Last Results and Questions From Planck

- 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

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

Silvia Galli

IAP

on behalf of the Planck Collaboration

EDSU2020 08/03/2020

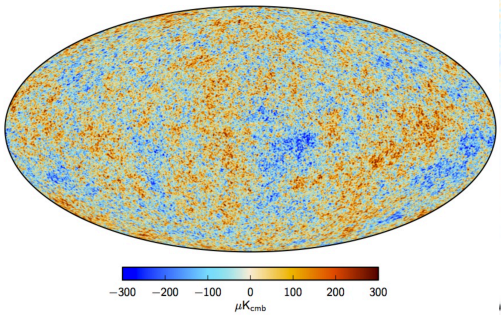
Outline

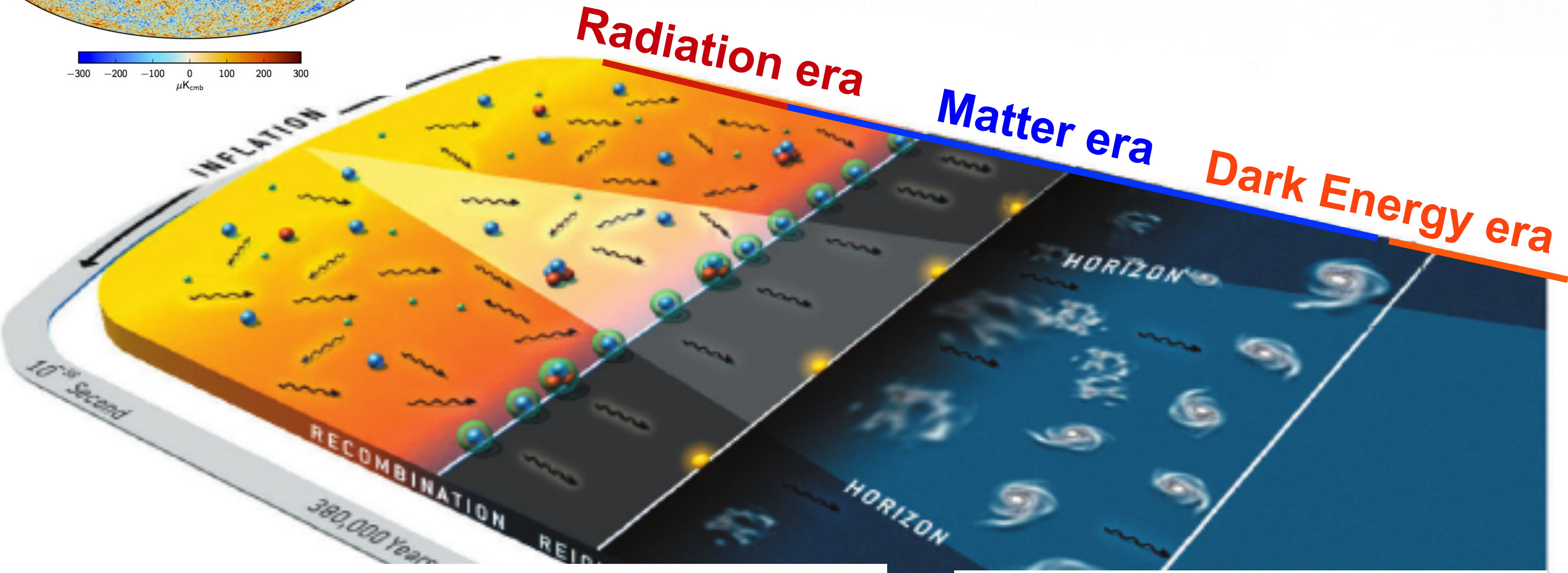
1. Short recap on Planck results
2. Post-Planck Issue 1: Comparison with other probes. The H_0 problem and the σ_8 discrepancies
3. Post-Planck Issue 2: Internal "curiosities" in the Planck data (A_L, curvature etc..)
4. Are Issue 1 and Issue 2 related?

Outline

1. Short recap on Planck results
2. Post-Planck Issue 1: Comparison with other probes. The H_0 problem and the σ_8 discrepancies
3. Post-Planck Issue 2: Internal "curiosities" in the Planck data (A_L, curvature etc..)
4. Are Issue 1 and Issue 2 related?

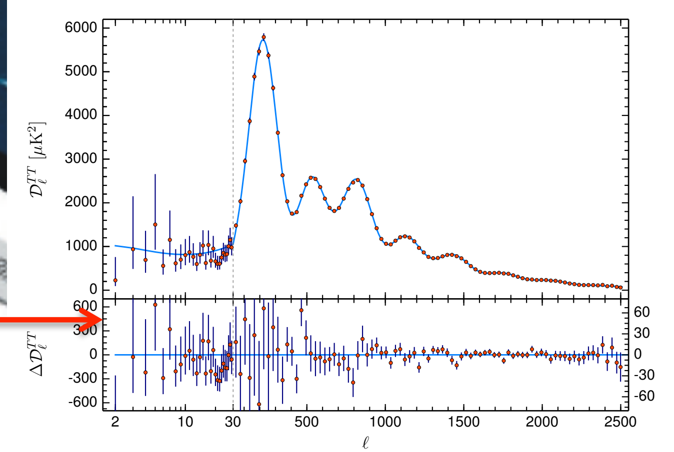
Cosmic History





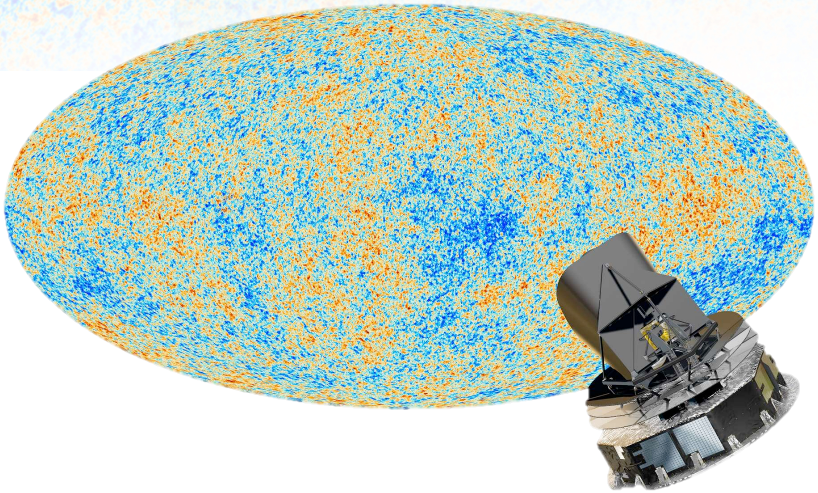
$$\Theta(\vec{x},\hat{p},\eta)=\sum_{l=1}^{\infty}\sum_{m=-l}^{l}a_{lm}(\vec{x},\eta)Y_{lm}(\hat{p})$$

$$\langle a_{lm}a^{*}_{l'm'}\rangle=\delta_{ll'}\delta_{mm'}C_l$$



Hu & White (2004); artist: B. Christie/SciAm; available at http://background.uchicago.edu

The Planck satellite



3^{rd} 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.**

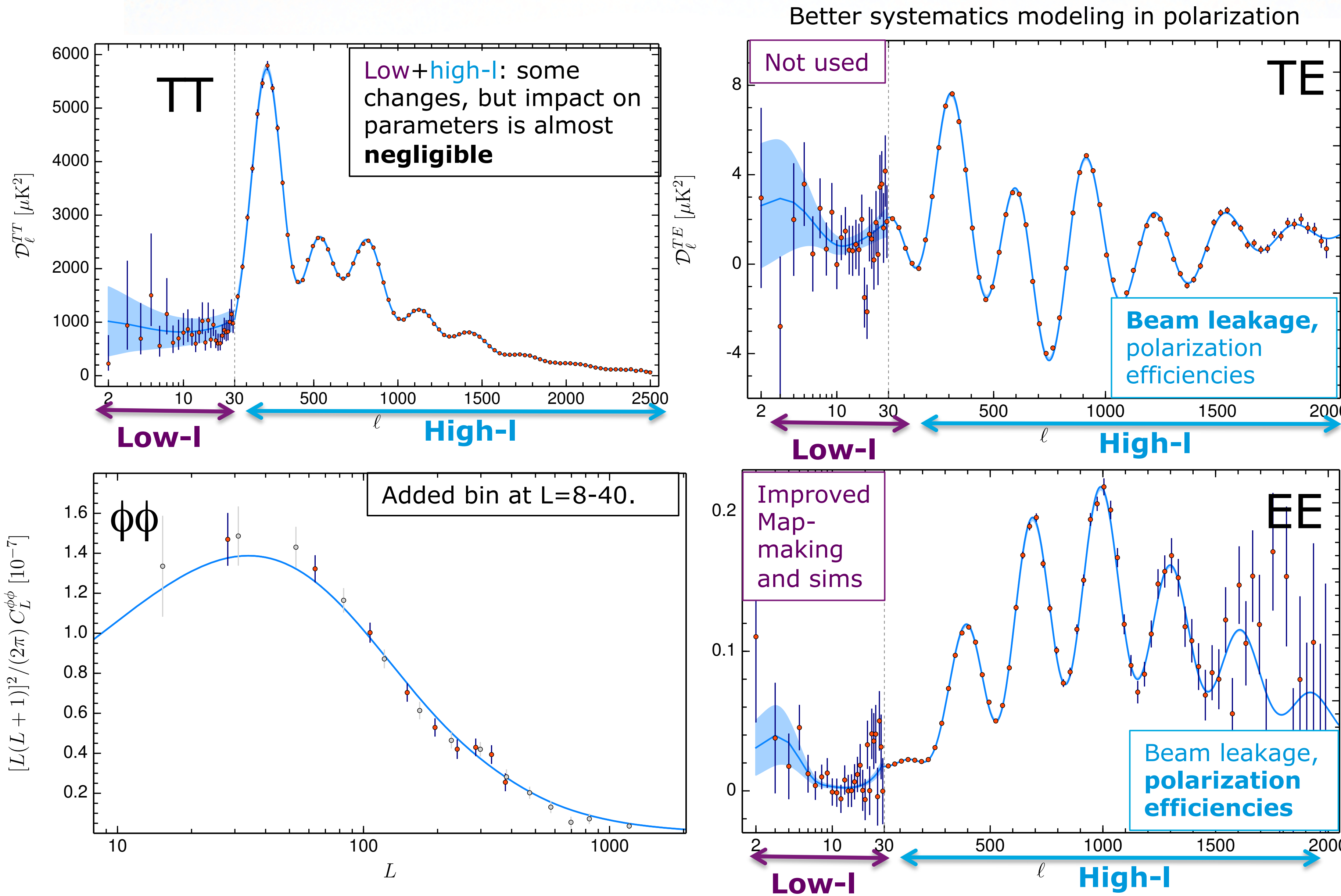
- **1^{st} release 2013: Nominal mission**,15.5 months, Temperature only (large scale polarization from WMAP).

- **2^{nd} 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

- **3^{nd} release 2018: Full mission, improved polarization, low/high-l from HFI.** Better control of systematics specially in pol., still systematics limited.

2018 Power spectra

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



Baseline ΛCDM results 2018

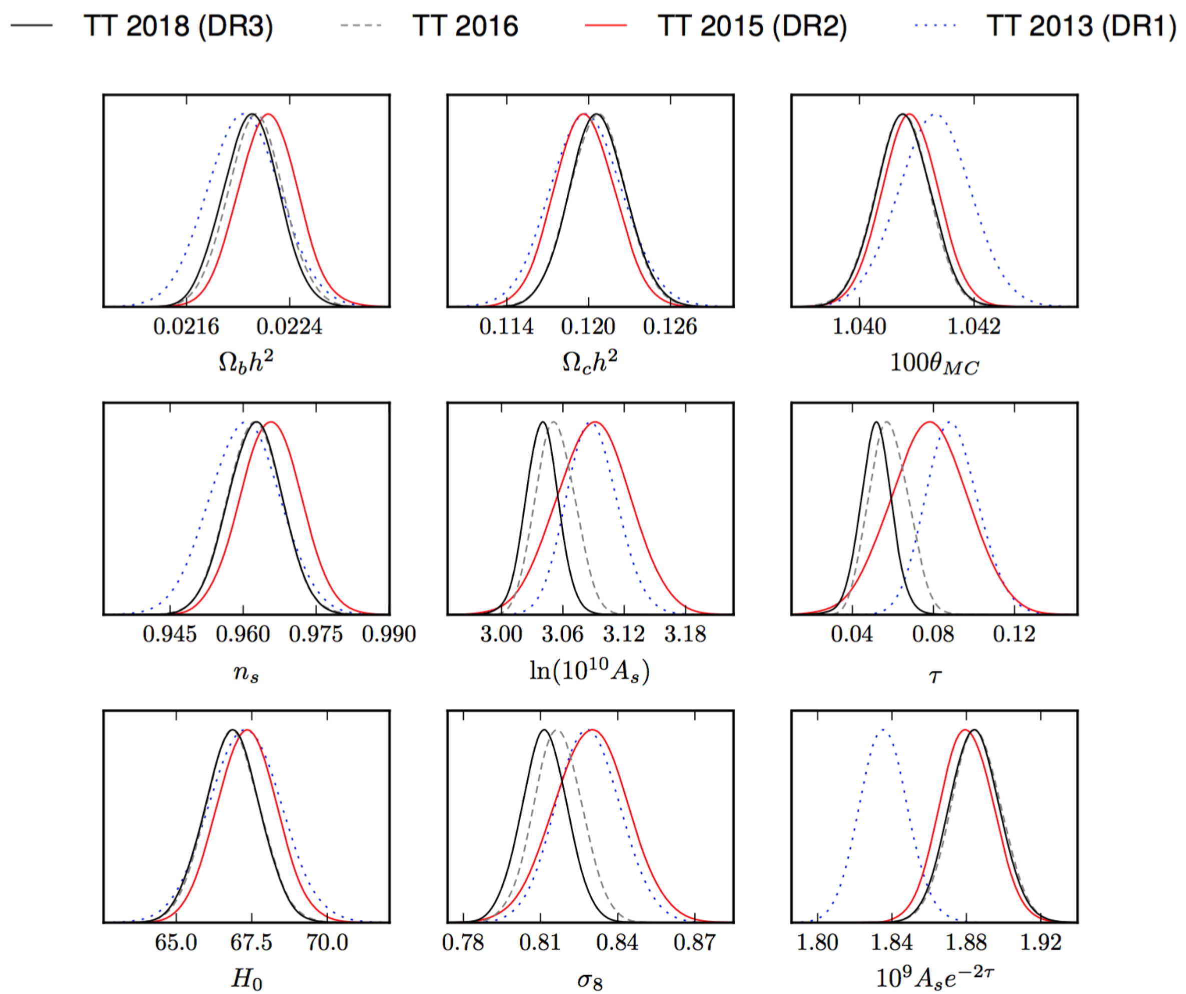
(Temperature+polarization+CMB lensing)

	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, <0.5σ.

- 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.
- 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.

Take away message stable across releases



Changes across releases compatible with statistical fluctuations and systematics corrections.

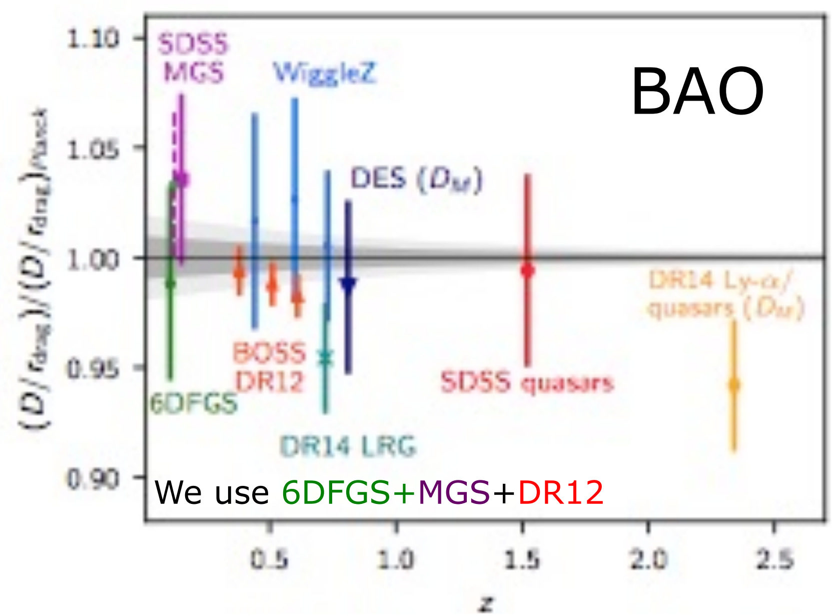
ΛCDM is a good fit to the data
No evidence of preference for classical extensions of ΛCDM

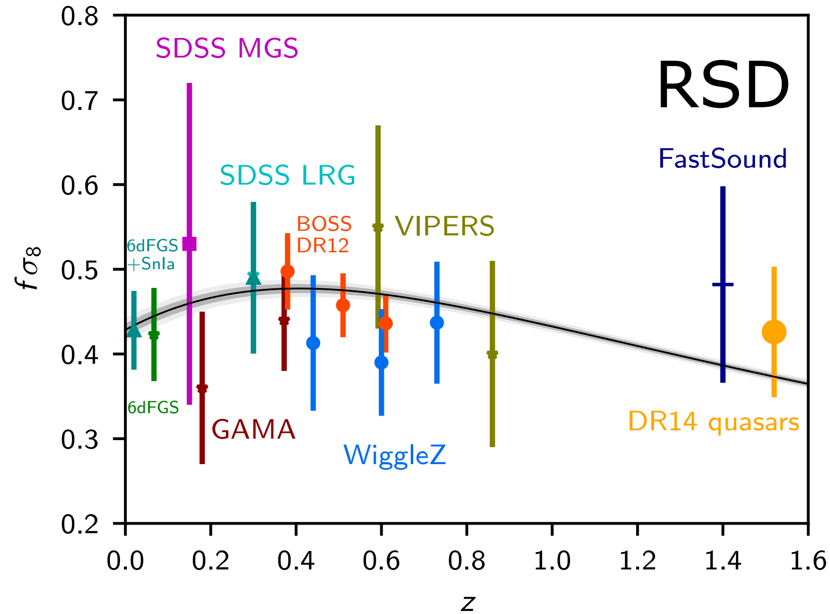
Just a few (2-3σ) outliers.

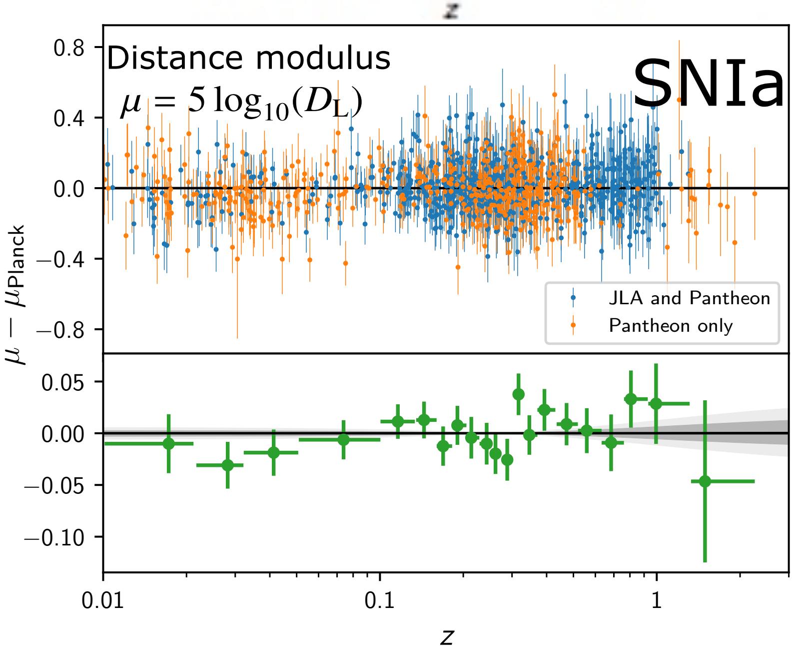
Outline

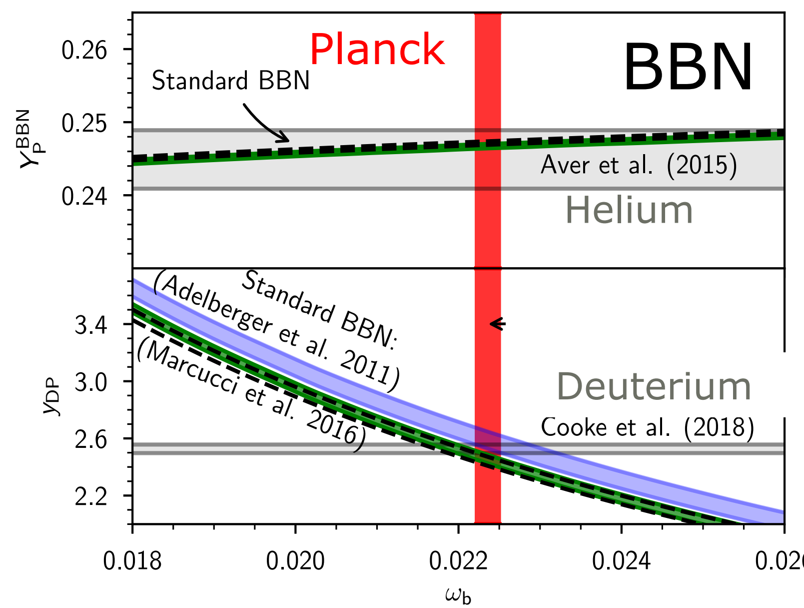
1. Short recap on Planck results
2. Post-Planck Issue 1: Comparison with other probes. The H_0 problem and the σ_8 discrepancies
3. Post-Planck Issue 2: Internal "curiosities" in the Planck data (A_L, curvature etc..)
4. Are Issue 1 and Issue 2 related?

Good consistency with BAO, RSD, SnIa, BBN



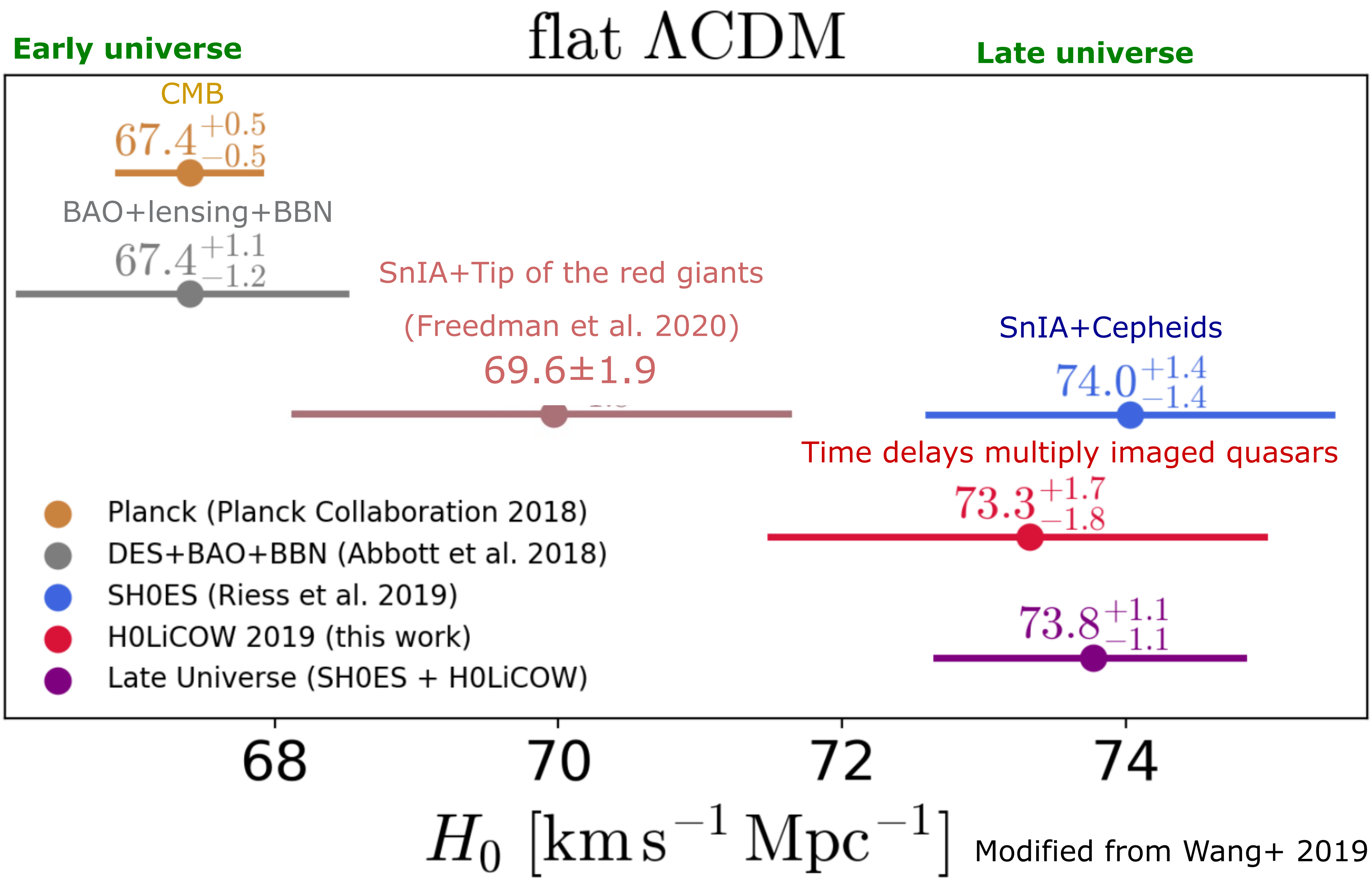






Strong tension between early and late universe probes of H_0.

See Sherry Suyu's and Dillon Brout's talks



Modified from Wang+ 2019

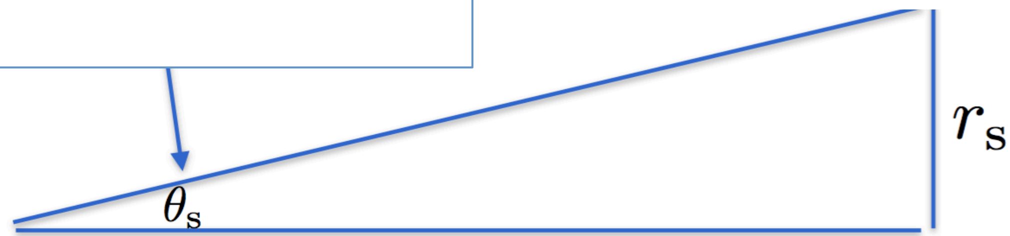
Indirect measurement of the Hubble constant from the CMB

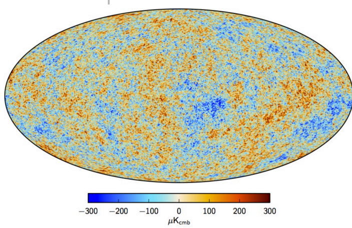
See Vivian Poulin's talk

Calculate the **physical dimension of sound horizon** assumes model for sound speed and expansion of the universe before recombination (after measuring ω_m and ω_b)

$$r_s = \int_{z_s}^{\infty} \frac{c_s(z)}{H(z)} dz$$

Measure the **angular scale of sound horizon** from the position of the peaks





$$D_A(z = 1100) = \int_0^z dz'/H(z')$$

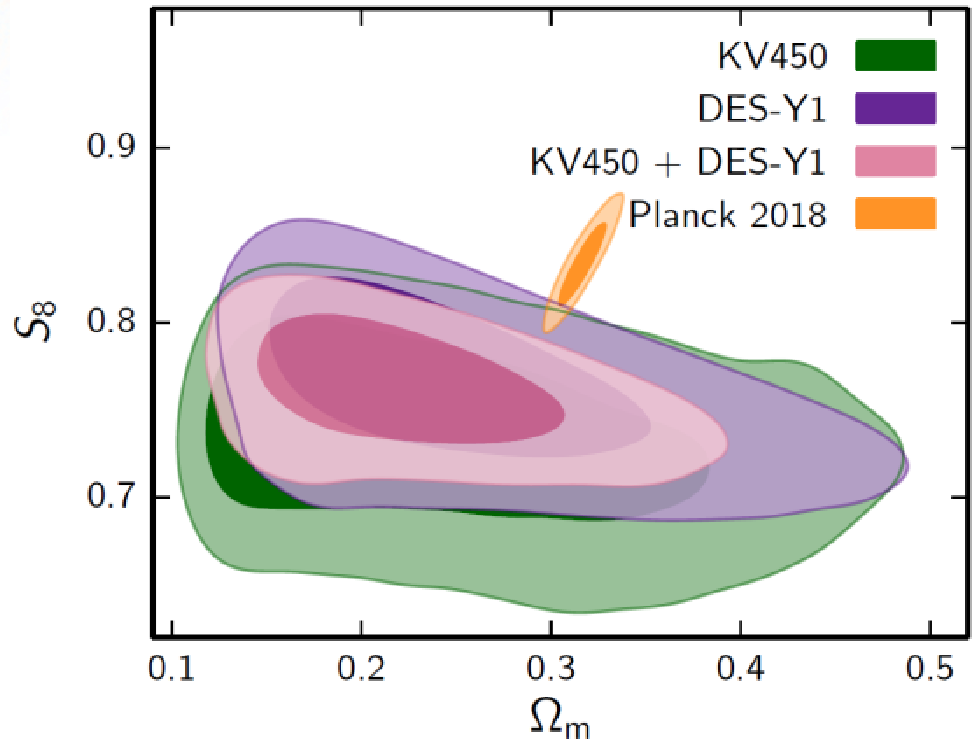
Infer the distance to the last scattering surface, which depends on H_0 Friedmann equation, infer H_0.

Expansion rate after recombination

$$\boxed{H^2(z) = \mathbf{H_0}^2(\Omega_m (z+1)^3 + \Omega_{DE} + ..)}$$

Model dependent!

Discrepancy with weak lensing data?



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

Planck 2018 TTTEEE+lowE +CMB lensing
$S_8 = 0.832 \pm 0.013$

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

See Henk Hoekstra's and Laura Salvati's talks

Numbers change for different experiments and data combinations

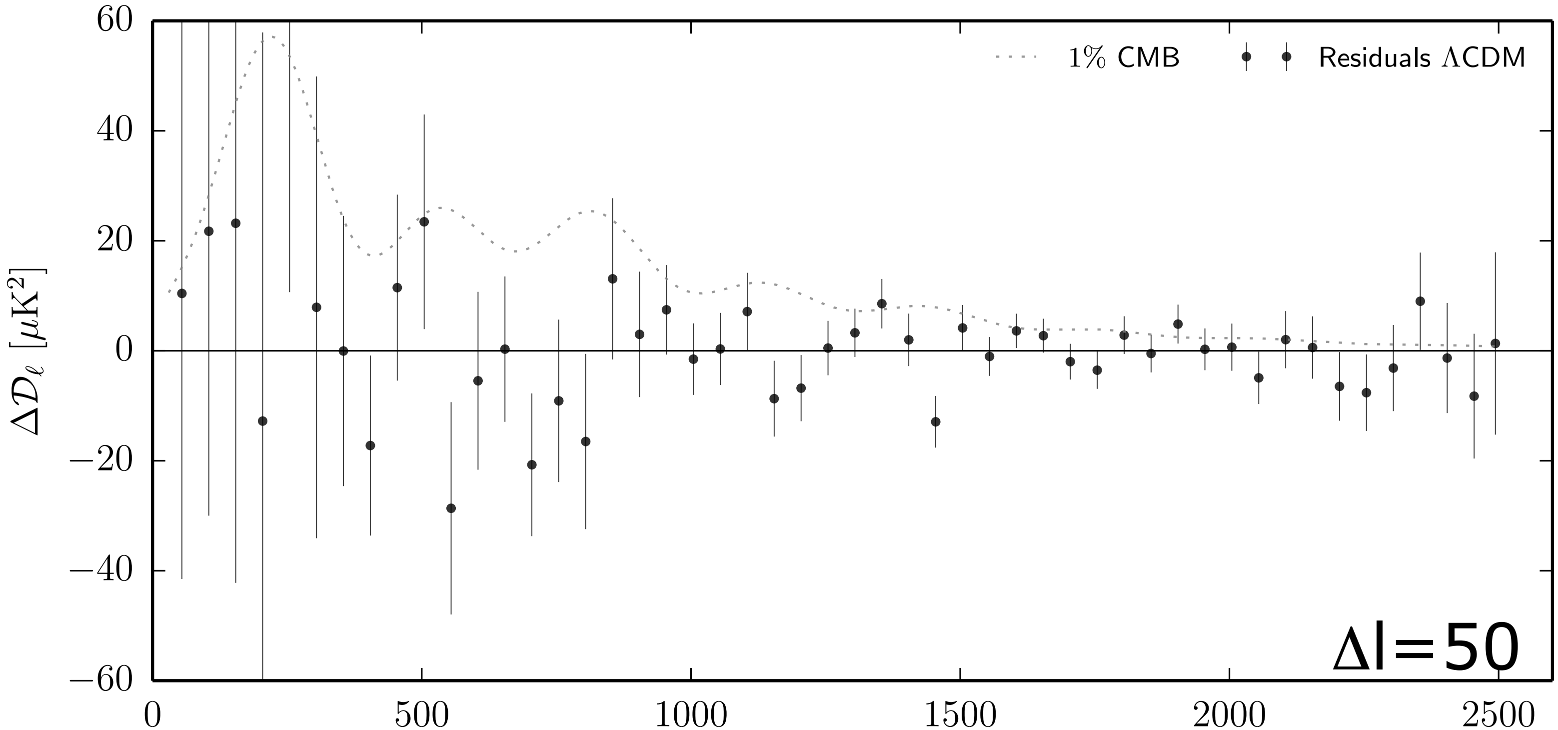
Outline

1. Short recap on Planck results
2. Post-Planck Issue 1: Comparison with other probes. The H_0 problem and the σ_8 discrepancies
3. Post-Planck Issue 2: Internal "curiosities" in the Planck data (A_L, curvature etc..)
4. Are Issue 1 and Issue 2 related?

Residuals TT with respect to LCDM

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

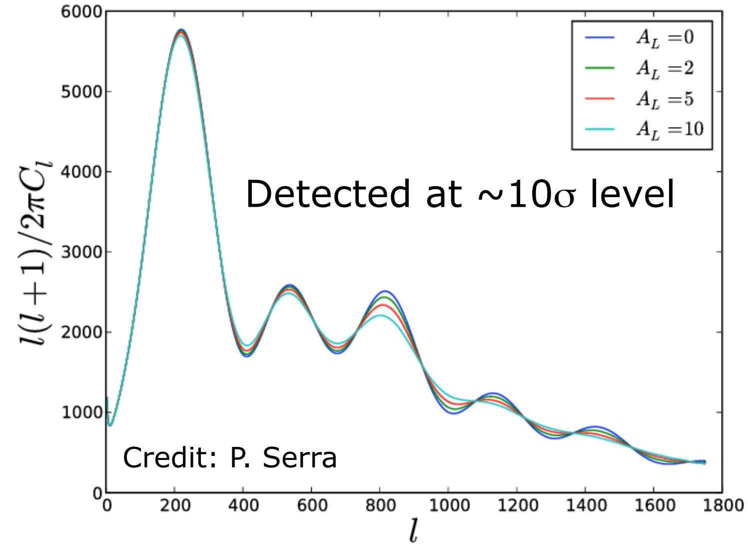
CMB lensing and A_{Lens}

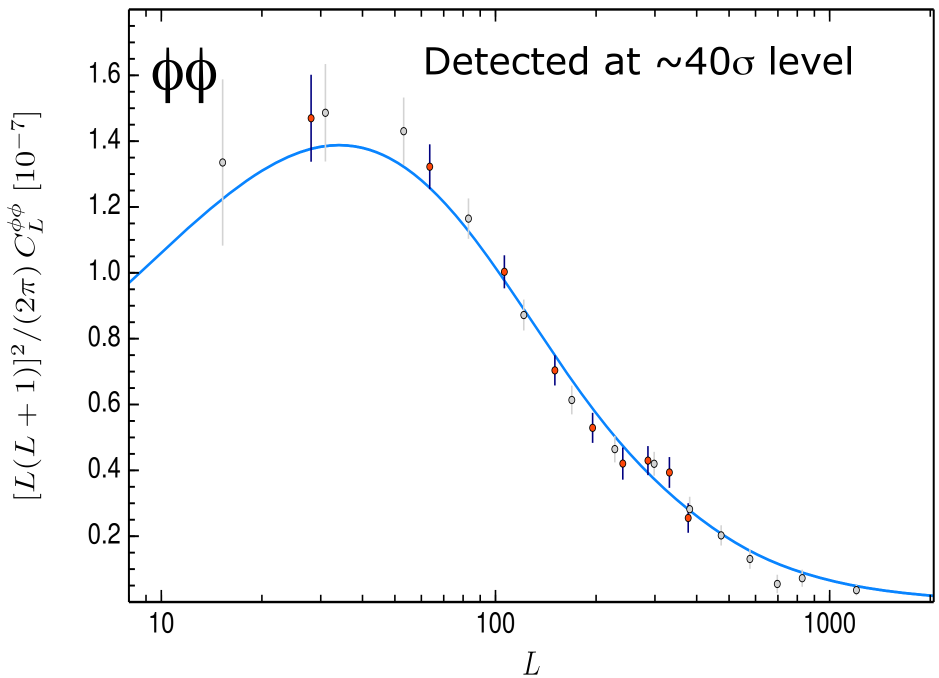
- Lensed CMB power spectrum is a convolution of unlensed CMB with lensing potential power spectrum=>**smoothing of the peaks and throughs**.

- 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

- A_l is an unphysical parameter used for consistency check.

- Since 2013 preference for high value, TT spectrum prefers 2.4σ deviation from 1.

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

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

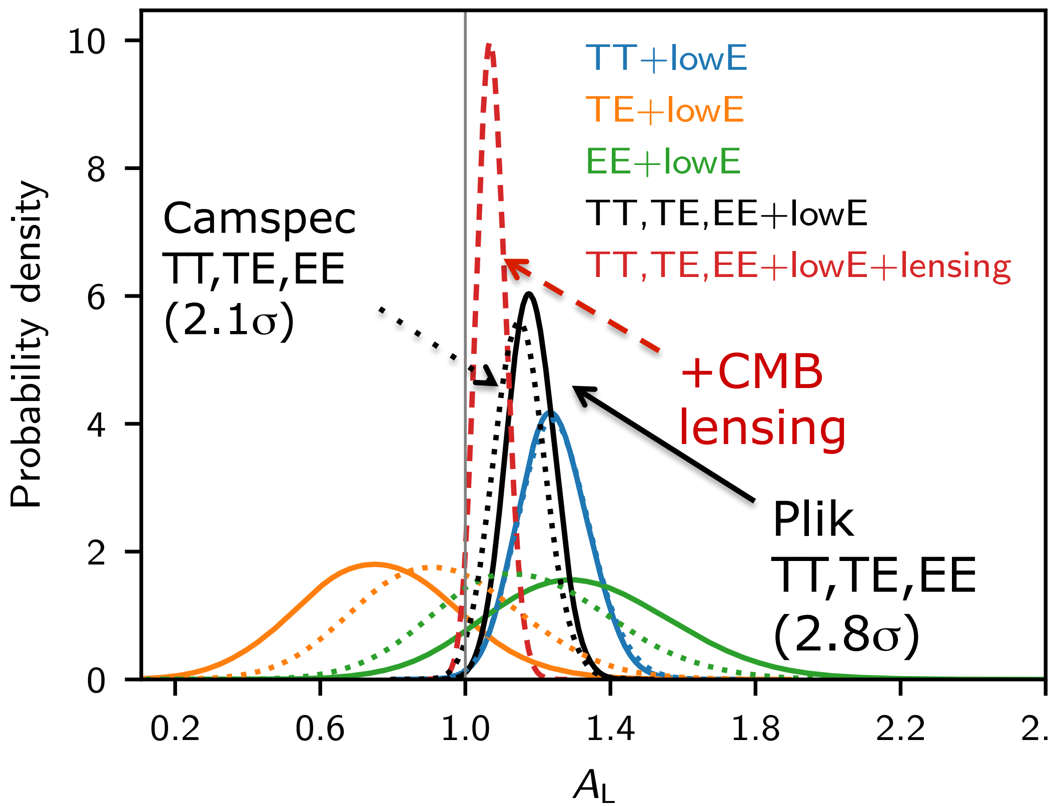
- Preference for higher lensing projects into small deviations in extensions which have analogous effect on lensing (Ω_k, w, Σm_ν).

- Adding polarization, A_L degenerate with systematics corrections and thus likelihood used.

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

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

Amplitude of the lensing potential power spectrum.

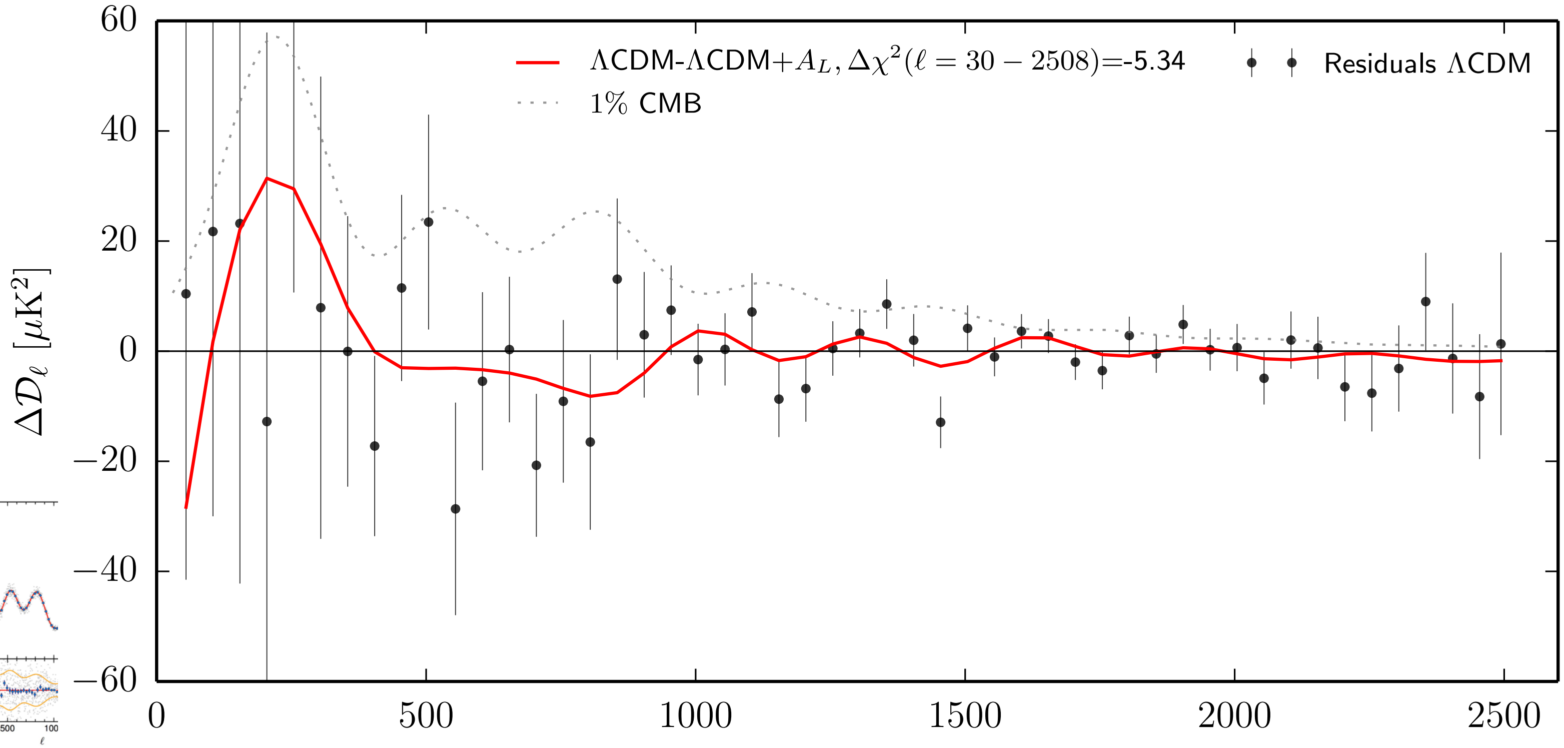


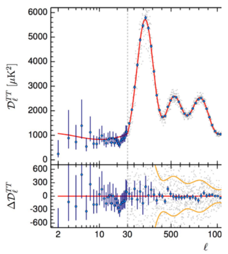
Planck **2018** results. VI. Cosmological parameters

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

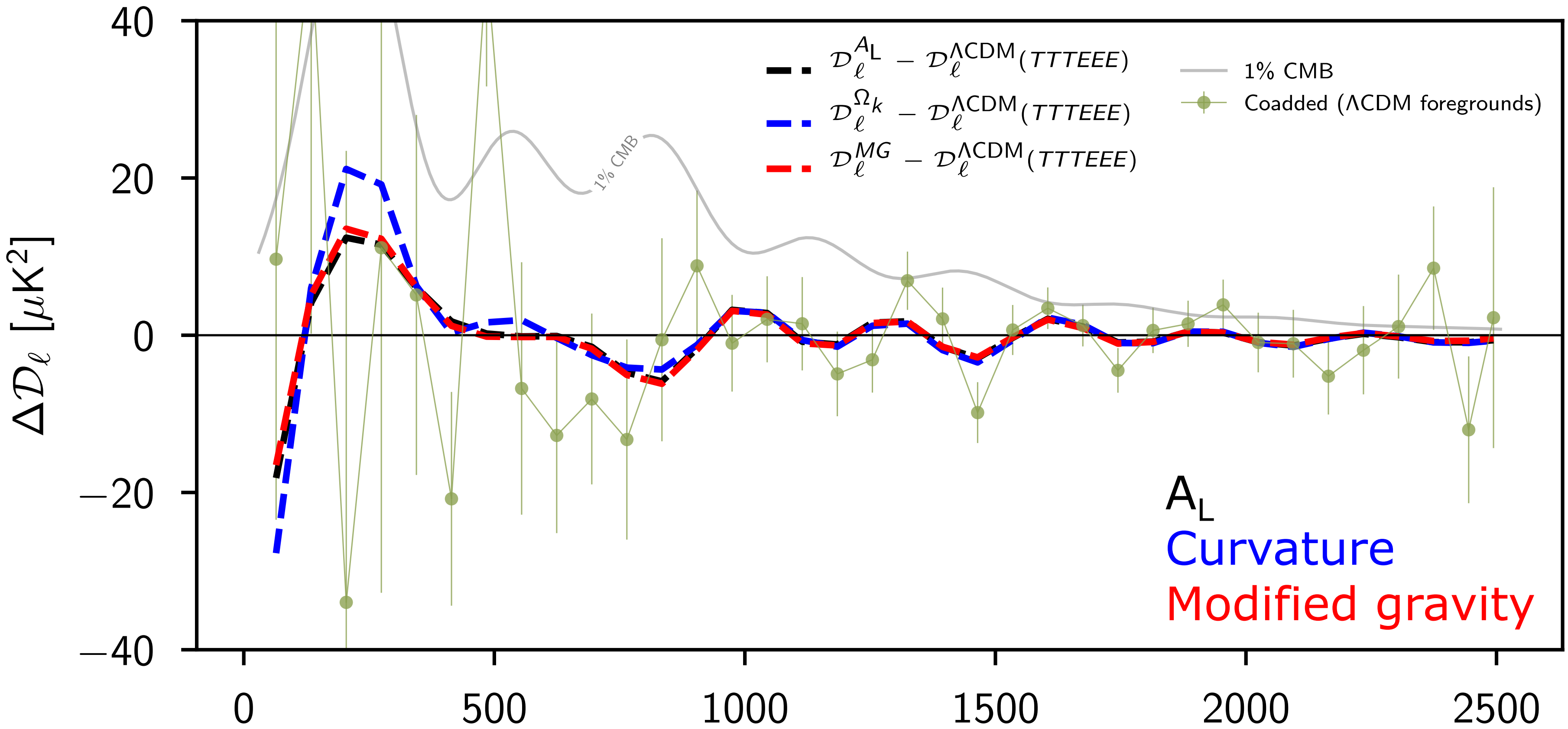
Residuals TT

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)





- **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**.

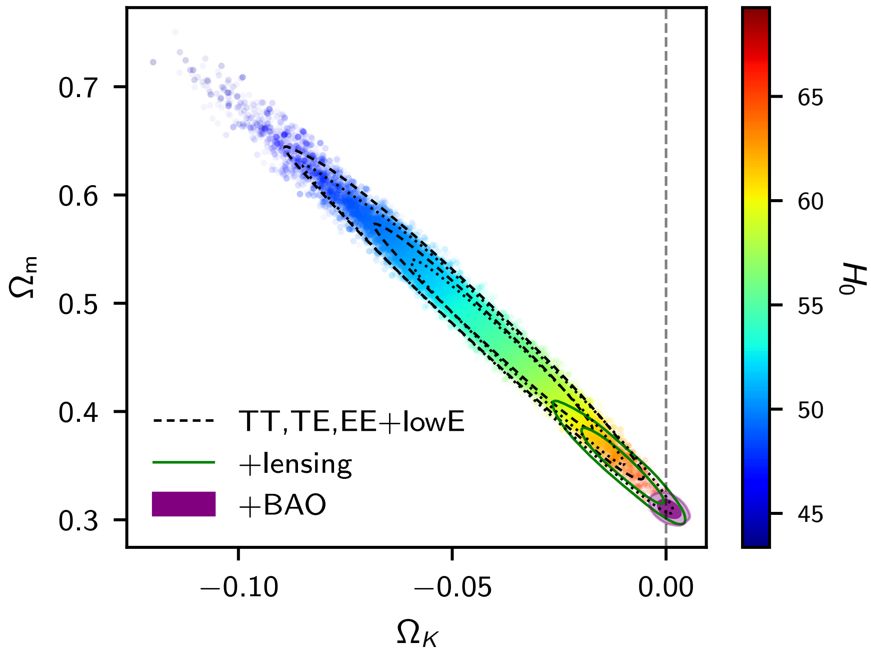
However, fitting these features with these parameters is in disagreement with other datasets.

Curvature, dark energy, modified gravity etc..

- Curvature $\Omega_k<1$, phantom dark energy $w<-1$, modified gravity etc.. can allow larger lensing amplitude, thus preferred by Planck spectra at the 2-3σ level.

- In the baseline likelihood configuration, the delta-chi2 between ΛCDM and ΛCDM $+\Omega_k$ is 11. With a different correction for systematic effects, it reduces to 5.
- **Thus, deviation from ΛCDM depends somewhat on systematic effects.**

- **Furthermore, when adding CMB lensing reconstruction, less preference for deviations, further tightened by BAO.**



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

Outline

1. Short recap on Planck results
2. Post-Planck Issue 1: Comparison with other probes. The H_0 problem and the σ_8 discrepancies
3. Post-Planck Issue 2: Internal "curiosities" in the Planck data (A_L, curvature etc..)
4. Are Issue 1 and Issue 2 related?

Can the A_L deviation solve the tensions with other probes?

Riess+ 2019 $H_0 = 74.03 \pm 1.42$ 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.

Conclusions

1. Correction in systematics in the legacy release have improved spectacularly the robustness of the Planck results.
2. The ΛCDM model is an excellent fit to the data.
3. 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.

Improvement of polarization systematics in 2018

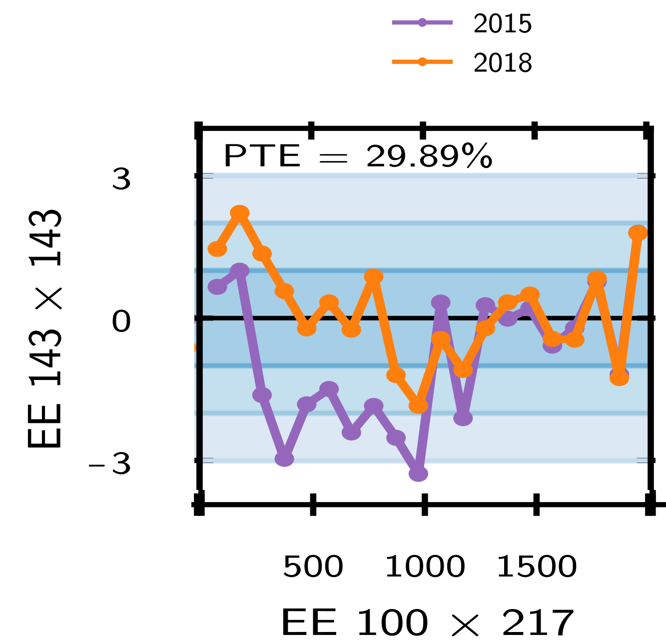
- **Correction of systematics** in polarization (large scales: map-making and sims. Small scales: beam leakage (improved TE by $\Delta\chi^2=37$) and polarization efficiency corrections (improved TE by $\Delta\chi^2=50$). Changes of $< 1\sigma$ on parameters.

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)).

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.

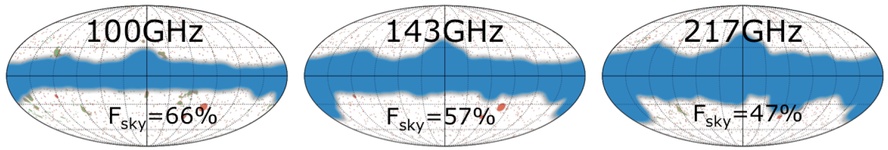
3. Can curiosities explain the tensions?

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

5. Polarization

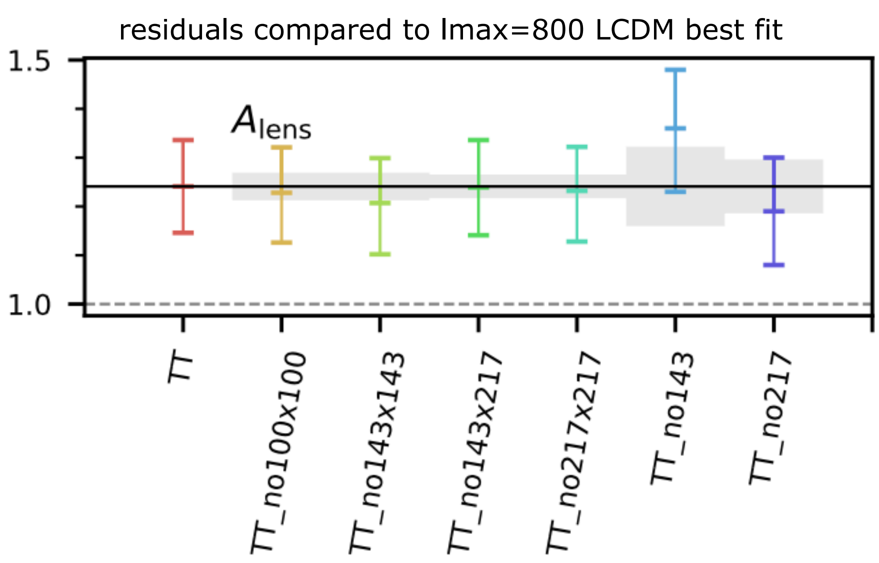
Is Alens due to a problem with galactic dust?

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

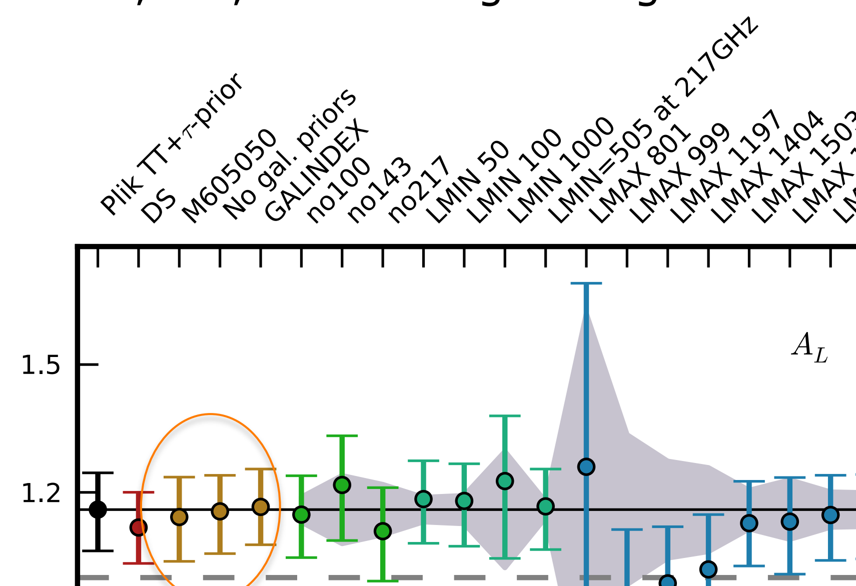


Changes in Alens estimated **eliminating 1 frequency** at the time are compatible with statistical fluctuations.

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

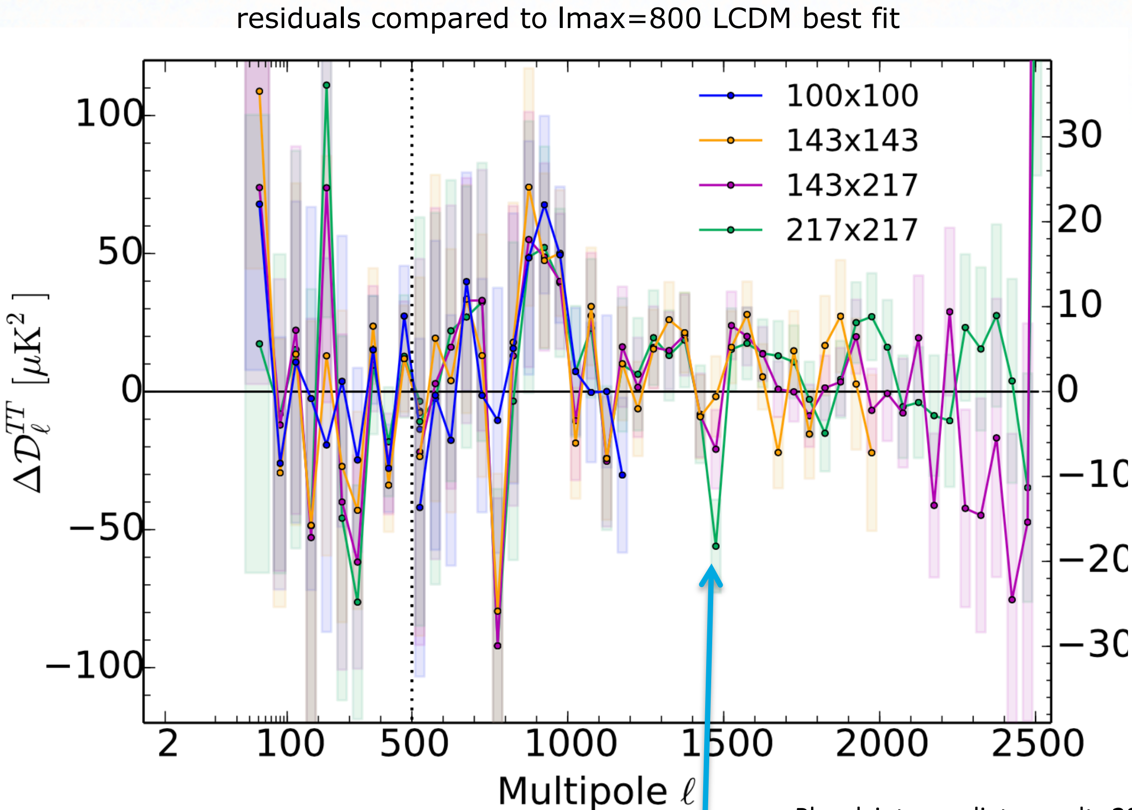


- Planck **2018** results. V. Legacy Power Spectra and Likelihoods



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

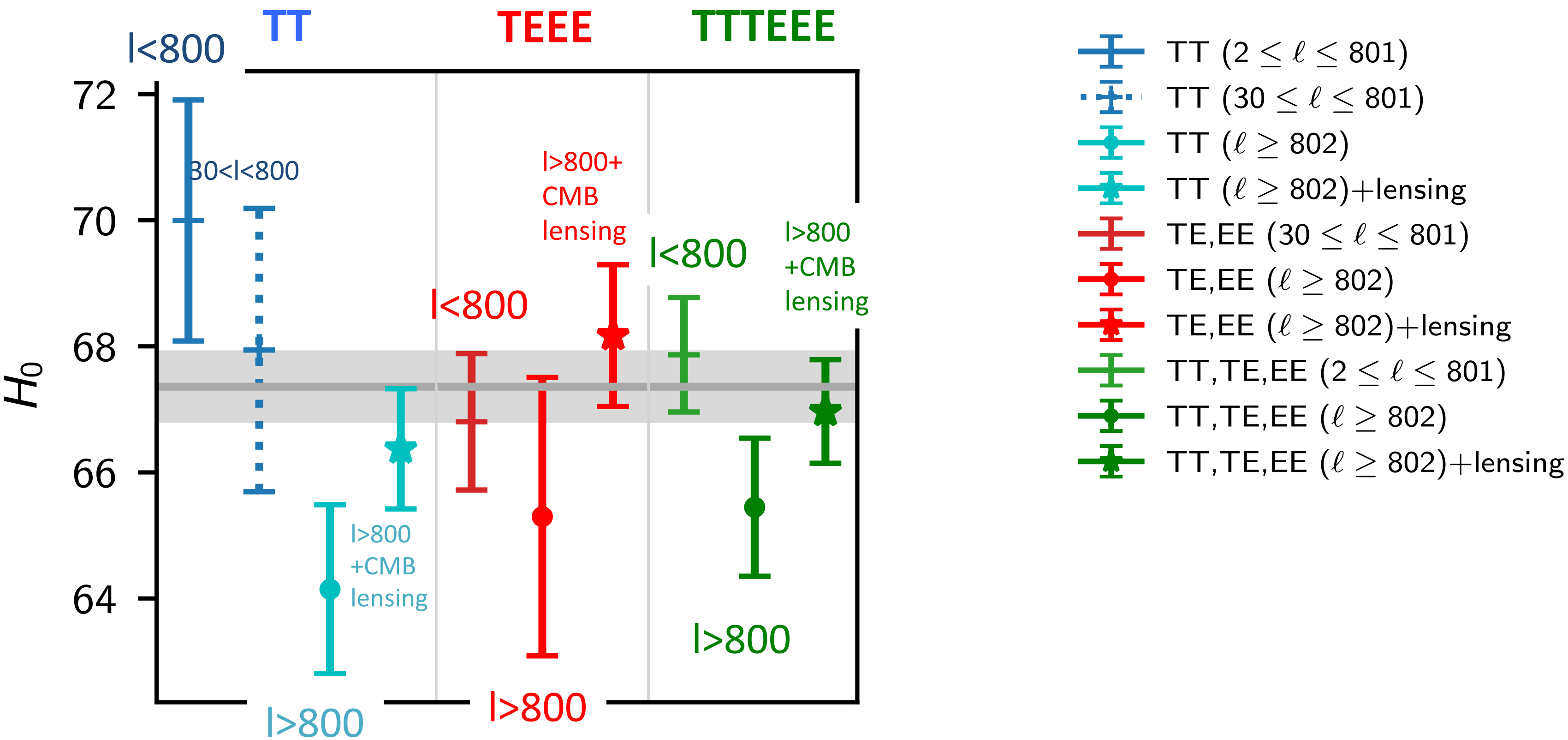
Is Alens due to a problem with galactic dust?



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.

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

Planck collaboration VI 2018