Cosmology from Planck and ACT

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Planck Collaboration: The Planck mission

Fig. 7. Maximum posterior CMB intensity map at 50 resolution derived from the joint baseline analysis of Planck, WMAP, and 408 MHz observations. A small strip of the Galactic plane, 1.6% of the sky, is filled in by a constrained realization that has the same statistical properties as the rest of the sky.

Fig. 8. Maximum posterior amplitude Stokes Q (left) and U (right) maps derived from Planck observations between 30 and 353 GHz. These maps have been highpass-filtered with a cosine-apodized filter between $\ell = 20$ and 40, and the a 17% region of the Galactic plane has been replaced with a constrained Gaussian realization (Planck Collaboration IX 2015). From Planck Collaboration X (2015).

8.2.2. Number of modes

One way of assessing the constraining power contained in a particular measurement of CMB anisotropies is to determine the effective number of $a_m$ modes that have been measured. This is equivalent to estimating 2 times the square of the total $S/N$ in the power spectra, a measure that contains all the available information viewed as work in progress. Nonetheless, we find a high level of consistency in results between the TT and the full TT + TE + EE likelihoods. Furthermore, the cosmological parameters (which do not depend strongly on $\tau$) derived from the TE spectra have comparable errors to the TT-derived parameters, and they are consistent to within typically 0.5 or better.

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Temperature anisotropy

Planck Collaboration 2015
Planck Collaboration: The Planck mission

Fig. 7. Maximum posterior CMB intensity map at 5° resolution derived from the joint baseline analysis of Planck, WMAP, and 408 MHz observations. A small strip of the Galactic plane, 1.6% of the sky, is filled in by a constrained realization that has the same statistical properties as the rest of the sky.

A

Fig. 8. Maximum posterior amplitude Stokes \(Q\) (left) and \(U\) (right) maps derived from Planck observations between 30 and 353 GHz. These maps have been highpass-filtered with a cosine-apodized filter between \(\ell = 20\) and 40, and the a 17% region of the Galactic plane has been replaced with a constrained Gaussian realization (Planck Collaboration IX 2015). From Planck Collaboration X (2015).

8.2.2. Number of modes

One way of assessing the constraining power contained in a particular measurement of CMB anisotropies is to determine the effective number of \(a_m\) modes that have been measured. This is equivalent to estimating 2 times the square of the total power in the power spectra, a measure that contains all the available 16 polarization anisotropy \(l < 50\) scales removed Planck Collaboration 2015.

\(l < 50\) scales removed

Planck Collaboration 2015
Lensing potential anisotropy

\[ T(n) = \tilde{T}(n + \nabla \phi) \]

\[ \hat{\phi}^{\text{WF}} \text{ (Data)} \]

\[ \propto T(\ell) T^*(L - \ell) \]

Planck Collaboration 2015
$T(n) = \tilde{T}(n + \nabla \phi)$

The lensing potential estimate in Fig. 3.5 is the lensing potential power spectrum in our fiducial gravitational-wave model.

$\phi^{\text{WF}}$ (Data)

$\propto T(\ell)T^*(L - \ell)$
The $\Lambda$CDM model

(1) Contents and expansion

Baryon density \( \Omega_b h^2 = 0.02222 \pm 0.00023 \)

CDM density \( \Omega_c h^2 = 0.1197 \pm 0.0022 \)

Peak angle \( 100\theta \sim r_s/D_A = 1.04085 \pm 0.00047 \)

(1) Contents and expansion rate

Baryon fraction \( \Omega_b \)

CDM fraction \( \Omega_c = 0.265 \pm 0.013 \)

Cosmol constant fraction \( \Omega_\Lambda = 1 - \Omega_b - \Omega_c \)

Expansion rate \( H_0 = 67.3 \pm 1.0 \)

(2) Initial fluctuations

Amplitude at \( k=0.05/\text{Mpc} \)
\[ \ln(10^{10}A_s) = 3.089 \pm 0.036 \]

Spectral index \( n_s = 0.9655 \pm 0.0062 \)

(2) Late-time size of fluctuations

Amplitude on \( 8 \text{ Mpc/h scales} \) \( \sigma_8 = 0.829 \pm 0.014 \)

(3) Impact of reionization

Reionization optical depth \( \tau = 0.078 \pm 0.019 \)

(3) Reionization

Redshift of reonization \( z_{re} \)

Assumptions:

- Geometry/contents: Flat, \( w=-1, \Sigma m_\nu=0.06\text{eV}, \) no warm dark matter, \( N_{\text{eff}}=3.04, Y_P=0.25 \)
- Primordial fluctuations: adiabatic, power-law \( P(k) = A(k/k_0)^{n-1}, \) no tensors, no cosmic strings
- Smooth, quick reionization of universe
CMB polarization (E-mode)

Greatly limits vast zoo of alternatives to LCDM
CMB lensing

\[ \frac{[\ell(\ell+1)]^2 C_{\ell}^{\phi\phi}}{2\pi} \times 10^7 \]

\[ \ell \]

Planck Collaboration 2015
more speculatively, there has been interest recently in “multi-
tra. These limits are improved significantly by the inclusion

Fig. 26.

Fig. 25.

Curvature

0.75

0.60

0.50

0.30

0.30

0.45

0.50

0.60

0.75

\( \Omega_m \)

\( \Omega_\Lambda \)

\( \Omega_K \) ............... -0.052 \( ^{+0.049}_{-0.055} \) -0.005 \( ^{+0.016}_{-0.017} \) -0.0001 \( ^{+0.0054}_{-0.0052} \)

T

T+phi

T+phi+BAO (95%)

Planck Collaboration 2015
Primordial fluctuations

$\phi^2$

Convex

Concave

$N=50$

$N=60$

$r_0,002$

$ns$

$0.95$ $0.96$ $0.97$ $0.98$ $0.99$ $1.00$

Planck TT+lowP

Planck TT+lowP+BKP

+lensing+ext

Planck/BAO/lowP

Pl

Planck Collaboration 2015

Planck/BICEP2/Keck Collaborations 2015

$B > 0$

$r < 0.09$ (95%, Planck+Bicep2/Keck)
B-modes

Lensing of the E modes into B modes

1503, SPTPol: 2σ on large scales, allowing room for a slightly larger contribution

shifts are compensated by a change in amplitude scale CMB power. To maintain the fit to the

Planck collaboration 2015 analyses (about 0.0062)

This shift was caused by the

parameter in base
default configuration of the BICEP2 mission 217

reionization and last scattering. However,

modes, the

and it is also model dependent. In polarization, in addition to

limited by cosmic variance of the dominant scalar anisotropies,

of significance compared to the

TT+lowP. These are similar to the constraints shown in Fig. 23

Figure 30 do not significantly change the results from temperature

BAO or the

TT

plus

CDM model when adding

models coming from reionization and last scattering. However,

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Primordial fluctuations

![Graph showing Power-law and Adiabatic distributions](image)

### Table: Constraints on $f_{NL}$

<table>
<thead>
<tr>
<th>Shape and method</th>
<th>Independent</th>
<th>ISW-lensing subtracted</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMICA $(T)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Local</td>
<td>$10.2 \pm 5.7$</td>
<td>$2.5 \pm 5.7$</td>
</tr>
<tr>
<td>Equilateral</td>
<td>$-13 \pm 70$</td>
<td>$-16 \pm 70$</td>
</tr>
<tr>
<td>Orthogonal</td>
<td>$-56 \pm 33$</td>
<td>$-34 \pm 33$</td>
</tr>
</tbody>
</table>

Planck Collaboration 2015
\[ N_{\text{eff}} = 3.13 \pm 0.32 \quad \text{Planck TT+lowP; (68\%)} \]

\[ N_{\text{eff}} = 3.15 \pm 0.23 \quad \text{Planck TT+lowP+BAO} \]
Neutrino mass

Next decade: should detect 0.06 eV at few sigma
Problems/clues?

Cosmic shear

Cluster constraints

Peak smearing
Cerro Toco, Northern Chile

High and dry: 5200m, 0.49mm PWV

6m off-axis Gregorian primary 1' resolution

Currently ACTPol:
148 GHz (plus 90 GHz to come)

Atacama Cosmology Telescope

PI: Lyman Page
2013 data

2014, 2015 coverage

Fig: Steve Choi
Fig by Erminia Calabrese

ACTPol Data in Real Space

Stacking new ACTPol 'deep56' polarization map on PLANCK hot spots: From Zhiqi Huang and Dick Bond.
Advanced ACTPol Survey:
20,000 square degrees, complete overlap with LSST

PI: Suzanne Staggs
NSF-funded

Five channels: 28, 41, 90, 150, 230 GHz
Same telescope, new detectors
Estimated noise levels after foreground removal: ~ 8 uK/amin
Three year survey starting 2016
Expect to reach $\sigma(r) \sim 0.003$ (assumes simple dust models!)
Data redundancy: check for common signal in different regions and different channels
Cosmic microwave background data continue to demand LCDM cosmological model. It holds up to new lensing and polarization measurements from the Planck satellite.

- *If inflation is not correct scenario, it has to look a lot like it. Gravitational wave search on; quadratic potential disfavored.*

- *Neutrino sector holds questions that cosmology can help answer in coming decade.*