Gravitational Lensing of the CMB:
Mass Maps, Power Spectra, and B-modes with the South Pole Telescope

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as part of:
SPT collaboration
Outline

• CMB gravitational lensing overview
• lensing power spectra
• mass maps and cross-correlations
• first detection of “B-modes”
Planck has higher resolution than WMAP

WMAP 60 GHz

Planck 143 GHz
South Pole Telescope

10m mm-wave (3 different wavelengths) telescope at the south pole

• extremely dry
• very stable
• good support

photo by Dana Hrubes

Chicago   Colorado
UC Berkeley Case Western
McGill Harvard
UC Davis Munich +++

photo by Keith Vanderlinde
The evolution of SPT cameras

2007-2011: SPT
960 detectors

2012-2015: SPTpol
~1600 detectors

2016: SPT-3G
~15,200 detectors

Now with polarization!

2500 sq deg completed

100 sq deg completed
600 sq deg expected

2500 sq deg expected
SPT-SZ Survey (completed)

Final survey depths of:
- 100 GHz: < 40 uK$_{\text{CMB-arcmin}}$
- 150 GHz: < 18 uK$_{\text{CMB-arcmin}}$
- 220 GHz: < 80 uK$_{\text{CMB-arcmin}}$

2500 square degrees
SPT has higher resolution than Planck

Planck 143 GHz

Planck+SPT
CMB Angular Power Spectrum
• CMB fluctuations are relatively strongly polarized (~10%)
**E-modes/B-modes**

- E-modes vary spatially parallel or perpendicular to polarization direction
- B-modes vary spatially at 45 degrees
- CMB
  - scalar perturbations only generate *only* E
E-modes/B-modes

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- CMB
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- **Lensing of CMB is much more obvious in polarization!**

Image of positive $k_x$/positive $k_y$ Fourier transform of a 10x10 deg chunk of Stokes Q CMB map [simulated; nothing clever done to it]
E-mode polarization of ra23h30, dec -55 field (150 GHz)
CMB Polarization Angular Power Spectrum

only upper limits on B mode power

Barkats et al (BICEP)
Two Expected Sources of B Modes

Gravitational Radiation in Early Universe
(amplitude unknown!)

Gravitational lensing of E modes (amplitude well-predicted, but no measured B modes until later in talk)
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CMB Lensing

Photons get shifted

\[ T^L(\hat{n}) = T^U(\hat{n} + \nabla \phi(\hat{n})) \]

In WL limit, add many deflections along line of sight

\[ \nabla \phi(\hat{n}) = -2 \int_0^{\chi_*} d\chi \frac{\chi_* - \chi}{\chi_* \chi} \nabla_\perp \Phi(\chi \hat{n}, \chi) \]

- CMB is a unique source for lensing
  - Gaussian, with well-understood power spectrum (contains all info)
  - At redshift which is (a) unique, (b) known, and (c) highest

Broad kernel, peaks at \( z \sim 2 \)
Lensing simplified

- gravitational potentials distort shapes by stretching, squeezing, shearing
Lensing simplified

- gravitational potentials distort shapes by stretching, squeezing, shearing
Lensing simplified

- where gravity stretches, gradients become smaller
- where gravity compresses, gradients are larger
- shear changes direction
Mode Coupling from Lensing

\[ T^L(\hat{n}) = T^U(\hat{n} + \nabla \phi(\hat{n})) \]

\[ = T^U(\hat{n}) + \nabla T^U(\hat{n}) \cdot \nabla \phi(\hat{n}) + O(\phi^2), \]

- Non-gaussian mode coupling for \( l_1 \neq -l_2 \):

\[ \langle T^L(l_1)T^L(l_2) \rangle = L \cdot (l_1 C_{l_1}^T + l_2 C_{l_2}^T) \phi(L) + O(\phi^2) \]

\[ L = l_1 + l_2 \]

- We extract \( \phi \) by taking a suitable average over CMB multipoles separated by a distance \( L \)
- We use the standard Hu quadratic estimator.
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SPT Lensing Mass Map

+-0.05 color bar
(noise ~0.01)
Planck
(all-sky more noise)

SPT
(2500 sq deg less noise)
CMB Lensing Power Spectrum

- well measured with Planck, SPT, ACT
Cosmology with Lensing

large improvements over WMAP alone in measuring curvature

(BUT: BAO+H₀ are currently ~2x better than SPTLens for this)

van Engelen et al
Massive Neutrinos in Cosmology

\[ \Omega_{\nu} \approx \sum_i \left( \frac{m_i}{0.1 \text{ eV}} \right) 0.0022 h^{-2}_{0.7} \]

- Below free-streaming scale, neutrinos act like radiation
  - \textit{drag on growth}
- Above free-streaming scale, neutrinos act like matter
Neutrinos & CMB Lensing

- Peak at \( l=40 \) (\( k_{eq} = [300 \text{ Mpc}]^{-1} \) at \( z = 2 \)): coherent over degree scales
- RMS deflection angle is only \( \sim 2.7' \)
Upper limits on neutrino masses

- CMB experiments closing in on interesting neutrino mass range
- CMB lensing adds new information
  - forecast \( \sim 0.05 \text{ eV} \) sensitivity in \( \sim 4 \text{ yrs} \)

Planck collaboration 2013
Not everything makes total sense

- combining all cosmological information leads to a preference for a high neutrino mass and some form of new light particle in the universe

Wyman et al 2013
SPT Lensing Mass Map

+-0.05 color bar
(noise ~0.01)
CMB Lensing X Galaxies

linear bias:
\[ \rho_{\text{gal}} = b \rho_{\text{matter}} \]

- Galaxy-galaxy correlation: \( b^2 \)
- Galaxy-lensing correlation: \( b^1 \)
- Lensing-lensing correlation: \( b^0 \)

Bleem et al 2012
Optical galaxy counts
(19.5 < i < 22.5)

IR galaxy counts
(15 < [3.4] < 17 or (15 < [4.5] < 17)

CMB lensing
(smoothed to only show scales with S/N > 1)

Using < 5% of completed SPT survey

Bleem et al
Galaxy-Mass Cross-Correlation Detected

Prediction from DES mocks

4 different $x$-correlations, ranging in significance from $4.2-5.4\sigma$
Herschel (SPIRE)

- 100 sq deg with full overlap with SPT deep field (23h30,-55d)
- 250,350,500 um
Cosmic Infrared
Background Traces Mass

SPT TT Lensing map 100 sq deg

Herschel 500 um
simple model of flux traces mass at any given $z$

depending on $z$ distribution of CIB, bias of CIB sources is 1.5-2
AGN Selection with WISE

Geach et al
Quasar-Mass Cross-Correlation
Detected: SPT X WISE

stacked SPT lensing map in bins of AGN density

Geach et al
Quasar-Mass Cross-Correlation
Detected: SPT X WISE

Planck and SPT in excellent agreement
bias measurements agree with expectations

Geach et al
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Cosmic Infrared
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SPT TT Lensing map 100 sq deg
Herschel 500 um
Predicting B-Modes

**measured E modes**

**estimated \( \phi \)**

**predicted \( B \)**

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Hanson, Hoover, Crites et al 2013
Many Ways of Predicting B-Modes

Measured E modes

Estimated $\phi$

Predicted $B$

$E_{150}$ GHz
$E_{90}$ GHz
$E$ from Temperature

$\phi$ CIB
$\phi$ TT
$\phi$ EE
$\phi$ TE
($\phi$ Spitzer cat)

X B $150$ GHz
X B $90$ GHz

Hanson, Hoover, Crites et al 2013
First Detection of B-Modes

\[ \chi^2 \leq N \]  to estimate the lensing potential

\[ B \times B \]

not zero at 7.7\sigma

Hanson, Hoover, Crites et al 2013
Summary & Outlook

• high resolution CMB maps give new information about the universe
• gravitational lensing of the CMB a powerful new probe
  – power spectrum of mass fluctuations
  – directly connecting galaxies to mass
• B-mode polarization anisotropy has now been detected
  – next up: B modes from early universe!