CMB Lensing Measurements, Present and Future

Blake D. Sherwin
(UC Berkeley, Department of Physics / Miller Institute for Basic Research in Science)

with Chang Feng, Alex van Engelen, David Spergel et al.
ACTPol and POLARBEAR collaborations
Introduction to CMB Lensing

- Cosmic Microwave Background (CMB) photons are gravitationally lensed by the large scale mass distribution
- Many small deflections remap the observed CMB
Unlensed CMB

CMB Temp.

10°
Observable: Lensing Deflection $d(\hat{n})$

remaps the CMB: $T(\hat{n})_{\text{lensed}} = T(\hat{n} + d(\hat{n}))_{\text{unlensed}}$

$$|d(\hat{n})|_{\text{filt}}$$

small $\sim 3$ arcminute deflections, coherent on degree scales

In this talk, I will plot the magnitude of the deflection $|d(\hat{n})|_{\text{filt}}$

(actually, the gradient high-pass-filtered magnitude a.k.a. lensing convergence)
Lensing Deflection Field Measures Mass

• Amount of lensing deflection depends on the projected (dark) matter density in that direction, from redshift 0.5-3

\[ |d(\hat{n})|_{\text{filt}} = \int dz W(z) \delta(\hat{n}, \hat{z}) \]

\[ \delta: \text{fractional matter overdensity } \delta = (\rho - \bar{\rho})/\bar{\rho} \]

\[ W(z): \text{geometric projection kernel} \]

• Measurement of projected matter distribution will help address some of the most important questions in cosmology

<table>
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<th>NAS Decadal Survey: Key Questions</th>
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<td>Cosmology and Fundamental Physics</td>
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<td>CFP 1 How did the universe begin?</td>
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<td>CFP 2 Why is the universe accelerating?</td>
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<td>CFP 3 What is dark matter?</td>
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<td>CFP 4 What are the properties of neutrinos?</td>
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will explain in this talk
Talk Outline

• Progress in CMB temperature lensing measurements and constraints on parameters, e.g. neutrino mass
• CMB polarization lensing: why it is important, e.g. for delensing, and early measurements
• CMB polarization lensing: cosmological constraints from upcoming experiments
Lensing Reconstruction (How to Measure Lensing)

- **Lensing changes CMB statistics**, correlates formerly independent modes:
  \[
  \langle T(l)T^*(1-L) \rangle_{\text{CMB}} \propto d(L)
  \]
  \[
  \langle E(l)B^*(1-L) \rangle_{\text{CMB}} \propto d(L)
  \]

- Use this statistics-change: estimate CMB lensing deflection by measuring lensing-induced mode-correlations:

  \[
  d(L) = \int \frac{d^2l}{(2\pi)^2} \frac{g_{TT}(l, L)T(l)T^*(1-L)}{l^2} [\text{Hu, Okamoto 2002}]
  \]

  CMB temperature / polarization maps
  CMB lensing Map
  \(C_{\ell}^{dd}\)  \(C_{\ell}^{dq}\)
  lensing power spectrum  lensing cross-correlations
• Consistent with LCDM prediction - direct gravitational probe of mass/dark matter at high redshifts (z~0.3-3)
• Early cosmological constraints on dark energy density
• With Planck lensing at >25 sigma, has become precise probe!

[CMB Lensing Power Spectrum: First Detection in Temperature with ACT

\[ l^2 \frac{C_{\ell\ell}}{4} \]

\[ A_L = 1.06 \pm 0.23 \]

[Das, Sherwin et al. 2011]
[Sherwin, Das et al. 2011]

4 sigma (2011)
(4.6 sigma, update)
Rapid Progress and New Applications: Constraints on Neutrino Masses

- Can measure sum of neutrino masses with lensing
- Massive neutrinos suppress growth of structure on small scales relative to large scales (by up to $5\%/0.1\text{eV}$)
- Lensing power spectrum reflects suppression of growth

Constraint with Planck CMB lensing: $\sum m_\nu < 0.85 \text{eV}, \quad (95\%; \text{Planck+WP+highL})$, 

[Planck Collaboration 2013]
Polarization Lensing Measurements: Motivation and Early Results from POLARBEAR and ACTPol
Differences Between Temp. and Pol. Lensing

- Lensing remaps polarization, converts E to B
- Because we know all B on small scales is from lensing, and B cosmic variance doesn’t contribute, polarization estimators are much more powerful below ~8uK noise

\[ d(L) = \int \frac{d^21}{(2\pi)^2} g_{EB}(l, L) E^*(l) B(1 - L) \]

reconstruction with polarization lensing pipeline:
high resolution / correlation

estimate of lensing deflection with Polarization
Differences Between Temp. and Pol. Lensing

- Lensing remaps polarization, converts E to B
- Because we know all B on small scales is from lensing, and B cosmic variance doesn’t contribute, polarization estimators are much more powerful below ~8uK’ noise

\[ d(\mathbf{L}) = \int \frac{d^2}{(2\pi)^2} g^{TT}(l, \mathbf{L}) T(l) T^*(1 - \mathbf{L}) \]
Application of Polarization Lensing: Delensing The CMB

- Primordial B-mode polarization is a key observable for understanding the early universe.
- Lensing B-mode will be limiting noise (either will limit $n_T$ or will limit constraint on $r$).
- Idea: if know lensing, $d$, subtract off lensing B mode $\sim E d$ i.e., delens

[POLARBEAR Collaboration 2014 incl. BDS, BICEP2 Collaboration 2014]
Delensing with CMB Polarization

- The B-mode power removed depends on the correlation of “delensing field” with true lensing, $\sim r^2$ (at $l=10-1000$)

- Polarization lensing is best due to highest correlation, though some large scale structure fields also work well (e.g., CIB)

- Ongoing work on improving methods, combining CMB + LSS delensing fields, demonstrating with data
Polarization Lensing Reconstruction: Pipelines

- Polarization lensing pipeline (near-optimal) developed for two high-resolution CMB telescopes:
  
  - POLARBEAR, so far, measured polarization to great depth, \( \sim 5\mu K' \) over \( \sim 30 \text{ sq. deg} \)

  [Pearson, Sherwin, Lewis 2014]

- ACTPol, so far, measured \( \sim 200 \text{ sq. deg.} \) of polarization at \( \sim 12\mu K' \)

ACTPol telescope

POLARBEAR telescope
Lensing Power Spectrum: Detection in Polarization with POLARBEAR

- 4.2 sigma result, first CMB-only detection of pol. Lensing – and lensing B-modes
- Novel measurement: proof of concept
- Blind analysis; passes a number of null tests and systematic checks; signal seen in two channels on three maps

[POLARBEAR Collaboration 2013, incl. BDS]
Lensing Cross-correlations: POLARBEAR Lensing x Infrared Background (CIB)

- 4 sigma detection: early measurement of polarization lensing / B-modes (with Hanson et al. 2013)
- Robust: systematics don’t correlate!
- Blind analysis; passes numerous null-tests and systematic checks

[polarization lensing × CIB]

\[ l^3 C_{\ell} \nu_\perp = \frac{1}{2} \frac{\nu}{S_r} \]

[POLARBEAR Collaboration 2013, incl. BDS (corr. auth.)]
Polarization Lensing Measurements with ACTPol

- 5 sigma polarization-only lensing with ACTPol, with only first 3 months of data
- Soon: higher (~10+ sigma) S/N cross and auto power spectra
- (See also: high S/N EE power spectrum)
Upcoming Cosmological Constraints from CMB Polarization Lensing Experiments
Upcoming Polarization Lensing Science with ACTPol-wide / PB-II...

ACTPol, POLARBEAR-II, SPTPol and similar experiments will soon measure the lensing signal at ~50+ sigma and hence

• Measure neutrino masses, with e.g., ACTPol + Planck, to <0.1eV.

• Via cross-correlations: calibrate astrophysical and systematic biases in galaxy and weak lensing surveys; constrain neutrino masses + DE

[e.g. Hand, Das, Leautheaud, Sherwin et al. 2013]
AdvancedACT, Simons Array, SPT 3G, CMB S4…

- Progress expected to continue with upcoming experiments
- AdvancedACT/ S.A./ SPT3G – 2015 onwards can measure lensing at >>100 sigma, neutrino mass to within ~0.02eV
- Exciting prospects, but lots of work to do!

![Graph](chart.png)
Summary

• Rapid progress in CMB temperature lensing measurements (e.g. ACT to Planck) has made lensing a powerful probe of fundamental physics, e.g. neutrino mass

• Recently: first measurements of polarization lensing (with SPTPol, POLARBEAR, ACTPol) – this technique allows for much higher accuracy. Allows delensing to study primordial B!

• Work has begun on higher precision CMB (polarization) lensing surveys, which will become one of our most powerful tools for cosmology
Bonus slides...
Fig. 1.— ACTPol maps and overlapping surveys. The maps have been filtered to emphasize $\ell > 300$. The power spectra are obtained with only the high S/N region of each map. Going from left to right across the equator, the red circles indicate patches D1, D6, D5, D4, D3, D2 (the first ACTPol season focused on D1, D2, D5, and D6). More than half the sky, as indicated by the light colored area, is accessible to ACTPol. Overlapping surveys include SDSS (SDSS 2014), BOSS (BOSS 2014), CFHTLS (CFHTLS 2014; Hand et al. 2013), XMM-XXL (XMM-XXL 2014), Herschel (HerMES & HeLMS, Oliver et al. (2012); Viero et al. (2014)), HSC (Subaru 2014), DES (DES 2014), GAMA (Driver et al. 2009), and KiDS (de Jong et al. 2013).
Observations in 2012 & 2013

Intensity (FDS Dust Map)

RA=0
Dec=90
Total area: \( \sim 30 \text{ deg}^2 \)

Observing every 36 hrs fridge cycle

RA23
RA12
RA4.5

\( \sim 3,300 \text{ hrs} \)

Select low dust regions
FIG. 2: Curl null power spectra for each of the three patches for the \(<EEBE>\) and \(<EBEB>\) estimators. The patch-combined curl null power spectra are shown in red for the two lensing estimators. All the curl null power spectra are consistent with zero.
FIG. 3: Polarization lensing power spectra for each lensing estimator. Measured polarization lensing power spectra for each of POLARBEAR’s three patches, for both lensing estimators $\langle EEEB \rangle$ (left) and $\langle EEBB \rangle$ (right). The lensing signal predicted by the $\Lambda$CDM model is shown as the solid black curve. The measured lensing power spectra are shown for each patch in dark green (RA23), blue (RA12) and magenta (RA4.5), respectively and are offset in $L$ slightly for clarity. The patch-combined lensing power spectrum is shown in red.

FIG. 4: Polarization lensing power spectra. Polarization lensing power spectra co-added from the three patches and two estimators are shown in red. The lensing signal predicted by the $\Lambda$CDM model is shown as the solid black curve. The polarization lensing power spectrum $\langle EEEB \rangle$ is in blue and $\langle EEBB \rangle$ dark green. Left: A 4.2$\sigma$ rejection of the null hypothesis of no lensing. These data indicate a lensing amplitude $A = 1.37 \pm 0.30 \pm 0.13$ normalized to the fiducial $\Lambda$CDM value. Right: The same data, assuming the existence of gravitational lensing to calculate error bars— including sample variance and including the covariance between $\langle EEEB \rangle$ and $\langle EEBB \rangle$. In this case, the lensing amplitude is measured as $A = 1.06 \pm 0.47^{+0.32}_{-0.27}$, corresponding to 53% uncertainty on the amplitude of the $C_L^{\ell d}$ power spectrum (26% uncertainty on the amplitude of matter fluctuations). The histograms of the amplitudes $A$ from 500 unlensed and lensed simulations are shown in the inset boxes.
FIG. 2: **Upper panel**: Curl null tests for all four combinations of estimator / map – $EB/RA23$ (dark blue), $EE/RA23$ (green), $EE/RA12$ (red), $EB/RA12$ (cyan). In this figure, curl null test values and errors have been scaled down by a factor of two for the $EE$ estimator, for ease of plotting ($PTE$s are unaffected). **Lower panel**: Swap-field null tests. Note that the four sets of points are not entirely statistically independent. The null tests are consistent with zero and thus provide no evidence for any systematic errors.
FIG. 1: Cross-power spectra of CMB polarization lensing and the 500μm _Herschel_ CIB flux. **Top panel:** the minimum variance combination of all polarization lensing measurements cross-correlated with the _Herschel_ maps; this result corresponds to 4.0σ evidence for gravitational lensing of CMB polarization. **Middle panel:** the cross power of _EB_-reconstructed lensing with the _Herschel_ maps, constructed from the _EB_ estimator applied to both POLARBEAR maps; this result corresponds to 2.3σ evidence for lensing Ω-modes. **Bottom panel:** all four combinations of the two lensing estimators (EE, EB) applied to two different POLARBEAR maps (RA23, RA12) and cross-correlated with _Herschel_ - _EB_/RA23 (dark blue), EE/RA23 (green), EE/RA12 (red), _EB_/RA12 (cyan), listing from left to right for each band-power. The fiducial theory curve for the lensing – CIB cross-spectrum [10] is also shown (solid line).