

Gravitational Lensing with ACTPol

Alexander van Engelen for the ACTPol collaboration



CMB Lensing

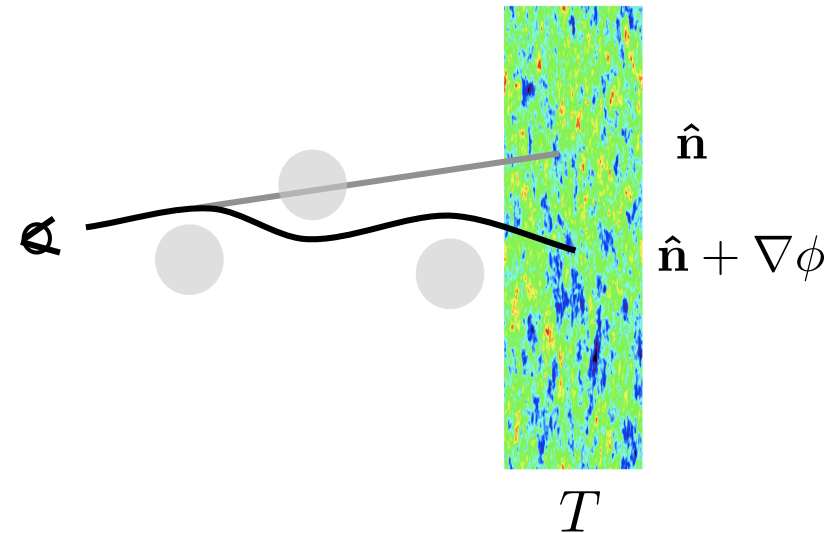
Photons get shifted by
intervening mass:

$$T^L(\hat{\mathbf{n}}) = T^U(\hat{\mathbf{n}} + \nabla\phi(\hat{\mathbf{n}}))$$

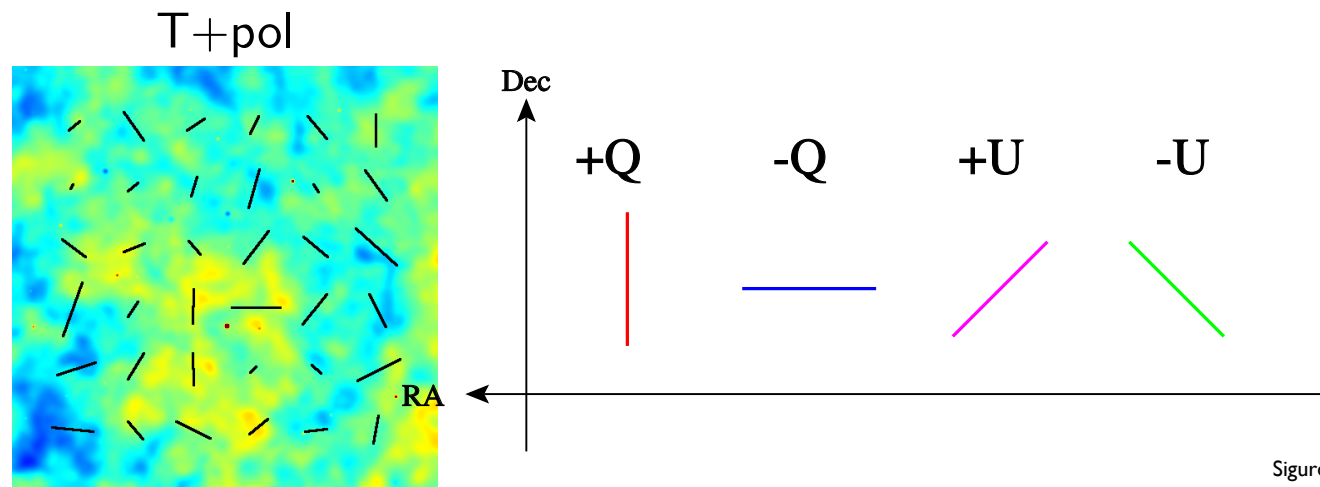
For large-scale structure:

$$\nabla\phi_{\text{rms}} = 2.7 \text{ arcmin}$$

Coherent on 10-deg scales

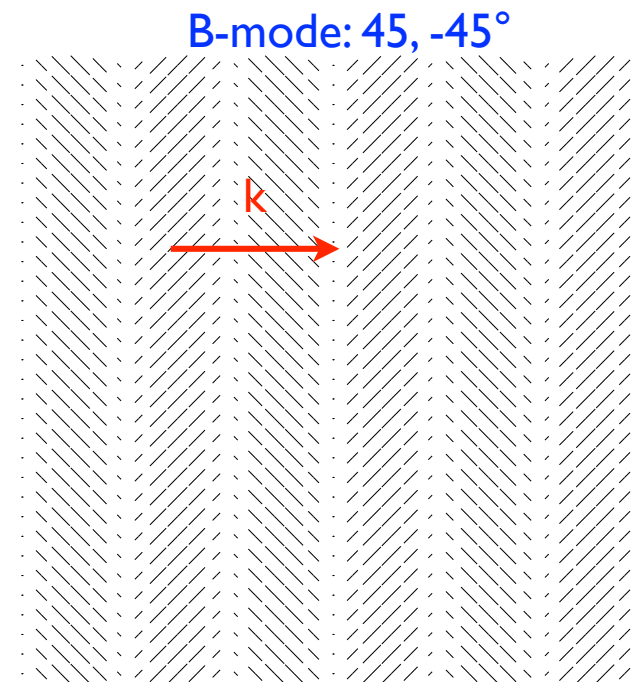
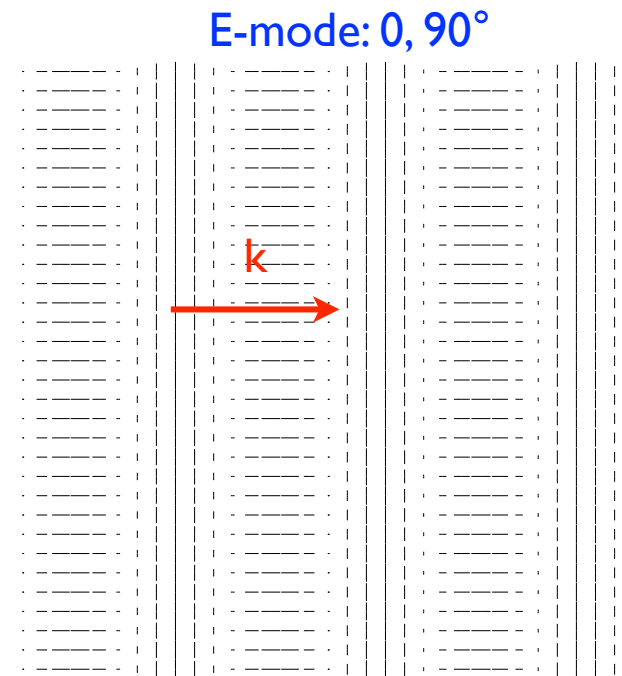


T, Q, U all lensed in same way.

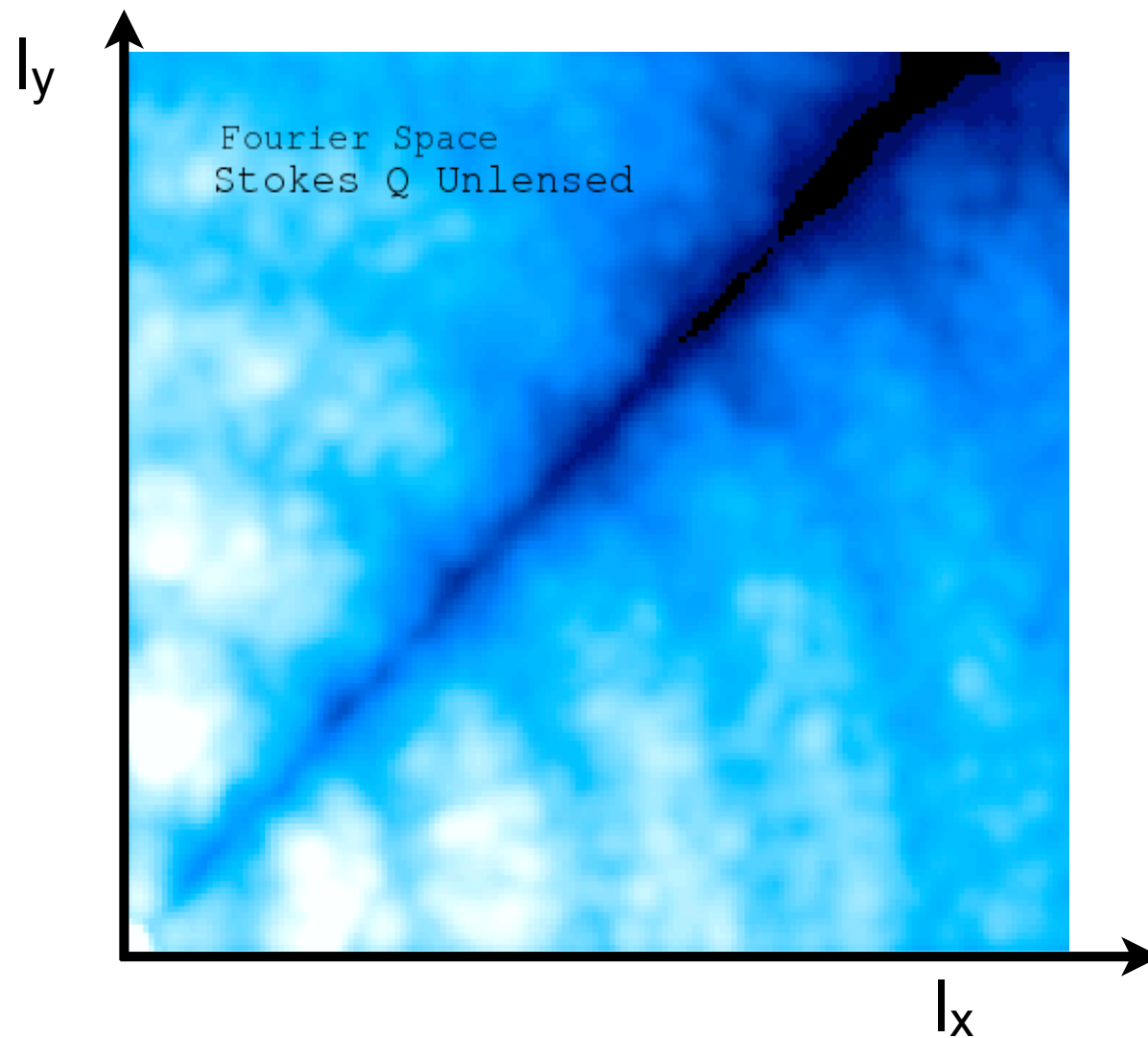


CMB Polarization

- E-modes vary spatially only parallel and perpendicular to polarization direction
- Density perturbations give E only, in linear theory



CMB Polarization

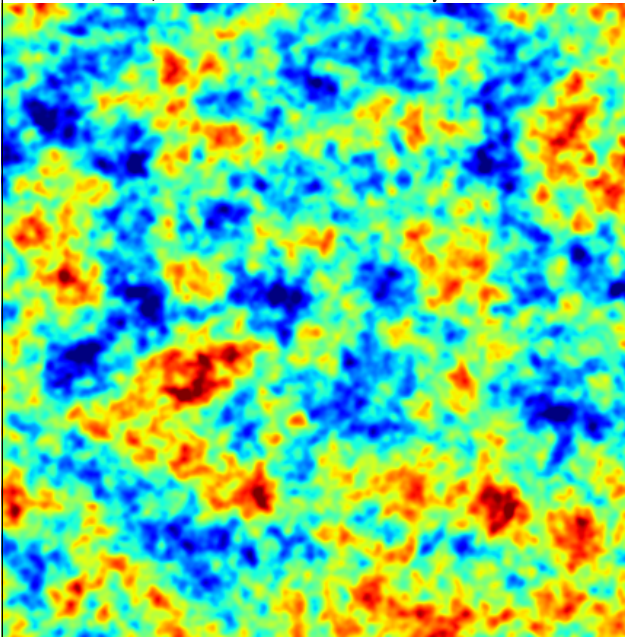


2d Power Spectrum of
Q from pure E mode

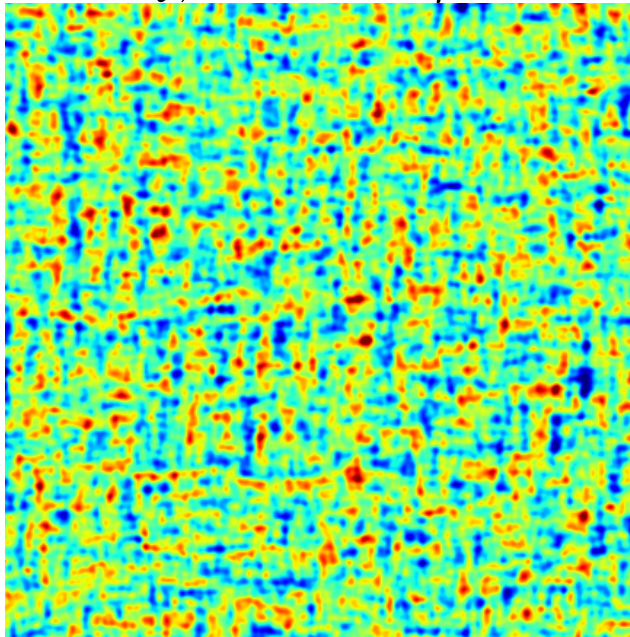
Unlensed

$10^\circ \times 10^\circ$

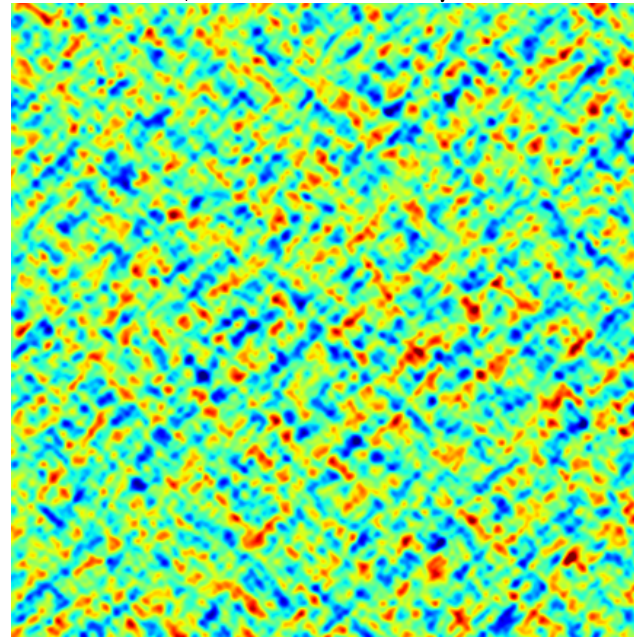
$T, \pm 267 \mu\text{K}$



$Q, \pm 15 \mu\text{K}$



$U, \pm 15 \mu\text{K}$

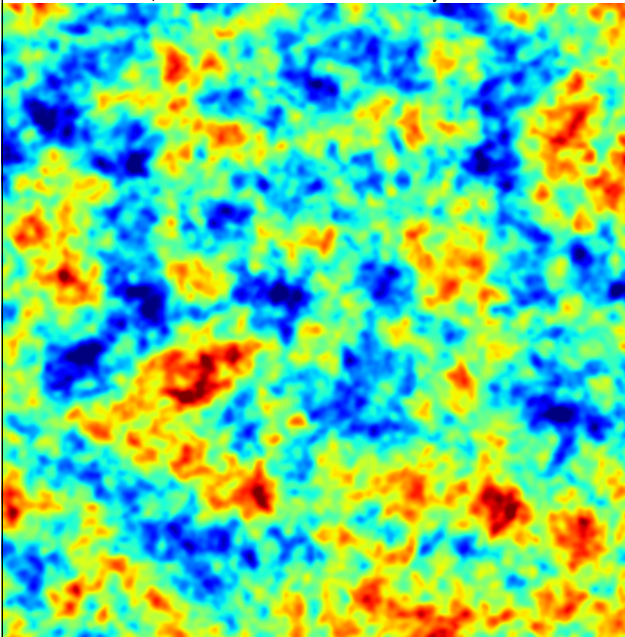


Unlensed

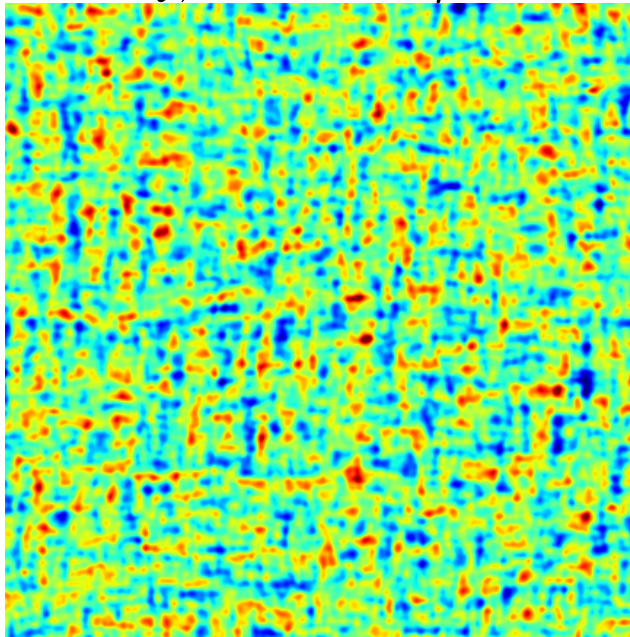
Lensed

$10^\circ \times 10^\circ$

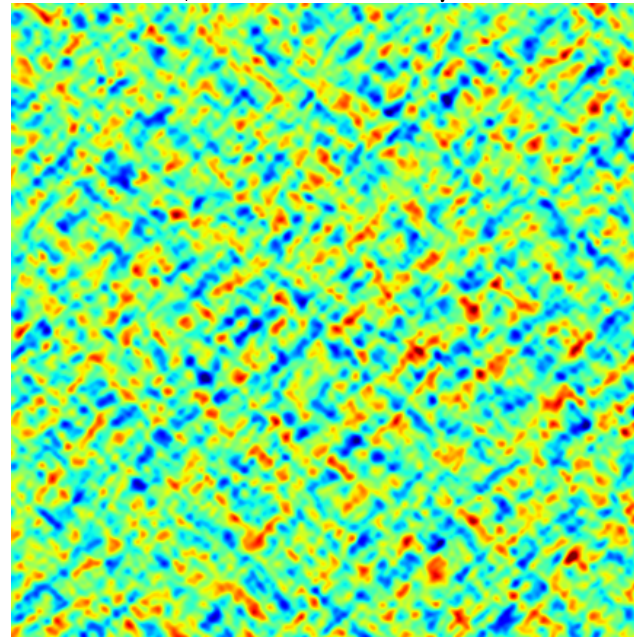
$T, \pm 267 \mu\text{K}$



$Q, \pm 15 \mu\text{K}$



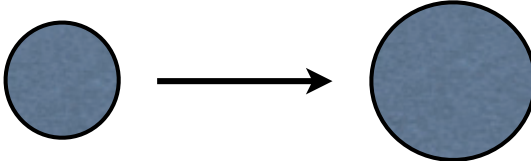
$U, \pm 15 \mu\text{K}$

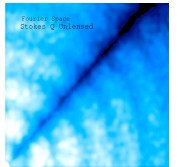
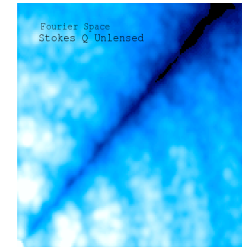


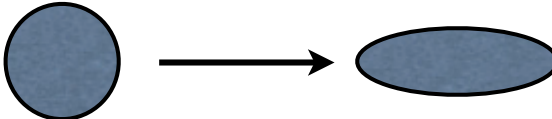
Lensed

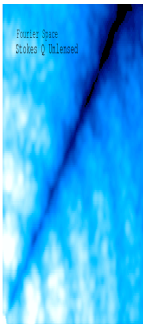
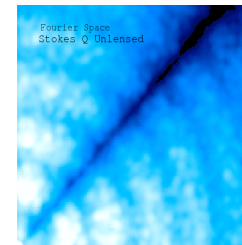
Effect of lensing: breaking statistical isotropy

- CMB still Gaussian but power spectrum locally *distorted*

convergence: 



shear: 

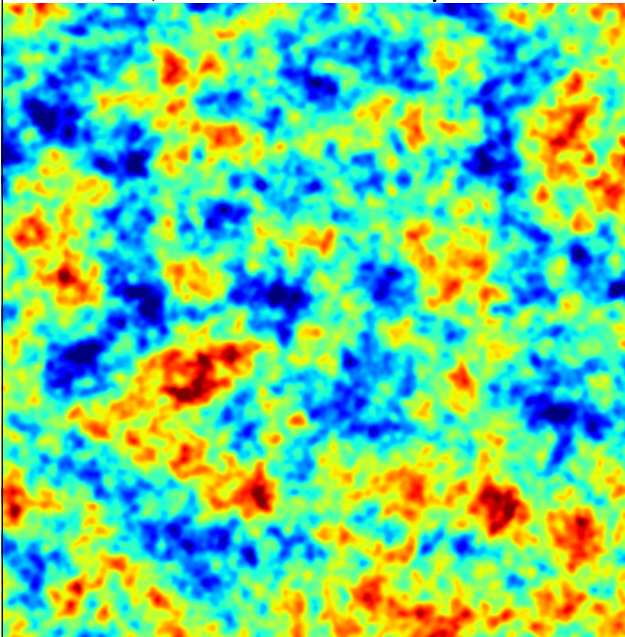


- Generation of B from E!

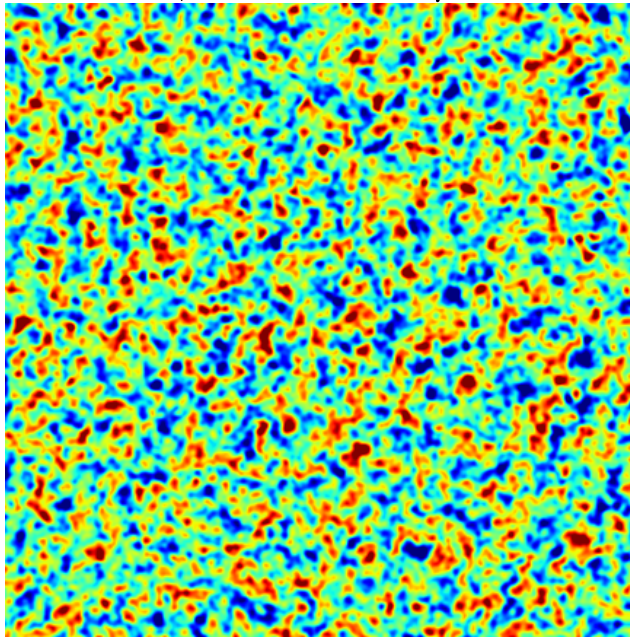
Unlensed

$10^\circ \times 10^\circ$

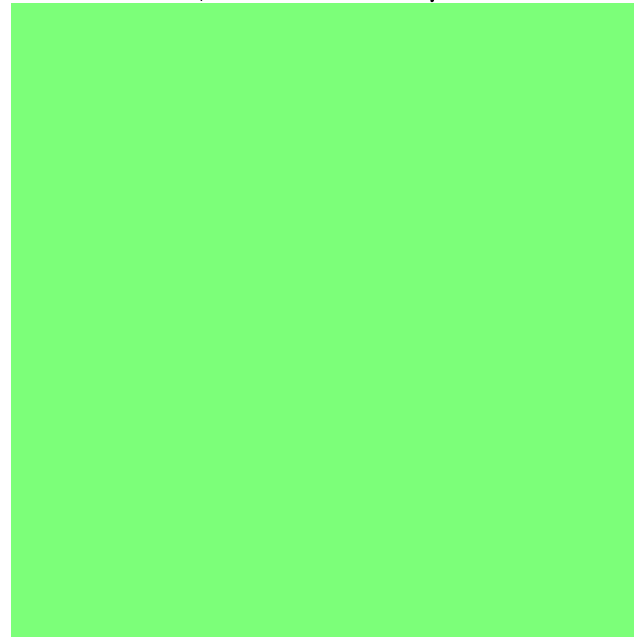
$T, \pm 267 \mu\text{K}$



$E, \pm 15 \mu\text{K}$



$B, \pm 1 \mu\text{K}$

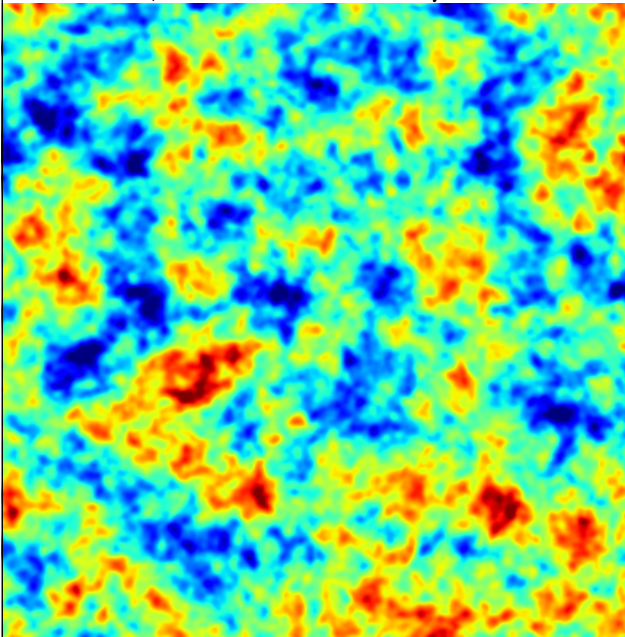


Unlensed

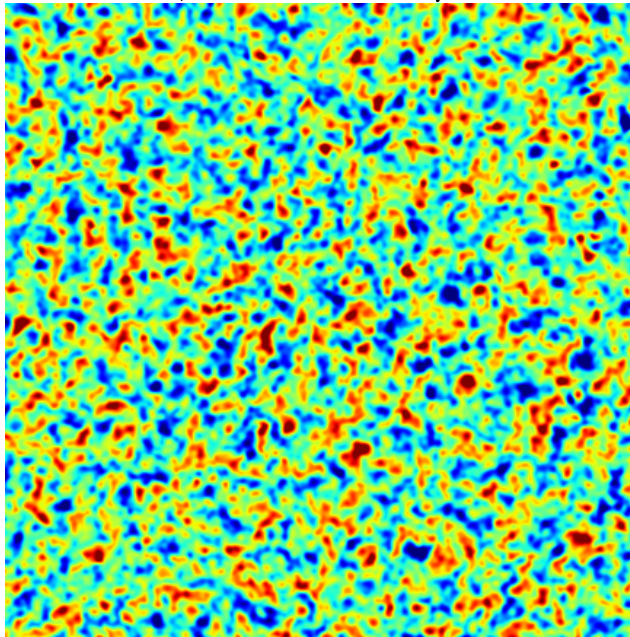
Lensed

$10^\circ \times 10^\circ$

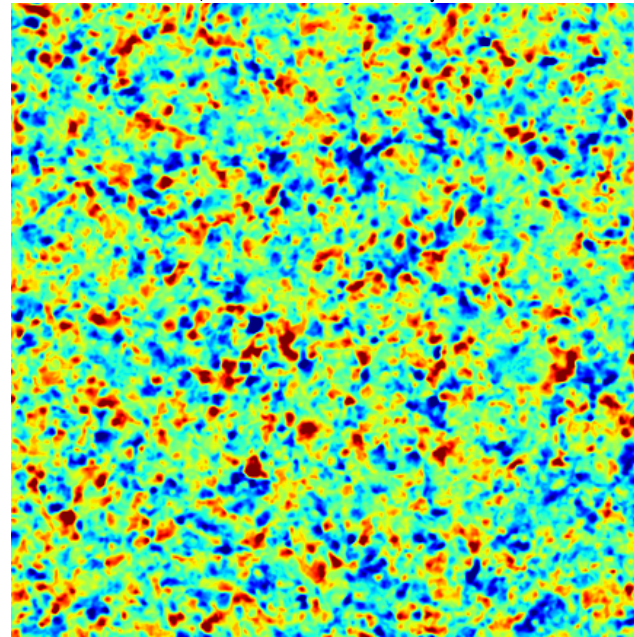
$T, \pm 267 \mu\text{K}$



$E, \pm 15 \mu\text{K}$



$B, \pm 1 \mu\text{K}$



Lensed

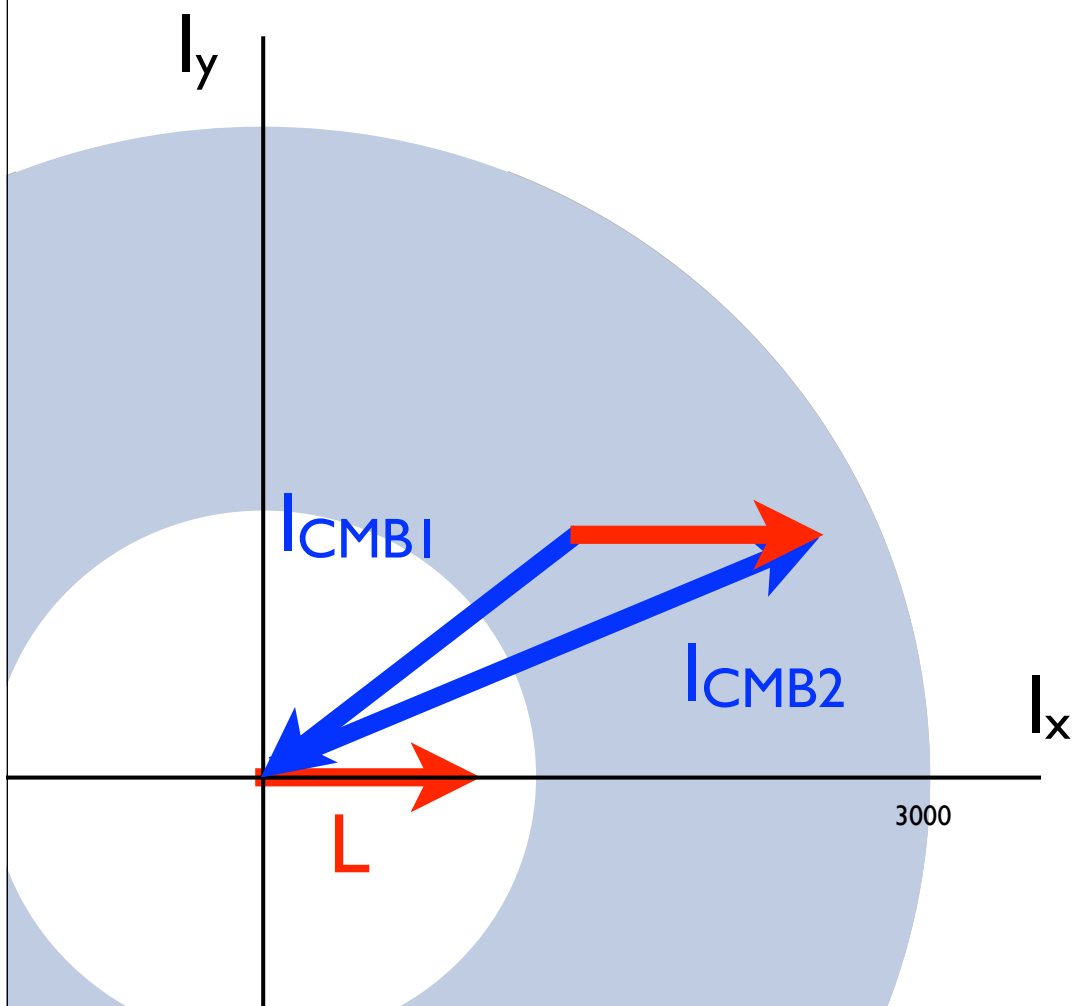
Lensing effective mode coupling on a big patch:

$$\langle X(\mathbf{l}_1) X'(\mathbf{l}_2) \rangle_{\text{CMB}} = f_{XX'}^{\mathcal{D}}(\mathbf{l}_1, \mathbf{l}_2) \phi(\mathbf{l}_1 + \mathbf{l}_2),$$

$$X, X' \in \{T, E, B\}$$

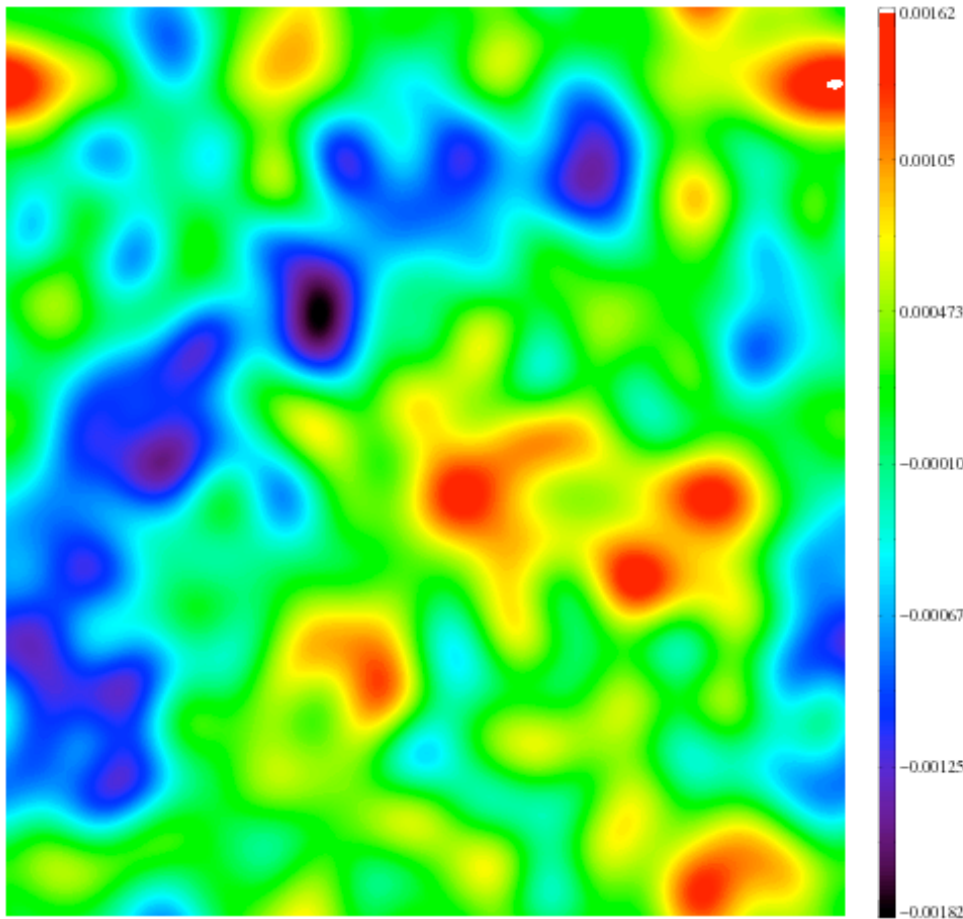
Quadratic estimator:

$$\hat{\phi}(\mathbf{L}) \sim \sum_l X(\mathbf{l}) X'(\mathbf{L} - \mathbf{l})$$

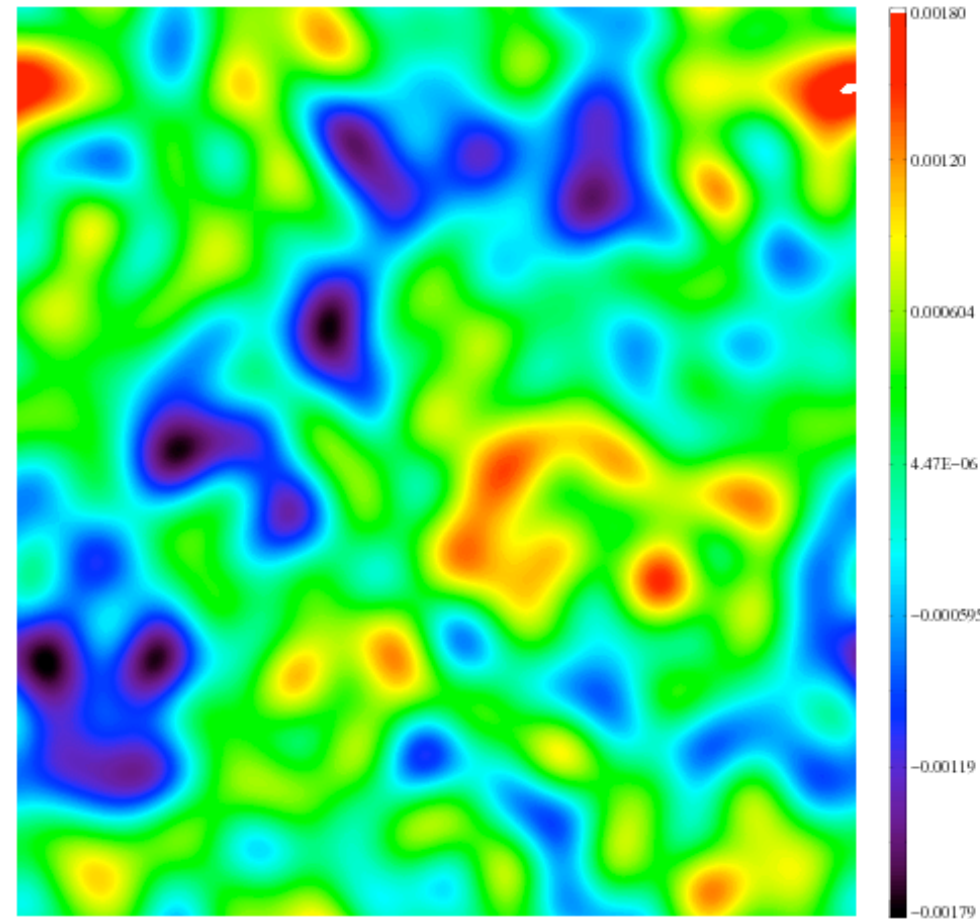


Reconstruction

- Input and recovered deflection angle maps, $17^\circ \times 17^\circ$
 - filtered for display at $l < 200$



Input



Recovered at 15 $\mu\text{K}'$ white, l'

- Temperature (TT) lensing now well-measured
 - Integrated measure of matter power spec. on large scales and high z !
- Polarization is new, and ultimately more sensitive given upcoming low-noise maps
- ACTPol: we do TT, TE, EE, EB pairings

Atacama Cosmology Telescope

Located in **Cerro Toco, Northern Chile**

High and dry:

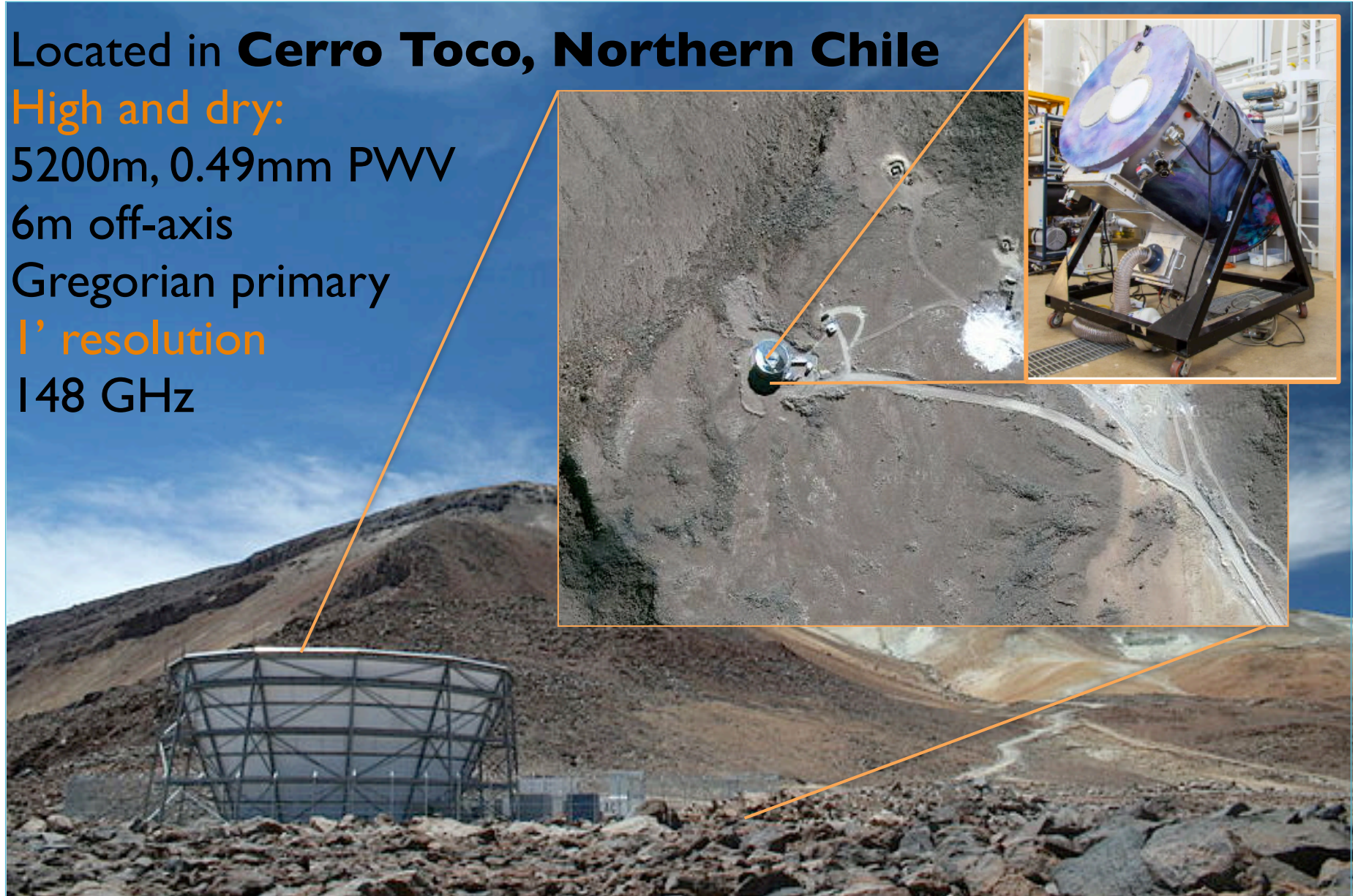
5200m, 0.49mm PWV

6m off-axis

Gregorian primary

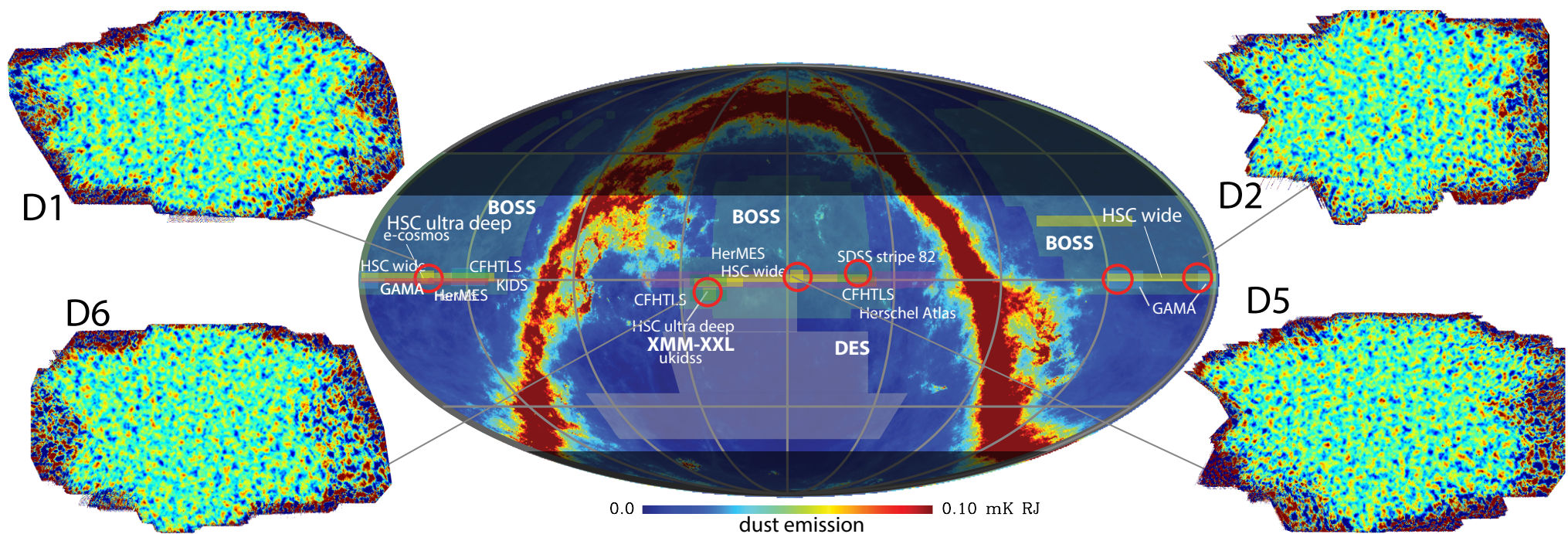
I' resolution

148 GHz



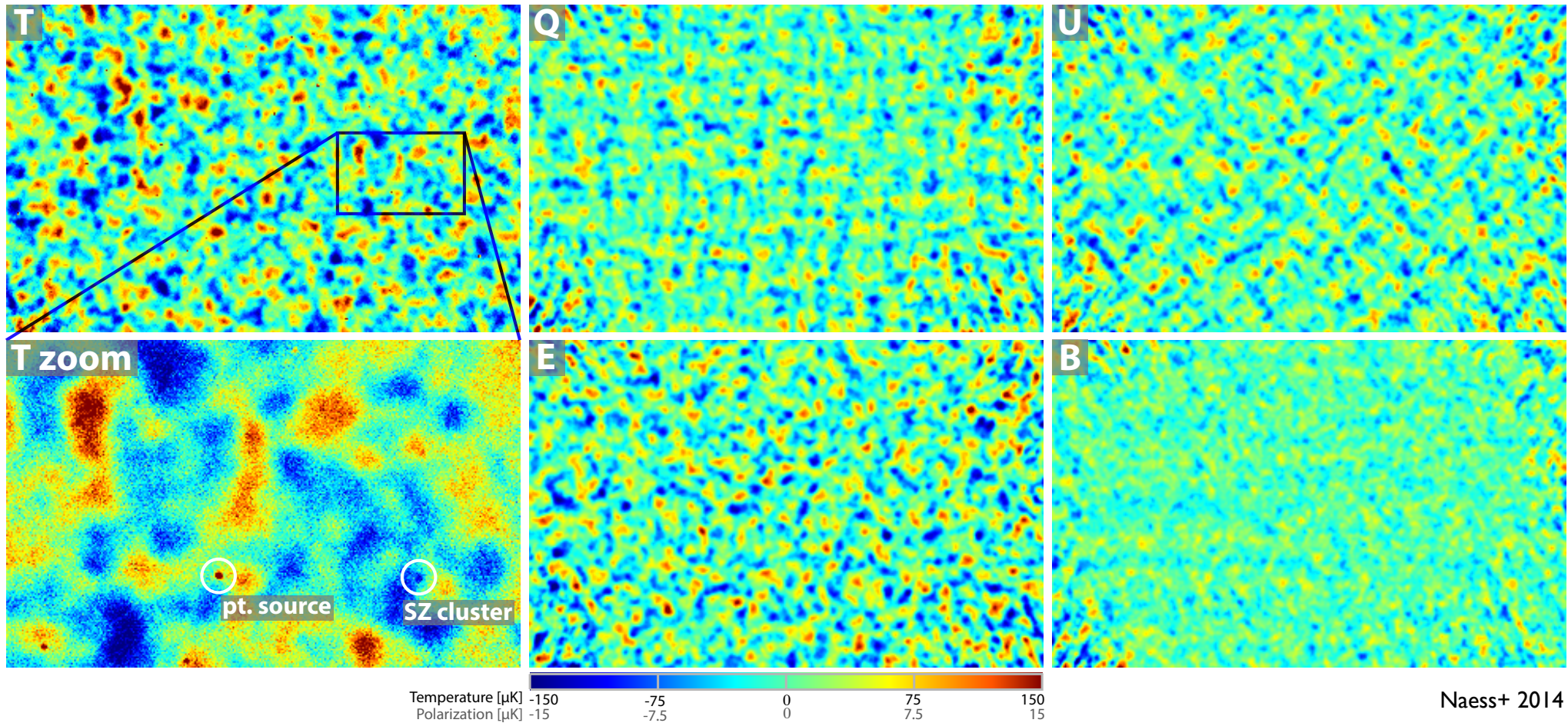
ACTPol 2013 survey

- 150 GHz, 11 Sept - 24 Dec 2013
- Four 70 sq. deg. patches, overlapping with other surveys



ACTPol 2013 survey

$10^\circ \times 7^\circ$ cutout of D6



ACTPol: Three lensing topics

1. Pol. and Temp. large-scale lensing x Planck CIB

van Engelen+, arxiv:1412.0626

2. Halo lensing detection

Madhavacheril+, arxiv:1411.1799

3. Pol. and Temp. large-scale lensing autospectrum

In prep.

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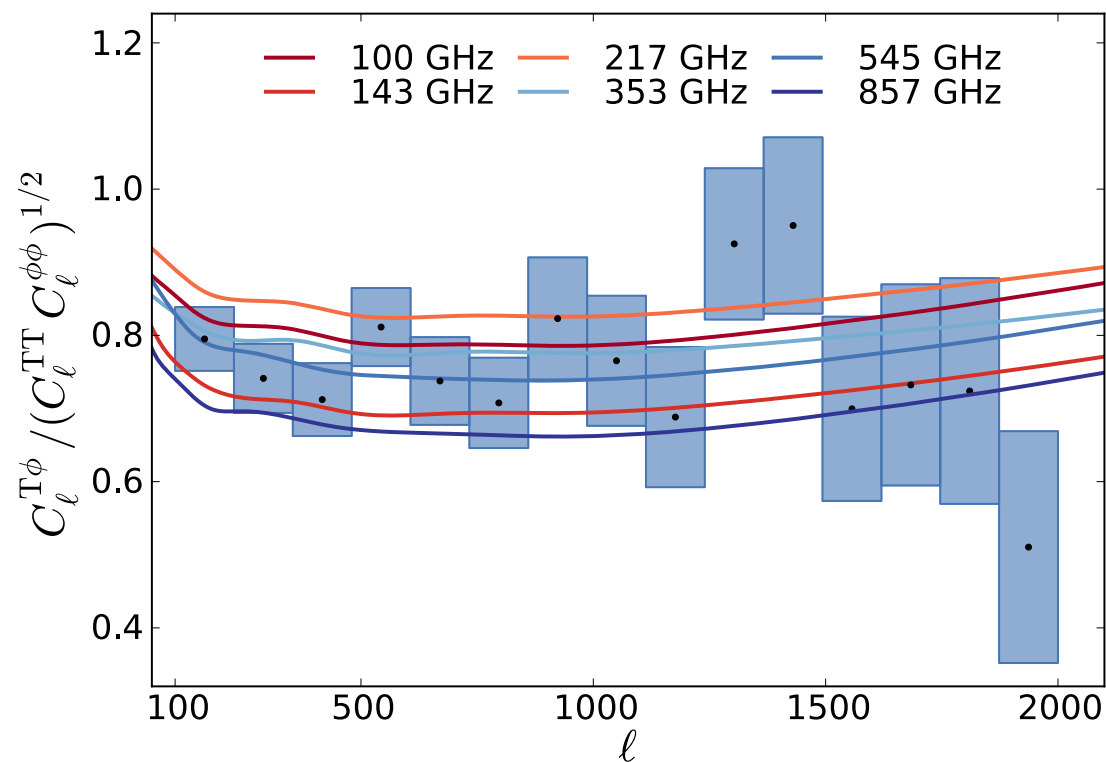
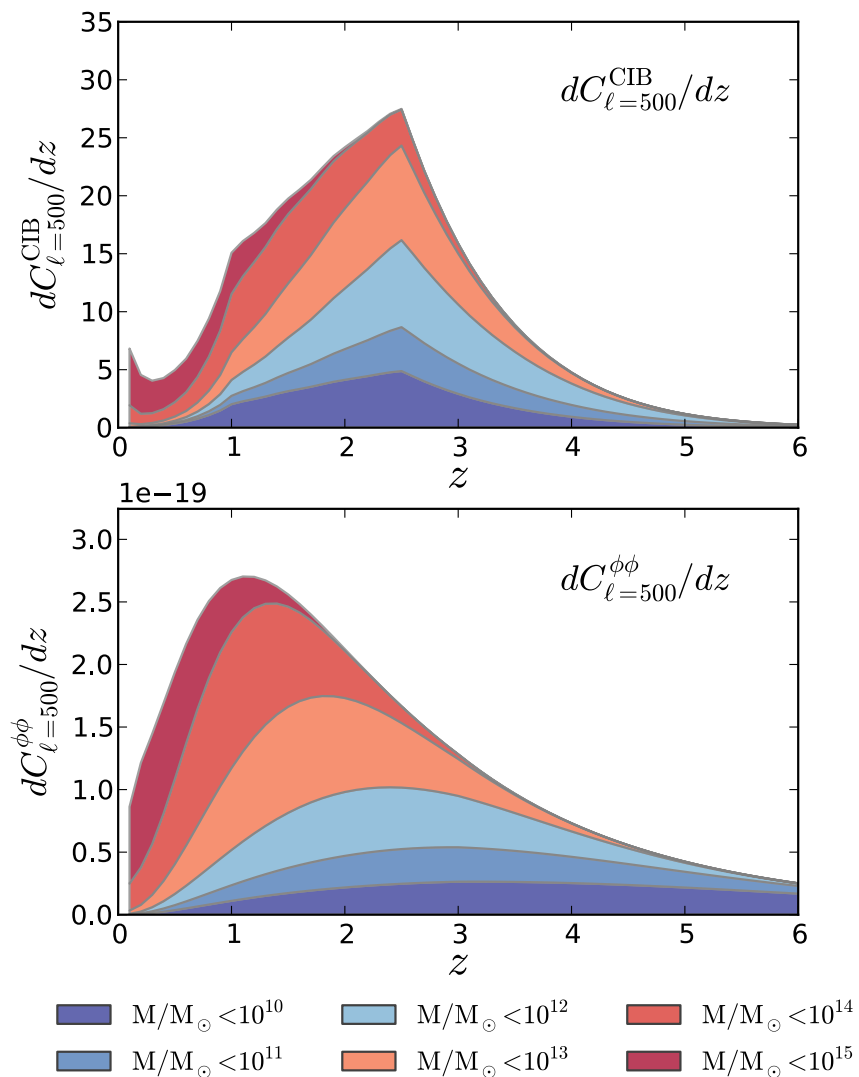
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In prep.

CIB-lensing cross-correlation

- Very similar z distributions

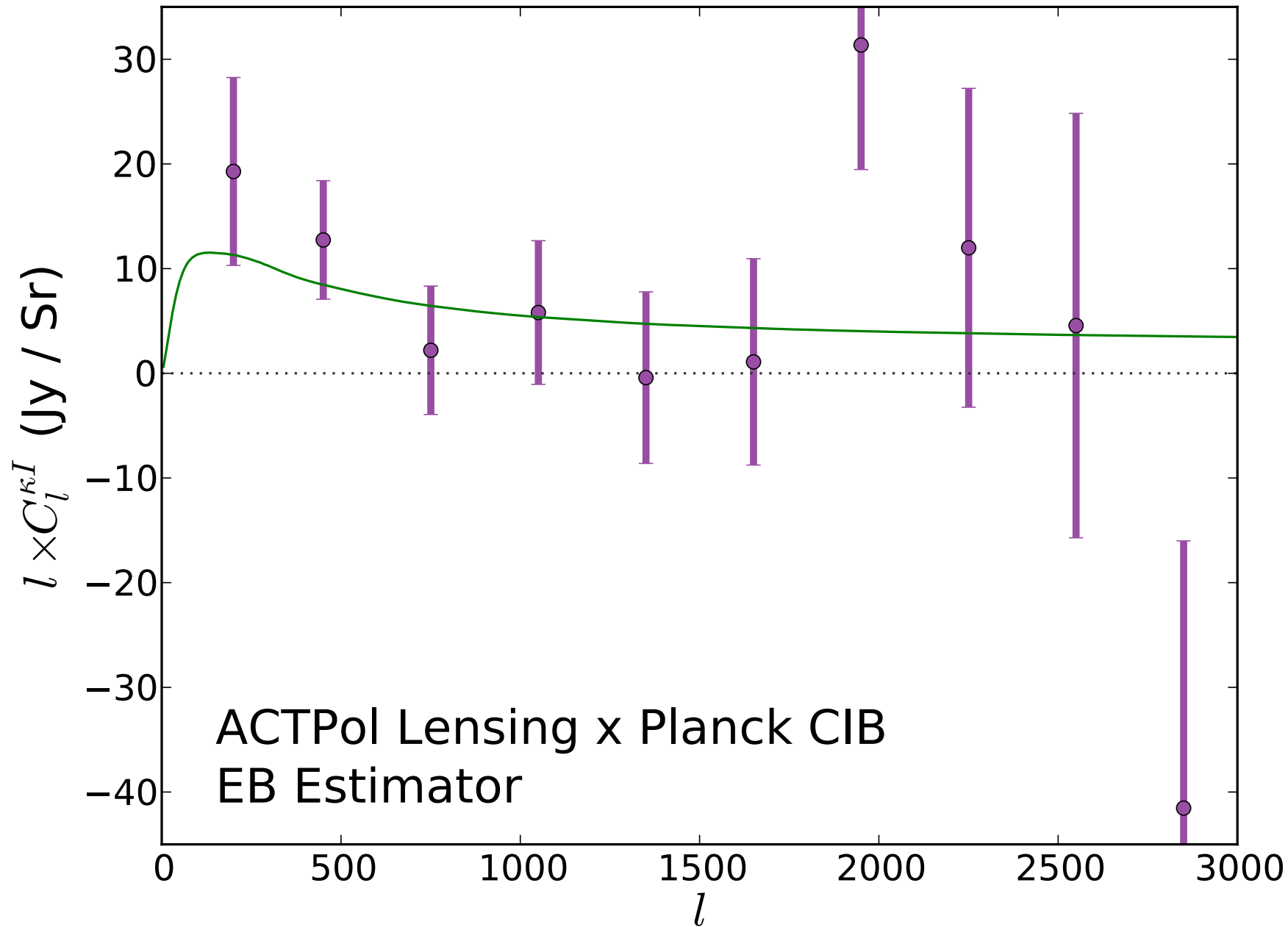
- 80% correlation
(neglecting Poisson term at high ℓ)



Planck 2013
Data from $\kappa(l_{43}) \times l_{545}$

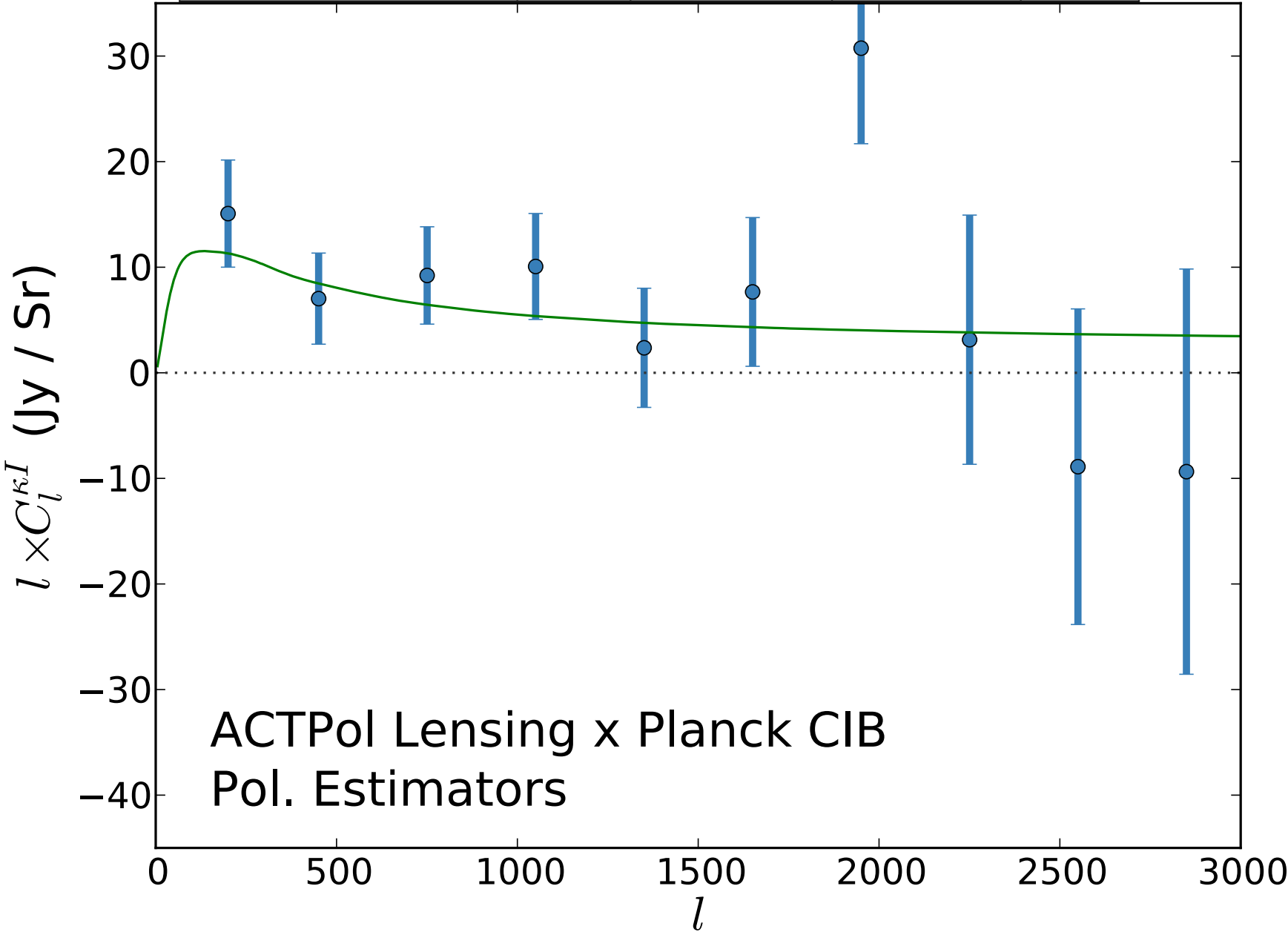
Results arXiv:1412.0626

	S/N	A	$\chi^2_{\min}(\nu)$	PTE
EB, all	3.2	1.30 ± 0.40	25.9 (29)	0.63



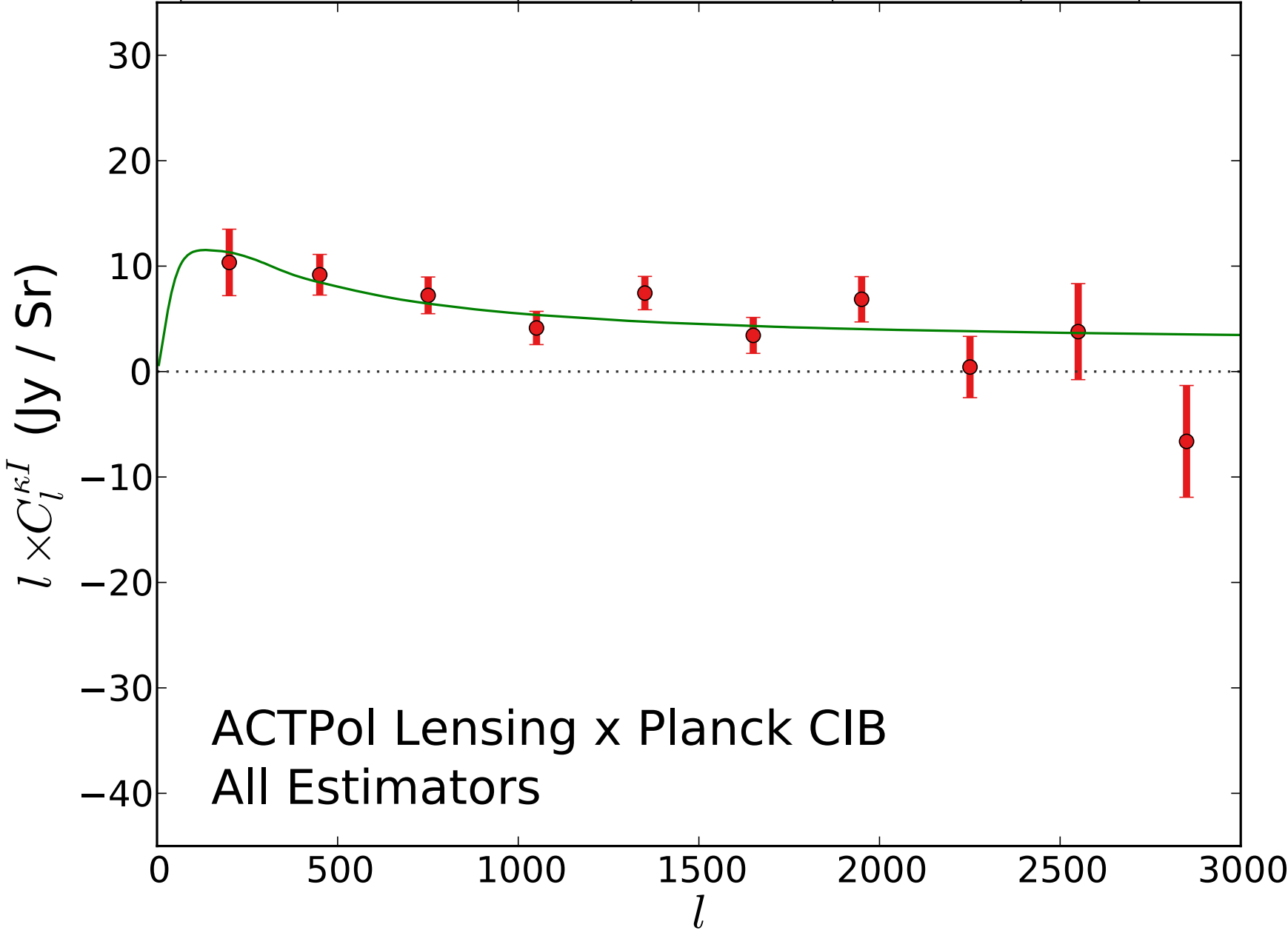
Results arXiv:1412.0626

	S/N	A	$\chi^2_{\min} (\nu)$	PTE
Pol. estimators, all	4.5	$1.26^{+0.28}_{-0.24}$	30.4 (29)	0.39

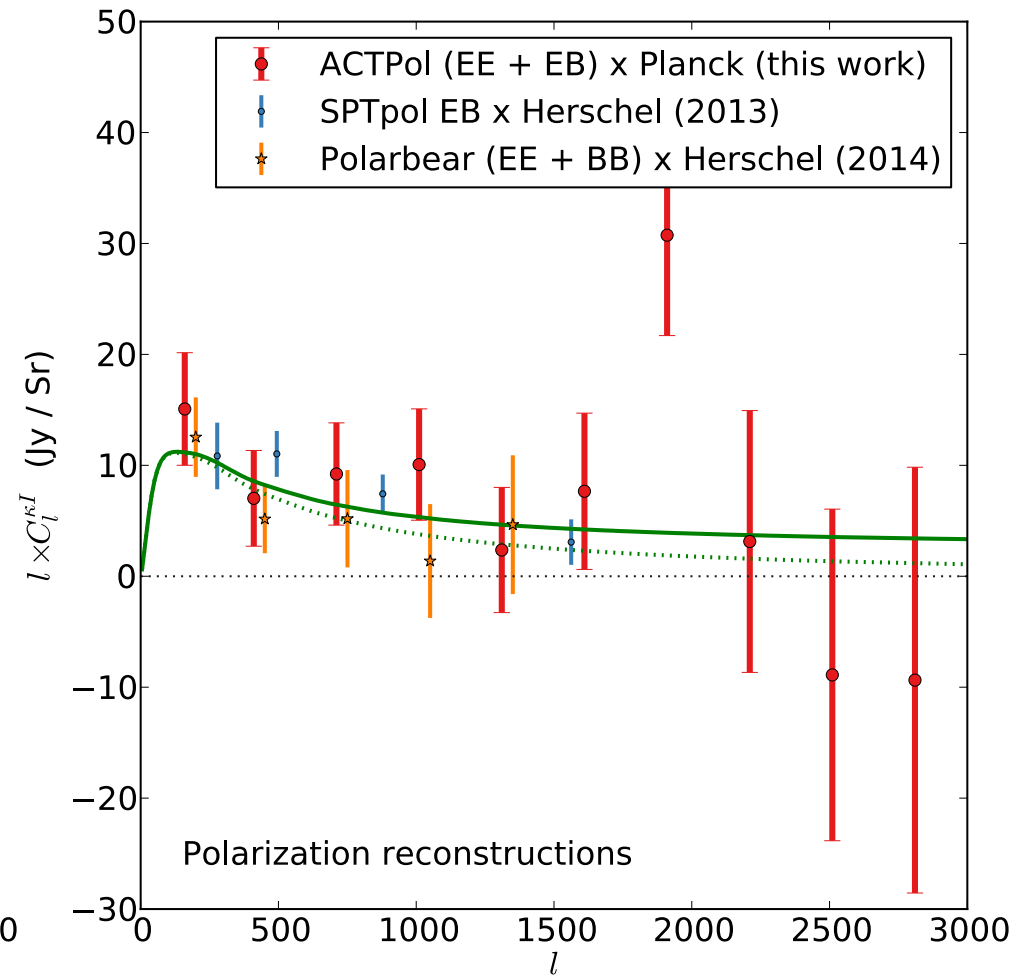
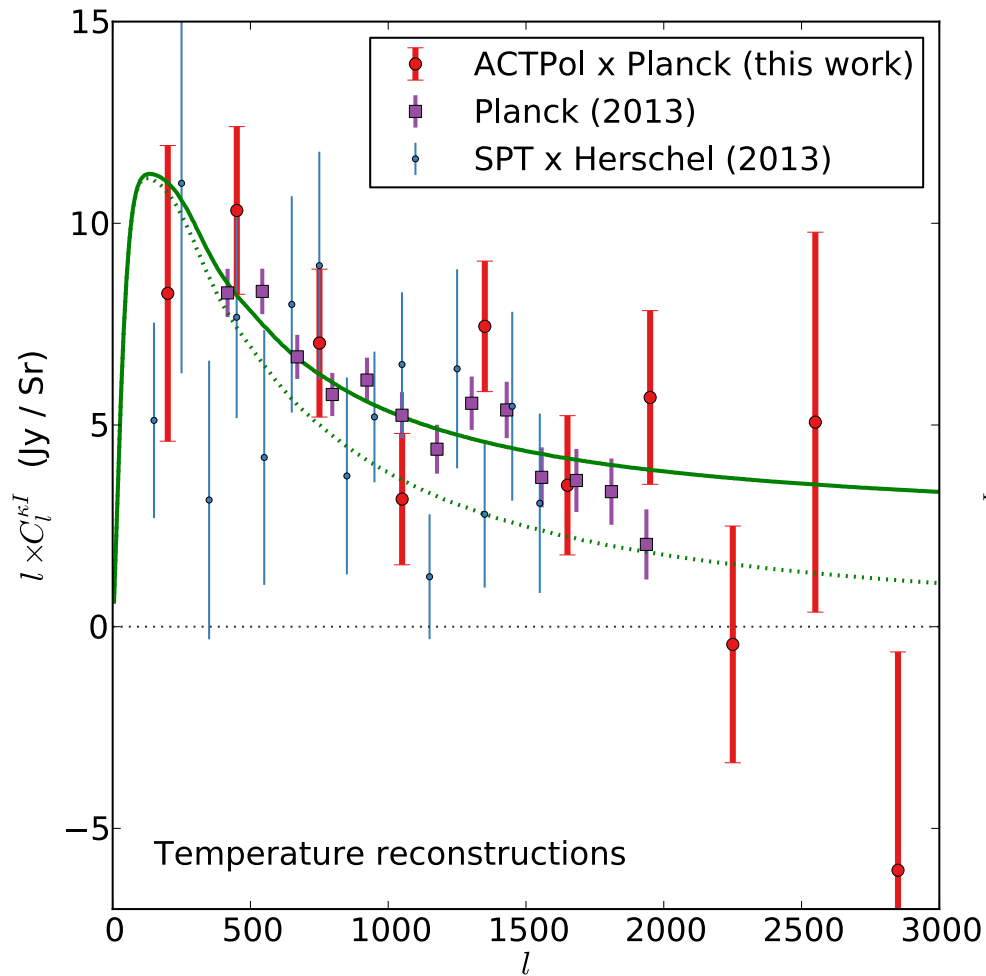


Results arXiv:1412.0626

	S/N	A	$\chi^2_{\min}(\nu)$	PTE
All estimators, all	9.1	$1.02^{+0.12}_{-0.08}$	37.2 (29)	0.14



Comparison with other surveys

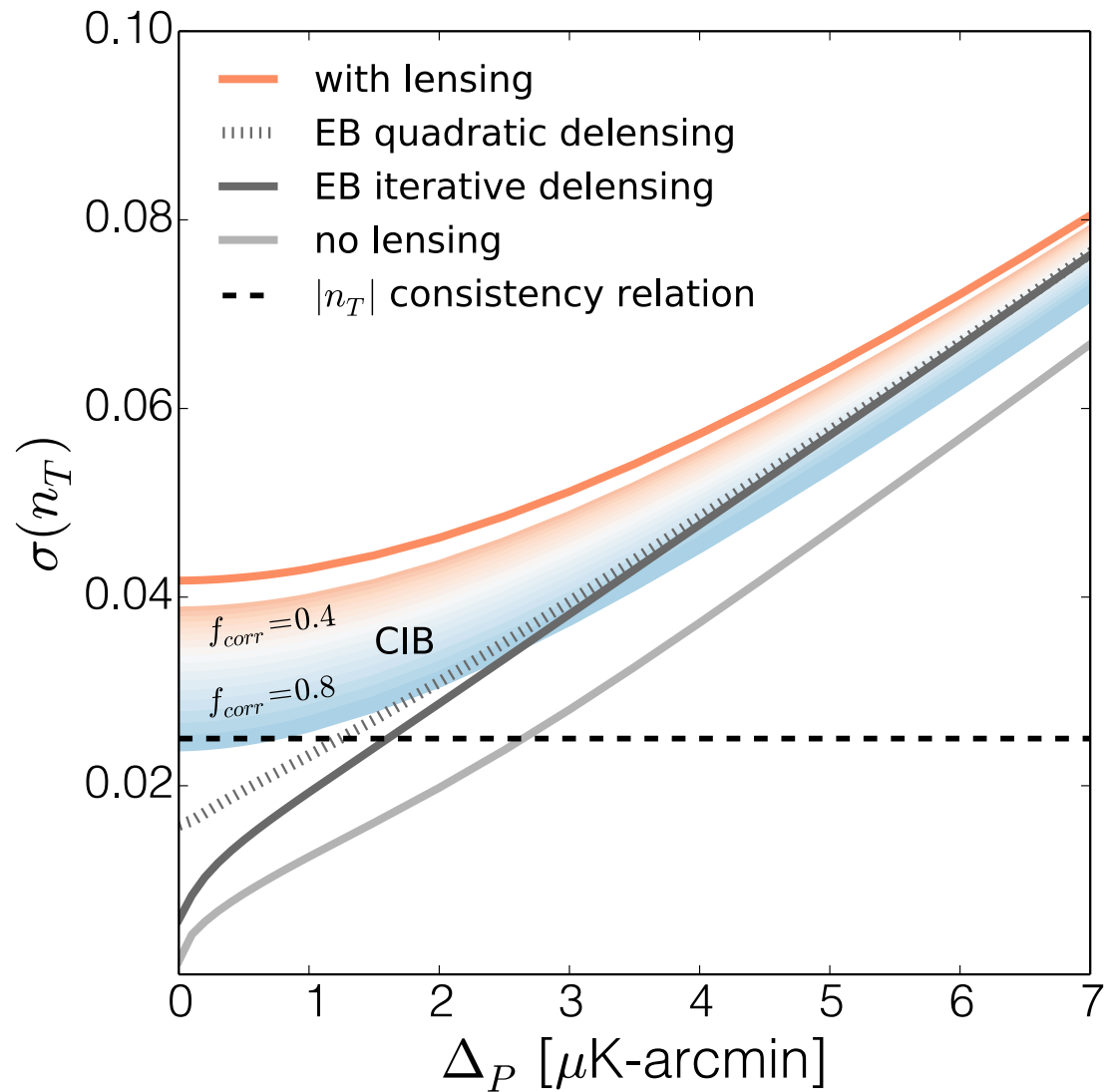


n.b., ACTPol: only 3 months of data

Delensing with the CIB

Error on n_T
assuming $r = 0.2$

Simard+ 2014



c.f. ACTPol first season: 15 $\mu\text{K-arcmin}$

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Madhavacheril+, arxiv:1411.7999

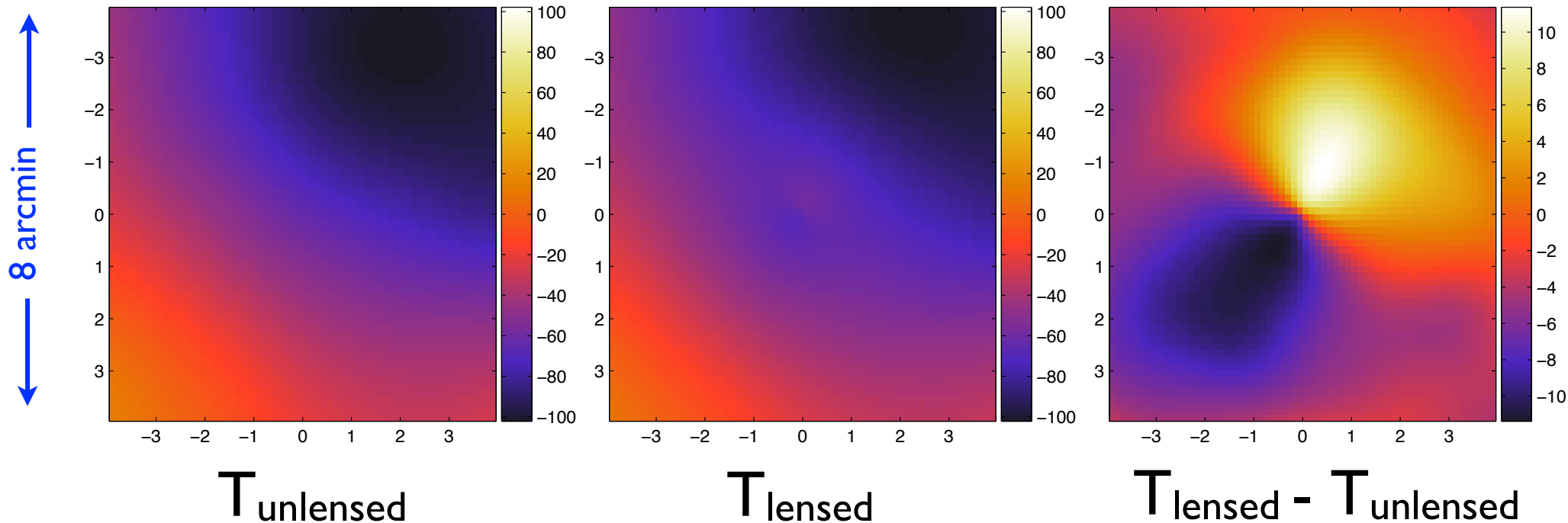
3. Pol. and Temp. large-scale lensing autospectrum

In prep.

Lensing by Individual Halos

E.g.: sim by Lewis & King (2006)

- Cluster at $z = 1$ with $M_{200} = 10^{15} M_{\text{sol}}$



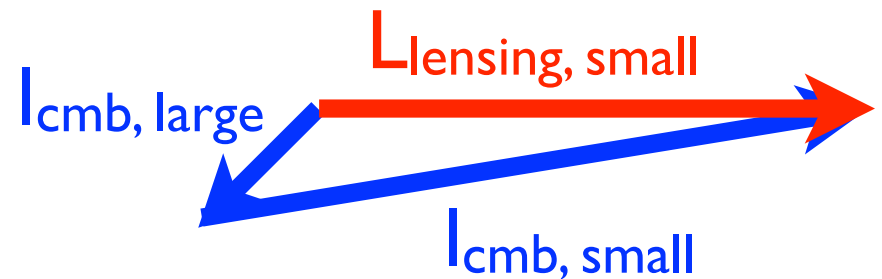
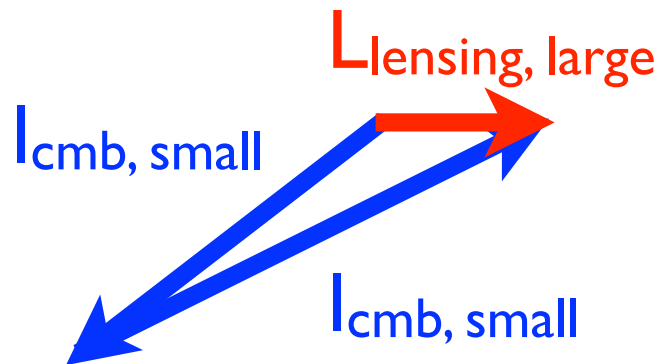
aka “cluster CMB lensing”, but we stack on galaxies

Lensing by Individual Halos

- Reconstruction concept is same as for LSS

$$\hat{\phi}(\mathbf{L}) \sim \sum_l X(\mathbf{l})X'(\mathbf{L} - \mathbf{l})$$

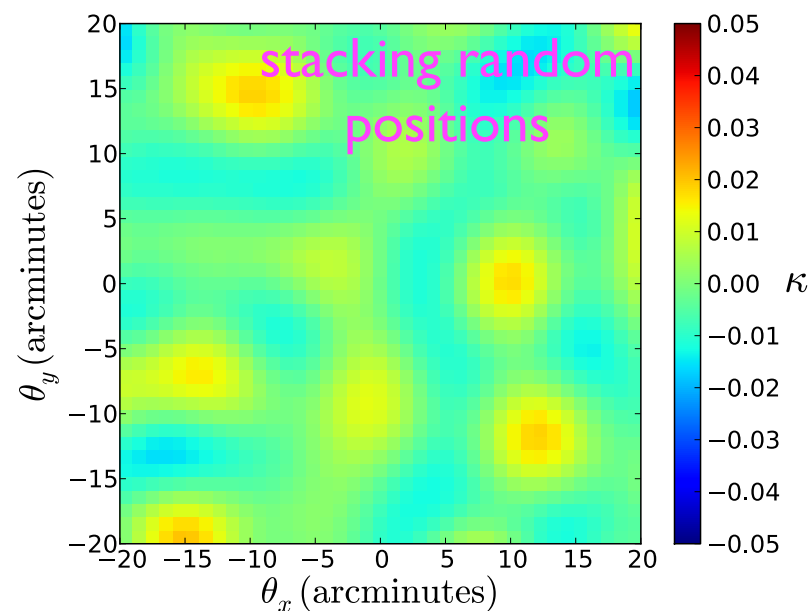
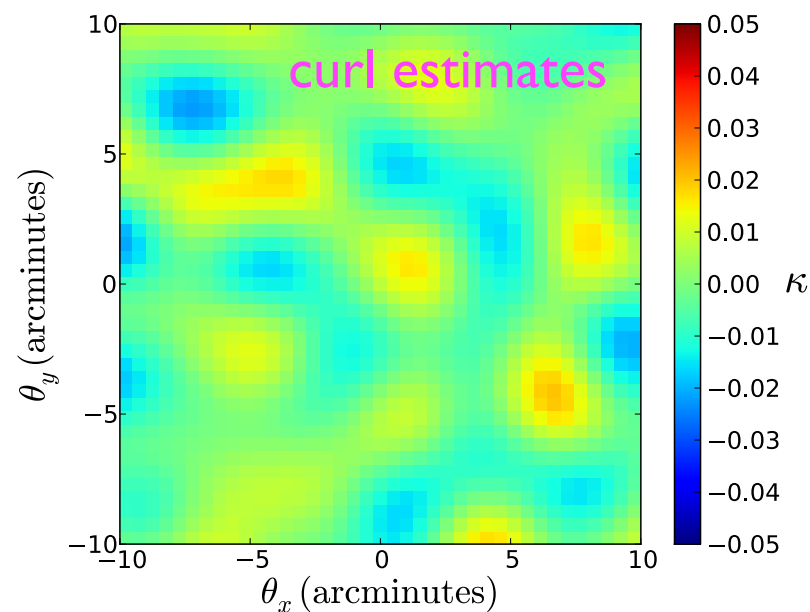
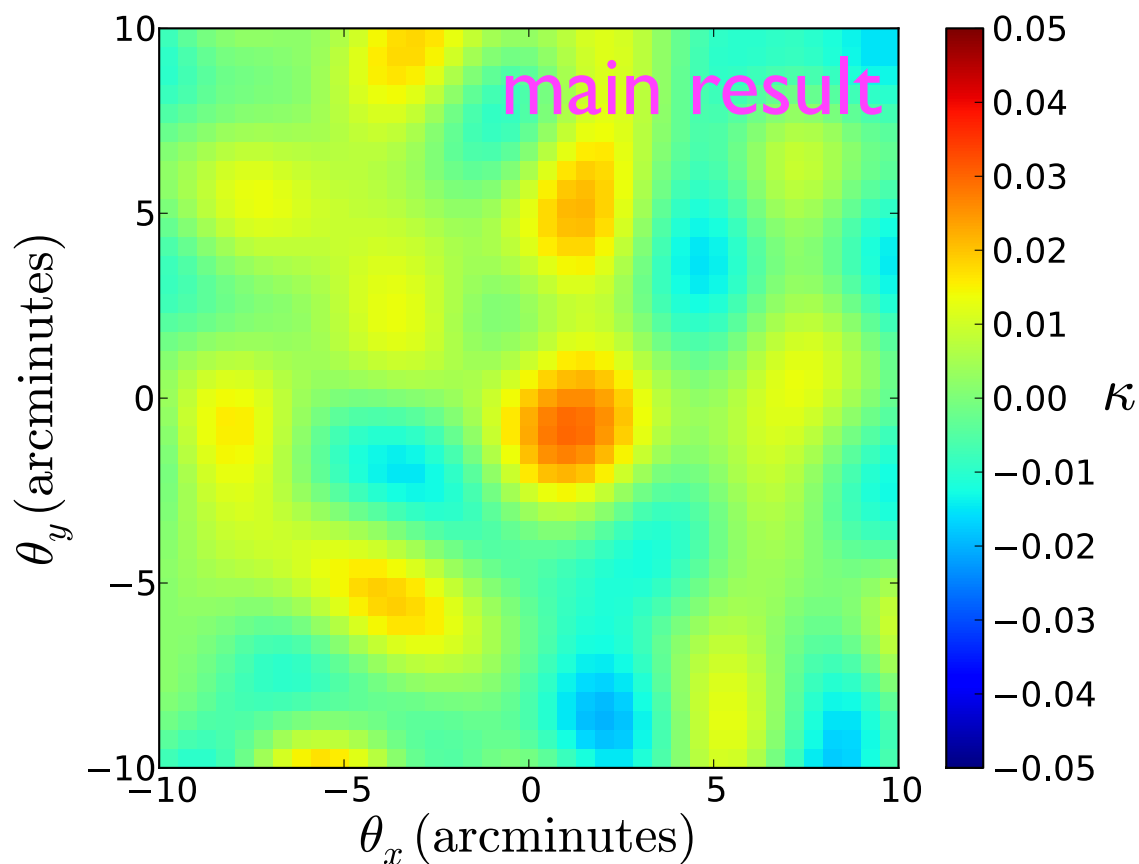
- ...but different triangle configurations



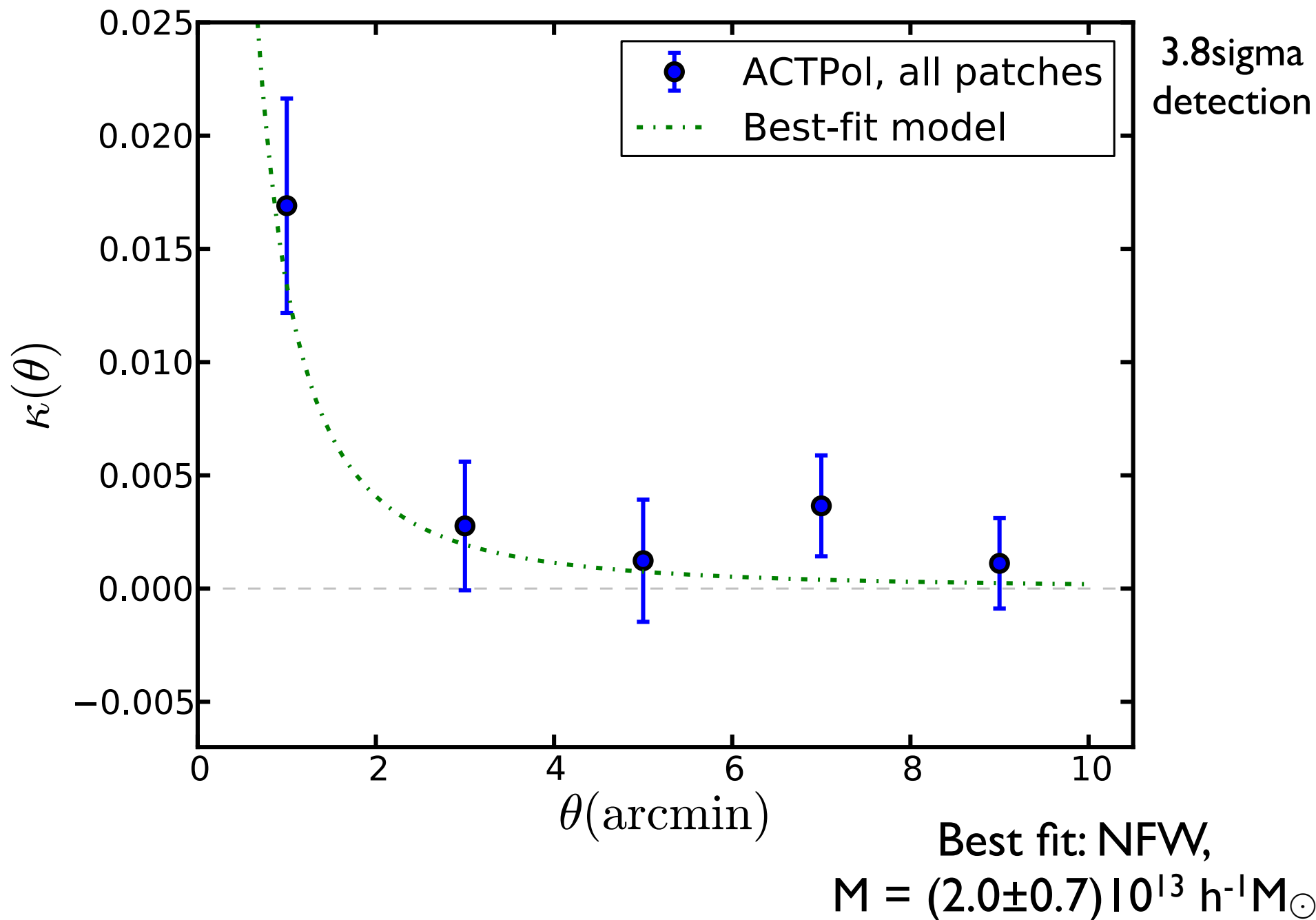
Lensing by Individual Halos

- Proposed 10 years ago (“CMB cluster lensing”), but results coming out now
- ACTPol 2014: CMASS sample of 12,000 CMASS SDSSIII/BOSS galaxies
 - $\langle z \rangle \sim 0.4$, $\langle M \rangle \sim 10^{13} M_{\odot}$
- c.f. SPT: SZ-selected clusters, $10^{14} - 10^{15} M_{\odot}$ (Baxter+ 2014)

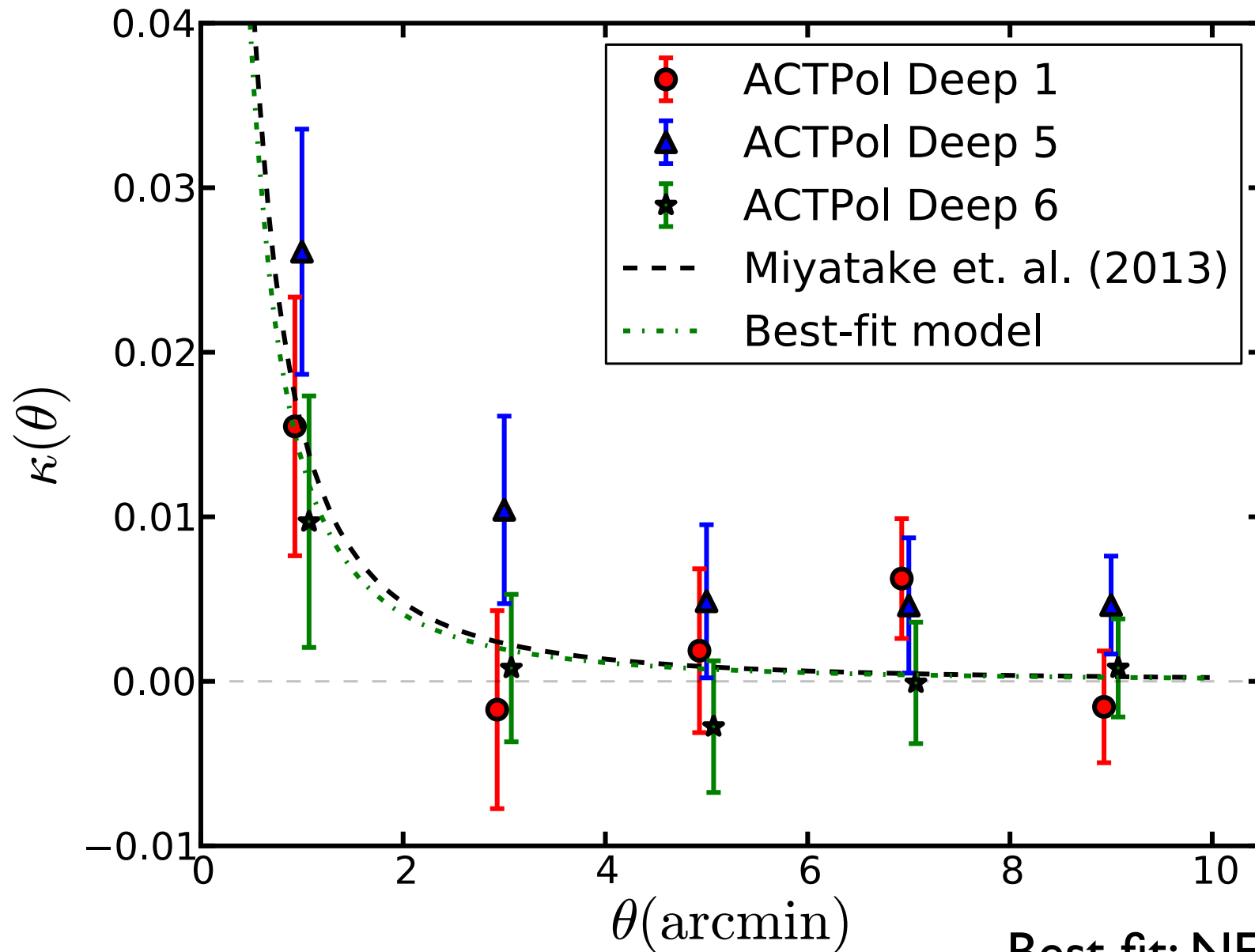
Halo Lensing - stacking results



Halo Lensing - convergence



Halo Lensing - Results



Best fit: NFW,
 $M = (2.0 \pm 0.7) 10^{13} h^{-1} M_{\odot}$

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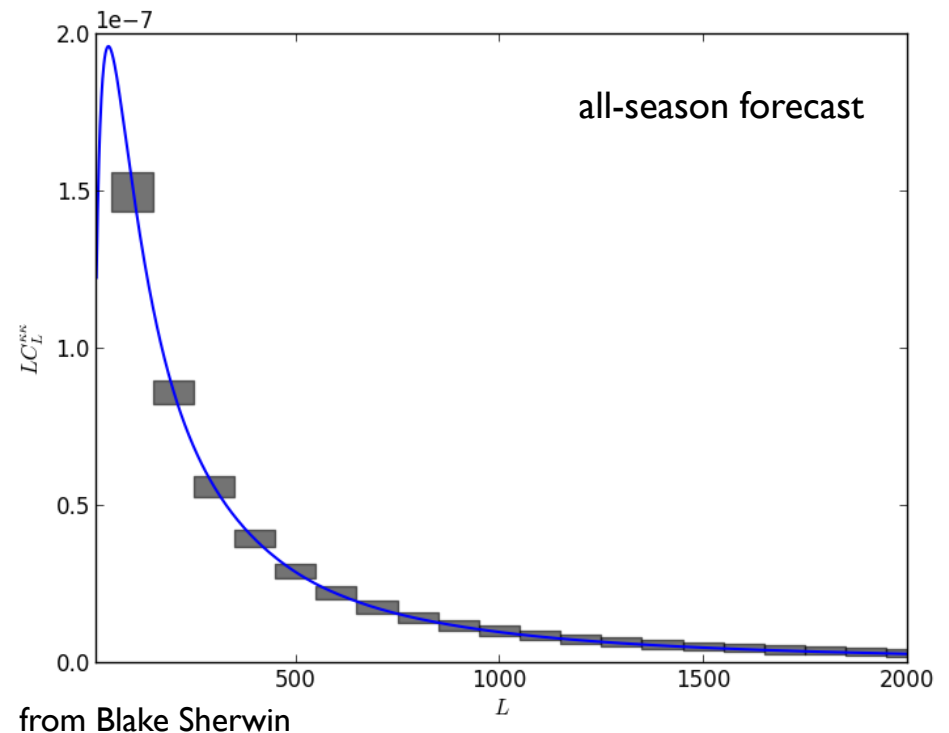
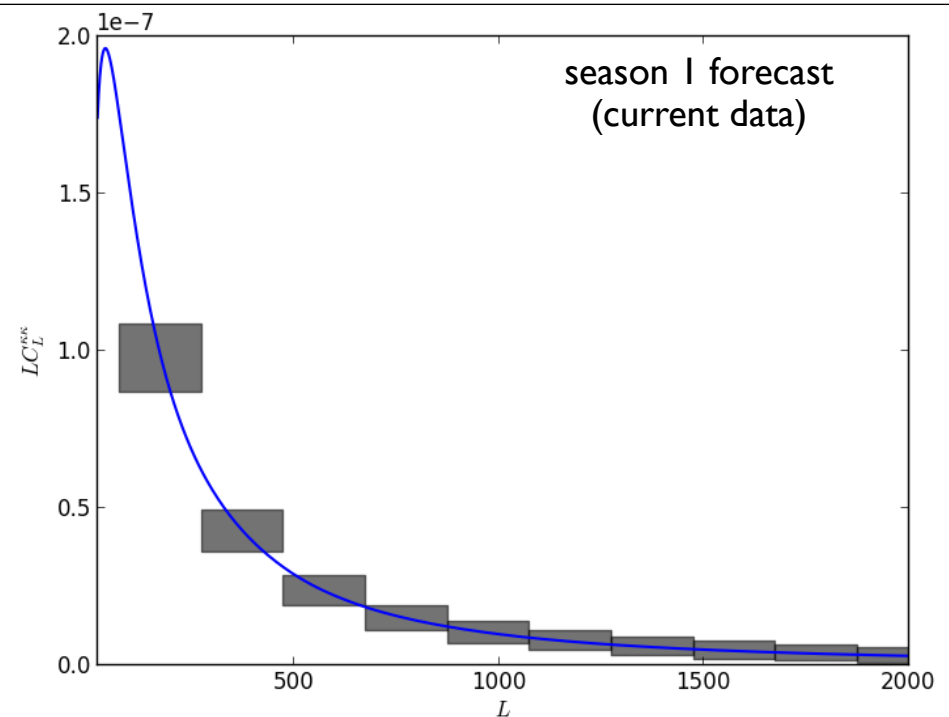
Madhavacheril+, arxiv:1411.1799

3. Pol. and Temp. large-scale lensing autospectrum

In prep.

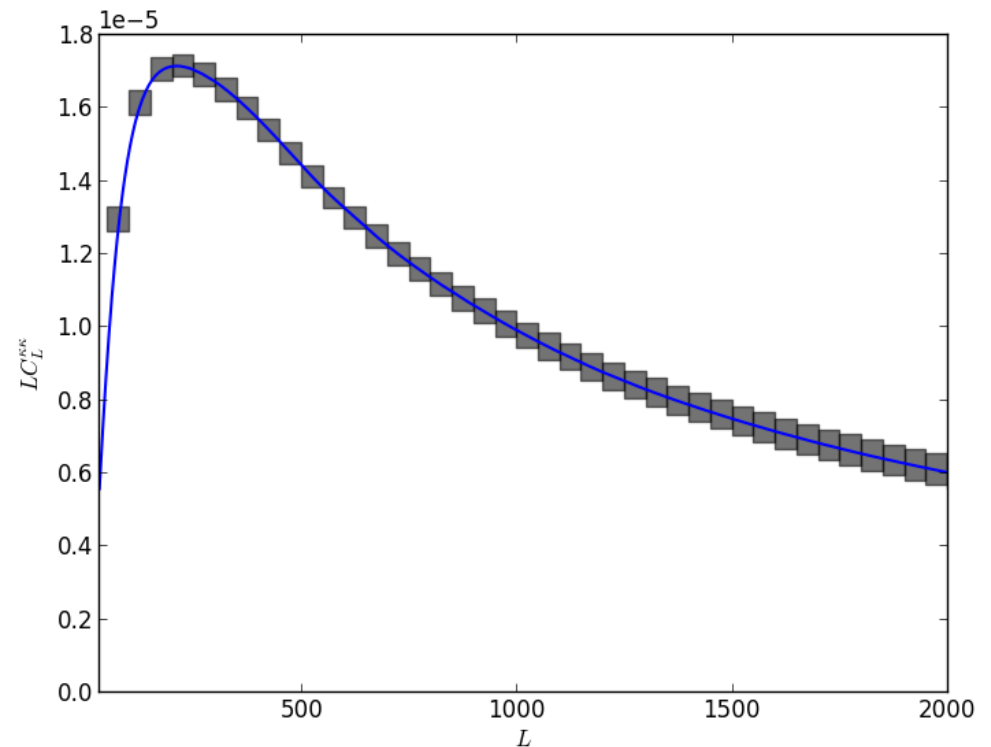
Lensing auto-power spectrum

- ACTPol season 1 autospectrum now at $>8\sigma$ with 200 sq. deg (in prep.)
- 1-2 years: ~ 50 sigma on ~ 2500 sq. deg.
- neutrino mass to $<\sim 0.1$ eV, together with *Planck*



Lensing auto-power spectrum

- AdvACT (“stage III CMB”):
Map mass over nearly full sky
to high res; overlap with LSST
- $\sim 220\sigma$ lensing on 20k sq. deg.
(2016-17)
- Neutrino mass to 0.04 eV



Summary

- Lensing of pol. and temp. seen with ACTPol survey, in cross-correlation with *Planck* CIB
- First detection of lensing by individual dark matter halos
- To come: tight constraints on cosmology