Planck Cosmological Results 2015

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On behalf of the Planck Collaboration

International Meeting on Fundamental Physics, Benasque, 18th March 2015
Cosmic evolution
The Cosmic Microwave Background (CMB)

- The CMB is a homogeneous and isotropic radiation that fills the universe
- This radiation is a relic of the hot, dense, early phase of the Universe (the hot Big Bang)
- It has travelled to us from a surface of last scattering when the Universe was 380,000 years old
- The CMB has a blackbody spectrum with $T_0=2.725K$

However, the CMB presents small anisotropies at the level of $\sim10^{-5}$, which encode a wealth of information about the content and evolution of the universe

- Primary anisotropies: generated up to the last scattering surface
- Secondary anisotropies: generated in the path of the photons from last scattering until today
Description of the anisotropies

- The CMB fluctuations are described as a random field on the sphere. It is usually written as a expansion on spherical harmonics

\[
\frac{\Delta T}{T_0}(\vec{n}) = \frac{T - T_0}{T_0}(\vec{n}) = \sum_{\ell=1}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\vec{n}) , \quad \ell \sim 180^0 / \theta
\]

\(\vec{n}\) is a unit vector on the sphere

- The \(a_{\ell m}\) are complex random variables of zero mean that, assuming isotropy of the fluctuations, satisfy

\[
\langle a_{\ell m} a_{\ell' m'}^* \rangle = C_\ell \delta_{\ell \ell'} \delta_{m m'}
\]

- The \(C_\ell\)s constitute the power spectrum, which is determined by the cosmological parameters
\[ \frac{\Delta T}{T_0}(\vec{n}) = \sum_{\ell=2}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\vec{n}) \]
CMB temperature power spectrum

[Figure from Wayne Hu]

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• Acoustic oscillations of the baryon-photon fluid when the fluctuations enter the horizon produce the characteristics CMB peaks
• The first acoustic peak corresponds to a scale that has just started to oscillate before recombination, corresponding approximately to the sound horizon at recombination
CMB power spectrum: dependence on geometry of the Universe

The same physical scale in the Last Scattering Surface corresponding to the first acoustic peak will be projected in a different angular scale in the sky depending on the geometry of the Universe. Therefore the position of the first peak and the characteristic size of the CMB anisotropies will be different.

\[ \theta_{\text{closed}} > \theta_{\text{flat}} > \theta_{\text{open}} \]

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Different cosmological parameters affect in different ways to the shape of the CMB power spectrum

By fitting the observed $C_\ell$'s to theoretical predictions, the cosmological parameters can be estimated
CMB polarization

- CMB partially polarised (polarization produced by Thomson scattering in the Last Scattering Surface)
- Measured through Stokes parameters: I, Q, U (V=0 since polarization is linear)
- From Q and U, two quantities (invariant under rotation) are constructed: E and B
- Scalar perturbations produce only E-mode of polarization
- Primordial gravitational waves (predicted by inflation) produce both E and B-mode polarization → if we detect primordial B polarization, direct proof of GWB
- Secondary anisotropies can also be imprinted in the CMB polarization on its way to us (lensing, reionization)
CMB power spectra: TT, TE, EE, BB (TB=EB=0)

Primary effects
- Sachs-Wolfe
- Acoustic Oscillations
- Reionisation

Secondary effects
- Diffusion Damping
- Gravitational Lensing
- Gravitational Wave ‘Bump’

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Secondary anisotropies: CMB lensing

- CMB photons are deflected (typically 2-3 arcminutes) on their way to us by the potentials of the large-scale structure
- It produces a smearing effect of the acoustic peaks of the TT power spectrum
- It transforms a fraction of E-mode polarization into B-mode at small scales
- It gives information about the low z universe
  - Peak sensitivity around z~2
- It allows to break some degeneracies between cosmological parameters from Planck data alone
- Provides a consistency check between the model inferred at low and high redshift
Secondary anisotropies: CMB lensing

A simulated patch of CMB sky – before lensing

typical deflection: 2.4 arcmin

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Secondary anisotropies: CMB lensing

A simulated patch of CMB sky – after lensing

typical deflection: 2.4 arcmin

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Secondary anisotropies: ISW effect

- CMB photons are blue (red) shifted when fall into (out of) gravitational potential wells.

- An evolution of the gravitational potential during the photon crossing implies a net change in the photon energy → secondary anisotropy of the CMB anisotropies.

- Very weak signal → can be detected through cross-correlation with Large Scale Structure Surveys.

- It provides an independent confirmation of Dark Energy (the effect is zero for a flat Universe without cosmological constant).

Granett et al.
According to the cosmological principle, the CMB is expected to be isotropic, i.e., to have the same properties in all directions.

CMB fluctuations are predicted to be very close to Gaussian in the simplest inflationary scenarios. Any intrinsic deviation from Gaussianity could be an indication of new physics beyond the standard cosmological model.

Detections of non-Gaussianity can also point out to the presence of secondary anisotropies, foreground contamination or systematics.
The Planck Mission

- ESA satellite launched in May 2009 to measure the CMB temperature and polarization over the full sky with high sensitivity at an angular resolution ~5 arcminutes

- Two instruments:
  - LFI: observing at 30, 44 and 70 GHz (PI. N. Mandolesi)
  - HFI: observing at 100, 143, 217, 353, 545 and 857 GHz (PI. J.L. Puget)

- Nominal Mission
  - 2 full sky surveys

- Extended mission
  - 5 sky surveys with HFI
  - 8 sky surveys with LFI

- End of operations: October 2013
Planck: third generation space mission

COBE

WMAP

Planck

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Planck publications and products

2010: Planck pre-launch papers
13 publications describing the technical capabilities of Planck’s instruments

2011: Planck Early papers
26+1 publications coming with the 1st delivered product: The Early Release Compact Source Catalogue

2012 - : Planck intermediate papers
35 publications (and rising) on galactic and extragalactic astrophysics

2013 : Planck 2013 results
31 publications on cosmology science from CMB temperature data (published on 2014). Maps, $C_l$’s and likelihoods delivered

2015 (Feb.-June): Planck 2015 results
28 publications mainly on cosmology science from CMB temperature and polarization data (full mission). Update of the delivered products, including polarization.

Early 2016: Planck 2016 results
Updated products and final results

Planck products can be found at:  http://pla.esac.esa.int/pla/

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2015 Papers

I. Overview of products and results
II. Low Frequency Instrument data processing
   III. LFI systematic uncertainties
   IV. LFI beams and window functions
   V. LFI calibration
   VI. LFI maps
VII. High Frequency Instrument data processing: Time-ordered information and beam processing
VIII. High Frequency Instrument data processing: Calibration and maps
IX. Diffuse component separation: CMB maps
X. Diffuse component separation: Foreground maps
XI. CMB power spectra, likelihood, and consistency of cosmological parameters
XII. Simulations
XIII. Cosmological parameters
XIV. Dark energy and modified gravity
XV. Gravitational lensing
XVI. Isotropy and statistics of the CMB
XVII. Primordial non-Gaussianity
XVIII. Background geometry and topology of the Universe
XIX. Constraints on primordial magnetic fields
XX. Constraints on inflation
XXI. The integrated Sachs-Wolfe effect
XXII. A map of the thermal Sunyaev-Zeldovich effect
XXIII. The thermal Sunyaev-Zeldovich effect–cosmic infrared background correlation
XXIV. Cosmology from Sunyaev-Zeldovich cluster counts
XXV. Diffuse, low-frequency Galactic foregrounds
XXVI. The Second Planck Catalogue of Compact Sources
XXVII. The Second Planck Catalogue of Sunyaev-Zeldovich Sources
XXVIII. The Planck Catalogue of Galactic Cold Clumps
The sky as seen by Planck: intensity
The sky as seen by Planck: polarization

Polarization Q and U $[\mu K_{\text{CMB}}]$
The sky as seen by Planck: polarization

70GHz

353GHz

Q

U

Polarization Q and U [μK_CMB]
Component separation

- The observed microwave sky is the sum of the CMB plus other astrophysical signals (contaminants) along the line of sight.
- The CMB and the contaminants have a different frequency dependence.
- Planck observes at 9 frequencies in order to disentangle the different components.
- The main contaminants are diffuse emission from our own Galaxy (synchrotron, free-free, thermal dust) and compact emission from extragalactic sources.
CMB contaminants: intensity
CMB contaminants: polarization

The graph shows the RMS brightness temperature (in μK) as a function of frequency (in GHz). The CMB is depicted by a cyan line, synchrotron radiation by a green line, thermal dust by a red line, and a sum of foreground contributions (fg) by a black dashed line. The graph illustrates how different components contribute at various frequencies.
Recovered components: intensity

- **CMB**
  - $A_{\text{cmb}}$
  - $-250$ to $250 \mu K$

- **Synchrotron**
  - $A_{\text{s}}$
  - $5$ K @ $408$ MHz
  - $0$ to $500$

- **Free - free**
  - $A_{\text{ff}}$
  - $0$ to $1000 \text{ cm}^{-6} \text{ pc}$

- **Spinning dust**
  - $A_{\text{sd}}$
  - $0.01$ mK$_{\text{RJ}}$ @ $30$ GHz
  - $0$ to $10$

- **Thermal dust**
  - $A_{d}$
  - $0.001$ mK @ $545$ GHz
  - $0$ to $10$

Positions of detected point sources (30,143 and 857 GHz)

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CMB recovery: intensity

Robustness of reconstruction tested with four different component separation methods. Unreliable regions are masked.
Recovered components: polarization

CMB intensity overlaid with polarization direction (5 degrees resolution)

Synchrotron polarization amplitude map \( P (P^2=Q^2+U^2) \)

Position of detected point sources (30, 44, 70 GHz)

Dust polarization amplitude map \( P (P^2=Q^2+U^2) \)

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During the last decades, the availability of high-quality data (CMB, SN, LSS, BBN...) has allowed the establishment of a concordance cosmological model

- The Universe is highly homogenous and isotropic at large scales due to an early phase of cosmic inflation
- Its spatial geometry is flat
- Most of the energetic content of the Universe is in one of following forms:
  - Baryonic matter (around 5%)
  - Weakly interactive cold dark matter (around 26%)
  - Dark energy (around 69%), which is responsible of the current accelerated expansion of the Universe

The flat $\Lambda$CDM model is defined with only 6 parameters
Cosmological parameters

Defining:
\[ \Omega_i = \rho_{i0}/\rho_{c0}, \quad \rho_{c0} = \frac{3c^2H_0^2}{8\pi G} \Rightarrow \text{critical density} \]

- \( \Omega_b \): fraction of baryonic matter
- \( \Omega_c \): fraction of dark matter
- \( \Omega_m = \Omega_c + \Omega_b \) fraction of total matter
- \( \Omega_\Lambda \): dark energy fraction
- \( \Omega_k = 1 - \Omega_m - \Omega_\Lambda \) curvature of universe
  \[ \Omega_k = \begin{cases} 
  = 0 & \text{flat} \\
  > 0 & \text{open} \\
  < 0 & \text{close}
  \end{cases} \]

- \( H_0 \): Hubble parameter (at current time)

\[ H(t) = \frac{\dot{a}(t)}{a(t)} \]
\[ h = H_0/[100\text{km/s/Mpc}] \]
Cosmological parameters

- Primordial power spectrum of density fluctuations $P(k) = A_s k^{(n_s-1)}$
  - $A_s$: amplitude of primordial power spectrum (scalar)
  - $n_s$: spectral index (scalar)

- $r = A_t / A_s$ scalar to tensor ratio
- $\tau$: optical depth at reionisation (fraction of CMB photons scattered during that process)

- For flat $\Lambda$CDM: $\Omega_k = 0$, $r = 0$
  - 6 parameters: $\{\Omega_b, \Omega_c, H_0, n_s, \tau, A_s\}$
CMB power spectrum: TT

Excellent fit to the standard flat $\Lambda$CDM model
The red line is not a fit to the data but corresponds to the best model derived from the TT power spectrum + polarization from low $\ell$ (from LFI)

- Systematics not well understood in polarization at large scales (HFI)
- Hints of systematics (at low level) in polarization $\Rightarrow$ constraints using polarization should be taken with caution
Best fit model for flat $\Lambda$CDM model

- Flat $\Lambda$CDM provides an excellent fit to Planck data
- No compelling evidence for extensions
- Percentage level precision on most parameters
- $n_s$ significantly different from 1
- Reionization: $\tau$ significantly lower than before
  - WMAP: $\tau=0.089+/-0.014$
- General good consistency between temperature, polarization and lensing results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>TT+lowP 68% limits</th>
<th>TT+lowP+lensing 68% limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_b h^2$</td>
<td>0.0222 ± 0.00023</td>
<td>0.02226 ± 0.00023</td>
</tr>
<tr>
<td>$\Omega_c h^2$</td>
<td>0.1197 ± 0.0022</td>
<td>0.1186 ± 0.0020</td>
</tr>
<tr>
<td>$100\theta_M$</td>
<td>1.04085 ± 0.00047</td>
<td>1.04103 ± 0.00046</td>
</tr>
<tr>
<td>$\tau$</td>
<td>0.078 ± 0.019</td>
<td>0.066 ± 0.016</td>
</tr>
<tr>
<td>$\ln(10^9 A_s)$</td>
<td>3.089 ± 0.036</td>
<td>3.062 ± 0.029</td>
</tr>
<tr>
<td>$n_s$</td>
<td>0.9655 ± 0.0062</td>
<td>0.9677 ± 0.0060</td>
</tr>
<tr>
<td>$H_0$</td>
<td>67.31 ± 0.96</td>
<td>67.81 ± 0.92</td>
</tr>
<tr>
<td>$\Omega_A$</td>
<td>0.685 ± 0.013</td>
<td>0.692 ± 0.012</td>
</tr>
<tr>
<td>$\Omega_m$</td>
<td>0.315 ± 0.013</td>
<td>0.308 ± 0.012</td>
</tr>
</tbody>
</table>

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Flat $\Lambda$CDM model: temperature vs polarization

Planck polarization shows good consistency with simple flat $\Lambda$CDM model
When the first stars form, they ionised the universe.

The free electrons scattered the CMB photons in their way to us, which leaves imprints in the temperature and polarization power spectra:
- The earlier the first stars form, the stronger this effect.
- Measured through the optical depth $\tau$, higher $\tau$ implies earlier reionisation.

The previous analysis from WMAP implied that reionization occurred around $\sim 420$ millions years after the Big Bang ($z_{\text{re}} \sim 10.6$).

However, astrophysical surveys did not find enough luminous objects at sufficiently early times to support this timing → there did not seem to be enough objects during that era to reionize the universe.

Current value for Planck solves this problem, pushing the epoch of reionization to around $\sim 560$ millions years ($z_{\text{re}} \sim 8.8$).
Reionization

WMAP: $\tau = 0.089 \pm 0.014$

Planck TT + low P
$\tau = 0.078 \pm 0.019$

Planck TT + lensing (independent of polarization)
$\tau = 0.079 \pm 0.024$

Planck TT + low P + lensing
$\tau = 0.066 \pm 0.016$

WMAP (Galactic contamination cleaned with 353 GHz Planck channel): $\tau = 0.075 \pm 0.013$

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The lensing potential is an integrated measure of the mass distribution back to the last scattering surface.

Generally good agreement with primary anisotropies results.

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Consistency with other data

BAO (Baryonic Acoustic Oscillations): good

Supernovae data
- Some tension between SN data and CMB in 2013 analysis
- Improved SN data: now consistent with CMB

Good agreement with Big Bang Nucleosynthesis

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Some tensions

Measurements of $H_0$

- Direct measurements find higher values of $H_0$ than CMB (or BAOs)
- Cepheid
  
  $H_0 = 73.8 \pm 2.4$ (Riess et al. 2011)
  $H_0 = 70.6 \pm 3.3$ (Efstathiou et al. 2014)

- CMB
  
  $H_0 = 67.8 \pm 0.92$ (TT+lowP +lensing)

Present-day matter fluctuations $\sigma_8$

Higher values inferred from CMB than from

- Weak lensing
- Cluster counts

- Analysis and interpretation of this astrophysical data is complicated:
  - Systematics?
  - New physics?
- More work needs to be done

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Impressive consistency with flat universe:
$\Omega_k = 0.000 \pm 0.005$ (95%, Planck TT+low P+lensing+BAO)
Extensions from $\Lambda$CDM: neutrino physics

$\sum m_\nu < 0.23 \text{ eV} \quad \Omega_\nu h^2 < 0.0025 \quad N_{\text{eff}} = 3.15 \pm 0.23$

95\%, Planck TT+low P+lensing+ext.

No evidence for new neutrino physics
More extensions from $\Lambda$CDM

- No evidence for tensor modes
  - $r < 0.11$ (95%) Planck TT + low P + lensing + ext
- No evidence of running of the spectral index of primordial fluctuations
- Isocurvature modes strongly constrained
  - Less than $\sim 3\%$ of the adiabatic modes
- Dark energy
  - Consistent with a cosmological constant ($w=p/\rho=-1$)
- No detection of topological defects
- No evidence of dark matter annihilation

None of the considered extensions can alleviate the tensions found with certain astrophysical data

The 6-parameter $\Lambda$CDM model provides an excellent match to the Planck data
The simplest models of inflation predict:

<table>
<thead>
<tr>
<th>A spatially flat Universe</th>
<th>$\Omega_K = 0.000 \pm 0.0025$</th>
</tr>
</thead>
<tbody>
<tr>
<td>with <em>nearly</em> scale-invariant (red) spectrum of density perturbations</td>
<td>$0.968 \pm 0.006$</td>
</tr>
<tr>
<td>which is almost a power-law</td>
<td>$dn_s/d\ln k = -0.0065 \pm 0.0076$</td>
</tr>
<tr>
<td>dominated by scalar perturbations</td>
<td>$r_{0.002} &lt; 0.09 \ (95%)$</td>
</tr>
<tr>
<td>which are Gaussian</td>
<td>$f_{NL} = 2.5 \pm 5.7$</td>
</tr>
<tr>
<td>and adiabatic</td>
<td>$\beta_{iso} &lt; 3% \ (95%)$</td>
</tr>
<tr>
<td>with negligible topological defects</td>
<td>$f_{10} &lt; 0.04 \ (G_\mu/c^2 &lt; 10^{-7} - 10^{-6})$</td>
</tr>
</tbody>
</table>

And a background of primordial gravitational waves... not detected yet

[Table from Martin White]
Isotropy and statistics

- Analyses based on clean CMB maps (not on power spectrum)
- In general, no deviations of the CMB from Gaussianity or isotropy found using a battery of (generic) tests:
  - Skewness, kurtosis
  - N-point distribution function
  - Minkowski functionals
  - Stacking of fluctuations
  ...
Stacking in polarization

- Polarization is a very weak signal, maps have low signal to noise ratio.
- Not possible to see pattern in individual spots.
- Use stacking: superimpose regions of the sky selected to have a hot (or cold) spot in intensity.
- The stacking in polarization probes degrees angular scales and shows good consistency with Gaussianity.
Anomalies

- However, some large scale anomalies, most of them found originally in WMAP, are present in Planck data, including:
  - Power asymmetry between hemispheres
  - Deficit of power at low multipoles
  - Dipolar modulation of the sky
  - Variance lower than expected from the best-fit model
  - A large and cold spot in the southern hemisphere

- The fact that the anomalies have been seen by two independent instruments increases confidence of these detections as real sky signals

- The origin of anomalies is uncertain
  - Foregrounds? Secondary anisotropies from our local universe? Anisotropic models of the Universe? Cosmic defects?
Power asymmetry

Figure from G. Polenta


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The Cold Spot

- Very large cold spot detected when filtering the map at large scales
- Probability of finding such a spot (obtained from simulations) is 0.3%

<table>
<thead>
<tr>
<th>Area</th>
<th>Scale [']</th>
<th>C-R</th>
<th>NILC</th>
<th>SEVEM</th>
<th>SMICA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold</td>
<td>200</td>
<td>1.6</td>
<td>1.1</td>
<td>1.2</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>250</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Hot</td>
<td>200</td>
<td>2.3</td>
<td>1.6</td>
<td>1.8</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>250</td>
<td>2.7</td>
<td>2.2</td>
<td>2.4</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>4.9</td>
<td>3.7</td>
<td>4.1</td>
<td>3.8</td>
</tr>
</tbody>
</table>

A possible explanation: signature from a cosmic texture (not confirmed yet)

Planck 2013 results. XXIII

Pixels about 3σ in map filtered with the SMHW at R=300’
A curiosity: fit to an anisotropic model of the universe

- WMAP data fitted to an anisotropic model of the universe of Bianchi type $\text{VII}_h$
- Removing the template, reduces the power asymmetry and the cold spot
- Unfortunately, not consistent with best-fit cosmological parameters ($\Omega=0.5$)
- Model also disfavoured by Planck data

Jaffe et al. 2005
ISW effect: cross-correlation with surveys and signal reconstruction

<table>
<thead>
<tr>
<th>LSS data</th>
<th>SEVEM</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \Lambda \pm \sigma_{\Lambda} )</td>
<td>S/N</td>
</tr>
<tr>
<td>NVSS</td>
<td>0.95 ± 0.36</td>
<td>2.62</td>
</tr>
<tr>
<td>WISE-AGN (( \ell_{\text{min}} \geq 9 ))</td>
<td>0.95 ± 0.60</td>
<td>1.58</td>
</tr>
<tr>
<td>WISE-GAL (( \ell_{\text{min}} \geq 9 ))</td>
<td>0.74 ± 0.53</td>
<td>1.38</td>
</tr>
<tr>
<td>SDSS-CMASS/LOWZ</td>
<td>1.37 ± 0.56</td>
<td>2.43</td>
</tr>
<tr>
<td>SDSS-MphG</td>
<td>1.61 ± 0.68</td>
<td>2.36</td>
</tr>
<tr>
<td>Kappa (( \ell_{\text{min}} \geq 8 ))</td>
<td>1.05 ± 0.33</td>
<td>3.17</td>
</tr>
<tr>
<td>NVSS and Kappa</td>
<td>1.05 ± 0.28</td>
<td>3.81</td>
</tr>
<tr>
<td>WISE</td>
<td>0.84 ± 0.45</td>
<td>1.88</td>
</tr>
<tr>
<td>SDSS</td>
<td>1.50 ± 0.55</td>
<td>2.74</td>
</tr>
<tr>
<td>NVSS and WISE and SDSS</td>
<td>0.89 ± 0.31</td>
<td>2.87</td>
</tr>
<tr>
<td>All</td>
<td>1.00 ± 0.25</td>
<td>4.00</td>
</tr>
</tbody>
</table>

Reconstruction of ISW from all surveys (correlation with true signal \( \sim 0.67 \))

Signal detected at 4\( \sigma \) as expected from \( \Lambda \text{CDM} \)
The quest for the primordial gravitational background

BICEP2 (March 2014)
It observes a region of the sky of 380 squared degrees @ 150 GHz with high-sensitivity
\[ r = 0.20^{+0.07}_{-0.05} \text{ (68\% CL)} \]

Constraint from Planck 2013 + other CMB experiments (flat \( \Lambda \)CDM)
\[ r < 0.11 \text{ (95\% CL)} \]

¿Was the B-mode really detected?
- Galactic contamination?
- Only one frequency available
- Large uncertainty in level of foreground contamination

- Model extension?
\[ r < 0.26 \text{ (95\% CL) Planck} \]

BICEP Collaboration 2014

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FIG. 3.—Left: BICEP2 apodized $E$-mode and $B$-mode maps filtered to $50 < \ell < 120$. Right: The equivalent maps for the first of the lensed-$\Lambda$CDM+noise simulations. The color scale displays the $E$-mode scalar and $B$-mode pseudoscalar patterns while the lines display the equivalent magnitude and orientation of linear polarization. Note that excess $B$-mode is detected over lensing+noise with high signal-to-noise ratio in the map ($s/n > 2$ per map mode at $\ell \approx 70$). (Also note that the $E$-mode and $B$-mode maps use different color/length scales.)

BICEP Collaboration 2014

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Dust polarization from Planck

- Using Planck multifrequency observations, it is found that the dust polarised emission follows a modified blackbody spectrum with $T_d=19.6$ and $\beta_d=1.59$
- The Planck 353 GHz channel is dominated by dust, extrapolating to BICEP2 frequency → find a contribution from dust similar to the BICEP2 signal
- However, uncertainties are large → needs joint Planck+BICEP2 analysis

Planck prediction of dust contribution at 150 GHz in a region similar to BICEP2
Joint Planck + Keck/BICEP2 analysis

Planck + BICEP2 + additional data from Keck Array (same region of the sky, same frequency)

No GWB detection!!
$r_{0.05} < 0.12$ (95%)
BICEP2 signal was significantly contributed by dust
Constraint from Planck TT+BK + other astrophysical data
$r_{0.002} < 0.09$ (95%)

Clean spectrum
# Polarization experiments

<table>
<thead>
<tr>
<th>Name</th>
<th>Platform</th>
<th>Area [deg^2]</th>
<th>FWHM</th>
<th>Freq [GHz]</th>
<th>Detectors</th>
<th>$r_{\text{lim}}$</th>
<th>Starts</th>
</tr>
</thead>
<tbody>
<tr>
<td>BICEP</td>
<td>Ground</td>
<td>800</td>
<td>~1°</td>
<td>100,150</td>
<td>PSB bolom.</td>
<td>0.1</td>
<td>2010</td>
</tr>
<tr>
<td>QUIET-II</td>
<td>Ground</td>
<td>1600</td>
<td>4'-30'</td>
<td>40, 90</td>
<td>MMIC HEMT</td>
<td>0.01</td>
<td>2010</td>
</tr>
<tr>
<td>QUIJOTE</td>
<td>Ground</td>
<td>5000</td>
<td>~1°</td>
<td>10-40</td>
<td>MMIC HEMT</td>
<td>0.05</td>
<td>2012</td>
</tr>
<tr>
<td>PolarBear</td>
<td>Ground</td>
<td>1200</td>
<td>3'-7'</td>
<td>90,150,220</td>
<td>TES bolom</td>
<td>0.01</td>
<td>2012</td>
</tr>
<tr>
<td>QUBIC</td>
<td>Ground</td>
<td>800</td>
<td>~1°</td>
<td>90,150,220</td>
<td>Bol interf</td>
<td>0.01</td>
<td>2014</td>
</tr>
<tr>
<td>ACTPol</td>
<td>Ground</td>
<td>4000</td>
<td>~1’</td>
<td>150,218,277</td>
<td>Bolometer</td>
<td>0.03?</td>
<td>2013</td>
</tr>
<tr>
<td>SPTPol</td>
<td>Ground</td>
<td>500</td>
<td>1’-1.6’</td>
<td>100,150,220</td>
<td>TES Bolom.</td>
<td>0.03</td>
<td>2013</td>
</tr>
<tr>
<td>EBEX</td>
<td>Balloon</td>
<td>350</td>
<td>8’</td>
<td>150,250,350,450</td>
<td>TES bolom</td>
<td>0.03</td>
<td>2012</td>
</tr>
<tr>
<td>SPIDER</td>
<td>Balloon</td>
<td>24000</td>
<td>17'-50'</td>
<td>90,145,280</td>
<td>TES bolom</td>
<td>0.03</td>
<td>2013</td>
</tr>
<tr>
<td>LSPE</td>
<td>Balloon</td>
<td>9500</td>
<td>30’</td>
<td>40-250GHz</td>
<td>Bolo+HEMTs</td>
<td>0.03</td>
<td>2015</td>
</tr>
<tr>
<td>Planck</td>
<td>Satellite</td>
<td>Full sky</td>
<td>5'-33'</td>
<td>30-353</td>
<td>MMIC/Bol</td>
<td>0.05</td>
<td>2009</td>
</tr>
<tr>
<td>LiteBIRD</td>
<td>Satellite</td>
<td>Full sky</td>
<td>30’</td>
<td>50-270</td>
<td>TES bol</td>
<td>0.001</td>
<td>2020</td>
</tr>
<tr>
<td>PIXIE</td>
<td>Satellite</td>
<td>Full sky</td>
<td>1.6°</td>
<td>30-6000</td>
<td>Bolometers</td>
<td>0.001</td>
<td>2018</td>
</tr>
<tr>
<td>PRISM</td>
<td>Satellite</td>
<td>Full sky</td>
<td>17'-5”</td>
<td>30-6000</td>
<td>Bolometers</td>
<td>0.0005</td>
<td>2028</td>
</tr>
<tr>
<td>EPIC/CMBPol</td>
<td>Satellite</td>
<td>Full sky</td>
<td>~10’</td>
<td>30-300</td>
<td>Bolometers</td>
<td>0.001</td>
<td>2025</td>
</tr>
</tbody>
</table>

[Compilation from J.A. Rubiño-Martín (2013)]
The QUIJOTE experiment

- **QUIJOTE Consortium**
  - Instituto de Astrofísica de Canarias
  - Instituto de Física de Cantabria (CSIC-Univ. Cantabria)
  - DICOM (Univ. Cantabria)
  - Univ. of Manchester
  - Univ. of Cambridge
  - IDOM

- **Three instruments**
  - MFI, operating at 11, 13, 17 y 19 GHz (taking data since 2012)
  - TFI, at 30 GHz (to start operations in 2015)
  - FFI, at 40 GHz (on construction)

- **Main goals**
  - To detect the primordial B-mode (if $r>0.05$)
  - To improve our knowledge of Galactic polarised foregrounds at low frequency

- **Unique frequency coverage**
- **Perfect complement for Planck low frequency channels**
The QUIJOTE experiment

Left: Example of the QUIJOTE scientific goal after the Phase I: 1 year (effective) observing time, and a sky coverage of 3,000 deg$^2$. The red line corresponds to $r = 0.1$.

Right: QUIJOTE Phase II. Here we consider 3 years of effective operations with the TGI, and that during the last 2 years, the FGI will be also operative. The red line now corresponds to $r = 0.05$. 
QUIJOTE: first scientific results

- Study of the anomalous microwave emission (AME) in the region of Perseus
- First constraints on AME polarization at 11-19 GHz frequencies

Spectrum of AME

Génova-Santos et al. 2015
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.