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. II. Features in the cosmic microwave background temperature power spectrum and shifts in cosmological parameters”
arXiv:1608.02487
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](http://background.uchicago.edu)
Cosmic History

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

- Polarization generated by local quadrupole in temperature.

- Sources of quadrupole:
  - Scalar: E-mode
  - Tensor: E-mode and B-mode

Credit: W. Hu
The Planck satellite

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
\[ \chi^2 = 2546 \text{ for 2479 degrees of freedom (PTE=17\%)} \]

**Excellent fit to the data**

**No significant deviation from \( \Lambda \)CDM in extended models**

Most of parameters at the ~1% level.
Comparison with other datasets:

### BAO

Cluster counts ($\sigma_8 - \Omega_m$)

- SDSS MGS
- WiggleZ
- BOSS LOWZ
- BOSS CMASS

- 6DFGS

### Supernovae ($\Omega_m$)

- C11 (combined)
- JLA
- Union 2.1 (Suzuki et al. 2012)
- WMAP9 (Hinshaw et al. 2013)
- Planck (2013)

- Betoule et al. 2014

### BBN

- $\gamma_{BBN}$

- $\gamma_{DP}$

### Direct measurements $H_0$

- $H_0 = 67.8 \pm 0.92$ [in Km/s/Mpc] (PlanckTT+lowP+lensing)
- $H_0 = 72.8 \pm 2.4$ [2\sigma tension] (Riess+11)
- $H_0 = 70.6 \pm 3.3$ [1\sigma tension] (Efstathiou+14)
- $H_0 = 74.3 \pm 2.6$ [2.5\sigma tension] (Freedman+12)
- $H_0 = 73.1 \pm 1.8$ [2.7\sigma tension] (Riess+16)
Comparison with other datasets:

**BAO**

Baryon acoustic oscillations measure acoustic-scale/distance ratio (BOSS z~0.1-0.9)

**Supernovae (Ω_m)**

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

**BBN**

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


Betoule et al. 2014

Cooke + 2016 arXiv:1607.03900v1

w. theory $d(p, \gamma)^3\text{He}$

w. exp. $d(p, \gamma)^3\text{He}$
Comparison with other datasets:

**BAO**

Cluster counts ($\sigma_8$-$\Omega_m$) and Weak Lensing ($\sigma_8$-$\Omega_m$) data compared with various datasets.

**Supernovae ($\Omega_m$)**

Planck collaboration XXIV, Betoule et al. 2014,

**BBN**

$\gamma_{BBN}$ and $\gamma_{DP}$ comparisons with different measurements.

**Direct measurements $H_0$**

$H_0=66.9\pm0.91$ [in Km/s/Mpc] (Planck TT+SimHFI)

$H_0=72.8\pm2.4$ [2$\sigma$ tension] (Riess+11)

$H_0=70.6 \pm 3.3$ [1$\sigma$ tension] (Efstathiou+14)

$H_0=74.3 \pm 2.6$ [2.5$\sigma$ tension] (Freedman+12)

$H_0=73.\pm1.8$ [3$\sigma$ 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-Zeldovitch 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.
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.

<table>
<thead>
<tr>
<th>Prior name</th>
<th>Quantity</th>
<th>Value &amp; Gaussian errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weighing the Giants (WtG)</td>
<td>$1 - b$</td>
<td>$0.688 \pm 0.072$</td>
</tr>
<tr>
<td>Canadian Cluster Comparison Project</td>
<td>$1 - b$</td>
<td>$0.780 \pm 0.092$</td>
</tr>
<tr>
<td>CMB lensing (LENS)</td>
<td>$1/(1 - b)$</td>
<td>$0.99 \pm 0.19$</td>
</tr>
</tbody>
</table>

- For perfect agreement with CMB, $(1 - b) = 0.58 \pm 0.04$. $1\sigma$ 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
Direct measurements $H_0$

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

$H_0 = 66.9 \pm 0.91$ 
(PlanckTT+SIMlow_HFI)

$H_0 = 73.3 \pm 1.8$  [~3$\sigma$ tension] 
(Riess+16)

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

Riess+16

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

Bonvin et al.arXiv:1607.01790
Number of relativistic species?

- Combining Planck TT with a gaussian prior $73 \pm 1.8\ \text{Km/s/Mpc}$ as from Riess+ 16, in LCDM+Neff model $H_0$ prior pushes Neff high, but:
  - Planck $\chi^2$ worsens when combining with Riess both in LCDM and LCDM+Neff model, high Neff
  - This is because for Planck alone, even in LCDM+Neff $H_0=68\pm2.8$, i.e. the tension is still at the $2.4\sigma$ level.
  - When additionally adding BAO and SN, Neff nor DE can relieve the tension (see Di Valentino+ 2016, Bernal+ 2016 )

<table>
<thead>
<tr>
<th></th>
<th>Neff</th>
<th>$H_0$</th>
<th>$\Delta\chi^2$ Planck</th>
<th>$\Delta\chi^2$ Riess</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planck</td>
<td>-</td>
<td>67.3 $\pm$ 0.95</td>
<td>Reference Planck</td>
<td>-</td>
</tr>
<tr>
<td>Planck+Riess</td>
<td>-</td>
<td>68.7 $\pm$ 0.88</td>
<td>+2</td>
<td>Reference Riess</td>
</tr>
<tr>
<td>Planck</td>
<td>3.12$\pm$0.32</td>
<td>68.0 $\pm$ 2.8</td>
<td>+0</td>
<td>-</td>
</tr>
<tr>
<td>Planck+Riess</td>
<td>3.51$^{+0.19}_{-0.23}$</td>
<td>71.7 $\pm$ 1.6</td>
<td>+2</td>
<td>-4</td>
</tr>
</tbody>
</table>

For this slide, Planck uses TT+lowP_LFI
Not only a Planck tension

Planck15 +SIMlowHFI

Riess+ 2016

WMAP

\[ H_0 = 66.9 \pm 0.9 \]  
\[ H_0 = 73.02 \pm 1.79 \]  
\[ H_0 = 69.7 \pm 2.1 \] [Km/s/Mpc]

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

- **WMAP9+BAO** (BOSSDR11+6dFGS+Lyman \( \alpha \)) + high-z Sne
  \[ H_0 = 68.1 \pm 0.7 \] (2.5\( \sigma \) tension) (Aubourg+ 2015)

- **WMAP9+ACT+SPT + BAO** (BOSSDR11+6dFGS)
  \[ H_0 = 69.3 \pm 0.7 \] (1.9\( \sigma \) tension) (Bennet+ 2014)

- **SPT** alone prefers very high \[ H_0 = 75.0 \pm 3.5 \]
Planck and WMAP

Planck sample variance limited till $l \sim 1600$ (data points till $\sim 2500$, $f_{\text{sky}} \sim 40-70\%$)

WMAP sample variance limited till $l \sim 600$ (data points till $l \sim 1200$)
Compare apples to apples

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

Planck

<table>
<thead>
<tr>
<th>Baselines</th>
<th>TT 2-2500</th>
<th>TE,EE 2-30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planck</td>
<td>WMAP</td>
<td></td>
</tr>
<tr>
<td>WMAP</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Only TT, same $\tau$

<table>
<thead>
<tr>
<th>Planck</th>
<th>WMAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>TT 2-800</td>
<td></td>
</tr>
</tbody>
</table>

- 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 $l_{\text{max}}=800$ and $l_{\text{max}}=2500$ for Planck itself are consistent with expectations!**
Are the cosmological parameters inferred from the low (l<800) and the (l<2500) consistent?

Planck l<800
Planck l<2500
WMAP
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).

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

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)
Parameter shifts and their statistical significance

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


PTE=15.9%, equivalent to 1.4\(\sigma\).

i.e. 15.9% of the sims exceed the data. Corresponds to the number of outliers larger than 1.4\(\sigma\) 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 $\sigma$.
- This includes look elsewhere effect (there are 6 cosmo. parameters, we picked the one with the largest shift). Without look-elsewhere is 2.2 $\sigma$. 
The differences are not statistically very significant.
Effect of lower tau-prior

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

<table>
<thead>
<tr>
<th>Data set 1</th>
<th>Data set 2</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\ell &lt; 800$</td>
<td>$\ell &lt; 2500$</td>
<td>$\chi^2$</td>
</tr>
<tr>
<td>$\ell &lt; 800$</td>
<td>$\ell &gt; 800$</td>
<td>$1.8 \sigma^\dagger$</td>
</tr>
<tr>
<td>$\ell &lt; 1000$</td>
<td>$\ell &lt; 2500$</td>
<td>$1.9 \sigma^\dagger$</td>
</tr>
<tr>
<td>$\ell &lt; 1000$</td>
<td>$\ell &gt; 1000$</td>
<td>$1.9 \sigma$</td>
</tr>
</tbody>
</table>

$[-0.1\sigma, 0.3\sigma]$ 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 $l_{\text{max}}=800$ and $l_{\text{max}}=2500$?

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.
Lensing in LCDM

\( H_0 \)

\[ \ell < 2500 \]

\[ \ell < 800 \]

\[ \ell < 2500 \ A_L \]

\[ \ell < 2500 \text{ fixlens} \]

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.
$H_0$

- $\ell < 2500$
- $\ell < 800$
- $\ell < 2500$ $A_L$
- $30 < \ell < 2500$ $A_L$
- $30 < \ell < 800$

Lensing in LCDM+Alens
Lensing in LCDM
Low-l anomaly
Eliminating the low-$\ell$ reduces further the parameter shift.

<table>
<thead>
<tr>
<th>Data set 1</th>
<th>Data set 2</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\ell &lt; 800$</td>
<td>$\ell &lt; 2500$</td>
<td>$1.4\sigma$†</td>
</tr>
<tr>
<td>$\ell &lt; 800$</td>
<td>$\ell &gt; 800$</td>
<td>$1.6\sigma$</td>
</tr>
<tr>
<td>$\ell &lt; 1000$</td>
<td>$\ell &lt; 2500$</td>
<td>$1.8\sigma$†</td>
</tr>
<tr>
<td>$\ell &lt; 1000$</td>
<td>$\ell &gt; 1000$</td>
<td>$1.6\sigma$</td>
</tr>
<tr>
<td>$30 &lt; \ell &lt; 800$</td>
<td>$\ell &gt; 30$</td>
<td>$1.2\sigma$†</td>
</tr>
<tr>
<td>$30 &lt; \ell &lt; 800$</td>
<td>$\ell &gt; 800$</td>
<td>$1.2\sigma$</td>
</tr>
<tr>
<td>$30 &lt; \ell &lt; 1000$</td>
<td>$\ell &gt; 30$</td>
<td>$1.4\sigma$†</td>
</tr>
<tr>
<td>$30 &lt; \ell &lt; 1000$</td>
<td>$\ell &gt; 1000$</td>
<td>$1.2\sigma$</td>
</tr>
</tbody>
</table>
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.