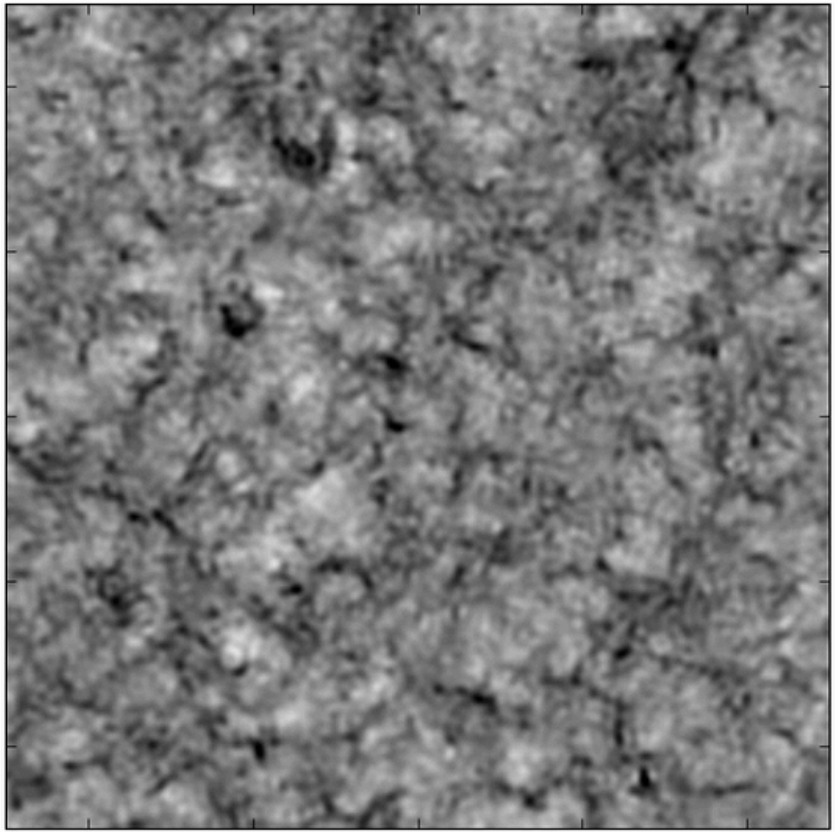
CMB Lensing Measurements with ACT and ACTPol



Blake D. Sherwin (Princeton University, Dept. of Physics)
with Sudeep Das, David N. Spergel, Jo Dunkley and others

Outline

- Introduction to CMB Lensing
- Lensing reconstruction
- The first detection of the CMB lensing power spectrum with the Atacama Cosmology Telescope (ACT) and resulting cosmological constraints
- Cross-correlations with ACT Lensing
- Polarization lensing with ACTPol

Dark Matter

- 80 percent of matter is invisible dark matter, distributed in structures across the universe.

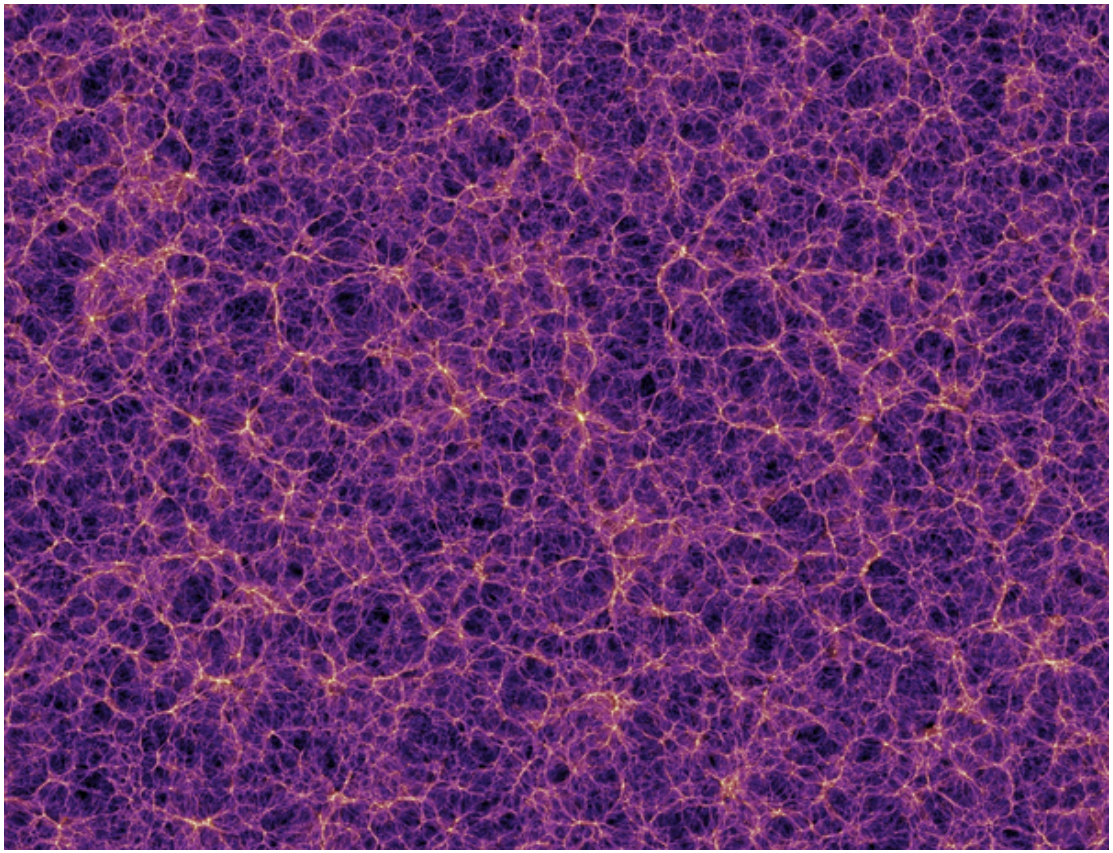


Image Credit: Millenium Simulation (Springel et al 2005)

Observing Dark Matter

- Dark matter only interacts through gravity (on most scales).
- Gravity from dark matter deflects/lenses light rays that pass by

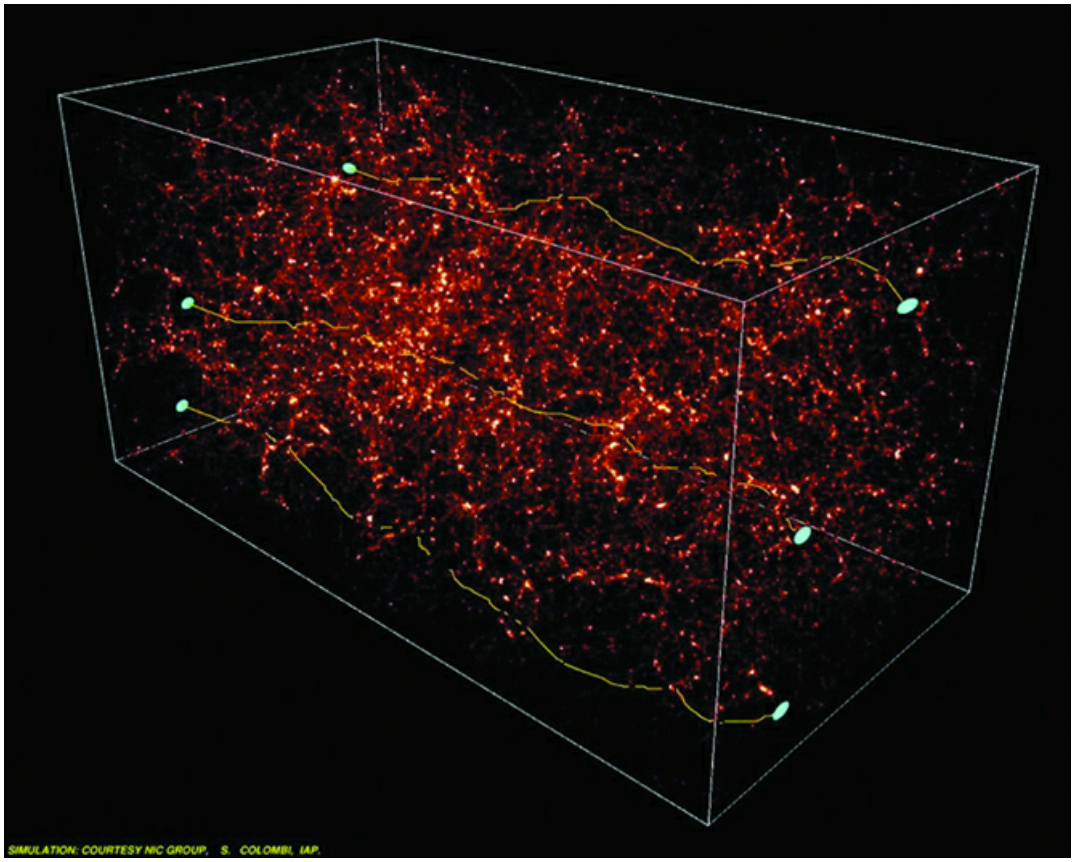
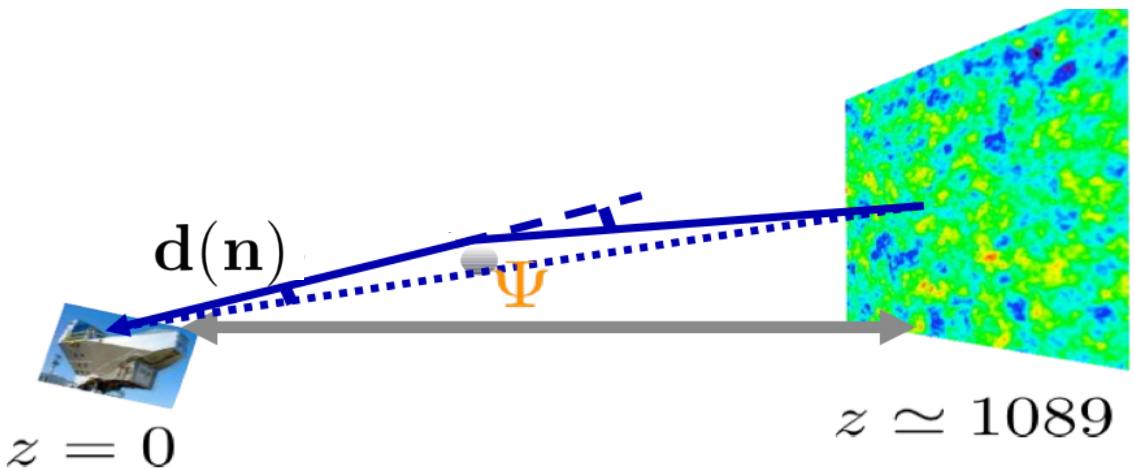


Image Credit: MPA

Introduction to CMB Lensing

- Cosmic Microwave Background (CMB) photons are gravitationally deflected by large scale structure

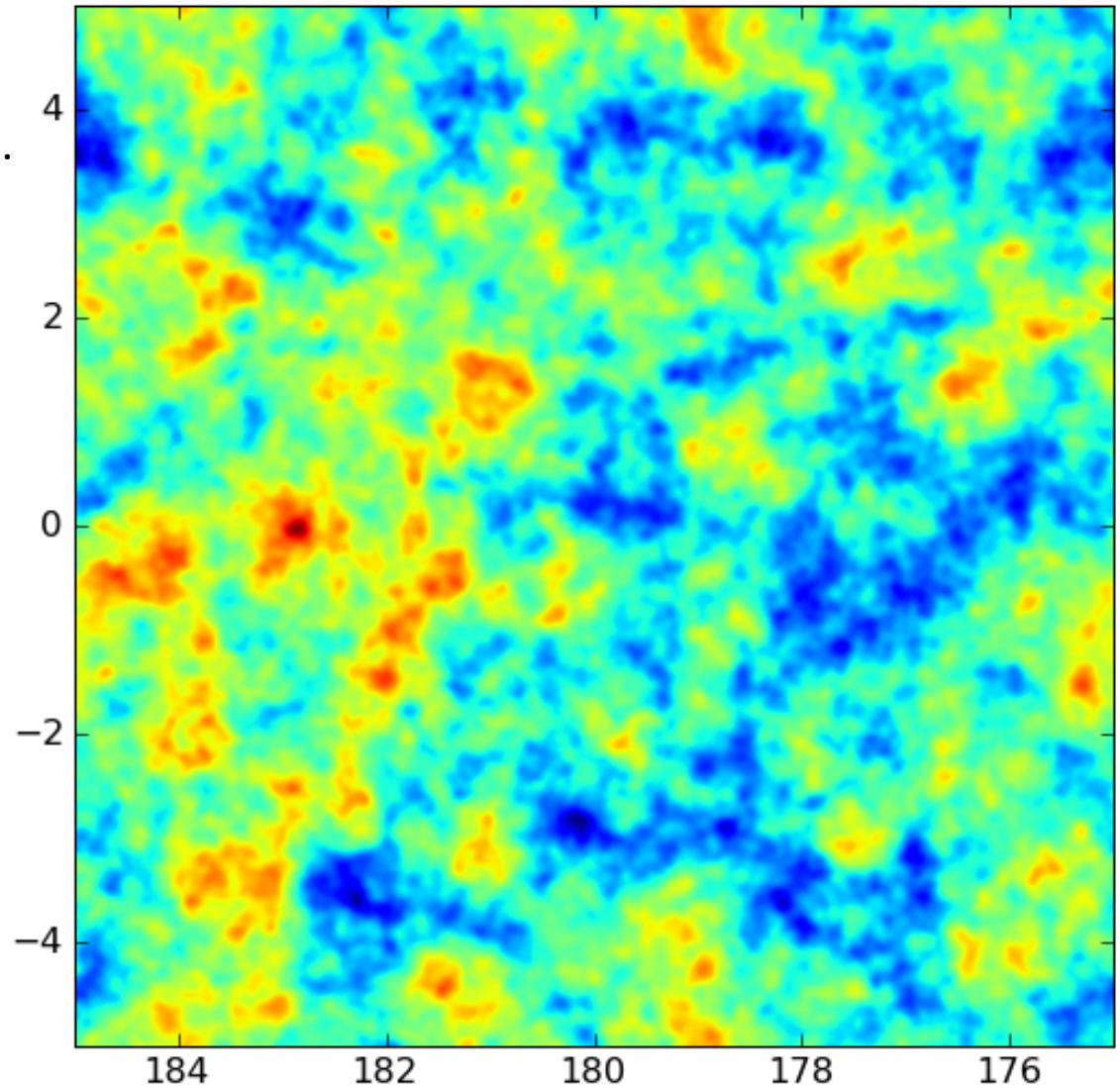


- Many (≈50) small random deflections lead to net deflection $\mathbf{d}(\mathbf{n})$ (≈3 arcmins) which remaps the CMB:

$$T(\hat{\mathbf{n}})_{\text{lensed}} = T(\hat{\mathbf{n}} + \mathbf{d}(\hat{\mathbf{n}}))_{\text{unlensed}}$$

Unlensed CMB

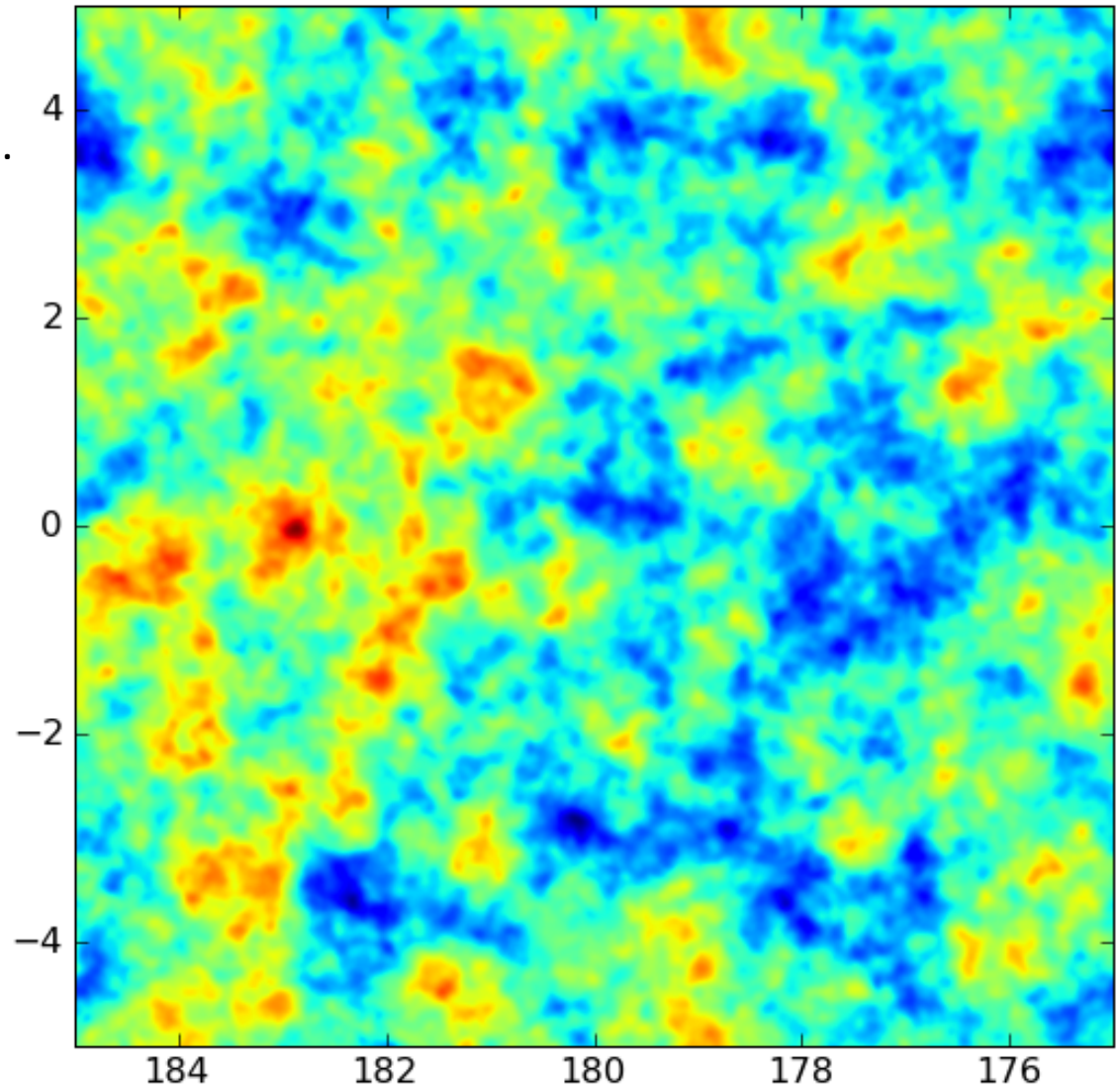
CMB Temp.



10°

Lensed CMB

CMB Temp.

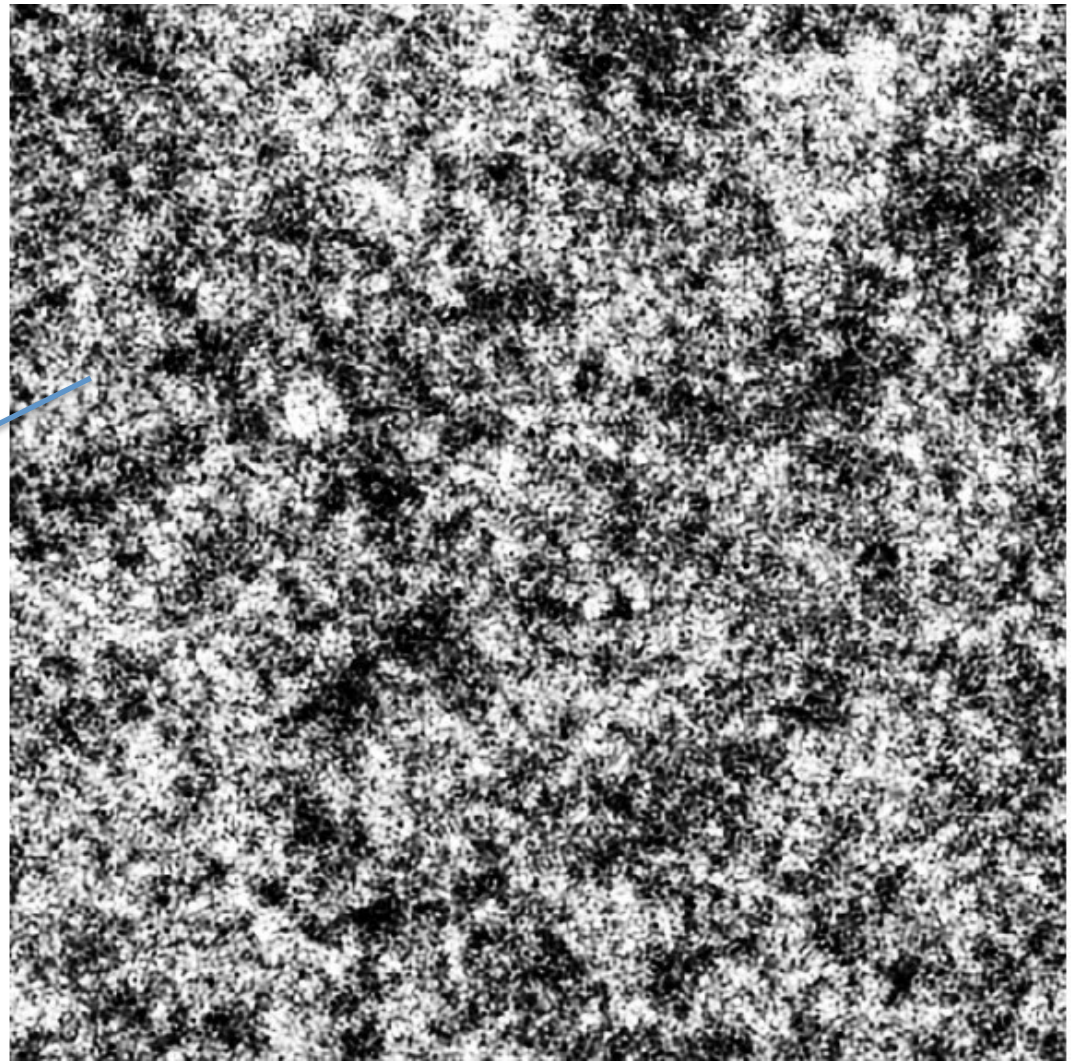


10°

Lensing Deflection

$|\mathbf{d}(\hat{\mathbf{n}})|_{\mathrm{filt}}$

small arcminute-scale deflections, coherent on degree scales



10°

In this talk, I will plot the magnitude of the deflection $|\mathbf{d}(\hat{\mathbf{n}})|_{\mathrm{filt}}$
(actually, the gradient-high-pass-filtered magnitude a.k.a. lensing convergence)

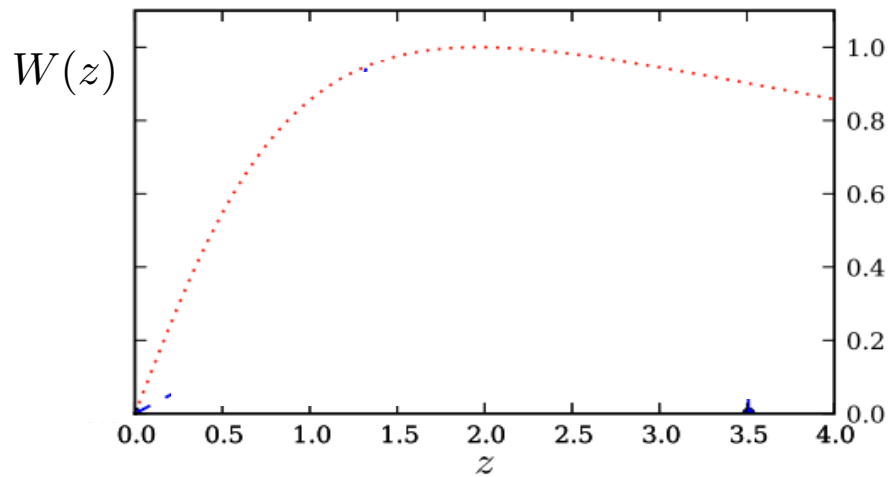
Lensing Deflection Field as a Mass Probe

- Amount of lensing deflection depends on the projected (dark) matter density in that direction

$$|\mathbf{d}(\hat{\mathbf{n}})|_{\rm filt} = \int dz W(z) \delta(\hat{\mathbf{n}}, z)$$

δ: fractional matter overdensity $\delta = (\rho - \bar{\rho})/\bar{\rho}$
$W(z)$: geometric projection kernel

- Sensitive to a wide redshift range peaking at z~2



- If we can measure the lensing deflection, we can determine the projected distribution of dark matter.

Lensing Changes CMB Statistics

- Without lensing, CMB temperature and its gradient are uncorrelated (due to statistical isotropy; unlensed CMB doesn't have a preferred direction)

$$\langle T \nabla T \rangle_{\mathrm{CMB}} = 0$$

- Expand T in small deflections, find a gradient dependence

$$T(\hat{\mathbf{n}})_{\mathrm{lensed}} = T(\hat{\mathbf{n}} + \mathbf{d}(\hat{\mathbf{n}}))_{\mathrm{unlensed}} = T(\hat{\mathbf{n}})_{\mathrm{unl.}} + \mathbf{d}(\hat{\mathbf{n}}) \cdot \nabla T(\hat{\mathbf{n}})_{\mathrm{unl.}}$$

➡ **Lensing correlates temperature with its gradient such that**

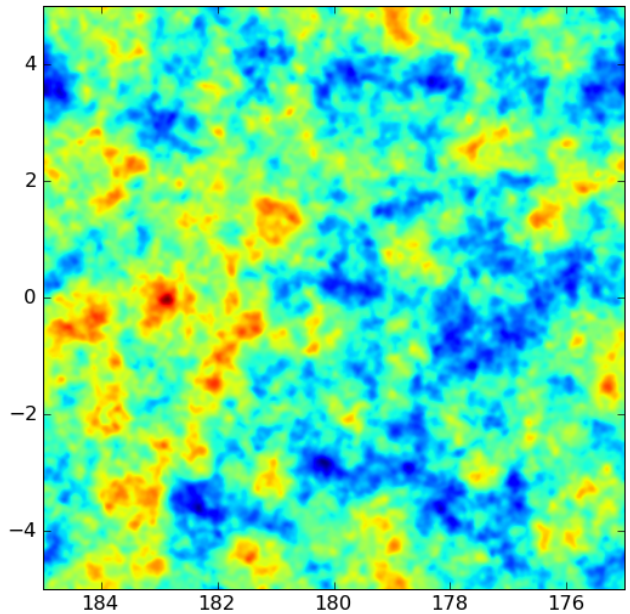
$$\langle T \nabla T \rangle_{\mathrm{CMB}} \propto \mathbf{d}$$

How to Measure CMB Lensing: Reconstruction

[Zaldarriaga, Seljak 1997]

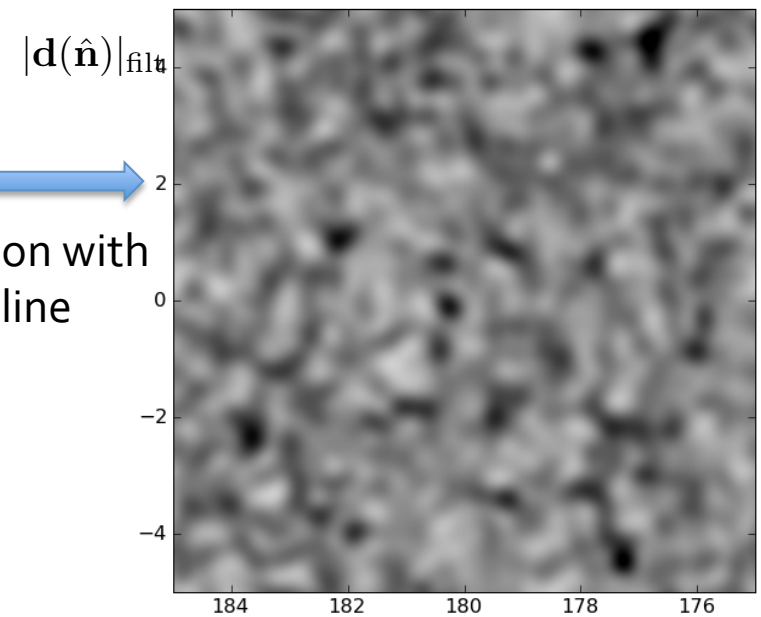
- Use this change in statistics of small scale CMB fluctuations:
- Estimate lensing deflection by measuring correlations between temperature and its gradient [Hu, Okamoto 2002]

$$\hat{\mathbf{d}}(\hat{\mathbf{n}}) = \left[T_{\text{Filter 1}} \nabla T_{\text{Filter 2}}\right]_{\text{Filter 3}} (\hat{\mathbf{n}})$$



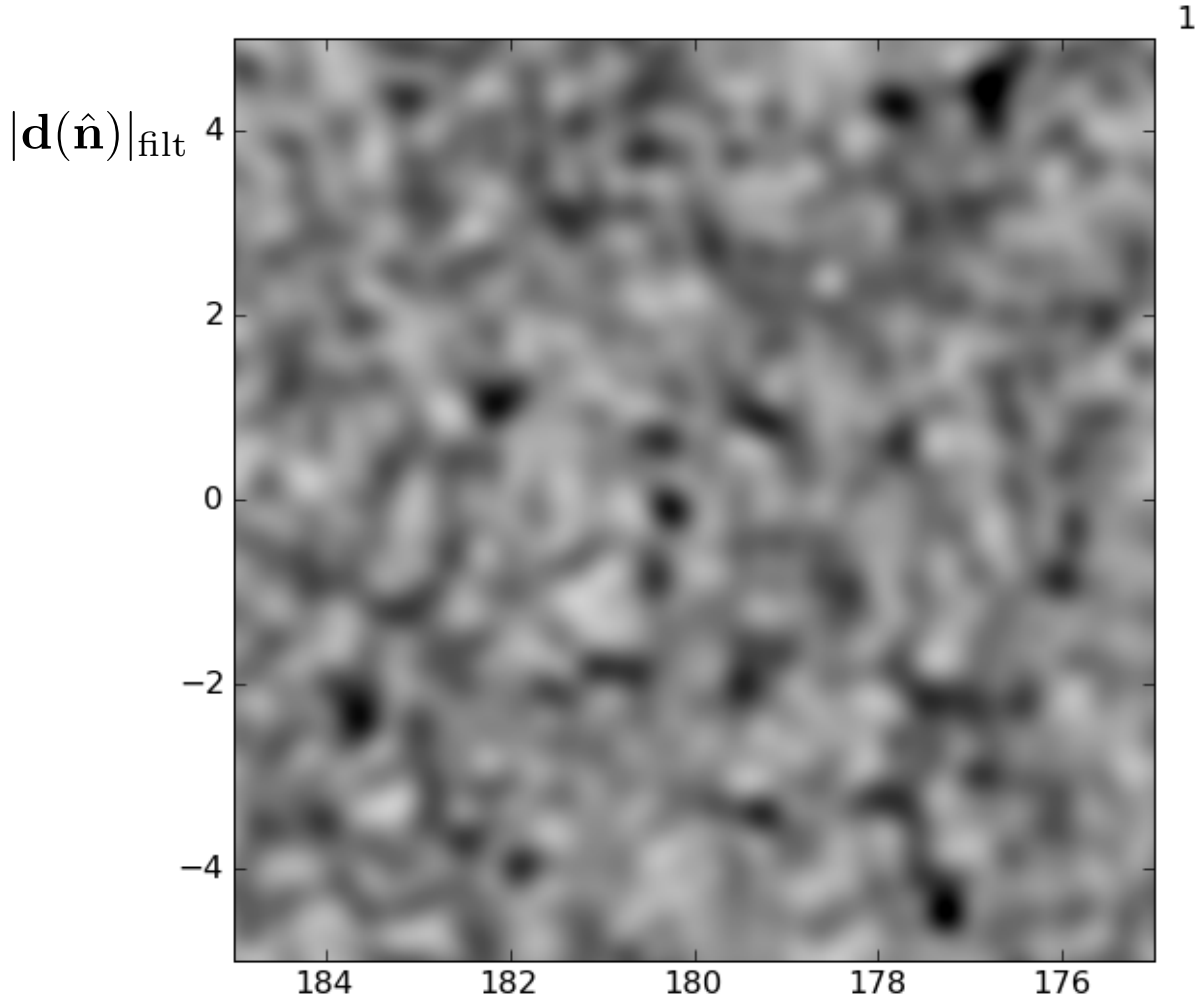
lensed temperature

reconstruction with lensing pipeline



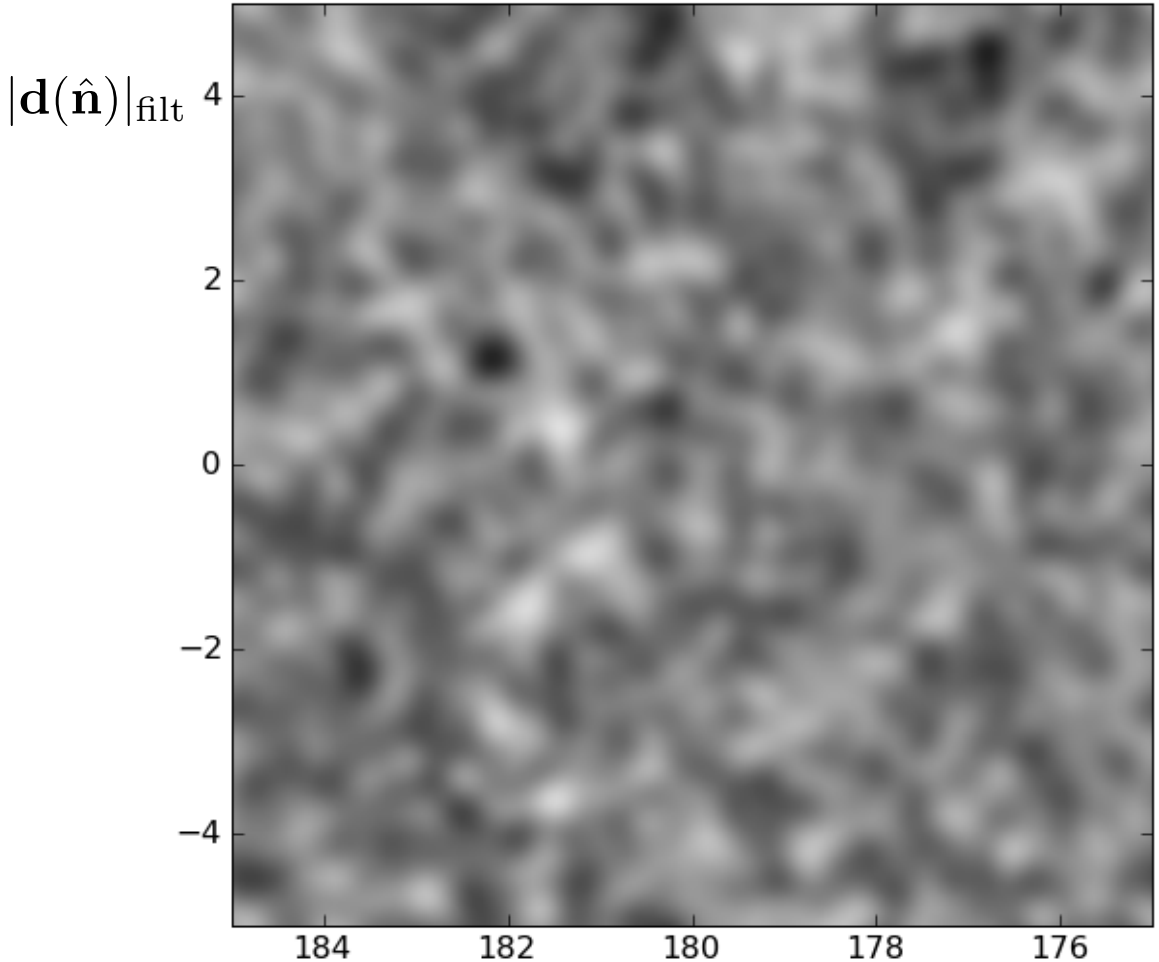
estimate of lensing deflection (noisy)

ACT CMB Temperature Lensing Pipeline



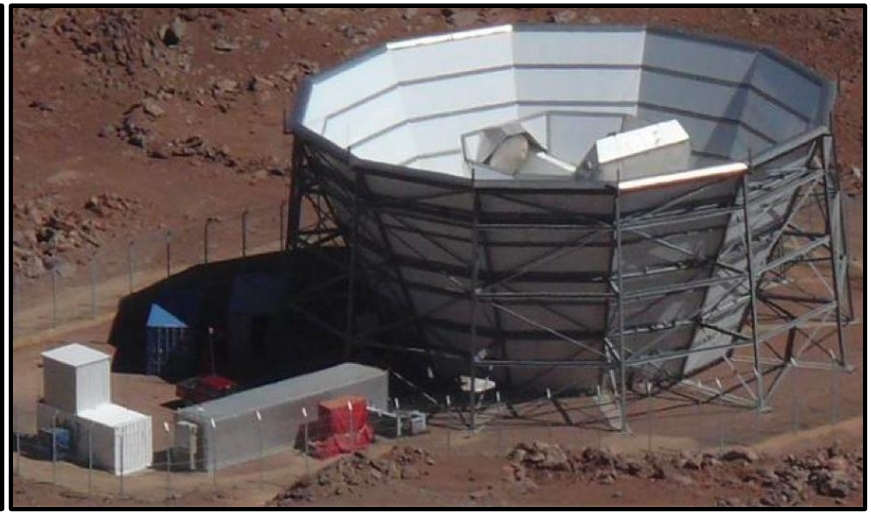
Simulation: reconstructed lensing (noisy estimate)

ACT CMB Temperature Lensing Pipeline



Simulation: true lensing deflection (used to make the sims)

CMB Lensing Reconstruction with ACT Data



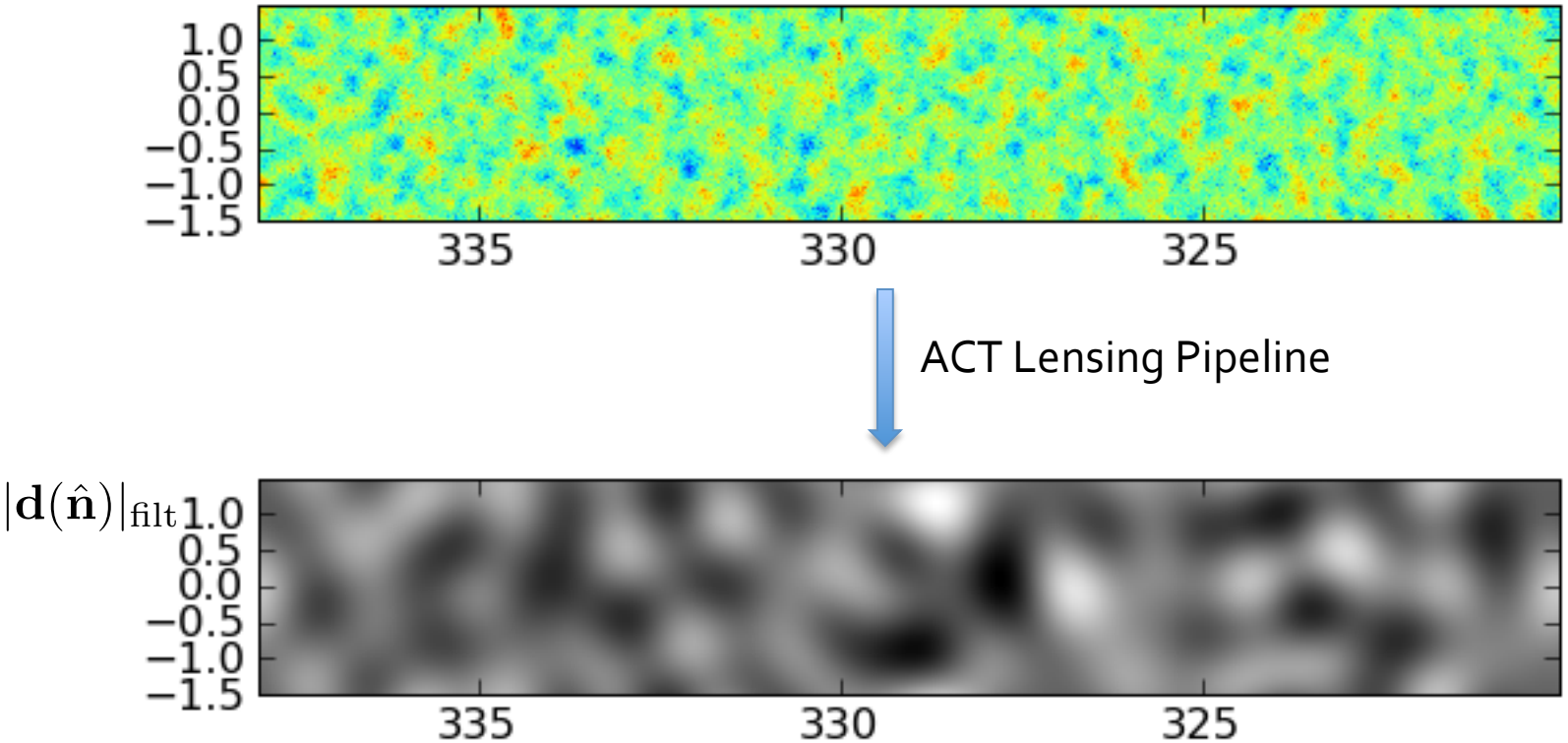
CMB temperature data from the **Atacama Cosmology Telescope**:

- CMB temperature telescope with arcminute resolution (1.4 arcmin beam)
- For the lensing analysis we used 324 sq. deg of maps with ~20uK-arcmin noise levels (on SDSS stripe 82)
- For the lensing power spectrum, we used only the cleanest, signal dominated scales (l=500-2300) to avoid atmospheric noise/IR source/SZ contamination

[See also many interesting results from ACT collaboration on power spectrum, clusters, parameters…]

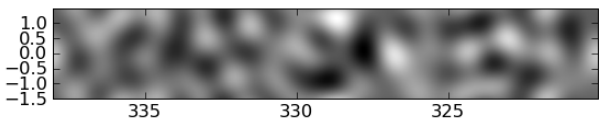
CMB Lensing Reconstruction with ACT Data

- Lensing pipeline designed to minimize systematics: finite size/window effects, IR/SZ/radio sources, atmospheric and anisotropic noise…



Note: Large scale lensing information comes from much smaller temperature scales

Cosmology from a lensing map



$$|\mathbf{d}(\hat{\mathbf{n}})|_{\rm filt} = \int dz W(z) \delta(\hat{\mathbf{n}}, z)$$

Geometry Growth of Structure

q:galaxy, quasar, lensing…

$$\mathrm{d} \times \mathrm{d}$$

$$\mathrm{d} \times q$$

Lensing power spectrum C_ℓ^{dd}

Lensing cross-correlations C_ℓ^{dq}

(+other ways: cluster mass reconstruction, de-lensing to improve B-mode detection)

$\mathrm{d} \times \mathrm{d}$

First Detection of the CMB Lensing Power Spectrum C_ℓ^{dd} and Cosmological Constraints

Why measure the CMB lensing power spectrum?

$$\frac{\ell^2}{4} C_\ell{}^{dd} = \int_0^{\eta_*} d\eta \, \underbrace{W^2(\eta)}_{\text{geometry}} \, \underbrace{\left[D(\eta)/a(\eta)\right]^2}_{\text{growth}}$$

We can learn a lot about cosmology from such measurements

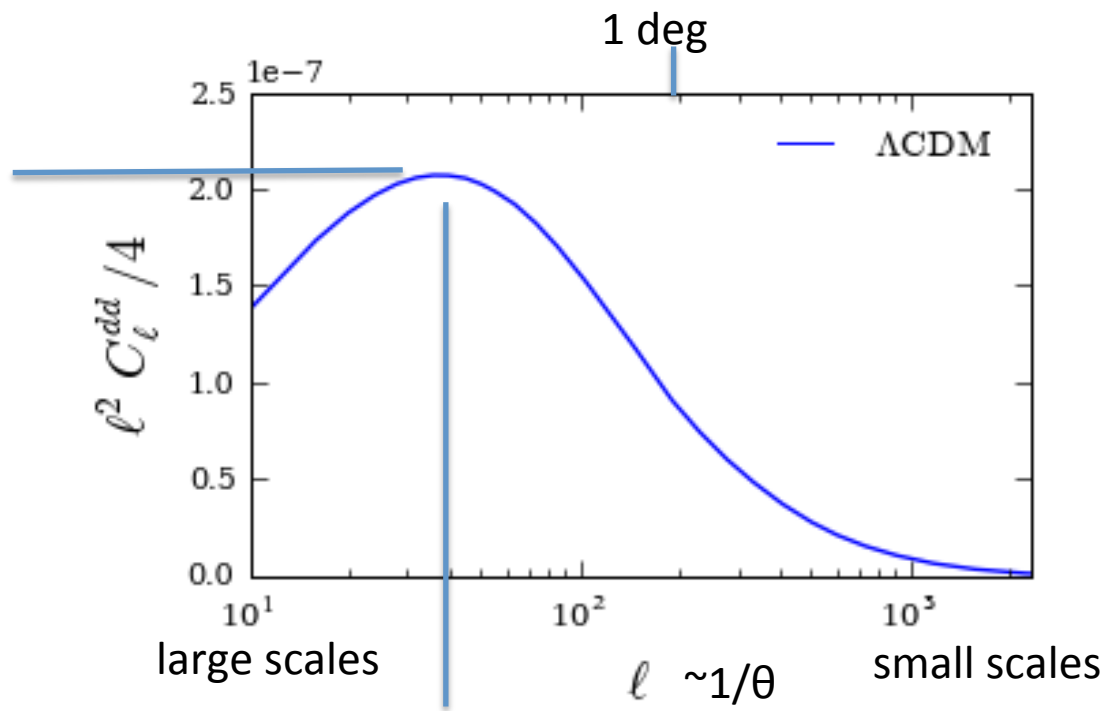
- Constrain dark energy density and properties,
- Constrain and measure neutrino masses
- Test LCDM model for large-scale distribution of dark matter
- Measure amplitude of fluctuations, H_0 and many other parameters

The CMB Lensing Power Spectrum

$$< \mathbf{d}(\mathbf{l}) \cdot \mathbf{d}(\mathbf{l}') >= (2\pi)^2 C_l^{dd} \delta(\mathbf{l} - \mathbf{l}')$$

Y axis: "How much deflection² ...."

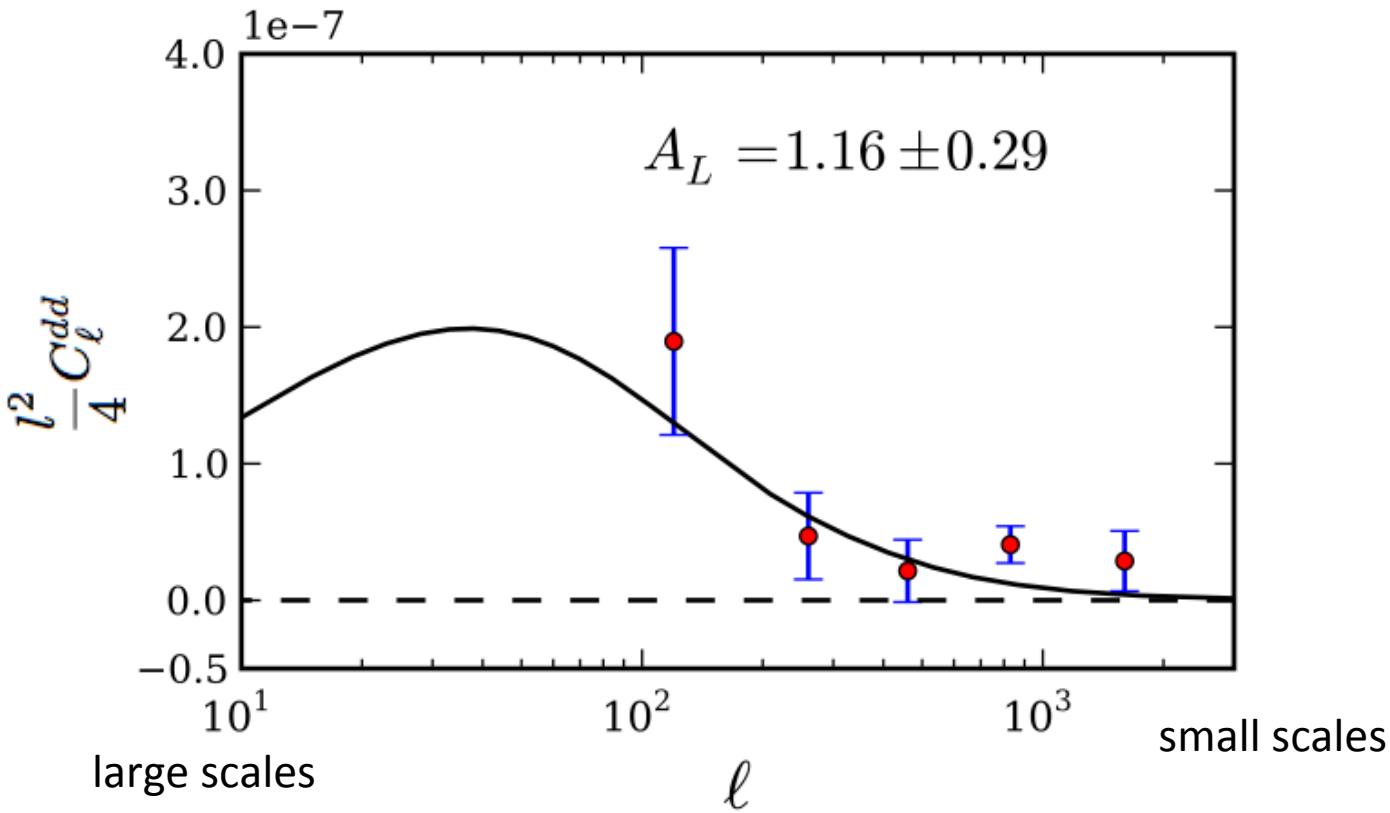
l = 200 lensing information comes from temperature modes *separated* by 200, e.g. l = 2000 and l = 2200



X axis: "for a deflected patch of this scale?"

First Detection of the CMB Lensing Power Spectrum

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

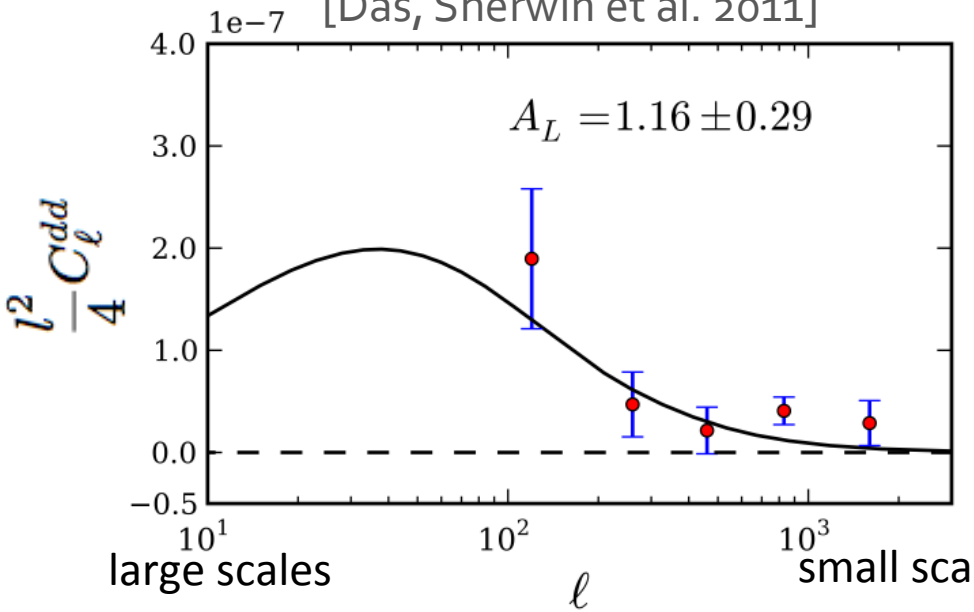


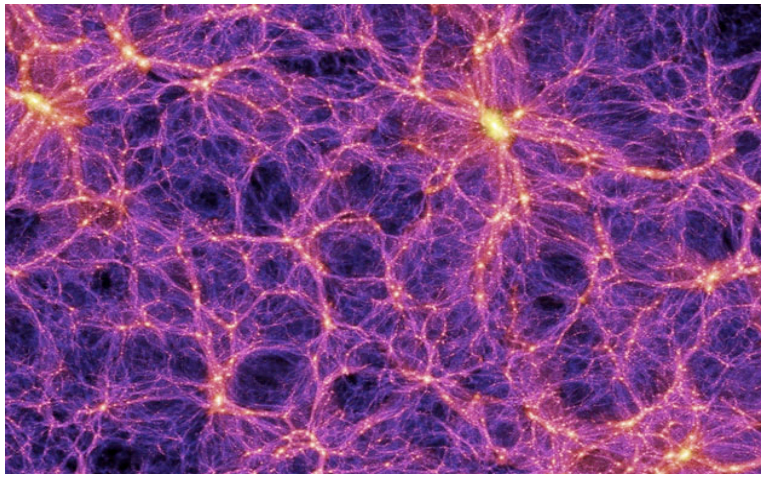
[Das, Sherwin et al. 2011]

First Detection of the CMB Lensing Power Spectrum

- Consistent with WMAP LCDM prediction
- Includes multiple null and systematic tests. tSZ, kSZ, IR-source, noise contamination found to be negligible.

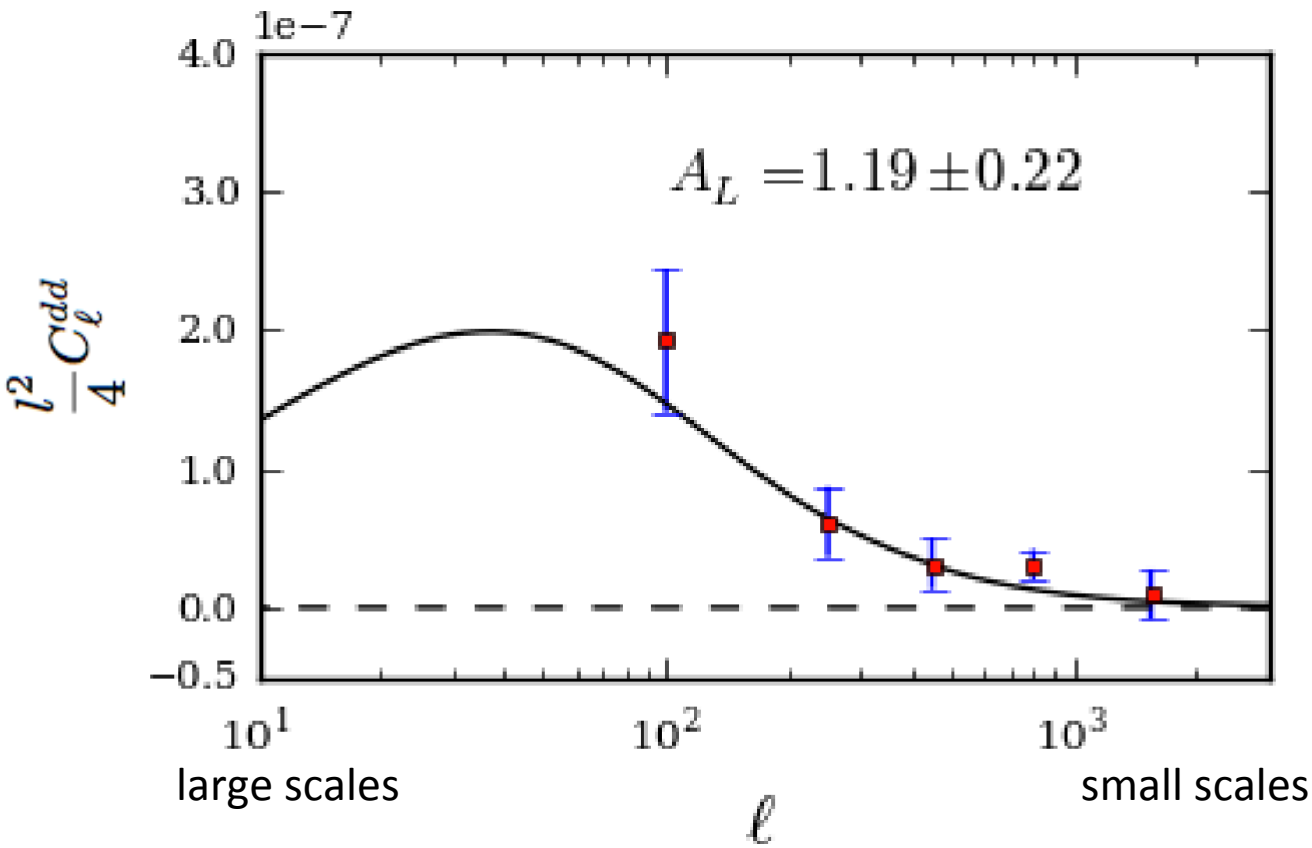
[Das, Sherwin et al. 2011]





- Direct gravitational probe of dark matter to z~1100 (though most sensitive to z~0.5-3) on large linear scales

Spectrum Update with More Data (Preliminary)

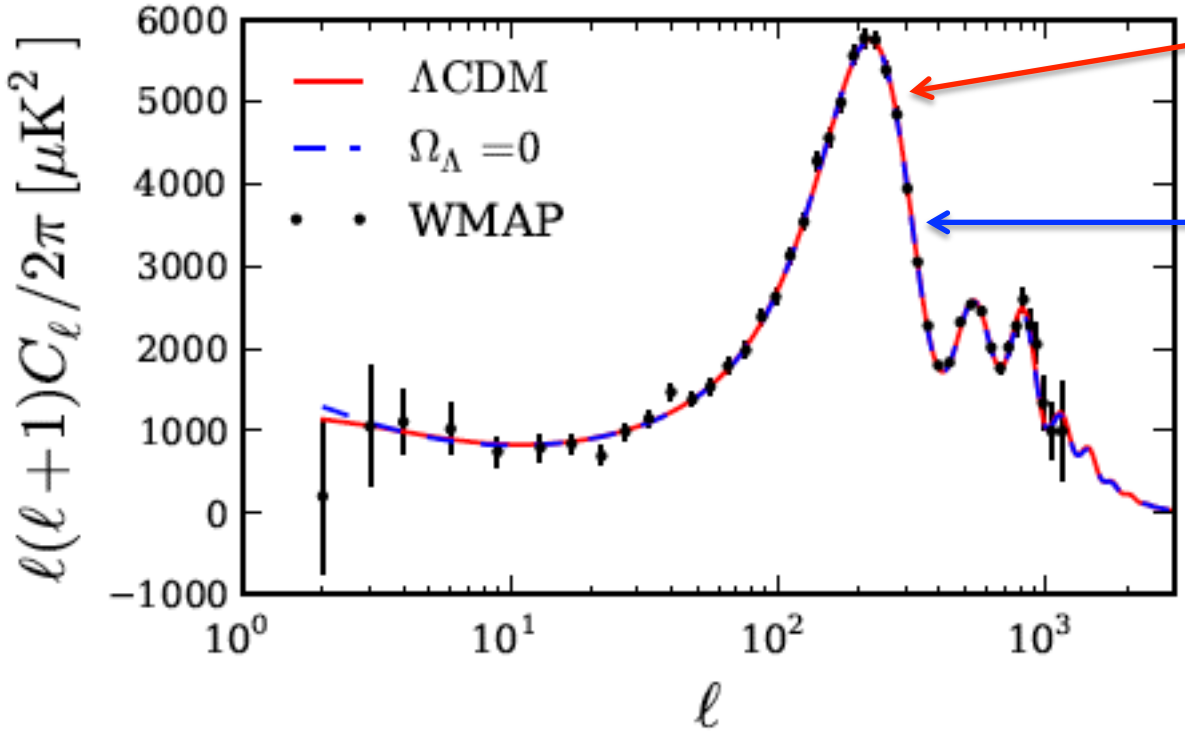


[Das, Sherwin, or a permutation, in prep.]

>5 sigma

What information about Ω_Λ can we get from the CMB alone?

- Universes with and without Lambda have nearly the same CMB temperature power spectrum (geometric degeneracy):



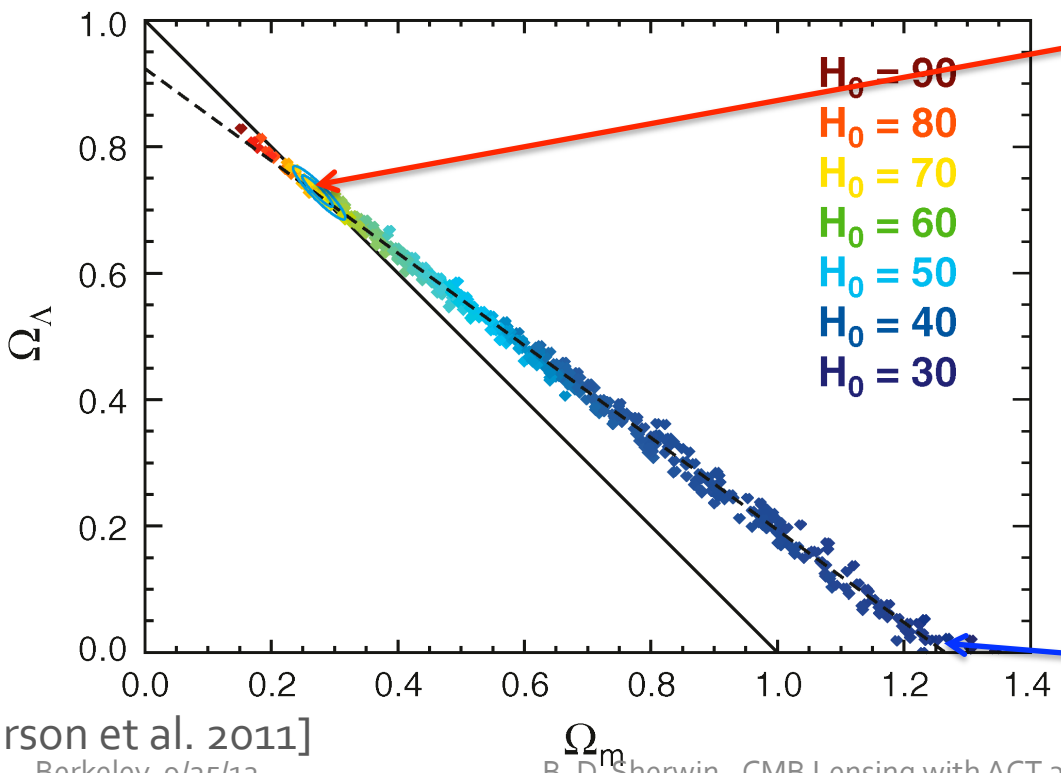
Standard flat LCDM model with D.E.

Curved model with no dark energy

[e.g. Bond, Efstathiou, Tegmark 1997]

What information about Ω_Λ can we get from the CMB alone?

- CMB power spectra constrain Lambda, curvature and other "late time" parameters through the angular scale of peaks
- Degeneracy arises because both Lambda and curvature can give the same scale (same ang. diameter distance to z=1100)



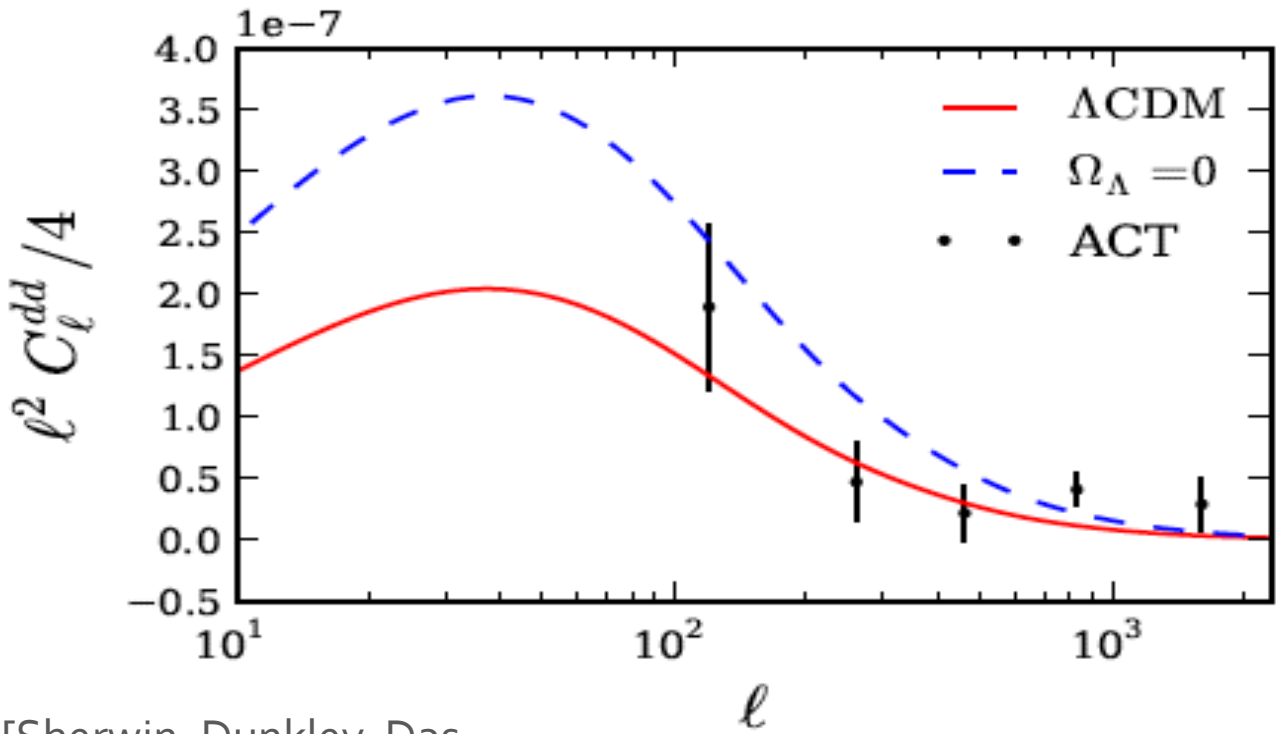
Standard flat LCDM model with D.E.

[density of points prop. to probability]

Curved model with no dark energy

[Larson et al. 2011]

Lensing breaks degeneracy…

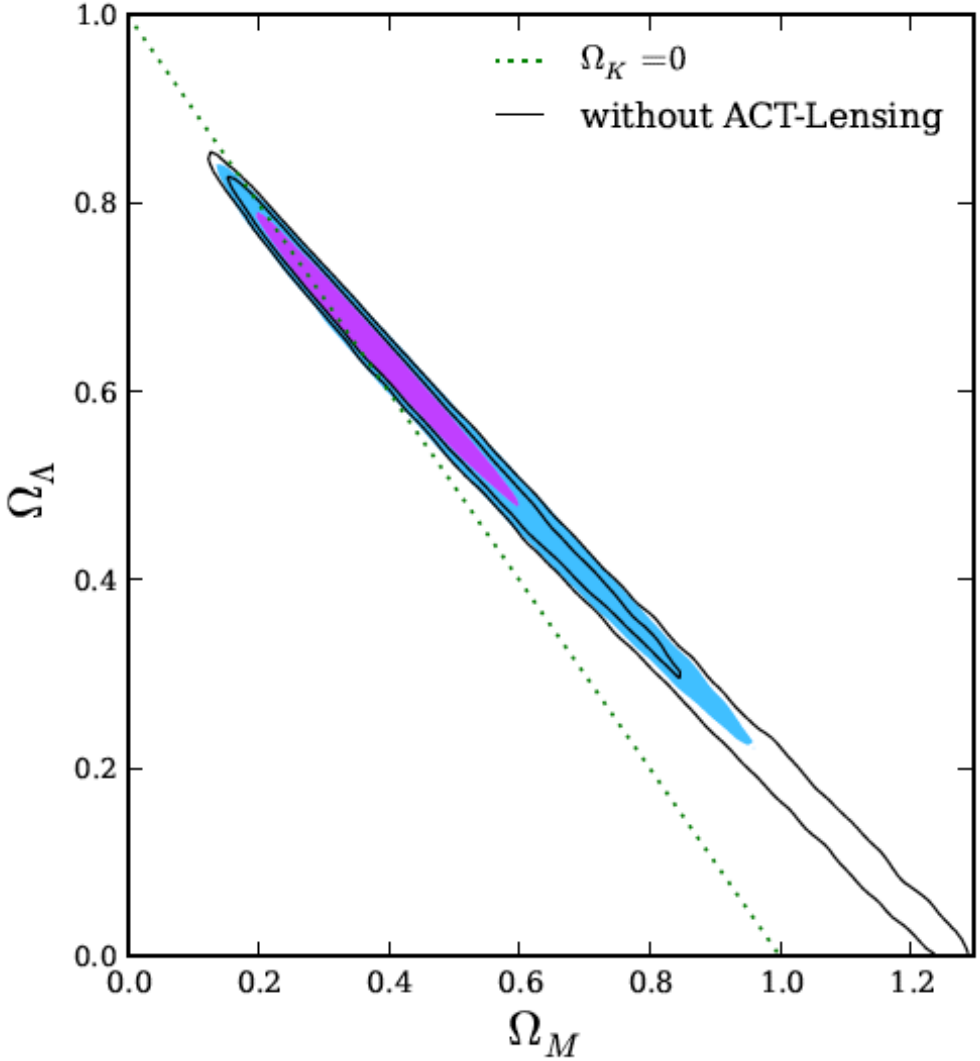


[Sherwin, Dunkley, Das et al. 2011]

…as the amount of lensing is sensitive to the size of the universe / H_0.

Lensing: CMB-only Evidence for Ω_Λ

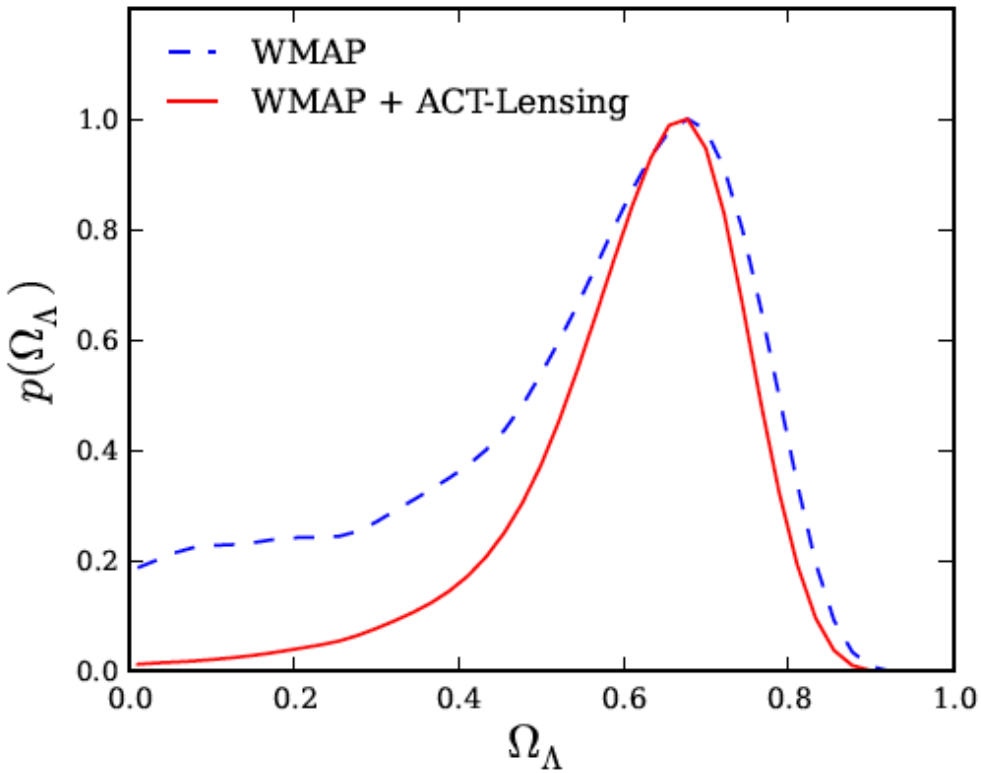
2D confidence contours:



[Sherwin, Dunkley, Das et al. 2011]

Lensing: CMB-only Evidence for Ω_Λ

1-D Posterior probability distribution for Ω_Λ:



Peak at $\Omega_\Lambda = 0.67$

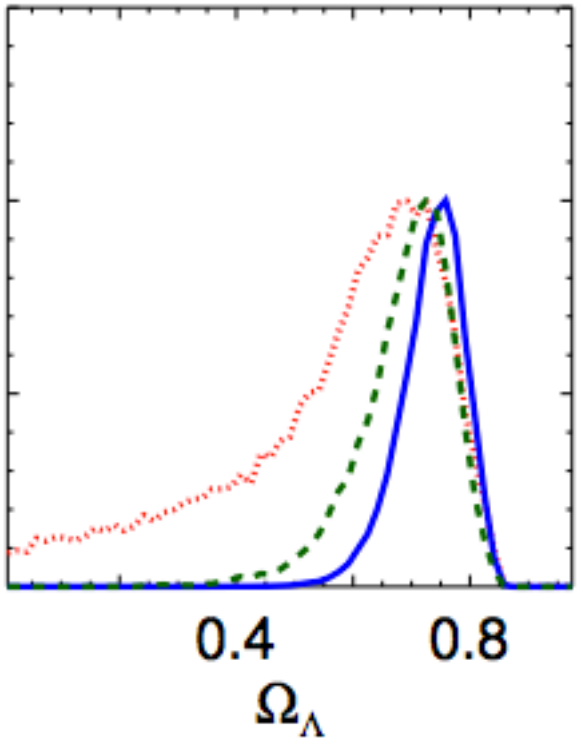
[Sherwin, Dunkley, Das et al. 2011]

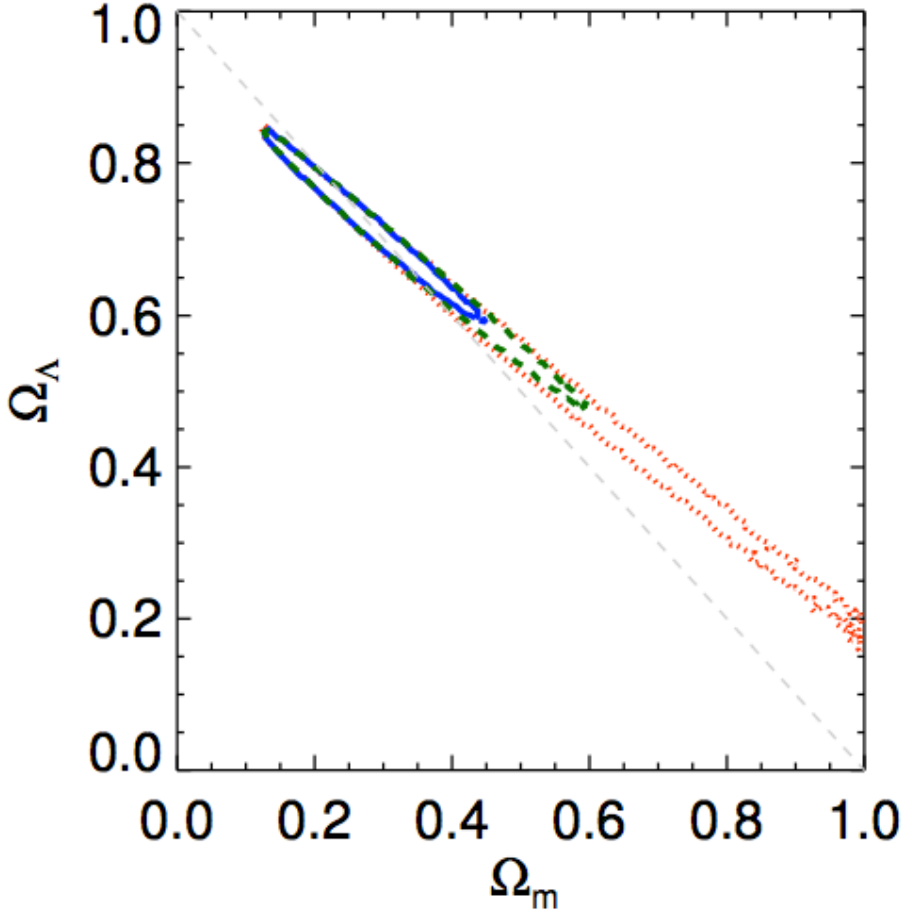
With lensing: LCDM model favored at **3.2 sigma** over best model with no DE .

Evidence for Ω_Λ From the CMB Alone

- Using WMAP + ACT - Lensing only, we can disfavor a universe without Dark Energy at 3.2 sigma. This is an independent confirmation of the existence of Ω_Λ from just the CMB
- Lensing is from known redshifts, insensitive to bias, from large, linear scales that are theoretically well understood, provides internal detection
- Can do MUCH better with SPT, Planck, ACTPOL…now well above 5 sigma.

2012 Update: SPT Lensing Constraints



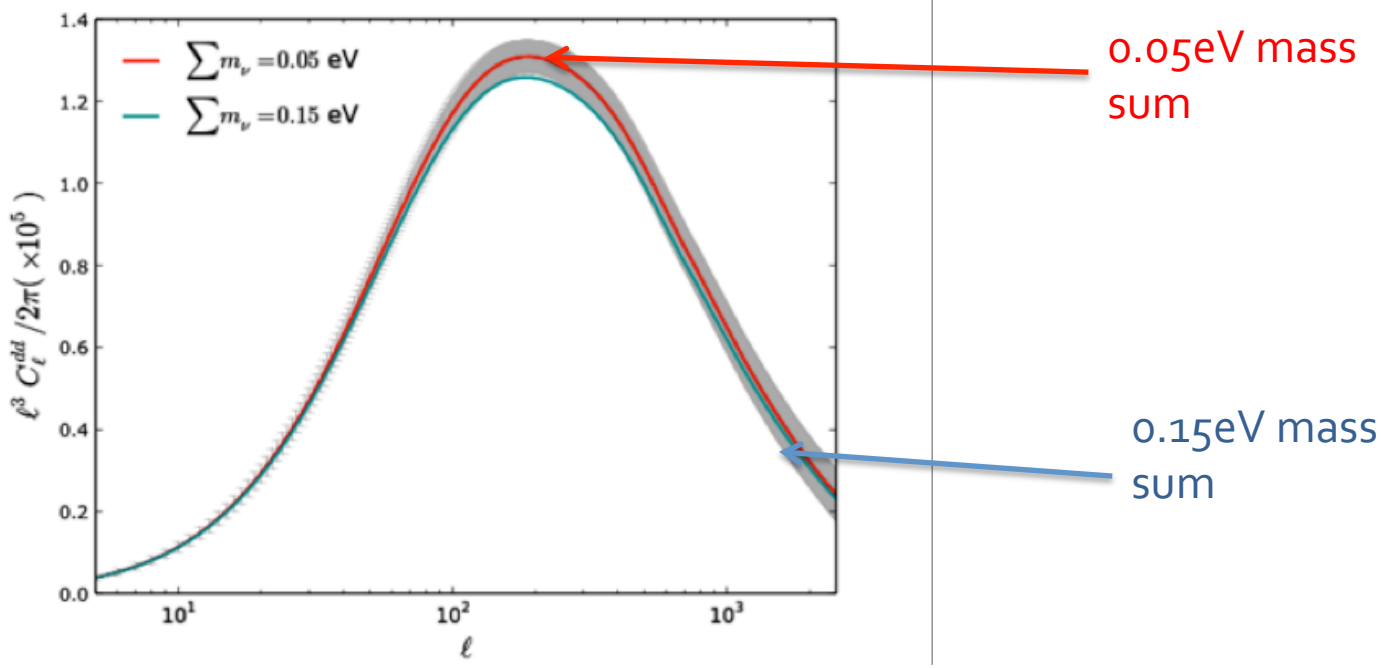


>5 sigma preference for LCDM

[Van Engelen, Keisler, Zahn et al. 2012]

Soon, similar constraints on neutrino masses possible

- Oscillation experiments only measure the difference between neutrino masses, but with lensing we can measure their sum



- Massive neutrinos don't cluster on small scales so small structures don't grow as much
- Shape of lensing power spectrum reflects this suppression of growth (5% change for a 0.1 eV change in neutrino mass sum)

$$\mathrm{d} \times q$$

CMB Lensing Cross-Correlations C_ℓ^{dq}

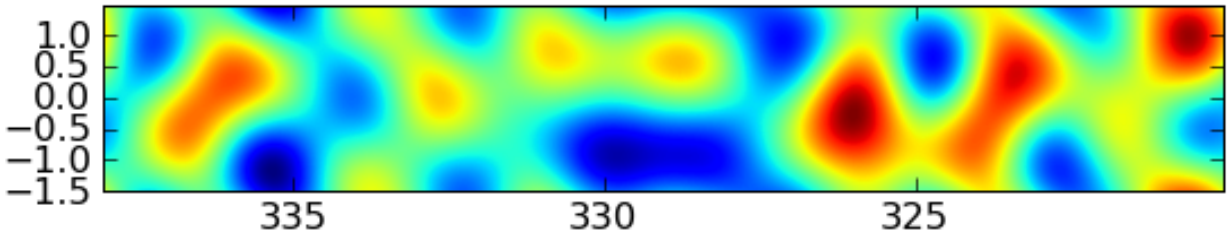
Why cross-correlate CMB lensing with matter tracers?

We can learn a lot about astrophysics from such measurements

- bias of tracers as a function of redshift
- masses of host halos
- other properties: e.g. quasar duty cycle and its evolution
- properties of backgrounds e.g. infrared background
- CMB lensing x galaxy-galaxy lensing: tomography
- CMB lensing x galaxy-galaxy: systematics control

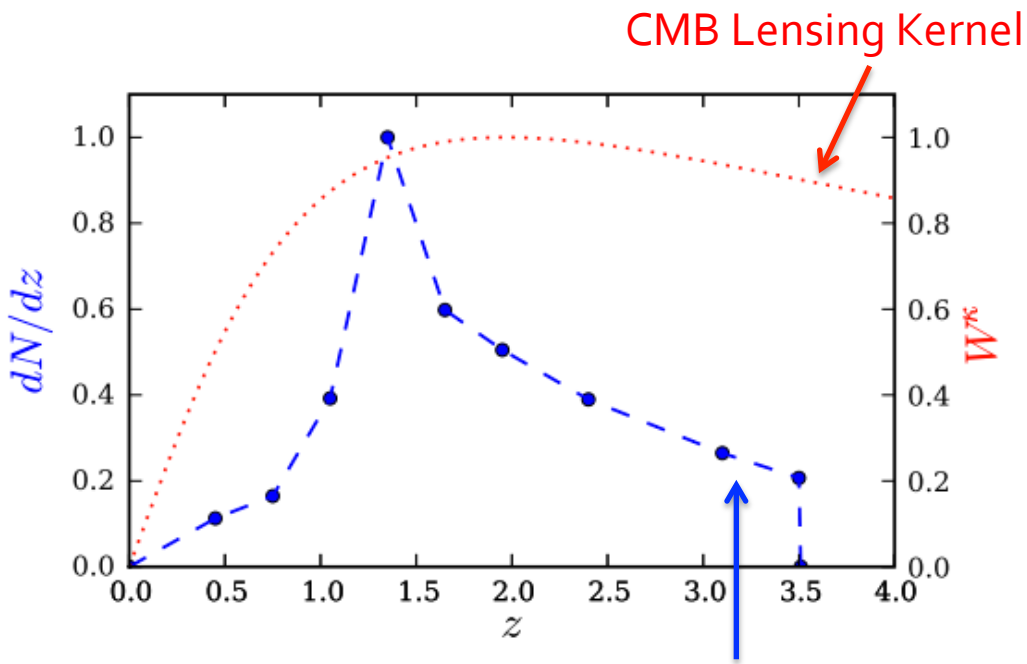
Tracers for cross-correlations could be: galaxies, quasars, clusters/SZ, Ly-alpha, gal-gal lensing, x-ray/IR backgrounds, etc.

Quasar-CMB lensing Cross-correlation



A quasar density map

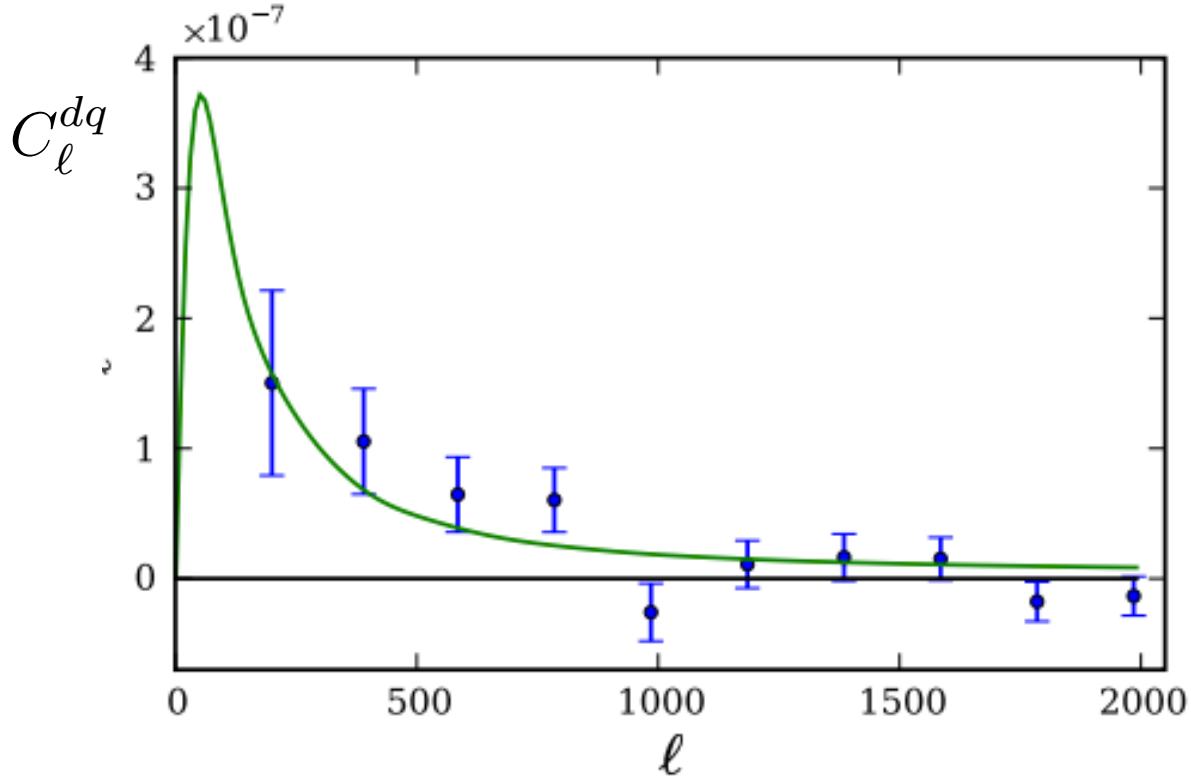
- Lensing depends on the matter distribution. QSOs trace the matter distribution, and their redshift distribution matches the lensing kernel.
- This implies both are correlated



Quasar-CMB lensing Cross-correlation

Cross-power with SDSS-QSO (XDQSO) photometric catalog (Bovy et al 2010):
4 sigma detection

(+many systematic tests…)



➡ quasars trace mass.

[Sherwin, Das, Hajian et al. 2012]

Quasar-CMB lensing Cross-correlation

[Reminder: bias relates tracer- to matter-overdensity $\delta_q = b\ \delta$]

- Theory cross-power between lensing and tracer density depends on bias b, matter power spectrum P and geometry

$$C_\ell^{dq} = \int dz\ b(z) \frac{dN}{dz} P(l/d_A(z), z) f(d_A(z))$$

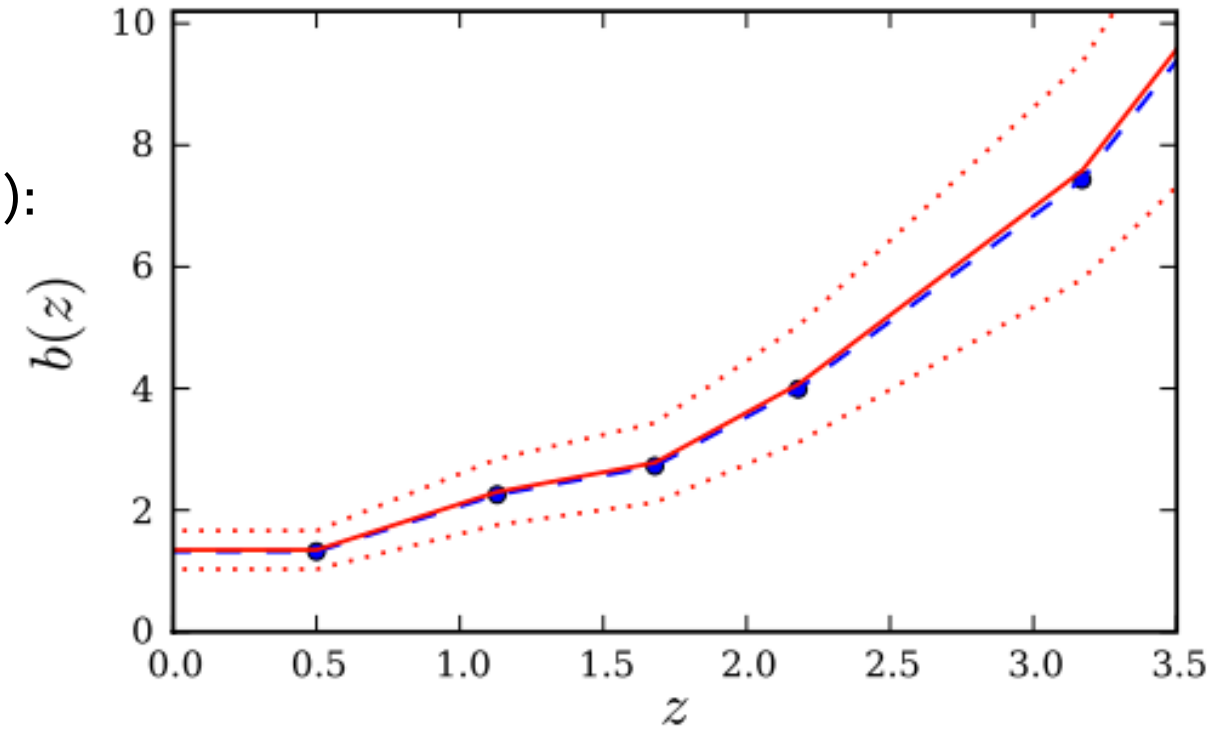
bias redshifts power spec. geometry

- Can extract bias from a measurement of the cross correlation

Quasar-CMB lensing Cross-correlation

Constraint on bias (assuming template): b(z=1.4)=2.5 ± 0.6

This translates to a halo mass of $\log_{10}(M_{200}/M_{\odot})$= 12.9 +0.3/-0.5



[Sherwin, Das, Hajian et al. 2012]

Constraints will improve considerably very soon…

WISE (IR Galaxies) - CMB lensing cross-correlation

[Wright et al 2010]

Work in progress

≈ 8 sigma detection of the cross-power-spectrum: $_{dg}$

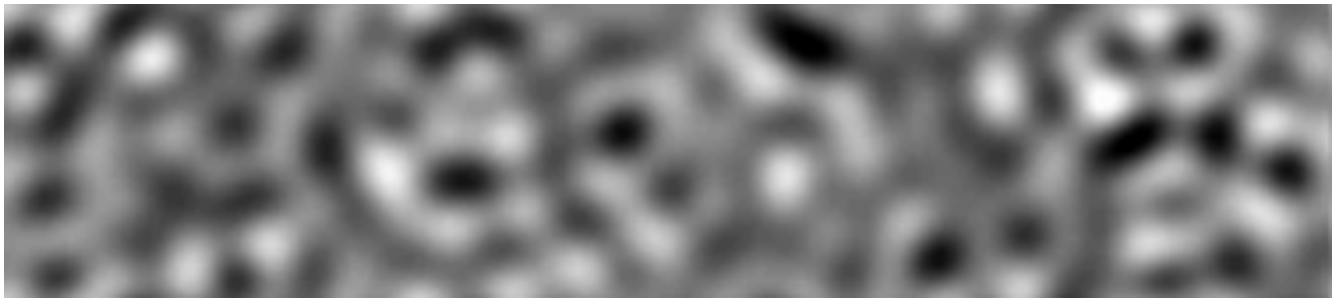
extract b(z) …

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

[see also SPT paper: Bleem et al. 2012]

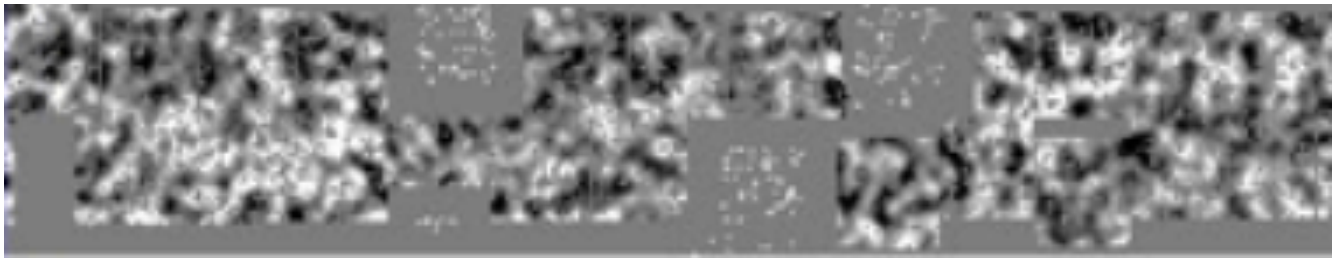
CFHT weak lensing – CMB lensing cross-correlation

CMB lensing



X

CFHT lensing



[Hand, Das, Leauthaud, Sherwin et al. in prep]

In progress… preliminary detection.

CMB Lensing: larger scales, higher z, fewer systematics than galaxy-galaxy lensing, somewhat lower S/N

Bright future: lensing tomography, systematics control

CMB Lensing Timeline

Past:

- 2007: First detection of lensing cross-correlation in WMAP x NVSS (3.4 sigma), WMAP x SDSS + (2.5 sigma) [Smith, Zahn, Dore 2007, Hirata et al. 2007]
- 2008: Peak-smoothing effect seen with ACBAR [Reichardt et al 2008]
- 2011: First detection of lensing power spectrum, ACT (4 sigma)
- 2012: SPT lensing power spectrum (6.3 sigma) [Van Engelen, Keisler, Zahn et al. 2012]

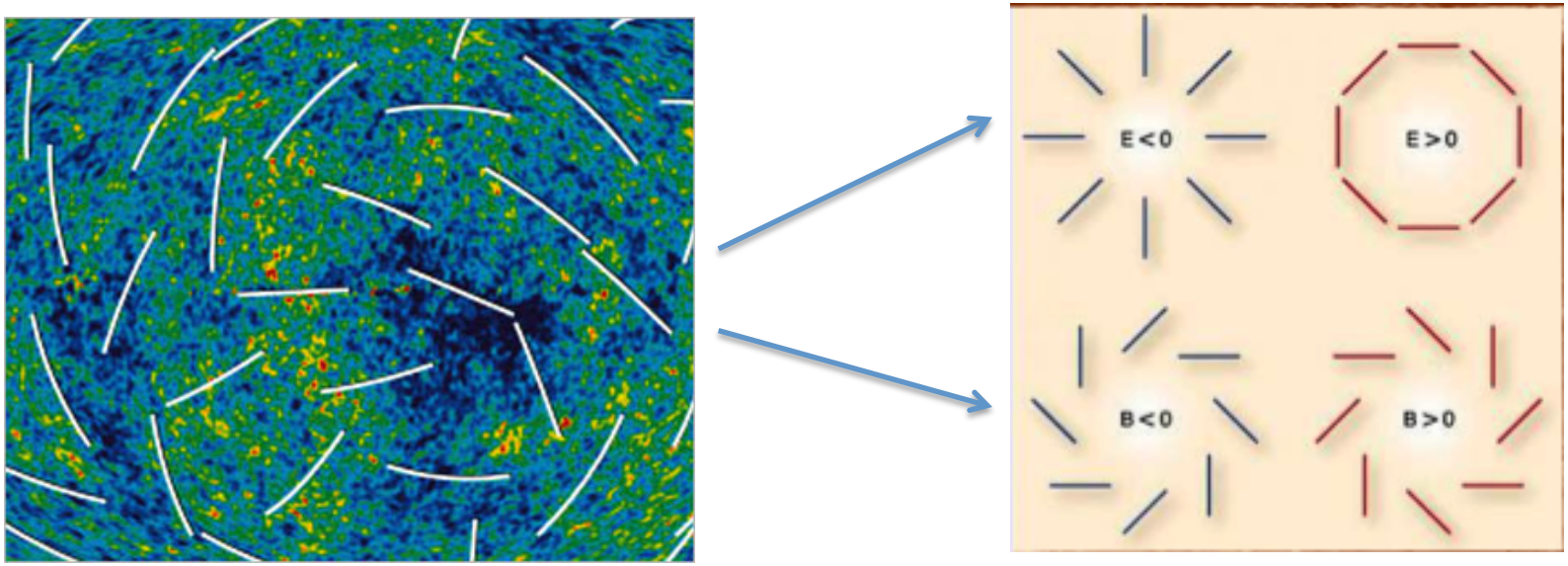
Future - next two years (!!):

- 2012-2013: SPT wide field lensing power spectrum
- 2013: Planck lensing power spectrum
- 2012- 2014+: ACTPol/SPTPol/PolarBear/Polar…

CMB Polarization Lensing with ACTPol

Why is Polarization Lensing Great?

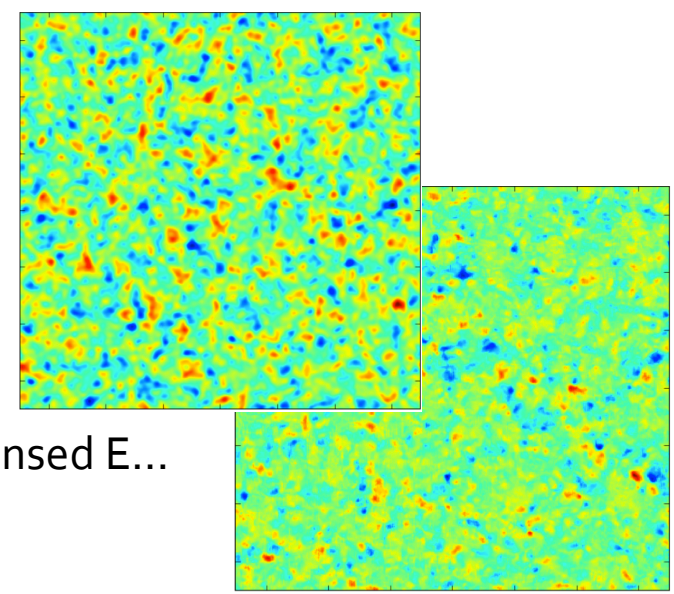
- Reminder: we describe the polarization field with E (even parity) and B mode (odd parity) maps. Without lensing no B! (except very large scales)



[Image credit: CMBPol and S. Das]

Why is Polarization Lensing Great?

- Lensing remaps polarization, converts E to B
- Because we know that all B is due to lensing, polarization estimators are more powerful
- 6 different estimators e.g.: $\hat{\mathbf{d}}(\hat{\mathbf{n}})_{EB} = [E_{\text{Filter 1}} \nabla B_{\text{Filter 2}}]_{\text{Filter 3}}(\hat{\mathbf{n}})$

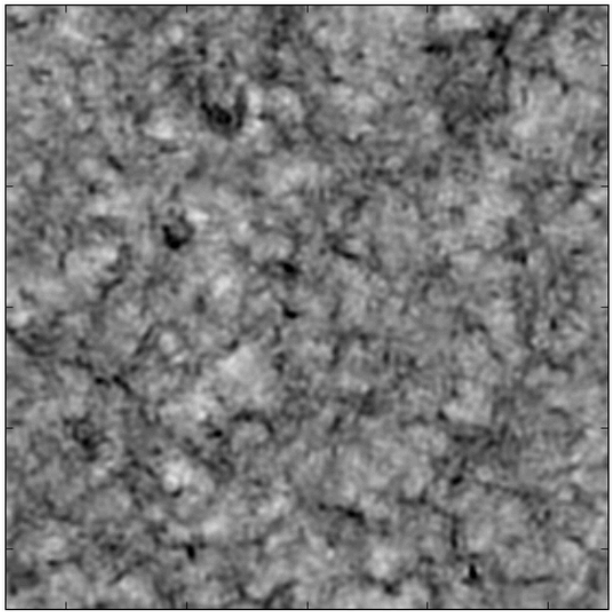


lensed E…

and B mode maps

reconstruction with **polarization lensing** pipeline: **high resolution**

$|\mathbf{d}(\hat{\mathbf{n}})|_{\text{filt}}$



estimate of lensing deflection

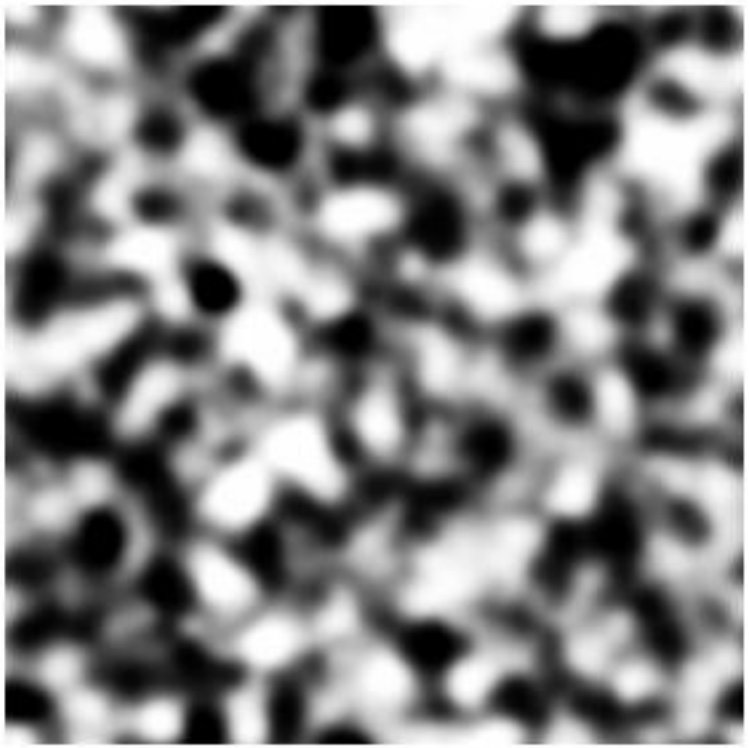
CMB Lensing With ACTPol

- ACTPol: polarization sensitive, much lower noise detector array fitted to ACT telescope (small scale polarization information is perfect for lensing reconstruction).
- 1.) Beginning of 2013, **ACTPol Deep Field**: small patch of the sky (~150 sq. deg) with very low noise in both temperature and polarization.
- 2.) Next 1-2 years, **ACTPol Wide Field**: measure temperature and polarization on large fraction of the sky (at least 4000 sq. deg).

Deep Field: Map Mass with Polarization

$|\mathbf{d}(\hat{\mathbf{n}})|_{\mathrm{filt}}$

10°



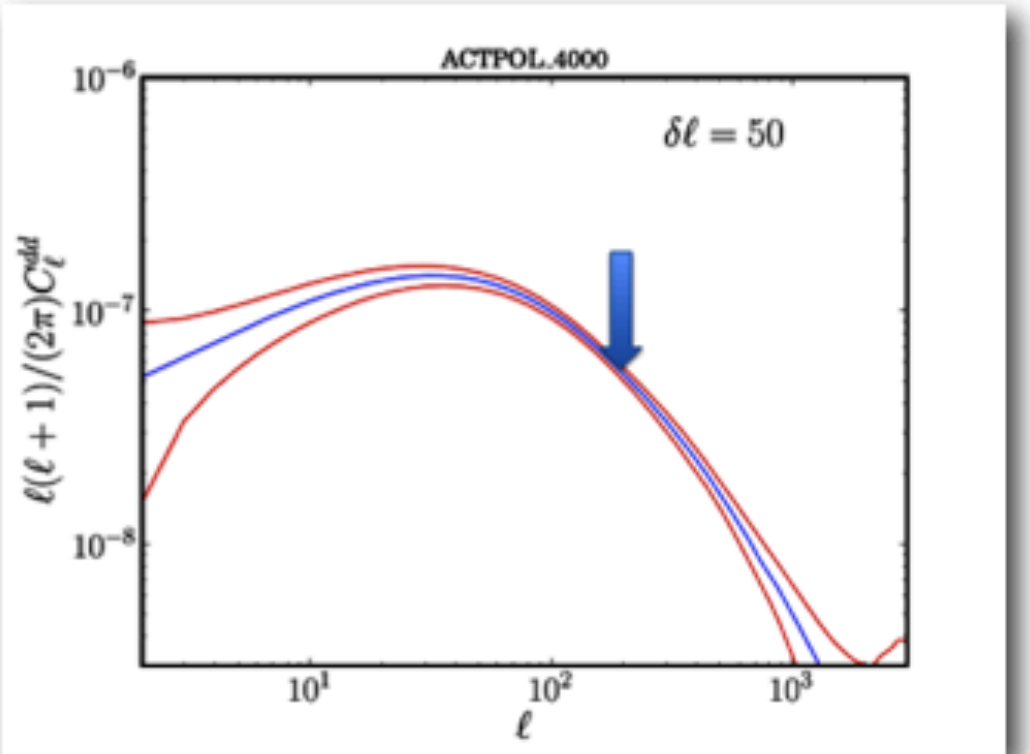
Simulated polarization lensing: (reconstructed and true) for deep field.

Maps contain realistic noise level, beam, etc.

Possible systematics being checked [Sherwin, Yoon, Louis, Das (in prep)]

ACTPOL Deep:
-detect lensing in polarization: data soon (end 2012)
-make detailed mass map
-power spectra ~20 sigma and interesting cross correlations

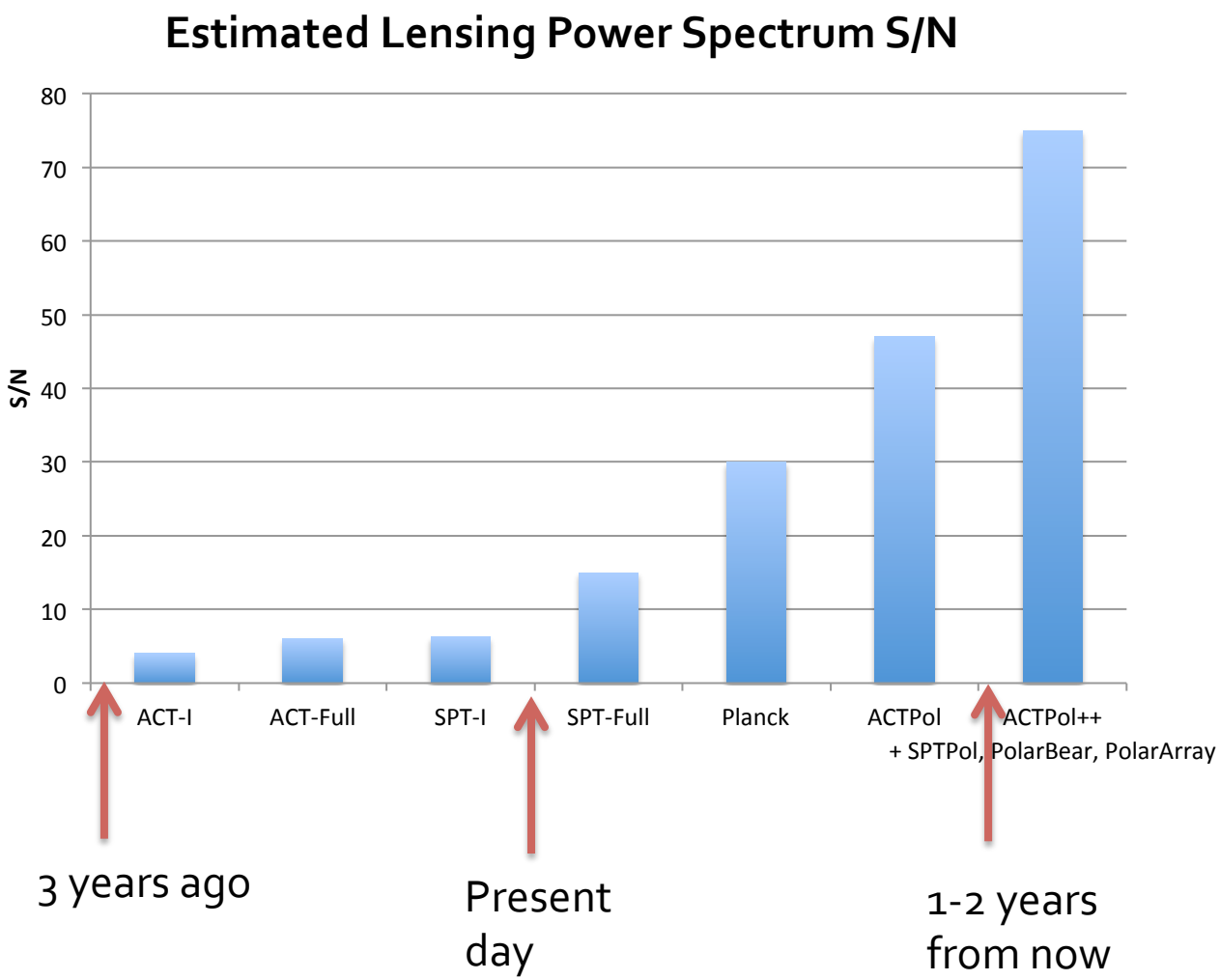
Wide Field: High S/N Power Spectra (+ Mapping)



ACTPOL-WIDE:
4000 sq-deg @ 20 μK-arcmin (temp)
and 28 μK-arcmin (pol)

ACTPOL Wide:
-50 sigma lensing power spectrum
-neutrino mass constraints order 0.1 eV (0.05eV + Planck)
-galaxy, quasar, Ly-alpha, lensing-lensing cross-correlations
-mapping of mass on large parts of the sky
-possible extension to up to 20000 sq. deg.

A bright future for CMB lensing science: high precision CMB lensing power spectra



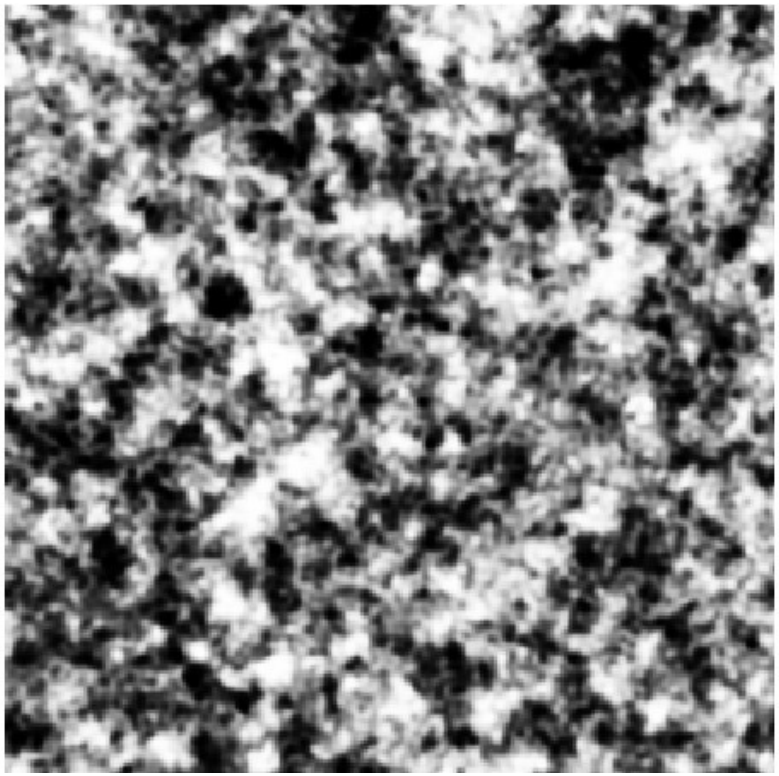
Not a bad time to be doing this…

Still: lots of work left to make sure systematics are well controlled.

A bright future for CMB lensing science: scientific returns

Decadal survey key science questions			How CMB Lensing can address them
Cosmology and Fundamental Physics	CFP 1	How did the universe begin?	De-lens CMB, important for finding inflationary B-modes
	CFP 2	Why is the universe accelerating?	Constrain dark energy properties (esp. early D.E.) Reduce weak lensing shear systematics to constrain D.E.
	CFP 3	What is dark matter?	Measure the distribution of dark matter
	CFP 4	What are the properties of neutrinos?	Measure the masses of neutrinos
Galaxies Across Cosmic Time	GCT 1	How do cosmic structures form and evolve?	Measure biases/halo masses vs redshift Probe growth of perturbations
	GCT 2	How do baryons cycle in and out of galaxies, and what do they do while they are there?	
	GCT 3	How do black holes grow, radiate, and influence their surroundings?	Constrain quasar bias, halo mass, activity and evolution
	GCT 4	What were the first objects to light up the universe, and when did they do it?	Study high-z galaxies and quasars with lensing cross-correlations

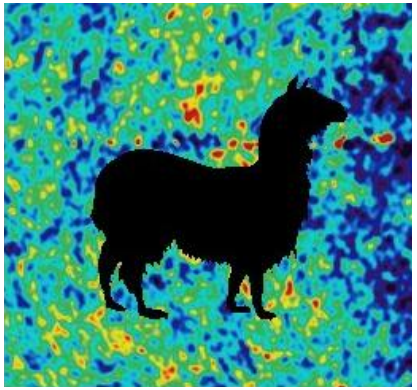
A bright future for CMB lensing science: mapping mass across the sky with polarization



Mapping dark matter with increasing precision (e.g. 1uK-arcmin lensing reconstruction)

10°

...across much of the sky

Summary

- CMB lensing directly probes dark matter distribution
- First detection of lensing power spectrum with ACT last year gives evidence for Ω_Λ from CMB alone
- Cross-correlation with QSO maps, IR galaxies, other tracers in progress
  can learn about mass tracer astrophysics
- ACTPol polarization data allows high accuracy lensing reconstruction
  gives mass mapping, cosmological constraints, cross-correlations…