Dark Energy Probes

in

light of the CMB

Wayne Hu

Tuscon, March 2004

Dark Energy Tests

- Standard Candles
- Standard Ruler

  Sound horizon (2%); matter radiation horizon (8%)

  Angular $\rightarrow D_A(z)$ - galaxy/cluster $C_l(z)$

  Radial $\rightarrow H(z)$ - galaxy/cluster $P(k, z)$

  Ratio (standard sphere): Alcock-Pacynski test
- Standard Fluctuation

  Initial amplitude at $k = 0.05$ Mpc^{-1} ($\delta\tau\%$)

  Cosmic Shear

  Galaxy-galaxy lensing + clustering (self-calibrating bias)

  Cluster abundance (even $z = 0$ gives cosmology; requires standard masses)

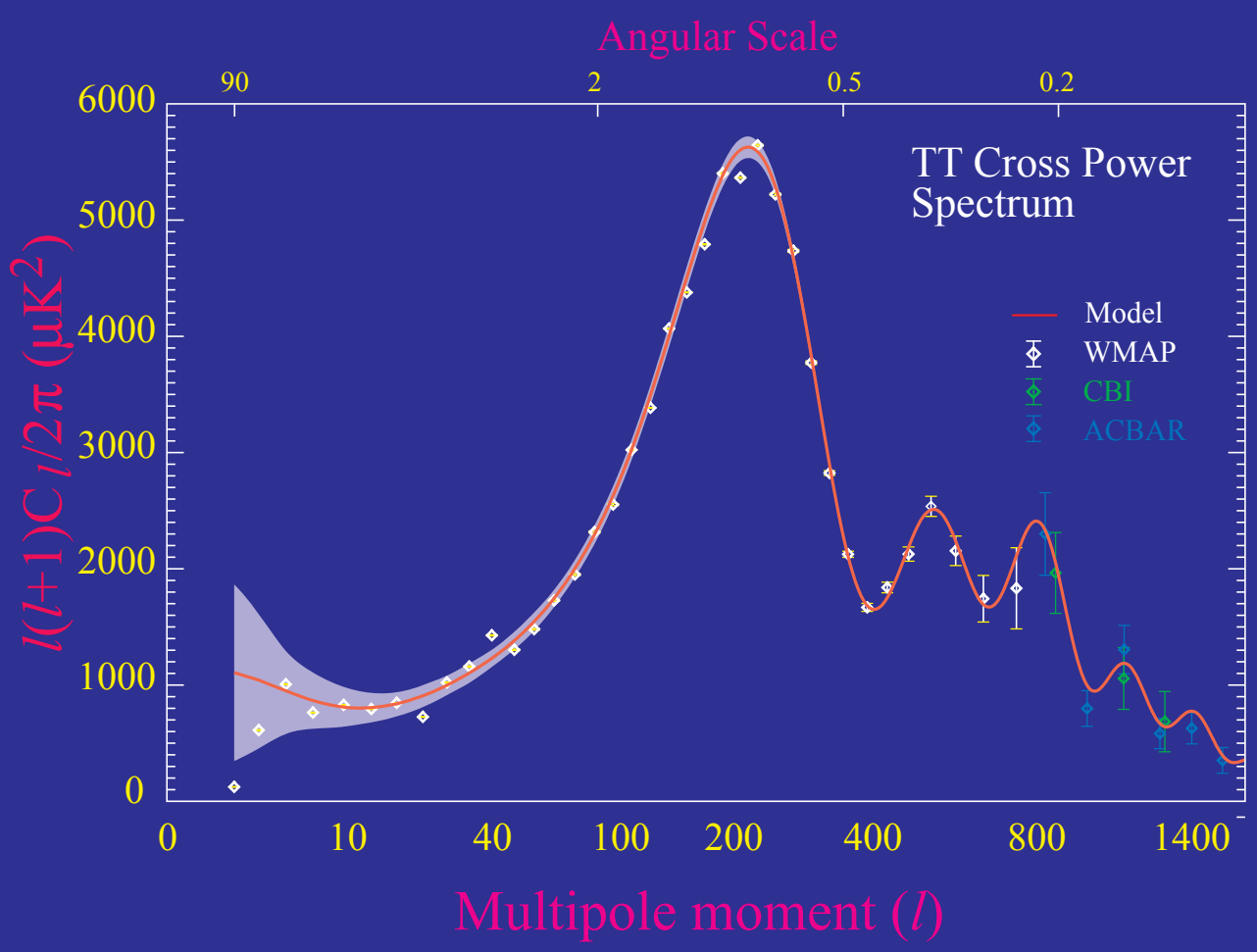
  Initial amplitude near horizon scale: ISW (polarization; lensing)

Forecasting Philosophy

- Equal (but optimistic...) footing
- Planck+ext-like CMB priors - τ: 0.5%; $\Omega_m h^2$: 1%; flat
- 4000 deg^2 optical survey with photometric redshifts of $\Delta z = 0.1$ out to $z = 1$
- Need for accurate calibration (starting with the CMB example) - complementarity/statistical precision is not enough!
- Recent Collaborators
  - Zoltan Haiman
  - Bhuvnesh Jain
  - Andrey Kravtsov
  - Marcos Lima

Leveraging the CMB

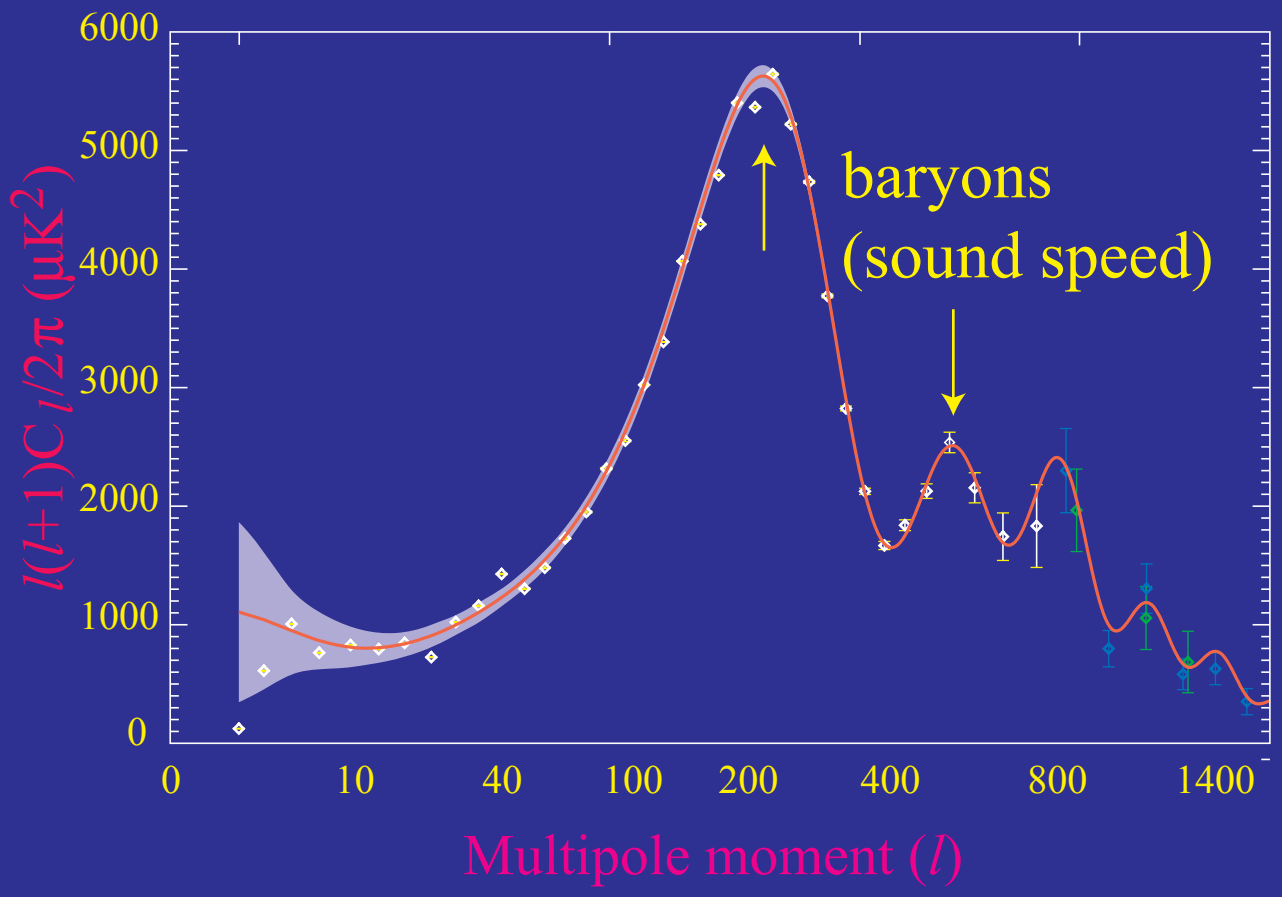
- WMAP + small scale temperature and polarization measures provides self-calibrating standards for the dark energy probes



WMAP: Bennett et al (2003)

Leveraging the CMB

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



Leveraging the CMB

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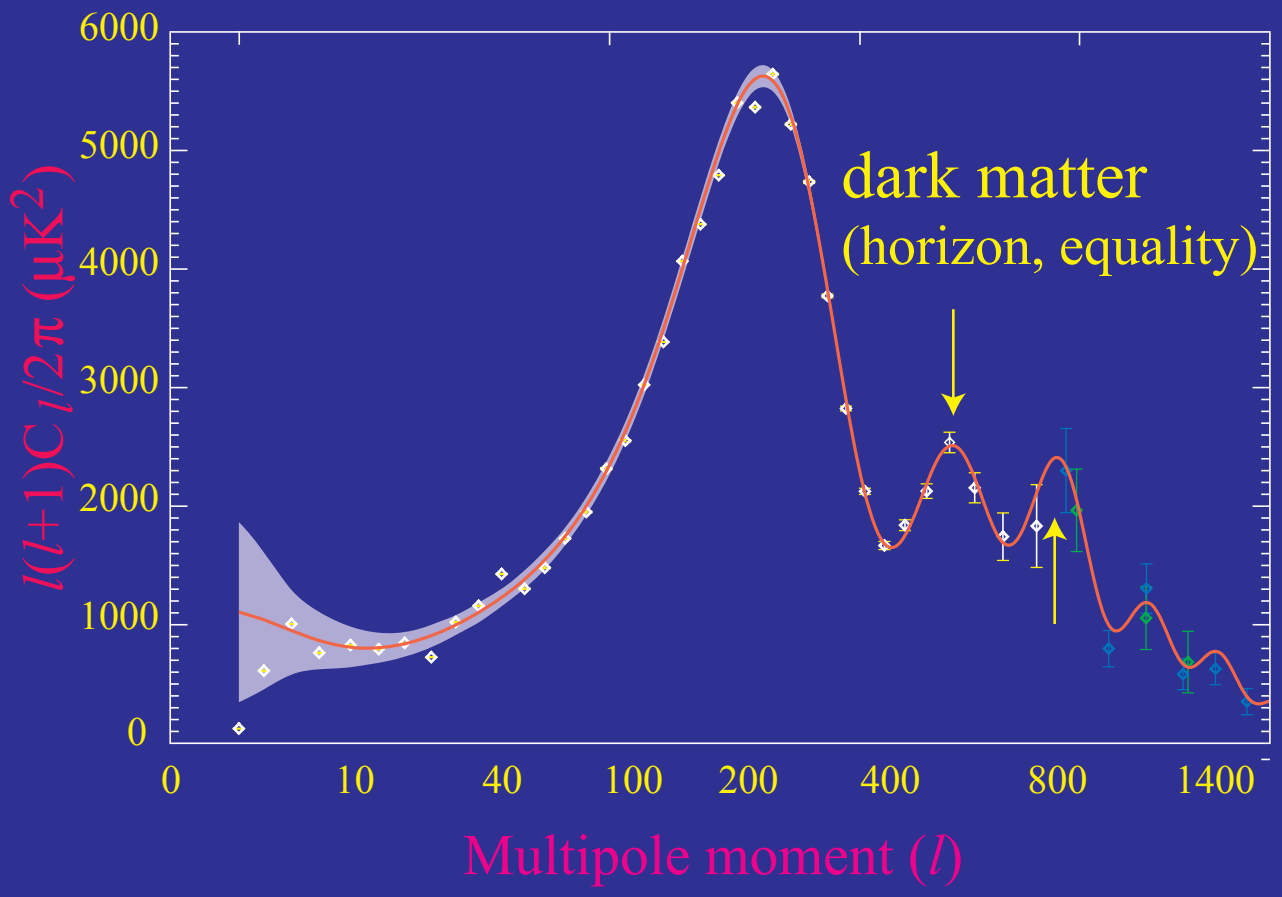
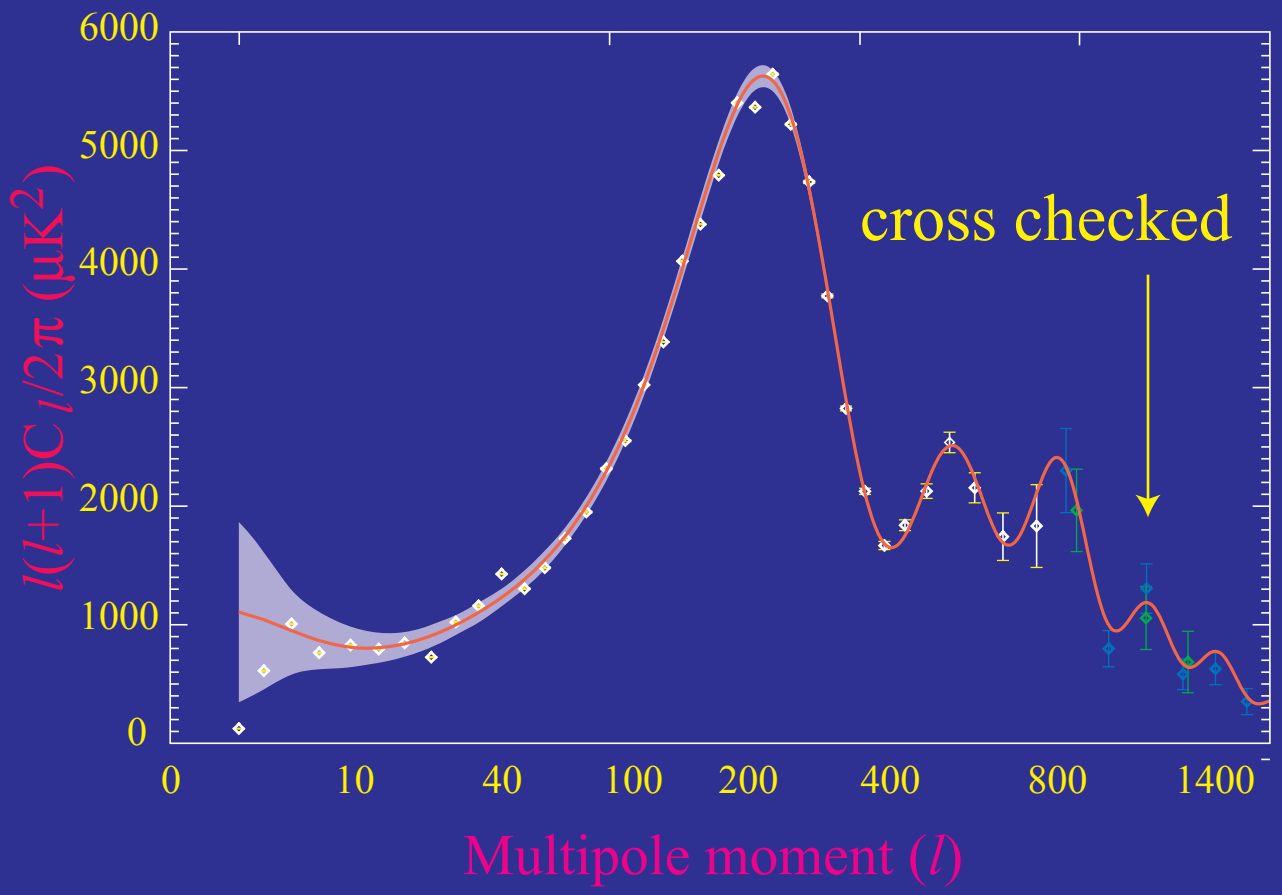


leading source of error!

Leveraging the CMB

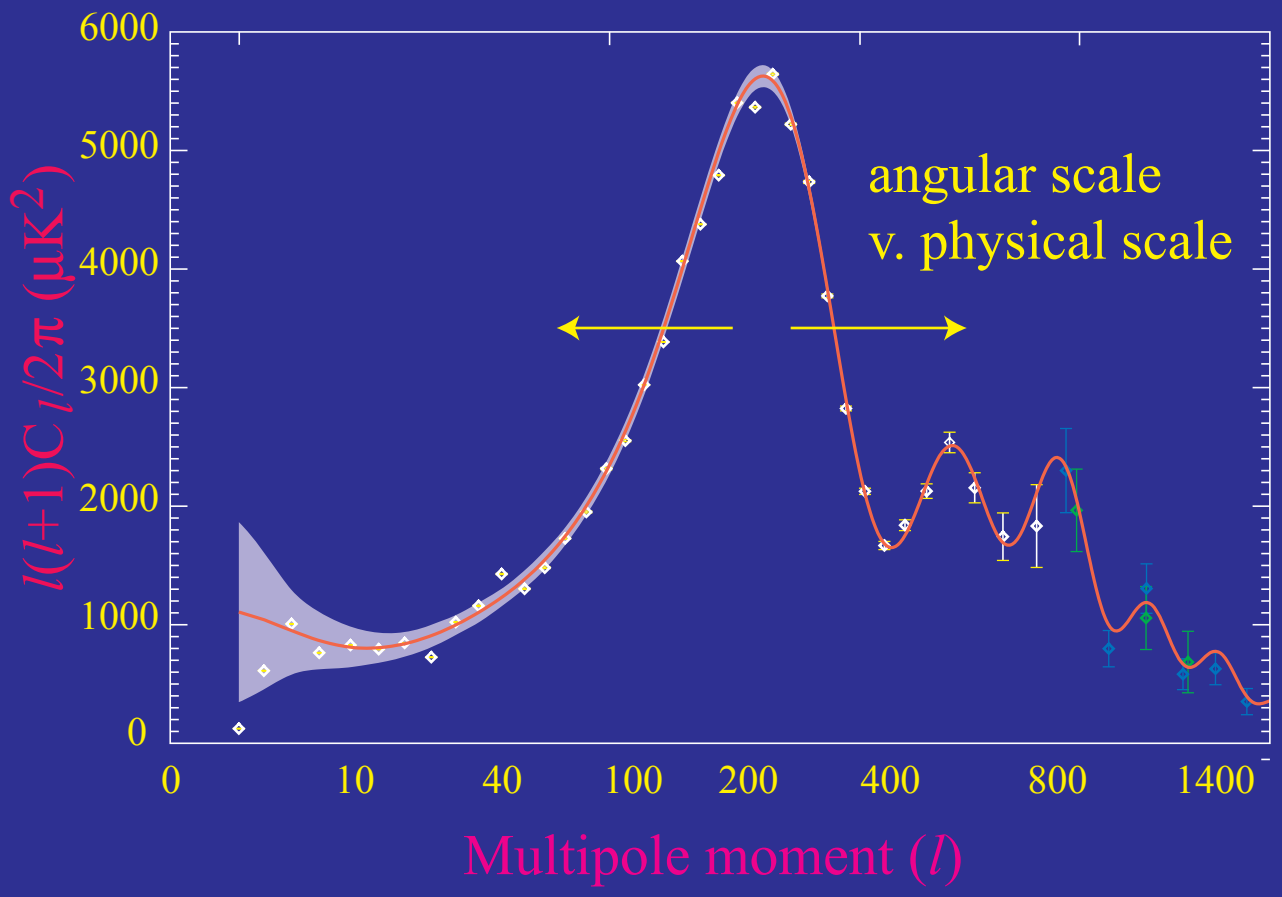
- Cross checked with damping scale (diffusion during horizon time) and polarization (rescattering after diffusion): self-calibrated and internally cross-checked



WMAP: Bennett et al (2003)

Leveraging the CMB

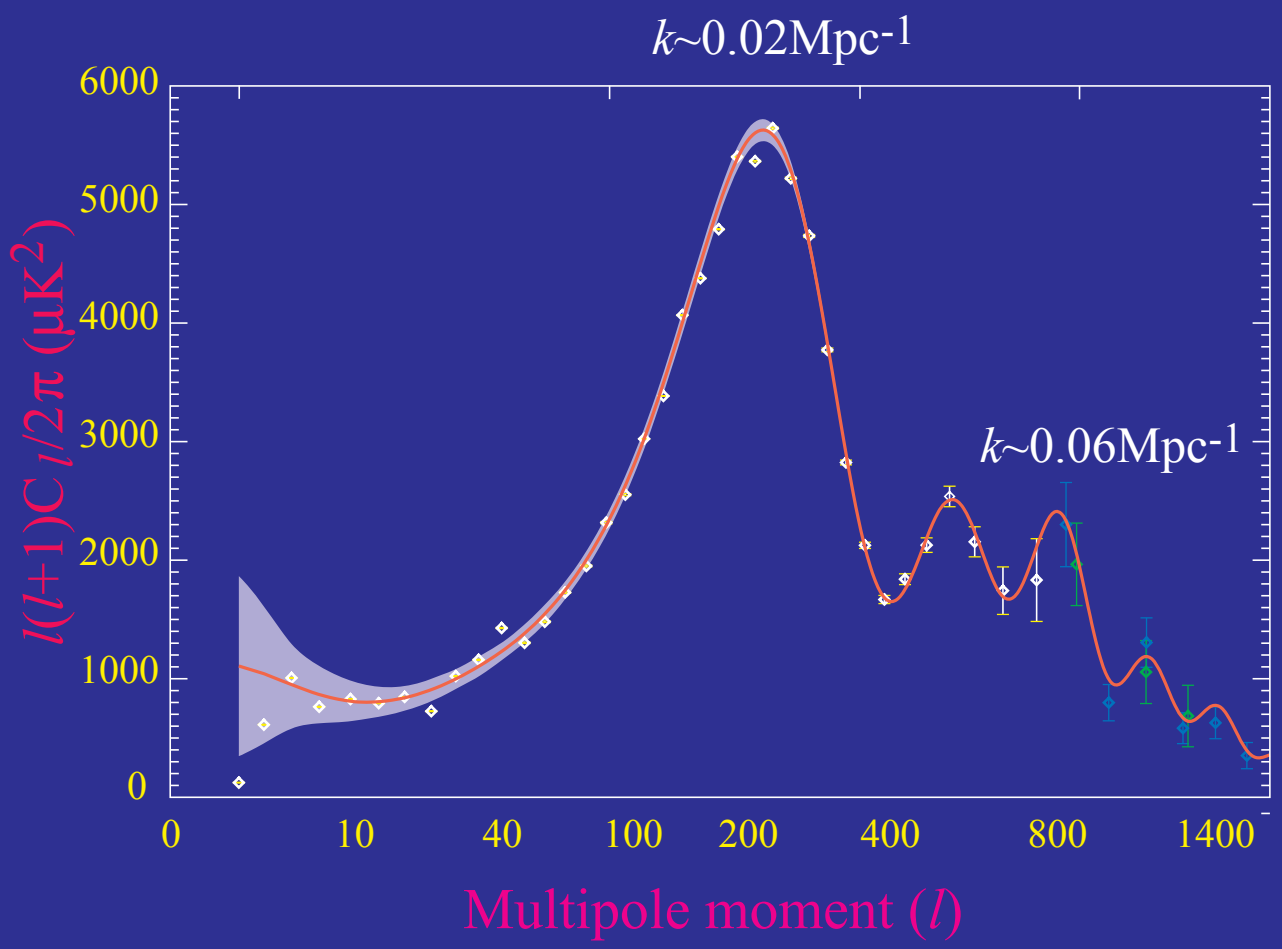
- Standard ruler used to measure the angular diameter distance to recombination (z~1100; currently 2-4%) or any redshift for which acoustic phenomena observable



WMAP: Bennett et al (2003)

Leveraging the CMB

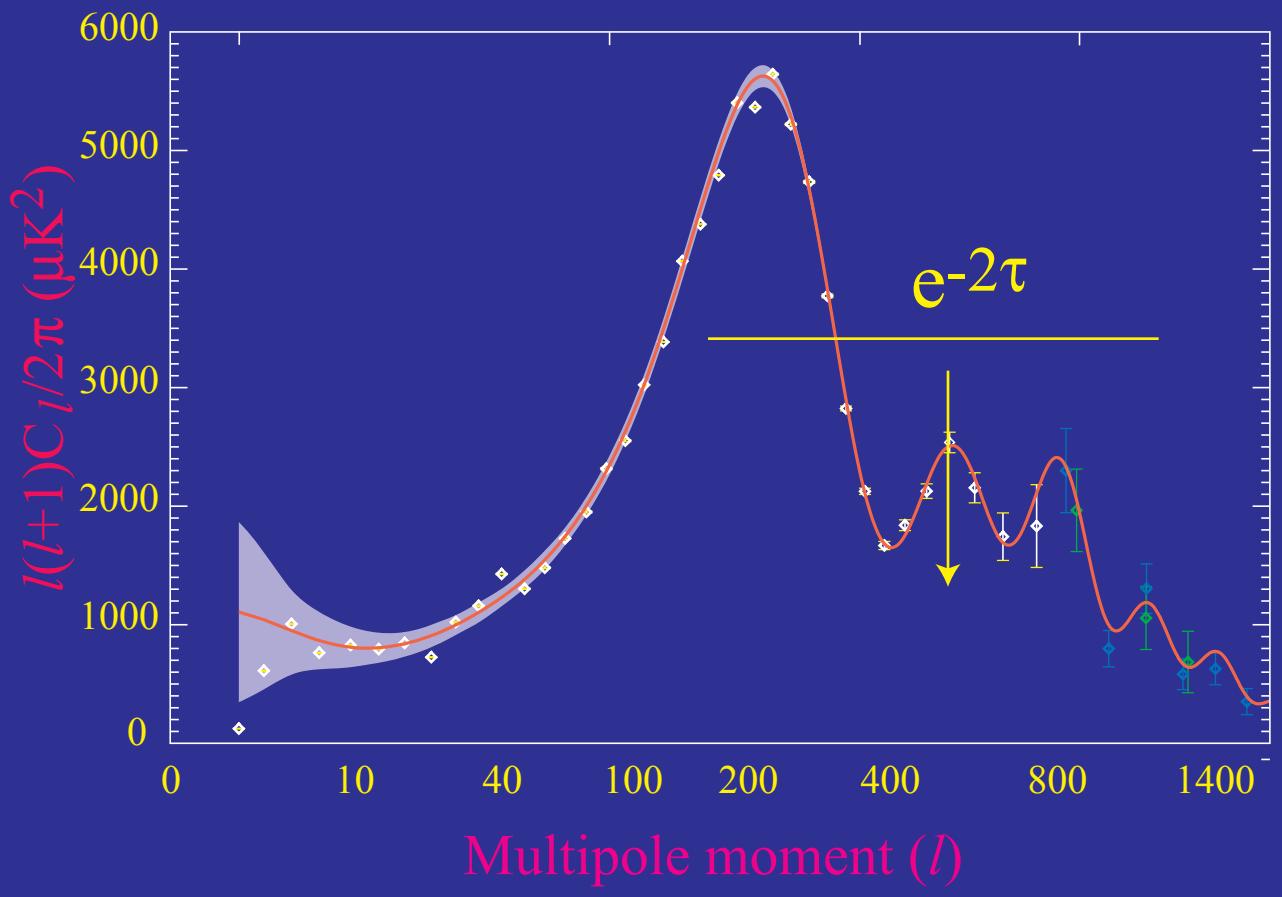
- Standard fluctuation: absolute power determines initial fluctuations in the regime 0.01-0.1 Mpc^{-1}



WMAP: Bennett et al (2003)

Leveraging the CMB

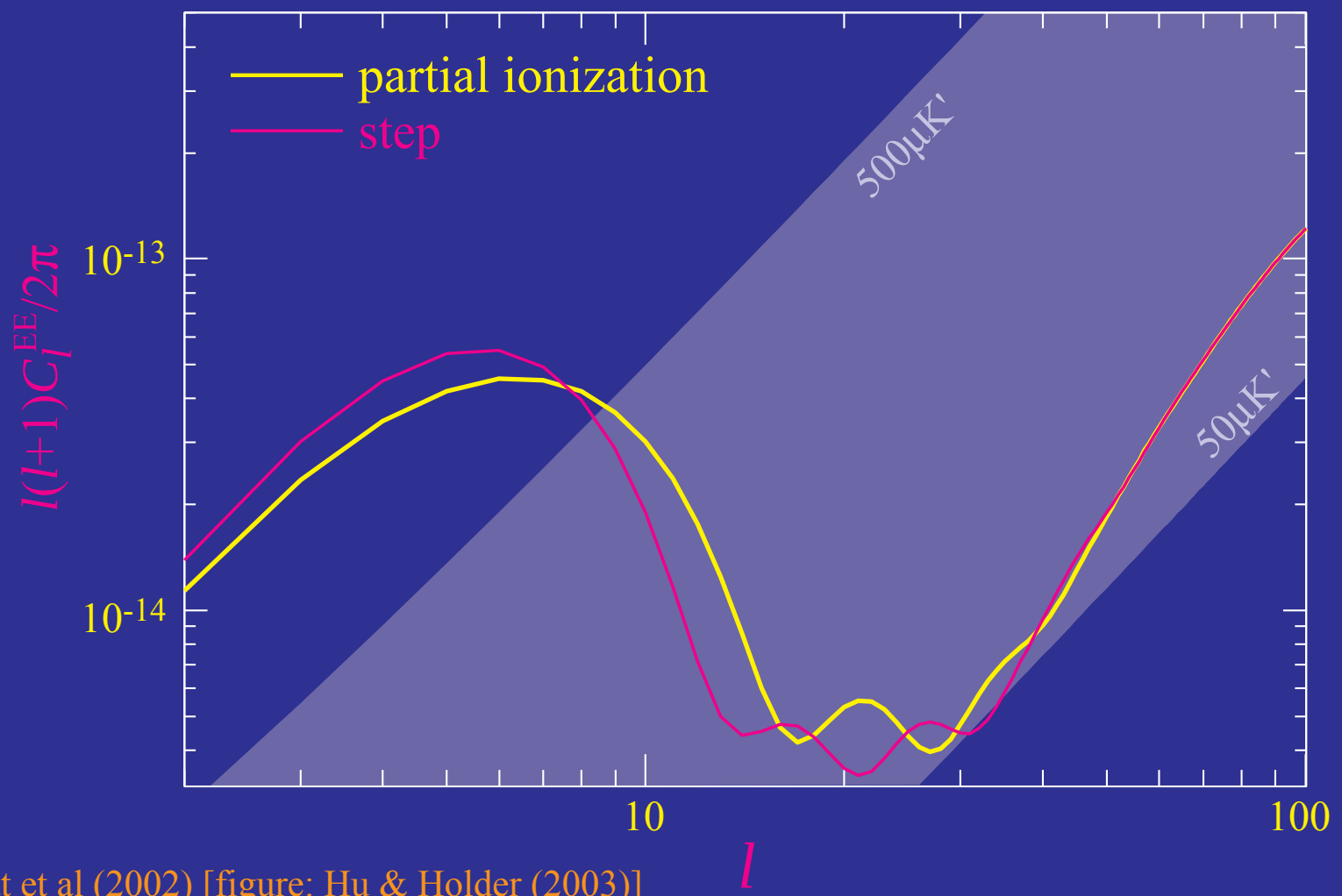
- Standard fluctuation: precision mainly limited by reionization which lowers the peaks as $e^{-2\tau}$; self-calibrated by polarization, cross checked by CMB lensing in future



WMAP: Bennett et al (2003)

Polarization Power Spectrum

- Most of the information on ionization history is in the polarization (auto) power spectrum - two models with same optical depth but different ionization fraction - model independent measure 1%



Kaplinghat et al (2002) [figure: Hu & Holder (2003)]

$\sigma_8(z)$

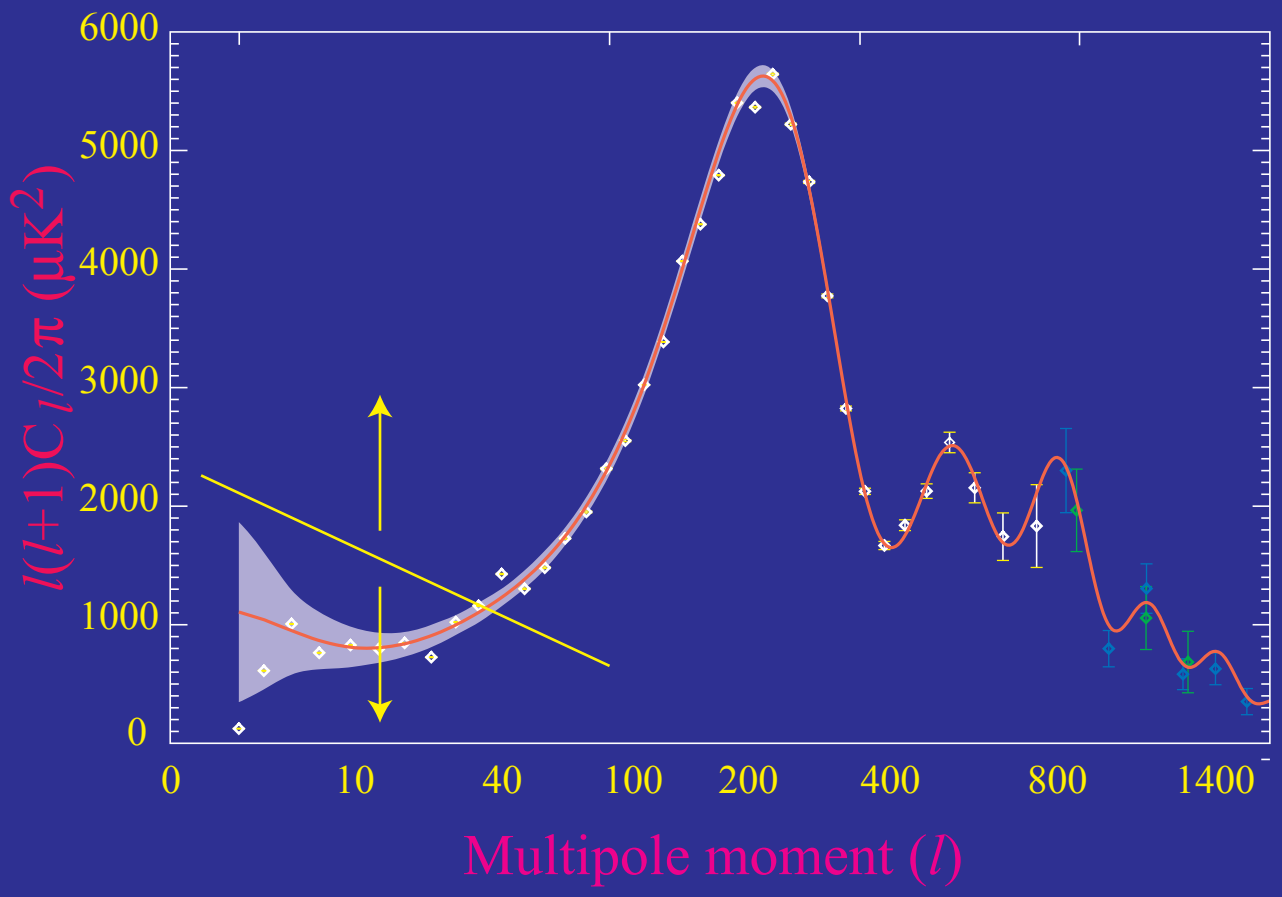
- Determination of the normalization during the acceleration epoch, even σ_8, measures the dark energy with negligible uncertainty from other parameters
- Approximate scaling (flat, negligible neutrinos: Hu & Jain 2003)

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

- 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

Leveraging the CMB

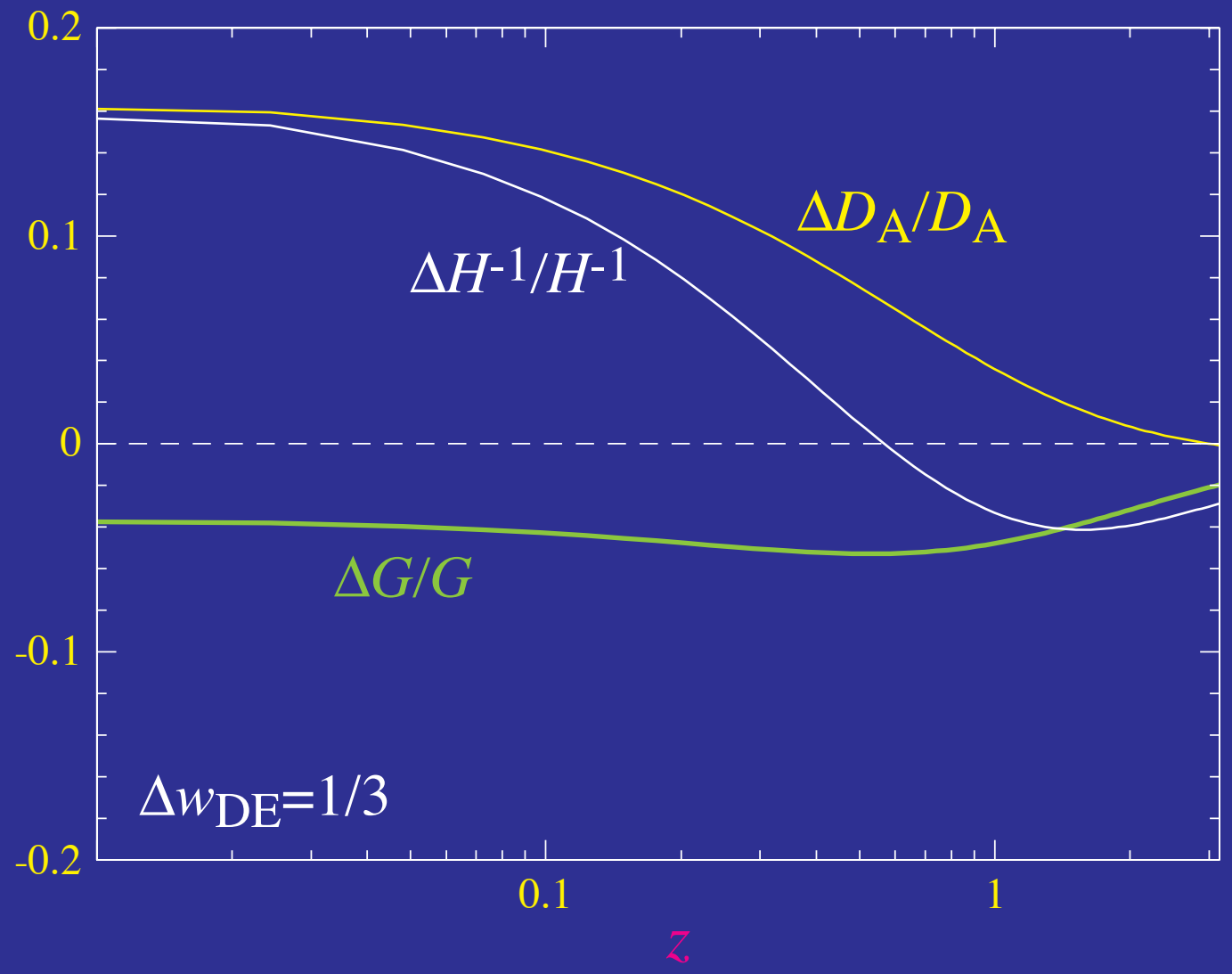
- Standard fluctuation: large scale - ISW effect; correlation with large-scale structure; clustering of dark energy; low multipole anomalies? polarization



WMAP: Bennett et al (2003)

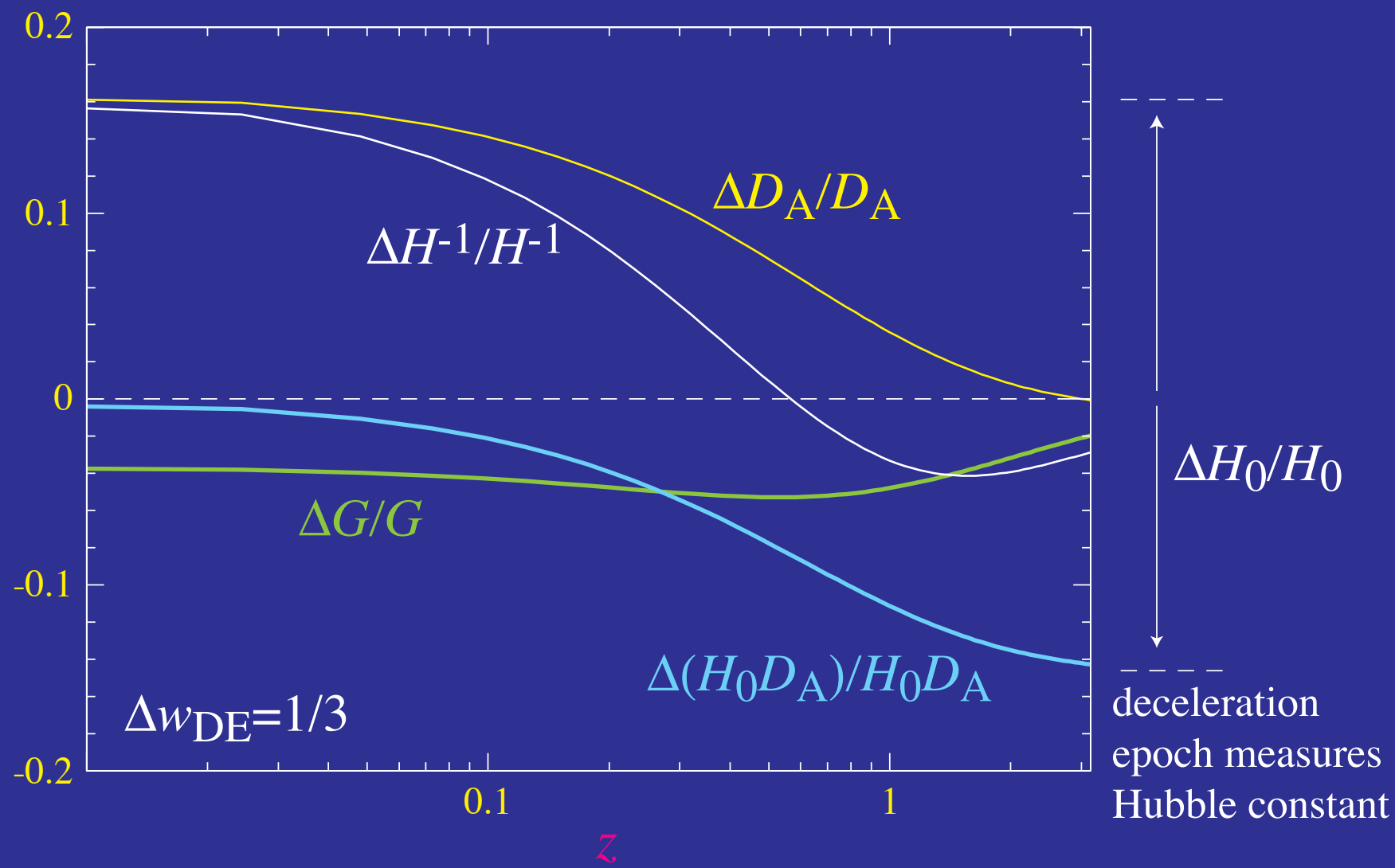
Dark Energy Sensitivity

- 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)



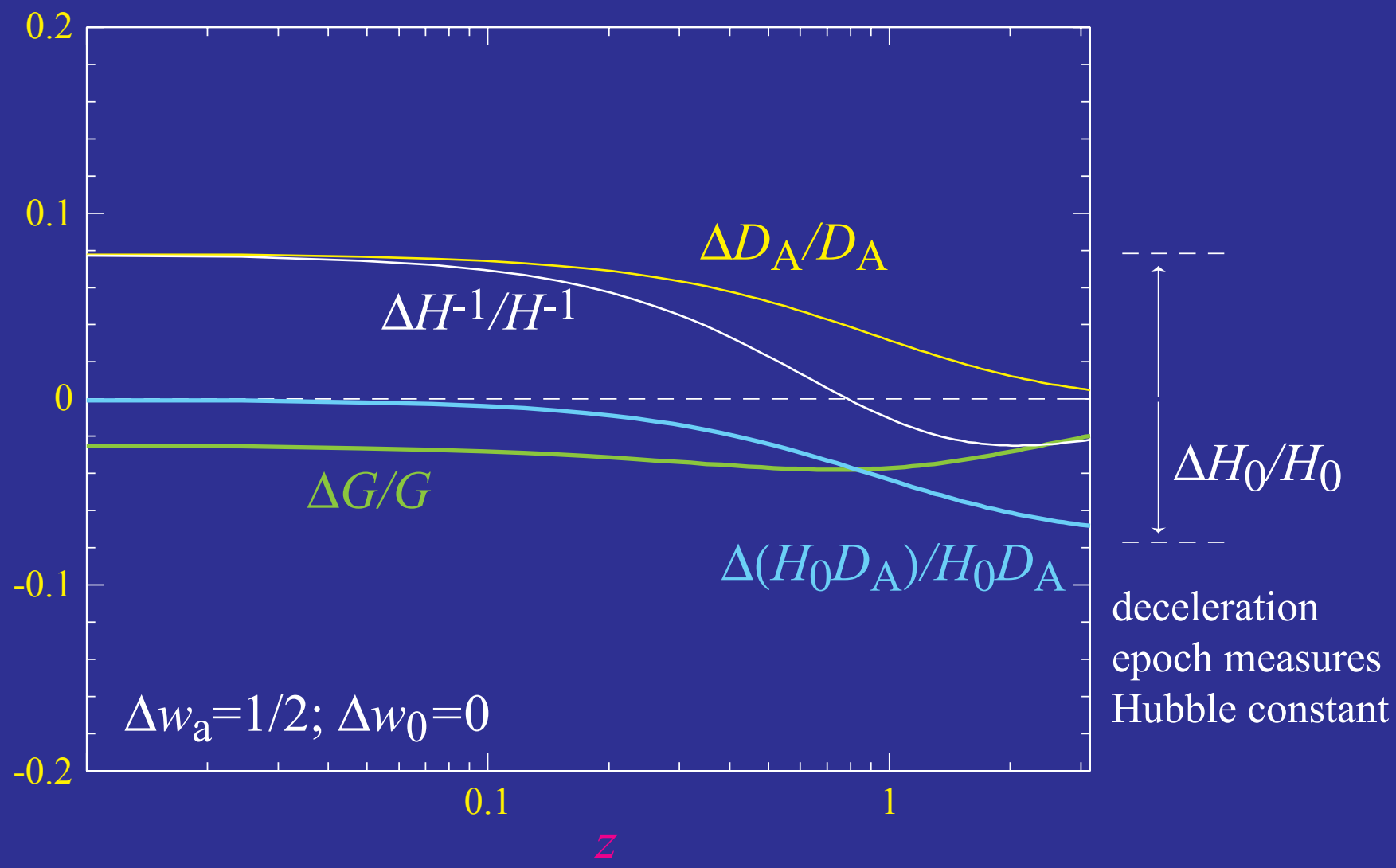
Dark Energy Sensitivity

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



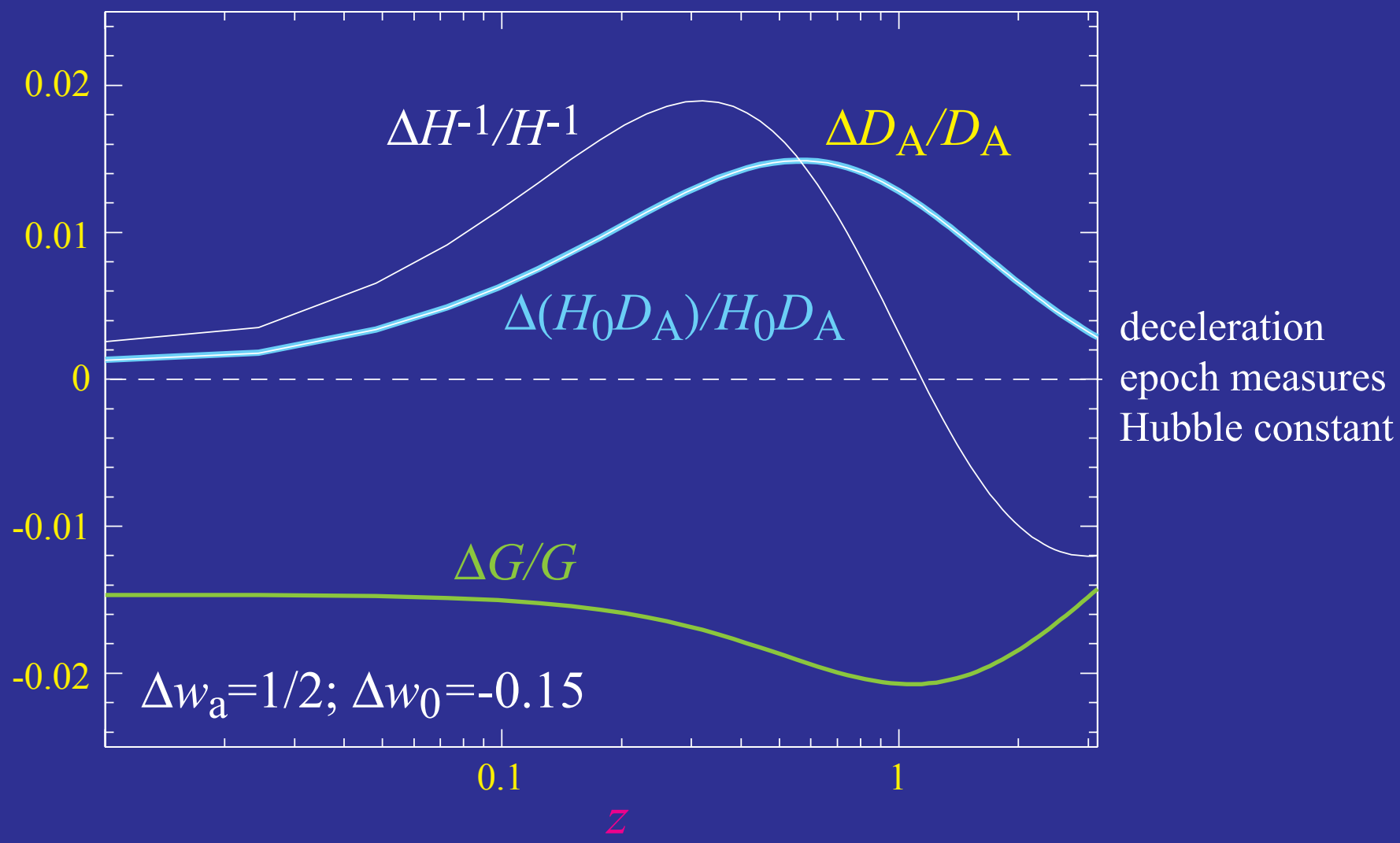
Dark Energy Sensitivity

- 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)



Dark Energy Sensitivity

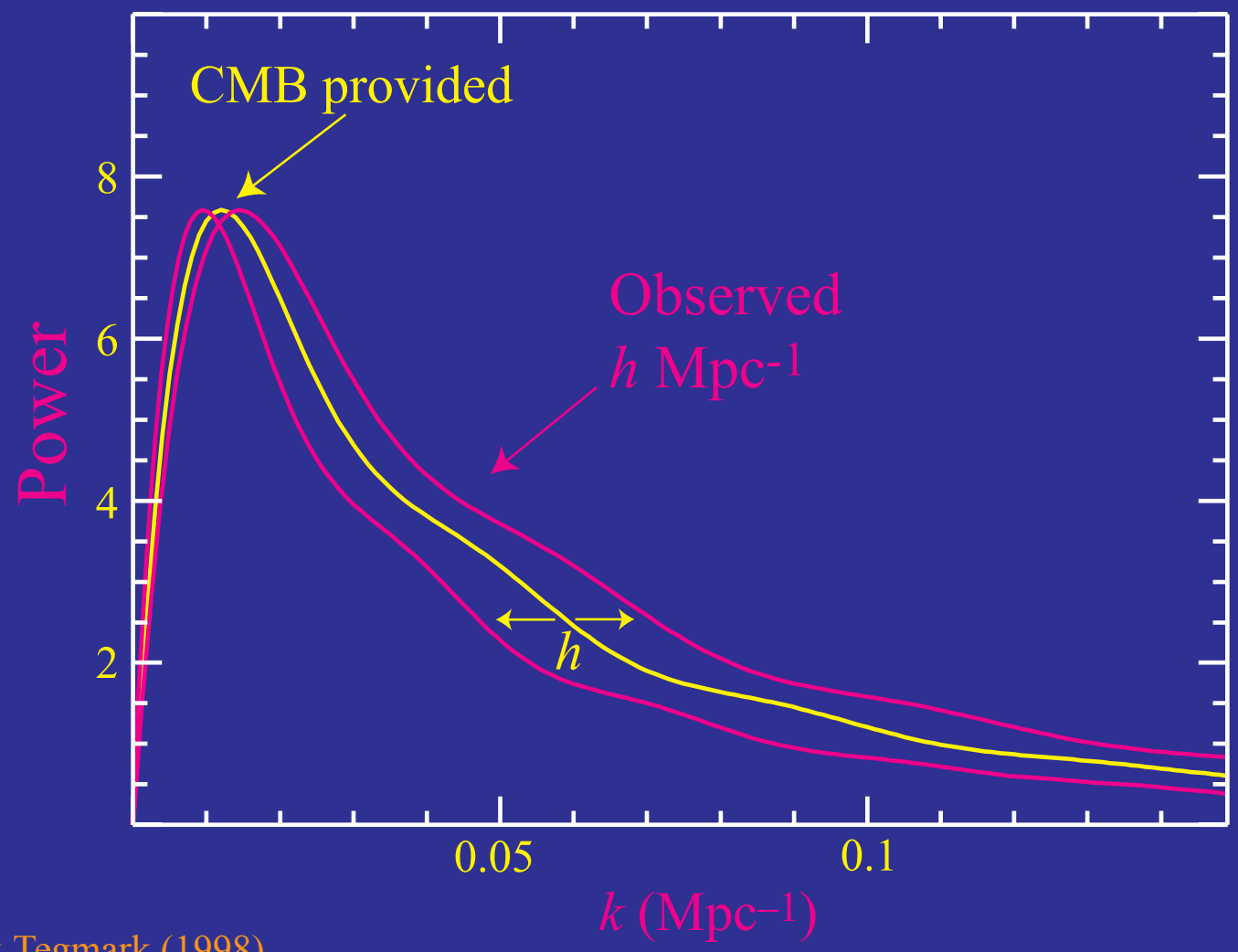
- Three parameter dark energy model: $w(z=0)=w_0$; $w_a=-\mathrm{d}w/\mathrm{d}a$; Ω_{DE}
- H_0 fixed (or Ω_{DE}); remaining w_0-w_a degeneracy
- Note: degeneracy does not preclude ruling out Λ ($w(z)\neq-1$ at some z)



Standard Rulers

Local Test: H_0

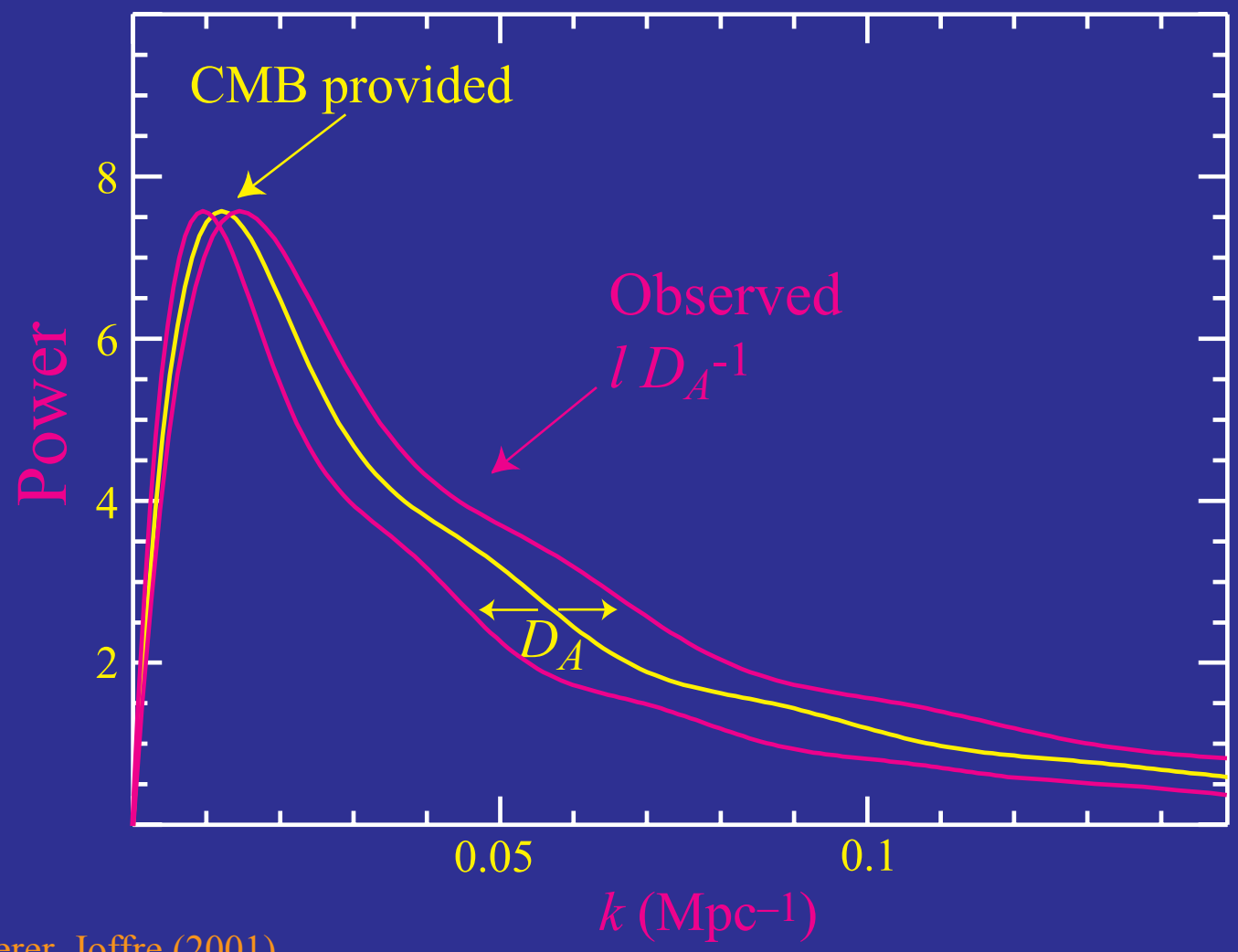
- Locally $D_A = \Delta z/H_0$, and the observed power spectrum is isotropic in h Mpc^{-1} space
- Template matching the features yields the Hubble constant



Eisenstein, Hu & Tegmark (1998)

Cosmological Distances

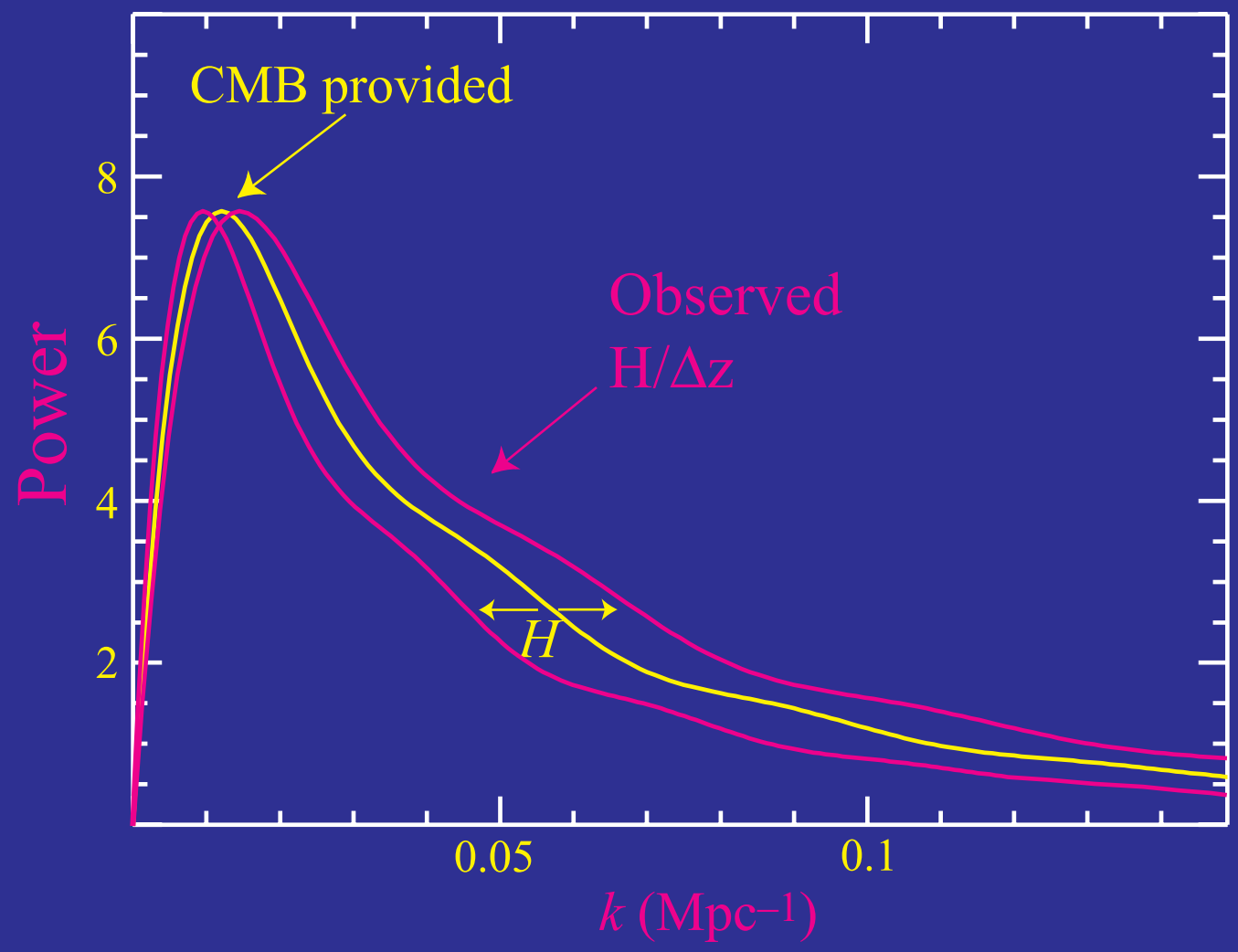
- Modes perpendicular to line of sight measure angular diameter distance



Cooray, Hu, Huterer, Joffre (2001)

Cosmological Distances

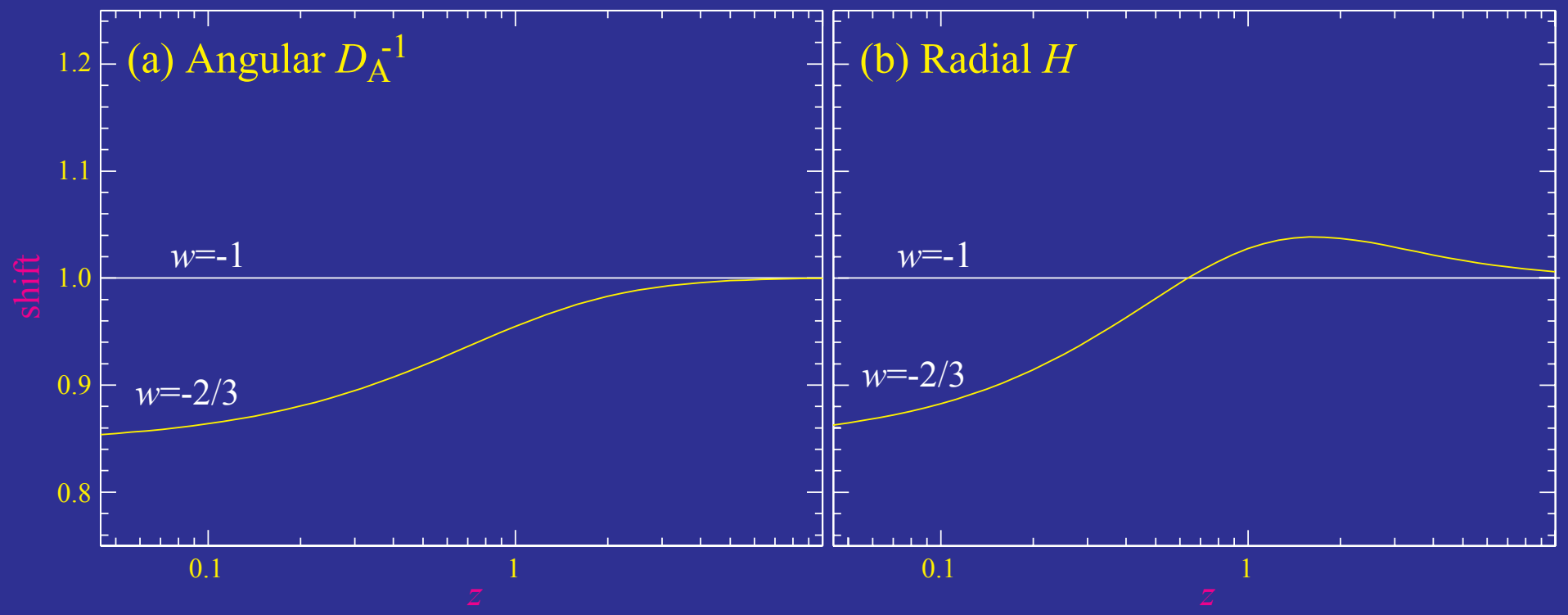
- Modes parallel to line of sight measure the Hubble parameter



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

$D_A(z)$ and $H(z)$

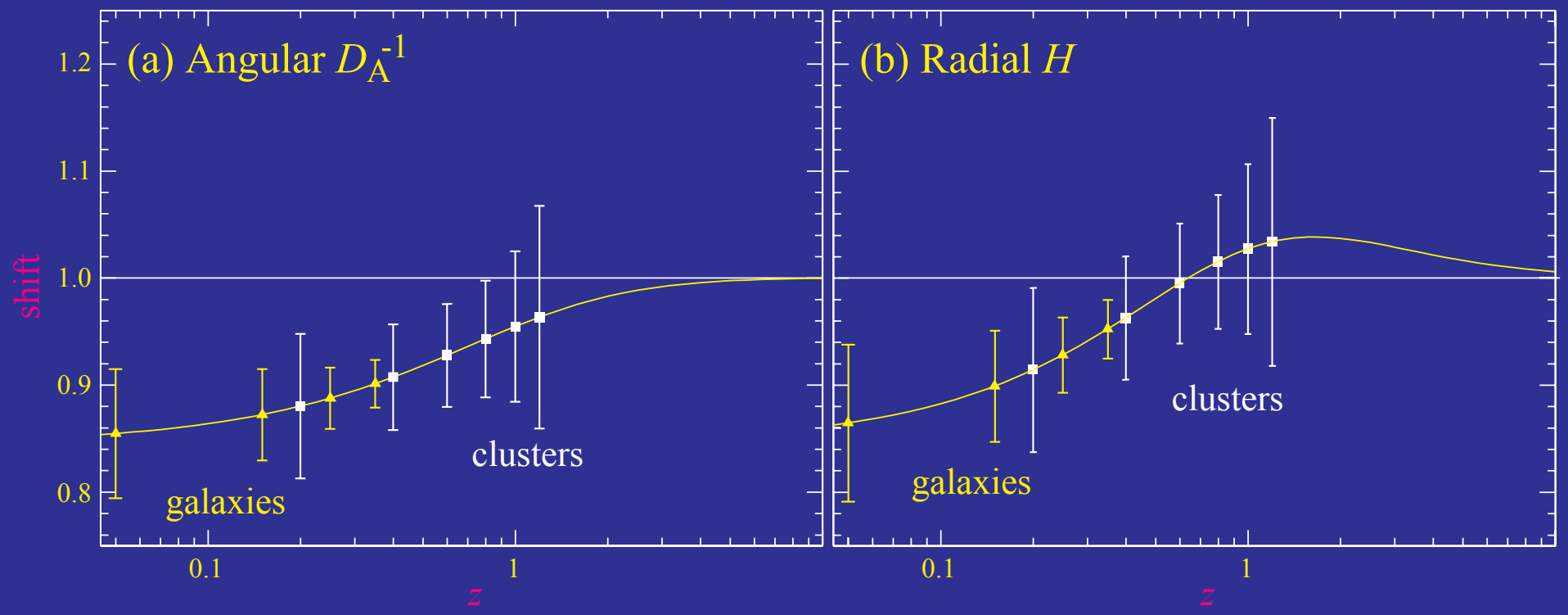
- Shifts at moderate redshift are comparable to deviation in w
- High-z D_A, H fixed by CMB - in a flat universe fixes Ω_m given w
- Future: analysis of surveys with power spectrum shape fixed
  - replace band powers with bands in D_A and H



Hu & Haiman (2003)

$D_A(z)$ and $H(z)$

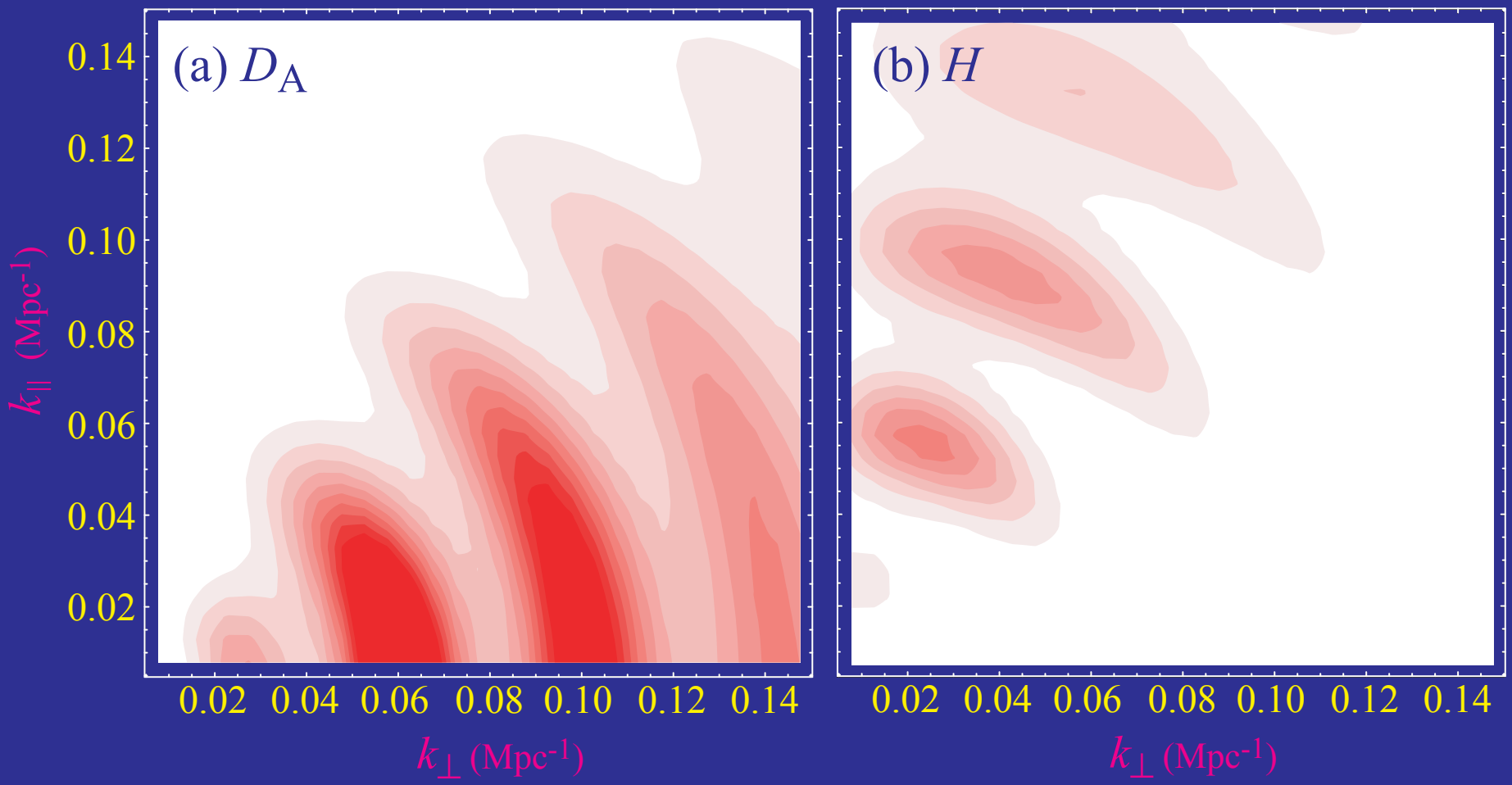
- Complementary D_A measures at $z<1$ - requires photo-z $\delta z<0.1$
- Complementary H measures at $z<2$ - requires good redshifts $\delta z<0.01$ (approaching possible with cluster photo-z)



Hu & Haiman (2003)

Information Density

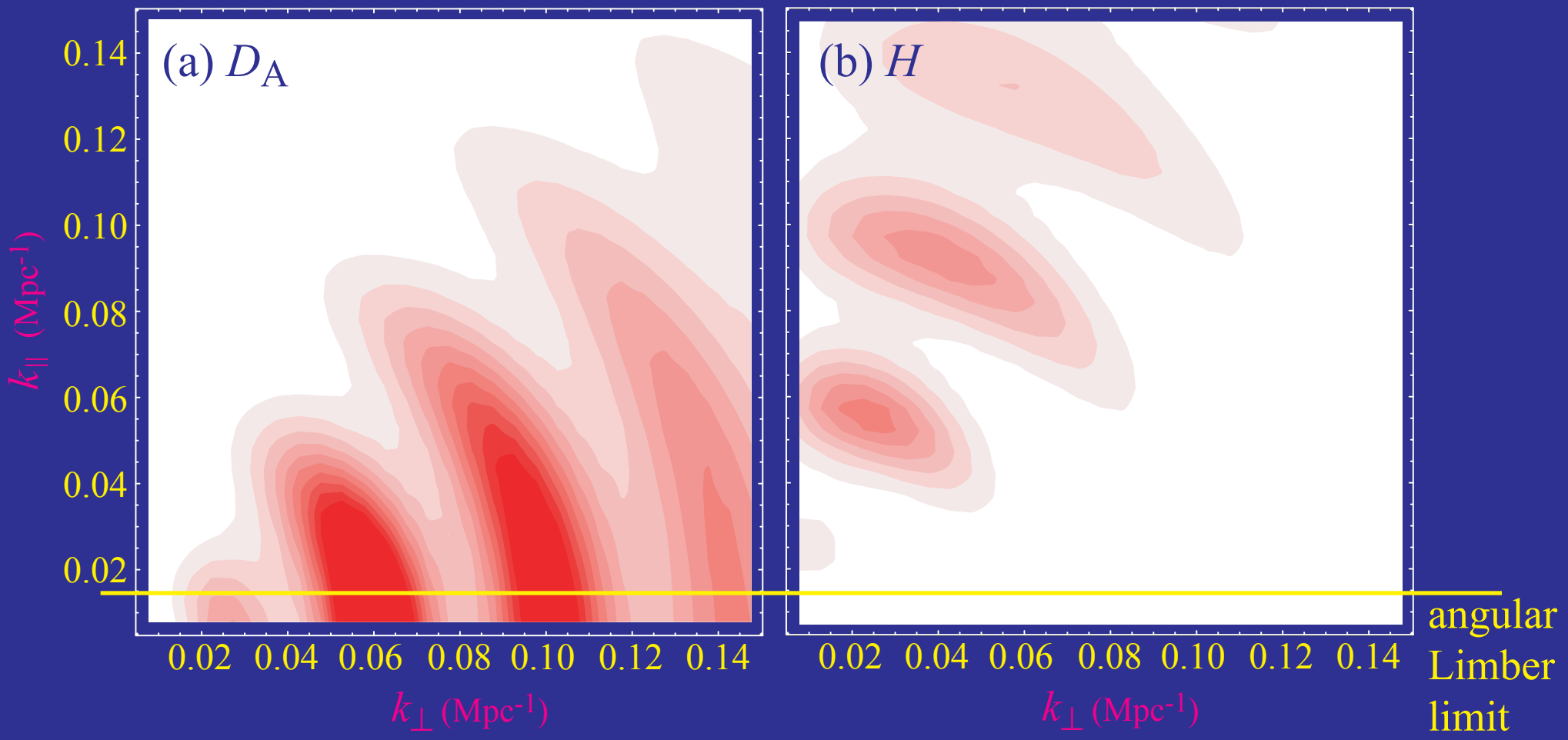
- Information density in k-space sets requirements for the redshifts
- A cluster based example



Haiman & Hu (2003)

Projected Power

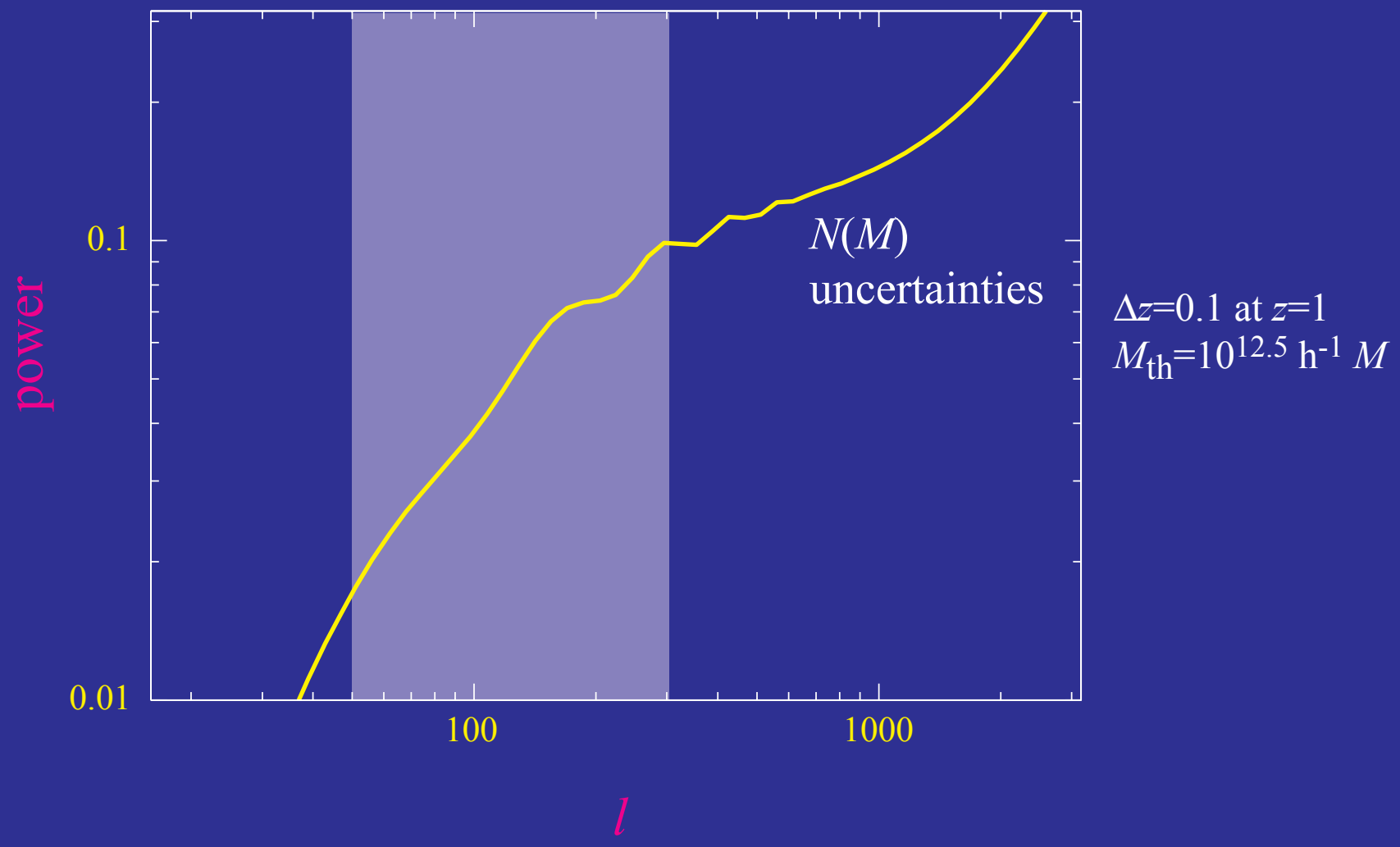
- Information density in k-space sets requirements for the redshifts
- Purely angular limit corresponds to a low-pass $k_{||}$ redshift survey in the fundamental mode set by redshift resolution



Haiman & Hu (2003)

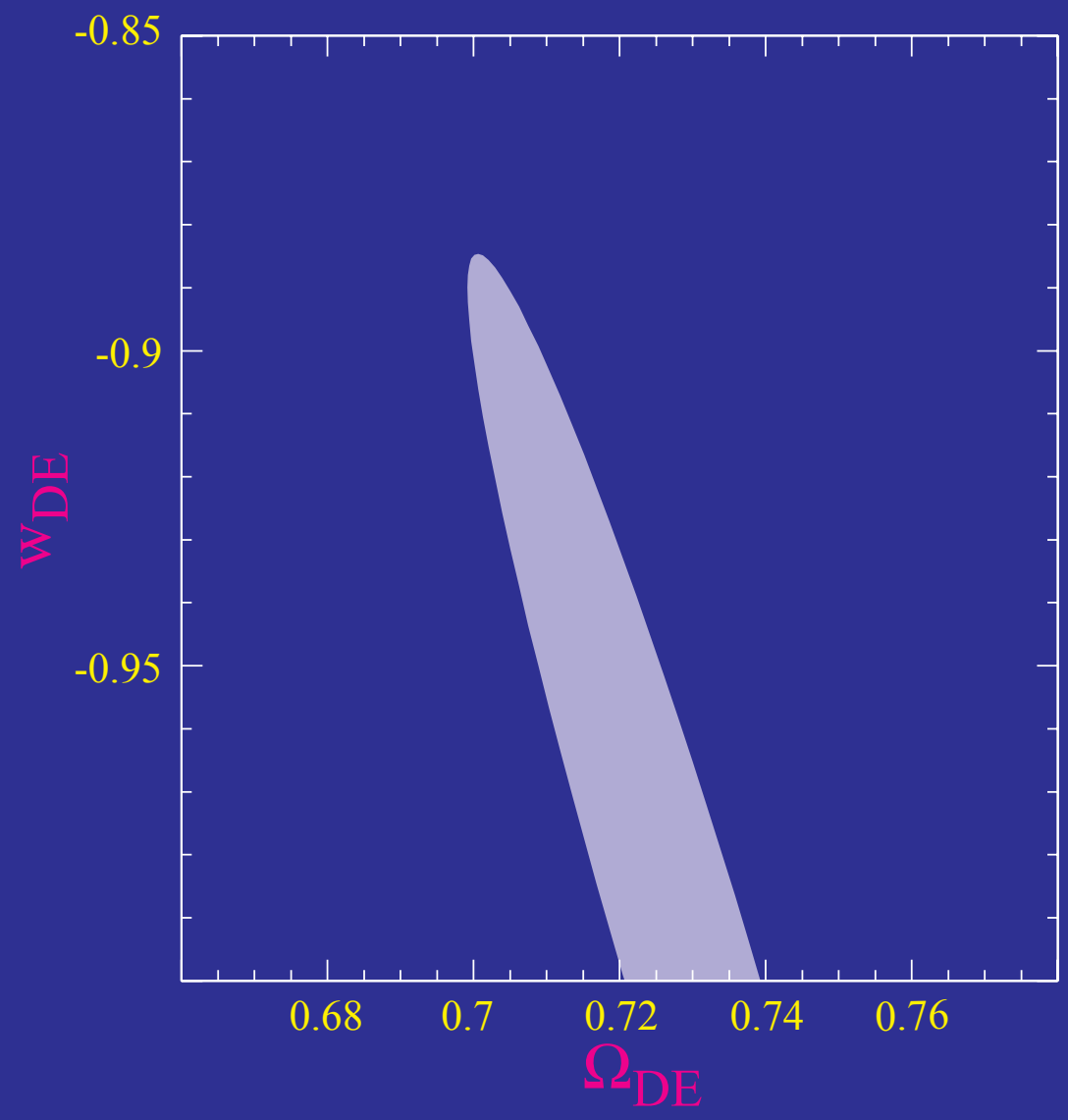
Angular Power Spectra

- Wiggles preserved at high redshift even for thick redshift shells; destroyed by non-linear effects, $N(M)$



Angular Power Spectrum

- Purely geometric constraint, absolutely calibrated at all z
- Combine with CMB distance [$\Omega_m h^2$ 1%] with constant w



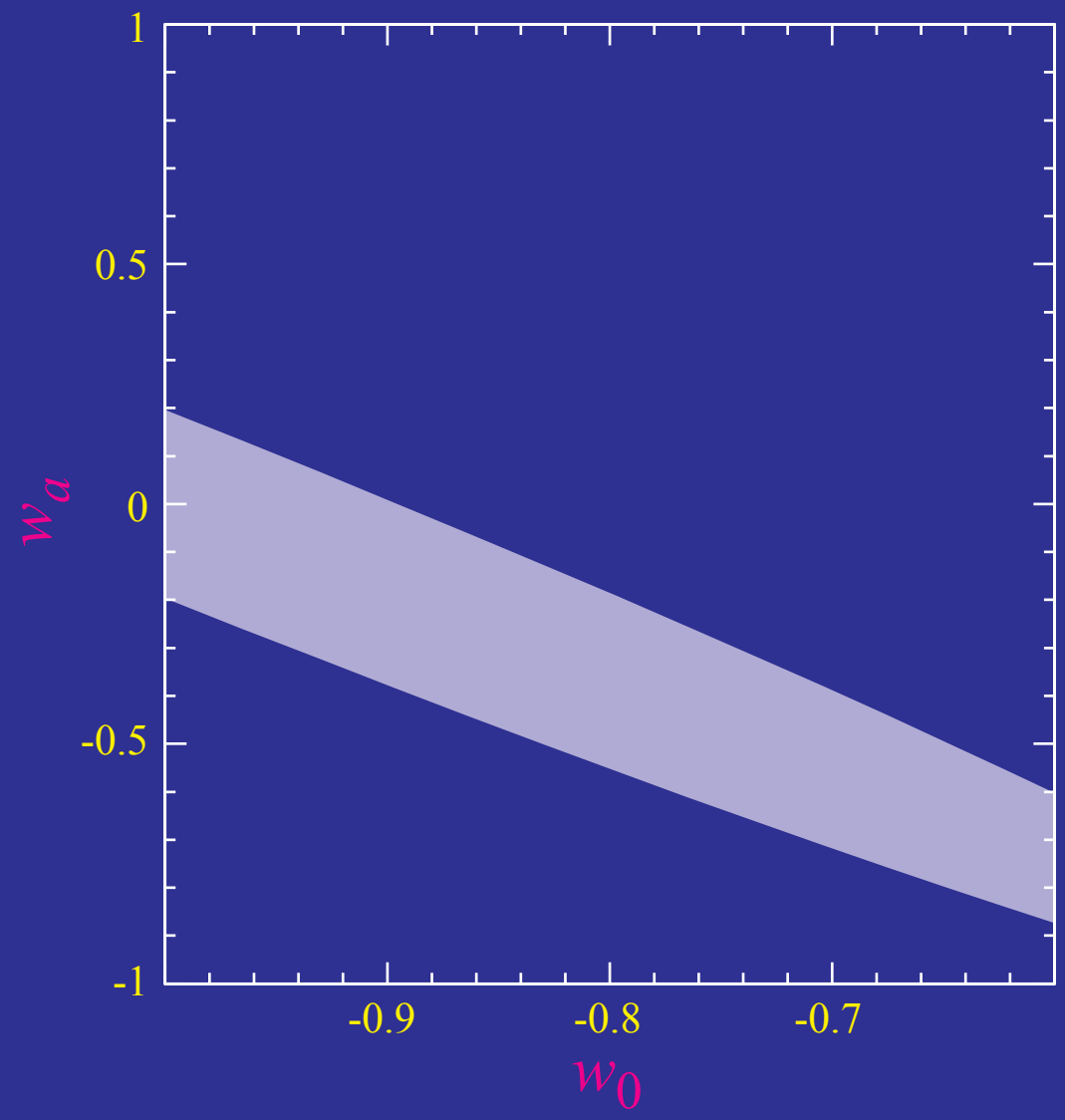
10 power spectra
Δz=0.1 to z=1
l=50-300

4000 deg^2
$M_{th}=10^{12.5}$ h^{-1} $M_\odot$

nonlinear bias
marginalized with
50 halo parameters

Angular Power Spectrum

- Purely geometric constraint
- Degeneracy in $w(z)$ remains



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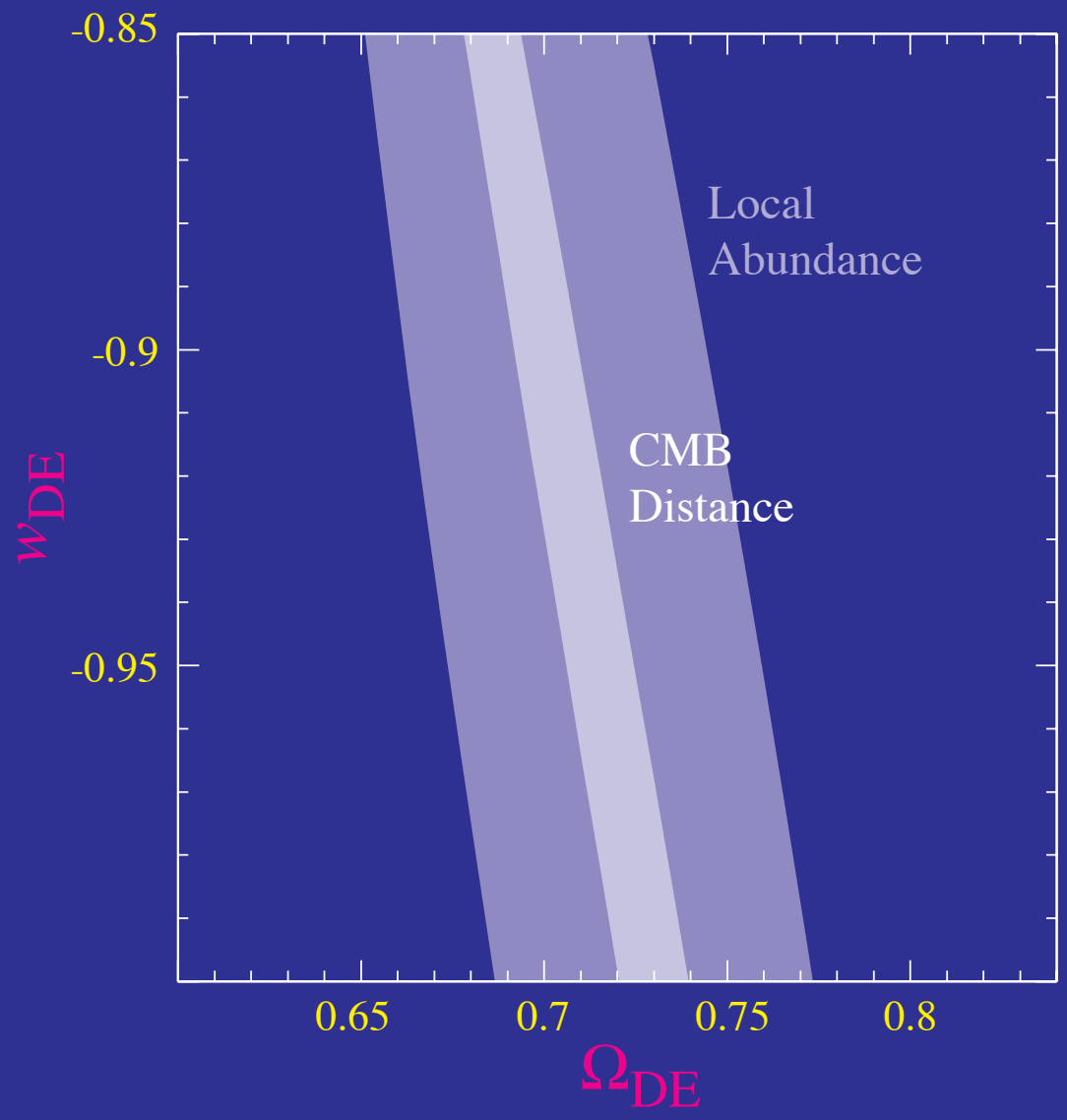
Standard Fluctuations

Local Abundance

- Local abundance constrains constant w in a flat universe in the same direction as $D_A(z=1100)$; consistency check on flatness, $m_\nu \ll 1$eV
- CMB distance power spectrum priors only + current X-ray sample:

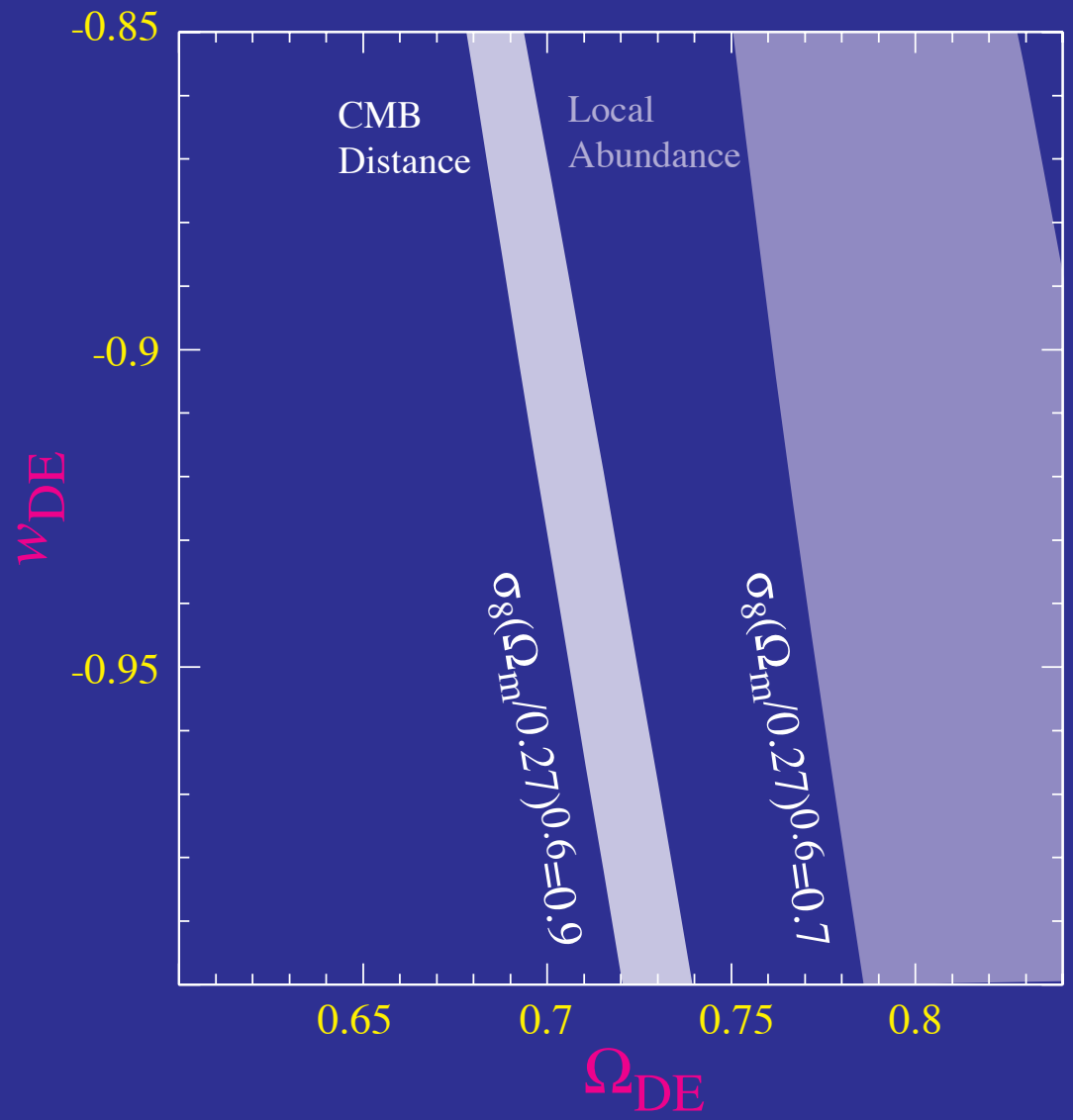


X-rays:
$f_{lim}=2\times10^{-14}$ Wm^{-2}
$z_{lim}=0.09$

CMB:
τ: 0.5%
$\Omega_m h^2$:1%

Caveat Emptor!

- Empirical calibration of M-T_X relation would imply inconsistency
- Without cross checks, infer wrong w from complementary probes
- Accurate calibration of mass-observable relations will be required

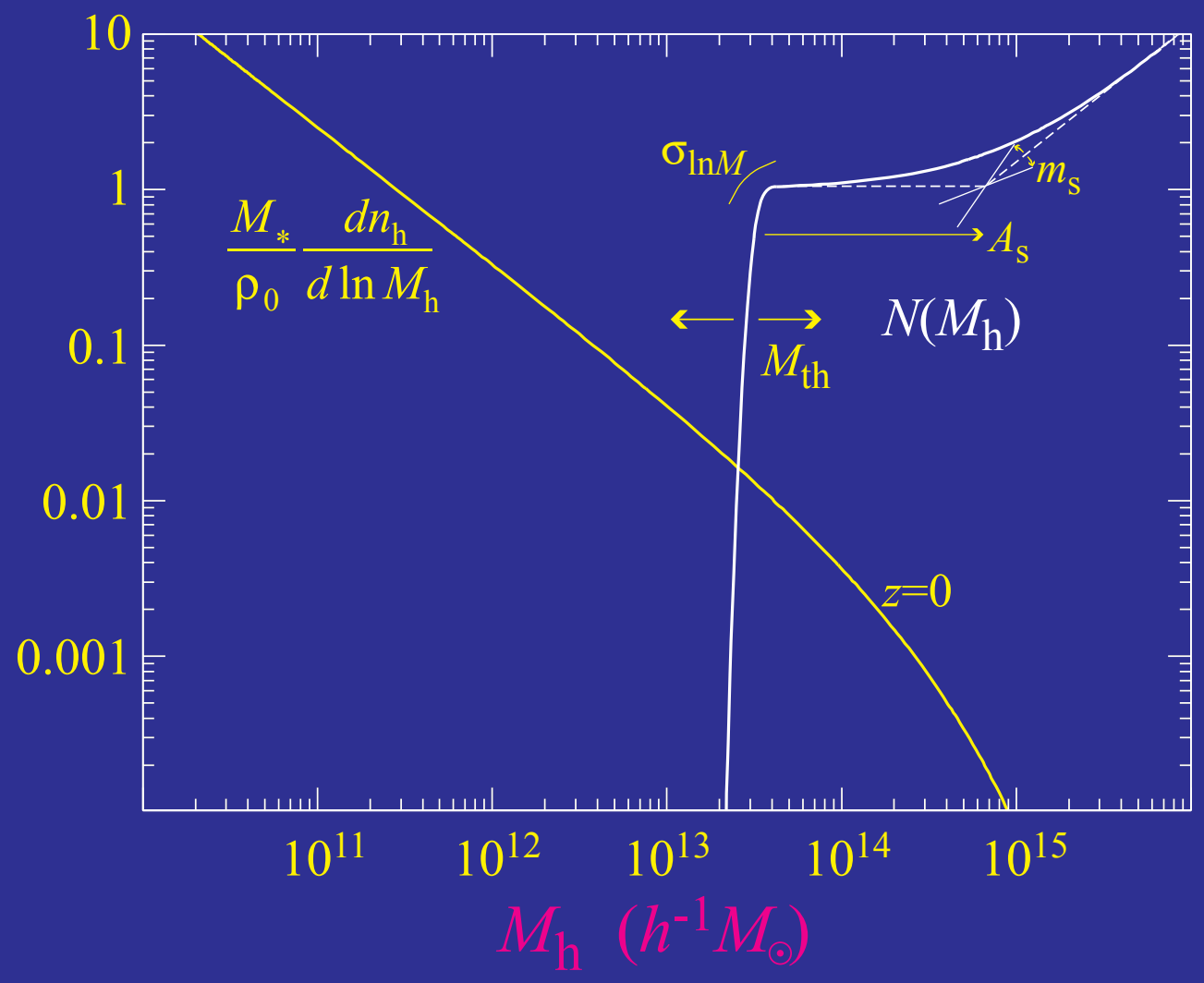


X-rays:
$f_{lim}=2\times10^{-14}$ Wm^{-2}
$z_{lim}=0.09$

CMB:
τ: 0.5%
$\Omega_m h^2$:1%

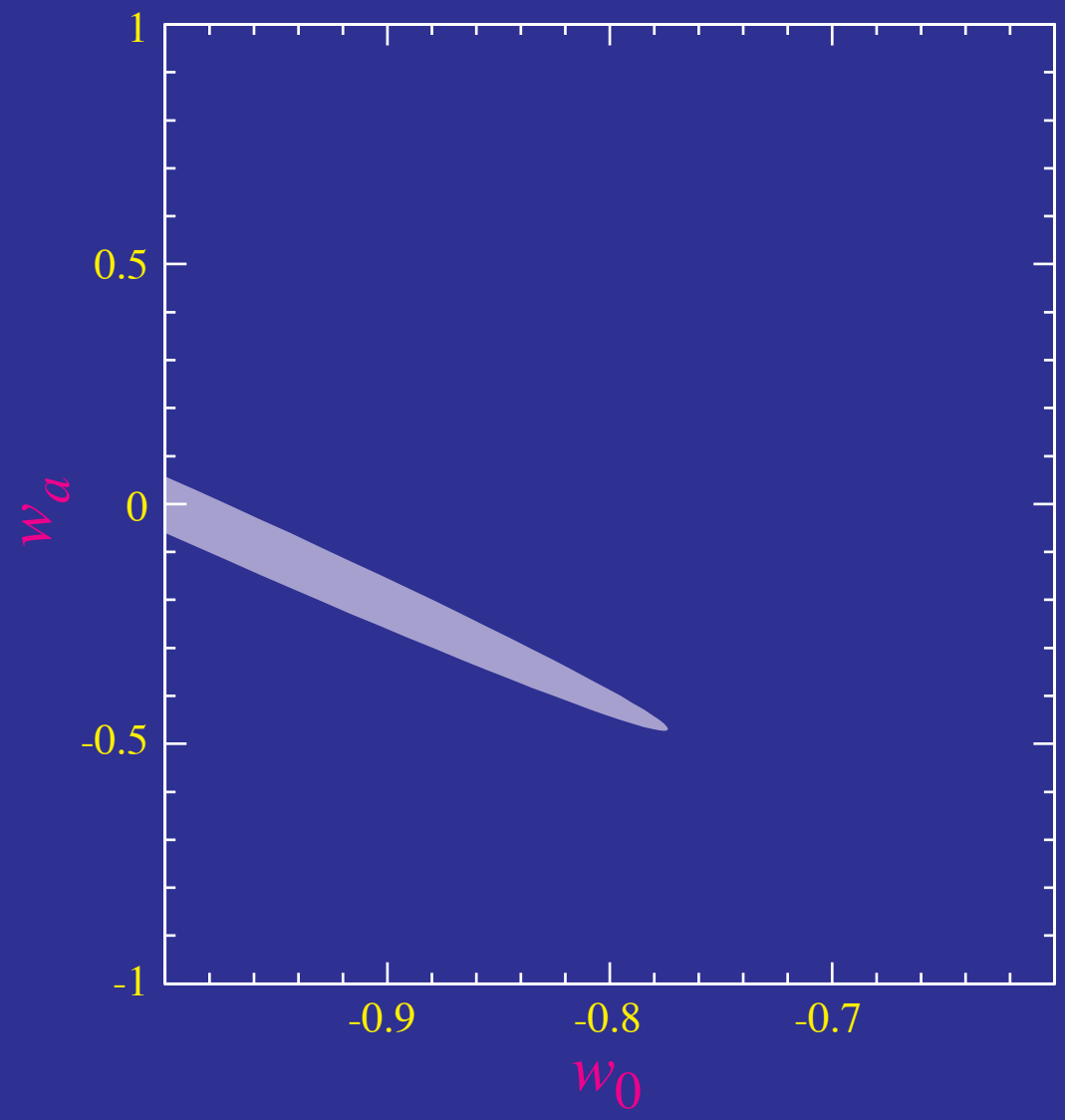
Mass-Observable Relation

- 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



Cluster Abundance

- Powerful probe of growth rate combined with CMB high-z normalization and distance [τ – 0.5%, $\Omega_m h^2$ – 1%]

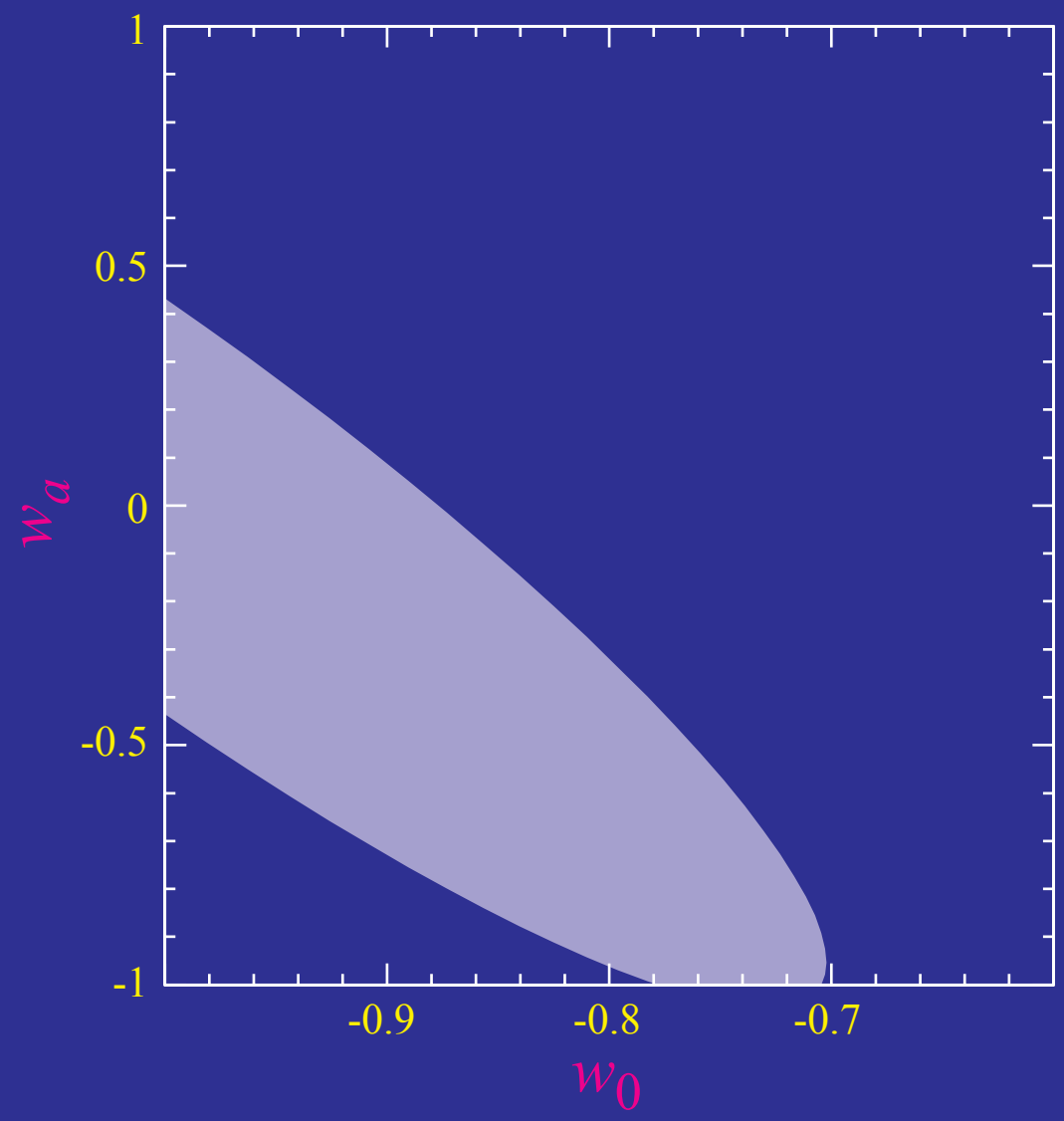


10 redshift bins
Δz=0.1 to z=1

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

Cluster Abundance

- Power law evolution in mass-observable relation

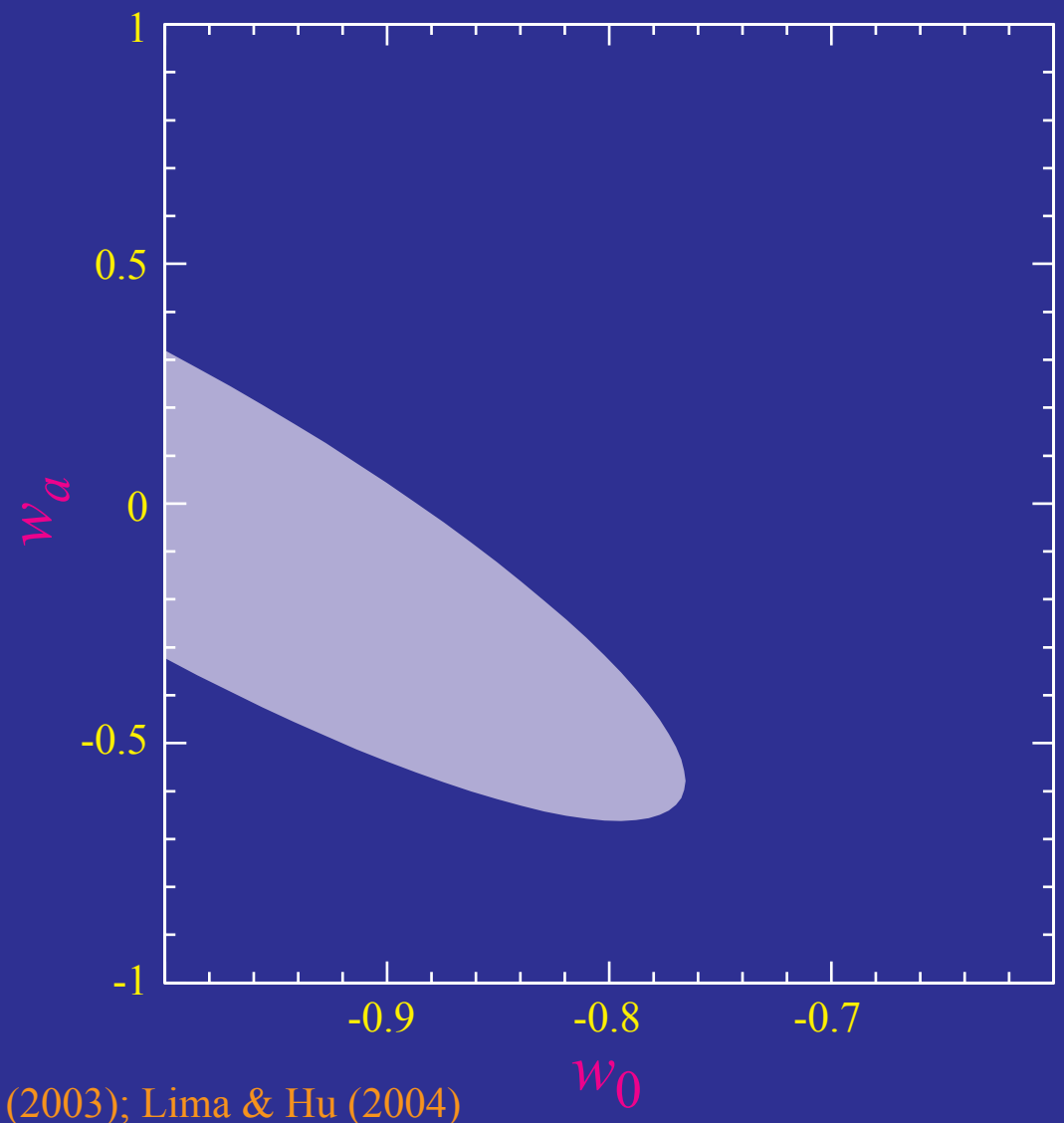


10 redshift bins
Δz=0.1 to z=1

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

Cluster Abundance

- Self calibration with variance of counts



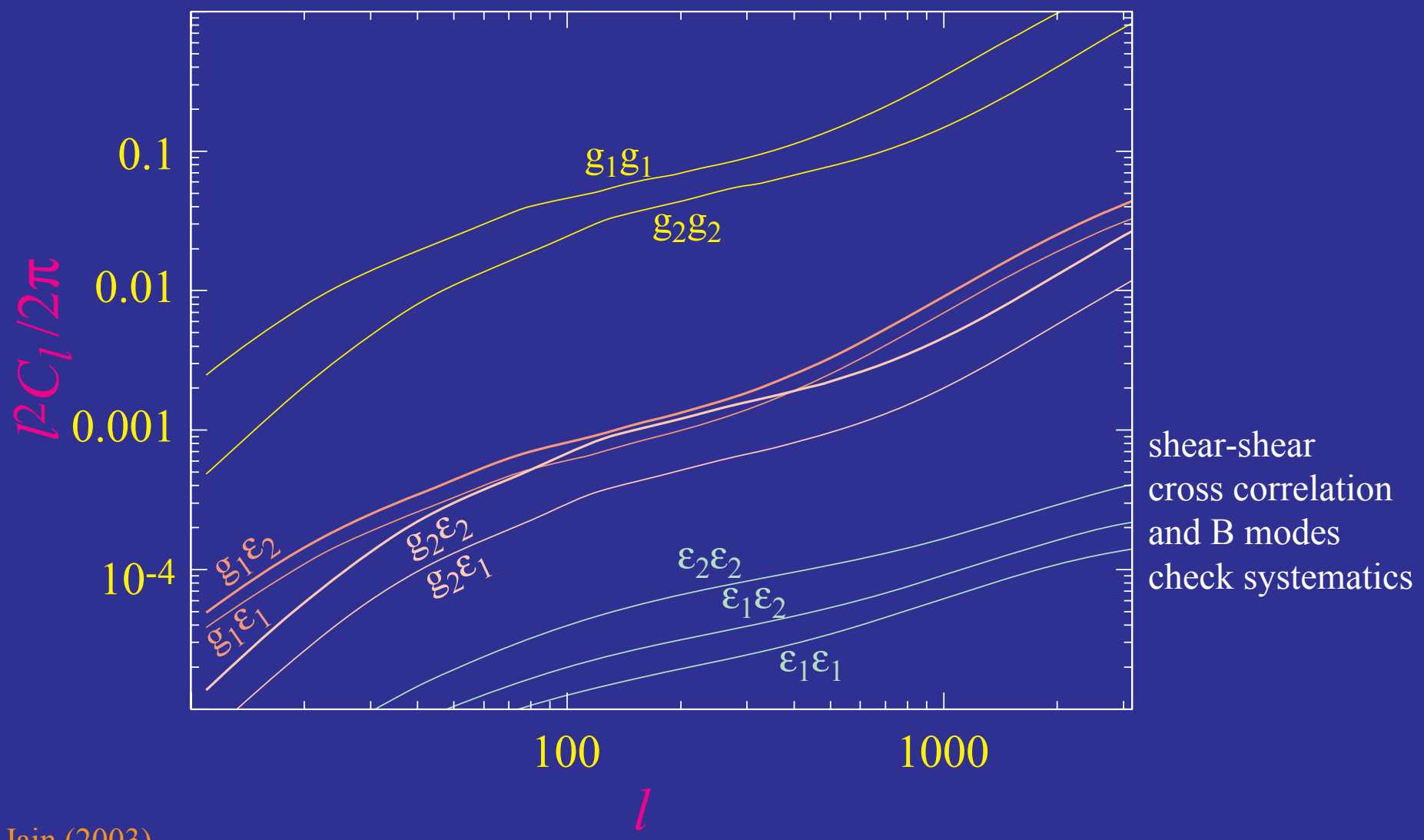
10 redshift bins
Δz=0.1 to z=1
10 degree cells

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

Majumdar & Mohr (2003); Lima & Hu (2004)

Galaxy-Shear Power Spectra

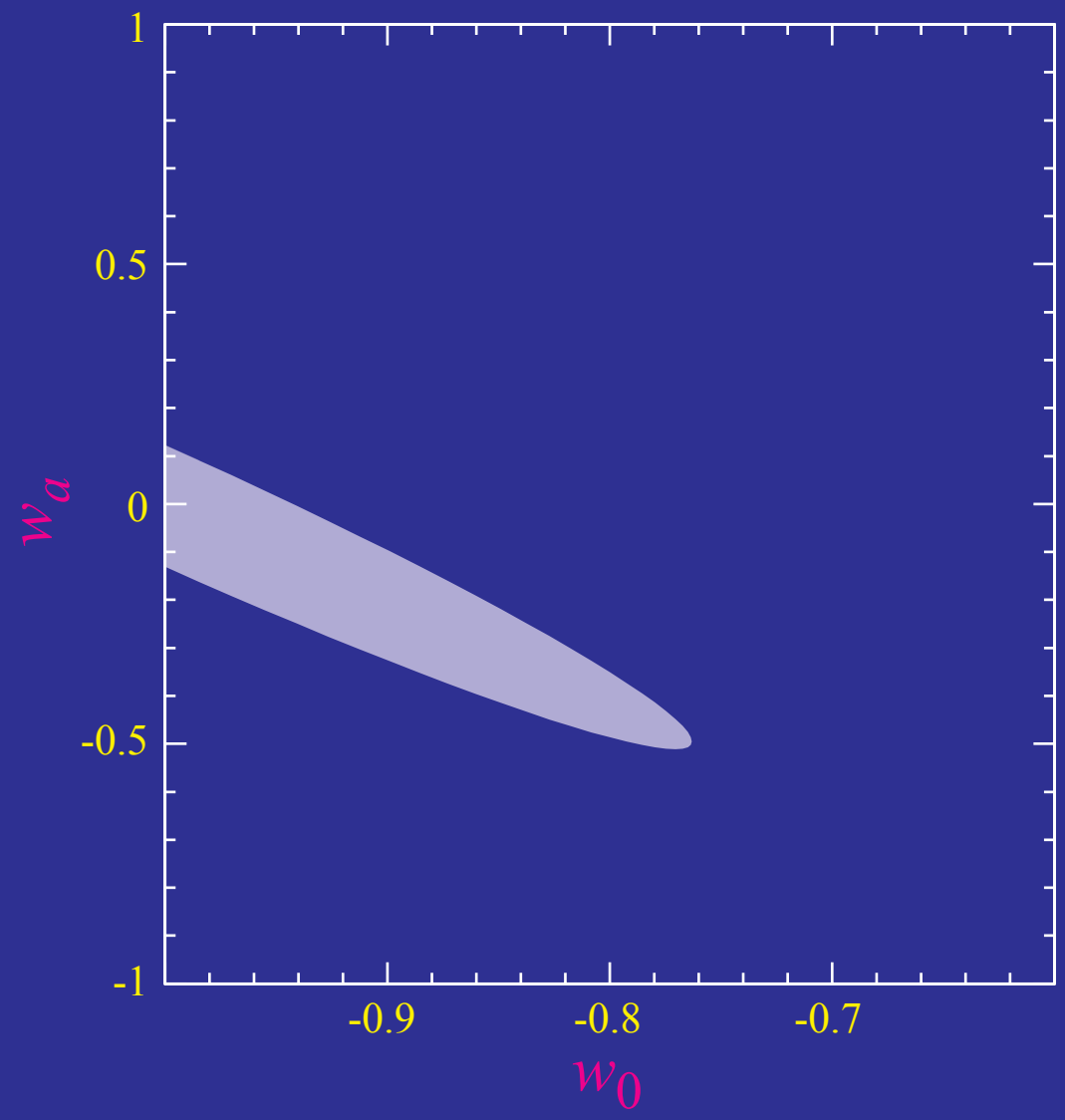
- Auto and cross power spectra of galaxy density and shear in multiple redshift bins



Hu & Jain (2003)

Galaxy-Shear Correlations

- Galaxy-shear cross spectrum and galaxy-galaxy power spectrum allow for a calibration of galaxy bias hence measure growth



10 redshift bins
Δz=0.1 to z=1
l=50-1000

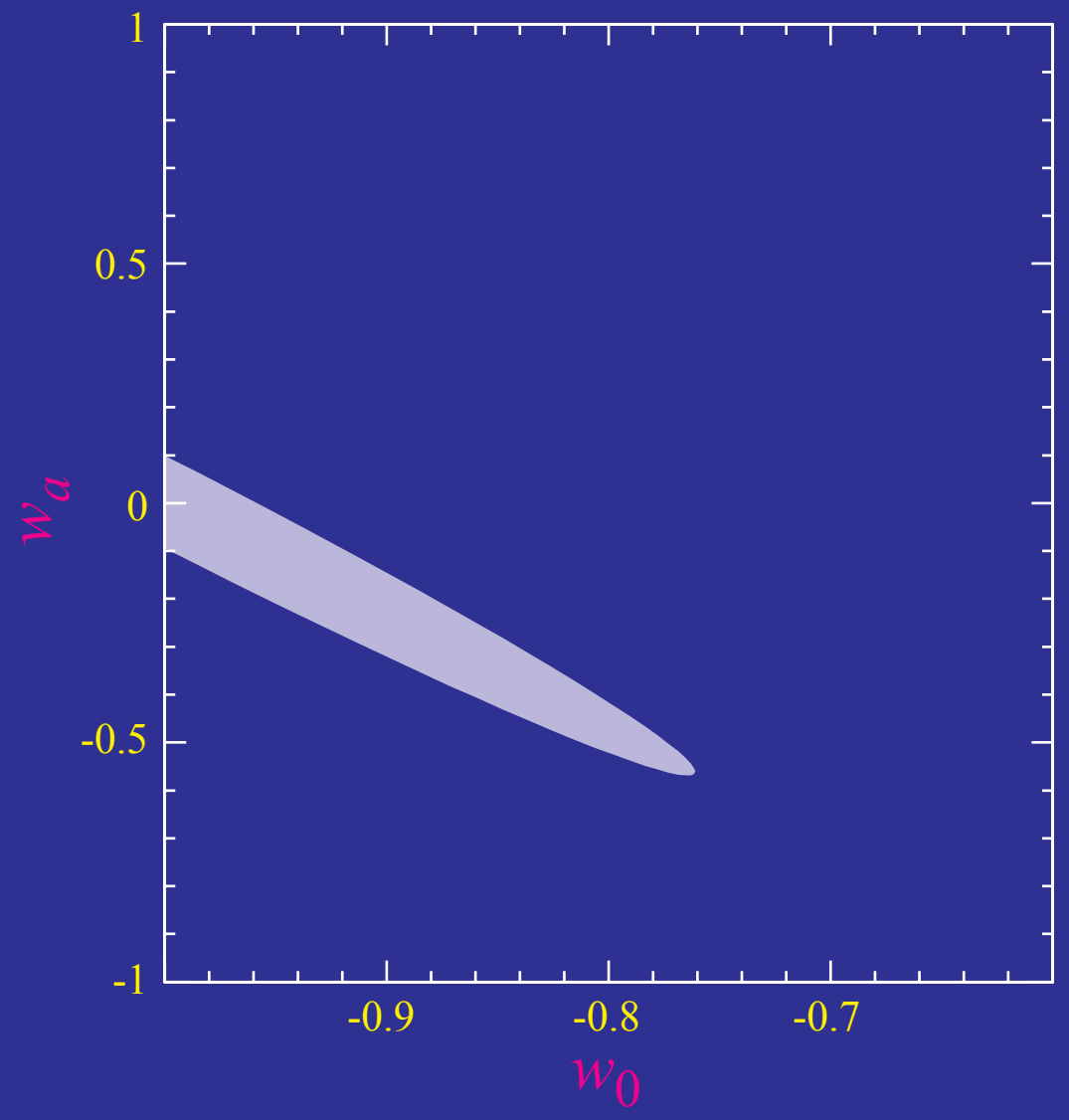
5 shear bins
Δz=0.25 to z=1 + z>1
γ_{rms}=0.16; z_{med}=0.7
n=10 gal/arcmin^2

4000 deg^2
$M_{th}=10^{12.5}$ h^{-1} $M_\odot$

nonlinear bias or N(M)
marginalized with
50 halo parameters

Shear-Shear Correlations

- Cosmic shear statistical forecast:



l=50-3000

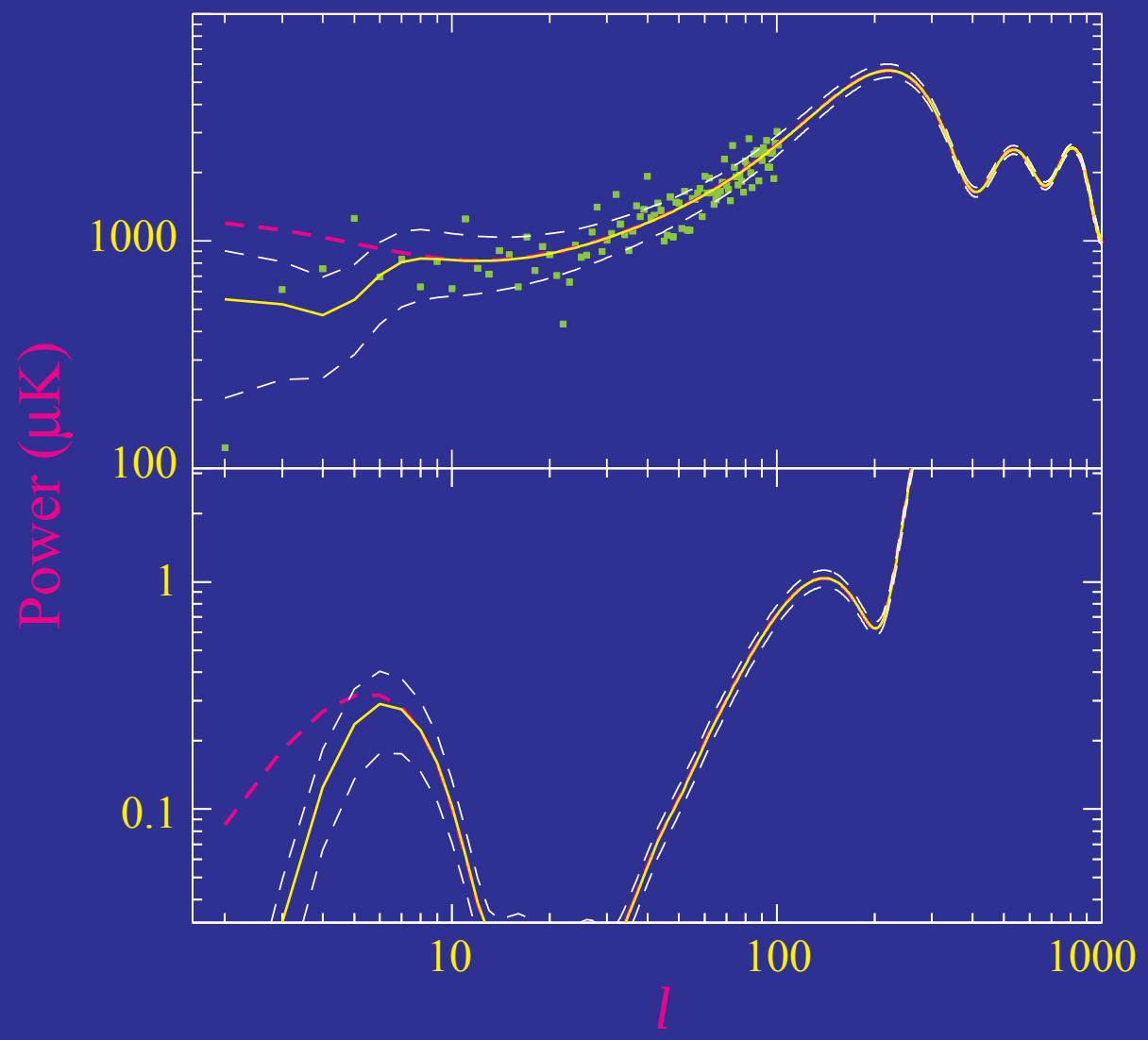
5 shear bins
Δz=0.25 to z=1 + z>1
γ_{rms}=0.16; z_{med}=0.7
n=10 gal/arcmin^2

4000 deg^2
no systematic floor

ISW

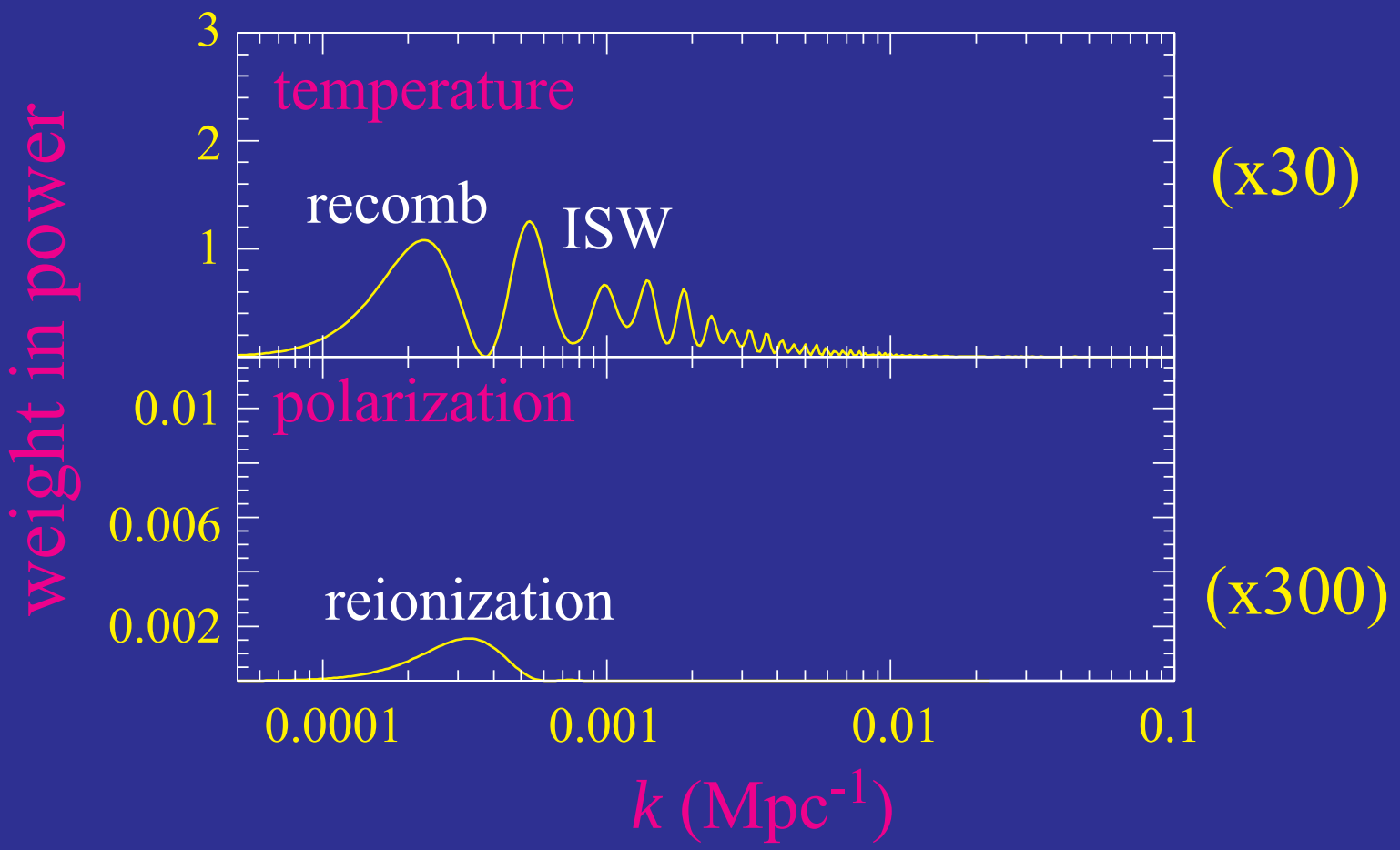
Naive Interpretation?

- No long-wavelength power? cut off near horizon scale $k=0.005\ \mathrm{Mpc}^{-1}$ - problematic due to ISW & polarization



Temperature v. Polarization

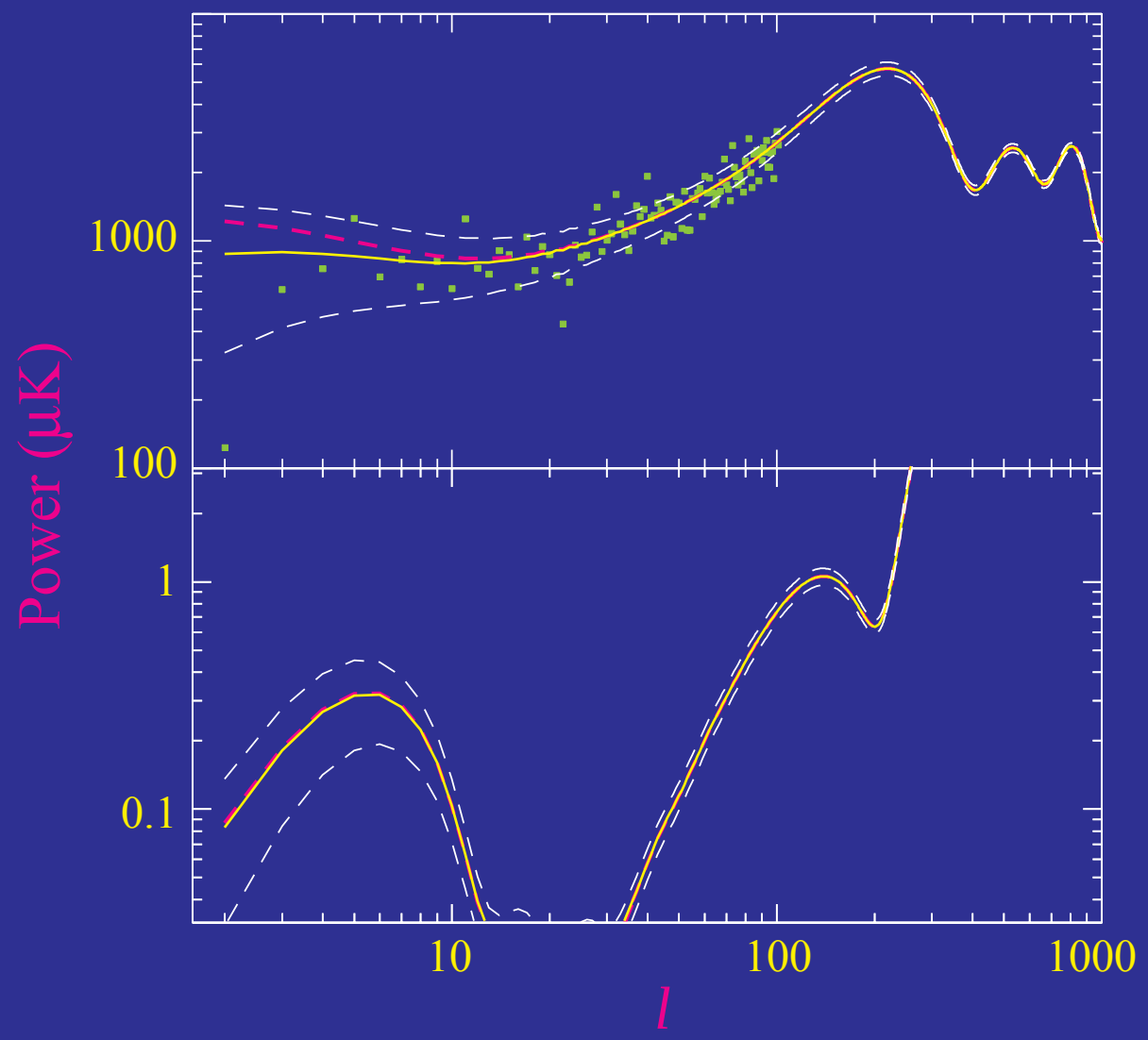
- Quadrupole in polarization originates from a tight range of scales around the current horizon
- Quadrupole in temperature gets contributions from 2 decades in scale



Hu & Okamoto (2003)

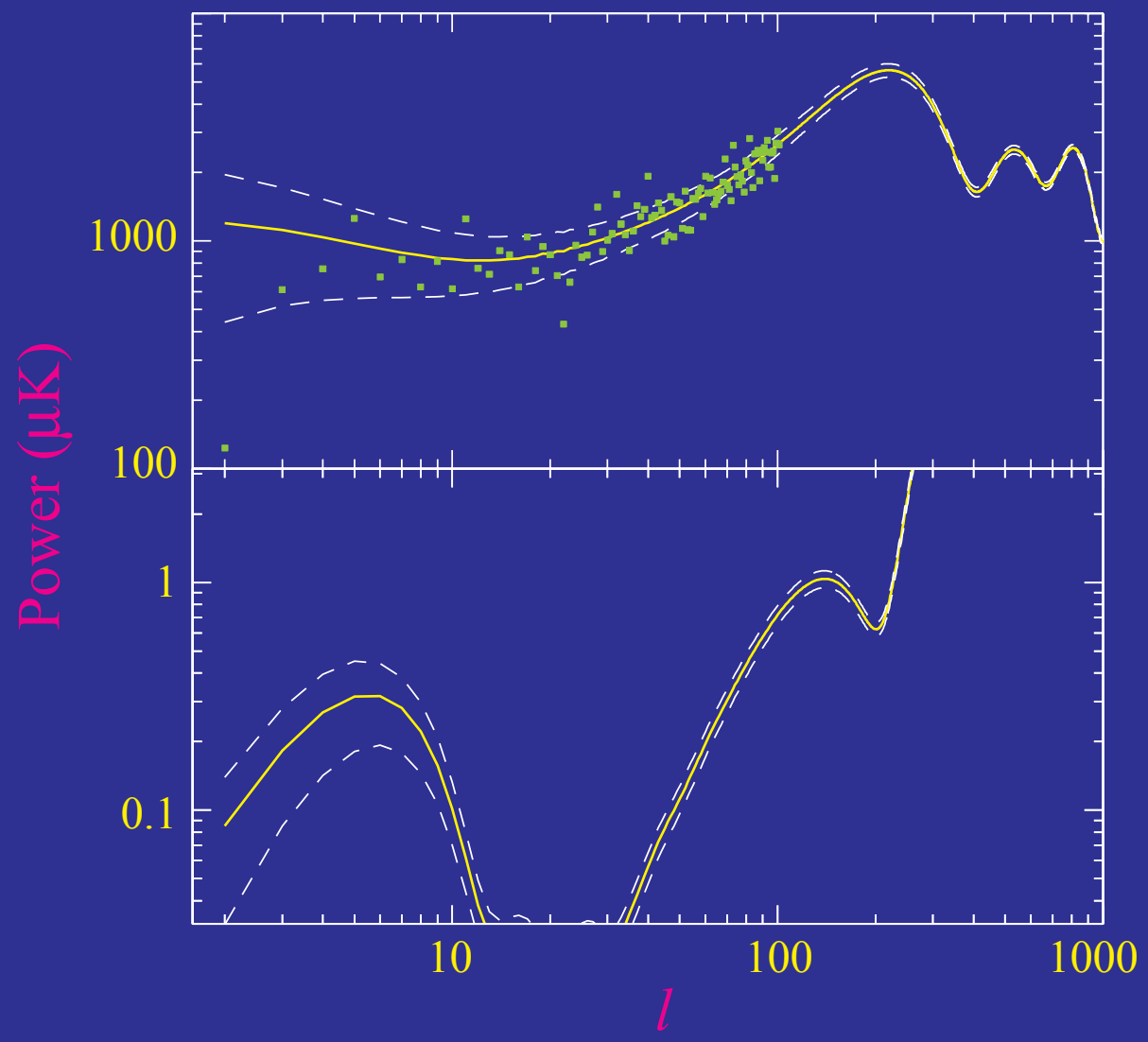
Exotic Dark Energy?

- Modify the clustering of the dark energy to eliminate low-*l* ISW effect - helps moderately, leaves polarization unaffected



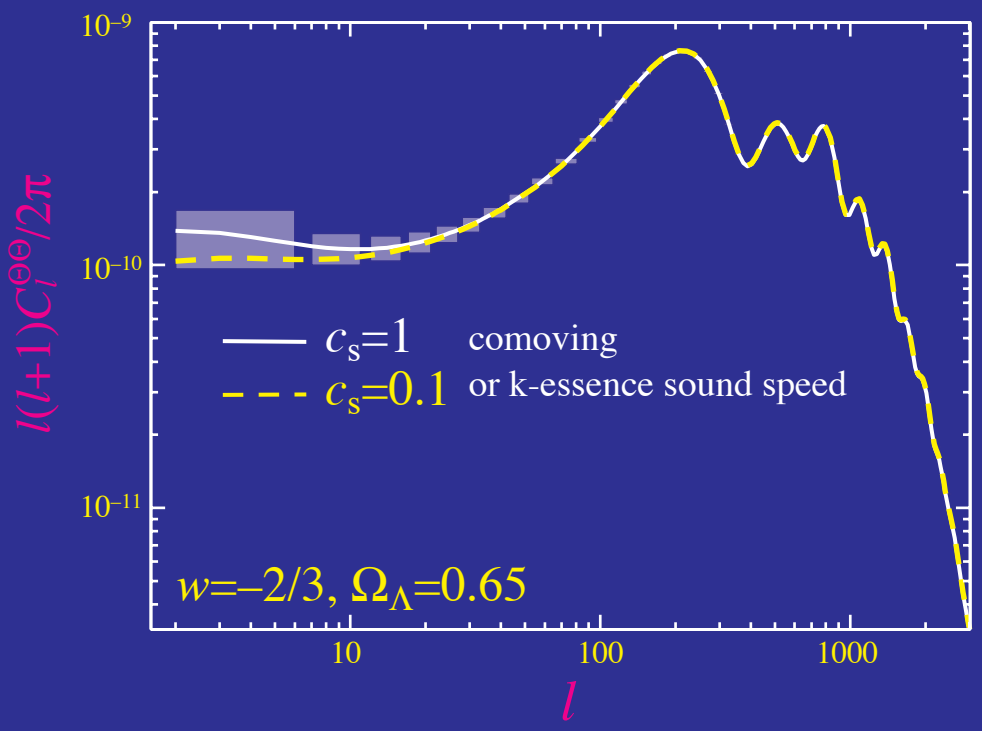
Chance Cancellation?

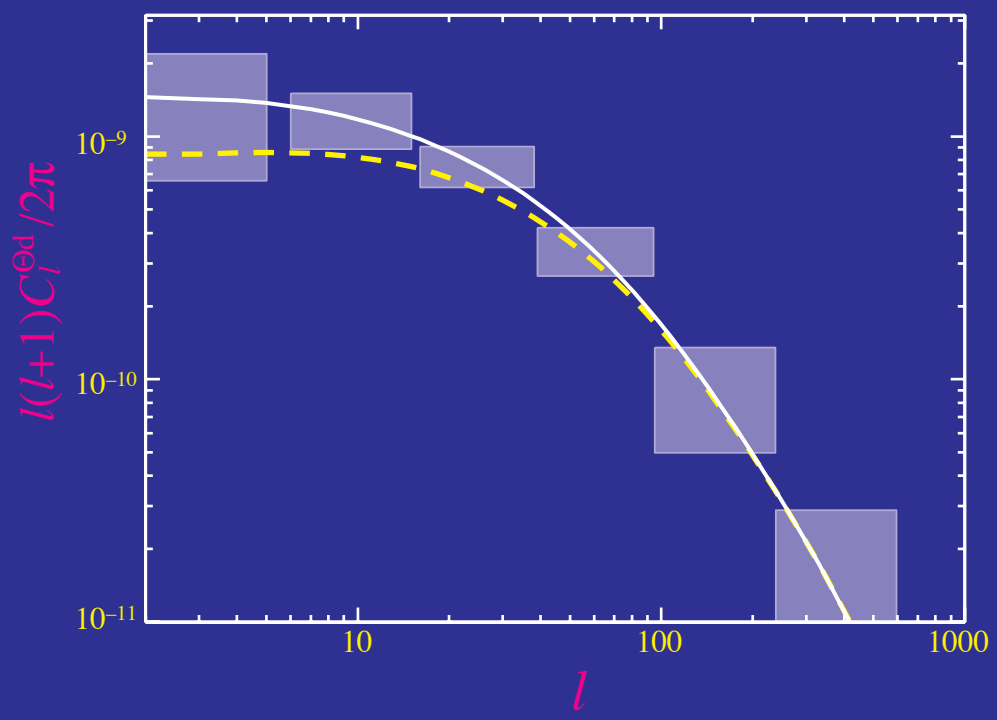
- Small physical scale ISW fluctuations happen to cancel large scale SW fluctuations locally - polarization unaffected



Dark Energy Clustering

- Cross correlation with CMB lensing maps eventually can provide a cosmic variance limited measurement on large scales where ISW maximized and test the smoothness of the dark energy
- Quintessence vs k-essence





Hu (2002)

Summary

- CMB directly impacts structure-based dark energy probes
- CMB provides an absolutely calibrated template for the shape of $P(k)$ – limited $\Omega_m h^2$ from $>$ 2nd peak and polarization
- CMB provides a reionization limited measurement of the initial amplitude on large-scale structure scales
- CMB calibrations imply accurate measurement of $P(k)$ shape or amplitude at any $z < 2$ constrains dark energy (including $z = 0$)
- Multiple redshifts allow for separation of $w_0 - w_a$, dark energy evolution or evolution of dark energy
- But other tests must match or exceed the CMB calibration uncertainty of $< 1\%$
- ISW effect may hold hints beyond phenomenological models and will be assisted by polarization and CMB lensing in the future