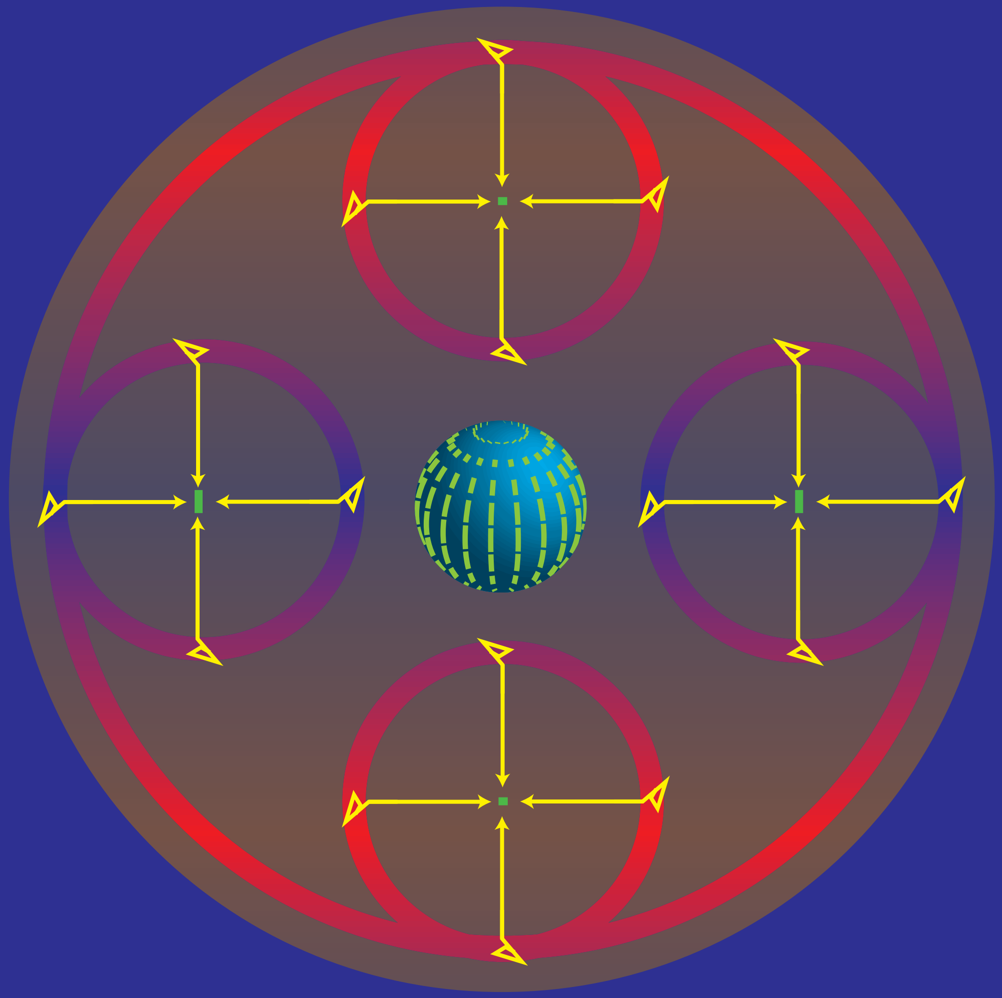
CMB Polarization and Cosmology



Wayne Hu

KIPAC, May 2004

Outline

- Reionization and its Applications

  Dark Energy

  The Quadrupole

  Gravitational Waves

- Acoustic Polarization and Initial Power
- Gravitational Lensing as Signal and Contaminant
- Recent Polarization Collaborators:

  Christopher Gordon

  Matt Hedman

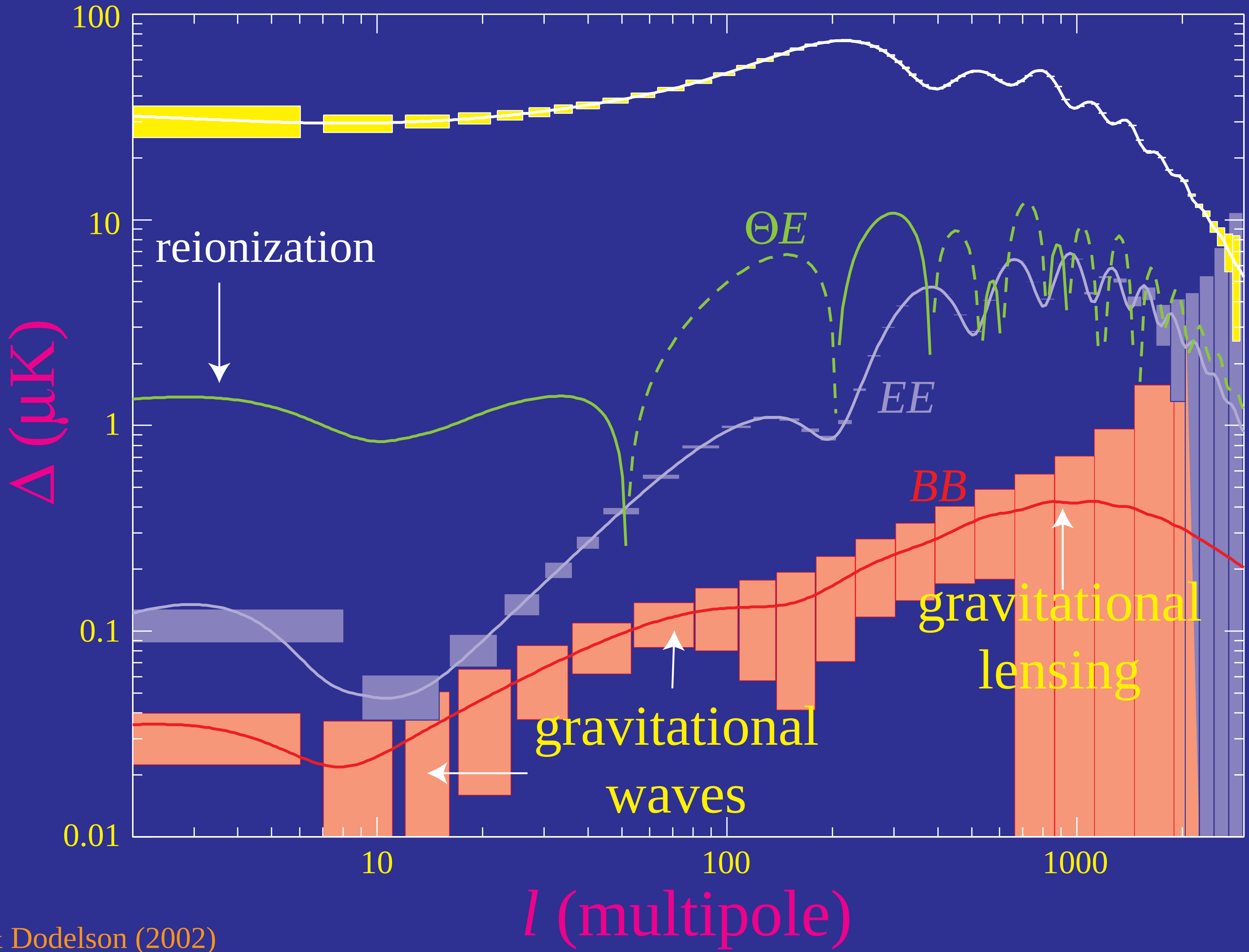
  Gil Holder

  Manoj Kaplinghat

  Takemi Okamoto

  Kendrick Smith

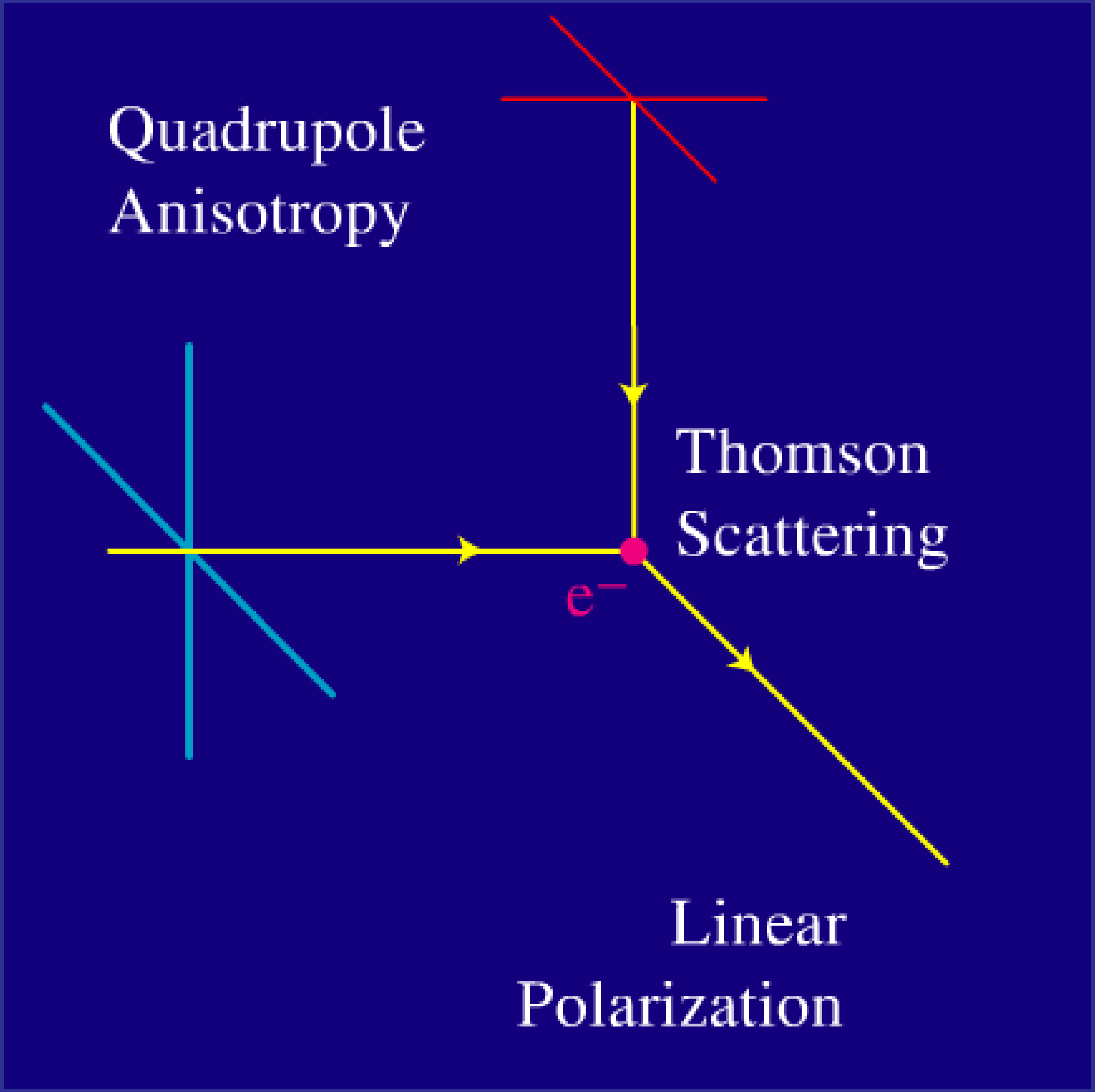
Polarized Issues



Hu & Dodelson (2002)

Polarization from Thomson Scattering

- Quadrupole anisotropies scatter into linear polarization

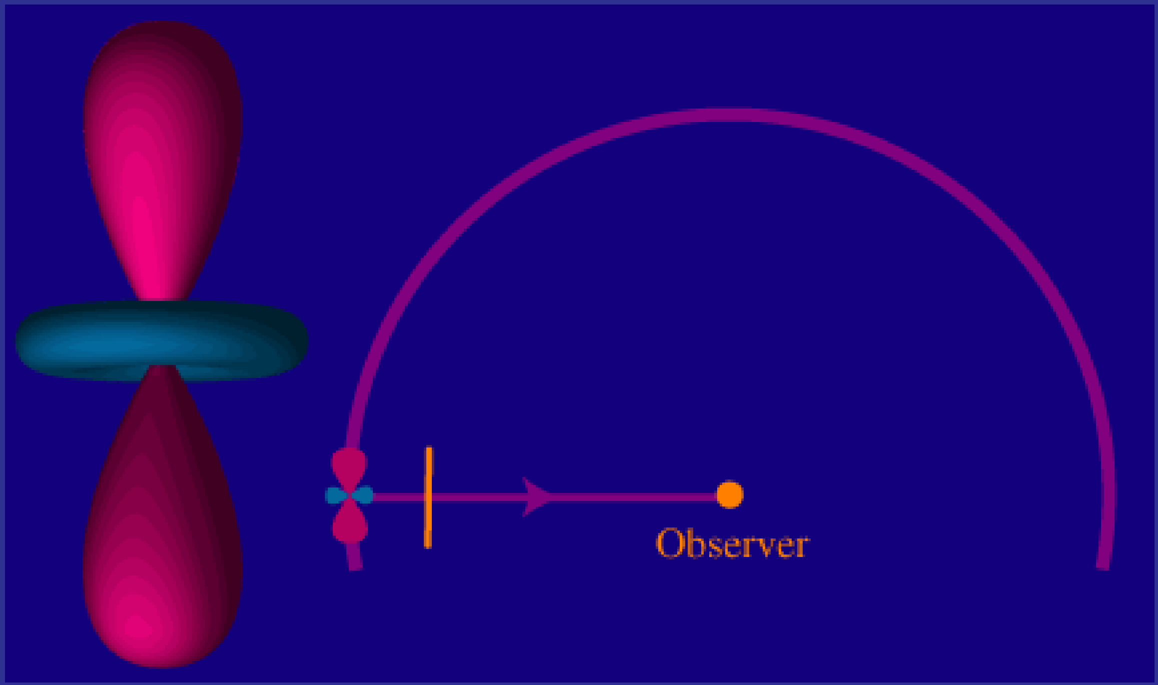


aligned with
cold lobe

Hu & White (1997)

Whence Polarization Anisotropy?

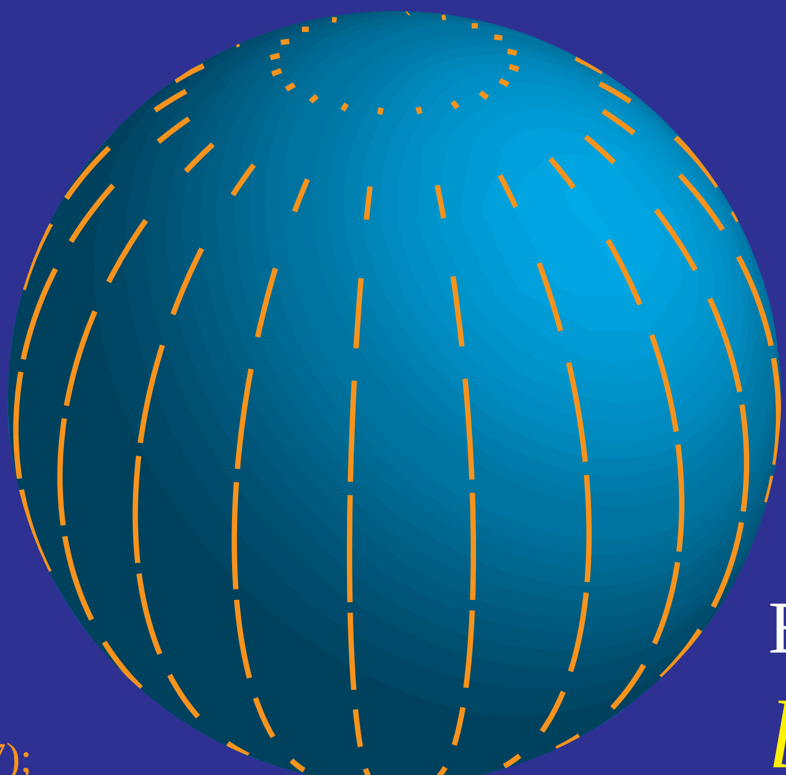
- Observed photons scatter into the line of sight
- Polarization arises from the projection of the quadrupole on the transverse plane



Hu & White (1997)

Polarization Multipoles

- Mathematically pattern is described by the tensor (spin-2) spherical harmonics [eigenfunctions of Laplacian on trace-free 2 tensor]
- Correspondence with scalar spherical harmonics established via Clebsch-Gordan coefficients (spin x orbital)
- Amplitude of the coefficients in the spherical harmonic expansion are the multipole moments; averaged square is the power



E-spin harmonic

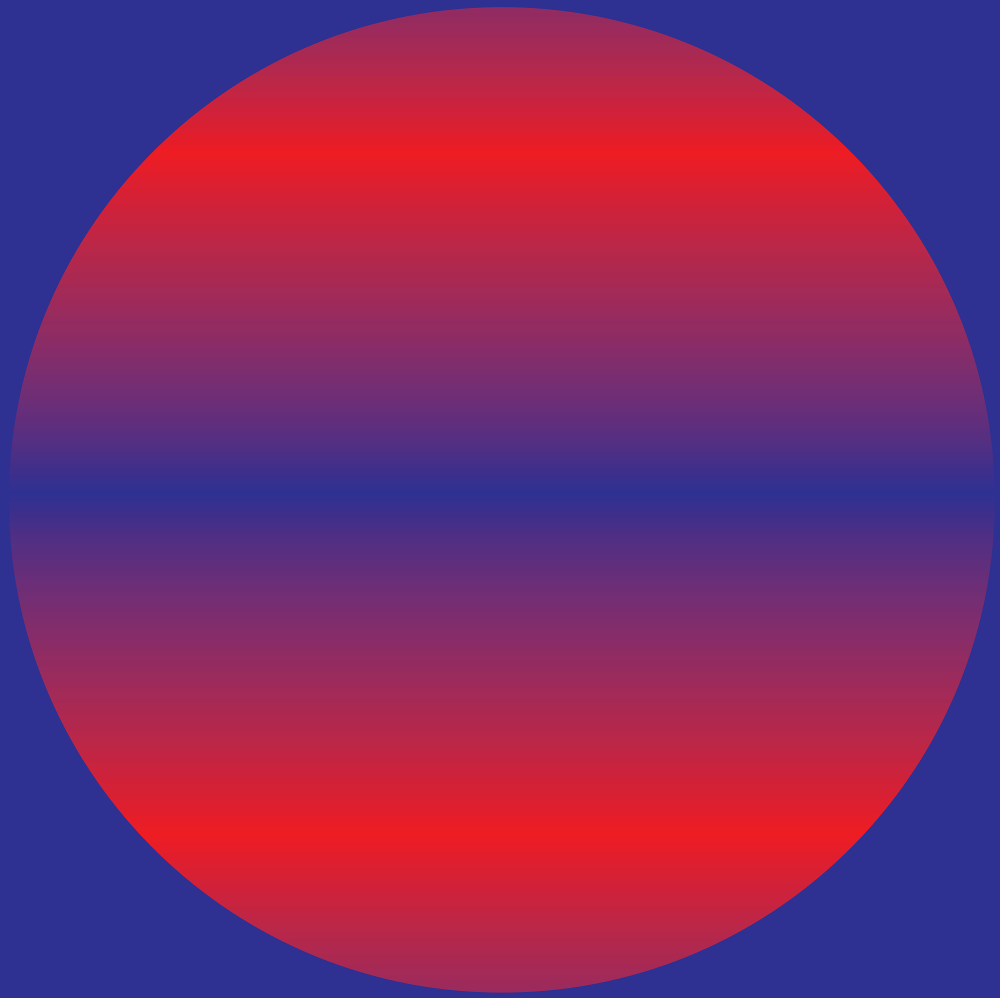
l=2, m=0

Seljak & Zaldarriaga (1997);
Kamionkowski, Kosowsky & Stebbins (1997)

Reionization

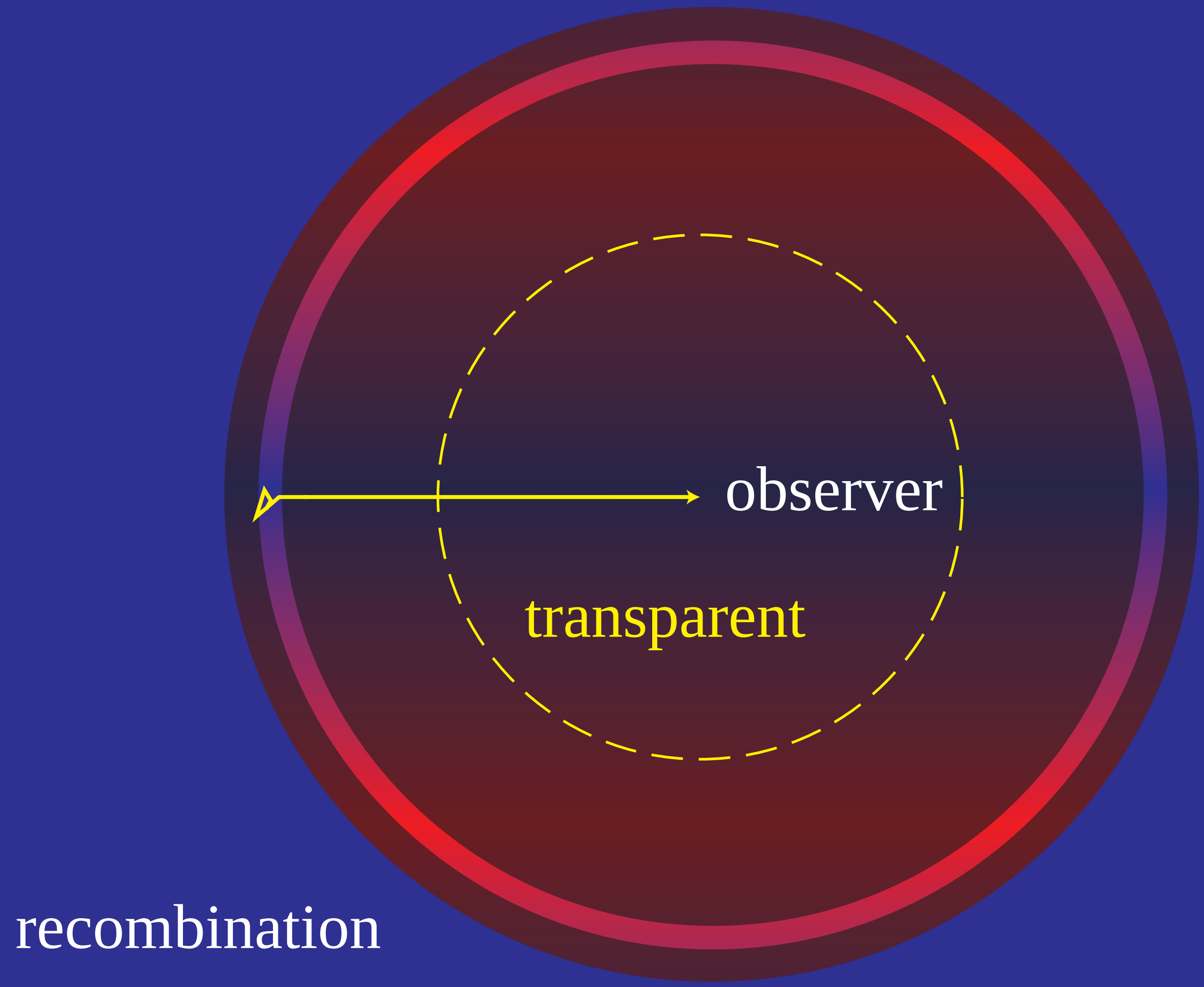
Temperature Inhomogeneity

- Temperature inhomogeneity reflects initial density perturbation on large scales
- Consider a single Fourier moment:



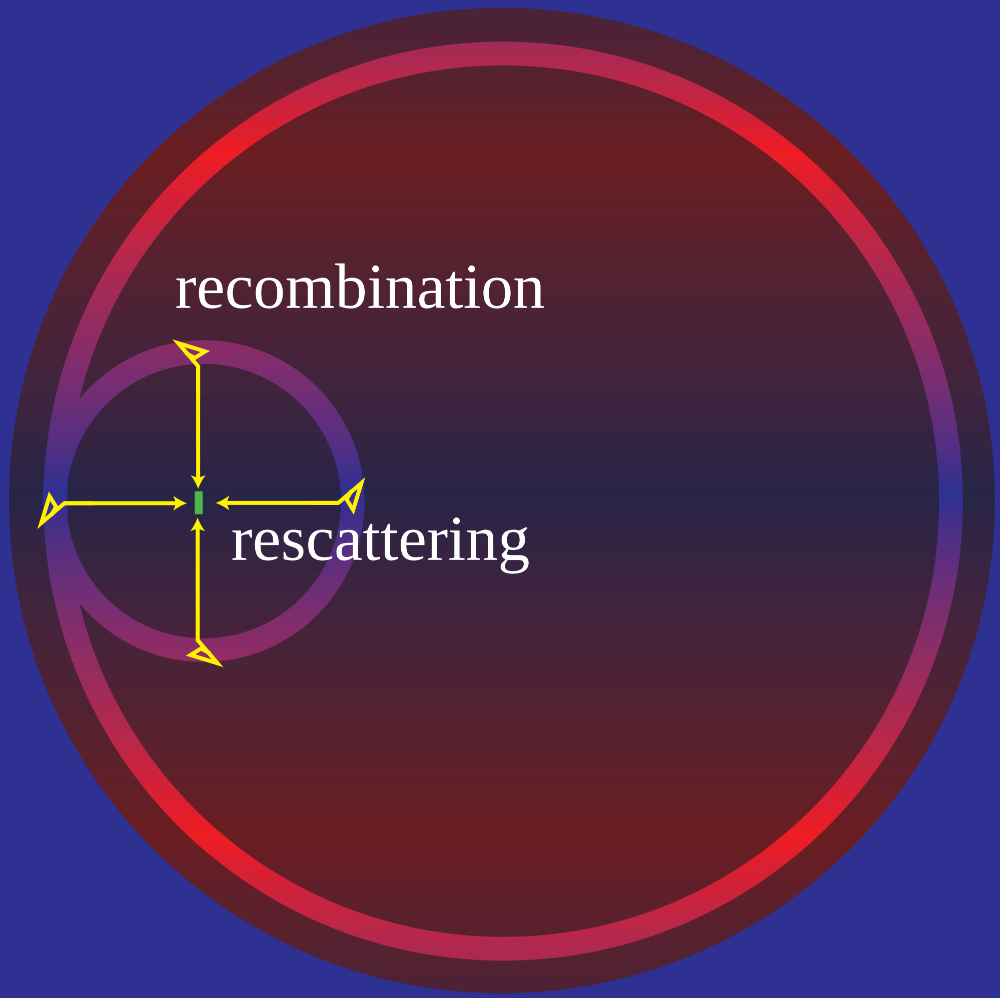
Locally Transparent

- Presently, the matter density is so low that a typical CMB photon will not scatter in a Hubble time (~age of universe)



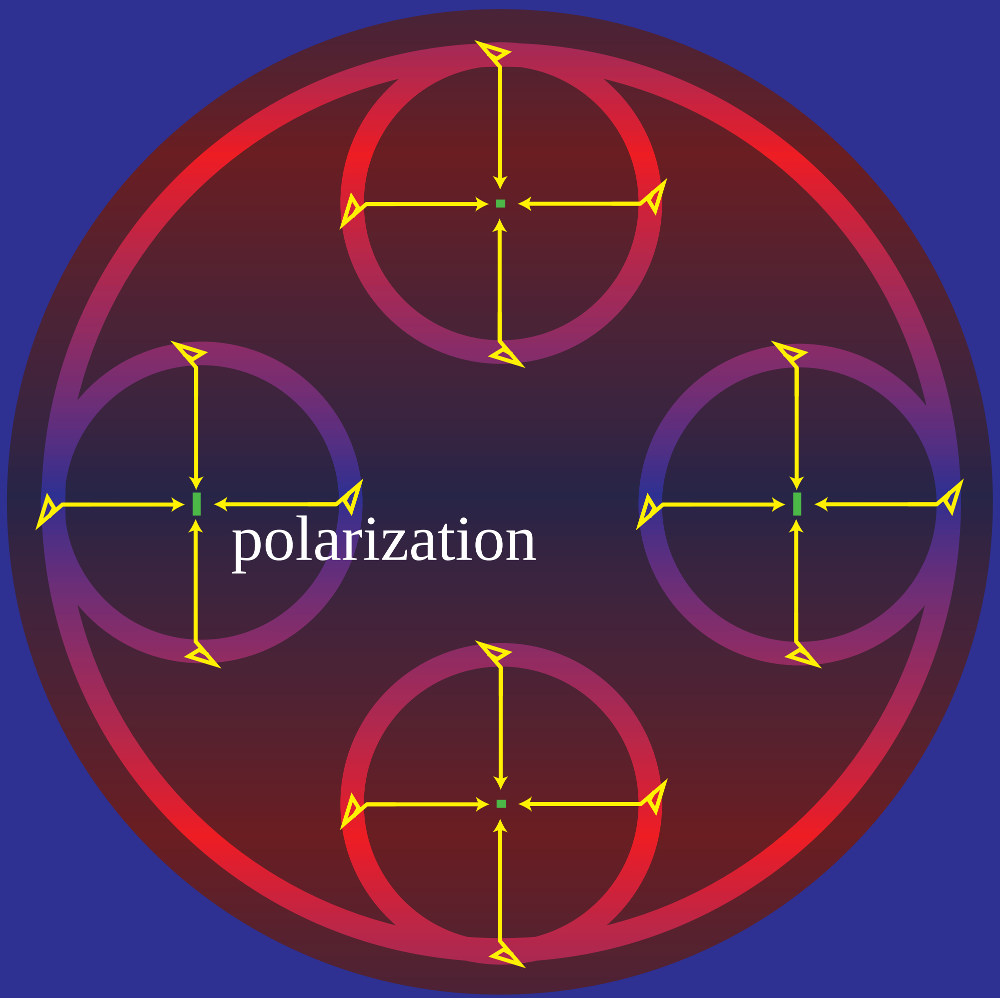
Reversed Expansion

- Free electron density in an ionized medium increases as scale factor a^{-3}; when the universe was a tenth of its current size CMB photons have a finite (~10%) chance to scatter



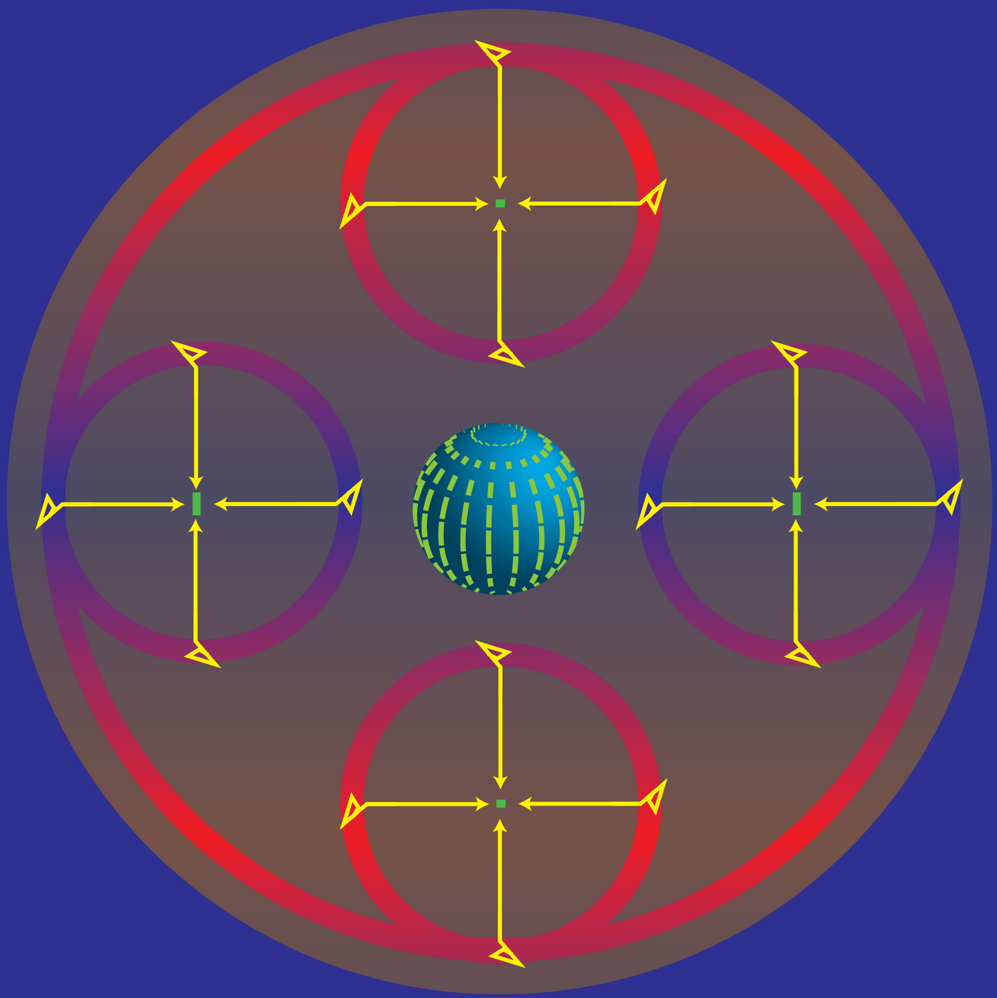
Polarization Anisotropy

- Electron sees the temperature anisotropy on its recombination surface and scatters it into a polarization



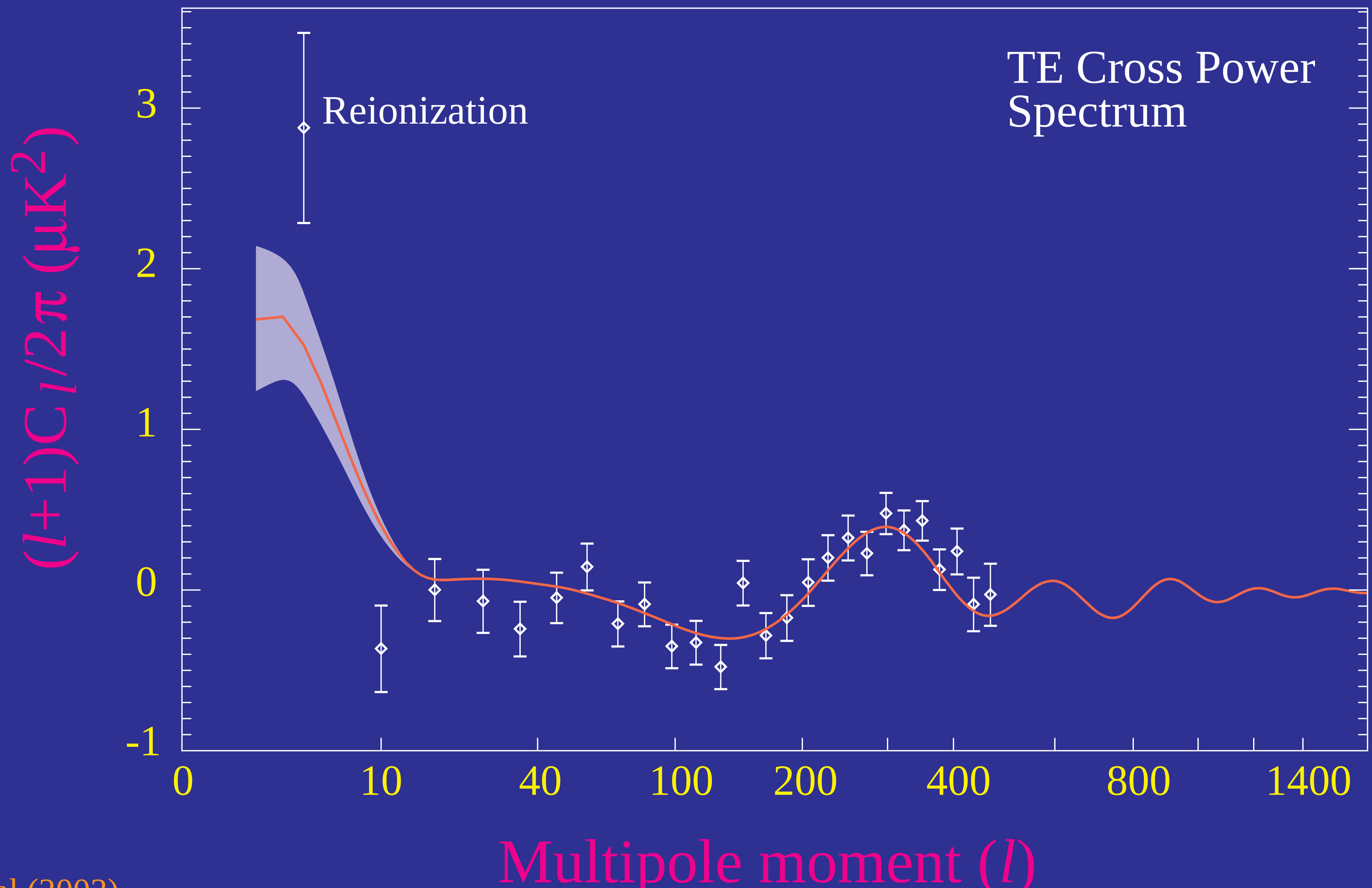
Temperature Correlation

- Pattern correlated with the temperature anisotropy that generates it; here an m=0 quadrupole



WMAP Correlation

- Measured correlation indicates the universe remained at least partially ionized to a surprisingly large redshift or early time (z>10)



Kogut et al (2003)

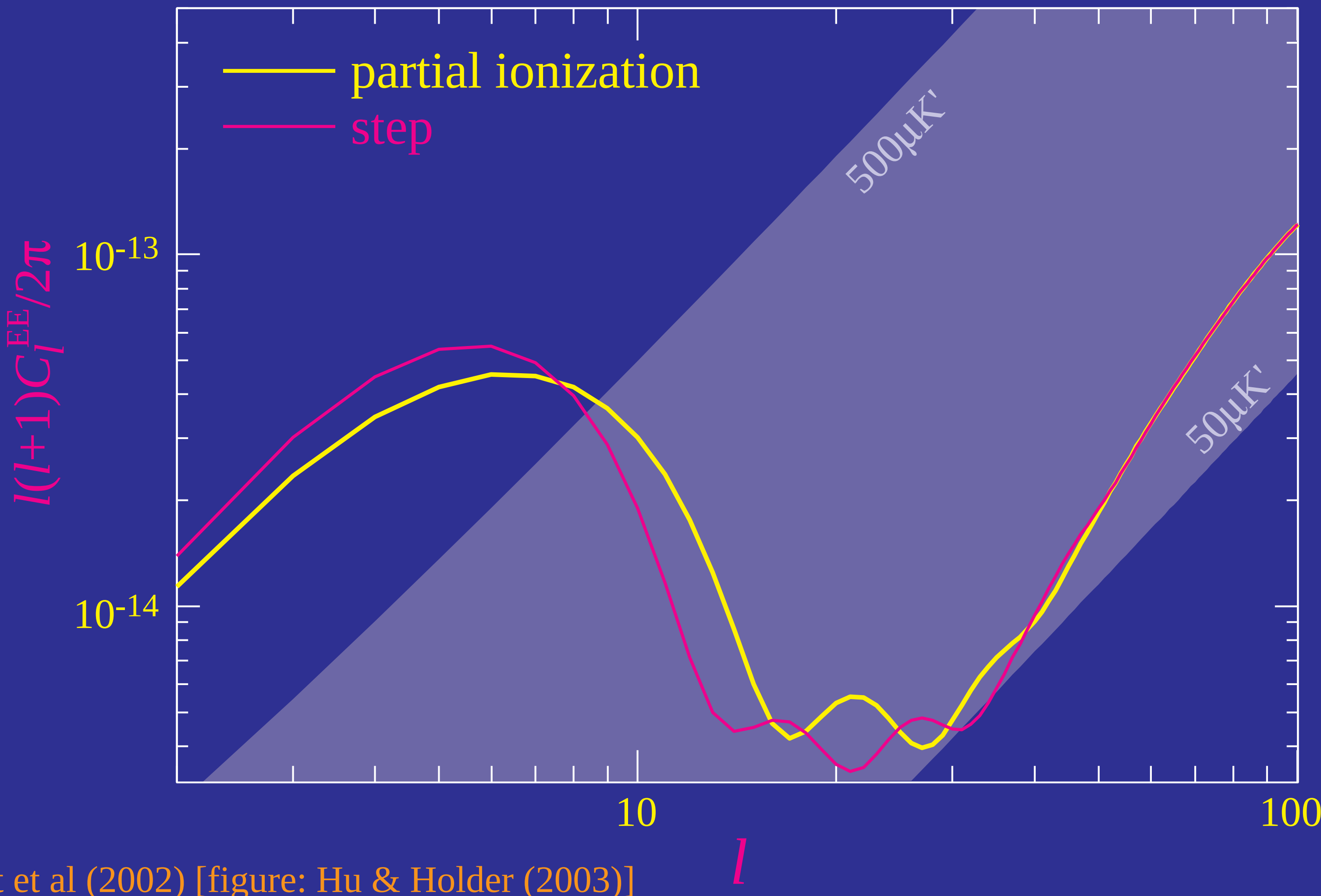
Why Care?

- Early ionization is puzzling if due to ionizing radiation from normal stars; may indicate more exotic physics is involved
- Reionization screens temperature anisotropy on small scales making the true amplitude of initial fluctuations larger by e^{τ}
- Measuring the growth of fluctuations is one of the best ways of determining the neutrino masses and the dark energy
- Offers an opportunity to study the origin of the low multipole statistical anomalies
- Presents a second, and statistically cleaner, window on gravitational waves from the early universe

Ionization History

Polarization Power Spectrum

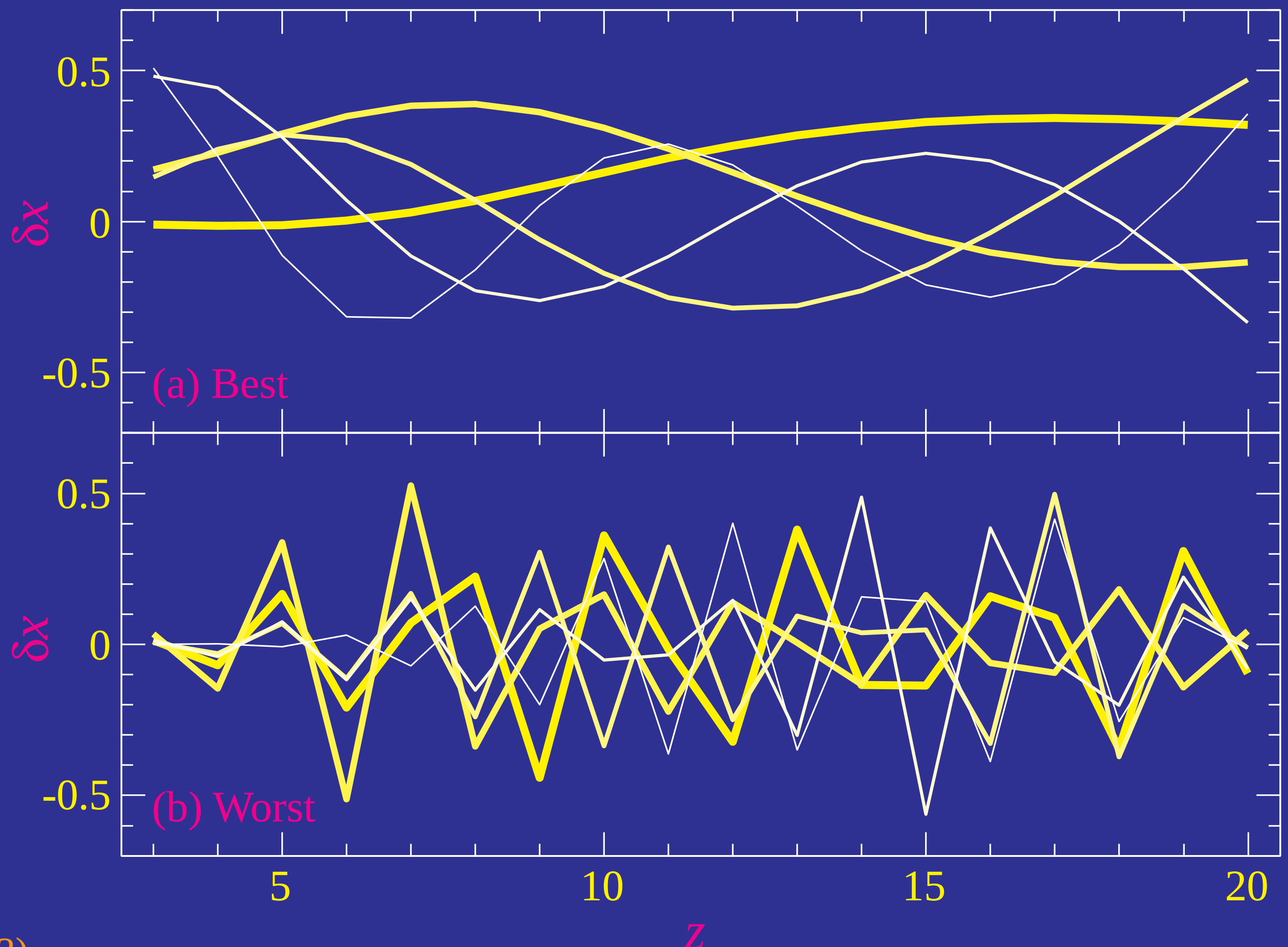
- Most of the information on ionization history is in the polarization (auto) power spectrum - two models with same optical depth but different ionization fraction



Kaplinghat et al (2002) [figure: Hu & Holder (2003)]

Principal Components

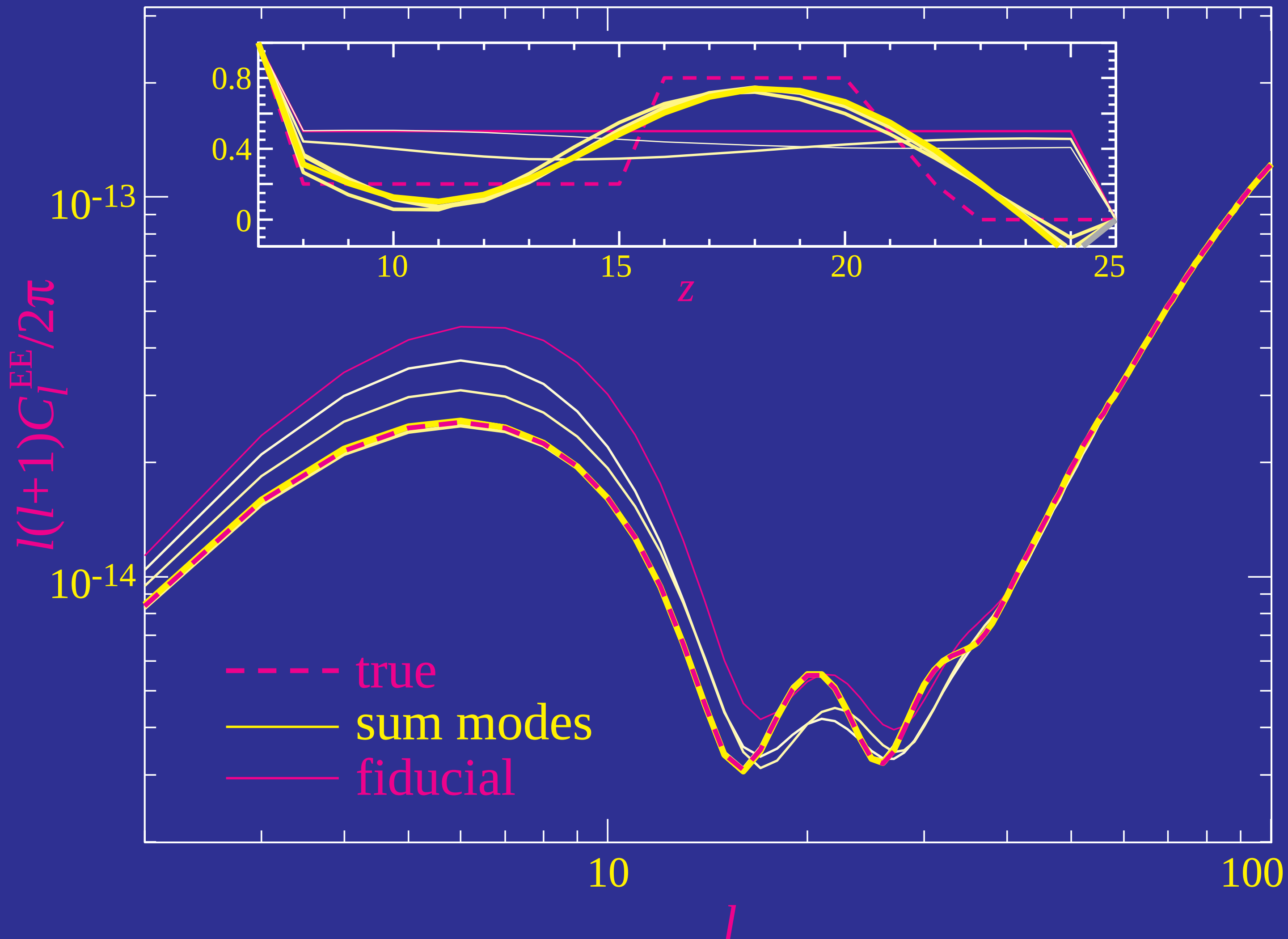
- Information on the ionization history is contained in ~5 numbers
  - essentially coefficients of first few Fourier modes



Hu & Holder (2003)

Representation in Modes

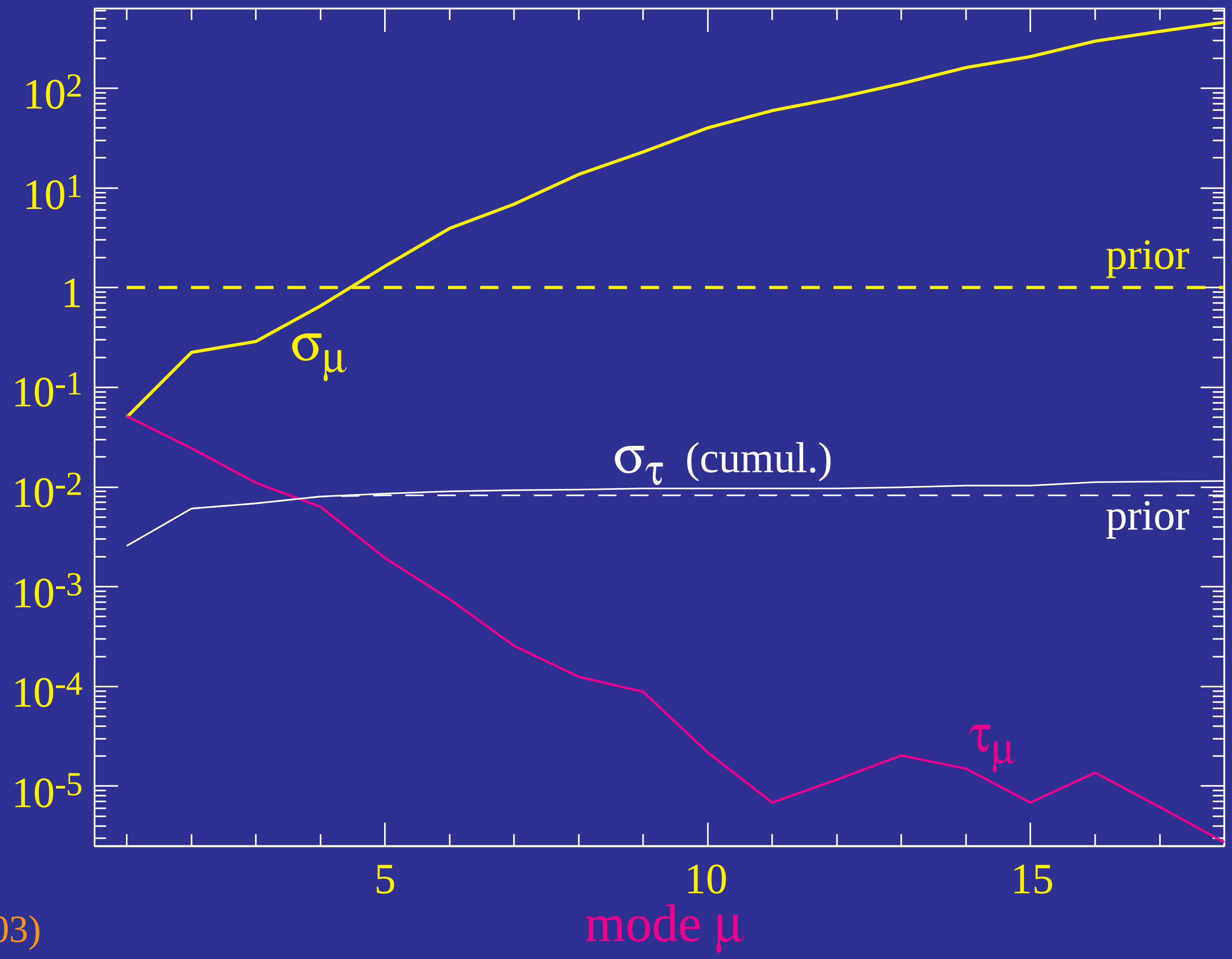
- Reproduces the power spectrum and net optical depth (actual τ=0.1375 vs 0.1377); indicates whether multiple physical mechanisms suggested



Hu & Holder (2003)

Total Optical Depth

- Optical depth measurement unbiased
- Ultimate errors set by cosmic variance here 0.01
- Equivalently 1% determination of initial amplitude for dark energy

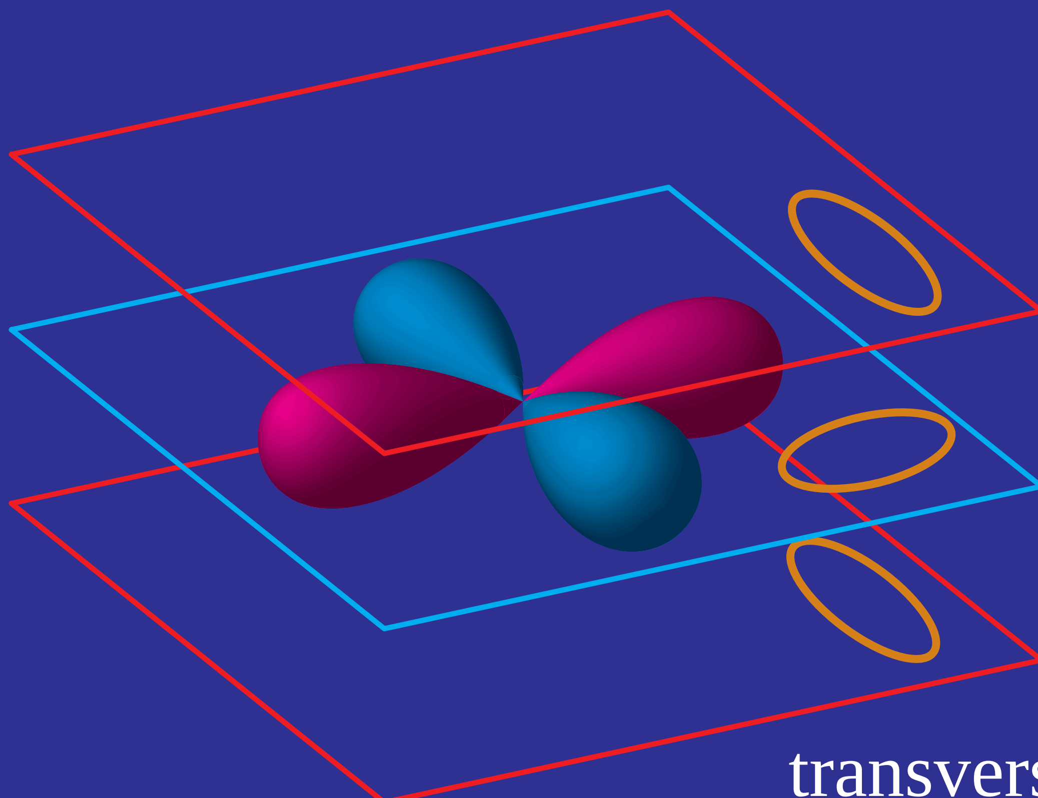


Hu & Holder (2003)

Gravitational Waves

Gravitational Waves

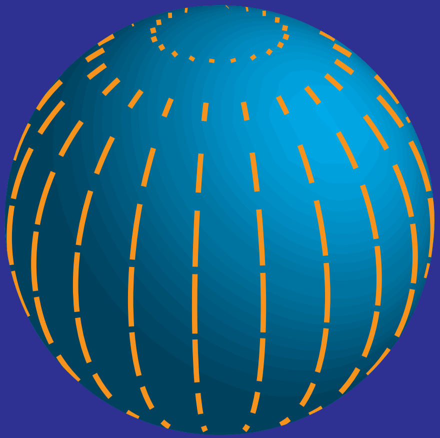
- Inflation predicts near scale invariant spectrum of gravitational waves
- Amplitude proportional to the square of the $E_{\rm i}$=$V^{1/4}$ energy scale
- If inflation is associated with the grand unification $E_{\rm i}$~10^{16} GeV and potentially observable



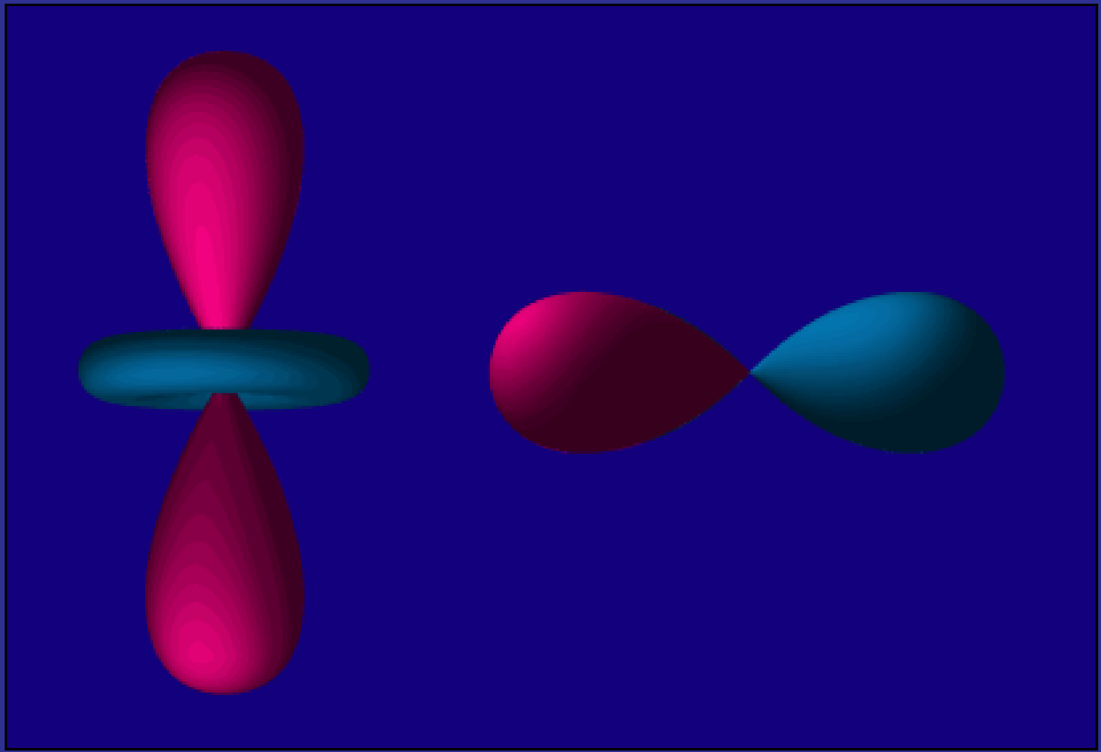
transverse-traceless
distortion

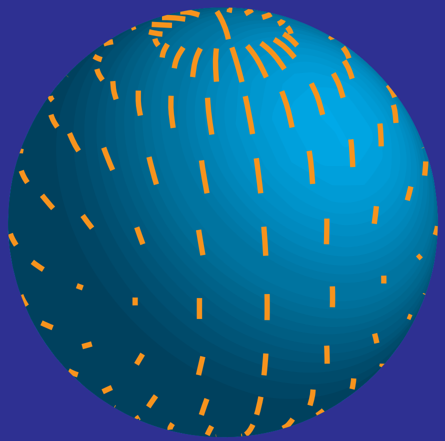
Gravitational Wave Pattern

- Projection of the quadrupole anisotropy gives polarization pattern
- Transverse polarization of gravitational waves breaks azimuthal symmetry



density
perturbation

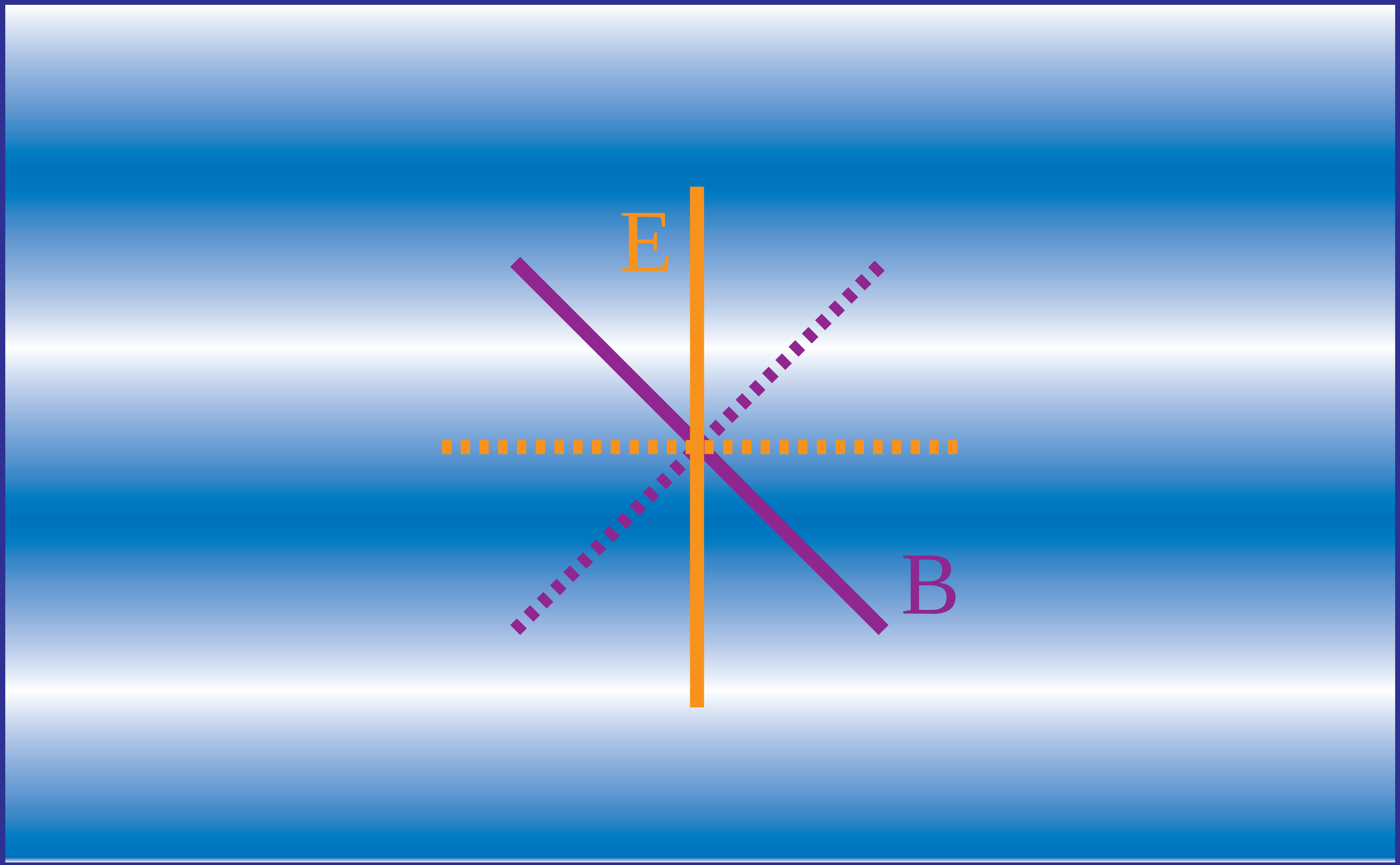




gravitational
wave

Electric & Magnetic Polarization
(a.k.a. gradient & curl)

- Alignment of principal vs polarization axes
  (curvature matrix vs polarization direction)

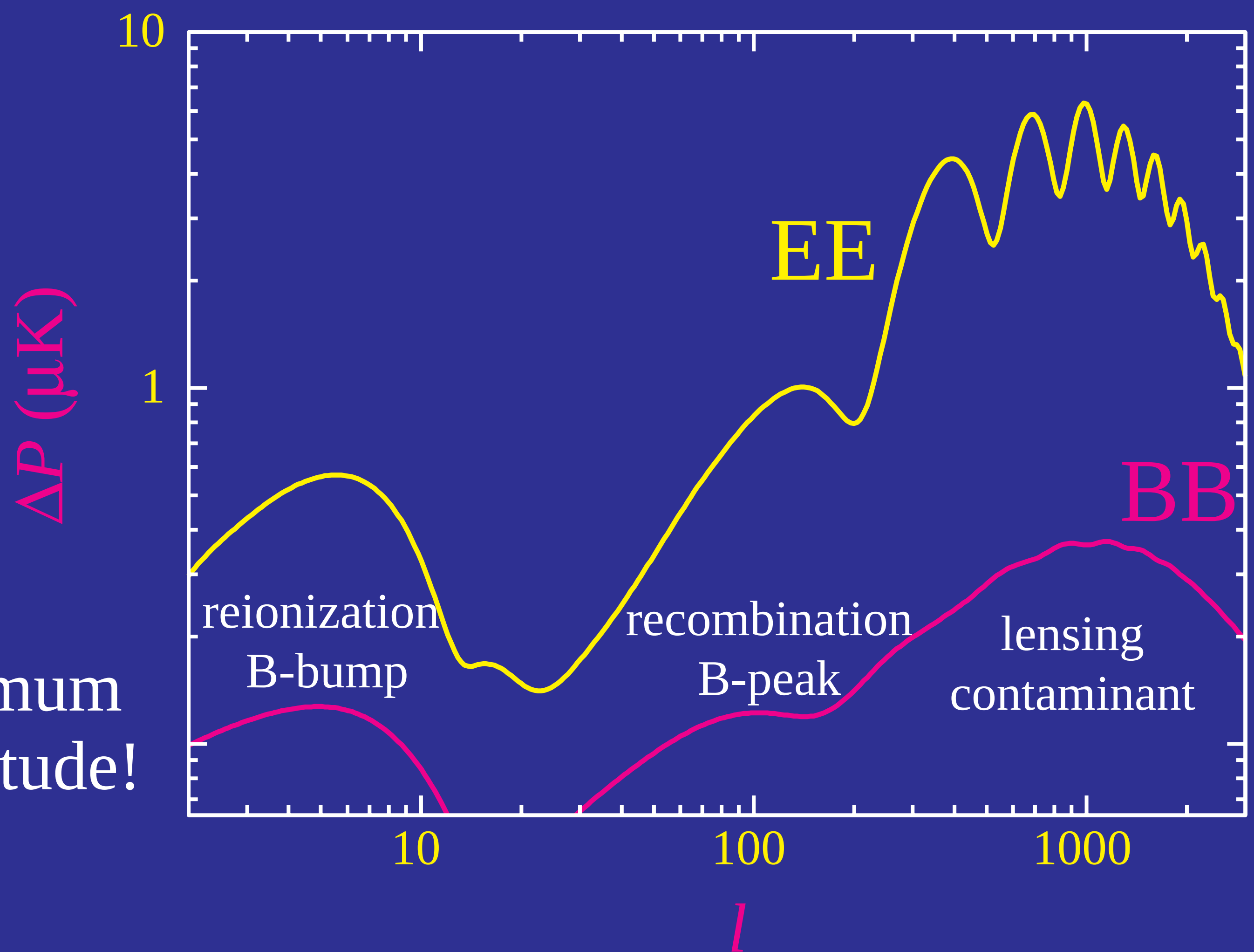


Kamionkowski, Kosowsky, Stebbins (1997)
Zaldarriaga & Seljak (1997)

The B-Bump

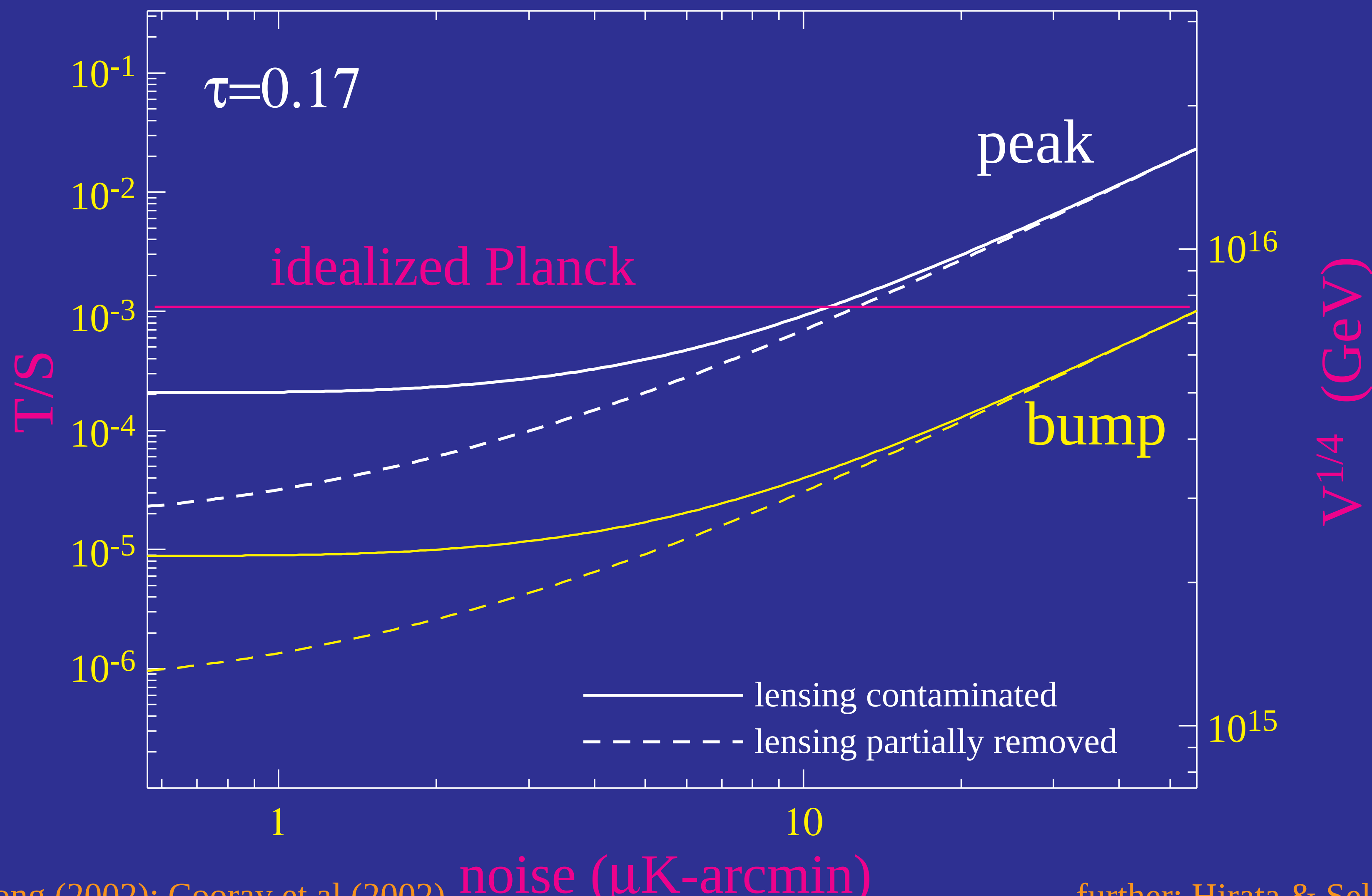
- Rescattering of gravitational wave anisotropy generates the B-bump
- Potentially the most sensitive probe of inflationary energy scale

maximum
amplitude!



T/S, Inflation and the B-Bump

- B-bump up to 20x more sensitive to T/S
- In combination with recombination peak, constrain spectrum



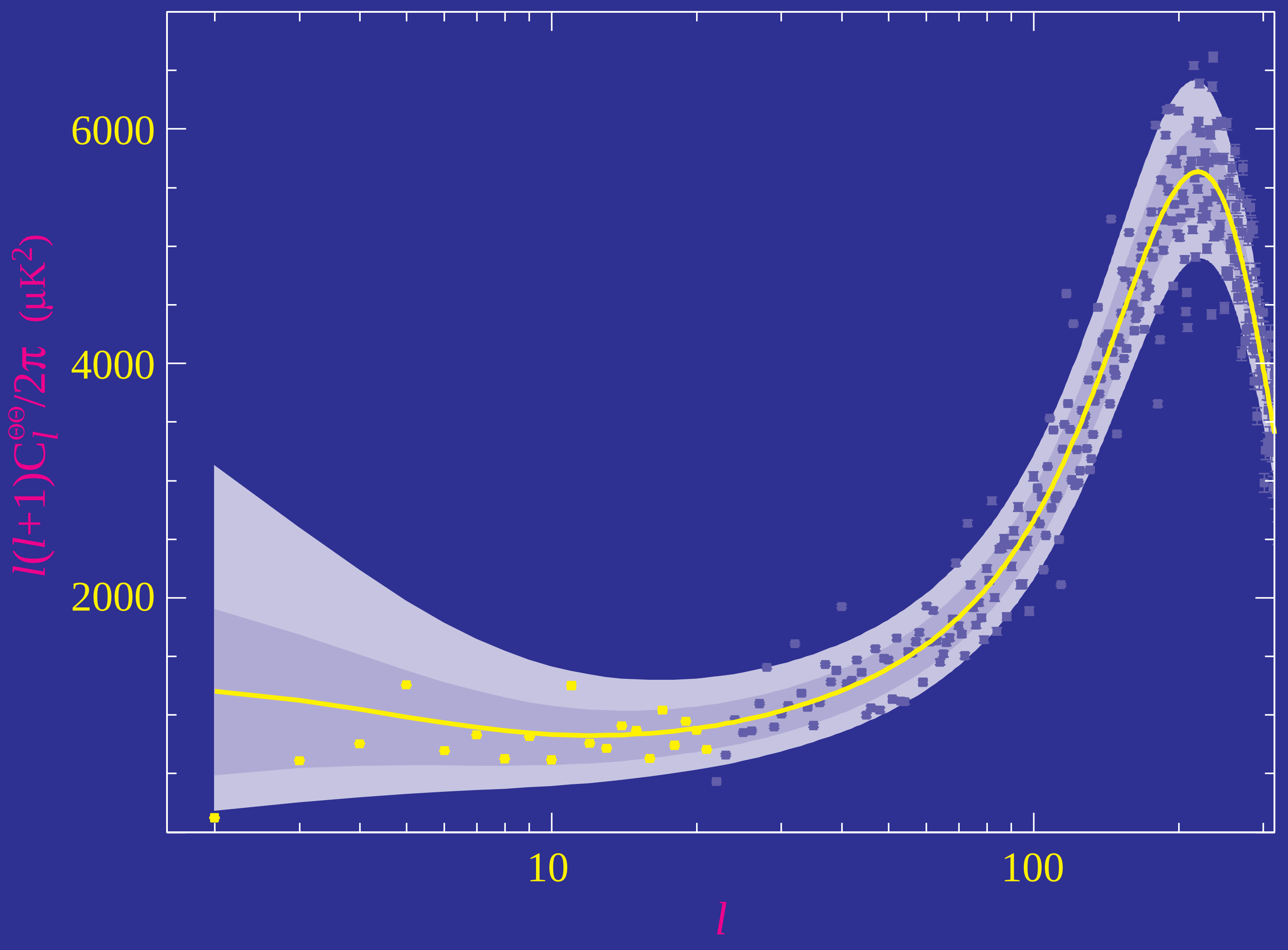
Hu (2001)
Knox & Song (2002); Cooray et al (2002)

further: Hirata & Seljak (2003)

Quadrupole Aside

Low Quadrupole

- Known since COBE: a ~2σ problem

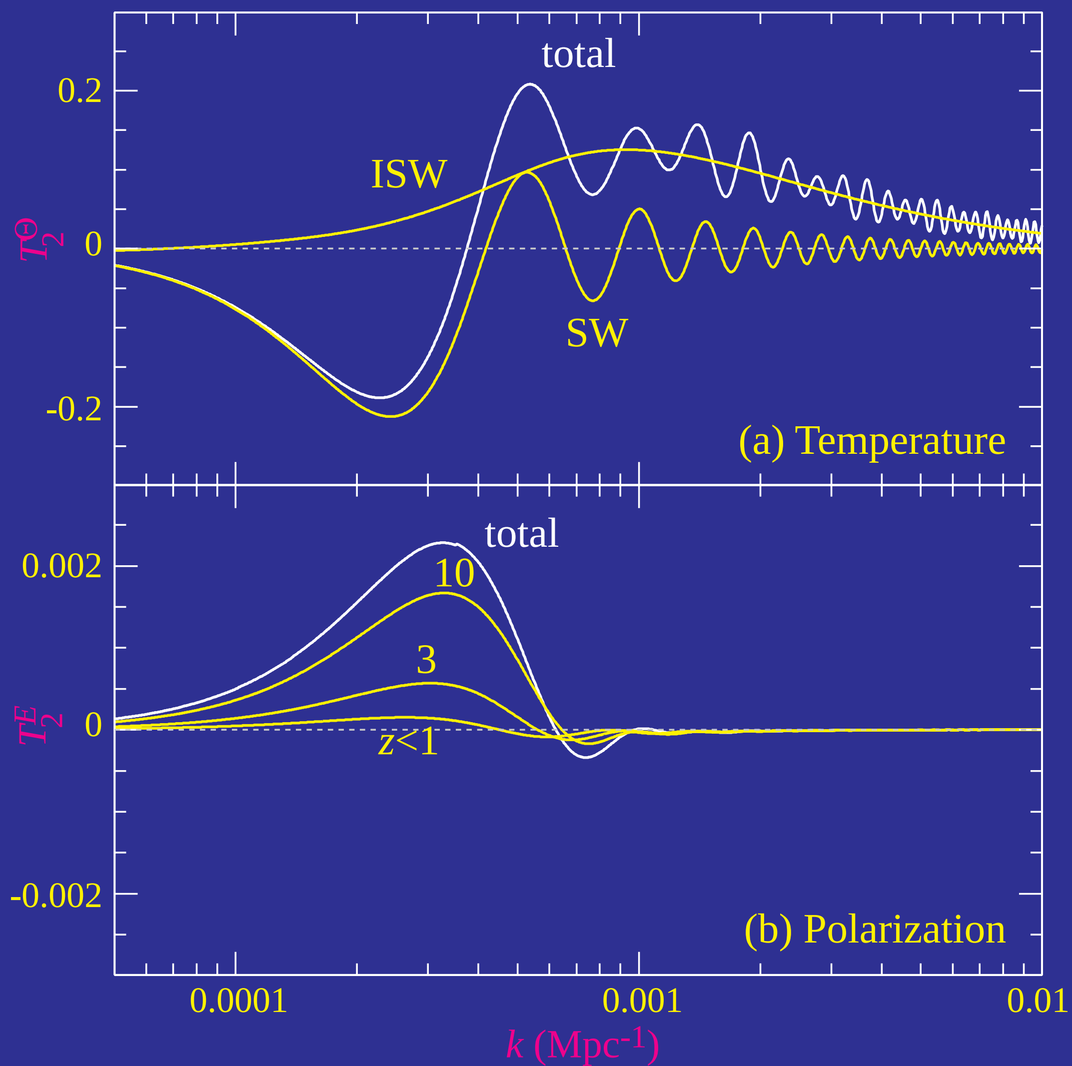


ISW Spatial Modes

- ISW effect comes from nearby acceleration regime
- Shorter wavelengths project onto same angle

Quadrupole Origins

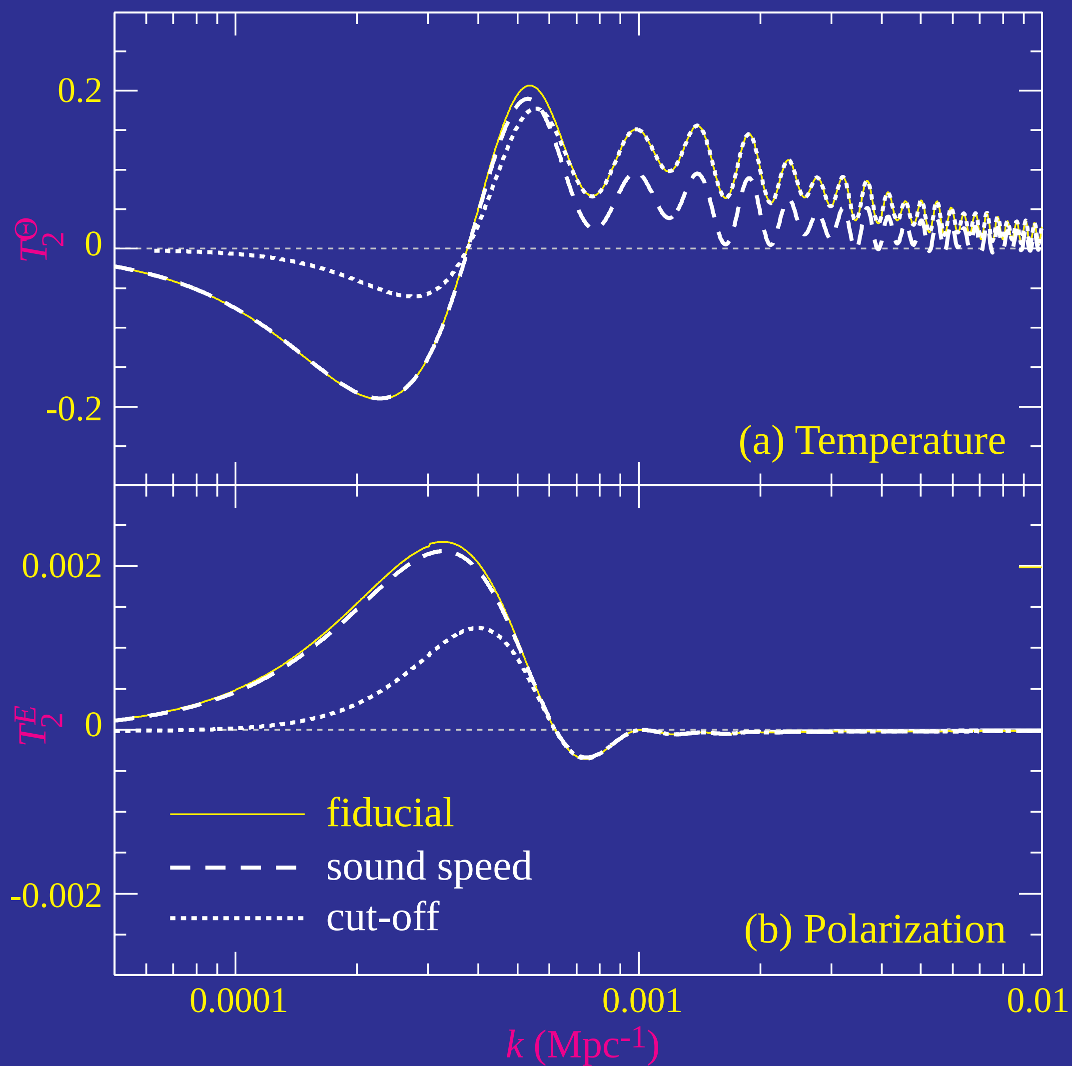
- Transfer function for the quadrupole



Gordon & Hu (2004)

Lowering the Quadrupole

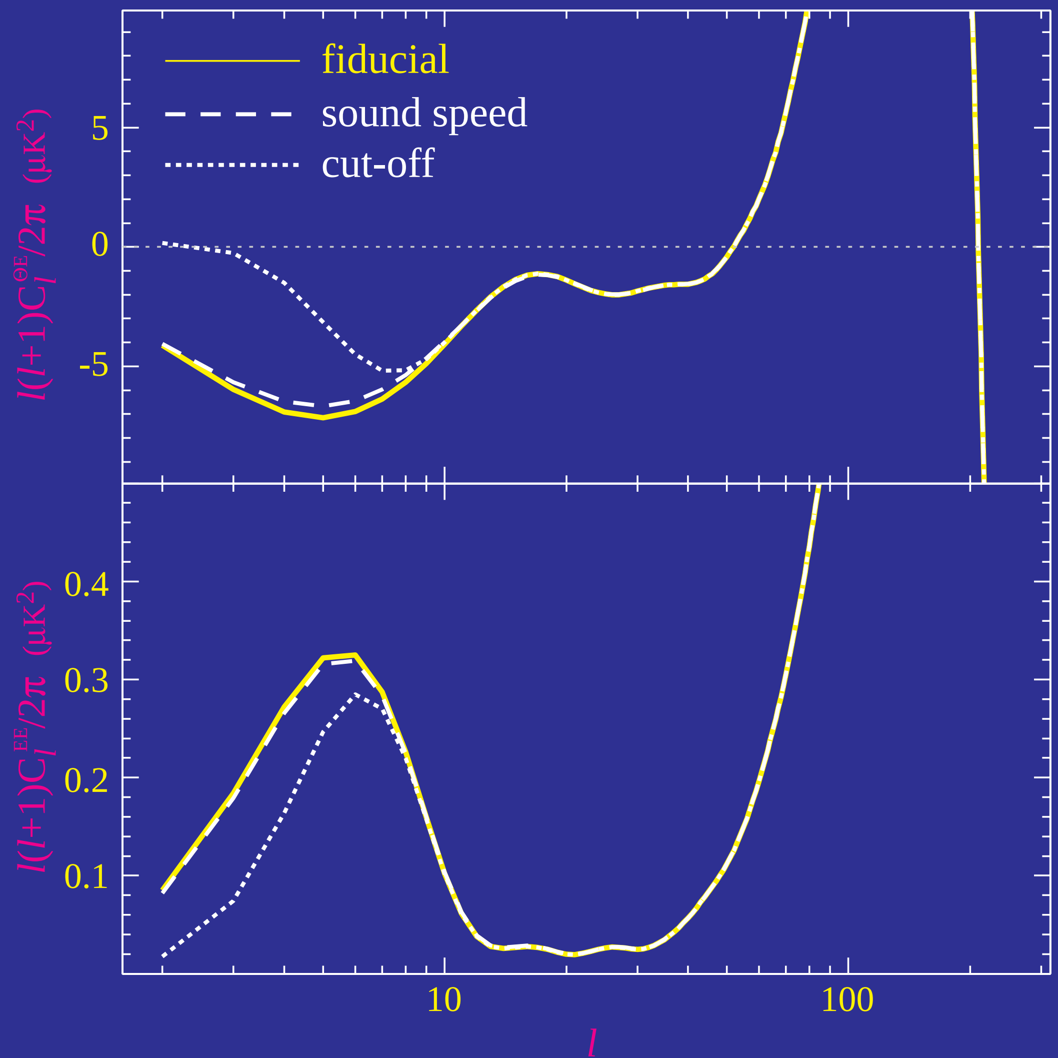
- Transfer function for the quadrupole



Gordon & Hu (2004) [Contaldi et al 2003; Hu 1998; Erikson et al 2002; Bean & Dore 2003]

Low Quadrupole Models

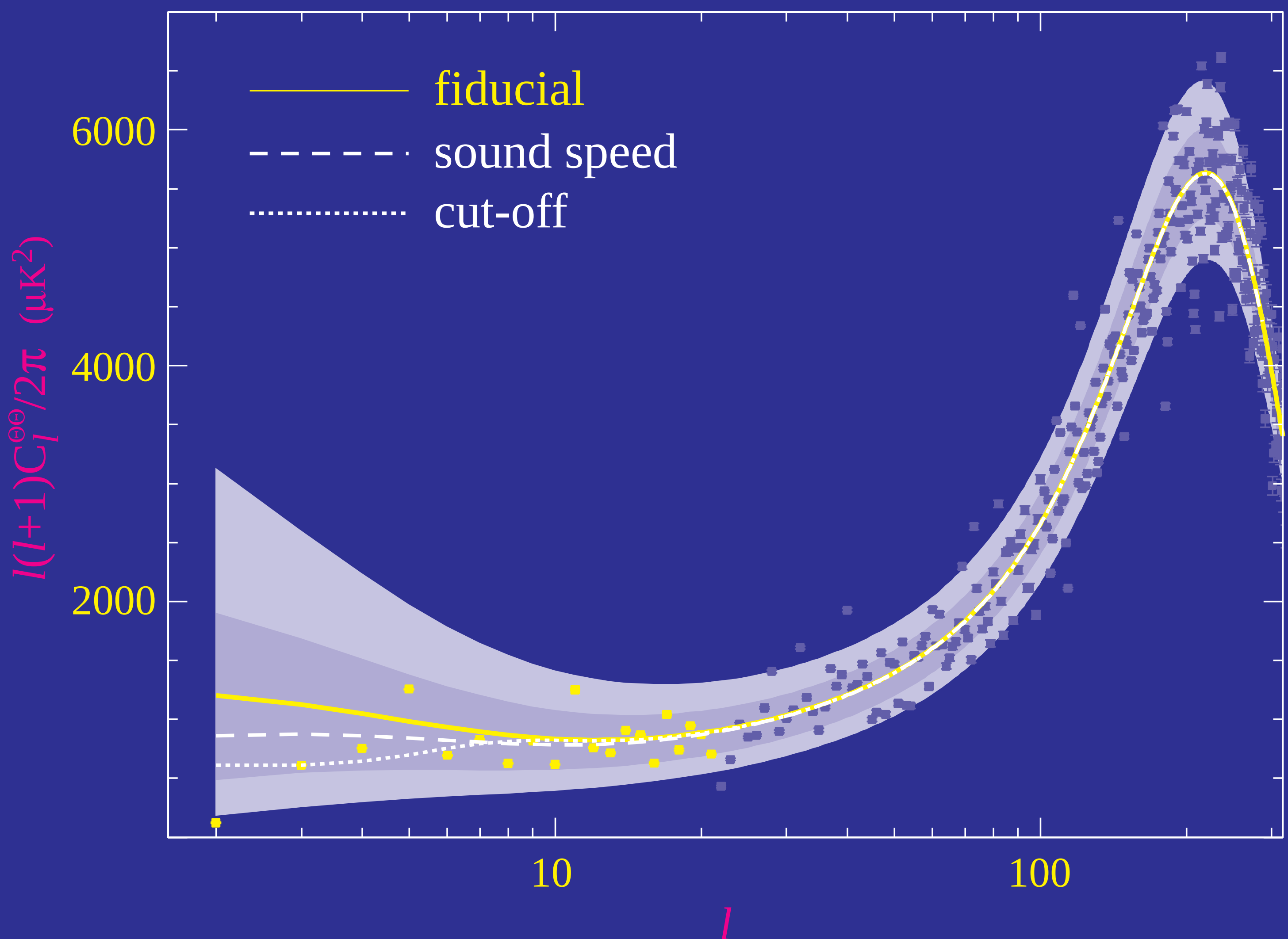
- Distinguished by polarization



Gordon & Hu (2004) [Dore, Holder & Loeb 2003]

Low Quadrupole Models

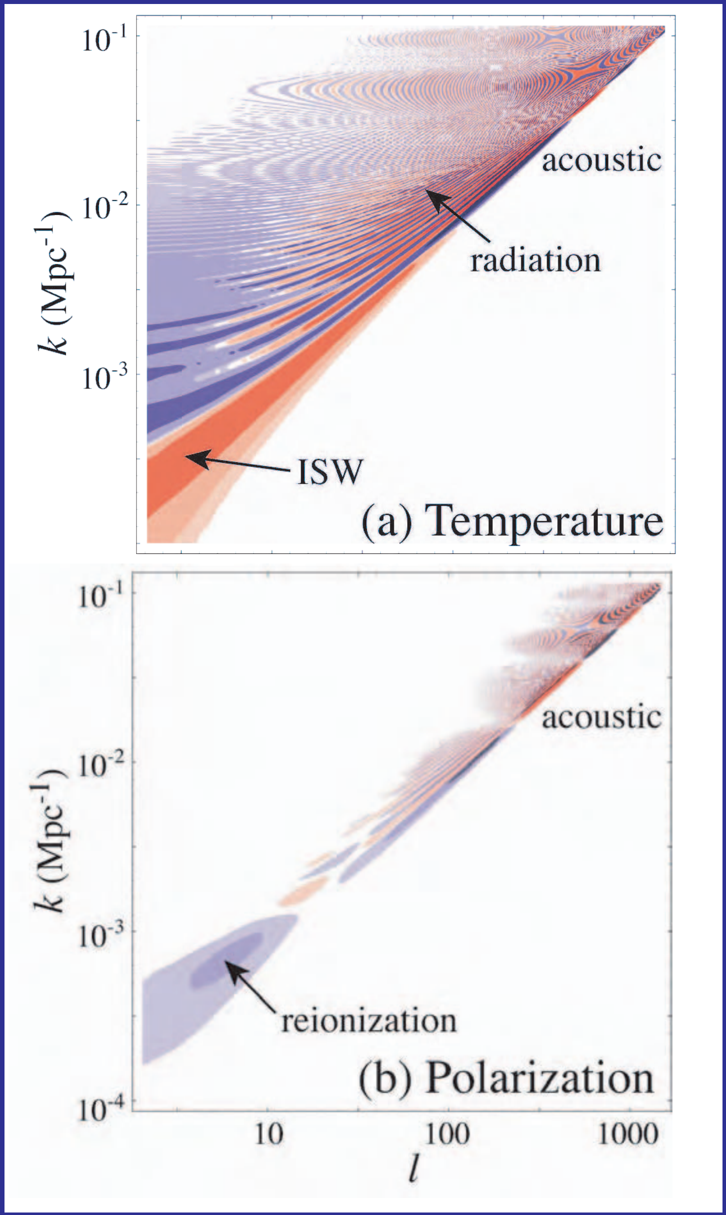
- Models: initial conditions vs. dark energy



Gordon & Hu (2004) [Contaldi et al 2003; Hu 1998; Erikson et al 2002; Bean & Dore 2003]

Initial Spectrum

Transfer of Initial Power

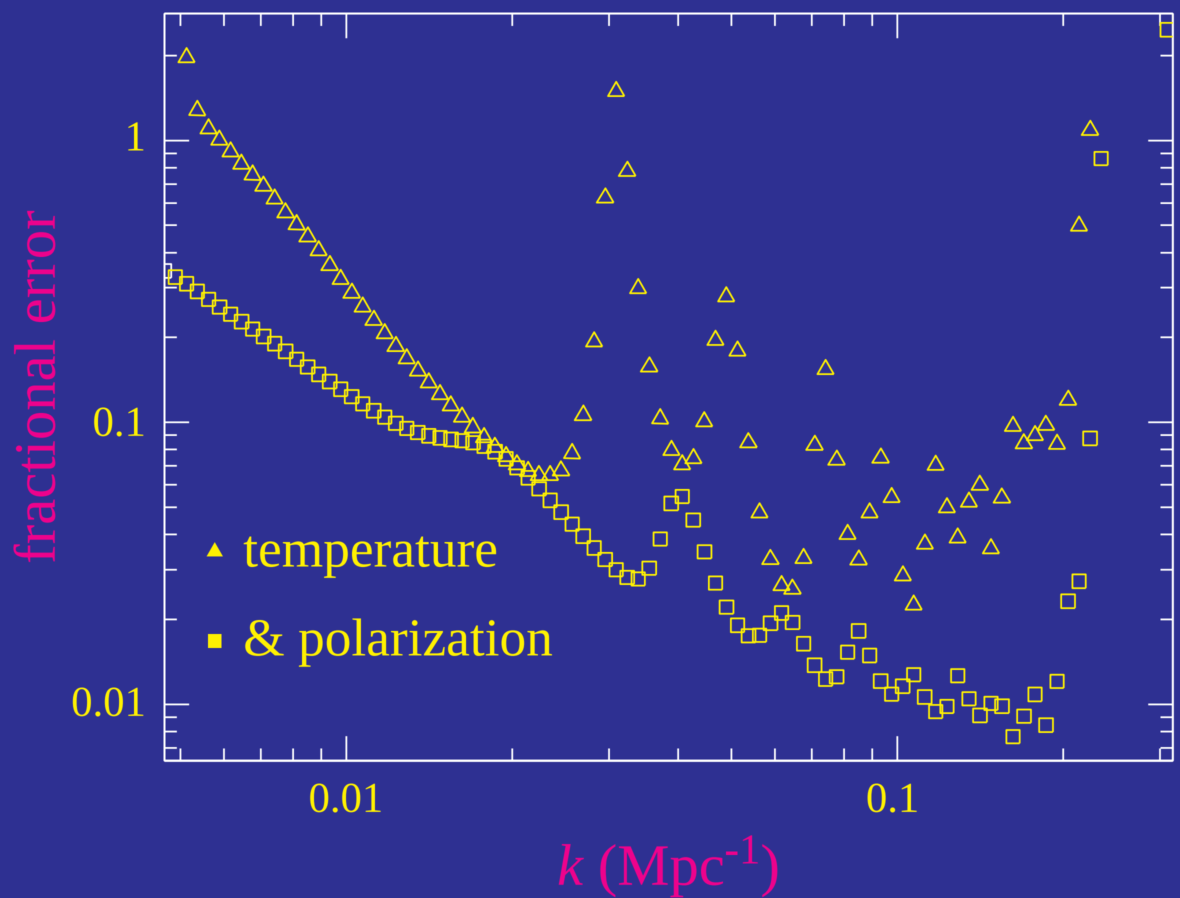


Hu & Okamoto (2003)

Prospects for Initial Conditions

- Polarization crucial for detailed study of initial conditions, decade in scale of the acoustic peaks can provide exquisite tests of scale free initial conditions

Hu & Okamoto (2003)



cosmological parameters fixed

even with large lever arm other tests must match accuracy

Wang et al (1999); Kinney (2001); Miller et al (2002); Tegmark & Zaldarriaga (2002); Bridle et al (2003)

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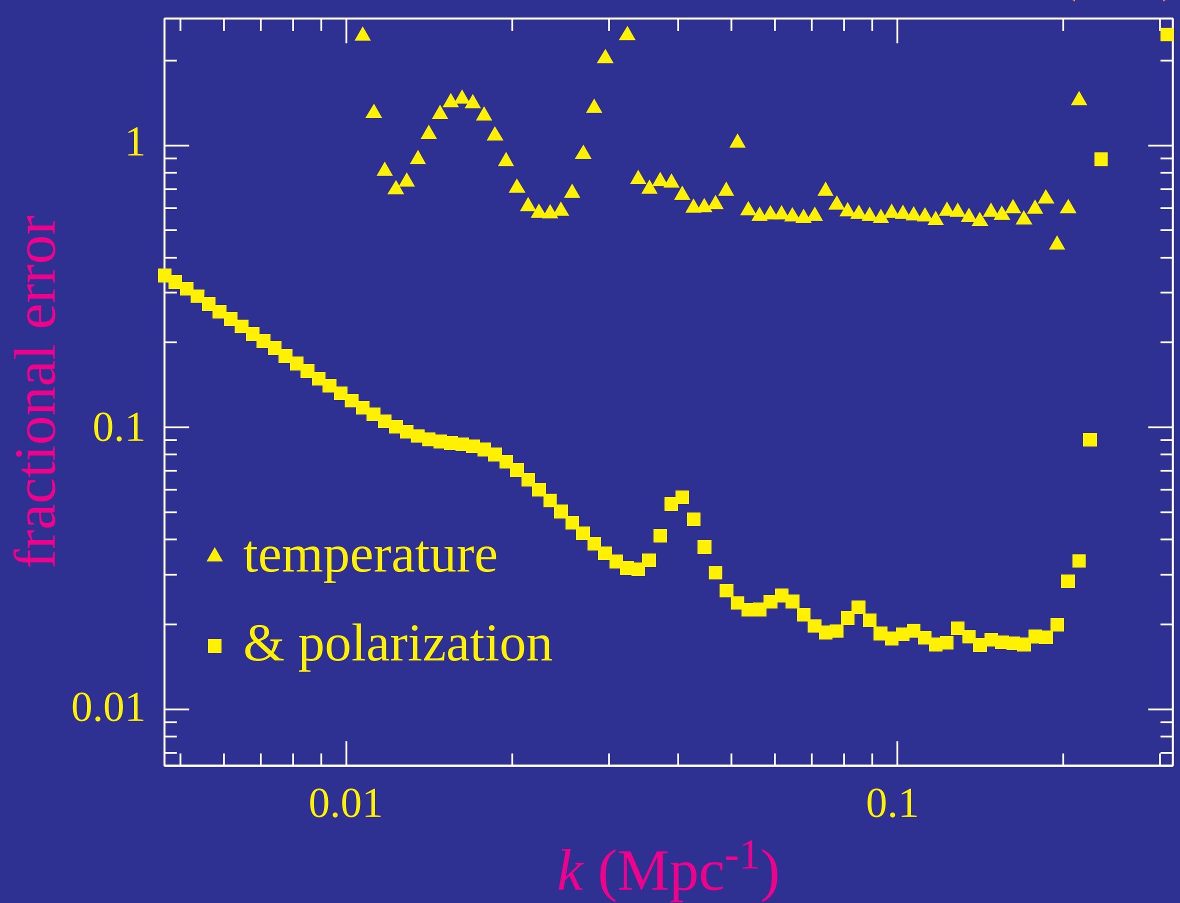
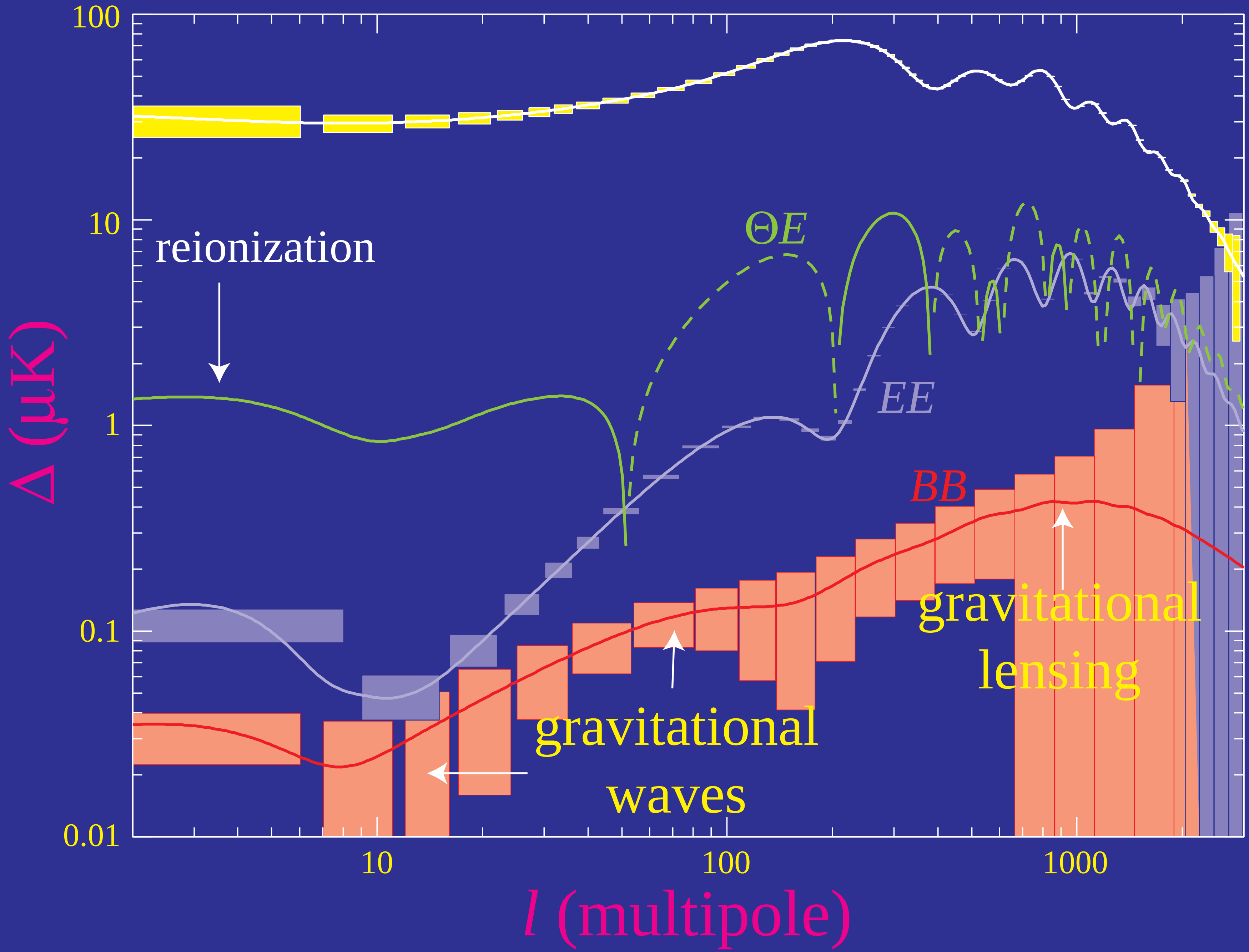


cosmological parameters marginalized

even with large lever arm other tests must match accuracy

Wang et al (1999); Kinney (2001); Miller et al (2002); Tegmark & Zaldarriaga (2002); Bridle et al (2003)

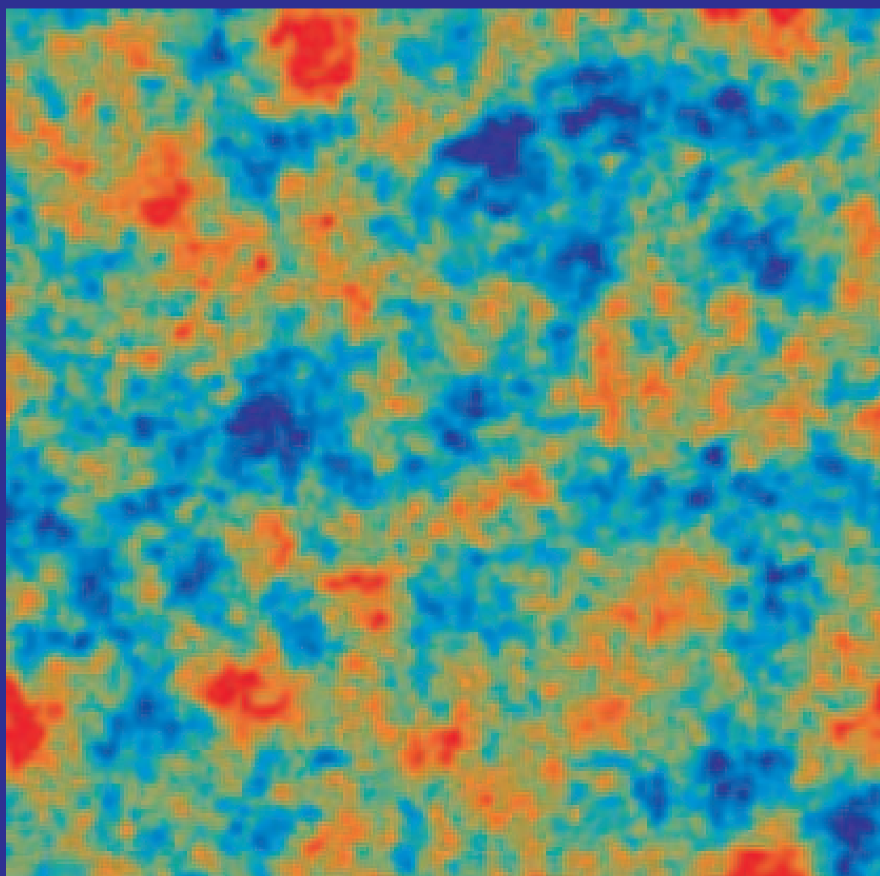
Temperature and Polarization Spectra



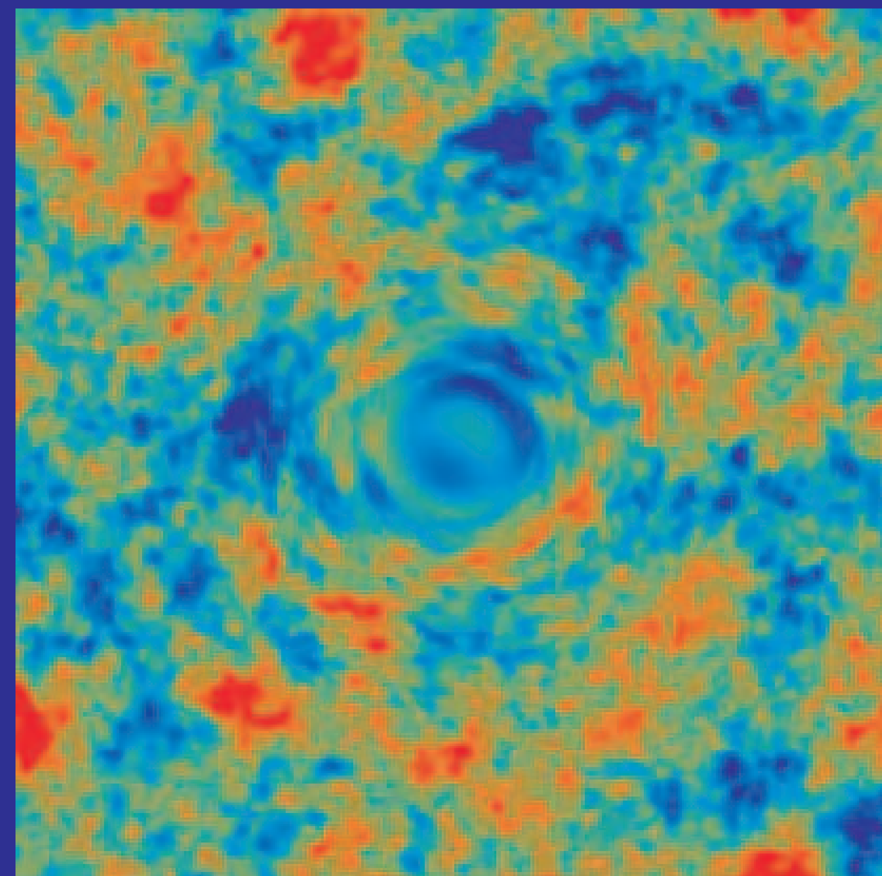
Gravitational Lensing

Gravitational Lensing

- Gravitational lensing by large scale structure distorts the observed temperature and polarization fields
- Exaggerated example for the temperature

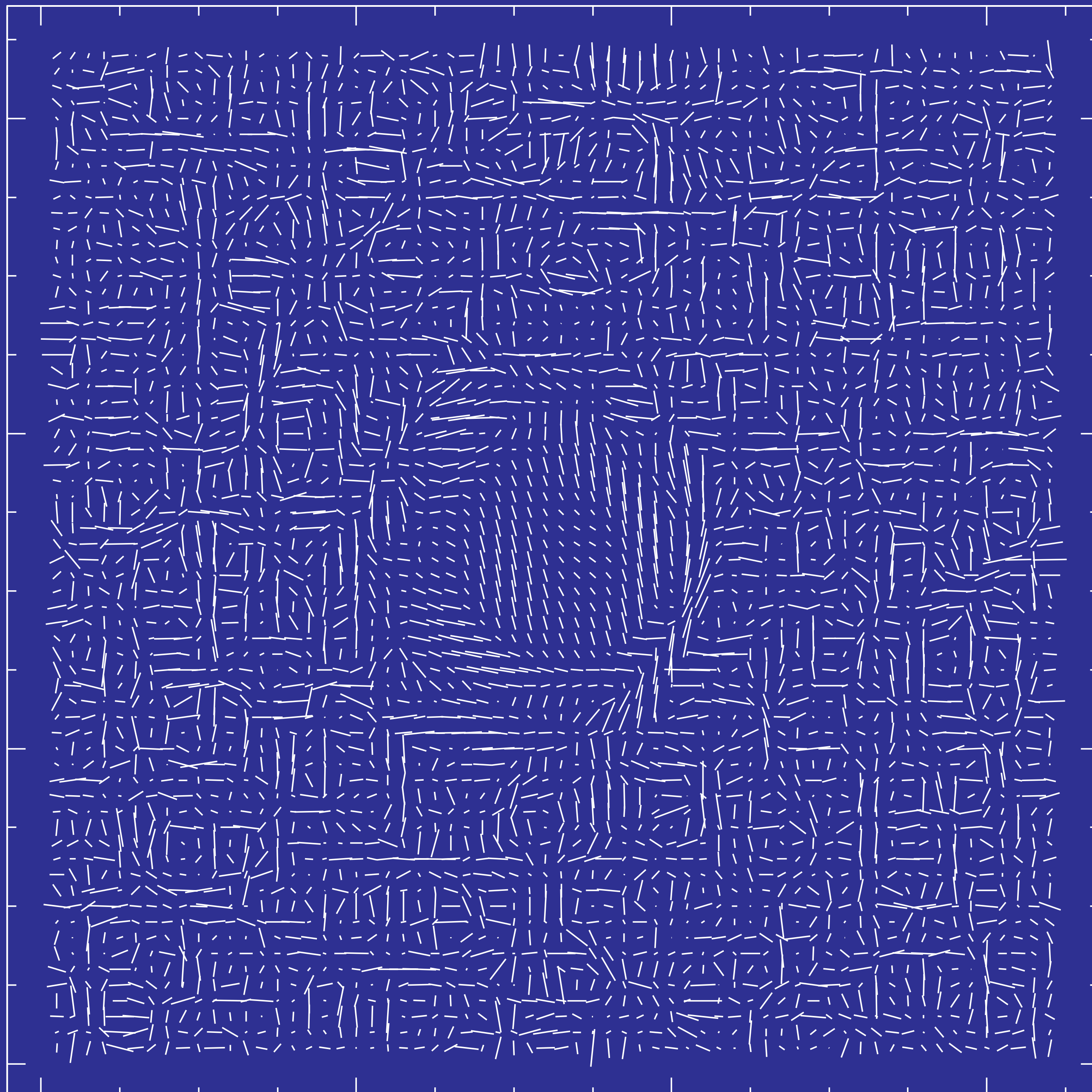


Original



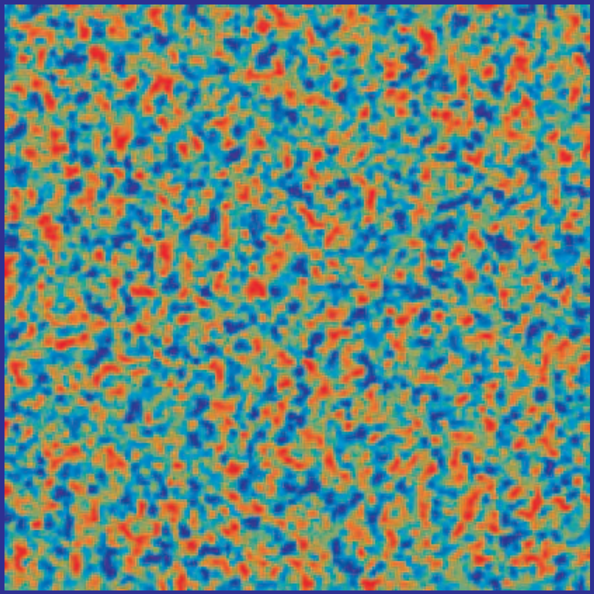
Lensed

Polarization Lensing

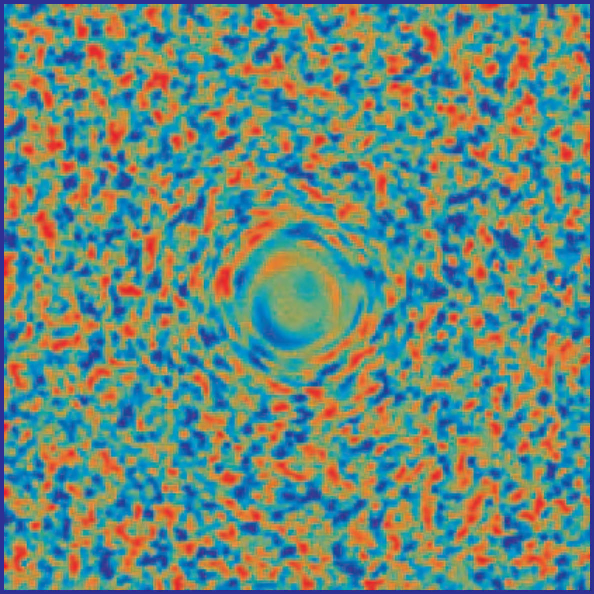


Polarization Lensing

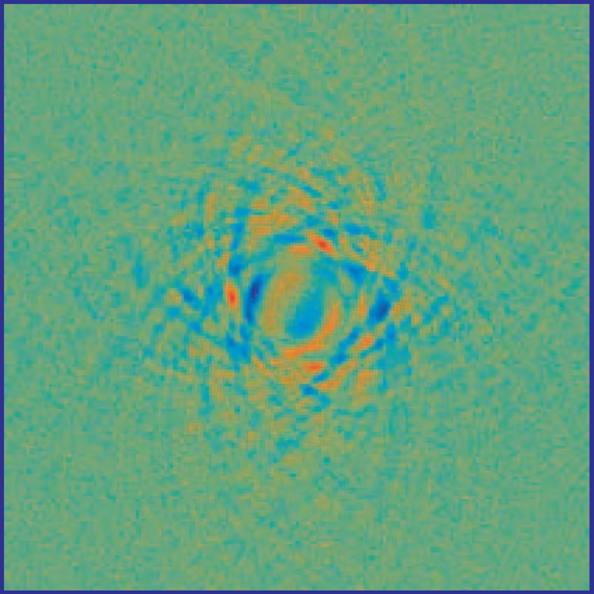
- Since E and B denote the relationship between the polarization amplitude and direction, warping due to lensing creates B-modes



Original



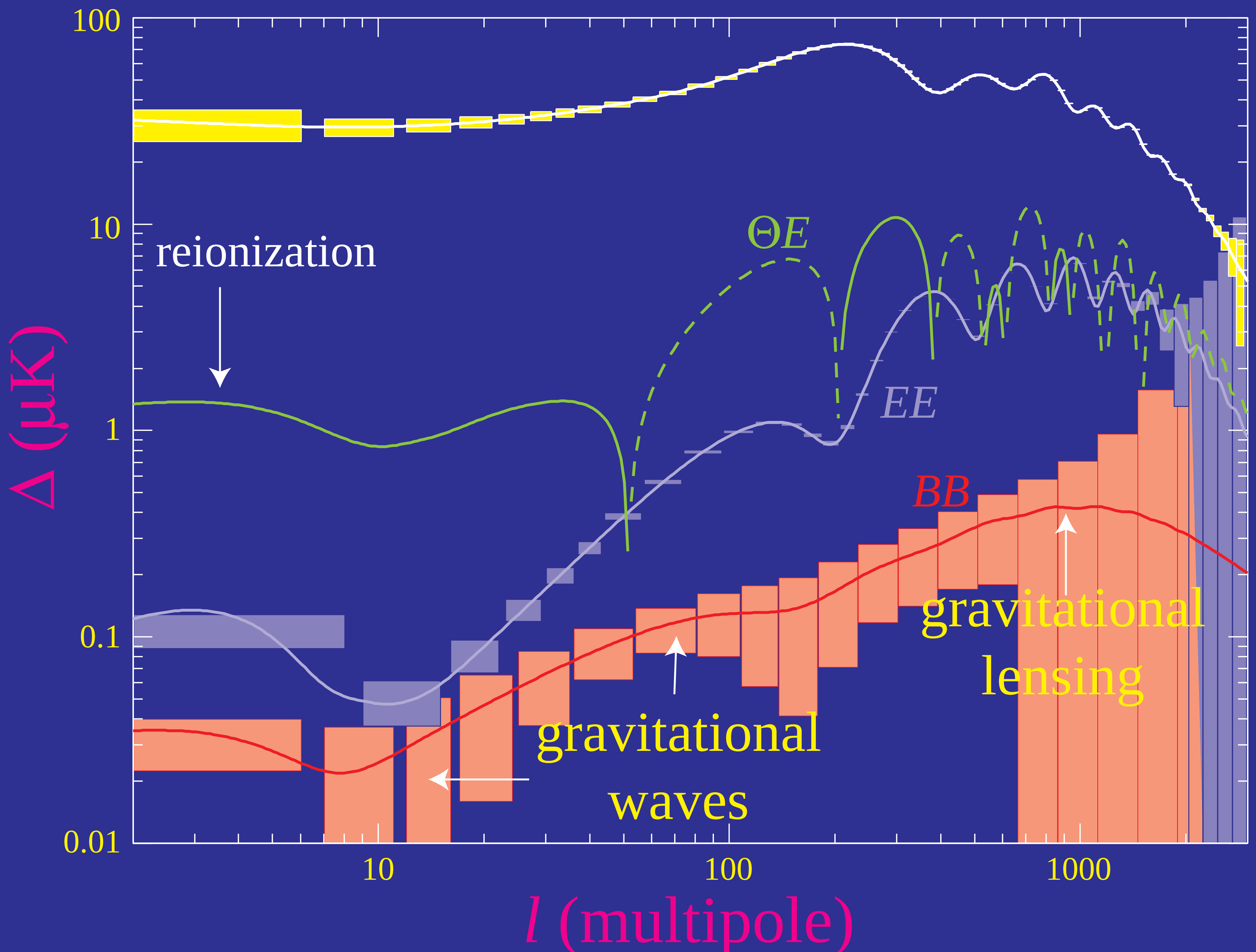
Lensed E



Lensed B

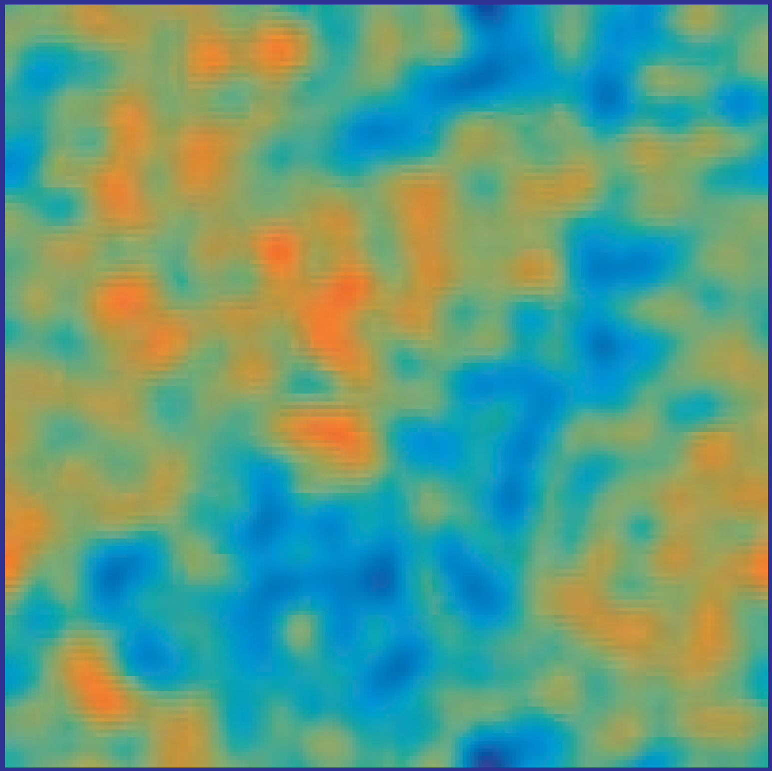
Zaldarriaga & Seljak (1998) [figure: Hu & Okamoto (2001)]

Temperature and Polarization Spectra



Lensing by a Gaussian Random Field

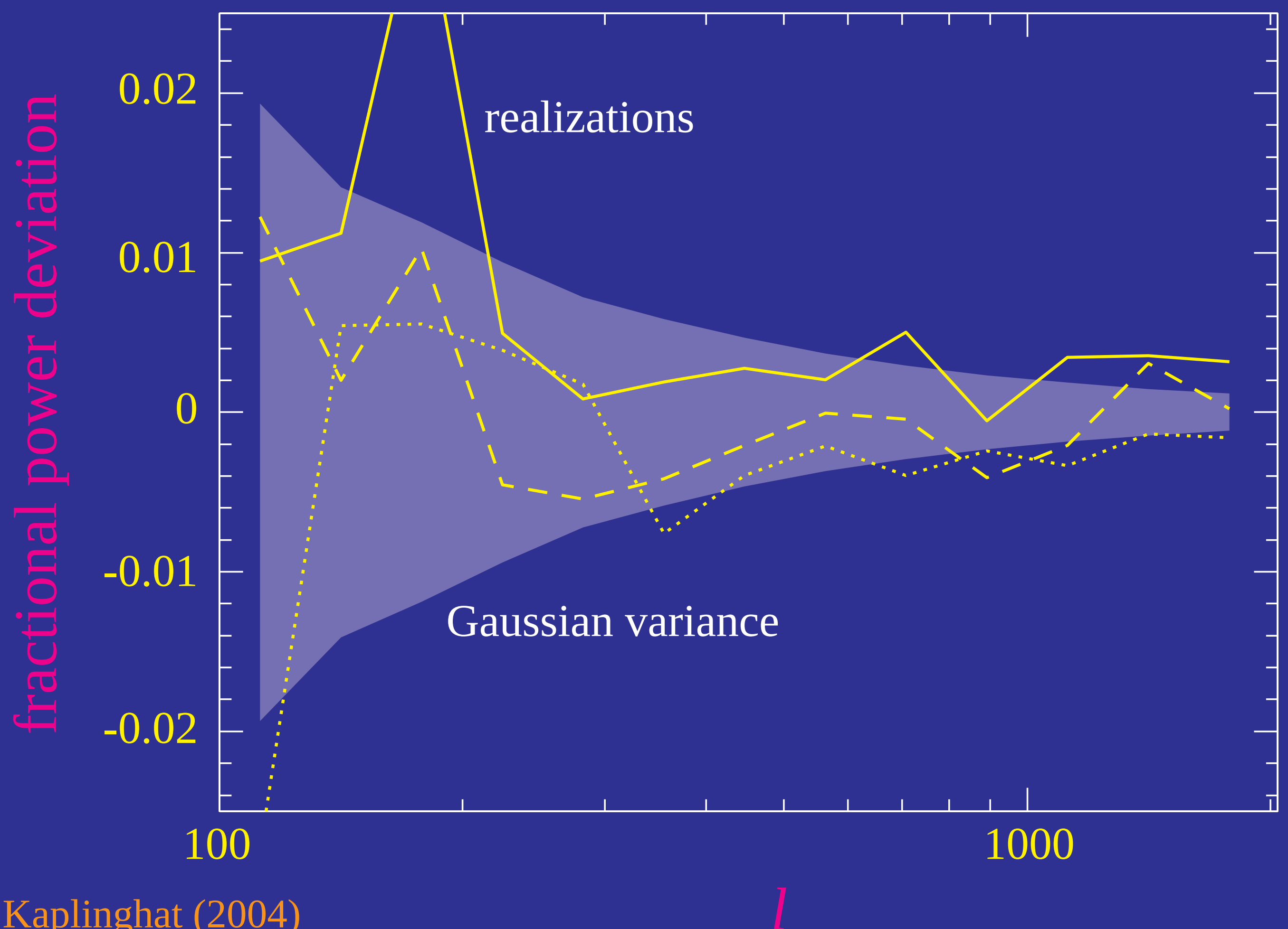
- Mass distribution at large angles and high redshift in in the linear regime
- Projected mass distribution (low pass filtered reflecting deflection angles): 1000 sq. deg



rms deflection
2.6'
deflection coherence
10°

Power Spectrum Measurements

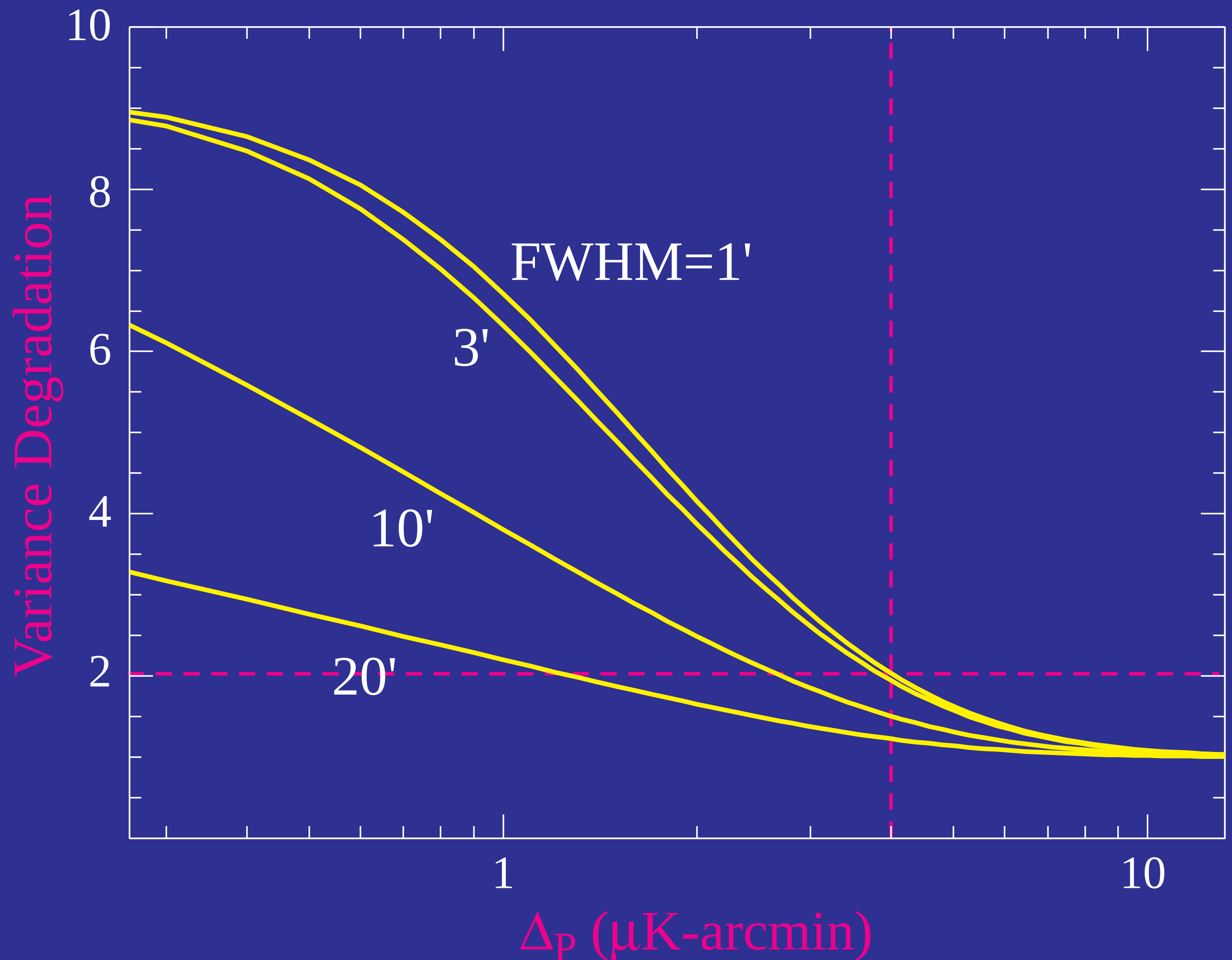
- Lensed field is non-Gaussian in that a single degree scale lens controls the polarization at arcminutes
- Increased variance and covariance implies that 10x as much sky needed compared with Gaussian fields



Smith, Hu & Kaplinghat (2004)

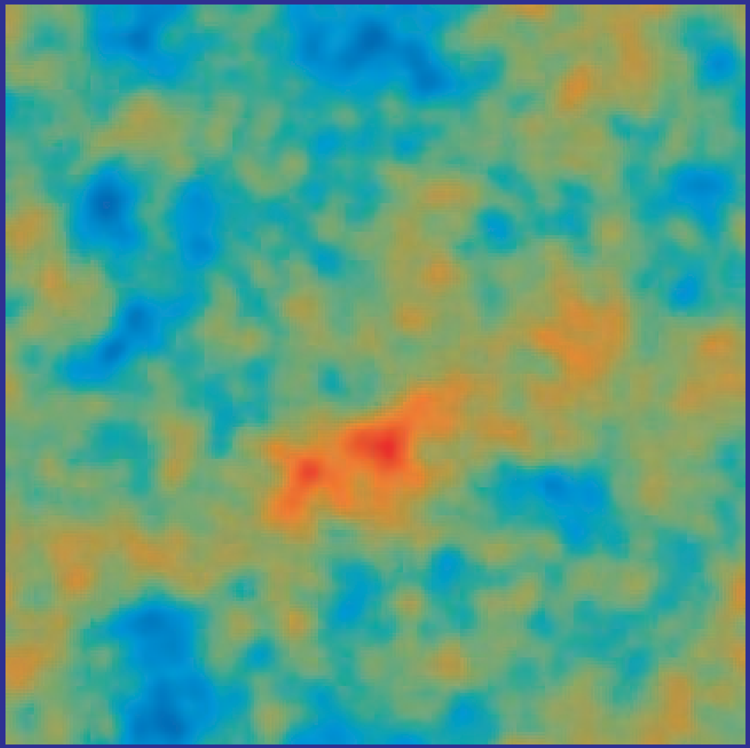
Sample vs Noise Variance

- Non-Gaussian sample variance doubles total variance at 4μK' for resolved B-modes

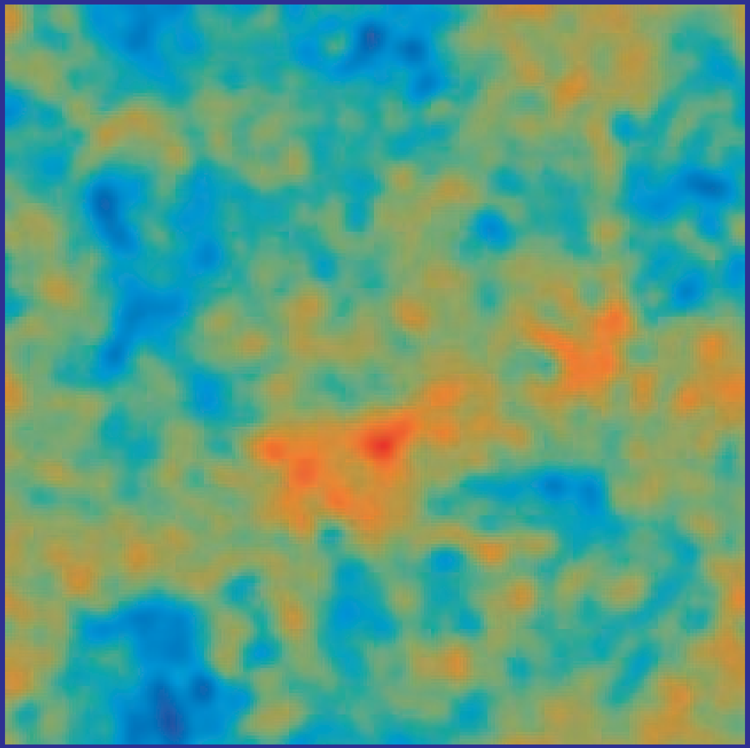


Reconstruction from Polarization

- Lensing B-modes correlated to the orignal E-modes in a specific way
- Correlation of E and B allows for a reconstruction of the lens
- Reference experiment of 4' beam, 1μK' noise and 100 deg^2



Original Mass Map

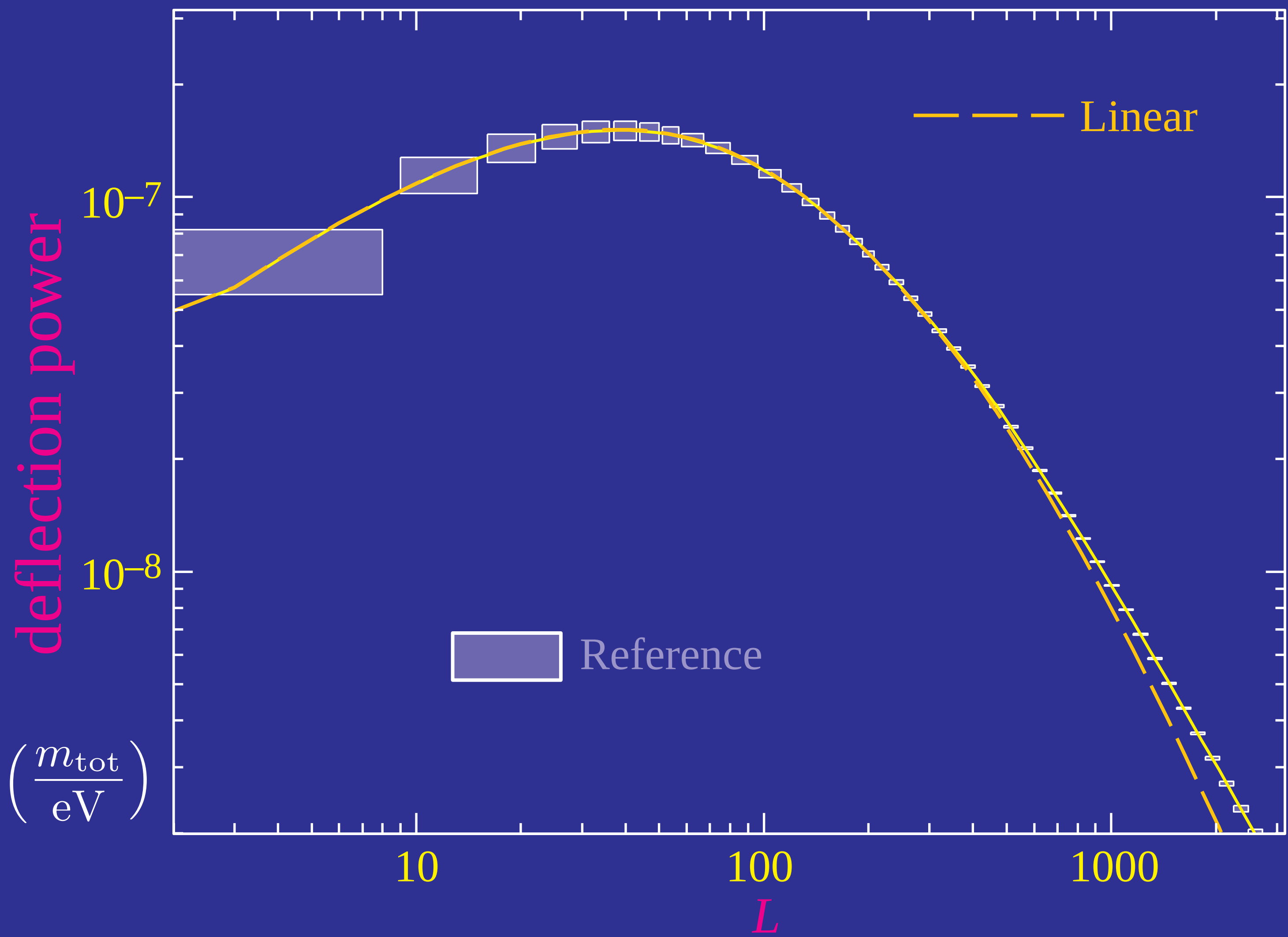


Reconstructed Mass Map

Hu & Okamoto (2001) [iterative improvement Hirata & Seljak (2003)]

Matter Power Spectrum

- Measuring projected matter power spectrum to cosmic variance limit across whole linear regime 0.002< k < 0.2 *h*/Mpc



$$\frac{\Delta P}{P} \approx -0.6 \left(\frac{m_{\rm tot}}{\rm eV}\right)$$

Hu & Okamoto (2001) [parameter forecasts: Kaplighat et al 2003]

$\sigma(w)$~0.06

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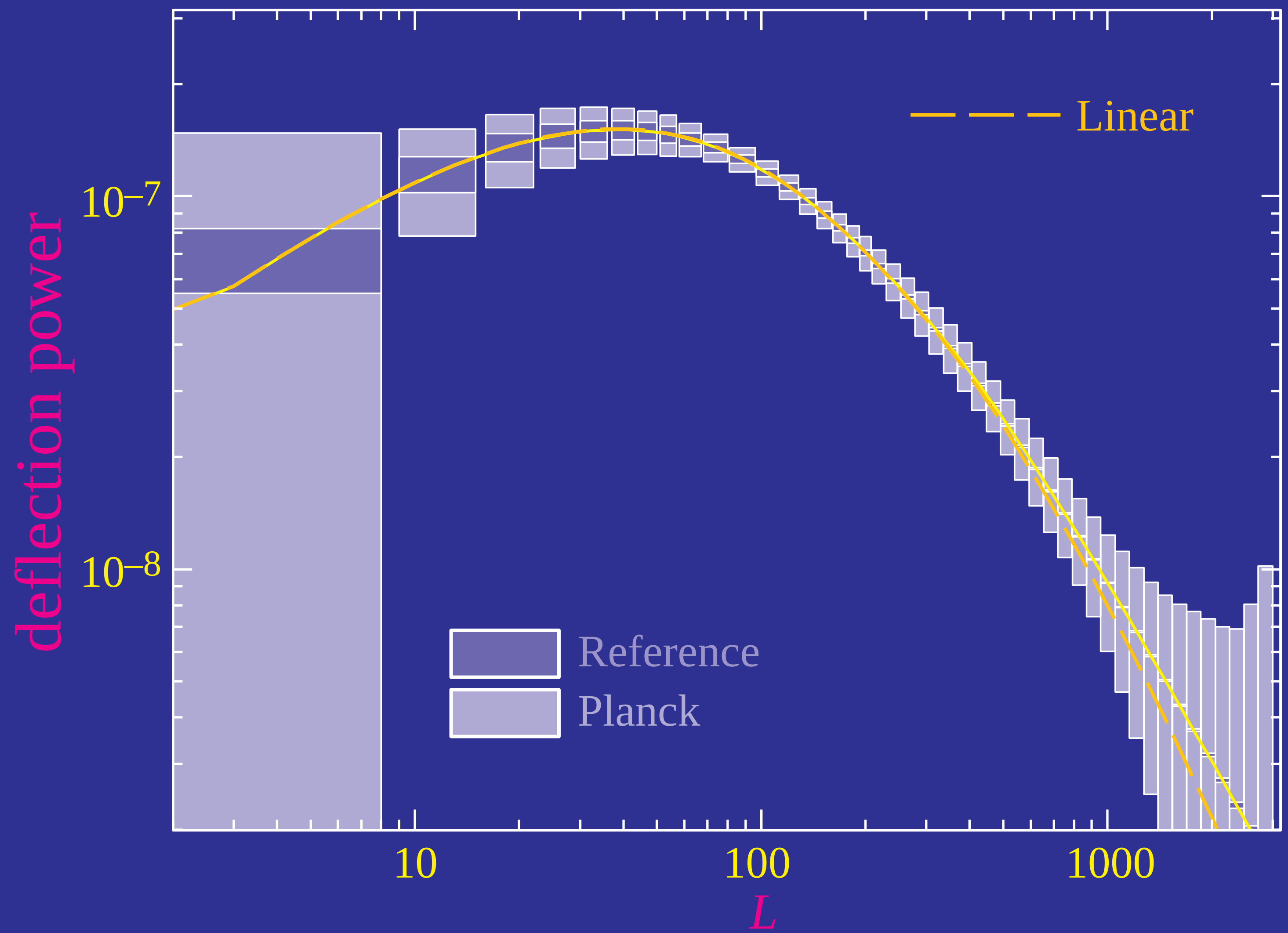

Hu & Okamoto (2001) [non-linear: see Amblard, Vale & White (2004)]

$\sigma(w)$~0.06; 0.14

Summary

- CMB polarization generated by scattering alone and hence provides probes that are well localized in time and space
- Early reionization provides a new window not only on the first generation of structure but also on gravitational waves, statistical anomalies on large scales, and calibration of fluctuations for dark energy studies
- Acoustic polarization can provide exceedingly precise measurements of the initial power spectrum and any features that might exist in the decade of the peaks
- Lensing of the acoustic polarization provides a means of reconstructing the mass distribution and hence constrain the neutrino mass and the dark energy