CMB Lensing Cross-Correlations (optical, IR, submm)

Gil Holder

McGill

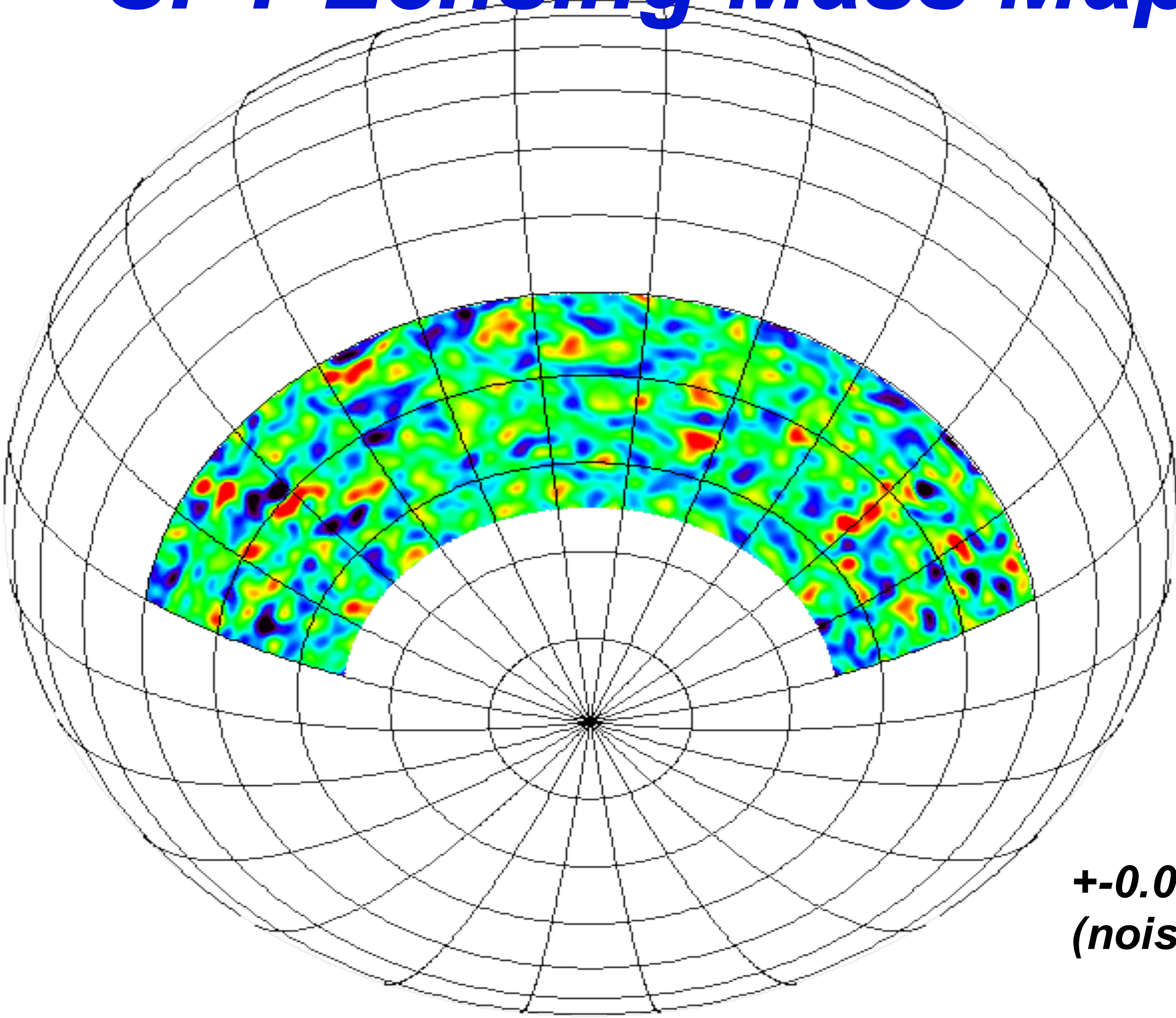
SPT

Bleem et al 2012
Holder et al 2013
Geach et al (soon!)

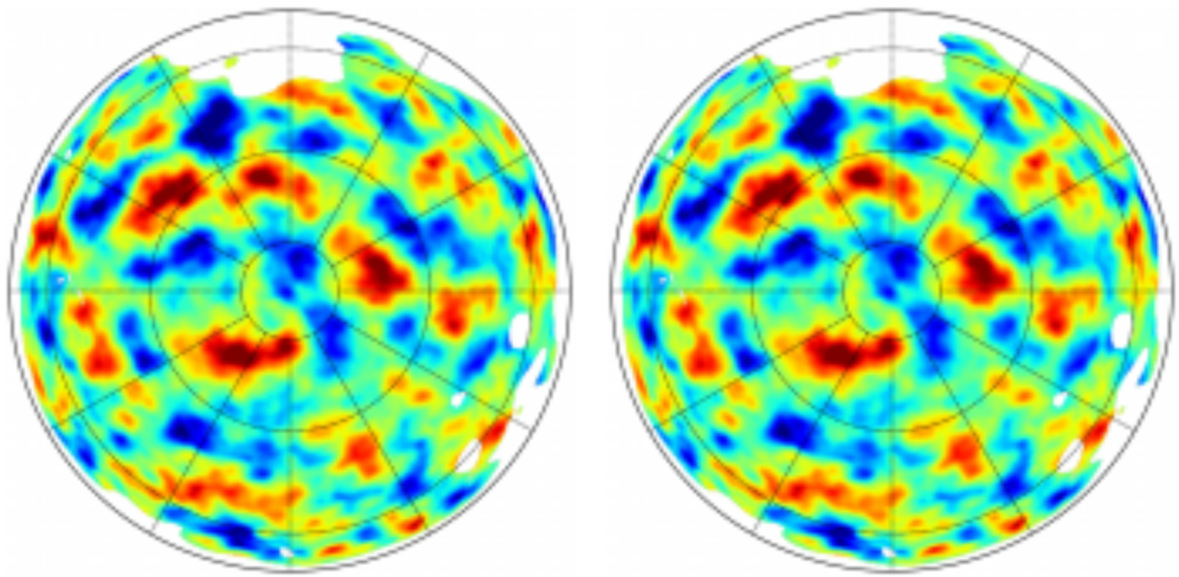
Why CMB Lensing?

- well-known source redshift
- highest source redshift possible (for photons)
- very different systematics from galaxy-based cosmic shear
- wide areas
- lots of good data coming in now

SPT Lensing Mass Map

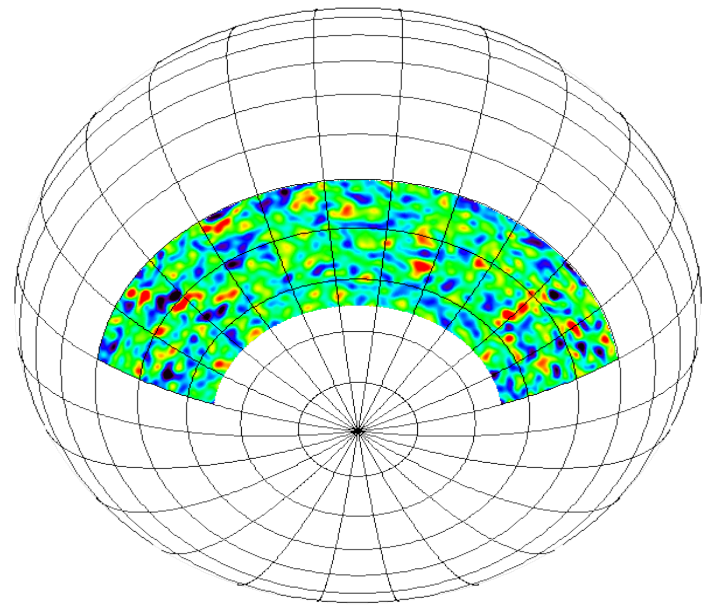


+-0.05 color bar
(noise ~0.01)

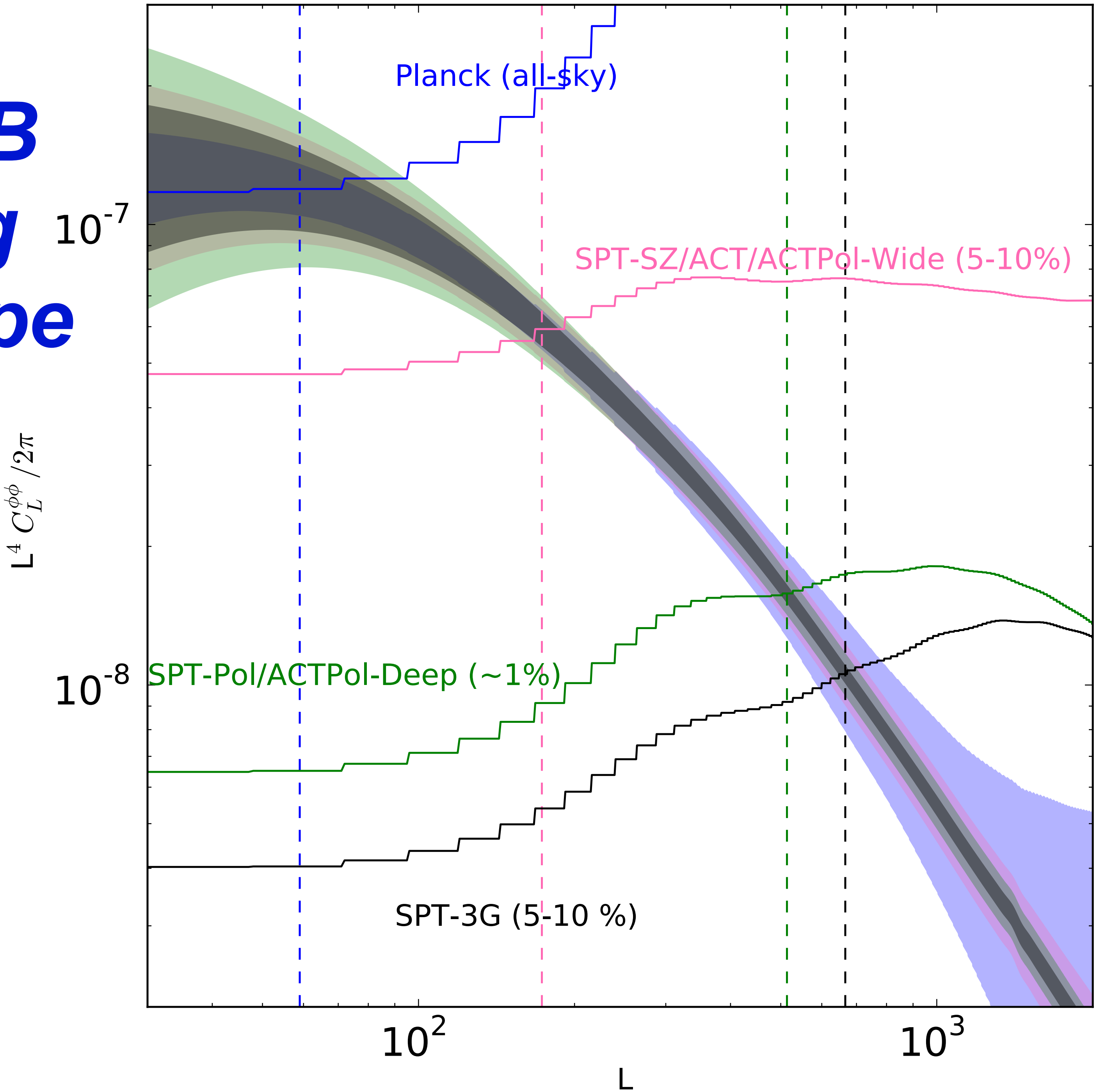


Planck
(all-sky)

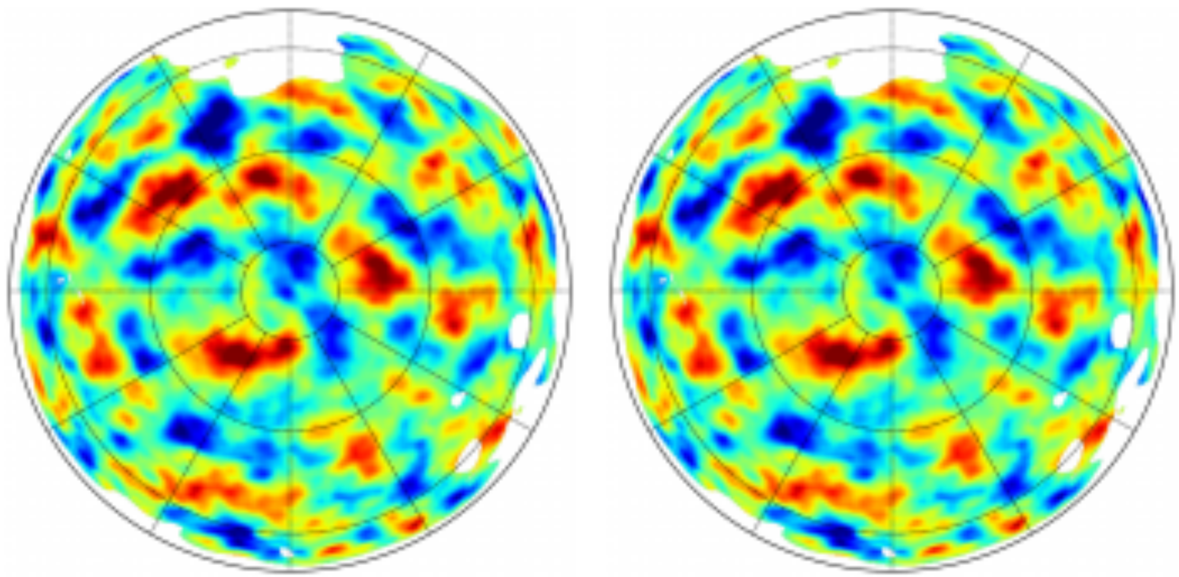
SPT
(2500 sq deg)



The CMB Lensing Landscape



best maps are being made when noise curve is below signal curve



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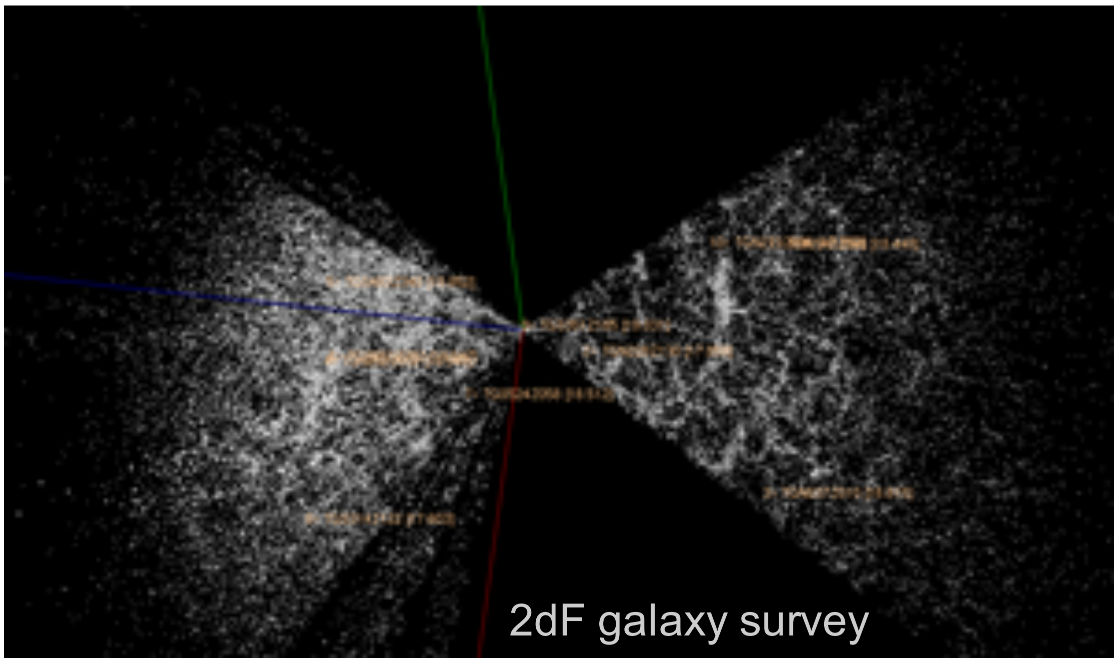
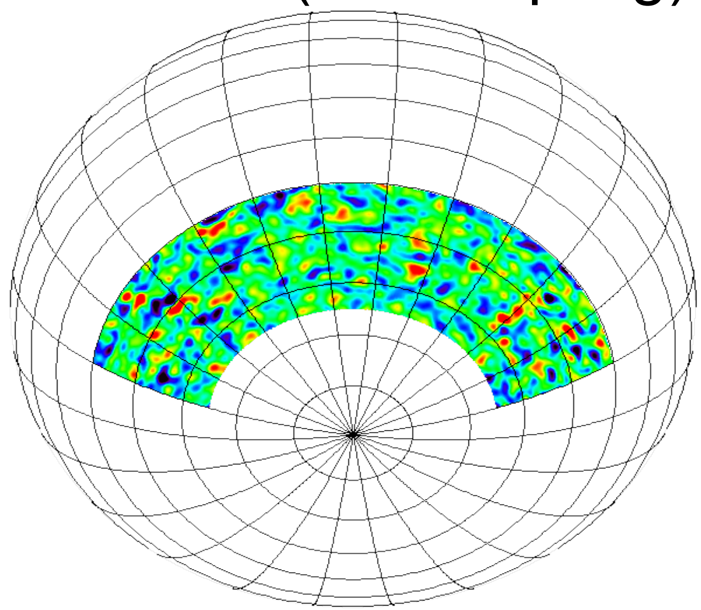
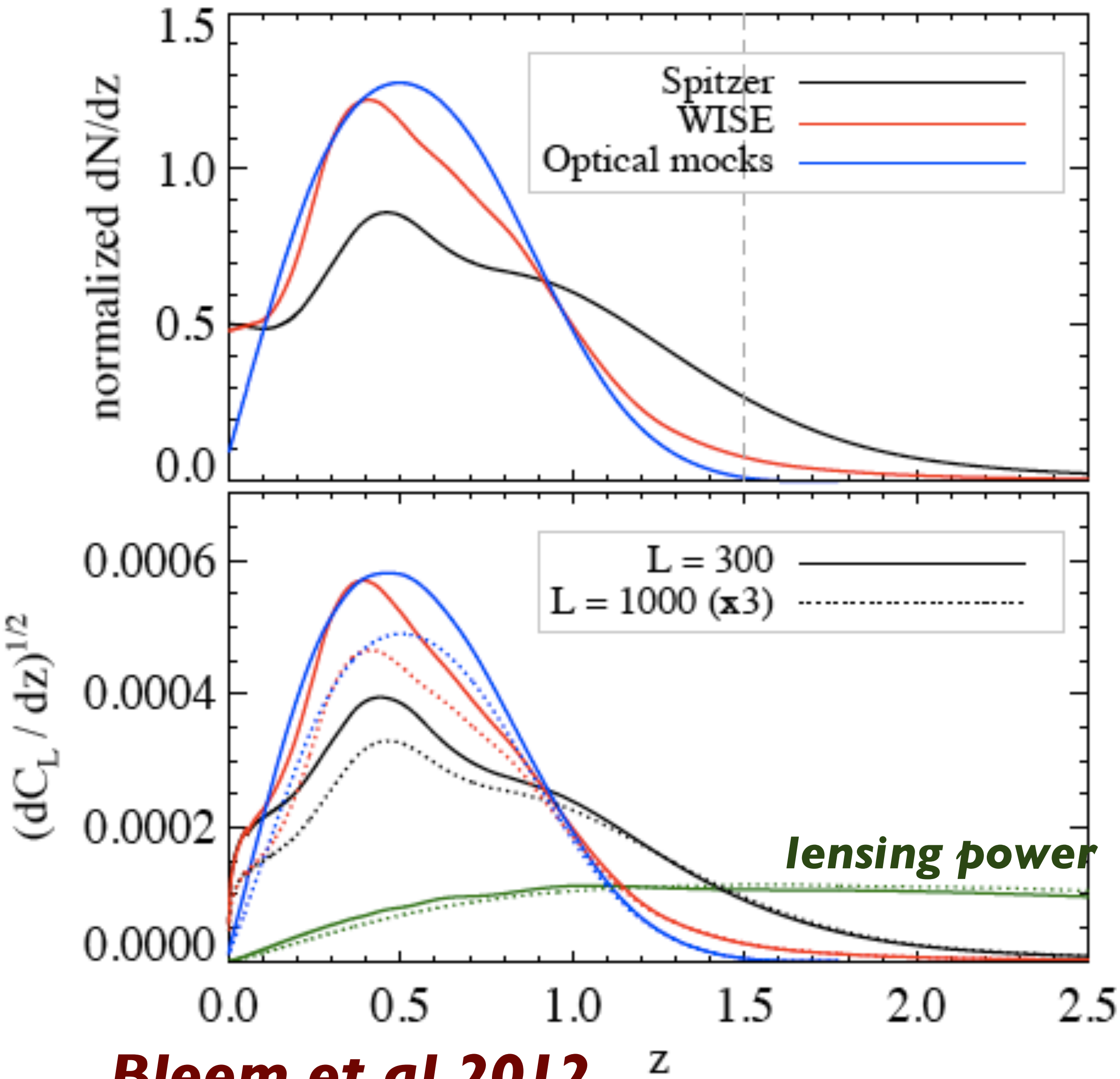




CMB Lensing X Galaxies

CMB lensing power comes from z>0.5, but still plenty of overlap with structure at z~1

(another lensing source screen at z=1100)



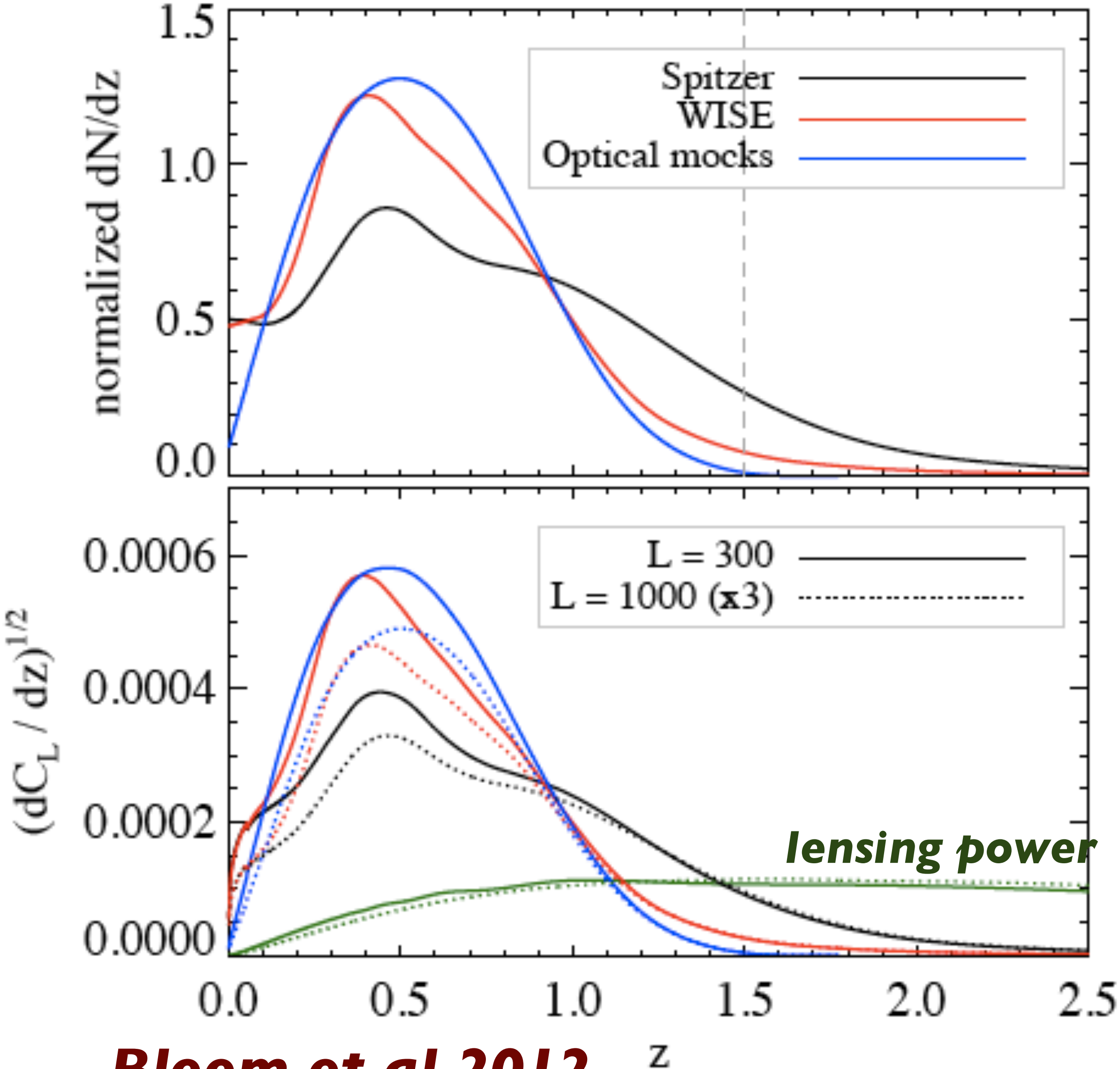
Bleem et al 2012

CMB Lensing X Galaxies

linear bias:

$r_{gal}=br_{matter}$

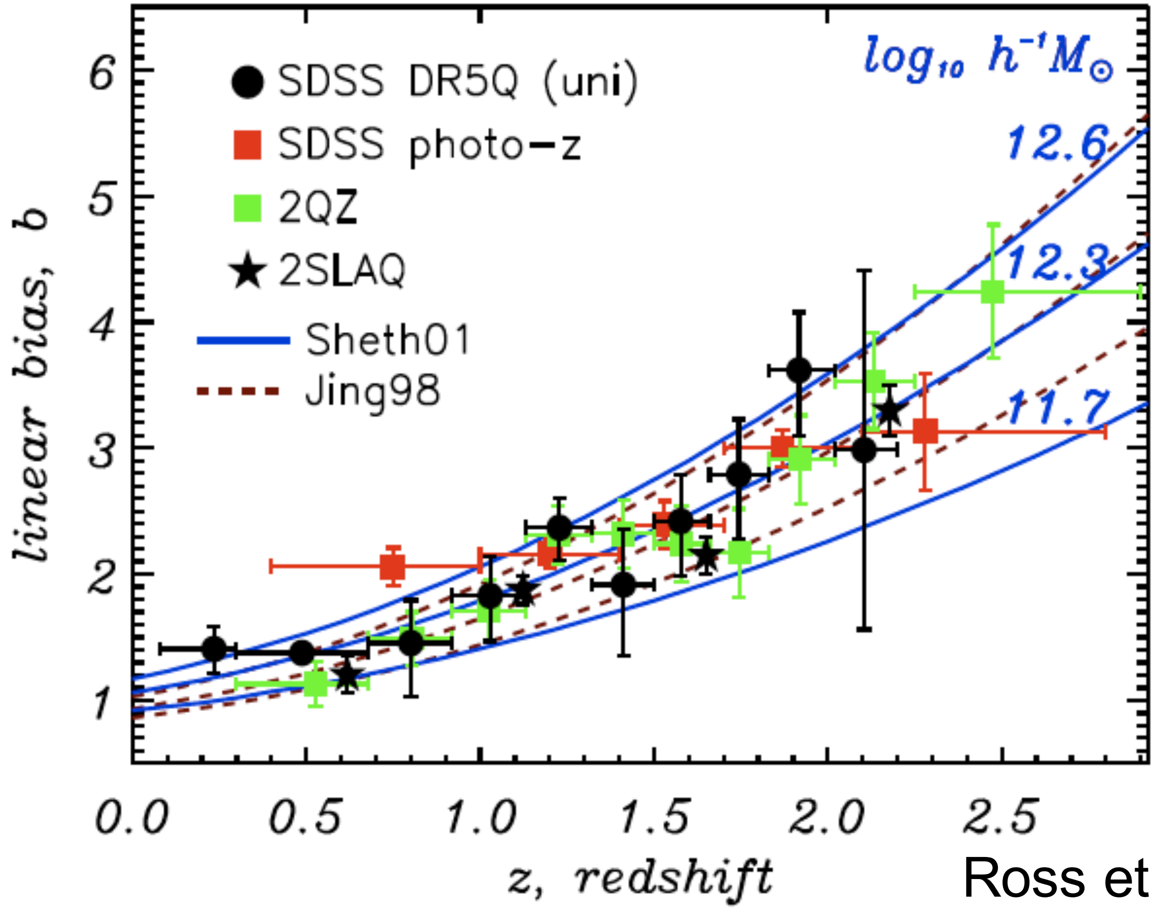
- *Galaxy-galaxy correlation: b^2*
- *Galaxy-lensing correlation: b^1*
- *Lensing-lensing correlation: b^0*



Bleem et al 2012

Measuring Quasar Host Galaxy Masses

- linear bias tells you host galaxy mass in simple halo models

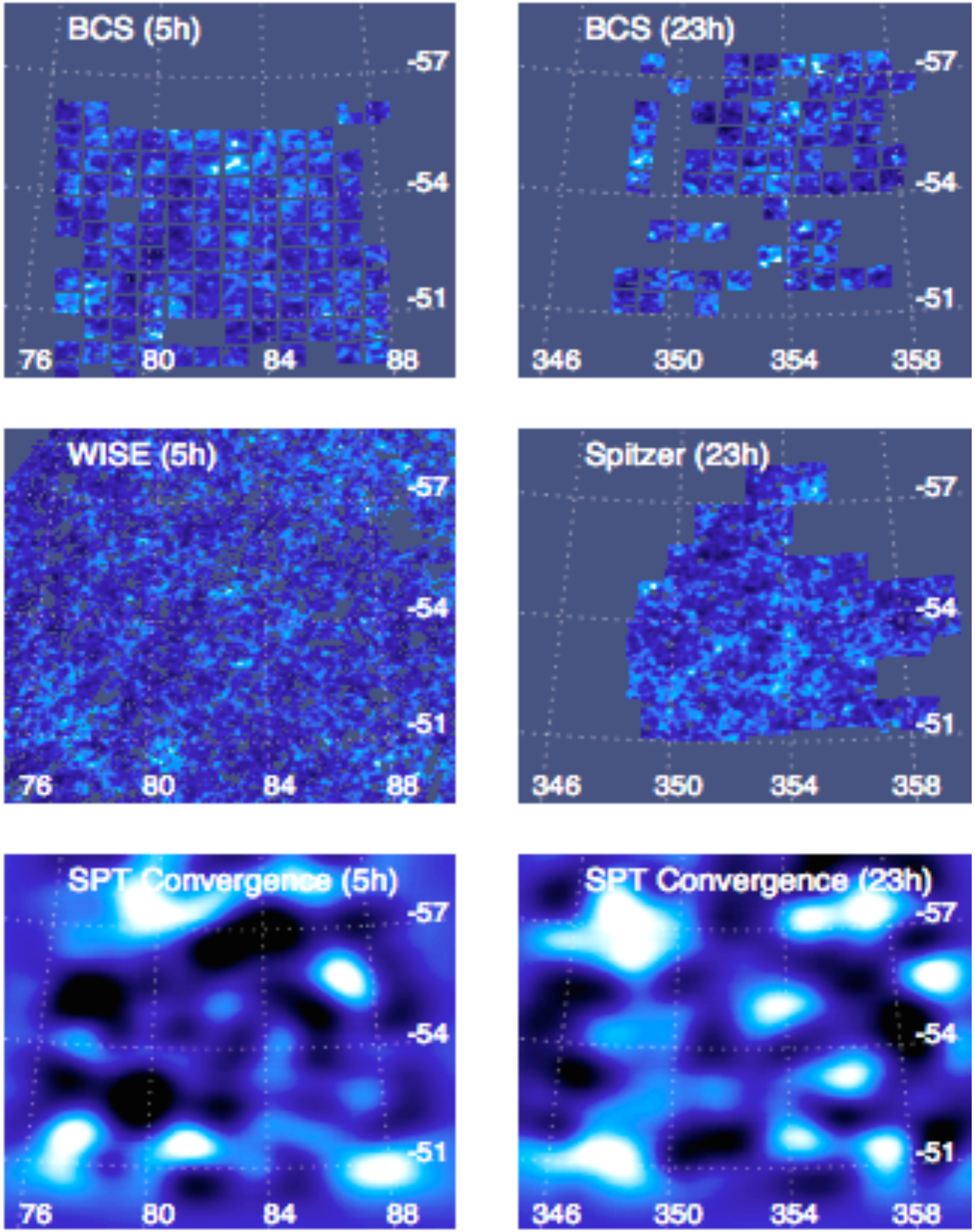


Ross et al 2009

Optical galaxy counts
(19.5<i<22.5)

IR galaxy counts
(15<[3.4]<17 or
(15<[4.5]<17)

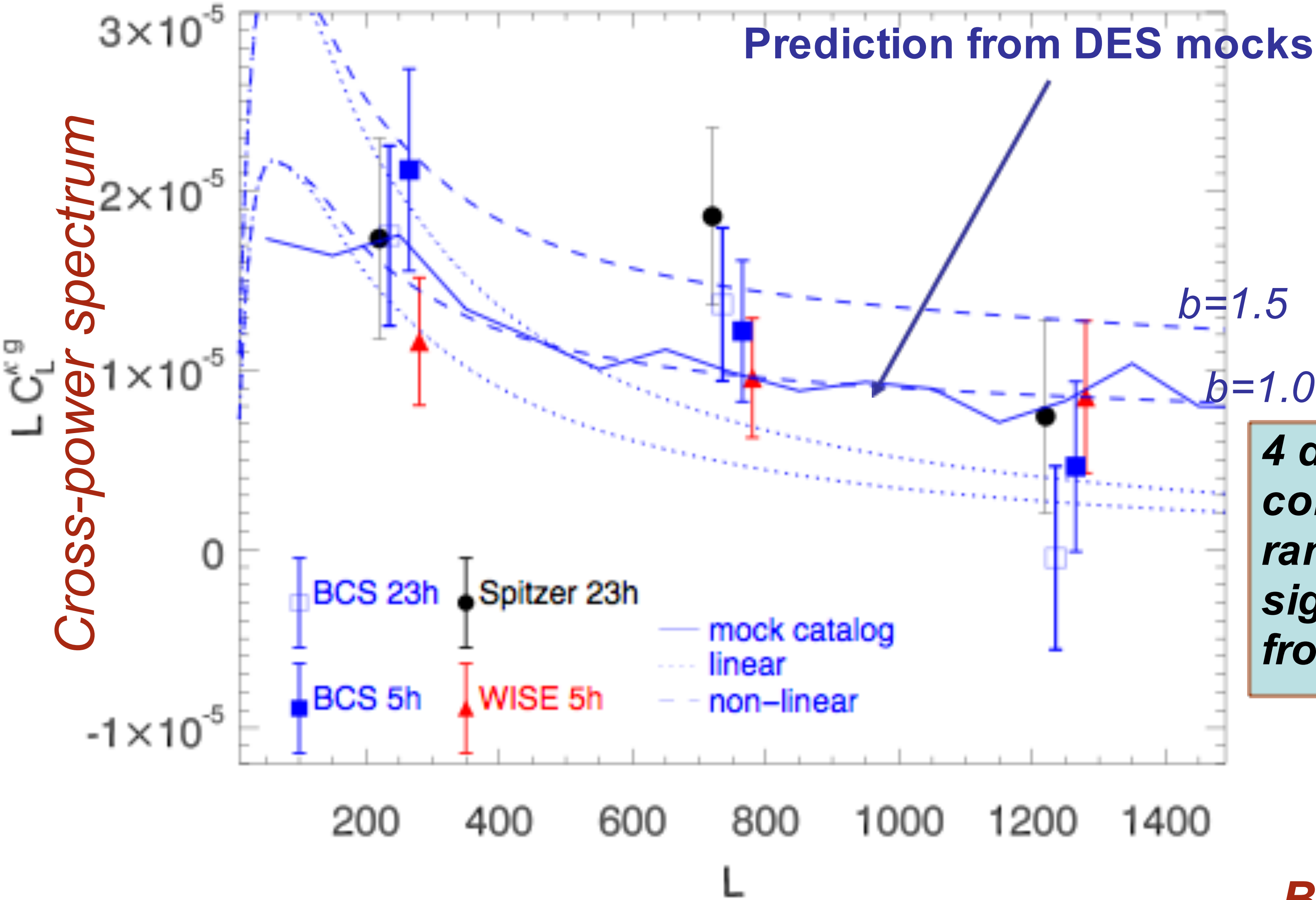
CMB lensing
(smoothed to only show scales with S/N>1)



Using <5% of completed SPT survey

Bleem et al

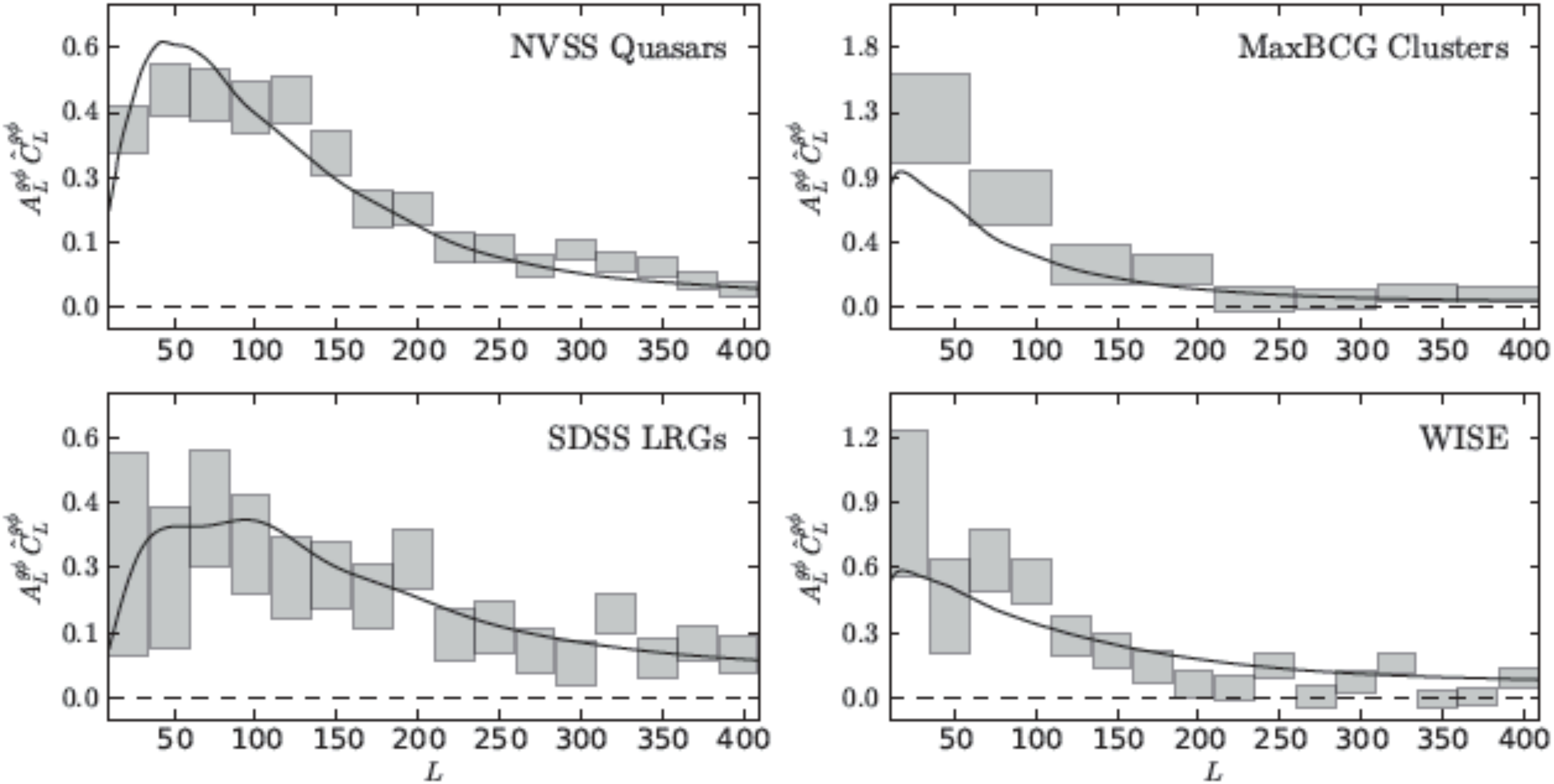
Galaxy-Mass Cross-Correlation Detected



4 different x-correlations, ranging in significance from 4.2-5.4s

Bleem et al

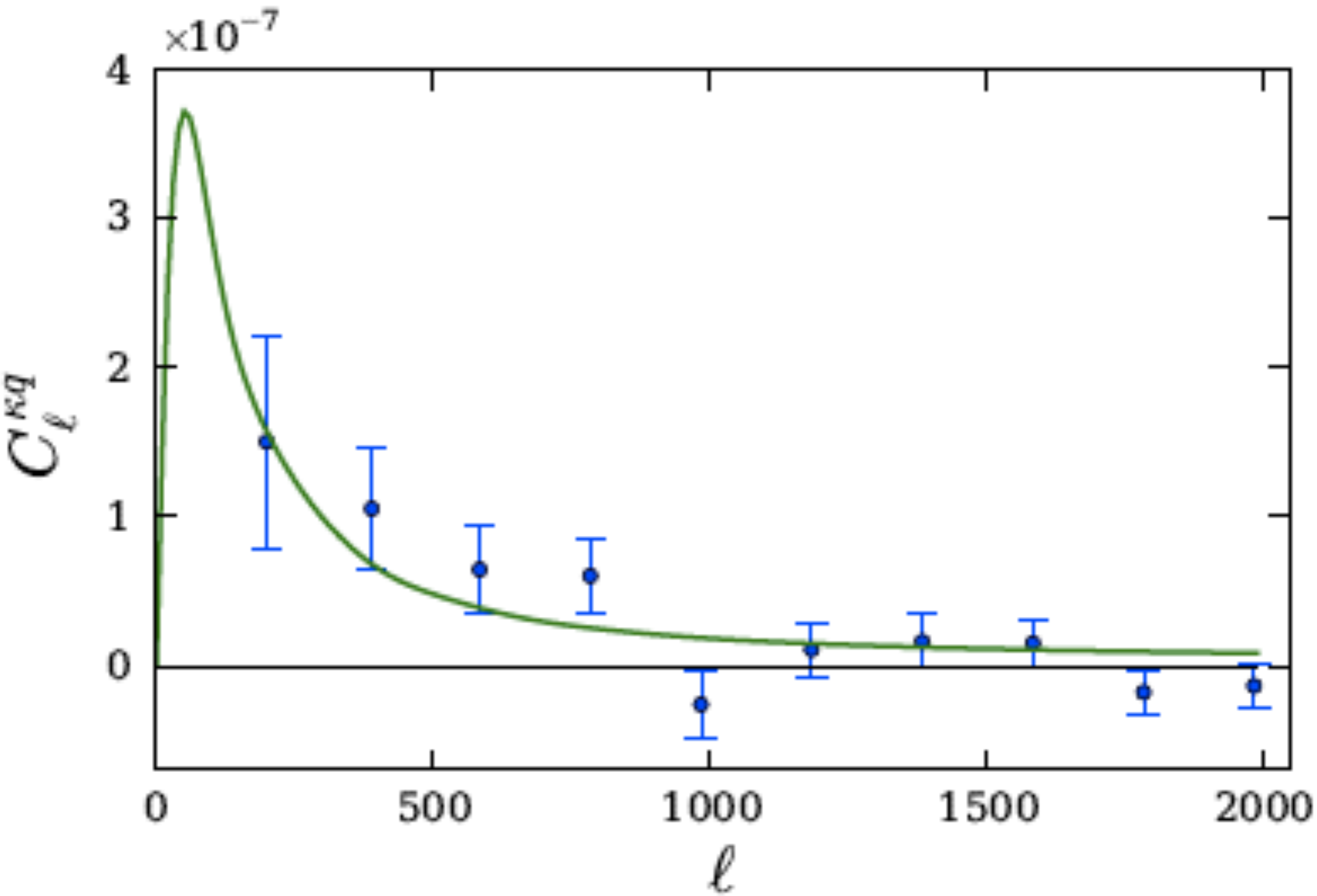
Planck X Galaxies, etc.



Planck 2013-#17

Quasar-Mass Cross-Correlation Detected: ACT X SDSS

Cross-power spectrum

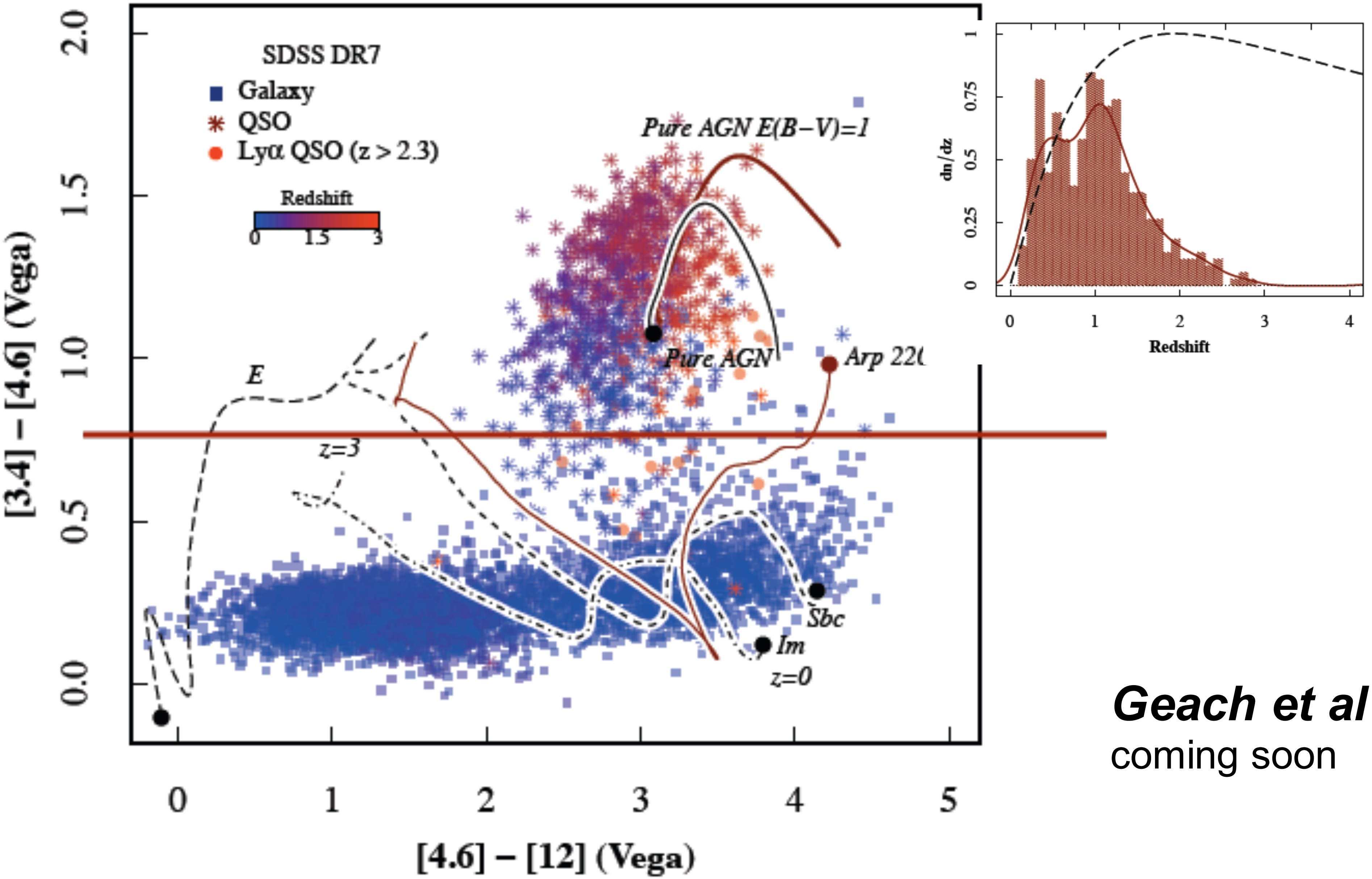


b=2.5±0.6

3.8s in good agreement with expected bias

Sherwin et al 2012

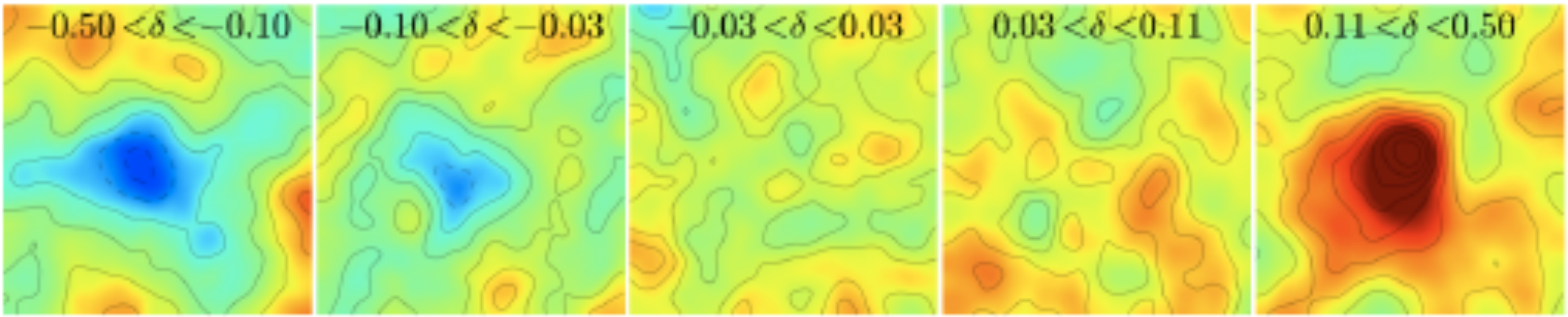
AGN Selection with WISE



Geach et al
coming soon

Quasar-Mass Cross-Correlation Detected: SPT X WISE

stacked SPT lensing map in bins of AGN density



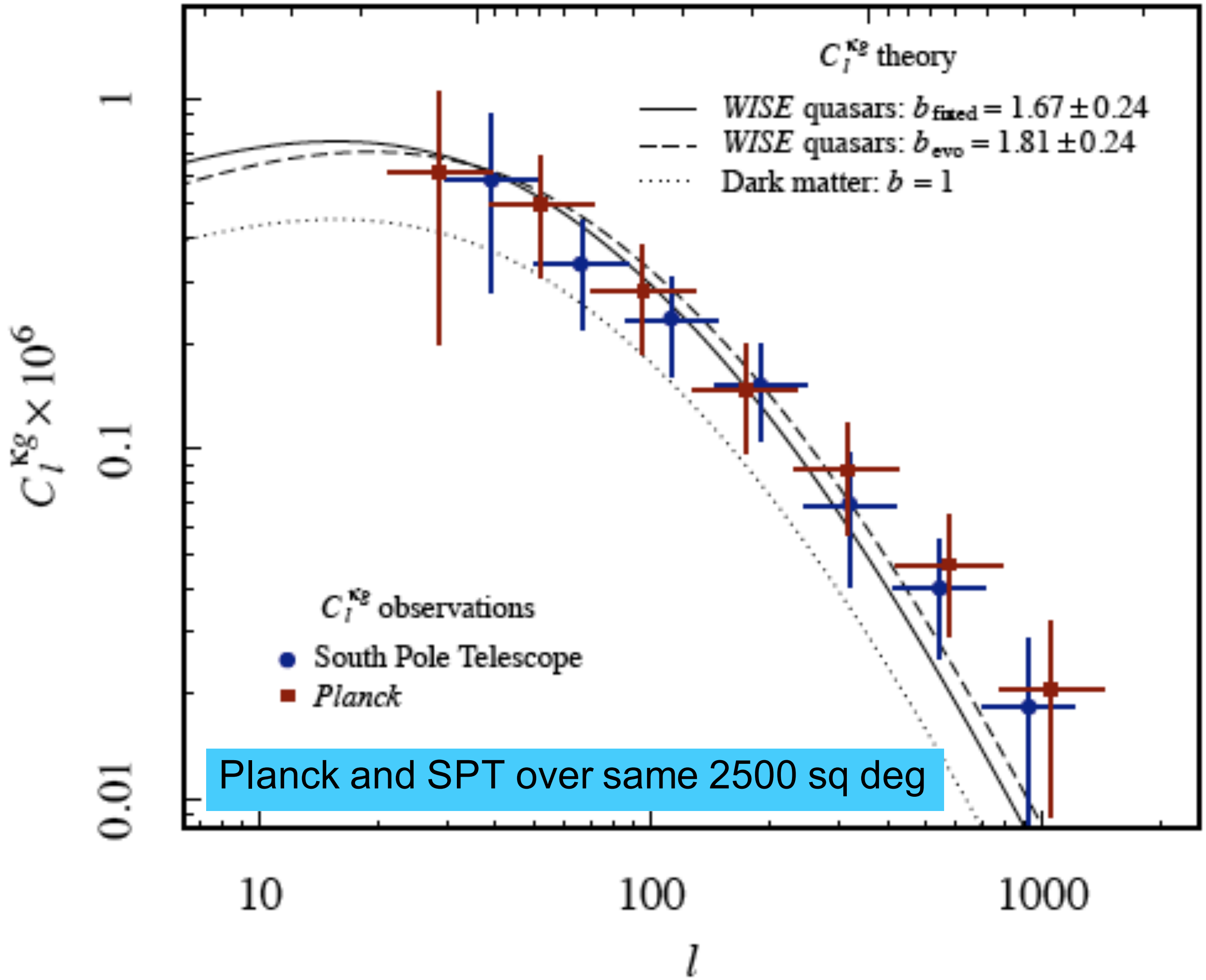
5^o

low AGN density

high AGN density

Geach et al
coming soon

Quasar-Mass Cross-Correlation Detected: SPT X WISE

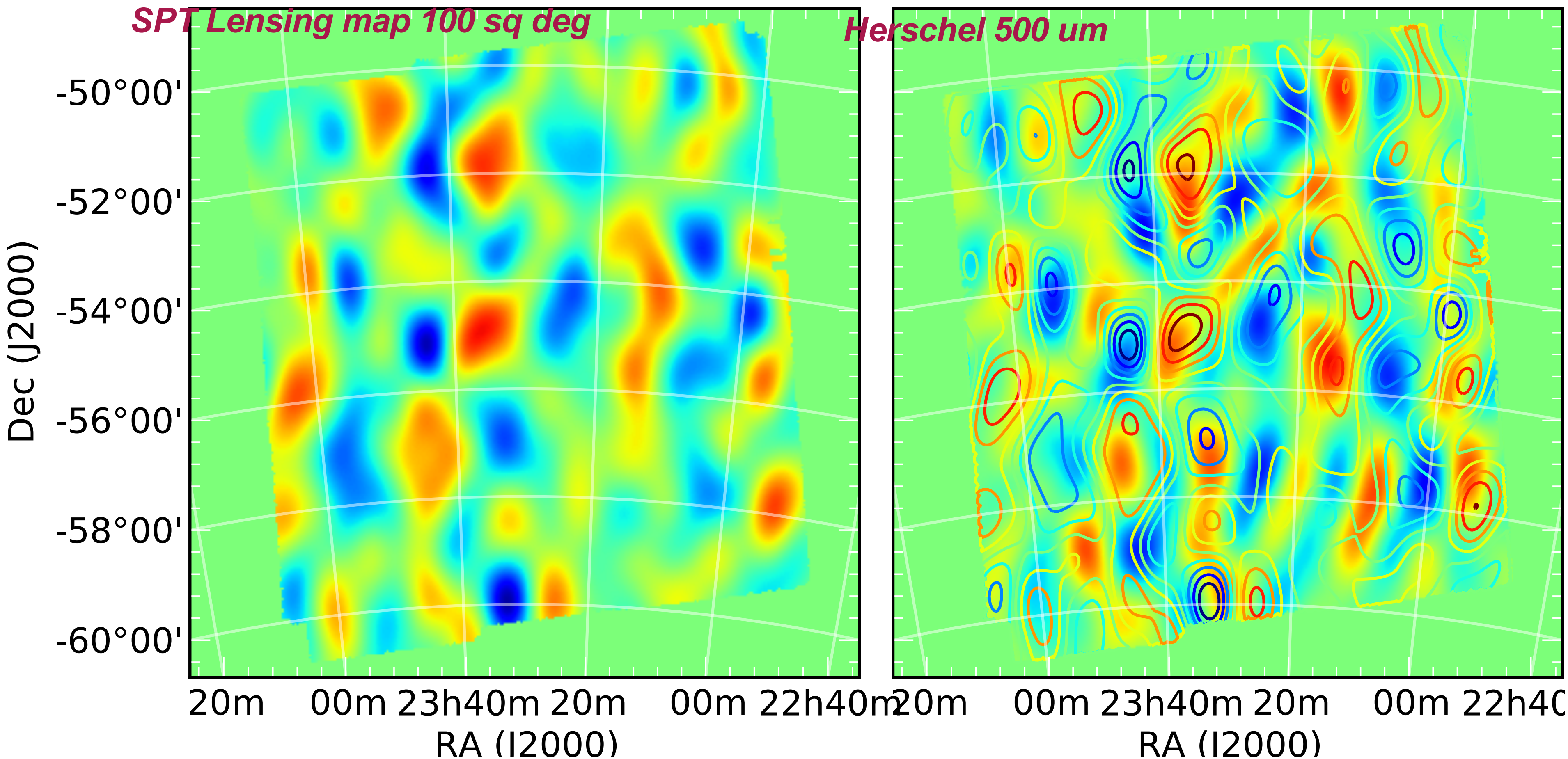


Planck and SPT in excellent agreement

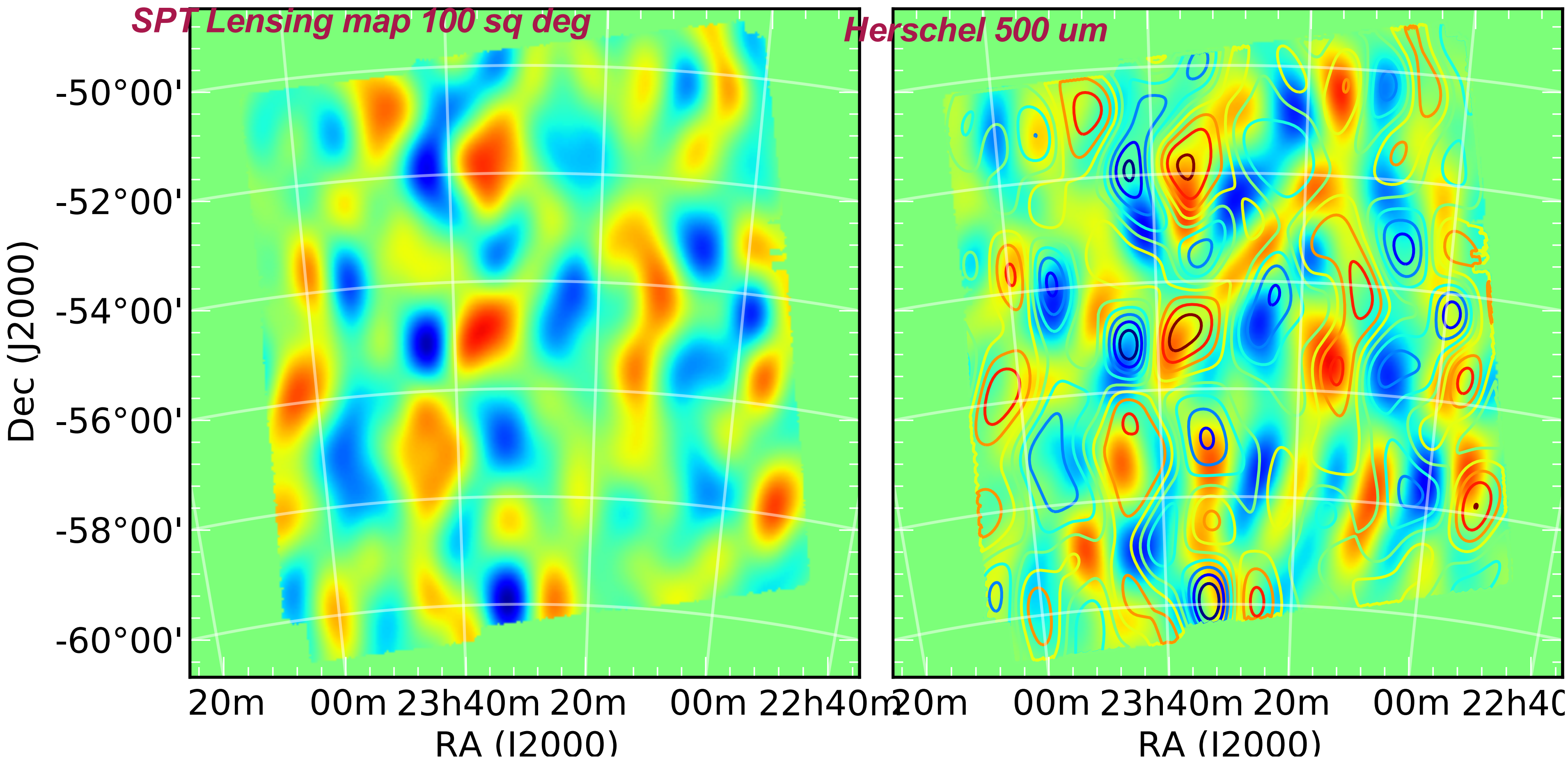
bias measurements agree with expectations

Geach et al
coming soon

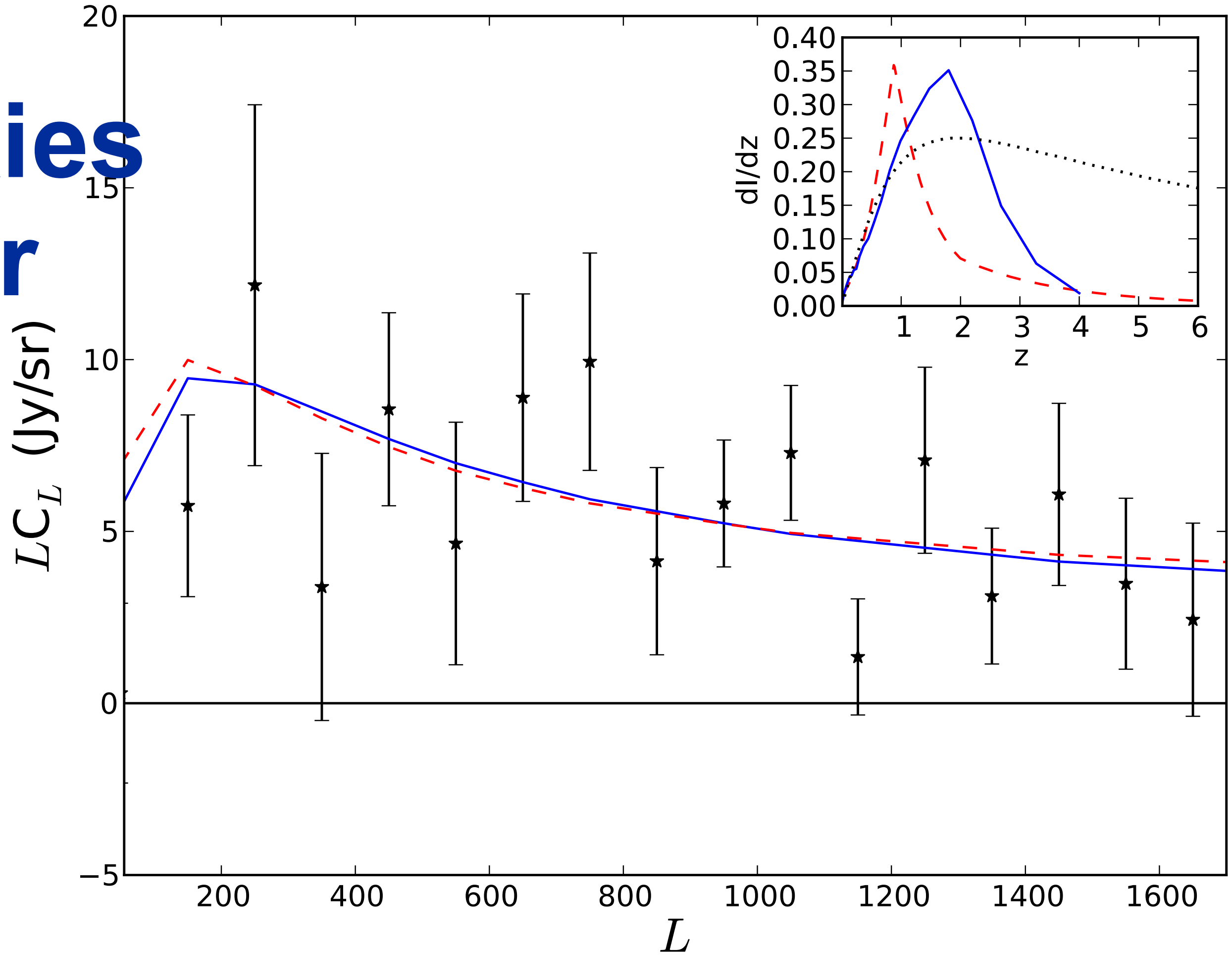
CMB Lensing/Herschel



Light Traces Mass



Lensing/Galaxies Cross-Power Spectrum

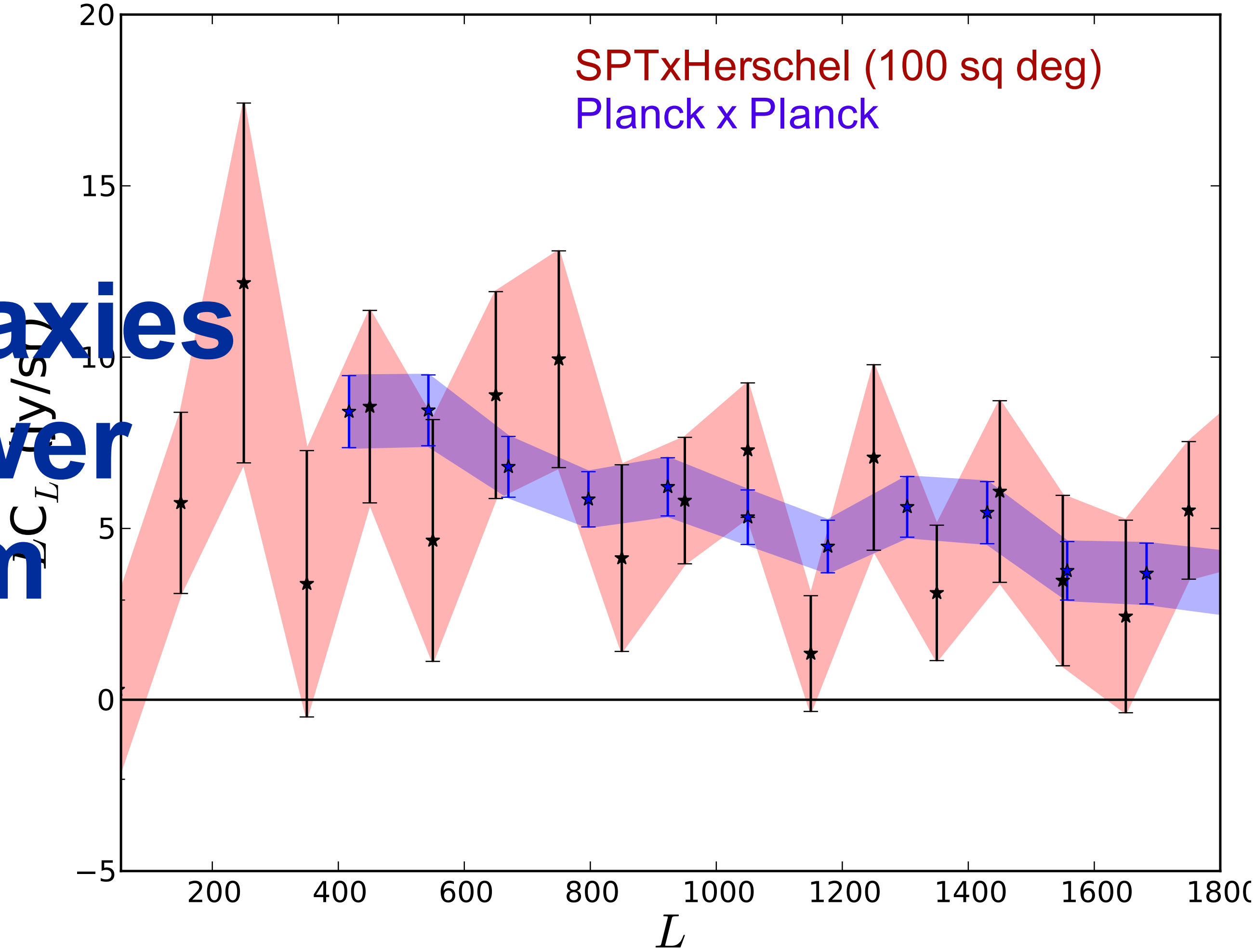


strong detection of correlated structure

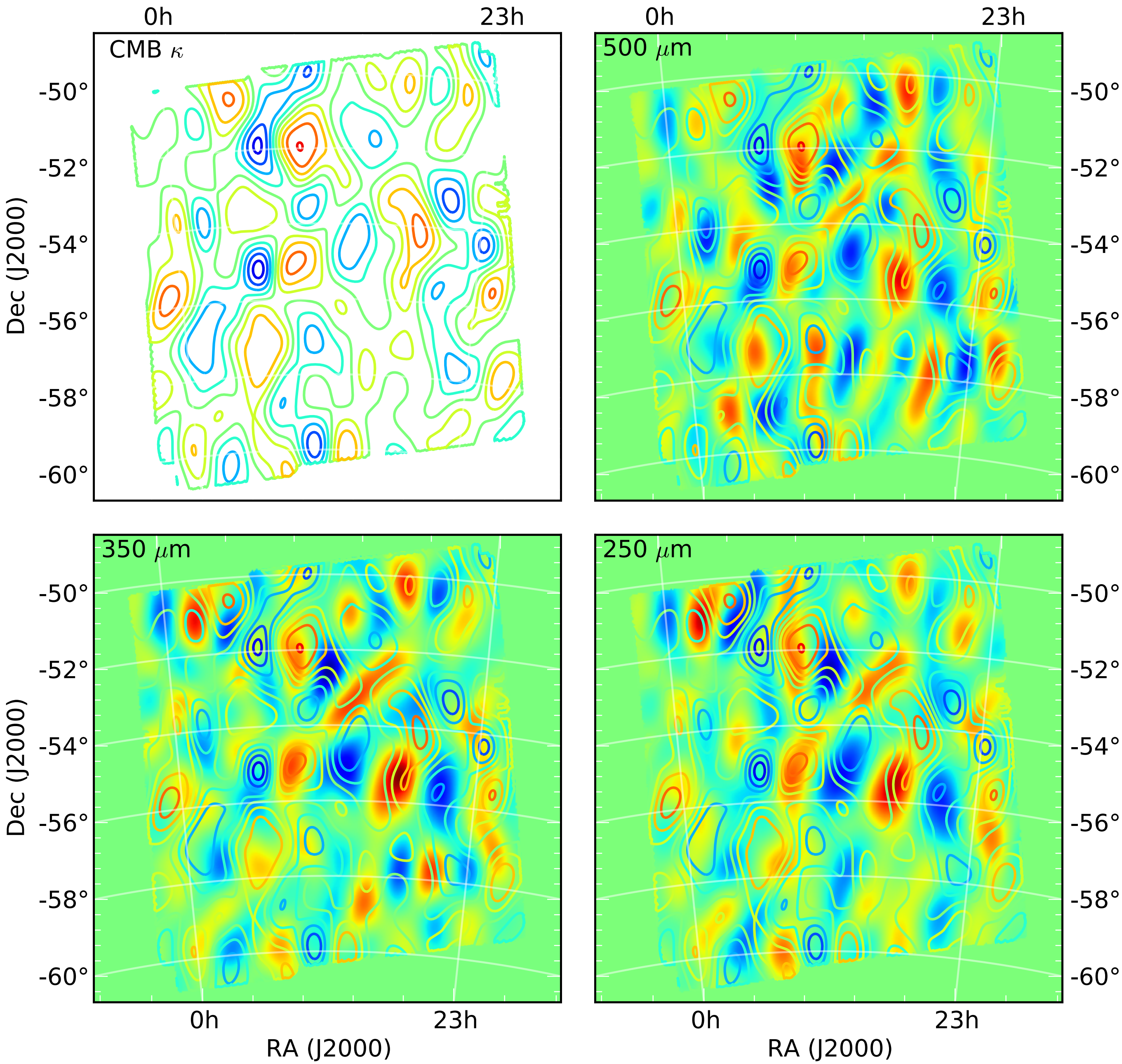
bias relative to non-linear P(k):
b=1.3-1.8,
depending on assumed dI/dz

Holder et al

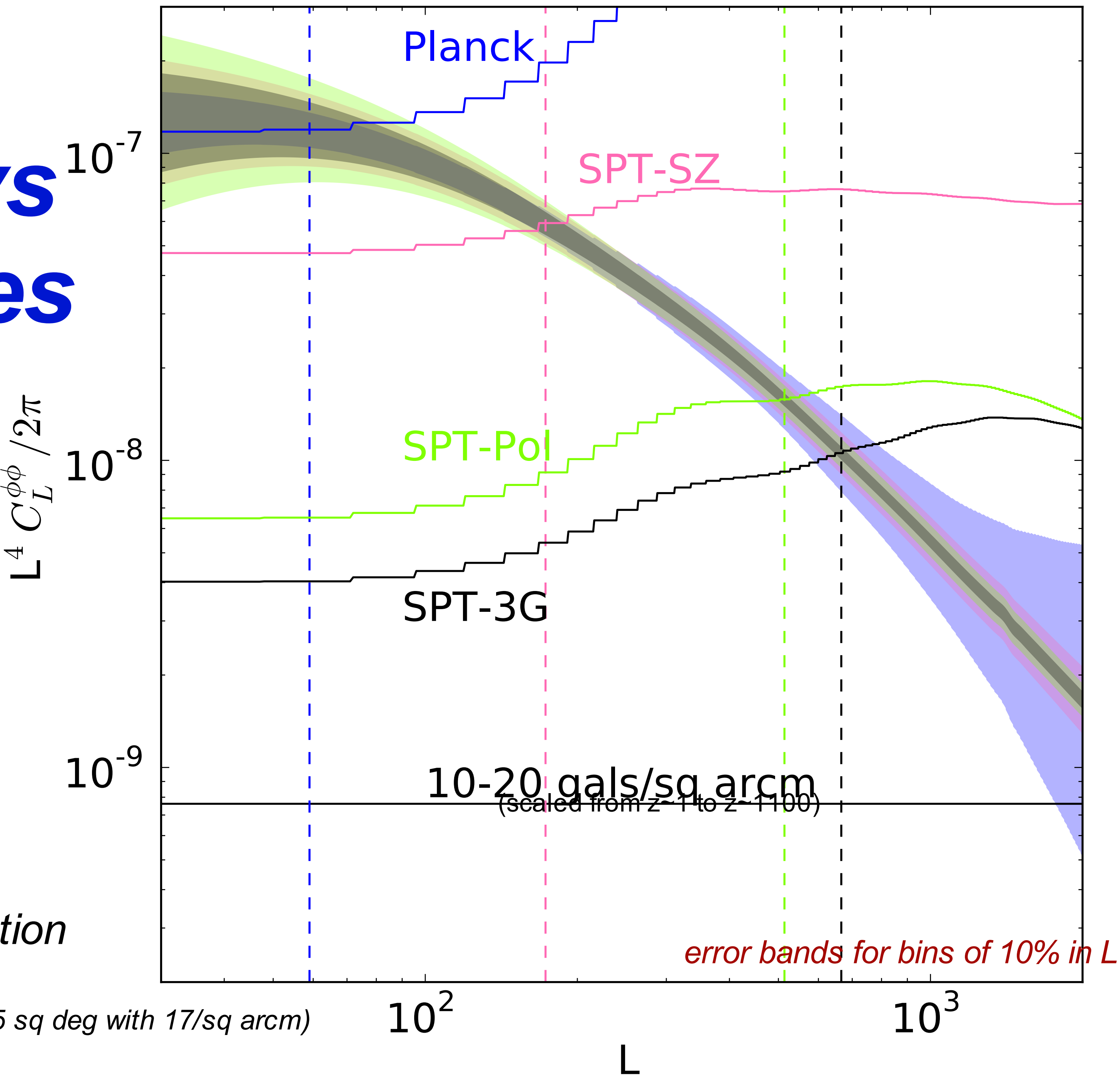
Lensing/Galaxies Cross-Power Spectrum



CMB Lensing/Herschel



CMB vs Galaxies

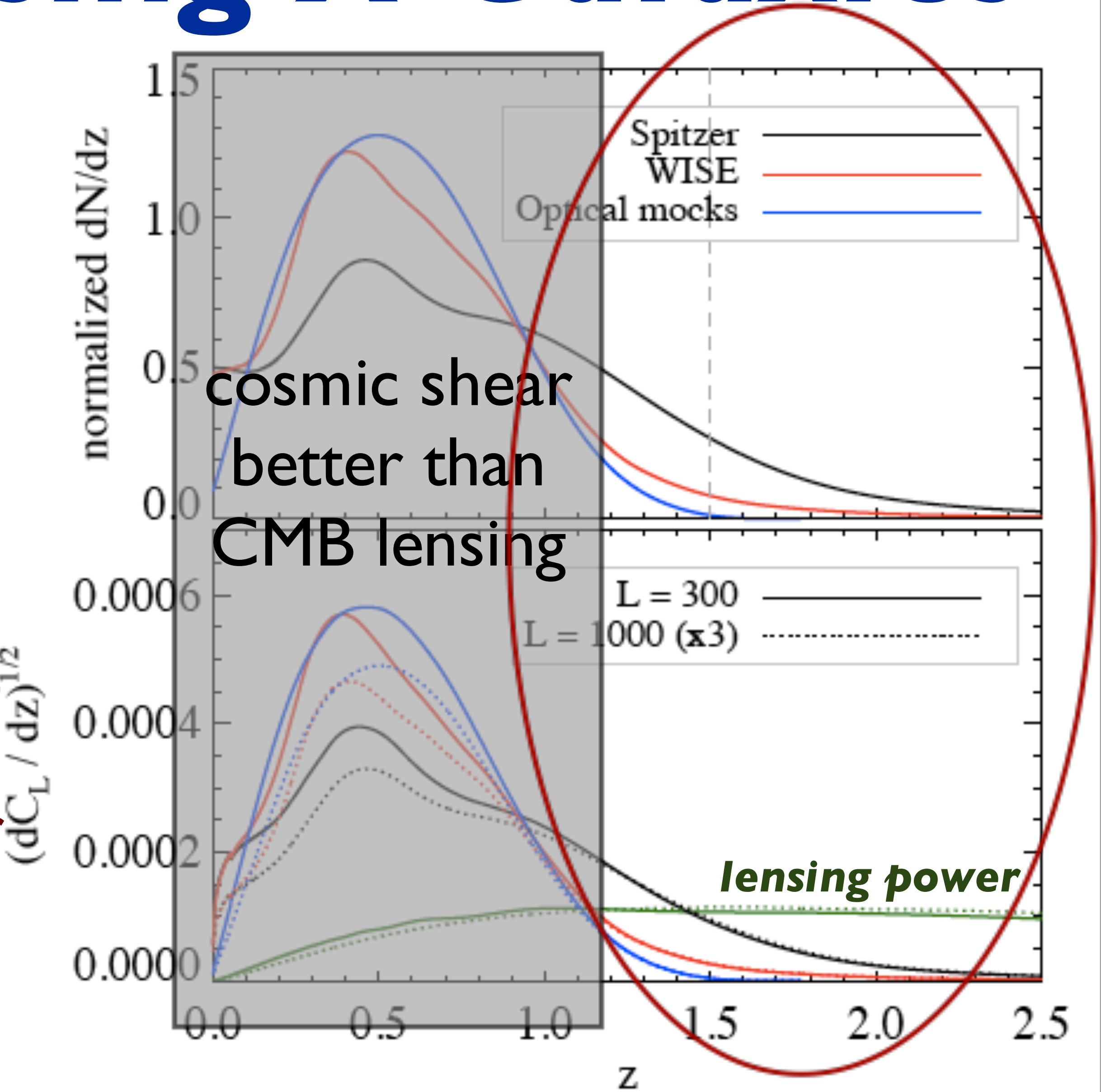


cosmic shear also has redshift information

(e.g., CFHTLens has155 sq deg with 17/sq arcm)

CMB Lensing X Galaxies

- cosmic shear good at lower z (z~1.5?)
- galaxy auto-spectra are also very useful
  - we “know” s_8 at % level, so autospectrum good enough to measure simple linear bias
- CMB lensing is unique at higher z
- we can use cosmic shear to clean out low z structure



Summary

CMB lensing is being measured

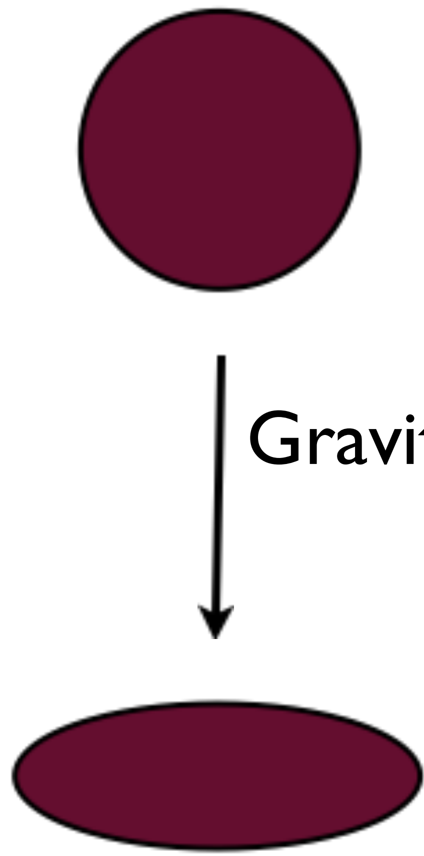
strong cross-correlation with LSS

independent measures of galaxy bias

lots more to come

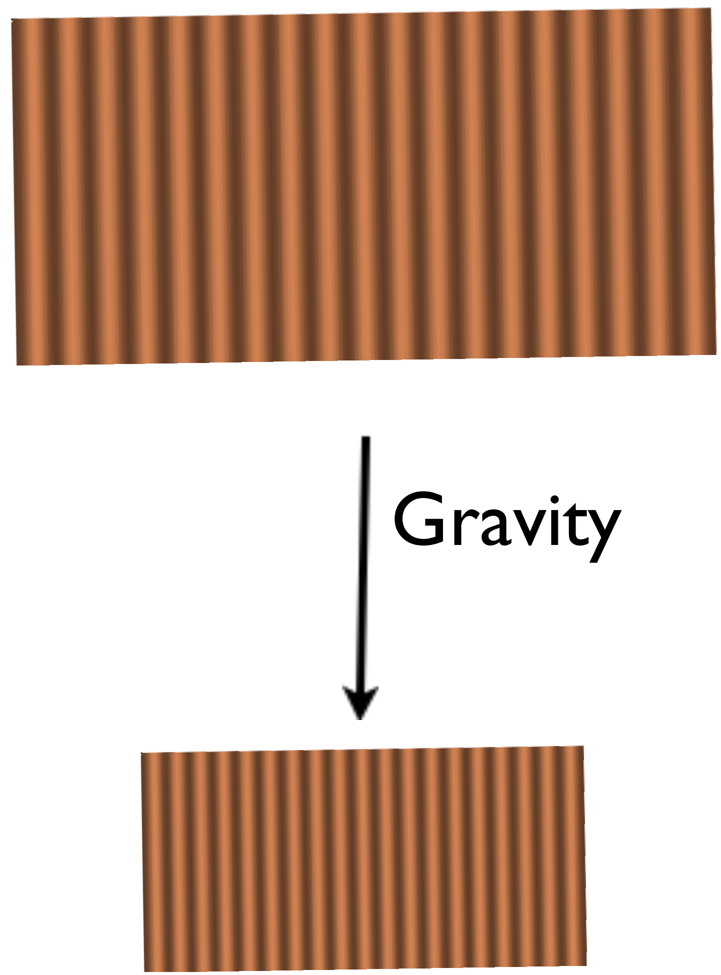
Lensing simplified

- gravitational potentials distort shapes by stretching, squeezing, shearing

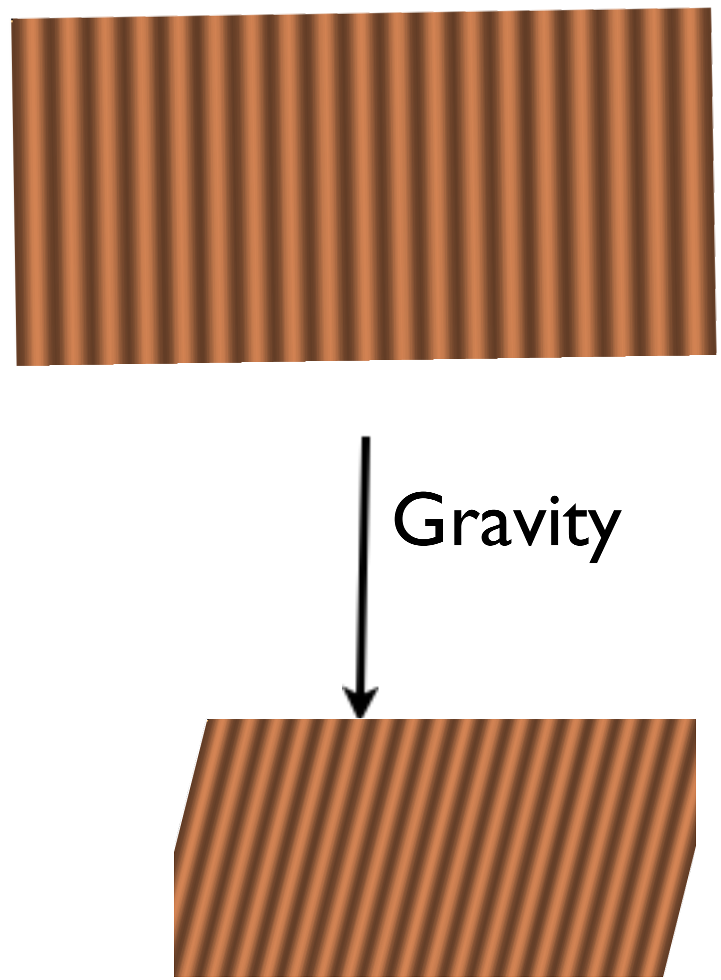


Lensing simplified

- where gravity stretches, gradients become smaller
- where gravity compresses, gradients are larger



Lensing simplified



- where gravity stretches, gradients become smaller
- where gravity compresses, gradients are larger
- shear changes ***direction***

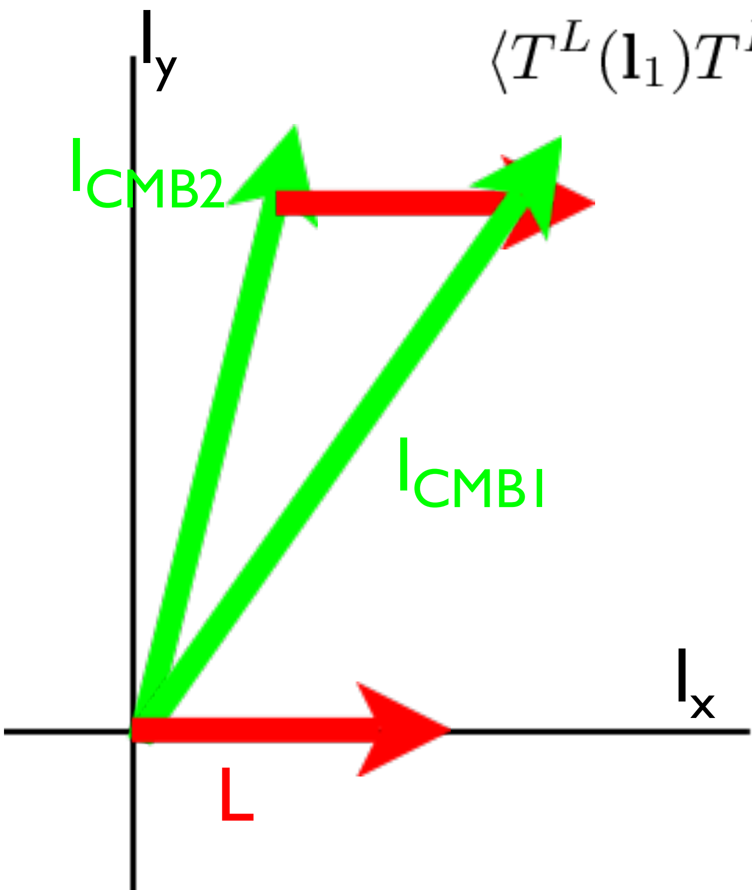
Mode Coupling from Lensing

$$
\begin{aligned}
T^L(\hat{\mathbf{n}}) &= T^U(\hat{\mathbf{n}} + \nabla\phi(\hat{\mathbf{n}})) \\
&= T^U(\hat{\mathbf{n}}) + \nabla T^U(\hat{\mathbf{n}}) \cdot \nabla\phi(\hat{\mathbf{n}}) + O(\phi^2),
\end{aligned}
$$

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

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

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



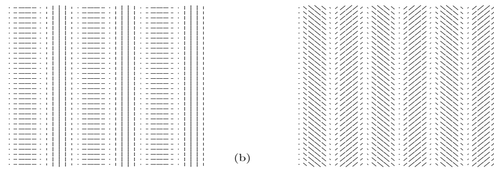
- We extract ϕ by taking a suitable average over CMB multipoles separated by a distance L

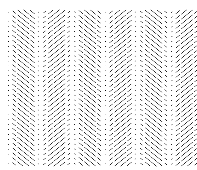
- We use the Hu quadratic estimator.

E-modes/B-modes

E modes

- E-modes vary spatially parallel or perpedicular to polarization direction
- B-modes vary spatially at 45 degrees
- CMB
  - scalar perturbations only generate *only* E

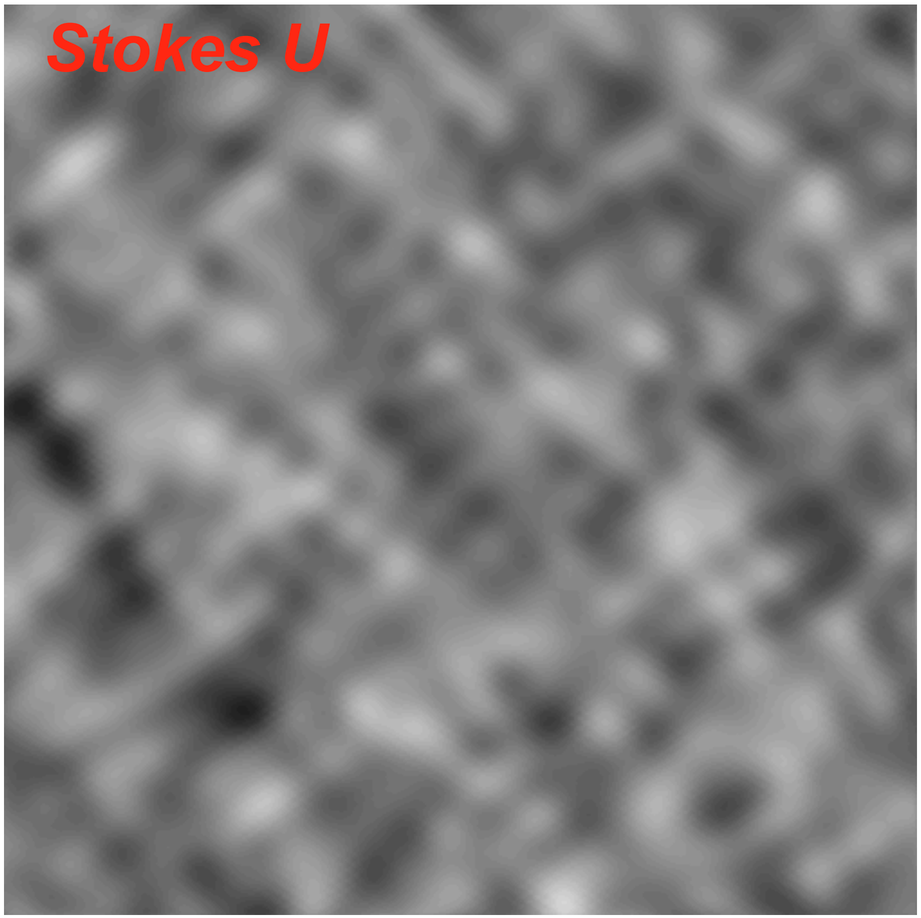


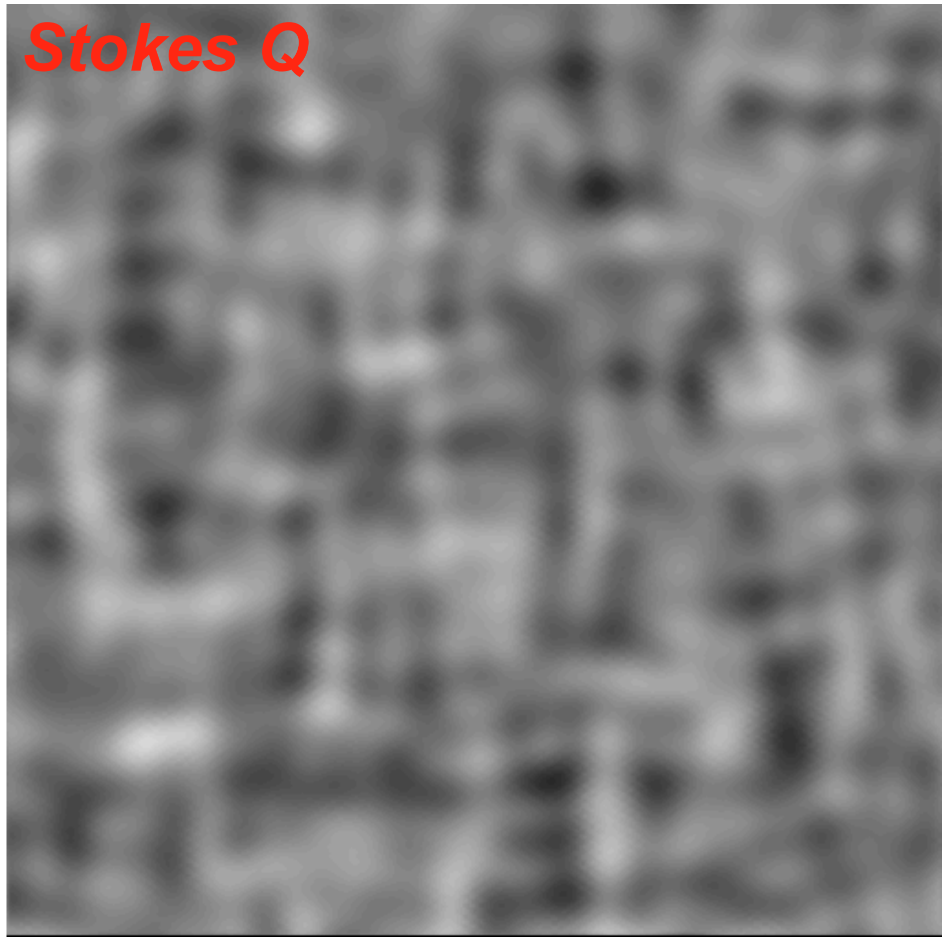


B modes

Bunn

Simulated Polarized CMB Maps





E-modes/B-modes

- E-modes vary spatially parallel or perpedicular to polarization direction
- B-modes vary spatially at 45 degrees
- CMB
    - scalar perturbations only generate *only* E
- ***Lensing of CMB is much more obvious in polarization!***

E modes

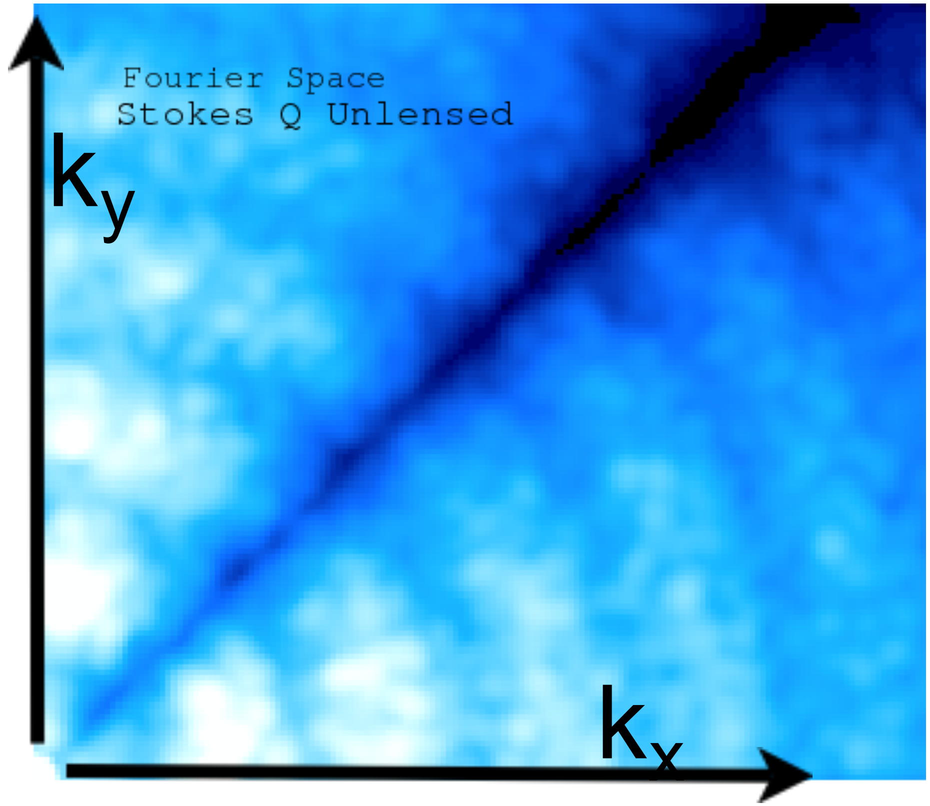


Image of positive kx/positive ky Fourier transform of a 10x10 deg chunk of Stokes Q CMB map [simulated; nothing clever done to it]