PLANCK 2015 RESULTS

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FOR THE PLANCK COLLABORATION

Astrophysics Subcommittee
NASA HQ
2015 March 18
Planck, the 3\textsuperscript{rd} Generation Space CMB Mission

- Goal: measure the temperature anisotropies of the CMB to fundamental limits down to 5', also measure polarization better than ever before
  - Two state-of-the-art cryogenic instruments
  - Nine bands, 30 GHz to 857 GHz. 30–353 GHz polarized.
Enabling US Hardware Contributions to Planck

- Detectors for the High Frequency Instrument (JPL)
- Detector technology, receiver prototypes, and MICs and MMICs for the Low Frequency Instrument (JPL, TRW, UCSB)
- 20-K hydrogen sorption coolers (JPL)
- Thermal design (JPL)
- Supercomputers (LBNL; National Energy Research Scientific Computing center)
The CMB and Foregrounds

Temperature

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

Polarization

- All components smoothed to 40’
- Sky fractions 73–93% of sky
$L_2$ Orbit

- Scanned nearly great circles at 1 rpm
- Mapped the sky approximately every six months
2013 and 2015 Data Releases

- **2013**
  - “Nominal mission” data: 15.5 months
  - Temperature only
  - 31 papers

- **2015**
  - Full mission data: 29 months HFI; 50 months LFI
  - Temperature and polarization
  - 20 (submitted) + 8 (on the way) papers
What’s Changed?

• More data
  – Lower noise
  – More importantly, more checks on consistency and systematics

• Better beams

• Better calibration
  – Better beams
  – Could use “orbital dipole”, rather than WMAP “Solar dipole”

• Polarization

  Important note: HFI polarization data on large angular scales still contain systematics that are not fully characterized. Sources known; fixes not completely and self-consistently applied.
  – $Q$ and $U$ CMB maps are high-pass filtered: $\ell > 20$, cosine apodization $20 < \ell < 40$
  – Low $\ell$ polarization results, e.g., $\tau$, are based on 70 GHz alone
The Universe: Temperature, Nine Frequencies

30–353 GHz: $\delta T [\mu K_{\text{CMB}}]$; 545 and 857 GHz: surface brightness [kJy sr]
Planck Polarization, Seven Frequencies
Two schemes

- **For CMB and foreground maps** (Used for higher-order statistics, foreground studies)
  
  - Separate diffuse foregrounds at map level
    
    Commander — parametric model fitting in pixel space
    NILC — needlet (wavelet) internal linear combination
    SEVEM — template fitting in pixel space
    SMICA — non-parametric (low rank) spectral fitting and filtering
    
    - Handle “discrete” foregrounds various ways depending on use

- **For likelihood and parameters (second-order statistics)**
  
  - Model and subtract both diffuse and discrete foregrounds at the power spectrum level
CMB and Foreground Stokes $I$ Maps

Fig. 5. Maximum posterior amplitude intensity maps derived from the joint baseline analysis of Planck, WMAP and 408 MHz observations. From left to right and top to bottom, the components are 1) CMB temperature; 2) synchrotron brightness temperature at 408 MHz; 3) free-free emission measure; 4) spinning dust brightness temperature at 30 GHz; 5) thermal dust brightness temperature at 545 GHz; 6) 94/100 GHz line emission, evaluated for the 100-ds1 detector map; and 7–9) CO line emission for $J = 1!0$, $J = 2!1$, $J = 3!2$. Panels 2–5 employ the non-linear HDR color scale, while all other employ linear color scales.

Thermal Sunyaev-Zeldovich

The last of the main astrophysical components included in this analysis is the thermal Sunyaev-Zeldovich (SZ) effect, which is caused by CMB photons scattering on hot electrons in clusters. After such scattering, the effect on the CMB is no longer a perfect blackbody, but is rather given by the expression

$$\text{SZ effect} \propto \frac{1}{\rho(\nu)}$$

with $\rho(\nu)$ the electron density. The only free parameter for this effect is the Compton parameter, $y_{\text{SZ}}$, which for our purposes acts as a simple amplitude parameter. Note that the effective SZ spectrum is negative below and positive above 217 GHz, and this distinct feature provides a unique observational signature. Still, the effect is small for all but the very brightest clusters on the sky, and the $y_{\text{SZ}}$ map is therefore particularly sensitive to both modeling and systematic errors. In this paper, we only fit for the thermal SZ effect in two separate regions around the Coma and Virgo clusters, which are by far the two strongest SZ objects on the sky, in order to prevent these from contaminating the other components. Full-sky SZ reconstruction within the present global analysis framework requires significantly better control of systematic effects than what is achieved in the current analysis, in particular at high frequencies.

Monopoles and dipoles

In addition to the above astrophysical components, the microwave sky exhibits important signal contributions in the form of monopoles and dipoles. The prime example of the former is the CMB monopole of $2.7255 \pm 0.0005$ K itself, and a second important contributor is the cosmic infrared background (CIB; see Planck Collaboration XXX 2014 and references therein). The main dipole contribution comes from the CMB dipole, which has an amplitude of 3.365.5 (3.364.0) $\mu$K as measured by LFI (HFI); the difference between the LFI and HFI measurements of 1.5 $\mu$K is within quoted uncertainties (Planck Collaboration A01 2014). Ideally, the CMB dipole contribution should be removed during the map making step (Planck Collaboration A07 2014; 10 Planck 2015 results. X).
Free-Free
Spinning Dust
All Together, Color-Coded
Fig. 16. Maximum posterior amplitude polarization maps derived from the Planck observations between 30 and 353 GHz. Left and right columns show the Stokes $Q$ and $U$ parameters, and rows show, from top to bottom, CMB, synchrotron polarization at 30 GHz and thermal dust polarization at 353 GHz. The CMB map has been highpass-filtered with a cosine-apodized filter between $\ell = 20$ and 40, and the Galactic plane has been replaced with a constrained Gaussian realization (Planck Collaboration A11 2014). The two top rows employ linear color scales, and the bottom row employs the non-linear HDR color scale.
Polarized Synchrotron Emission (30 GHz)

Planck 2015 Results Lawrence—19 Astrophysics Subcommittee, 2015 March 18
Polarized Dust Emission (353 GHz)

Planck 2015 Results Lawrence—20 Astrophysics Subcommittee, 2015 March 18
(The plane of the Milky Way is filled in with a “constrained realization”.)
A “simple” 6-parameter $\Lambda CDM$ model still fits the Planck data extremely well!

- The $TT$, $TE$, $EE$, and CMB lensing spectra are consistent with each other under the assumption of the base $\Lambda CDM$ cosmology.
The Six

1. Density of baryonic matter in the Universe $\Omega_b h^2$
2. Density of cold dark matter in the Universe $\Omega_c h^2$
3. Angle subtended by the distance sound travelled in the first 370,000 years after the Big Bang $\theta_{MC}$
4. Fraction of CMB photons scattered on their 13.8 billion year journey by electrons and protons (hydrogen) reionized by stars, quasars, etc. $\tau$
5. Amplitude of the initial fluctuation spectrum $A_s$
6. Slope of the initial fluctuation spectrum $n_s$
Angular Power Spectrum + Best-Fit Model

Planck 2015 results. XIII.
Polarization Spectra, Same Model

Planck 2015 results. XIII.

**TE**

Temperature-polarization cross-spectrum

**EE**

Polarization auto-spectrum
Response of $D^\ell_{TT}$ to 1% increases in $\omega_m$, $A_s e^{-2\tau}$, $\theta_s$, and $\omega_b$, and changes of 0.01 to $\tau$ and $n_s$. All changes are made with the other parameters held fixed. For the matter density, the dashed line shows the contribution of gravitational lensing to the power spectrum change resulting from a 1% increase in $\omega_m$. The dot-dashed line is the change that would occur in the absence of lensing. For the baryon density, the dashed line shows the contribution of diffusion damping to the power spectrum change resulting from a 1% increase in $\omega_b$. The dot-dashed line is the change that would occur in the absence of diffusion damping.
How Parameter Changes Affect the Power Spectrum — II

Response of $D^T_T$ to 1% increases in $\omega_m$, $A_s e^{-2\tau}$, $\theta_S$, and $\omega_b$, and changes of 0.01 to $\tau$ and $n_s$. All changes are made with the other parameters held fixed. For the matter density, the dashed line shows the contribution of gravitational lensing to the power spectrum change resulting from a 1% increase in $\omega_m$. The dot-dashed line is the change that would occur in the absence of lensing. For the baryon density, the dashed line shows the contribution of diffusion damping to the power spectrum change resulting from a 1% increase in $\omega_b$. The dot-dashed line is the change that would occur in the absence of diffusion damping.
Changes in $\Lambda$CDM Model Parameters, 2013 → 2015

- Typical uncertainty reduced by more than 25%.
- Photometric calibration, now on orbital dipole, increased by 0.8%.
  - Uncertainty 0.05%. Excellent agreement between WMAP, LFI, & HFI!
- $\tau$ (reionization optical depth) lower by $\sim 1\sigma$ (so $z_{\text{re}}$ decreased $\sim 1\sigma$)
  - $\tau = 0.066 \pm 0.016$; $z_{\text{re}} = 8.8^{+1.7}_{-1.4}$
  - In good agreement with those inferred from WMAP9 polarization data cleaned for polarized dust emission with 353 GHz maps.
  - But calibration increased power, so $\sigma_8$ hardly changed
- $n_s$ increased by $\sim 0.7\sigma$
- $\Omega_b h^2$ increased by $\sim 0.6\sigma$ and error decreased.
- Limits on isocurvature modes, $\Omega_K$, $m_\nu$, $\Delta N_{\text{eff}}$, $f_{\text{NL}}$, DM annihilation, etc., all tighter. No deviations detected.
# ΛCDM Model Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$TT$, $TE$, $EE$ + lowP + lensing + ext</th>
<th>$N_\sigma$</th>
</tr>
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<tbody>
<tr>
<td>$\Omega_b h^2[18.79$ yg m$^{-3}]$</td>
<td>$0.02230 \pm 0.00014$</td>
<td>159</td>
</tr>
<tr>
<td>$\Omega_c h^2[18.79$ yg m$^{-3}]$</td>
<td>$0.1188 \pm 0.0010$</td>
<td>119</td>
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<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>147</td>
</tr>
<tr>
<td>$\Omega_m$</td>
<td>$0.3089 \pm 0.0062$</td>
<td>50</td>
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<tr>
<td>$z_{\text{reionization}}$</td>
<td>$8.8 \pm 1.2$</td>
<td>7</td>
</tr>
<tr>
<td>$z_{\text{recombination}}$</td>
<td>$1089.90 \pm 0.23$</td>
<td>4740</td>
</tr>
<tr>
<td>Age[$\text{Gyr}$]</td>
<td>$13.799 \pm 0.021$</td>
<td>657</td>
</tr>
</tbody>
</table>

68% confidence limits

Planck 2015 results. XIII.
• Deflection of light by matter is well-observed in astronomy

• CMB is the most distant “source,” with a precisely known redshift
- RMS of deflection angle is $\sim 2.5$
- Coherent on degree scales
Simulation: Lensed

- RMS of deflection angle is $\sim 2.5$
- Coherent on degree scales
Lensing now measured at $40\sigma$. Better than predicted by anisotropy!
Lensing power spectrum

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

Planck 2014
Planck 2013
van Engelen et. al. 2012
Das et. al. 2013

Conservative L range, contains most of S/N.

- Constrains $\sigma_8 \Omega_M^{1/4}$ to 3.5%!
Consistency with Other Data

- Baryon Acoustic Oscillations (BAO; distance scale)
- Primordial nucleosynthesis
- Type Ia supernovae
- Direct measures of $H_0$
- Redshift-space distortions
- Rich clusters of galaxies
Distance Scale Comparison: Baryon Acoustic Oscillations

- Acoustic oscillations at \( z \sim 1100 \) and \( z < 1 \) tell the same story about the distance scale: \( \Lambda \)CDM!

\[ \frac{D_V(z)}{r_s} \] is the acoustic-scale distance ratio
\[ r_s = \text{comoving sound horizon at end of baryon drag epoch} \]
\[ D_V = \left[(1 + z)^2D_A(z)\frac{cz}{H(z)}\right]^{1/3} \]
\[ D_A = \text{angular diameter distance} \]
The width of the green stripes corresponds to 68% uncertainties in nuclear reaction rates and on the neutron lifetime. The horizontal bands show observational bounds on primordial element abundances compiled by various authors, and the red vertical band shows the Planck TT+lowP+BAO bound on $\Omega_b h^2$ (all with 68% errors). The BBN predictions and CMB results shown here assume $N_{\text{eff}} = 3.046$ and no significant lepton asymmetry.
Hydrogen $2s \rightarrow 1s$ Transition Rate

- Hydrogen $2s \rightarrow 1s$ two-photon rate crucial for recombination dynamics
- Best lab measurement has 43% uncertainty
- Planck data directly constrain its value

$A_{2s\rightarrow 1s} = 7.75 \pm 0.61 \text{s}^{-1}$

Planck $TT$, $TE$, $EE$ + $\text{lowP} + \text{BAO}$

8% uncertainty

- Planck measurement in excellent agreement with theoretical value

$A_{2s\rightarrow 1s}^{\text{theory}} = 8.2206 \text{s}^{-1}$
Type Ia Supernovae

- In 2013 compared with two SN samples
  - SNLS (Conley et al. 2011)
  - Union2.1 (Suzuki et al. 2012)

- SNLS was about $2\sigma$ from Planck in $\Omega_m$, 0.23 vs. $0.315 \pm 0.017$

- Betoule et al. (2013) worked on relative calibrations between SNLS and SDSS SN surveys ⇒ “Joint Light-curve Analysis” (JLA)
  - $\Omega_m = 0.295 \pm 0.034$
  - Relieves tension between SNLS and Planck
Direct Measures of $H_0$

- **CMB determination of $H_0$ is model-dependent**
  - Planck TT+lowP: $H_0 = 67.3 \pm 1.0$ km s$^{-1}$ Mpc$^{-1}$
    \[ \Omega_m = 0.315 \pm 0.013 \]
  - Planck TT+lowP+lensing: $H_0 = 67.8 \pm 0.9$
    \[ \Omega_m = 0.308 \pm 0.012 \]
  - WMAP9: $H_0 = 69.7 \pm 2.1$
  - WMAP9+BAO: $68.0 \pm 0.7$

- **Direct measures are higher**
  - Reiss et al. (2011): $73.8 \pm 2.4$
  - Freedman et al. (2012): $74.3 \pm 2.6$
  - Efstathiou (2014) reanalysis of Reiss et al. (2011) Cepheid data (Cepheids in SNe host galaxies compared to those in NGC 4258) using the more recent Humphreys et al. (2013) geometric maser distance to NGC 4258: $70.6 \pm 3.3$

- **Planck estimates are consistent with small errors.** If a persuasive case can be made that direct measurements of $H_0$ conflict, it will be strong evidence for physics beyond the base $\Lambda$CDM model
Clusters of Galaxies

Comparison of constraints from the CMB to those from the cluster counts in the \((\Omega_m, \sigma_8)\)-plane. The green, blue, and violet contours give the cluster constraints (two-dimensional likelihood) at 1 and 2\(\sigma\) for the WtG, CCCP, and CMB lensing mass calibrations, respectively, as listed in Table 2. These constraints are obtained from the MMF3 catalogue with the SZ+BAO+BBN data set and \(\alpha\) free. Constraints from the Planck TT,TE,EE+lowP CMB likelihood (hereafter, Planck primary CMB) are shown as the dashed contours enclosing 1 and 2\(\sigma\) confidence regions (Planck Collaboration XIII 2015), while the grey shaded region also includes BAO. The red contours give results from a joint analysis of the cluster counts, primary CMB, and the Planck lensing power spectrum (Planck Collaboration XV 2015), leaving the mass bias parameter free and \(\alpha\) constrained by the X-ray prior.

- “The situation is still murky.” Mass estimates and bias factors are the key.
Extensions To the Base $\Lambda$CDM Model

The standard $\Lambda$CDM model fits really well. Do more complicated models fit better?

- $\Omega_K$ (curvature)
- $\Sigma m_\nu$ (neutrino mass), $N_{\text{eff}}$ (effective number of “neutrino” species)
- Isocurvature modes
- $Y_P$ (helium fraction)
- $dn_s/d\ln k$ (“running” of the input fluctuation spectral index)
- Tensor modes
- $w$ (dark energy equation of state, constant)
1-Parameter Extensions

68% and 95% confidence regions

Horizontal dashed lines correspond to the parameter values assumed in the base $\Lambda$CDM cosmology. Vertical dashed lines show the mean posterior values in the base model for Planck TT, TE, EE + lowP + BAO.
Curvature

- CMB + later-time data from lensing and BAO lead to remarkable constraints on spatial curvature...

$$\Omega_k = 0.000 \pm 0.005 (95\%)$$
Tighter Constraints on Neutrino Masses

- $\sum_\nu < 0.17 \, \text{eV} \quad (95\%) \quad \text{Planck TT,TE,EE+lowP+BAO}$
- $\Omega_\nu h^2 < 0.0018$

Samples from the Planck TT+lowP posterior in the $\sum m_\nu-H_0$ plane, colour-coded by $\sigma_8$. Higher $\sum m_\nu$ damps the matter fluctuation amplitude $\sigma_8$, but also decreases $H_0$ (grey bands show the direct measurement $H_0 = (70.6 \pm 3.3) \, \text{km s}^{-1} \, \text{Mpc}^{-1}$, Eq. 30). Solid black contours show the constraint from Planck TT+lowP+lensing (which mildly prefers larger masses), and filled contours show the constraints from Planck TT+lowP+lensing+BAO.
Samples from Planck TT+lowP chains in the $N_{\text{eff}}-H_0$ plane, colour-coded by $\sigma_8$. The grey bands show the constraint $H_0 = (70.6 \pm 3.3) \, \text{km s}^{-1} \, \text{Mpc}^{-1}$ of Eq. 30. Note that higher $N_{\text{eff}}$ brings $H_0$ into better consistency with direct measurements, but increases $\sigma_8$. Solid black contours show the constraints from Planck TT,TE,EE+lowP+BAO. Models with $N_{\text{eff}} < 3.046$ (left of the solid vertical line) require photon heating after neutrino decoupling or incomplete thermalization. Dashed vertical lines correspond to specific fully-thermalized particle models, for example one additional massless boson that decoupled around the same time as the neutrinos ($\Delta N_{\text{eff}} \approx 0.57$), or before muon annihilation ($\Delta N_{\text{eff}} \approx 0.39$), or an additional sterile neutrino that decoupled around the same time as the active neutrinos ($\Delta N_{\text{eff}} \approx 1$).
\[ ... and N_{\text{eff}} + \text{Neutrino Mass} \]

Samples from Planck TT+lowP in the \( N_{\text{eff}} - m^{\text{eff}}_{\nu, \text{sterile}} \) plane, colour-coded by \( \sigma_8 \), in models with one massive sterile neutrino family, with effective mass \( m^{\text{eff}}_{\nu, \text{sterile}} \), and the three active neutrinos as in the base \( \Lambda \)CDM model. The physical mass of the sterile neutrino in the thermal scenario, \( m^{\text{thermal}}_{\text{sterile}} \), is constant along the grey dashed lines, with the indicated mass in eV; the grey region shows the region excluded by our prior \( m^{\text{thermal}}_{\text{sterile}} < 10 \text{eV} \), which excludes most of the area where the neutrinos behave nearly like dark matter. The physical mass in the Dodelson-Widrow scenario, \( m^{\text{DW}}_{\text{sterile}} \), is constant along the dotted lines (with the value indicated on the adjacent dashed lines).
Isocurvature Modes

- Strong constraint from high-$\ell$ polarization
  
  \[ \alpha = -0.0025^{+0.0035}_{-0.0047} \quad (95\%) \quad \text{Planck TT+lowP} \]
  
  \[ \alpha = 0.0003^{+0.0016}_{-0.0012} \quad (95\%) \quad \text{Planck TT,TE,EE+lowP} \]

- Perturbations we see are almost fully adiabatic ($\delta_p \sim \delta_\rho$).

![Diagram showing the constraints on $\alpha$ and $n_S$ for Planck TT+lowP and Planck TT,TE,EE+lowP]
Tensor Modes

- **Planck:** \( r_{0.002} < 0.10 \) (95\%) Planck TT+lowP
  
  \( r_{0.002} \equiv \text{tensor-to-scalar ratio at } k_0 = 0.002 \text{Mpc}^{-1} \)

- Strongest Planck constraint still from CMB temperature at \( \ell < 100 \), **limited by cosmic variance**

- **Bicep2/Keck dust-cleaned with Planck:** \( r_{0.05} < 0.12 \) (95\%)
  - Constraint from B-mode polarization

- **Joint Planck+BKP likelihood analysis:** \( r_{0.002} < 0.08 \) (95\%)

- The only way of improving these limits or detecting gravitational waves is through direct \( B \)-mode detection
$B$-mode Polarization

- Three different sources:
  - Primordial tensor fluctuations, as produced by gravitational waves
  - Remapping of the CMB $E$-mode polarisation by gravitational lensing from intervening matter
  - Foregrounds — dust and synchrotron — in the Milky Way
We see from the significant excess apparent in the bottom center panel that a substantial amount of the signal detected at 150 GHz by BICEP2 and Keck Array indeed appears to be due to dust.
Dust Polarization

- Polarization fraction up to 20%
- Large dispersion of $p$ at all $N_H$, tracing changes in $B$-field orientation and depolarization within the beam
- Sharp decrease of $p$ for $N_H > 10^{22} \text{ cm}^{-2}$. Interpreted as loss of grain alignment in the shielded interiors of clouds.

Distribution of the polarization fraction ($p$) as a function of gas column density over the whole sky used in PIP XIX. The values of $p$ were computed at 1° resolution. The gas column density is derived from the dust optical depth at 353 GHz. The colour scale shows the pixel density in log$_{10}$ scale. The curves show, from top to bottom, the evolution of the upper 1 percentile, mean, median, and lowest 1 percentile of $p$ for pixels with $N_H > 10^{21} \text{ cm}^{-2}$. Horizontal dashed lines show the location of $p = 0$ and $p_{\text{max}} = 19.8%$. 

Planck intermediate results. XIX.
Constraints on Inflation

- Planck 2013 had a huge impact on inflationary model building

- With Planck 2015
  - Constraints on non-Gaussianity are tighter, and new different types are considered explicitly
  - Constraints on isocurvature modes are tighter
  - Running of $n_s$ is zero within $1\sigma$
  - Further, there are tighter constraints on features in the primordial power spectrum

- Planck/BICEP2/Keck joint analysis gives tighter constraints on $r$
### Non-Gaussianity: $f_{NL}$

<table>
<thead>
<tr>
<th>Type</th>
<th>2013</th>
<th>2014</th>
<th>Generated by…</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local</td>
<td>$2.7\pm5.8$</td>
<td>$0.7\pm5.1$</td>
<td>Curvaton, reheating, multifield, …</td>
</tr>
<tr>
<td>Equilateral</td>
<td>$-42\pm75$</td>
<td>$-9.5\pm44$</td>
<td>Non-canonical kinetic term or higher derivative (e.g. K-inflation, DBI, ghost inflation, with $c_s&lt;&lt;1$).</td>
</tr>
<tr>
<td>Orthogonal</td>
<td>$-25\pm39$</td>
<td>$-25\pm22$</td>
<td>Non-canonical kinetic term or higher derivative ($c_s&lt;&lt;1$).</td>
</tr>
</tbody>
</table>

Planck 2015 results. XII.

The initial fluctuations were random to a high degree.
Inflation

- $V(\phi) \propto \phi^2$ and natural inflation now disfavored compared to models predicting smaller $r$ such as $R^2$
Total intensity shown by colours
Magnetic field orientation shown by striations (line integral convolution method (Cabral 1993))
Polarization orientation is $90^\circ$ from the striations.
Total intensity shown by colours
Magnetic field orientation shown by striations (line integral convolution method (Cabral 1993))
Polarization orientation is 90° from the striations.
The CMB “Prior”

- We now have precise knowledge of the universe at $z = 1090$
- We have tightly constrained
  - The physical densities of matter and baryons
  - The amplitude of the fluctuations
  - The shape of the primordial (“input”) power spectrum.
- Our knowledge of physical conditions and large-scale structure at $z = 1090$ is better than our knowledge of such quantities at $z \sim 0$!
Conclusion

- The Planck mission has been stunningly successful.

- Impressive confirmation of the standard cosmological model.
  - Precise constraints on model and parameters.
  - Tight limits on deviations from base model.
  - No evidence for cosmological non-Gaussianity
  - Powerful evidence in favor of simple inflationary models, which provide an attractive mechanism for generating the slightly tilted spectrum of (nearly) Gaussian adiabatic perturbations that match the Planck data to high precision
  - Ties together many things: Distribution of matter (lensing), clusters, neutrinos, helium and deuterium abundances, hydrogen transitions
  - Plus a lot of astrophysics from all-sky surveys at nine frequencies

- Final data release at the beginning of 2016
  - Continued analysis will improve data quality even more for the final release!
Moreover...

- Planck is a brilliant example of an international mission
  - Could not have been done as it was in either the US or Europe
  - There are overheads...
  - ...but we know how to do this...
  - ...and the results are unprecedented!

- The US Planck team pioneered an agreement between NASA and DoE on supercomputing
  - Guaranteed Planck access to NERSC supercomputers
  - NASA contributed 2.3 FTE at LBL Computational Research Division
  - Last year (2014), e.g., US Planck team used 130 million CPU hours
  - All of the biggest computational tasks in Planck were done in the US

- Hardware/data analysis cost split for US was 48.4% / 51.6%.
Citations

- The “Planck 2013 results” papers have been out for almost exactly 2 years
  - 31 papers (992 pages)
  - 7143 citations in NASA ADS database
  - Eleven papers with more than 100 citations
  - Most-cited paper has 2864 citations
    
    The most cited paper with “Hubble” in the title is from 2004, with 2831 citations

- The “Planck 2015 results” papers have been out for 5 weeks
  - 19 papers so far, 9 more on the way
  - Already 80 citations

- No paper on cosmology or related subjects can be written without referencing Planck papers

- Planck results will be in textbooks for decades.
What’s Next — The Third Release

- Improve calibration and control of systematics, especially low-ℓ polarization

**LFI**

- Gain calibration. Optimal smoothing without including real jumps.
- Beams, far sidelobes in particular.
- Bandpass mismatch, $T \rightarrow P$ leakage

**HFI**

- ADC non-linearity
- Cosmic ray removal
- $T \rightarrow P$ leakage
- Cooler electronics EMC
- Beams
  - Accurate simulation of instrument behavior possible now for the first time. Major simulation effort of end-to-end analysis has the potential to improve corrections dramatically

- Simulations from instrument to science are demanding, huge, and an essential tool

- US team working flat out on the above, racing against the clock

- Expect absolute calibration of both instruments to better than 0.05%

- Uncertainty on τ should go down by a factor of three
WMAP9, for Comparison

Angular scale

\( I(l+1)C_l/2\pi (\mu K^2) \)

Multipole moment \( l \)
Angular Power Spectrum + Best-Fit Model, 2015

Planck TT spectrum

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

\[ \Delta D_\ell \] [\( \mu K^2 \)]

Multipole \( \ell \)

preliminary