The Planck Legacy and... beyond

Nazzareno Mandolesi
University of Ferrara & INAF

On behalf of the Planck Collaboration
Temperature and polarization variations across the microwave sky include the fingerprints of quantum fluctuations in the early universe. Will they reveal physics or new physics at unprecedented energy scales?
Introduction

Stability of main scientific results across the 2013, 2015 and intermediate product public deliveries, confirmed by the 2018 legacy release.

2018: Main Legacy results and improvements in understanding and correction of systematics in Polarization.

Issues to be addressed:

- Small remaining uncertainties of systematics in polarization
- Some 2.0/2.5 $\sigma$ “anomalies”: lack of power at low ell + minor “curiosities”
- 3.8 $\sigma$ tension with “distance ladder” measured $H_0$

Beyond Planck

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Planck function

2.726 ° K

the cosmic microwave background from space
Penzias & Wilson 1965; Dicke, Peebles, Roll & Wilkinson 1965


Predictions of the temperature oscillated between 5K and tens of K
Discovery: 3.5 ±1 K

Planck function

G. Smoot et al 1992 DMR experiment (COBE)

J. Mather et al 1990 FIRAS experiment
M. Hauser et al 1998 DIRBE experiment (COBE)
Planck is the 3rd generation ESA satellite devoted to CMB
Ultimate characterization of the temperature anisotropies
74 detectors (radiometers and bolometers) in 9 frequency bands from 30 to 857 GHz
angular resolution between 30’ and 5’, $\Delta T/T \sim 2 \times 10^{-6}$
Final (legacy) release took place on 17 July 2018, for data and (most) papers.
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
9 papers (+3 to appear soon)
CMB monopole and dipole
The 2018 maps

Intensity

Polarization

30 GHz
44 GHz
70 GHz
100 GHz
143 GHz
217 GHz
353 GHz
545 GHz
857 GHz
The *ultimate* measurement of the CMB temperature anisotropy field.
LFI and HFI Solar dipole direction and amplitude

21 August 2018

J.L. Puget, IAS Orsay

0.7 arc min

WMA

P

LFI 70 GHz

HFI

Galactic Latitude [°]

48.28
48.24
48.20
48.16

263.9
264.0
264.1

Galactic Longitude [deg]

263.90
263.95
264.00
264.05
264.10

HFI

Amplitude [µK]

3370
3360
3355
3350

100 GHz
143 GHz
217 GHz
353 GHz
545 GHz

SMICA
Commander
NILC
SEVEM
1. the dipole due to the motion of the solar system w.r.t. the CMB has been measured with unprecedented accuracy
2. it is a very powerful tool for inter-calibration and testing
3. we remove the foregrounds and the CMB anisotropies with 4 different methods
4. the calibration of each detector is obtained from the orbital dipole (earth motion around the sun)
5. we then measure the solar dipole (direction and amplitude) for a set of galactic sky cuts (20 to 90 %)
6. finally we compare the results between frequencies

\[ v = (369.8160 \pm 0.0010) \text{km/s}; \]
\[ A = [3362.08 \pm 0.09 \text{(stat.)} \pm 0.45 \text{(syst.)} \pm 0.45 \text{(cal.)}] \mu \text{K}; \]
\[ l = 264.021 \pm 0.003 \text{(stat.)} \pm 0.008 \text{(syst.)}; \]
\[ b = 48.253 \pm 0.001 \text{(stat.)} \pm 0.004 \text{(syst.)}. \]
### Correlation Functions

\[
\frac{\Delta T}{T} (\bar{\gamma}) \frac{\Delta T}{T} (\bar{\gamma}')
\]

from Inflation

\[
\frac{\Delta T}{T} (\bar{\gamma}) \frac{\Delta T}{T} (\bar{\gamma}') \frac{\Delta T}{T} (\bar{\gamma}'')
\]

\[
\frac{\Delta T}{T} (\bar{\gamma}) \frac{\Delta T}{T} (\bar{\gamma}') \frac{\Delta T}{T} (\bar{\gamma}'') \frac{\Delta T}{T} (\bar{\gamma}''')
\]

... 

### Polarization

\[ P(\hat{\gamma}) = \nabla E + \nabla \times B \]

**E-modes**: even under parity  
**B-modes**: odd under parity

Density perturbations -> E-modes  
Gravitational Waves -> E- and B-modes
spatial curvature
relative abundance of matter and radiation
distance to the last scattering surface
$H_0$, $\Omega_m$, $\Omega_k$

Primordial power spectrum
late time expansion
$A_s$, $\Omega_\Lambda$

Baryon abundance
$\Omega_b$

Photon diffusion length at recombination
Slope of the primordial spectrum
$N_{\text{eff}}, \Omega_b, Y_p, n_s$

Angular scale
18° 1.8° 0.18°

$\theta_H$ $\theta_D$

+ Overall power
$A_s e^{-2\tau}$

+ low-ell polarization
Reionization history
$\tau$
Expectations

Prediction 1995 (Redbook)

Prediction 2005 (Bluebook)

2018 measurements Planck

Measurements 1995
The Planck Legacy in a snapshot

- Ultimate Anisotropy Temperature maps at all CMB scales

- To date, unprecedented sensitivity Anisotropy Polarization full sky maps

- And much more......
T map: 2013
T map: 2018
In 2018 sources are removed
**Statistical Description**

**Correlation Functions**

\[
\left\langle \frac{\Delta T}{T} (\vec{\gamma}) \frac{\Delta T}{T} (\vec{\gamma}') \right\rangle
\]

\[
\left\langle \frac{\Delta T}{T} (\vec{\gamma}) \frac{\Delta T}{T} (\vec{\gamma}') \frac{\Delta T}{T} (\vec{\gamma}'') \right\rangle
\]

\[
\left\langle \frac{\Delta T}{T} (\vec{\gamma}) \frac{\Delta T}{T} (\vec{\gamma}') \frac{\Delta T}{T} (\vec{\gamma}'') \frac{\Delta T}{T} (\vec{\gamma}''') \right\rangle
\]

... 

**Polarization**

\[
P(\hat{\gamma}) = \nabla E + \nabla \times B
\]

- **E-modes**: even under parity
- **B-modes**: odd under parity

Density perturbations -> E-modes
Gravitational Waves -> E- and B-modes
Two independent components: a grad-like (E) and a curl-like (B) mode
Different behaviour under parity
10°x10°, smoothed at 20°

-201 μK  (276.4, -29.8) Galactic

13.7 μK  309 μK

(Planck 2018 I)
**Planck-WMAP(V+W) comparison**

Stacking of polarization maps on intensity peaks

*Planck* sensitivity and resolution allow to show more defined stacking patterns than WMAP.

**Top:** WMAP: V+W band at $N_{\text{side}} = 512$ (30’)

**Bottom:** Planck: at $N_{\text{side}} = 1024$ (10’)

![Image of polarization maps](image.png)
2018 Planck TT
2018 Planck EE

Low-ell from HFI
Syncrothron cleaned with 30 GHz LFI
Comparison with ground-based experiments

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### $\Lambda$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>

- 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.

Robust against changes of likelihood, $<0.5\sigma$ ($\sigma$ is small!)
### ΛCDM results 2018

From a joint fit to Planck temperature, polarisation and lensing data.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Planck alone</th>
<th>Planck + BAO</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_b h^2$</td>
<td>$0.02237 \pm 0.00015$</td>
<td>$0.02242 \pm 0.00014$</td>
</tr>
<tr>
<td>$\Omega_c h^2$</td>
<td>$0.1200 \pm 0.0012$</td>
<td>$0.11933 \pm 0.00091$</td>
</tr>
<tr>
<td>$100\theta_{MC}$</td>
<td>$1.04092 \pm 0.00031$</td>
<td>$1.04101 \pm 0.00029$</td>
</tr>
<tr>
<td>$\tau$</td>
<td>$0.0544 \pm 0.0073$</td>
<td>$0.0561 \pm 0.0071$</td>
</tr>
<tr>
<td>$\ln(10^{10} A_s)$</td>
<td>$3.044 \pm 0.014$</td>
<td>$3.047 \pm 0.014$</td>
</tr>
<tr>
<td>$n_s$</td>
<td>$0.9649 \pm 0.0042$</td>
<td>$0.9665 \pm 0.0038$</td>
</tr>
<tr>
<td>$H_0$</td>
<td>$67.36 \pm 0.54$</td>
<td>$67.66 \pm 0.42$</td>
</tr>
<tr>
<td>$\Omega_{\Lambda}$</td>
<td>$0.6847 \pm 0.0073$</td>
<td>$0.6889 \pm 0.0056$</td>
</tr>
<tr>
<td>$\Omega_m$</td>
<td>$0.3153 \pm 0.0073$</td>
<td>$0.3111 \pm 0.0056$</td>
</tr>
<tr>
<td>$\Omega_m h^2$</td>
<td>$0.1430 \pm 0.0011$</td>
<td>$0.14240 \pm 0.00087$</td>
</tr>
<tr>
<td>$\Omega_m h^3$</td>
<td>$0.09633 \pm 0.00030$</td>
<td>$0.09635 \pm 0.00030$</td>
</tr>
<tr>
<td>$\sigma_8$</td>
<td>$0.8111 \pm 0.0060$</td>
<td>$0.8102 \pm 0.0060$</td>
</tr>
<tr>
<td>$\sigma_8 (\Omega_m/0.3)^{0.5}$</td>
<td>$0.832 \pm 0.013$</td>
<td>$0.825 \pm 0.011$</td>
</tr>
<tr>
<td>$z_{re}$</td>
<td>$7.67 \pm 0.73$</td>
<td>$7.82 \pm 0.71$</td>
</tr>
<tr>
<td>Age [Gyr]</td>
<td>$13.797 \pm 0.023$</td>
<td>$13.787 \pm 0.020$</td>
</tr>
<tr>
<td>$r_s [\text{Mpc}]$</td>
<td>$144.43 \pm 0.26$</td>
<td>$144.57 \pm 0.22$</td>
</tr>
<tr>
<td>$100\theta_*$</td>
<td>$1.04110 \pm 0.00031$</td>
<td>$1.04119 \pm 0.00029$</td>
</tr>
<tr>
<td>$r_{\text{drag}} [\text{Mpc}]$</td>
<td>$147.09 \pm 0.26$</td>
<td>$147.57 \pm 0.22$</td>
</tr>
<tr>
<td>$z_{\text{eq}}$</td>
<td>$3402 \pm 26$</td>
<td>$3387 \pm 21$</td>
</tr>
<tr>
<td>$k_{\text{eq}} [\text{Mpc}^{-1}]$</td>
<td>$0.010384 \pm 0.000081$</td>
<td>$0.010339 \pm 0.000063$</td>
</tr>
<tr>
<td>$\Omega_k$</td>
<td>$-0.0096 \pm 0.0061$</td>
<td>$0.0007 \pm 0.0019$</td>
</tr>
<tr>
<td>$\Sigma m_\nu$ [eV]</td>
<td>$&lt; 0.241$</td>
<td>$&lt; 0.120$</td>
</tr>
<tr>
<td>$N_{\text{eff}}$</td>
<td>$2.89^{+0.36}_{-0.38}$</td>
<td>$2.99^{+0.34}_{-0.33}$</td>
</tr>
<tr>
<td>$r_{0.002}$</td>
<td>$&lt; 0.101$</td>
<td>$&lt; 0.106$</td>
</tr>
</tbody>
</table>
Improved consistency with BAO and RSD
2018 lensing map - MV

Here for long at these scales...

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Lensing smooths the peaks of the CMB power spectrum... and introduces non-gaussianities in the map (nonzero 4-point c.f.)
Lensing Potential Power Spectrum

\[ P_L = \frac{\langle L^2 \rangle}{2\pi} \]

- Planck 2018 (MV)
- SPT-SZ 2017 (T, 2500 deg²)
- ACTPol 2017 (MV, 626 deg²)
- SPTpol 2015 (MV, 100 deg²)

Amplitude constrained to 2.5 %

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

Polarisation lensing detected at 9\( \sigma \)

Shifts from 2015 explained from different masks and SMICA weights
Are tensor modes required?

Primary parameter $r$ the tensor-to-scalar ratios at $k=0.002 \text{ Mpc}^{-1}$ (approximately $\ell<100$) with theoretical prior $n_t = -r/8$

**Planck 2018 + BK14**

$r_{0.002} < 0.064$ \hspace{1cm} $n_t = -r/8$ \hspace{1cm} (95\%CL)

A stochastic background of gravitational waves (GW) with a blue tensor tilt can be further constrained at much shorter wavelength as those probed by ground-based interferometers dedicated to the direct detection of GWs. The LIGO/VIRGO upper bound (Abbott et al. 2016) on the GW energy density translates in an upper bound on $r$ on short scales.

$$\Omega_{GW}(f) \leq 1.7 \times 10^{-7} \hspace{1cm} (95\%CL)$$

at $f = 20 \text{ Hz}$

$$\Omega_{GW}(k) = \frac{k}{\rho_{\text{critical}}} \frac{d\rho_{GW}}{dk} = \frac{A_{t1}(k/k_1)^{n_t}}{24z_{eq}} \hspace{1cm} r \leq 2.6 \times 10^7 \hspace{1cm} (95\%CL)$$

at $k = 1.3 \times 10^{16} \text{ Mpc}^{-1}$

**Planck 2018 + BK14 + LIGO/VIRGO**

$r_{0.002} < 0.069$ \hspace{1cm} $-0.62<n_t<0.53$ \hspace{1cm} (95\%CL)

and relaxing $n_t = -r/8$
Beyond Planck
The OPEN (?) questions

- Anomalies at large angular scales
- Omega-k and Alens
- Tensions between large and small scales
- Tensions between low and high redshift probes

Need for high precision (goal: cosmic variance limited) full sky polarization maps

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• At large angles, the CMB field is known to exhibit anomalies:
  • Lack of power
  • Hemispherical asymmetry
  • Even-odd asymmetry
  • And others...
• For temperature, Planck has reached cosmic variance. For polarization, there is much room for improvement.
The **Cold Spot** is an **anomalous** CMB feature of **large area** and a **very negative amplitude**, and a **large kurtosis** at scales of around **5 deg**. Besides the **Cold Spot** we are also investigating the multipolar profiles of **four more large-scale peaks**, which have been previously identified anomalous features at very large scales (**at 10 deg**).
Planck 2018 TT power spectrum

Blue curve is a 6p. LCDM model

CVL

CVL

1σ line
A \_\text{Lens} \text{ issue: a statistical fluke?}

- Unphysical parameter used for consistency check.
- Preference for high $A_L$ from Planck since 2013 ($A_L$ expected to be 1)
- Not due to lensing: Predicted 4 points correlation function (lensing) is exactly what Planck measures.
- Due to contrast on high ell acoustic peaks.
- It could be a statistical fluctuation/new physics/systematics (but no evidence so far).

Amplitude of the lensing potential power spectrum. In $\Lambda$CDM=1

Different treatment of systematics in polarization (as done in our two likelihoods Camspec and Plik) can impact extensions of $\Lambda$CDM at $\sim0.5\sigma$ level.
Curvature and Dark Energy

- Both curvature $\Omega_k < 1$ and phantom dark energy $w < -1$ can provide larger lensing amplitude, thus preferred by TTTEEE.
- Results between Plik and CAMspec differ at $\sim < 0.5\sigma$ level.
- When adding CMB lensing reconstruction, less preference for deviations, further tightened by BAO.

**Curvature**

$$\Omega_K = 0.0007 \pm 0.0019 \quad (68\%, \text{TT,TE,EE+lowE +lensing+BAO}).$$

**Dark energy equation of state**

$$w_a = 0,$$
$$w_0 = -1.028 \pm 0.032 \quad (68\%, \text{Planck TT,TE,EE+lowE +lensing+SNe+BAO}).$$
The results of Planck analysis comparing parameters measured from ell=30-1000 with those measured from 1000-2500 agree with what published in the Planck papers but are cleaner because taking into account of reduced foregrounds. Therefore there is nothing anomalous -- the parameters shifts are consistent with expectations. There is, however (see previous slides), some tension when we add the low ells from ell=2-30 (LFI).

This might be just a consequence of the low amplitudes at ell<30 that we have known about since WMAP. It's possible that there is new physics that suppresses the low ell multipoles -- but the statistical significance is not high.
Tension: $H_0$ (3.8 sigma)

Low-High redshift evolution?

New physics or systematics?

Primordial deuterium abundances allow to constrain the sound horizon and this gives constraints that agree with the base LCDM model. So, if we want to resolve the tension between CMB and $H_0$, we have to change the sound horizon while preserving BBN and the acoustic peak structure of the CMB!!!!!!
The neutrino legacy of Planck (1)

- Effective number of relativistic species is consistent with the standard expectation $N_{\text{eff}} = 3.046$
- Data are consistent with these relativistic species behaving as free-streaming neutrinos – a strong indication that they are indeed the SM neutrinos!
- A fourth thermalized species ($N_{\text{eff}}=4$) is excluded at 3.5 to 6 $\sigma$, depending on the dataset
- A light sterile neutrino species is allowed if not thermalized. Still, the sterile neutrino interpretation of the short-baseline anomalies is excluded by Planck

$N_{\text{eff}} = 3.00^{+0.57}_{-0.53}$ (95% CL, TT+lowE)

$N_{\text{eff}} = 3.11^{+0.44}_{-0.43}$ (95% CL, TT+lowE+lensing +BAO)
The neutrino legacy of Planck (2)

- Tightest constraint from a single experiment
- First constraint exploiting the information encoded in the CMB weak lensing
- One order of magnitude better than present kinematic constraints, already at the same level than future expectations for KATRIN
- The combined limits from Planck and large scale structure probes are starting to corner the inverted hierarchy scenario

\[ M_\nu < 0.44 \text{ eV} \quad (95\% \text{CL, TT + lowE + lensing}) \]

\[ M_\nu < 0.13 \text{ eV} \quad (95\% \text{CL, TT + lowE + lensing + BAO}) \]

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Planck exhausted the temperature
Polarization is the future

- The quest for B-modes
- Full sky E-modes cosmic variance limited
  - Lack of power
  - Reionization History
  - Primordial Universe
  - Neutrinos

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Beyond Planck: Deal with the foregrounds and lensing

Courtesy of Molinari, Mandolesi, Burigana

\[ \ell (\ell + 1) C_\ell / 2\pi [\mu K^2] \]

Planck (2018)
ACT pol (2014)
SPT pol (2017)
BICEP2/Keck/Planck (2015)
PolarBear (2014)

\[ f_{\text{sky}} = 73\% \]

Galaxy (100 GHz)
Galaxy (70 GHz)
Galaxy (44 GHz)
Galaxy (150 GHz)
Extragal. sources (70 GHz)

Lensing BB

Multipole \( \ell \) (linear scale)
10^8

Multipole \( \ell \) (logarithmic scale)
2 5 10 20 50 100 500 1000 1500 2000 2500 3000 3500
Planck Legacy: main points

✓ Planck results stable across releases
✓ Polarization now better understood (~0.5 $\sigma$ systematic uncertainty)
✓ Consistency with BAO, SN, RSD, DES lensing (in $\Lambda$CDM)
✓ Strong 3.8 $\sigma$ tension with $H_0$ from distance ladder results
✓ Planck value in agreement with inverse distance ladder independent of CMB ($BAO+D/H+CMB$ lensing).
✓ Some « anomalies » (low ell lack of power, $A_L$, low-high features, etc.), but not more than $2\sigma - 3\sigma$, no evidence for extensions of $\Lambda$CDM. Further investigations are needed.
✓ New Physics: ?????
The legacy of Planck not only represents the status of the art of full sky microwave observations but the path to the future of CMB is:

**POLARIZATION**

“Foregrounds in polarization” are still very poorly known and this require a deep investigation. You will never be sure of a B-mode as long as foregrounds are not perfectly known beyond any doubt.

TO PERFORM THE BEST POSSIBLE SEPARATION OF THE SKY COMPONENTS AS “MANY FREQUENCY CHANNELS” AS POSSIBLE ARE REQUIRED. AND THE WIDEST FREQUENCY RANGE IN ORDER TO DISENTANGLE LOW FREQUENCY FOREGROUND COMPLEXITY.

“Delensing”. On small angular scales B-modes signal are dominated by the lensing. The only hope are delensing algorithms which need high resolution to be performant.

THE FUTURE OF THE CMB MIGHT BE PROMISING BUT “COMPLEXITY WILL BE ORDERS OF MAGNITUDE HIGHER”
Experiments Beyond Planck

- Ground
- Balloon
- Space

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## Planck Legacy: Conclusions

<table>
<thead>
<tr>
<th>Prediction</th>
<th>Measurement</th>
</tr>
</thead>
</table>
| A spatially flat universe with a *nearly* scale-invariant (red) spectrum of density perturbations, which is almost a power law, dominated by scalar perturbations, which are Gaussian and adiabatic, with negligible topological defects | \[\Omega_K = 0.0007 \pm 0.0019\]  
\[n_s = 0.967 \pm 0.004\]  
\[dn/d \ln k = -0.0042 \pm 0.0067\]  
\[r_{0.002} < 0.07\]  
\[f_{\text{NL}} = 2.5 \pm 5.7\]  
\[\alpha_{-1} = 0.00013 \pm 0.00037\]  
\[f < 0.01\] |

*This pictorial denotes a hundred fold improvement in precision since (at most) COBE*
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.
Thank you