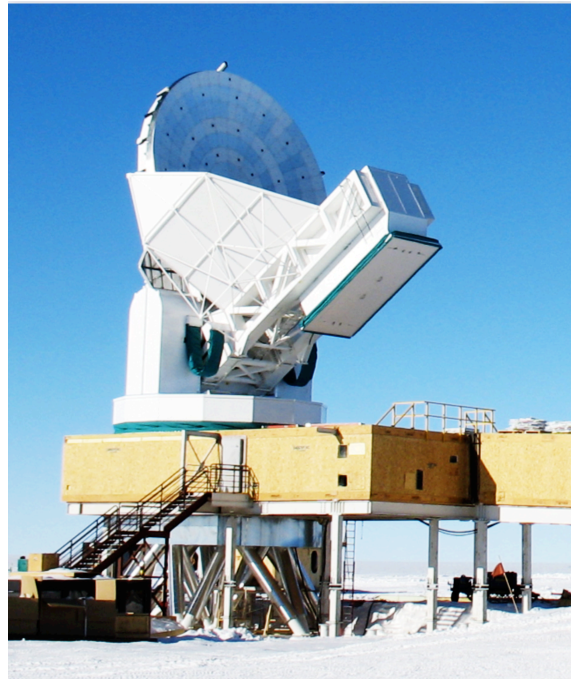
CMB Lensing reconstruction with the South Pole Telescope

A. van Engelen, G. Holder, SPT collaboration

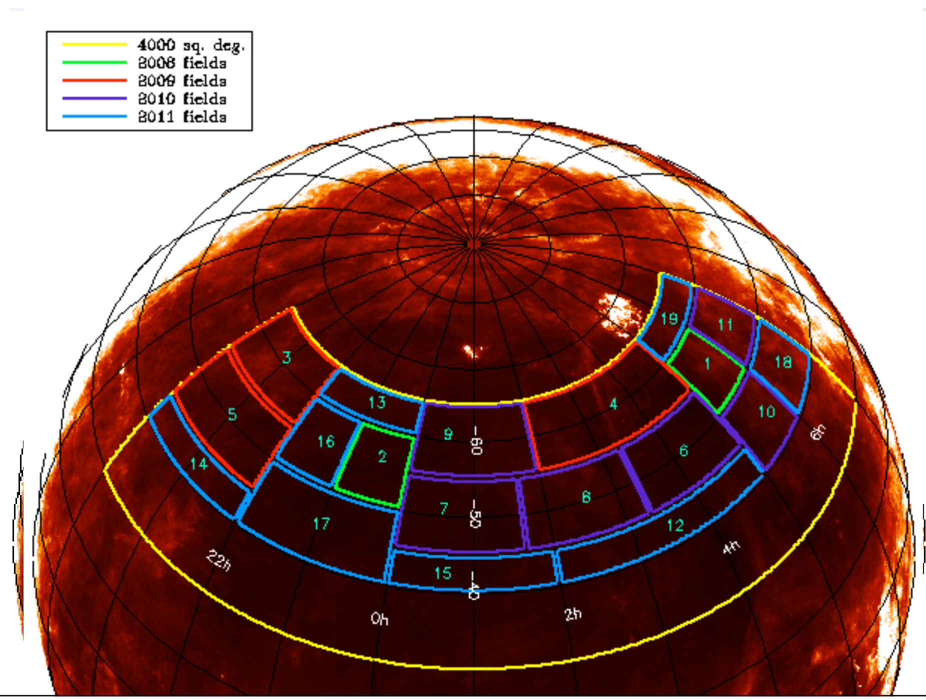
SPT

- 10 m dish - 1' FWHM beam
- Observes at 3 frequencies: 90, 150, 220 GHz
- ~1000 detectors



SPT survey

- Survey Depth is 18 uK-arcmin
- 2500 sq deg by ~end of 2011; ~1400 right now; we use ~500 sq deg from 2008 and 2009 surveys

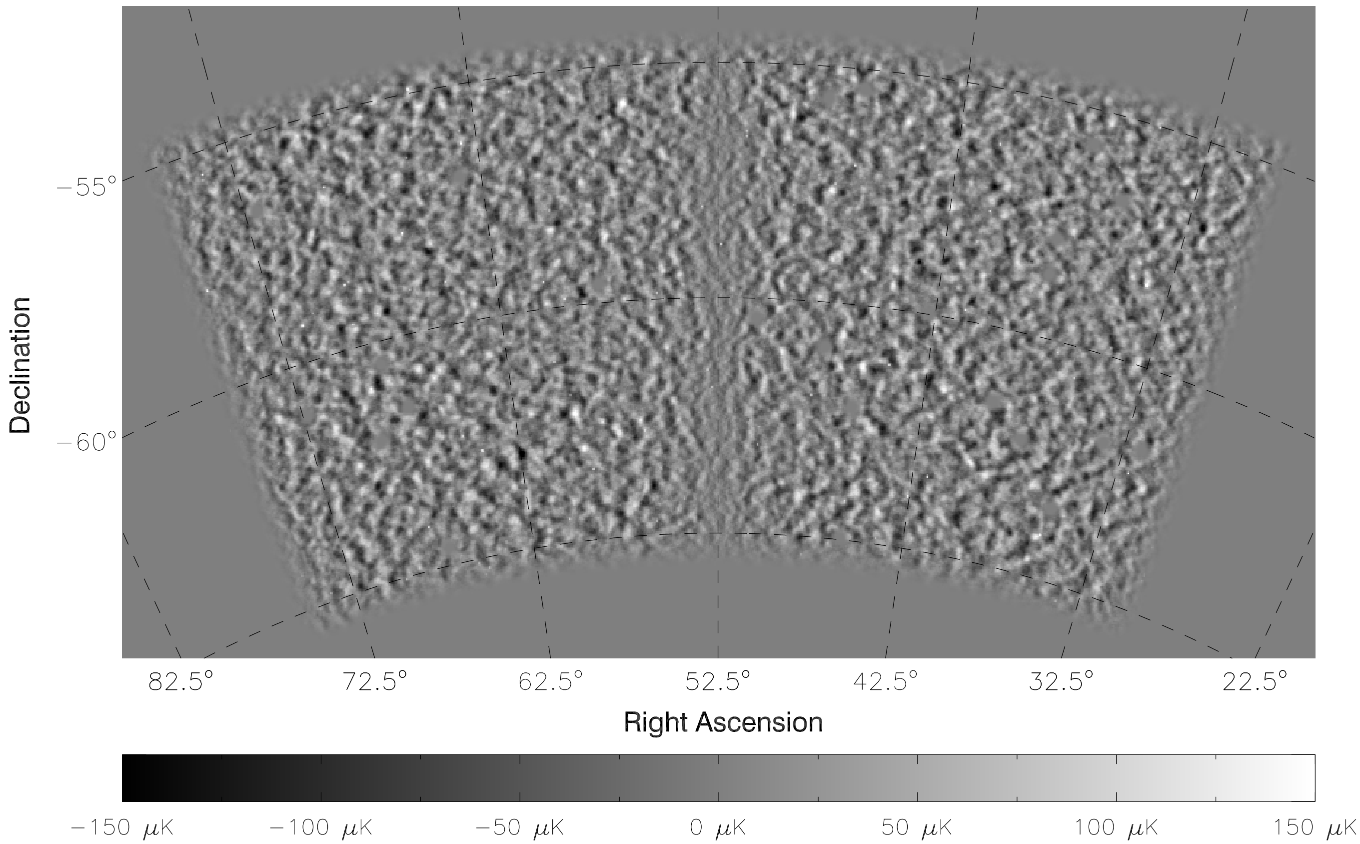


These properties make it ideal for studying lensing!

$\delta\theta_{rms} \sim 2.4'$

Sample-variance dominated well into the damping tail

Map for primary CMB science (1 of 4)



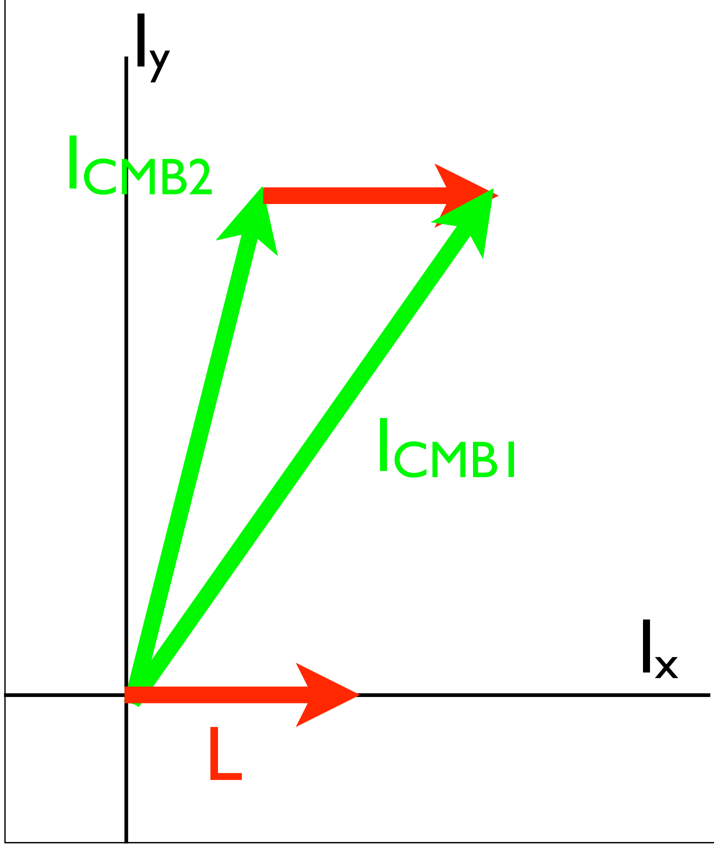
- Led by Ryan Keisler - see his talk (following this one)
- Filtered for 500 < l < 3000
- ~500 sq deg at 18 uK'
- 150 GHz only

Lensing

- Non-gaussian mode coupling for $\mathbf{l_1} \neq -\mathbf{l_2}$:

$$\langle T^L(\mathbf{l}_1) T^L(\mathbf{l}_2) \rangle = \mathbf{L} \cdot (\mathbf{l}_1 C^T_{l_1} + \mathbf{l}_2 C^T_{l_2}) \phi(\mathbf{L}) + O(\phi^2)$$

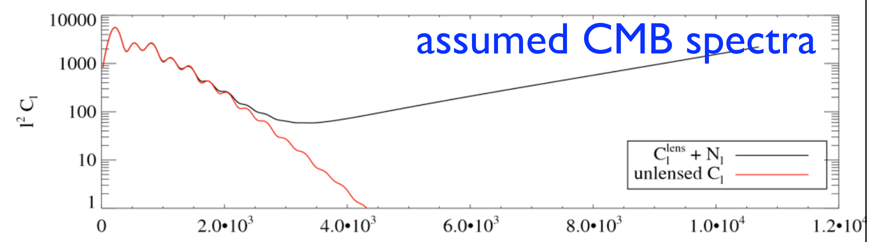
$$\mathbf{L} = \mathbf{l}_1 + \mathbf{l}_2$$

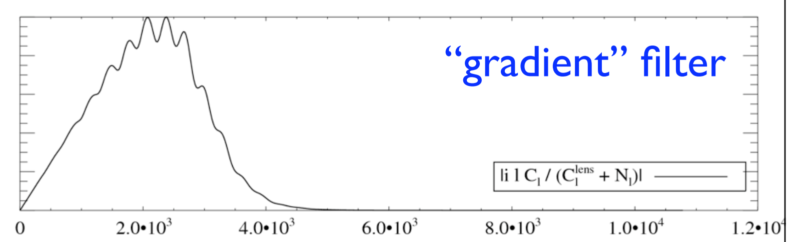


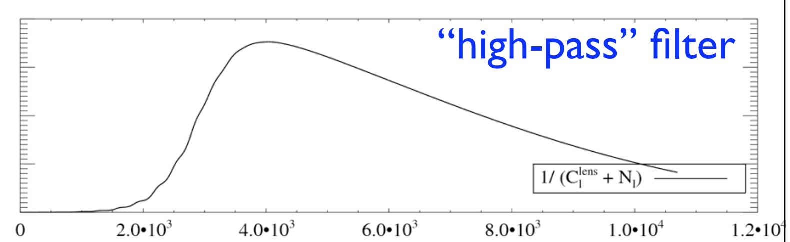
- We extract ϕ by taking an average over CMB multipoles separated by a distance L
- We use the standard Hu quadratic estimator.

Quadratic Estimator (Hu 2002)

- We adopt the standard Optimal Quadratic Estimator
    - Make a filtered gradient map (filtered)
    - Make a high-pass filtered map
    - Multiply them in real space
    - Take the divergence
    - Renormalize to ensure $\langle\phi^{est}(L)\rangle_{CMB} = \phi(L)$, to first order in ϕ
- Power in this map probes CMB trispectrum; $\phi^{est} \sim T^2$; $|\phi^{est}|^2 \sim T^4$
- Filters are tuned to maximize S/N; downweight noisy modes
    -

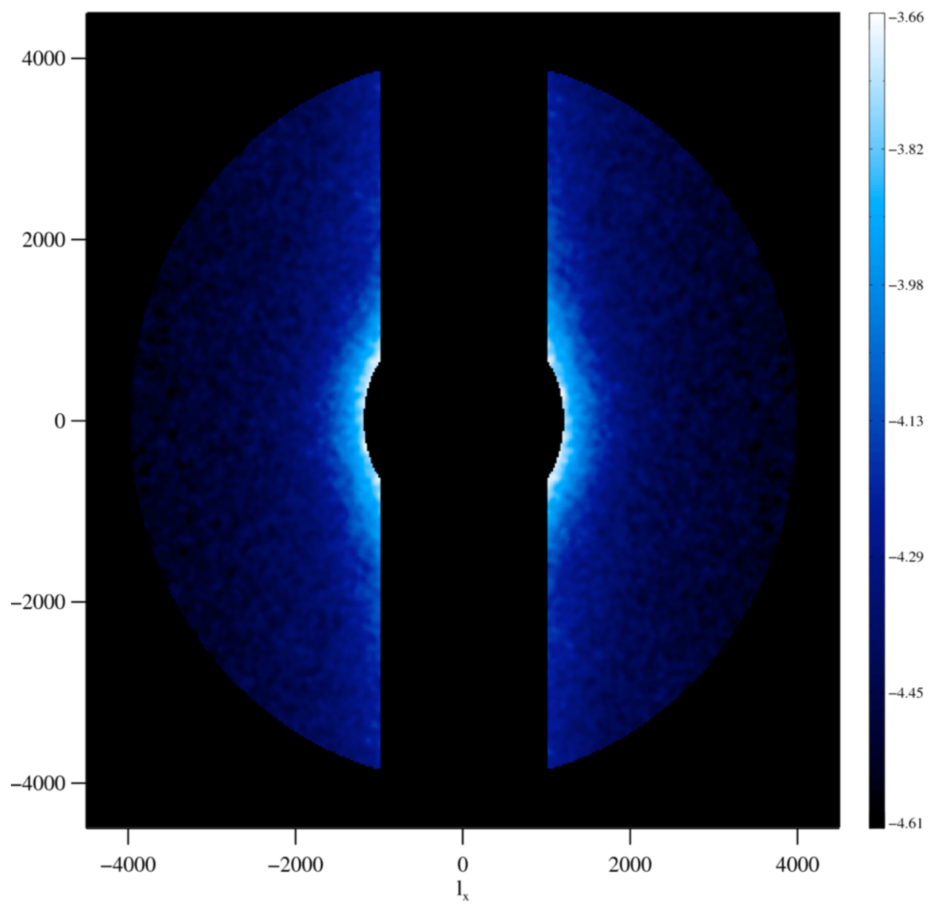


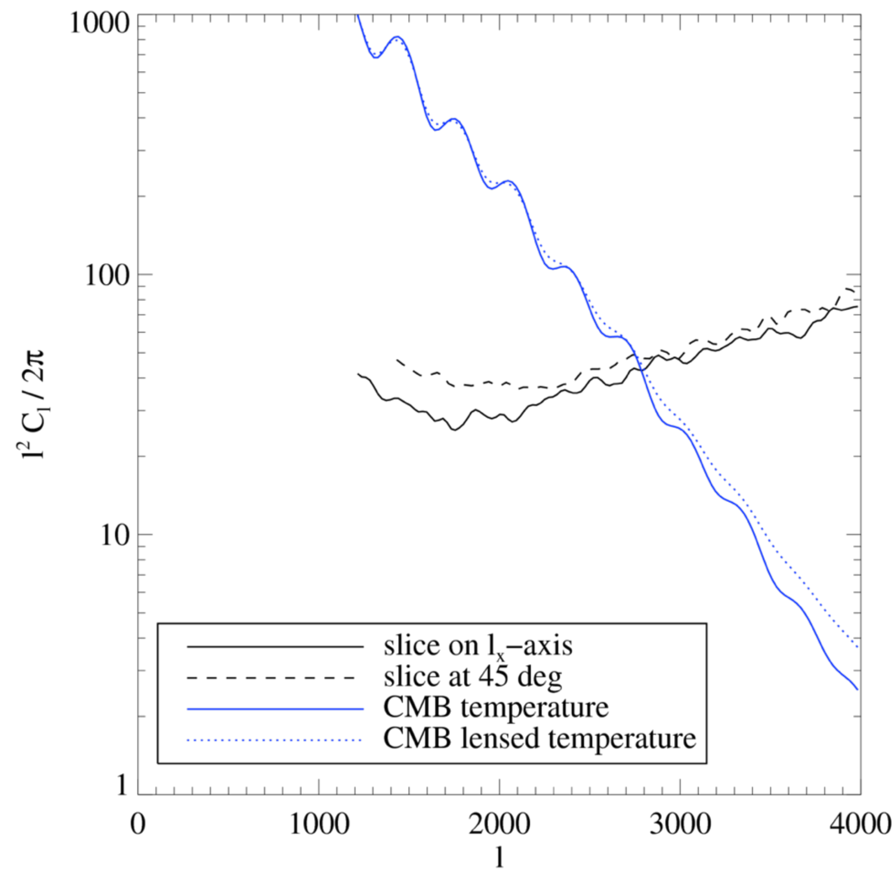




SPT noise power

- Due to SPT azimuthal scan strategy, noise is lowest in lx-direction in Fourier space
- We cut at 1200 < l < 4000, as well as a vertical strip with $|l_x| < 1000$
- This makes the recovered lensing field anisotropic

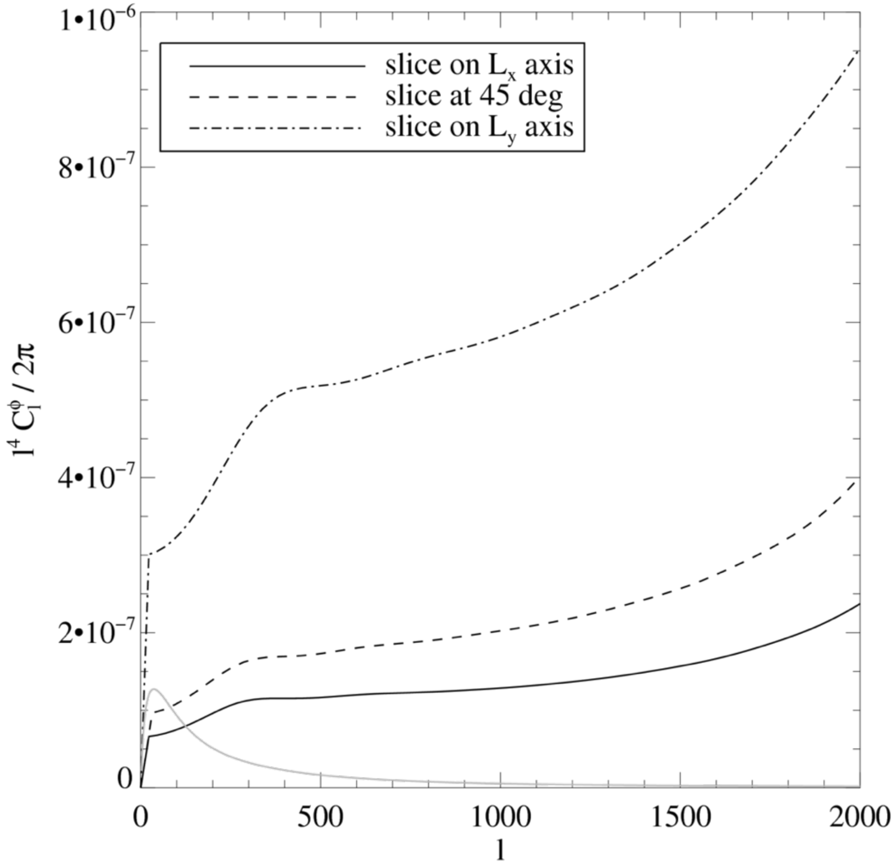


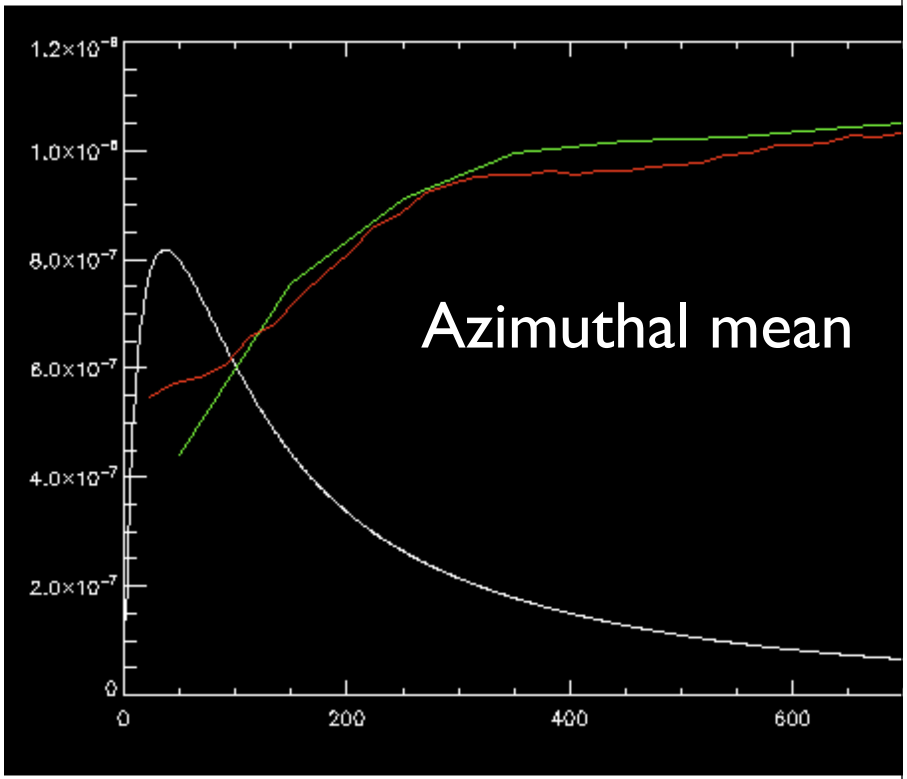


SPT 2d noise

- reconstruction is ~4x noisier in L_y than L_x direction

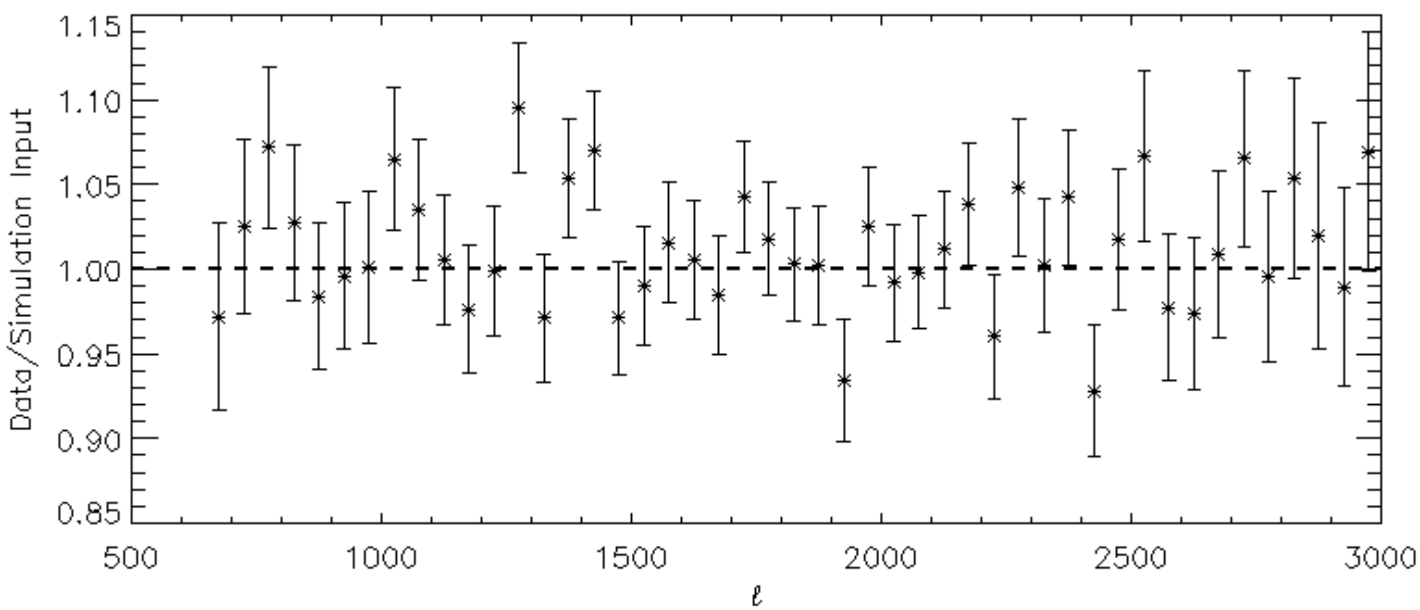
- Inverse-variance weight when computing power spectrum
- gives overall noise bias





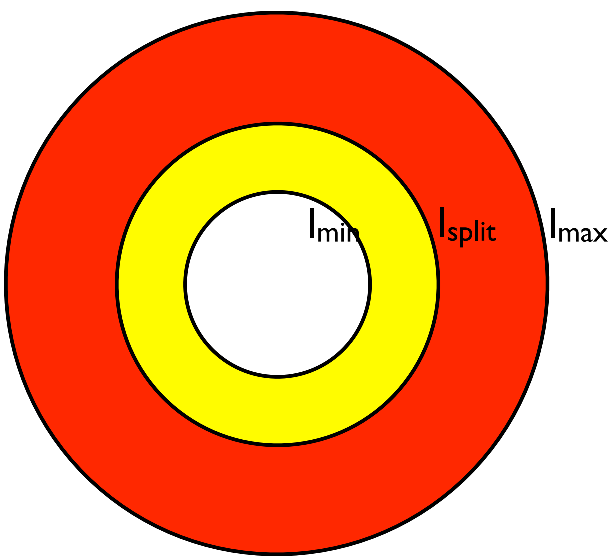
Mitigating the noise bias

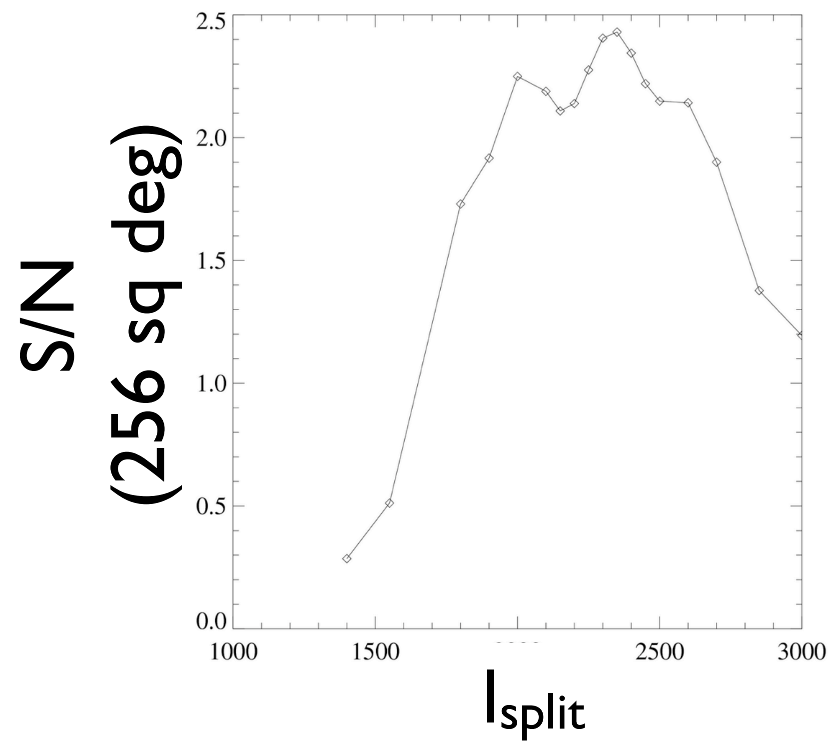
- Noise bias comes from gaussian power (unconnected four-point function) in map
  - Das et al (2011) run simulations with measured map amplitude (and random phases) through pipeline
- The power found in SPT maps agrees well with that in our simulations (up to a measurable, constant factor); we can subtract
  - SPT calibration uncertainty (5% in power) still feeds into lensing signal from off-diagonal couplint



Another way to mitigate the noise bias

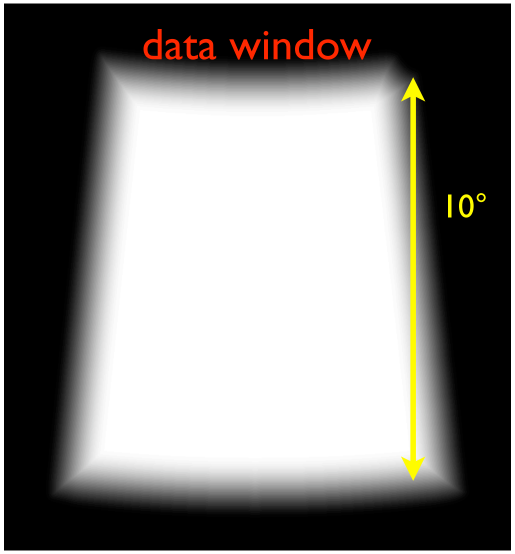
- Can use disjoint pieces of temperature Fourier space (from same field), constructing two Φ maps; then compute cross-power
- Result will not contain bias from Gaussian signal (Hu 2001, Sherwin & Das 2010)
- S/N hit ~ 3/8

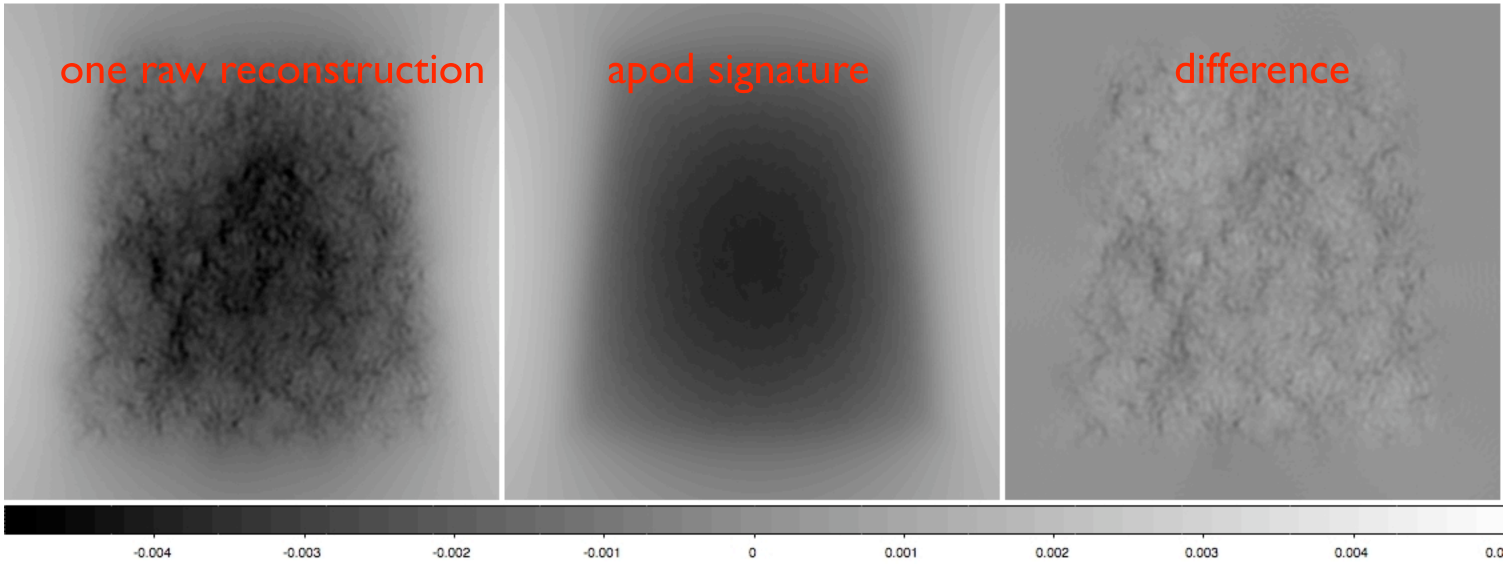




Apodization effects

- Apodization leads to mode coupling
- We run estimator initially neglecting this, then deal with effects
- Additive large-scale signature. Peaks at low L; factor of 5 brighter than the deflection signal
- Monte Carlo it & subtract



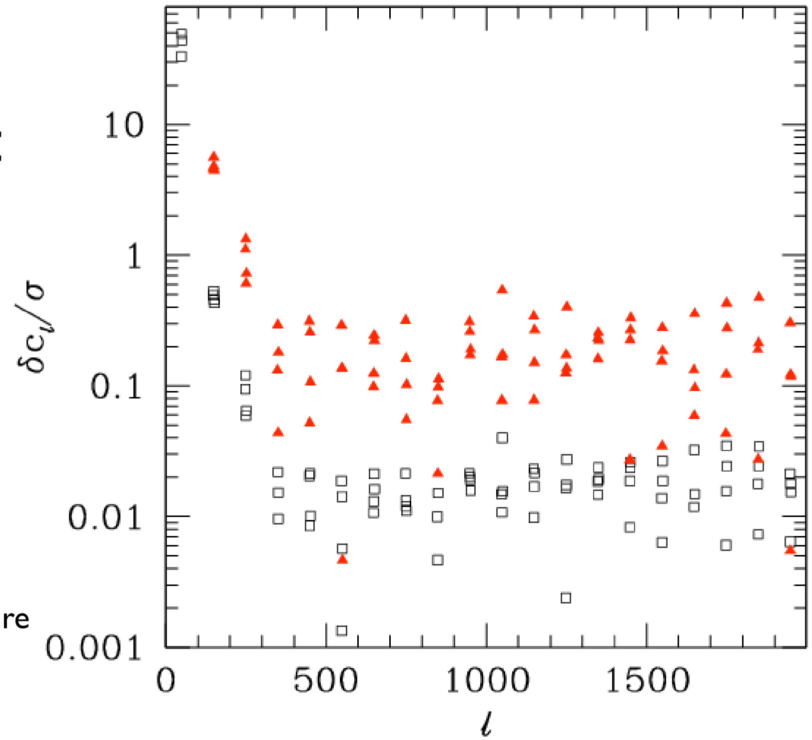


Apodization effects

- The window signature depends on the total power in the map:

$$\langle \hat{D}(\mathbf{L}) \rangle = \frac{A_L}{L} \int \frac{d^2\mathbf{l}_1}{(2\pi)^2} \int \frac{d^2\mathbf{l}'}{(2\pi)^2} \times F(\mathbf{l}_1, \mathbf{L}-\mathbf{l}_1) \times C^t_{\ell'} A(\mathbf{l}_1 - \mathbf{l}') A(\mathbf{L} - \mathbf{l}_1 + \mathbf{l}')$$

- Appears at very low L
- A misestimate gives ~0.5σ scatter at L = 150; negligible for L > 300
- We choose to throw out data at L < 150



Scatter on lensing bandpowers (rel. to statistical errors)...

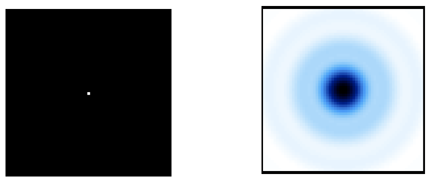
▲ : when no correction for apod. feature is applied

□ : when feature is subtracted, but power in map is misestimated at 5%

Point sources

- Spread from one point source

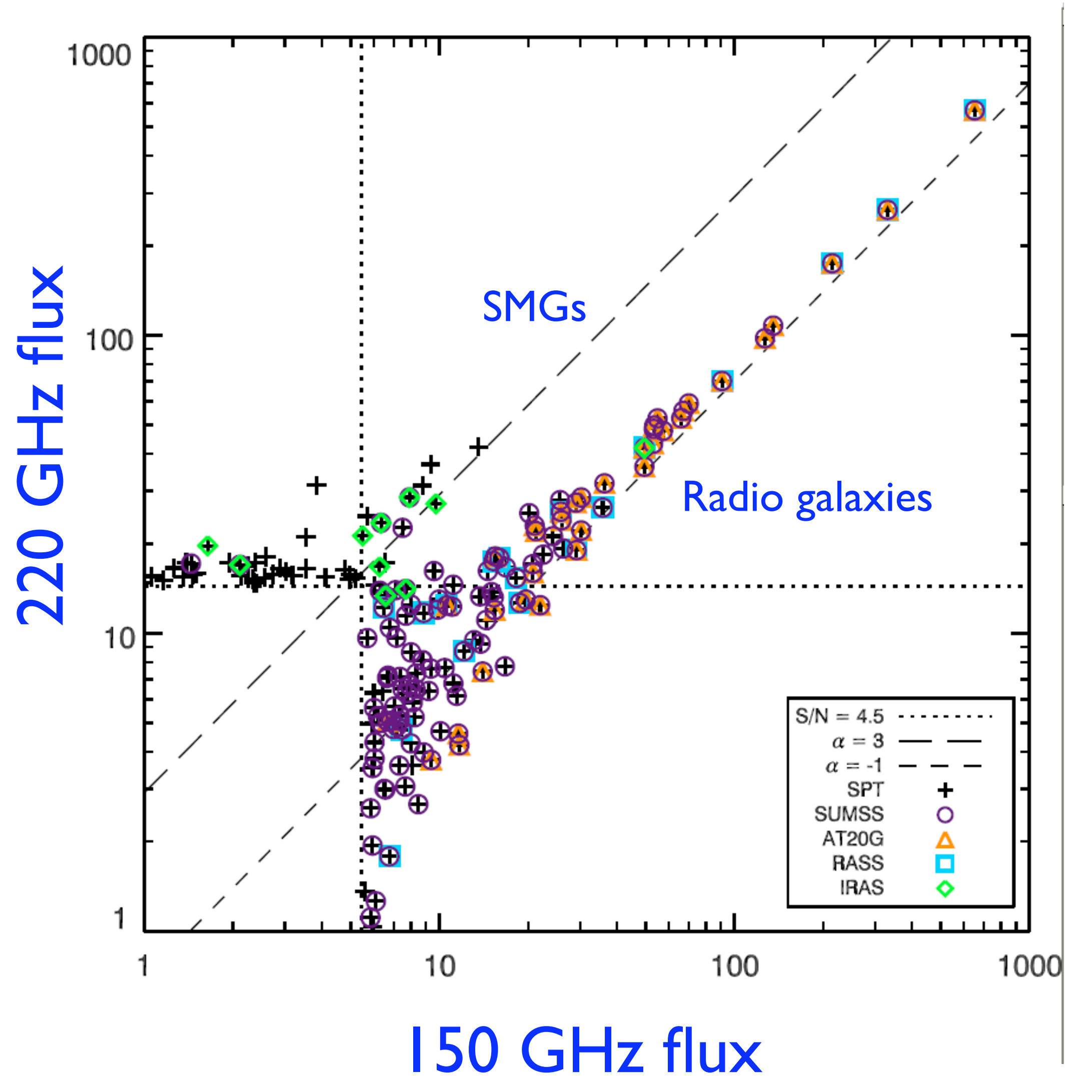
1°



in out

- Low SPT noise allows us to detect point sources down to a 5σ depth of ~5 mJy at 150 GHz

Vieira et al 2009

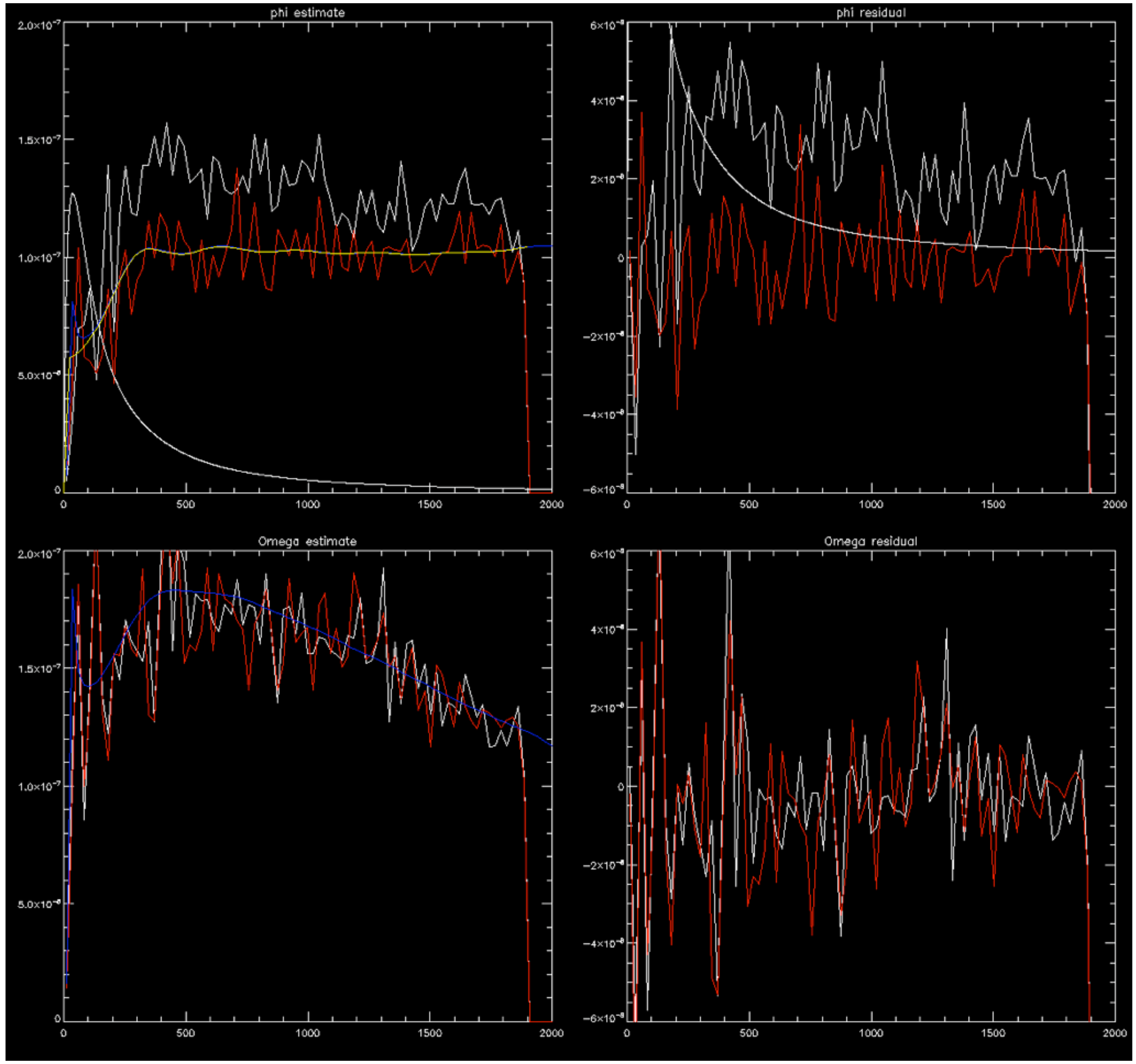


Poisson point sources

- Cut at 65 mJy

CMB + 18 uK' whitenoise + Poisson field

CMB + 18 uK' whitenoise + Gaussian field with same power



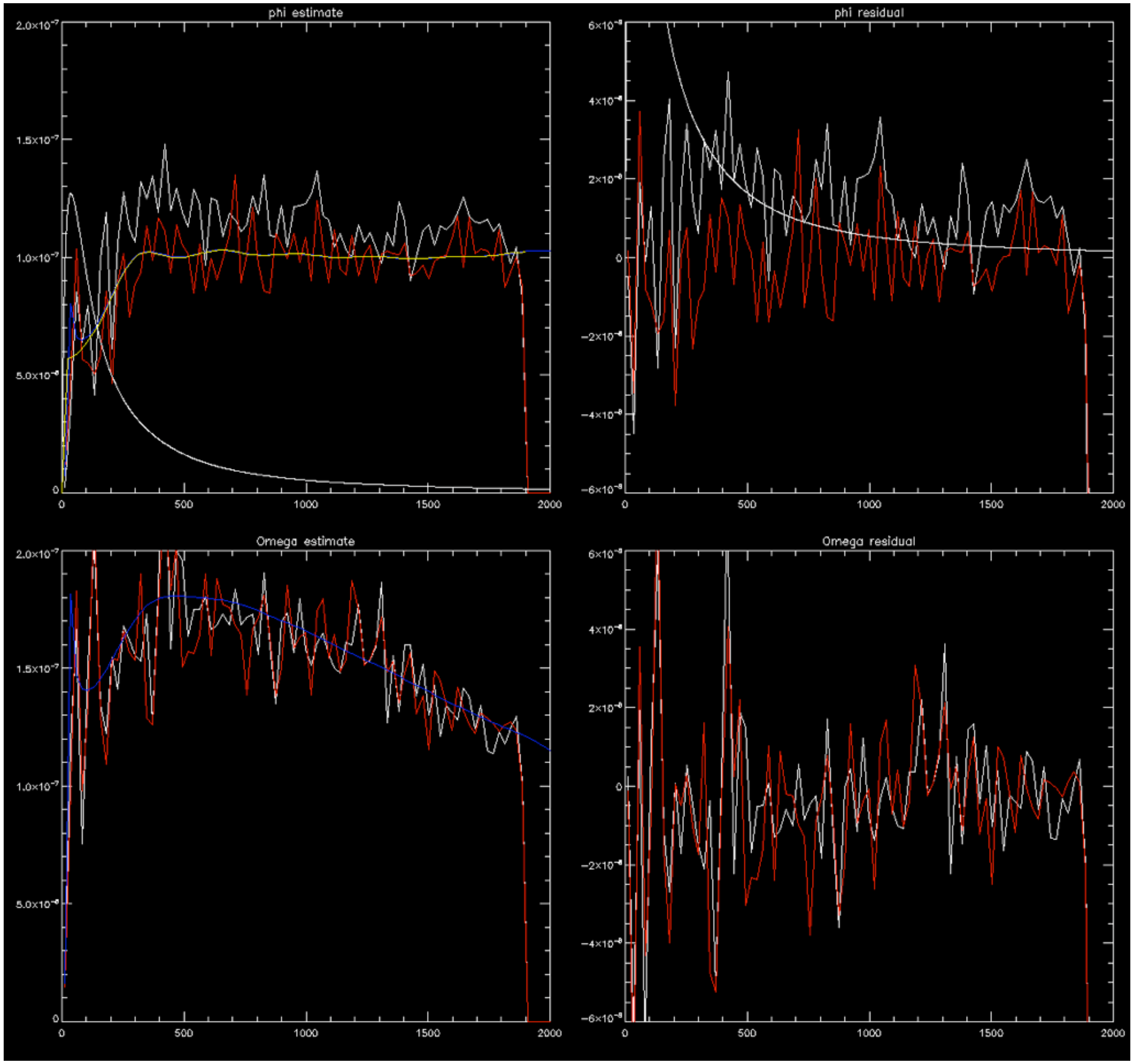
Top: gradient estimator; bottom: curl estimator

Poisson point sources

- Cut at 41 mJy

CMB + 18 uK' whitenoise + Poisson field

CMB + 18 uK' whitenoise + Gaussian field with same power



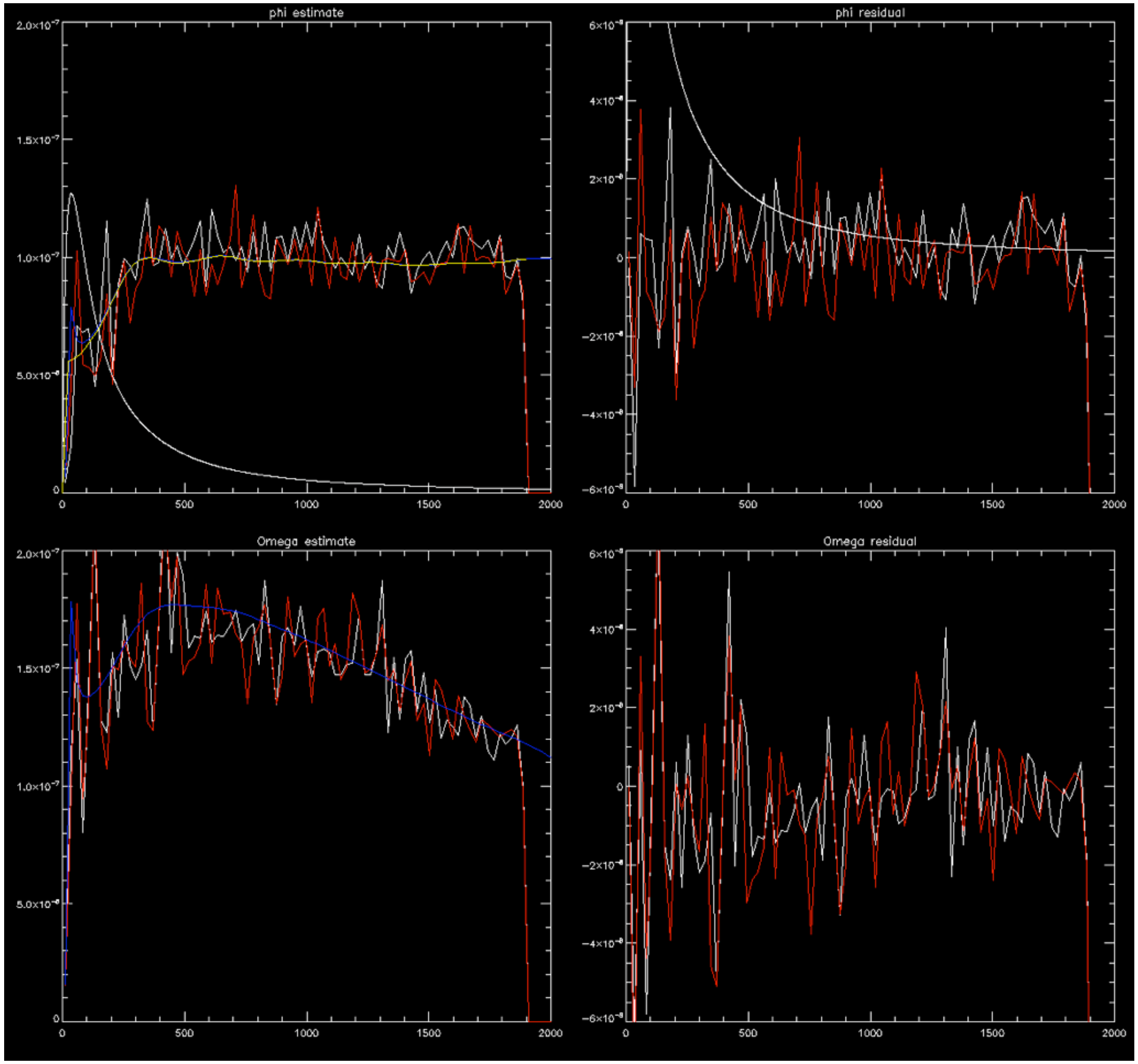
Top: gradient estimator; bottom: curl estimator

Poisson point sources

- Cut at 26 mJy

CMB + 18 uK' whitenoise + Poisson field

CMB + 18 uK' whitenoise + Gaussian field with same power



Top: gradient estimator; bottom: curl estimator

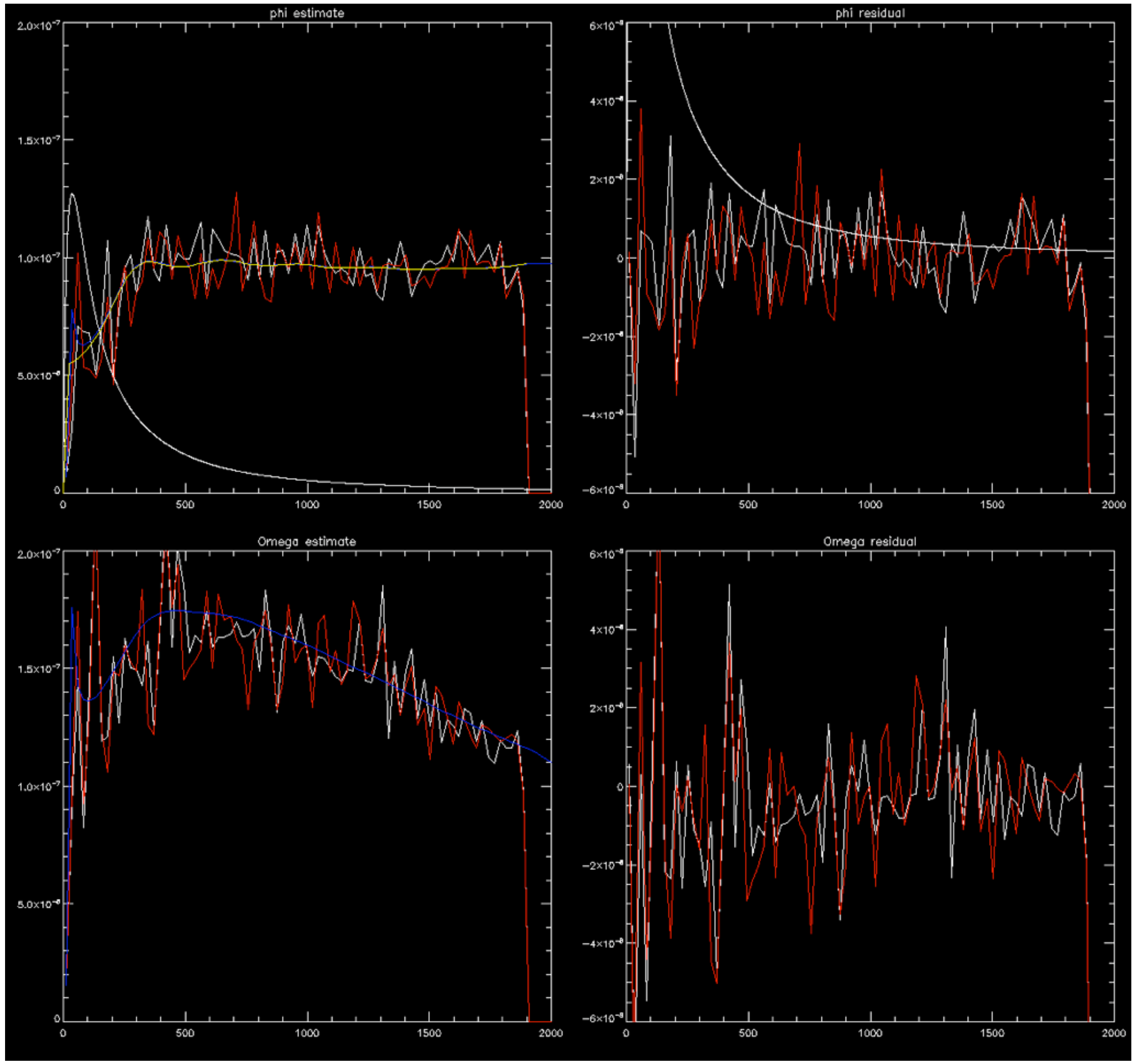
Poisson point sources

- Cut at 16 mJy

CMB + 18 uK' whitenoise + Poisson field

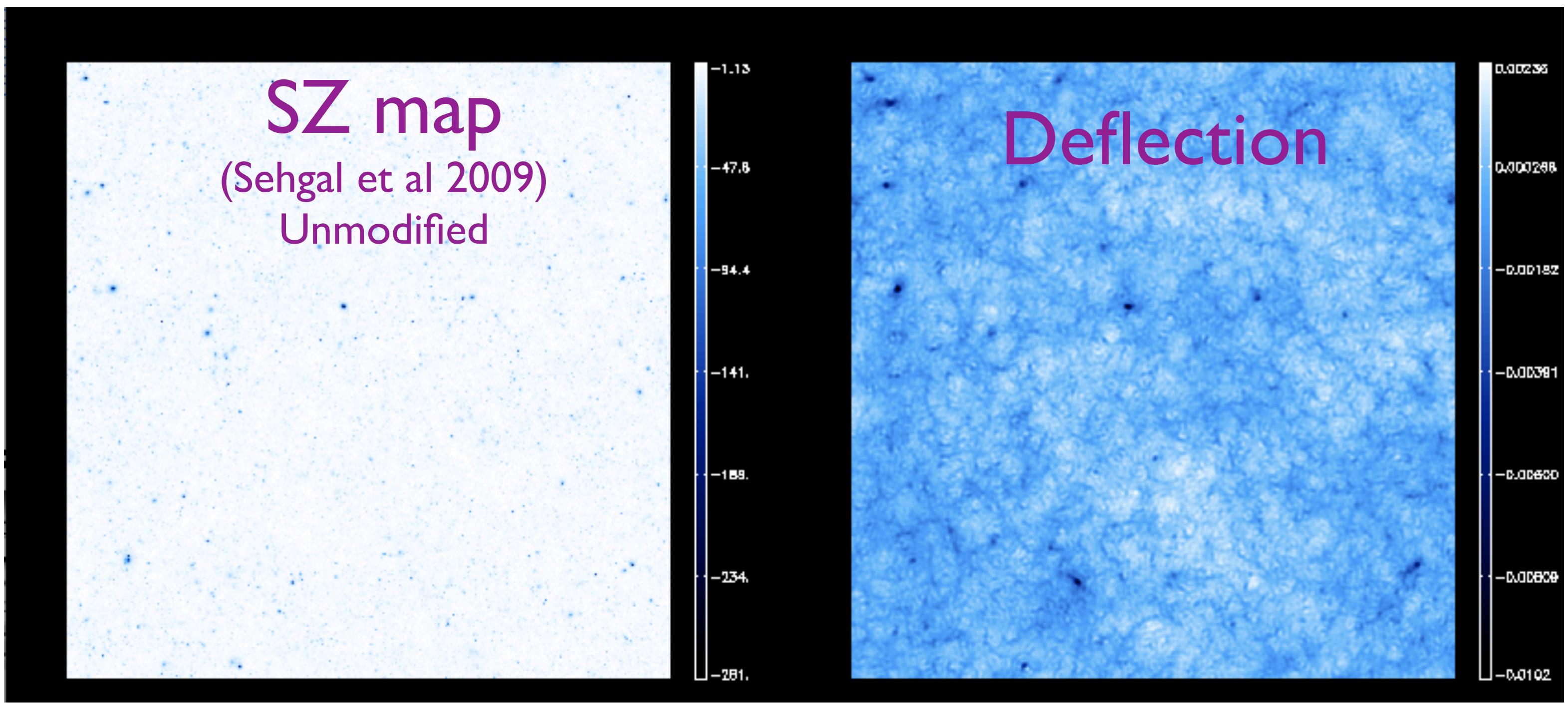
CMB + 18 uK' whitenoise + Gaussian field with same power

Top: gradient estimator; bottom: curl estimator



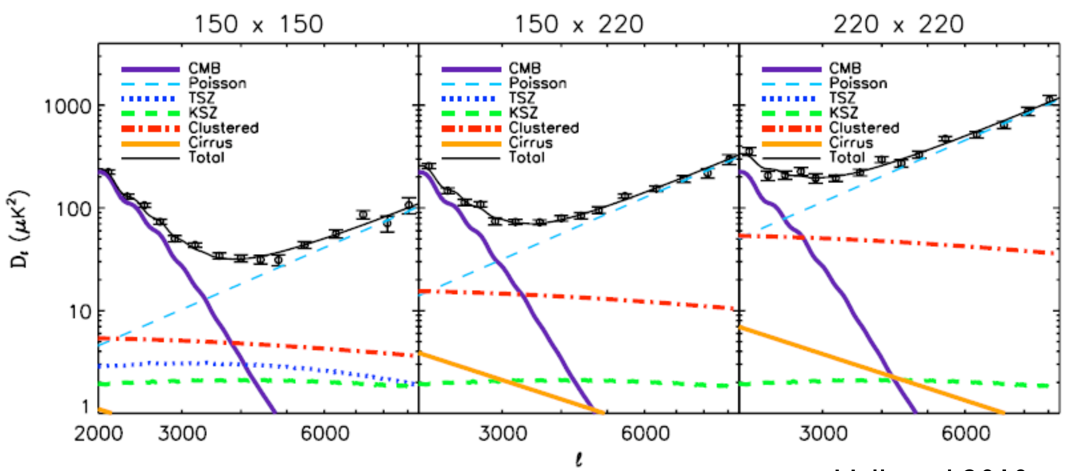
tSZ

- Clusters pop out in reconstruction:

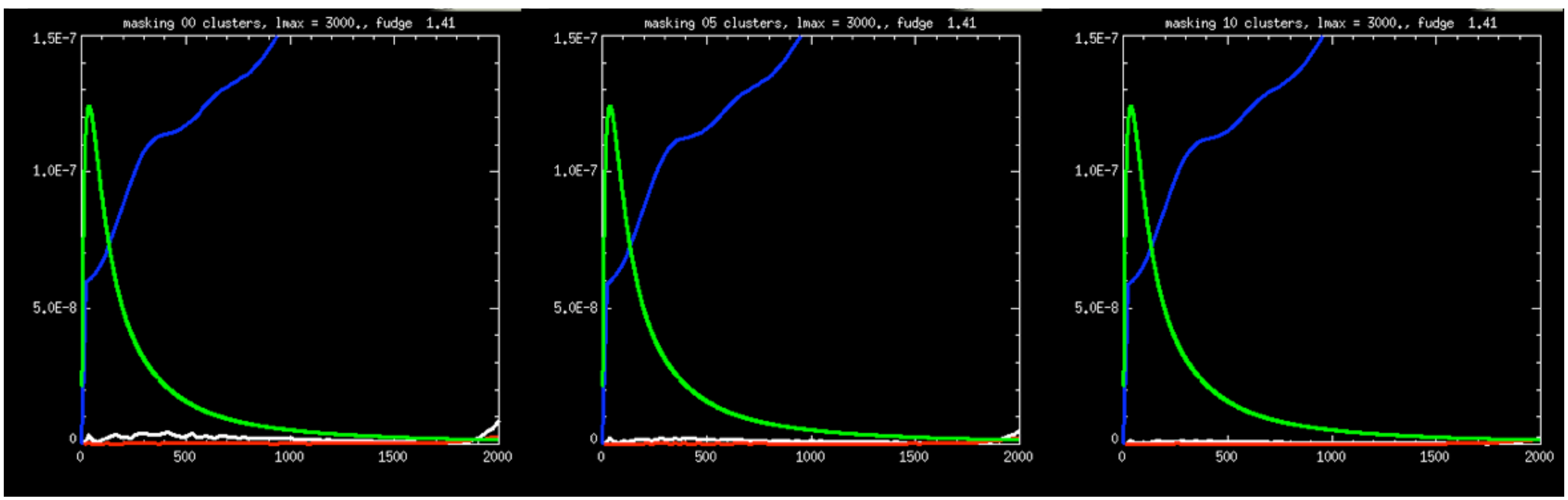


tSZ

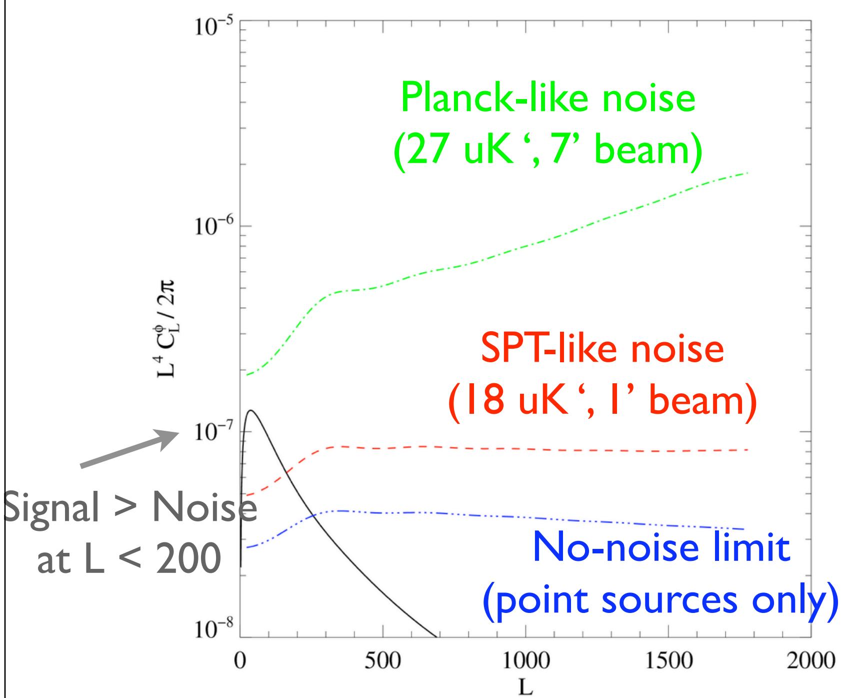
- tSZ power in sims is ~double the measured value
- Knock down power in Sehgal sims
- SZ bias vs. masking level:



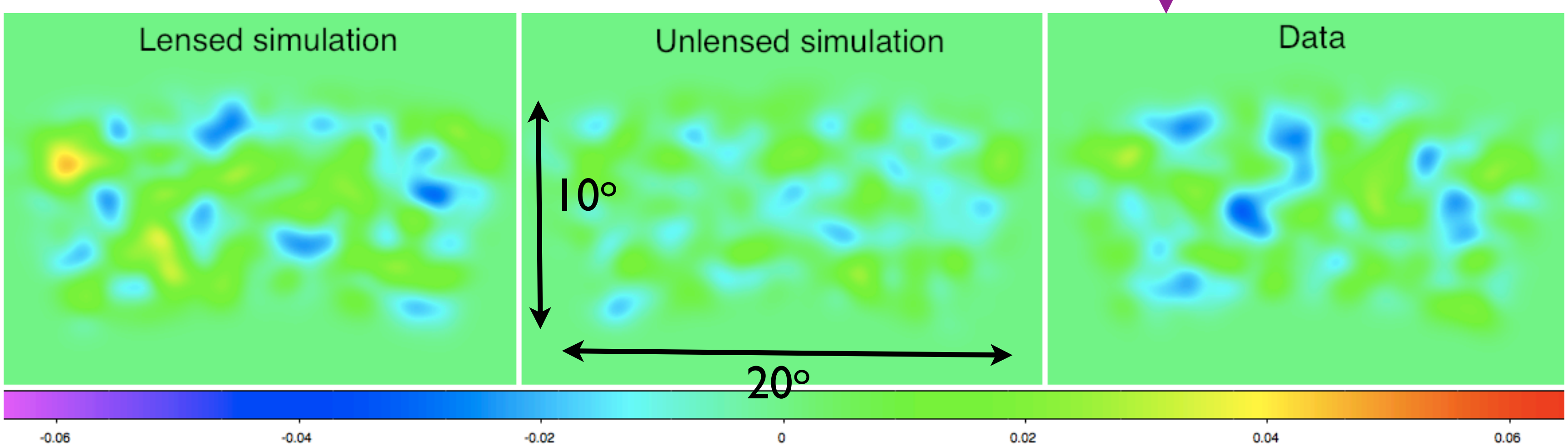
Hall et al 2010



Results: mapping structure at z ~ 2

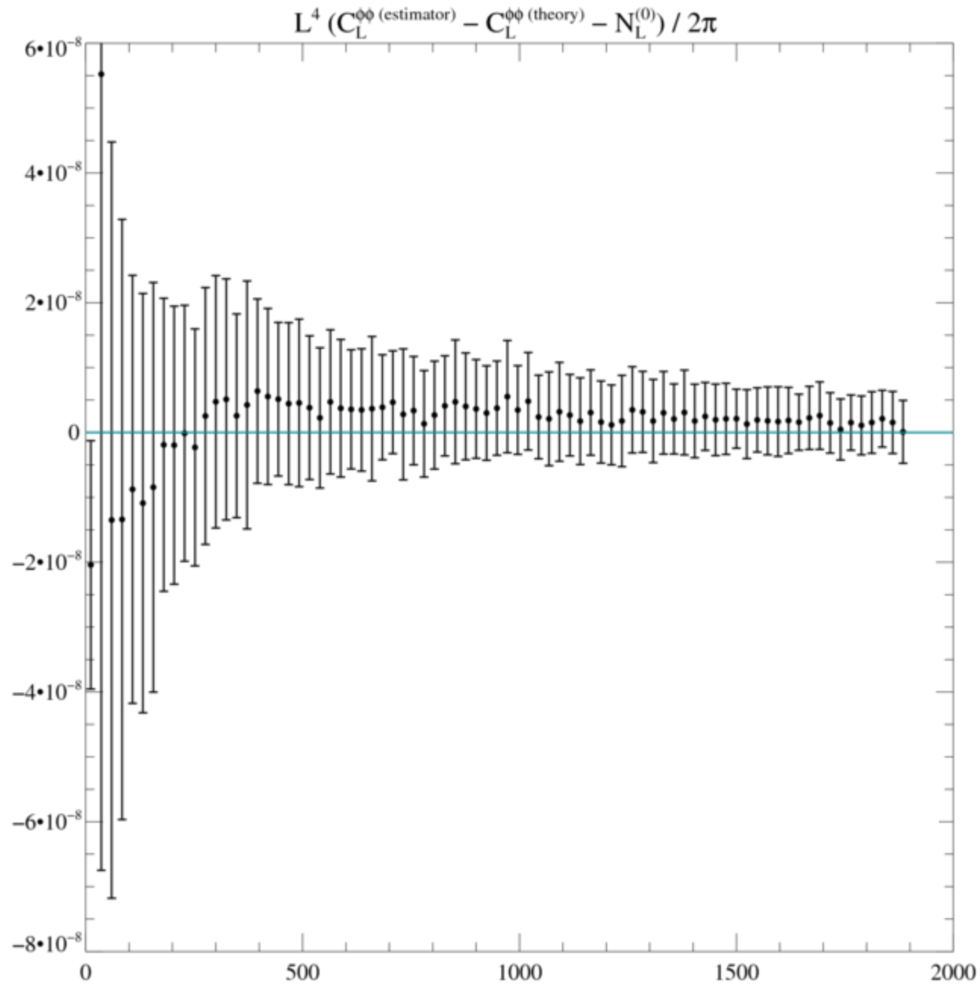


- High-res., low-noise experiments like SPT and ACT can map individual modes on large scales with S/N > 1
- Lensing convergence map, filtered on degree scales; real map of real structure



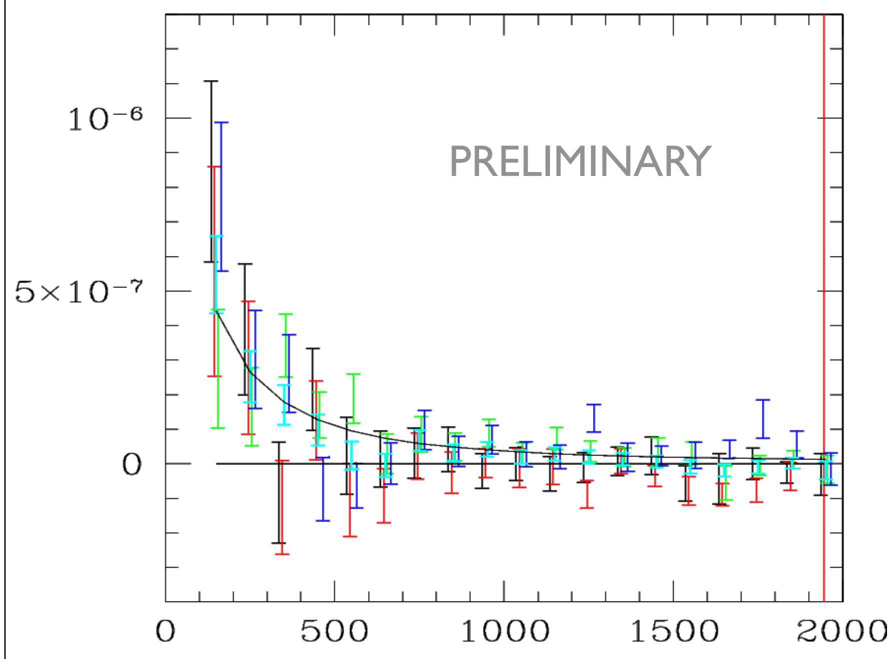
Power spectrum: Higher-order noise biases

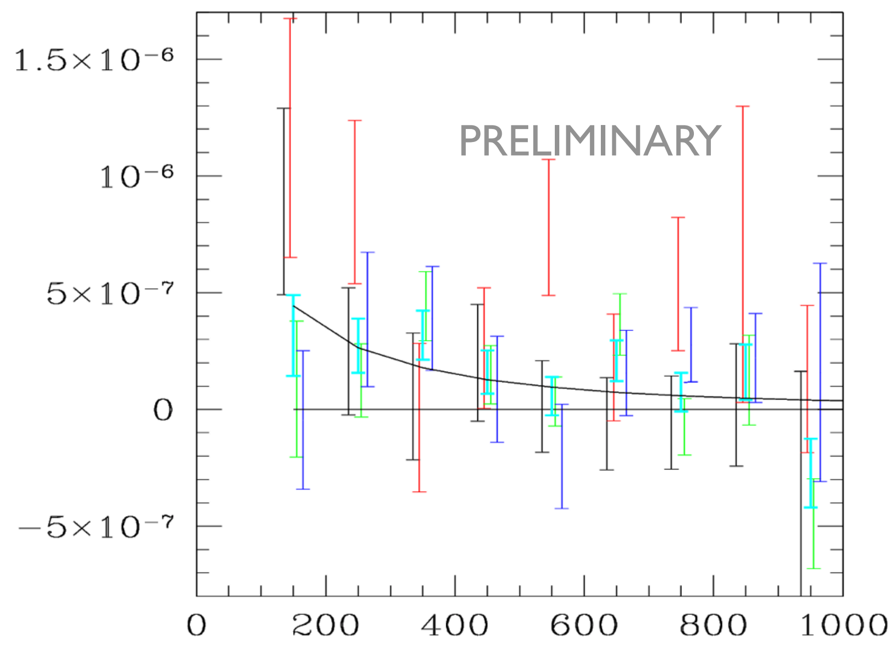
- At high L (> 200): positive noise bias due to extra terms in trispectrum NL[(1)] (Kesden et al 2003)
  - $\propto C_L^{\phi\phi}$
- At low L: negative bias due to terms of order ϕ^2, neglected in estimator formalism (Hanson et al 2010)
- We treat both of these as simple transfer functions on $C_L^{\phi\phi}$



Lensing power spectra

- Obtain gaussian bias from simulations which closely match the SPT observations;
- Obtain lensing transfer functions from diff. between observations of lensed and unlensed CMB





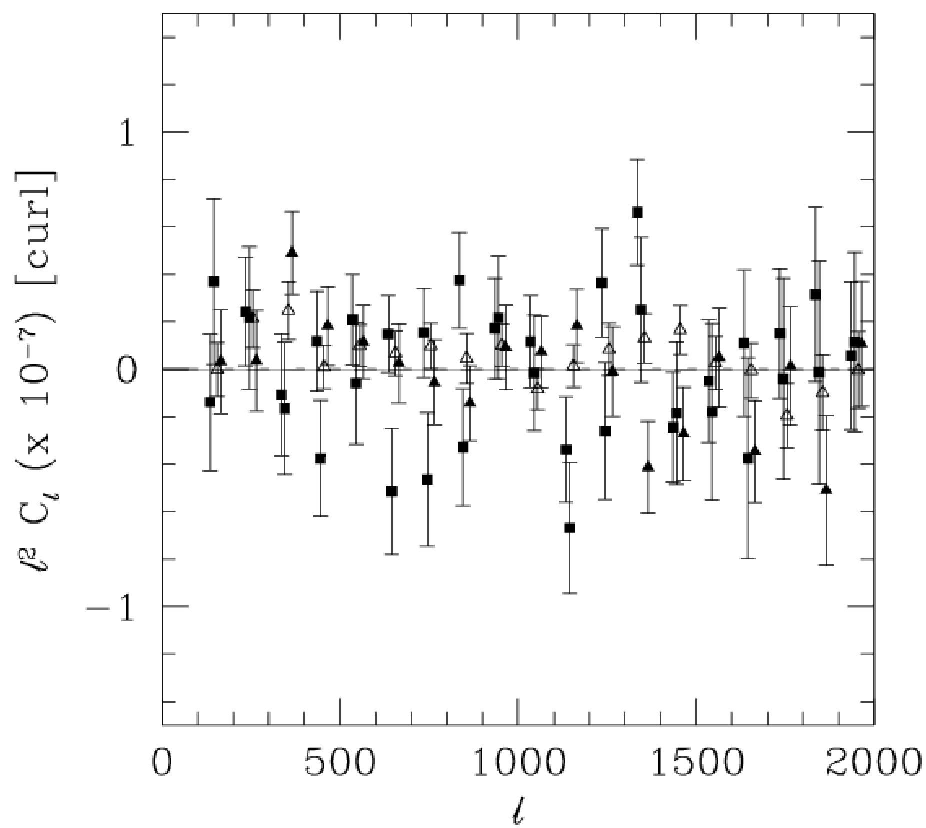
Cyan shows combined fields

Curl null test (Cooray et al 2005)

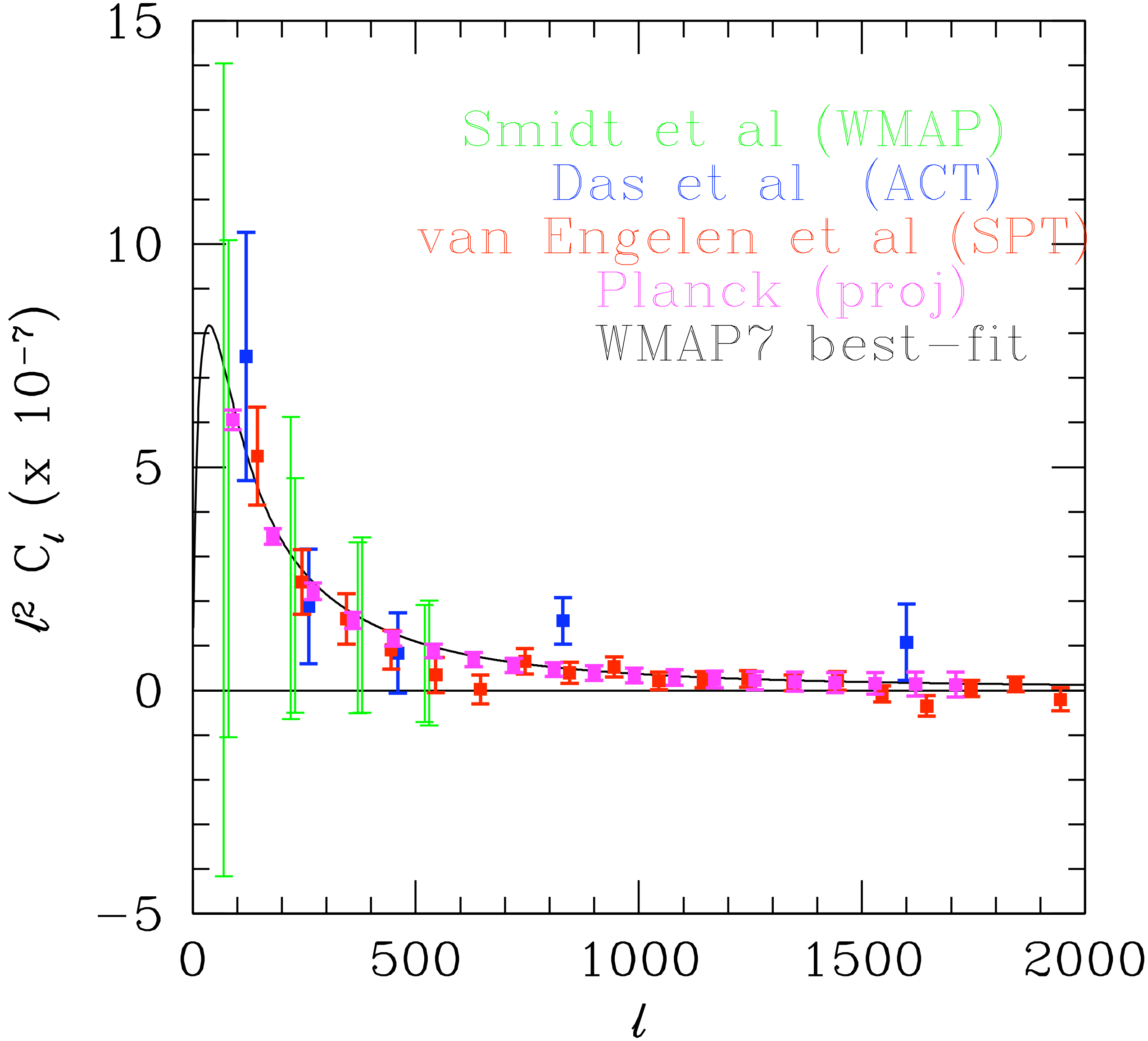
- In reconstruction, replace divergence of gradient with "curl" of gradient

$$\partial_x g_x + \partial_y g_y \rightarrow \partial_y g_x - \partial_x g_y$$

- No signal detected (after subtracting noise bias similar to gradient case)



Various datasets



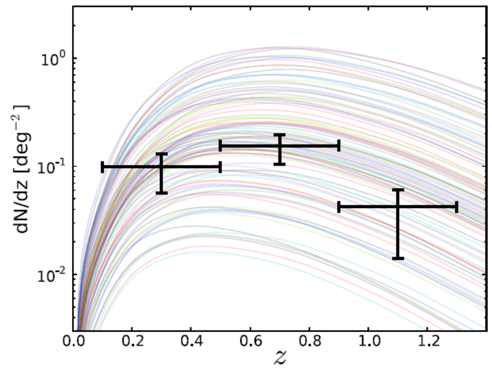
Summary & Outlook

- Detection of lensing power spectrum from SPT is forthcoming, at very high significance based on ~500 sq deg
  - Foregrounds not a huge problem
- Full SPT temperature survey will be 2500 sq deg at 18 uK' depth - plus maps at 90 and 220 GHz
- SPTpol upcoming

Very quick overview of some SPT science (relevant for lensing)

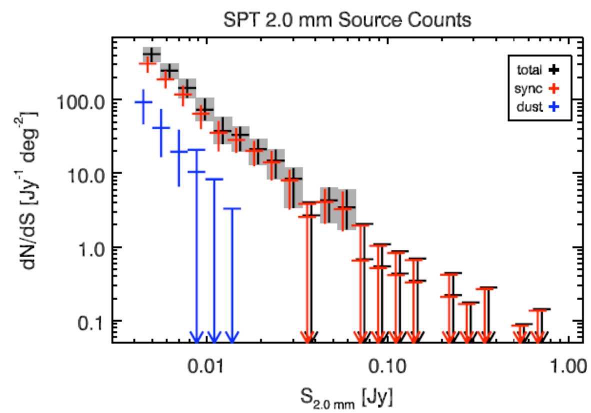
Galaxy cluster survey

- Staniszewski et al 2009: first clusters detected in SZ
- Vanderlinde et al 2010:



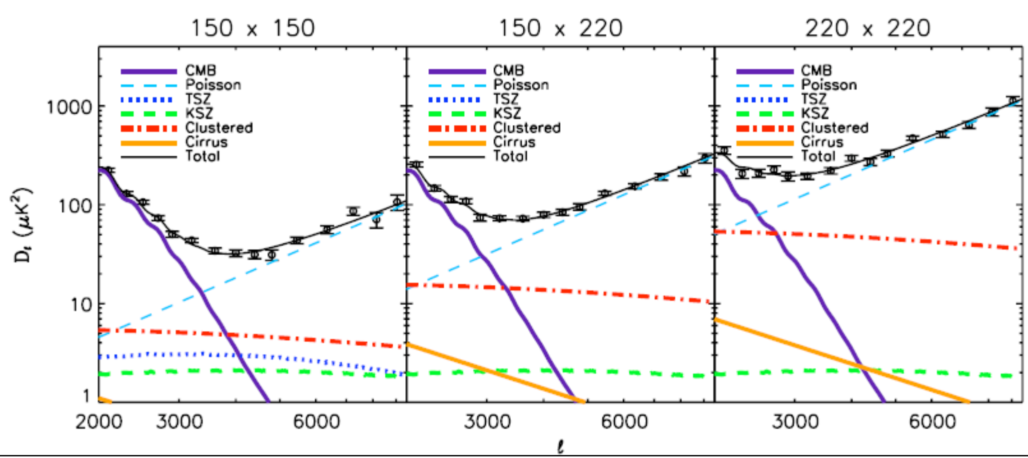
Microwave point sources

Vieira et al 2009



Microwave power spectra at high multipole: secondaries

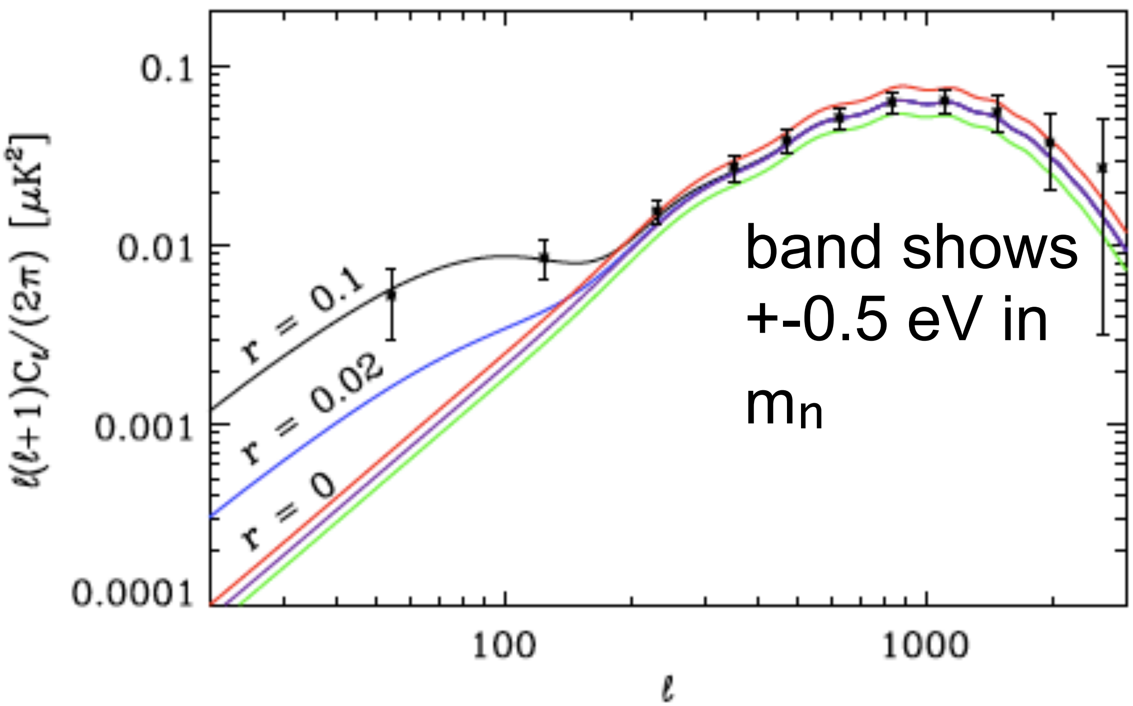
Lueker et al 2010, Hall et atl 2010
Shirokoff et al 2011



Hall et al 2010

SPT-pol lensing

- polarization upgrade coming to SPT at end of 2011 or so
-

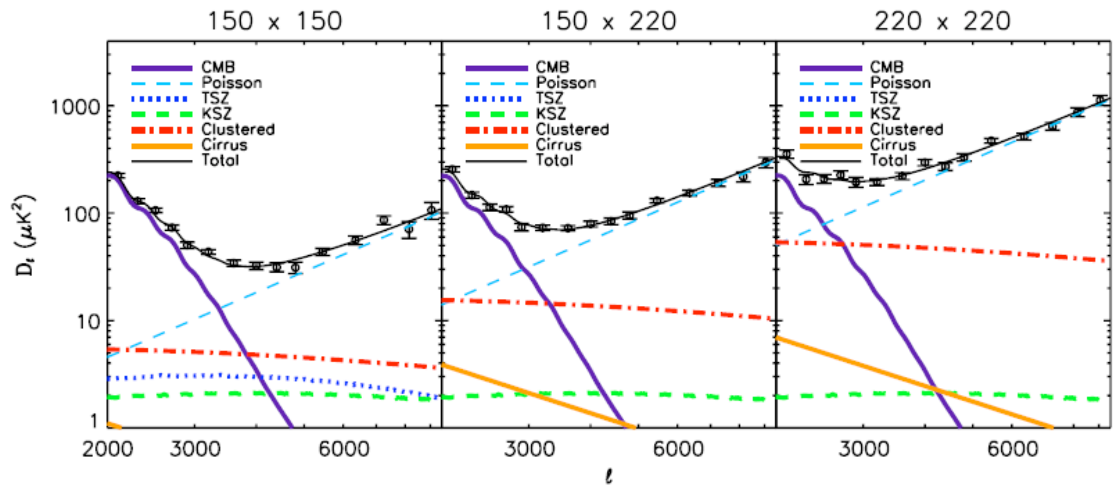


band shows +-0.5 eV in m_n

CMB Power spectrum science

- Detection of secondary anisotropy and measurement of low tSZ power (Lueker et al 2010);
  Detection of clustered dusty sources (Hall et al 2010);
  tighter constraints with more sky(Shirokoff et al 2010)
- Next result will be power spectra covering primary CMB 500 < L < 3000
  - See Ryan Keisler's talk, next
- We use these fields for the lensing analysis

Hall et al 2010



Simulation similar to upcoming primary CMB paper (Keisler et al)