# Cosmic Microwave Background Polarization

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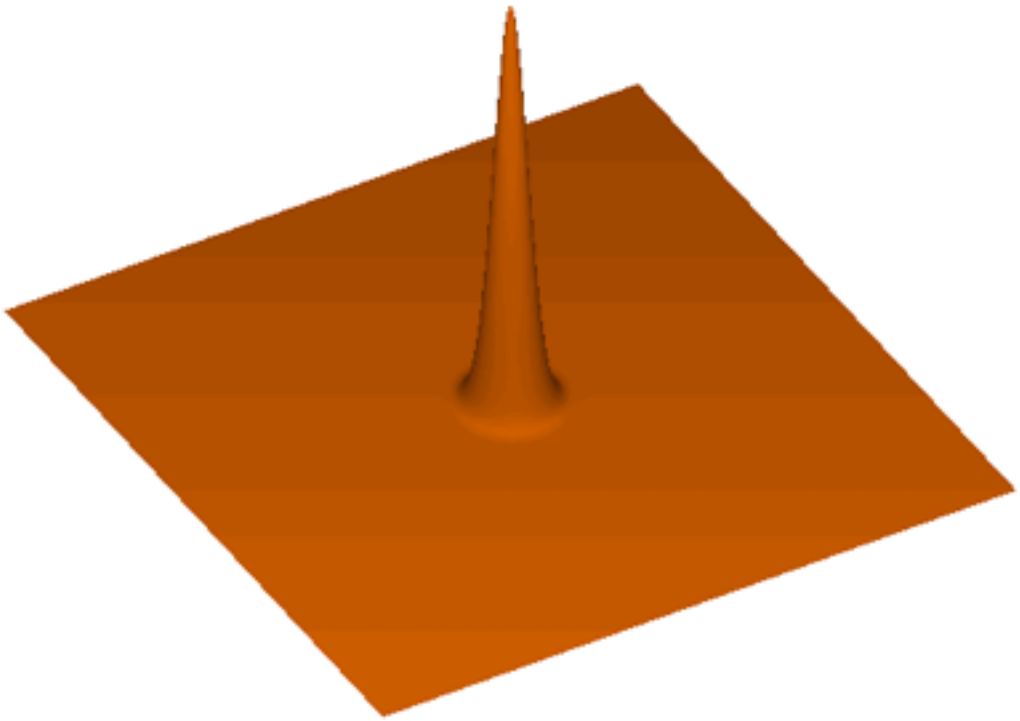
# Outline

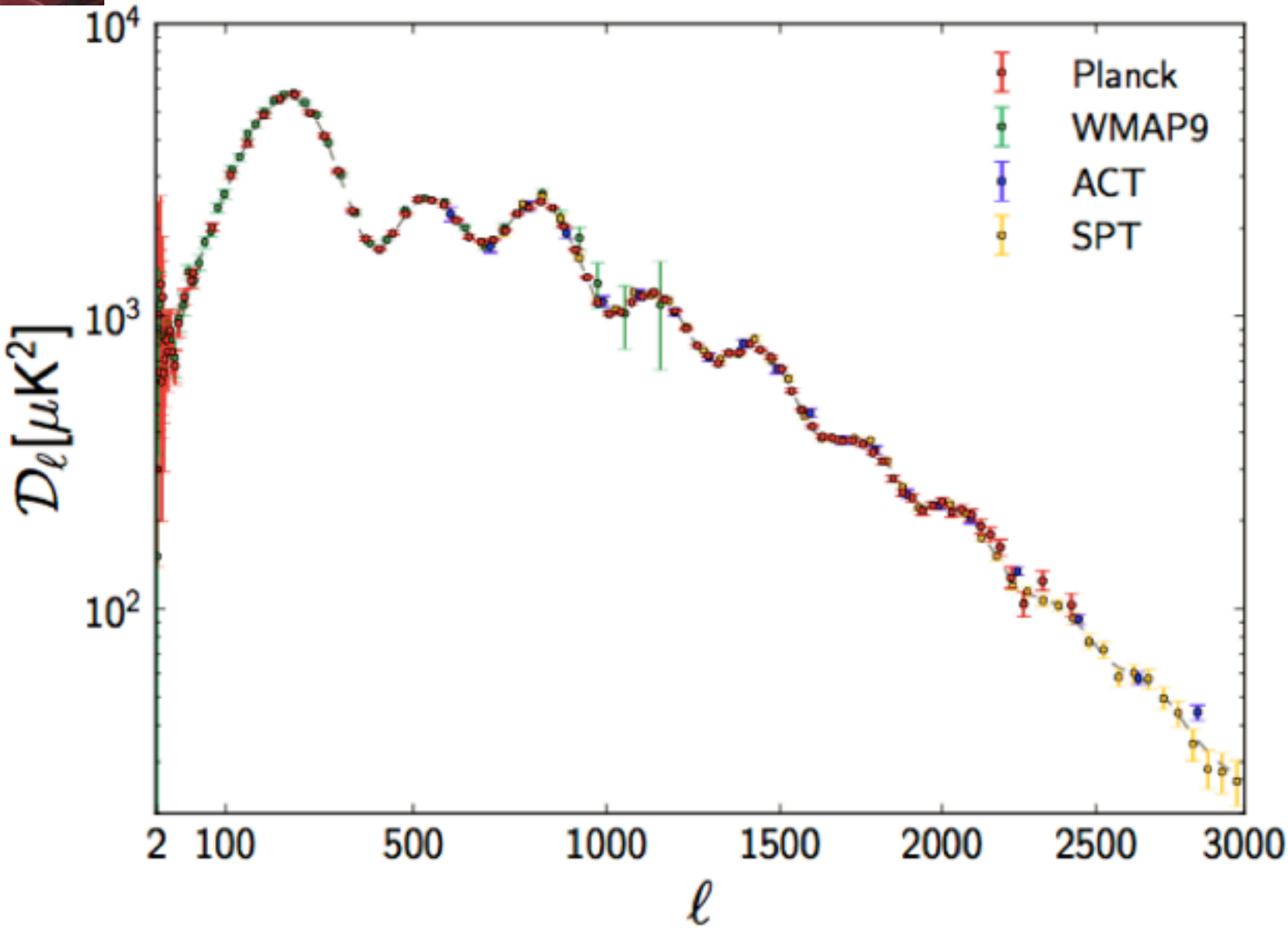
- 1: Overview of Primary CMB Anisotropies and Polarization
- 2: Primary, Secondary Anisotropies and Foregrounds
    - cmb parameters + extensions
    - SZ effect and other foregrounds
    - gravitational lensing
- 3: CMB Polarization Measurements

# *Acoustic Waves*

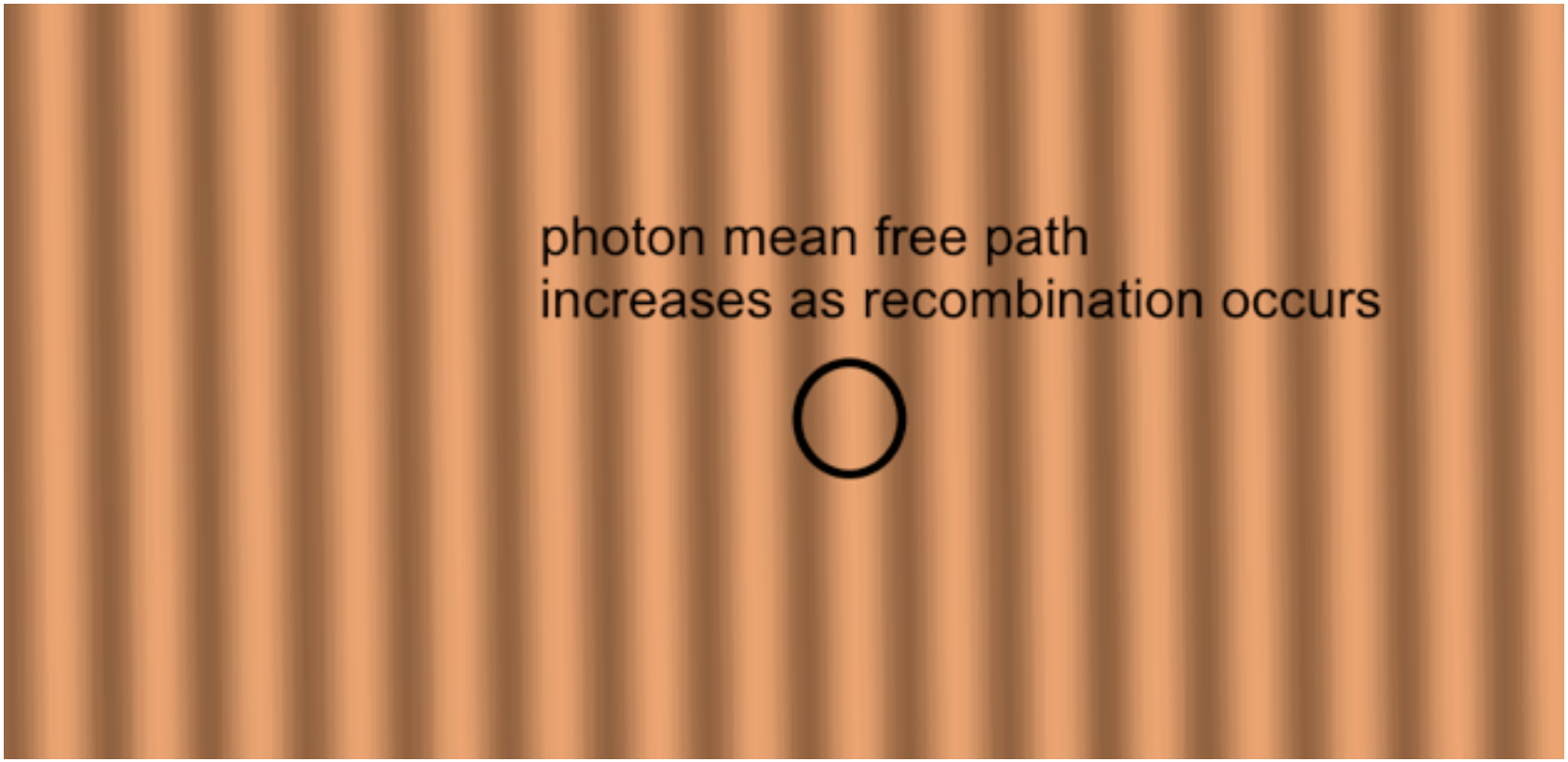


- cmb anisotropy measures sound waves, gravitational redshifts, intrinsic photon overdensities, diffusion

# CMB Angular Power Spectrum

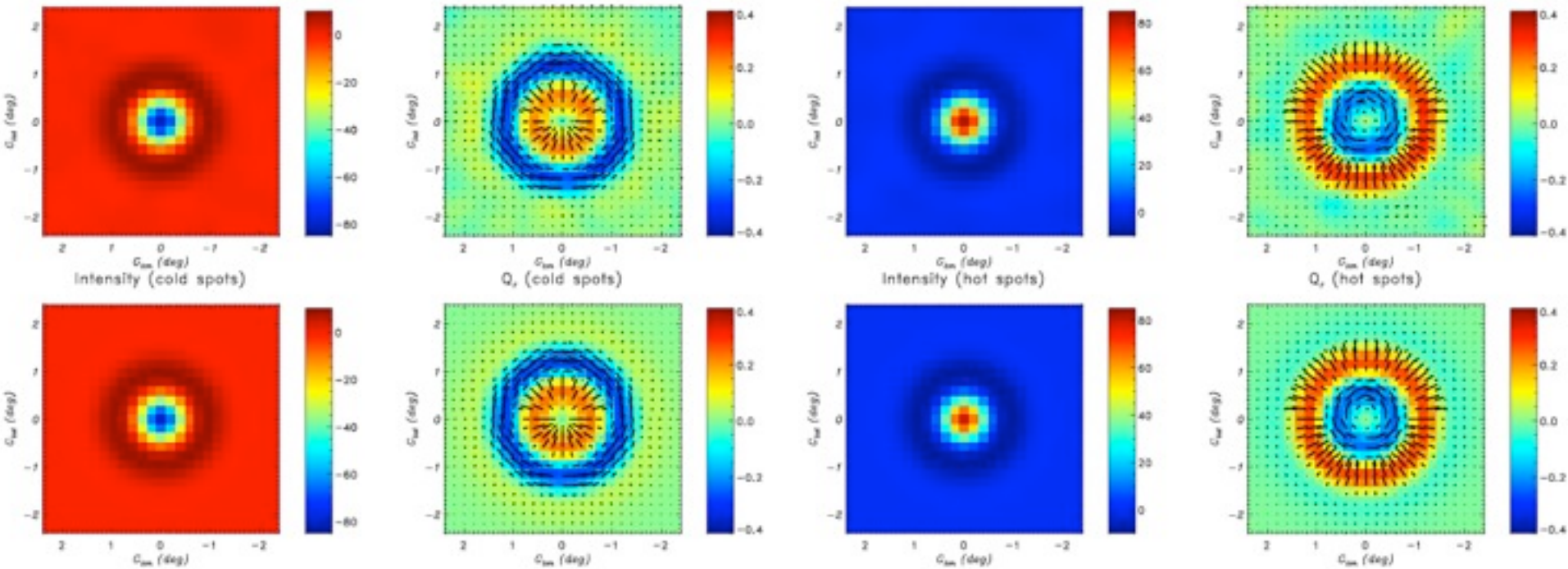


# Density fluctuations generate pure E mode




- E-modes <=> polarization
- lensing convergence <=> shear

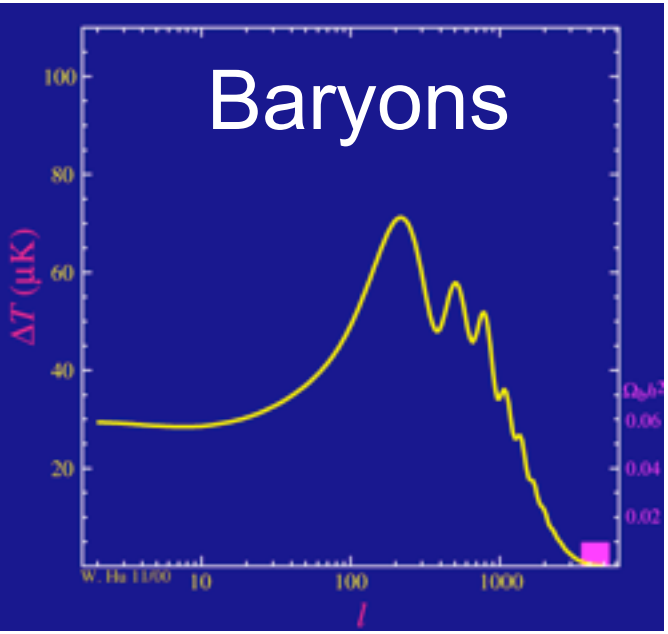
# Temperature/Polarization Correlation

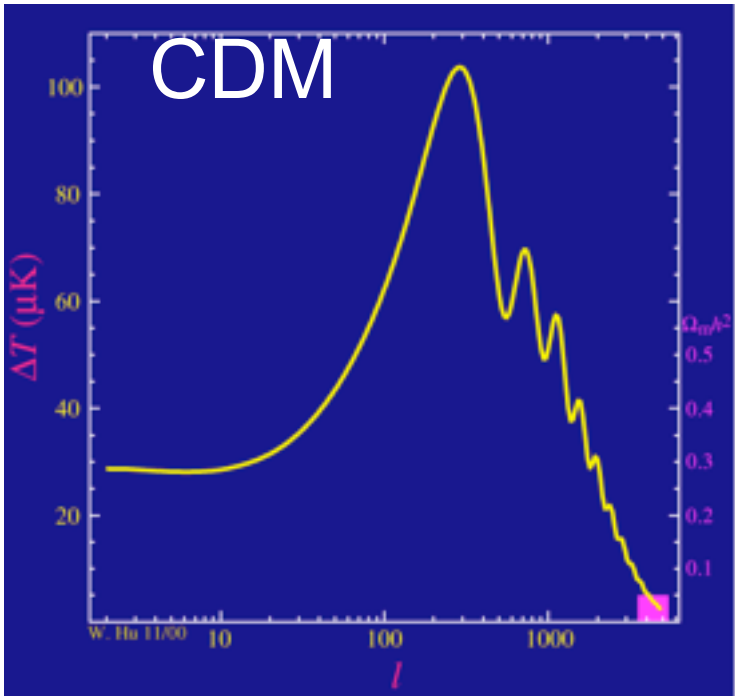


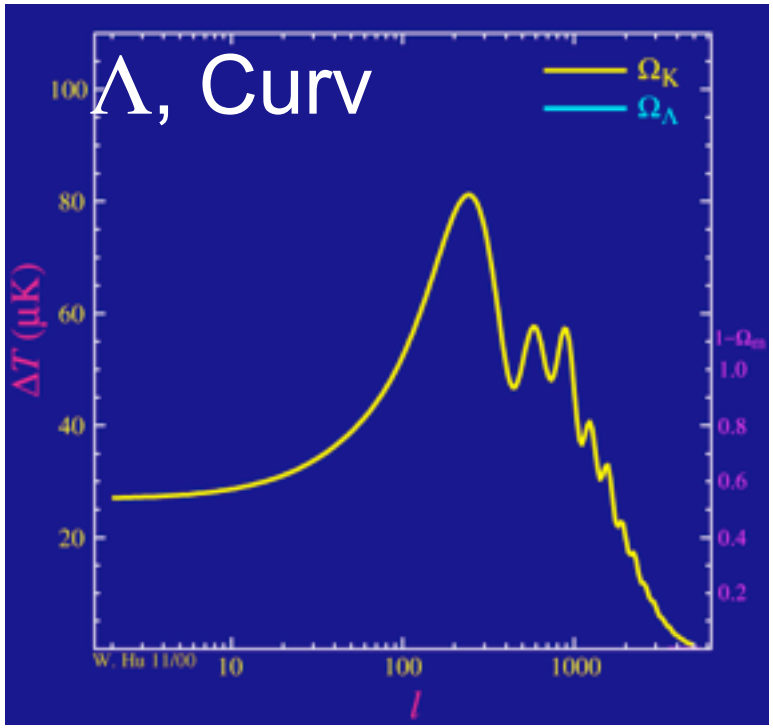

- Stack in Planck (first shown by WMAP)
- top: data, bottom: sim

# What Does the CMB Measure Well?

| Parameter | *Planck* | | *Planck*+lensing | | *Planck*+WP | |
|---|---|---|---|---|---|---|
| | Best fit | 68% limits | Best fit | 68% limits | Best fit | 68% limits |
| $\Omega_b h^2$ . . . . . | 0.022068 | $0.02207 \pm 0.00033$ | 0.022242 | $0.02217 \pm 0.00033$ | 0.022032 | $0.02205 \pm 0.00028$ |
| $\Omega_c h^2$ . . . . . | 0.12029 | $0.1196 \pm 0.0031$ | 0.11805 | $0.1186 \pm 0.0031$ | 0.12038 | $0.1199 \pm 0.0027$ |
| $100\theta_{MC}$ . . . . . | 1.04122 | $1.04132 \pm 0.00068$ | 1.04150 | $1.04141 \pm 0.00067$ | 1.04119 | $1.04131 \pm 0.00063$ |
| $\tau$ . . . . . | 0.0925 | $0.097 \pm 0.038$ | 0.0949 | $0.089 \pm 0.032$ | 0.0925 | $0.089^{+0.012}_{-0.014}$ |
| $n_s$ . . . . . | 0.9624 | $0.9616 \pm 0.0094$ | 0.9675 | $0.9635 \pm 0.0094$ | 0.9619 | $0.9603 \pm 0.0073$ |
| $\ln(10^{10}A_s)$ . . . . . | 3.098 | $3.103 \pm 0.072$ | 3.098 | $3.085 \pm 0.057$ | 3.0980 | $3.089^{+0.024}_{-0.027}$ |
| $\Omega_\Lambda$ . . . . . | 0.6825 | $0.686 \pm 0.020$ | 0.6964 | $0.693 \pm 0.019$ | 0.6817 | $0.685^{+0.018}_{-0.016}$ |
| $\Omega_m$ . . . . . | 0.3175 | $0.314 \pm 0.020$ | 0.3036 | $0.307 \pm 0.019$ | 0.3183 | $0.315^{+0.016}_{-0.018}$ |
| $\sigma_8$ . . . . . | 0.8344 | $0.834 \pm 0.027$ | 0.8285 | $0.823 \pm 0.018$ | 0.8347 | $0.829 \pm 0.012$ |
| $z_{re}$ . . . . . | 11.35 | $11.4^{+4.0}_{-2.8}$ | 11.45 | $10.8^{+3.1}_{-2.5}$ | 11.37 | $11.1 \pm 1.1$ |
| $H_0$ . . . . . | 67.11 | $67.4 \pm 1.4$ | 68.14 | $67.9 \pm 1.5$ | 67.04 | $67.3 \pm 1.2$ |

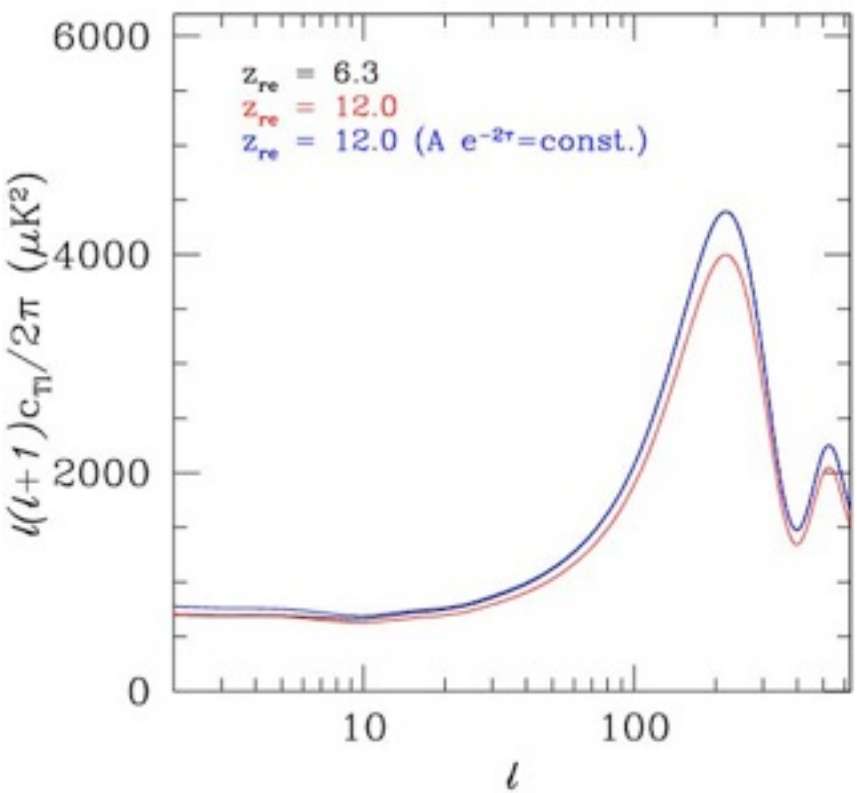


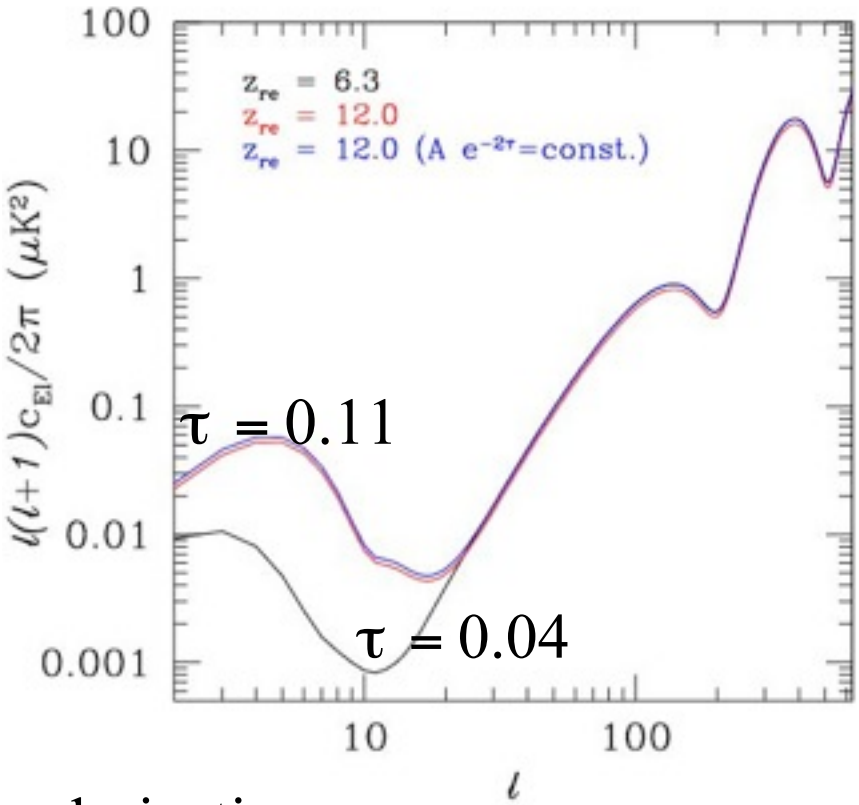




Wayne Hu tutorials

# Reionization and the CMB




temperature

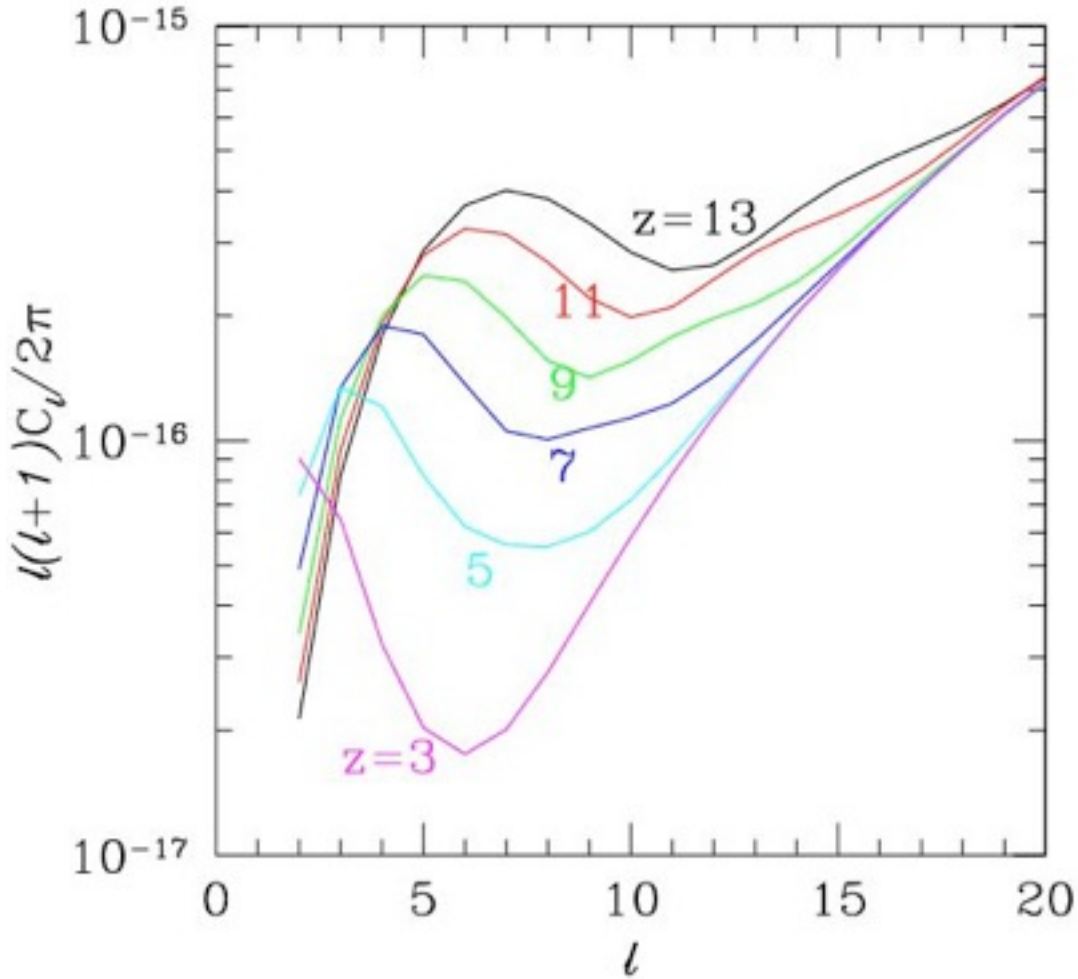



polarization

WMAP: +- 0.01 ; Planck: +-0.005 ; ???: +-0.002

# Ionization and CMB Polarization

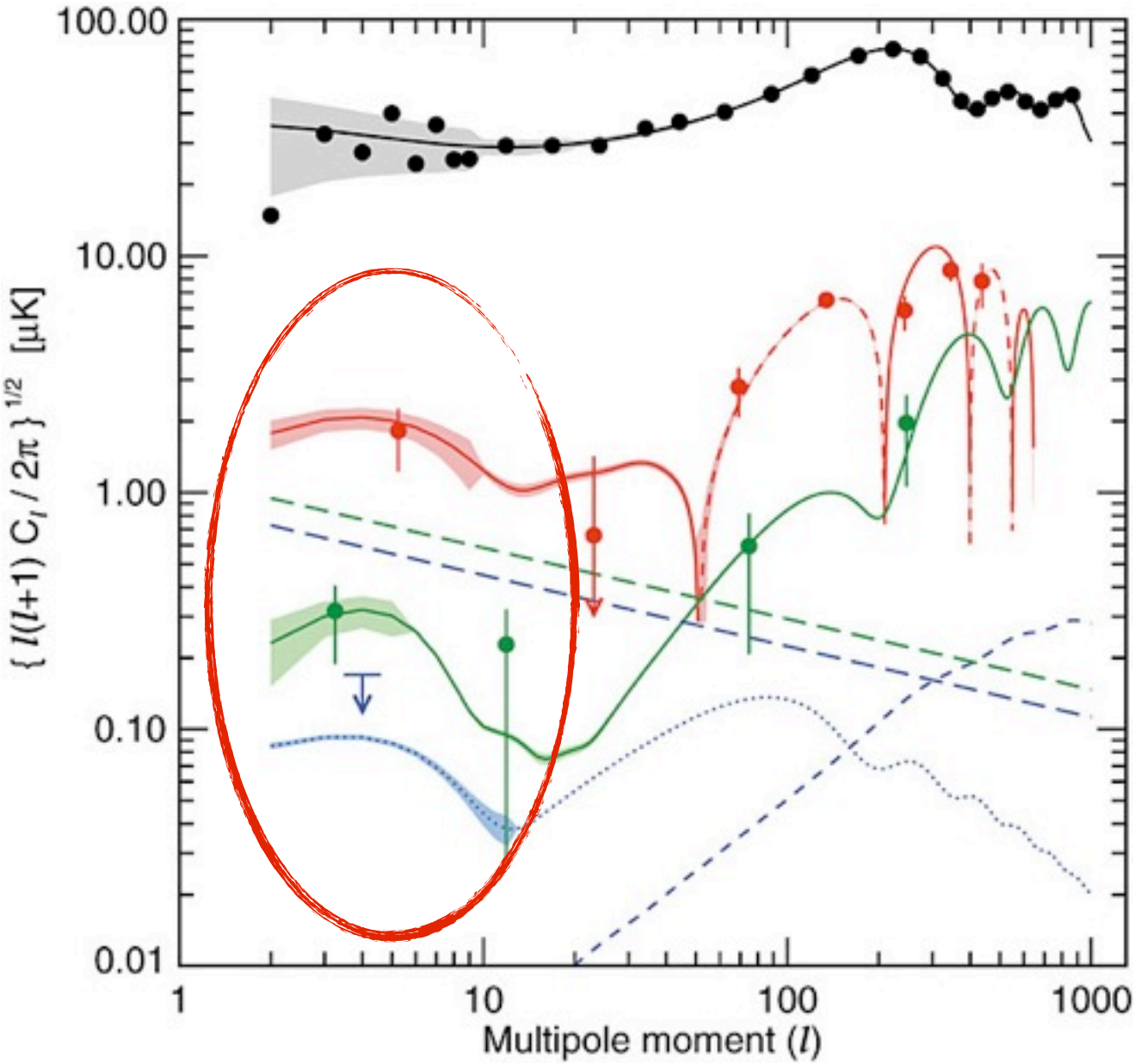
"Pulse" of ionization dz=1




***Reionization bump tells you about reionization!***

***(very coarsely, and in a foreground-laden part of the CMB spectrum)***

# Thomson Optical Depth



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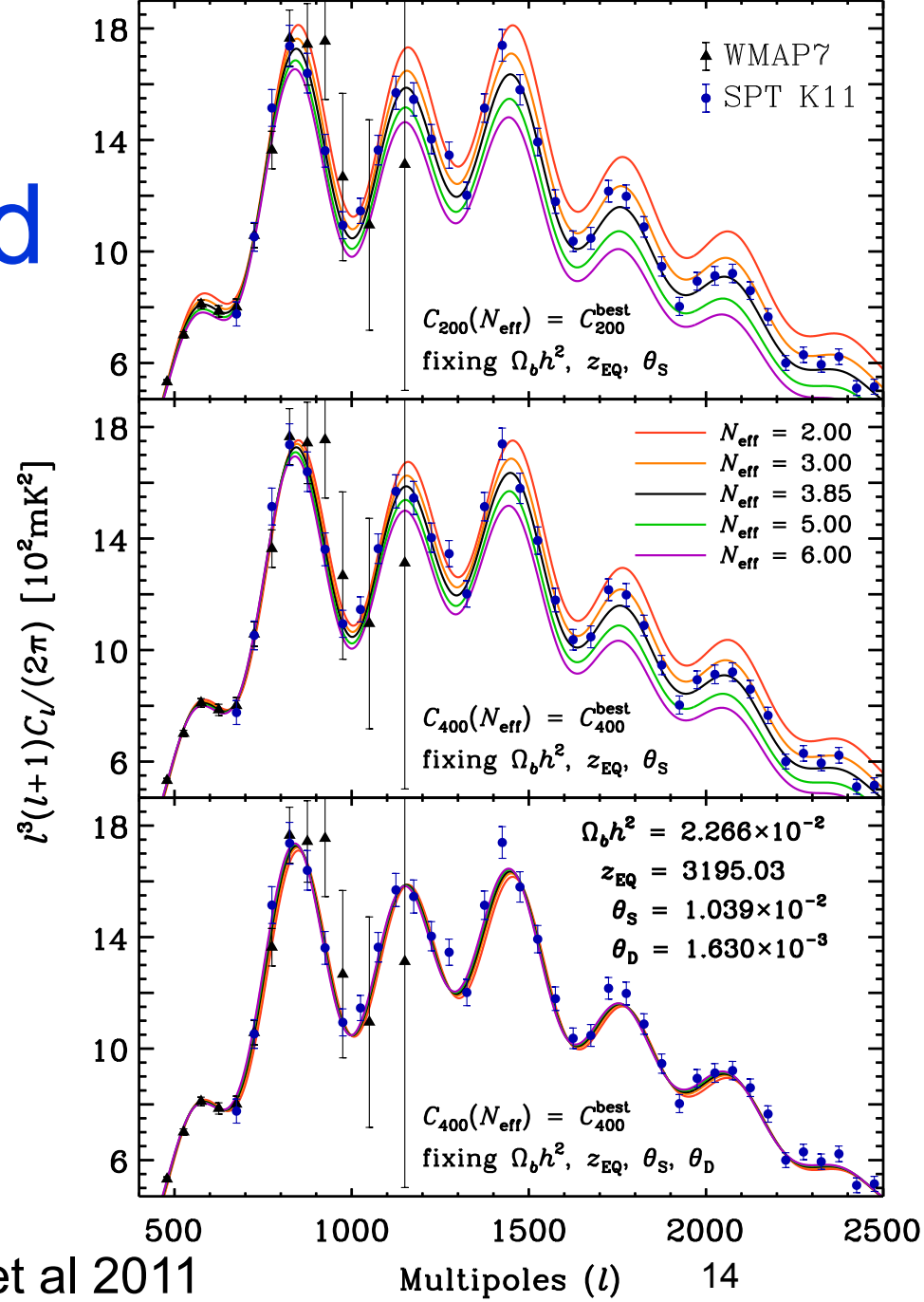
from Planck parameters paper

# What else does the CMB measure?

- dark energy
- neutrino masses
- helium
- amount of radiation: “$N_{eff}$”

# Extra Neutrinos and the CMB

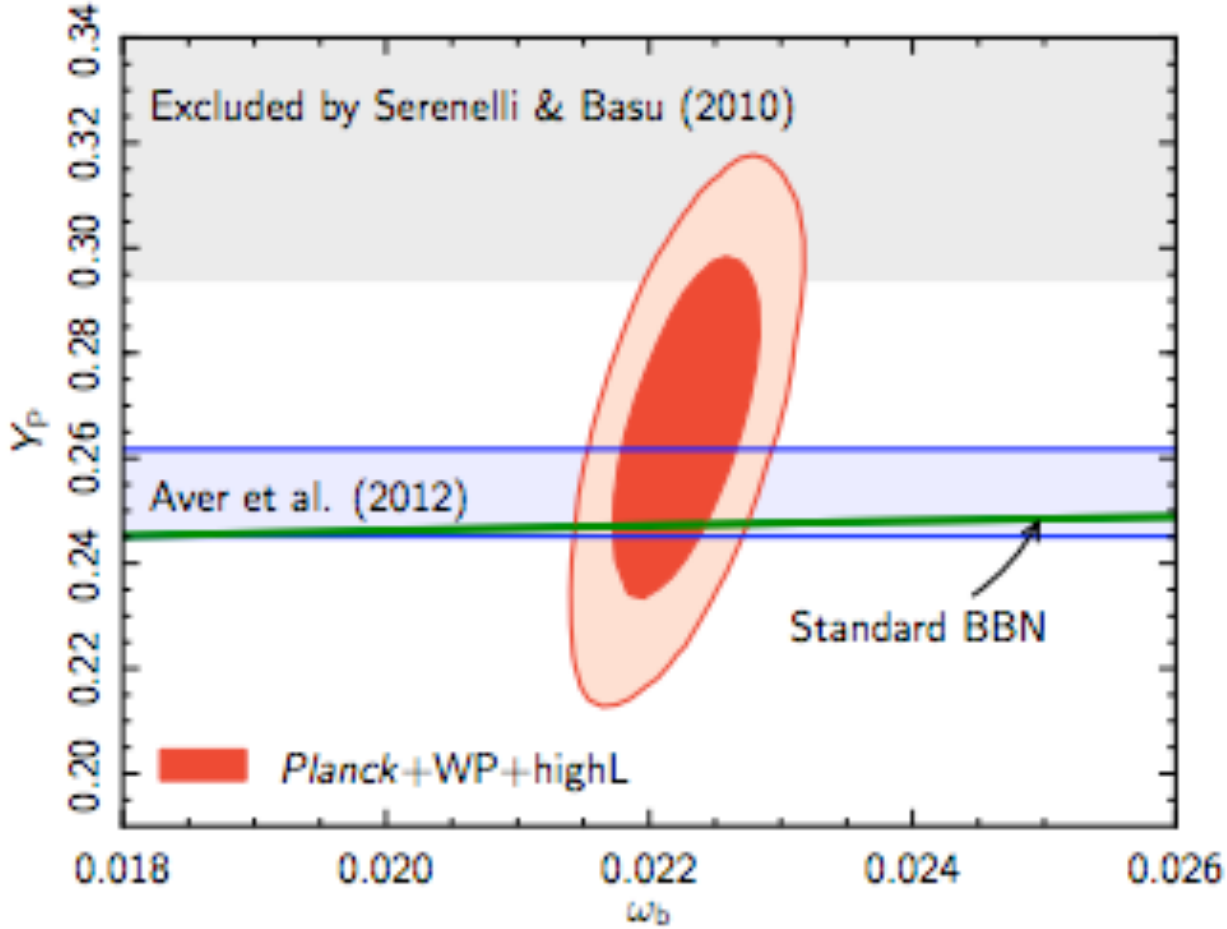
- all other things held fixed, increasing $N_{eff}$ leads to increased damping on small scales




Hou et al 2011

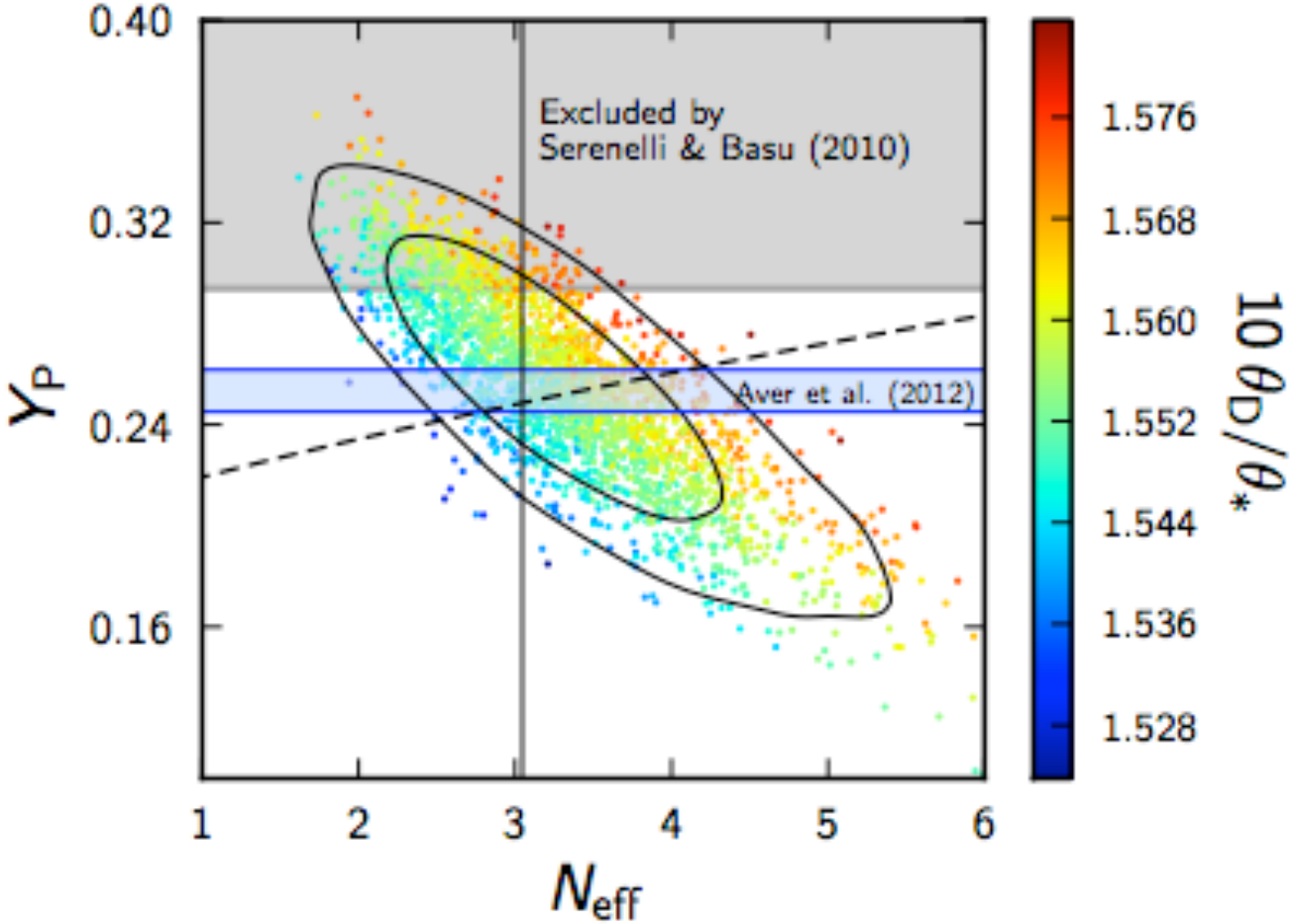
# CMB Comparisons with BBN

- measured Helium consistent



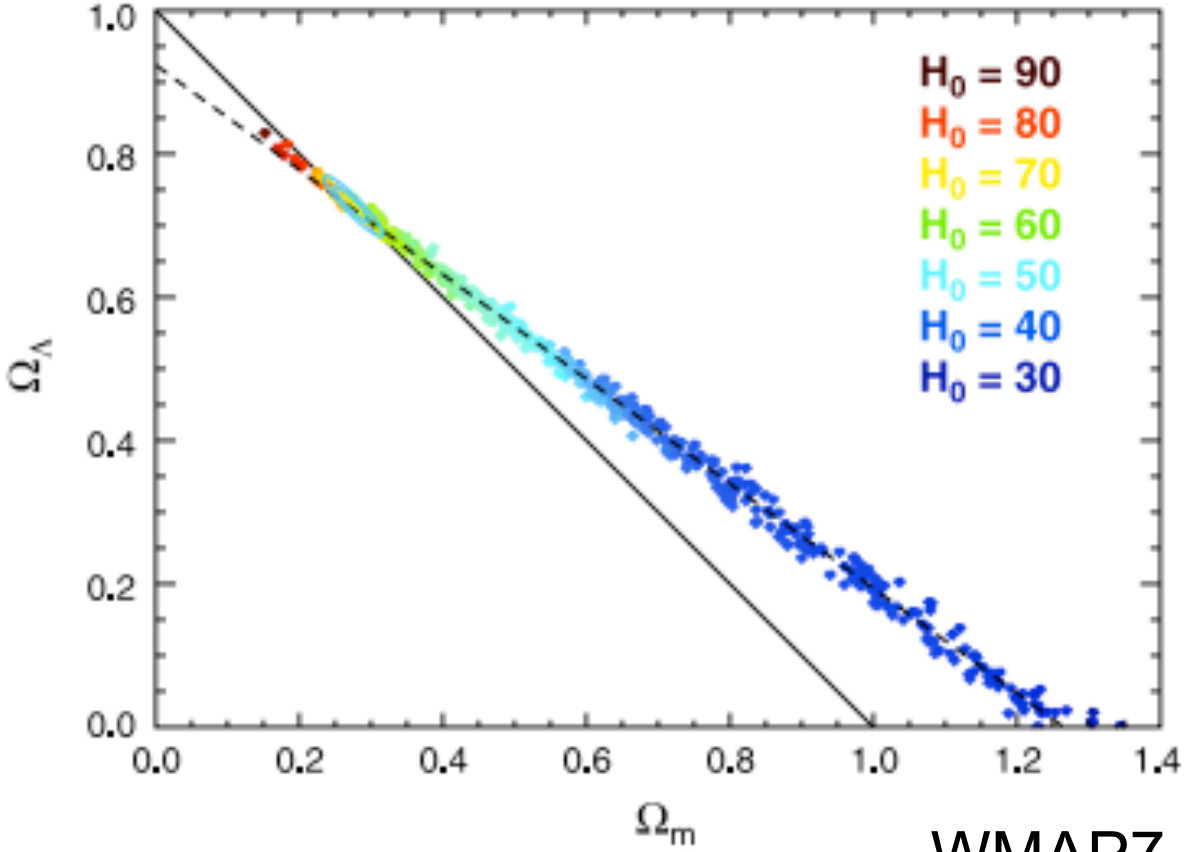
# CMB Comparisons with BBN

- extra "neutrinos" can't be too numerous



# Low-z parameters difficult

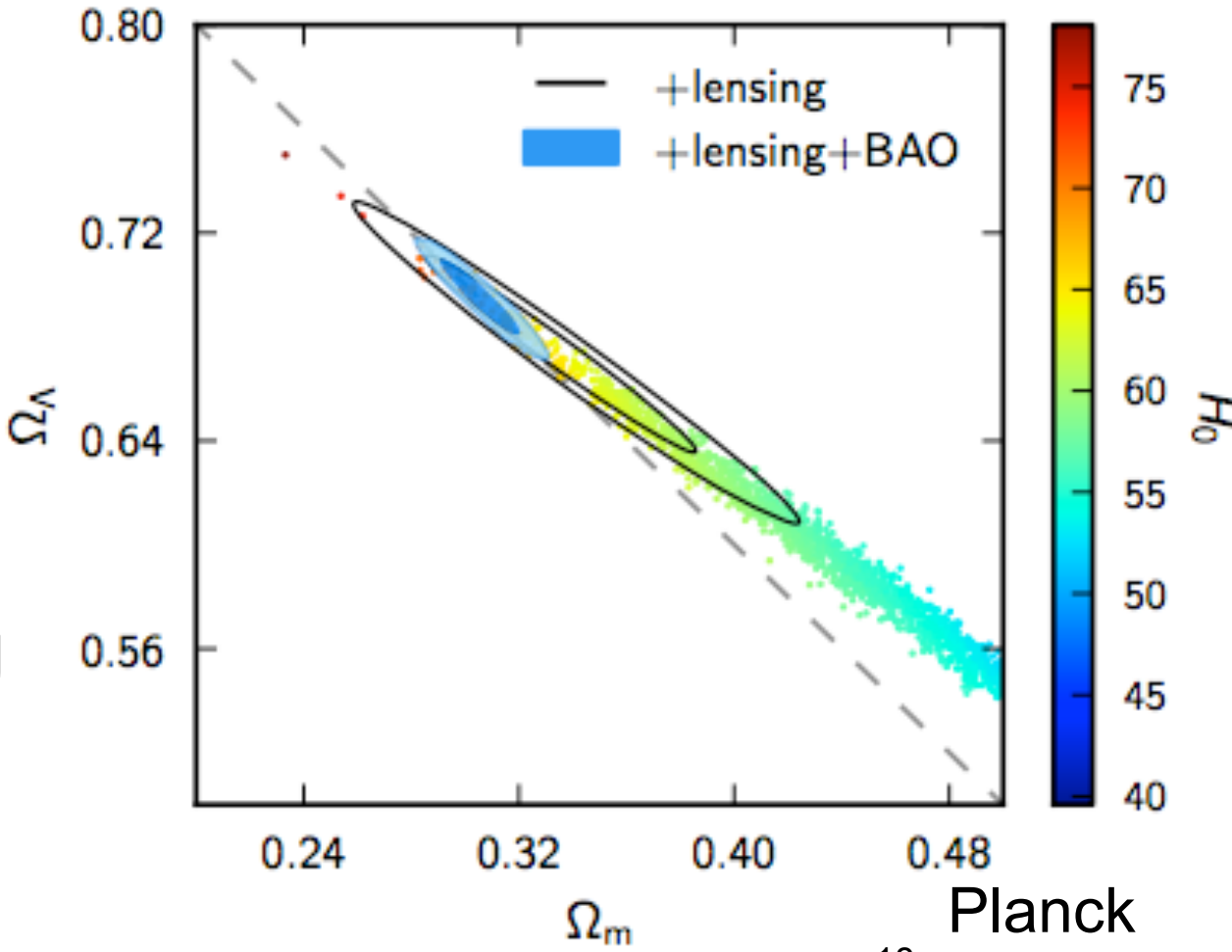
- angular size of sound horizon well-measured, but can trade off Hubble constant with a bit of curvature




WMAP7

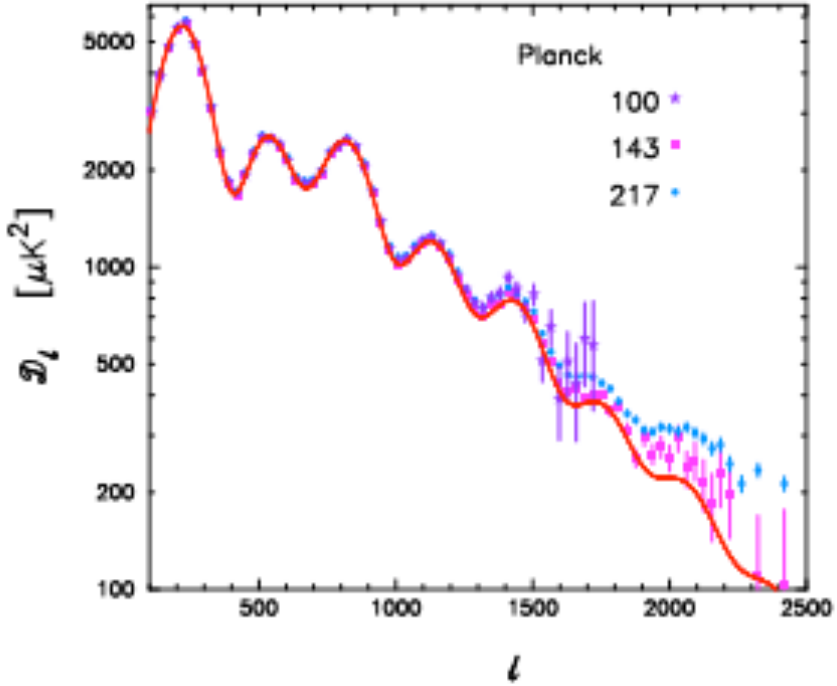
# Low-z parameters difficult

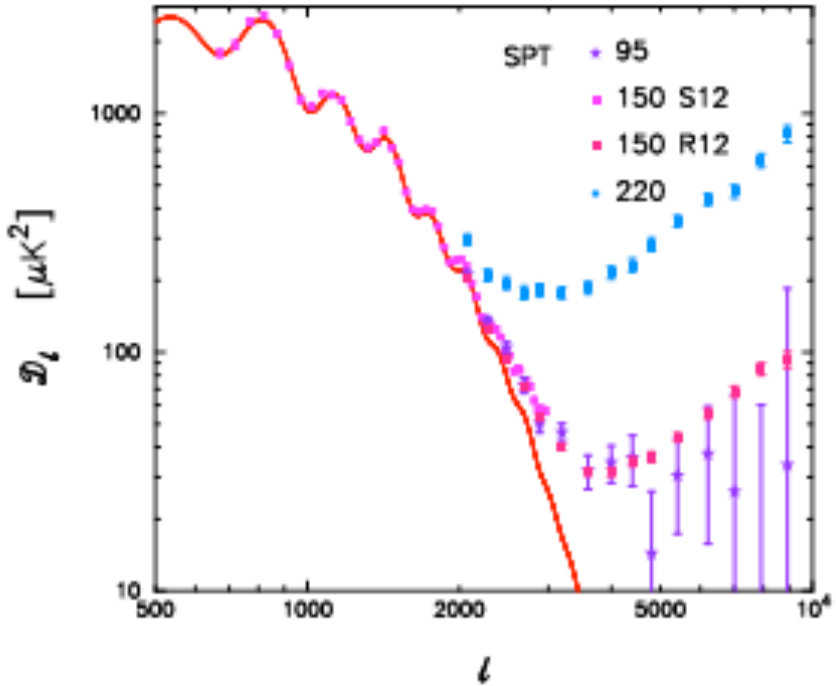
- degeneracy broken with almost any other measurement (e.g., amount of CMB lensing or BAO)




Planck

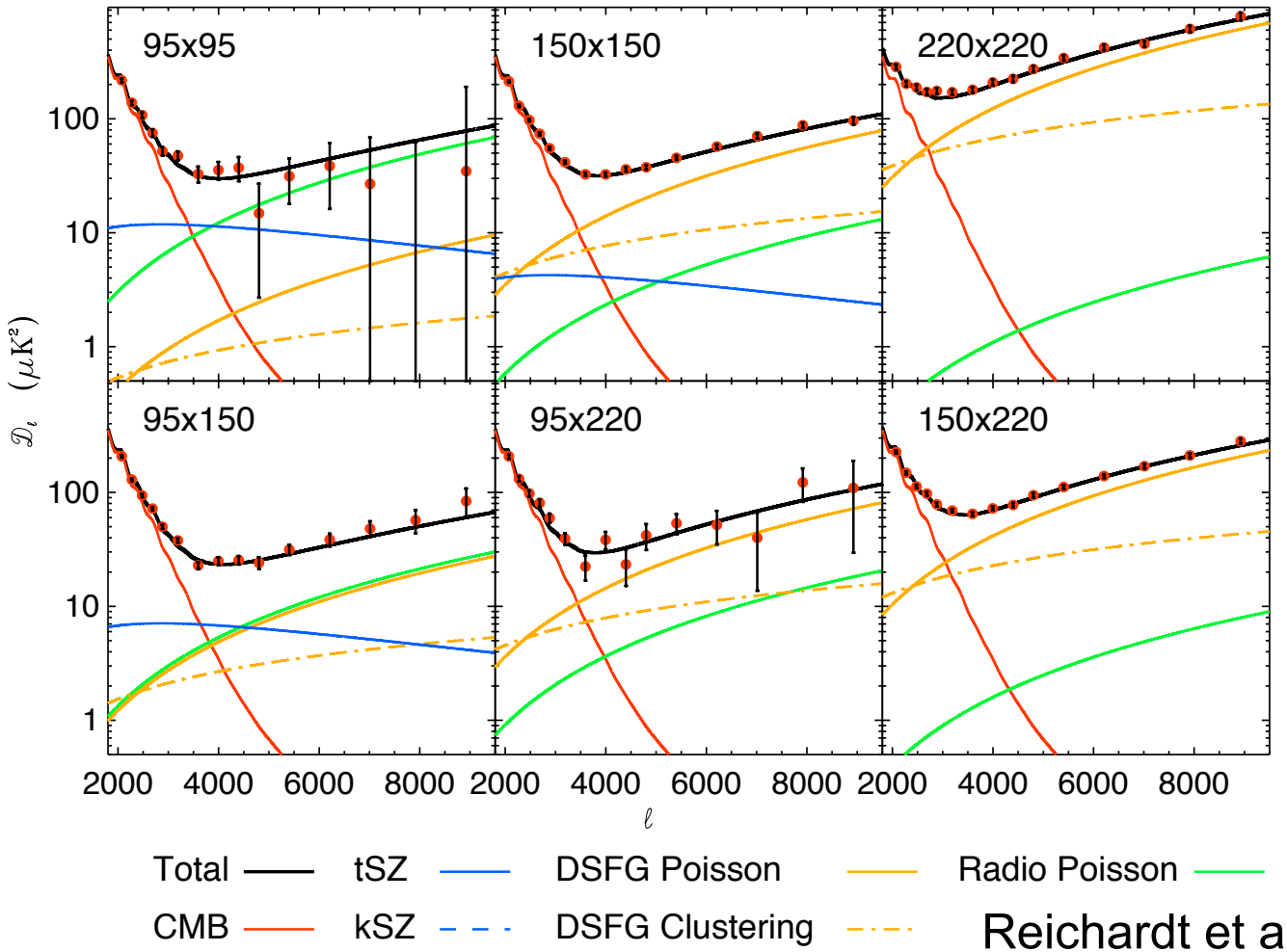
# Small Scales Limited by Foregrounds



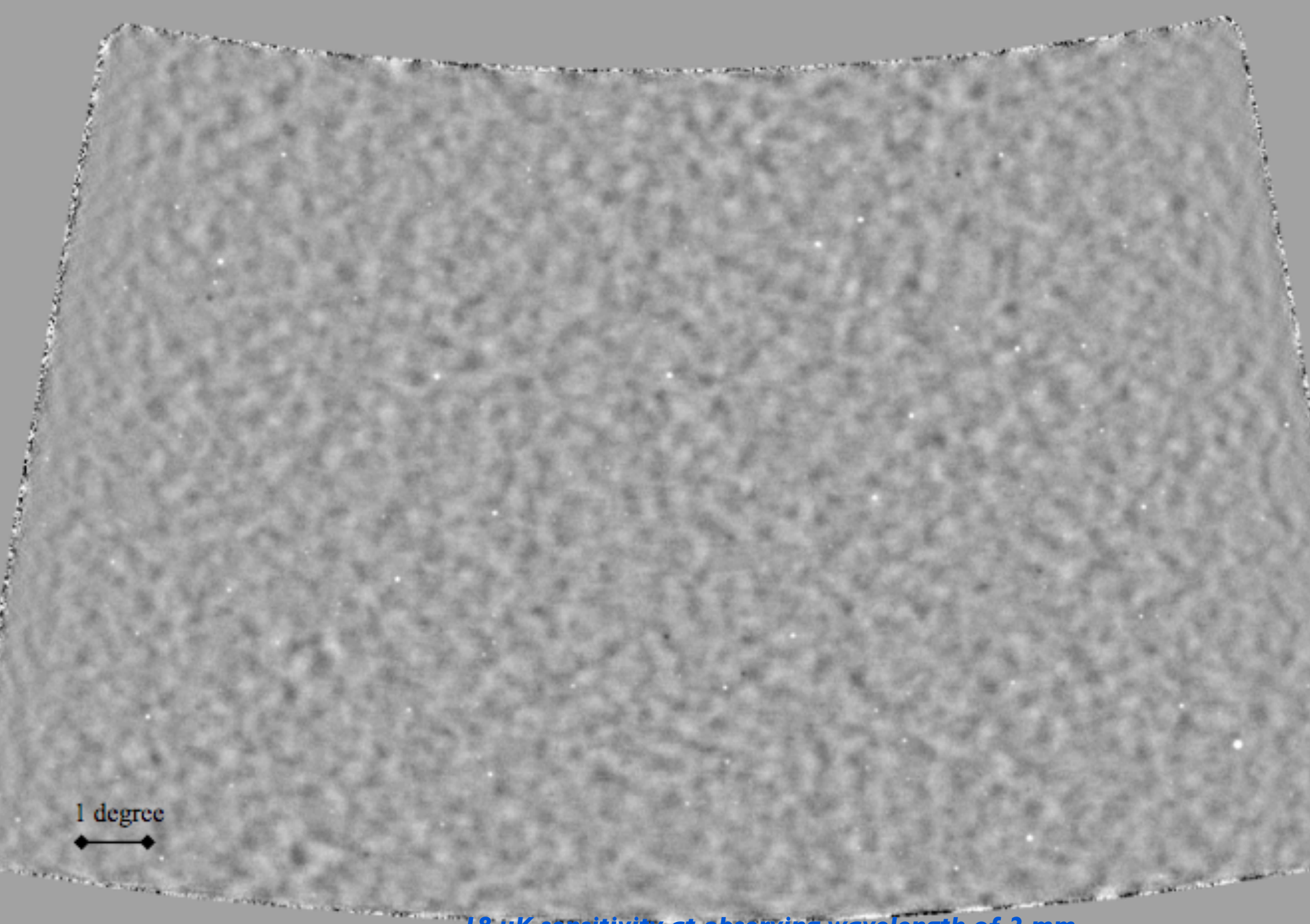



# Separation into Components

- dusty galaxies a huge problem at 150 and 220 GHz




Reichardt et al




*18 uK sensitivity at observing wavelength of 2 mm*
*roughly same resolution as your eye*

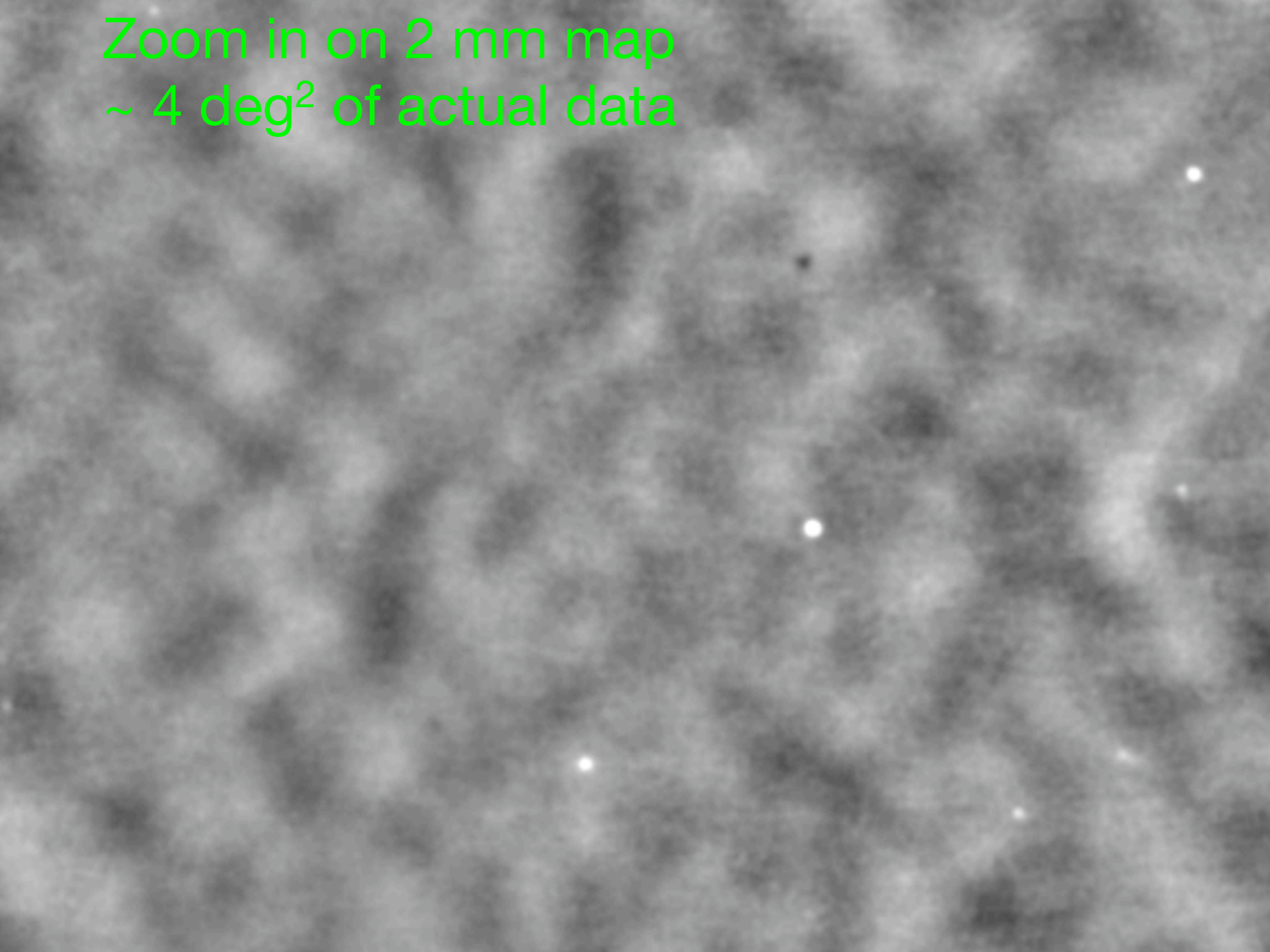
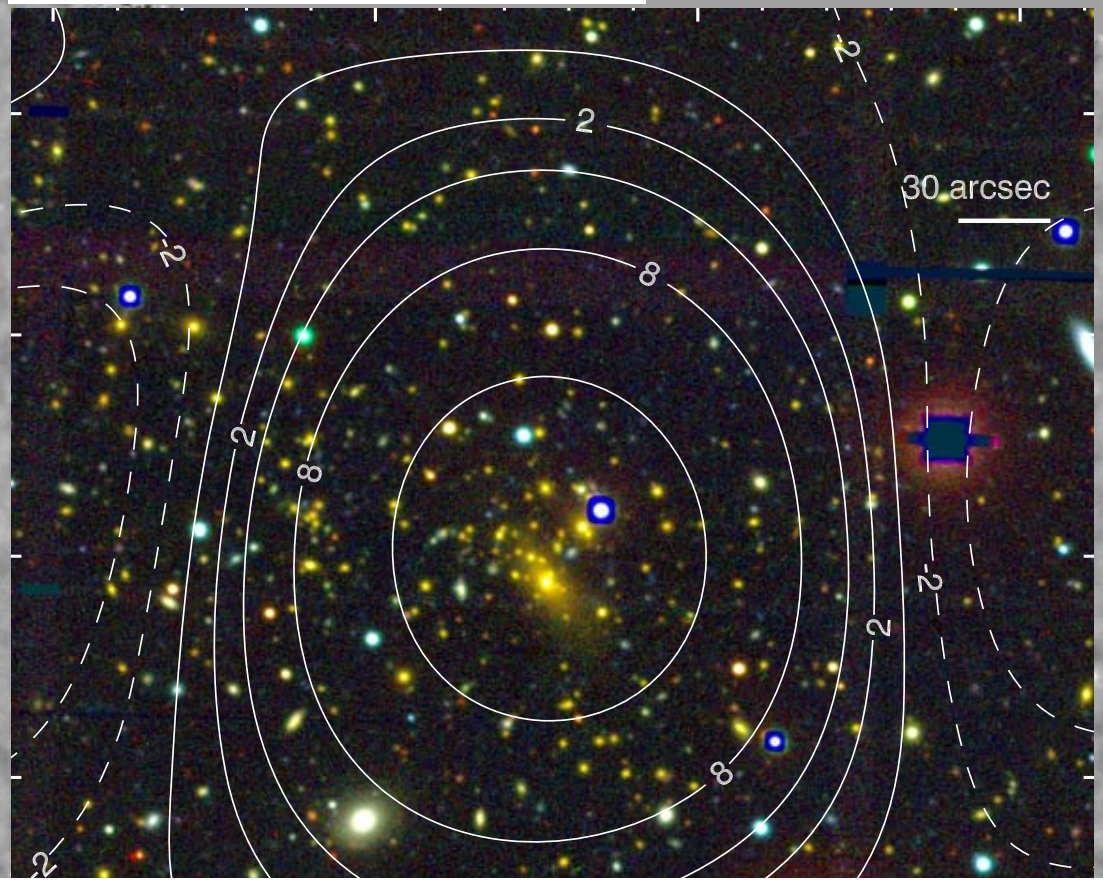

Zoom in on 2 mm map
~ 4 deg$^2$ of actual data

*Image by Will High in recent paper by Williamson et al*

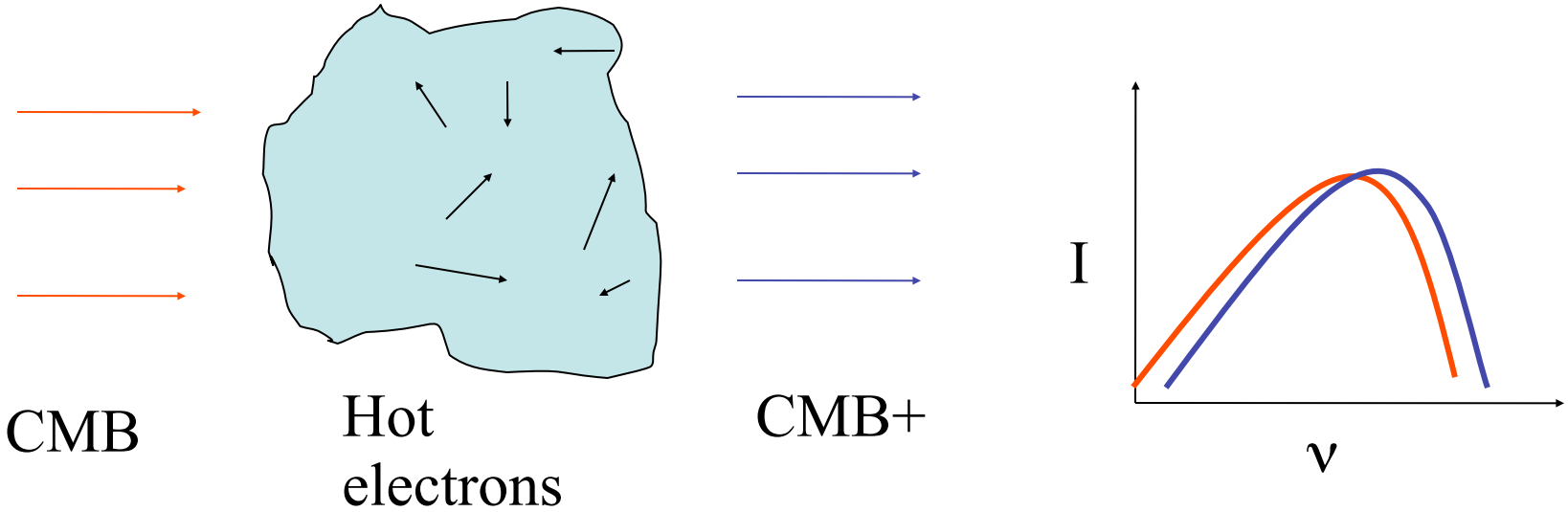



*One of the heaviest objects in the universe*
*>$10^{15}$ solar masses*

patch of isolated cosmic fog

1 degree

# Thermal Sunyaev-Zel'dovich Effect

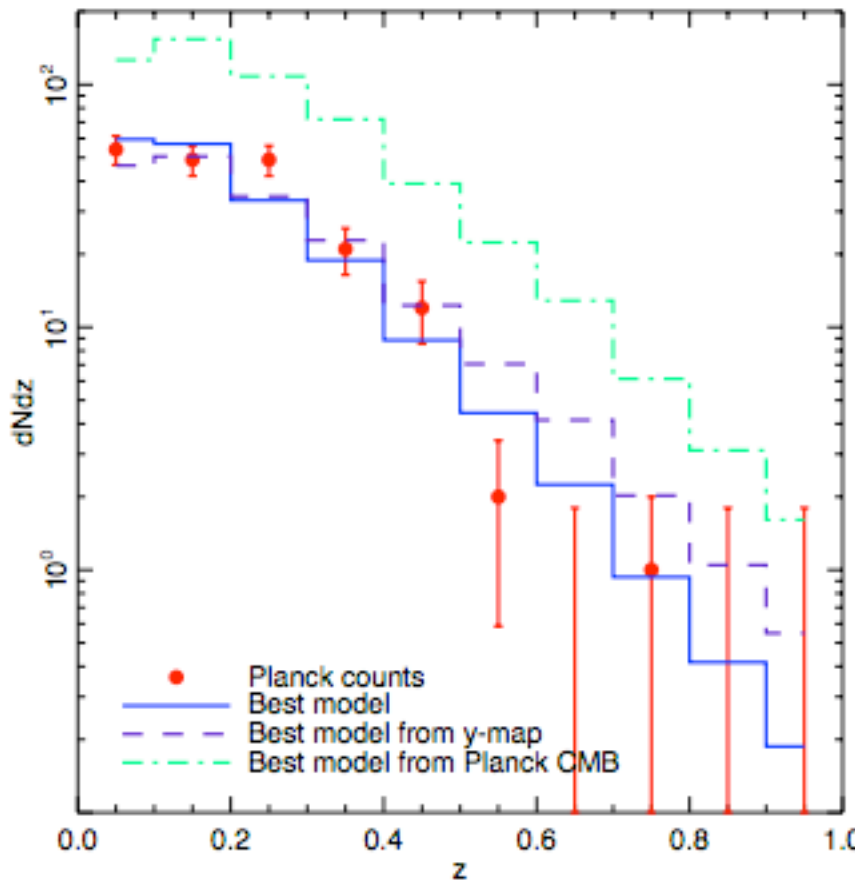



Optical depth: $\tau \sim 0.01$

Fractional energy gain per scatter: $\frac{kT}{m_e c^2} \sim 0.01$

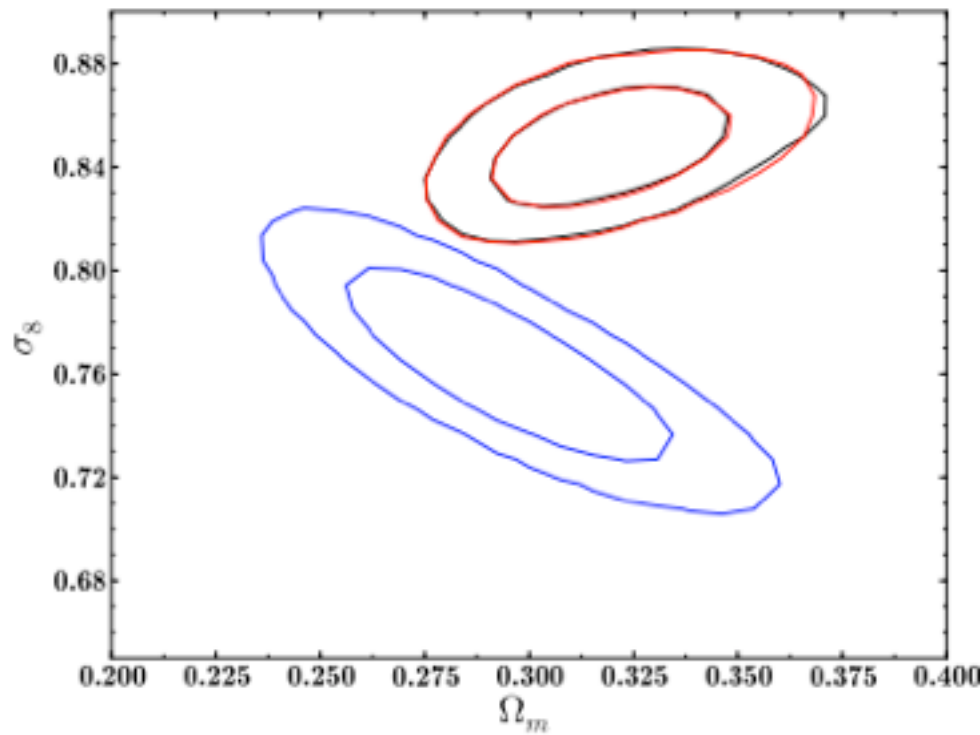
*Typical cluster signal: ~500 uK*

# Not Enough SZ?




fewer clusters than expected given estimated masses

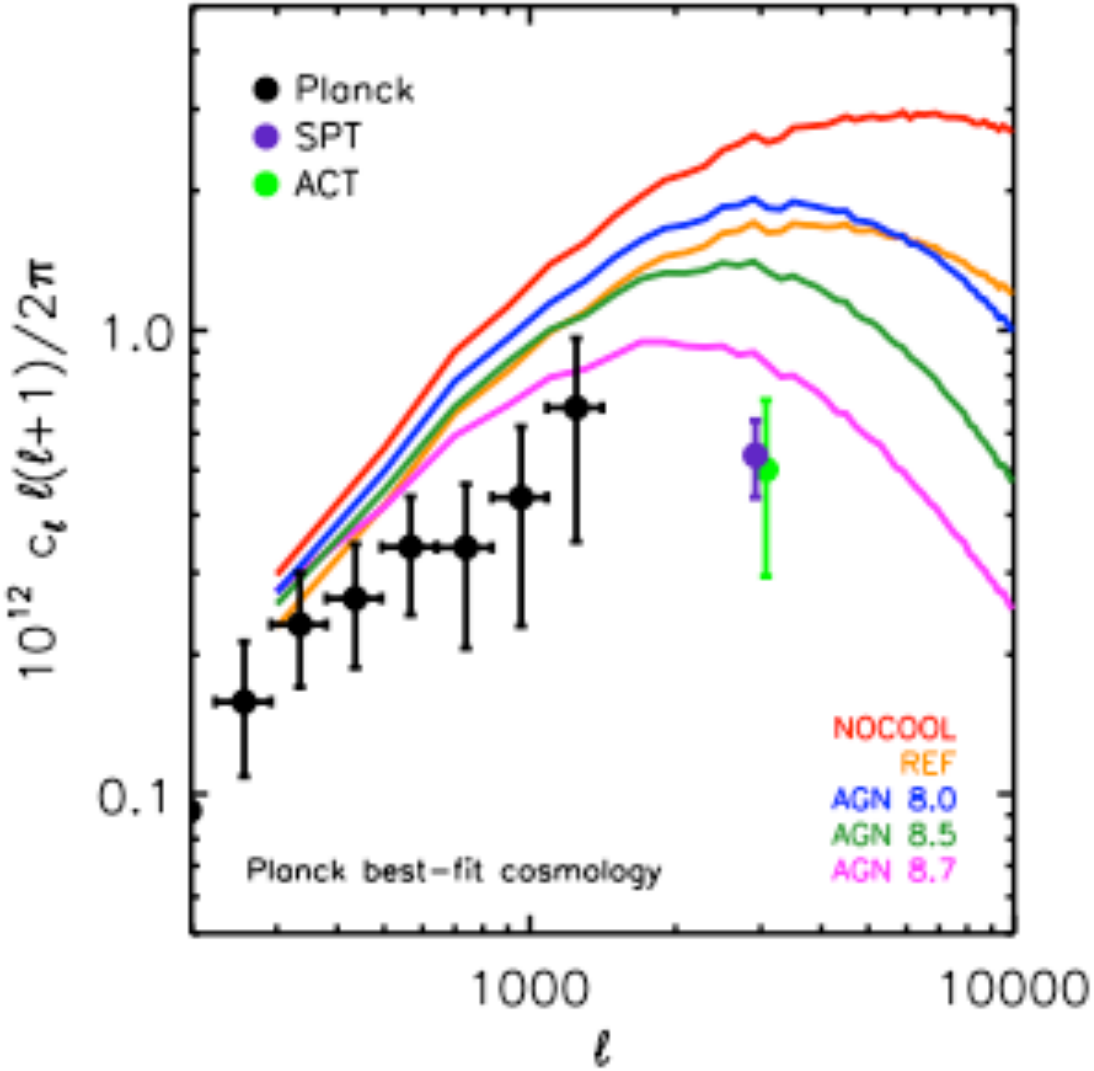
Planck XX




possible solutions:
1) less low-z structure than CMB predicts
2) mass estimates are wrong

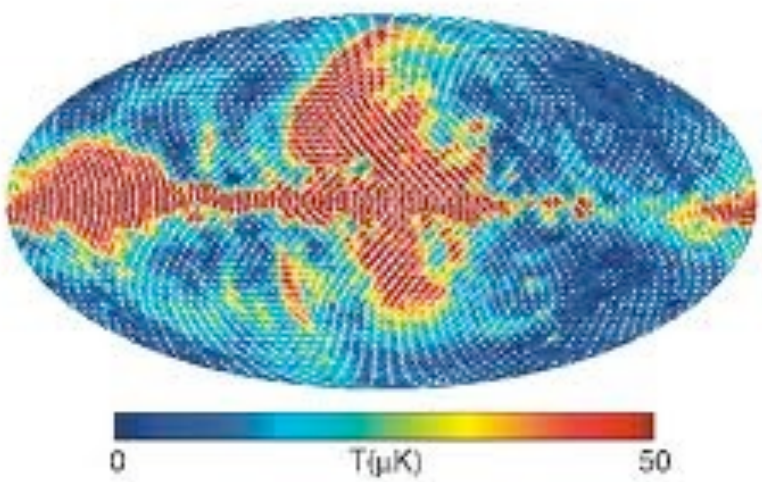
# Not Enough SZ?

- power spectrum from unresolved clusters lower than predicted in simulations tuned to match X-ray observations

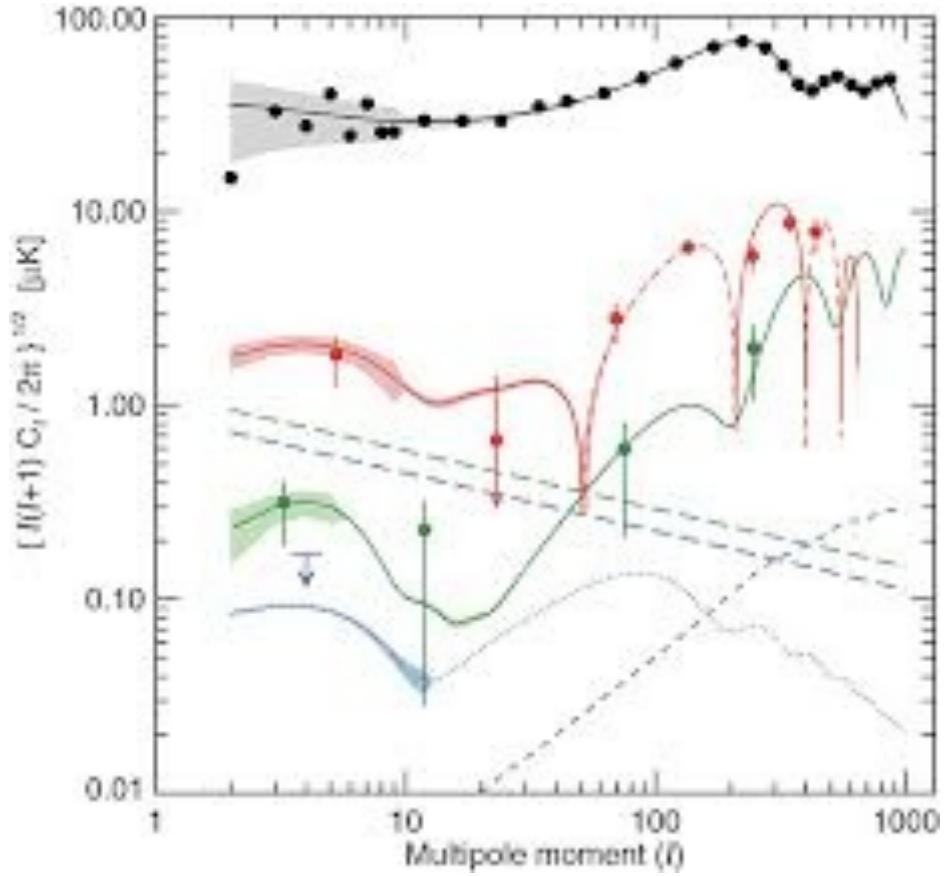



McCarthy et al 2013

# The Galaxy is a Nasty Polarized Foreground




Hinshaw et al. 2008




Need multifrequency to do all-sky polarization

# Synchrotron

- Electrons spiraling in magnetic field
- Can be highly polarized
- Non-relativistic: “cyclotron”
- Relativistic: “synchrotron”
- Can be highly (75%) polarized!

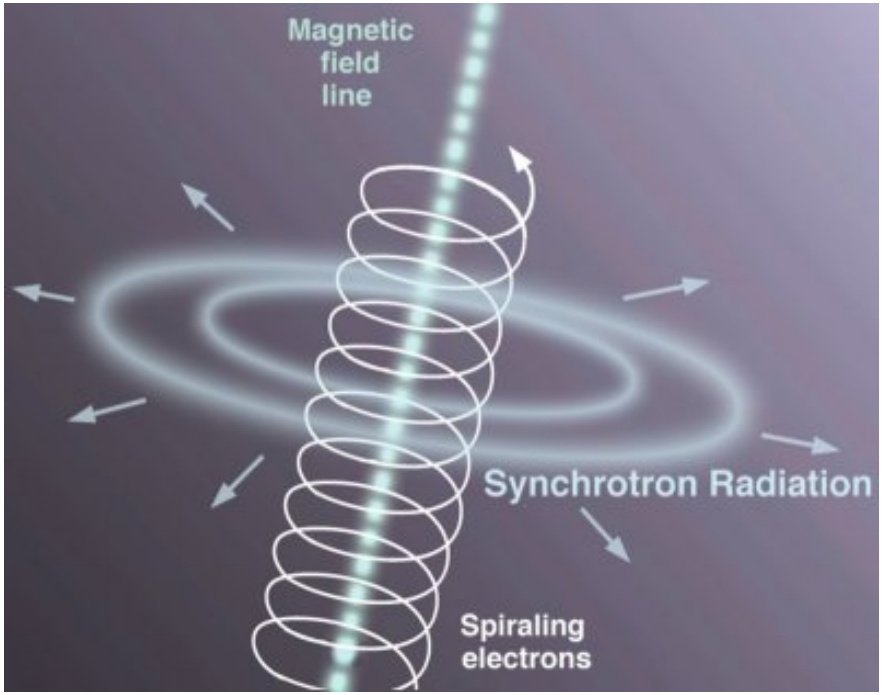
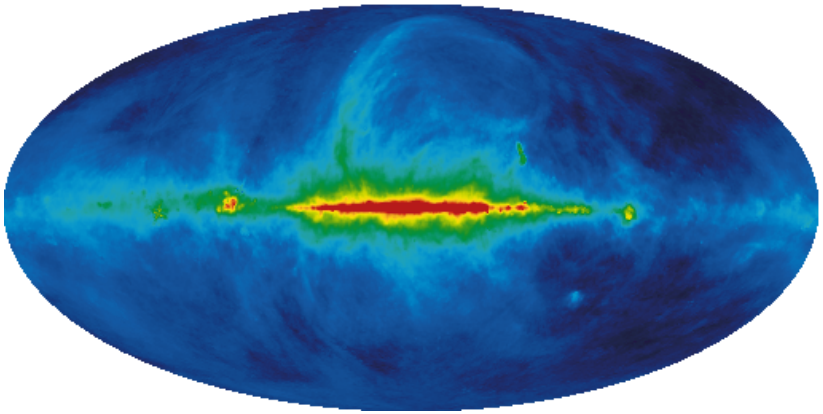
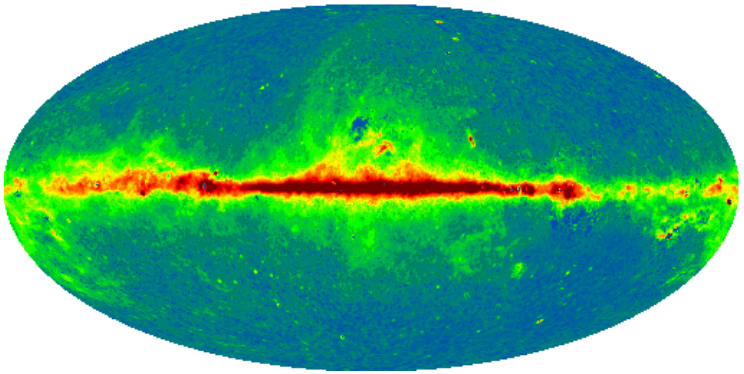



Image Credit: "Gemini Observatory"

# Synchrotron Distribution?

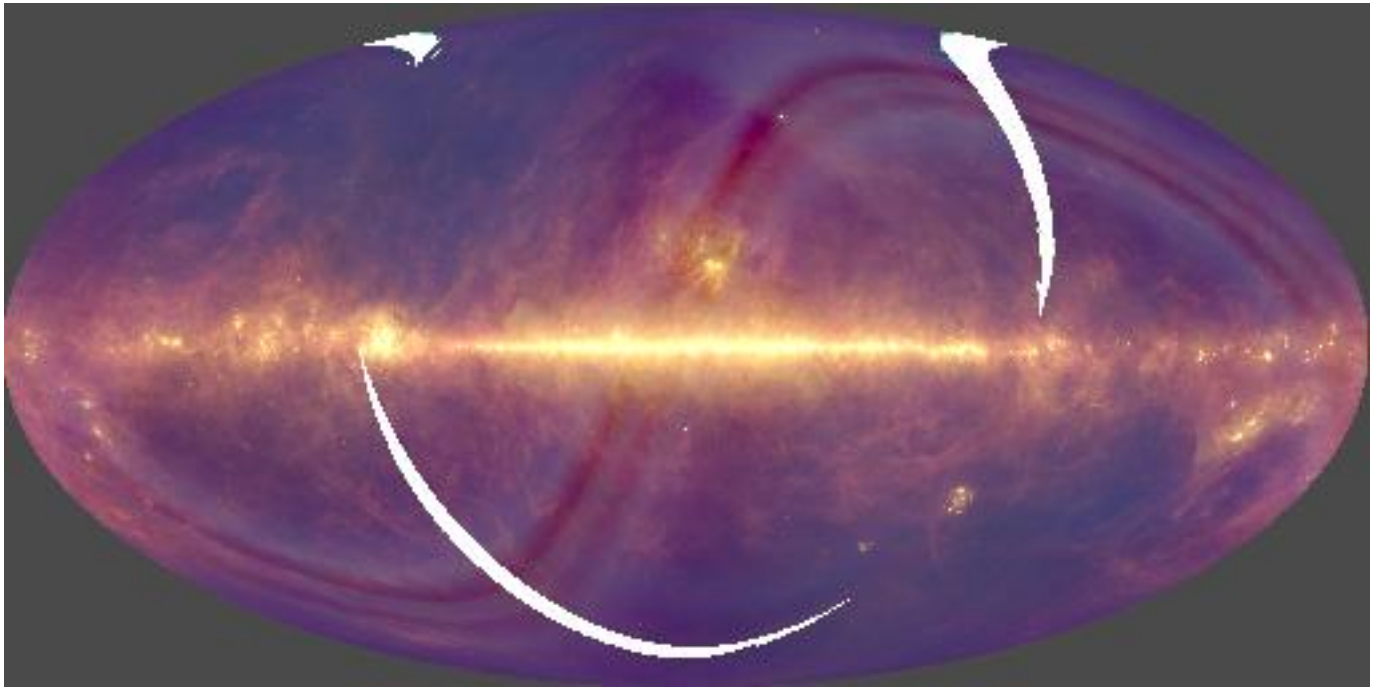
- Possible template: “Haslam map”
- 408 MHz
- Index expected to (and appears to) vary by +-0.3 spatially, and probably steepens with frequency





*From LAMBDA*

# Thermal Dust

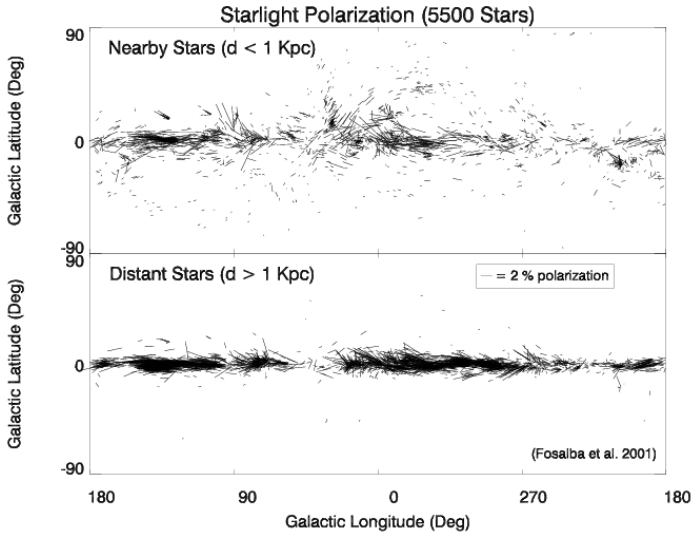


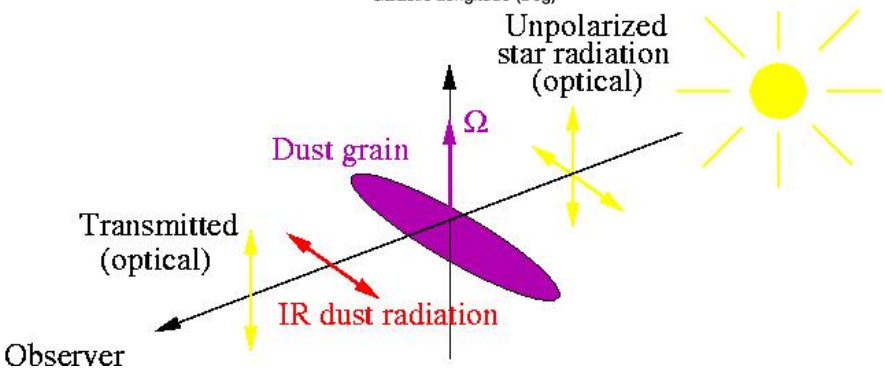
- Thermal emission from few nm-few um (or mm, or km) sized dust grains
- T~20-150K => peaks in the submm-IR

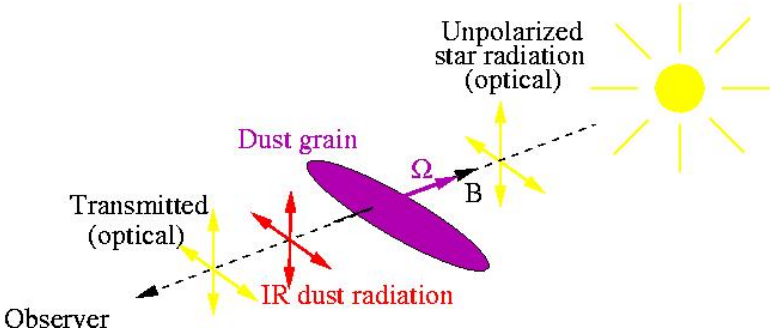
*From LAMBDA*

# Dust Polarization

- Dust grains could be aligned by magnetic field
- Evidence for this through polarization of optical starlight
- Preferential alignment of grains leads to partially polarized thermal dust emission

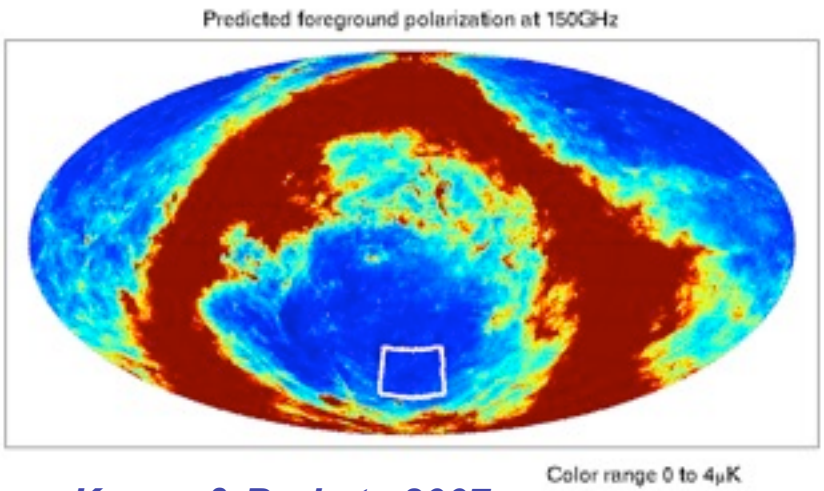


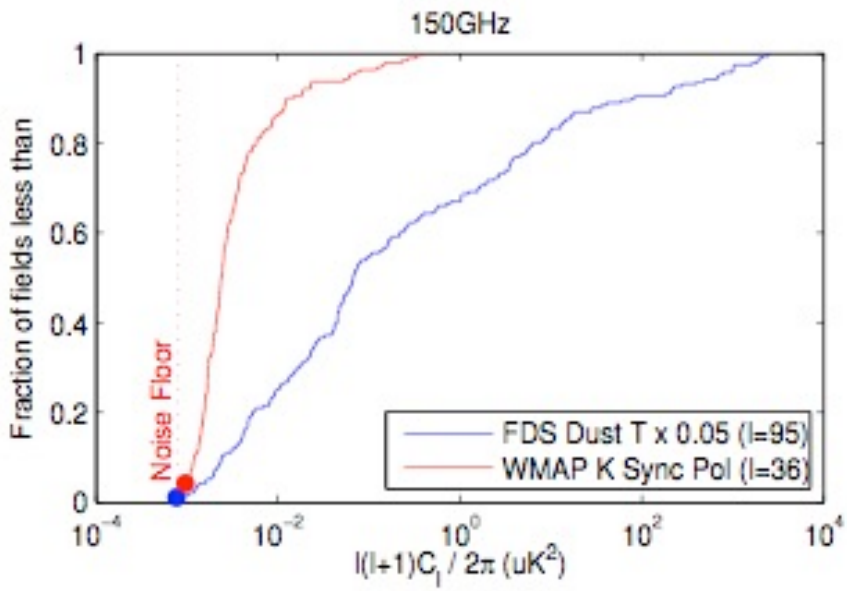




***From Planck website***

# “The Southern Hole”

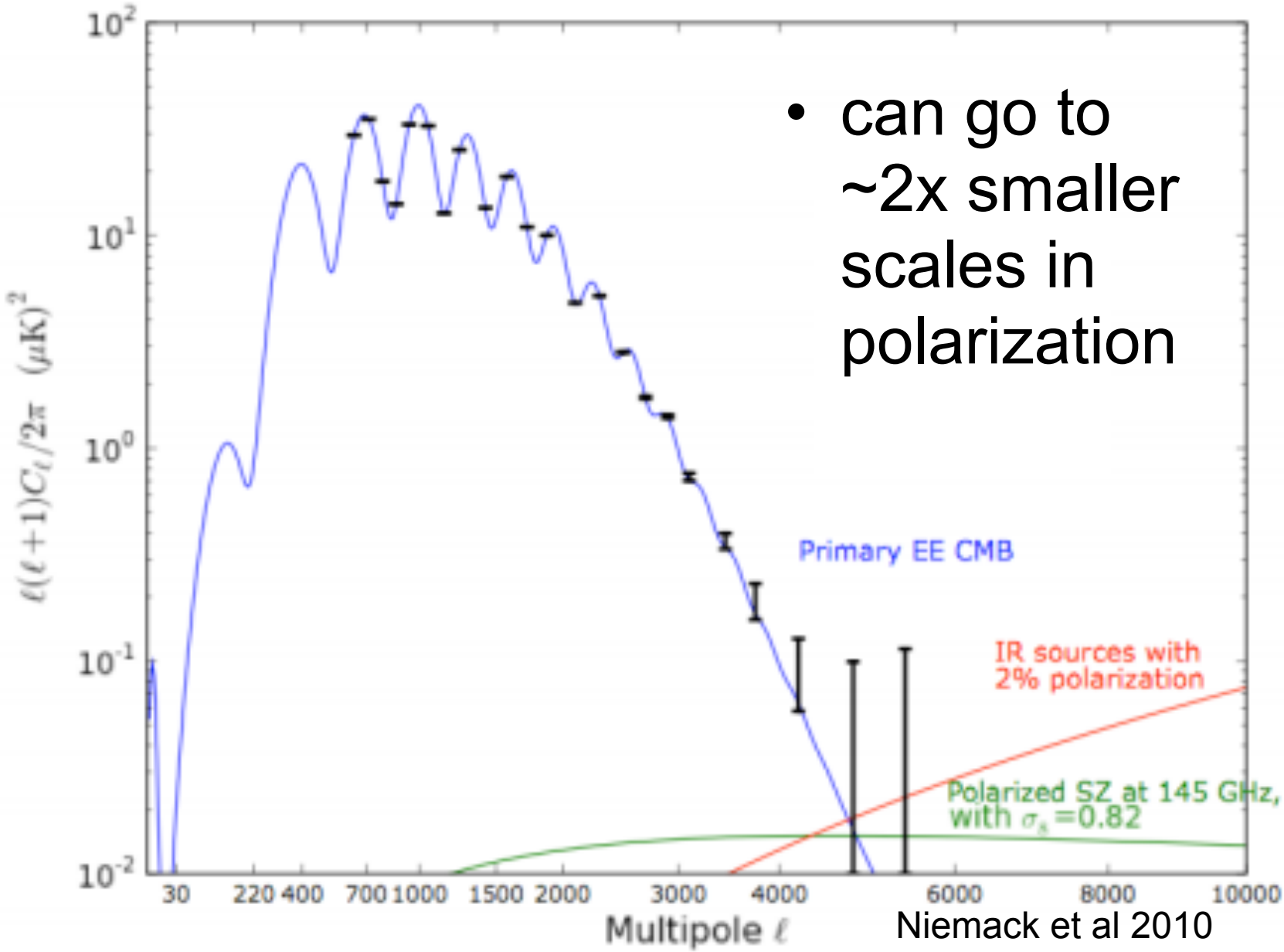



*Kovac & Barkats 2007*




- There exist very clean patches
- “southern hole” has ~2% of the sky at very low foreground level
- Cleanest parts of the sky can be orders of magnitude cleaner than typical regions

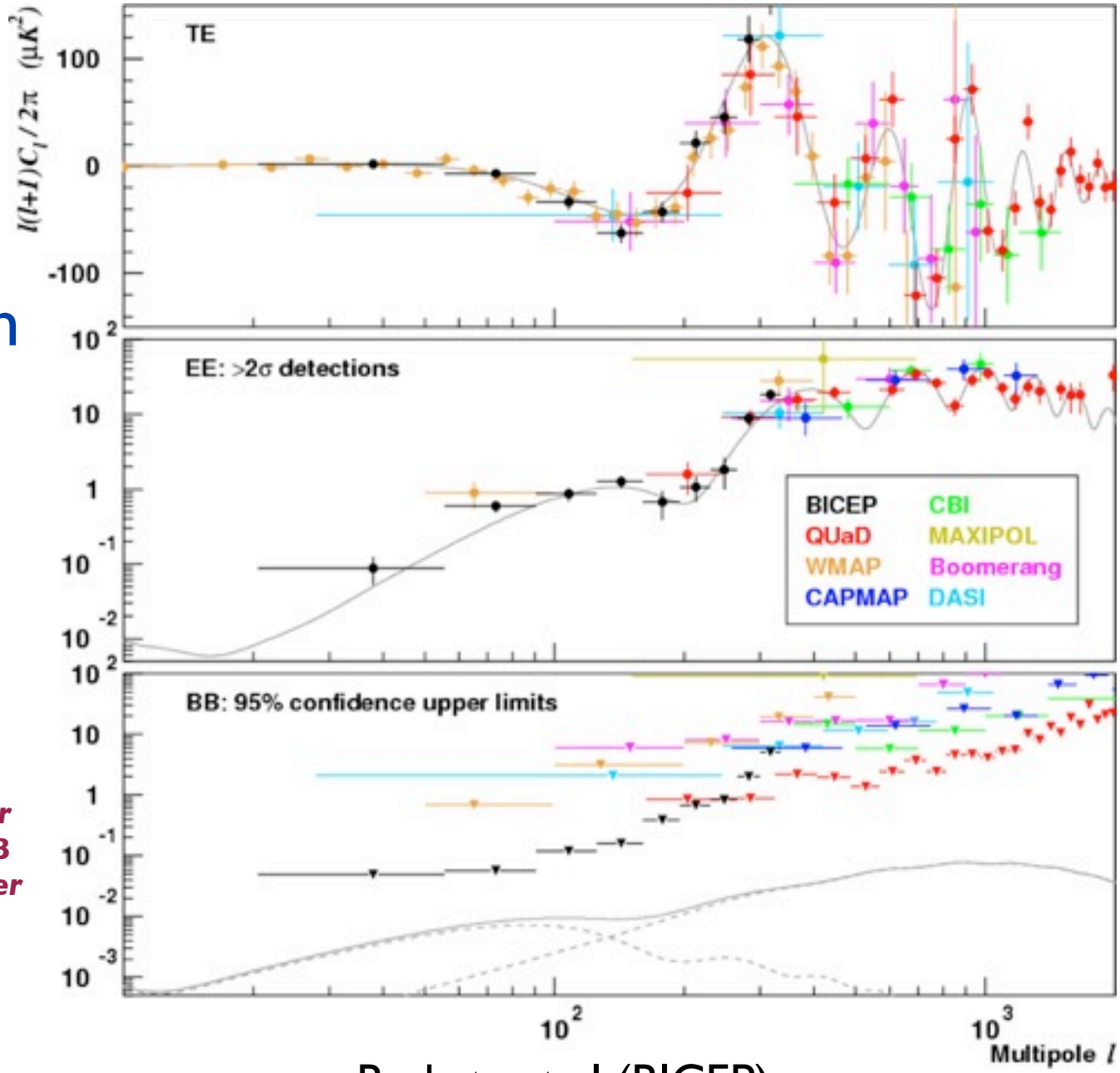
# Small-Scale Polarized Foregrounds




- can go to ~2x smaller scales in polarization

Niemack et al 2010

# CMB Polarization Angular Power Spectra




***only upper limits on B mode power***

Barkats et al (BICEP)

# E-modes and B-modes

$$Q(\boldsymbol{l}) = [E(\boldsymbol{l})\cos(2\phi_l) - B(\boldsymbol{l})\sin(2\phi_l)]$$
$$U(\boldsymbol{l}) = [E(\boldsymbol{l})\sin(2\phi_l) + B(\boldsymbol{l})\cos(2\phi_l)].$$

- E/B is a different way to express polarization field
- easy to understand in flat-sky limit (i.e. Fourier modes)

# Full-Sky E/B: Spin-2 Spherical Harmonics

$$(Q \pm iU)(\hat{n}) = \sum_{lm} a_{\pm 2,lm}\, {}_{\pm 2}Y_{lm}(\hat{n}).$$

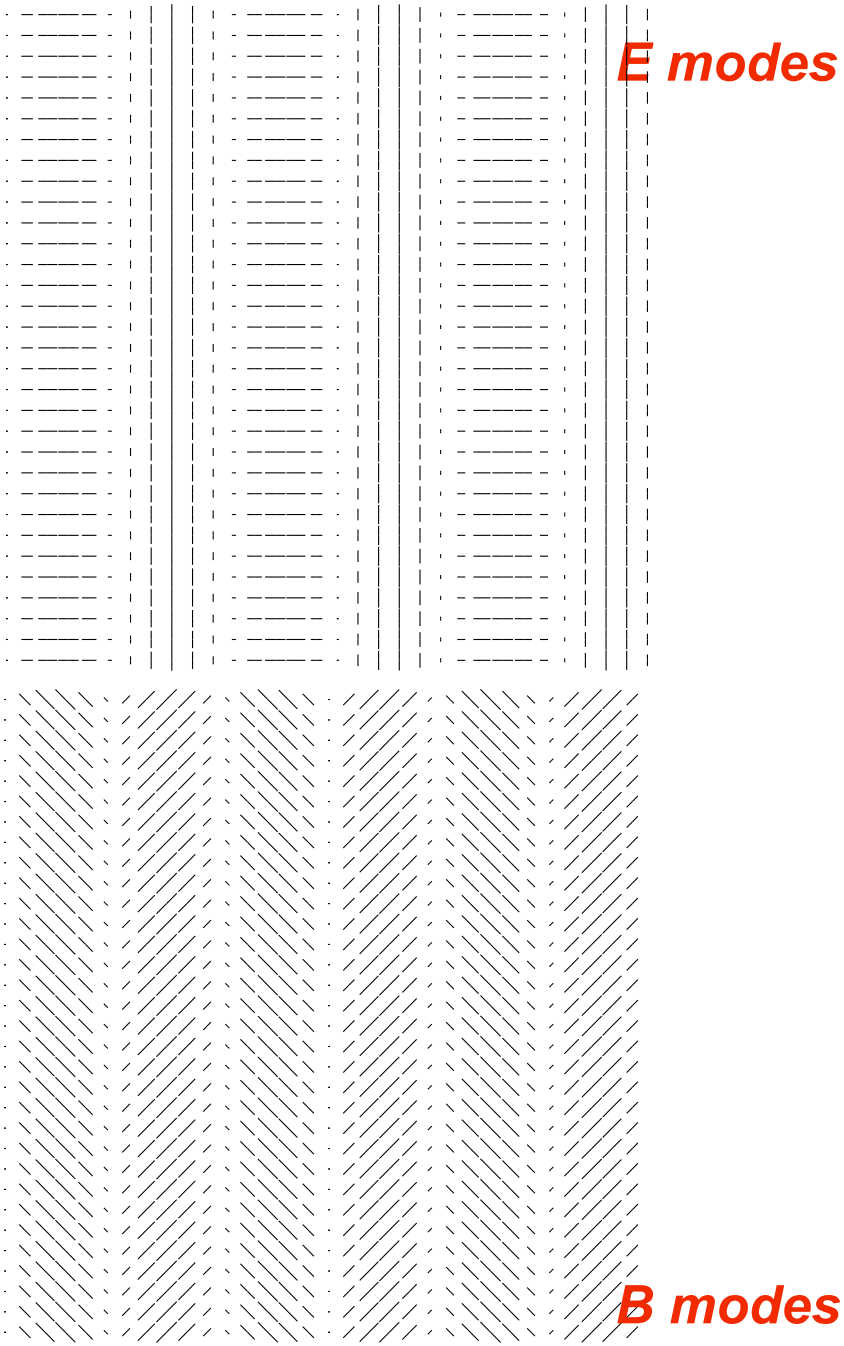
$$a^E_{lm} = -(a_{2,lm} + a_{-2,lm})/2$$

$$a^B_{lm} = i(a_{2,lm} - a_{-2,lm})/2.$$

- spin-2 S.H. easily derived from regular old S.H. through derivatives
  - recall flat-sky mapping from Q/U to E/B had terms $\cos(2\phi_l)$, $\sin(2\phi_l)$
    - » $[(l_x^2-l_y^2)/l^2,\ 2l_xl_y/l^2$

# E-modes/B-modes

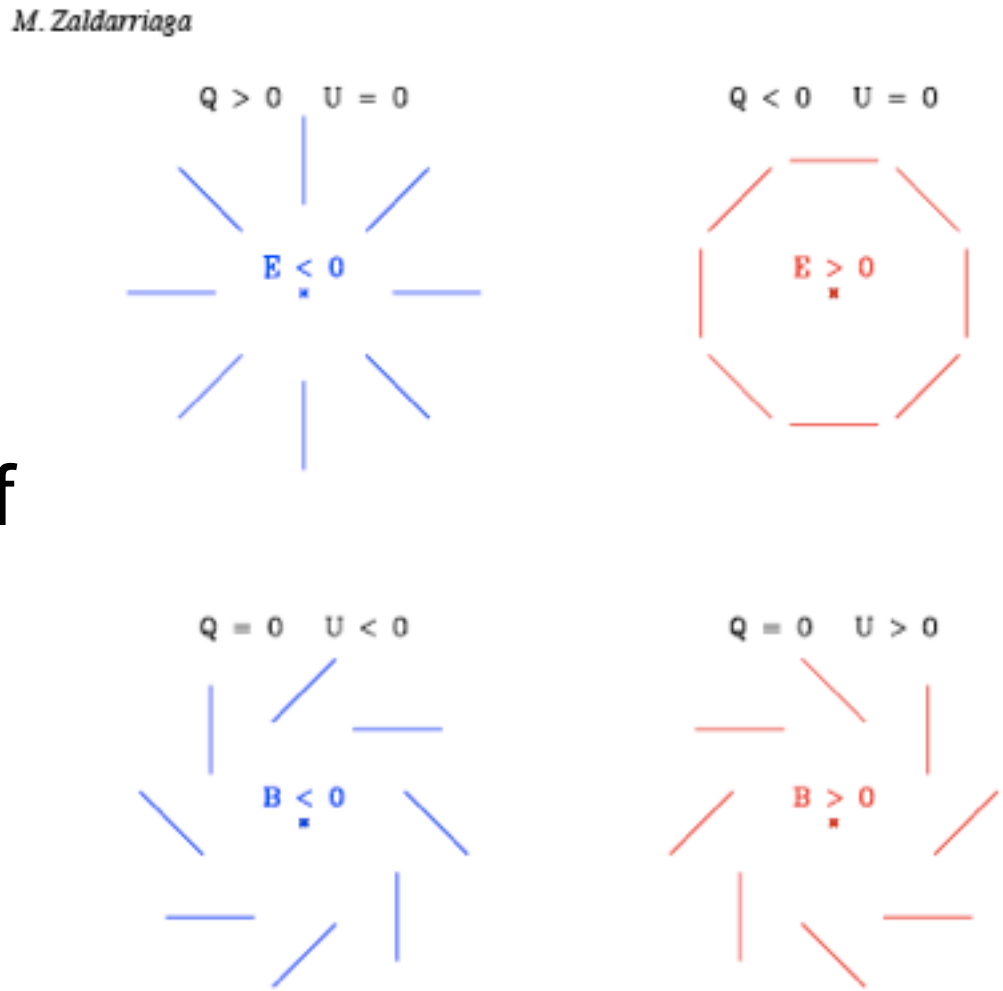
- E-modes vary spatially parallel or perpedicular to polarization direction
- B-modes vary spatially at 45 degrees
- CMB
    - scalar perturbations only generate *only* E



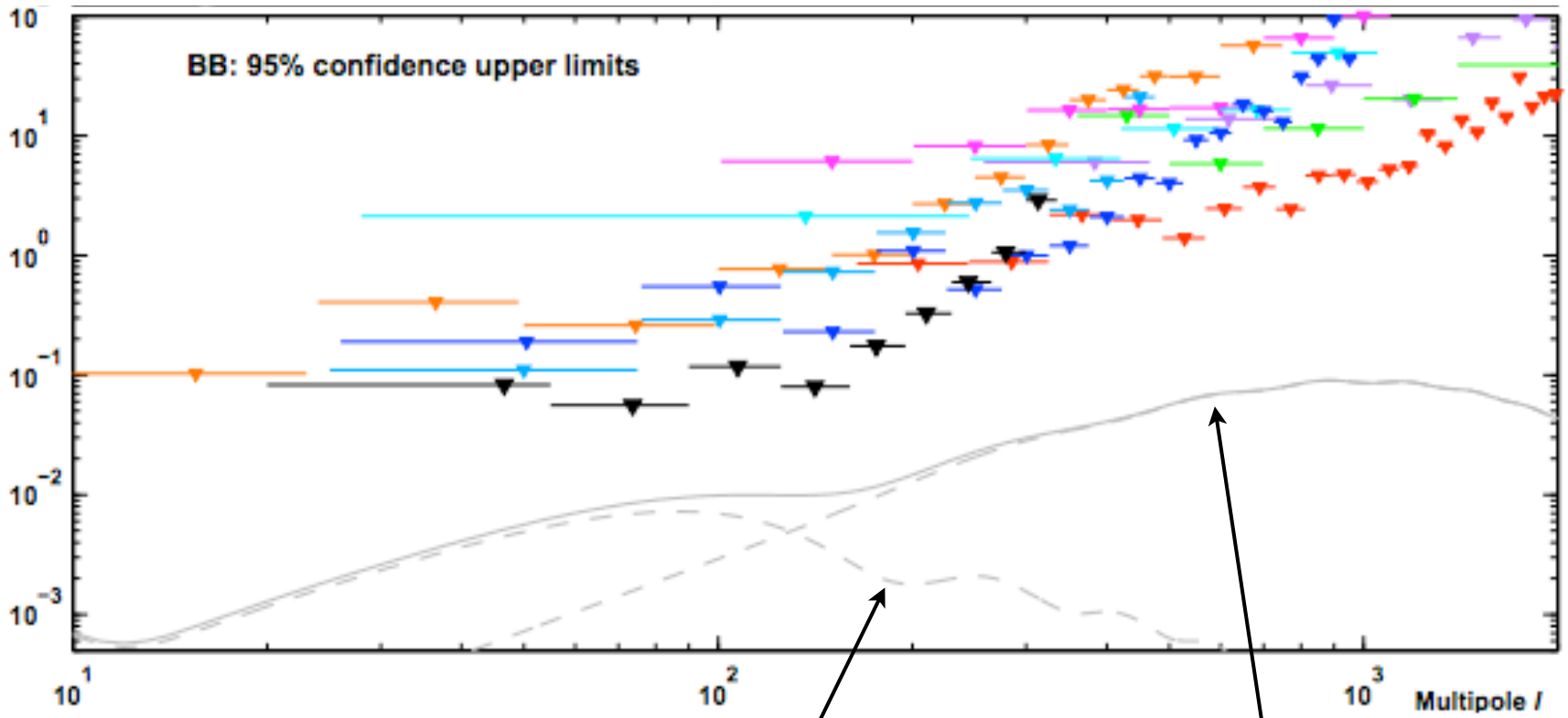

*Bunn*

# Another View of E/B

- E/B can be thought of as divergence/ curl modes of polarization (but spin-2, not spin-1)



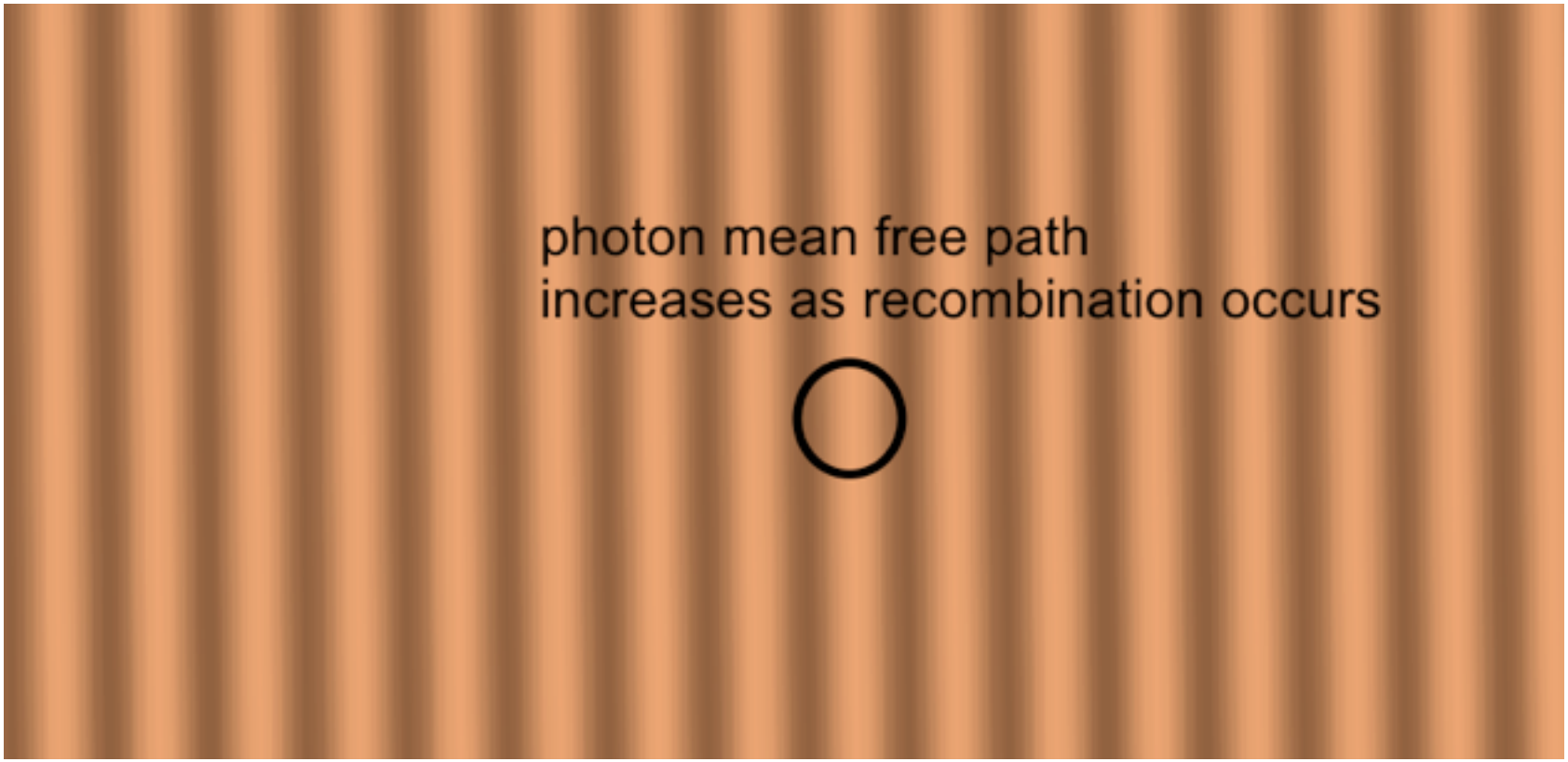
# Two Expected Sources of B Modes




Gravitational Radiation in Early Universe (amplitude unknown!)

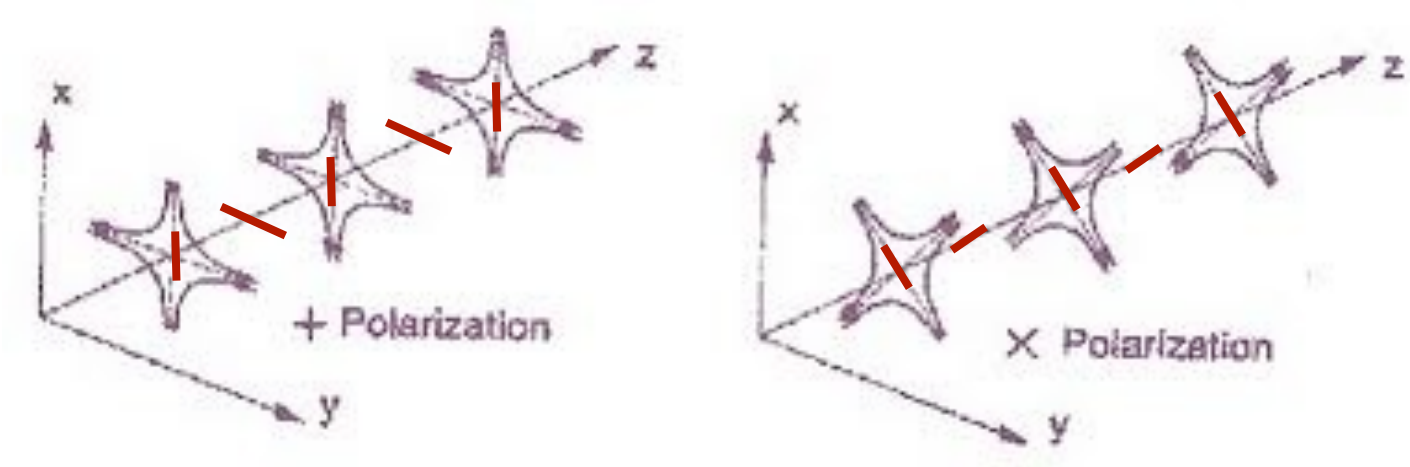
Gravitational lensing of E modes (come back on Thursday!!)

# Density fluctuations generate pure E mode




- E-modes <=> polarization
- lensing convergence <=> shear

# Gravitational Waves Generate E and B




B modes are a great probe of gravitational radiation in the early universe!!

# *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!***

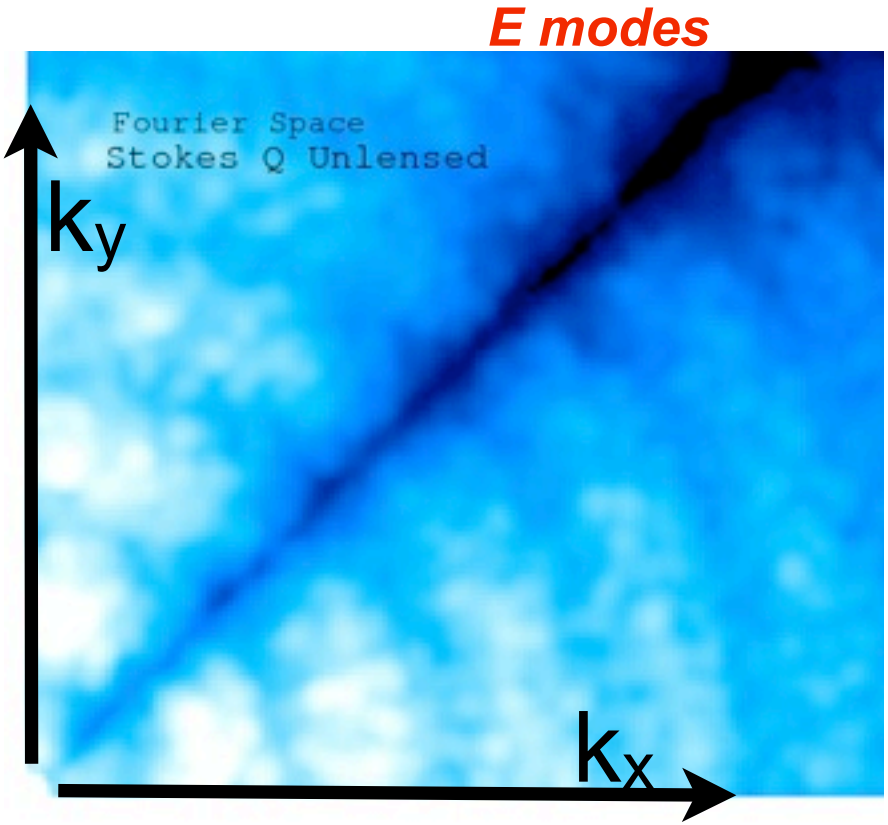
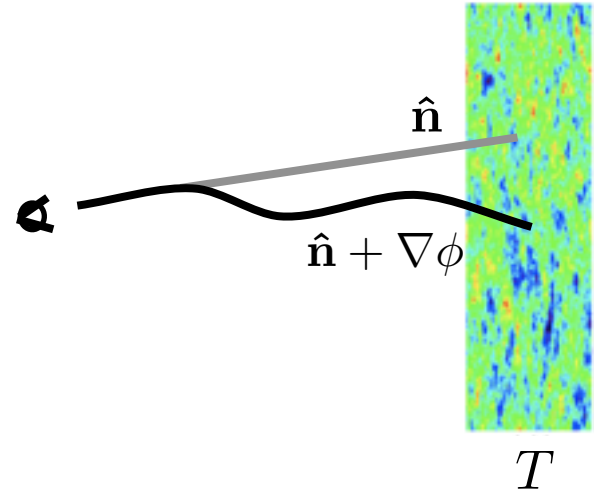



*Image of positive kx/positive ky Fourier transform of a 10x10 deg chunk of Stokes Q CMB map [simulated; nothing clever done to it]*

# Gravitational deflection

# 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

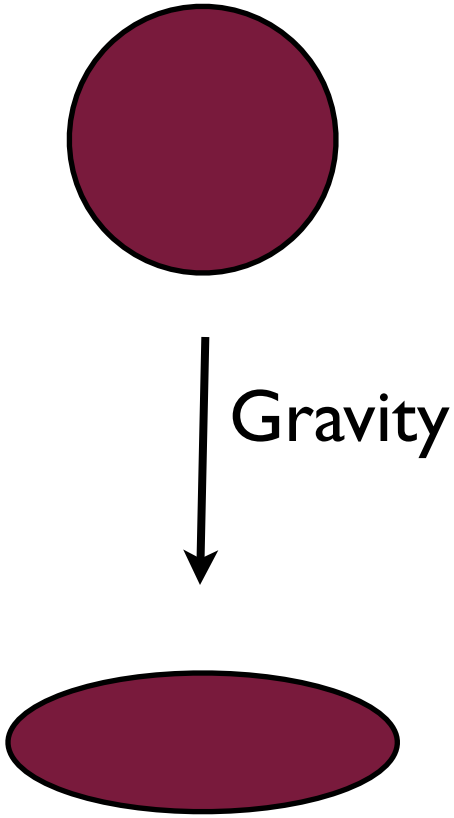
$$\nabla\phi(\hat{\mathbf{n}}) = -2\int_0^{\chi_\star} d\chi\, \frac{\chi_\star - \chi}{\chi_\star \chi} \nabla_\perp \Phi(\chi\hat{\mathbf{n}}, \chi)$$

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



# Lensing simplified

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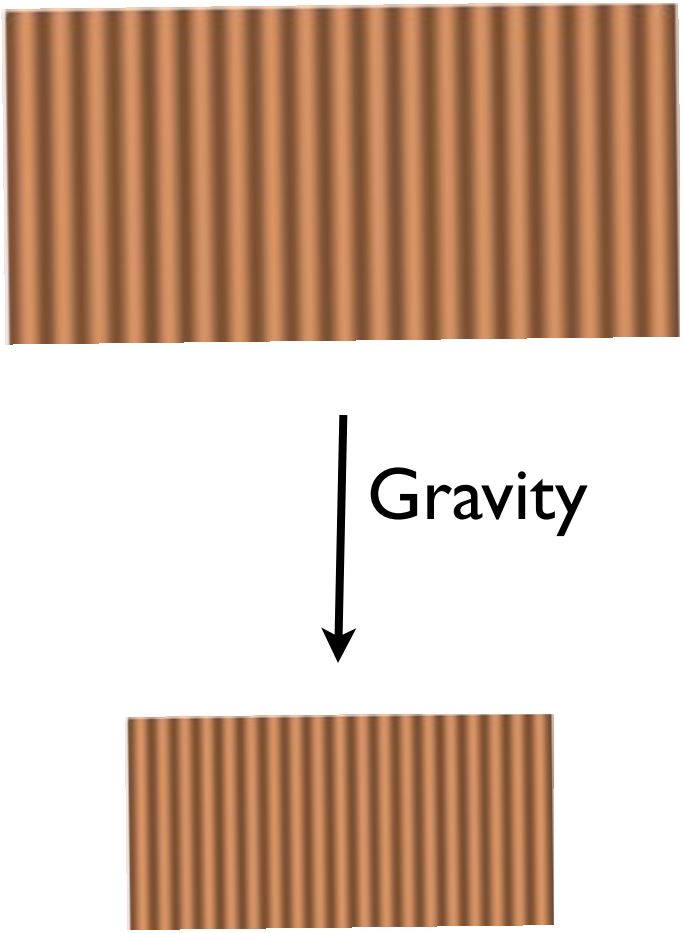
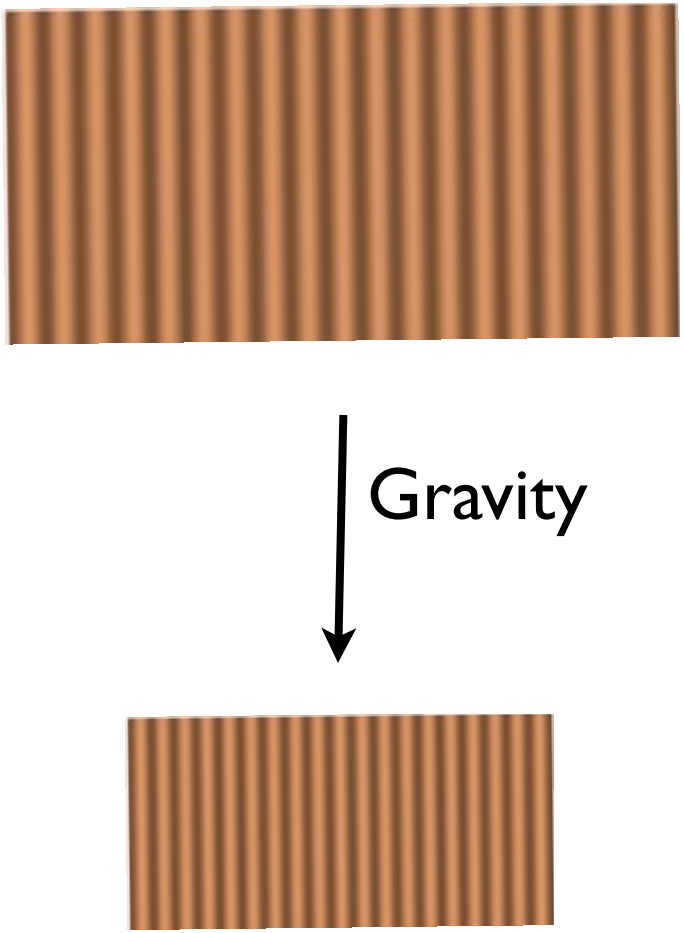


# Lensing simplified

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



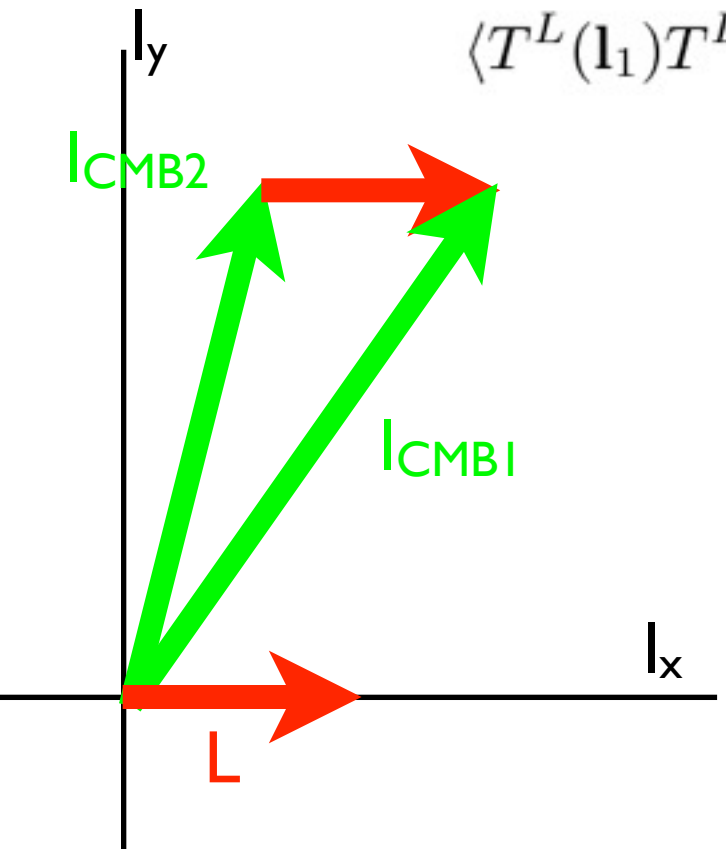
# Mode Coupling from Lensing

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

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

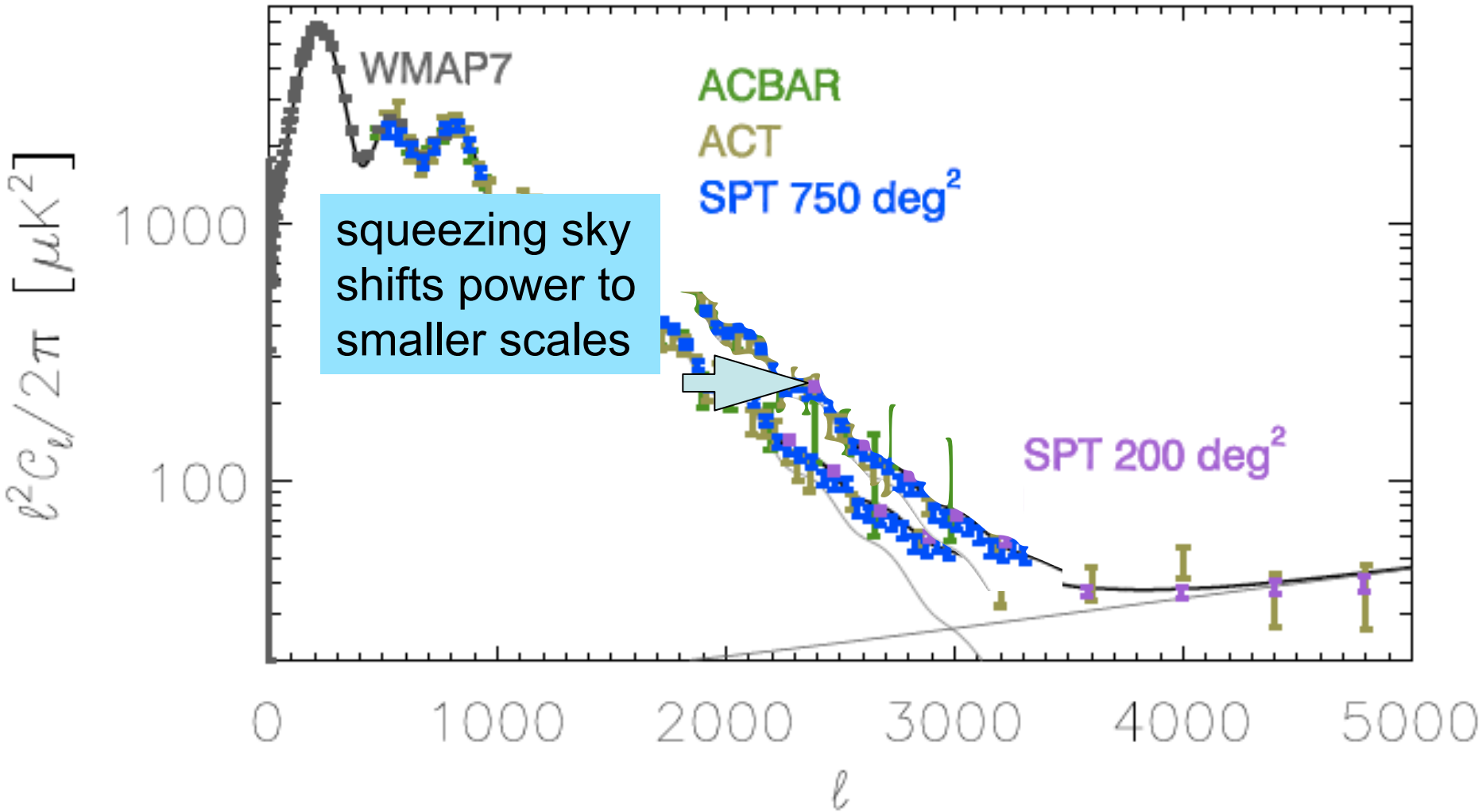
$$\langle T^L(\mathbf{l}_1) T^L(\mathbf{l}_2) \rangle = \mathbf{L} \cdot (\mathbf{l}_1 C^T_{l_1} + \mathbf{l}_2 C^T_{l_2}) \phi(\mathbf{L}) + O(\phi^2)$$

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

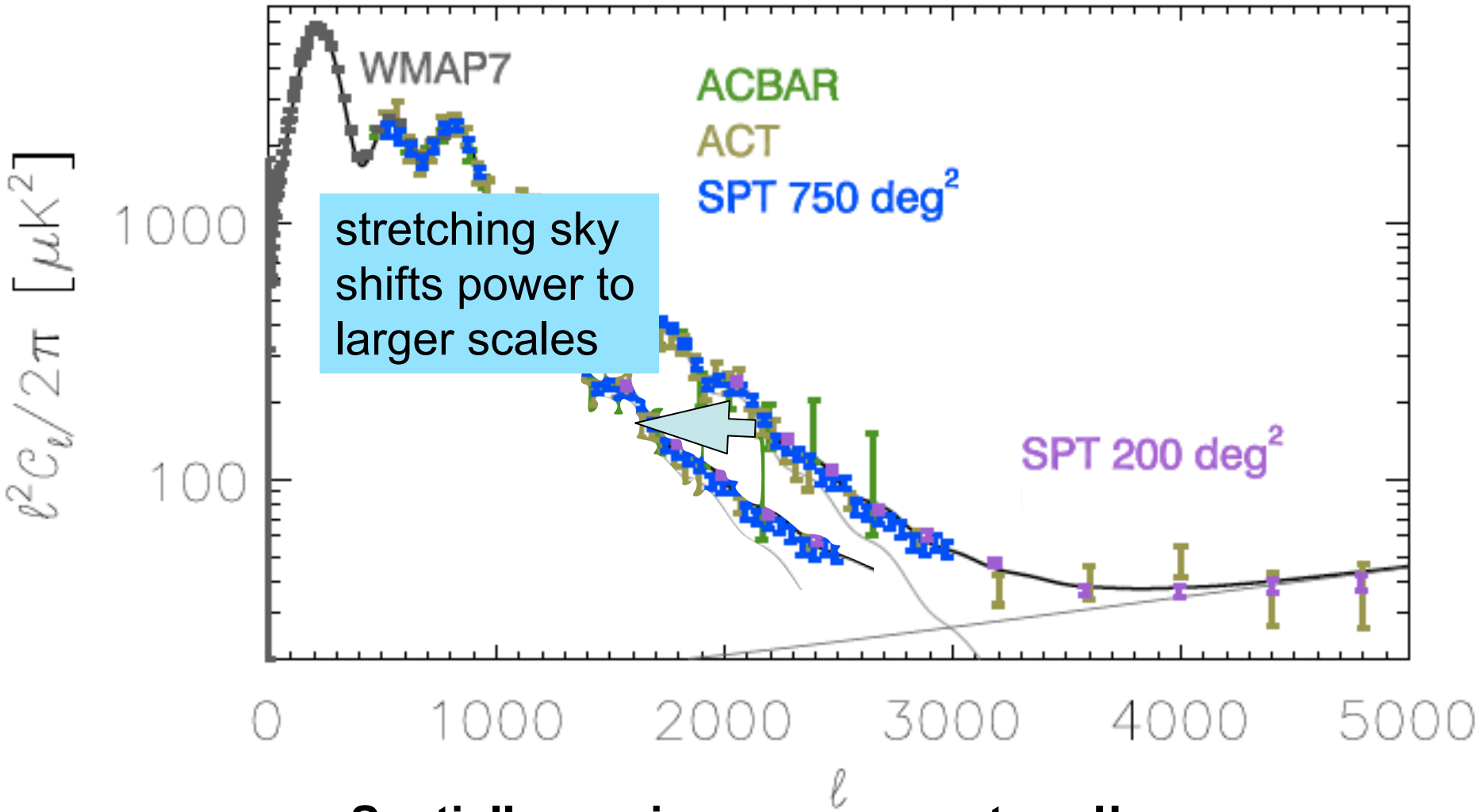



- We extract ϕ by taking a suitable average over CMB multipoles separated by a distance L
- We use the standard Hu quadratic estimator.

# CMB Power Spectrum



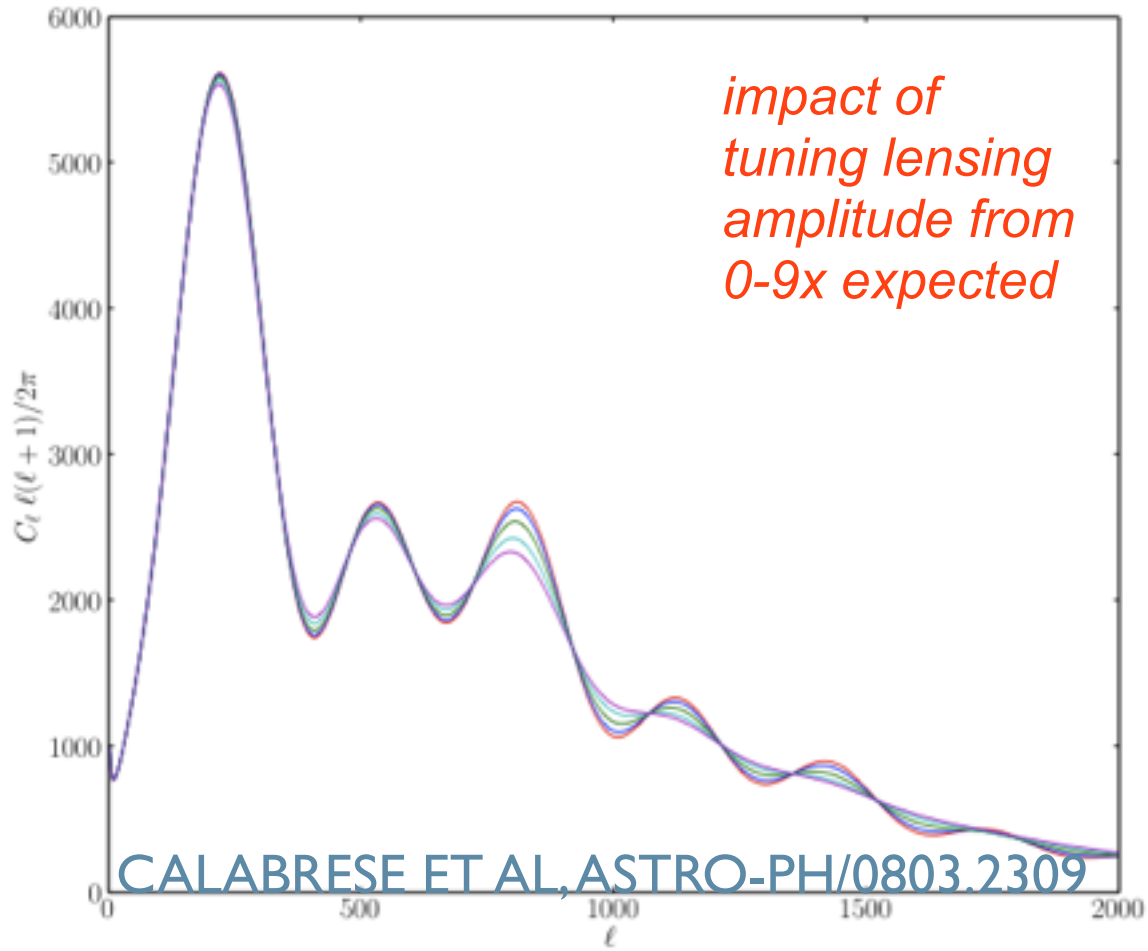
# CMB Power Spectrum



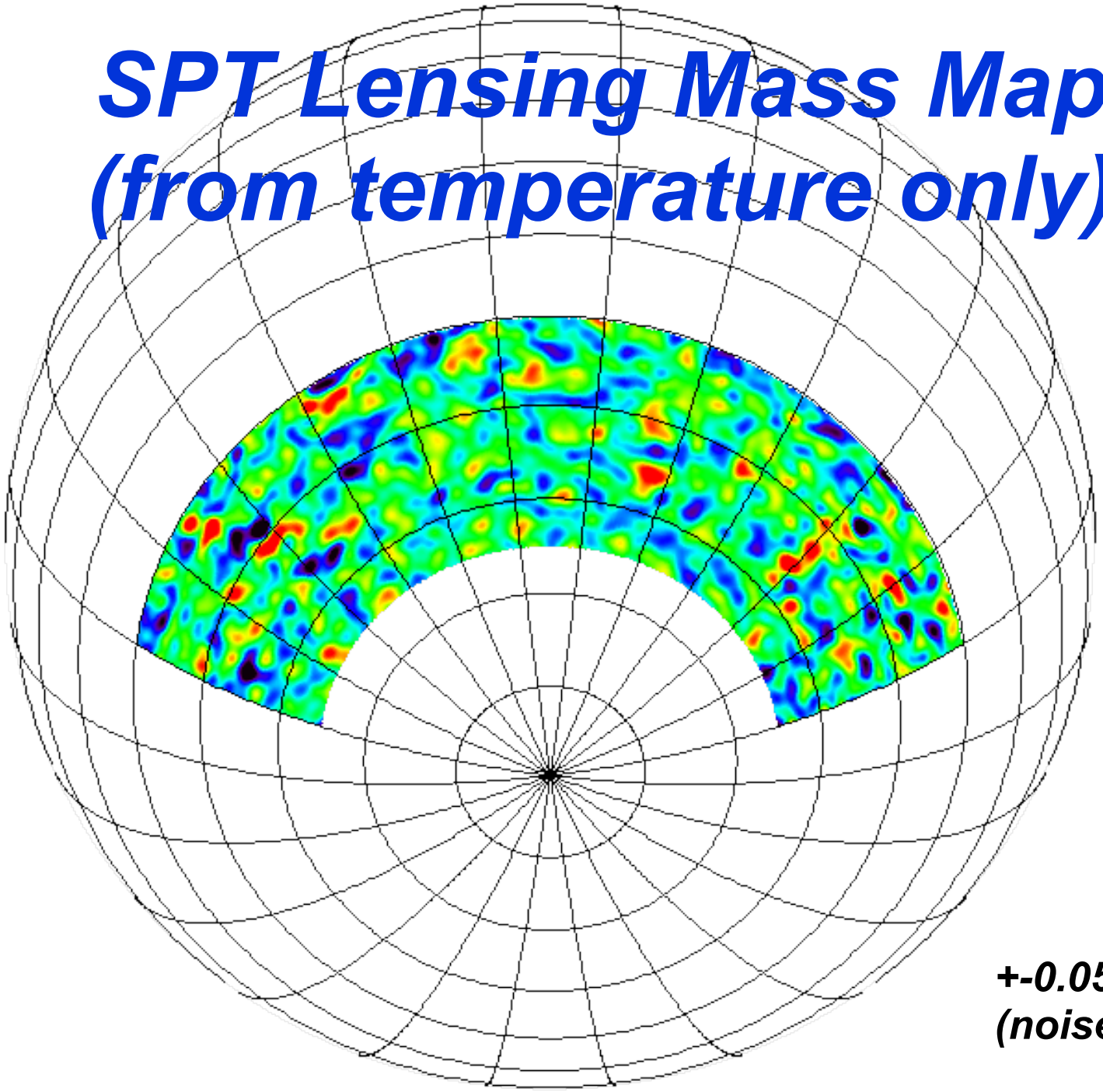

**Spatially varying power spectrum!!**

# Effect on CMB Power Spectrum

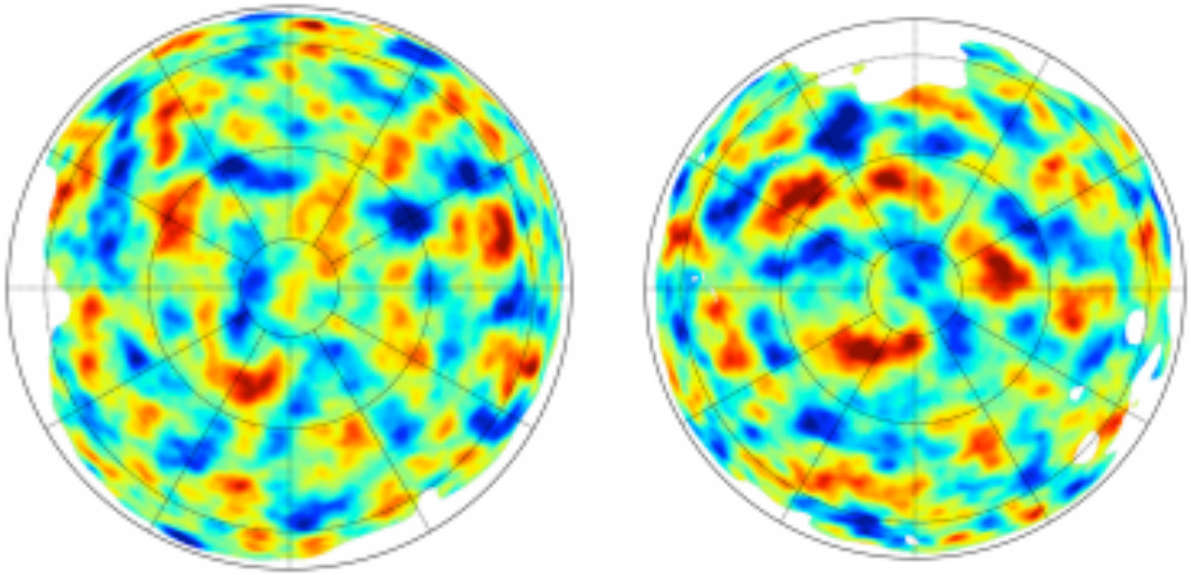
- mixing of power leads to smoothing of acoustic peaks
- small effect but data is really good



# SPT Lensing Mass Map (from temperature only)

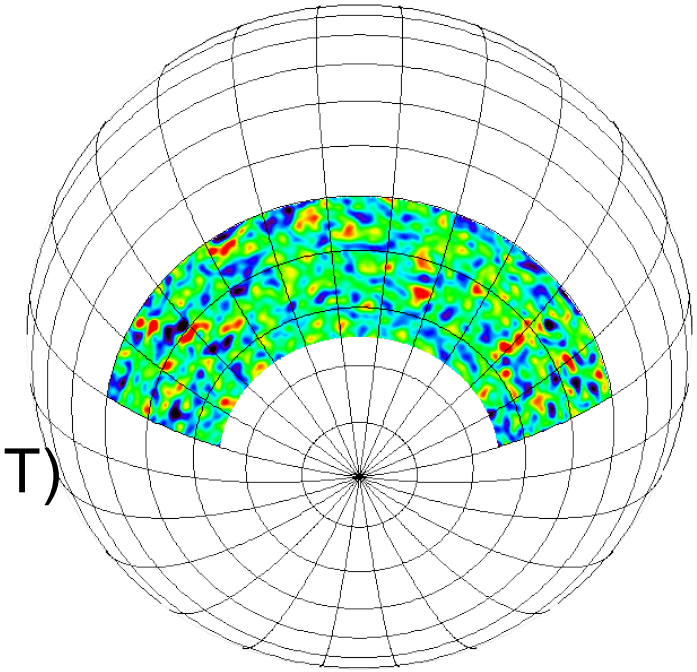


***+-0.05 color bar***
***(noise ~0.01)***



Planck

(all-sky, T)

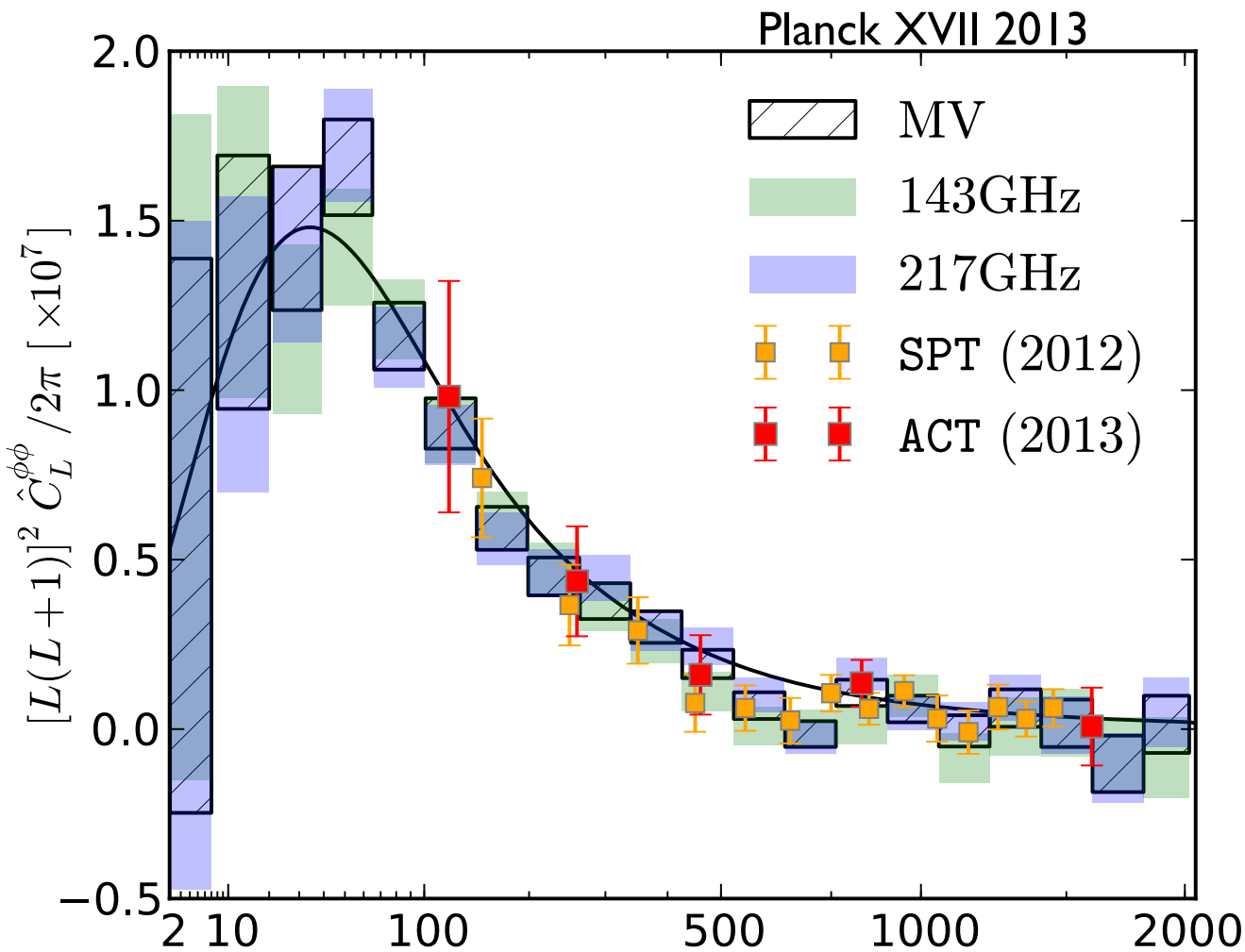


SPT

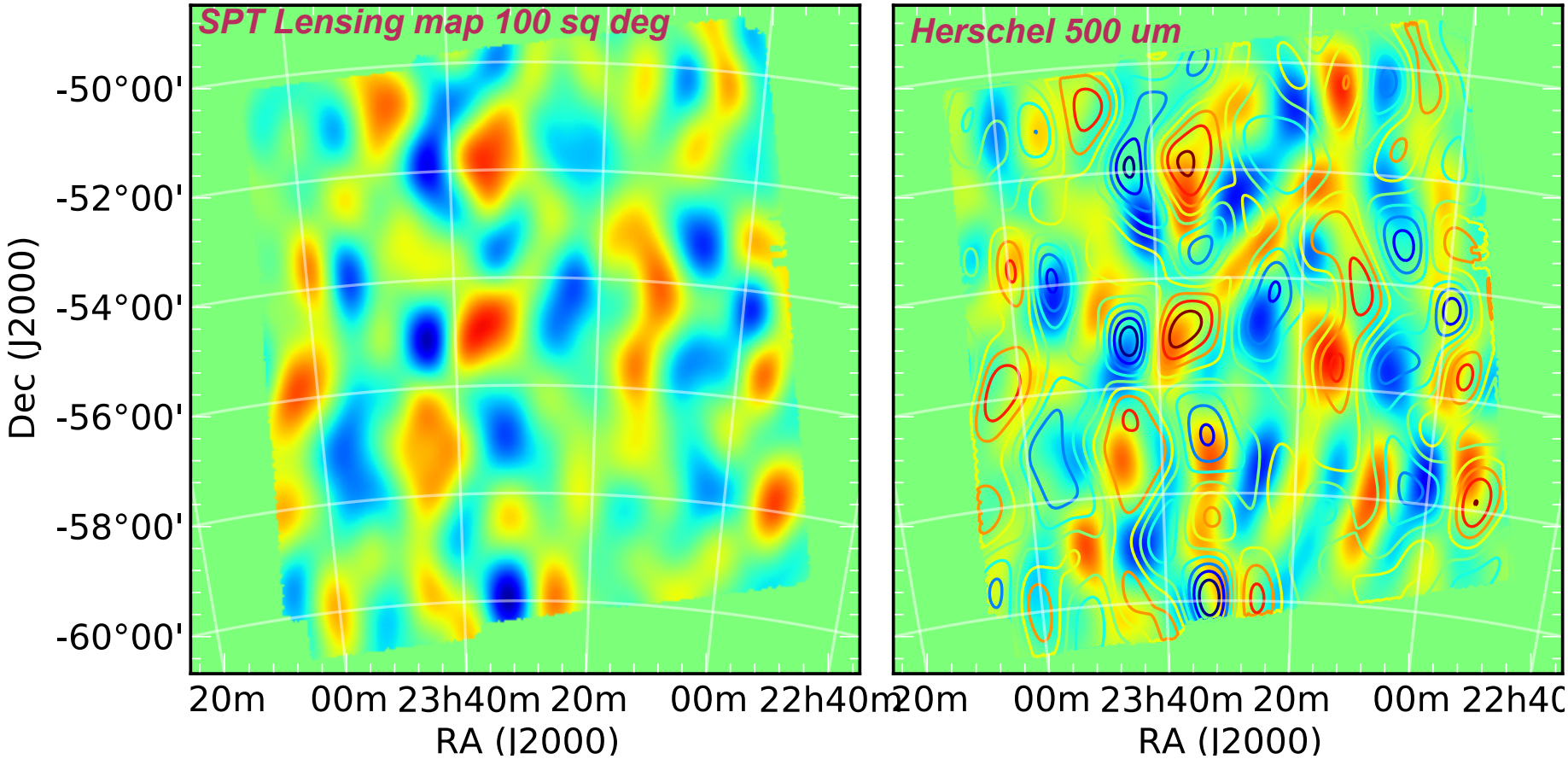
(2500 sq deg, T)

# CMB Lensing Power Spectrum

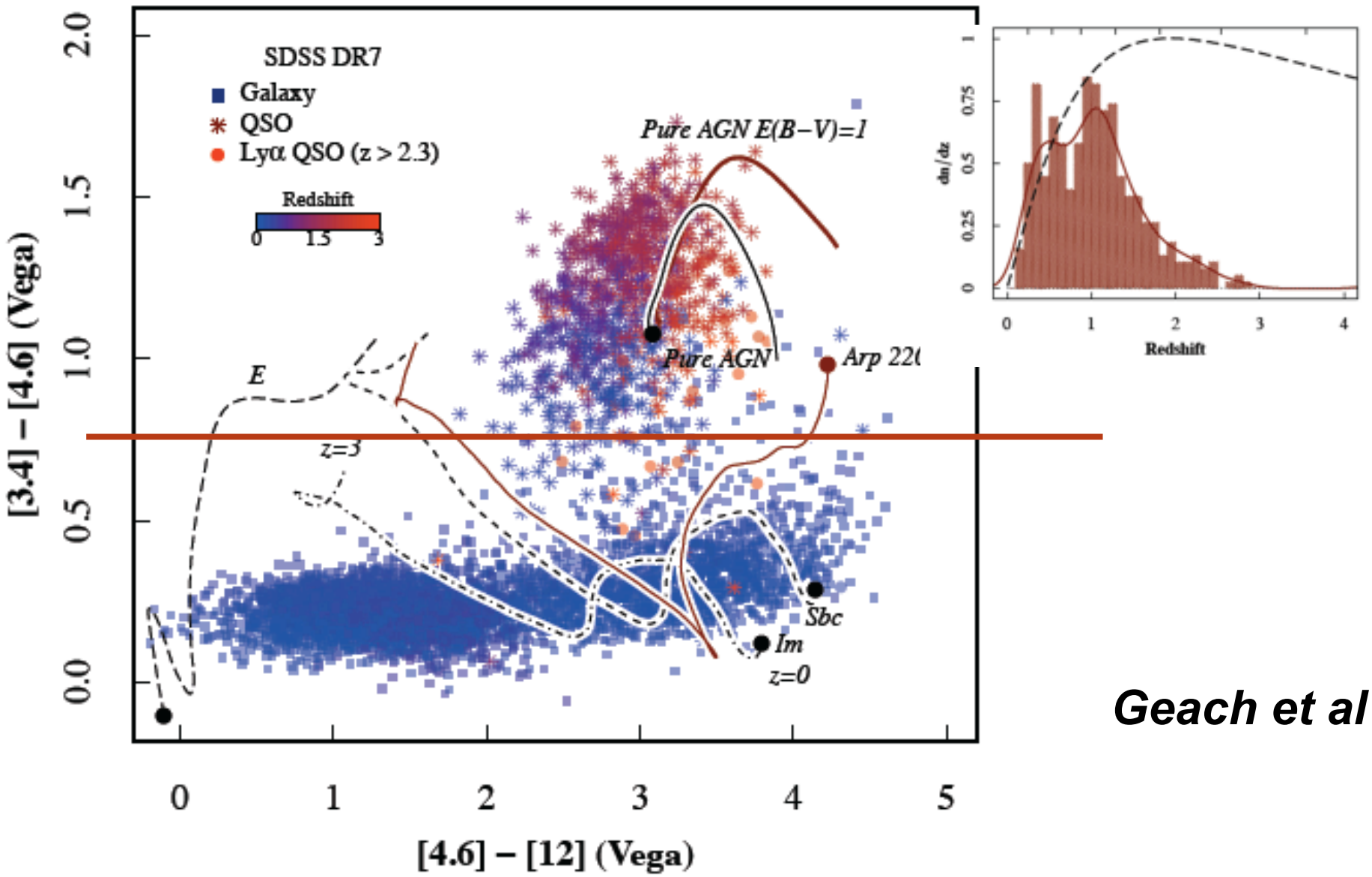
- well measured with Planck, SPT, ACT



# CMB Lensing/Herschel



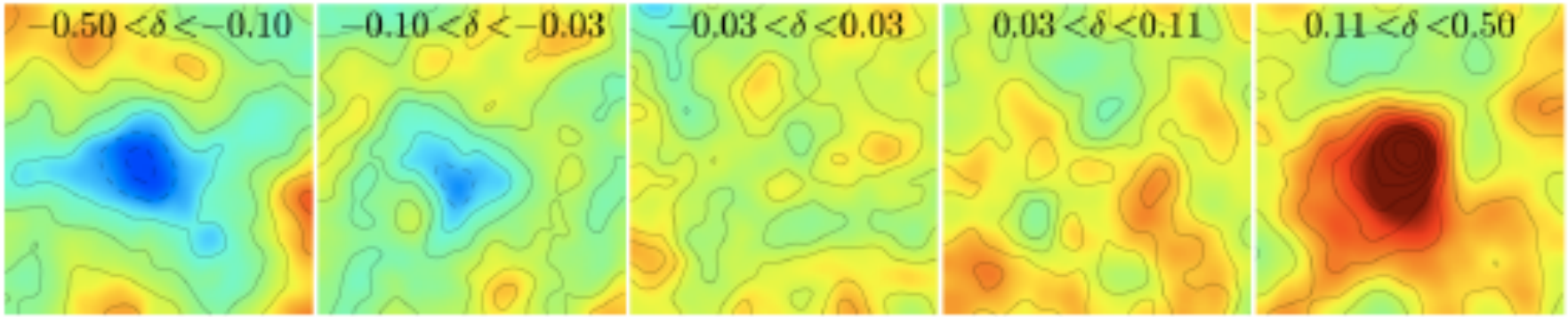
# AGN Selection with WISE




Geach et al

# *Quasar-Mass Cross-Correlation Detected: SPT X WISE*

stacked SPT lensing map in bins of AGN density



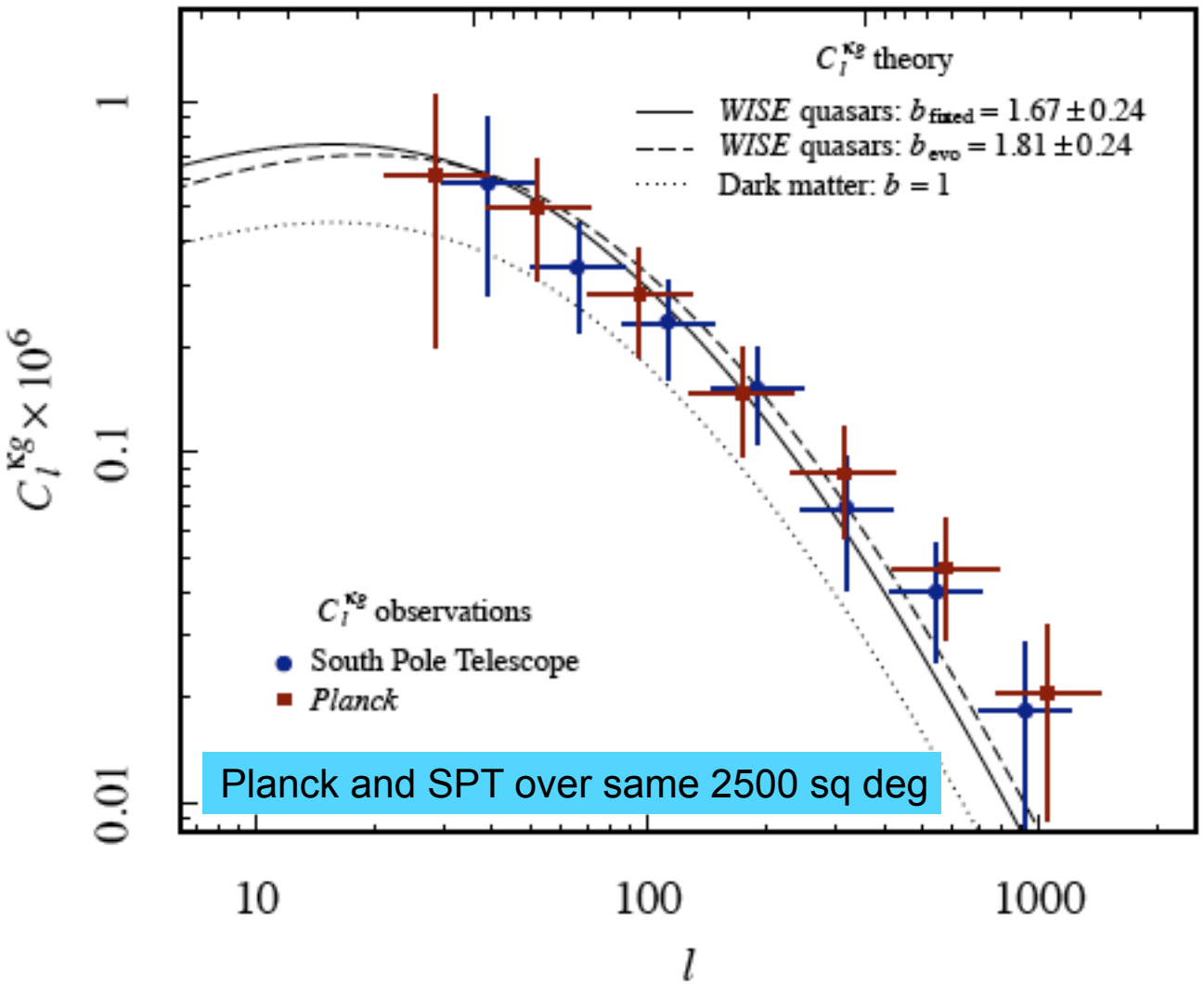

low AGN density

5°

high AGN density

***Geach et al***

# Quasar-Mass Cross-Correlation Detected: SPT X WISE




Planck and SPT in excellent agreement

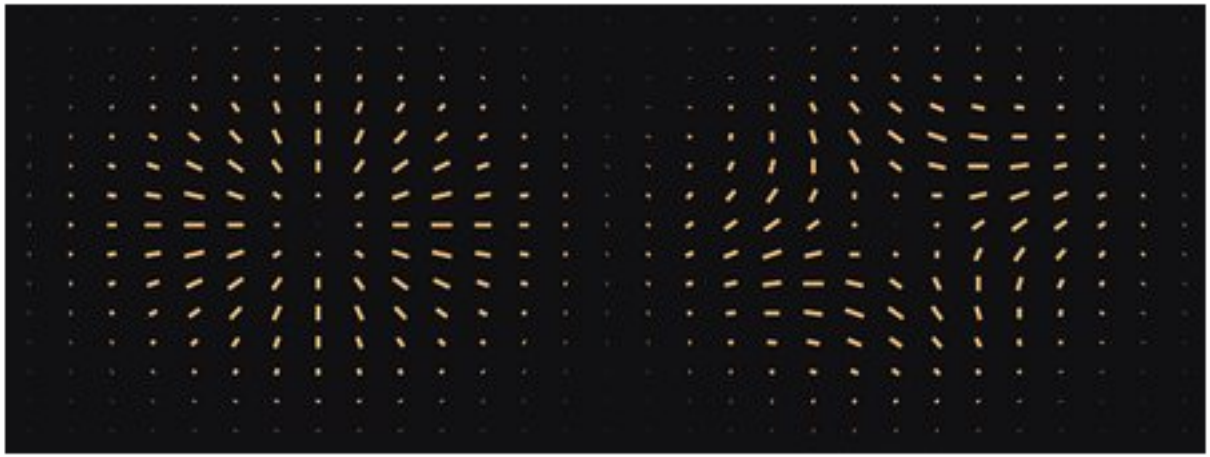
bias measurements agree with expectations

***Geach et al***

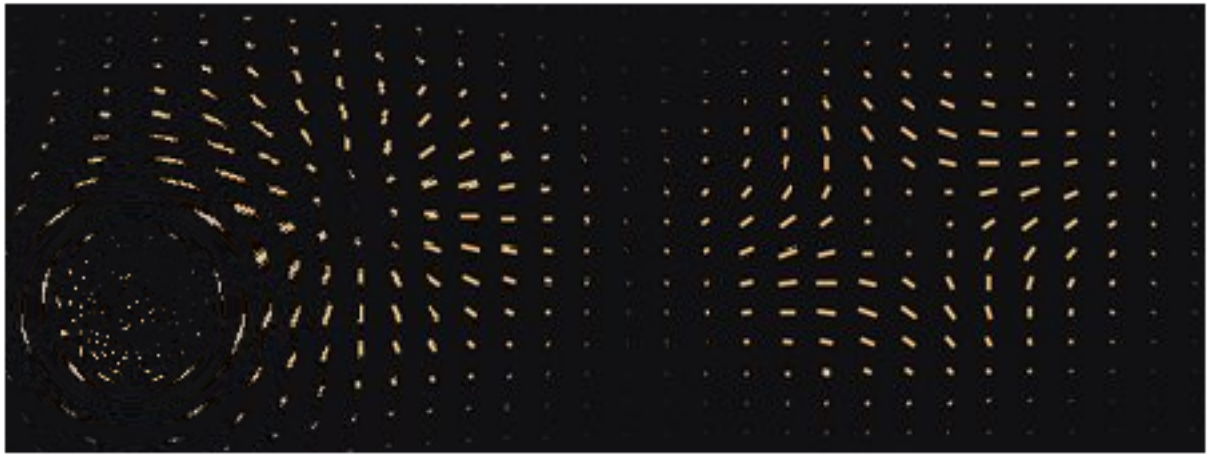
# B Modes from E Modes

*Before: pure E mode (left) and pure B mode (right)*

*From B-pol.org*



*After: large point mass lenses image*



*Lensing done with "Lens an astrophysicist"*

http://theory2.phys.cwru.edu/~pete/GravitationalLens/

# *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!***

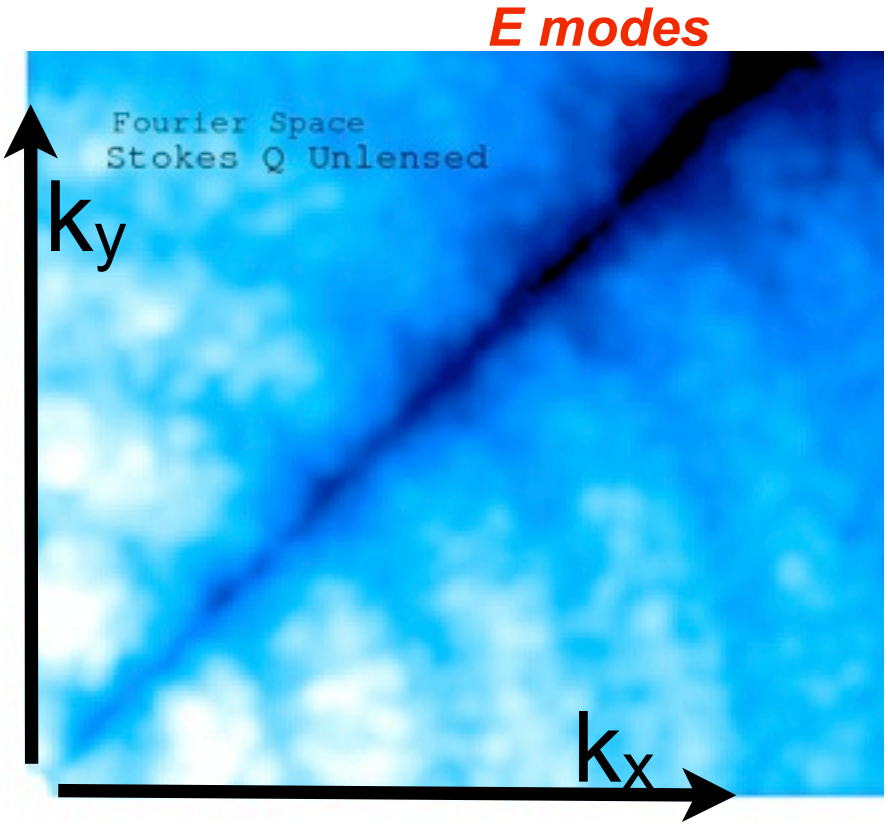
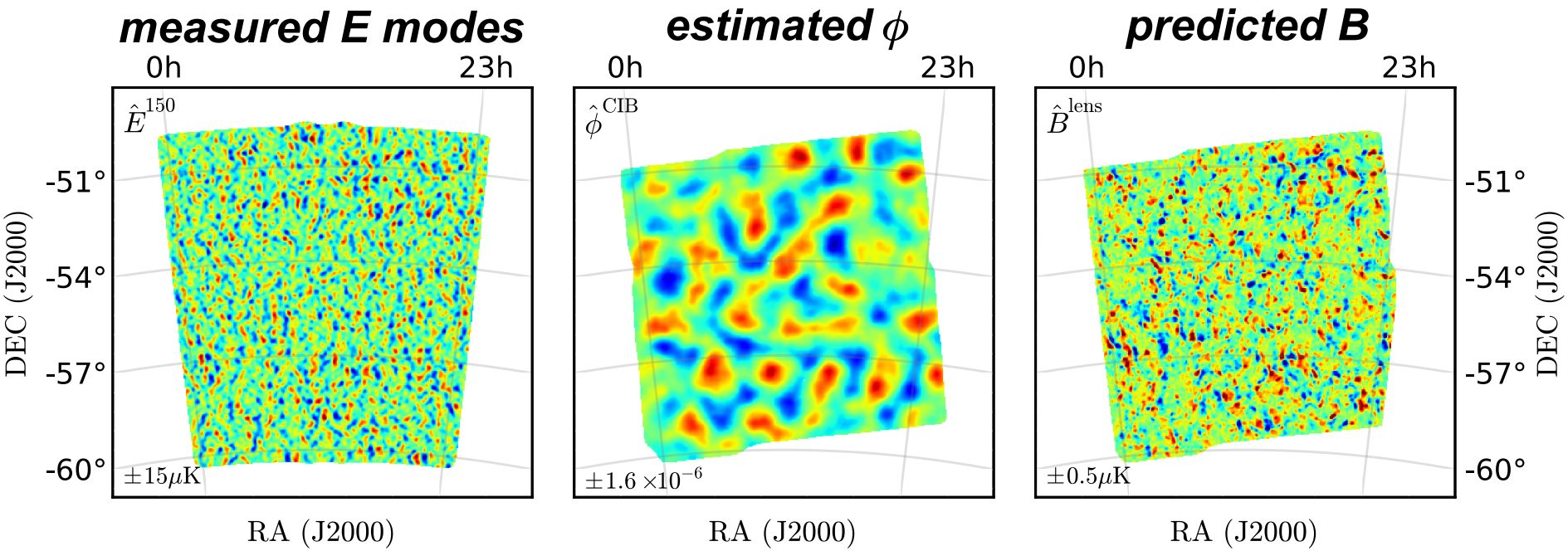


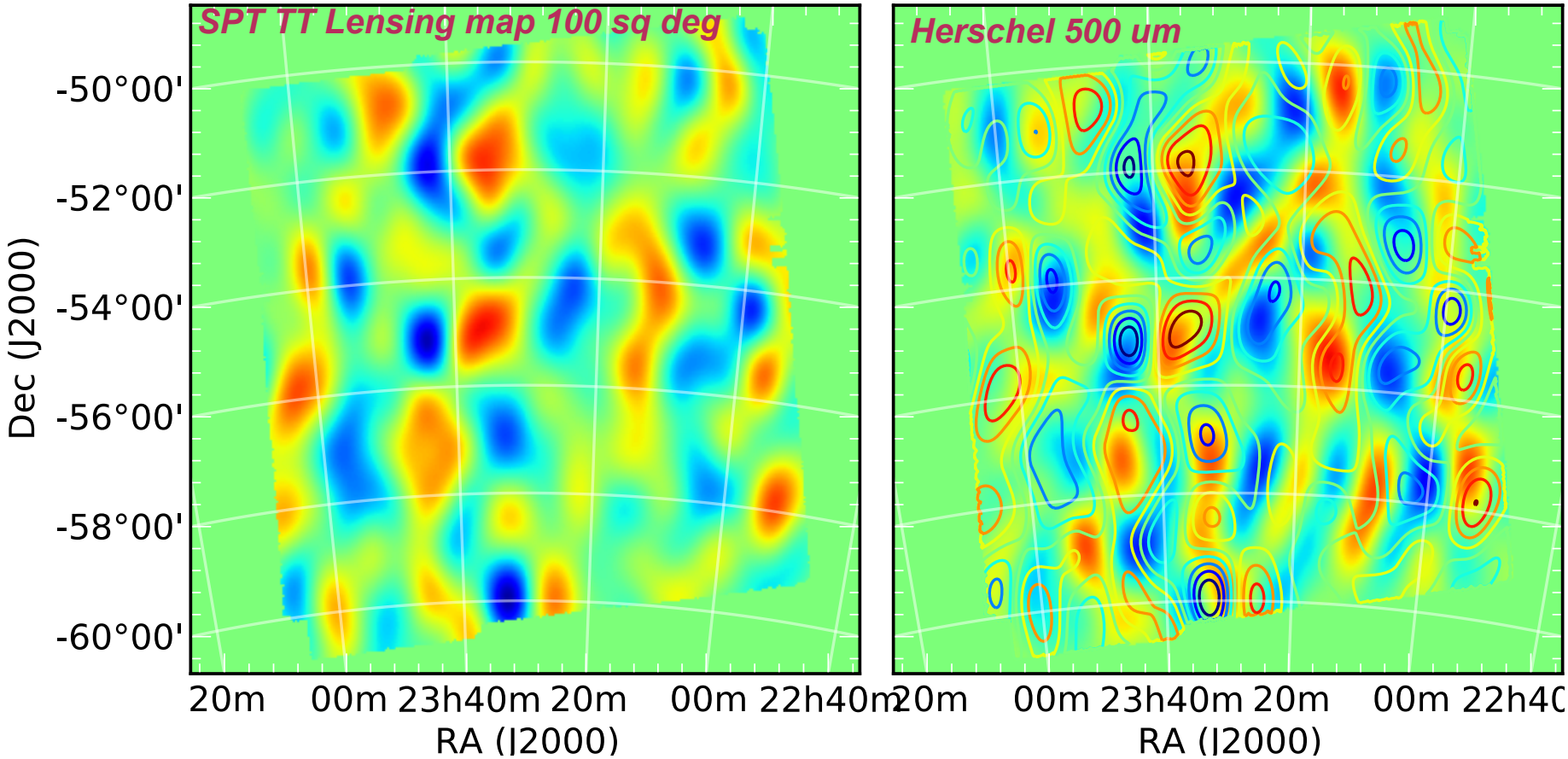

*Image of positive kx/positive ky Fourier transform of a 10x10 deg chunk of Stokes Q CMB map [simulated; nothing clever done to it]*

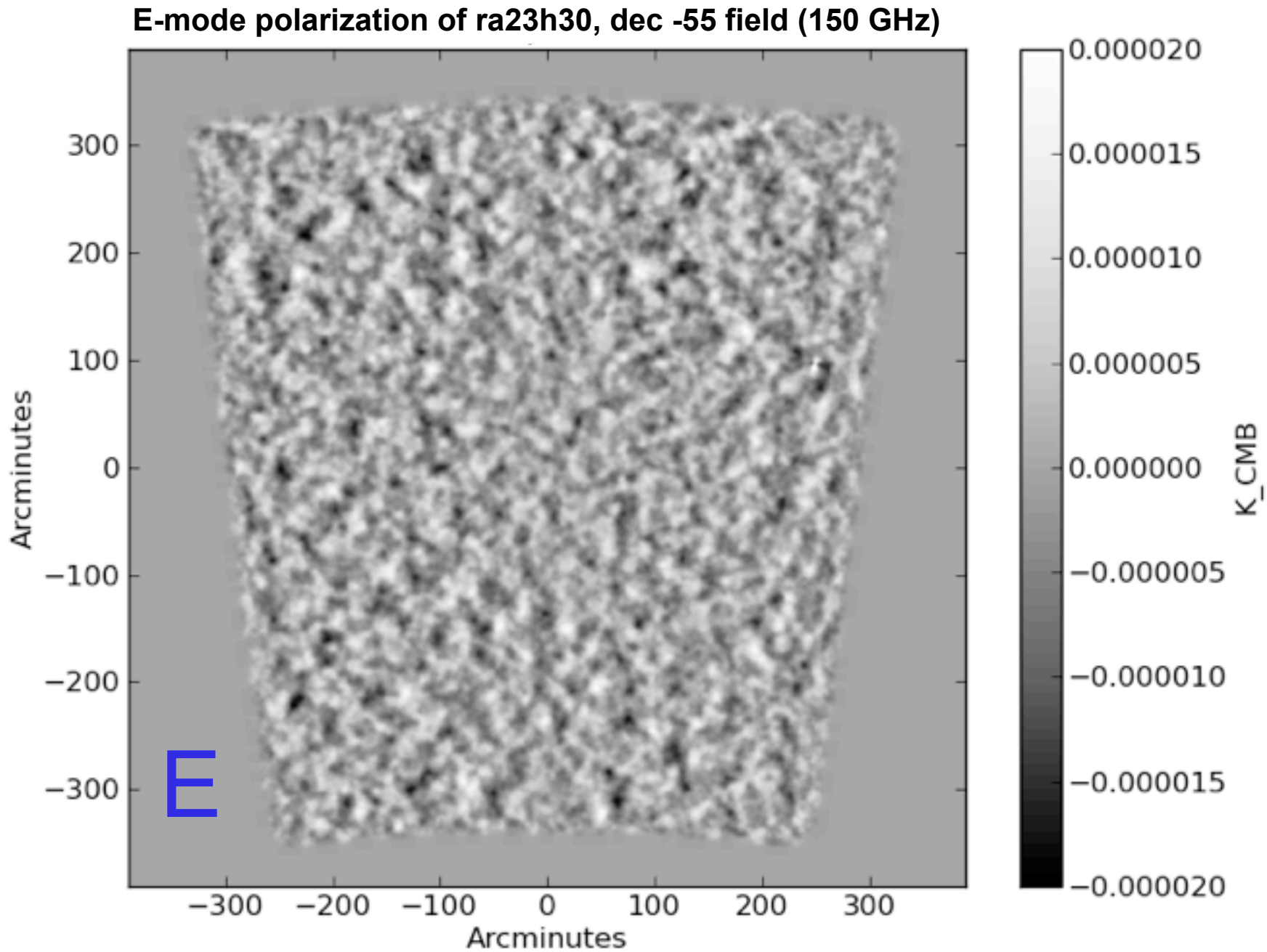
# Predicting B-Modes



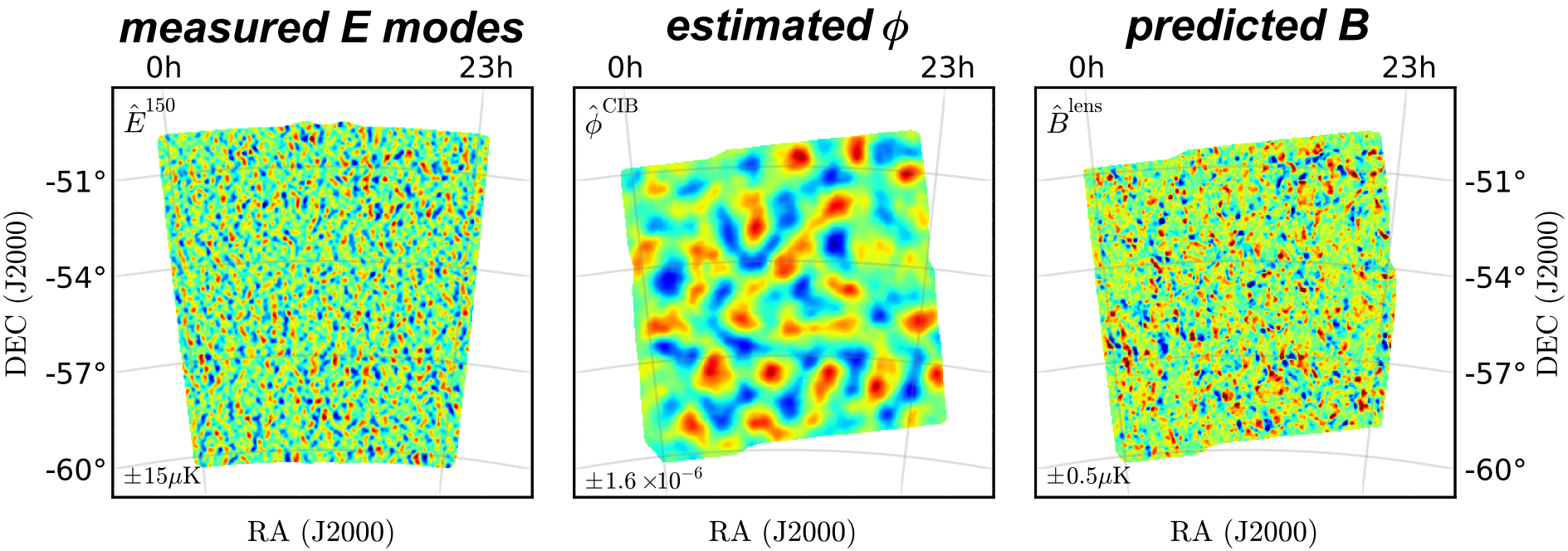

**Hanson, Hoover, Crites et al 2013**

# Cosmic Infrared Background Traces Mass




E-mode polarization of ra23h30, dec -55 field (150 GHz)
Arcminutes
300
200
100
0
−100
−200
−300
−300
−200
−100
0
100
200
300
Arcminutes
E
0.000020
0.000015
0.000010
0.000005
0.000000
−0.000005
−0.000010
−0.000015
−0.000020
K_CMB

# Many Ways of Predicting B-Modes




**E 150 GHz**
E 90 GHz
E from Temperature

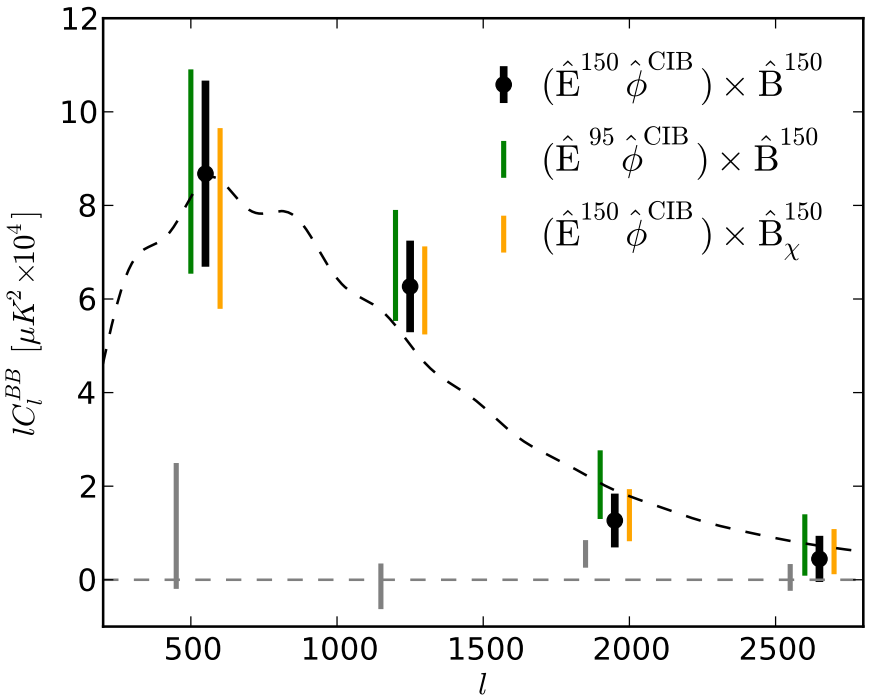
**$\phi$ CIB**
$\phi$ TT
$\phi$ EE
$\phi$ TE
($\phi$ Spitzer cat)

**X B 150 GHz**
X B 90 GHz

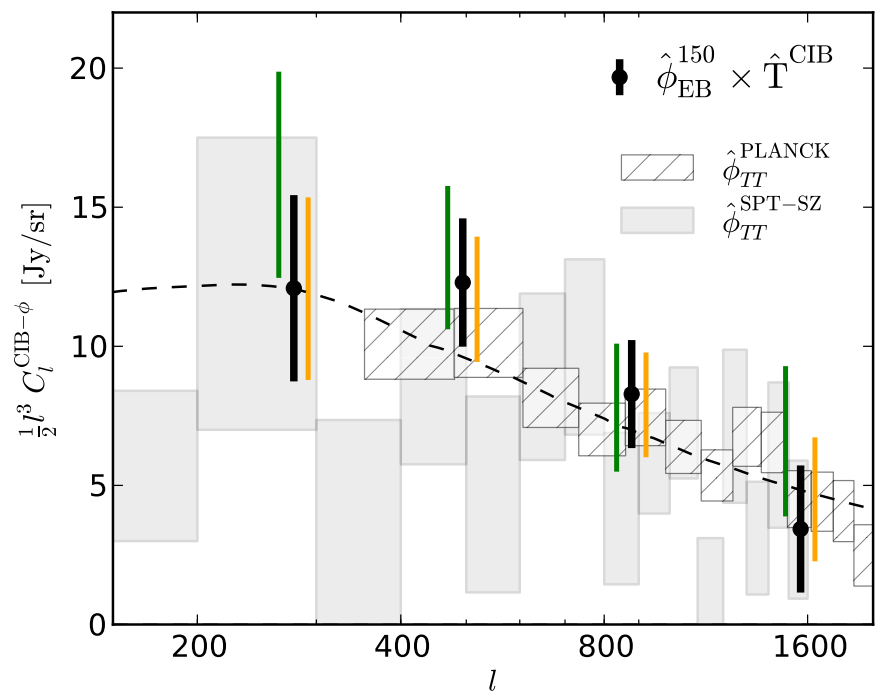
**Hanson, Hoover, Crites et al 2013**

# Detection of Lensing B-Modes!

*(predicted B) X (measured B)*




$\phi^{EB}$ X $T^{cib}$

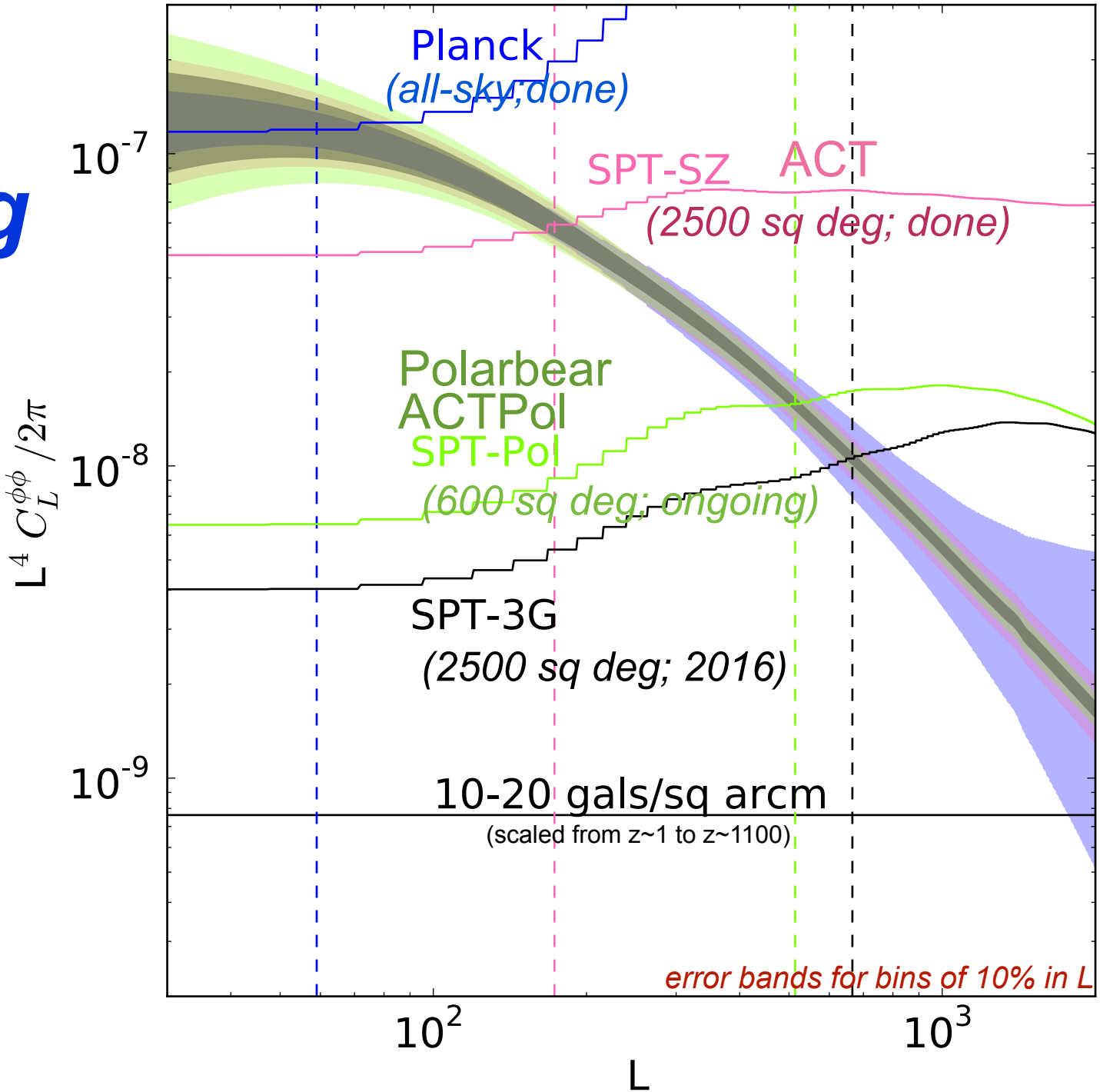



**Hanson, Hoover, Crites et al 2013**

**not zero at 7.7$\sigma$**

now also detected with Polarbear

# CMB Lensing Noise Levels



# Summary

- CMB gives great snapshot at early times
- late universe physics also imprinted in CMB
- polarized sky less polluted on small scales
- CMB lensing now being measured by many experiments