A distorted view of the CMB?

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Lensing of the CMB

- O(50) deflections by O(100) Mpc scale lenses
  - Peak efficiency around $z=2$
  - Predicts 2.5 arcmin r.m.s. deflections coherent over several degrees
CMB lensing power spectrum

- Deflection field $d = \nabla \varphi$ in linear theory

$$\phi(\hat{n}) = - \int_0^{\chi_*} d\chi \frac{\chi_* - \chi}{\chi_* \chi} (\Phi + \Psi)(\chi \hat{n}; \eta_0 - \chi)$$

2.5 arcmin r.m.s. deflections
Coherent over several degrees
Effects of lensing on the CMB

\[ \tilde{T}(x) = T(x + \nabla \phi) \]

\[ (\tilde{Q} \pm i\tilde{U})(x) = (Q \pm iU)(x + \nabla \phi) \]
$T(\hat{n}) \ (\pm 350 \mu K)$

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

$B(\hat{n}) \ (\pm 2.5 \mu K)$

Credit: Duncan Hanson
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Effects of lensing on the CMB

\[ \tilde{T}(x) = T(x + \nabla \phi) \]
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- Smooths out acoustic peaks in $TT$, $TE$, and $EE$ power
- Generates power at arcmin scales in $TT$, $TE$, and $EE$
- Generates $B$-modes from $E$-modes with almost white noise power
- Introduces non-Gaussianity
  - 4-point function proportional to $C_{L}^{\phi\phi}$
  - 3-point function with LSS tracers correlated with $\phi$
• Geometric degeneracy in CMB power spectra broken by different amounts of lensing in models with same $d_A(z^*)$
  - Access to curvature, sub-eV neutrino masses, dark energy etc. from CMB alone
but also hides it

- Additional cosmic variance from lensing B-modes obstacle for instrument noise better than 5 μKarcmin
Lensing peak smoothing

$C_l^{\phi\phi} \rightarrow A_L C_l^{\phi\phi}$

- Smoothing effect in $TT$ detected at $10\sigma$ with Planck
- Contains information on a single (eigen)mode of $C_{l}^{\phi\phi}$
Lens reconstruction

• Fixed lenses introduce statistically-anisotropic correlations:

\[ \Delta \langle X_{l_1 m_1} Y_{l_2 m_2} \rangle_{\text{CMB}} = \sum_{LM} (-1)^M \begin{pmatrix} l_1 & l_2 & L \\ m_1 & m_2 & -M \end{pmatrix} W_{l_1 l_2 L}^{XY} \phi_{LM} \]

• Noisy lensing estimates from quadratic CMB combinations:

\[ \hat{\phi}_{LM} = \frac{(-1)^M}{2} \frac{1}{R_{LM}^{XY}} \sum_{l_1 m_1, l_2 m_2} \begin{pmatrix} l_1 & l_2 & L \\ m_1 & m_2 & -M \end{pmatrix} [W_{l_1 l_2 L}^{XY}]^* \bar{X}_{l_1 m_1} \bar{Y}_{l_2 m_2} \]

**Normalisation**

**Known lensing-induced correlations**

**Inverse-variance-weighted CMB fields**
Reconstruction is noisy

- Chance correlations in noisy CMB introduce statistical noise in reconstruction (like shape noise in galaxy lensing)

Input

Recovered at Planck noise levels
Planck reconstruction noise levels

Almost white noise on $L(L+1)\varphi_{LM}$ on large scales
Recent lens reconstructions

Planck Collaboration 2016

Omori+ 2017: 2500 deg$^2$ SPT+Planck

Sherwin+ 2016: 500 deg$^2$ two-season ACTPol
40σ measurement of lensing power from Planck

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

- SPT-SZ 2017 (T, 2500 deg^2)
- BICEP2/KECK 2016 (EB)
- POLARBEAR 2014 (EB)
- Planck 2015 (MV)
- SPTPol 2015 (MV)
- ACTPol 2016 (MV)
Constraining curvature

\[
\Omega_K = -0.052^{+0.032}_{-0.018} \quad (68\%; \text{Planck TT+lowP})
\]
\[
\Omega_K = -0.0053^{+0.0089}_{-0.0075} \quad (68\%; \text{Planck TT+lowP+lensing})
\]
\[
\Omega_K = -0.0002 \pm 0.0026 \quad (68\%; \text{Planck TT+lowP+lensing+BAO})
\]
Growth of structure

\[ \langle \Sigma \Sigma \rangle \propto b^2(z)D^2(z) \]

\[ \langle \kappa_{\text{CMB}} \Sigma \rangle \propto b(z)D^2(z) \]
Direct BB measurements

\[ \ell C^{BB}_{\ell} / (2\pi) [\mu K^2] \]

Multipole \( \ell \):

- ACTPol
- POLARBEAR
- SPTpol
- BICEP2/Keck

Louis+ 2017
Delensing B-modes

- Improve limits on amplitude of GWs
  - Soon be critical
  - Limits $\sigma(r) = 10^{-3}$ from $l > 30$ over $10^4 \text{ deg}^2$

Residual lensing power:

$$B_{\text{delens}} \sim B - E \hat{\phi}$$

$$C_l^{\phi \phi, \text{delens}} = C_l^{\phi \phi} (1 - \rho_l^2)$$
Implications for inflation constraints

**CORE**

2.1 μK arcmin

**Lensing relatively more important for recombination signal for non-zero r**

Factor 6.5 hit by lensing for both scales (no signal c.v.)

Lensing limits ability to test these models at high significance

No lensing

AC+CORE Collaboration 2017
Which scales matter for BB?

\[
\frac{C_{l}^{BB,\text{delens}}}{C_{l}^{BB,\text{lens}}} \approx \sum_{L} \frac{\partial \ln C_{l}^{BB,\text{lens}}}{\partial \ln C_{L}^{\phi \phi}} (1 - \rho_{L}^{2})
\]
Internal delensing currently inefficient

Scales for lensing B-modes

Reconstruction very noisy

Carron, Lewis & AC 2017
Delensing with CIB

Planck 545 GHz

\[ M_{545} - M_{857/77} \]

Residual dust

Instrument and shot noise

Expect only 30% efficiency

Relevant scales for TT delensing

BB delensing

Mak, AC+ 2016; see also Planck XLVII 2016

Larsen, AC, Sherwin & Mak 2016
Undoing peak smoothing: \( TT \)

Larsen, AC, Sherwin & Mak 2016

- See Carron, Lewis & AC 2017 for internal recon. and pol.
Proof-of-concept B-mode delensing

- 7σ detection of change in $BB$ from delensing SPT with CIB
- Planck too noisy to detect $BB$ directly at high significance but 10% change from internal delensing detected at 4σ
• **EB** particularly helpful for pol. noise < 5 \( \mu K \) arcmin
  - *Polarization reconstructions less susceptible to extragalactic contamination* (e.g., tSZ)
Prospects for internal delensing

Factor by which delensing improves $\sigma(r)$ for $r=0$

Factor 1.6–2 improvement by internal delensing with future satellites; better from ground

AC+CORE Collaboration 2017
• Large-area reconstructions with S/N>1 to $L \sim 1000$
  - Excellent prospects for cross-correlation science with Euclid/DESI/LSST etc. (few $\times 10^5$ resolved CMB lensing modes)
  - Summed neutrino mass to 15 meV with future BAO (contingent on $\tau$)