# Cosmic Microwave Background Polarization

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# Outline

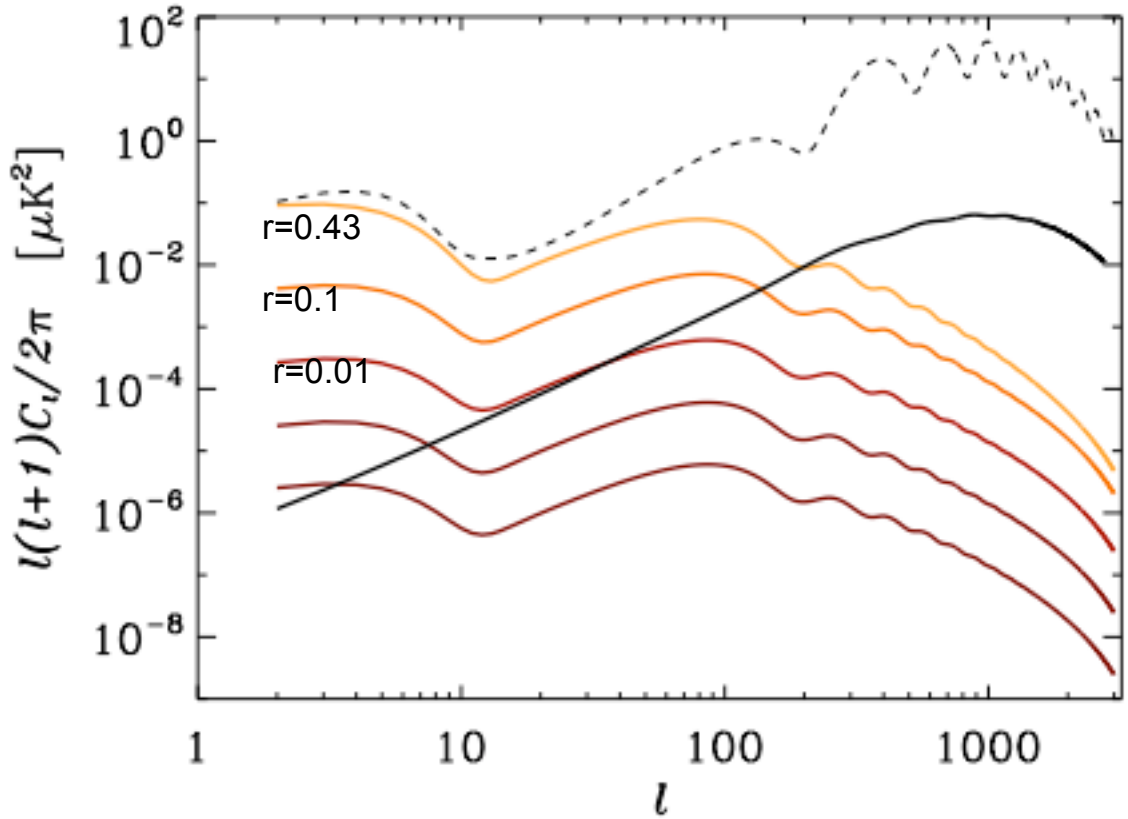
- 1: Overview of Primary CMB Anisotropies and Polarization
- 2: Primary, Secondary Anisotropies and Foregrounds
- 3: CMB Polarization Measurements
    - Cartoon version of experiments
    - Two exciting new frontiers
        - gravitational waves from inflation
            - » cartoon inflation
        - gravitational lensing of the CMB

# Excellent Reviews

- Wayne Hu tutorials:
  - http://background.uchicago.edu/index.html
- Kosowsky:
  - http://ned.ipac.caltech.edu/level5/Kosowsky/Kosowsky_contents.html
  - http://arxiv.org/abs/astro-ph/9904102
- Zaldarriaga
  - http://arxiv.org/abs/astro-ph/0305272
- Weiss report:
  - http://arxiv.org/abs/astro-ph/0604101
- CMBPol white papers:
  - http://arxiv.org/abs/0811.3919
  - http://arxiv.org/abs/0811.3916

# Lensing B Modes vs GW

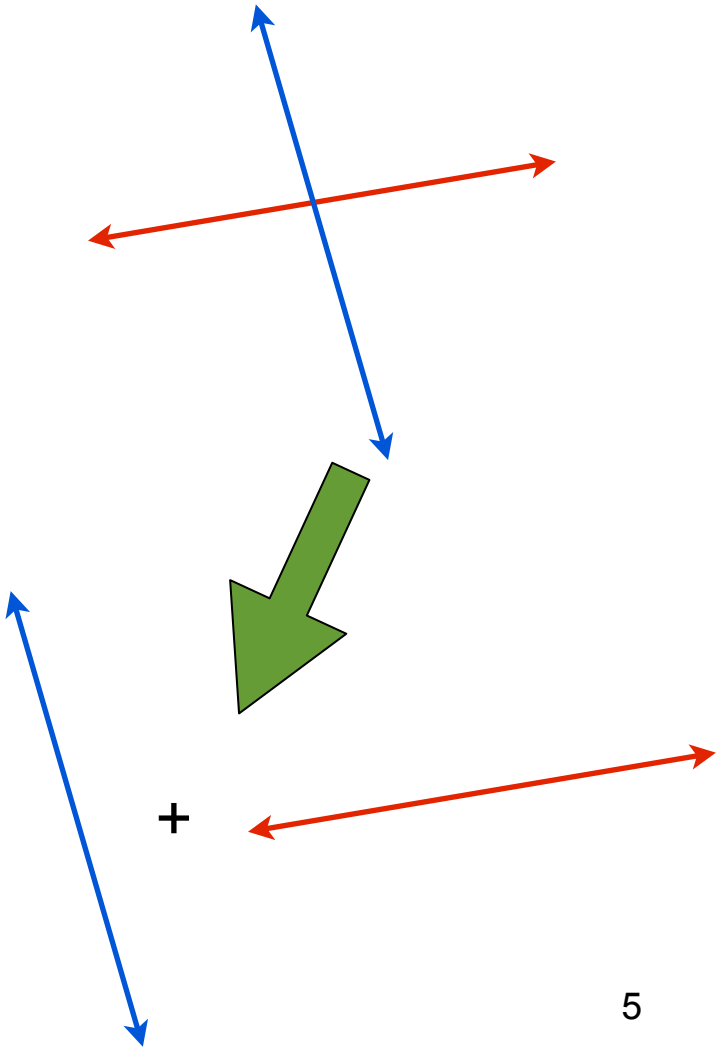
- on small scales, lensing B modes always dominate




from CMBPol lensing paper

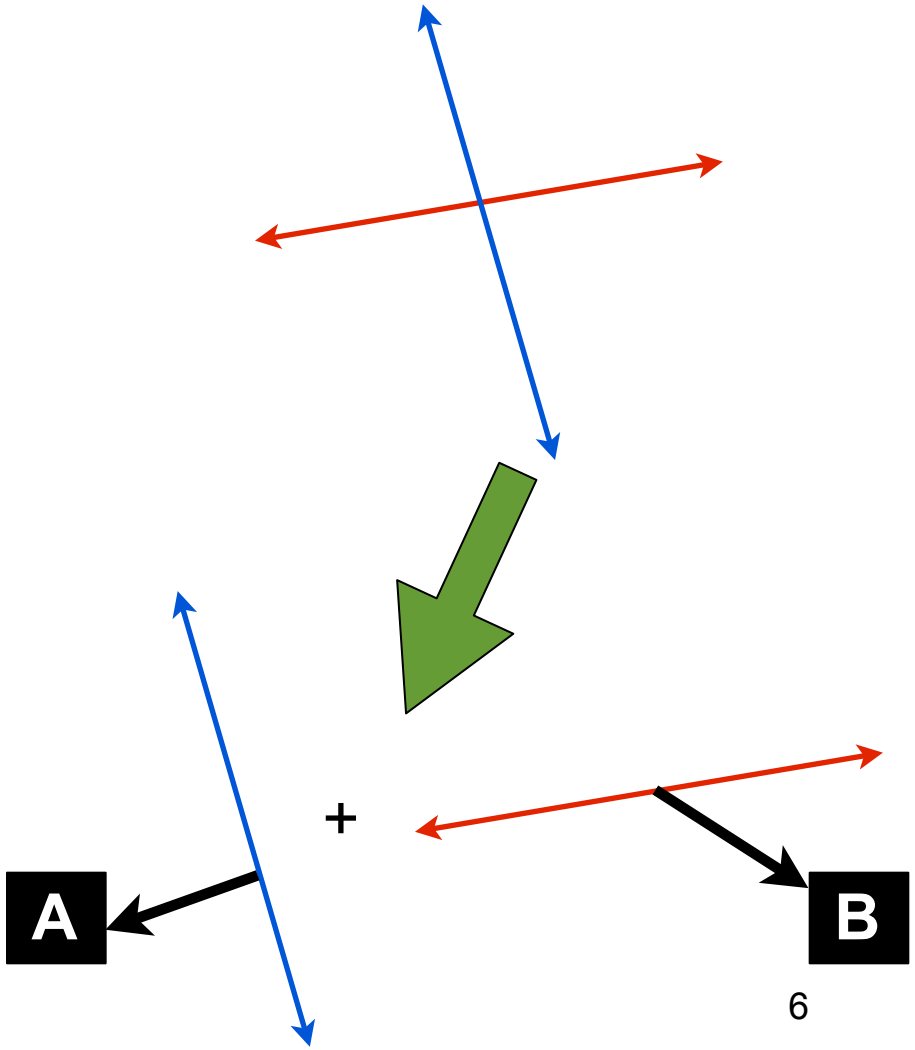
# Measuring Polarization

- need to measure the relative power in E field at different orientations



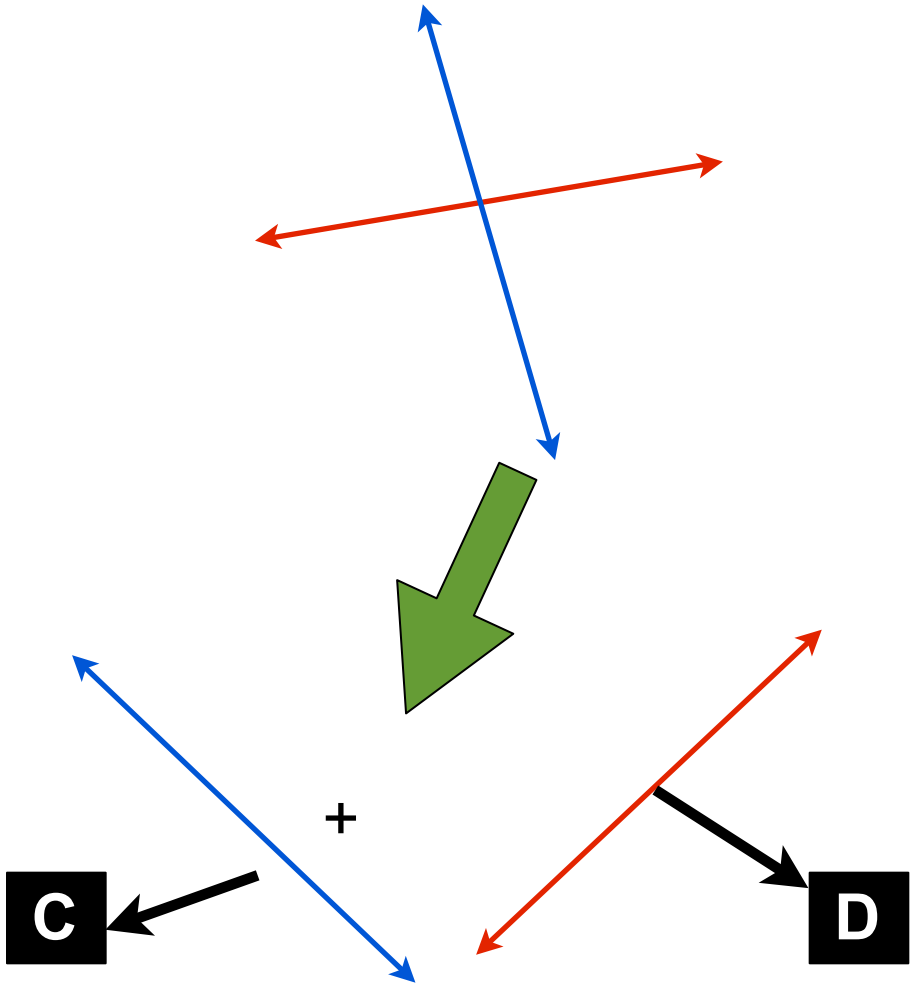
# Measuring Polarization

- need to measure the relative power in E field at different orientations
- split polarizations, send to different detectors



# Measuring Polarization

- measure at different angles to get Q, U



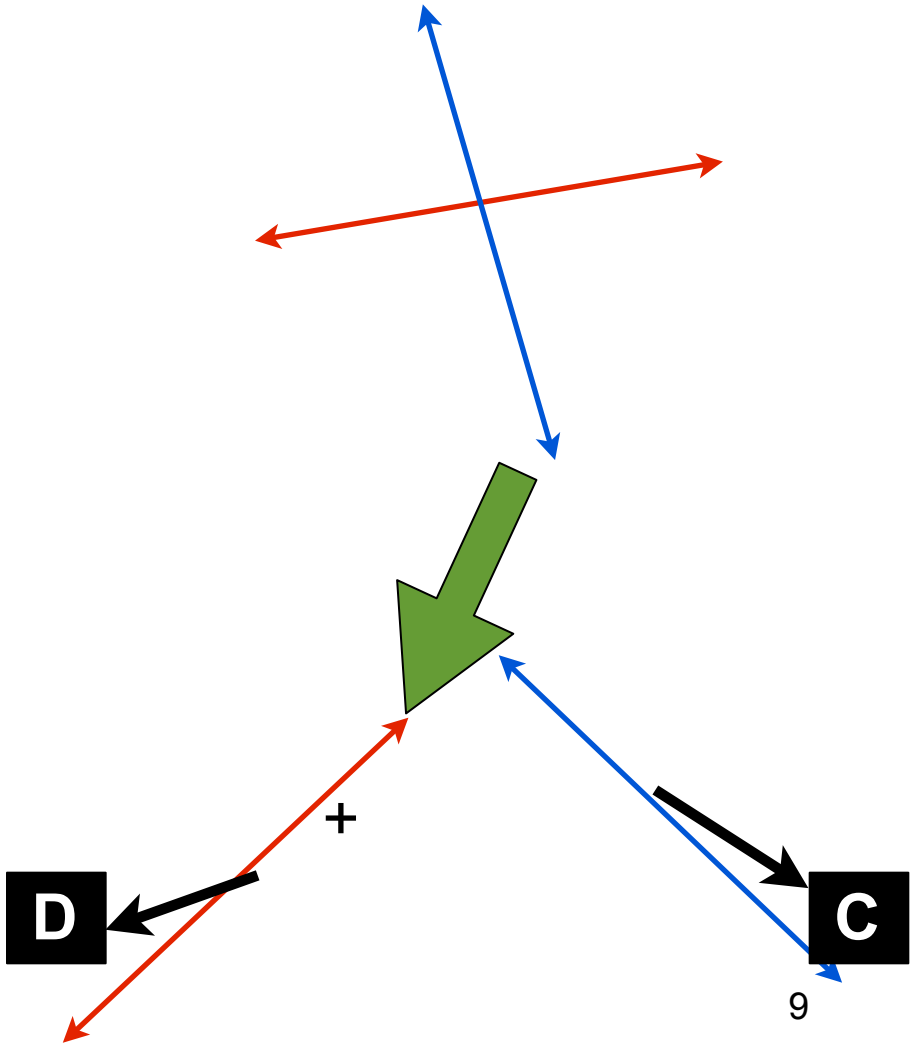
# The Experimental Challenge to reach r=0.01

***Table from Weiss Report***

| Parameter | Effect | Goal |
|---|---|---|
| | | |
| Cross-Polar Beam response | $E \rightarrow B$ | $< 0.003$ |
| Main lobe ellipticity (0.5° beam) | $dT \rightarrow B$ | $< 10^{-4}$ |
| Polarized sidelobes (response at Galaxy) | $dT \rightarrow B$ | $< 10^{-6}$ |
| Instrumental polarization | $dT \rightarrow B$ | $< 10^{-4}$ |
| Polarization angle | $E \rightarrow B$ | $< 0.2°$ |
| Relative pointing (of differenced samples) | $dT \rightarrow B$ | $< 0.1''$ |
| Relative calibration | $dT \rightarrow B$ | $< 10^{-5}$ |
| Relative calibration drift (scan synchronous) | $T \rightarrow B$ | $< 10^{-9}$ |
| Lyot Stop Temperature (10% spill, scan synch.) | $dT_{opt} \rightarrow B$ | $dT_{opt} < 30$ nK |
| Cold stage T drifts (scan synch.) | $dT_{CS} \rightarrow B$ | $dT_{CS} < 1$ nK |

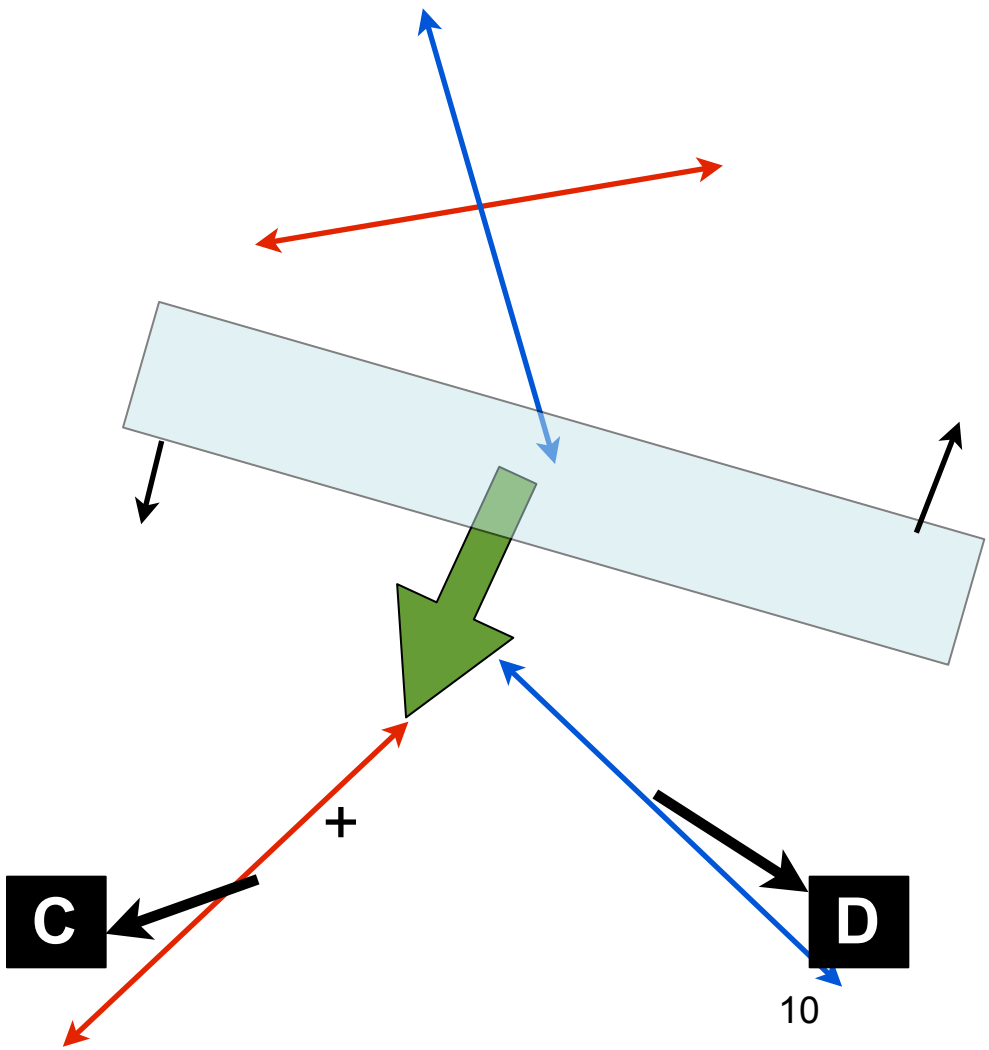
# Measuring Polarization

- possible extra tricks:
  - rotate experiment so that response to sky is swapped



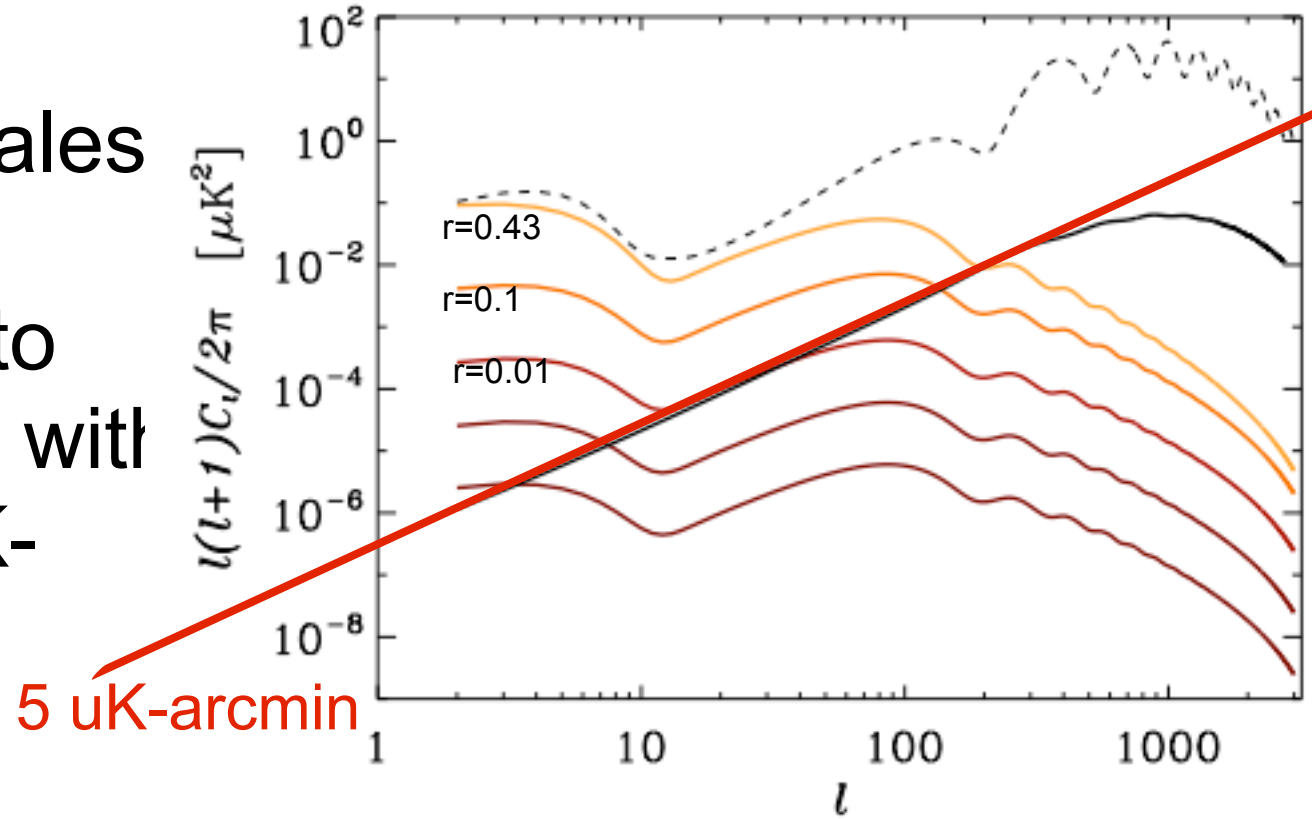
# Measuring Polarization

- possible extra tricks:
  - insert half-wave plate or something else which can rotate polarization directions
  - then spin it to modulate pol response



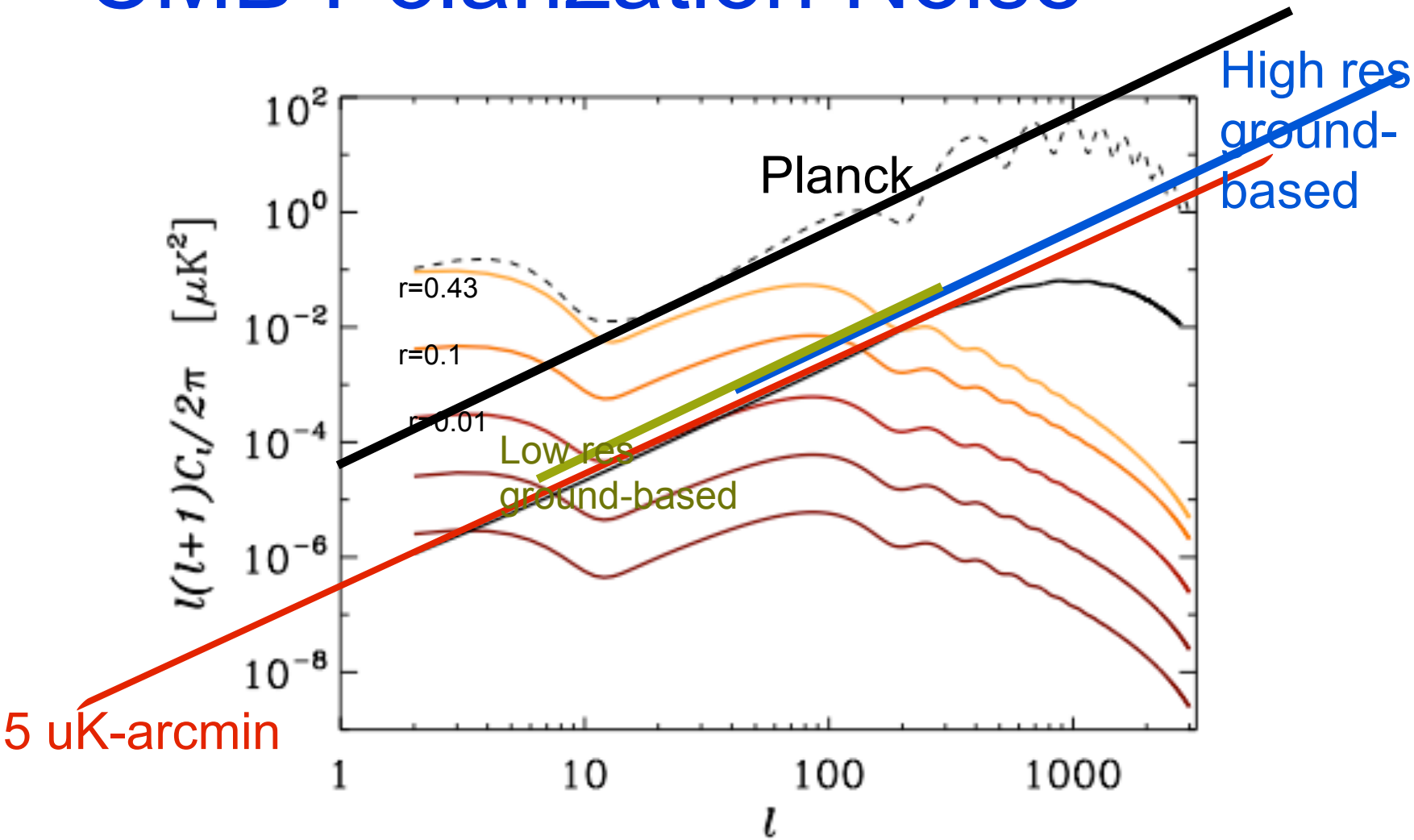
# Lensing B Modes vs GW

- on large scales spectrum equivalent to white noise with rms of 5 uK-arcmin



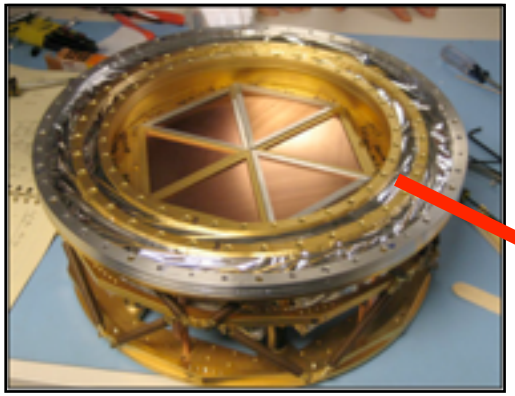

from CMBPol lensing paper

# CMB Polarization Noise

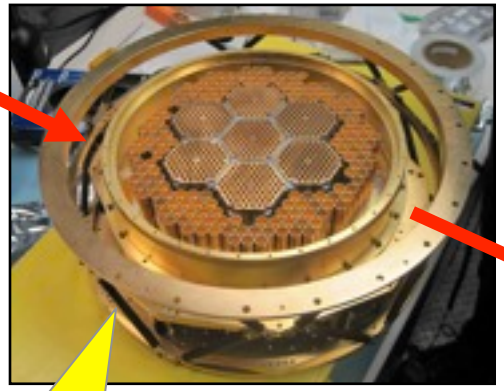


# The evolution of SPT cameras

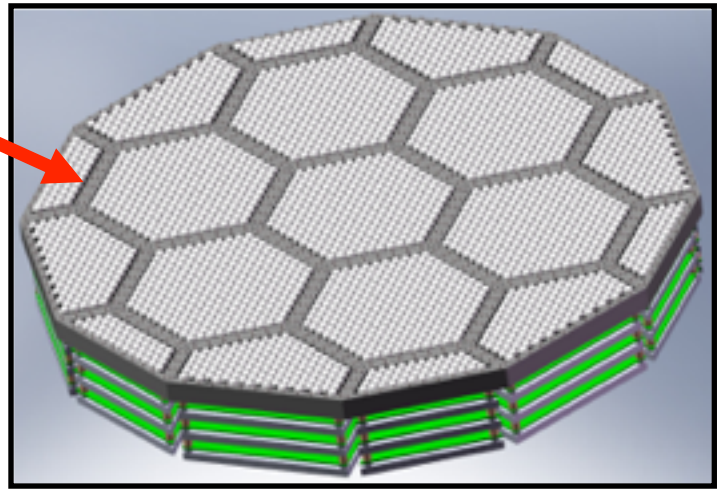
2007-2011: SPT
960 detectors



2012-2015: SPTpol
~1600 detectors



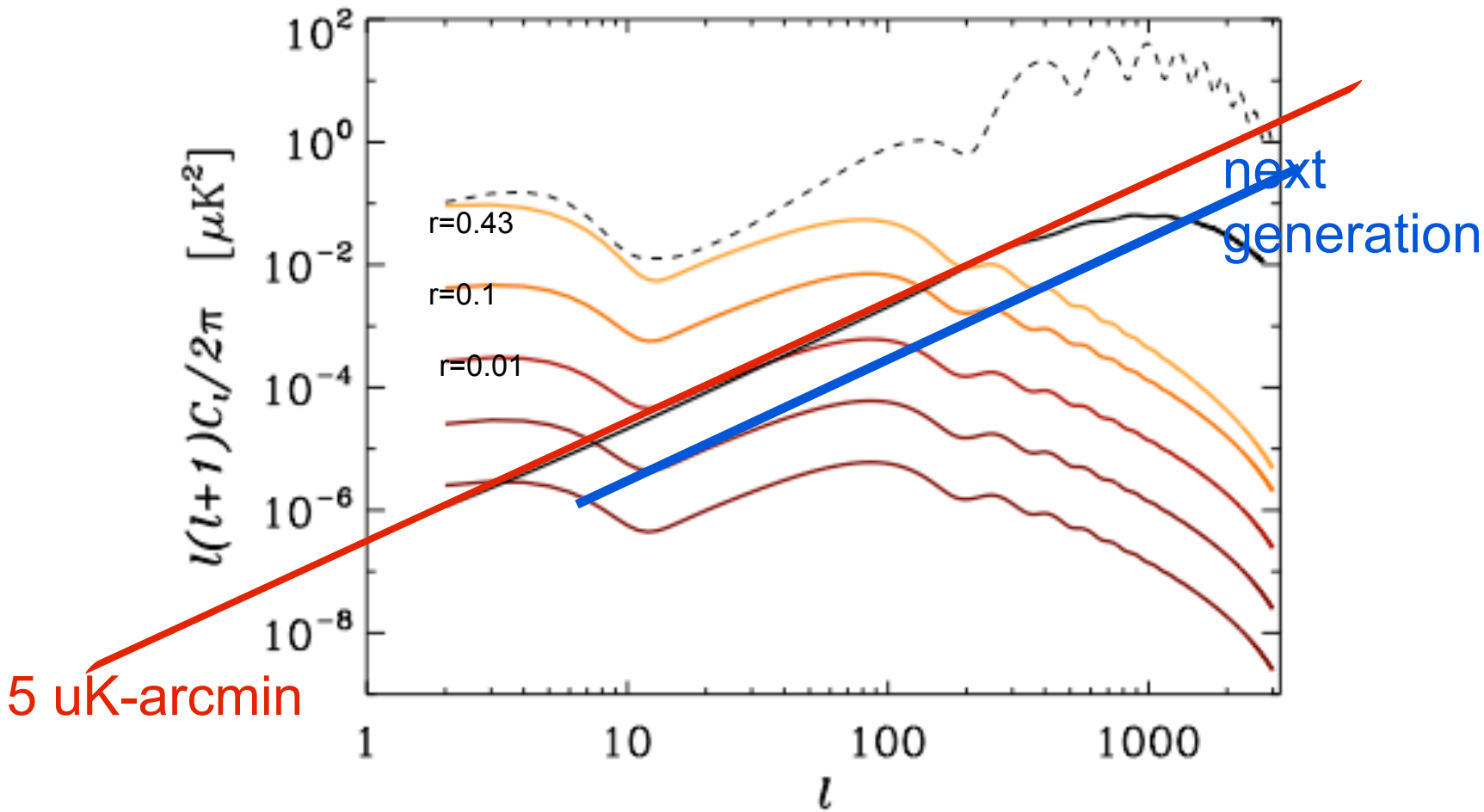
2016: SPT-3G
~15,200 detectors



Now with polarization!

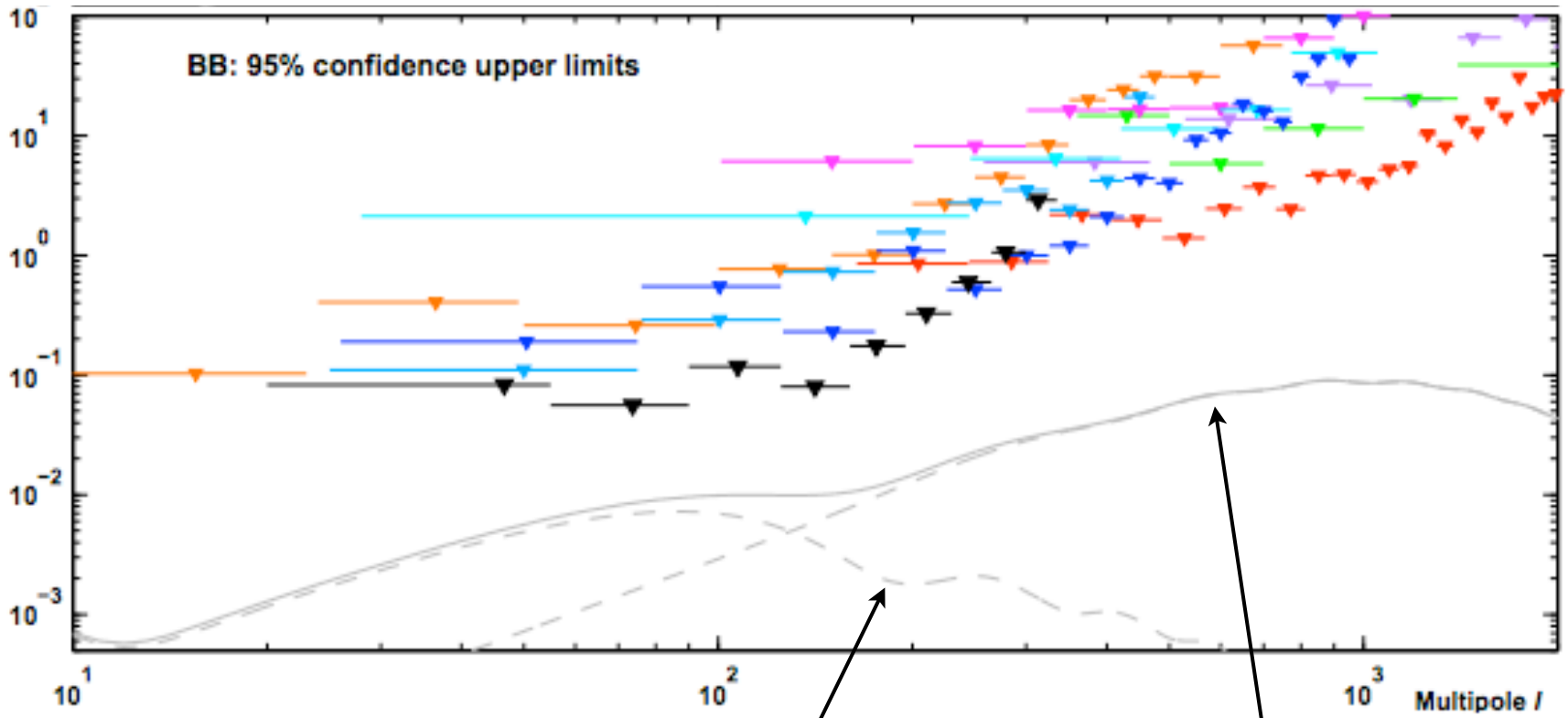
slide from S Hoover

# CMB Polarization Noise




in <3 years several experiments will have ***sensitivity*** for r~0.01

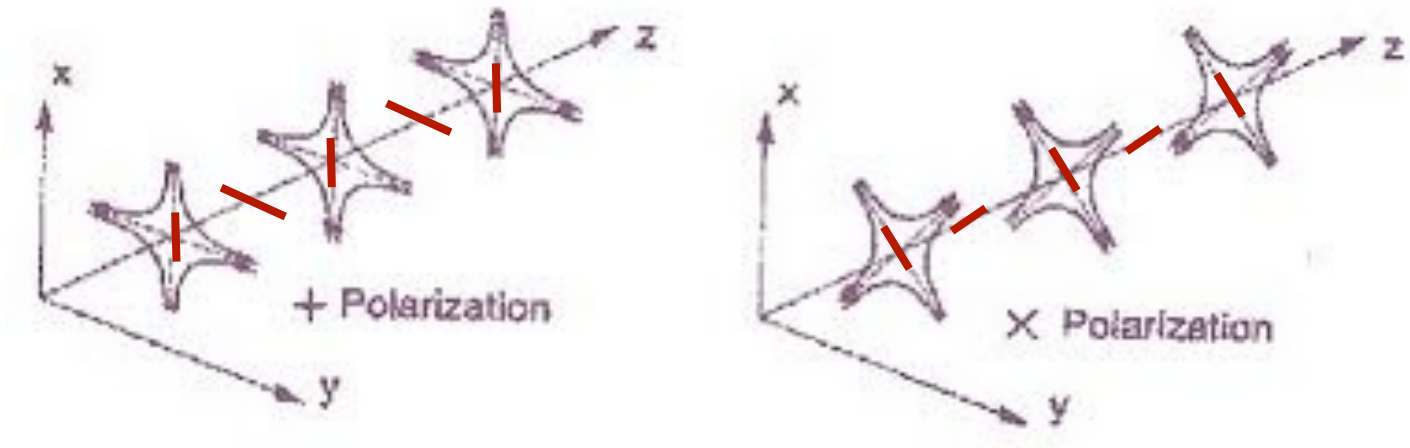
# Two Expected Sources of B Modes




Gravitational Radiation in Early Universe
(amplitude unknown!)

Gravitational lensing of
E modes

# Gravitational Waves Generate E and B




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

# Inflation According to an Astrophysicist

(Peacock Chapter 11)

see also http://ned.ipac.caltech.edu/level5/Sept02/Kinney/Kinney_contents.html)

- early universe period of dark energy domination
- some potential energy V at every location, which depends on something, call it $\phi$ (the "inflaton" field)
- exponential expansion for many e-foldings (>60?) solves classic problems
- $\phi$ has fluctuations from quantum mechanics

# Hawking Radiation from a Black Hole

$$kT_H = \frac{1}{8\pi^2}\frac{hc}{R_s}$$

# Hawking Radiation from a ~~Black Hole~~ Horizon

$$kT_H = \frac{1}{8\pi^2}\frac{hc}{R_s}$$

In de Sitter, horizon $r \sim cH^{-1}$

# Fluctuations during inflation

- at a single point, horizon is continuously radiating
- fluctuations in $\phi$ continue to be generated
- variance $\delta\phi^2 \sim N(t)\, H^2$
- inflation ends at some value of $\phi$, which happens at slightly different times (randomly)

# Gravitational potential fluctuations

- different amounts of expansion mean gravitational potential differences
- $\delta_H \sim H\,\delta t = H\,\delta\phi/(d\phi/dt) \sim H^2/(d\phi/dt)$
- slow roll => $(d\phi/dt) \sim (dV/df)/H = V'/H$
- $\delta_H \sim H^3/V'$
- potential fluctuations depend on slope of potential

# Gravitational Radiation from Inflation

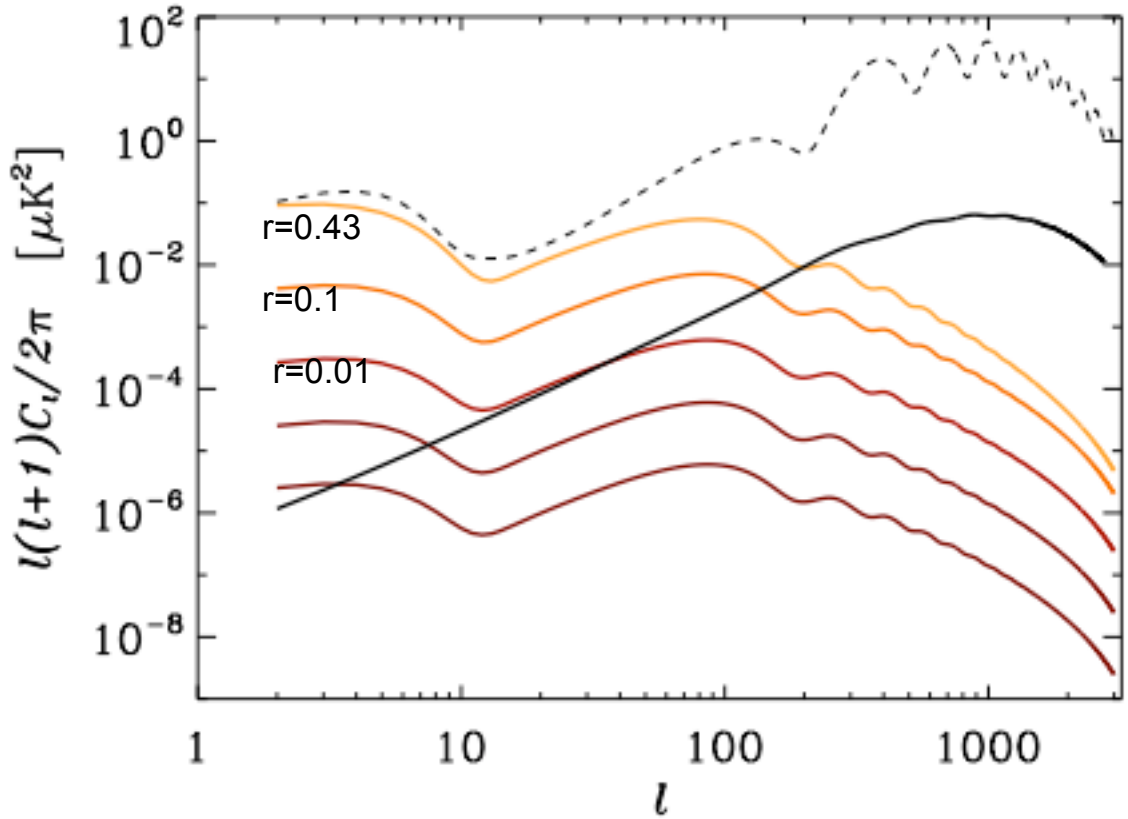
- Hawking radiation from horizon gives gravity waves with T~H
- variance of wave amplitudes ~ $H^2$
- Friedmann equation: $H^2 \sim V$
- gravity waves directly sourced by inflation (not via fluctuations in "inflaton")
- tensor/scalar power $\Delta^2_T/\Delta^2_S \sim (V/V')^2$

# Tensor Power

- note tensor power scales as potential energy V
- dimensionally:
  - energy density~(temperature)$^4$
- tensor power scales as $T_{inflation}^4$
  - GUT scale ($10^{15}$ GeV): T/S~0.1
  - just past LHC (~TeV): T/S~hopeless

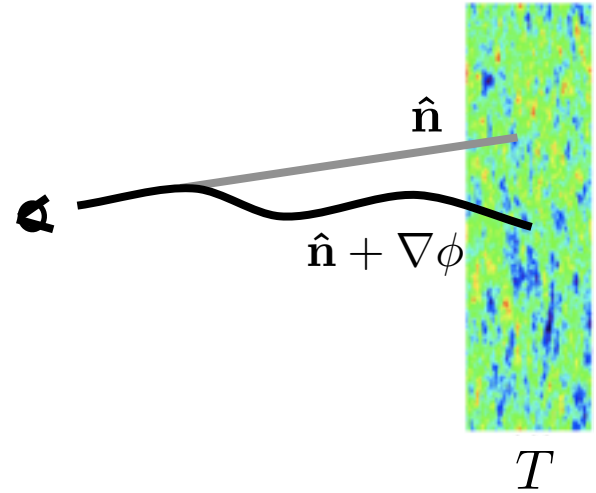
# Lensing B Modes vs GW

- on small scales, lensing B modes always dominate




from CMBPol lensing paper

# 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

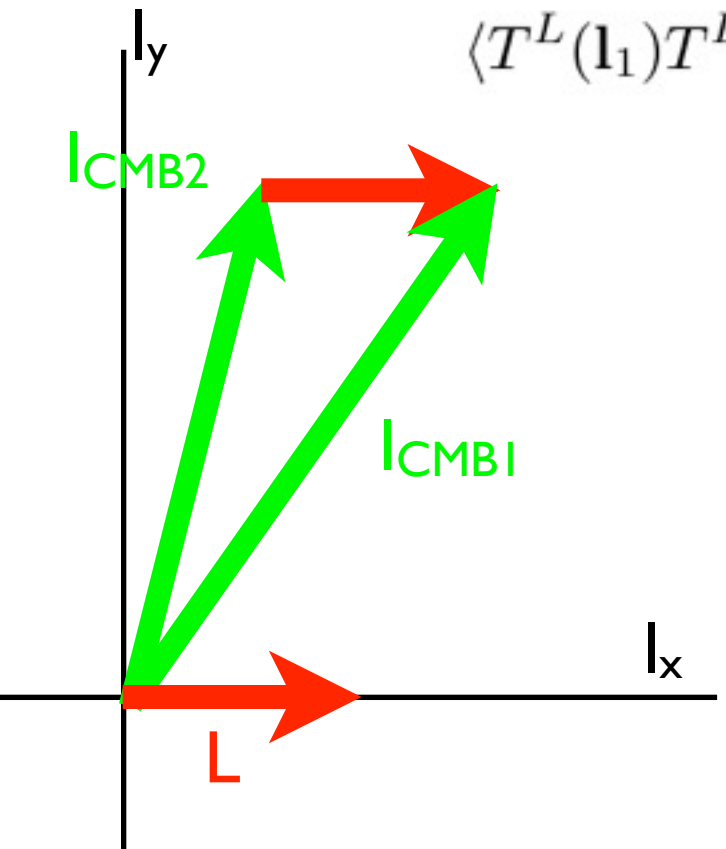
# Mode Coupling from Lensing

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

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

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

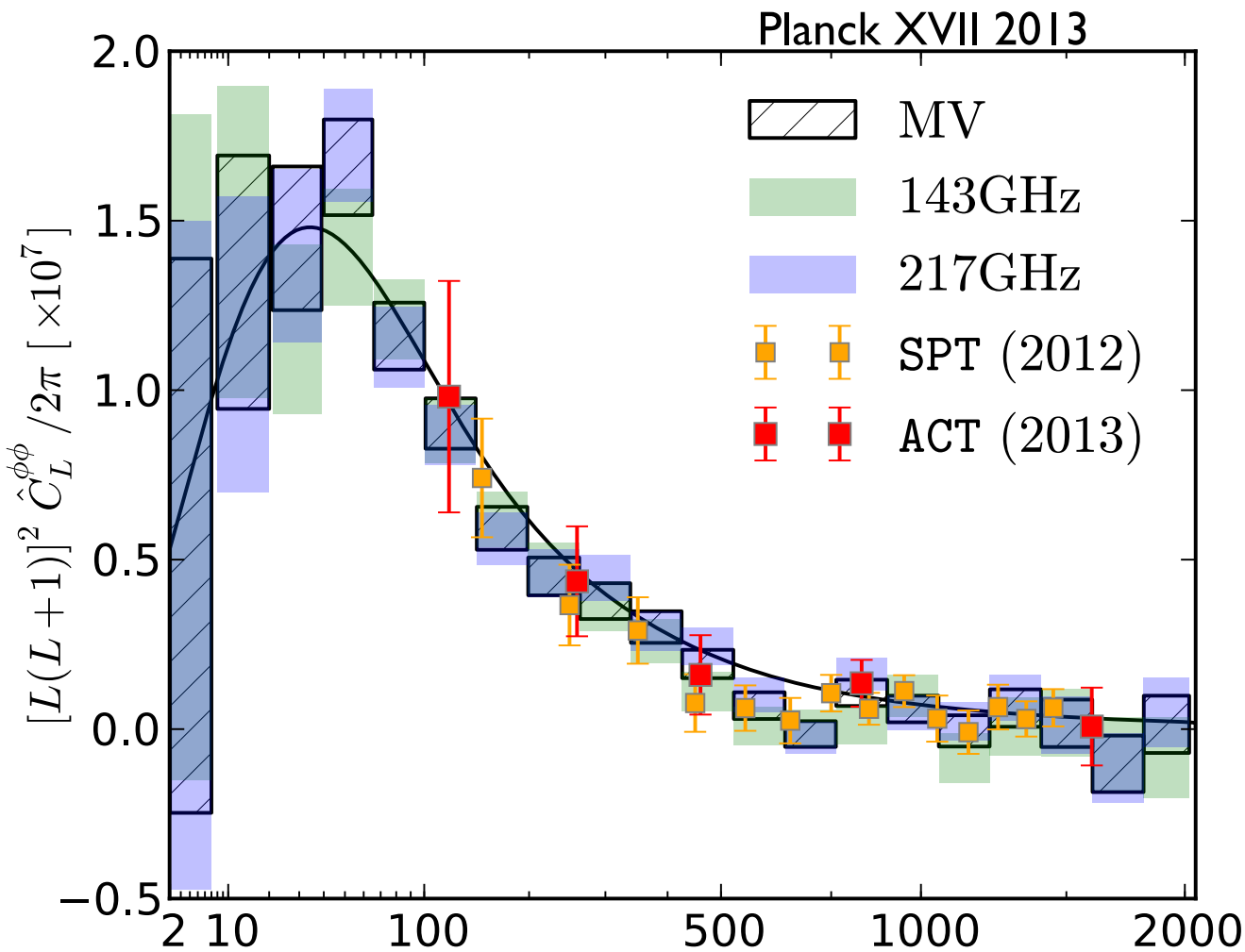
$$\mathbf{L} = \mathbf{l}_1 + \mathbf{l}_2$$




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

# CMB Lensing Power Spectrum

- well measured with Planck, SPT, ACT

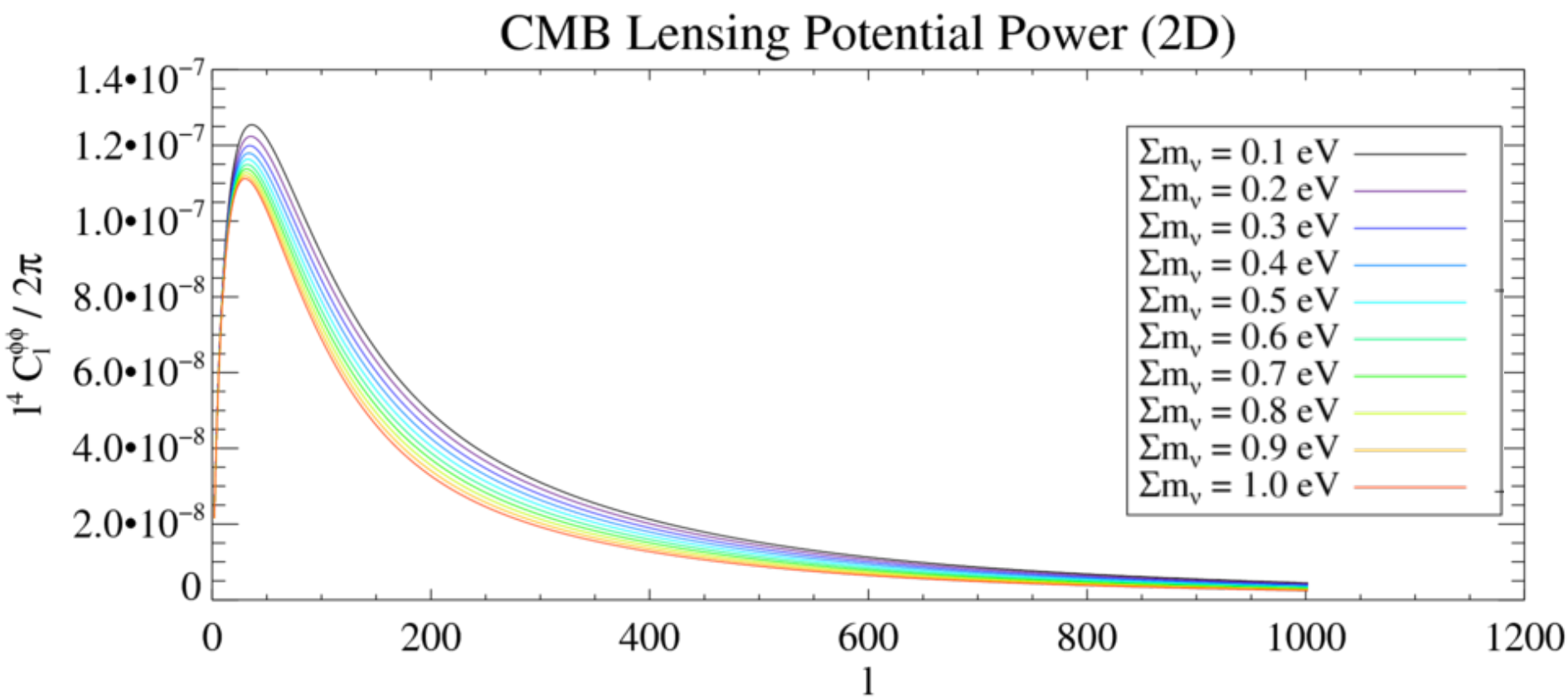


# *Massive Neutrinos in Cosmology*

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

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

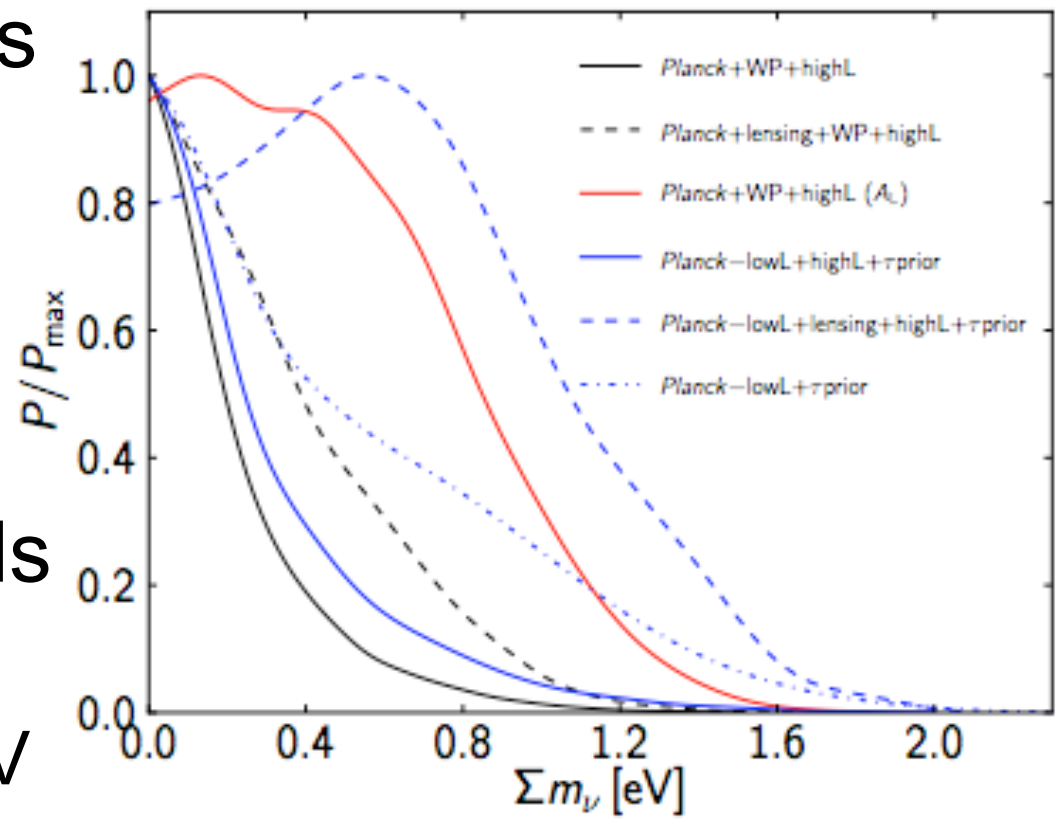
# Neutrinos & CMB Lensing




- 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

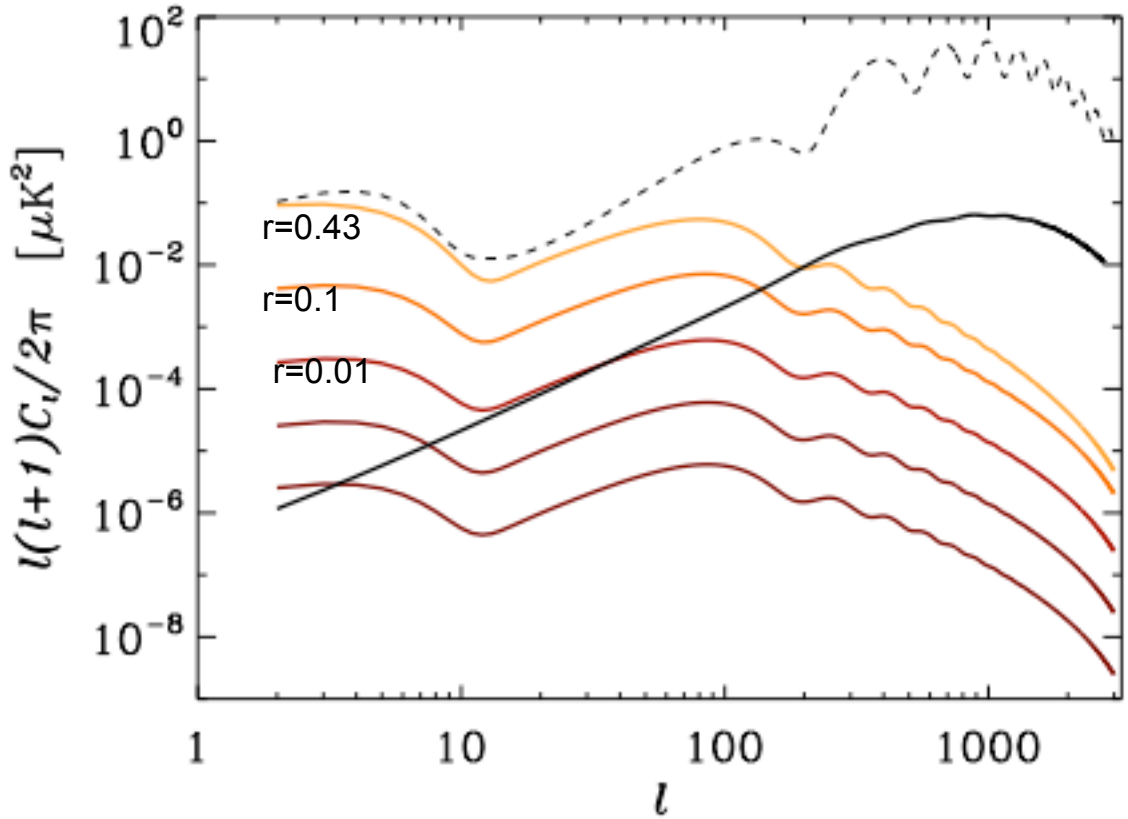
- CMB experiments closing in on interesting neutrino mass range
- CMB lensing adds new information
  - forecast ~0.05 eV sensitivity in ~4 yrs




*Planck collaboration 2013*

# Lensing B Modes vs GW

- to reach small r, must remove lensing B modes

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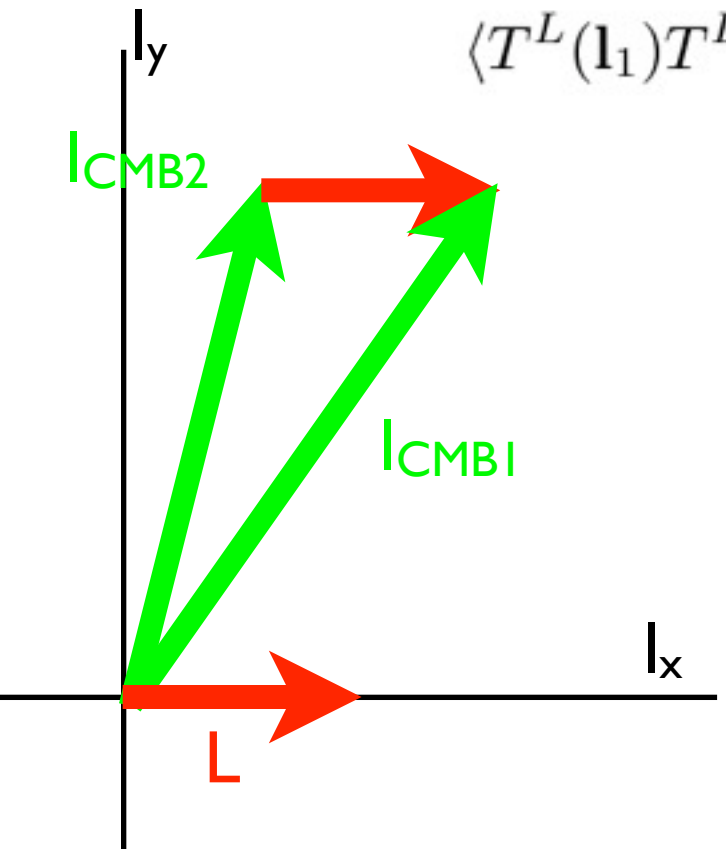


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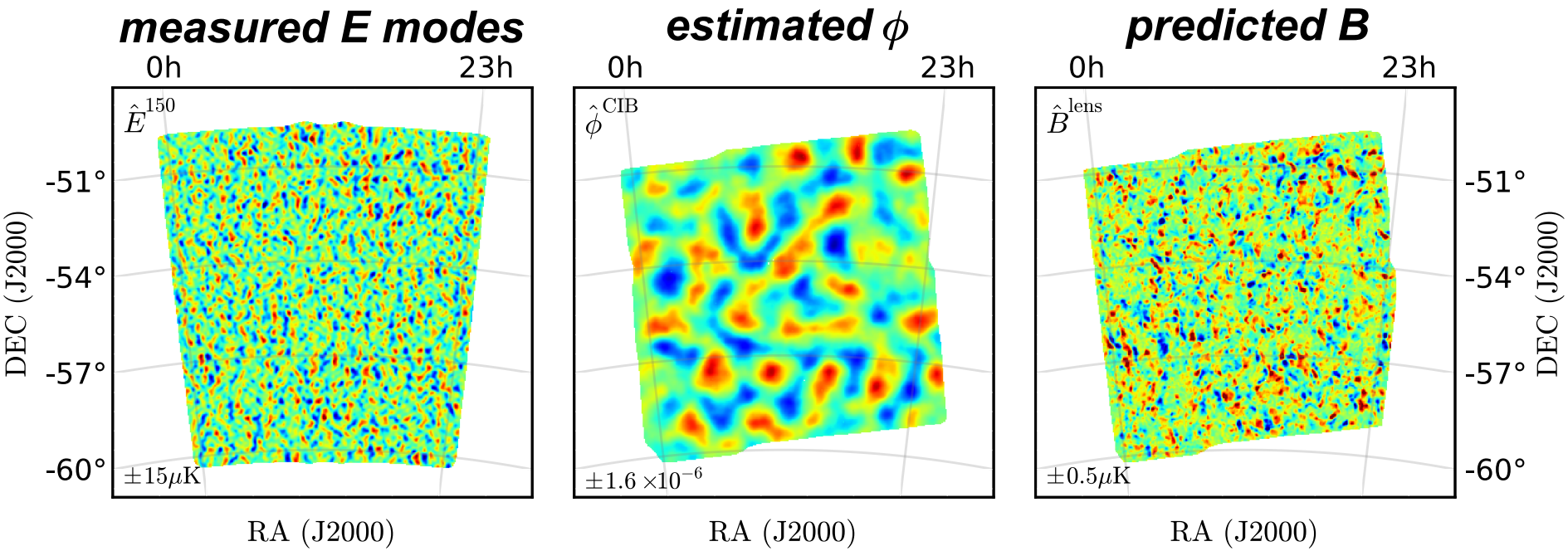
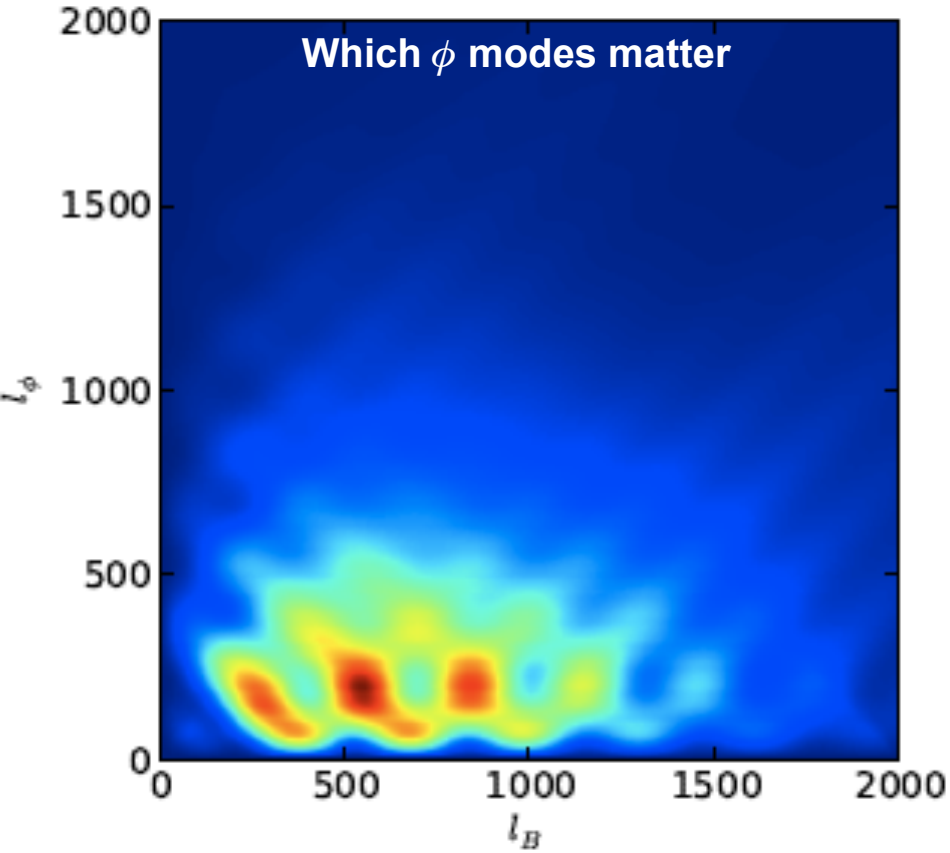
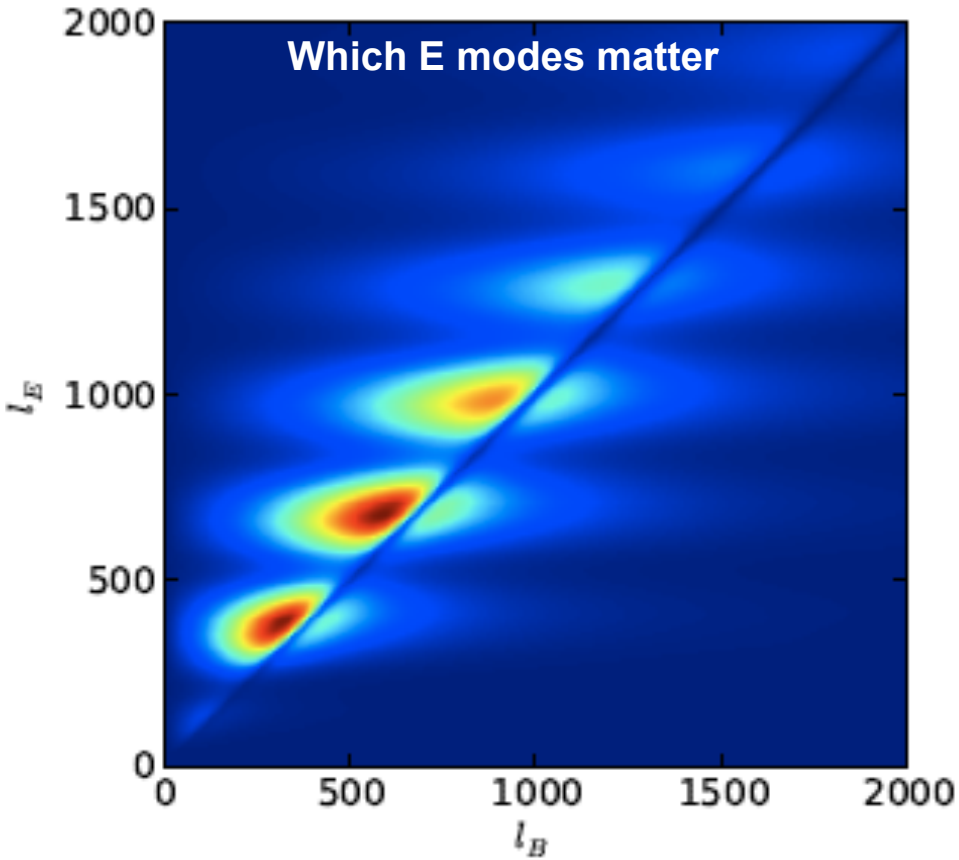
# Predicting B-Modes




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

# Source of Lensed B Modes




from Duncan Hanson

# *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!***

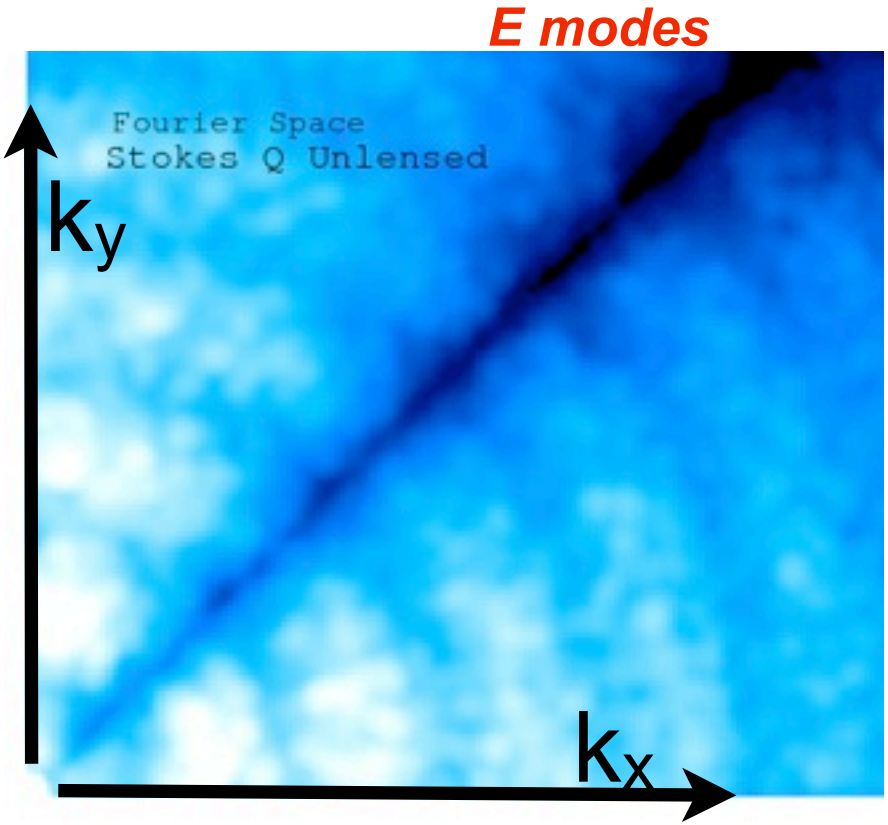



*Image of positive kx/positive ky Fourier transform of a 10x10 deg chunk of Stokes Q CMB map [simulated; nothing clever done to it]*

# “Delensing” Improves GW sensitivity

- can’t remove what you can’t see: delensing limited by how well you image lensing B modes

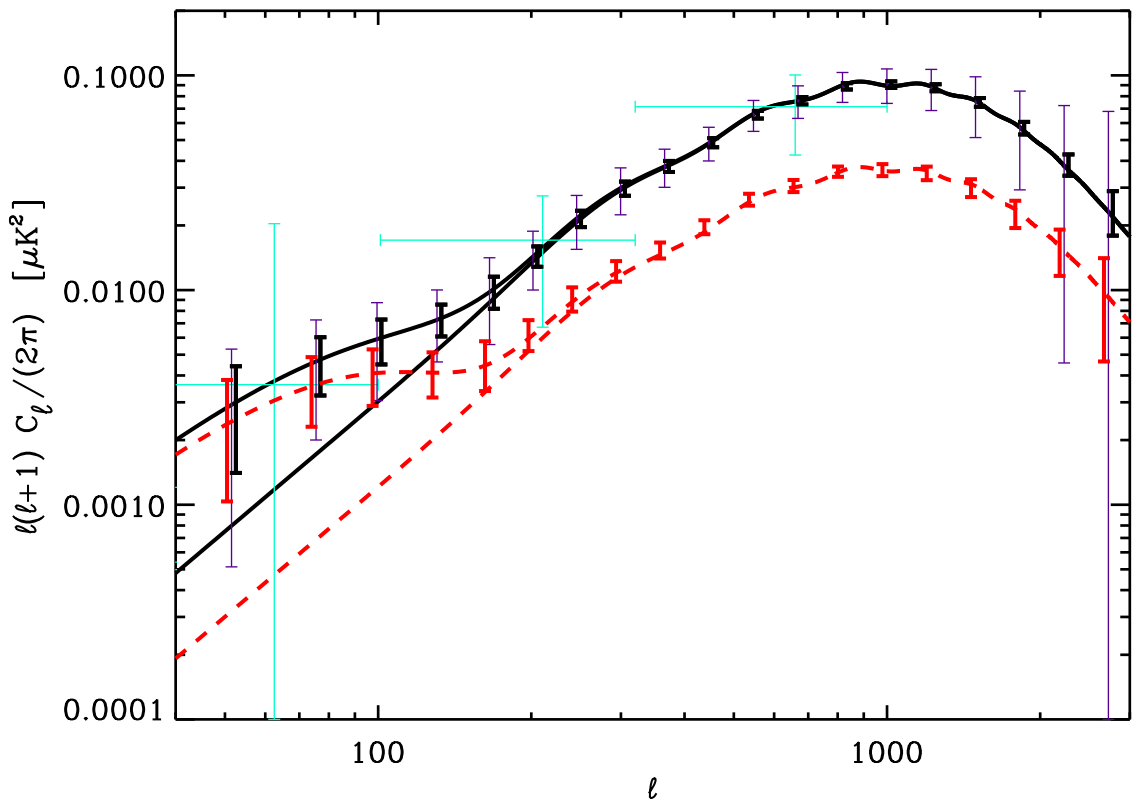



fig from SPT-3G proposal

see Smith et al
http://arxiv.org/abs/1010.0048

# Summary

- exciting stuff ahead for CMB polarization
  - neutrino mass measurements
  - inflationary gravitational radiation B modes
- instruments advancing quickly
  - B mode measurements about to become routine