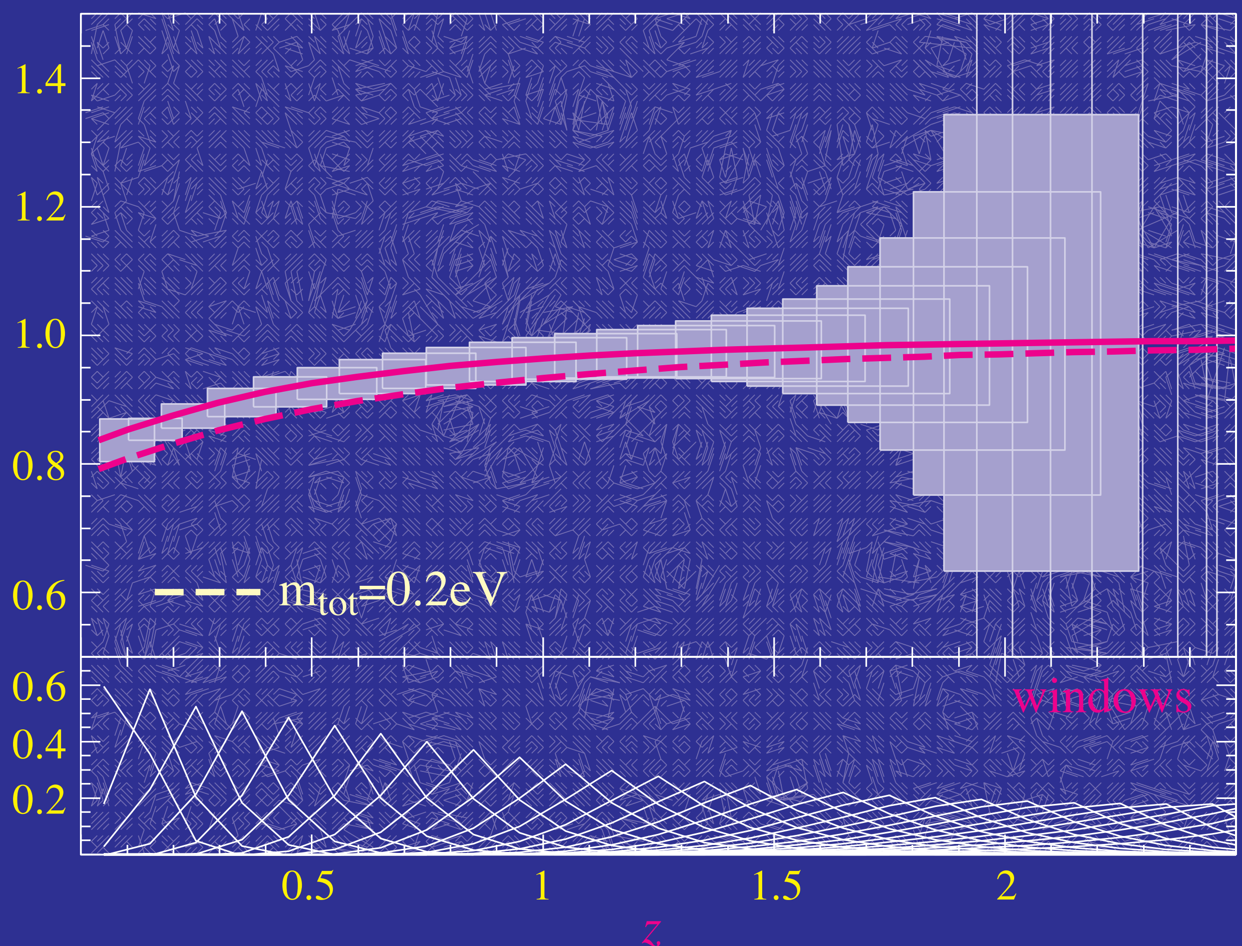
Weak Lensing Tomography



Wayne Hu

Fermilab, October 2002

Collaborators

- Chuck Keeton
- Takemi Okamoto
- Max Tegmark
- Martin White

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Microsoft

http://background.uchicago.edu

/~whu/Presentations/ferminu.pdf

Massive Neutrinos

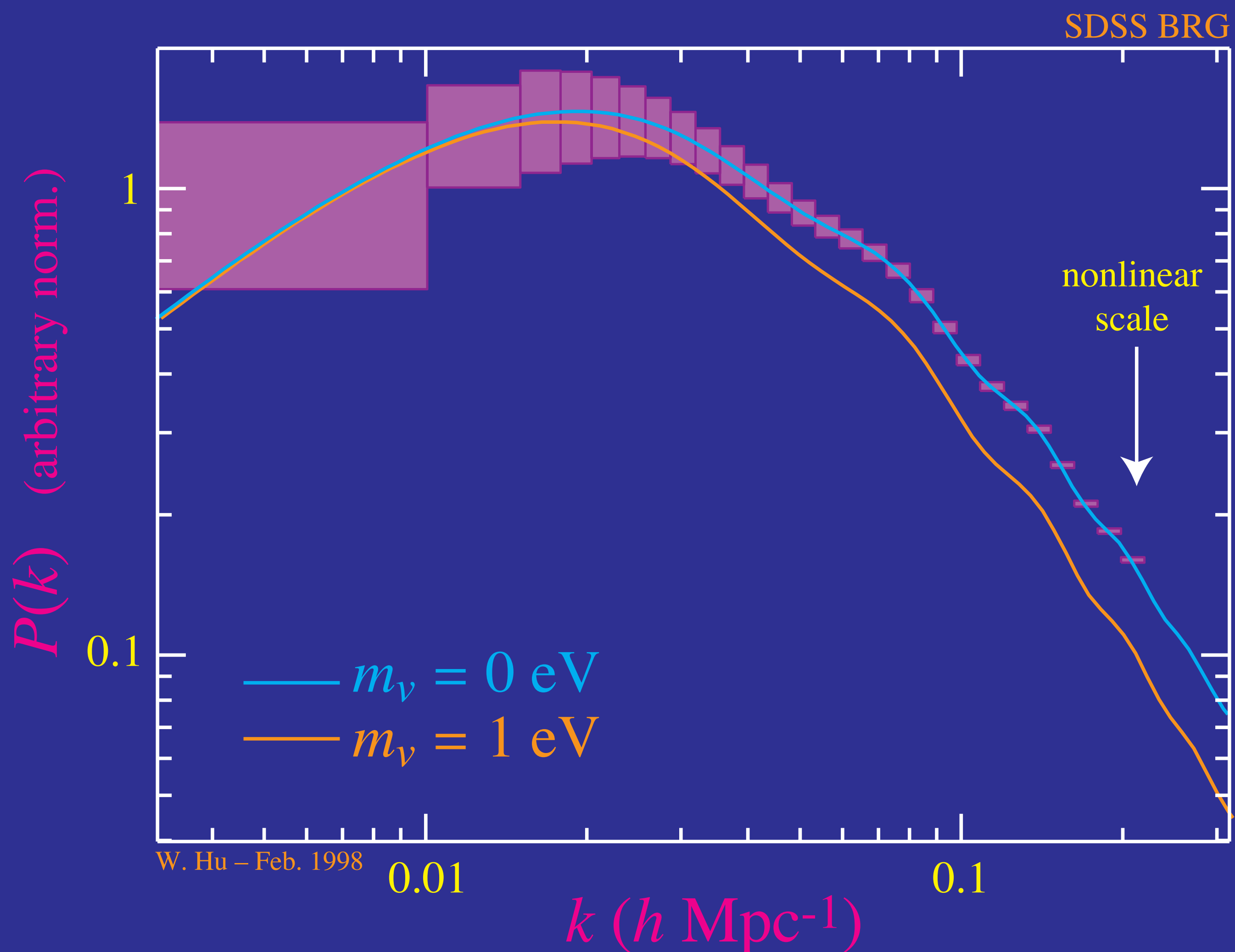
- Relativistic stresses of a light neutrino slow the growth of structure
- Neutrino species with cosmological abundance contribute to matter as $\Omega_\nu h^2 = m_\nu/94\text{eV}$, suppressing power as $\Delta P/P \approx -8\Omega_\nu/\Omega_m$

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

min. ~3% (atmospheric)

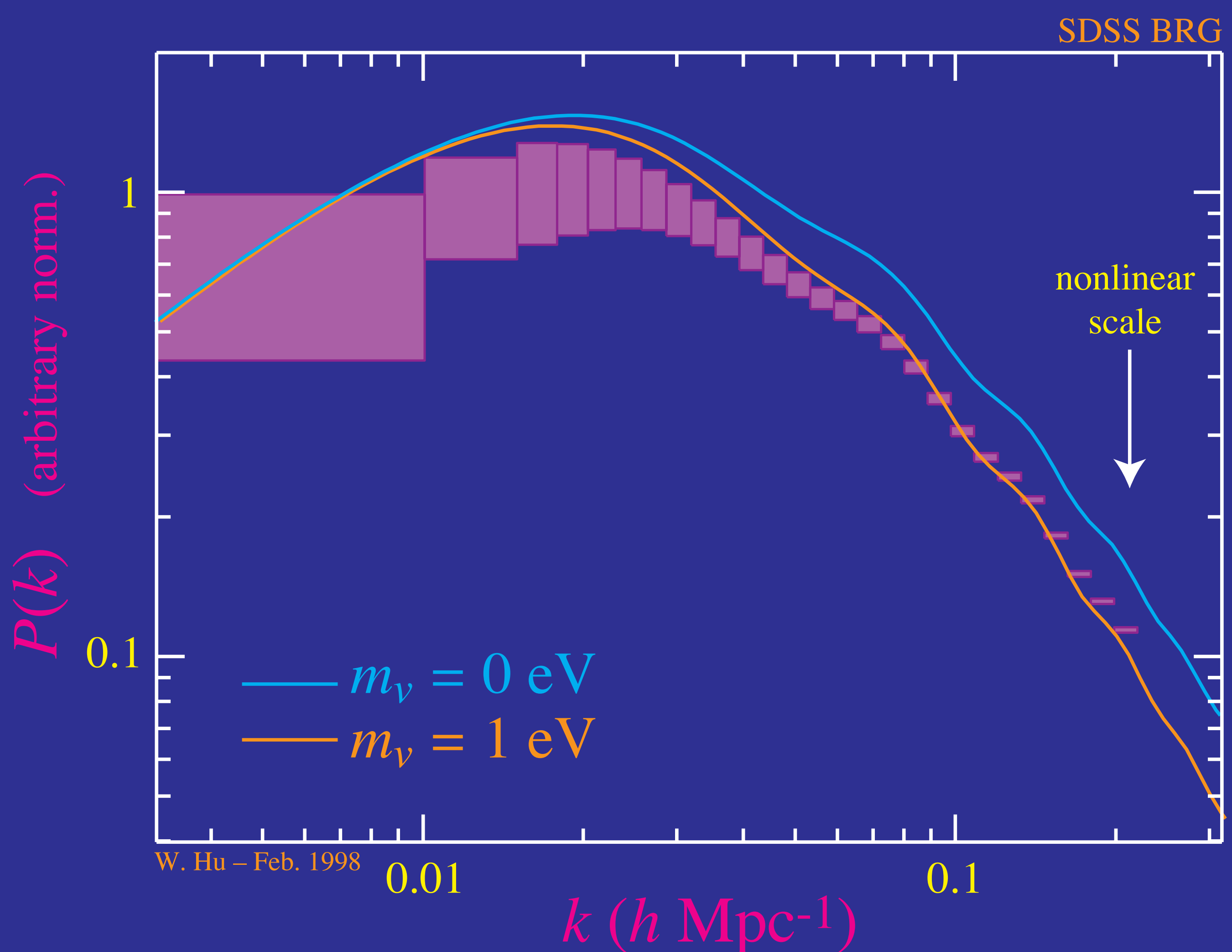
Galaxy Surveys

- Absolute effect is large!



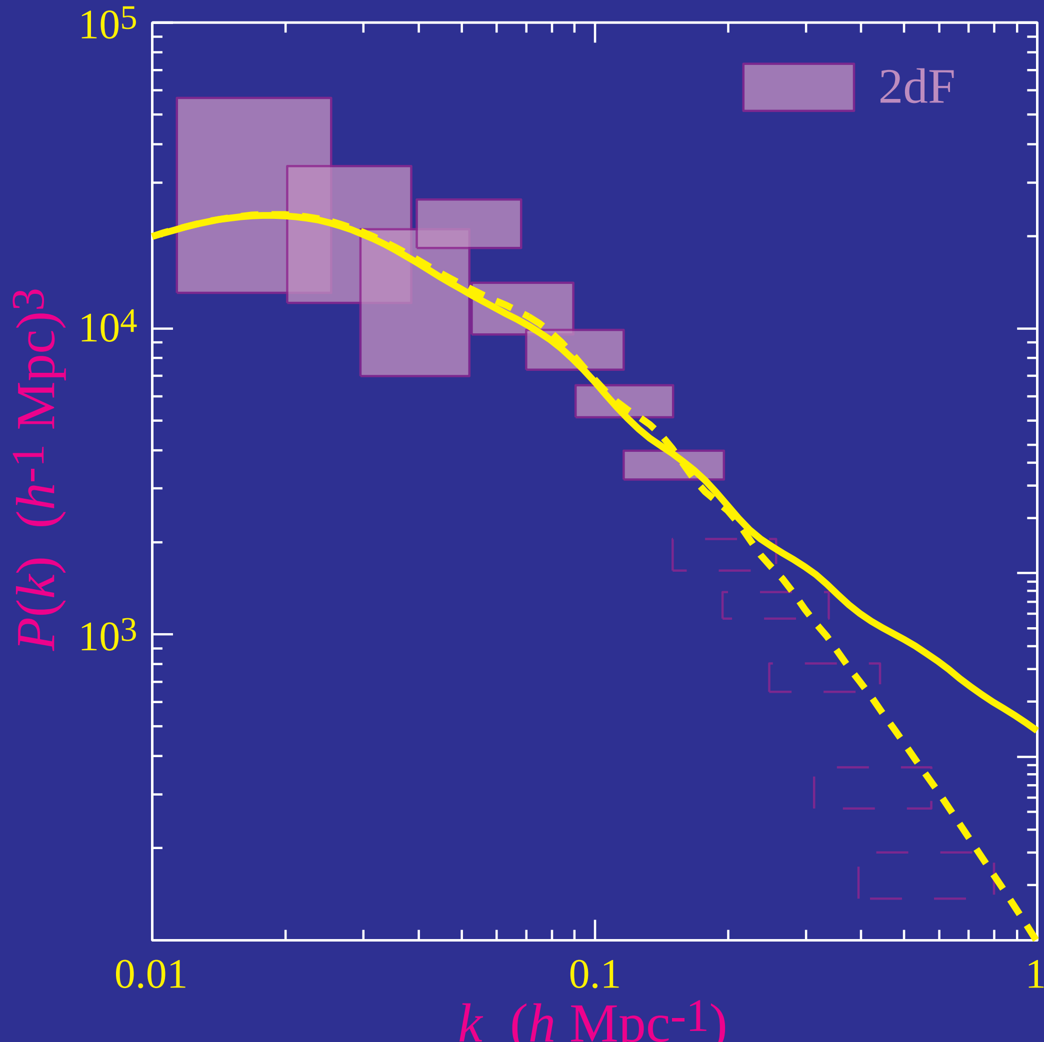
Galaxy Surveys

- But because of bias we can only use the shape information not the much larger overall suppression
- Current constraints from 2dF suggest $m_\nu < 1.8$eV



Massive Neutrinos

- Current data from 2dF galaxy survey indicates m_ν<1.8eV assuming a ΛCDM model with parameters constrained by the CMB. Elgaroy et al (2002)



decorrelation by Tegmark, Hamilton, Xu (2002)

Example of Weak Lensing

- Toy example of lensing of the CMB primary anisotropies
- Shearing of the image

Lensing Observables

- Image distortion described by Jacobian matrix of the remapping

$$\mathbf{A} = \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1-\kappa+\gamma_1 \end{pmatrix},$$

where κ is the convergence, γ_1, γ_2 are the shear components

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- related to the gravitational potential Φ by spatial derivatives

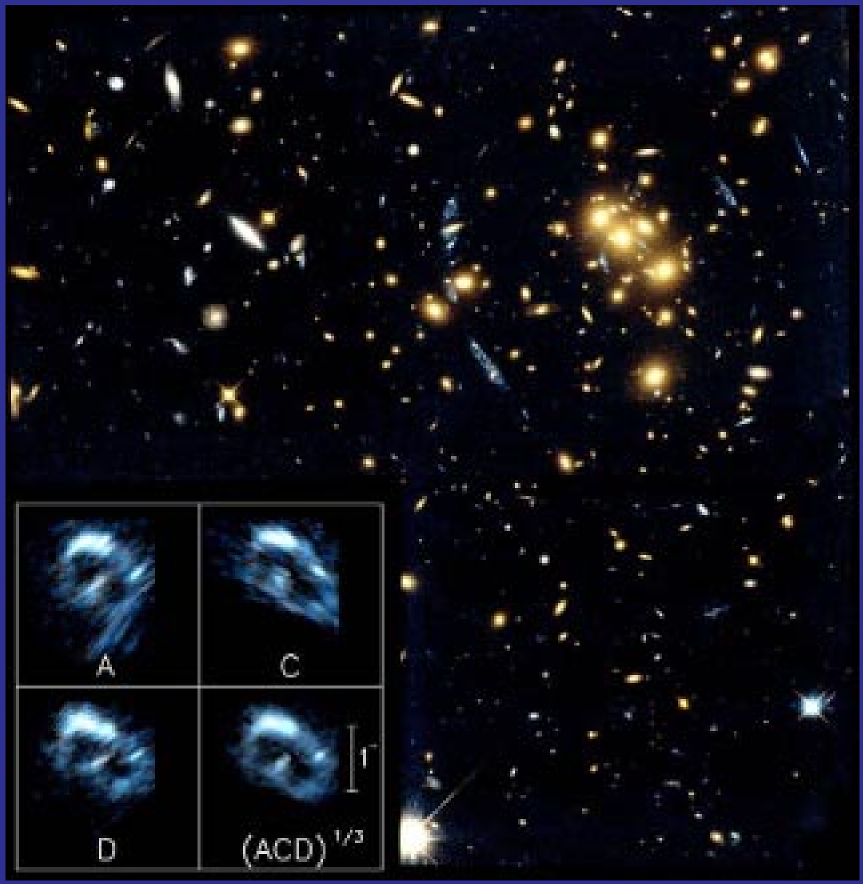
$$\psi_{ij}(z_s) = 2\int_0^{z_s} dz \frac{dD}{dz}\frac{D(D_s-D)}{D_s}\Phi_{,ij},$$

  $\psi_{ij} = \delta_{ij} - A_{ij}$, i.e. via Poisson equation

$$\kappa(z_s) = \frac{3}{2}H_0^2\Omega_m \int_0^{z_s} dz \frac{dD}{dz}\frac{D(D_s-D)}{D_s}\delta/a,$$

Gravitational Lensing by LSS

- Shearing of galaxy images reliably detected in clusters
- Main systematic effects are instrumental rather than astrophysical

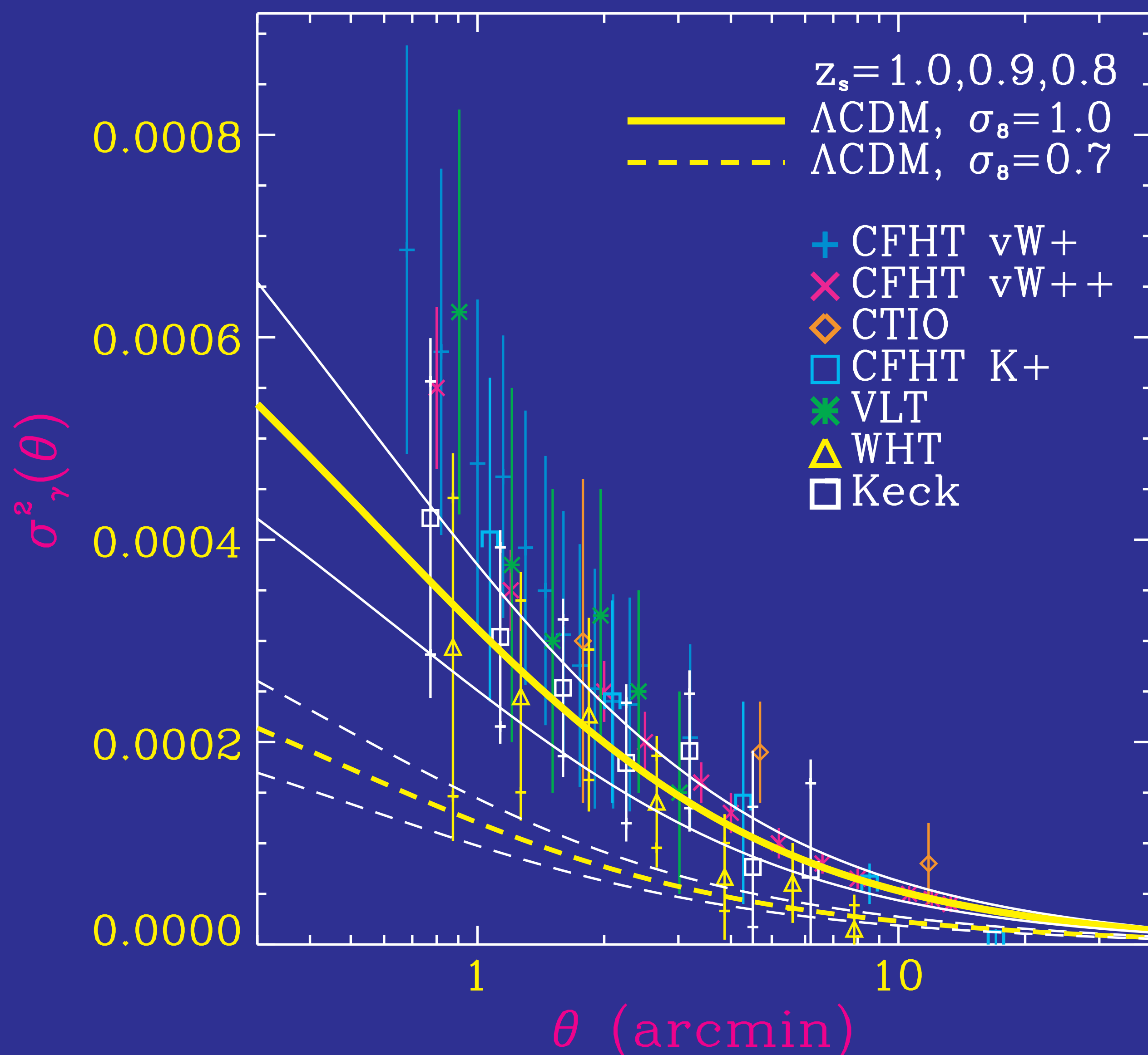


Cluster (Strong) Lensing: 0024+1654

Colley, Turner, & Tyson (1996)

Cosmic Shear Data

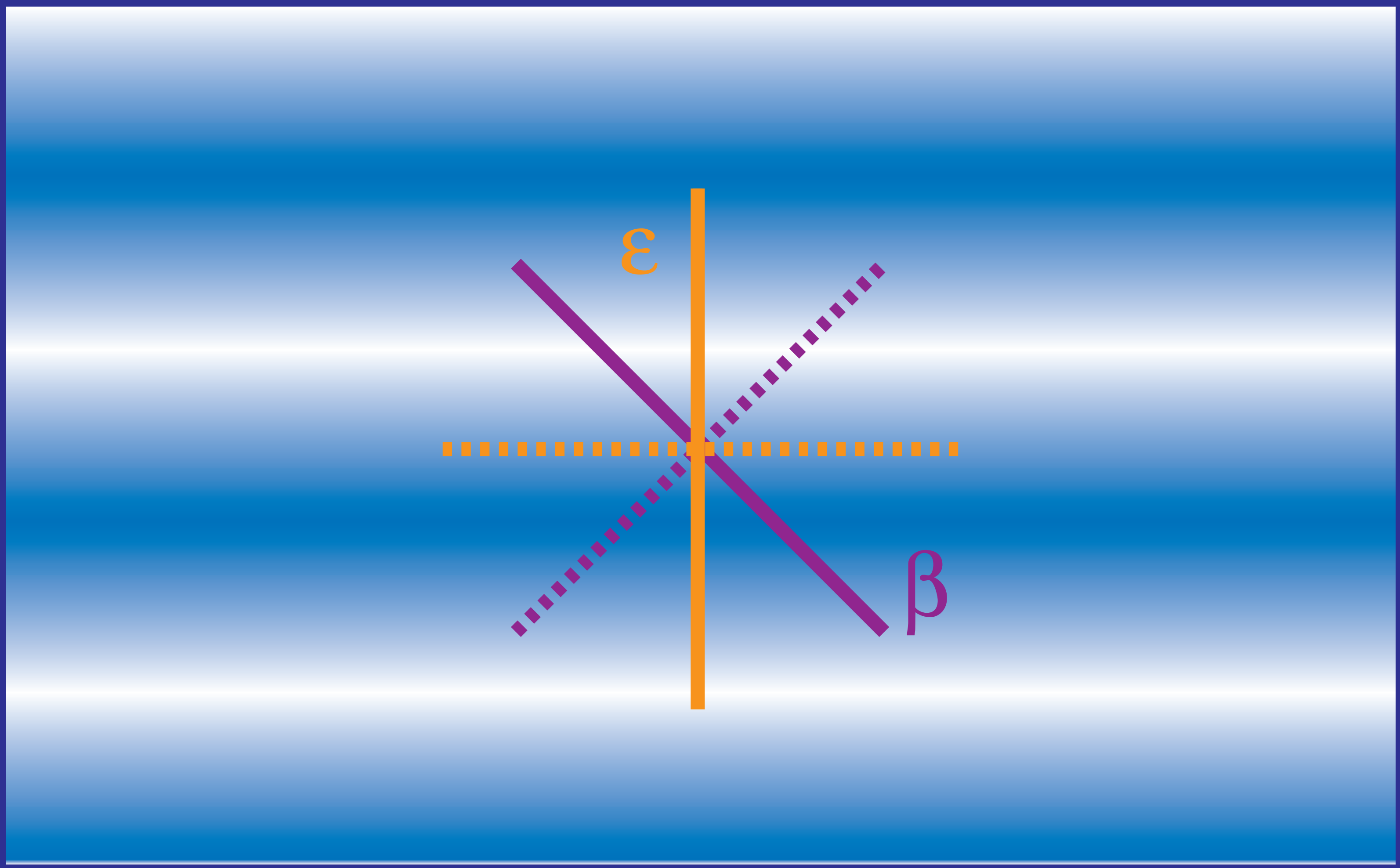
- Shear variance as a function of smoothing scale



compilation from Bacon et al (2002)

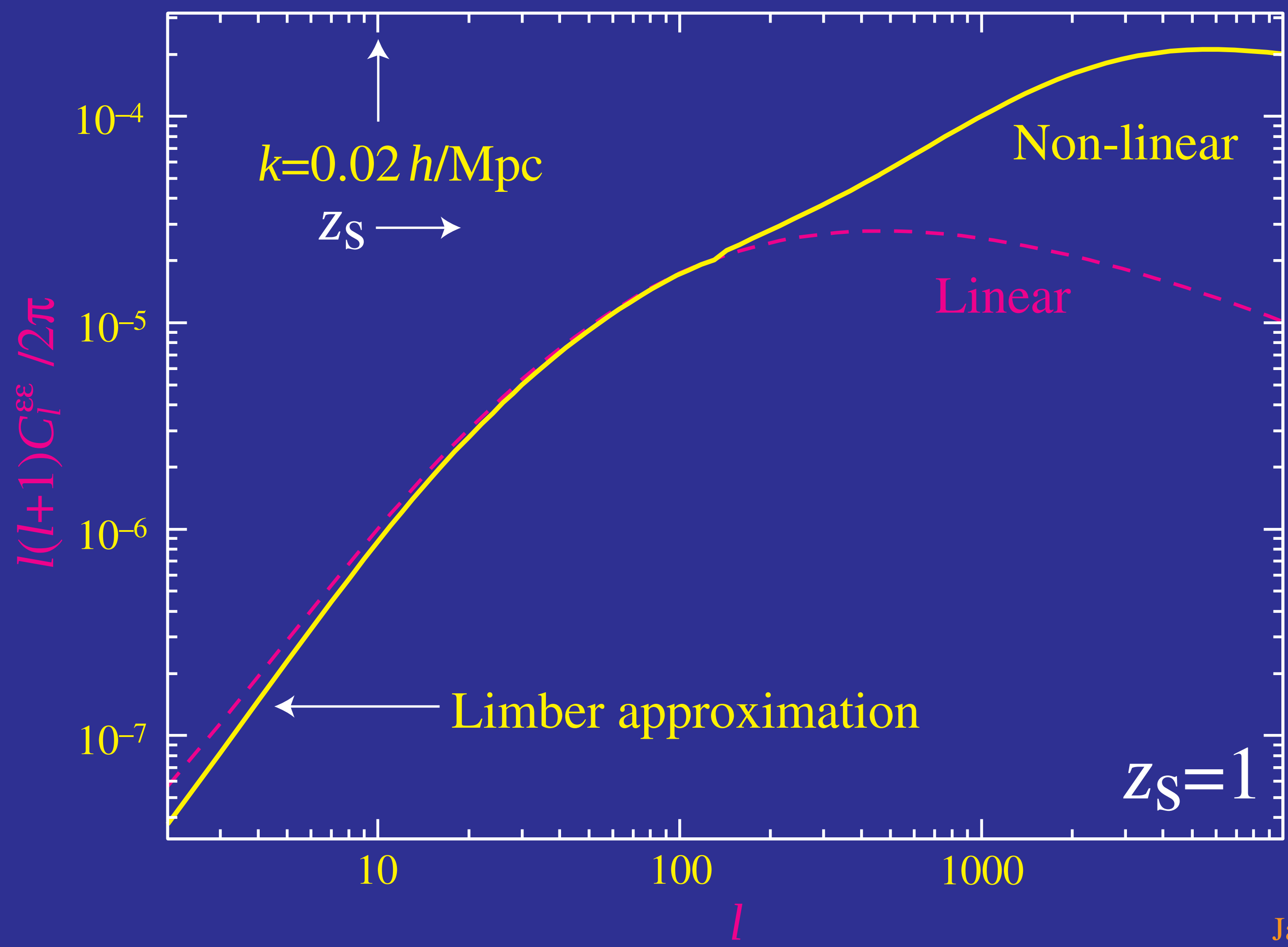
Shear Power Modes

- Alignment of shear and wavevector defines modes



Shear Power Spectrum

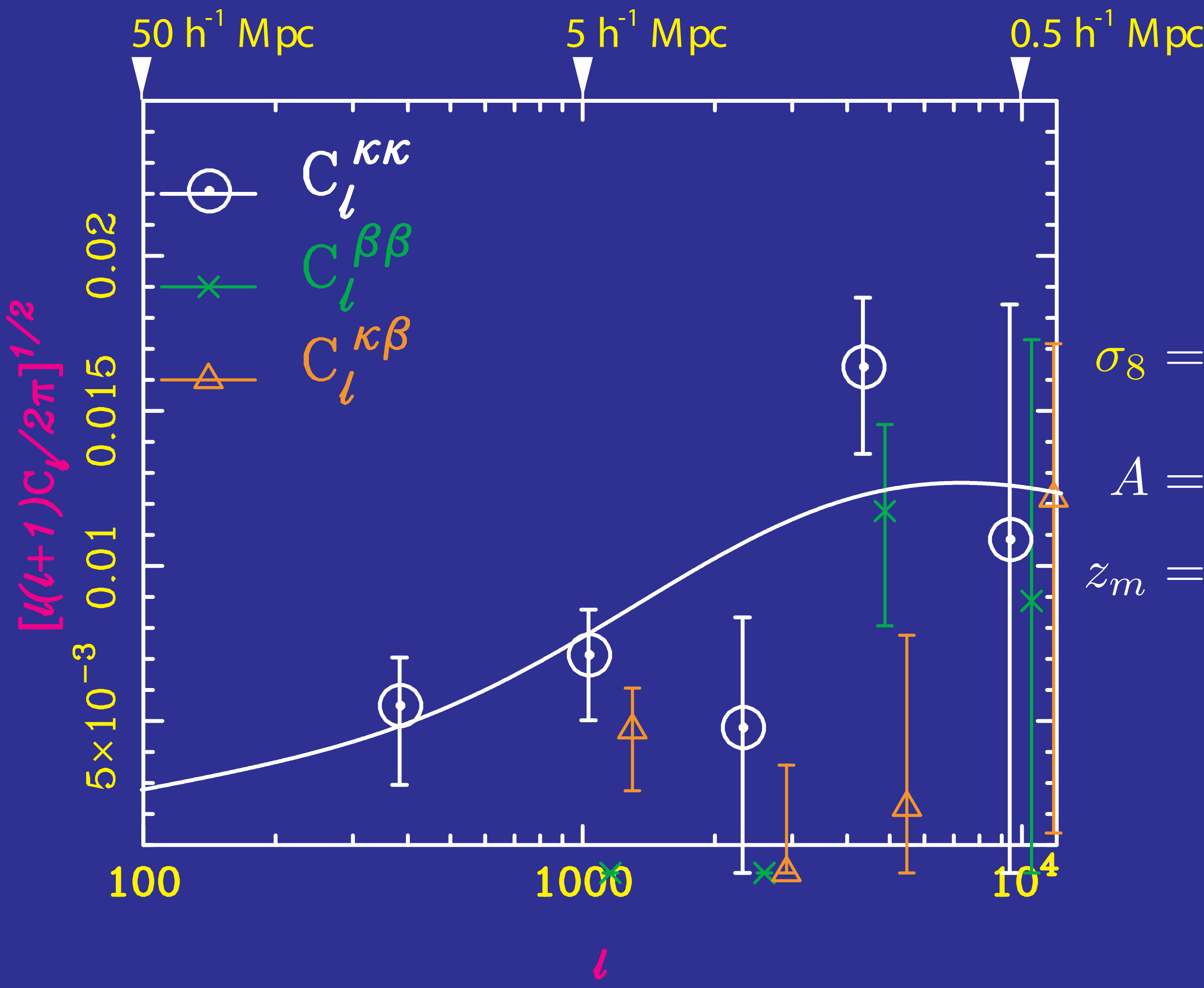
- Lensing weighted Limber projection of density power spectrum
- ε–shear power = κ power



Kaiser (1992)
Jain & Seljak (1997)
Hu (2000)

Recent Measurement

- COMBO-17 Brown et al (2002)



$$\sigma_8 = (0.74 \pm 0.09)\left(\frac{\Omega_m}{0.3}\right)^{0.5}$$

$$A = 1.25\mathrm{deg}^2$$

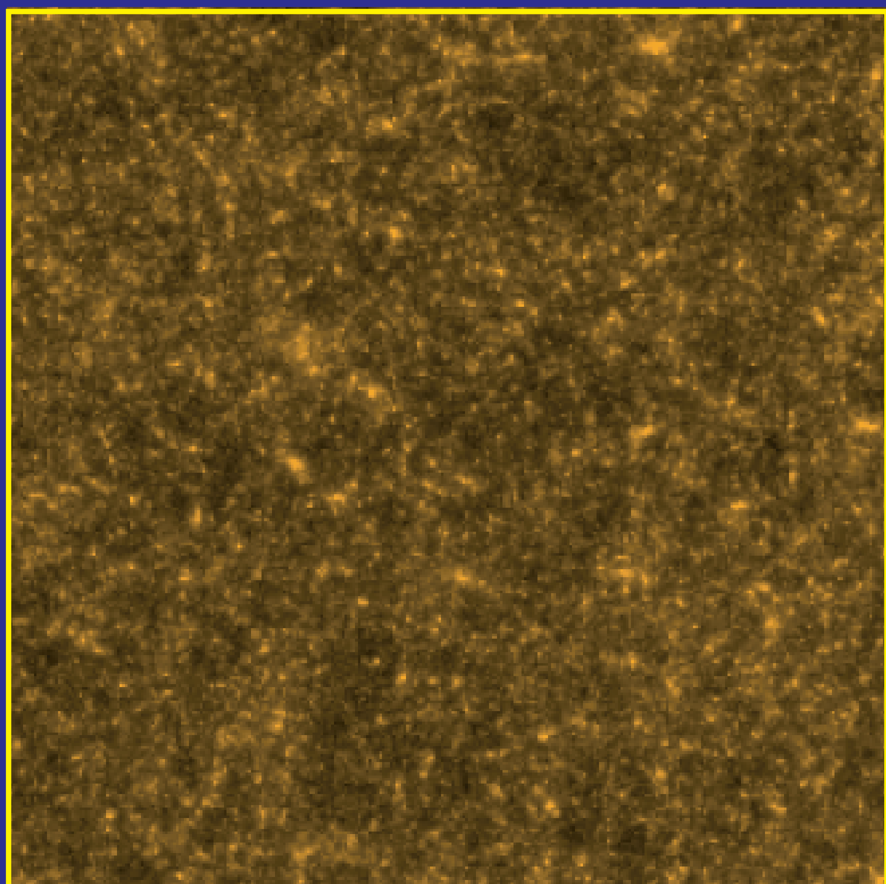
$$z_m = 0.85 \pm 0.05$$

iterated quadratic estimator a la Bond, Jaffe, Knox (1998); Hu & White (2001)

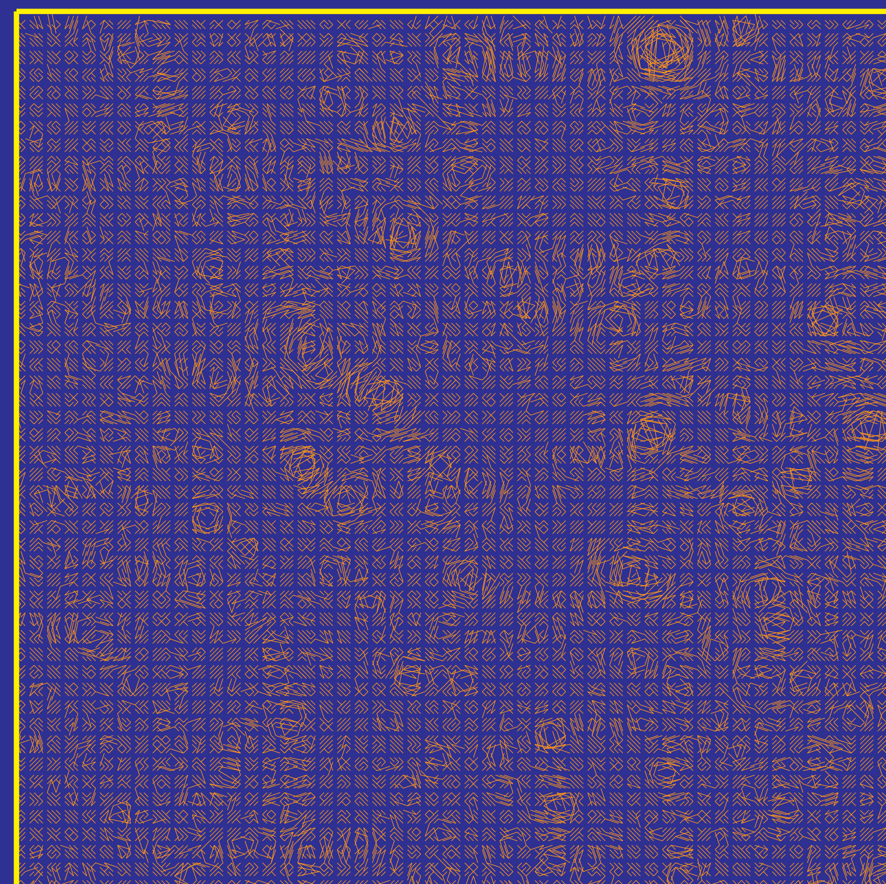
PM Simulations

- Simulating mass distribution is a routine exercise

Convergence



Shear

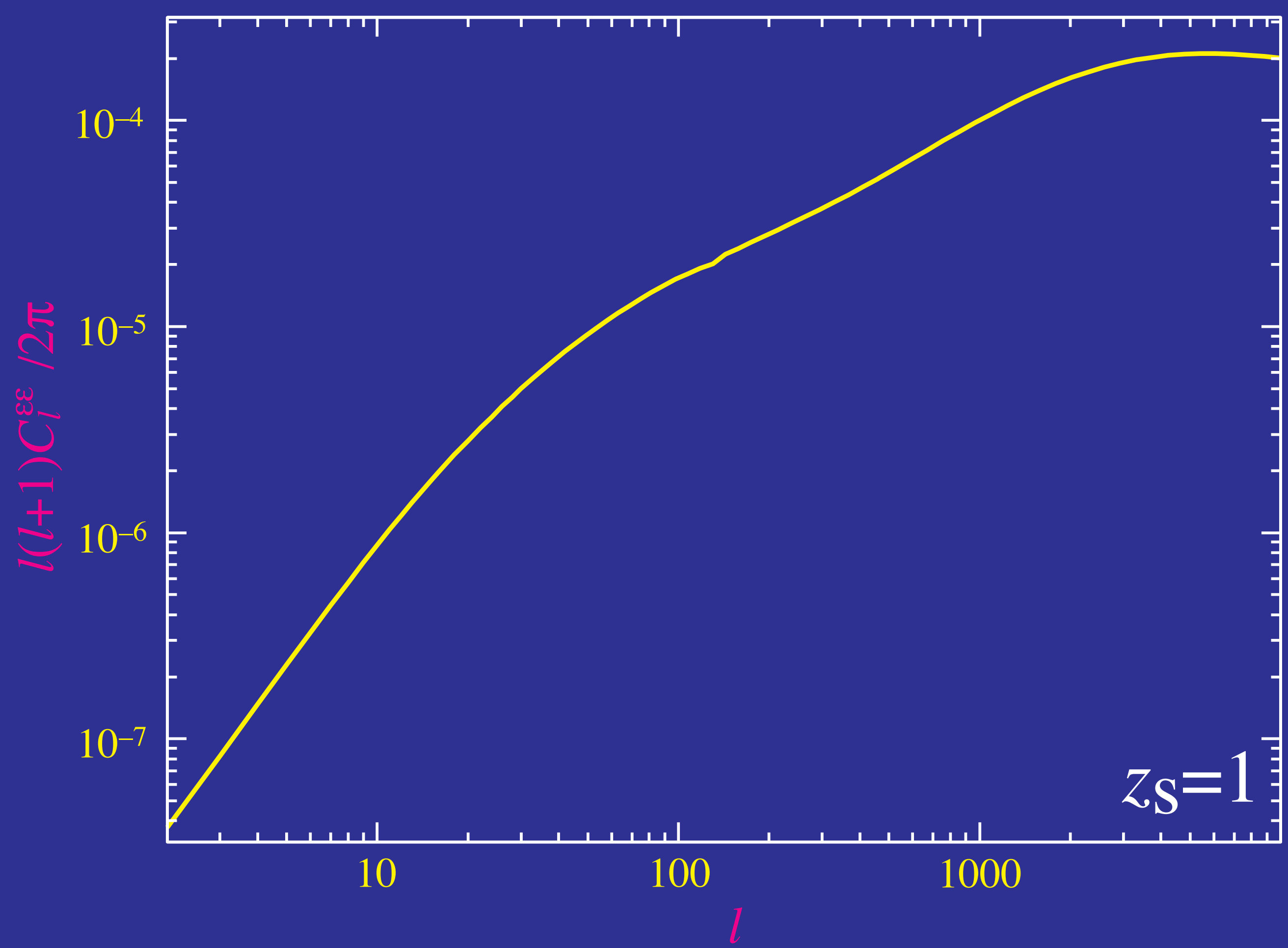


6∞× 6∞FOV; 2' Res.; 245–75 h^{-1}Mpc box; 480–145 h^{-1}kpc mesh; 2–70 10^9 $M_\odot$

White & Hu (1999)

Degeneracies

- All parameters of initial condition, growth and distance redshift relation $D(z)$ enter
- Nearly featureless power spectrum results in degeneracies



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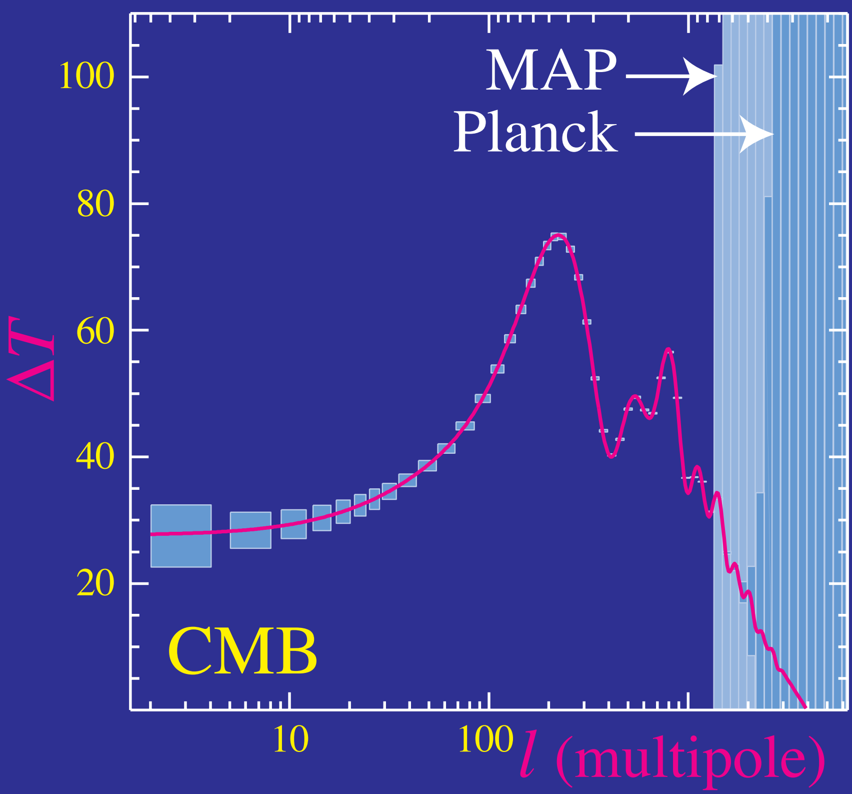
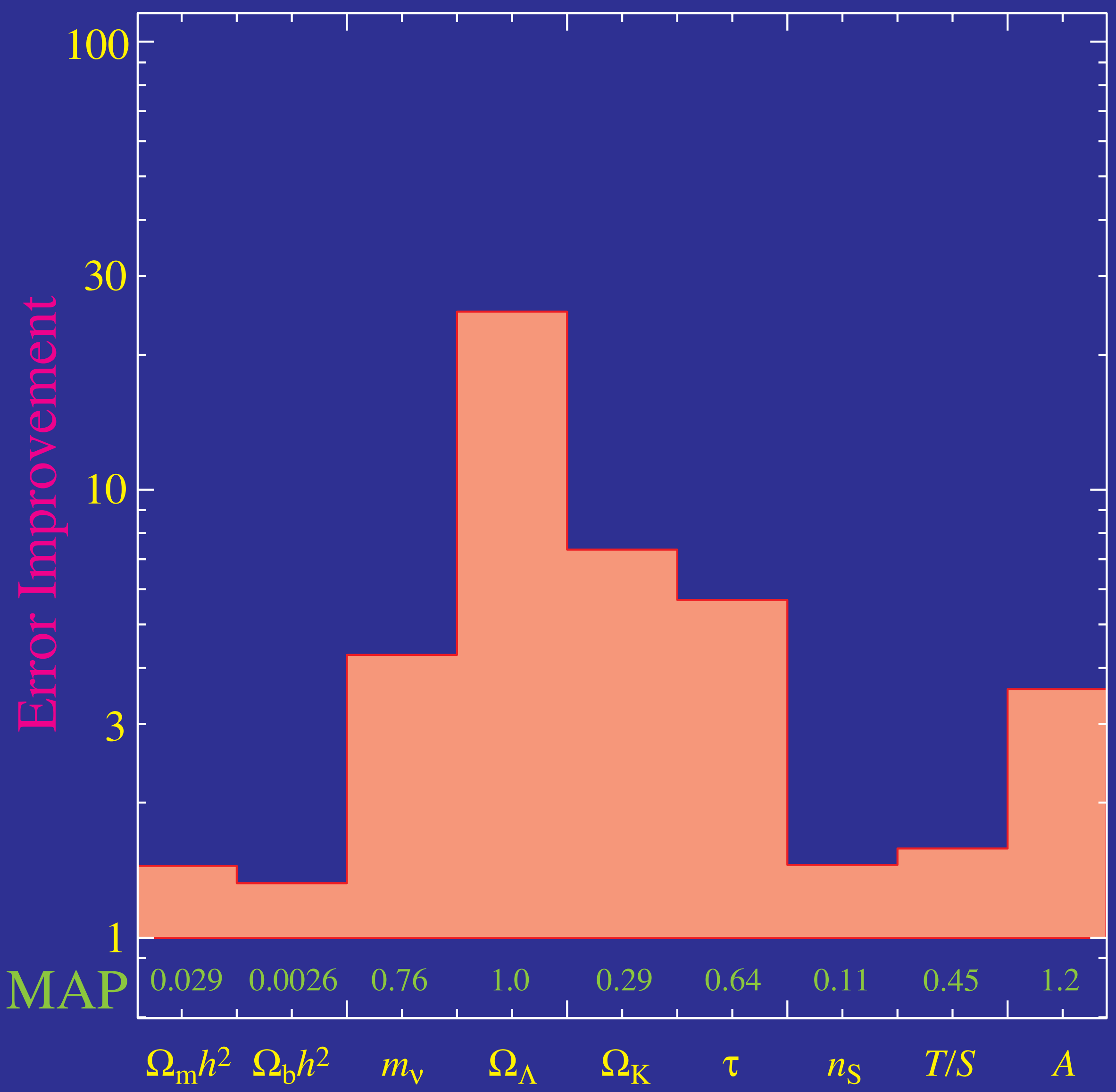


- Combine with information from the CMB: complementarity (Hu & Tegmark 1999)
- Crude tomography with source divisions (Hu 1999; Hu 2001)
- Fine tomography with source redshifts (Hu & Keeton 2002; Hu 2002)

Error Improvement

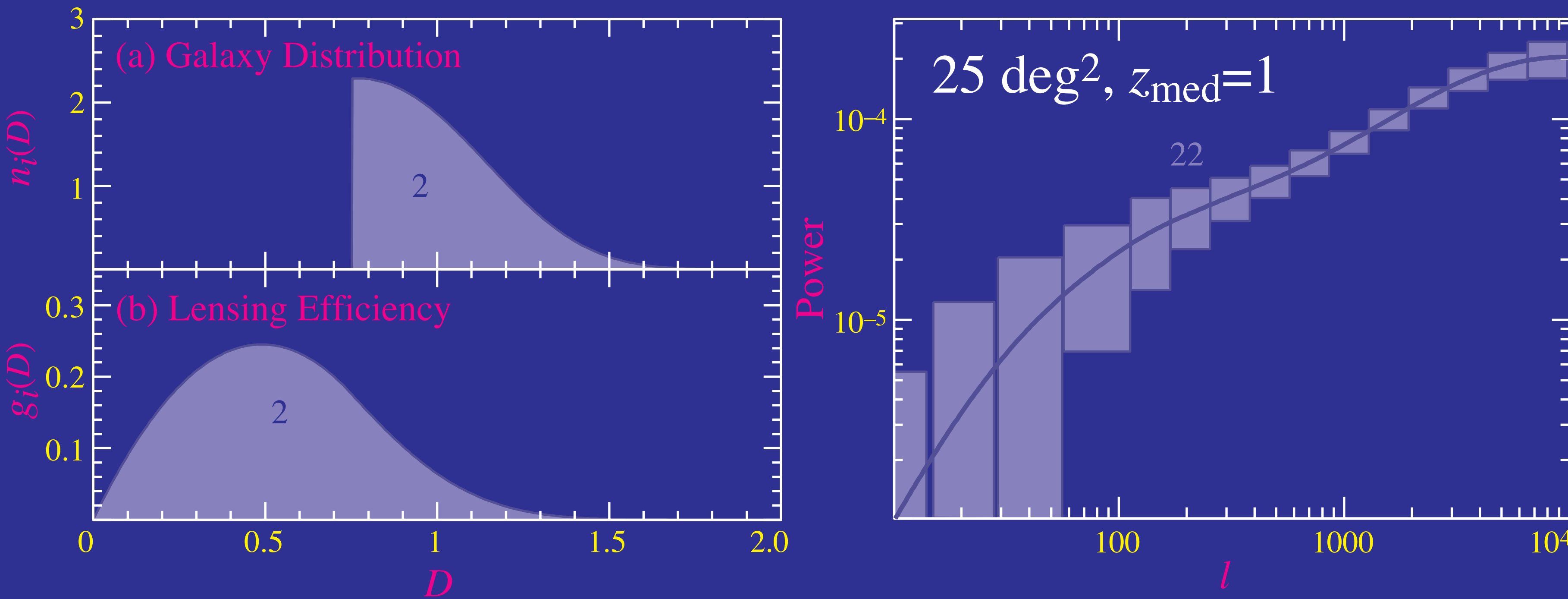
- Error improvements over MAP/CMB with a 1000 deg^2 survey



Hu & Tegmark (1999)

Crude Tomography

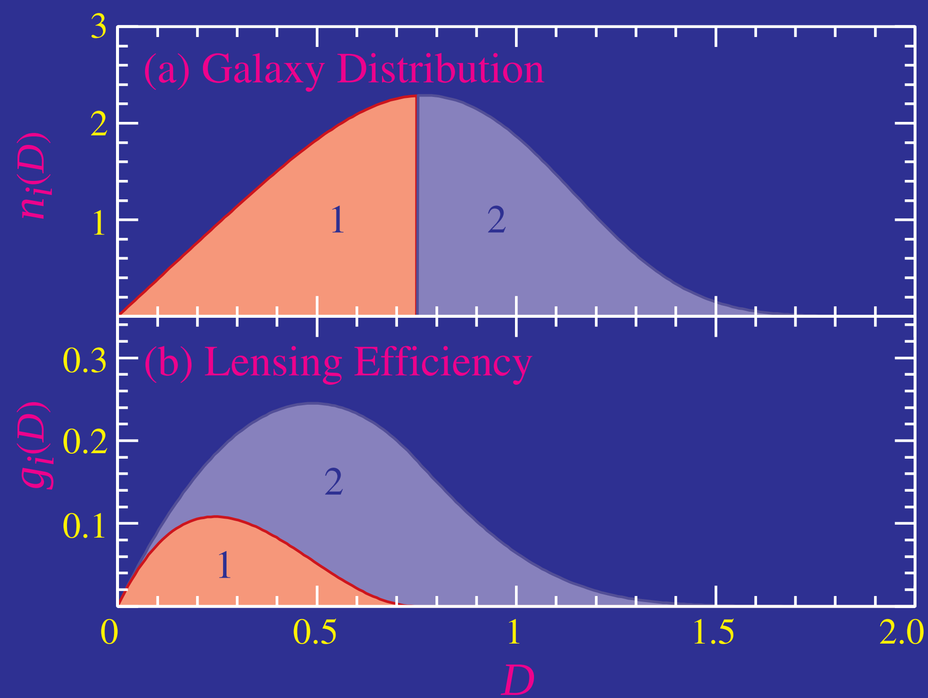
- Divide sample by photometric redshifts

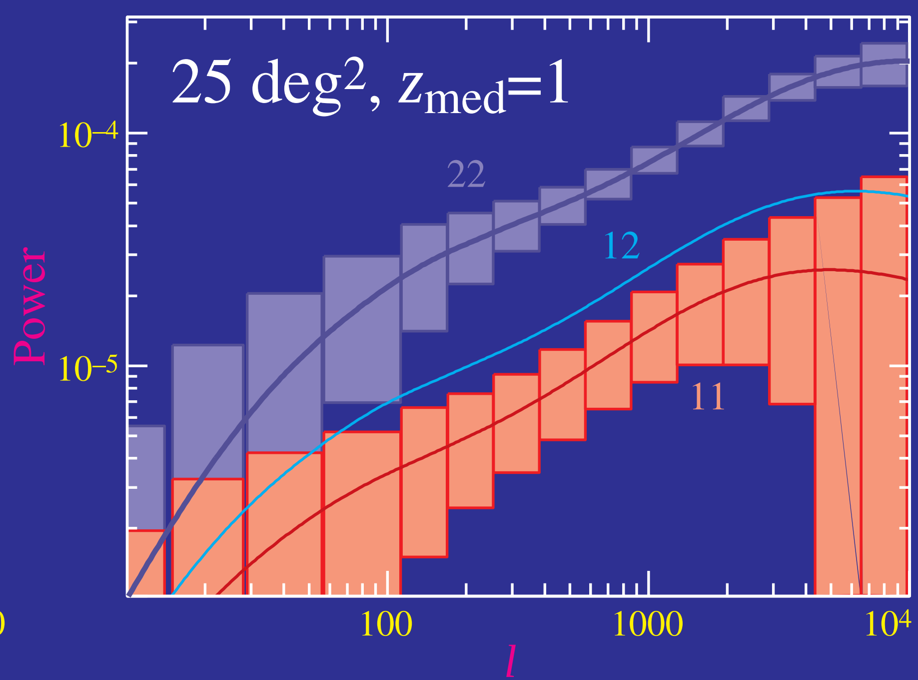


Hu (1999)

Crude Tomography

- Divide sample by photometric redshifts
- Cross correlate samples



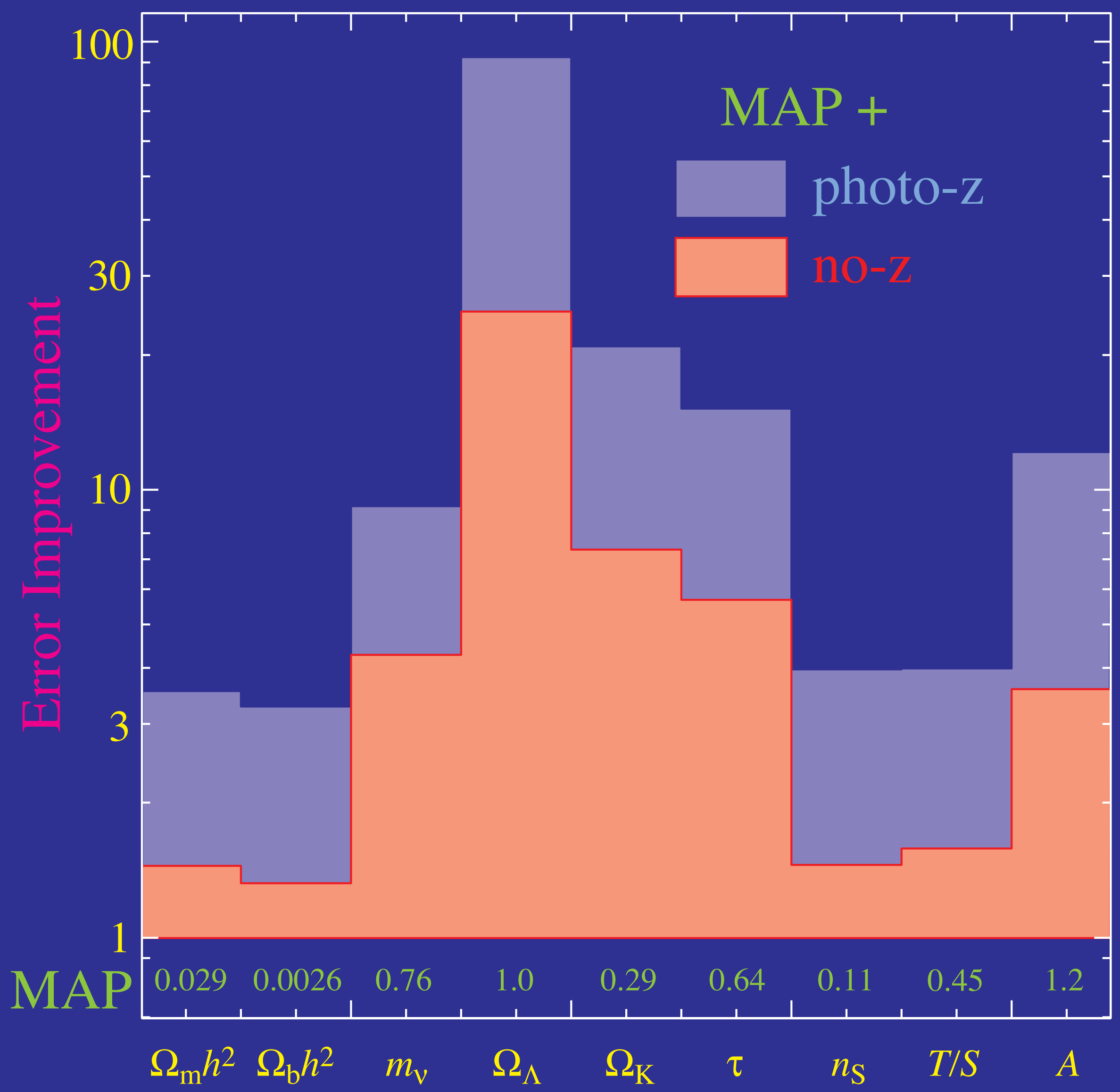


- Order of magnitude increase in precision even after CMB breaks degeneracies

Hu (1999)

Efficacy of Crude Tomography

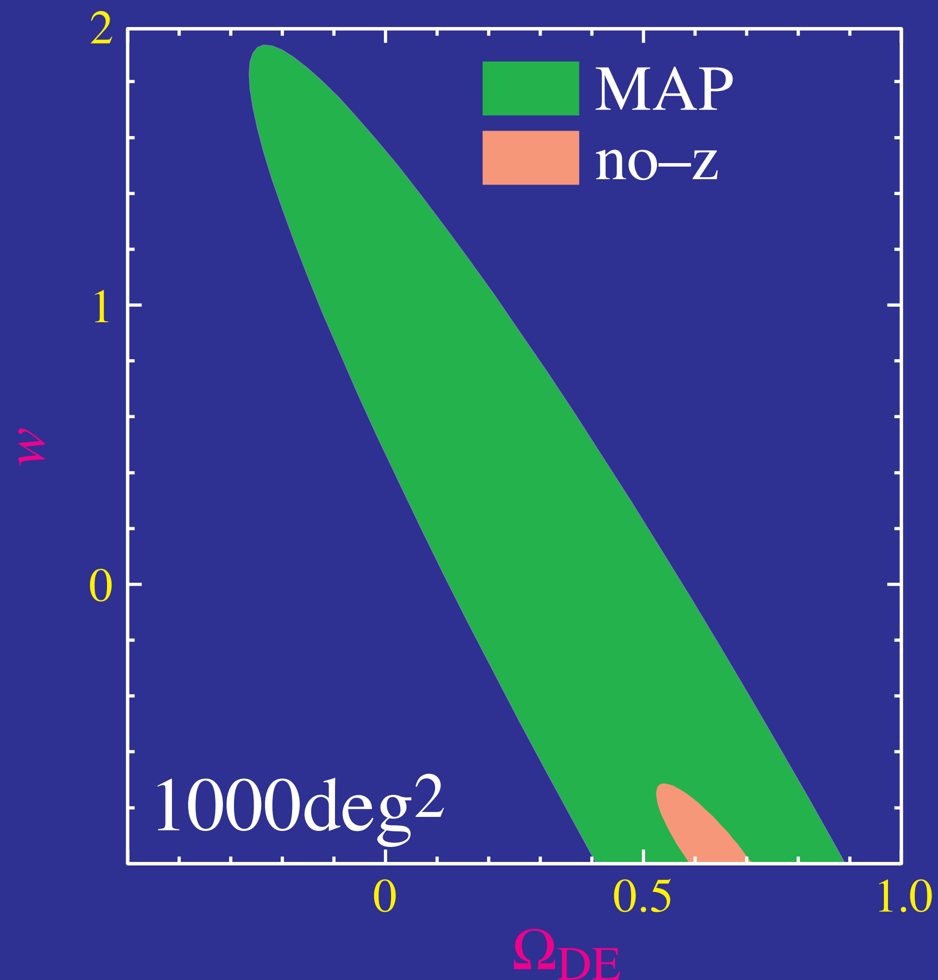
- Error improvements over MAP/CMB with a 1000 deg^2 survey



Hu & Tegmark (1999); Hu (2000)

Dark Energy & Tomography

- Both CMB and tomography help lensing provide interesting constraints on dark energy



l<3000; 56 gal/deg^2

Hu (2001)

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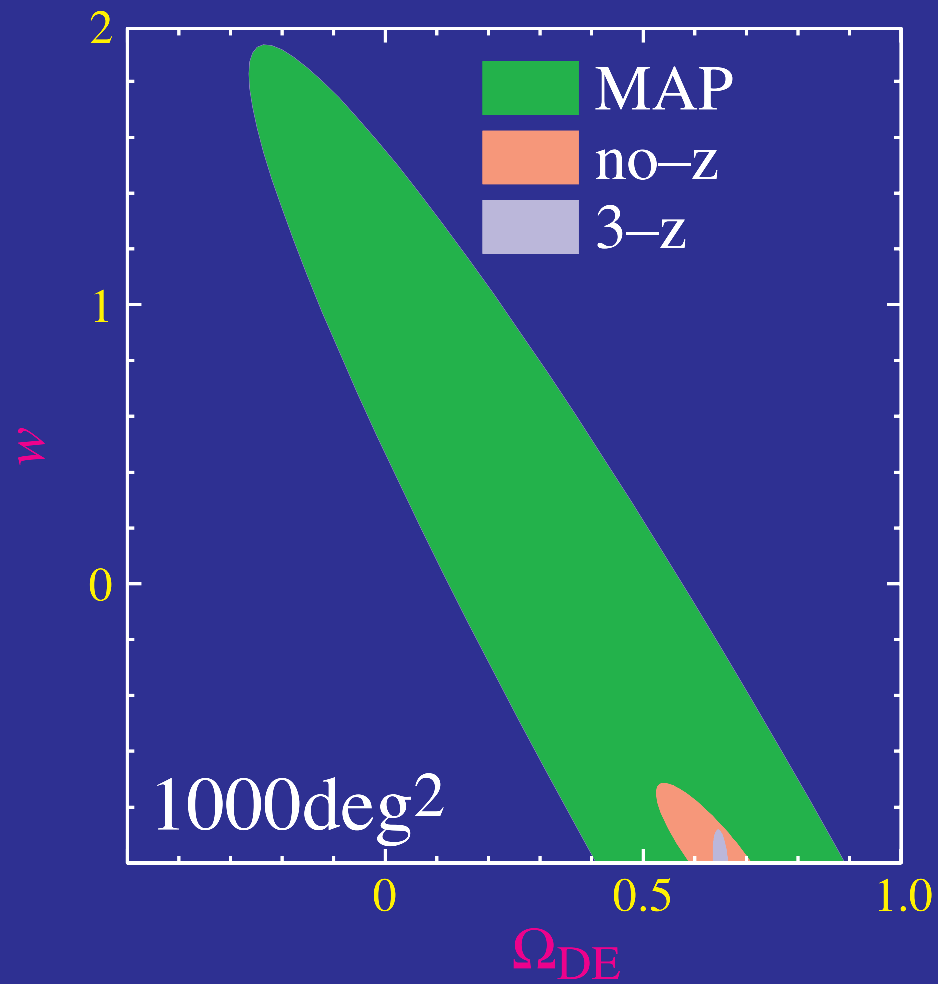

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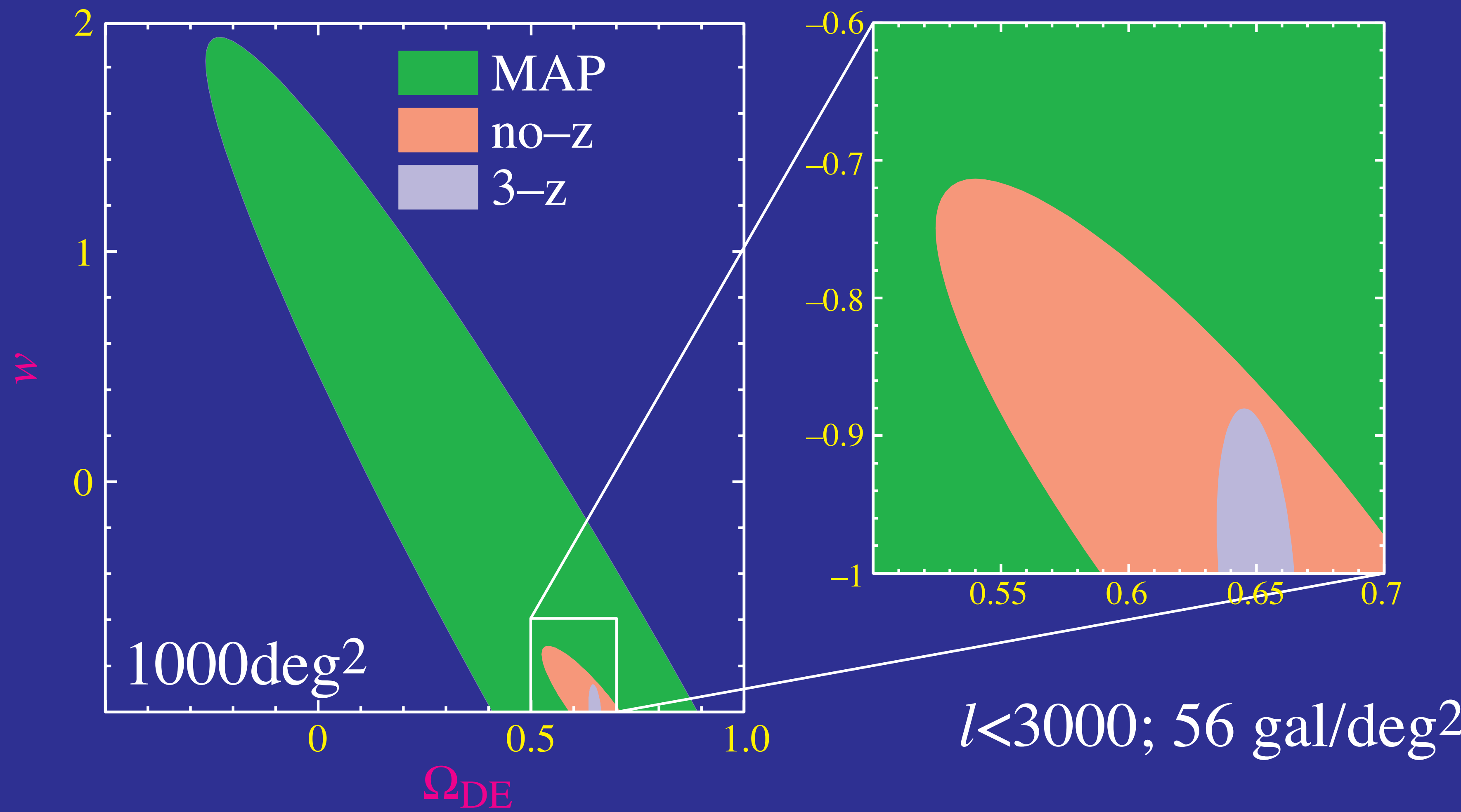


Hu (2001)

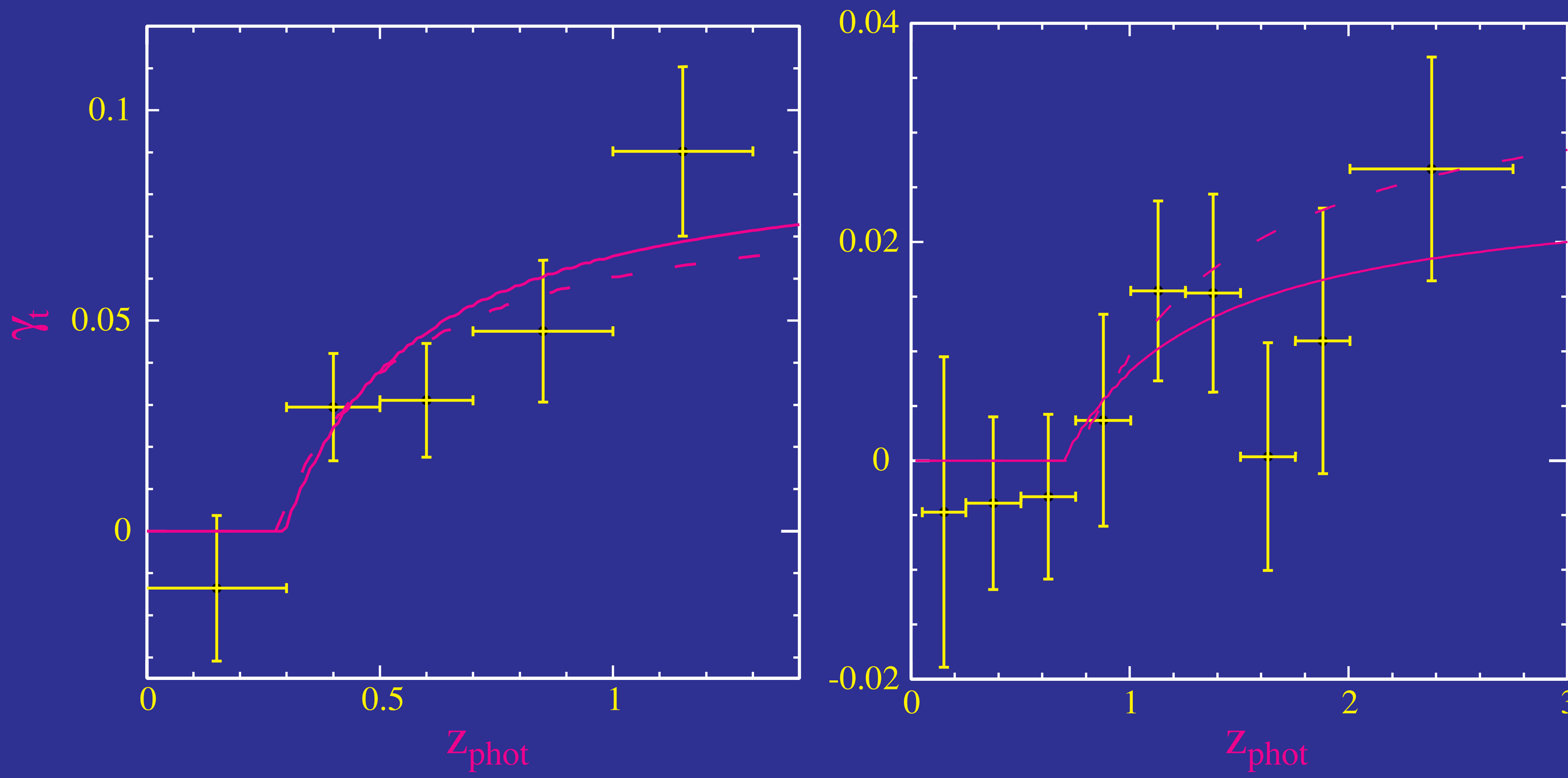
Dark Sector and Radial Information

- Much of the information on the dark sector is hidden in the temporal or radial dimension
- Evolution of growth rate (dark energy pressure slows growth)
- Evolution of distance-redshift relation

- Lensing is inherently two dimensional: all mass along the line of sight lenses
- Tomography implicitly or explicitly reconstructs radial dimension with source redshifts
- Photometric redshift errors currently $\Delta z < 0.1$ out to $z \sim 1$ and allow for ”fine” tomography

Tomography in Practice

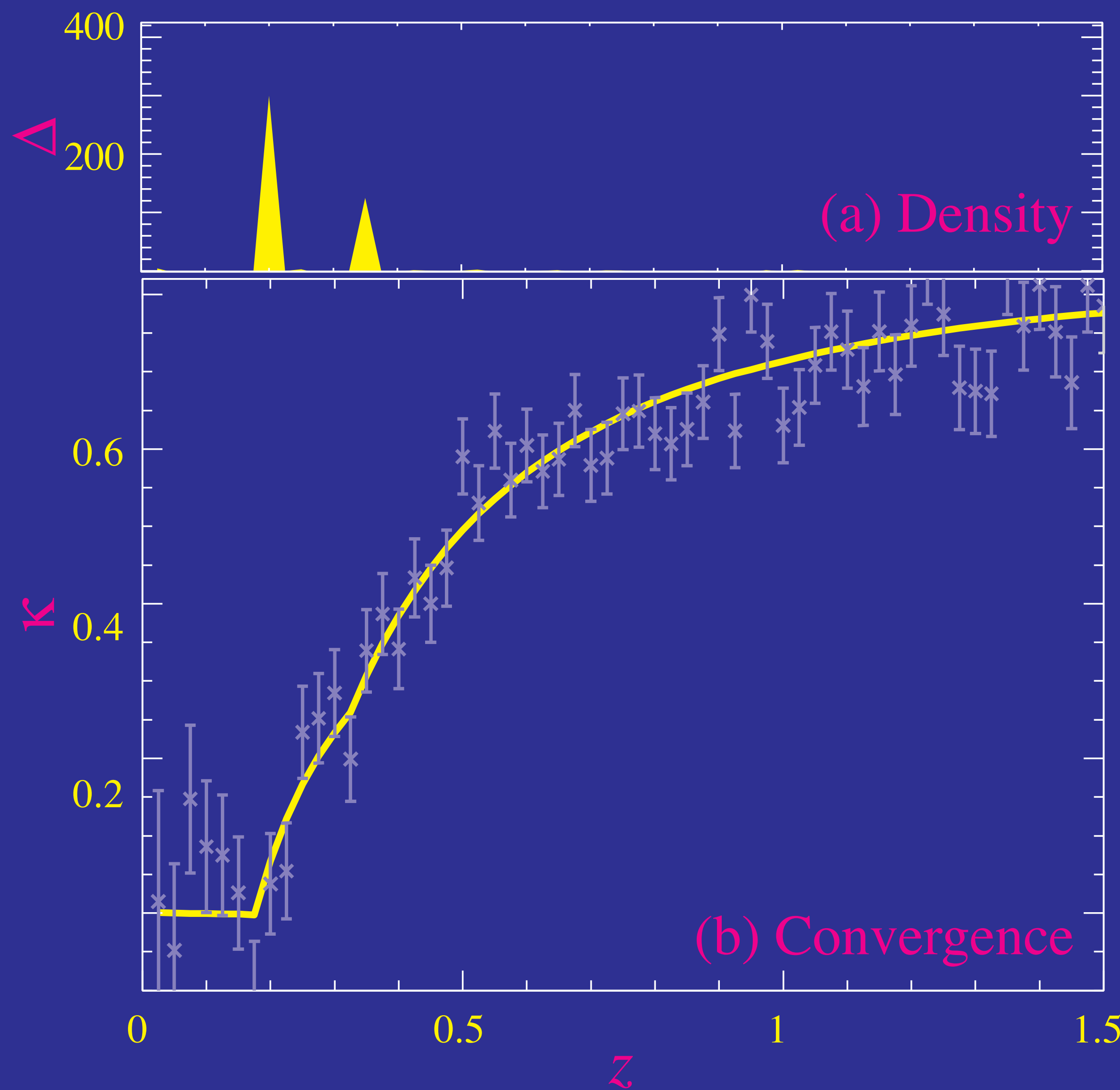
- Localization and selection of clusters



Wittman et al. (2001; 2002)

Hidden in Noise

- Derivatives of noisy convergence isolate radial structures



Hu & Keeton (2001)

Fine Tomography

- Convergence – projection of $\Delta = \delta/a$ for each z_s

$$\kappa(z_s) = \frac{3}{2} H_0^2 \Omega_m \int_0^{z_s} dz \, \frac{dD}{dz} \, \frac{D(D_s - D)}{D_s} \, \Delta \, ,$$

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- Data is linear combination of signal + noise

$$\mathbf{d}_\kappa = \mathbf{P}_{\kappa\Delta} \mathbf{s}_\Delta + \mathbf{n}_\kappa \, ,$$

$$[\mathbf{P}_{\kappa\Delta}]_{ij} = \begin{cases} \frac{3}{2} H_0^2 \Omega_m \delta D_j \frac{(D_{i+1} - D_j) D_j}{D_{i+1}} & D_{i+1} > D_j \, , \\ 0 & D_{i+1} \leq D_j \, , \end{cases}$$

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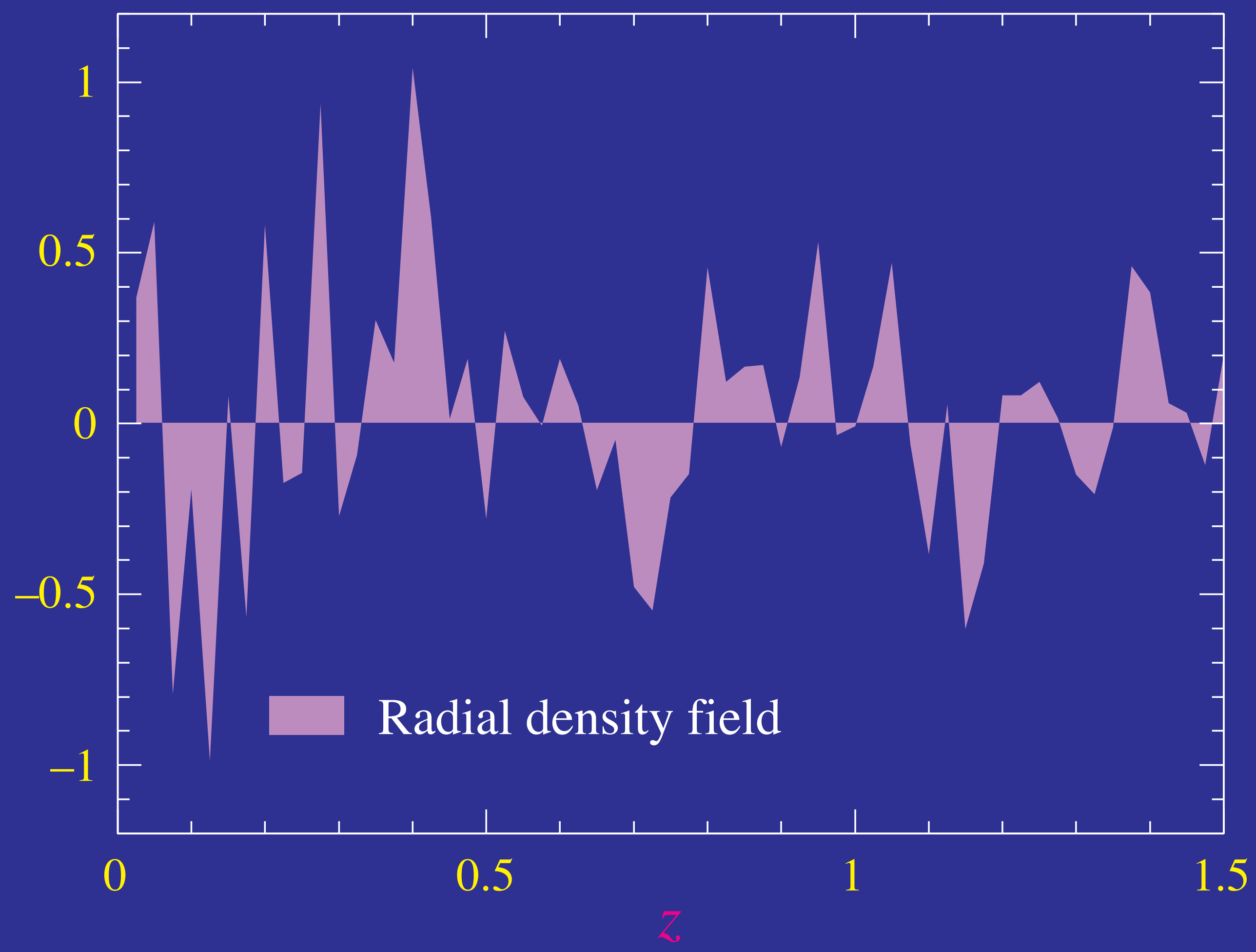
- Well-posed (Taylor 2002) but noisy inversion (Hu & Keeton 2002)
- Noise properties differ from signal properties $\rightarrow$ optimal filters

Fine Tomography

- Tomography can produce direct 3D dark matter maps, but realistically only broad features (Hu & Keeton 2002)



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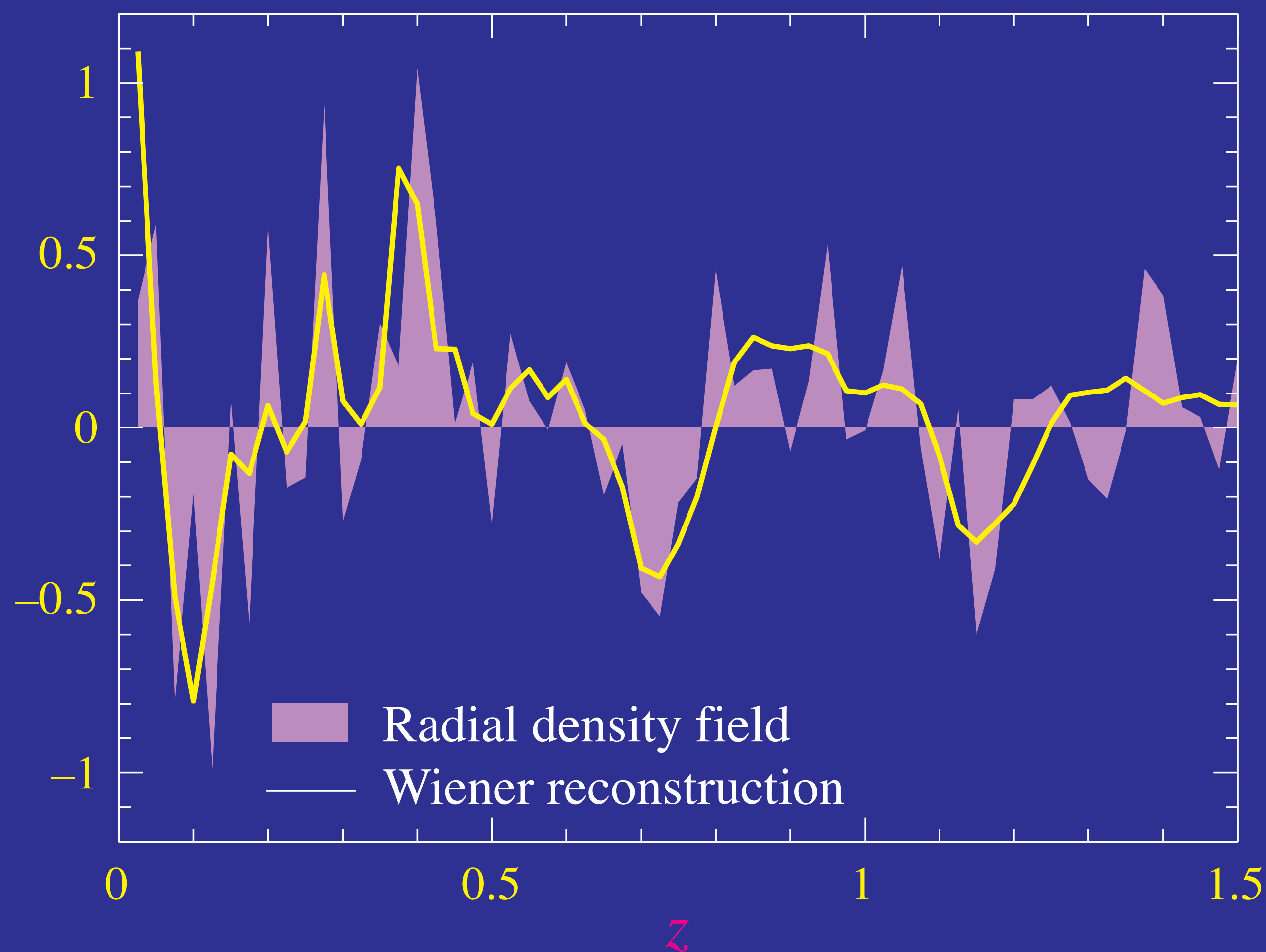

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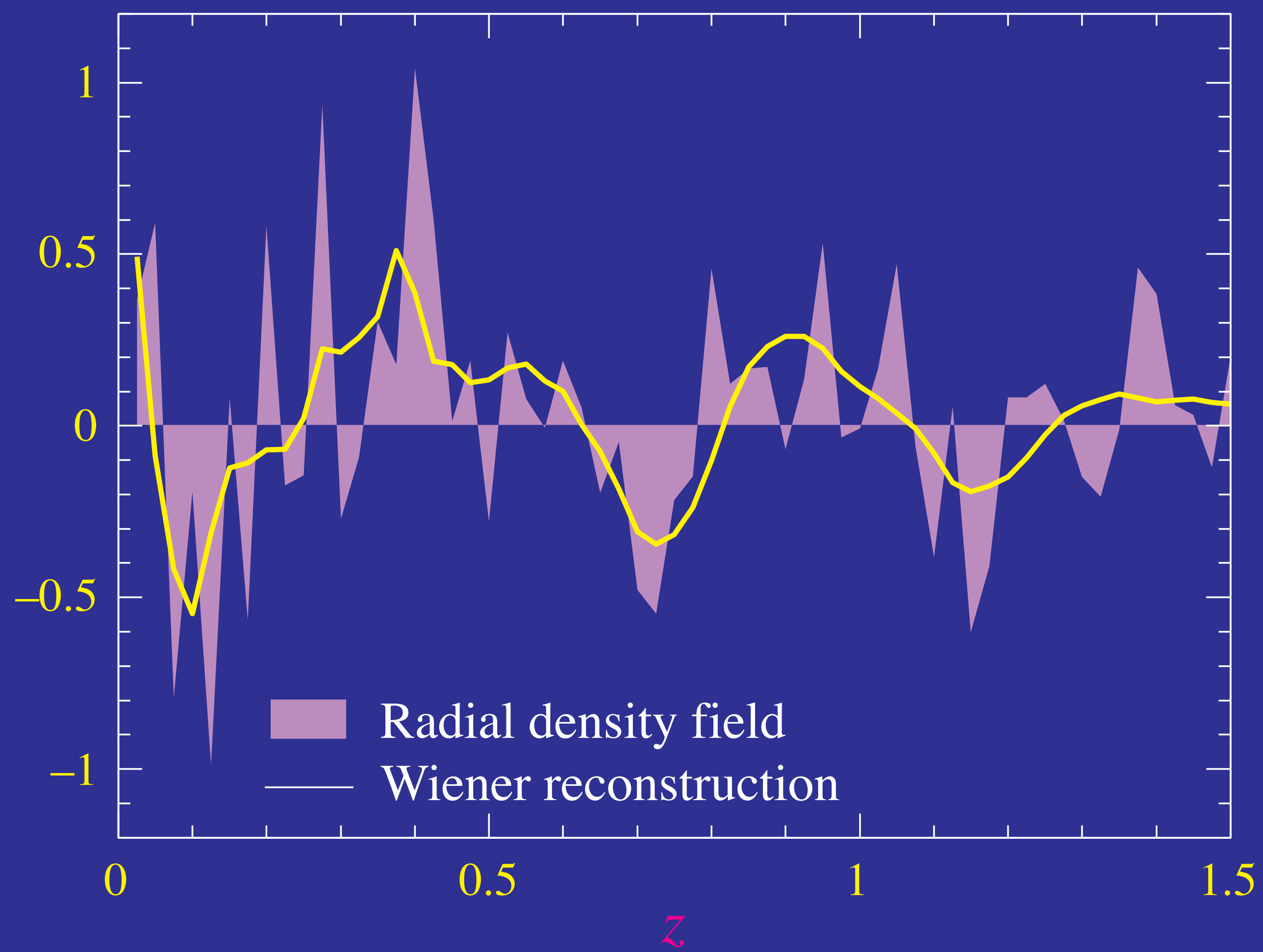

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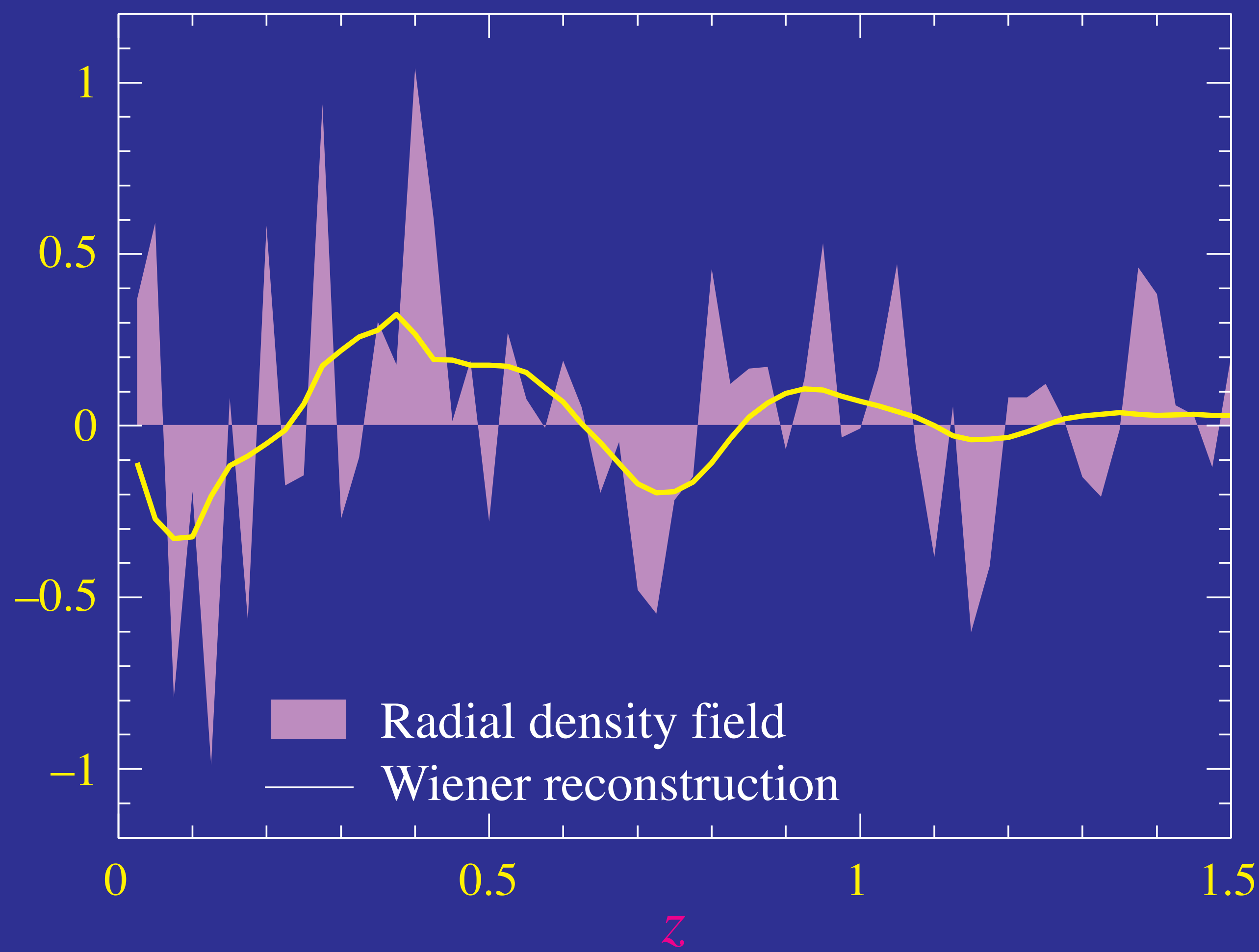

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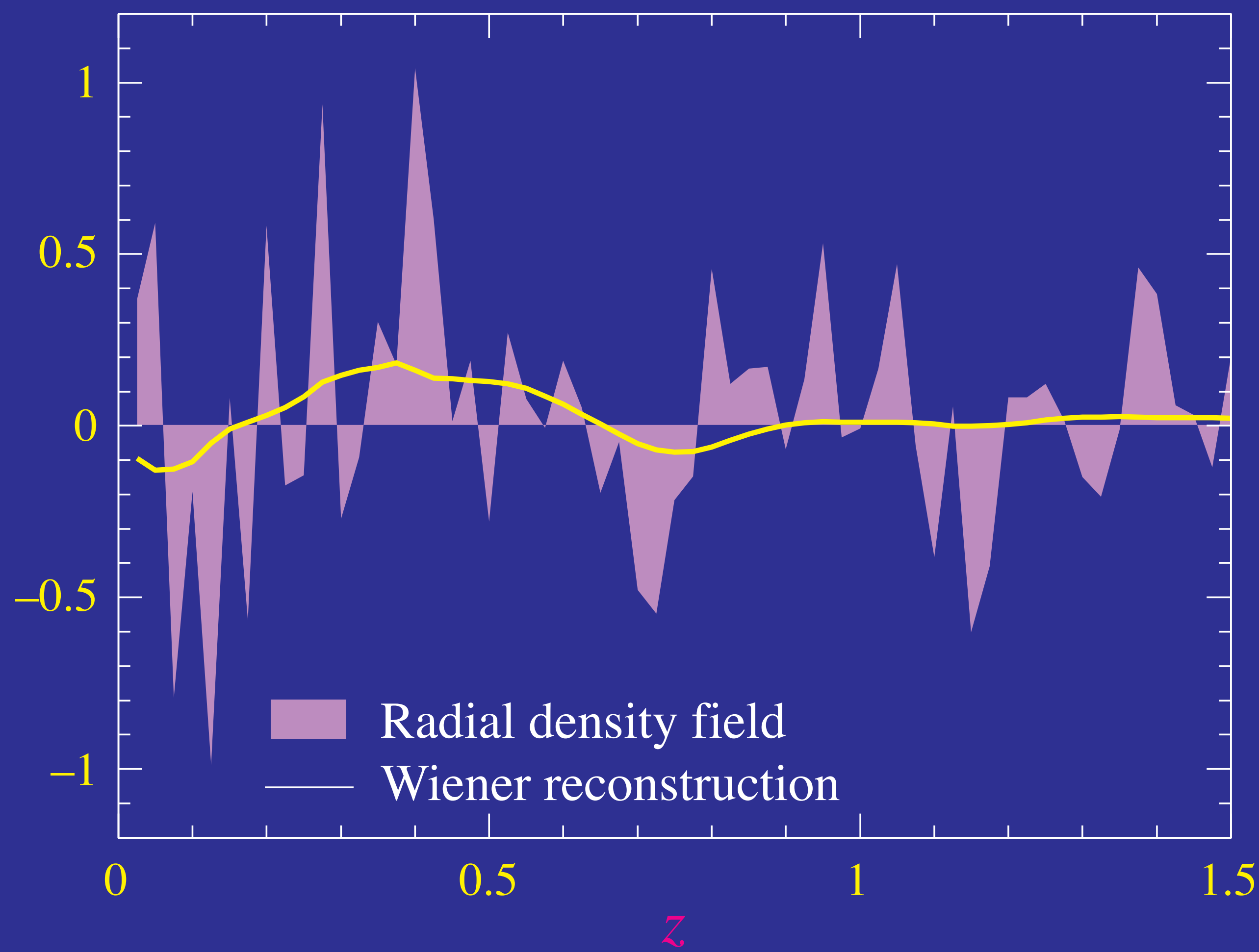
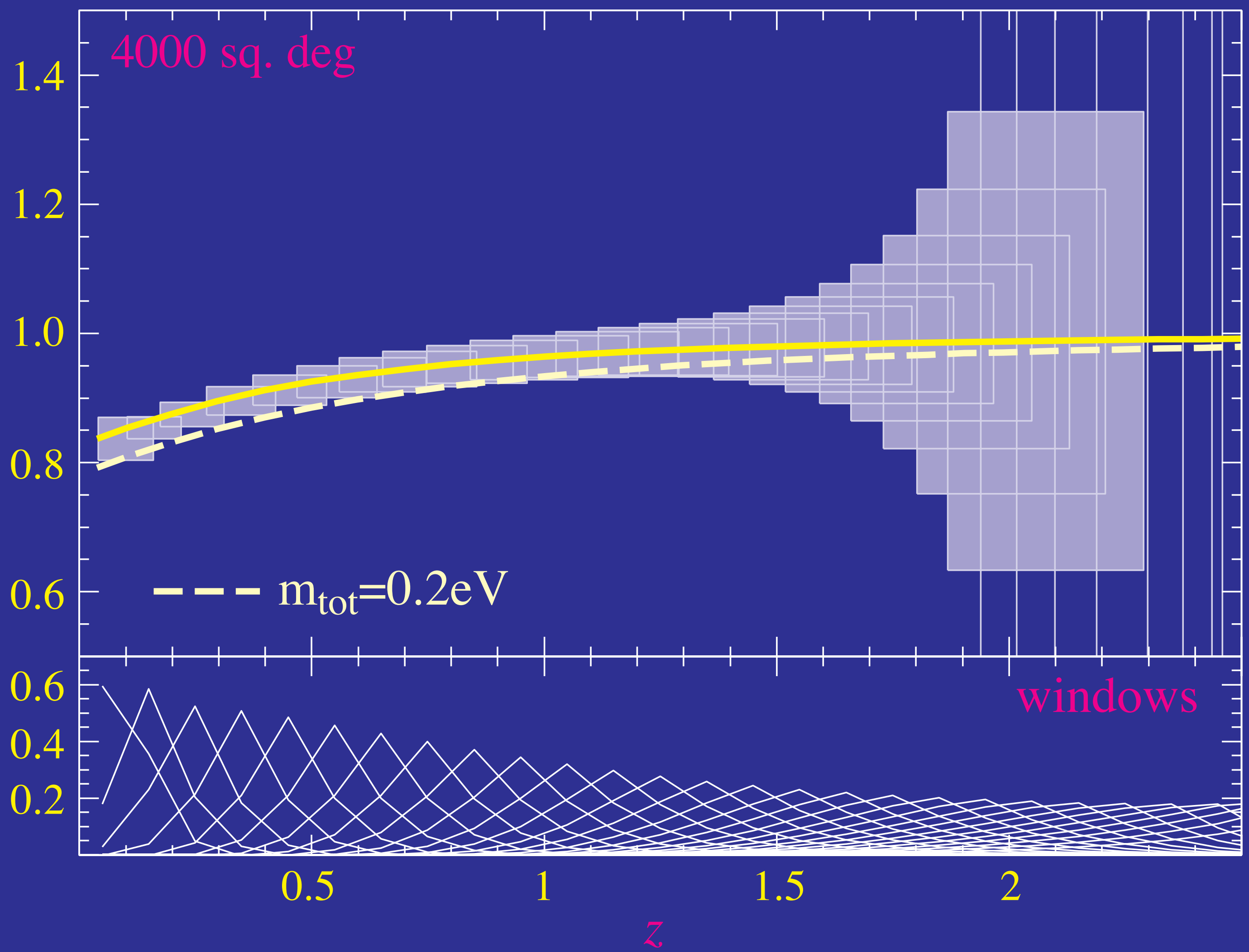


Growth Function

- Localized constraints (fixed distance-redshift relation)

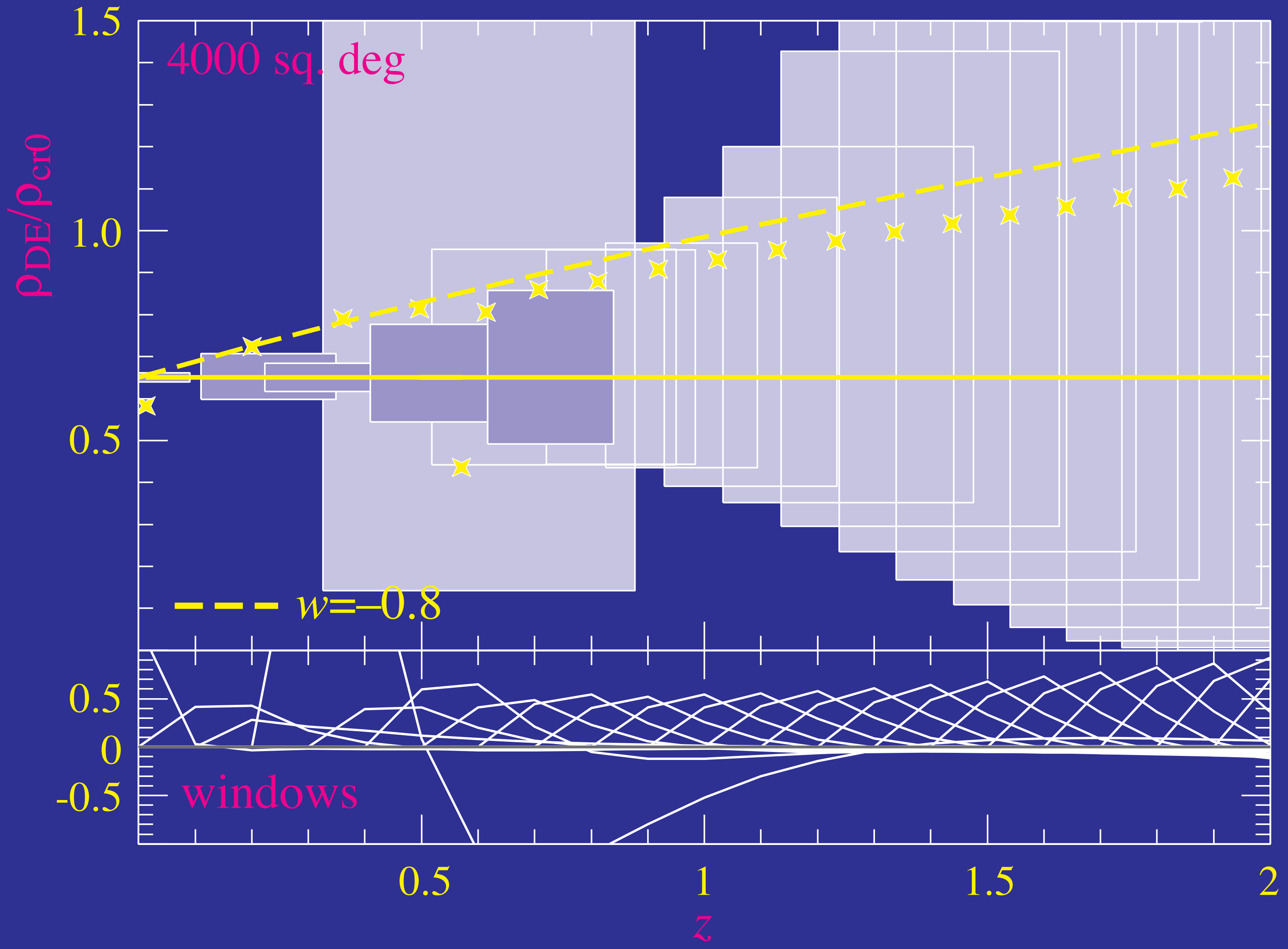


Hu (2002)

3 degenerate mass ν's assumed e.g. Beacom & Bell (2002)

Dark Energy Density

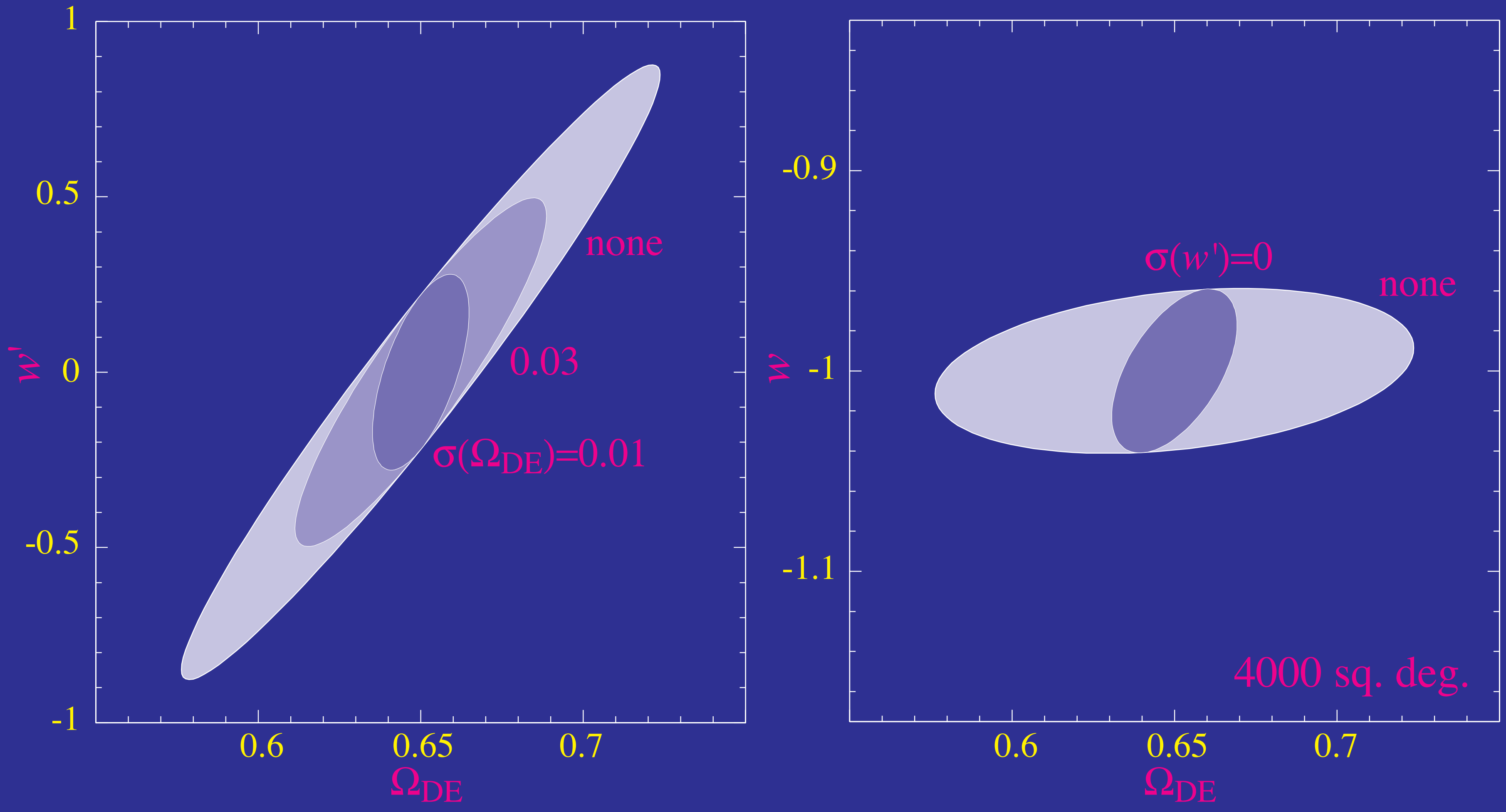
- Localized constraints (with cold dark matter)



Hu (2002)

Dark Energy Parameters

- Three parameter dark energy model (Ω_{DE}, w, $dw/dz = w'$)



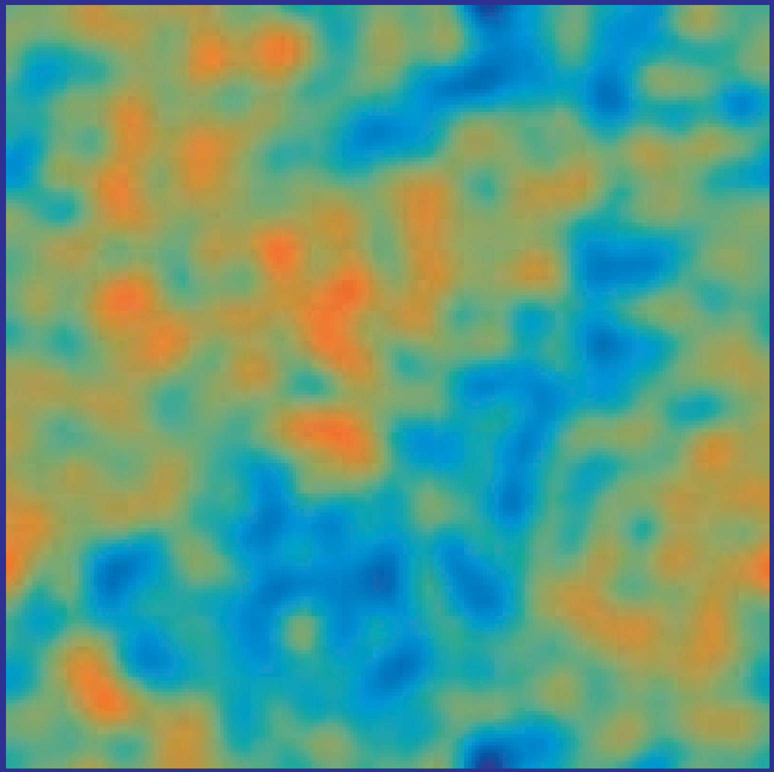
Hu (2002)

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

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

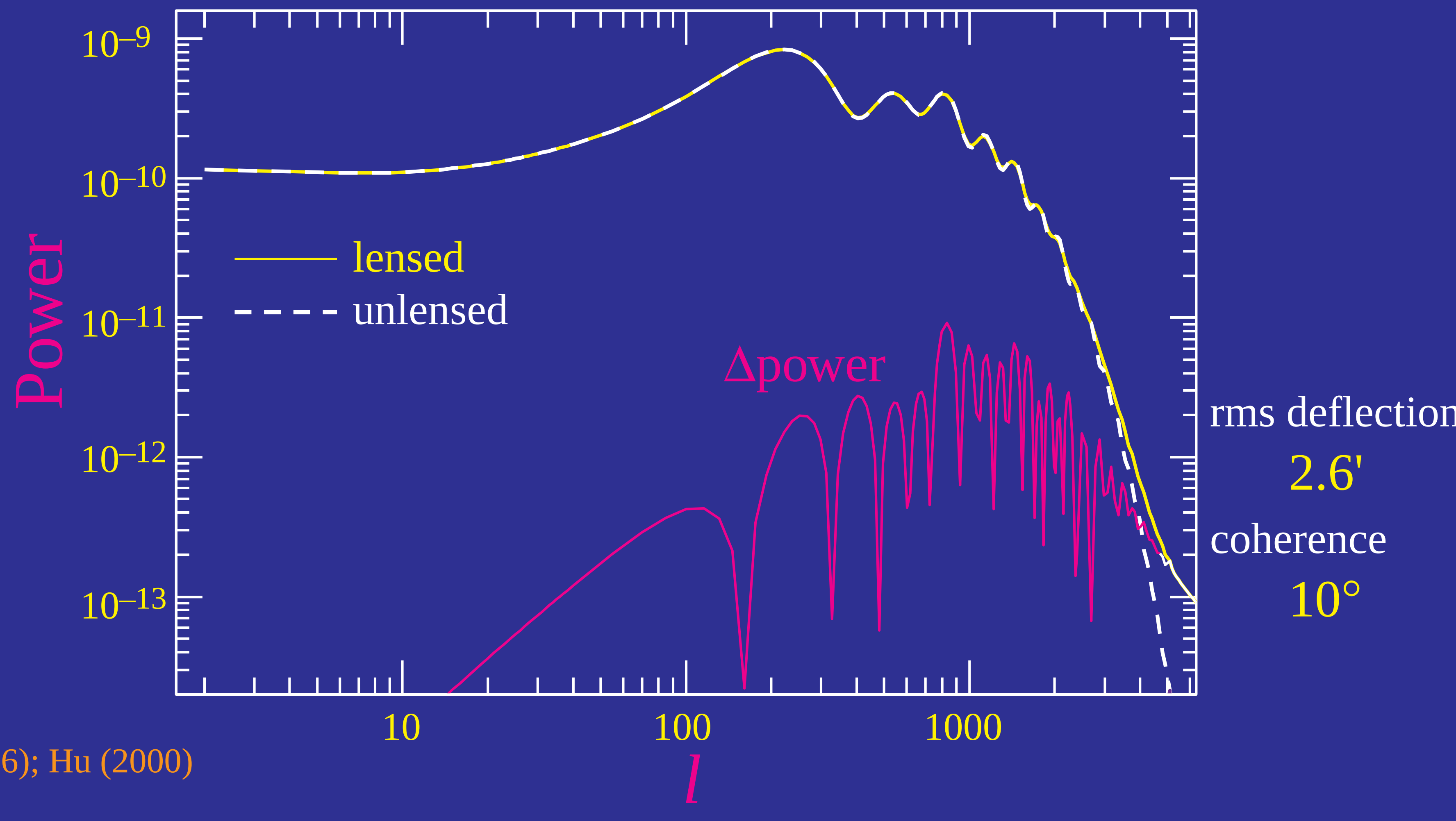
2.6'

deflection coherence

10°

Lensing in the Power Spectrum

- Lensing smooths the power spectrum with a width $\Delta l \sim 60$
- Convolution with specific kernel: higher order correlations between multipole moments – not apparent in power



Seljak (1996); Hu (2000)

Reconstruction from the CMB

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

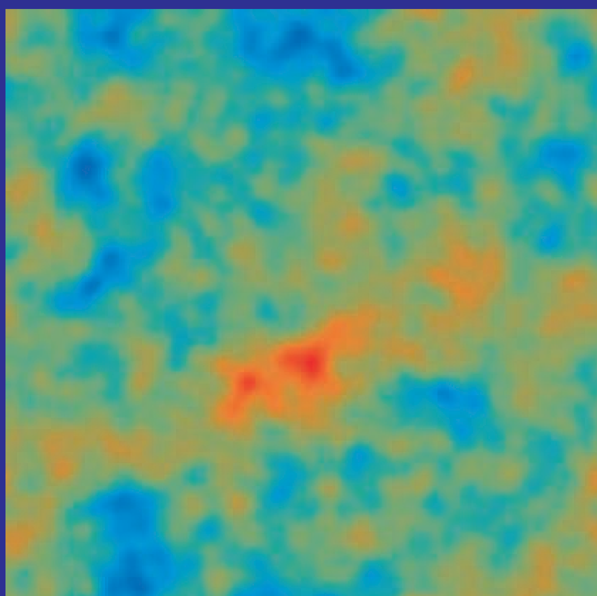
$$\langle x(\mathbf{l}) x'(\mathbf{l}')\rangle_{\rm CMB} = f_\alpha(\mathbf{l},\mathbf{l}')\phi(\mathbf{l}+\mathbf{l}')\,,$$

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

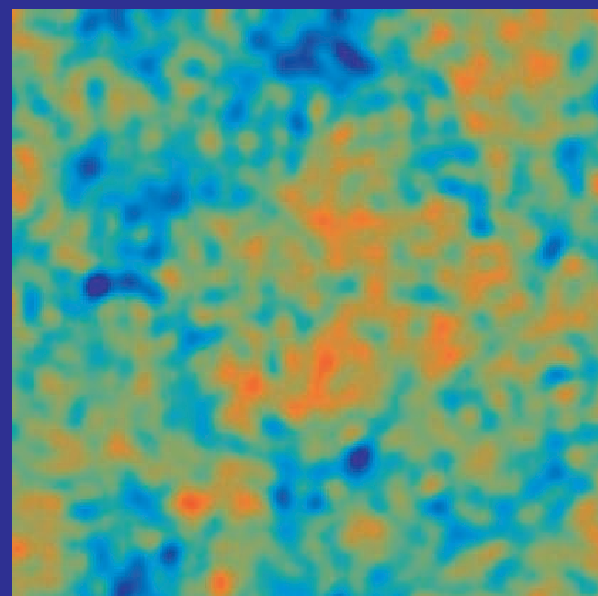
- Each pair forms a noisy estimate of the potential or projected mass - just like a pair of galaxy shears
- Minimum variance weight all pairs to form an estimator of the lensing mass

Ultimate (Cosmic Variance) Limit

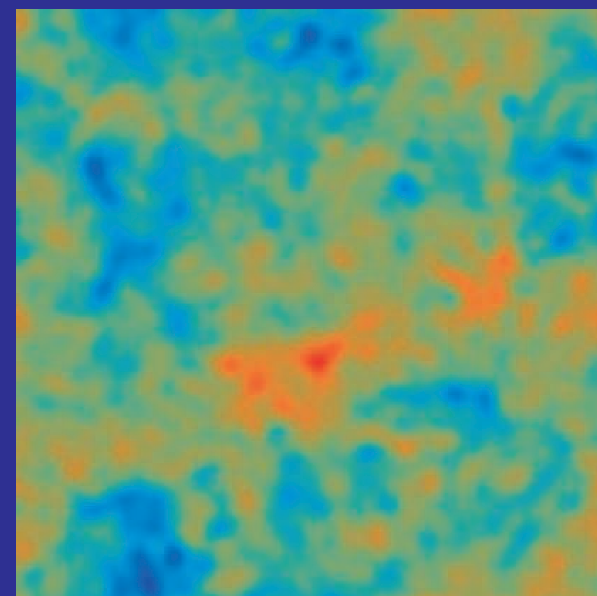
- Cosmic variance of CMB fields sets ultimate limit
- Polarization allows mapping to finer scales (~10')



mass



temp. reconstruction



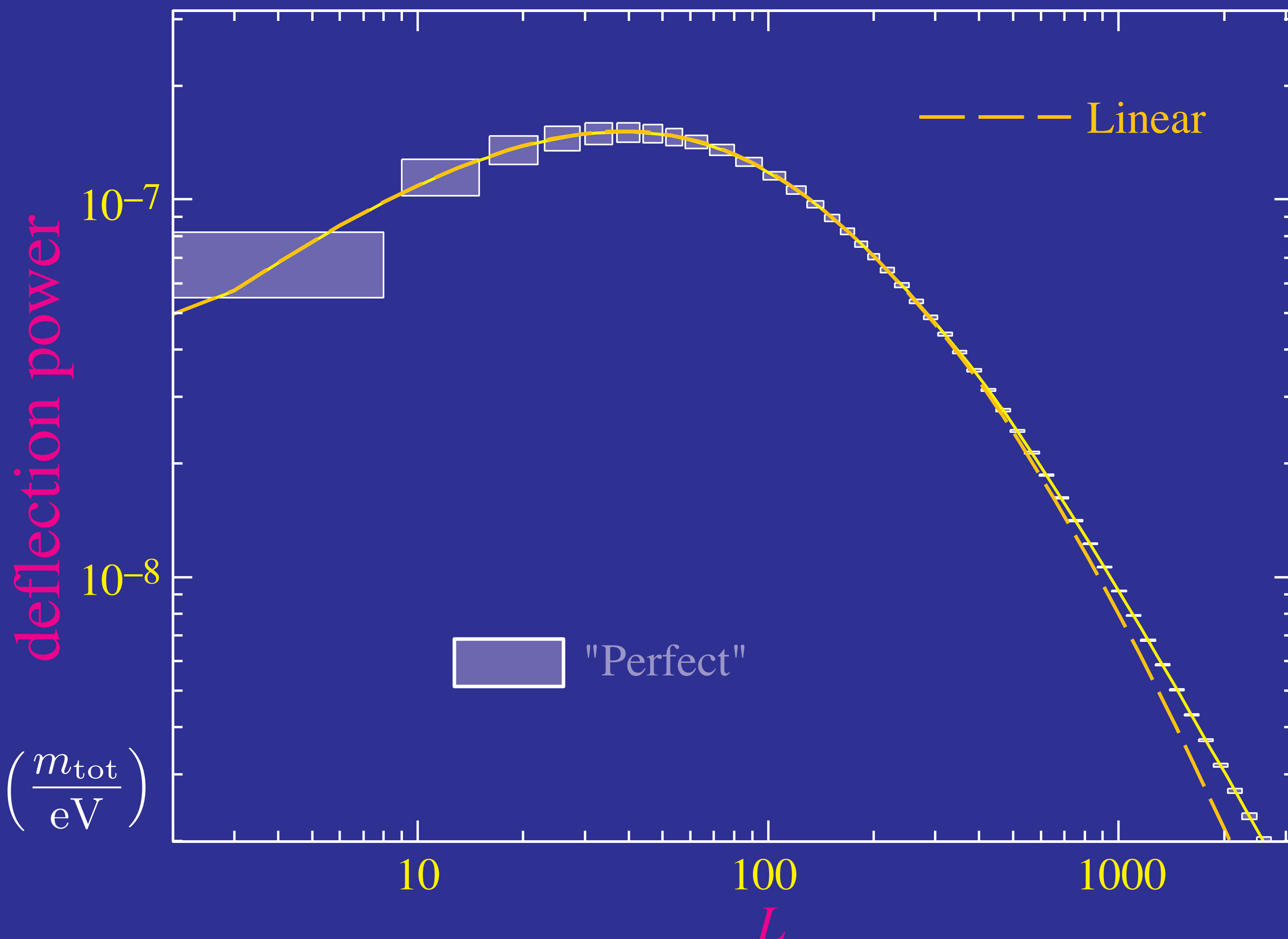
EB pol. reconstruction

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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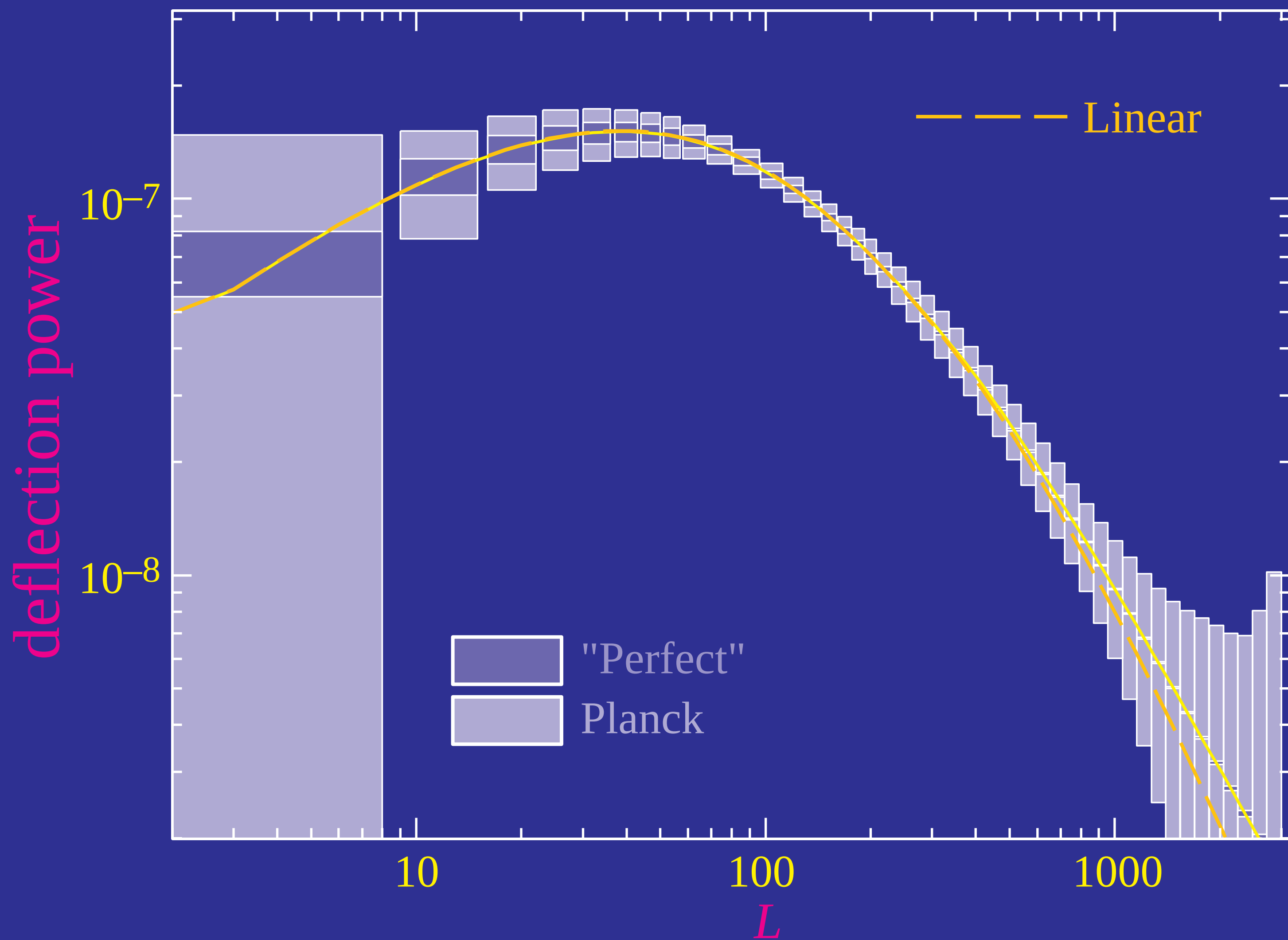

Hu & Okamoto (2001)

$\sigma(w)$~0.06; 0.14

Summary

- Gravitational lensing is the only direct probe of the dark sector:

  composition of dark matter: massive neutrinos

  nature of the dark energy: scalar field? Λ?

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- Coarse radial resolution sufficient for recoving

  linear growth rate

  dark energy density evolution
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- CMB provides ultimate high-z source for tomography; precision neutrino constraints in principle possible