PLANCK 2016 COSMOLOGY

Eric Hivon on behalf of the Planck Collaboration
to perform the “ultimate” measurement of the Cosmic Microwave Background (CMB) temperature anisotropies:

- full sky coverage & angular resolution / to survey all scales at which the CMB primary anisotropies contain information (~5')
- sensitivity / essentially limited by ability to remove the astrophysical foregrounds
  ⇒ enough sensitivity within large frequency range [30 GHz, 1 THz] (~CMB photon noise limited for ~1yr in CMB primary window)

get the best performances possible on the polarization with the technology available

⇒ ESA selection in 1996 (after ~ 3 year study)

NB: This required a number of technological breakthrough

NB: with the Ariane 501 failure delaying us by several years (03 → 07) and WMAP then flying well before us, polarization measurements became more and more a major goal
Now available in a store near you

30 GHz
1.3µK.deg,9.7'

44 GHz
0.8µK.deg,5.0'

3.5µK.deg,13’ 70 GHz

100 GHz
1.3µK.deg,9.7'

0.5µK.deg,7.3’ 143 GHz

0.8µK.deg,5.0’ 217 GHz

353 GHz

545 GHz

857 GHz
Planck 2015 T anisotropies map

SMICA 2015

Eric Hivon "Planck 2016 cosmology" PaSCos, Quy Nhon, Vietnam, July 12 2016
Planck cosmology

- Planck?
- **CMB Temperature anisotropies**
  - *Universe initial conditions*
    - Primordial power spectrum
    - (Non-)Gaussianity
  - *Constraints on Inflation*
- CMB Polarization
  - *Consistency with temperature*
  - *Adiabaticity of initial conditions*
- Secondary anisotropies
  - *Gravitational lensing*
  - *Re-ionization*
- Consistency with other probes
  - *BAO, BBN, SN1a*
  - *ΛCDM fits all?*
- Tensions
- Overall picture
Planck 2015 TT power spectrum

8 acoustic peaks well detected

CVL till $\ell \sim 1600$ on 40-70% of the sky
Base $\Lambda$CDM model with 6 parameters

- 3 parameters to set (though General Relativity) the **dynamics** of the Universe,
  - $\Omega_b h^2$ **Baryon density today** - The amount of ordinary matter
  - $\Omega_c h^2$ **Cold dark matter density today** – only weakly interacting
  - $\Theta$ **Sound horizon size** when optical depth $\tau$ reaches unity
    (Distance travelled by a sound wave since inflation, when universe became transparent at recombination at $t \sim 380,000$ years)

- 2 parameters to describe the characteristics of **primordial fluctuations**,  
  - $A_s$ **Amplitude of the curvature power spectrum**  
    Overall contrast of primordial fluctuations
  - $n_s$ **Scalar power spectrum power law index**  
    ($n_s$-1 measures departure from scale invariance)

- 1 parameter to capture the effect of **reionisation** (end of the dark ages),
  - $\tau$ **Optical depth at reionisation** (due to Thomson scattering of photons on $e^+$),
    i.e., fraction of the CMB photons re-scattered during that process

- **Flat spatial geometry** assumed.

- Others parameters are **derived** parameters within the model, in particular
  - $\Omega$ “Dark Energy” fraction of the critical density (derived only if assumed flat)
  - $H_0$ the expansion rate today (in km/s per Mpc of separation)
  - $t_0$ the age of the universe (in Gy)
  - $\sigma_8$ linear density contrast at $8 h^{-1}$Mpc
What is the value of $n_s$?

Mukhanov & Chibisov (1981): 1st calculation of (scalar) quantum fluctuation of the vacuum in an inflating background. $n_s$ must be $\sim 0.96 < 1$ for inflation to end.

A hundred-fold improvement in 20 years
(Unsuccessful) search for features

Feature in the potential:

$$V(\phi) = \frac{m^2}{2} \phi^2 \left[ 1 + c \tanh \left( \frac{\phi - \phi_c}{d} \right) \right]$$

Non vacuum initial conditions/instanton effects in axion monodromy:

$$V(\phi) = \mu^3 \phi + \Lambda^4 \cos \left( \frac{\phi}{f} \right)$$

$$P_R^0(k) = P_R^0(k) \left[ 1 + A_{\text{lin}} \cos \left( \omega_{\text{lin}} \ln \left( \frac{k}{k_*} \right) + \varphi_{\text{lin}} \right) \right].$$

Linear oscillations as from Boundary EFT:

$$P_R^{\text{lin}}(k) = P_R^0(k) \left[ 1 + A_{\text{lin}} \left( \frac{k}{k_*} \right)^{m_{\text{lin}}} \cos \left( \omega_{\text{lin}} \ln \left( \frac{k}{k_*} \right) + \varphi_{\text{lin}} \right) \right].$$

Just enough e-folds, i.e. inflation preceded by a kinetic stage.

- $\Delta \chi^2$ data sims
  - Cutoff model
    - cutoff (1 extra parameter)
  - Step model
    - step (3 extra parameters)
  - Linear oscillation model
    - $\Delta \chi^2_{\text{eff}}$ log oscillations (3 extra parameters)
  - Linear oscillation model
    - $\Delta \chi^2_{\text{eff}}$ linear oscillations (4 extra parameters)
Power spectra reconstruction

\[ \ell_k \equiv kD_{\text{rec}} \]

\[ n_s = 0.968 \]

fixed \( r_{0.05} = 0.1 \); TT + low-z

(TT+lowP+BAO+SN+HST+z_{re} > 6)

12-knots power spectra

(actually used 3 different methods, all with similar results)
NG of **local** type
(k\textsubscript{1} \ll k\textsubscript{2} \sim k\textsubscript{3})
- Multi-field models
- Curvaton
- Ekpyrotic/cyclic models

(Also NG of **Folded** type
- Non Bunch-Davis
- Higher derivative)

NG of **equilateral** type
(k\textsubscript{1} \sim k\textsubscript{2} \sim k\textsubscript{3}):
- Non-canonical kinetic term
  - K-inflation
  - DBI inflation
- Higher-derivate terms in Lagrangian
  - Ghost inflation
- Effective field theory

NG of **orthogonal** type
(k\textsubscript{1} \sim 2k\textsubscript{2} \sim 2k\textsubscript{3}):
- Distinguishes between different variants of
  - Non-canonical kinetic term
  - Higher derivative interactions
- Galileon inflation
**New bispectrum constraints w. full mission data**

<table>
<thead>
<tr>
<th>Shape and method</th>
<th>Independent</th>
<th>ISW-lensing subtracted</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SMICA (T)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Local</td>
<td>9.5 ± 5.6</td>
<td>1.8 ± 5.6</td>
</tr>
<tr>
<td>Equilateral</td>
<td>-10 ± 69</td>
<td>-9.2 ± 69</td>
</tr>
<tr>
<td>Orthogonal</td>
<td>-43 ± 33</td>
<td>-20 ± 33</td>
</tr>
<tr>
<td><strong>SMICA (T+E)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Local</td>
<td>6.5 ± 5.1</td>
<td></td>
</tr>
<tr>
<td>Equilateral</td>
<td>-8.9 ± 44</td>
<td></td>
</tr>
<tr>
<td>Orthogonal</td>
<td>-35 ± 22</td>
<td></td>
</tr>
</tbody>
</table>

**Planck 2013**

<table>
<thead>
<tr>
<th>ISW-lensing subtracted</th>
<th>KSW</th>
<th>Binned</th>
<th>Modal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>local NL</td>
<td>2.7 ± 5.8</td>
<td>2.2 ± 5.9</td>
<td>1.6 ± 6.0</td>
</tr>
<tr>
<td>equil NL</td>
<td>-42 ± 75</td>
<td>-25 ± 73</td>
<td>-20 ± 77</td>
</tr>
<tr>
<td>ortho NL</td>
<td>-25 ± 39</td>
<td>-17 ± 41</td>
<td>-14 ± 42</td>
</tr>
</tbody>
</table>

Constraint volume in LEO space shrunk by factor of 3. wrt Planck 2013

\[ \Phi = \phi + f_{NL}(\phi^2 - \langle \phi^2 \rangle) \left| f_{NL}^{loc} \right| < 10^3 \text{ (Maxima 2001),} \]
\[ 10^2 \text{ (WMAP7),} \]
\[ 10 \text{ (Planck 2015)} \]

A hundred-fold improvement in 14 years
Planck cosmology

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  - \( \Lambda \)CDM fits all ?
- Tensions
- Overall picture
Thomson scatterings are polarised

- Before recombination, successive scatterings destroy polarization and the radiation arrives at recombination unpolarized.
- During recombination, Gradients in the velocity field can produce a quadrupole in the rest frame of the scattering electron.

A diverging flow leads to a tangential pattern of polarization
Polarisation around hot spots

Data (top) versus expectation (bottom)

- Planck “sees” precisely the dynamics of fluctuations, at ~380 000 years

- It would be different with a different content
PLANCK'S POLARISATION OF THE COSMIC MICROWAVE BACKGROUND

Filtered at 5 degrees

Filtered at 20 arcminutes

Full sky map
Filtered at 5 degrees
(and high-passed filtered at ~7°)

30 GHz

357 GHz
Filtered at 20 arcminutes
3 observables: T, E, B

B Modes:
- Not generated by scalar modes
- "Smoking gun" of tensorial perturbations
- At best 300 times weaker than T fluctuations
- Case $T/S = r = 0.1$ (cf. fig).
- $E_{\text{inf}} = 1.6 \times 10^{16} \, \text{GeV} \, (\sim \text{GUT})$.

B mode Spectrum peaks at $l < 200$, i.e. $\theta > 1$ deg
Red curve is the prediction based on the best fit TT in base $\Lambda$CDM

2015 polarisation data and results are not final yet because all systematic and foreground uncertainties have not been exhaustively characterised at $O(1\mu K^2)$.
### Base $\Lambda$CDM model

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>$\Omega_b h^2$</td>
<td>0.02222 ± 0.00023</td>
<td>0.02228 ± 0.00025</td>
</tr>
<tr>
<td>$\Omega_c h^2$</td>
<td>0.1197 ± 0.0022</td>
<td>0.1187 ± 0.0021</td>
</tr>
<tr>
<td>$100\theta_{MC}$</td>
<td>1.04085 ± 0.00047</td>
<td>1.04094 ± 0.00051</td>
</tr>
<tr>
<td>$\tau$</td>
<td>0.078 ± 0.019</td>
<td>0.053 ± 0.019</td>
</tr>
<tr>
<td>$\ln(10^{10} A_s)$</td>
<td>3.089 ± 0.036</td>
<td>3.031 ± 0.041</td>
</tr>
<tr>
<td>$n_s$</td>
<td>0.9655 ± 0.0062</td>
<td>0.965 ± 0.012</td>
</tr>
<tr>
<td>$H_0$</td>
<td>67.31 ± 0.96</td>
<td>67.73 ± 0.92</td>
</tr>
<tr>
<td>$\Omega_m$</td>
<td>0.315 ± 0.013</td>
<td>0.300 ± 0.012</td>
</tr>
<tr>
<td>$\sigma_8$</td>
<td>0.829 ± 0.014</td>
<td>0.802 ± 0.018</td>
</tr>
<tr>
<td>$10^9 A_s e^{-2\tau}$</td>
<td>1.880 ± 0.014</td>
<td>1.865 ± 0.019</td>
</tr>
</tbody>
</table>

TT & TE have quite similar uncertainties (but for $n_s$),
but beware that they are still some low level systematics in the polarisation data.
Adiabaticity?
Adiabaticity ✔

Planck Data Release 2 (February 2015)

Adiabatic IC

Isocurvature IC

(Data: Planck Legacy Archive)

© Kinney 2015
Isocurvature modes fraction

Percentage of isocurvature:

- Planck TT+lowP
- Planck TT,TE,EE+lowP

Planck (2015) (conservative)
Planck 2015: $n_s$ vs $r$

$V_*= (1.88 \times 10^{16} \text{ GeV})^4 \ (r/0.1)$

$r_{0.002} < 0.10 \, @ \, 95\% \, \text{CL}$, similar (indirect) $r$ constraint than with 2013 release (was 0.11)
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The gravitational effects of intervening matter bend the path of CMB light on its way from the early universe to the Planck telescope. This “gravitational lensing” distorts our image of the CMB (smoothing of the power spectrum, and correlations between scales).

\[
\hat{T}(\vec{\theta}) = T(\vec{\theta} + \vec{\nabla}\phi) \approx T(\vec{\theta}) + \vec{\nabla}\phi \cdot \vec{\nabla}T(\vec{\theta}) + ...
\]

\[
\vec{\phi} = \Delta^{-1} \vec{\nabla} \cdot \left[ C^{-1} T \, \vec{\nabla} (C^{-1} T) \right]
\]
Projected mass map

The (grey) masked area is where foregrounds are too strong to allow an accurate reconstruction.

Eric Hivon "Planck 2016 cosmology"  
PaSCos, Quy Nhon, Vietnam, July 12 2016
Planck for the first time measured the lensing power spectrum with higher accuracy than it is predicted by the base CDM model that fits the temperature data.
Lensing potential versus distribution of external tracers

\[ b(z) = 1.7 \rightarrow \hat{A}_{\text{NVSS}}^{\phi} = 1.03 \pm 0.05 \ (\approx 20\sigma) \]

NVSS Quasars
\[ z_{\text{mean}} = 1.1 \]

\[ b(z) = 3 \rightarrow \hat{A}_{\text{MaxBCG}}^{\phi} = 1.54 \pm 0.21 \ (\approx 7\sigma) \]

MaxBCG Clusters
\[ 0.1 < z < 0.3 \]

\[ b(z) = 2 \rightarrow \hat{A}_{\text{LRGs}}^{\phi} = 0.96 \pm 0.10 \ (\approx 10\sigma) \]

SDSS LRGs
\[ z_{\text{mean}} = 0.55 \]

\[ b(z) = 1 \rightarrow \hat{A}_{\text{WISE}}^{\phi} = 0.97 \pm 0.13 \ (\approx 7\sigma) \]

WISE
\[ z_{\text{mean}} = 0.18 \]

No particular effort here to optimize the model for the external survey
Optical depth $\tau$ vs $z$

Planck CMB $1\sigma$ $2\sigma$
for tanh model

High $z$ galaxies:
- Bouwens++15
- Robertson++15
- Ishigaki++15
Optical depth $\tau$ vs time

Spergel et al., 2006
$\tau = 0.090 \pm 0.030$

Hinshaw et al., 2013
$\tau = 0.089 \pm 0.014$

Planck Coll. XV, 2014
$\tau = 0.081 \pm 0.012$

Planck Coll. XVI, 2014
$\tau = 0.075 \pm 0.013$

Planck Coll. XIII, 2015
$\tau = 0.067 \pm 0.022$

Planck Coll., pre-2016
$\tau = 0.053 \pm 0.012$

WMAP 3-years TT,TE,EE

WMAP 9-years

WMAP + eCMB + BAO + H0

WMAP TT, TE, EE + Planck353

Planck TT

Planck lowP

Planck TT + lowP

Planck TT + lensing + BAO

Planck TT + lowP + lensing + BAO

Planck (EE 70x143) PCL

Planck lowE (EE HFI 100X143) PCL

Planck lowE (EE HFI 100x143) QML
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Spatial curvature constraint

\[ \Omega_k = 0.000 \pm 0.005 \text{ (95\% CL)} \]
Spatial curvature constraint

\[ \Omega_K = -0.05^{+0.40}_{-0.40} \]

Melchiorri et al. 2000

\[ \Omega_K = -0.11^{+0.07}_{-0.07} \]

Jaffe et al. 2001

Planck 2015

\[ \Omega_K = 0.000 \pm 0.005 \ (95\% \ CL) \]

A hundred-fold improvement in 15 years

Note the change of axes
For Planck below

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We can test & constrain a lot more…

**Optical depth constraints**

Neutrinos masses $\sum m_\nu < 0.23$ eV (95%)

BBN – Neff, Yp

Allowing neutrinos extensions

A new, independent, way to look at $r$
- Consistency of lensing versus LowP constraints on $r$
- Pointing to lower values than previous WMAP based values

**Recombination history**

Planck is impressively sensitive to details of the recombination history... and is therefore sensitive to
- $\Lambda$CDM+$\Delta A + H_0$
- Planck TT$+$EE breaks degeneracies and sets a limit 3 times stronger than WMAP$+$SPT
- A cosmological constant corresponds to $H_0$

**Dark matter annihilation?**

PCA of $w(z)$

Comparison of $H_0$

**Inflation: constraints on running**

(Unsuccessful) Search for features

Axion monodromy inflation

Isocurvature modes fraction

Eric Hivon “Planck 2016 cosmology”

PaSCos, Quy Nhon, Vietnam, July 12 2016
The CMB TT, TE, EE, Φ-Φ, as well as BAO, BBN ($^{2}$H and He), and SN1a measurements are all consistent, among themselves and across experiments, within ΛCDM.

This network of consistency tests is passed with percent level precision.

These tests allow many different checks of the robustness of this base ΛCDM model and of some of its extensions, including

- $\tau$ constrained two-ways thanks to CMB lensing,
- flatness at $5 \times 10^{-3}$ level,
- neutrinos masses and number,
- DM annihilation limits,
- $w(z)$,
- details of the recombination history ($A_{2s\rightarrow1}$, $T_{0}$, and also fundamental constants variation, or any energy input…).
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- **Tensions**
- Overall picture
Number counts of SZ clusters

2013 tension only remains with some mass proxy calibration
Some tensions exist

Weak Lensing from CFHTLens

Growth rate of fluctuations from redshift space distortions

i.e. some tensions with astrophysical measurements of the amplitude of matter fluctuations at low z.

NB: Ly BAO measurements at high redshift are discrepant at 2.7σ, and it is quite difficult to find physical explanation not disrupting BAO consistency elsewhere, see eg Aubourg etal. 2015
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- **Overall picture**
TT, EE, BB – mid 2015 status

Angular scale

Only keeping points w. sufficiently small error bars
and TE !
Since January 30\textsuperscript{th} 2015, the direct constraints on $r$ (Planck X Bicep2 & Keck) have reached the level of the previous best indirect constraints (from Planck alone $T$), i.e.,

$r < 0.11 @ 95\%\text{CL}$

($r = A_T/A_S$ at, e.g., $k=0.05\text{Mpc}^{-1}$)

A new era has begun…
CMB + LSS provide a consistent picture within ΛCDM. Content known with percent accuracy.

Primordial fluctuations are, to a very good approximation:
- Isotropic
- Gaussian
- Adiabatic (fluctuations in pressure α to the density)
- Coherent (fluctuations start @same time, harm. osc)
- Close to Scale invariant
- but not exactly \( n_s = 1 \) is excluded at more than 5σ

With minimal cosmological content,
- Flat spatial geometry (is a very good approximation)
- Matter is mostly dark (and cold)
- “Dark energy” consistent with Λ (w=-1)
- Small fraction of baryon, consistent with BBN

No gravitational waves (10 percent level)

Large scale power, with TT versus TE anti-correlation (5° > θ > 1°):
- apparently a-causal physics, calling for a period of accelerated expansion

I.e. all consistent within the generic inflationary framework, completing the standard model of cosmology (w. Hot Big Bang phase)

"Anomalies" are present at tantalizing levels, but at large scales.
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