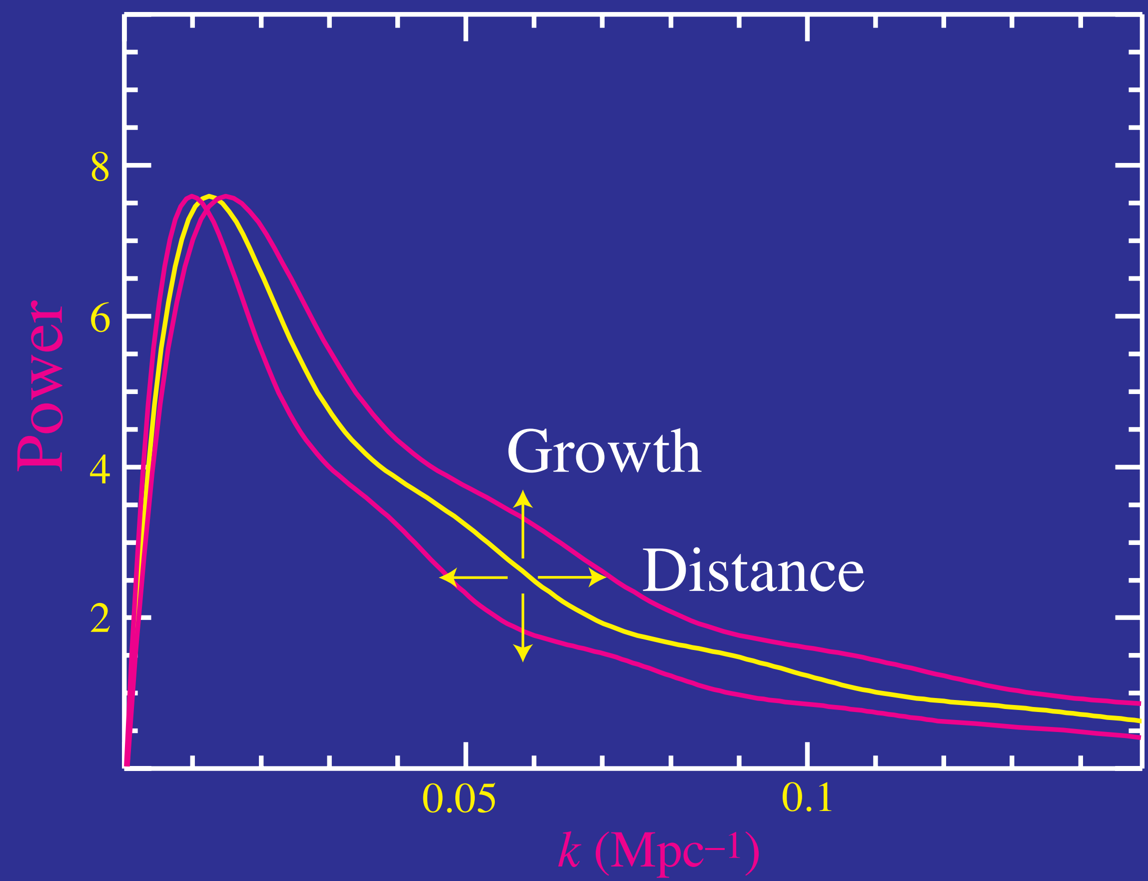
Power Spectra Tests



of the Dark Energy

Wayne Hu

NASA/Goddard Space Flight Center

Outline

Power spectrum tests of the dark energy in light of the CMB

From crude to precision measurements

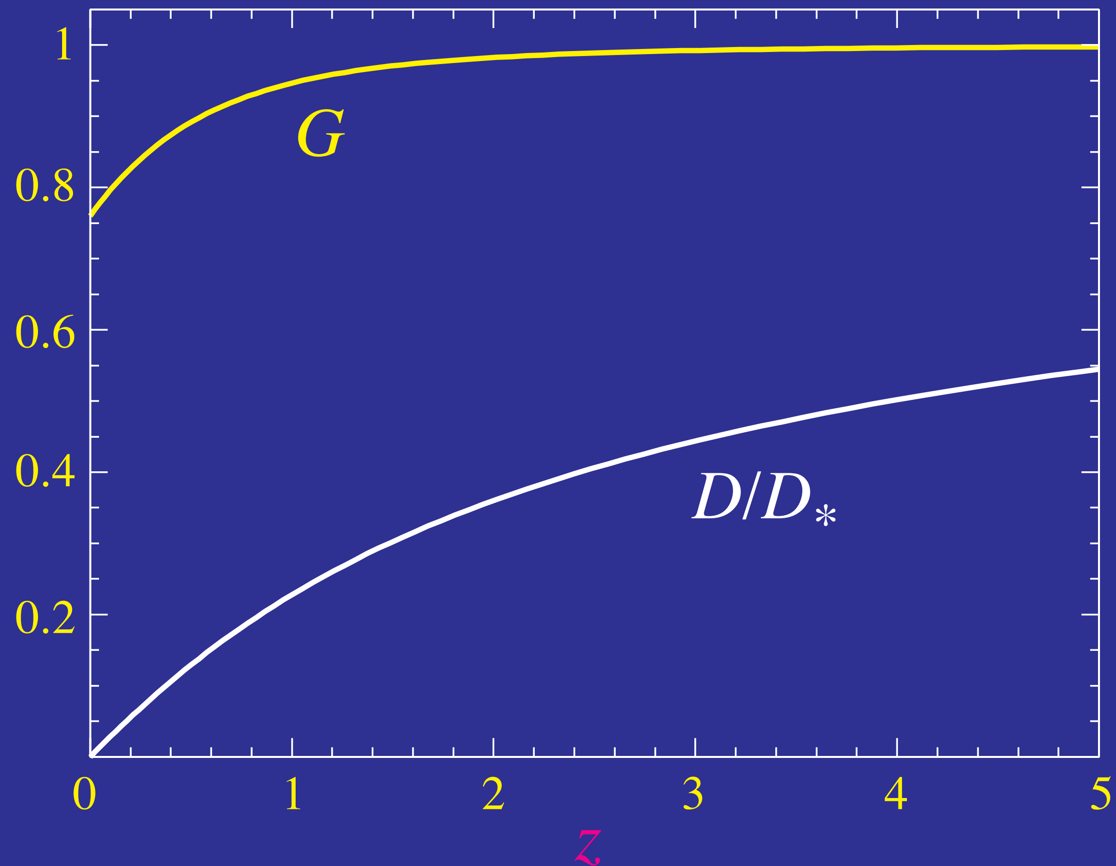
- Variance of cluster counts in cells
- Angular power spectra
- 3D power spectra with $\delta z < 0.01$

Collaborators:

- Zoltan Haiman
- Bhuvnesh Jain
- Andrey Kravtsov
- Marcos Lima

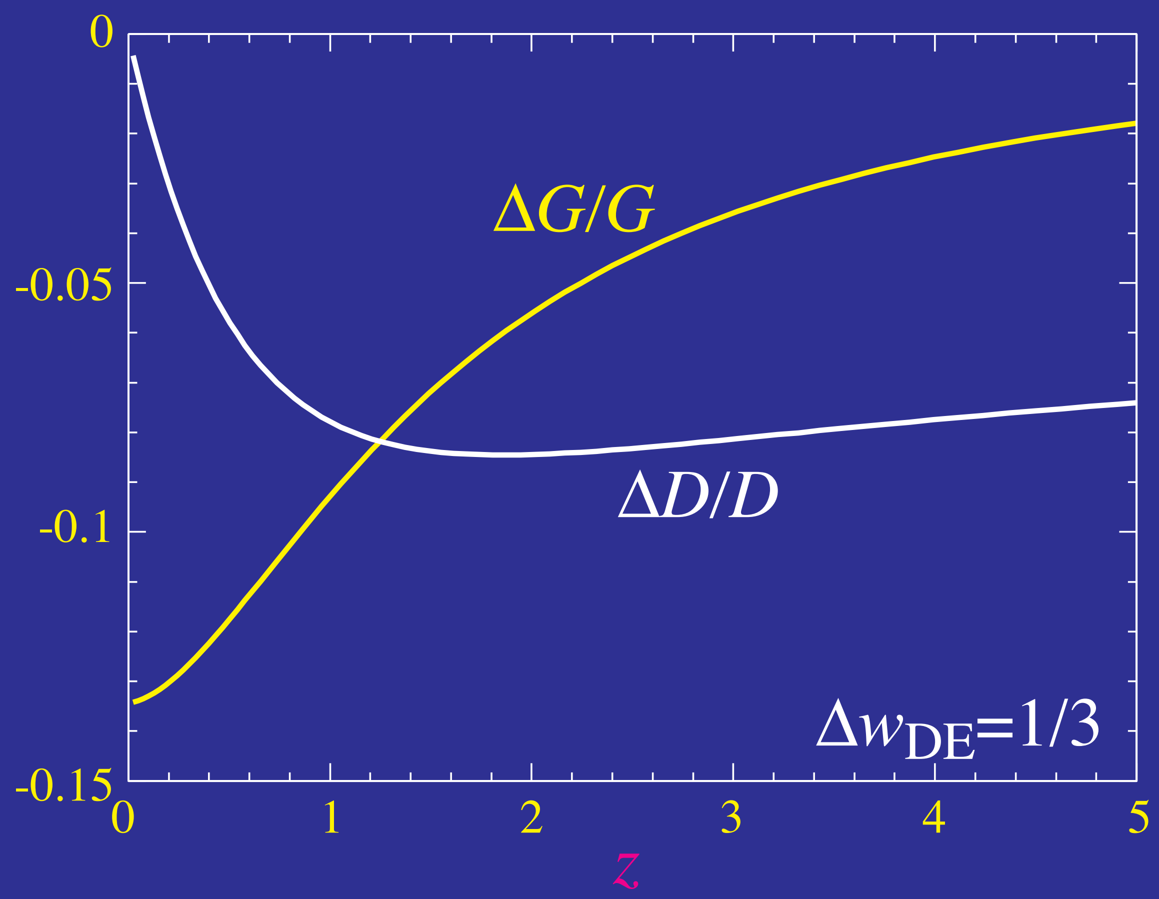
Dark Energy Sensitivity

- Growth: G=(growth rate)/a; normalized to high z
- Distances: D=comoving distance; D_*=to recombination



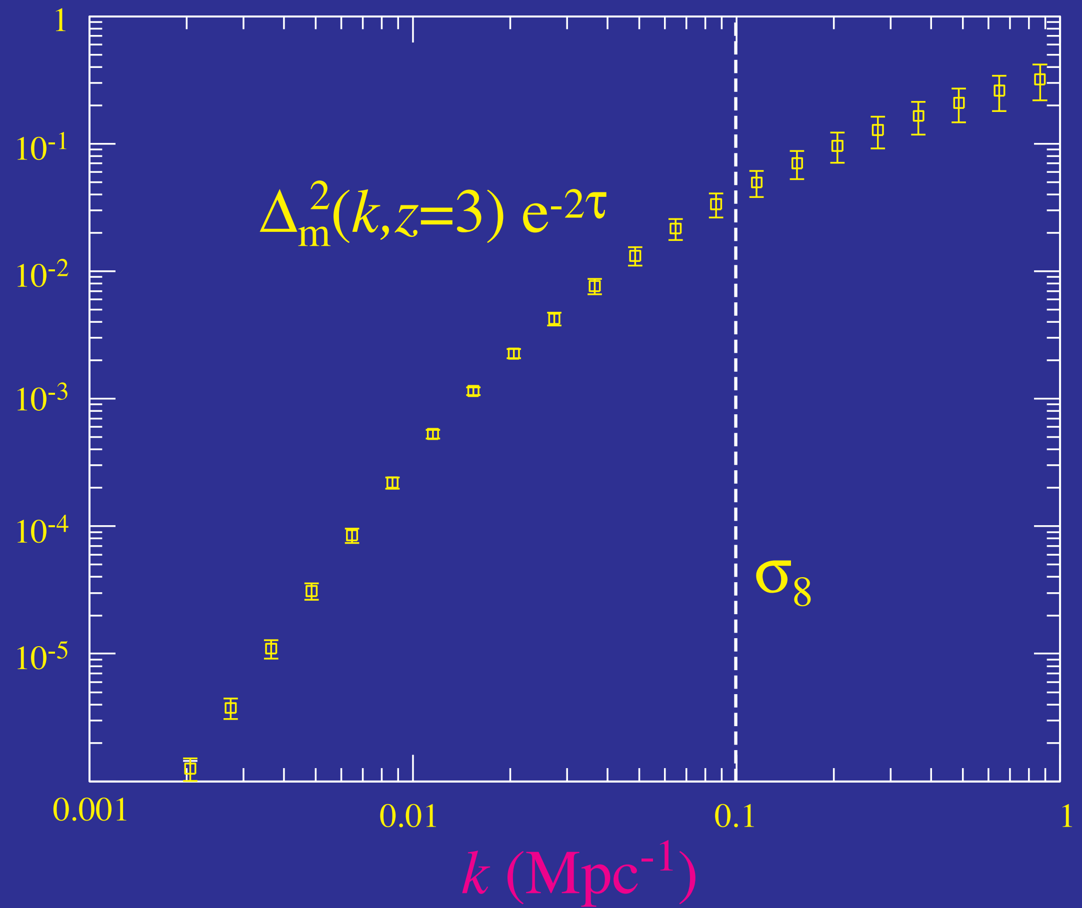
Dark Energy Sensitivity

- Growth: G=(growth rate)/a; normalized to high z
- Distances: D=comoving distance; D_*=to recombination
- Sensitivity to w_{DE}: comparable



Initial Power Spectrum

- Initial power spectrum on scales relevant for clusters determined by CMB
- Improvement goes with the reionization optical depth τ



WMAPext; M. White

σ_8

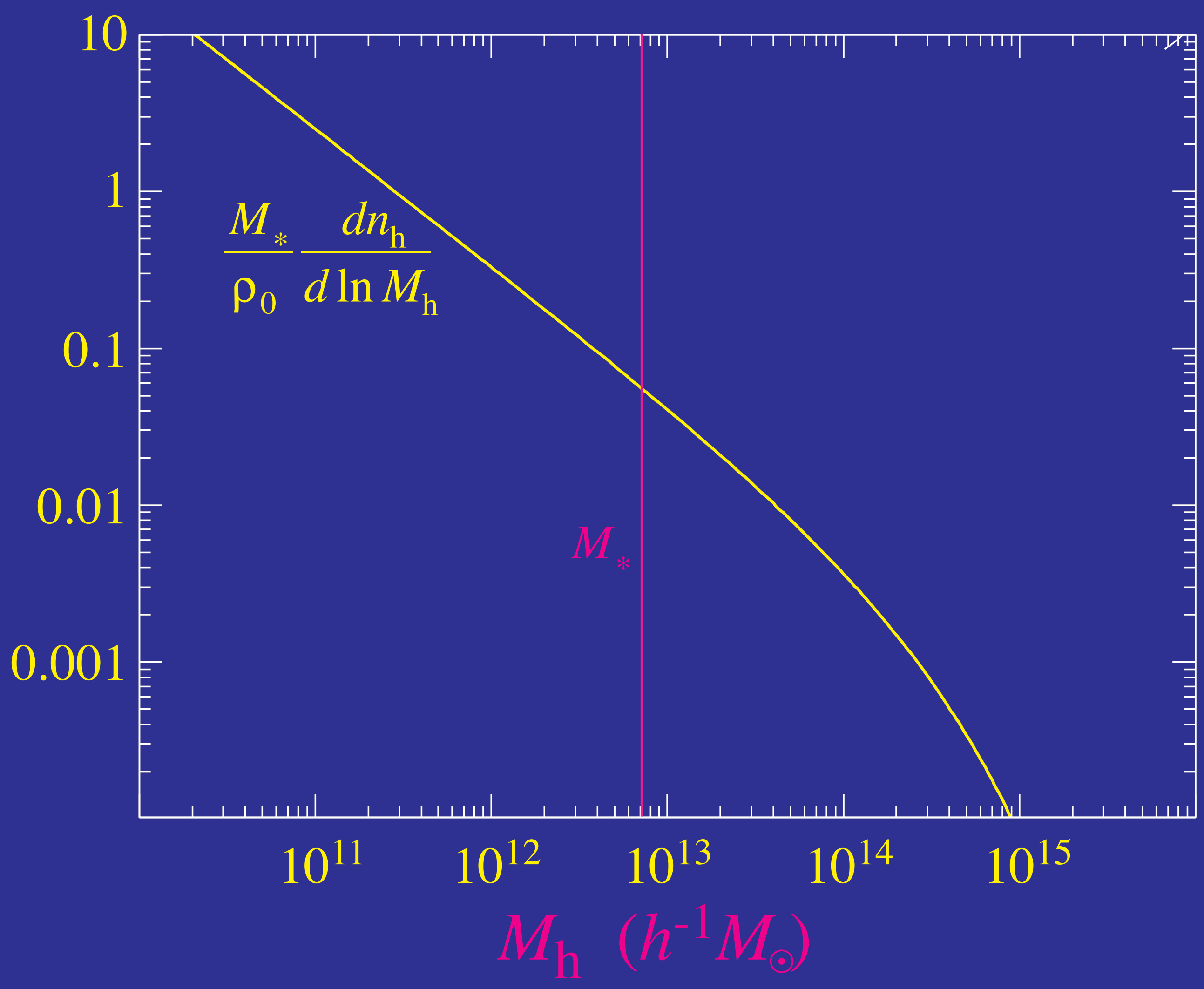
- Determination of the normalization during the acceleration epoch, even σ_8, measures the dark energy with negligible uncertainty from other parameters
- Approximate scaling (flat, negligible neutrinos: Hu & Jain 2003)

$$\sigma_8 \approx \frac{\delta_\zeta}{5.6 \times 10^{-5}} \left(\frac{\Omega_b h^2}{0.024}\right)^{-1/3} \left(\frac{\Omega_m h^2}{0.14}\right)^{0.563} (3.12h)^{(n-1)/2} \times \left(\frac{h}{0.72}\right)^{0.693} \frac{G_0}{0.76},$$

- δ_ζ, $\Omega_b h^2$, $\Omega_m h^2$, n all well determined; eventually to $\sim 1\%$ precision
- $h = \sqrt{\Omega_m h^2/\Omega_m} \propto (1 - \Omega_{\rm DE})^{-1/2}$ measures dark energy density
- G_0 measures dark energy dependent growth rate

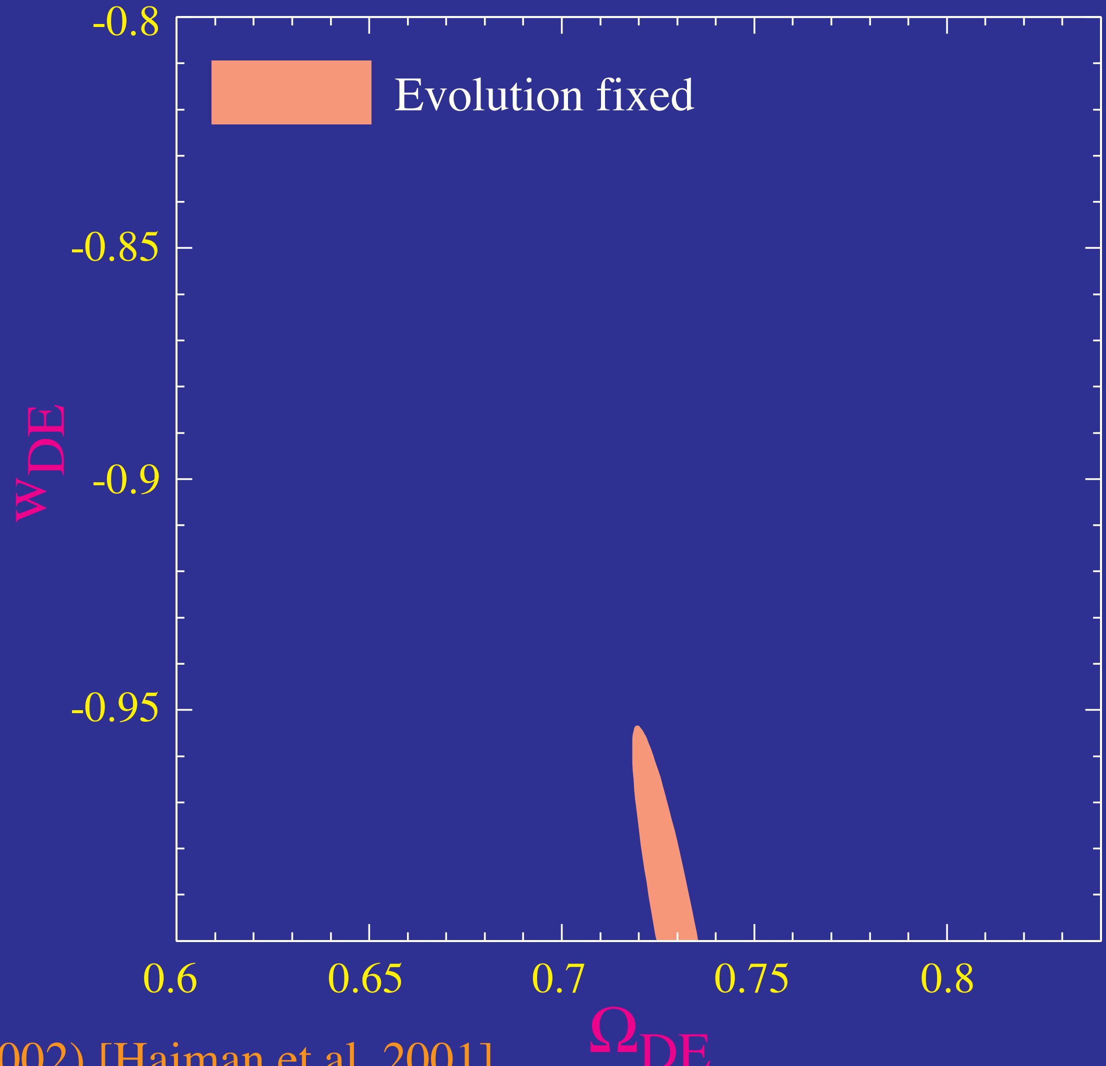
Cluster Abundance

- Power spectrum controls halo abundance; exponential sensitivity above M_*; $\sigma(M_*)=1$
- Abundance evolution determines dark energy evolution



Idealized Constraints

- Fixed high-z power inverts redshift trends and eliminates σ_8 as parameter
- Sampling errors neither dominant nor negligible

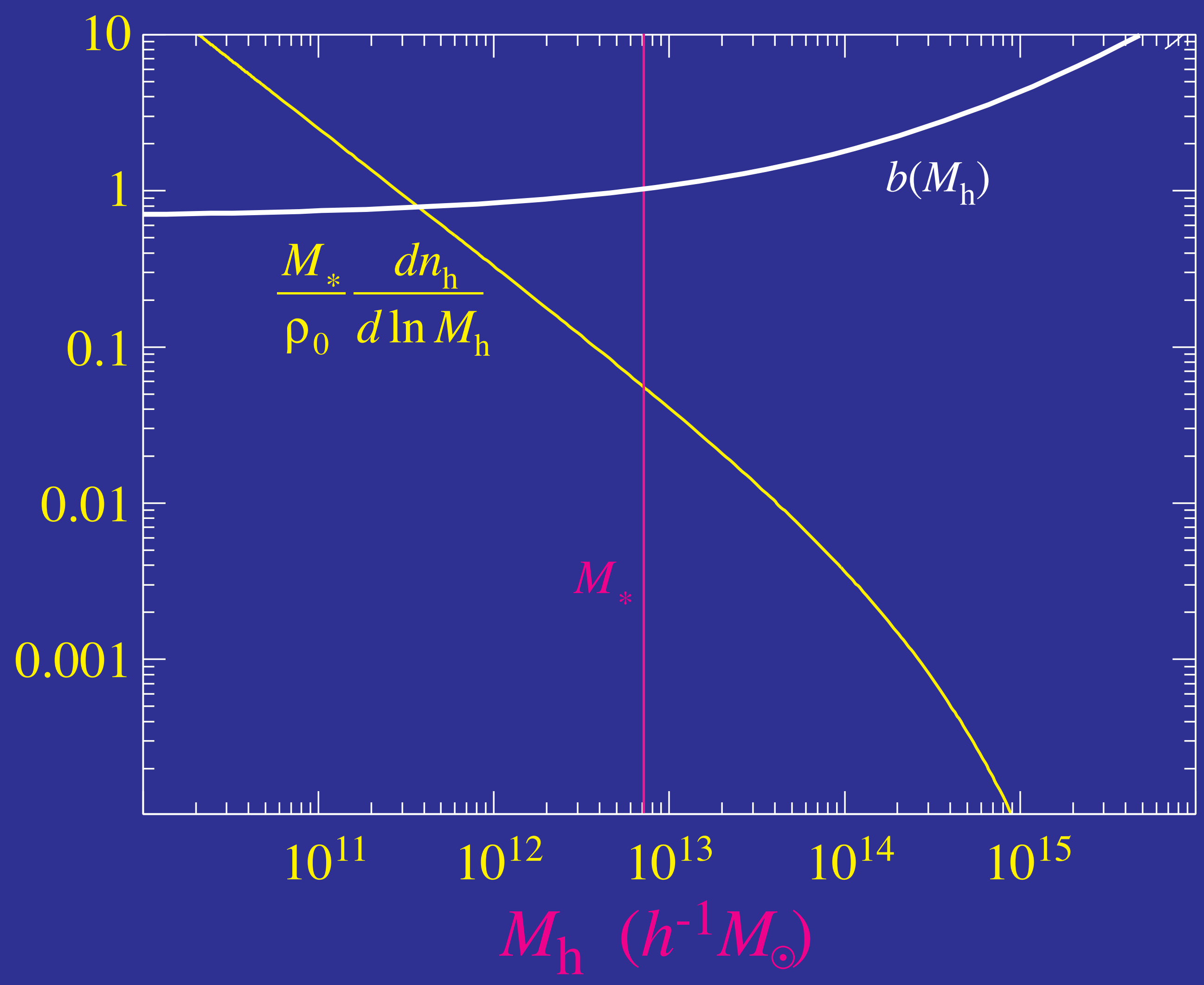


4000 deg^2
$M_{th}=10^{14.2}\ h^{-1}\ M_\odot$
1% CMB Priors

Hu & Kravtsov (2002) [Haiman et al 2001]

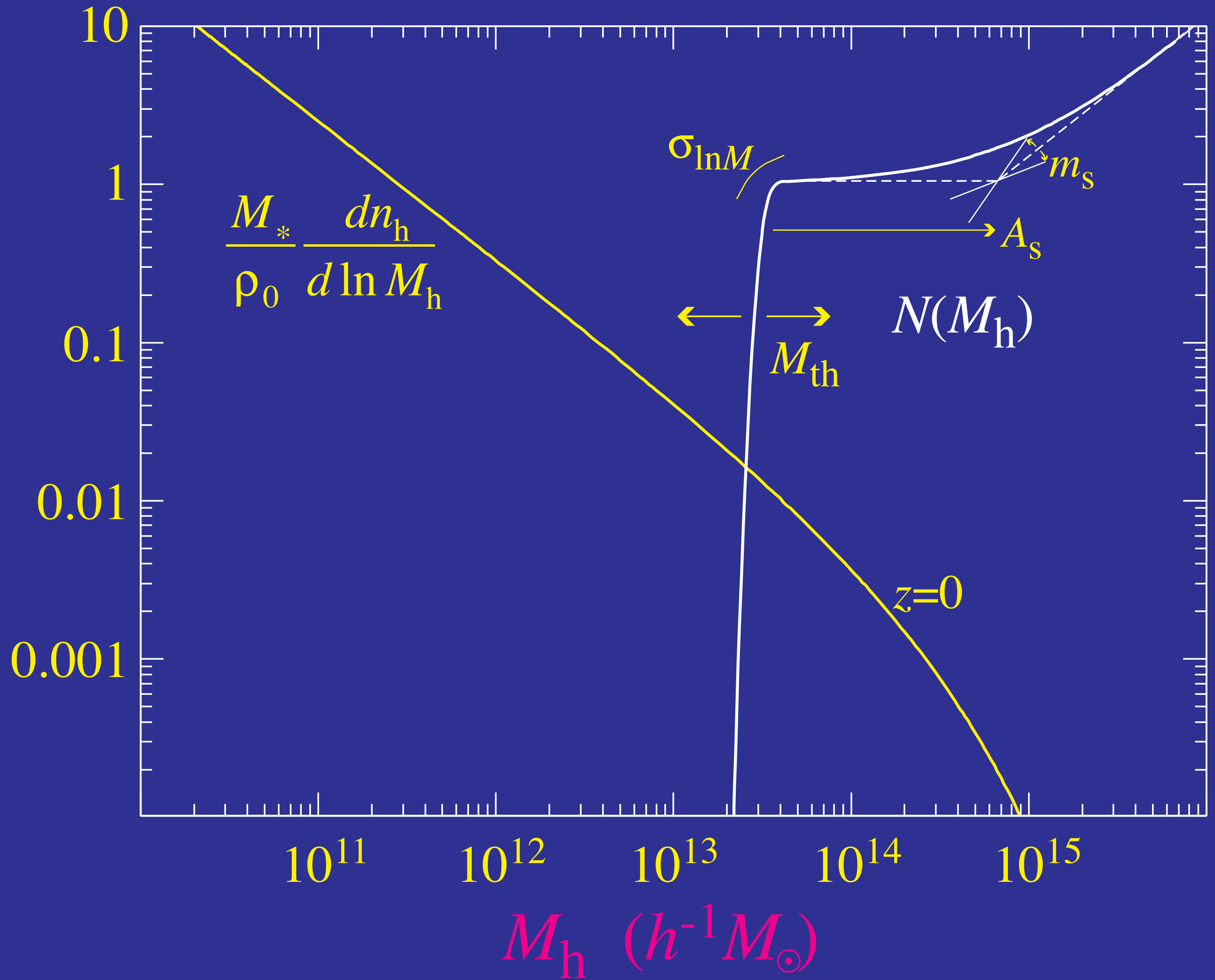
Sample Variance

- Cluster mass halos are rare, strongly clustered
- Sample variance increases noise on abundance but also provides a handle on the mass threshold



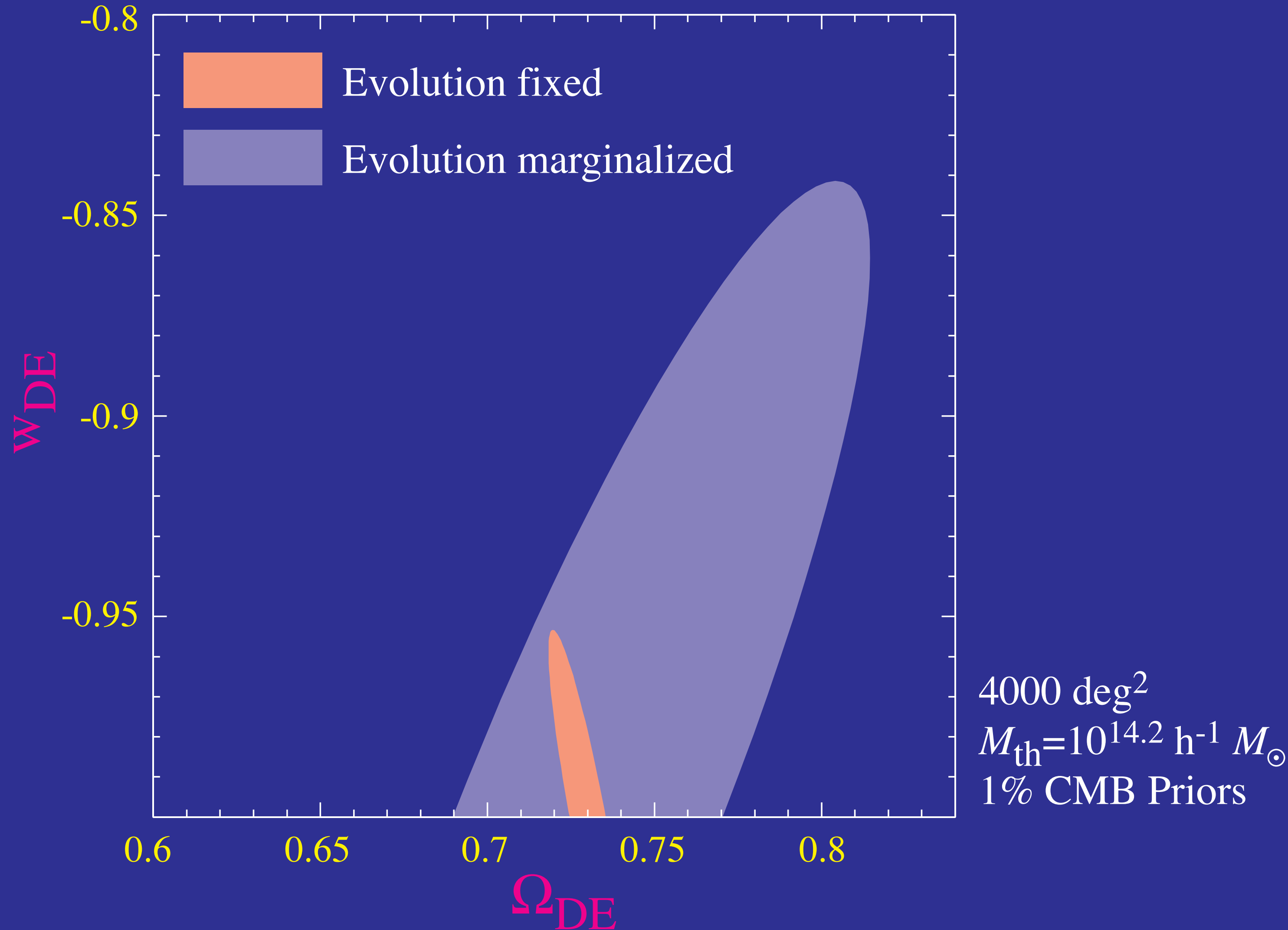
Mass-Observable Relation

- Relationship between halos of given mass and observables sets mass threshold and scatter around threshold
- Clusters largely avoid $N(M_h)$ problem with multiple objects in halo



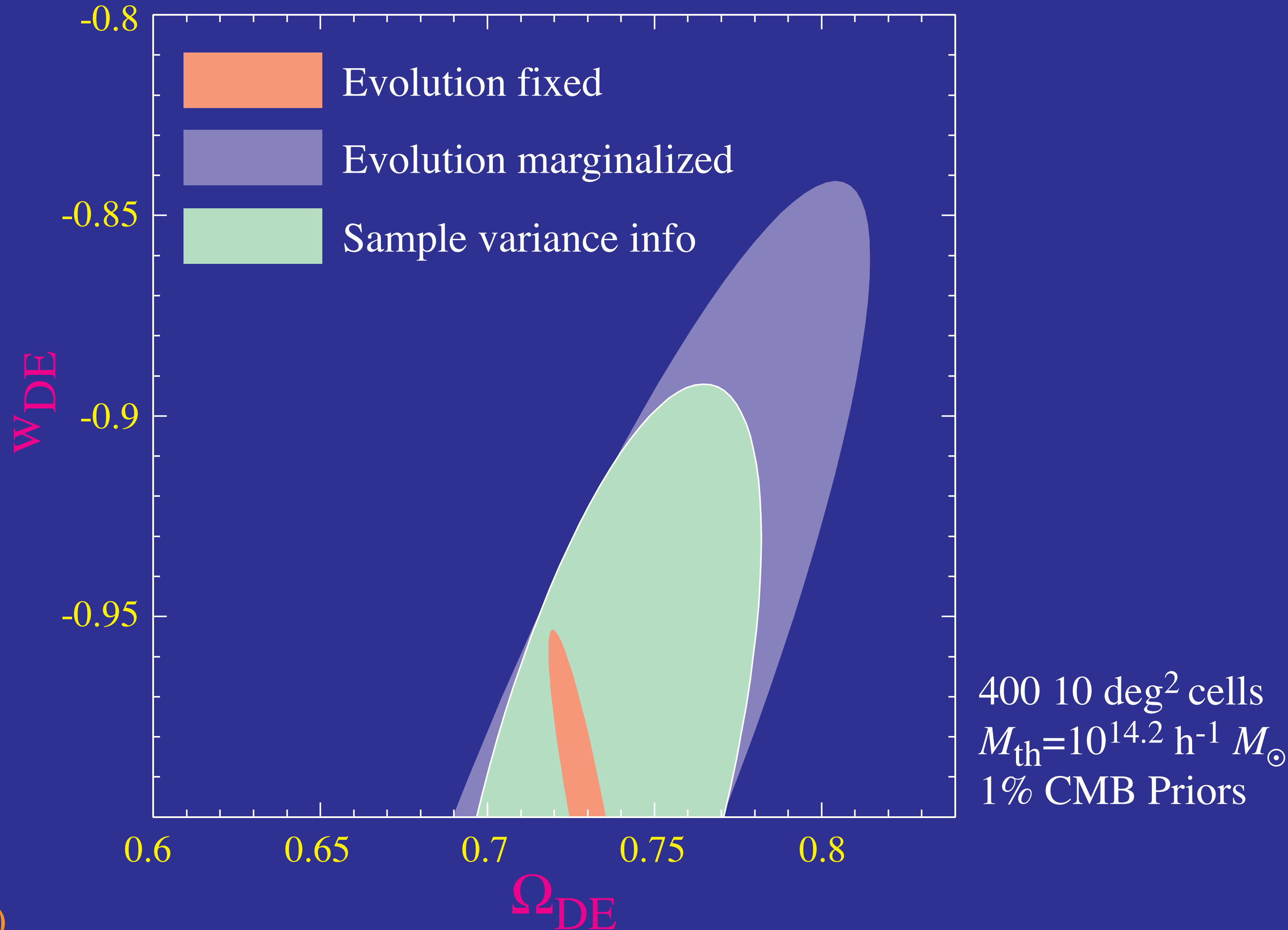
Mass-Observable Evolution

- Jointly fitting an unknown normalization and power law evolution degrades constraints (Levine et al 2003; Hu 2003; Majumdar & Mohr 2003)



Mass-Observable Evolution

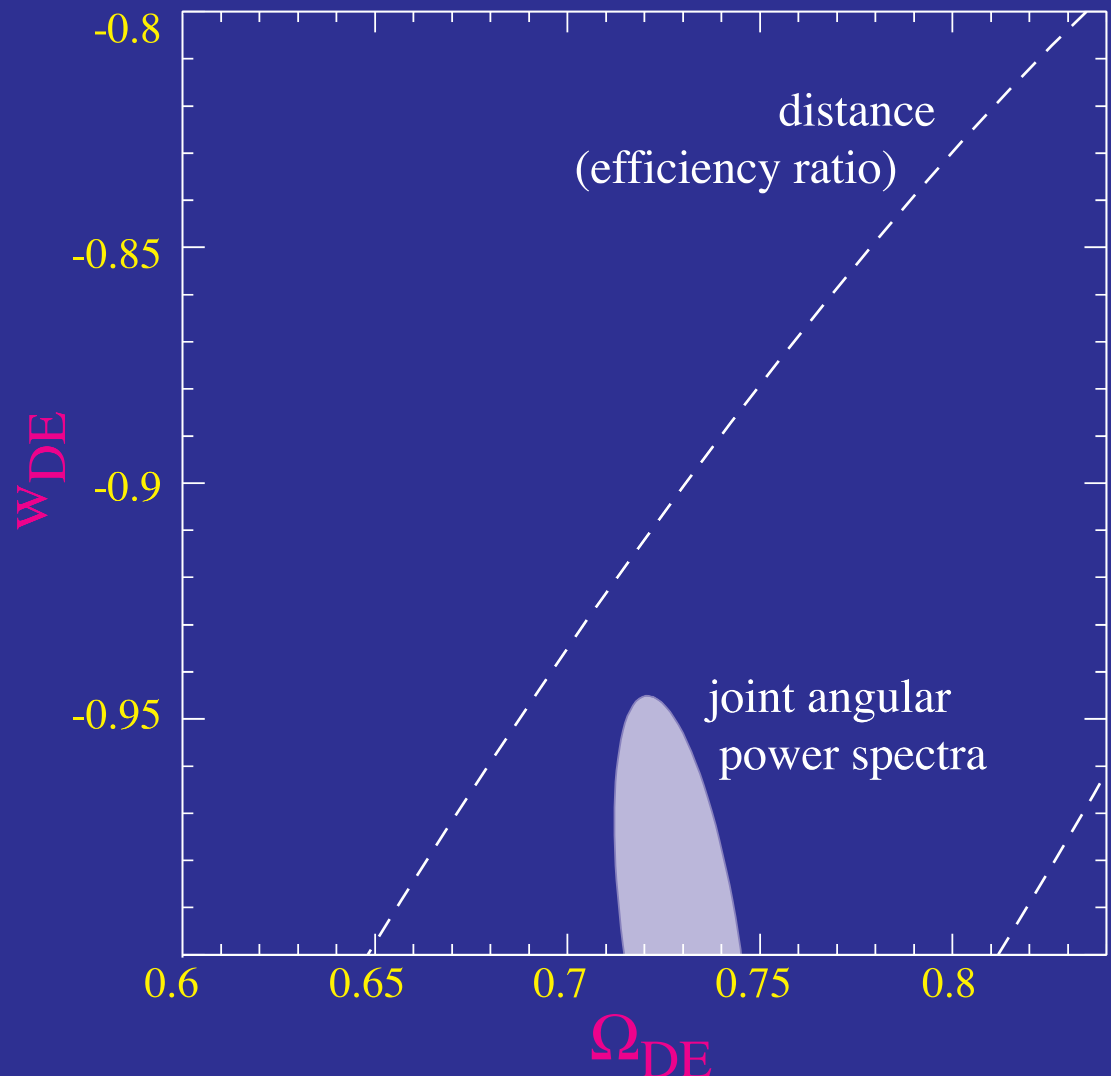
- (Sampling) noise is signal!
- Excess variance of counts in cells measures mass-dependent bias in clustering (requires only photometric redshifts $\Delta z \sim 0.1$)



Lima & Hu (2004)

Angular Power Spectrum

- Match mass threshold to counts for given cosmology
- Angular power spectra including cluster weak lensing (cluster mass correlation) gives dark energy

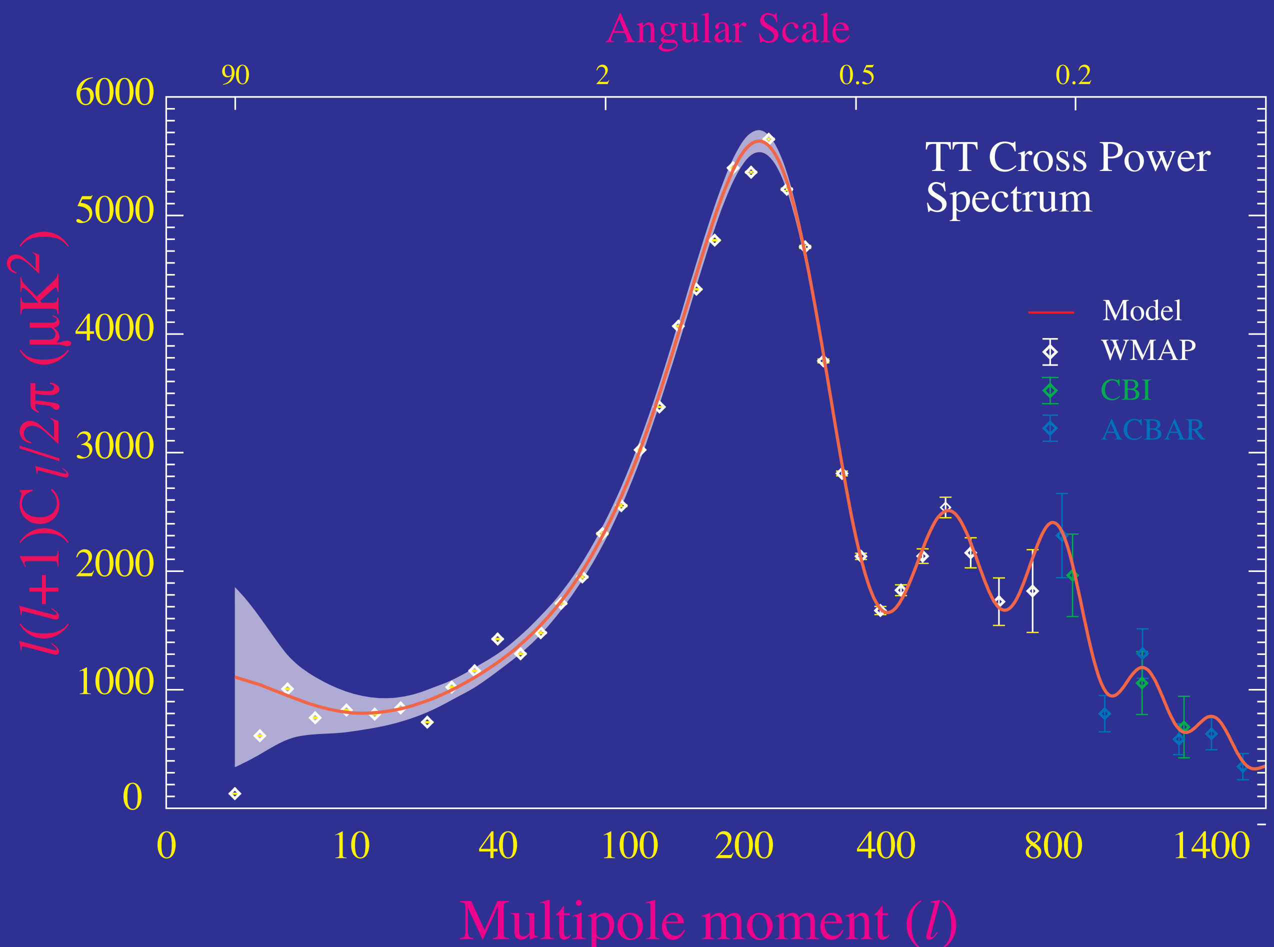


4000 deg^2 l<3000
M_{th}=$10^{14.2}$ h^{-1} $M_\odot$
1% CMB Priors

Hu & Jain (2003)

Standard Rulers

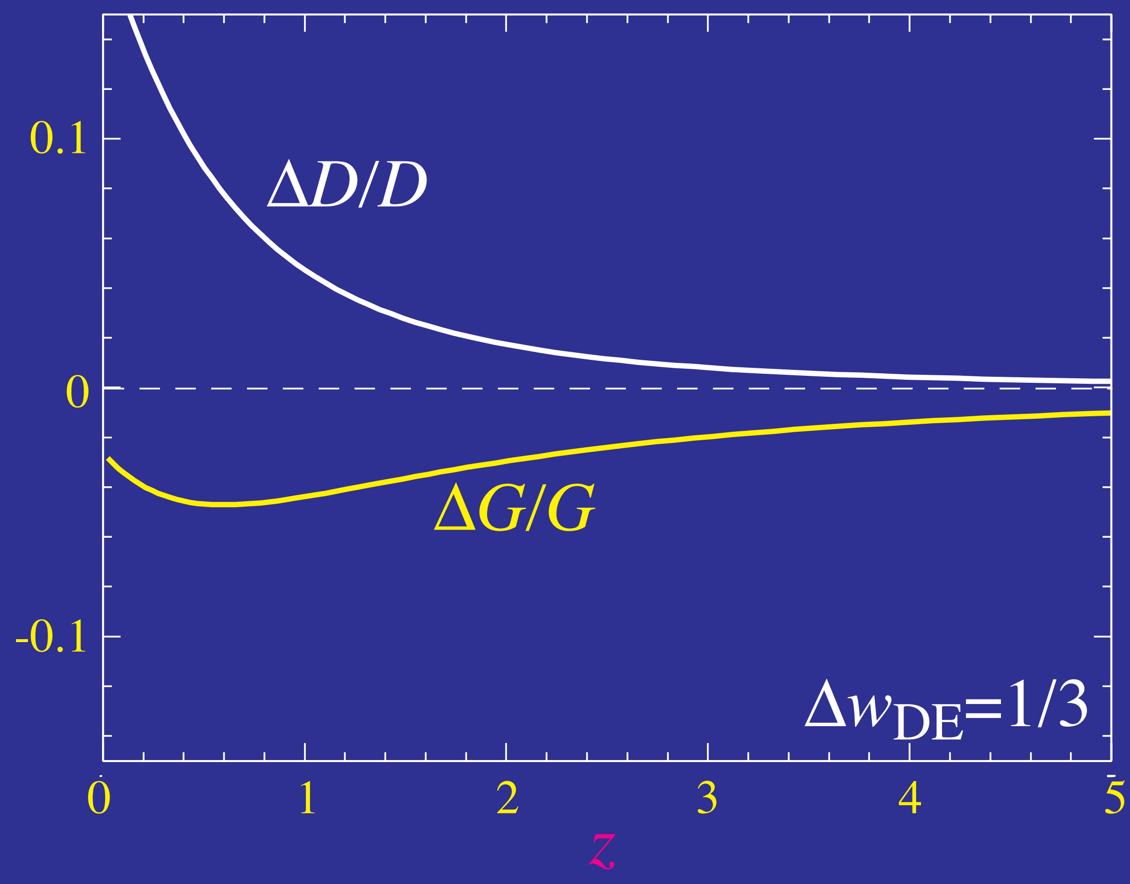
- CMB peaks provide standard ruler for distance measures to recombination and potentially lower redshifts: sound horizon and particle horizon at equality imprinted in transfer function



WMAP: Bennett et al (2003)

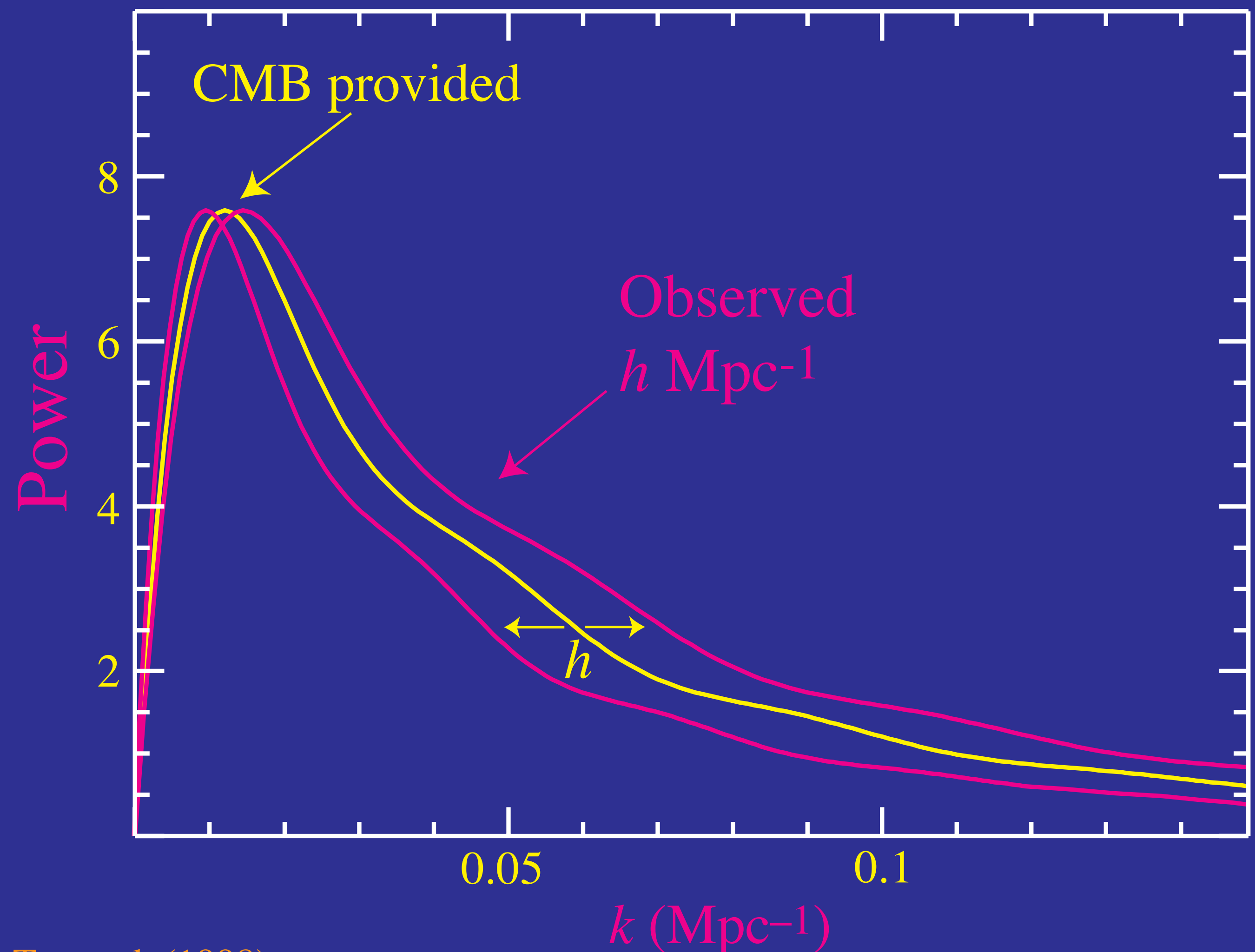
Dark Energy Sensitivity

- Angular diameter distance to recombination fixed to 4%
- Follow degeneracy line in w_{DE}, Ω_{DE} for flat universe
- Sensitivity to w_{DE} changes:



Local Test: H_0

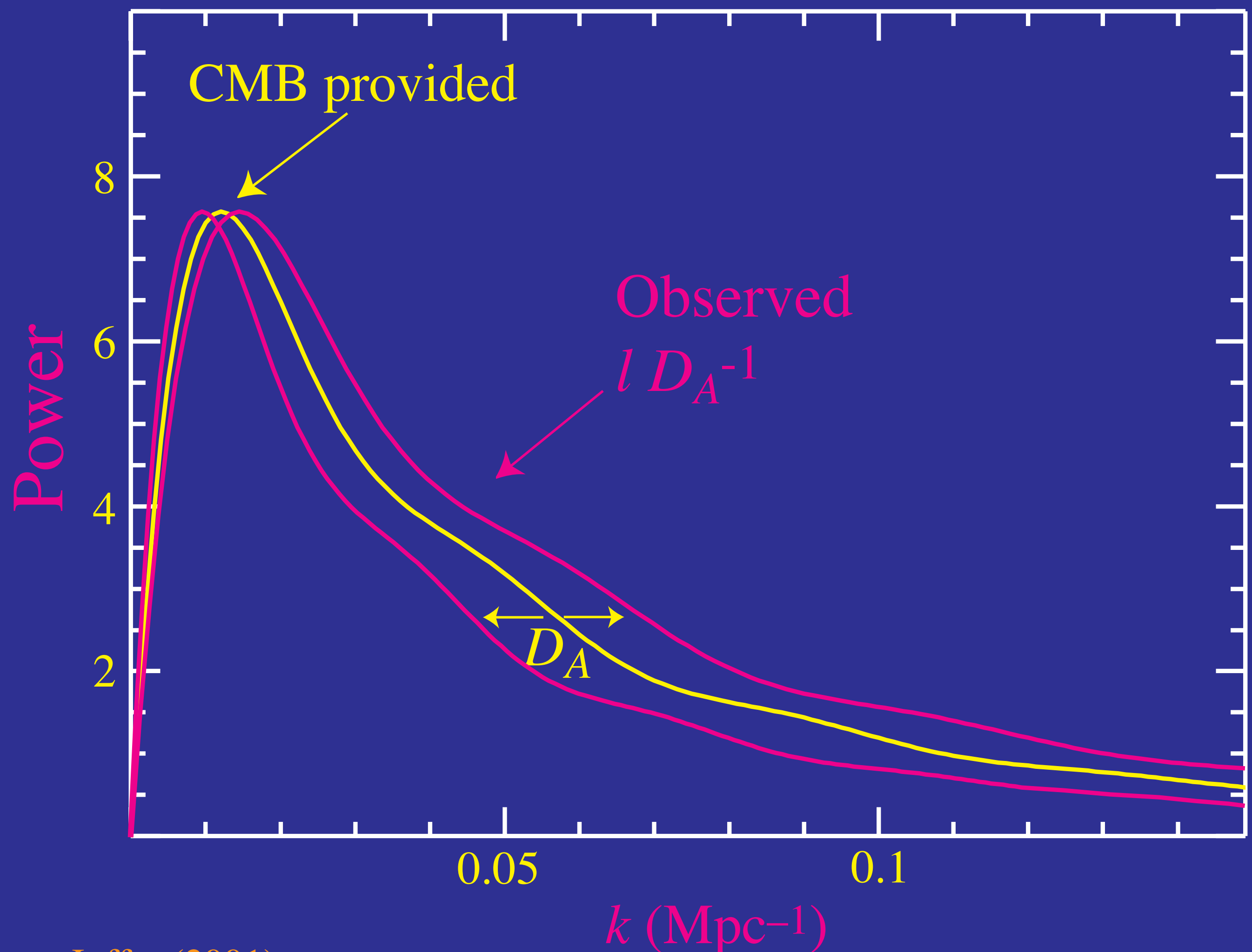
- Locally $D_A = \Delta z / H_0$, and the observed power spectrum is isotropic in h Mpc^{-1} space
- Template matching the features yields the Hubble constant



Eisenstein, Hu & Tegmark (1998)

Cosmological Distances

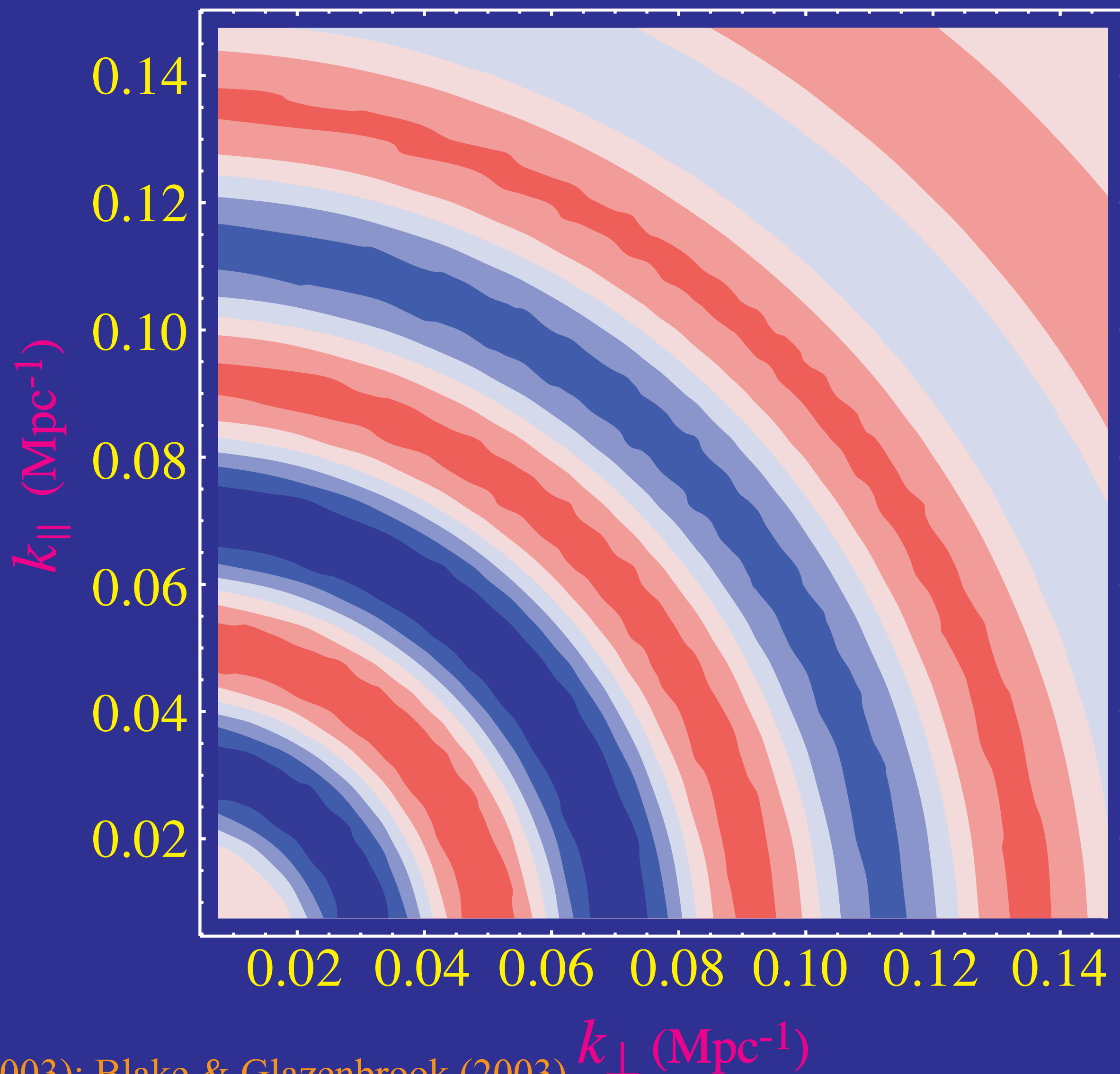
- Modes perpendicular to line of sight measure angular diameter distance



Cooray, Hu, Huterer, Joffre (2001)

Acoustic Rings

- Baryon oscillations appear as rings in a 2D power spectrum with modes parallel and perpedicular to the line of sight

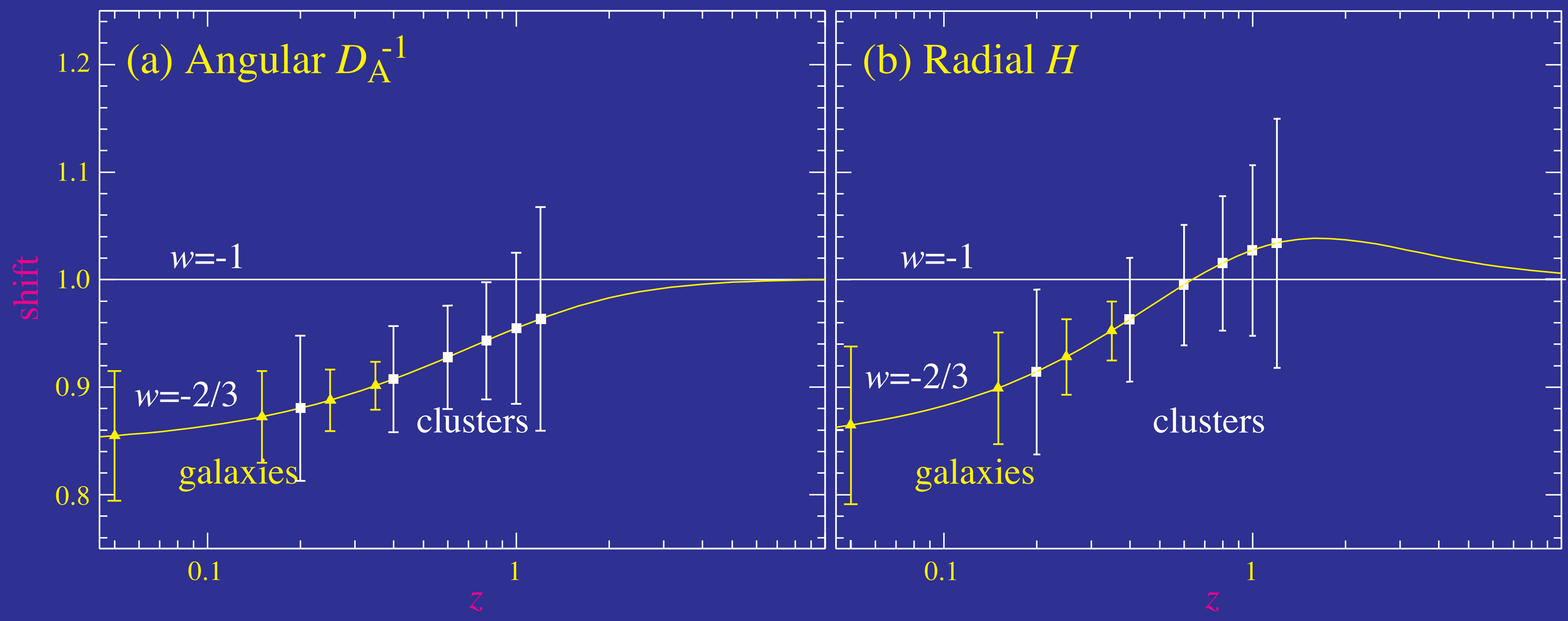


~10% peak to trough

Seo &Eisenstein (2003); Blake & Glazenbrook (2003)

$D(z)$ and $H(z)$

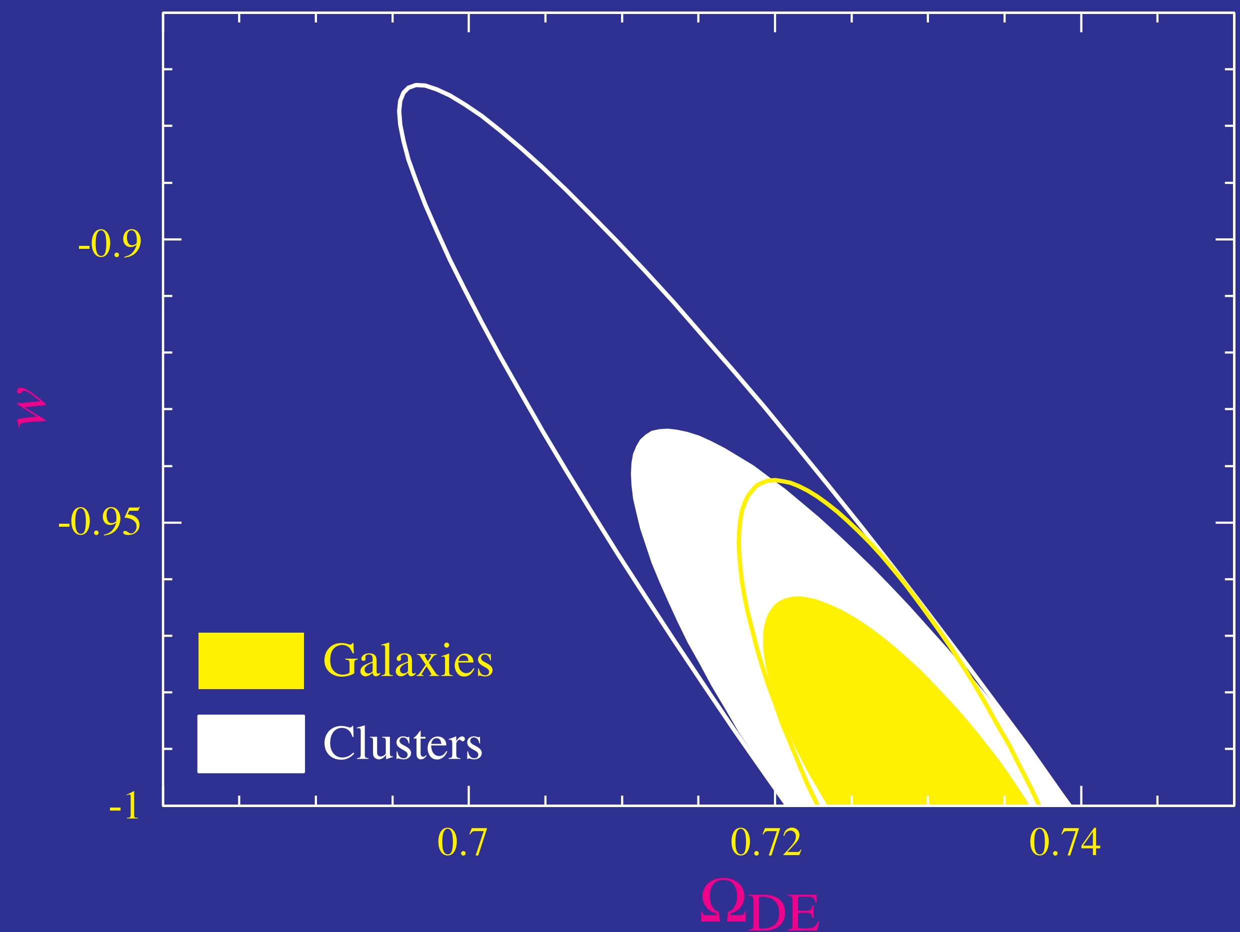
- Galaxy survey similar to SDSS Main + LRG; cluster survey similar to SPT but with redshift followup



Hu & Haiman (2003)

Dark Energy

- Even marginalizing bias evolution $b(z)$ and redshift space distortions β, dark energy constraints possible with a reasonable extrapolation from current CMB power spectrum priors



Hu & Haiman (2003)

Summary

- Amplitude and shape of the power spectrum known precisely from the CMB at high z and will continue to improve
- Determination of amplitude (σ_8) or distance (H_0) at $z = 0$ measures well defined dark energy parameters
- Intermediate redshifts probe the dark energy evolution
  - Cluster abundance for known mass-observable relation
  - Variance of counts in cells to calibrate mass-observable relation
  - Angular power spectra at fixed counts
  - 3D power spectra to measure $D(z)$ and $H(z)$