CMB Lensing Cross-Correlations (optical, IR, submm)

Gil Holder

McGill

SPT

Bleem et al 2012
Holder et al 2013
Geach et al (soon!)
Why CMB Lensing?

- well-known source redshift
- highest source redshift possible (for photons)
- very different systematics from galaxy-based cosmic shear
- wide areas
- lots of good data coming in now
SPT Lensing Mass Map

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

SPT (2500 sq deg)
The CMB Lensing Landscape

best maps are being made when noise curve is below signal curve
Planck (all-sky)

SPT (2500 sq deg)

2dF galaxy survey
CMB lensing power comes from $z > 0.5$, but still plenty of overlap with structure at $z \approx 1$.

(Another lensing source screen at $z = 1100$)
CMB Lensing X Galaxies

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

• Galaxy-galaxy correlation: \[ b^2 \]

• Galaxy-lensing correlation: \[ b^1 \]

• Lensing-lensing correlation: \[ b^0 \]

Bleem et al 2012
Measuring Quasar Host Galaxy Masses

- linear bias tells you host galaxy mass in simple halo models

Ross et al 2009
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

Bleem et al
Planck X Galaxies, etc.
Quasar-Mass Cross-Correlation
Detected: ACT X SDSS

Cross-power spectrum

\[ C_{\kappa g} \]

\[ 3.8 \text{s in good agreement with expected bias} \]

b=2.5±0.6

Sherwin et al 2012
AGN Selection with WISE

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

stacked SPT lensing map in bins of AGN density

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

Planck and SPT in excellent agreement

bias measurements agree with expectations

Geach et al coming soon
CMB Lensing/Herschel

SPT Lensing map 100 sq deg

Herschel 500 um
Light Traces Mass

SPT Lensing map 100 sq deg

Herschel 500 um
strong detection of correlated structure

bias relative to non-linear $P(k)$:

$b = 1.3 - 1.8$, depending on assumed $dl/dz$
Lensing/Galaxies
Cross-Power Spectrum
CMB vs Galaxies

cosmic shear also has redshift information

(e.g., CFHTLens has 155 sq deg with 17/sq arcmin)

error bands for bins of 10% in L

(scaled from $z=1$ to $z=1100$)

10-20 gals/sq arcmin
CMB Lensing X Galaxies

- cosmic shear good at lower $z$ ($z \sim 1.5$?)
- galaxy auto-spectra are also very useful
  - we “know” $s_8$ at % level, so autospectrum good enough to measure simple linear bias
- CMB lensing is unique at higher $z$
- we can use cosmic shear to clean out low $z$ structure

**Figure:**
- cosmic shear better than CMB lensing
Summary

CMB lensing is being measured

strong cross-correlation with LSS

independent measures of galaxy bias

lots more to come
Lensing simplified

- gravitational potentials distort shapes by stretching, squeezing, shearing

Gravity
Lensing simplified

- where gravity stretches, gradients become smaller
- where gravity compresses, gradients are larger

Gravity
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 \( l_1 \neq -l_2 : \)

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

\[ \mathbf{L} = l_1 + l_2 \]

- We extract \( \phi \) by taking a suitable average over CMB multipoles separated by a distance \( L \)

- We use the Hu quadratic estimator.
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
Simulated Polarized CMB Maps

Stokes $U$

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

Image of positive kx/positive ky Fourier transform of a 10x10 deg chunk of Stokes Q CMB map [simulated; nothing clever done to it]