Planck results, curiosities and tensions in the ΛCDM model

- 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

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?

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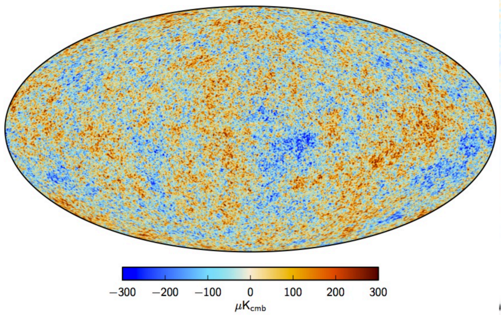
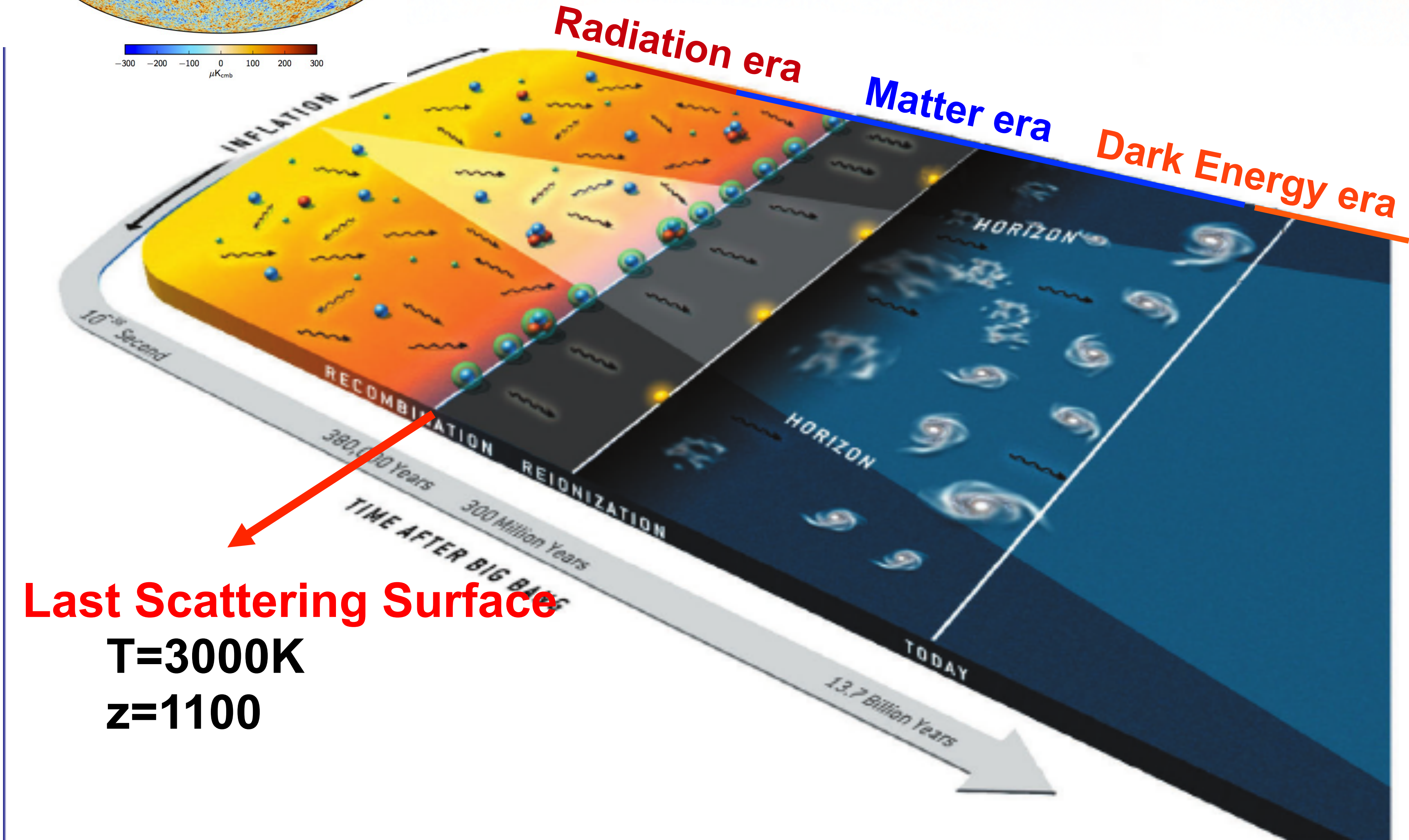
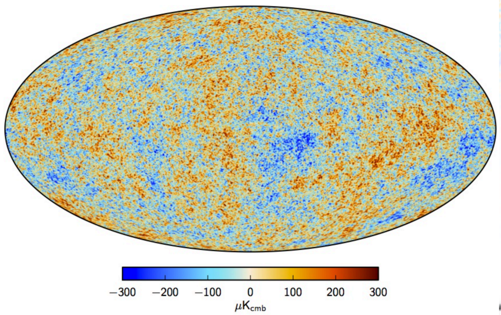
CMB



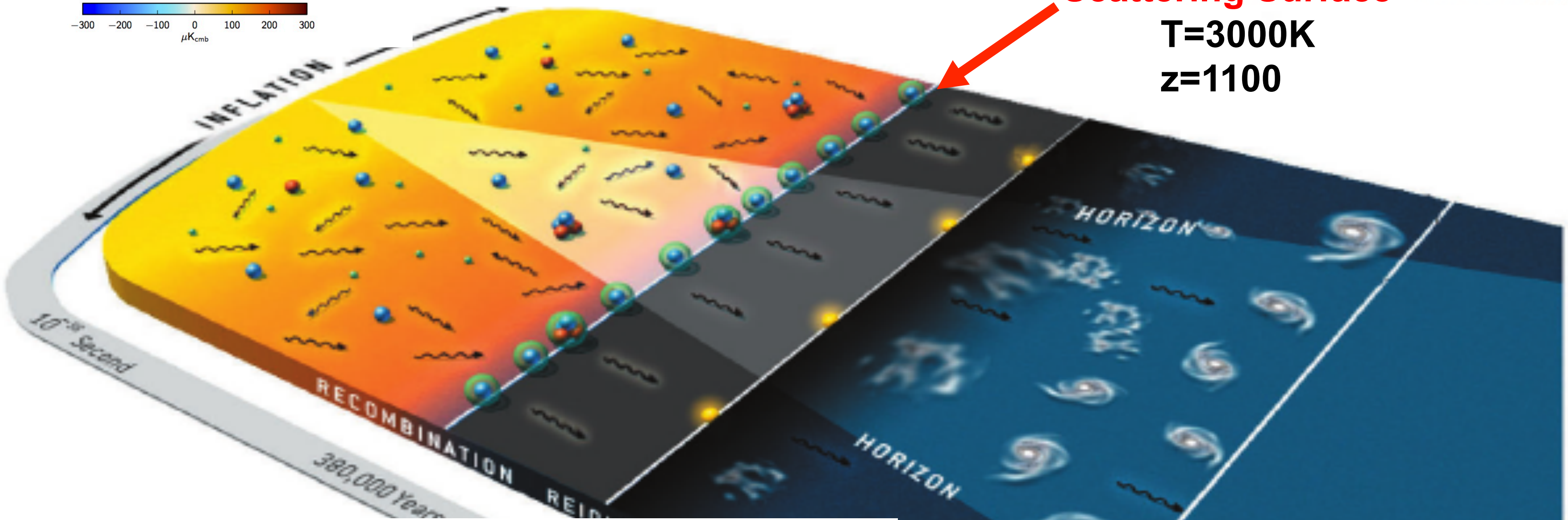


Hu & White (2004); artist: B. Christie/SciAm; available at http://background.uchicago.edu

CMB

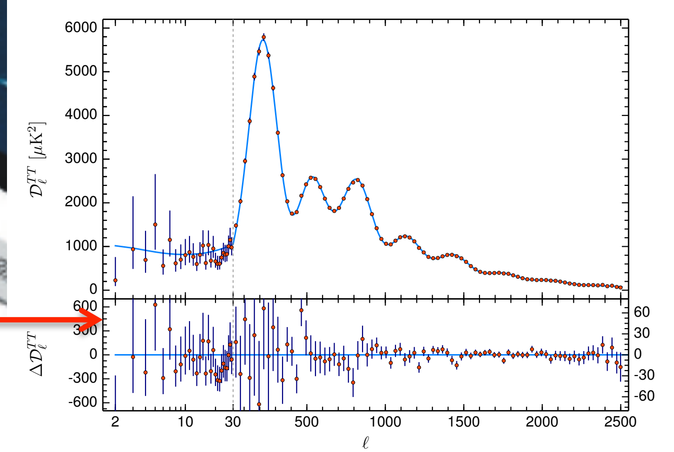


CMB from last Scattering Surface
T=3000K
z=1100



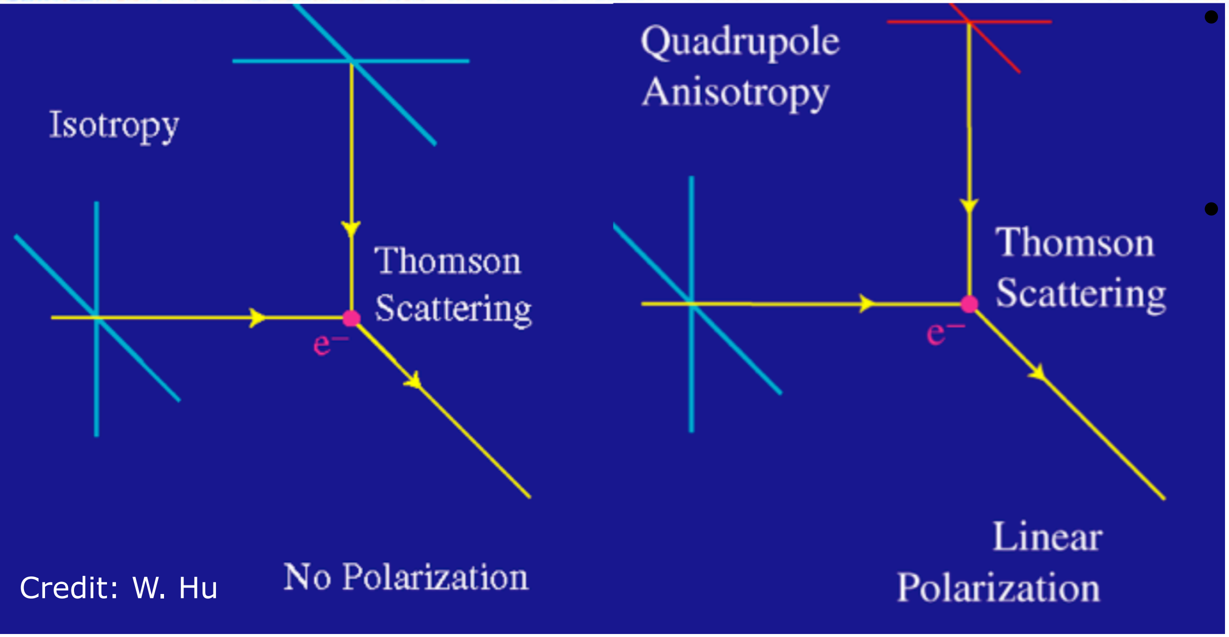
$$\Theta(\vec{x},\hat{p},\eta) = \sum_{l=1}^{\infty}\sum_{m=-l}^{l} a_{lm}(\vec{x},\eta)Y_{lm}(\hat{p})$$

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

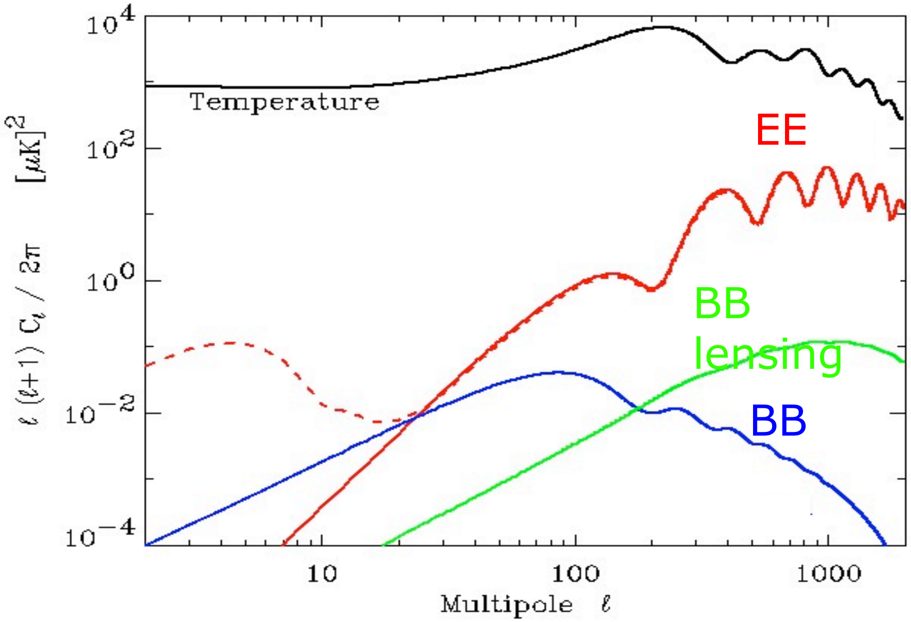


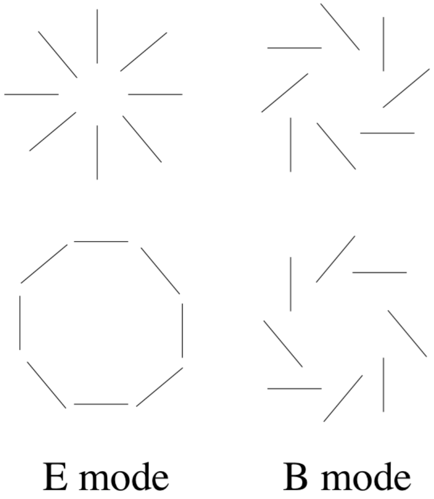
Hu & White (2004); artist: B. Christie/SciAm; available at http://background.uchicago.edu

CMB Polarization

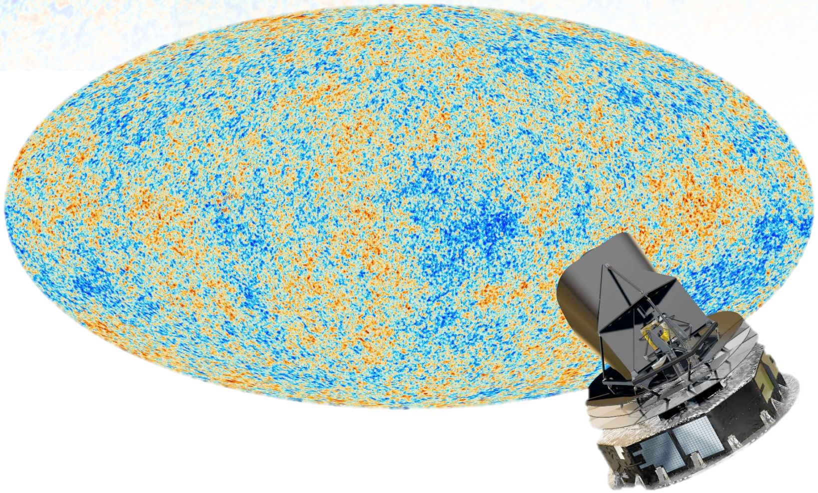


- Polarization generated by local quadrupole in temperature.
- Sources of quadrupole:
  - Scalar: E-mode
  - Tensor: E-mode and B-mode





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.**

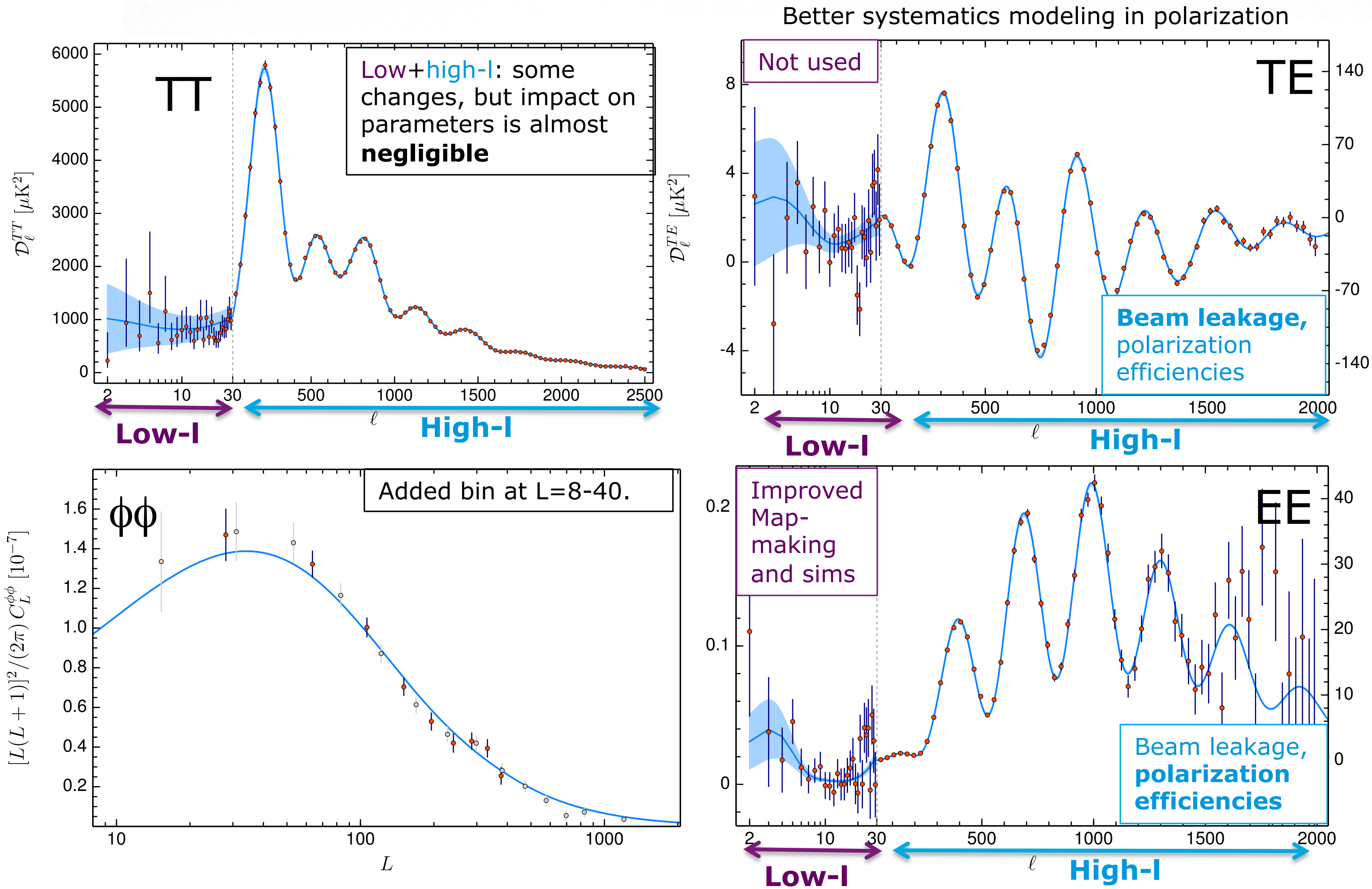
- **1st release 2013: Nominal mission**, 15.5 months, Temperature only (large scale polarization from WMAP).

- **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

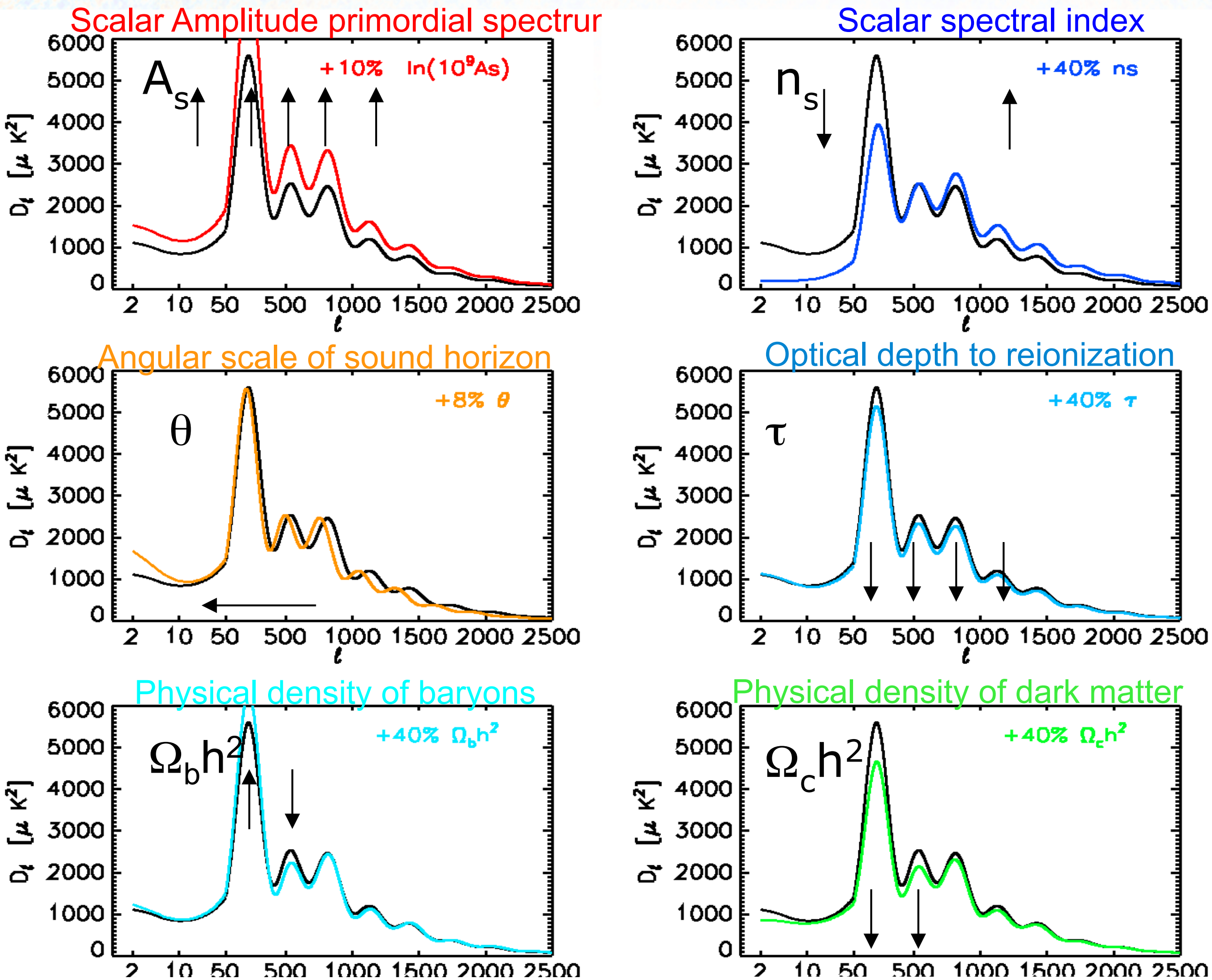
- **3nd release 2018: Full mission, improved polarization, low/high-l from HFI.** Better control of systematics specially in pol., still systematics limited.

2018 Power spectra

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



6 ΛCDM parameters



- Initial conditions A_s, n_s:

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

- Acoustic scale of sound horizon θ
- Reionization τ

- Dark Matter density $\Omega_c h^2$
- Baryon density $\Omega_b h^2$

Assumptions:

- Adiabatic initial conditions
- Neff=3.046
- 1 massive neutrino 0.06eV.
- Tanh reionization (Δz=0.5)

planck

Baseline ΛCDM results 2018

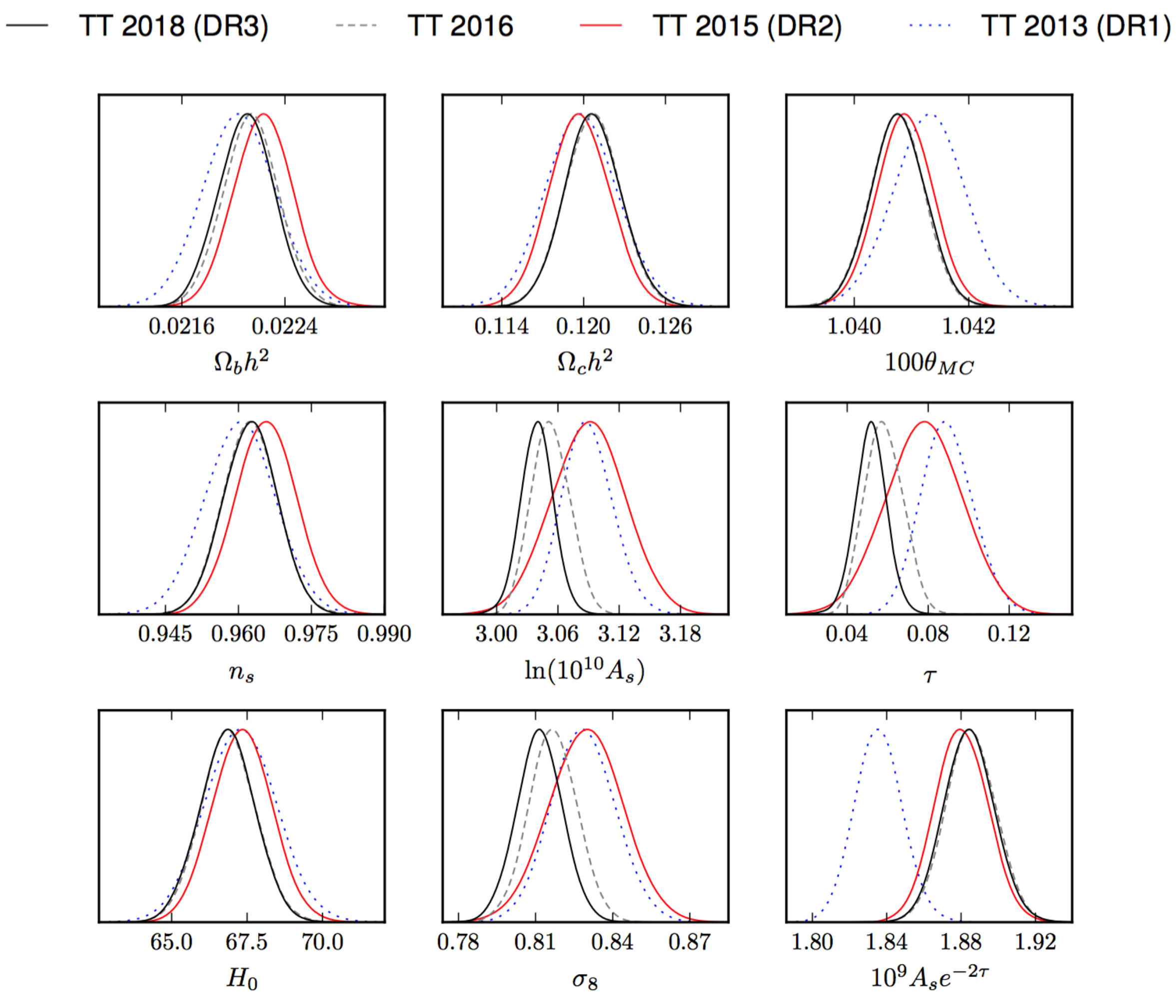
(Temperature+polarization+CMB lensing)

	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.

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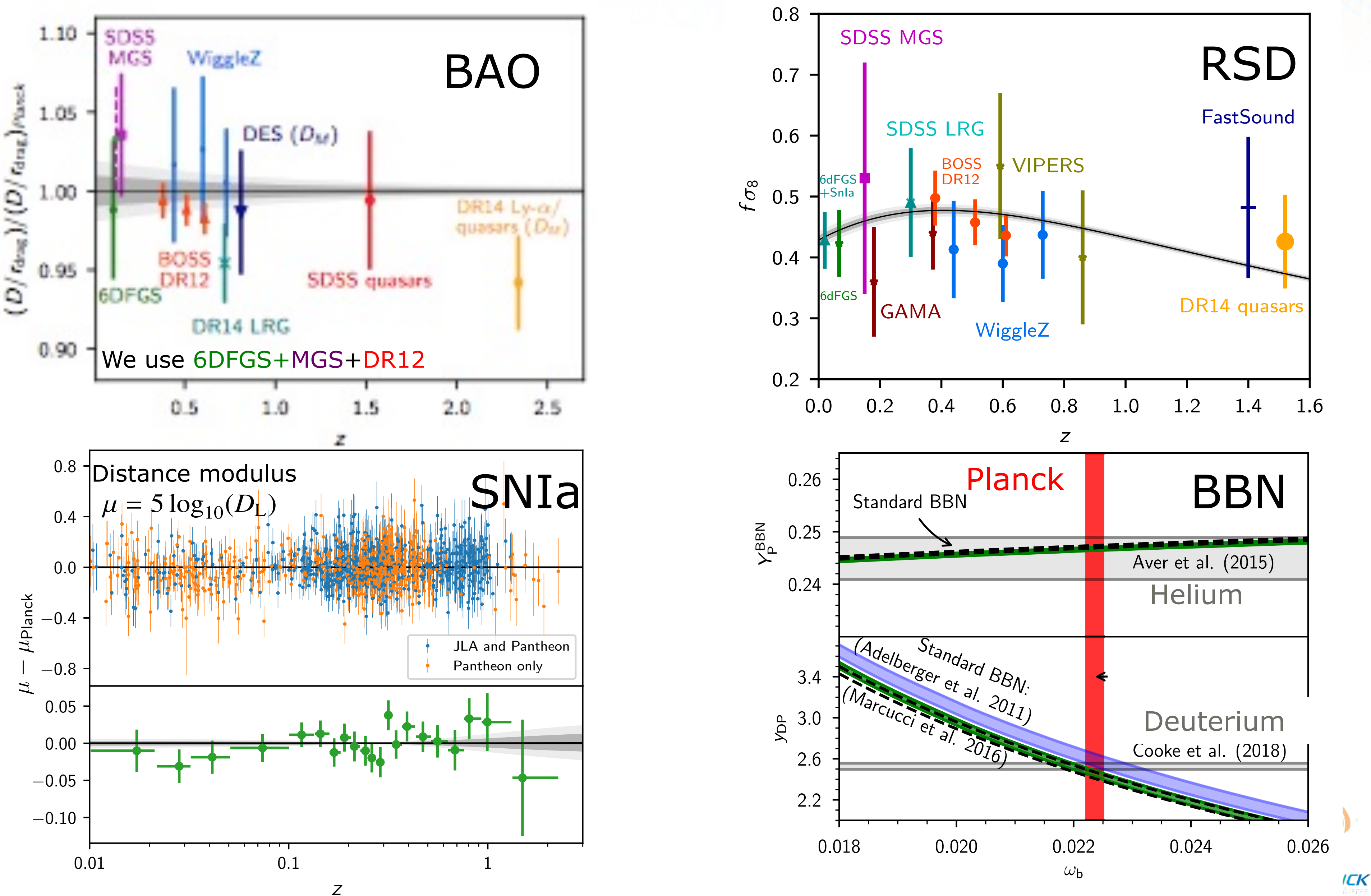
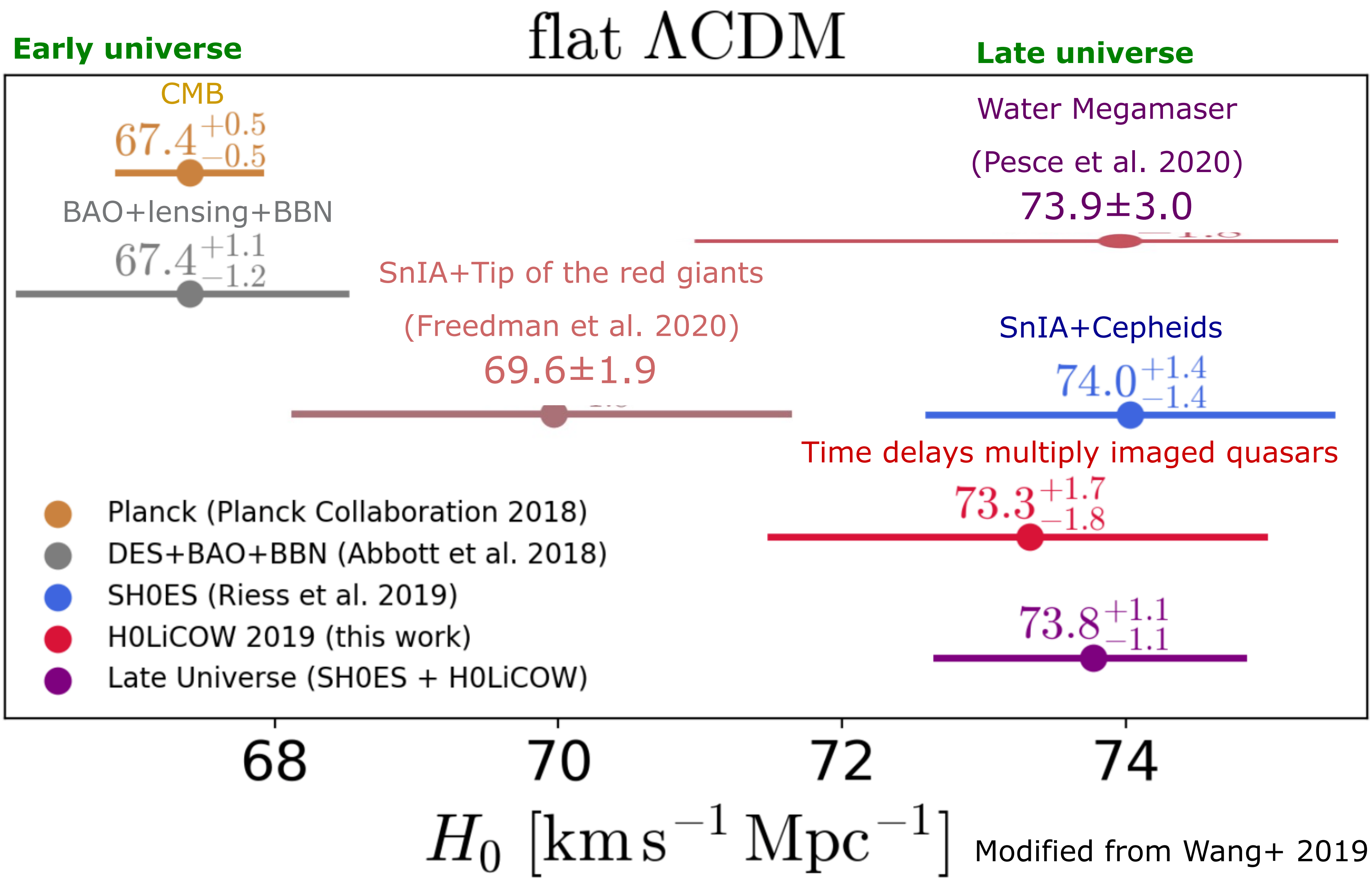
Good consistency with BAO, RSD, SnIa, BBN



Strong tension between early and late universe probes of H_0.

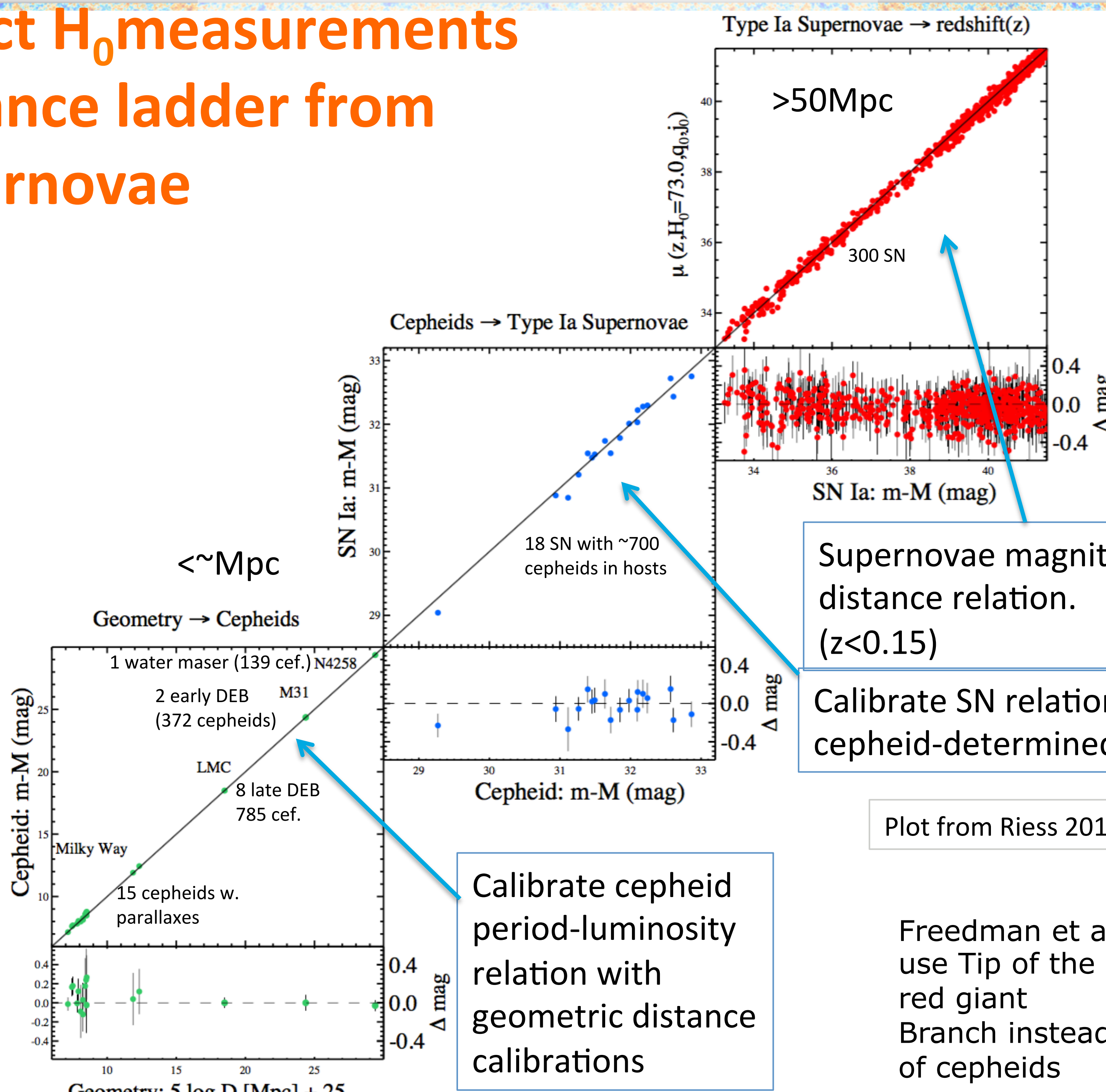


Modified from Wang+ 2019

So what's wrong?

- ~~Statistical fluctuation unlikely~~
- Systematics in distance ladder and time delays?
- Systematics in CMB and BAO?
- New physics

Direct H_0 measurements distance ladder from supernovae



Supernovae magnitude-distance relation. (z<0.15)

Calibrate SN relation with cepheid-determined distances

Plot from Riess 2016

Calibrate cepheid period-luminosity relation with geometric distance calibrations

Freedman et al. use Tip of the red giant Branch instead of cepheids

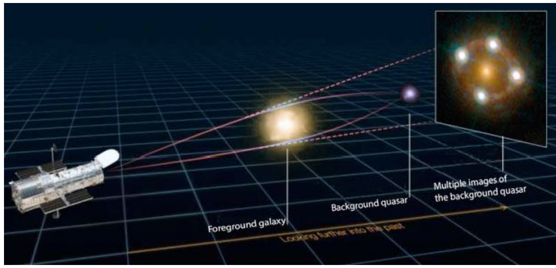
Systematics in direct measurements?

- H_0 reanalysis of the Riess (2011/2016) data:
  - Zhang et al. 2017 (arXiv:1706.07573v1): Riess 2011 data,global fit, impact of systematics from cepheids (outliers, anchors, period) and SNIA. Applied on R11, finds H_0 = 72.5 ± 3.1(stat) ± 0.77(sys) km/s/Mpc
  - Follin & Knox 2017 (arXiv:1707.01175) (modelling of cepheid photometry. H_0=73.3 ± 1.7 (stat) km/s/Mpc)
  - Cardona et al. 2017 (arxiv:1611.06088): Bayesian hyper-parameters for outlier rejection. H_0 = 73.75 ± 2.11 km/s/Mpc
  - Feeney et al. 2017 (arXiv:1707.00007): Bayesian hierarchical model, impact of non-gaussian likelihoods. H_0 = 72.72 ± 1.67 km/s/Mpc
  - Dhawan et al 1707.00715.pdf. Use of NIR observations of a subsample of the Riess 2016 supernovae (9/19 for the intermediate calibration rung, 27/300 SN in the Hubble flow). H_0=72.8 ± 1.6 (stat.) ± 2.7 (syst.) km/s/Mpc.

H_0 consistently high! But there are still remaining issues..

A few examples of open debates in late time measurements

1. Direct distance ladder measurements:
    a. For tip of the red giants branch: extinction of TRGB in large magellan cloud overestimated (Yuan+ 2019) which underestimated H0. Reply from Freedman+ 2020: that analysis is wrong. Still open debate.
    b. For cepheids: differences in photometry of cepheids (observed in crowded environments) between first and second ladder might bias results.
    c. For SNIA in general: SN brighness might be different in galaxies with different ages=> bias between 2 and 3rd step of the ladder (Rigault 2018, 2015). Reply from Jones+ 2015: nope that effect is too small. Still open debate.
2. Time delays measurements: uncertainties in lens modeling might be underestimated (see eg. Kochanek 2019, Blum+ 2020).



Courtesy: Martin Mill

Systematics in the CMB ? Consistency between different experiments

Planck vs WMAP

Baselines

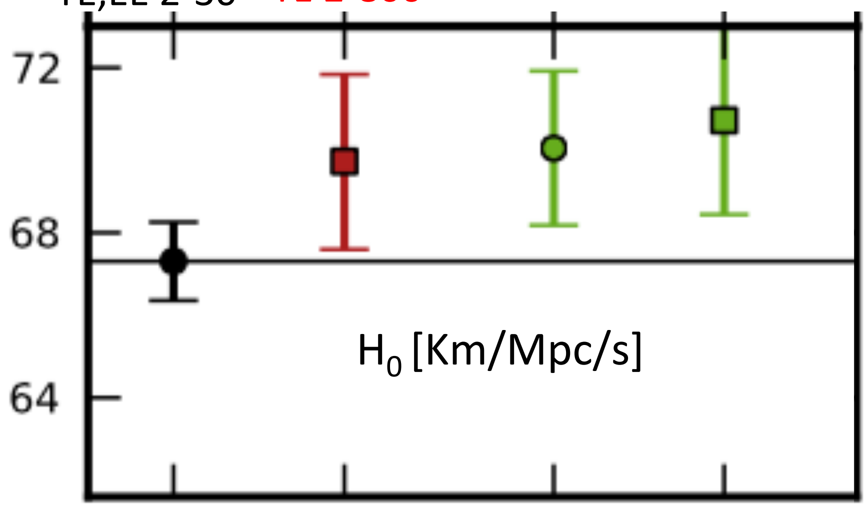
Planck
TT 2-2500
TE,EE 2-30

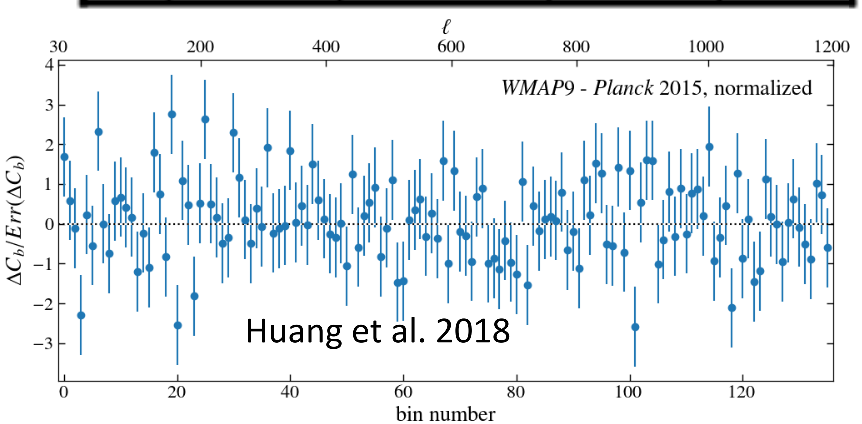
WMAP
TT 2-1200
TE 2-800

Only TT, same τ

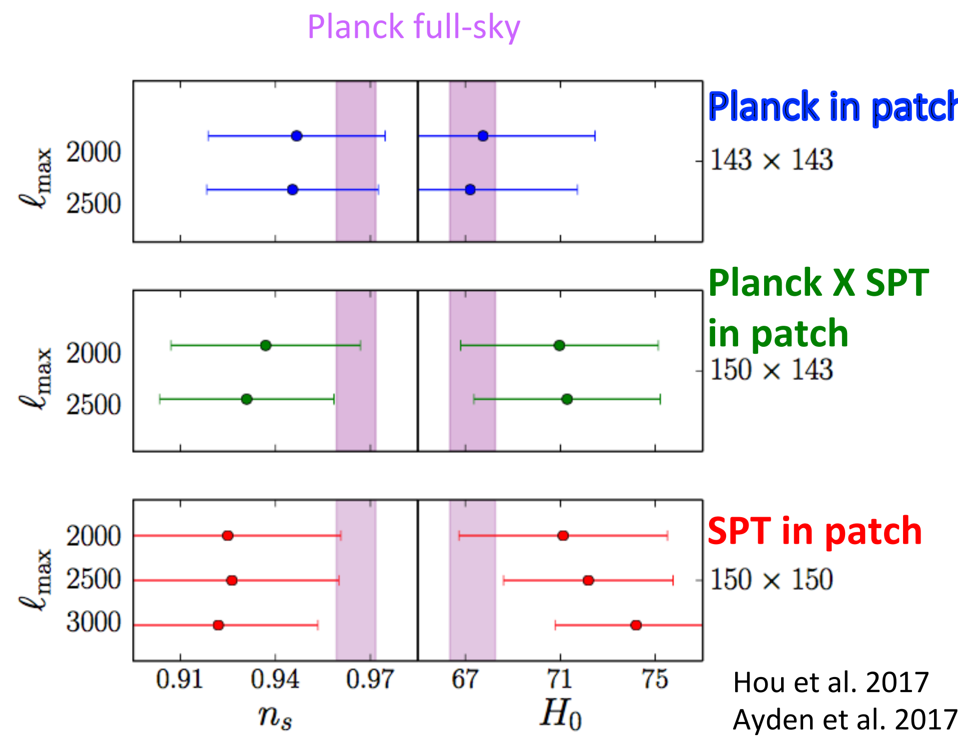
Planck WMAP

TT 2-800





Planck vs SPT-SZ



Aylor et al. 2017 arXiv:1706.10286
Hou et al. 2017 arXiv: 1704.00884

Systematics in the CMB ?
Consistency between different experiments

Planck 2018	H_0=67.4±0.5
Riess+ 2019	H_0=74.0±1.4

See also
SPTPol (TE,EE)
H_0 =71.2 ± 2.12 (Henning+17)

ACTPol (TT,TE,EE)
H_0 =67.3 ± 3.6 (Louis+17)

- WMAP and SPT give somewhat larger but still consistent with Planck values of H_0
  - WMAP9* H_0=70±2.2 [Km/s/Mpc] (Hinshaw et al. 2013)
  - SPT-SZ H_0=73.3 ± 3.5 (Aylor et al. 2017)

- Are these consistent with the low H_0 Planck measurement? When adding BAO, yes!

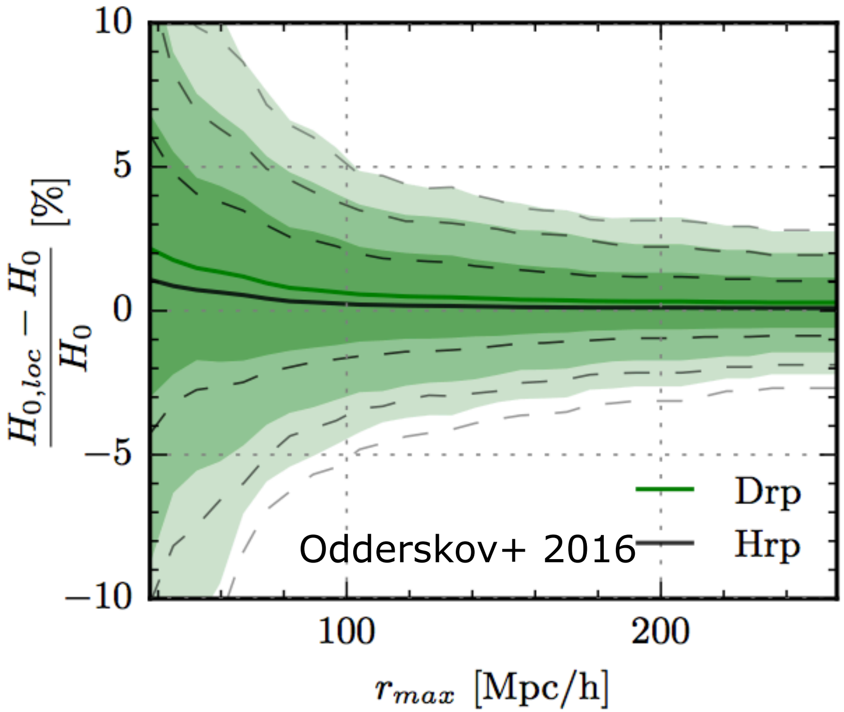
  - Combining WMAP ACT and SPT with BAO to decrease errors low H_0
    - WMAP9+BAO (BOSSDR11+6dFGS+Lyman α)+high-z Sne
      H_0= 68.1 ± 0.7 (Aubourg+ 2015)
    - WMAP9+ACT+SPT + BAO (BOSS DR11+6dFGS)
      H_0 = 69.3 ± 0.7 (Bennet+ 2014)

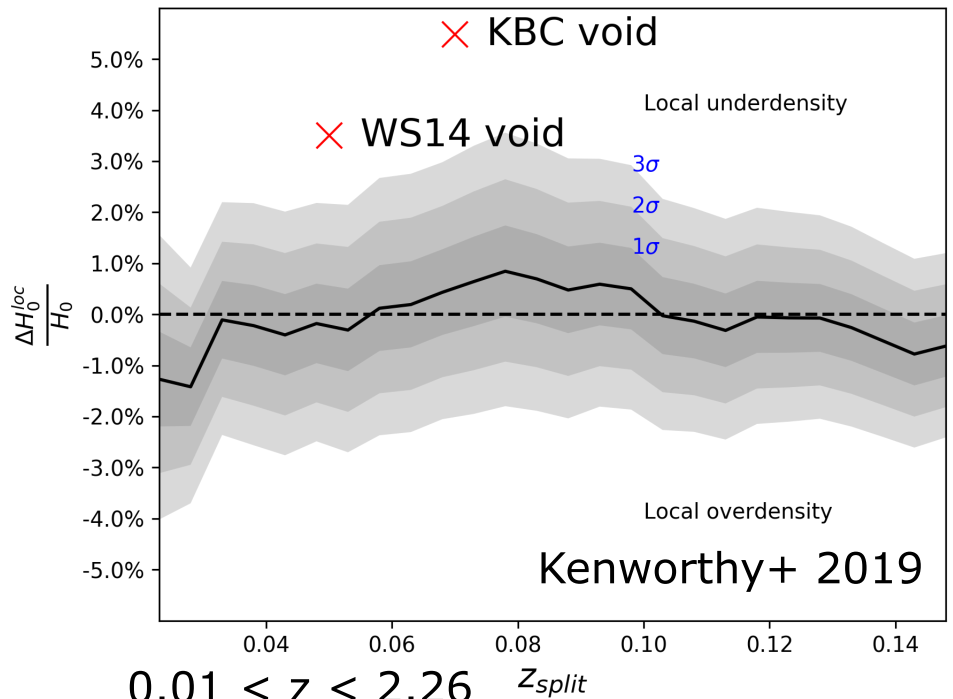
  - Planck, WMAP and SPT are consistent with each other.

*NB: these were obtained using slightly different assumptions for neutrino mass and optical depth w.r.t. Planck, see also Calabrese+16

A giant void in ΛCDM cannot explain it

Peculiar velocities. If we live in a large void and peculiar velocities are not properly taken into account when measuring redshifts, the local measurements of H_0 might be biased (e.g. Keenan 2013, Romano+ 2016). However, simulations show it would need to be a very atypical void (e.g. Marra+ 2013, Wojtak+ 2013, Odderskov+ 2016, Wu+ 2017), sample variance at the level of ~0.3km/s/Mpc. Supernovae at different redshifts do not show any deviation.





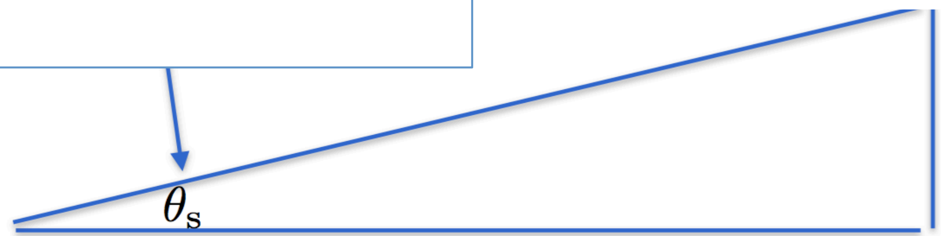
0.01 < z < 2.26

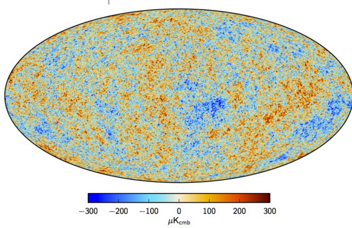
Indirect measurement of the Hubble constant from the CMB

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

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

Model dependent=> New physics can change the inferred value of H_0!

Early and late time solutions

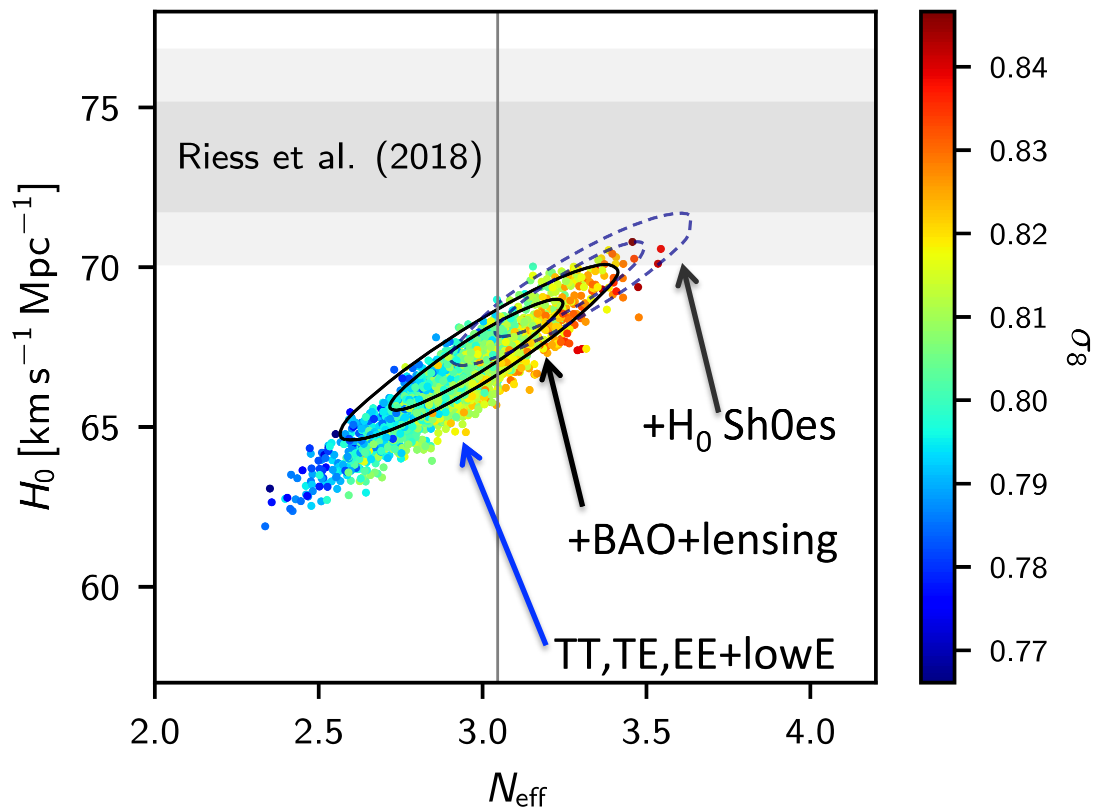
1. **Change in late time universe**
   - **(**late-time dynamics of dark matter and/or dark energy, e.g. dynamical dark energy, decaying DM (Poulin+ 2018, Vattis+ 2019) interacting dark matter-dark energy etc..) => highly constrained by BAO, Supernovae and other probes.
   - Modified gravity changes to Cepheid period-luminosity relation (Desmond et al. 1907.03778)=> but might be constrained by time delays.

See also e.g. Bernal +2016, Lemos+ 2018, Aylor 2018

1. **Change in the early time physics**. BAO and CMB measure angles, assuming calculation of sound horizon r_s.one can infer the distances and thus H_0=> changing r_s can change inferred H_0, but hard because usually these models impact other observables as well.

Early universe proposed solutions

- **Number of relativistic species** CMB is sensitive to radiation density. N_{eff} is radiation density other than photon. N_{eff}=3.046 (standard).
- Non-standard could be radiation (sterile neutrino, light relics) or non-standard thermal history.
- Planck 2018 constraint consistent to standard value.
- Proposed as possible solution to H_0 tension (N_{eff}-H_0degeneracy)
- Tension remains still at ~**3σ**



- **Early Dark Energy** model (Poulin et al 1811.04083), but also Smith +2019, Agrawal+ 2019 but many others.
- **Neutrino strong interaction** model (Kreisch et al. 1902.00534) (but bimodal and interactions order of magnitude stronger than standard weak ones).

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

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

Problems with the early dark energy solution.

Planck alone | +LSS+SH0ES | +LSS

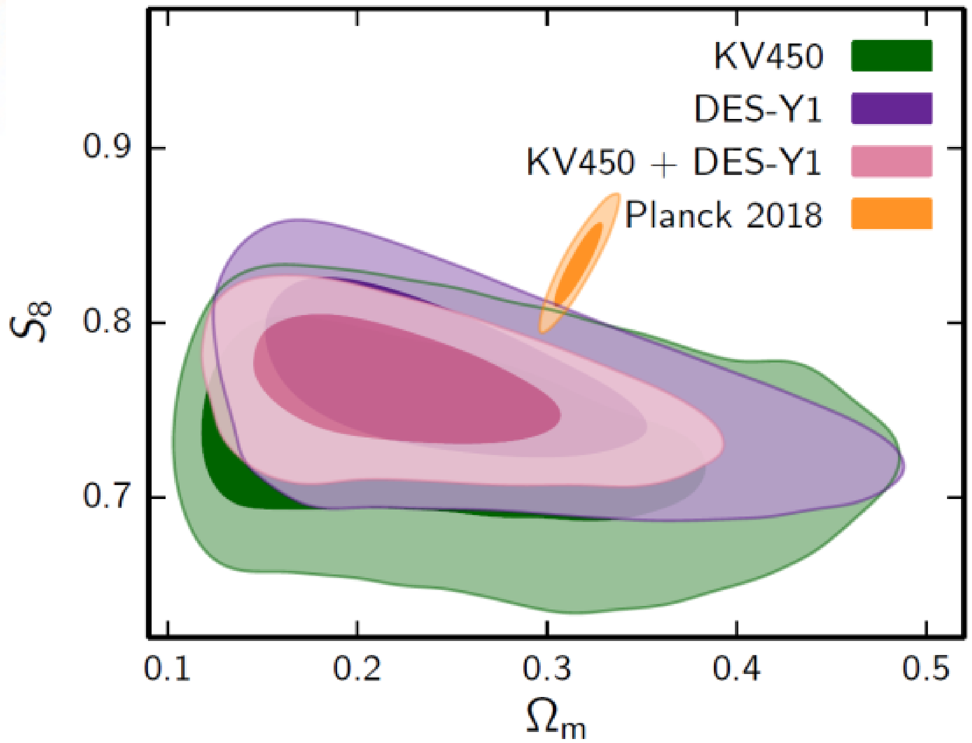
Constraints on EDE ($n = 3$) for varying data sets

Parameter	*Planck* 2018 TT+TE+EE	*Planck* 2018 TT+TE+EE, CMB lensing, BAO, RSD, SNIa, and SH0ES	*Planck* 2018 TT+TE+EE, CMB lensing, BAO, RSD, SNIa, SH0ES, and DES-Y1	*Planck* 2018 TT+TE+EE, CMB lensing, BAO, RSD, SNIa, SH0ES, DES-Y1, and HSC, KiDS (S_8)	*Planck* 2018 TT+TE+EE, CMB lensing, BAO, RSD, SNIa, DES-Y1, and HSC, KiDS (S_8) (no SH0ES)
$f_{\rm EDE}$	< 0.087	0.091 ± 0.034	$0.067^{+0.033}_{-0.035}$	$0.052^{+0.031}_{-0.032}$	< 0.053
$\log_{10}(z_c)$	$3.66^{+0.28}_{-0.24}$	$3.63^{+0.17}_{-0.11}$	$3.70^{+0.20}_{-0.17}$	$3.75^{+0.27}_{-0.23}$	> 3.17
θ_i	> 0.36	$2.53^{+0.35}_{-0.20}$	$2.47^{+0.42}_{-0.44}$	$2.34^{+0.53}_{-0.74}$	> 0.34
H_0 [km/s/Mpc]	$68.29^{+1.02}_{-1.00}$	70.73 ± 1.07	$70.33^{+1.05}_{-1.08}$	$70.00^{+0.99}_{-0.97}$	68.75 ± 0.50
σ_8	$0.8198^{+0.0109}_{-0.0107}$	0.8320 ± 0.0107	0.8200 ± 0.0103	0.8126 ± 0.0095	0.8050 ± 0.0064

Hill 2020+

1. Planck alone does not prefer early dark energy solution. Planck+LSS excludes early dark energy since it increases σ_8 through increase in $\Omega_c h^2$.
2. Requires early dark energy to kick in at a very fine tuned redshift around matter-radiation equality, and to then dilute faster than radiation.

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]

Numbers change for different experiments
and data combinations

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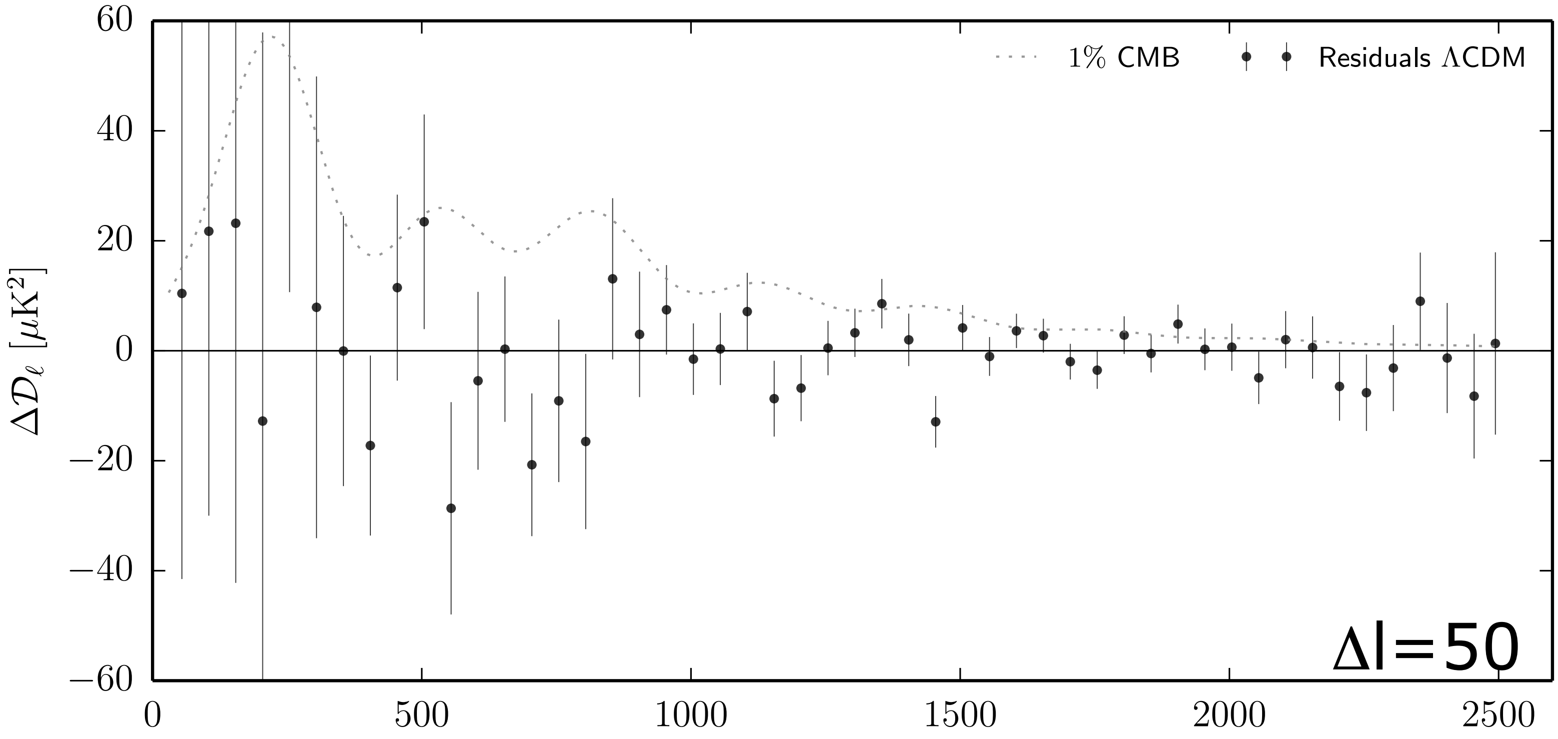
Residuals TT with respect to LCDM

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

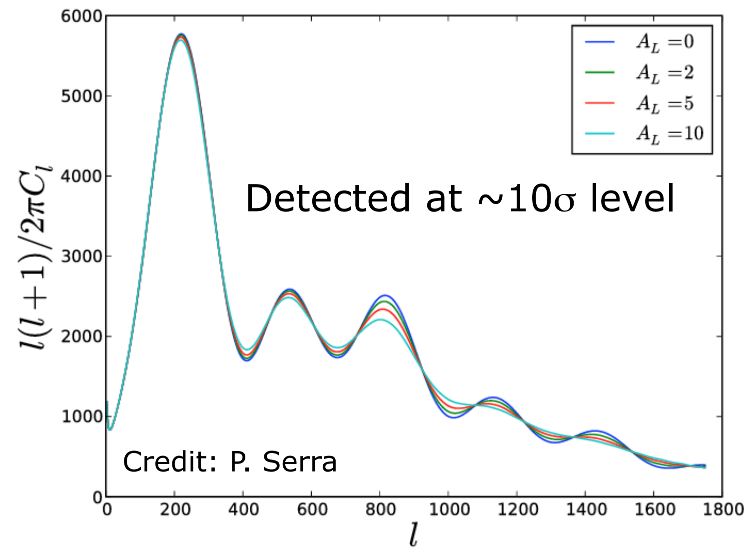
CMB lensing and A_{Lens}

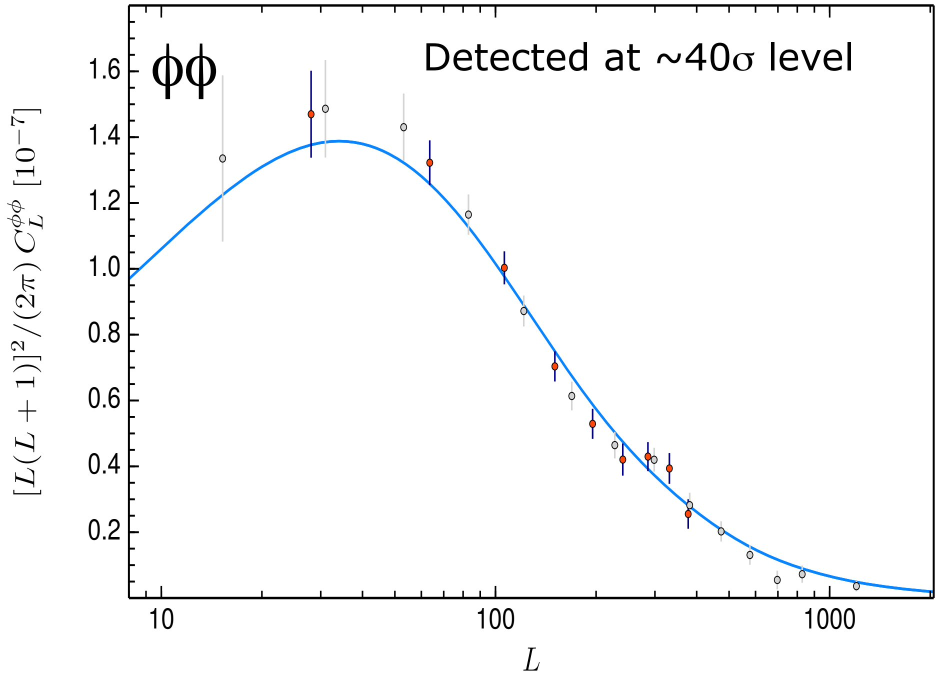
- Lensed CMB power spectrum is a convolution of unlensed CMB with lensing potential power spectrum=>**smoothing of the peaks and throughs**.

- 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

esa

Peak smoothing in the power spectra

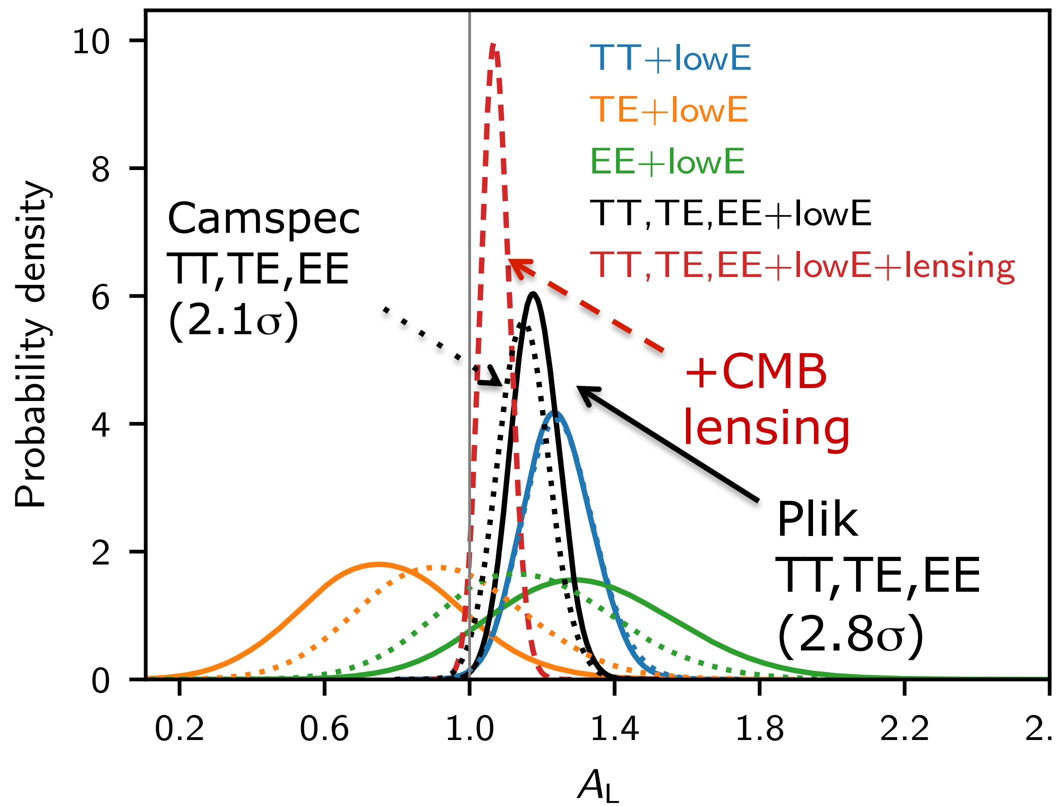
- A_l is an unphysical parameter used for consistency check.
- Since 2013 preference for high value, TT spectrum prefers 2.4σ deviation from 1.

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

- 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.

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

Amplitude of the lensing potential power spectrum.

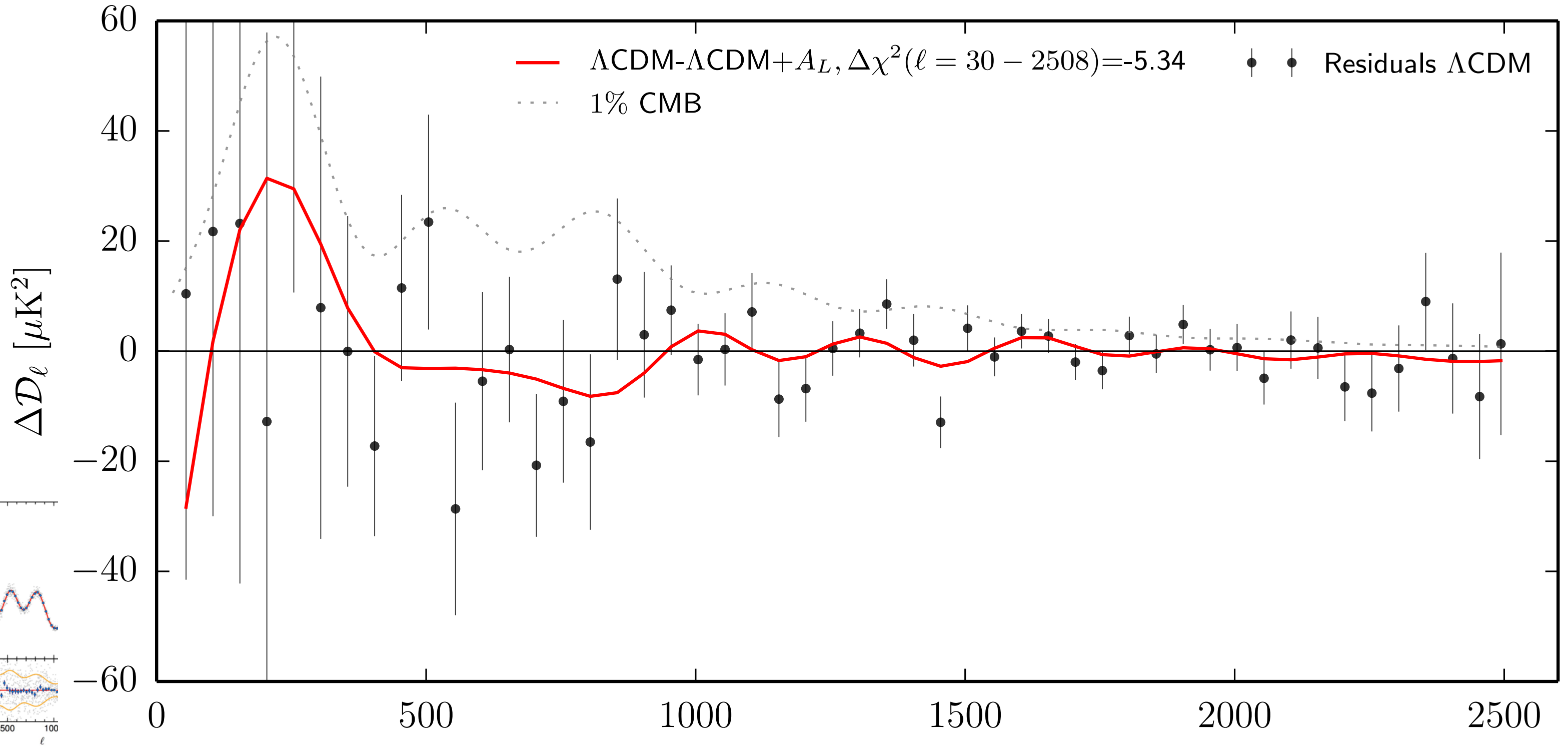


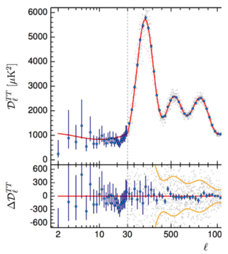
Planck **2018** results. VI. Cosmological parameters

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

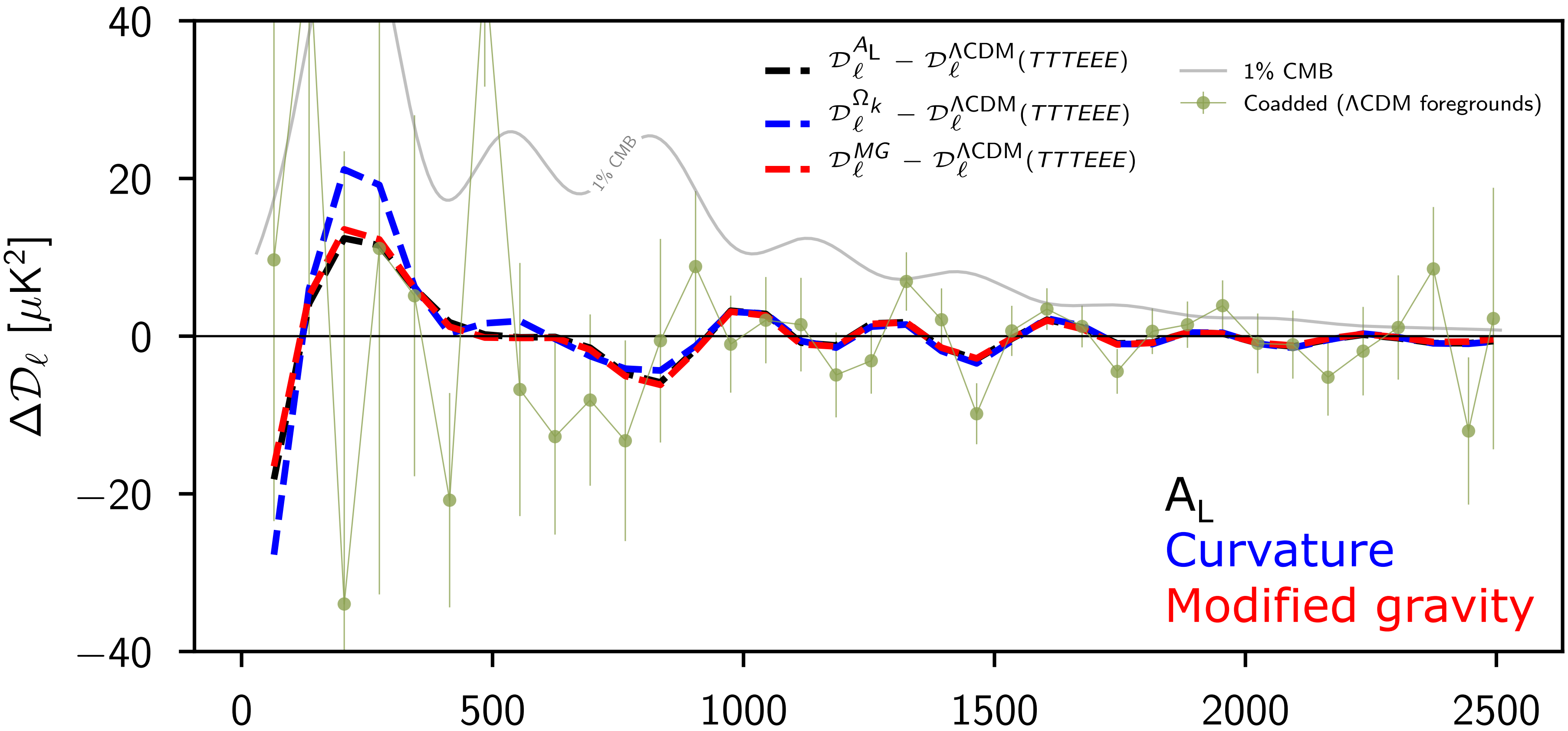
Residuals TT

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.

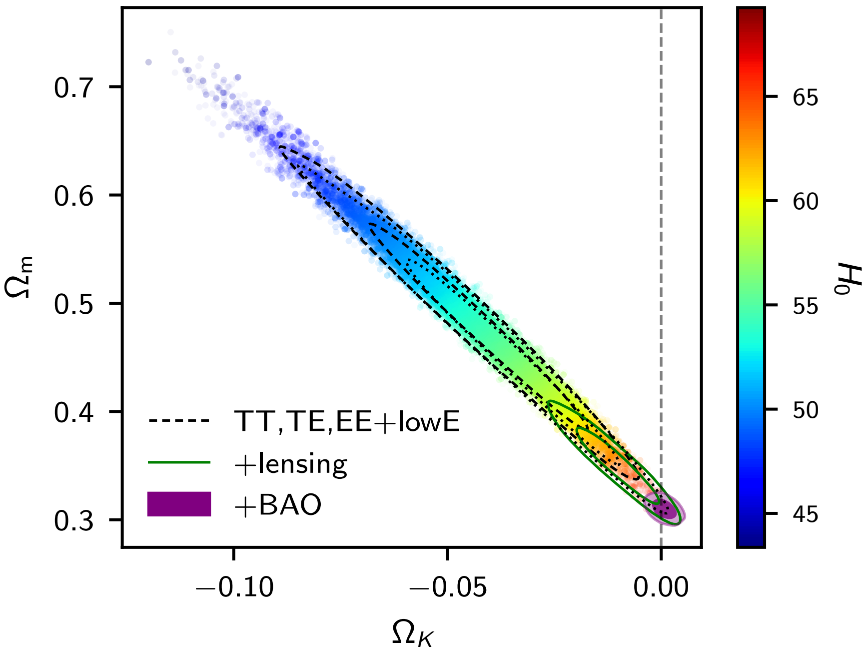
Curvature, dark energy, modified gravity etc..

- Curvature Ω_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 +Ω_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 ± 1.42 km s^{-1} Mpc^{-1}

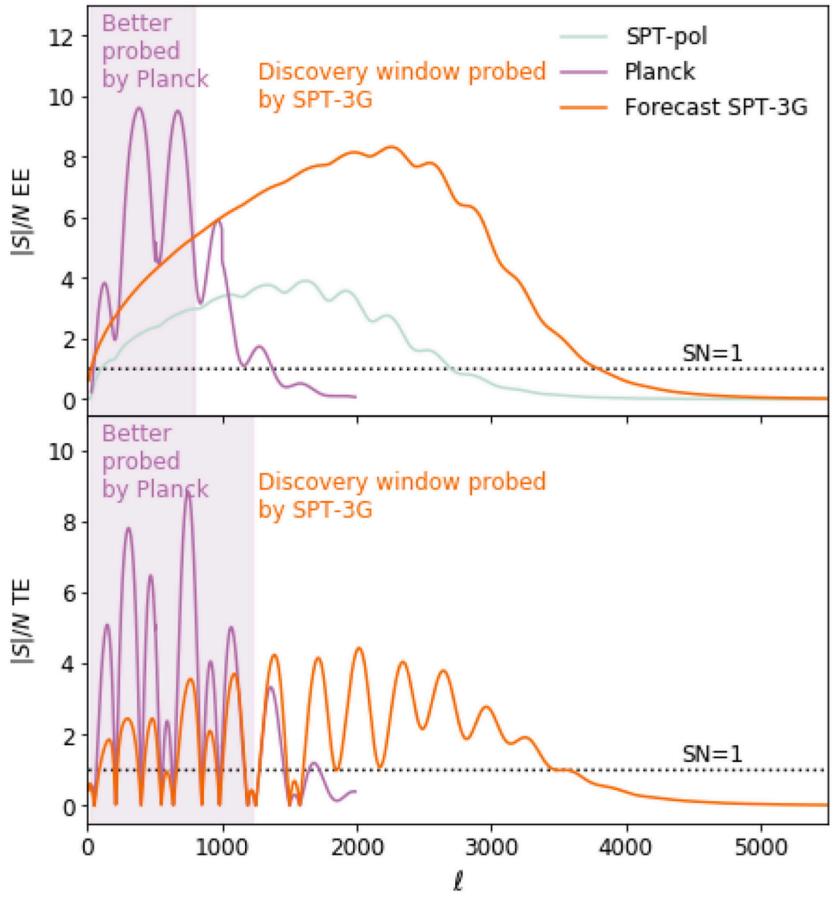
Joudaki+ 2019 $\mathbf{S_8}$ = 0.762+0.025

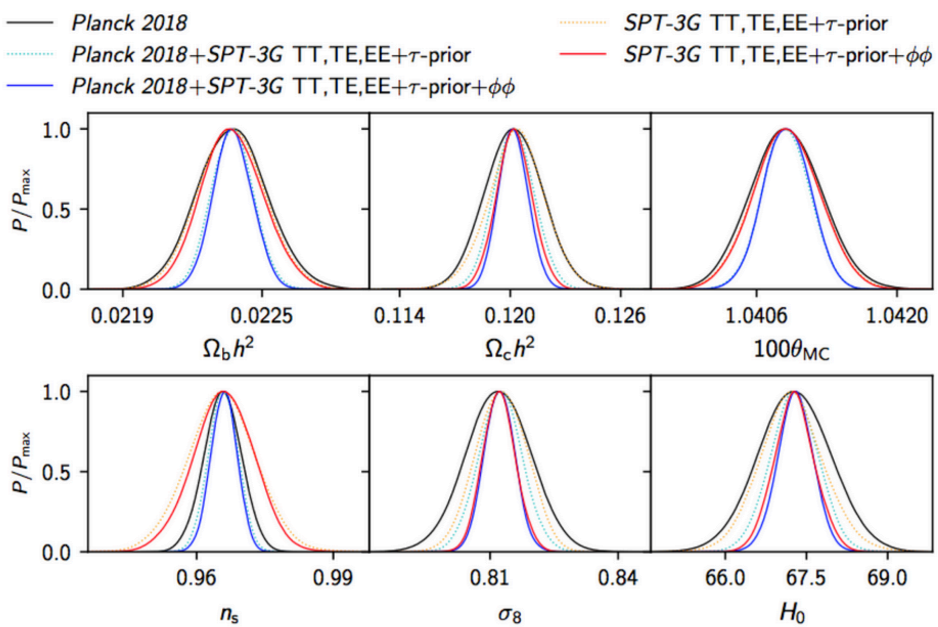
Planck TT+lowlEE 2018	H_0	S_8	A_L
ΛCDM	66.88 ± 0.92 **[4.2σ]**	0.840 ± 0.024 **[2.3σ]**	1.
ΛCDM+Alens	68.9 ± 1.2 **[2.7σ]**	0.788 ± 0.029 **[0.6σ]**	1.24±0.096
Planck TTTEEE +lowlEE 2018			
ΛCDM	67.27 ± 0.60 **[4.2σ]**	0.834 ± 0.016 **[2.4σ]**	1
ΛCDM+Alens	68.28 ± 0.72 **[3.6σ]**	0.804 ± 0.019 **[1.3σ]**	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 future is bright and full of new data!





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

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