The Silk Damping Tail of the CMB

Wayne Hu

Oxford, December 2002

Outline

- Damping tail of temperature power spectrum and its use as a standard ruler
- Generation of polarization through damping
- Unveiling of gravitational lensing from features in the damping tail

Outline

- Damping tail of temperature power spectrum and its use as a standard ruler
- Generation of polarization through damping
- Unveiling of gravitational lensing from features in the damping tail

- Collaborators:

    Matt Hedman

    Takemi Okamoto

    Joe Silk

    Martin White

    Matias Zaldarriaga

Outline

- Damping tail of temperature power spectrum and its use as a standard ruler
- Generation of polarization through damping
- Unveiling of gravitational lensing from features in the damping tail

- Collaborators:

  Matt Hedman

  Takemi Okamoto

  Joe Silk

  Martin White

  Matias Zaldarriaga

http://background.uchicago.edu

("Presentations" in PDF)

Damping Tail

Photon-Baryon Plasma

- Before $z\sim1000$ when the CMB had $T>3000$K, hydrogen ionized
- Free electrons act as "glue" between photons and baryons by Compton scattering and Coulomb interactions
- Nearly perfect fluid

Anisotropy Power Spectrum

Damping

- Perfect fluid: no anisotropic stresses due to scattering isotropization; baryons and photons move as single fluid

Damping

- 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

Damping

- 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 Thompson 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

Damping

- 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 $>$ 3rd to be affected by dissipation

Equations of Motion

- Continuity

$$\dot{\Theta} = -\frac{k}{3}v_\gamma \,, \quad \dot{\delta}_b = -kv_b$$

where gravitational effects ignored and $\Theta \equiv \Delta T/T$.

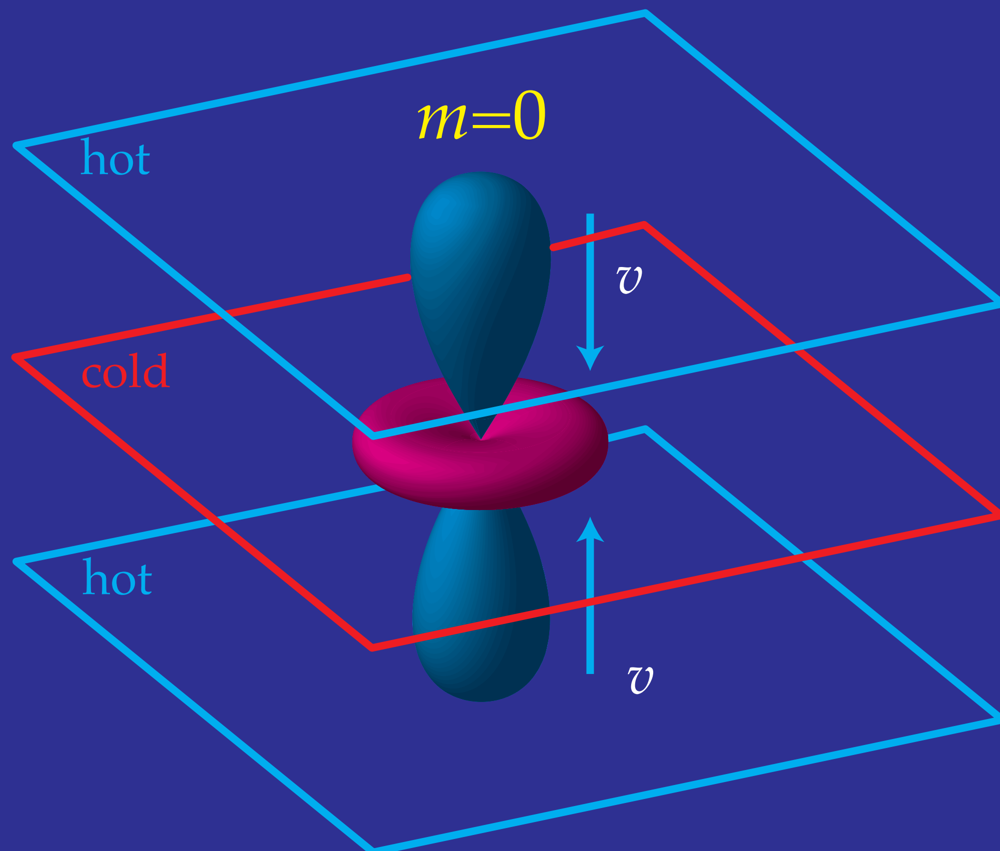
- Euler

$$\dot{v}_\gamma = k\Theta - \frac{k}{6}\pi_\gamma - \dot{\tau}(v_\gamma - v_b)$$
$$\dot{v}_b = -\frac{\dot{a}}{a}v_b + \dot{\tau}(v_\gamma - v_b)/R$$

where $k\Theta$ is the pressure gradient term, $k\pi_\gamma$ is the viscous stress term, and $v_\gamma - v_b$ is the momentum exchange term with $R \equiv 3\rho_b/4\rho_\gamma$ the baryon-photon momentum ratio.

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



Damping Term

- Oscillator equation contains a $\dot{\Theta}$ damping term

$$\ddot{\Theta} + \frac{k^2}{\dot{\tau}} A_{\rm d} \dot{\Theta} + k^2 c_s^2 \Theta = 0$$

- Solve in the adiabatic approximation

$$\Theta \propto \exp(i \int \omega d\eta)$$

$$\exp(i \int \omega d\eta) = e^{\pm ik \int c_s d\eta} \exp[-(k/k_D)^2]$$

- Diffusion wavenumber, geometric mean between horizon and mfp:

$$k_D^{-2} = \frac{1}{2} \int \frac{d\eta}{\dot{\tau}} A_{\rm d} \sim \frac{\eta}{\dot{\tau}}$$

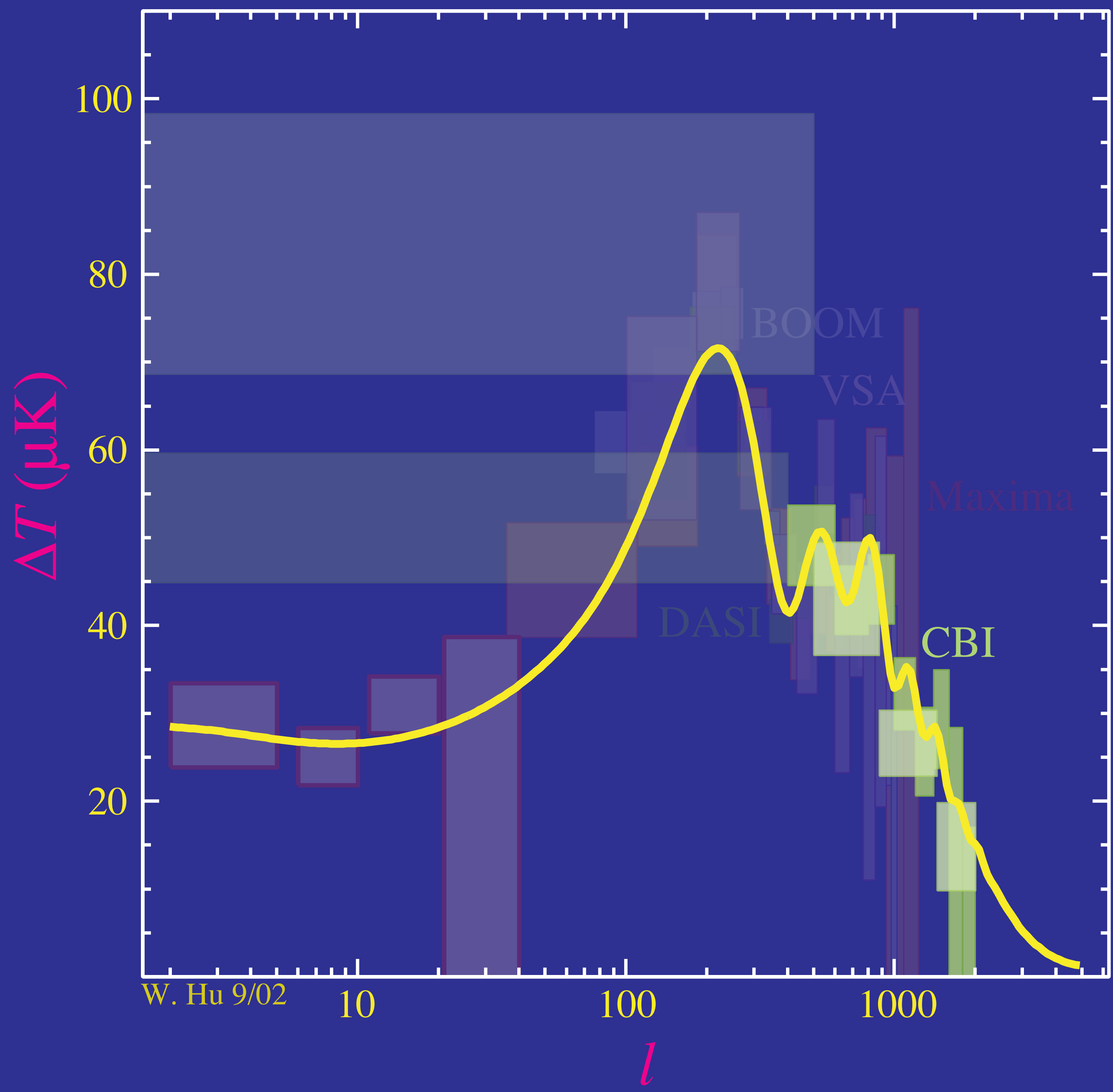
Standard Ruler

- Damping length is a fixed physical scale given properties at recombination
- Gemoetric mean of mean free path and horizon: depends on baryon-photon ratio and matter-radiation ratio

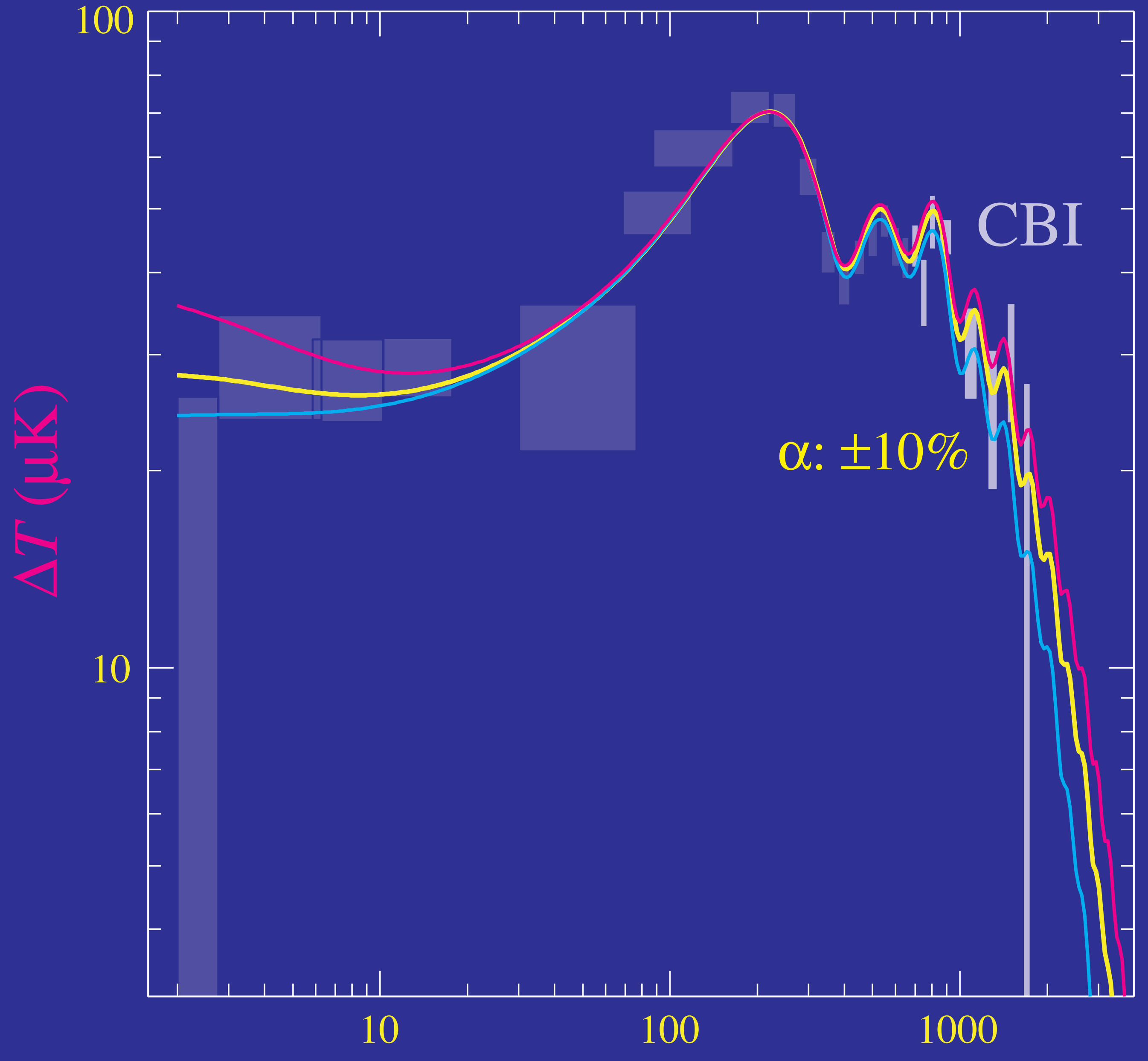
Curvature

- Calibration from lower peaks of $\Omega_b h^2$ and $\Omega_m h^2$ allows measurement of curvature from damping scale
- Independently of peak scale, confirms flat geometry

Damping Tail Measured



Beyond the Standard Model



fixed l_A, ρ_b/ρ_γ, ρ_m/ρ_r

Polarization

Damped Acoustic Oscillations

- From inhomogeneity to anisotropy:

Polarization from Thomson Scattering

- Differential cross section depends on polarization and angle

Polarization from Thomson Scattering

- Isotropic radiation scatters into unpolarized radiation

Polarization from Thomson Scattering

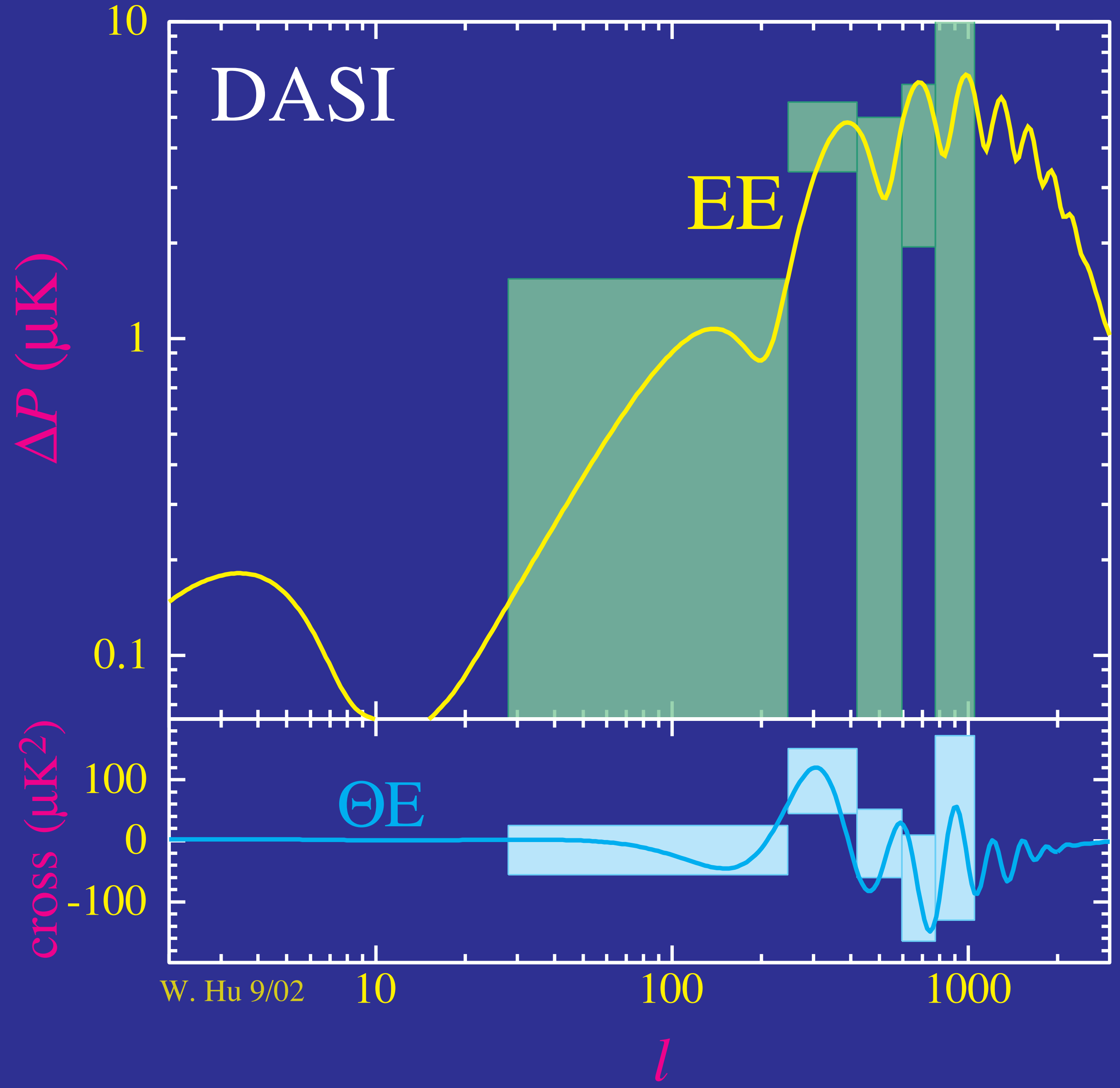
- Quadrupole anisotropies scatter into linear polarization

aligned with
cold lobe

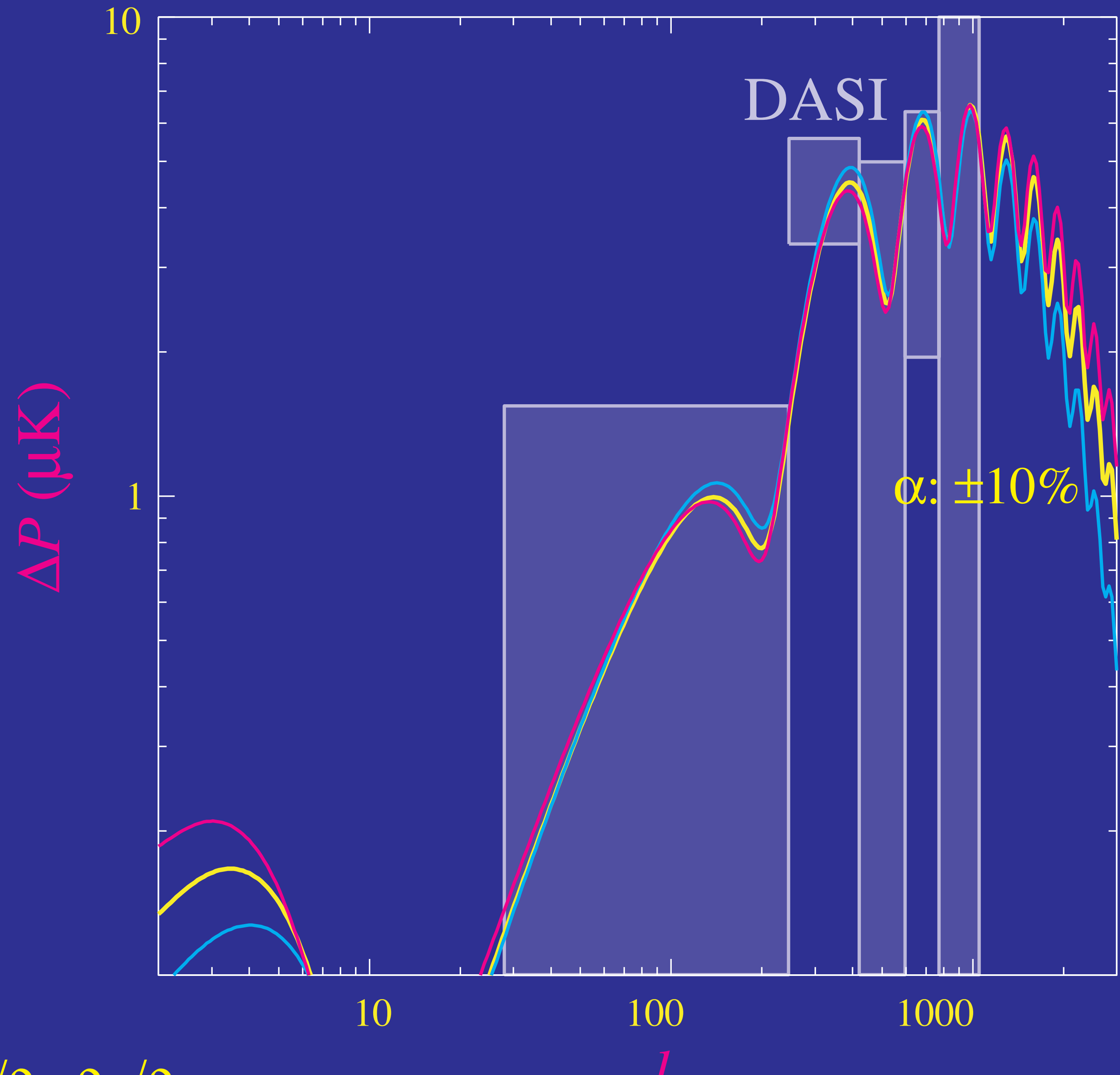
Polarization on the Sphere

- Polarization direction oriented with the cold lobe of the quadrupole
- A local observer will see a $\sin^2\theta$ pattern of Q-polarization: spin–spherical harmonic: l=2, m=0, s=2: ${}_2Y_2^0$.

Polarization Detected



Beyond the Standard Model



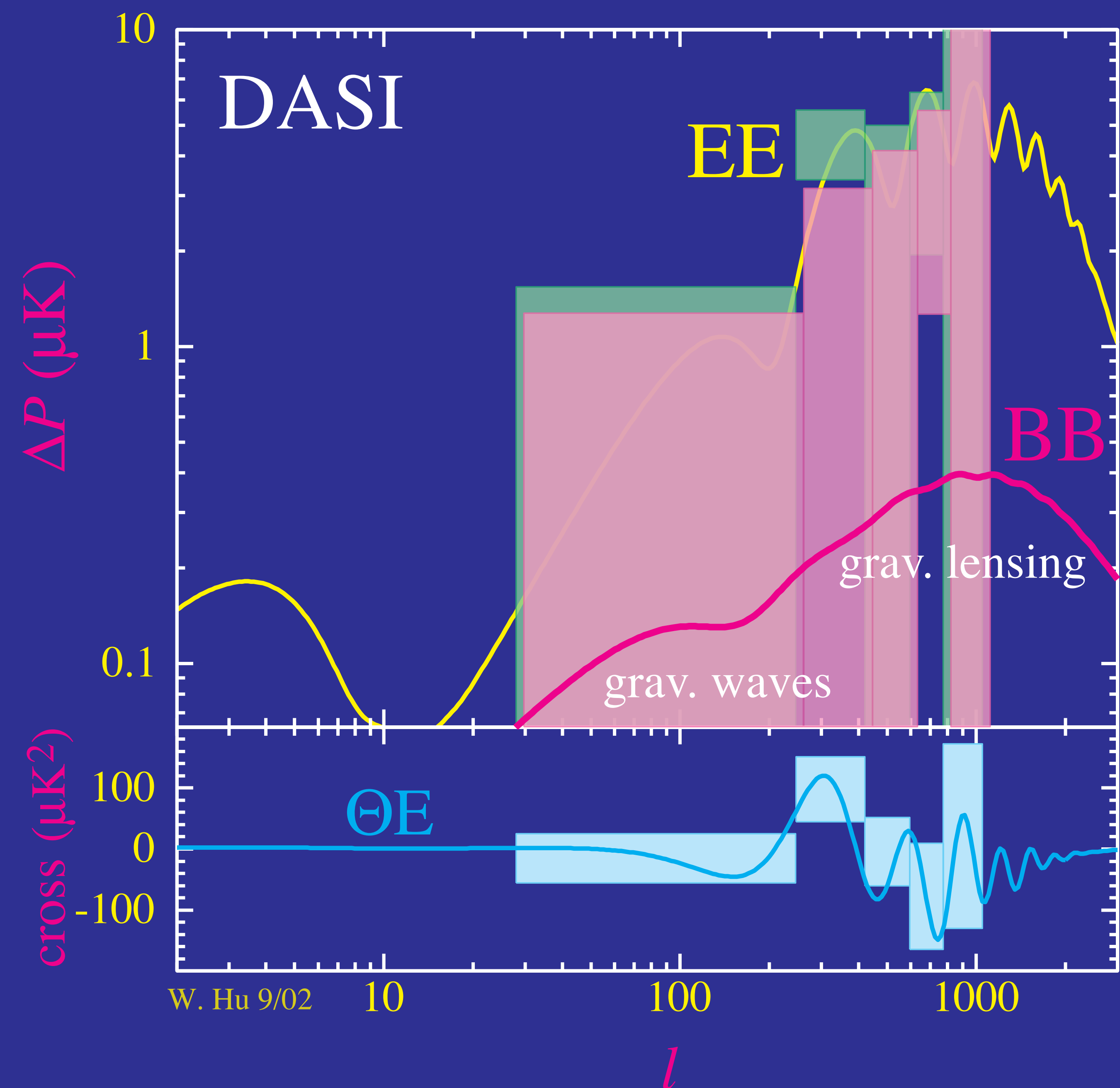
fixed l_A, ρ_b/ρ_γ, ρ_m/ρ_r

Polarization on the Sphere

- Polarization due to gravitational waves follows similarly
- m=±2 quadrupole viewed at different angles

- Difference: no symmetry – *Q* and *U* polarization
- Coordinate independent description of polarization

B-mode Spectrum



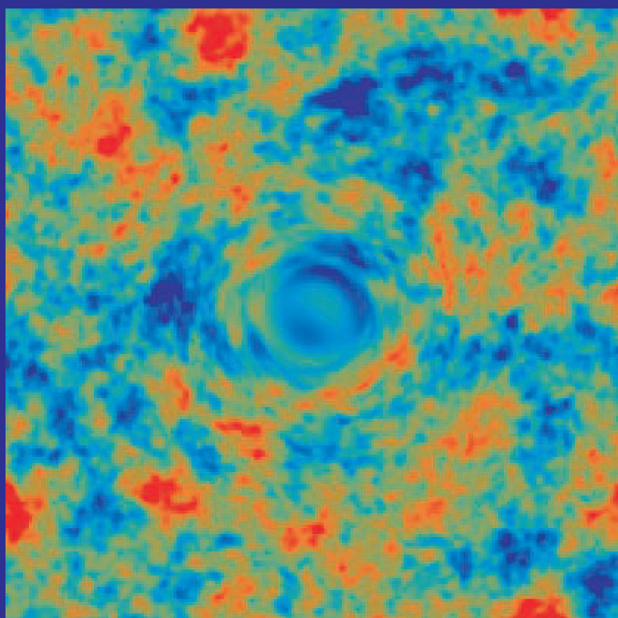
Gravitational Lensing

Lensing of a Gaussian Random Field

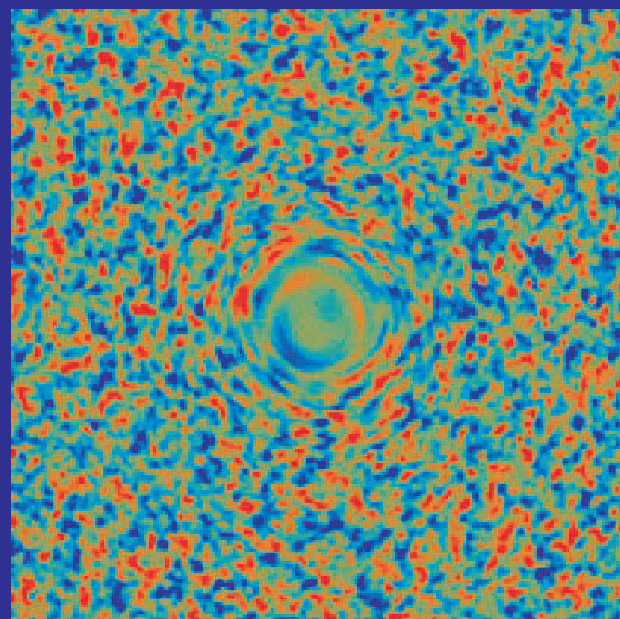
- CMB temperature and polarization anisotropies are Gaussian random fields – unlike galaxy weak lensing
- Average over many noisy images – like galaxy weak lensing

B-Mode Mapping

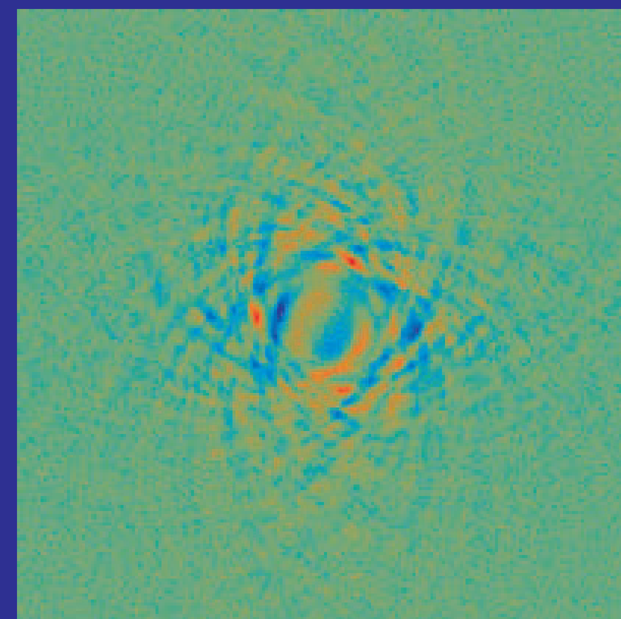
- Lensing warps polarization field and generates B-modes out of E-mode acoustic polarization - hence correlation



Temperature



E-polarization



B-polarization

Zaldarriaga & Seljak (1998)

Hu (2000); Benabed et al. (2001)

Gravitational Lensing

- Lensing is a surface brightness conserving remapping of source to image planes by the gradient of the projected potential

$$\phi(\hat{\mathbf{n}}) = 2\int_{\eta_*}^{\eta_0} d\eta\, \frac{(D_* - D)}{D\, D_*} \Phi(D\hat{\mathbf{n}}, \eta)\,.$$

such that the fields are remapped as

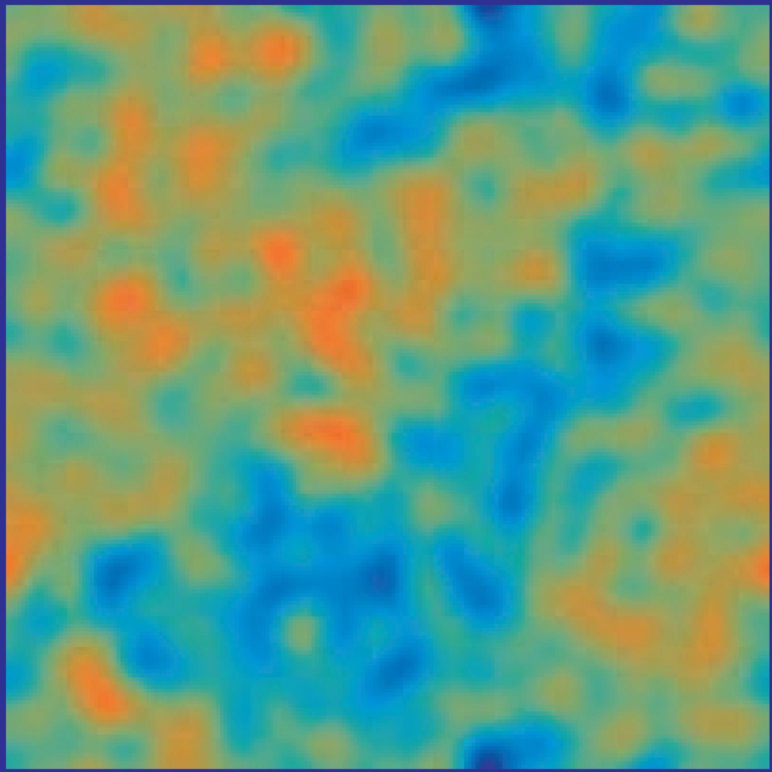
$$x(\hat{\mathbf{n}}) \to x(\hat{\mathbf{n}} + \nabla\phi)\,,$$

where $x \in \{\Theta, Q, U\}$ temperature and polarization.

- Taylor expansion leads to product of fields and Fourier convolution (or mode coupling) - features in damping tail

Lensing by a Gaussian Random Field

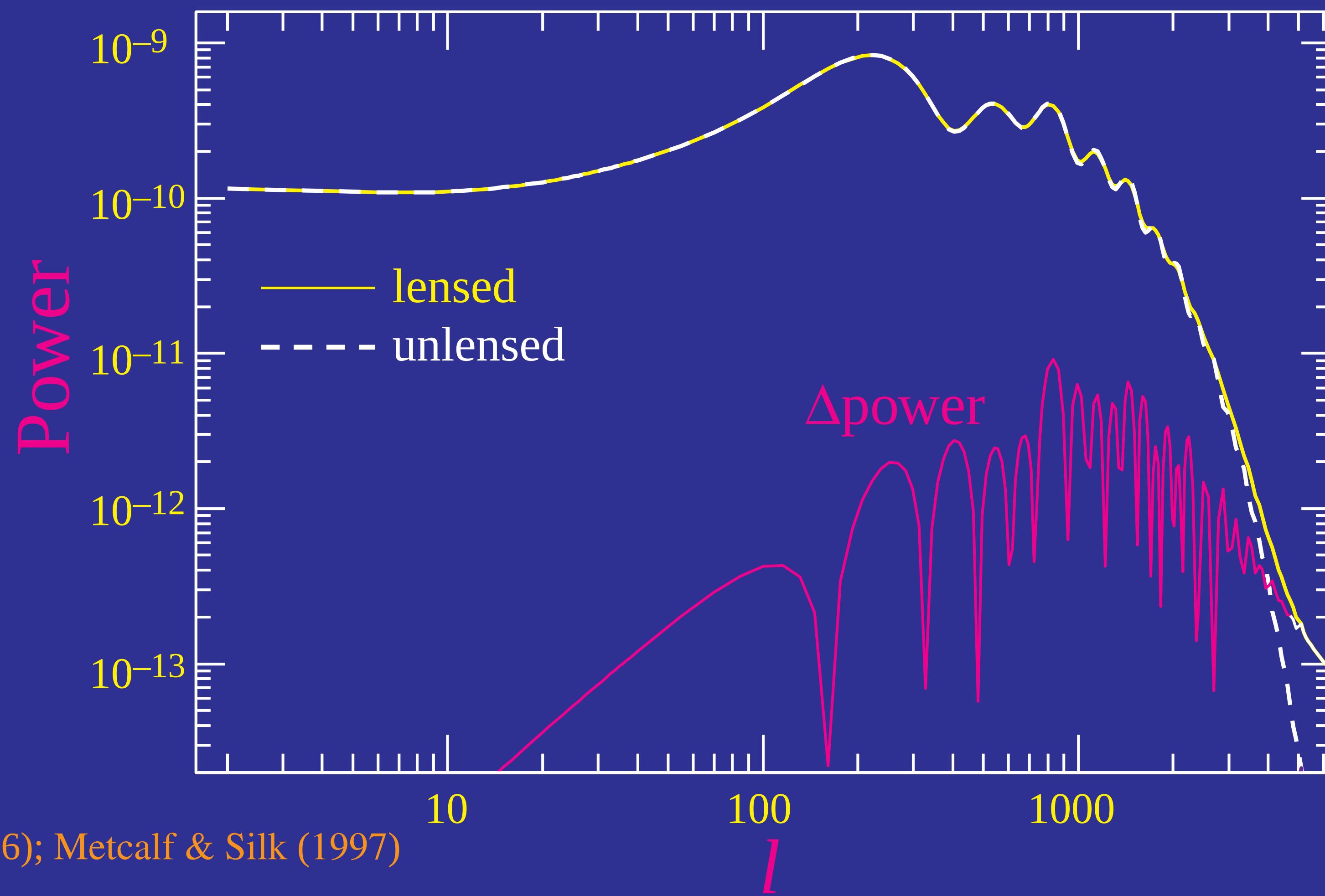
- Mass distribution at large angles and high redshift in in the linear regime
- Projected mass distribution (low pass filtered reflecting deflection angles): 1000 sq. deg



rms deflection
2.6'
deflection coherence
10°

Lensing in the Power Spectrum

- Lensing smooths the power spectrum with a width $\Delta l \sim 60$
- Sharp feature of damping tail is best place to see lensing



rms deflection
2.6'
coherence
10°

Seljak (1996); Metcalf & Silk (1997)

Reconstruction from the CMB

- Correlation between Fourier moments reflect lensing potential $\kappa = \nabla^2\phi$

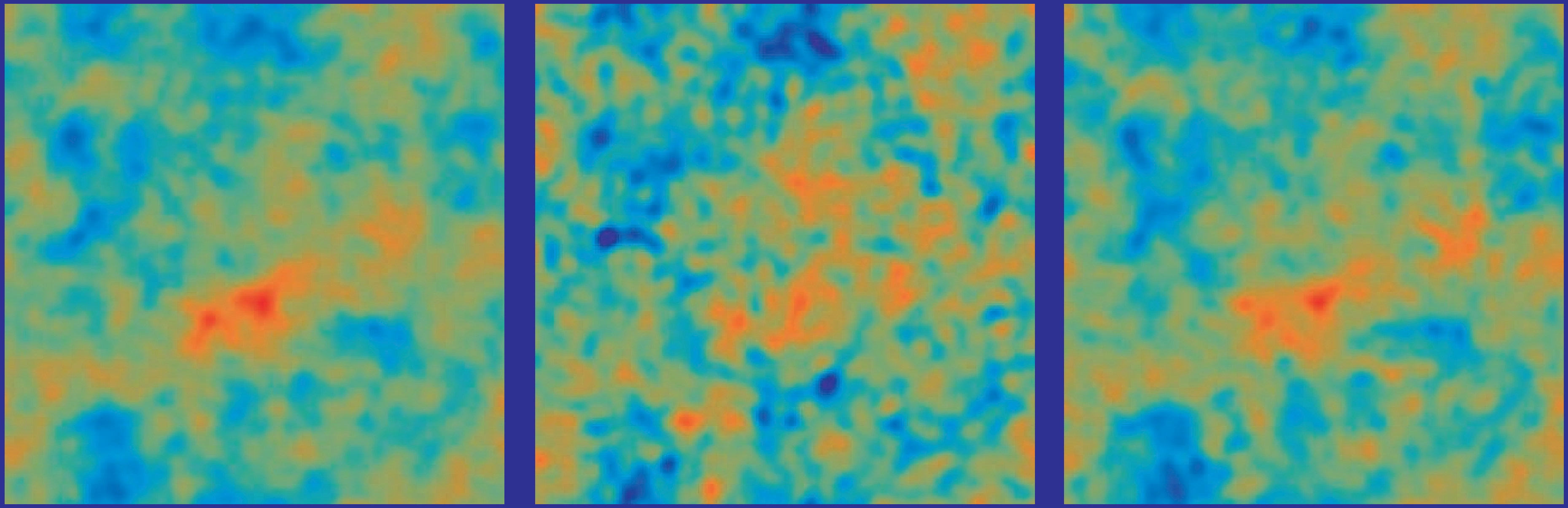
$$\langle x(\mathbf{l})x'(\mathbf{l}')\rangle_{\rm CMB} = f_\alpha(\mathbf{l},\mathbf{l}')\phi(\mathbf{l}+\mathbf{l}')\,,$$

  where $x \in$ temperature, polarization fields and f_α is a fixed weight that reflects geometry

- Each pair forms a noisy estimate of the potential or projected mass - just like a pair of galaxy shears
- Fundamentally relies on features in the power spectrum as found in the damping tail

Ultimate (Cosmic Variance) Limit

- Cosmic variance of CMB fields sets ultimate limit
- Polarization allows mapping to finer scales (~10')



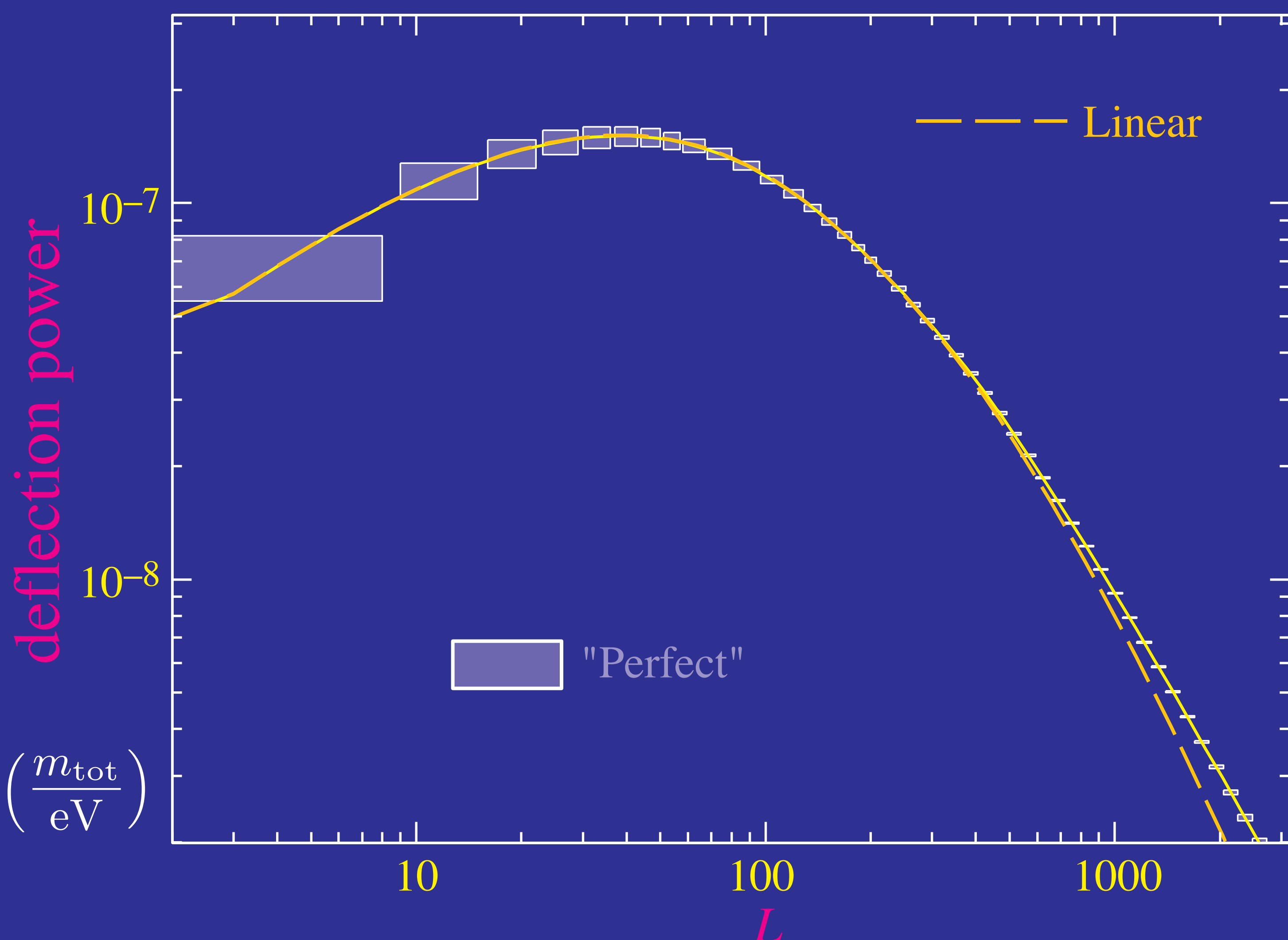
mass | temp. reconstruction | EB pol. reconstruction

100 sq. deg; 4' beam; 1μK-arcmin

Hu & Okamoto (2001)

Matter Power Spectrum

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



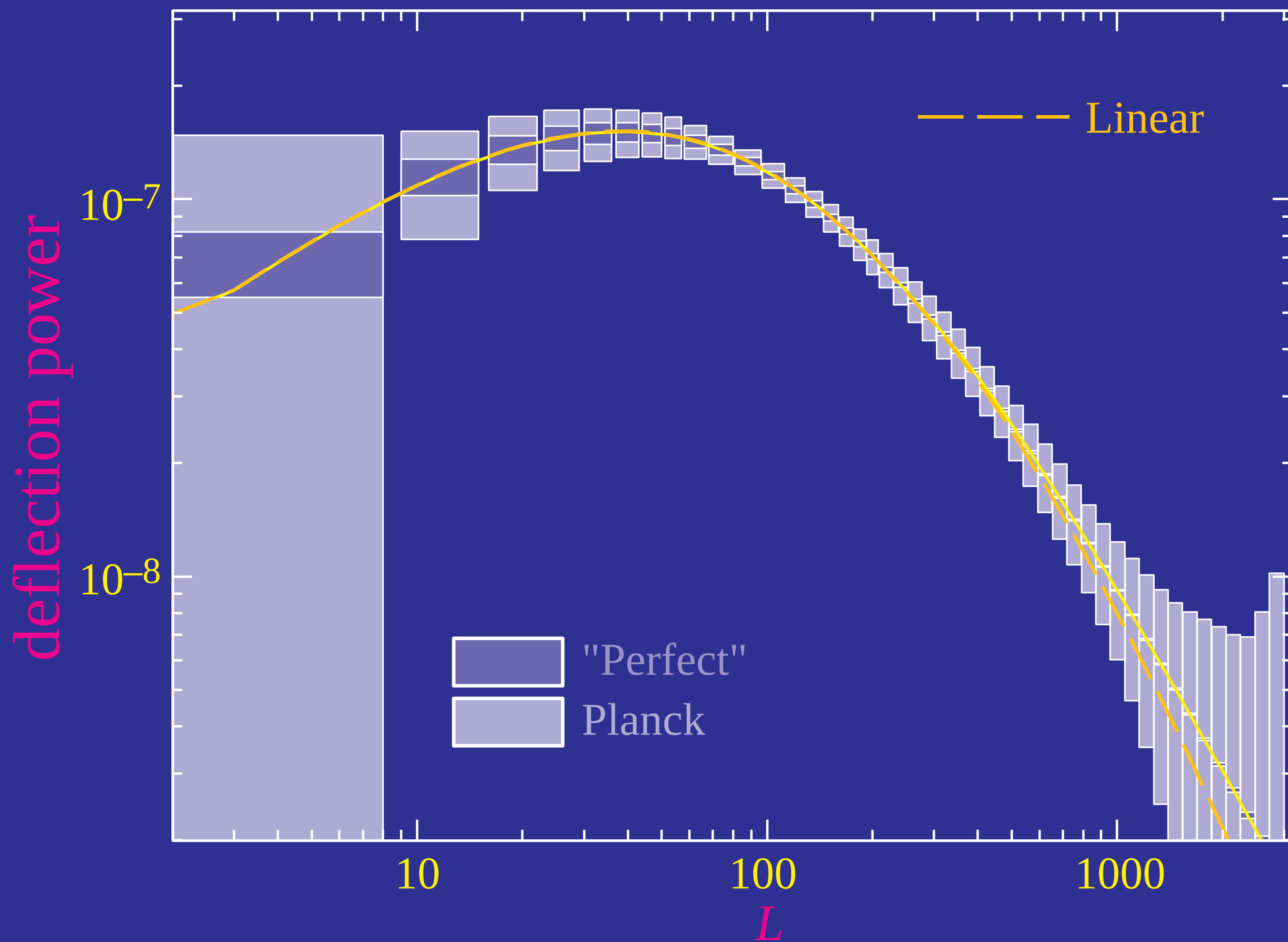
$$\frac{\Delta P}{P} \approx -0.6 \left(\frac{m_{\rm tot}}{\rm eV}\right)$$

Hu & Okamoto (2001)

$\sigma(w)$~0.06

Matter Power Spectrum

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

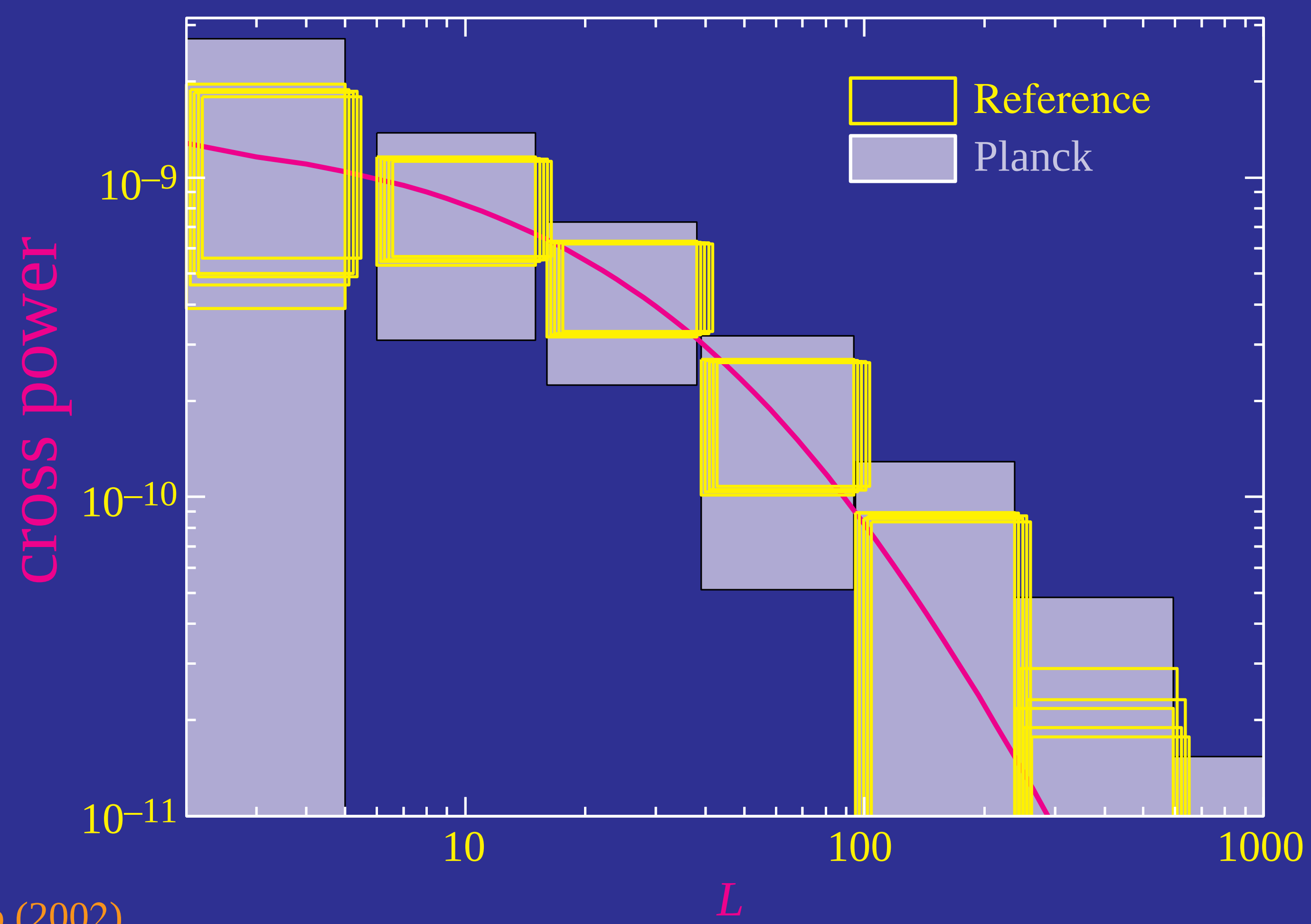


Hu & Okamoto (2001)

$\sigma(w)$~0.06; 0.14

Cross Correlation with Temperature

- Any correlation is a direct detection of a smooth energy density component through the ISW effect
- Dark energy smooth >5-6 Gpc scale, test scalar field nature

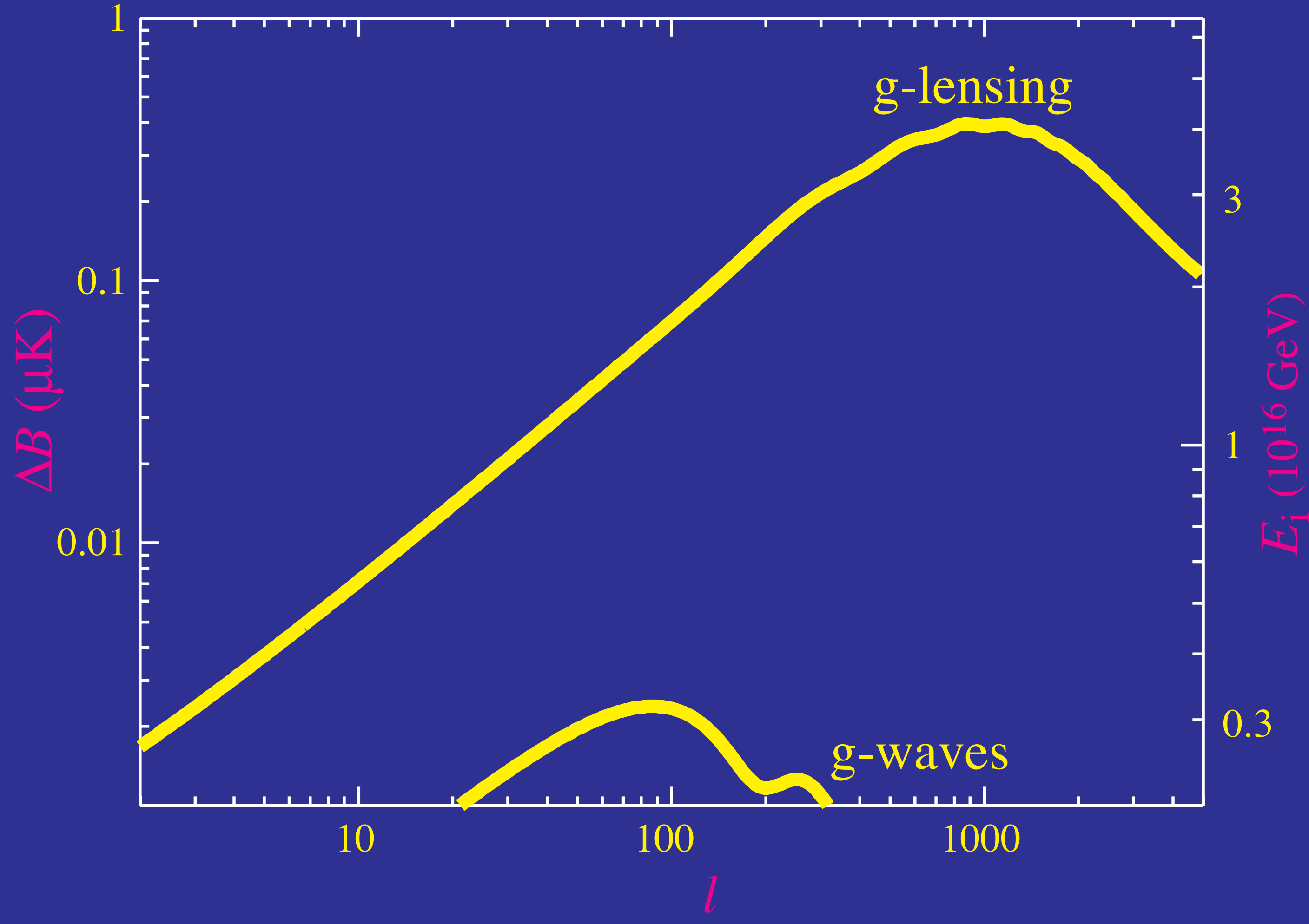


Hu & Okamoto (2002)

Contamination for Gravitational Waves

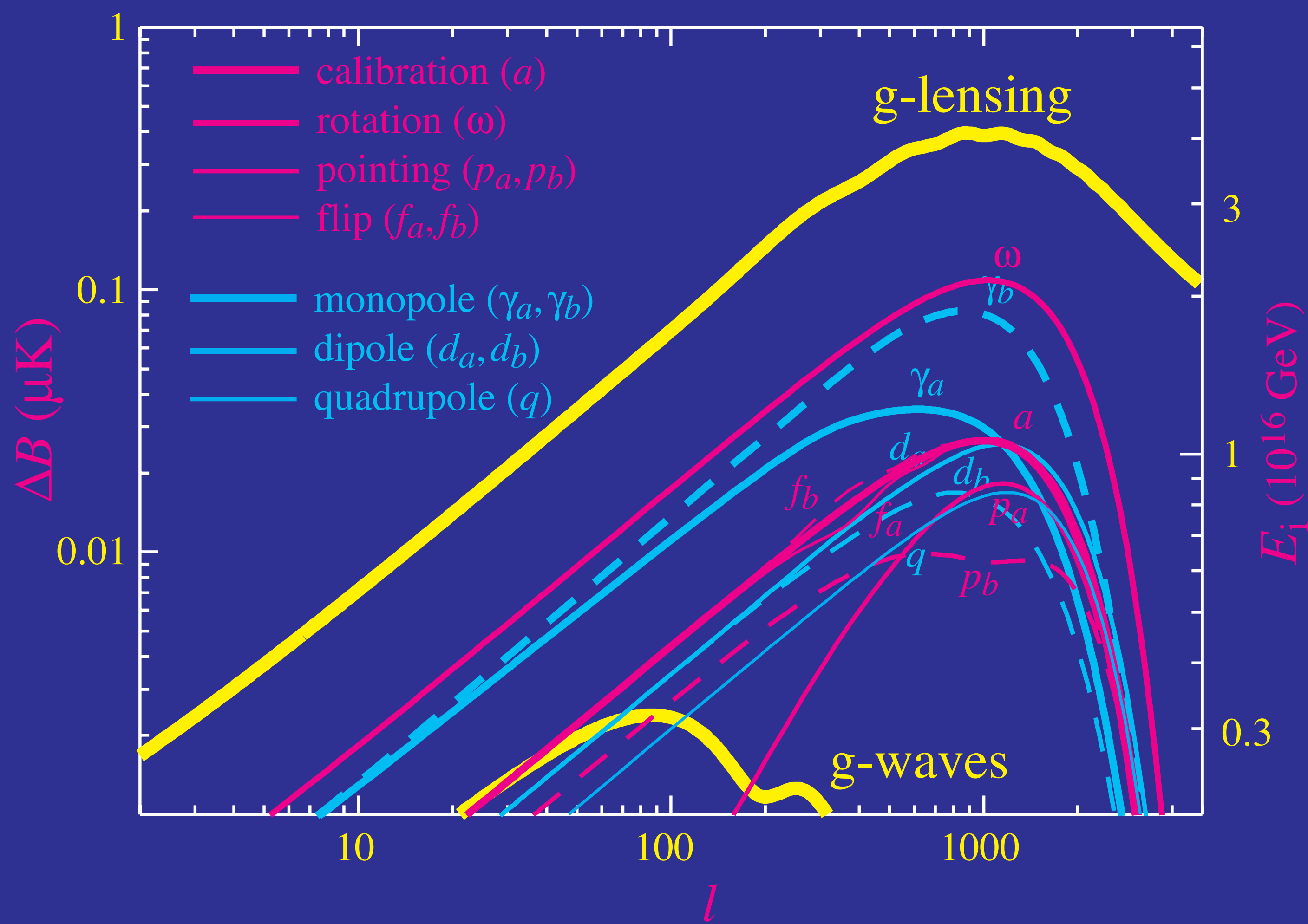
- Gravitational lensing contamination of B-modes from gravitational waves cleaned to E_i~0.3 x 10^{16} GeV

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



Contamination for Gravitational Waves

- A long road ahead:
  catalogue of some systematics



Stability!
Space?

Foregrounds?
MAP will tell..

10^{-3} rms
10^{-2} rms

Hu, Hedman & Zaldarriaga (2002)

Summary

- Damping of acoustic oscillations in CMB is due to the finite opacity of the plasma during recombination
- Damping length is a standard ruler for cosmology: independent of peak scale and tests recombination physics, e.g α

Summary

- Damping of acoustic oscillations in CMB is due to the finite opacity of the plasma during recombination
- Damping length is a standard ruler for cosmology: independent of peak scale and tests recombination physics, e.g α
- Damping is the fundamental source of acoustic polarization, recently detected

Summary

- Damping of acoustic oscillations in CMB is due to the finite opacity of the plasma during recombination
- Damping length is a standard ruler for cosmology: independent of peak scale and tests recombination physics, e.g α
- Damping is the fundamental source of acoustic polarization, recently detected
- Features in damping tail allow the distribution of matter to be mapped through gravitational lensing
- Damping eliminates primary anisotropy and allows smaller secondary signals to be measured at arcminute scales, e.g. the SZE.