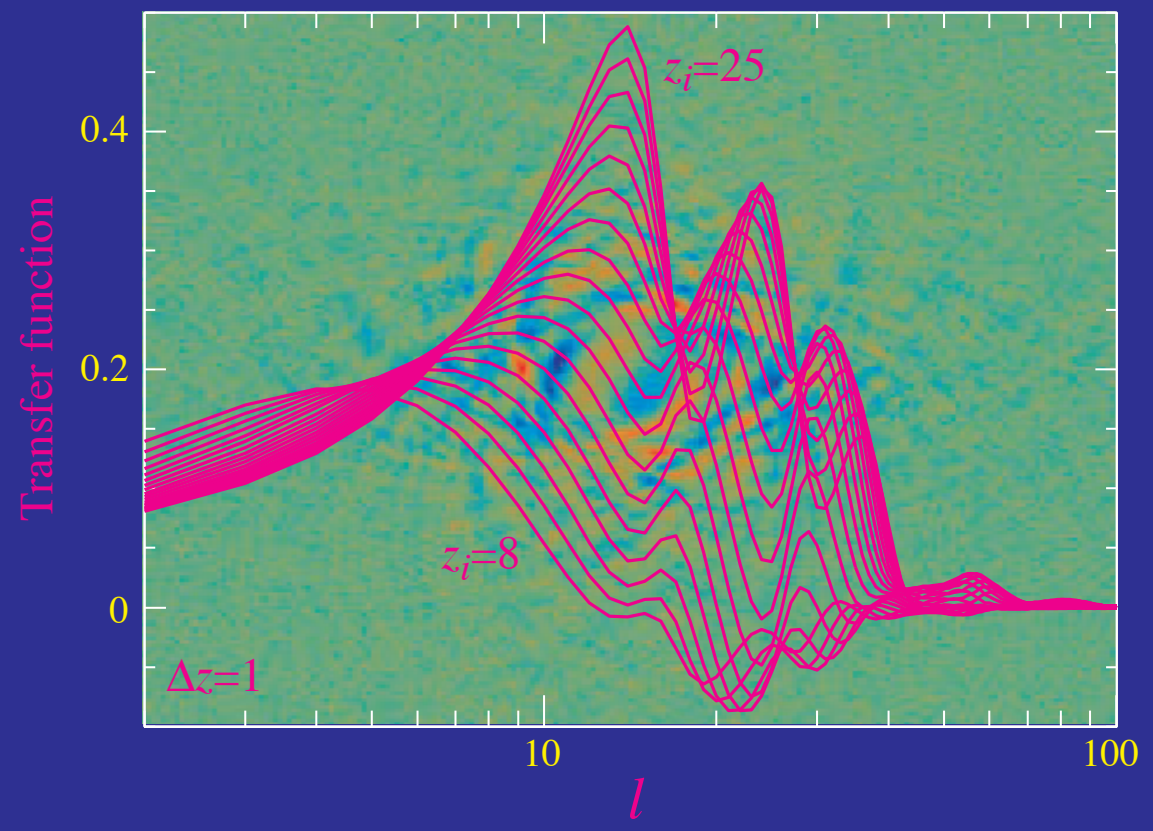
Secondary Polarization



Reionization and Gravitational Lensing

Wayne Hu

Minnesota, March 2003

Outline

- Reionization Bump

  Model independent treatment of ionization history

  Linear response and the inverse problem

  Compact representation in principal components

  Unbiased measurement of initial amplitude

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  E-B correlation

  Minimum variance estimator

  Dark energy applications

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  Dark energy applications

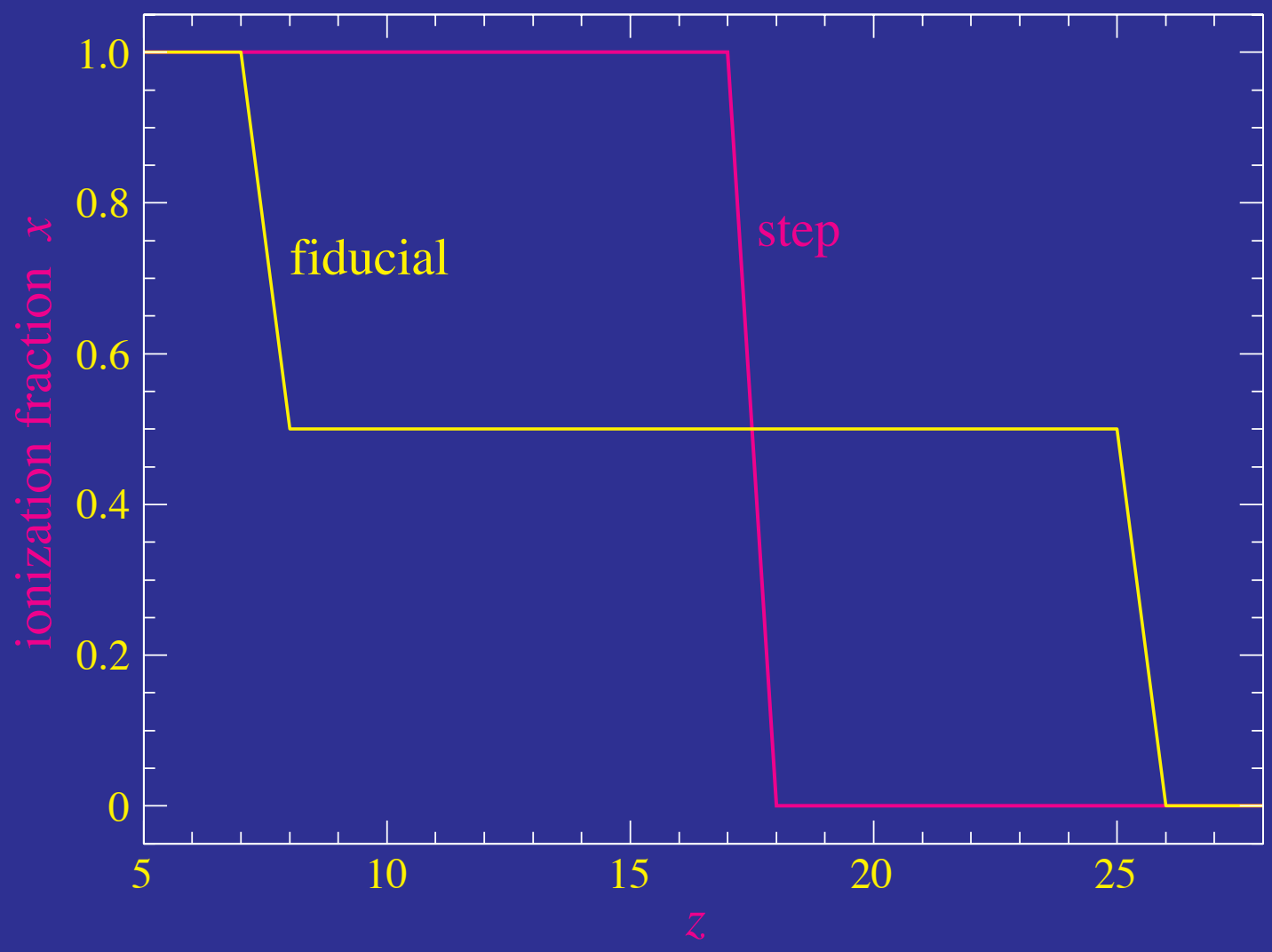
- Collaborators:

Matt Hedman	Gil Holder
Takemi Okamoto	Matias Zaldarriaga

Reionization

Ionization History

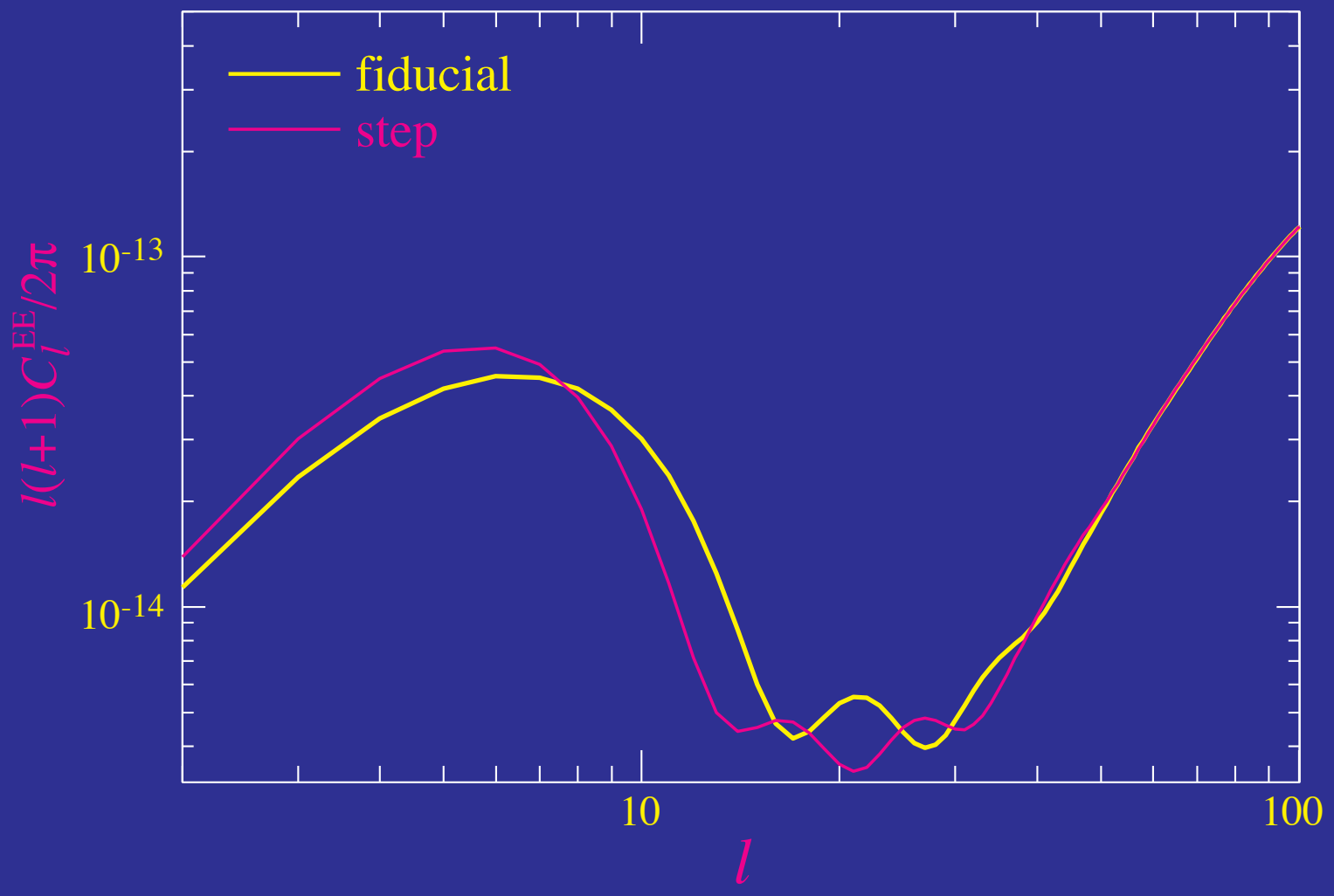
- Two models with same optical depth τ but different ionization history



Kaplinghat et al. (2002); Hu & Holder (2003)

Distinguishable History

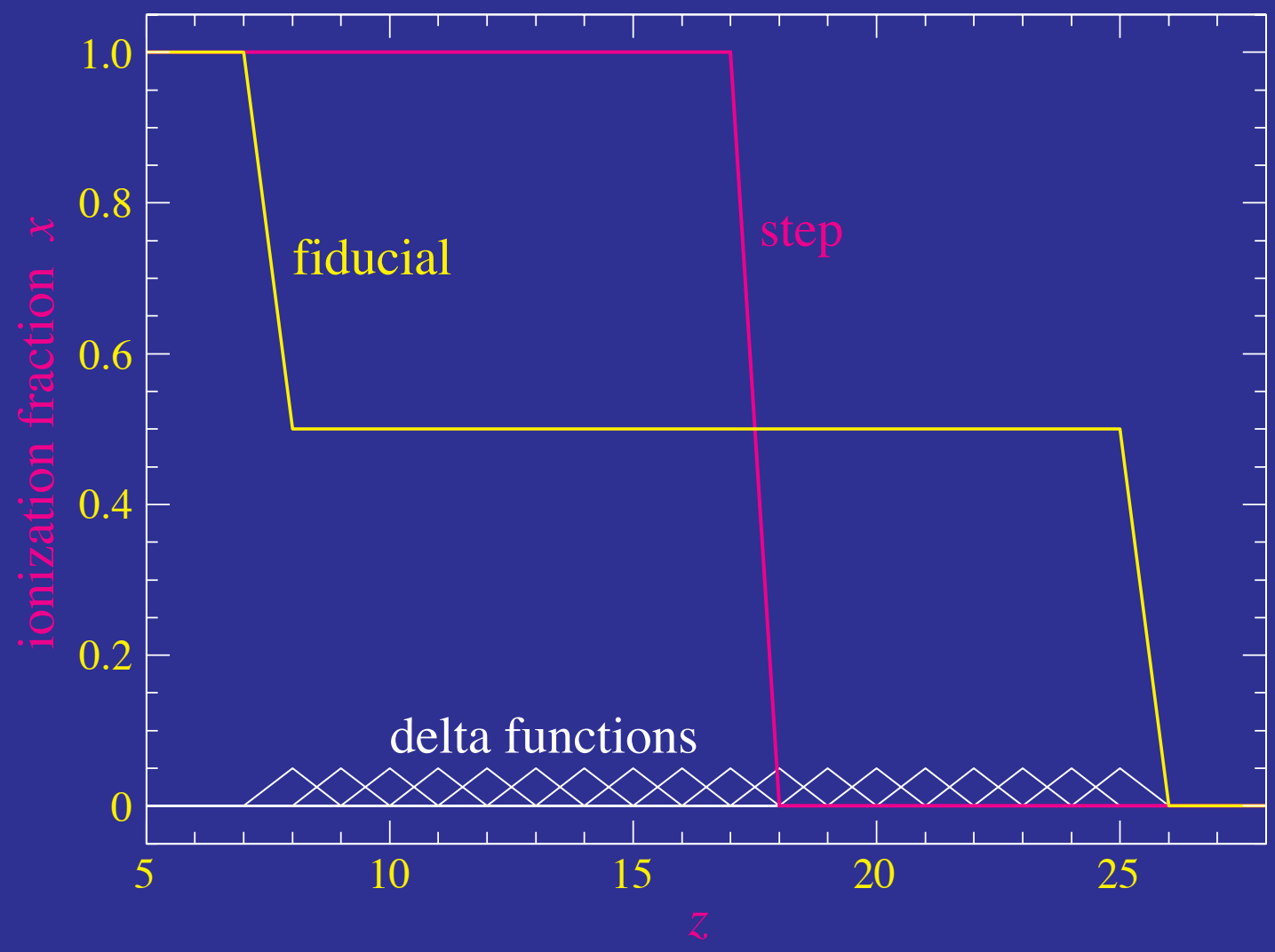
- Same optical depth, but different coherence - horizon scale during scattering epoch



Kaplinghat et al. (2002); Hu & Holder (2003)

Complete Basis

- Define a complete representation of the ionization history in the discrete (linear interpolation) approximation

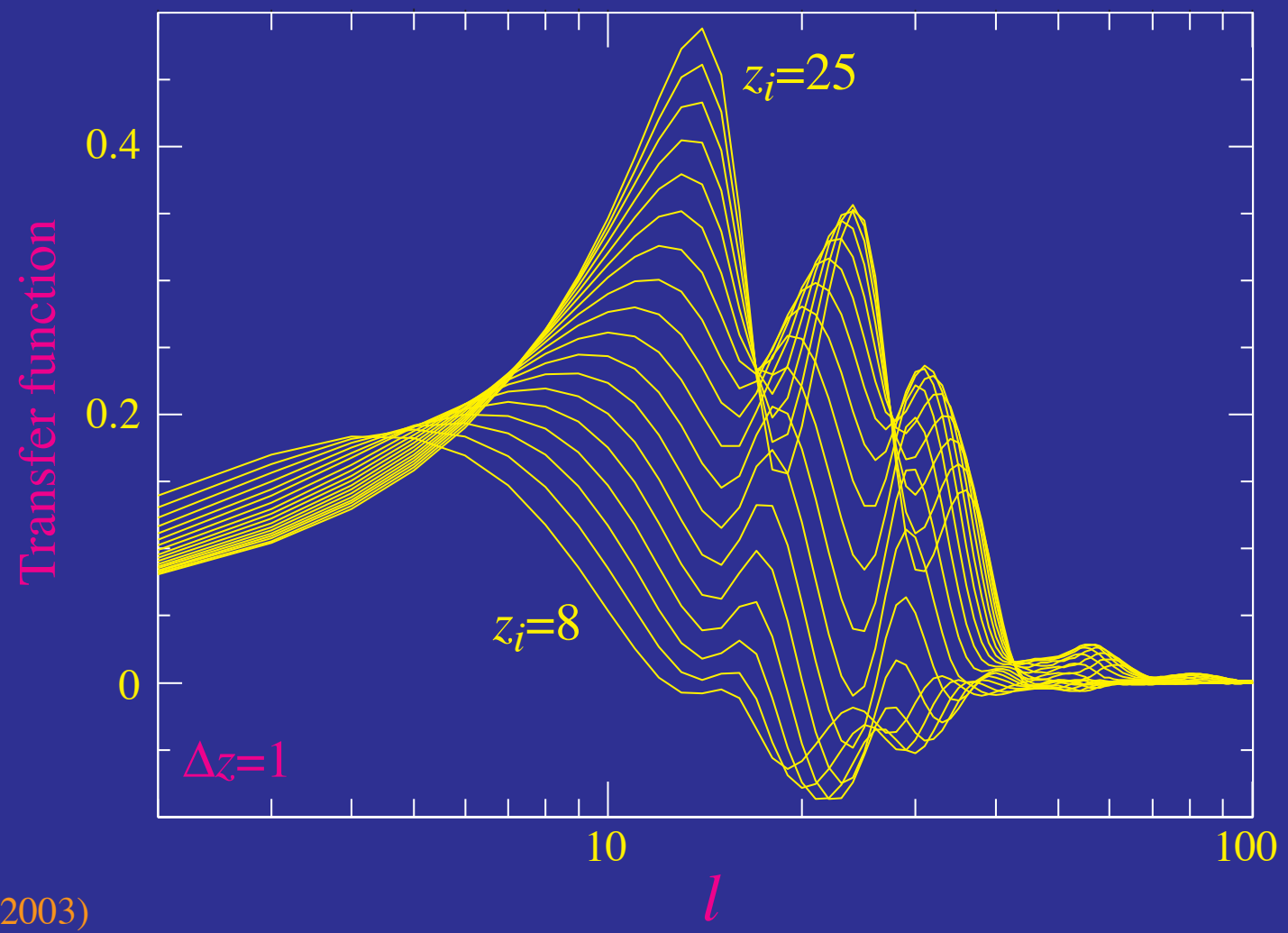


Hu & Holder (2003)

Transfer Function

- Linearized response to delta function ionization perturbation

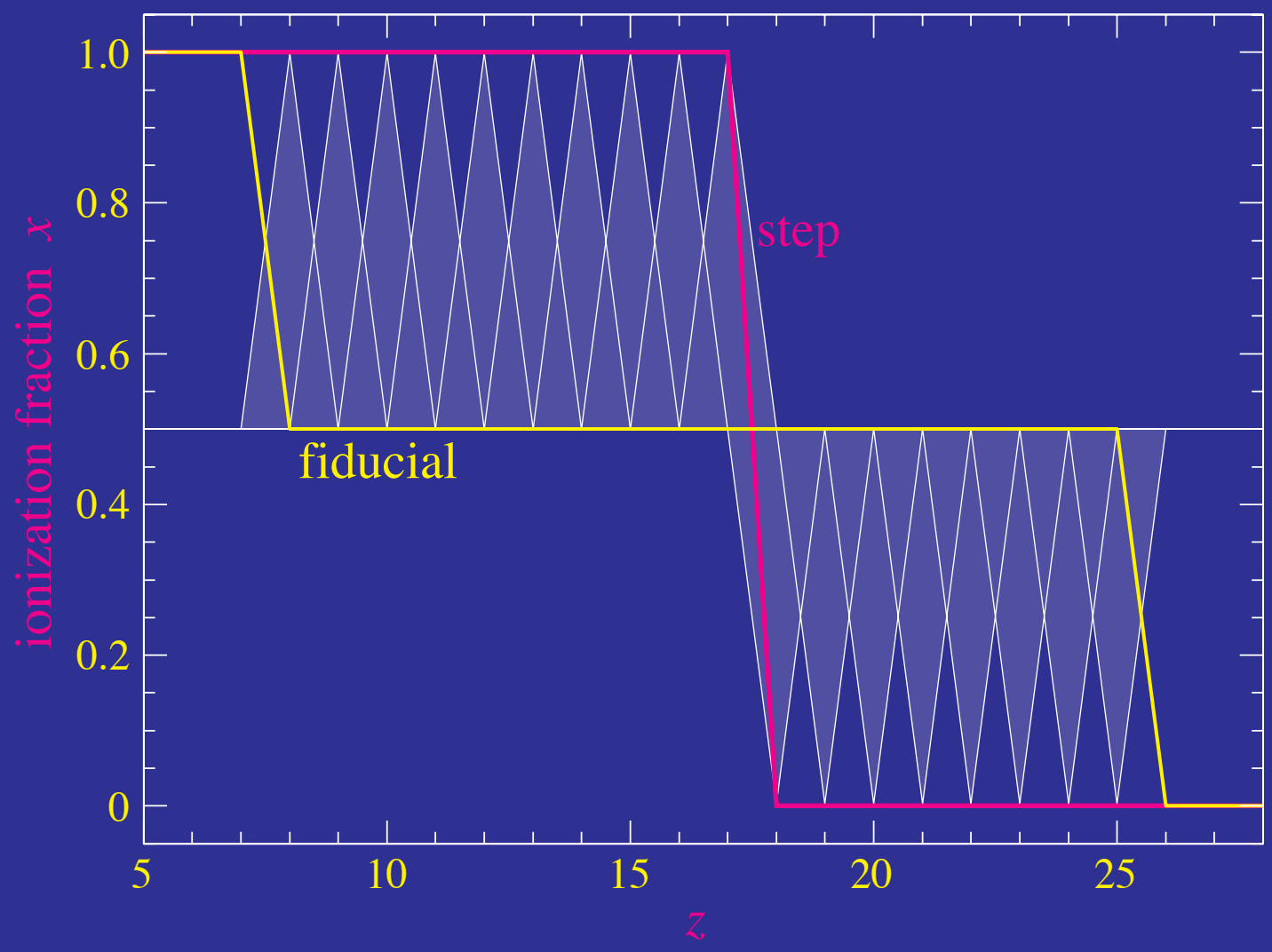
$$T_{\ell i} \equiv \frac{\partial \ln C_\ell^{EE}}{\partial x(z_i)}, \qquad \delta C_\ell^{EE} = C_\ell^{EE} \sum_i T_{\ell i} \delta x(z_i)$$



Hu & Holder (2003)

Linear Response

- Worst case scenario: maximal perturbations from fiducial model

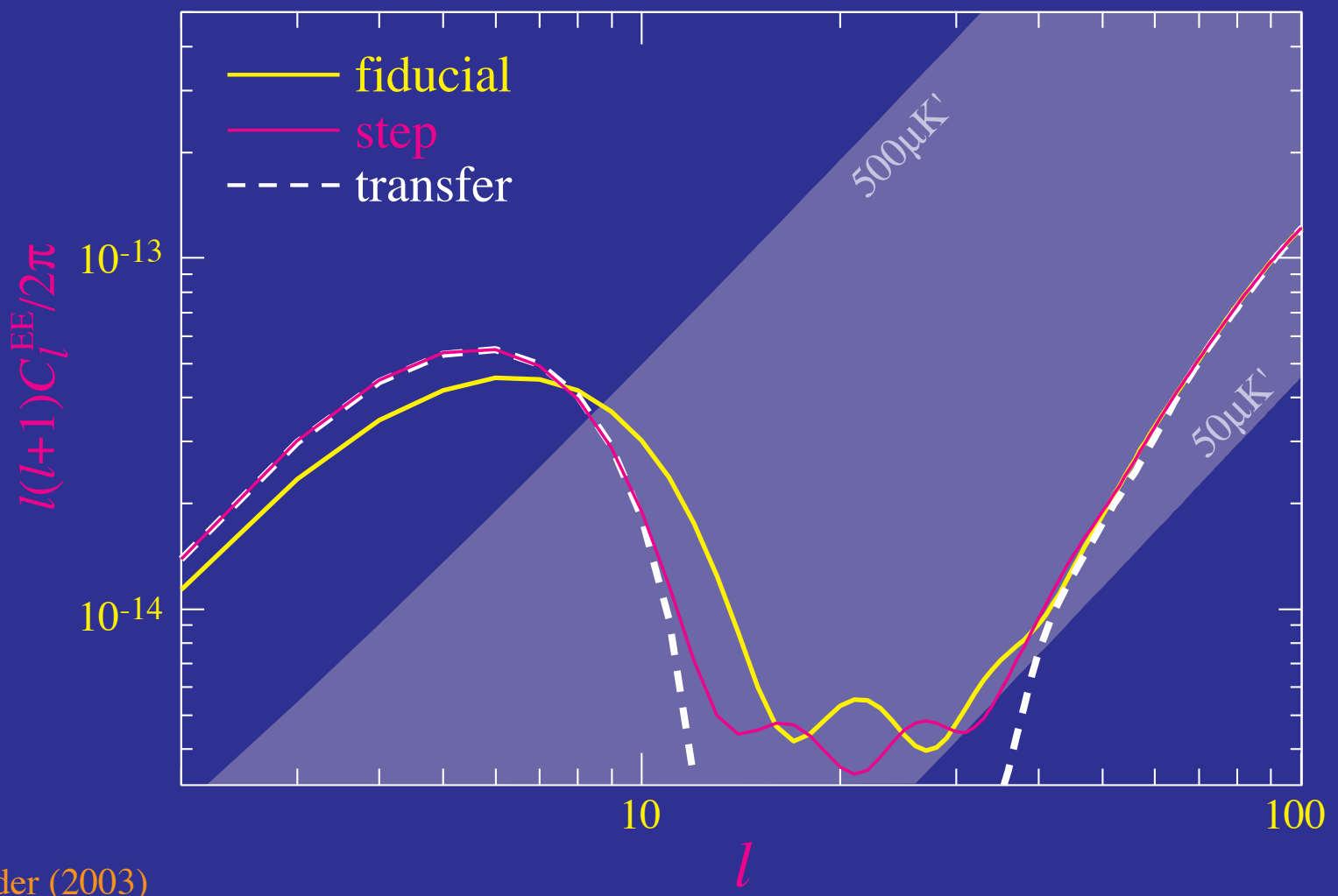


Hu & Holder (2003)

Linear Response

- Worst case scenario: maximal perturbations from fiducial model

$$\delta C_\ell^{EE} = C_\ell^{EE} \sum_i T_{\ell i} \delta x(z_i) + N_\ell \,,$$

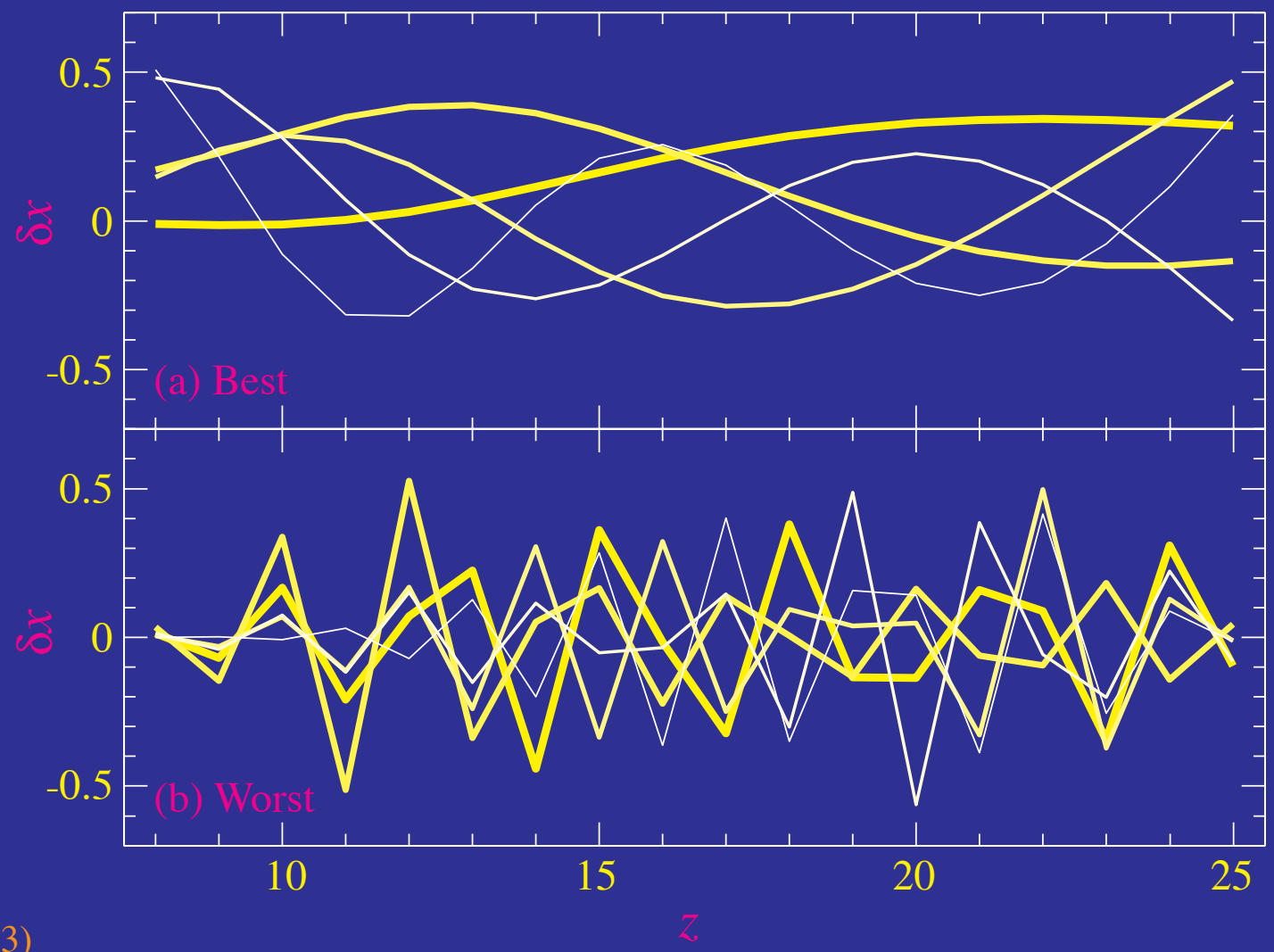


Hu & Holder (2003)

Principal Components

- Eigenvectors of the Fisher Matrix

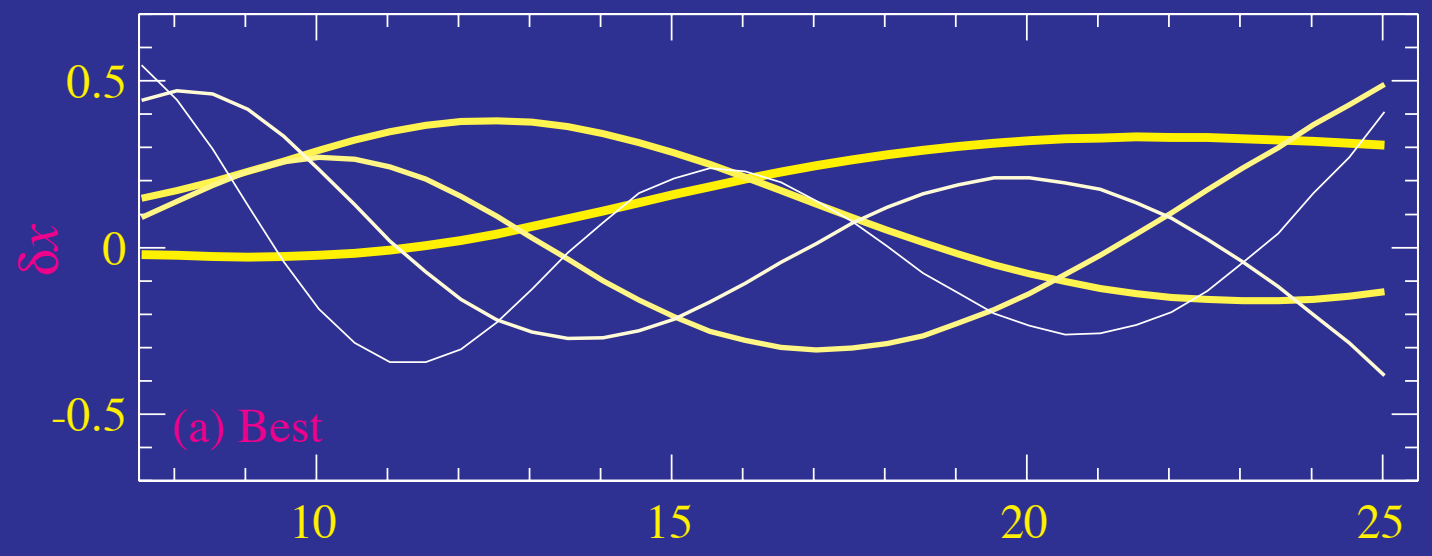
$$F_{ij} \equiv \sum_{\ell} (\ell + 1/2) T_{\ell i} T_{\ell j} = \sum_{\mu} S_{i\mu} \sigma_{\mu}^{-2} S_{j\mu}$$



Hu & Holder (2003)

Principal Components

- Low modes robust to refinement of binning Δz=0.5 (small shift is due to lower $z_{\min}$)



Hu & Holder (2003)

Mode Representation

- Eigenvectors form a complete basis for a new representation

$$m_\mu = \sum_i S_{i\mu} \delta x_i$$

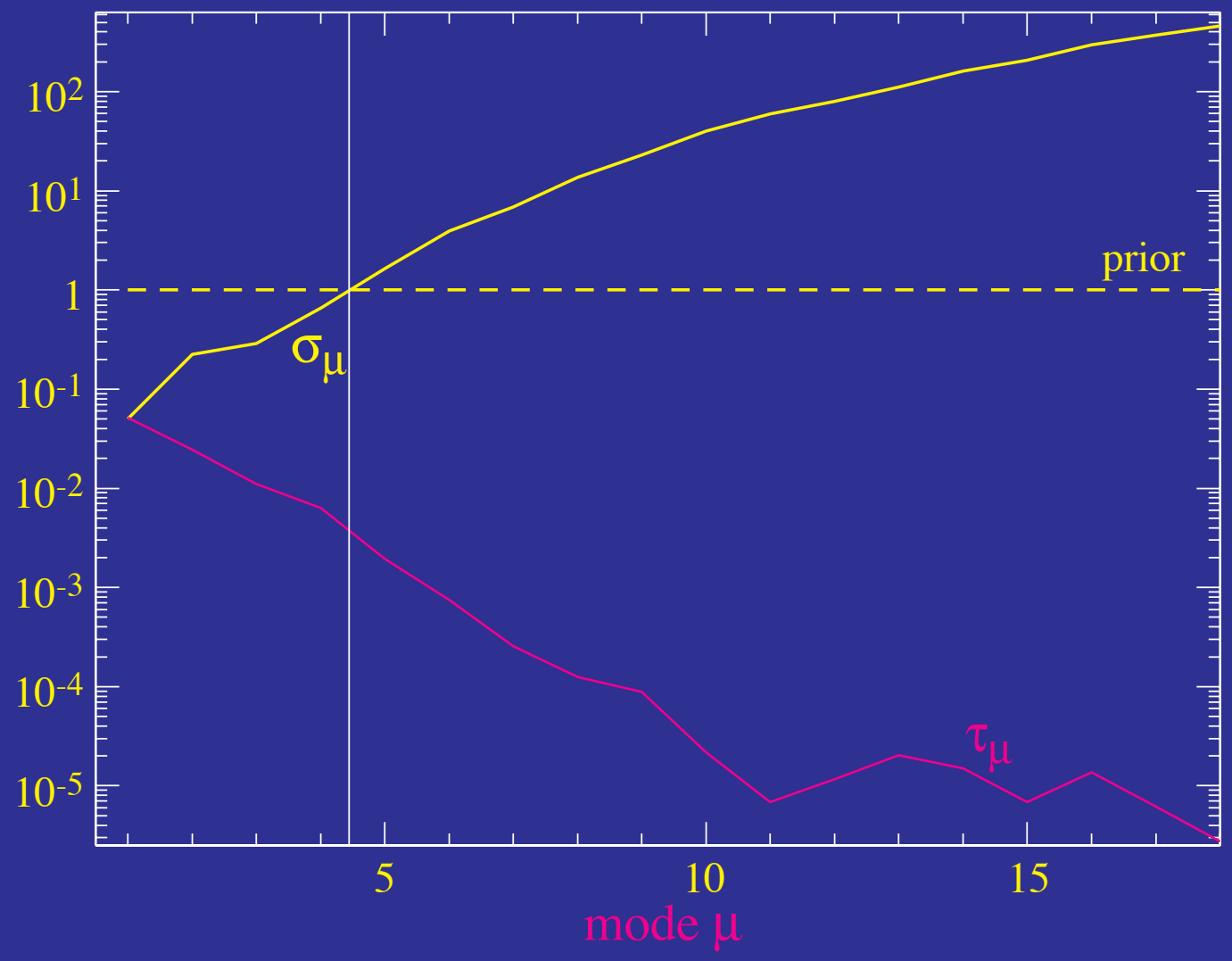
- Yields uncorrelated variance given by the inverse eigenvalue

$$\langle m_\mu m_\nu \rangle = \sigma_\mu^2 \delta_{\mu\nu}$$

- 1st mode: average high z ionization and low ℓ power
- 2nd mode: average low z ionization and high ℓ power
- 3rd-5th mode: z features and ringing in high ℓ power
- $>$5th mode: compensating ionization fluctuations in neighboring z and negligible ℓ power

Capturing the Observables

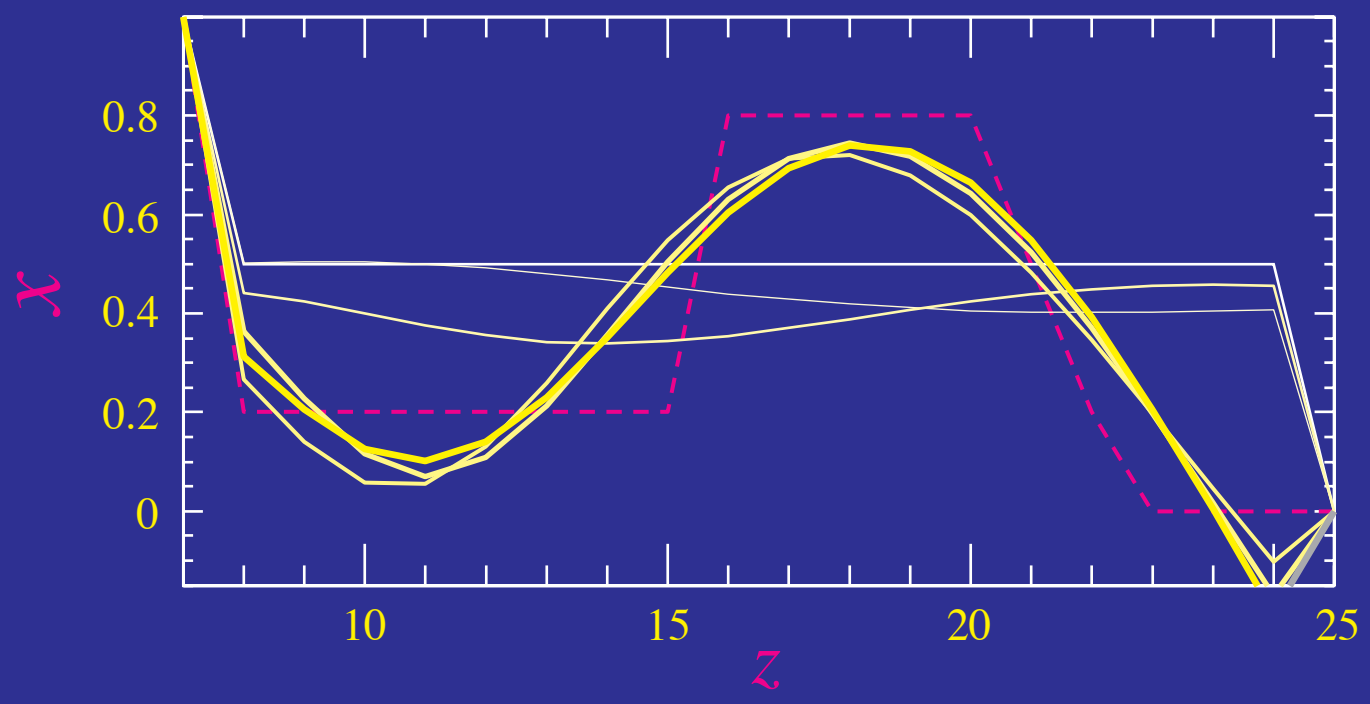
- First 5 modes have the information content and most of optical depth



Hu & Holder (2003)

Representation in Modes

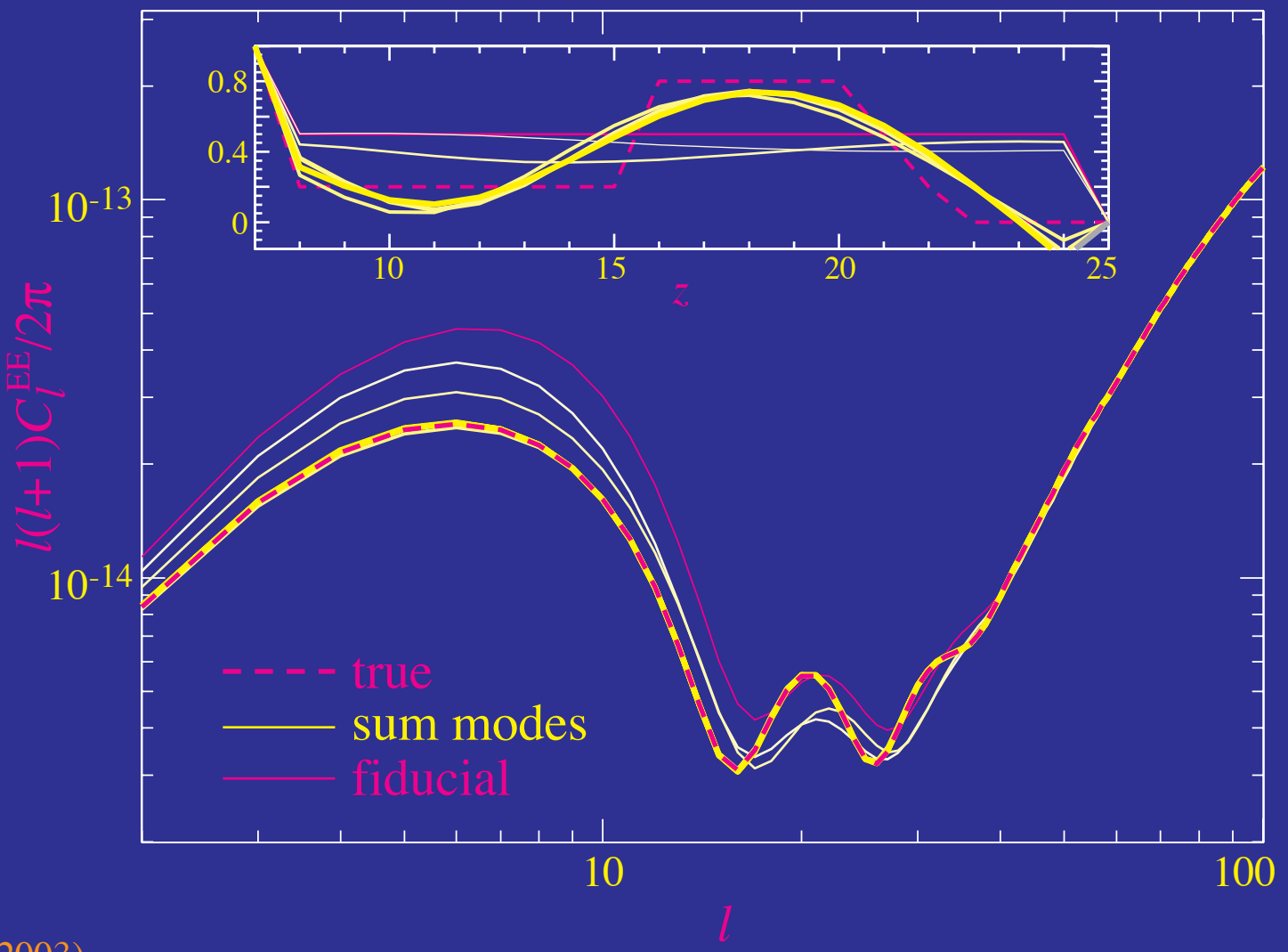
- Truncation at 5 modes leaves a low pass filtered of ionization history
- Ionization fraction allowed to go negative (Boltzmann code has negative sources)



Hu & Holder (2003)

Representation in Modes

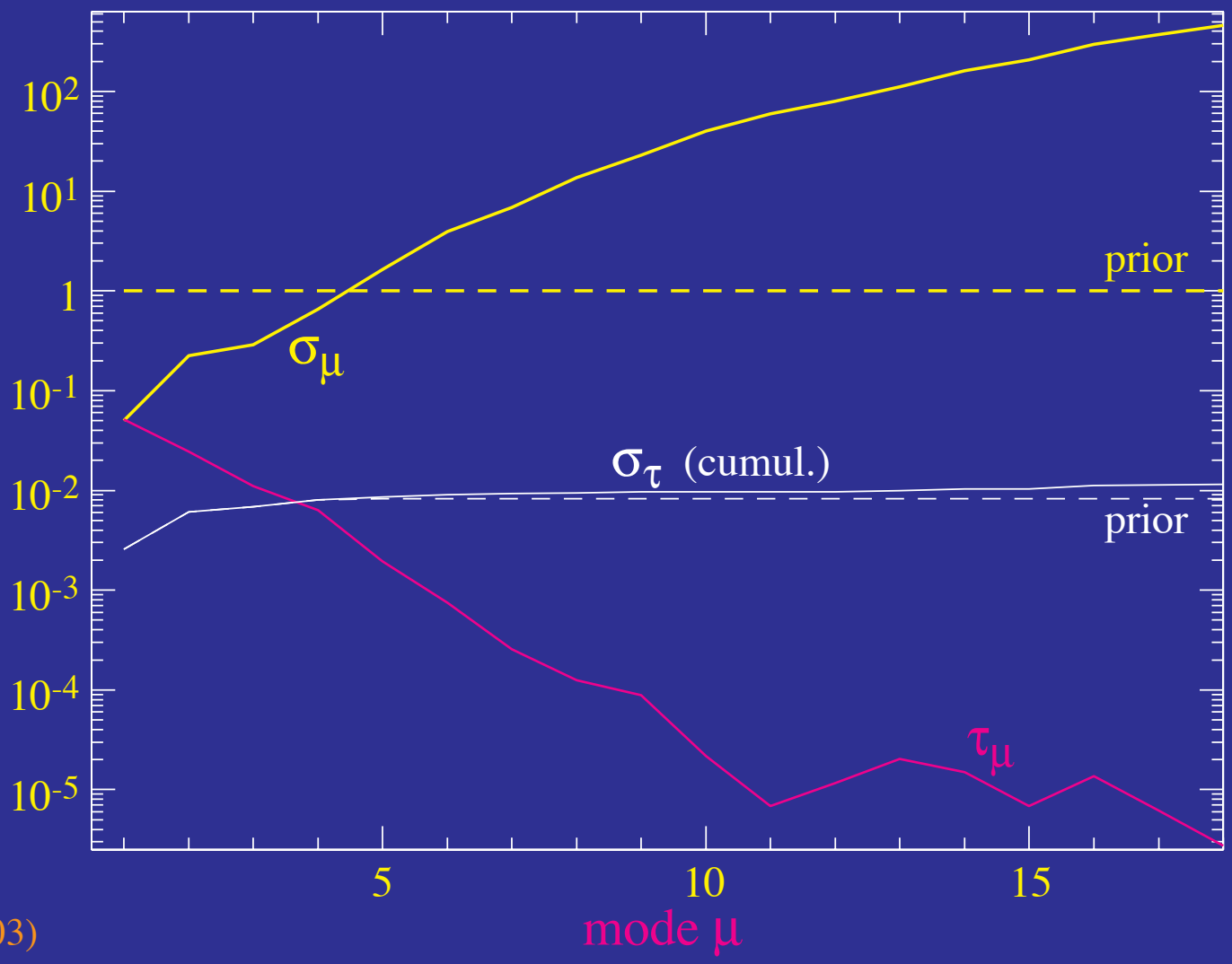
- Reproduces the power spectrum with sum over >3 modes
  more generally 5 modes suffices: e.g. total τ=0.1375 vs 0.1377



Hu & Holder (2003)

Total Optical Depth

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

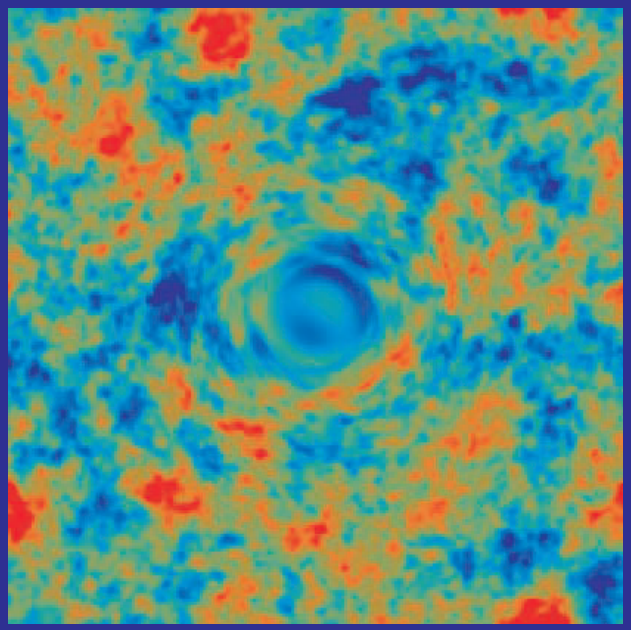


Hu & Holder (2003)

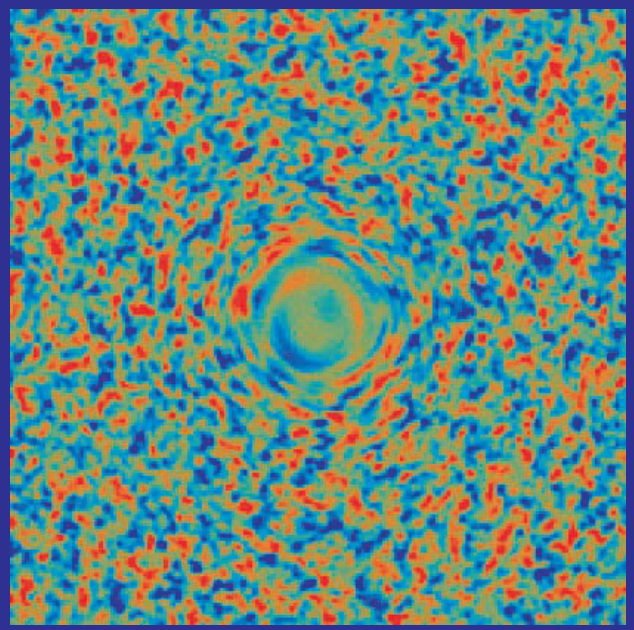
Gravitational Lensing

B-Mode Mapping

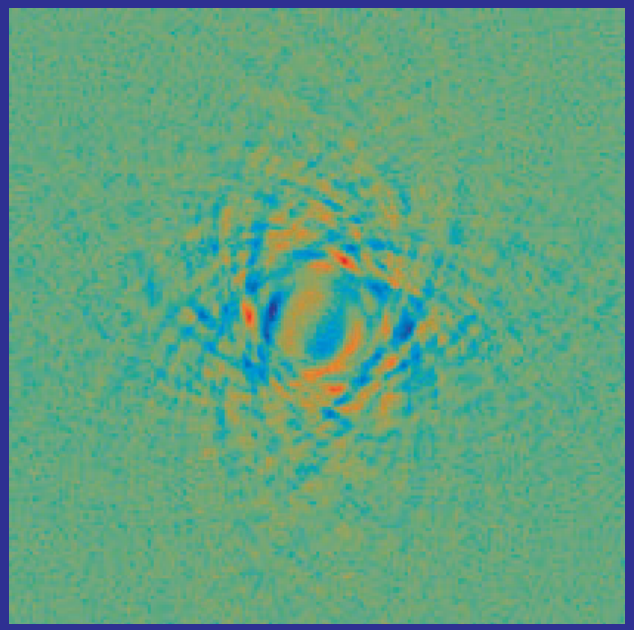
- Lensing warps polarization field and generates B-modes out of E-mode acoustic polarization - hence correlation



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

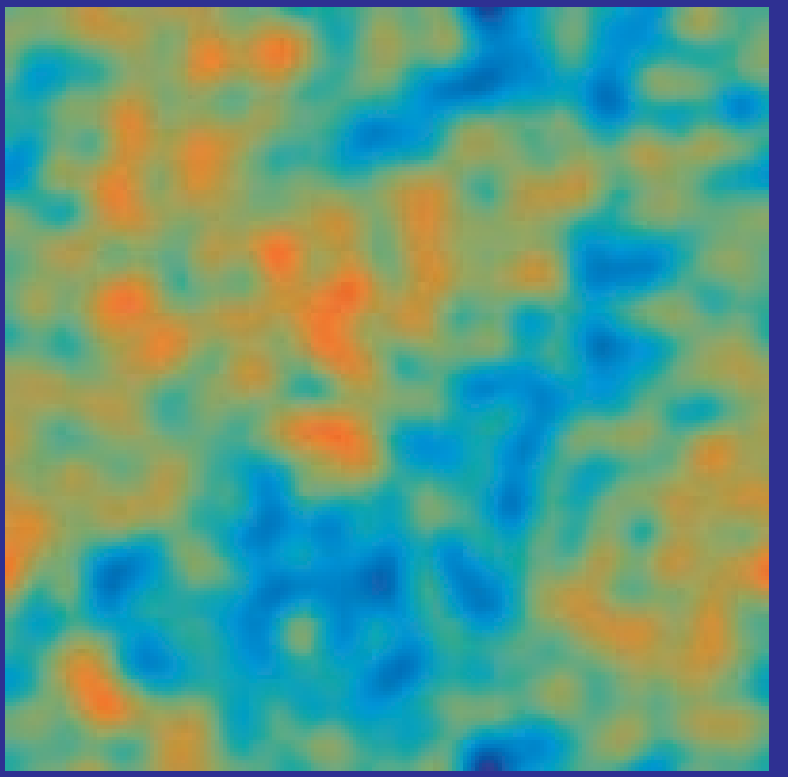
$$x(\hat{\mathbf{n}}) \to x(\hat{\mathbf{n}} + \nabla\phi) \, ,$$

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

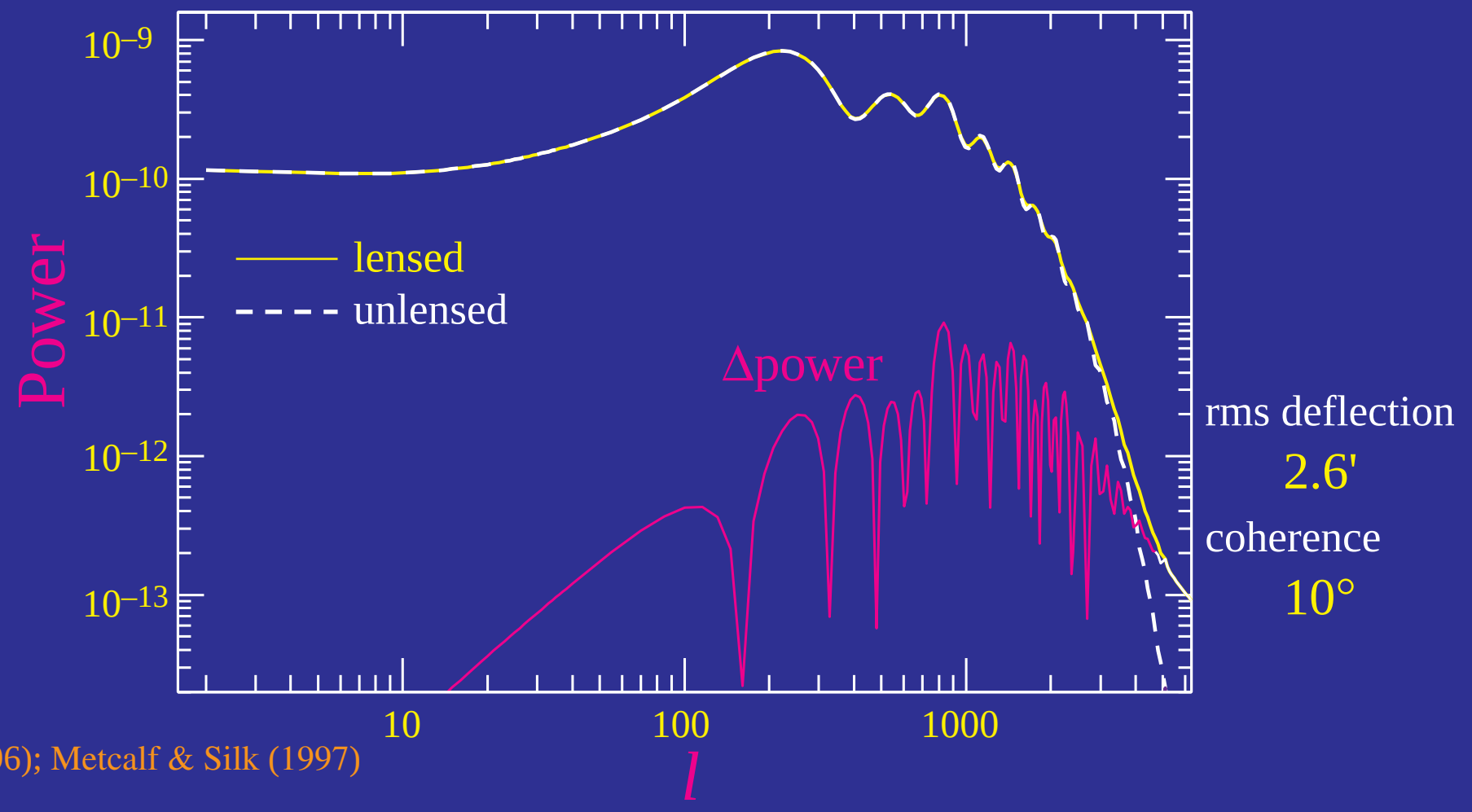
- Mass distribution at large angles and high redshift in in the linear regime
- Projected mass distribution (low pass filtered reflecting deflection angles): 1000 sq. deg



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



Seljak (1996); Metcalf & Silk (1997)

Reconstruction from the CMB

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

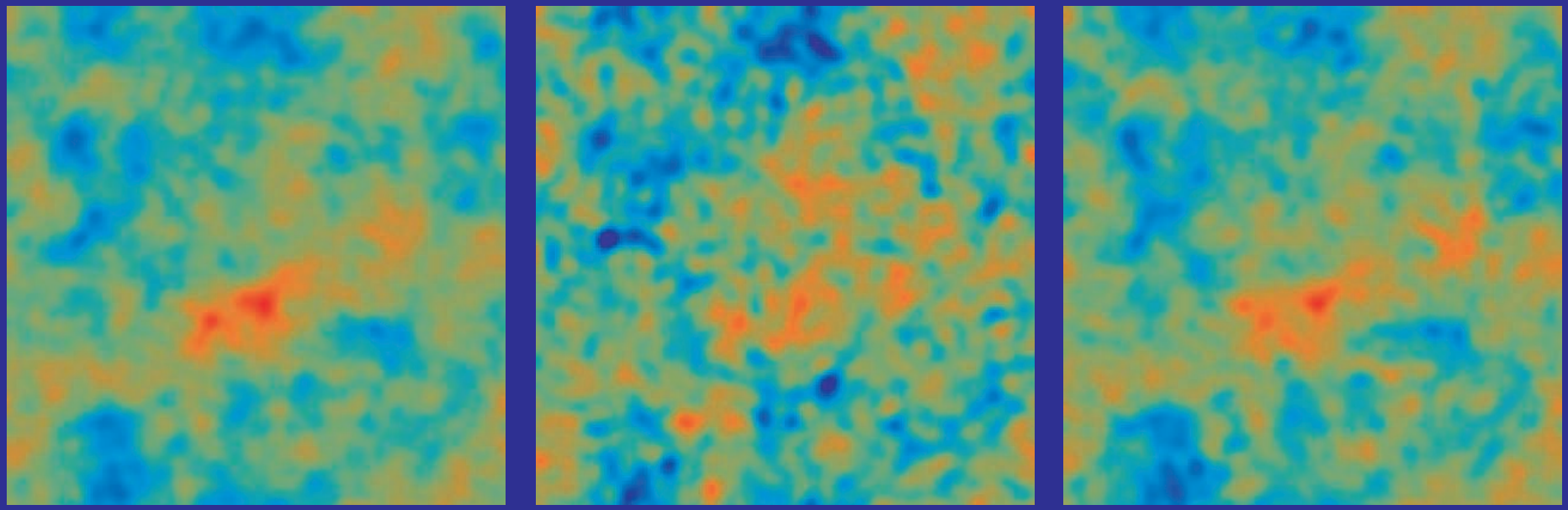
$$\langle x(\mathbf{l}) x'(\mathbf{l}') \rangle_{\rm CMB} = f_\alpha(\mathbf{l}, \mathbf{l}') \phi(\mathbf{l} + \mathbf{l}') \, ,$$

  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')



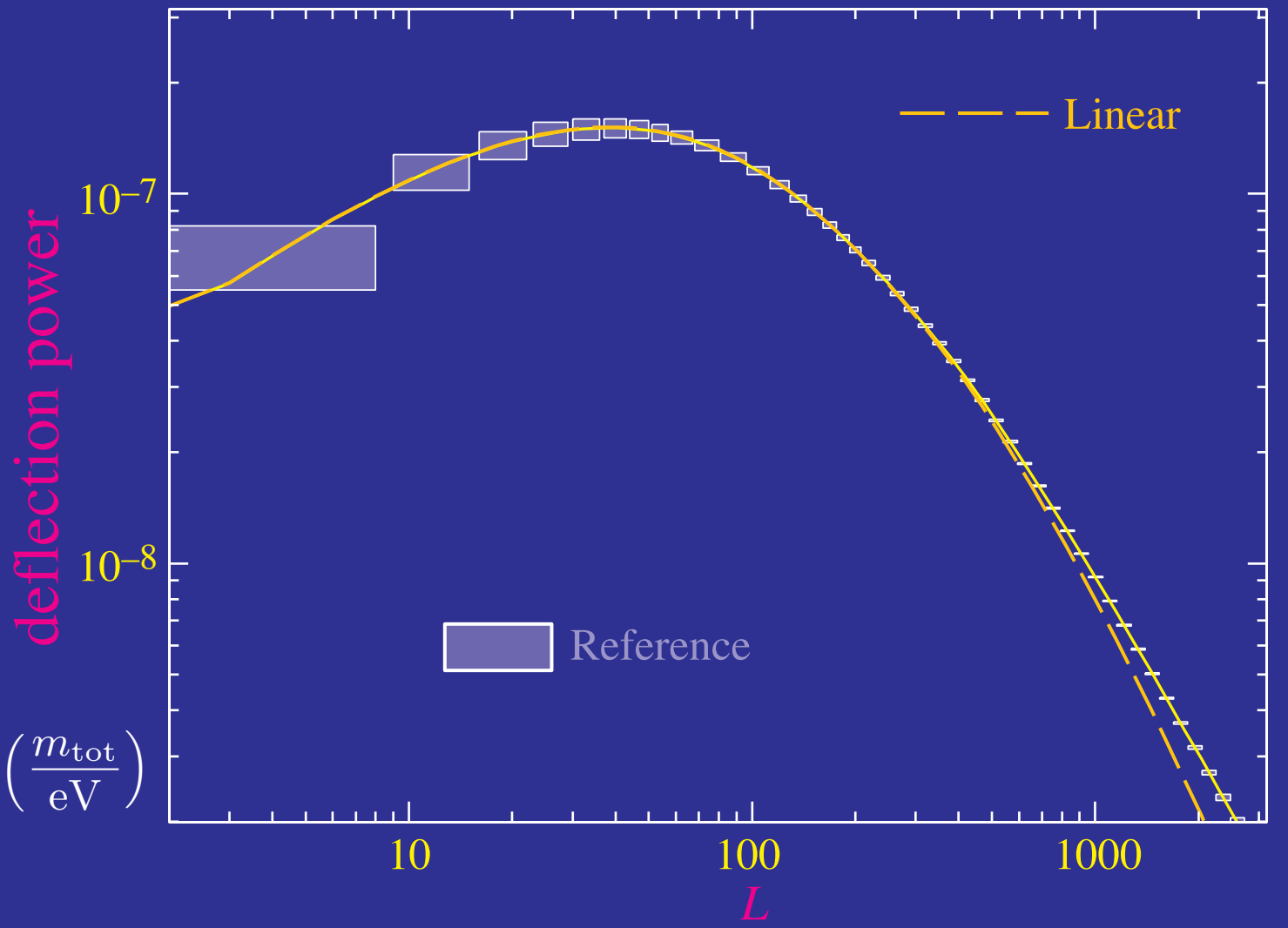
mass | temp. reconstruction | EB pol. reconstruction

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

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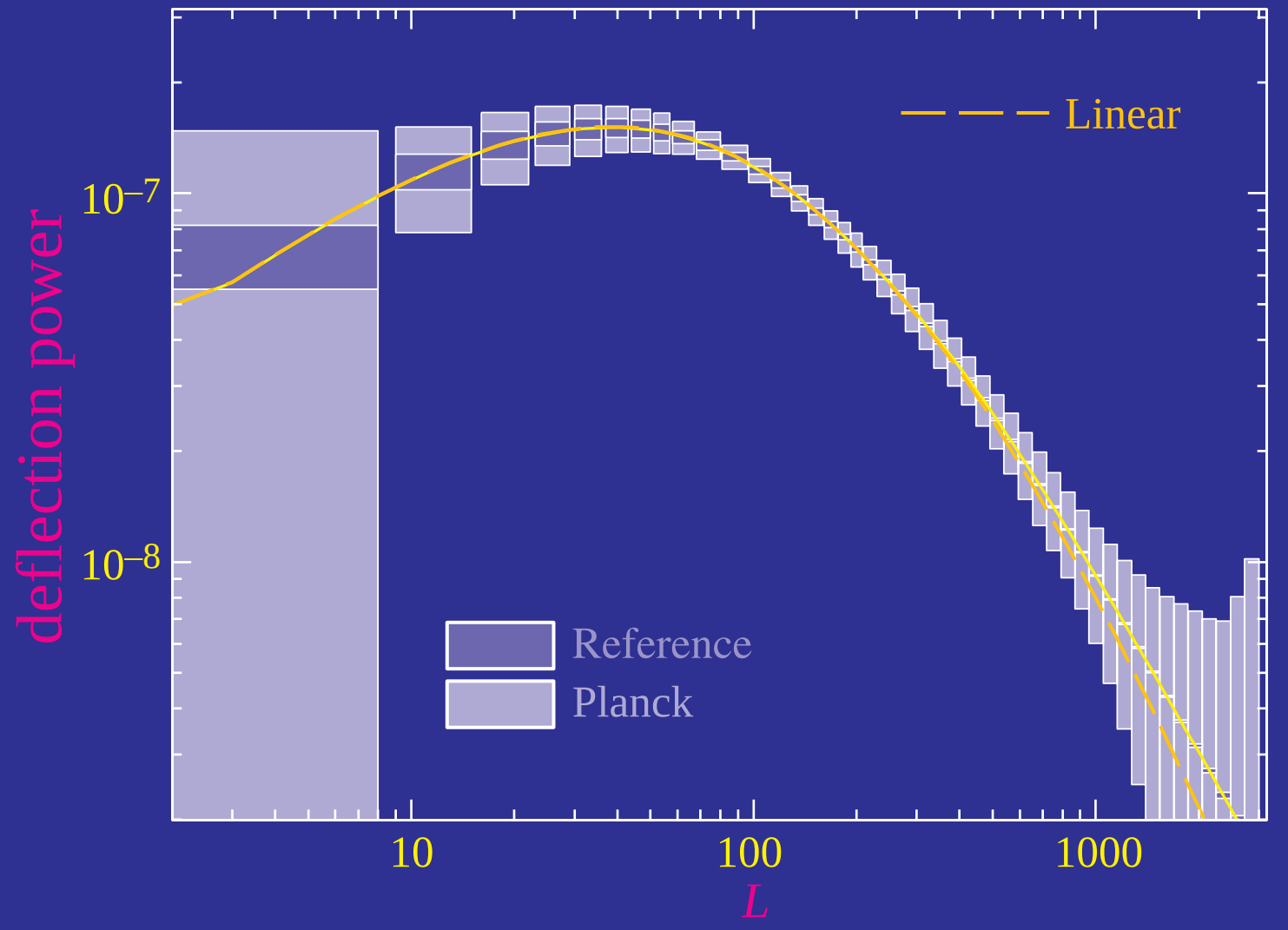
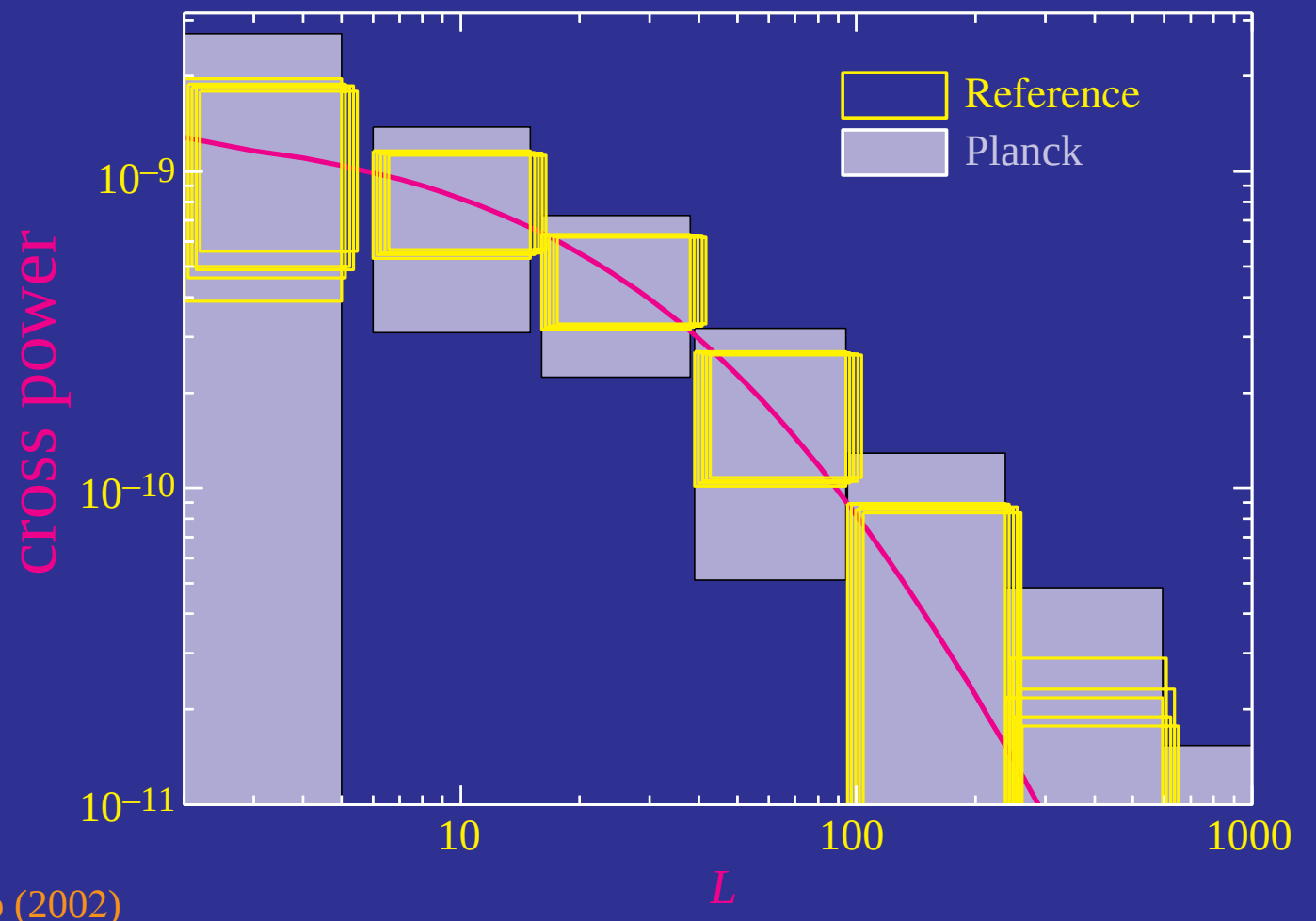


Hu & Okamoto (2001)

$\sigma(w)$~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

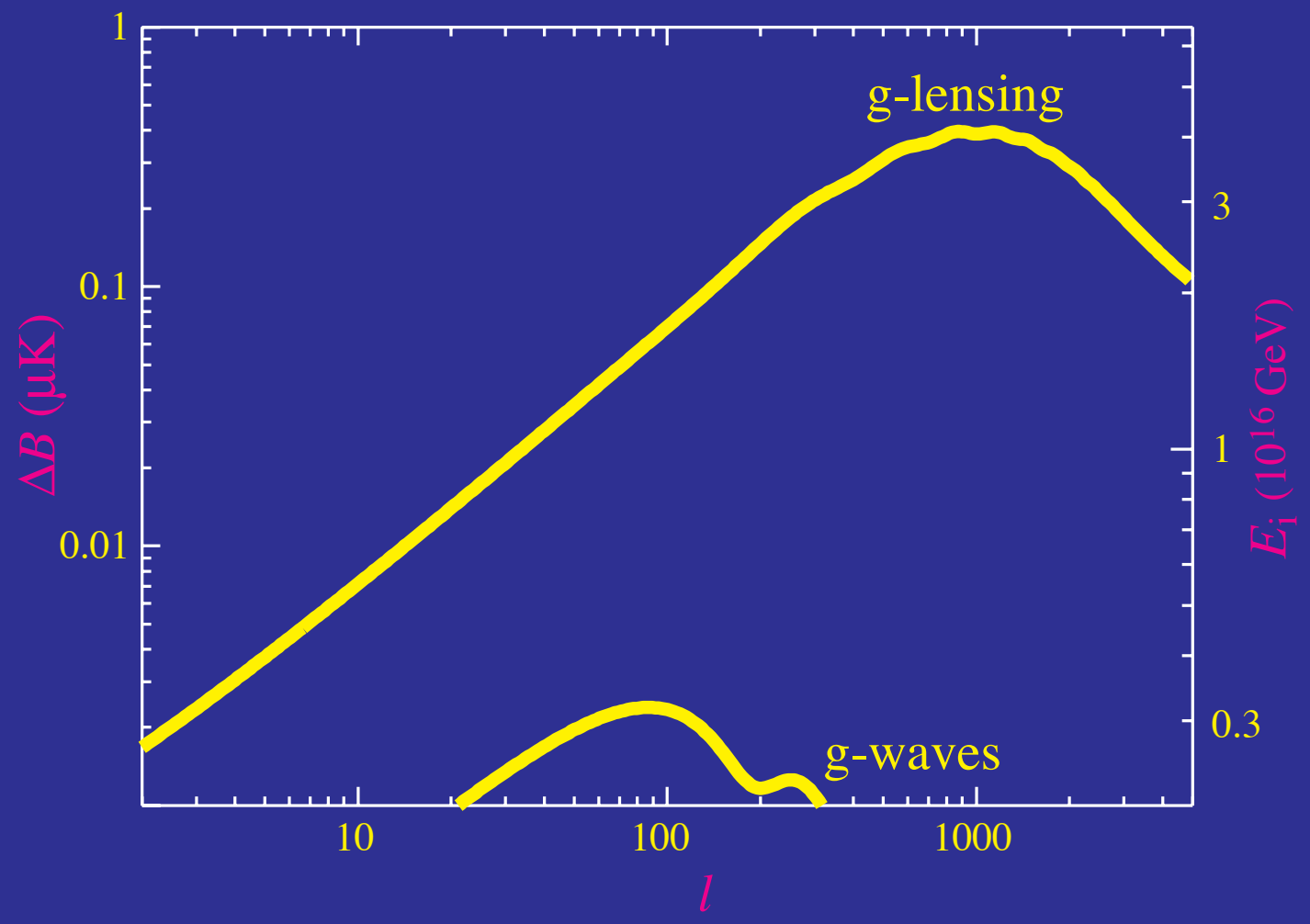


Hu & Okamoto (2002)

Contamination for Gravitational Waves

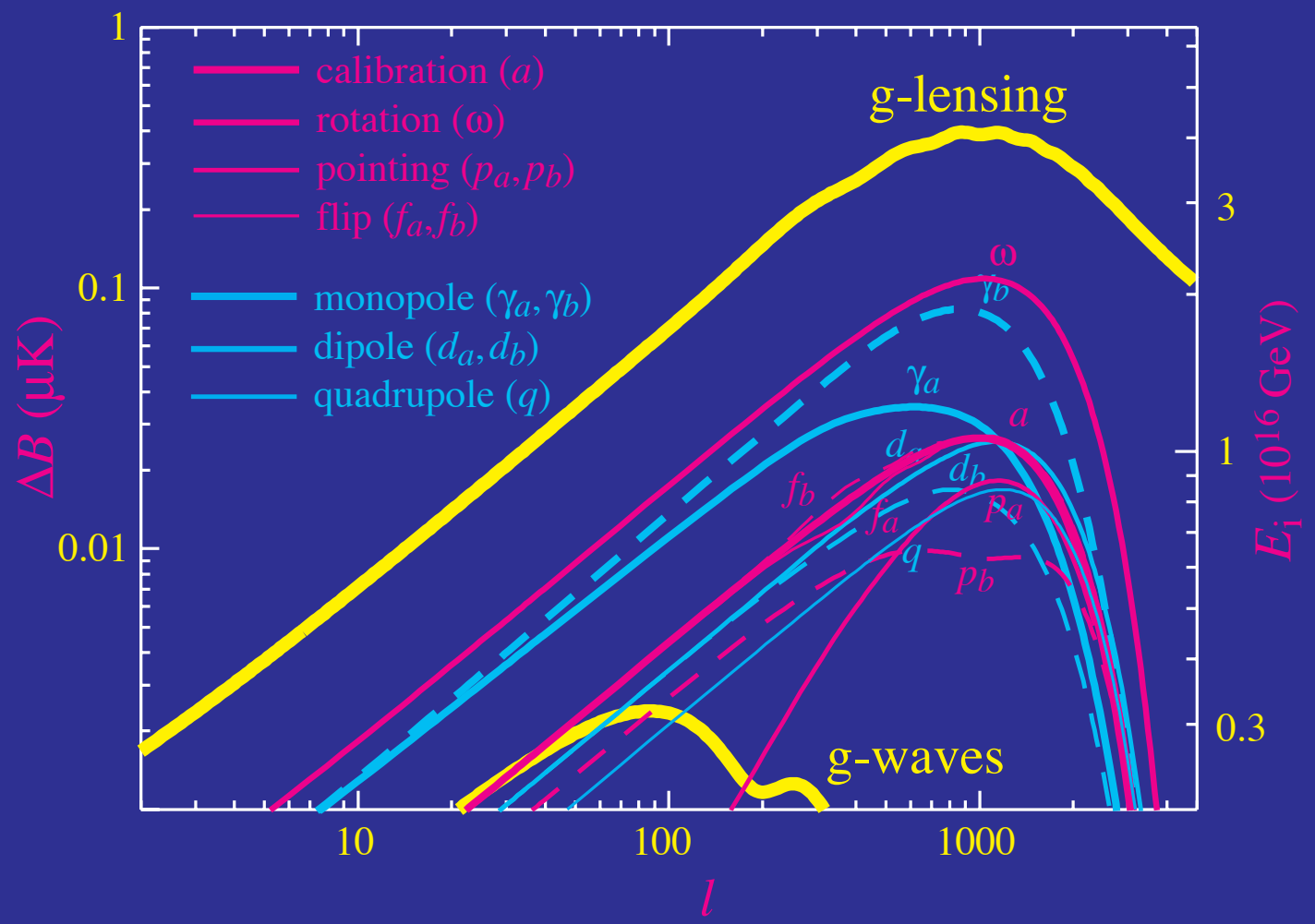
- Gravitational lensing contamination of B-modes from gravitational waves cleaned to E_i~0.3 x 10^{16} GeV

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



A (Partial) Catalogue of B Systematics

- Small scale systematics can leak to large scales due to the small, damping scale coherence of T and E modes



Stability!
Space?

Foregrounds!

10^{-3} rms

10^{-2} rms

Hu, Hedman & Zaldarriaga (2002)

Summary

- Form of reionization bump depends on ionization history, mainly through horizon scale at scattering epoch
- Traditional approach of model-based parameterization added to likelihood chain is dangerous given the relative crudeness of reionization models

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- Modes are a good meeting ground between observations, models
- Best modes can be precisely constrained but even the total optical depth, hence the initial amplitude of fluctuations to 1%
- Gravitational lensing of polarization can pin down the absolute amplitude of structure at intermediate redshifts
- Combination constrains the growth of structure and hence the high redshift properties of the dark energy