CMB Polarization

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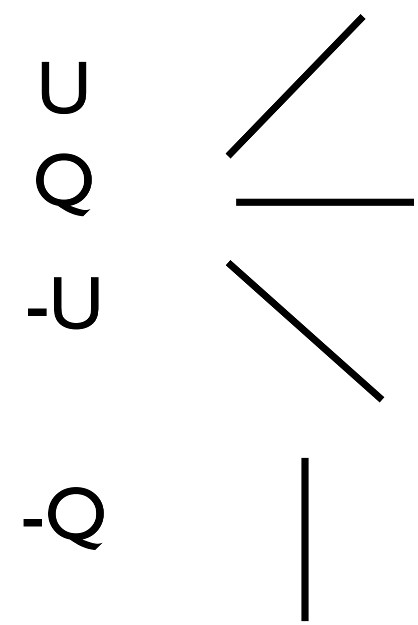
CMB is polarized

- Amplitude of polarization fluctuations is small (0.5-3% of temperature fluctuations)
- Independent probe of the nature of the fluctuations
- Sensitive to re-ionization signal
- Sensitive to gravity waves
- POLARIZATION IS THE FUTURE!

Stokes Parameters

$$E_x = a_x(t)\cos\left[\omega_0 t - \theta_x(t)\right], \quad E_y = a_y(t)\cos\left[\omega_0 t - \theta_y(t)\right].$$

$$\begin{aligned}
I &\equiv \langle a_x^2 \rangle + \langle a_y^2 \rangle; \\
Q &\equiv \langle a_x^2 \rangle - \langle a_y^2 \rangle; \\
U &\equiv \langle 2 a_x a_y \cos(\theta_x - \theta_y) \rangle; \\
V &\equiv \langle 2 a_x a_y \sin(\theta_x - \theta_y) \rangle.
\end{aligned}$$

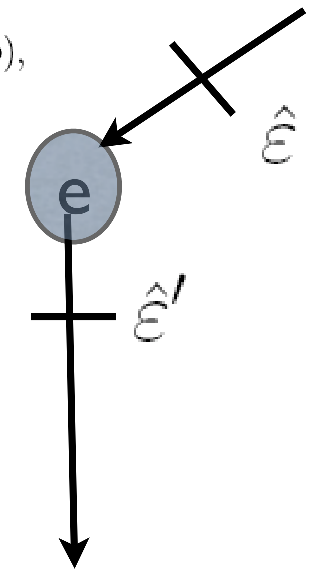


Thomson Scattering Generates Polarization

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

Photon field around the electron along the line of sight

$$I'(\theta, \phi) = \sum_{lm} a_{lm} Y_{lm}(\theta, \phi),$$



$$I(\hat{\mathbf{z}}) = \frac{3\sigma_T}{16\pi\sigma_B} \int d\Omega (1 + \cos^2\theta) I'(\theta, \phi),$$

$$Q(\hat{\mathbf{z}}) - iU(\hat{\mathbf{z}}) = \frac{3\sigma_T}{16\pi\sigma_B} \int d\Omega \sin^2\theta e^{2i\phi} I'(\theta, \phi).$$

Local quadruple is converted into polarization

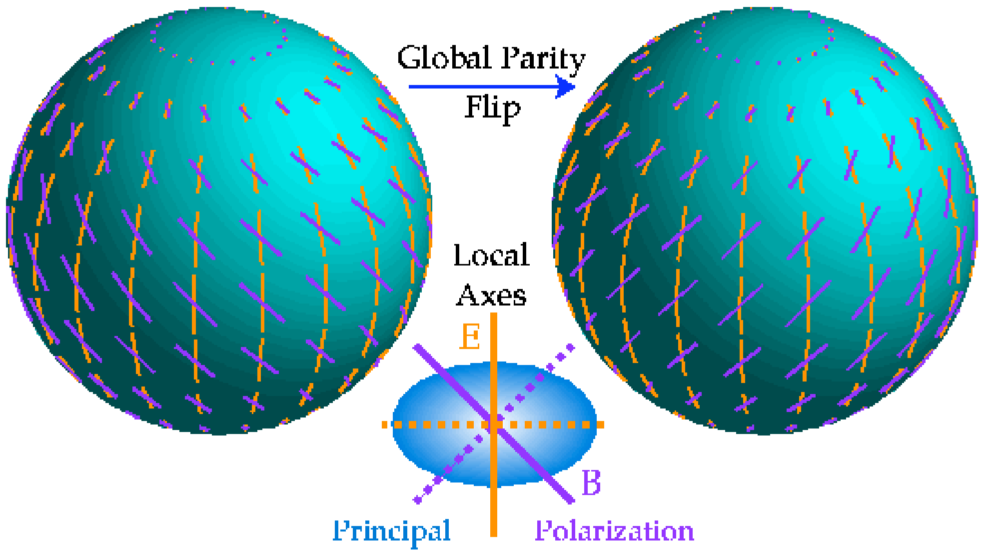
$$Q(\hat{\mathbf{z}}) - iU(\hat{\mathbf{z}}) = \frac{3\sigma_T}{4\pi\sigma_B} \sqrt{\frac{2\pi}{15}} a_{22}.$$

E + B modes

$$T(\hat{n}) = \sum_{lm} a_{lm} Y_{lm}(\hat{n})$$

$$Q(\hat{n}) \pm iU(\hat{n}) = \sum_{lm} a_{\mp 2,lm} \; {}_{\mp 2}Y_{lm}(\hat{n})$$

$$a_{\pm 2,lm} = E_{lm} \pm iB_{lm}.$$

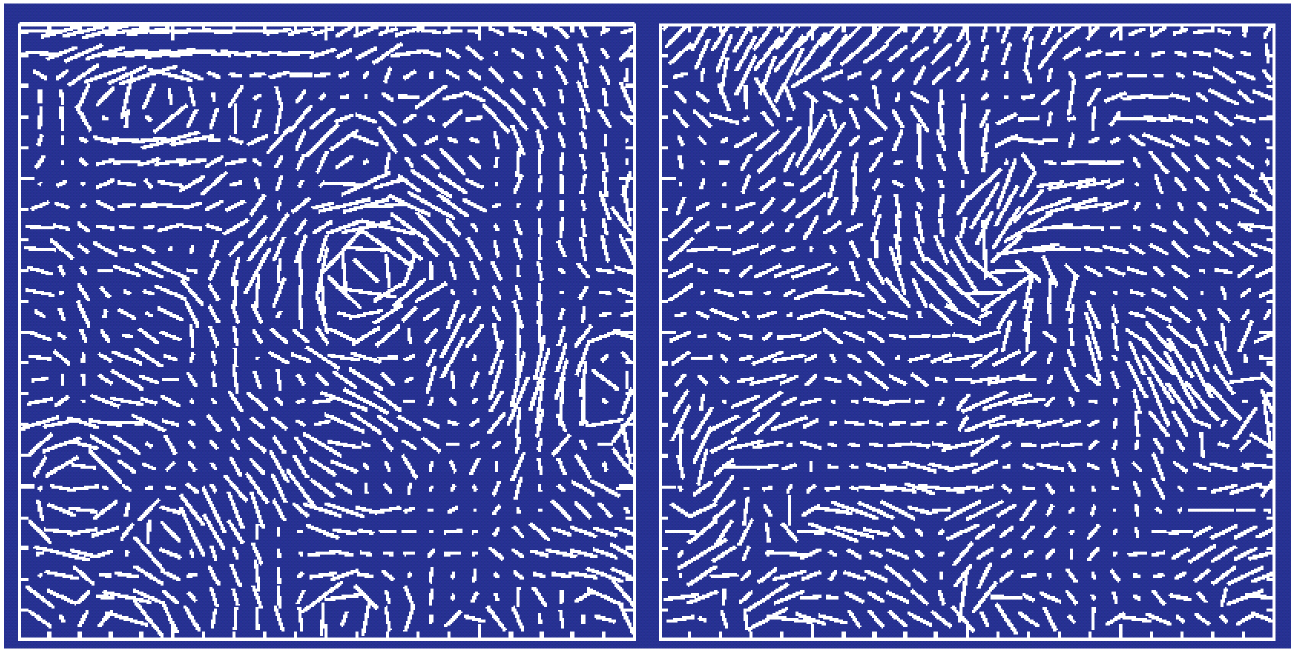


E modes are symmetric under parity rotation

Scalar fluctuations generate only E modes

Tensor fluctuations generate only E + B modes

E + B modes



Hu and White

E modes

B modes

More Rigorous Temperature and Polarization Equations

$$\Theta^{T,P}(\vec{k},\hat{n}) = \sum_l (2l+1)(-i)^l \Theta_l^{T,P} P_l(\mu)$$

$$\mu = \hat{k}\cdot\hat{n}$$

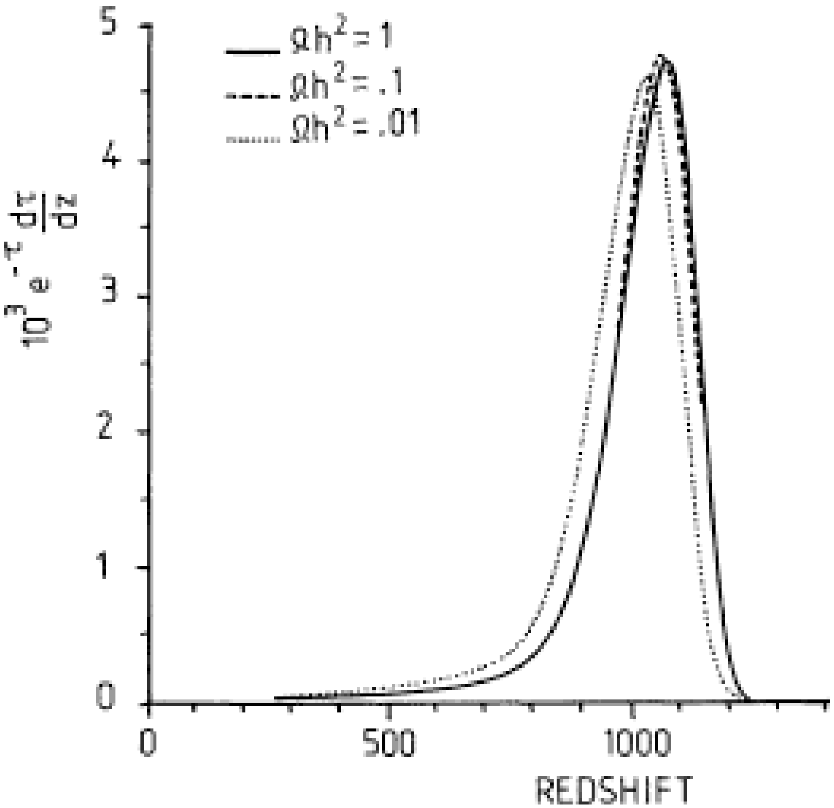
$$\dot{\tau} = n_e \sigma_T a$$

$$\Pi = \Delta_{T2} + \Delta_{P2} + \Delta_{P0}$$

$$\Theta_T(k,\mu,\eta_0) = \int_0^{\tau_0} d\eta e^{ik\mu(\eta-\eta_0)} e^{-\tau}\left[\dot{\tau}(\Theta_0^T + i\mu v_b + \frac{1}{2}\Pi P_2(\mu)) + \dot{\phi} - ik\mu\psi\right]$$

$$\Theta_P(k,\mu,\eta_0) = -\frac{1}{2}\int_0^{\eta_0} d\eta e^{ik\mu(\eta-\eta_0)} e^{-\tau}\dot{\tau}[1-P_2(\mu)]\Pi$$

Visibility Function



Wyse and Jones 1985

Power Spectrum

$$C_l^{TT} = (4\pi)^2 \int k^2 dk P_\psi(k) |\Theta_{Tl}(k,\tau_0)|^2$$

$$C_l^{EE} = (4\pi)^2 \int k^2 dk P_\psi(k) |\Theta_{El}(k,\tau_0)|^2$$

Polarization Signal Generated at Surface of Last Scatter

Tight Coupling Approximation

$$\Theta_P = 0.51(1-\mu^2)e^{ik\mu(\eta_D-\eta_0)}(\Delta\eta)_D k\Theta_1$$

Thickness of S.L.S.

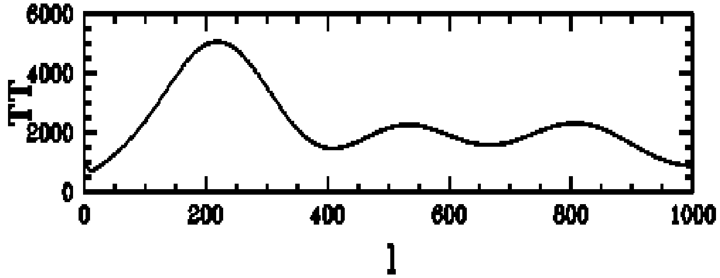
Gradient of velocity field

$$\Theta_P \propto k\sin(kr_s)\exp(-k^2/k_D^2)j_l(k(\eta_0-\eta_D))$$ Adiabatic

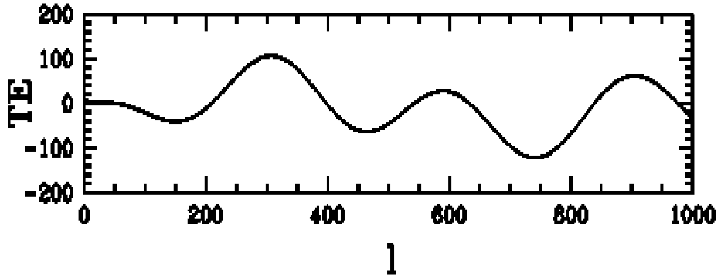
$$\Theta_P \propto k\cos(kr_s)\exp(-k^2/k_D^2)j_l(k(\eta_0-\eta_D))$$ Isocurvature

Zaldarriaga and Harari 1995

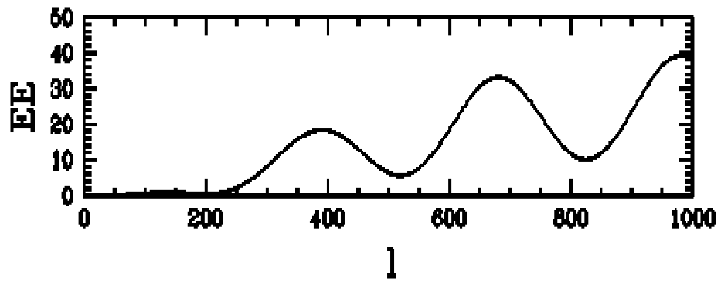
Adiabatic Modes



$$\cos^2(kr_s)$$



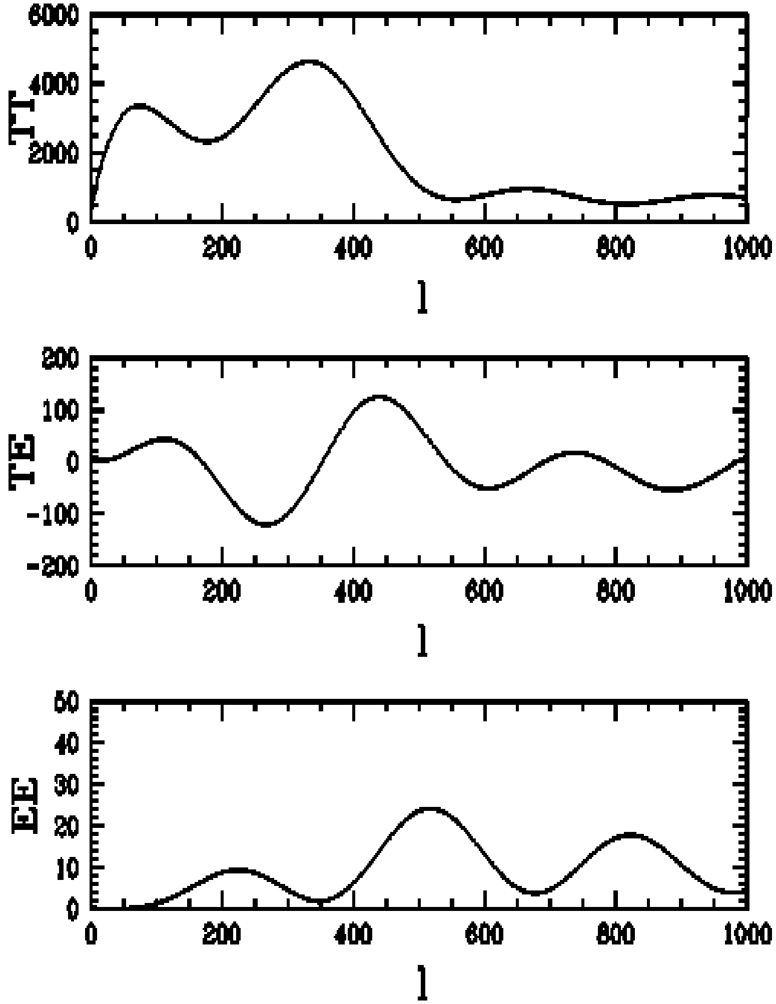
$$-k\sin(kr_s)\cos(kr_s)$$



$$k^2\sin^2(kr_s)$$

+Silk damping at high k

Isocurvature Modes

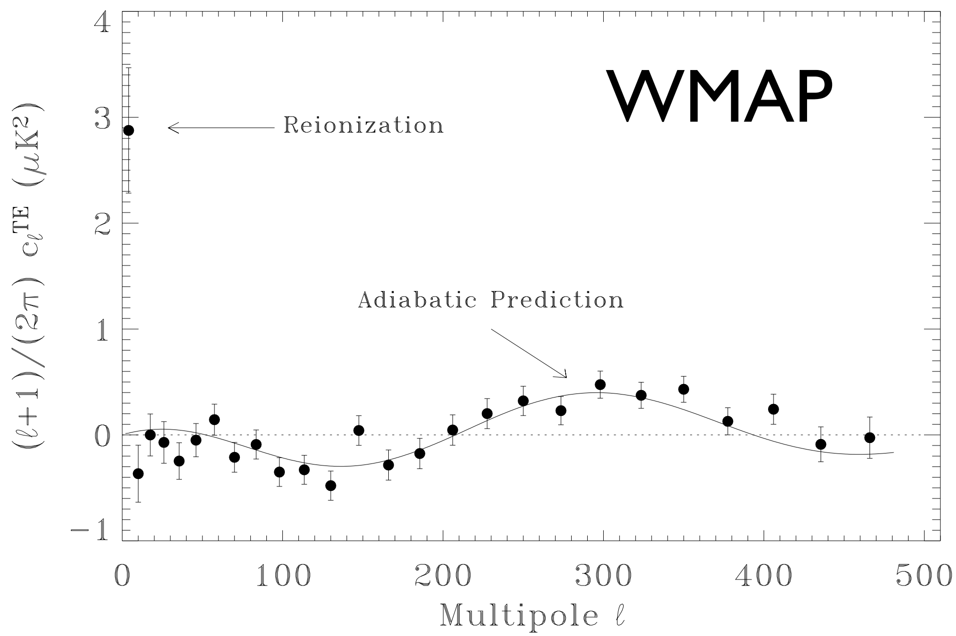


$$\sin^2(kr_s)\exp(-k^2/k_D^2)$$

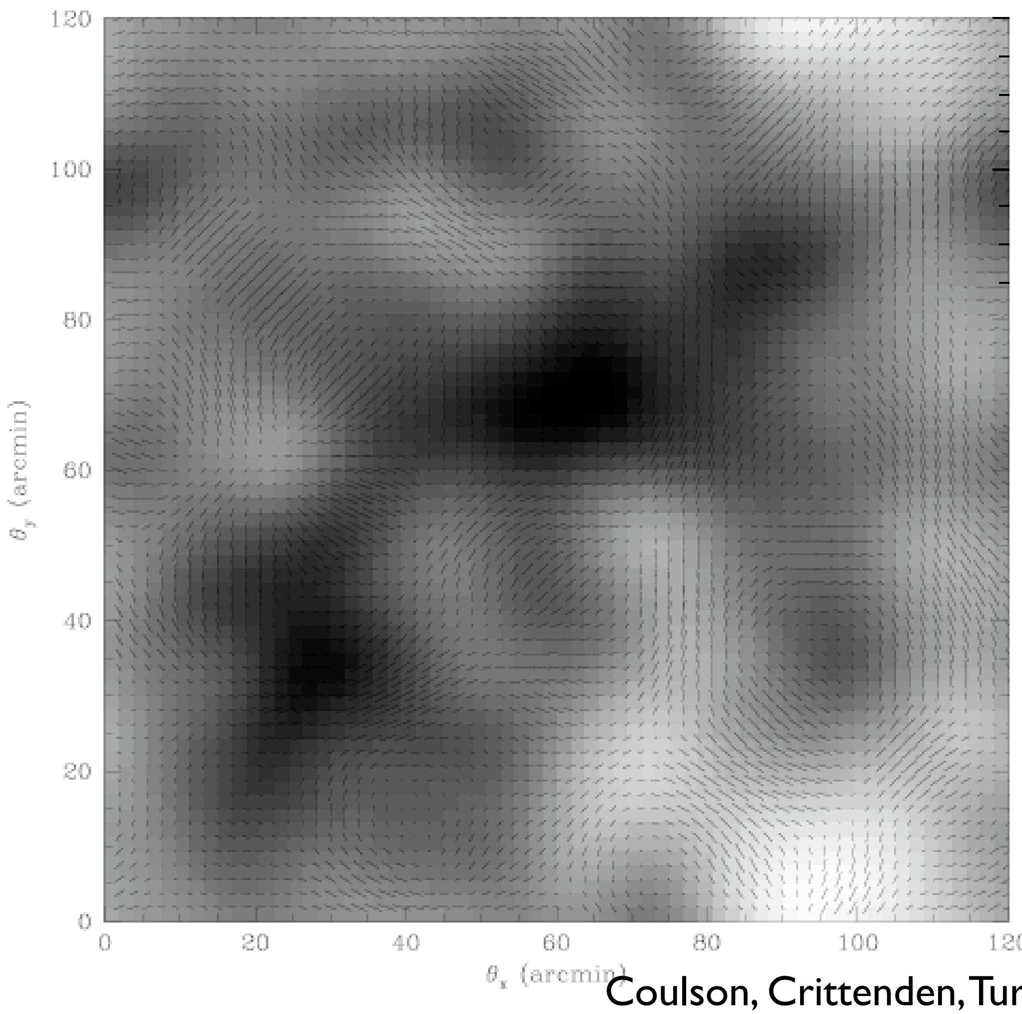
$$k\sin(kr_s)\cos(kr_s)\exp(-k^2/k_D^2)$$

$$k^2\cos^2(kr_s)\exp(-k^2/k_D^2)$$

Current Data

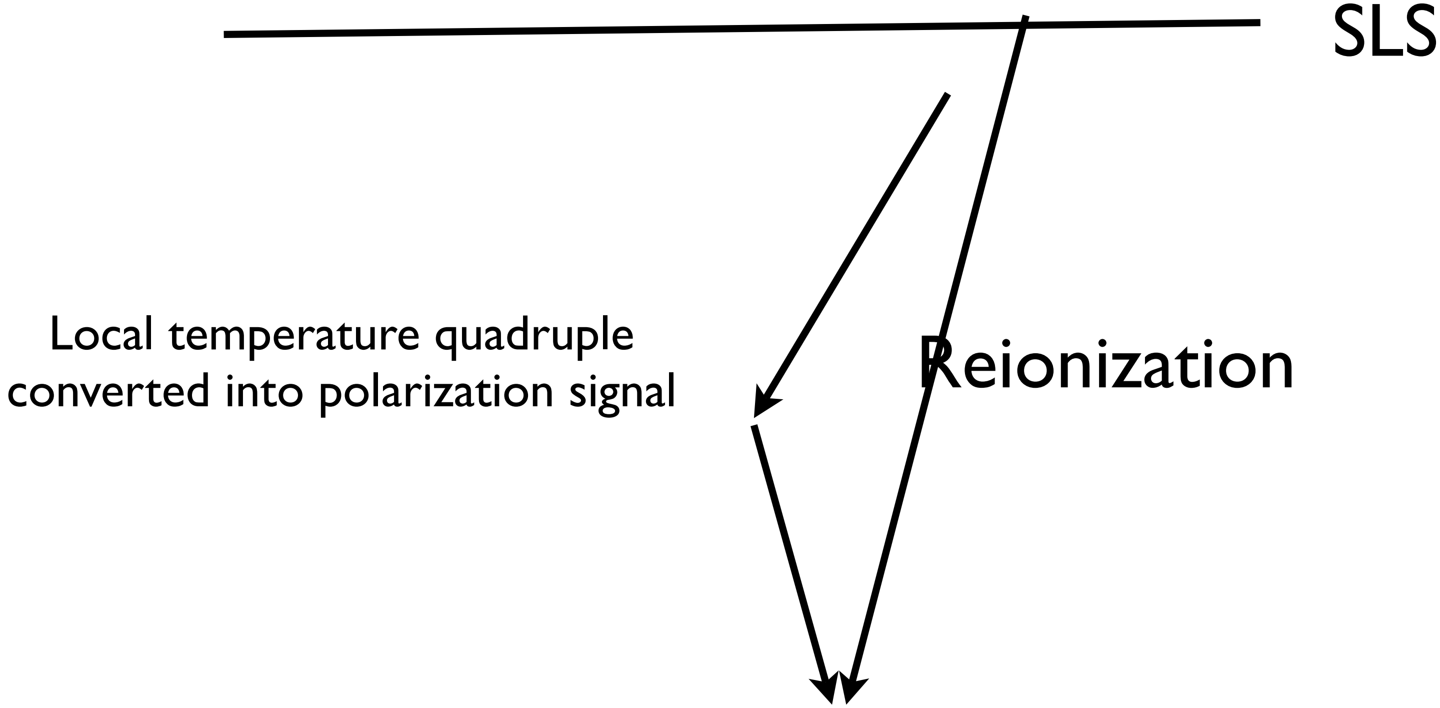


TE Correlation



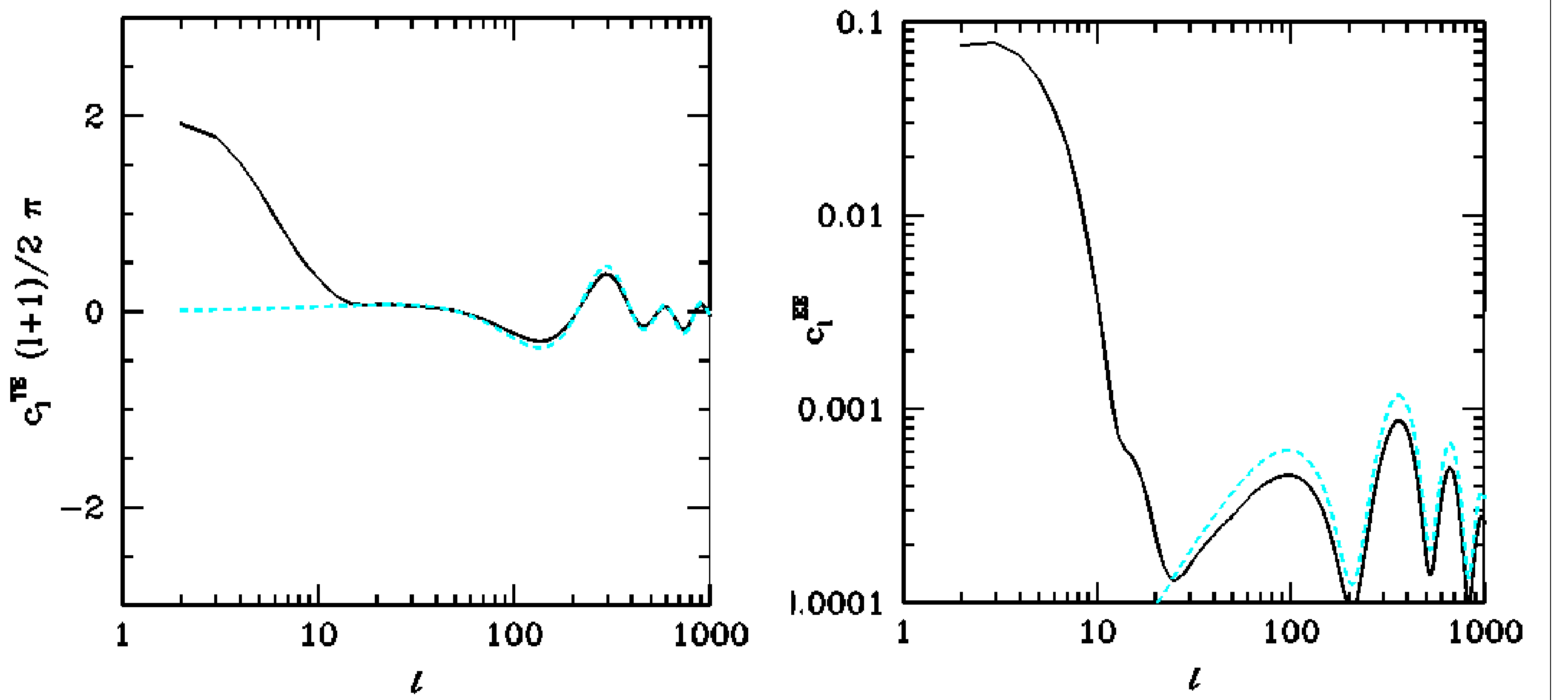
Coulson, Crittenden, Turok 1994

Reionization



$$\tau_{reioni} = \int_0^{z_{reion}} n_e(z)\sigma_T c dt \propto (1 + z_{reion})^{3/2}$$

Re-ionization Power Spectrum



EE and Reionization History

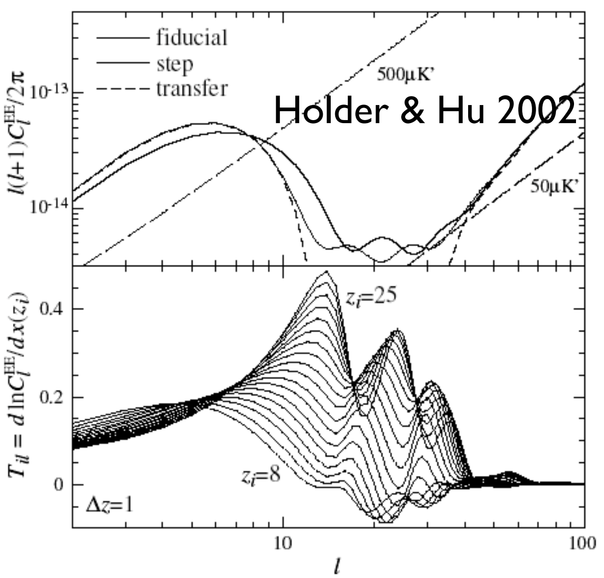
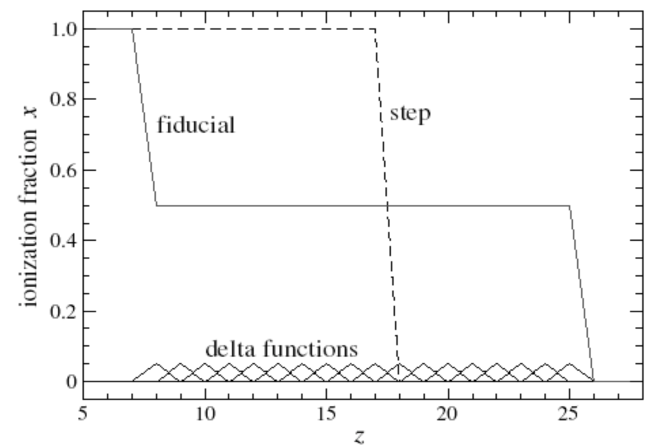
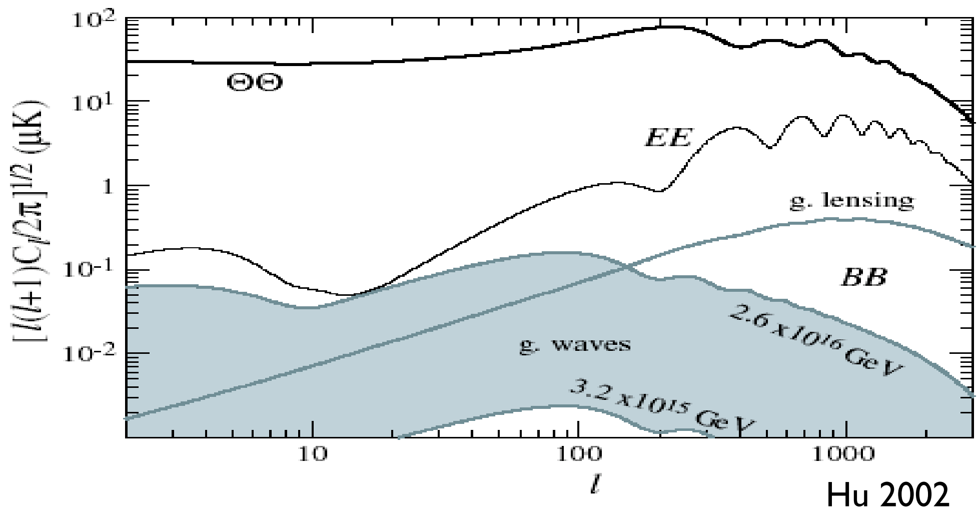


FIG. 2: Top: E-mode polarization power spectrum for: the fiducial model of Fig. 1 (thick); the step function model (thin); the step function model with deviations transferred onto the fiducial model (dashed); instrumental noise $w_P^{-1/2}$ (denoted in μK-arcmin) that roughly brackets expectations from WMAP and Planck (long dashed). Bottom: the transfer function or fractional power spectrum response to a delta function perturbation of unit amplitude at $8 \le z_i \le 25$.



Gravity Waves

r = Tensor/Scalar ratio
r= 7(1-n)



Hu 2002

$$c_l^{EE} \propto \tau^2(1+r)$$

$$c_l^{BB} \propto \tau^2 r$$

Gravitational Lensing rotates E modes into B modes

Challenges of measuring Gravity Waves

- Weak Signal 0.01uK
  - competing with mK CMB dipole
  - instrumental noise (5 mK/observation)
  - instrument can alias T into polarization or E into B modes
- Galactic Foregrounds
  - dust
  - synchrotron
- Gravitational Lensing

High Science Payoff, Technical Challenging:
Many Planned Experiments

WMAP Long-term Goal

- Detect spectral index variation and gravity wave signal predicted by simple inflationary models ($r \sim 0.2 - 0.3$; $n \sim 0.95\text{-}0.97$)
- Hopeful that we will achieve this goal

Key Concepts

- Thomson scattering is anisotropic: Converts temperature quadruple into polarized signal
- Small angular scales: Polarization signal comes from photon dipole (velocity) and tests nature of fluctuations. Data consistent with adiabatic modes.
- Large angular scales: temperature quadruple is converted into a polarization signal. Amplitude depends on reionization history
- Polarization can be decomposed into E and B modes
  - Scalar fluctuations generate E modes
  - Tensor fluctuations generate E + B mode

Questions

- If there was no reionization, does the late ISW effect generate any polarization fluctuations?
- Cosmic strings generate uncorrelated motions on large scales. Would these produce any B modes?
- The galactic magnetic field is thought to be primarily in the plane and follow the spiral structure. Synchrotron polarization emission is polarized perpendicular to the B field direction. Is foreground emission mostly E or B mode? Which multiple?