

NeoClassical Probes



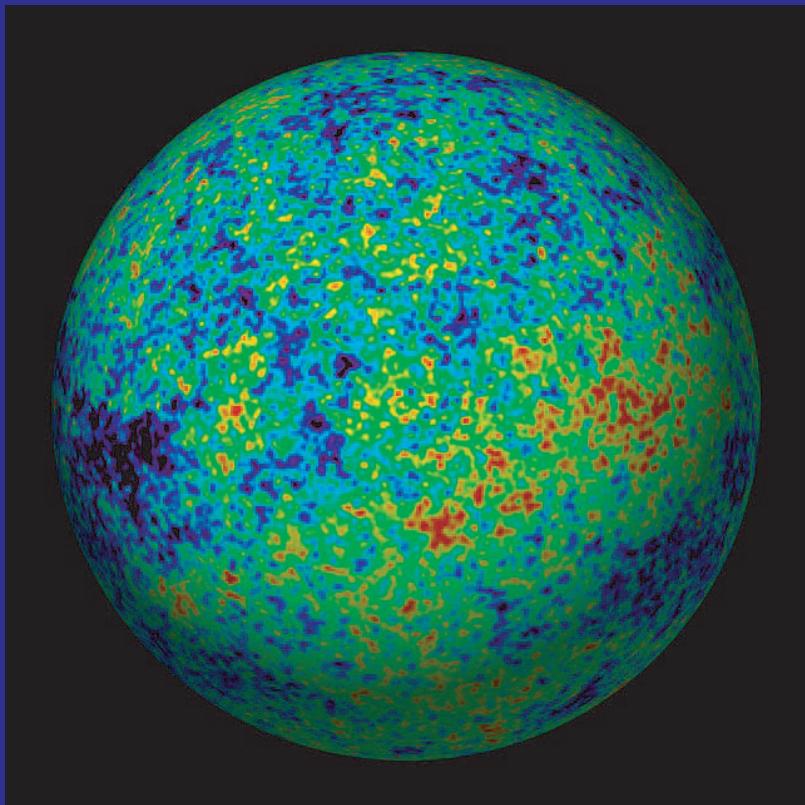
of the Dark Energy

Wayne Hu

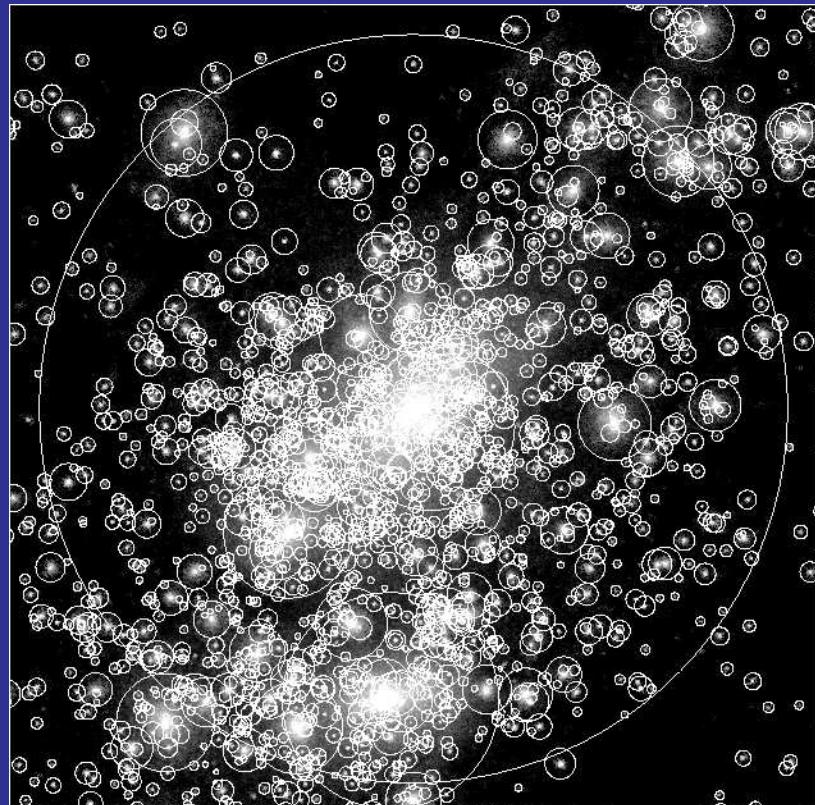
Faculty Research Seminar

Structural Fidelity

- Dark matter simulations approaching the accuracy of CMB calculations



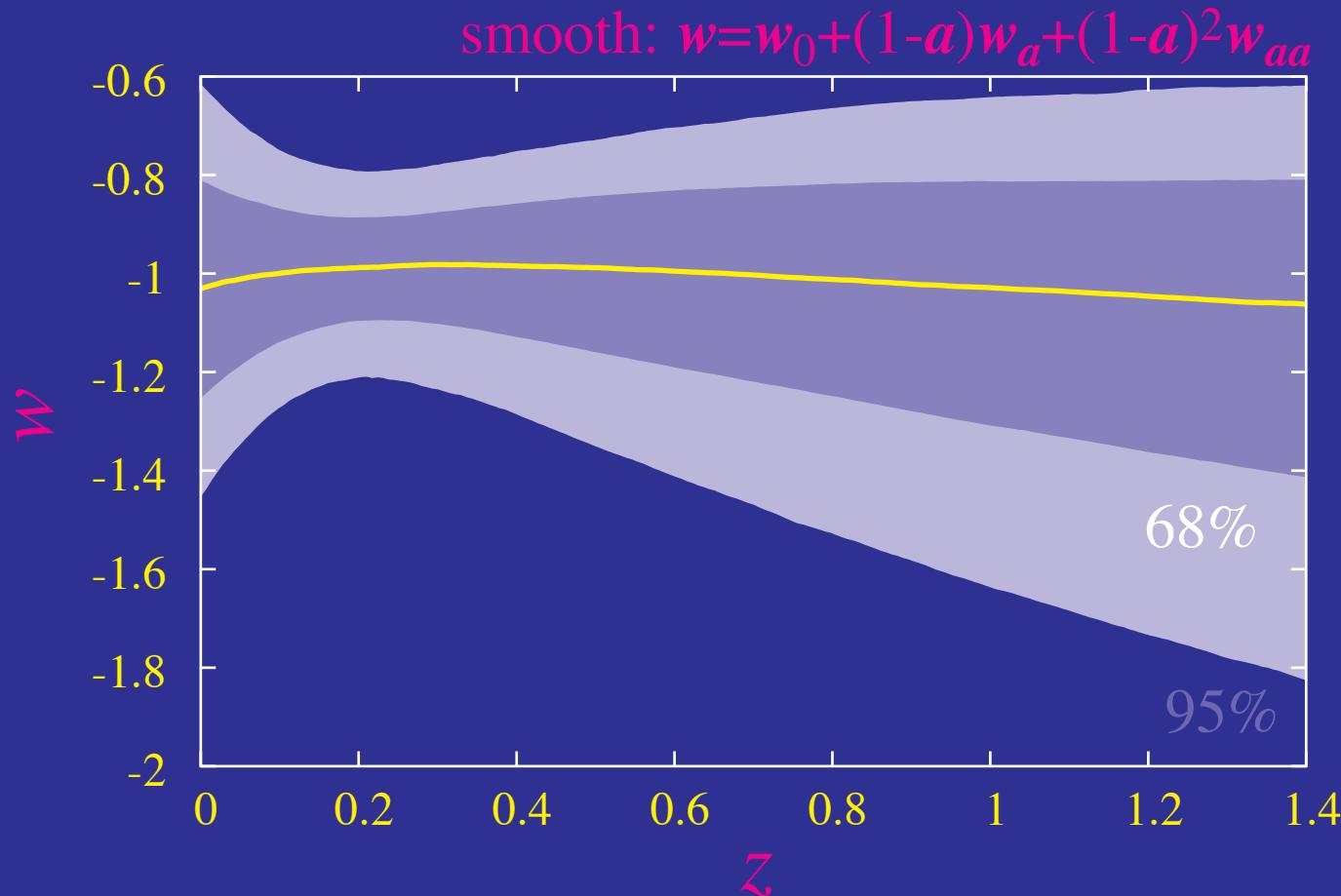
WMAP



Kravtsov et al (2003)

Equation of State Constraints

- NeoClassical probes statistically competitive already
CMB+SNe+Galaxies+Bias(Lensing)+Ly α



- Future hinges on controlling systematics

Seljak et al (2004)

Collaborators

Recent Dark Energy Collaborators

- Christopher Gordon
- Zoltan Haiman
- Bhuvnesh Jain
- Marcos Lima
- Ryan Scranton
- Kendrick Smith
- Takemi Okamoto

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

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

with initial conditions $G = \text{const.}$

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

CMB Background

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 (SPT/DES examples)

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

Cosmic Shear

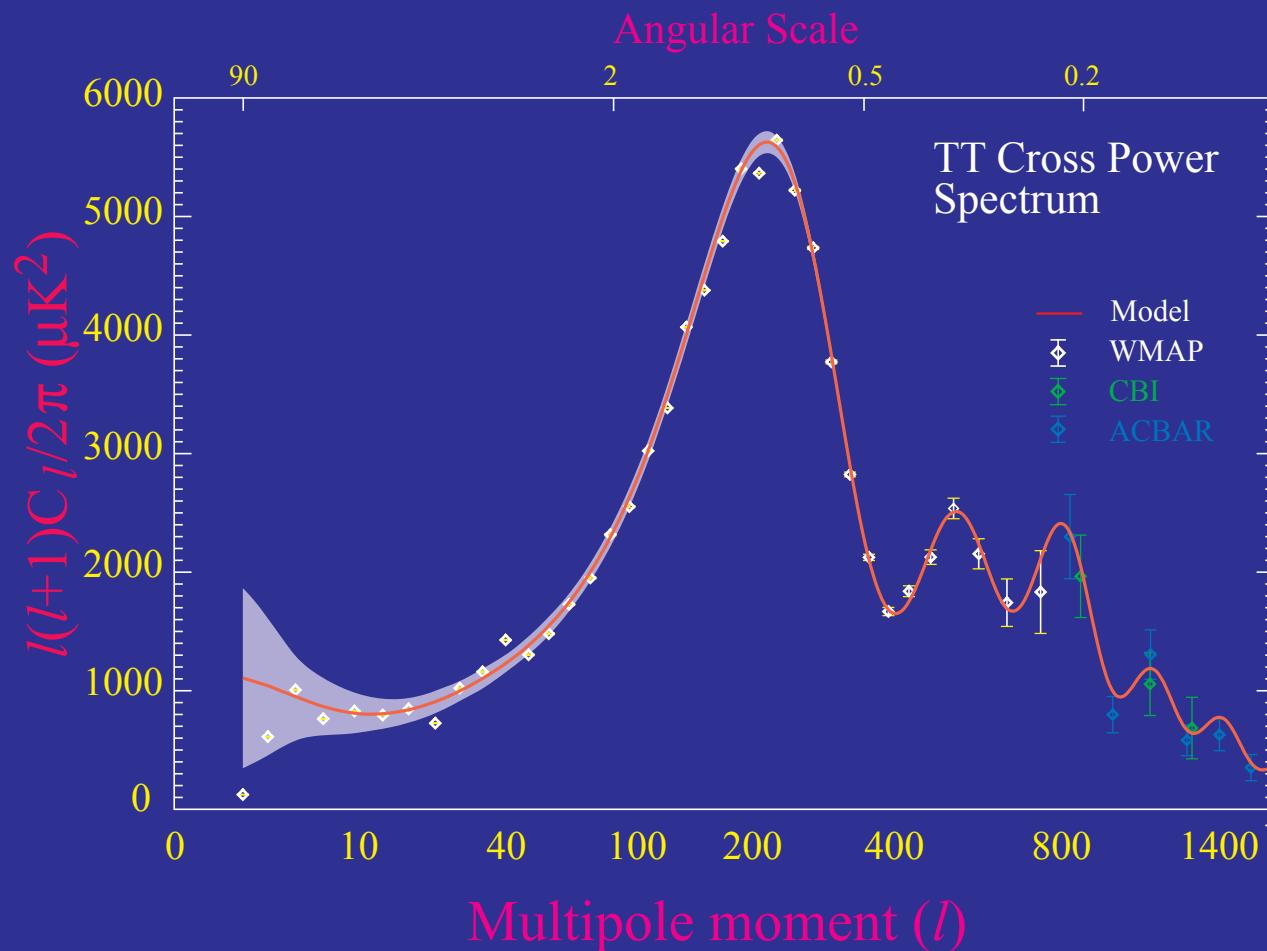
Galaxy-galaxy lensing + clustering (self-calibrating bias)

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

Amplitude near horizon scale: ISW (polarization; lensing)

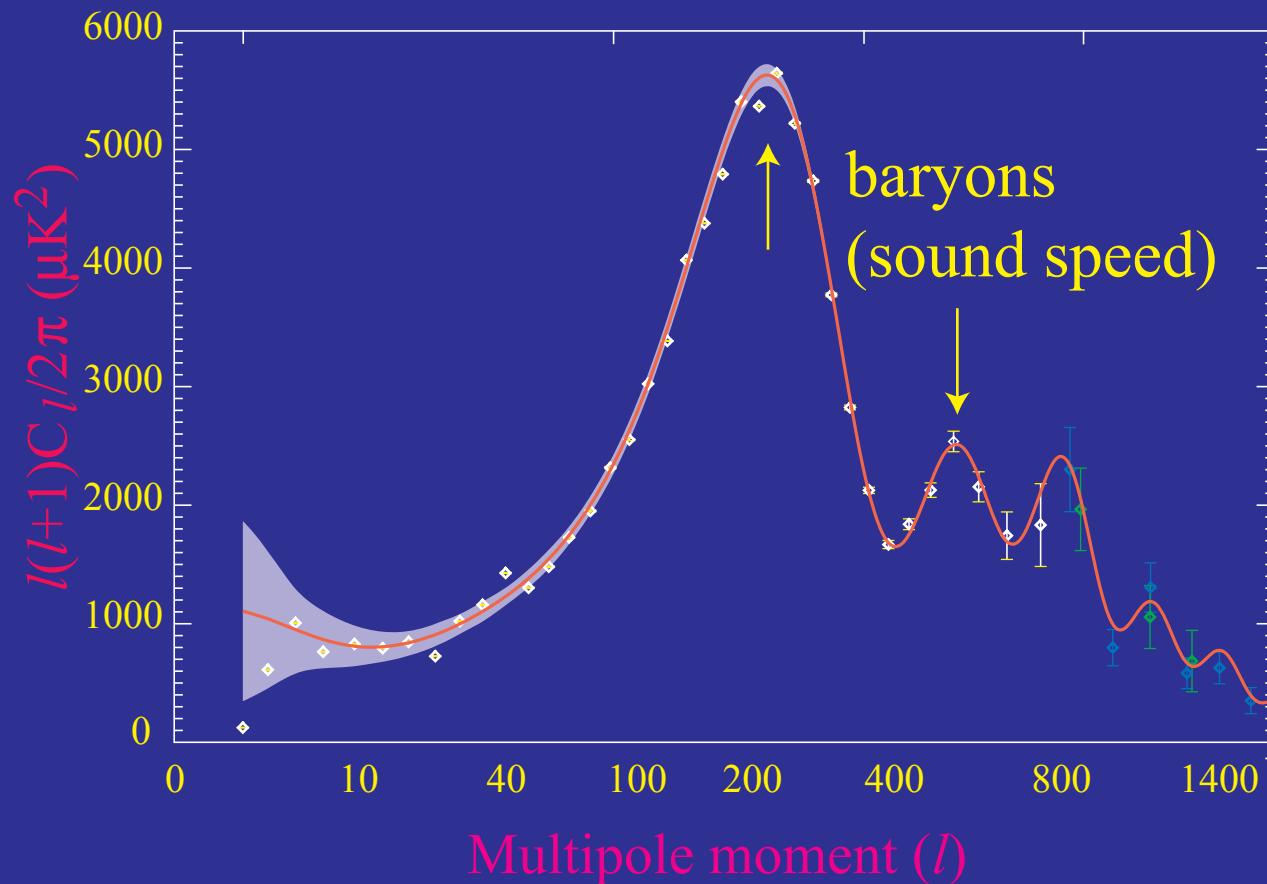
Leveraging the CMB

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



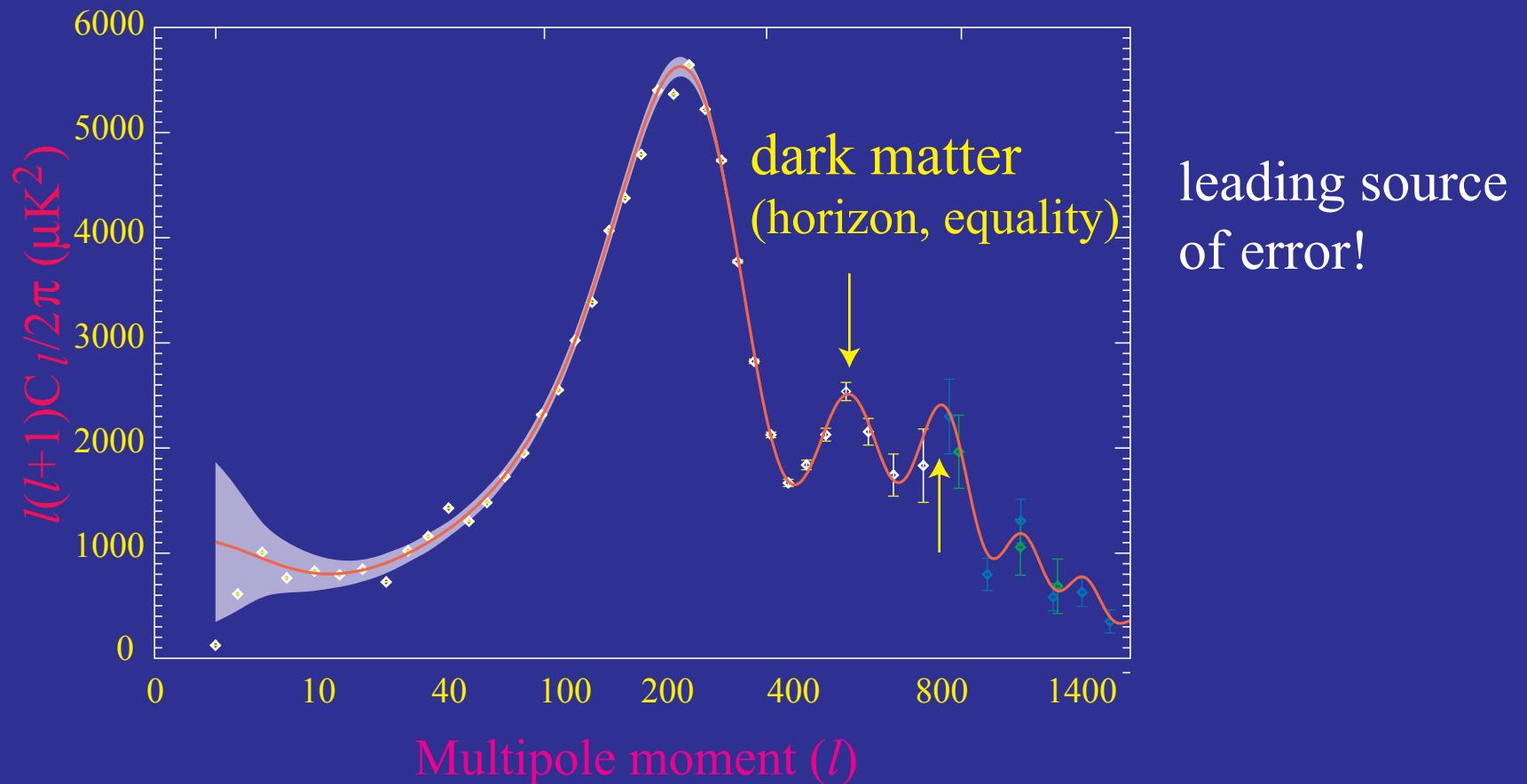
Leveraging the CMB

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



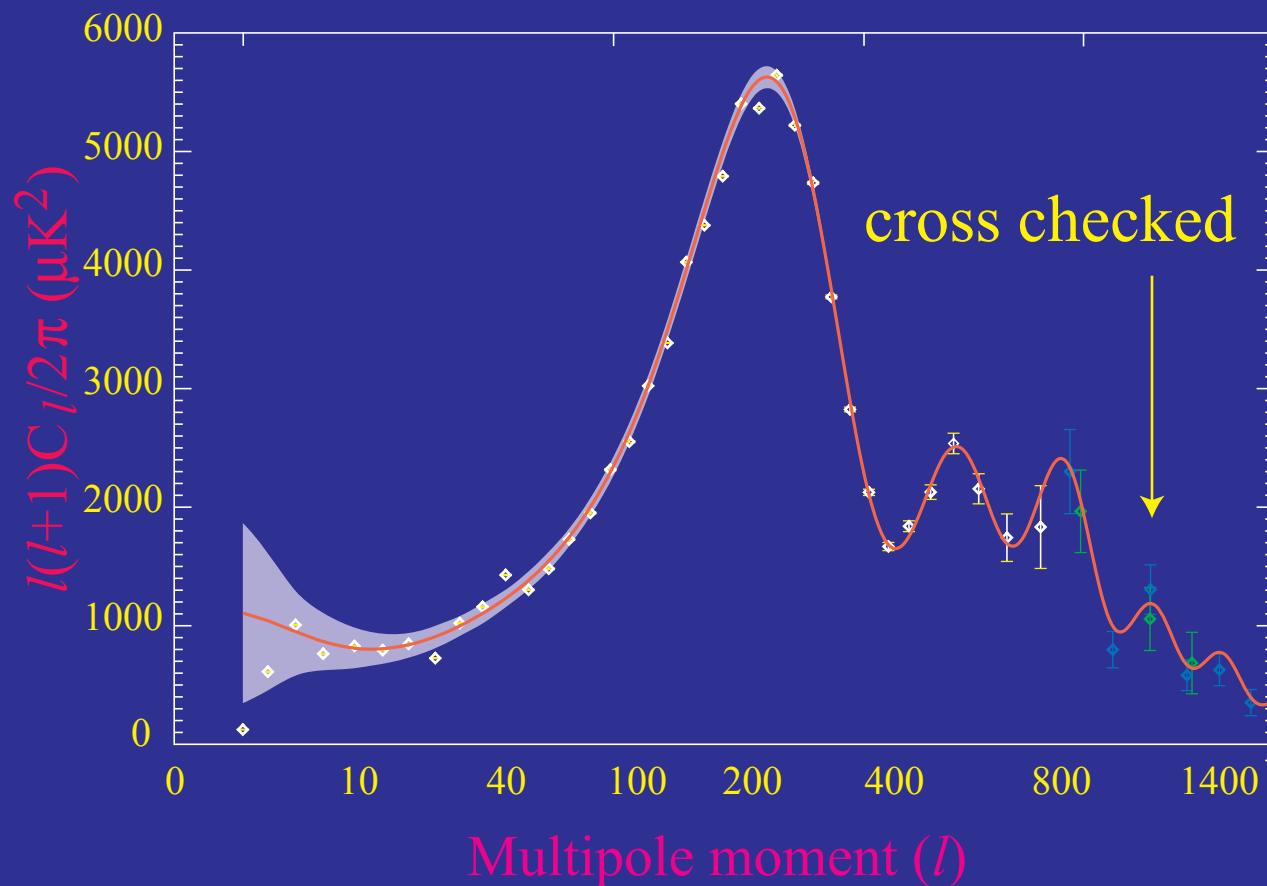
Leveraging the CMB

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



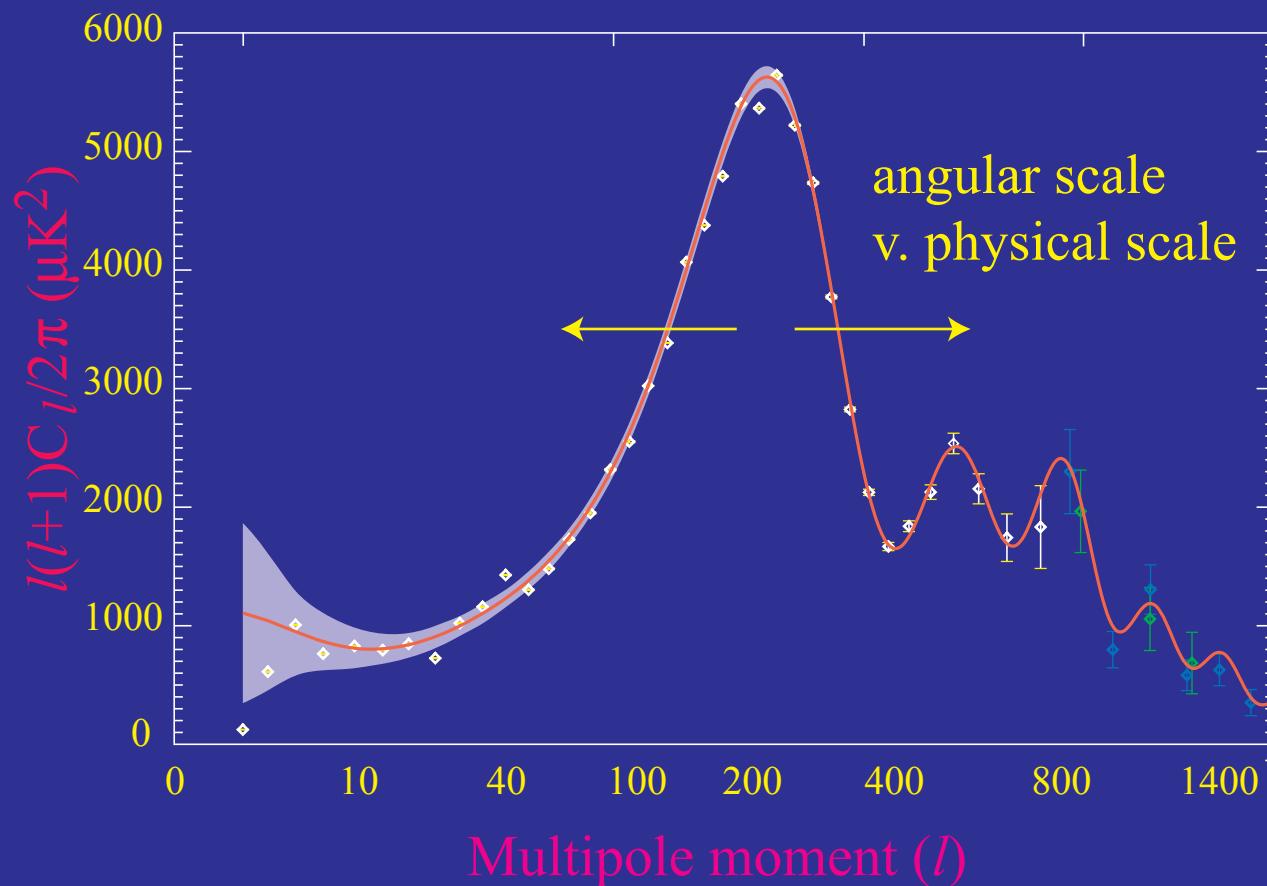
Leveraging the CMB

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



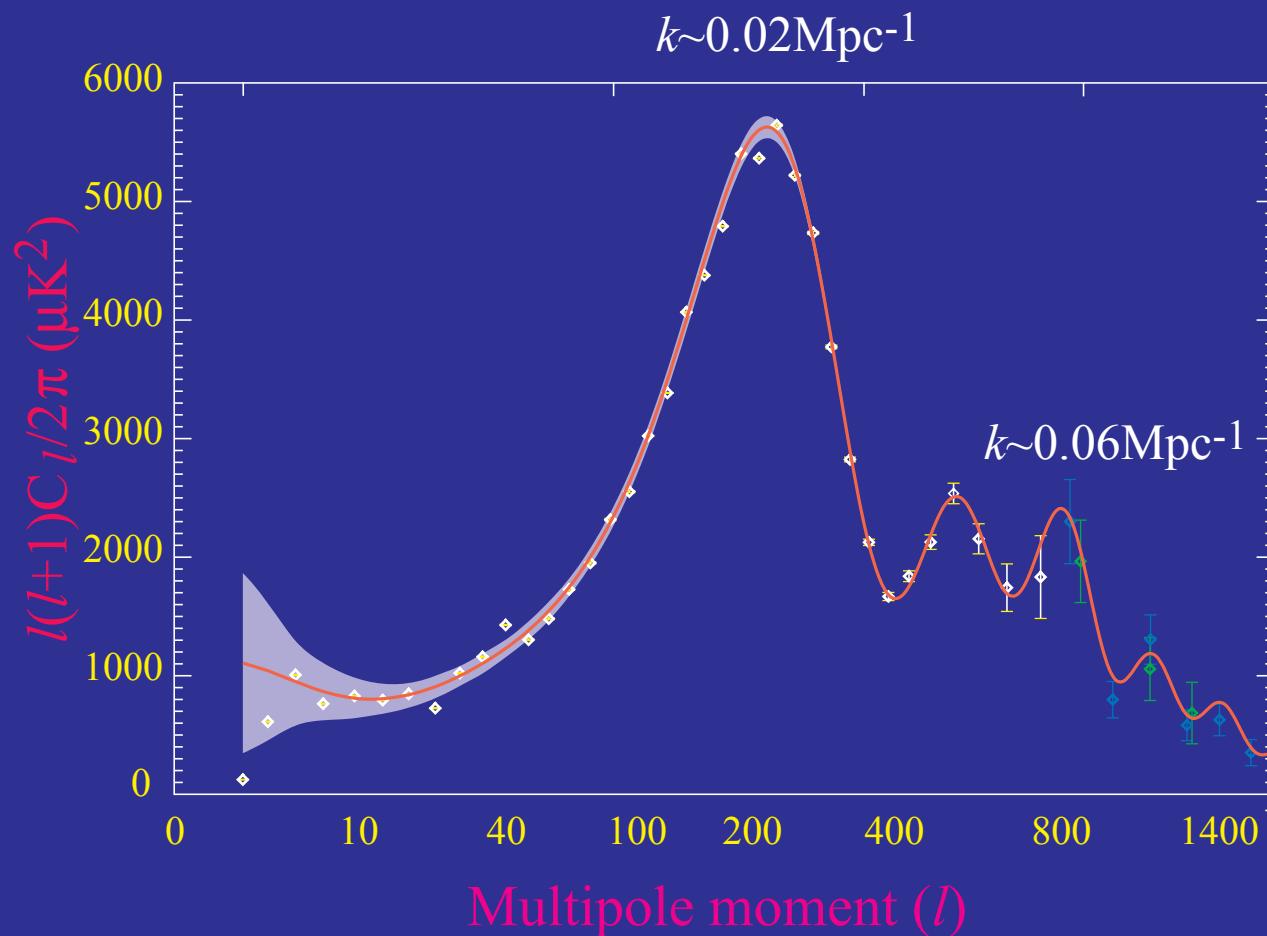
Leveraging the CMB

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



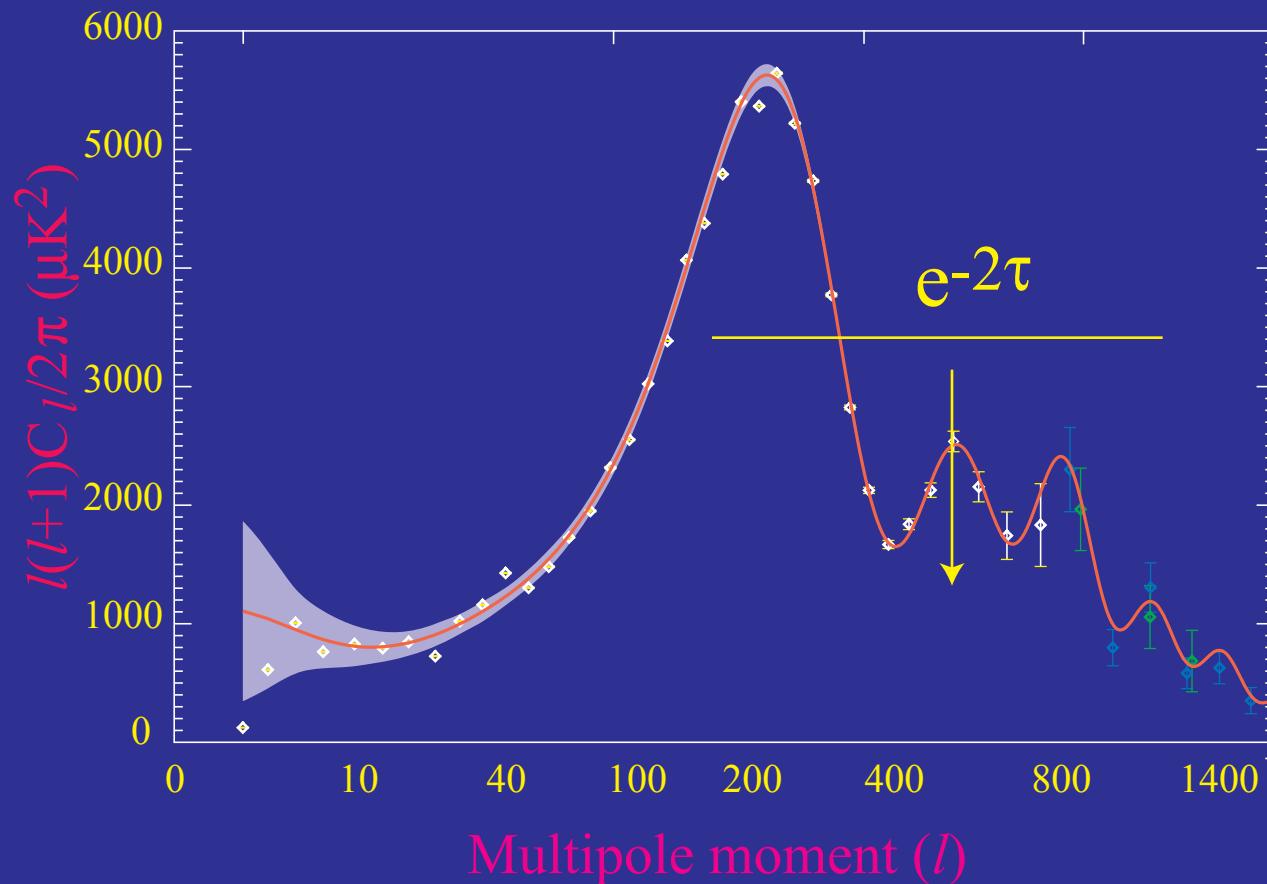
Leveraging the CMB

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



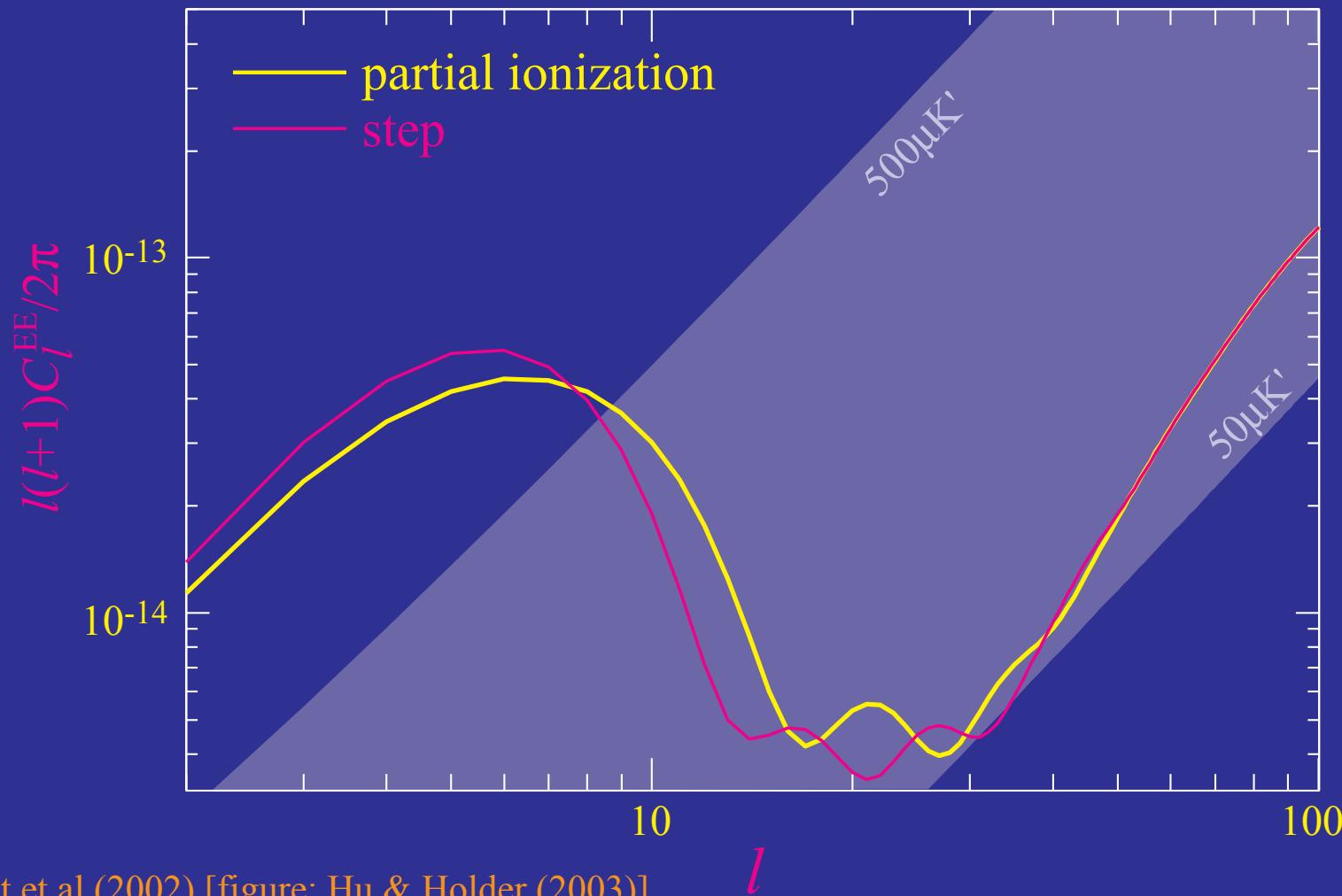
Leveraging the CMB

- 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



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%



$$\sigma_8(z)$$

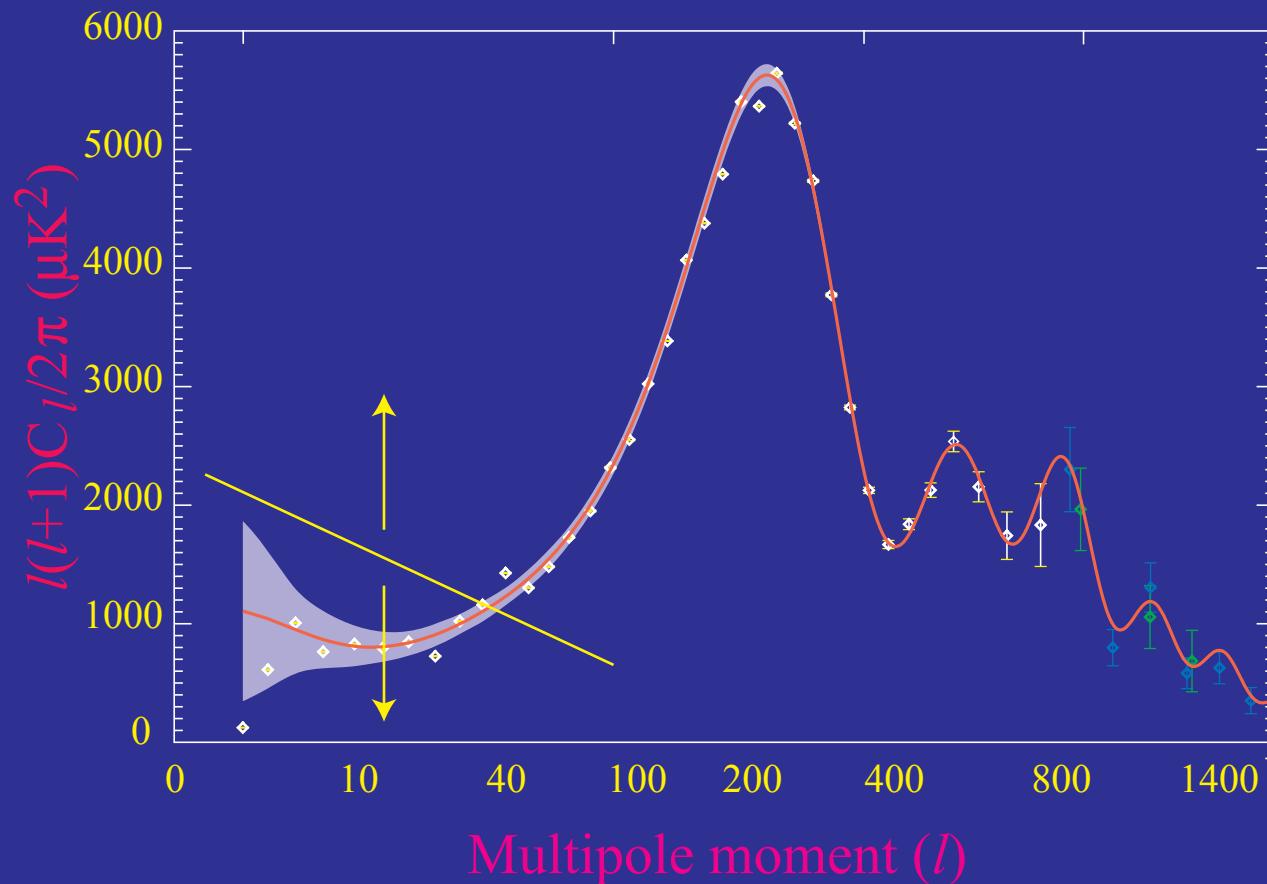
- Determination of the normalization during the acceleration epoch, even σ_8 , measures the dark energy with negligible uncertainty from other parameters
- Approximate scaling (flat, negligible neutrinos: Hu & Jain 2003)

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

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

Leveraging the CMB

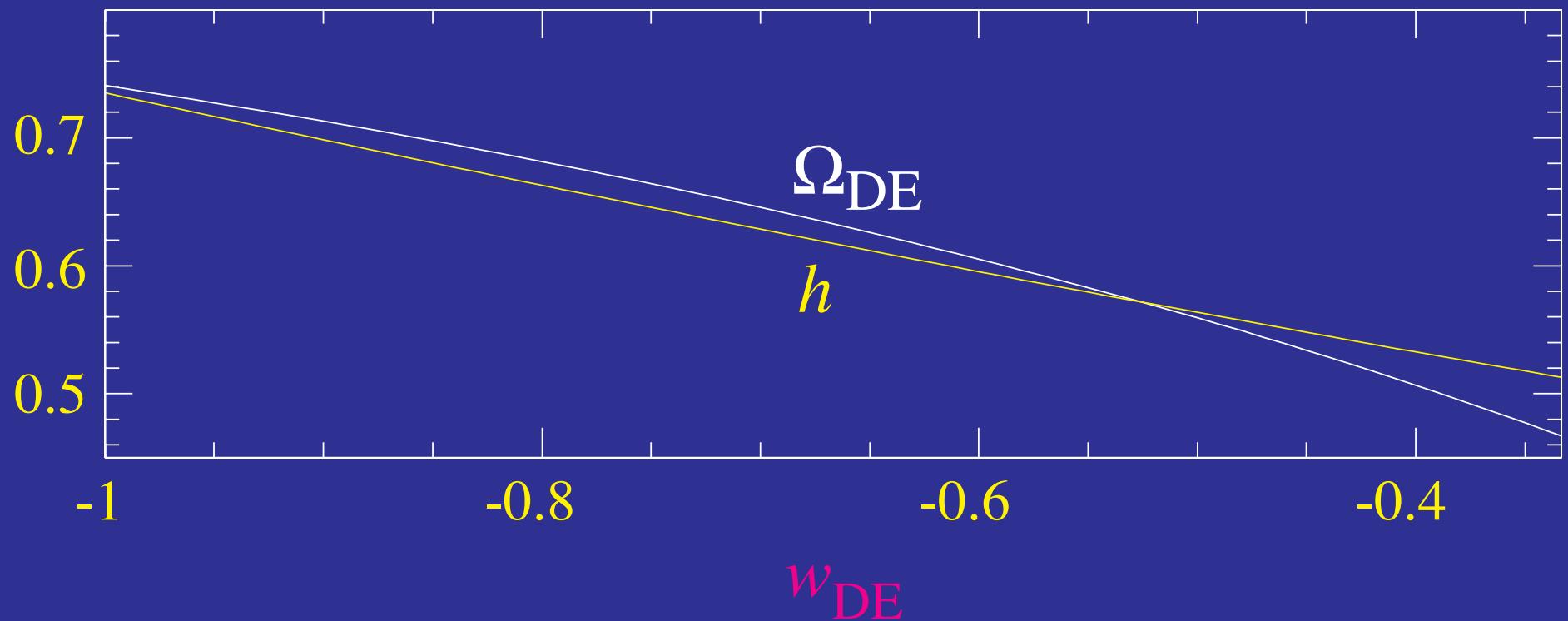
- Standard fluctuation: large scale - ISW effect; correlation with large-scale structure; clustering of dark energy; low multipole anomalies? polarization



Standard Deviants

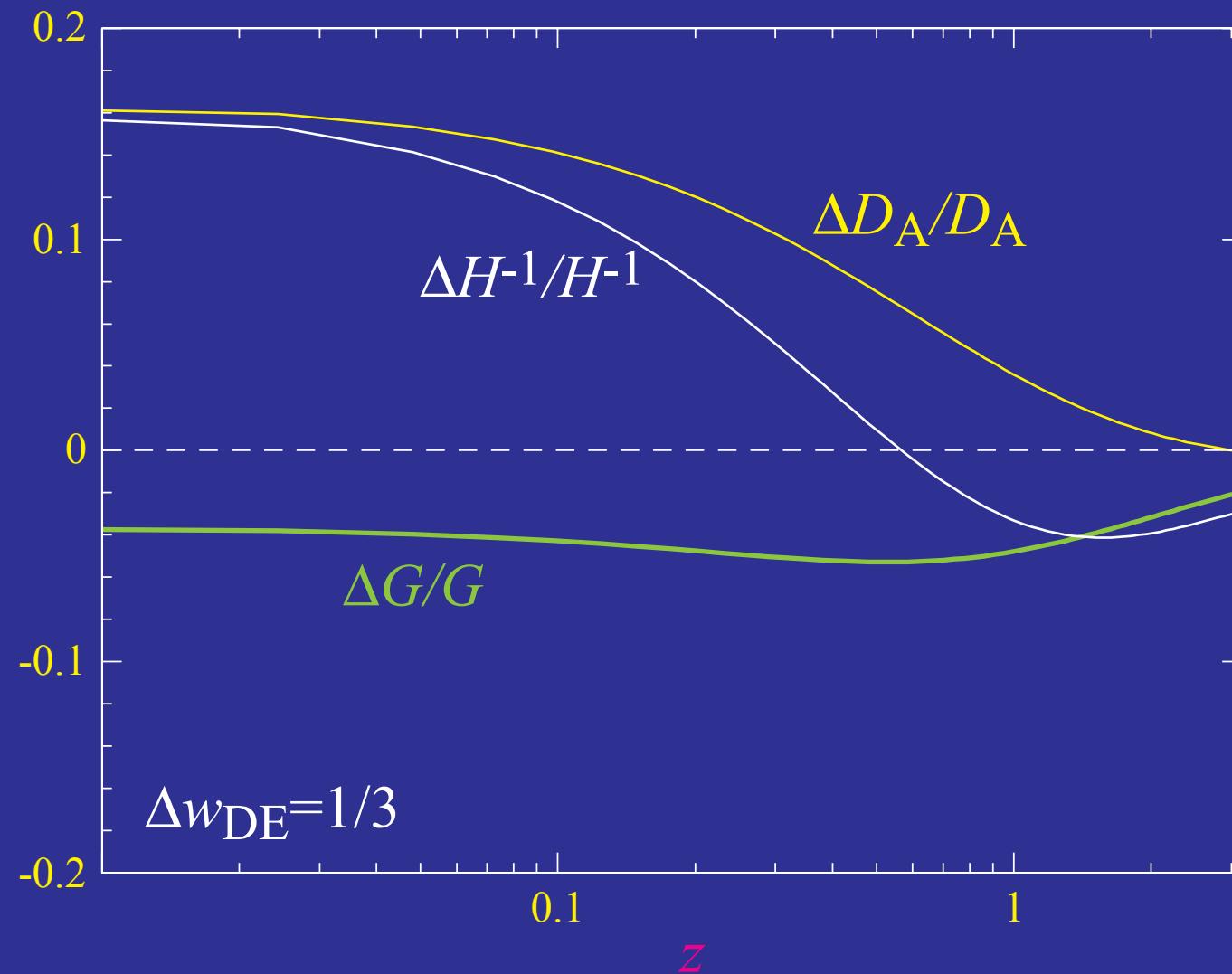
Keeping the High- z Fixed

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



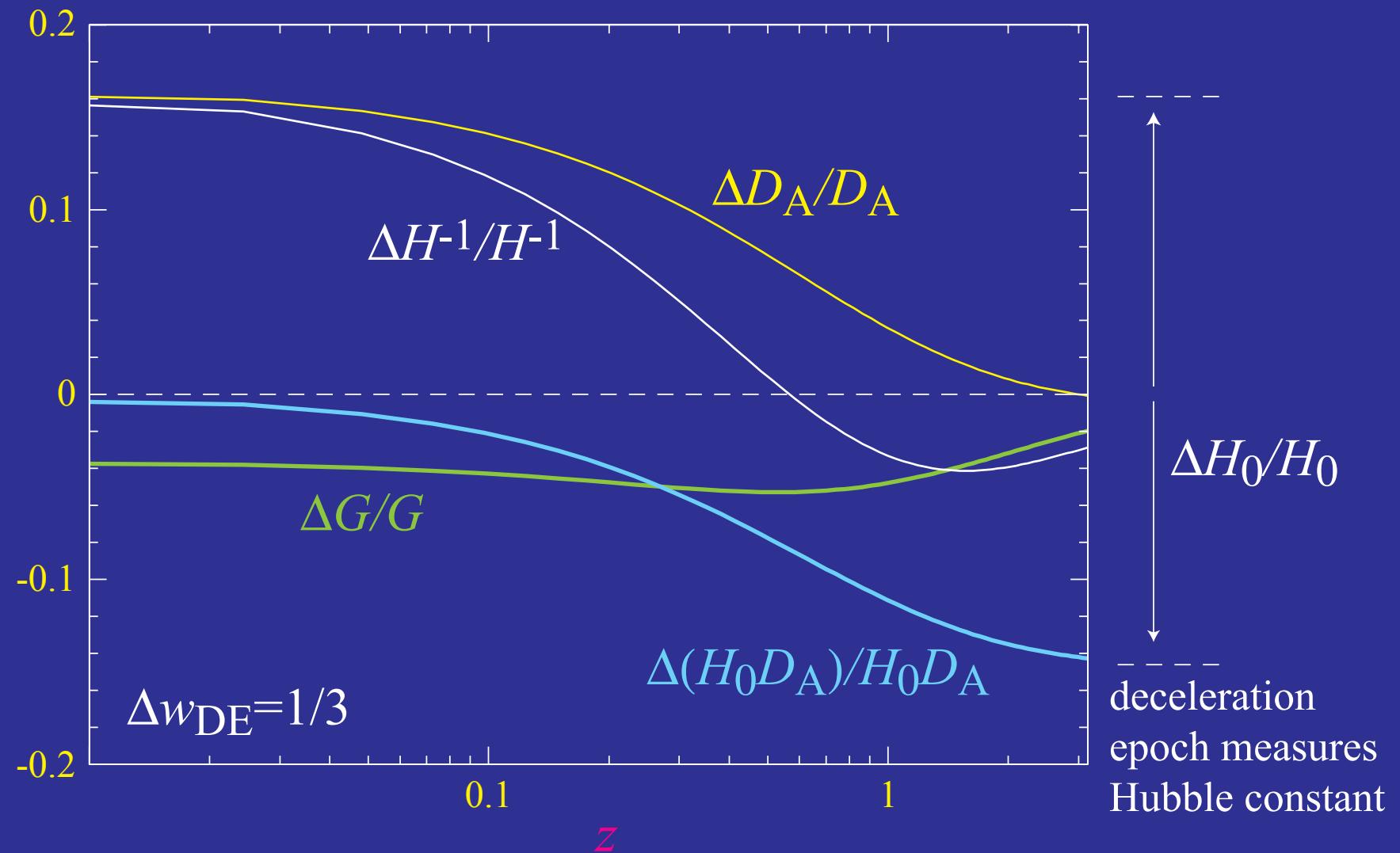
Dark Energy Sensitivity

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



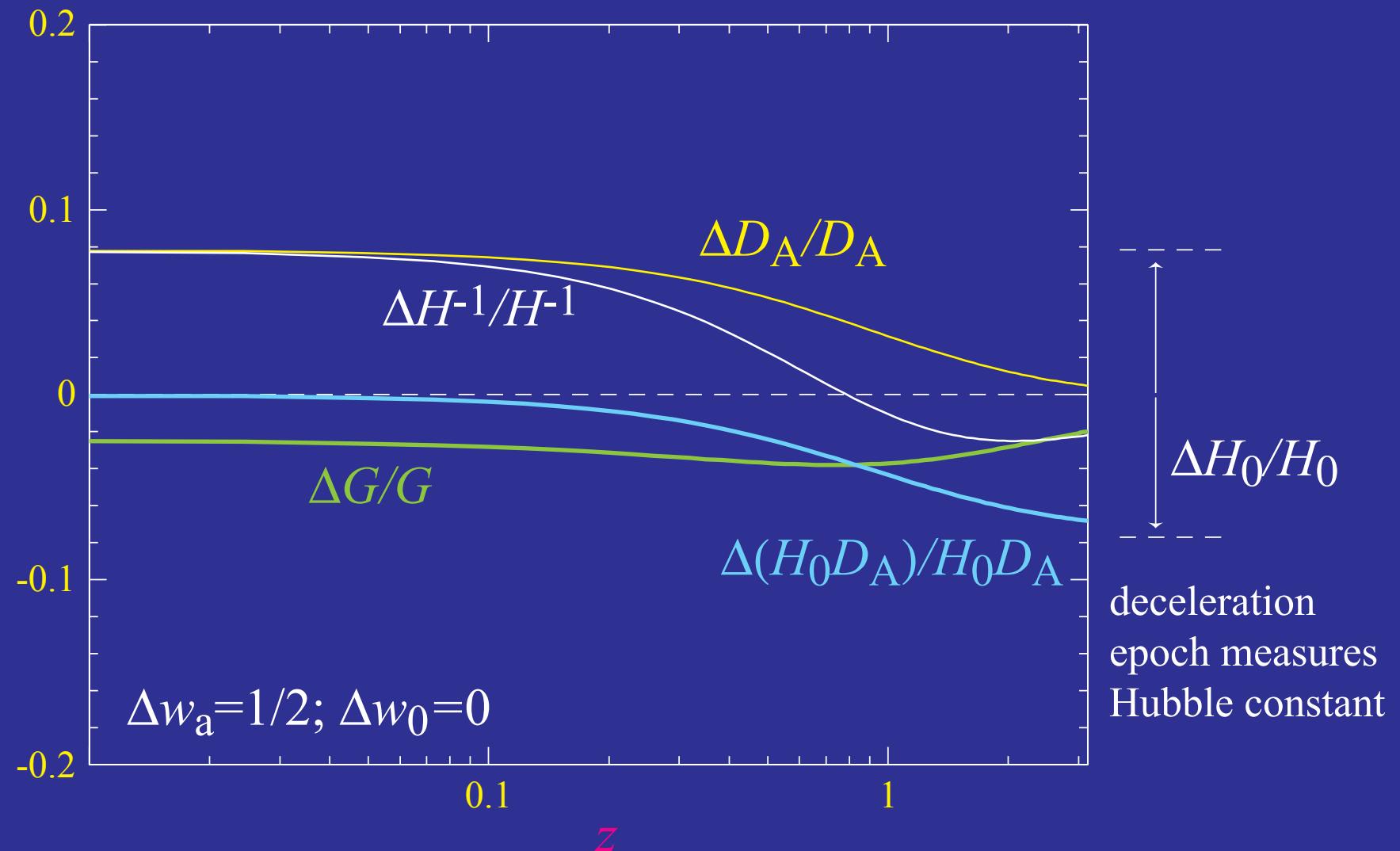
Dark Energy Sensitivity

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



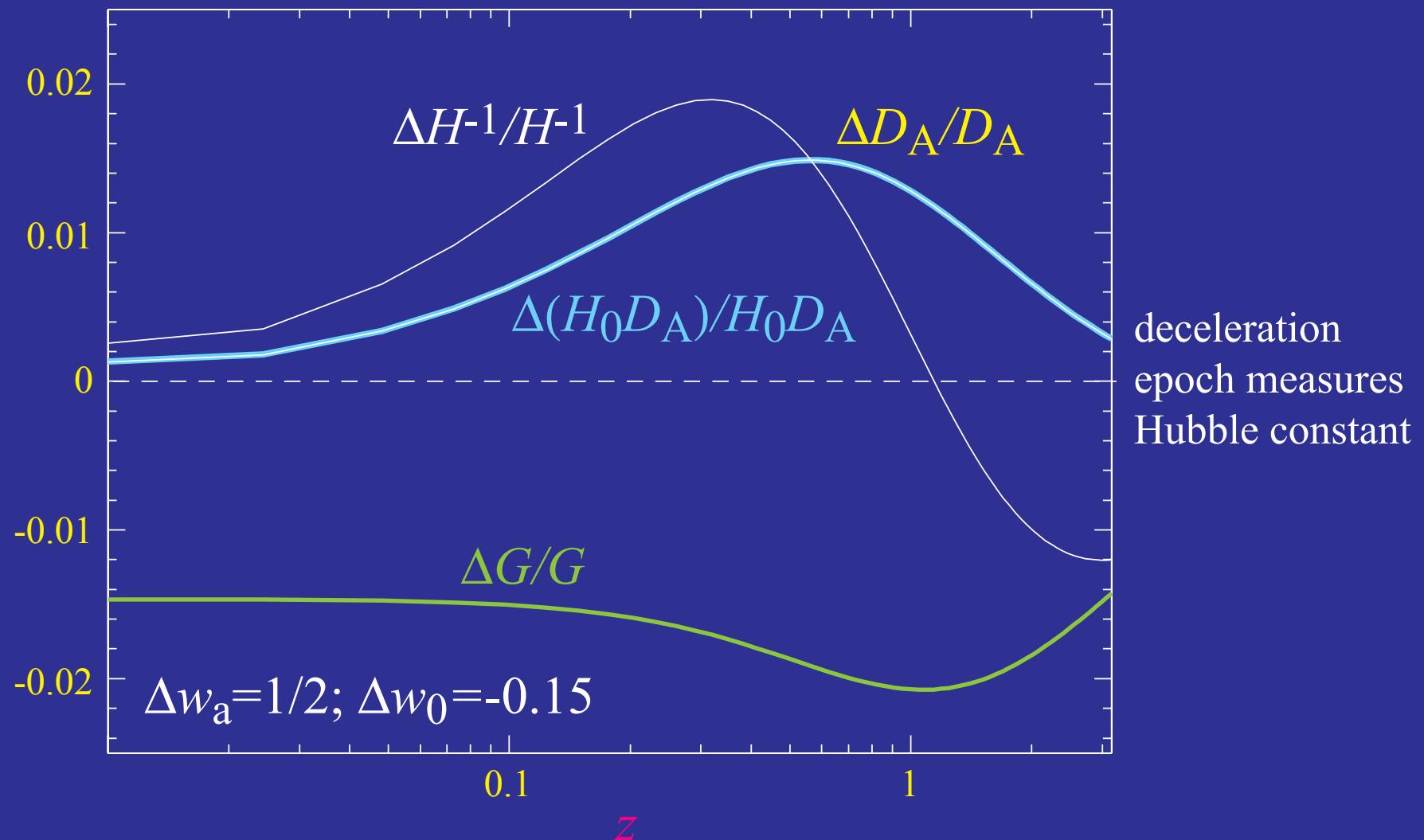
Dark Energy Sensitivity

- 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)



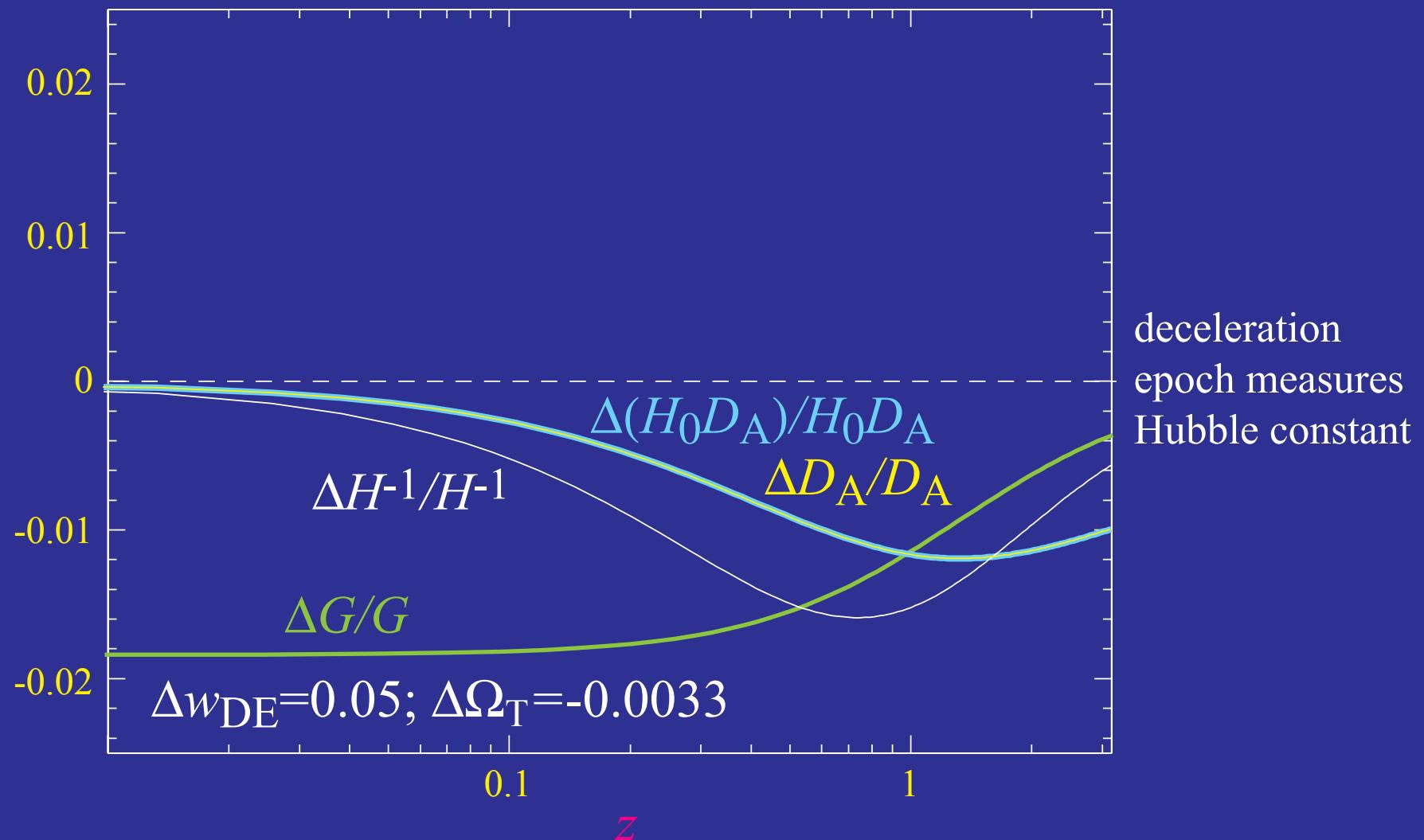
Dark Energy Sensitivity

- Three parameter dark energy model: $w(z=0)=w_0$; $w_a=-dw/da$; 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)



Dark Energy Sensitivity

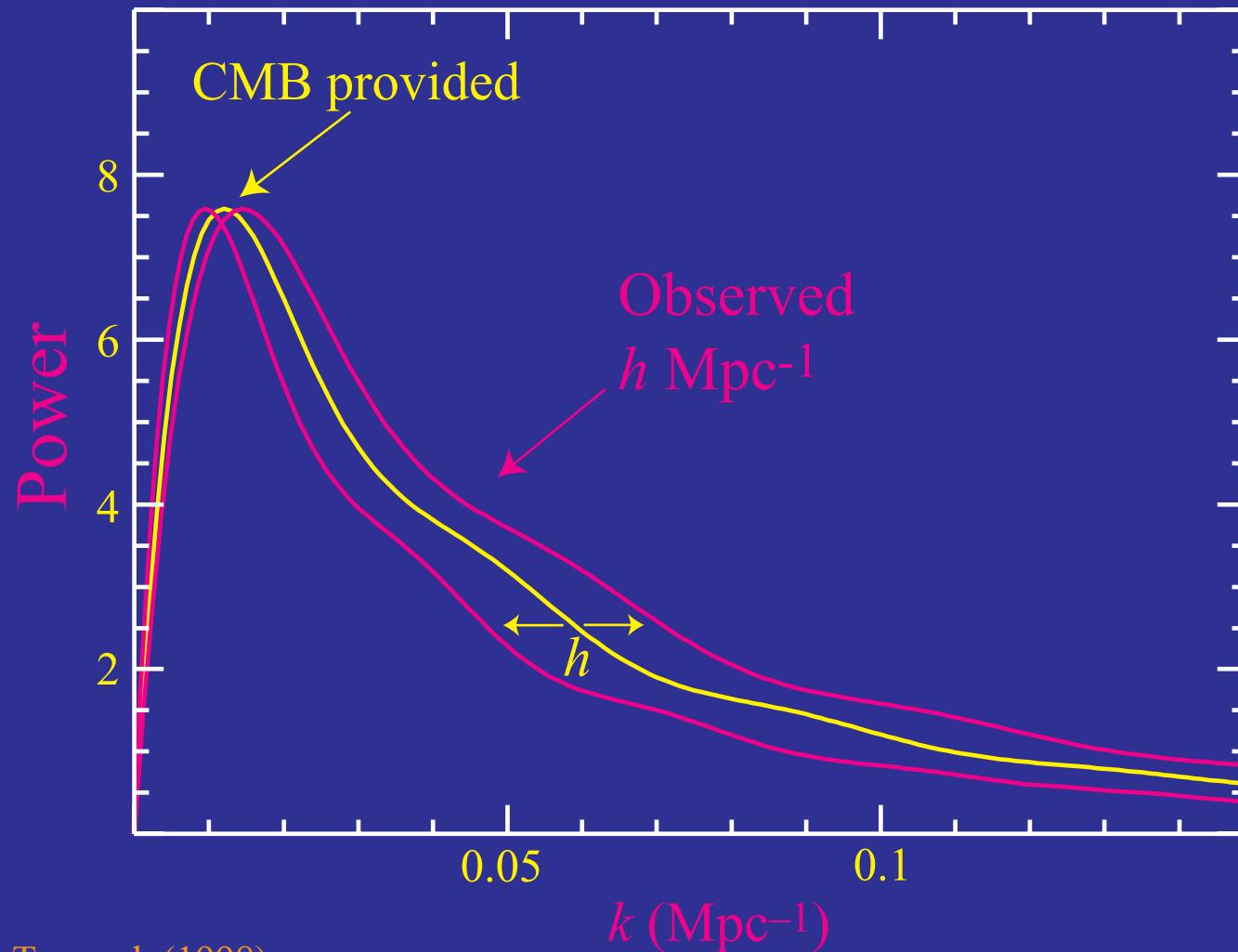
- H_0 fixed (or Ω_{DE}); remaining $w_{\text{DE}}-\Omega_{\text{T}}$ spatial curvature degeneracy
- Growth rate breaks the degeneracy anywhere in the acceleration regime



Rings of Power

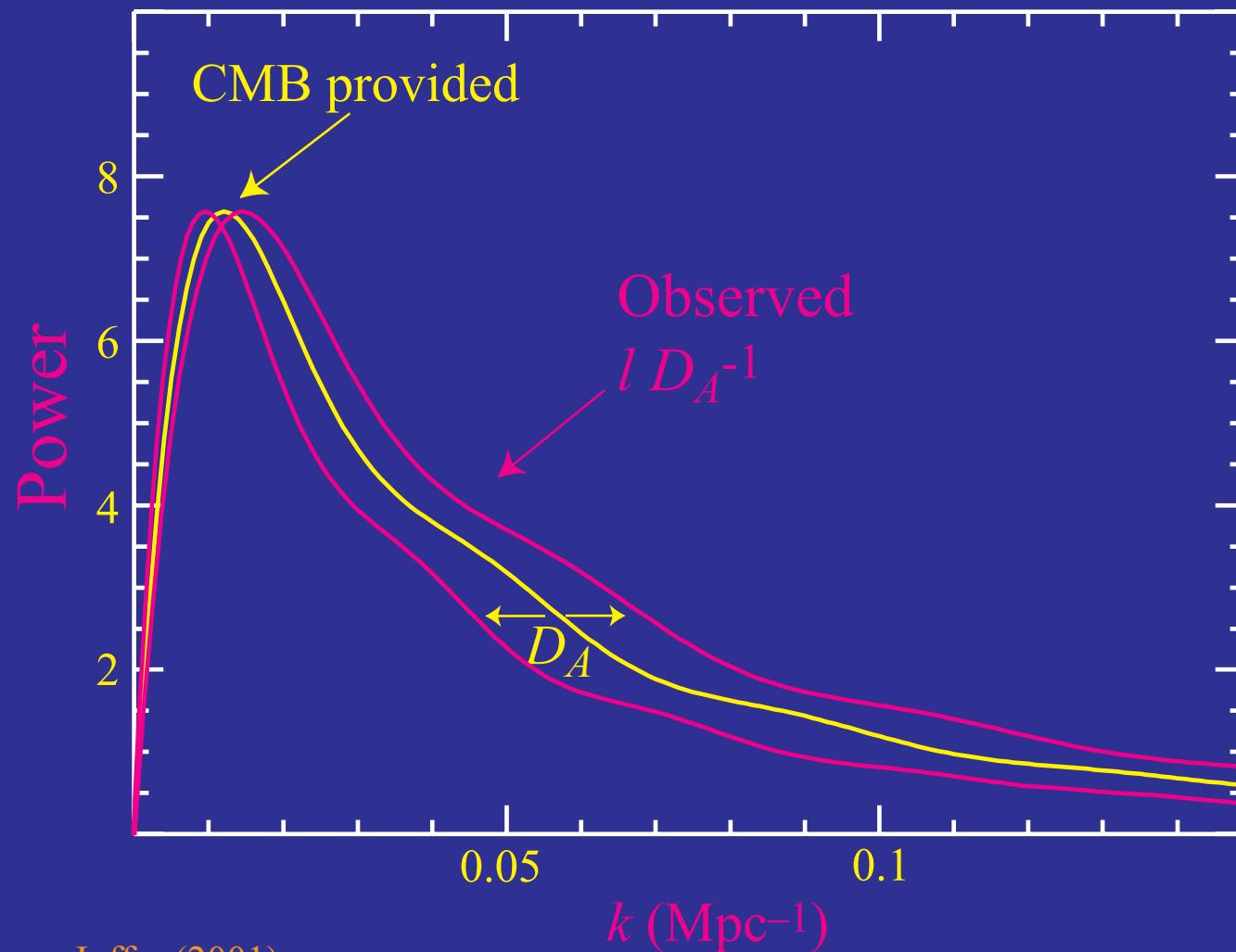
Local Test: H_0

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



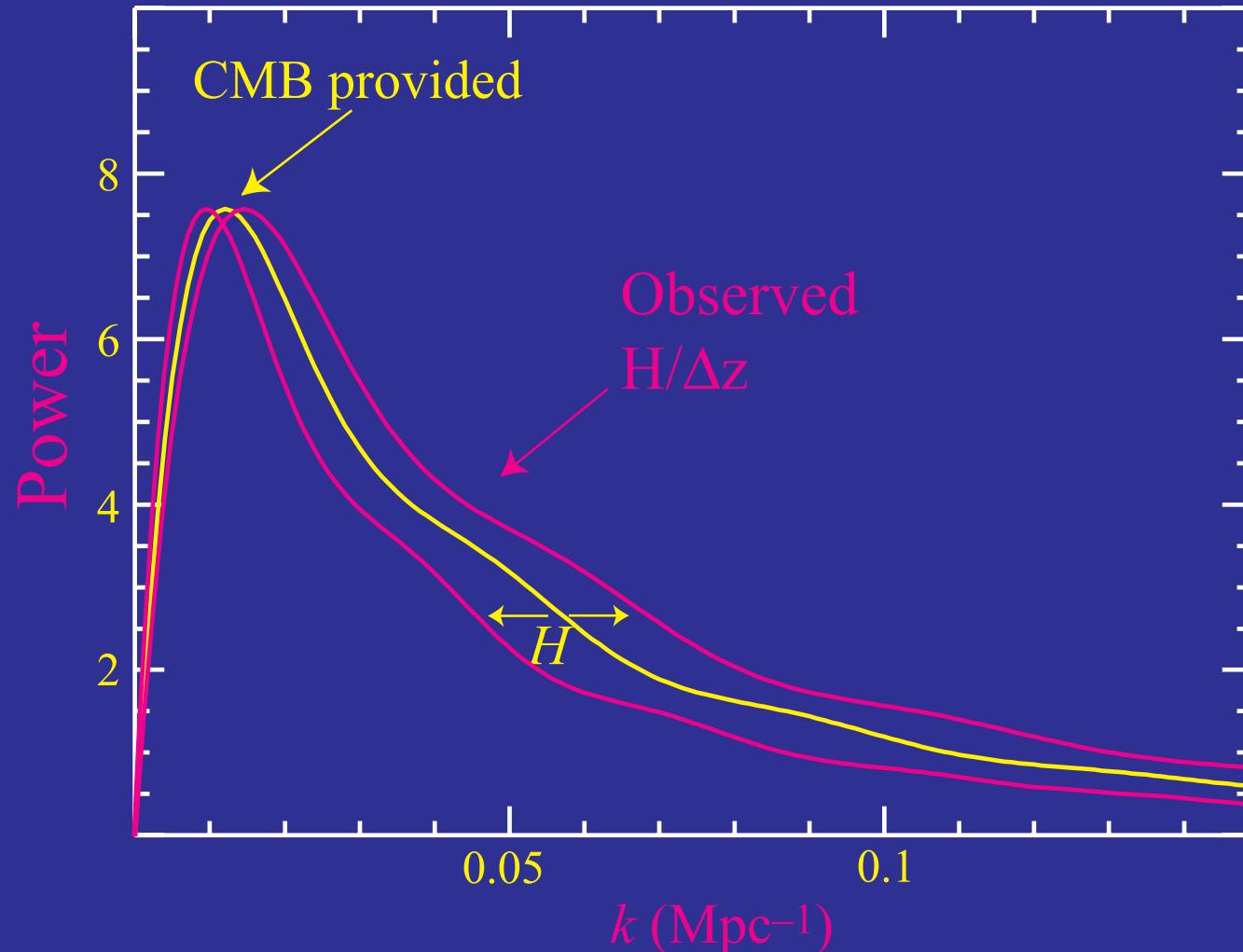
Cosmological Distances

- Modes perpendicular to line of sight measure angular diameter distance



Cosmological Distances

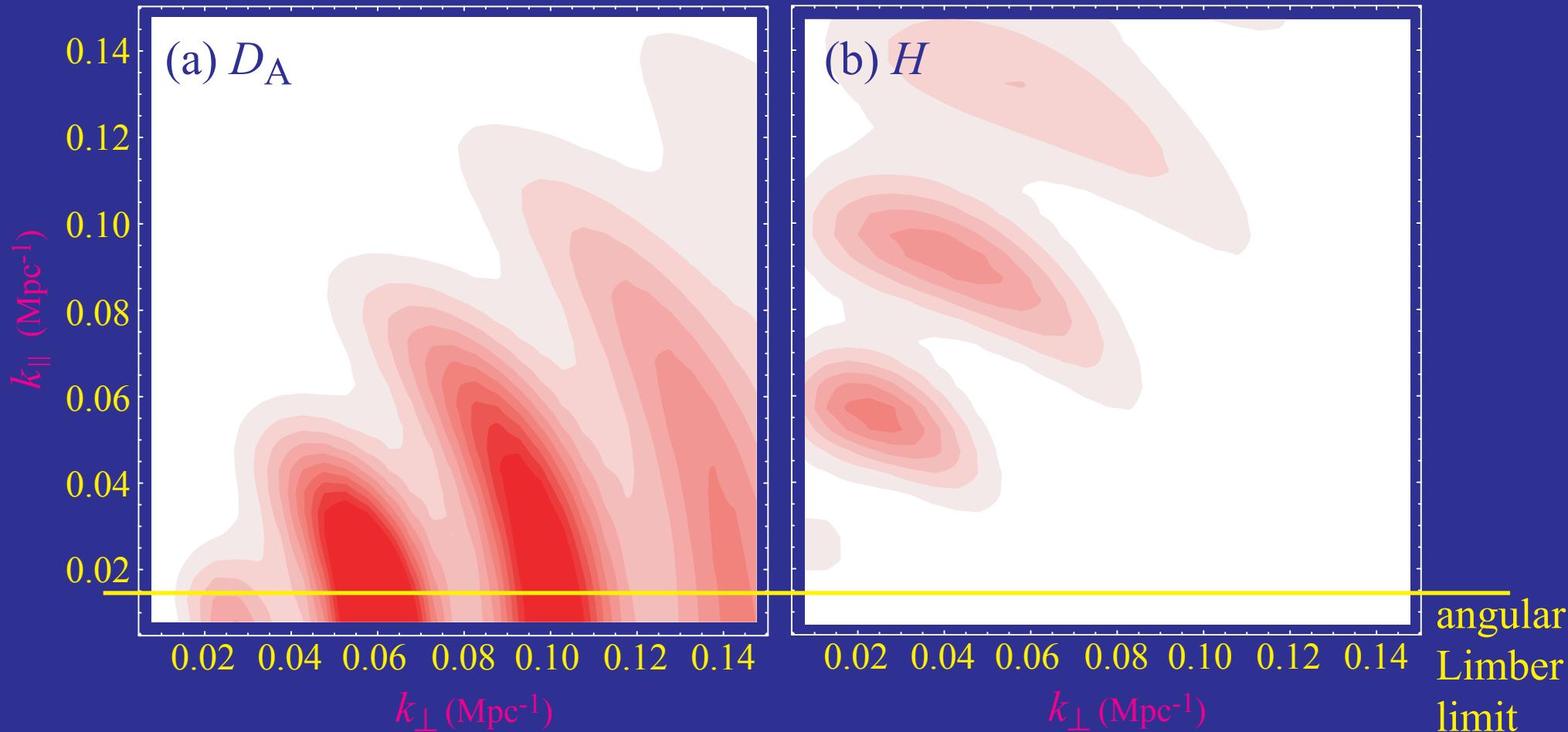
- Modes parallel to line of sight measure the Hubble parameter



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

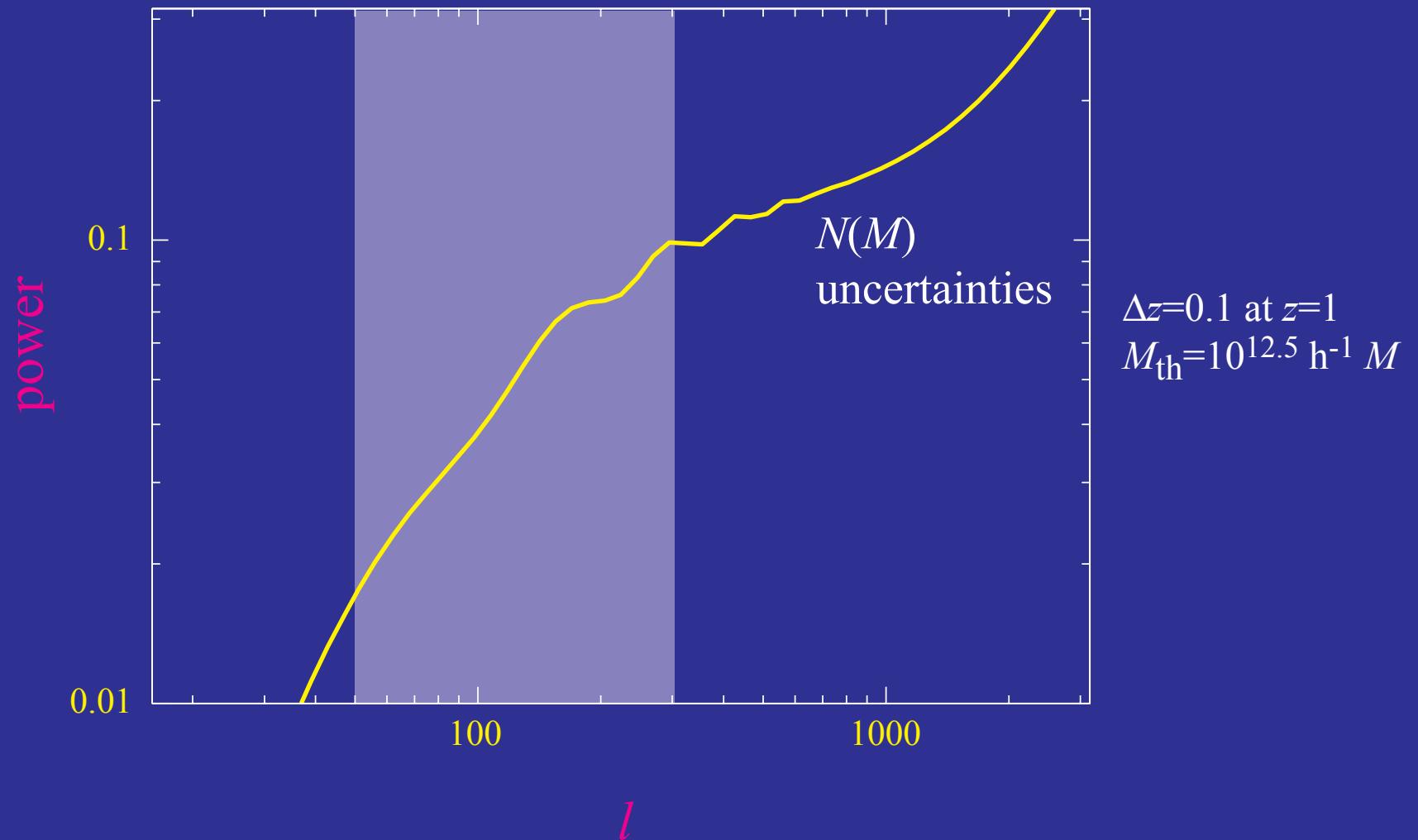
Projected Power

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



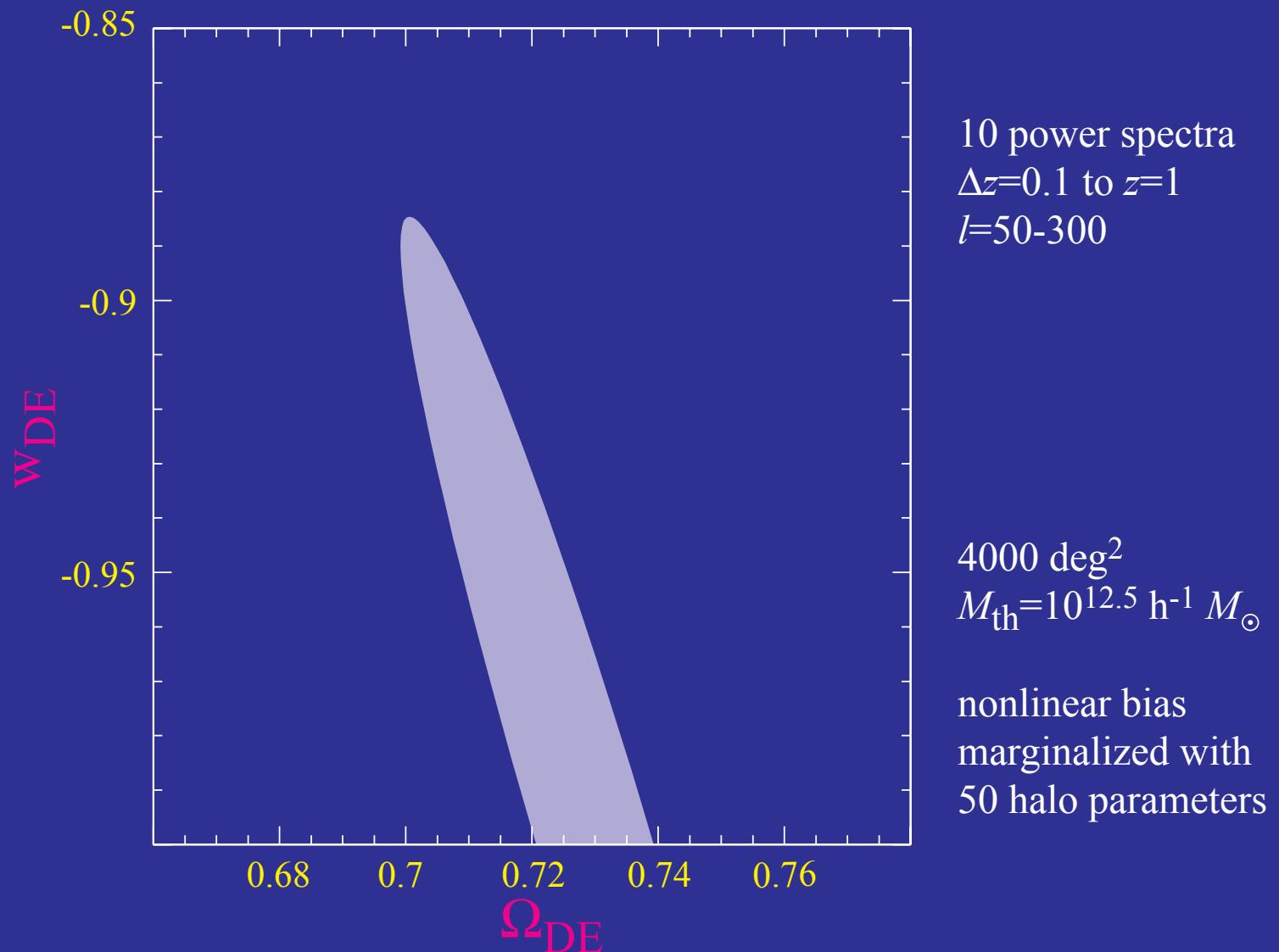
Angular Power Spectra

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



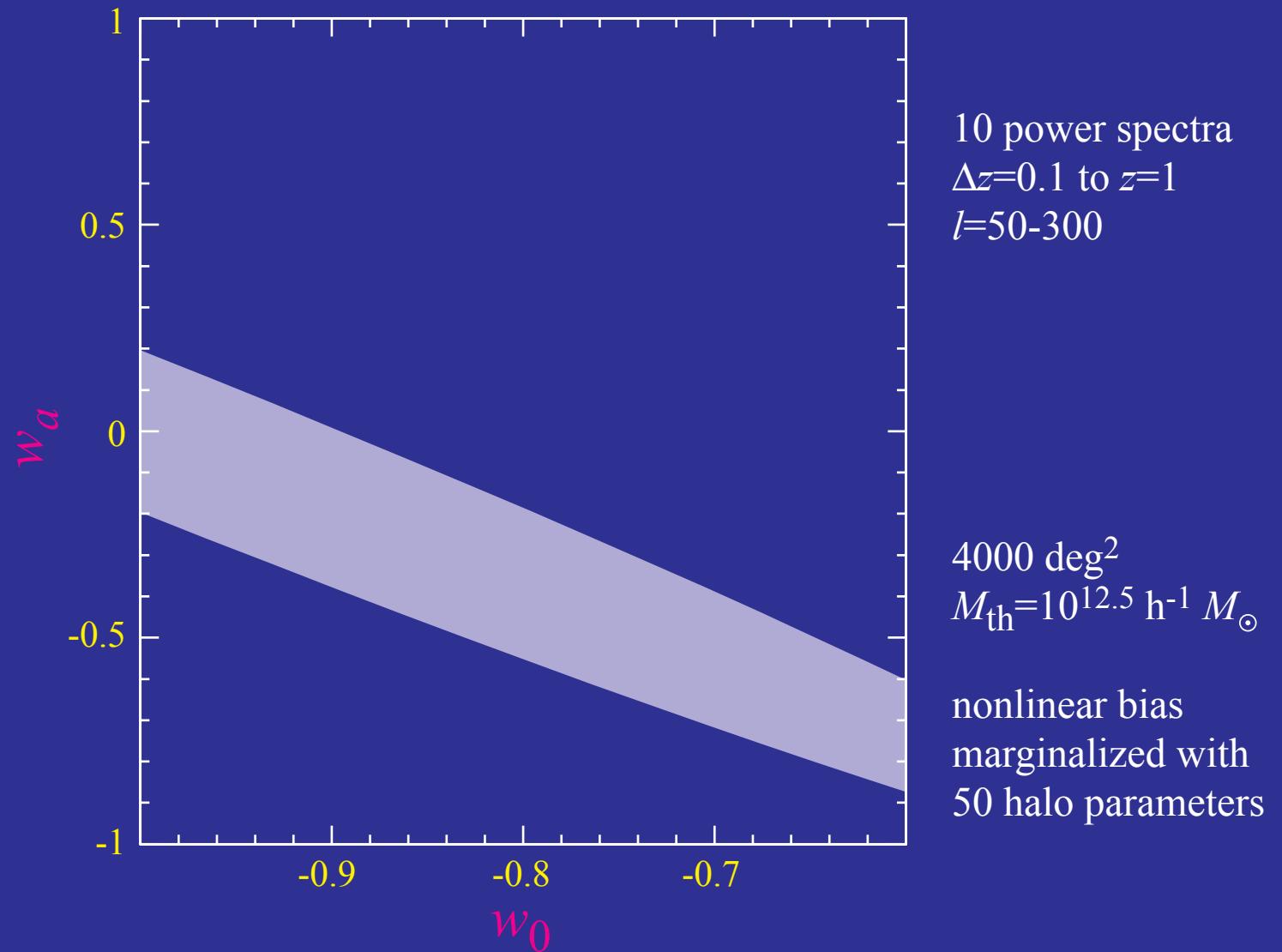
Angular Power Spectrum

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



Angular Power Spectrum

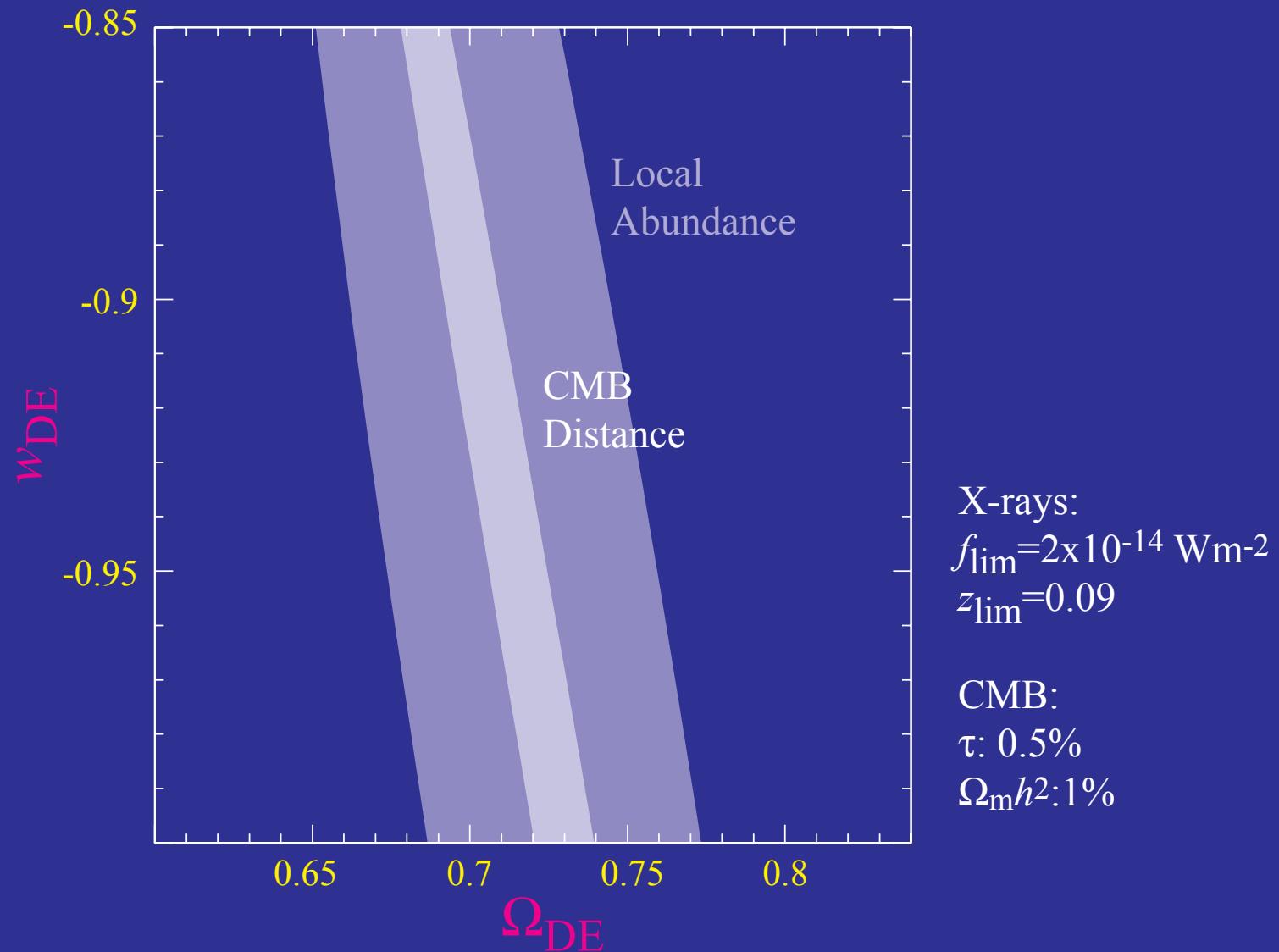
- Purely geometric constraint
- Degeneracy in $w(z)$ remains



Cluster Abundance

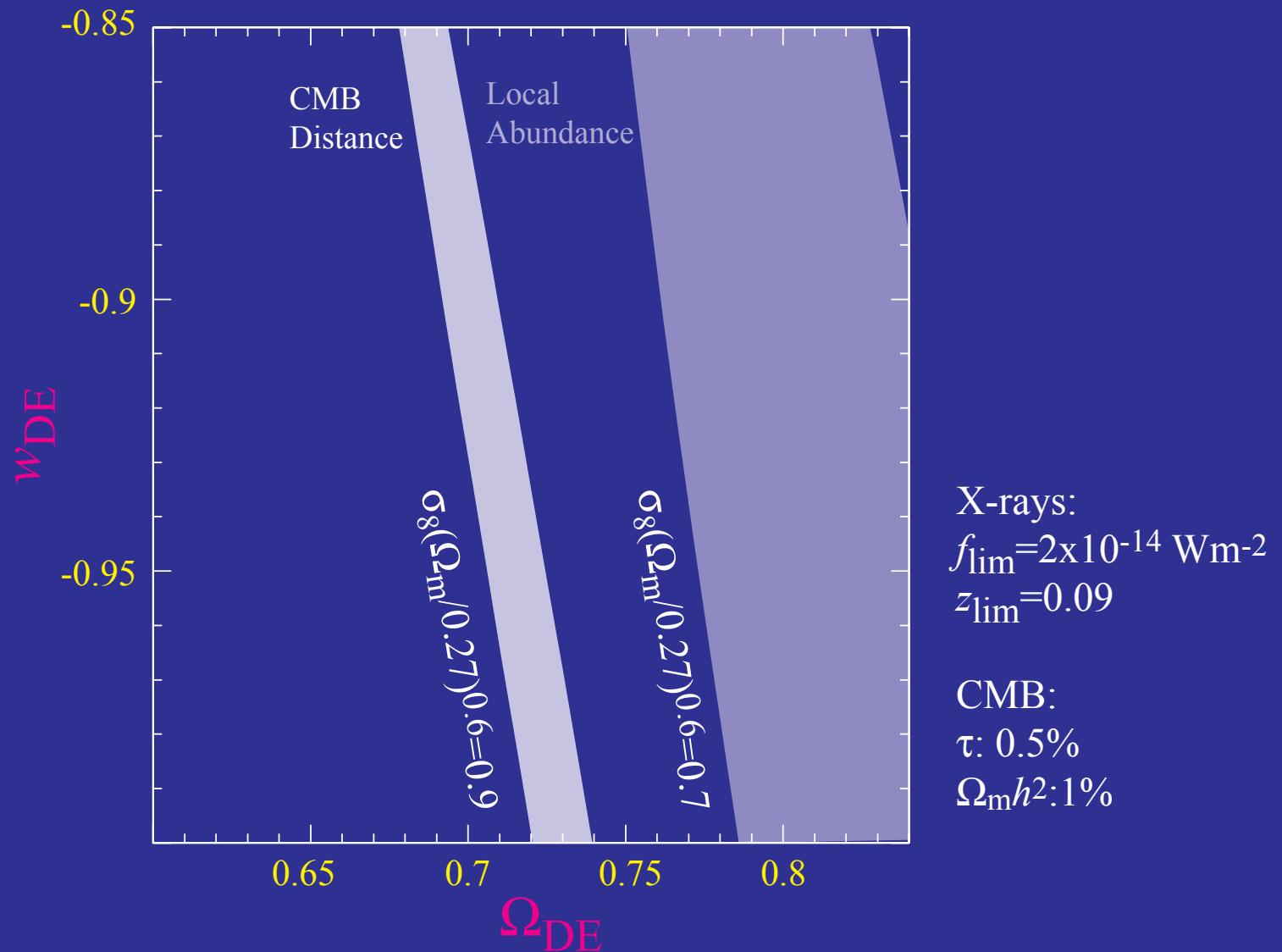
Local Abundance

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



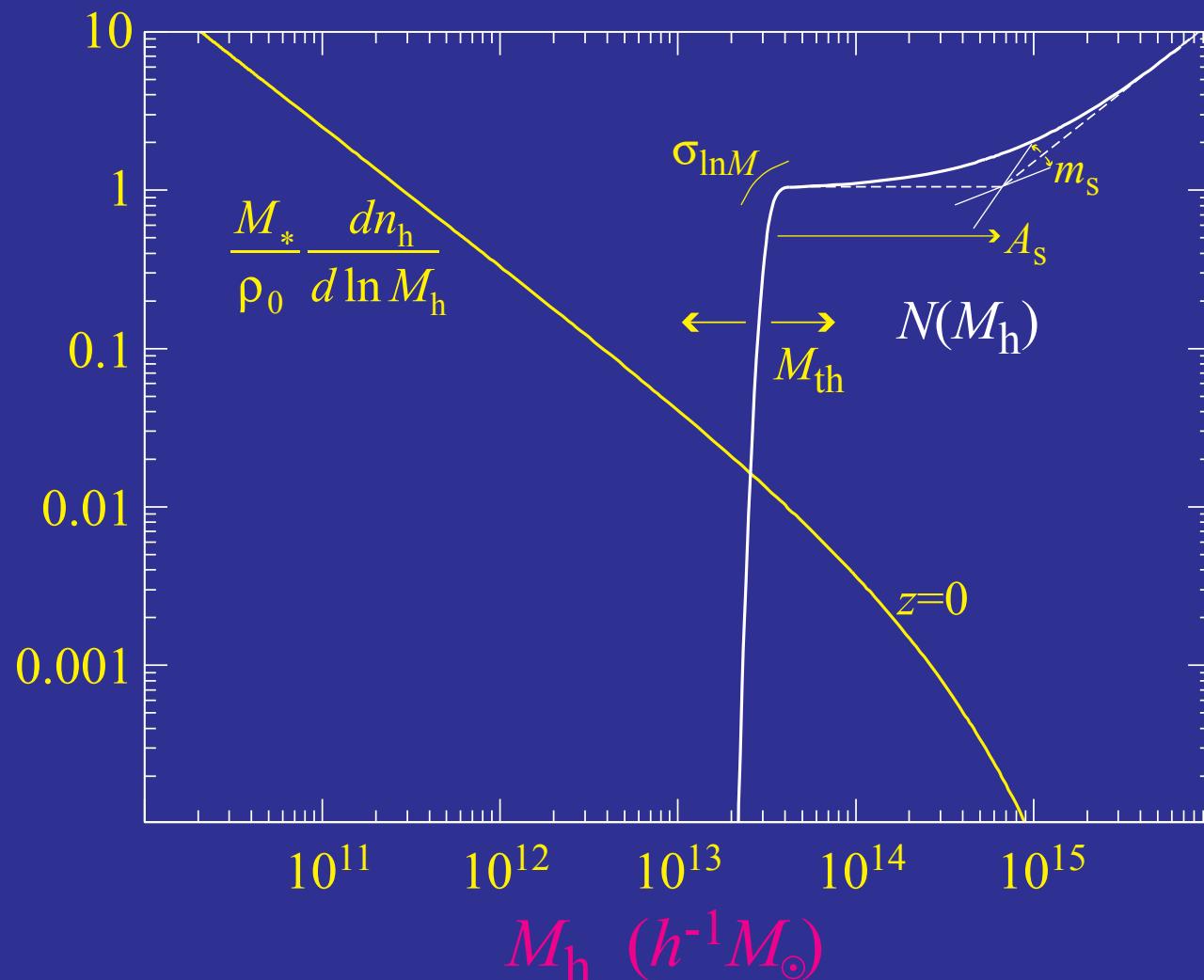
Caveat Emptor!

- 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



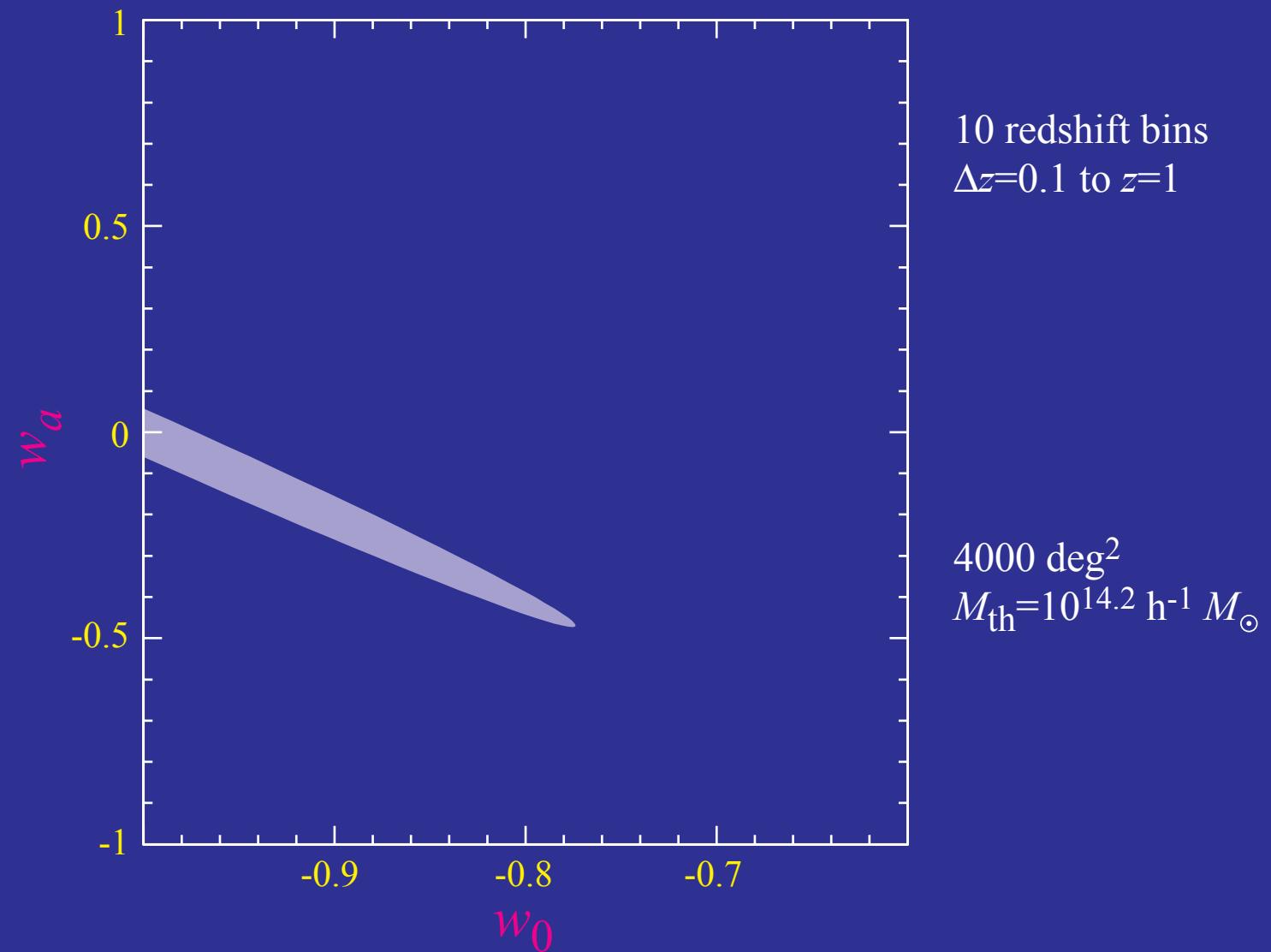
Mass-Observable Relation

- 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



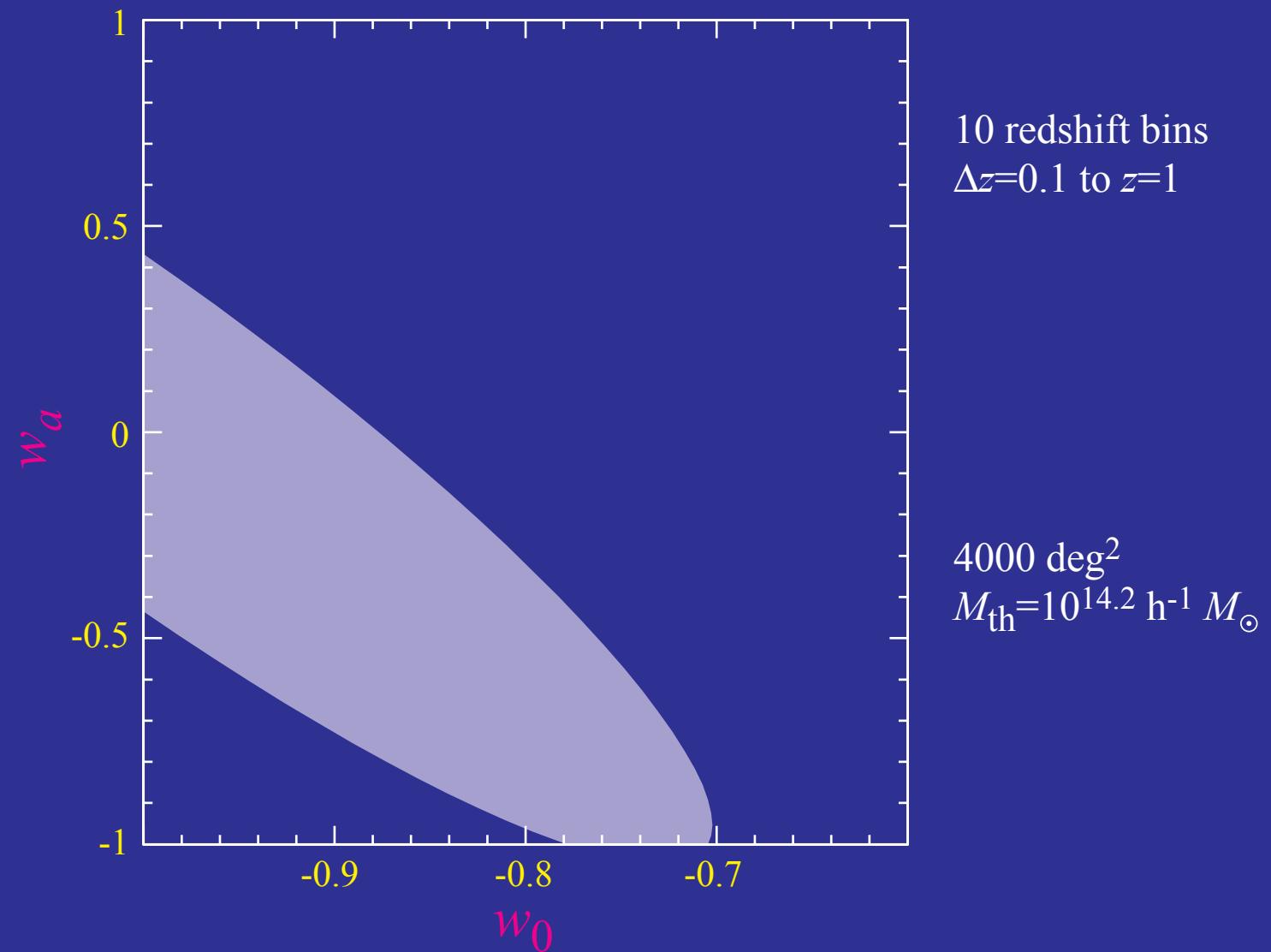
Cluster Abundance

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



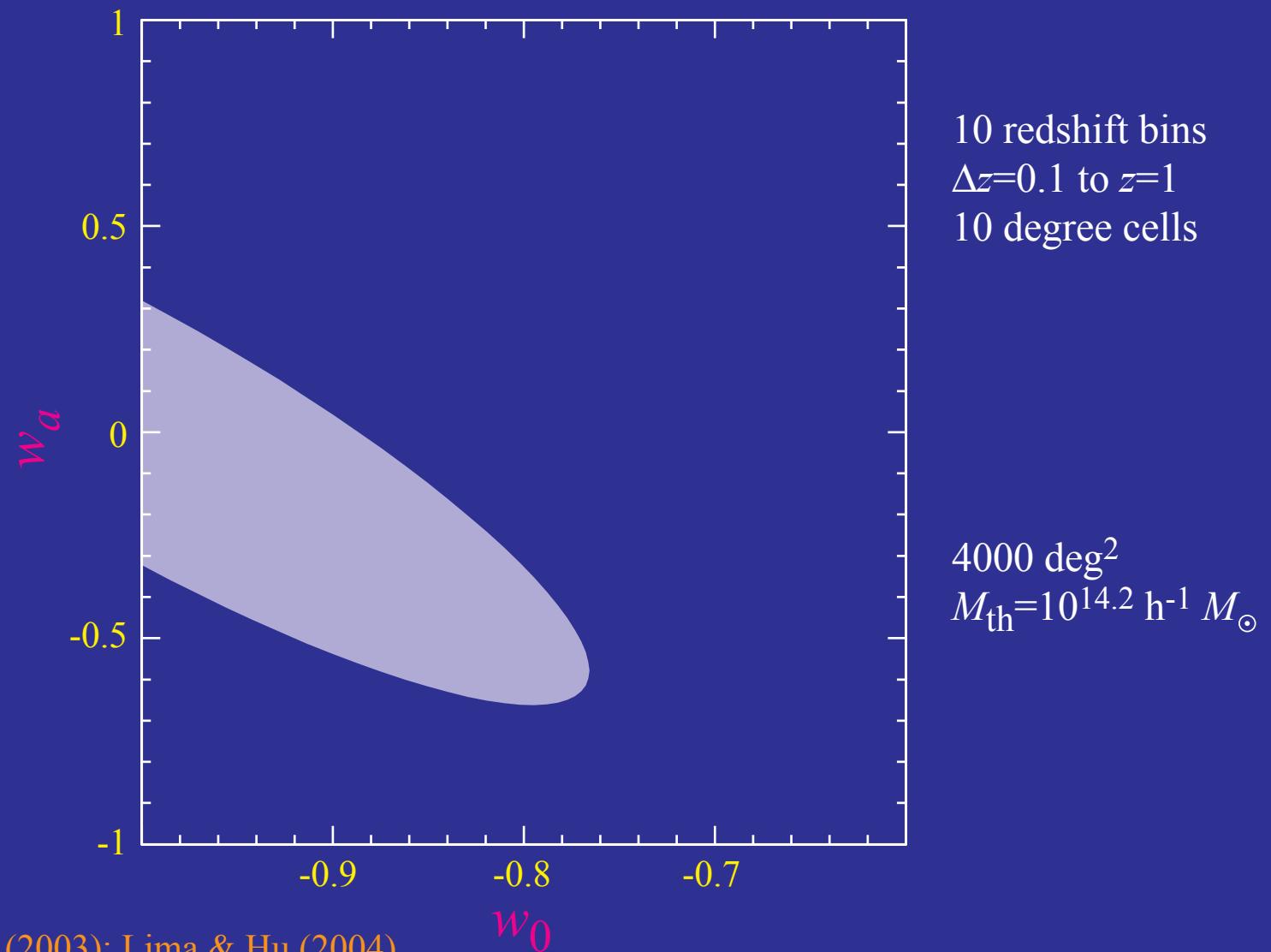
Cluster Abundance

- Power law evolution in mass-observable relation



Cluster Abundance

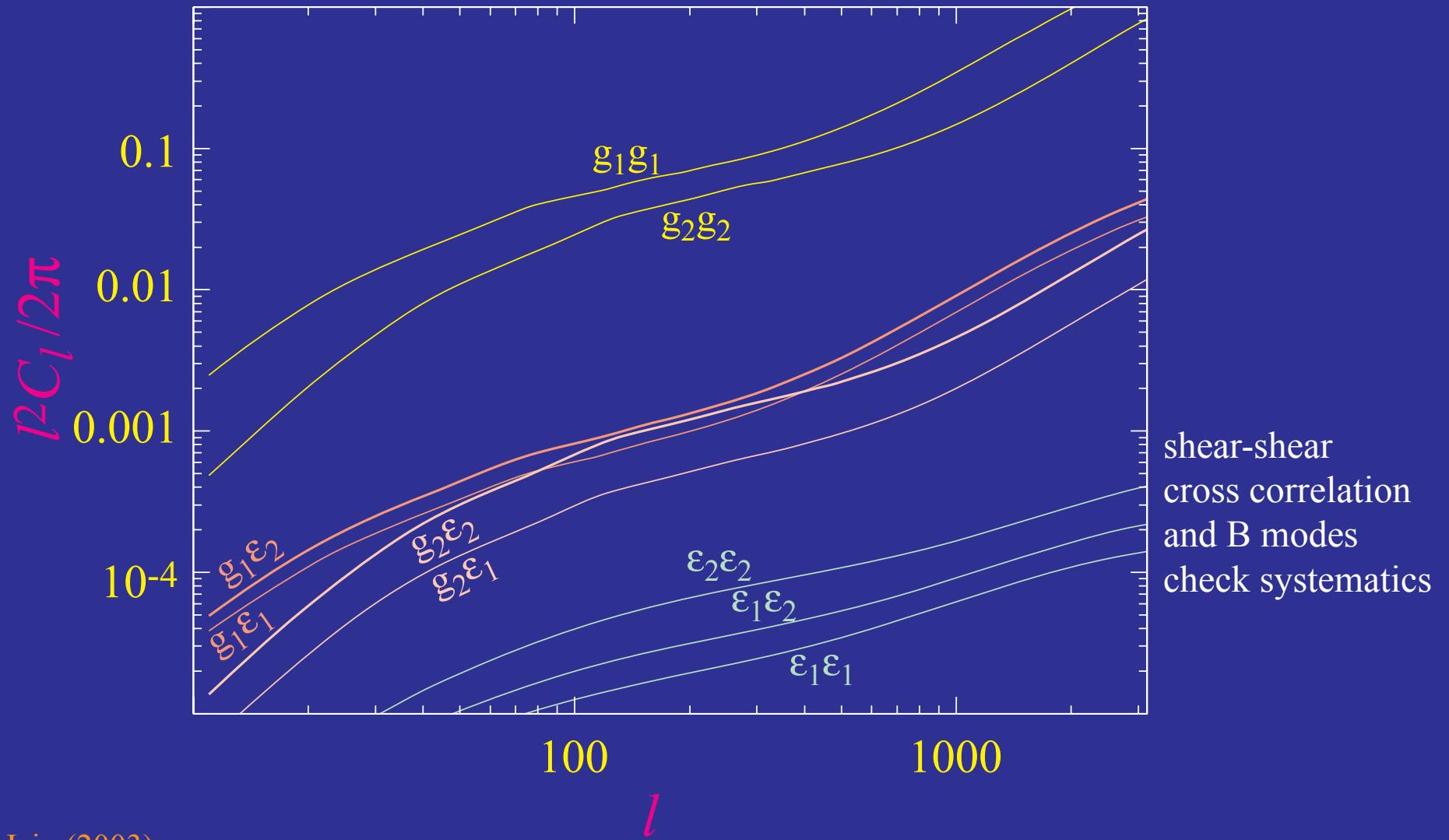
- Self calibration with variance of counts



Gravitational Lensing

Galaxy-Shear Power Spectra

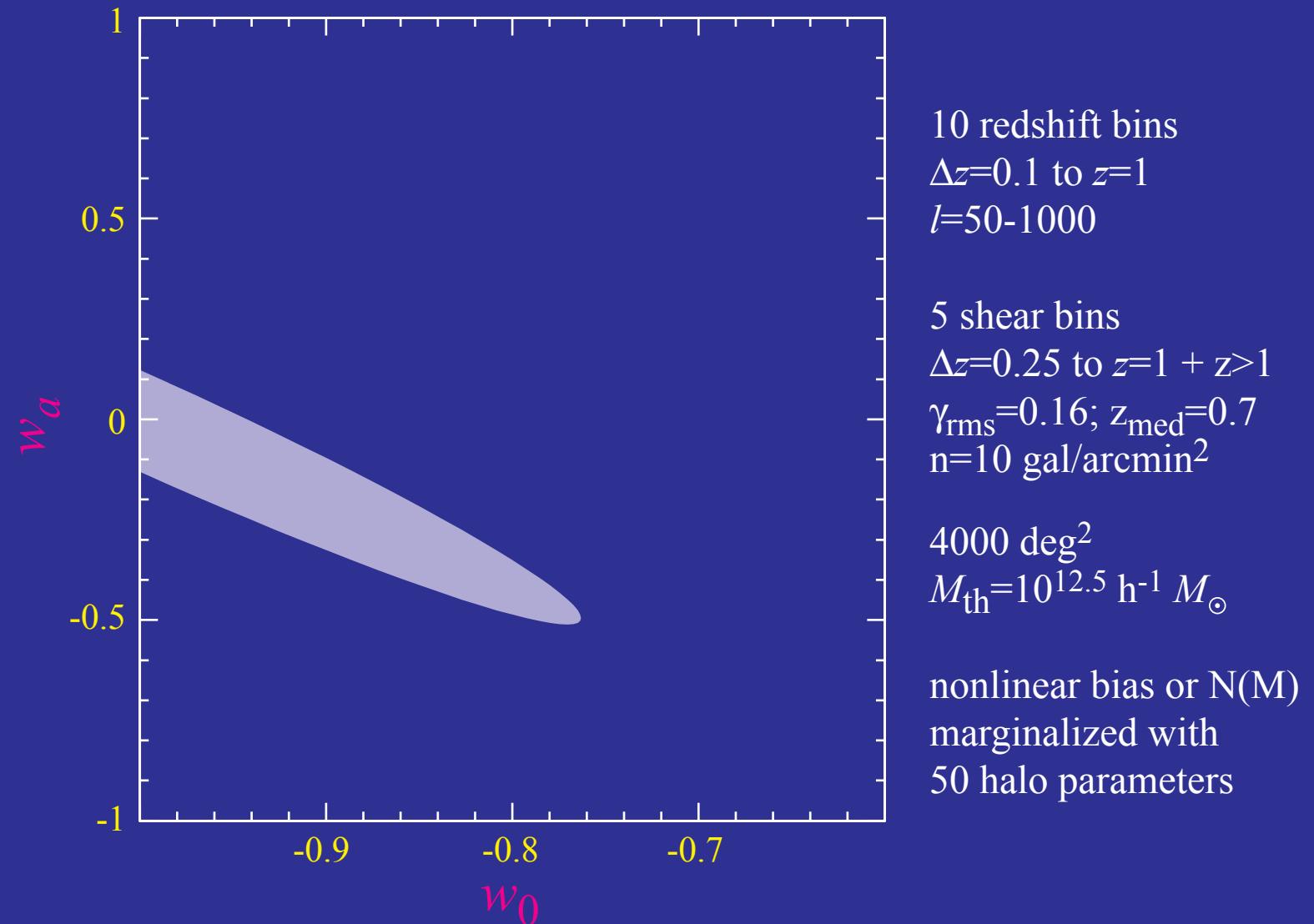
- Auto and cross power spectra of galaxy density and shear in multiple redshift bins



Hu & Jain (2003) [also geometric constraints: Jain & Taylor (2003); Bernstein & Jain (2003); Zhang, Hui, Stebbins (2003); Knox & Song (2003)]

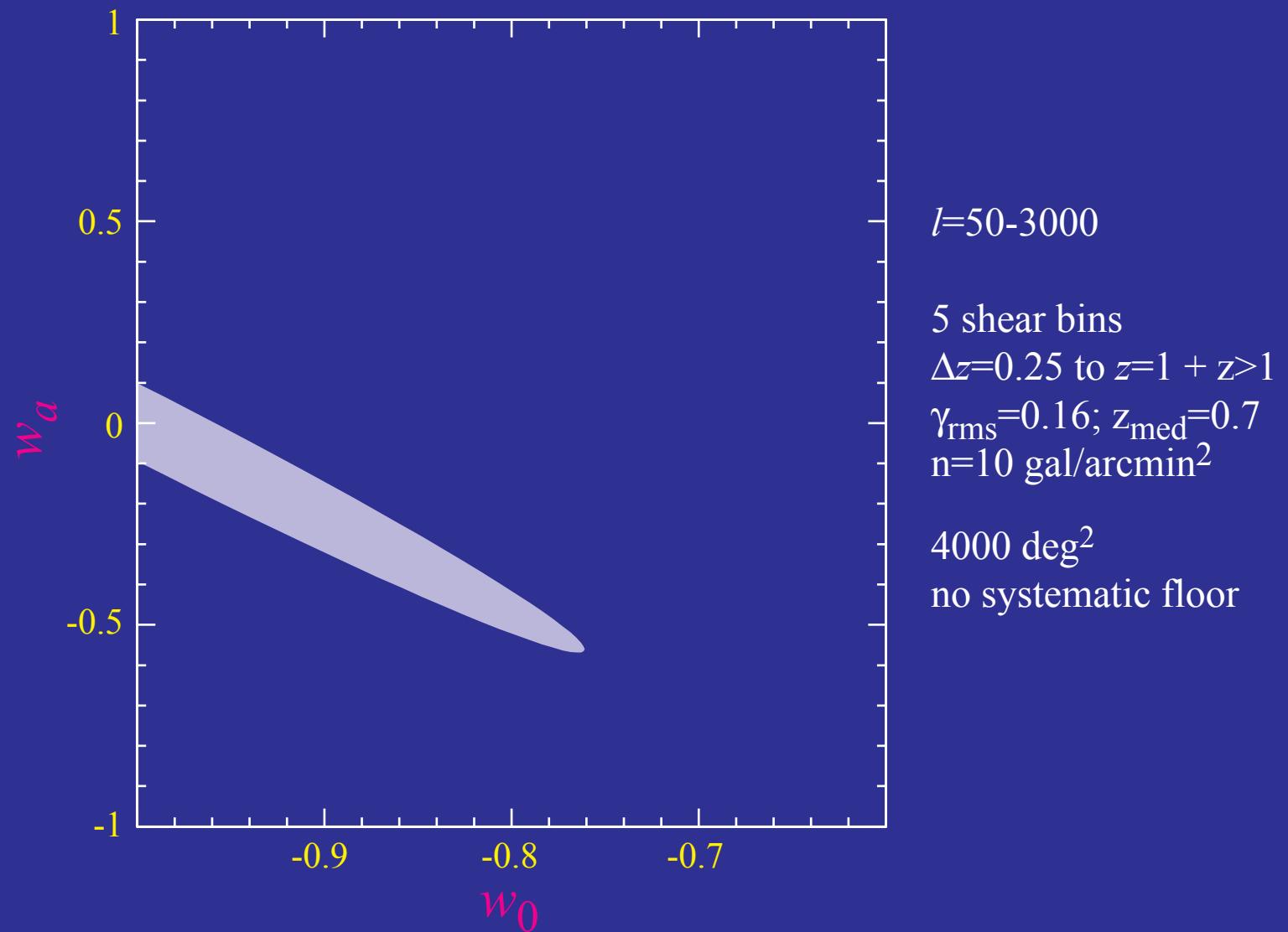
Galaxy-Shear Correlations

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

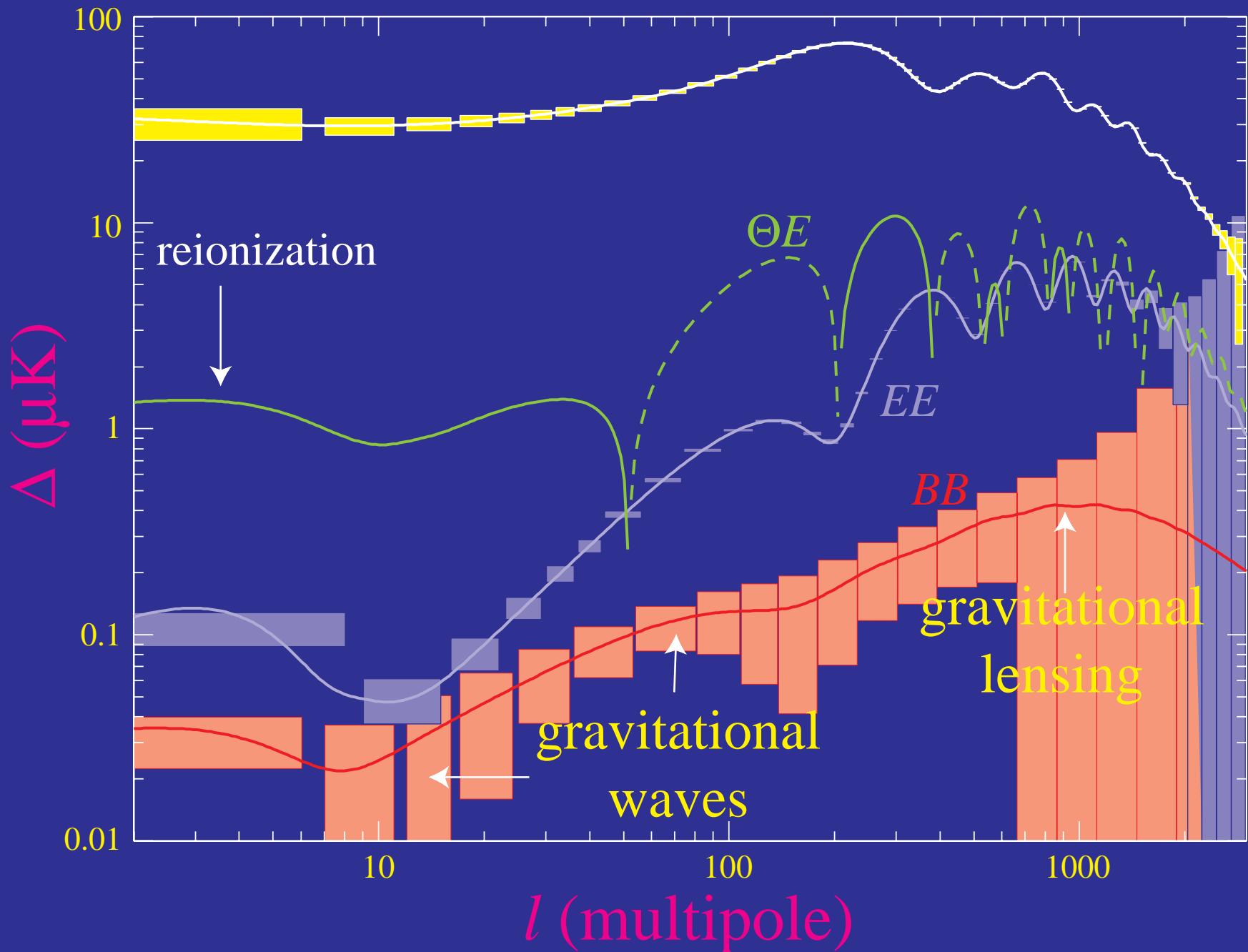


Shear-Shear Correlations

- Cosmic shear statistical forecast:

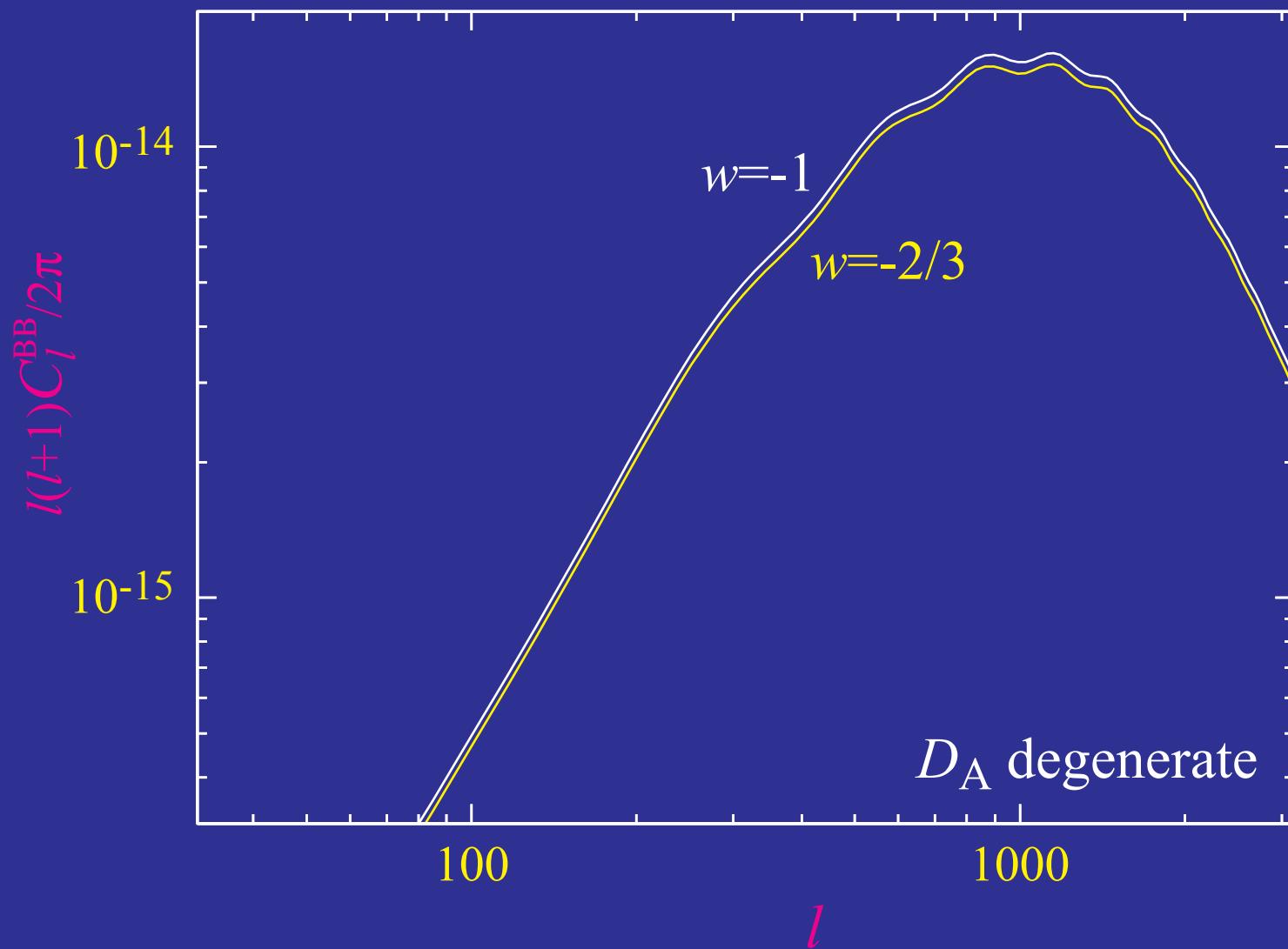


Temperature and Polarization Spectra



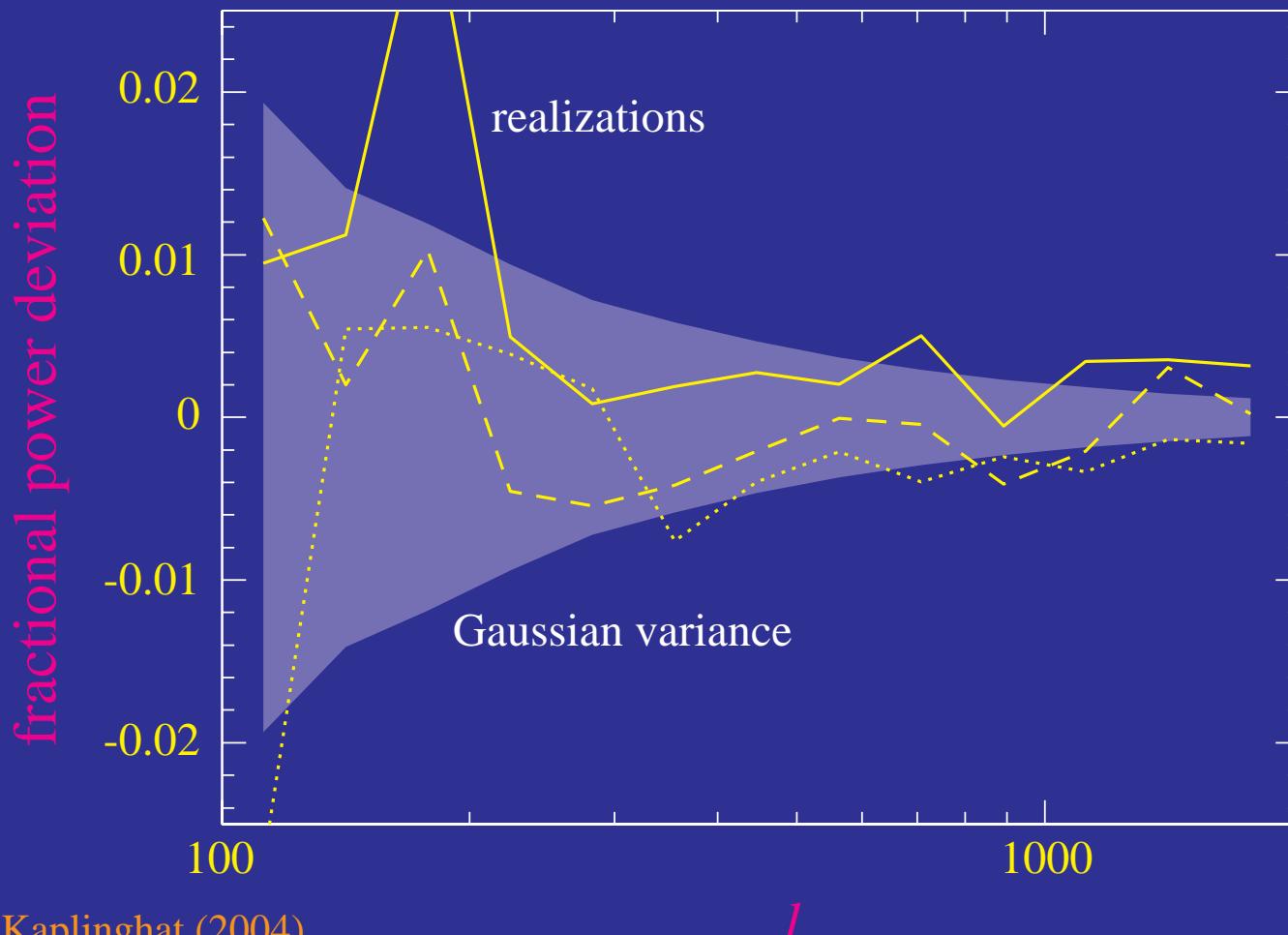
Dark Energy Sensitivity

- B mode power spectrum sensitive to structure at $z \sim 1-3$
- Limits the dark energy for large w



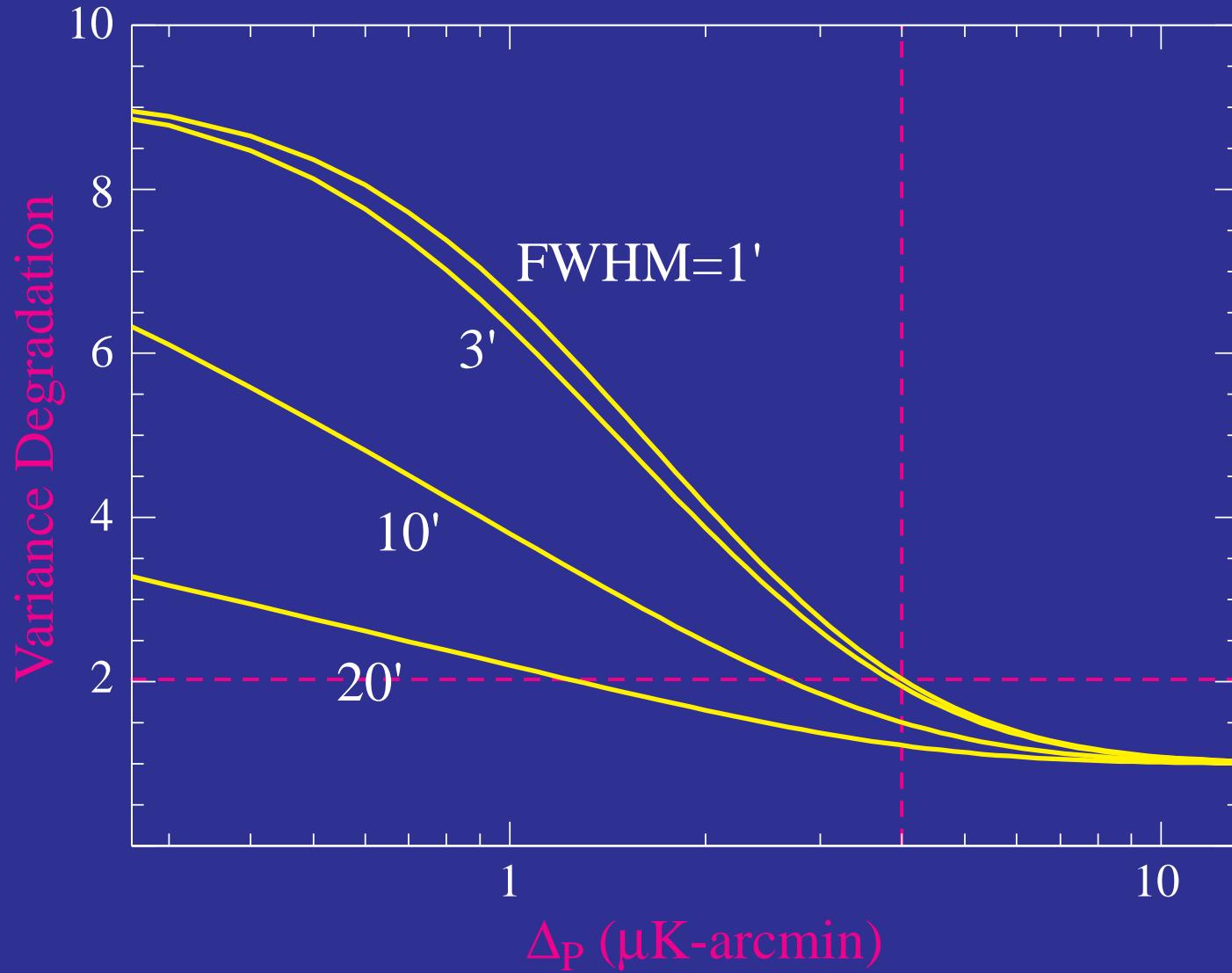
Power Spectrum Measurements

- Lensed field is non-Gaussian in that a single degree scale lens controls the polarization at arcminutes
- Increased variance and covariance implies that 10x as much sky needed compared with Gaussian fields



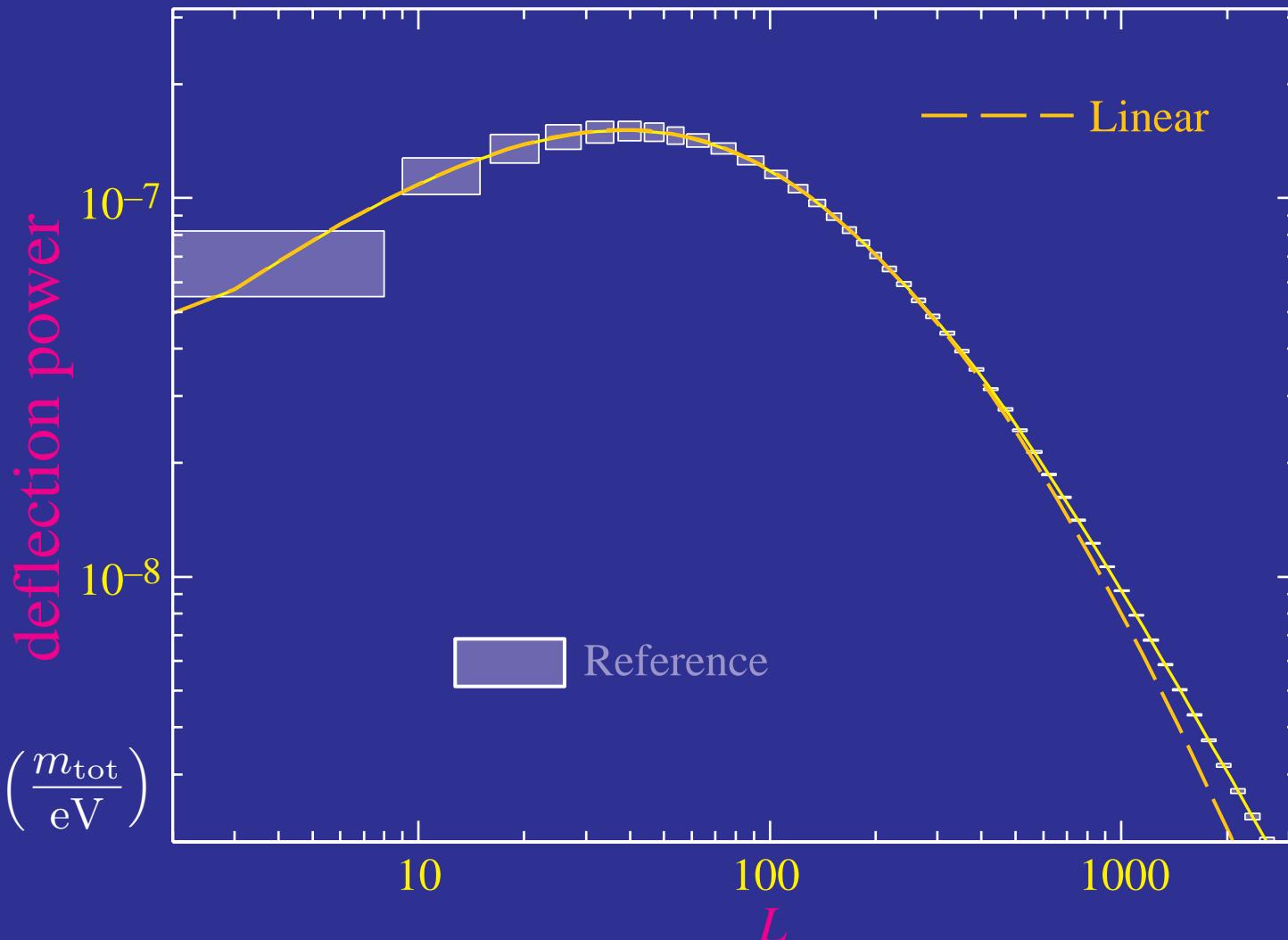
Sample vs Noise Variance

- Non-Gaussian sample variance doubles total variance at $4\mu\text{K}'$ for resolved B-modes



Matter Power Spectrum

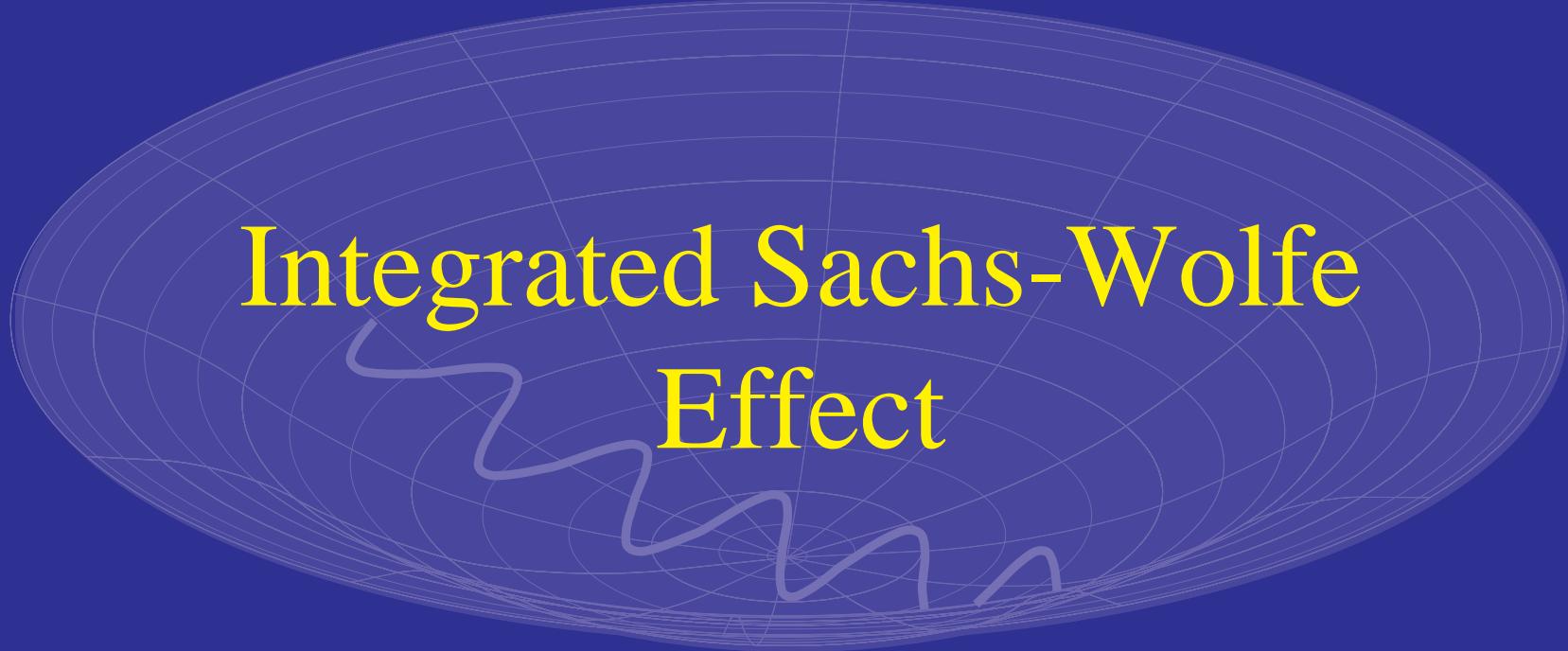
- Measuring projected matter power spectrum to cosmic variance limit across whole linear regime $0.002 < k < 0.2 \text{ } h/\text{Mpc}$



Hu & Okamoto (2001) [parameter forecasts: Kaplinghat et al 2003]

[systematics: Amblard et al 2004; Okamoto 2004]

$\sigma(w) \sim 0.06$



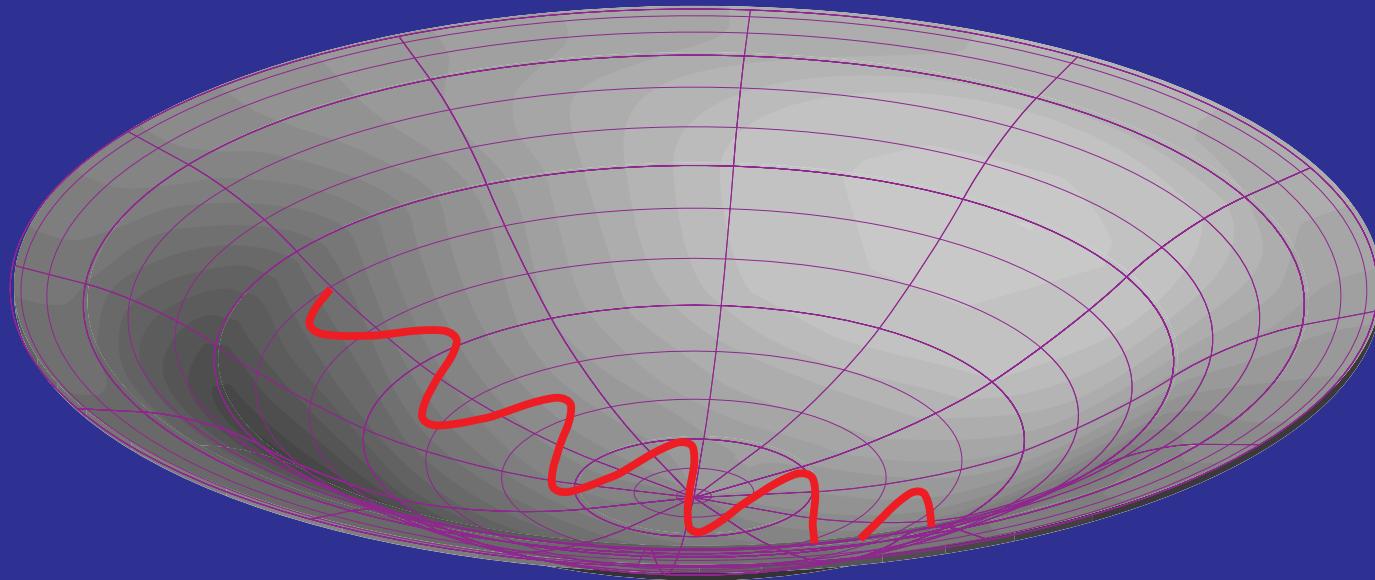
Integrated Sachs-Wolfe Effect

Smooth Energy Density & Potential Decay

- A smooth component contributes density ρ to the expansion but not density fluctuation $\delta\rho$ to the Poisson equation
- Imbalance causes potential to decay once smooth component dominates the expansion

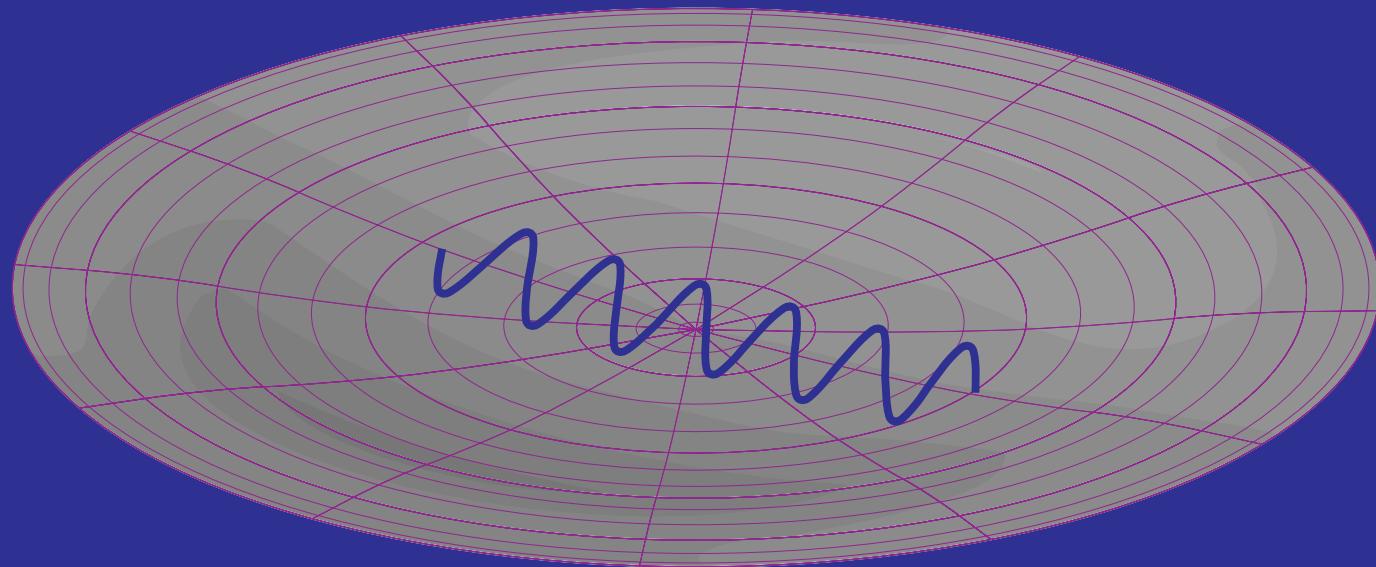
ISW Effect

- 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



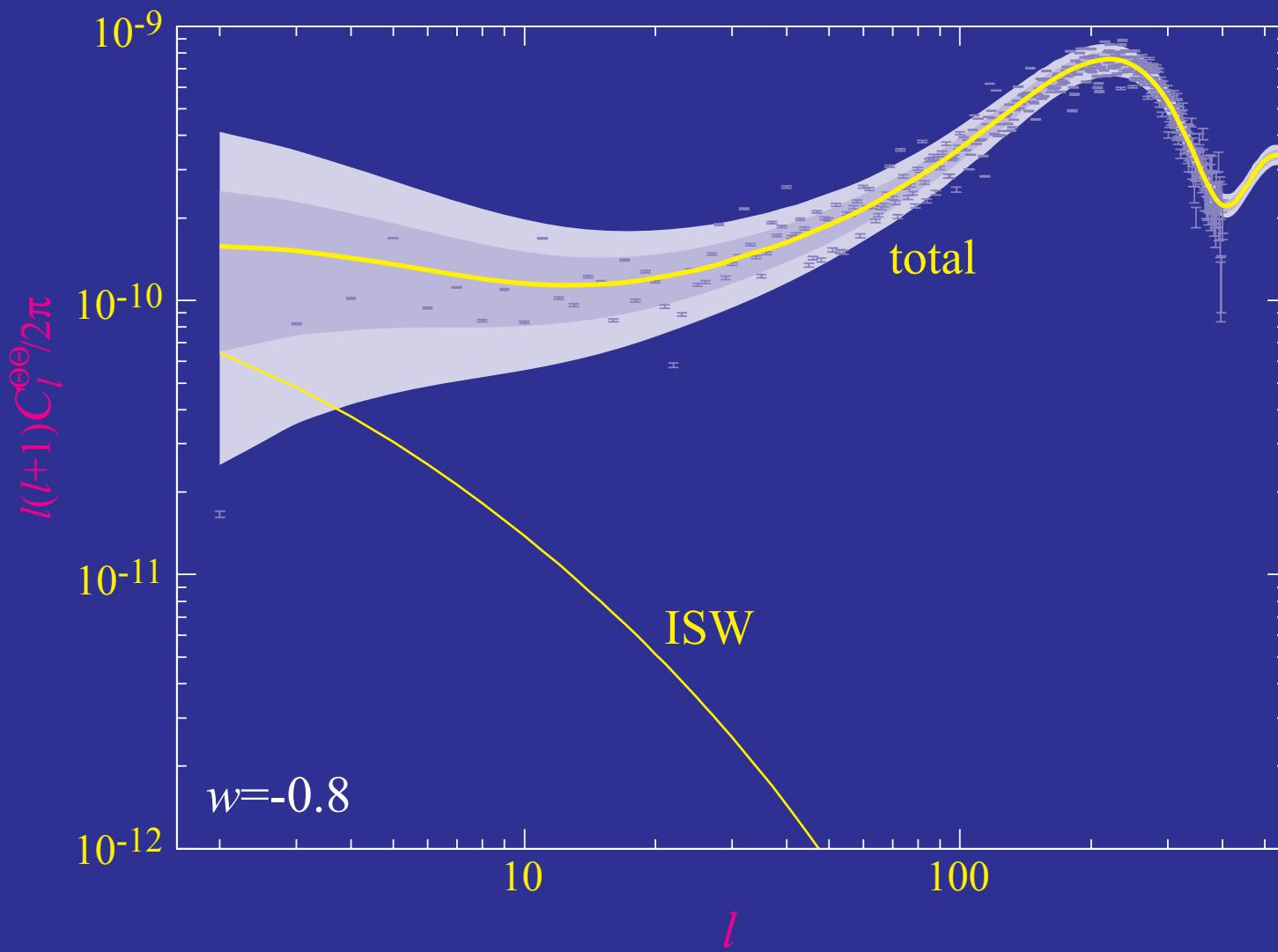
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ISW Effect

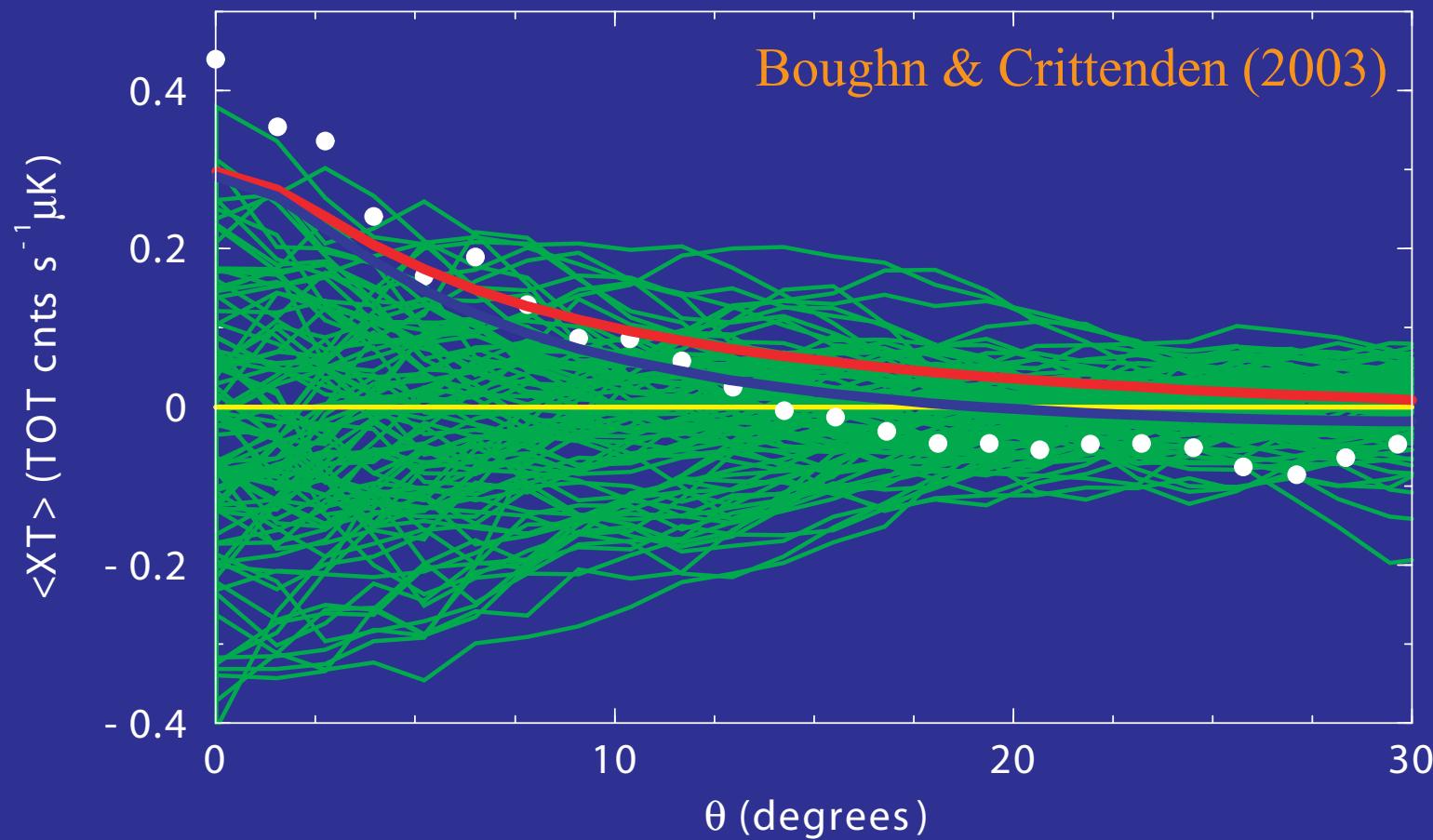
- ISW effect hidden in the temperature power spectrum by primary anisotropy and cosmic variance



[plot: Hu & Scranton (2004)]

ISW Galaxy Correlation

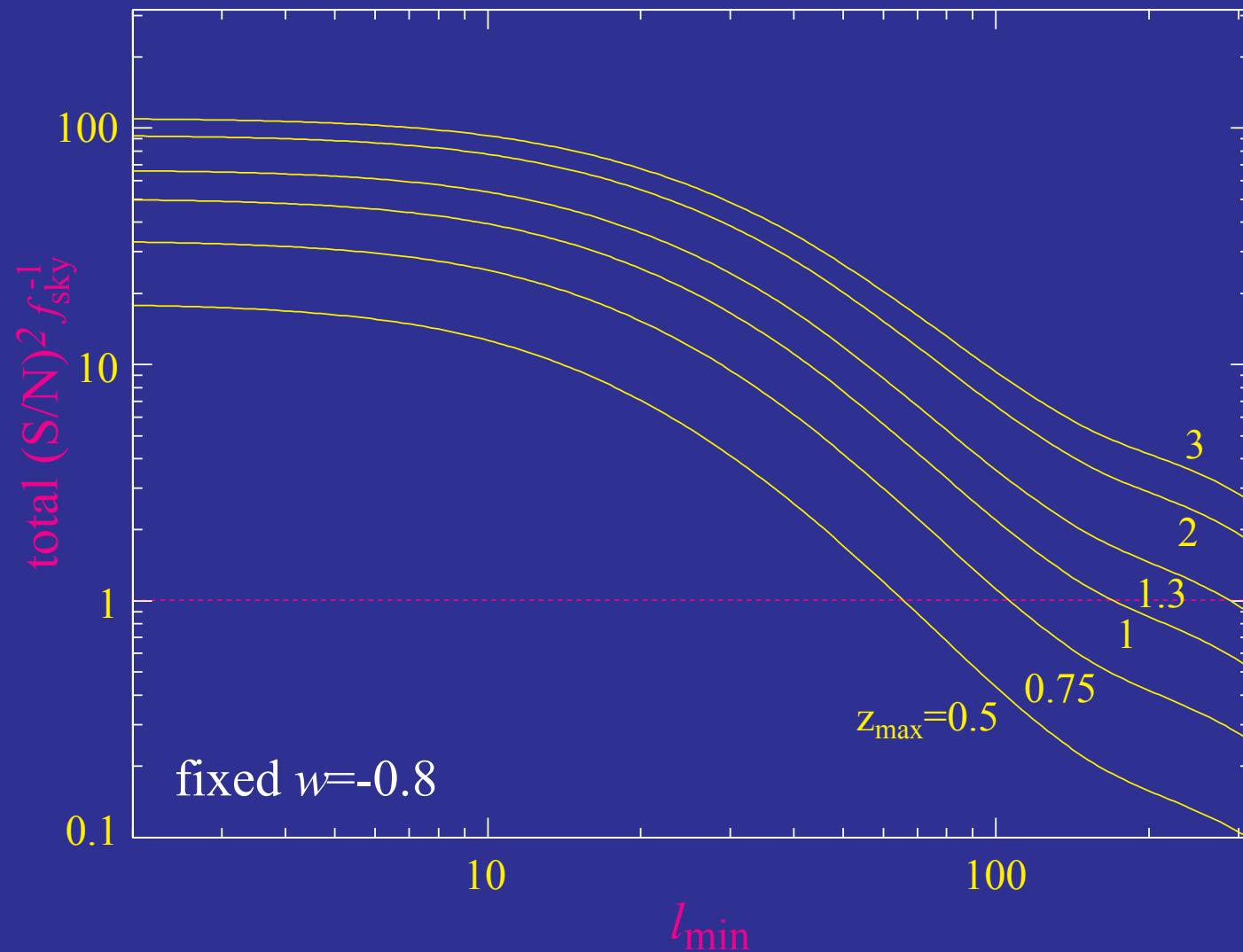
- A $2-3\sigma$ detection of the ISW effect through galaxy correlations



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

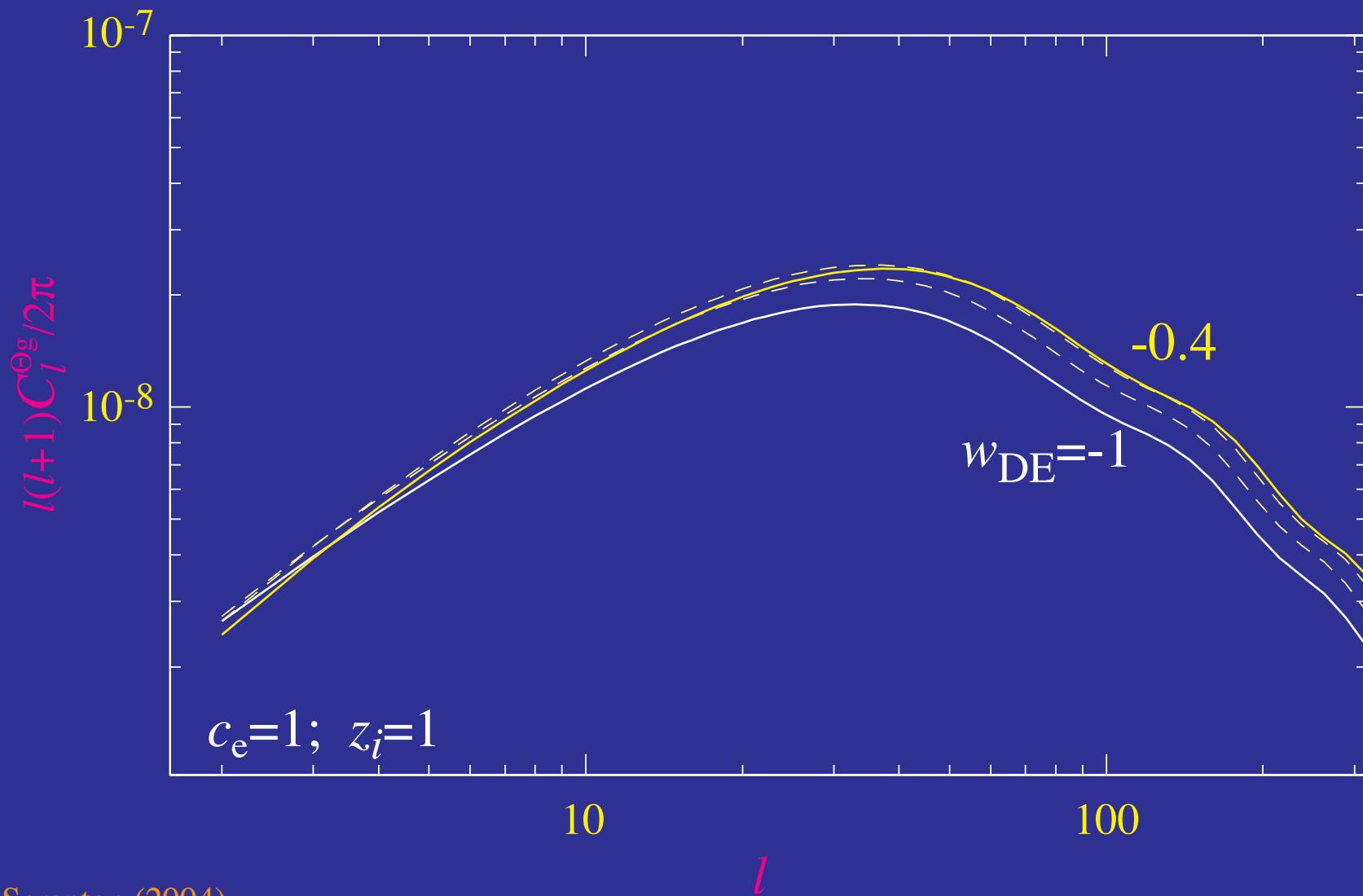
Galaxy Cross Correlation

- Total signal-to-noise for cross correlation detection limited by CMB cosmic variance



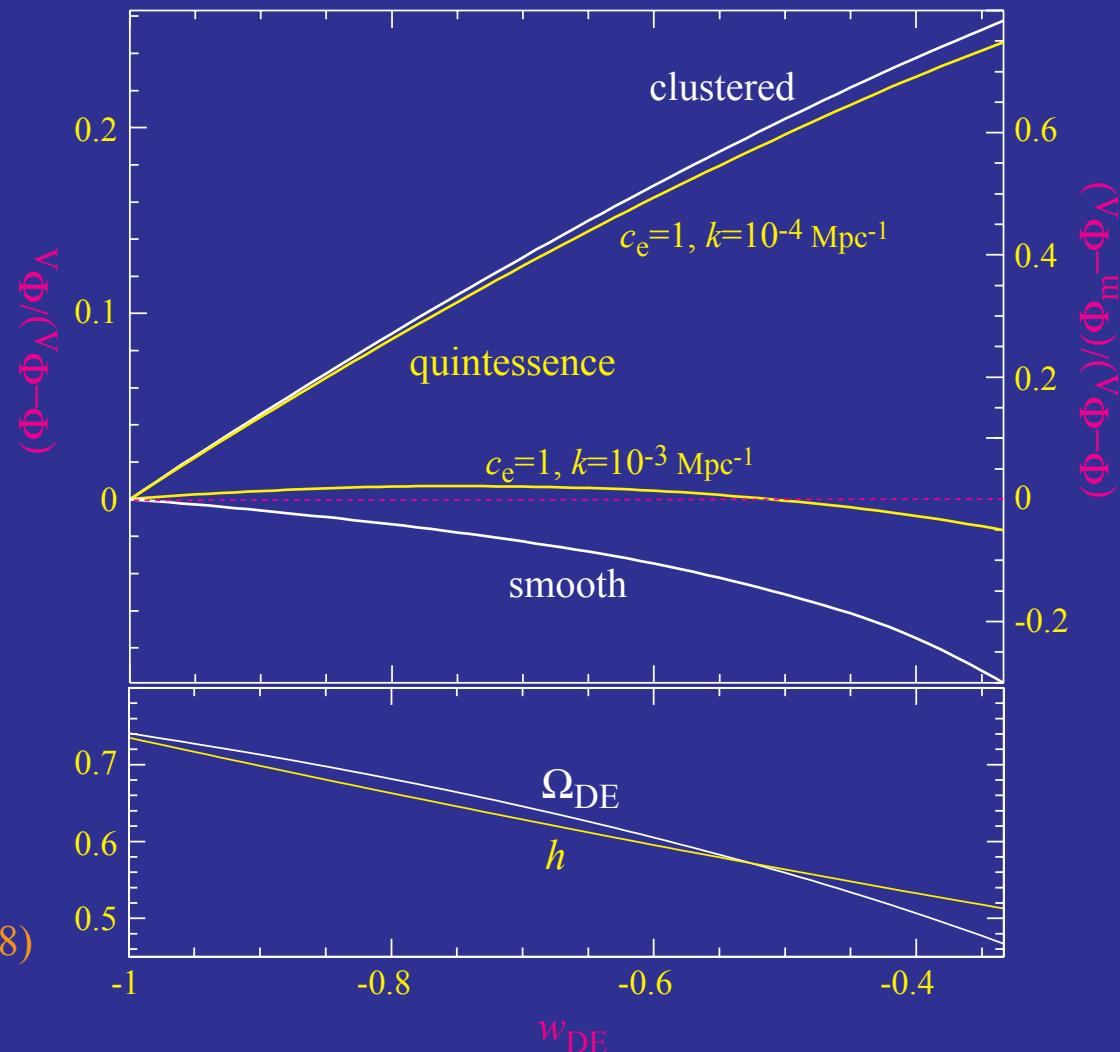
Galaxy Cross Correlation

- Cross correlation relatively **insensitive** to w_{DE} for quintessence since smooth growth factor nearly degenerate with distance



Dark Energy Clustering

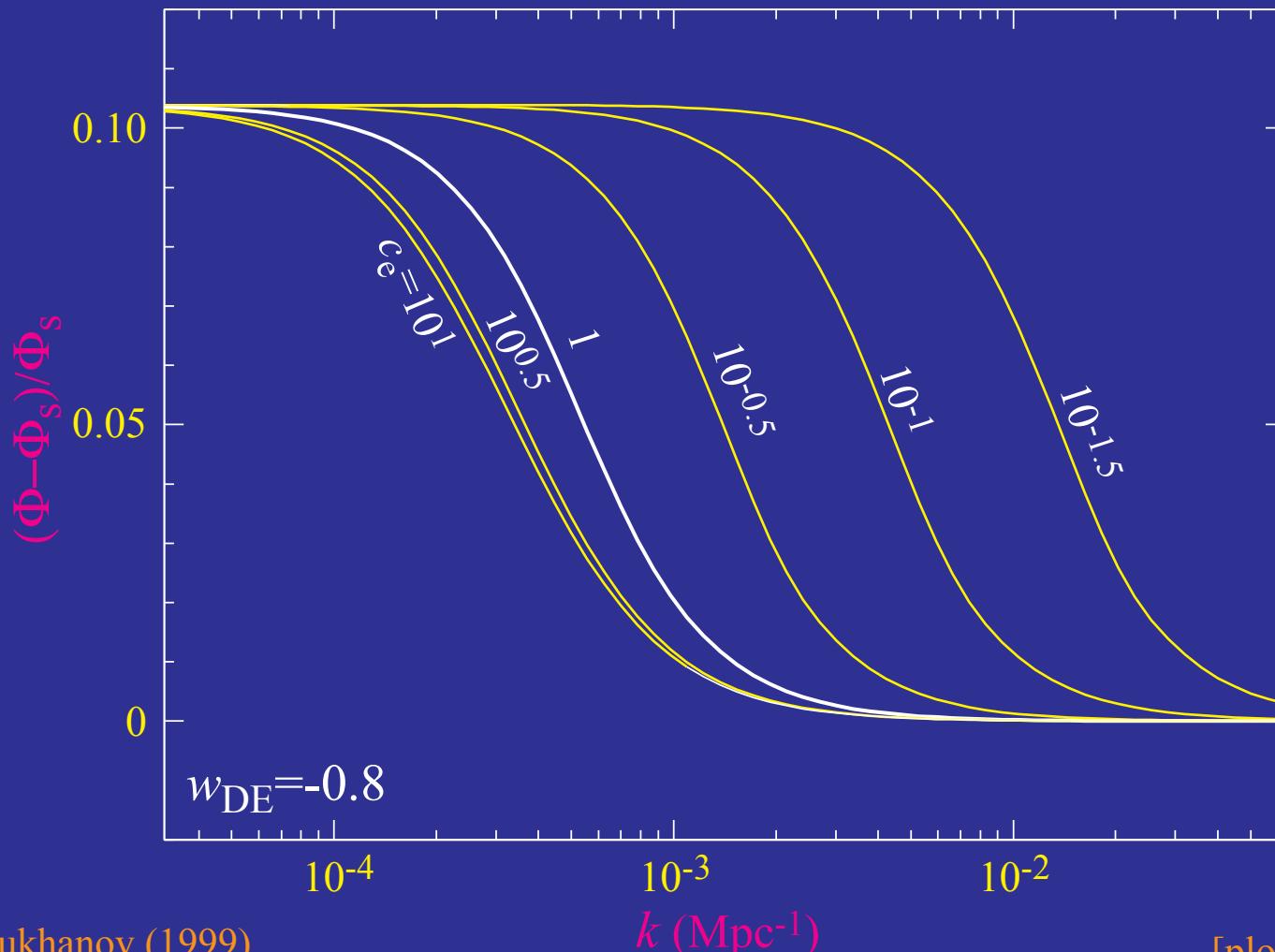
- Gravitational forces only: dark energy clustered (ζ conserved)
- Relativistic stresses keep dark energy smooth on small scales
- Gravitational potential:



Bardeen (1980); Caldwell et al (1998)
[plot Hu & Scranton (2004)]

Dark Energy Sound Speed

- Smooth and clustered regimes separated by sound horizon
- Covariant definition: $c_e^2 = \delta p / \delta \rho$ where momentum flux vanishes
- For scalar field dark energy uniquely defined by kinetic term



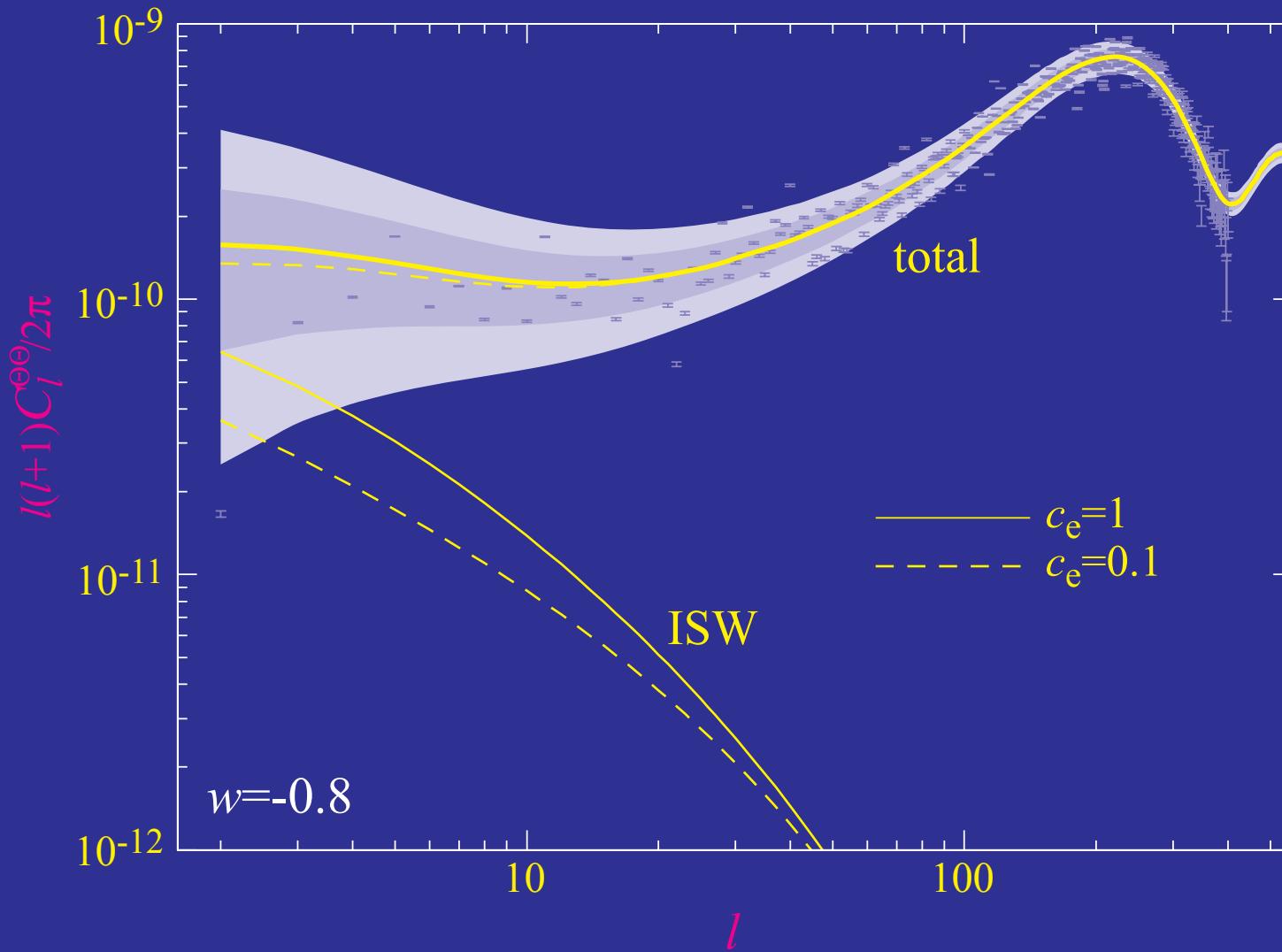
Hu (1998)

Garriga & Mukhanov (1999)

[plot: Hu & Scranton (2004)]

Dark Energy Clustering

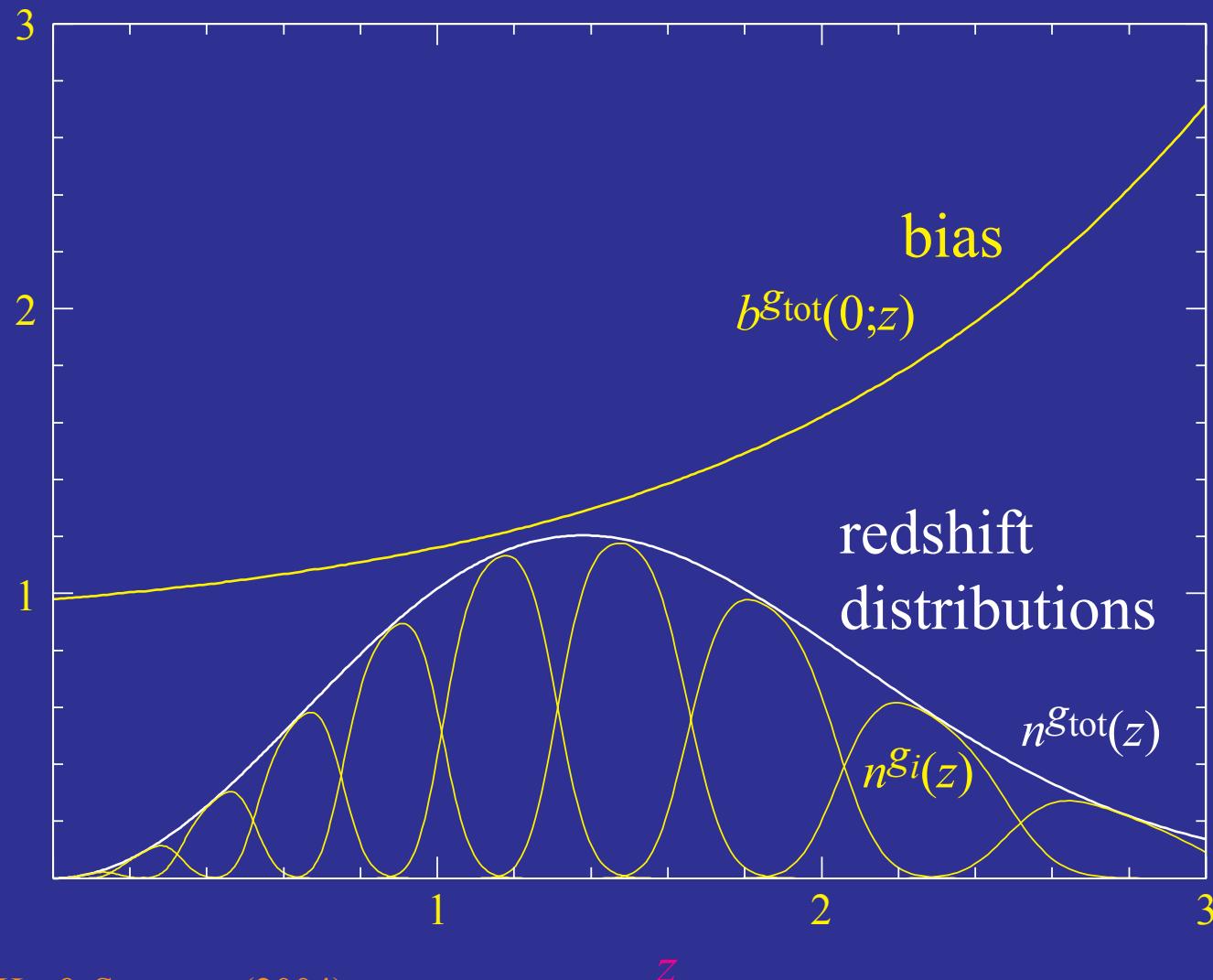
- ISW effect intrinsically sensitive to dark energy smoothness
- Large angle contributions reduced if clustered



Hu (1998); [plot: Hu & Scranton (2004)]

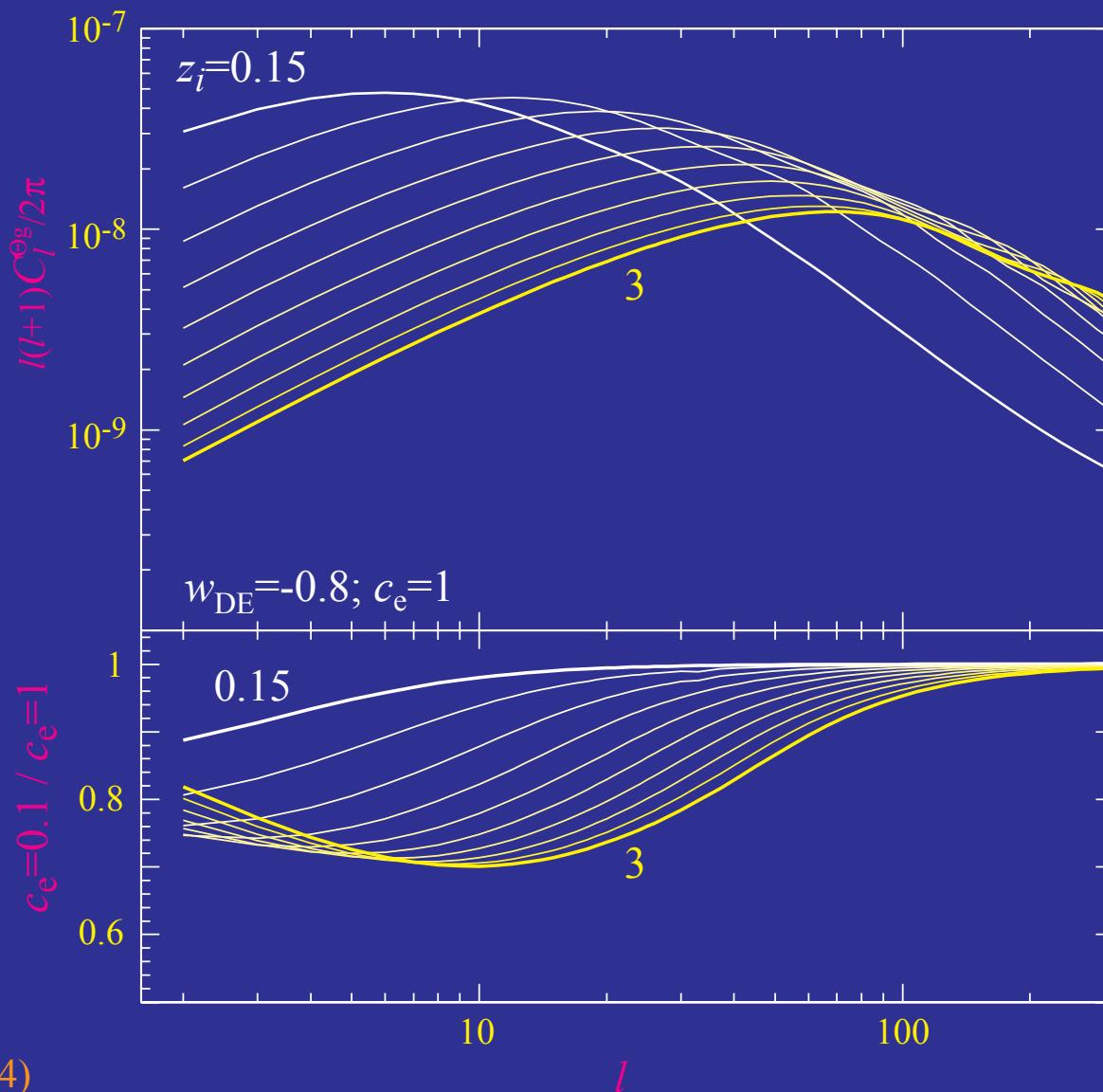
Ultra-Deep Wide Survey

- Ultimate limit: deep wide-field survey with photometric redshift errors of $\sigma(z)=0.03(1+z)$, median redshift $z=1.5$, 70 gal/arcmin 2



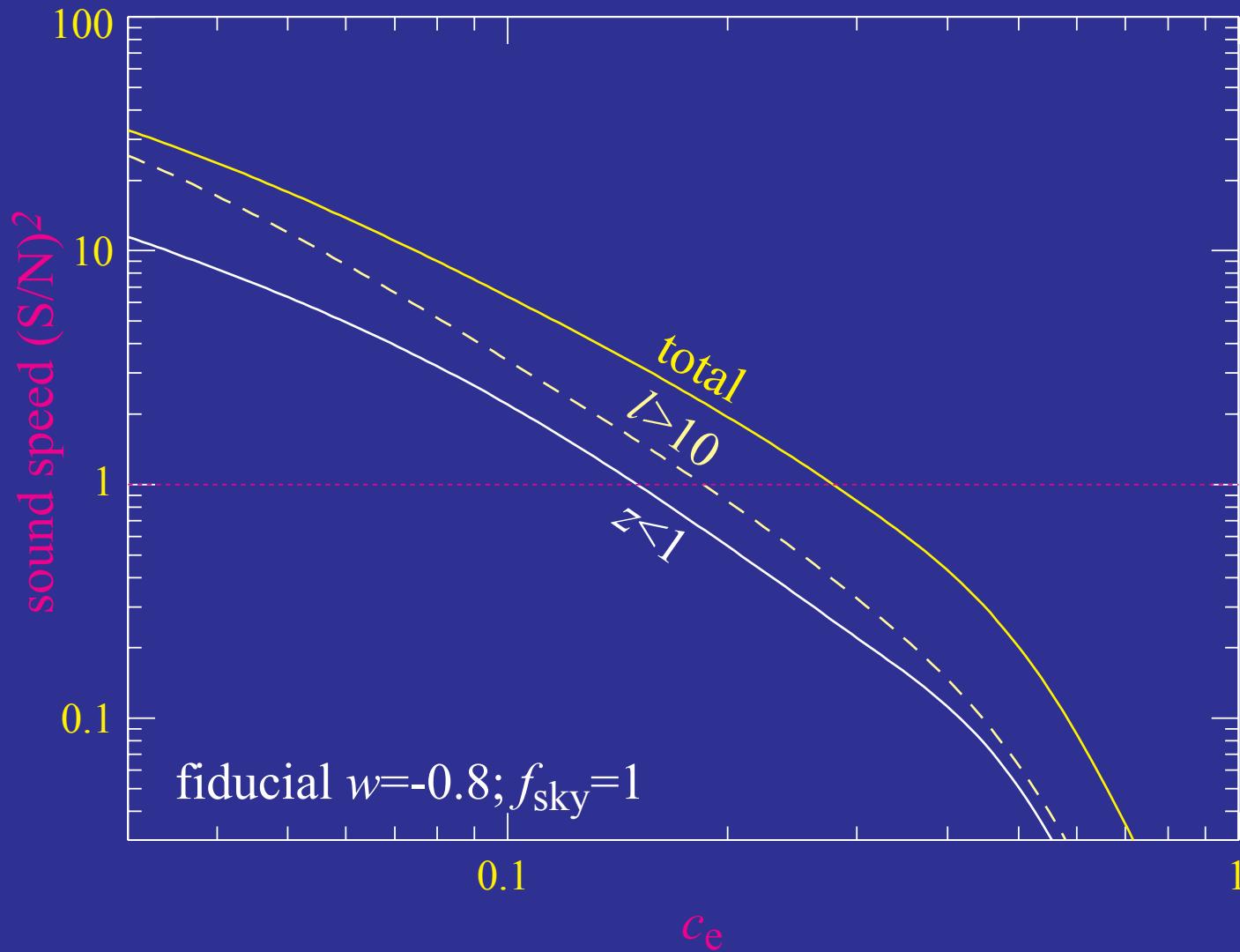
Galaxy Cross Correlation

- Cross correlation highly sensitive to the dark energy smoothness (parameterized by sound speed)



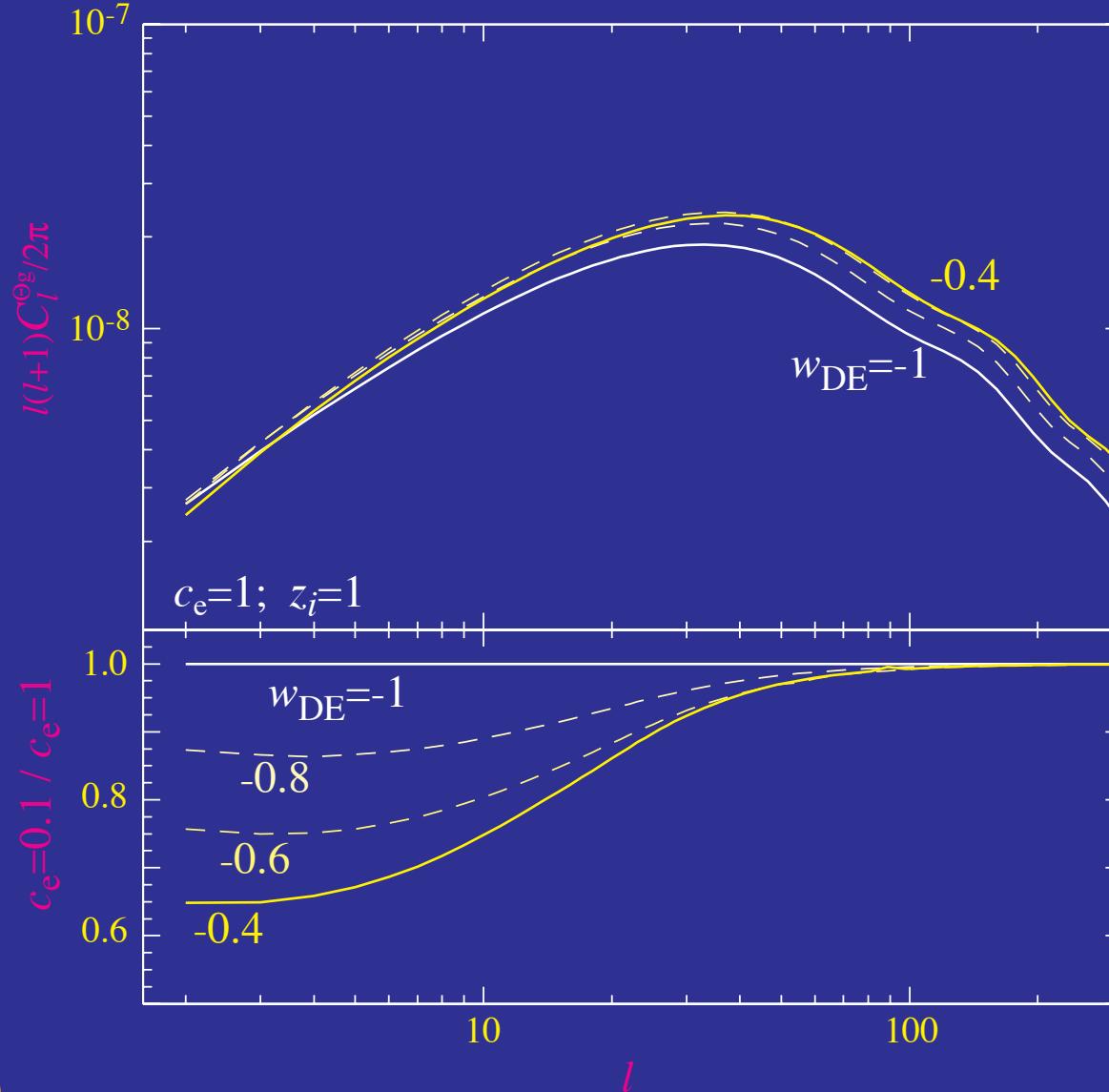
Galaxy Cross Correlation

- Significance of the separation between quintessence and a more clustered dark energy with sound speed c_e



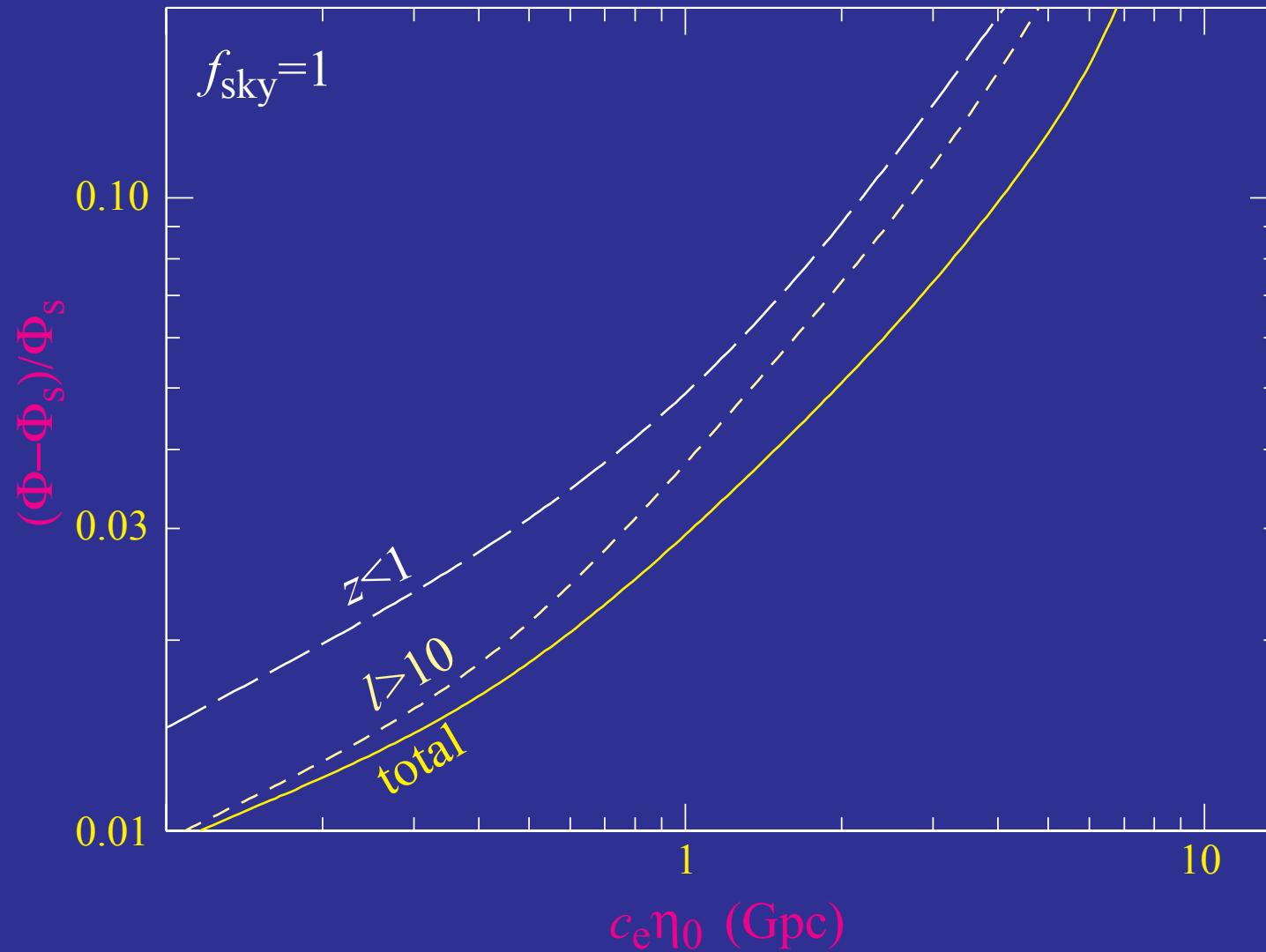
Clustering Predictions

- Predicted effect of clustering in an adiabatic model depends strongly on equation of state



Dark Energy Smoothness

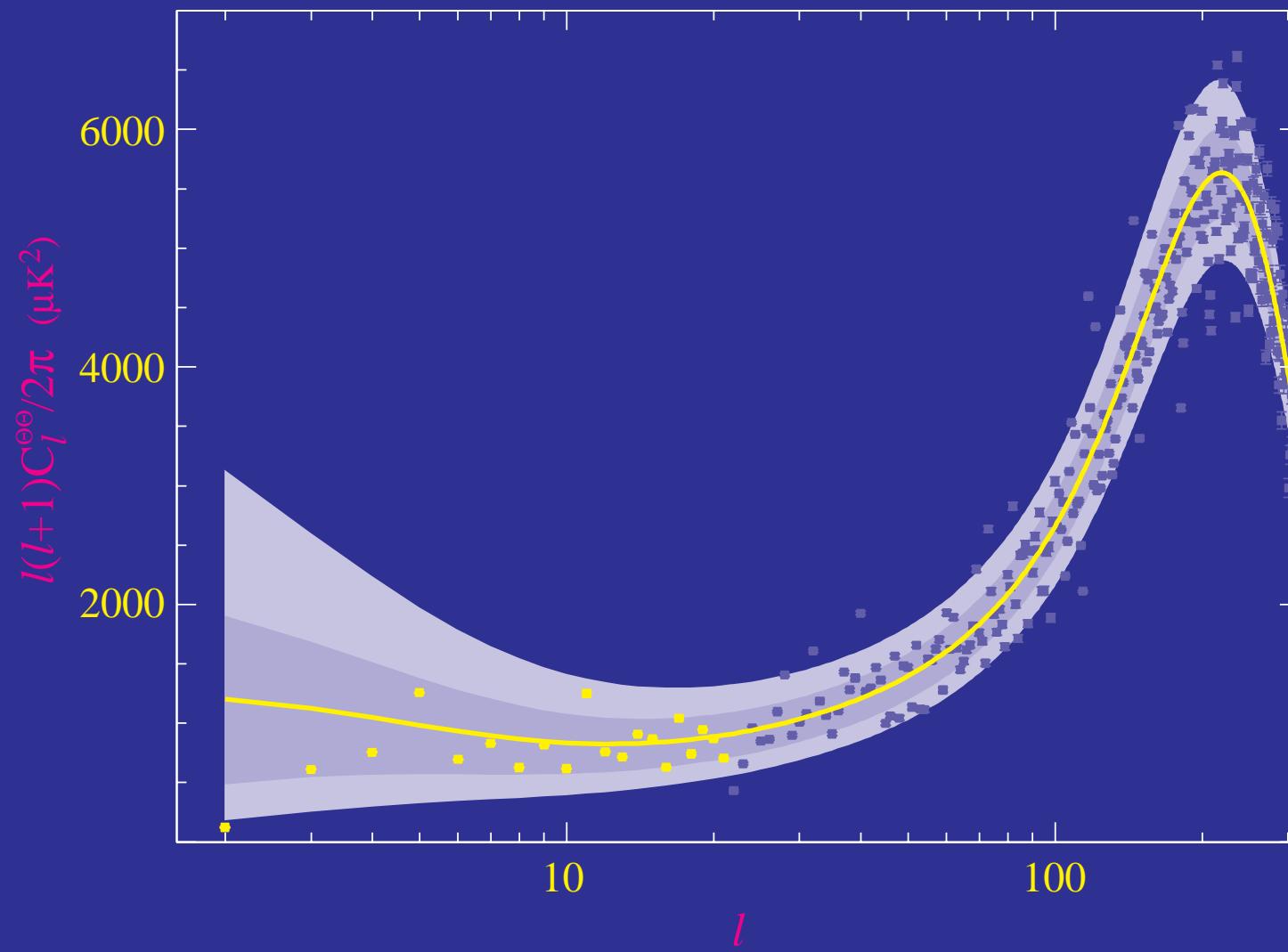
- More robust way of quoting constraints: how smooth is the dark energy out to a given physical scale:



Has
Dark Energy Clustering
Already Been Detected?

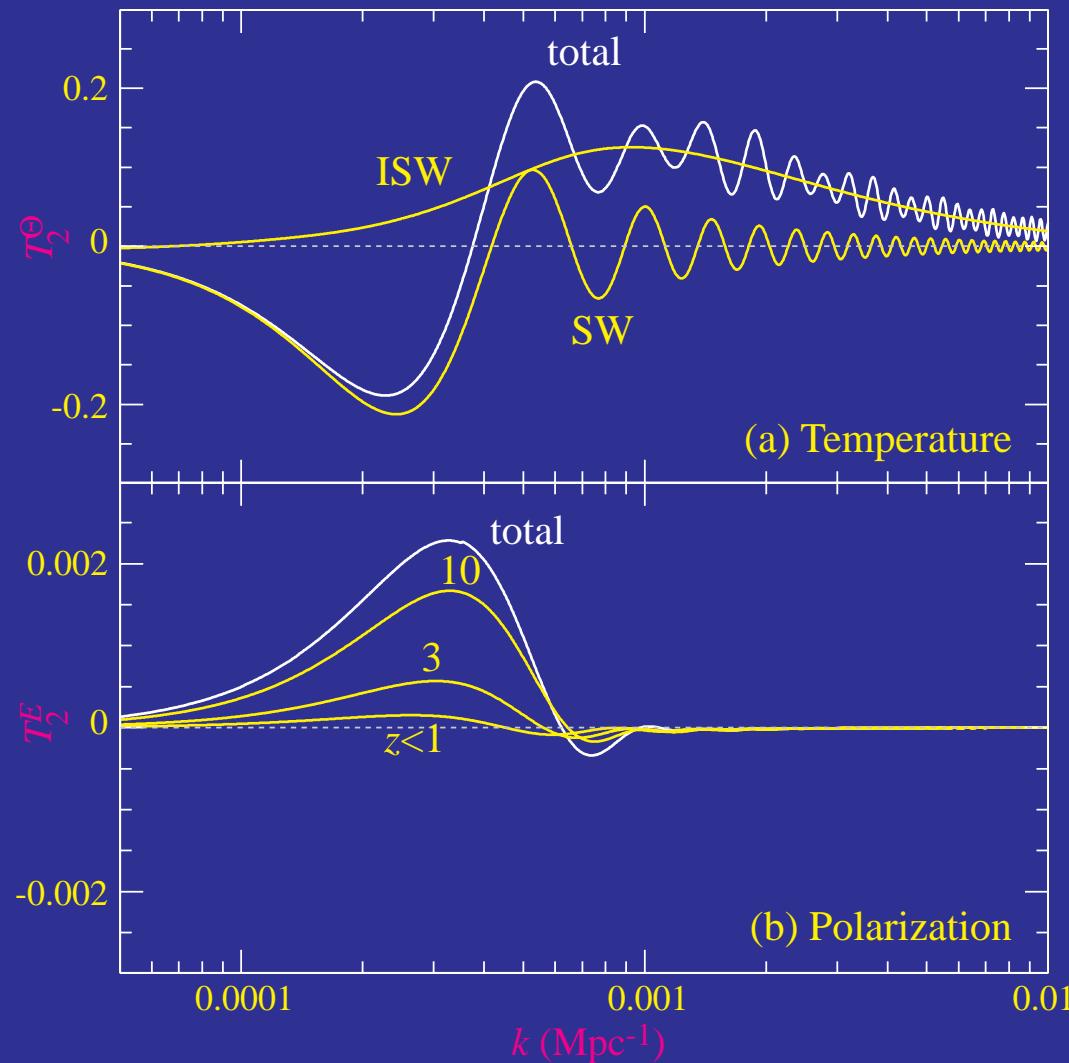
Low Quadrupole

- Known since COBE: a $\sim 2\sigma$ problem



Quadrupole Origins

- Transfer function for the quadrupole



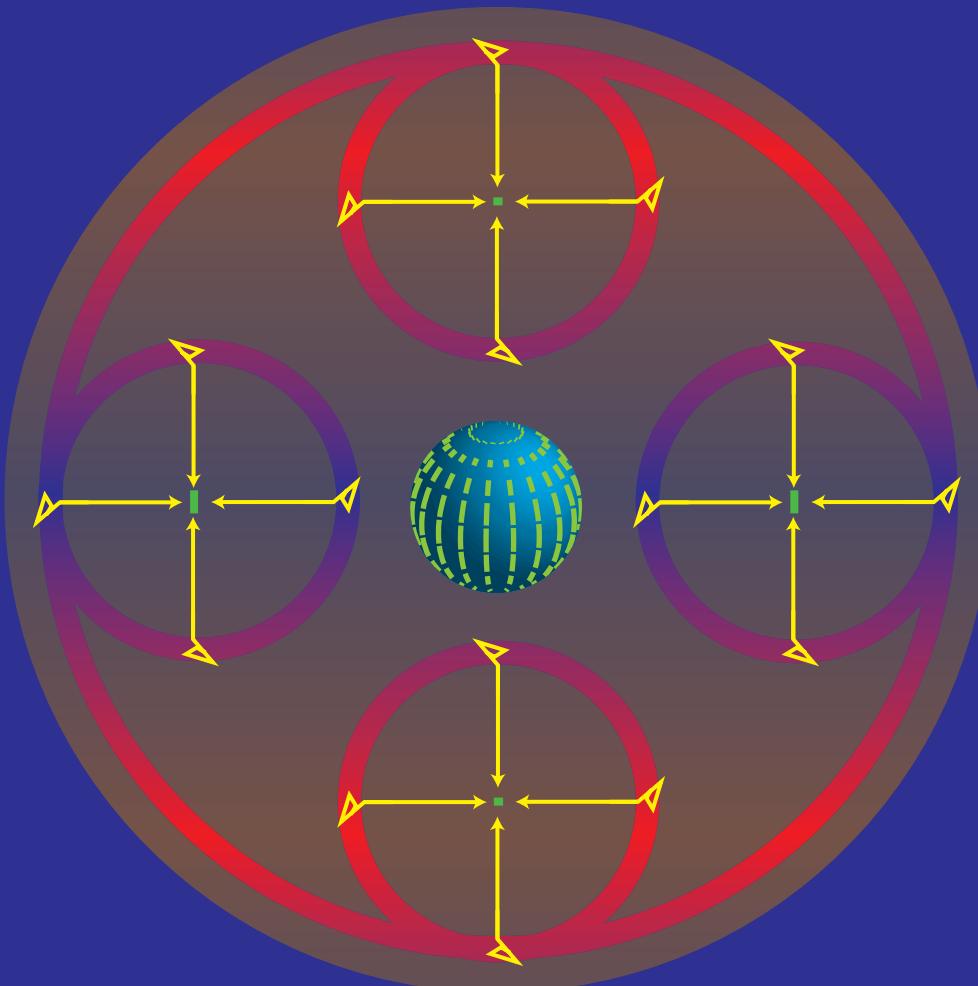
ISW Spatial Modes

- ISW effect comes from nearby acceleration regime
- Shorter wavelengths project onto same angle



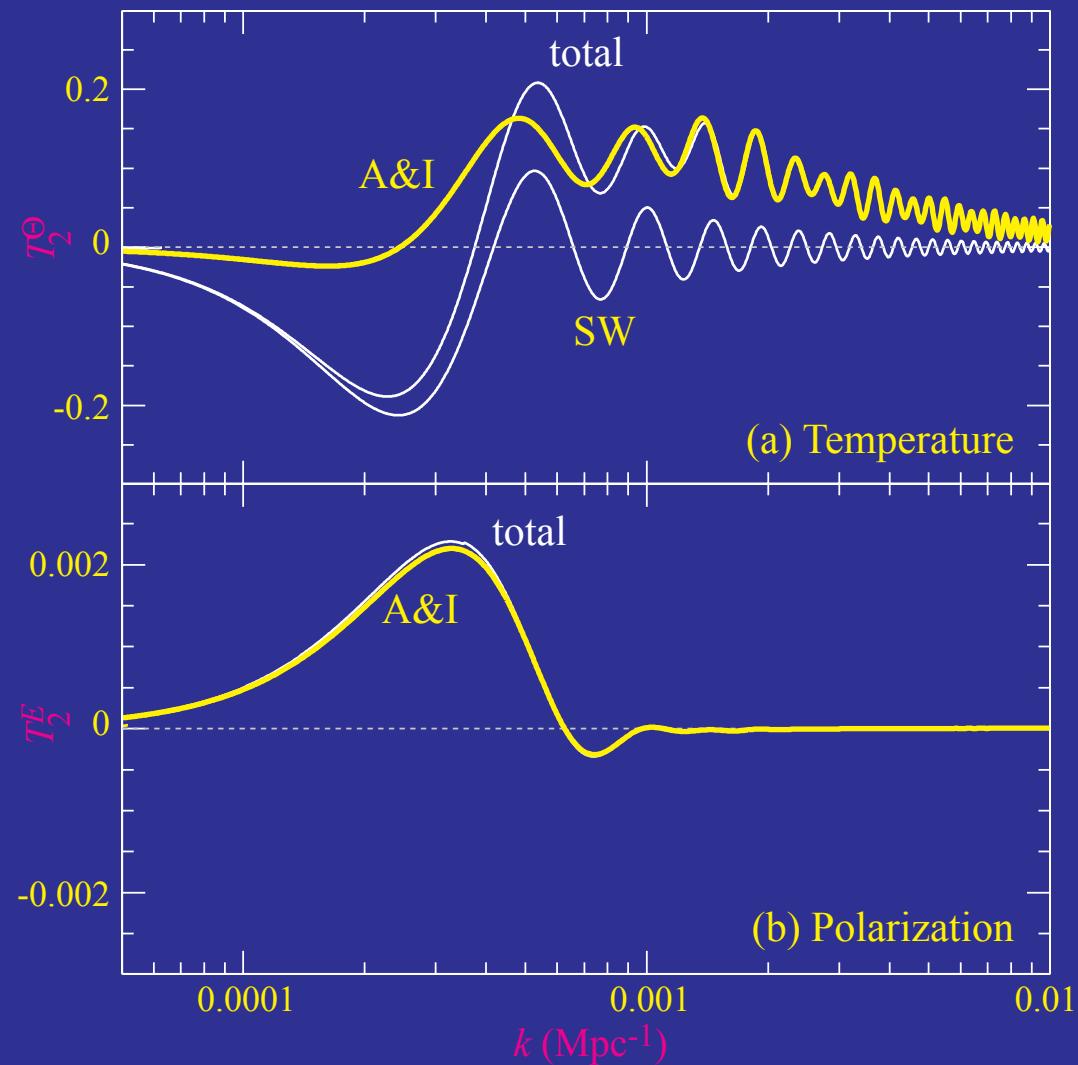
Polarization Temperature Correlation

- Pattern correlated with the temperature anisotropy that generates it; here an $m=0$ quadrupole; unlike galaxy correlation, rejects ISW



Isocurvature DE Perturbations

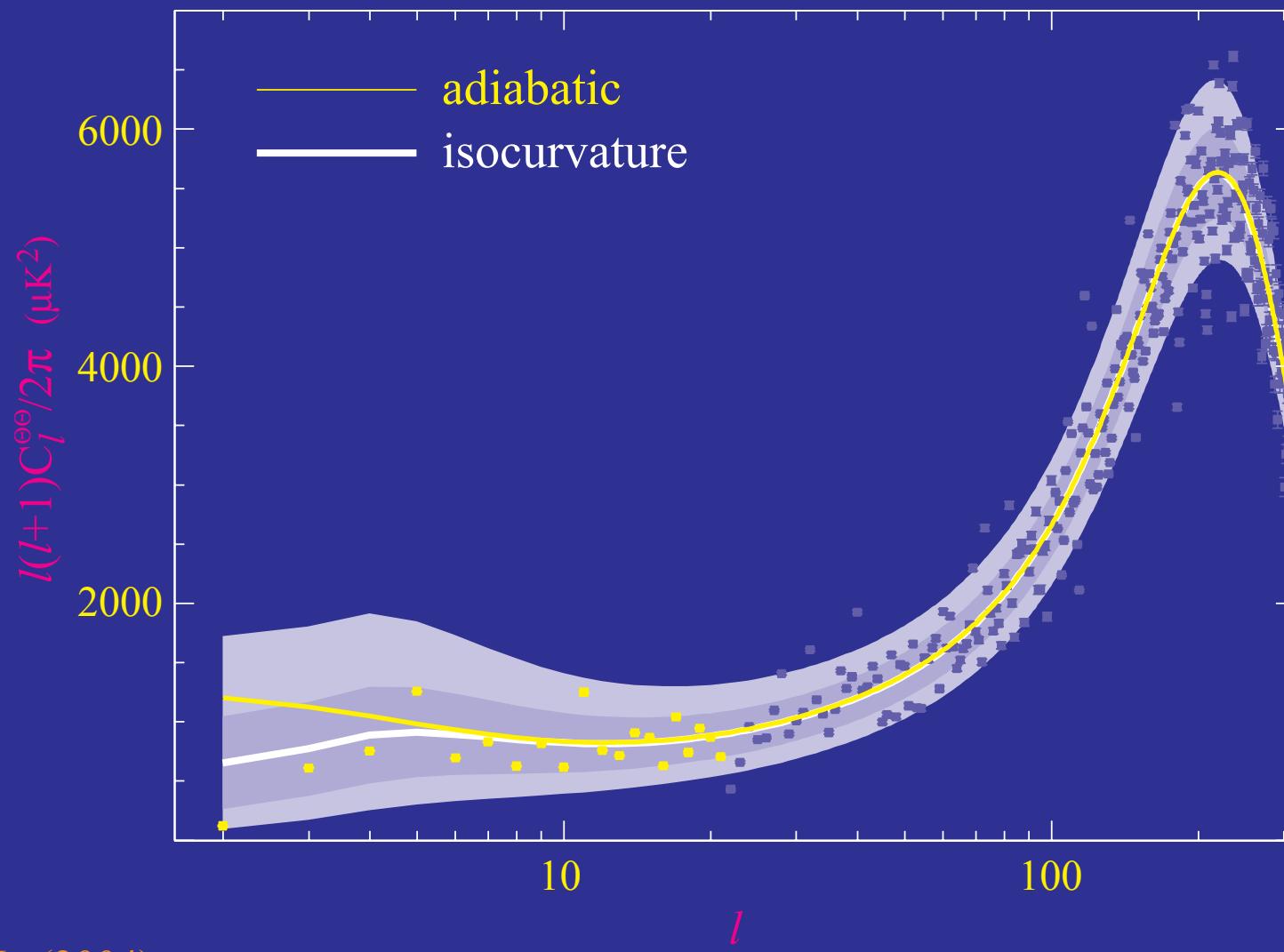
- Anti-correlated DE perturbations: ISW cancel SW effect



Moroi & Takahashi (2004); Gordon & Hu (2004)

Low Quadrupole Models

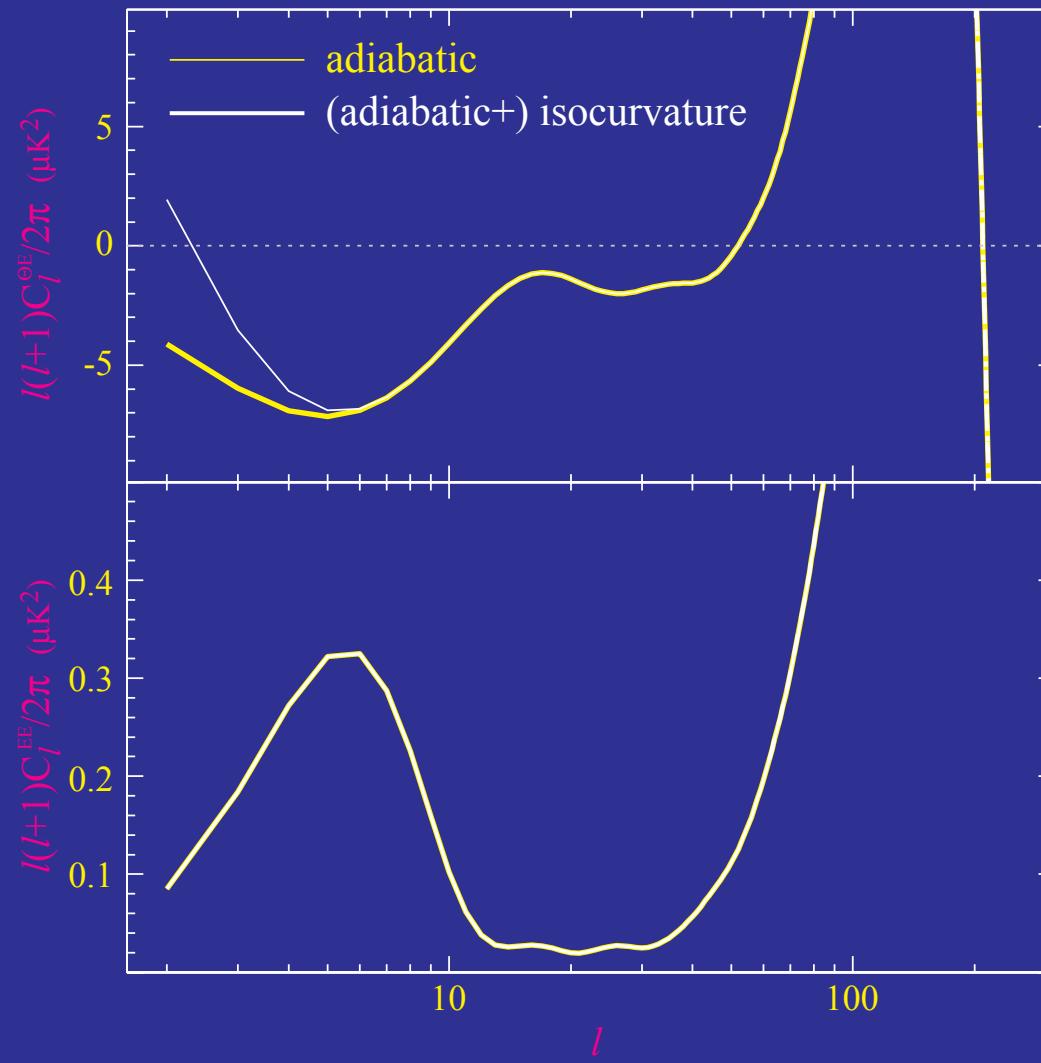
- Required isocurvature perturbation can be generated by variable decay reheating mechanism but overpredicts grav w.



Gordon & Hu (2004) [Dvali, Gruzinov, Zaldarriaga (2004) reheating]

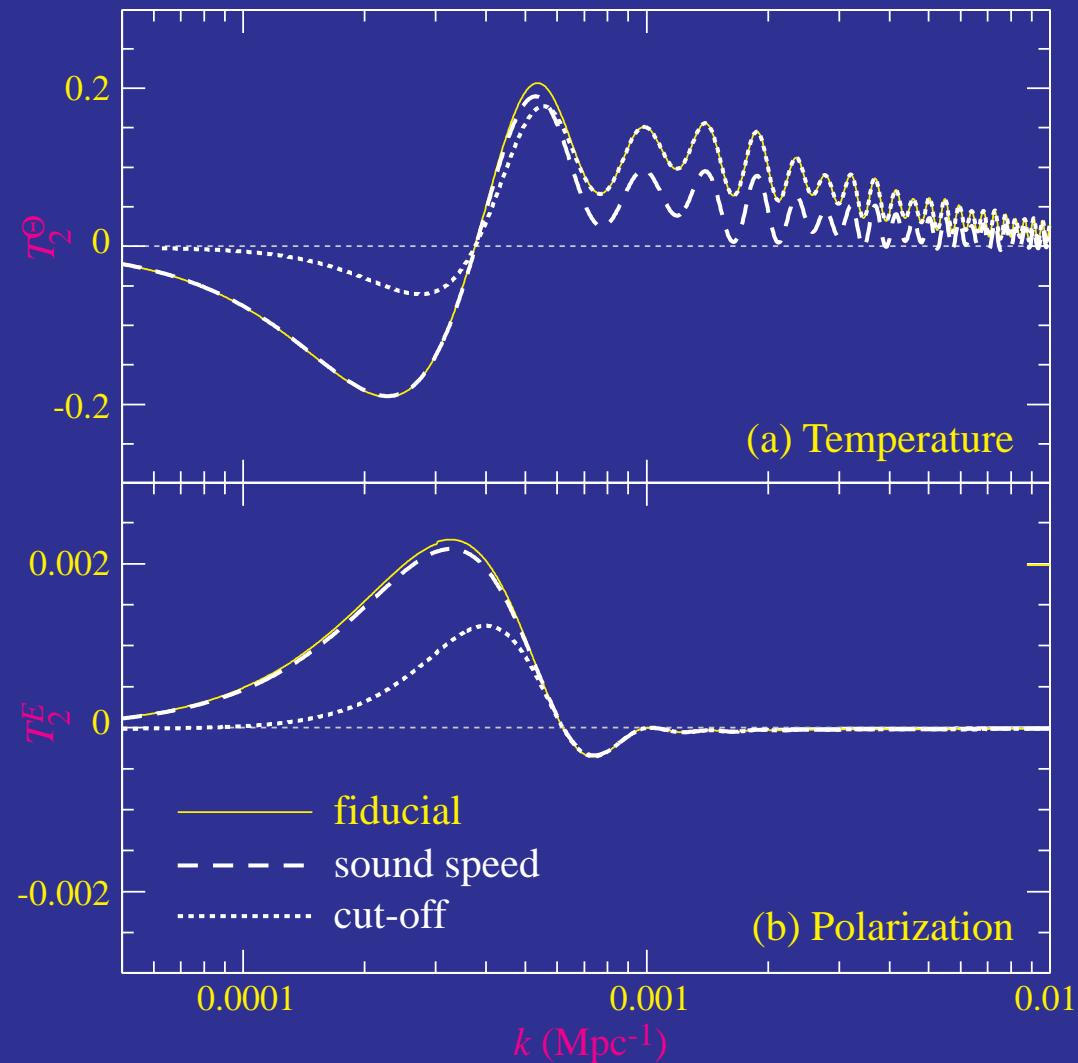
Polarization Rejects ISW

- Polarization unchanged; cross correlation lowered



Alternate Low Quadrupole Models

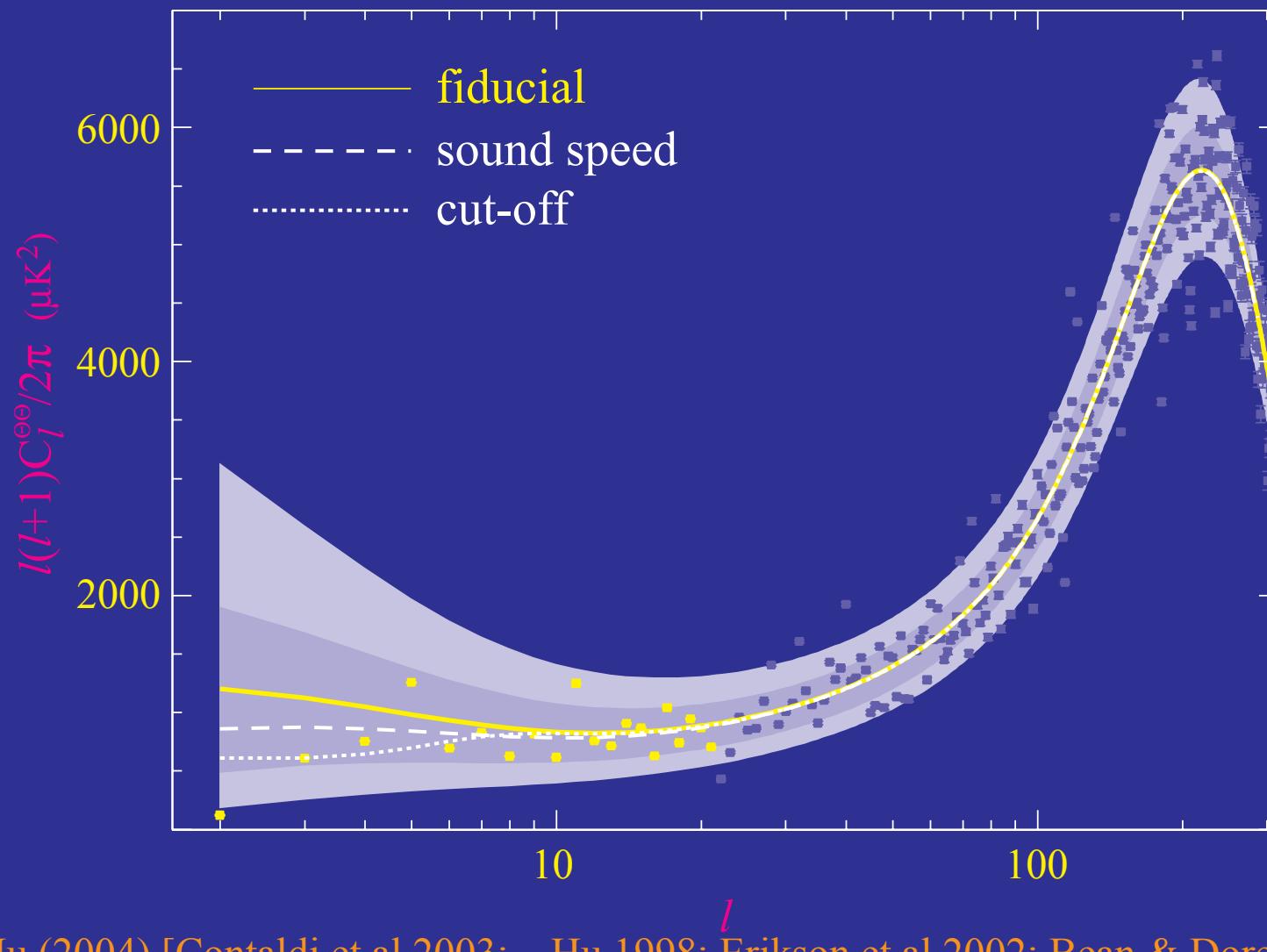
- Transfer function for the quadrupole



Gordon & Hu (2004) [Contaldi et al 2003; Hu 1998; Erikson et al 2002; Bean & Dore 2003]

Low Quadrupole Models

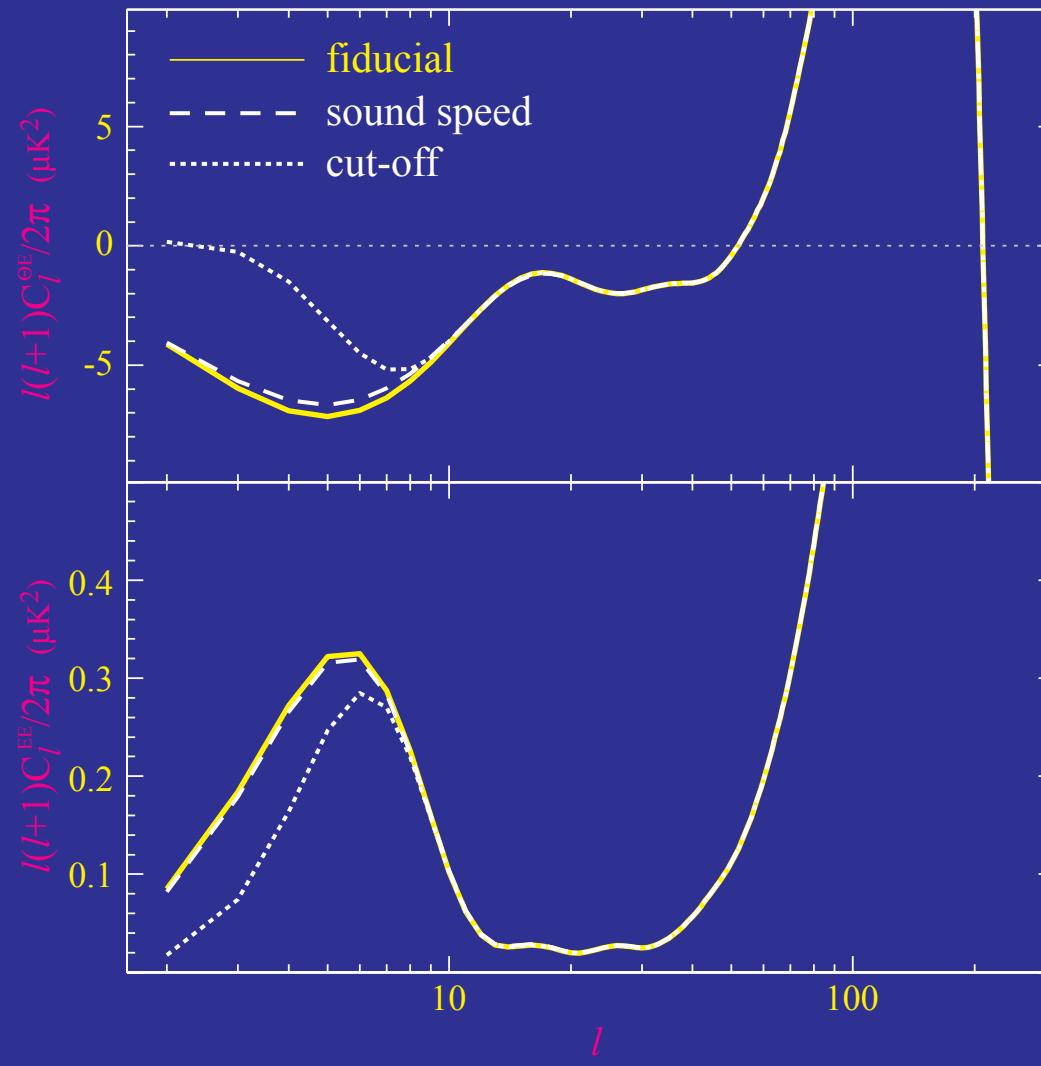
- Models: initial conditions vs. dark energy



Gordon & Hu (2004) [Contaldi et al 2003; Hu 1998; Erikson et al 2002; Bean & Dore 2003]

Low Quadrupole Models

- Distinguished by polarization



Gordon & Hu (2004) [Dore, Holder & Loeb 2003]

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 > 2 nd 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, lensing may test the nature of the dark energy through clustering