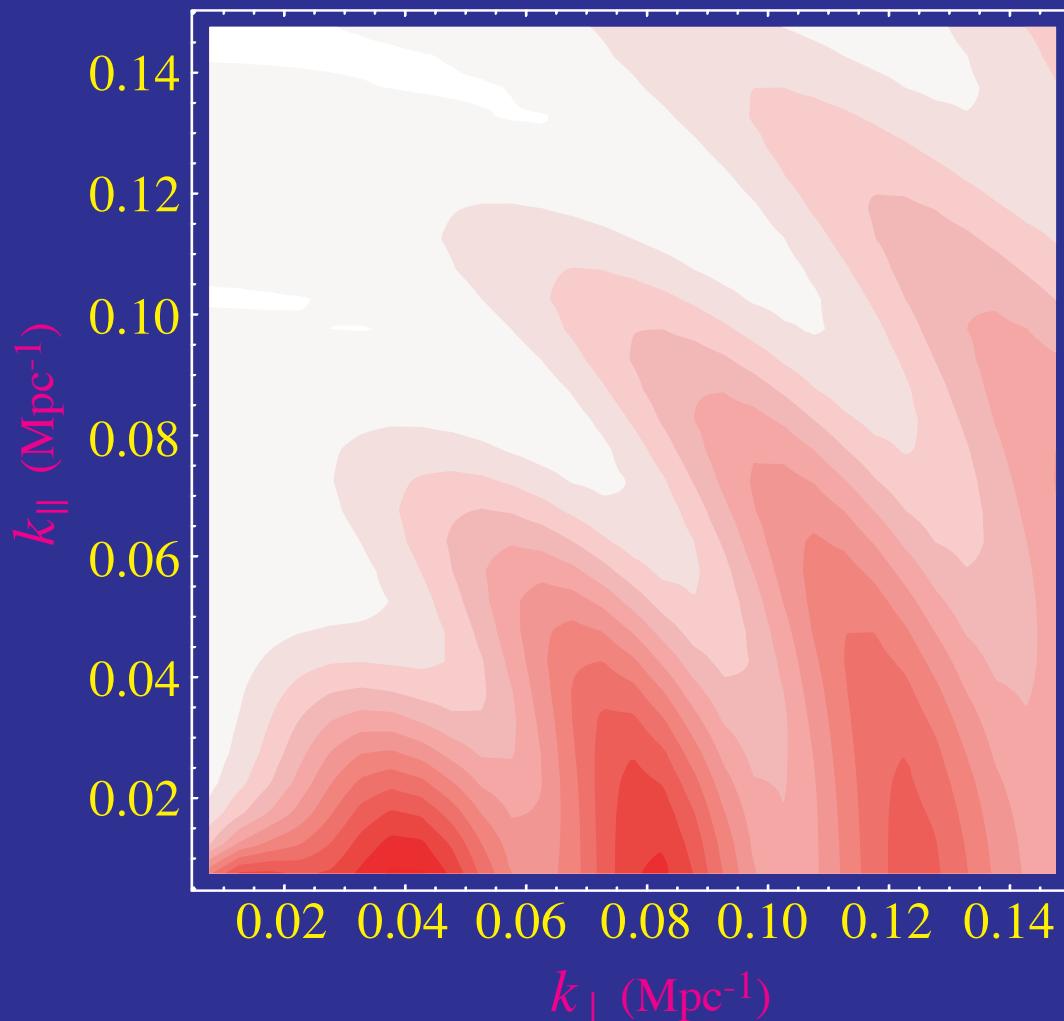


Redshifting Rings of Power



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U. Michigan, May 2003

Absolutely Calibrated Rulers

- Acoustic physics calibrates rulers
- Sound Horizon, Equality Horizon



- Damping Scale



Baryon & Inertia

- Baryons add **inertia** to the fluid like mass on a spring

Baryons in the Power Spectrum

Radiation and Dark Matter

- Radiation domination:
potential wells created by CMB itself
- Pressure support \Rightarrow potential decay \Rightarrow driving
- Heights measures when dark matter dominates

Dark Matter in the Power Spectrum

Damping

- Perfect fluid: no **anisotropic stresses** due to scattering isotropization; baryons and photons move as **single fluid**
- Fluid imperfections are related to the **mean free path** of the photons in the baryons

$$\lambda_C = \dot{\tau}^{-1} \quad \text{where} \quad \dot{\tau} = n_e \sigma_T a$$

is the conformal opacity to **Thompson scattering**

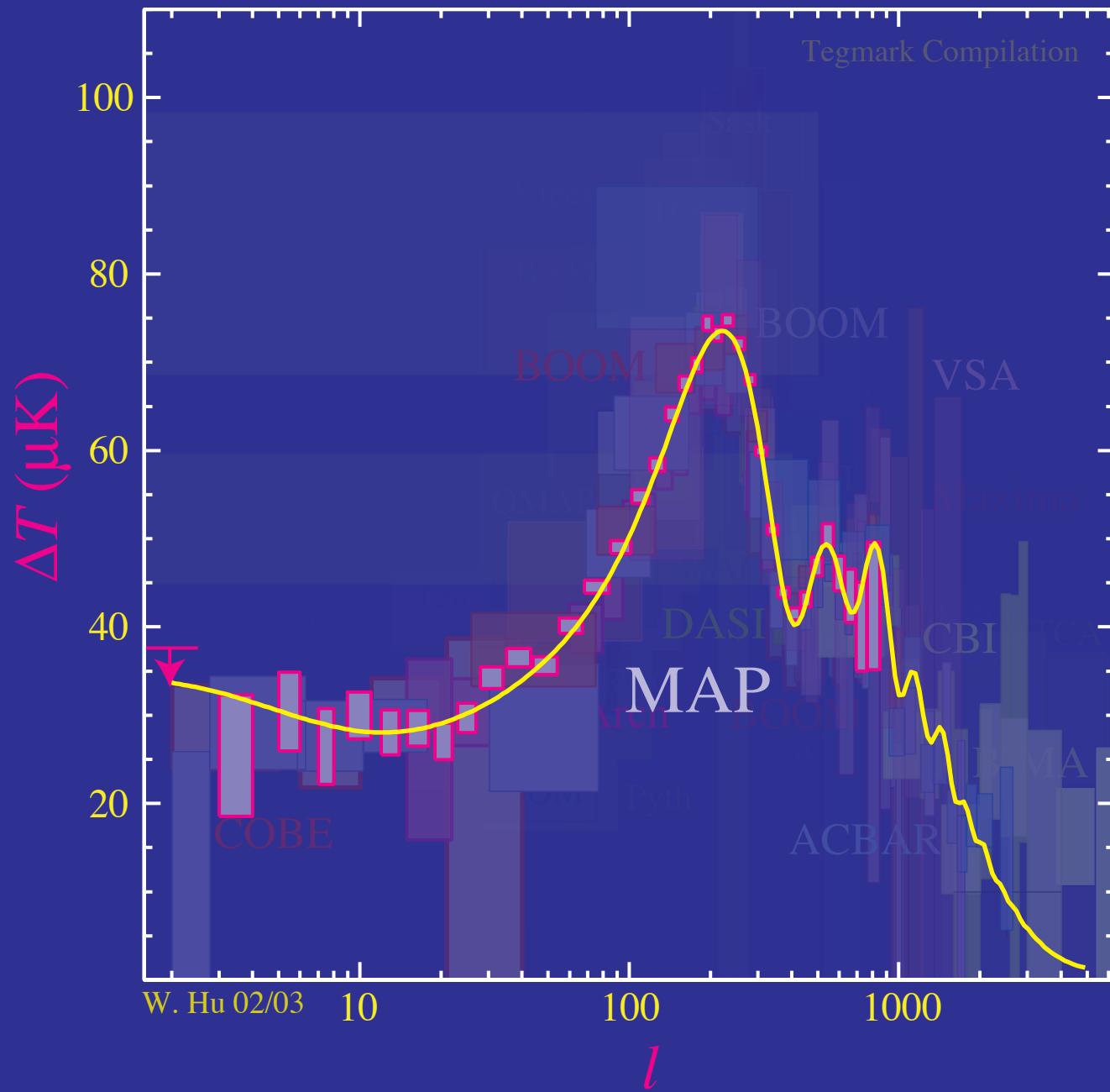
- Dissipation is related to the **diffusion length**: random walk approximation

$$\lambda_D = \sqrt{N} \lambda_C = \sqrt{\eta / \lambda_C} \lambda_C = \sqrt{\eta \lambda_C}$$

the **geometric mean** between the horizon and mean free path

- $\lambda_D / \eta_* \sim \text{few \%}$, so expect the **peaks > 3rd** to be affected by dissipation

The Angular Power Spectrum



Standard Ruler Status Report

- Parameter Estimates (1σ range)

Peak Parameters	Before (Wang et al; Knox et al)	WMAP (Spergel et al)
ℓ_A	$300 - 308$	$297 - 301$
$\Omega_m h^2$	$0.118 - 0.135$	$0.12 - 0.16$
$\Omega_b h^2$	$0.020 - 0.026$	$0.023 - 0.025$
Initial Spectrum		
n_s	$0.93 - 1.05$	$0.95 - 1.03$
Reionization		
τ	$0 - 0.1$	$0.1 - 0.24$

- WMAP + CMB Damping Tail > WMAP
- Sound horizon: absolute calibration of 2 % in distance
- Horizon at matter-radiation equality: absolute calibration of 8%
- Room for further improvement with precision damping tail

Peak Location

- The fundamental physical scale is translated into a fundamental angular scale by simple projection according to the angular diameter distance D_A

$$\theta_A = \lambda_A / D_A$$

This test is implemented in the CMB by the peak locations

- If the radial dimension $D = \int dz/H$ were visible in the redshift then

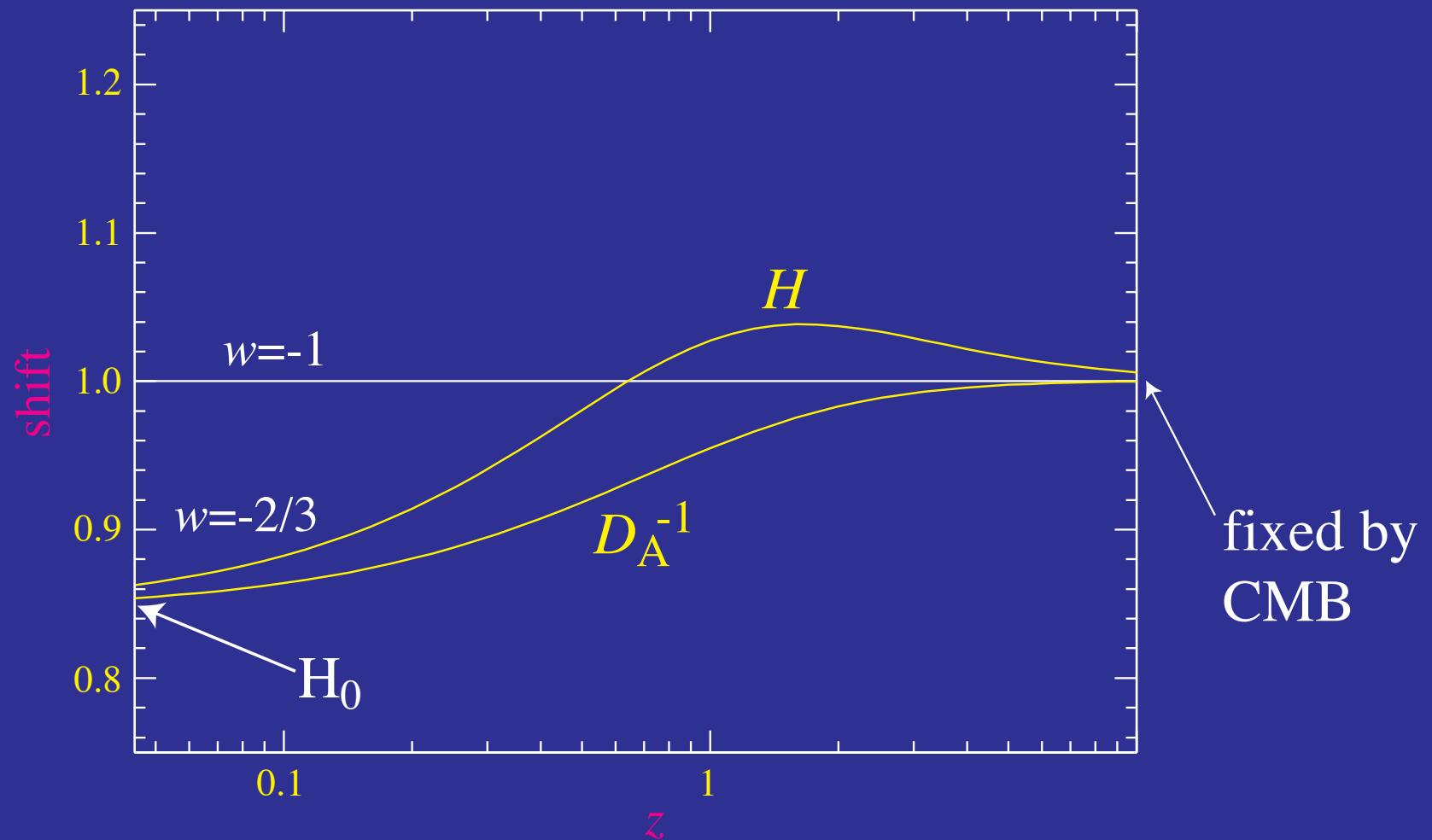
$$\Delta z = \lambda_A H(z)$$

and the Hubble parameter at the redshift, and hence the energy density would also be observable

- Not observable in the CMB but the Hubble parameter is fixed by $\Omega_m h^2$.

Complementing the CMB

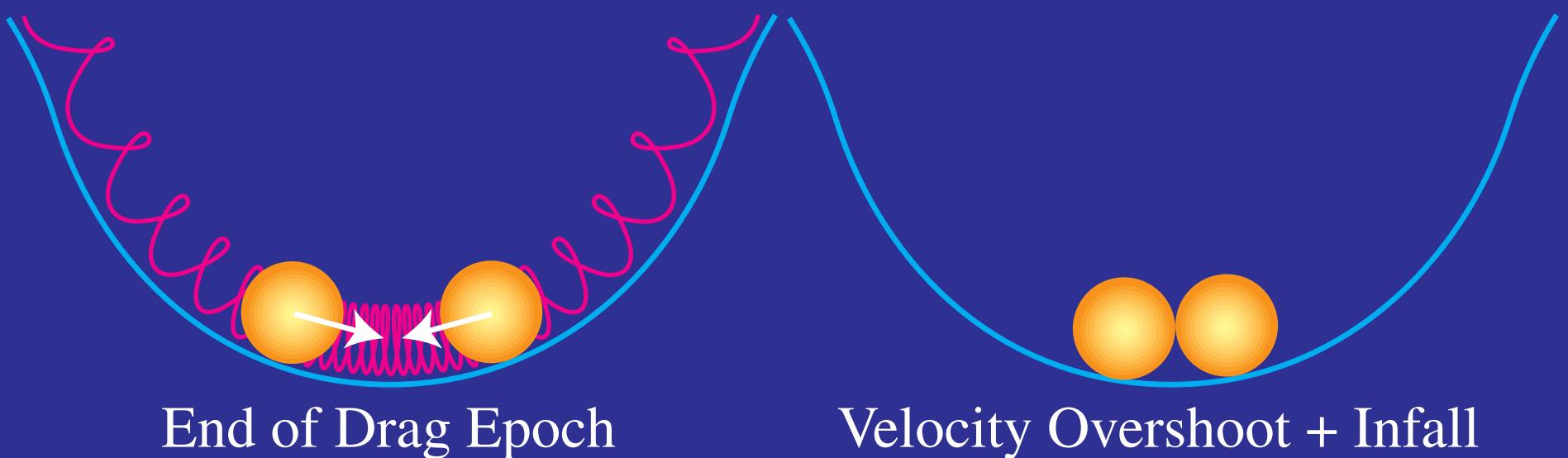
- CMB fixes the angular diameter distance and Hubble parameter at high z ; variation with dark energy appears at low z



CMB as Template

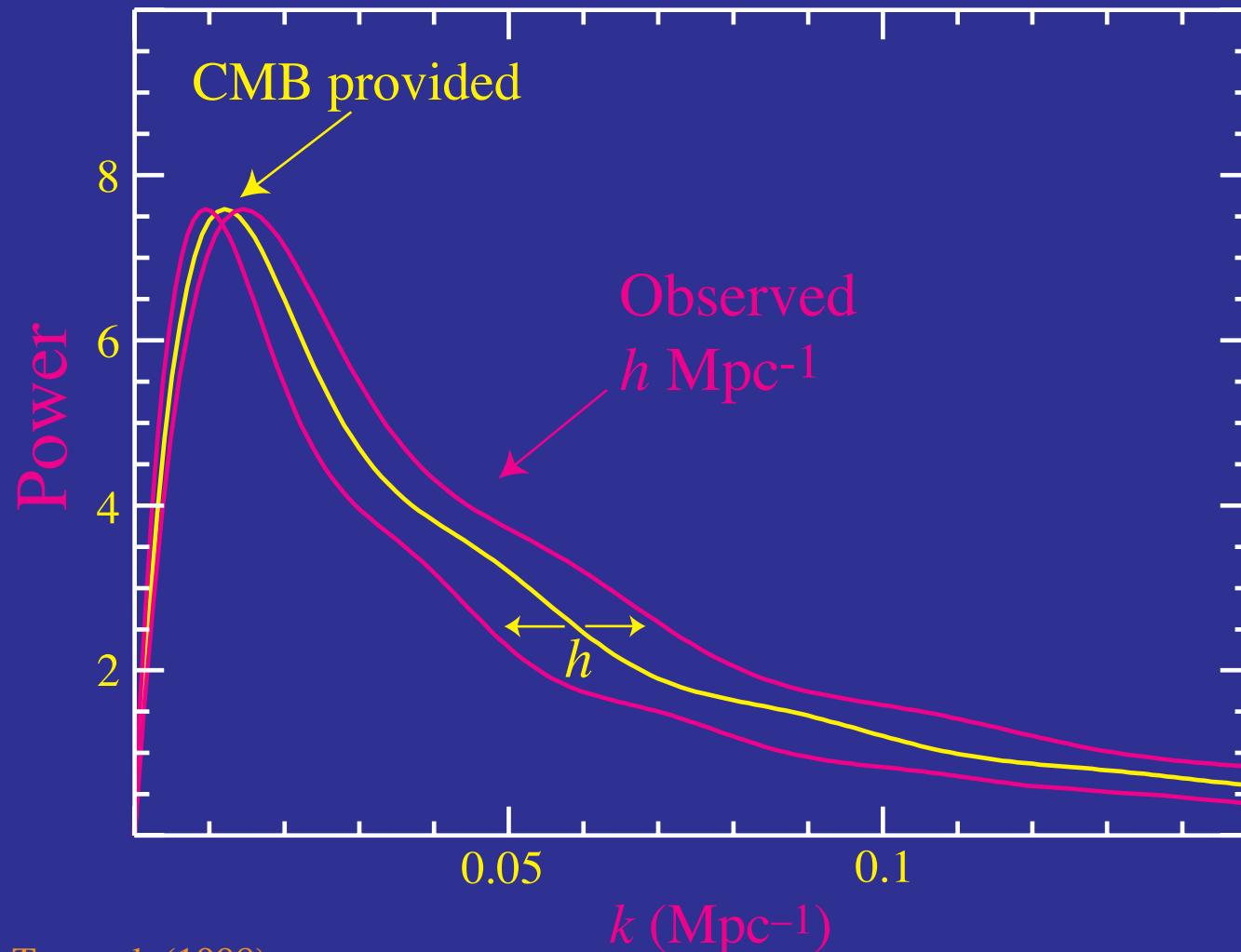
Acoustic Peaks in the Matter

- Baryon density & velocity oscillates with CMB
- Baryons decouple at $\tau/R \sim 1$, the end of Compton drag epoch
- Decoupling: $\dot{\delta}_b(\text{drag}) \sim V_b(\text{drag})$, but not frozen
- Continuity: $\dot{\delta}_b = -kV_b$
- Velocity Overshoot Dominates: $\delta_b \sim V_b(\text{drag})$ $k\eta \gg \delta_b(\text{drag})$
- Oscillations $\pi/2$ out of phase with CMB
- Infall into potential wells (DC component)



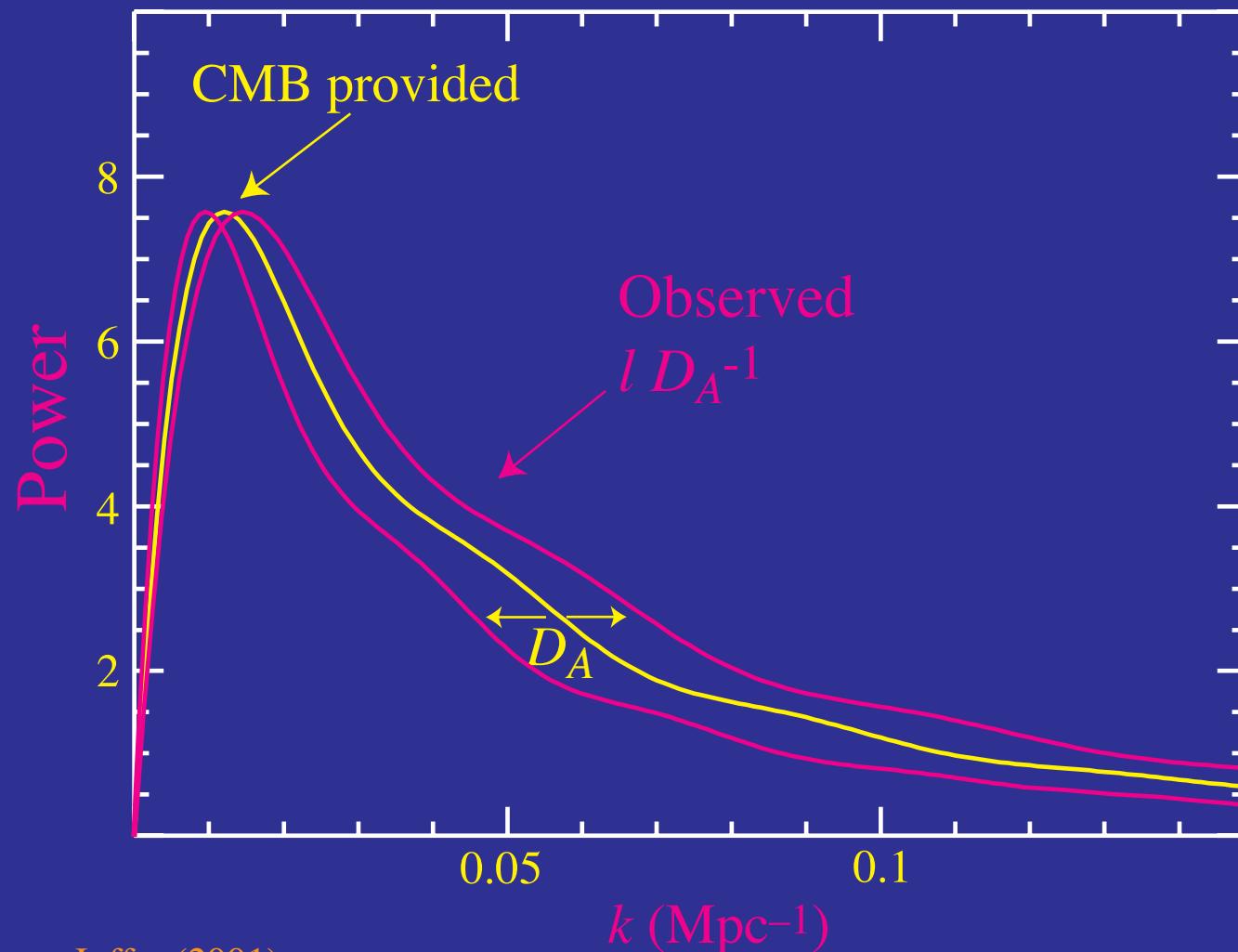
Local Test: H_0

- 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



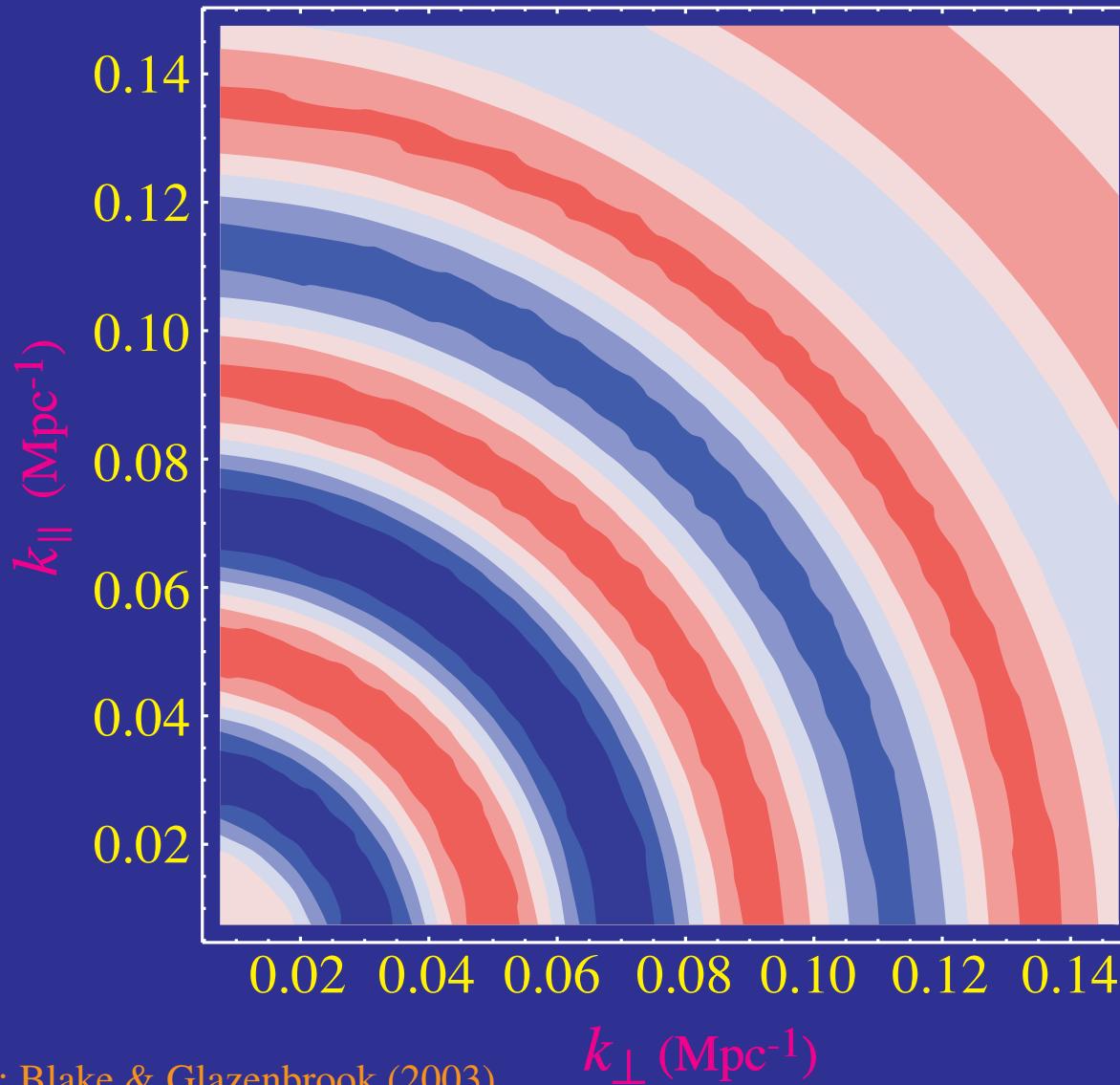
Cosmological Distances

- Modes perpendicular to line of sight measure angular diameter distance



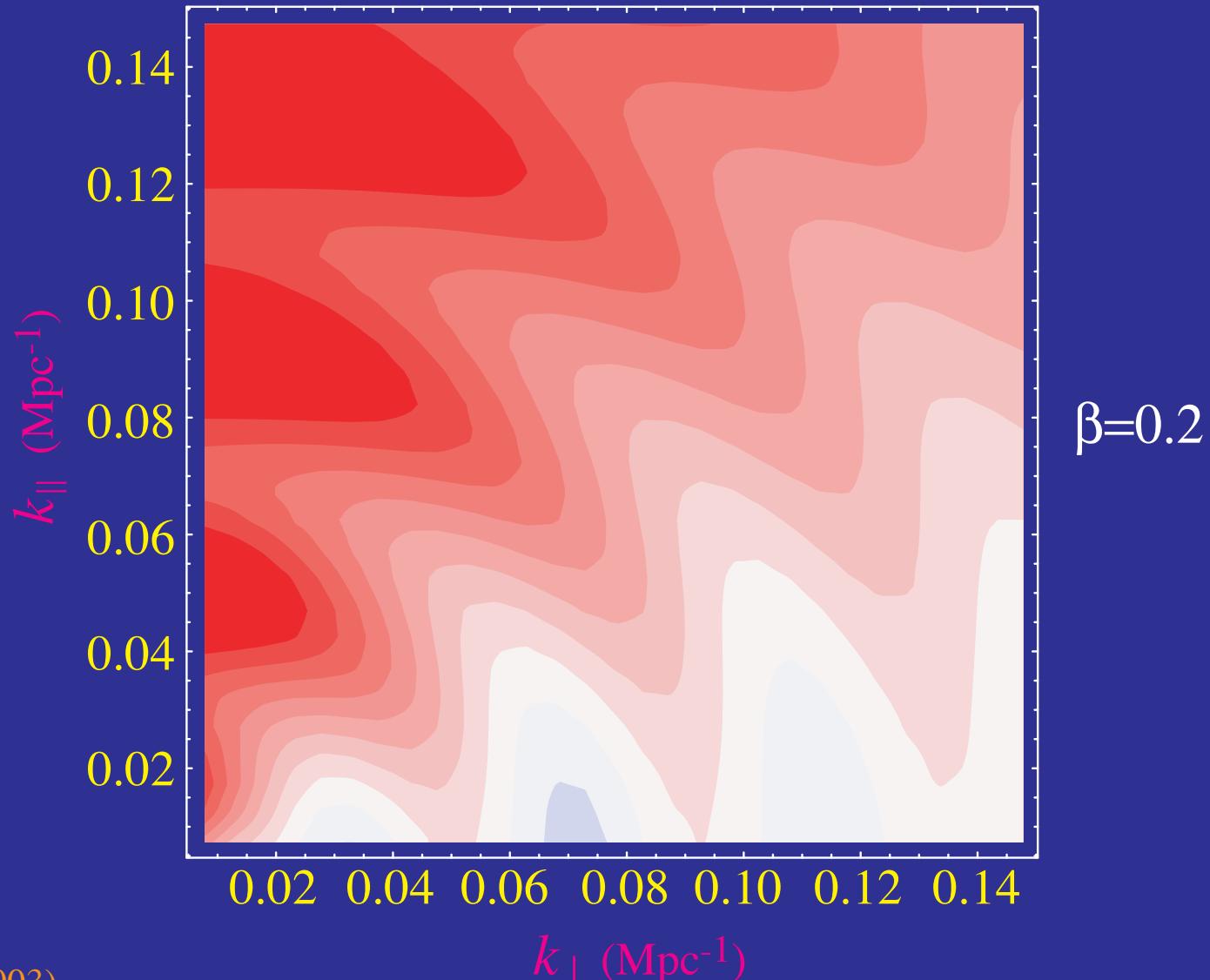
Acoustic Rings

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



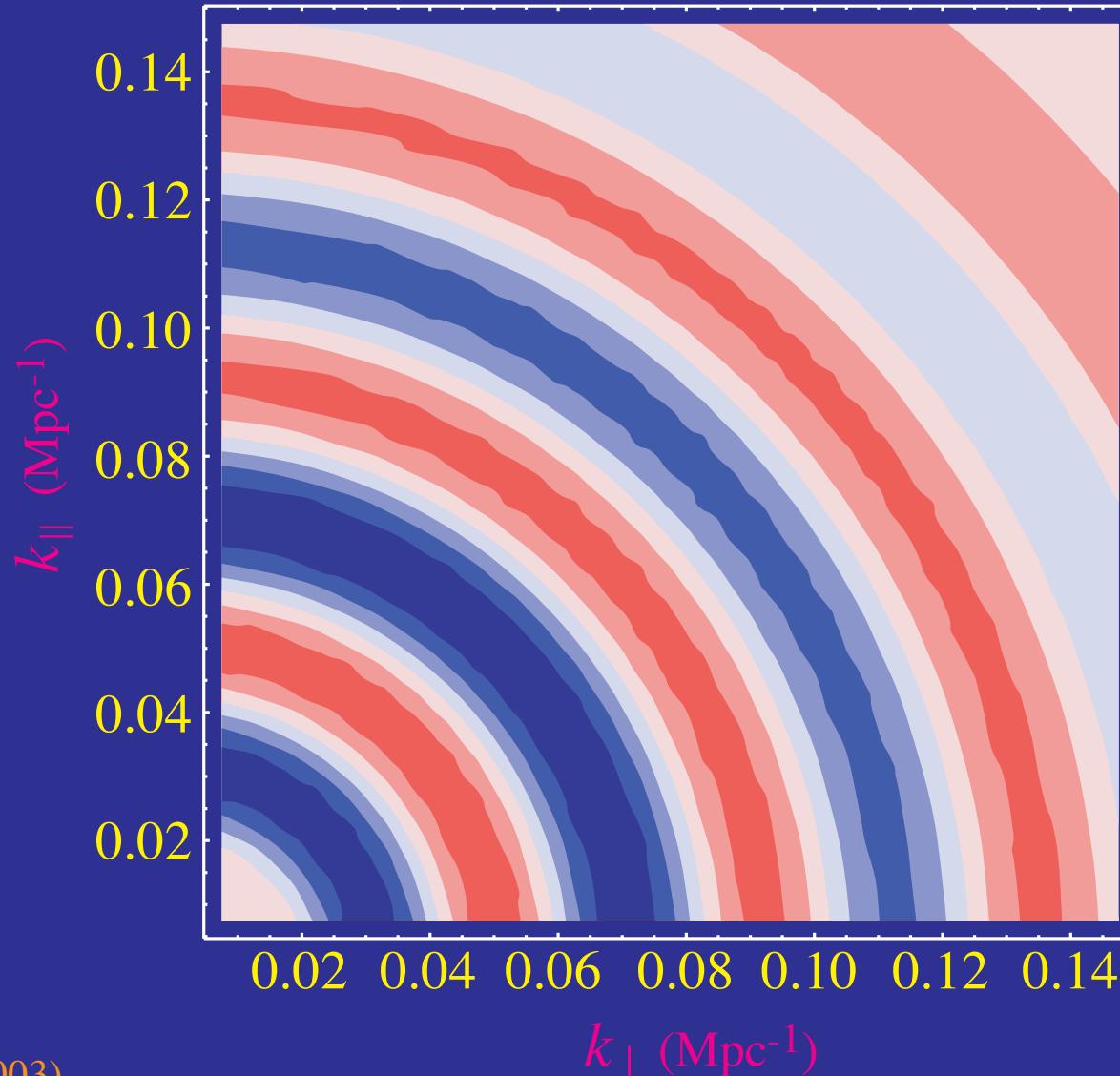
Redshift Space Distortion

- Peculiar velocities enhance parallel power and hence obscure cosmological shifting



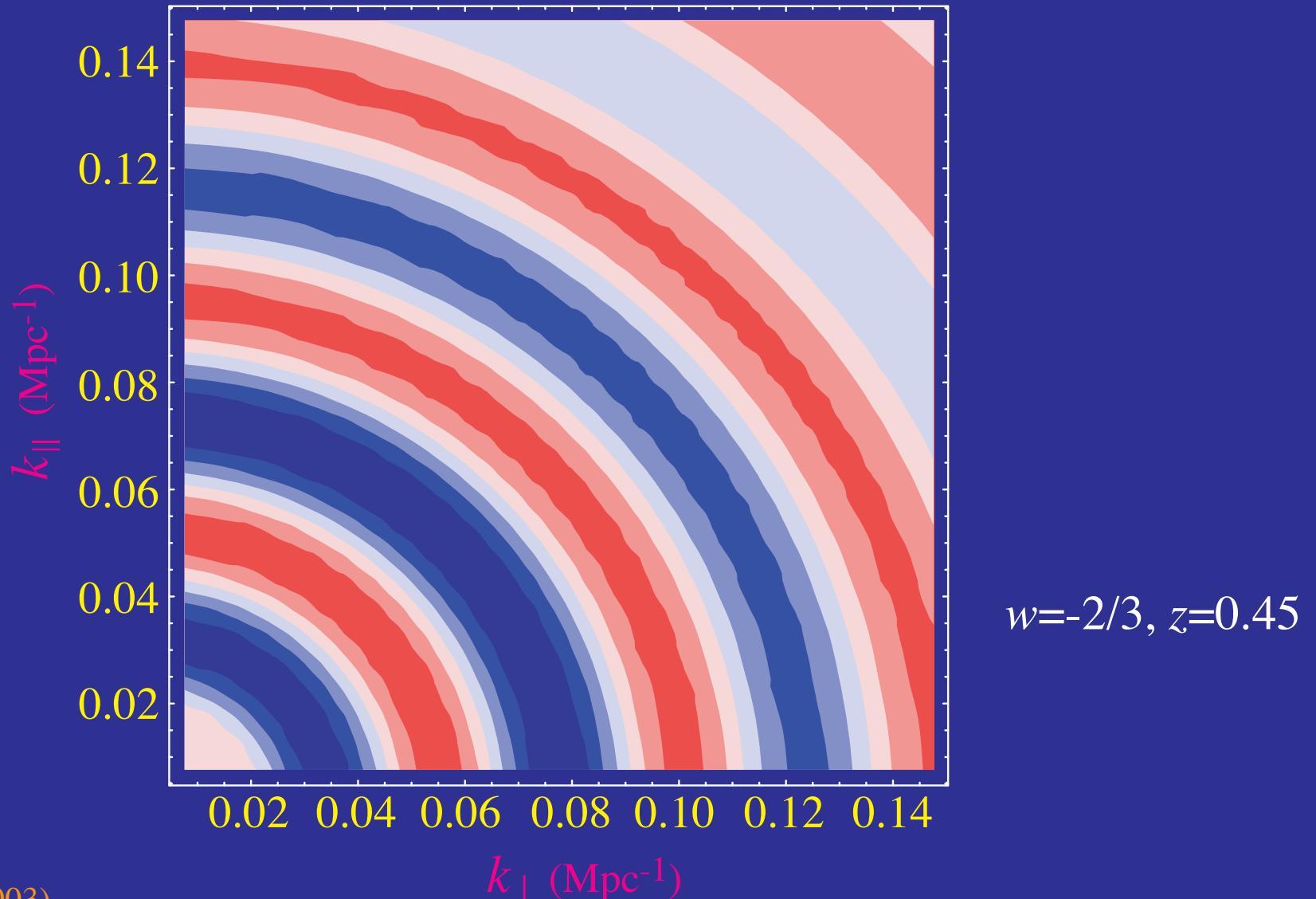
Acoustic Rings Remain

- Removing the overall redshift space distortions rings remain at fixed locations



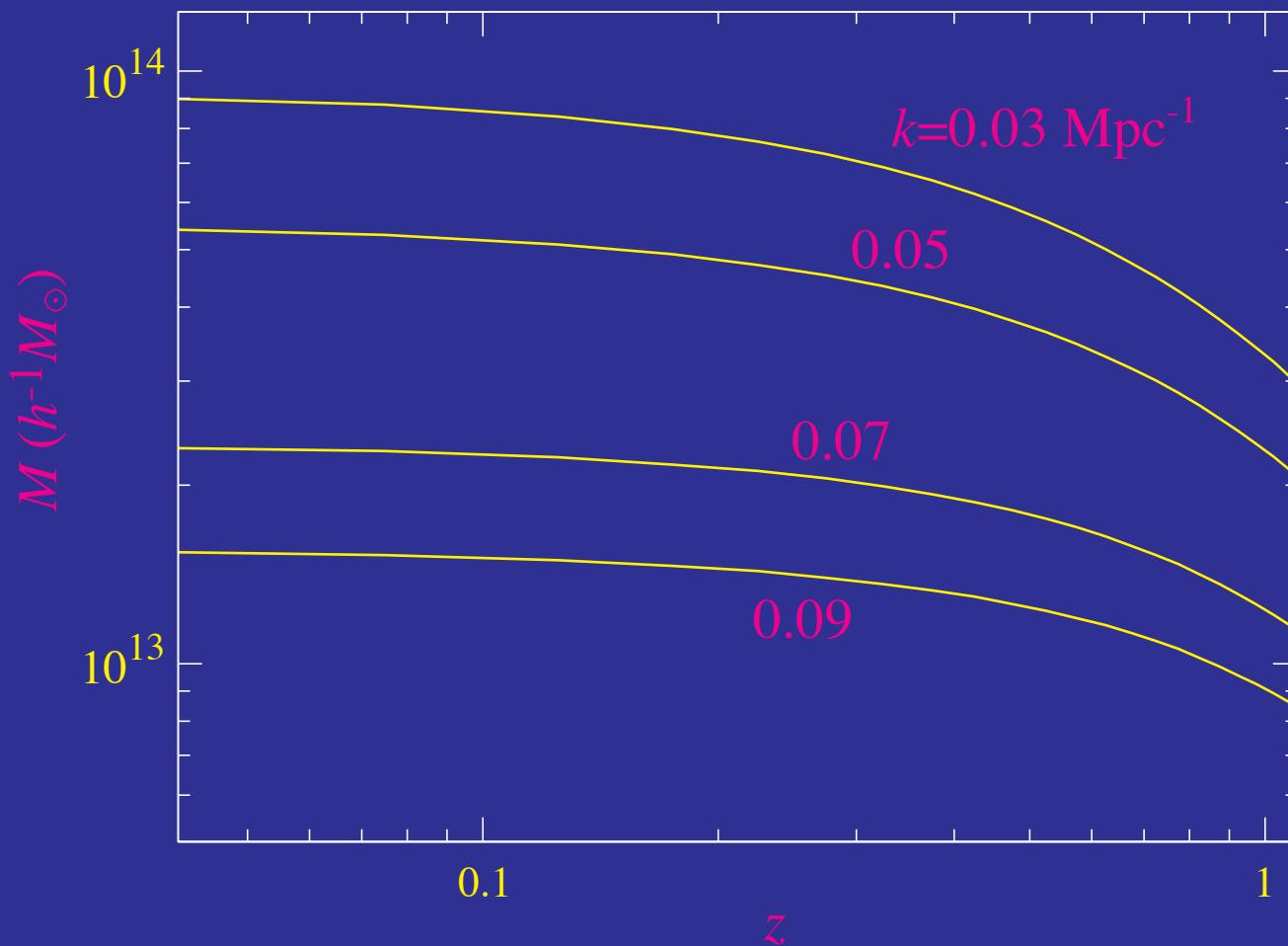
Acoustic Rings

- Location of rings shifted by $D_A^{-1}(z)$ in the perpendicular direction by $H(z)$ in parallel direction



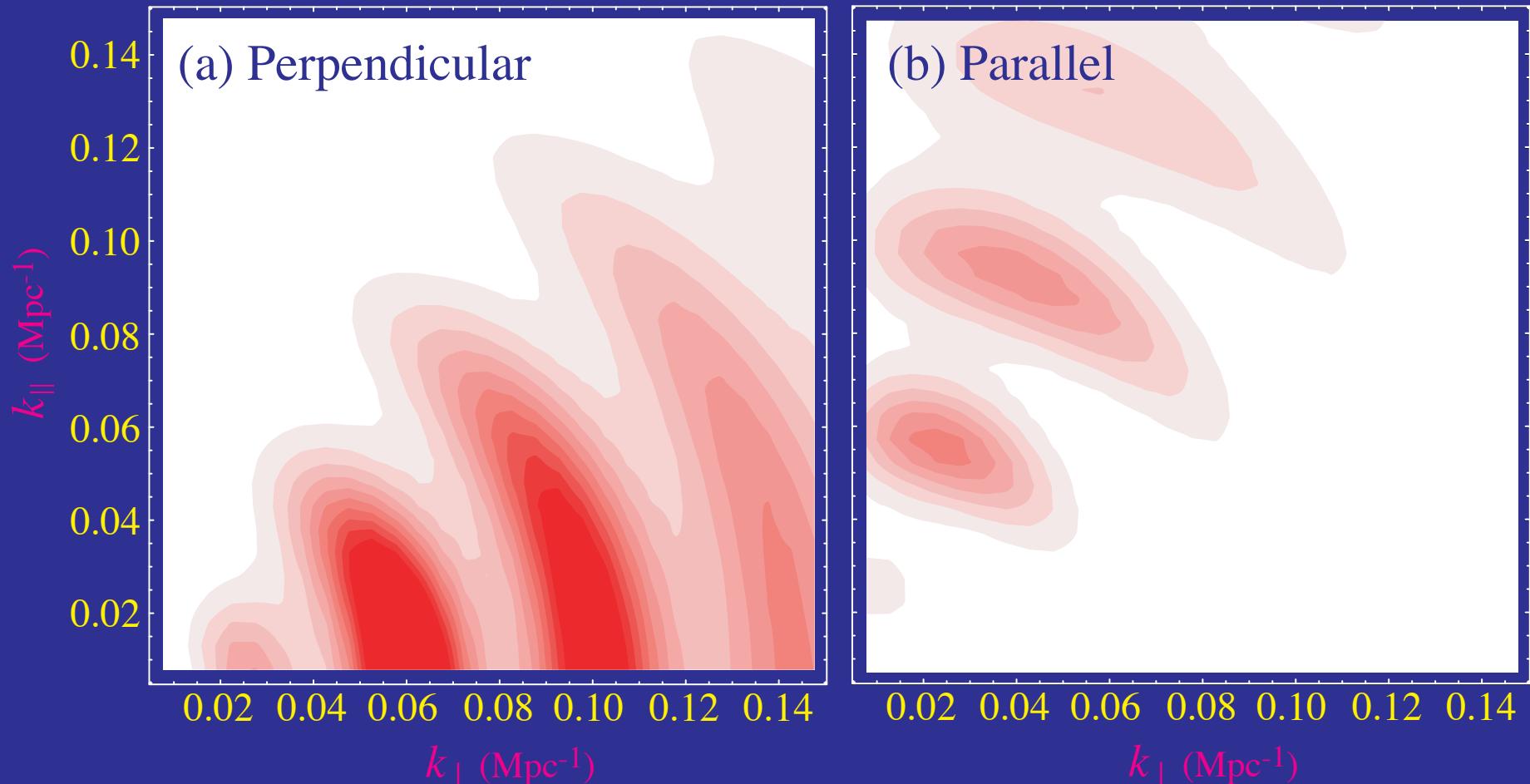
FKP Errors

- Competition between shot noise and sample variance - wiggles best measured with tracers between abundance and bias galaxies and clusters



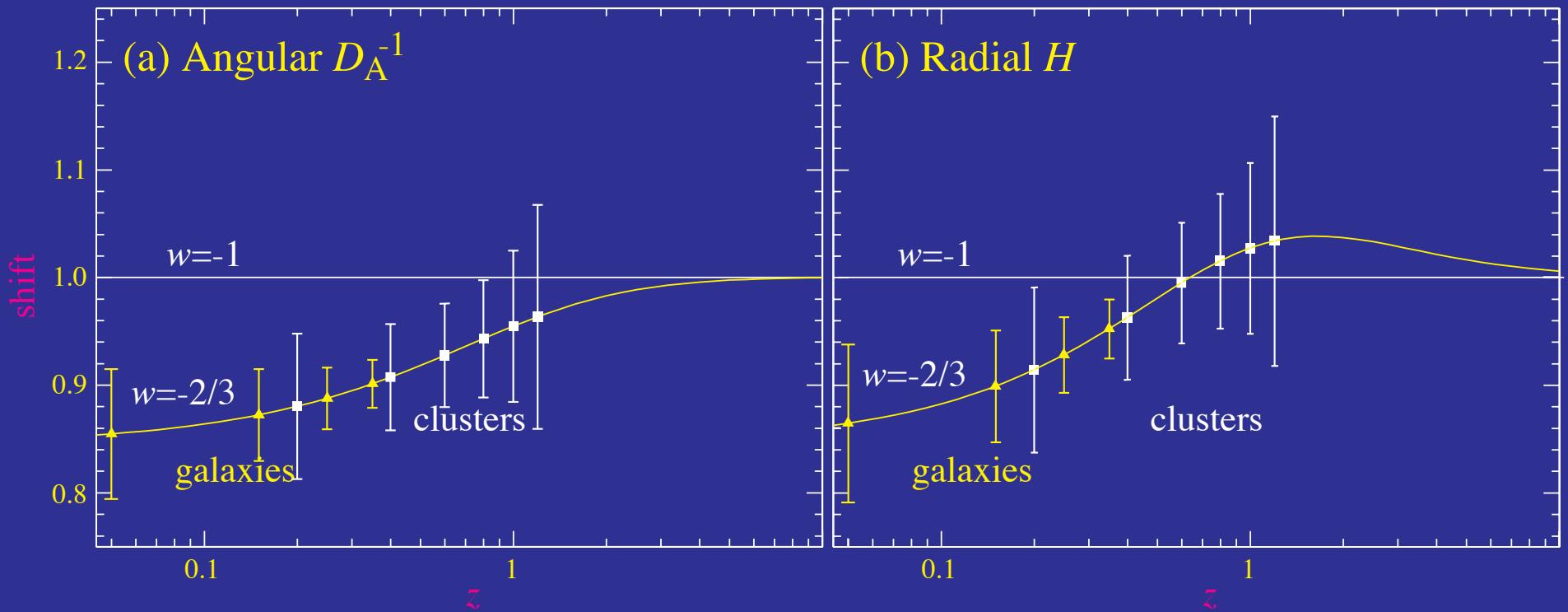
Signal to Noise

Factoring the sample variance from number of k-modes and shot variance according to FKP prescription



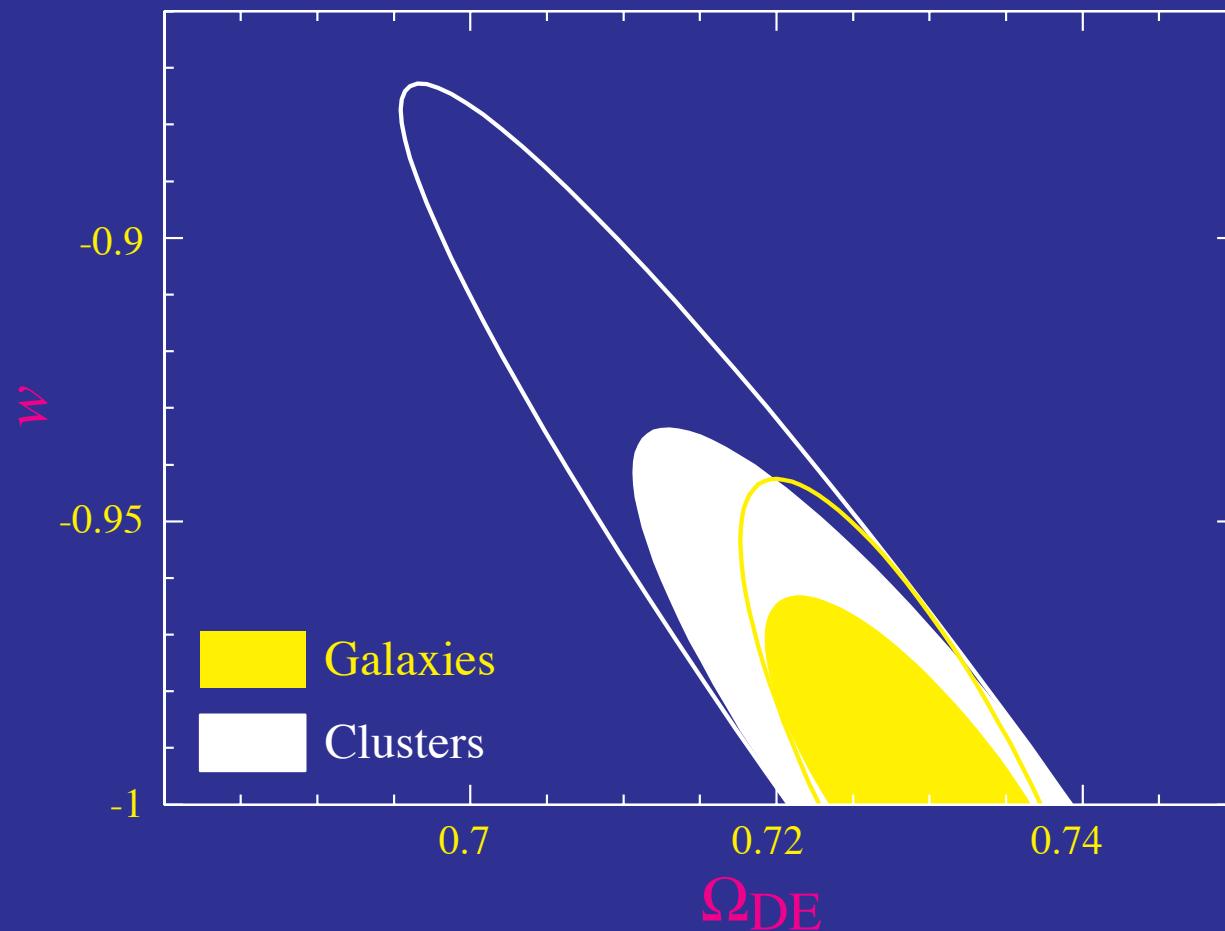
$D(z)$ and $H(z)$

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



Dark Energy

- Even marginalizing bias evolution $b(z)$ and redshift space distortions β , dark energy constraints possible with a small extrapolation from current measurements



Summary

- CMB measurements hang together extraordinarily well
- Yields an absolute calibration of the acoustic standard ruler to 1.4% and the matter radiation scale to few %
- These parameters yield a fixed template for features in the matter power spectrum.
- Features form rings in a 2D angular-redshift power spectrum
- Tangential distortion measures $D_A(z)$; radial $H(z)$
- Best complement to CMB is at moderate redshift $z < 1$; best single redshift measurement at $z = 0$, i.e. H_0
- Potential for a purely geometric dark energy test with better than 10% w -precision



the
ring

Seven Days