CMB lensing and delensing

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Lensing of the CMB

• $O(50)$ deflections by 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
Lensing adds information

- 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
\[ T(\hat{n}) \ (\pm 350 \mu K) \]
\[ E(\hat{n}) \ (\pm 25 \mu K) \]
\[ B(\hat{n}) \ (\pm 2.5 \mu K) \]
Lens reconstruction

\[
\Delta \langle X_{l_1m_1} Y_{l_2m_2} \rangle_{\text{CMB}} = \sum_{LM} (-1)^M \begin{pmatrix} l_1 & l_2 & L \\ m_1 & m_2 & -M \end{pmatrix} W_{l_1l_2L}^{XY} \phi_{LM}
\]
Representative T and P noise levels

$T$ vs $l$ for
- COrE+ (M4) with 2.1 $\mu$Karcmin noise
- LiteCOrE-I20 with 3 $\mu$Karcmin noise

$E$ vs $l$ for
- B (lensing)
- Pol. noise
Lens reconstruction noise levels

- $EB$ particularly helpful for pol. noise $< 5 \, \mu K \text{ arcmin}$
Applications of CMB lensing

- Cosmology from auto-power spectrum
  - *Neutrino masses, curvature, (early) dark energy etc.*
- Cross-correlation with other LSS tracers
  - *Degeneracy breaking, self-calibration, high-z astrophysics*
- Delensing
  - *Improve GW constraints (r and n_t)*
  - *Delens high-l EE (sharpen peaks for N_{eff} etc.)*
- Measure cluster masses of full internal cluster sample
  (see clusters talks)
Neutrino physics

\[ \sigma(\sum m_\nu) = 40 \text{ meV} \quad \text{COre}+ \]
\[ \sigma(\sum m_\nu) = 15 \text{ meV} \quad +\text{DESI/Euclid BAO} \]

Similar constraints for LiteCOre-120

\[ \sigma(m_{\nu, \text{sterile}}) = 20 \text{ meV} \]
\[ \sigma(\sum N_{\text{eff}}) = 0.04 \]

Sufficient to rule out any post-QCD thermal relic
Role of reionization optical depth

Allison+ 2015
• Probes redshifts intermediate to CMB lensing and galaxy autos
• X-correlation more immune to additive systematic effects
• Full joint analysis can calibrate multiplicative bias effects in shape measurement and intrinsic alignments
Evidence for lensing systematics?

CFHTLenS `conservative' cut
(Heymans+ 13)+ω_b+η_s priors

Multiplicative bias in measured shear
\[ \gamma_{\text{measured}} = m \gamma_{\text{true}} \]

Other causes?
- photo-z errors
- Intrinsic alignments
Delensing degree-scale B-modes

- Improve limits on amplitude of GWs
- Access primordial B-modes on smaller scales
  - Tensor tilt
  - Oscillations?

Some proxy for lensing potential

\[ B_{\text{delens}} \sim B - E\phi \]
What scales are important?

• Intermediate-scale lenses important for large-scale BB
Impact of delensing

High S/N reconstruction on these scales

Integral under curve gives residual lensing power as fraction of original

LiteCOre-120: 1/2.1
COre+ (M4): 1/2.5
Requirements for delensing BB

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

$\alpha \equiv \frac{\sigma(r)_{\text{no delens}}}{\sigma(r)_{\text{delens}}}$

Factor 1.6-2 improvement by internal delensing

$\alpha = 2 \mu K$-arcmin

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$\alpha = 3 \mu K$-arcmin

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Implications for inflation constraints

Factor 2.0 improvement by delensing for both scales (no signal c.v.)

Delensing relatively more important for recombination signal for non-zero $r$

Significant detection at both scales for e.g., Starobinsky inflation
Implications for inflation constraints

COrE+ (M4)

LiteCOrE−120

$3\sigma(r)$ [$\times 10^3$]

$l<30$  $l>30$  $l<30$  $l>30$  $l<30$  $l>30$

$r=0$  $r=2\times 10^{-3}$  $r=0.01$
Towards delensing: indirect BB

• “Correction” in $B_{\text{delens}} \sim B - E\phi$ correlated with $B$ at expected level

$$C^{BB}_\ell \sim B(E\hat{\phi})$$

See also Hanson+2013, Ade+2014, and van Engelen+2014
Iterative delensing?

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

Iterative delensing beneficial at low noise

Feeney & Errard
CIB-CMB lensing

- CIB well-matched in $z$ and halo mass with CMB lensing
  - 80% correlated

Planck Collaboration 2014

- High-$z$ clustering and emissivity of star-forming galaxies
- Scale-dependent bias and $f_{\text{NL}}^\text{loc}$

545 GHz

$\ell, C_{\ell}(\nu)$

$C_{\ell}^T (\nu)$ [uK sr$^{-1}$]

$\ell$ range from 100 to 2000 for different frequencies.
First demonstration of CIB delensing

- CIB from $857-\alpha545$ Planck channels
  - Reduces correlation with CIB below 80%

Larsen, AC+ in prep.
On what scales does CIB help?

- Reconstruction+CIB delensing improves \( \sigma(r) \) by factor 2 for \( r=0 \) for LiteCOreE-120, cf. 1.6 with only reconstruction.

CIB helps where S/N on reconstruction falls, but limited to \( l = \rho^2 = 0.4 \).

No gain from adding CIB where S/N on recon. high.
Summary

- CMB lensing important part of science case at intermediate (space) and high-resolution (e.g., S3 and S4)
- CMB lensing power spectrum enhances cosmology
  - E.g., at least 4σ detection of neutrino mass (with DESI/Euclid BAO)
- $O(2 \times 10^5)$ well-understood lensing modes for cross-correlation and other legacy science
- Can improve $\sigma(r)$ by factor 1.6-2.3 with internal delensing (for low r) at few arcmin resolution
  - Modest further improvements in combination with CIB
- Cluster masses of full SZ-selected samples