The Atacama Cosmology Telescope:

Detection of the CMB Lensing Power Spectrum and First Applications

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Das, Sherwin et al. arXiv: 1103.2124; Sherwin, Dunkley, Das et al. in prep
Outline

• Reconstructing the lensing power spectrum
• Results: The ACT detection
• Null tests, contaminant levels and other checks
• Application of results: CMB-only constraints on $\Omega_{\Lambda}$
Recap: CMB Lensing

• Large scale structure potentials gravitationally deflect CMB photons by a lensing deflection angle \( d(n) \)

• Measurement of the deflection field is a measurement of matter fluctuations AND the geometry of the universe
  -> very useful for cosmological constraints
Reconstructing Lensing Power from CMB Data

• Can find lensing because it breaks Gaussianity: non-Gaussian part of lensed T 4-point function \sim deflection power spectrum

• Hence we can estimate the lensing power spectrum from lensing-type non-Gaussianity in the four-point function:

\[
(2\pi)^2 \delta(L - L') \hat{C}_L^{dd} = |N^\kappa(L)|^2 \int \frac{d^2 \ell}{(2\pi)^2} \int \frac{d^2 \ell'}{(2\pi)^2} |g(\ell, L)|^2 \\
\times \left[ T^*(\ell) \ T^*(L - \ell) \ T(\ell') \ T(L' - \ell') \\
- \langle T^*(\ell) \ T^*(L - \ell) \ T(\ell') \ T(L' - \ell') \rangle_{\text{Gauss}} \right] \tag{1}
\]

[Hu & Okamoto (2002), Kesden, Cooray, Kamionkowski (2003)]
Reconstructing Lensing Power from CMB Data

\[ (2\pi)^2 \delta(L - L') \hat{C}^d_L = |N^\kappa(L)|^2 \int \frac{d^2 \ell}{(2\pi)^2} \int \frac{d^2 \ell'}{(2\pi)^2} |g(\ell, L)|^2 \times \left[ T^*(\ell) T^*(L - \ell) T(\ell') T(L' - \ell') \right. \\
\left. - \langle T^*(\ell) T^*(L - \ell) T(\ell') T(L' - \ell') \rangle_{\text{Gauss}} \right] \]

1. Must subtract off Gaussian part (= unconnected part = N(0) bias)
2. How can we estimate this Gaussian bias (unconnected part)?
Estimating the Gaussian Bias

\[
(2\pi)^2 \delta(L - L') \, \hat{C}_L^{dd} = |N^\kappa(L)|^2 \int \frac{d^2 \ell}{(2\pi)^2} \int \frac{d^2 \ell'}{(2\pi)^2} |g(\ell, L)|^2 \\
\times \left[ T^*(\ell) \, T^*(L - \ell) \, T(\ell') \, T(L' - \ell') \\
- \langle T^*(\ell) \, T^*(L - \ell) \, T(\ell') \, T(L' - \ell') \rangle_{\text{Gauss}} \right] \tag{1}
\]

• One approach: obtain from Monte-Carlos
  – Problem: simulating a large number
  – Small fractional error in bias calculation -> large systematic error in reconstructed power. Especially true on noise-dominated scales
  – Need to know window functions, true power spectra, noise very accurately
A More Robust Approach – Bias from Data

• Better: *estimate Gaussian $N(0)$ bias from the data*
• One way to do this: just use observed power spectrum to evaluate the unconnected part directly
A More Robust Approach – Bias from Data

• Method 2: Obtain a \( \sim \)Gaussian field with the same power spectrum from the observed T map by randomizing phases of all the Fourier modes (similar to Method 1...)

\[
T(l) = \tilde{T}(l) - \int \frac{d^2 l'}{(2\pi)^2} \tilde{T}(l') d(l - l') \cdot l'
\]

• Monte Carlo small residual bias, due to noise correlations, window functions, etc

• *Only Simulate small quantities*

[Hanson et al. 2010]
Aside: No-Bias Method

Can also directly calculate lensing power from regions of parameter space with no bias.

\[
\left( \left[ \begin{array}{c} \right. \end{array} \right] \ast \left[ \begin{array}{c} \right. \end{array} \right] \right) \times \left( \left[ \begin{array}{c} \right. \end{array} \right] \ast \left[ \begin{array}{c} \right. \end{array} \right] \right) = \\
\left( \bullet + o \right) \ast \left( \bullet + o \right) \times \left( \bullet + o \right) \ast \left( \bullet + o \right) = \\
\left( \bullet \bullet \bullet \right) + \left( \bullet \bullet o \right) + \left( o \bullet o \right) + \left( o \bullet \bullet \right) \times \left( \bullet \bullet \bullet \right) + \left( \bullet \bullet o \right) + \left( o \bullet o \right) + \left( o \bullet \bullet \right)
\]

[Sherwin & Das 2010, Hu 2001]
Difficulties in Lensing Power Estimation

• Correlated atmospheric noise at low $l$ can contaminate signal
  – Filter out modes below $l=500$
• Unresolved IR point sources and SZ dominate power at high $l$
  – Only use modes below $l=2300$
• Point sources can add spurious power
  – Remove using template subtraction method
Test Reconstruction Pipeline with Simulations

Find that pipeline gives unbiased reconstruction (simulation also gives error bars):

Higher order biases not important for our S/N.
Note: Error bars are for 1 realization, not for the mean shown in red.
Detection of the Lensing Power Spectrum

4-sigma detection of the power spectrum of the lensing deflection angle on ACT equatorial data:

\[ \frac{l^2 C_{\ell}}{4} = 1.16 \pm 0.29 \]

Detection of the Lensing Power Spectrum

- Consistent with WMAP LCDM prediction
- Constrains amplitude of Matter Fluctuations at $z \sim 0.5-3$ to 12%.

\[ A_L = 1.16 \pm 0.29 \]

- Direct gravitational probe of dark matter to $z \sim 1100$ (though most sensitive to $z \sim 0.5-3$)
Null Tests

• Cross-correlate reconstruction on different patches:

• Reconstruction on noise-only maps:

• Check phase randomization, check reconstruction by eye, etc. – all tests successful

Levels of Potential Contaminants

- Test level of spurious lensing signal due to IR point sources, tSZ, kSZ using simulations [Sehgal et al. 2009]
- Find negligible contamination:

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

true lensing power

[Berkeley, 4/21/11]  
[B. D. Sherwin - ACT Lensing Detection and Applications]
First Constraints From The ACT CMB Lensing Power Spectrum
What Constraints can we Obtain from the CMB Alone?

- CMB geometric degeneracy: $\Omega_{\Lambda} = 0$ consistent with temperature power spectra

Can we tell these apart with CMB-only data?
Models Indistinguishable from CMB Power Spectra

- Expected degeneracy clearly visible (only small difference at high $l$ due to lensing, low $l$ due to ISW):
Can Lensing Break the CMB Degeneracy?

- Measurement of the lensing power is a clean measurement of matter fluctuations and the geometry of the universe:

\[
\frac{\ell^2}{4} C_\ell^{dd} = \int_0^{\eta_*} d\eta \, W^2(\eta) \underbrace{P \left( k = \frac{\ell + 1/2}{d_A(\eta)}, \eta \right)}_{\text{geometry}}
\]

- Power spectrum of deflection field is sensitive to the large differences in fluctuations and geometry
Why is There More Lensing Without $\Omega_\Lambda$?

Geometry

Matter Fluctuations

Total Lensing Kernel (all at $l=120$)

[Sherwin, Dunkley, Das et al. in prep.]
Constraints from the Lensing Power Spectrum

- Appears ACT Lensing power spectrum data might favor a universe with $\Omega_\Lambda$ ...

- So construct WMAP + ACT-lensing Likelihood, calculate constraints on $\Omega_\Lambda$
Lensing: CMB-only Evidence for $\Omega_\Lambda$

2D confidence contours:

[Sherwin, Dunkley, Das et al. in prep.]
Lensing: CMB-only Evidence for $\Omega_\Lambda$

1-D Posterior distribution for $\Omega_\Lambda$:

Peak at $\Omega_\Lambda = 0.67$

Comparing difference in -2 ln L favors LCDM model at **3.5 sigma** over best model with no DE.

[Sherwin, Dunkley, Das et al. in prep.]
Evidence for $\Omega_\Lambda$ From the CMB Alone

- Using WMAP + ACT - Lensing only, we can rule out a universe without Dark Energy at 3.5 sigma
- Different systematics than SN, LSS probes, small
- Can do MUCH better with SPT, Planck, ACTPOL...
- This is an independent confirmation of the existence of $\Omega_\Lambda$ from just the CMB

On arXiv in the next few days
The Future of CMB Lensing Science

- SPT, Planck power spectra, cross-correlations
- Polarization Lensing: lots of interesting questions
  - What is the best estimator on small scales for real data?
  - Best way to deal with biases?
  - How to deal with sky-cuts, real noise, instrumental systematics?
Summary

• CMB Lensing directly probes dark matter distribution
• Measurement of lensing power spectrum – robust 4-sigma detection with ACT
• Evidence for $\Omega_\Lambda$ at 3.5 sigma from CMB only using WMAP + ACT lensing
• Higher S/N spectra, cross-correlations, polarization lensing... the beginning of an exciting research program