Reviewing tensions between Planck and other data

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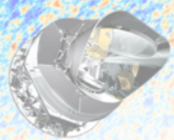
with Marius Millea, Lloyd Knox, Ali Narimani, Douglas Scott, Martin White
and the rest of the Planck collaboration

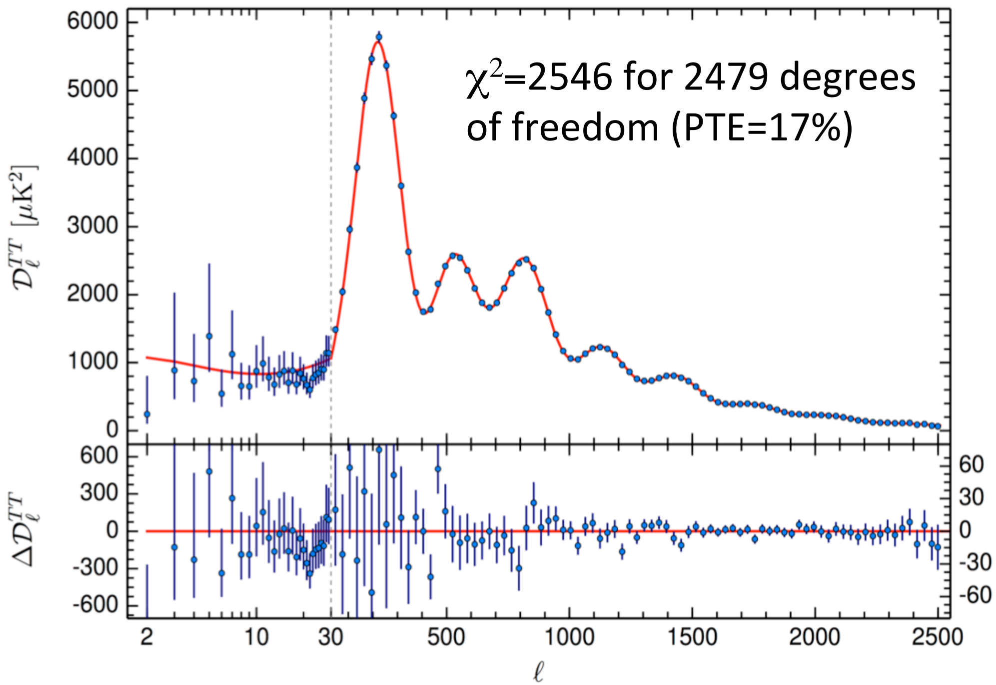
"Planck 2016 intermediate results. LI. Features in the cosmic microwave background temperature power spectrum and shifts in cosmological parameters"
arXiv:1608.02487

Stockholm, 18/07/2017



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)

$\sum m_\nu < 0.23$ 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

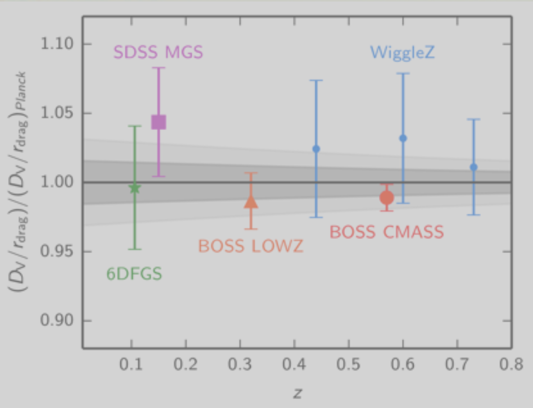
$\frac{dn_s}{d\ln k} = -0.0084 \pm 0.0082$
(PlanckTT+lowP)

No significant deviation from ΛCDM in extended models

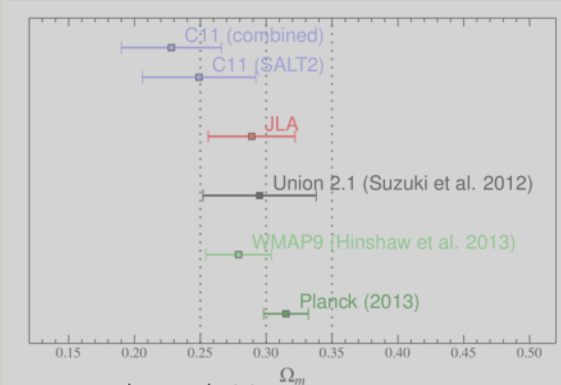
ΛCDM excellent fit to the Planck data

Comparison with other datasets:

BAO

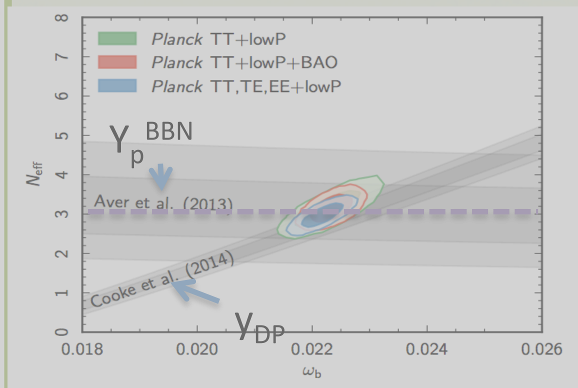


Supernovae (Ω_m)

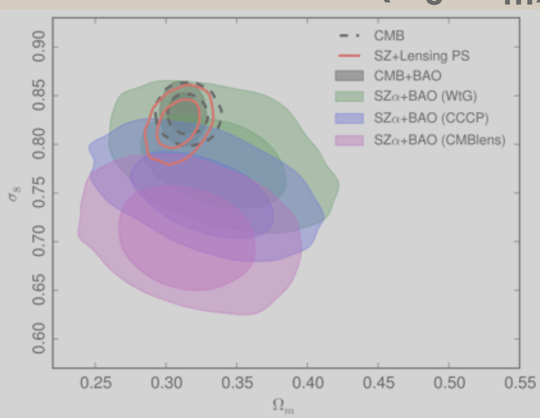


Betoule et al. 2014

BBN

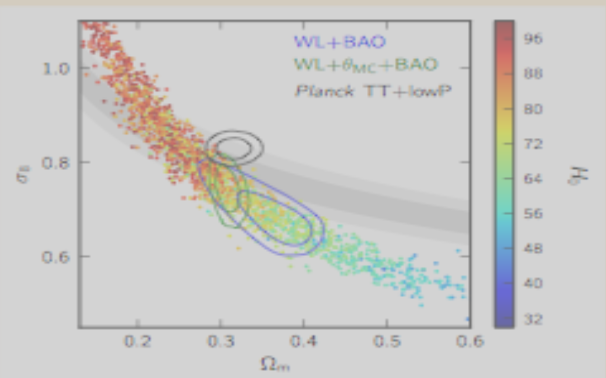


Cluster counts (σ_8-Ω_m)



Planck collaboration XXIV

Weak Lensing (σ_8-Ω_m)



Direct measurements H_0

H_0=66.9±0.91 [in Km/s/Mpc]
(PlanckTT+SIMlow_HFI, Planck 2016)

H_0=73.±1.8 **[3σ tension]**
(Riess+16)

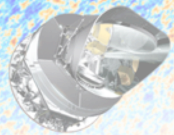
Extensions of ΛCDM, systematics in direct measurements or systematics in the CMB?

Extensions or systematics in direct measurements?

- 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**

- 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



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 H_0=75.0 ± 3.5 (Story et al. 2012)

NB: these were obtained using slightly different assumptions for neutrino mass and optical depth w.r.t. Planck

- Are these consistent with the low H_0 Planck measurement?

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- Are these consistent with the low H_0 Planck measurement?

    - 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)

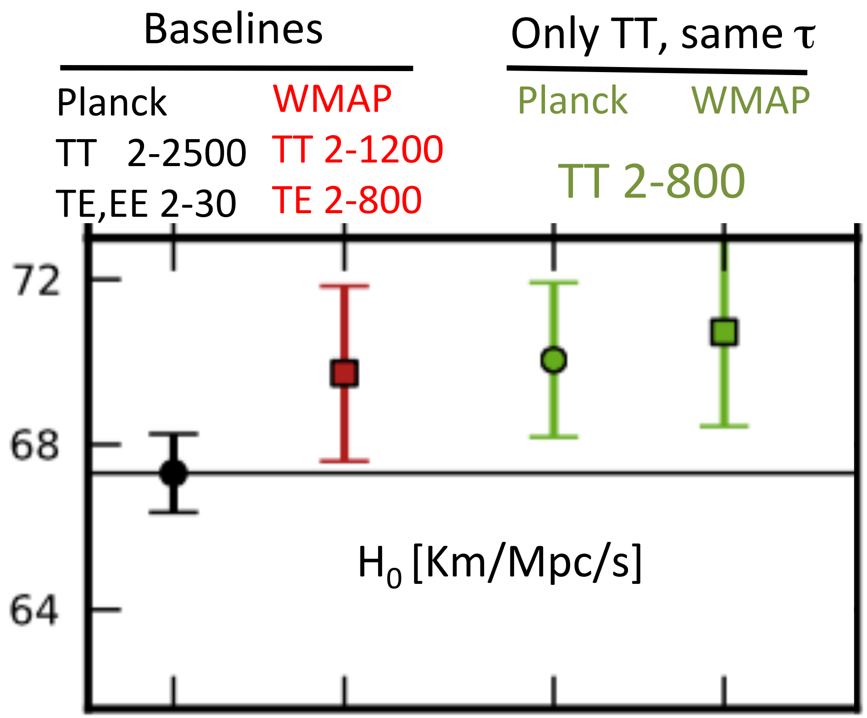
        - WMAP9+ACT+SPT + BAO (BOSS DR11+6dFGS)

          H_0 = 69.3 ± 0.7 (1.9s tension) (Bennet+ 2014)

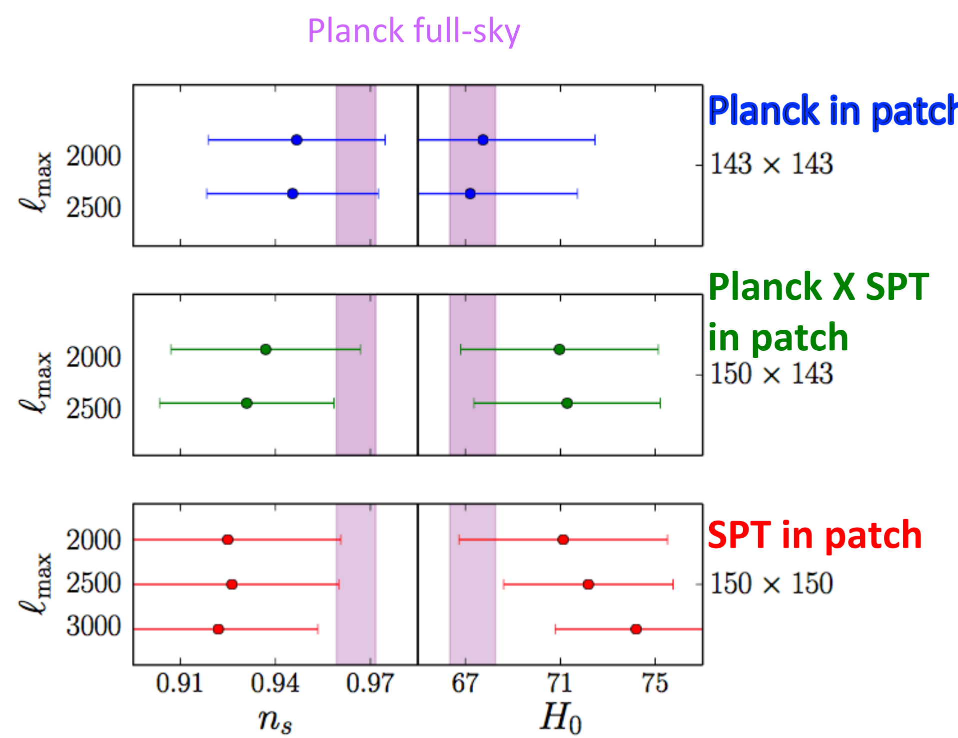
    - Planck, WMAP and SPT are consistent with each other.

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

Planck vs WMAP



Planck vs SPT-SZ



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

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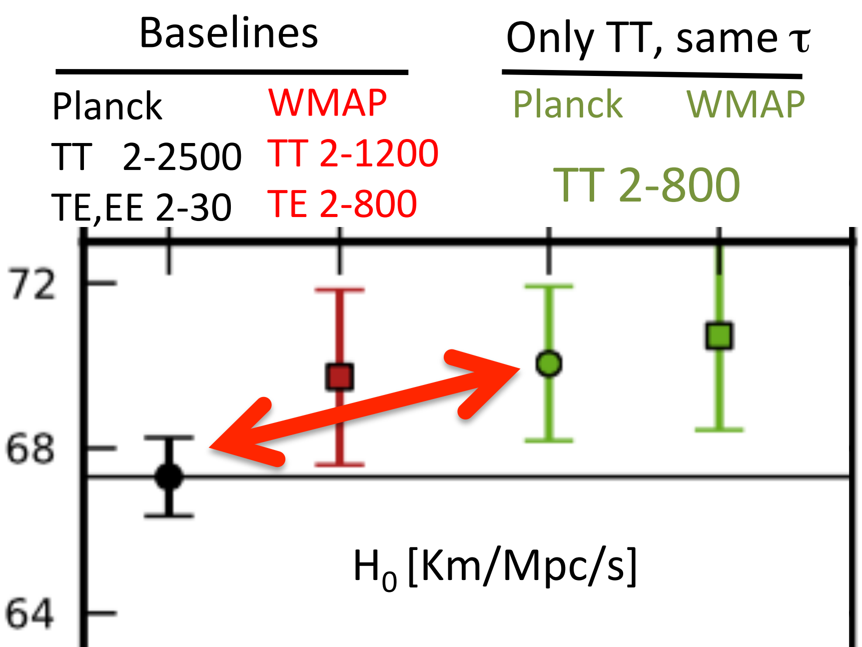
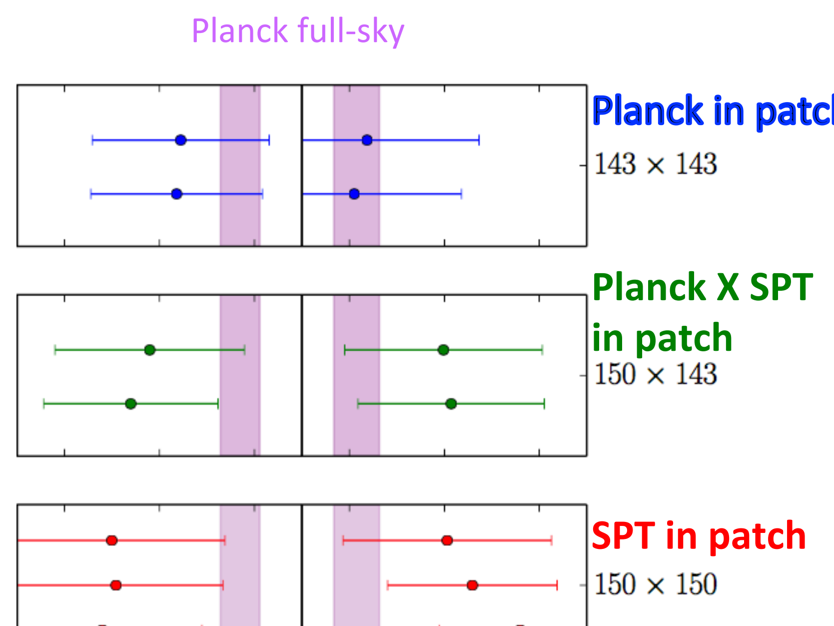


Planck vs SPT-SZ



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

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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 $\tau=0.07\pm0.02$ as a proxy of the large scale polarization data (but we also tested the a prior $\tau=0.055\pm0.01$, compatible with the latest HFI results 2016).

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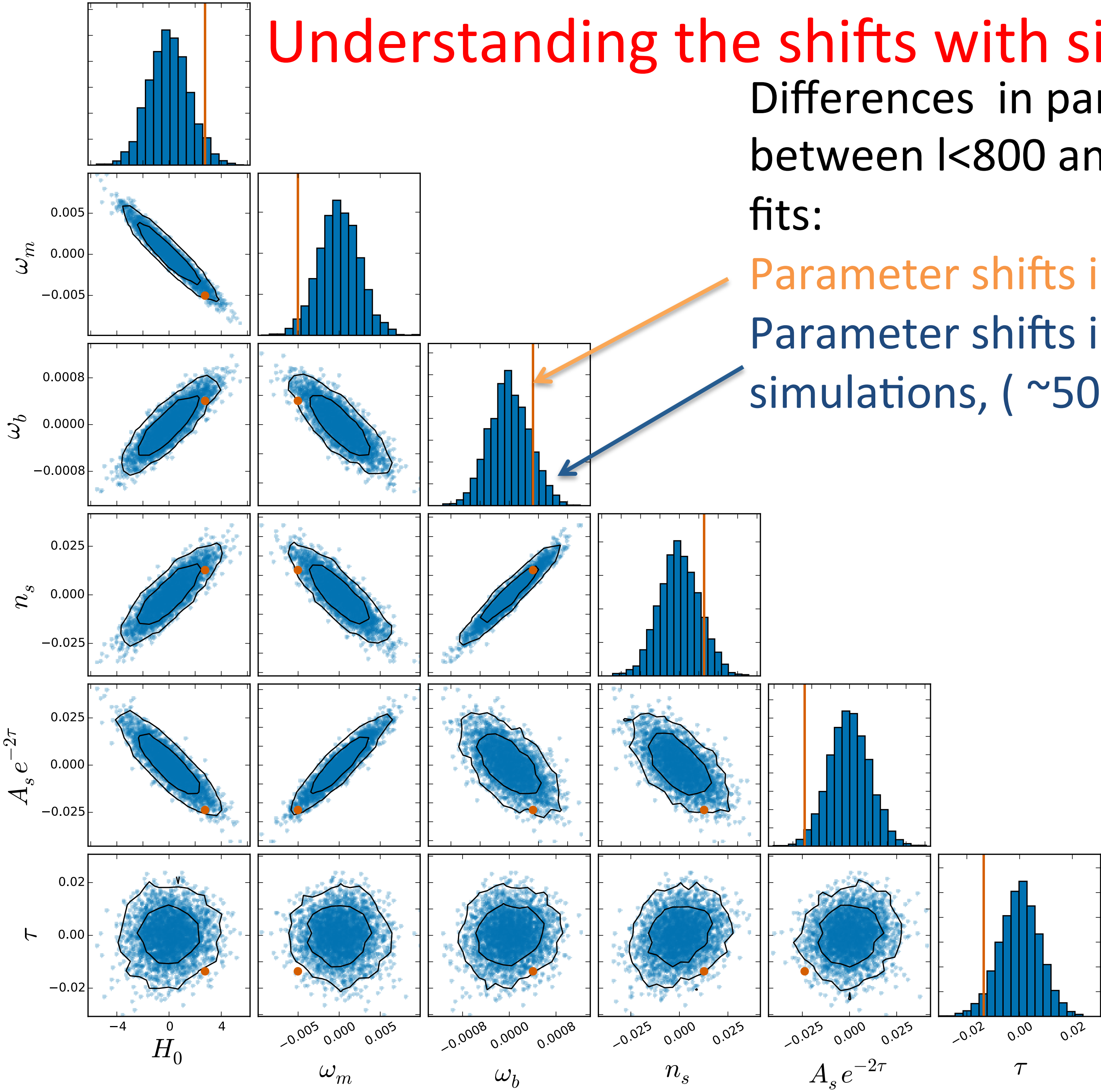
Understanding the shifts with simulations



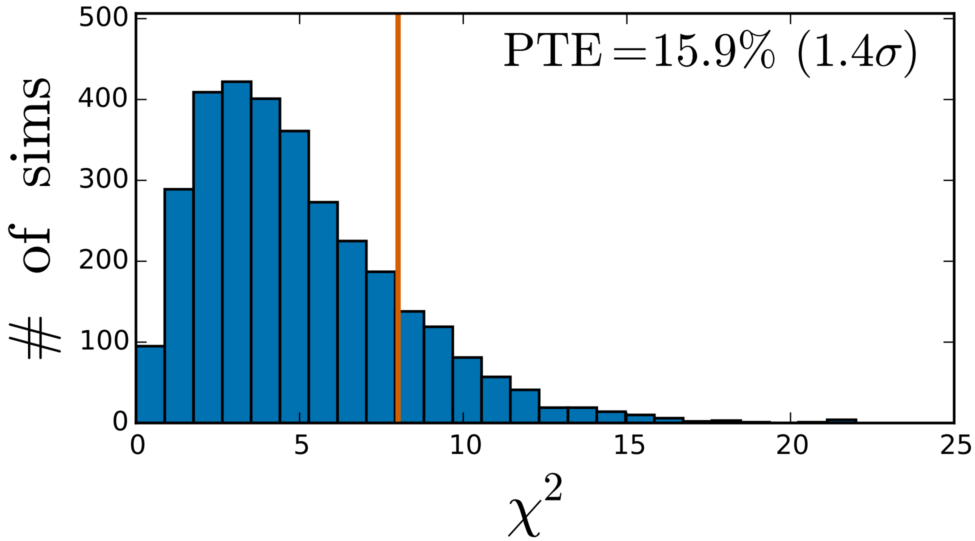
Differences in parameters between l<800 and l<2500 best-fits:

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.

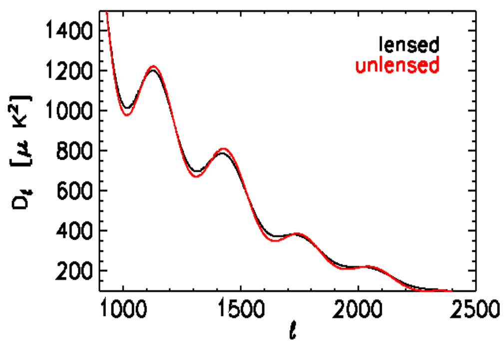
The difference is **not** statistically very significant.

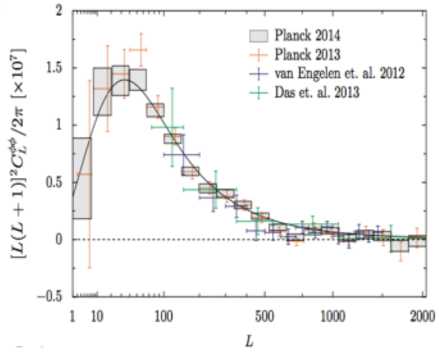
What is driving the shifts between lmax=800 and lmax=2500?

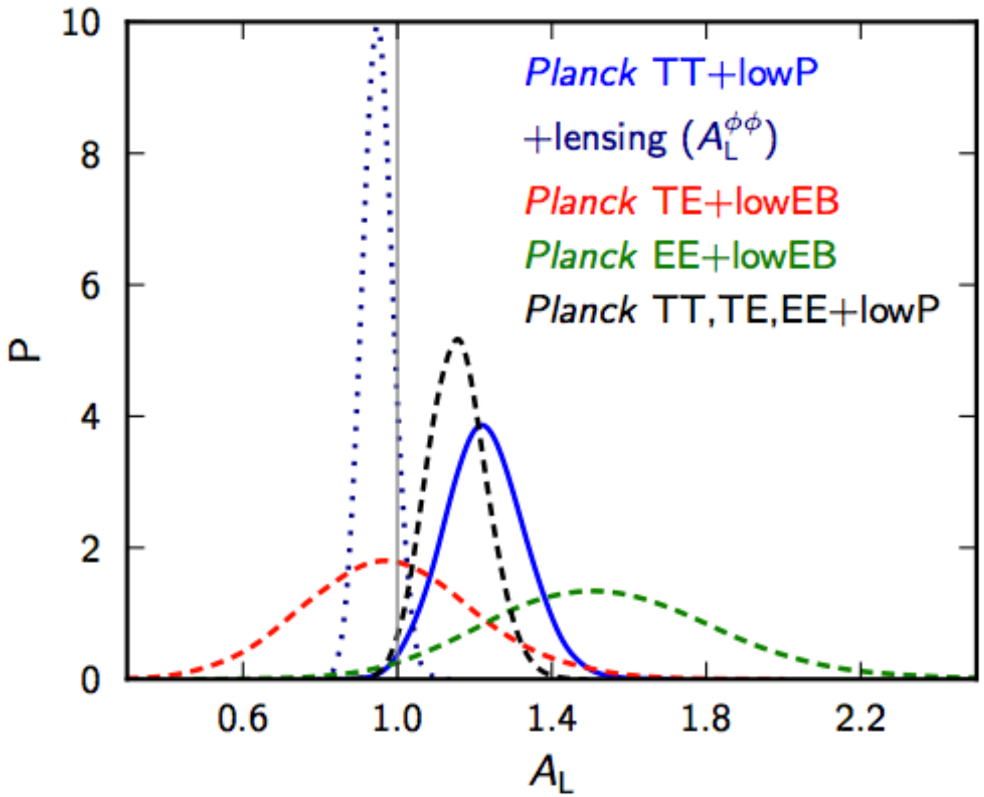
1. Is there a preference for extra-peak smoothing at high-l (“lensing”)?

2. Is it the low-l anomaly?

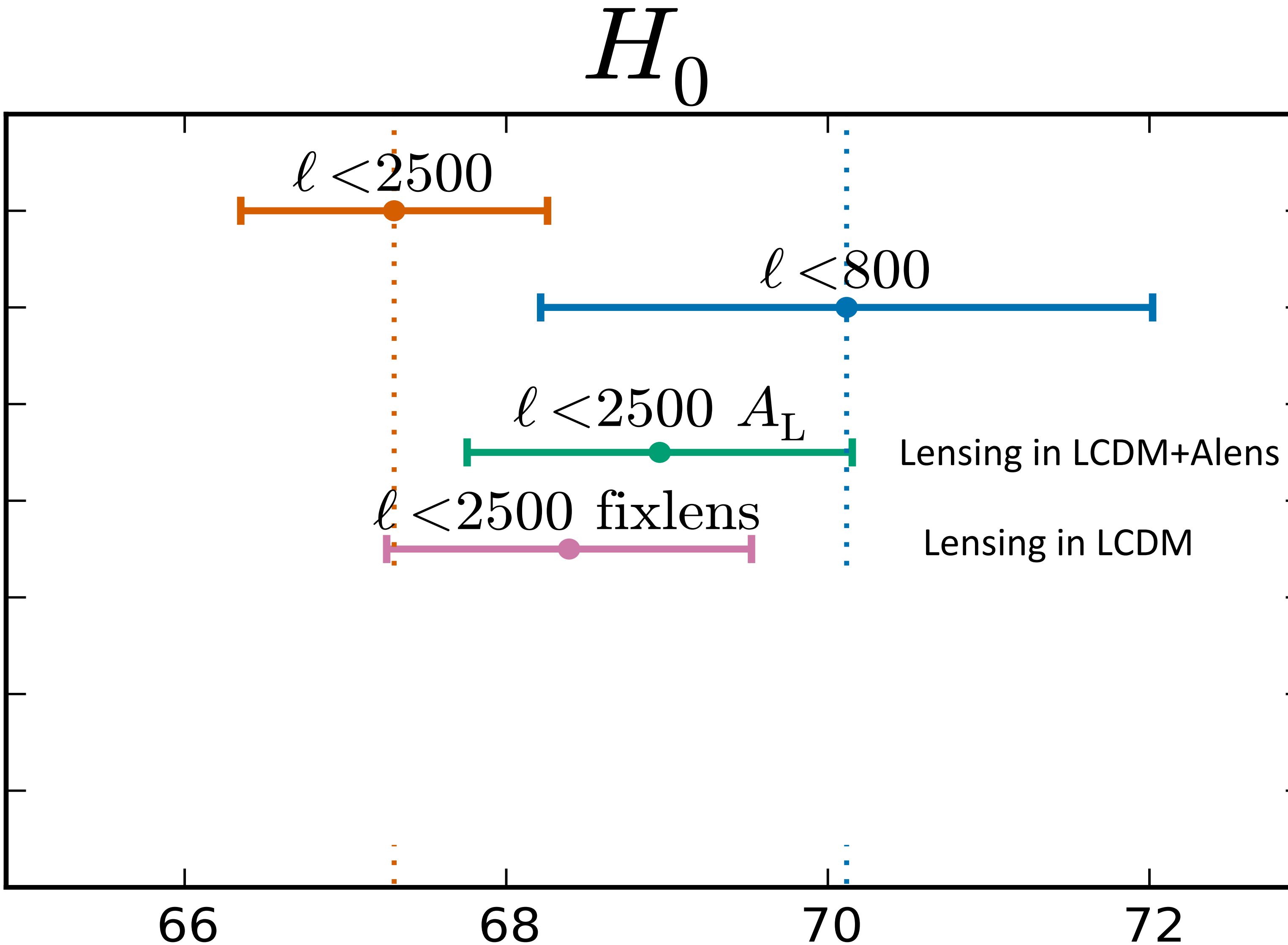
A slight preference for high lensing in the power spectrum





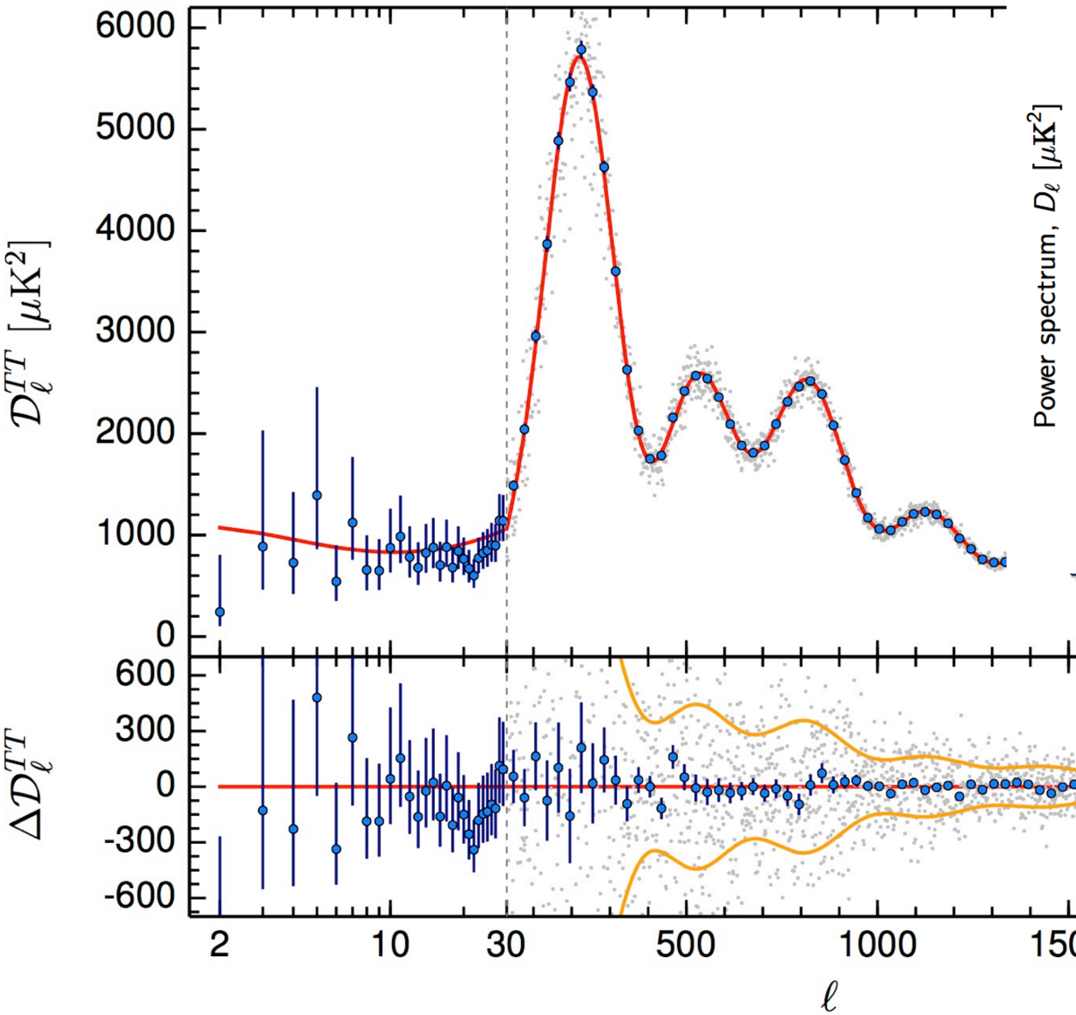


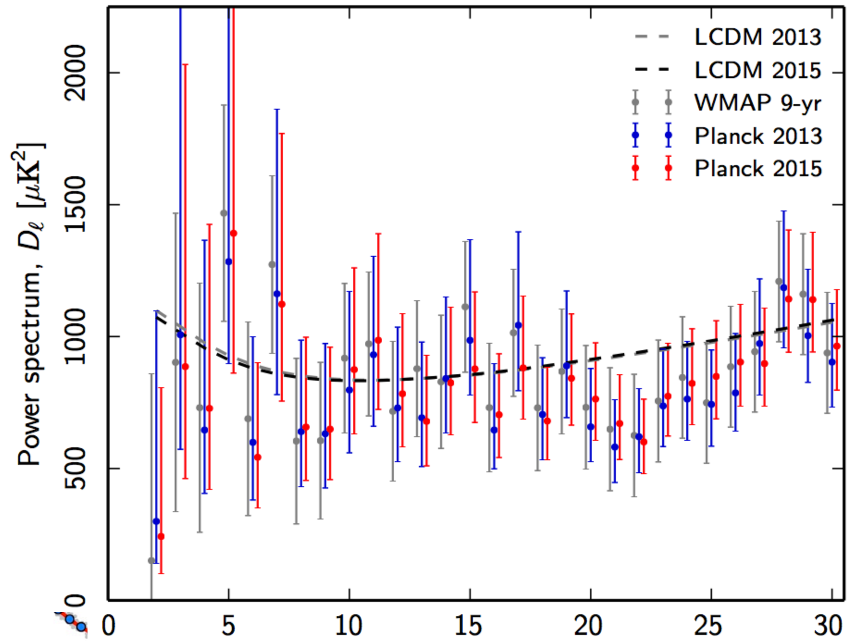
- A_L parametrizes amplitude of lensing power spectrum.
- In LCDM+A_L model, TT power spectrum prefers a ~2-sigma larger lensing amplitude than LCDM prediction.
- We do not think this is physical, because the lensing reconstruction does not share this preference for high amplitude.
- **This could just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

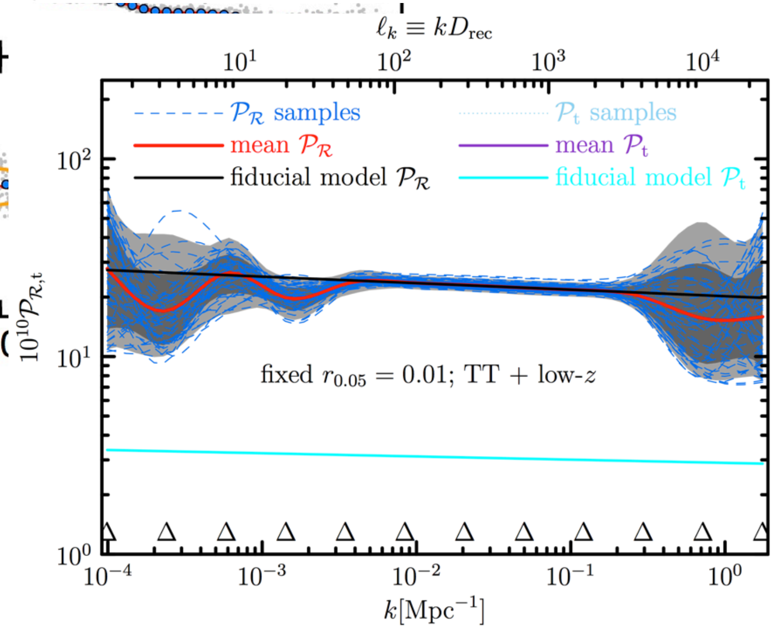


H_0
$\ell < 2500$
$\ell < 800$
$\ell < 2500\ A_L$
Lensing in LCDM+Alens
$\ell < 2500$ fixlens
Lensing in LCDM
66
68
70
72

Is it the low-l anomaly?

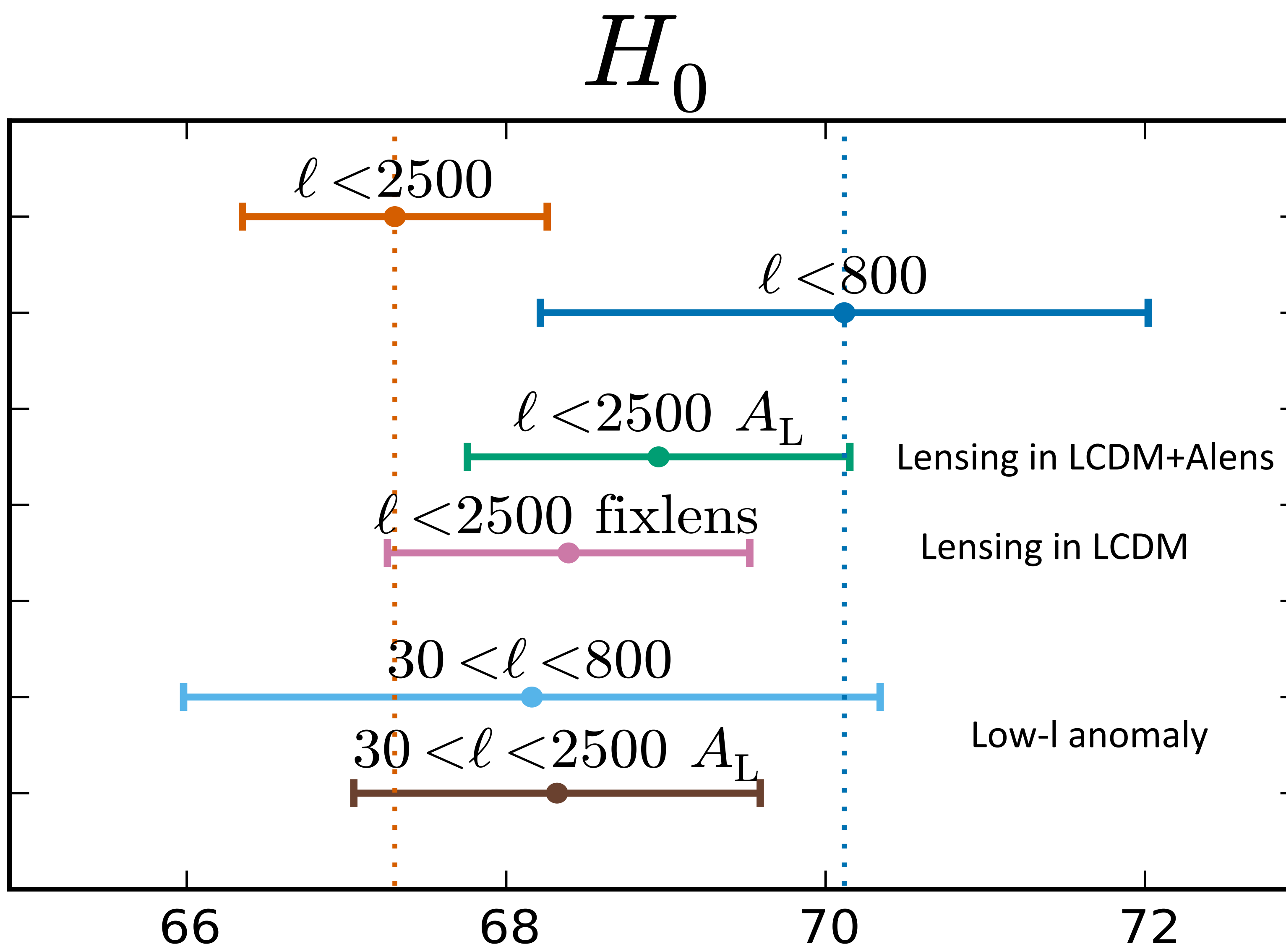






See also Cora Dvorkin's talk this morning.

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


H_0
$\ell < 2500$
$\ell < 800$
$\ell < 2500 \;\; A_\mathrm{L}$
Lensing in LCDM+Alens
$\ell < 2500$ fixlens
Lensing in LCDM
$30 < \ell < 800$
$30 < \ell < 2500 \;\; A_\mathrm{L}$
Low-l anomaly
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.

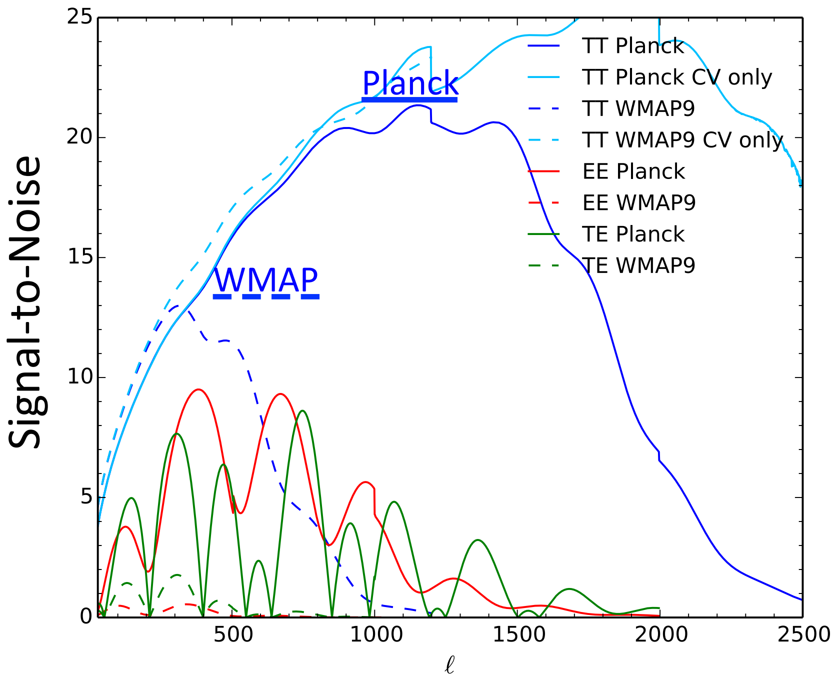
Planck 3rd release is coming soon, stay tuned!

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.

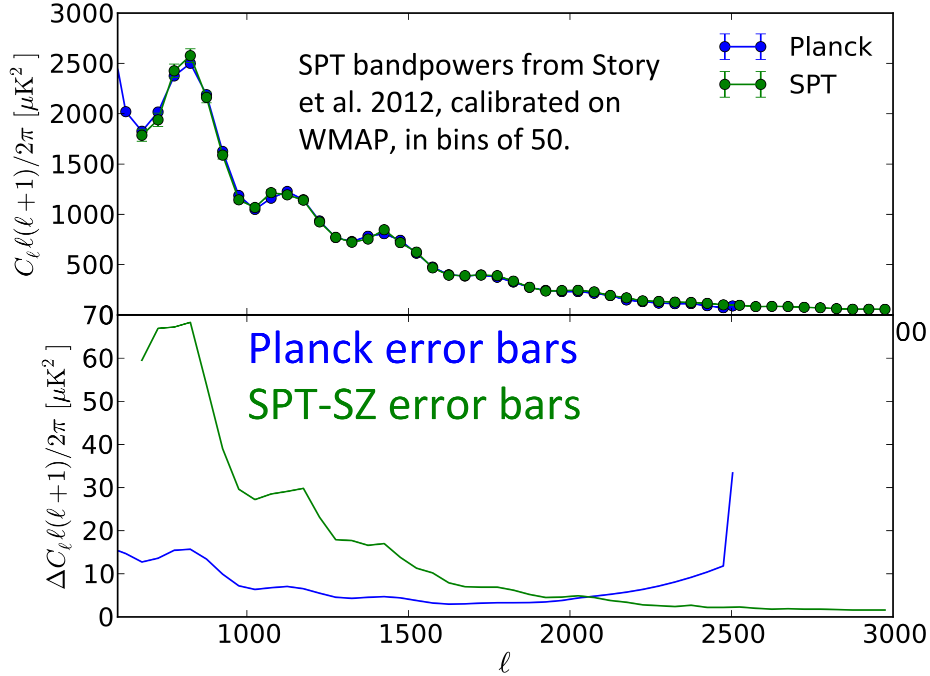
Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

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

Planck vs WMAP



Planck vs SPT-SZ



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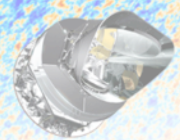
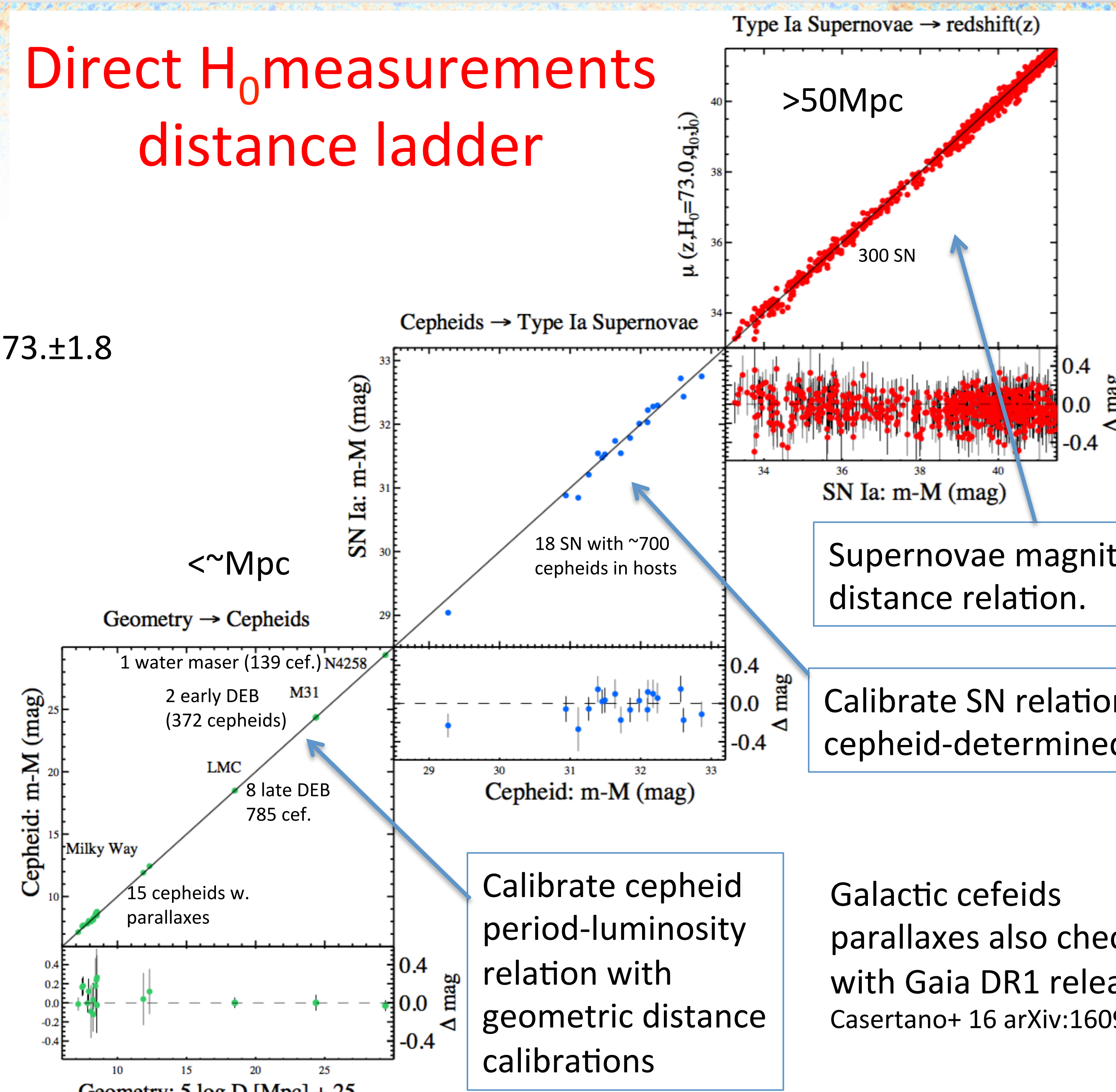
WMAP sample variance limited till **l~600** (data points till l~1200)
SPT uses ~ **6%** of the sky. Error bar due to sample variance ~3 times larger than Planck.

Properly assessing consistency is not trivial.



Direct H_0 measurements distance ladder

R16 H_0=73.±1.8



Supernovae magnitude-distance relation.

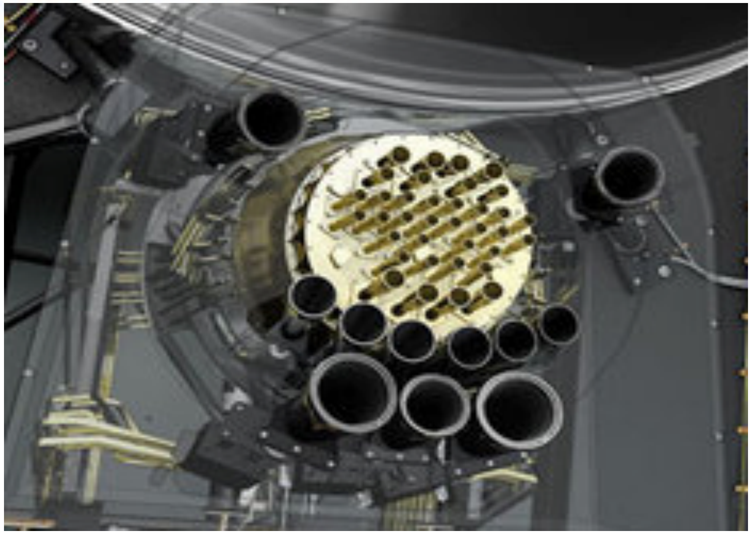
Calibrate SN relation with cepheid-determined distances

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

The Planck satellite



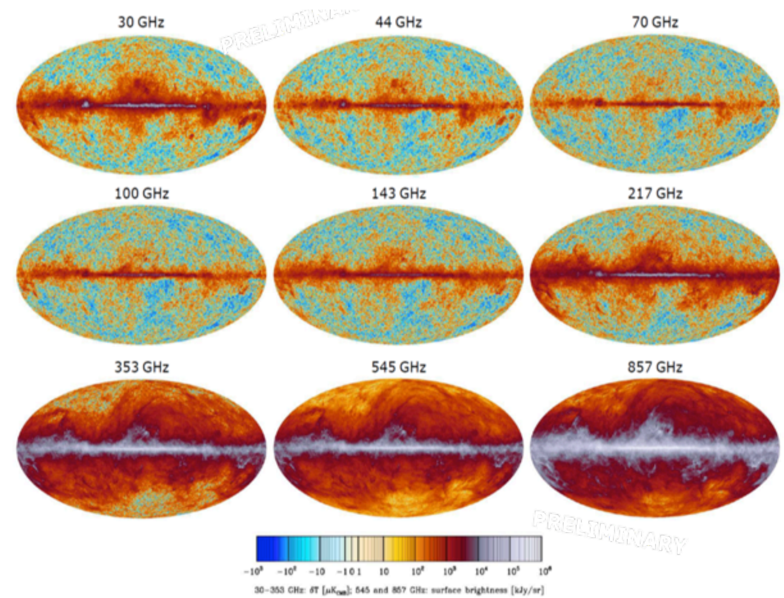
Launched in 2009, operated till 2013.
2 Instruments, 9 frequencies.

LFI:

- 22 radiometers at **30, 44, 70 Ghz.**

HFI:

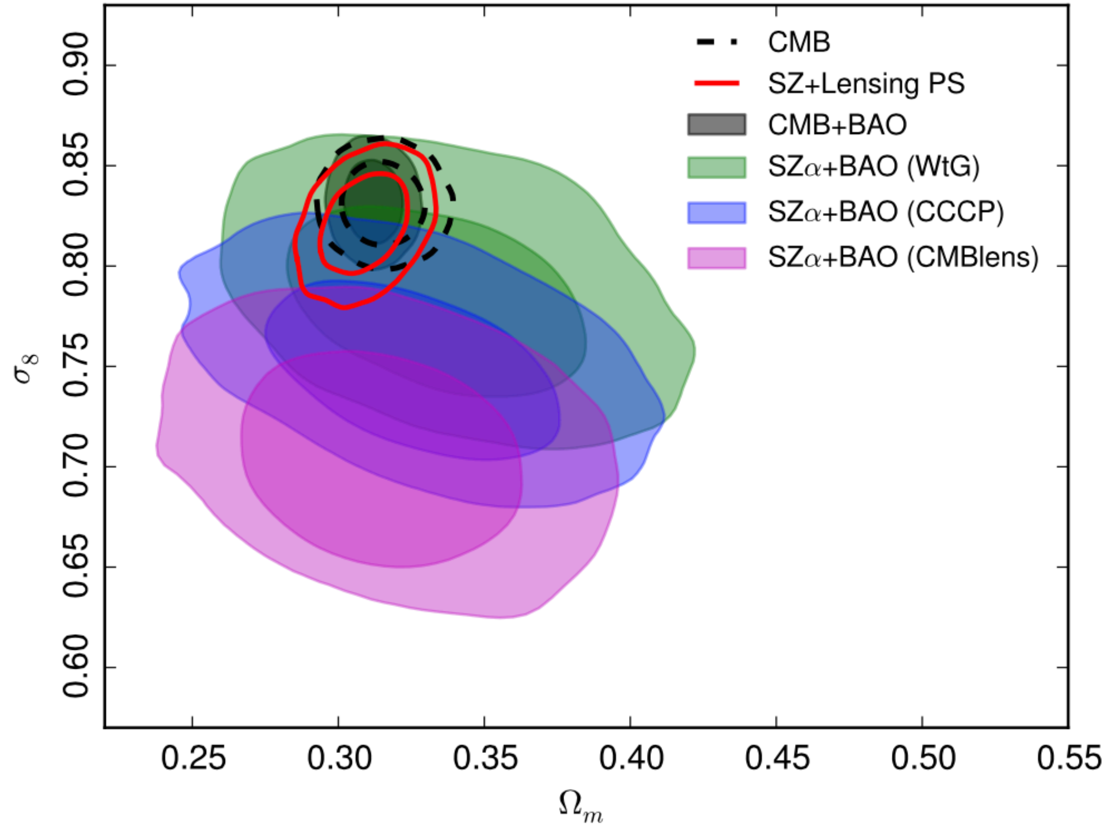
- 50 bolometers (32 polarized) at **100, 143, 217, 353, 545, 857 Ghz.**
- **30-353 Ghz polarized.**



- **1st release 2013: Nominal mission**, 15.5 months, Temperature only.
- **2nd release 2015: Full mission**, 29 months for HFI, 48 months for LFI, Temperature + Polarization

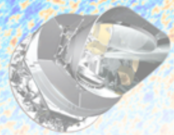
Cluster counts with Planck 2015

- **Number of clusters** as a function of **z** sensitive to cosmology.
- Detected through **Sunyaev-Zeldovitch effect in CMB** surveys.
- Need to know the **mass** of the observed clusters -> Need Ysz-mass relation-> Calibrated with X-ray observations-> Assume hydrostatic equilibrium-> **mass bias!**
- Mass bias can be measured from lensing measurements.



Prior name	Quantity	Value & Gaussian errors
Weighing the Giants (WtG)	$1-b$	0.688 ± 0.072
Canadian Cluster Comparison Project (CCCP)	$1-b$	0.780 ± 0.092
CMB lensing (LENS)	$1/(1-b)$	0.99 ± 0.19

- For perfect agreement with CMB, $(1-b) = 0.58 \pm 0.04$. 1σ lower than WtG.
- Tension can be relieved with non-zero neutrino mass, but detection disappears if BAO data is also included.



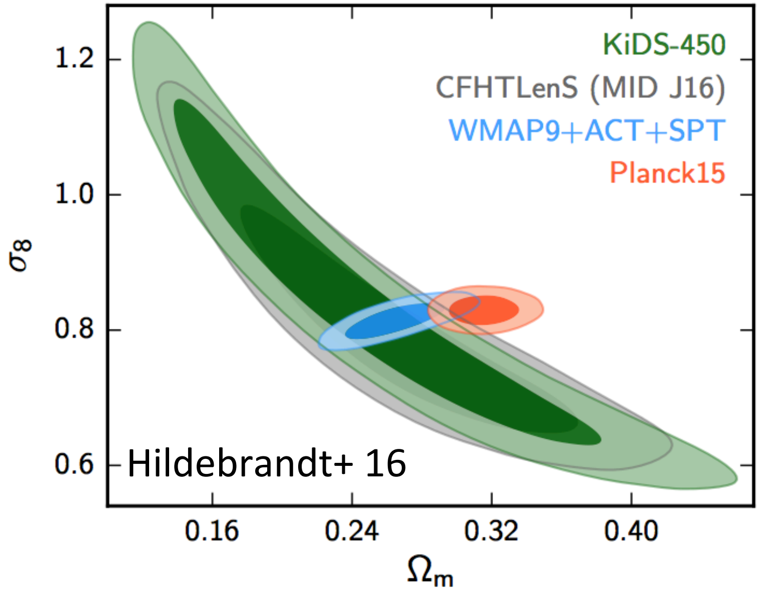
Significances

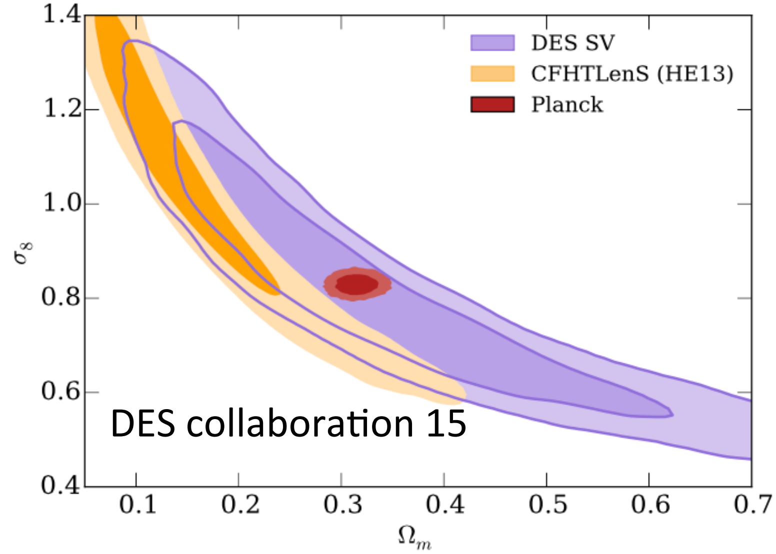
		Test	
Data set 1	Data set 2	χ^2	`max-param`
$\ell < 800$	$\ell < 2500$	$1.4\,\sigma^{\dagger}$	$1.7\,\sigma$ $(A_s e^{-2\tau})$
$\ell < 800$	$\ell > 800$	$1.6\,\sigma$	$2.1\,\sigma$ $(A_s e^{-2\tau})$
$\ell < 1000$	$\ell < 2500$	$1.8\,\sigma^{\dagger}$	$1.5\,\sigma$ $(A_s e^{-2\tau})$
$\ell < 1000$	$\ell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

The differences are not statistically very significant.

Weak Lensing: CFHTLenS, KIDS and DES

Cosmic shear correlation functions sensitive to the combination $\sim\sigma_8\Omega_m^{0.5}$

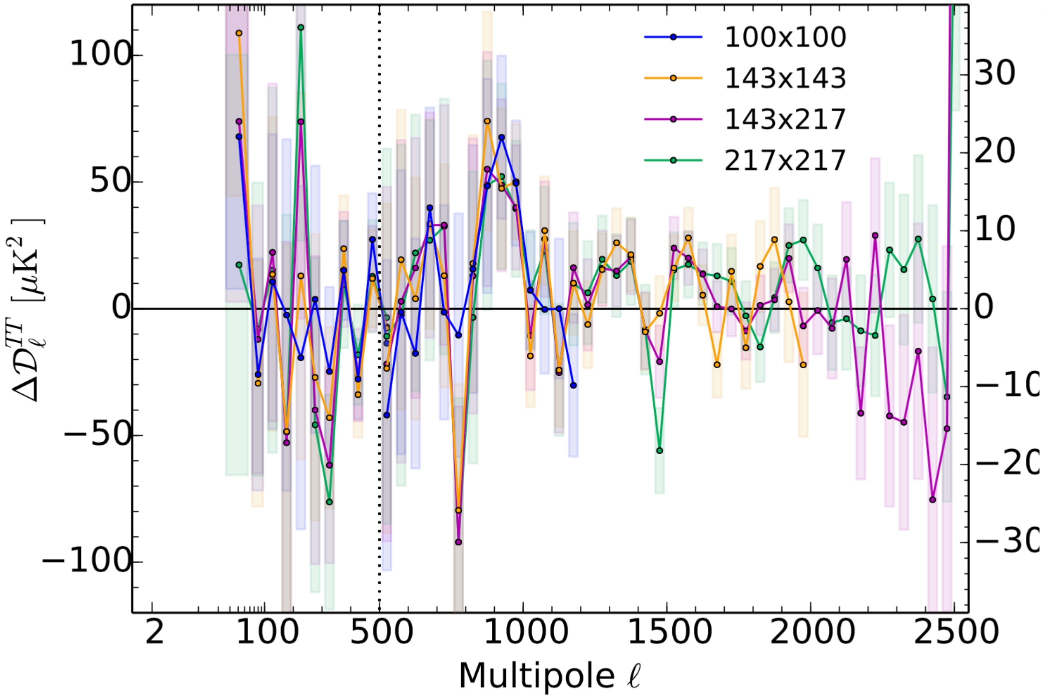




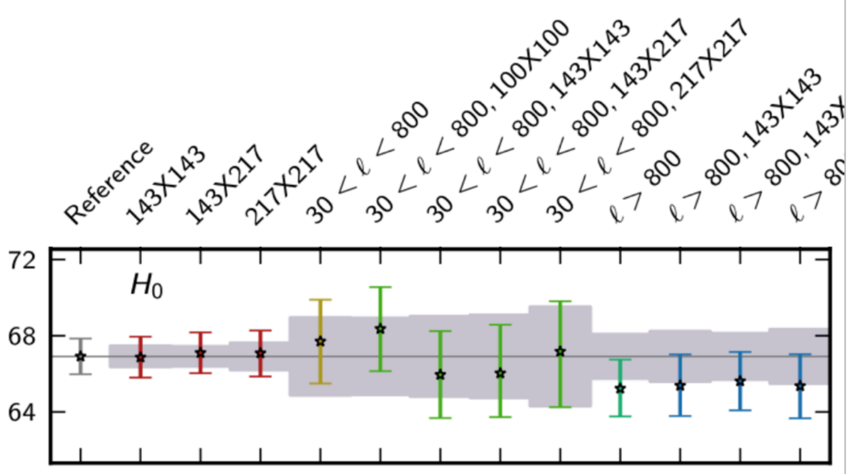
- CFHTLenS and KiDS in agreement, ~2.3σ discrepancy on $\sigma_8\Omega^{0.5}$ with Planck.
- Can be relaxed if one adds one sterile neutrino. (2σ detection).
- DES Science Verification results not enough constraining yet.

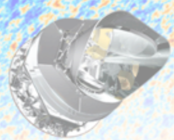
For CFHTLenS, see also Heymans+ 13, Kitching+ 14, Joudaki +16 (CFHTLenS), Joudaki +16 (KiDS). Recent reanalisys from Kitching+ 2016 of CFHTLenS.

Consistency between frequencies



Power spectrum features are very similar across frequencies. Cosmological parameters inferred from different frequencies are in very good agreement.





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(Riess+16)

Anchor(s)	Value [km s^{-1} Mpc^{-1}]
One anchor	
NGC 4258: Masers	72.39 ± 2.56
MW: 15 Cepheid Parallaxes	76.09 ± 2.41
LMC: 8 Late-type DEBs	71.93 ± 2.70
M31: 2 Early-type DEBs	74.45 ± 3.34
Two anchors	
NGC 4258 + MW	73.85 ± 1.97
Three anchors (preferred)	
NGC 4258 + MW + LMC	**73.02 ± 1.79** km s^{-1} Mpc^{-1}
Four anchors	
NGC 4258 + MW + LMC + M31	73.24 ± 1.75
Optical only (no NIR), three anchors	
NGC 4258 + MW + LMC	71.19 ± 2.55

Riess+ 16

H_0 can be also measured from multiply-imaged quasar systems with measured gravitational time delays. H0licow project from 3 lenses: $H_0 = 71.9^{+2.4}_{-3.0}\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$

Bonvin et al.arXiv:1607.01790

What if it's not systematics?

- **Extensions of LCDM.** Since CMB measurements of H_0 are indirect and assume LCDM, one might consider extensions of LCDM (e.g. extra relativistic species). It was shown however that there is no easy extension of LCDM that can accommodate all the observations (see Di Valentino+ 2016, Bernal+ 2016)

- **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, Odderskov+ 2016).

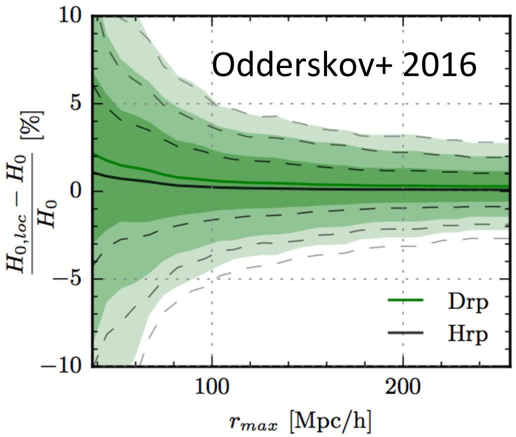
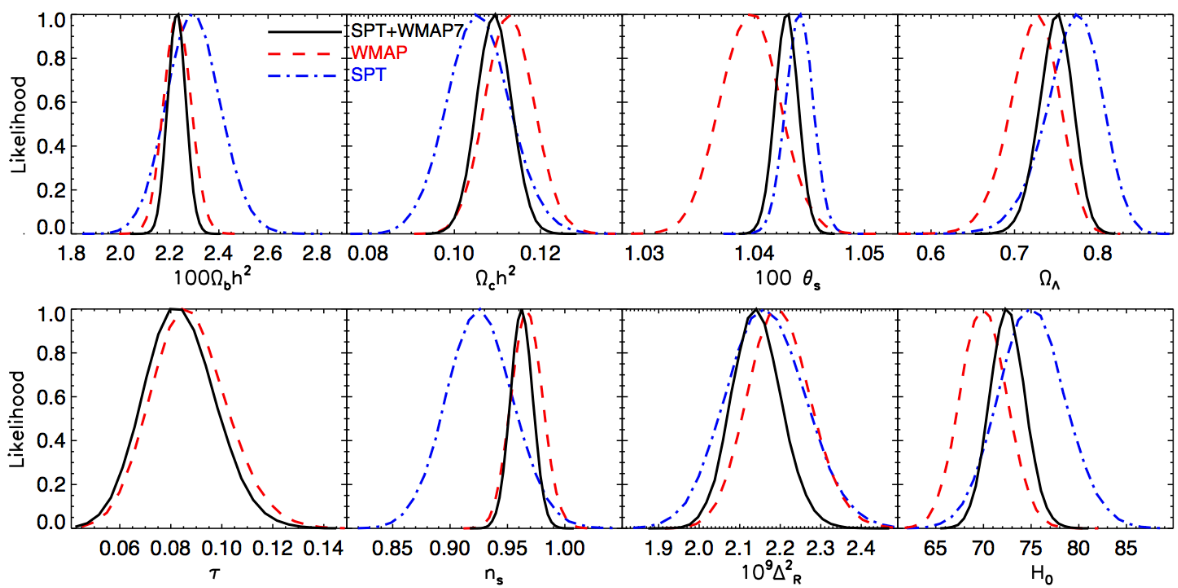


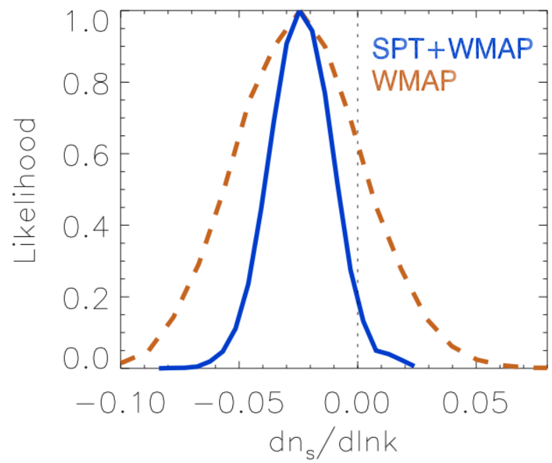
TABLE I. Standard ΛCDM parameters with 68% confidence level from the combination of WMAP9, ACT and SPT, and including a τ prior folding in recent *Planck* HFI measurements [20]. The last two columns report a direct comparison with constraints from *Planck* 2015 data derived with the same τ prior.

Parameter	WMAP9 +ACT	WMAP9 +SPT	WMAP9 +ACT+SPT	(2017)-(2013) [in units of σ]	PlanckTT	PlanckTTTEEE
$100\Omega_b h^2$	2.243 ± 0.040	2.223 ± 0.033	2.242 ± 0.032	-0.25	2.217 ± 0.021	2.222 ± 0.015
$100\Omega_c h^2$	11.56 ± 0.43	11.26 ± 0.36	11.34 ± 0.36	$+0.41$	12.05 ± 0.21	12.03 ± 0.14
$10^4\theta$	103.95 ± 0.19	104.23 ± 0.10	104.24 ± 0.10	-0.21	104.078 ± 0.047	104.069 ± 0.032
τ	0.060 ± 0.009	0.057 ± 0.009	0.058 ± 0.009	-2.1	0.064 ± 0.010	0.065 ± 0.009
n_s	0.966 ± 0.010	0.9610 ± 0.0089	0.9638 ± 0.0087	-0.37	0.9625 ± 0.0056	0.9626 ± 0.0044
$\ln(10^{10} A_s)$	3.037 ± 0.023	3.018 ± 0.021	3.025 ± 0.021	-1.9	3.064 ± 0.020	3.067 ± 0.019
Ω_Λ [a]	0.703 ± 0.025	0.726 ± 0.019	0.723 ± 0.019	-0.71	0.680 ± 0.013	0.6812 ± 0.0086
$\Omega_{\rm m}$	0.296 ± 0.025	0.273 ± 0.019	0.277 ± 0.019	$+0.71$	0.320 ± 0.013	0.3188 ± 0.0086
σ_8	0.792 ± 0.020	0.774 ± 0.018	0.780 ± 0.017	-1.5	0.820 ± 0.010	0.8212 ± 0.0086
t_0	13.813 ± 0.093	13.729 ± 0.063	13.715 ± 0.062	$+0.81$	13.823 ± 0.035	13.822 ± 0.025
H_0	68.5 ± 2.0	70.5 ± 1.6	70.3 ± 1.6	-0.74	67.00 ± 0.90	67.03 ± 0.61

Calabrese et al. 2017

South Pole Telescope





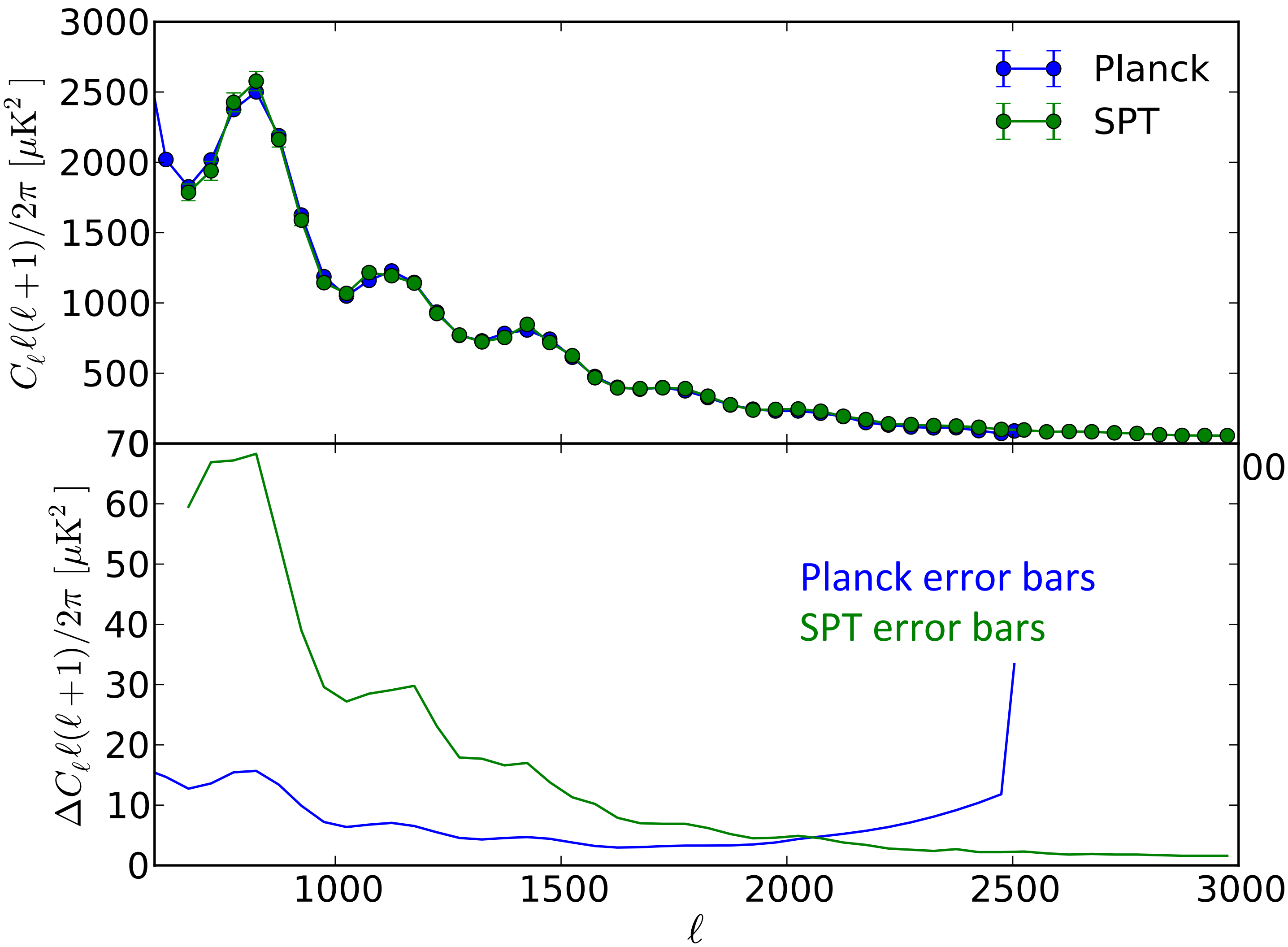
Parameter	*WMAP7*	SPT[a]	CMB (SPT+*WMAP7*)
Baseline parameters			
$100\,\Omega_b h^2$	2.231 ± 0.055	2.30 ± 0.11	2.229 ± 0.037
$\Omega_c h^2$	0.1128 ± 0.0056	0.1056 ± 0.0072	0.1093 ± 0.0040
$10^9\,\Delta^2_R$	2.197 ± 0.077	2.164 ± 0.097	2.142 ± 0.061
n_s	0.967 ± 0.014	0.926 ± 0.029	0.9623 ± 0.0097
$100\,\theta_s$	1.0396 ± 0.0027	1.0441 ± 0.0012	1.0429 ± 0.0010
τ	0.087 ± 0.015	0.087 ± 0.015	0.083 ± 0.014
Derived parameters[b]			
Ω_Λ	0.724 ± 0.029	0.772 ± 0.033	0.750 ± 0.020
H_0	70.0 ± 2.4	75.0 ± 3.5	72.5 ± 1.9
σ_8	0.819 ± 0.031	0.772 ± 0.035	0.795 ± 0.022
z_{EQ}	3230 ± 130	3080 ± 170	3146 ± 95
$100\,\frac{r_s}{D_V}(z = 0.35)$	11.43 ± 0.37	12.15 ± 0.55	11.81 ± 0.29
$100\,\frac{r_s}{D_V}(z = 0.57)$	7.58 ± 0.21	7.98 ± 0.31	7.80 ± 0.16

SPT alone prefers very high H_0=**75.0 ± 3.5.**

2-sigma detection of running of the scalar spectral index.

Planck cosmology discrepant at pte=3.2% level in a LCDM model.

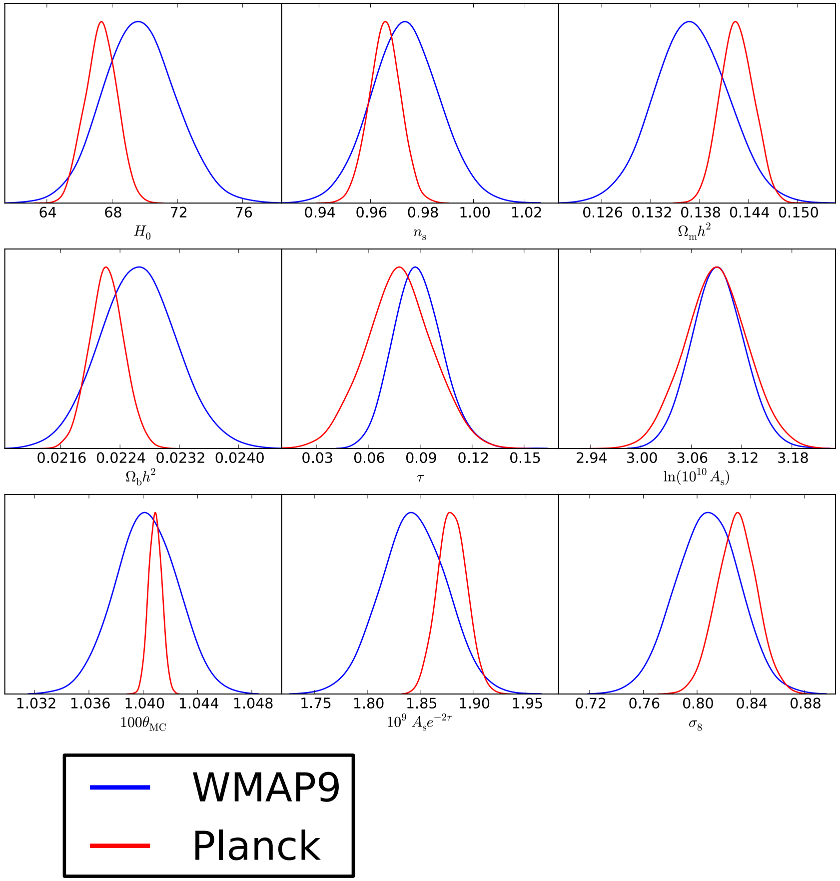
South Pole Telescope

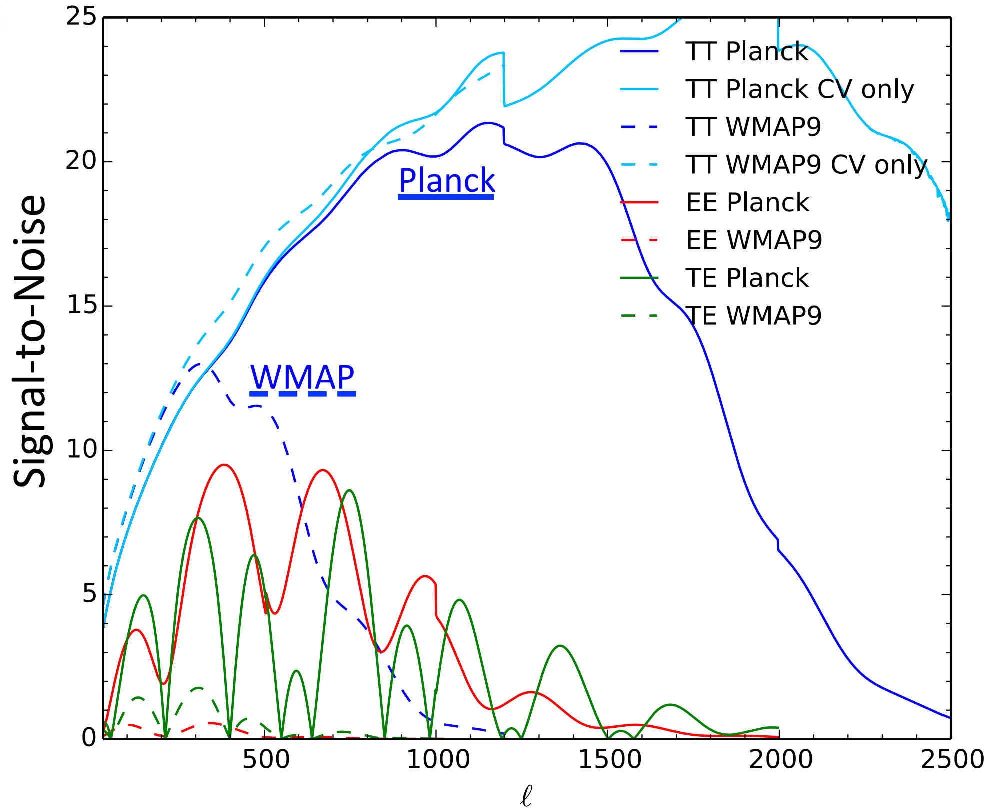


SPT uses ~ 6% of the sky.
Error bar due to sample variance ~3 times larger than Planck.

*SPT bandpowers from Story et al. 2012, calibrated on WMAP, in bins of 50.

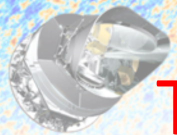
Planck and WMAP





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)



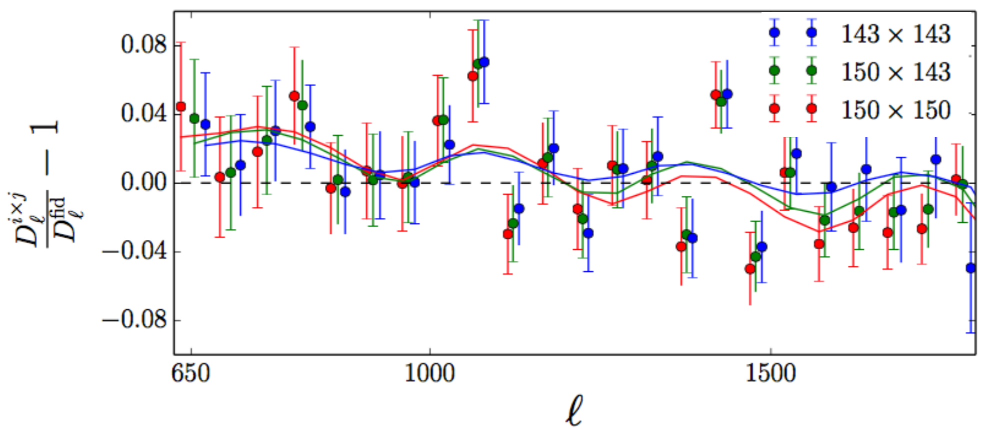
Extensions of ΛCDM?
The case of the number of relativistic species

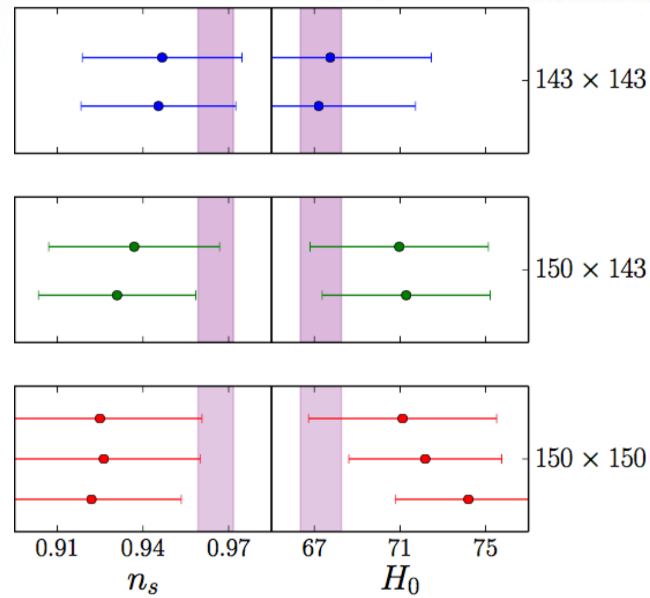
- Adding Neff relaxes the tension with Riess et al. only because H_0 error from Planck is increased. But Planck still prefers low H_0 and the tensions is still at ~2 sigma level.
- Combining gaussian prior H0=73 ± 1.8 Km/s/Mpc from Riess+ 16, the push for large Neff is all from Riess et al. Planck χ^2 worsens when combining with Riess both in LCDM and ΛCDM+Neff model

		Neff	H_0	$\Delta\chi^2$ Planck	$\Delta\chi^2$ Riess
ΛCDM	Planck	-	**67.3 ± 0.95**	0 (Reference Planck)	-
	Planck+Riess	-	68.7 ± 0.88	+2	0 (Reference Riess)
ΛCDM +Neff	Planck	3.12±0.32	**68.0 ± 2.8**	+0	-
	Planck+Riess	$3.51^{+0.19}_{-0.23}$	71.7 ± 1.6	+2	-4

No easy extension that can solve all tensions and accommodate all data (see Di Valentino+ 2016, Bernal+ 2016)

Planck and SPT-SZ





- LCDM Parameters from Planck full sky and SPT 150x150 are discrepant at **the 3.2% level**.

- However, Parameters from Planck in-patch 143x143 or 143x150 cosmology in good agreement with SPT 150x150.

- Difference in n_s due to in-patch versus full sky. High H_0 in SPT driven by l>2000.

TABLE 1

PTEs Between Parameters in SPT Sky Patch.

	$\ell_{\rm max}$		
	2000	2500	3000
150 × 150 – 150 × 143	0.74	0.66	0.57
150 × 150 – 143 × 143	0.32	0.38	0.20
150 × 143 – 143 × 143	0.62	0.73	

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