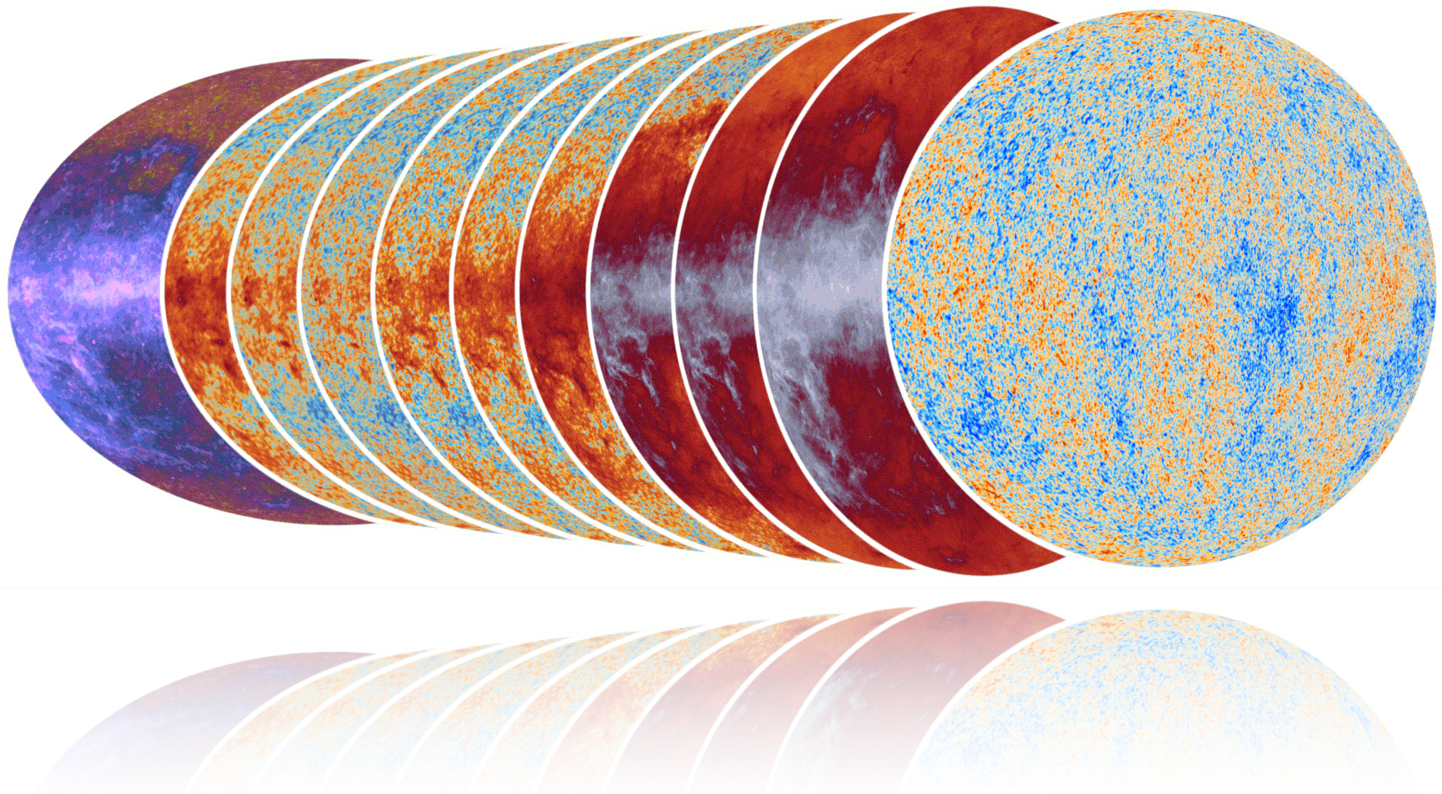
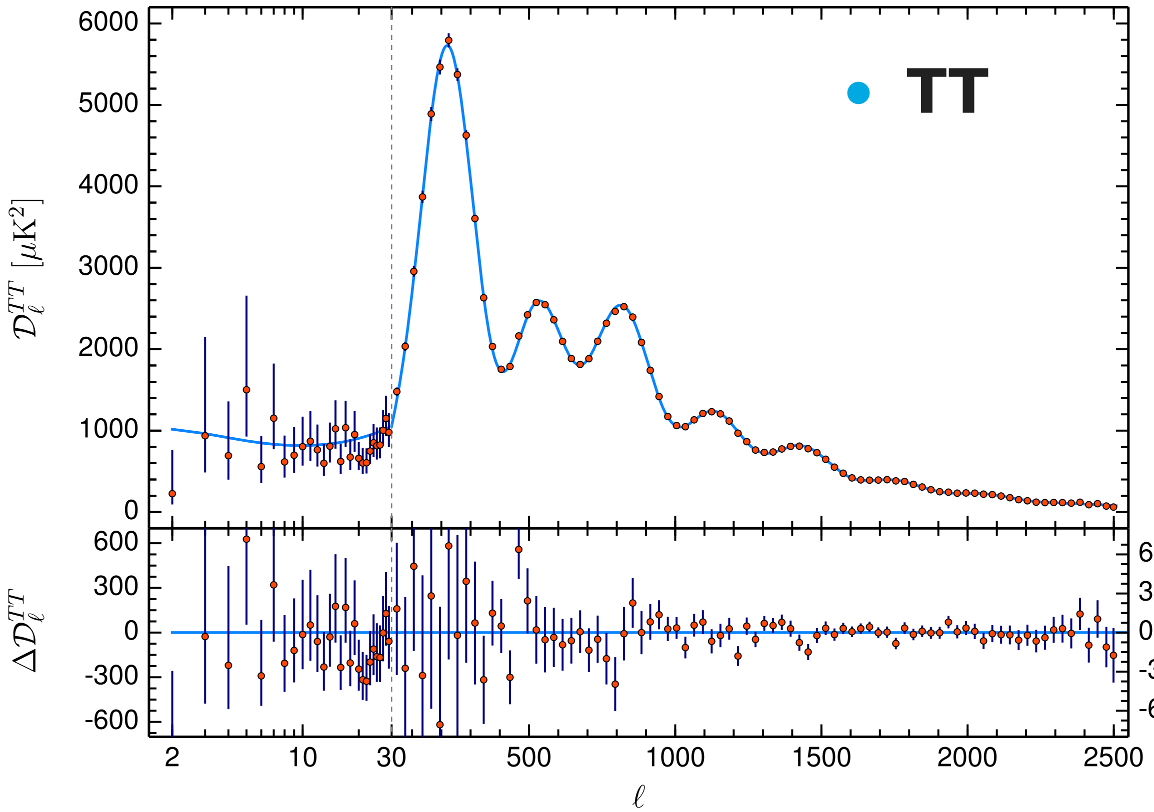


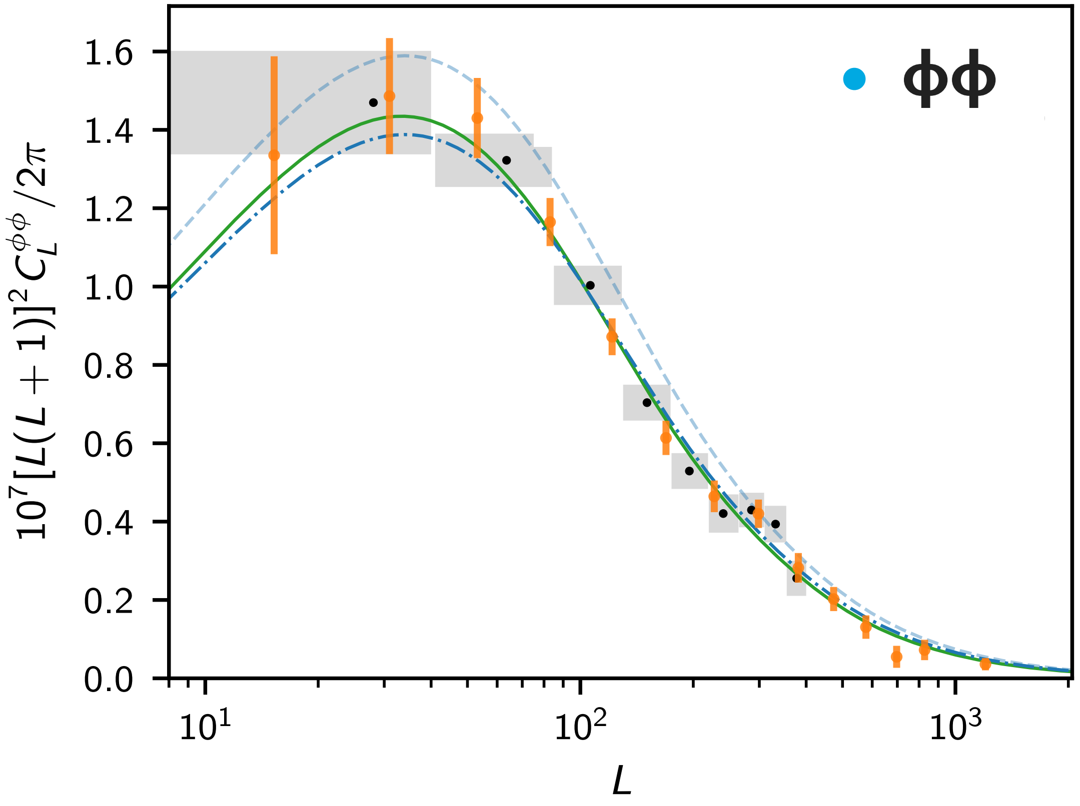
CMB in (relative) tensions

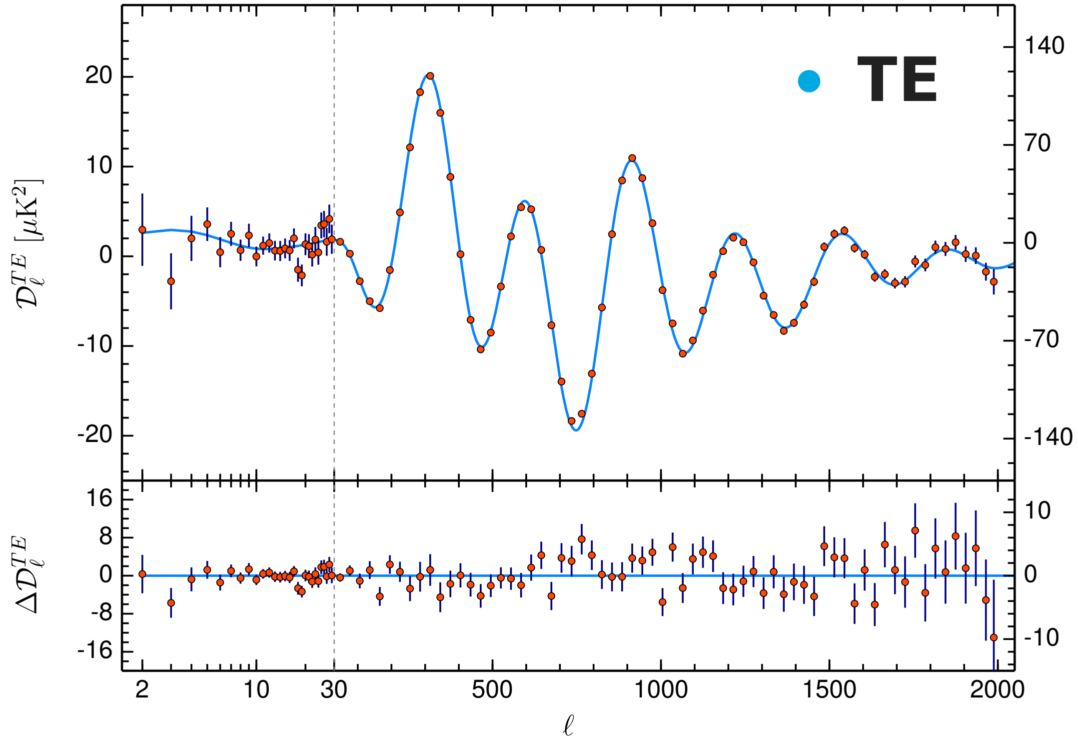
Matthieu TRISTRAM
CNRS
LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

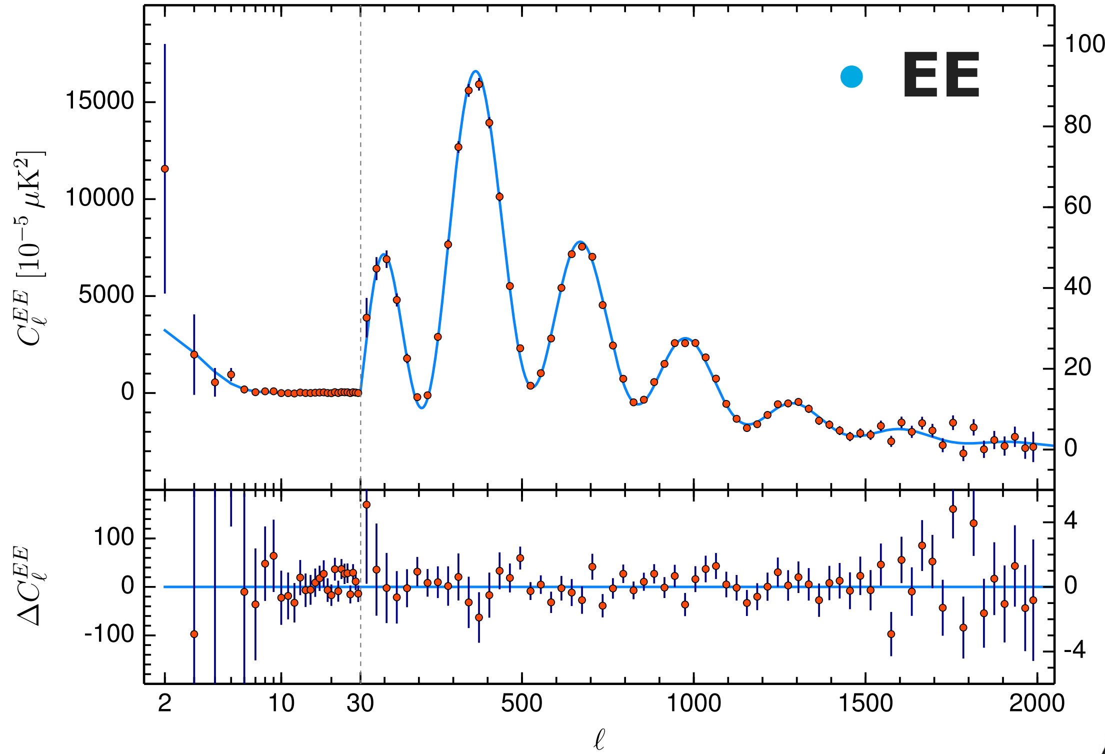
CMB power spectra

[Planck 2018 results. VI]
[Planck 2018 results. VIII]









ΛCDM

- **6 parameters**
  - 2 for the primordial matter spectrum

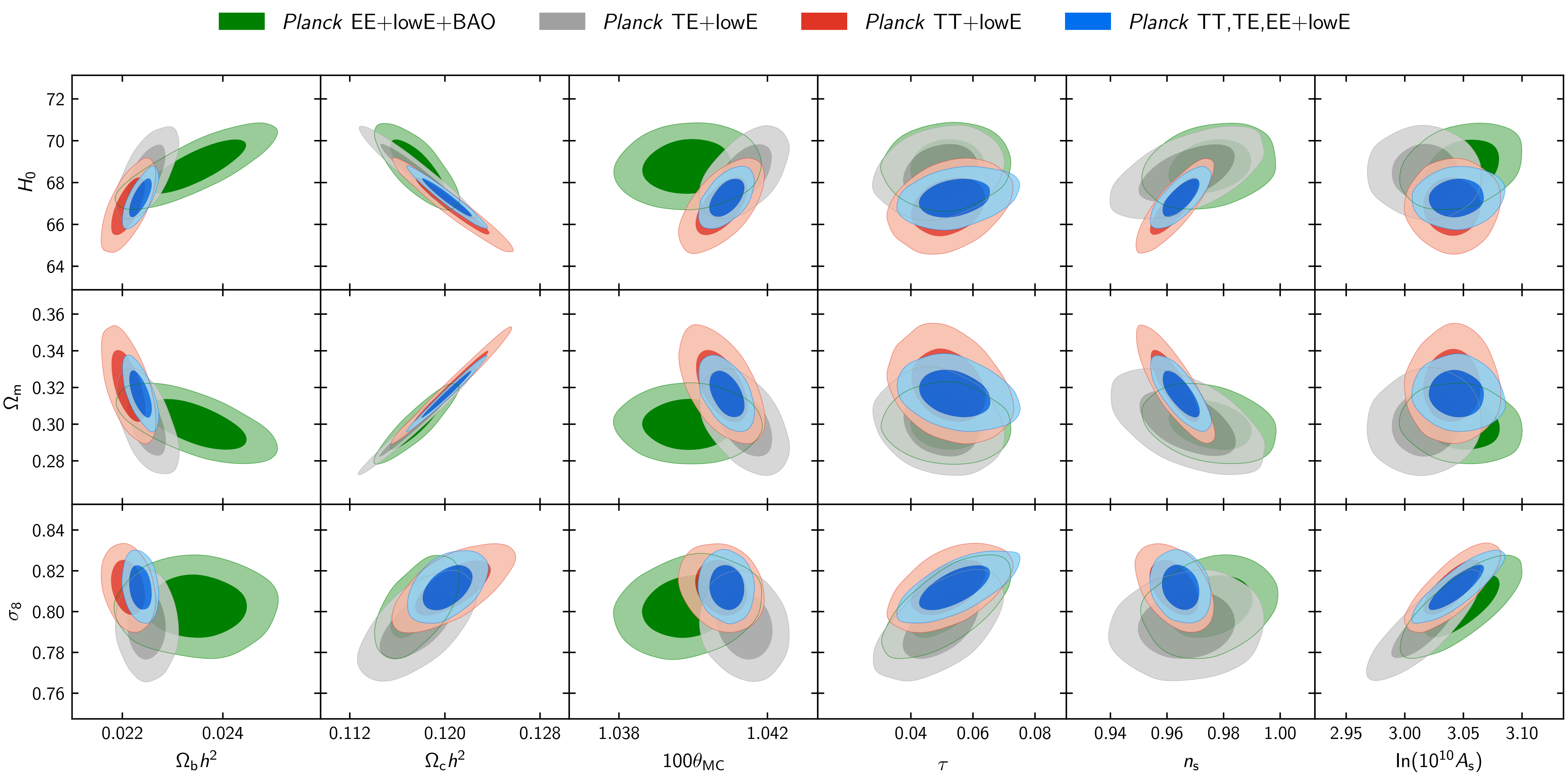
$$\mathcal{P}_{\mathcal{R}}(k) = \boxed{A_s} \left(\frac{k}{k_0}\right)^{\boxed{n_s}-1}$$

  - 1 expansion rate $\boxed{H_0}$ (in practice sound horizon $\boxed{\theta_s}$)
  - 2 parameters for densities $\boxed{\Omega_b h^2}$ $\boxed{\Omega_c h^2}$
  - reionization $\boxed{\tau}$

- **hypothesis (released in the extensions to ΛCDM)**
  - flat Universe $\Omega_k = 0$
  - No running $dn_s/d\ln k = 0$
  - No tensor $\mathcal{P}_t(k) = A_t \left(\frac{k}{k_0}\right)^{n_t} = 0$
  - 3 neutrinos $N_{\rm eff} = 3.046$
  - standard neutrinos with low mass $\sum m_\nu = 0.06\ eV$

ΛCDM results
with spectra

[Planck 2018 results. VI]



polarization spectra are generally highly consistent with TT spectra

ΛCDM results
with time

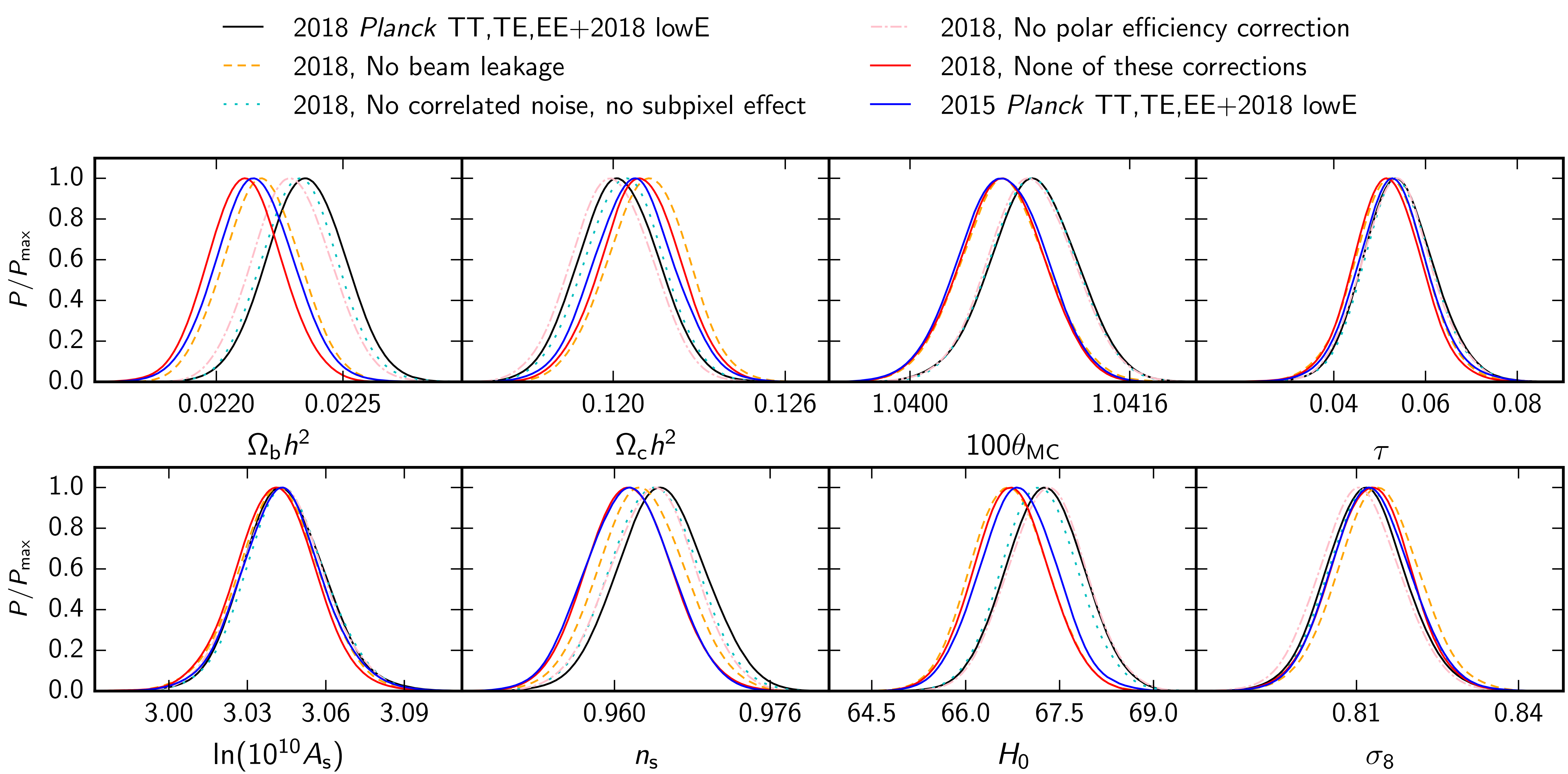
	WMAP	Planck 2013	Planck 2015	Planck 2018
$\Omega_b h^2$	0.02264 ± 0.00050	0.02205 ± 0.00028	0.02225 ± 0.00016	0.02236 ± 0.00015
$\Omega_c h^2$	0.1138 ± 0.0045	0.1199 ± 0.0027	0.1198 ± 0.0015	0.1202 ± 0.0014
H_0	70.0 ± 2.2	67.3 ± 1.2	67.27 ± 0.66	67.27 ± 0.60
n_s	0.972 ± 0.013	0.960 ± 0.007	0.964 ± 0.005	0.965 ± 0.004
$10^9 A_s$	2.189 ± 0.090	2.196 ± 0.060	2.207 ± 0.074	2.101 ± 0.033
τ	0.089 ± 0.014	0.089 ± 0.014	0.079 ± 0.017	0.054 ± 0.007
Ω_Λ	0.721 ± 0.025	0.685 ± 0.018	0.684 ± 0.009	0.685 ± 0.007
Ω_m	0.279 ± 0.023	0.315 ± 0.018	0.316 ± 0.009	0.315 ± 0.007

- **Very stable with time**
- **Precision cosmology (below 1% error bar for most of them)**

ΛCDM results

Planck 2015-2018

[Planck 2018 results. VI]



"A total systematic uncertainty of round 0.5σ may be more realistic, and values should not be overinterpreted beyond this level."

[Planck 2018 results. VI]

Extensions

[Planck 2018 results. VI]

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	$3.029^{+0.018}_{-0.016}$

ΛCDM impressively stable when opening one extension at a time

Extensions

[Planck 2018 results. VI]

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).

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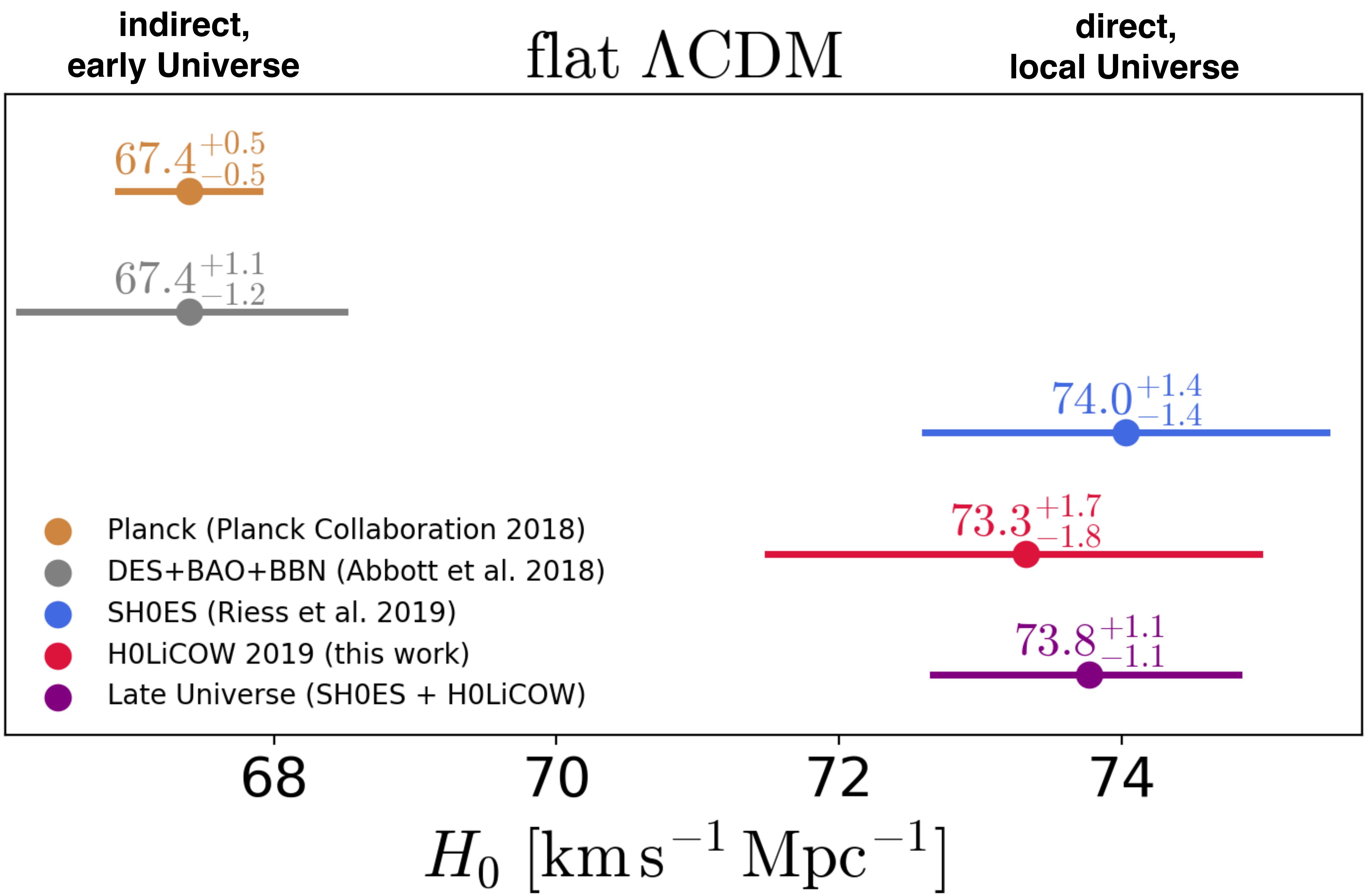
ΛCDM impressively stable when opening one extension at a time

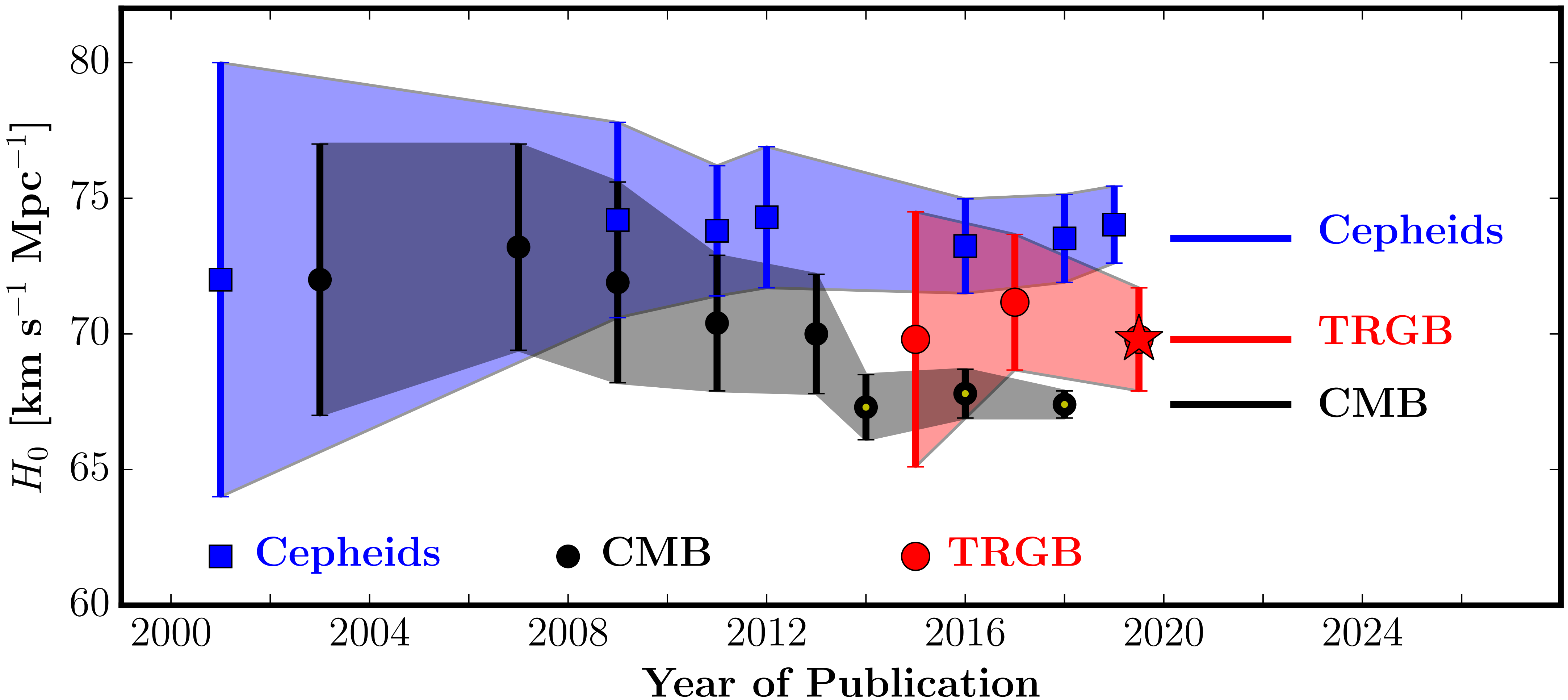
Hubble constant

[Wong et al. 2019]



Hubble constant

[Freedman et al. 2019]
cf. talk on GAIA companion parallaxes (L. Breuval)

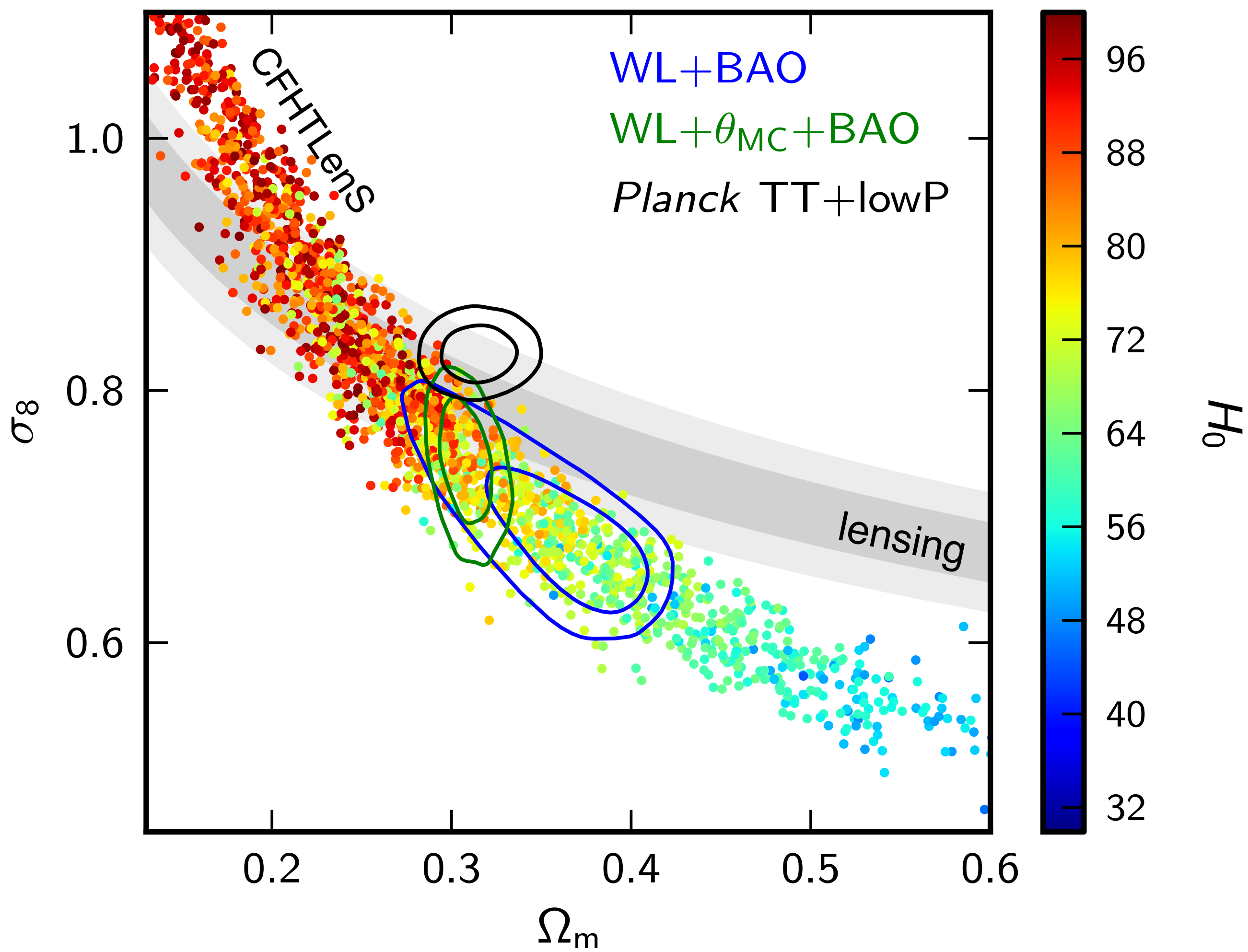


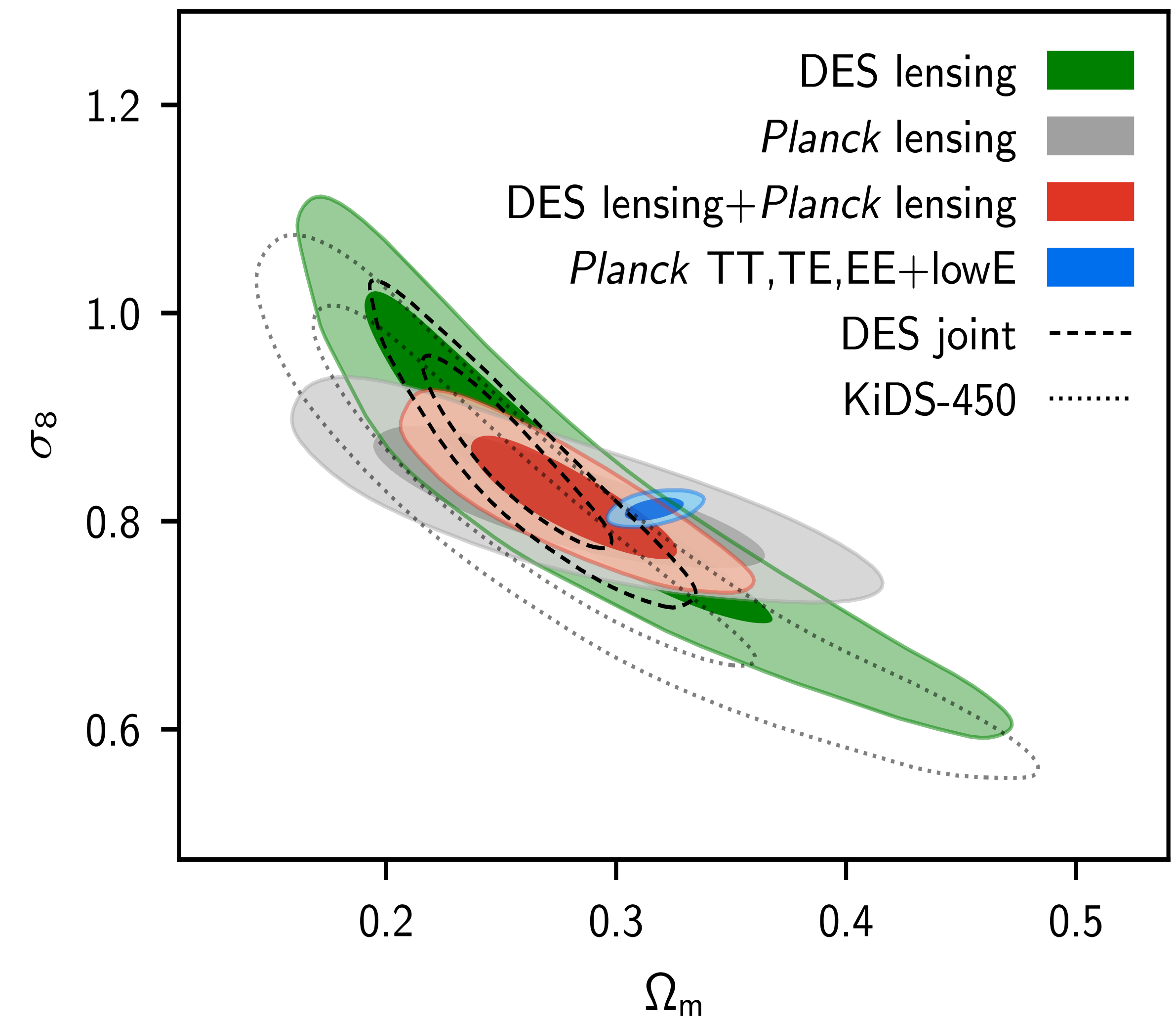
		H_0	
indirect	PlanckTT,TE,EE+lowE+lens	67.4 ± 0.5	[Planck 2018 results. VI]
	DES + BAO + BBN	67.4 ± 1.1	[Abbott et al. 2018]
direct	Cepheid+SNe	74.0 ± 1.4	[Riess et al. 2019]
	H0LiCOW	73.3 ± 1.7	[Wong et al. 2014]
	TRGB+SNe	69.8 ± 0.8 (stat) ± 1.7 (sys)	[Freedman et al. 2019]

amplitude of the fluctuation σ_8

[Planck 2015 results. XIII]
[Planck 2018 results. VI]

tension with WL and SZ cluster count





2-3σ in 2015

$\sigma_8 = 0.8233 \pm 0.0097$

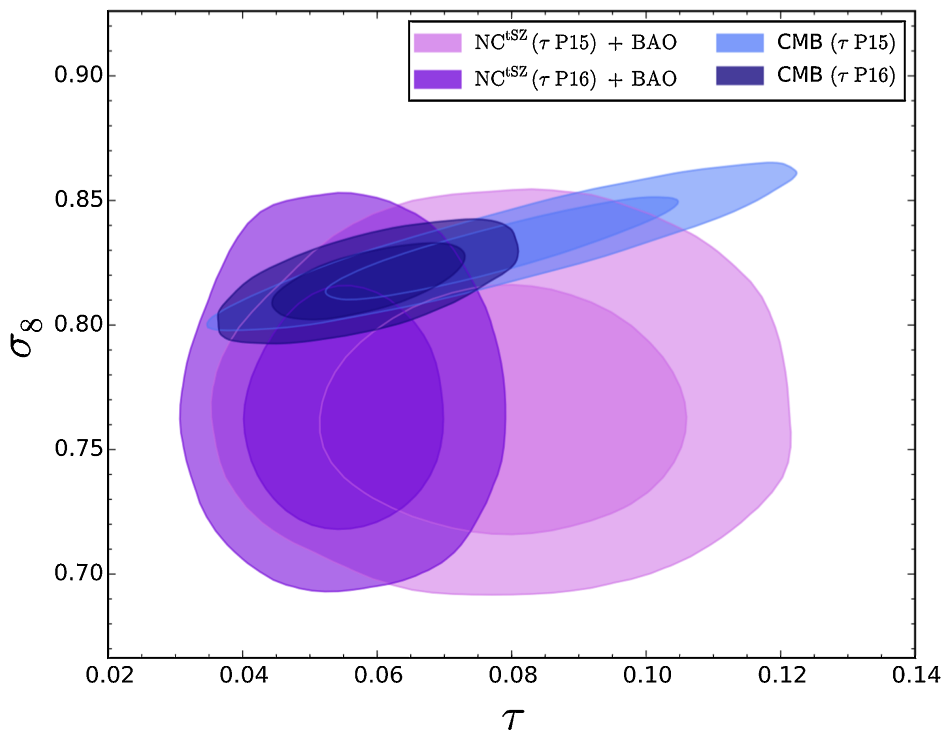
including polarization
and
reionization optical depth

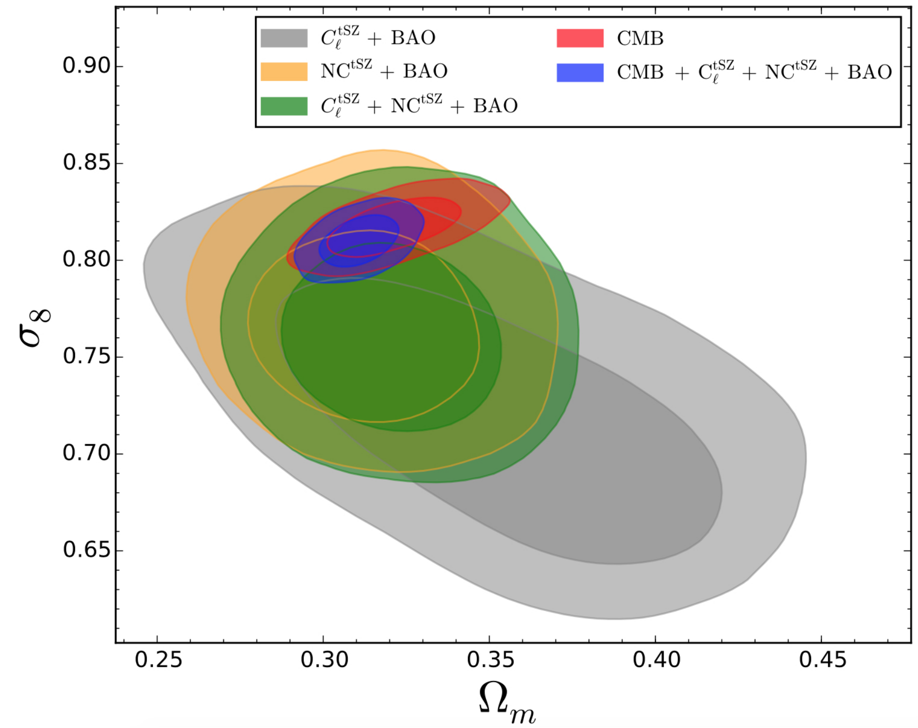
< 2σ sig in 2018

$\sigma_8 = 0.8111 \pm 0.0060$

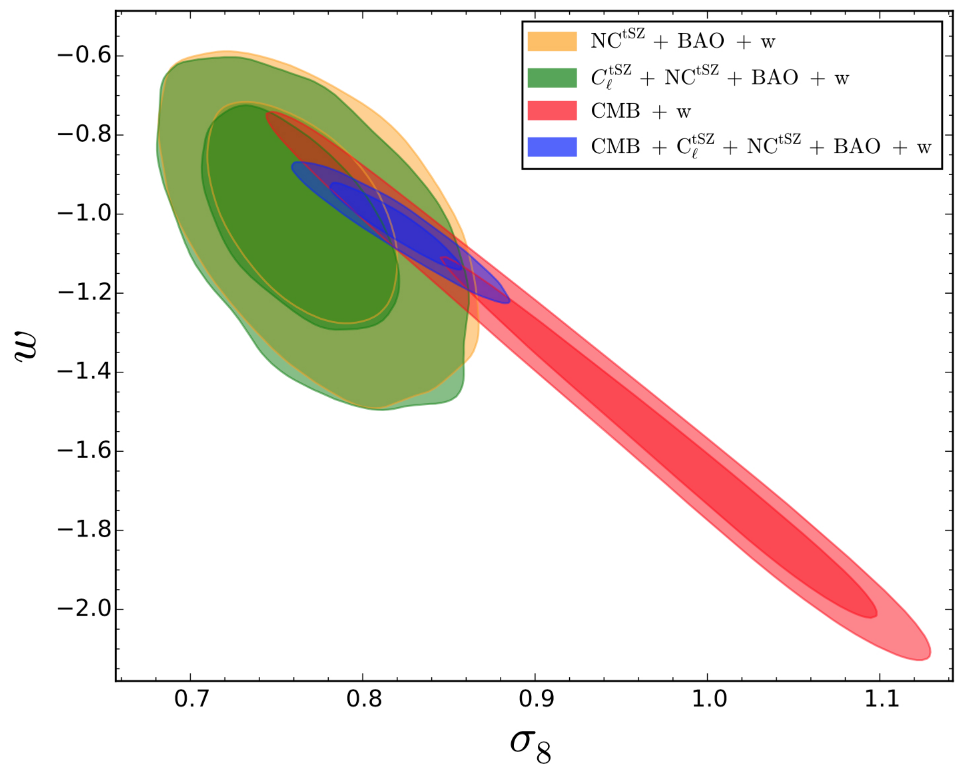
amplitude of the fluctuation σ_8
consistency with SZ

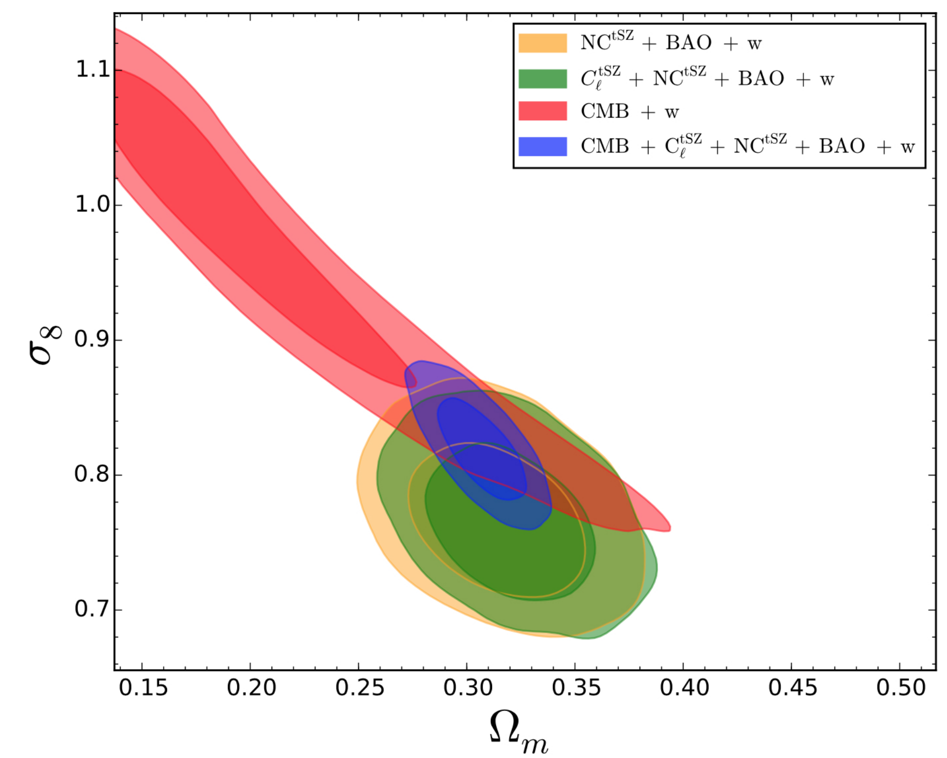
[Salvati et al. 2018]





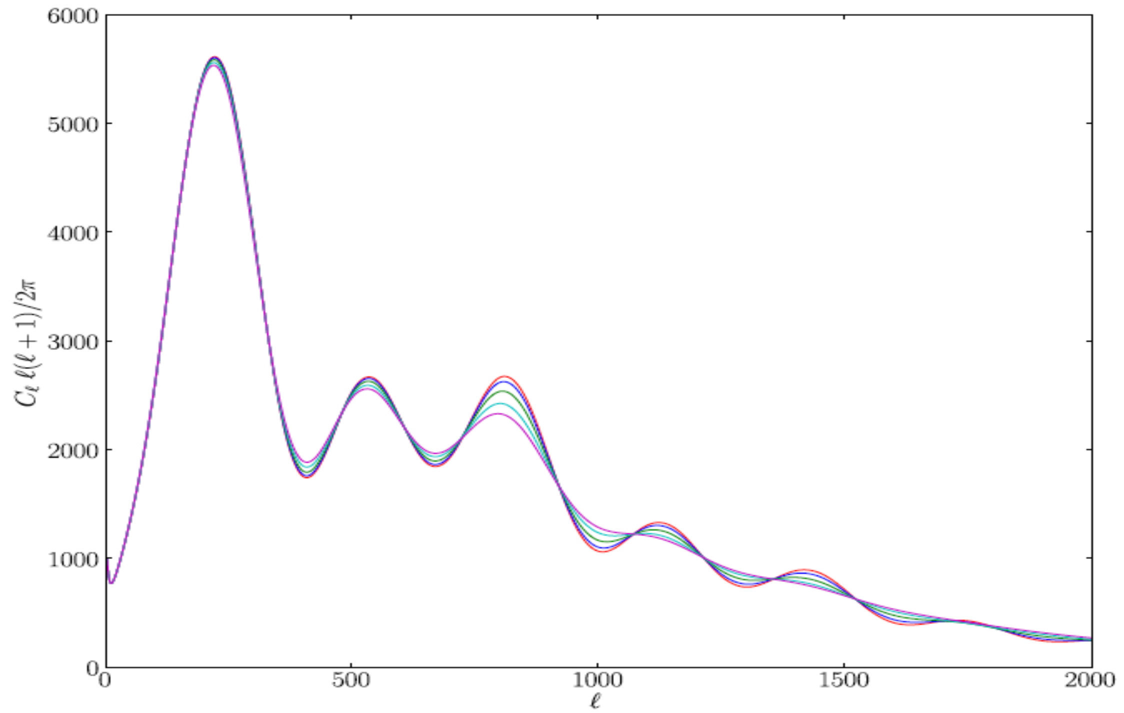
ΛCDM+w





the A_L parameter

- **weak lensing enters the prediction of the CMB spectrum through a convolution of the unlensed spectrum with the lensing potential power spectrum** C_ℓ^Ψ
  - ➡ smooth out the acoustic peaks



- **The A_L parameter is a fudge factor defined as:**
  - A_L =0 : weak lensing ignored
  - A_L =1 : standard ΛCDM

$$C_\ell^\Psi \to A_L C_\ell^\Psi$$

[Lewis&Challinor, Phys. Rept. 429 1 (2006)]
[Calabrese et al, PRD 77 123531 (2008)]

- **PLANCK lensing measurements**

$$\boxed{A_L = 1.011 \pm 0.028 \quad (\text{Planck } \phi\phi)}$$

[Planck 2018 results. VIII]

- **Measuring $A_L \neq 1$ indicates either a problem in the model (e.g. modification of the gravity) or remaining systematics in the data**

the A_L parameter
results

[Planck 2018 results. VI]
[Couchot et al. 2017a]

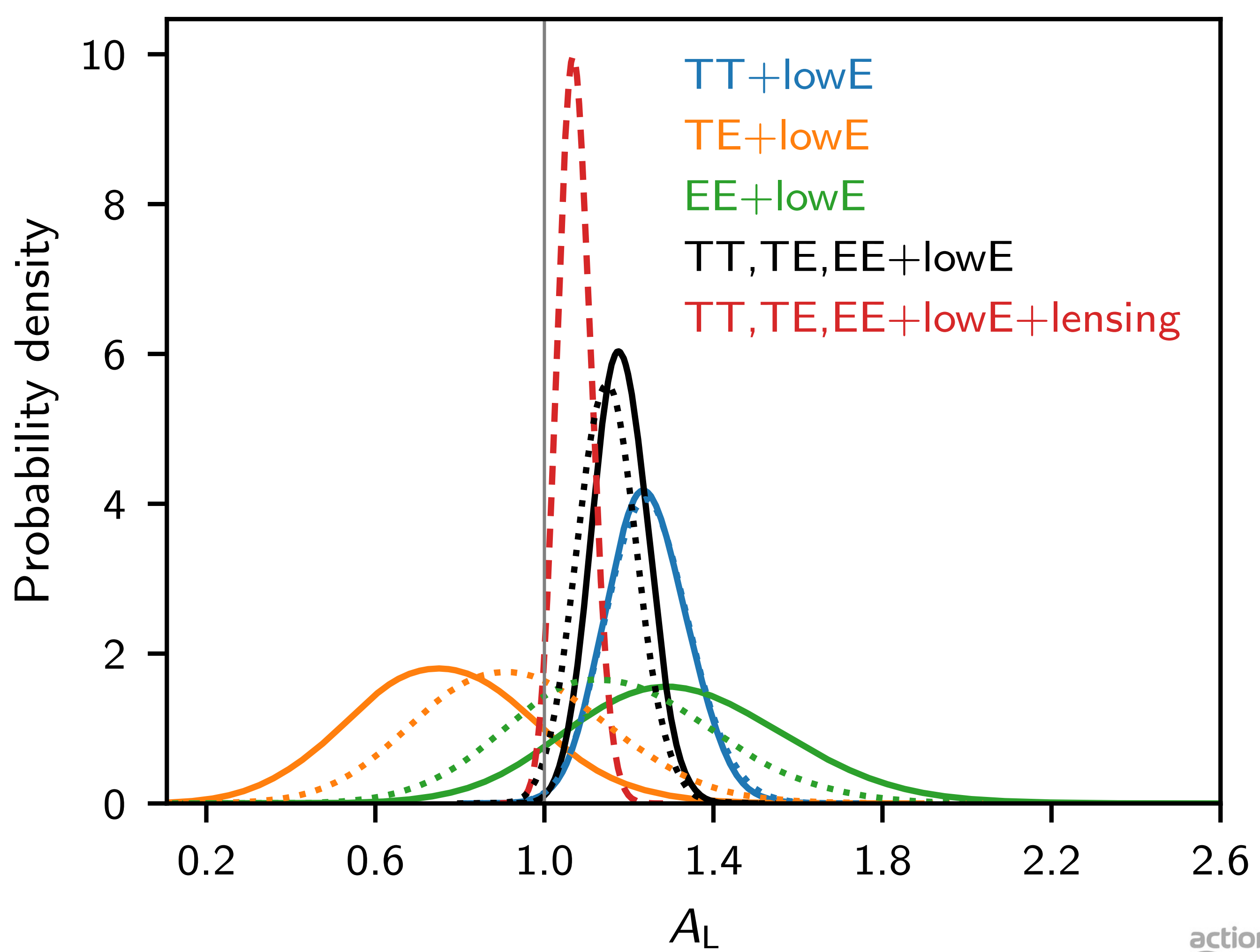
the three likelihoods share the same data but different foreground modelling. Reveal the impact of the uncertainties related to foregrounds.

$$A_L = 1.243 \pm 0.096 \quad (68\,\%\,, \mathrm{TT+lowE}\ [\mathrm{Plik}])$$

$$A_L = 1.246 \pm 0.095 \quad (68\,\%\,, \mathrm{TT+lowE}\ [\mathrm{CamSpec}])$$

$$A_L = 1.160 \pm 0.075 \quad (68\,\%\,, \mathrm{TT+lowE}\ [\mathrm{Hillipop}])$$

TT, TE and EE are barely compatible



A_L and optical depth

[Planck 2018 results. VI]
[Couchot et al. 2017a]

- **tension on optical depth**

$$\tau = 0.1274 \pm 0.0366 \quad (68\,\%\,, \mathrm{TT}\ [\mathrm{Plik}]) \qquad \text{Planck 2018}$$

$$\tau = 0.0507 \pm 0.0080 \quad (68\,\%\,, \mathrm{EE}\ [\mathrm{lowE}])$$

- **relation with A_L**

low-ℓ: pulls $\tau \searrow$
high-ℓ: amplitude $C_\ell \propto A_\mathrm{s} e^{-2\tau} \to A_\mathrm{s} \searrow$
high-ℓ: to preserve lensing information $(C_\ell^\Phi \propto A_\mathrm{s} A_\mathrm{L})$: $A_\mathrm{L} \nearrow$

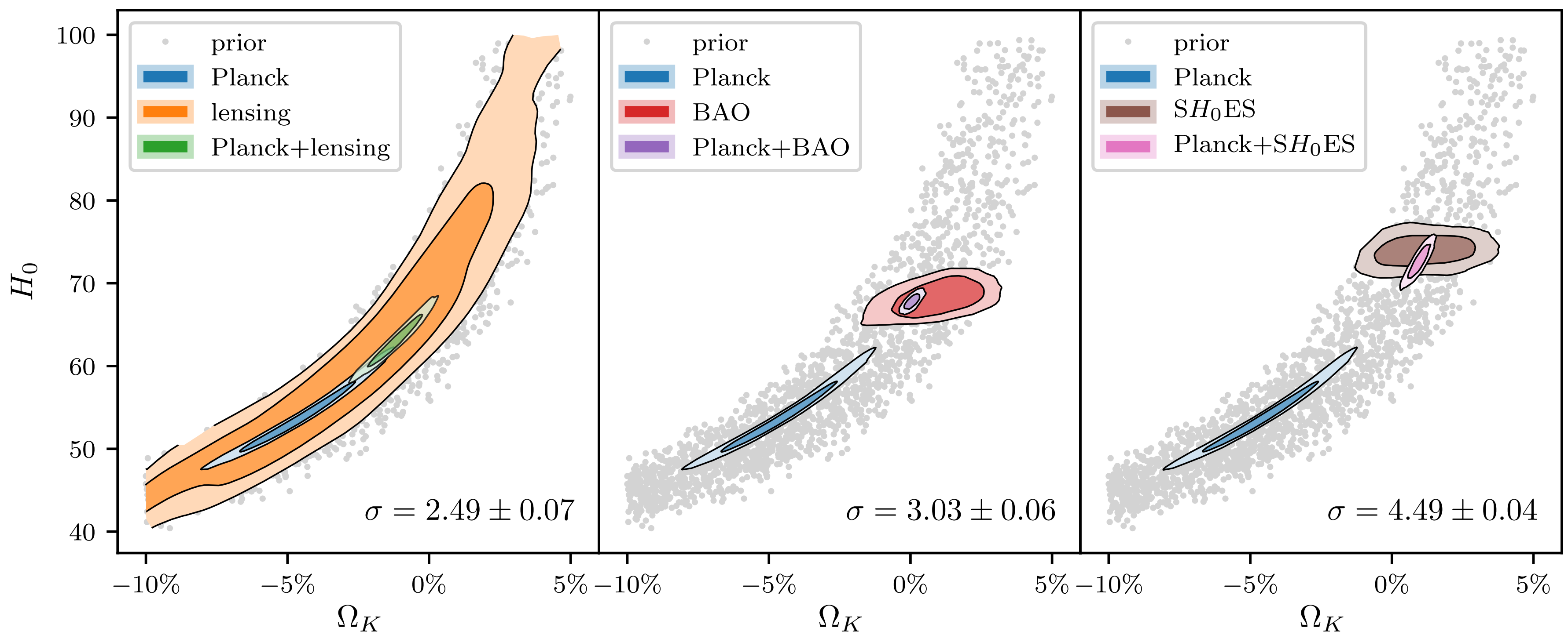
curvature

[Planck 2018 results. VI]

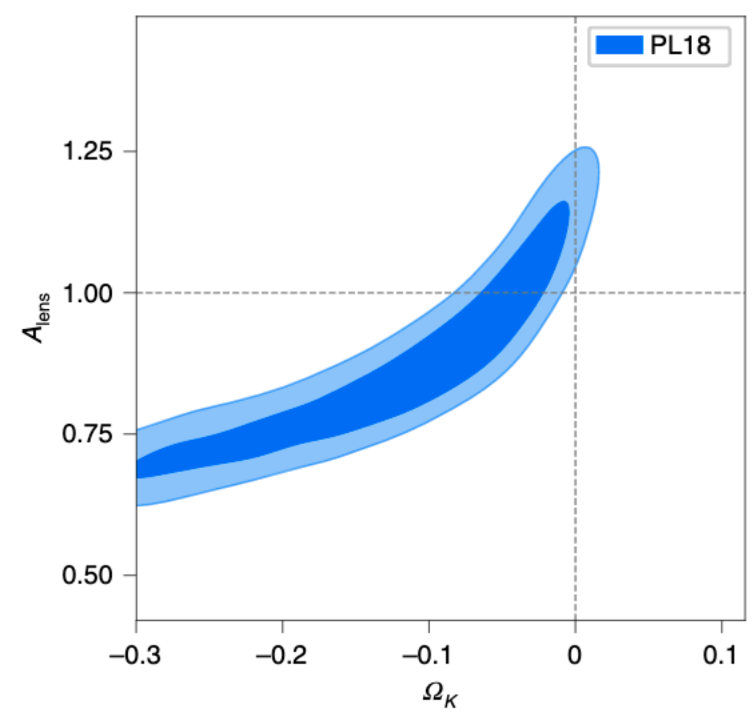
data	Ω_k
PlanckTT + lowE	$-0.056^{+0.028}_{-0.018}$
PlanckTT,TE,EE + lowE	$-0.044^{+0.018}_{-0.015}$
PlanckTT,TE,EE + lowE + lensing	-0.0106 ± 0.0065
PlanckTT,TE,EE + lowE + lensing + BAO	-0.0007 ± 0.0019

$$H_0 = 63.6 \pm 2.2$$

[Handley 2019]



[Di Valentino et al., Nature 2019]

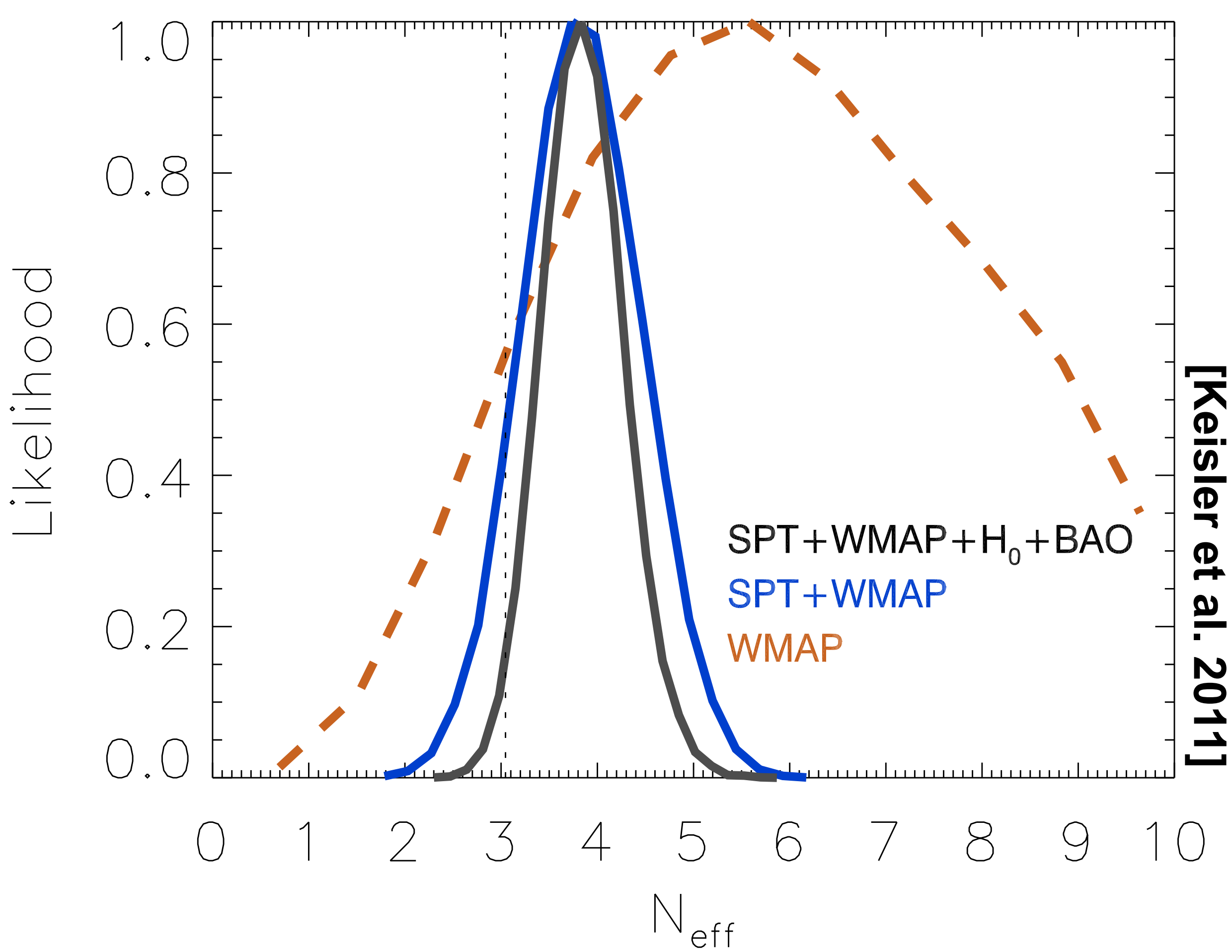


neutrino sector
N_{eff}

- **CMB sensitive to the number of relativistic species at decoupling**
  - standards neutrinos : N_{eff} = 3.046
  - confuse situation since WMAP + SPT + ACT…

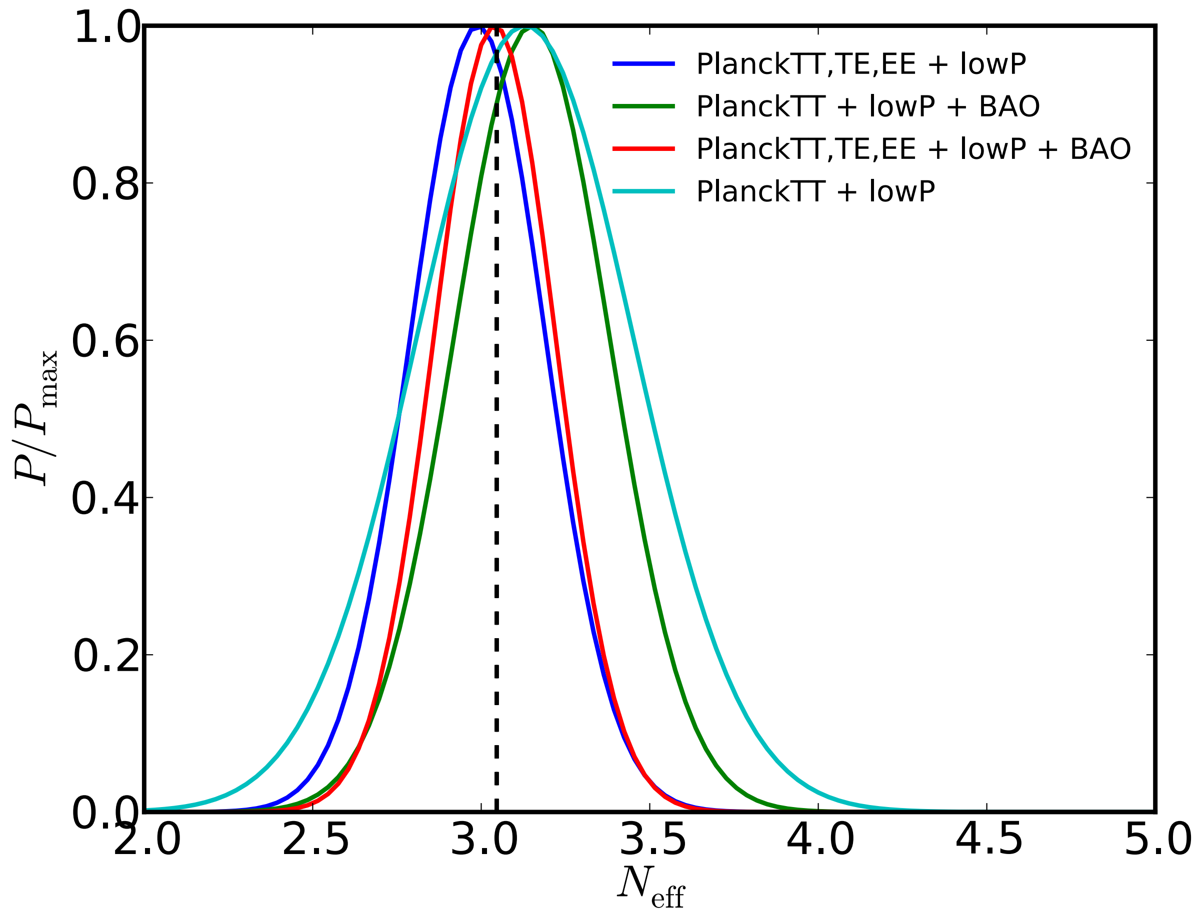
$$\rho = N_{\rm eff}\frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\rho_\gamma.$$

WMAP + SPT



[Keisler et al. 2011]

Planck

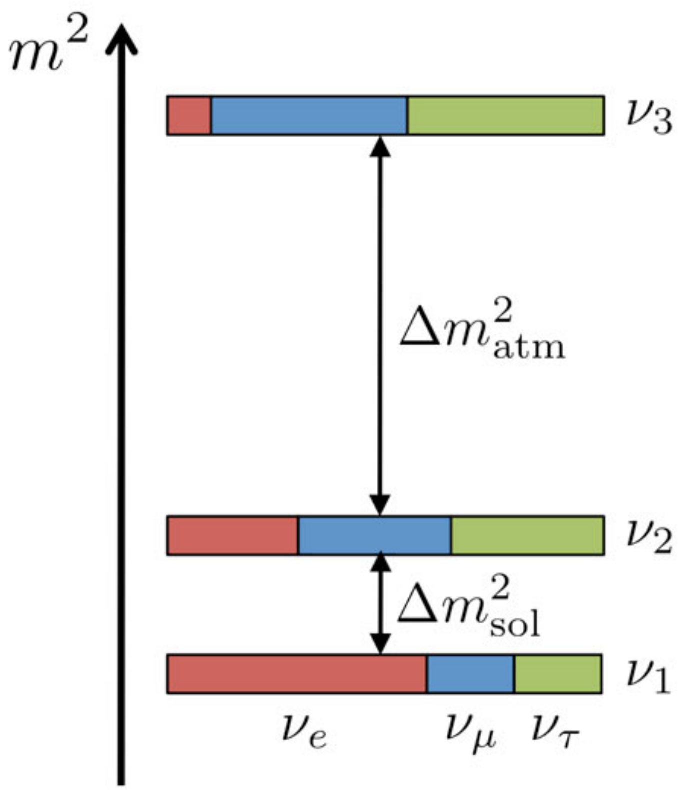


compatible with 3

neutrino sector
Σm_ν

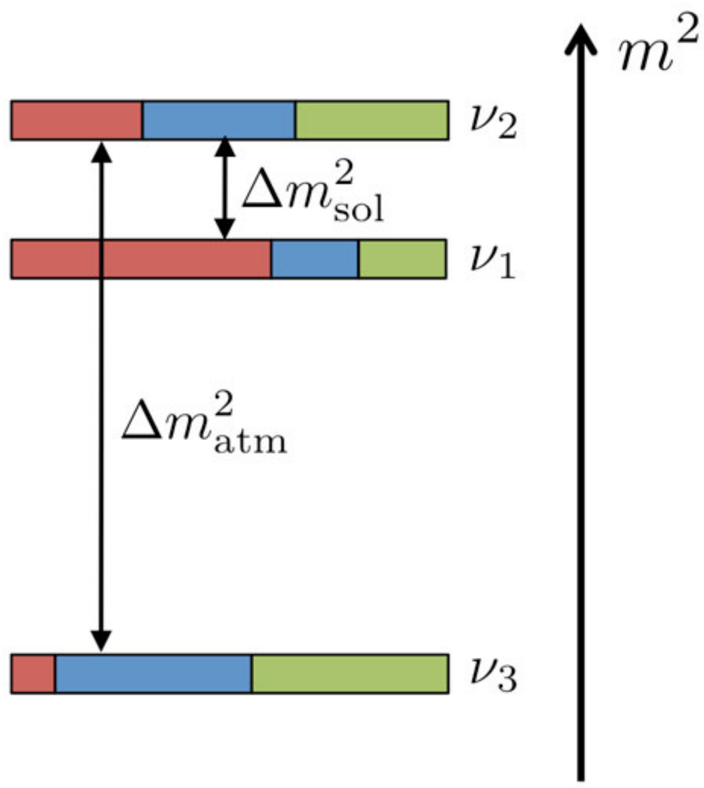
- **constraints on the sum of neutrino masses is important for the neutrino hierarchy**

normal hierarchy (NH)



$$\sum m_\nu > 0.06$$

inverted hierarchy (IH)



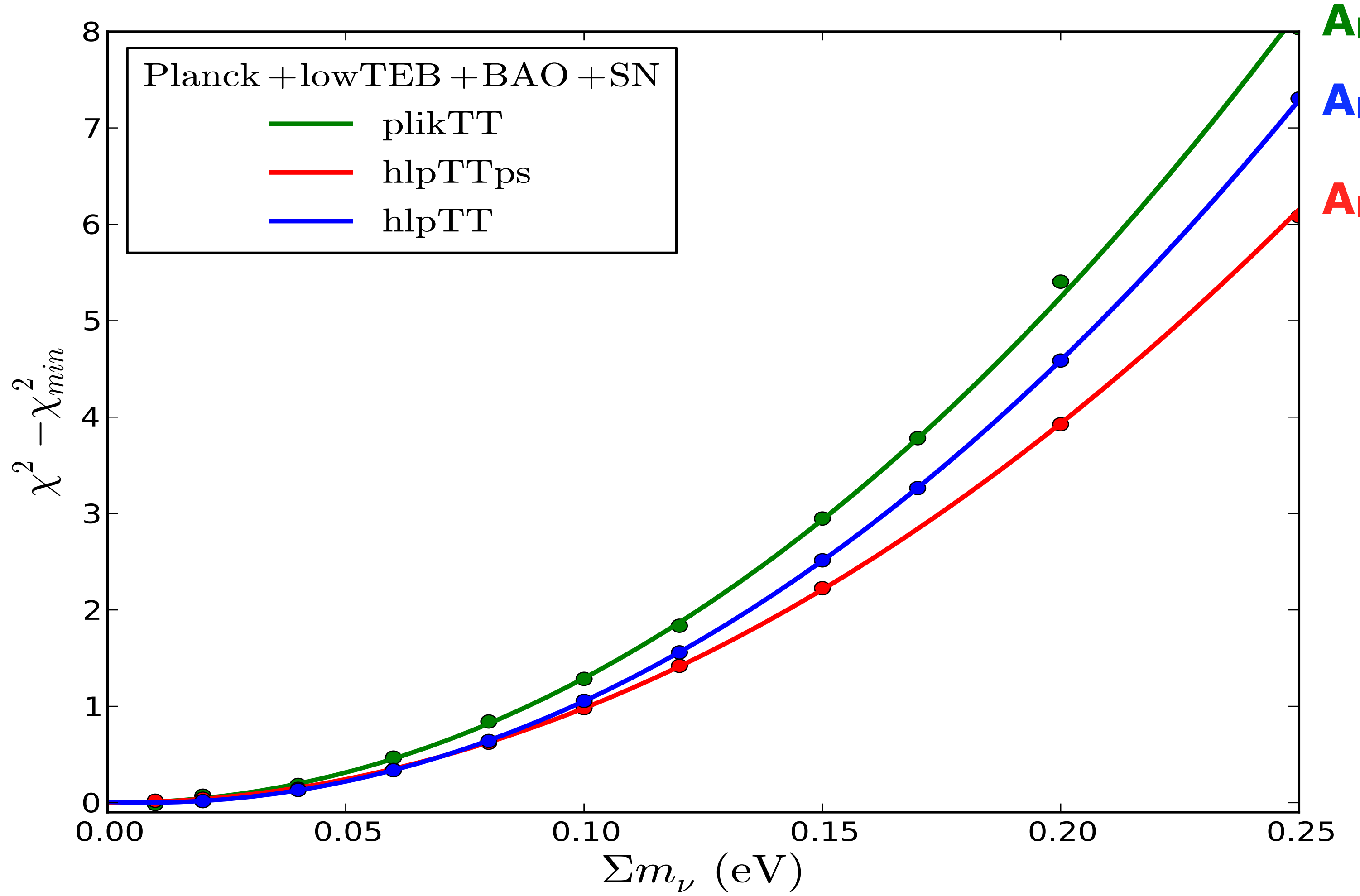
$$\sum m_\nu > 0.10$$

neutrino sector

Σm_ν and A_L

[Couchot et al. 2017b]

- **tension on A_L shows up on the neutrino sector**
  - high value for A_L → **artificially tighter constraints** on Σm_ν



A_L = 1.19 ± 0.09

A_L = 1.16 ± 0.09

A_L = 1.14 ± 0.08

	ΛCDM+	ΛCDM+
PlanckTT+lowTEB BAO+SNIa 2015	Σm_ν limit (eV)	A_L
`hlpTT`	0.18	1.16±0.09
`hlpTTps`	0.20	1.14±0.08
`PlikTT`	0.17	1.19±0.09

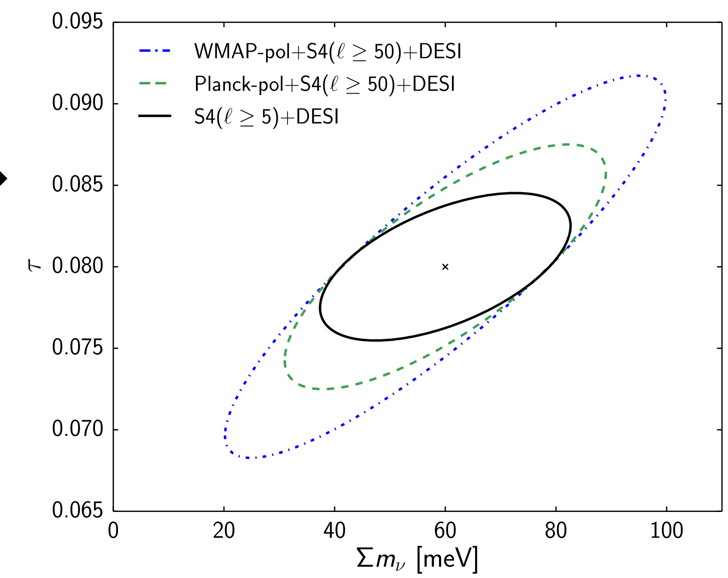
neutrino sector

Σm_ν and reionization

[Planck 2015 results. XIII]
[Planck intermediate results. XLVII (2016)]
[Planck 2018 results. VI]

$$\sum m_\nu < 0.49\ \mathrm{eV} \quad (95\,\%\,, \mathrm{TT}, \mathrm{TE}, \mathrm{EE} + \mathrm{lowP}) \quad 2015$$

$$\sum m_\nu < 0.26\ \mathrm{eV} \quad (95\,\%\,, \mathrm{TT}, \mathrm{TE}, \mathrm{EE} + \mathrm{lowE}) \quad 2018$$



$\tau = 0.050 \pm 0.006$ Planck lowE

$\tau = 0.050^{+0.008}_{-0.009}$ Planck lollipop
alternative analysis using a full likelihood

error bar **underestimated** because simulations do not include properly **systematic effects**

lower limit on sum of neutrino masses is **too optimistic**

CMB error bars

error budget

- cosmic variance
- statistical noise
- systematic effects

- **Cosmic Variance**
  driven by the cosmology. Easy to simulate and propagate using a fiducial model (valid given our current level of sensitivity on power spectra and the range allowed for parameters)

- **Statistical Noise**
  more complicated to estimate from the data. Current **Planck noise simulations need to be rescaled** **a posteriori** to match data jack-knives.

- **Systematic effects**
  should include foreground models uncertainty + instrumental parameter uncertainties. not only important for potential bias but also for their effect on **increasing the variance**. Very hard but no other way than realistic Monte Carlo. Currently only **300 sims** for Planck **neglecting correlations with foregrounds and CMB**.

CMB tensions

- **Hubble constant** **(H_0, up to 5σ)**
  - hard to change with CMB measurements except changing cosmo
    - number of relativistic species, non-standard thermal history or radiation (light relics)
    - early DE (e.g. [Poulin et al. 2019])
    - non-standard neutrino interactions (e.g. [Kreisch et al. 2019])
  - large variations on the local measurements depending on the first ladder

- **Amplitude of the fluctuations** **(S_8, σ_8 less than 2σ)**
  - reduced by 1σ with new optical depth constraints
  - large degeneracy with DE

- **Internal consistency** **(A_L, more than 2σ)**
  - more subtil, depends on the details of foreground models
  - relation with τ, Ω_k, Σm_ν...
  - no effect on LCDM but important for extensions

conclusions

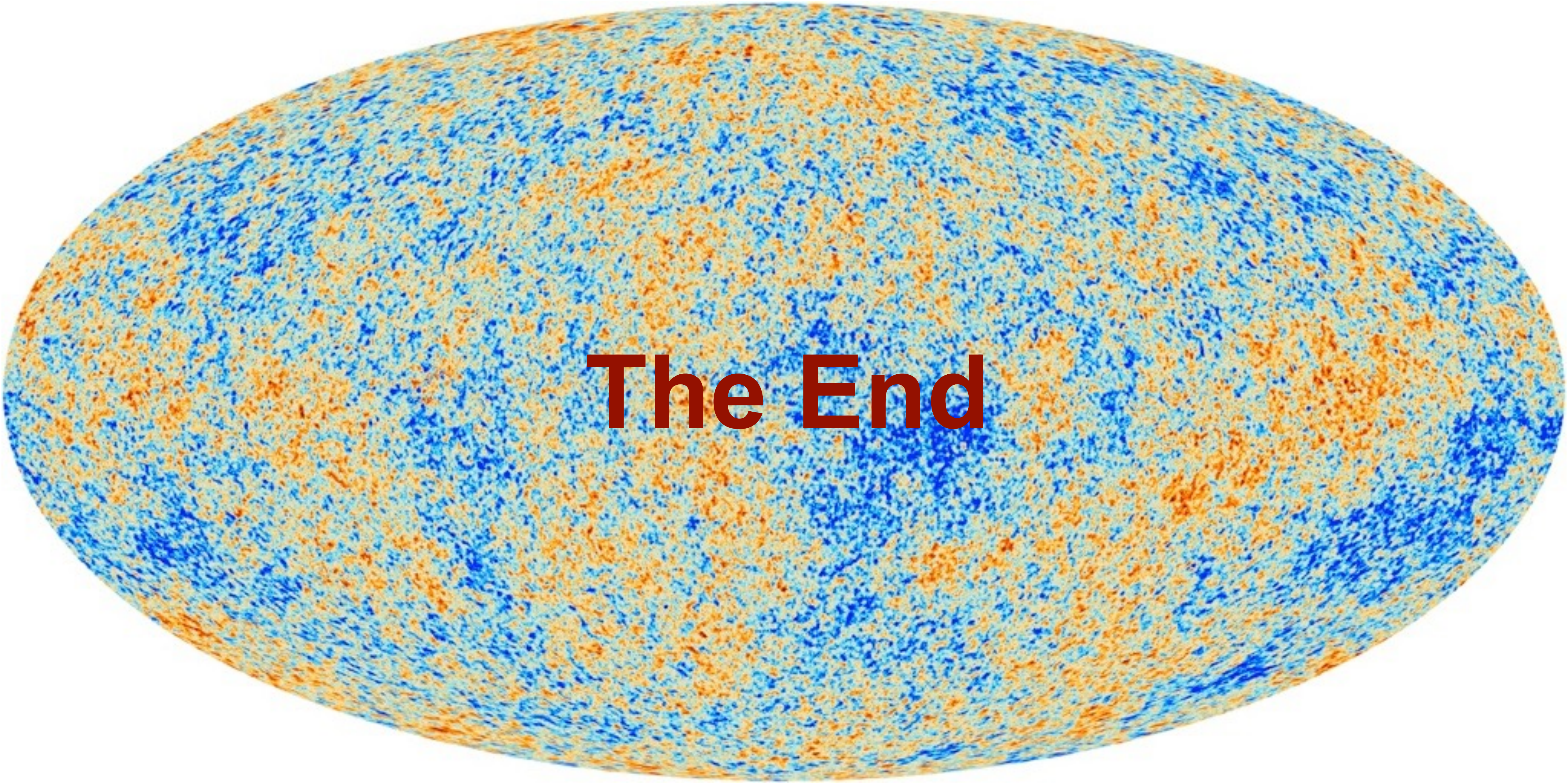
- **CMB results on ΛCDM are robust and stable**
  - in time
  - for various spectra (TT,TE,EE,ϕϕ)
  - when opening extensions one by one

- **Error bars**
  - given the precision on cosmological parameters, error bars need to be even more accurate
  - in particular at low-ℓ: uncertainties are underestimated

- **Consequences**
  - need to work on foreground modelling (how to build a realistic stochastic description of the foregrounds ?) → **ANR BxB (F. Boulanger)**
  - need to rely on heavy Monte Carlo simulations

→ **next Planck map release (NPIPE)**

coming soon !


The End