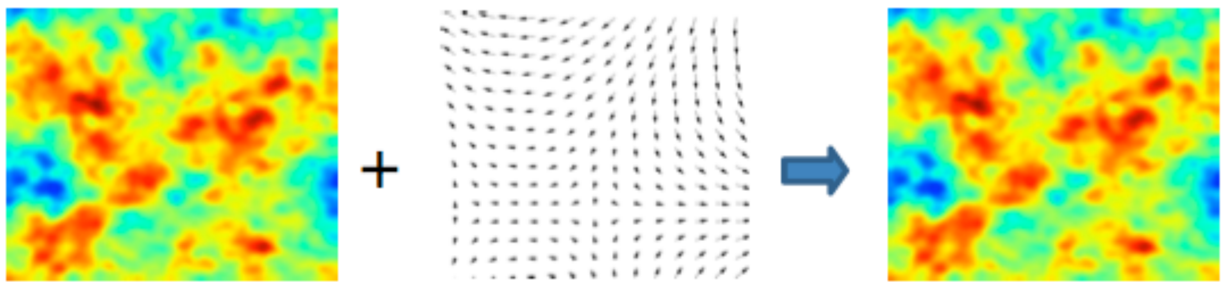
The Atacama Cosmology Telescope:

Detection of the CMB Lensing Power Spectrum and First Applications



Blake D. Sherwin (Princeton Physics)

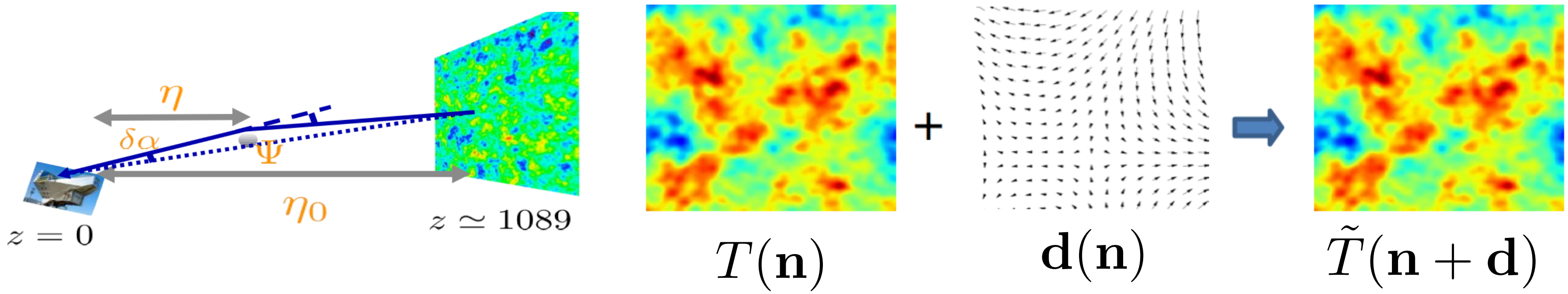
Sudeep Das, Jo Dunkley, David N. Spergel and others

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 Ω_Λ

Recap: CMB Lensing



- Large scale structure potentials gravitationally deflect CMB photons by a lensing deflection angle $\mathbf{d}(\mathbf{n})$

- 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 ~ deflection power spectrum

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

$$
\begin{aligned}
(2\pi)^2 \delta(\mathbf{L}-\mathbf{L}')\ \hat{C}_L^{dd} = |N^\kappa(\mathbf{L})|^2 \int \frac{d^2\boldsymbol{\ell}}{(2\pi)^2} \int \frac{d^2\boldsymbol{\ell}'}{(2\pi)^2} |g(\boldsymbol{\ell},\mathbf{L})|^2 \\
\times \Big[T^*(\boldsymbol{\ell})\ T^*(\mathbf{L}-\boldsymbol{\ell})\ T(\boldsymbol{\ell}')\ T(\mathbf{L}'-\boldsymbol{\ell}') \\
- \langle T^*(\boldsymbol{\ell})\ T^*(\mathbf{L}-\boldsymbol{\ell})\ T(\boldsymbol{\ell}')\ T(\mathbf{L}'-\boldsymbol{\ell}') \rangle_{\mathrm{Gauss}} \Big] (1)
\end{aligned}
$$

[Hu & Okamoto (2002), Kesden, Cooray, Kamionkowski (2003)]

Reconstructing Lensing Power from CMB Data

$$(2\pi)^2\delta(\mathbf{L}-\mathbf{L}')\ \hat{C}_L^{dd} = |N^\kappa(\mathbf{L})|^2 \int \frac{d^2\boldsymbol{\ell}}{(2\pi)^2} \int \frac{d^2\boldsymbol{\ell}'}{(2\pi)^2} |g(\boldsymbol{\ell},\mathbf{L})|^2 \times \Big[T^*(\boldsymbol{\ell})\ T^*(\mathbf{L}-\boldsymbol{\ell})\ T(\boldsymbol{\ell}')\ T(\mathbf{L}'-\boldsymbol{\ell}') - \langle T^*(\boldsymbol{\ell})\ T^*(\mathbf{L}-\boldsymbol{\ell})\ T(\boldsymbol{\ell}')\ T(\mathbf{L}'-\boldsymbol{\ell}')\rangle_{\rm Gauss} \Big] \quad (1)$$

- Must subtract off Gaussian part (= unconnected part = N(0) bias)
- How can we estimate this Gaussian bias (unconnected part)?

Estimating the Gaussian Bias

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

- 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

[Hanson et al. 2010]

A More Robust Approach – Bias from Data

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

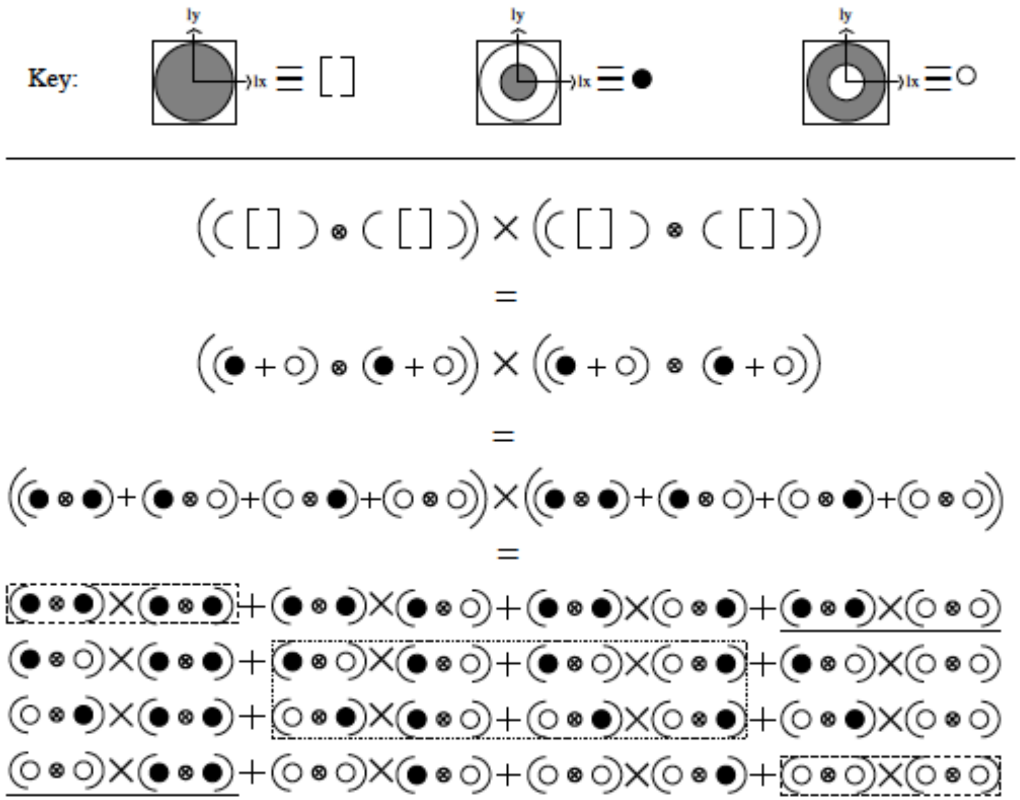
$$T(\mathbf{l}) = \tilde{T}(\mathbf{l}) - \int \frac{d^2\mathbf{l}'}{(2\pi)^2} \tilde{T}(\mathbf{l}')\mathbf{d}(\mathbf{l}-\mathbf{l}')\cdot\mathbf{l}'$$

- 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.



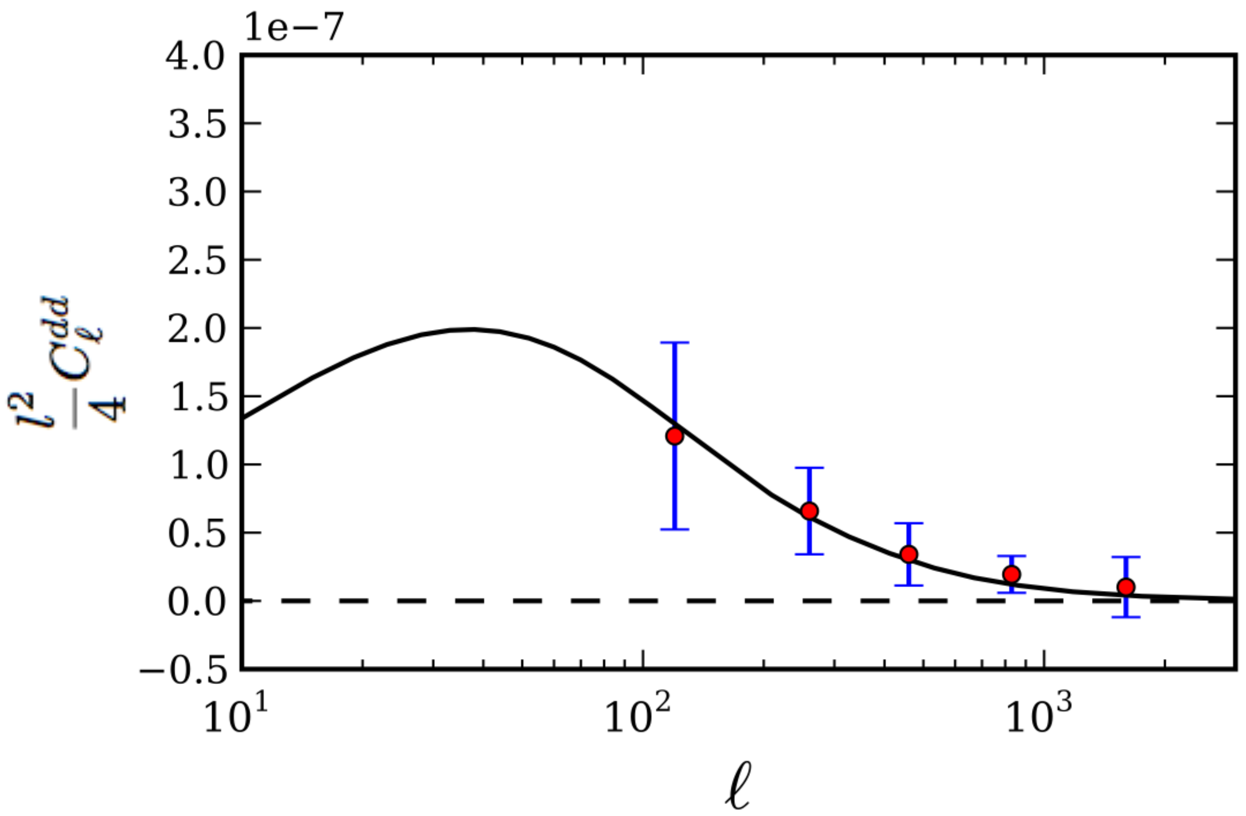
[Sherwin & Das 2010, Hu 2001]

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

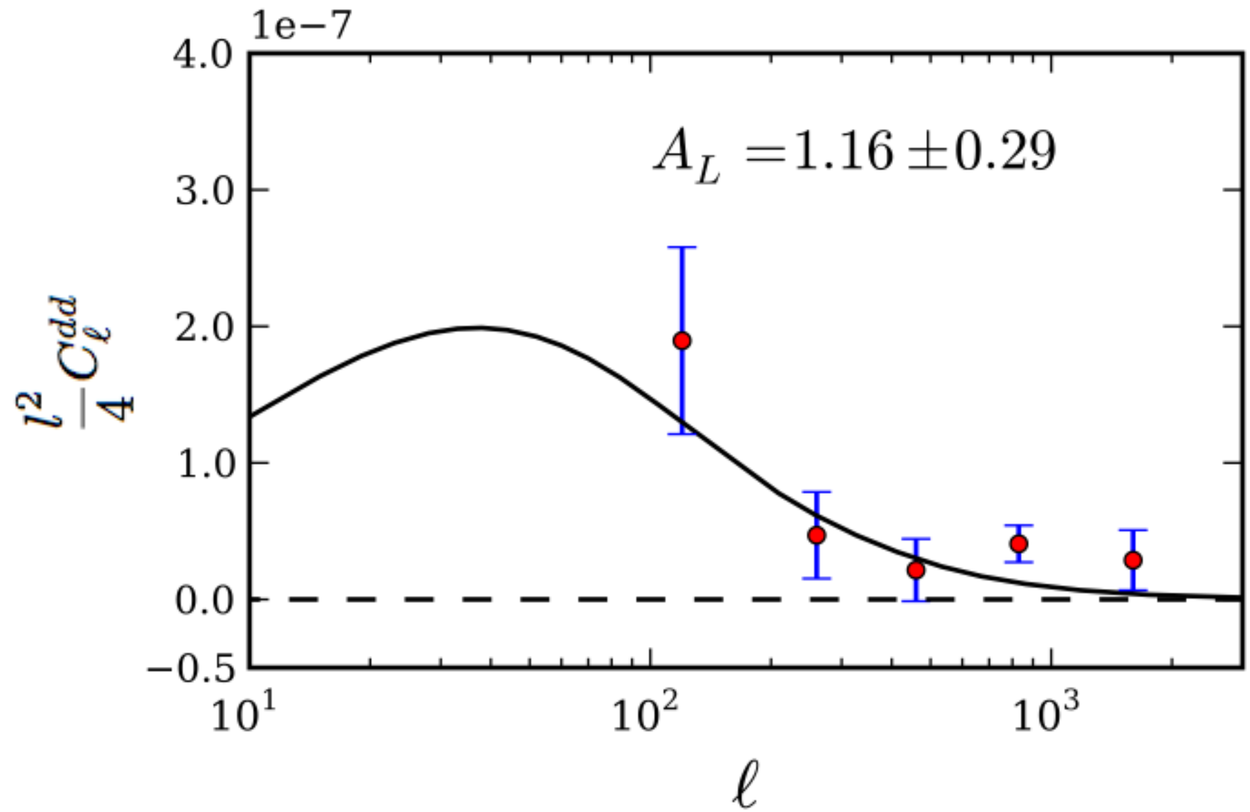
Find that pipeline gives unbiased reconstruction (simulation also gives error bars):



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

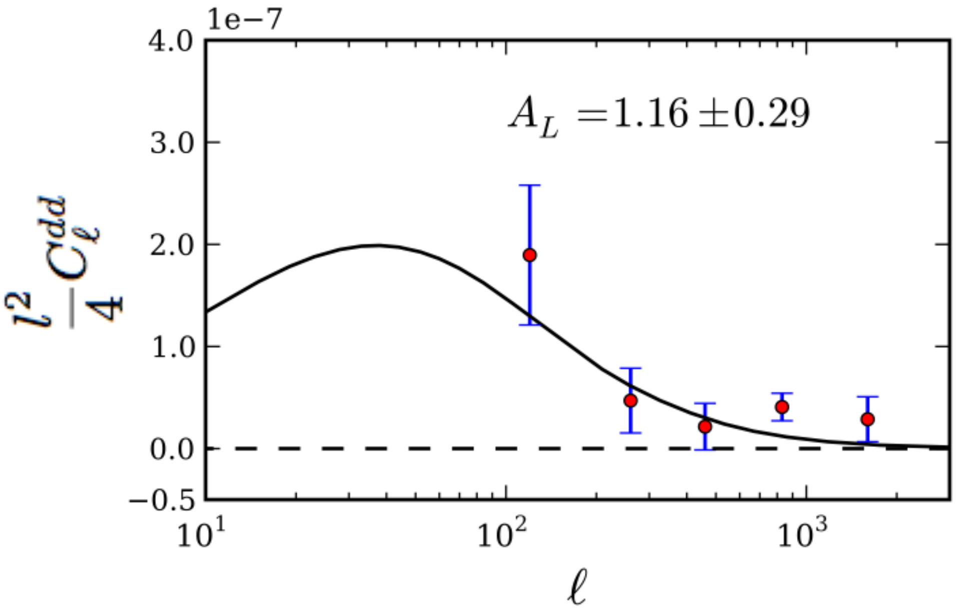
4-sigma detection of the power spectrum of the lensing deflection angle on ACT equatorial data:

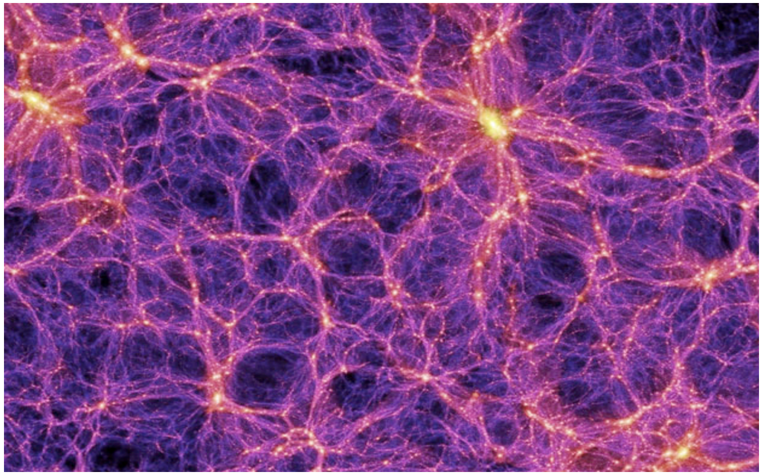


[Das, Sherwin et al. 2011, arXiv:1103.2124]

Detection of the Lensing Power Spectrum

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

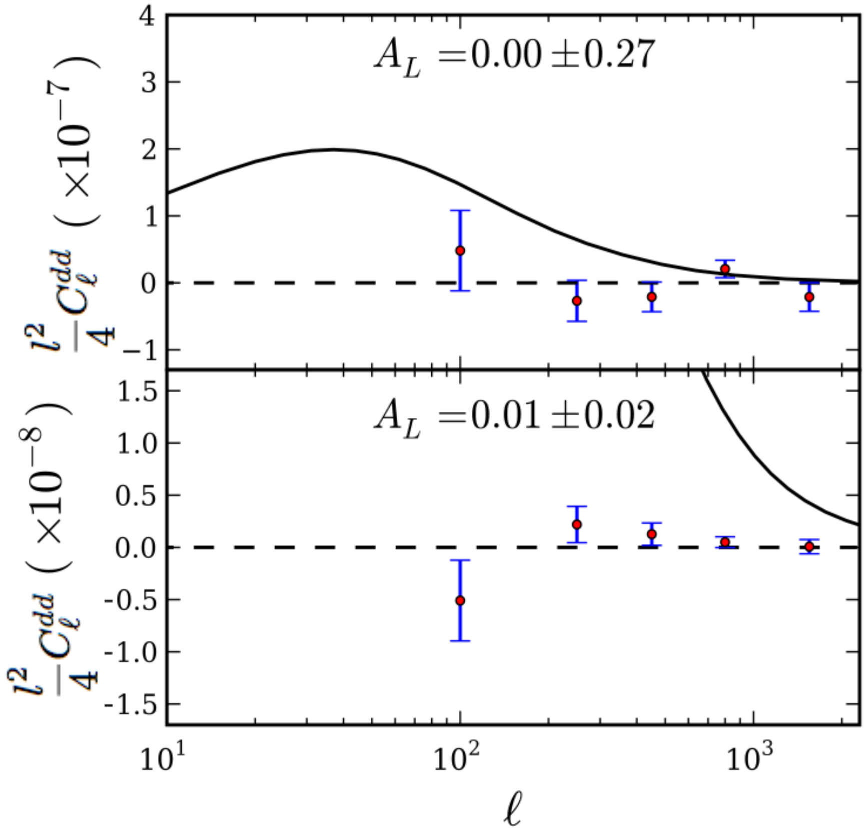




- <u>Direct gravitational probe of dark matter to z~1100</u> (though most sensitive to z~0.5-3)

Null Tests

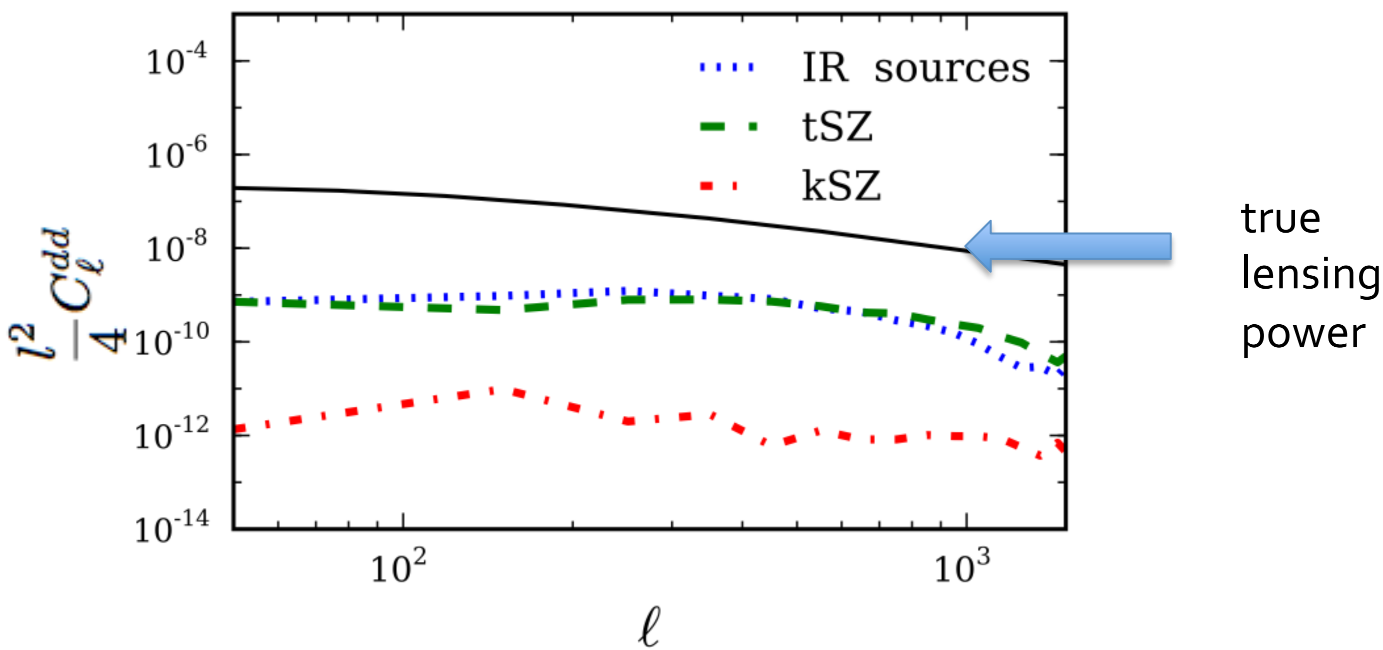
- Cross-correlate reconstruction on different patches:
- Reconstruction on noise-only maps:
- Check phase randomi- zation, check reconstruction by eye, etc. – all tests successful



[Das, Sherwin et al. 2011, arXiv:1103.2124]

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:



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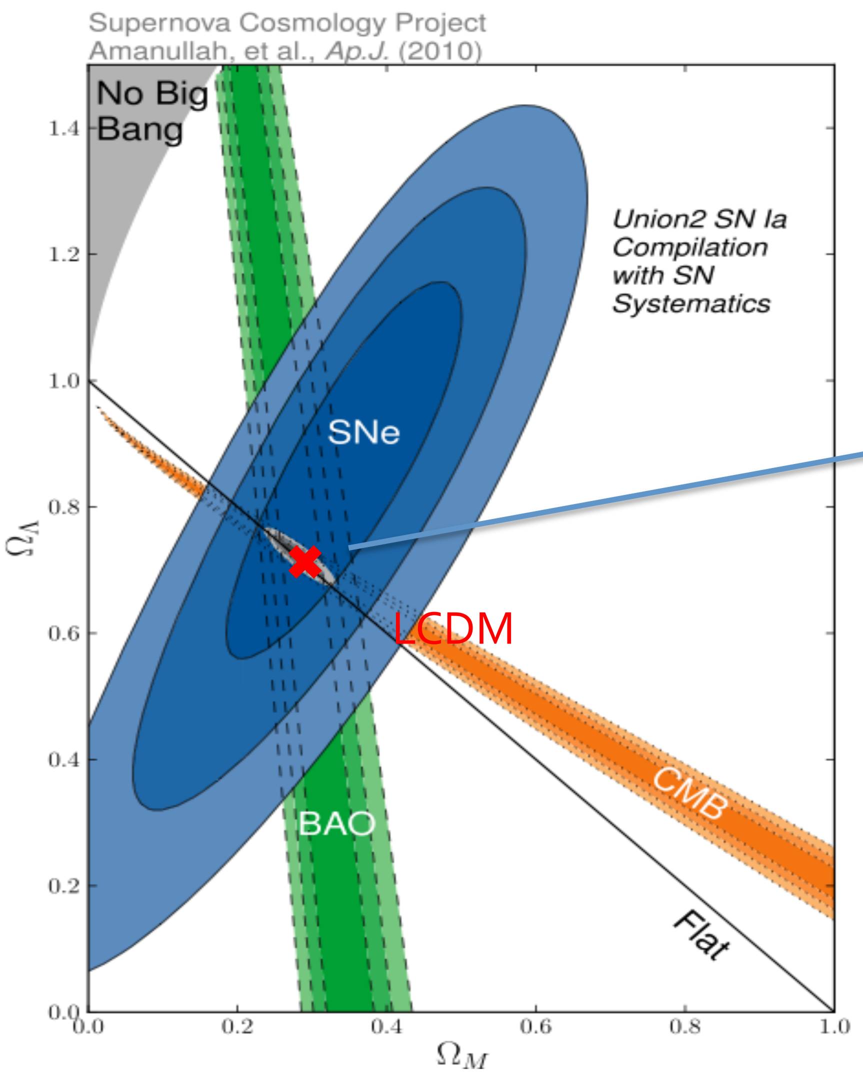
First Constraints From The ACT CMB Lensing Power Spectrum

What Constraints can we Obtain from the CMB Alone?



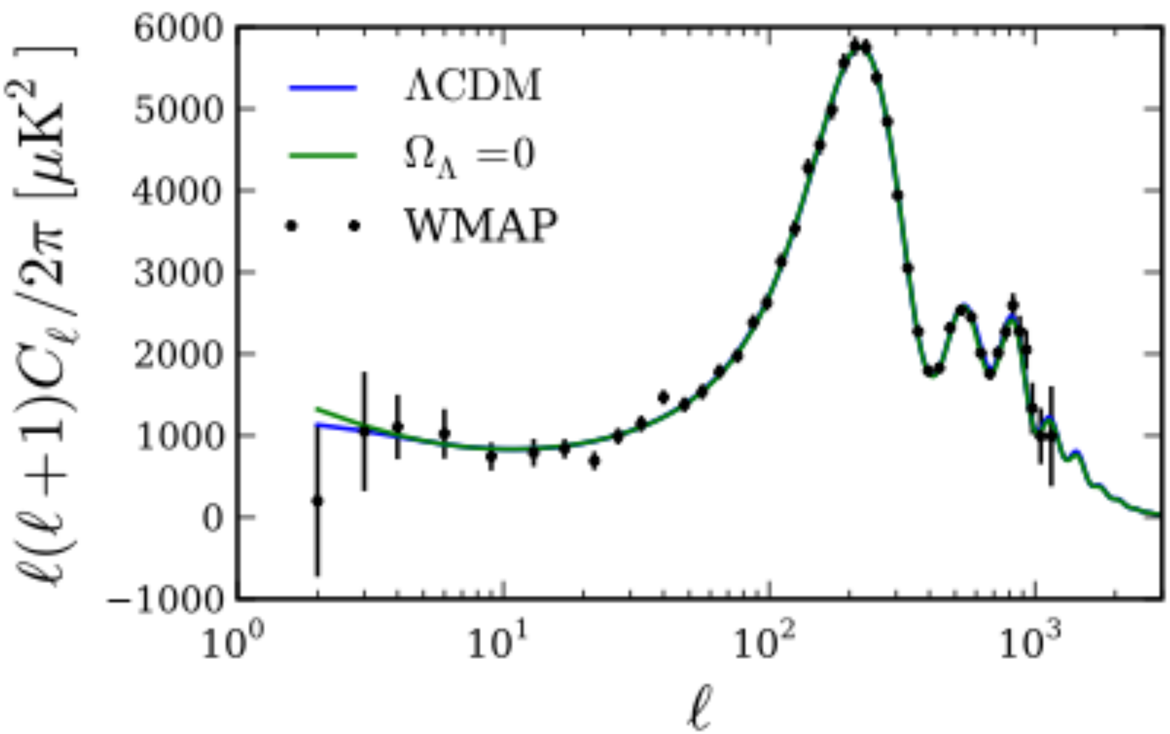
- CMB geometric degeneracy: $\Omega_\Lambda = 0$ consistent with temperature power spectra

Can we tell these apart with CMB-only data?

✖ $\Omega_\Lambda = 0$

Models Indistinguishable from CMB Power Spectra

- Expected degeneracy clearly visible (only small difference at high l due to lensing, low l due to ISW):

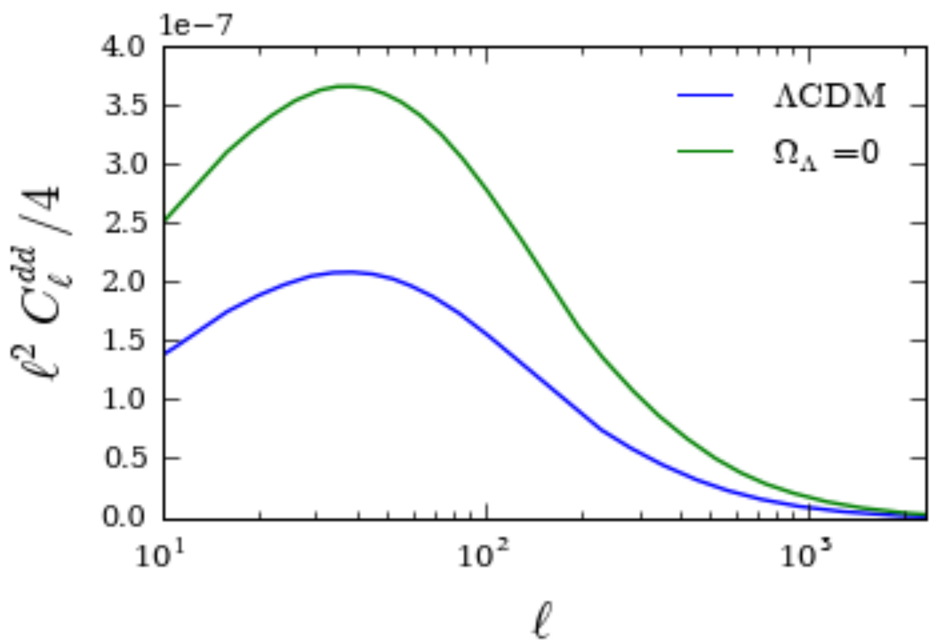


Can Lensing Break the CMB Degeneracy?

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

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

- Power spectrum of deflection field is sensitive to the large differences in fluctuations and geometry

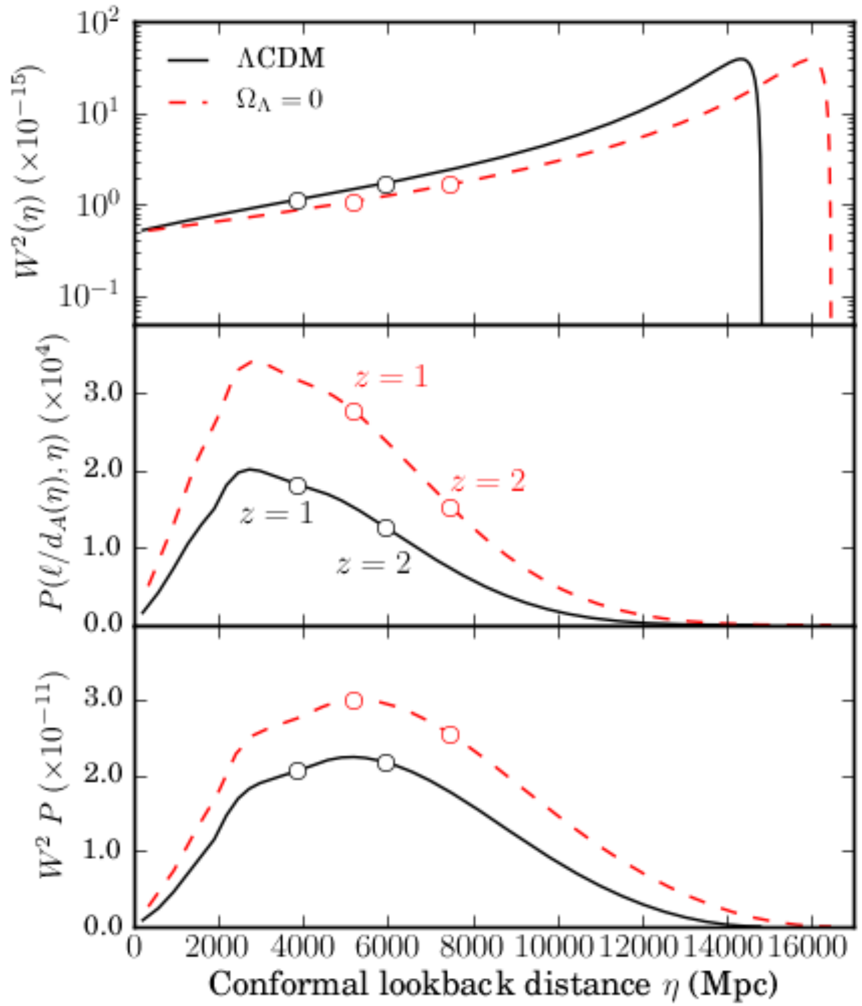


Why is There More Lensing Without Ω_Λ?

Geometry

Matter Fluctuations

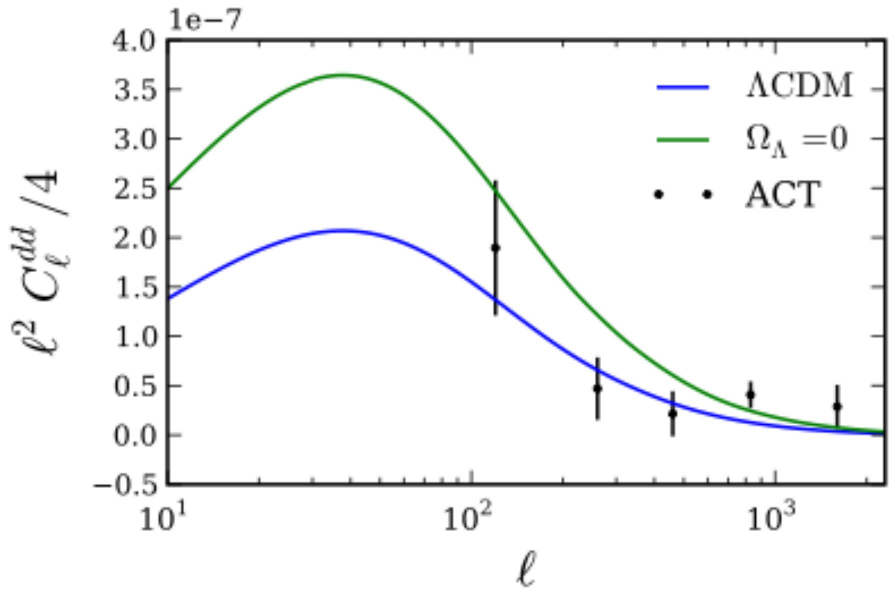
Total Lensing Kernel
(all at l=120)



[Sherwin, Dunkley, Das et al. in prep.]

Constraints from the Lensing Power Spectrum

- Appears ACT Lensing power spectrum data might favor a universe with Ω_Λ …



[Sherwin, Dunkley, Das et al. in prep.]

- So construct WMAP + ACT-lensing Likelihood, calculate constraints on Ω_Λ

Lensing: CMB-only Evidence for Ω_Λ

2D confidence contours:

[Sherwin, Dunkley, Das et al. in prep.]

Lensing: CMB-only Evidence for Ω_Λ

1-D Posterior distribution for Ω_Λ:

Peak at $\Omega_\Lambda = 0.67$

[Sherwin, Dunkley, Das et al. in prep.]

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

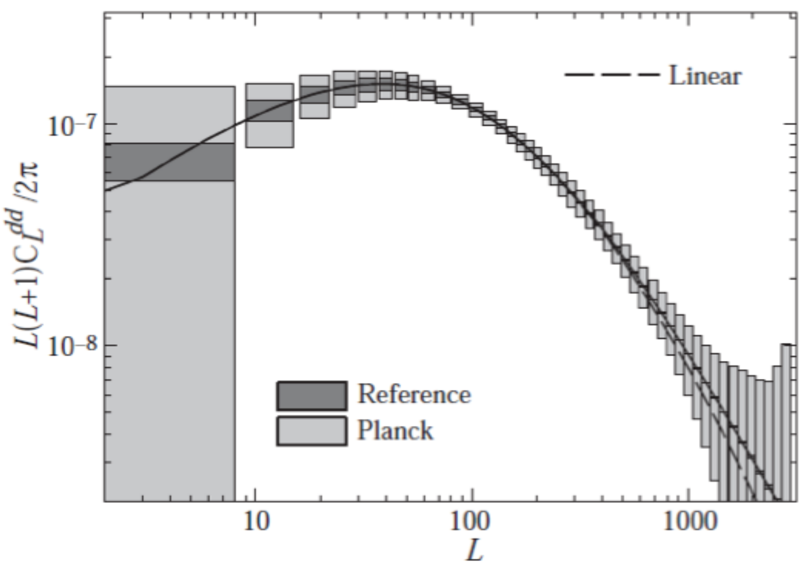
Evidence for Ω_Λ From the CMB Alone

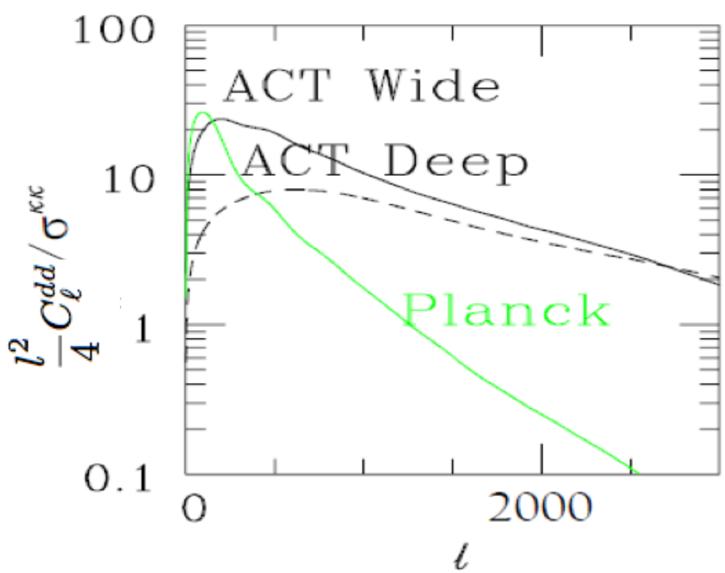
- Using WMAP + ACT - Lensing only, we can rule out a universe without Dark Energy at 3.5 sigma
- Different systematics than SN, LSS probes, small
- Can do MUCH better with SPT, Planck, ACTPOL…
- This is an independent confirmation of the existence of Ω_Λ from just the CMB

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 Ω_Λ 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