large scale polarization

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on behalf of the Planck Collaboration
Large scale polarization science

Planck provides full sky measurements of the polarized sky in 7 bands from 30 to 353GHz

1. **Reionization history**
   - Planck is able to measure reionization optical depth accurately (or \( z_{\text{re}} \) given a simple model)
   - but also go beyond and give constraints on ionization fraction evolution models

2. **Tensor modes**
   - Planck is able to give constraints on tensor modes in BB spectrum both
     - at the reionization bump (\( \ell = 2-30 \)) **TO BE PUBLISHED IN 2017 !**
     - at the recombination bump (\( \ell = 50-150 \))
   - sensitivity is not at the level of ground-based measurements

3. **Foregrounds**
   - essential for large scale measurements
     - at low frequency: Synchrotron
     - at high frequency: Dust

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[Planck intermediate results. XLVII (2016)]

[Planck 2015 results. XIII (2016)]

[Planck 2015 results. X. (2016)]

[Planck 2015 results. XXV. (2016)]

[Planck Intermediate results. XXX (2016)]
Status of PLANCK polarization data

• Planck detectors are sensitive to one polarization direction

• Planck scanning strategy do not allow for polarization reconstruction for each detector independently
  ➔ need to combine detectors with different polarization orientation

• Any flux mismatch between detectors will create spurious polarization signal through well known I-to-P leakage.  
  In particular: ADC non-linearity, bandpass mismatch, calibration mismatch, ...

  **this is the major systematic we have to face in polarization at large scales**

• We performed a lot of consistency checks in order to assess the impact on cosmological parameters
  - the radiometer from LFI have shown negligible residuals with respect to noise
  - the bolometer from HFI are more sensitive but show some residuals at the level of the noise
Planck-HFI low-\(\ell\) data

- **results on E2E Monte-Carlo simulations** including systematics (ADC-NL)
  - no bias on cross-spectra
  - increase error bars by a factor \(\sim 2\)

- **likelihood analysis based on cross-spectra between frequency maps** (lollipop)
  Hamimeche\&Lewis approximation modified for cross-spectra
  - propagates systematic uncertainties

![Graph showing \(\Delta C_\ell\) vs. Multipole \(\ell\)]

[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.]

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.

[Mangilli et al. (2015)]
The Epoch of Reionization (EoR) describes the period during which the cosmic gas went from neutral to ionized at the onset of the first emitting sources.

\[ \chi_e \text{ is the ionization fraction as a function of the redshift} \]

\[ \tau = \int_0^{\eta_0} a n_e \sigma_T d\eta \]

\( \eta_0 \) is the ionization optical depth is defined as
effect on CMB polarisation at low-$\ell$

reionization optical depth

$\ell(\ell+1)C_{\ell} / 2\pi$

$\ell(\ell+1)C_{\ell} / 2\pi$
From CMB data:

1. **WMAP 9yr**
   - $\tau = 0.089 \pm 0.014$

2. **Planck 2013**
   - $\tau = 0.089 \pm 0.014$ (TT with WMAP Polar)
   - $\tau = 0.075 \pm 0.013$ (TT with WP&Planck dust)

3. **Planck 2015**
   - $\tau = 0.078 \pm 0.019$ (TT + lowP)
   - $\tau = 0.066 \pm 0.016$ (TT + lowP + lensing)
   - $\tau = 0.067 \pm 0.016$ (TT + lensing + BAO)

4. **Planck HFI EE low-$\ell$**
   - decreasing trend continues...
“Planck constraints on reionization history”
[Planck intermediate results. XLVII (2016)]

\[ \tau = 0.058 \pm 0.012 \ (\pm 0.009 \text{ (stat)}) \pm 0.008 \ (\text{sys}) \]

now use Planck-HFI EE low-\( \ell \)
(lollipop)

\[ \tau = 0.053^{+0.014}_{-0.016}, \ \text{lollipop}^5; \]
\[ \tau = 0.058^{+0.012}_{-0.012}, \ \text{lollipop}+\text{PlanckTT}; \]
\[ \tau = 0.058^{+0.011}_{-0.012}, \ \text{lollipop}+\text{PlanckTT}+\text{lensing}; \]
reionization history : CMB degeneracies

[Planck intermediate results. XLVII (2016)]

\( \chi^2 \)

\( \ell (\ell + 1) C_\ell / 2\pi \)
reionization models

symmetric model  asymmetric model

[Planck intermediate results. XLVII (2016)]
• integrated optical depth for an instantaneous reionization model
• models from Bouwens et al. (2015), Robertson et al. (2015), Ishigaki et al. (2015), using high redshift galaxy UV and IR flux and/or direct measurements.
Planck constraints on reionization history

\[ \tau = 0.058 \pm 0.012 \]

“Planck constraints on reionization history”
[Planck intermediate results. XLVII (2016)]

1. the lower value for \( \tau \) published by Planck is
   - consistent with a fully reionised Universe at \( z \sim 6 \)
     (Gunn-Peterson effect showing Universe is mostly ionized up to \( z \sim 6 \) [Fan et al.])
   - in good agreement with recent constraints on reionisation in the direction of particular objects (in particular distant GRB and Ly-\( \alpha \) emitters)

2. constraints on the reionisation history with such a low optical depth disfavor large abundances of star-forming galaxies beyond \( z = 15 \)

3. maintaining a UV-luminosity density at the maximum level allowed by the luminosity density constraints at redshifts \( z < 9 \) and considering only the currently observed galaxy population at \( M_{UV} < -17 \) seems to be sufficient to comply with all the observational constraints without the need for high redshift (\( z = 10 \) to \( 15 \)) galaxies.
Impact for B-modes

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Galactic polarized foregrounds

Synchrotron

Dust

Planck Collaboration: Diagnose component separation: Foreground maps

**Fig. 38.** Planck polarization amplitude maps, $P = p_Q + p_U$. The top panel shows synchrotron emission at 30 GHz, smoothed to an angular resolution of 40, and the bottom panel shows thermal dust emission at 353 GHz, smoothed to an angular resolution of 10.

Planck Collaboration: Diagnose component separation: Foreground maps

Planck 2015 results. X. [2016]
1. **BICEP2** claimed $5\sigma$ detection of primordial B-modes with $r=0.2$

2. Planck showed that BICEP2 results are compatible with dust. Polarized dust emission cannot be neglected.

3. Joint analysis Planck-BICEP2/Keck shows no primordial signal

![Graph showing constraints obtained when adding dust realizations](image)

**[BICEP2/Keck - Planck collaborations, PRL 114, 101301 (2015)]**

- $BB(I+1)C_{\ell}/2\pi$ vs. Multipole $\ell$

- $r < 0.09$ (95% CL)
Dust angular power spectra

- 353 GHz $EE$ and $BB$ angular power spectra
- First detection of the dust polarized angular power spectra at $\ell > 10$
- Even on 30% of the sky, the dust polarized emission dominates the CMB, at all scales

1. spectra behave like power-law
2. amplitudes scales like column density
3. difference in $BB/EE$ amplitudes
4. polarized SED

[Planck Intermediate XXX A&A 586, A133 (2016)]
Planck large scales polarization

[Planck intermediate results. XLVII (2016)]

1. Reionization
   - $\tau = 0.058 \pm 0.012$
   - disfavor large abundances of star-forming galaxies beyond $z = 15$
   - no need for high redshift ($z = 10$ to $15$) galaxies.

2. B-modes
   - cosmic variance limited constraint based on large scales temperature data ($r < 0.10$ 95% CL)
   - polarization constraints based on BB to be published in 2017

3. Foregrounds
   - essential for large scale CMB cleaning
   - lots of information already available (see Planck papers)
   - work on polarized Galactic emissions (Synchrotron and dust) still continue...

PLANCK is the only experiment that can provide such large scales information for the next 10 years!
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