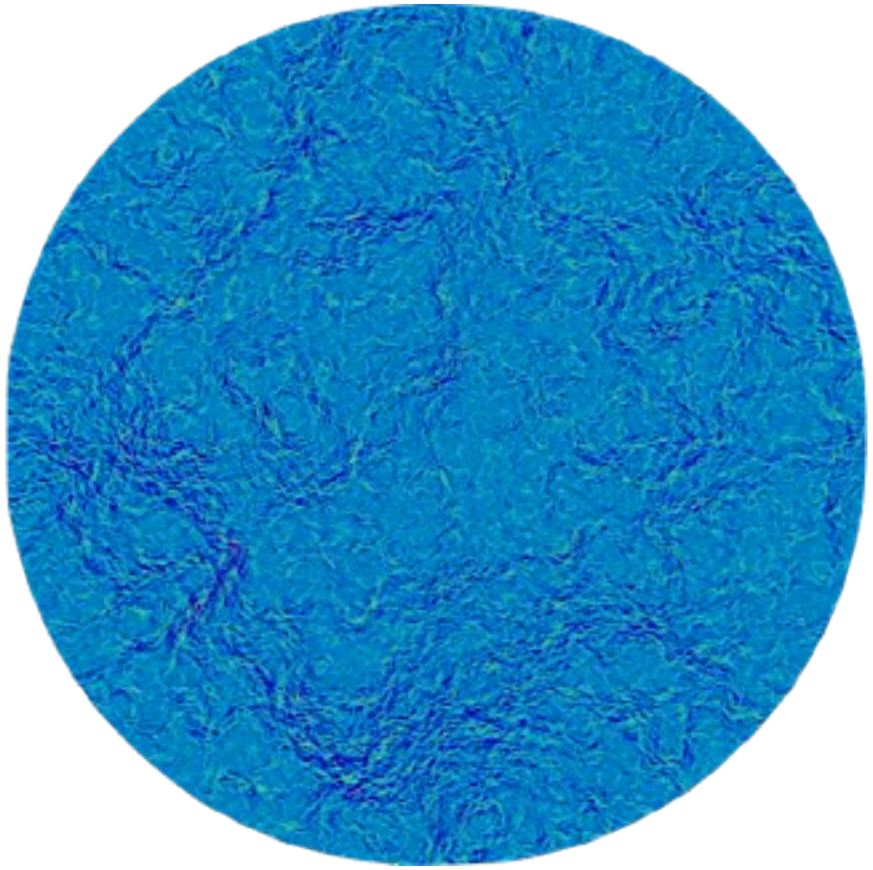
SYNERGY OF THE CMB WITH OTHER COSMOLOGICAL PROBES

Science with CMB Lensing



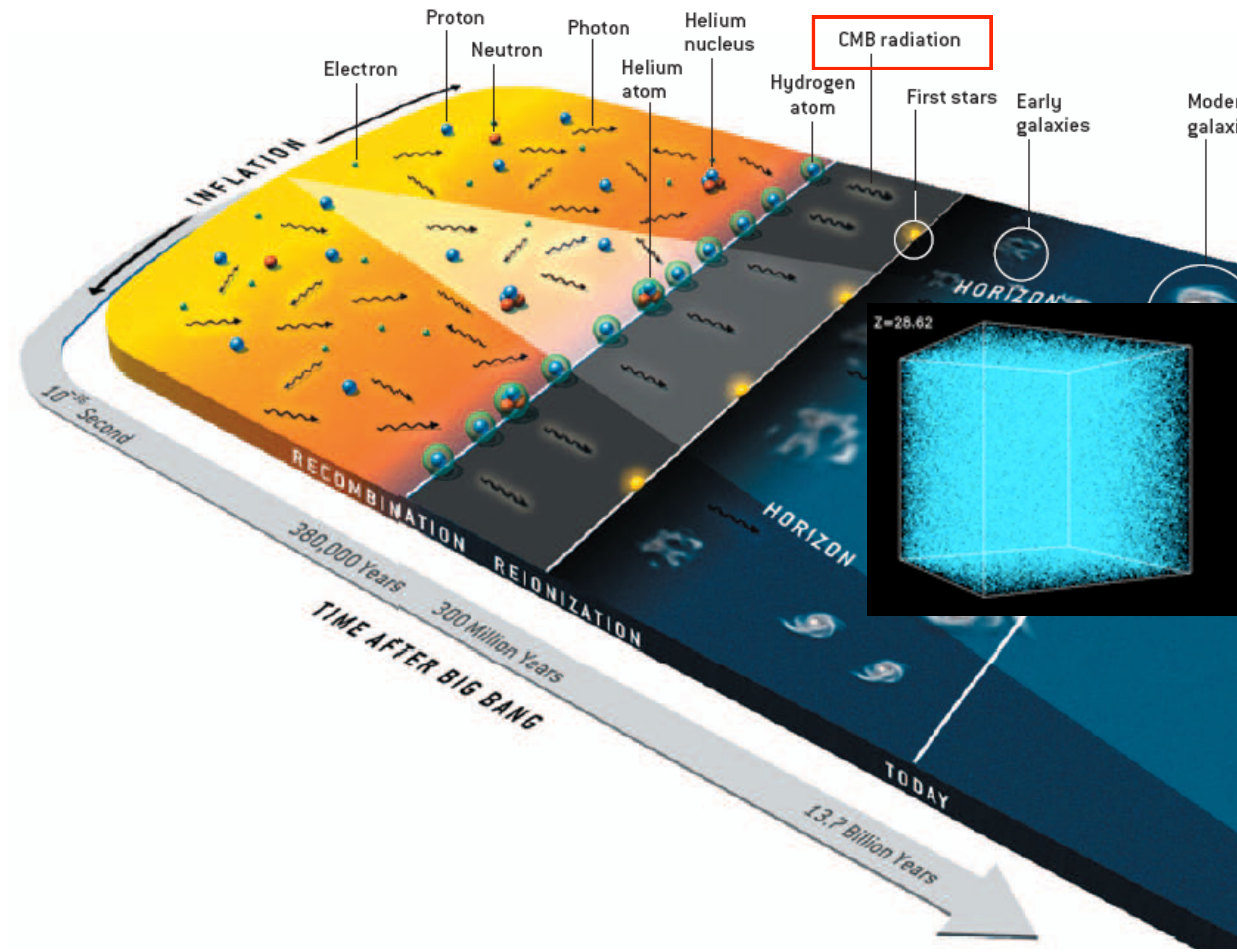
Sudeep Das

Argonne National Laboratory

26th International Symposium on
LEPTON PHOTON
INTERACTIONS at HIGH ENERGIES

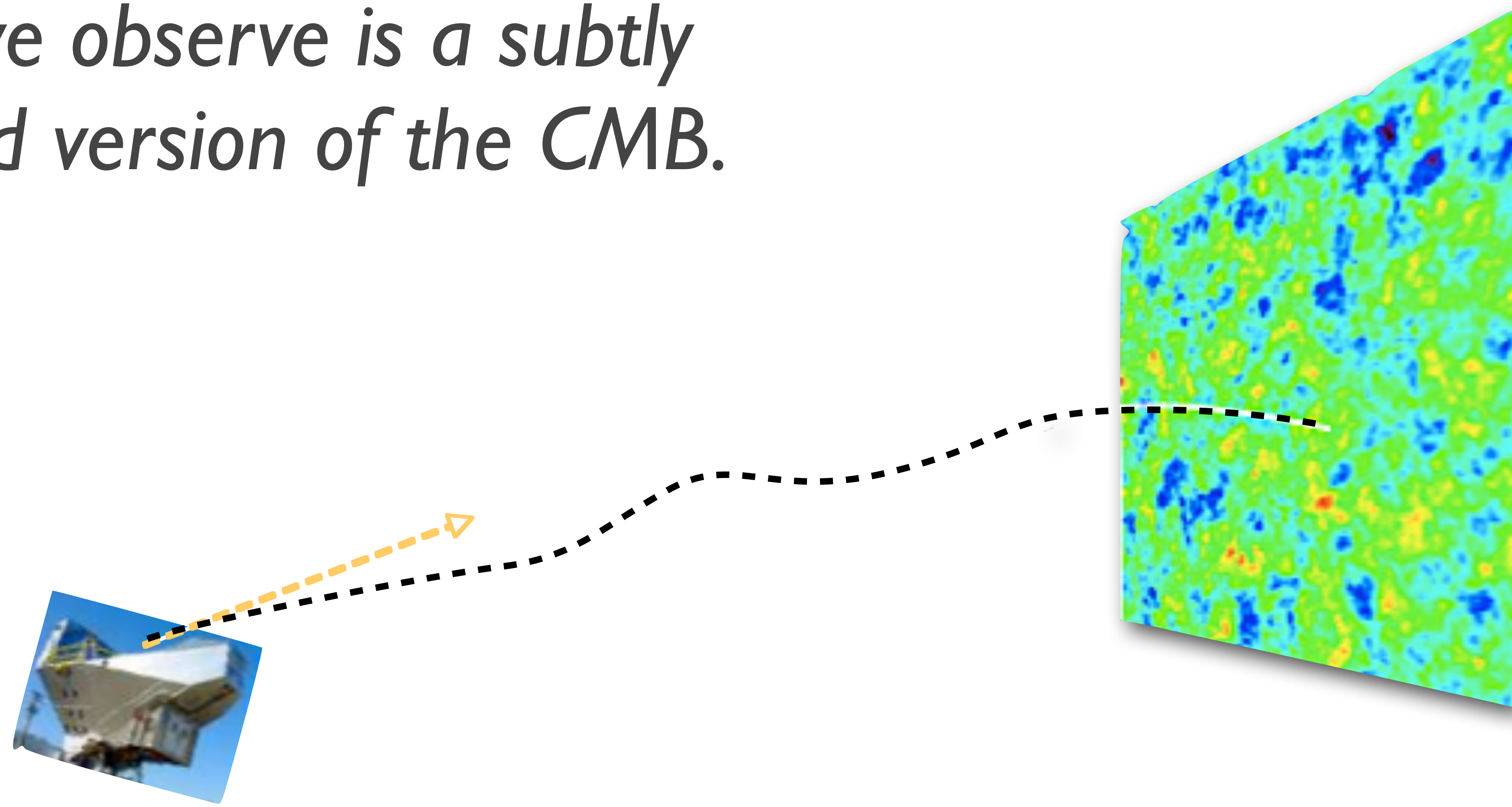
June 27 2013

CMB photons propagate through evolving large scale structure



Intervening large-scale structure potentials deflect CMB photons

What we observe is a subtly distorted version of the CMB.

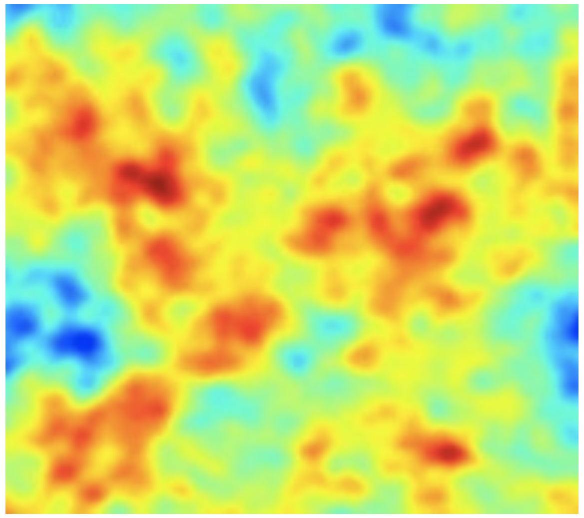


This is CMB Lensing!

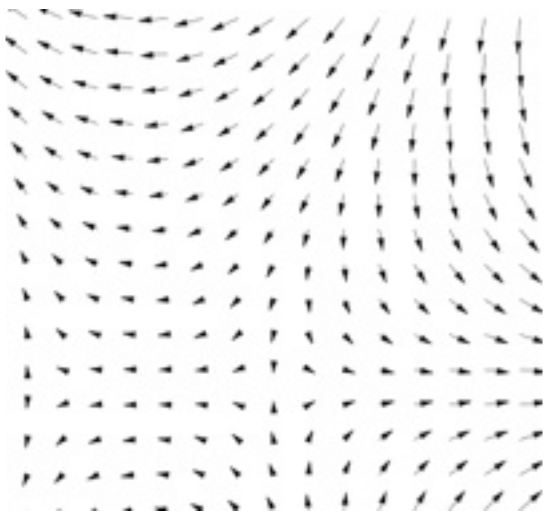
DEFLECTION FIELD IS THE KEY QUANTITY

CMB lensing is essentially a remapping of the CMB fields by the deflection field.

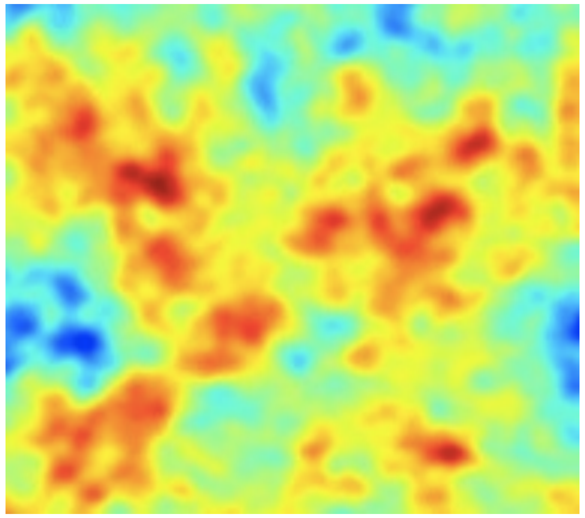
Unlensed



Deflection



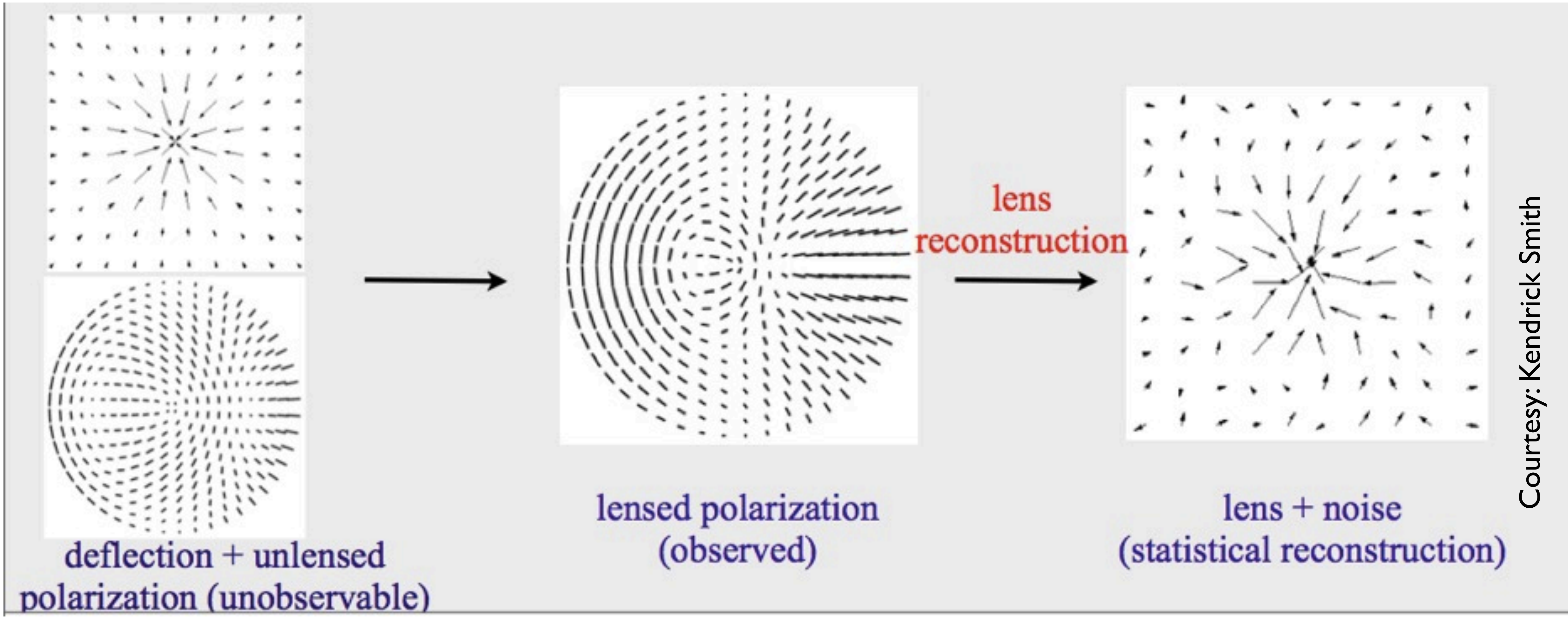
Lensed



$$\tilde{T}(\hat{n}) = T(\hat{n} + \vec{d})$$

CMB lensing can be discussed completely in terms of the deflection field (no shear/convergence necessary).

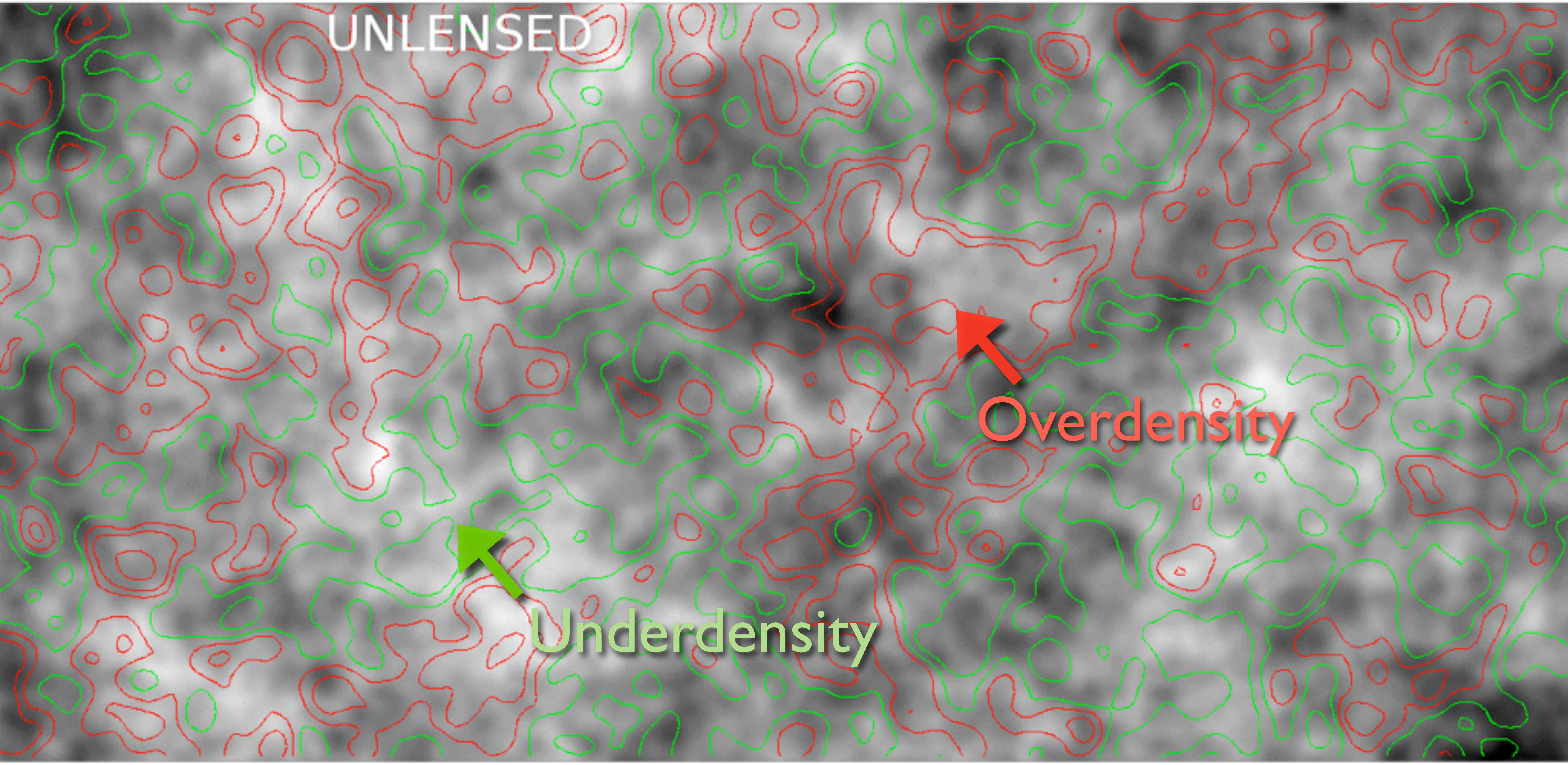
USING CMB POLARIZATION IS THE NEXT BIG THING IN LENSING



From pure E-modes lensing will create a mixture of E and B-modes.

PolarBeaR, ACTPol, SPTPol are gearing up to be premier CMB lensing experiments using polarization.

Lensing remaps & magnifies/de-magnifies CMB patches.



Simulation from Das & Bode (2008)

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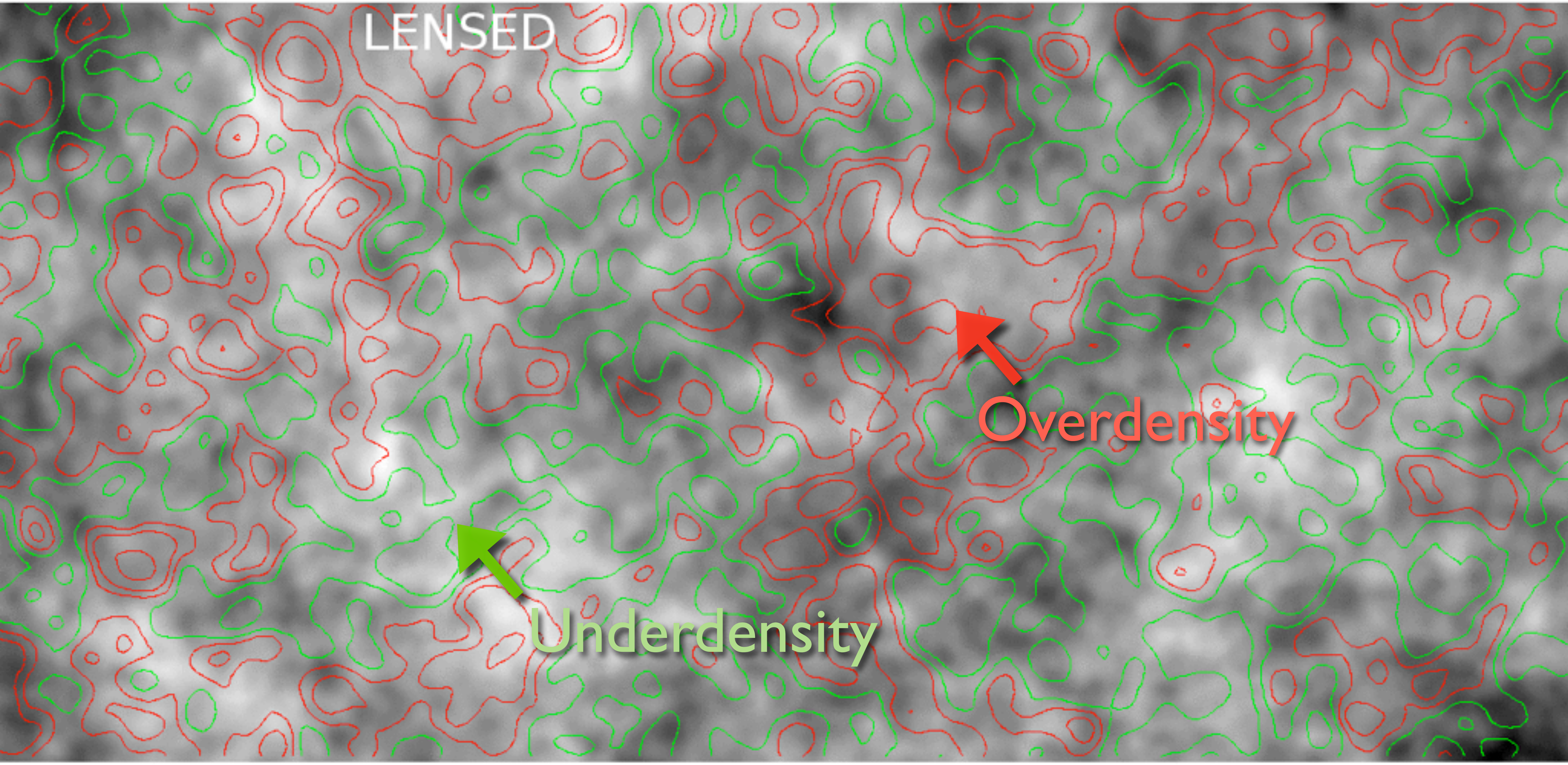
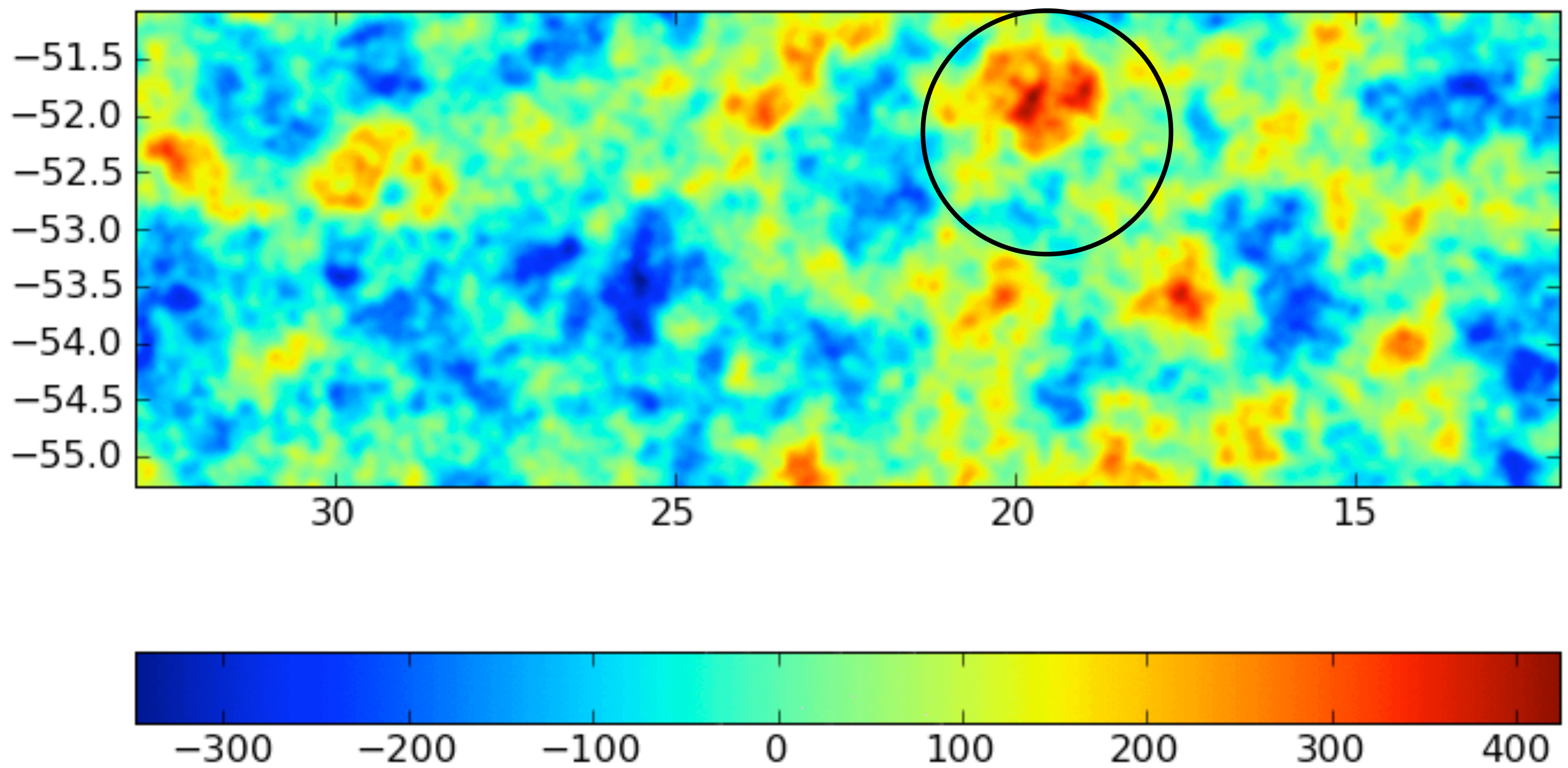


Simulation from Das & Bode (2008)

CMB Lensing in action ...



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" 2-3 arcmin deflections, coherent over 2-3 degrees, mainly coming from redshifts of 2-3 !"

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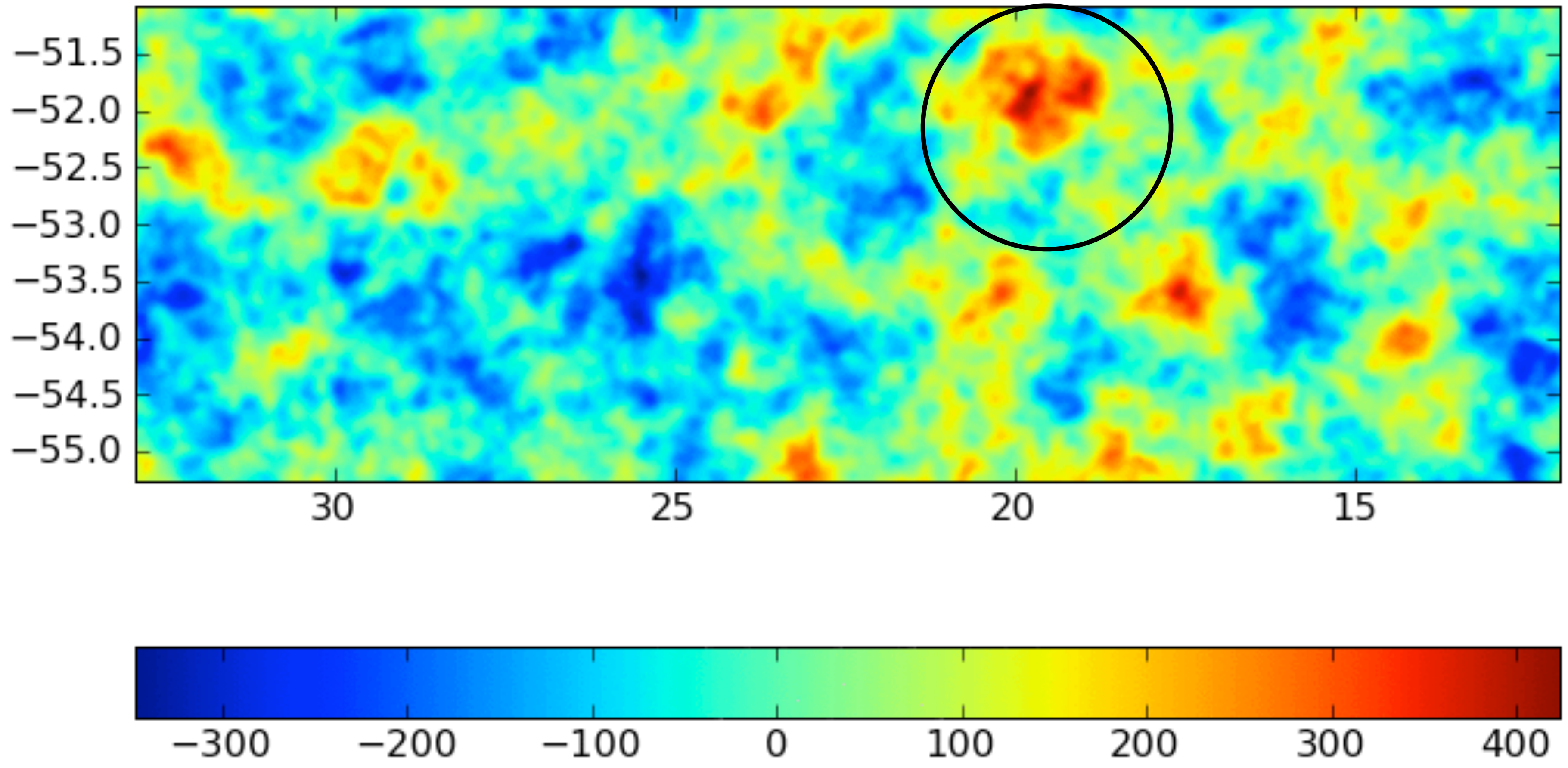


Simulation from Das & Bode (2008)

" 2-3 arcmin deflections, coherent over 2-3 degrees, mainly coming from redshifts of 2-3 !"

THERE ARE THREE MAIN AVENUES FOR COSMOLOGY WITH CMB LENSING

Smearing of CMB power spectrum peaks and small scale B-mode power.

Reconstruction of the deflection/ convergence field and its power spectrum.

$$\phi = -2\int \frac{d_A(\eta_0-\eta)}{d_A(\eta)\,d_A(\eta_0)}\,\Phi(\eta\hat{n},\eta)\,d\eta$$

Effective Lensing Potential

Geometry

Matter potential

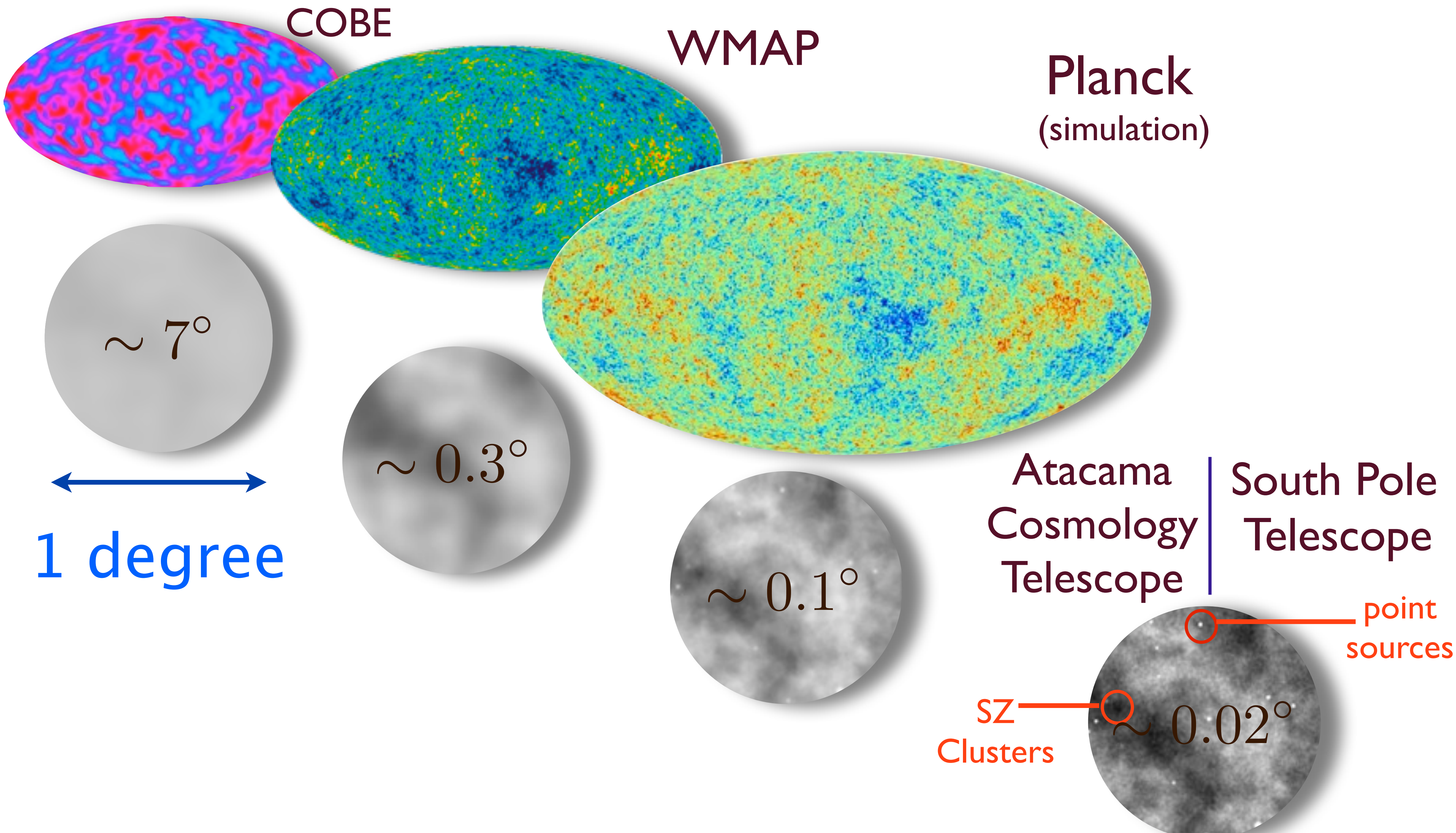
Cross correlation of the deflection field with other cosmological probes.

e.g. *weak lensing, galaxy counts, CIB* ...

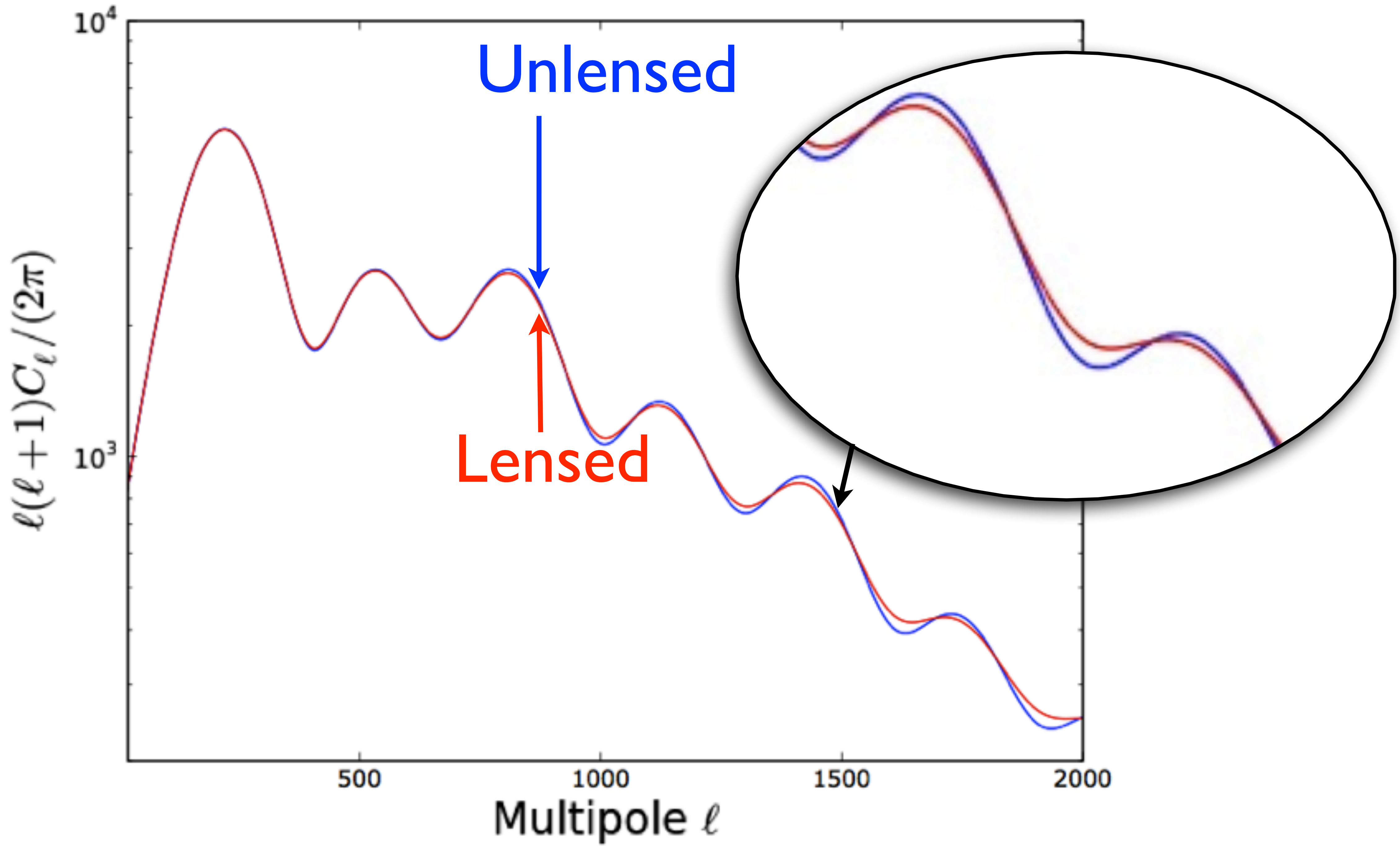
- *break degeneracies.*
- *constrain systematics.*
- *constrain galaxy bias*

Highest science impact expected on: *neutrino mass sum, (early) dark energy, test of GR, and understanding galaxy evolution.*

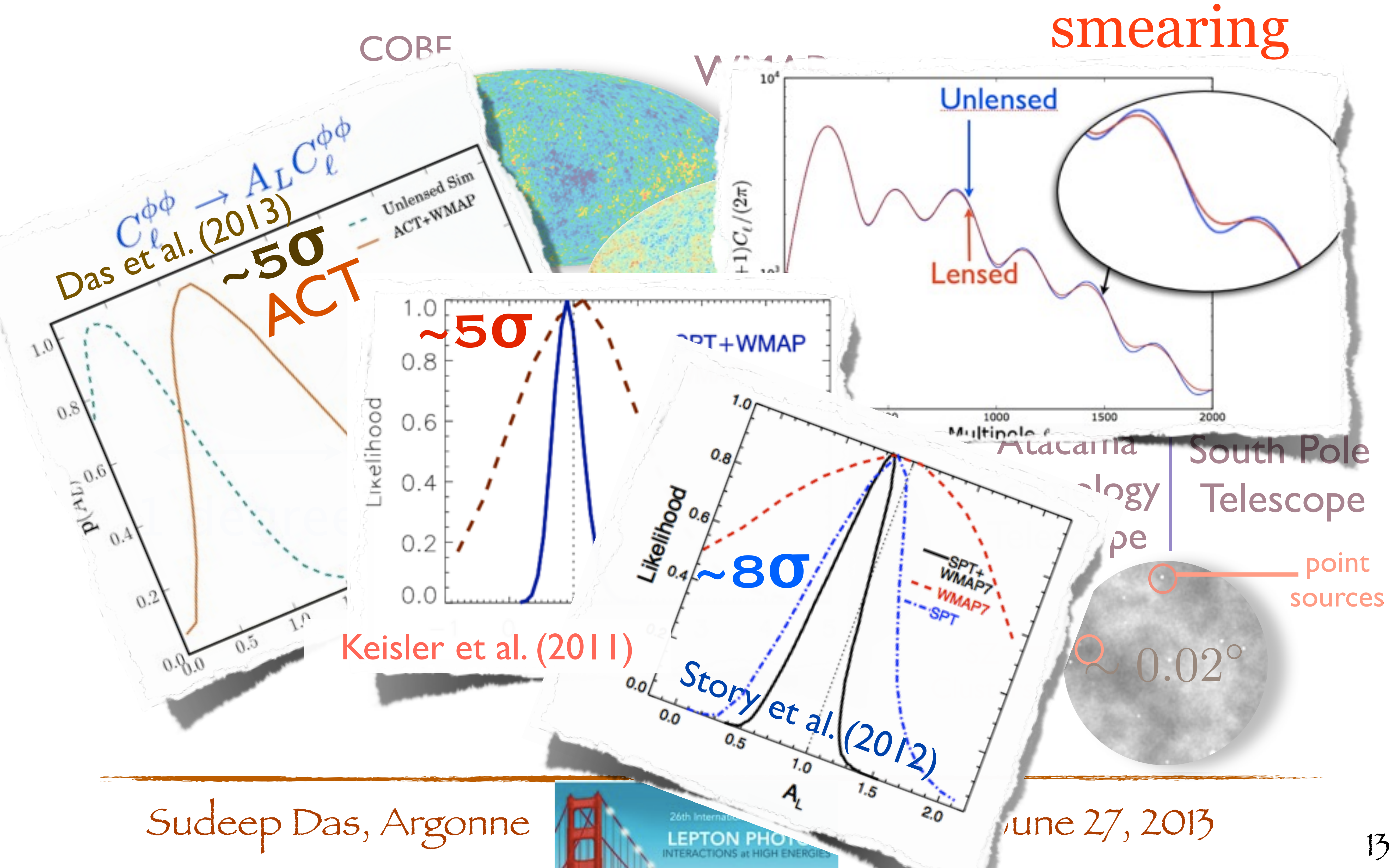
To study the lensing effect we need to look at the CMB at high resolution



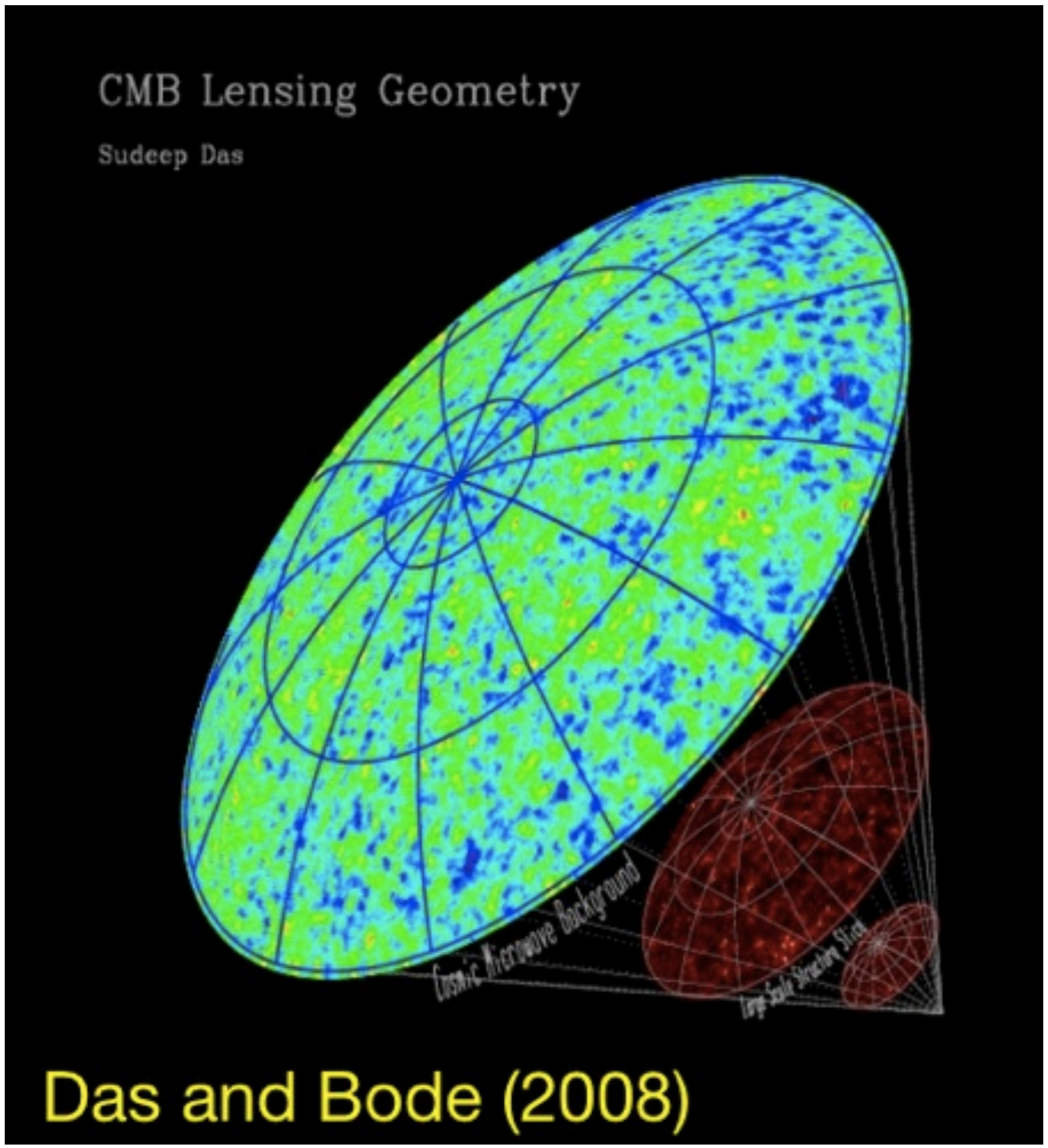
Lensing smears out acoustic peaks



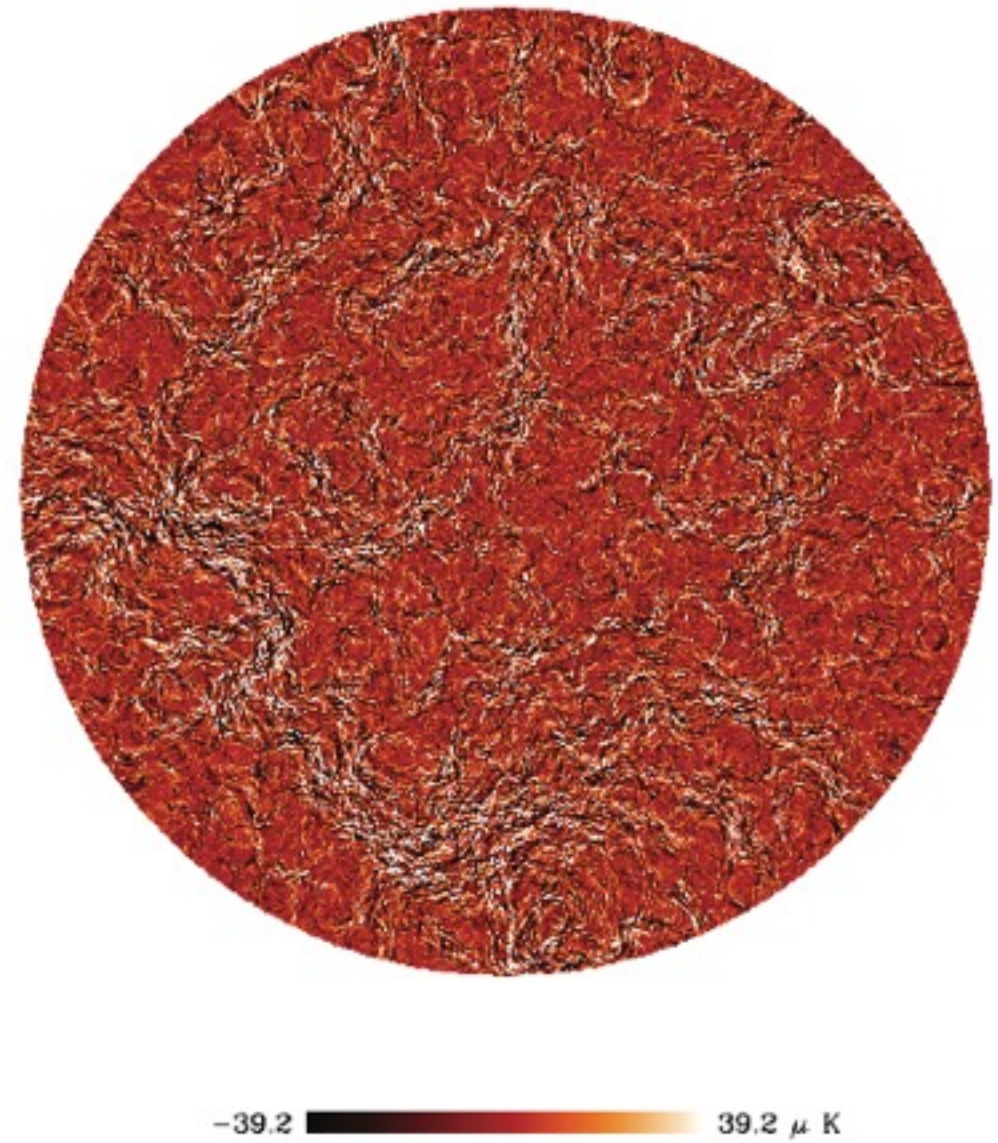
HIGH RESOLUTION AND SENSITIVITY HAS ENABLED ACT, SPT, PLANCK TO DETECT LENSING IN SMEARING OF PEAKS



LENSING INDUCES NON-GAUSSIANITY

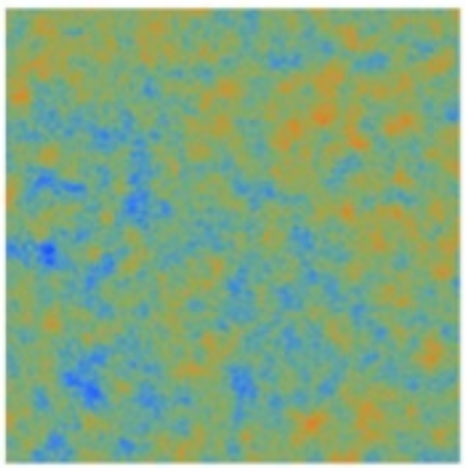


Difference between lensed and unlensed CMB



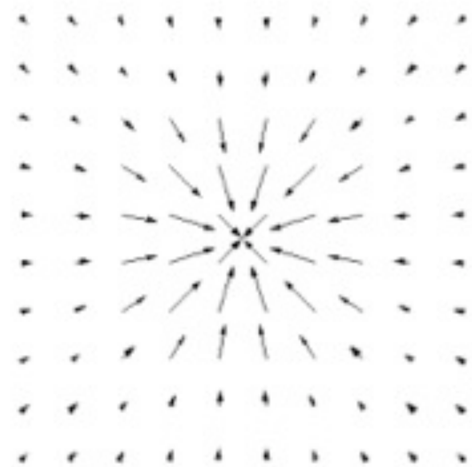
LENSING RECONSTRUCTION

Given only the lensed CMB sky, can we estimate the deflection field?

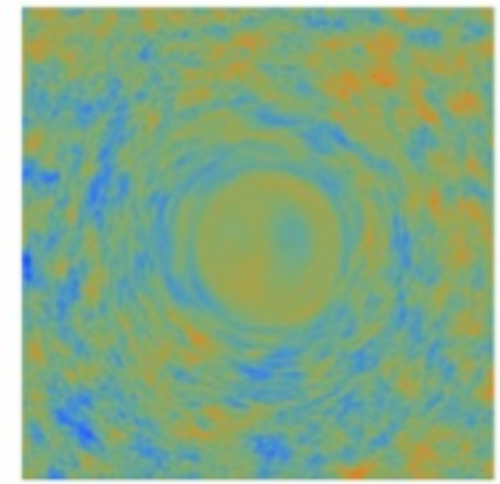


Unlensed CMB

+

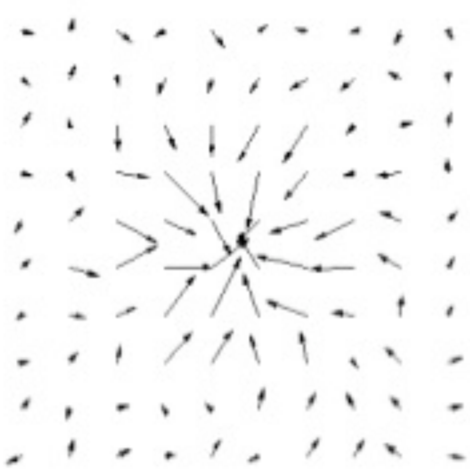


Deflection Field



Lensed CMB

Statistics Altered

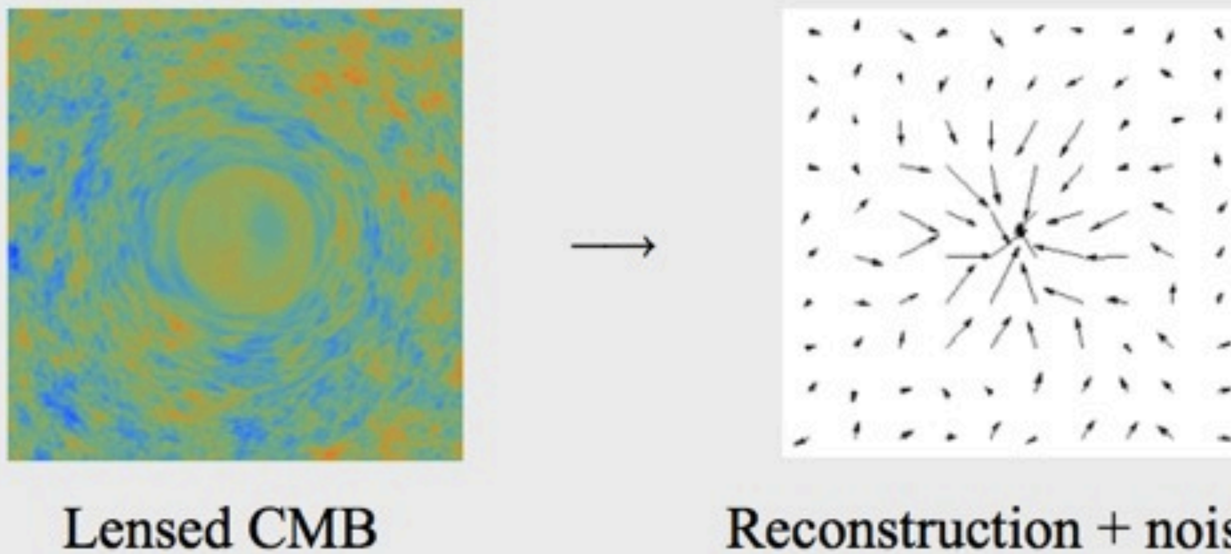


Reconstruction +Noise

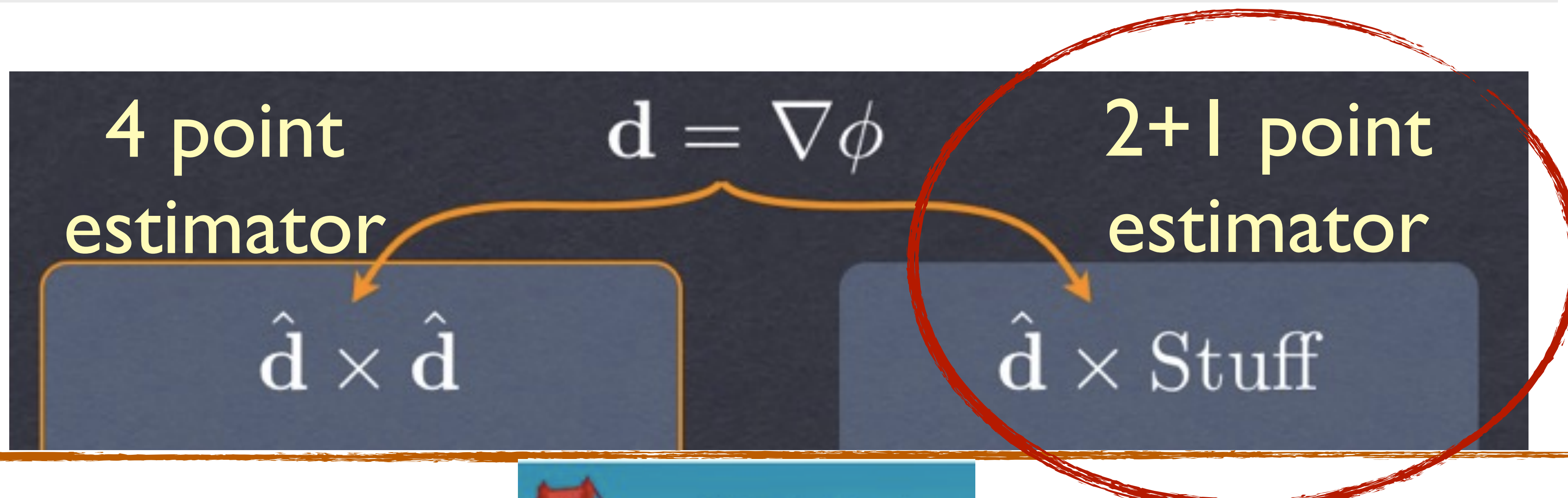
Hu (2001), Hu & Okamoto (2002)

Detections using higher point statistics

$$\hat{\mathbf{d}}(\mathbf{l}) \propto \int \frac{d^2\mathbf{l}_1}{(2\pi)^2}[\mathbf{l}_1 C_{\ell_1} + \mathbf{l}_2 C_{\ell_2}] \frac{T(\mathbf{l}_1)T(\mathbf{l}_2)}{(C_{\ell_1}+N_{\ell_1})(C_{\ell_2}+N_{\ell_2})}$$

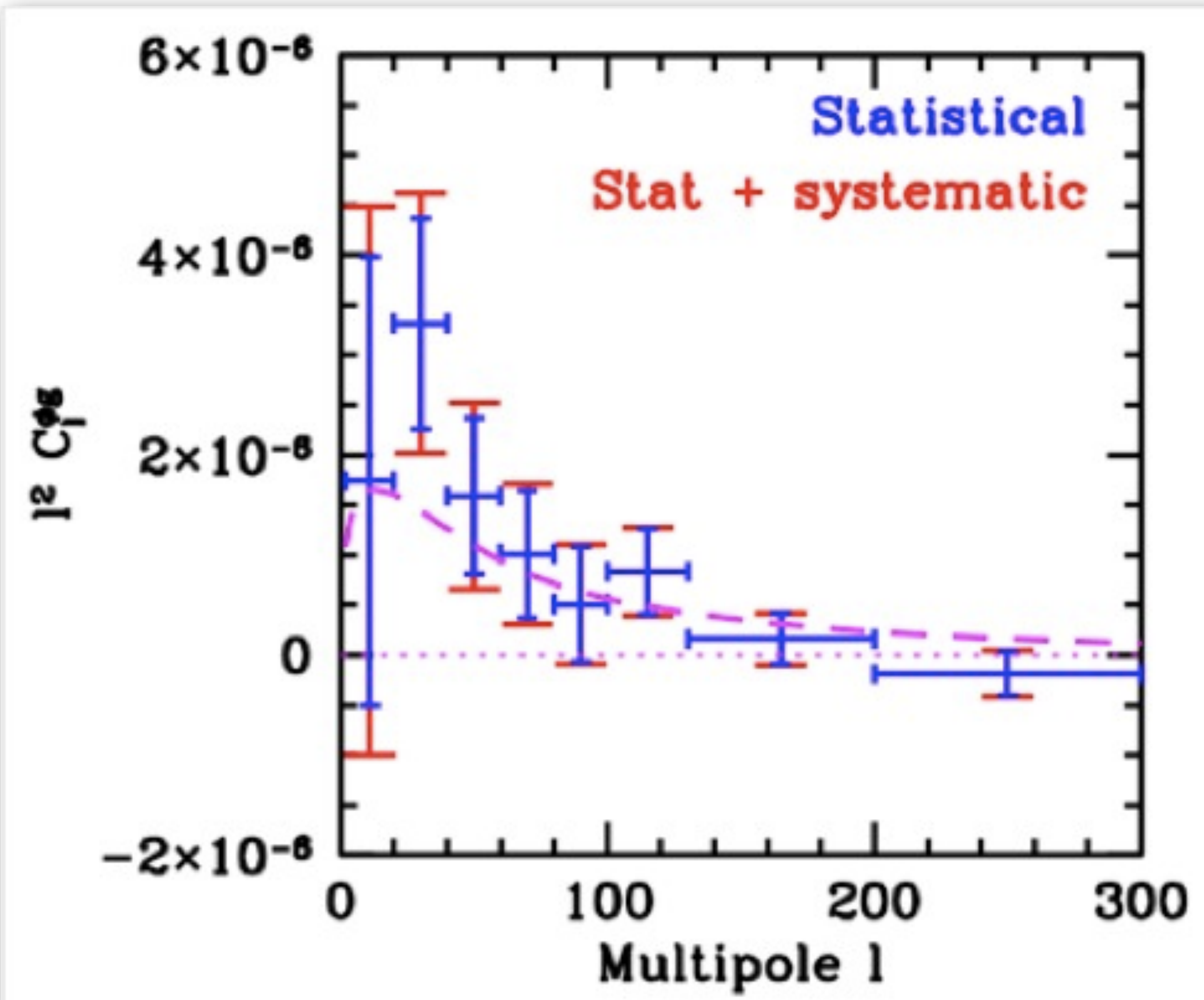


Courtesy: Kendrick Smith



WMAP-NVSS ANALYSIS

Detection (3.4σ) of CMB lensing, via 3-point signal

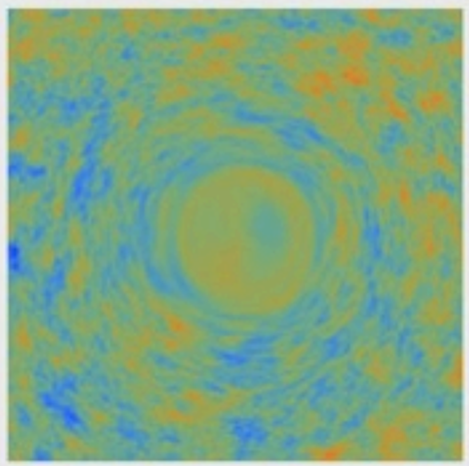


Smith, Zahn, Dore & Nolta (2007)

(see also Hirata et al 2008 and Feng et. al 2013)

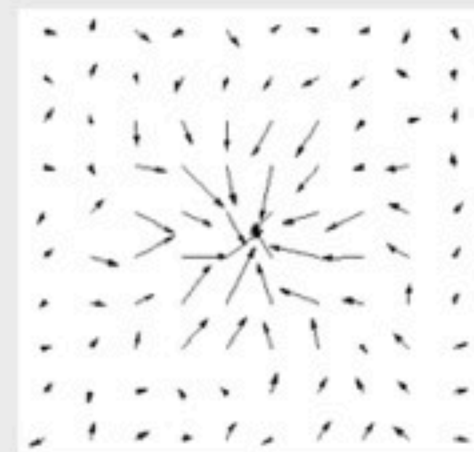
Detections using higher point statistics

$$\hat{\mathbf{d}}(\mathbf{l}) \propto \int \frac{d^2\mathbf{l}_1}{(2\pi)^2}[\mathbf{l}_1 C_{\ell_1} + \mathbf{l}_2 C_{\ell_2}] \frac{T(\mathbf{l}_1)T(\mathbf{l}_2)}{(C_{\ell_1}+N_{\ell_1})(C_{\ell_2}+N_{\ell_2})}$$



Lensed CMB

$\longrightarrow$



Reconstruction + noise

Courtesy: Kendrick Smith

$\mathbf{d} = \nabla\phi$

4 point estimator: $\hat{\mathbf{d}} \times \hat{\mathbf{d}}$

2+1 point estimator: $\hat{\mathbf{d}} \times \text{Stuff}$

First internal detection of lensing (4-sigma) from the CMB 4-point function

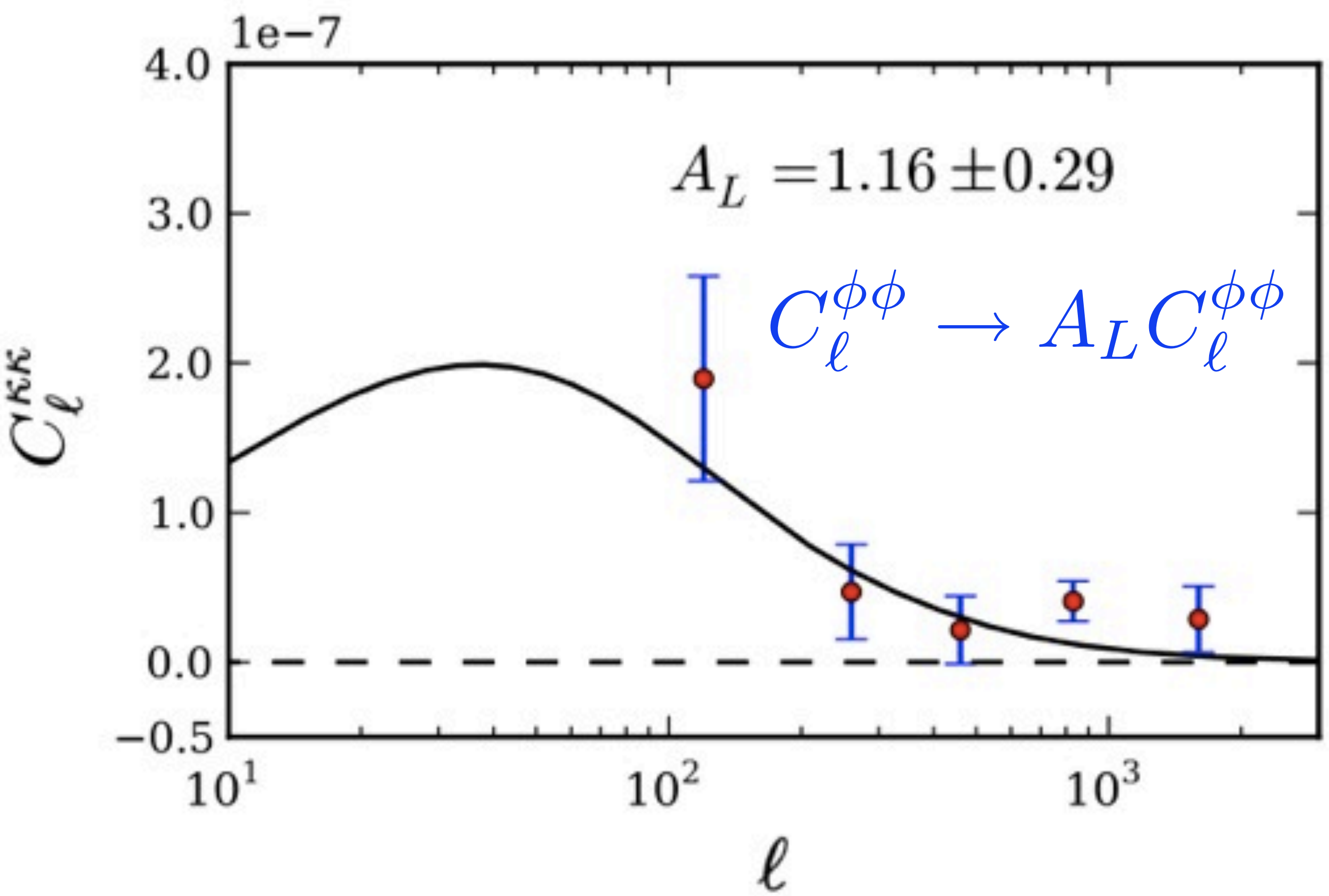


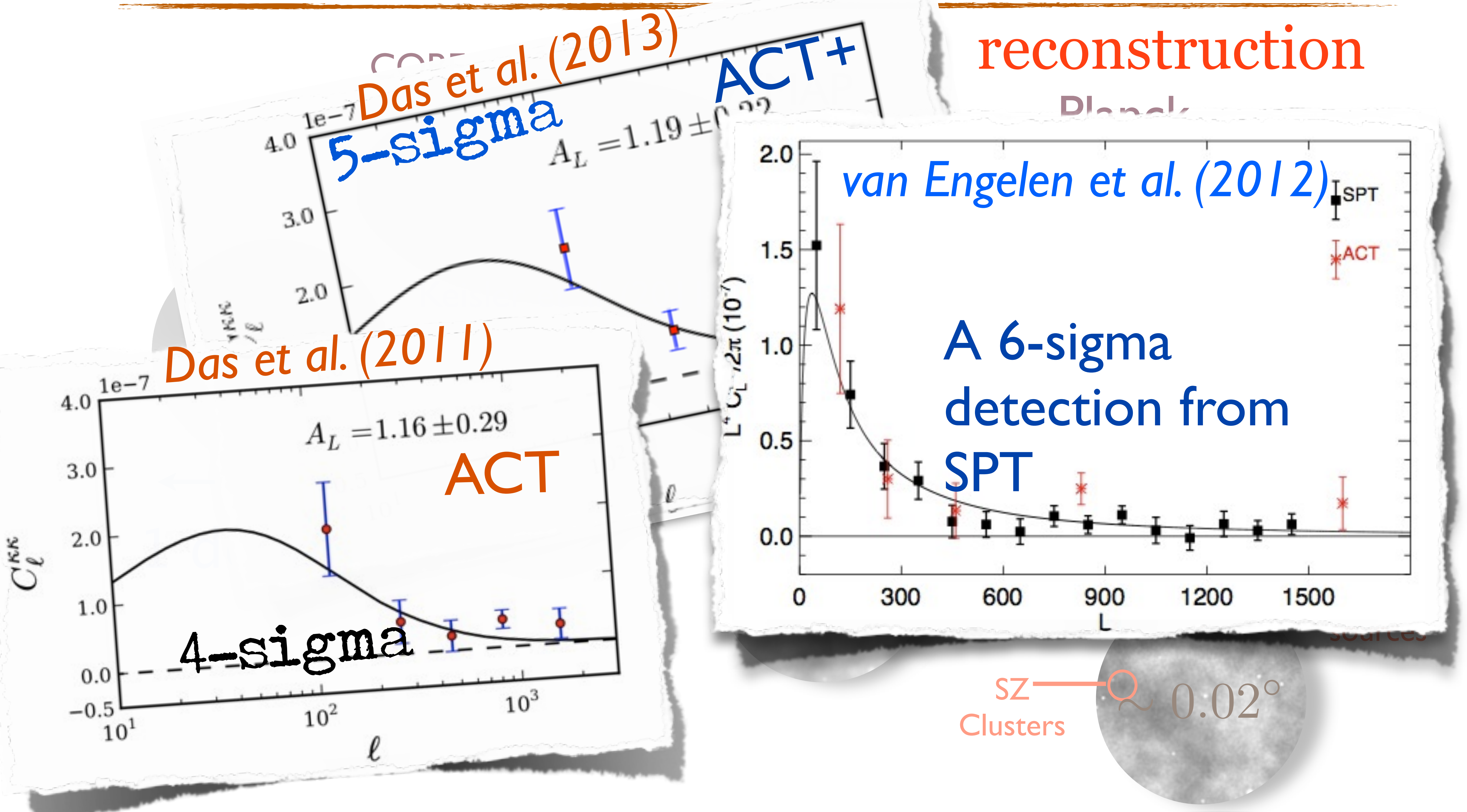
FIG. 2. Convergence power spectrum (red points) measured from ACT equatorial sky patches. The solid line is the power spectrum from the best-fit WMAP+ACT cosmological model with amplitude $A_L = 1$, which is consistent with the measured points. The error bars are from the Monte Carlo simulation results displayed in Fig. 1. The best-fit lensing power spectrum amplitude to our data is $A_L = 1.16 \pm 0.29$

Das, Sherwin et al., PRL 107:021301 (2011)

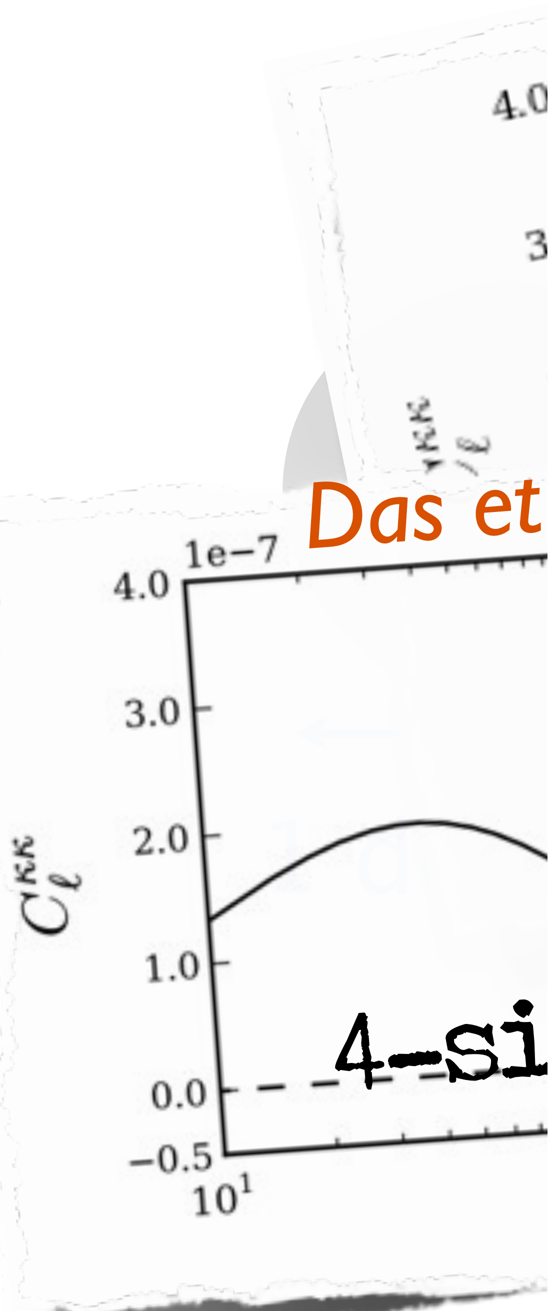
First CMB-only detection of CMB lensing.

Detection is from 320 sq. degrees of ACT equatorial data only.

HIGH RESOLUTION AND SENSITIVITY HAS ENABLED ACT, SPT TO BREAK NEW GROUNDS IN ALL THREE AREAS OF CMB LENSING



HIGH R… TIVITY HAS ENABL… EW GROUNDS IN ALL … ENSING



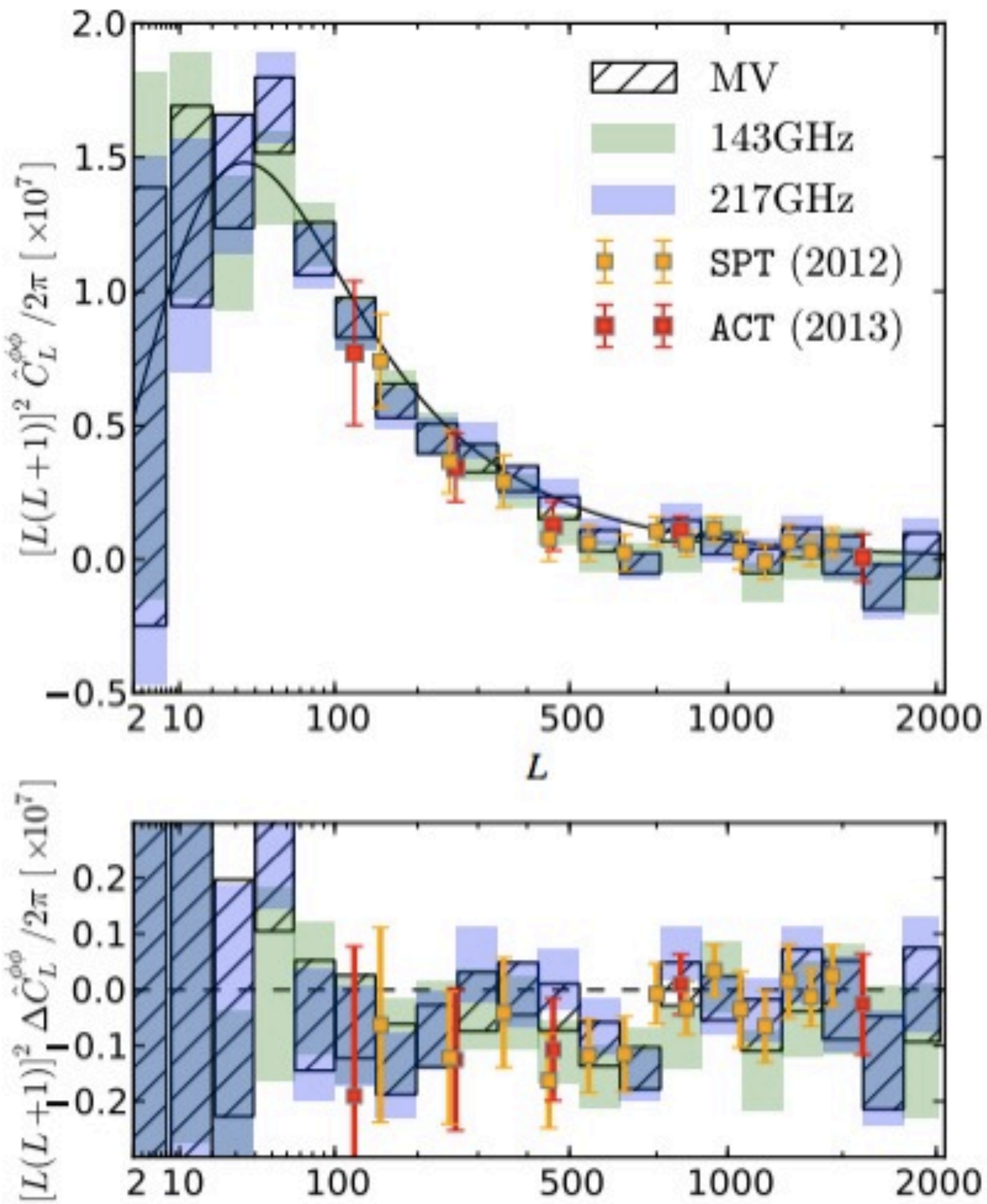
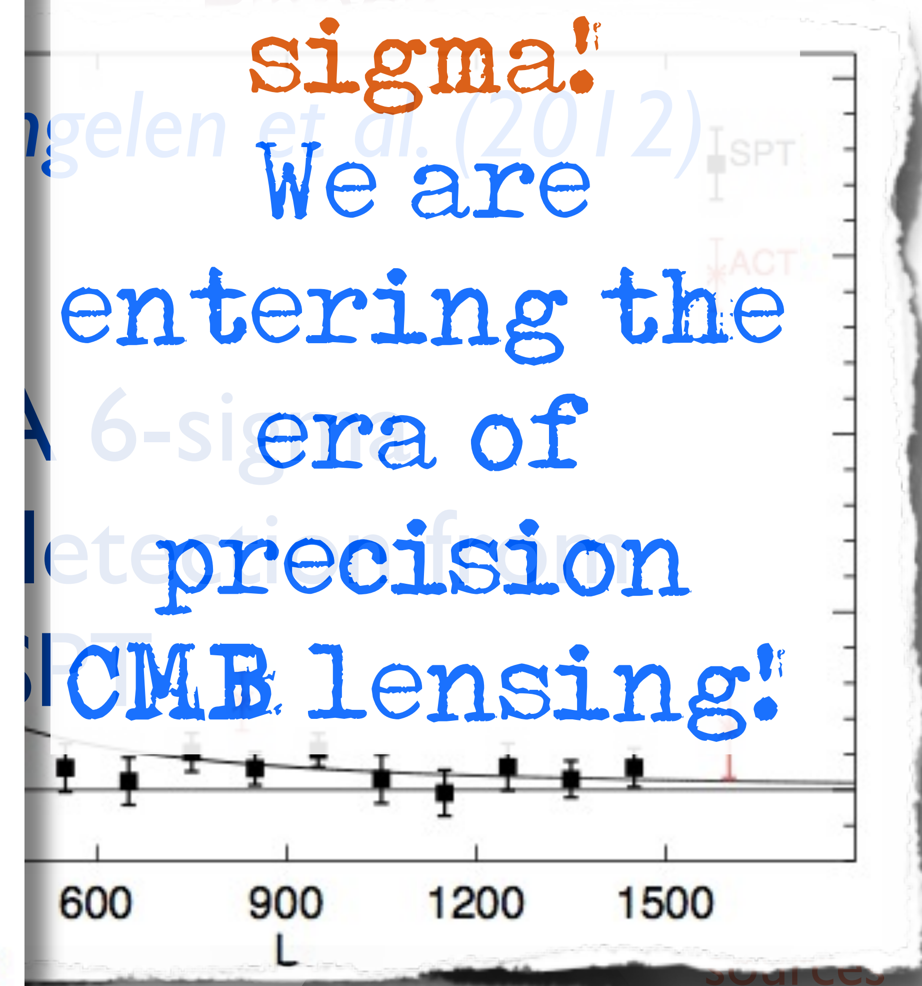


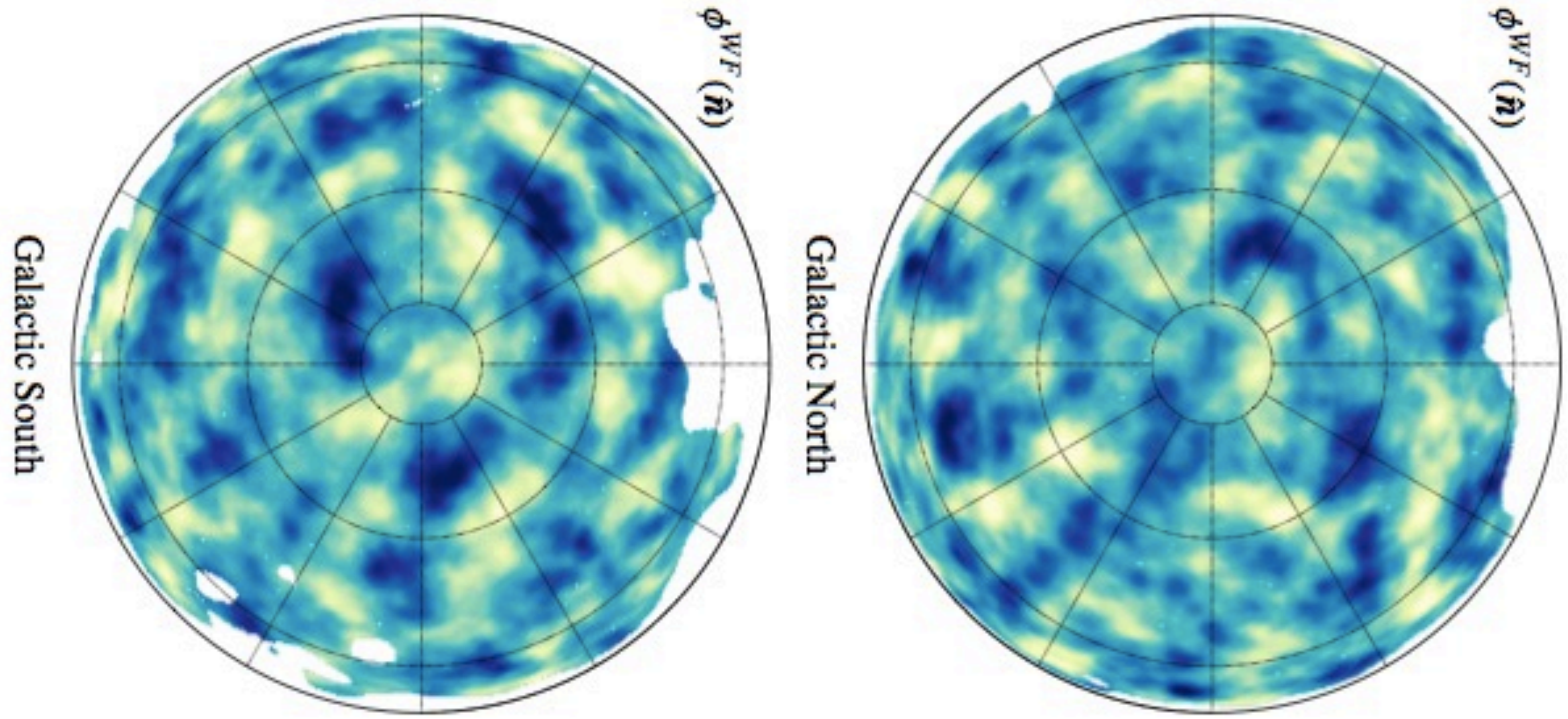
Fig. 11. Replotting of Fig. 10, removing 100 GHz for easier comparison of 143 and 217 GHz. Also plotted are the SPT bandpowers from van Engelen et al. (2012), and the ACT bandpowers from Das et al. (2013). All three experiments are very consistent. The lower panel shows the difference between the measured bandpowers and the fiducial best-fit ΛCDM model.



Planck = 25 sigma!

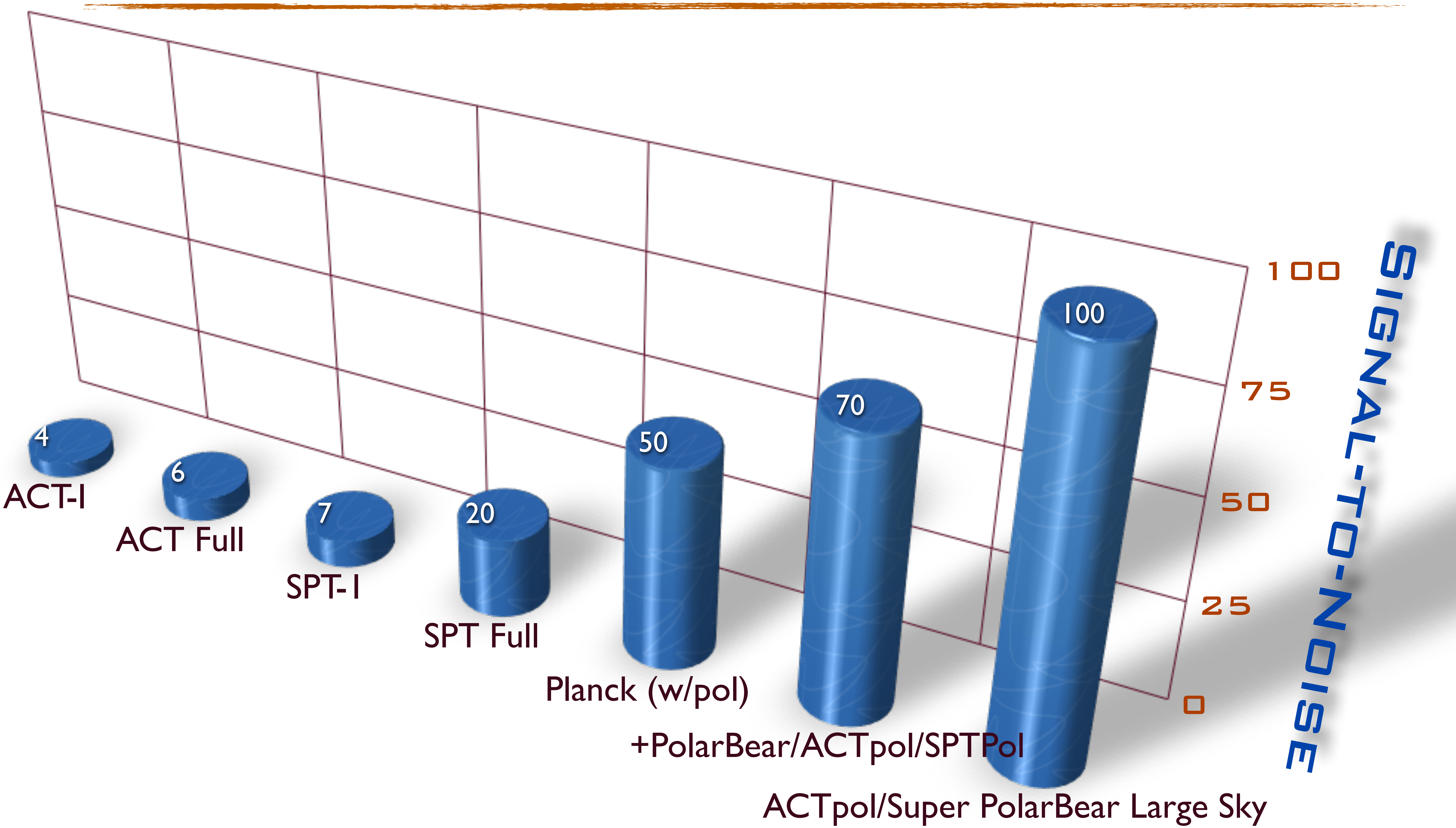
We are entering the era of precision CMB lensing!

SOON WE WILL BE MAKING MATTER BEACH BALLS



Note that this is mostly noise!

CMB Lensing is going to explode as a field in the next few years



LENSING MAKES THE CMB UNIQUELY SENSITIVE TO GEOMETRY AND STRUCTURE

CMB lensing can be fully described via the deflection field:

$$\Theta(\hat{n}) = \tilde{\Theta}(\hat{n} + \nabla\phi)$$

Lensed — Unlensed — Deflection Field

$$\phi = -2 \int \frac{d_A(\eta_0 - \eta)}{d_A(\eta) d_A(\eta_0)} \Phi(\eta\hat{n}, \eta)\, d\eta$$

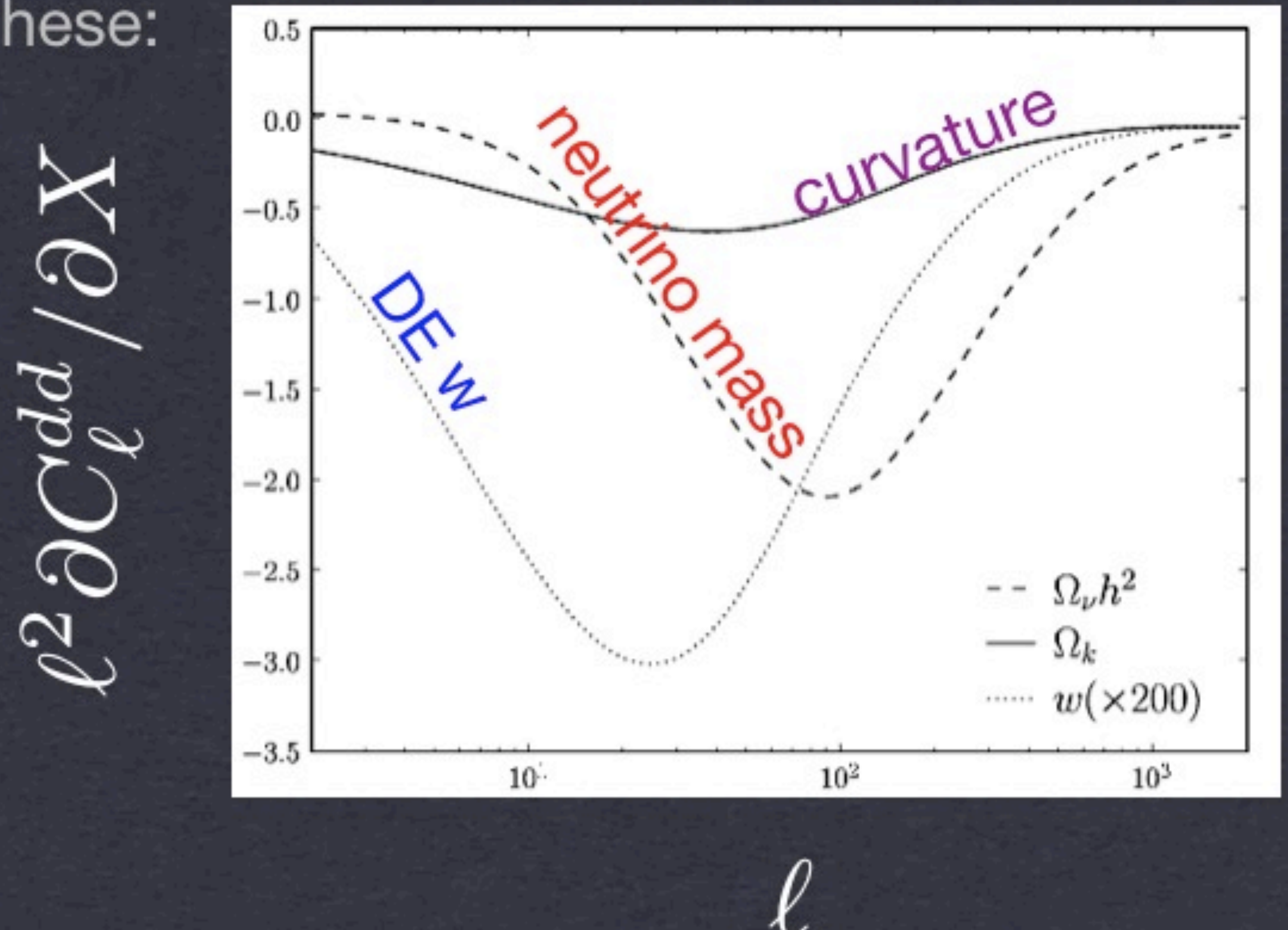
Effective Lensing Potential — Geometry — Matter potential

Affected by parameters that affect distance scales and growth of structure in the late universe.

For high z lenses (clusters, galaxies) CMB is the only source !

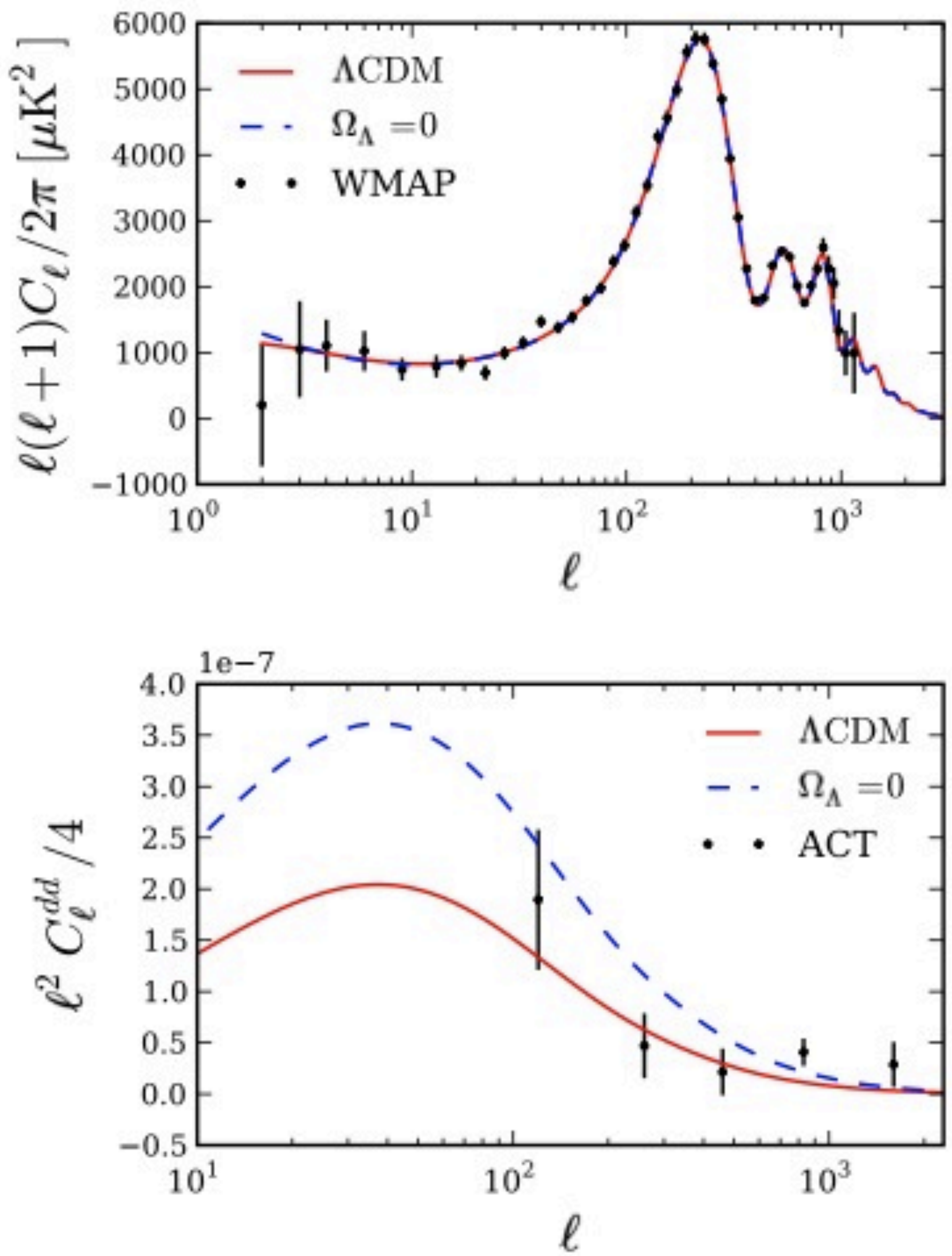
The deflection power spectrum is a clean and unique probe

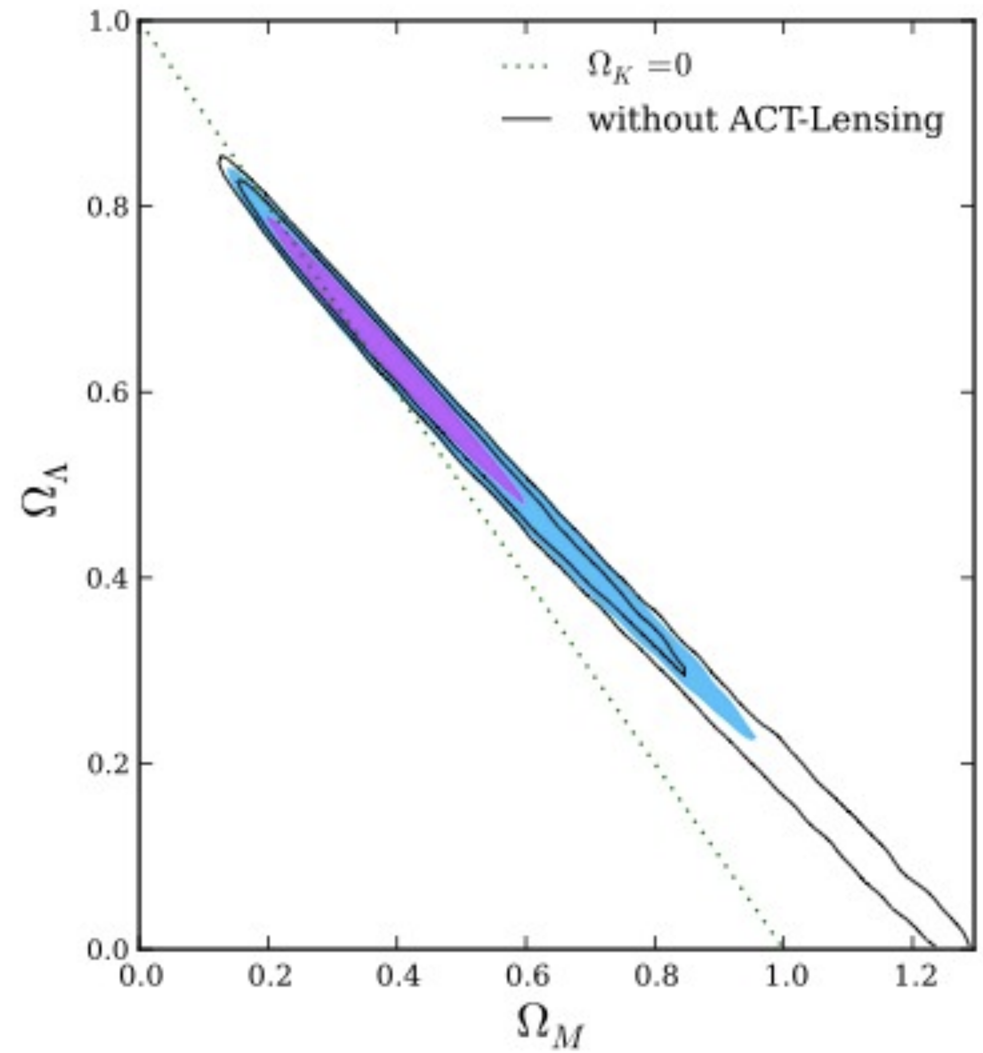
The primary CMB can be kept nearly unchanged under variations of neutrino mass, dark energy equation of state or curvature. But the deflection field cares about these:



Lensing breaks the angular diameter distance degeneracy!

A COOL FIRST APPLICATION: DARK ENERGY FROM CMB ALONE (3.2 SIGMA)





Sherwin, Dunkley, Das et al., PRL 107:021302(2011)

see also van Engelen et al. 2012

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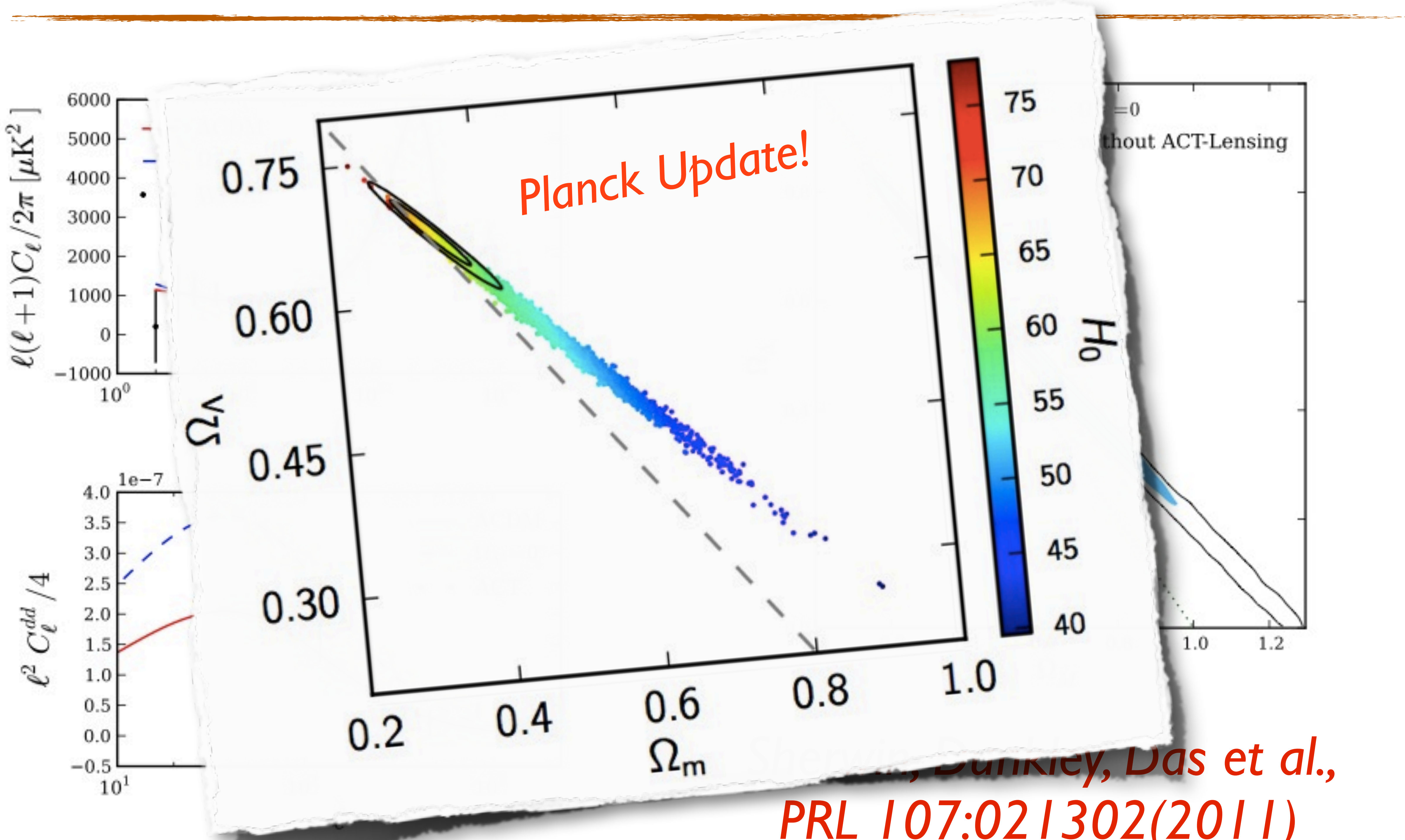

Sherwin, Dunkley, Das et al.,
PRL 107:021302(2011)

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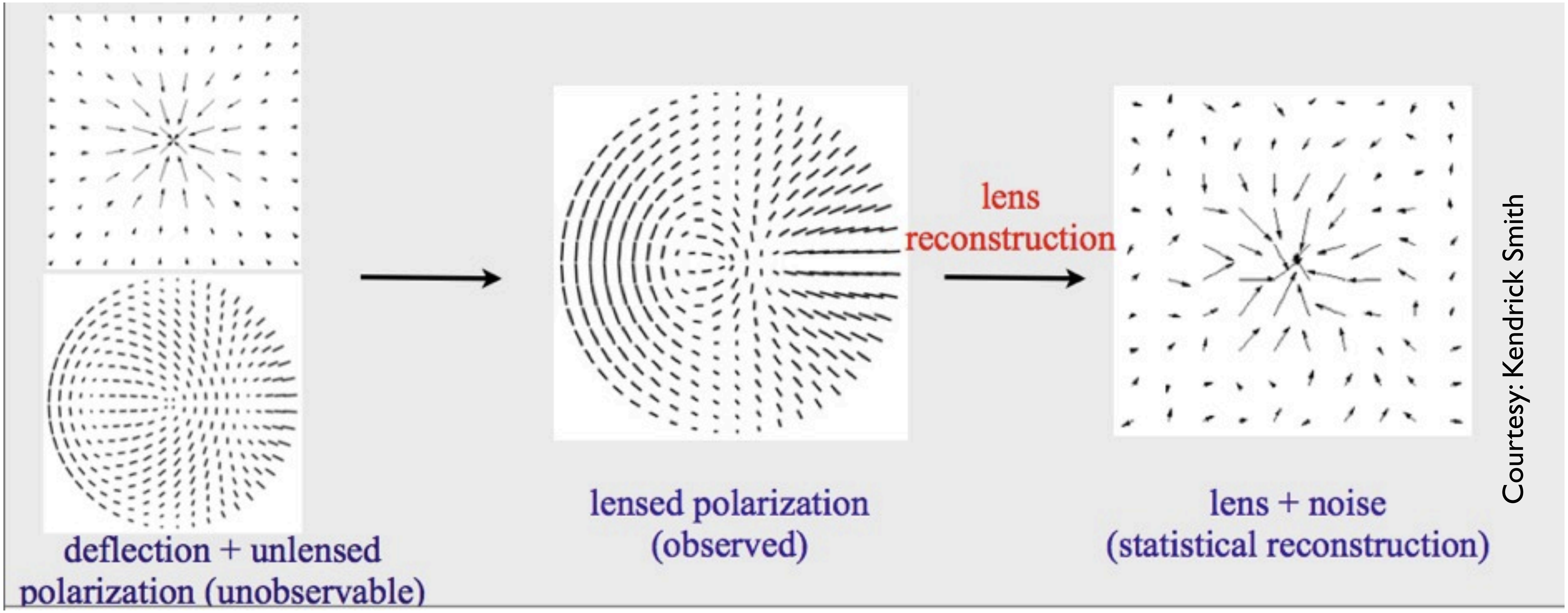
USING CMB POLARIZATION IS THE NEXT BIG THING IN LENSING



From pure E-modes lensing will create a mixture of E and B-modes.

PolarBeaR, ACTPol, SPTPol are gearing up to be premier CMB lensing experiments using polarization.

POLARIZATION GIVES EXTRA LEVERAGE FOR LENSING RECONSTRUCTION

Gravitational lensing remaps the primordial CMB temperature and polarization fields through the deflection field **d(n)**:

$$\begin{aligned} \tilde{T}(\hat{\mathbf{n}}) &= T(\hat{\mathbf{n}} + \mathbf{d}(\hat{\mathbf{n}})) \\ [\tilde{Q} \pm i\tilde{U}](\hat{\mathbf{n}}) &= [Q \pm iU](\hat{\mathbf{n}} + \mathbf{d}(\hat{\mathbf{n}})) \end{aligned}$$

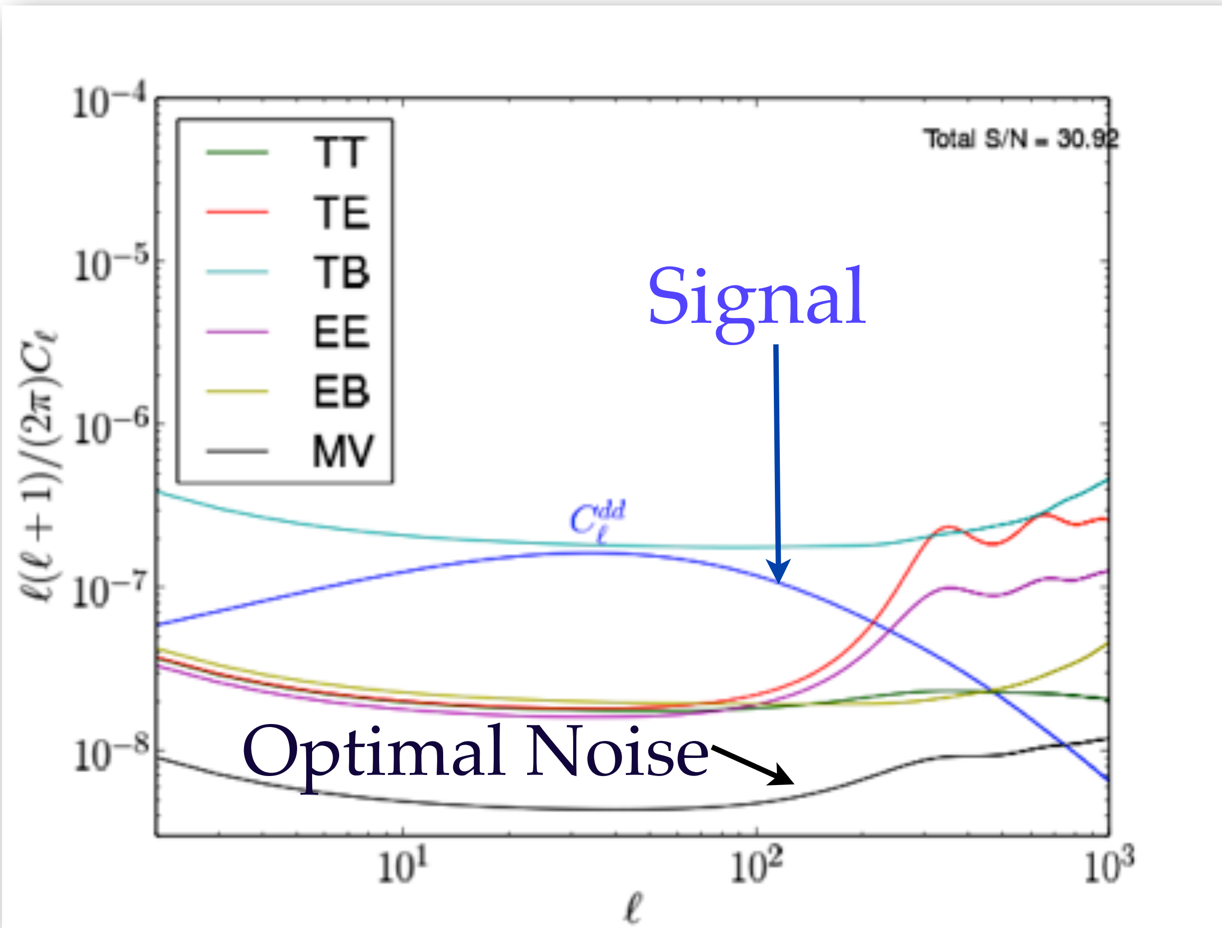
In the Fourier space, lensing introduces correlations between different Fourier modes $\boldsymbol{\ell}, \ \boldsymbol{\ell}'$, which are uncorrelated for the primordial signals. This correlation is used to write down an estimator of the deflection field from the observed fields. Schematically:

$$\hat{\mathbf{d}}_{XY}(\mathbf{L}) \propto \tilde{X}(\boldsymbol{\ell})\tilde{Y}(\mathbf{L} - \boldsymbol{\ell})$$

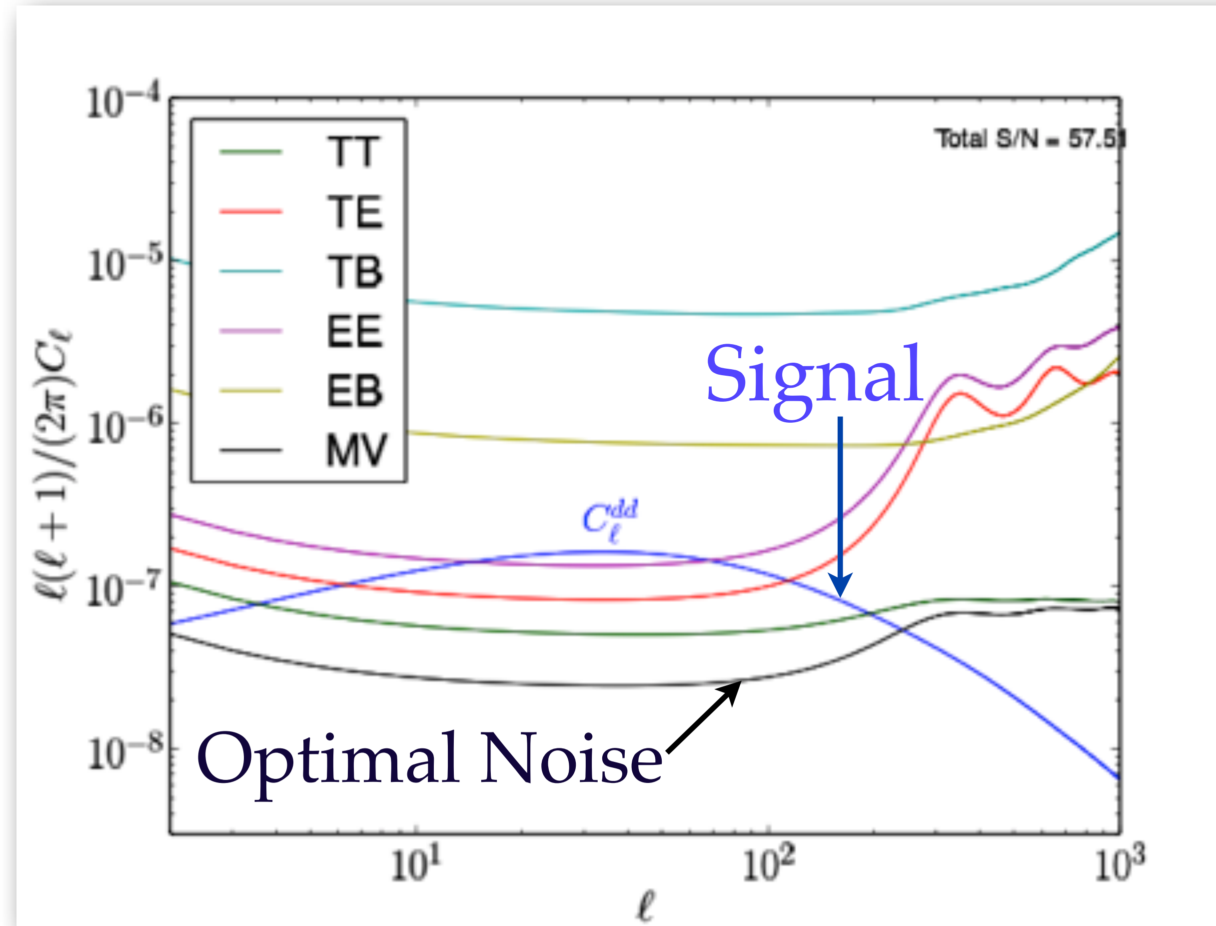
where $X, Y \in (\tilde{T}, \tilde{E}, \tilde{B})$

HIGH RES. POLARIZATION EXPERIMENTS ARE POWERFUL CMB LENSING MACHINES

Assuming no systematics other than instrumental noise, these plots show the signal and noise power spectra for the ACTPol Deep and Wide configurations.



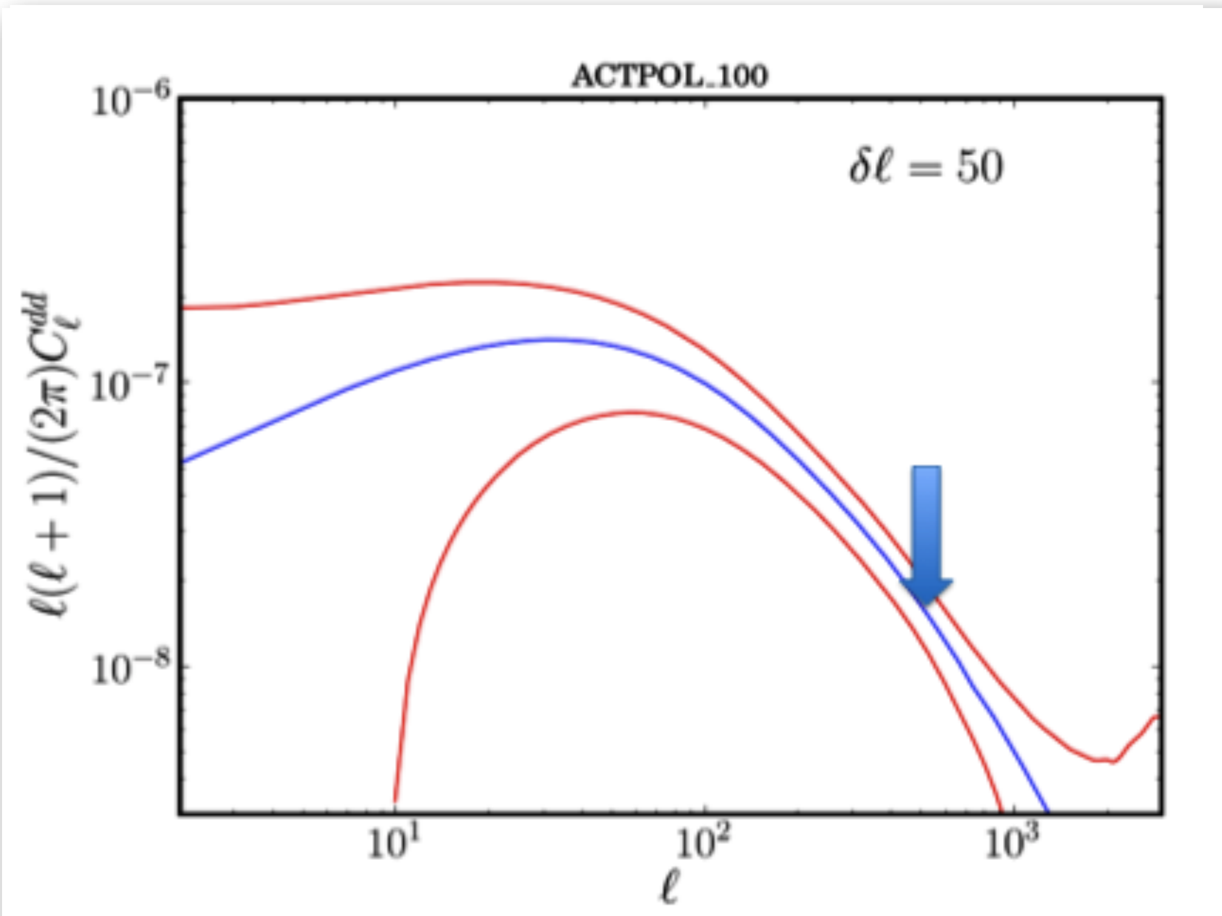
ACTPOL-DEEP:
150 sq-deg @ 3 μK-arcmin (temp) and 5 μK-arcmin (pol)



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

ACTPOL: DESIGNED TO BE A POWERFUL CMB LENSING MACHINE

Assuming no systematics other than instrumental noise, these plots show the signal and noise power spectra for the Deep and Wide configurations.



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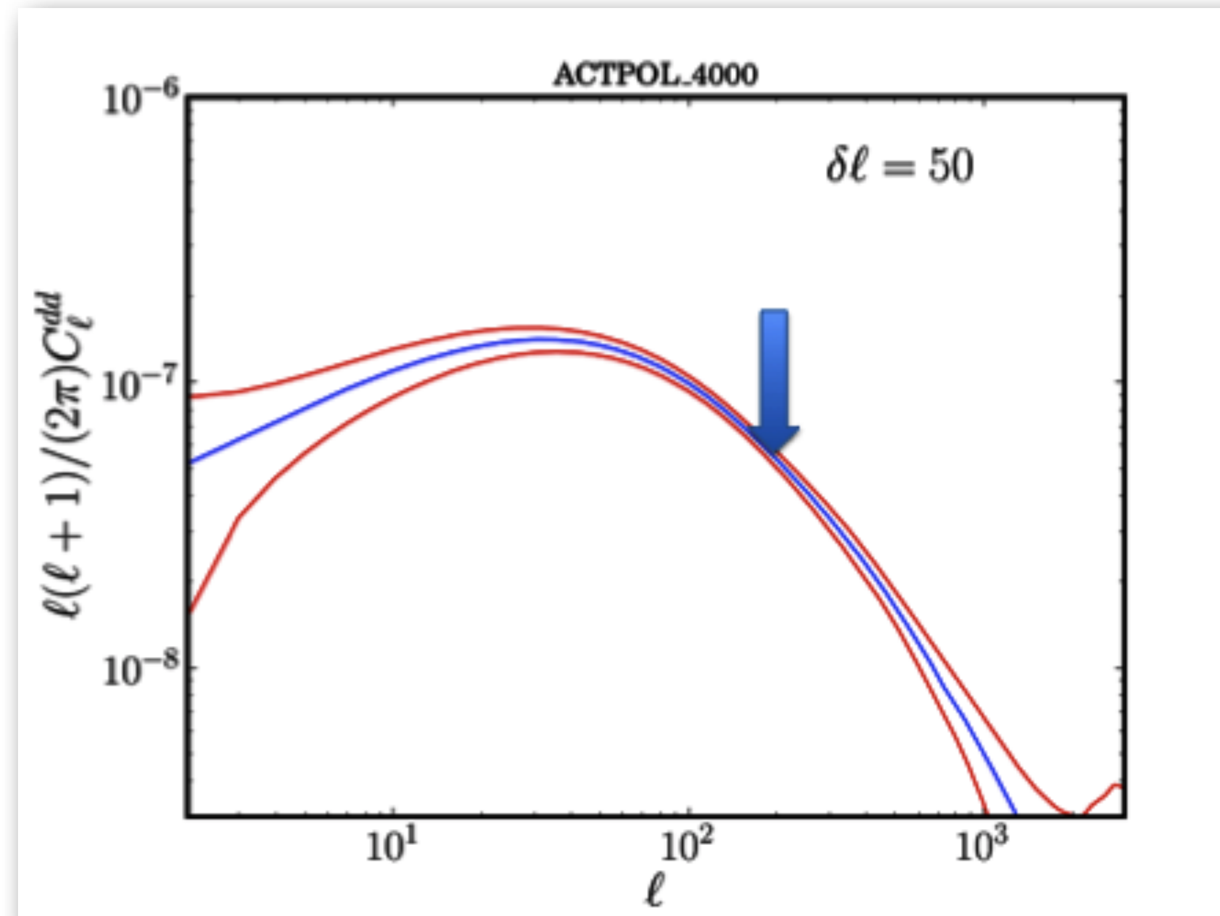

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4000 sq-deg @ 20 μK-arcmin (temp)
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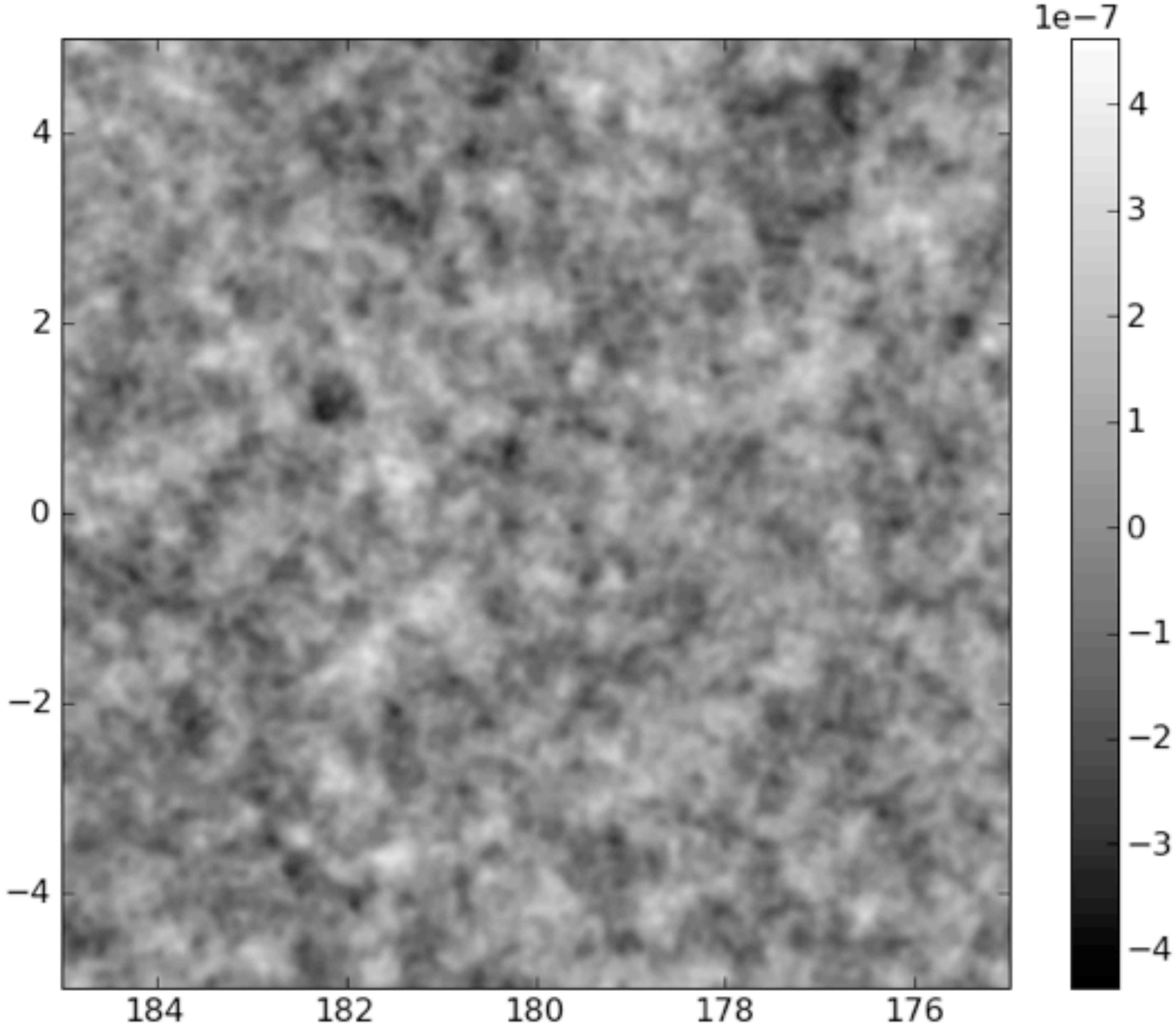
DEEP POLARIZATION OBSERVATIONS WILL ENABLE US TO MAP THE DARK MATTER



2(3) microK-arcmin experiment

10 degree x10 degree

Work done with Blake Sherwin

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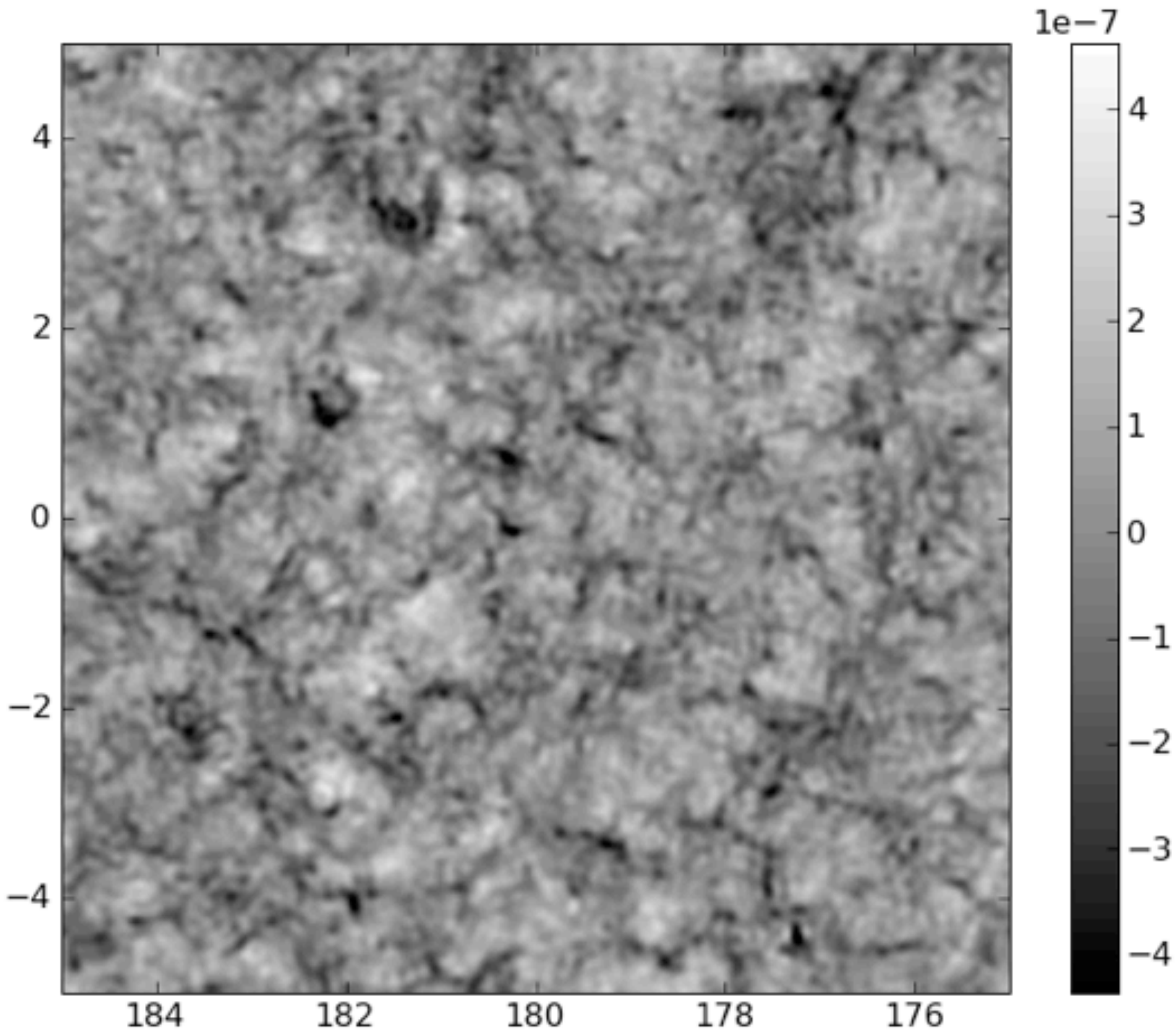
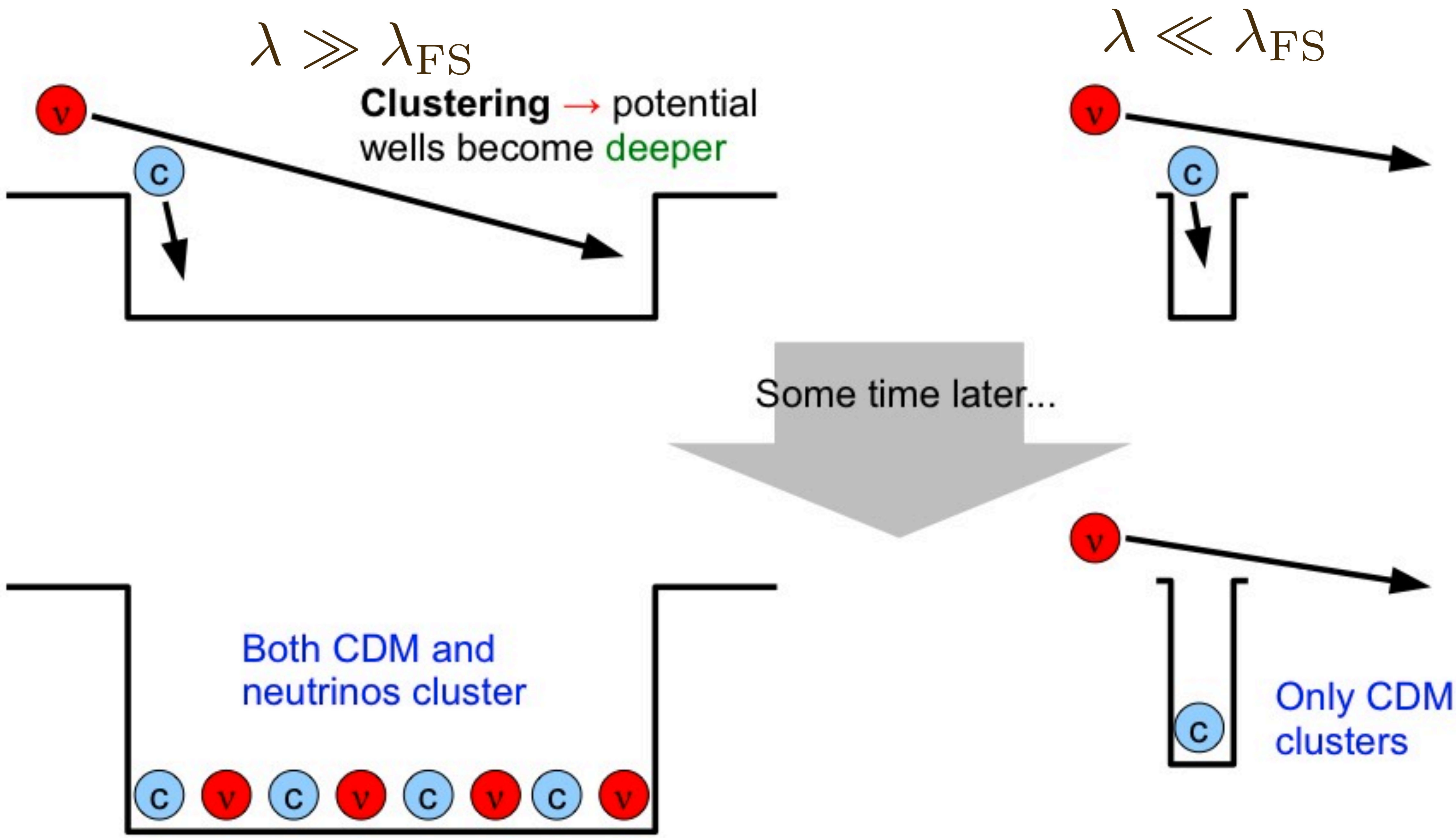


2(3) microK-arcmin experiment

10 degree x10 degree

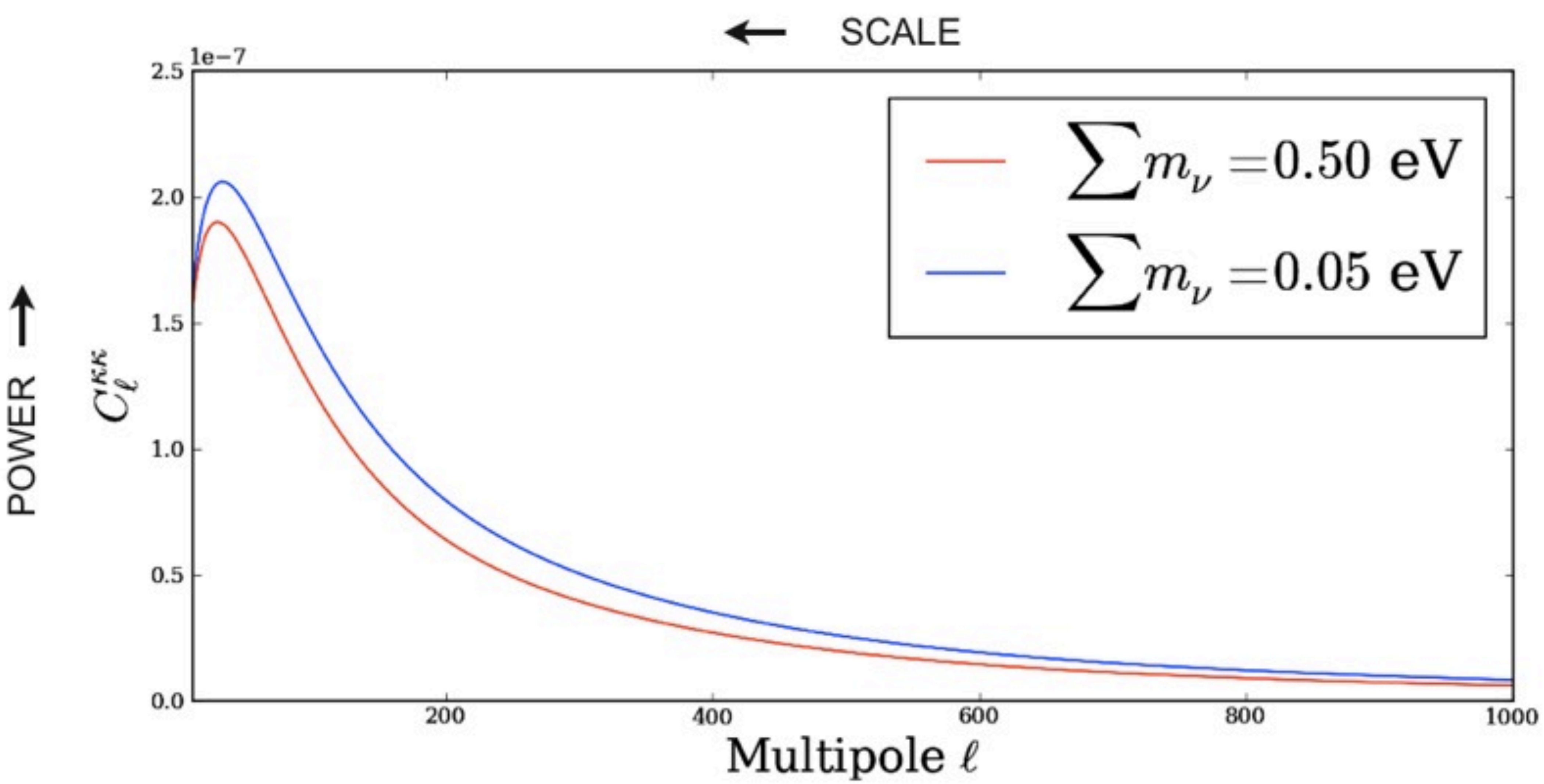
Work done with Blake Sherwin

MASSIVE NEUTRINOS DO NOT CLUSTER ON SMALL SCALES

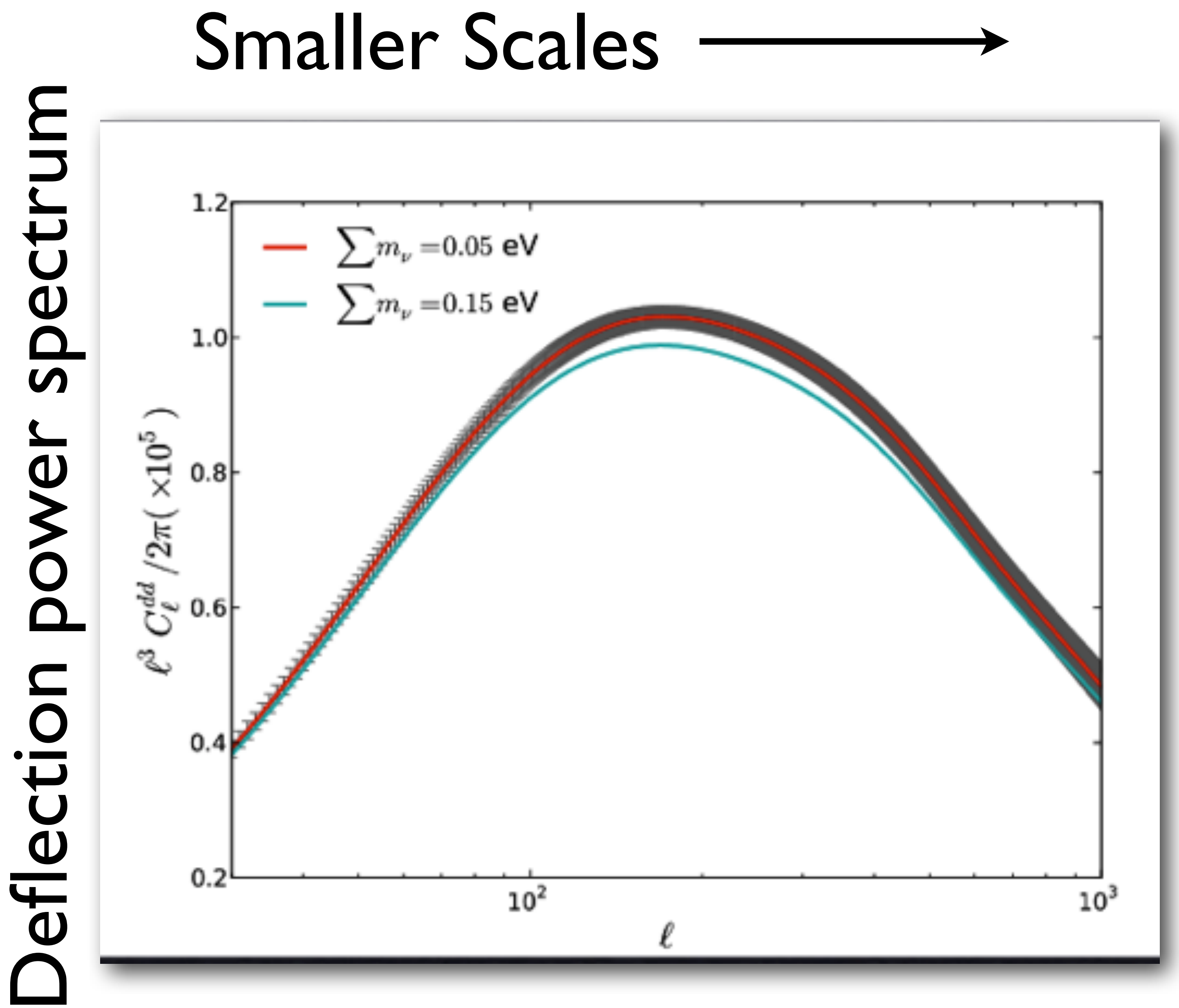


Graphics from Y. Wong

SOON, INTERESTING CONSTRAINTS ON NEUTRINO MASS WILL BE COMING IN



CMB LENSING IS A CLEAN AND SENSITIVE PROBE OF NEUTRINO MASS



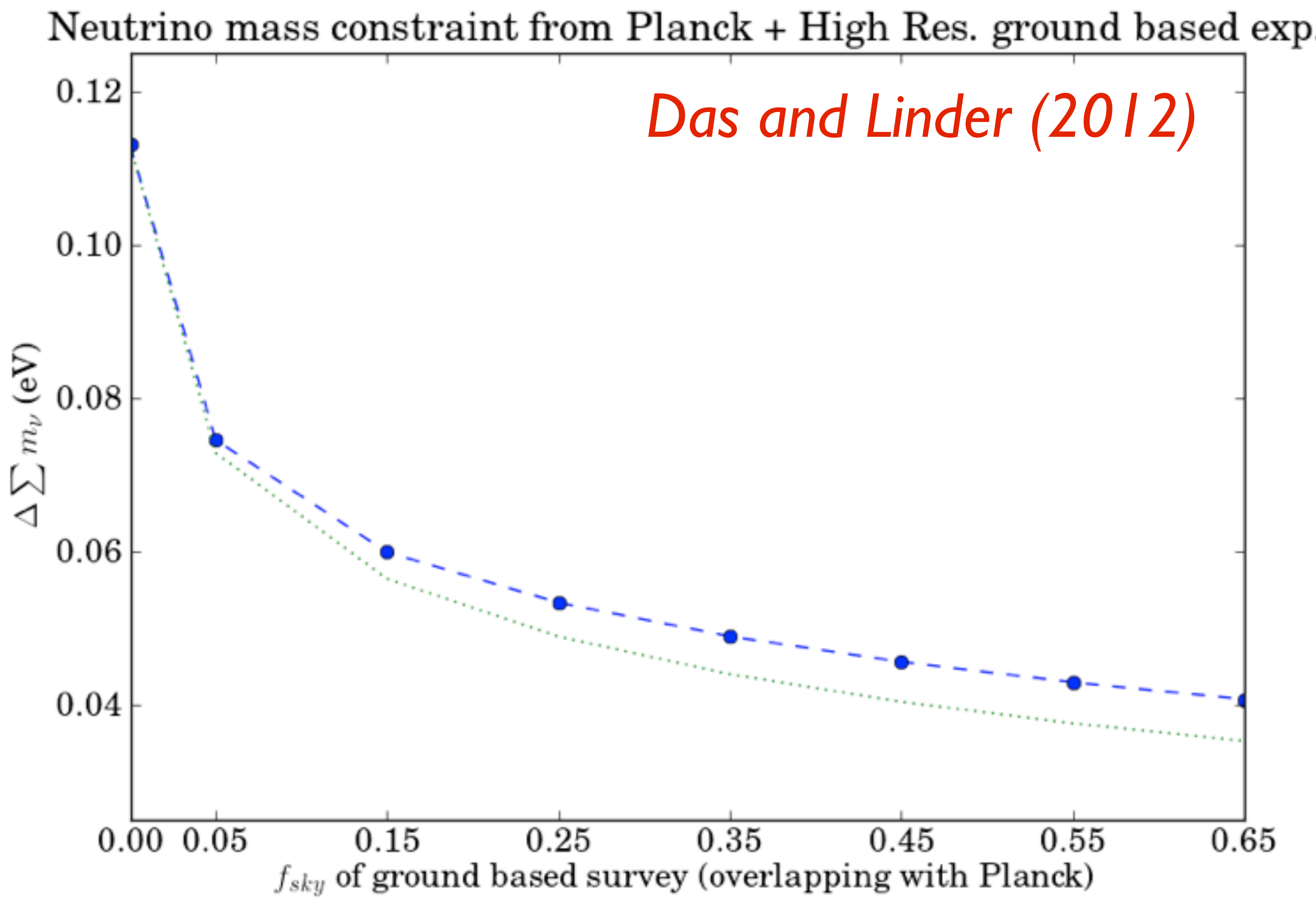
CMB lensing is sensitive:

The deflection field contains cumulative information from a large range of redshift, peaking around z~ 2-3.

CMB lensing is clean:

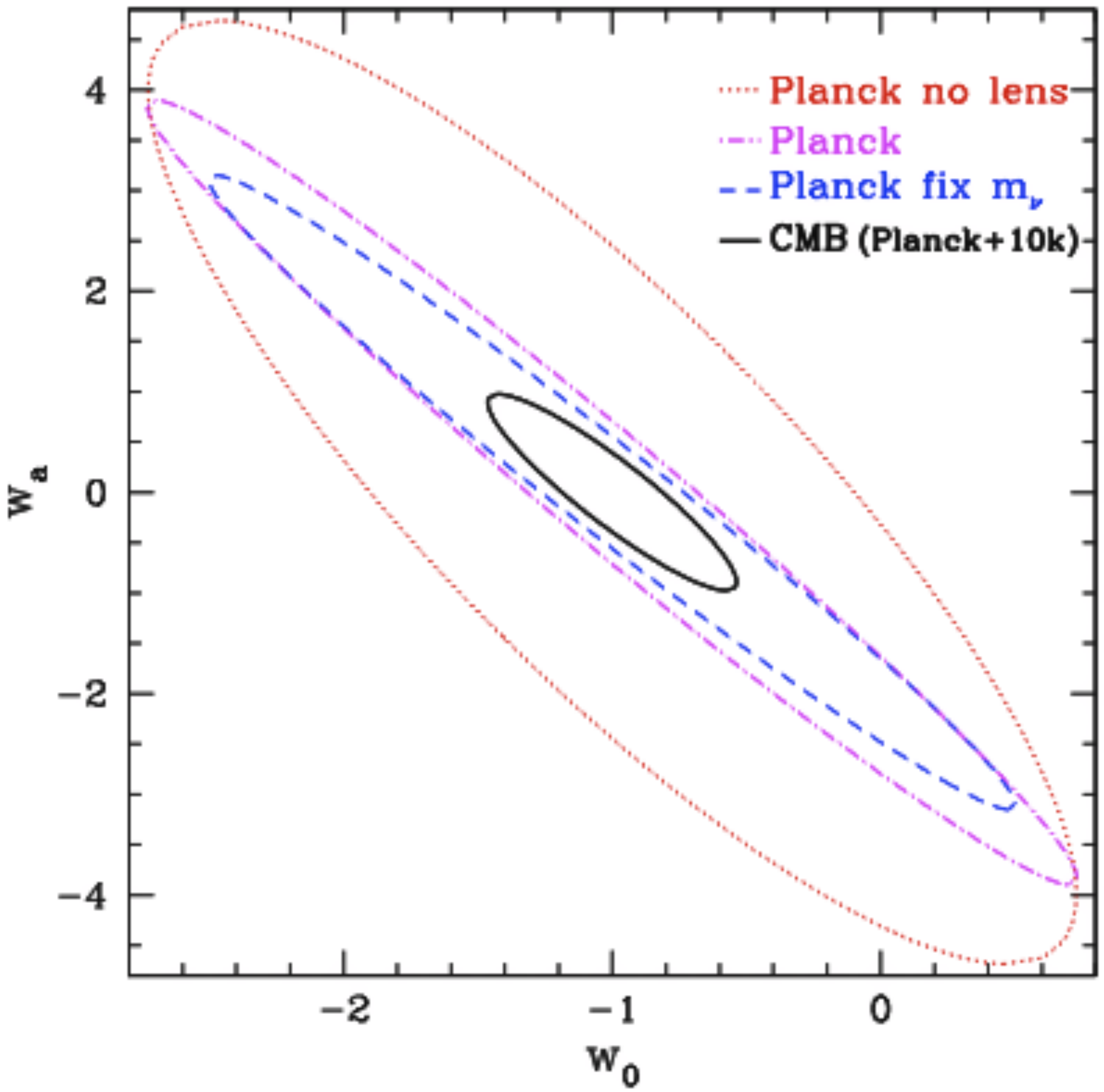
- CMB redshift known
- Most contributions from linear scales.
- No confusion from galaxy bias.

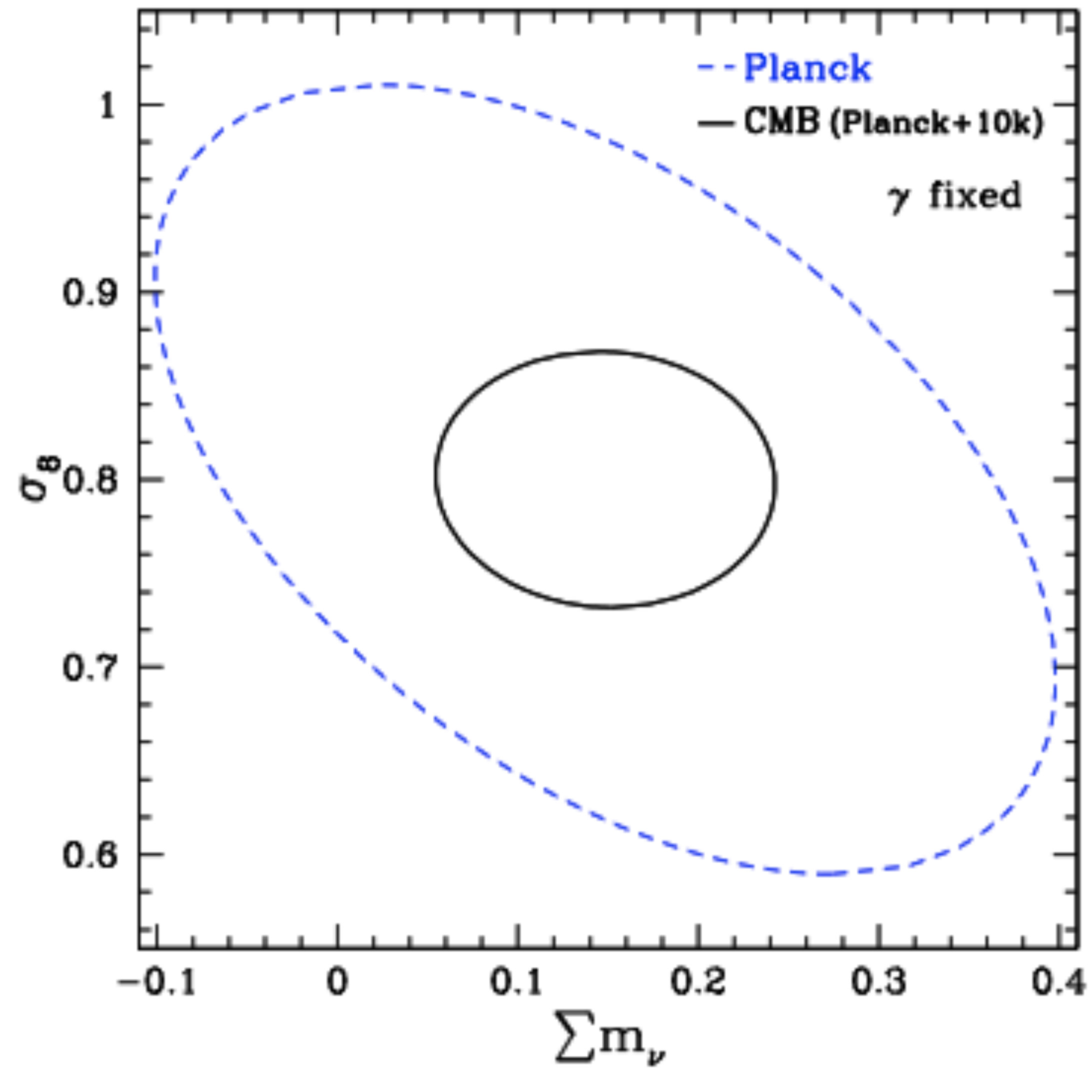
COMBINED WITH PLANCK, HIGH RES EXPERIMENTS WILL BE VERY POWERFUL



COMBINED WITH PLANCK, HIGH RES EXPERIMENTS WILL BE VERY POWERFUL

Assume Planck + 10,000 sq deg high res. data at 5 muk-arcmin.





Das and Linder (2012)

THERE ARE THREE MAIN AVENUES FOR COSMOLOGY WITH CMB LENSING

- ☑ Smearing of CMB power spectrum peaks and small scale B-mode power.
- ☑ Reconstruction of the deflection/ convergence field and its power spectrum.

$$\phi = -2\int \frac{d_A(\eta_0-\eta)}{d_A(\eta)d_A(\eta_0)}\Phi(\eta\hat{n},\eta)\,d\eta$$

Effective Lensing Potential

Geometry

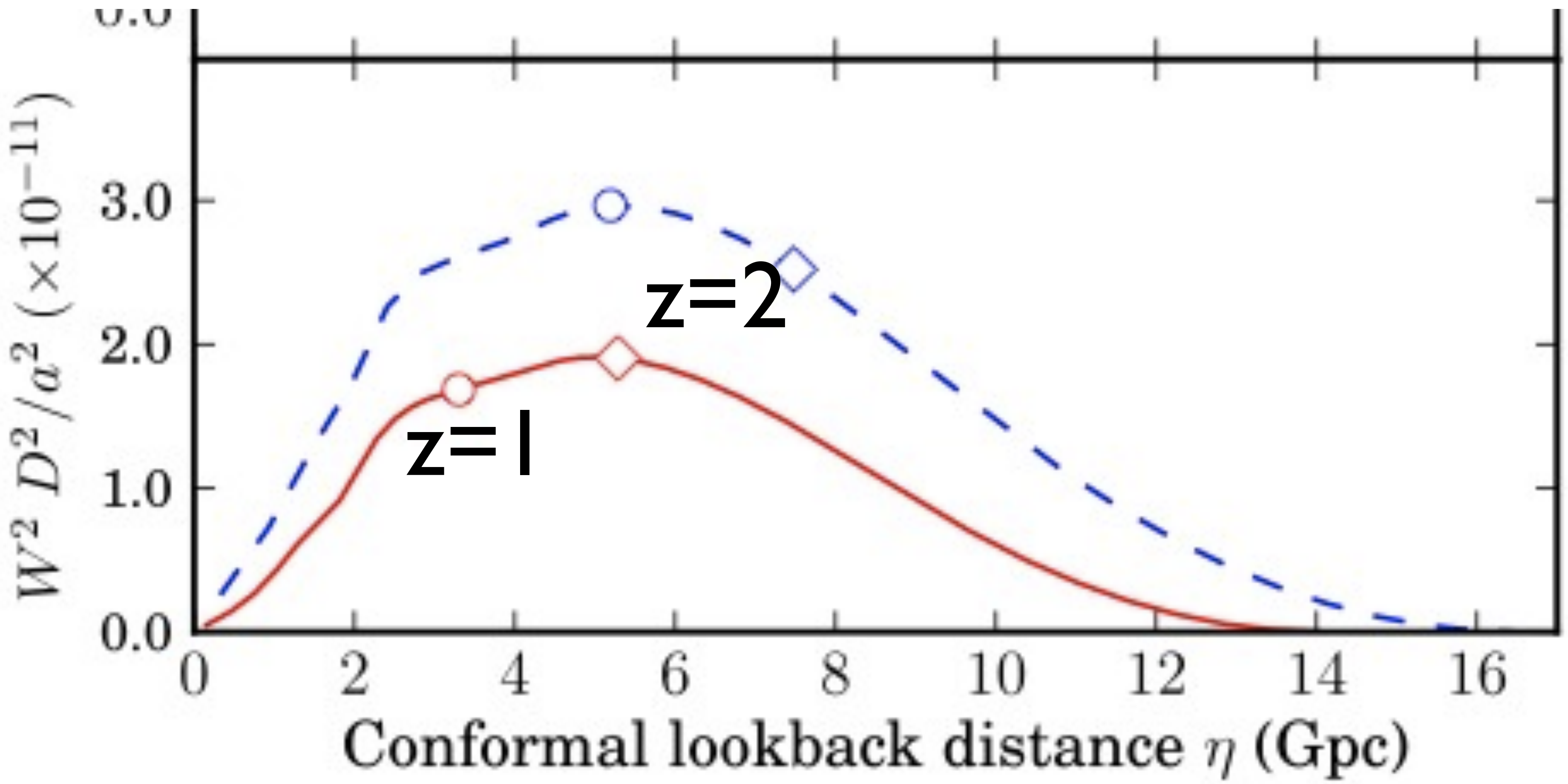
Matter potential

- ☐ Cross correlation of the deflection field with other cosmological probes.

  e.g. *weak lensing, galaxy counts, CIB* ...
  - *break degeneracies.*
  - *constrain systematics.*
  - *constrain galaxy bias*

Highest science impact expected on: *neutrino mass sum, dark energy, test of GR, and understanding galaxy evolution.*

CMB lensing Kernel - ideal for cross correlations



Kernel is broad and large over z~0.5-4

LOGIC: GALAXIES TRACE THE SAME LARGE SCALE STRUCTURE THAT LENS THE CMB:

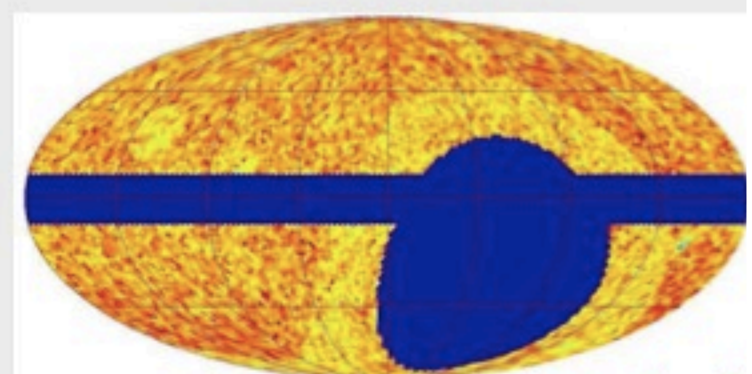
Therefore, a non-zero cross correlation is expected between galaxies and reconstructed deflection field

Smith, Zahn, Dore & Nolta 2007 (see also Hirata et al 2008)

Courtesy: Kendrick Smith

NVSS: NRAO VLA Sky Survey

1.4 GHz source catalog,
50% complete at 2.5 mJy



galaxy counts (masked)

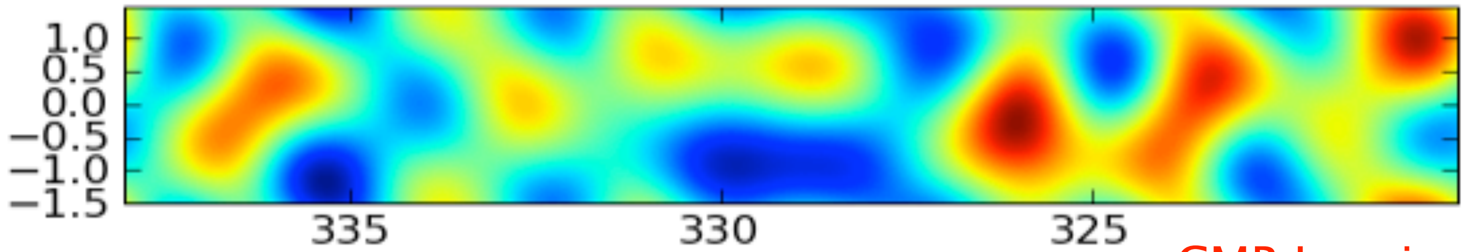
Mostly extragalactic sources:
- AGN-powered radio galaxies
- Quasars
- Star-forming galaxies

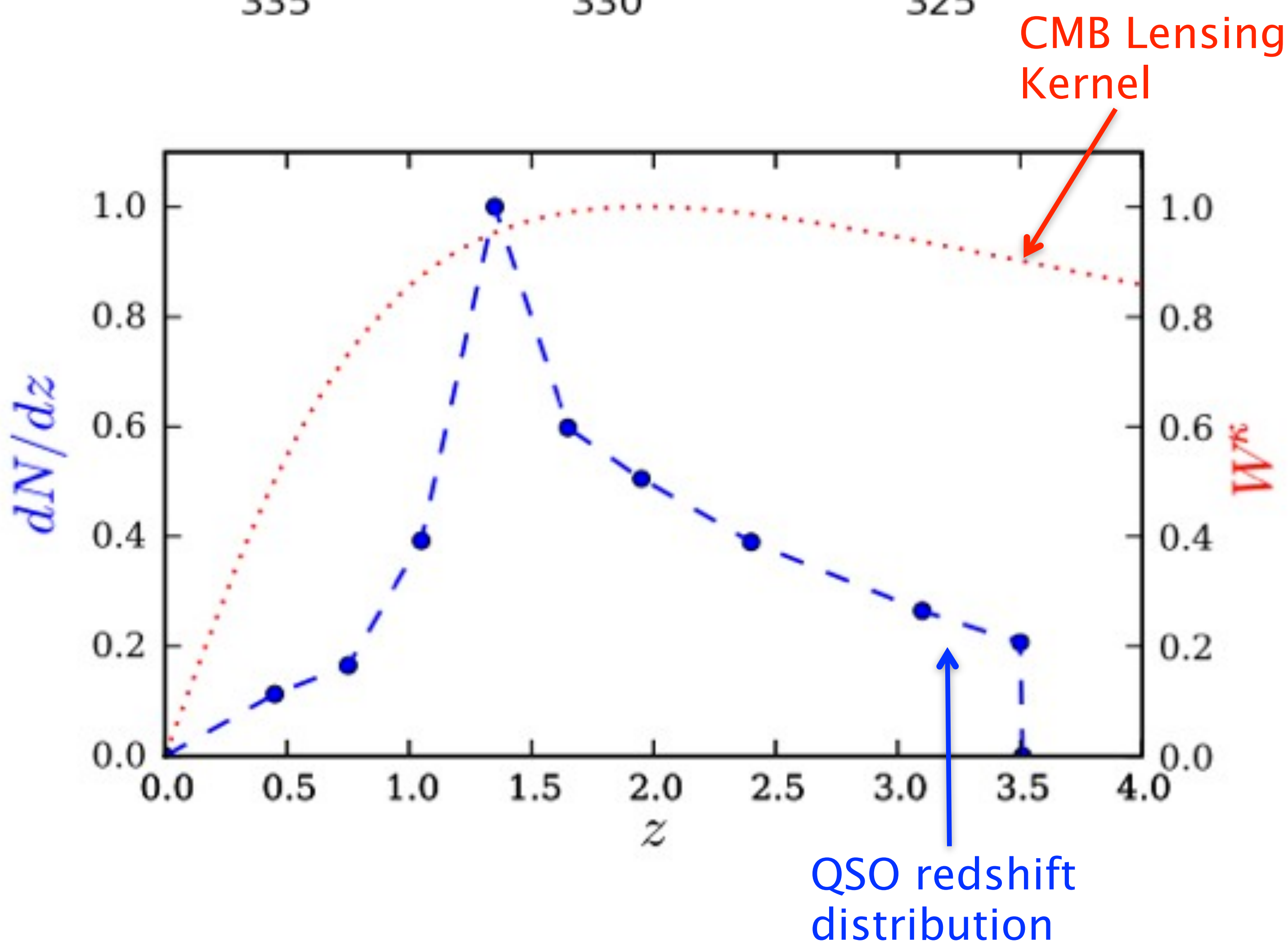
Well-suited for cross-correlating to WMAP lens reconstruction:

- Nearly full sky coverage ($f_{\rm sky} = 0.8$)
- Low shot noise ($b_g = 2,\ N_{\rm gal} = 1.8 \times 10^6$)
- High redshift ($z_{\rm median} = 2$)

SDSS x ACT
Quasar-CMB lensing Cross-correlation

A quasar density map



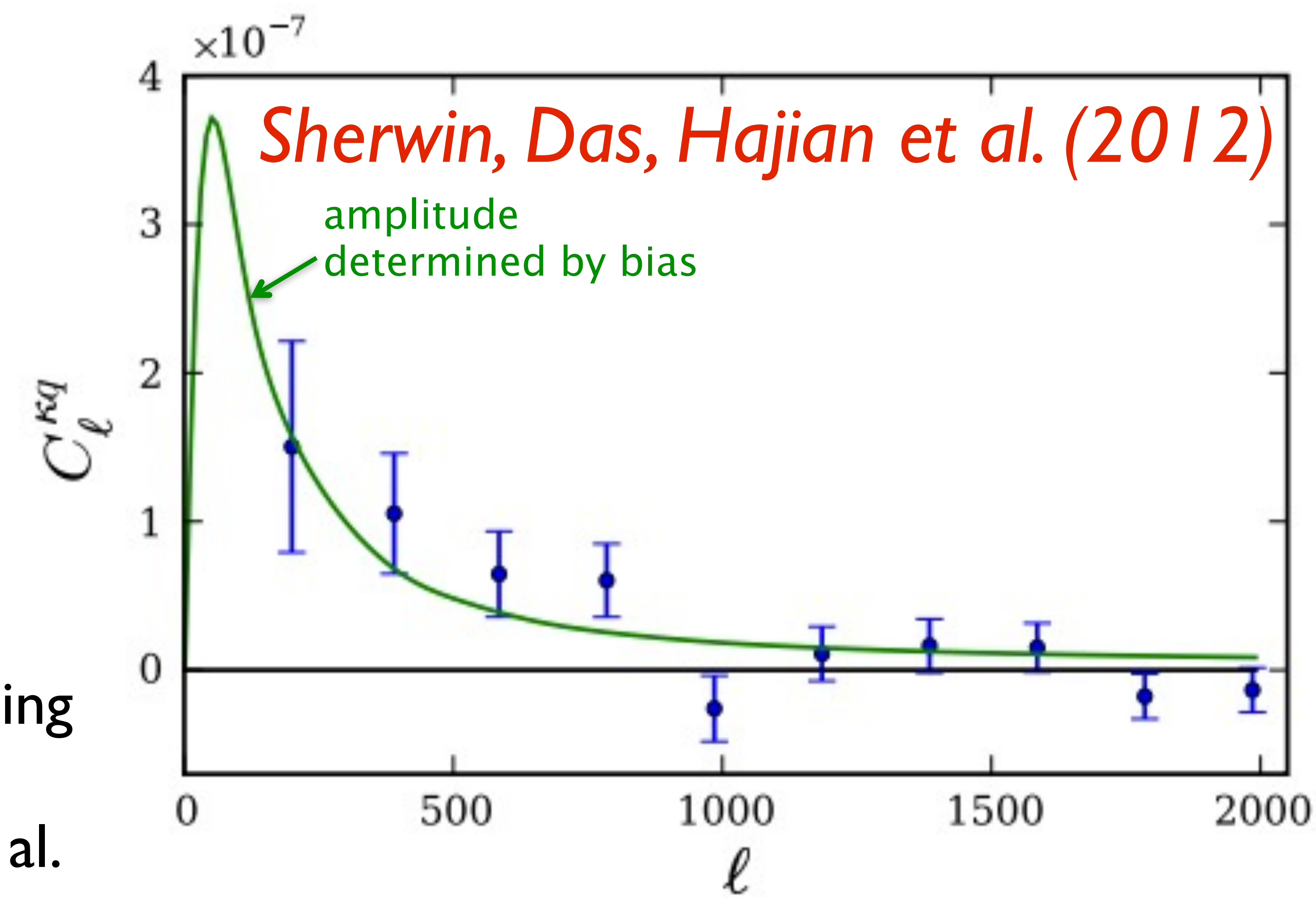


SDSS x ACT
Quasar-CMB lensing Cross-correlation

Cross-power with SDSS photometric QSO catalog (Bovy et al 2010):

4 sigma detection (quasars do trace mass)

- Constraint on bias (assuming shape of redshift dependence from Shen et al. 2008): b(z~1.4)=2.5 ± 0.6
- This translates to a halo mass of $\log_{10}(M_{200}/M_{sun})$= 12.9 +0.3/-0.5



Multipole ℓ

See also, Bleem, van Engelen et al. 2012

Planck cross correlations show the promise already!

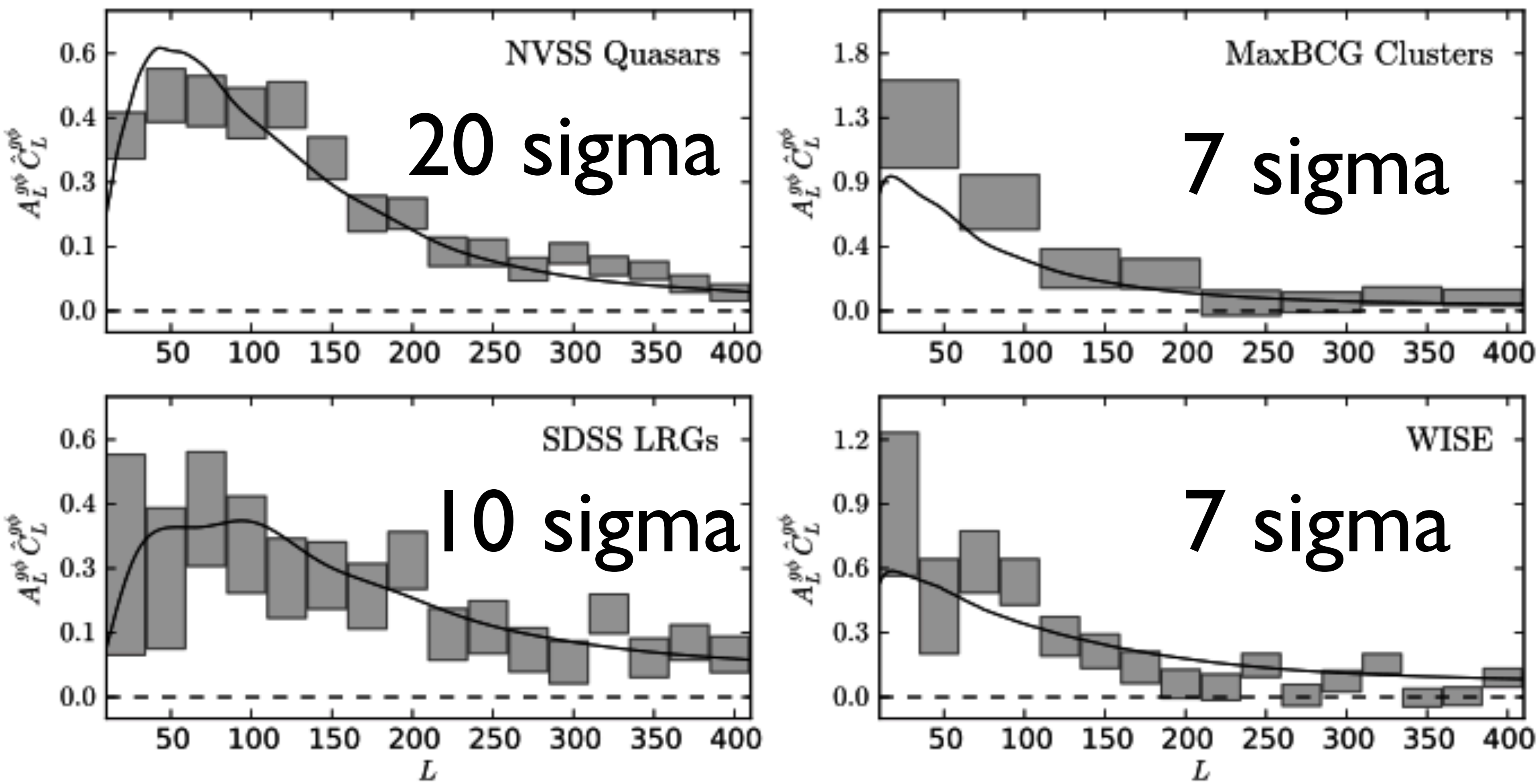
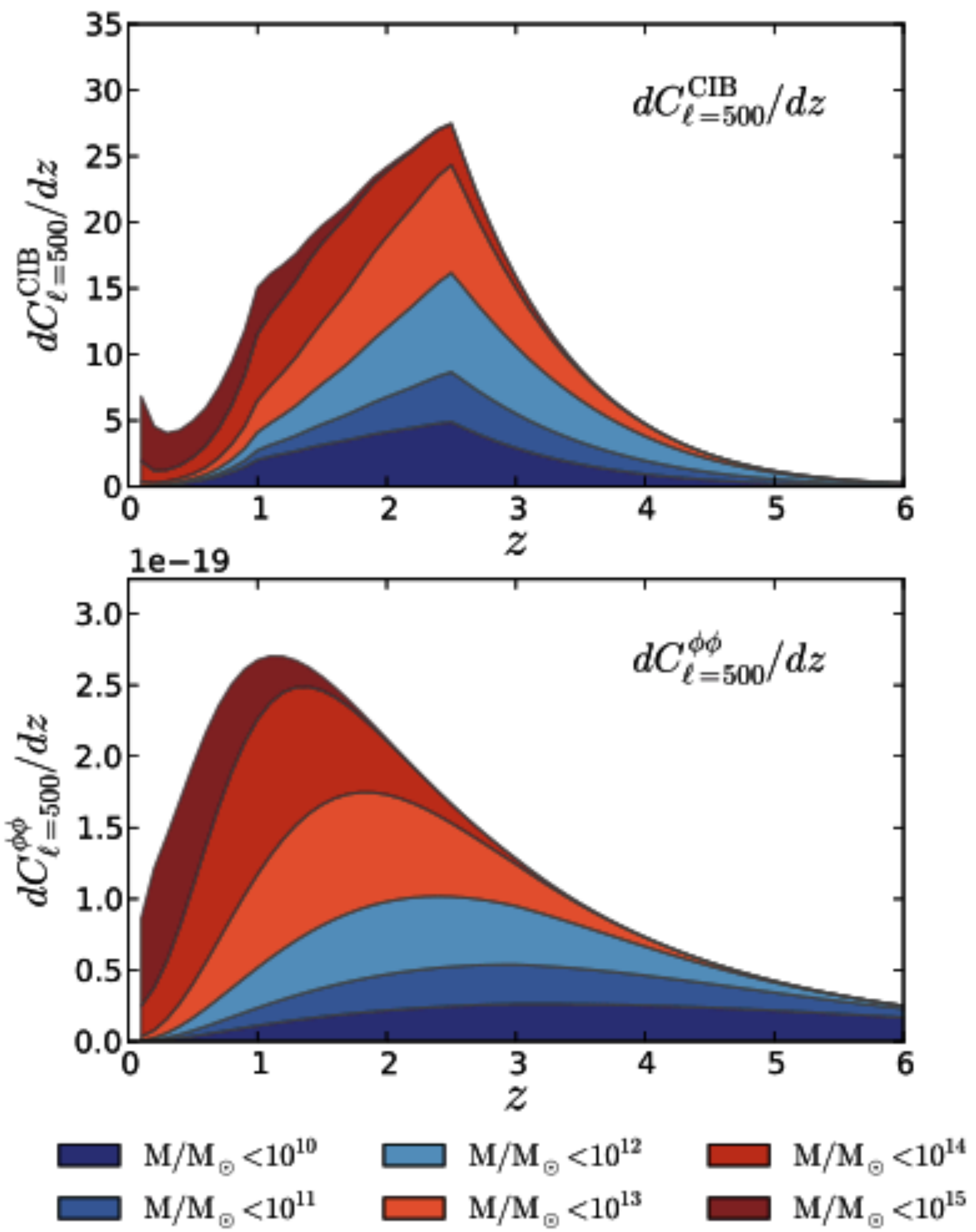


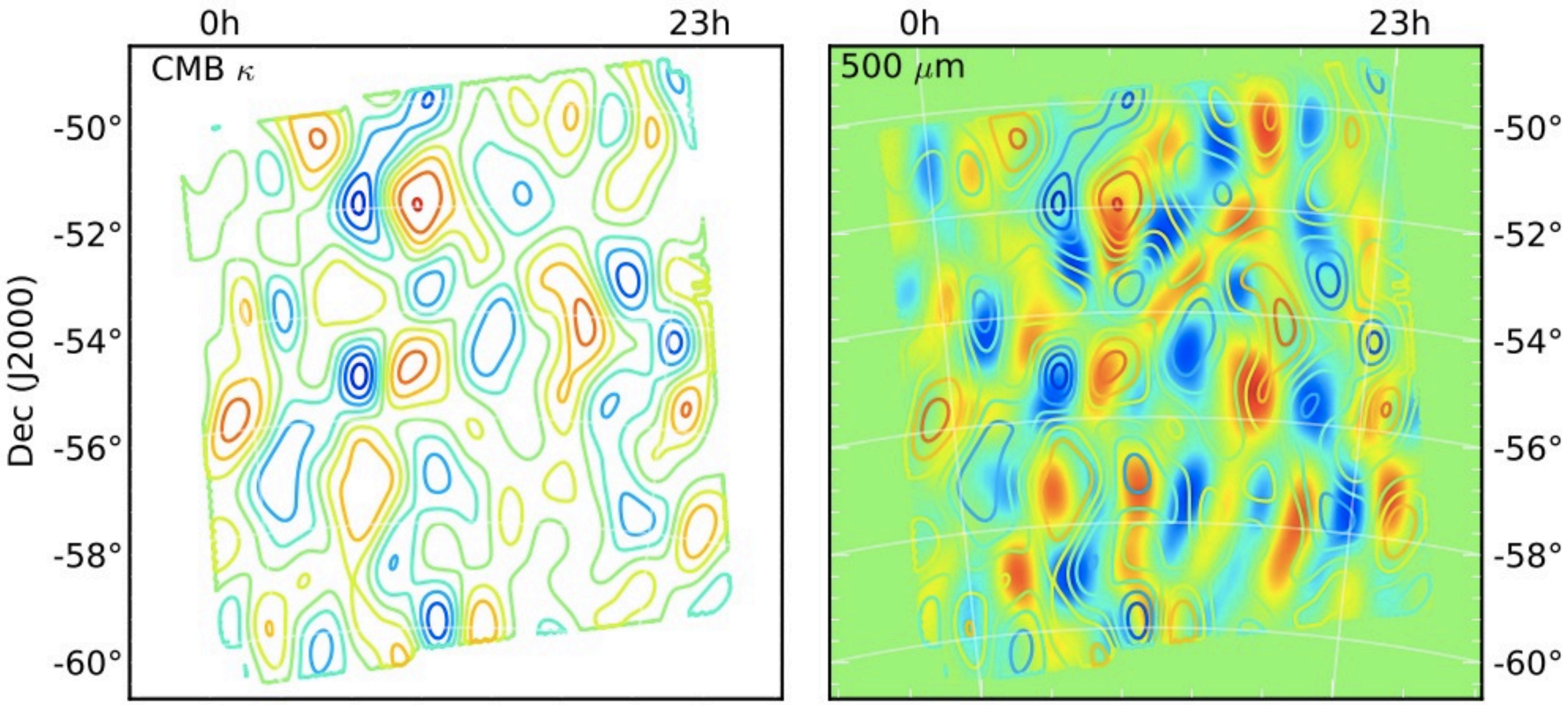
Fig. 17. Cross-spectra of the *Planck* MV lensing potential with several galaxy catalogs, scaled by the signal-to-noise weighting factor $A_L^{g\phi}$ defined in Eq. (52). Cross-correlations are detected at approximately 20σ significance for NVSS, 10σ for SDSS LRGs and 7σ for both MaxBCG and WISE.

CIB x CMB Lensing correlations



CIB (Cosmic Infrared Background) and CMB lensing kernels are made-for-each-other!

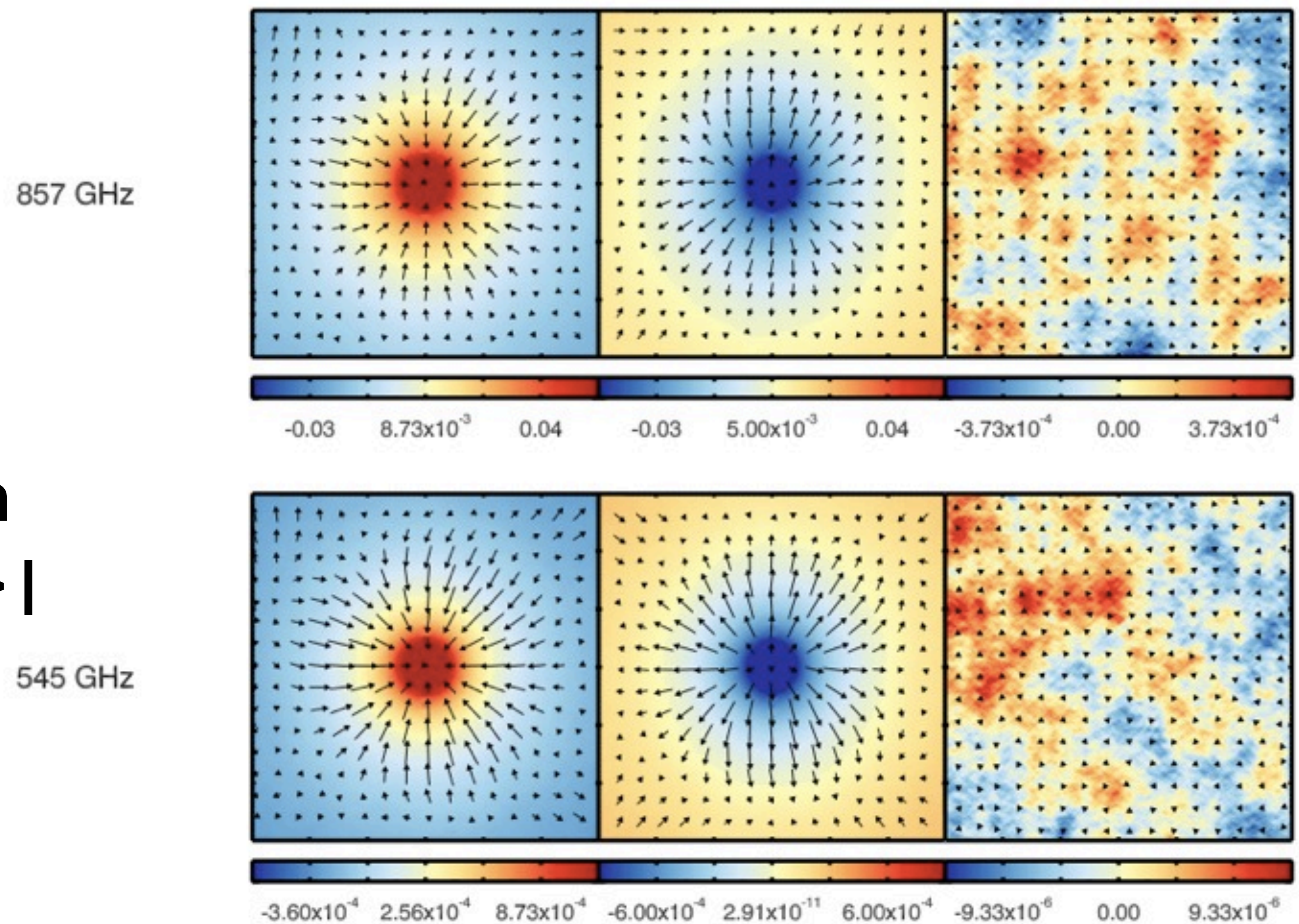
CIB x CMB Lensing correlations



SPT 150 GHz x Herschel/SPIRE *Holder et al. (2013)*

CIB x CMB Lensing correlations

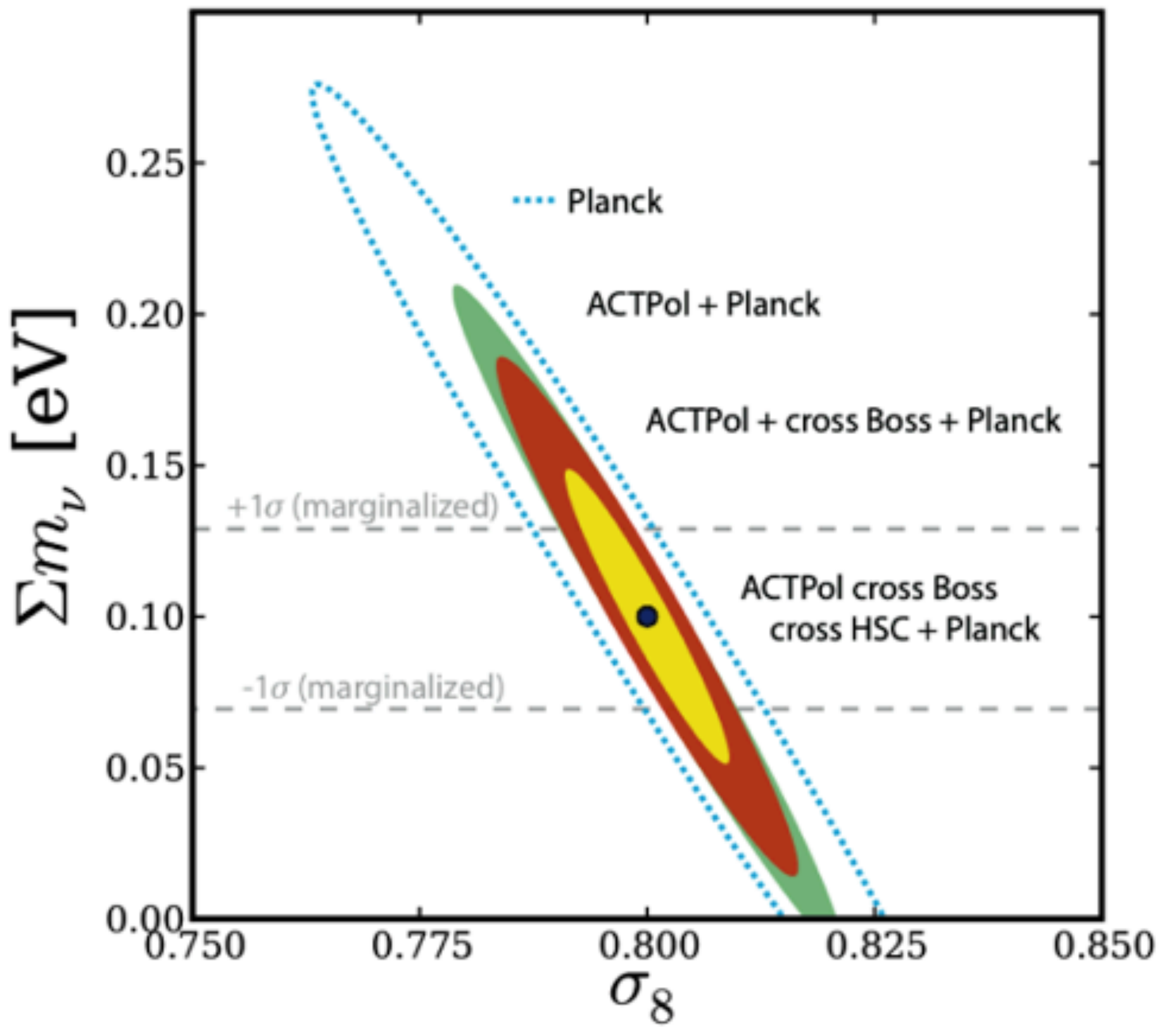
Constrain Star Formation Rate at z>1

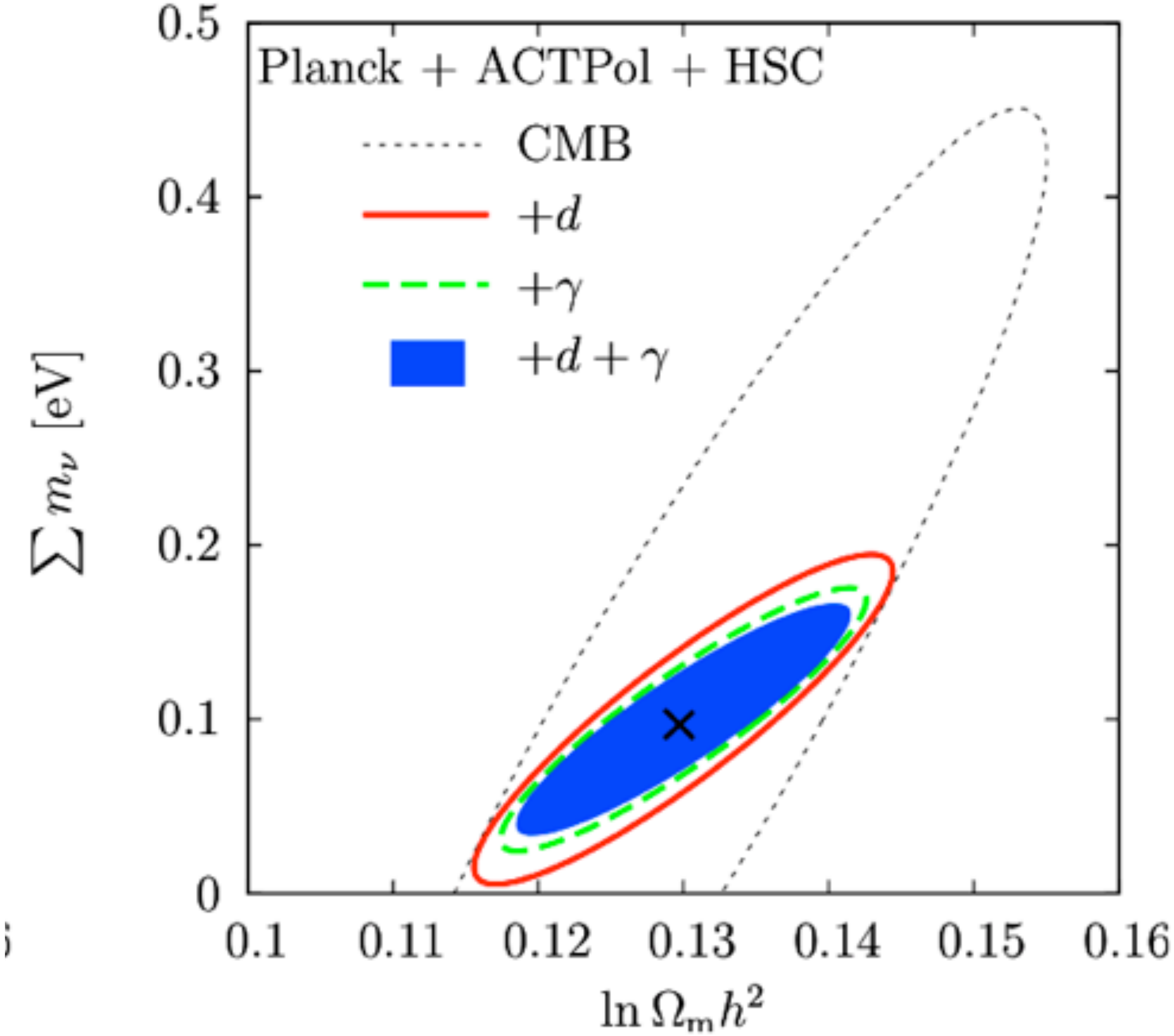


Planck temp x Planck CMB lensing

Cross correlations: SYNERGY WITH GALAXY AND WEAK LENSING SURVEYS (MS-DESI,DES, LSST)

CMB lensing X Galaxy density X Galaxy Lensing





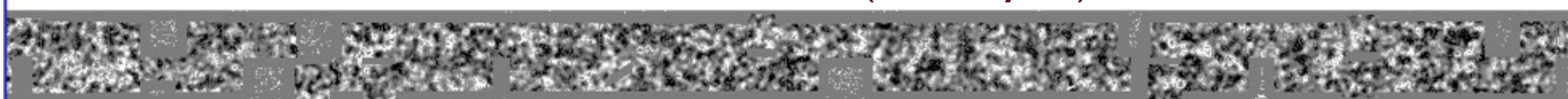
Namikawa et al (2010)

A PILOT CMB LENSING x COSMIC SHEAR CROSS-CORRELATION STUDY WITH CFHT ON STRIPE 82 IS UNDERWAY

CMB lensing
X Galaxy Shear

In collaboration with Alexie Leauthaud (LBL/IPMU Japan), Catherine Heymans, Jean Paul Knieb (Merseille), Ludovic Van Waerbeke (UBC), Martin Makler (ICRA/CBPF - LIneA, Brazil) and the Canada France Hawaii Telescope Team.

Part of the work done with LBL summer intern
Charlotte Welker (ENS, Lyon)



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

Cross correlations can be used to control systematics in cosmic shear surveys

Example: *Cosmic shear multiplicative bias*

$$\kappa_{opt} = m \times \kappa_{true}$$

$$\frac{\text{CMBL x WL}}{\text{CMBL x CMBL}} \qquad \frac{C_l^{\kappa_{CMB}\kappa_{opt}}}{C_l^{\kappa_{CMB}\kappa_{CMB}}} = \boxed{m} \frac{\int d\eta \left(\frac{g_{opt}(\eta)}{a(\eta)}\right)\left(\frac{g_{CMB}(\eta)}{a(\eta)}\right) P\left(\frac{l}{d_A}, \eta\right)}{\int d\eta \left(\frac{g_{CMB}(\eta)}{a(\eta)}\right)^2 P\left(\frac{l}{d_A}, \eta\right)}$$

(Vallinotto 2012)

Cross correlations can be used to control systematics in cosmic shear surveys

Primary systematics: *Cosmic shear multiplicative bias*

$$\kappa_{opt} = m \times \kappa_{true}$$

$$C_\ell^{\kappa_{\rm CMB}\Sigma} = \frac{3}{2}\Omega_{\rm m} H_0^2 \int d\eta b_\ell(\eta) W_f(\eta) \frac{g_{\rm CMB}(\eta)}{a(\eta)} P(\frac{\ell}{d_A}, \eta),$$

$$C_\ell^{\kappa_{\rm opt}\Sigma} = m\ \frac{3}{2}\Omega_{\rm m} H_0^2 \int d\eta\ b_\ell(\eta) W_f(\eta) \frac{g_{\rm opt}(\eta)}{a(\eta)} P(\frac{\ell}{d_A}, \eta).$$

$$\frac{C_\ell^{\kappa_{\rm opt}\Sigma}}{C_\ell^{\kappa_{\rm CMB}\Sigma}} = \boxed{m} \frac{g_{\rm opt}(\eta)}{g_{\rm CMB}(\eta)}$$

Cross correlations can be used to control systematics in cosmic shear surveys

Primary systematics: *Cosmic shear multiplicative bias*

$$\kappa_{opt} = m \times \kappa_{true}$$

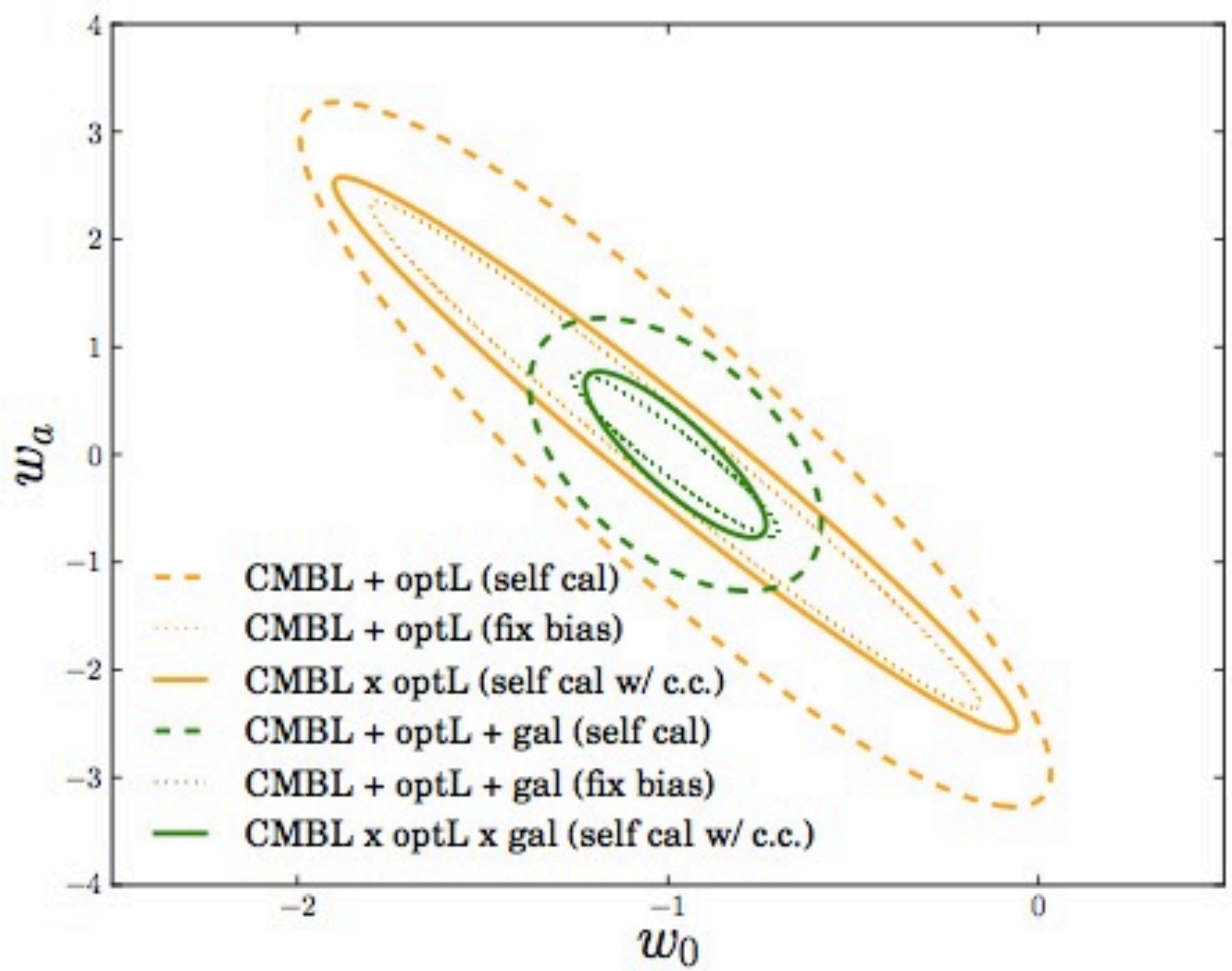
$$C_\ell^{XY} \equiv \Bigg\{ C_\ell^{\kappa_{\rm CMB}\kappa_{\rm CMB}}, \underbrace{\{C_\ell^{\kappa_{\rm CMB}\kappa_{\rm opt}}\}}_{N_{\rm opt}\ \rm spectra}, \underbrace{\{C_\ell^{\kappa_{\rm CMB}\Sigma}\}}_{N_{\rm f}\ \rm spectra},$$

$$\underbrace{\{C_\ell^{\kappa_{\rm opt}\kappa_{\rm opt}}\}}_{N_{\rm opt}(N_{\rm opt}+1)/2\ \rm spectra}, \underbrace{\{C_\ell^{\kappa_{\rm opt}\Sigma}\}}_{N_{\rm opt}N_{\rm f}\ \rm spectra},$$

$$\underbrace{\{C_\ell^{\Sigma\Sigma}\}}_{N_{\rm f}(N_{\rm f}+1)/2\ \rm spectra} \Bigg\}.$$

Cross correlations can be used to control systematics in cosmic shear surveys

ACTPol+ HSC+ BOSS



For the BOSS-like survey, we assume three redshift bins $0.3 < z < 0.4$, $0.4 < z < 0.5$ and $0.5 < z < 0.6$ with the linear bias parameter of 2.0 in each bin (which are marginalized over), and a total galaxy density of 0.011 per arcmin^2.

FOR HSC

$z_0 = 0.69$

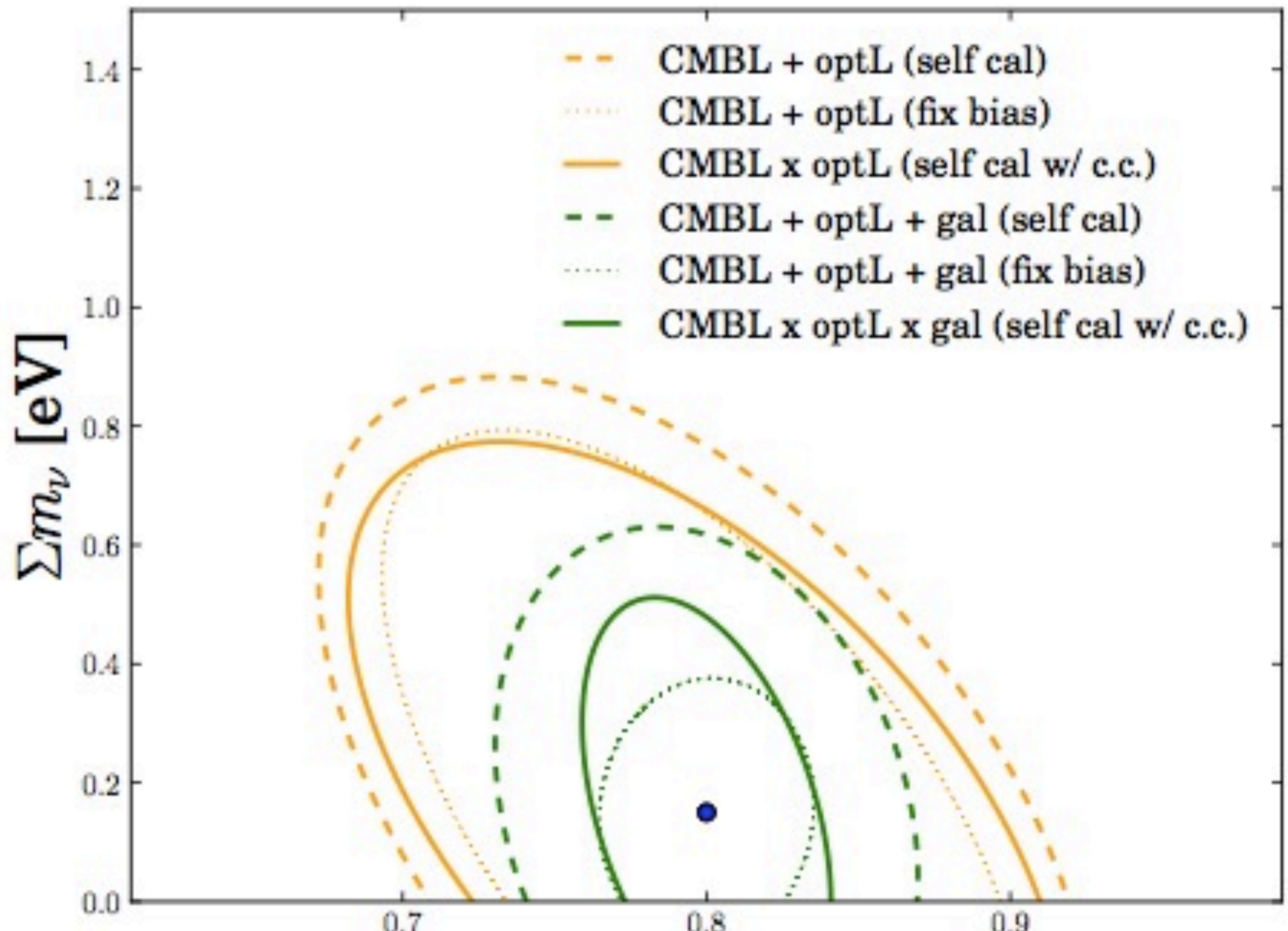
$\bar{N}_g = 35$ galaxies per arcmin^2

Das, Spergel, Errard et al., in prep.

Cross correlations can be used to control systematics in cosmic shear surveys

ACTPol+ HSC+ BOSS

No primary CMB prior



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Cross correlations can be used to control systematics in cosmic shear surveys

ACTPo

TABLE I. Estimated marginalized 1-σ error on the shear multiplicative bias parameter $m_i = (1 + \alpha_i)$ in the tomographic bin i, and the galaxy bias parameter b_j in spectroscopic bin j for various ways of combining data sets.

Bias parameter	Fiducial value	CMBL + optL	CMBL × optL	CMBL + optL + gal.	CMBL × optL × gal
α_1	0.008	0.058	0.026	0.047	0.021
α_2	0.014	0.063	0.010	0.054	0.008
α_3	0.020	0.063	0.007	0.053	0.005
b_1	2.000	-	-	0.070	0.053
b_2	2.000	-	-	0.058	0.044
b_3	2.000	-	-	0.073	0.055

w_0

Das, Sp

Sudee

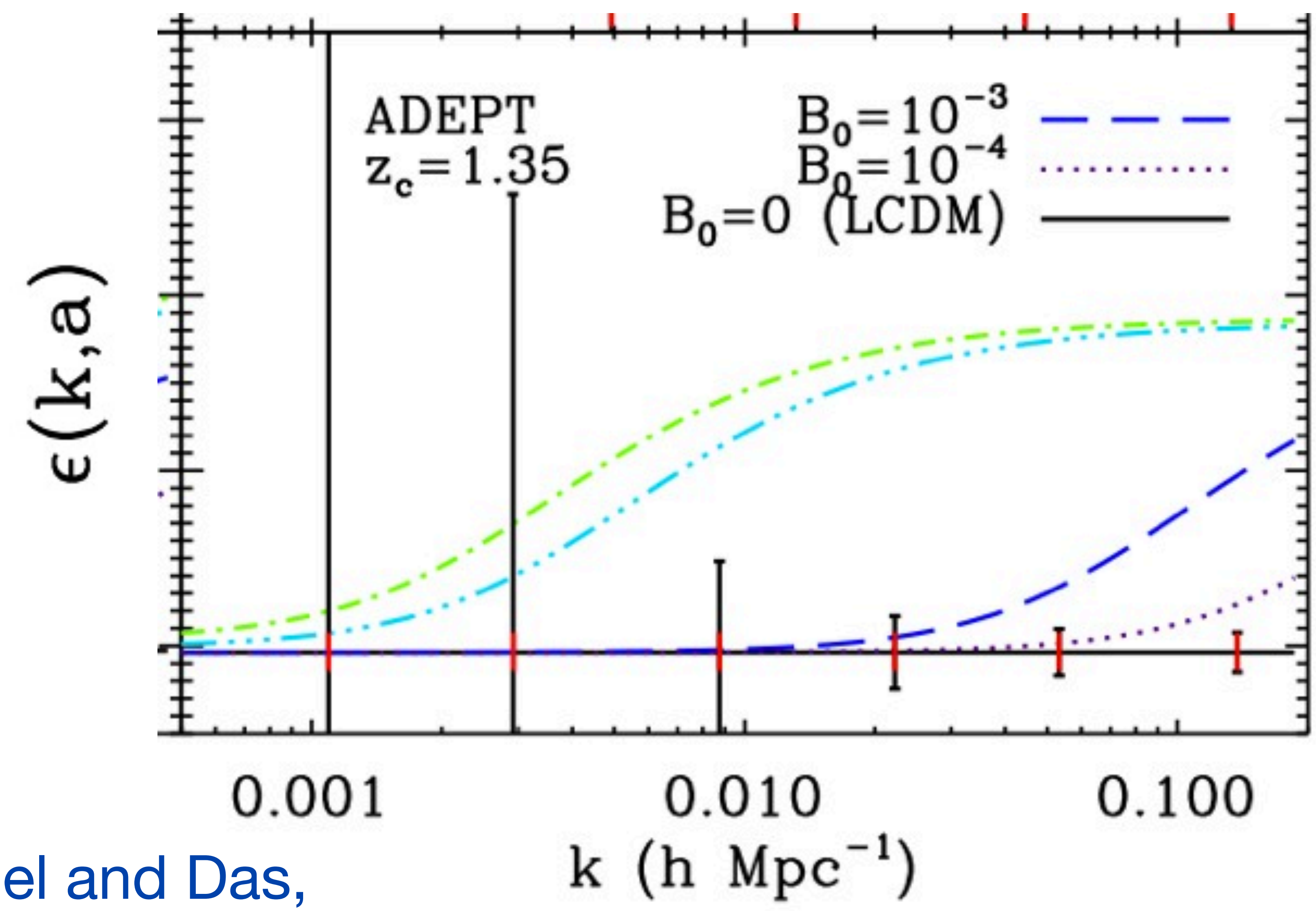
TESTING GENERAL RELATIVITY

$$\epsilon(k,a) = \Omega_m^{-\gamma(a)} \frac{d \ln D}{d \ln a} - 1$$

$\gamma(z) \simeq 0.557 - 0.02z$ is accurate at the 0.3% level

$$P^s(\mathbf{k}) = (1 + \beta \mu_{\mathbf{k}}^2)^2 P(k),$$

$$\beta(a) = \frac{1}{b} \frac{d \ln D}{d \ln a};$$



Acquavivia, Hajian, Spergel and Das, PRD 78, 043514 (2008)

SUMMARY

- Two keywords in the future of CMB: high resolution, polarization
- CMB lensing is a new and powerful tool. First measurements and applications and coming in.
- High resolution polarization experiments like PolarBeaR, ACTPol and SPTPol will be primarily CMB lensing machines.
- CMB lensing will provide new constraints on neutrino mass, dark energy, curvature, ...
- A large array of cross-correlation projects are possible with the wealth of data in multiple frequencies. These will help constrain galaxy formation models, GR. geometry, and other cosmological parameters.
- *Be prepared to witness a very productive interplay of CMB, fundamental physics, and astrophysics in the coming years!*