Planck legacy results and tensions

- 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
- **Planck 2018 results. V. Legacy Power Spectra and Likelihoods (Aug. 2019)**
- Planck 2018 results. VII. Isotropy and statistics
- Planck 2018 results. IX. Constraints on primordial non-Gaussianity

CMB likelihoods with likelihood paper.

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

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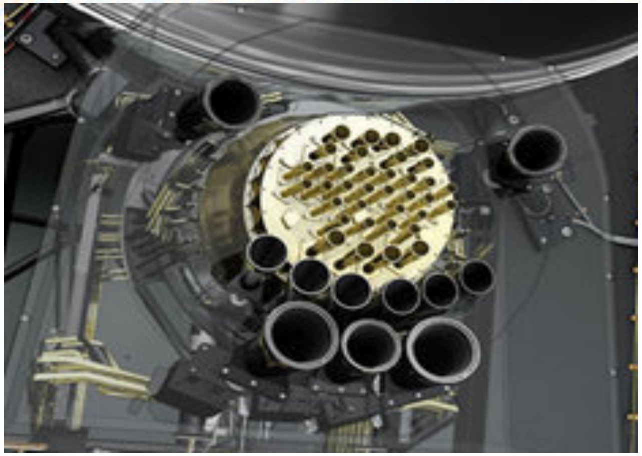
IAP

on behalf of the Planck Collaboration

MPA 16/12/2019

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, large scale pol. from LFI.
  Intermediate results 2016: low-l polarization from HFI
- **3nd release 2018: Full mission, improved polarization, low/high-l from HFI.** Better control of systematics specially in pol., still systematics limited.

Improvement of polarization systematics in 2018

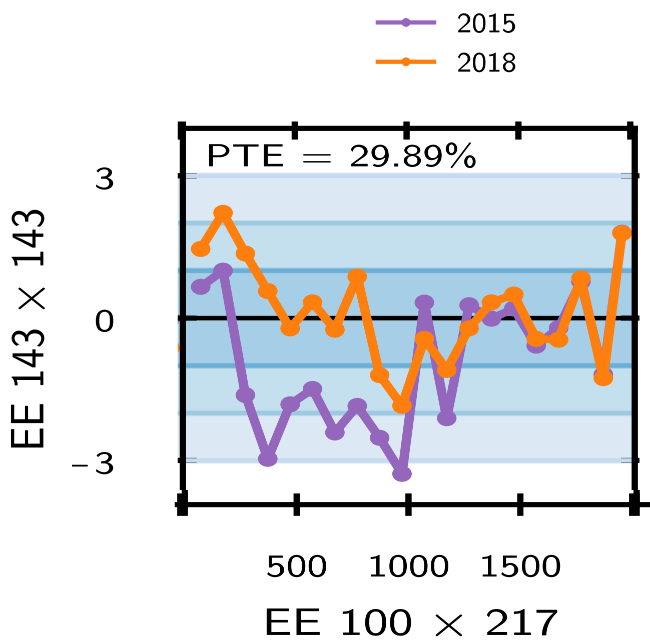
- **Correction of systematics** in polarization (large scales: map-making and sims. Small scales: beam leakage (improved TE by $\Delta\chi^2=37$) and polarization efficiency corrections (improved TE by $\Delta\chi^2=50$). Changes of $< 1\sigma$ on parameters.

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

- Cleaning for these systematics dramatically improved the interfrequency agreement and χ^2.

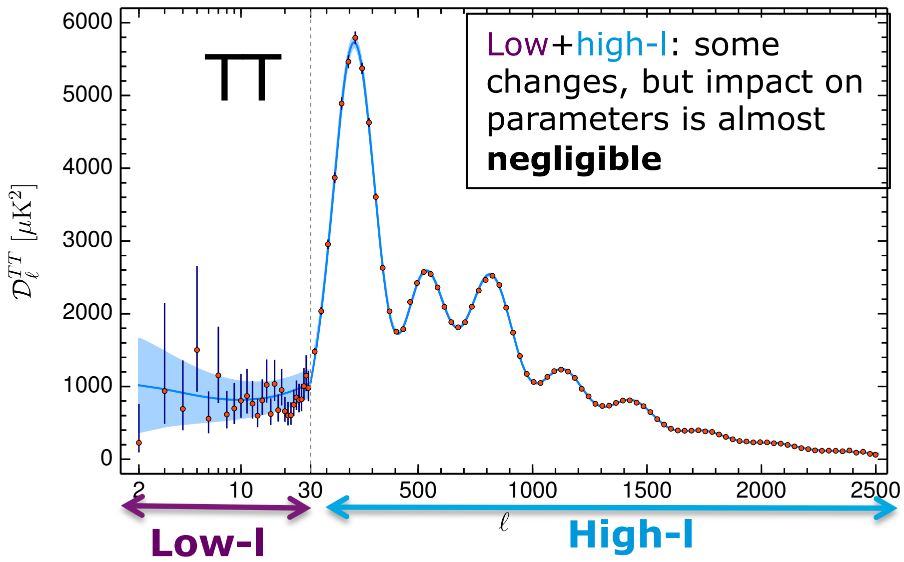


Planck **2018** results. V. Legacy Power Spectra and Likelihoods

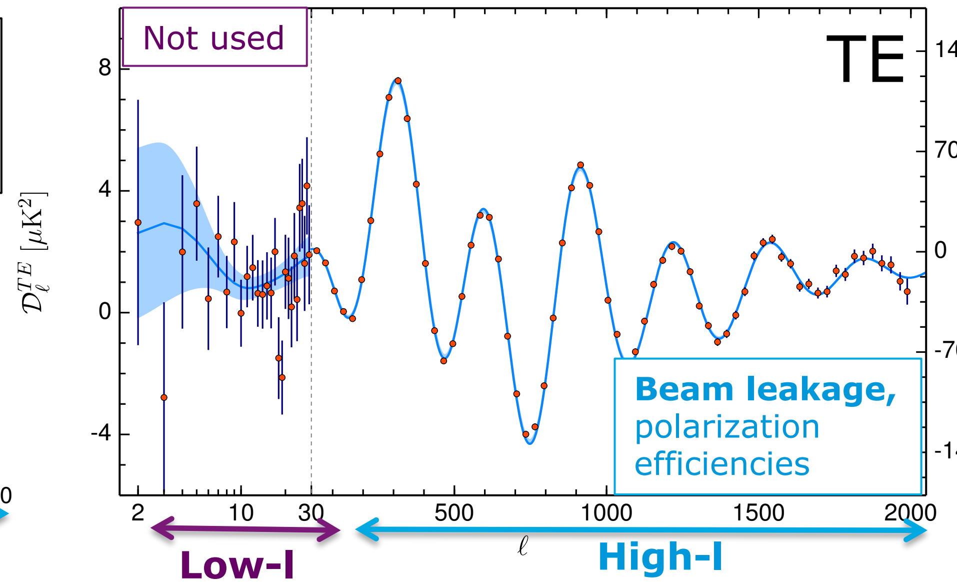
- **Limitations** small remaining uncertainties of systematics in polarization (~0.5s on cosmo. parameters) (quantified with alternative likelihood(CAMspec) at high-l which uses different choices than baseline (Plik)).

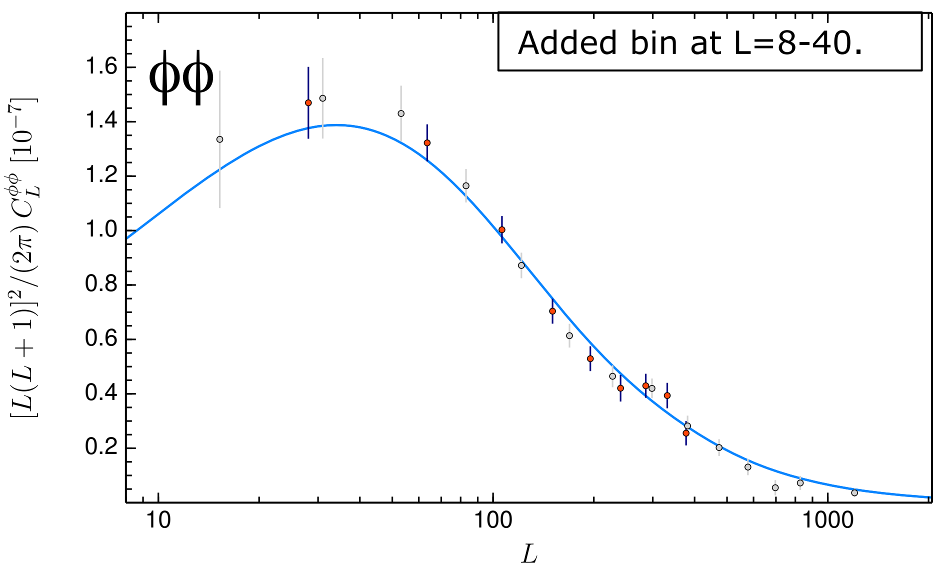
2018 Power spectra

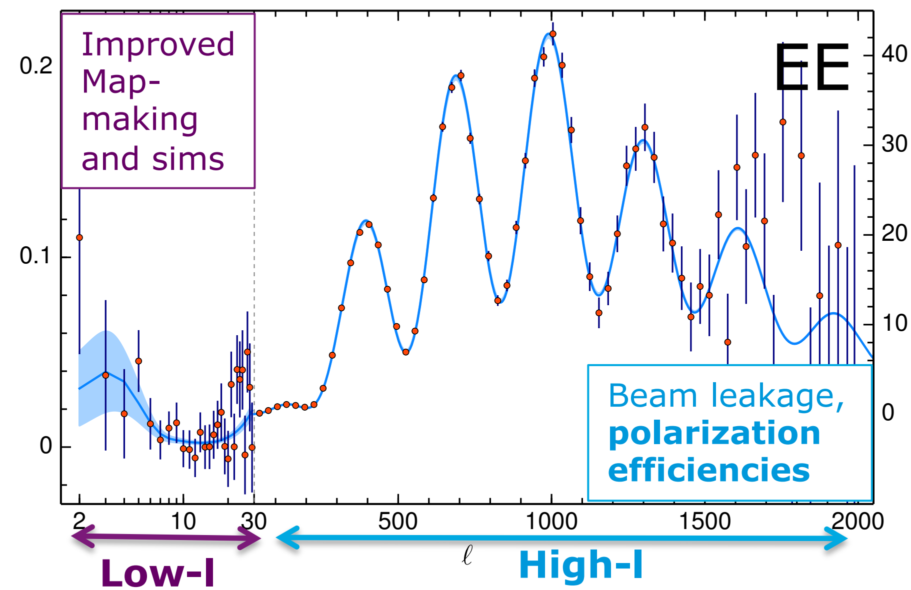
TT, TE, EE: different likelihoods at low-l (<30) and high-l (>30).



Better systematics modeling in polarization







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

Robust against changes of likelihood, $<0.5\sigma$.

- 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.
- n_s is 8σ away from scale invariance (even in extended models, always $>3\sigma$)
- Best (indirect) **0.8%** determination of the Hubble constant to date.

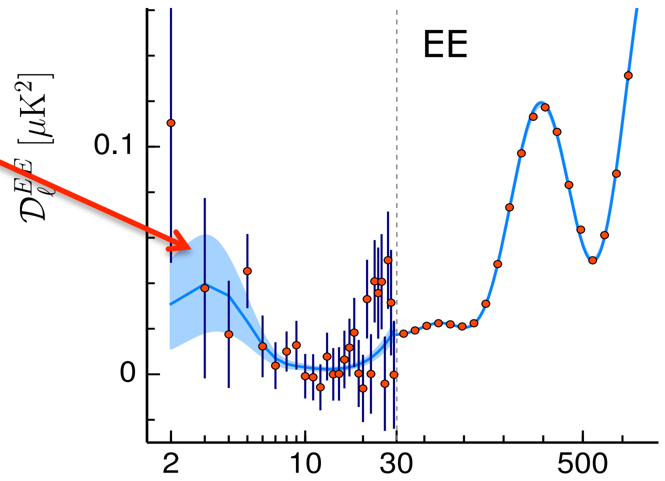
Optical depth to reionization

- τ is a measure of the line-of-sight Thompson scattering rate since reionization.

$$\tau_e(z_r) = \int_0^{z_r} n_e \sigma_T (1+z)^{-1} \, [c/H(z)] \, dz$$

- Causes CMB large scale polarization bump.

Planck 2018: τ = 0.0506 ± 0.0086 (68% lowE)
z_{re}=7.68 ± 0.79 (TTTEEE+lowE)



Planck 2015: τ = 0.067 ± 0.022 (LFI, TT, TE, EE)

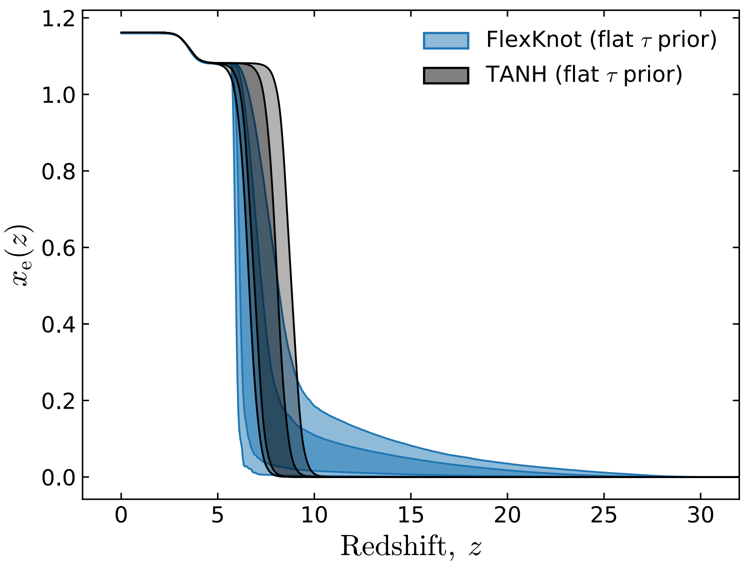
WMAP9: τ = 0.089 ± 0.014 z_{re}=10.6 ± 1.1
(0.067±0.013 if cleaned with Planck 353Ghz)

SROLL2 (Pagano+ 2019)
τ= 0.0566+0.0053

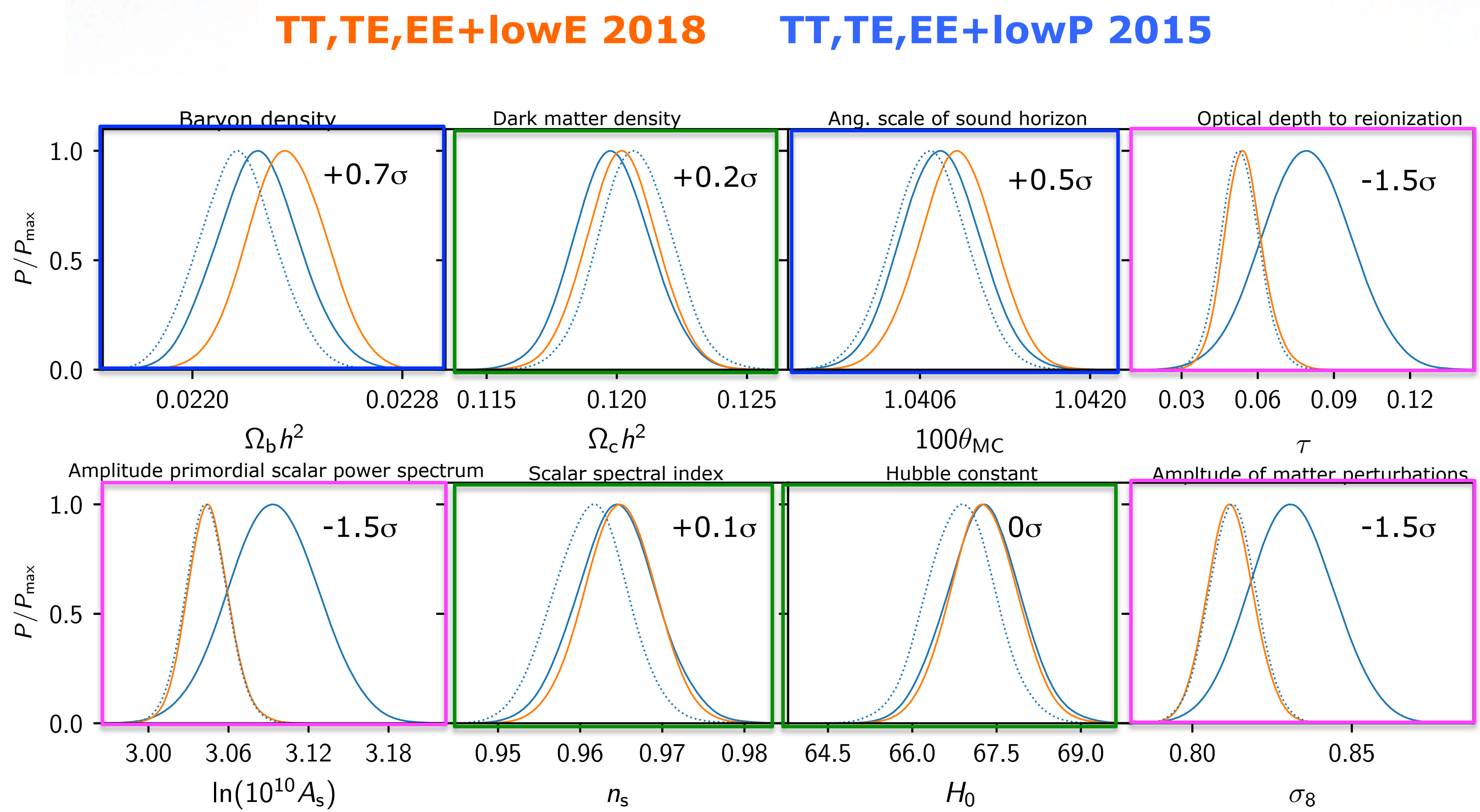
- τ measurement robust against model-indep. reconstruction of reionization history.
No evidence of deviation from baseline.

- No evidence for reionization a z>15:

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

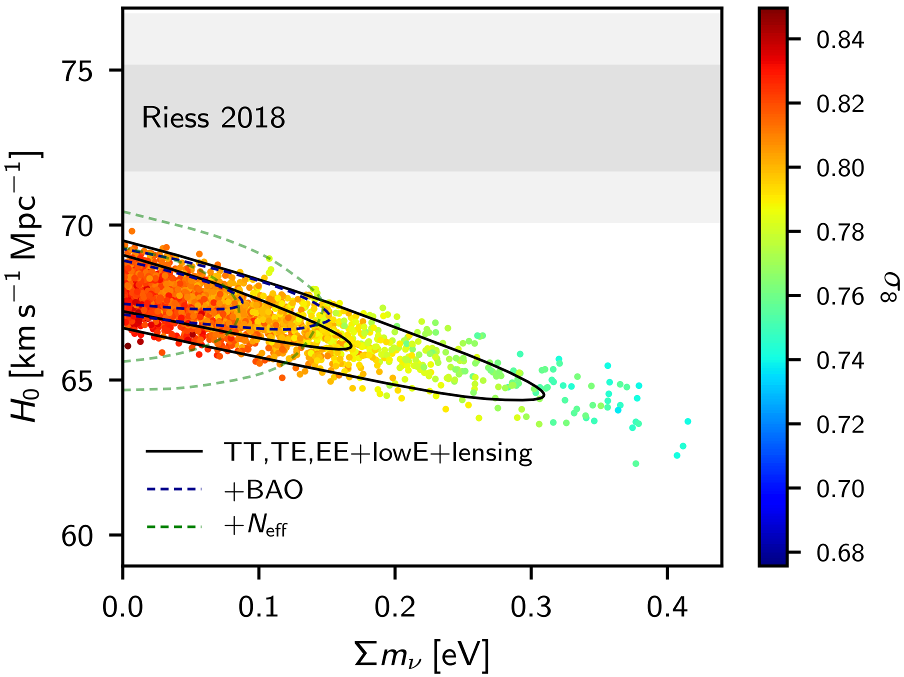


Stability of the results across releases: ΛCDM results 2018 (DR3) vs 2015 (DR2)



- 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.

Neutrino masses



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

- 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.

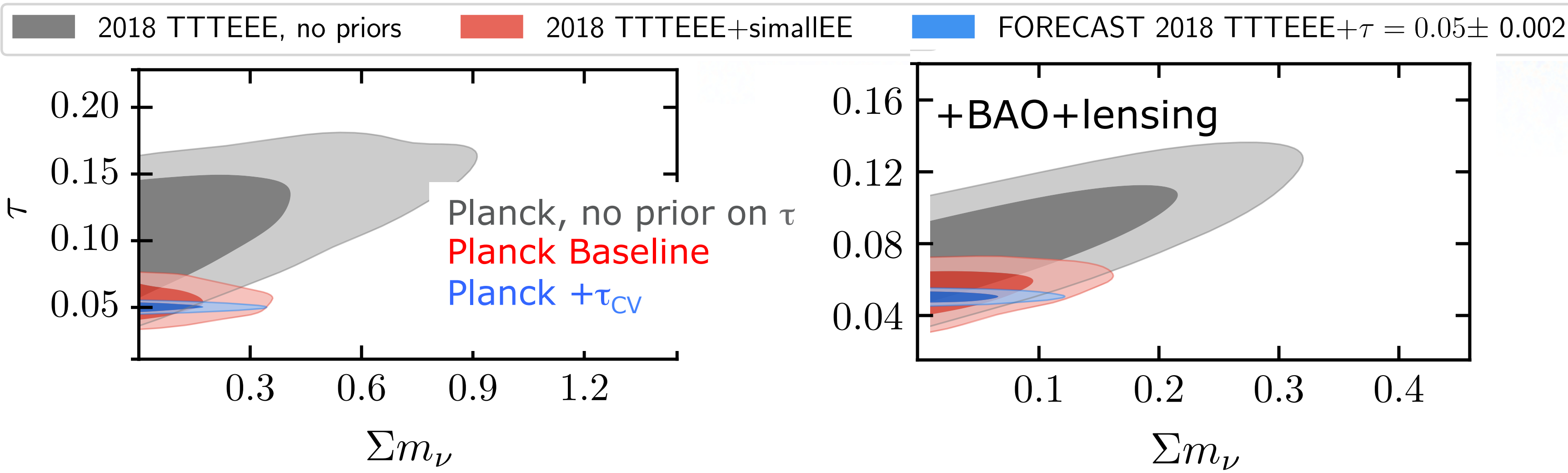
- Constraint from 2015 improved by about 30% (TT)-50%(TTTEEE) **due to lower and tighter τ and change in polarization systematics.**

TTTEEE 2019+	
τ=0.05±0.009	<0.29 eV
τ=0.05±0.020	<0.34 eV
τ=0.07±0.020	<0.39 eV

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

$$\sum m_\nu < 0.12 \text{ eV} \quad (95\,\%, \textit{Planck} \text{ TT,TE,EE+lowE} \text{ +lensing+BAO}).$$ [<0.215 (2015 TTTEEE+lowP +BAO+lensing)]

Planck+Cosmic Variance limited τ



Further decreasing the error on τ would not improve further Σmν for Planck power spectra alone, since limiting factor is degeneracy with H_0.

When adding BAO to Planck, H_0 degeneracy lifted, constraint on Σmν could slightly improve to 0.1eV (95% cl).
Need better CMB and LSS

τ uncertainty will be a limiting uncertainty for CMB+LSS.

Allison+ 2015, Archidiacono+ 2016, Boyle+ 2018

Take away message stable across releases

ΛCDM is a good fit to the data

Likelihood	Multipoles	$\log(\mathcal{L})$	$\chi^2_{\rm eff}$	$N_{\rm dof}$	PTE
TT, full, binned	30–2508	−380.34	760.68	765	0.54
TE, full, binned	30–1996	−428.68	857.36	762	0.0090
EE, full, binned	30–1996	−371.48	742.96	762	0.68
TTTEEE, full, binned	30–2508	−1172.47	2344.94	2289	0.20
TT, coadded, unbinned	30–2508	−1274.57	2549.14	2479	0.16
TE, coadded, unbinned	30–1996	−1035.77	2071.54	1967	0.050
EE, coadded, unbinned	30–1996	−1028.55	2057.10	1967	0.077
TTTEEE, coadded, unbinned . .	30–2508	−3328.51	6657.02	6413	0.016
Low-ℓ TT (Commander)	2–29	−11.63	23.25	27	. . .
Low-ℓ EE (SimAll)	2–29	−198.02	. . .	27	. . .

No evidence of preference for classical extensions of ΛCDM, but a few **curiosities ($A_{\rm Lens}$, curvature, MG, low-l vs high-l parameters?!)**….

Parameter	TT+lowE	TT, TE, EE+lowE	TT, TE, EE+lowE+lensing	TT, TE, EE+lowE+lensing+BAO
Ω_K	$-0.056^{+0.044}_{-0.050}$	$-0.044^{+0.033}_{-0.034}$	$-0.011^{+0.013}_{-0.012}$	$0.0007^{+0.0037}_{-0.0037}$
Σm_ν [eV]	< 0.537	< 0.257	< 0.241	< 0.120
$N_{\rm eff}$	$3.00^{+0.57}_{-0.53}$	$2.92^{+0.36}_{-0.37}$	$2.89^{+0.36}_{-0.38}$	$2.99^{+0.34}_{-0.33}$
$Y_{\rm P}$	$0.246^{+0.039}_{-0.041}$	$0.240^{+0.024}_{-0.025}$	$0.239^{+0.024}_{-0.025}$	$0.242^{+0.023}_{-0.024}$
$dn_s/d\ln k$	$-0.004^{+0.015}_{-0.015}$	$-0.006^{+0.013}_{-0.013}$	$-0.005^{+0.013}_{-0.013}$	$-0.004^{+0.013}_{-0.013}$
$r_{0.002}$	< 0.102	< 0.107	< 0.101	< 0.106
w_0	$-1.56^{+0.60}_{-0.48}$	$-1.58^{+0.52}_{-0.41}$	$-1.57^{+0.50}_{-0.40}$	$-1.04^{+0.10}_{-0.10}$

Terminology

$\sim 0\sigma$	Too good to be true
$\sim 1\sigma$	Consistency
$>2\sigma$	**Curiosity**
$>3\sigma$	Tension/Discrepancy
$>4\sigma$	Problem
$>5\sigma$	Crisis?

From KITP conference in Santa Barbara July 2019

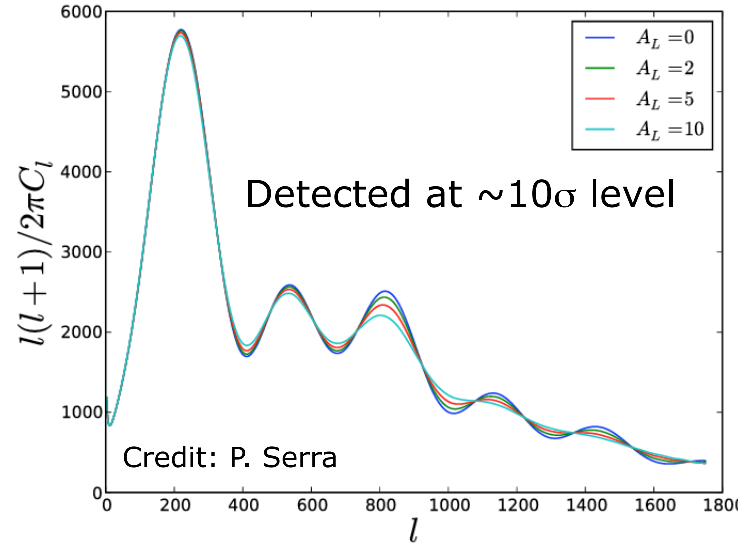
CMB lensing and A_{Lens}

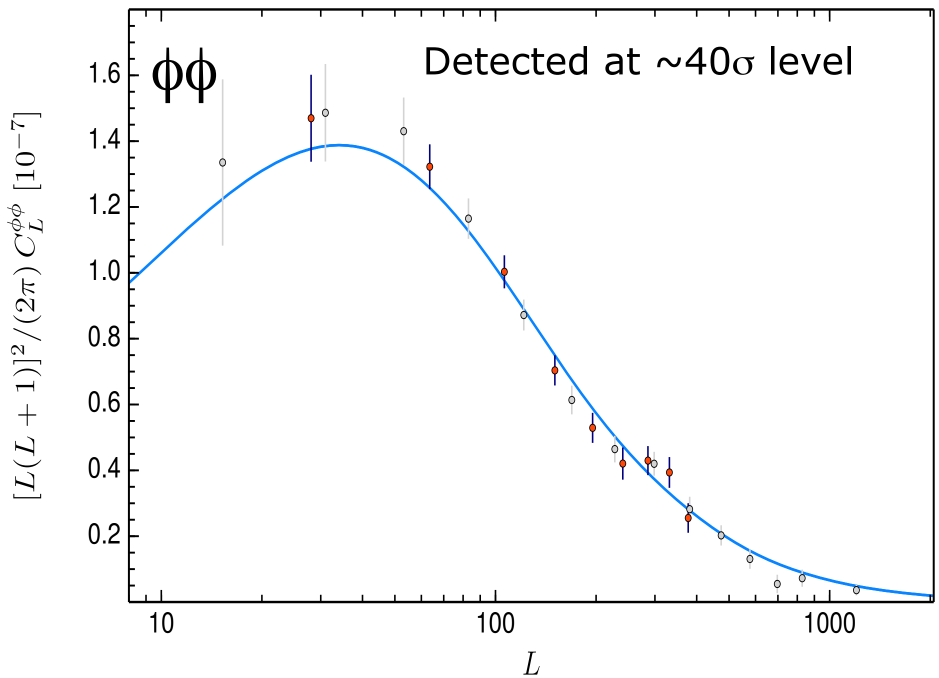
- Lensed CMB power spectrum is a convolution of unlensed CMB with lensing potential power spectrum=>**smoothing of the peaks and throughs**.

- A_L is a consistency parameter, which rescales the amplitude of the lensing potential which smooths the power spectrum.

$$C_\ell^\Psi \to A_L C_\ell^\Psi$$ Calabrese+ 2008

- Lensing is better measured taking the 4-point correlation function of the CMB maps, since lensing breaks isotropy of the CMB, giving a non-gaussian signal.





See e.g. Lewis & Challinor 2006

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).

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

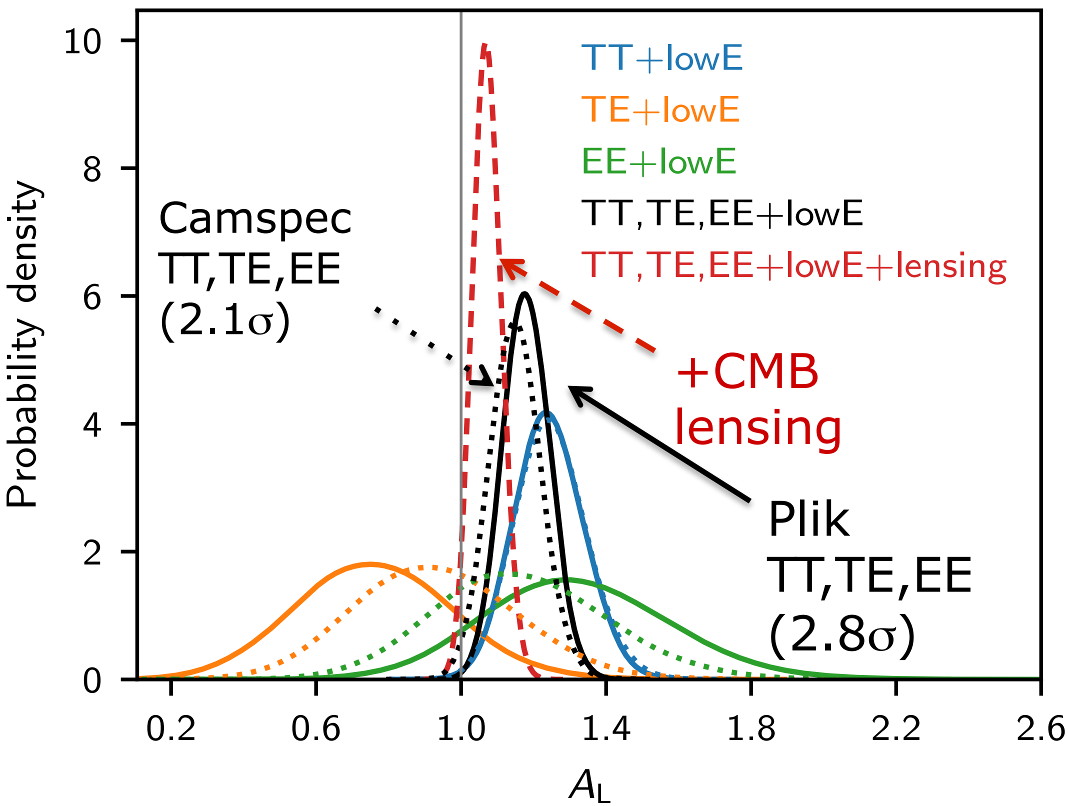
- Not really lensing, not preferred by CMB lensing reconstruction.

- 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.

$$A_L = 1.180 \pm 0.065 \quad (68\,\%,\ Planck\ \mathrm{TT,TE,EE{+}lowE})$$
$$A_L = 1.149 \pm 0.072\ (68\,\%,\ \mathrm{TT,TE,EE{+}lowE\ [CamSpec]})$$

Amplitude of the lensing potential power spectrum.



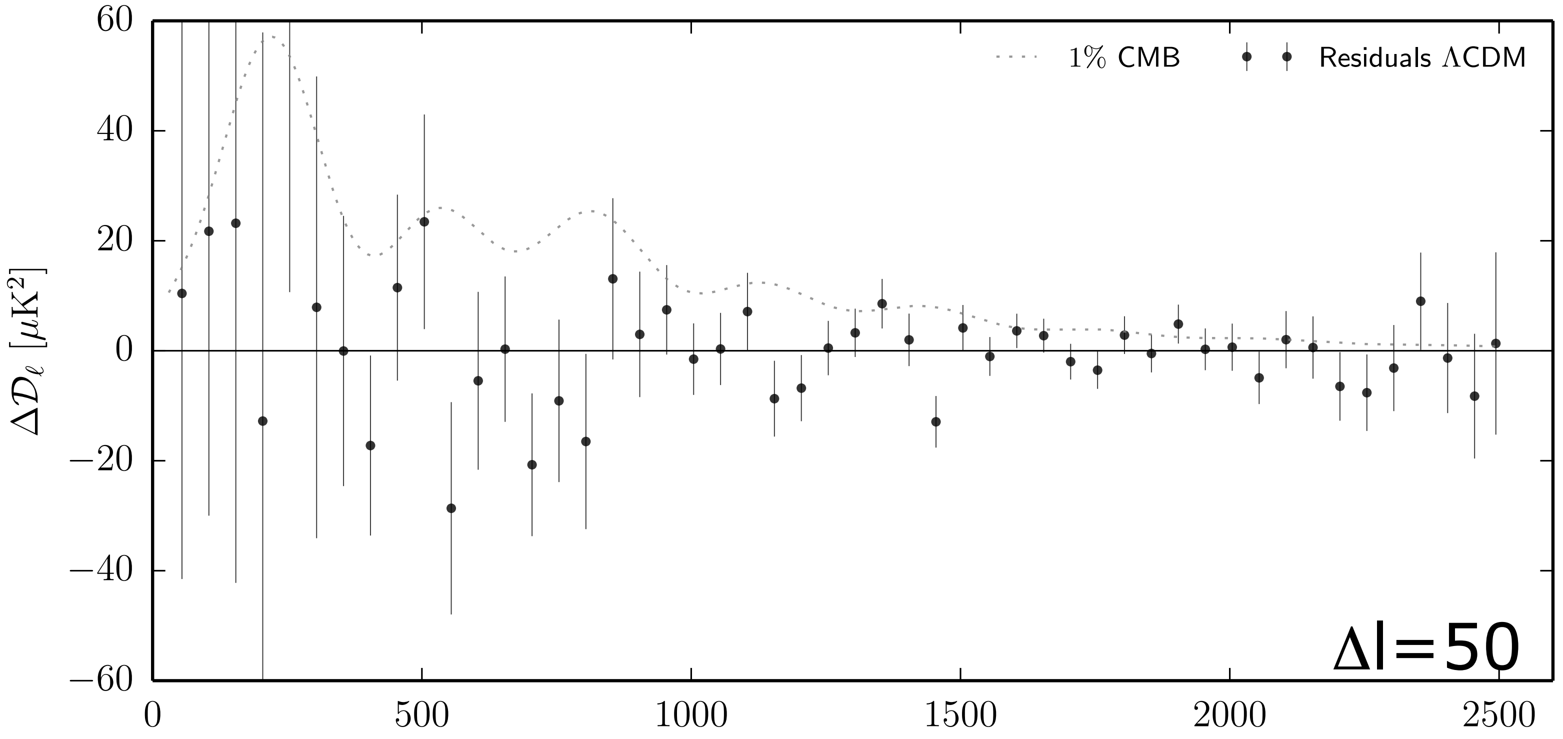
Planck **2018** results. VI. Cosmological parameters

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

Residuals TT

Well behaved residuals, very good χ^2 (unbinned coadded* at l=30-2508 PTE=16% dof=2478).

TT+lowlTT+lowE
(lowlTTnot shown in this plot)

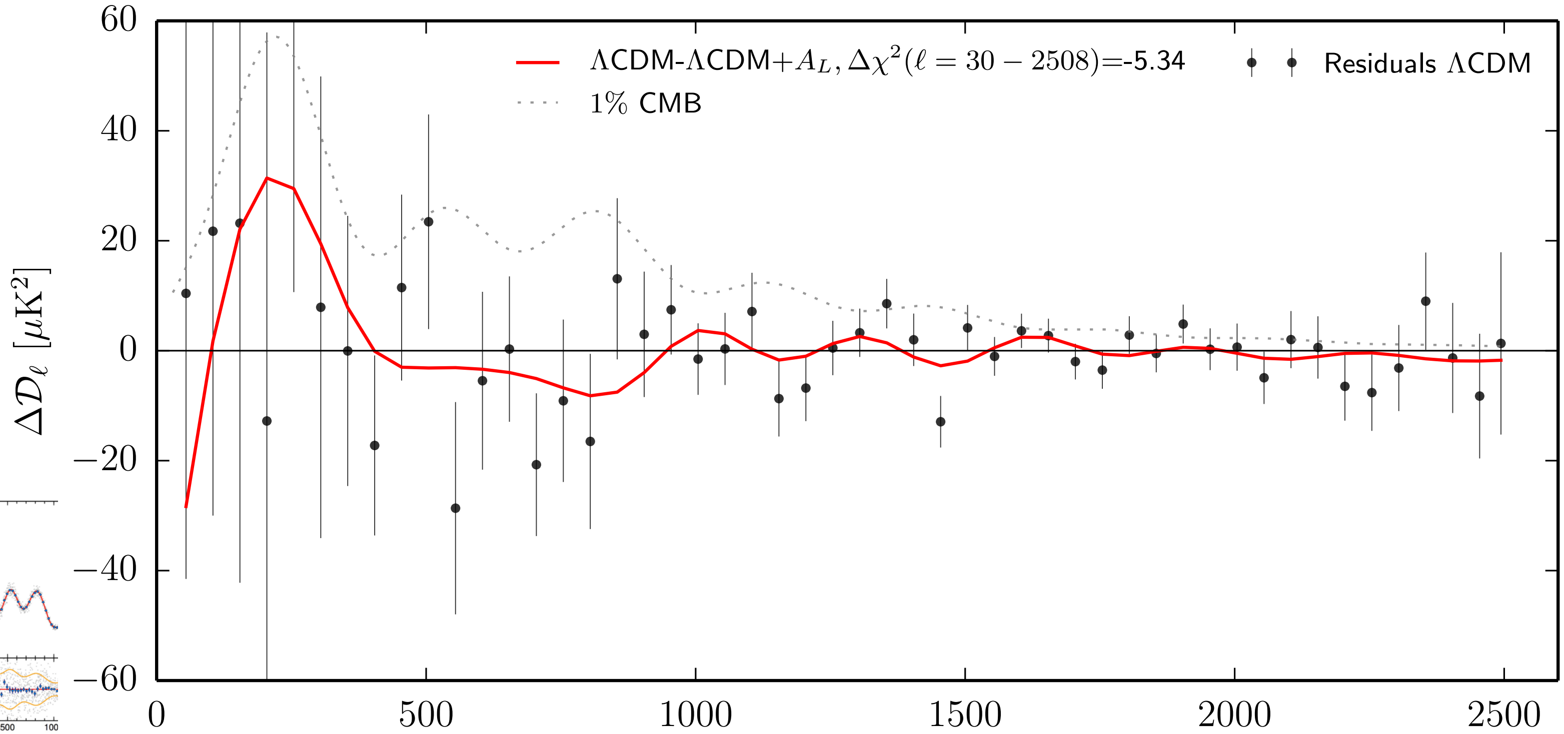


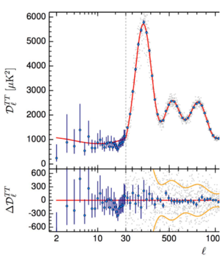
Residuals of the coadded CMB spectrum, assuming the ΛCDM best fit cosmology and foreground model
(coadded~weighted average of foreground cleaned 100x100, 143x143, 143x217 and 217x217 spectra)

*[χ^2 slightly different because for full-frequency binned

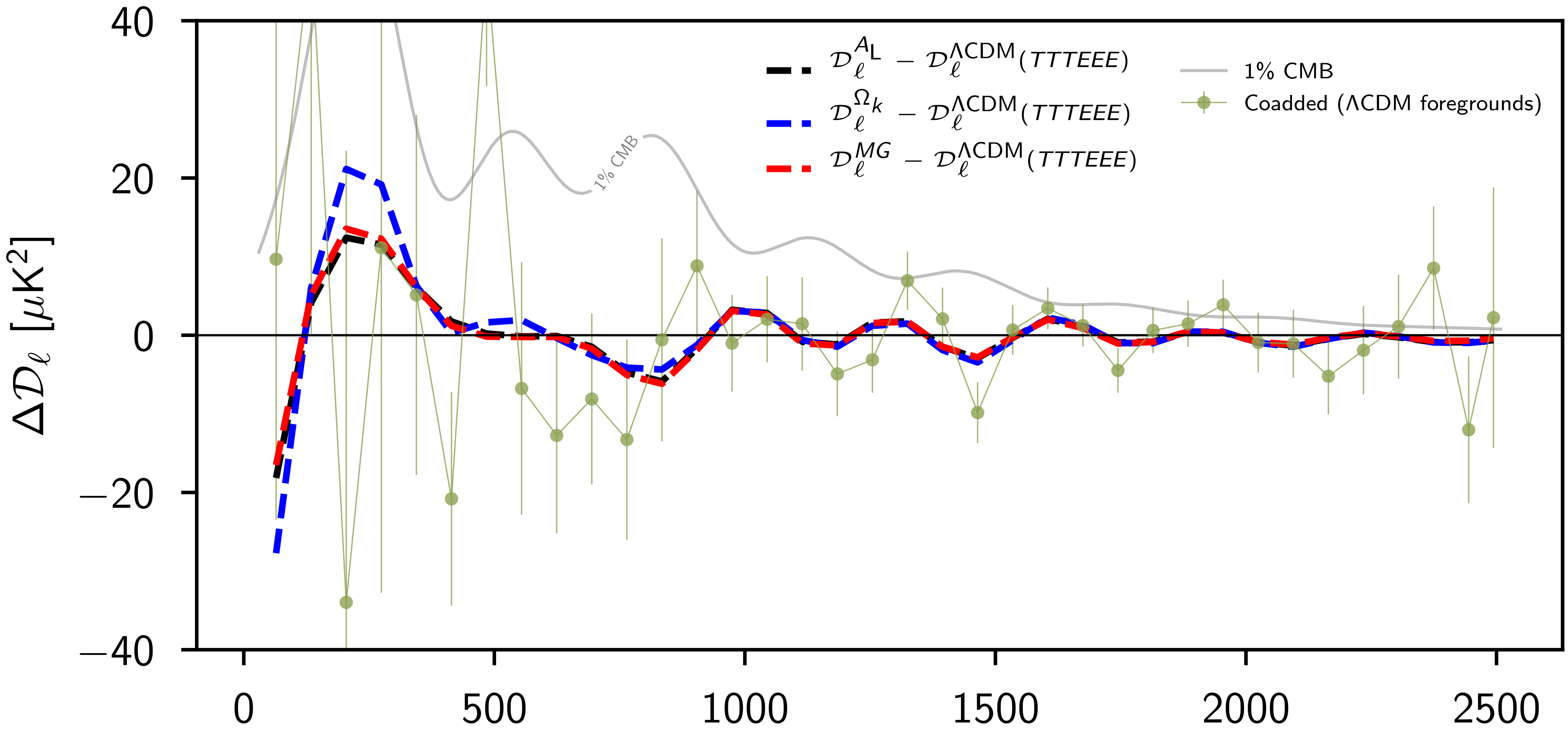
Residuals TT

A_L is a phenomenological parameter which allows to better fit both the high and low-ell by $\Delta\chi^2$=5.3 (A_L=1.24 ±0.1) (plus $\Delta\chi^2$=2.3 from lowl TT)





- **Alens can be used as a tracer of the l<800 vs>800 difference.**
- **The features which lead the the high Alens could just be due to statistical fluctuations!** In other words, Alens might just be fitting noise/cosmic variance.

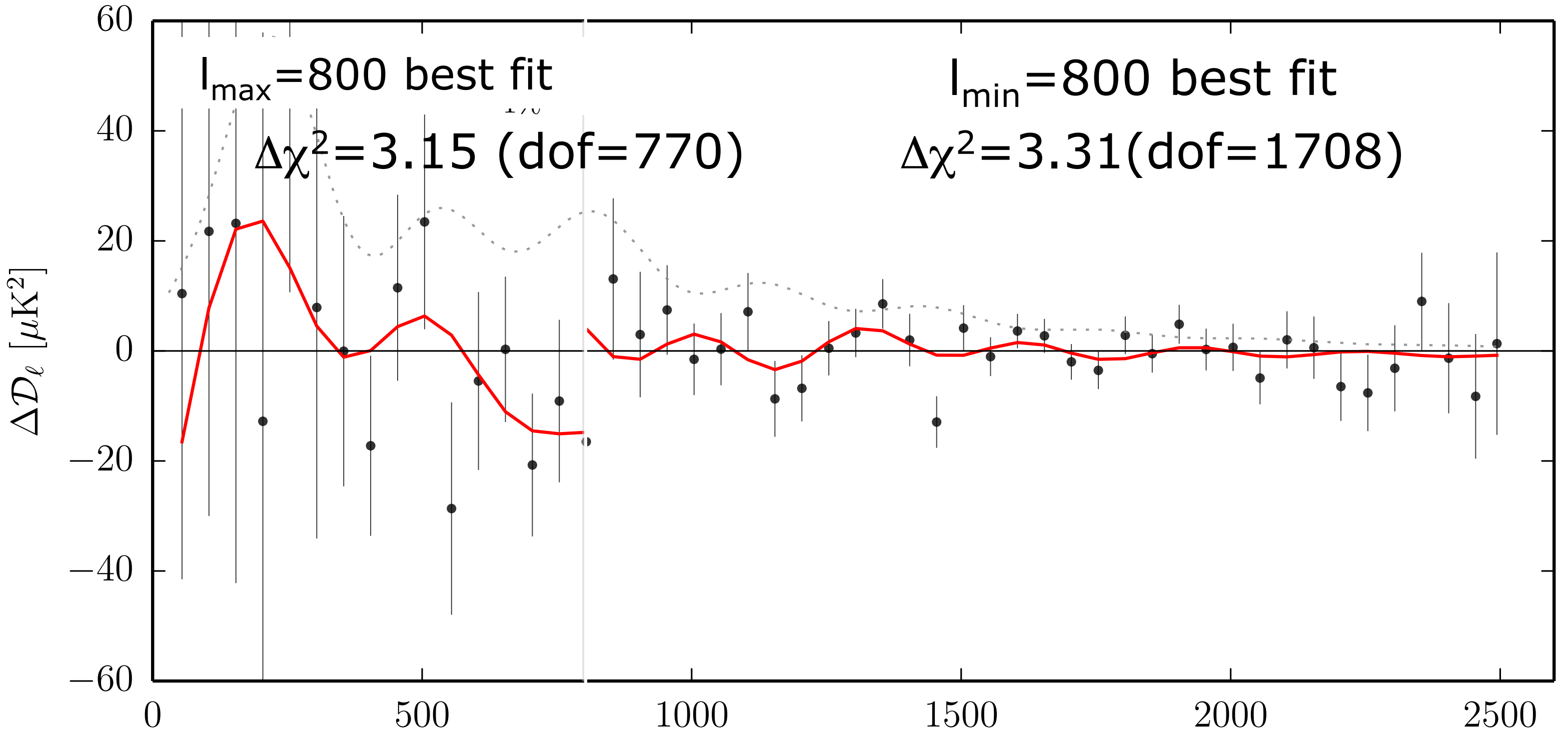


The difference between low and high-l, the deviation in **A_L, Ω_k, w, and MG** with Planck power spectra alone **all fit similar features in the power spectra**.
However, fitting these features with these parameters is in disagreement with other datasets.

Residuals TT

TT(lmax=800)+lowlTT*+lowE
(*not shown in this plot)

TT(lmin=800)+lowE
(*not shown in this plot)



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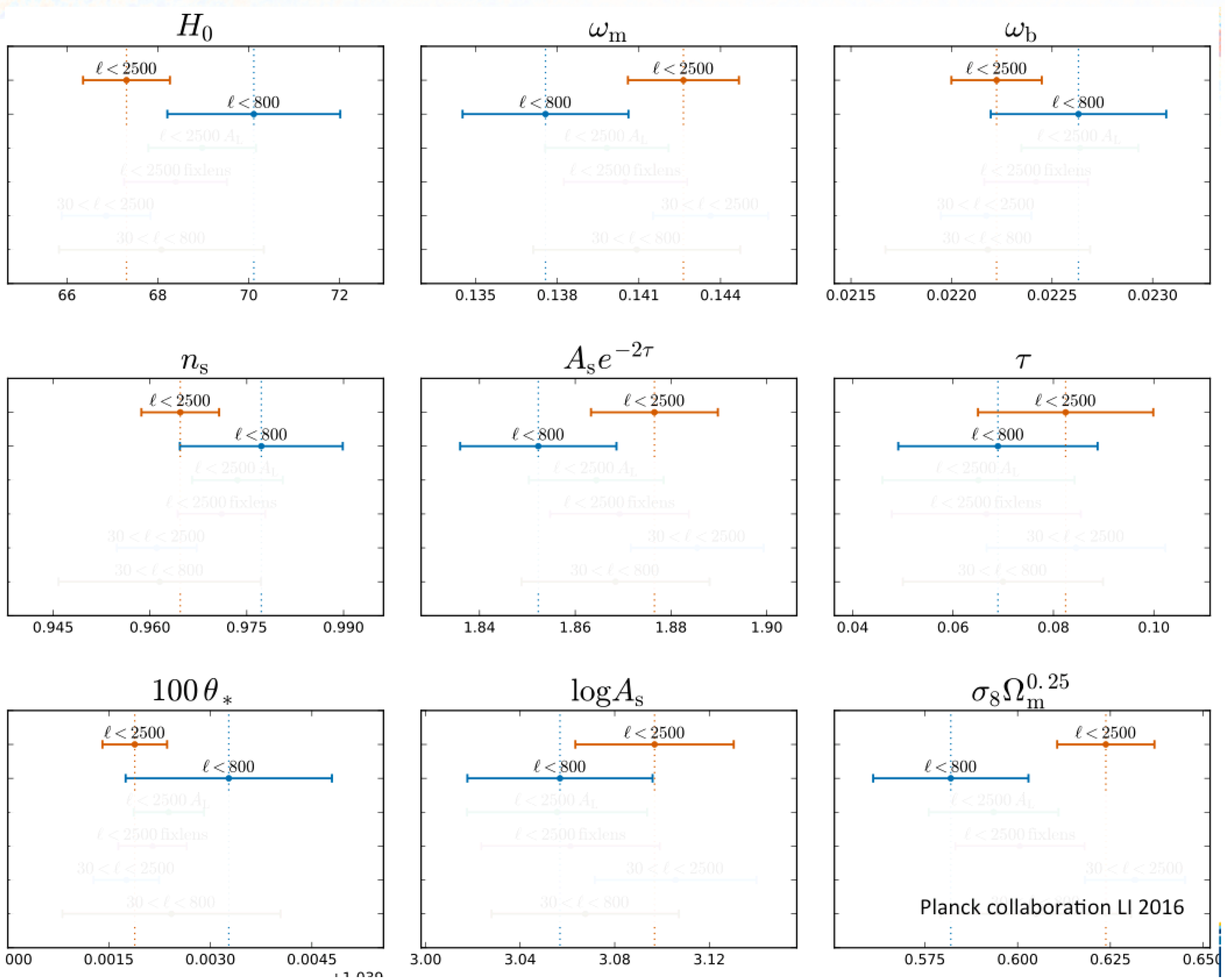
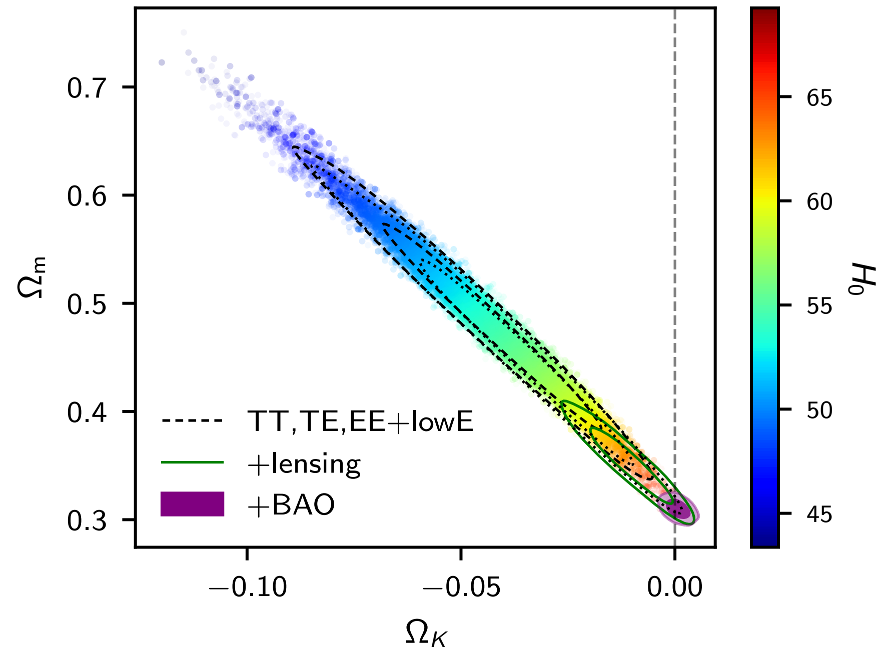
High-l versus low-l curiosity



- Parameters evaluated from l<800 and l<2500, or l<800 vs l>800 are different at the 2-3 σ level (Planck **2015** results. XI. CMB power spectra, likelihoods, and robustness of parameters)
- Overall, shifts are significant at <~2σ level from simulations (Planck collaboration LI 2017, see also Addison+ 2016).
- The low-highl and the Alens deviations are connected.
- We see differences in polarization as well, but error-bars are too large at high-l to be determinant.

Curvature and Dark Energy

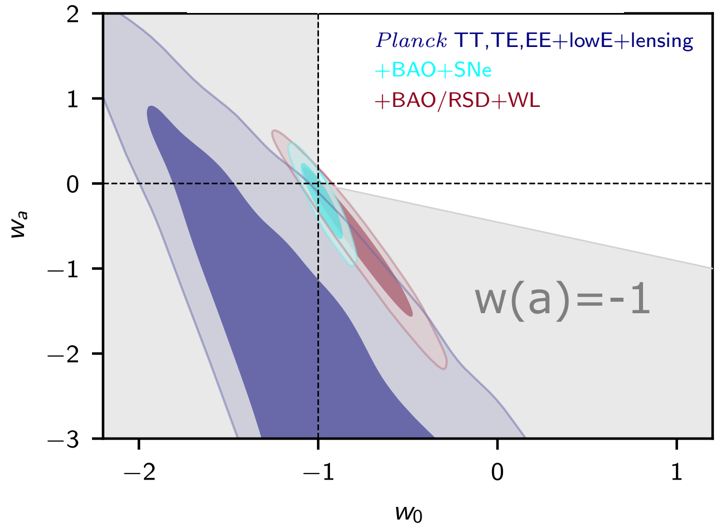
- Both curvature Ω_k<1 and phantom dark energy w<-1 can provide larger lensing amplitude, thus preferred by TTTEEE
- Results from CAMspec differ at **~<0.5σ level.**
- When adding CMB lensing reconstruction, less preference for deviations, further tightened by BAO.



Curvature

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

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

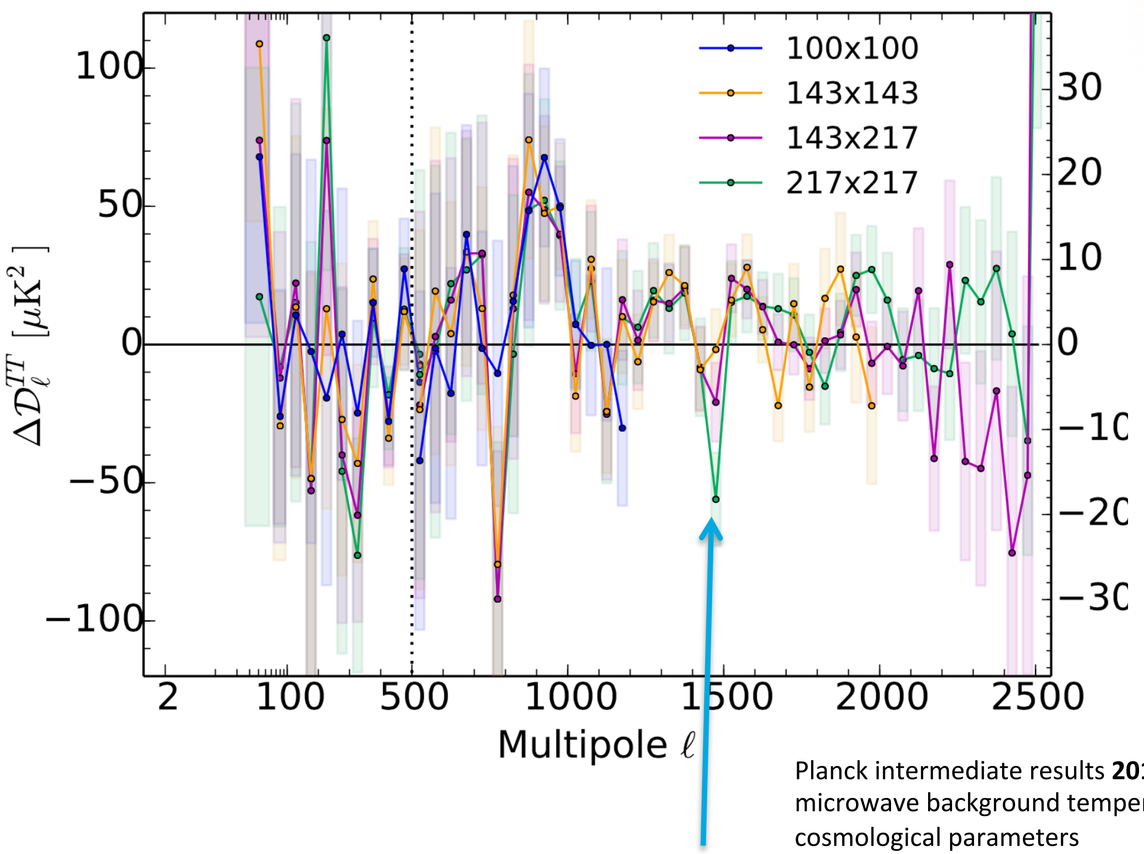


Dark energy equation of state

$$w_a = 0,$$

$$w_0 = -1.028 \pm 0.032$$ (68 %, *Planck* TT,TE,EE+lowE +lensing+SNe+BAO),

Is Alens due to a problem with galactic dust?



Planck intermediate results **2017**. LI. Features in the cosmic microwave background temperature power spectrum and shifts in cosmological parameters

- The residuals at **high-l look very similar at 143 and 217** (100 have too poor resolutions).
- Only the deep at **l~1450** is larger in 217Ghz than 143Ghz, and could be due just in part to (chance correlations with) galactic dust.

Can A_L solve the H_0 and σ_8 tensions?

Riess+ 2019 H_0 = 74.03 ± 1.42 km s^{-1} Mpc^{-1}

Joudaki+ 2019 $\mathbf{S_8}$ = 0.762+0.025

Planck TT+lowlEE 2018	H_0	S_8	A_L
ΛCDM	66.88 ± 0.92 **[4.2σ]**	0.840 ± 0.024 **[2.3σ]**	1.
ΛCDM+Alens	68.9 ± 1.2 **[2.7σ]**	0.788 ± 0.029 **[0.6σ]**	1.24±0.096
Planck TTTEEE +lowlEE 2018			
ΛCDM	67.27 ± 0.60 **[4.2σ]**	0.834 ± 0.016 **[2.4σ]**	1
ΛCDM+Alens	68.28 ± 0.72 **[3.6σ]**	0.804 ± 0.019 **[1.3σ]**	1.180 ± 0.065

For H_0, not that much. Tension remains at the 3.6σ level.

For S_8, it could help, but it does not help in disantangling whether this is a statistical fluctuation in Planck and WL exp., a systematic or new physics.

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.