CMB Lensing: Present and Future

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Outline

• Introduction to CMB lensing and lensing reconstruction

• CMB lensing power spectra: probing neutrino mass and structure growth

• CMB lensing B-modes as noise for inflationary cosmology
Gravitational Lensing of the CMB

- CMB: most distant radiation source. Affected by travel:
- Distribution of mass deflects / lenses CMB passing through
Unlensed CMB

\[ T(\hat{n})_{\text{lensed}} = T(\hat{n})_{\text{unlensed}} + d(\hat{n}) \]

\[ T(\hat{n})_{\text{unlensed}} \]
$T(\hat{n})_{\text{lensed}} = T(\hat{n} + d(\hat{n}))_{\text{unlensed}}$
Observable: Lensing Deflection $d(\hat{n})$

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

I will usually plot the gradient filtered magnitude of the deflection $|d(\hat{n})|_{\text{filt}}$ – i.e. the lensing convergence (N.B. lensing estimates both shear and convergence).
Probes Mass Projected Back to the CMB

- Amount of lensing deflection depends on the projected (dark) matter density in that direction – mainly at z~0.5-3

\[ \nabla \cdot d(\hat{n}) = \int_0^{r_{\text{CMB}}} dr W(r) \delta(\hat{n}, r) \]

\[ |d(\hat{n})|_{\text{filt}} \]
Probes Mass Projected Back to the CMB

- Amount of lensing deflection depends on the projected (dark) matter density in that direction – mainly at $z \sim 0.5-3$

\[
\nabla \cdot d(\hat{n}) = \int_0^{r_{\text{CMB}}} dr W(r) \delta(\hat{n}, r)
\]

- How to measure: look for new lensing-induced correlations in $T$: \[
\hat{d}(L) \sim \int d^2l \ T(l)T^*(1 - L)
\]
CMB Lensing Measurement: An Approximate Picture

[CMB Temp.]

d: lensing deflection field

local 2D power spectrum

[Bucher++ 2012]
CMB Lensing Measurement: An Approximate Picture

CMB Temp.

\[ d: \text{lensing deflection field} \]

\[ \text{Infer lensing from “stretching” of the local CMB power spectrum (+ shearing)} \]

\[ \text{N.B. polarization much better!} \]

\[ \text{local 2D power spectrum} \]

[Bucher++ 2012]
First CMB-only Lensing Map and Lensing Power Spectrum

ACT CMB Lensing Dark Matter Map

- Describe statistically with lensing power spectrum $C_{l}^{dd}$
- Probes any physics that affects structure growth

Y axis: “How much lensing ….”

X axis: “for a lens of this angular scale?”
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Neutrino masses (unknown!) suppress small structure and lensing $d$, and its power spectrum $C_{l}^{dd}$ – measure!

- Also: early dark energy, geometric degeneracy breaking

[Sherwin++ 2011, van Engelen++ 2012, Planck 2013]
Lensing Power Spectrum Measurements: Temperature

2011 (+2013), ACT, S/N~4

- ACT: first measurement of CMB lensing power spectrum. Challenging to extract signal under noise and foregrounds.

[Das, Sherwin++ 2011 Sherwin, Dunkley, Das++2011]
Lensing Power Spectrum Measurements: Polarization

2014, POLARBEAR, S/N~4

- First detection of important polarization lensing technique

[POLARBEAR, incl.BDS 2014a,b]
Progress in CMB Lensing Power Spectrum Measurements 2011-now

2015, Planck, S/N~40

$L^4 C_{LL}^{dd}/A$

Temperature (+Pol.)

[Planck collaboration 2015]
Timeline of CMB Experiments

Figure 6. Plot illustrating the evolution of the raw sensitivity of CMB experiments, which scales as the total number of bolometers. Ground-based CMB experiments are classified into Stages with Stage II experiments having $O(1000)$ detectors, Stage III experiments having $O(10,000)$ detectors, and a Stage IV experiment (such as CMB-S4) having $O(100,000)$ detectors.
Current Work: Preliminary ACTPol Lensing Results

- A preliminary lensing map, reconstructed from temperature+polarization:

  [Sherwin et al. in prep.]

  ACTPol CMB Lensing Convergence Map (51 degs. long)

- Power spectrum bias subtraction: estimate corrections from data
Current Work: Preliminary ACTPol Lensing Results

- ACTPol lensing power spectrum (preliminary, 12% of data analyzed!)
- Currently finalizing analysis, systematic testing (curl?).

Preliminary (12% of existing ACTPol data!)

[Sherwin et al. in prep.]
The Future: **Stage-III** and CMB Stage-IV

Precision Lensing Power Spectra

AdvancedACT (+PB2,3G): **S/N~100-200** lensing, half sky (2016-19)

Errors inflated by 10x (for display)!
The Future: Stage-III and CMB Stage-IV
Precision Lensing Power Spectra

• Neutrino mass constraint near min. (>60 meV): \( \sigma(\sum m_\nu) \sim 50 \text{ meV} \) (AdvancedACT, SPT3G, PB2…)

Neutrino mass constraint near min. (>60 meV): \( \sigma(\sum m_\nu) \sim 15 \text{ meV} \) (CMB S4)
Aside: Great Potential for Cross-correlation Science

- Half-sky lensing maps to high z (see $3\times10^{13}M_\odot$ halos to $z>2$)
- Lots of overlap with other surveys (DES / DESI / LSST…);

Galaxies (color) trace lensing (contours):

CMB lensing correlated with:
- Quasars [Sherwin++2012]
- Optical lensing [Hand, Leauthaud, Das, Sherwin++]
- Herschel [POLARBEAR, Sherwin corr. author., 2015]
- WISE [Ferraro, Sherwin, Spergel 2015]
- Planck CIB [v. Engelen, Sherwin+ 2015]
- Galaxy halos [Madhavacheril+ 2015]
- Radio Galaxies [Alllison, Lindsay, Sherwin++] ...

[Holder++ 2013]
Example Challenge: Higher Order Corrections

- Structure formation non-linear -> many-sigma bias to CMB-S3/S4 temperature estimator, must be accounted for! [+Post-Born effects,..]
- Other challenges: dust foregrounds, bias subtraction, beams, …

[Boehm, Schmittfull, Sherwin 2016; Pratten and Lewis 2016; Namikawa++ 2016, Liu++ in prep.]
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Constraining the Physics of Inflation with the CMB

• Many models of inflation produce gravitational waves

• Strength would tell us the energy scale of inflation. Even improved upper limits interesting: could kill large-field inflation models

• These gravitational waves create characteristic CMB B-polarization
CMB B-polarization* with Small Inflationary Signal

See signal clearly as there is no background variance from scalar density perturbations.

B-modes are a “null channel”

*ignoring lensing and dust for now
Gravitational lensing $d$ converts E-to B-polarization

Lensing-B noise obscures Inflation-B signal

$$B^{\text{lens}}(l) = \int \frac{d^2l'}{(2\pi)^2} W(l,l') E(l') d(l - l')$$
Future: CMB Stage-IV Error Budget for Measuring Inflationary Grav. Wave Signal

- **error from instrument noise only (1uK-arcmin)**
- **error including lensing noise**
  - Delensing is essential for future experiments!!!!!

![Graph showing error budget with delensing importance](graph.png)
Delensing The CMB

• How to reduce lensing noise?

• Delensing: undo lensing deflection (construct $B_{\text{lensing}}$ map from measured lensing $d$ and subtract)

• Want to demonstrate!
Aside: Lensing Effect on CMB Temperature Power Spectra

The lensing effect arises from averaging of magnified and demagnified regions. It smears peaks in the power spectra, as shown in the graph. The effect is visible in the temperature fluctuations depicted in the inset.
Demonstrating Delensing with (Temp.) Data

Planck CMB Temp. Data

“Lensing Map” (from CIB)

Reverse Lensing Deflections

Delensed Planck CMB Temp. Data

Measure power before...

+ measure power after delensing

Take difference!

[Larsen, Challinor, Sherwin, Mak 2016]

[Sherwin, Schmittfull 2015]
Demonstrating Delensing: Difference of Lensed and Delensed Temp. Spectra

Expected difference showing sharpening of CMB peaks
First Demonstration of Delensing in Data
(Difference of Lensed and Delensed Temp. Spectra
– Peaks Show Successful Delensing)

Planck data result
16 sigma detection

[Sherwin, Schmittfull 2015]
[Larsen, Challinor, Sherwin, Mak 2016]
Future B Mode Map – Lensing-Dominated
Delensed B Map – Inflation Signal?
Summary

- CMB lensing directly probes high-z mass
- Measurements have already progressed rapidly, but with CMB Stage-III / Stage-IV they will be much more powerful still!
- These lensing measurements will allow us to
  - measure neutrino masses
  - enable remarkably powerful probes of inflation via delensing
  - constrain astrophysics via cross-correlation

Thanks!