Cosmological and fundamental physics legacy of Planck

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The scientific results that I 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.
The image illustrates the cosmic timeline from the Big Bang to the present day. It shows:
- Cosmic horizon
- Cosmic microwave background
- Cosmic dark age
- Bright galaxies forming
- Big galaxies forming
- Solar system forming today

The diagram depicts the evolution of the universe, highlighting key stages in its development.
May 2009: Launched from Kourou

Mar 2013: Data Release and Cosmology Results
Nominal Mission Temperature data

Oct 2013: Planck ‘Shut Down’

Feb 2015: Data Release and Cosmology Results
Full Mission Temperature and (preliminary) Polarization data

Jul 2018: Legacy Data & Paper Release
The ultimate measurement of the CMB temperature anisotropy field
T map: 2018
Two independent components: a grad-like (E) and a curl-like (B) mode
Different behaviour under parity
10°x10°, smoothed at 20′

(Planck 2018 I)
2018 lensing map - MV

Here for long at these scales...

+ Small scale extension w. CIB

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Huge compression of Information to a few hundred numbers

$\ell = 1^\circ$
2018 Planck EE

Low-ell from HFI
Syncrotron cleaned with 30 GHz LFI
Shifts from 2015 explained from different masks and SMICA weights

amplitude constrained to 2.5 %

40 **sigma** detection of lensing (T+P)

Polarisation lensing detected at **9σ**
**$\Lambda$CDM results 2018 (T+Pol+lensing)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean</th>
<th>$\sigma$</th>
<th>[%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_b h^2$ Baryon density</td>
<td>0.02237</td>
<td>0.00015</td>
<td>0.7</td>
</tr>
<tr>
<td>$\Omega_c h^2$ DM density</td>
<td>0.1200</td>
<td>0.0012</td>
<td>1</td>
</tr>
<tr>
<td>$100\theta$ Acoustic scale</td>
<td>1.04092</td>
<td>0.00031</td>
<td>0.03</td>
</tr>
<tr>
<td>$\tau$ Reion. Optical depth</td>
<td>0.0544</td>
<td>0.0073</td>
<td>13</td>
</tr>
<tr>
<td>$\ln(A_s 10^{10})$ Power Spectrum amplitude</td>
<td>3.044</td>
<td>0.014</td>
<td>0.7</td>
</tr>
<tr>
<td>$n_s$ Scalar spectral index</td>
<td>0.9649</td>
<td>0.0042</td>
<td>0.4</td>
</tr>
<tr>
<td>$H_0$ Hubble</td>
<td>67.36</td>
<td>0.54</td>
<td>0.8</td>
</tr>
<tr>
<td>$\Omega_m$ Matter density</td>
<td>0.3153</td>
<td>0.0073</td>
<td>2.3</td>
</tr>
<tr>
<td>$\sigma_8$ Matter perturbation amplitude</td>
<td>0.8111</td>
<td>0.0060</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Robust against changes of likelihood, <0.5$\sigma$ ($\sigma$ is small!)

- Most of parameters determined at (sub-) percent level!
- Best determined parameter is the angular scale of sound horizon $\theta$ to 0.03%.
- $n_s$ is 8$\sigma$ away from scale invariance (even in extended models, always >3$\sigma$)
- Best **(0.8%)** determination of the Hubble constant to date.
Conclusions

• Planck has observed the ultimate cosmic variance limited “primary” temperature anisotropies

• Robust support to the standard six parameters cosmological model (ΛCDM) at the level of percent or sub-percent error.

• Tight constraints on possible deviations from the standard models

• CMB lensing as a cosmological tool

• Some hints of anomalies (with modest statistical significance but not to be forgotten)

• Tensions with external datasets (i.e. H₀)
But........:

Fundamental origin of the 95% of the Universe energy budget is still unknown.
Future Experiments should do for CMB polarization anisotropies (primordial B Modes?+…?) what Planck did for temperature.

- Ground
- Balloon
- **Space** (“LiteBIRD” 2027 – “Flagship: Pol + Spectral distortions – future ESA Beyond 2050???)
Thank you