CMB Lensing Constraints on Neutrino Masses

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with help from:
SPT collaboration
Alex van Engelen

Outline

- review of neutrino masses & cosmology
- overview of CMB lensing
  - mode coupling, E-modes, B-modes
- recent results
  - clear detections at high significance
- near-future measurements
  - opportunities for high precision in the next 2 years (SPT, Planck, SPTPol, ACTPol)

WARNING: I am not reporting any neutrino mass measurements today!!

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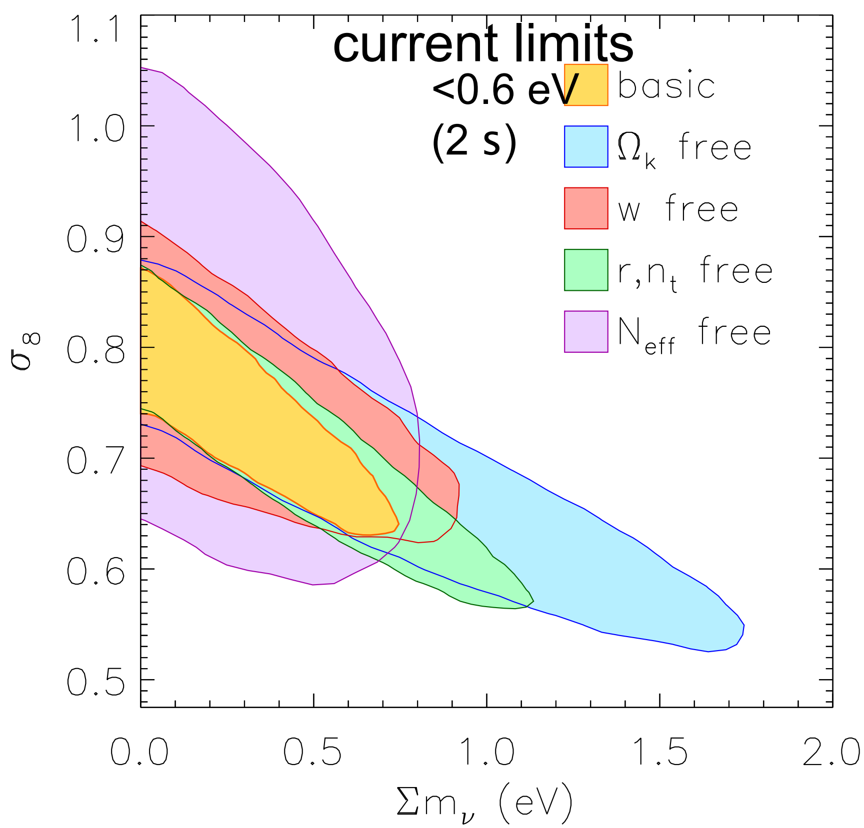
Massive Neutrinos in Cosmology

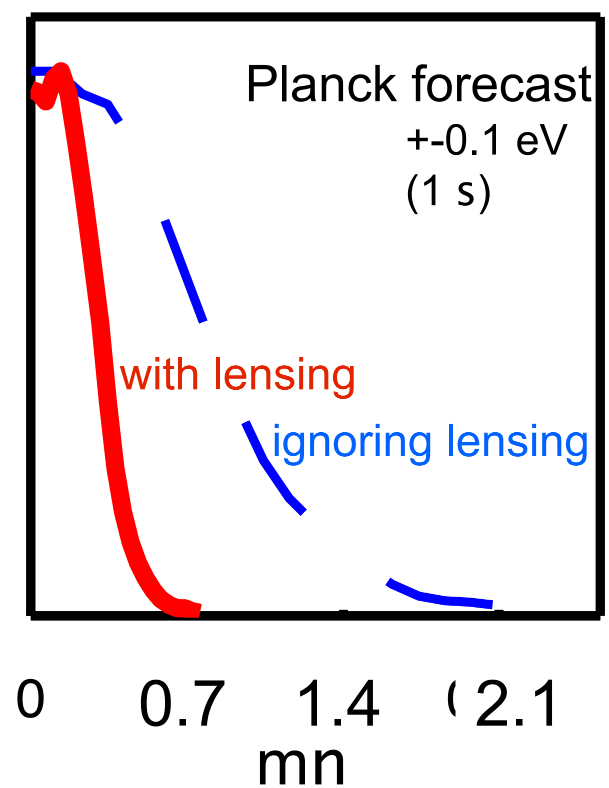
$$\Omega_\nu \approx \sum_i (m_i / 0.1\ eV) \quad 0.0022\ h_{0.7}^{-2}$$

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

Neutrino Masses Today and Soon



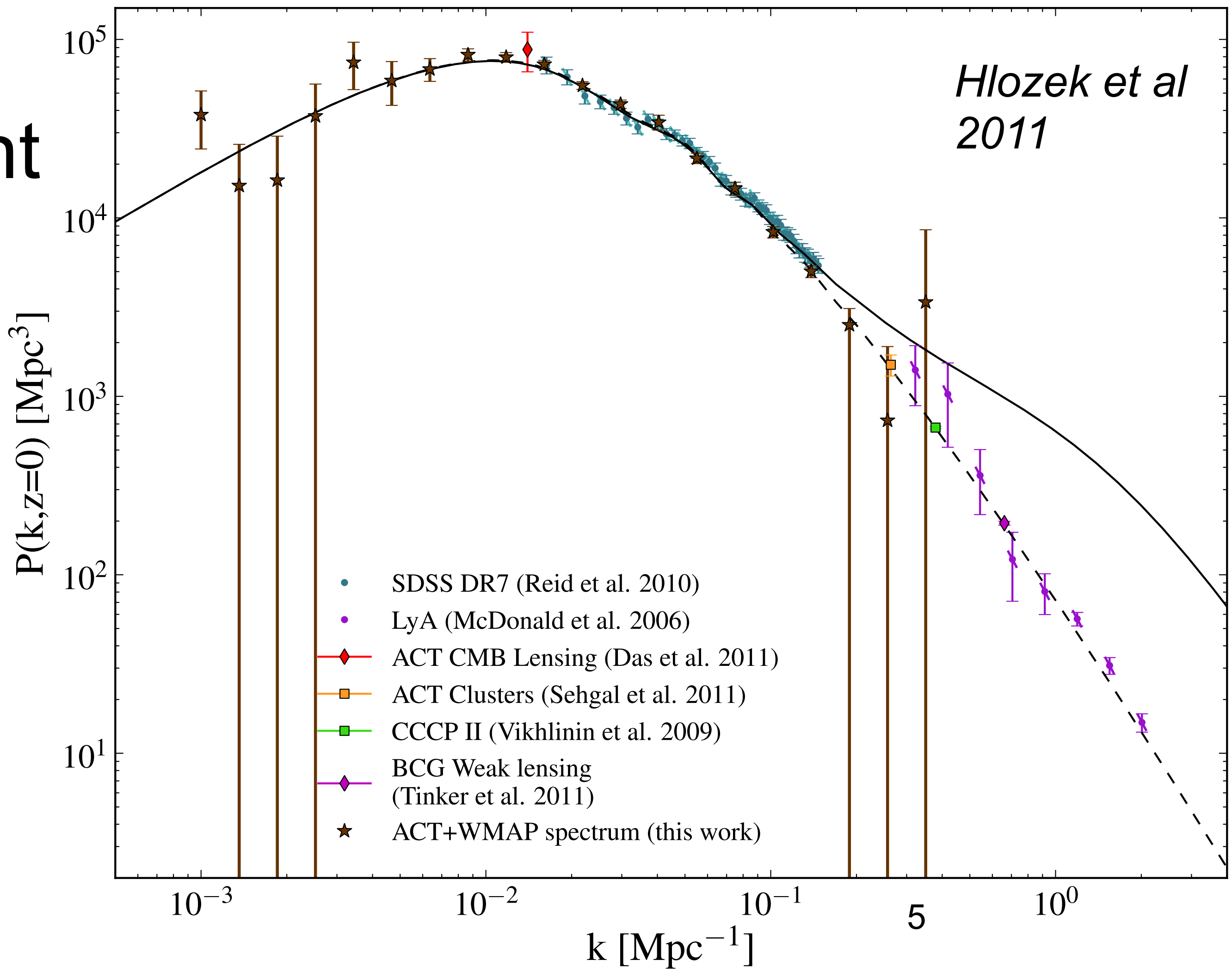
Mantz et al 2011



Perotto et al 2006

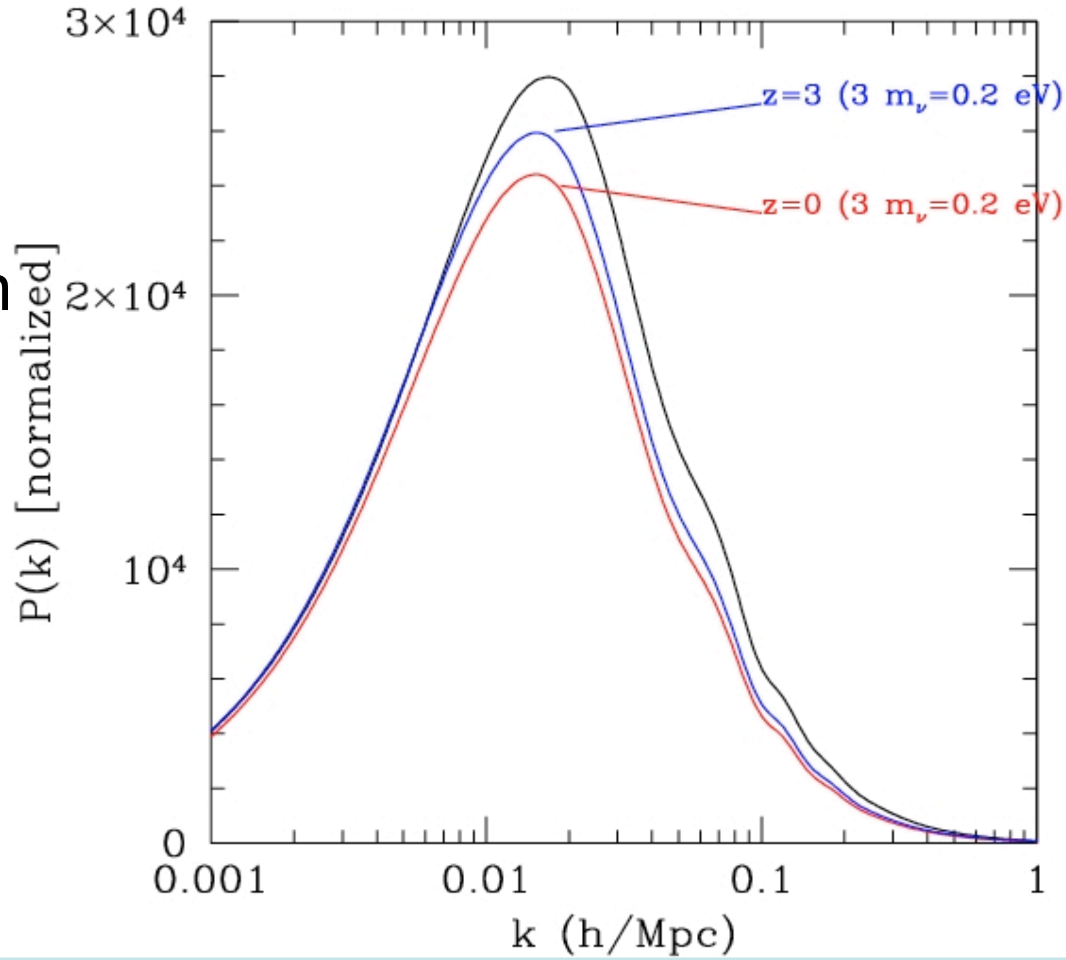
Matter Power Spectrum

- many independent probes of matter clustering



Massive Neutrinos in Cosmology

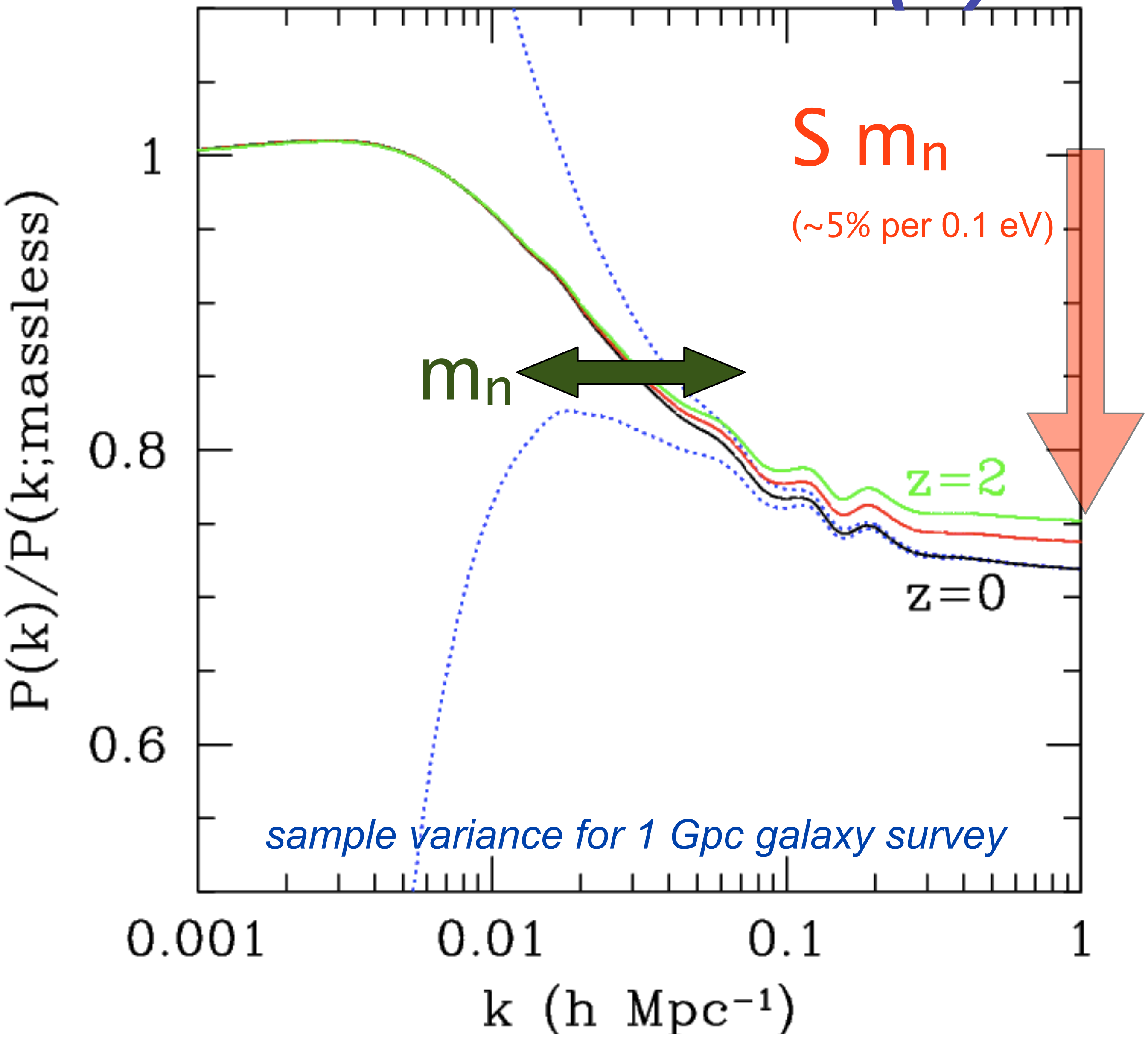
- Free streaming of neutrinos on small scales leads to time-dependent suppression of power
- CMB only sensitive to matter-radiation equality epoch (not affected by m<0.3 eV)
- Free-streaming scale roughly (m/1 eV) 0.1 h/Mpc



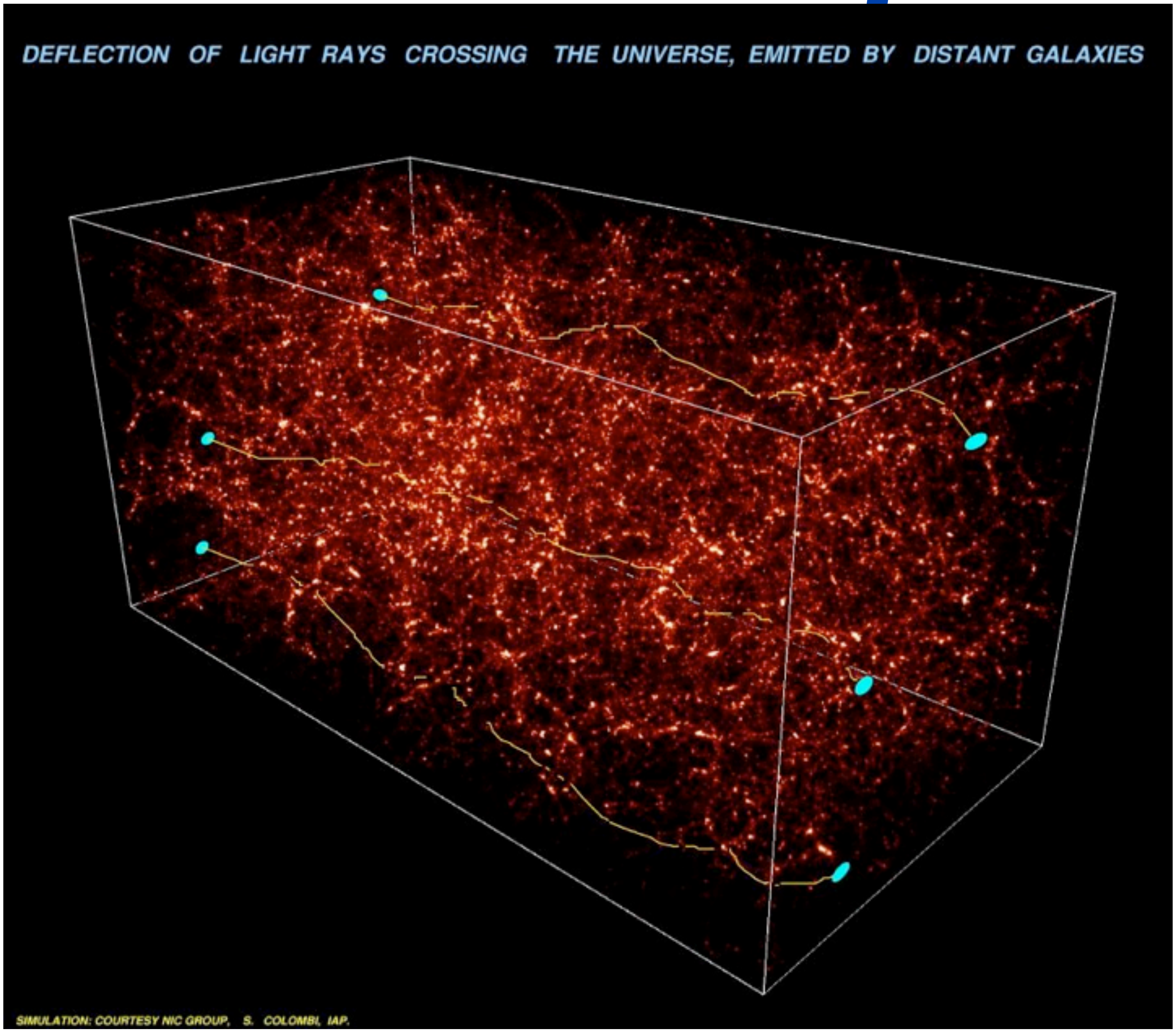
TIME DEPENDENT SCALE DEPENDENCE

Massive Neutrinos and P(k)

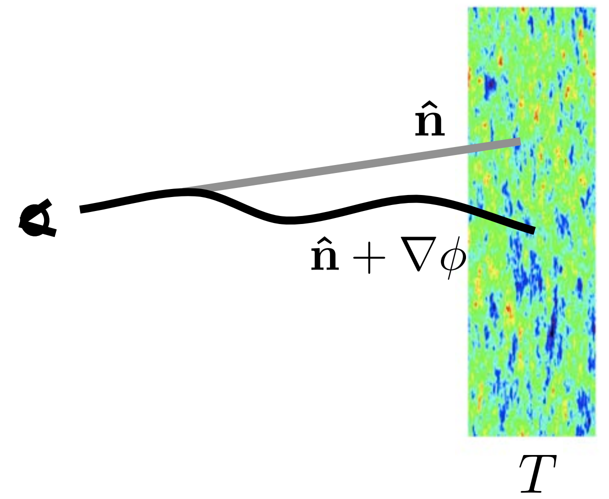
- e.g: 3 neutrinos, each 0.2 eV
- total amount of damping mainly set by sum of masses
- damping scale set by individual masses



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

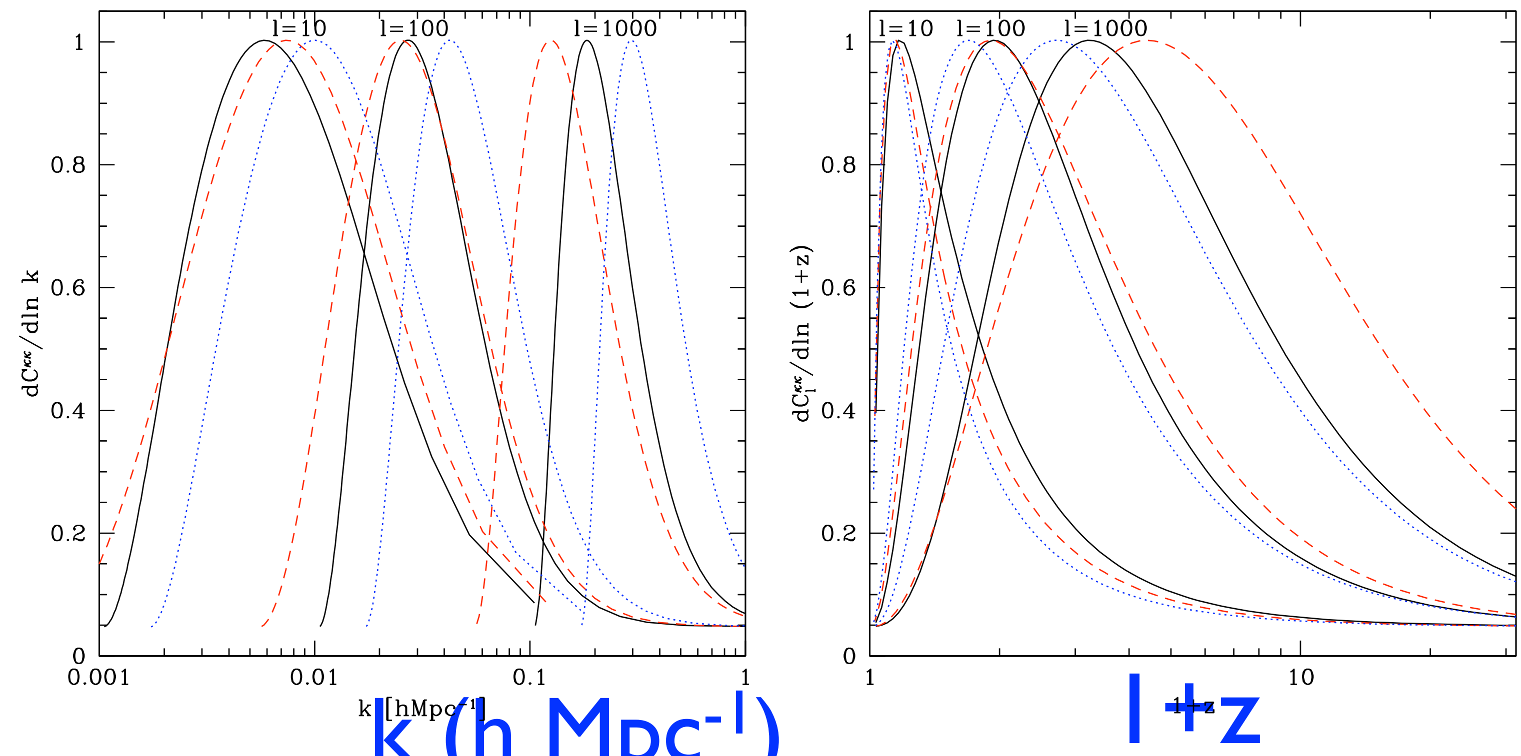
$$\nabla\phi(\hat{\mathbf{n}}) = -2\int_0^{\chi_\star} d\chi\, \frac{\chi_\star - \chi}{\chi_\star \chi} \nabla_\perp \Phi(\chi\hat{\mathbf{n}}, \chi)$$

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 potential

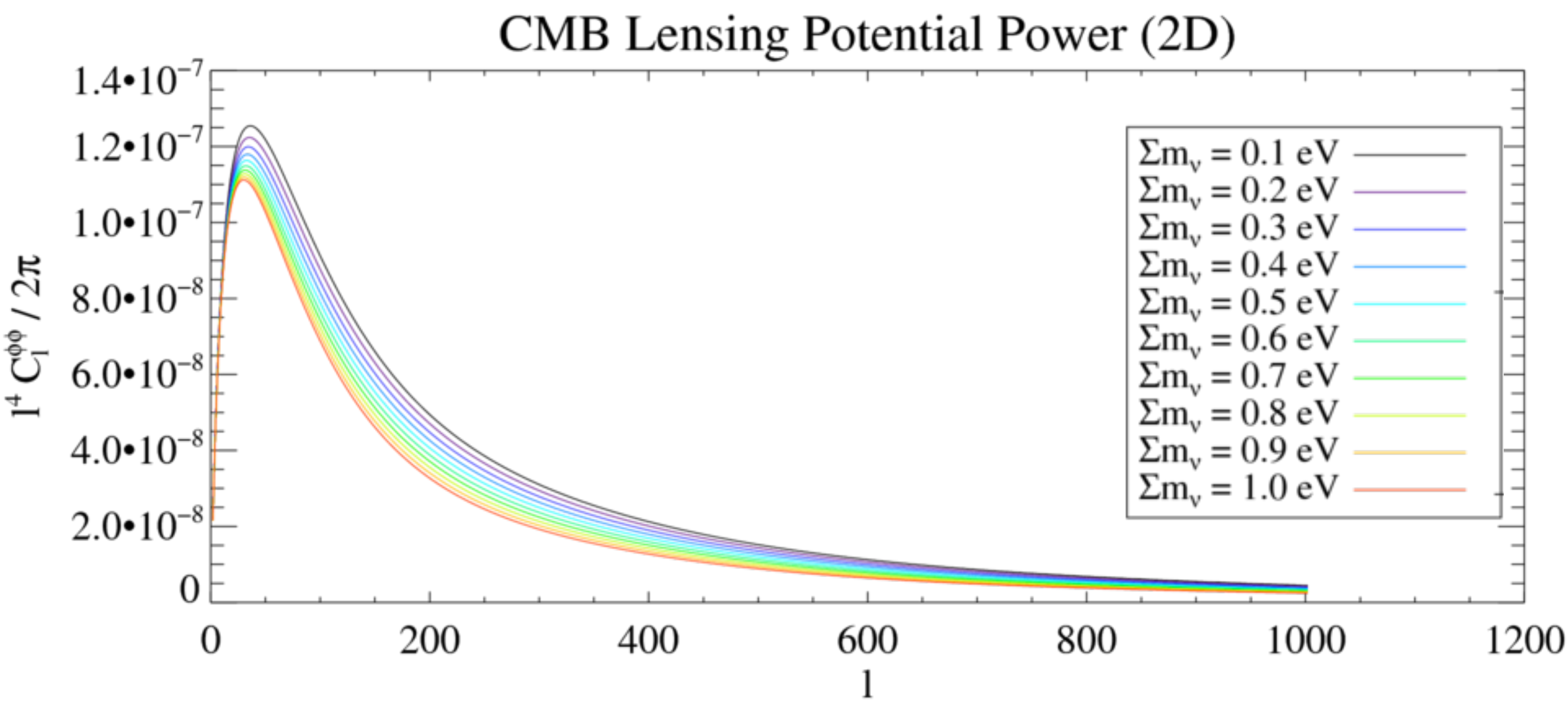
- 3-d potential still (mostly) Gaussian on such large scales => ϕ is a 2-d Gaussian random field
- LOS integral over matter power spectrum



Zaldarriaga & Seljak 1999

FIG. 7. Left: logarithmic contribution to $C_l^{\kappa\kappa}$ as a function of k for $l = 10$, 100, 1000 (the normalization is arbitrary). The models are flat CDM model (dotted), open CDM model with $\Omega_m = 0.3$ (dashed) and cosmological constant model with with

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'

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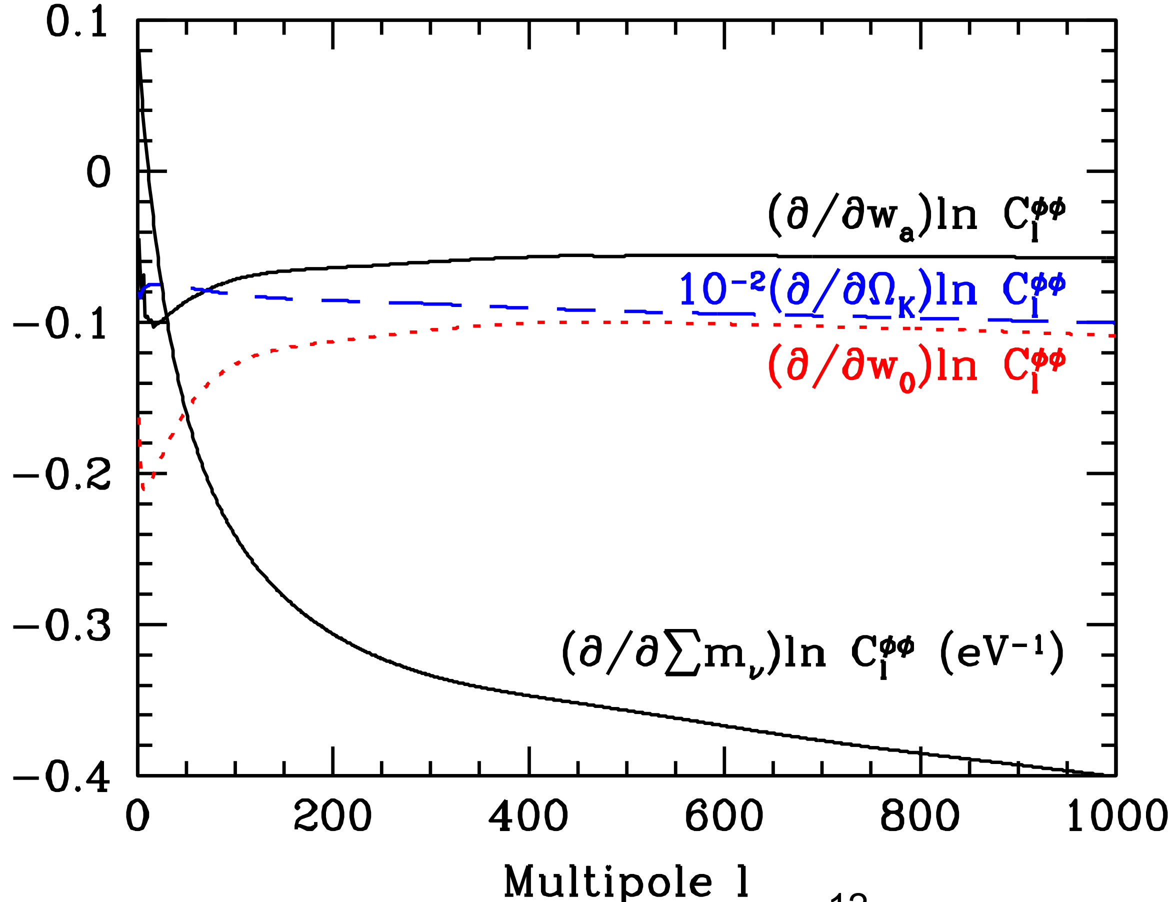
Neutrinos & CMB Lensing

Smith et al 2006

- scale dependent effect of neutrino masses shows up in lensing on large scales



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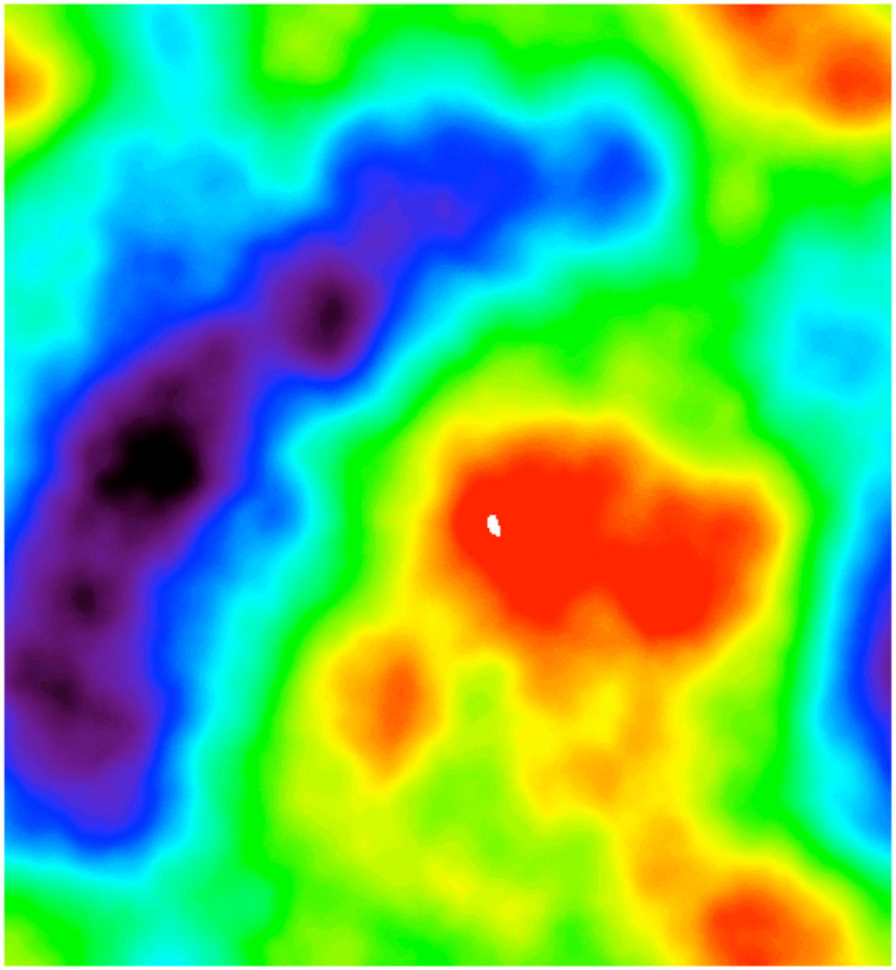
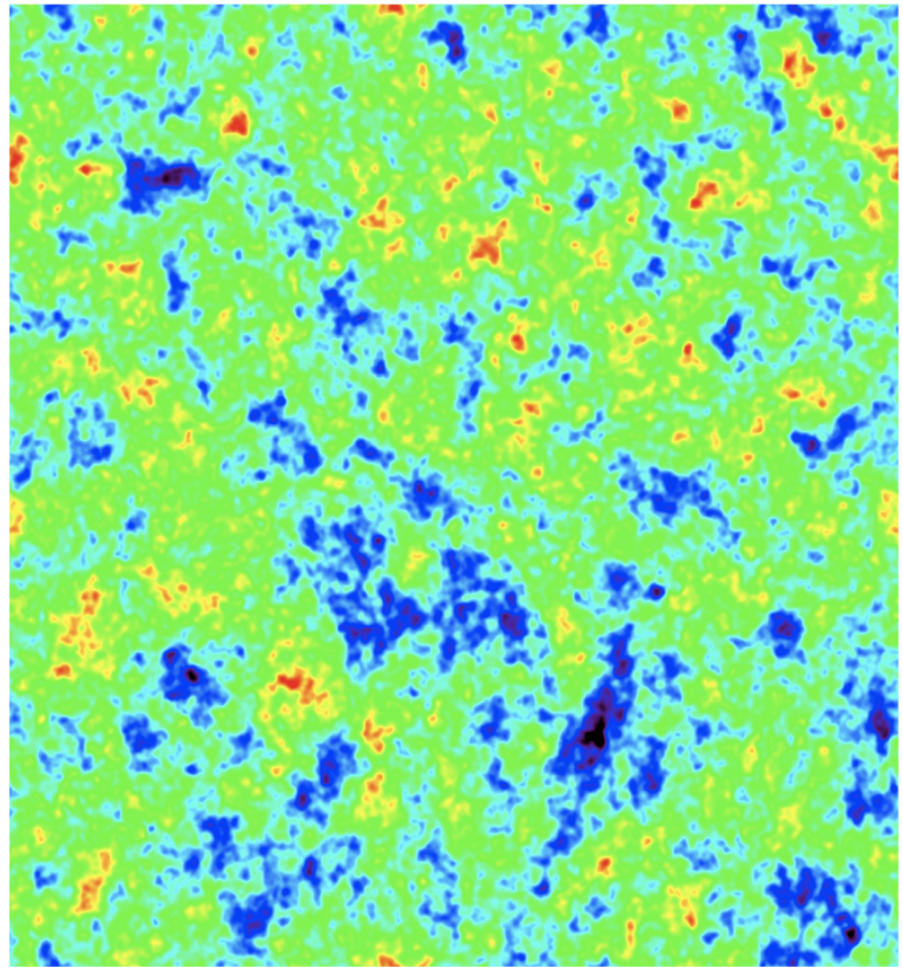
Lensing of the CMB

17°x17°



lensing potential

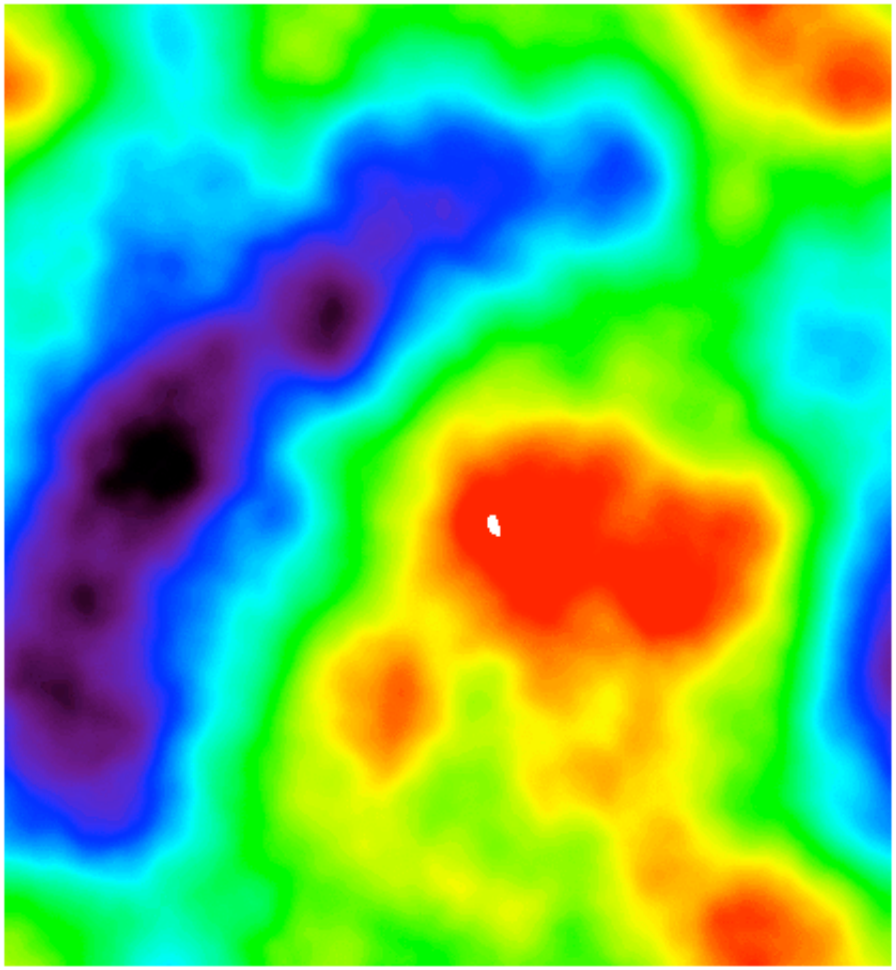


unlensed cmb

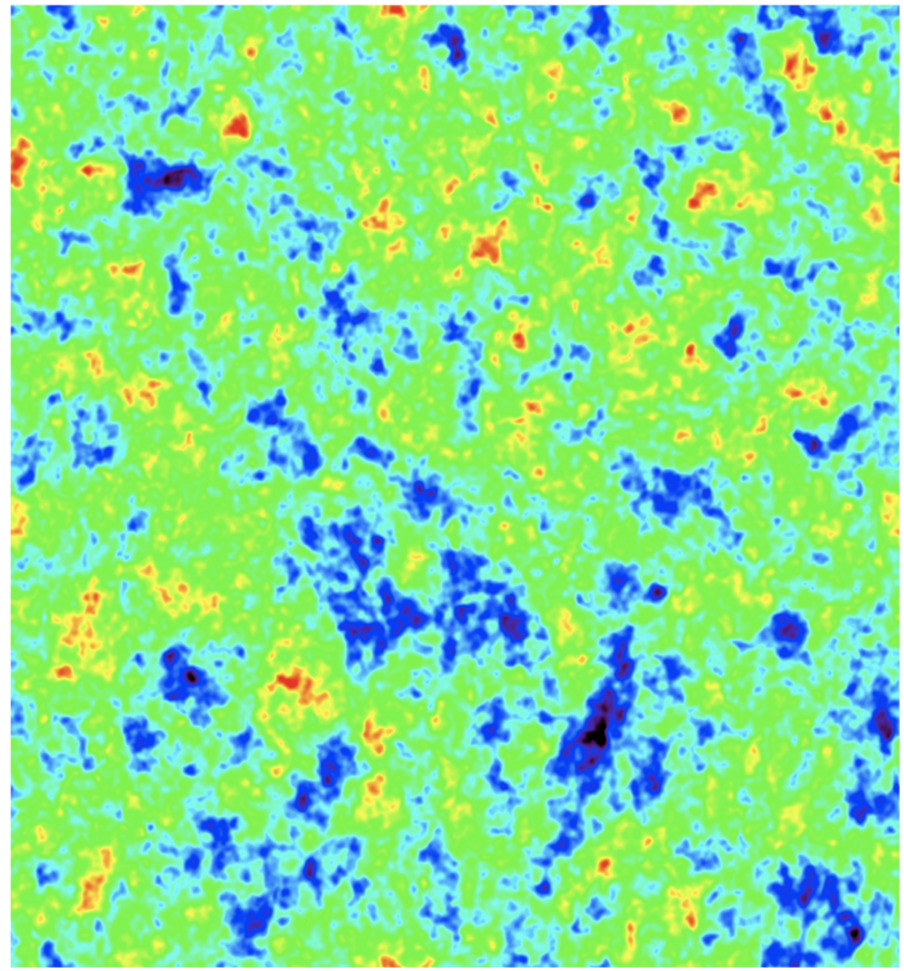
from Alex van Engelen

Lensing of the CMB

17°x17°



lensing potential

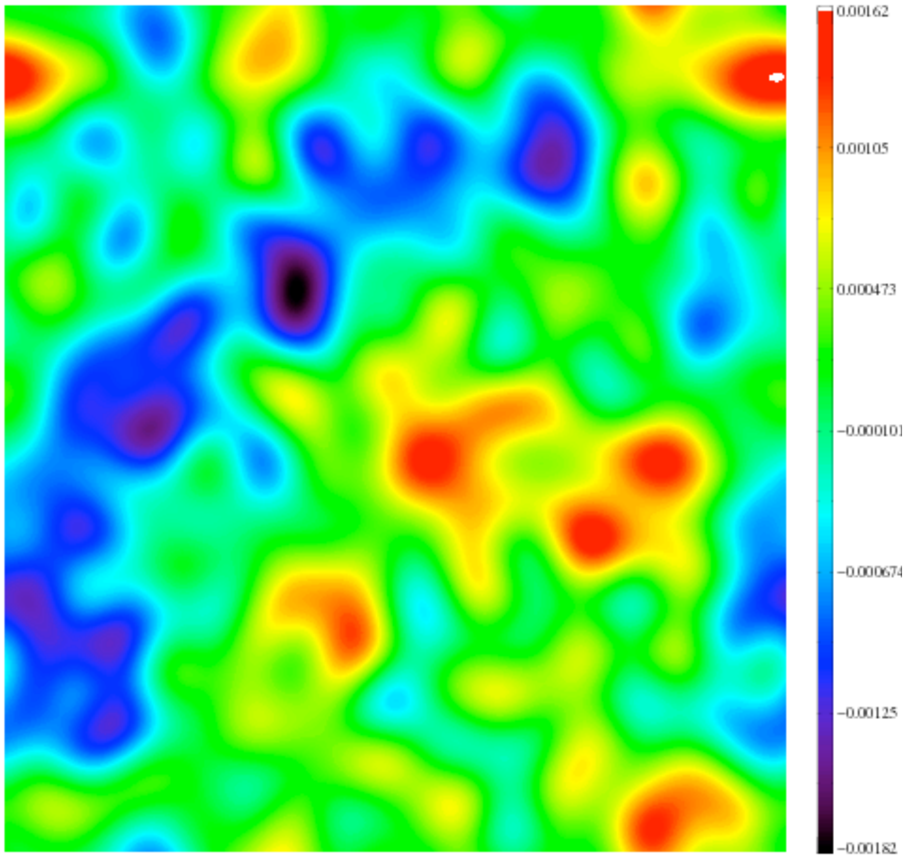


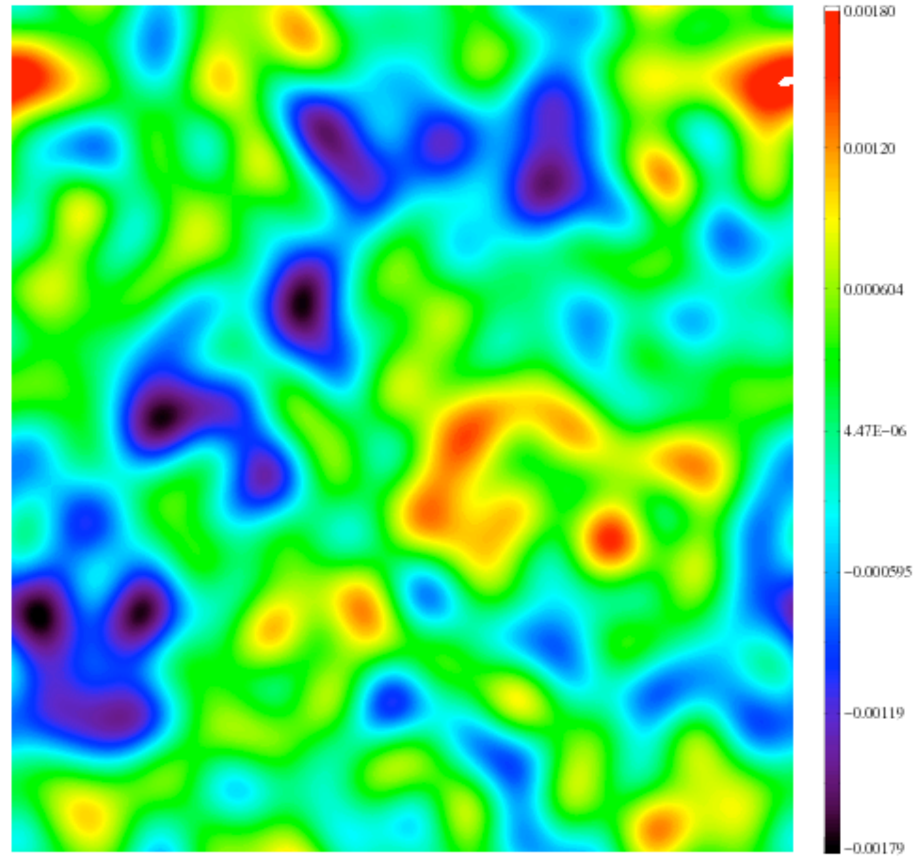
lensed cmb

from Alex van Engelen

Simulated reconstructions

- Input and recovered deflection angle maps, 17°x17°
  - filtered for display at l < 200





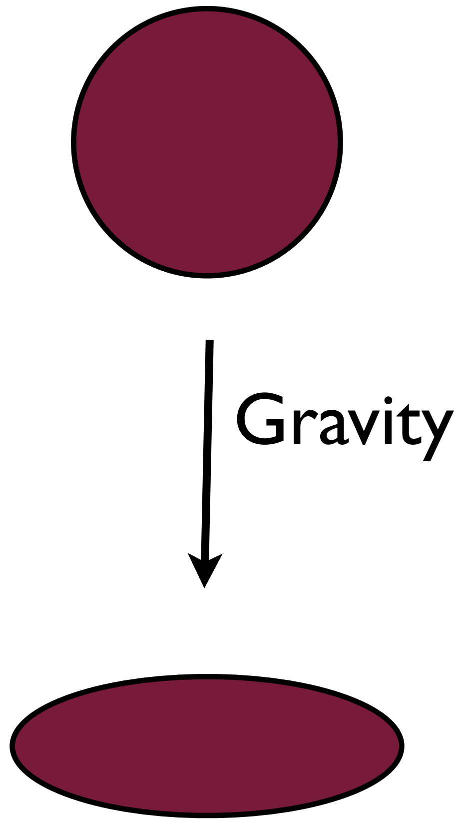
from Alex van Engelen

Input

Recovered at 15 uK’ white, 1’

Lensing simplified

- gravitational potentials distort shapes by stretching, squeezing, shearing



Lensing simplified

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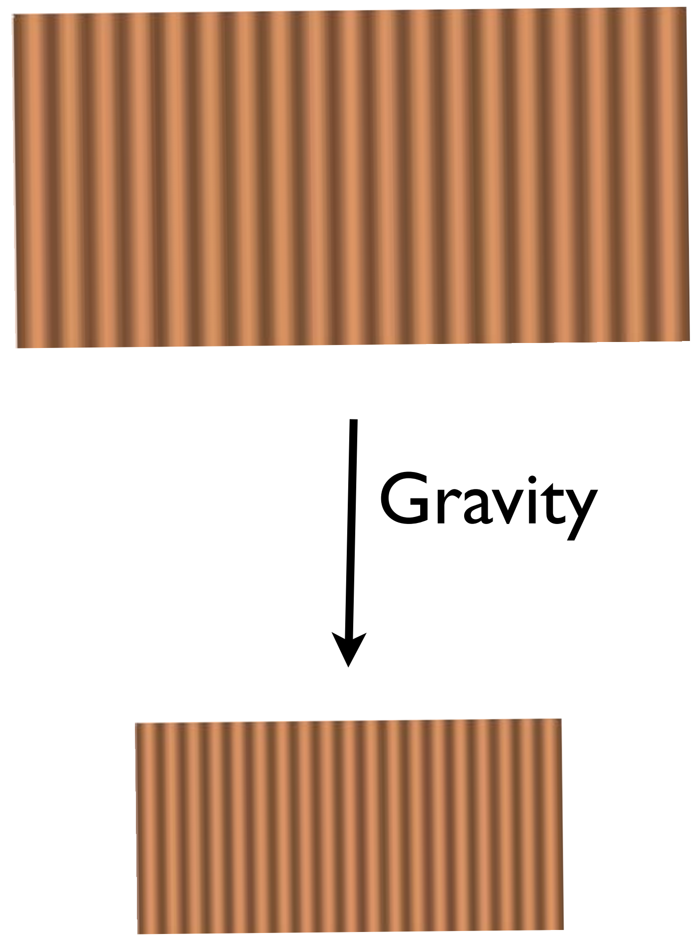
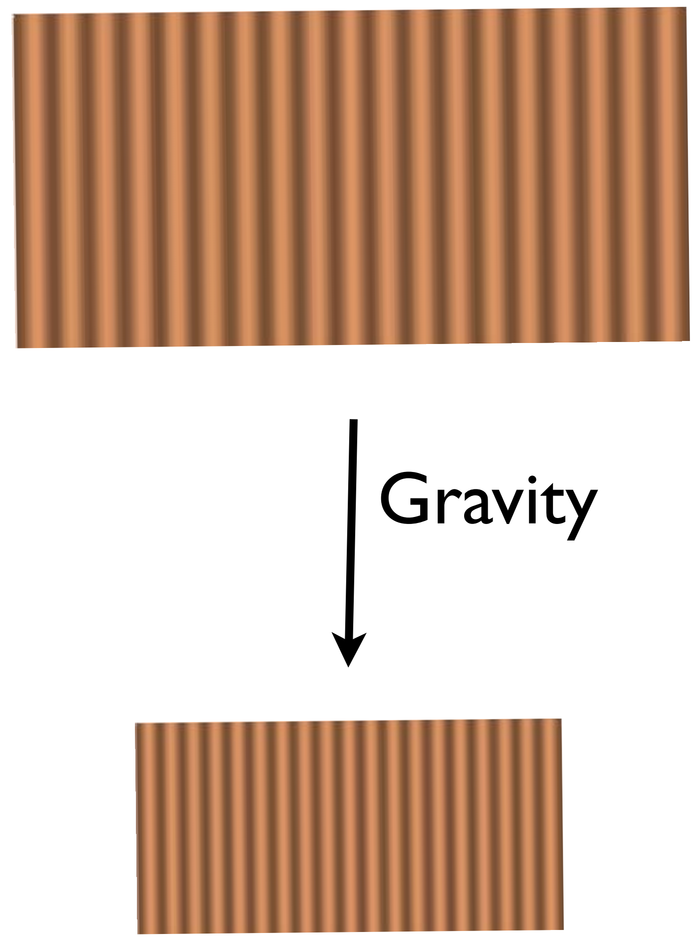


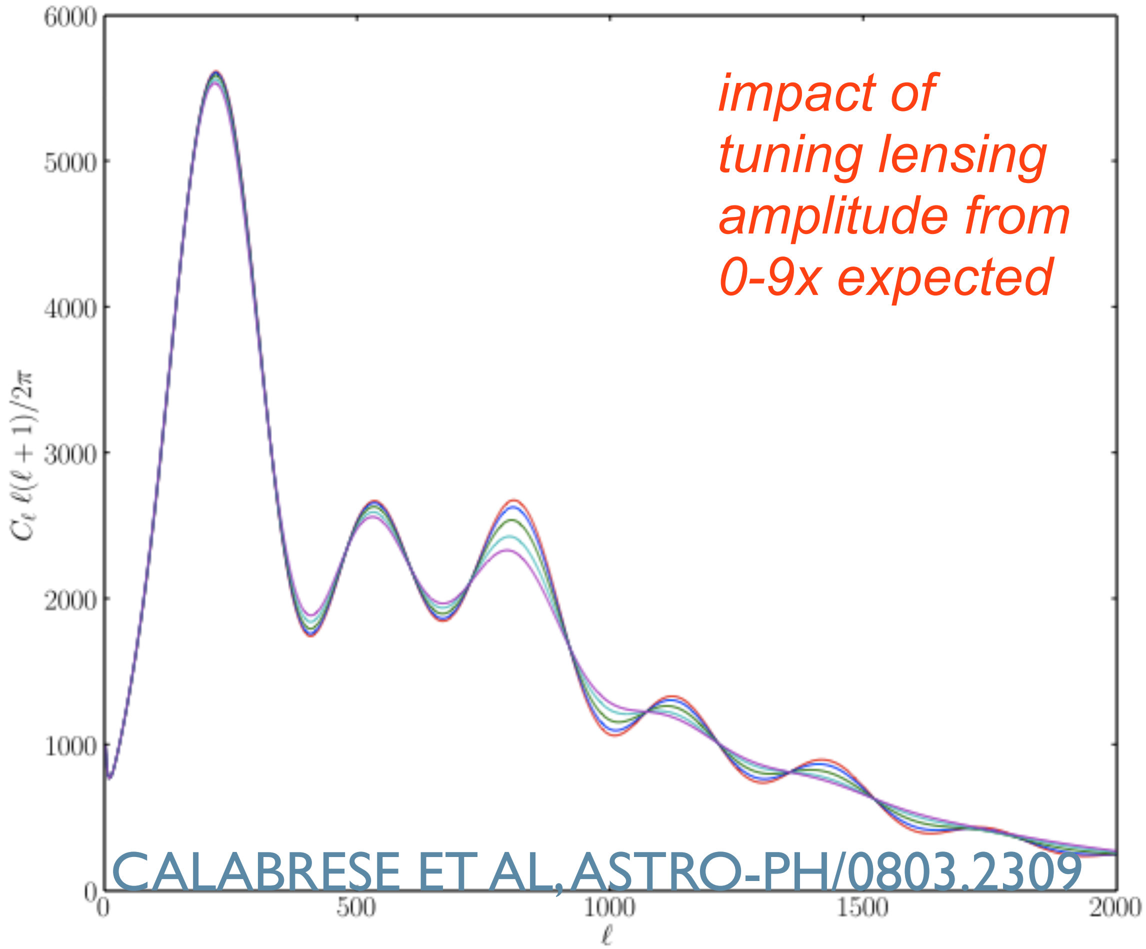
Lensing simplified

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



Effect on CMB Power Spectrum

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



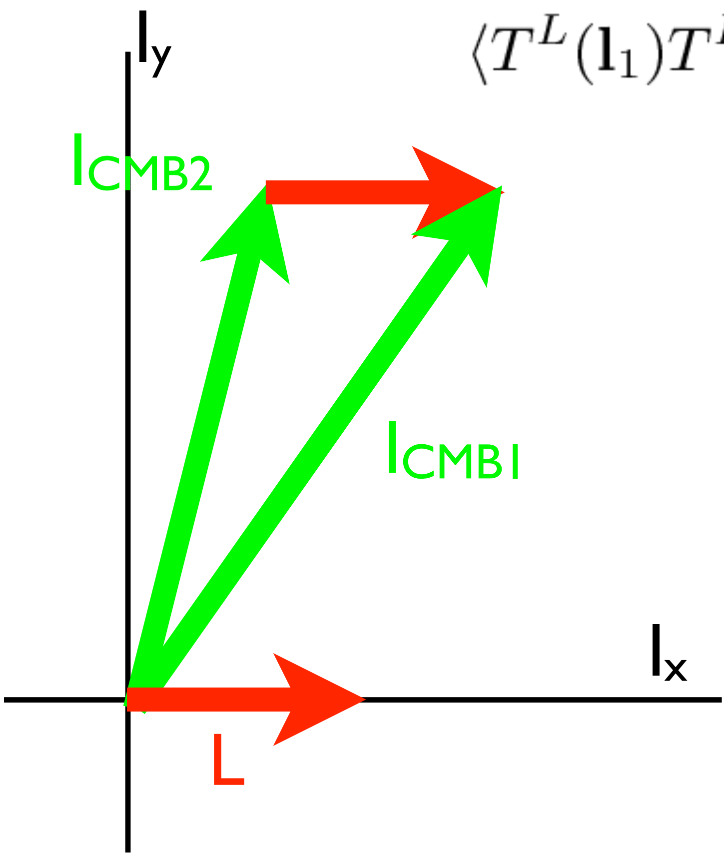
Mode Coupling from Lensing

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

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

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

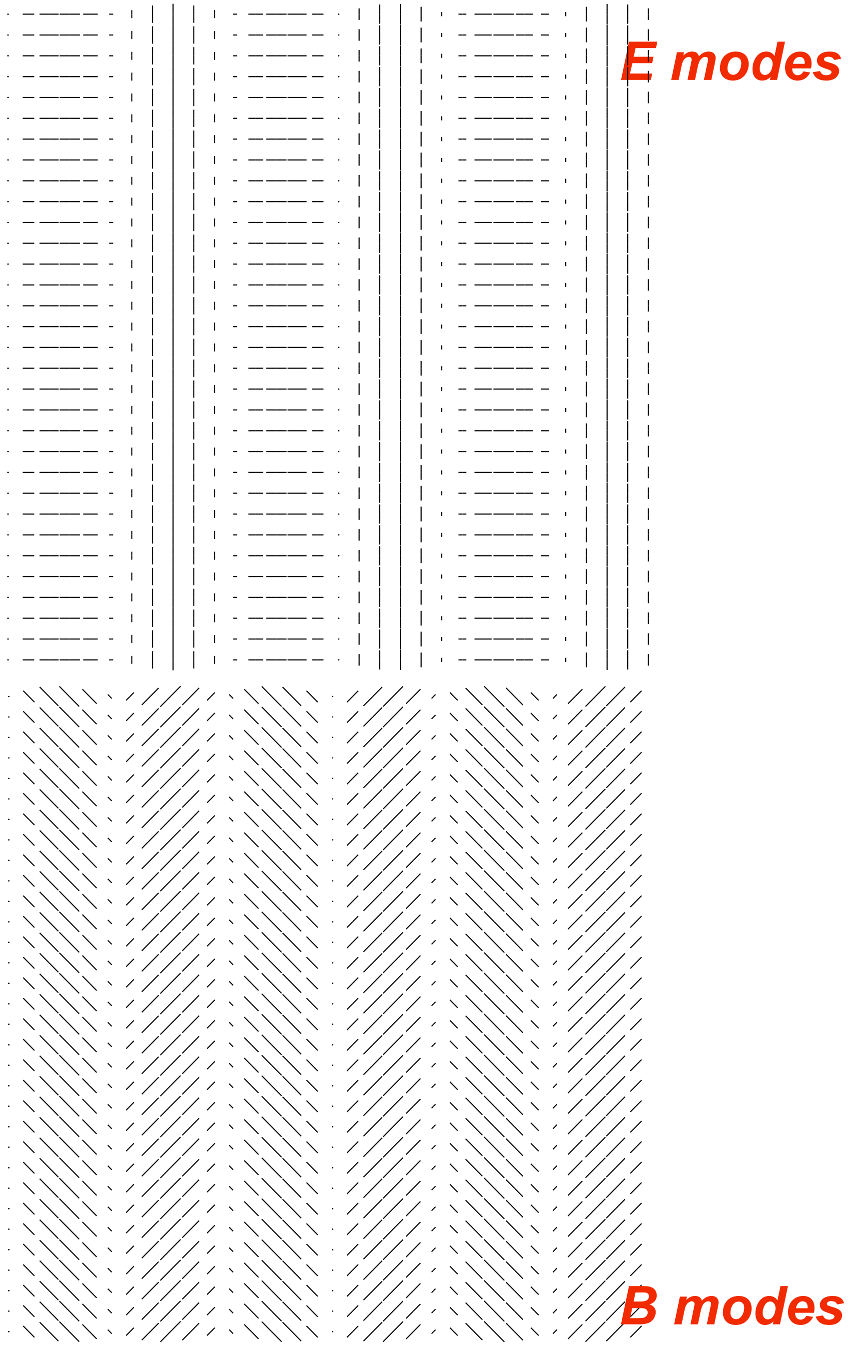
$$\mathbf{L} = \mathbf{l}_1 + \mathbf{l}_2$$



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

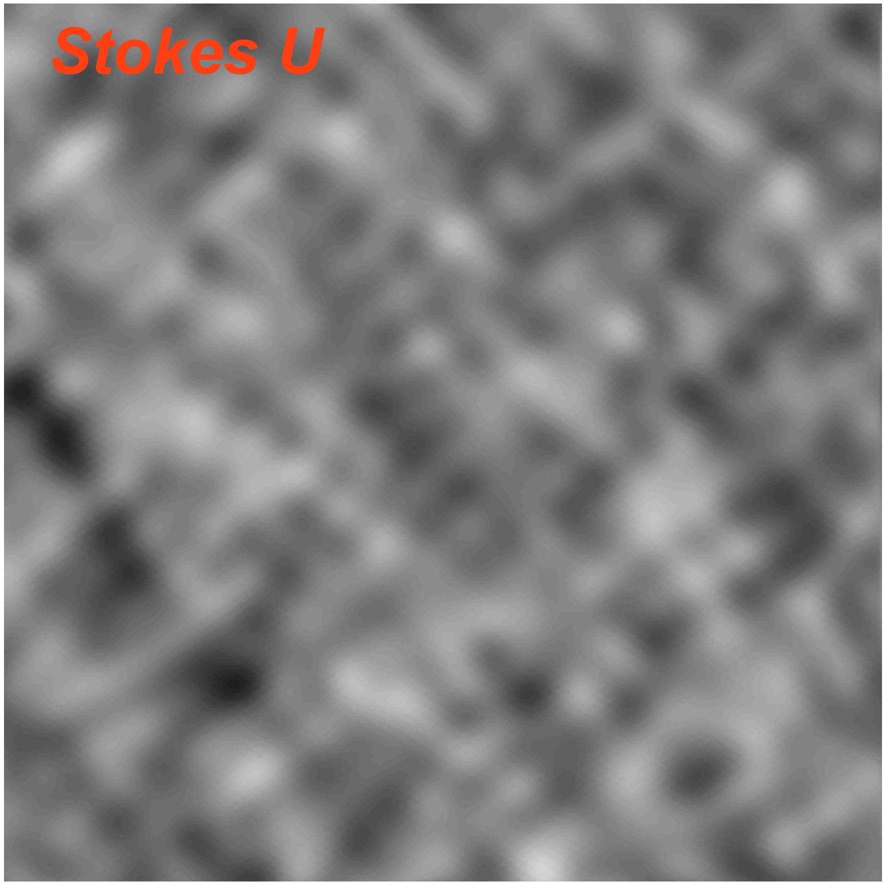
E-modes/B-modes

- 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

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!***

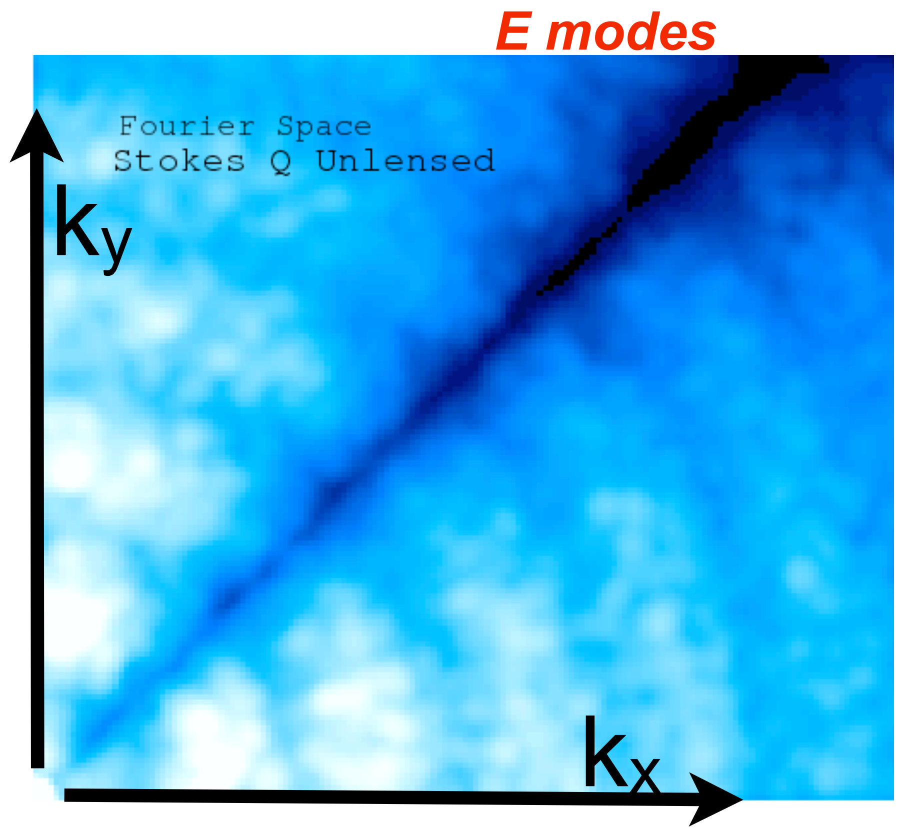


Image of positive kx/positive ky Fourier transform of a 10x10 deg chunk of Stokes Q CMB map [simulated; nothing clever done to it]

Lensing CMB Experiments

- (ACBAR)
- WMAP7
  - all-sky, 20’, 600 uK-arcmin
- Atacama Cosmology Telescope (ACT)
  - ~1000 sq deg, 1.4’, 21 uK-arcmin
- South Pole Telescope (SPT)
  - 2500 sq deg, 1’, 18 uK-arcmin
- Planck ***(taking data; release 2013)***
  - all-sky, 7’, 20 uK-arcmin
- SPTPol/ACTPol ***(under construction; on the sky 2012)***
  - 500-3000 sq deg, 1’, 5 uK-arcmin
- (CMBPol)

Timeline for CMB Lensing

- 2007: detection in cross-correlation
- 2008: detection of peak smoothing (ACBAR)
- 2011: <2 s (WMAP7)
- 2011: 4 s (ACT)

Recall:
0.1 eV ~ 5% amplitude shift

- 2011: 7+ s (SPT)
- 2012: 30+ s (SPT)
- 2013: 30+ s (PLANCK)
- 2013: >40 s (SPTPol; ACTPol)
- ????: <2000 s

South Pole Telescope

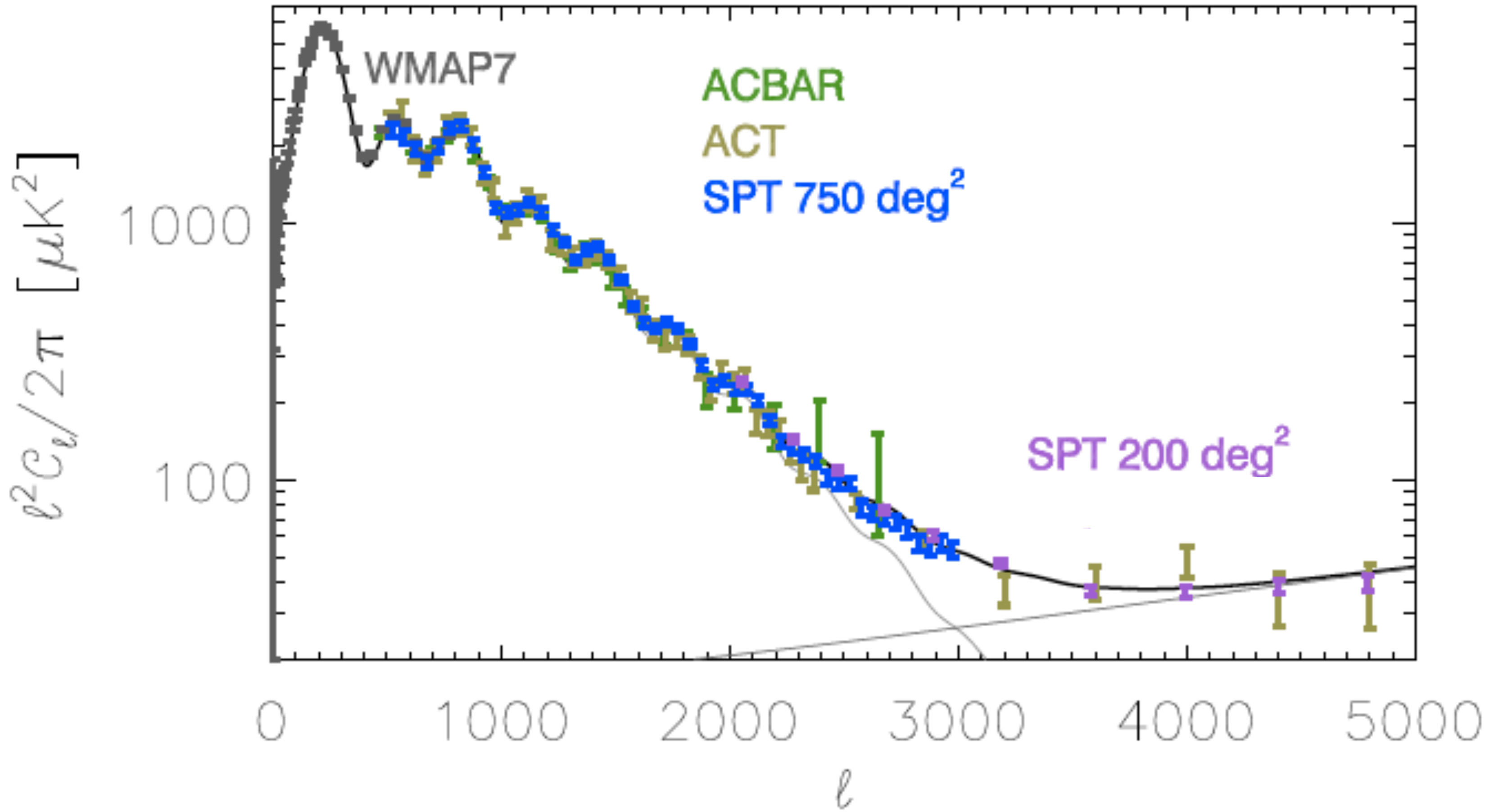
10m mm-wave (3 different wavelengths) telescope at the south pole

- extremely dry
- very stable
- good support

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

CMB Power Spectrum

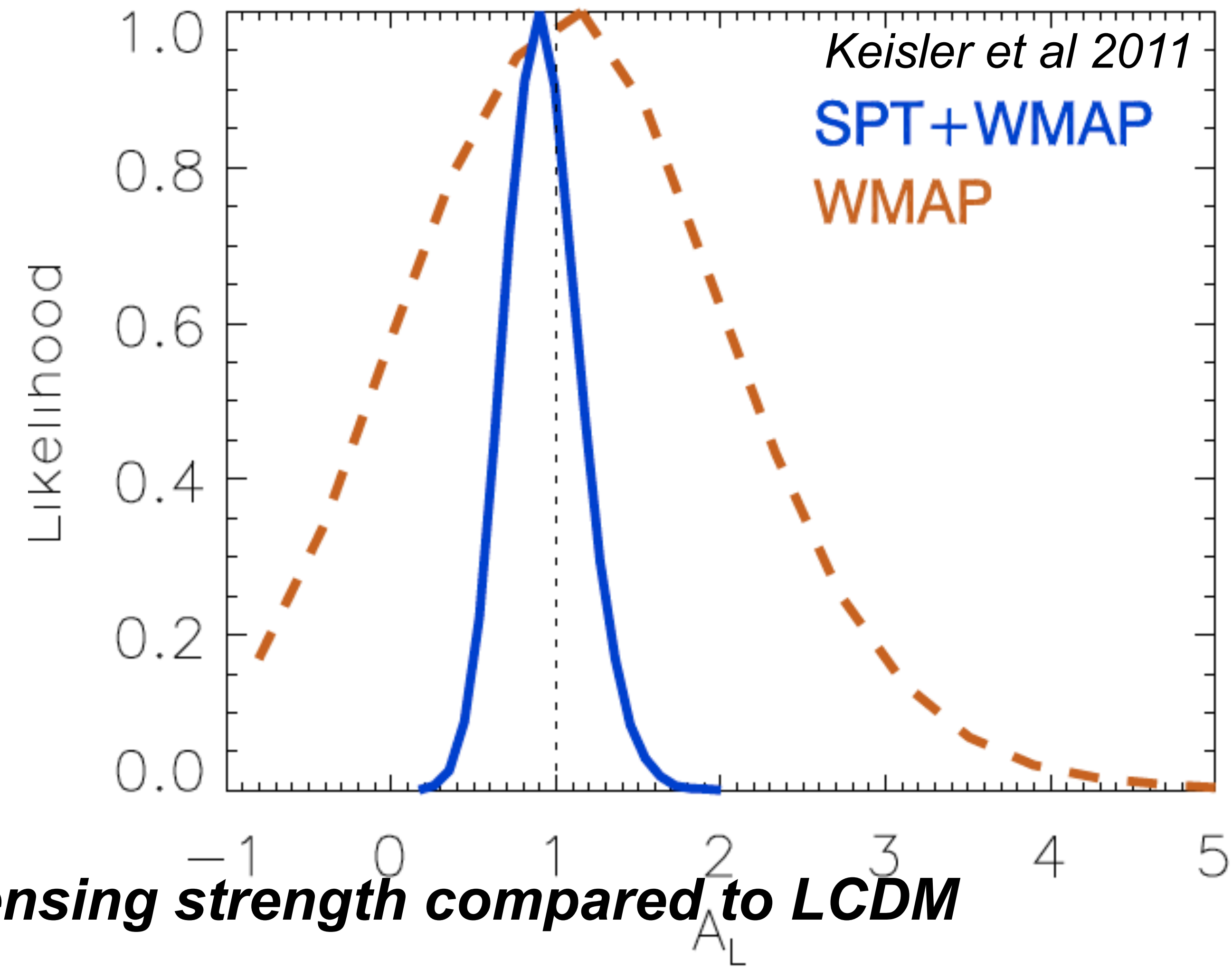
Plot by Ryan Keisler



Ryan Keisler; Christian Reichardt; Erik Shirokoff

Power spectrum measurement of lensing

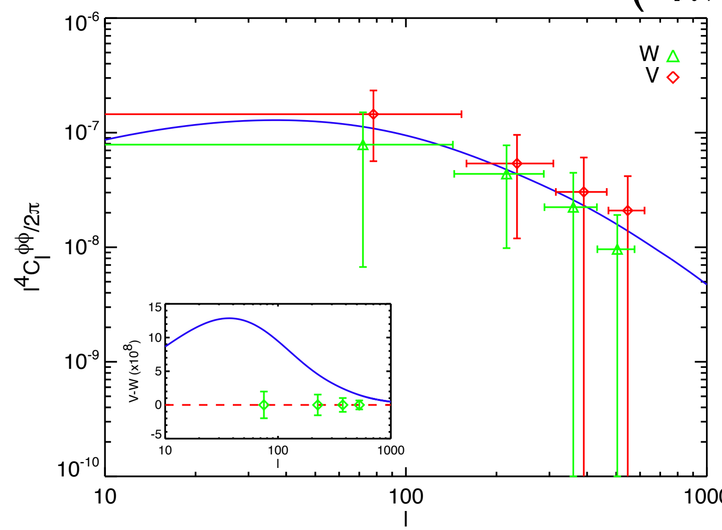
- consistent with standard expectation (~5 s detection)

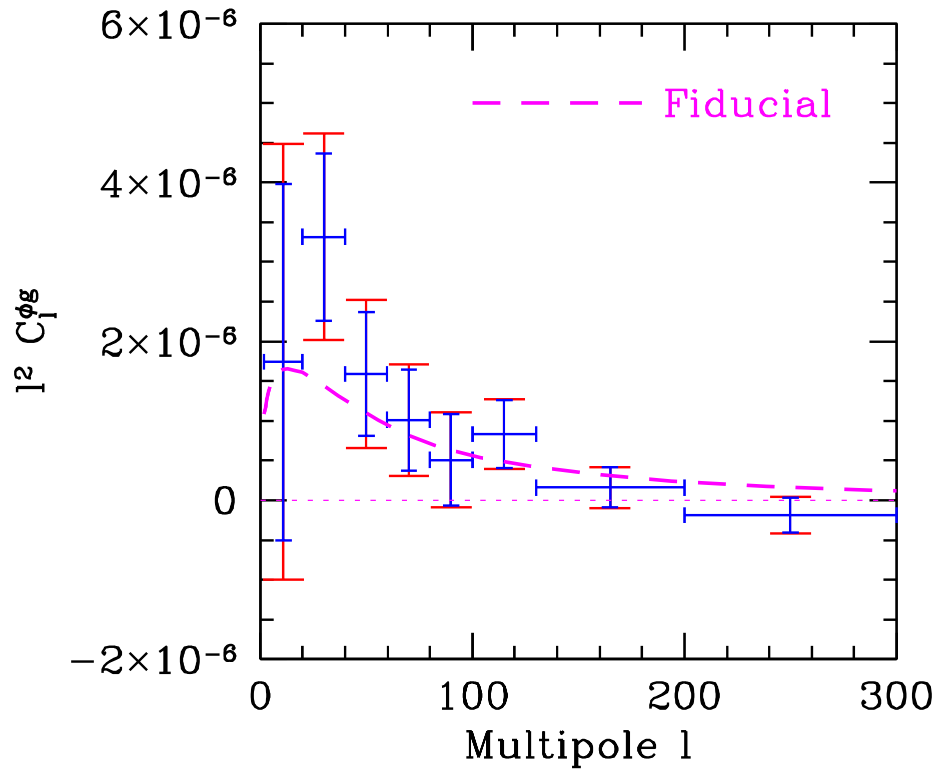


Lensing strength compared to LCDM

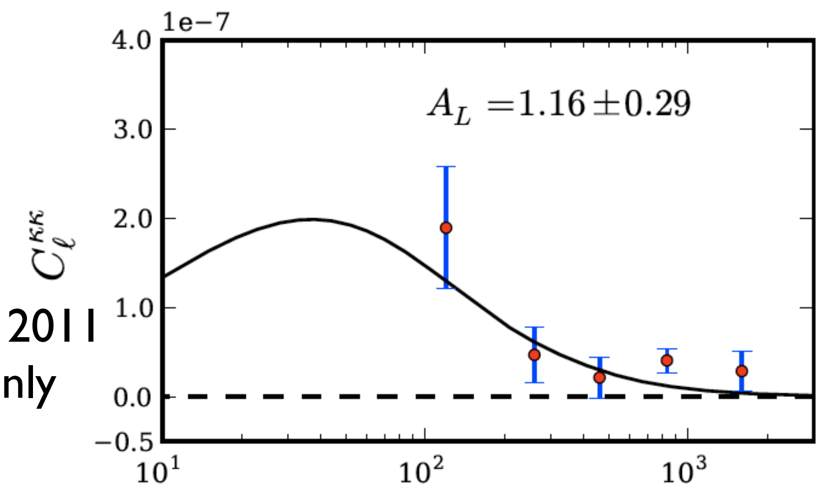
CMB Lensing Detections

Smidt et al 2011
WMAP only
("1.9"s)





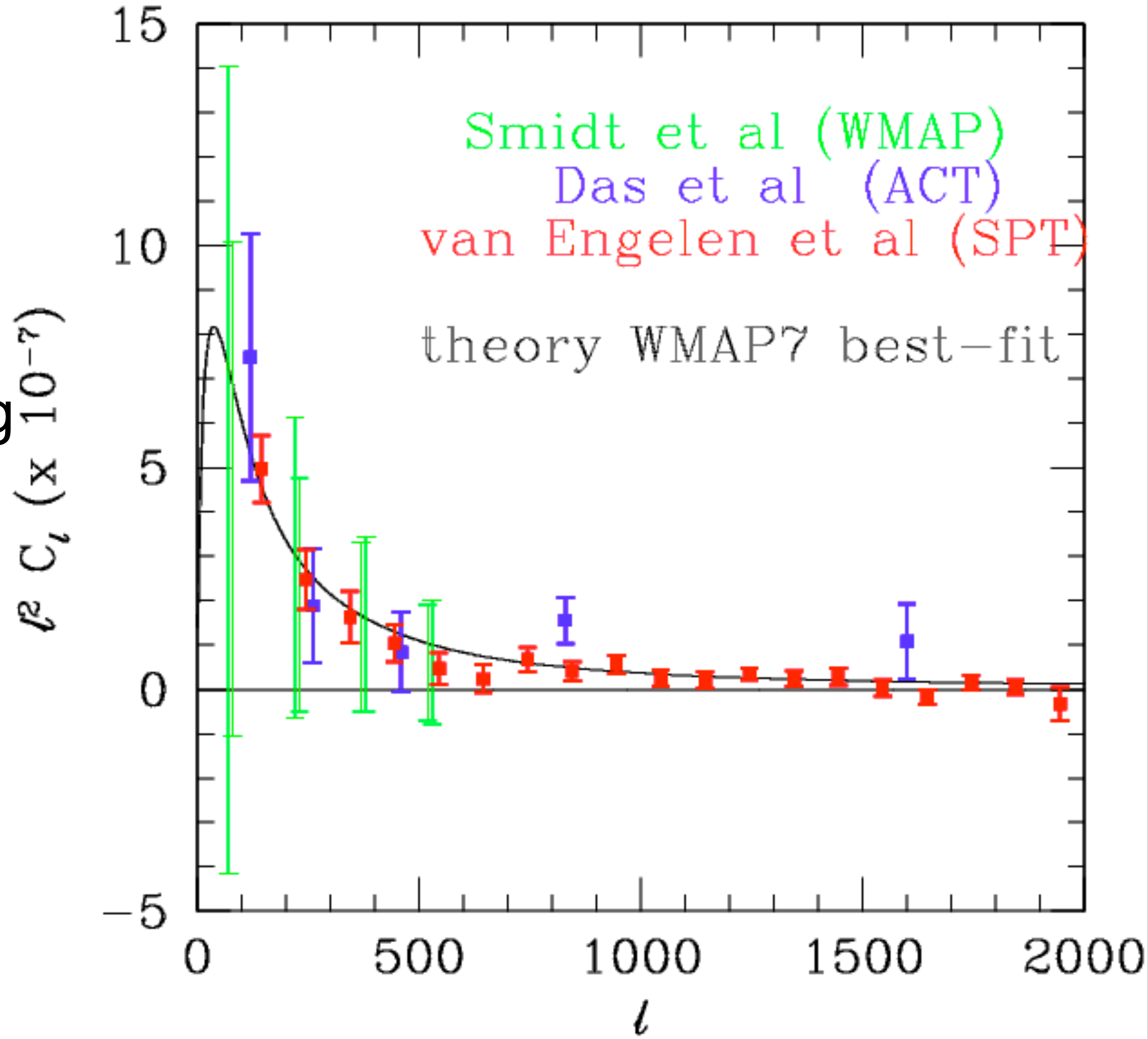
Smith et al 2007
WMAPxNVSS
(3.4s)



Das et al 2011
ACT only
(4s)

SPT Lensing Power Spectrum

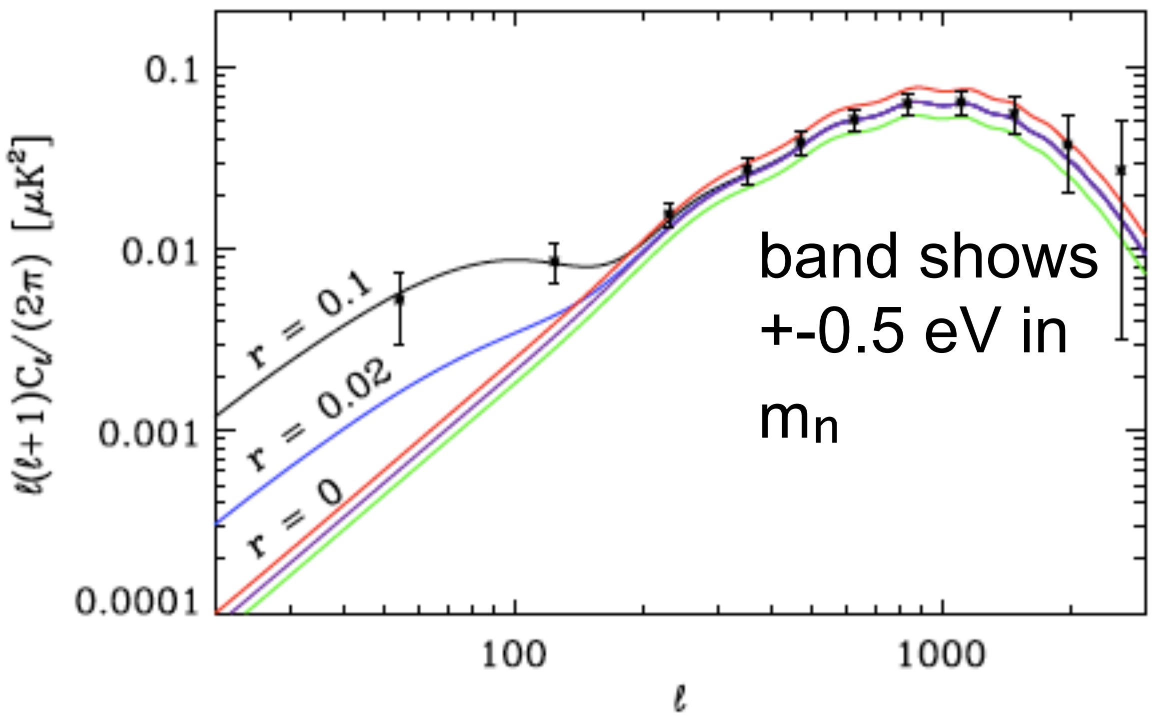
- high significance detection of non-Gaussianity in the CMB induced by gravitational lensing
- based on ~1/5 of SPT area, single-frequency only, heavily-filtered
- project >30 s detection with 2500 deg^2 survey



van Engelen et al, coming soon!

SPT-Pol Lensing

- gravitational lensing signal should be relatively easy to see in CMB B-modes
- in principle, measure sum of neutrino masses to ~0.1 eV
- polarization upgrade coming to SPT at end of 2011 or so



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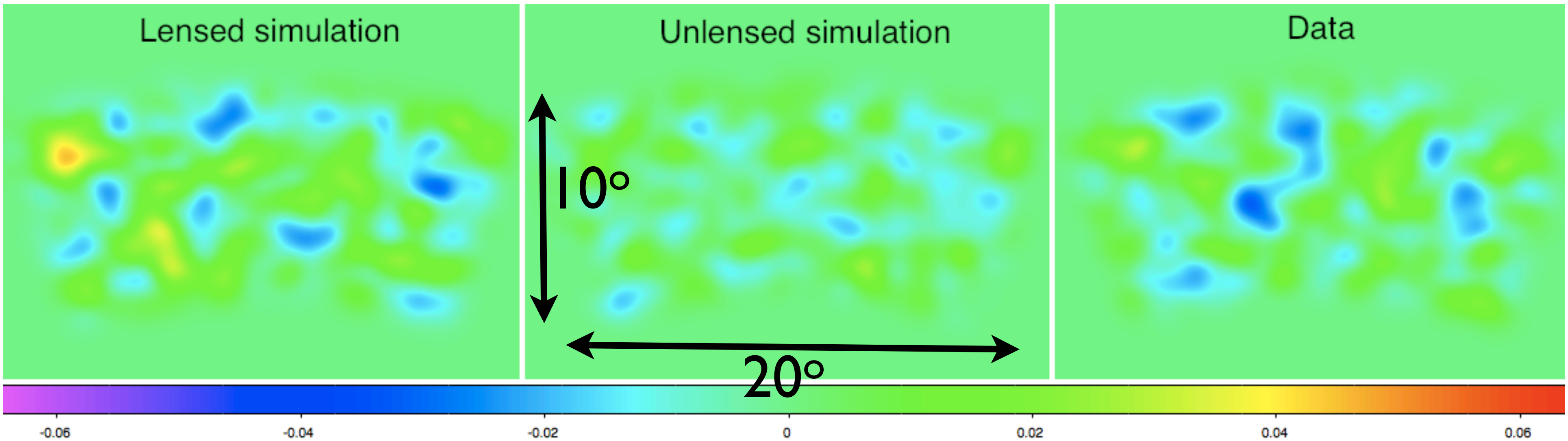
Mapping the universe



- SPT making maps of total matter (including dark matter) between z=0-1100
- Planck will have all-sky map (higher noise per mode but many more modes)

Summary & Outlook

- gravitational lensing changes the CMB power spectrum
- lensing induces mode coupling (non-Gaussianity)
- new generation of experiments measuring this at high precision
- sum of neutrino masses to better than +-0.1 eV expected in 1-2 years