Large Scale Polarization from Planck

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Outline

• Planck Satellite:
  - Cosmological releases
• Improvements in the 2016 analysis
• Large scale polarization evolution:
  - WMAP results
  - First LFI results
  - First HFI results
• Impact on Cosmological Model
• Taste of 2018 forthcoming Release
Launched in 2009, operated till 2013
2 Instruments, 9 frequencies
Low Frequency Instrument (LFI):
• 22 radiometers at 30, 44, 70 GHz
High Frequency Instrument (HFI):
• 50 bolometers (32 polarized) at 100, 143, 217, 353, 545, 857 GHz
• 30-353 Ghz polarized.
Planck Cosmological Timeline

★ 2013 Release
- HFI and LFI temperature 15.5 months
- Likelihood:
  - Large scale component separation based likelihood (Commander)
  - HFI small scale temperature likelihood

★ 2015 Release
- HFI temperature and polarization 29 months
- LFI temperature and polarization 48 months
- Likelihood:
  - HFI small scale temperature and polarization
  - Large scale Planck+WMAP Commander likelihood
  - LFI large scale polarization

Intermediate results 2016
- First results from large scale HFI polarization
- Not released likelihood:
  - HFI large scale EE focussed on estimation of re-ionization optical depth

★ 2018 Release (coming soon)
- Final official Planck release
- Likelihood:
  - HFI large scale EE and BB polarization
2016 HFI Analysis
Improvements HFI 2016 Map-making

In 2015 T-to-P leakage mainly due to **ADC non-linearity (ADCNL)**

During the HFI warming phase we measure ADCNL of detectors

ADCNL non-linearity correction applied in TOI processing
Good for high-ell polarization analysis in 2015, not for large scale polarization

**2016 Analysis**

\[ g \cdot M = f(I, Q, U; \rho, \phi) + Dip + Of f + FSL + \sum_{\text{comp}} \alpha \cdot C + \sum_{\text{harm}} \gamma \cdot V + g \cdot N \]

New map-making based on **de-stripping** algorithm (**SRoll**) able to correct for systematics:
- Gain variation to correct residual ADC non-linearity
- Temperature-to-polarization leakage due to calibration mismatch on the CMB dipole
- Pick-up of Galactic emission and the orbital and solar dipoles in the **FSL**
- Temperature-to-polarization leakage due to bandpass mismatch between bolometers, from foreground emission, namely dust, free-free, and CO
- Large-scale residual transfer functions that are not corrected by deconvolution

PIR XLVI. Reduction of large-scale systematic effects
Improvements HFI 2016 Map-making

Single detector, single survey calibration

Effect of variable gain

PIR XLVI. Reduction of large-scale systematic effects
Improvements 2016 Map-making

PIR XLVI. Reduction of large-scale systematic effects
Large scale polarization
Planck low multipoles Likelihood 2013

Planck internal Commander solution in Temperature

In polarization WMAP Ka Q V bands cleaned by WMAP team

• K band and dust template as tracers
• Planck temperature Alms for TE estimation
• Analogue to WMAP 9yr polarization likelihood

\[ \tau = 0.089 \pm 0.013 \text{ WMAP} \]

We attempted to clean dust using experimental 353GHz map
\( \tau \) shifted towards lower values.
Suggesting unaccounted dust contamination in WMAP maps

\[ \tau = 0.075 \pm 0.013 \text{ WMAP + 353GHz} \]

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Planck 2013 results. XV. CMB power spectra and likelihood
Planck polarization Likelihood 2015

Based on 70GHz polarization map without survey 2 and 4

Cleaned by 30GHz and 353GHz

353 GHz corrected by global fit template to correct for T-to-P leakage residuals

\[
m = \frac{1}{1 - \alpha - \beta} \left( m_{70} - \alpha m_{30} - \beta m_{353} \right)
\]

minimizing \( \chi^2 = (1 - \alpha - \beta)^2 m^T C_{S+N} m \)

\[
C_{S+N} \simeq S(C_\ell) + N_{70}
\]

\[
N = \frac{1}{(1 - \alpha - \beta)^2} \left[ N_{70} + \delta^2 m_{30} m_{30}^T + \delta^2 m_{353} m_{353}^T \right]
\]
Planck polarization Likelihood 2015

Pixel based likelihood

\[ \mathcal{L}(C_\ell) = \mathcal{P}(m|C_\ell) = \frac{1}{2\pi|M|^{1/2}} \cdot \exp \left( -\frac{1}{2}m^T M^{-1} m \right) \]

Monte Carlo Validation

\[ \tau = 0.067 \pm 0.023 \text{ lowTEB} \]
\[ \tau = 0.067 \pm 0.013 \text{ WMAP + 353GHz} \]
Planck polarization Likelihood 2016

100GHz and 143GHz most sensitive channels
Maps both ILC cleaned by 30GHz and 353GHz
Auto-spectrum estimators not feasible:
• Poor noise description
• Residual systematics

**Solution:** Likelihood based on cross-spectrum

Quadratic Maximum likelihood estimation of 100x143
• Covariance matrices based on 1/f + white noise reshaped using simulations
• Cross-spectrum ensures un-biased estimation for mis-estimation of the covariance
Given the residual systematics we implement a EE simulation based likelihood

- Estimate empirically

\[ \ln \left( P \left( C^\text{sim}_\ell | \ell, \tau, \Omega \right) \right) \sim f_\ell \left( C^\text{sim}_\ell; \tau, \Omega \right) \]

- Compute

\[ \hat{t} = \arg \max_{\tau} \sum_{\ell_{\min}}^{\ell_{\text{max}}} f_\ell \left( C^\text{data}_\ell; \tau, \Omega \right) \]

- Use simulation to determine \( P \left( \hat{t} | \tau, \Omega \right) \) and than \( P \left( \tau | \hat{t}, \Omega \right) \)

\[ \tau = 0.055 \pm 0.009 \text{ SimLow} \]

\[ \begin{array}{cccccccccccccccccc}
\ell & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 & 13 & 14 & 15 & 16 & 17 & 18 & 19 & 20 \\
\end{array} \]
Re-ionization optical depth

- WMAP
- LFI 70 GHz
- Planck no polarization
- HFI 100x143
Effect of the low value of $\tau$:
- Pushes down the amplitude of the perturbations
- As consequence down $n_s$
- Reduce the tension with SZ number counts and CMB on $\sigma_8$

- Hubble constant down by half-$\sigma$, tension now at $3.7\sigma$ w.r.t. Riess 2018
- Reduce the space for the total neutrino mass

\[
\sum m_\nu < 0.34\text{eV} \quad \text{PlanckTTTEEE + lowP}
\]
\[
\sum m_\nu < 0.49\text{eV} \quad \text{PlanckTTTEEE + SimLow}
\]
\[
\sum m_\nu < 0.14\text{eV} \quad \text{PlanckTTTEEE + SimLow + BAO}
\]
**Small scales** likelihood substantially almost unchanged:
- Implemented new beam leakage model

**LFI Large scales** likelihood same algorithm substantial changes:
- New 30GHz map with better residuals (<4uK, <0.2uK @ 70GHz)
- New gain leakage template to remove dipole leakage from 70GHz
- Survey 2 and 4 back in the data
- New 353GHz map, no leakage template

**HFI Large scales** likelihood, still simulation based but new implementation:
- New 30GHz map (<4uK, <0.1uK @ 100GHz)
- New simulation procedure with larger variance
- EE and BB large scale likelihood
Thanks