Cosmic concordance in the CMB and other probes

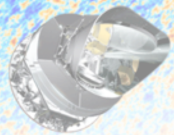
(Reviewing tensions between Planck and other data)

Silvia Galli
IAP-Paris

with Marius Millea, Lloyd Knox, Ali Narimani, Douglas Scott, Martin White
and the rest of the Planck collaboration

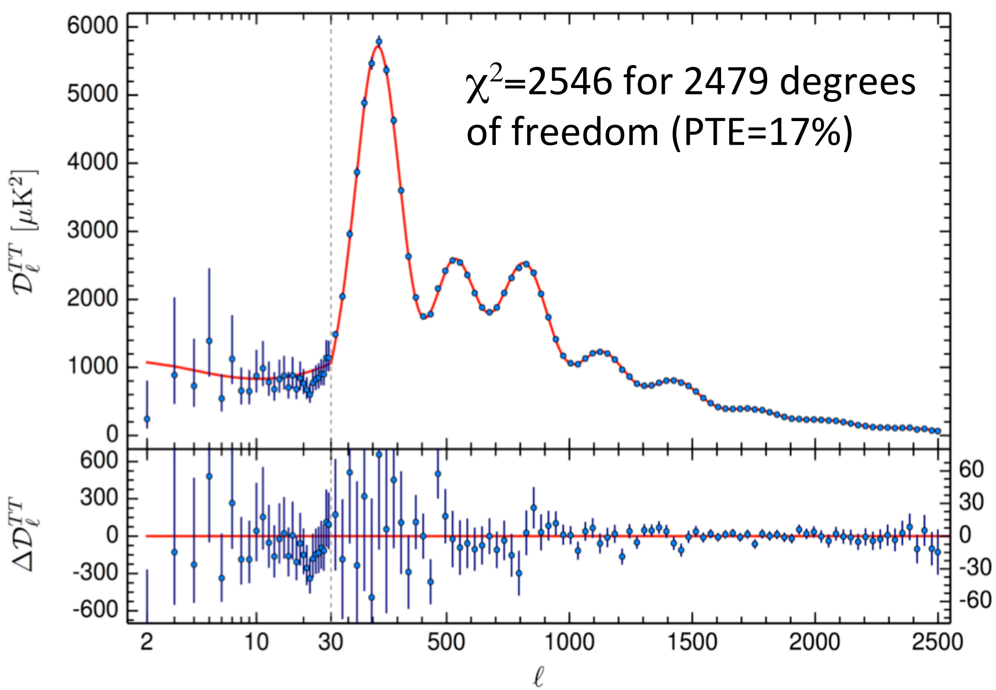
"Planck 2016 intermediate results. LI. Features in the cosmic microwave background temperature power spectrum and shifts in cosmological parameters "
arXiv:1608.02487

COSMO, Paris, 29/08/2017



ΛCDM and Planck

General relativity+standard model particles. Homogeneous and isotropic universe.
Cold dark matter, dark energy, baryons, radiation (photons+3 neutrinos).
Basic ΛCDM controlled by 6 parameters: ω_m, ω_b, A_s, n_s, τ, θ



Most of parameters at the ~1% level.

Curvature:
Compatible with flatness at the level of 10^{-3}

$$\Omega_K = 0.000 \pm 0.005 \ (95\%)$$
(PlanckTT+lowP+Lensing+BAO)

Sum of neutrino masses:
Bound already stronger than what achievable by Katrin (tritium beta decay)

$$\sum m_\nu < 0.23 \text{ eV}$$
(PlanckTT+lowP+Lensing+ext)

Number of relativistic species:
Compatible with standard predition N_{eff}=3.046 with 3 active neutrinos

$$N_{\rm eff} = 3.13 \pm 0.32$$
(PlanckTT+lowP)

Helium abundance
Good agreement with measurements of primordial abundances and BBN predictions

$$Y_P^{\rm BBN} = 0.253 \pm 0.021$$
(PlanckTT+lowP)

Running of the scalar spectral index
Compatible with no running

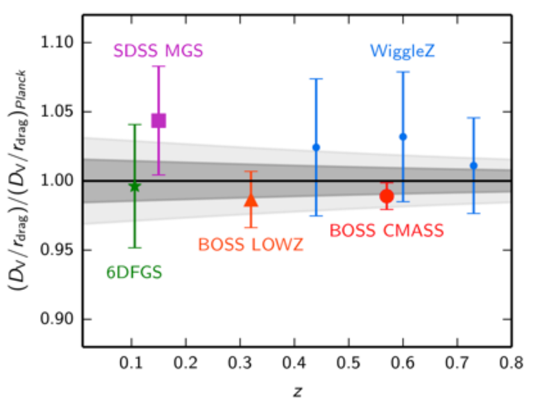
$$\frac{dn_s}{d\ln k} = -0.0084 \pm 0.0082$$
(PlanckTT+lowP)

No significant deviation from ΛCDM in extended models

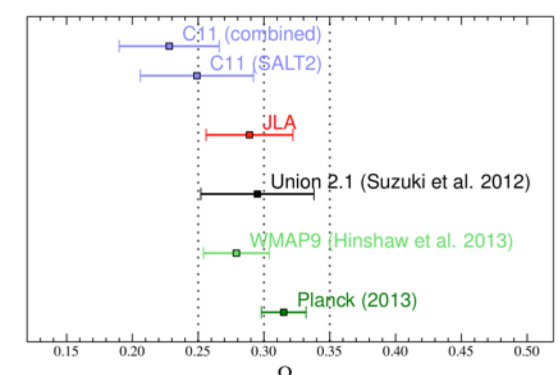
ΛCDM excellent fit to the Planck data

Comparison with other datasets:

BAO

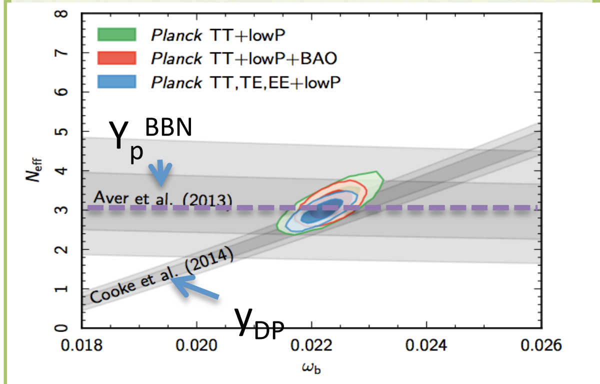


Supernovae (Ω_m)

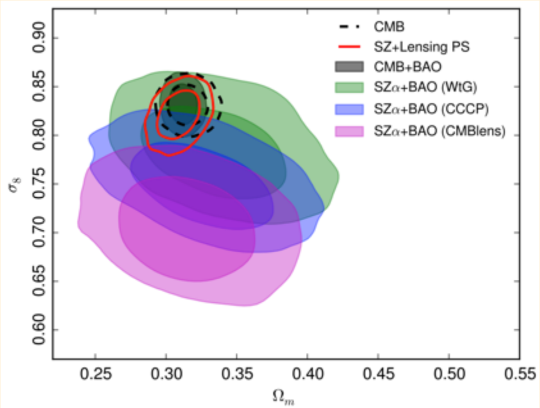


Betoule et al. 2014

BBN

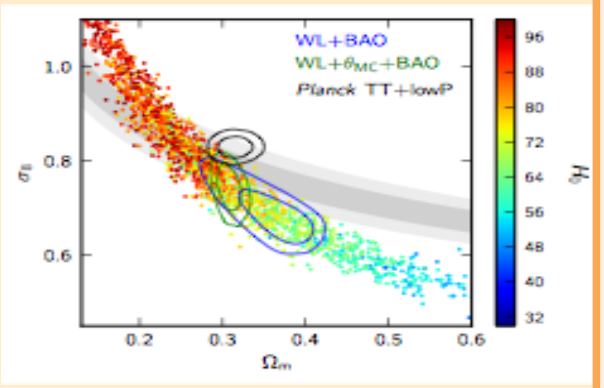


Cluster counts (σ_8-Ω_m)



Planck collaboration XXIV

Weak Lensing (σ_8-Ω_m)



Direct measurements H_0

H_0=66.9±0.91 (PlanckTT+ SIMlow_HFI, Planck 2016)

H_0=73.±1.8 (Riess+16)

H_0=72.8±2.4 (Riess+11)

H_0=70.6 ± 3.3 (Efstathiou+14)

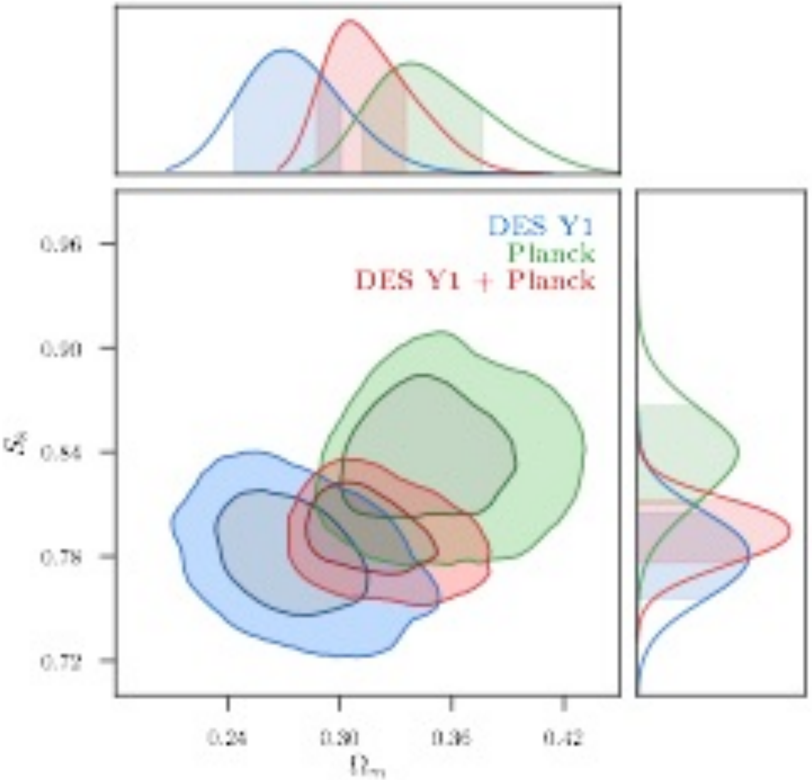
H_0=74.3 ± 2.6 (Freedman+12)

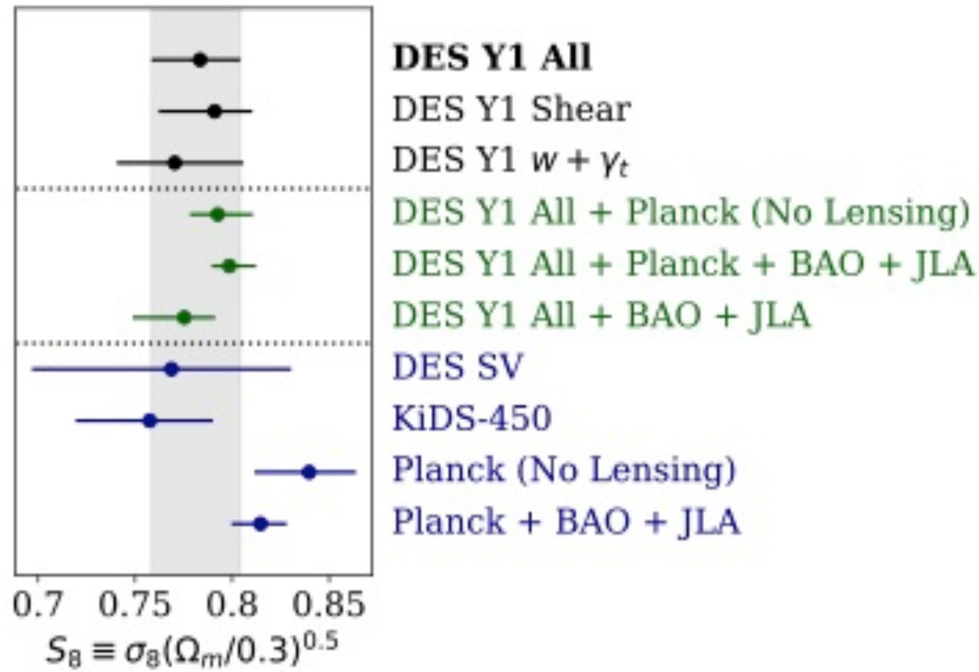
[Km/s/Mpc]

Extensions of ΛCDM, systematics in direct measurements or systematics in the CMB?

Weak Lensing: CFHTLenS, KIDS, DES Y1

DES Y1= shear+galaxy clustering+ galaxy-galaxy lensing





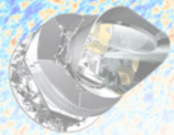
NB*: With sum of neutrino mass free to vary

« The Bayes factor here is R = 4.2, indicating "substantial" evidence for consistency on the Jeffreys scale, so any inconsistency apparent in [the 2D plots between Planck and DES] is not statistically significant according to this metric. »

DES collaboration+ 17

also Heymans+ 13(CFHTLens), Hildebrandt+ 16 (KiDS), KiDS:Kohlinger+ 17, Van Uitert+ 17, Joudaki+ 17

See talk from Shahab Joudaki (Mon.), Fabian Koehlinger (Tue.), Hendrik Hildebrandt (Wed.)

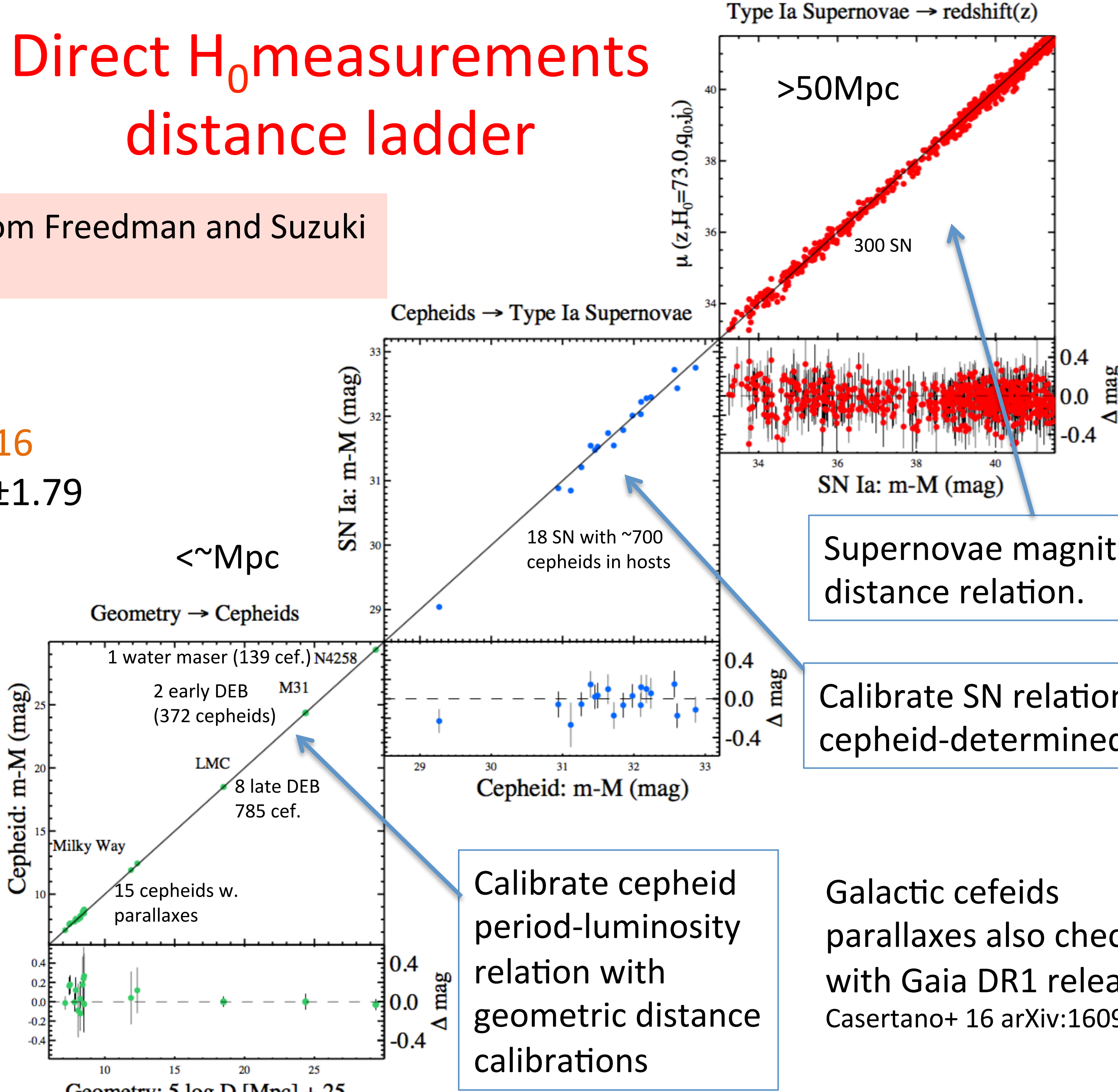


Direct H_0 measurements distance ladder

See talk from Freedman and Suzuki (Today)

Riess+ 2016

H_0=73.02±1.79



Supernovae magnitude-distance relation.

Calibrate SN relation with cepheid-determined distances

Calibrate cepheid period-luminosity relation with geometric distance calibrations

Galactic cefeids parallaxes also checked with Gaia DR1 release

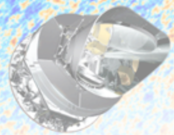
Casertano+ 16 arXiv:1609.05175

Riess+ 16

Extensions or systematics in direct measurements?

- H_0 reanalysis of the Riess data:
  - Error bars vary, but the best fit value remains high.
  - Zhang et al. 2017 (arXiv:1706.07573v1): 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.
- Extensions of LCDM:
  - No easy extension can solve all tensions and accommodate all data (see also Di Valentino+ 2016, Bernal+ 2016)
  - The case of extra relativistic species: adding Neff relaxes the tension with Riess et al. only because H_0 error from Planck is increased, but central value still low H_0 . Tensions is still at ~2 sigma level.

	Neff	H_0
Planck (ΛCDM)	-	**66.9 ± 0.91**
Planck (ΛCDM+Neff)	2.97 ± 0.28	**66.3 ± 2.4**



Systematics in the CMB ? Consistency between different experiments

PlanckTT15+lowP_HFI	H_0=66.9±0.9
Planck coll. 2016 arXiv:1605.02985	
Riess+ 2016	H_0=73.02±1.79

3σ tension

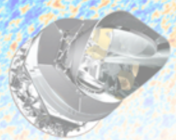
- However, WMAP and SPT give somewhat larger values of H_0
  - WMAP9 H_0=70±2.2 [Km/s/Mpc] (Hinshaw et al. 2013)
  - SPT-SZ H_0=75.0 ± 3.5 (Story et al. 2012)

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

See talk from Henning (Monday)

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

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



Systematics in the CMB ?
Consistency between different experiments

PlanckTT15+lowP_HFI	H_0=66.9±0.9
Planck coll. 2016 arXiv:1605.02985	
Riess+ 2016	H_0=73.02±1.79

3σ tension

- However, WMAP and SPT give somewhat larger values of H_0
  - WMAP9 H_0=70±2.2 [Km/s/Mpc] (Hinshaw et al. 2013)
  - SPT-SZ H_0=75.0 ± 3.5 (Story et al. 2012)

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

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

- Are these consistent with the low H_0 Planck measurement?

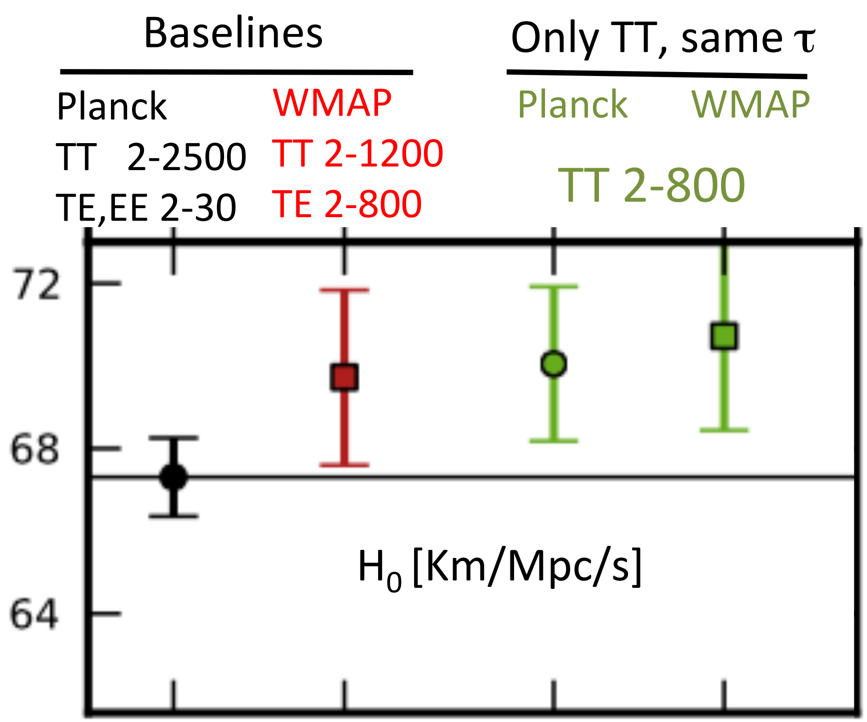
1. Combining WMAP ACT and SPT with BAO to decrease errors low H_0
   - WMAP9+BAO (BOSSDR11+6dFGS+Lyman α)+high-z Sne
     H_0= 68.1 ± 0.7 (2.5σ tension) (Aubourg+ 2015)
   - WMAP9+ACT+SPT + BAO (BOSS DR11+6dFGS)
     H_0 = 69.3 ± 0.7 (1.9s tension) (Bennet+ 2014)
   - BAO (galaxy+Ly-α)+Ydp
     H_0 = 66.98 ± 1.18 (Addison+ 2017)

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

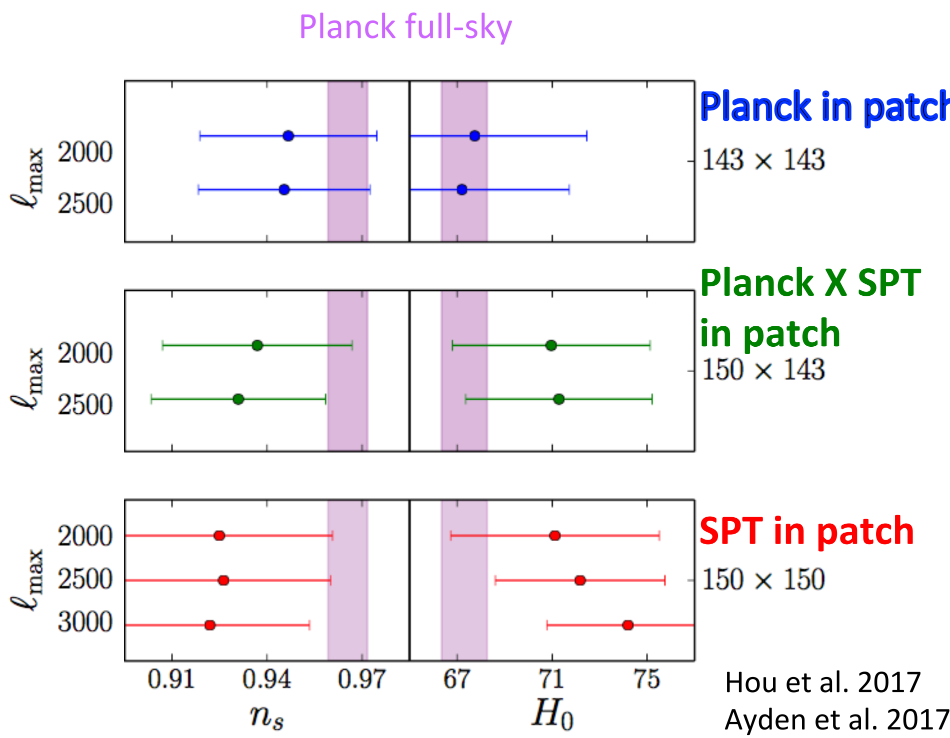
2. Planck, WMAP and SPT are consistent when compared on common modes

Consistency between CMB experiments: the role of cosmic variance and multipole range

Planck vs WMAP



Planck vs SPT-SZ



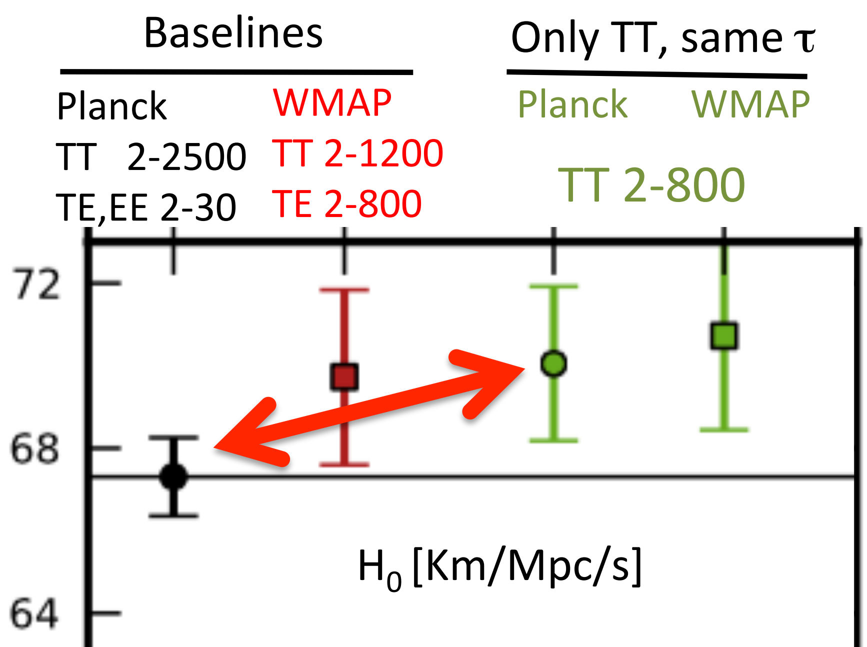
Hou et al. 2017
Ayden et al. 2017

Planck sample variance limited till **l~1600** (data points till ~2500, fsky~40-70%)
WMAP sample variance limited till **l~600** (data points till l~1200)
SPT uses ~ **6%** of the sky. Error bar due to sample variance ~3 times larger than Planck.

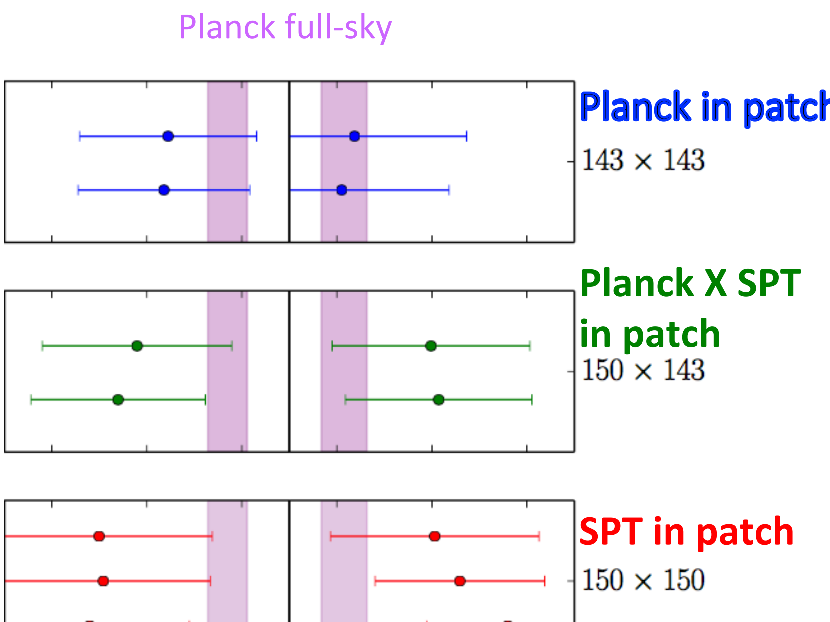
Aylor et al. 2017 arXiv:1706.10286
Hou et al. 2017 arXiv: 1704.00884

Consistency between CMB experiments: the role of cosmic variance and multipole range

Planck vs WMAP



Planck vs SPT-SZ



Still need to prove that shifts between lmax=800 and lmax=2500 for Planck itself are consistent with expectations!

WMAP sample variance limited till **l~600** (data points till l~1200)

SPT uses ~ **6%** of the sky. Error bar due to sample variance ~3 times larger than Planck.

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

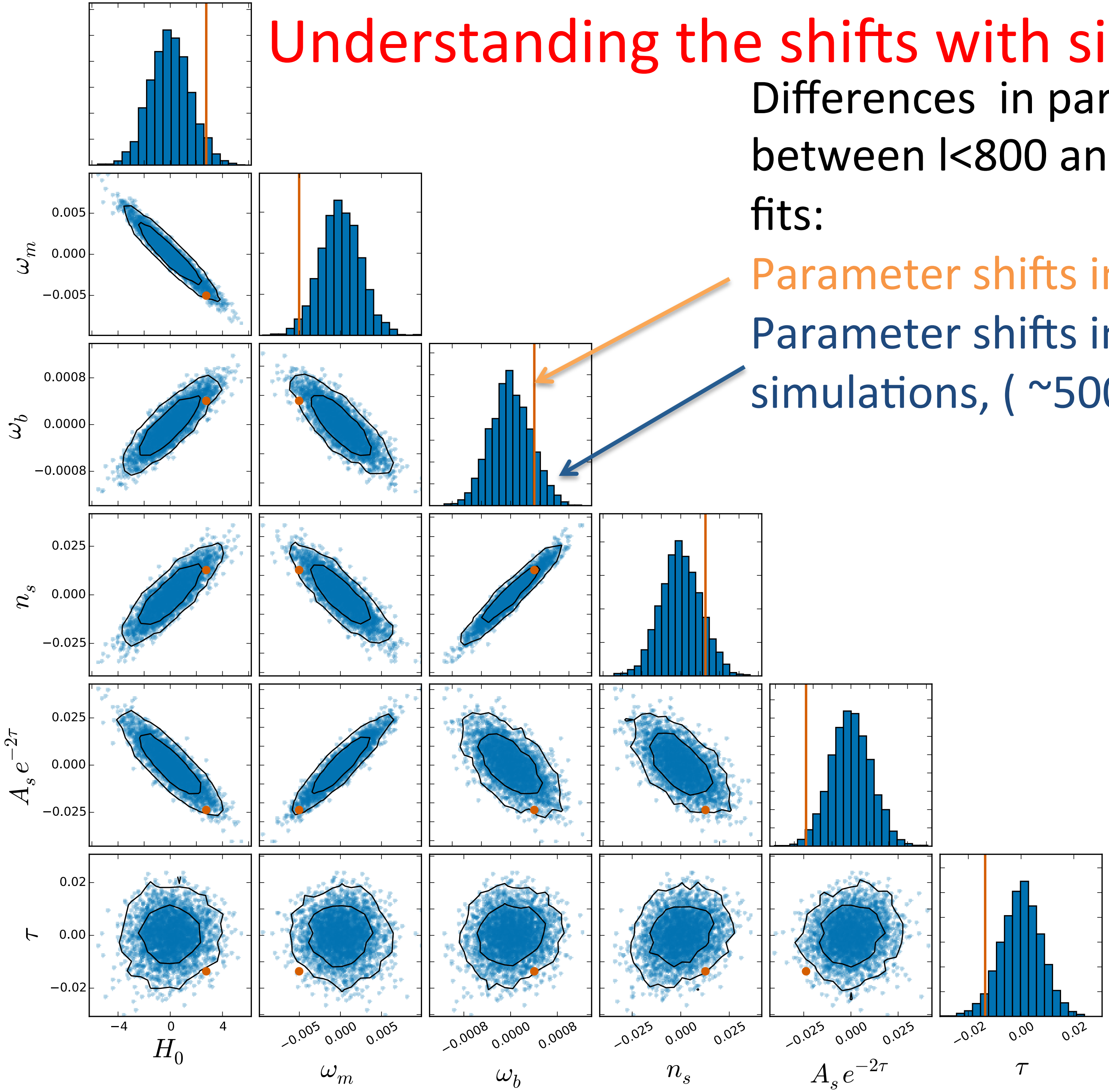
Simulations

- We simulate ~5000 TT power spectra and estimate cosmological parameters from each different l-ranges (e.g. $l<800$ and $l<2500$).

- We only use **TT data** and use a prior on the optical depth τ=0.07+-0.02 as a proxy of the large scale polarization data (but we also tested the a prior τ=0.055+-0.01, compatible with the latest HFI results 2016).

"Planck 2016 intermediate results. LI. Features in the cosmic microwave background temperature power spectrum and shifts in cosmological parameters "
arXiv:1608.02487

Understanding the shifts with simulations



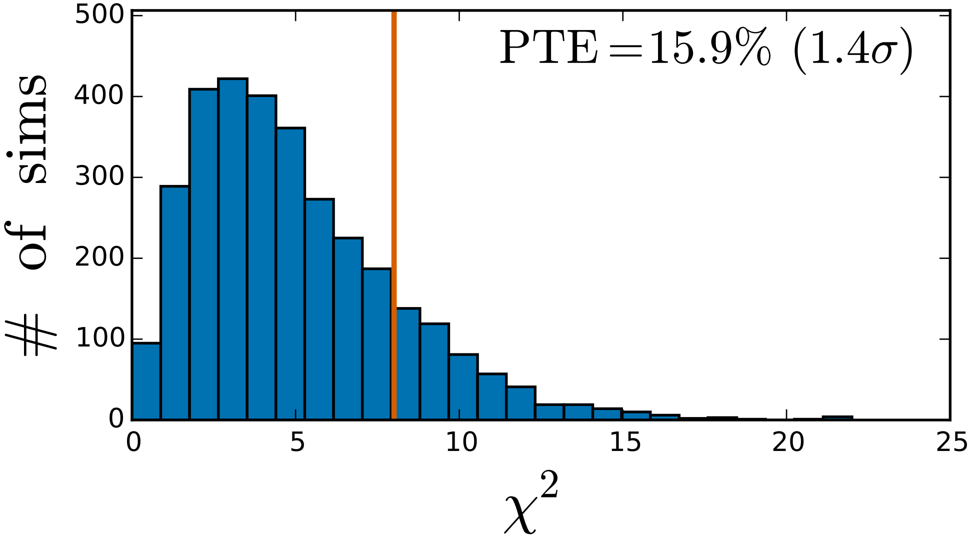
Differences in parameters between l<800 and l<2500 best-fits:

Parameter shifts in the data

Parameter shifts in the simulations, (~5000 sims)

Planck collaboration LI 2016

Parameter shifts and their statistical significance



χ^2 of the parameter differences

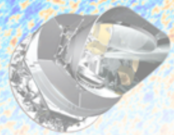
$\chi^2 = \Delta p^T \Sigma^{-1} \Delta p$

Δp = p[2-2500] - p[2-800]

PTE=15.9%, equivalent to 1.4σ.

i.e. 15.9% of the sims exceed the data. Corresponds to the number of outliers larger than 1.4σ for a 1D gaussian.

The difference is **not** statistically very significant.



Significances

Data set 1	Data set 2	Test: χ^2	Test: max-param
$\ell < 800$	$\ell < 2500$	$1.4\,\sigma^{\dagger}$	$1.7\,\sigma$ $(A_s e^{-2\tau})$
$\ell < 800$	$\ell > 800$	$1.6\,\sigma$	$2.1\,\sigma$ $(A_s e^{-2\tau})$
$\ell < 1000$	$\ell < 2500$	$1.8\,\sigma^{\dagger}$	$1.5\,\sigma$ $(A_s e^{-2\tau})$
$\ell < 1000$	$\ell > 1000$	$1.6\,\sigma$	$1.6\,\sigma$ (ω_m)

Using $\tau = 0.055 \pm 0.1$ instead of $\tau = 0.07 \pm 0.02$ $[-0.1\sigma, 0.3\sigma]$ changes

Data set 1	Data set 2	χ^2	max-param
$\ell < 800$	$\ell < 2500$	$1.8\,\sigma^{\dagger}$	$2.1\,\sigma$ $(A_s e^{-2\tau})$
$\ell < 800$	$\ell > 800$	$1.9\,\sigma$	$2.2\,\sigma$ $(A_s e^{-2\tau})$
$\ell < 1000$	$\ell < 2500$	$1.9\,\sigma^{\dagger}$	$1.9\,\sigma$ $(A_s e^{-2\tau})$
$\ell < 1000$	$\ell > 1000$	$1.9\,\sigma$	$1.5\,\sigma$ (ω_m)

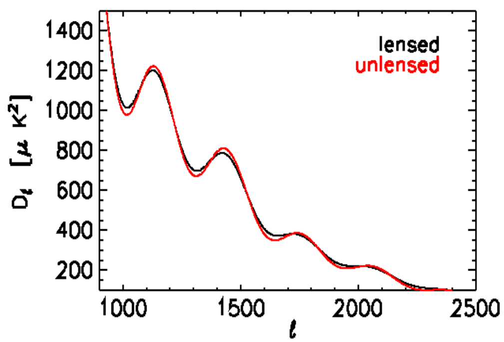
The differences are not statistically very significant.

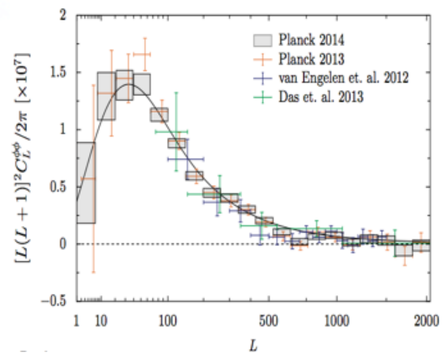
What is driving the shifts between lmax=800 and lmax=2500?

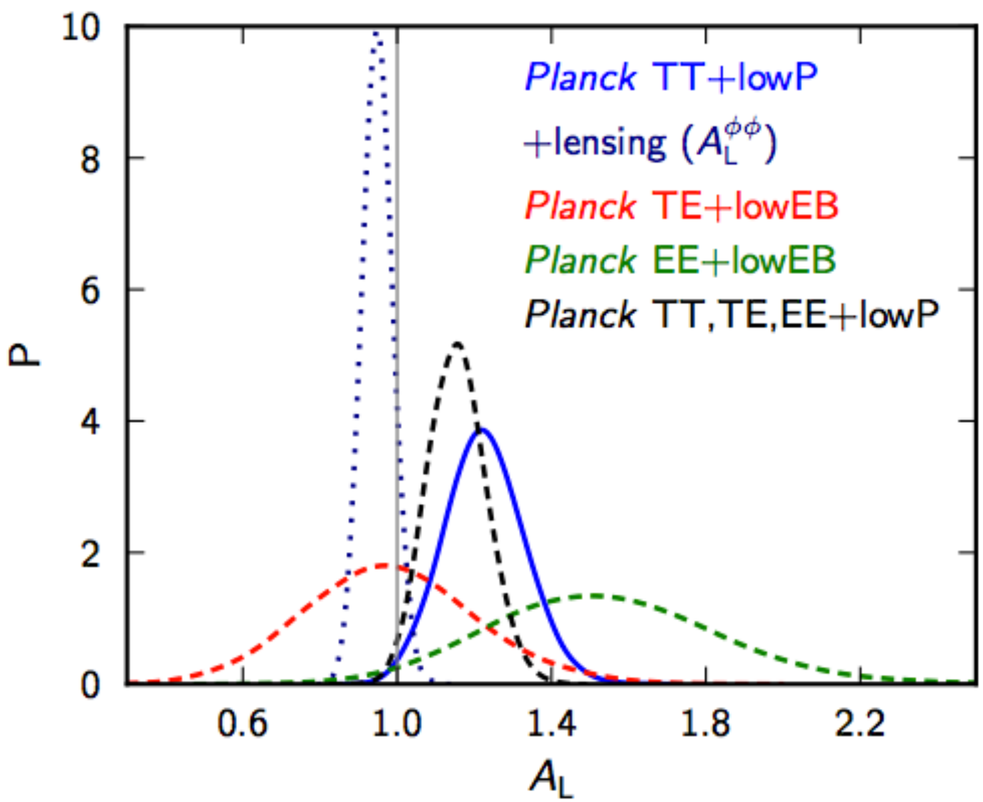
1. Is there a preference for extra-peak smoothing at high-l ("lensing")?

2. Is it the low-l anomaly?

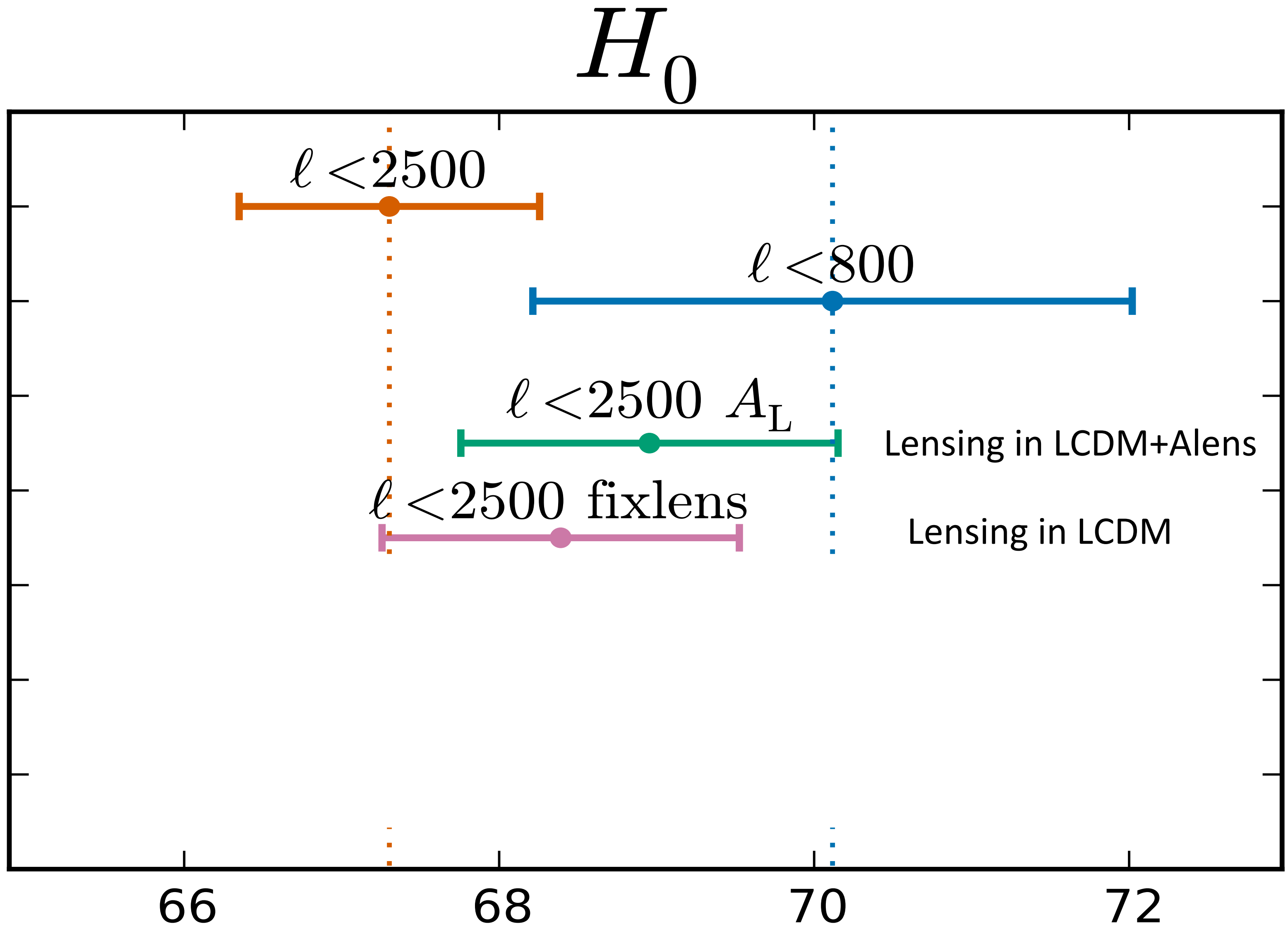
A slight preference for high lensing in the power spectrum





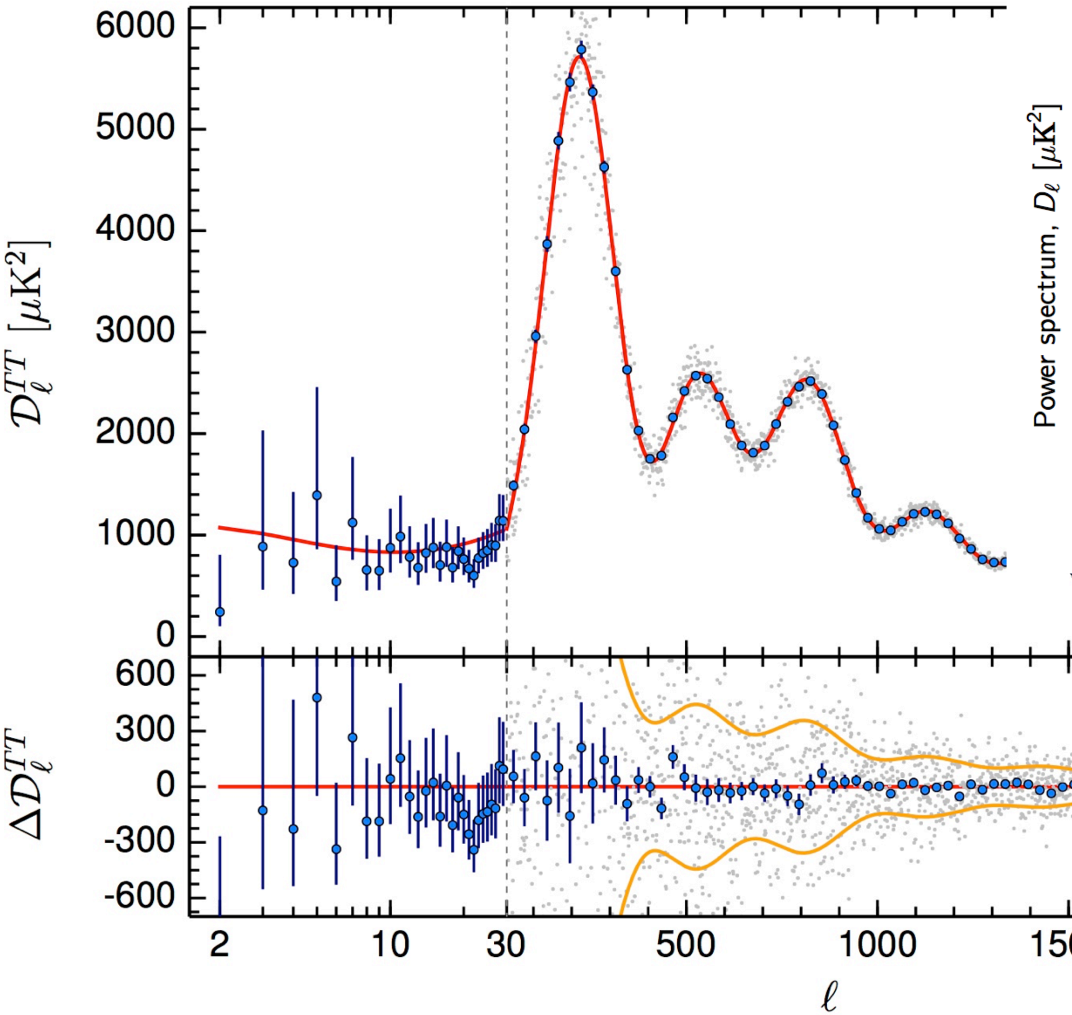


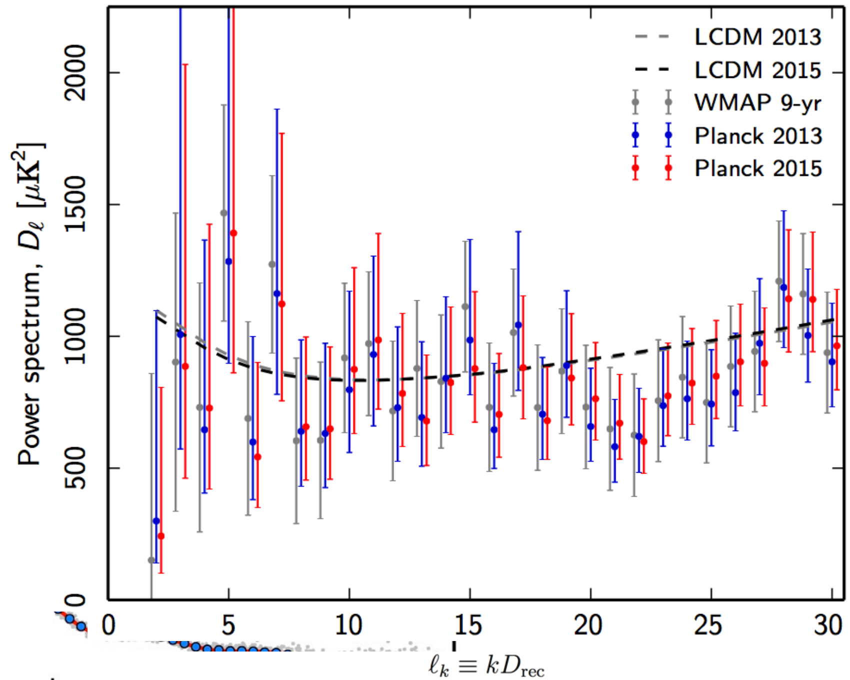
- A_L parametrizes amplitude of lensing power spectrum.
- In LCDM+A_L model, TT power spectrum prefers a ~2-sigma larger lensing amplitude than LCDM prediction.
- We do not think this is physical, because the lensing reconstruction does not share this preference for high amplitude.
- **This could just be a statistical fluctuation in the data.**

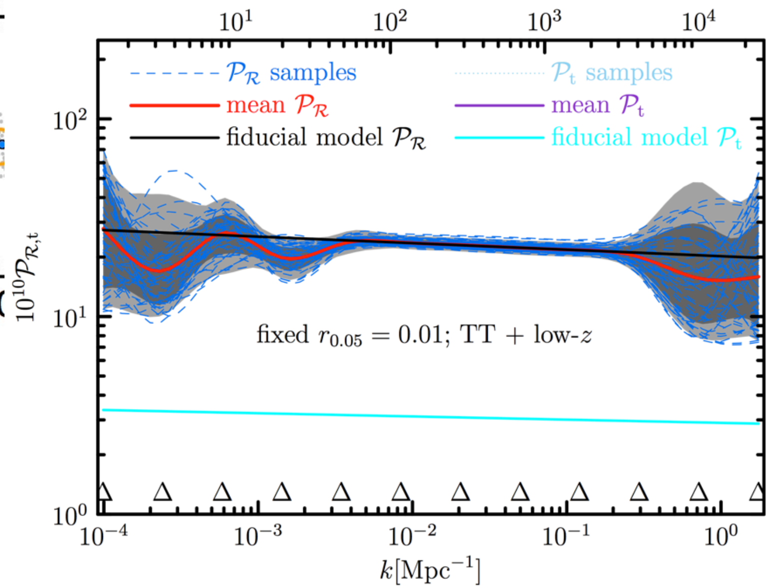


H_0
$\ell < 2500$
$\ell < 800$
$\ell < 2500\ \ A_{\rm L}$
Lensing in LCDM+Alens
$\ell < 2500$ fixlens
Lensing in LCDM
66
68
70
72

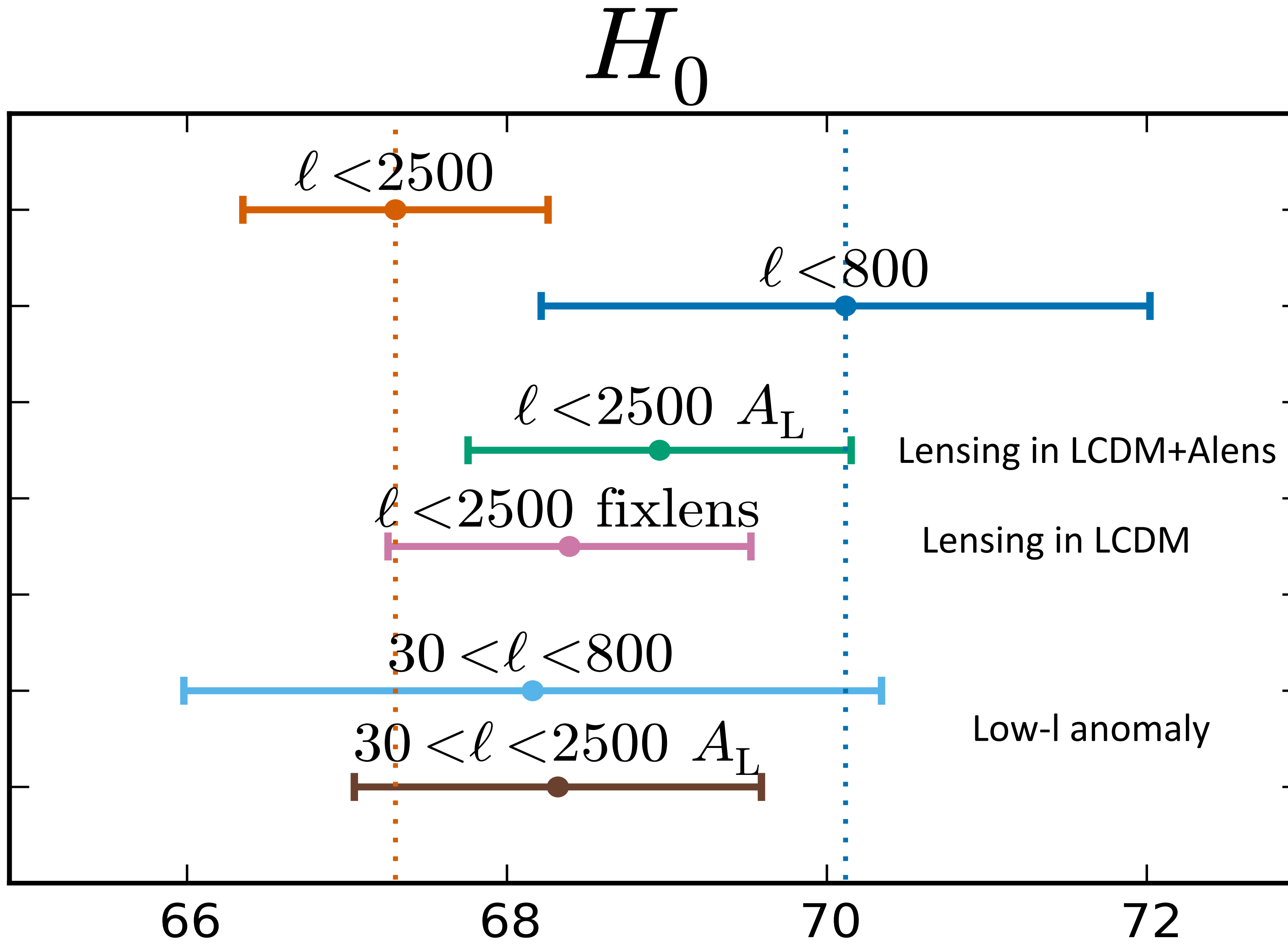
Is it the low-l anomaly?







See Hannestad 03, Shafieloo 03,
Bennet et al. 2011, Mortonson et al. 2009 and many others



H_0
$\ell < 2500$
$\ell < 800$
$\ell < 2500 \;\; A_{\rm L}$
Lensing in LCDM+Alens
$\ell < 2500$ fixlens
Lensing in LCDM
$30 < \ell < 800$
Low-l anomaly
$30 < \ell < 2500 \;\; A_{\rm L}$
66
68
70
72

Conclusions

- Planck consistent with BAO, SN, BBN. Open issue with clusters, weak lensing. Tension with direct measurements of H_0.
- H_0 tension present also in WMAP+BAO+SN.
- Good consistency between WMAP, Planck and SPT.
- Planck low-l Planck high-l in good statistical agreement
- Smoothing of high-l peaks and low-l deficit possibly responsible for shifts between low and high-l.

Planck 3rd release is coming soon, stay tuned!

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.