Planck parameter constraints

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On behalf of the Planck Collaboration
http://cosmologist.info/
Planck 2014 frequency maps: Temperature

30 GHz

44 GHz

70 GHz

100 GHz

143 GHz

217 GHz

353 GHz

545 GHz

857 GHz

30-353 GHz: $\delta T$ [mK_{reduced}]; 545 and 857 GHz: surface brightness [K/ly/sr]
Planck TT spectrum

2014

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

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

Preliminary
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 $L\sim1800$ feature)
- Bug fixes and numerous analysis changes
- Binned Plik likelihood rather than unbinned CamSpec
- Many new internal consistency checks
### Consistency between likelihoods at 0.5σ level for TT

- **Nominal** (2 sky surveys)
  - 2013 TT + WP
  - 2014 calibration change moves $C_l$ (hence also $A_s e^{-2\tau}$) up by $\sim 2\%$
  - Switching WP to lowP (LFI) shifts $\tau$ down by $\sim 10\% \Rightarrow e^{-2\tau}$ shifts up by $\sim 2\%$
  - $\Rightarrow$ little change to inferred amplitudes $A_s$ and $\sigma_8$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2013N(DS)</th>
<th>2013N(DS)</th>
<th>2013N(CY)</th>
<th>2014F(CHM)</th>
<th>2014F(CHM) (P11k)</th>
<th>$\frac{(2) - (6)\sigma}{\sigma}$</th>
<th>$\frac{(5) - (6)\sigma}{\sigma}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$100\theta_{MC}$</td>
<td>$1.04131 \pm 0.00063$</td>
<td>$1.04126 \pm 0.00047$</td>
<td>$1.04126 \pm 0.00048$</td>
<td>$1.04094 \pm 0.00048$</td>
<td>$1.04086 \pm 0.00048$</td>
<td>0.71</td>
<td>0.17</td>
</tr>
<tr>
<td>$\omega_b$</td>
<td>$0.02205 \pm 0.00028$</td>
<td>$0.02234 \pm 0.00023$</td>
<td>$0.02230 \pm 0.00023$</td>
<td>$0.02225 \pm 0.00023$</td>
<td>$0.02222 \pm 0.00023$</td>
<td>-0.61</td>
<td>0.13</td>
</tr>
<tr>
<td>$\omega_c$</td>
<td>$0.1199 \pm 0.0027$</td>
<td>$0.1189 \pm 0.0022$</td>
<td>$0.1188 \pm 0.0022$</td>
<td>$0.1194 \pm 0.0022$</td>
<td>$0.1199 \pm 0.0022$</td>
<td>0.00</td>
<td>-0.23</td>
</tr>
<tr>
<td>$H_0$</td>
<td>$67.3 \pm 1.2$</td>
<td>$67.8 \pm 1.0$</td>
<td>$67.8 \pm 1.0$</td>
<td>$67.48 \pm 0.98$</td>
<td>$67.26 \pm 0.98$</td>
<td>0.03</td>
<td>0.22</td>
</tr>
<tr>
<td>$n_s$</td>
<td>$0.9603 \pm 0.0073$</td>
<td>$0.9665 \pm 0.0062$</td>
<td>$0.9655 \pm 0.0062$</td>
<td>$0.9682 \pm 0.0062$</td>
<td>$0.9652 \pm 0.0062$</td>
<td>-0.67</td>
<td>0.48</td>
</tr>
<tr>
<td>$\Omega_m$</td>
<td>$0.315 \pm 0.017$</td>
<td>$0.308 \pm 0.013$</td>
<td>$0.308 \pm 0.013$</td>
<td>$0.313 \pm 0.013$</td>
<td>$0.316 \pm 0.014$</td>
<td>-0.06</td>
<td>-0.23</td>
</tr>
<tr>
<td>$\sigma_8$</td>
<td>$0.829 \pm 0.012$</td>
<td>$0.831 \pm 0.011$</td>
<td>$0.823 \pm 0.012$</td>
<td>$0.829 \pm 0.015$</td>
<td>$0.830 \pm 0.015$</td>
<td>-0.08</td>
<td>-0.07</td>
</tr>
<tr>
<td>$10^3A_s e^{-2\tau}$</td>
<td>$1.836 \pm 0.013$</td>
<td>$1.833 \pm 0.011$</td>
<td>$1.831 \pm 0.011$</td>
<td>$1.875 \pm 0.014$</td>
<td>$1.881 \pm 0.014$</td>
<td>-3.46</td>
<td>-0.42</td>
</tr>
</tbody>
</table>

**Note:**

* Consistency between likelihoods at 0.5σ level for TT
* 2014 calibration change moves $C_l$ (hence also $A_s e^{-2\tau}$) up by $\sim 2\%$
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New: E-mode polarization

- Visually very good fit to prediction from TT best fit
- Evidence for small T-E leakage
Base LCDM

Preliminary
…but beware.. There are still low level systematics in the polarization spectra.

Differences between likelihood implementations (Plik/CamSpec) ∼ 1 σ in some extended models
Updated: Planck CMB lensing power spectrum

Amplitude constrained to $\sim2.5\%$ (40σ detection of lensing).
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

Riess et al 2011:

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

Humphreys et al 2013, Efstathiou 2013

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

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

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

Consistent (or a bit low?)

BOSS variants: solid – Samushia et al; dashed - Chuang, Beutler, Reid et al.

Preliminary
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.
Planck CMB Lensing
$T(\hat{n}) \ (\pm 350 \mu K)$

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

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

$$\frac{[L(L+1)]^2 C_L^{\phi\phi}}{2\pi} \times 10^7$$

Amplitude constrained to ~2.5% (40\sigma detection of lensing).

Planck 2014
Planck 2013
van Engelen et. al. 2012
Das et. al. 2013

Preliminary
Individual Cross-spectra

\[ \left( \frac{L(L+1)}{2\pi} \right)^2 C_L^{\phi \phi} \]
Null Tests

Conservative likelihood uses $40 \leq L \leq 400$
LCDM 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

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

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LCDM Parameter Constraints from CMB Lensing Only

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

Planck TT + lowP

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

Planck TT + lowP + lensing

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

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

... are consistent with low-L polarization.
Planck \( \sigma_8 \) in the base LCDM model

Only consistent with \( \sigma_8 > 0.8 \)
Beyond the base LCDM model
Base LCDM + tensors:

\[ r_{0.002} < 0.11, \quad \text{Planck TT+lowP} \]
\[ r_{0.002} < 0.12, \quad \text{Planck TT+lowP+lensing+ext} \]
The figures show the relation between $n_s$ and $\frac{d \ln k}{d \ln k}$ for two scenarios:

- **Base LCDM + running**
  - \[ \frac{dn_s}{d \ln k} = -0.0084 \pm 0.0082, \text{ Planck TT+lowP}, \]
  - \[ \frac{dn_s}{d \ln k} = -0.0057 \pm 0.0071, \text{ Planck TT, TE, EE+lowP}. \]

- **Base LCDM + running + tensors**
  - \[ \frac{dn_s}{d \ln k} = -0.0126^{+0.0098}_{-0.0087}, \text{ Planck TT+lowP}, \]
  - \[ \frac{dn_s}{d \ln k} = -0.0085 \pm 0.0076, \text{ Planck TT, TE, EE+lowP}. \]
Isocurvature: e.g. (anti-)correlated matter density isocurvature

Consistent with adiabatic

Polarization dramatically improves constraint
Lensing amplitude and extended parameters

Lensing reduces $A_L$ pulls in CMB power spectrum likelihood.
Joint constraints consistent with flat universe
Massive neutrinos

\[ \sum m_\nu < 0.72 \text{eV} \quad \text{Planck TT+lowP} \]
\[ \sum m_\nu < 0.21 \text{eV} \quad \text{Planck TT+lowP+BAO} \]
\[ \sum m_\nu < 0.49 \text{eV} \quad \text{Planck TT, TE, EE+lowP} \]
\[ \sum m_\nu < 0.17 \text{eV} \quad \text{Planck TT, TE, EE+lowP+BAO.} \] (95% CL)

\[ H_0 = 67.7 \pm 0.6 \]
\[ \sigma_8 = 0.810^{+0.015}_{-0.012} \] (68% CL)
Extra relativistic degrees of freedom

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

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

Thermalized sterile

\[ m^{\text{eff}}_{\nu, \text{sterile}} = (T_s/T_{\nu})^3 m^{\text{thermal}}_{\text{sterile}} = (\Delta N_{\text{eff}})^{3/4} m^{\text{thermal}}_{\text{sterile}} \]

Dodelson-Widrow production by oscillation:

\[ m^{\text{eff}}_{\nu, \text{sterile}} = \chi_s m^{\text{DW}}_{\text{sterile}} \]

\[
\begin{align*}
N_{\text{eff}} < 3.7 \\
m^{\text{eff}}_{\nu, \text{sterile}} < 0.38 \text{ eV}
\end{align*}
\]

95%, Planck TT+lowP+lensing+BAO

(assuming \( m_{\text{phys}} < 2 \text{ eV} \))
Can neutrino models reconcile Planck and lensing/other data?

\( +N_{\text{eff}} \)
\( +N_{\text{eff}} + \Sigma m_\nu \)
\( +N_{\text{eff}} \)
\( +N_{\text{eff}} + \Sigma m_\nu \)

\( +\Sigma m_\nu \)
\( +N_{\text{eff}} + m_{\nu, \text{sterile}}^{\text{eff}} \)
\( +\Sigma m_\nu \)
\( +N_{\text{eff}} + m_{\nu, \text{sterile}}^{\text{eff}} \)

\( \Omega_m \)
\( \Omega_m \)
\( H_0 \)
\( H_0 \)

CHFTlens+BAO+H_0+\theta_s
Comparison with BBN predictions and abundance observations

Good consistency with standard BBN and published abundance results
Joint BBN + abundance observation constraints

Aver et al. Helium measurement:

\[
N_{\text{eff}} = \begin{cases} 
3.11^{+0.59}_{-0.57} & \text{heli. + Planck TT+lowP,} \\
3.14^{+0.44}_{-0.43} & \text{heli. + Planck TT+lowP+BAO,} \\
2.99^{+0.39}_{-0.39} & \text{heli. + Planck TT,TE,EE+lowP,}
\end{cases} \quad (95\% \text{ CL})
\]

Cooke et al. D/H measurement:

\[
N_{\text{eff}} = \begin{cases} 
2.95^{+0.52}_{-0.52} & \text{deu. + Planck,TT} \\
3.01^{+0.38}_{-0.37} & \text{deu. + Planck TT+lowP+BAO,} \\
2.91^{+0.37}_{-0.37} & \text{deu. + Planck TT,TE,EE+lowP,}
\end{cases} \quad (95\% \text{ CL})
\]

Fully consistent with standard $N_{\text{eff}} = 3.046$
Tests for non-standard neutrinos

- consistent with free-streaming non-interacting neutrinos: $c_{\text{eff}}^2 = c_{\text{vis}}^2 = 1/3$
- Polarization greatly strengthens results (sensitive to phase shifts)
Dark matter annihilation

\[ \frac{dE}{dtdV}(z) = 2 g \rho_c^2 c^2 \Omega_m^2 (1 + z)^6 p_{\text{ann}}(z) \]

\[ p_{\text{ann}}(z) \equiv f(z) \frac{\langle \sigma v \rangle}{m_\chi} \]

Huge gain from polarization!
Preliminary conclusions

Main cosmology conclusions of 2013 unchanged, smaller errors

Many analysis improvements/corrections, many more to come
- including low-L HFI polarization

Powerful CMB lensing constraint on the amplitude

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 (DM annihilation, isocurvature..)
- work in progress, more robust analysis next year

Coming soon…. Planck+BICEP+Keck B-mode $r$ constraints
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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