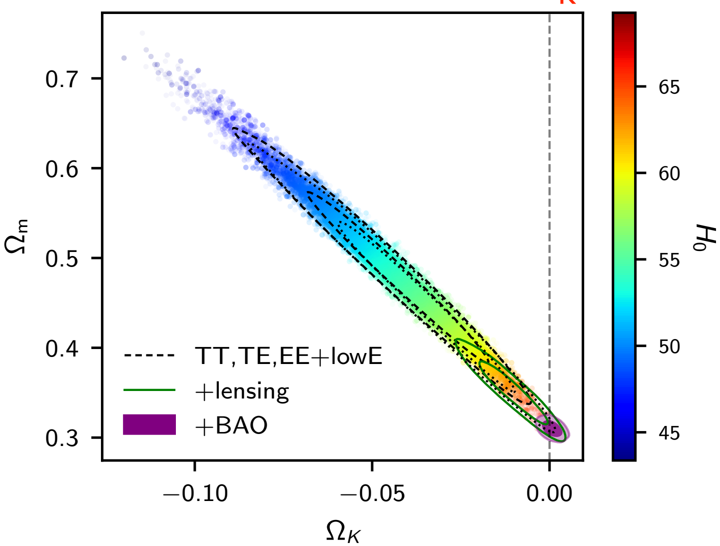
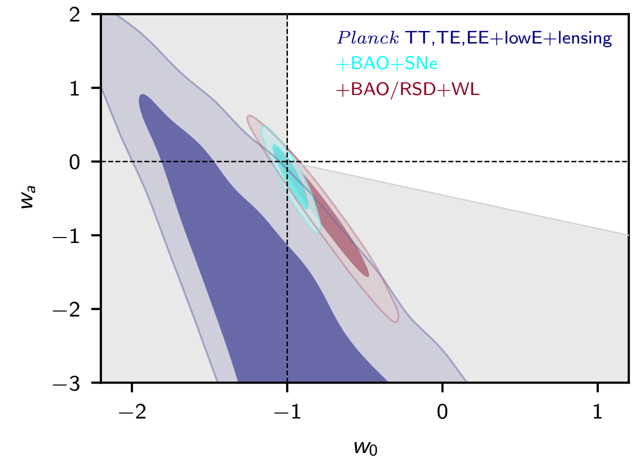
Curvature Ω_k



Dark energy equation of state w

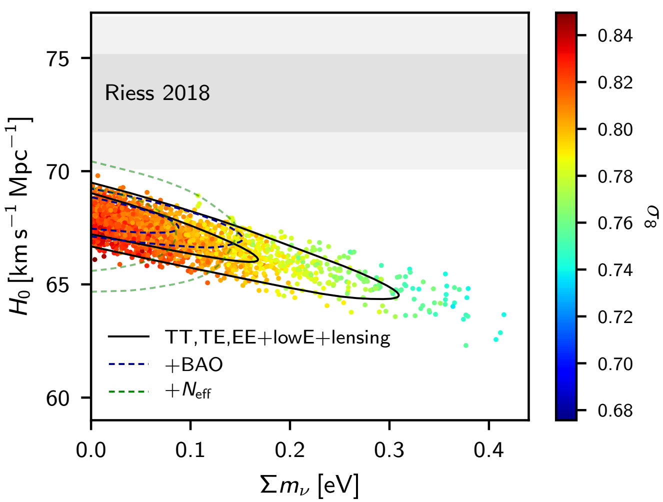


Both Ω_k<1 and phantom w<-1 can provide larger lensing amplitude. Agreement w. LCDM in combination with BAO.
Results from CAMspec differ at **~<0.5σ level.**

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

$$w_a = 0, \quad w_0 = -1.028 \pm 0.032 \quad (68\,\%, \textit{Planck}\ \text{TT,TE,EE+lowE+lensing+SNe+BAO}),$$

Sum of neutrino mass



TTTEEE constraint differ in CAMspec by **15%**.
Reduced when adding BAO.
Constraint from 2015 improved by about 30% (TT)-50%(TTTEEE) due to lower and tighter τ and change in polarization systematics.
Close to disantangle inverted/normal hierarchy

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

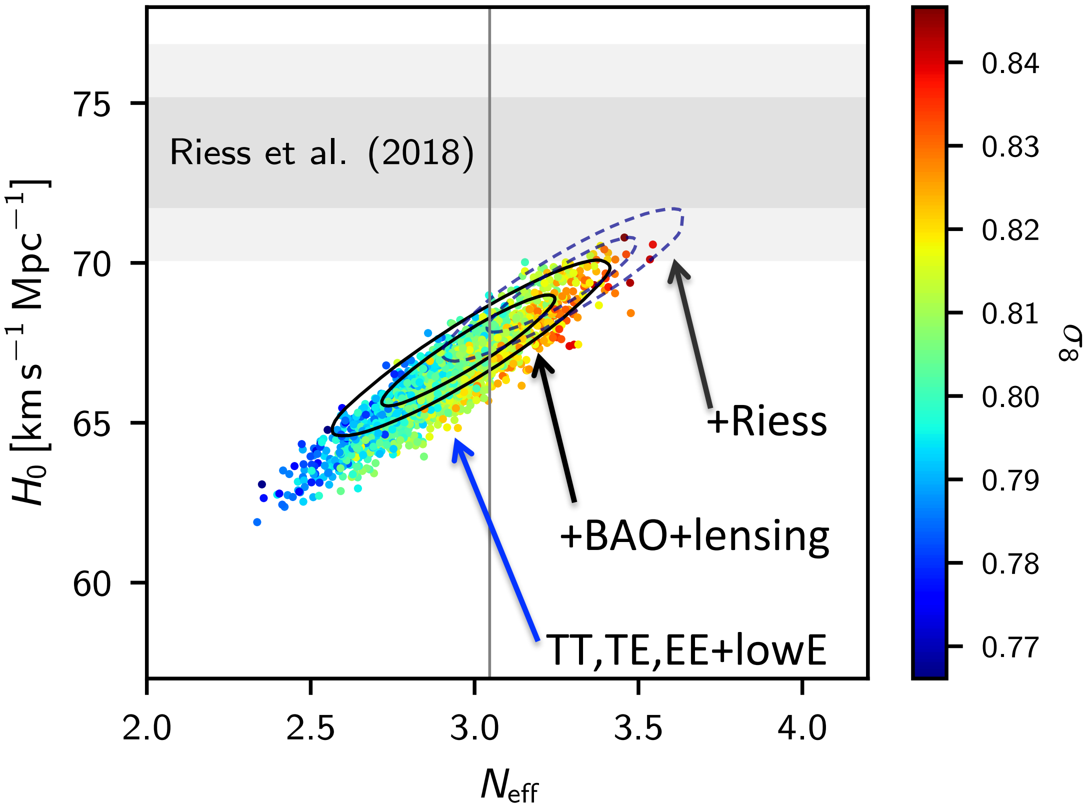
$$\sum m_\nu < 0.12 \text{ eV} \quad (95\,\%, \textit{Planck}\ \text{TT,TE,EE+lowE+lensing+BAO}).$$

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**



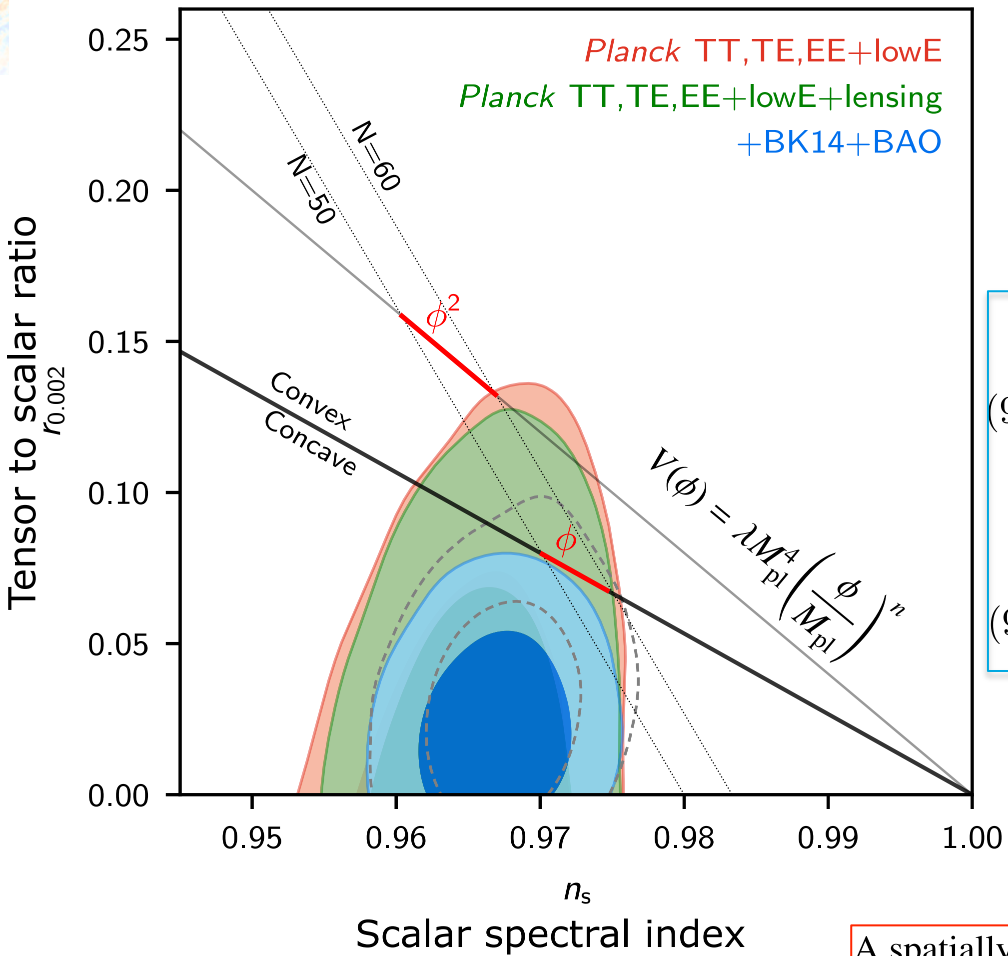
Planck TT,TE,EE+lowE+lensing+BAO

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

esa

HFI PLANCK

Constraints on inflation



$r_{0.002} < 0.10$
(95 % CL, *Planck* TT,TE,EE+lowE+lensing)

$r_{0.002} < 0.064$
(95 % CL, *Planck* TT,TE,EE+lowE+lensing + BK14)

A spatially flat universe	$\Omega_K = 0.0007 \pm 0.0019$
with a *nearly* scale-invariant (red)	
spectrum of density perturbations,	$n_s = 0.967 \pm 0.004$
which is almost a power law,	$dn/d\ln k = -0.0042 \pm 0.0067$
dominated by scalar perturbations,	$r_{0.002} < 0.07$
which are Gaussian	$f_{NL} = 2.5 \pm 5.7$
and adiabatic,	$\alpha_{-1} = 0.00013 \pm 0.00037$
with negligible topological defects	$f < 0.01$

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.