Cosmological parameters from Planck and other datasets
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On behalf of the Planck collaboration

Planck unveils the Cosmic Microwave Background
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.

A. Zacchei
"Frequency maps
The $\Lambda$CDM model of the Universe

$\Lambda$CDM = « Lambda-cold-dark-matter » model

- General Relativity [lots of laboratory tests, we’ll hear more]
- Isotropic and homogeneous Universe [CMB, Copernican principle]
- Expanding space (hot big bang) $\rightarrow H_0$ ($h = H_0/[100\text{km/s/Mpc}]$)
- Contents:
  - Ordinary (baryonic) matter $\rightarrow \Omega_b$ [probes the physics of early universe]
  - Cold dark matter $\rightarrow \Omega_c$ [galaxy rotation curves, slows down expansion]
  - Dark energy $\rightarrow \Omega_\Lambda$ [distance scale measurements, accelerated expansion]
- Small Gaussian initial fluctuations $\rightarrow A_s$ (amplitude), $n_s$ (tilt) [inflation]
- Space is flat $\rightarrow \Omega_b + \Omega_c + \Omega_\Lambda = 1$ [inflation]
- Late-time reionization $\rightarrow \tau \rightarrow$ 6 parameters in total ($\tau$ is WMAP provided for now)
Planck TT spectrum

$D_l [\mu K^2]$

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

$l$

[Graph showing the power spectrum of cosmic microwave background]
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (68%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_b h^2$</td>
<td>0.02207±0.00027</td>
</tr>
<tr>
<td>$\Omega_ch^2$</td>
<td>0.1198±0.0026 (is it high?)</td>
</tr>
<tr>
<td>$100\theta_*$(acoustic scale at recombination)</td>
<td>1.04148±0.00062 (~ 500 parts per million accuracy)</td>
</tr>
<tr>
<td>$\tau$</td>
<td>0.091±0.014 (WMAP “seeded”)</td>
</tr>
<tr>
<td>$\ln(10^{10}A_s)$</td>
<td>3.090±0.025</td>
</tr>
<tr>
<td>$n_s$</td>
<td>0.9585±0.0070 (&lt;1 at &gt; 5 $\sigma$)</td>
</tr>
<tr>
<td>$H_0$</td>
<td>67.3±1.2 (is it low?)</td>
</tr>
<tr>
<td>$\Omega_\Lambda$</td>
<td>0.685±0.017</td>
</tr>
<tr>
<td>$\sigma_8$</td>
<td>0.828±0.012</td>
</tr>
<tr>
<td>$z_{re}$</td>
<td>11.1±1.1</td>
</tr>
</tbody>
</table>
Tension with Hubble Constant astrophysical measurements

Planck value for the Hubble constant is in at tension with several other measurements (most notably the HST determination).

Systematics in luminosity distance measurements can be clearly there, however this tension could be also hinting towards new physics.

The determination of $H_0$ from Planck is indeed model dependent.

UGC 3789 distance recalibrated, now $H_0 = 68.9 \pm 7.1 \text{Km/s/Mpc}$
BAO scale distance ratio

\[
\frac{r_s}{D_V}/\left(\frac{r_s}{D_V}\right)_{\text{Planck}}
\]

- 6dF
- SDSS-DR7 2012
- WiggleZ
- SDSS-DR7 2010
- BOSS-DR9

Planck Prediction (shaded area)

DE equation of state is consistent with \(1+w = 0\)

⇒ Planck & BAO are in tight agreement (and thus can be used jointly)
Further tests of the standard model

- Sum of neutrino masses:
  - We know that neutrinos are massive (oscillations)
  - Minimum possible sum mass is around 0.07 eV
  - Planck: no detection, limit from all data is 0.23 eV
- Extra particles? $N_{\text{eff}}$ consistent with 3 neutrinos only, $N_{\text{eff}} < 4$ at 95%
- Is ‘$\Lambda$’ really a cosmological constant? Consistent with $\rho = -\rho$
- Topology of the universe: limits close to horizon size
- Decaying dark matter, varying constants: no detections
- Tests of assumptions (isotropy, Gaussianity): strong limits, some anomalies
- Tensor fluctuations: $r < 0.11$ (from temperature, model dependent, no B mode polarization (so far).
- Tests of initial conditions for perturbations: no surprises
- Further constraints on inflation (running spectra index, etc) …
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (95%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_K$</td>
<td>-0.0005±0.0066</td>
</tr>
<tr>
<td>$\Sigma m_\nu$ (eV)</td>
<td>&lt;0.23</td>
</tr>
<tr>
<td>$N_{\text{eff}}$</td>
<td>3.30±0.54</td>
</tr>
<tr>
<td>$Y_P$</td>
<td>0.267±0.040</td>
</tr>
<tr>
<td>$dn_s/d\ln k$</td>
<td>-0.014±0.017</td>
</tr>
<tr>
<td>$r_{0.002}$</td>
<td>&lt;0.11</td>
</tr>
<tr>
<td>$w$</td>
<td>-1.13±0.24</td>
</tr>
</tbody>
</table>
Is space really flat?

The 0.06% precision measurement of the sound horizon scale at last scattering gives us a known ruler!

A single measurement only gives one constraint → geometric degeneracy

The models in the tail have a higher lensing signal, and so CMB lensing breaks partially the geometric degeneracy, allowing us to rule out $\Lambda=0$ and constrain $\Omega_k$ at the percent-level with CMB data alone.

(first done by ACT/SPT in 2011/12)
the first three minutes

Looking into the fireball, back to the first three minutes

• at high energies the nuclei of heavier elements are kicked apart by the high energy photons, they can only form at $\sim 0.1$ MeV
• final abundance depends strongly on baryons to photon ratio
• CMB measures both, so can compare to direct observations!

Great consistency test using known physics over most of the age of the universe!

Also tests for extra relativistic degrees of freedom, $N_{\text{eff}} = 3.36 \pm 0.34$ (Planck+WP+highL, expected 3.05)
Example: extra degrees of freedom from Planck+HST?

While the Planck+WP+highL dataset is consistent with the standard 3 neutrino families framework, when we include the HST value for the Hubble constant we see a preference for extra degrees of freedom at about 95% c.l. with $N_{eff}=3.6$.

A sterile neutrino with non standard decoupling could explain this effect.

Other new physics mechanisms could explain this tension.
Corrected an error in Planck Cosmology from clusters paper: now $m_{\text{nu}} > 0.06$ consistently. Still a three sigma discrepancy.
Main constraint on Inflation physics

Consistent with single field slow roll, standard kinetic term & vacuum (with f_{NL} upper limits).
Isocurvature modes?

A mixed adiabatic-isocurvature model can provide a better fit to the low-l region.

In the Figure we see 3 models:

CDI: Cold Dark Matter Density Isocurvature Mode
NDI: Neutrino Density Isocurvature Mode
NVI: Neutrino Velocity Isocurvature Mode

The isocurvature mode is favoured at the level of 2 sigmas. This kind of model is compatible with multi-field inflation. But as we can see from the data, isocurvature modes are not enough to compensate the low-low-l signal!
Angular scale

Multipole moment, $\ell$

$D_\ell [\mu K^2]$
The low-l anomaly

Angular scale

Multipole moment, \( \ell \)
The low-$l$ anomaly

Angular scale

$D_{\ell}[\mu K^2]$ vs. Multipole moment, $\ell$
The low-$l$ anomaly

Angular scale

$D_\ell [\mu K^2]$ vs Multipole moment, $\ell$
A simple amplitude test

- Rescale the power spectrum in amplitude:
  \[ C_\ell(A) = A C_\ell^{\Lambda CDM} \]

- Find the best-fit \( A \) as a function of maximum multipole \( \ell \).
- There is a 99% “anomaly” for \( \ell_{\text{max}} = 30 \).
- The anomaly fades away at higher multipoles \( \Rightarrow \) where theory and data agree remarkably well.

< 1 at more then two \( \sigma \)