Planck 2015 parameter constraints

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On behalf of the Planck Collaboration

http://cosmologist.info/
CMB temperature

End of inflation

Last scattering surface

gravity + pressure + diffusion
Observed CMB blackbody power spectrum

Observations

Constrain theory of early universe + evolution parameters and geometry
Planck TT spectrum

2013

\[ D_l = l(l+1)C_l/2\pi [\mu K^2] \]

\[ \Delta D_l [\mu K^2] \]

Multipole \( l \)
Main changes in TT analysis:

- Full mission data (2 → 5 sky surveys): *lower noise*

- Larger sky fractions (100Ghz 66.3%, 143Ghz 57.4%, 217Ghz 47.1%): *lower cosmic variance*

- Cross Half-Mission (CHM) rather than cross detector sets (DS): *avoids correlated noise at high L*

- More detailed dust modelling, weak foreground priors rather than +ACT/SPT

- LFI low-L polarization (lowP) rather than WMAP: *prefers lower optical depth \( \tau \)*

- Corrected calibration (now agrees with WMAP)

- 4K cooler line systematic (mostly) removed (removes L≈1800 feature)

- Bug fixes and numerous analysis changes (new beams, etc.)

- Binned Plik likelihood rather than unbinned CamSpec

- Many new internal consistency checks
### Table

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nominal (2 sky surveys)</th>
<th>Full mission (5 sky surveys)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(5) - [6]) / σ[6]</td>
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<tr>
<td>----------------------------</td>
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<tr>
<td>$100\theta_{MC}$</td>
<td>$1.04131 \pm 0.00063$</td>
<td>$1.04126 \pm 0.00047$</td>
</tr>
<tr>
<td></td>
<td>$1.04121 \pm 0.00048$</td>
<td>$1.04094 \pm 0.00048$</td>
</tr>
<tr>
<td>$\Omega_b h^2$</td>
<td>$0.02205 \pm 0.00028$</td>
<td>$0.02234 \pm 0.00023$</td>
</tr>
<tr>
<td></td>
<td>$0.02230 \pm 0.00023$</td>
<td>$0.02205 \pm 0.00023$</td>
</tr>
<tr>
<td>$\Omega_c h^2$</td>
<td>$0.1199 \pm 0.0027$</td>
<td>$0.1198 \pm 0.0022$</td>
</tr>
<tr>
<td></td>
<td>$0.1198 \pm 0.0022$</td>
<td>$0.1194 \pm 0.0022$</td>
</tr>
<tr>
<td>$H_0$</td>
<td>$67.3 \pm 1.2$</td>
<td>$67.8 \pm 1.0$</td>
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<tr>
<td></td>
<td>$67.8 \pm 1.0$</td>
<td>$67.48 \pm 0.98$</td>
</tr>
<tr>
<td>$n_s$</td>
<td>$0.9603 \pm 0.0073$</td>
<td>$0.9665 \pm 0.0062$</td>
</tr>
<tr>
<td></td>
<td>$0.9665 \pm 0.0062$</td>
<td>$0.9655 \pm 0.0062$</td>
</tr>
<tr>
<td>$\Omega_{th}$</td>
<td>$0.315 \pm 0.017$</td>
<td>$0.308 \pm 0.013$</td>
</tr>
<tr>
<td></td>
<td>$0.308 \pm 0.013$</td>
<td>$0.313 \pm 0.013$</td>
</tr>
<tr>
<td>$\sigma_8$</td>
<td>$0.829 \pm 0.012$</td>
<td>$0.831 \pm 0.011$</td>
</tr>
<tr>
<td></td>
<td>$0.828 \pm 0.012$</td>
<td>$0.829 \pm 0.015$</td>
</tr>
<tr>
<td>$\tau$</td>
<td>$0.089 \pm 0.013$</td>
<td>$0.096 \pm 0.013$</td>
</tr>
<tr>
<td></td>
<td>$0.094 \pm 0.013$</td>
<td>$0.079 \pm 0.019$</td>
</tr>
<tr>
<td>$10^9 A_s e^{-2\tau}$</td>
<td>$1.836 \pm 0.013$</td>
<td>$1.833 \pm 0.011$</td>
</tr>
<tr>
<td></td>
<td>$1.831 \pm 0.011$</td>
<td>$1.875 \pm 0.014$</td>
</tr>
</tbody>
</table>

Notes:

* Consistency between likelihoods at 0.5σ level for TT

* 2015 calibration change moves $C_l$ (hence also $A_s e^{-2\tau}$) up by ~ 2%

Switching WP to lowP (LFI) shifts $\tau$ down by ~ 10% ⇒ $e^{-2\tau}$ shifts up by ~ 2%

⇒ little change to inferred amplitudes $A_s$ and $\sigma_B$
New for 2015: Polarization

Dust polarization amplitude
Visually very good fit to prediction from TT best fit
Evidence for small T-E leakage
...but beware.. There are still low level systematics in the polarization spectra.

Differences between likelihood implementations (Plik/CamSpec) $\sim 1 \sigma$ in some extended models
CMB Lensing

Last scattering surface

Inhomogeneous universe - photons deflected

Observer
$T(\hat{n}) \ (\pm 350 \mu K)$

$E(\hat{n}) \ (\pm 25 \mu K)$

$B(\hat{n}) \ (\pm 2.5 \mu K)$
\( T(\hat{n}) \) (±350\( \mu K \))

\( E(\hat{n}) \) (±25\( \mu K \))

\( B(\hat{n}) \) (±2.5\( \mu K \))
Planck CMB Lensing Reconstruction
Lensing Reconstruction Improvements over 2013

★ Error bars reduced by nearly a factor of 2x.
  - Twice as much temperature data + all-new polarization data.
★ Full set of lensing estimators (TT, TE, EE, EB, TB) + All combined (MV)
  - Crosses give 15 possible lensing power spectrum estimators.
★ SMICA component-separated maps as baseline, on 67.3% sky.
★ Numerous analysis improvements.
  - Improved likelihood (N^{(1)} theory dependence, faster)
  - Many new consistency and null tests:
    Internal consistency of polarization and temperature estimator pairs.
    Half-mission nulls and crosses
Lensing Power Spectrum

2.5% measurement of amplitude (40σ detection)
LCMDM Parameter Constraints from CMB Lensing Only

\[ \sigma_8 \Omega_m^{0.25} = 0.592 \pm 0.021 \]
\[ \sigma_8 h^{-1} \Omega_m^{-1/4} = 1.59 \pm 0.05 \]
LCDM Parameter Constraints from CMB Lensing Only

\[ \sigma_8 \Omega_m^{0.25} = 0.622 \pm 0.013 \]

\[ \sigma_8 \Omega_m^{0.25} = 0.592 \pm 0.021 \]

\[ \sigma_8 h^{-1} \Omega_m^{-1/4} = 1.59 \pm 0.05 \]
LCDM Parameter Constraints from CMB Lensing Only

\[
\sigma_8 \Omega_{m}^{0.25} = 0.622 \pm 0.013
\]

\[
\sigma_8 \Omega_{m}^{0.25} = 0.607 \pm 0.008
\]

\[
\sigma_8 \Omega_{m}^{0.25} = 0.592 \pm 0.021
\]

\[
\sigma_8 h^{-1} \Omega_{m}^{-1/4} = 1.59 \pm 0.05
\]
Optical Depth Constraints

... are consistent with low-L polarization.
Only consistent with $\sigma_8 > 0.8$
Are Planck power spectrum likelihoods consistent with other data in the base LCDM model?
Baryon Oscillations (BAO)

\[ z < 1 \] BAO consistent in LCDM (adding BAO improves constraints) ✔

But BOSS \( z \sim 2.34 \) Ly–\( \alpha \) discrepant by \( \sim 2.7 \sigma \) ☒

(Delubac et al, Font-Ribera et al 2014)
Hubble parameter

*Planck*+lensing: $(67.8 \pm 0.9) \text{km s}^{-1} \text{Mpc}^{-1}$

Riess et al 2011:

$$H_0 = (73.8 \pm 2.4) \text{km s}^{-1} \text{Mpc}^{-1}$$  \[ \text{X} \]

Humphreys et al 2013, Efstathiou 2013

$$H_0 = 70.6 \pm 3.3 \text{ km s}^{-1}\text{Mpc}^{-1}, \quad \text{NGC 4258}, \quad \checkmark$$

Rigault et al. 2014

$$H_0 = 68.8 \pm 3.3 \text{ km s}^{-1}\text{Mpc}^{-1}$$  \[ \checkmark \]

$$H_0 = 69.7 \pm 2.1 \text{ km s}^{-1}\text{Mpc}^{-1}, \quad \text{WMAP9}, \quad \checkmark$$

$$H_0 = 68.0 \pm 0.7 \text{ km s}^{-1}\text{Mpc}^{-1}, \quad \text{WMAP9+BAO}. \quad \checkmark$$
Redshift distortions/growth

Looks quite consistent? ✓

BOSS variants: solid – Samushia et al; dashed - Chuang, Beutler et al.
Galaxy weak gravitational lensing

WL prefer higher $H_0$ or lower $\sigma_8$

WL: Heymans et al. 2013
Clusters etc.

• Complicated physics and selection effects… mass calibration etc.

Some analyses prefer lower $\sigma_8$, some OK – needs more work.
Beyond the base LCDM model
Base LCDM + tensors:

- $r_{0.002} < 0.10$, Planck TT+lowP,
- $r_{0.002} < 0.11$, Planck TT+lowP+lensing+ext.

Planck + BICEP2/Keck/Planck (BKP)

- $r_{0.002} < 0.08$, Planck TT+lowP+BKP,
- $r_{0.002} < 0.09$, Planck TT+lowP+lensing+ext+BKP

Reminder: result is model dependent

+BKP result also depends on dust model
\[ \frac{dn_s}{d \ln k} = -0.0084 \pm 0.0082, \quad \text{Planck TT+lowP}, \]
\[ \frac{dn_s}{d \ln k} = -0.0057 \pm 0.0071, \quad \text{Planck TT, TE, EE+lowP} \]
Isocurvature: e.g. (anti-)correlated matter density isocurvature

Consistent with adiabatic

Polarization dramatically improves constraint
Lensing amplitude and extended parameters

Planck TT+lowP+lensing
Planck TT+lowP+BAO
Planck TT+lowP+lensing+BAO
Joint constraints consistent with flat universe
Massive neutrinos

\[
\sum m_\nu < 0.72 \text{ eV} \quad \text{Planck TT+lowP} \\
\sum m_\nu < 0.21 \text{ eV} \quad \text{Planck TT+lowP+BAO} \\
\sum m_\nu < 0.49 \text{ eV} \quad \text{Planck TT, TE, EE+lowP} \\
\sum m_\nu < 0.17 \text{ eV} \quad \text{Planck TT, TE, EE+lowP+BAO.}
\]

\[
\sum m_\nu < 0.23 \text{ eV} \quad \text{95\%, Planck TT+lowP+lensing+ext} \\
\Omega_\nu h^2 < 0.0025 \quad \text{$H_0 = 67.7 \pm 0.6$} \\
\sigma_8 = 0.810^{+0.015}_{-0.012} \quad \text{(68\% CL)}
\]
Extra relativistic degrees of freedom

\[ \Delta N_{\text{eff}} < 4 \text{ at over } 3\sigma \]

\[ N_{\text{eff}} = 3.13 \pm 0.32 \quad \text{Planck TT+lowP} \]
\[ N_{\text{eff}} = 3.15 \pm 0.23 \quad \text{Planck TT+lowP+BAO} \]
\[ N_{\text{eff}} = 2.99 \pm 0.20 \quad \text{Planck TT, TE, EE+lowP} \]
\[ N_{\text{eff}} = 3.04 \pm 0.18 \quad \text{Planck TT, TE, EE+lowP+BAO} \]

(68% CL)
Can neutrino models reconcile Planck and lensing/other data?

\begin{align*}
\text{Planck } TT+\text{lowP} & \quad \text{+lensing} & \quad \text{+lensing+BAO} & \quad \Lambda CDM \\
+ N_{\text{eff}} & \quad + N_{\text{eff}} + \Sigma m_\nu & \quad + N_{\text{eff}} & \quad + N_{\text{eff}} + \Sigma m_\nu \\
+ \Sigma m_\nu & \quad + N_{\text{eff}} + m_{\nu, \text{sterile}} & \quad + \Sigma m_\nu & \quad + N_{\text{eff}} + m_{\nu, \text{sterile}} \\
\end{align*}
Conclusions

Main cosmology conclusions of 2013 unchanged, smaller errors

Somewhat lower optical depth than from WMAP $\tau \sim 0.08$

Powerful CMB lensing constraint on the fluctuation amplitude

*Planck*+BICEP+Keck gives strong upper limit on gravity waves

Broadly consistent with LCDM and minimal-mass standard neutrinos

but:
- tensions with external data; no obvious way to reconcile all
- some puzzles like high $A_L$
- significant variations from base LCDM still allowed
  (e.g. $\sum m_\nu \lesssim 0.2\,\text{eV, } \Delta N_{\text{eff}} \lesssim 0.4$)

Polarization can significantly tighten constraints
- work in progress, more robust analysis next year, + HFI low-$\ell$ polarization
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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