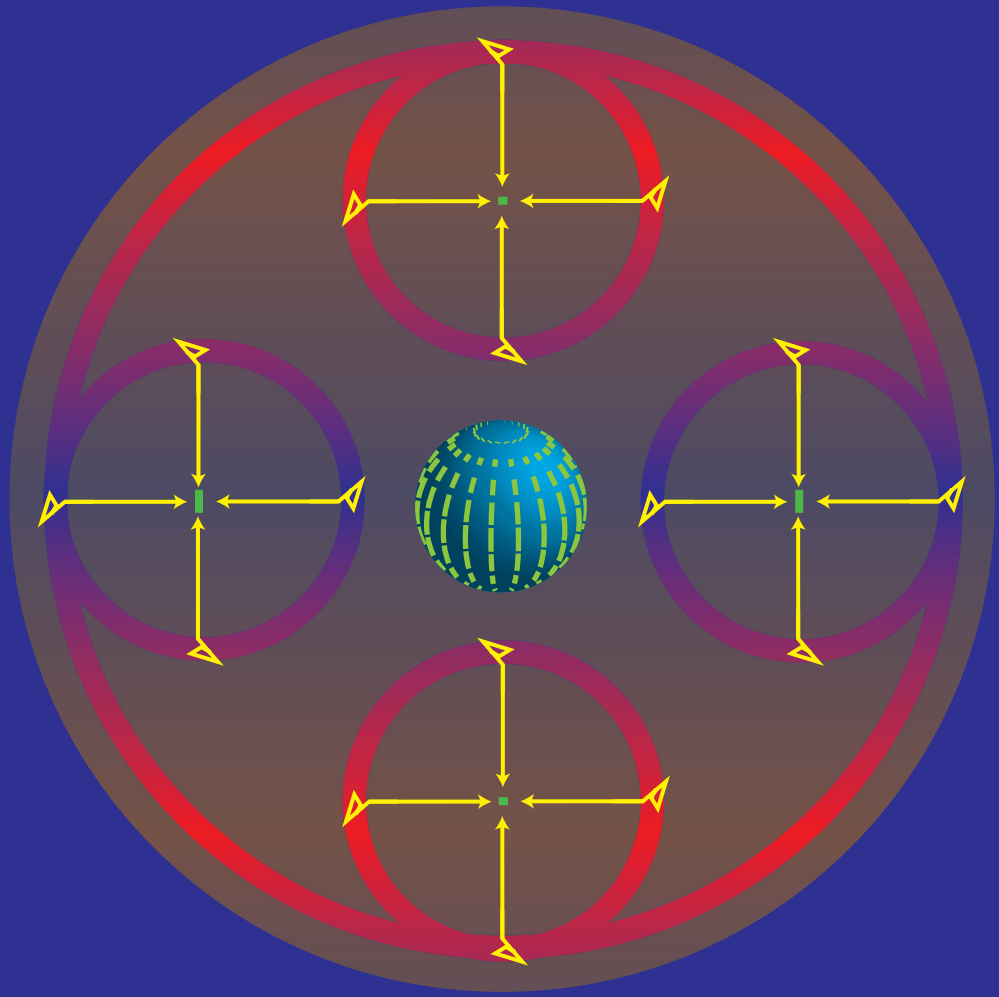
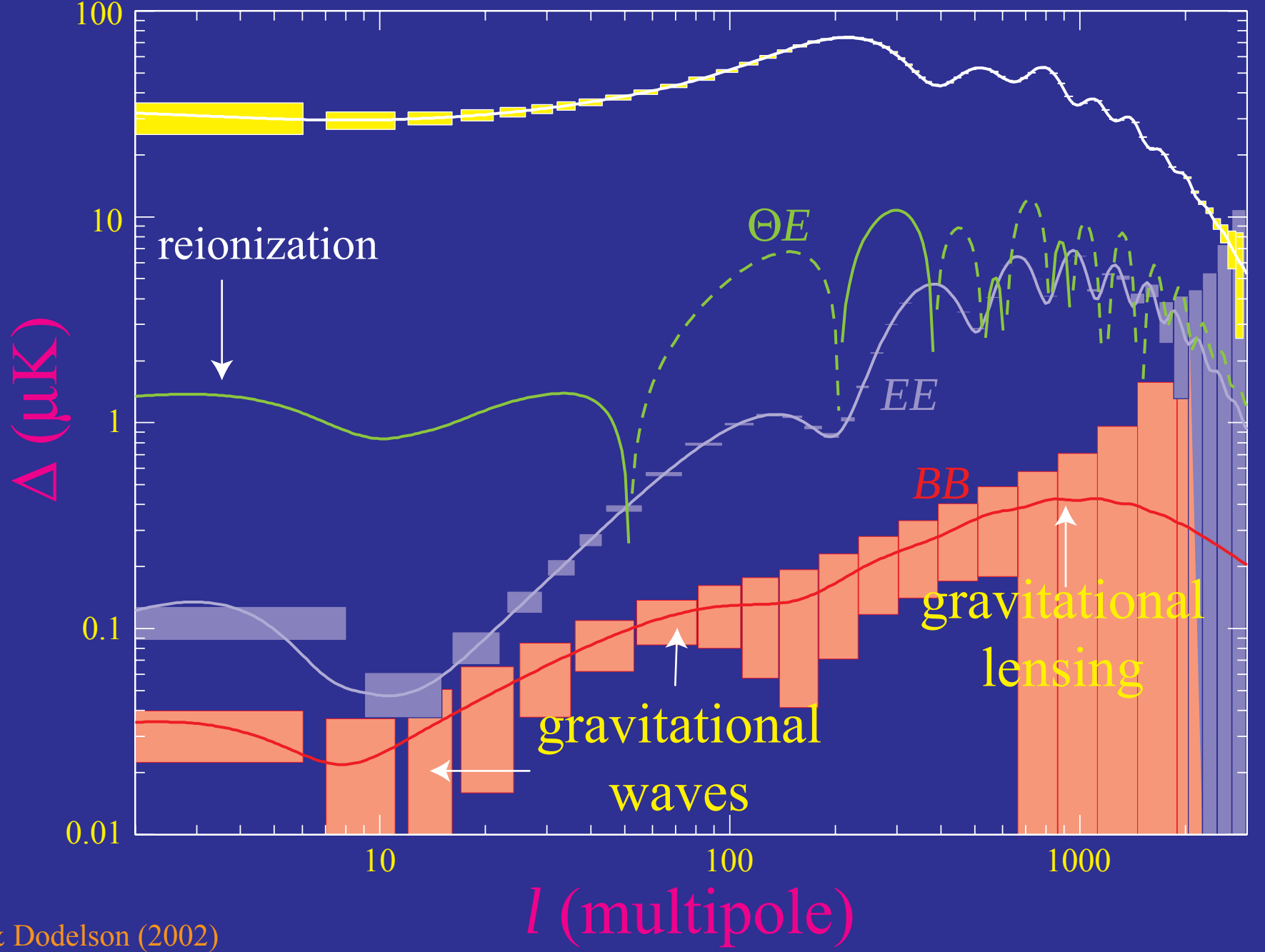
The Physics of CMB Polarization



Wayne Hu

Fermilab, November 2005

The Colloquial Landscape

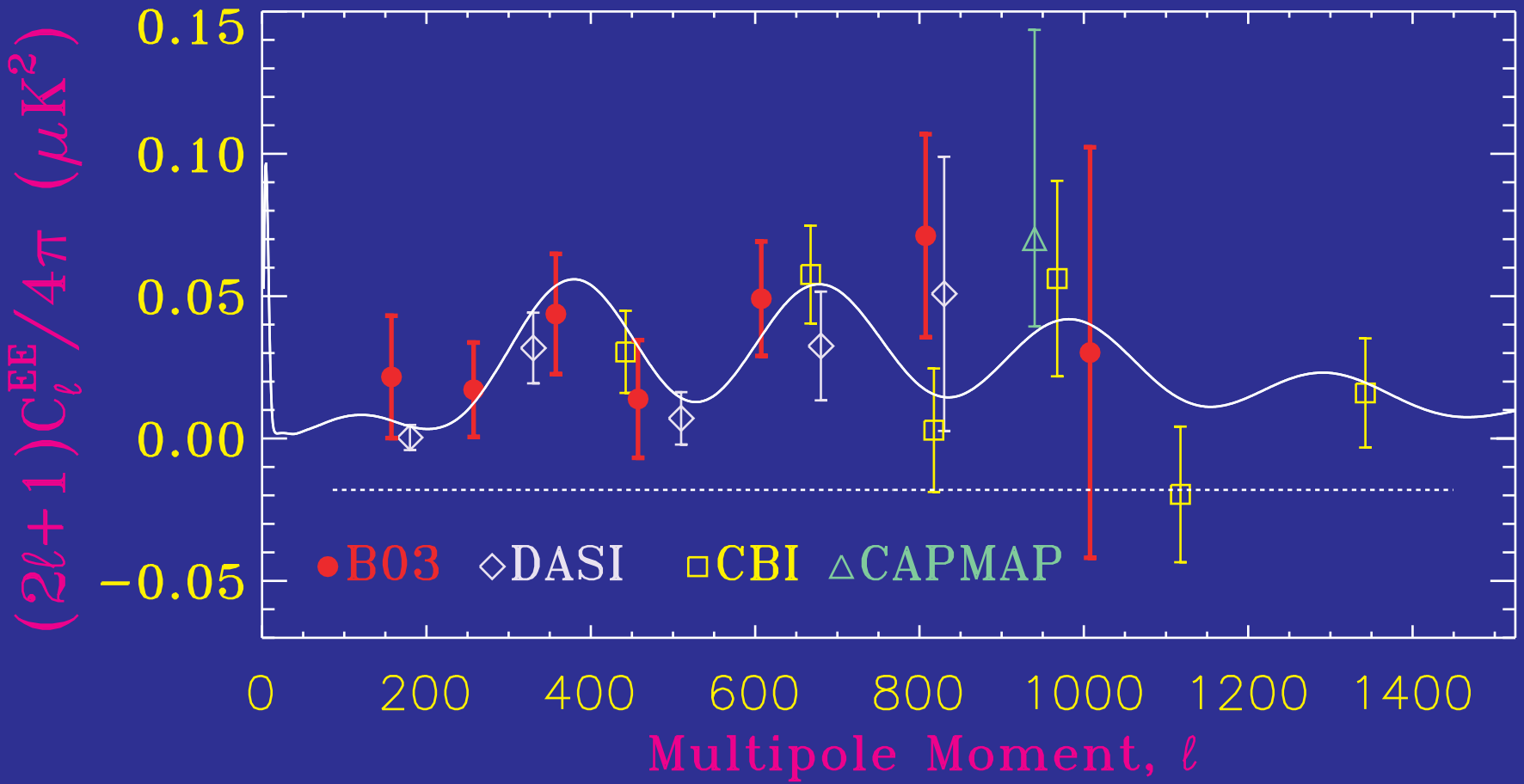


Hu & Dodelson (2002)

Current Status

- Polarization first detected by DASI (Kovac et al 2002)
- Temperature polarization cross correlation by WMAP (Kogut et al 2003)

Montroy et al 2005



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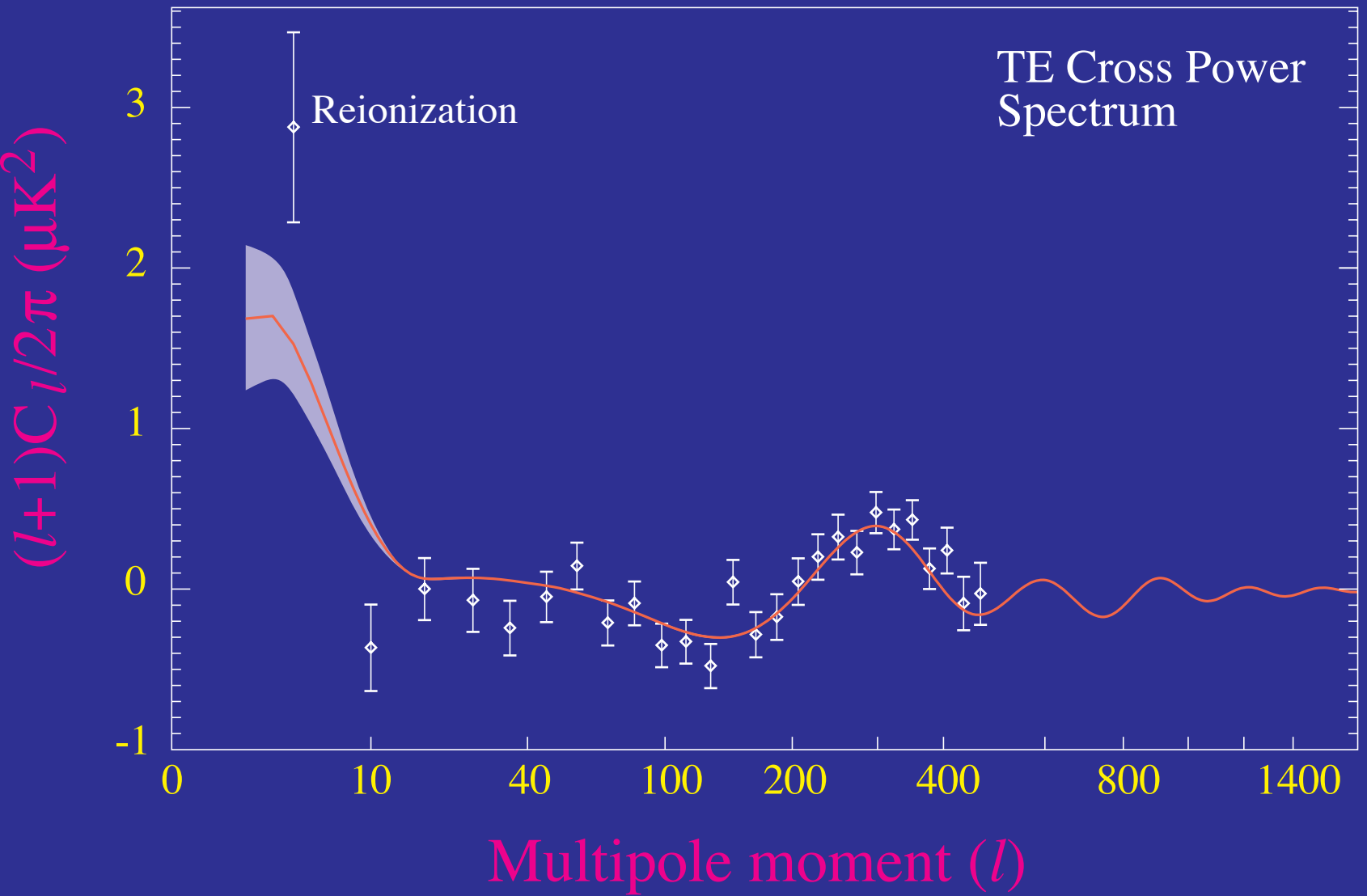
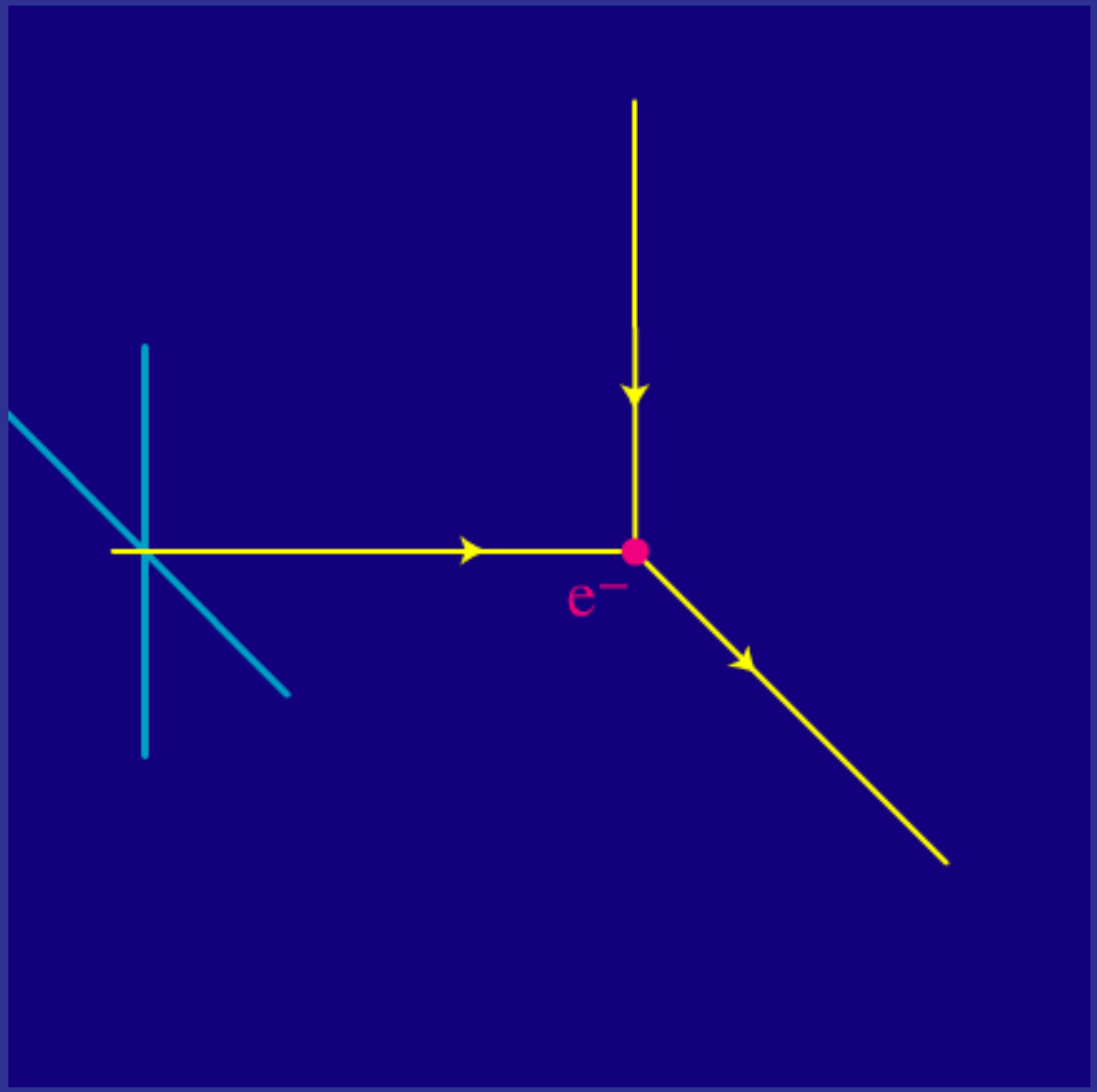


Why is the CMB polarized?

Polarization from Thomson Scattering

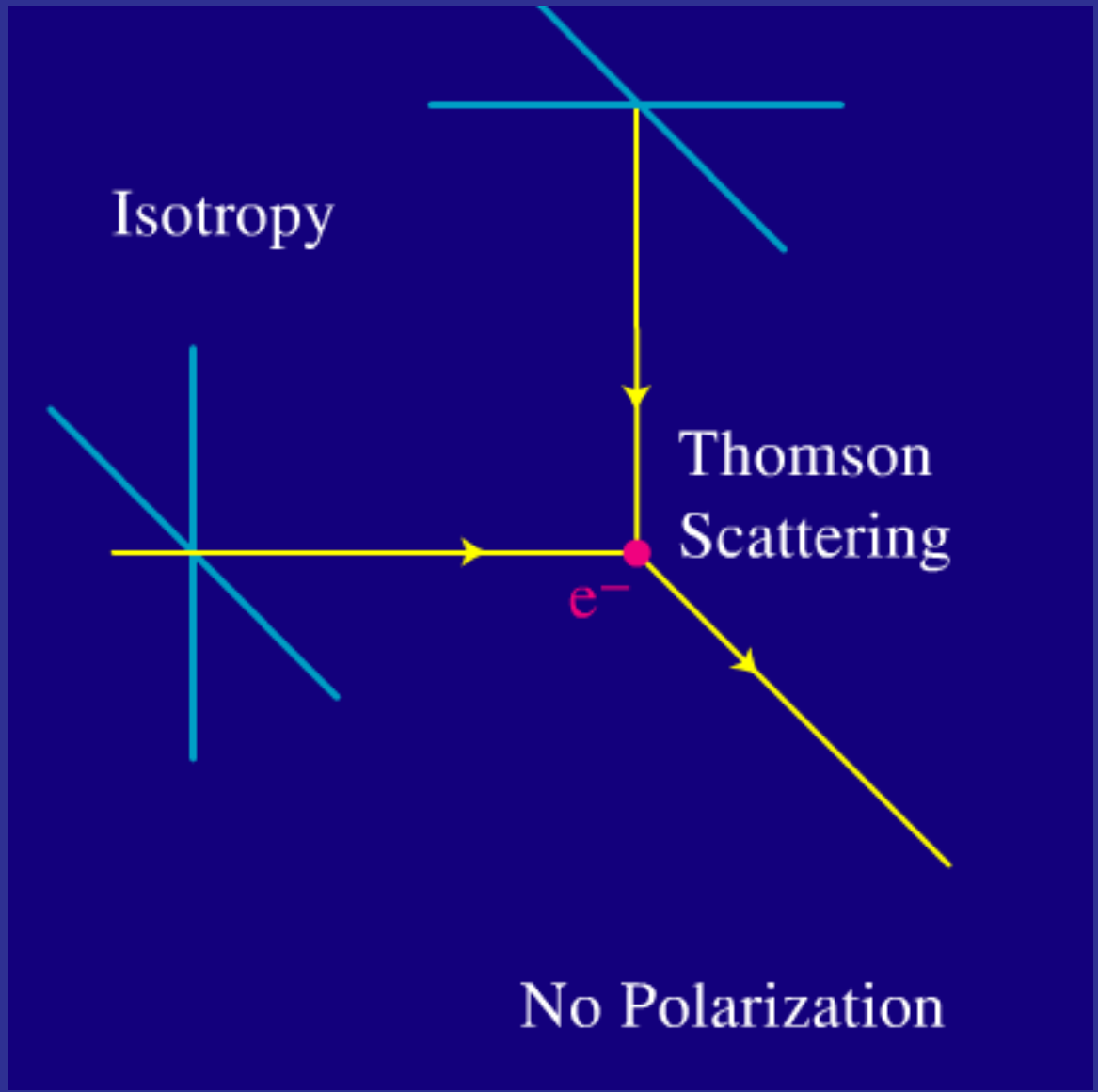
- Differential cross section depends on polarization and angle



$$\frac{d\sigma}{d\Omega} = \frac{3}{8\pi}|\hat{\varepsilon}' \cdot \hat{\varepsilon}|^2 \sigma_T$$

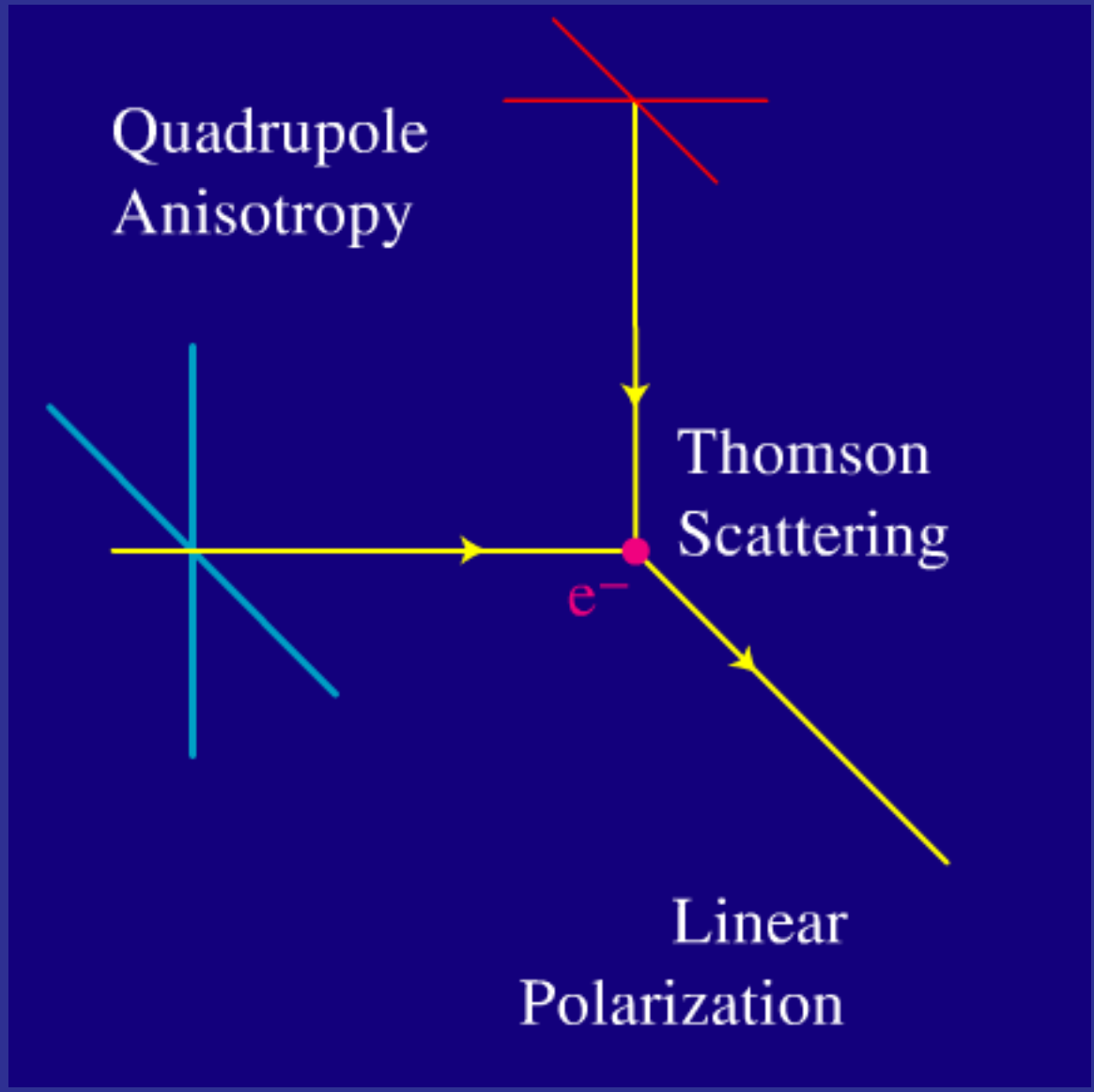
Polarization from Thomson Scattering

- Isotropic radiation scatters into unpolarized radiation



Polarization from Thomson Scattering

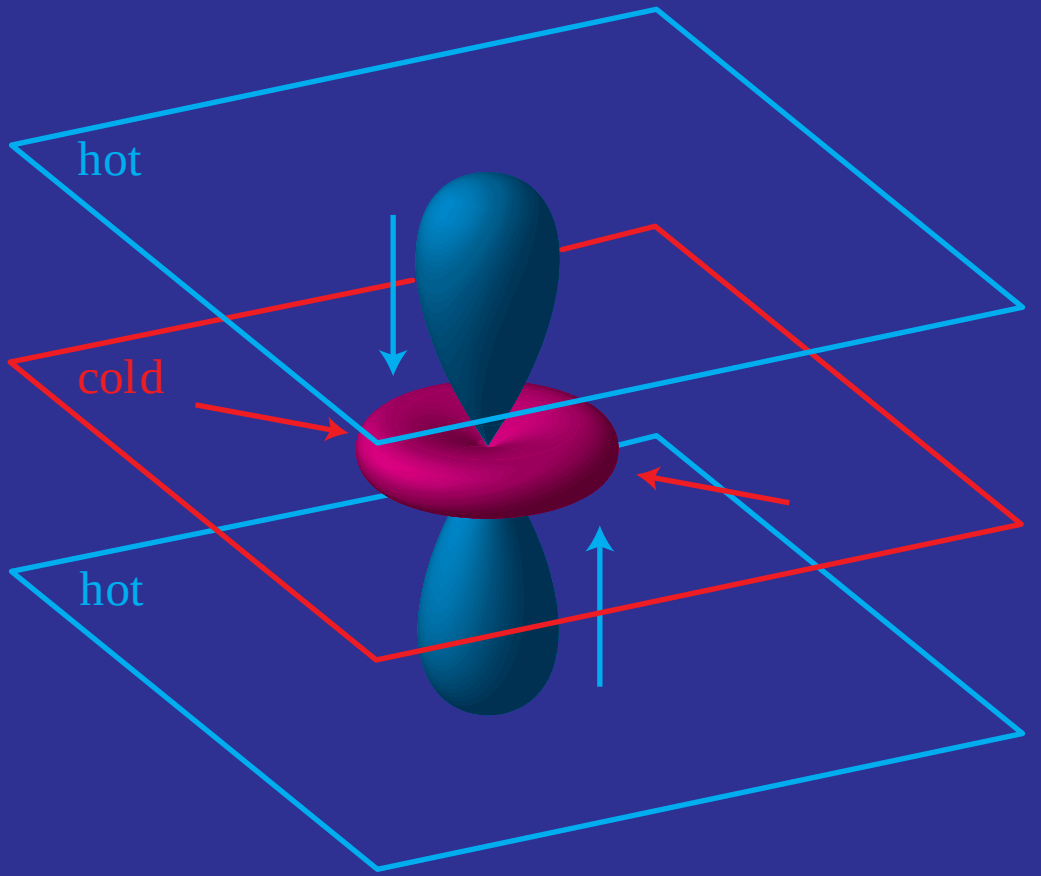
- Quadrupole anisotropies scatter into linear polarization



aligned with
cold lobe

Whence Quadrupoles?

- Temperature inhomogeneities in a medium
- Photons arrive from different regions producing an anisotropy

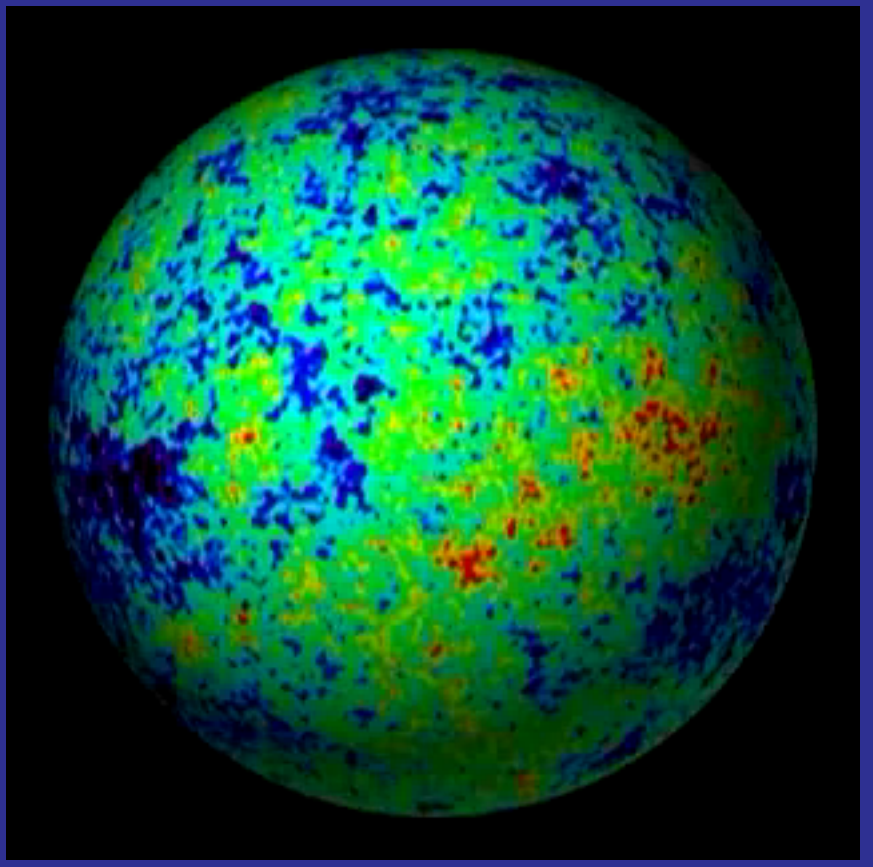


(Scalar) Temperature Inhomogeneity

Hu & White (1997)

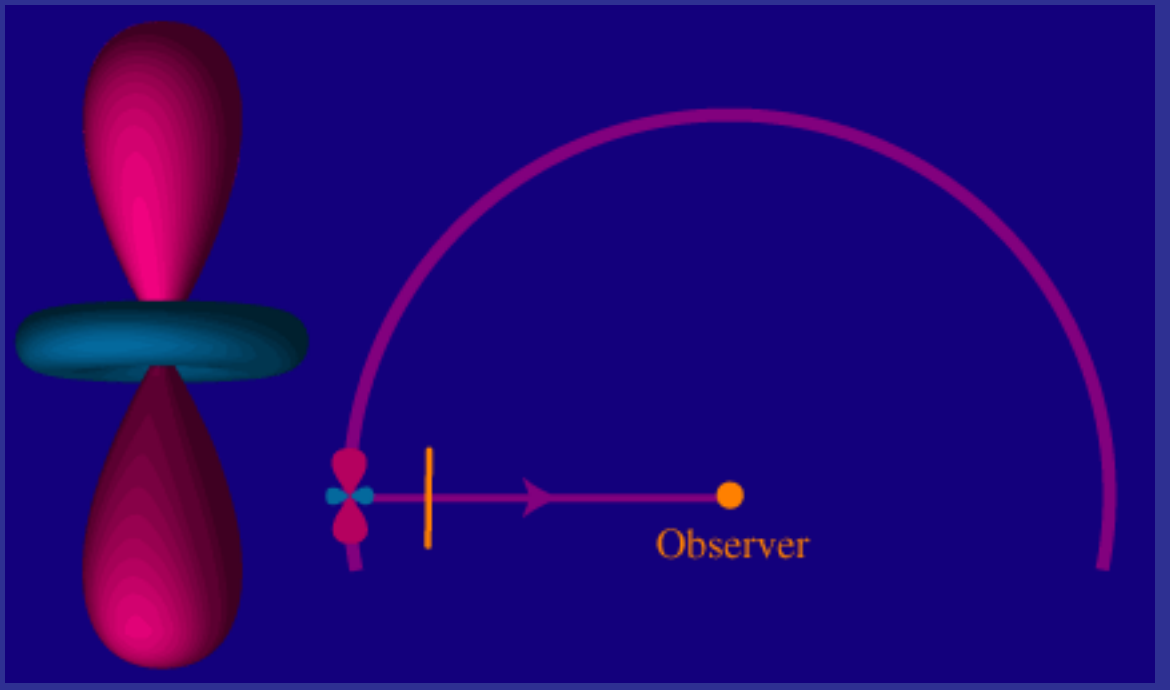
CMB Anisotropy

- WMAP map of the CMB temperature anisotropy



Whence Polarization Anisotropy?

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



Polarization Multipoles

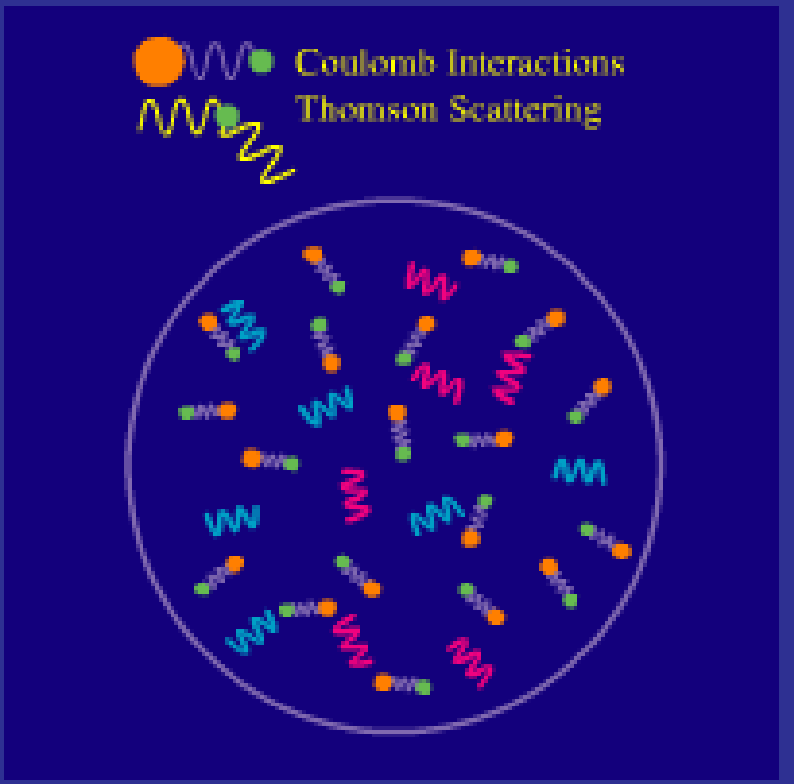
- Mathematically pattern is described by the tensor (spin-2) spherical harmonics [eigenfunctions of Laplacian on trace-free 2 tensor]
- Correspondence with scalar spherical harmonics established via Clebsch-Gordan coefficients (spin x orbital)
- Amplitude of the coefficients in the spherical harmonic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

E-tensor harmonic

$l=2,\ m=0$

A Catch-22

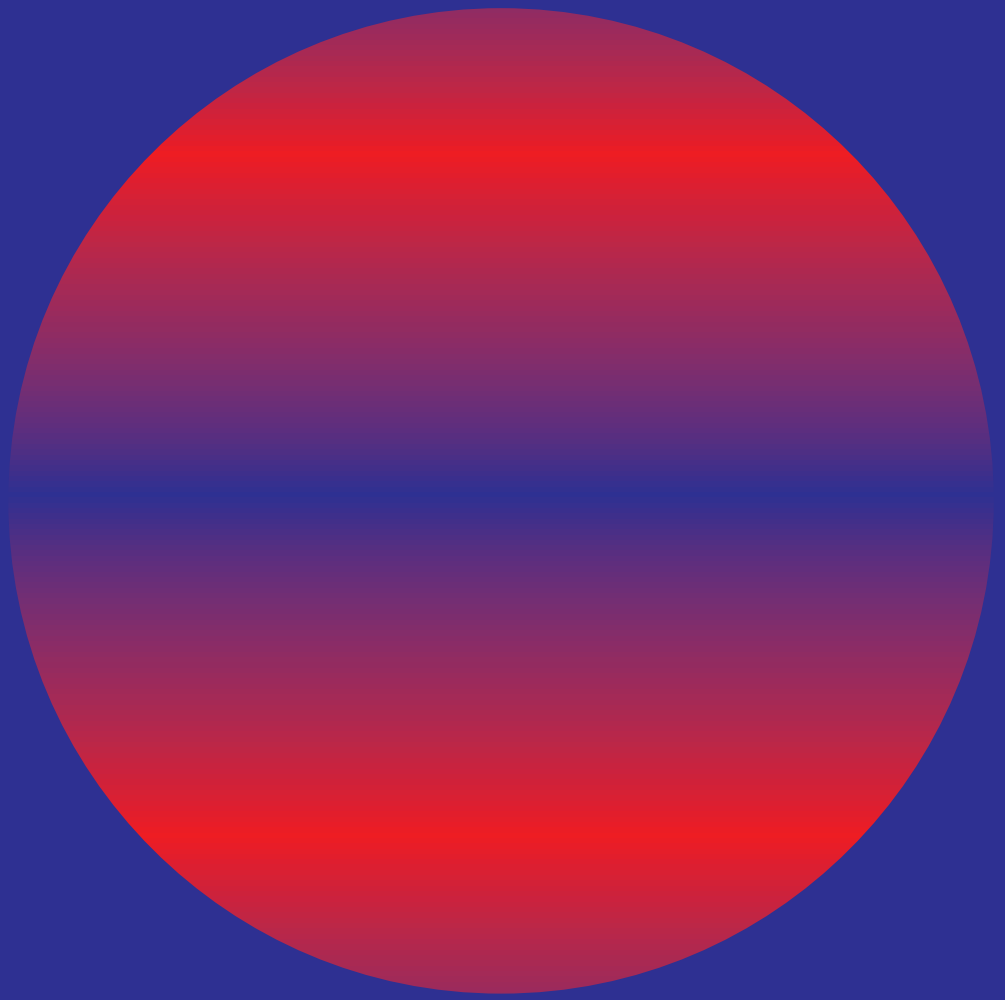
- Polarization is generated by scattering of anisotropic radiation
- Scattering isotropizes radiation
- Polarization only arises in optically thin conditions: reionization and end of recombination
- Polarization fraction is at best a small fraction of the 10^{-5} anisotropy: $\sim 10^{-6}$ or μK in amplitude



Reionization

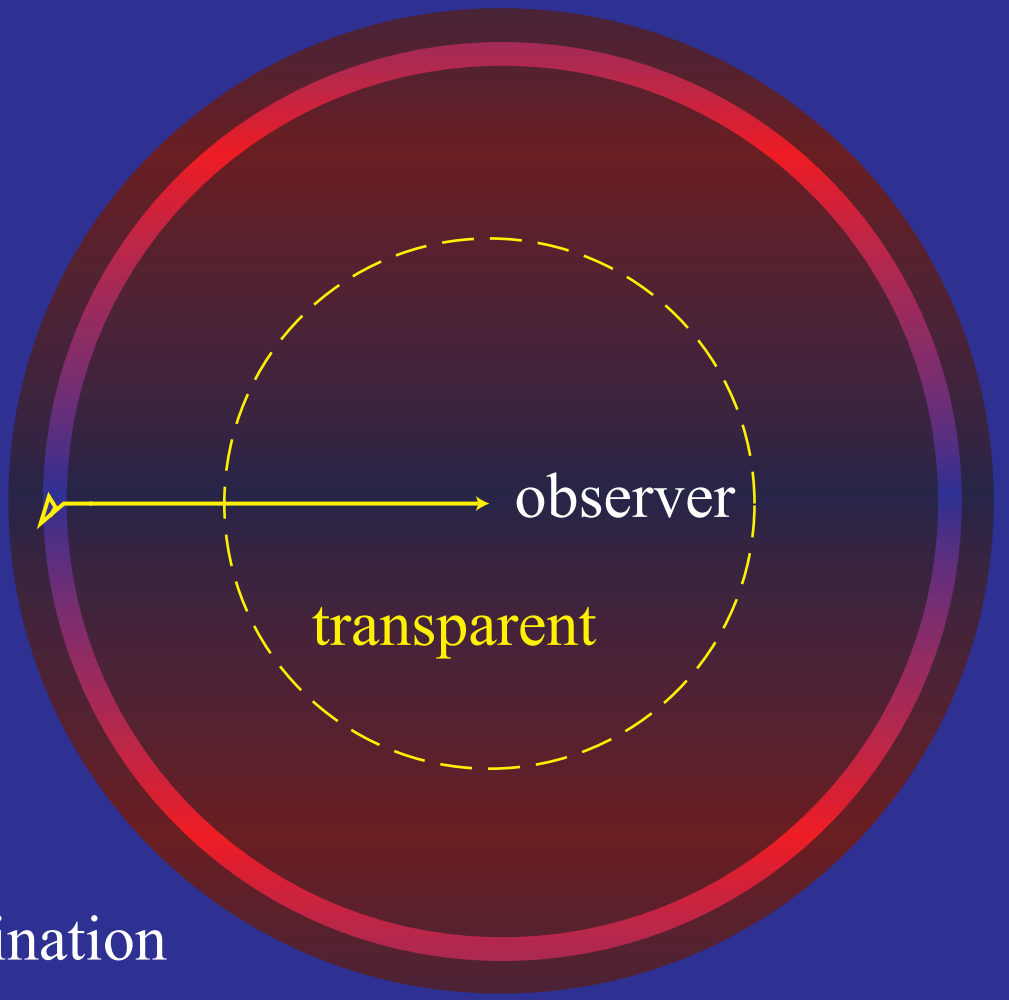
Temperature Inhomogeneity

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



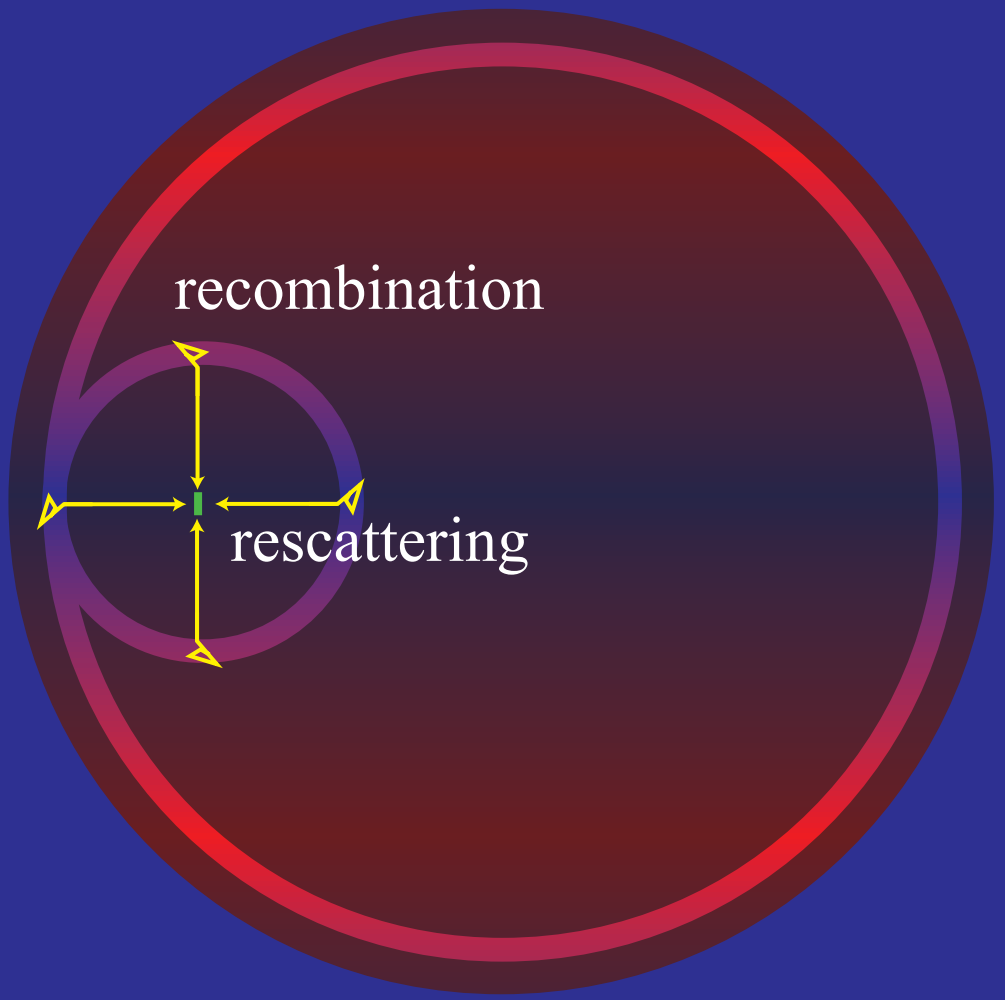
Locally Transparent

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



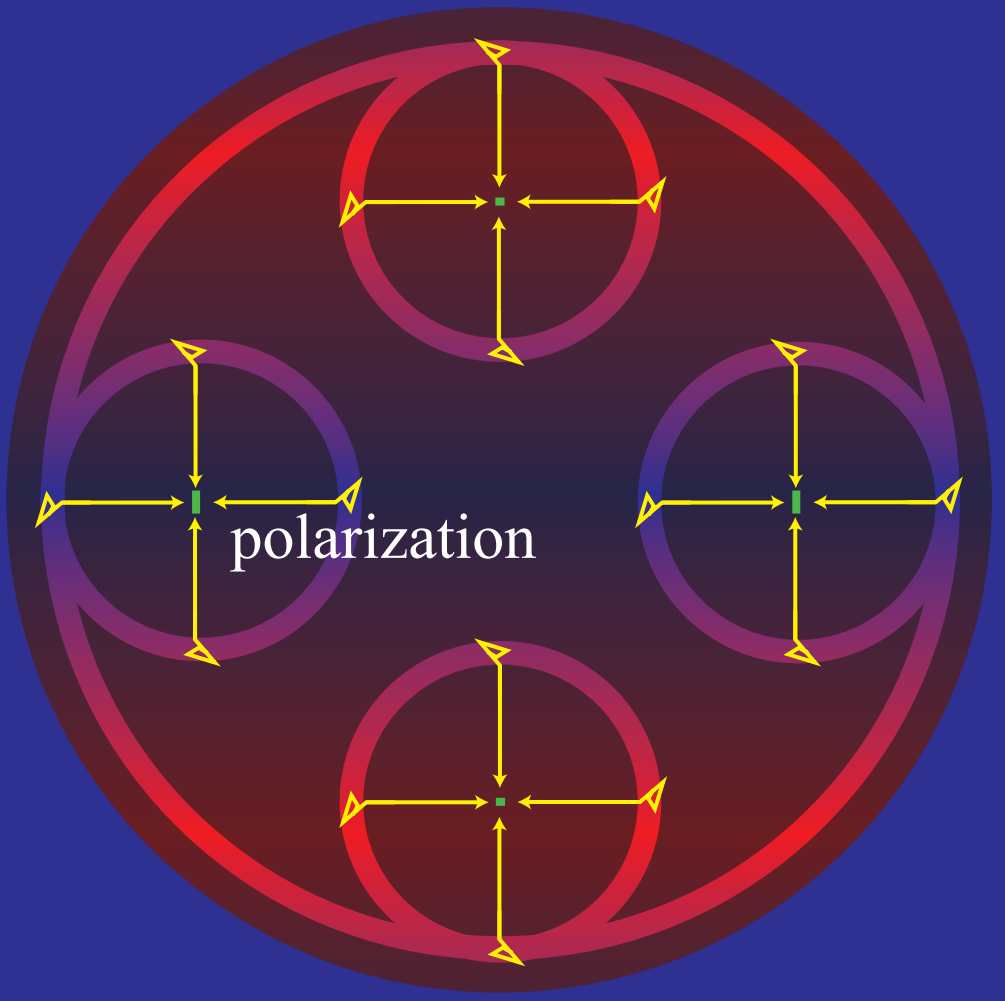
Reversed Expansion

- 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



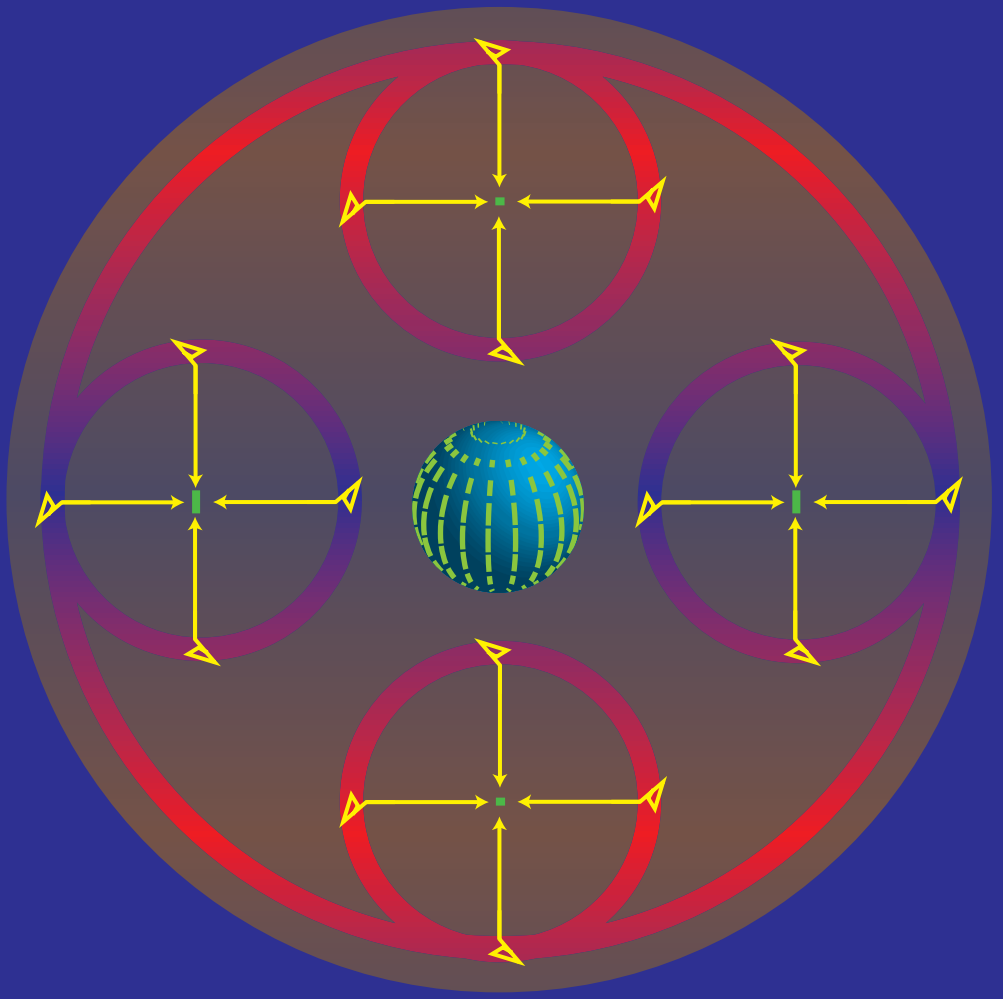
Polarization Anisotropy

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



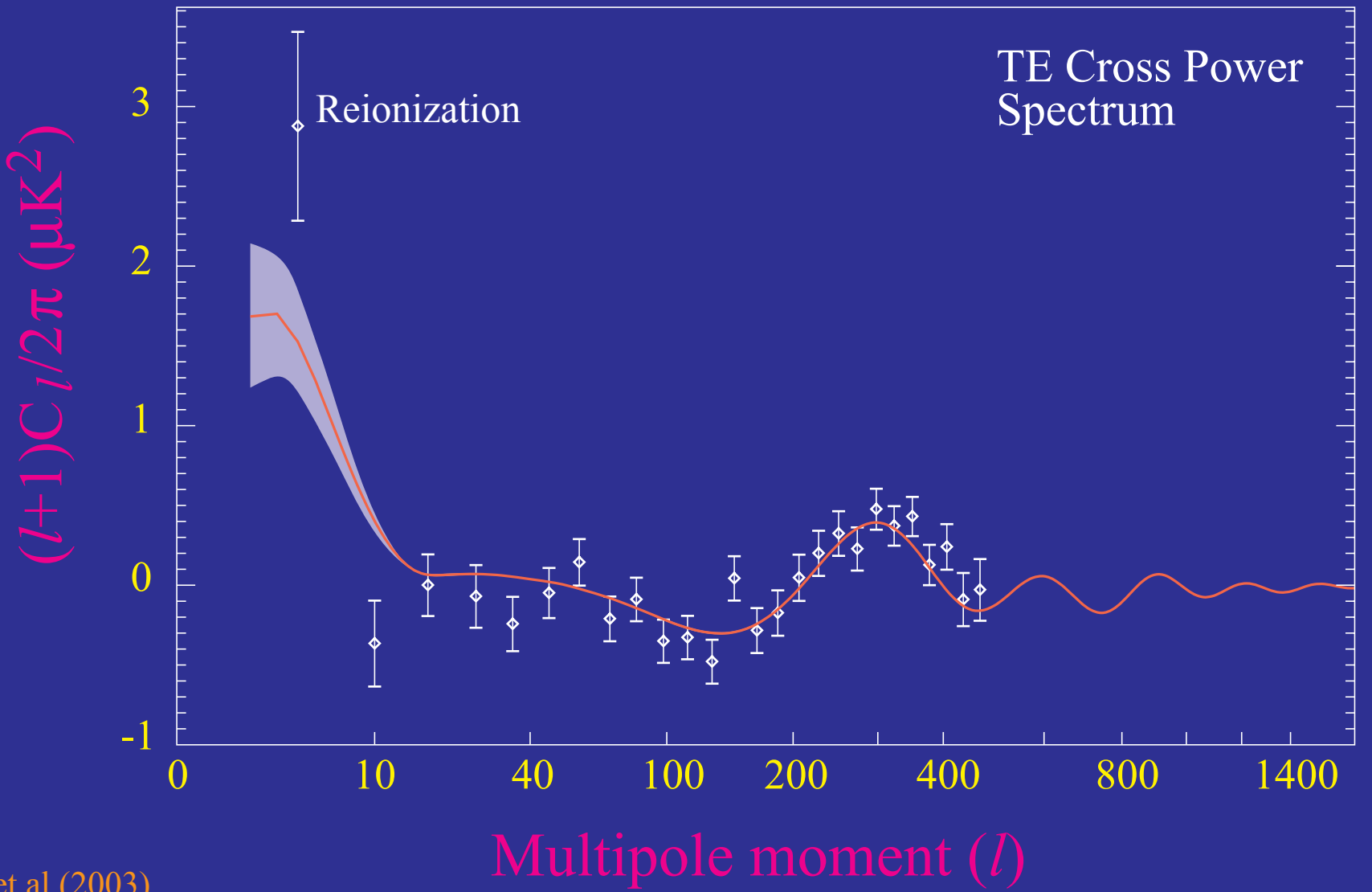
Temperature Correlation

- 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)



Hinshaw et al (2003)

Why Care?

- Early ionization is puzzling if due to ionizing radiation from normal stars; may indicate more exotic physics is involved

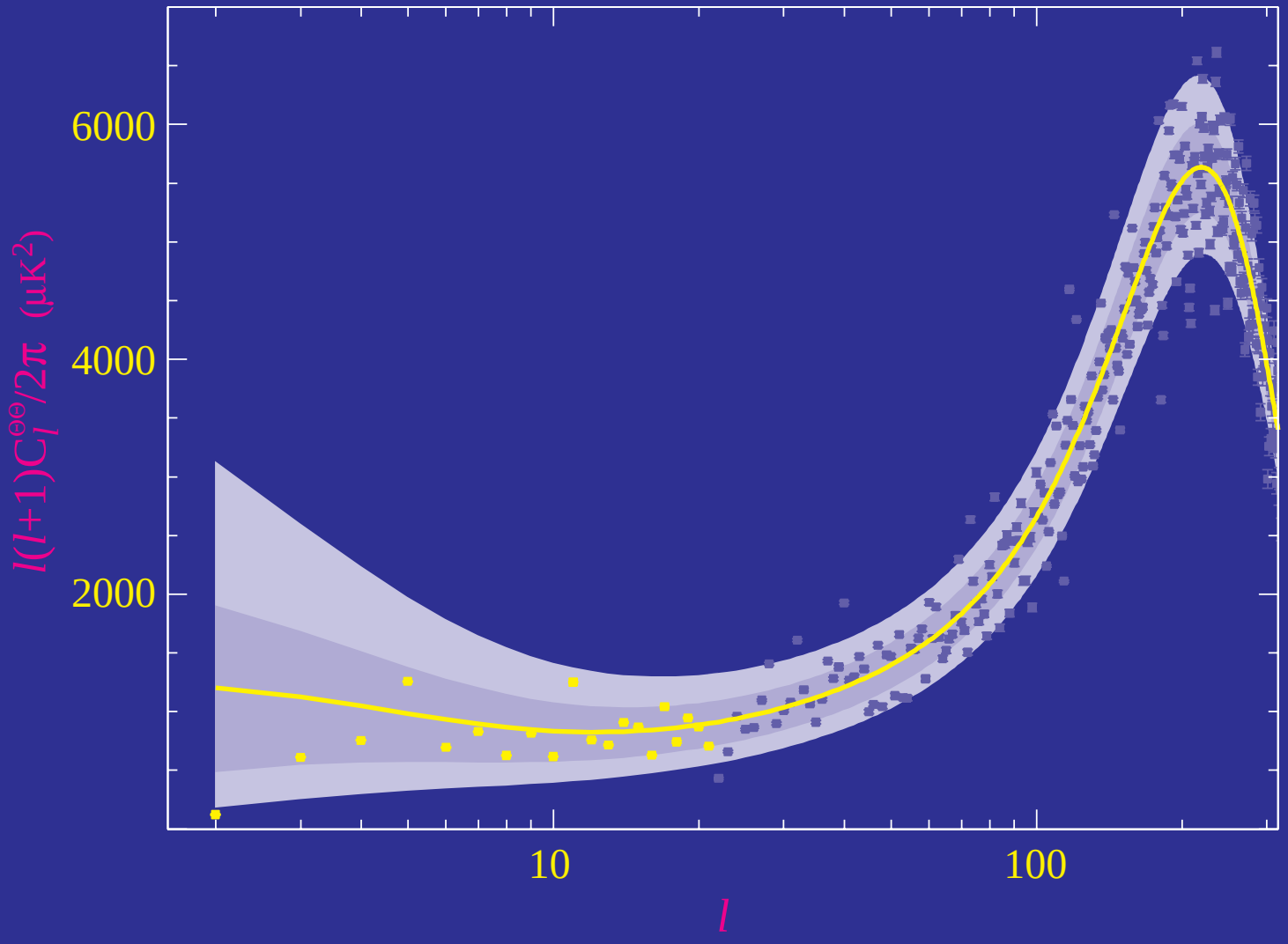
- Reionization screens temperature anisotropy on small scales making the true amplitude of initial fluctuations larger by e^{τ}
- Measuring the growth of fluctuations is one of the best ways of determining the neutrino masses and the dark energy

- 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

Low Multipole Anomalies

Low Quadrupole

- Known since COBE: a ~2σ problem

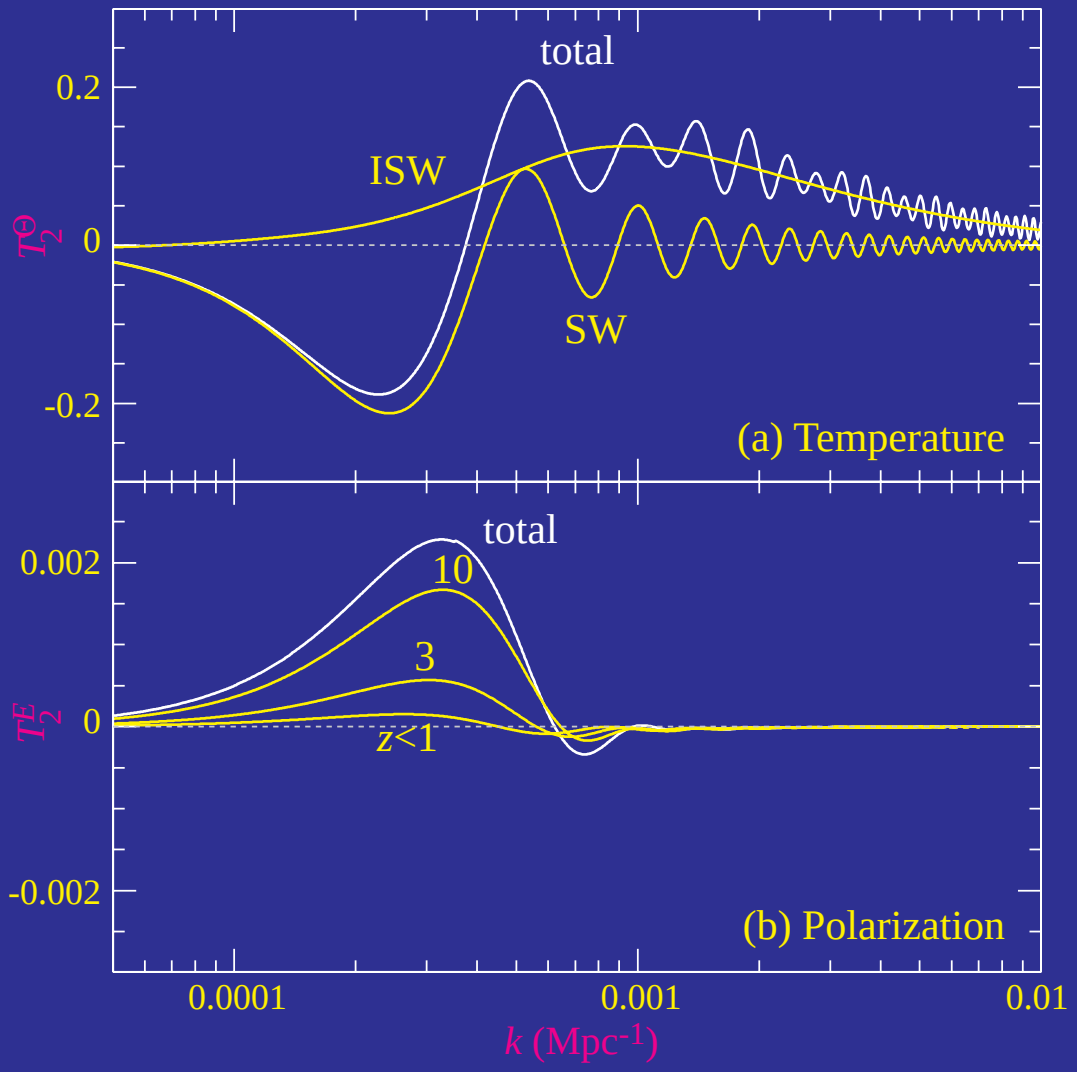


ISW Spatial Modes

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

Quadrupole Origins

- Transfer function for the quadrupole

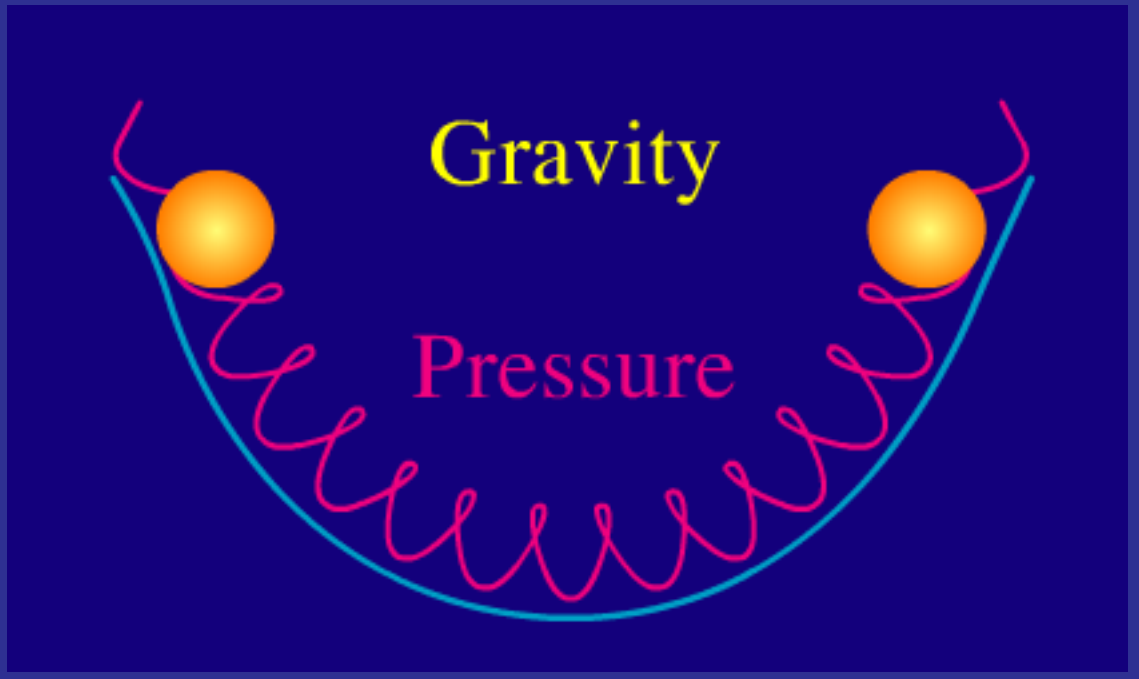


Gordon & Hu (2004)

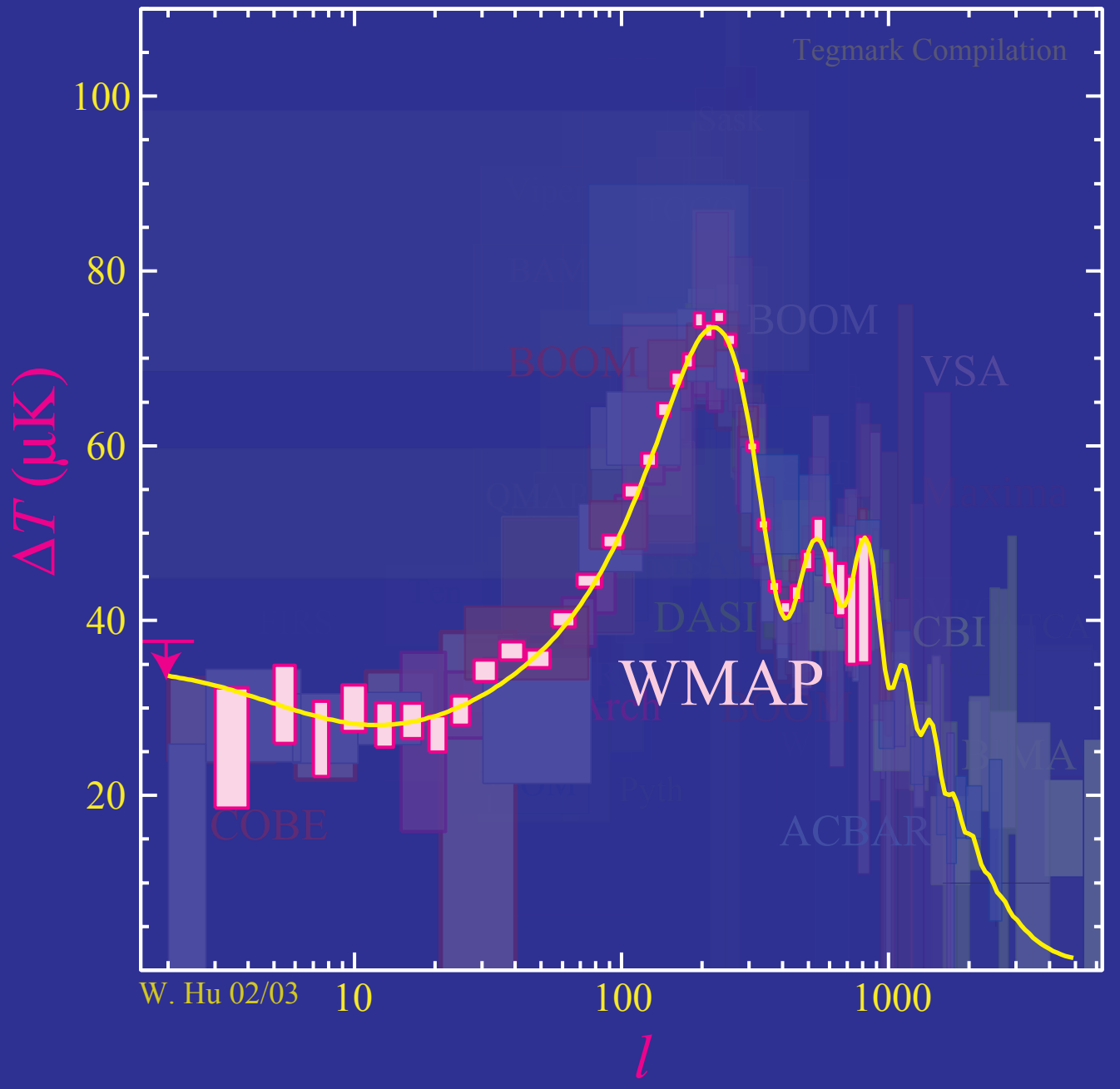
Acoustic Imperfections

Acoustic Oscillations

- When T>3000K, medium ionized
- Photons tightly coupled to free electrons via Thomson scattering; electrons to protons via Coulomb interactions
- Medium behaves as a perfect fluid
- Radiation pressure competes with gravitational attraction causing perturbations to oscillate



Temperature Spectrum



Quadrupoles at Recombination's End

- Acoustic inhomongeneities become anisotropies by streaming/diffusion

Quadrupoles at Recombination's End

- Electron "observer" sees a quadrupole anisotropy
- Polarization pattern is a projection quadrupole anisotropy

Fluid Imperfections

- Perfect fluid: no anisotropic stresses due to scattering isotropization; baryons and photons move as single fluid
- Fluid imperfections are related to the mean free path of the photons in the baryons

$$\lambda_C = \dot{\tau}^{-1} \quad \text{where} \quad \dot{\tau} = n_e \sigma_T a$$

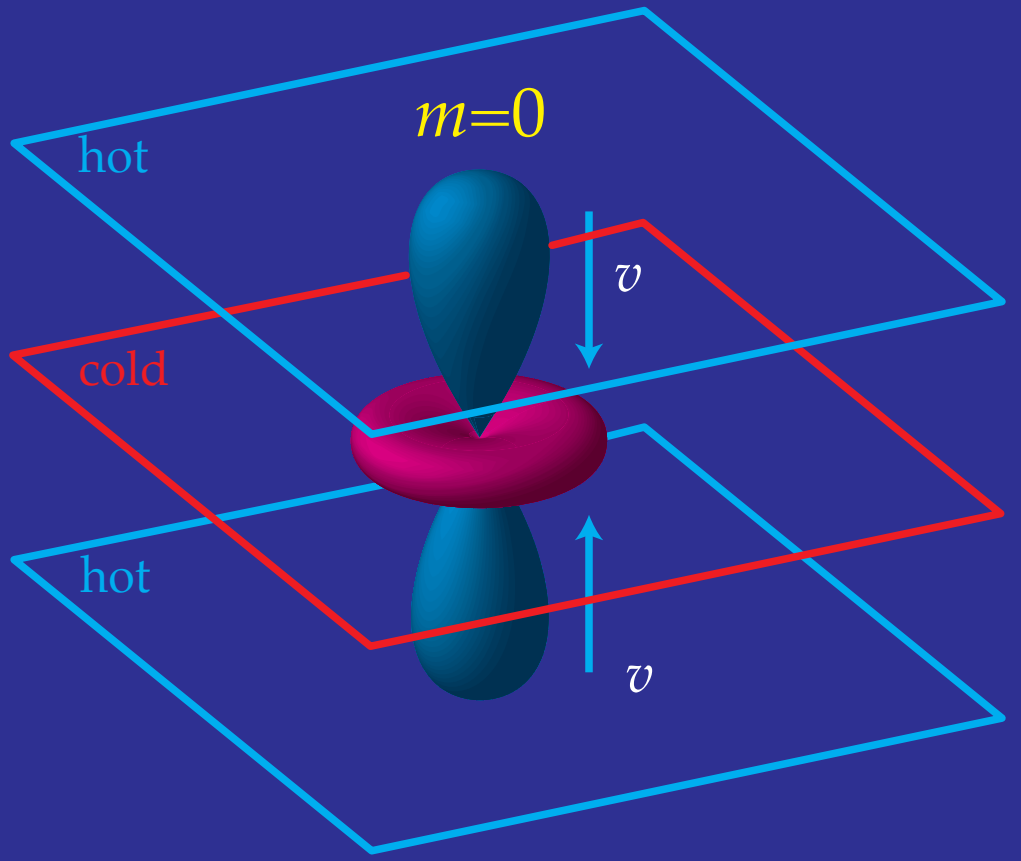
  is the conformal opacity to Thomson scattering
- Dissipation is related to the diffusion length: random walk approximation

$$\lambda_D = \sqrt{N}\lambda_C = \sqrt{\eta/\lambda_C}\,\lambda_C = \sqrt{\eta\lambda_C}$$

  the geometric mean between the horizon and mean free path
- $\lambda_D/\eta_* \sim$ few %, so expect the peaks >3 to be affected by dissipation

Viscosity & Heat Conduction

- Both fluid imperfections are related to the gradient of the velocity kv_γ by opacity $\dot{\tau}$: slippage of fluids $v_\gamma - v_b$.
- Viscosity is an anisotropic stress or quadrupole moment formed by radiation streaming from hot to cold regions



Dimensional Analysis

- Viscosity= quadrupole anisotropy that follows the fluid velocity

$$\pi_\gamma \approx \frac{k}{\dot{\tau}} v_\gamma$$

- Mean free path related to the damping scale via the random walk $k_D = (\dot{\tau}/\eta_*)^{1/2} \rightarrow \dot{\tau} = k_D^2 \eta_*$
- Damping scale at $\ell \sim 1000$ vs horizon scale at $\ell \sim 100$ so $k_D \eta_* \approx 10$
- Polarization amplitude rises to the damping scale to be $\sim 10\%$ of anisotropy

$$\pi_\gamma \approx \frac{k}{k_D} \frac{1}{10} v_\gamma \qquad \Delta_P \approx \frac{\ell}{\ell_D} \frac{1}{10} \Delta_T$$

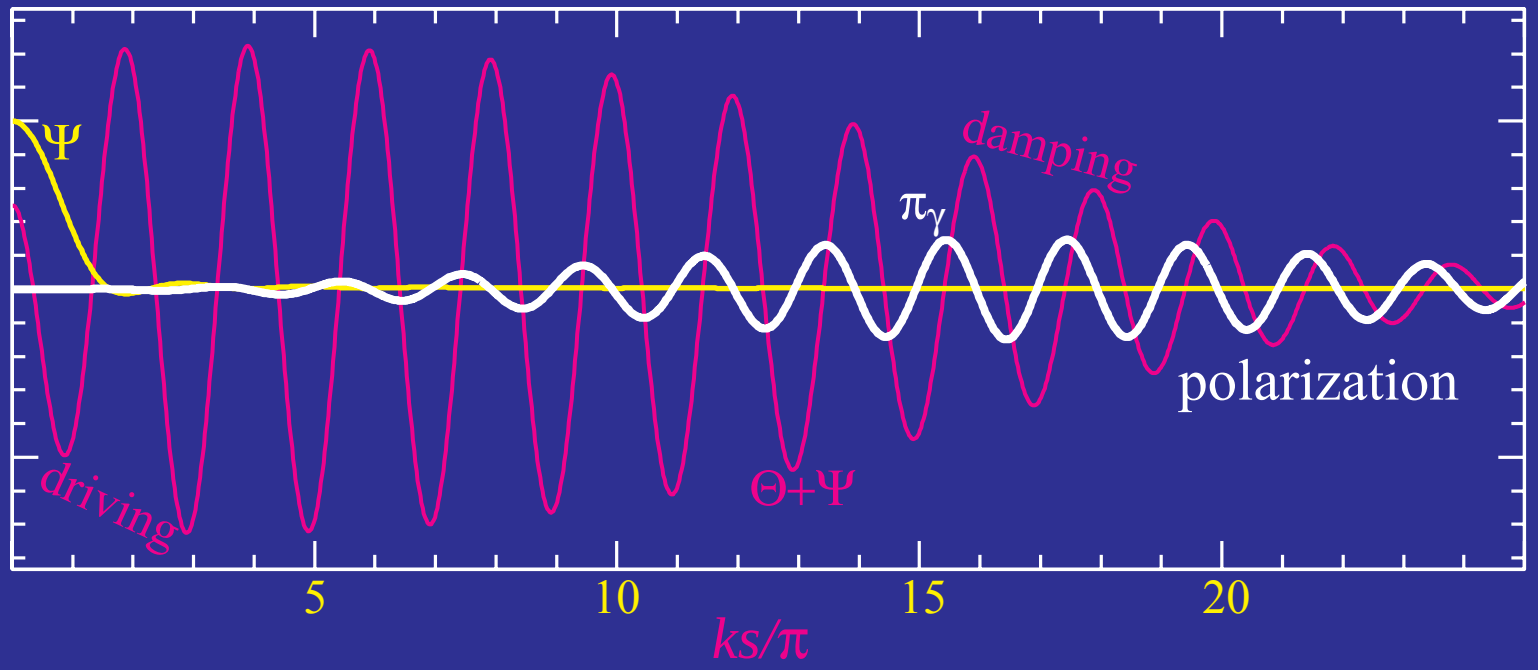
- Polarization phase follows fluid velocity

Damping & Polarization

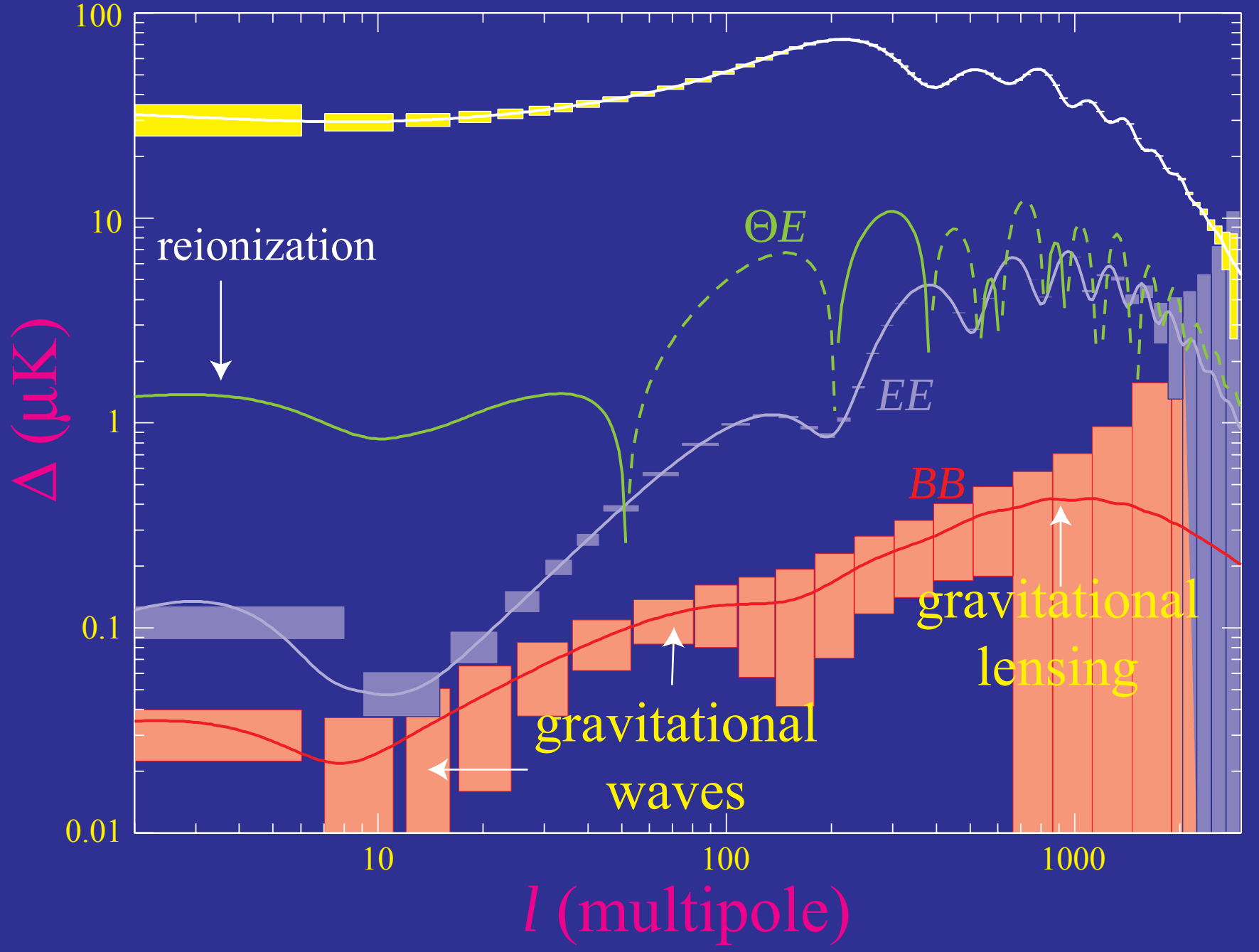
- Quadrupole moments:

  damp acoustic oscillations from fluid viscosity
  generates polarization from scattering

- Rise in polarization power coincides with fall in temperature power – $l \sim 1000$



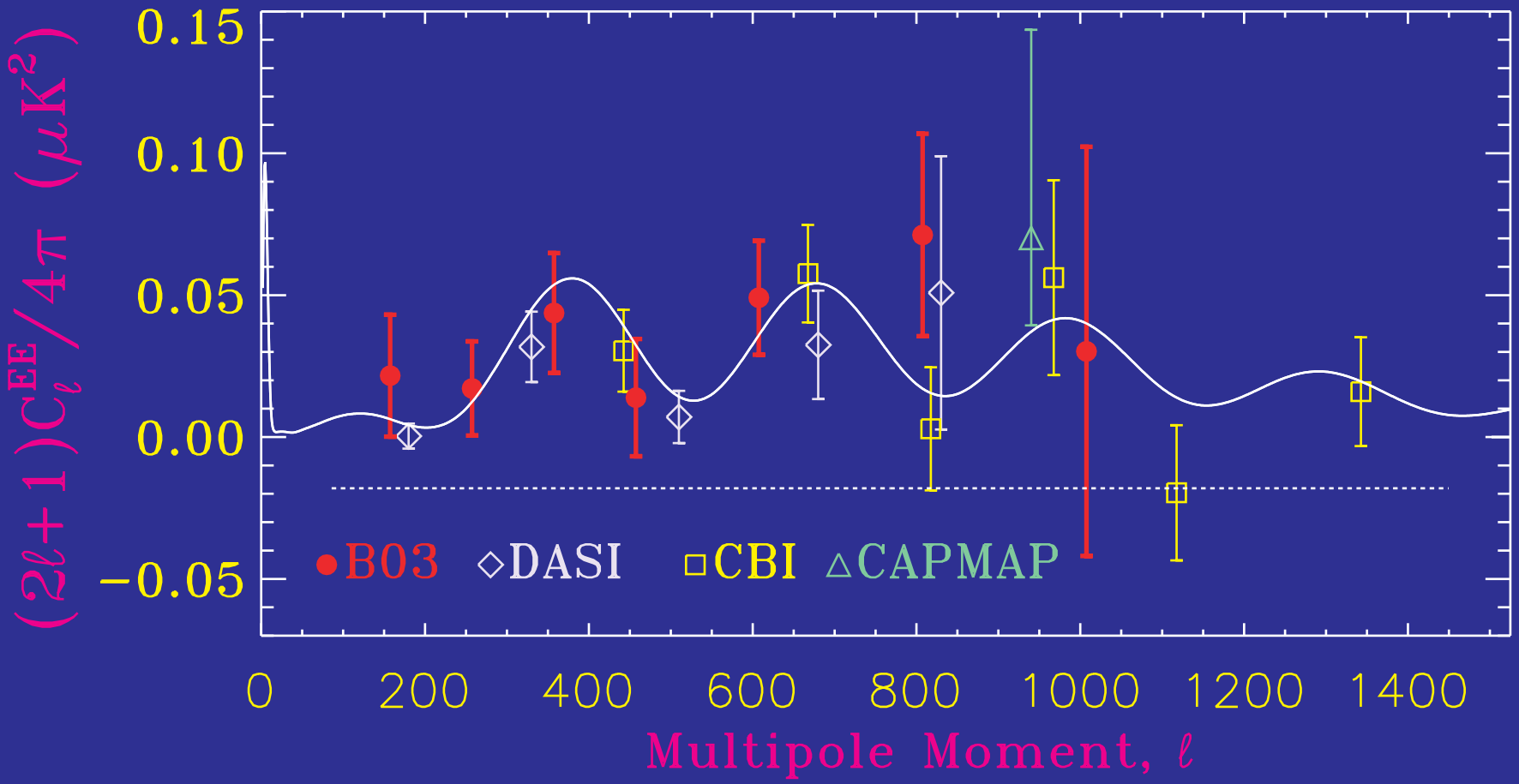
Temperature and Polarization Spectra



Current Status

- Polarization first detected by DASI (Kovac et al 2002)
- Many ongoing experiments expected to rapidly improve measurements (locally: CAPMAP, QUAD)

Montroy et al 2005



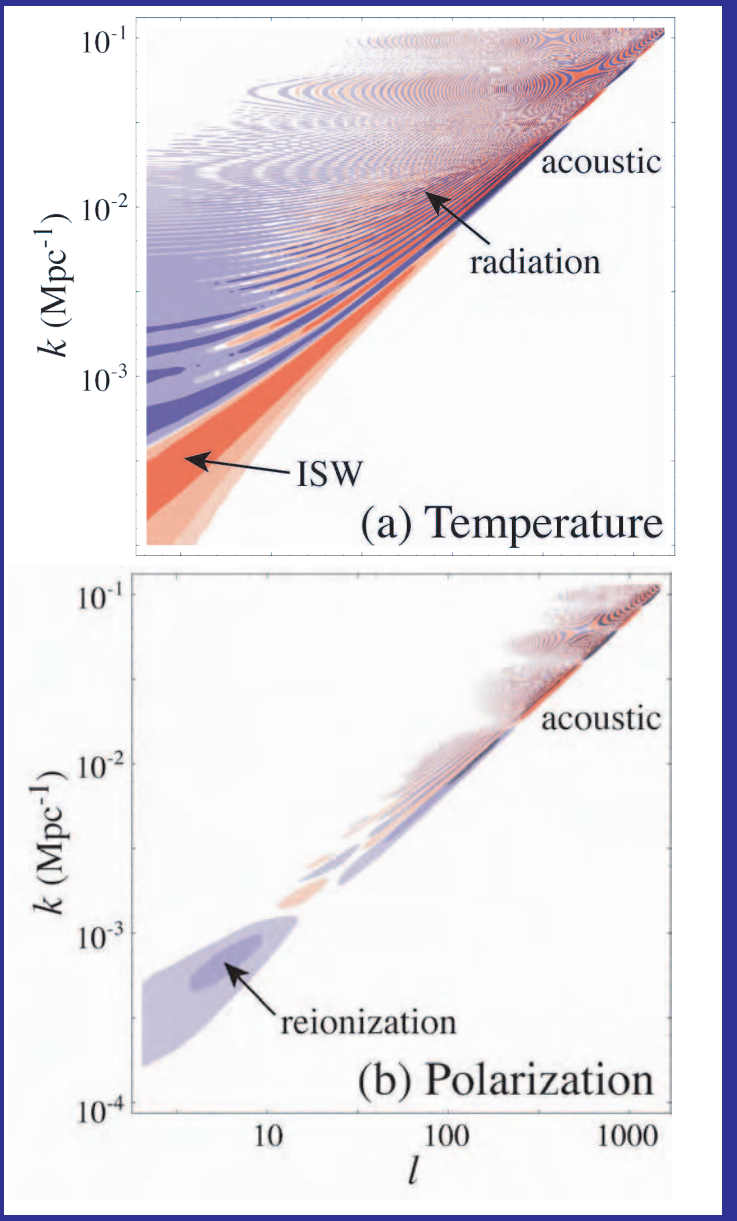
Why Care?

- In the standard model, acoustic polarization spectra uniquely predicted by same parameters that control temperature spectra
- Validation of standard model
- Improved statistics on cosmological parameters controlling peaks

- Polarization is a complementary and intrinsically more incisive probe of the initial power spectrum and hence inflationary (or alternate) models

- Acoustic polarization is lensed by the large scale structure into B-modes
- Lensing B-modes sensitive to the growth of structure and hence neutrino mass and dark energy
- Contaminate the gravitational wave B-mode signature

Transfer of Initial Power

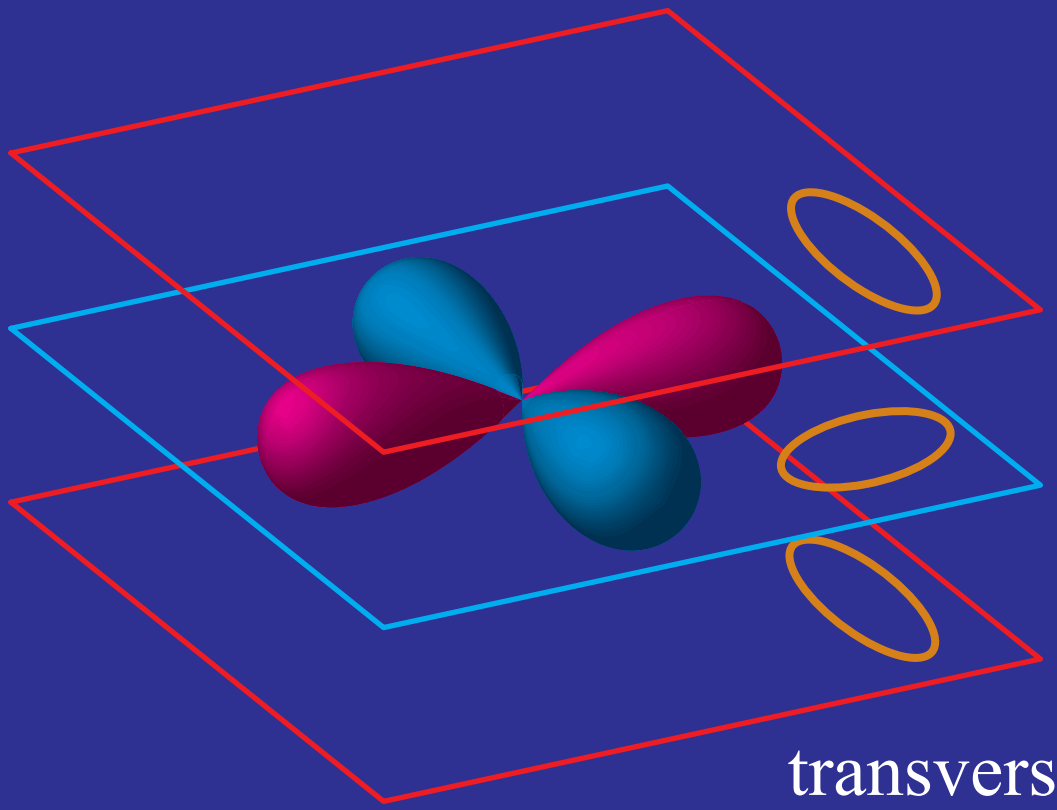


Hu & Okamoto (2003)

Gravitational Waves

Gravitational Waves

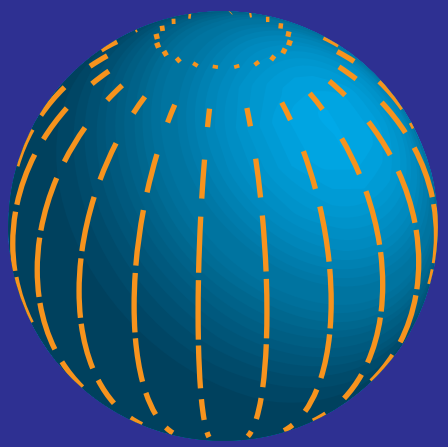
- Inflation predicts near scale invariant spectrum of gravitational waves
- Amplitude proportional to the square of the $E_I = V^{1/4}$ energy scale
- If inflation is associated with the grand unification $E_I \sim 10^{16}$ GeV and potentially observable

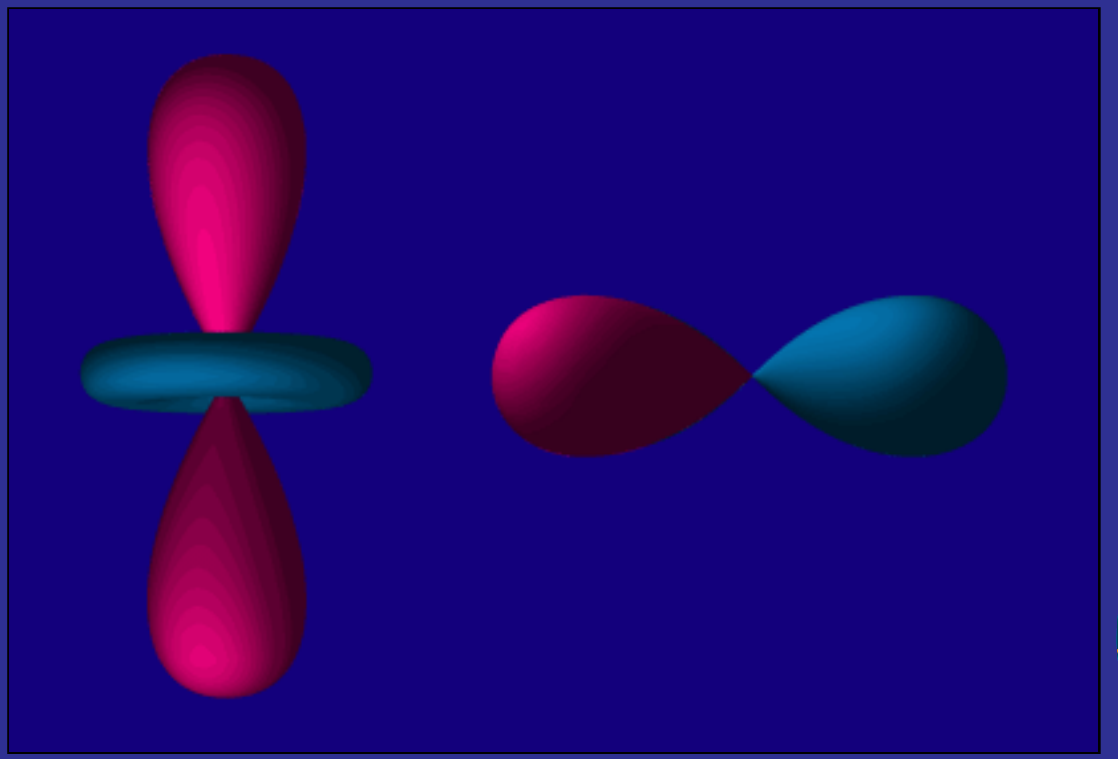


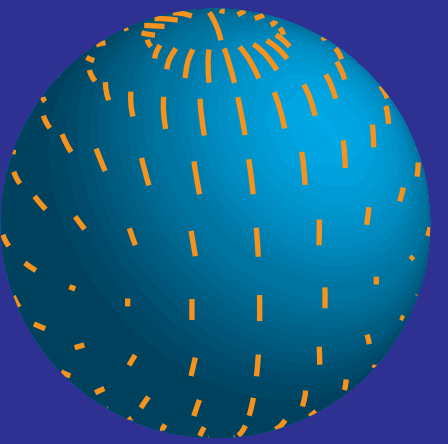
transverse-traceless distortion

Gravitational Wave Pattern

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







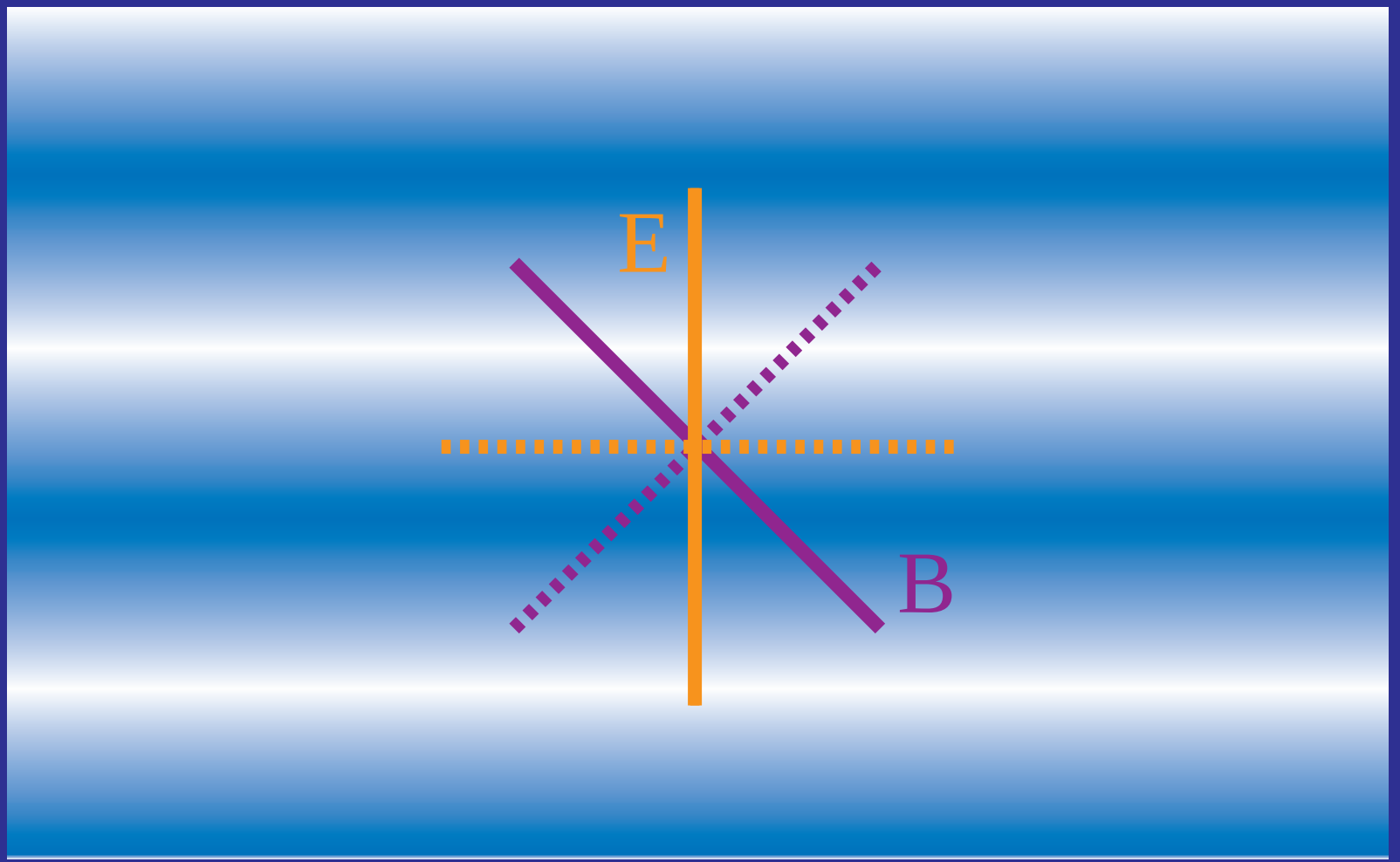
density perturbation

gravitational wave

Electric & Magnetic Polarization

(a.k.a. gradient & curl)

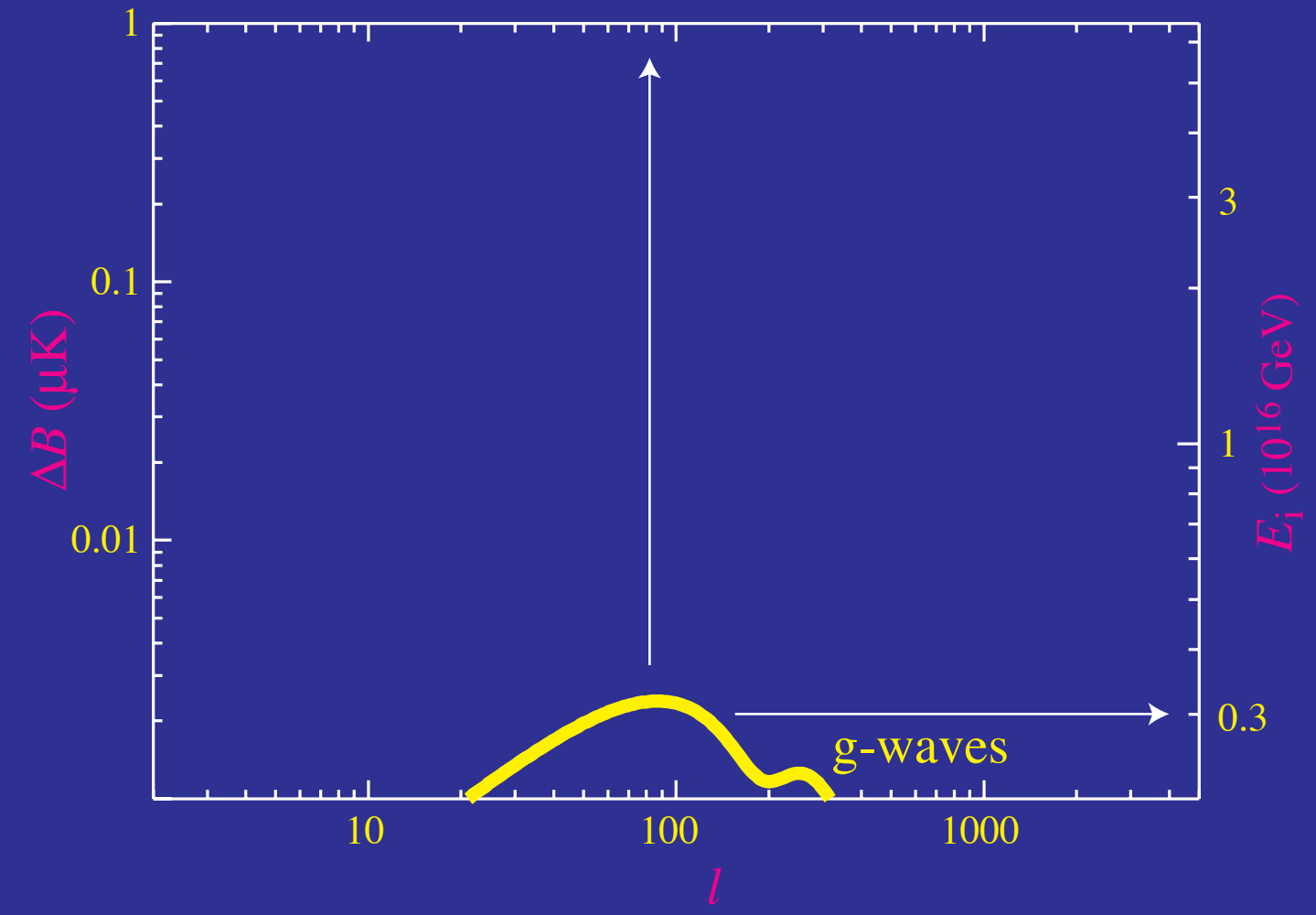
- Alignment of principal vs polarization axes (curvature matrix vs polarization direction)



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

Scaling with Inflationary Energy Scale

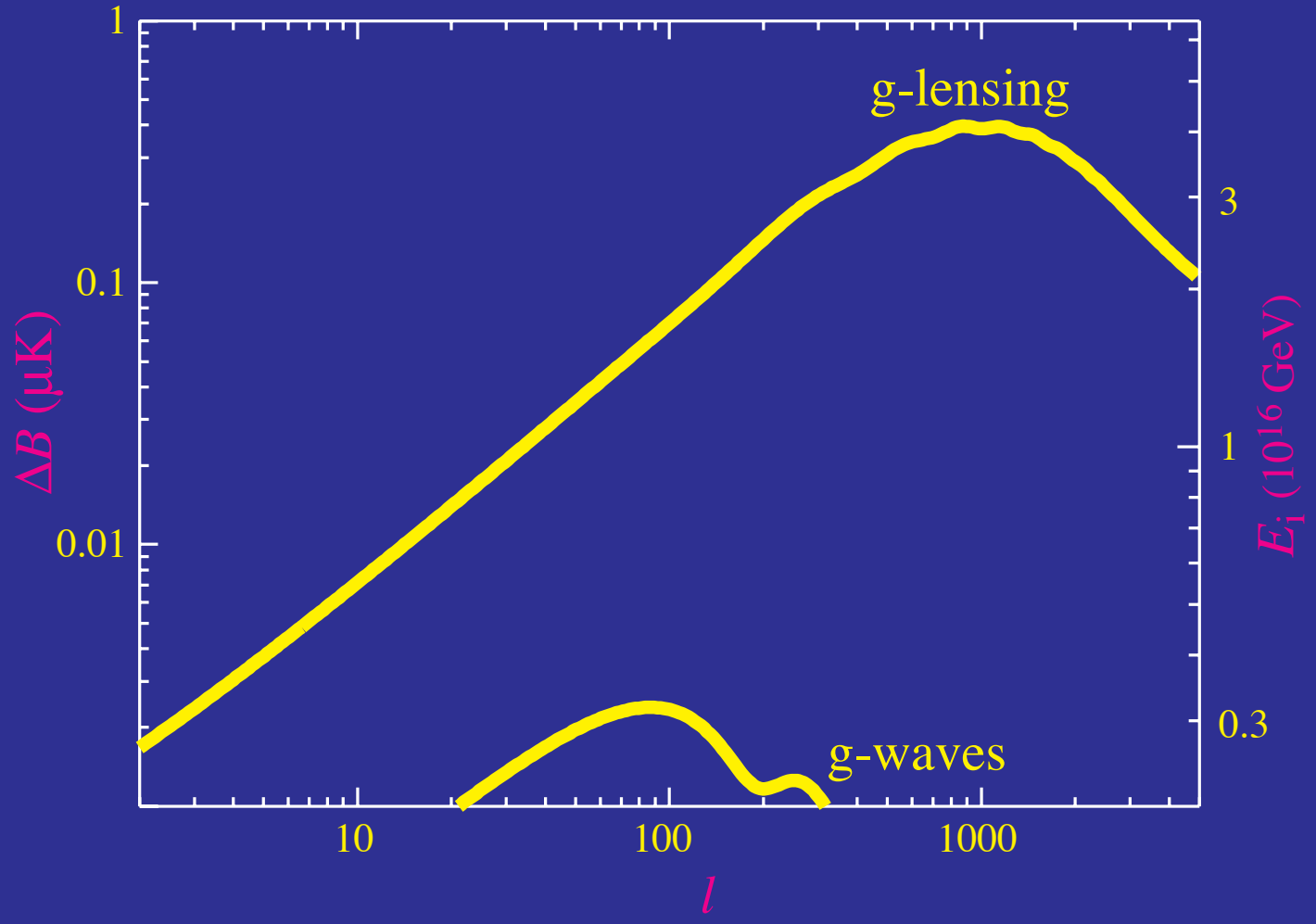
- RMS B-mode signal scales with inflationary energy scale squared E_i^2



Contamination for Gravitational Waves

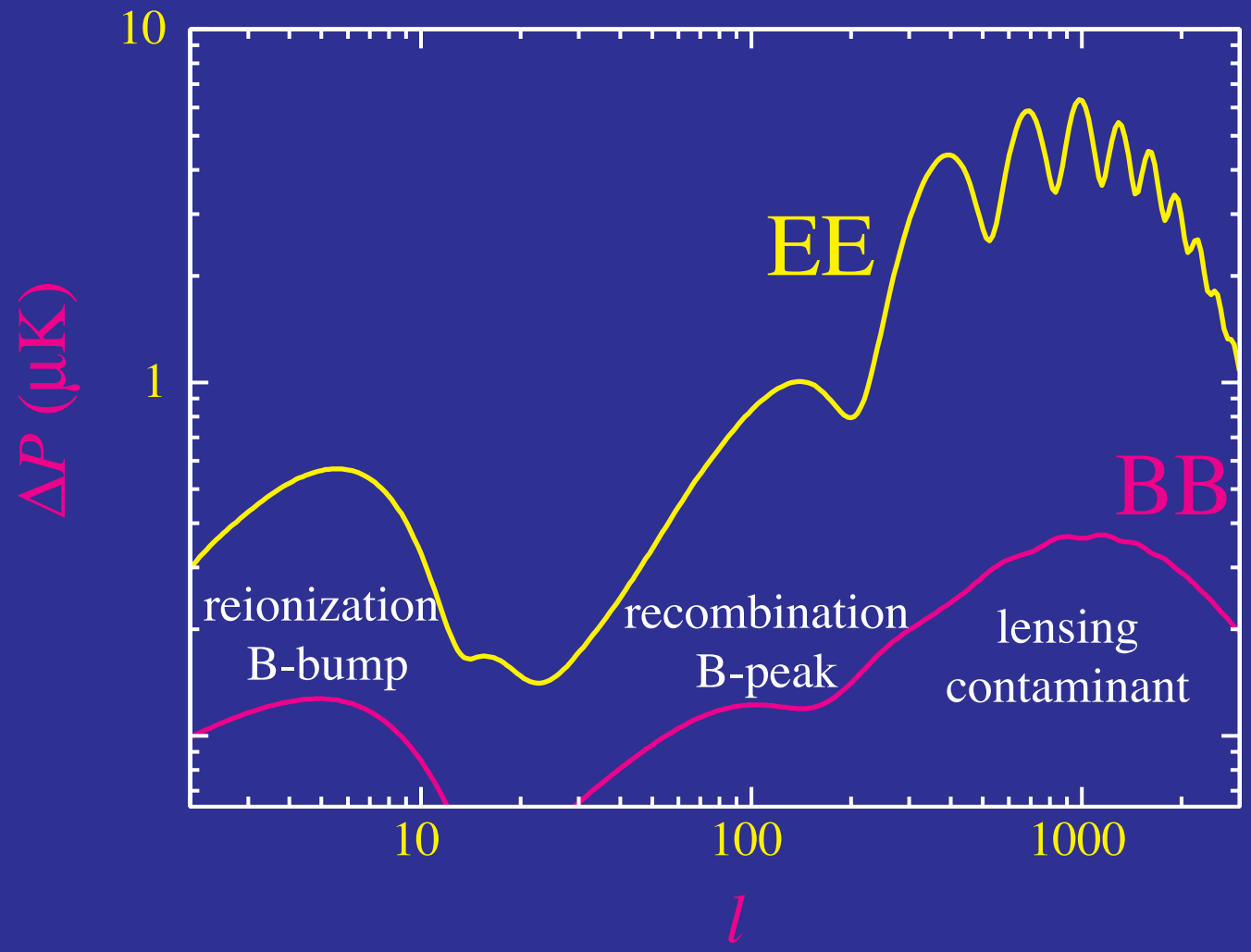
- Gravitational lensing contamination of B-modes from gravitational waves cleaned to $E_i \sim 0.3 \times 10^{16}$ GeV

  Hu & Okamoto (2002) limits by Knox & Song (2002); Cooray, Kedsen, Kamionkowski (2002)



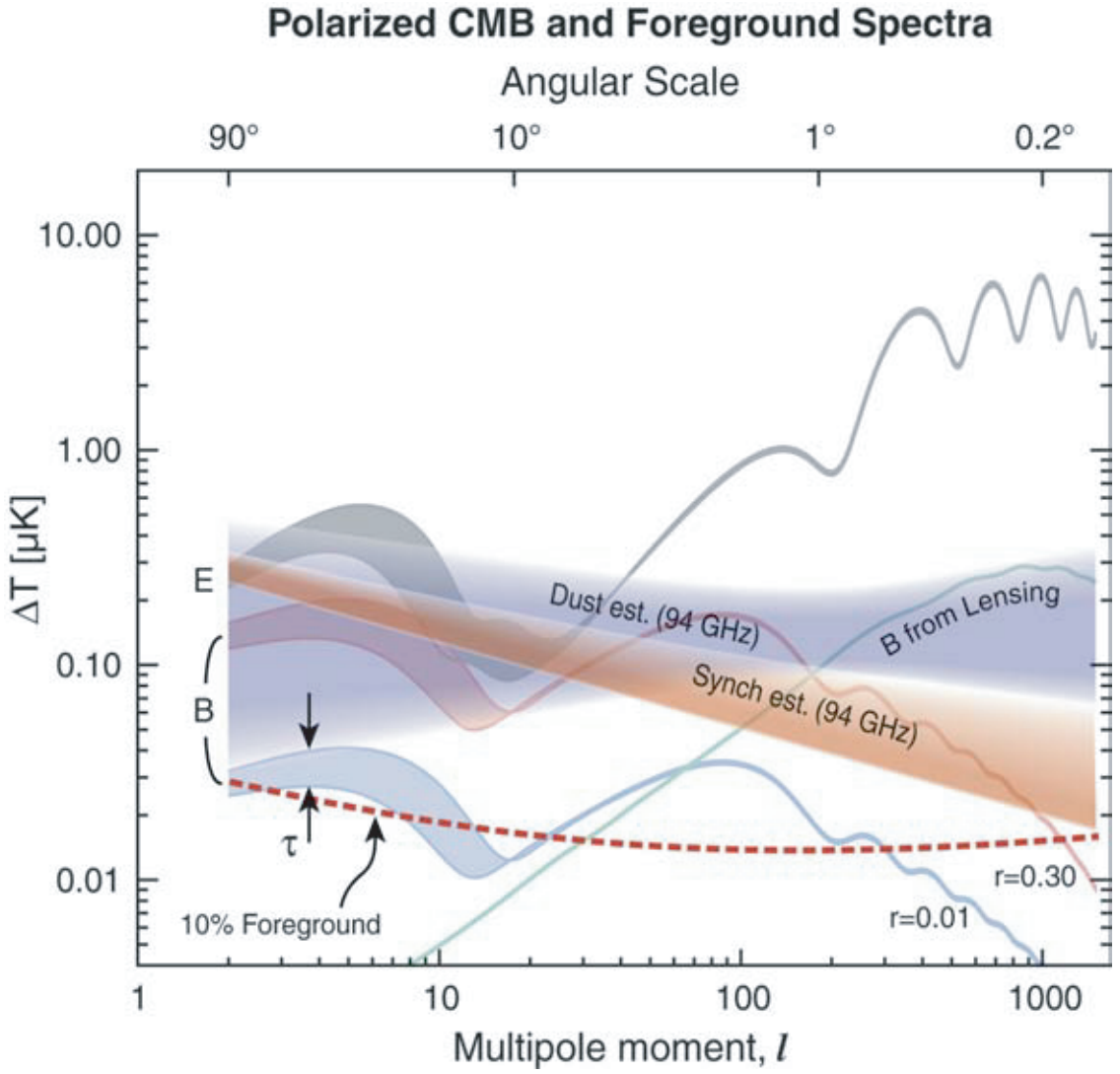
The B-Bump

- Rescattering of gravitational wave anisotropy generates the B-bump
- Potentially the most sensitive probe of inflationary energy scale
- Potentially enables test of scale invariance prediction (slow roll)



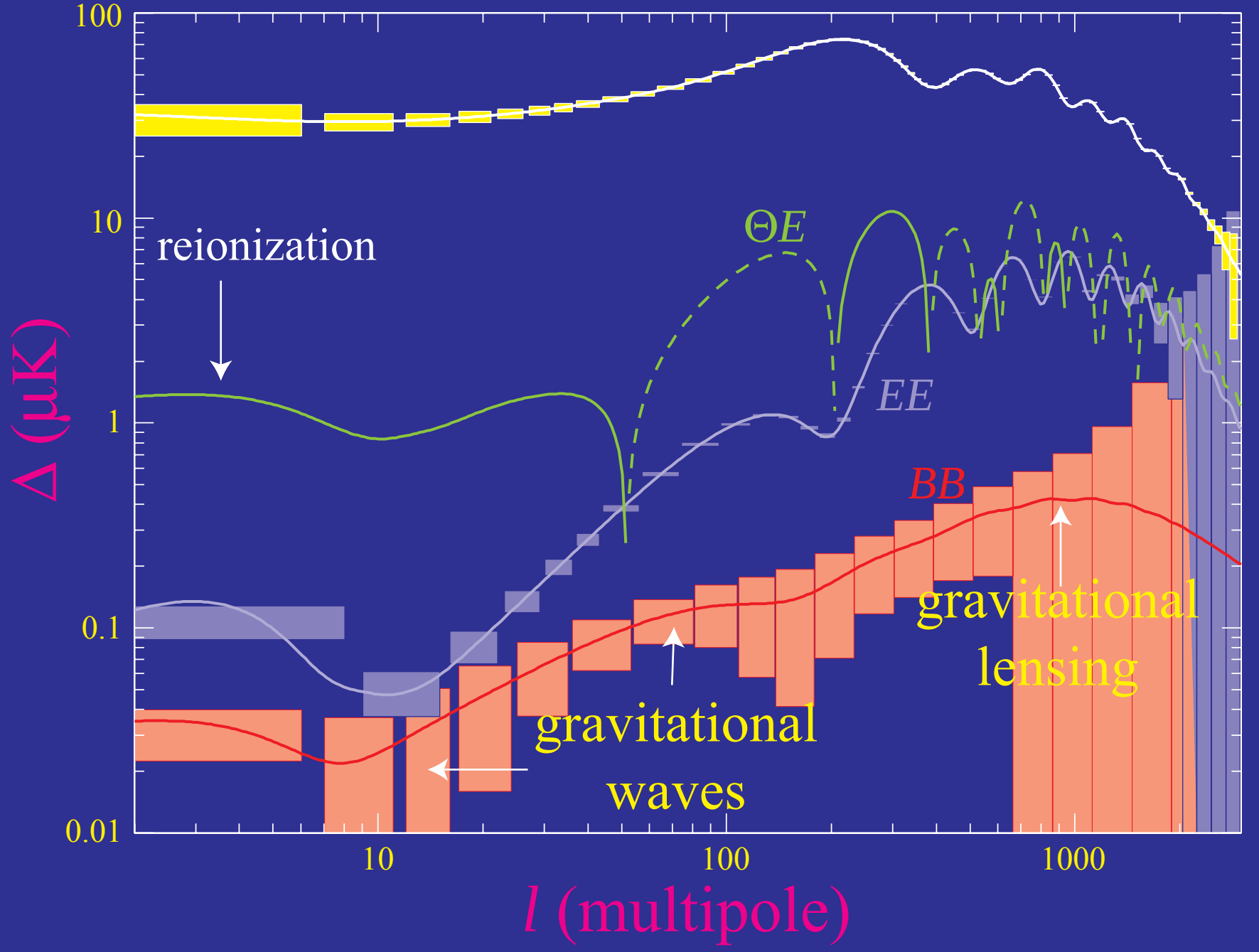
Foregrounds

- Foreground contamination likely larger at low multipoles - large angles: stay tuned for WMAP



CMB Task Force (2005)

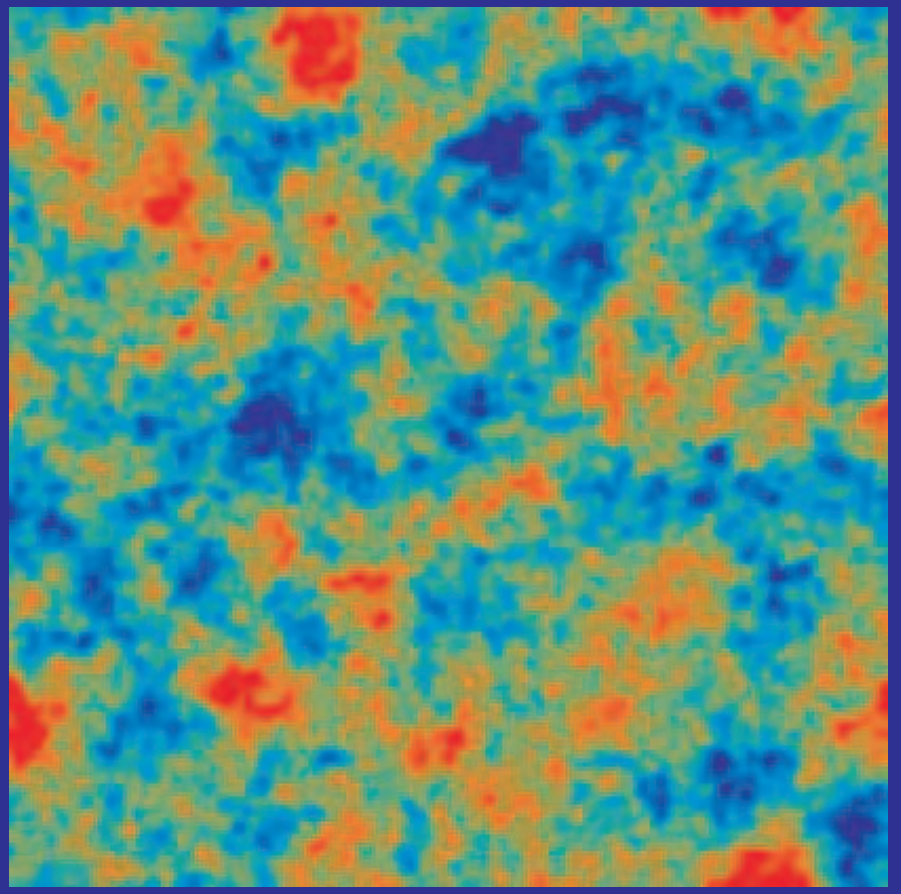
Temperature and Polarization Spectra



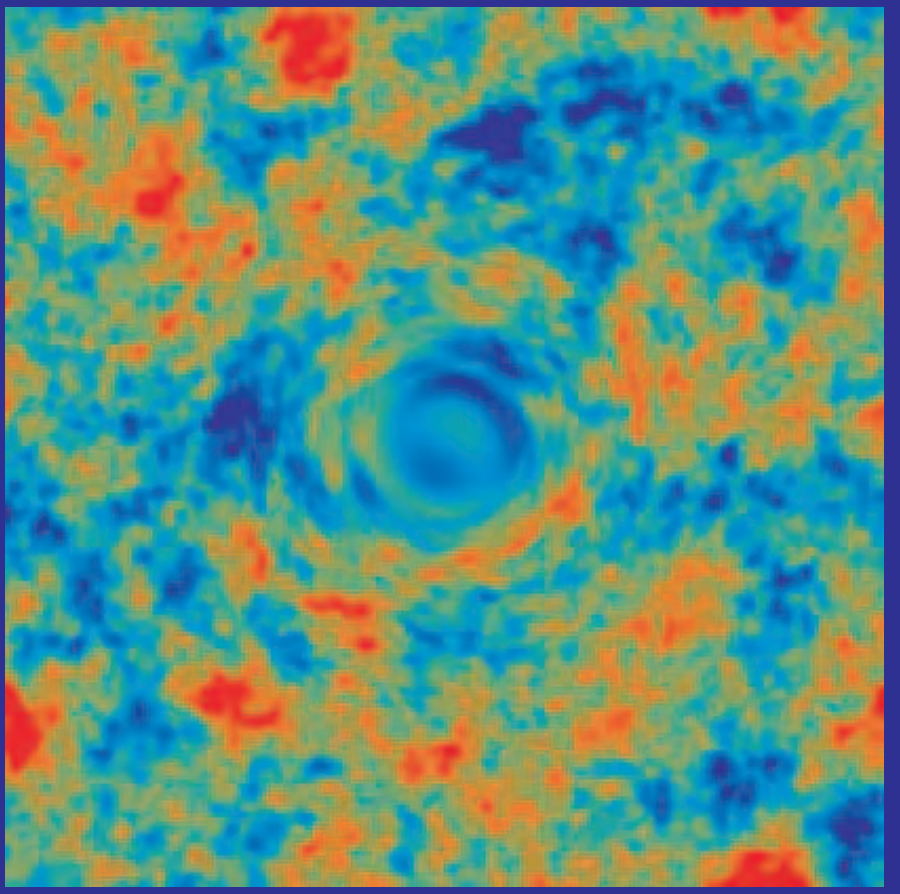
Gravitational Lensing

Gravitational Lensing

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

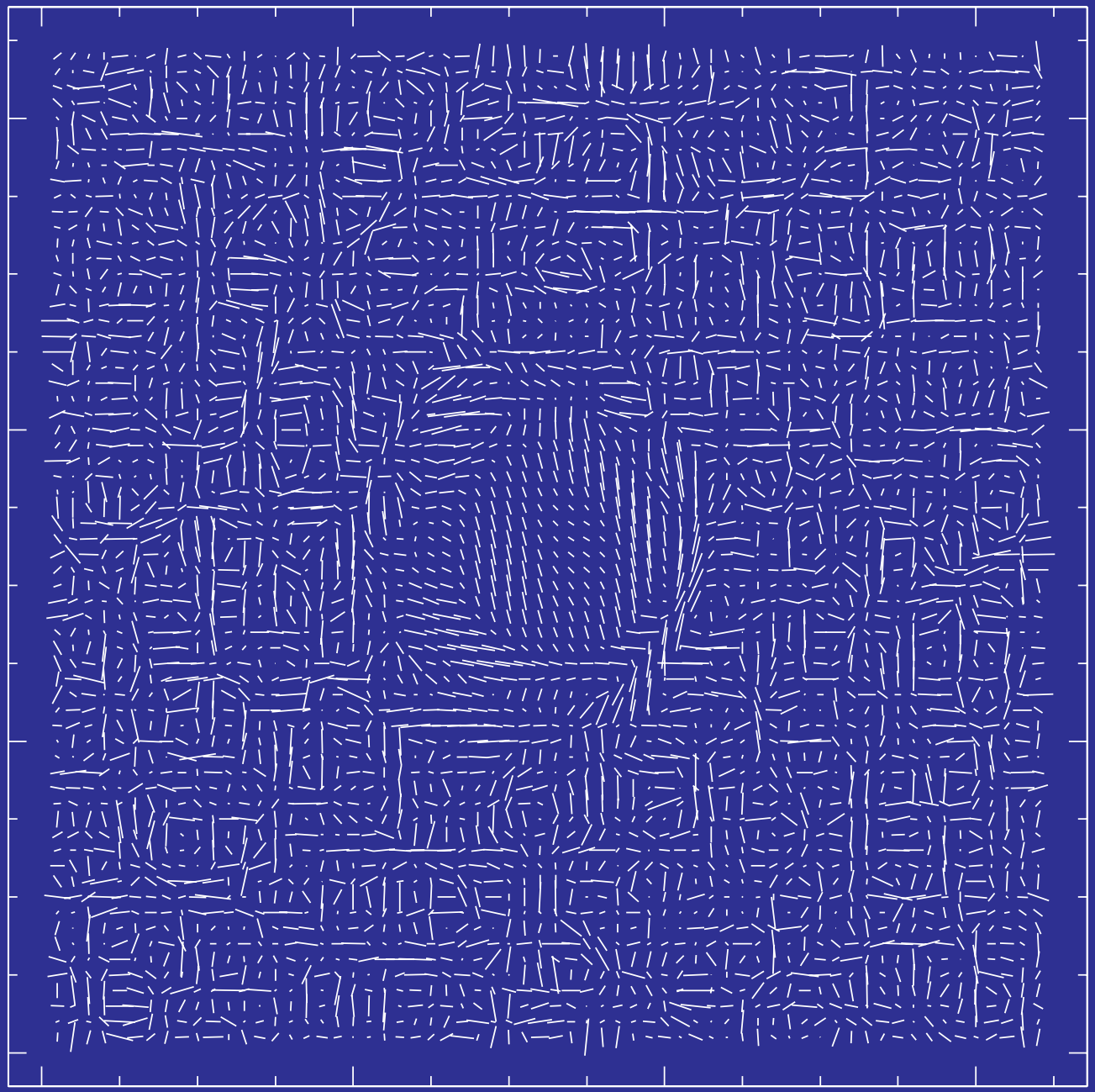


Original



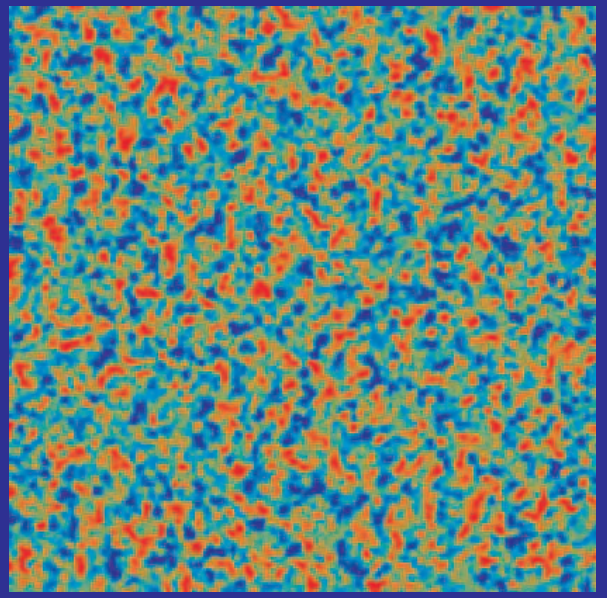
Lensed

Polarization Lensing

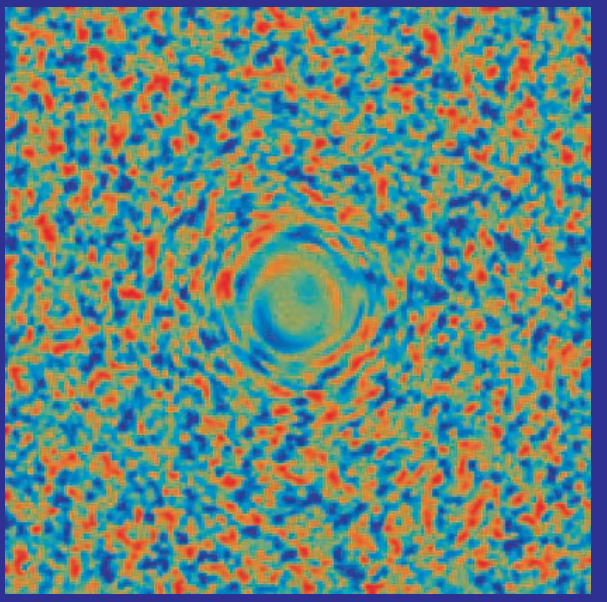


Polarization Lensing

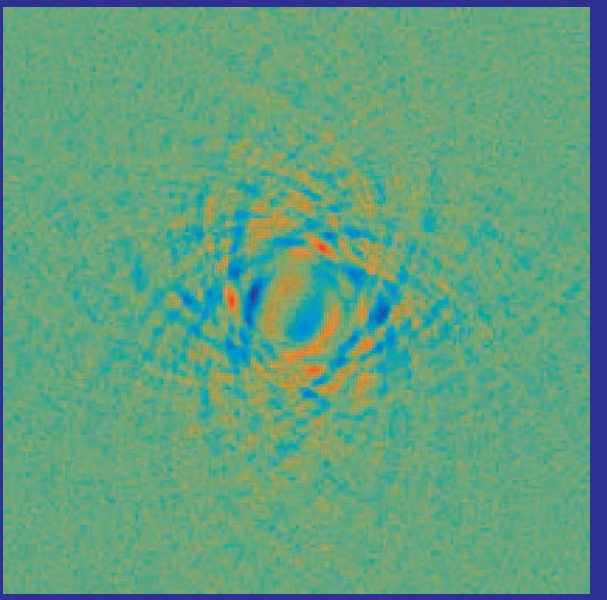
- Since E and B denote the relationship between the polarization amplitude and direction, warping due to lensing creates B-modes



Original



Lensed E

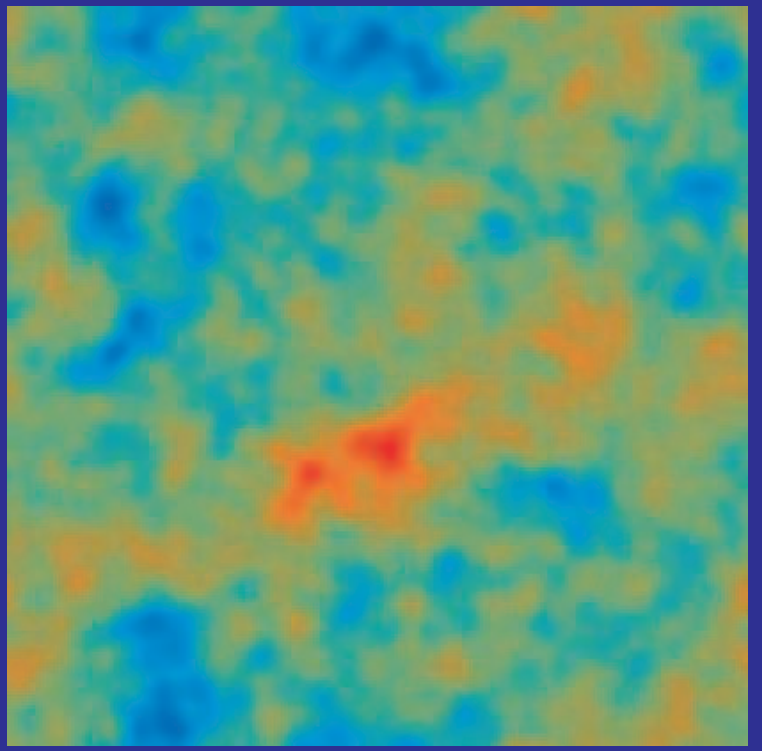


Lensed B

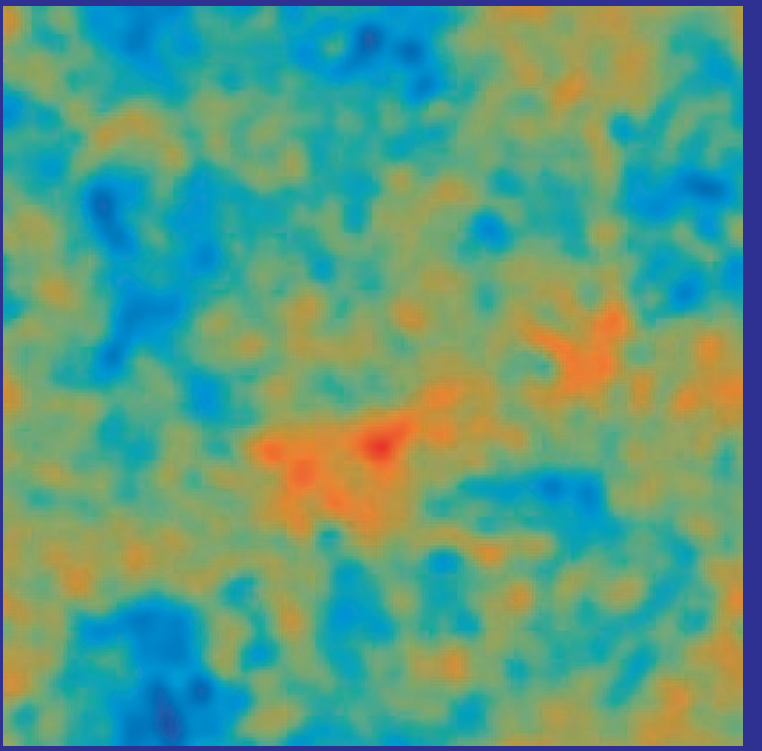
Zaldarriaga & Seljak (1998) [figure: Hu & Okamoto (2001)]

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)]

Summary

- CMB polarization generated by scattering alone and hence provides probes that are well localized in time and space
- Polarization carries a direction and hence can separate linear density and gravitational wave perturbations [E vs. B modes]
- Early reionization detected by WMAP provides a new window not only on the first generation of structure but also on gravitational waves and statistical anomalies on large scales
- Acoustic polarization detected by DASI eventually 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