Gravitational Lensing of the CMB:

Mass Maps, Power Spectra, and B-modes with the South Pole Telescope

Gil Holder

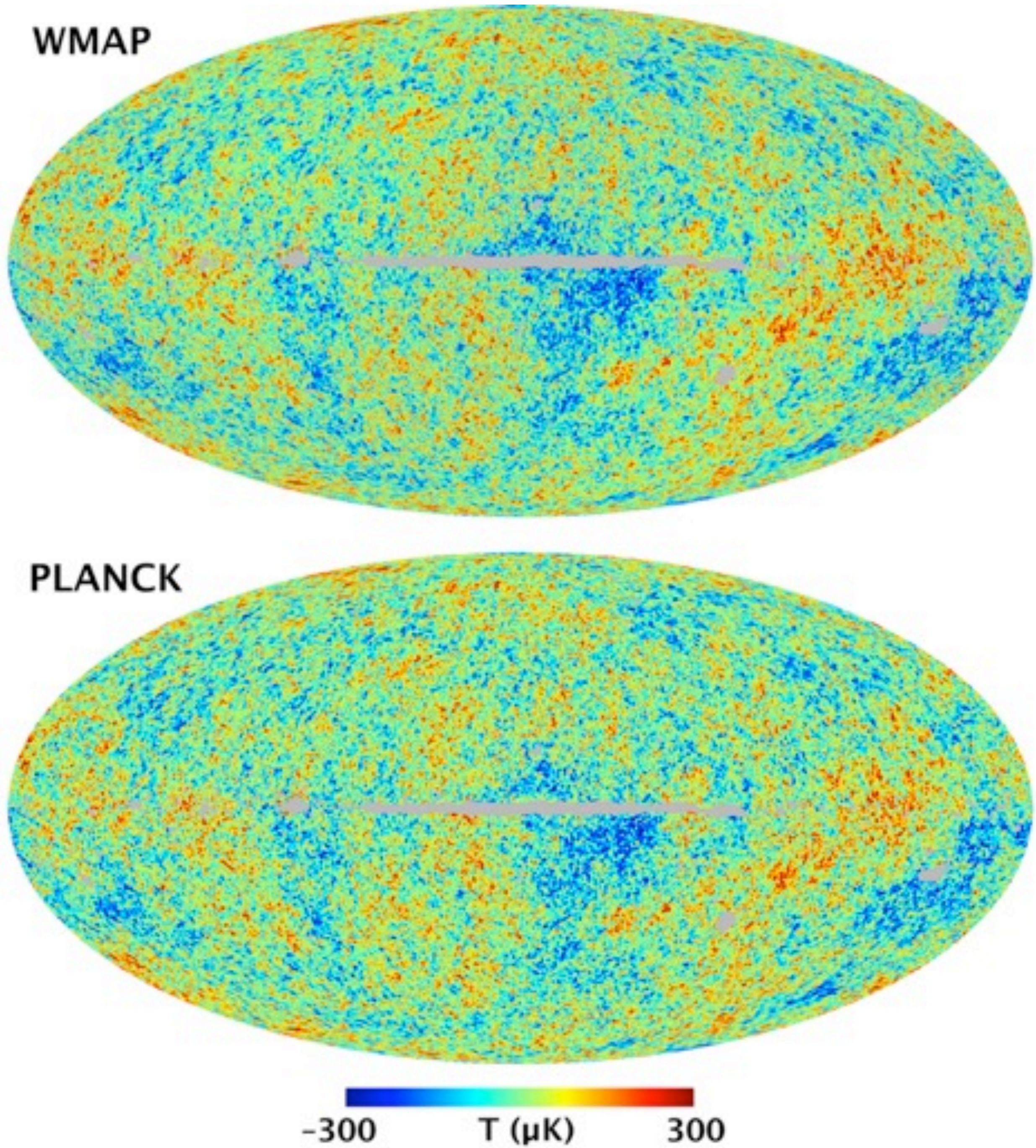
McGill

CIFAR
CANADIAN INSTITUTE for ADVANCED RESEARCH

as part of:
SPT collaboration

Outline

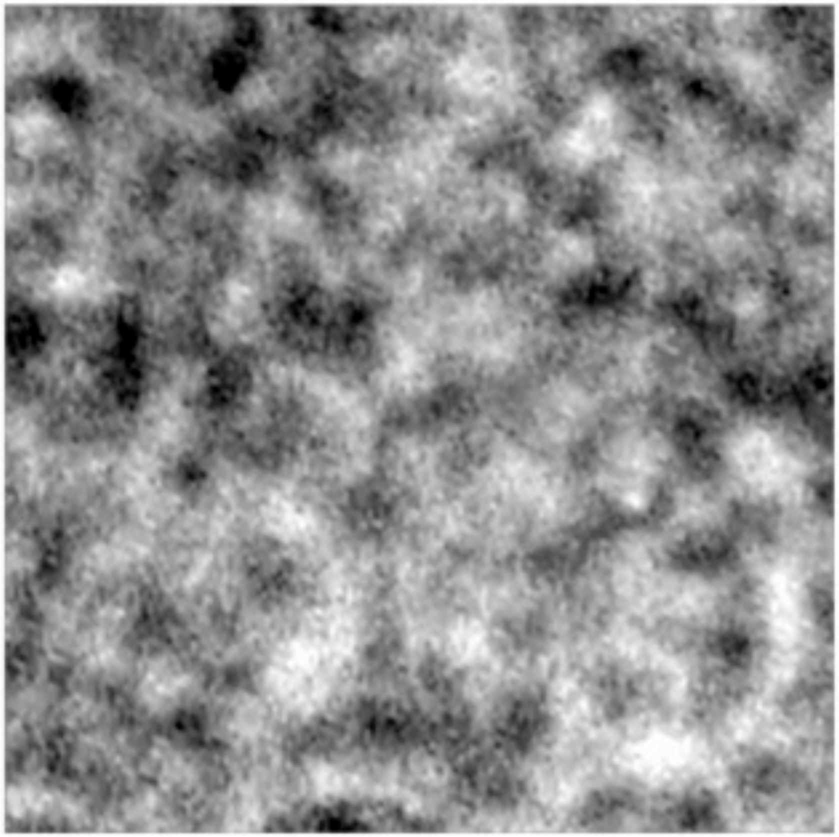
- CMB gravitational lensing overview
- lensing power spectra
- mass maps and cross-correlations
- first detection of “B-modes”



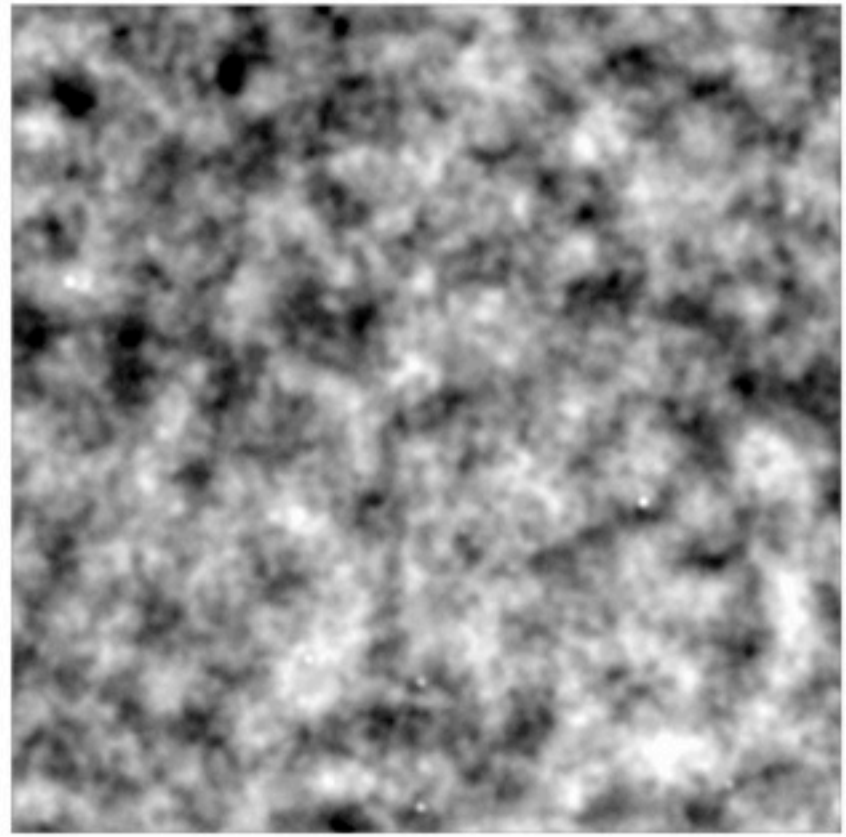
WMAP
PLANCK
-300
T (μK)
300

Planck has higher resolution than WMAP

WMAP 60 GHz



Planck 143 GHz



16^{o}

South Pole Telescope

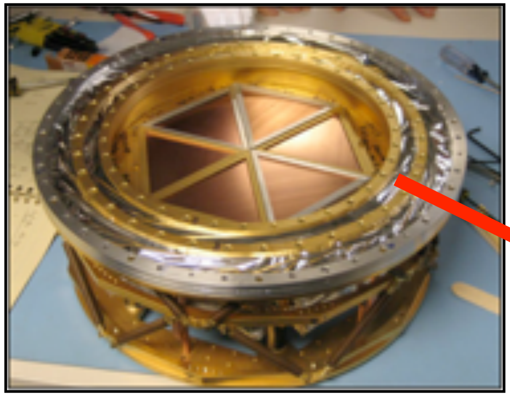
10 m mm-wave (3 different wavelengths) telescope at the south pole

- extremely dry
- very stable
- good support

Chicago Colorado
UC Berkeley Case Western
McGill Harvard
UC Davis Munich +++

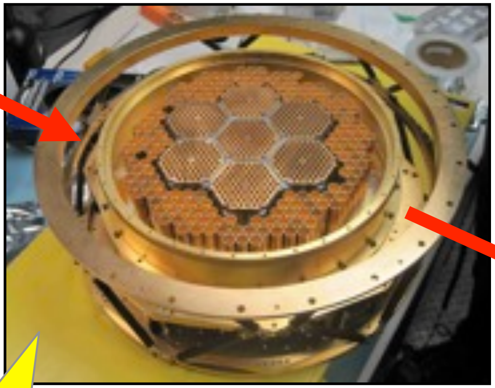
The evolution of SPT cameras

2007-2011: SPT
960 detectors



2500 sq deg
completed

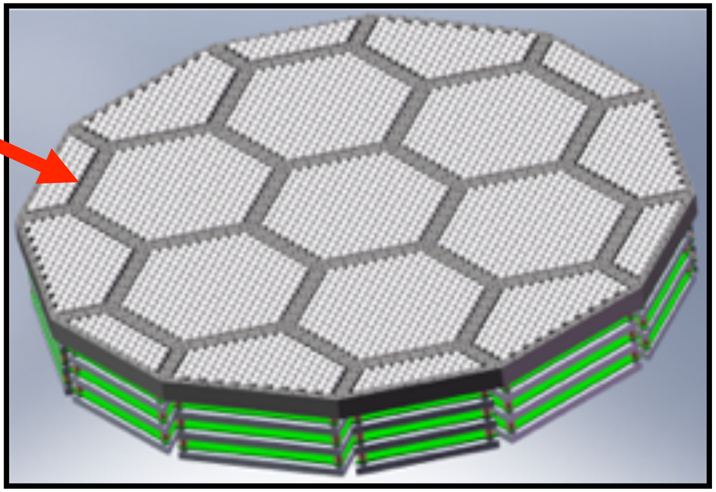
2012-2015: SPTpol
~1600 detectors



100 sq deg completed
600 sq deg expected

Now with polarization!

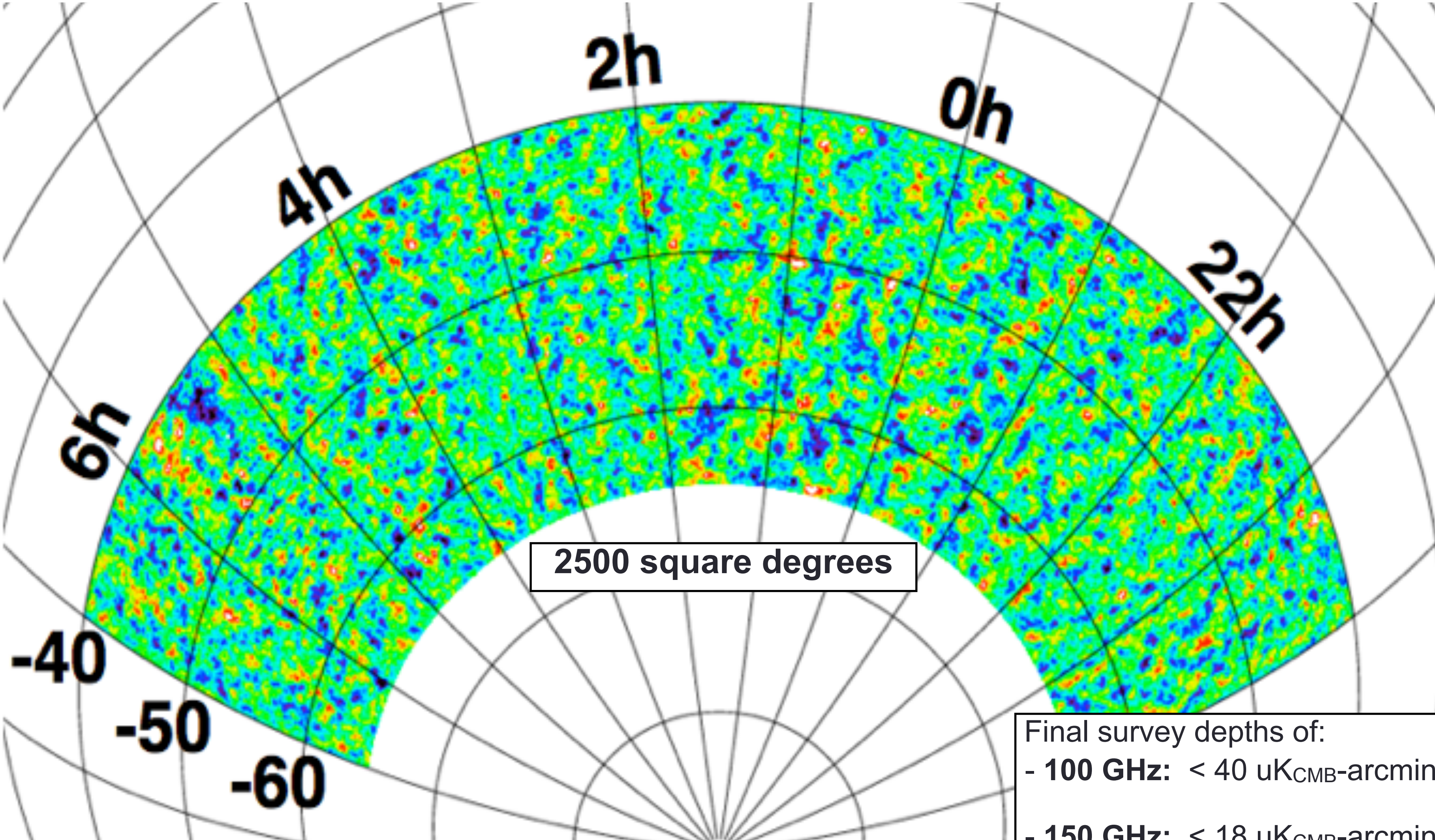
2016: SPT-3G
~15,200 detectors



2500 sq deg expected

slide from S Hoover

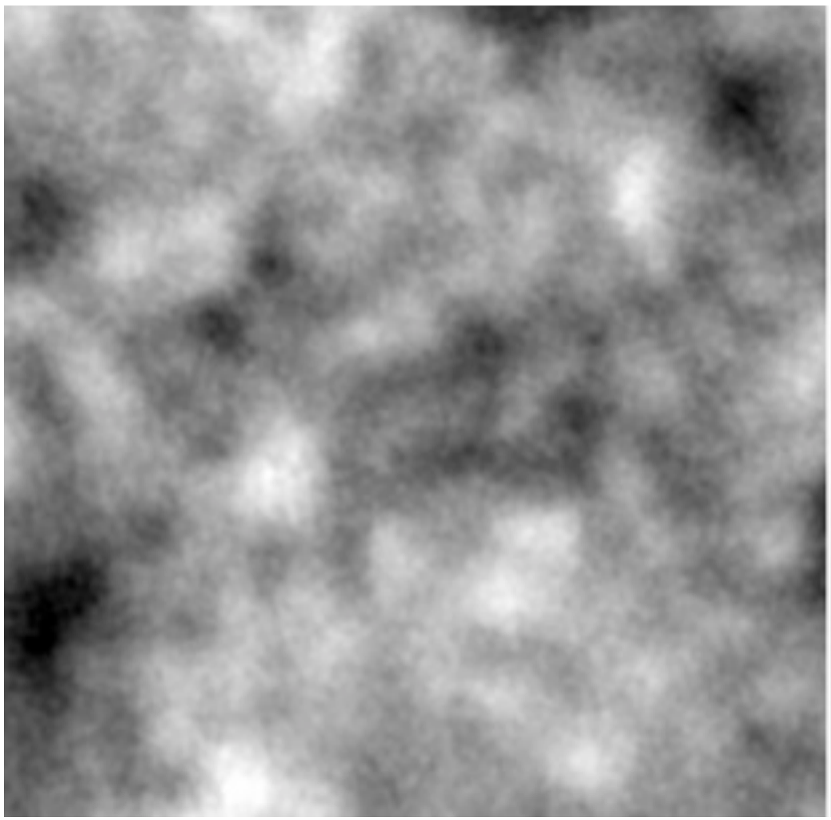
SPT-SZ Survey (completed)



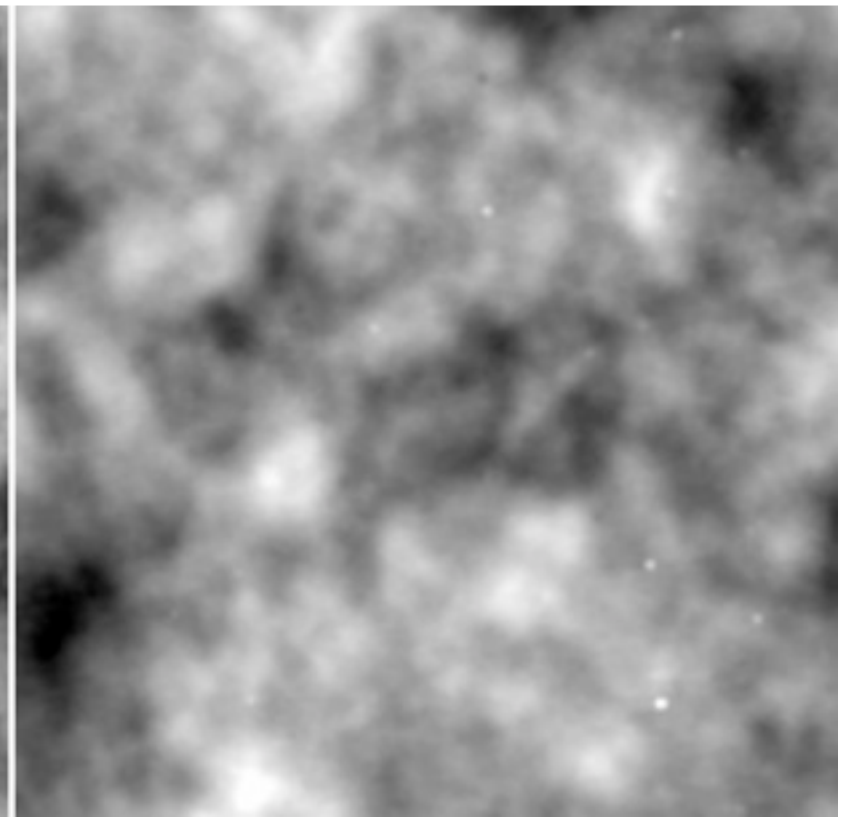
Final survey depths of:
- **100 GHz:** < 40 uK_{CMB}-arcmin
- **150 GHz:** < 18 uK_{CMB}-arcmin
- **220 GHz:** < 80 uK_{CMB}-arcmin

SPT has higher resolution than Planck

Planck 143 GHz

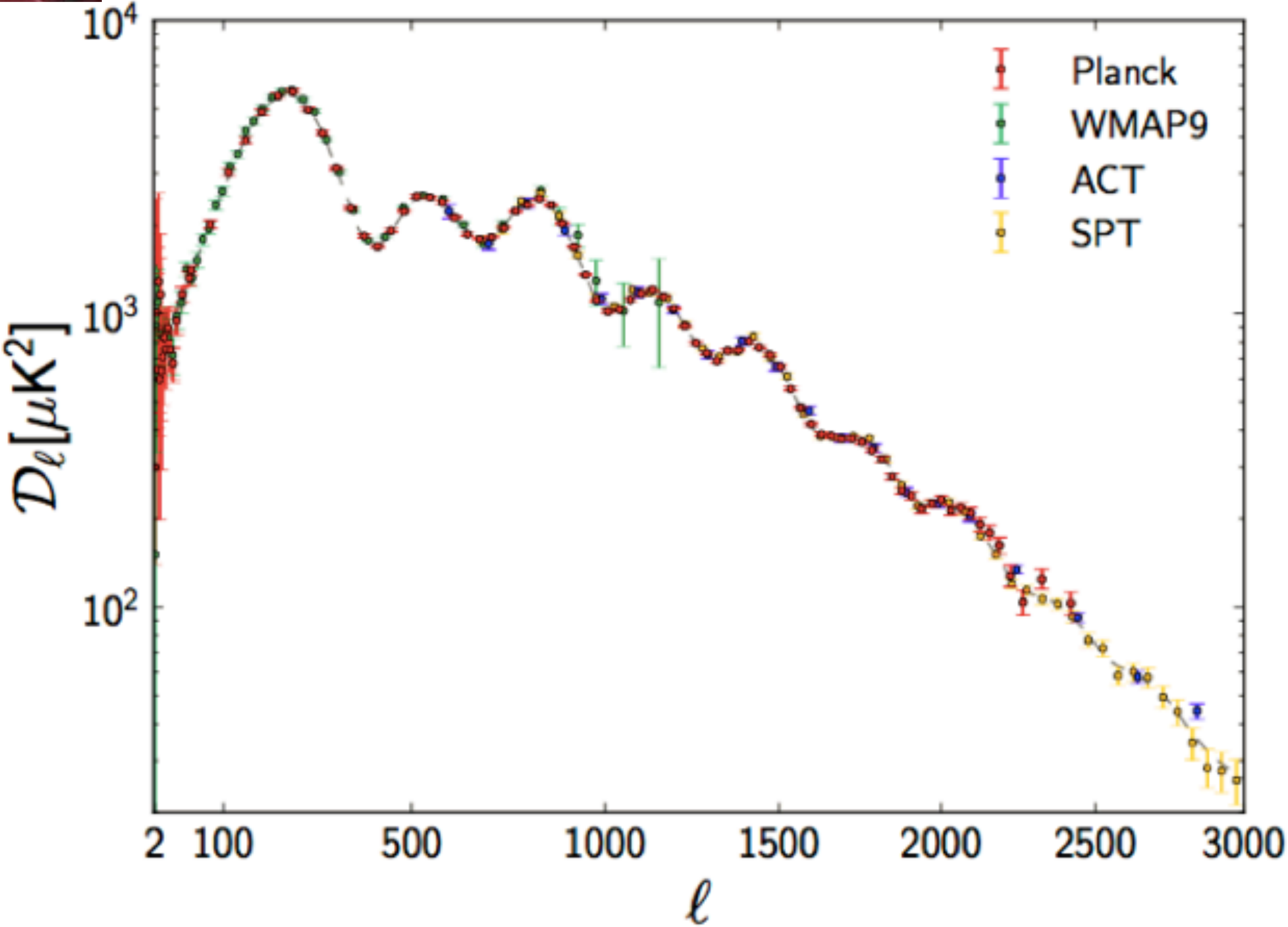


Planck+SPT

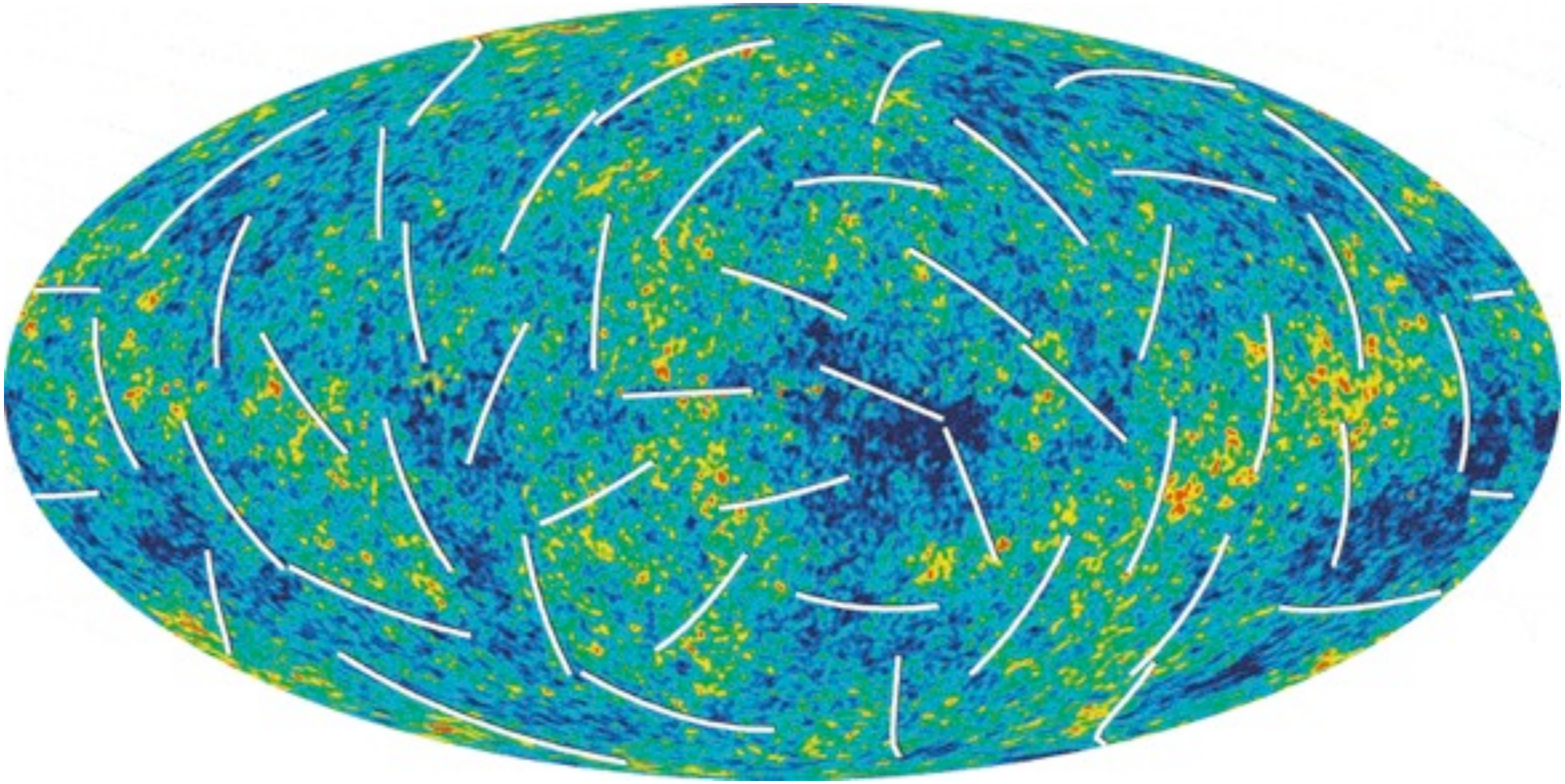


4^{o}

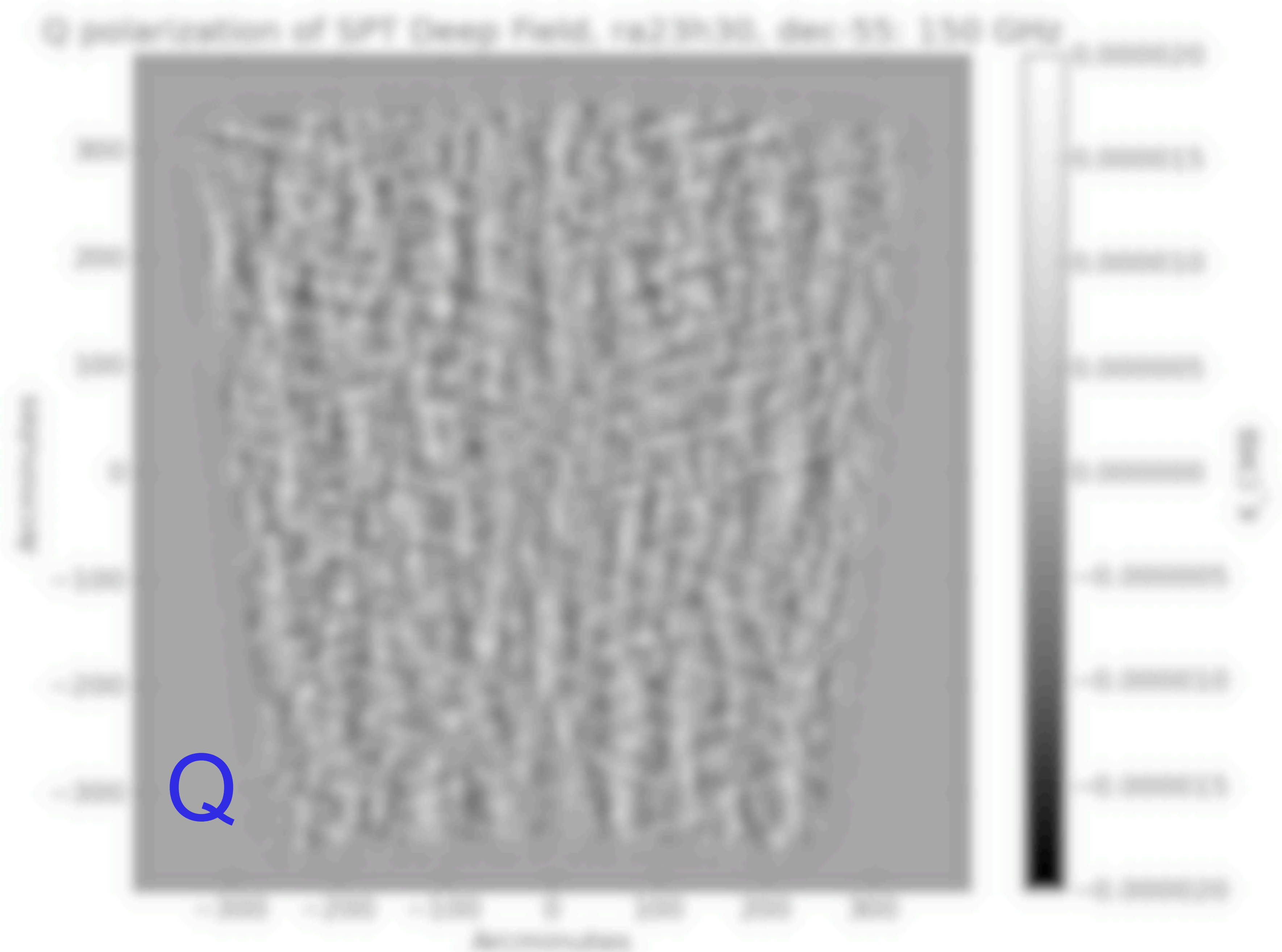
CMB Angular Power Spectrum

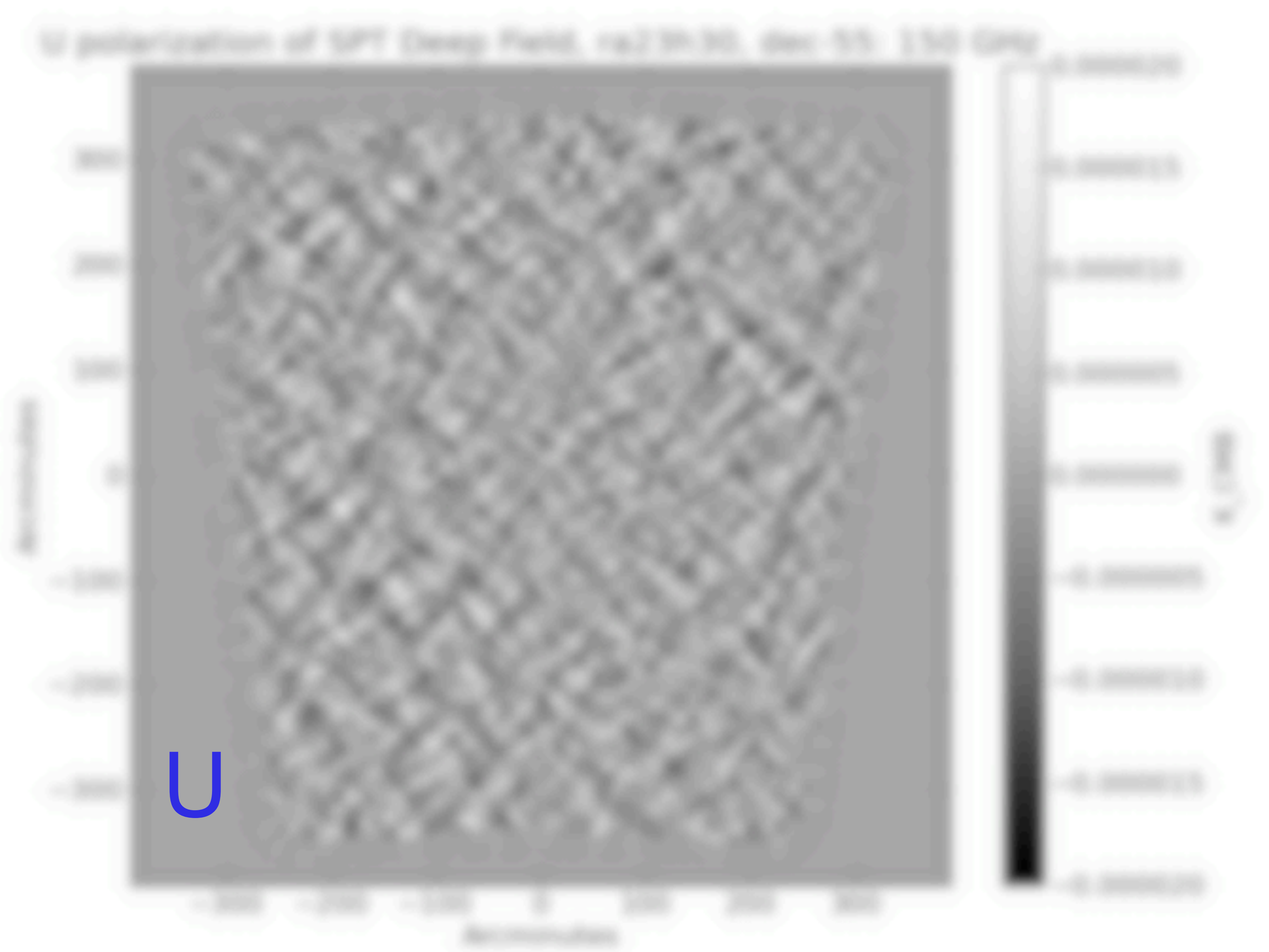


CMB Polarization



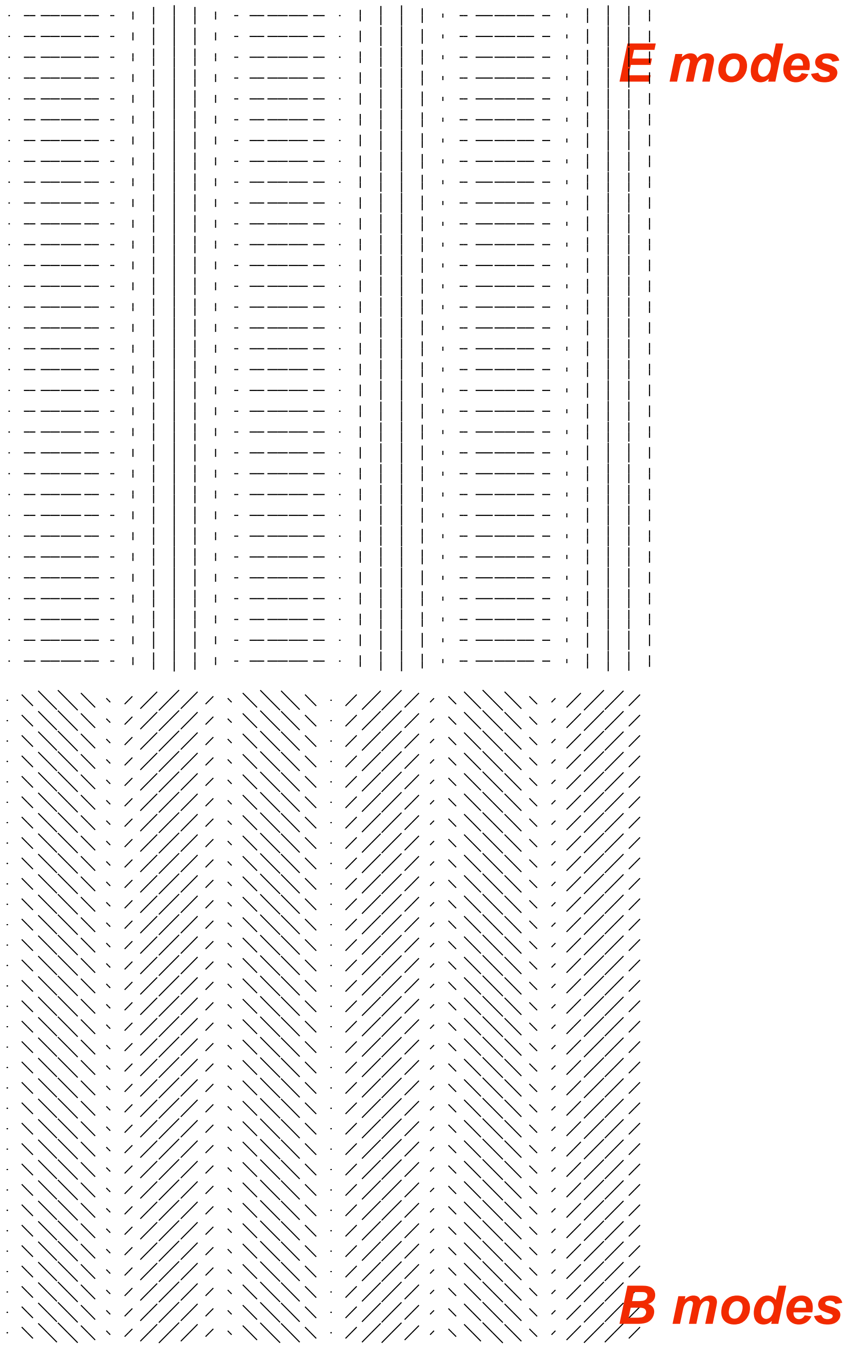
- CMB fluctuations are relatively strongly polarized (~10%)


Q


U

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



Bunn

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- ***Lensing of CMB is much more obvious in polarization!***

E modes

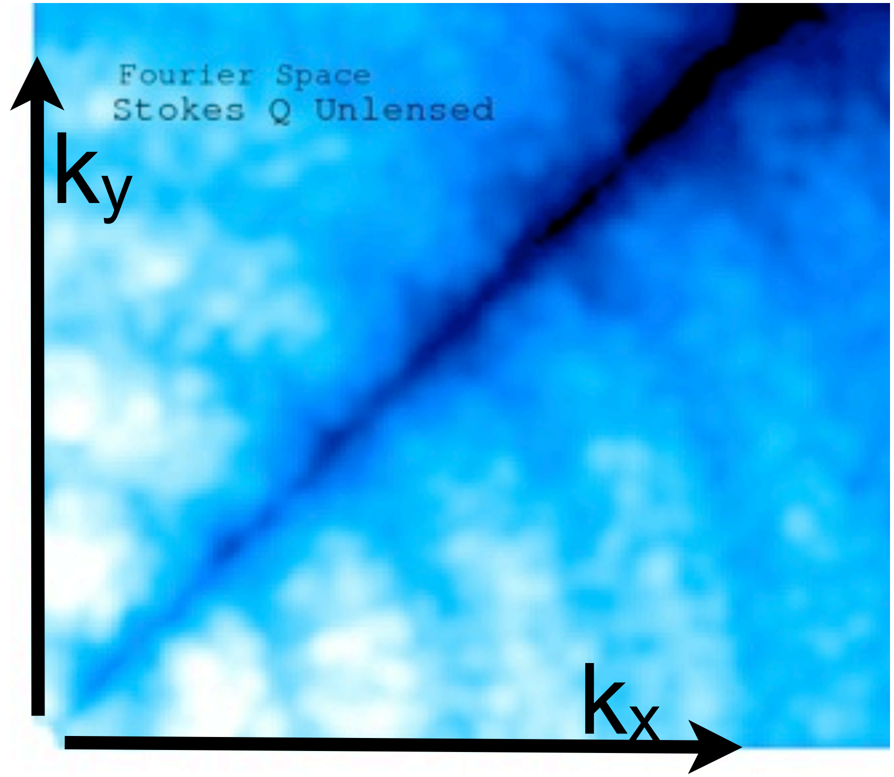
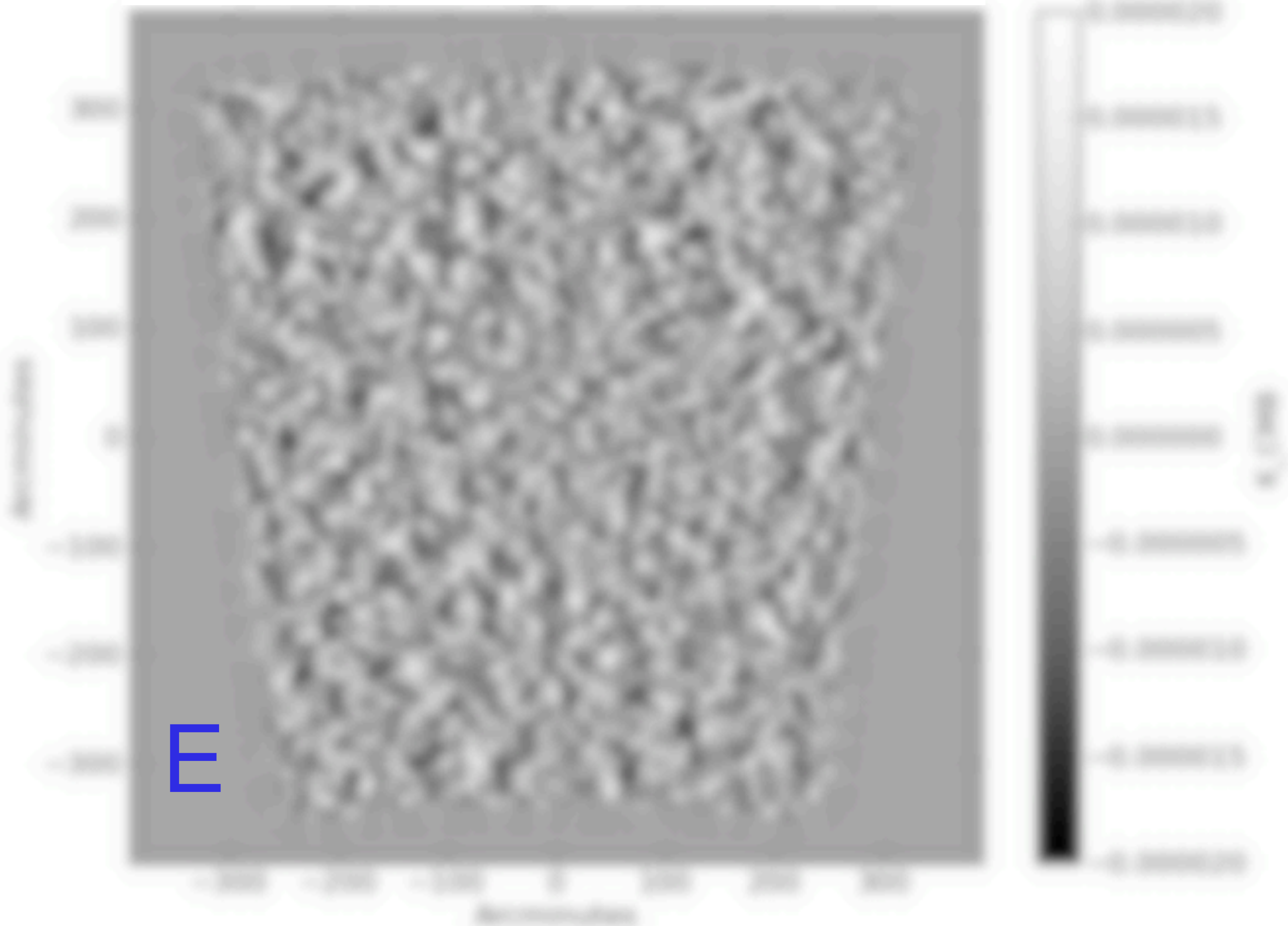
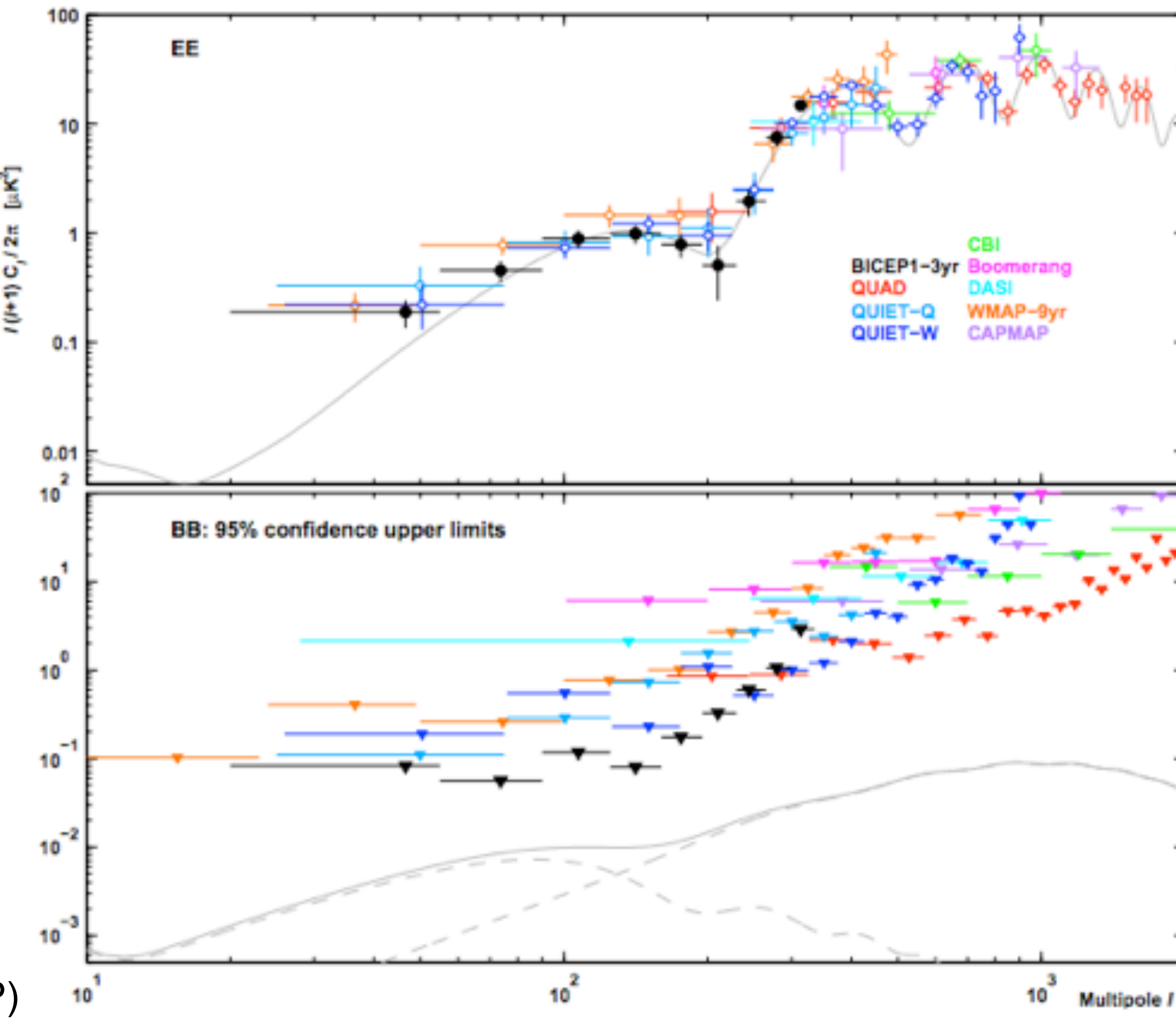


Image of positive kx/positive ky Fourier transform of a 10x10 deg chunk of Stokes Q CMB map [simulated; nothing clever done to it]

E-mode polarization of ra23h30, dec -55 field (150 GHz)



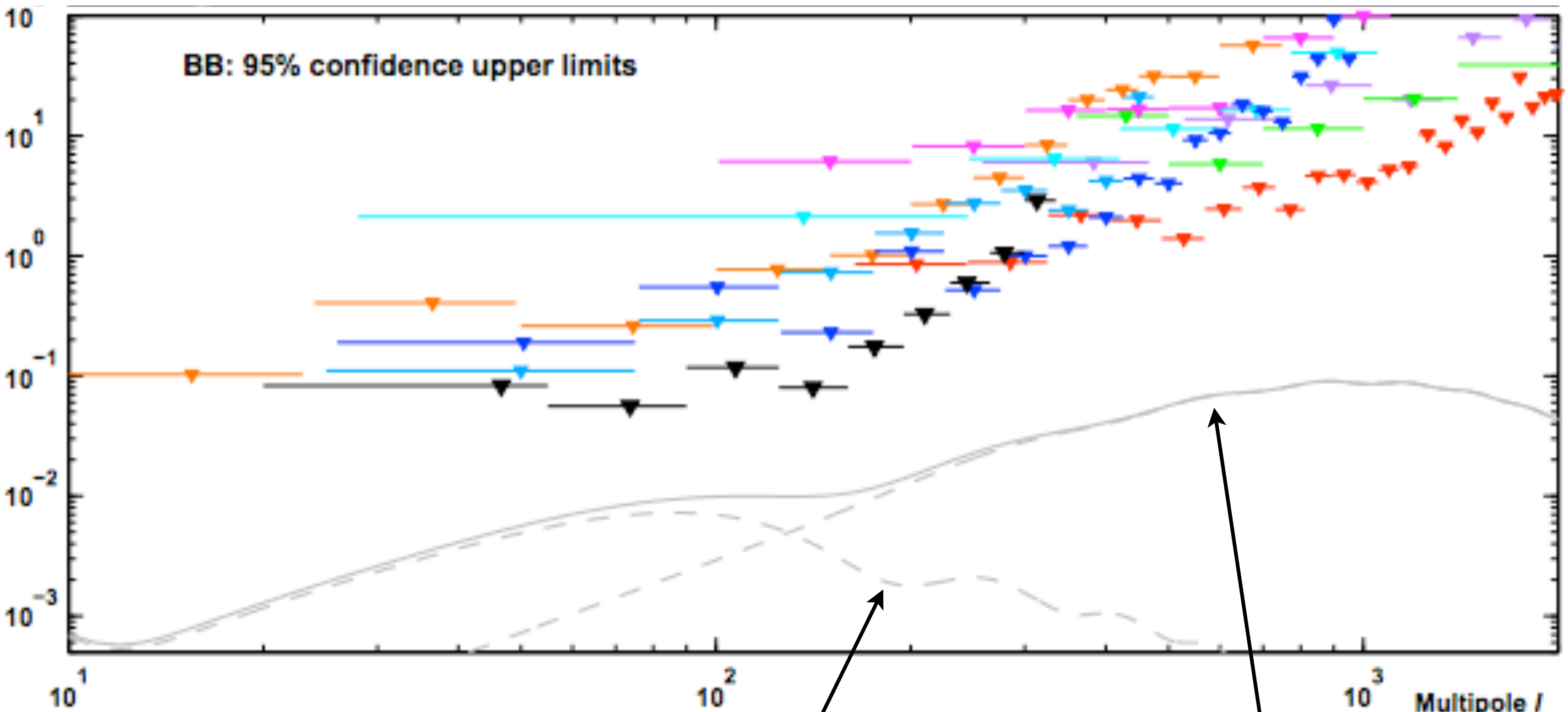
CMB Polarization Angular Power Spectrum



only upper limits on B mode power

Barkats et al (BICEP)

Two Expected Sources of B Modes



Gravitational Radiation in Early Universe (amplitude unknown!)

Gravitational lensing of E modes (amplitude well-predicted, but no measured B modes until later in talk)

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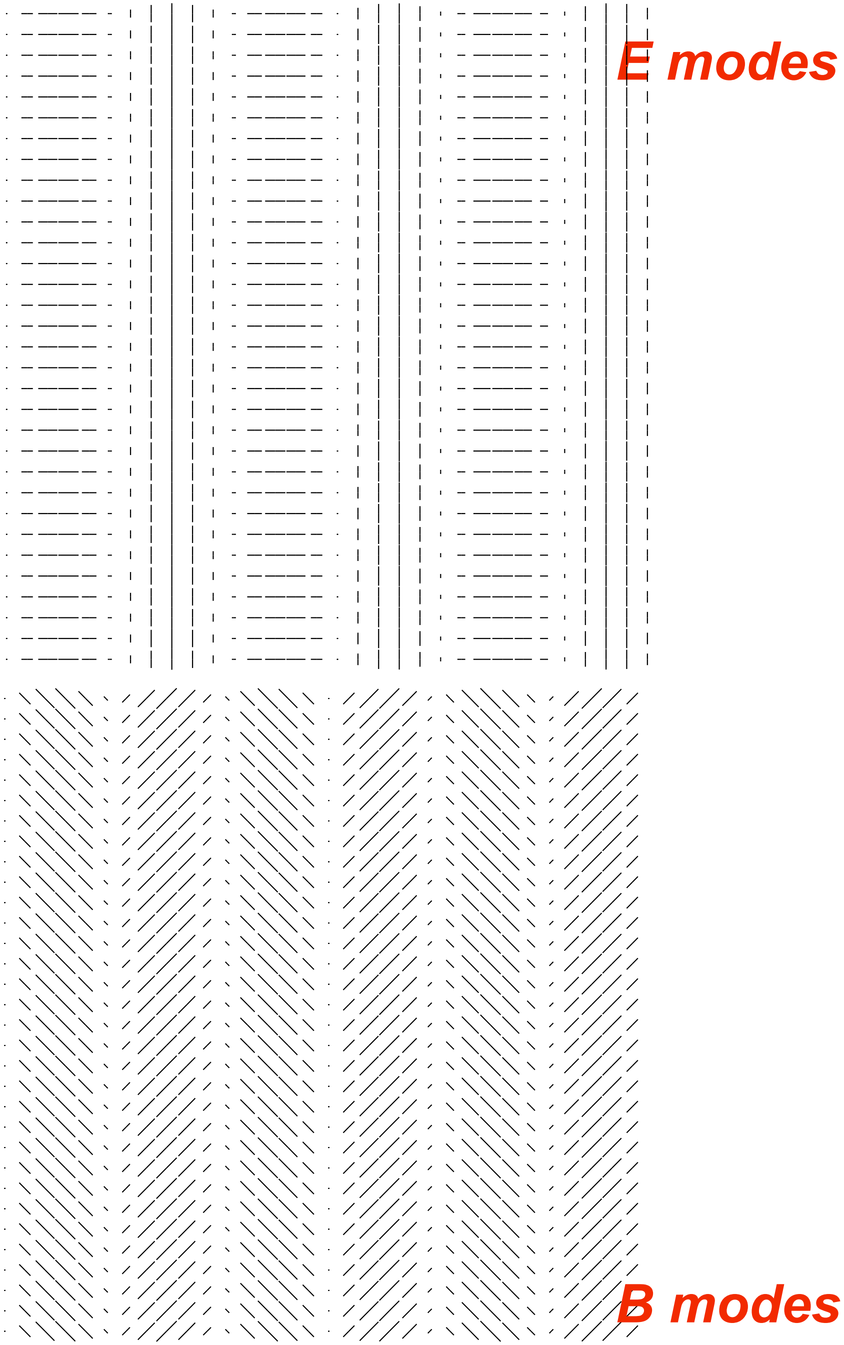
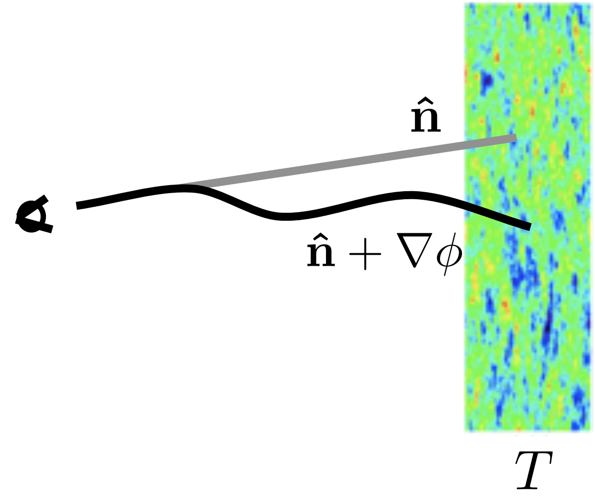


Bunn

CMB Lensing

Photons get shifted

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



In WL limit, add many deflections along line of sight

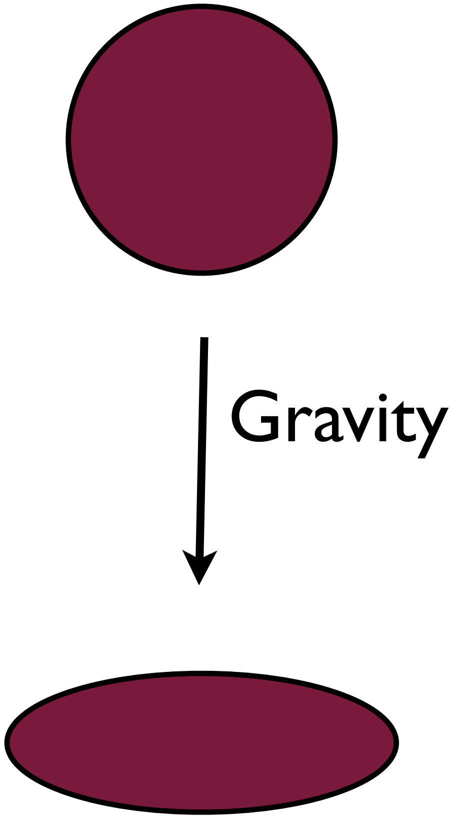
$$\nabla\phi(\hat{\mathbf{n}}) = -2\int_0^{\chi_\star} d\chi\, \frac{\chi_\star - \chi}{\chi_\star \chi} \nabla_\perp \Phi(\chi\hat{\mathbf{n}}, \chi)$$

Broad kernel, peaks at z ~ 2

- CMB is a unique source for lensing
  - Gaussian, with well-understood power spectrum (contains all info)
  - At redshift which is (a) unique, (b) known, and (c) highest

Lensing simplified

- gravitational potentials distort shapes by stretching, squeezing, shearing



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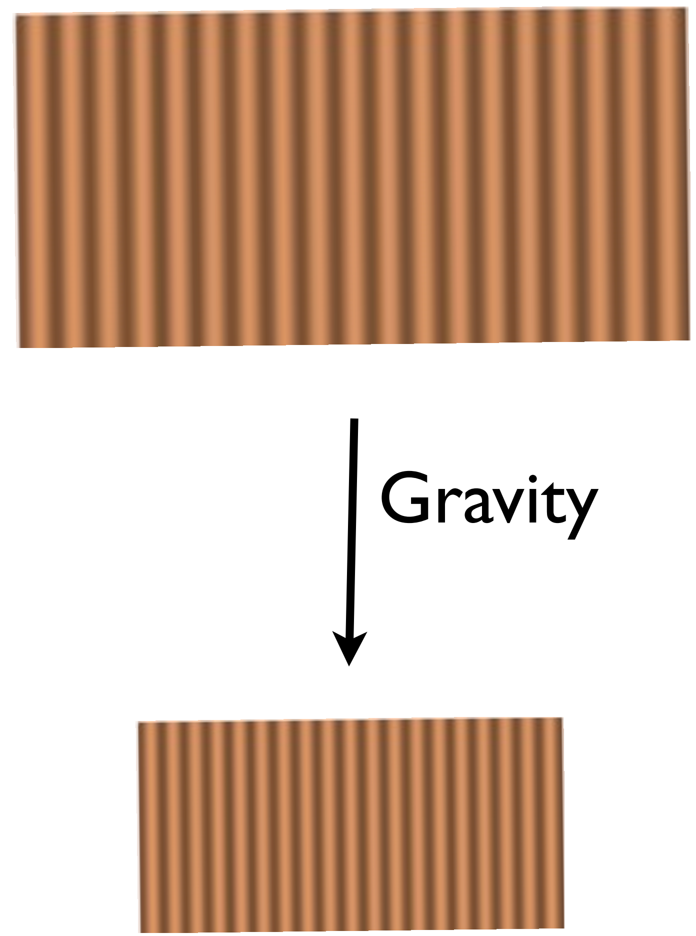
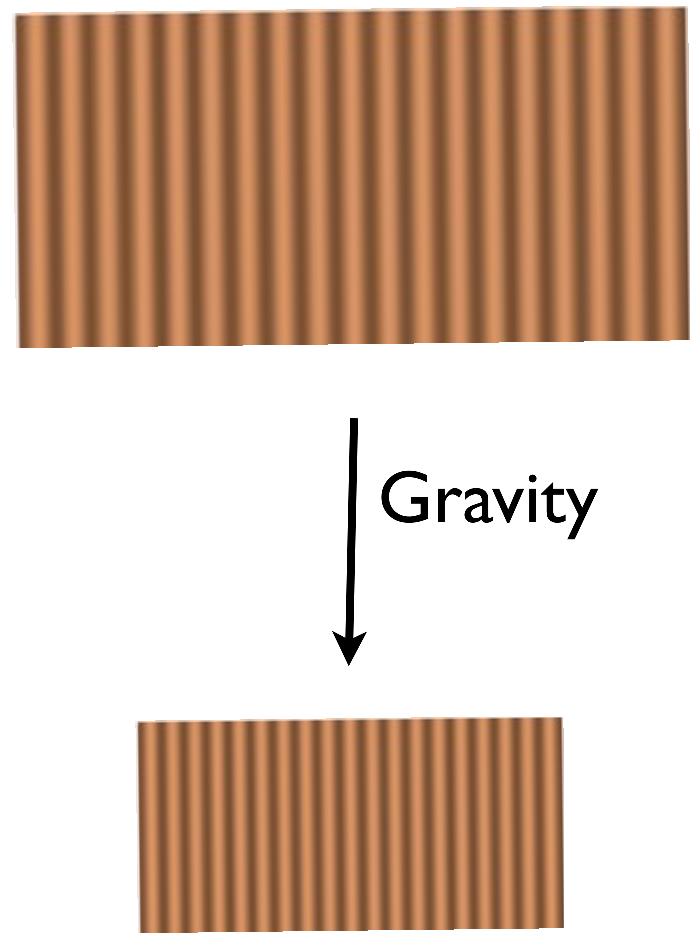


Lensing simplified

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



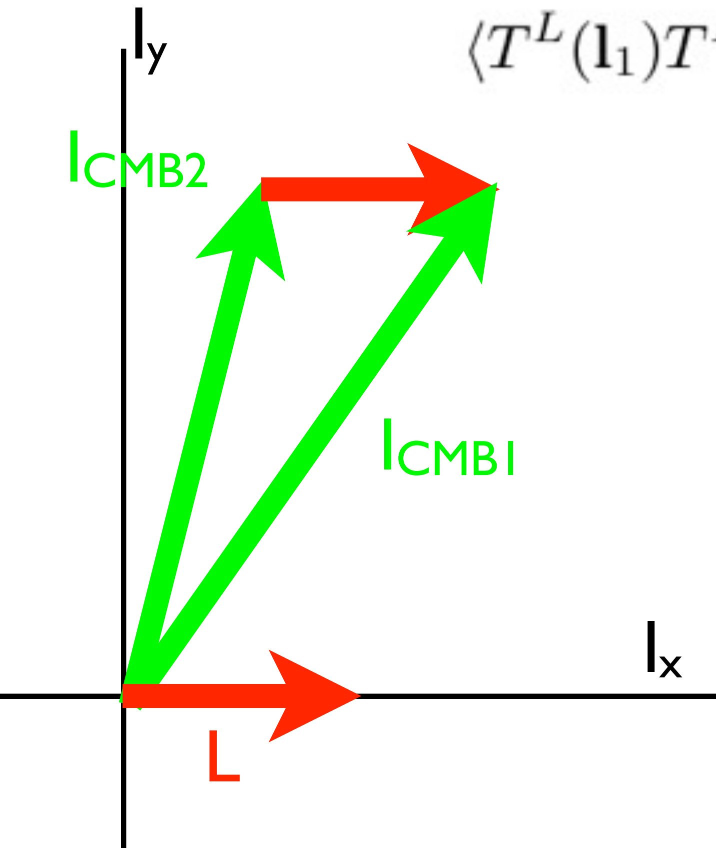
Mode Coupling from Lensing

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

- Non-gaussian mode coupling 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 a suitable average over CMB multipoles separated by a distance L
- We use the standard Hu quadratic estimator.

E-modes/B-modes

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- B-modes vary spatially at 45 degrees
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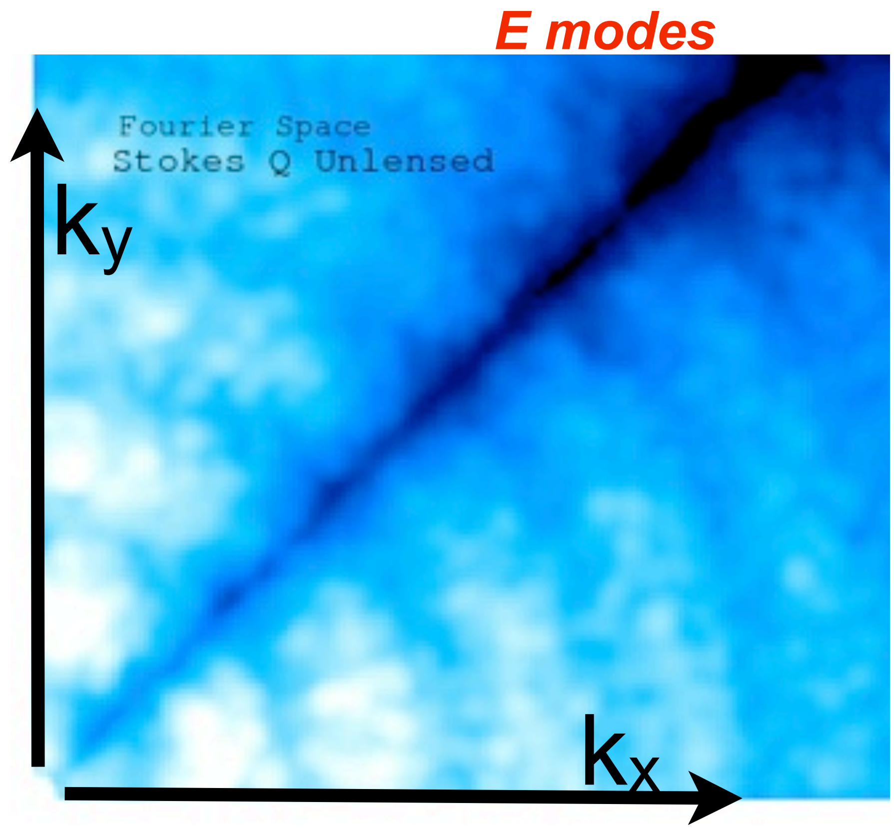

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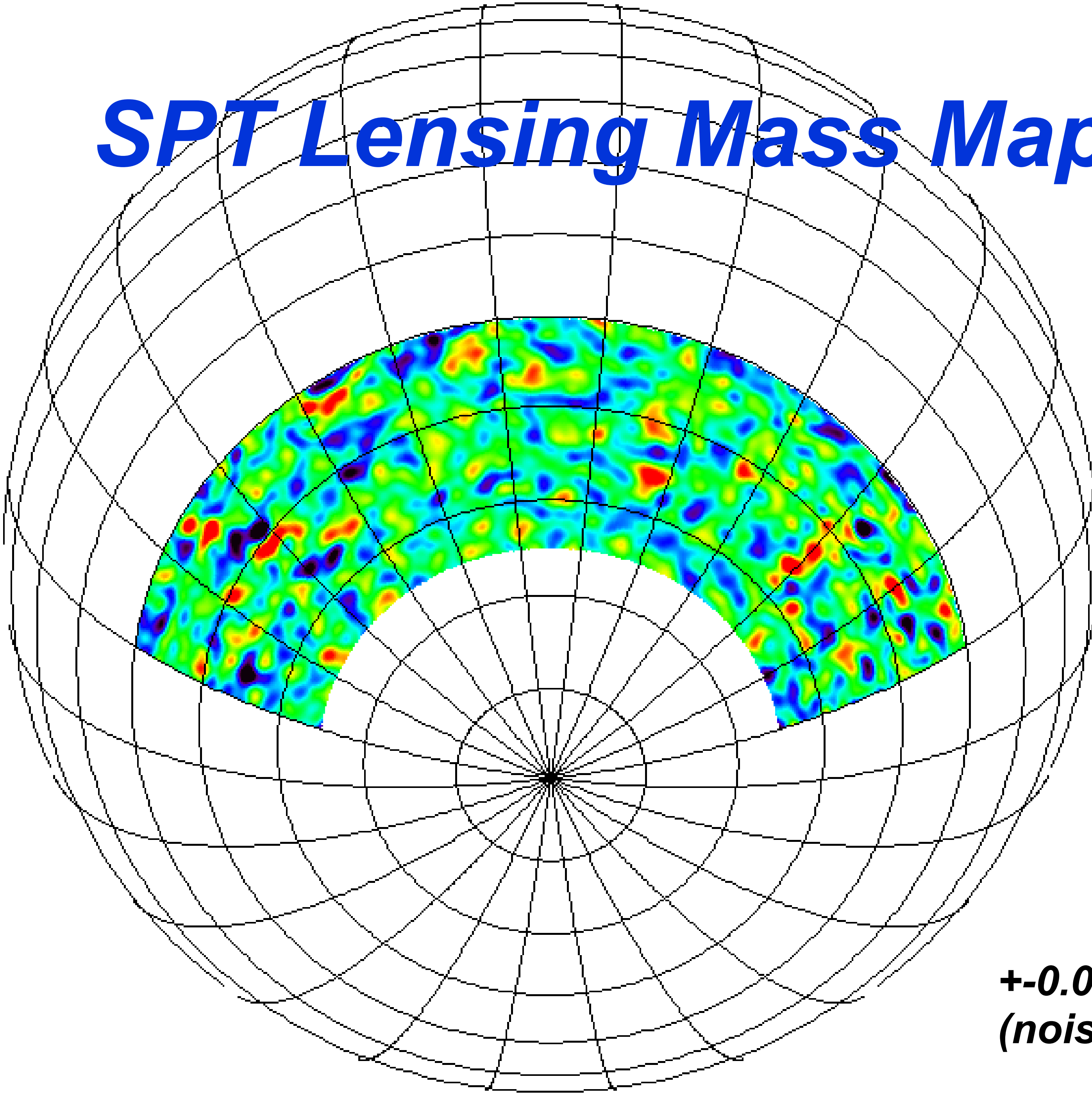
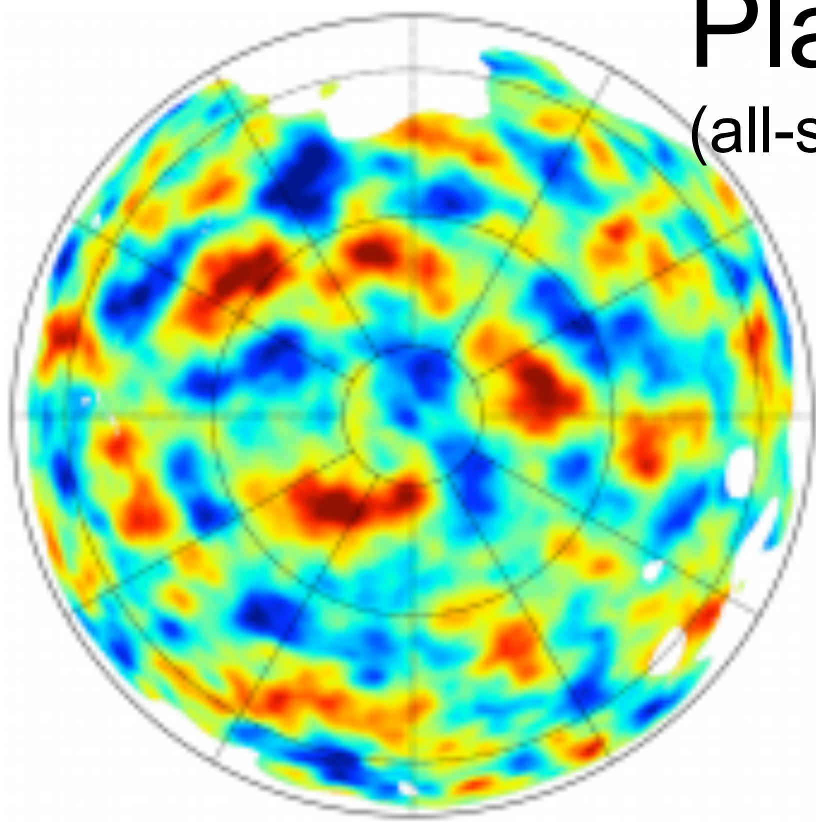
SPT Lensing Mass Map



+-0.05 color bar
(noise ~0.01)

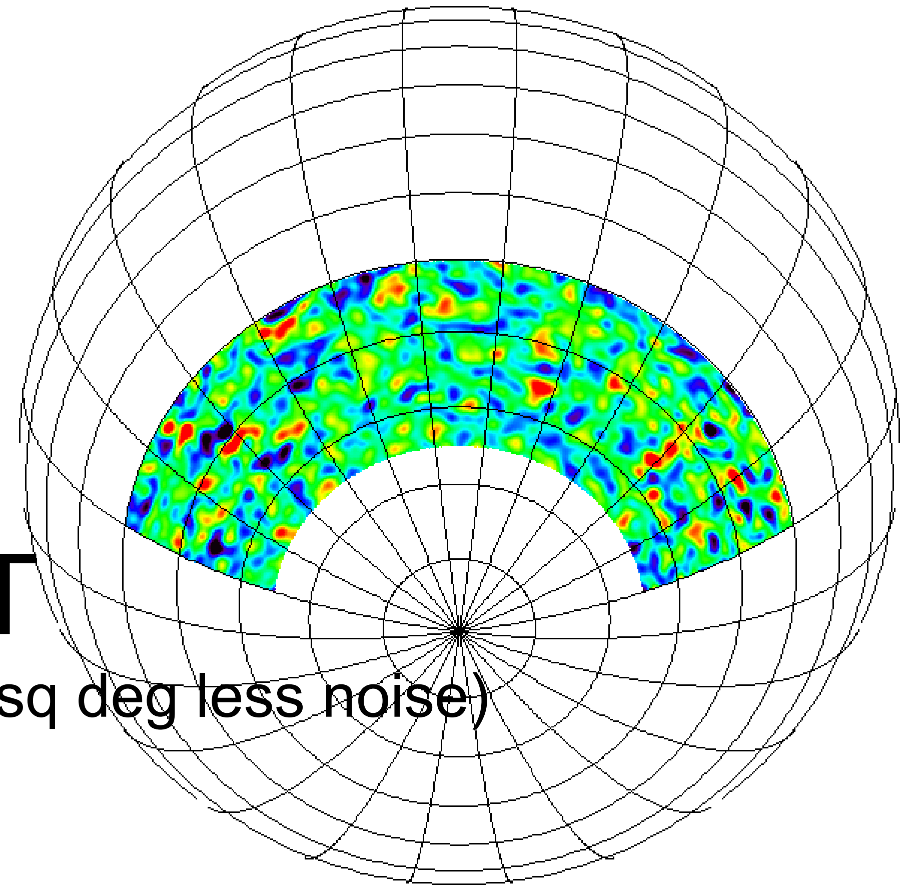
Planck

(all-sky more noise)



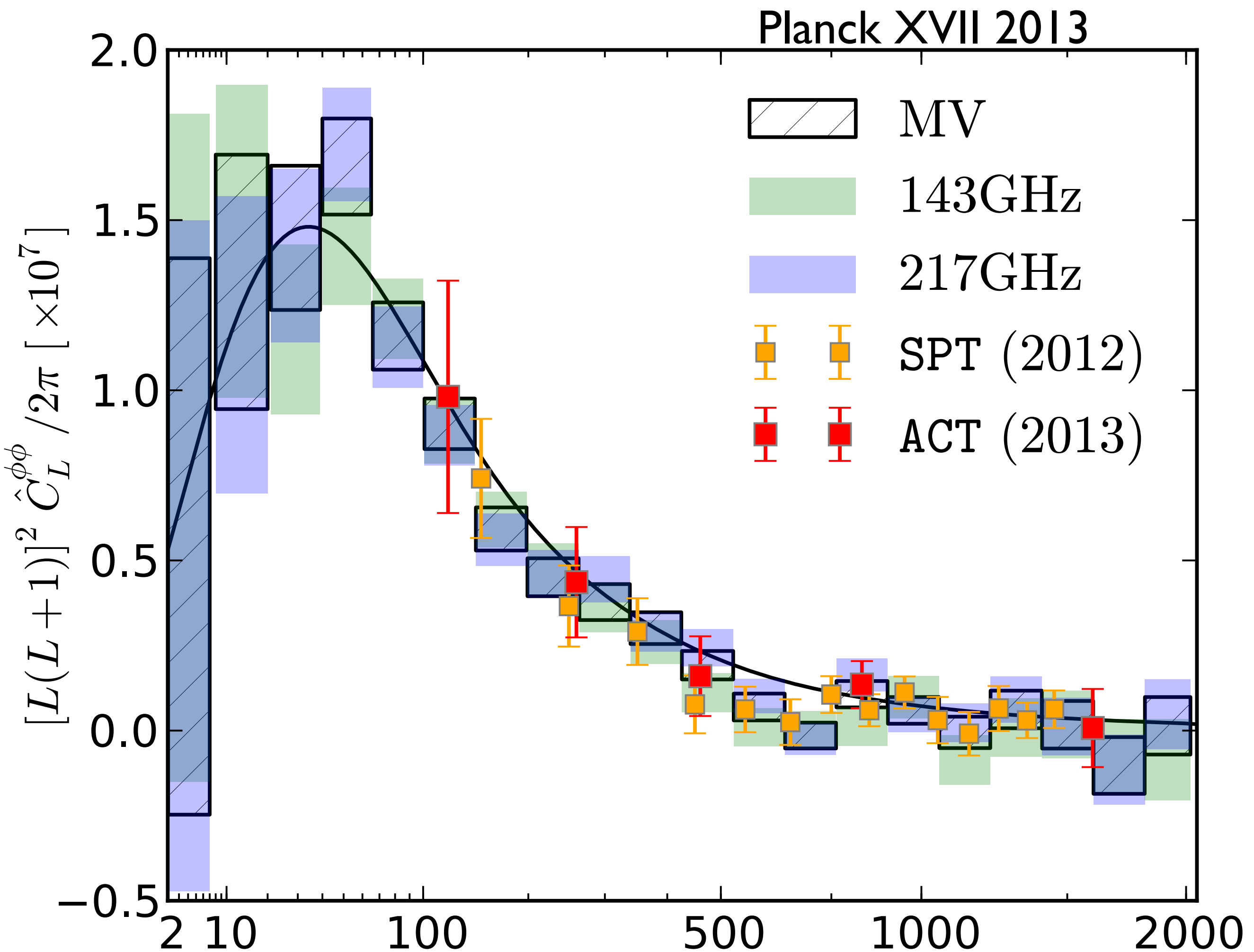
SPT

(2500 sq deg less noise)

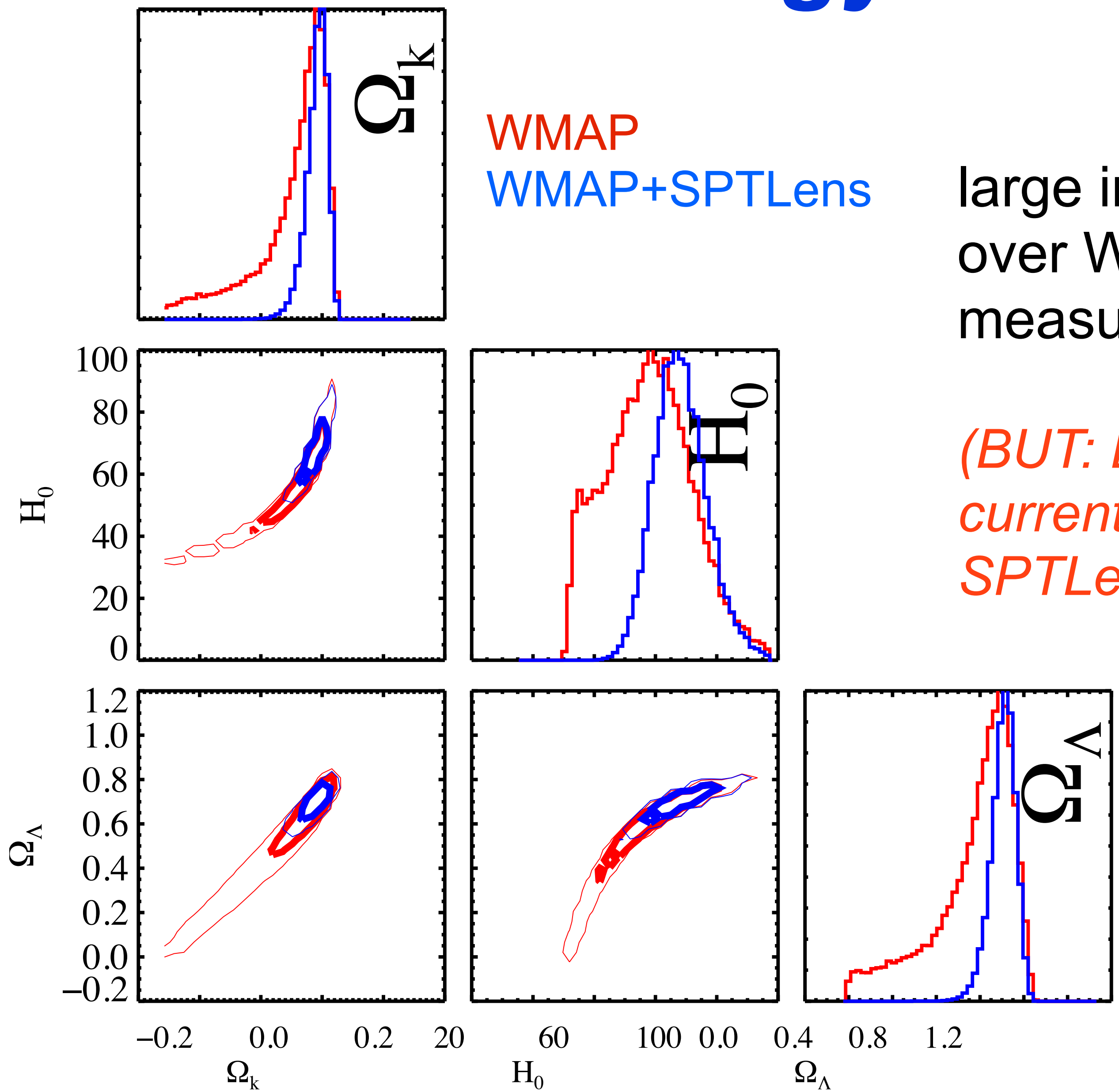


CMB Lensing Power Spectrum

- well measured with Planck, SPT, ACT



Cosmology with Lensing



large improvements over WMAP alone in measuring curvature

(BUT: BAO+H_o are currently ~2x better than SPTLens for this)

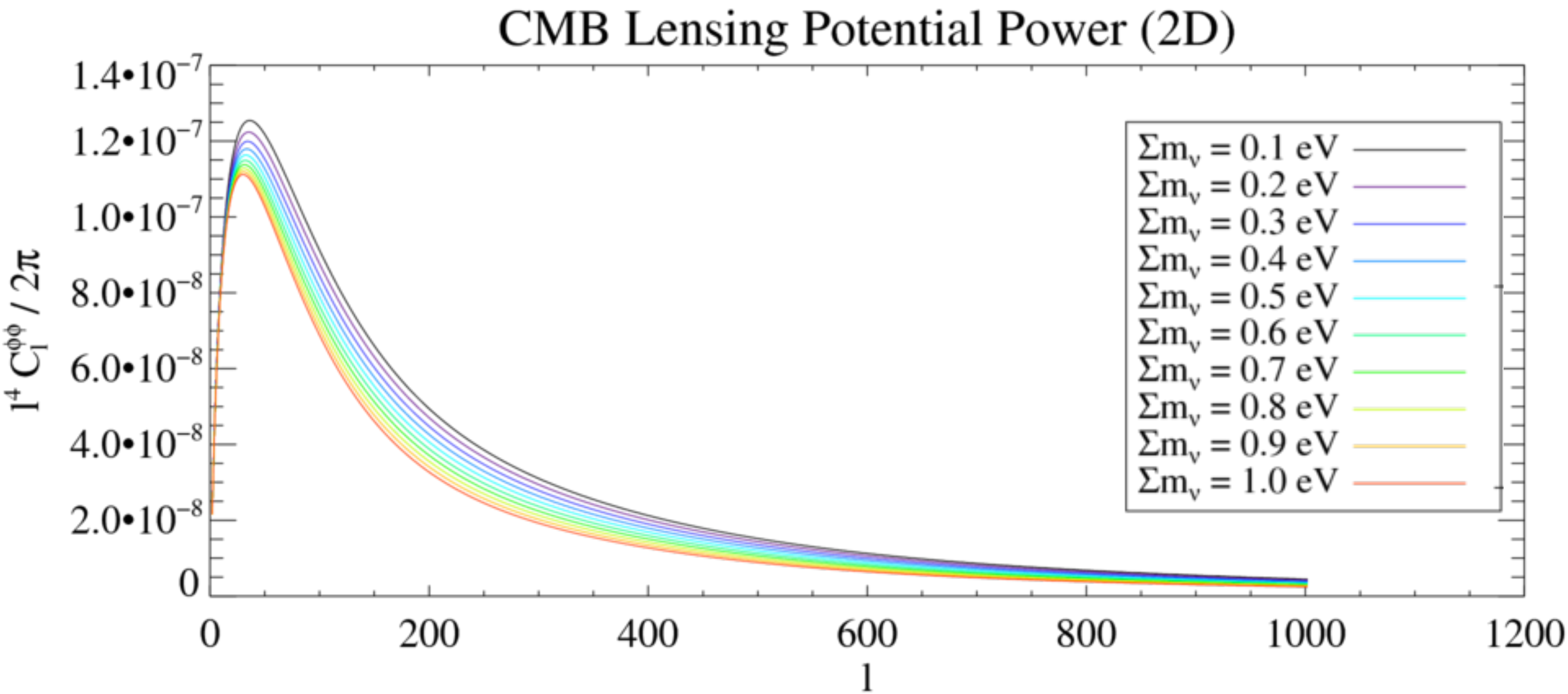
van Engelen et al

Massive Neutrinos in Cosmology

$$\Omega_\nu \approx \sum_i (m_i / 0.1\ eV) \quad 0.0022\, h_{0.7}^{-2}$$

- Below free-streaming scale, neutrinos act like **radiation**
  - *drag on growth*
- Above free-streaming scale, neutrinos act like **matter**

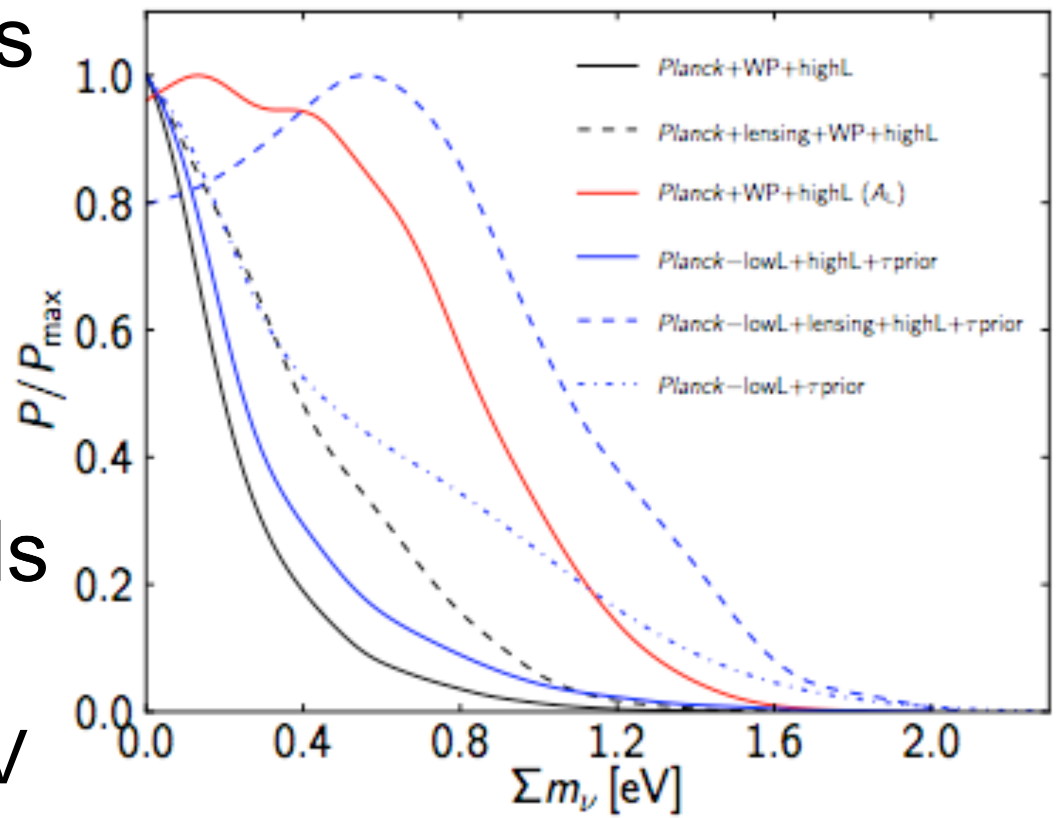
Neutrinos & CMB Lensing



- Peak at l=40 (k_{eq} =[300 Mpc]$^{-1}$ at z = 2): coherent over degree scales
- RMS deflection angle is only ~2.7'

Upper limits on neutrino masses

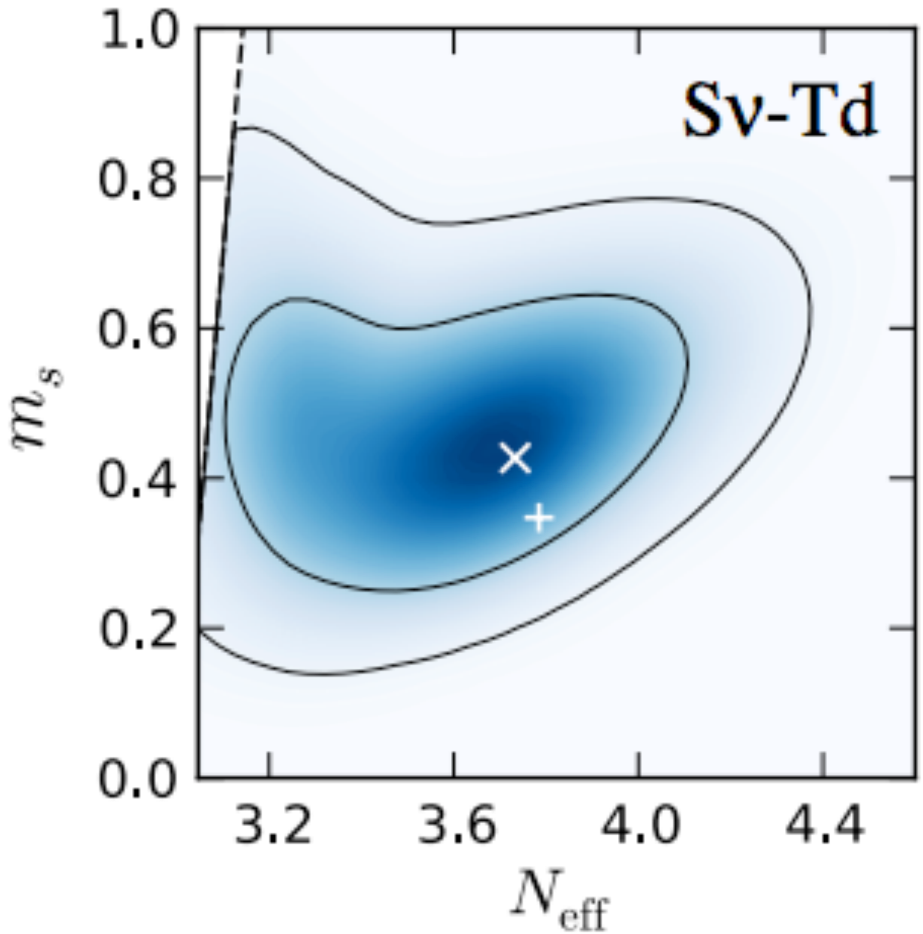
- CMB experiments closing in on interesting neutrino mass range
- CMB lensing adds new information
  - – forecast ~0.05 eV sensitivity in ~4 yrs



Planck collaboration 2013

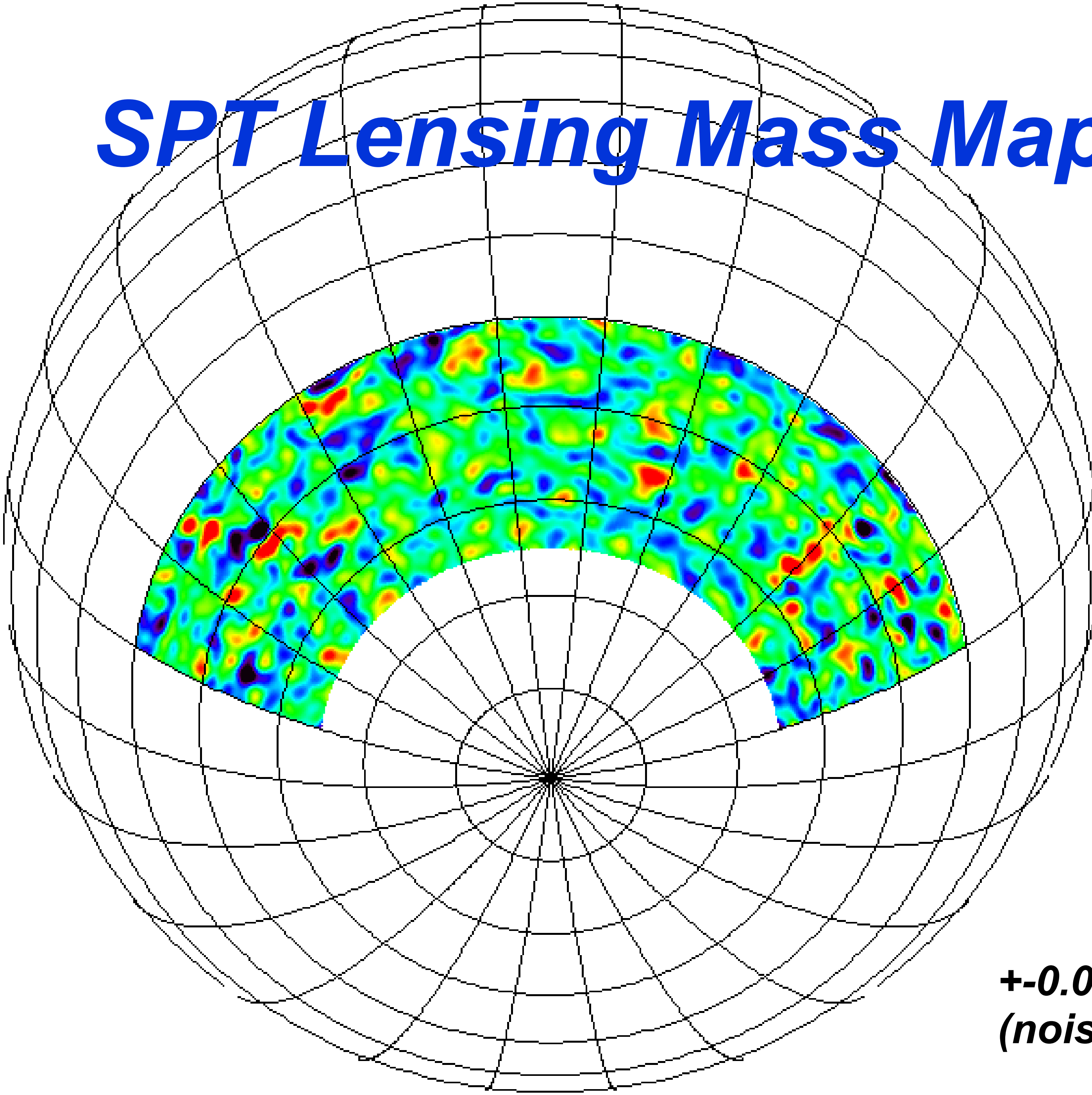
Not everything makes total sense

- combining all cosmological information leads to a preference for a high neutrino mass and some form of new light particle in the universe



Wyman et al 2013

SPT Lensing Mass Map



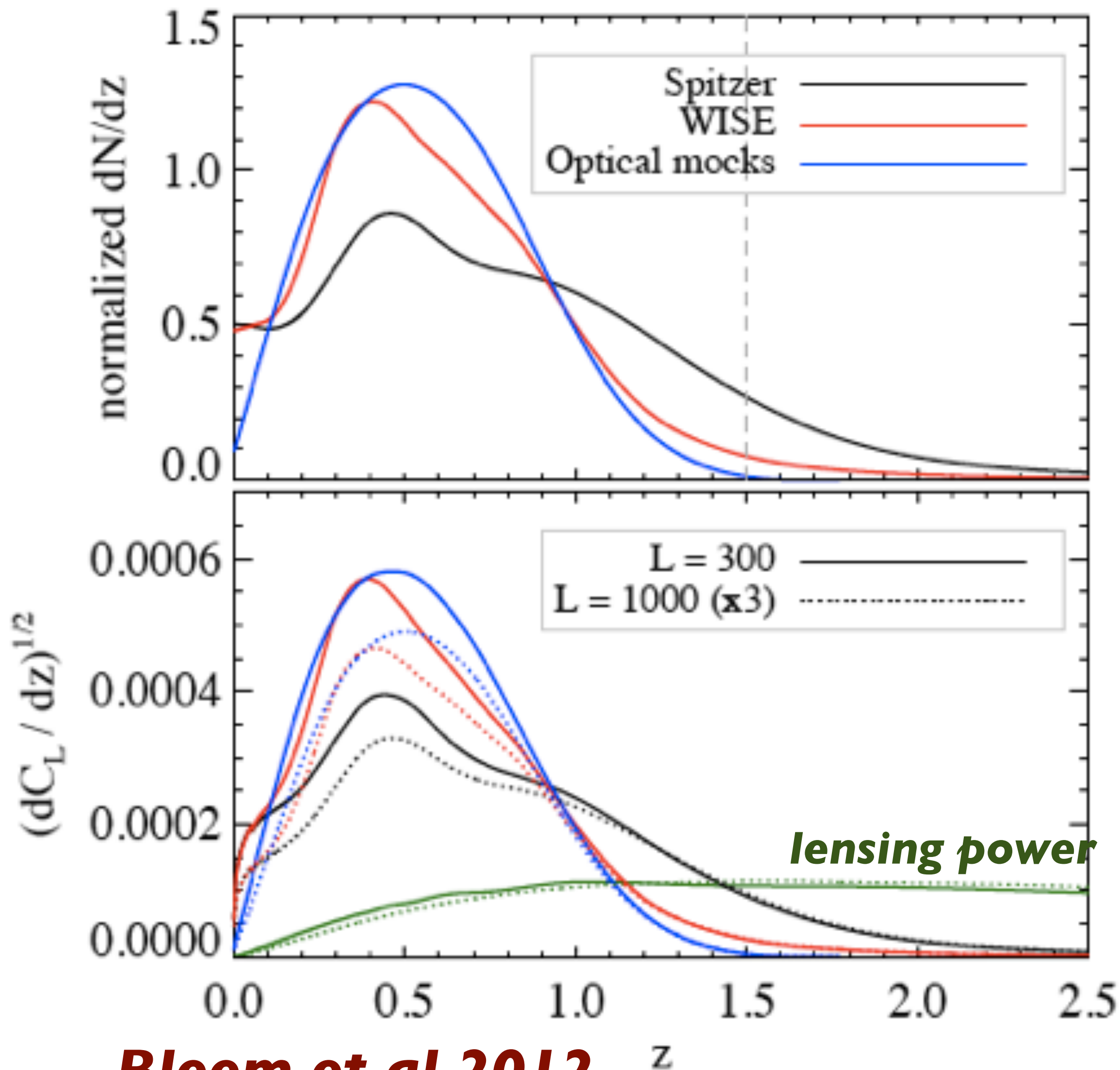
+-0.05 color bar
(noise ~0.01)

CMB Lensing X Galaxies

linear bias:

$\rho_{gal} = b\rho_{matter}$

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

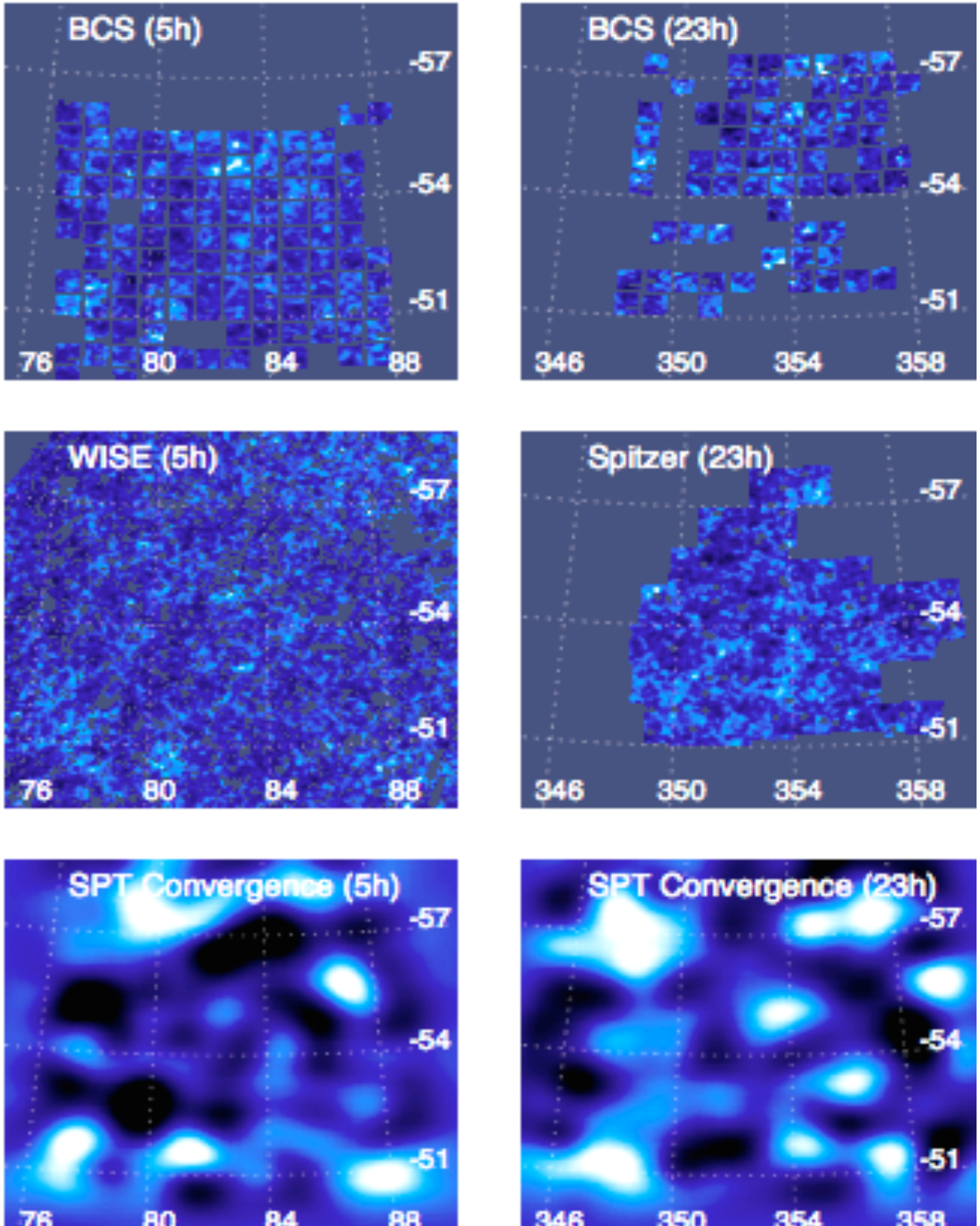


Bleem et al 2012

Optical galaxy counts
(19.5<i<22.5)

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

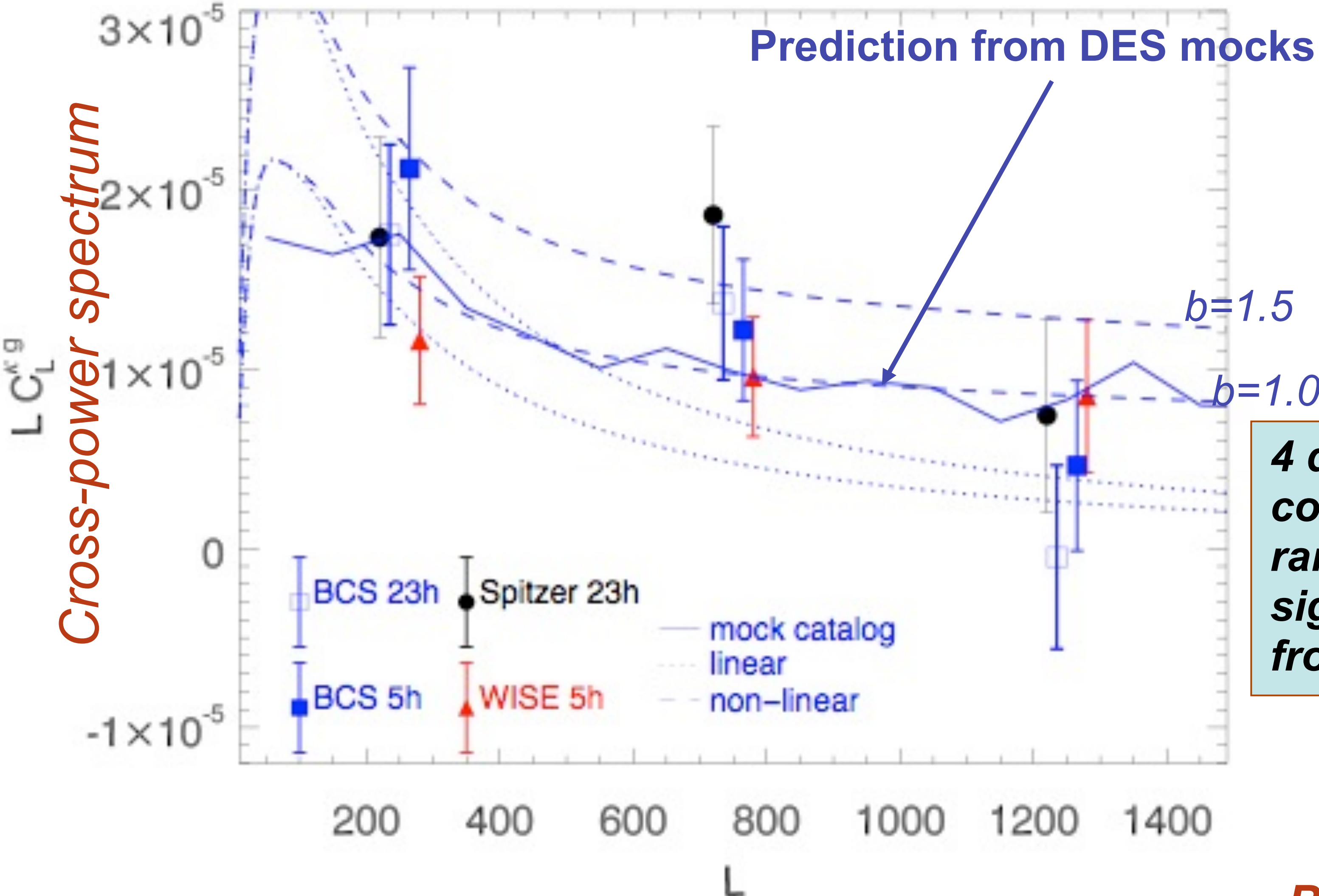
CMB lensing
(smoothed to only show scales with S/N>1)



Using <5% of completed SPT survey

Bleem et al

Galaxy-Mass Cross-Correlation Detected

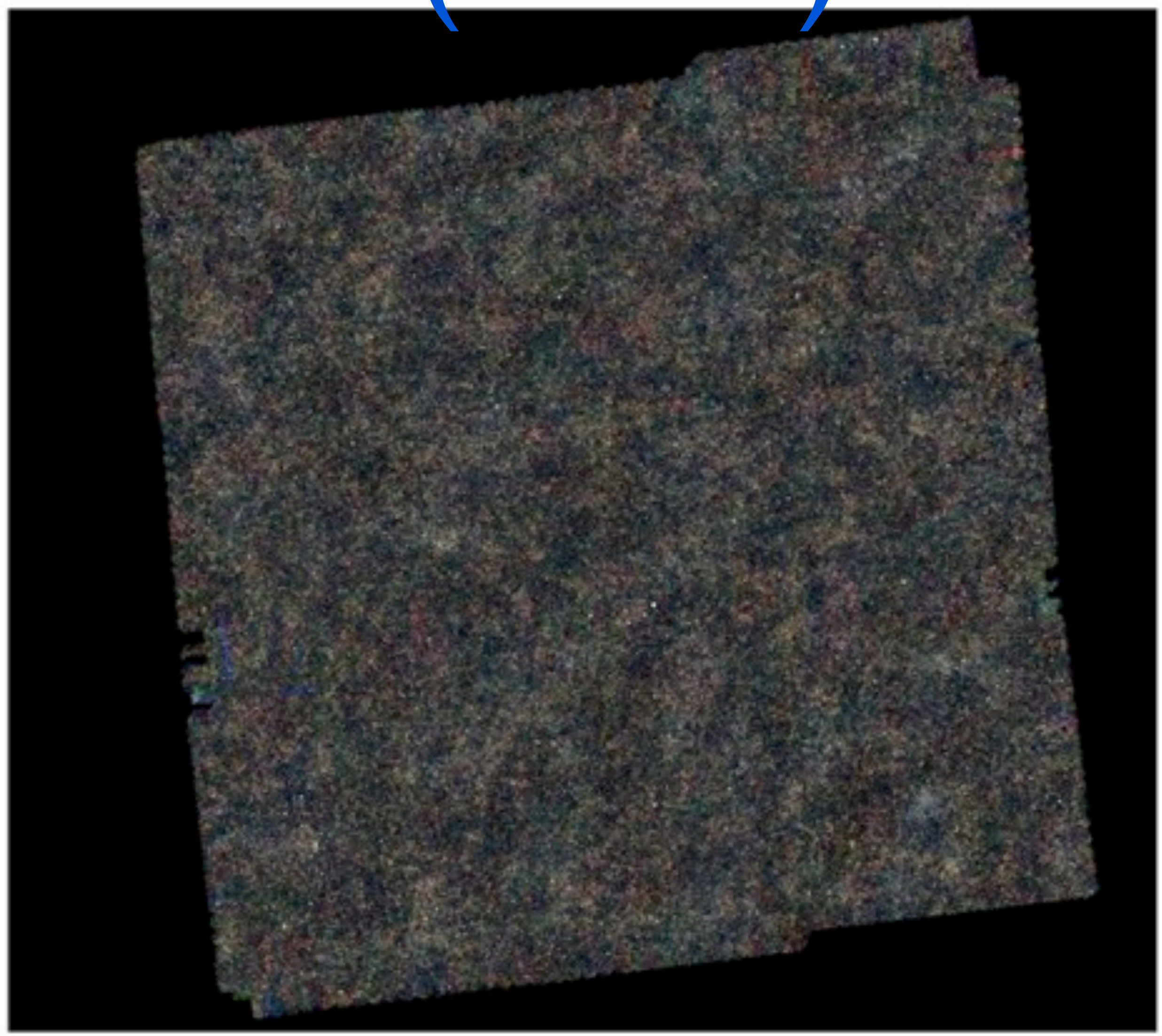


4 different x-correlations, ranging in significance from 4.2-5.4σ

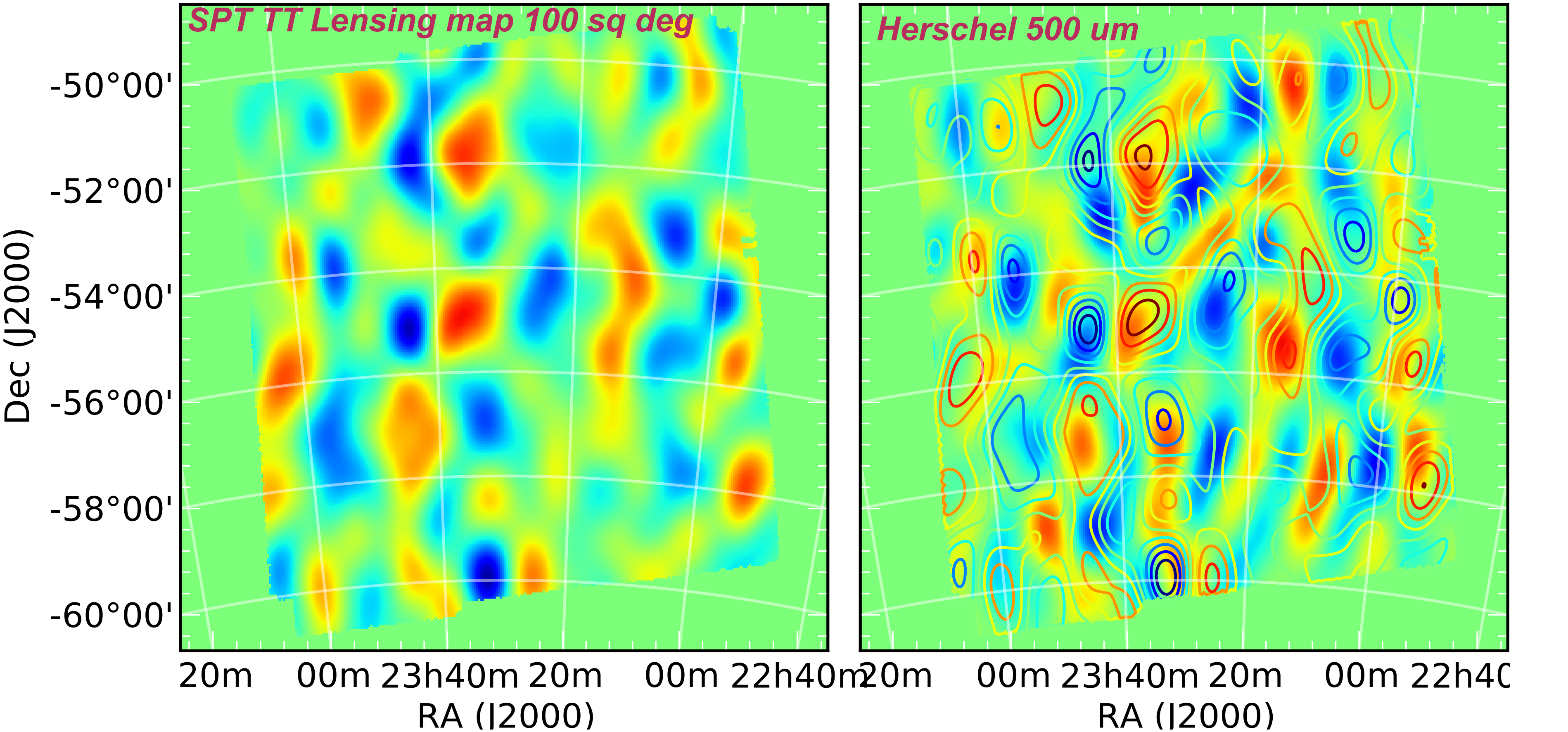
Bleem et al

Herschel (SPIRE)

- 100 sq deg with full overlap with SPT deep field (23h30,-55d)
- 250,350,500 um



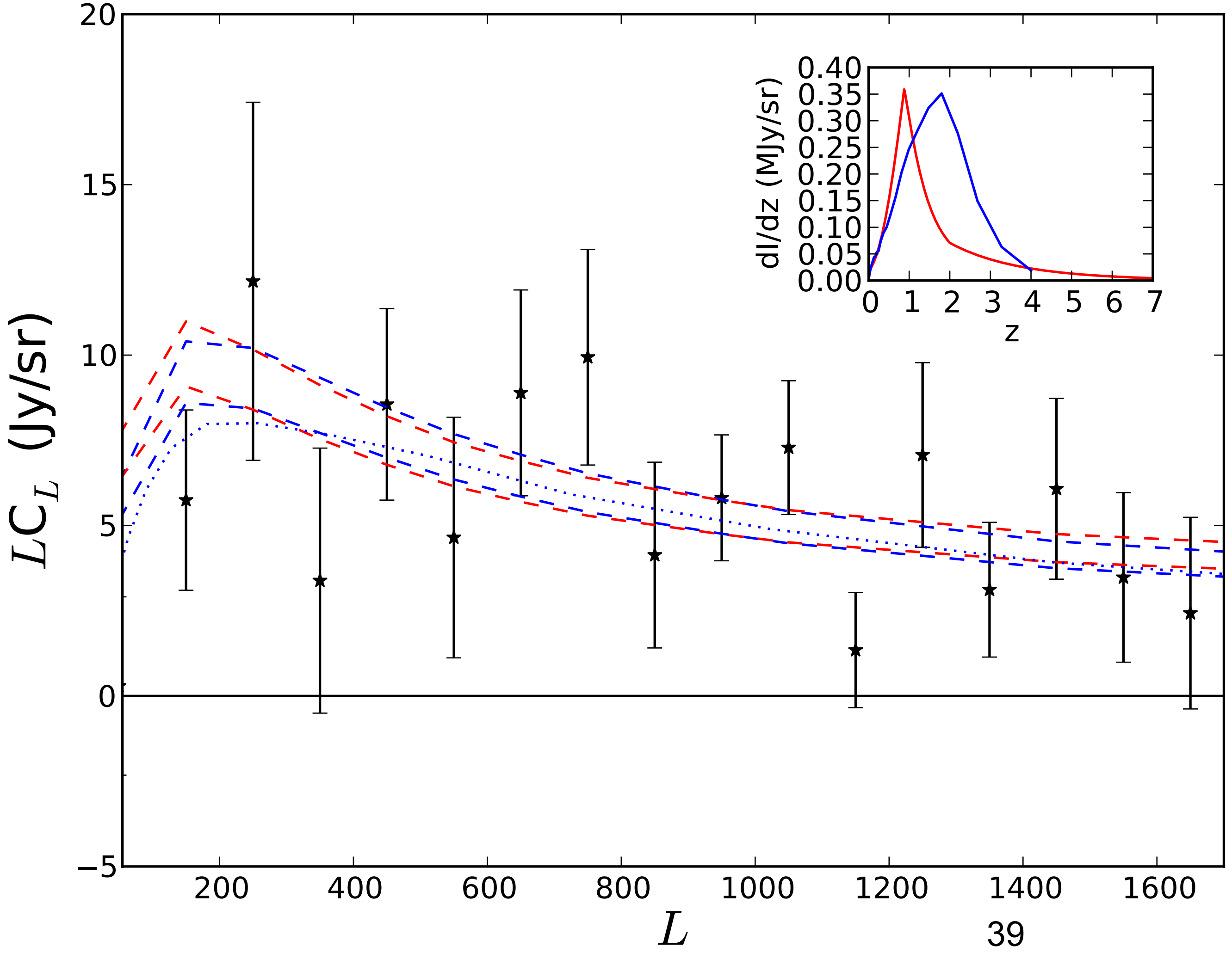
Cosmic Infrared Background Traces Mass



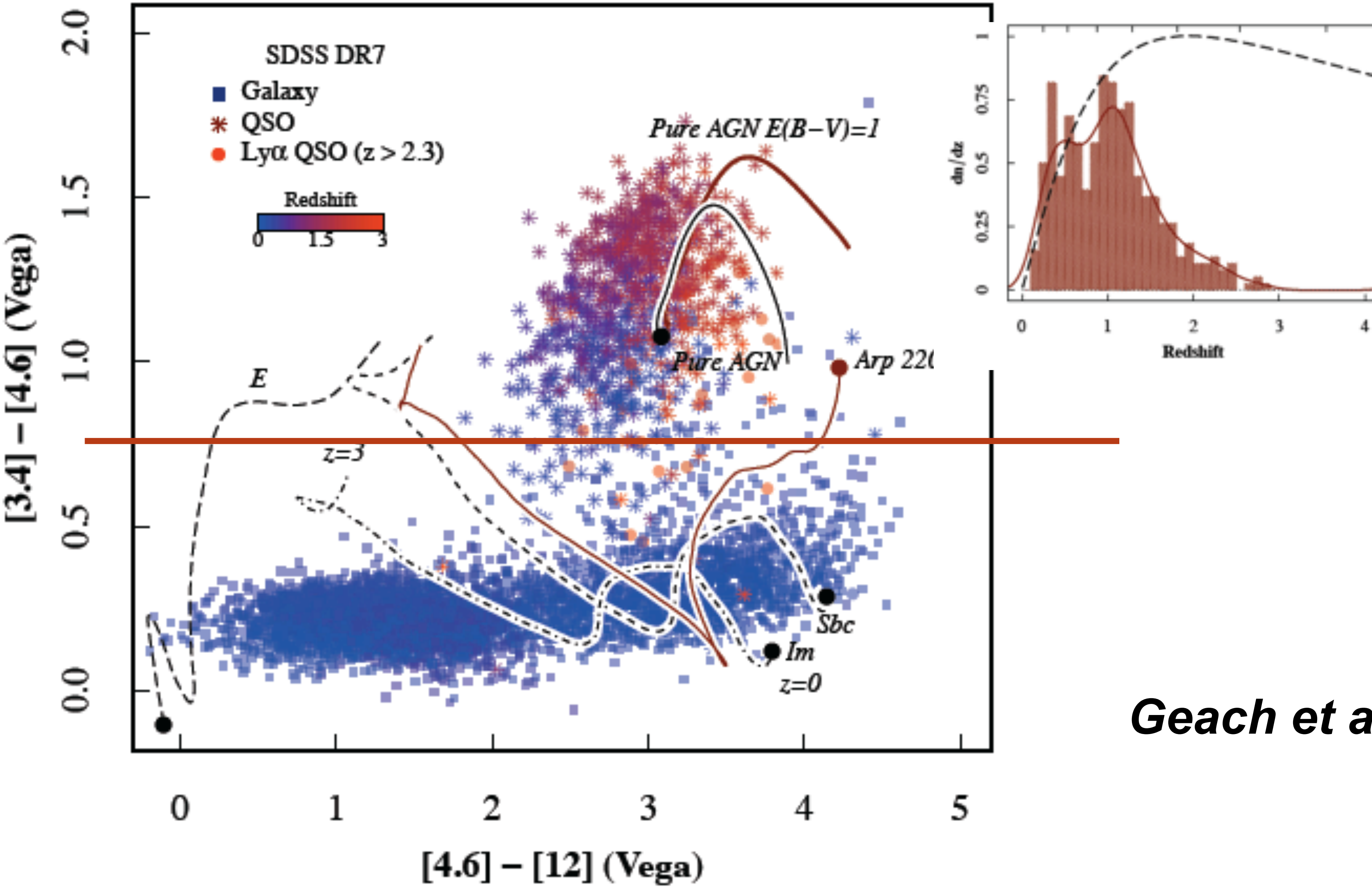
CMB Lensing/Herschel

simple model of flux traces mass at any given z

depending on z distribution of CIB, bias of CIB sources is 1.5-2



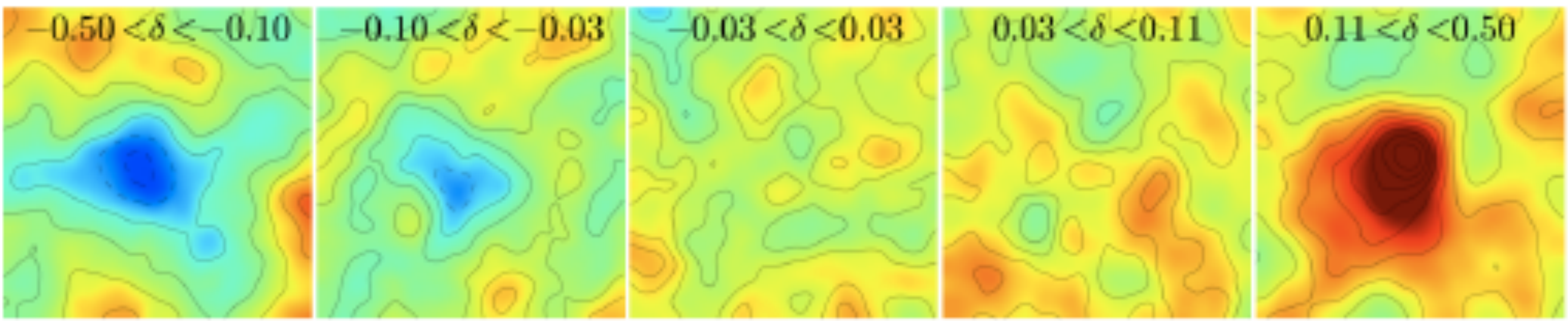
AGN Selection with WISE



Geach et al

Quasar-Mass Cross-Correlation Detected: SPT X WISE

stacked SPT lensing map in bins of AGN density



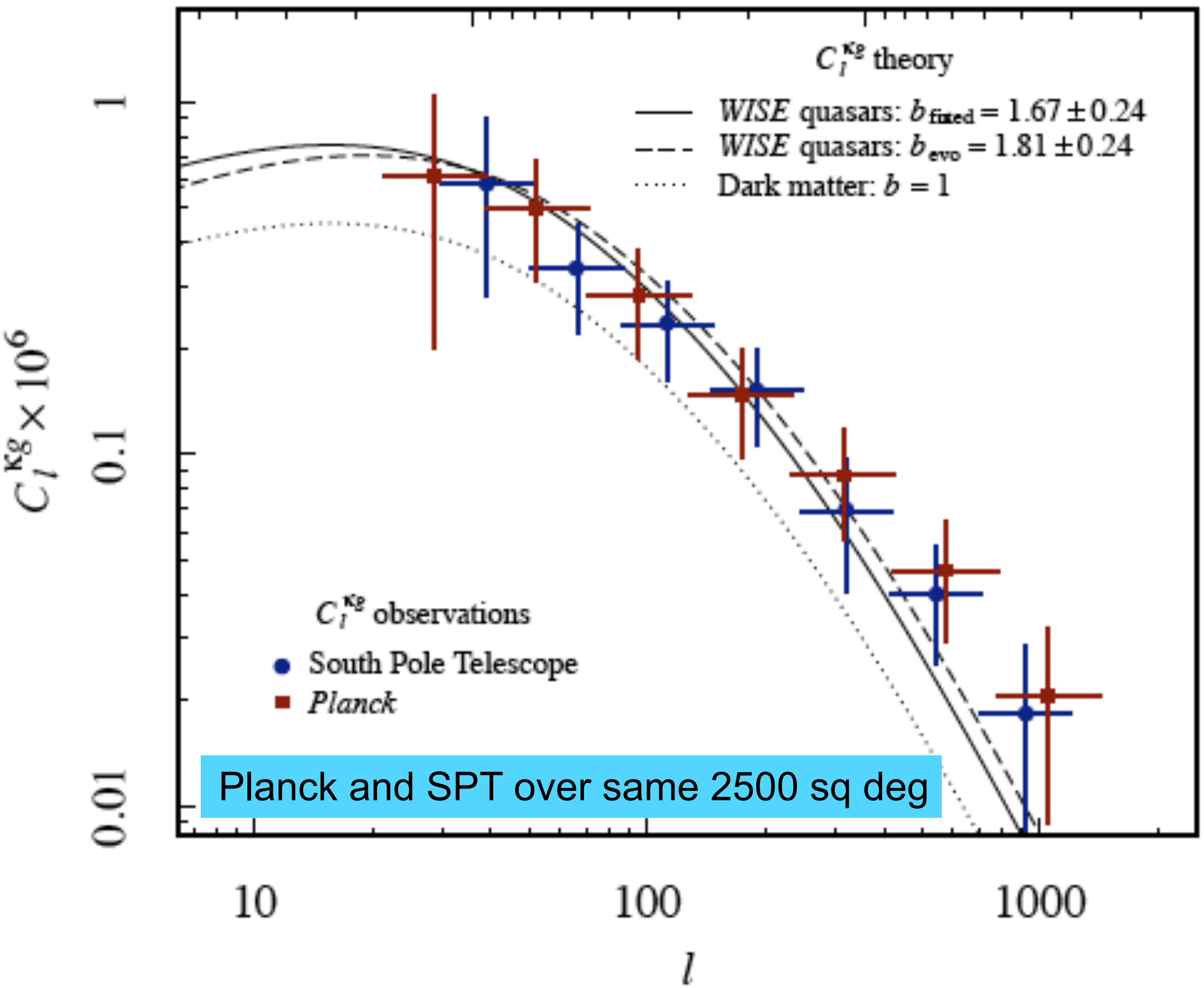
5^{o}

low AGN density

high AGN density

Geach et al

Quasar-Mass Cross-Correlation Detected: SPT X WISE

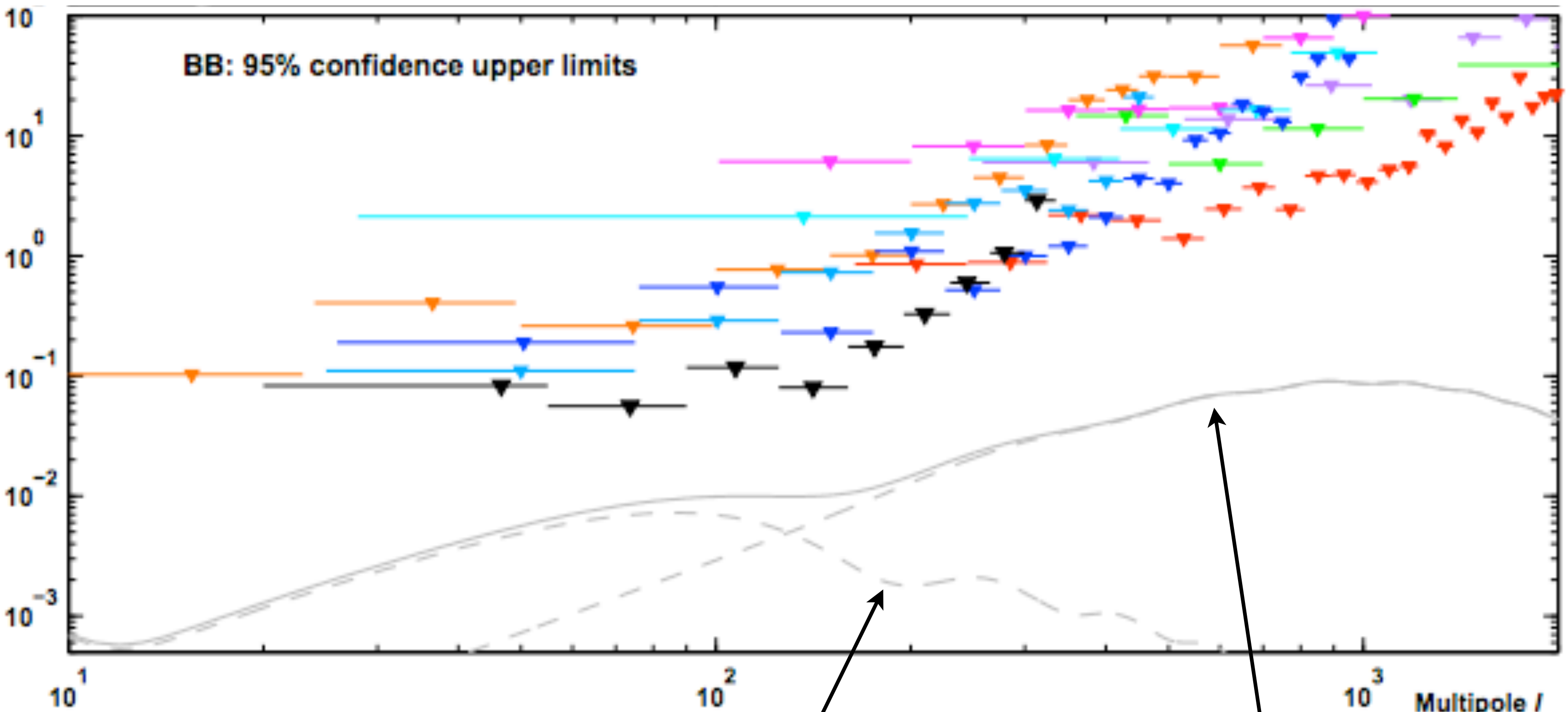


Planck and SPT in excellent agreement

bias measurements agree with expectations

Geach et al

Two Expected Sources of B Modes



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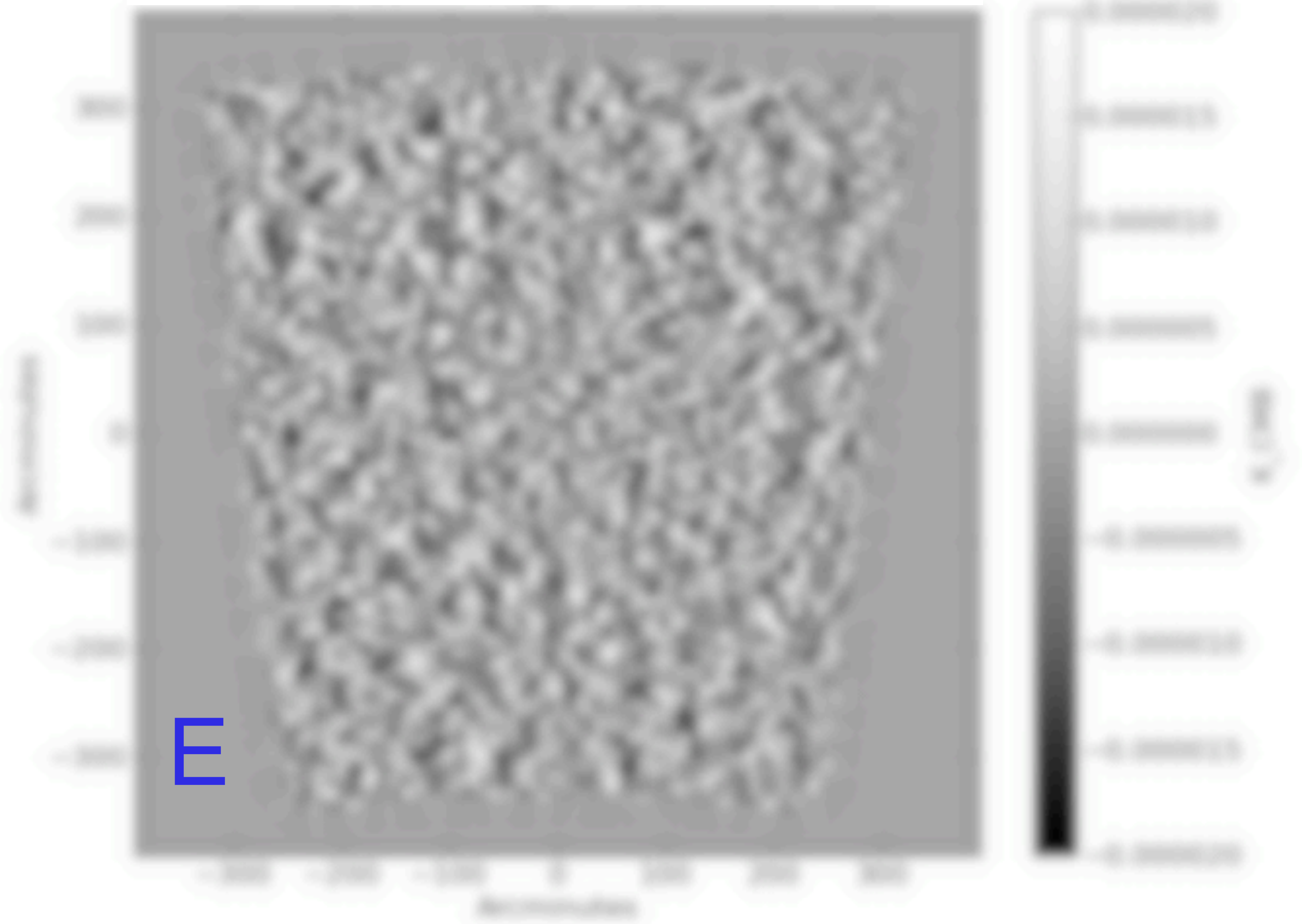
E-mode polarization of ra23h30, dec -55 field (150 GHz)



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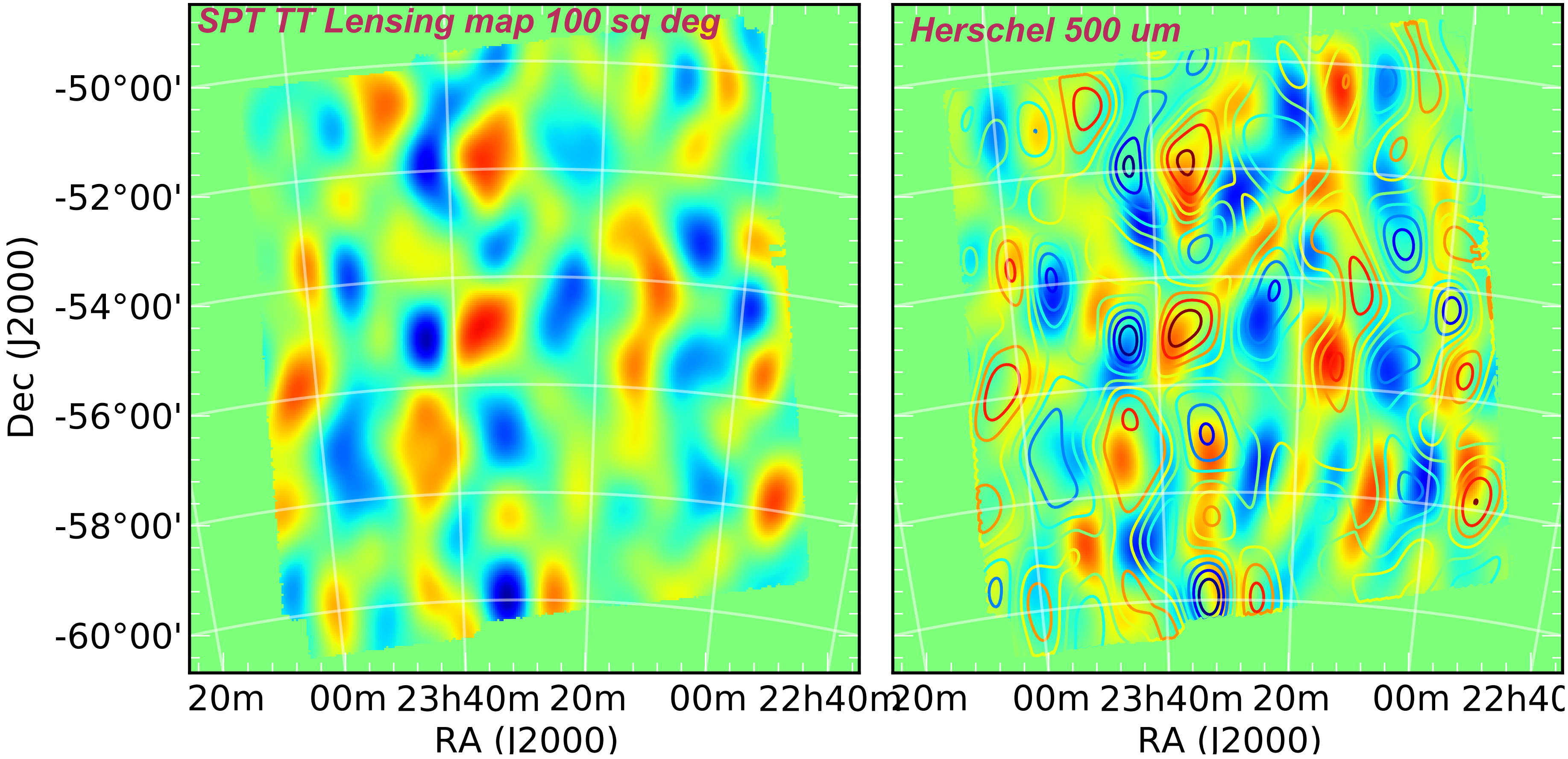
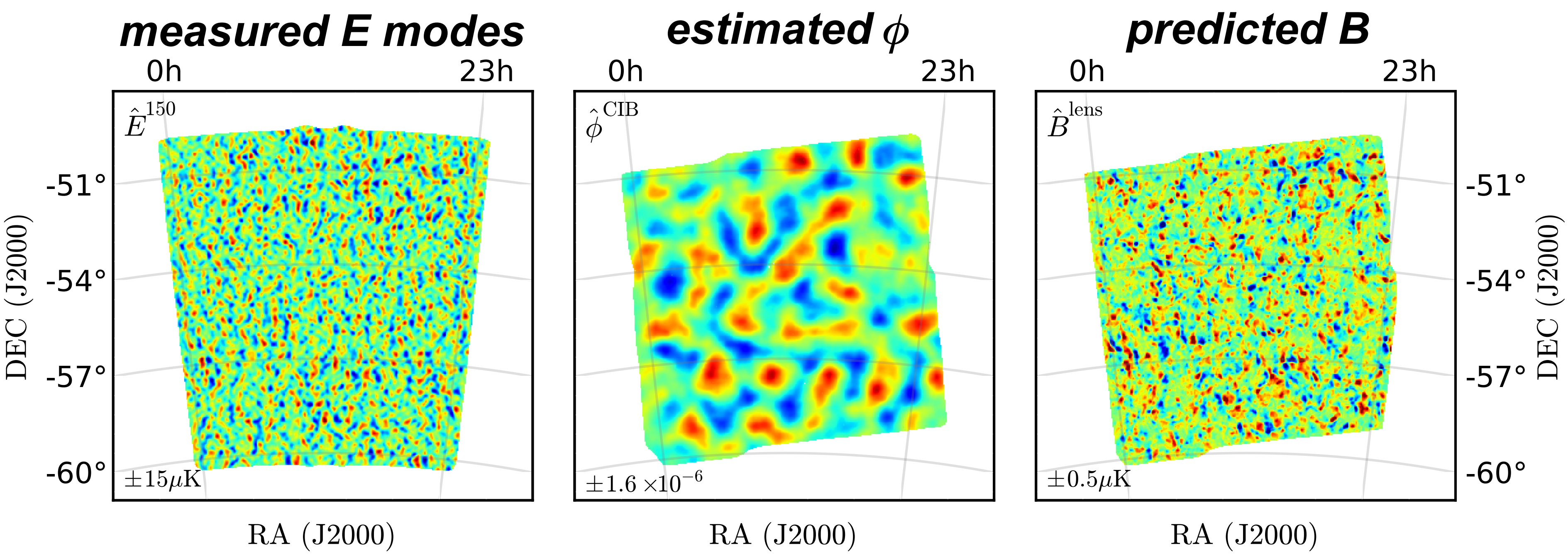
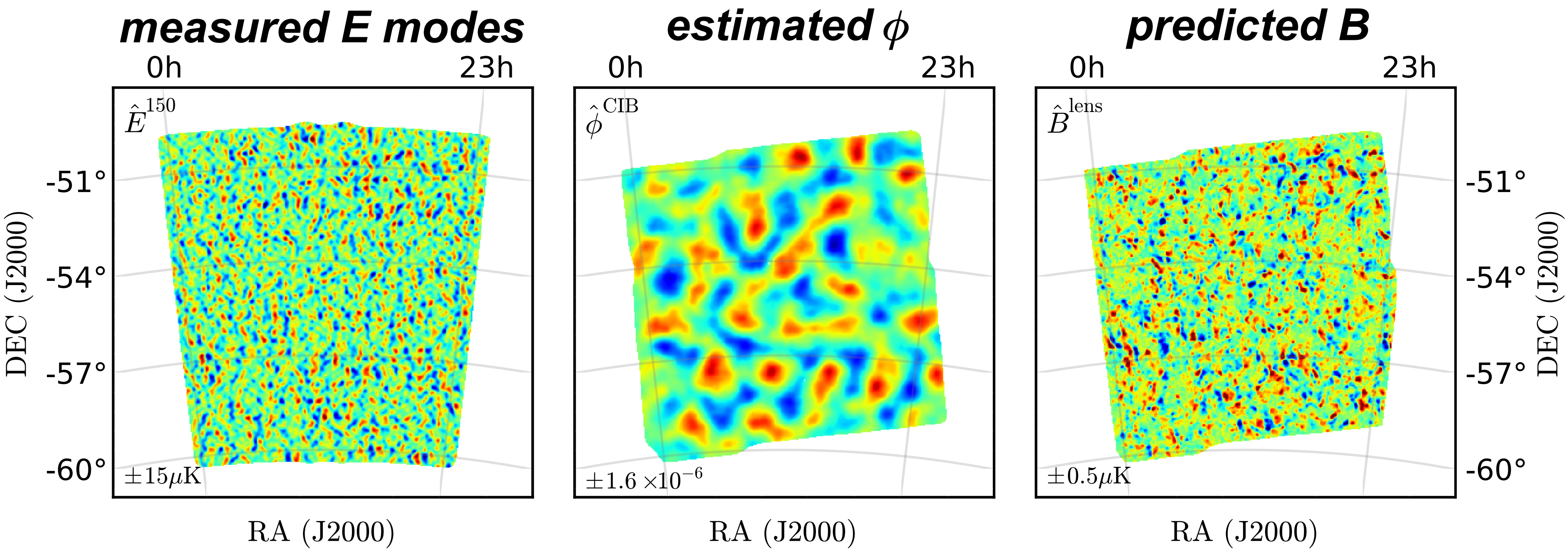


Predicting B-Modes



Hanson, Hoover, Crites et al 2013

Many Ways of Predicting B-Modes



E 150 GHz
E 90 GHz
E from Temperature

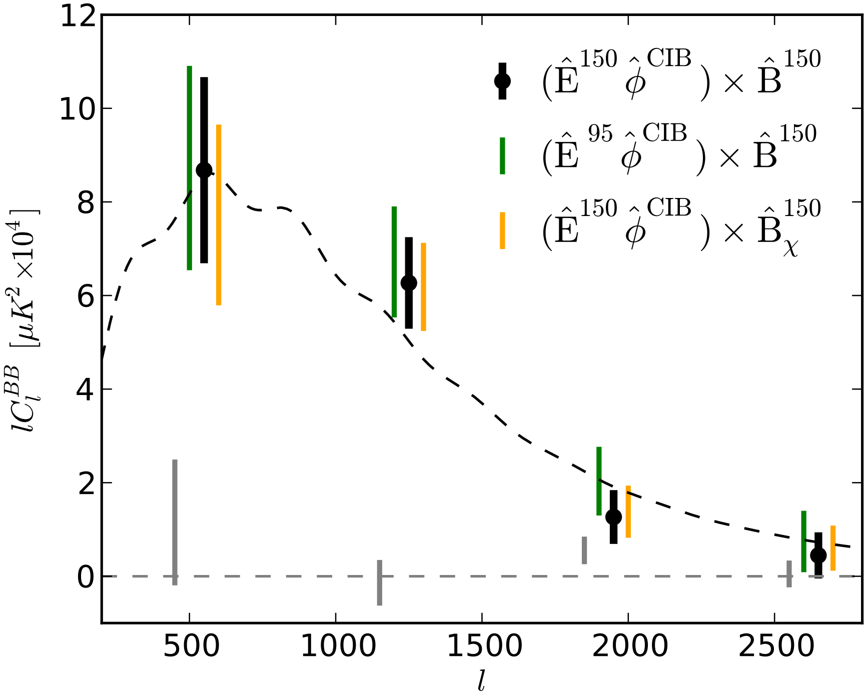
ϕ CIB
ϕ TT
ϕ EE
ϕ TE
(ϕ Spitzer cat)

X B 150 GHz
X B 90 GHz

Hanson, Hoover, Crites et al 2013

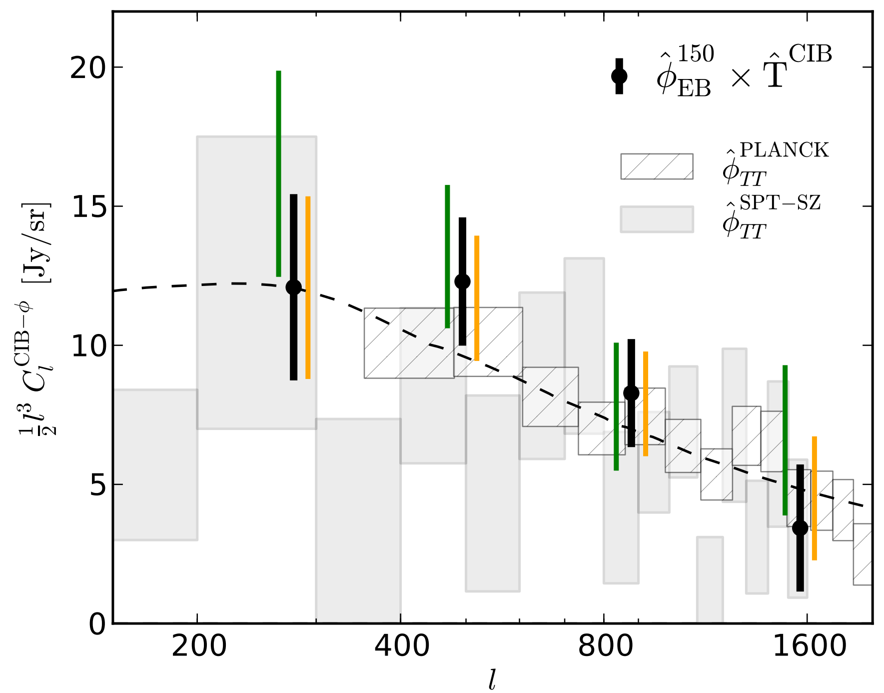
First Detection of B-Modes

(predicted B) X (measured B)



not zero at 7.7σ

ϕ^{EB} X T^{cib}



Hanson, Hoover, Crites et al 2013

Summary & Outlook

- high resolution CMB maps give new information about the universe
- gravitational lensing of the CMB a powerful new probe
  - power spectrum of mass fluctuations
  - directly connecting galaxies to mass
- B-mode polarization anisotropy has now been detected
  - next up: B modes from early universe!