OVERVIEW OF NEW CMB RESULTS

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for the Planck Collaboration

UCLA Dark Matter 2016
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Introduction

- Planck
  - First cosmological data release 2013 ("Planck 2013 results")
  - Second cosmological data release 2015 ("Planck 2015 results")
- BICEP and Keck/BICEP
- Future
  - Spider
  - Polar Bear
  - CLASS
The Standard Model of Cosmology . . .

. . . is based on a

- Spatially flat, expanding Universe . . .
- . . . whose dynamics are governed by general relativity . . .
- . . . and dominated by cold dark matter and \( \Lambda . \)
- The seeds of structure have Gaussian statistics . . .
- . . . and form an almost scale-invariant spectrum of adiabatic fluctuations.

The Planck 2015 data remain in excellent agreement with this paradigm, and continue to tighten the constraints on deviations and reduce the uncertainties on the key cosmological parameters.
Analysis Changes for 2015

- Use of Planck polarization data instead of WMAP
- Improved calibration — “orbital” dipole rather than the “Solar”
- More data — full mission, 29 months HFI and 50 months LFI vs. 15 months
- Changes in foreground masks — use more sky
  many fewer point source “holes”
- Improvements in foreground separation
- Better control of systematic errors

Good agreement with 2013 results, with increased precision
Overview of new CMB results

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Polarization Maps

Overview of new CMB results

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Separation of ‘Foregrounds’ from the CMB

**Temperature**
- All components smoothed to 1°
- Sky fractions 81–93% of sky

**Polarization**
- All components smoothed to 40'
- Sky fractions 73–93% of sky

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**Planck 2015 results.**
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(A few % of the sky in the plane of the Milky Way is filled in with a “constrained realization”.)
High-pass filtered, cosine apodization $20 \leq \ell \leq 40$, to avoid contamination from unremoved systematic errors in polarization on the largest angular scales.
Angular Power Spectrum + Best-Fit Model

Red line is the “best-fit” model to the temperature data.

Planck 2015 results. XIII.
Polarization Spectra, Same Model

Red line is again the "best-fit" model to the temperature data.

- Spectacular agreement between inferences from temperature and polarization

\[ D^T_E [\mu K^2] \]

\[ C^{EE} [10^{-5} \mu K^2] \]

\[ \Delta D^T_E \]

\[ \Delta C^{EE} \]

\[ \ell \]

\[ 30 \quad 500 \quad 1000 \quad 1500 \quad 2000 \]

\[ 0 \quad 10 \quad 20 \quad 30 \quad 40 \]

\[ 0 \quad 4 \quad 8 \quad 12 \quad 16 \]

\[ 0 \quad 4 \quad 8 \quad 12 \quad 16 \]

\[ -10 \quad 0 \quad 10 \quad 20 \quad 30 \]

\[ -140 \quad -70 \quad 0 \quad 70 \quad 140 \]
## Cosmological Parameters I

<table>
<thead>
<tr>
<th>Parameter</th>
<th>TT, TE, EE + lowP + lensing + ext</th>
<th>$N_\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_b h^2[18.79 \text{ yr m}^{-3}]$</td>
<td>$0.02230 \pm 0.00014$</td>
<td>159</td>
</tr>
<tr>
<td>$\Omega_c h^2[18.79 \text{ yr m}^{-3}]$</td>
<td>$0.1188 \pm 0.0010$</td>
<td>119</td>
</tr>
<tr>
<td>$100\theta_{MC}$</td>
<td>$1.04093 \pm 0.00030$</td>
<td>3470</td>
</tr>
<tr>
<td>$\tau$</td>
<td>$0.066 \pm 0.012$</td>
<td>5.5</td>
</tr>
<tr>
<td>$\ln(10^{10} A_s)$</td>
<td>$3.064 \pm 0.023$</td>
<td>133</td>
</tr>
<tr>
<td>$n_s$</td>
<td>$0.9667 \pm 0.0040$</td>
<td>242</td>
</tr>
<tr>
<td>$H_0[\text{km s}^{-1} \text{Mpc}^{-1}]$</td>
<td>$67.74 \pm 0.46$</td>
<td></td>
</tr>
<tr>
<td>$\Omega_\Lambda$</td>
<td>$0.6911 \pm 0.0062$</td>
<td></td>
</tr>
<tr>
<td>$\Omega_b$</td>
<td>$0.04860 \pm 0.00051$</td>
<td></td>
</tr>
<tr>
<td>$\Omega_c$</td>
<td>$0.2589 \pm 0.0057$</td>
<td></td>
</tr>
<tr>
<td>$\Omega_m$</td>
<td>$0.3089 \pm 0.0062$</td>
<td></td>
</tr>
<tr>
<td>$z_{\text{reionization}}$</td>
<td>$8.8 \pm 1.2$</td>
<td></td>
</tr>
<tr>
<td>$z_{\text{recombination}}$</td>
<td>$1089.90 \pm 0.23$</td>
<td></td>
</tr>
<tr>
<td>Age[Gyr]</td>
<td>$13.799 \pm 0.021$</td>
<td></td>
</tr>
</tbody>
</table>

68% confidence limits
Cosmological Parameters II

- Changes from 2013
  - Amplitude of power spectrum up about 2% (orbital dipole and beams)
  - $n_s$ increased by 0.7$\sigma$
  - $\Omega_b h^2$ increased by 0.6$\sigma$
  - $\tau$ down by 0.85$\sigma$
  
  These shifts approximately cancel in the derived normalization of the matter power spectrum

- Angular size of sound horizon, $\theta_s$, and CDM density $\Omega_c$ are significantly better determined

- High $\ell$ data so precise, polarization data so constraining, that
  - See strong evidence for three species of light neutrinos
  - Can measure the effective viscosity of the neutrino “fluid” to be non-zero at 9$\sigma$

- Constraint on baryon density $\Omega_b$ comparable with best errors from BBN
  - Possible to calibrate nuclear capture cross-sections from CMB observations?

- Addition of polarization improves upper limit on annihilation rate of DM by OoM
Cosmological Parameters III

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Cosmological Parameters IV

- We’ve tried a wide range of extensions to the basic 6-parameter model
  - $\Omega_K$ (curvature)
  - $\Sigma m_\nu$ (neutrino mass) and $N_{\text{eff}}$ (effective number of “neutrino” species)
  - $Y_P$ (helium fraction)
  - $dn_s/d\ln k$ (curvature in the input fluctuation spectrum)
  - $r_{0.002}$ (tensor-to-scalar ratio at $k_0 = 0.002 \text{ Mpc}^{-1}$)
  - $w$ (dark energy equation of state, constant)
  - Huge number of variations posted on the archive.

**Find no significant evidence for a failure of the model**

- Within each extension of the parameter space, the “default” parameter values remain a good fit
  - Continues to hold when we combine Planck data with other measurements, e.g., distance scale from BAO or Type Ia supernovae; growth of structure from redshift-space distortions
Little shift in cosmology since 2013, so we continue to see tensions with some astrophysical data sets

- Abundance of clusters of galaxies
- Weak lensing of galaxies or cosmic shear
- BAO distances in the Lyα forest at high \(z\)

These tensions cannot be resolved with standard single-parameters extensions of the base ΛCDM model
Constraints from Large Angular Scales

- Anisotropy at large angular scales, especially in polarization, places tight constraints on
  - $\tau$ — optical depth to Thomson scattering
  - $r$ — tensor-to-scalar ratio

- $\tau$
  - Temperature data + low-$\ell$ polarization from 70GHz + CMB lensing
    \[ \tau = 0.066 \pm 0.016 \]
  - WMAP9 got $\tau \approx 0.089$, which we used as a prior in our 2013 analysis
    But, when we clean WMAP9 data of dust using our 353GHz channel, WMAP polarization data are in good agreement with a lower optical depth of 0.07
    - $\tau = 0.066$ implies a lower redshift of reionization $z_{re} = 8.8^{+1.7}_{-1.4}$
  - Get an independent constraint from CMB lensing
    \[ \tau = 0.071 \pm 0.016 \]
Constraints from Large Angular Scales II

- Downward shift in $\sigma_8$ implied by lower $\tau$ largely cancelled by the increase in CMB amplitude from better calibration

- $r$
  - Strongest Planck constraint still comes from temperature anisotropies at $\ell < 10^2$
    - $r < 0.10$, limited by cosmic variance, and model-dependent
  - BICEP2 detected $B$ mode polarization, but it was mostly (or all) dust
  - Combining Planck and Bicep2/Keck Array likelihoods leads to
    $$ r_{0.002} < 0.09, \; 95\% $$
  - Addition of 95 GHz Keck Array data gives
    $$ r_{0.05} < 0.09, \; 95\% $$ (using Planck and WMAP to clean foregrounds)
    $$ r_{0.05} < 0.07, \; 95\% $$ (joint analysis with Planck)

$\Rightarrow$ Disfavors inflationary models with a $\phi^2$ potential
Results consistent with the simplest scenario, $\Lambda$CDM

All constraints on DE models — minimally-coupled scalar field
modified gravity (effective field theory, phenomenological, $f(R)$, coupled)
are considerable improved wrt past analyses

DE at early times is below 2% (95% confidence) of critical density
  
  If DE present since recombination, $\Omega_e < 0.0071$ for PlanckTT+lensing+BAO+SNe+$H_0$
Lensing of the CMB

- Seen at high significance

![Graph showing lensing of the CMB](Planck Collaboration I 2015)

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

- Planck (2015)
- SPT
- Planck (2013)
- ACT
Simulation: Unlensed

• Simulated patch (10° wide) of CMB fluctuations before or after lensing.
• The effect of lensing can be understood as a remapping of the unlensed CMB: $T_{\text{lens}}(\theta) = T_{\text{unlensed}}(\theta' + \gamma)$.
• It is a small effect:
  - The rms of the deflection angle is about 2.5′ (as compared to the 5′ beam FWHM).
  - The deflection angle is coherent on degree scales which enable the measurement.
• This measurement is performed using a tailored “4-point statistic”.

Simulated patch 10° wide

- RMS of deflection angle is $\sim 2.5′$
- Coherent on degree scales
Simulation: Lensed

Simulated patch (10° wide) of CMB fluctuations before or after lensing. The effect of lensing can be understood as a remapping of the unlensed CMB:

$$T_{\text{lens}}(\theta) = T_{\text{unlensed}}(\theta + \Delta \theta)$$

This is a small effect:

- The rms of the deflection angle is about 2.5' (as compared to the 5' beam FWHM).
- The deflection angle is coherent on degree scales which enable the measurement.

This measurement is performed using a tailored "4-point statistic".

An Important but Subtle Effect

Simulated patch 10° wide

- RMS of deflection angle is $\sim 2.5'$
- Coherent on degree scales
Lensing of the CMB II

- Consistent with basic 6-parameter $\Lambda$CDM model
  - Strong consistency check on the gravitational instability paradigm and the growth of structure over more than two decades in expansion factor.
- Provides sensitivity to the growth of structure between the surface of last scattering and the present epoch
  - Breaks parameter degeneracies, allows measurement of important parameters.
Inflation

- Data consistent with a purely adiabatic, power-law spectrum of initial fluctuations
  \[ n_s = 0.9677 \pm 0.06 \]
- Isocurvature modes now constrained at the percent level
- No statistically significant evidence for departures from a power law

Marginalized joint 68% and 95% CL regions for \( n_s \) and \( r_{0.002} \) from Planck in combination with other data sets, compared to the theoretical predictions of selected inflationary models. All monomial models \( V(\phi) \propto \phi^{2p} \) with \( p \geq 1 \) are disfavored.
Primordial non-Gaussianity

- Addition of polarization information reduces the allowed model space
  
  \[ f_{\text{local}}^{NL} = 0.8 \pm 5.0 \]
  \[ f_{\text{equil}}^{NL} = 0.8 \pm 5.0 \]
  \[ f_{\text{ortho}}^{NL} = 0.8 \pm 5.0 \]

- Covers a greatly extended range of primordial 3-point and 4-point signals

Consistent with the premises of \( \Lambda \)CDM cosmology, that the structure we observe today is the consequence of the passive evolution of adiabatic, Gaussian, nearly scale-invariant, primordial seed perturbations.
Isotropy and Statistics

- Planck 2013 found statistically anisotropic signals in the CMB
  - Confirm previous studies made using WMAP data
    - Real features of the microwave sky, potentially challenging fundamental assumptions of the standard cosmological model
- Planck 2015 extends these studies to full mission temperature data, and some polarization
  - Polarization limited to angular scales $< 10^\circ$ by large-scale systematics in HFI data
- First examination of polarization data by a stacking analysis
  - Morphology of stacked peaks is consistent with the expectations of statistically isotropic simulations
Isotropy and Statistics II

- $x = \varpi \cos \phi$  \quad $y = \varpi \sin \phi$; flat-sky coordinates

- $Q_\ell (\tilde{n}; \tilde{n}_0) = -Q (\tilde{n}) \cos (2\phi) - U (\tilde{n}) \sin (2\phi)$,

- $U_\ell (\tilde{n}; \tilde{n}_0) = Q (\tilde{n}) \sin (2\phi) - U (\tilde{n}) \cos (2\phi)$. 
The ISW Effect

- 2013 results refined and extended
- Now detect ISW effect at $4\sigma$ by cross-correlating CMB temperature map with tracers of large-scale structure:
  - NRAO VLA Sky Survey (NVSS)
  - SDSS III BOSS luminous galaxy catalog
  - SDSS-DR8 galaxies
  - WISE galaxy and AGN catalogs
  - Planck lensing map
The ISW Effect II

ISW anisotropies, in kelvin

Per ~ 1° pixel uncertainty

Overview of new CMB results

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2015 cluster analysis has

- 438 objects vs. 189 in 2013
- Greater control of the selection function
- Recent gravitational lensing determinations of mass bias (normalization of scaling relation between SZ signal and mass)

  Weighing the Giants (WtG; von der Linden et al. 2014)
  Canadian Cluster Comparison Project (CCCP; Hoekstra et al., priv. comm.)
  CMB lensing (Melin & Bartlett 2014)
2015 constraints on $\sigma_8$ and $\Omega_m$ are statistically identical to 2013 when adopting the same scaling relation and mass bias.

- WtG calibration reduces tension to $\sim 1\sigma$
- CCCP between 1 and $2\sigma$
- CMB lensing $> 2\sigma$

Mass bias remains the main uncertainty in interpretation of the cluster counts.

Red contours are from a joint analysis of cluster counts and the Planck lensing power spectrum. Fully independent of those from primary CMB, but in good agreement.
The Future

- Sub-orbital experiments underway
  - Spider: one flight completed (90, 150 GHz)
  - Bicep2–Keck Array–Bicep3 (95, 150 GHz)
  - CLASS, in Chile (38 GHz), (90, 150, 220 GHz) in future
  - POLARBEAR-2 (150, 220 GHz)
  - Etc.

- Space plans...

- Foregrounds and systematics are the key
  - Frequency coverage!!
  - Raw sensitivity is necessary, but not remotely sufficient
  - Space will be necessary to measure $B$-mode polarization $\ell < 10$
Summary

- The CMB continues to be a major contributor to cosmology and the establishment of a standard model
- Planck will have a third cosmological data release in 2016, and a final refinement to follow
- Foregrounds and instrumental systematics are the keys to the future, with primordial and “reionized” $B$ mode polarization the prize
  - Many suborbital experiments and at least one space mission will be necessary
Overview of new CMB results

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