Reviewing tensions between Planck and other data

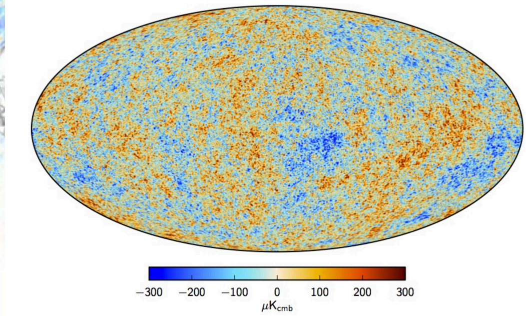
Silvia Galli

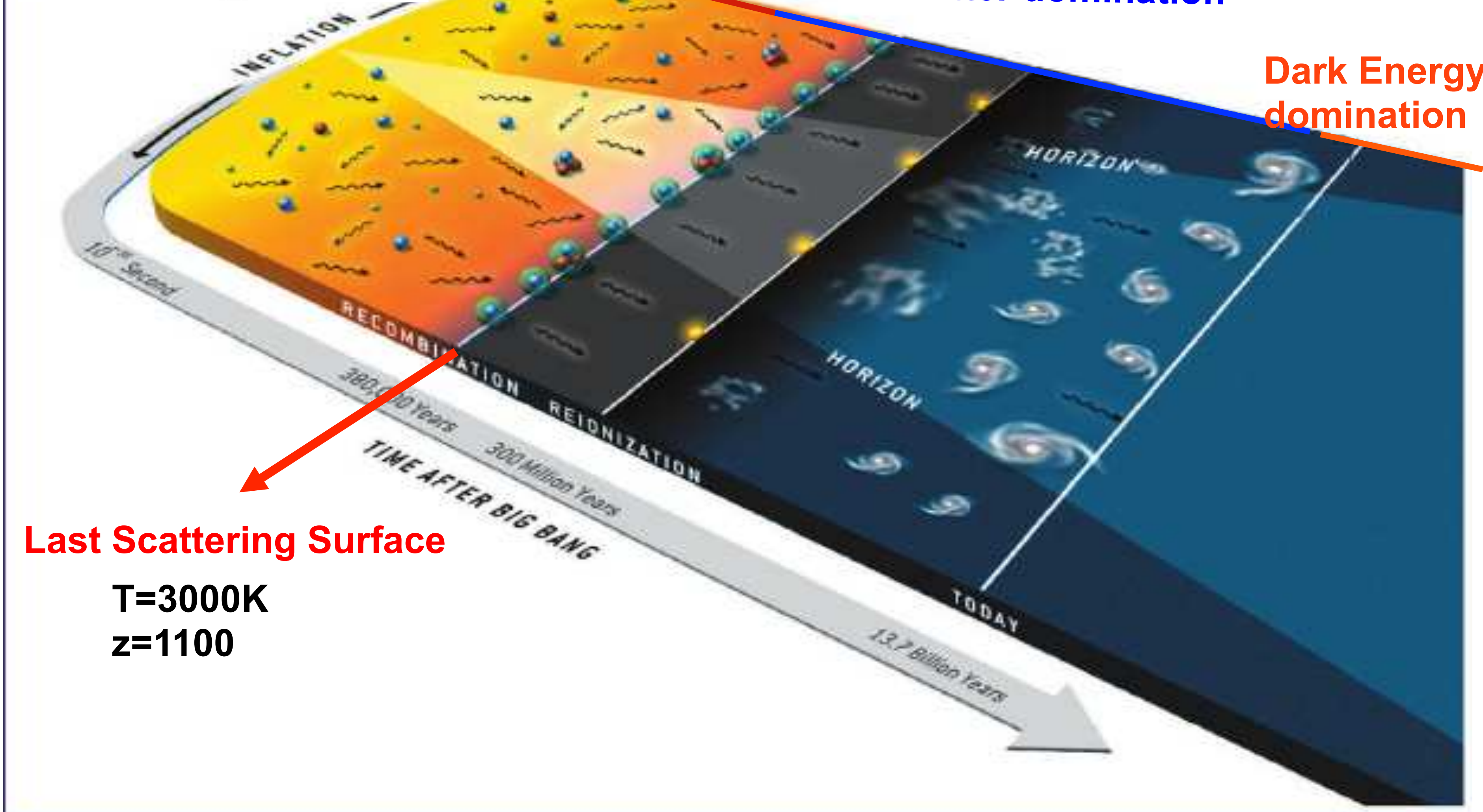
IAP-Paris

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

Helsinki, 03/05/2017

Cosmic History





Radiation domination

Matter domination

Dark Energy domination

Last Scattering Surface

T=3000K
z=1100

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

Cosmic History

Radiation domination

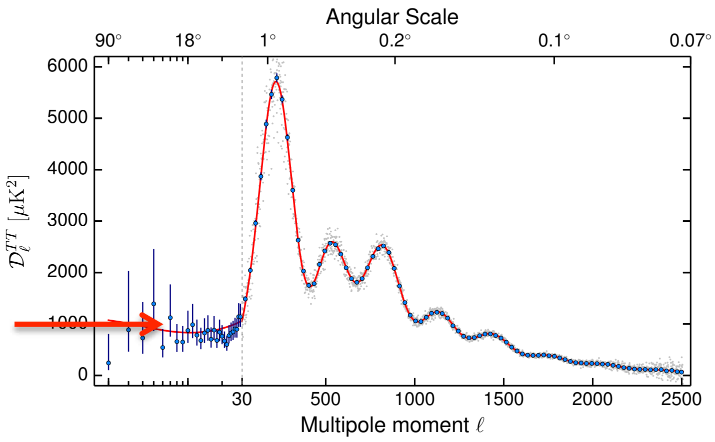
Matter domination

Dark Energ
dominatio

CMB is an extremely rich source of information about our universe!

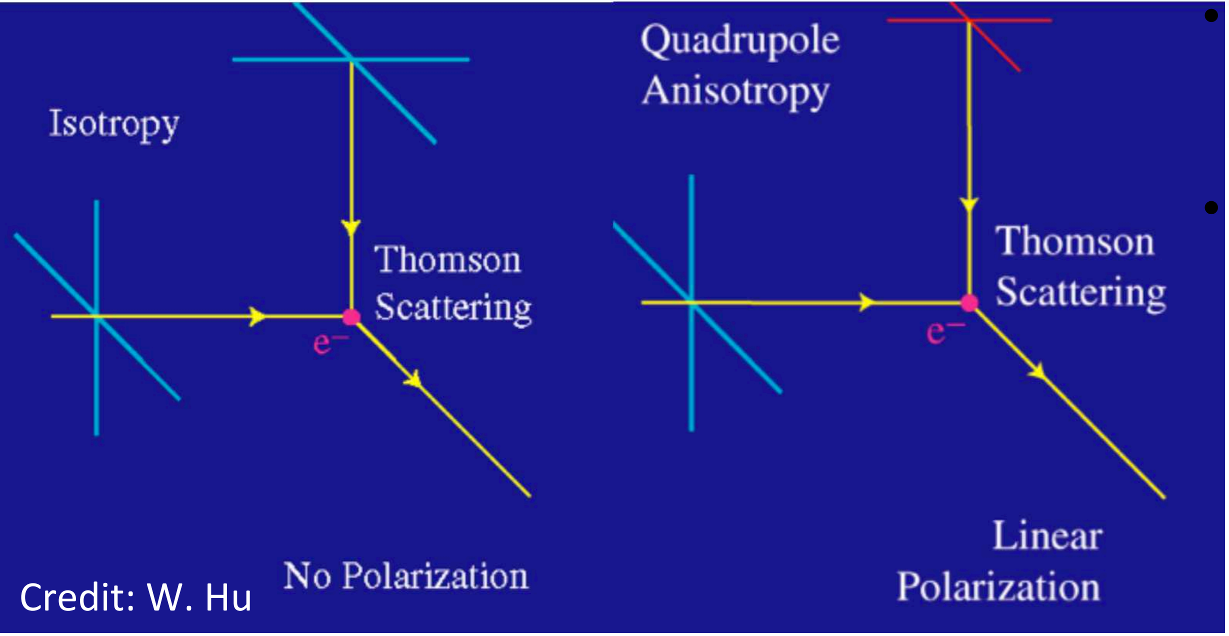
$$\Theta(\vec{x},\hat{p},\eta) = \sum_{l=1}^{\infty}\sum_{m=-l}^{l} a_{lm}(\vec{x},\eta)\,Y_{lm}(\hat{p})$$

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



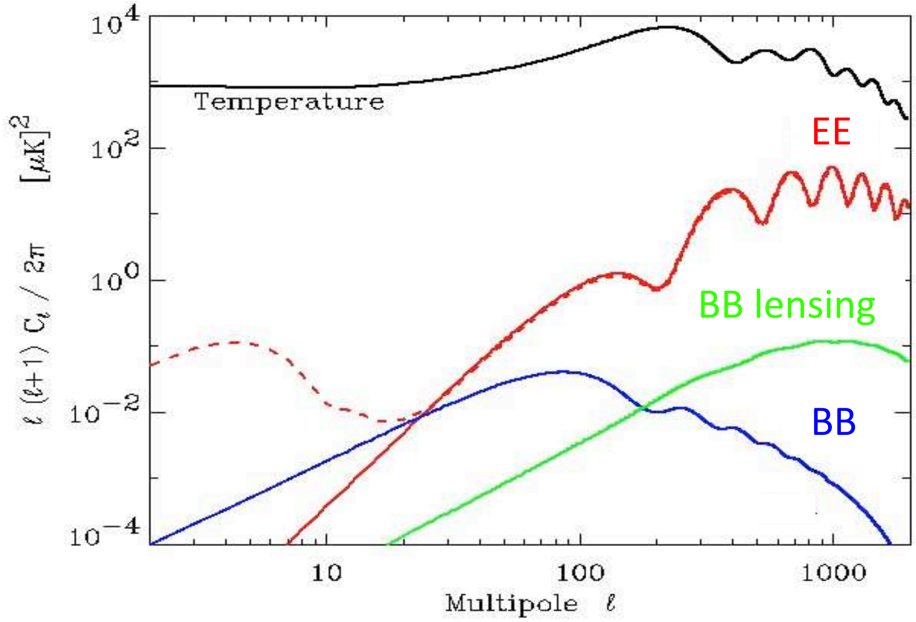
Hu & White (2004); artist B. Christie/SciAm; available at http://background.uchicago.edu

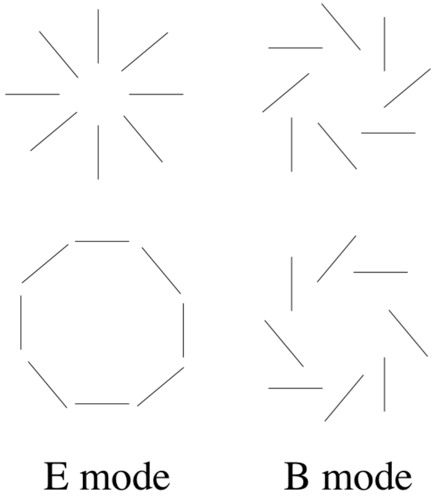
CMB Polarization

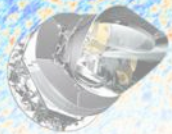


Credit: W. Hu

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







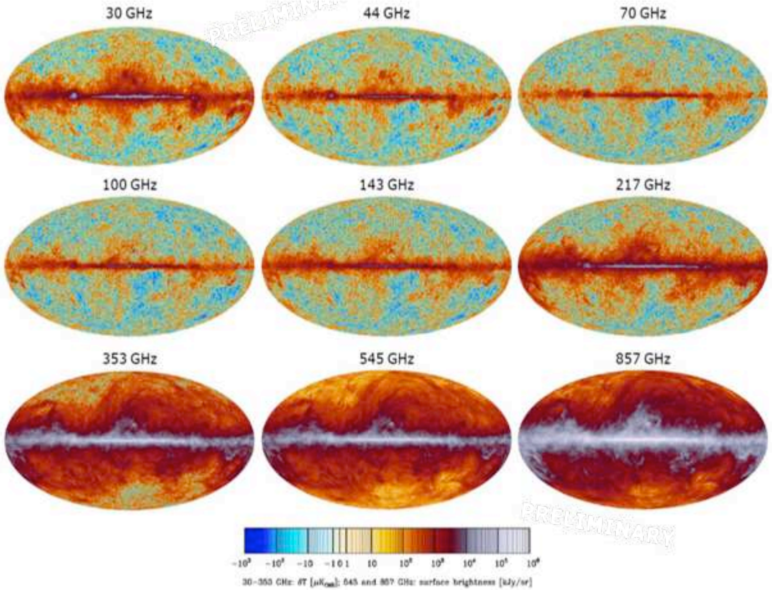
The Planck satellite

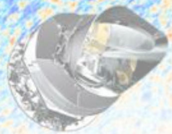
Launched in 2009, operated till 2013.
2 Instruments, 9 frequencies.

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

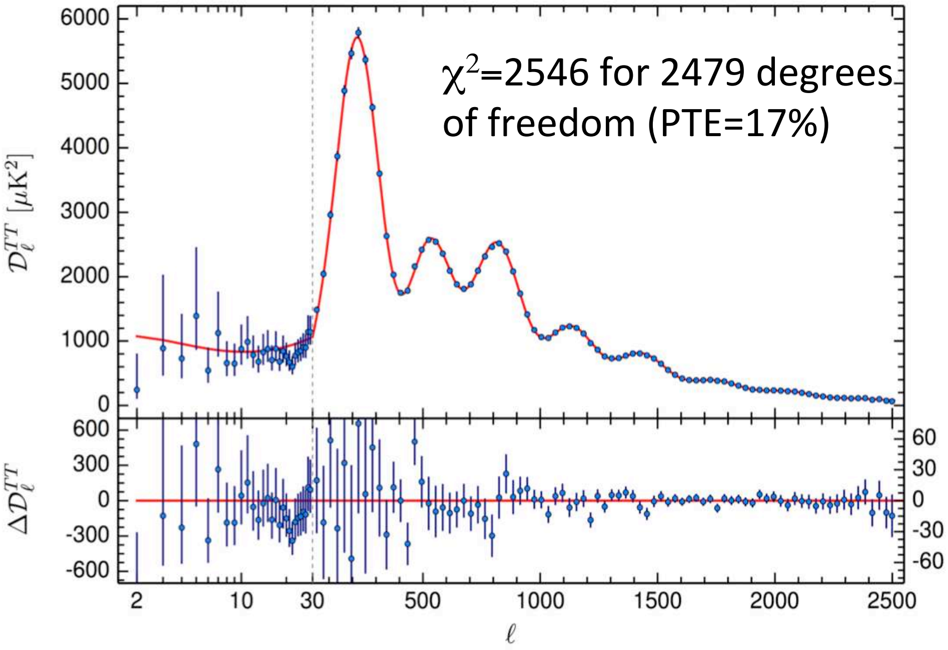




ΛCDM and Planck

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

Excellent fit to the data



χ^2=2546 for 2479 degrees of freedom (PTE=17%)

Most of parameters at the ~1% level.

No significant deviation from ΛCDM in extended models

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)

$$\sum m_\nu < 0.23\ \mathrm{eV}$$

(PlanckTT+lowP+Lensing+ext)

Number of relativistic species:

Compatible with standard predition N_{eff}=3.046 with 3 active neutrinos

$$N_{\mathrm{eff}} = 3.13 \pm 0.32$$

(PlanckTT+lowP)

Helium abundance

Good agreement with measurements of primordial abundances and BBN predictions

$$Y_P^{\mathrm{BBN}} = 0.253 \pm 0.021$$

(PlanckTT+lowP)

Running of the scalar spectral index

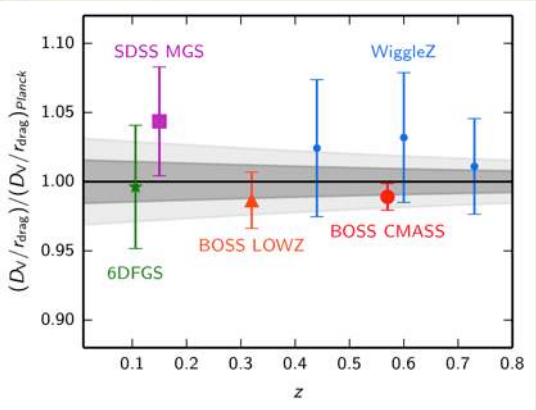
Compatible with no running

$$\frac{dn_s}{d\ln k} = -0.0084 \pm 0.0082$$

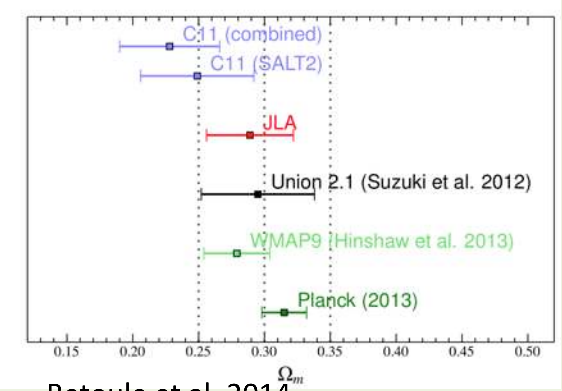
(PlanckTT+lowP)

Comparison with other datasets:

BAO

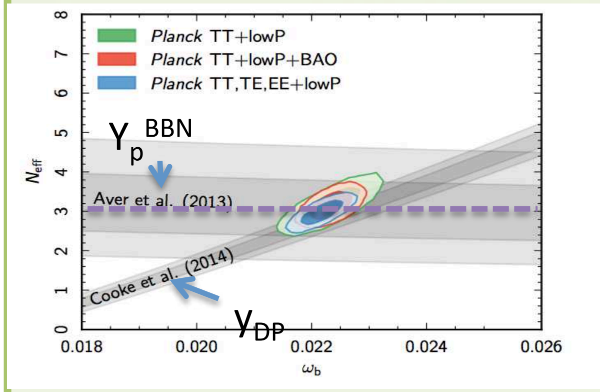


Supernovae (Ω_m)

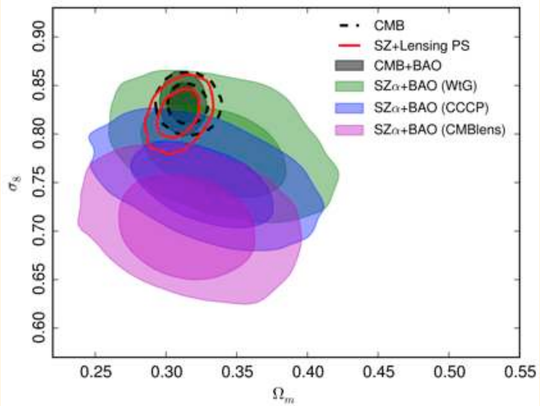


Betoule et al. 2014

BBN

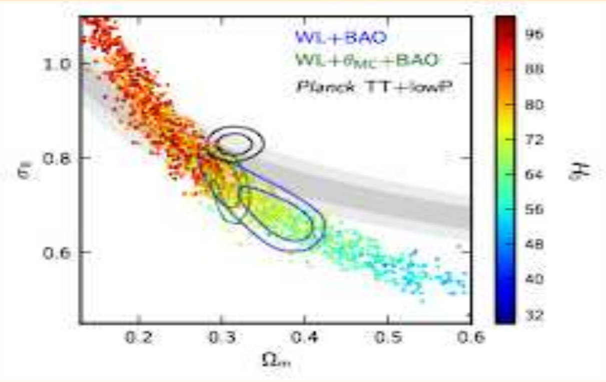


Cluster counts (σ_8-Ω_m)



Planck collaboration XXIV

Weak Lensing (σ_8-Ω_m)



Direct measurements H

H_0=67.8±0.92 [Km/s/Mpc]
(PlanckTT+lowP+lensing)

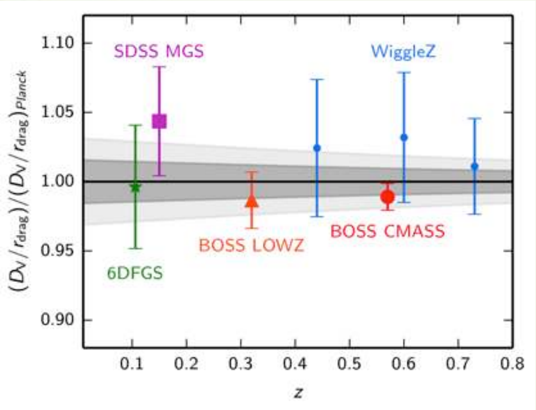
H_0=72.8±2.4 **[2σ tension]**
(Riess+11)
H_0=70.6 ± 3.3 **[1σ tension]**
(Efstathiou+14)

H_0=74.3 ± 2.6 **[2.5σ tension]**
(Freedman+12)

H_0=73.±1.8 **[2.7σ tension]**
(Riess+16)

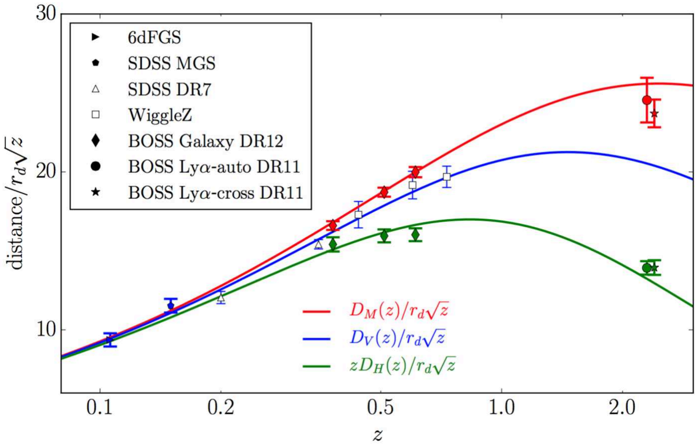
Comparison with other datasets:

BAO

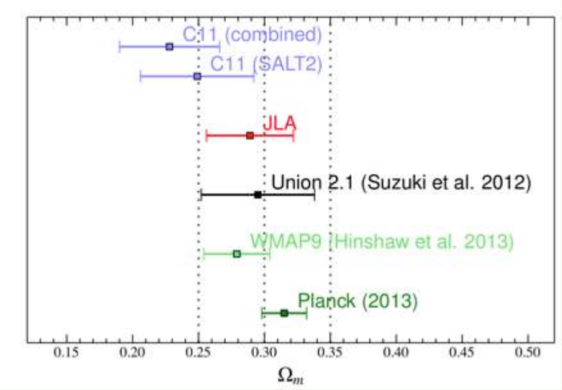


Baryon acoustic oscillations measure sound horizon/ distance ratio.

BOSS RD12 Alam+ 2016, arXiv:1607.03155v1

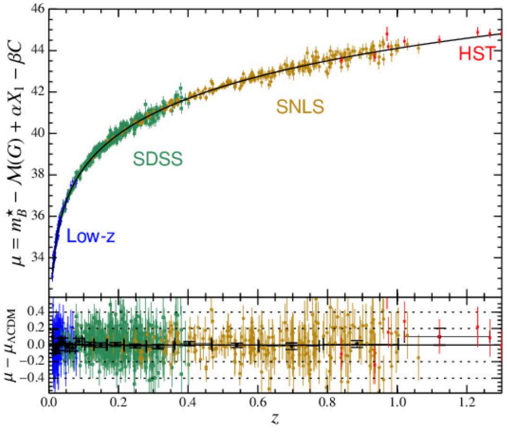


Supernovae (Ω_m)

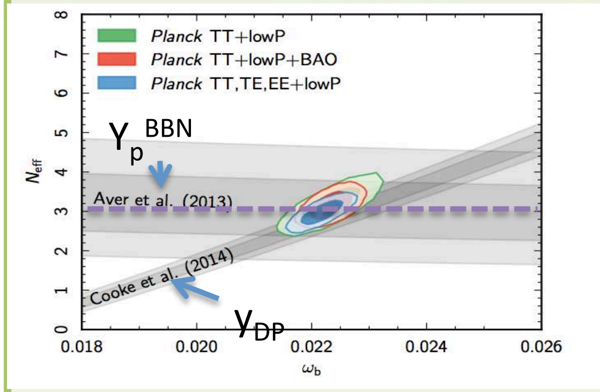


Measure relative luminosity distance with z, z=0-1.4

Betoule et al. 2014

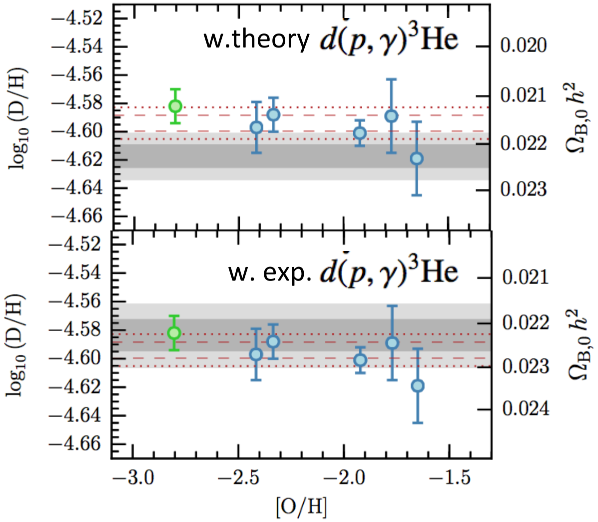


BBN



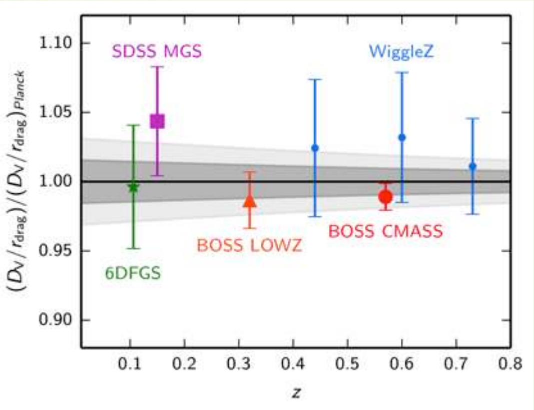
Primordial Helium and deuterium abundances good agreement with BBN+Planck (but 2.3σ w. latest Ydp.).

Cooke + 2016 arXiv:1607.03900v1

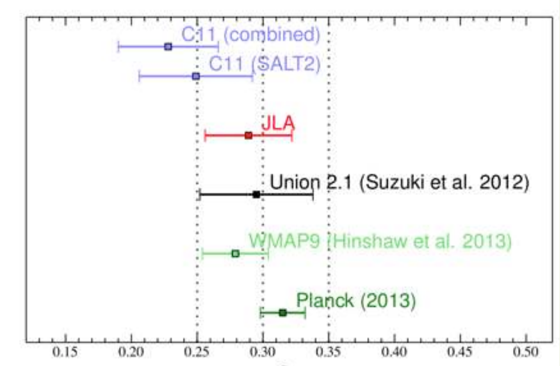


Comparison with other datasets:

BAO

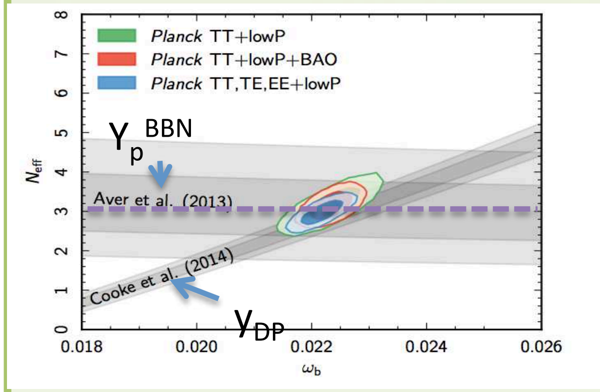


Supernovae (Ω_m)

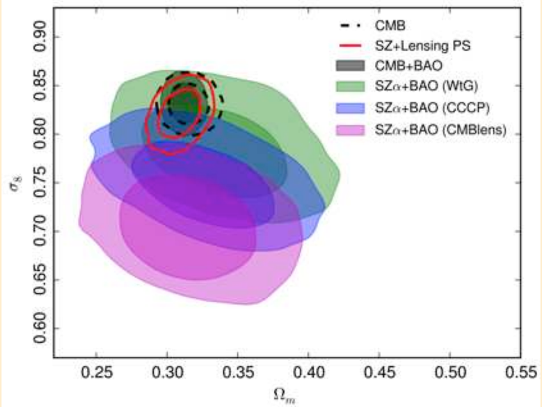


Betoule et al. 2014

BBN

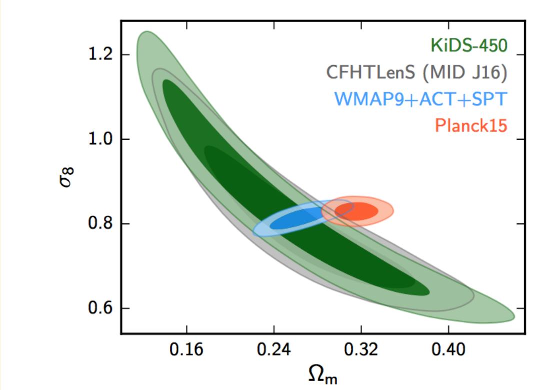


Cluster counts (σ_8-Ω_m)



Planck collaboration XXIV

Weak Lensing (σ_8-Ω_m)



Hildebrandt+ 16

Direct measurements H_0

H_0=66.9±0.91 [in Km/s/Mpc]
(PlanckTT+SIMlowHFI)

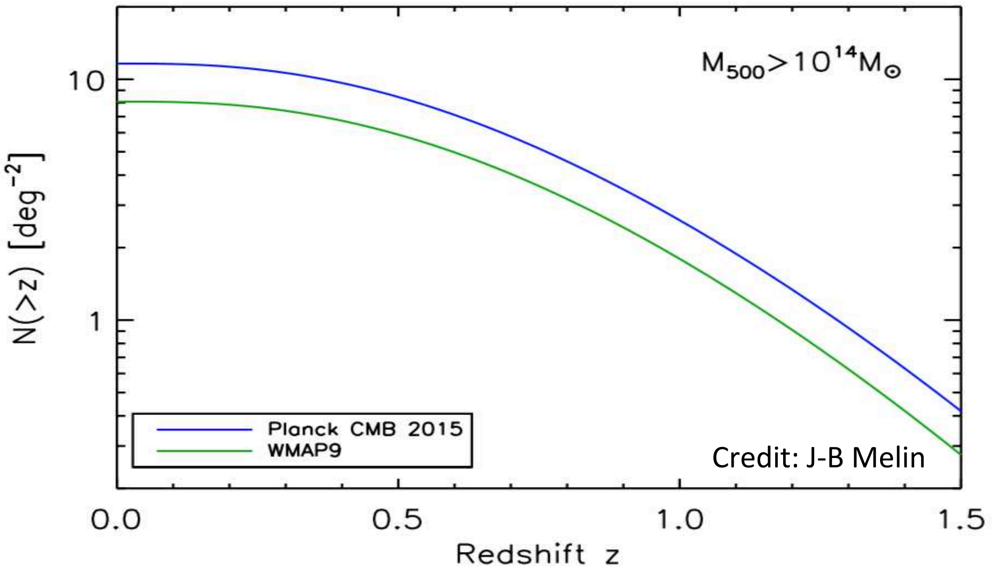
H_0=72.8±2.4 **[2σ tension]**
(Riess+11)
H_0=70.6 ± 3.3 **[1σ tension]**
(Efstathiou+14)

H_0=74.3 ± 2.6 **[2.5σ tension]**
(Freedman+12)

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

Counts of clusters of galaxies

- **Number of clusters** as a function of **z** sensitive to cosmological parameters.
- Clusters can be detected through **Sunyaev-Zeldovich effect in CMB** surveys (e.g. Planck, ACT, SPT).
- To compare observations to predictions, we need to know the **redshift and the mass** of the observed clusters.
- Relation between SZ observables and mass calibrated on X-ray observations. Mass estimate assume hydrostatic equilibrium and is thus biased.
- Amplitude of **mass bias** is **KEY** quantity.



Credit: J-B Melin

$$\frac{dN}{dz} = \int d\Omega \int dM_{500}\,\hat{\chi}(z, M_{500}, l, b)\,\frac{dN}{dz\,dM_{500}\,d\Omega}$$

Completeness!

Mass function

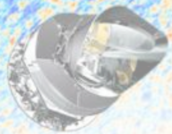
$$E^{-\beta}(z)\left[\frac{D_{\mathrm{A}}^{2}(z)\,\bar{Y}_{500}}{10^{-4}\,\mathrm{Mpc}^{2}}\right] = Y_{*}\left[\frac{h}{0.7}\right]^{-2+\alpha}\left[\frac{(1-b)\,M_{500}}{6\times10^{14}\,\mathrm{M_{sol}}}\right]^{\alpha}$$

SZ observable
(Integrated thermal pressure)

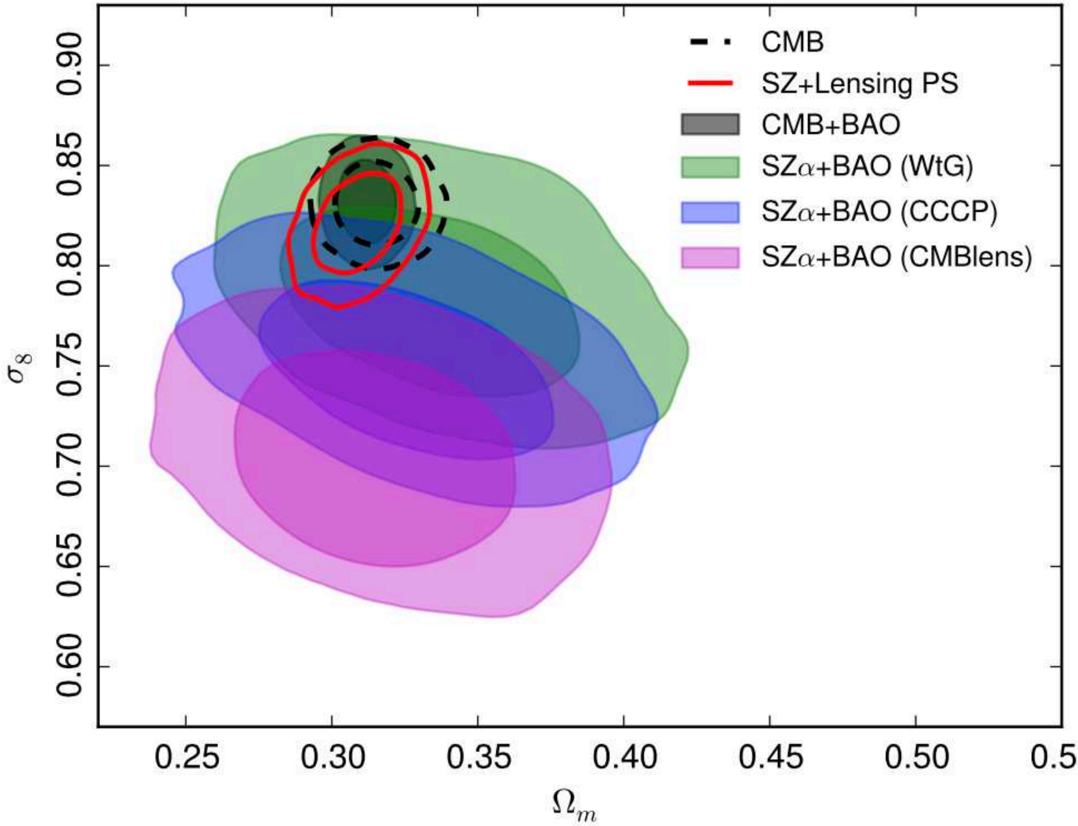
Bias
$M_x=M_{true}$ (1-b)

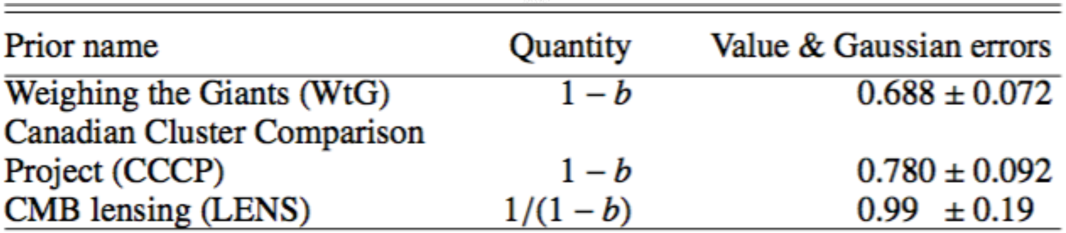
True
Cluster
Mass

Cluster counts with Planck 2015



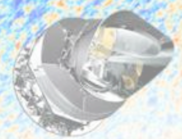
- **Number of clusters** as a function of **z** sensitive to cosmology.
- Detected through **Sunyaev-Zeldovitch effect in CMB** surveys.
- Need to know the **mass** of the observed clusters -> Need Ysz-mass relation-> Calibrated with X-ray observations-> Assume hydrostatic equilibrium-> **mass bias!**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



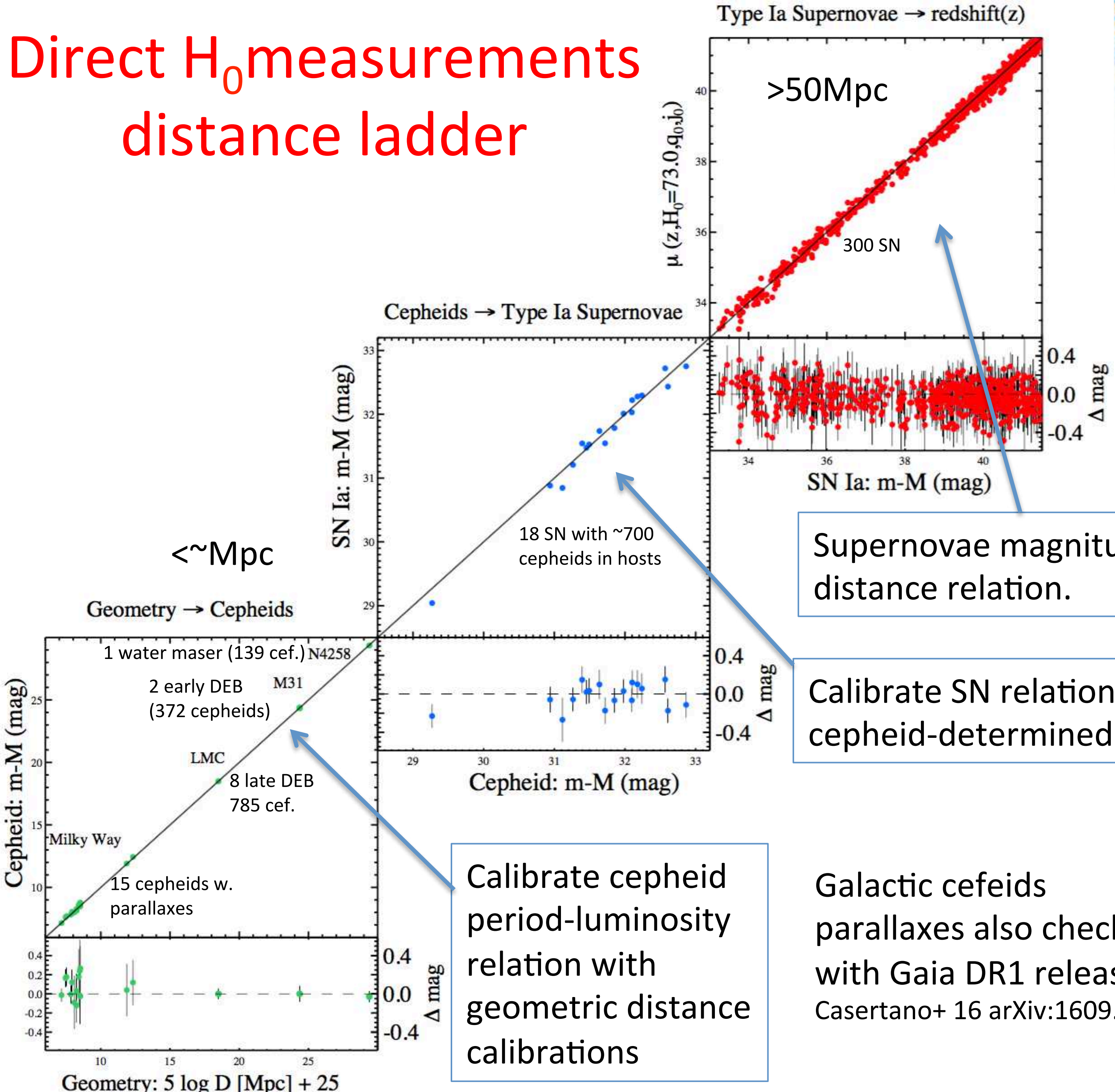


Prior name	Quantity	Value & Gaussian errors
Weighing the Giants (WtG)	$1 - b$	0.688 ± 0.072
Canadian Cluster Comparison Project (CCCP)	$1 - b$	0.780 ± 0.092
CMB lensing (LENS)	$1/(1 - b)$	0.99 ± 0.19

- 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.



Direct H_0 measurements distance ladder



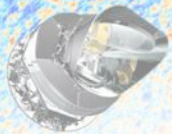
Supernovae magnitude-distance relation.

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



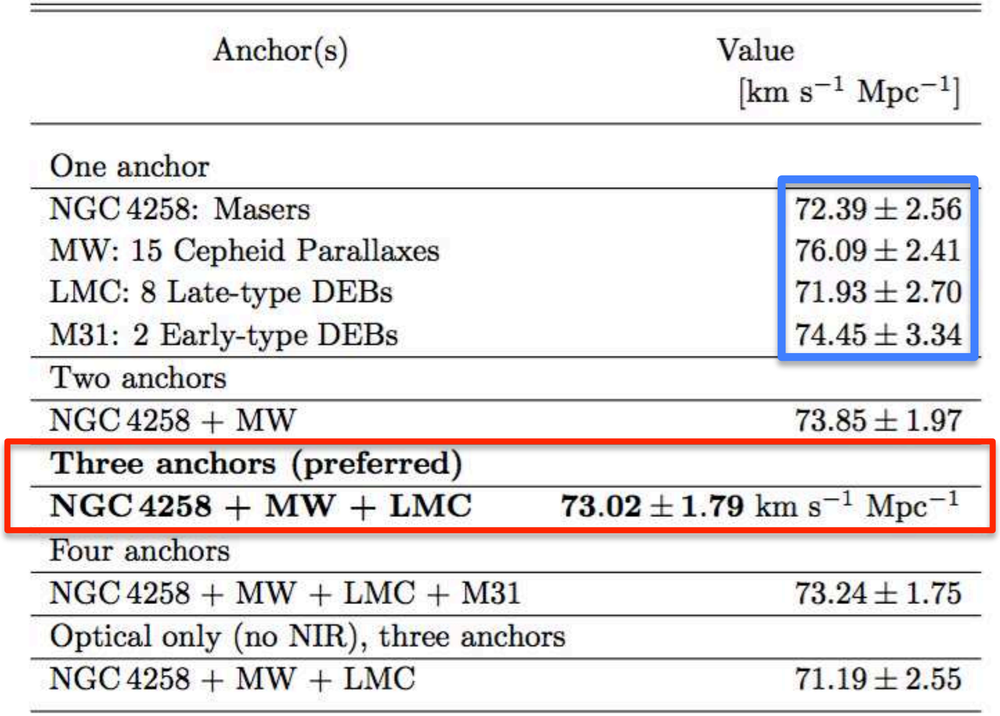
Direct measurements H_0

Direct measurements H_0

H_0=67.3±0.96 [in Km/s/Mpc]
(PlanckTT+lowP_LFI)

H_0=66.9±0.91
(PlanckTT+SIMlow_HFI)

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

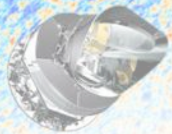


Anchor(s)	Value [km s^{-1} Mpc^{-1}]
One anchor	
NGC 4258: Masers	72.39 ± 2.56
MW: 15 Cepheid Parallaxes	76.09 ± 2.41
LMC: 8 Late-type DEBs	71.93 ± 2.70
M31: 2 Early-type DEBs	74.45 ± 3.34
Two anchors	
NGC 4258 + MW	73.85 ± 1.97
Three anchors (preferred)	
NGC 4258 + MW + LMC	**73.02 ± 1.79** km s^{-1} 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

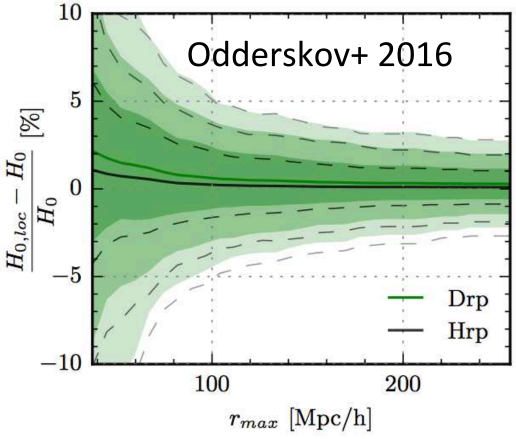
H_0 can be also measured from multiply-imaged quasar systems with measured gravitational time delays. H0licow project from 3 lenses: $H_0 = 71.9^{+2.4}_{-3.0}\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$

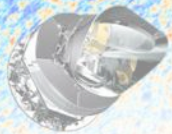
Bonvin et al.arXiv:1607.01790



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).





Not only a Planck tension

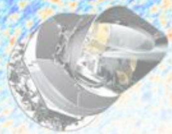
Planck15 +SIMlowHFI	H_0=66.9±0.9	3σ tension
Riess+ 2016	H_0=73.02±1.79	
WMAP	H_0=69.7±2.1 [Km/s/Mpc]	

*The direct measurement tension is *NOT only* a Planck problem:

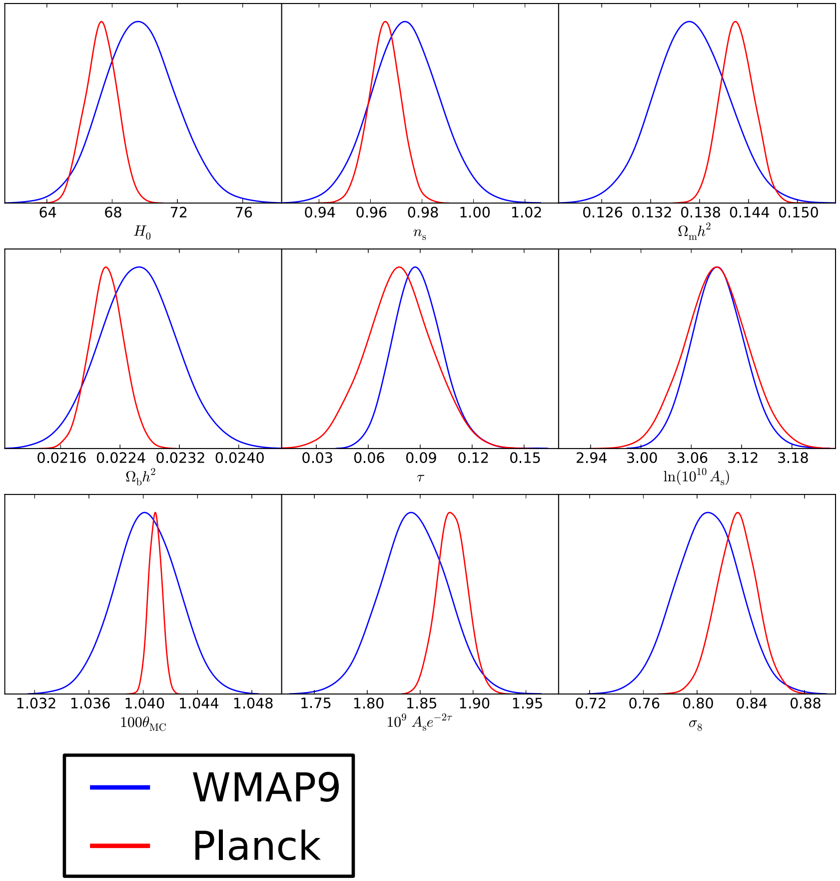
- WMAP9+BAO (BOSSDR11+6dFGS+Lyman α)+high-z Sne
  H_0= 68.1 ± 0.7 (2.5σ tension) (Aubourg+ 2015)

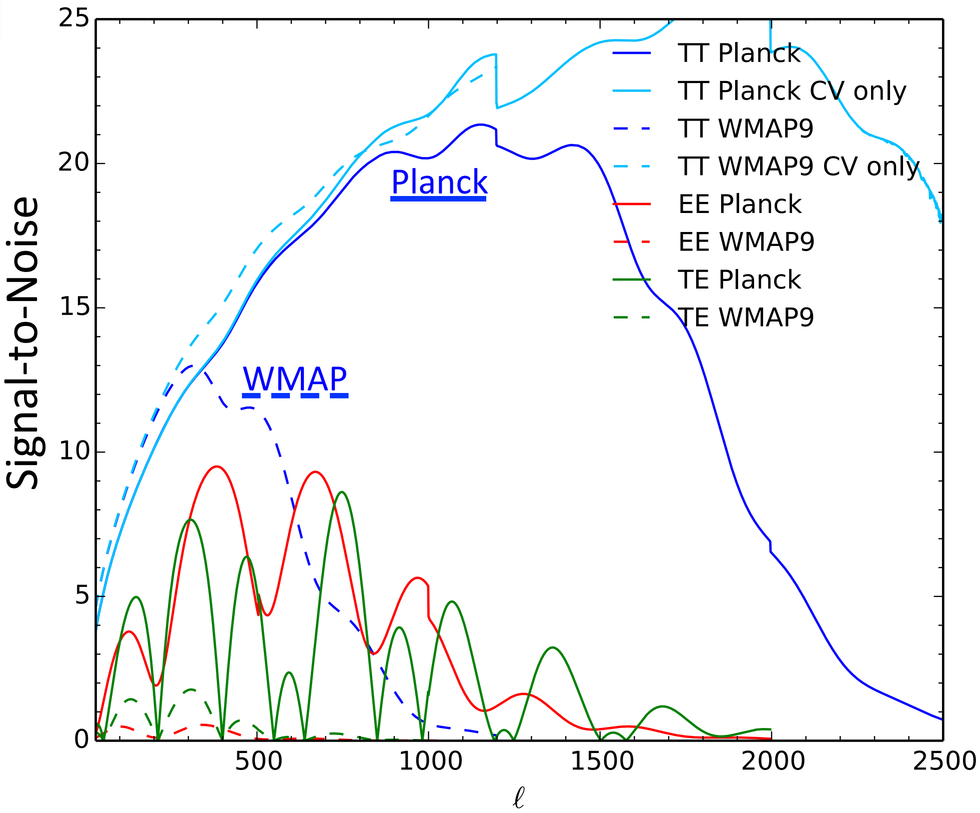
- WMAP9+ACT+SPT + BAO (BOSSDR11+6dFGS)
  H_0 = 69.3 ± 0.7 (1.9s tension) (Bennet+ 2014)

- SPT alone prefers very high H_0=75.0 ± 3.5



Planck and WMAP



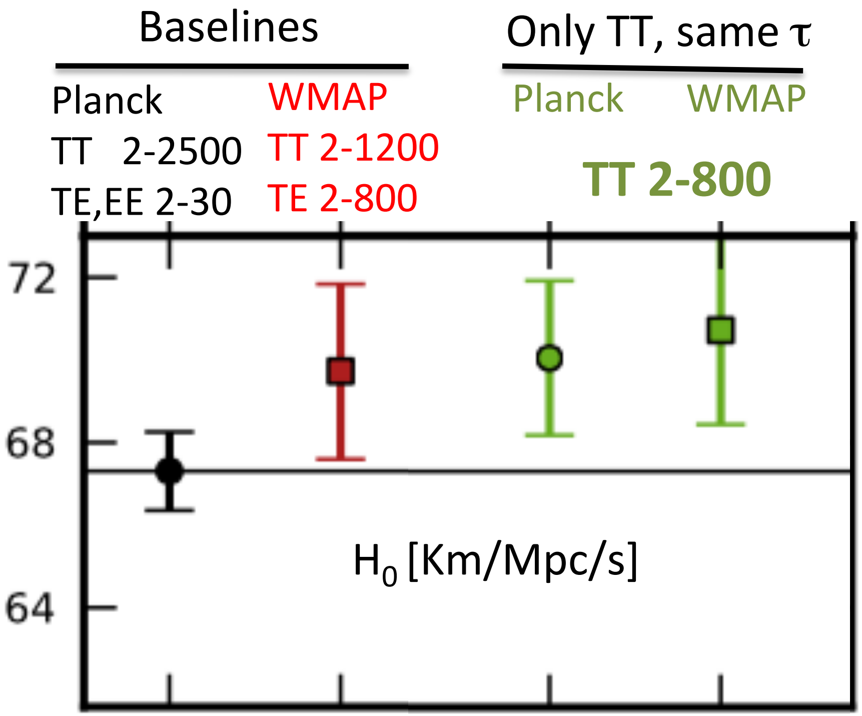


Planck sample variance limited till **l~1600** (data points till ~2500, fsky~40-70%)

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

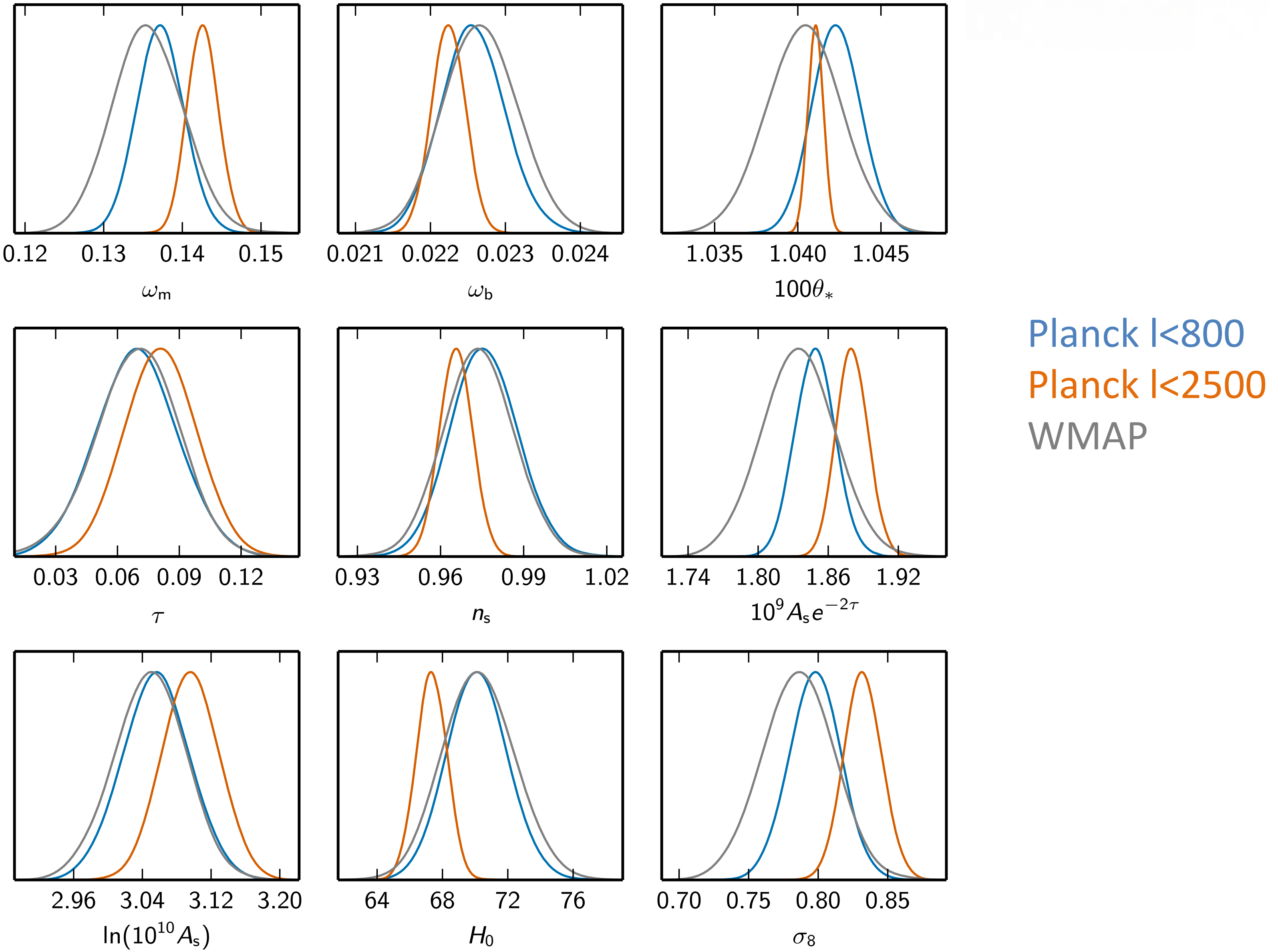
Compare apples to apples

- Same prior on the optical depth, temperature only, same multipole region (although noise properties and fsky are still different).



- Planck and WMAP agree very well when compared properly.
- This confirms the findings of comparison at map/power spectrum level.
- **Still need to prove that shifts between lmax=800 and lmax=2500 for Planck itself are consistent with expectations!**

Are the cosmological parameters inferred from the low (l<800) and the (l<2500) consistent?



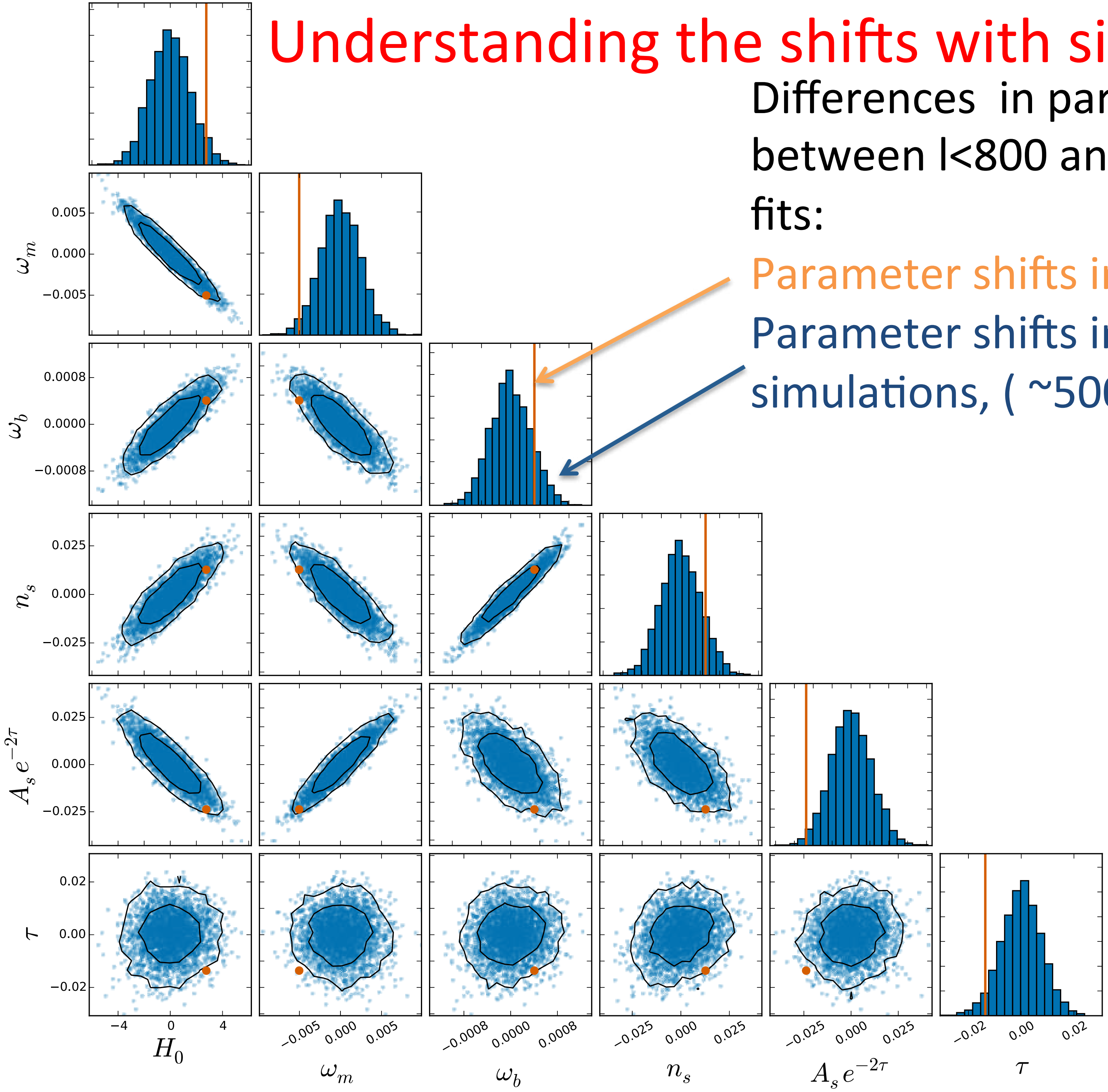
Simulations

- 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



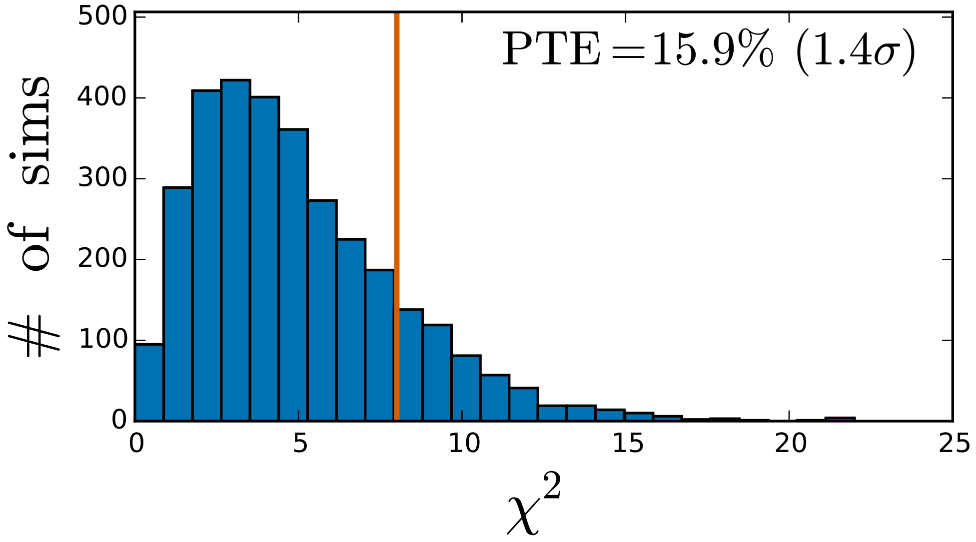
Differences in parameters between l<800 and l<2500 best-fits:

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

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

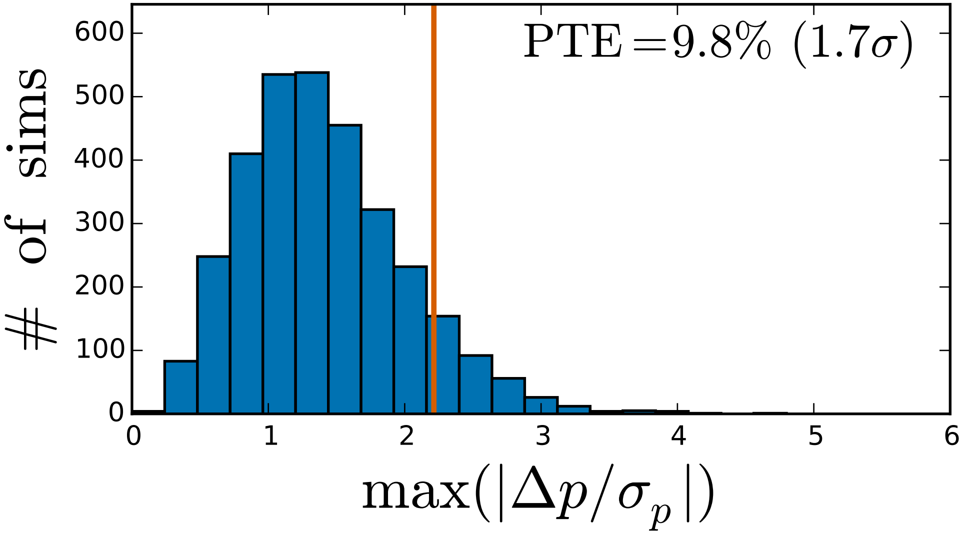
Δp = p[2-2500] - p[2-800]

PTE=15.9%, equivalent to 1.4σ.

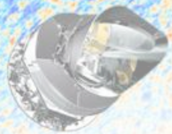
i.e. 15.9% of the sims exceed the data. Corresponds to the number of outliers larger than 1.4σ for a 1D gaussian.

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

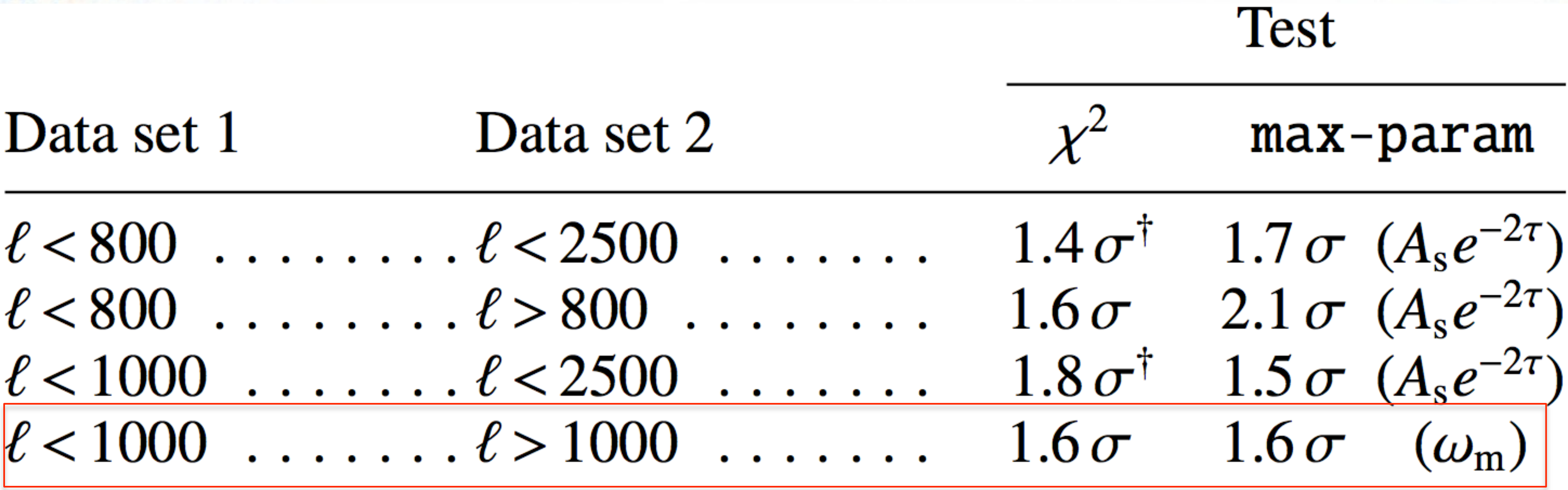
Significance of biggest outlier



- The largest outlier in the data is $A_s\ e^{-2\tau}$, at 1.7 σ.
- This includes look elsewhere effect (there are 6 cosmo. parameters, we picked the one with the largest shift). Without look-elsewhere is 2.2σ.

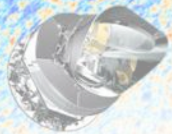


Significances



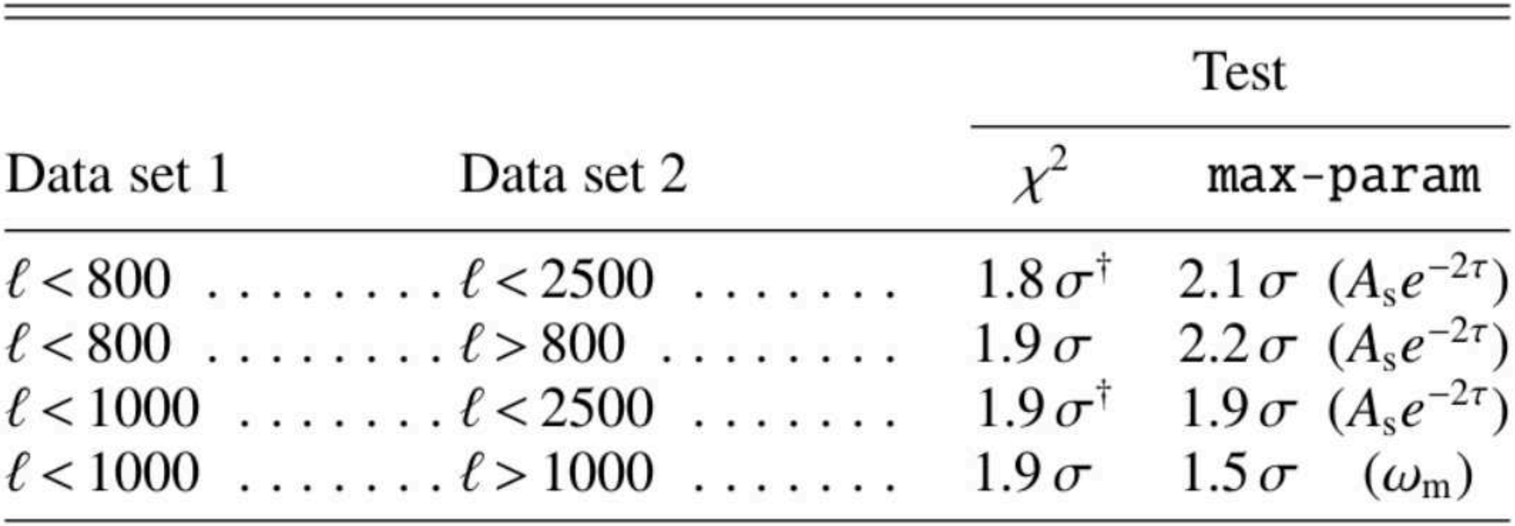
		Test	
Data set 1	Data set 2	χ^2	`max-param`
$\ell < 800$	$\ell < 2500$	$1.4\,\sigma^{\dagger}$	$1.7\,\sigma$ $(A_\mathrm{s}e^{-2\tau})$
$\ell < 800$	$\ell > 800$	$1.6\,\sigma$	$2.1\,\sigma$ $(A_\mathrm{s}e^{-2\tau})$
$\ell < 1000$	$\ell < 2500$	$1.8\,\sigma^{\dagger}$	$1.5\,\sigma$ $(A_\mathrm{s}e^{-2\tau})$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

The differences are not statistically very significant.



Effect of lower tau-prior

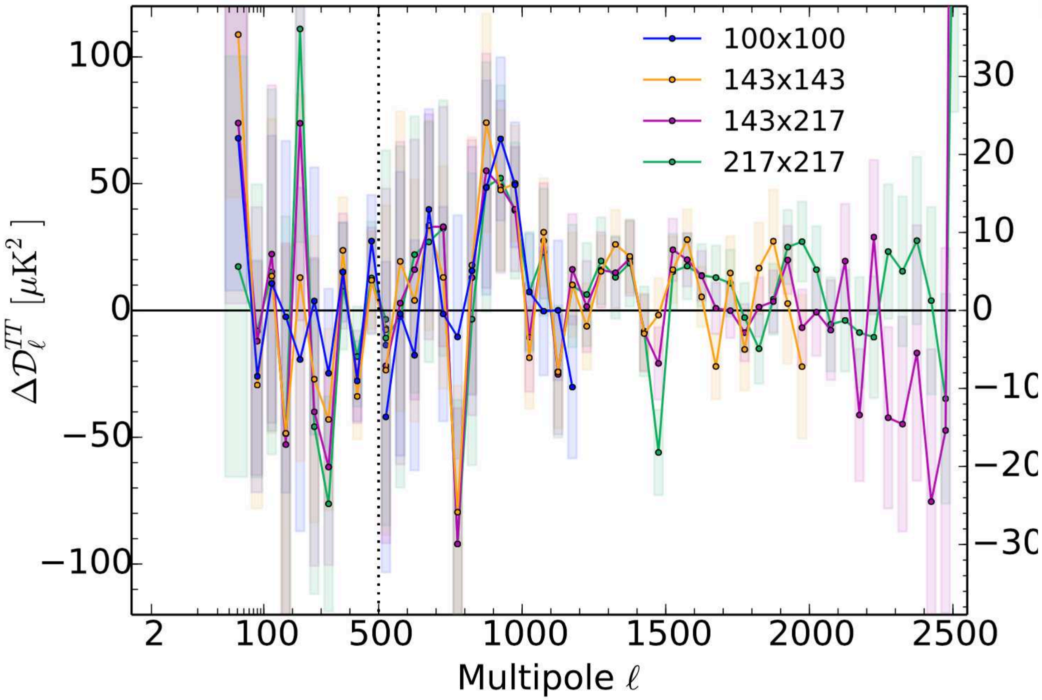
Using $\tau = 0.055 \pm 0.01$ instead of $\tau = 0.07 \pm 0.02$



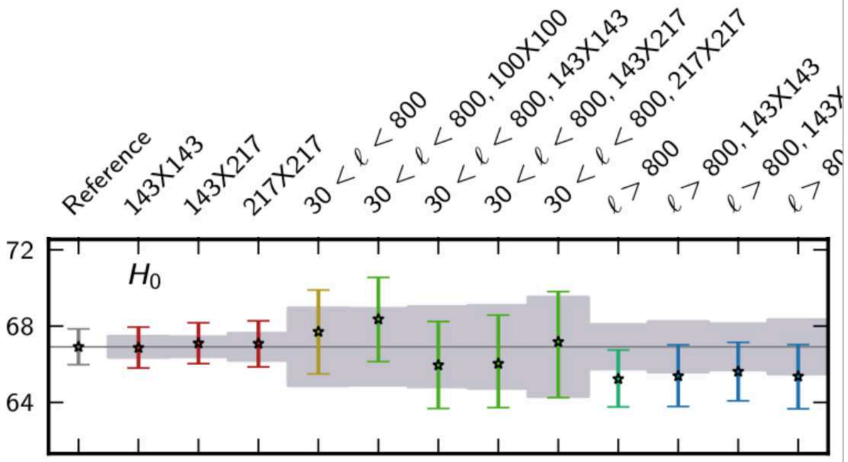
		Test	
Data set 1	Data set 2	χ^2	max-param
$\ell < 800$	$\ell < 2500$	$1.8\,\sigma^{\dagger}$	$2.1\,\sigma$ $(A_s e^{-2\tau})$
$\ell < 800$	$\ell > 800$	$1.9\,\sigma$	$2.2\,\sigma$ $(A_s e^{-2\tau})$
$\ell < 1000$	$\ell < 2500$	$1.9\,\sigma^{\dagger}$	$1.9\,\sigma$ $(A_s e^{-2\tau})$
$\ell < 1000$	$\ell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

$[-0.1\sigma, 0.3\sigma]$ changes

Consistency between frequencies



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

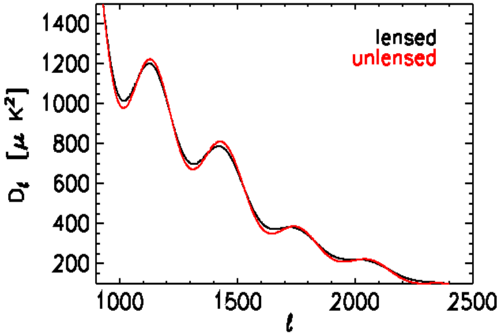


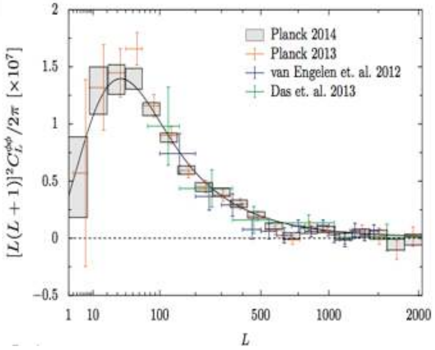
What is driving the shifts between lmax=800 and lmax=2500?

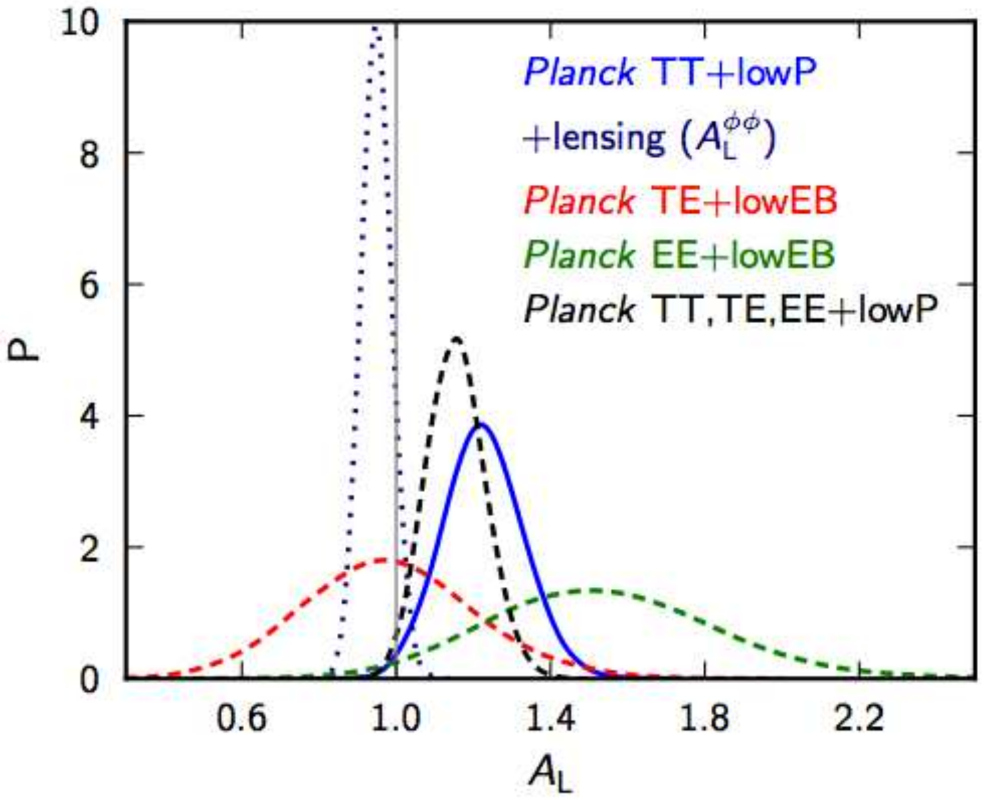
1. Is there a preference for extra-lensing?

2. Is it the low-l anomaly?

A slight preference for high lensing in the power spectrum

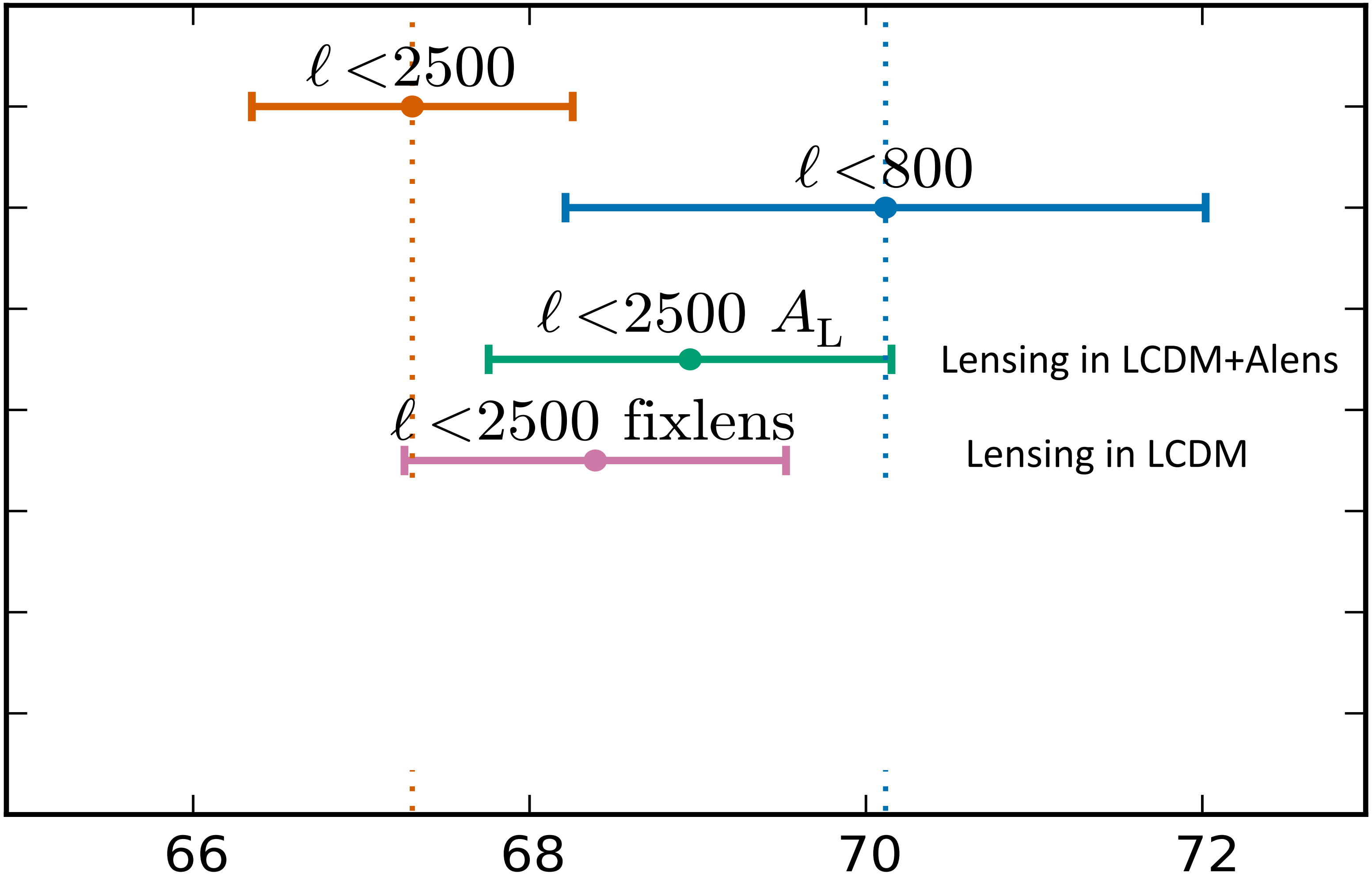






- A_L parametrizes amplitude of lensing power spectrum.
- In LCDM+A_L model, TT power spectrum prefers a ~2-sigma larger lensing amplitude than LCDM prediction.
- We do not think this is physical, because the lensing reconstruction does not share this preference for high amplitude.
- **This could just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

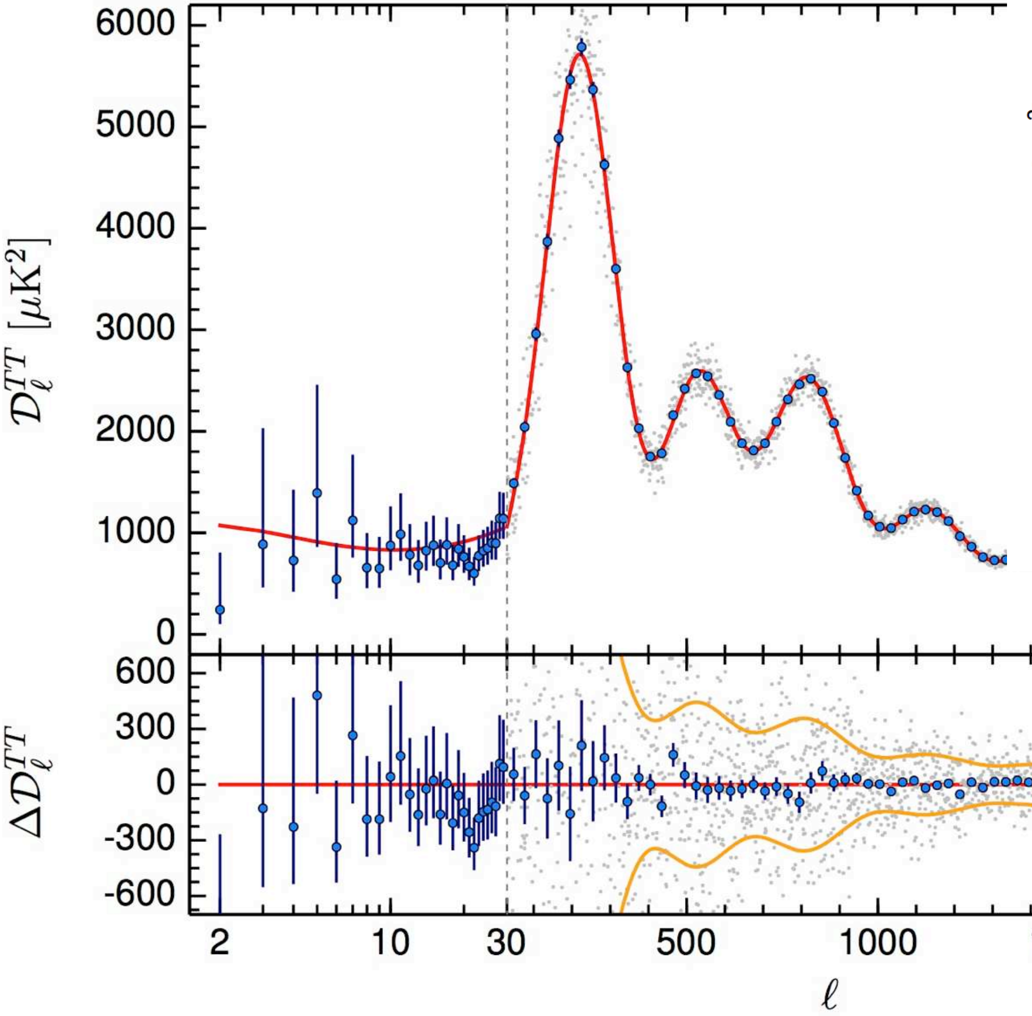
H_0

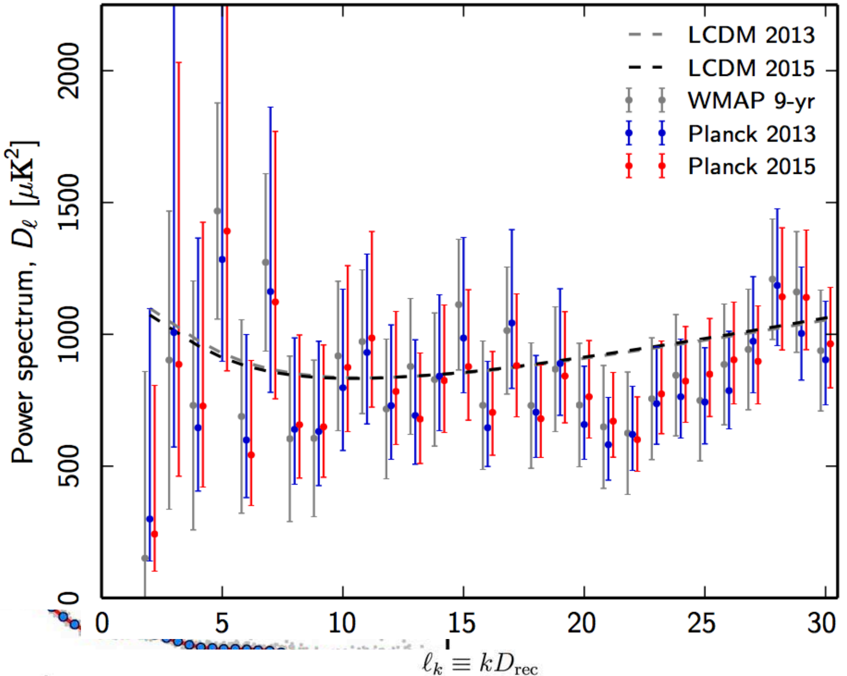


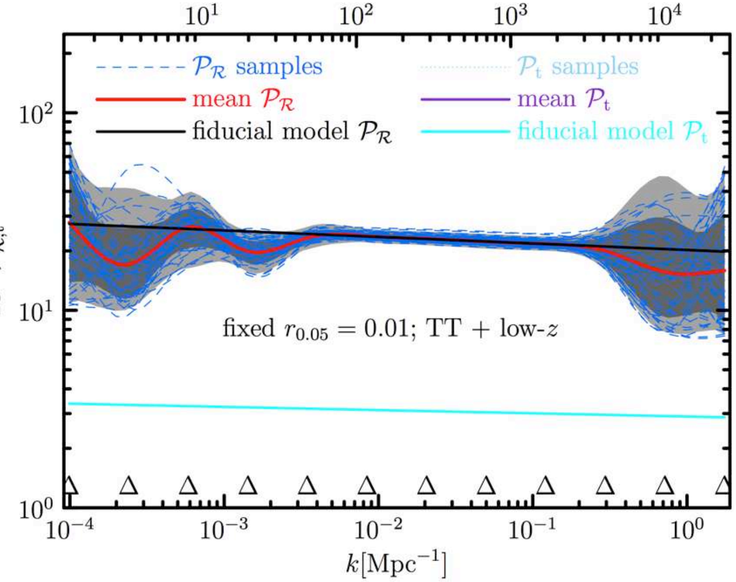
Lensing in LCDM+Alens

Lensing in LCDM

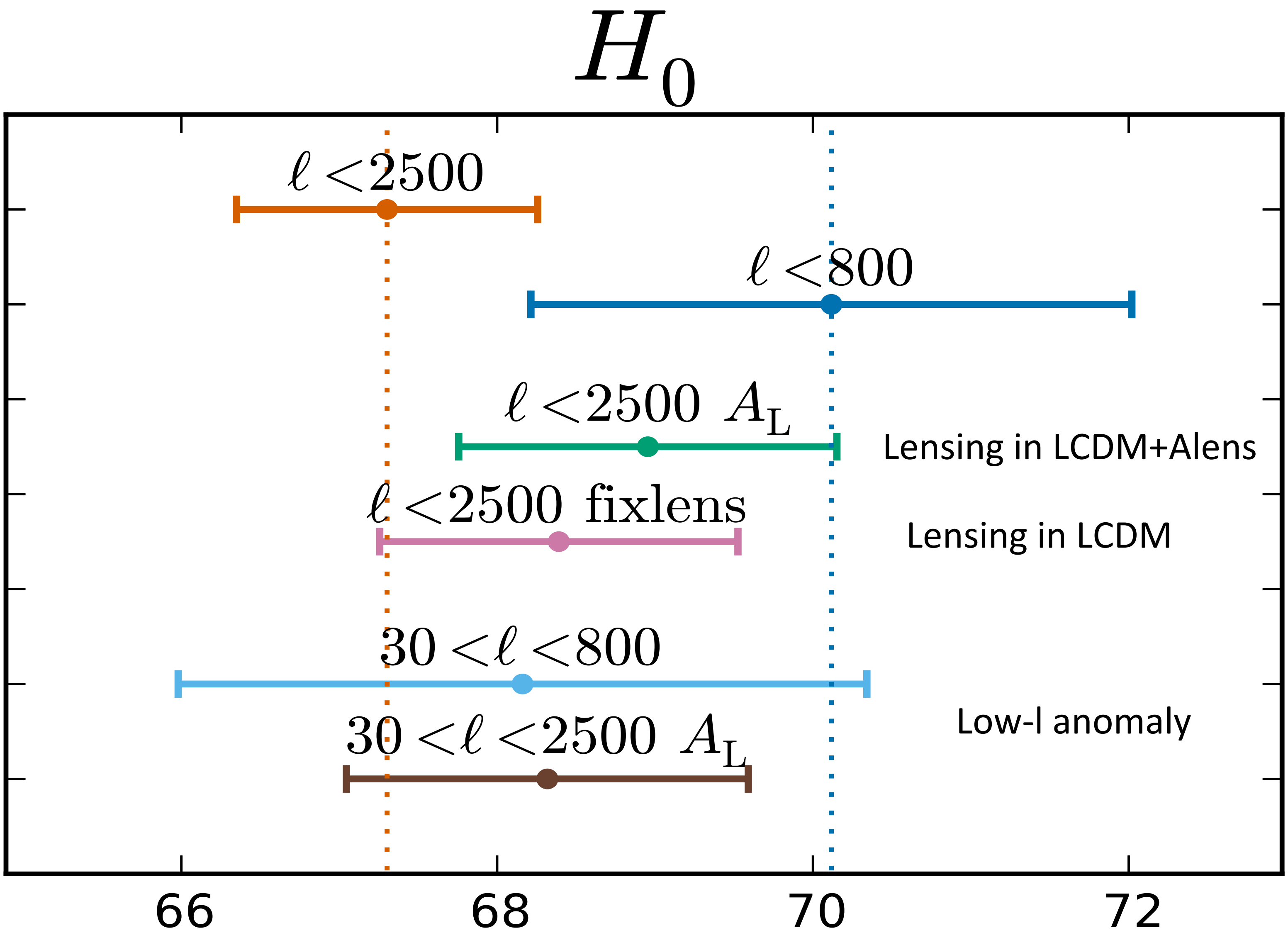
Is it the low-l anomaly?



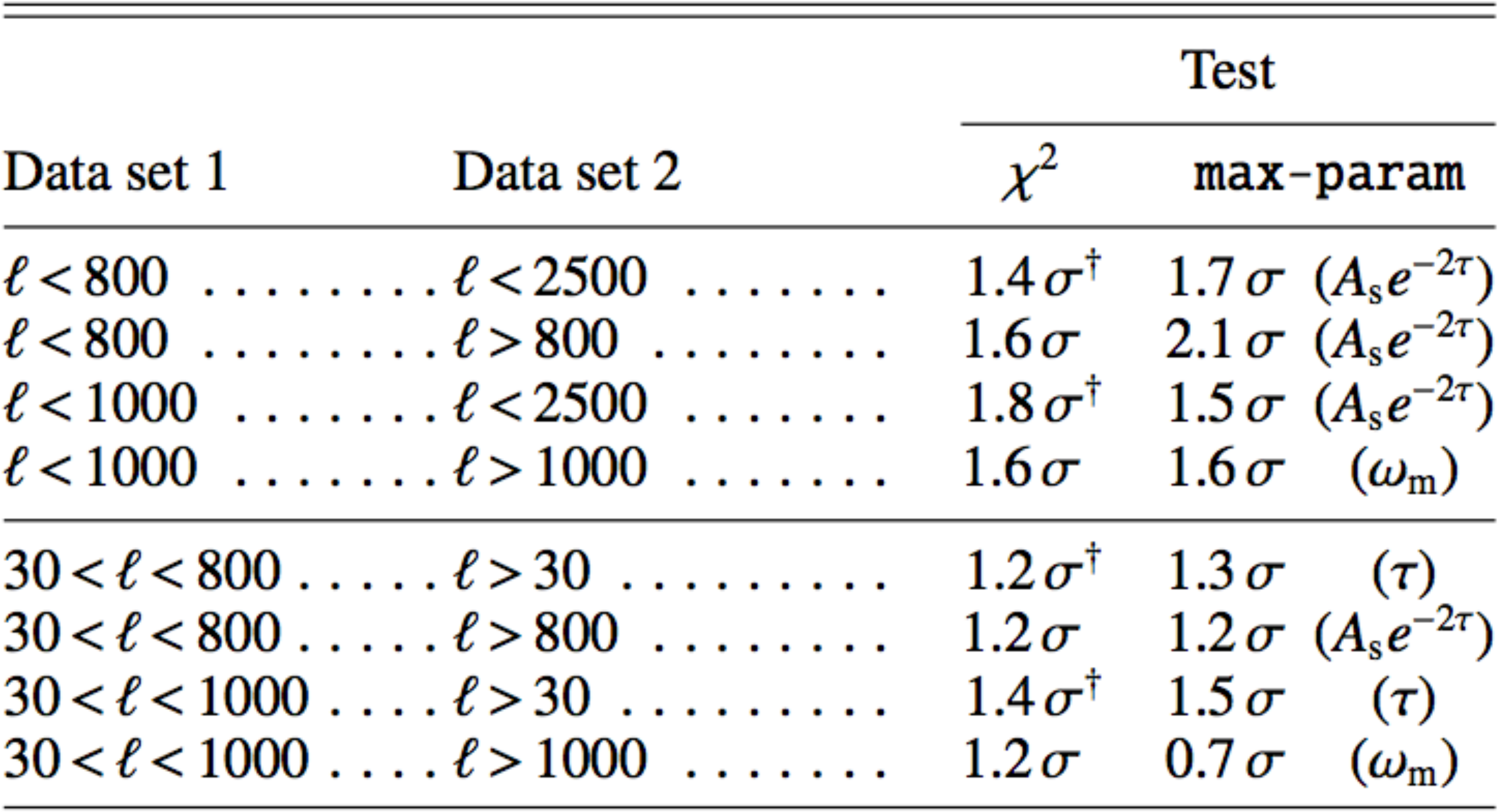




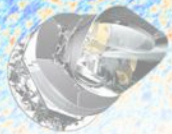
See also Hannestad 03, Shafieloo 03,
Bennet et al. 2011, Mortonson et al. 2009 and many others


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

Eliminating the low-l reduces further the parameter shift.



Data set 1	Data set 2	Test	
		χ^2	max-param
$\ell < 800$	$\ell < 2500$	$1.4\,\sigma^{\dagger}$	$1.7\,\sigma$ $(A_{\mathrm{s}}e^{-2\tau})$
$\ell < 800$	$\ell > 800$	$1.6\,\sigma$	$2.1\,\sigma$ $(A_{\mathrm{s}}e^{-2\tau})$
$\ell < 1000$	$\ell < 2500$	$1.8\,\sigma^{\dagger}$	$1.5\,\sigma$ $(A_{\mathrm{s}}e^{-2\tau})$
$\ell < 1000$	$\ell > 1000$	$1.6\,\sigma$	$1.6\,\sigma$ (ω_{m})
$30 < \ell < 800$	$\ell > 30$	$1.2\,\sigma^{\dagger}$	$1.3\,\sigma$ (τ)
$30 < \ell < 800$	$\ell > 800$	$1.2\,\sigma$	$1.2\,\sigma$ $(A_{\mathrm{s}}e^{-2\tau})$
$30 < \ell < 1000$	$\ell > 30$	$1.4\,\sigma^{\dagger}$	$1.5\,\sigma$ (τ)
$30 < \ell < 1000$	$\ell > 1000$	$1.2\,\sigma$	$0.7\,\sigma$ (ω_{m})



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.
- WMAP and Planck in very good agreement if compared at same scales.
- WMAP+SPT do not have statistical power of Planck
- 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.

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.

esa

planck

cnes

asi
agenzia spaziale italiana

NASA

cnrs

DTU Space
National Space Institute

Science & Technology Facilities Council

INAF ISTITUTO NAZIONALE DI ASTROFISICA

CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

National Research Council of Italy

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN

CSA ASC

DLR
Deutsches Zentrum für Luft- und Raumfahrt e.V.

UK SPACE AGENCY

MAX-PLANCK-GESELLSCHAFT

HFI PLANCK
a look back to the birth of Universe

PLANCK LFI

IAS orsay

IAP

INAF - IASF BO
ISTITUTO NAZIONALE DI ASTROFISICA
ISTITUTO DI ASTROFISICA SPAZIALE E FISICA COSMICA DI BOLOGNA

A" Aalto University

ioa

KICC Kavli Institute for Cosmology Cambridge

CAVENDISH ASTROPHYSICS

UNIVERSITY OF CAMBRIDGE

CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

irfu cea saclay

CEFCA

irap

CITA–ICAT

IASF

cnrs INSU
Observer & comprendre

cnrs IN2P3
Les deux infinis

BERKELEY LAB

ipac

HELSINKI INSTITUTE OF PHYSICS

INSTITUTO DE ASTROFISICA DE CANARIAS

IFCA
Instituto de Física de Cantabria

Imperial College London

UNIVERSITÀ DEGLI STUDI DI MILANO

NÉEL institut

IPAG
Institut de Planétologie et d'Astrophysique de Grenoble

ISDC
DATA CENTRE FOR ASTROPHYSICS

JPL

LAL
LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

l'Observatoire de Paris

LERMA

LPSC Grenoble
Laboratoire de Physique Subatomique et de Cosmologie

NERSC

MANCHESTER 1824
The University of Manchester

MilliLab

Science & Technology Facilities Council
Rutherford Appleton Laboratory

Max-Planck-Institut für Astrophysik

NUI MAYNOOTH

INAF OSSERVATORIO ASTRONOMICO DI PADOVA

UNIVERSITY OF OXFORD

DIPARTIMENTO DI FISICA
SAPIENZA UNIVERSITÀ DI ROMA

UNIVERSITÀ degli STUDI di ROMA TOR VERGATA

OSSERVATORIO ASTRONOMICO TRIESTE

UBC

UC
UNIVERSIDAD DE CANTABRIA

UCSB

SISSA

ALMA

ESO

US
University of Sussex

HAVERFORD

esa

UNIVERSITY OF HELSINKI

UNIVERSITÉ DE GENÈVE

UNIVERSITY OF TORONTO

UNIVERSITÉ DE PARIS-SUD XI

ISTI

asdc
ASI Science Data Center