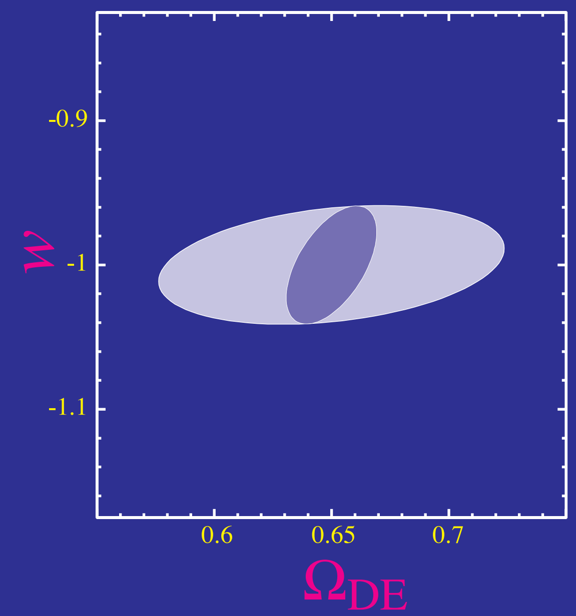
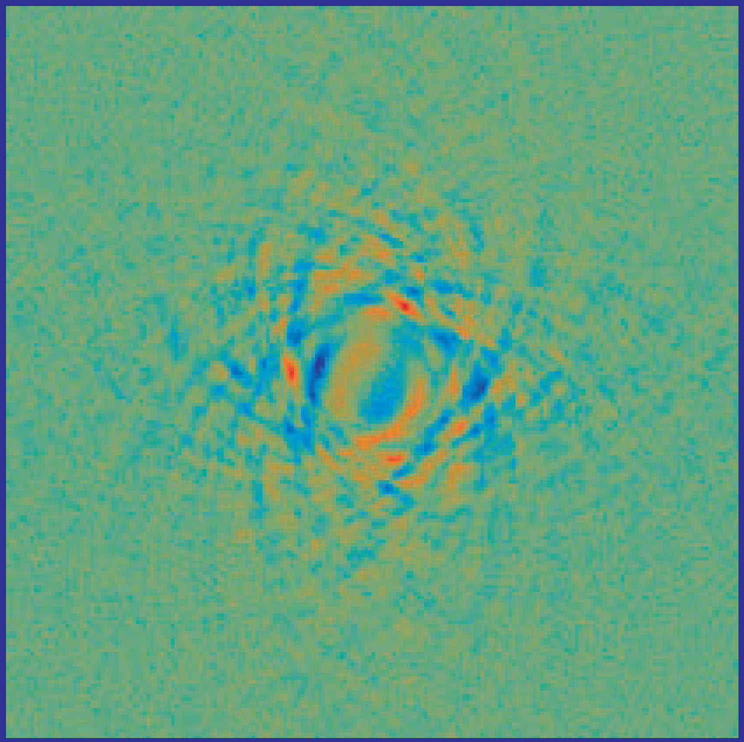
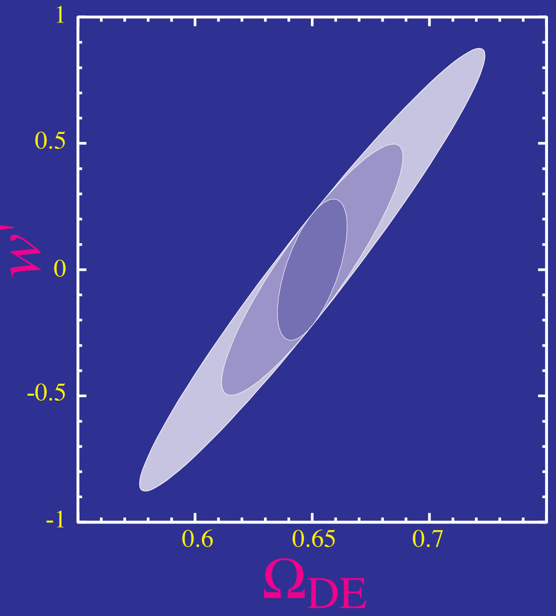
Gravitational Lensing and the Dark Energy







Future Prospects

Wayne Hu

SLAC, August 2002

Outline

- Standard model of cosmology
- Gravitational lensing
- Lensing probes of dark energy

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Collaborators

- Charles Keeton
- Takemi Okamoto
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Microsoft

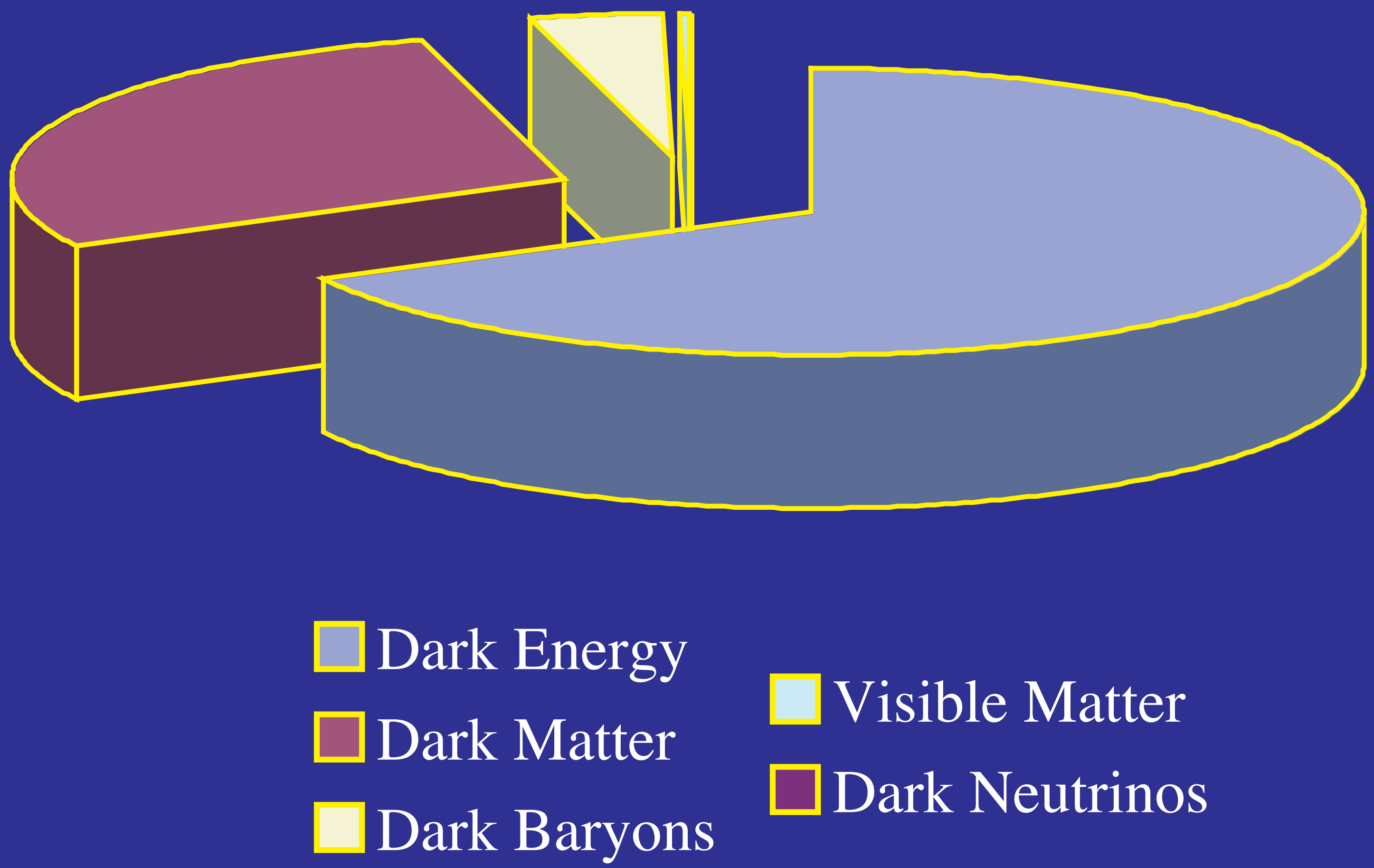
http://background.uchicago.edu

("Presentations" in PDF)

Dark Energy
and the
Standard Model of Cosmology

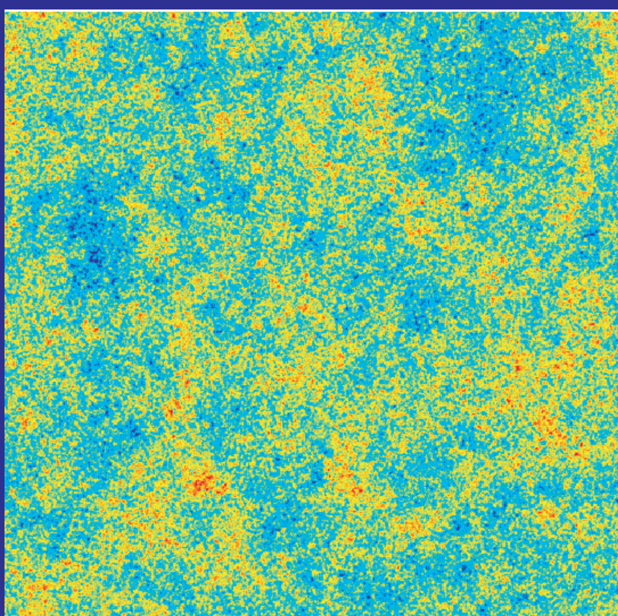
If its not dark, it doesn't matter!

- Cosmic matter-energy budget:

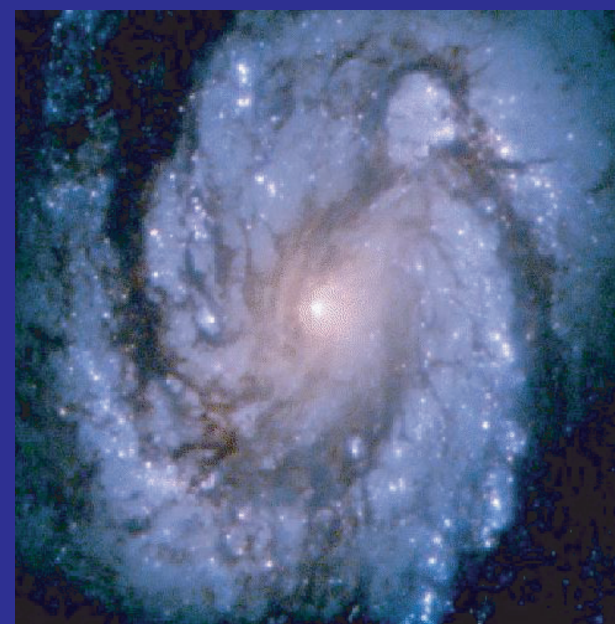


Making Light of the Dark Side

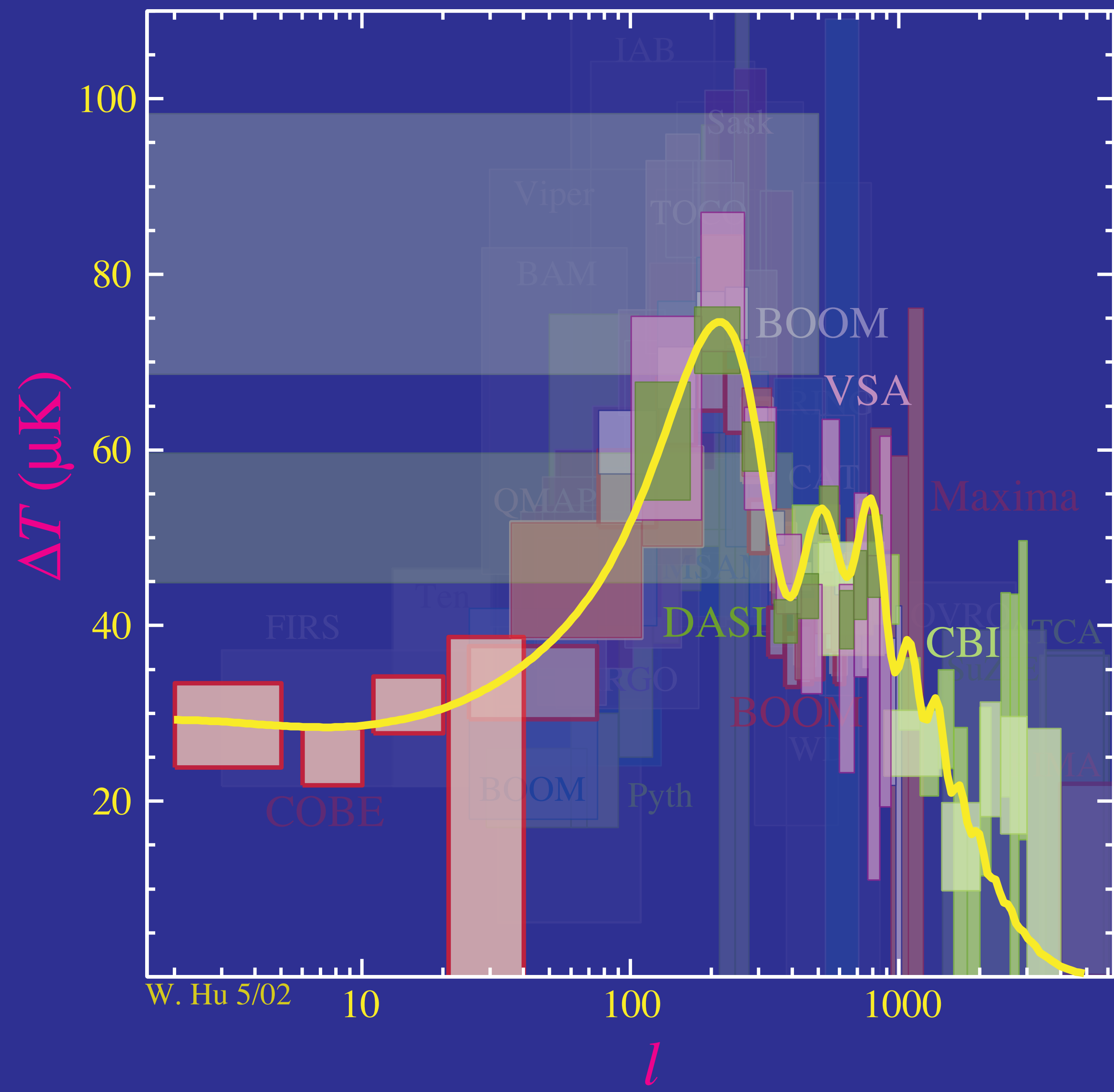
- Visible structures and the processes that form them are our only cosmological probe of the dark components
- In the standard, well-verified, cosmological model, structures grow through gravitational instability from small-fluctuations (perhaps formed during inflation)



15 Gyr

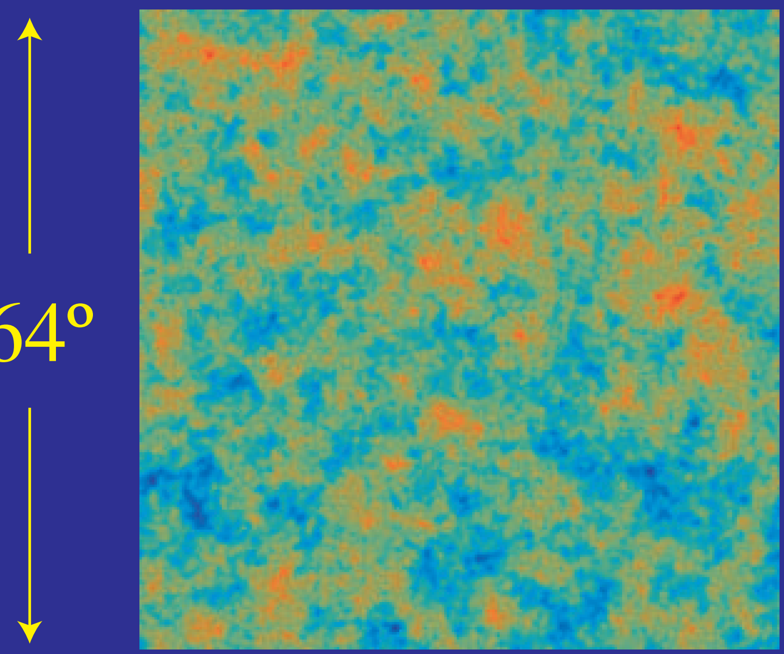


CMB: high redshift anchor



Power Spectra of Maps

- Original



- Band Filtered

Photon-Baryon Plasma

- Before z~1000 when the CMB was T>3000K, hydrogen ionized
- Free electrons act as "glue" between photons and baryons by Compton scattering and Coulomb interactions
- Nearly perfect fluid

Peak Location

- Fundmental physical scale, the distance sound travels, becomes an angular scale by simple projection according to the angular diameter distance D_A

$$
\begin{aligned}
\theta_A &= \lambda_A / D_A \\
\ell_A &= k_A D_A
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- In a flat universe, the distance is simply $D_A = D \equiv \eta_0 - \eta_* \approx \eta_0$, the horizon distance, and $k_A = \pi / s_* = \sqrt{3}\pi / \eta_*$ so

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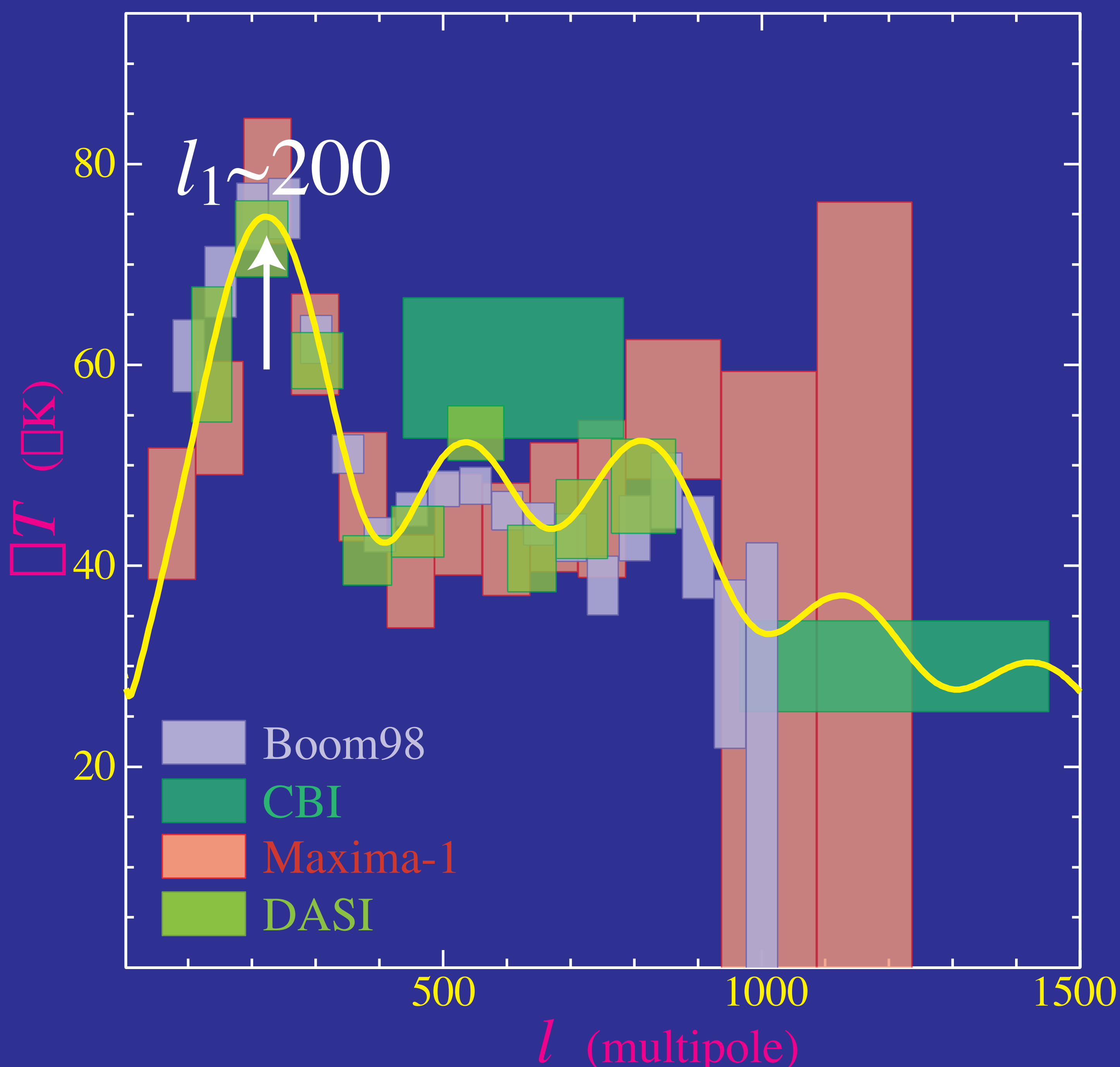
$$\theta_A \approx \frac{\eta_*}{\eta_0}$$

- In a matter-dominated universe $\eta \propto a^{1/2}$ so $\theta_A \approx 1/30 \approx 2^\circ$ or

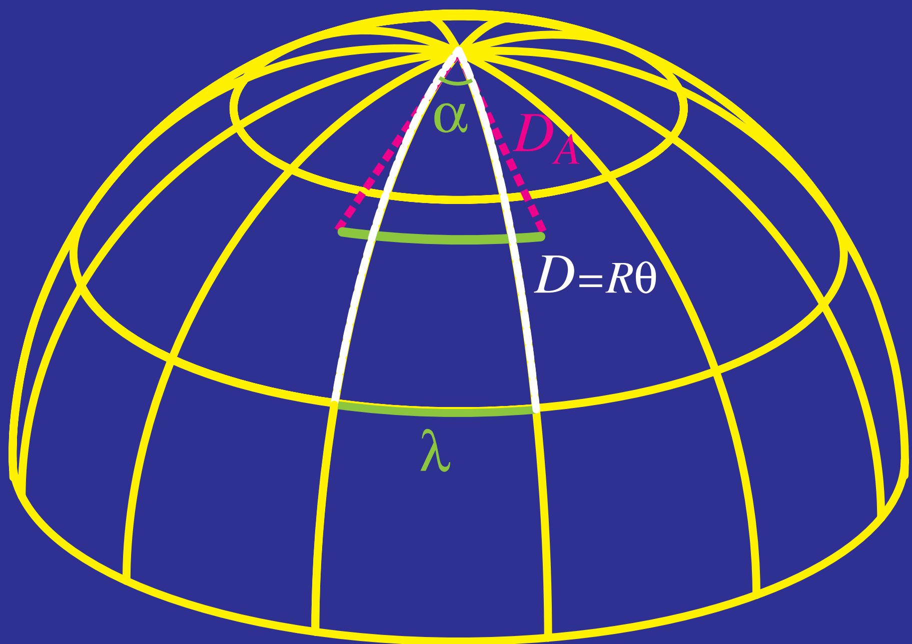
$$\ell_A \approx 200$$

Angular Diameter Distance Test



Curvature

- In a curved universe, the apparent or angular diameter distance is no longer the conformal distance $D_\mathrm{A} = R\sin(D/R) \neq D$



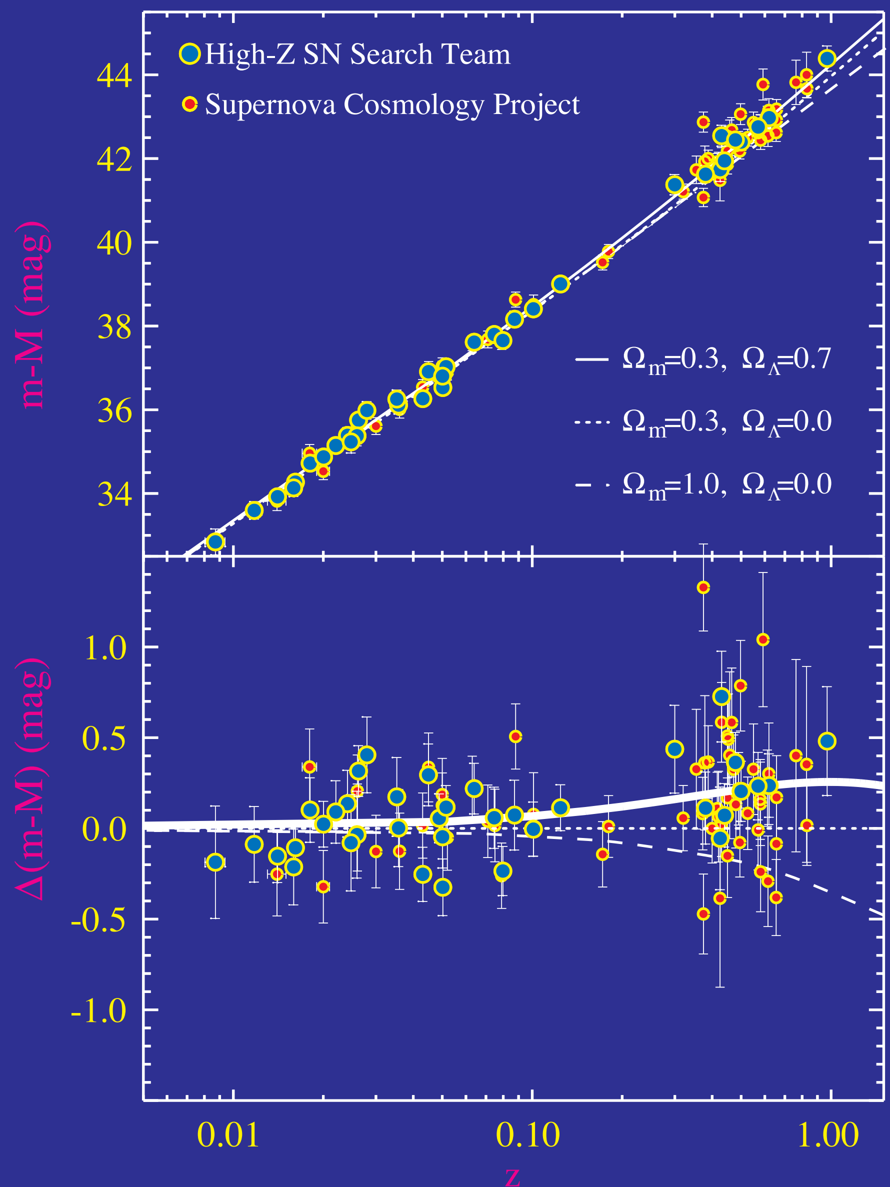
- Objects in a closed universe are further than they appear! gravitational lensing of the background...

Curvature in the Power Spectrum

- Angular location of harmonic peaks
- Flat = critical density = missing dark energy

Accelerated Expansion from SNe

- Missing energy must also accelerate the expansion at low redshift



compilation from High-z team

Acceleration Implies Negative Pressure

- Role of pressure in the background cosmology
- Homogeneous Einstein equations $G_{\mu\nu} = 8\pi G T_{\mu\nu}$ imply the two Friedman equations (flat universe, or associating curvature $\rho_K = -3K/8\pi G a^2$)

$$\left(\frac{1}{a}\frac{da}{dt}\right)^2 = \frac{8\pi G}{3}\rho$$

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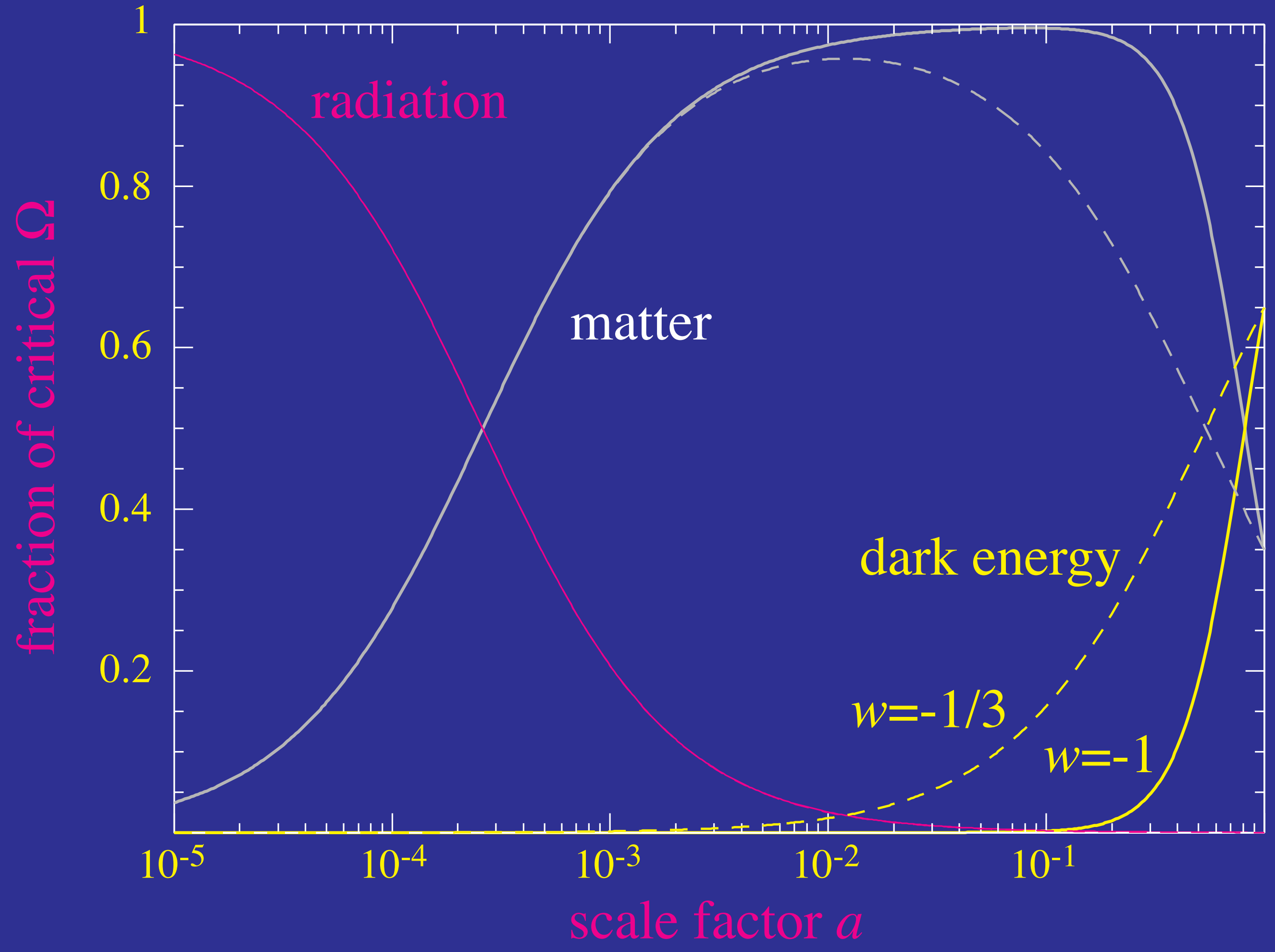
- Conservation equation $\nabla^\mu T_{\mu\nu} = 0$ implies

$$\frac{\dot\rho}{\rho} = -3(1+w)\frac{\dot a}{a}$$

- so that ρ must scale more slowly than a^{-2}

Dark Mystery?

- Coincidence: given different scalings with a, why are dark matter and energy densities comparable now?



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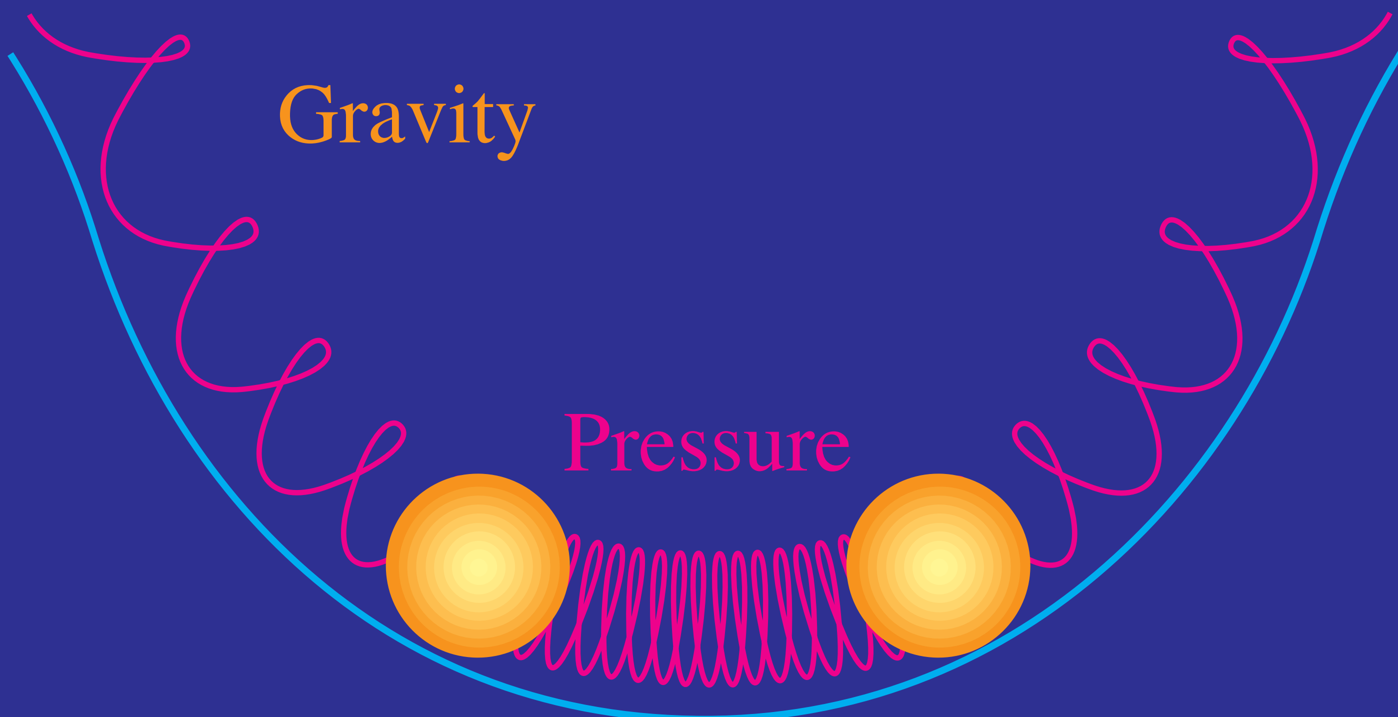

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  pressure gradients, not pressure, establish stability
- Candidates:

  Cosmological constant w=-1, constant in space and time, but >60 orders of magnitude off vacuum energy prediction

  Ultralight scalar field, slowly rolling in a potential, Klein-Gordon equation: sound speed $c_s^2=\delta p/\delta\rho=1$

  Tangled defects w=-1/3, -2/3 but relativistic sound speed ("solid" dark matter)

Dark Energy Probes

- (Comoving) distance-redshift relation: $a = (1+z)^{-1}$

$$D = \int_a^1 da \frac{1}{a^2 H(a)} = \int_0^z dz \frac{1}{H(a)}$$

$$H^2(a) = \frac{8\pi G}{3}(\rho_m + \rho_{DE})$$

in a flat universe, e.g. angular diameter distance, luminosity distance, number counts (volume)...

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- Pressure growth suppression: $\delta \equiv \delta\rho_m/\rho_m \propto a\phi$

$$\frac{d^2\phi}{d\ln a^2} + \left[\frac{5}{2} - \frac{3}{2}w(z)\Omega_{DE}(z)\right]\frac{d\phi}{d\ln a} + \frac{3}{2}[1 - w(z)]\Omega_{DE}(z)\phi = 0\,,$$

where $w \equiv p_{DE}/\rho_{DE}$ and $\Omega_{DE} \equiv \rho_{DE}/(\rho_m + \rho_{DE})$

e.g. galaxy cluster abundance, gravitational lensing...

Large-Scale Structure and Gravitational Lensing

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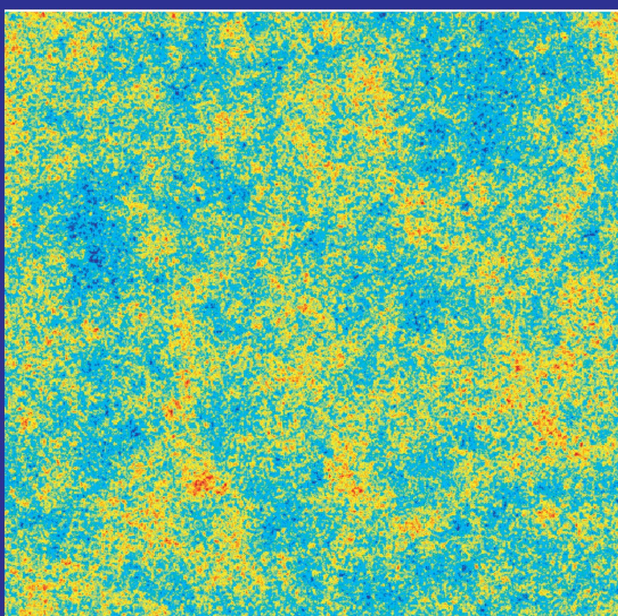

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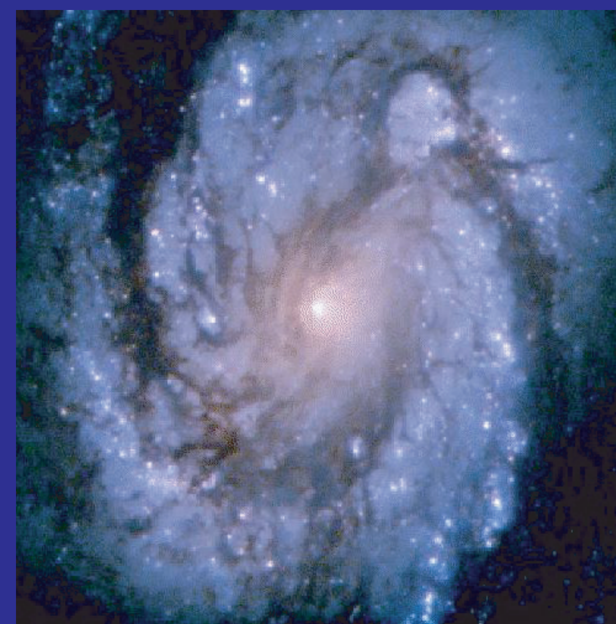
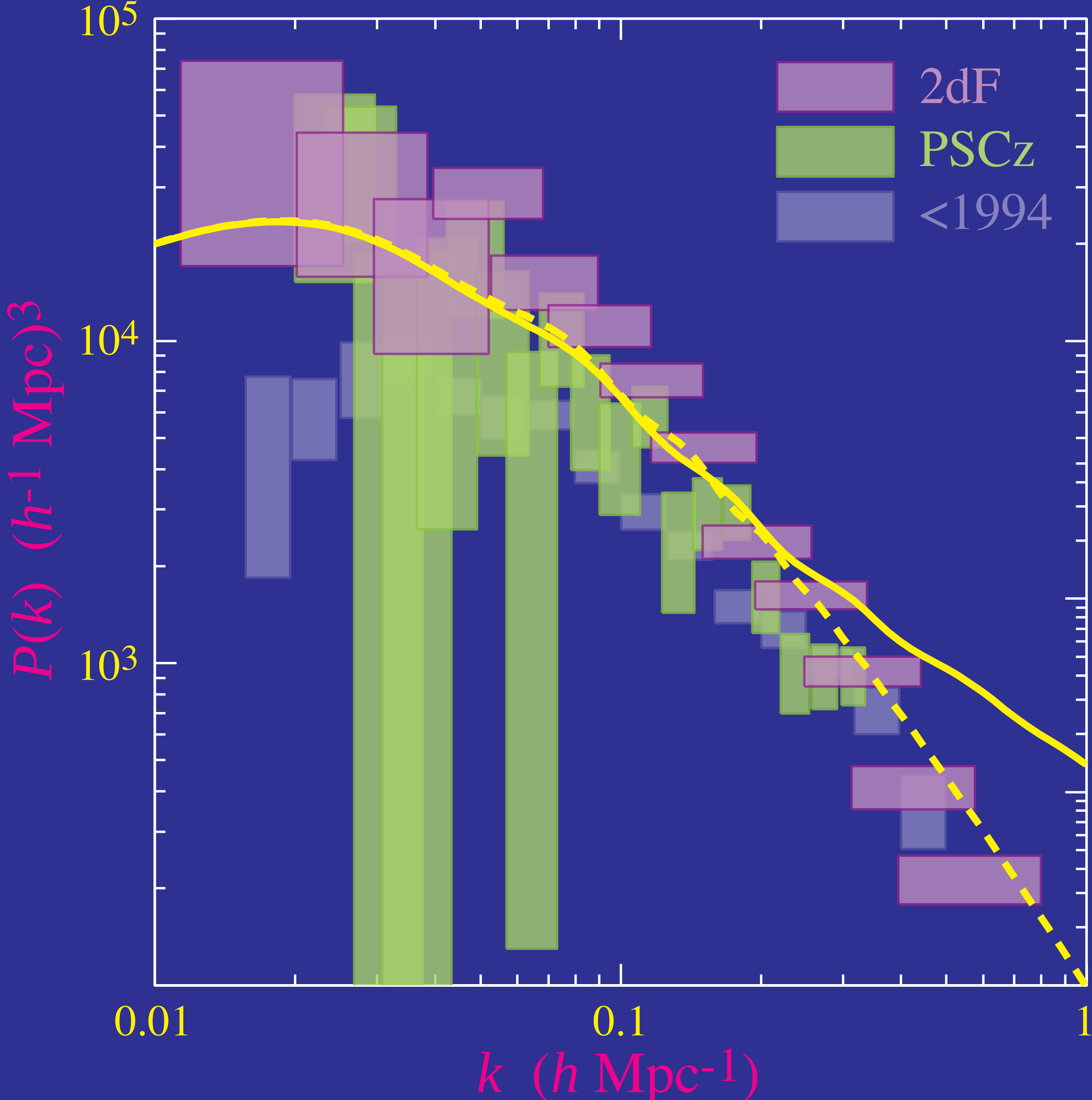


Structure Formation Simulation

- Simulation (by A. Kravstov)

Galaxy Power Spectrum Data

- Galaxy clustering tracks the dark matter – but bias depends on type



A Fundamental Problem

- All cosmological observables relate to the luminous matter: photon-baryon plasma, galaxies, clusters of galaxies, supernovae
- Implications for the dark energy or cosmology in general depend on modelling the formation and evolution of luminous objects
- Success of CMB anisotropy is in large part based on the solid theoretical grounding of its formation and evolution – well understood linear gravitational physics

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- Distortion of the images of luminous objects by gravitational lensing is equally well understood
- Problem: image distortion is typically at %-level – very demanding for the control of systematic errors – but recall CMB is 10^{-5} level! (Tyson, Wenk & Valdes 1990)

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

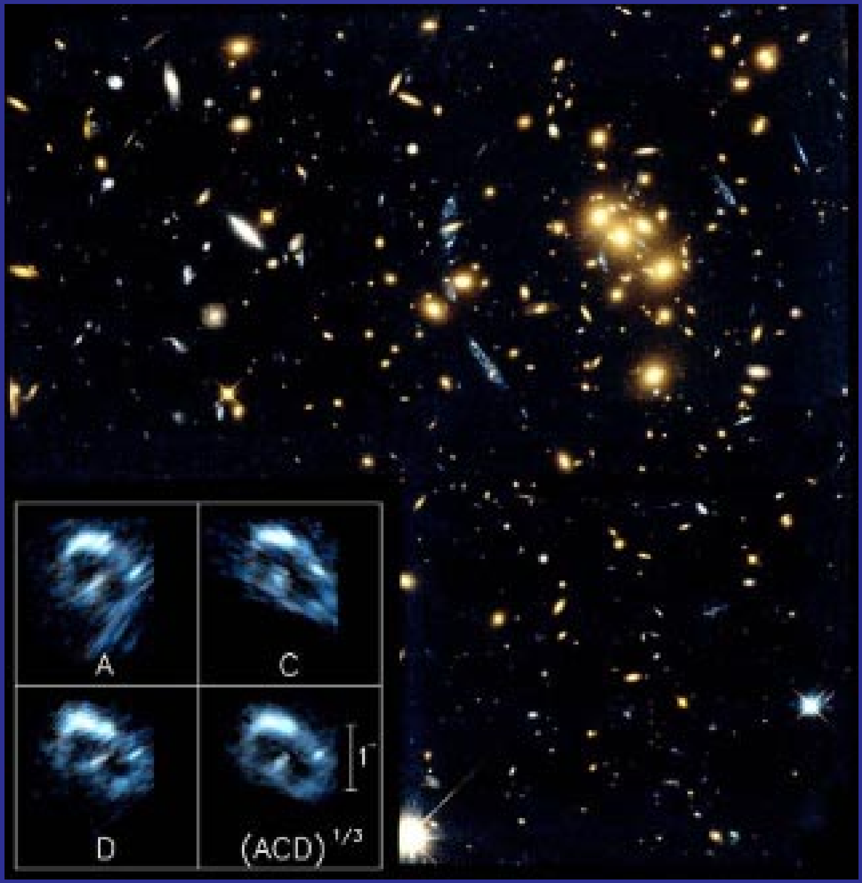
$$\psi_{ij}(z_s) = 2\int_0^{z_s} dz \frac{dD}{dz} \frac{D(D_s - D)}{D_s} \Phi_{,ij} \, ,$$

  $\psi_{ij} = \delta_{ij} - A_{ij}$, 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

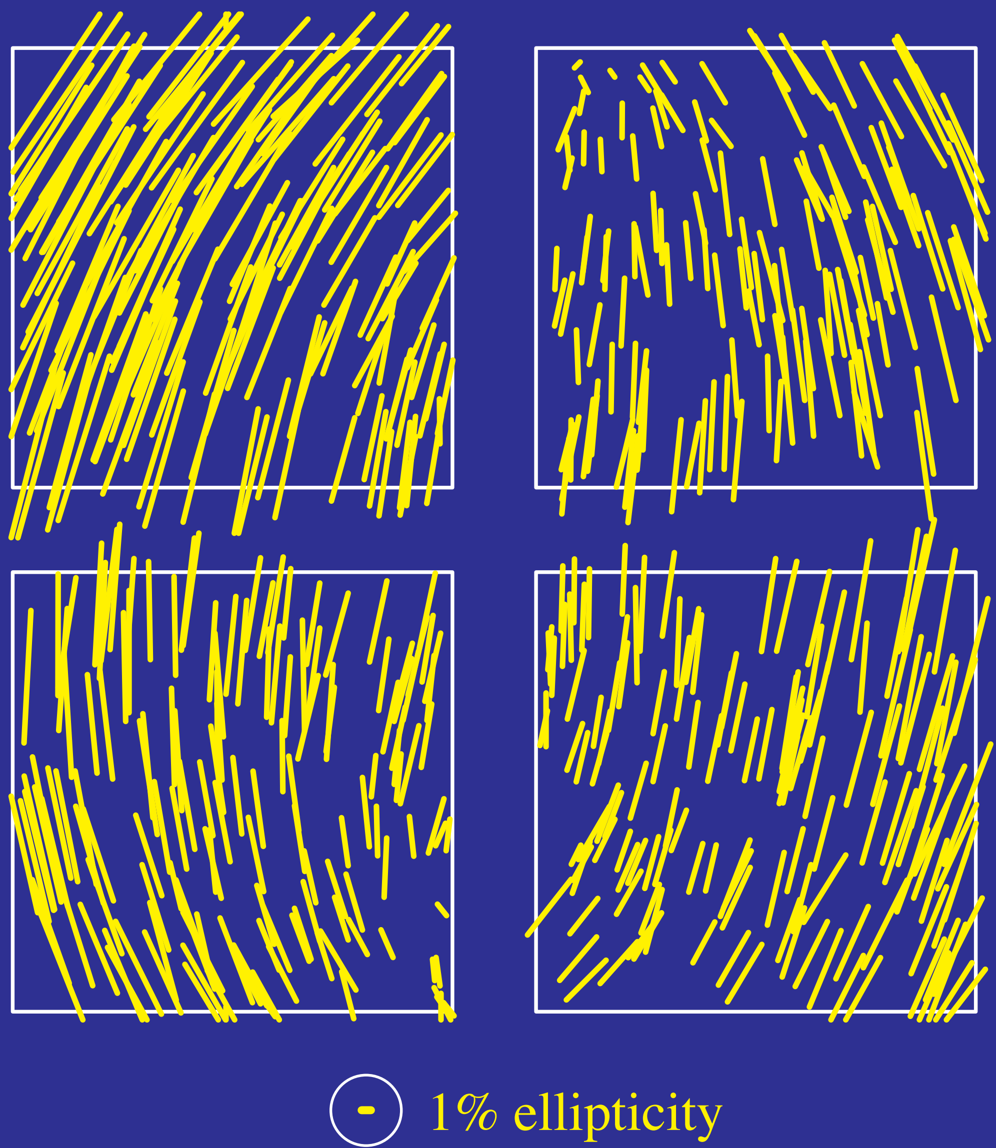


Cluster (Strong) Lensing: 0024+1654

Colley, Turner, & Tyson (1996)

Instrumental Systematics

- Raw data has instrumental systematics (PSF anisotropy) larger than signal, removed by demanding stars be round



Jarvis et al. (2002)

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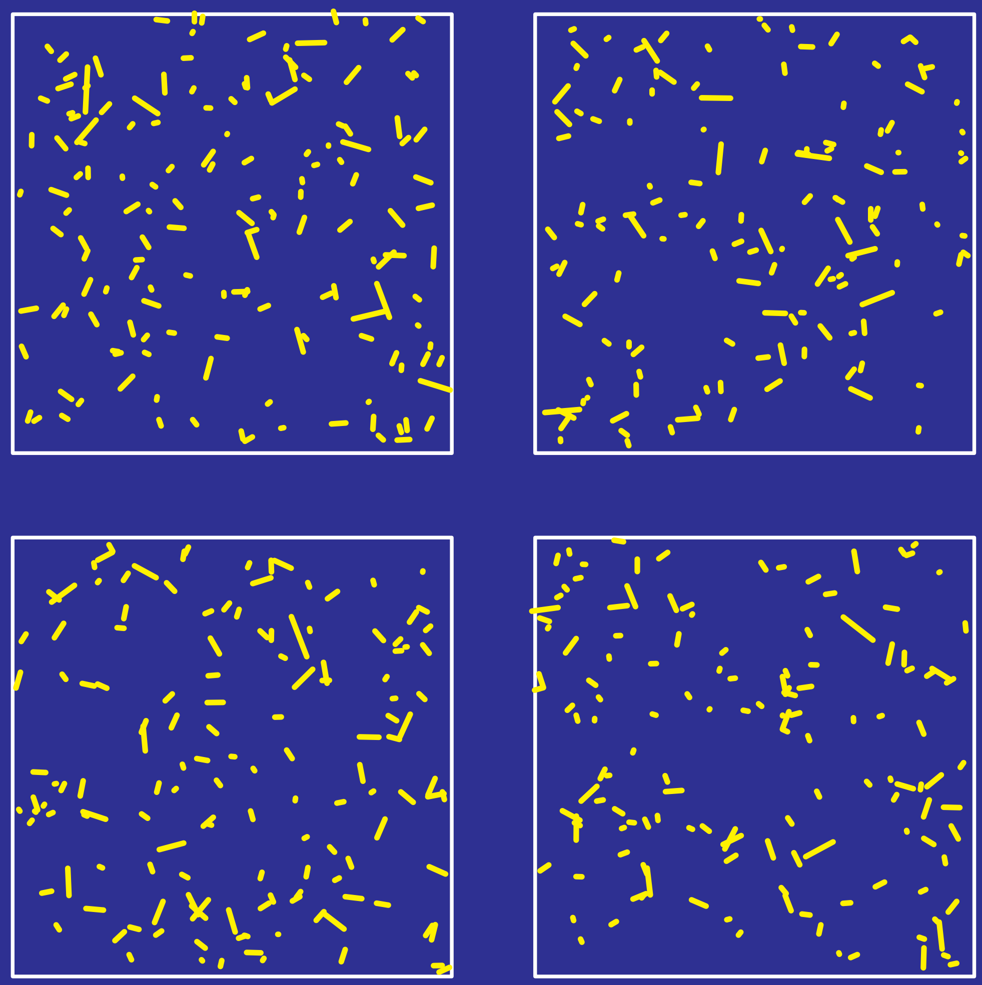
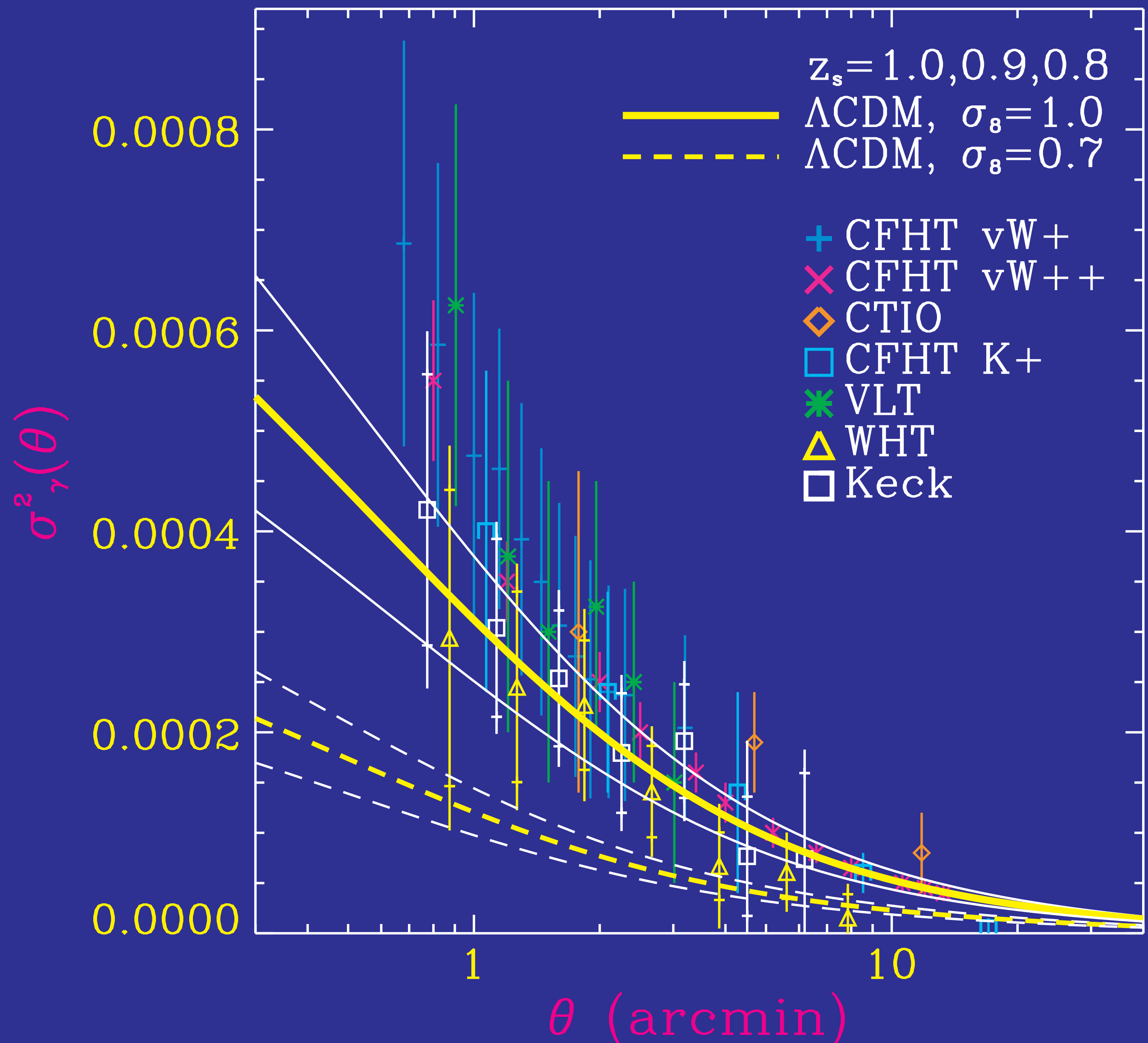


1% ellipticity

Jarvis et al. (2002)

Cosmic Shear Data

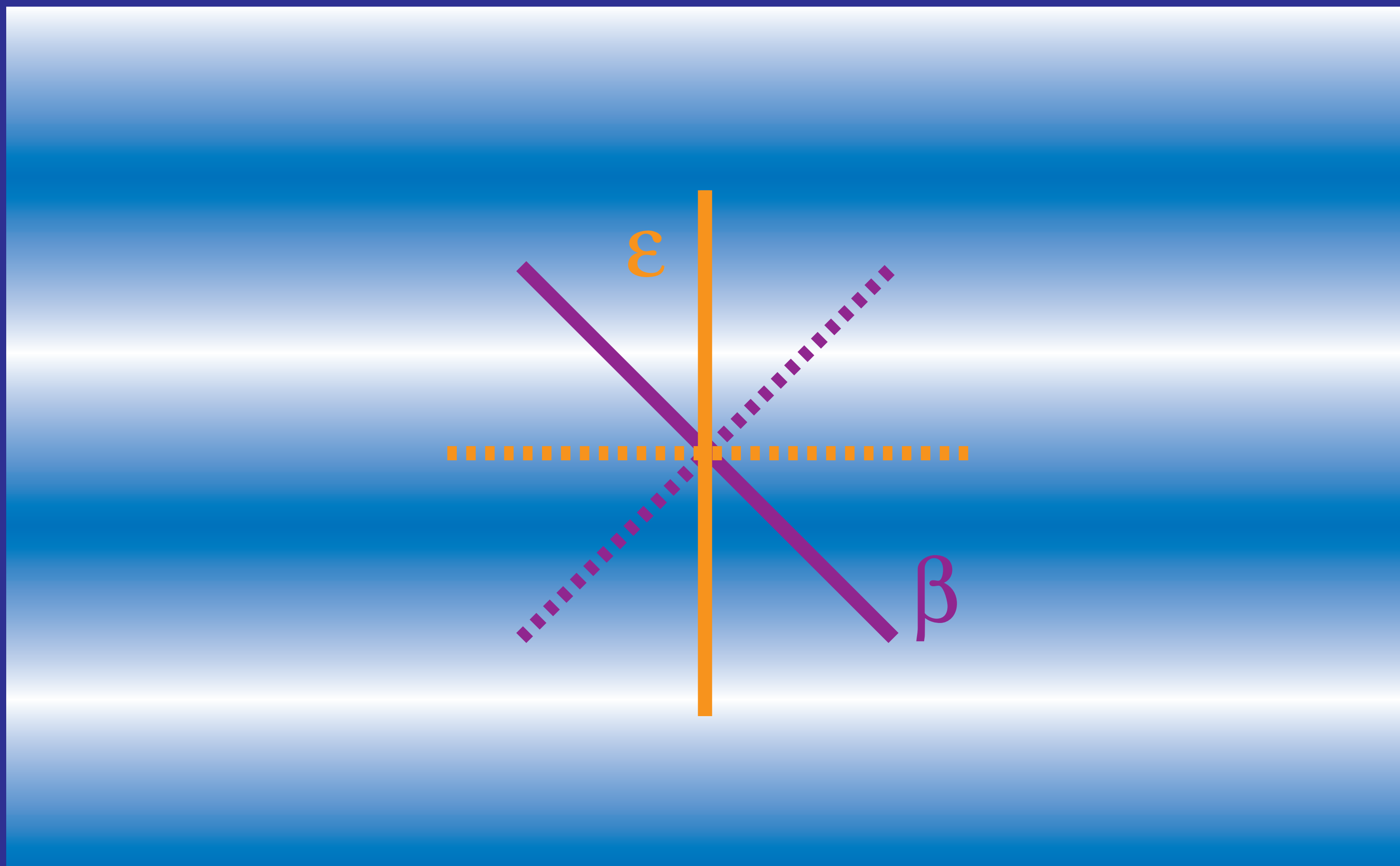
- Shear variance as a function of smoothing scale



compilation from Bacon et al (2002)

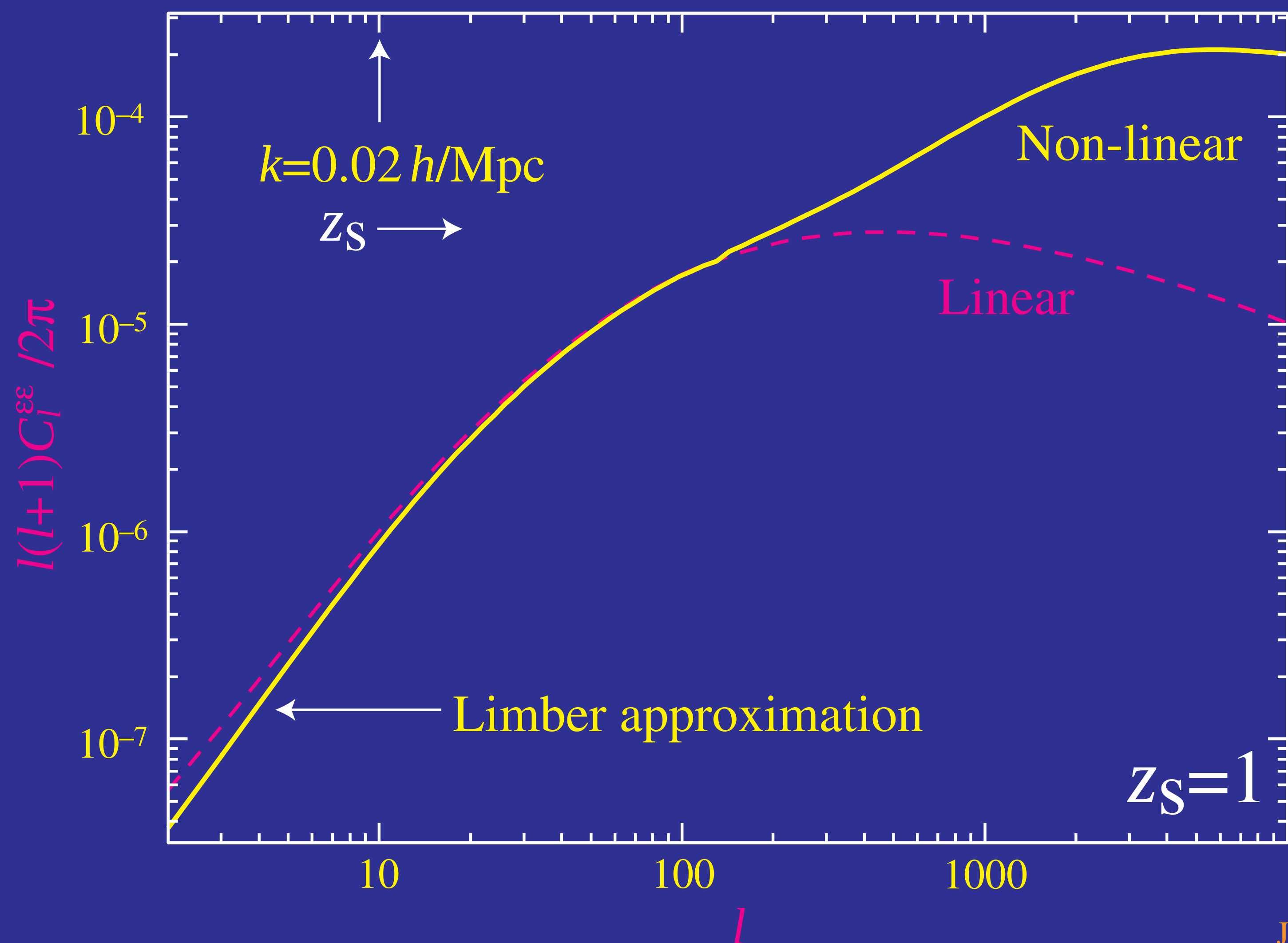
Shear Power Modes

- Alignment of shear and wavevector defines modes



Shear Power Spectrum

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

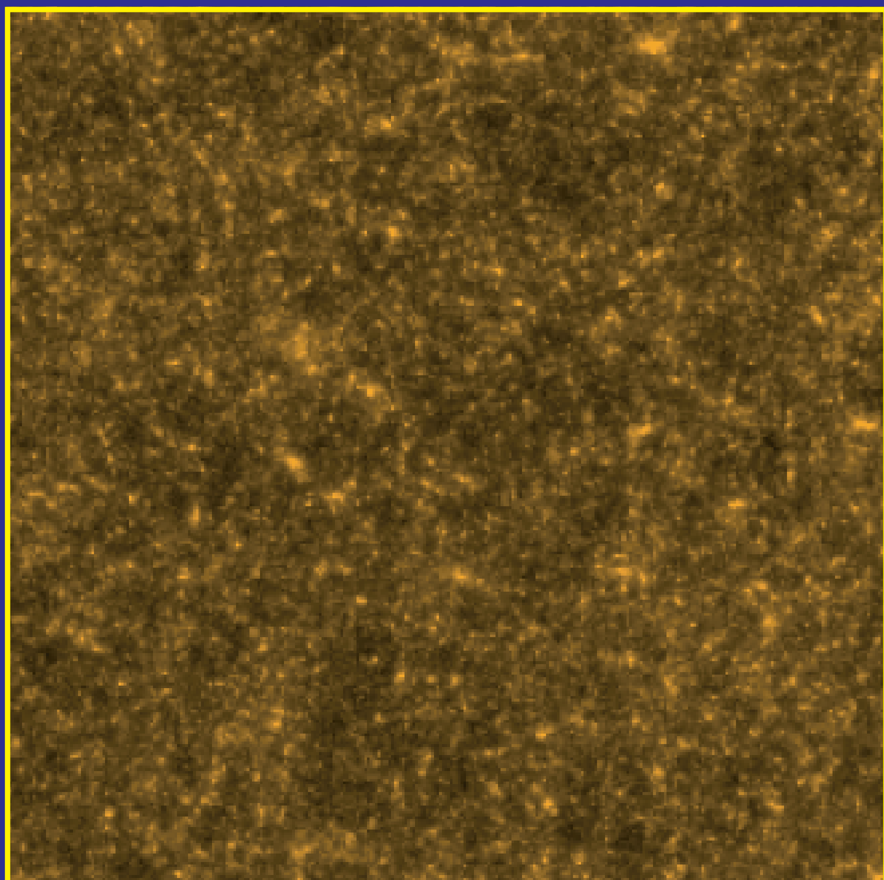


Kaiser (1992)
Jain & Seljak (1997)
Hu (2000)

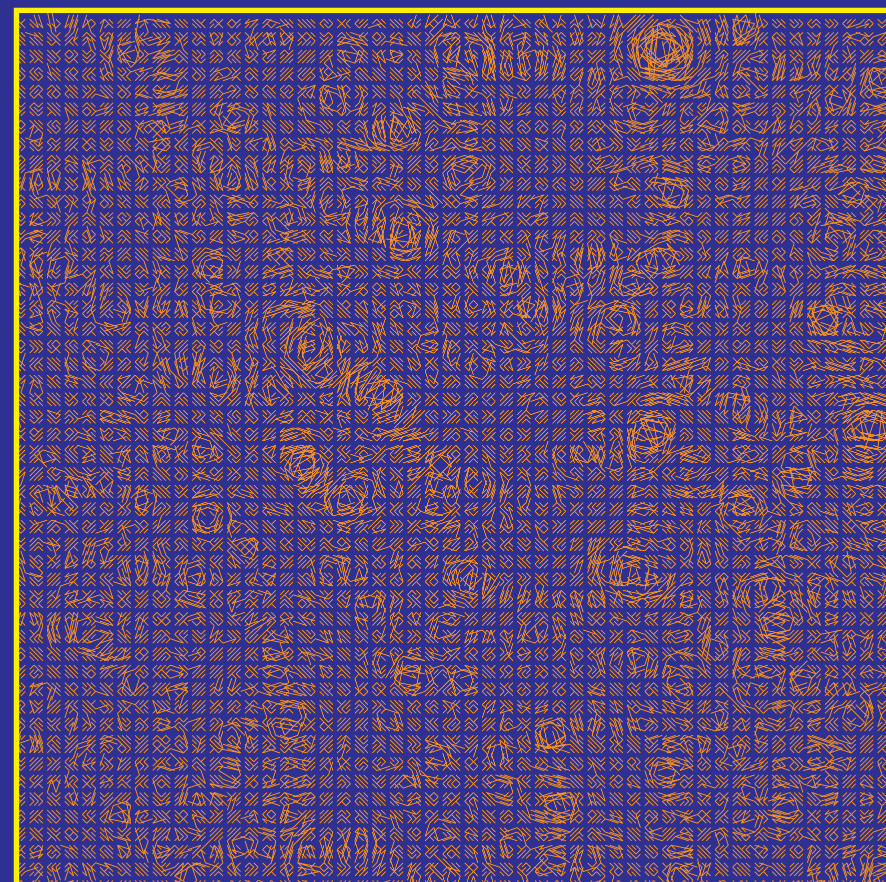
PM Simulations

- Simulating mass distribution is a routine exercise

Convergence



Shear



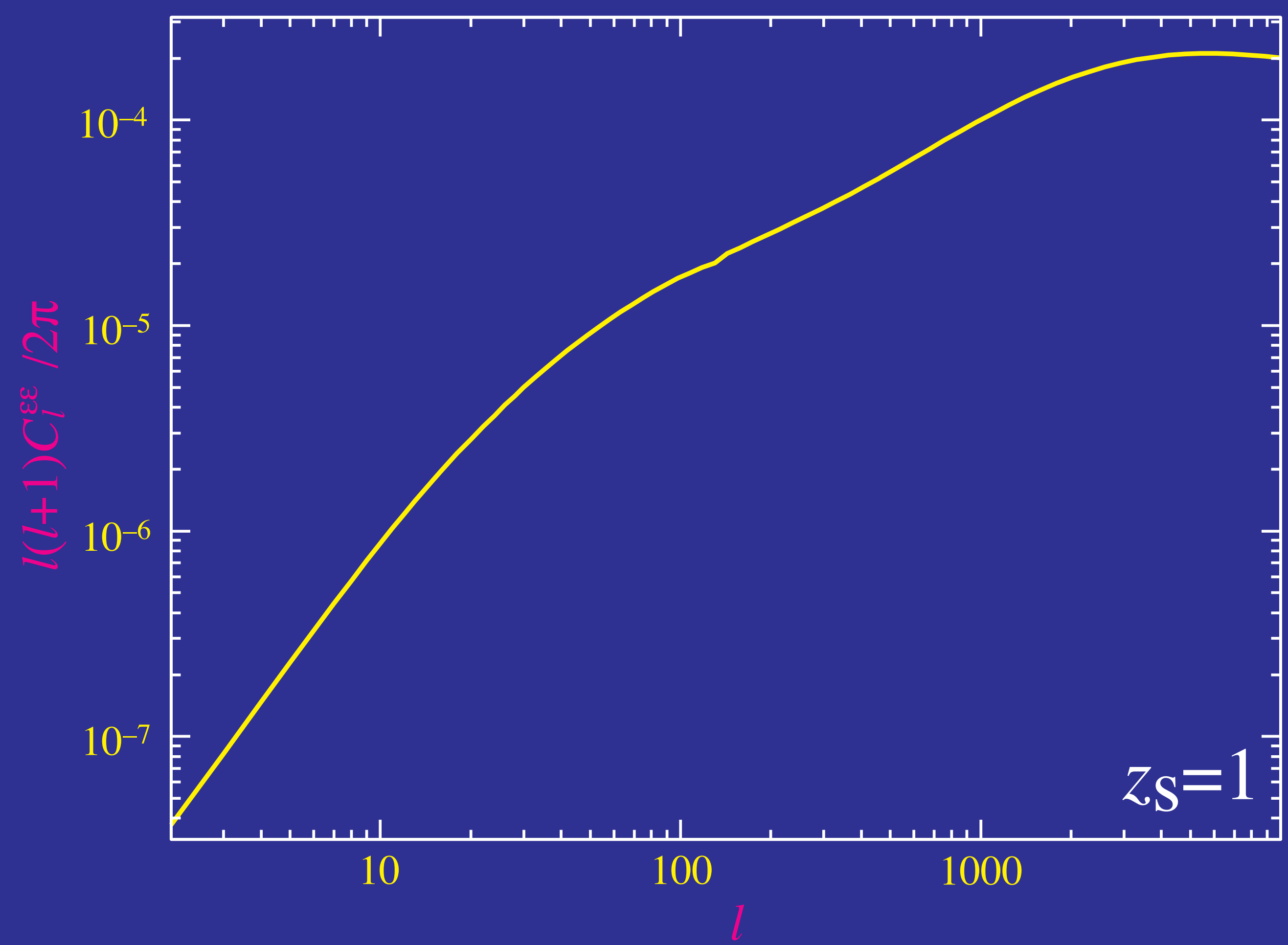
$6° \times 6°$ FOV; 2' Res.; 245–75 h^{-1}Mpc box; 480–145 h^{-1}kpc mesh; 2–70 10^9 $M_\odot$

White & Hu (1999)

Dark Energy
and
Gravitational Lensing

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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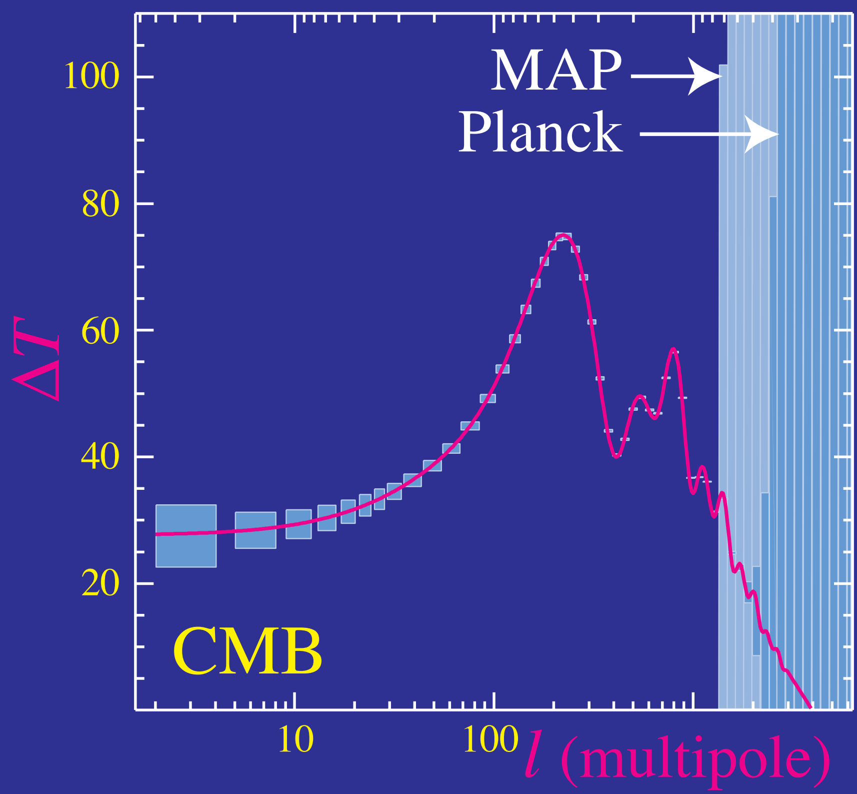
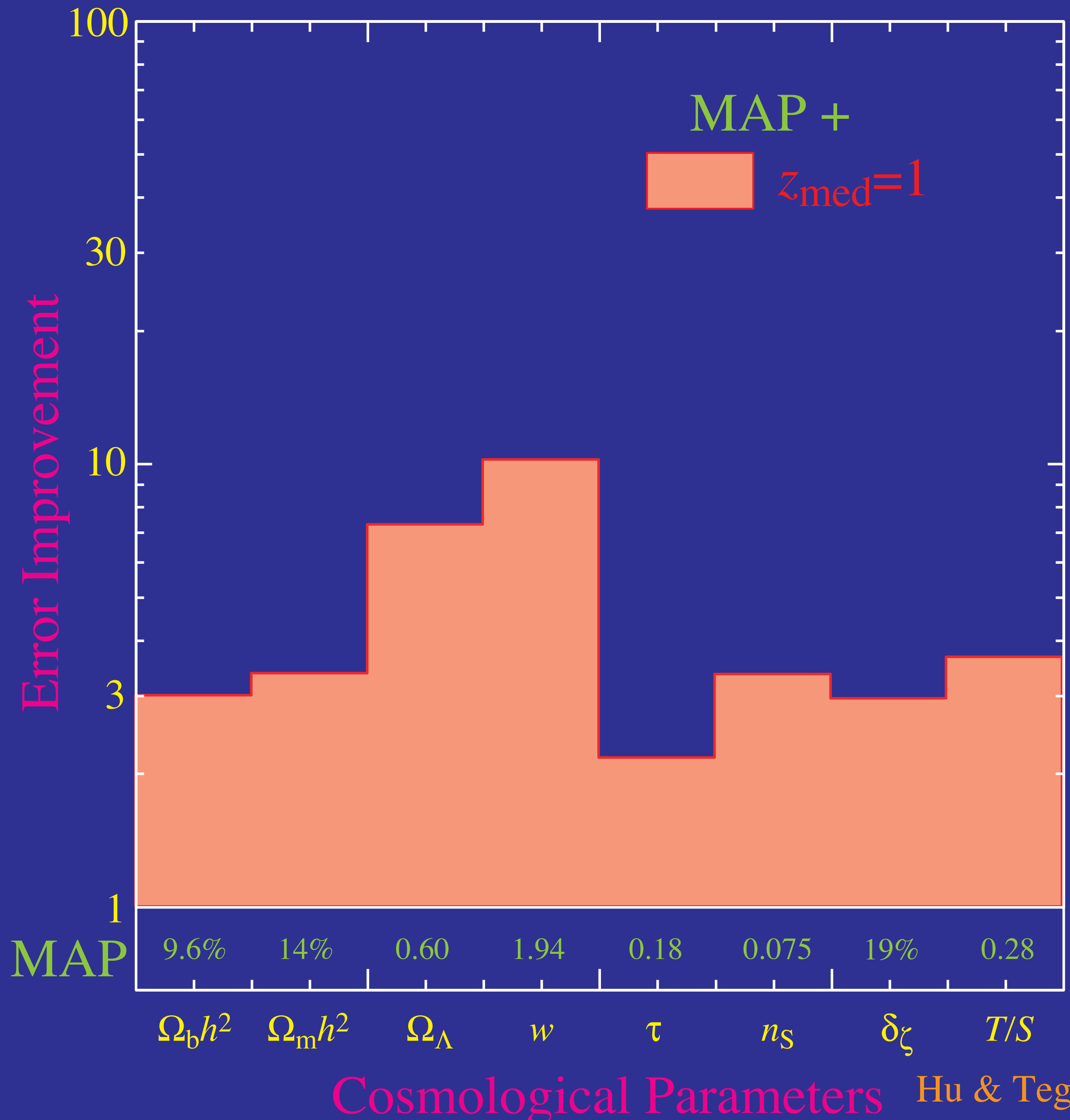


- Combine with information from the CMB: complementarity (Hu & Tegmark 1999)
- Crude tomography with source divisions (Hu 1999; Hu 2001)
- Fine tomography with source redshifts (Hu & Keeton 2002; Hu 2002)

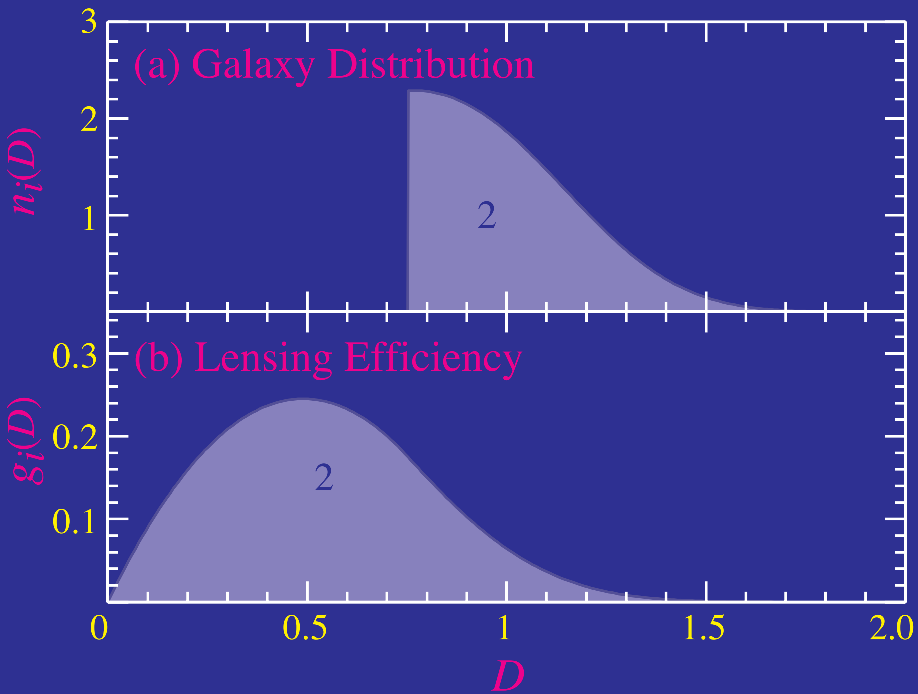
Error Improvement: 1000deg^2

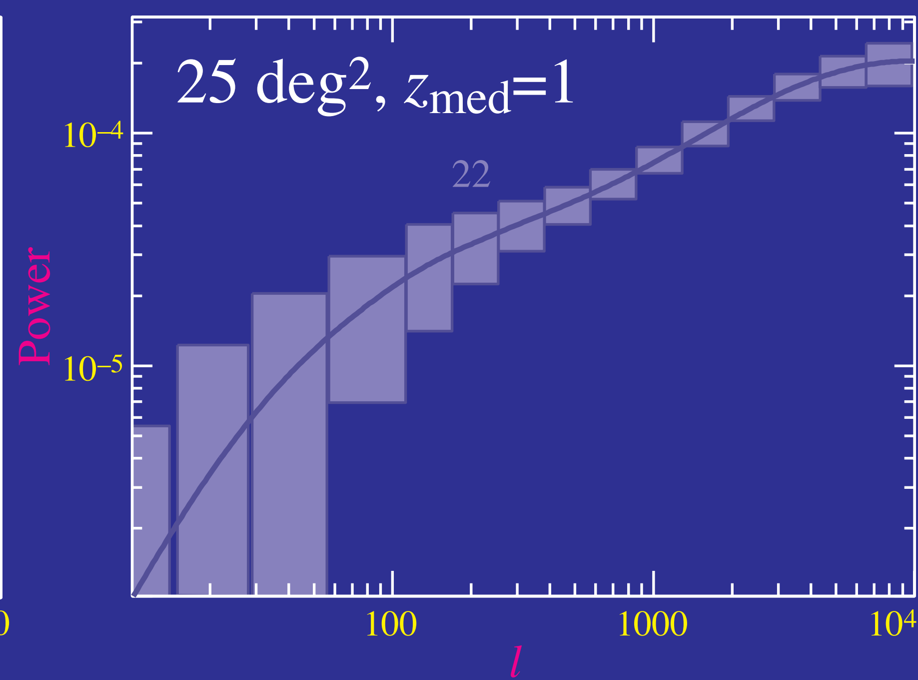


Hu & Tegmark (1999) Hu (2001)

Crude Tomography

- Divide sample by photometric redshifts

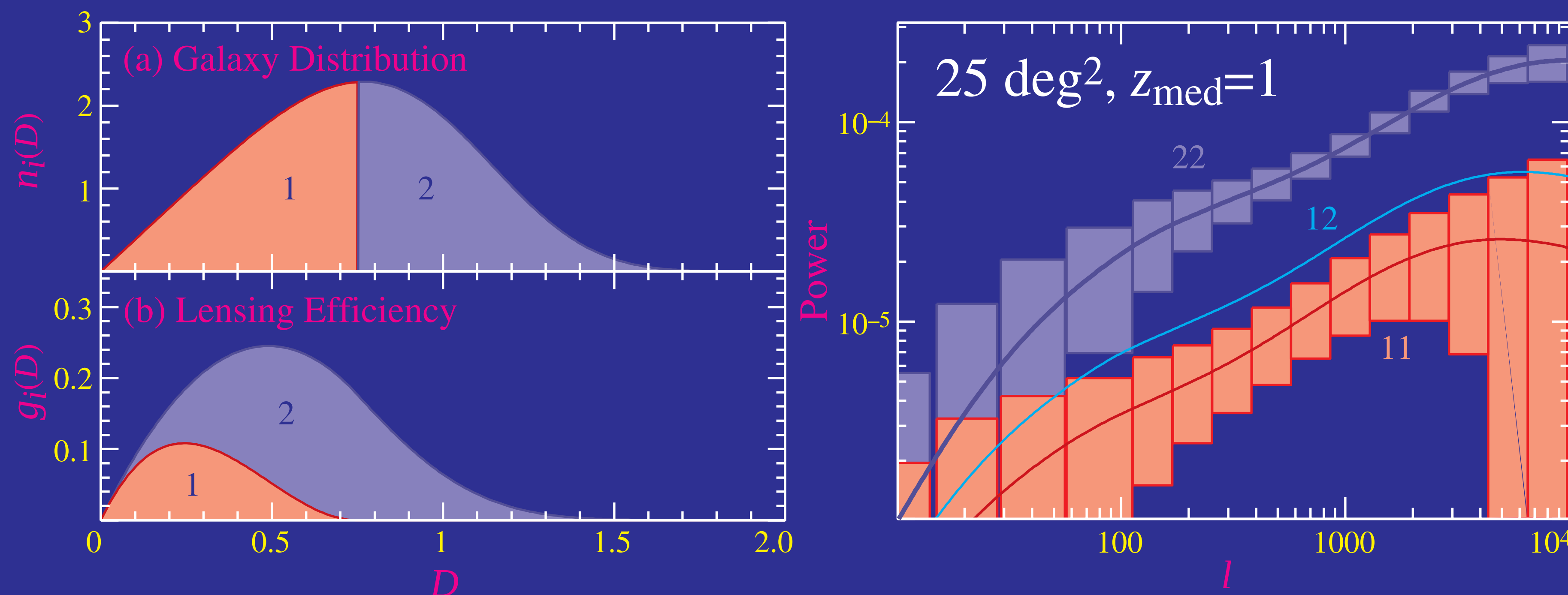




Hu (1999)

Crude Tomography

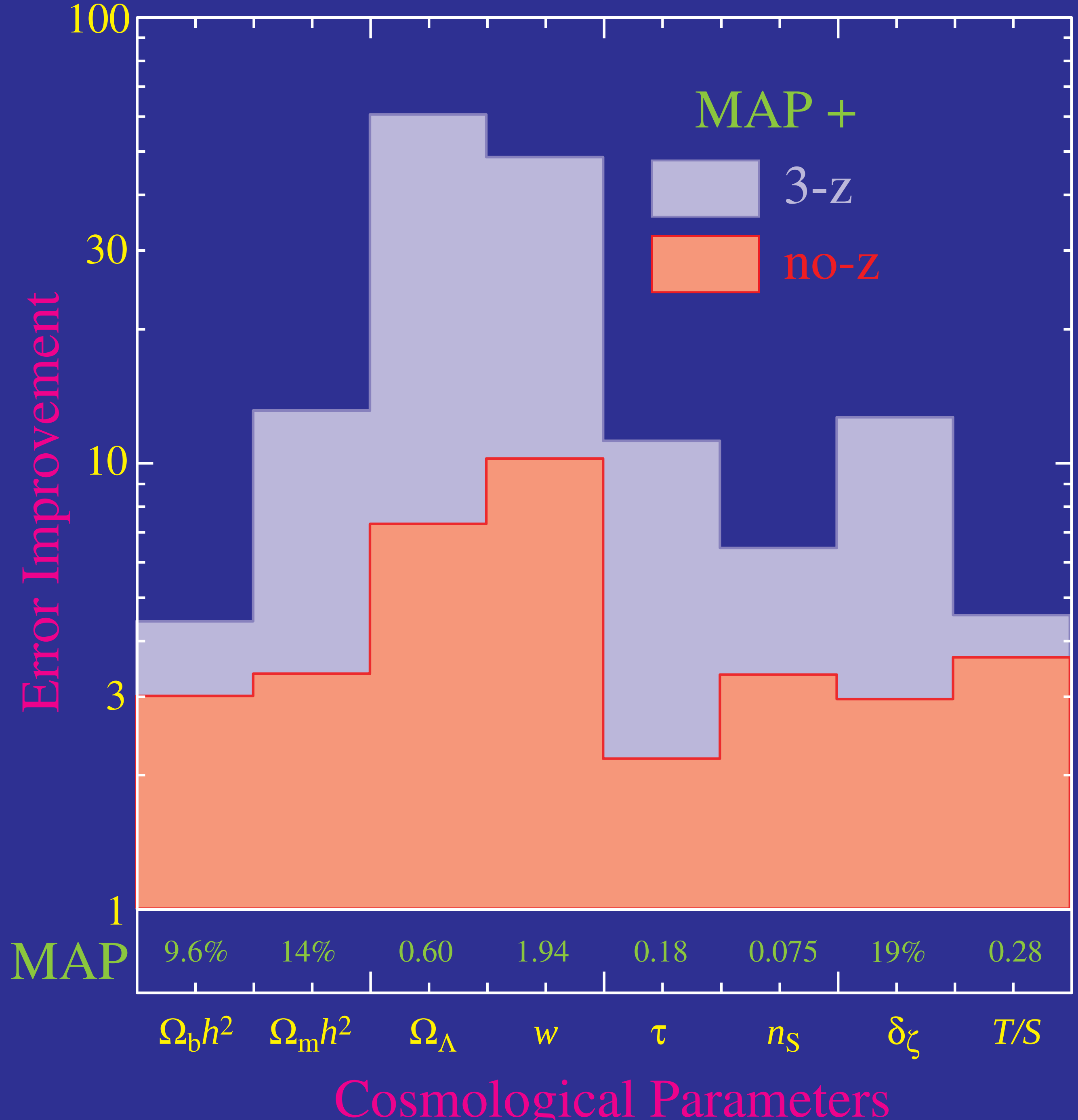
- Divide sample by photometric redshifts
- Cross correlate samples



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

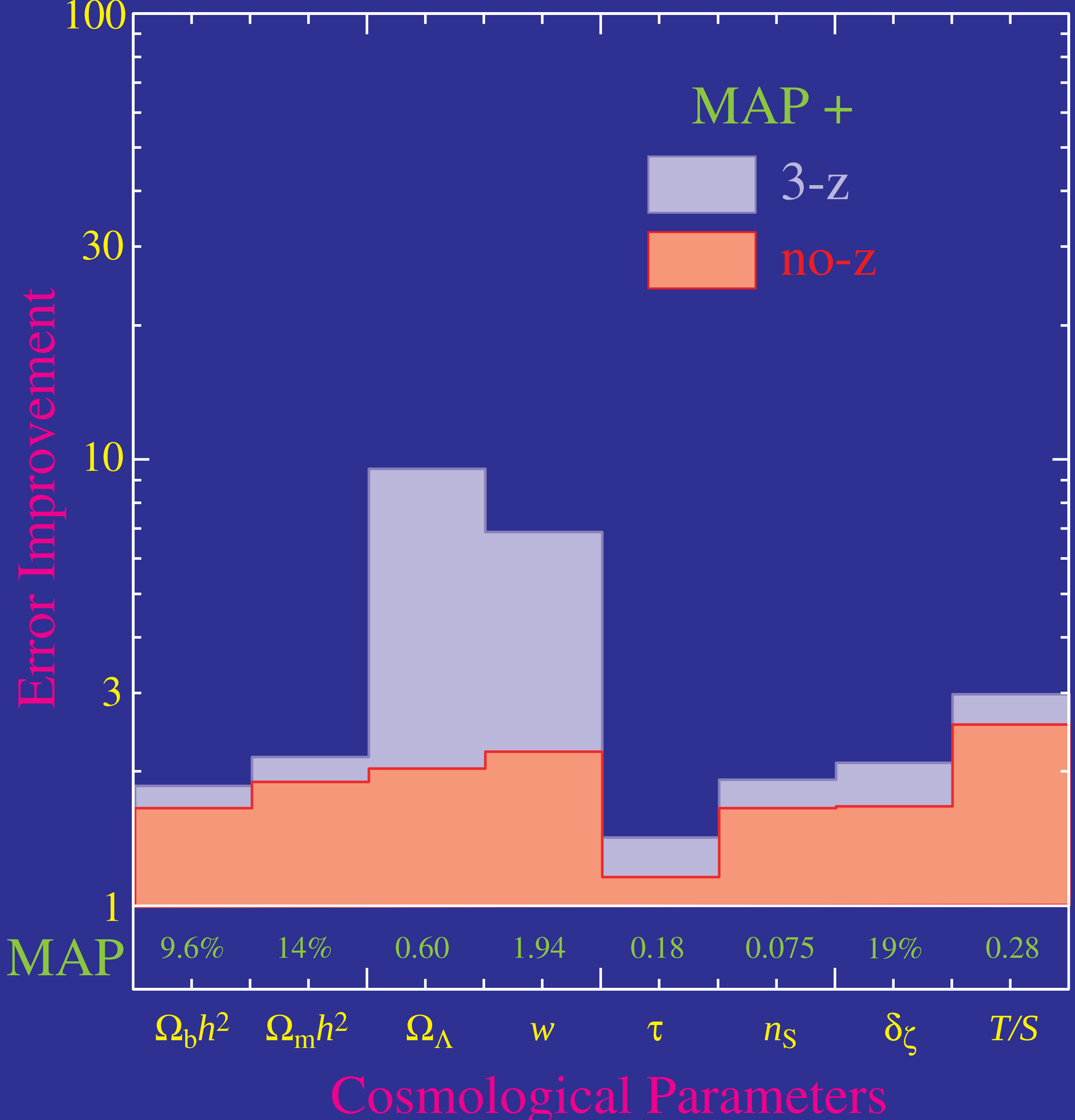
Hu (1999)

Error Improvement: 1000deg^2



Hu (1999; 2001)

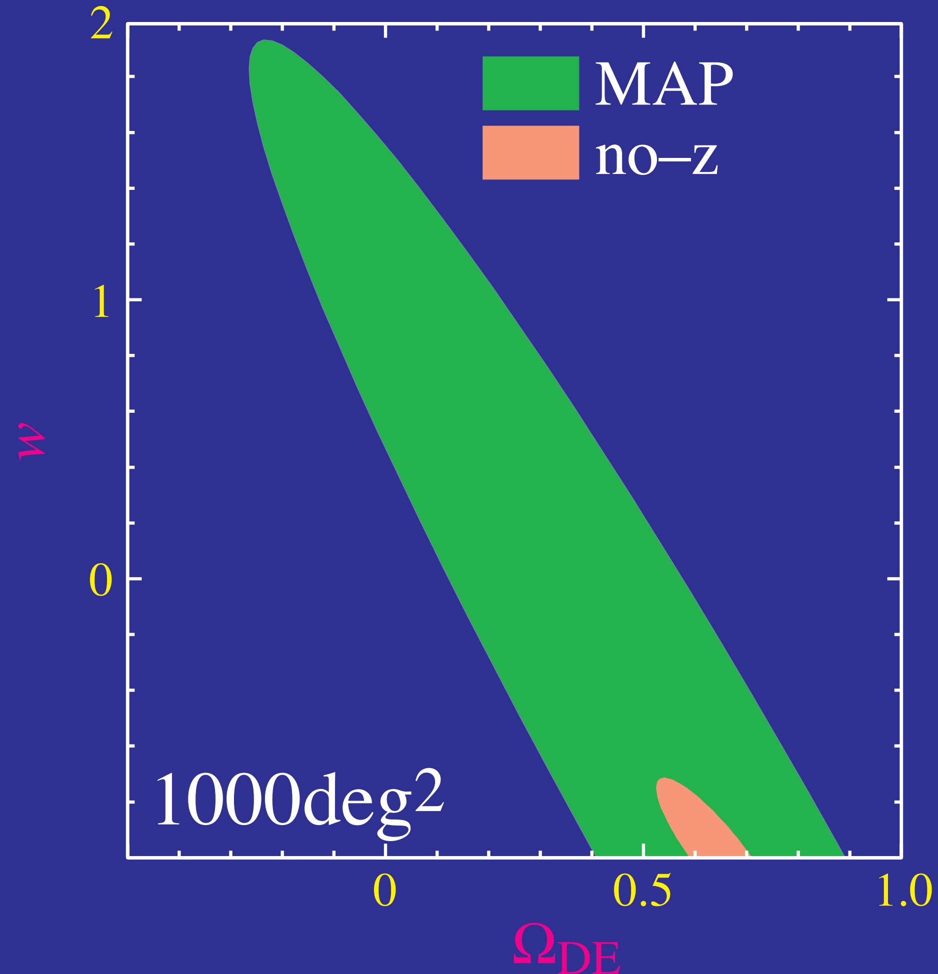
Error Improvement: 25deg^2



Hu (1999; 2001)

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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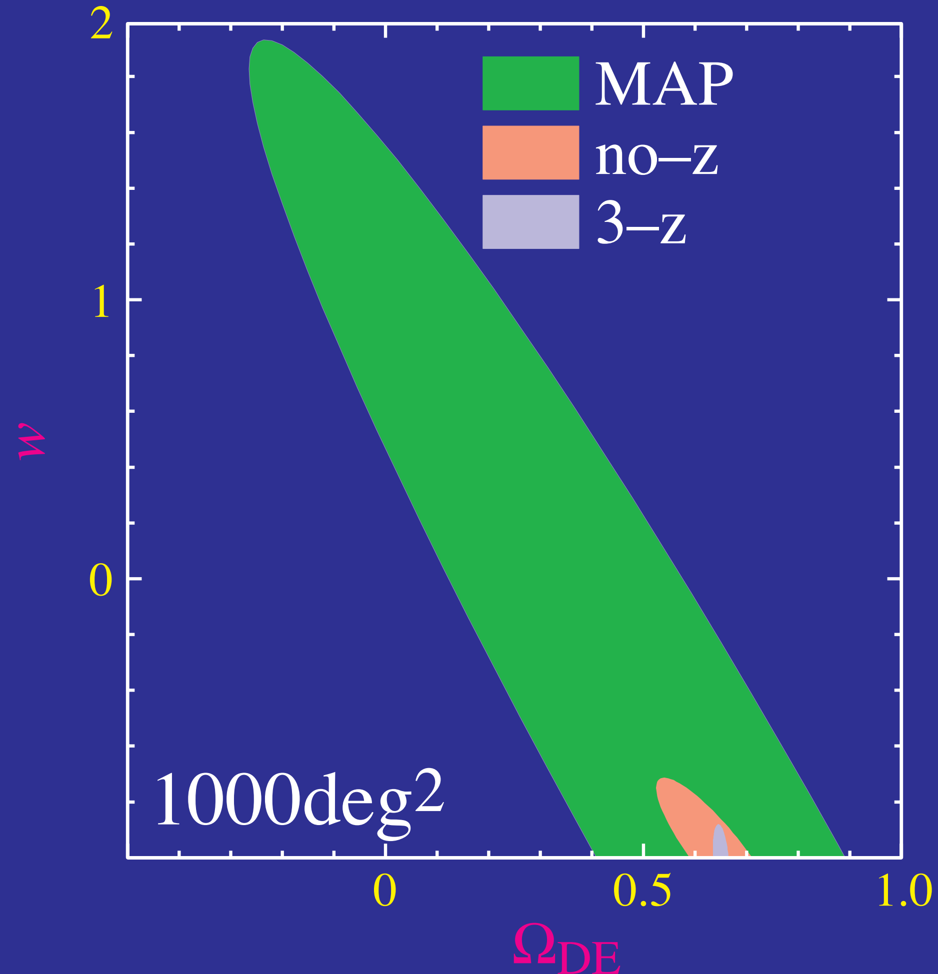

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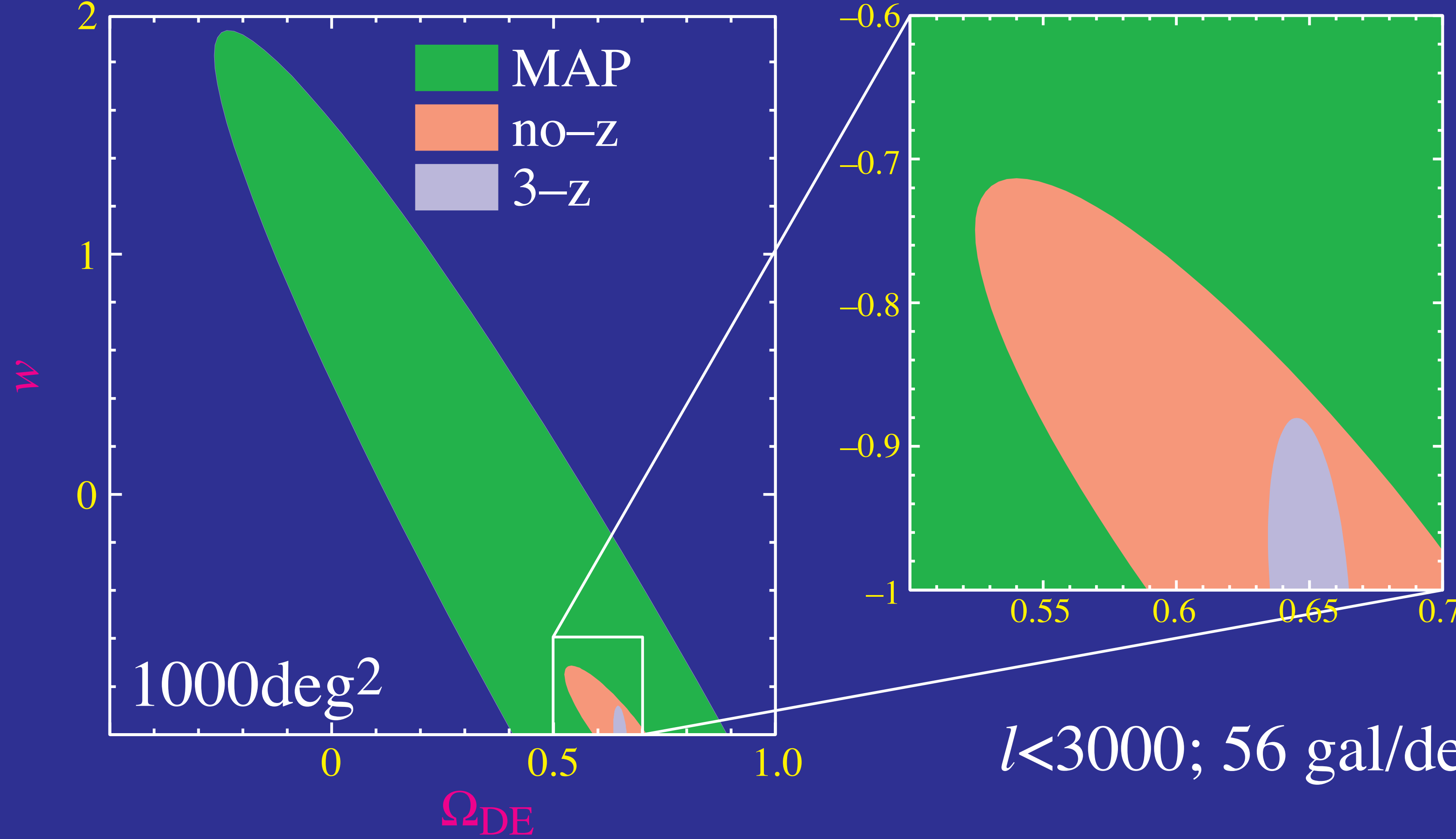

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Hidden Dark Energy Information

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

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- 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

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

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

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

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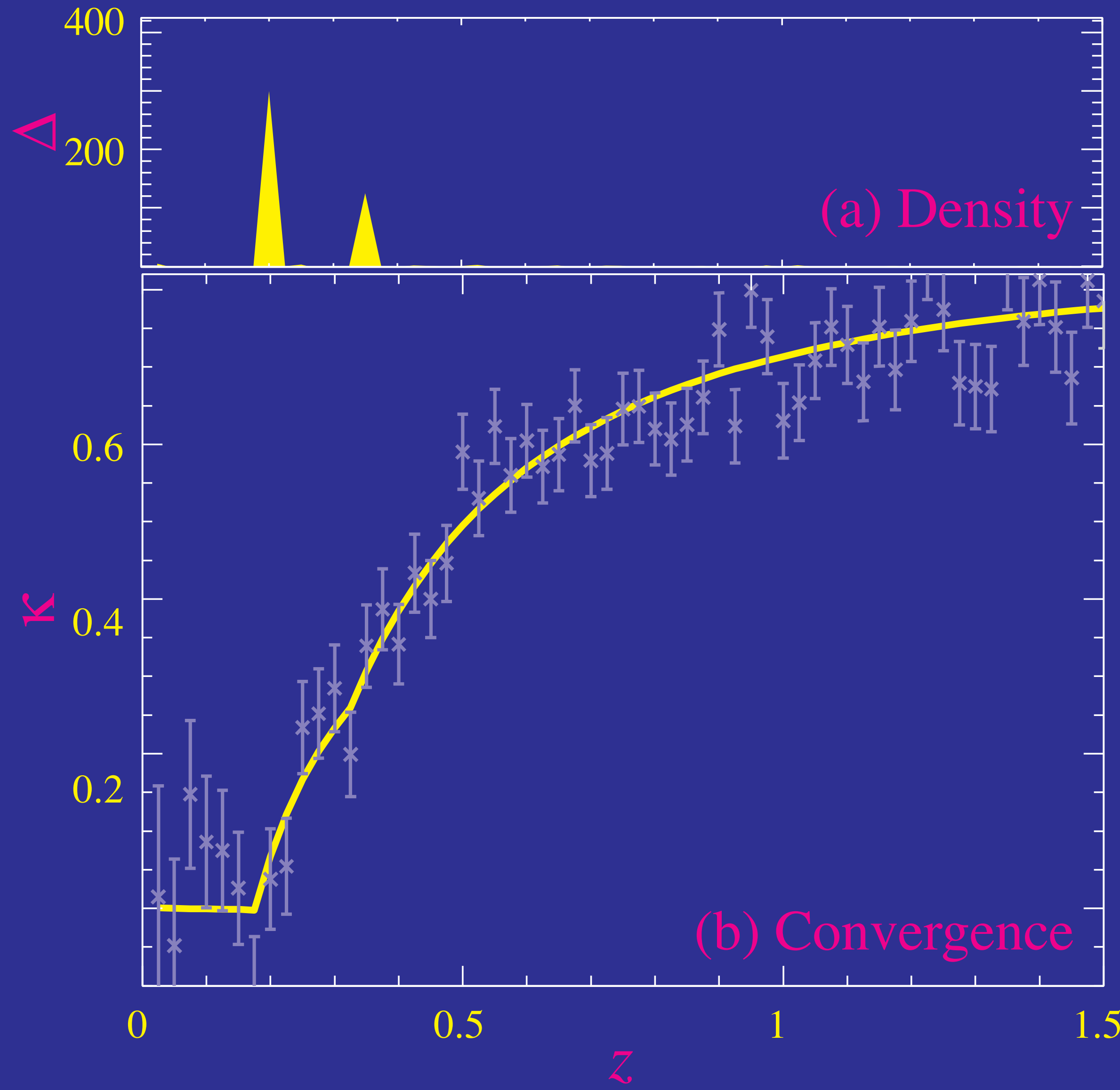
- Well-posed (Taylor 2002) but noisy inversion (Hu & Keeton 2002)
- Noise properties differ from signal properties $\rightarrow$ optimal filters

Hidden in Noise

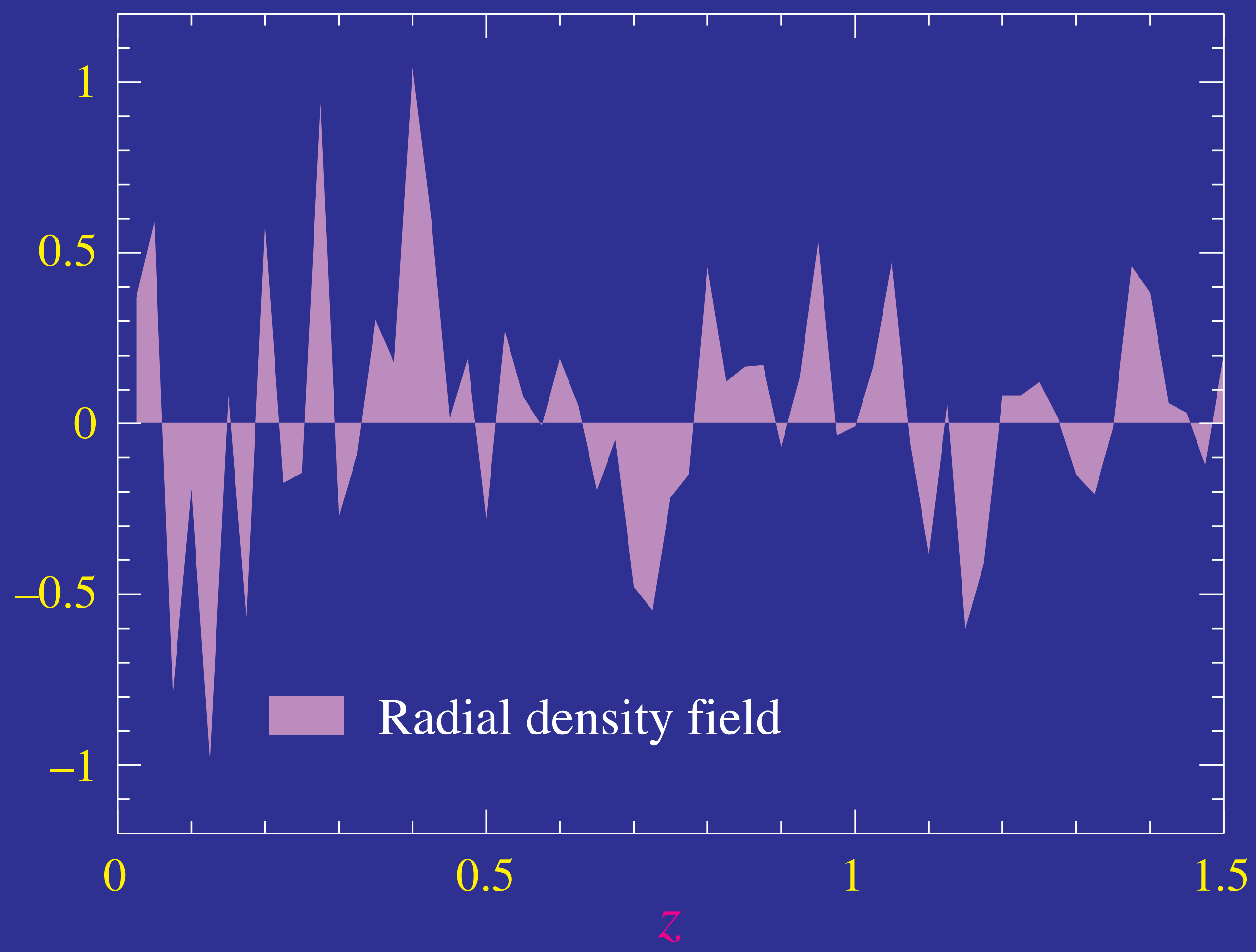
- Derivatives of noisy convergence isolate radial structures



Hu & Keeton (2001)

Fine Tomography

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



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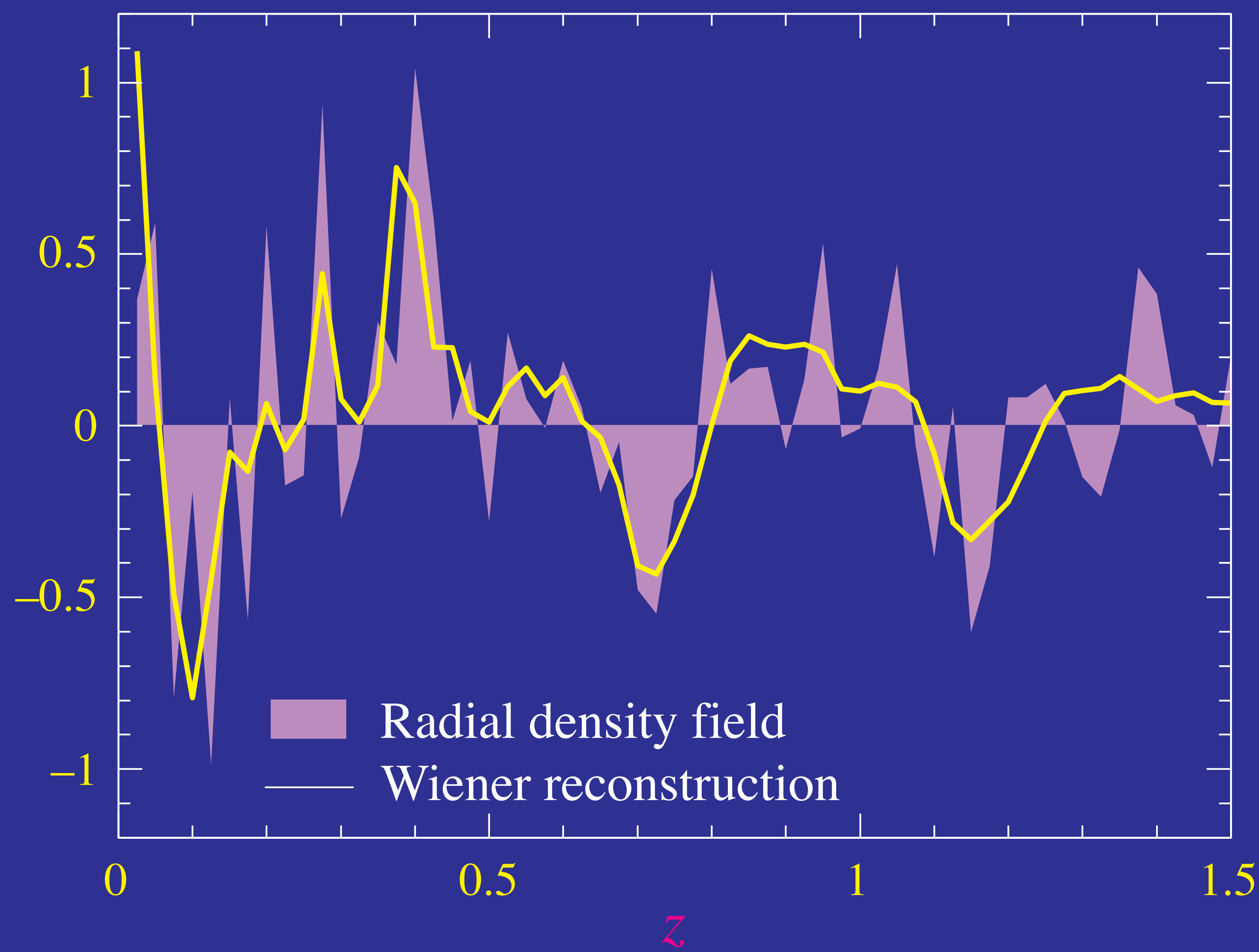

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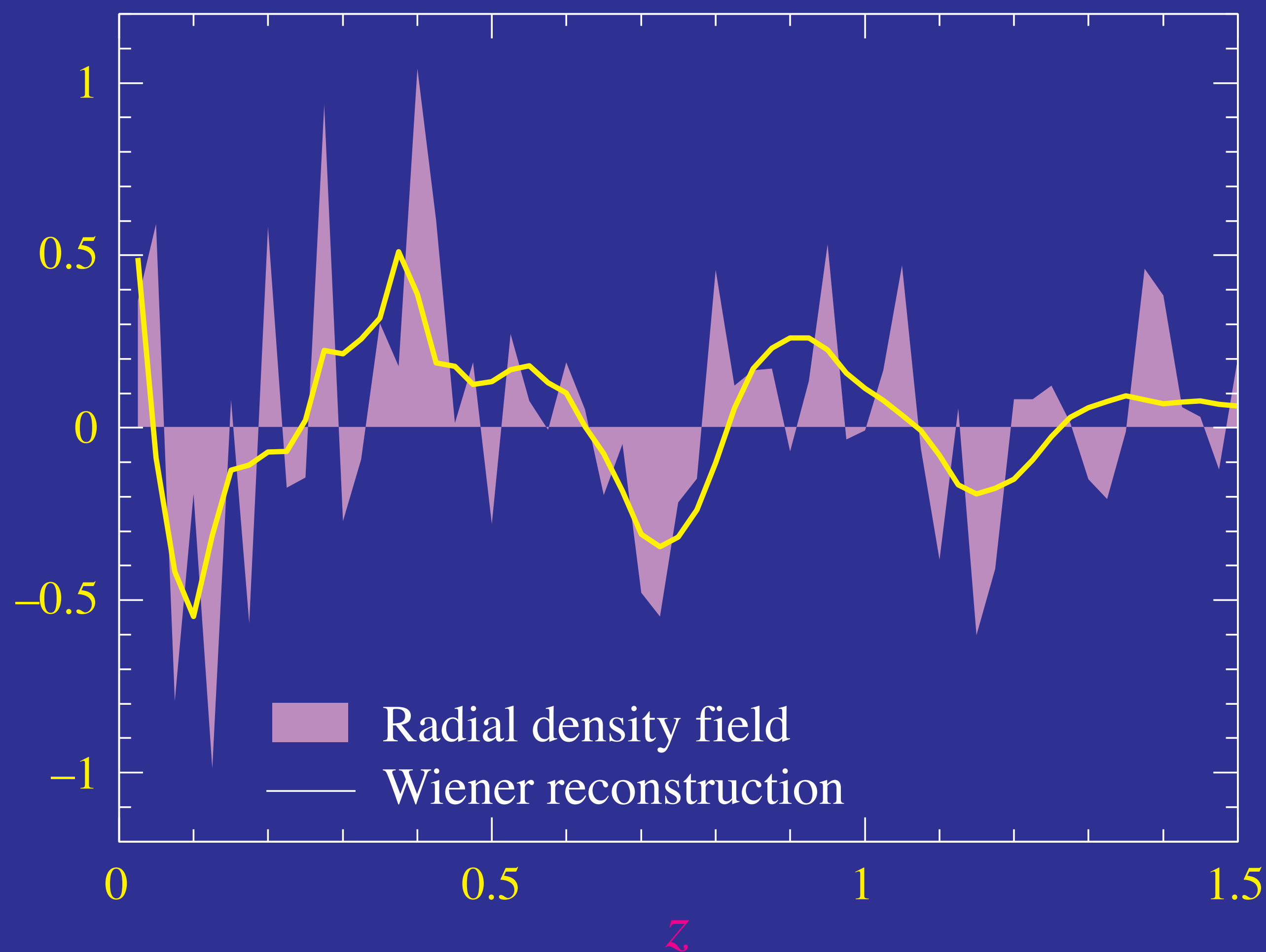

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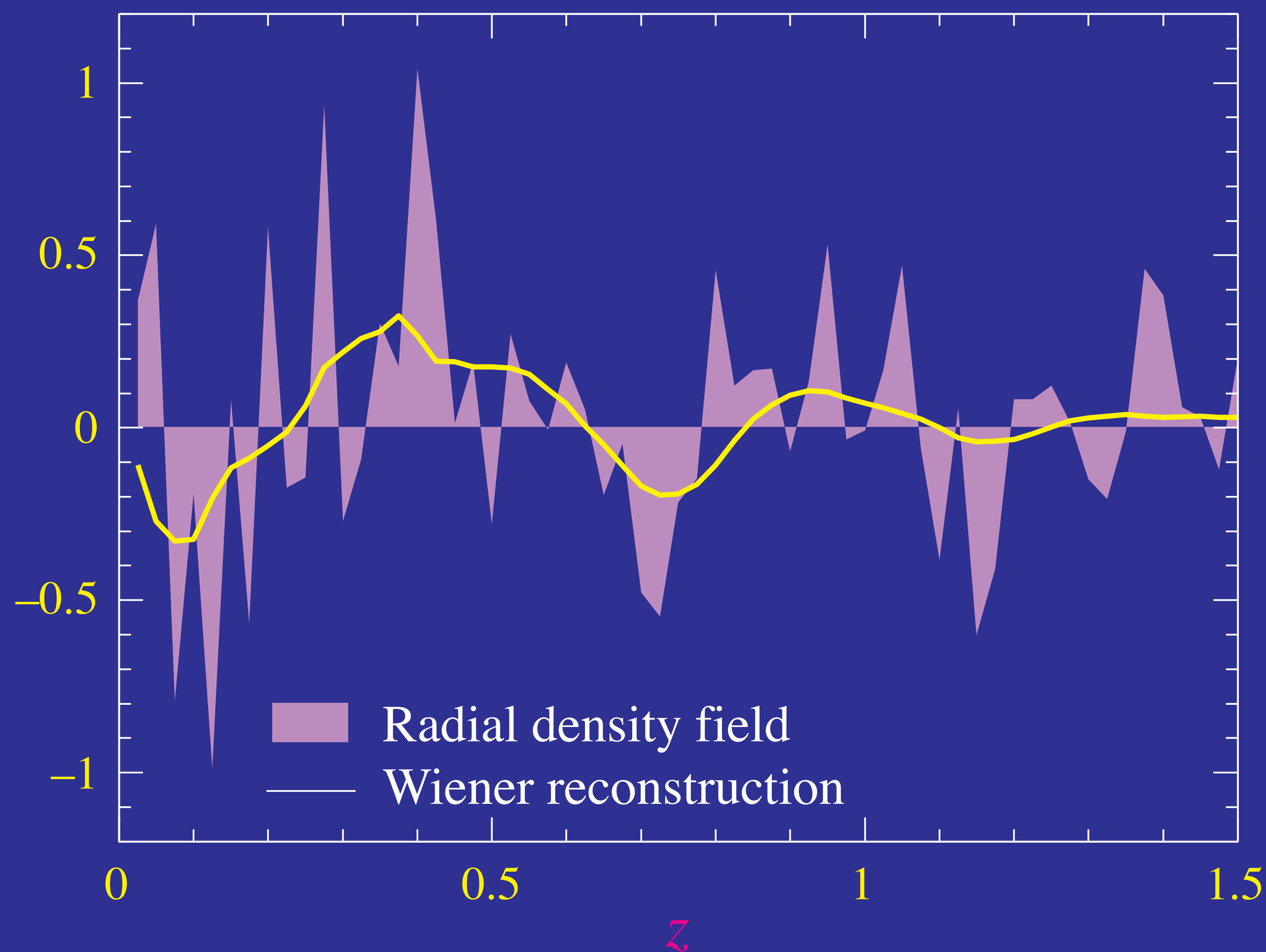

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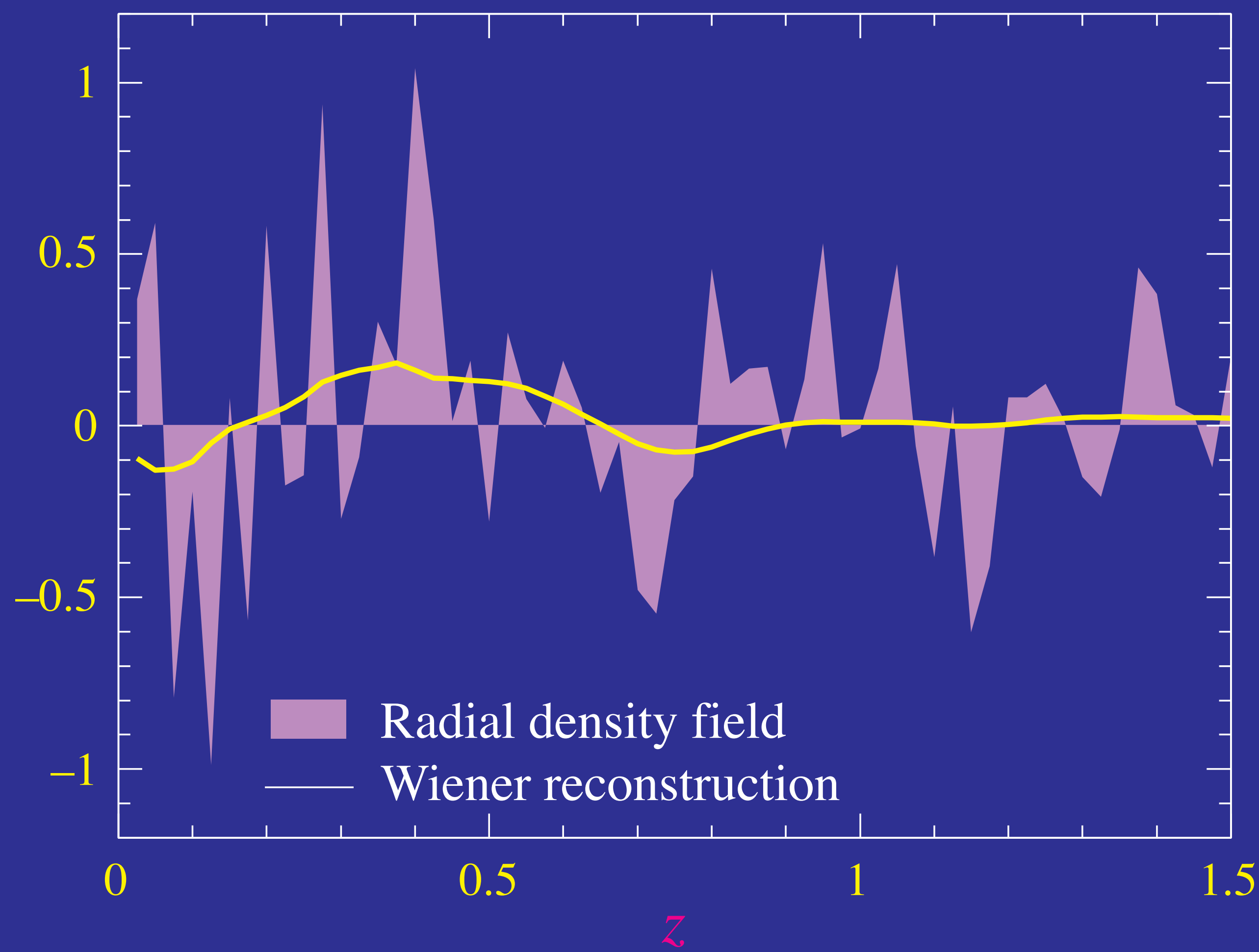
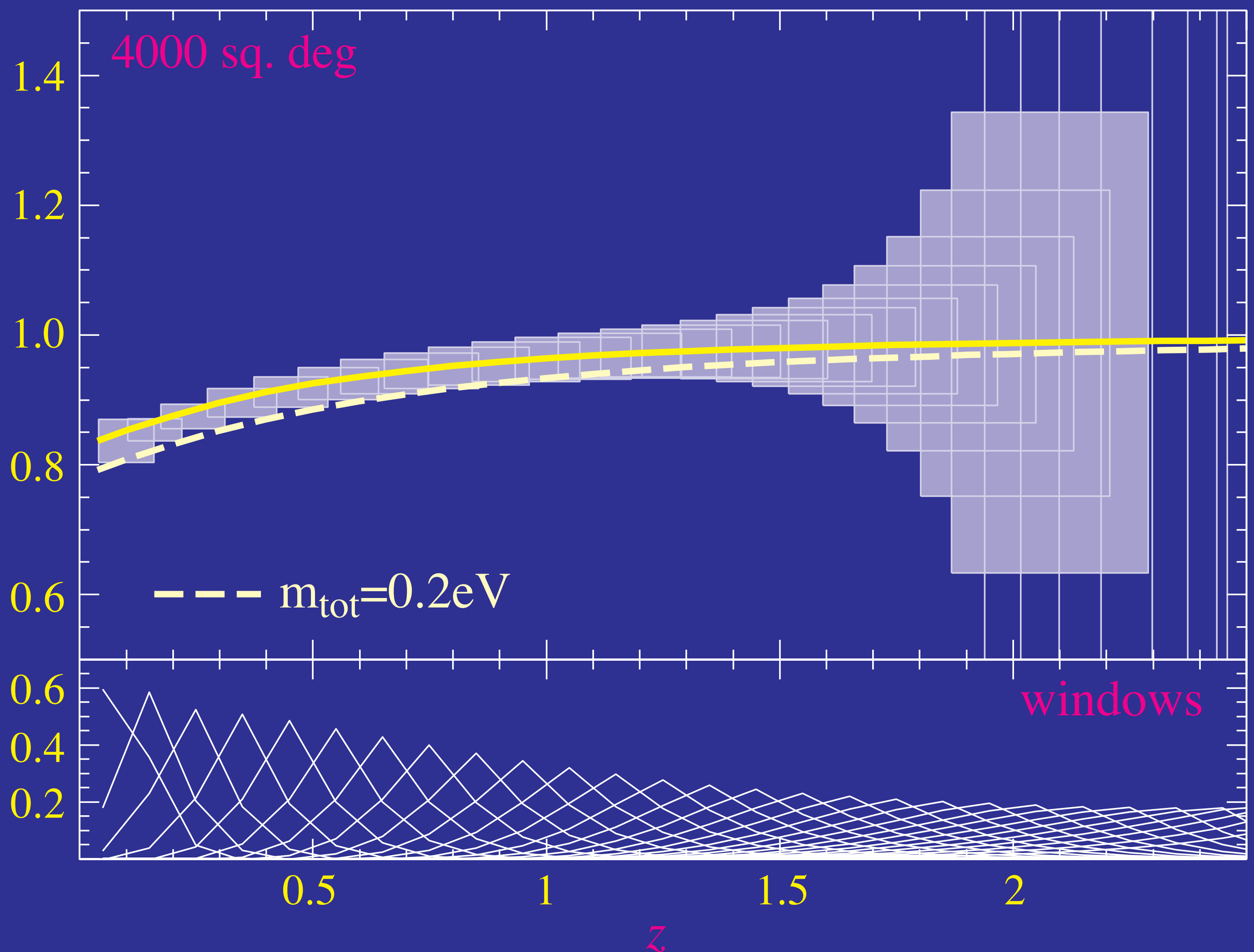


Growth Function

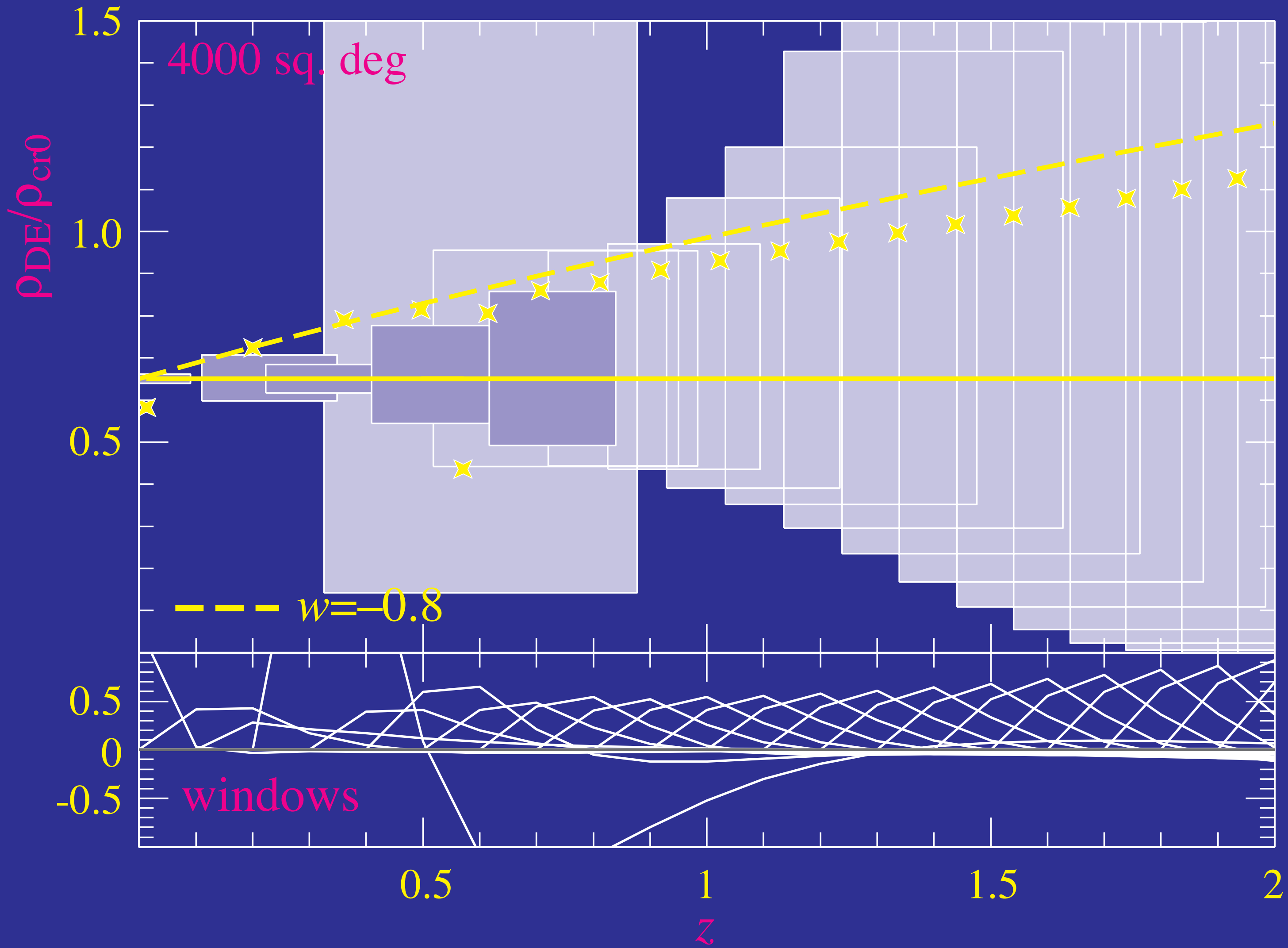
- Localized constraints (fixed distance-redshift relation)



Hu (2002)

Dark Energy Density

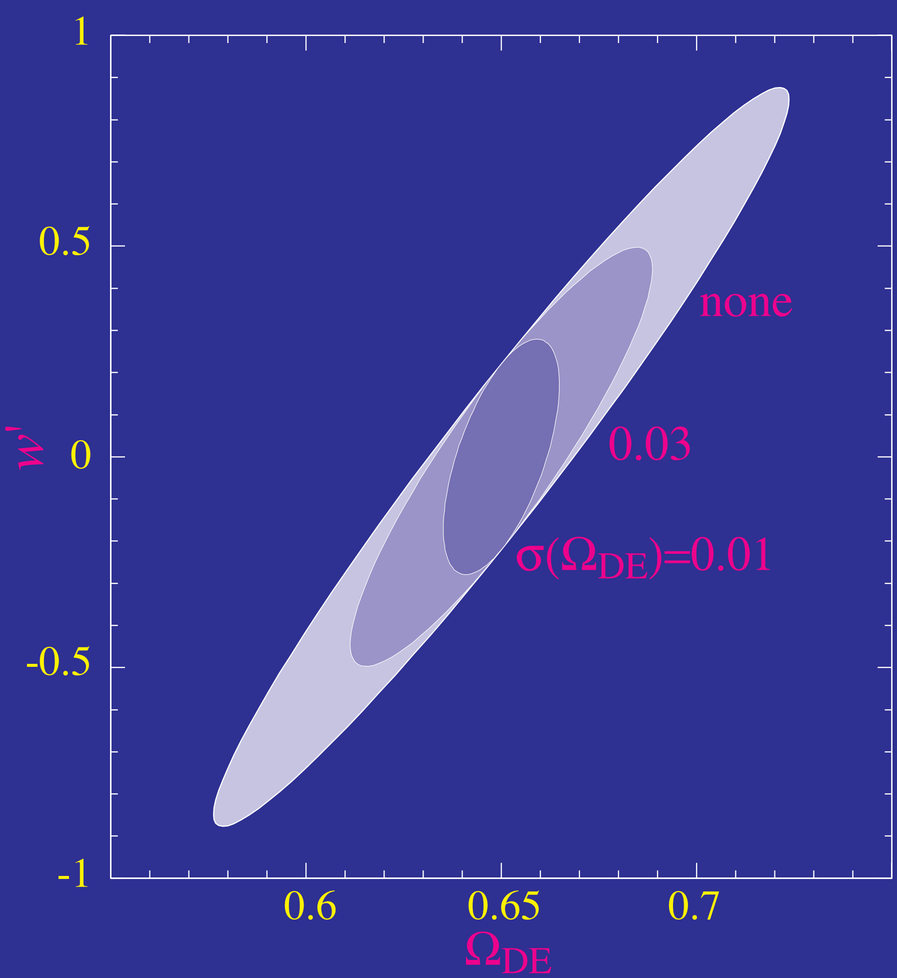
- Localized constraints (with cold dark matter)

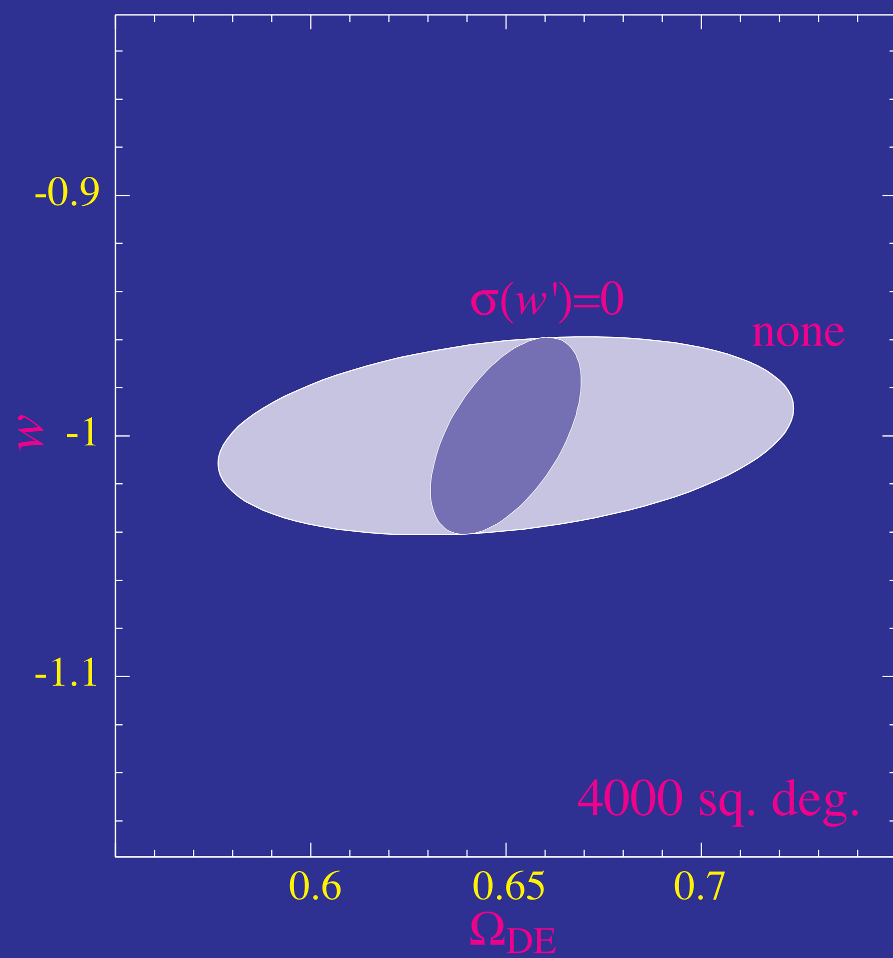


Hu (2002)

Dark Energy Parameters

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

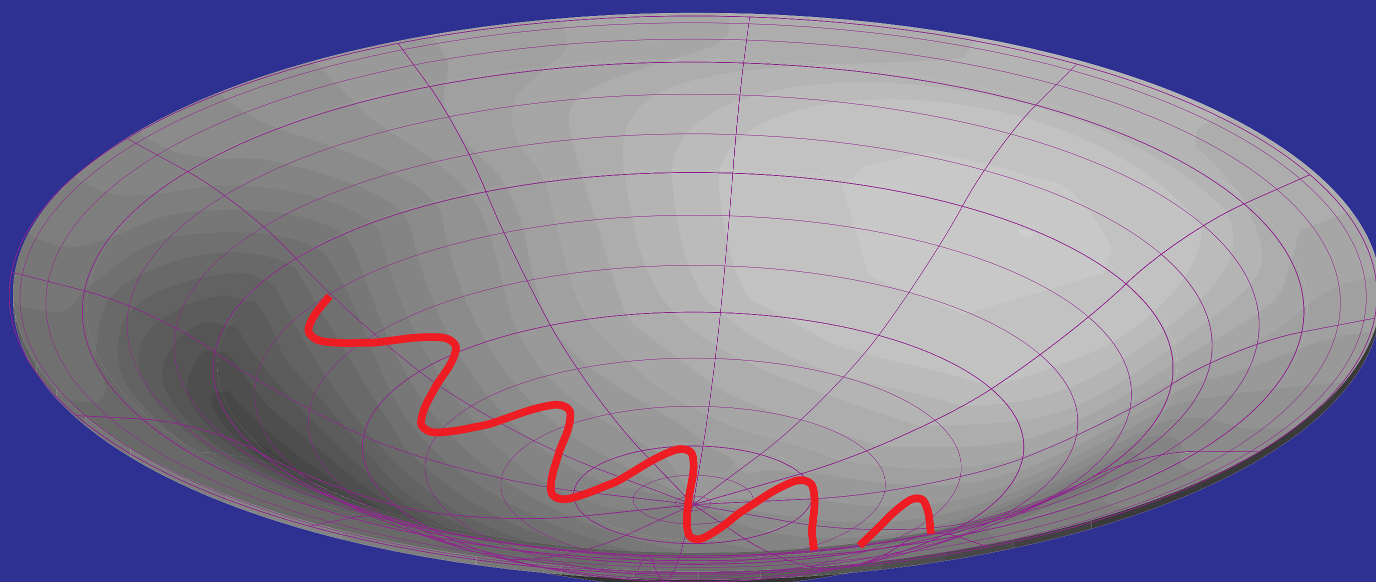




Hu (2002)

ISW Effect

- Gravitational blueshift on infall does not cancel redshift on climbing out
- Contraction of spatial metric doubles the effect: $\Delta T/T = 2\Delta\Phi$
- Effect from potential hills and wells cancel on small scales



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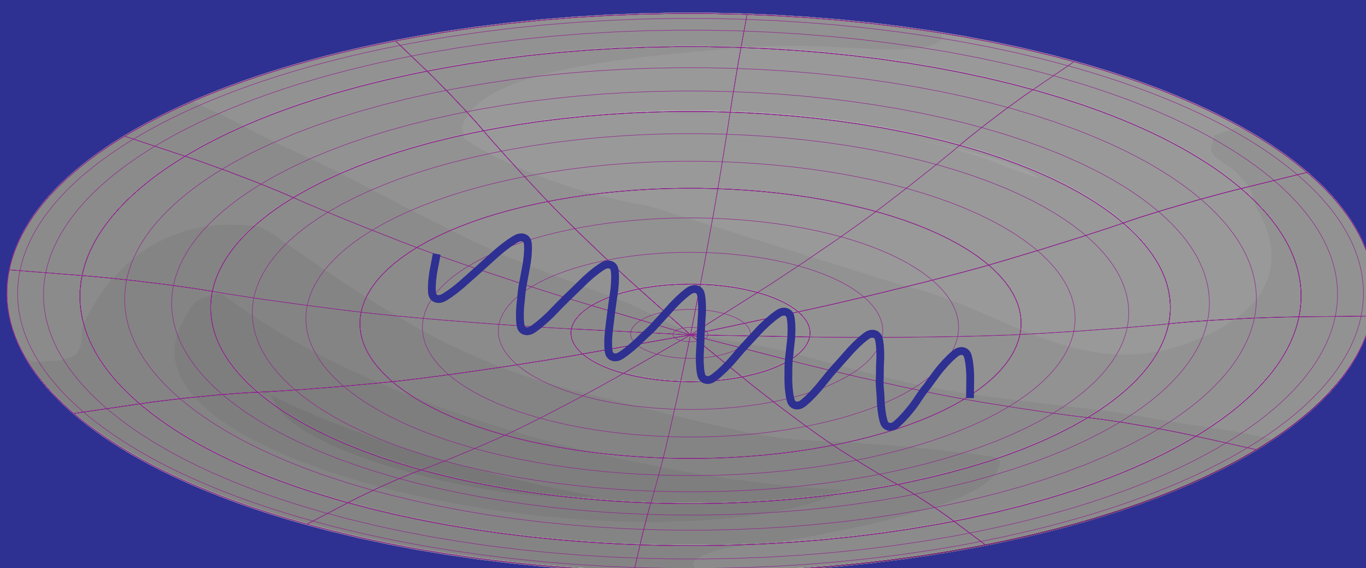
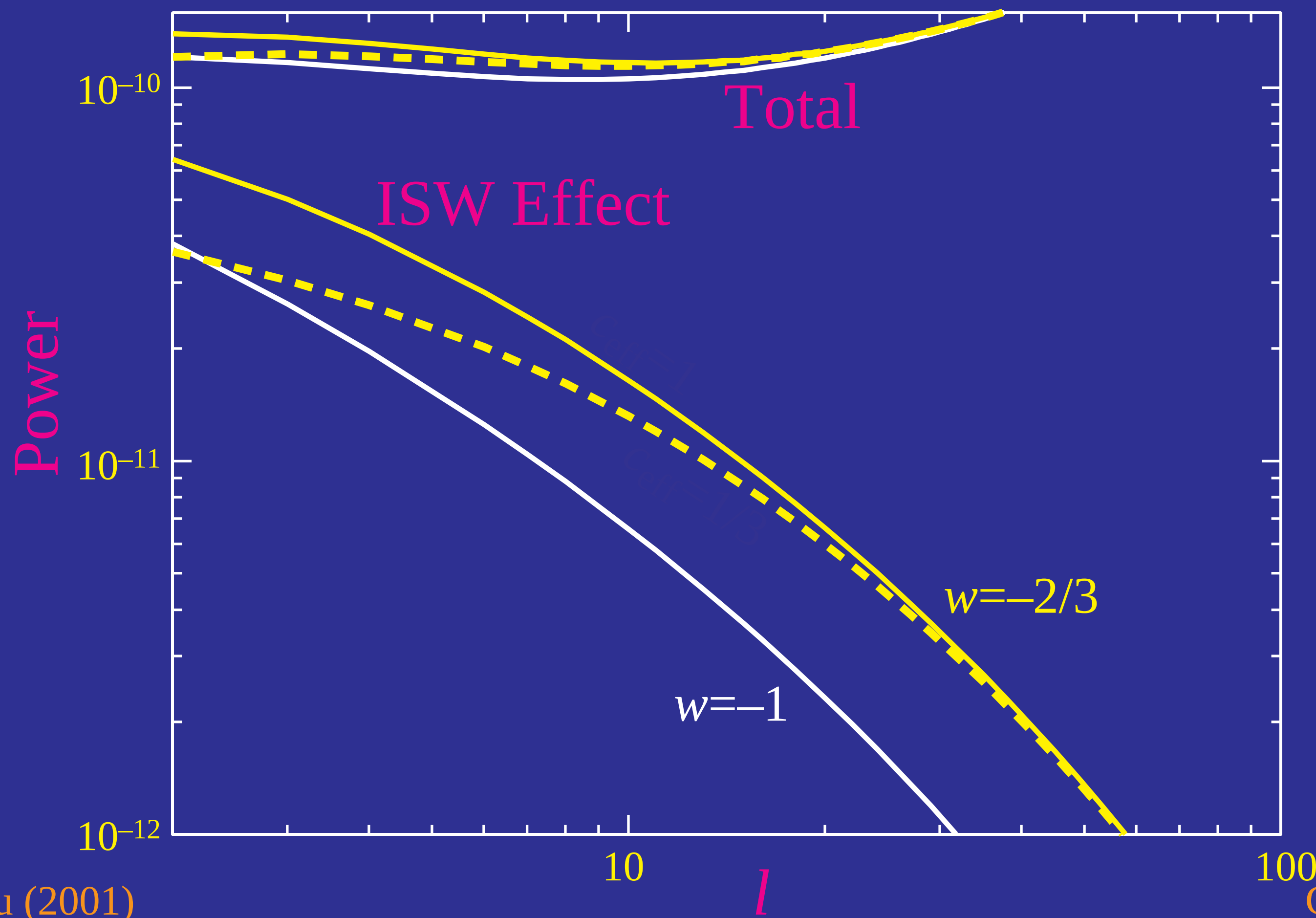


ISW Effect and Dark Energy

- Raising equation of state increases redshift of dark energy domination and raises the ISW effect
- Lowering the sound speed increases clustering and reduces ISW effect at large angles

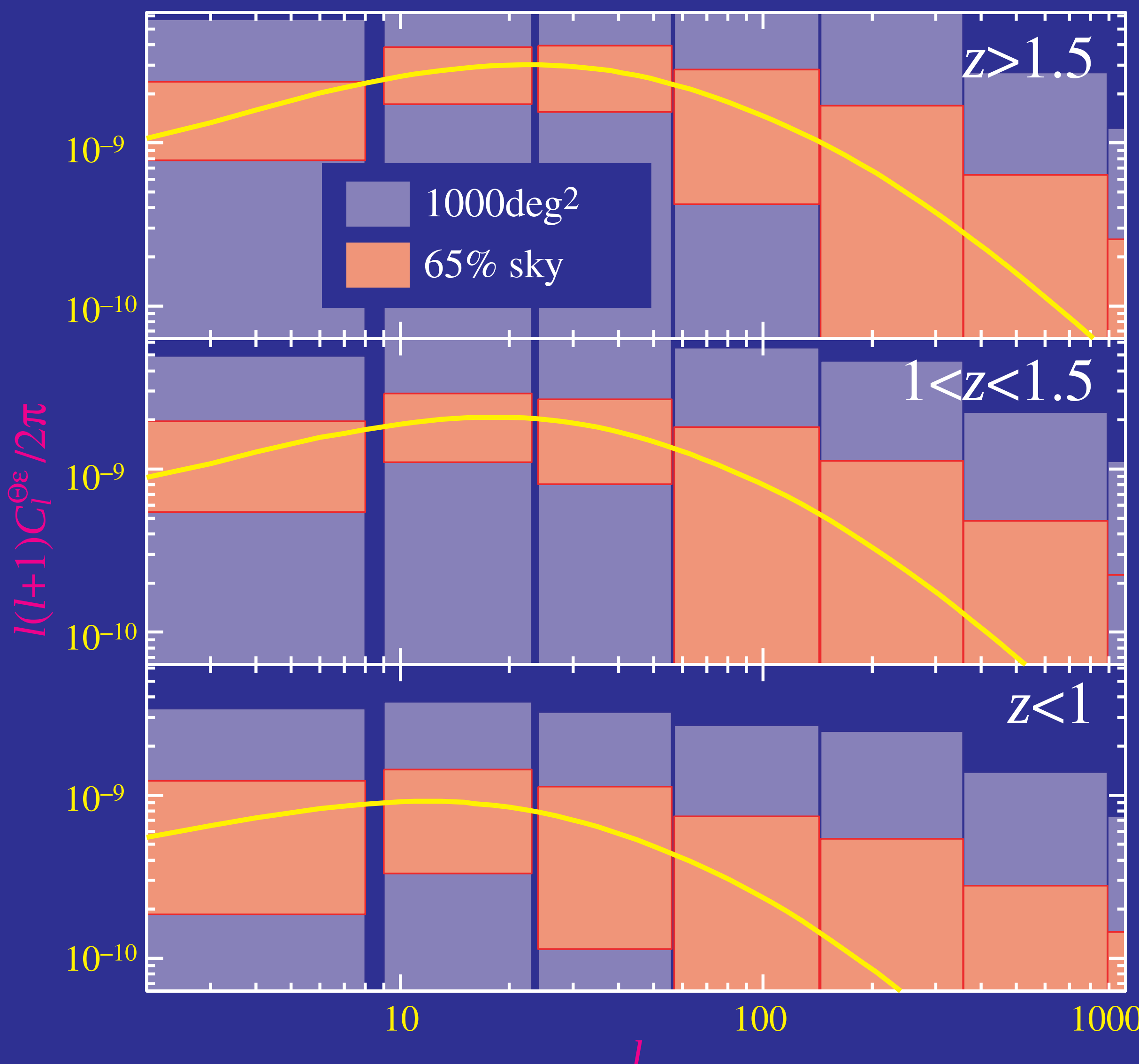


Hu (1998); Hu (2001)

Coble et al. (1997)
Caldwell et al. (1998)

Direct Detection of Dark Energy?

- In the presence of dark energy, shear is correlated with CMB temperature via ISW effect



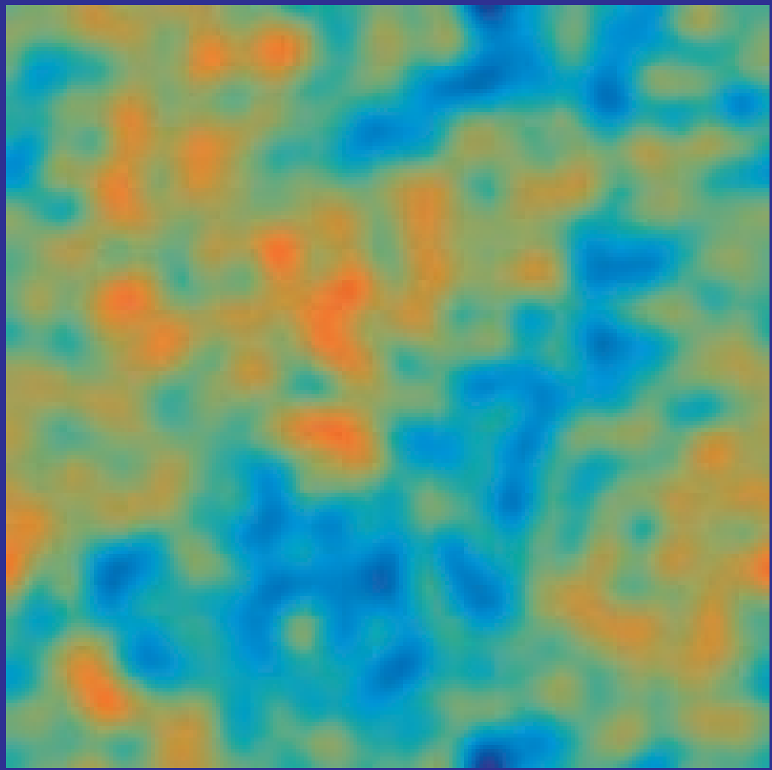
Hu (2001)

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

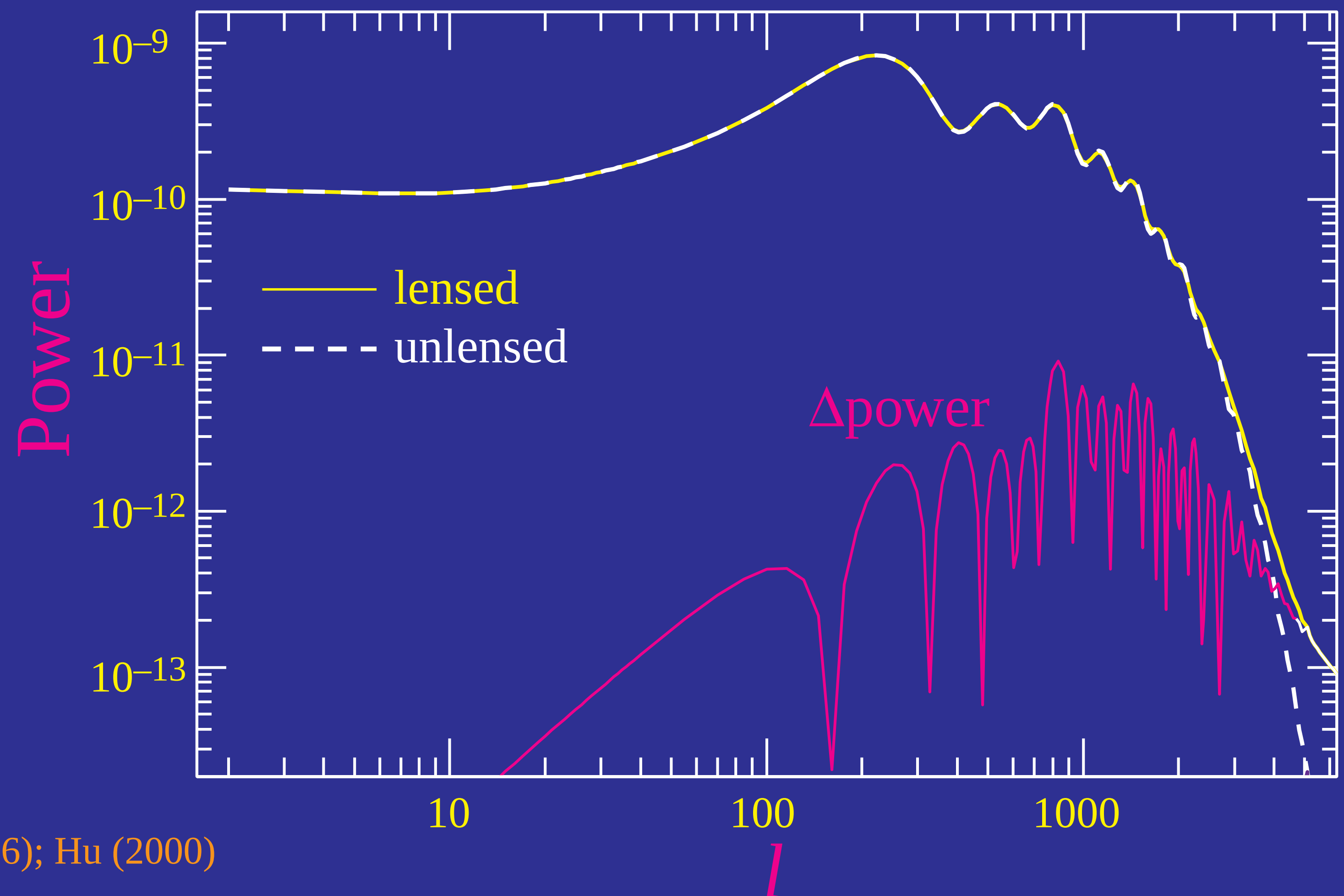
2.6'

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 $\kappa = \nabla^2\phi$

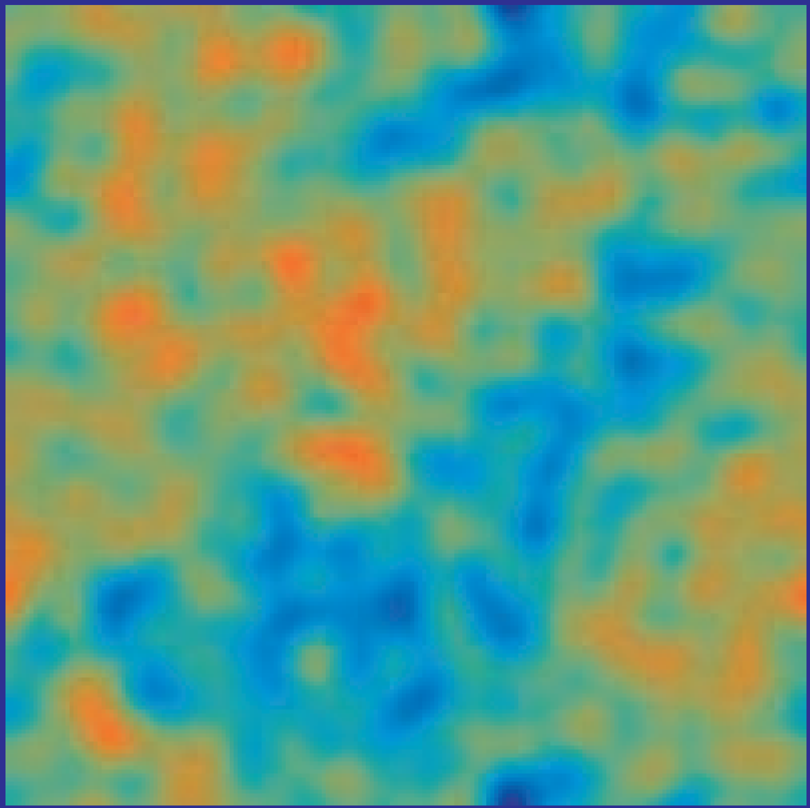
$$\langle x(\mathbf{l}) x'(\mathbf{l}') \rangle_{\rm CMB} = f_\alpha(\mathbf{l}, \mathbf{l}') \phi(\mathbf{l} + \mathbf{l}') \, ,$$

  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

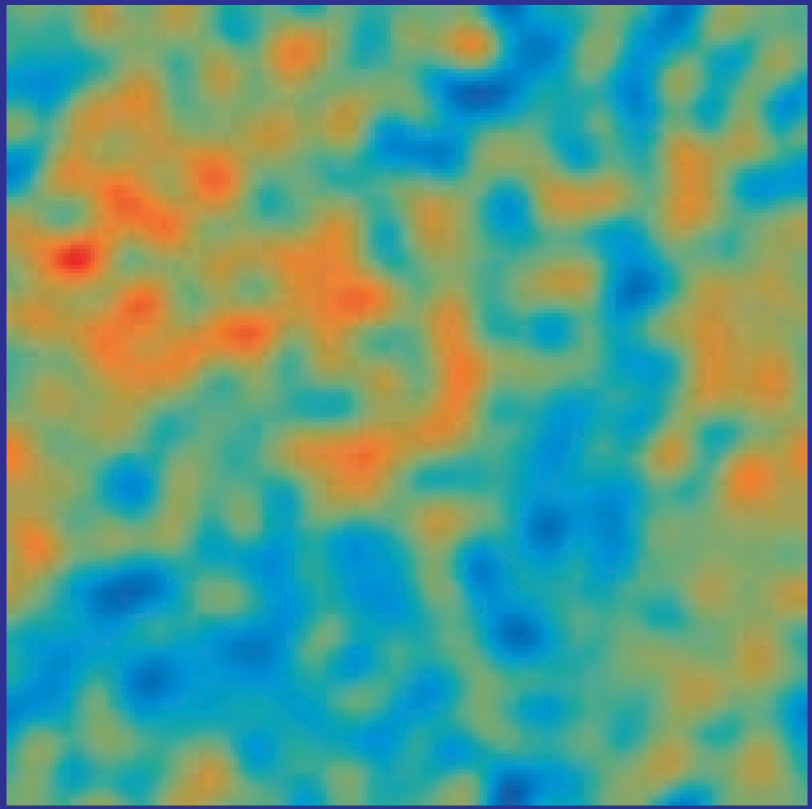
Quadratic Reconstruction

- Matched filter (minimum variance) averaging over pairs of multipole moments
- Real space: divergence of a temperature-weighted gradient



original

potential map (1000sq. deg)



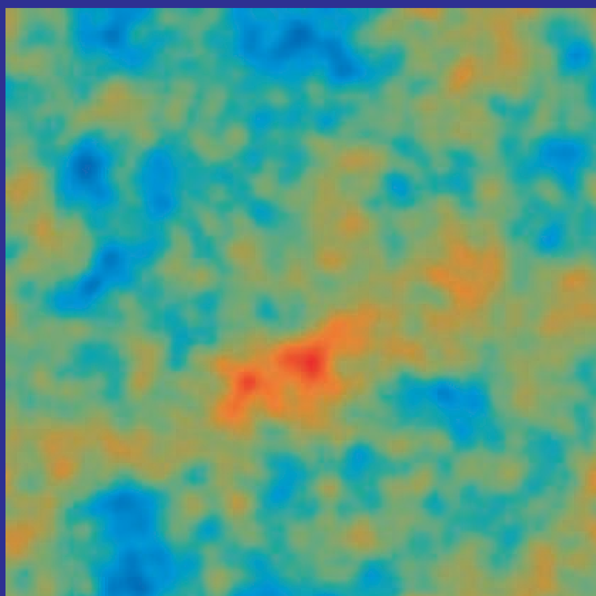
reconstructed

1.5' beam; 27μK-arcmin noise

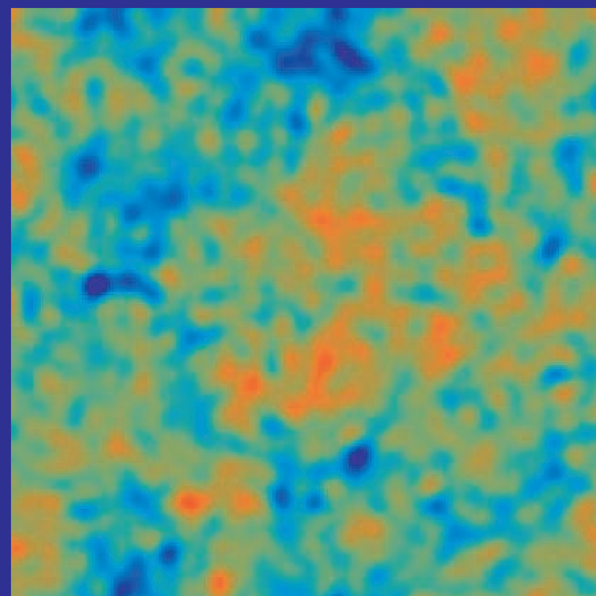
Hu (2001)

Ultimate (Cosmic Variance) Limit

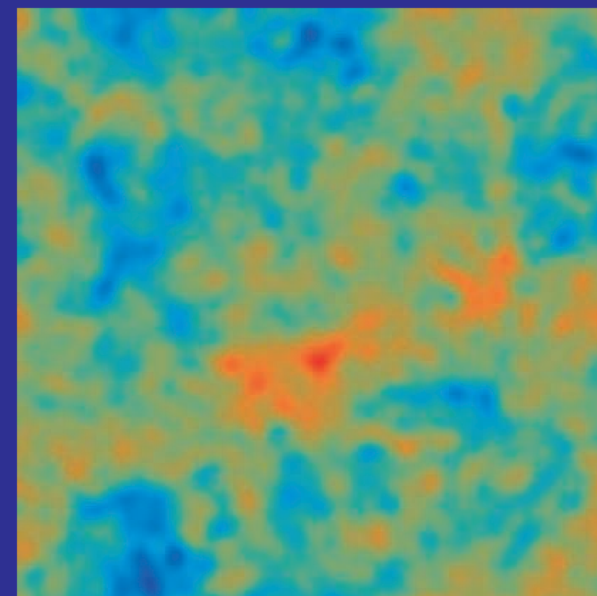
- Cosmic variance of CMB fields sets ultimate limit
- Polarization allows mapping to finer scales (~10')



mass



temp. reconstruction



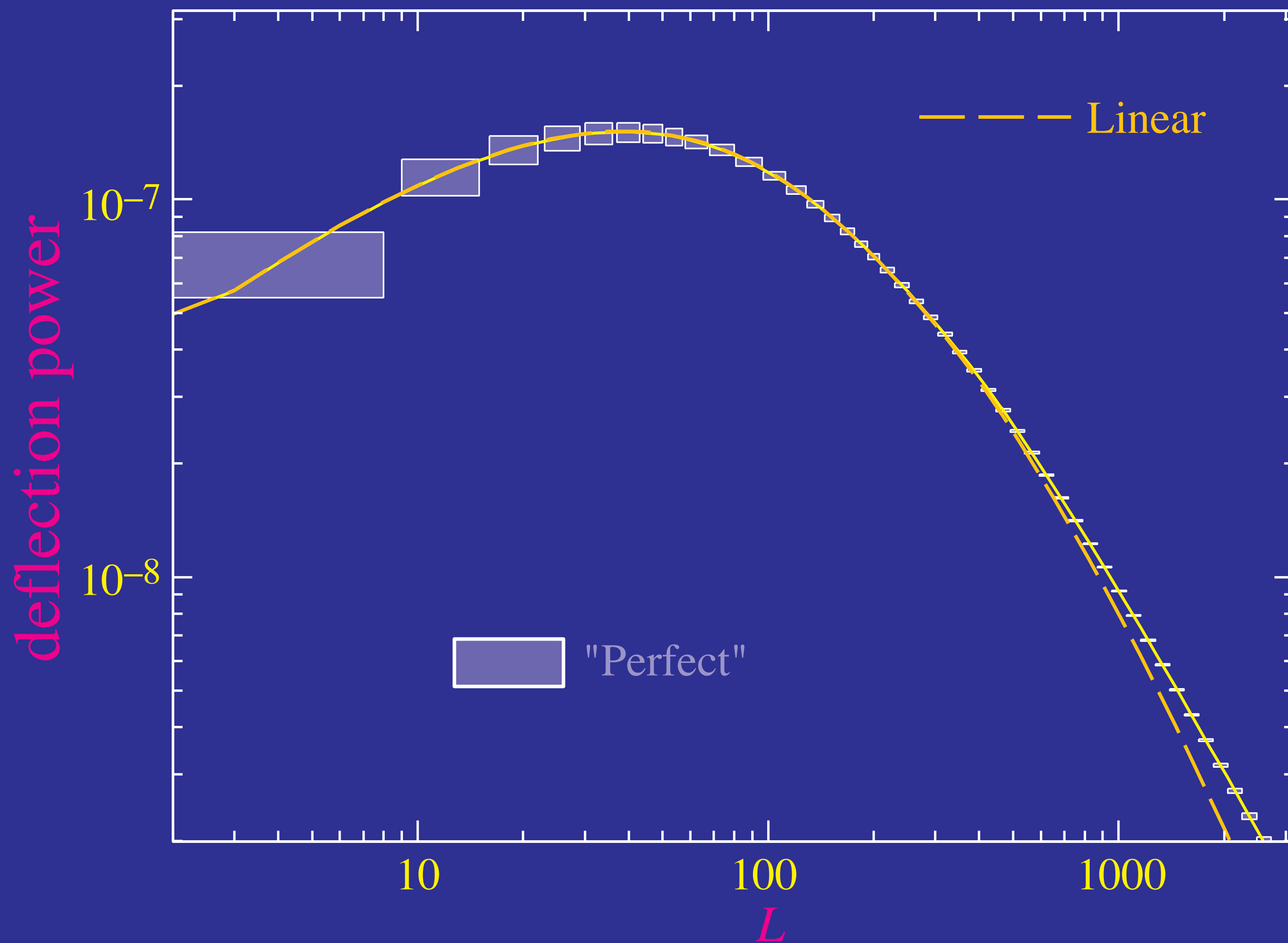
EB pol. reconstruction

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



Hu & Okamoto (2001)

$\sigma(w)\sim0.06$

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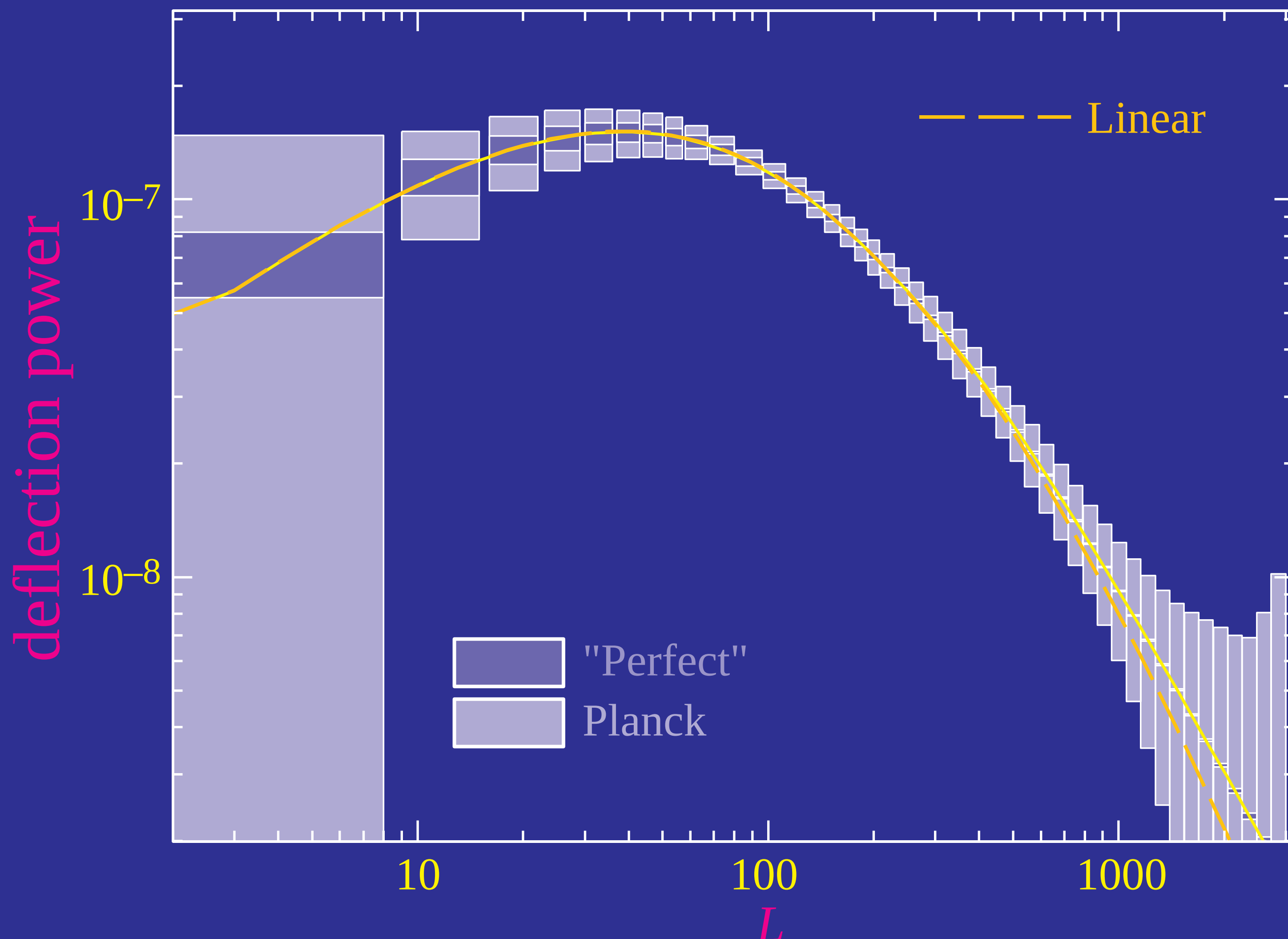
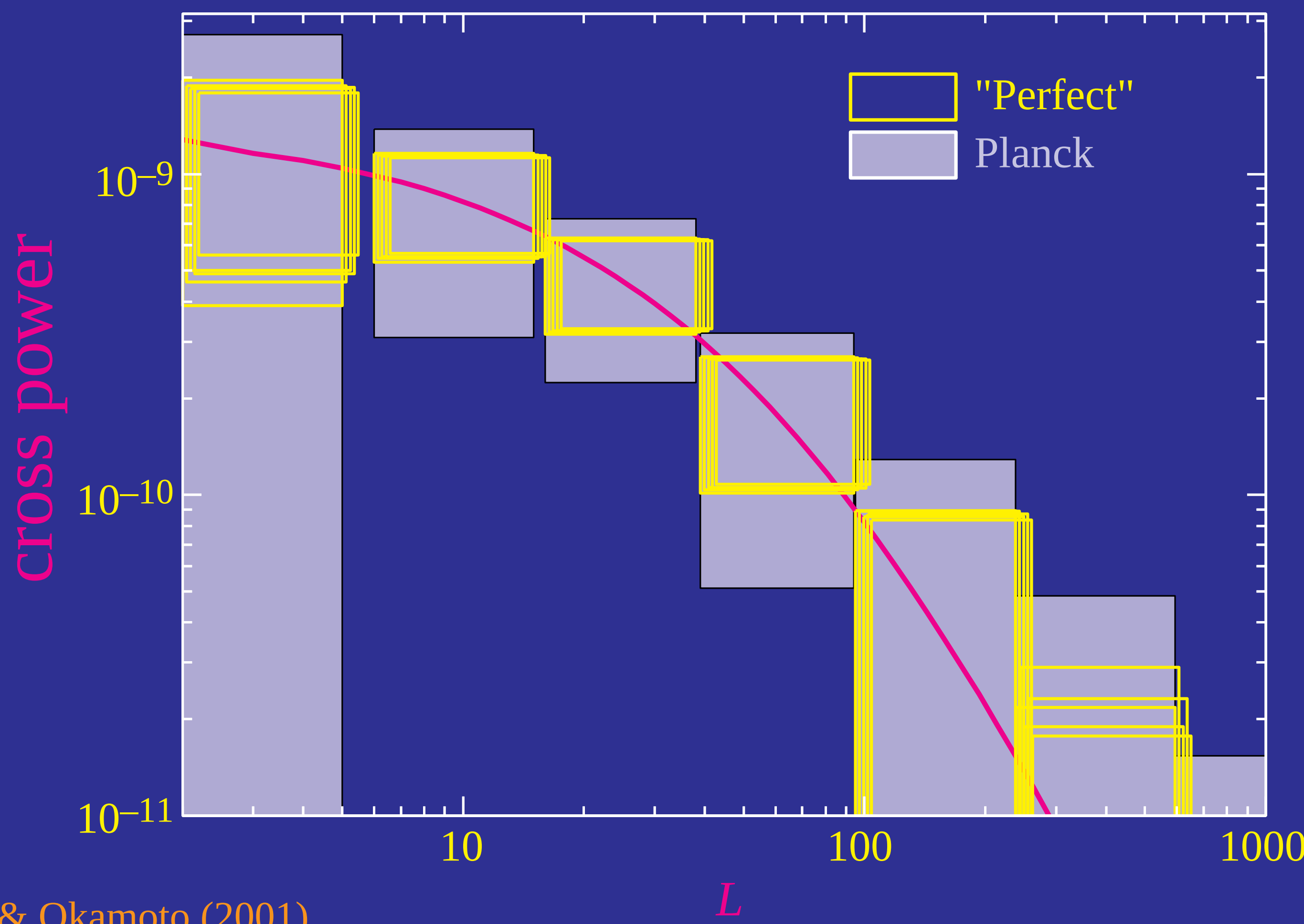


Hu & Okamoto (2001)

σ(*w*)~0.06; 0.14

Cross Correlation with Temperature

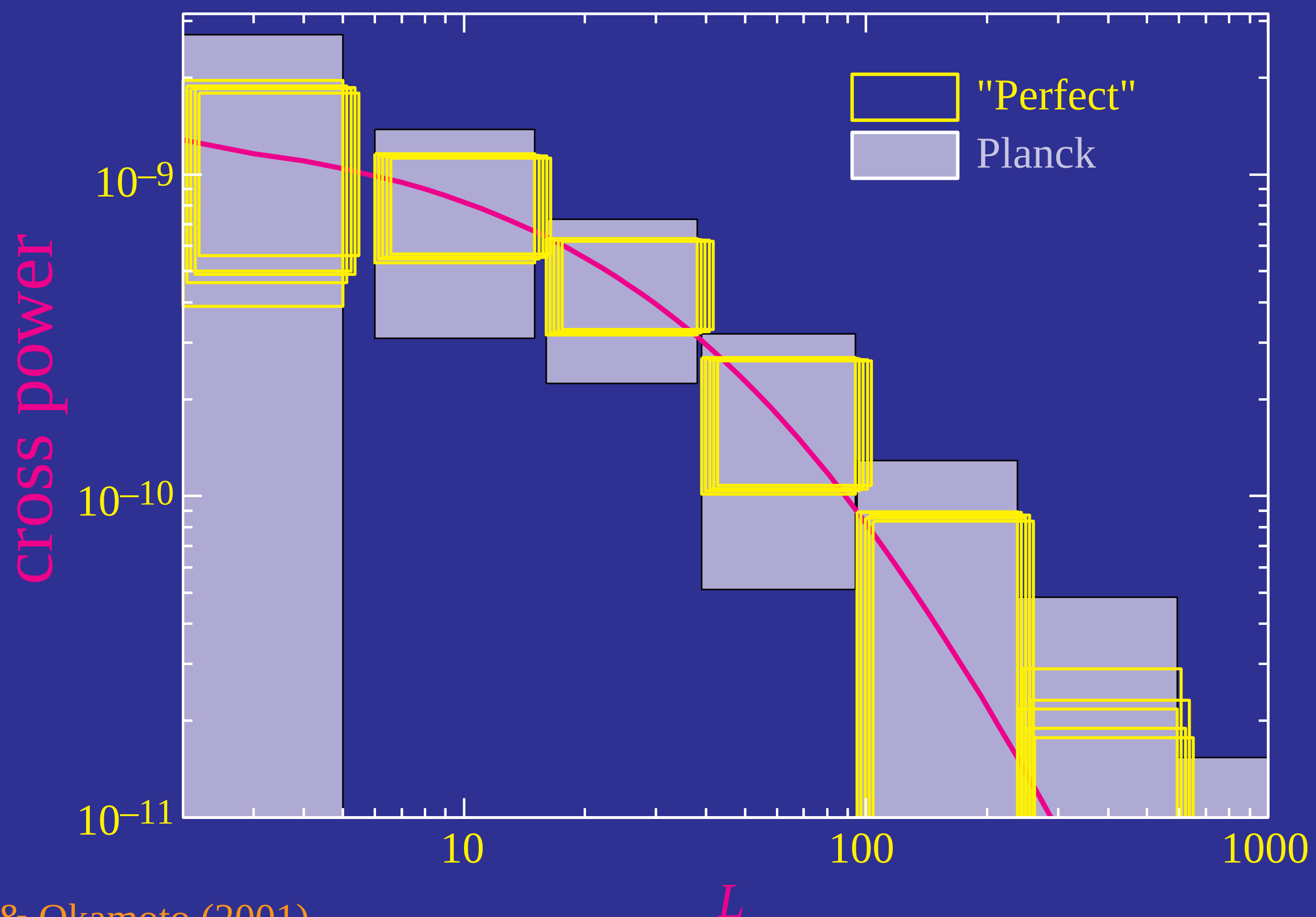
- Any correlation is a direct detection of a smooth energy density component through the ISW effect
- 5 nearly independent measures in temperature & polarization



Hu (2001); Hu & Okamoto (2001)

Cross Correlation with Temperature

- Any correlation is a direct detection of a smooth energy density component through the ISW effect
- Show dark energy smooth >5-6 Gpc scale, test quintesence



Hu (2001); Hu & Okamoto (2001)

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- Luminous tracers (supernovae/galaxies/clusters) require modelling of formation/evolution
- Gravitational lensing avoids ambiguity, utilizes luminous objects only as background image

- Evolution of dark energy can be extracted tomographically
- Clustering of dark energy (test of scalar field paradigm) extractable from wide-field CMB lensing