Delensing CMB B-modes: results from SPT.

With: K. Story, K. Wu and SPT

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BCCP talk 25th Oct
NOT IN THIS TALK: LSS AND CMB

ISW map reconstruction

Future surveys forecast

LargeScaleStructure effective field theory

CosmoSIS: modular parameter estimation

Super sample effect

Let’s talk!!
E-B DECOMPOSITION, DECOMPOSE POLARIZED CMB TO HIGHLIGHT INFLATION

- E mode: produced by scalar anisotropies when CMB photons scatter (recombination and reionization)
- B mode: produced by tensor (gravity waves) anisotropies when CMB photons scatter (recombination and reionization)
- B mode: produced by lensing. “Turning” E mode into B mode

Kamionkowski, Kosowsky, Stebbins (1997)  
Zaldarriaga & Seljak (1997)

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Unlensed

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

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

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

(no primordial B-modes)
$T(\hat{n}) \ (\pm 350 \mu K)$

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

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

(no primordial B-modes)
B-MODE LENsing Spectrum

Angular scale

[Diagram showing the power spectrum with angular scales and various power levels.]
DELENSING IS CRUCIAL
In 10 years (CMB Stage 4) it could be the main source of noise for primordial B mode signal.

- It can be seen as a white noise component at ~5 uK-arcmin.
- Not cleanable with multi frequencies.
- Well modeled, but cosmic variance would be a problem.

Abazajian, K.N. et al.
NO SURPRISE: IT WILL LIMIT INFLATIONARY CONSTRAINTS AND MORE

• Our constraint on the inflationary tensor perturbation and tilt will depend on it

• It will limit lensing reconstruction (a.k.a as iterative delensing)

• It will limit parameter that depends on peak position and damping tail information like $N_{\text{eff}}$
... AND MORE

Planck—2015
Stage IV Lensed
Stage IV Delensed

Green, Meyers, van Engelen

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WHAT CAN WE DO? BUILD A TEMPLATE AND REMOVE!

B-mode data

B-mode template $E \otimes \phi = B_{\text{lens}}$

B-mode data

B-mode template $E \otimes \phi = B_{\text{lens}}$

Angular scale $\theta$ [degrees]

$\ell(\ell+1) C_\ell / (2\pi)$ [$\mu K^2$]

Multipole number $\ell$
TEMPLATE: WHAT MODES DO WE NEED?

\[ E \otimes \phi = B_{\text{lens}} \]

\[ \phi = \text{Integral of structures along the line of sight} \]

\[ \ell_B \left( \frac{\partial C^B_{\ell B}}{\partial C^X_{\ell X}} \right) C^X_{\ell X} \]

- Mainly from large scale potential \( \ell > 100 \)
- \( E \)-mode from scales slightly smaller than \( B\)-lens

Simard, Hanson, Holder 2014

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How can we get those modes?

CIB
Cosmic Infrared Background
The **best method right now.** Already used on data by SPT (Hanson B-modes paper). CIB model uncertainties not limiting now, you can marginalize over it (Sherwin Schmittfull.)

CMB
In the **future** it will be the **best source** of phi reconstruction. Not there yet but already powerful if combined with the CIB

Galaxies
Low redshift. They do not probe well the sources that lens the CMB. Maybe useful to check for systematics.

We want

- Kernel overlap
- Low Noise

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OPTIMAL SOURCE FOR A LENSLING MAP?

Where the lenses are

How much are they correlated with lensing considering noise

Redshift

Angular Scale
DELENSING IS CRUCIAL, FEASIBLE BUT HARD.
HOWEVER A NEW PHASE IS BEGINNING: WE ARE NOW DELENSING
A (QUITE LOCAL) SUCCESS IN TEMPERATURE

Real space CIB delensing of Planck TT data.
THE SOUTH POLE TELESCOPE STORY, DELENSING THE B-MODES

SPT-SZ
SPTpol: 100d^2
SPTpol: 500d^2

100d^2 field
500d^2 field, Overlap with Bicek/Keck

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THE SPT STORY, THE DATA

- CIB map, from Herschel 500μm map.
- E mode (Crites, SPT 2015)
- B mode (Keisler, SPT 2015)
Construct a lensing template from the CIB map.

\[ \hat{\phi} = C_{\ell}^{CIB-\phi} (C_{\ell}^{\phi\phi} C_{\ell}^{CIB-CIB})^{-1} T_{\ell}^{CIB} \]

Filter the E-mode map with a C-inv Wiener filter:

\[ \ell_{\text{min}}^{x} \leq \ell \leq \ell_{\text{max}} \]

Build a B template

\[ B^{\text{lens}}(l) = \int \frac{d^2l'}{(2\pi)^2} W(l,l') E(l') \kappa(l-1') \]

Make it as similar as possible to the data. Apply Transfer function

Note: This is a signal to noise filtered template

\[ \overline{B}_{\text{lens}} \]
BB POWER: THE PIPELINE

Convolutional clean each bundles.

Split map into bundles.

Cross spectrum-pseudo Cl

Apply Wiener filter

Remove additional and multiplicative bias

\[ C_{\ell}^{BB} \]

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PUTTING THEM TOGETHER: DELENSING PIPELINE

E mode

CIB

Cinv filter

Phi Template

B-template

Apply transfer function

Buncted Bmode

Cleaning TE

Delens

Cross Spectrum power

$B_{\text{res}}(\ell) = B_{\text{lens}}(\ell) - \hat{B}_{\text{lens}}(\ell)$

Note: The subtraction happen in Fourier space
DATA
SPT 15-20% DeleNSing: The Maps

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Work 2 years on simulations, filtering …
SPT 15-20% DELENSING: THE BAND POWERS

\[ \ell C_\ell^{BB} [10^{-3} \mu K^2] \]

Combined

Old Analysis

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SPT 15-20% DELENSING: THE BAND POWERS

\[ C_{\ell}^{BB} \left[ 10^{-3} \mu K^2 \right] \]

Combined

Delens

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**SPT 15-20% DELENSING: THE BAND POWERS**

\[ A_{\text{Lens}} = 1.34 \pm 0.31 \]
\[ A_{\text{Delens}} = 1.02 \pm 0.30 \]

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slides at:
SPT 10% DELENSING: THE SYSTEMATIC TESTS

Run and passed so far

Low-ell cut in E mode: important push as low as possible
High-ell cut in E mode
CIB model assumed
  Curl Estimator
  Noise only maps
AND THE FUTURE WILL BE EVEN BRIGHTER, DELENSING WILL IMPROVE
SIMS

Note: we have filtering, foregrounds (gaussian), CIB from model.
DELENSING: LONG (EXCITING) WAY TO GO.

This analysis slides at:
DELENSING EFFICIENCY: BIG PICTURE

B template power spectrum

\[ C_{\text{template}} \]

\[ \ell \]

- \( E_{\text{unfiltered}} \) — \( \phi_{\text{noiseless}} \)
- \( E_{\text{noiseless}} \) — \( \phi_{\text{noiseless}} \)
- \( E_{\text{noisy}} \) — \( \phi_{\text{CIB}} \)
- \( E_{\text{unfiltered}} \) — \( \phi_{\text{CIB}} \)
- \( E_{\text{noisy}} \) — \( \phi_{\text{noiseless}} \)

better

iterative?
DELENSING EFFICIENCY: BIG PICTURE

Lensing Cl_{bb} residuals

\[ \phi_{CIB} \]
\[ \phi_{true} \]
\[ E_{\text{true}} \phi_{\text{true}} \]

iterative?

\[ C_{\text{delensed}} / C_B \]

\[ \ell \]

\[ 0 \]
\[ 0.2 \]
\[ 0.4 \]
\[ 0.6 \]
\[ 0.8 \]
\[ 1.0 \]

better (less residual power)

\[ E_{\text{unfiltered}} - \phi_{\text{noiseless}} \]
\[ E_{\text{noisy}} - \phi_{\text{CIB}} \]
\[ E_{\text{noisy}} - \phi_{\text{noisless}} \]
\[ E_{\text{unfiltered}} - \phi_{\text{CIB}} \]

BB Theory

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slides at:
DELENSING EFFICIENCY: MAPS

\( \bar{E}_{\text{true}} \bar{\phi}_{\text{true}} \)
DELENSING EFFICIENCY: PERFECT INPUT

iterative?
DELENSING EFFICIENCY: NOISELESS FILTERED $E$

$$\Phi_{\text{true}}$$

E noiseless

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slides at:
At least for SPT at this scales. E modes are not the problem.
Indeed perfect E but lensing from CIB.
DELENSING EFFICIENCY: MAPS
THE CHALLENGES

• The **B mode map** and the **B mode template** we want to subtract are coming from different analysis. They have **different filtering, missing modes, different point sources threshold.**

• We are **testing** the technique for the **first time** on data. **Using this** to improve r constraint **required** an **unprecedented control of systematics.**

• Analyze delensed data. Covariances?

• Estimate systematics contamination: dust.
Reasonable goals by end of 2017

- On the 500deg^2 SPT combine Planck CIB and CMB lensing reconstruction.
- Delens BICEP-KECK with the help of BICEP data.

Sherwin & Schmittfull 2015
We know how to get cosmology from 2D samples
Expand in $Y_{lm}(\theta)$ Compute $\langle a_l^m a_{l'}^{m'} \rangle$

For 3D, we usually expand in $e^{ikx}$... but if we want to cross-correlate with 2D:

Expand in $Y_{lm}(\theta)$ AND $j_l(kr)$
Compute $\langle a_l^m b_{l'}^{m'}(k) \rangle$ and $\langle b_l^m(k) b_{l'}^{m'}(k') \rangle$
Retains diagonality in $l$ and $m$
Application: Photo-z Galaxies and Clusters

Photometric surveys produce tomographic galaxy bins
Each bin essentially a 2D sample

We can use our framework to make optimal use of overlapping 3D samples
Ex: redMapper Clusters, Spectroscopic galaxies

For DES clustering analyses, clusters are lumped with galaxies

What if we treat clusters as a true 3D sample?
Results: Fisher Analysis for a DES-like survey
• Delensing is crucial and it is working. Results in agreement with sims. Right now all the collaborations and the CMB Stage 4 community are working hard.

• Happy to chat about:
  - 2Dx3D formalism
  - dark matter perturbation theory
  - LIGO early localization of electromagnetic counterparts,
  - modular software for parameters constraints,
  - CMB Stage 4 and galaxies forecast,
  - optimal map reconstruction: ISW
  - effect of long wave modes on deep CMB experiments.

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