Gravitational Lensing for Planck 2015

Antony Lewis
On behalf of the Planck Collaboration

Planck 2015 results. XV. Gravitational lensing

arXiv:1502.01591
$T(\hat{n}) \ (\pm 350 \mu K)$

$E(\hat{n}) \ (\pm 25 \mu K)$

$B(\hat{n}) \ (\pm 2.5 \mu K)$
Main Improvements over 2013

★ Error bars reduced by nearly a factor of 2x.
  • Twice as much temperature data + all-new polarization data.
★ Full set of lensing estimators (TT, TE, EE, EB, TB) + All combined (MV)
  • Crosses give 15 possible lensing power spectrum estimators.
★ SMICA component-separated maps as baseline, on 67.3% sky.
★ Numerous analysis improvements.
  • Improved likelihood ($N^{(1)}$ theory dependence, faster)
  • Many new consistency and null tests:
    • Internal consistency of polarization and temperature estimator pairs.
    • Half-mission nulls and crosses
2013 TT

(based on SMICA CMB map)  S/N–filtered,  $10 \leq L \leq 2048$
2015 TT

(based on SMICA CMB map)

S/N–filtered, $10 \leq L \leq 2048$
2015 TE

(based on SMICA CMB map)  
S/N-filtered, $10 \leq L \leq 2048$
2015 EE+EB

(based on SMICA CMB map) S/N–filtered, $10 \leq L \leq 2048$
2015 "MV"

(based on SMICA CMB map) S/N–filtered, $10 \leq L \leq 2048$
Best measured modes of MV estimator have S/N=1.
Simulated Lensing Potential $\phi$

S/N–filtered, $10 \leq L \leq 2048$
Simulated MV Estimate

S/N–filtered, $10 \leq L \leq 2048$
→ process input maps
→ estimate lensing potential from anisotropic 2-point
→ estimate lensing power spectrum.
Power Spectrum Estimation

1) Raw power spectrum of quadratic estimates.
Power Spectrum Estimation

2) Correct for noise bias estimated from sims.
Power Spectrum Estimation

2) Correct for noise bias estimated from sims.
3) Apply further data-based estimate of noise bias to reduce sensitivity to inaccuracy of sims.
Power Spectrum Estimation

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

4) Correct for "N1" bias.

(cosmetic: likelihood uses full result and calculates N1)
$\left[\frac{L(L+1)}{2\pi L}\right]^2 C_L^{\phi \phi}$ [$\times 10^7$]

5) MC correction for mode mixing / inaccuracies in normalization.
Power Spectrum Estimation

\[
\left[ \frac{L(L+1)}{2\pi} \right]^2 C^{\phi \phi}_L \times 10^7
\]

6) Correct for "PS" bias.

Done!
Lensing Power Spectrum

Power amplitude constrained to ~2.5% (40σ detection of lensing).

\[ \frac{[L(L+1)]^2 C_L^\phi}{2\pi} \times 10^7 \]
Reconstruction passes many internal consistency tests.

Highlights:
• Half-mission cross.
• Individual estimators.
• Replace one of four points in trispectrum with 353GHz.
Individual Cross-spectra

\[ [L(L+1)]^2 C_L^{\phi \phi}/2\pi \times 10^7 \]
Null Tests

Conservative likelihood uses $40 \leq L \leq 400$
LCDM Parameter Constraints from CMB Lensing Only

\[ \sigma_8 \Omega_m^{0.25} = 0.592 \pm 0.021 \]

\[ \sigma_8 h^{-1} \Omega_m^{-1/4} = 1.59 \pm 0.05 \]
LCDM Parameter Constraints from CMB Lensing Only

\[ \sigma_8 \Omega_m^{0.25} = 0.622 \pm 0.013 \]

\[ \sigma_8 h^{-1} \Omega_m^{-1/4} = 1.59 \pm 0.05 \]
LCDM Parameter Constraints from CMB Lensing Only

\[ \sigma_8 \Omega_m^{0.25} = 0.622 \pm 0.013 \]

\[ \sigma_8 \Omega_m^{0.25} = 0.607 \pm 0.008 \]
Optical Depth Constraints

... are consistent with low-L polarization
(low-L update soon)
Extended Parameter Spaces

Lensing reduces Alens pulls in CMB power spectrum likelihood.
Cross-correlation with the Infrared Background

Now detected at \( \sim 50\sigma \).

CIB provides an independent, high S/N probe of \( \phi \), useful for lensing B-mode estimates.
Lensing B-modes

Now detected at \( \sim 10\sigma \).

\[
B_{\ell_B}^{\text{lens}} = \sum_{LM} \sum_{\ell_{E,M}} \left( \ell_E - \ell_B - L \right) W_{\ell_E \ell_B L} \phi_{LM} \times B
\]
CMB cross-correlation
(lensing bispectrum)

ISW-lensing at $3\sigma$

Lensing potential estimate also combined with other tracers in dedicated ISW paper.
What’s next for Planck lensing?

- New maps may reduce map-level systematics (T->E etc)

- Better characterisation of foreground/SZ/NG contamination

- Origin of null test failures?

- More optimal weighting of polarization could improve S/N; possible improvements from more optimal estimators

- Full L-range likelihood and T-phi correlation likelihood