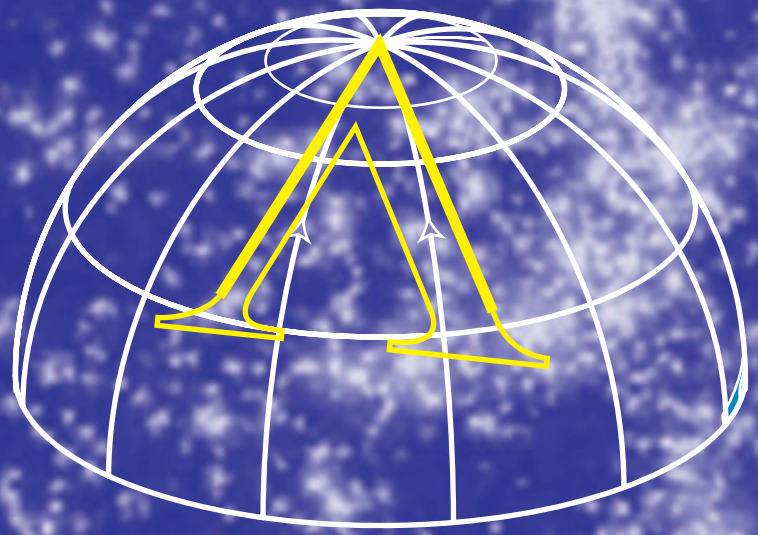
NeoClassical Probes



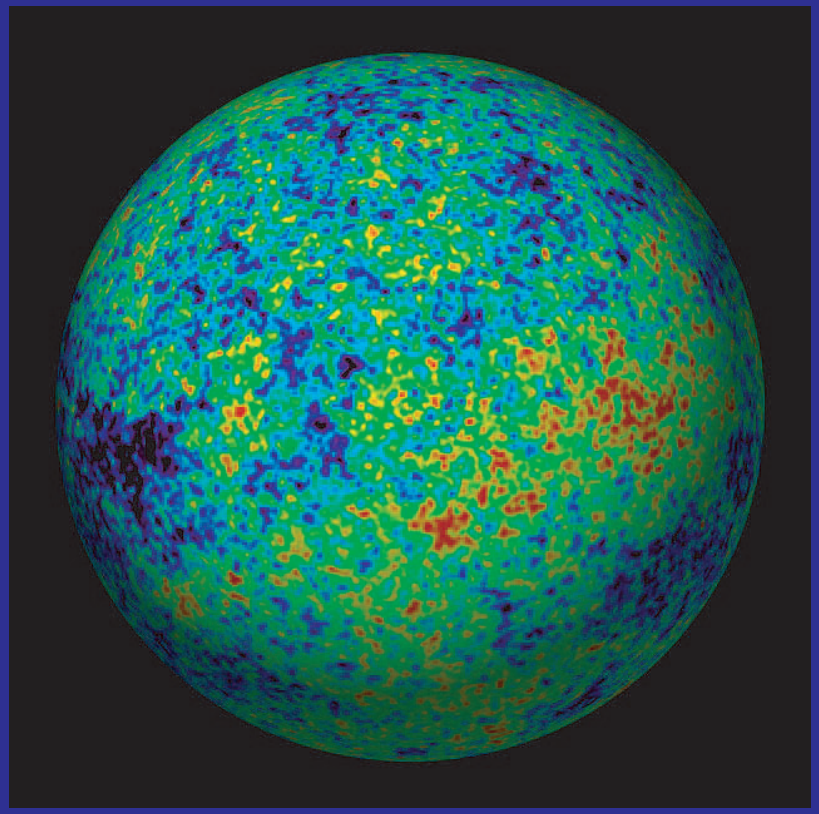
of the Dark Energy

Wayne Hu

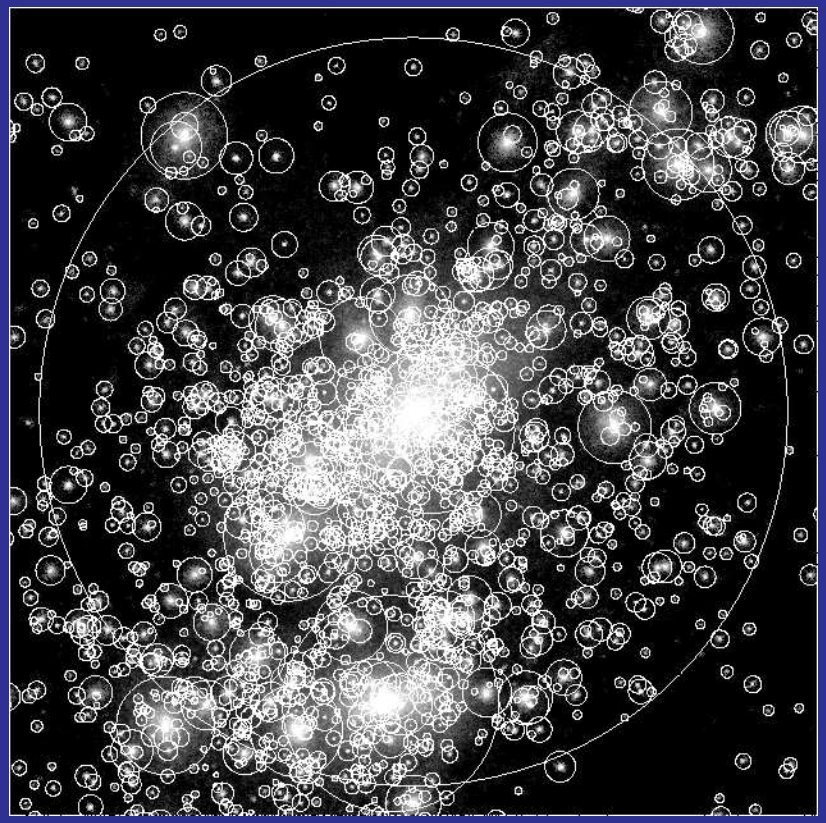
COSMO04 Toronto, September 2004

Structural Fidelity

- Dark matter simulations approaching the accuracy of CMB calculations



WMAP

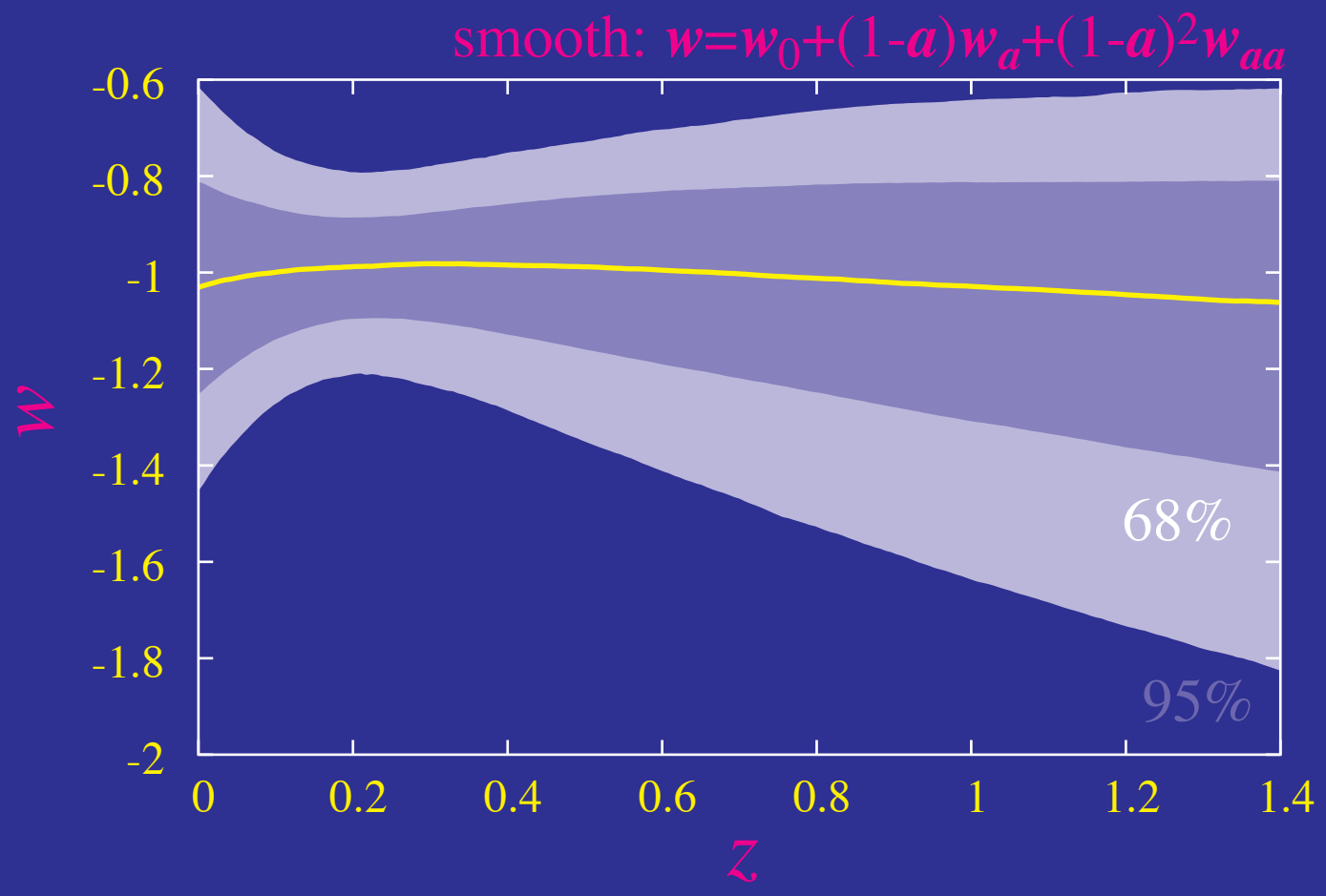


Kravtsov et al (2003)

Equation of State Constraints

- NeoClassical probes statistically competitive already

CMB+SNe+Galaxies+Bias(Lensing)+Lyα



- Future hinges on controlling systematics

Seljak et al (2004)

Dark Energy Observables

Making Light of the Dark Side

- Line element:

$$ds^2 = a^2[(1-2\Phi)d\eta^2 - (1+2\Phi)(dD^2 + D_A^2 d\Omega)]$$

  where η is the conformal time, D comoving distance, D_A the comoving angular diameter distance and Φ the gravitational potential

- Dark components visible in their influence on the metric elements a and Φ – general relativity considers these the same: consistency relation for gravity

- Light propagates on null geodesics: in the background $\Delta D = \Delta\eta$; around structures according to lensing by Φ

- Matter dilutes with the expansion and (free) falls in the gravitational potential

Friedmann and Poisson Equations

- Friedmann equation:

$$\left(\frac{d\ln a}{d\eta}\right)^2 = \frac{8\pi G}{3} a^2 \sum \rho \equiv [aH(a)]^2$$

implying that the densities of dark components are visible in the distance-redshift relation ($a = (1+z)^{-1}$)

$$D = \int d\eta = \int \frac{d\ln a}{aH(a)} = \int \frac{dz}{H}$$

- Poisson equation:

$$\nabla^2 \Phi = -4\pi G a^2 \delta\rho$$

implying that the (comoving gauge) density field of the dark components is visible in the potential (lensing, motion of tracers).

Growth Rate

- Relativistic stresses in the dark energy can prevent clustering. If only dark matter perturbations $\delta_m \equiv \delta\rho_m/\rho_m$ are responsible for potential perturbations on small scales

$$\frac{d^2\delta_m}{dt^2} + 2H(a)\frac{d\delta_m}{dt} = 4\pi G\rho_m(a)\delta_m$$

- In a flat universe this can be recast into the growth rate $G(a) \propto \delta_m/a$ equation which depends only on the properties of the dark energy

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

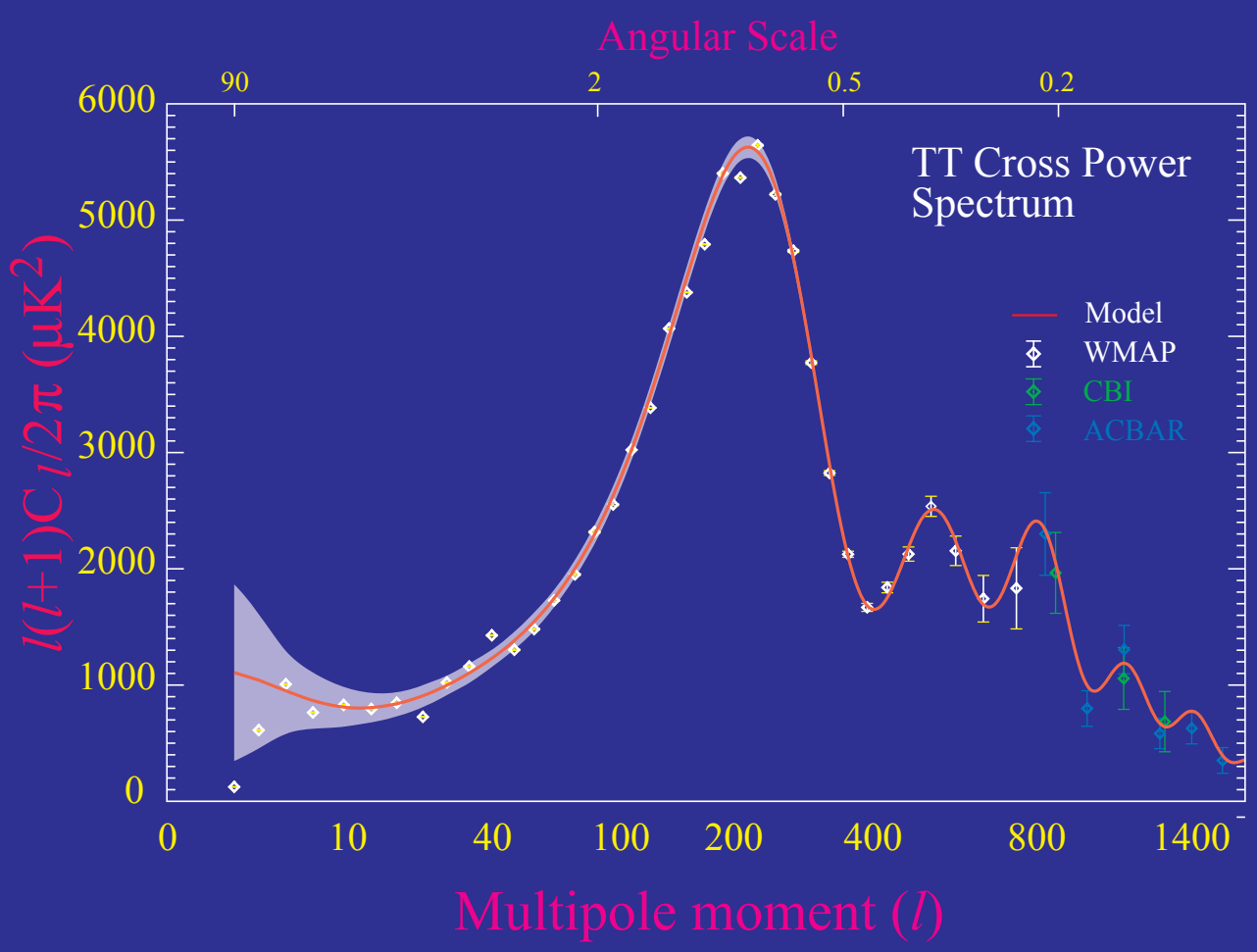
with initial conditions $G =$const.

- Comparison of distance and growth tests dark energy smoothness and/or general relativity

Fixed Deceleration Epoch

High-z Energy Densities

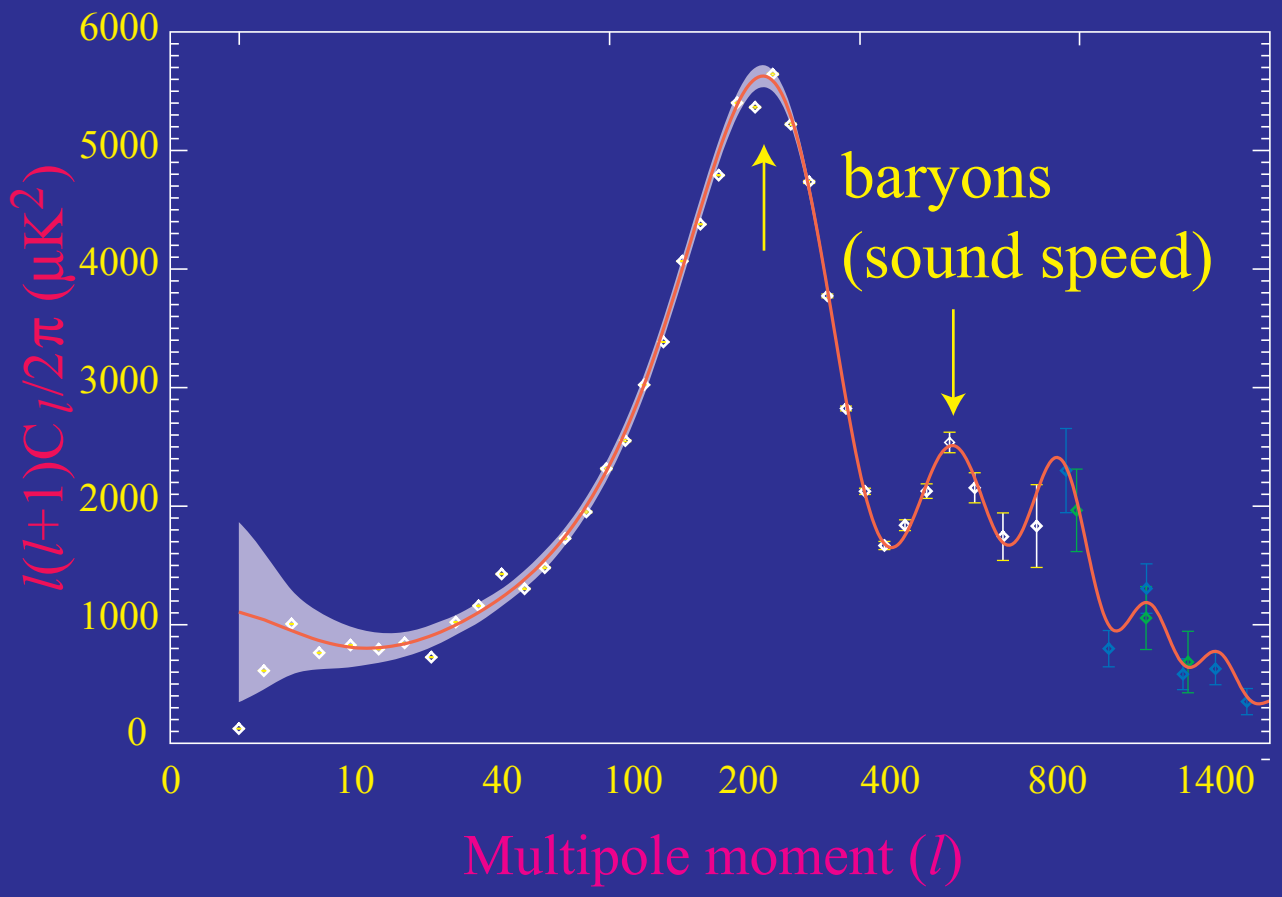
- WMAP + small scale temperature and polarization measures provides self-calibrating standards for the dark energy probes



WMAP: Bennett et al (2003)

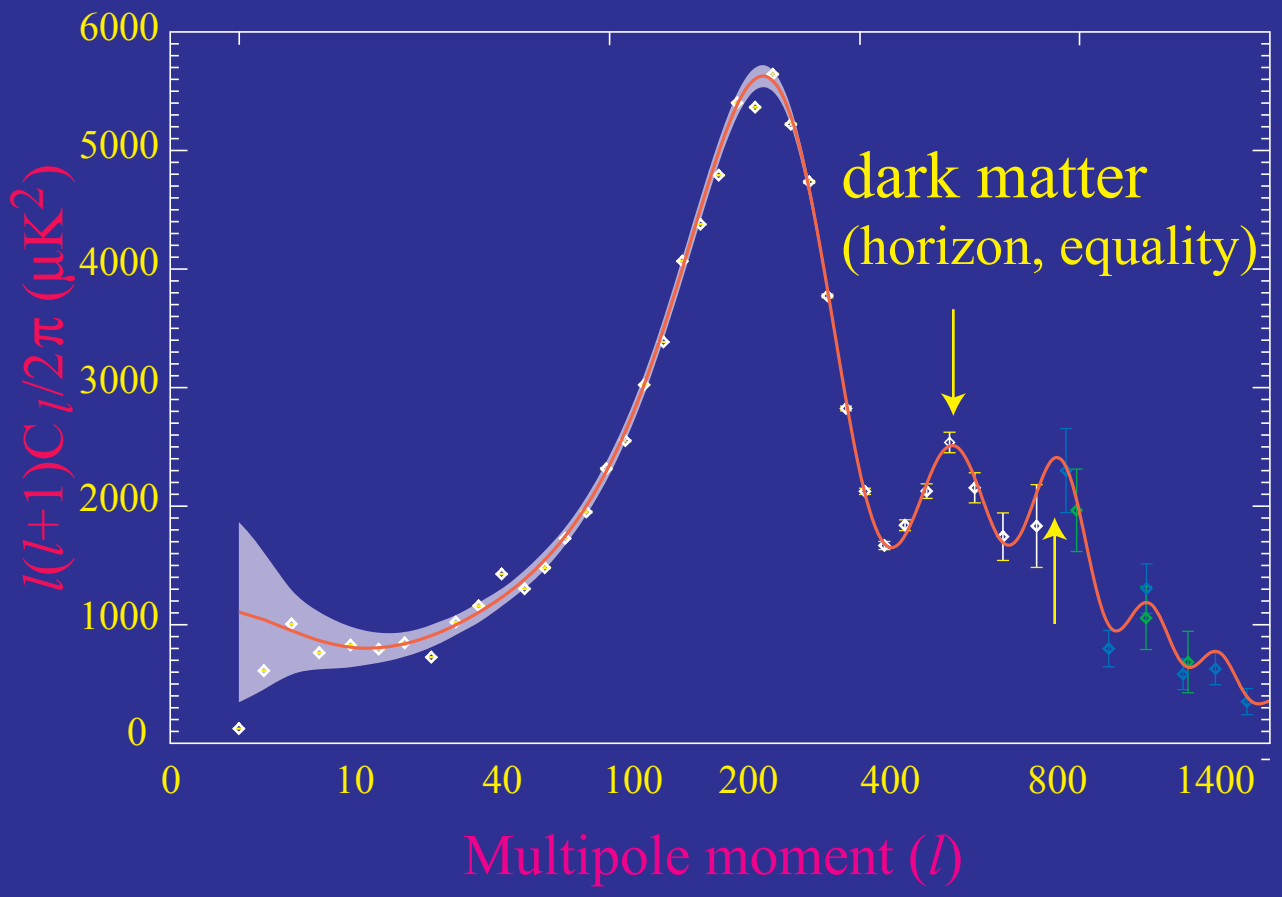
High-z Energy Densities

- Relative heights of the first 3 peaks calibrates sound horizon and matter radiation equality horizon



High-z Energy Densities

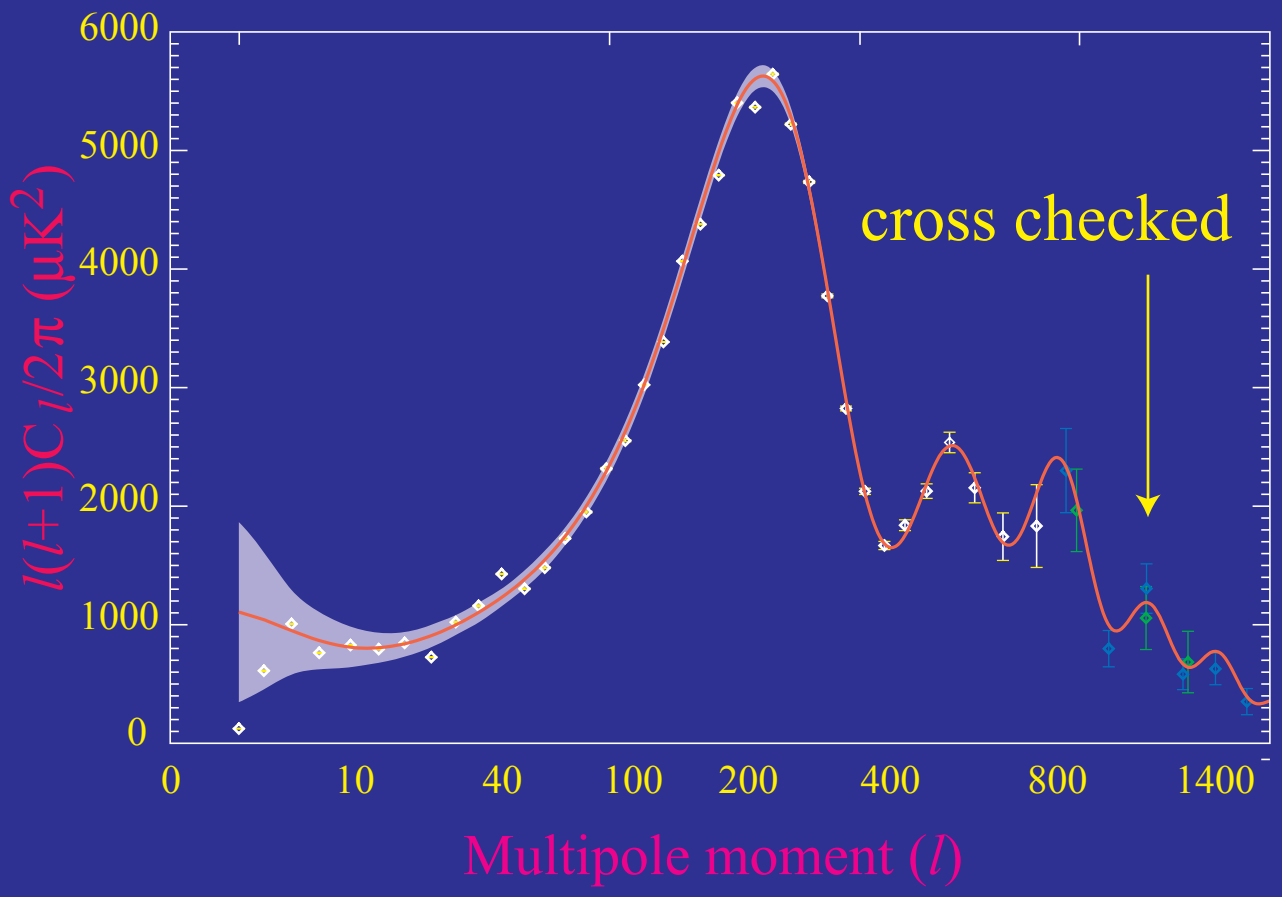
- Relative heights of the first 3 peaks calibrates sound horizon and matter radiation equality horizon



leading source of error!

High-z Energy Densities

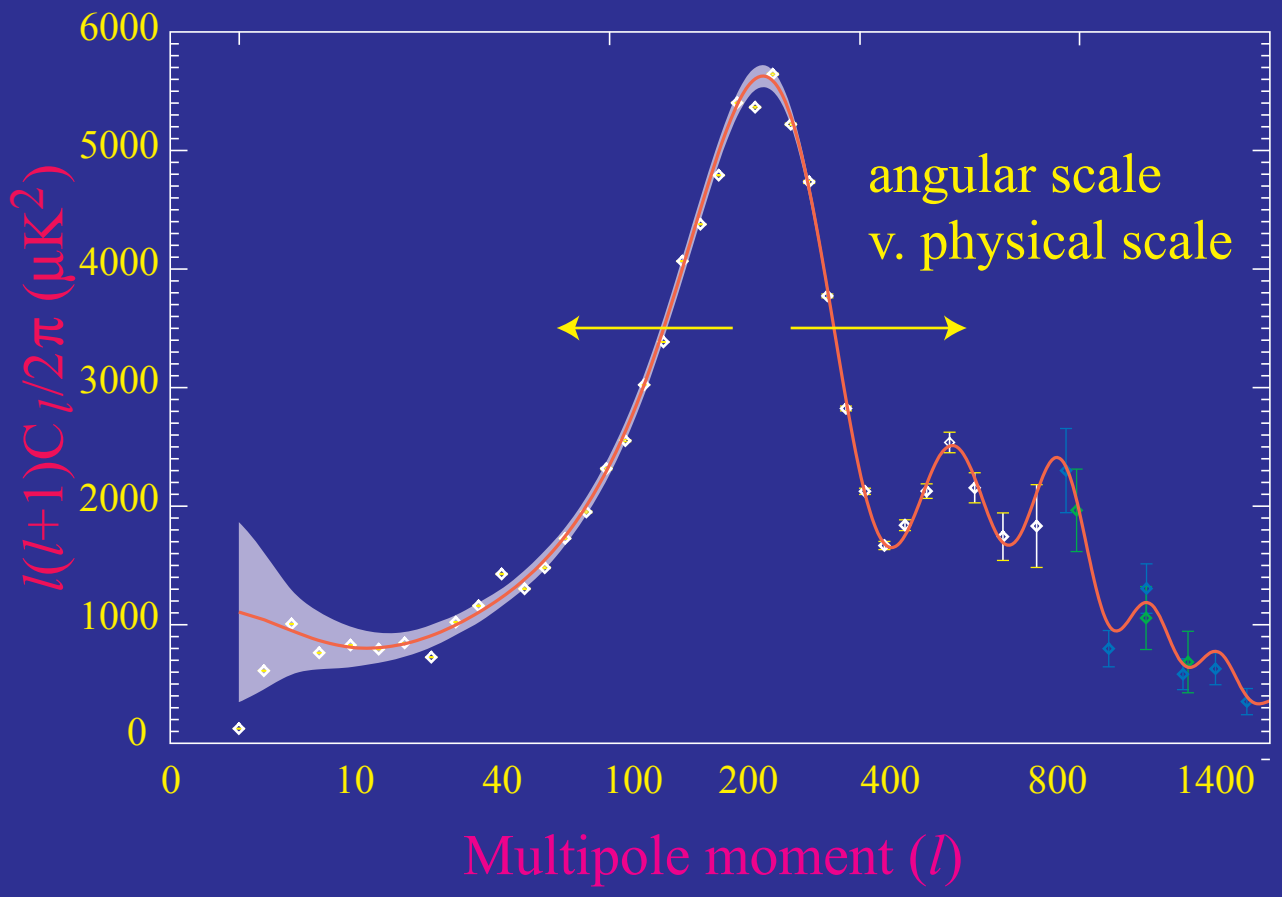
- Cross checked with damping scale (diffusion during horizon time) and polarization (rescattering after diffusion): self-calibrated and internally cross-checked



WMAP: Bennett et al (2003)

Standard Ruler

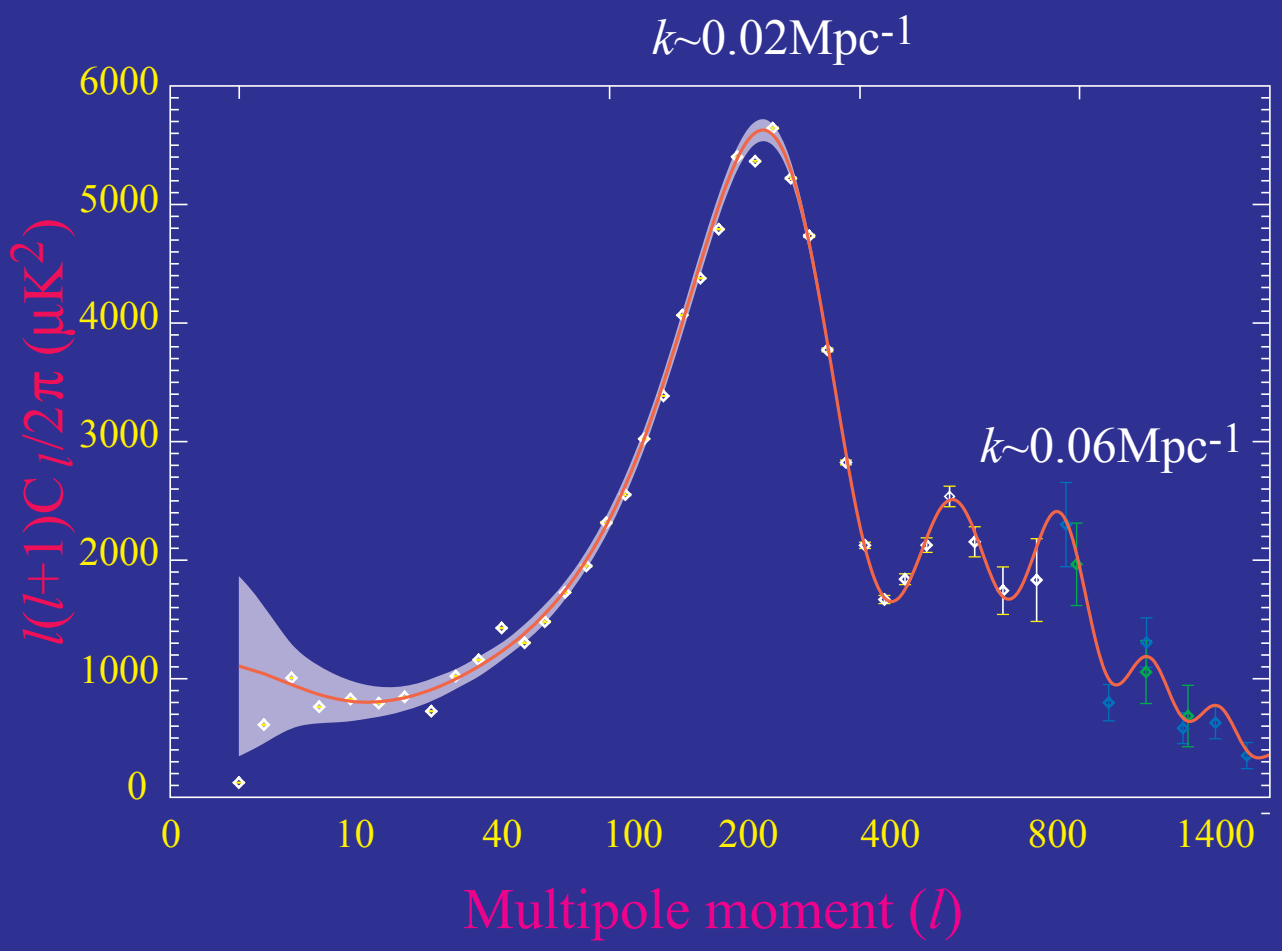
- Standard ruler used to measure the angular diameter distance to recombination (z~1100; currently 2-4%) or any redshift for which acoustic phenomena observable



WMAP: Bennett et al (2003)

Standard Amplitude

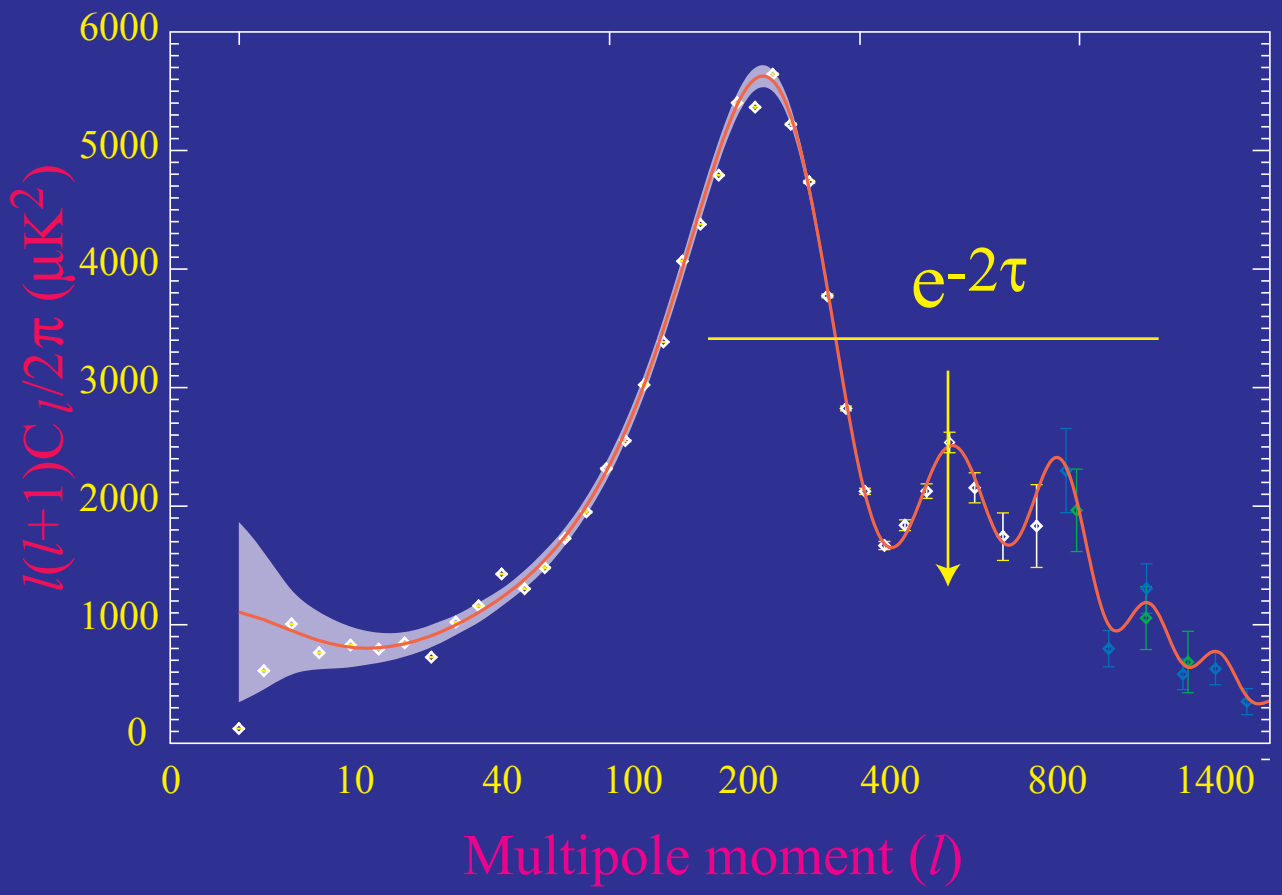
- Standard fluctuation: absolute power determines initial fluctuations in the regime 0.01-0.1 Mpc^{-1}



WMAP: Bennett et al (2003)

Standard Amplitude

- Standard fluctuation: precision mainly limited by reionization which lowers the peaks as $e^{-2\tau}$; self-calibrated by polarization, cross checked by CMB lensing in future



see saturday/astroph
CAPMAP, CBI, DASI

WMAP: Bennett et al (2003)

$\sigma_8(z)$

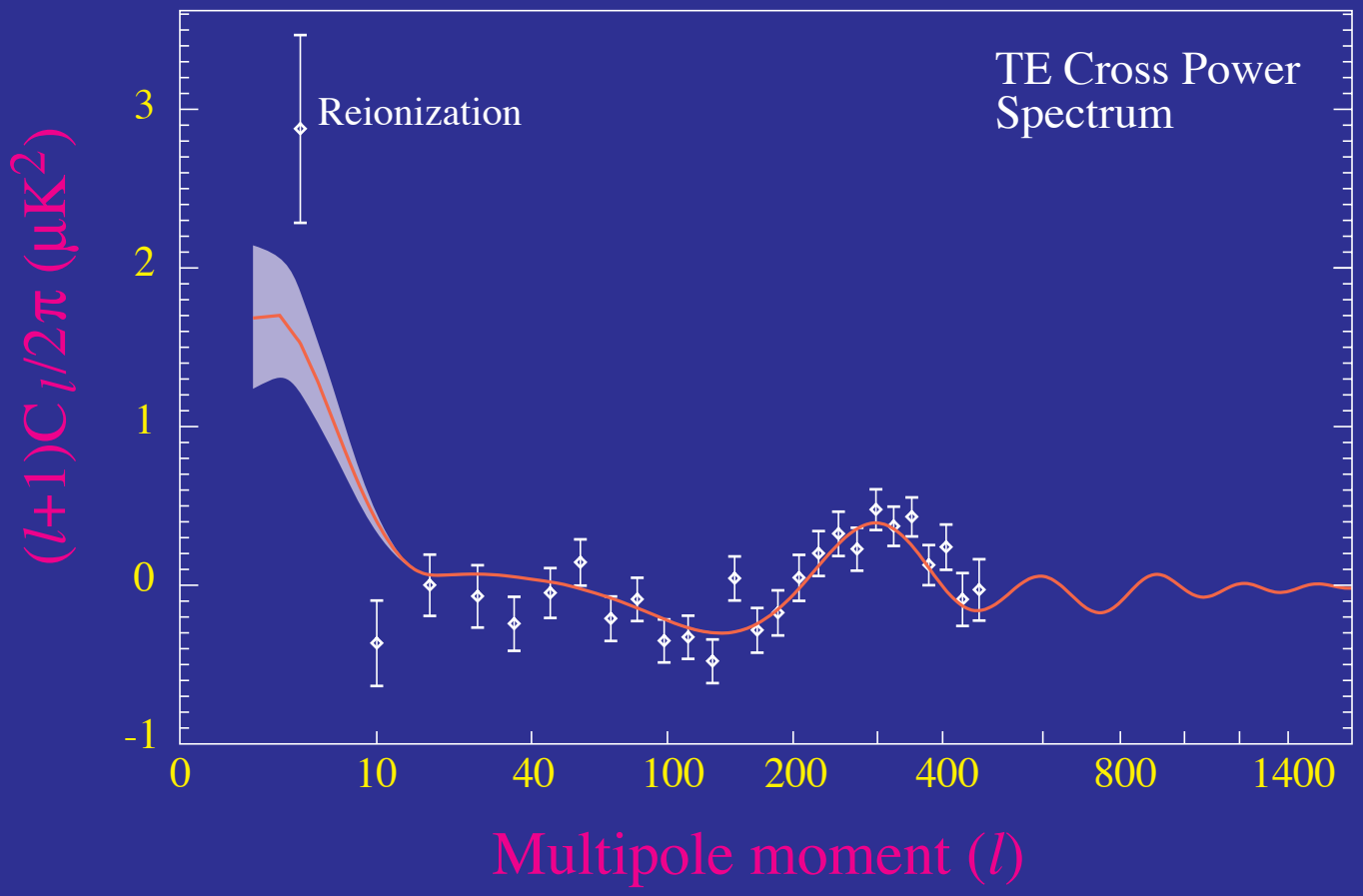
- Determination of the normalization during the acceleration epoch, even σ_8, measures the dark energy with negligible uncertainty from other parameters
- Approximate scaling (flat, negligible neutrinos: Hu & Jain 2003)

$$\sigma_8(z) \approx \frac{\delta_\zeta}{5.6\times10^{-5}}\left(\frac{\Omega_b h^2}{0.024}\right)^{-1/3}\left(\frac{\Omega_m h^2}{0.14}\right)^{0.563}(3.12h)^{(n-1)/2} \times\left(\frac{h}{0.72}\right)^{0.693}\frac{G(z)}{0.76},$$

- 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 measures dark energy dependent growth rate

Reionization

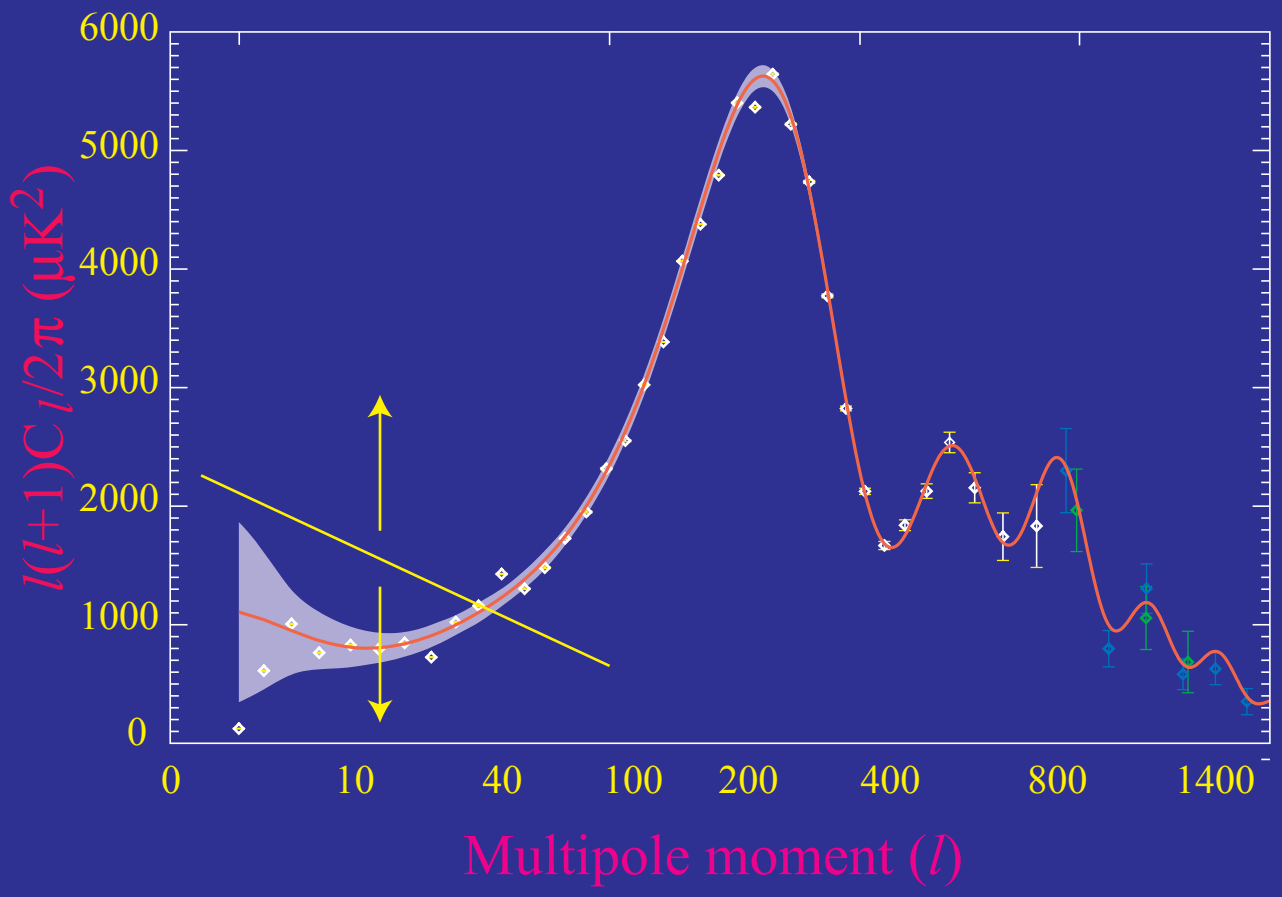
- Biggest surprise of WMAP: early reionization from temperature polarization cross correlation (central value τ=0.17)



Kogut et al (2003)

Leveraging the CMB

- Standard fluctuation: large scale - ISW effect; correlation with large-scale structure; clustering of dark energy; low multipole anomalies? polarization



WMAP: Bennett et al (2003)

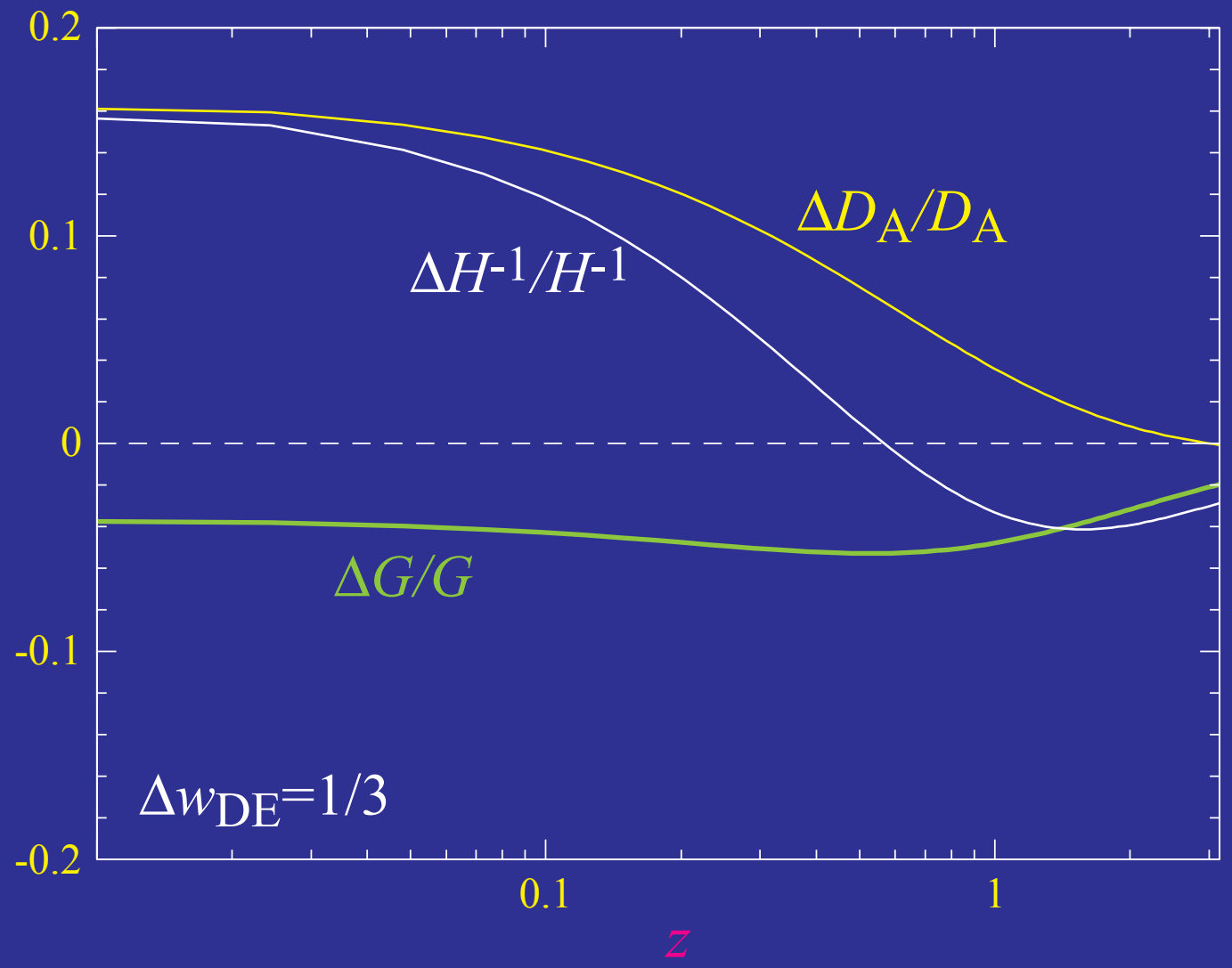
Standard Deviants

$[H_0 \leftrightarrow w(z = 0.4)]$

$[\sigma_8 \leftrightarrow \text{dark energy}]$

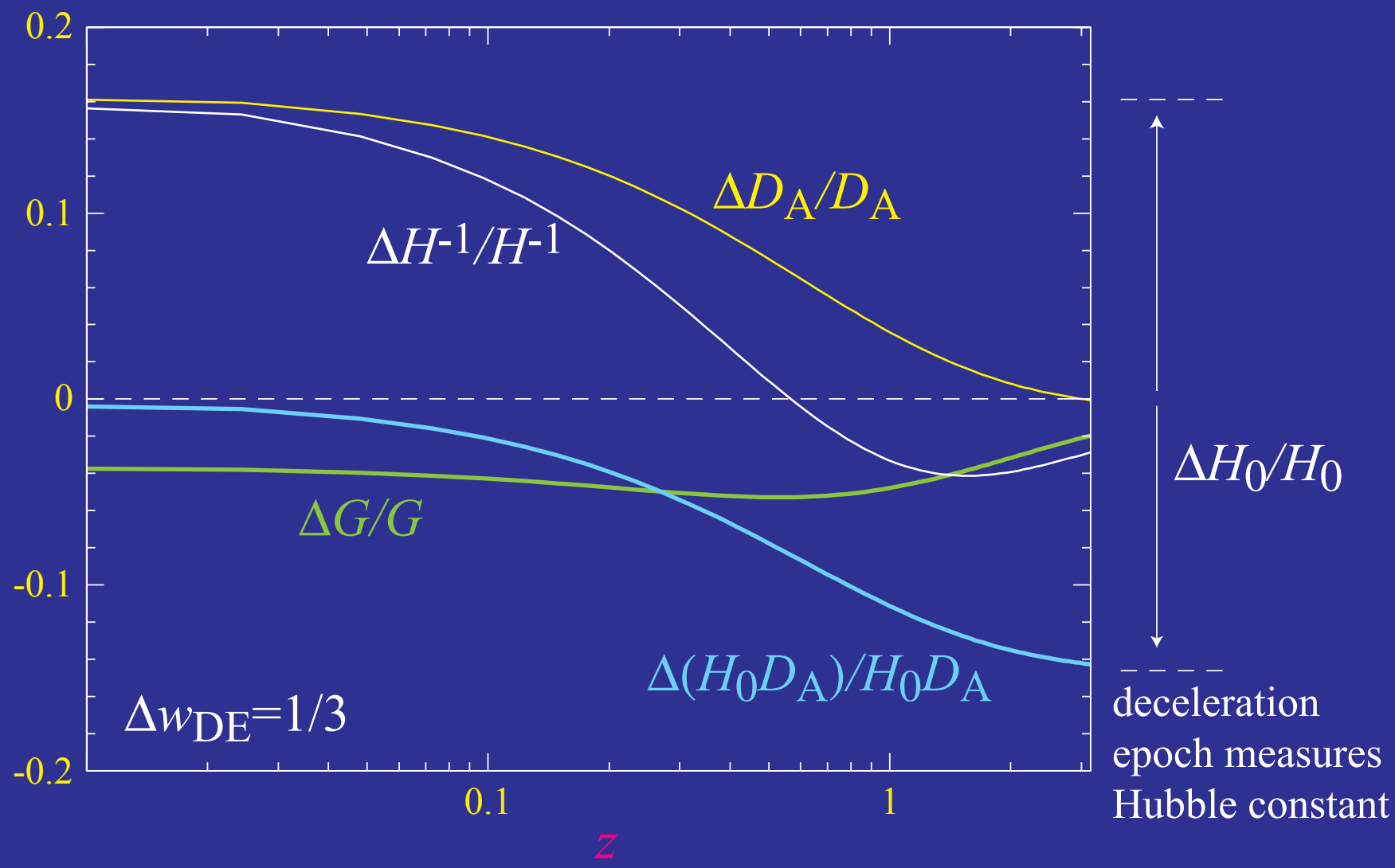
Dark Energy Sensitivity

- Fixed distance to recombination $D_A(z{\sim}1100)$
- Fixed initial fluctuation $G(z{\sim}1100)$
- Constant $w=w_{DE}$; (Ω_{DE} adjusted - one parameter family of curves)



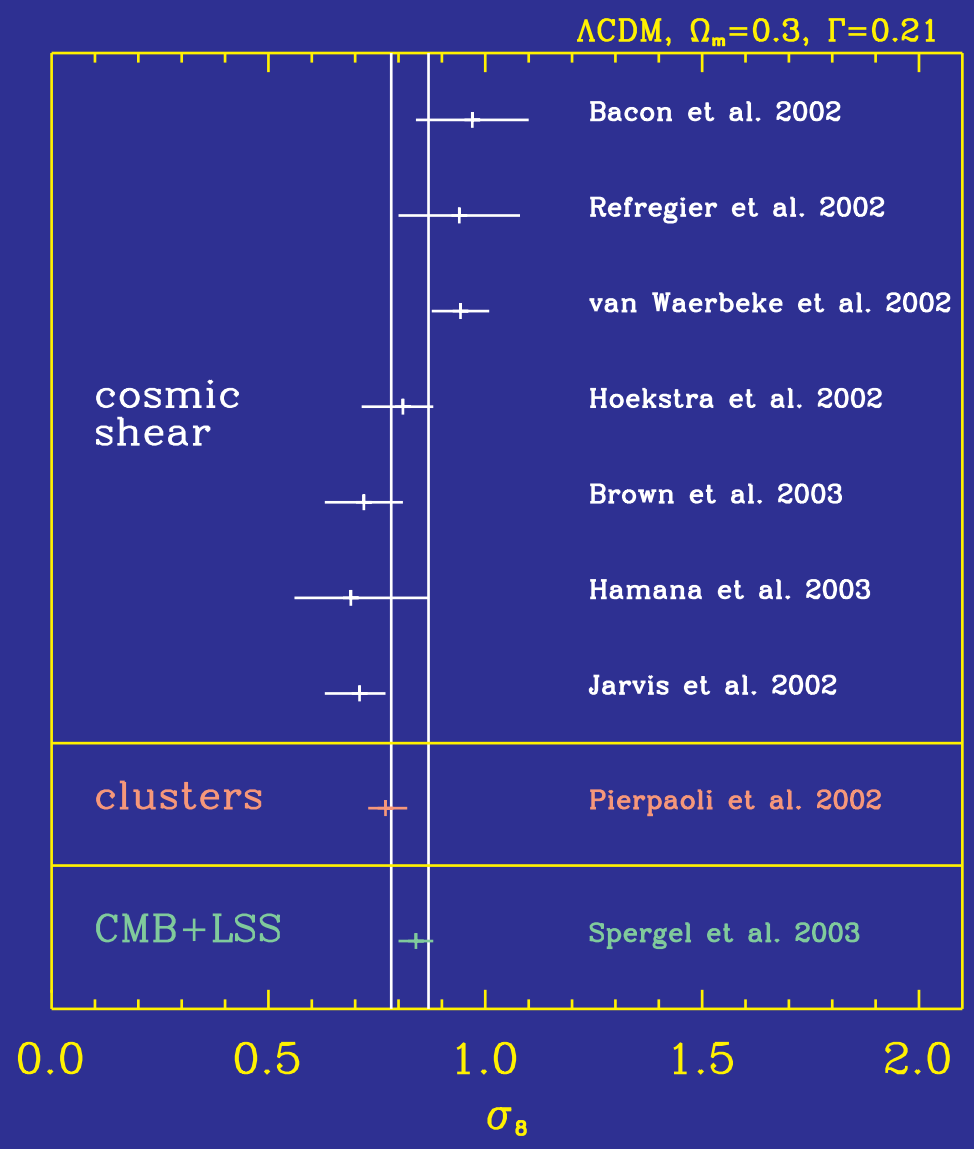
Dark Energy Sensitivity

- Other cosmological test, e.g. volume, SNIa distance constructed as linear combinations



Amplitude of Fluctuations

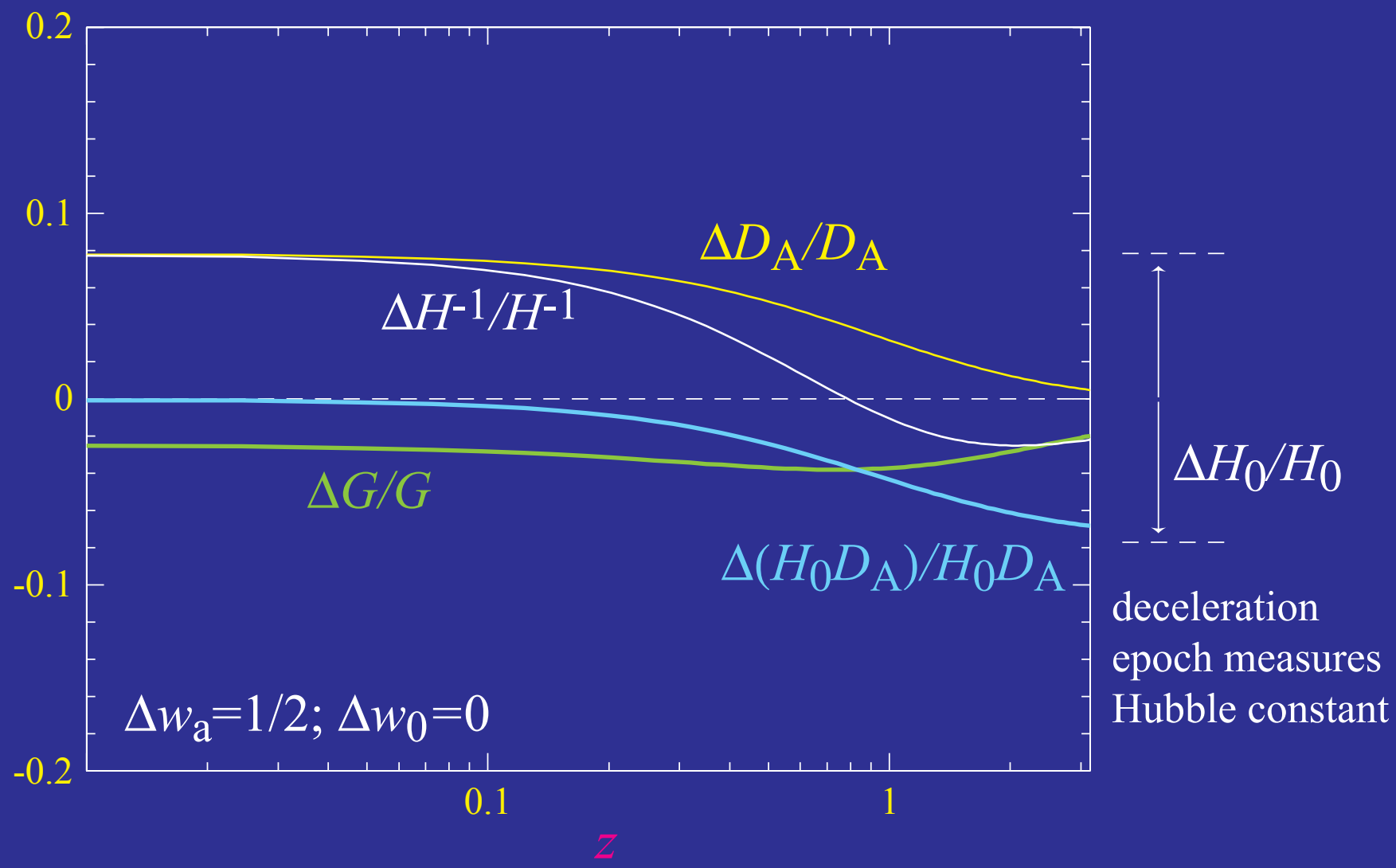
- Recent determinations:



compilation: Refrigier (2003)

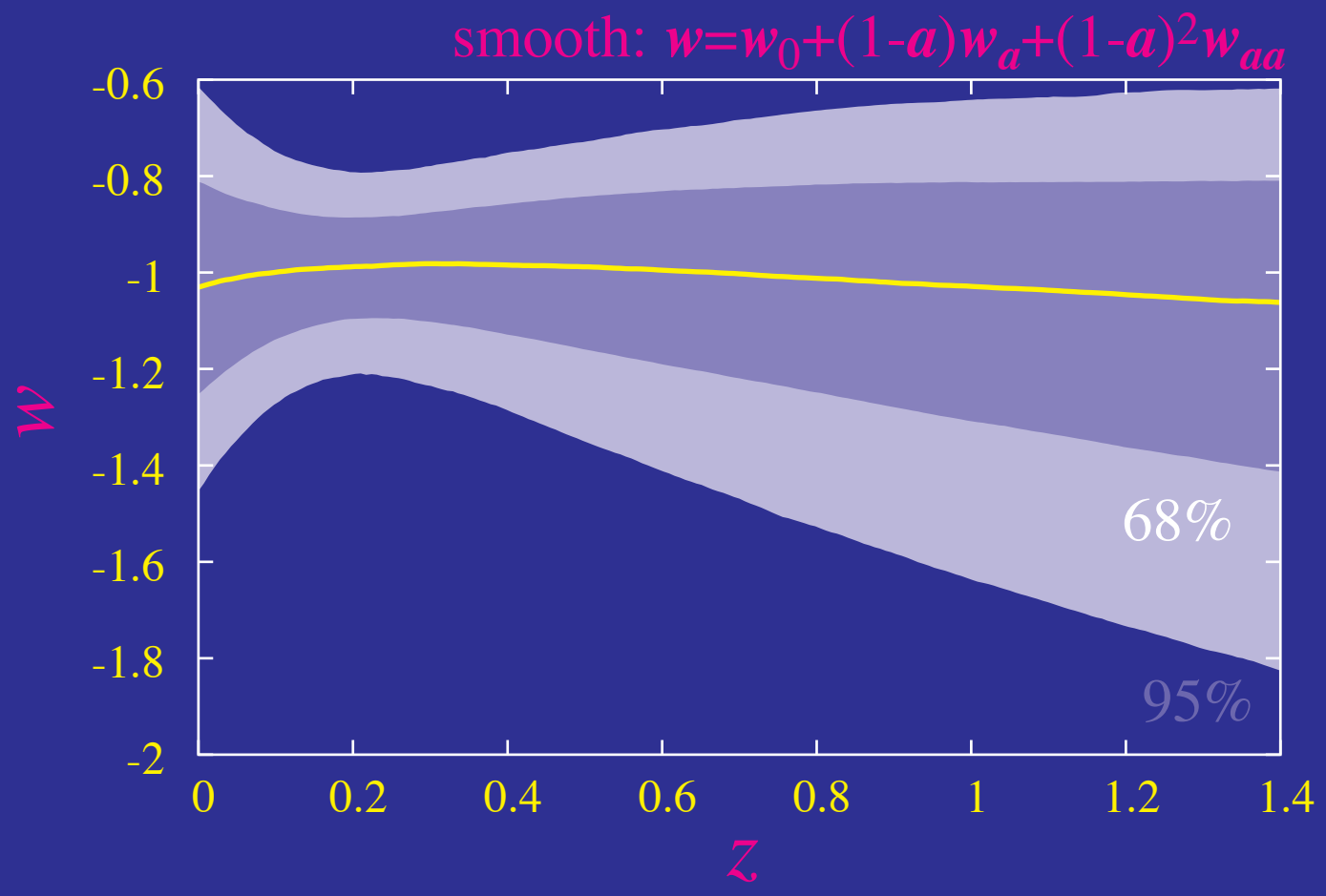
Dark Energy Sensitivity

- Three parameter dark energy model: $w(z{=}0){=}w_0$; w_a=-dw/da; Ω_{DE}
- w_a sensitivity; (fixed w_0 = -1; Ω_{DE} adjusted)



Pivot Redshift

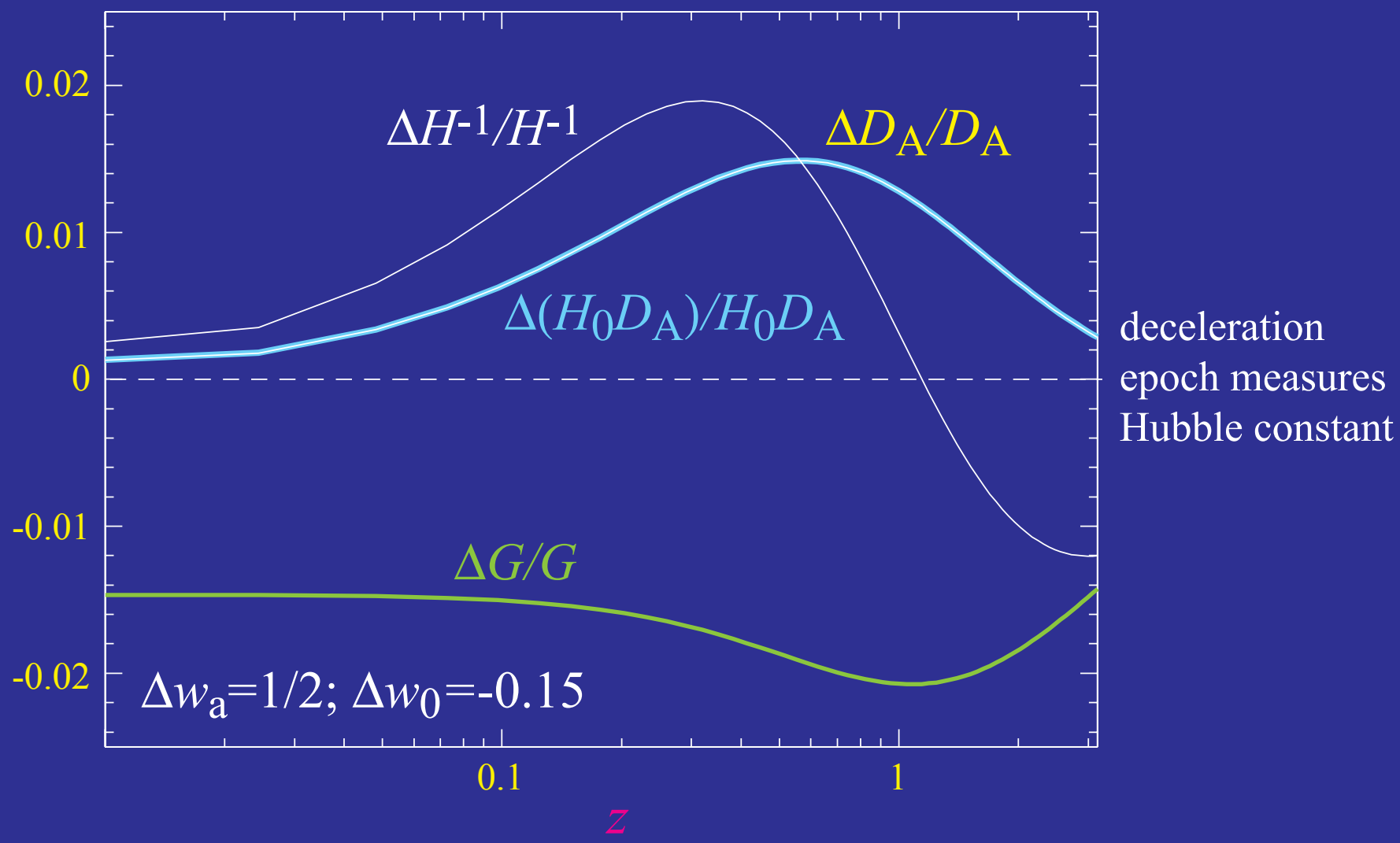
- Equation of state best measured at z~0.2-0.4 = Hubble constant
- Any deviation from w=-1 rules out a cosmological constant



Seljak et al (2004)

Dark Energy Sensitivity

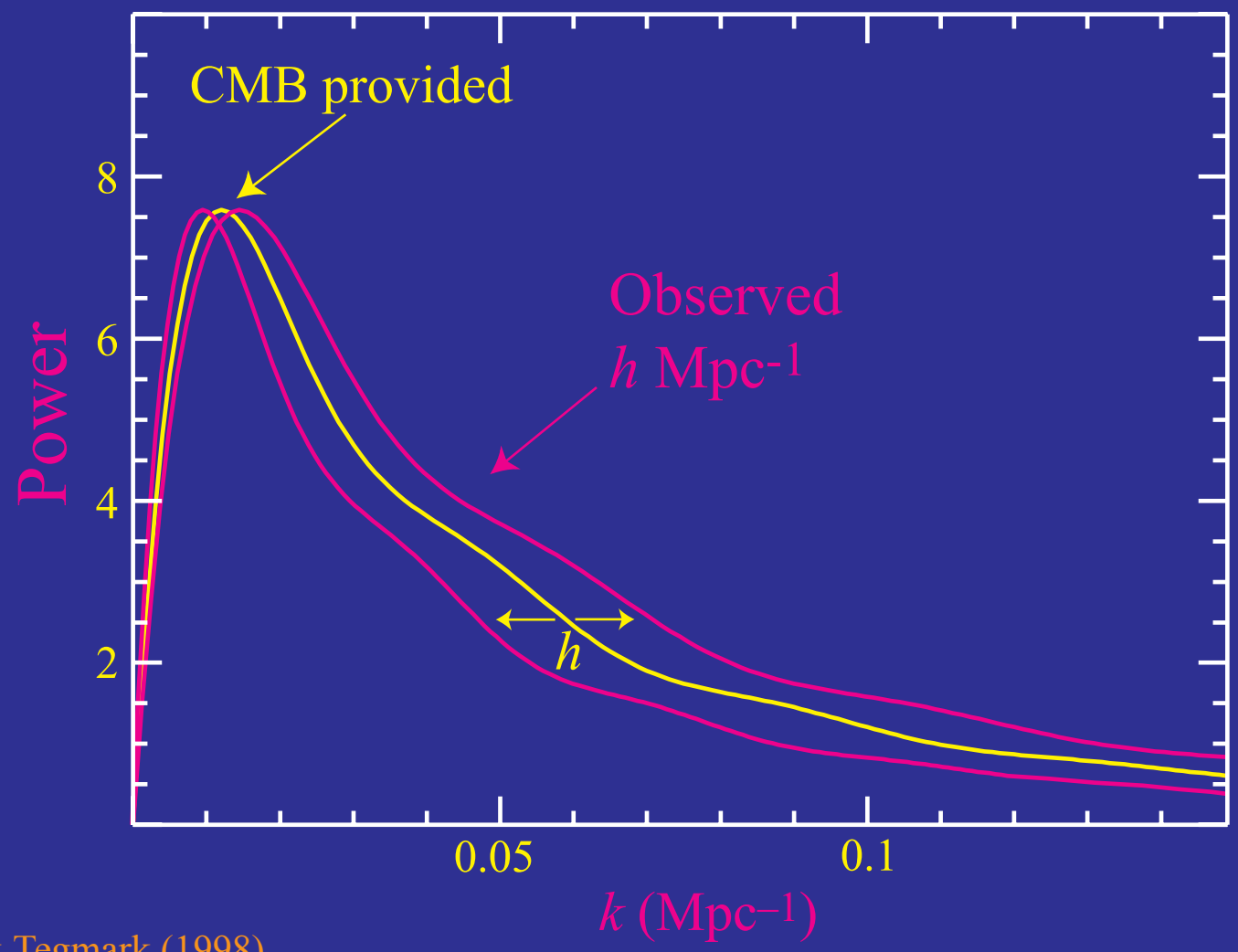
- Three parameter dark energy model: $w(z=0)=w_0$; $w_a=-\mathrm{d}w/\mathrm{d}a$; Ω_{DE}
- H_0 fixed (or Ω_{DE}); remaining w_0-w_a degeneracy
- Note: degeneracy does not preclude ruling out Λ ($w(z)\neq-1$ at some z)



Rings of Power

Local Test: H_0

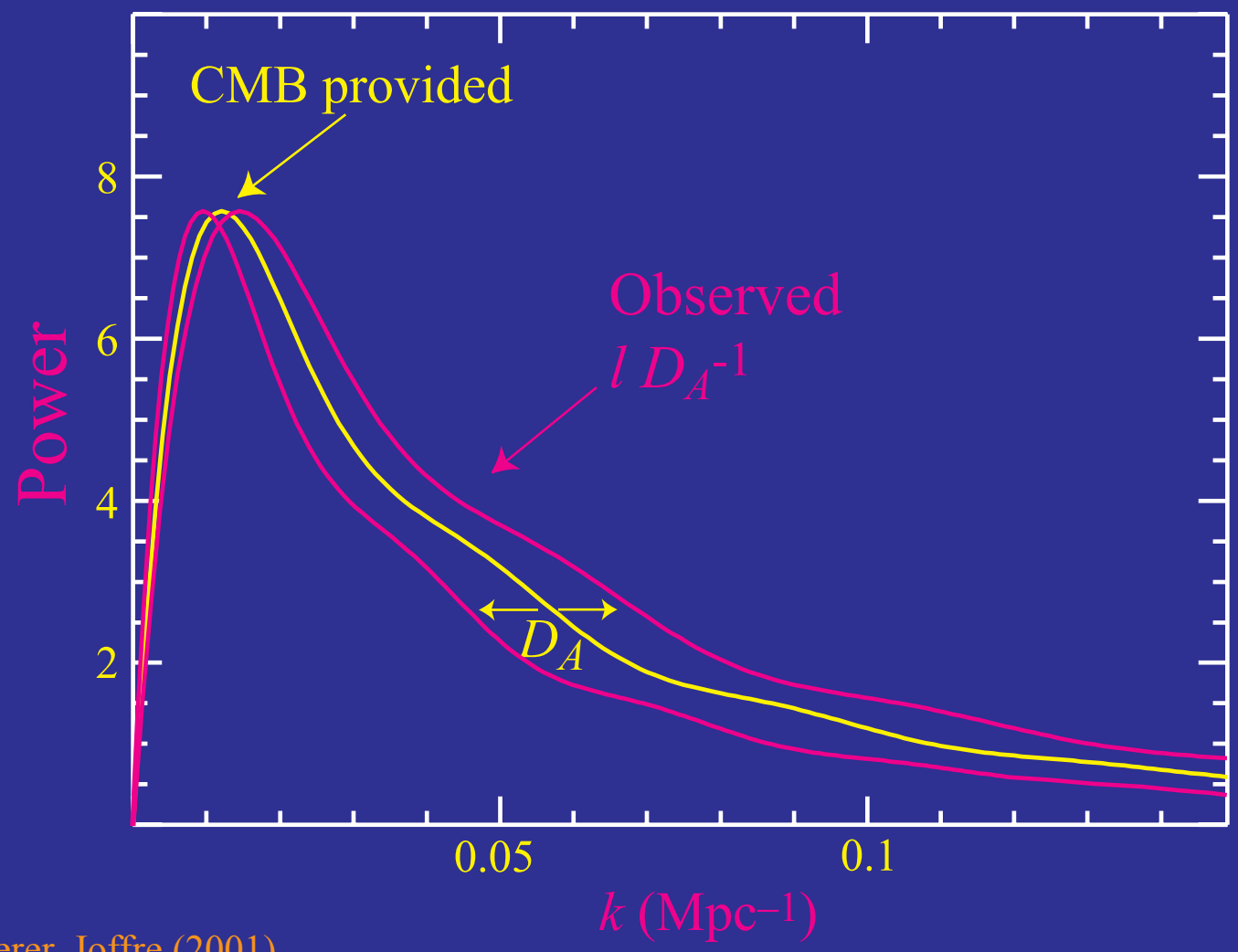
- Locally $D_A = \Delta z/H_0$, and the observed power spectrum is isotropic in h Mpc^{-1} space
- Template matching the features yields the Hubble constant



Eisenstein, Hu & Tegmark (1998)

Cosmological Distances

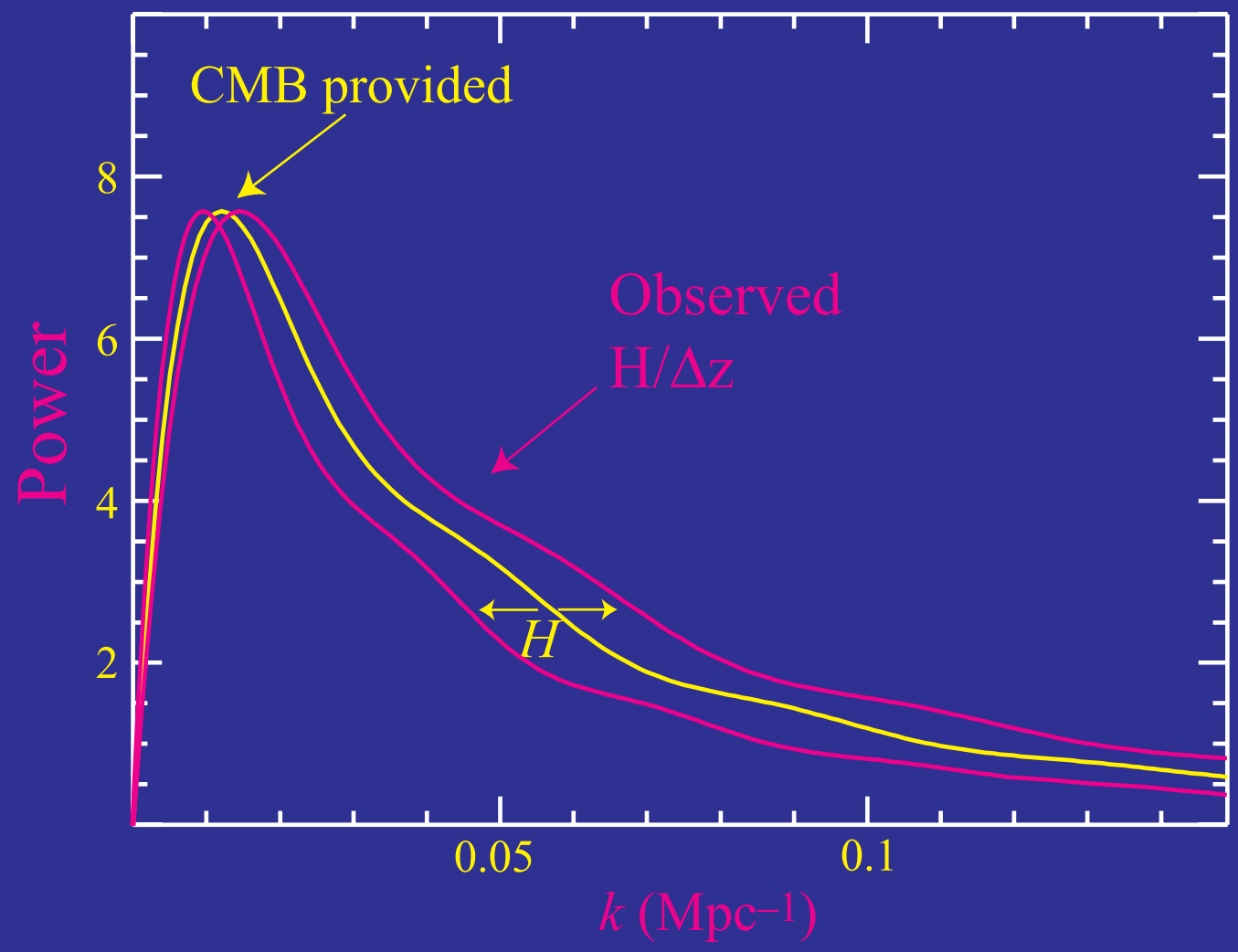
- Modes perpendicular to line of sight measure angular diameter distance



Cooray, Hu, Huterer, Joffre (2001)

Cosmological Distances

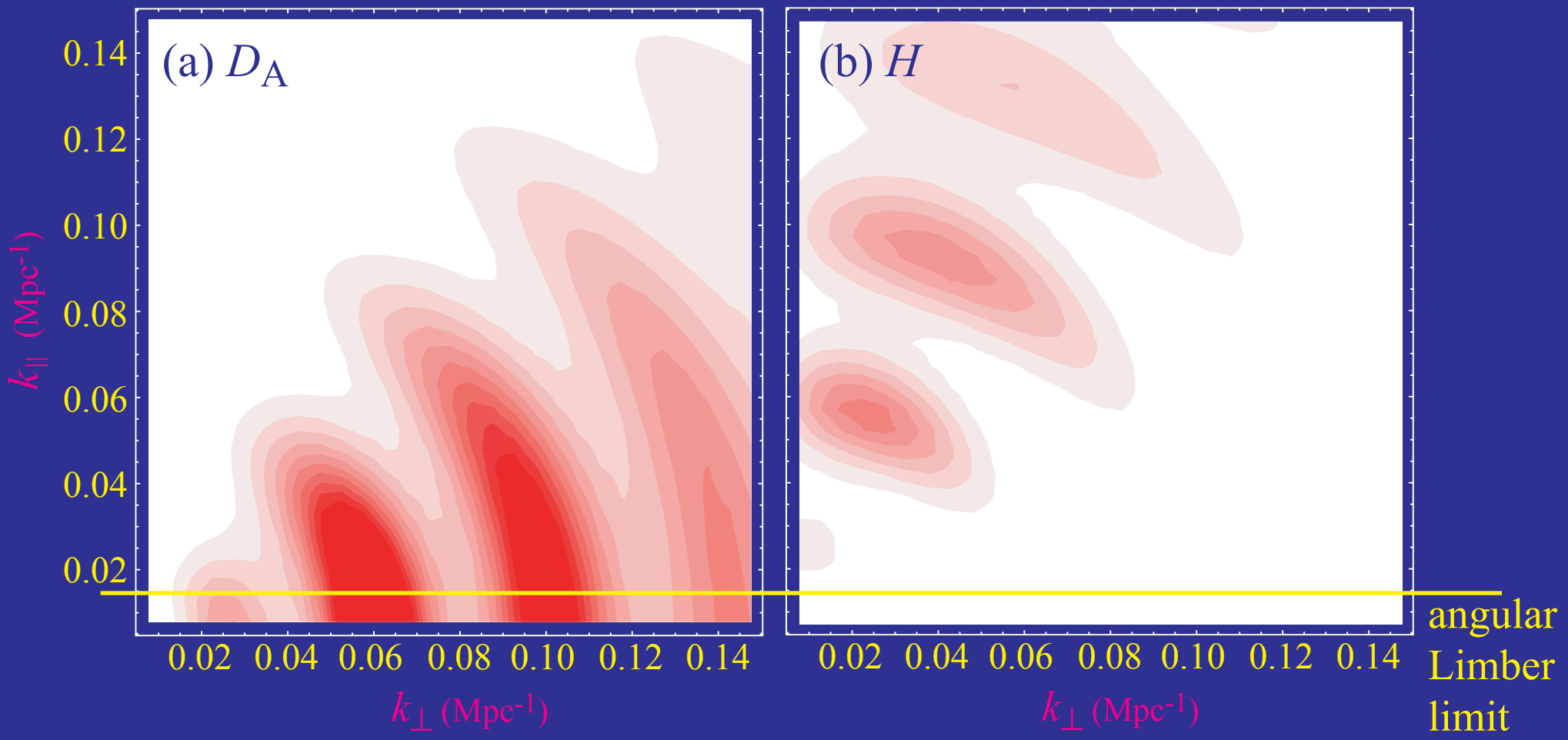
- Modes parallel to line of sight measure the Hubble parameter



Eisenstein (2003); Seo & Eisenstein (2003) [also Blake & Glazebrook 2003; Linder 2003; Matsubara & Szalay 2002]

Projected Power

- Information density in k-space sets requirements for the redshifts
- Purely angular limit corresponds to a low-pass $k_{||}$ redshift survey in the fundamental mode set by redshift resolution

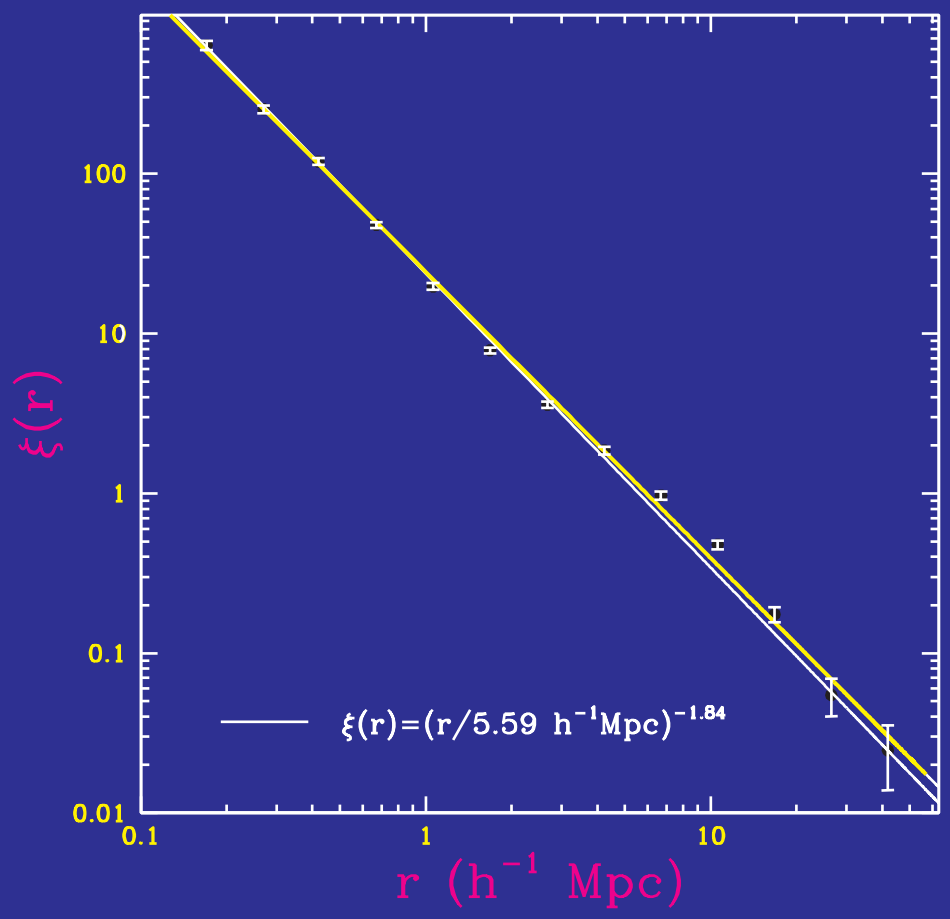


Hu & Haiman (2003)

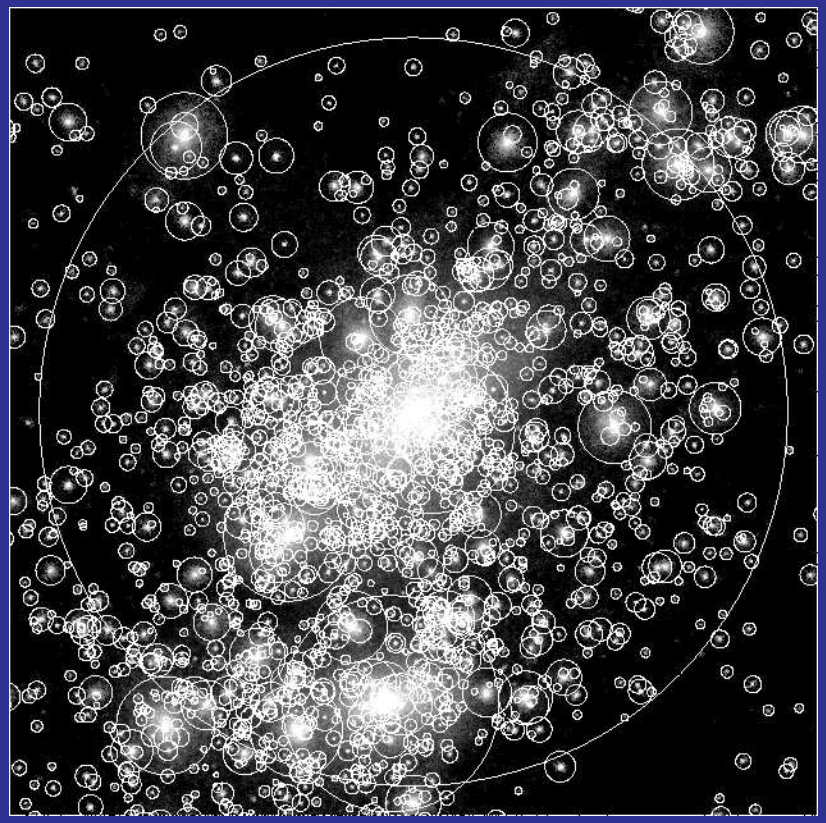
Galaxies and Halos

- Recent progress in the assignment of galaxies to halos and halo substructure reduces galaxy bias largely to a counting problem

SDSS: Zehavi et al (2004)



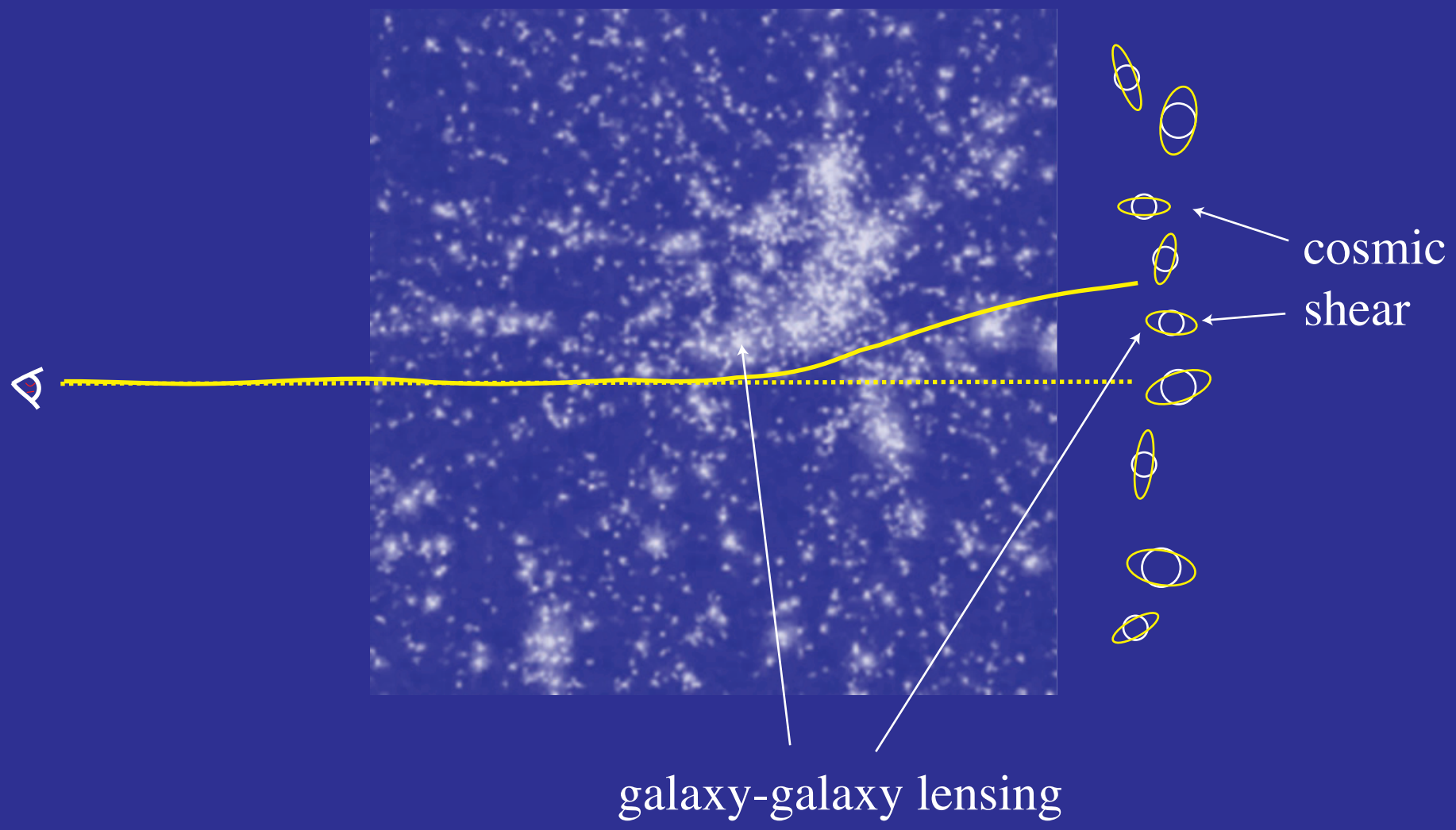
Kravtsov et al (2003)



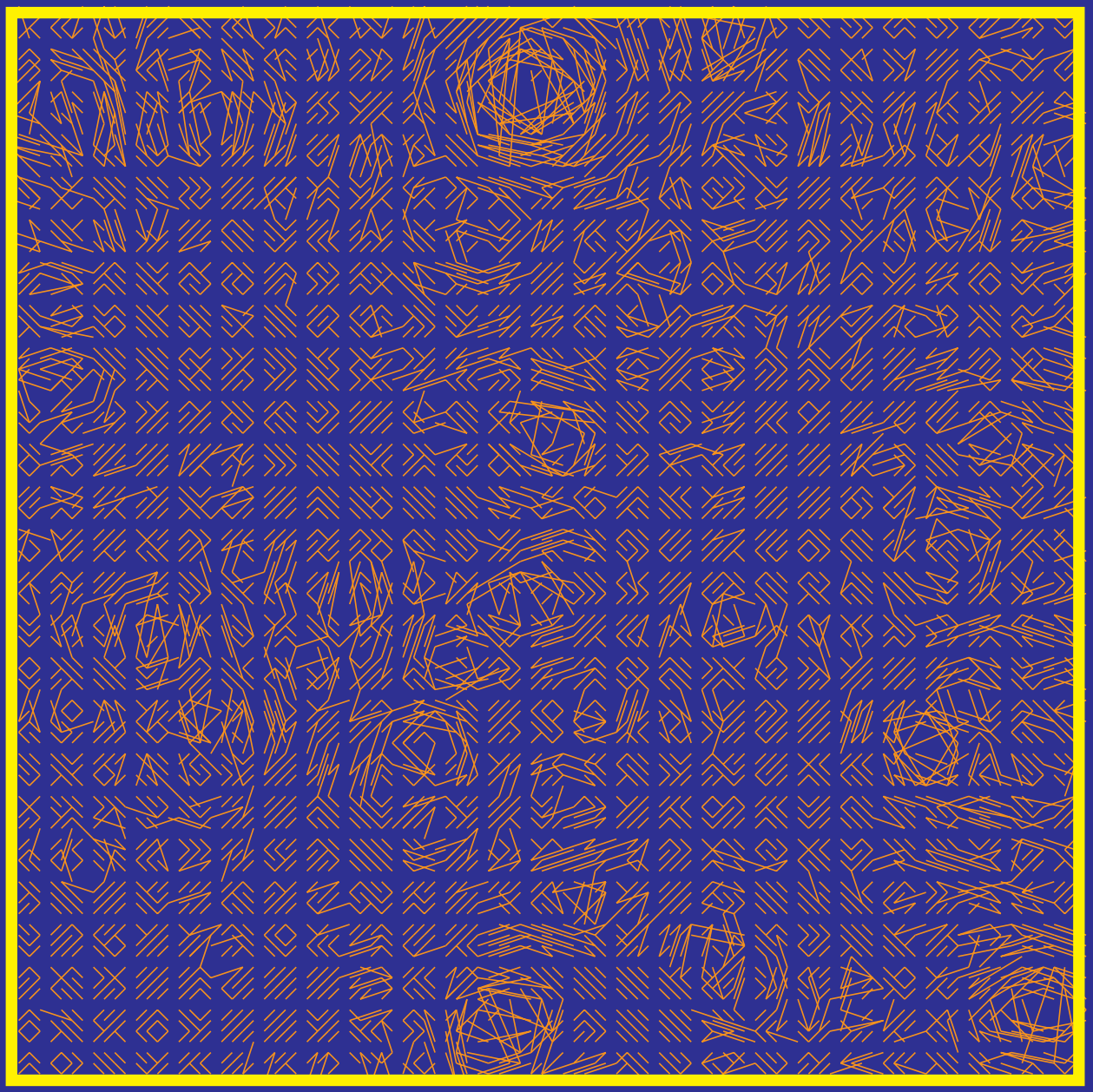
Gravitational Lensing

Lensing Observables

- Correlation of shear distortion of background images: cosmic shear
- Cross correlation between foreground lens tracers and shear: galaxy-galaxy lensing

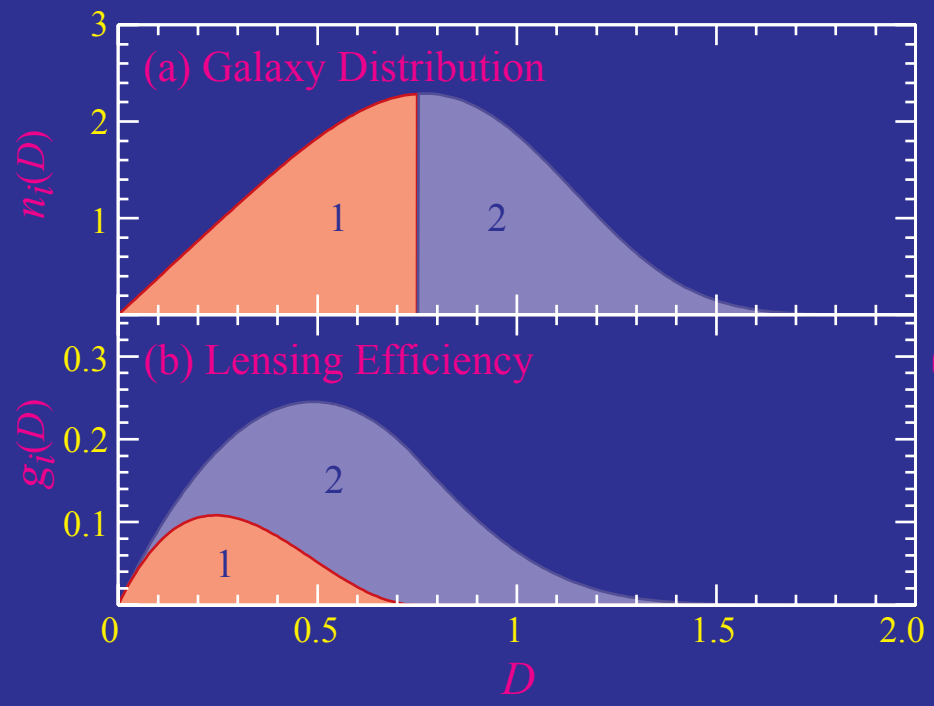


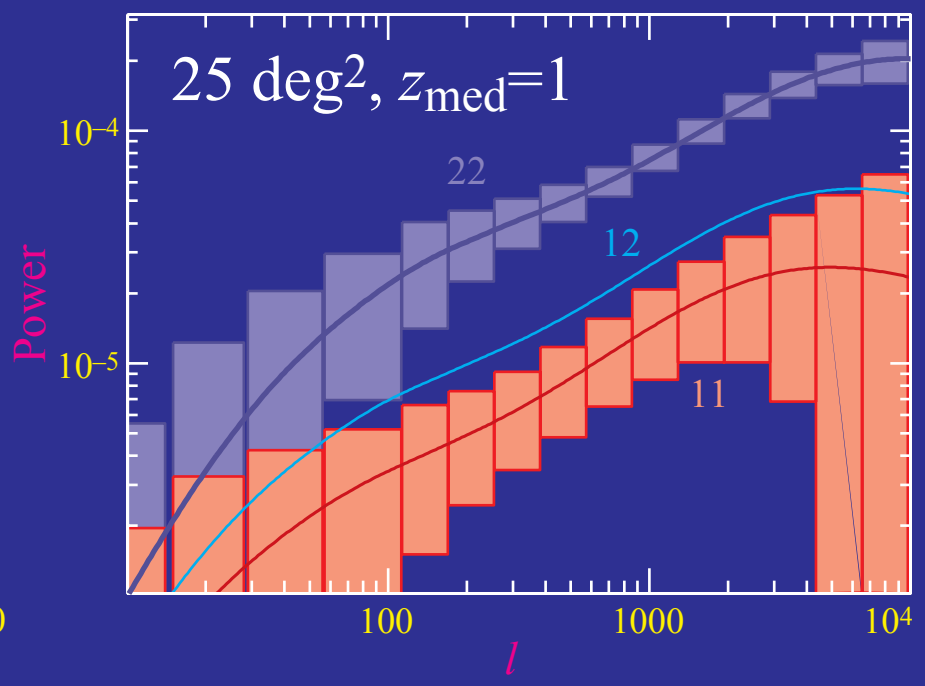
Halos and Shear



Lensing Tomography

- Divide sample by photometric redshifts
- Cross correlate samples



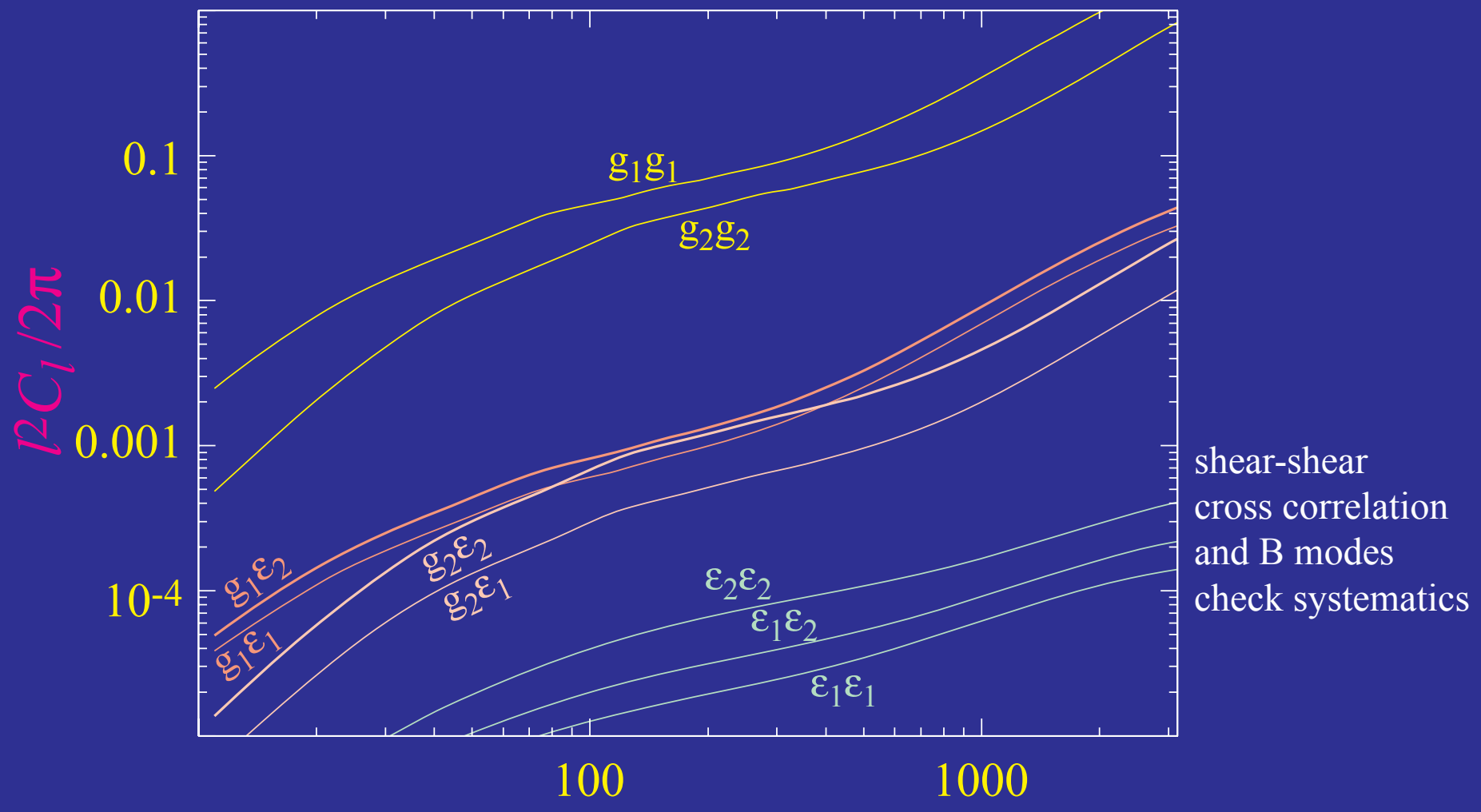


- Order of magnitude increase in precision even after CMB breaks degeneracies

Hu (1999)

Galaxy-Shear Power Spectra

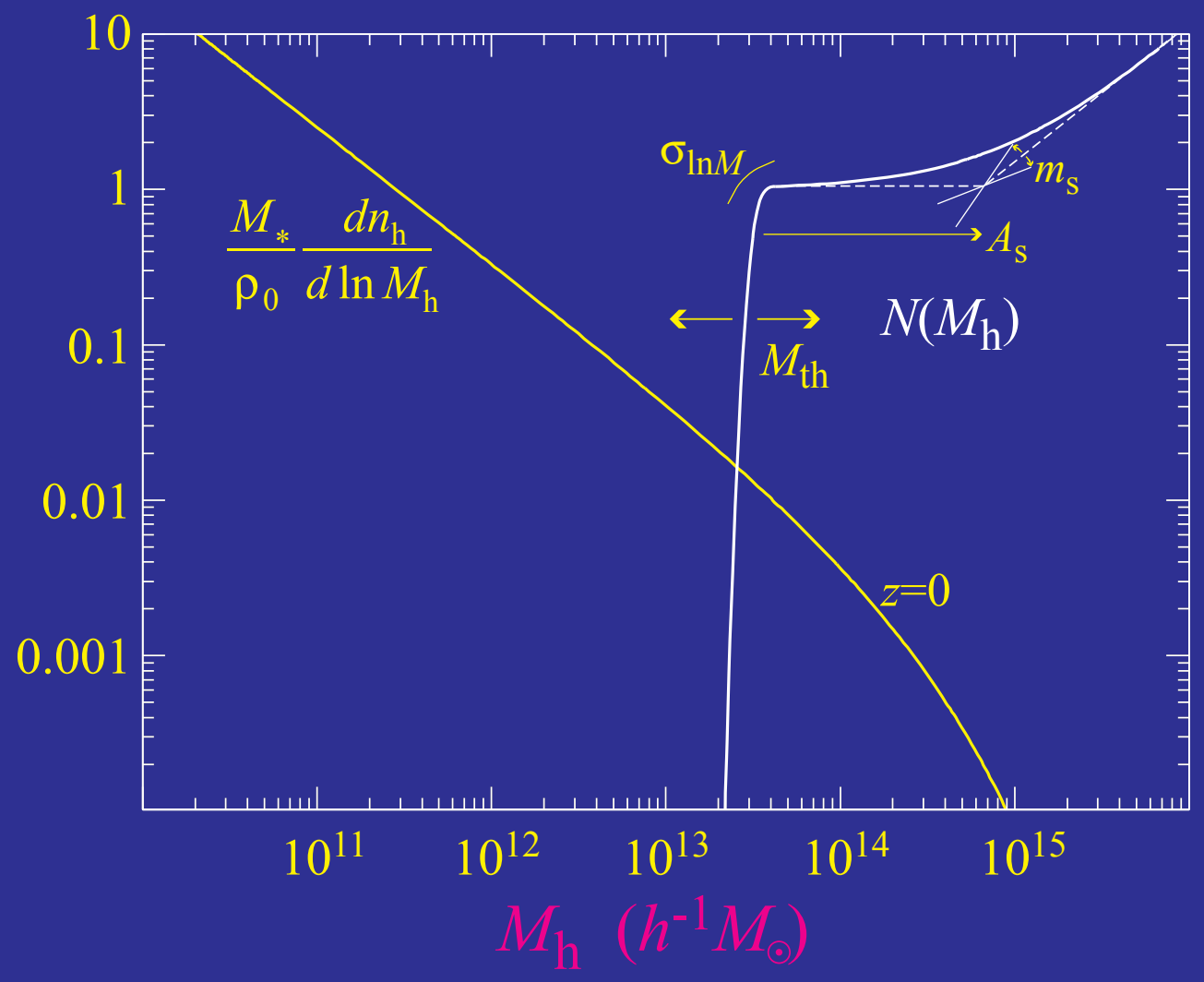
- Auto and cross power spectra of galaxy density and shear in multiple redshift bins



Hoekstra et al (2002); Guzik & Seljak (2001)
Hu & Jain (2003) [also geometric constraints: Jain & Taylor (2003); Bernstein & Jain (2003); Zhang, Hui, Stebbins (2003); Knox & Song (2003)]

Mass-Observable Relation

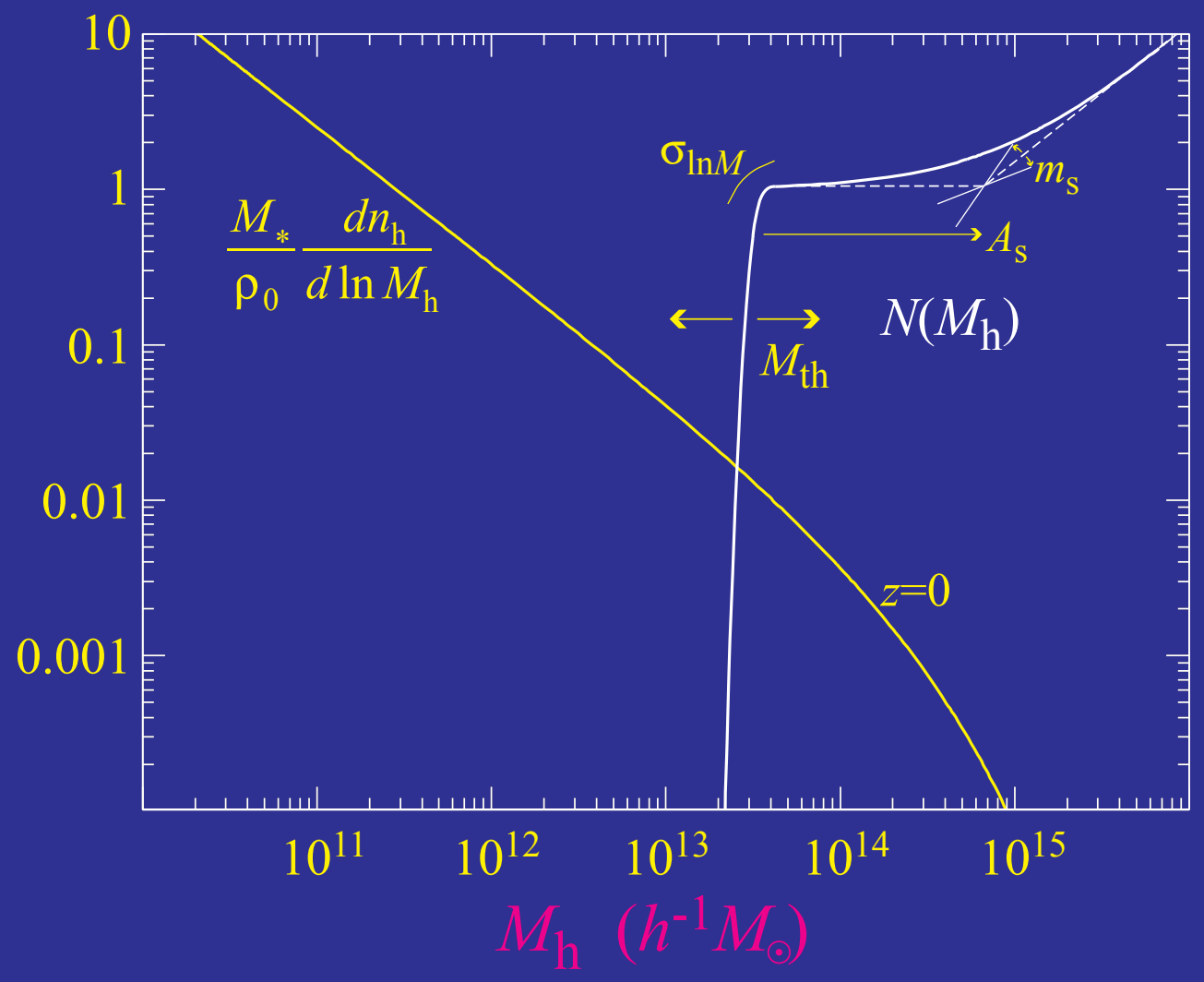
- Use galaxy-galaxy lensing to determine relation with halos or bias
- With bias determined, galaxy spectrum measures mass spectrum



Cluster Abundance

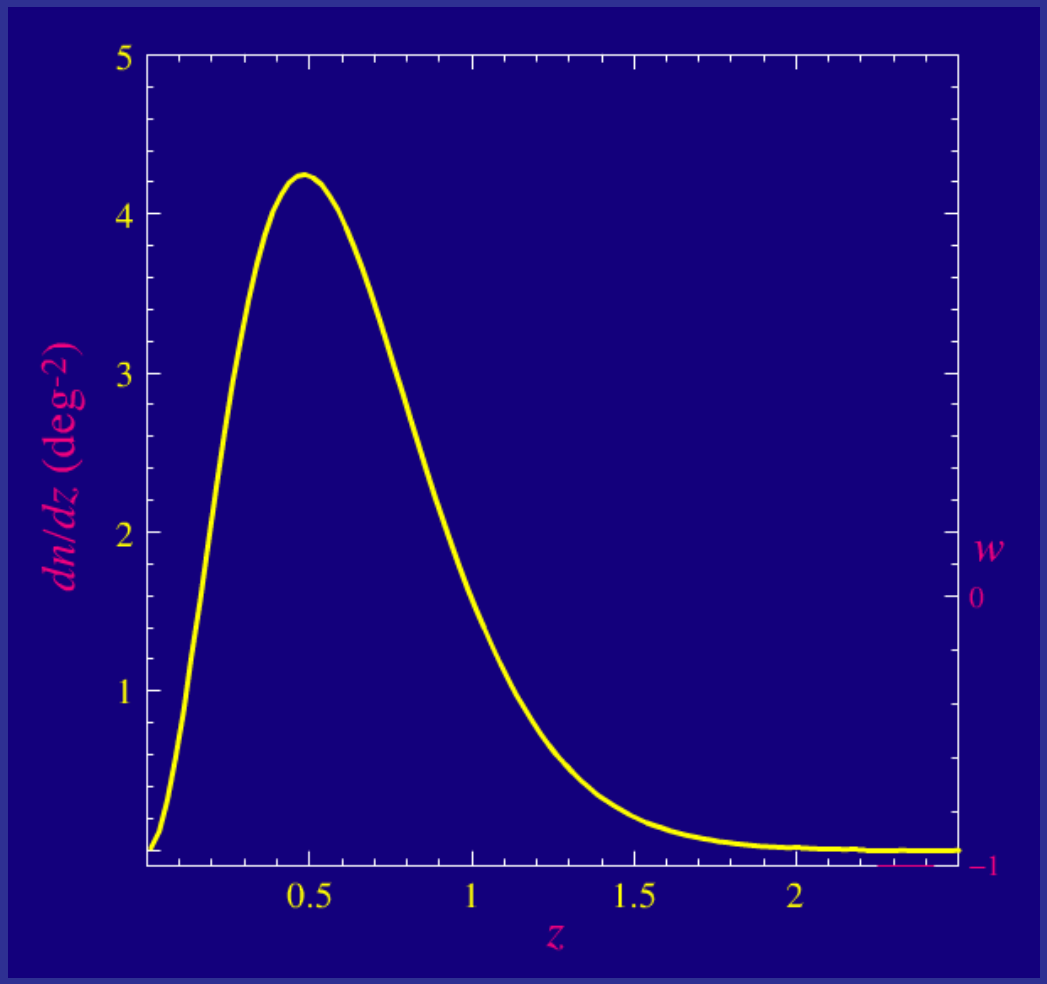
Counting Halos

- Massive halos largely avoid $N(M_h)$ problem of multiple objects



Counting Halos for Dark Energy

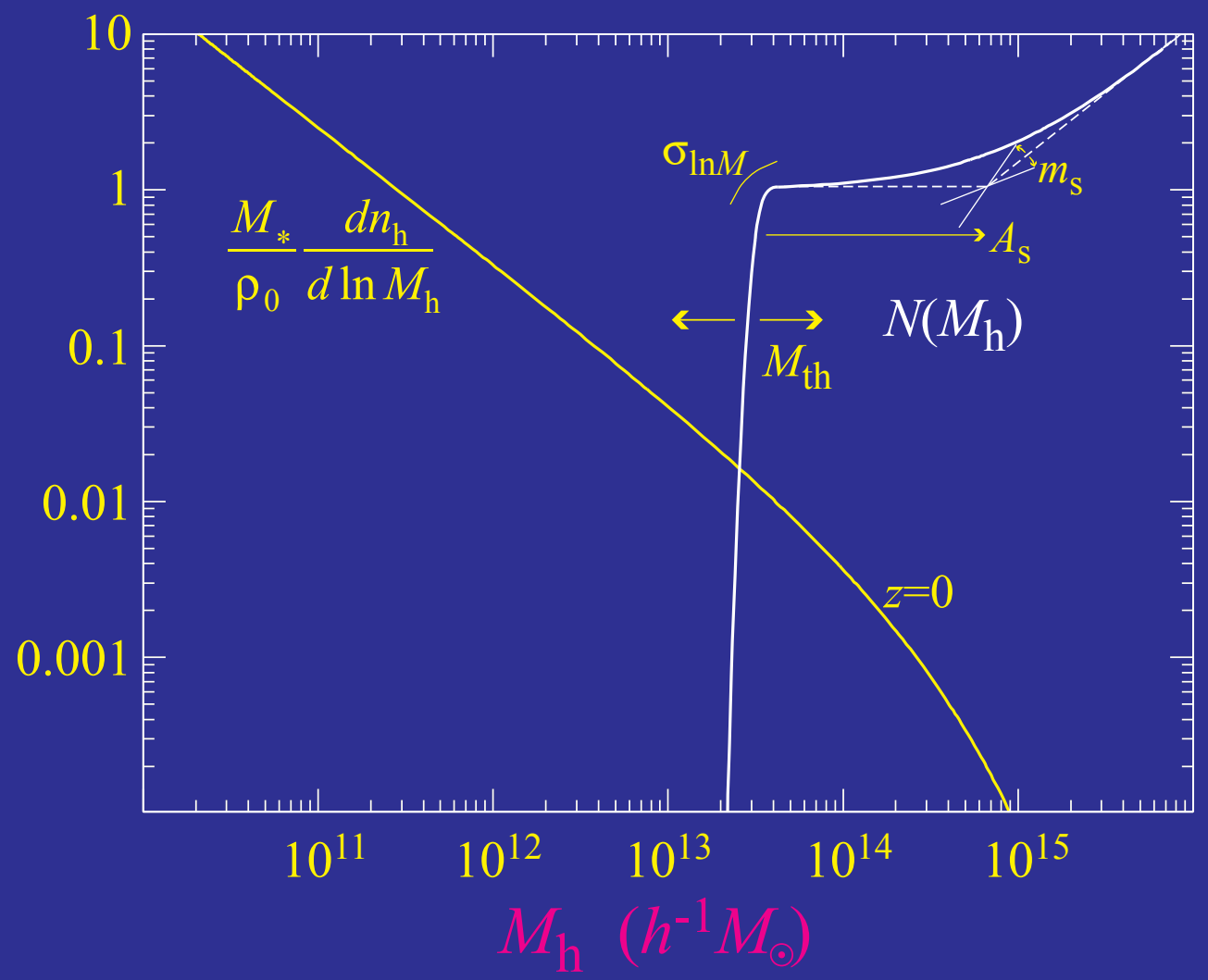
- Number density of massive halos extremely sensitive to the growth of structure and hence the dark energy
- Potentially %-level precision in dark energy equation of state



Haiman, Holder & Mohr (2001)

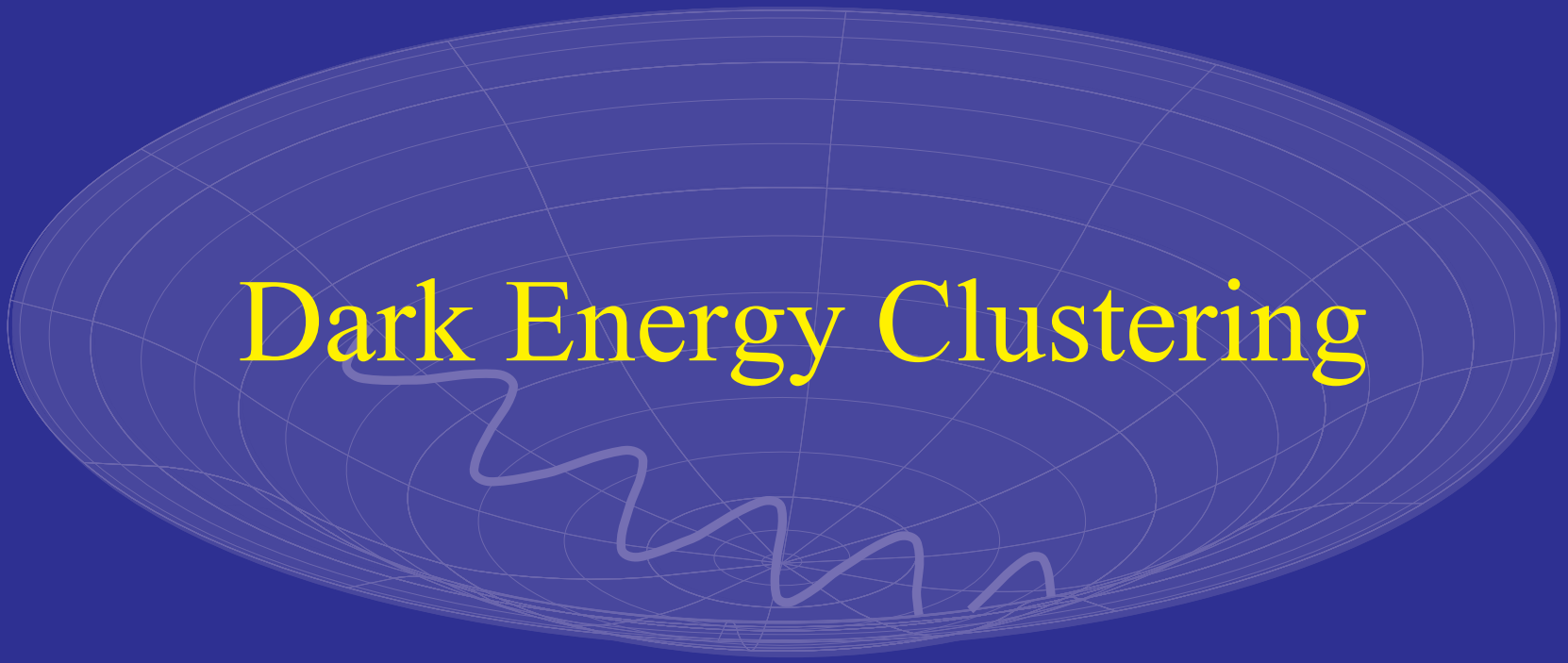
Mass-Observable Relation

- Relationship between halos of given mass and observables sets mass threshold and scatter around threshold
- Leading uncertainty in interpreting abundance; self-calibration?



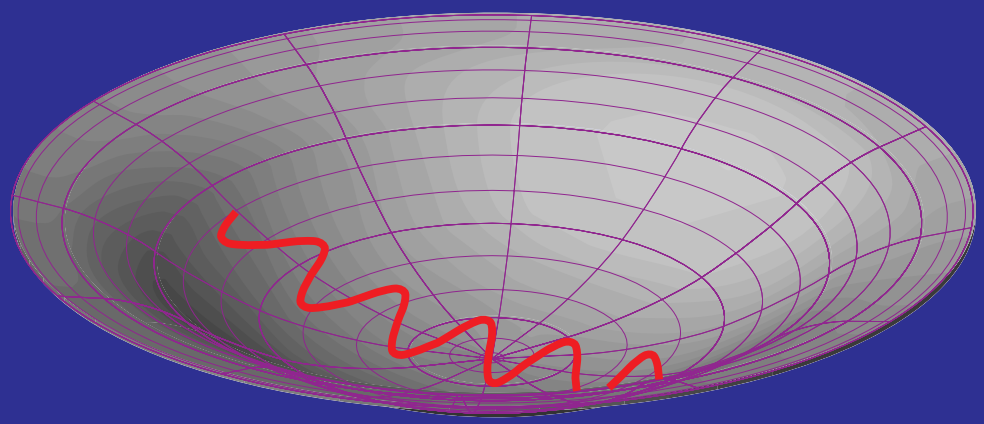
Pierpaoli, Scott & White (2001); Seljak (2002); Levine, Schultz & White (2002)

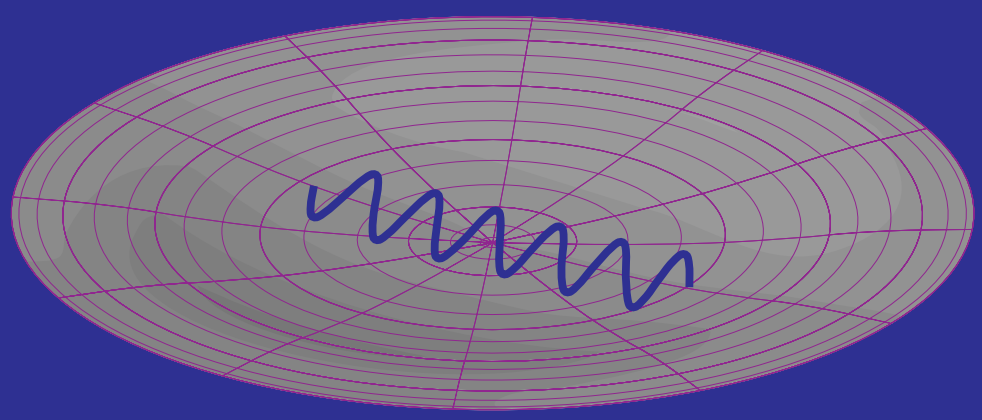
Dark Energy Clustering



ISW Effect

- If dark energy is smooth, gravitational potential decays with expansion
- Photon receives a blueshift falling in without compensating redshift
- Doubled by metric effect of stretching the wavelength

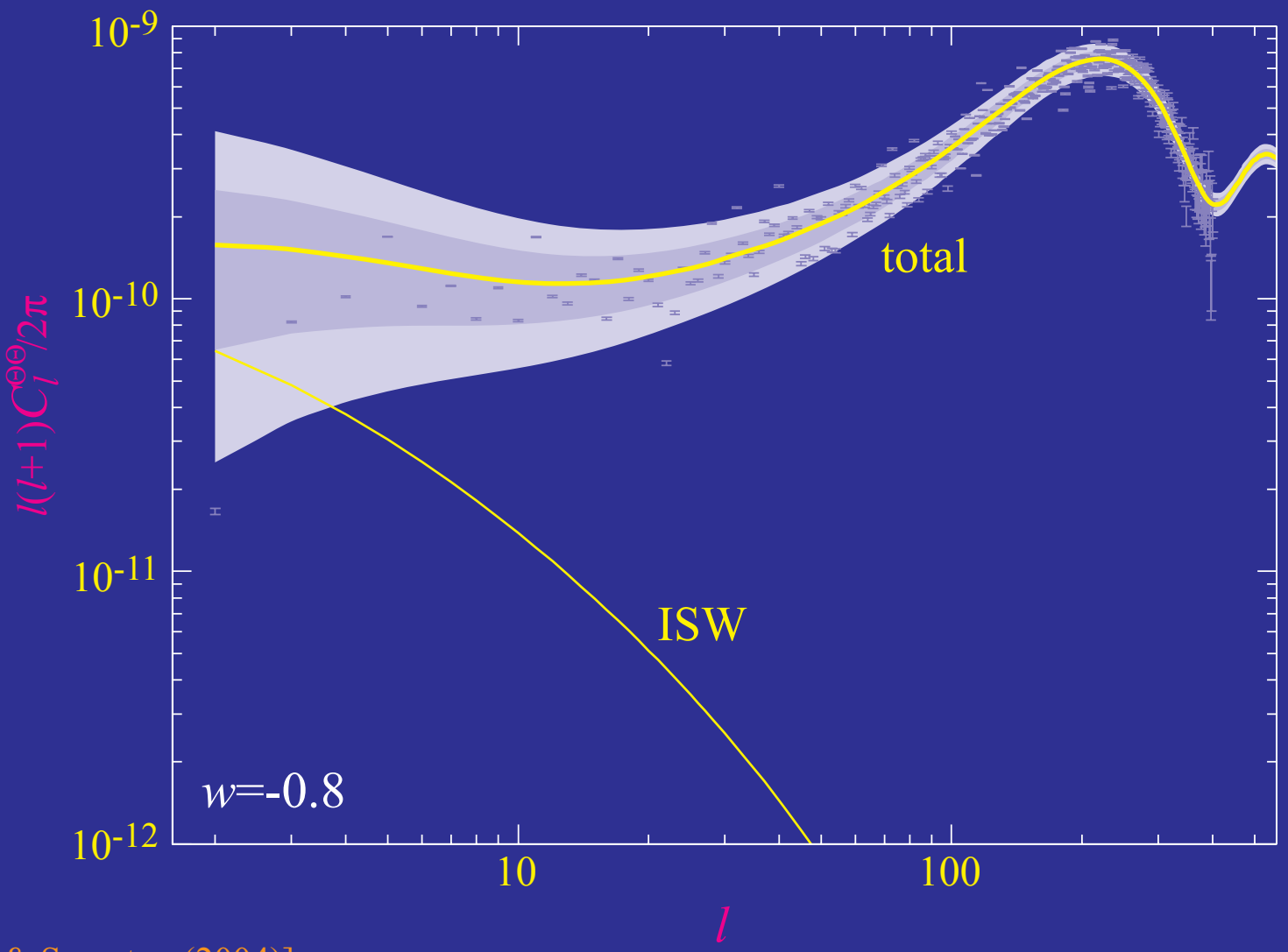




Sachs & Wolfe (1967); Kofman & Starobinski (1985)

ISW Effect

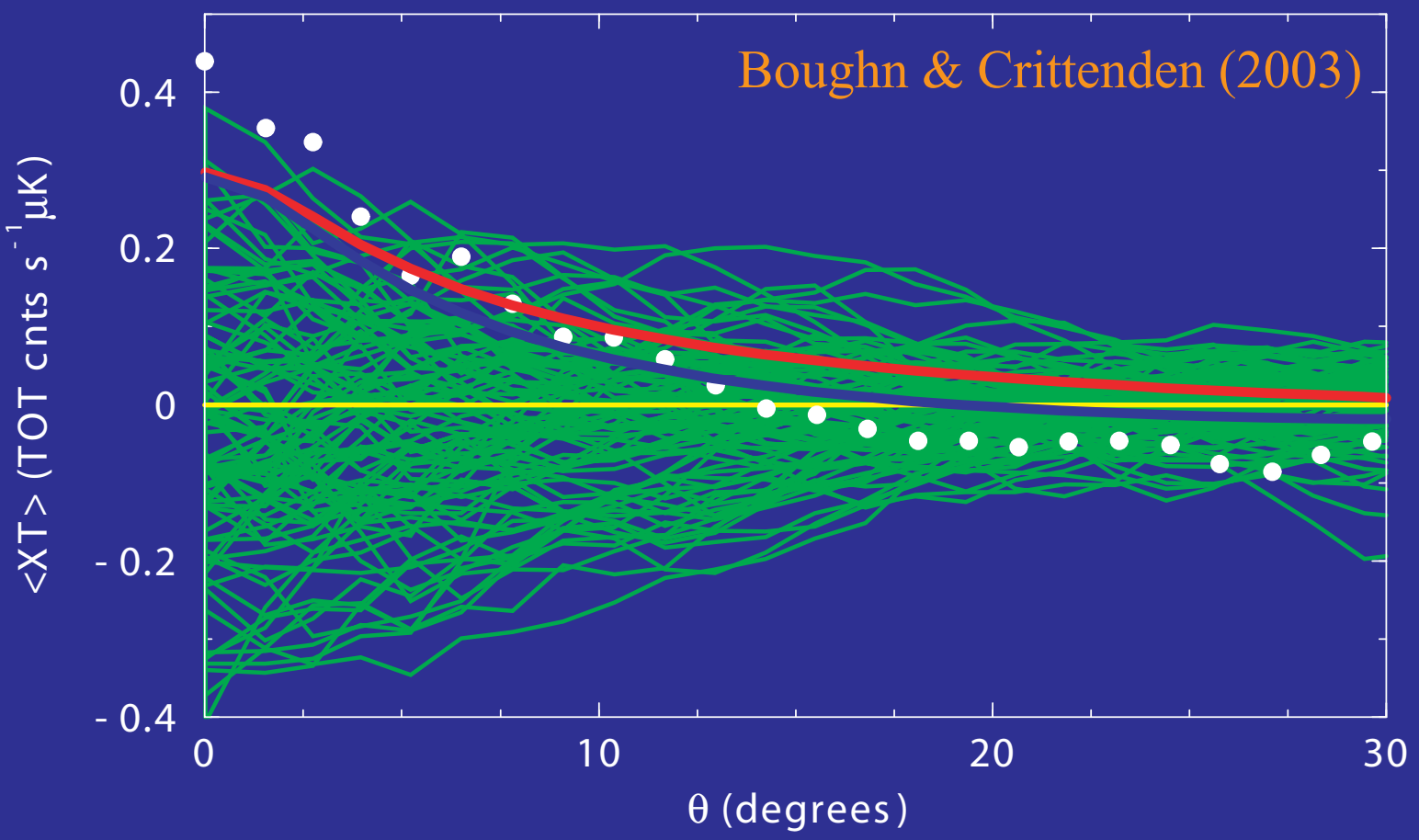
- ISW effect hidden in the temperature power spectrum by primary anisotropy and cosmic variance



[plot: Hu & Scranton (2004)]

ISW Galaxy Correlation

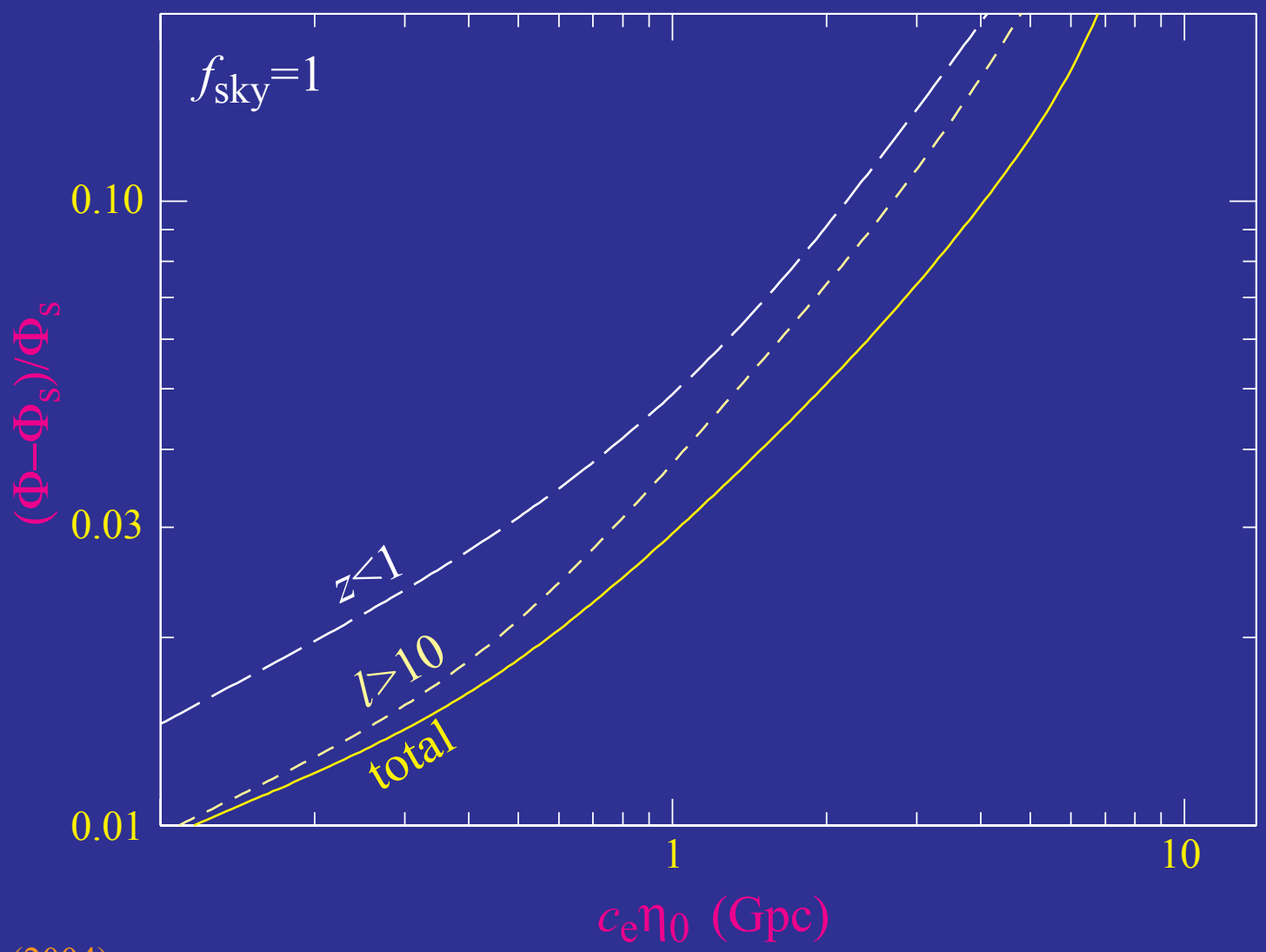
- A 2-3σ detection of the ISW effect through galaxy correlations



Boughn & Crittenden (2003); Nolte et al (2003); Fosalba & Gaztanaga (2003); Fosalba et al (2003); Afshordi et al (2003)

Dark Energy Smoothness

- Ultimately can test the dark energy smoothness to ~3% on 1 Gpc



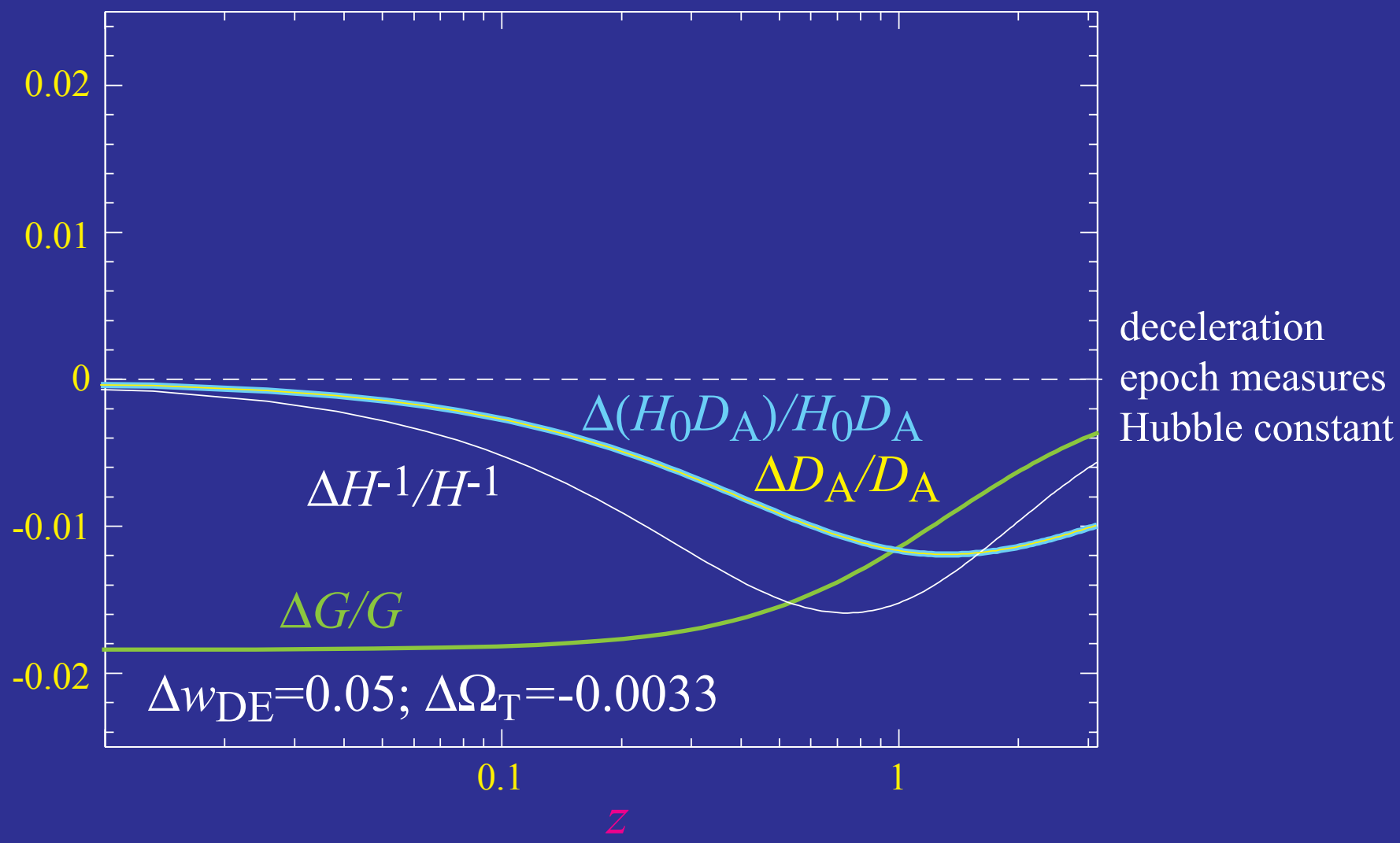
Hu & Scranton (2004)

Summary

- NeoClassical probes based on the evolution of structure
- CMB fixes deceleration epoch observables: expansion rate, energy densities, growth rate, absolute amplitude, volume elements
- General relativity predicts a consistency relation between deviations in distances and growth due to dark energy
- Leading dark energy distance observable is H_0 or equivalently $w(z \sim 0.4)$
- Leading growth observable σ_8 measures dark energy (and neutrinos)
- Many NeoClassical tests can measure the evolution of w but all will require a control over systematic errors at the $\sim 1\%$
- Promising probes are beginning to bear fruit: cluster abundance, cosmic shear, galaxy clustering, galaxy galaxy lensing,

Dark Energy Sensitivity

- H_0 fixed (or Ω_{DE}); remaining w_{DE}-Ω_T spatial curvature degeneracy
- Growth rate breaks the degeneracy anywhere in the acceleration regime



Keeping the High-z Fixed

- CMB fixes energy densities, expansion rate and distances to deceleration epoch fixed
- Example: constant $w=w_{DE}$ models require compensating shifts in Ω_{DE} and h