The view from Planck

- Planck **2015** results. XI. CMB power spectra, likelihoods, and robustness of parameters
- Planck **2015** results. XIII. Cosmological parameters
- Planck intermediate results **2017**. LI. Features in the cosmic microwave background temperature power spectrum and shifts in cosmological parameters
- Planck **2018** results. VI. Cosmological parameters
- Not out yet **(few days/weeks away….)**:
- Planck **2018** results. V. Legacy Power Spectra and Likelihoods

  Only lensing likelihoods release. CMB likelihoods with likelihood paper.

Silvia Galli

IAP

on behalf of the Planck Collaboration

Santa Barbara 15/07/2019

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

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?

Terminology with contributions from Chen, Nabila, Hendrik and Kimmy

Outline

1. Short recap on Planck results and tensions

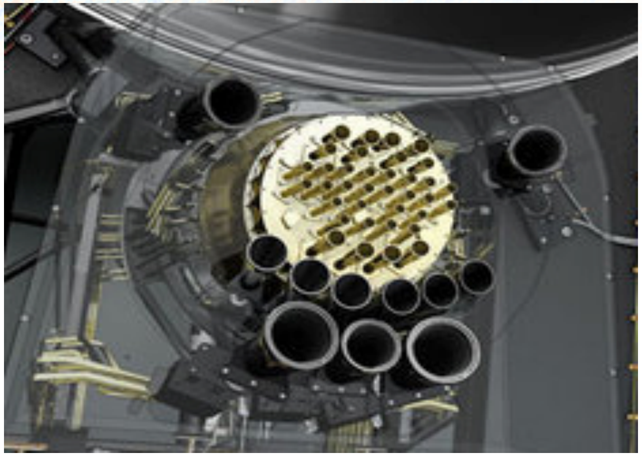
2. Curiosities (Alens and low vs high l difference) in the Planck data and their relation.

3. Can curiosities explain the tensions?

4. If curiosities are systematics, what could they be (in temperature)?

5. Polarization

The Planck satellite



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

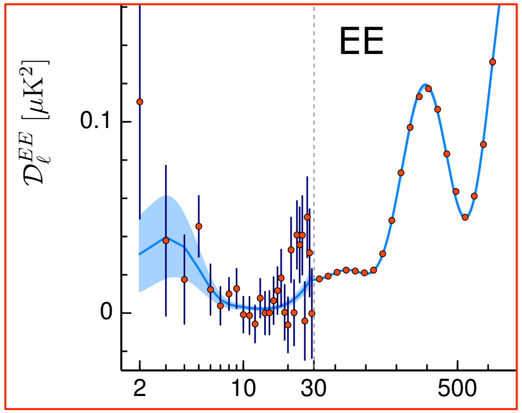
LFI:

- 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.



Planck **2018** results. VI

$$\tau = 0.0506 \pm 0.0086 \quad (68\,\%, \text{lowE})$$

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

$$\tau = 0.089 \pm 0.014$$ (WMAP9)

Improvement of polarization systematics in 2018

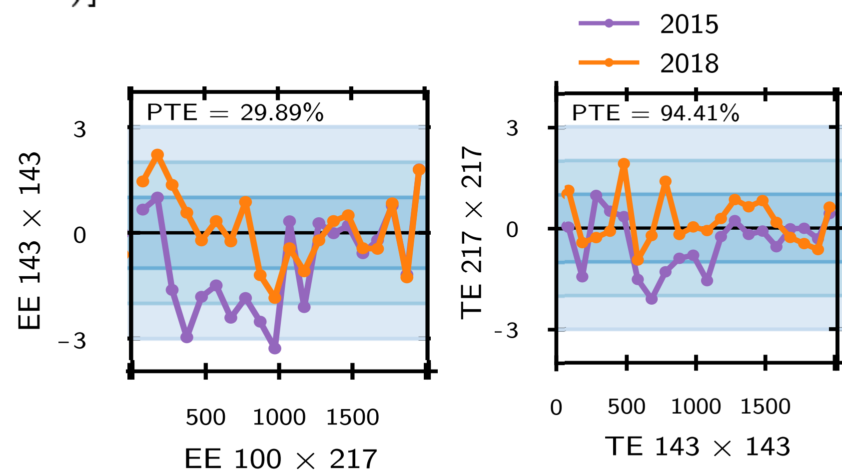
- **Correction of systematics** in polarization (large scales: map-making and sims. Small scales: beam leakage (improved TE by $\Delta\chi^2=37$) and polarization efficiency corrections (improved TE by $\Delta\chi^2=50$). Changes of $< 1\sigma$ on parameters.

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.



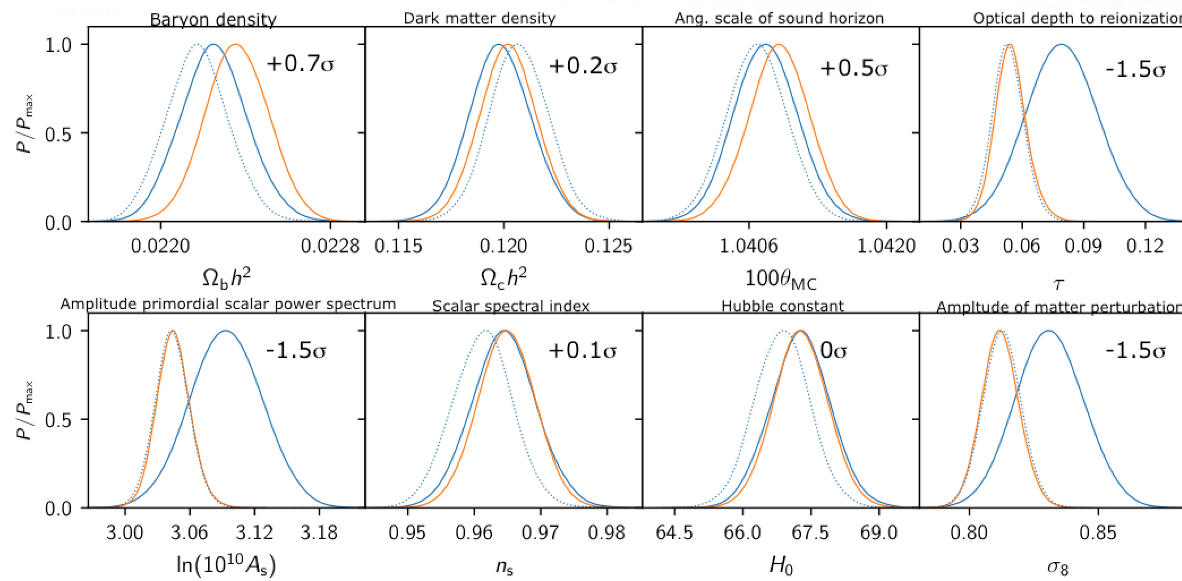
Planck **2018** results. V. Legacy Power Spectra and Likelihoods

- **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)).

Take away message stable across releases

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

Differences well understood, mainly due to change in τ

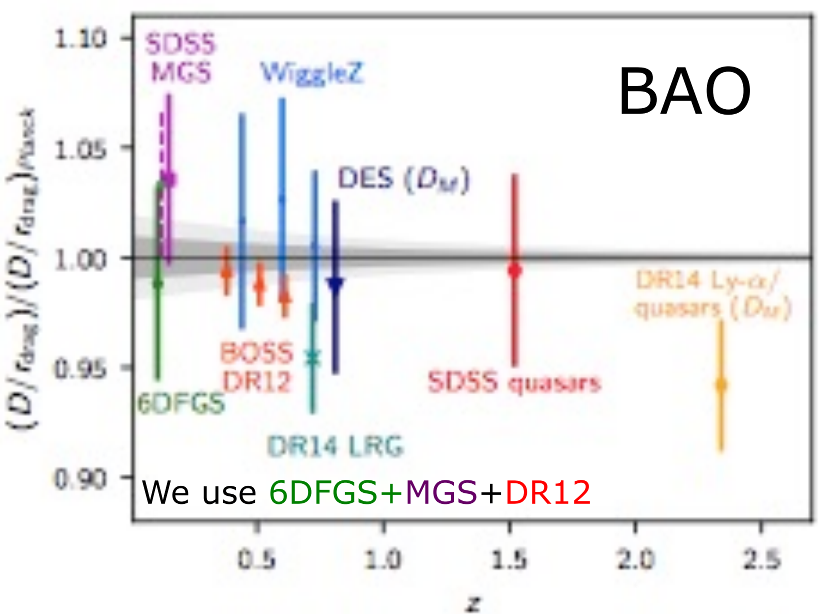


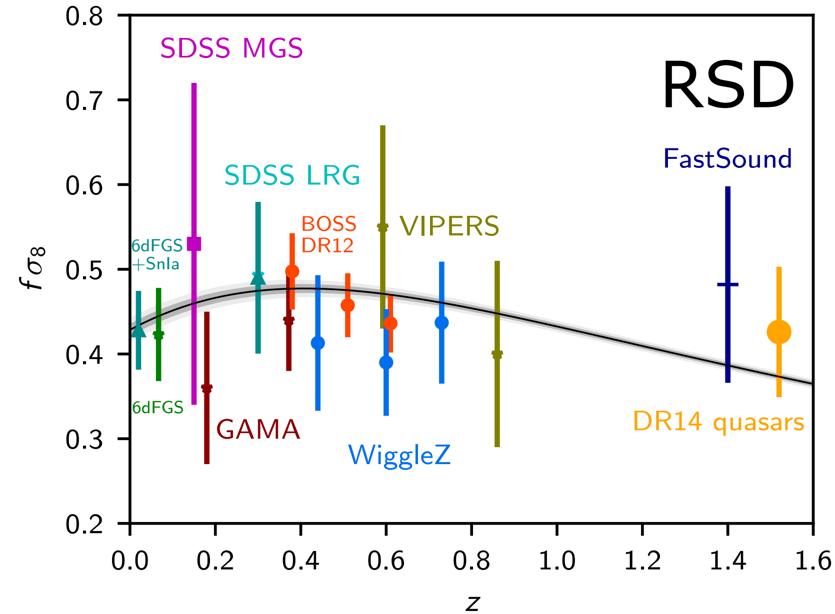
Planck **2018** results. VI. Cosmological parameters

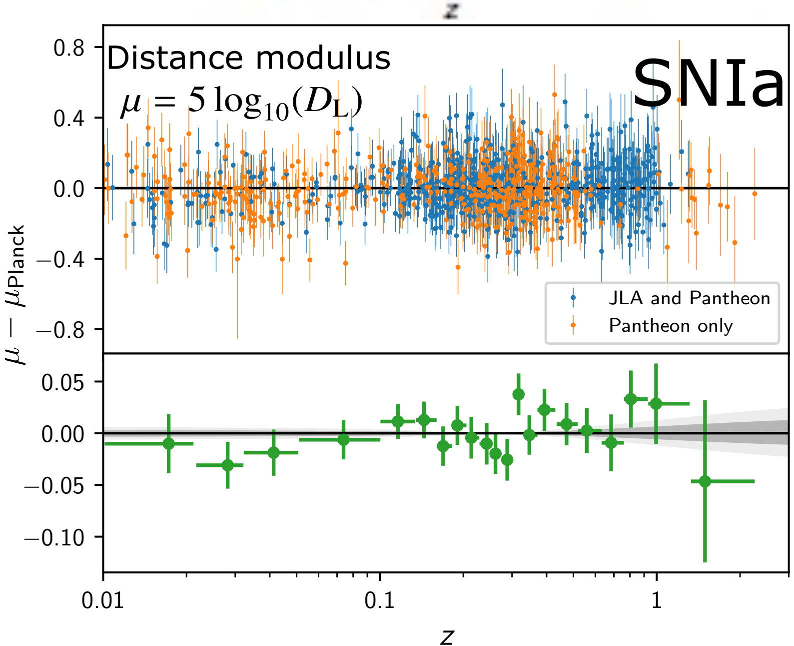
ΛCDM is a good fit to the data
No evidence of preference for classical extensions of ΛCDM

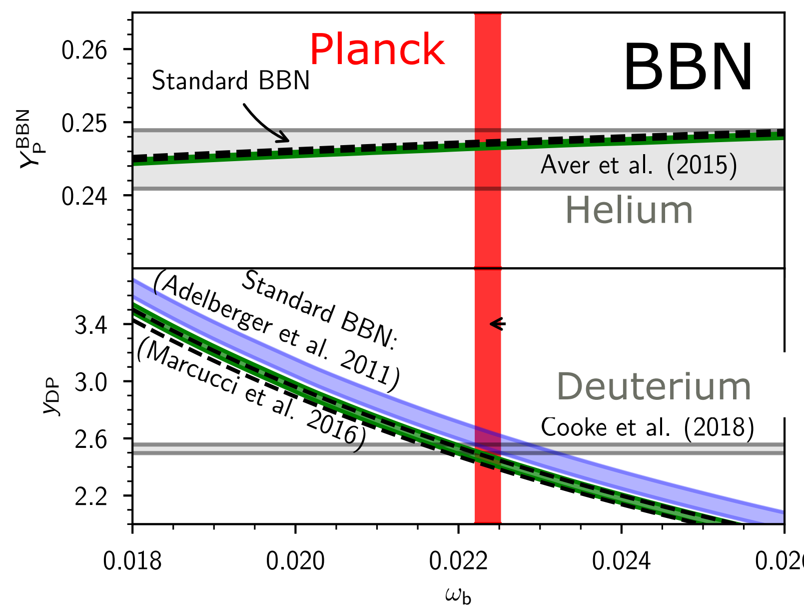
Likelihood	Multipoles	$\log(\mathcal{L})$	χ^2_{eff}	N_{dof}	PTE
TT, full, binned	30–2508	−380.34	760.68	765	0.54
TE, full, binned	30–1996	−428.68	857.36	762	0.0090
EE, full, binned	30–1996	−371.48	742.96	762	0.68
TTTEEE, full, binned	30–2508	−1172.47	2344.94	2289	0.20
TT, coadded, unbinned	30–2508	−1274.57	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	. . .

Good consistency with BAO, RSD, SnIa, BBN

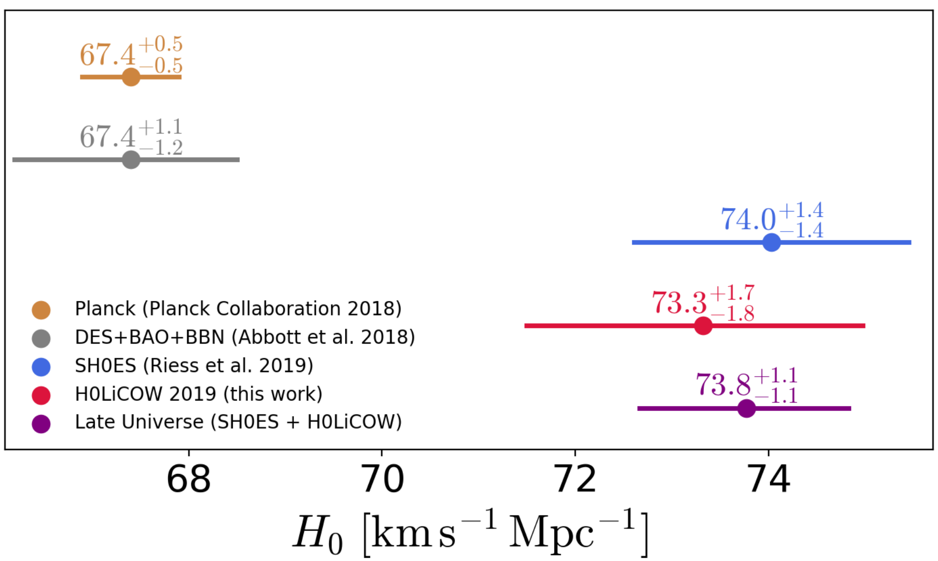




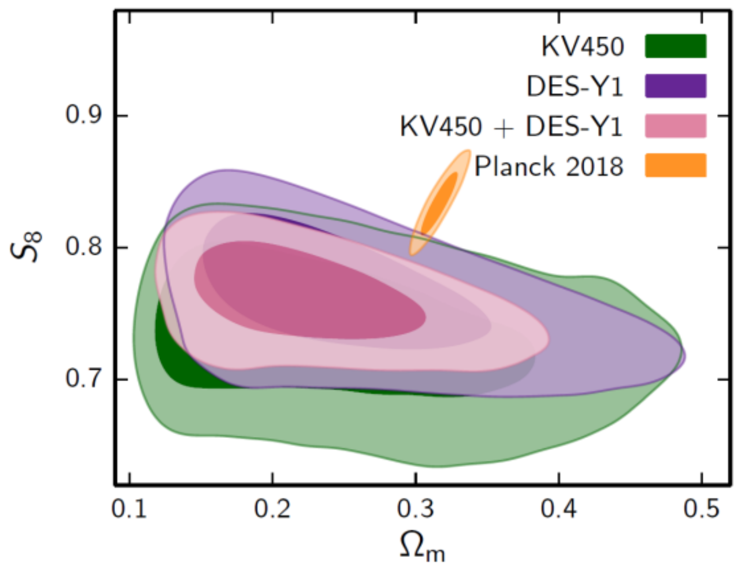




Problem with local measurements H_0 (and maybe a discrepancy with weak lensing?)



$S_8 = \sigma_8 \sqrt{\Omega_m/0.3}$,



Planck 2018 TTTEEE+lowE+CMB lensing
H_0 = 67.36 ± 0.54

Riess+ 2019
H_0 = 74.0 ± 1.42 km s^{-1} Mpc^{-1} [4.4σ]

Wong+ 2019
H_0 = 73.8 ± 1.1 km s^{-1} Mpc^{-1} [5.2σ]

Planck 2018 TTTEEE+lowE +CMB lensing
S_8 = 0.832 ± 0.013

Joudaki+ 2019 (DES+KiDS)
S_8 = 0.762+0.025 [2.6σ]

Numbers change for different experiments and data combinations

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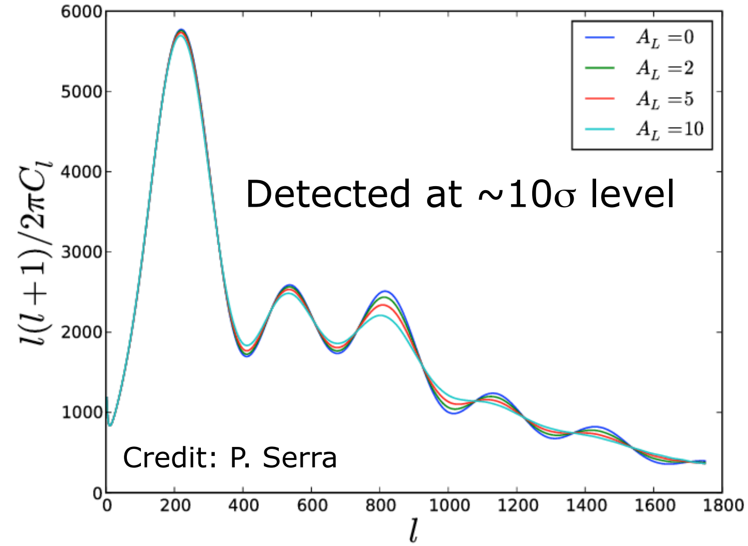
CMB lensing and A_{Lens}

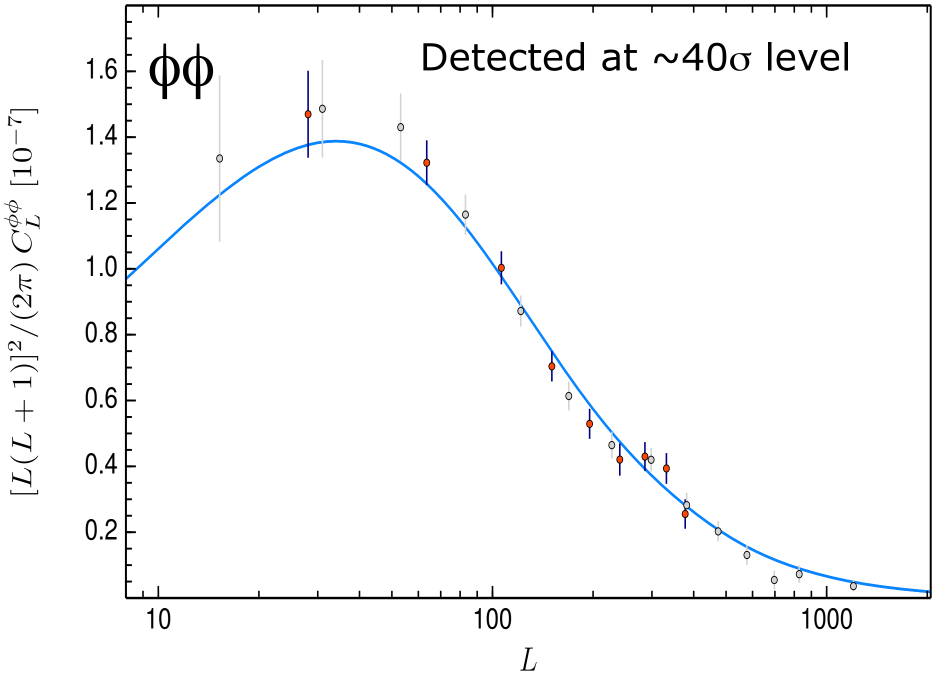
- Lensed CMB power spectrum is a convolution of unlensed CMB with lensing potential power spectrum=>**smoothing of the peaks and throughs**.

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

$$C_\ell^\Psi \rightarrow A_L C_\ell^\Psi$$ 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).

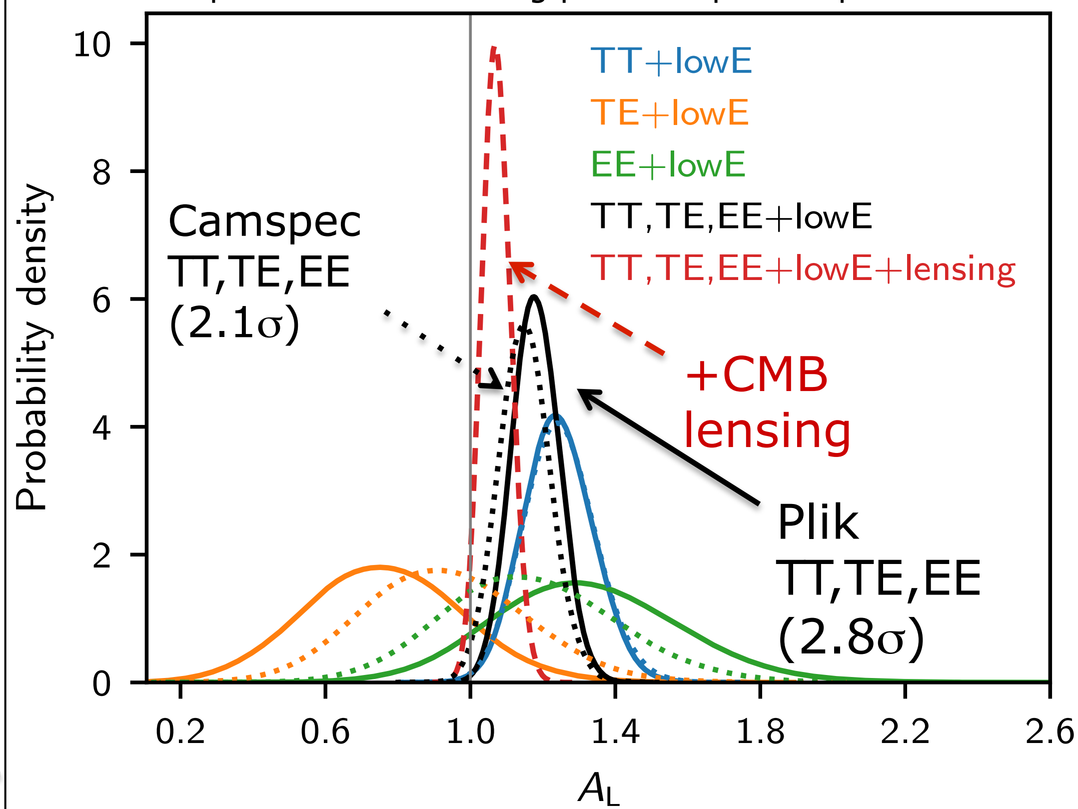
$$A_L = 1.243 \pm 0.096 \quad (68\,\%,\ \textit{Planck}\ \mathrm{TT{+}lowE}),$$

- 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.

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

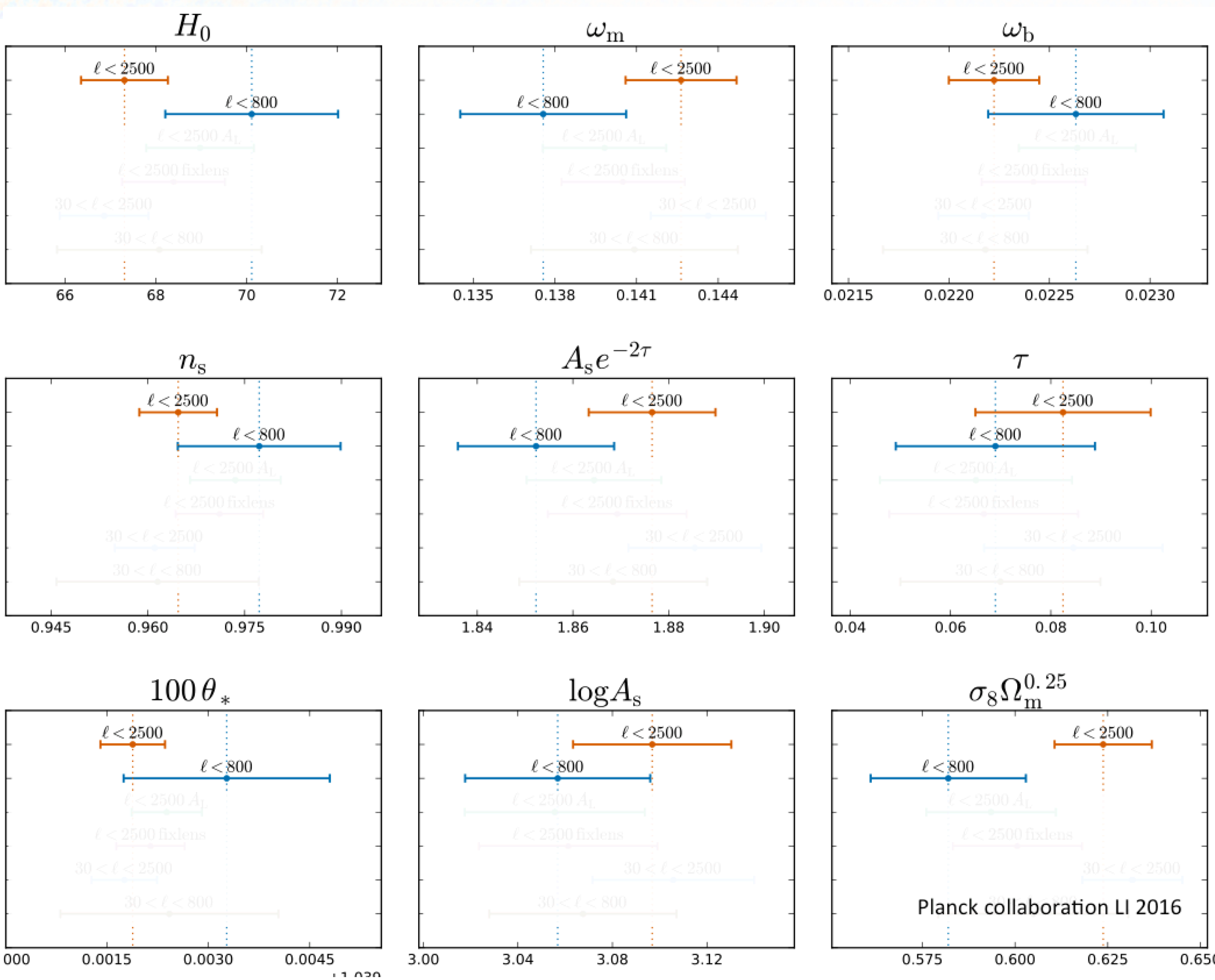
Amplitude of the lensing potential power spectrum.



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.

High-l versus low-l curiosity

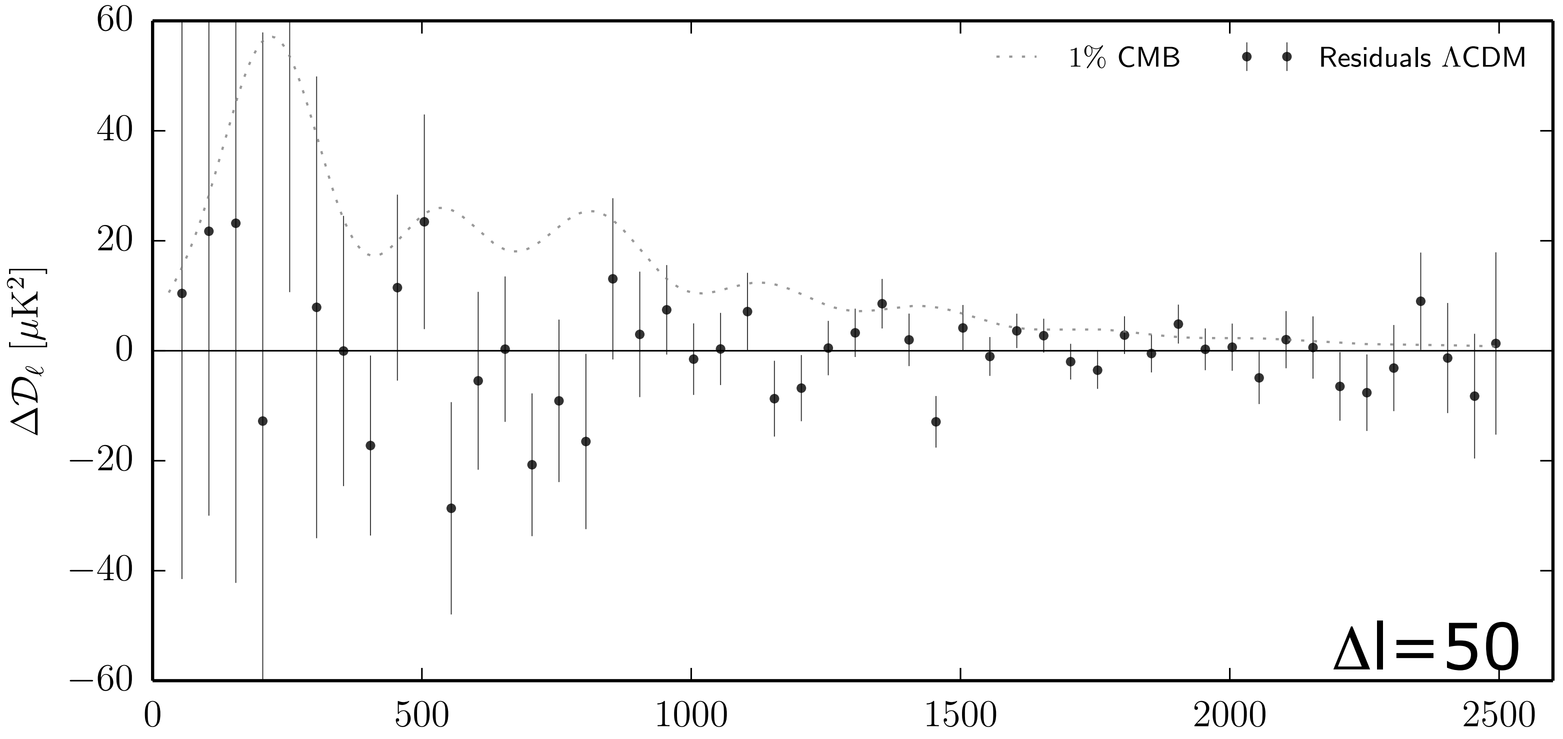


- Parameters evaluated from l<800 and l<2500, or l<800 vs l>800 are different at the 2-3 σ level (Planck **2015** results. XI. CMB power spectra, likelihoods, and robustness of parameters)
- Overall, shifts are significant at <~2σ level from simulations (Planck collaboration LI 2017, see also Addison+ 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.

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)



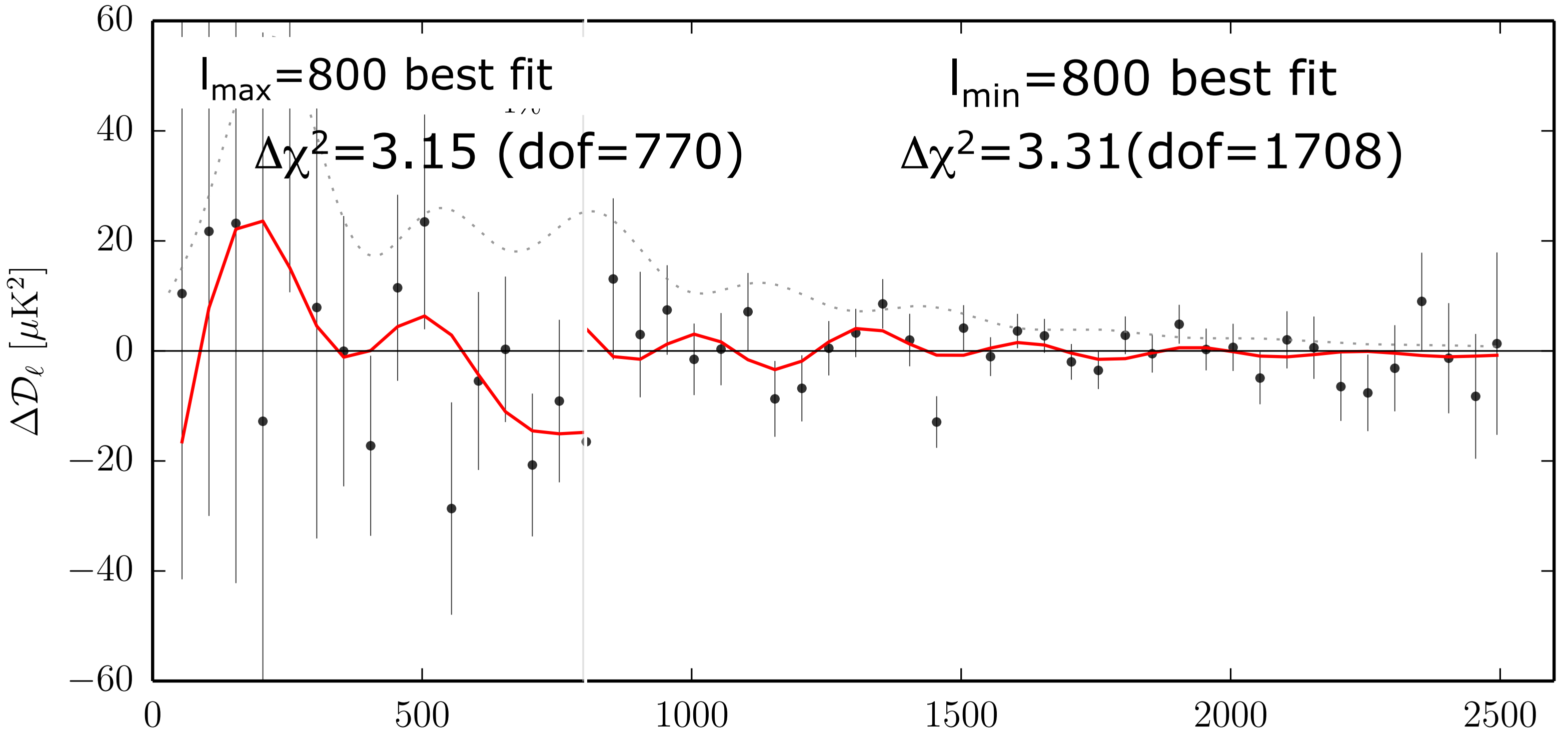
Residuals of the coadded CMB spectrum, assuming the ΛCDM best fit cosmology and foreground model
(coadded~weighted average of foreground cleaned 100x100, 143x143, 143x217 and 217x217 spectra)

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

Residuals TT

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

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

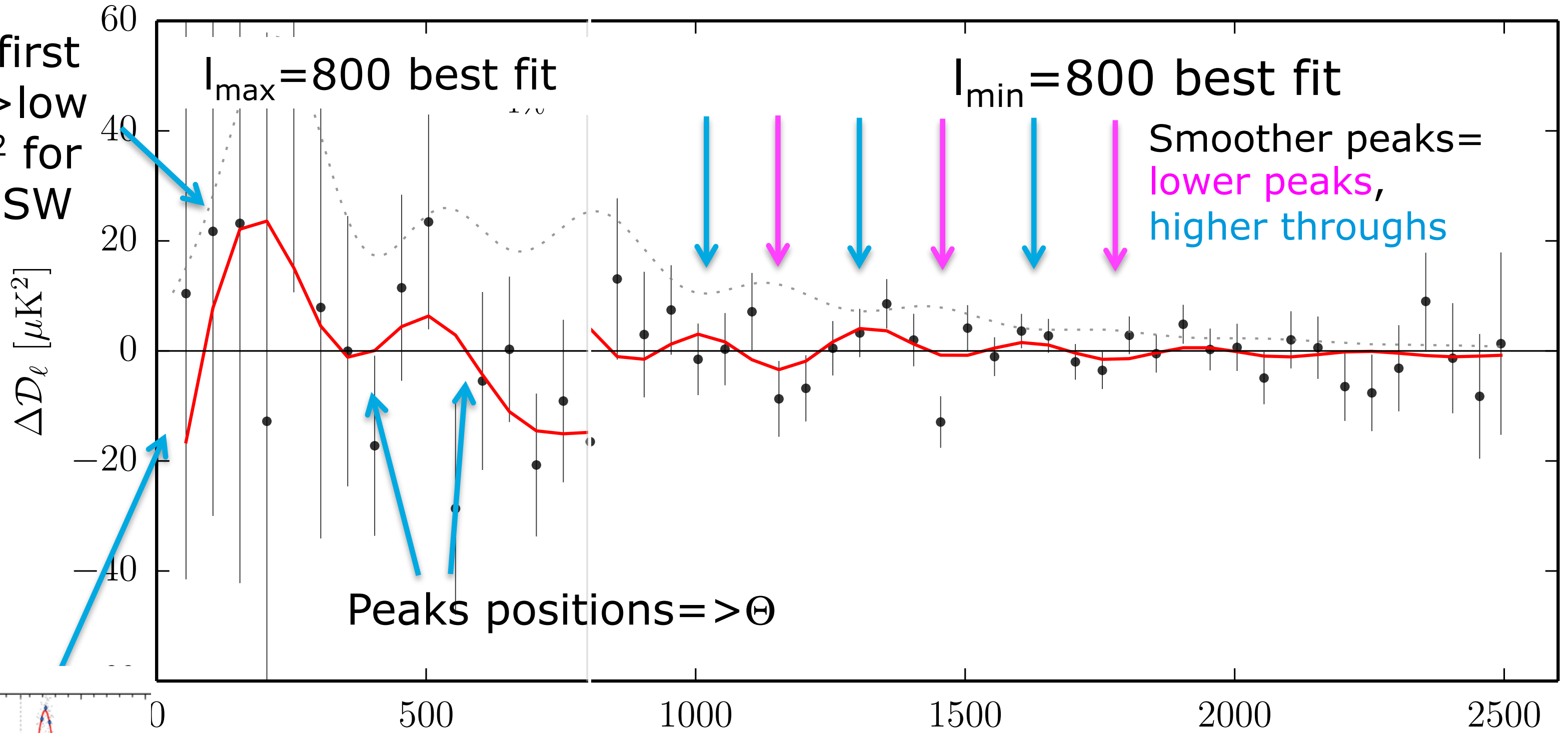


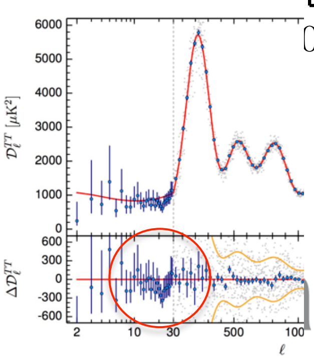
Residuals TT

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

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

Larger first peak=>lower $\Omega_m h^2$ for larger ISW



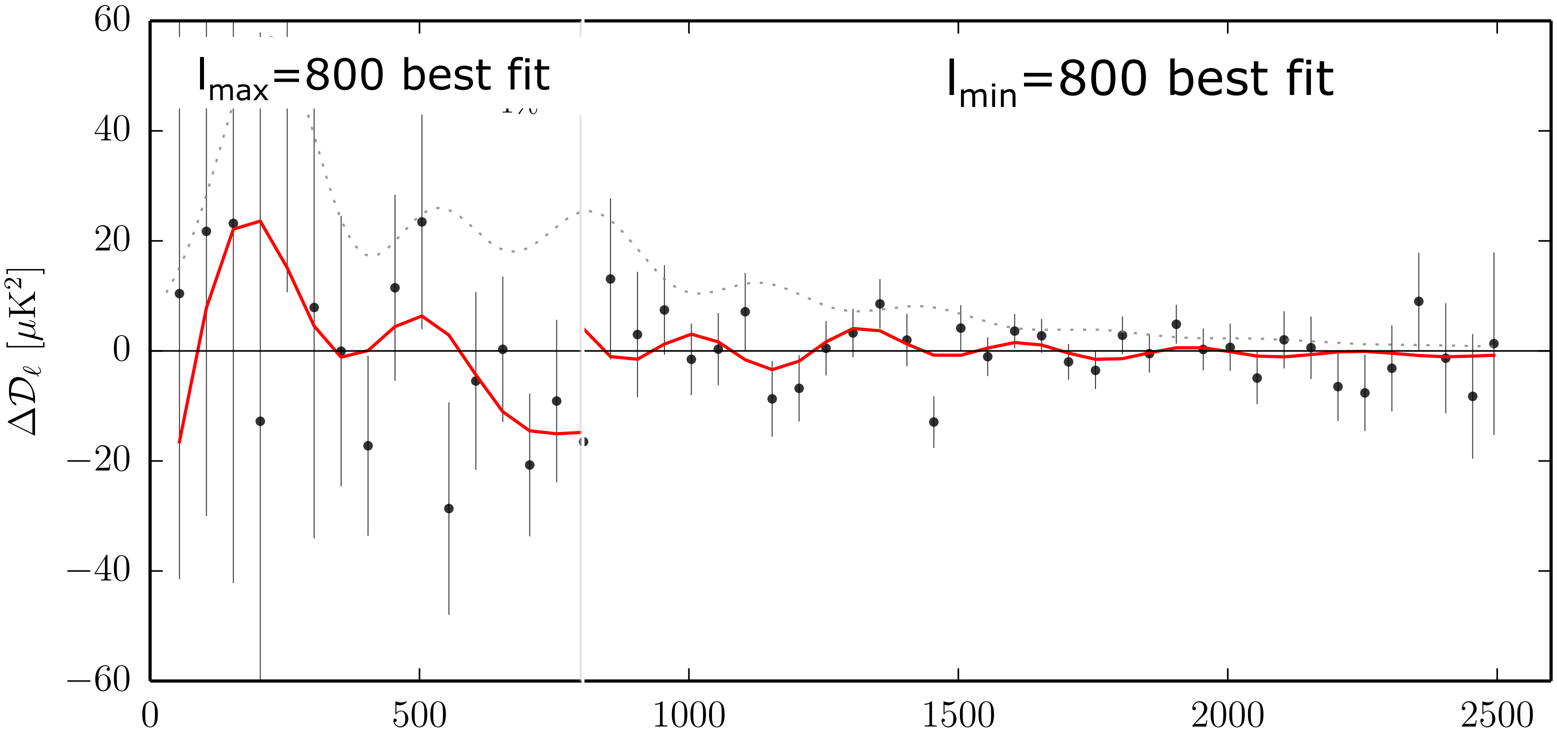


Lower low-l=>larger n_s for less power
at large scales, extra $\Delta\chi^2$=1.2 over dof=28

Residuals TT

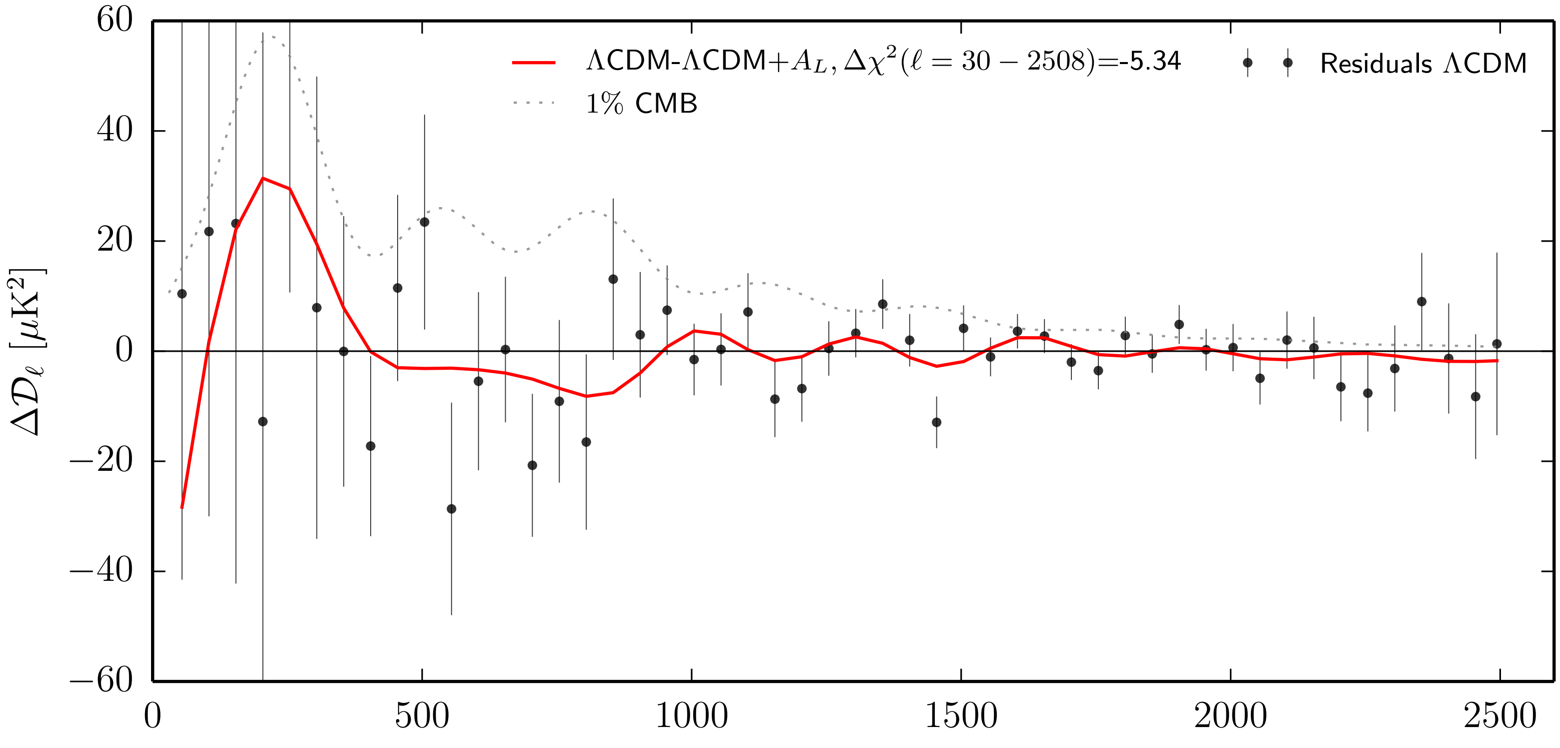
TT(lmax=800)+lowlTT*+lowE
(*not shown in this plot)

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



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.

Can A_L solve the 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.

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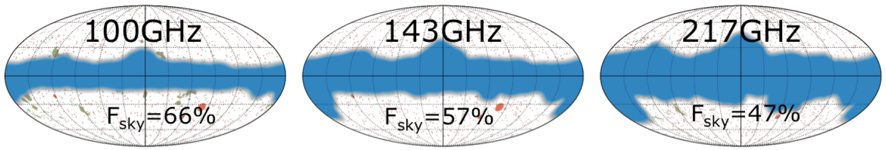
4. **If curiosities are systematics, what could they be?**
   a. **Galactic foregrounds**
   b. **Extra-galactic foregrounds**
   c. **Pointing errors**
   d. **Aberration**
   e. **Beam errors**

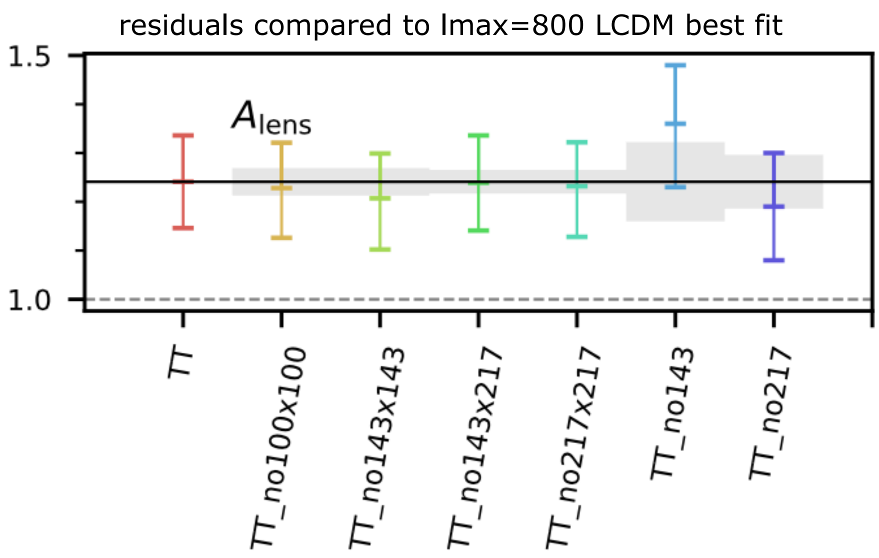
5. Polarization

Is Alens due to a problem with galactic dust?

100, 143 and 217 have **different level of galactic foregrounds** and use different masks.

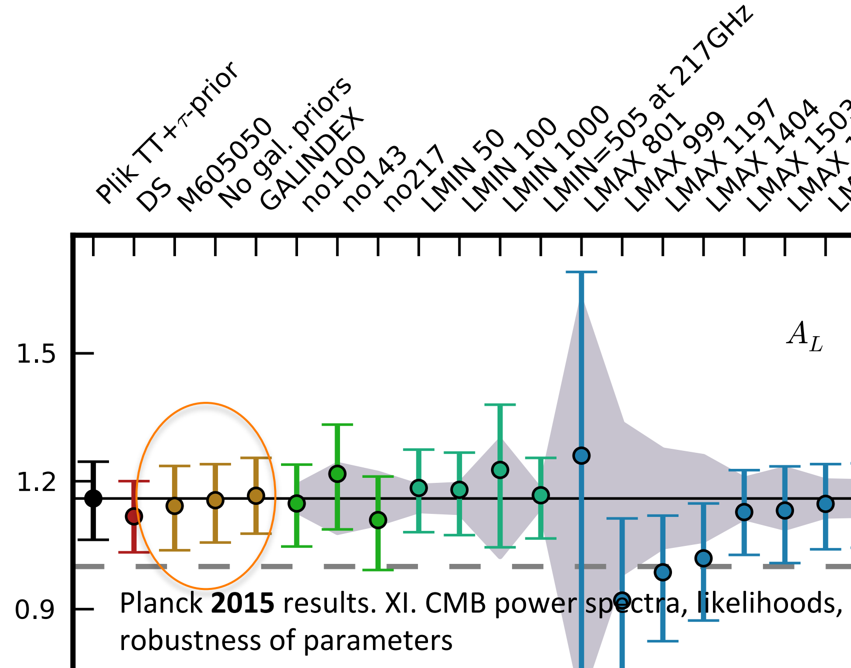


Changes in Alens estimated **eliminating 1 frequency** at the time are compatible with statistical fluctuations.



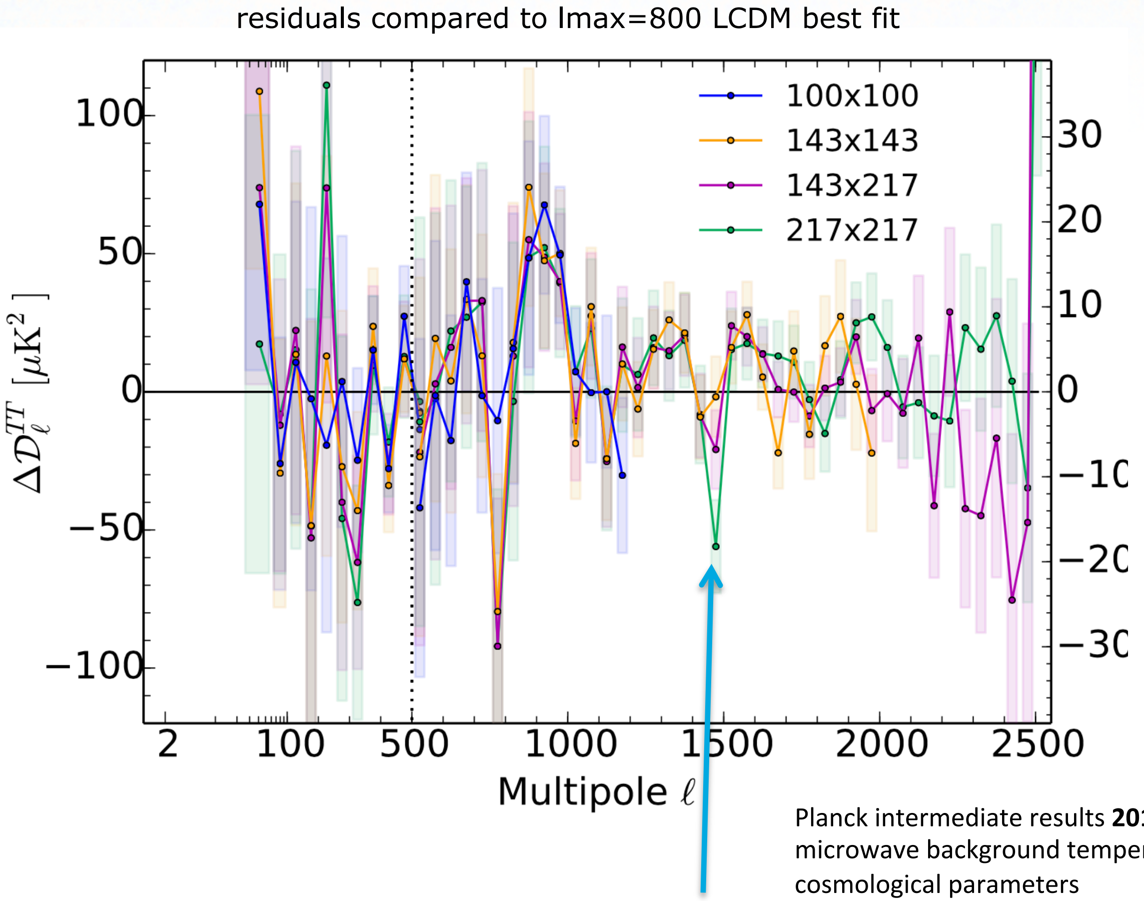
- Planck **2018** results. V. Legacy Power Spectra and Likelihoods

In 2015, we also estimated Alens using **different galactic masks with fsky 47%, 37%, 37%** at 100,143,217. Also gave high Alens.



Planck **2015** results. XI. CMB power spectra, likelihoods, robustness of parameters

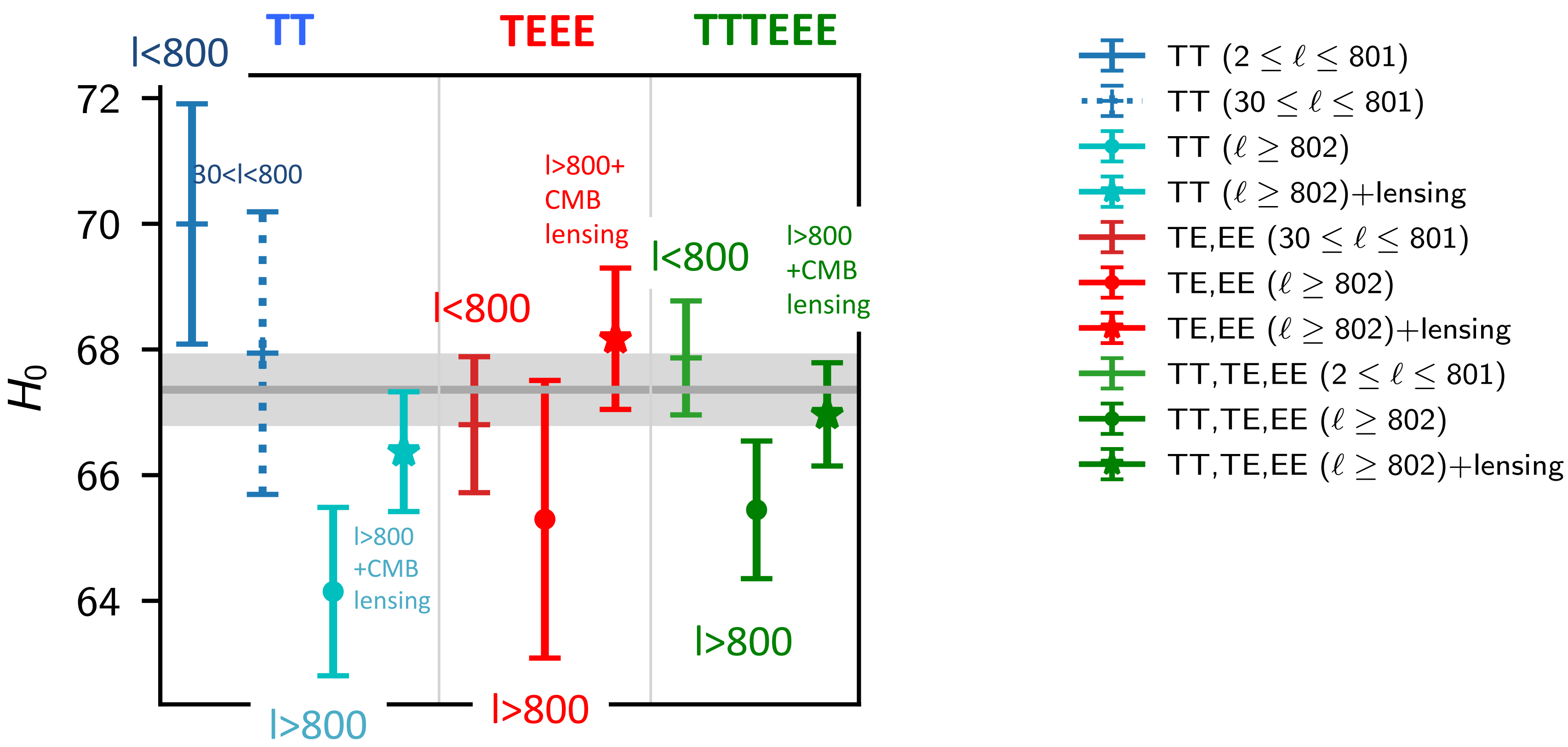
Is Alens due to a problem with galactic dust?



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.

The low-l vs high-l curiosity and polarization



Even the TT l<800 gives low H_0 when combined with BAO.

$$\left.\begin{aligned} H_0 &= (67.85 \pm 0.52)\ \mathrm{km\ s^{-1}Mpc^{-1}}, \\ \sigma_8 &= 0.8058 \pm 0.0063, \\ \Omega_\mathrm{m} &= 0.3081 \pm 0.0065. \end{aligned}\right\} \begin{array}{l} 68\ \%, \text{TT,TE,EE} \\ [\ell \leq 801]\text{+lowE} \\ \text{+lensing+BAO.} \end{array}$$

Planck collaboration VI 2018

Conclusions

- Correction in systematics in the legacy release have improved spectacularly the robustness of the Planck results.
- The ΛCDM model is an excellent fit to the data.
- Curiosities in the Planck data remain at the 2-3s level, and cannot explain the H_0 tension (partly related to the S_8 one.)

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.