Dark Energy and Cosmic Sound

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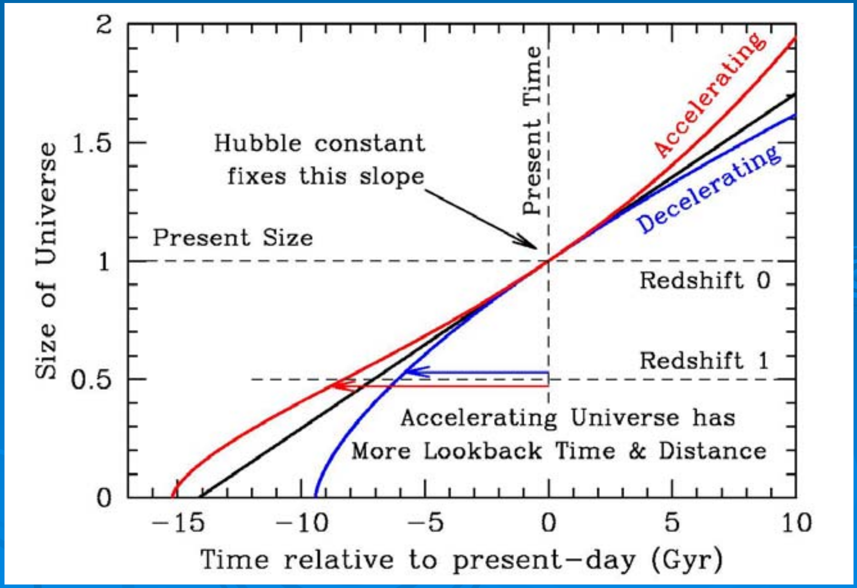
Dark Energy is Mysterious

- Observations suggest that the expansion of the universe is presently accelerating.
  - Normal matter doesn't do this!
  - Requires exotic new physics.
    - Cosmological constant?
    - Very low mass field?
    - Some alteration to gravity?
- We have no compelling theory for this!
  - Need observational measure of the time evolution of the effect.

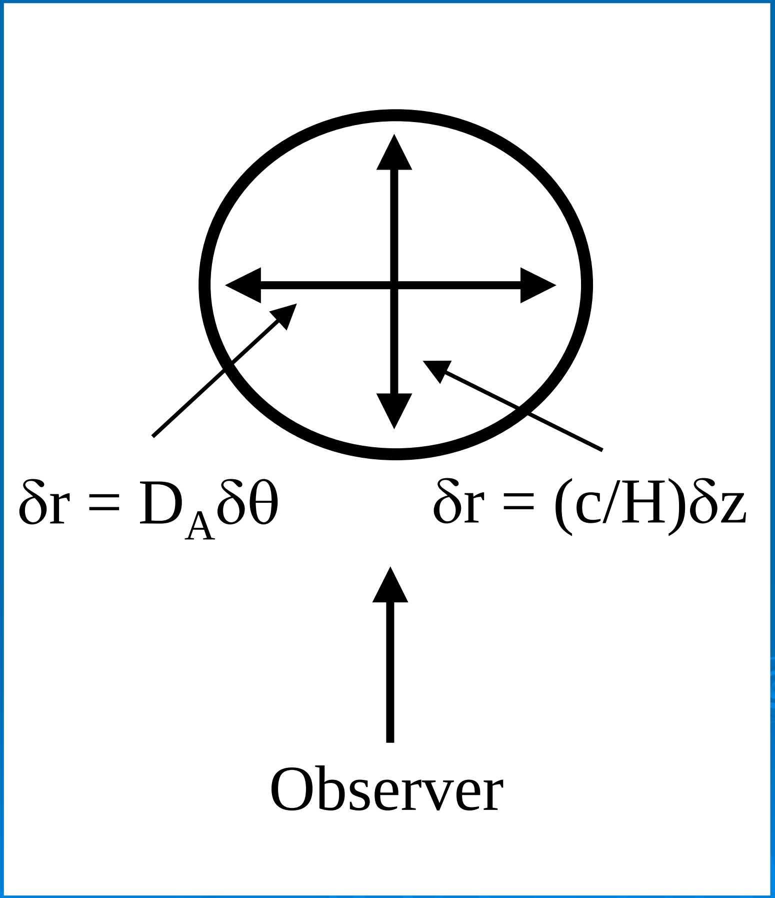


A Quick Distance Primer

- The homogeneous metric is described by two quantities:
  - The size as a function of time, $a(t)$. Equivalent to the Hubble parameter $H(z) = d\ln(a)/dt$.
  - The spatial curvature, parameterized by Ω_k.
- The distance is then

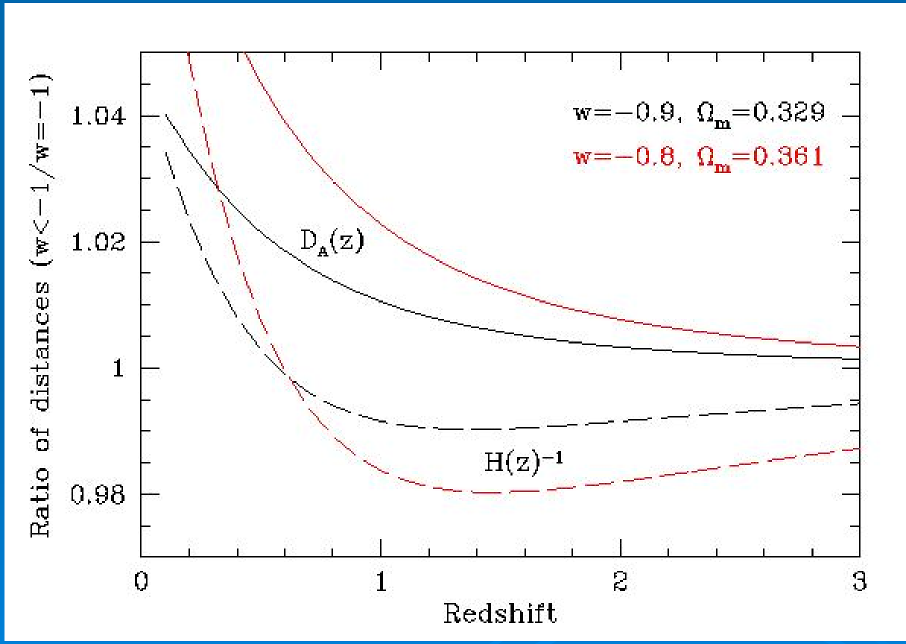
$$D = \int_0^z \frac{c\,dz}{H(z)} \text{ (flat)}$$

- $H(z)$ depends on the dark energy density.



Dark Energy is Subtle

- Parameterize by equation of state, $w = p/\rho$, which controls how the energy density evolves with time.
- Measuring $w(z)$ requires exquisite precision.



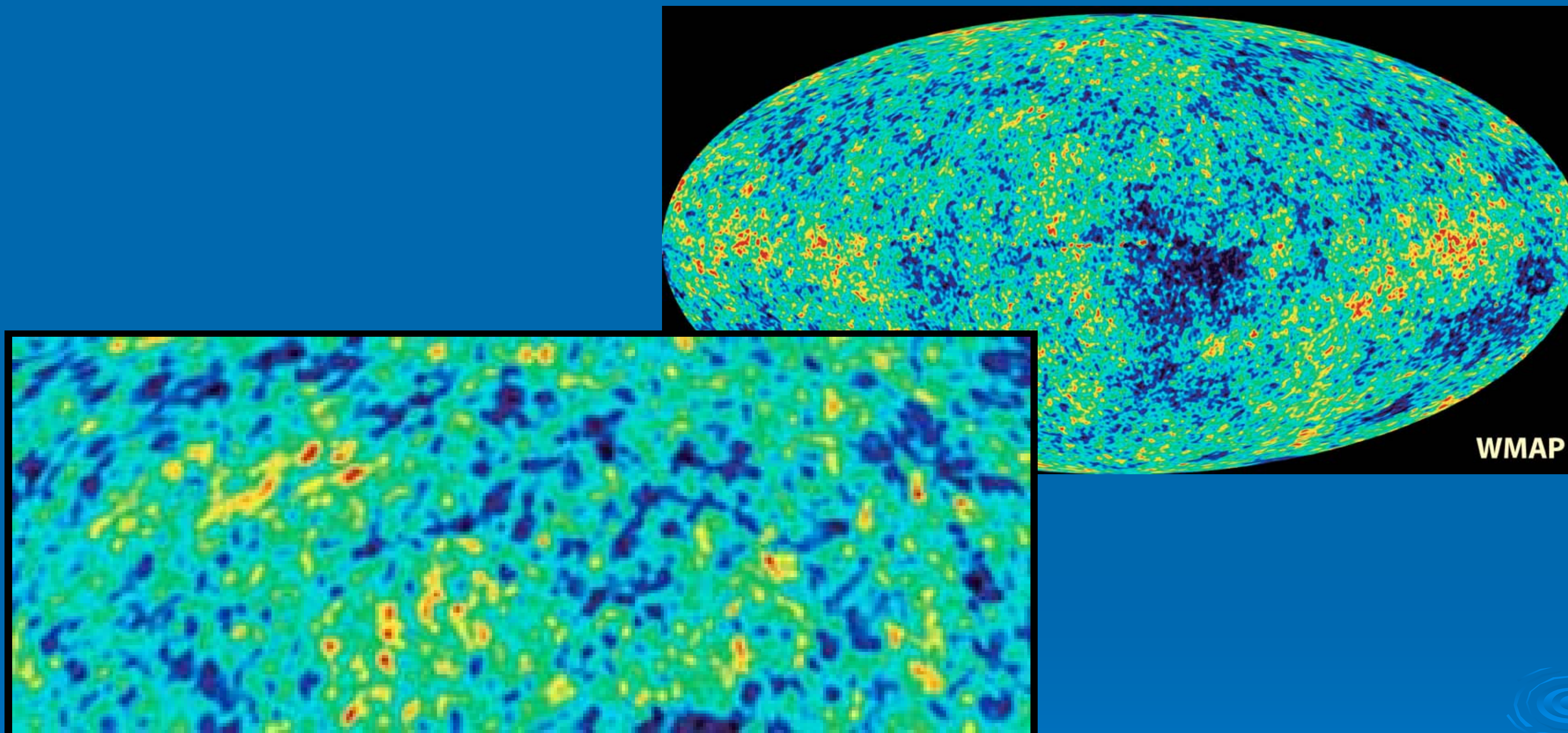
Comparing Cosmologies

- Varying w assuming perfect CMB:
  - Fixed $\Omega_m h^2$
  - $D_A(z=1000)$
- dw/dz is even harder.
- Need precise, redundant observational probes!

Outline

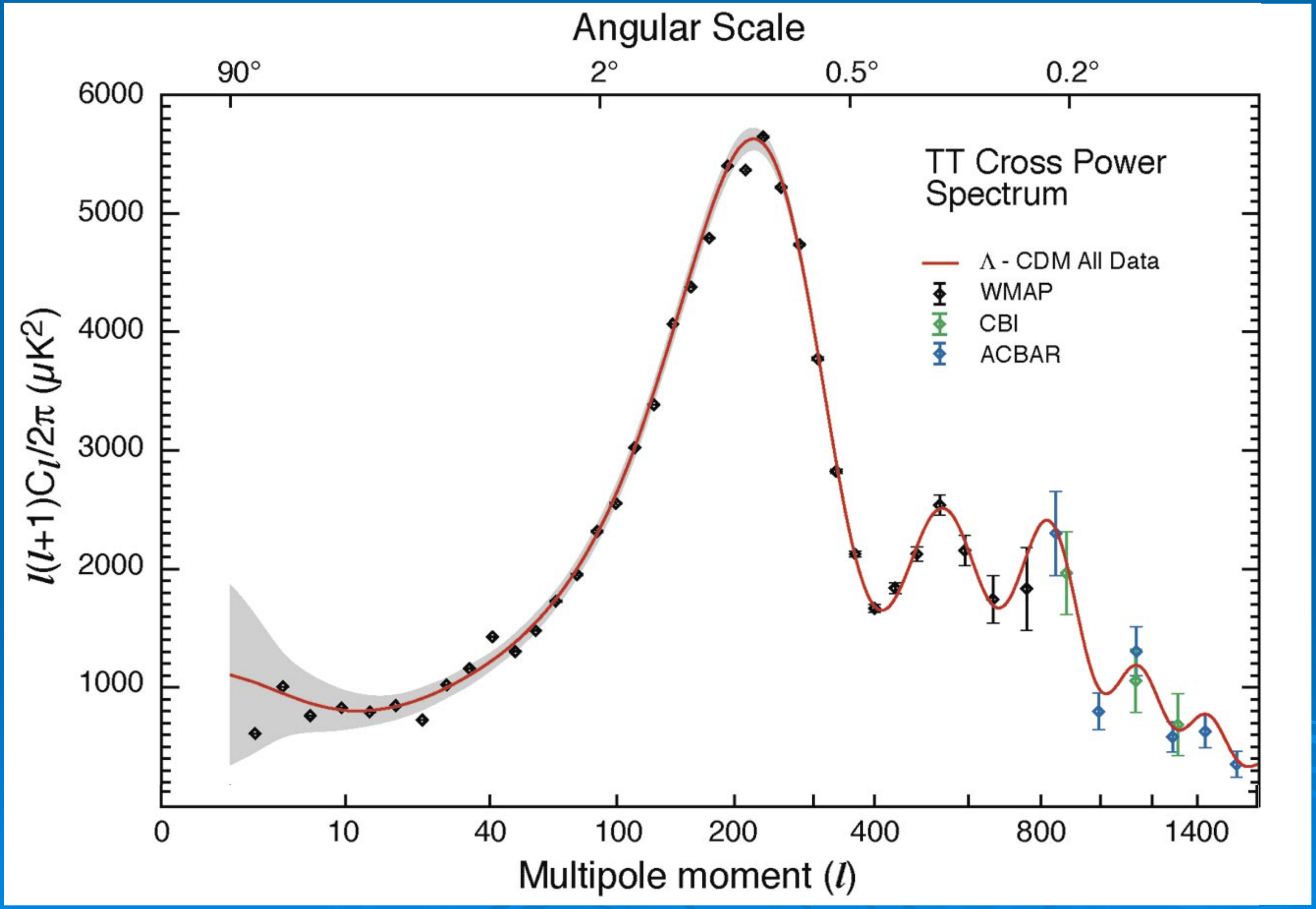
- Baryon acoustic oscillations as a standard ruler.
- Detection of the acoustic signature in the SDSS Luminous Red Galaxy sample at z=0.35.
  - Cosmological constraints therefrom.
- Large galaxy surveys at higher redshifts.
  - Future surveys could measure H(z) and $D_A(z)$ to few percent from z=0.3 to z=3.
  - Assess the leverage on dark energy and compare to alternatives.

Acoustic Oscillations in the CMB



- Although there are fluctuations on all scales, there is a characteristic angular scale.

Acoustic Oscillations in the CMB



WMAP team (Bennett et al. 2003)

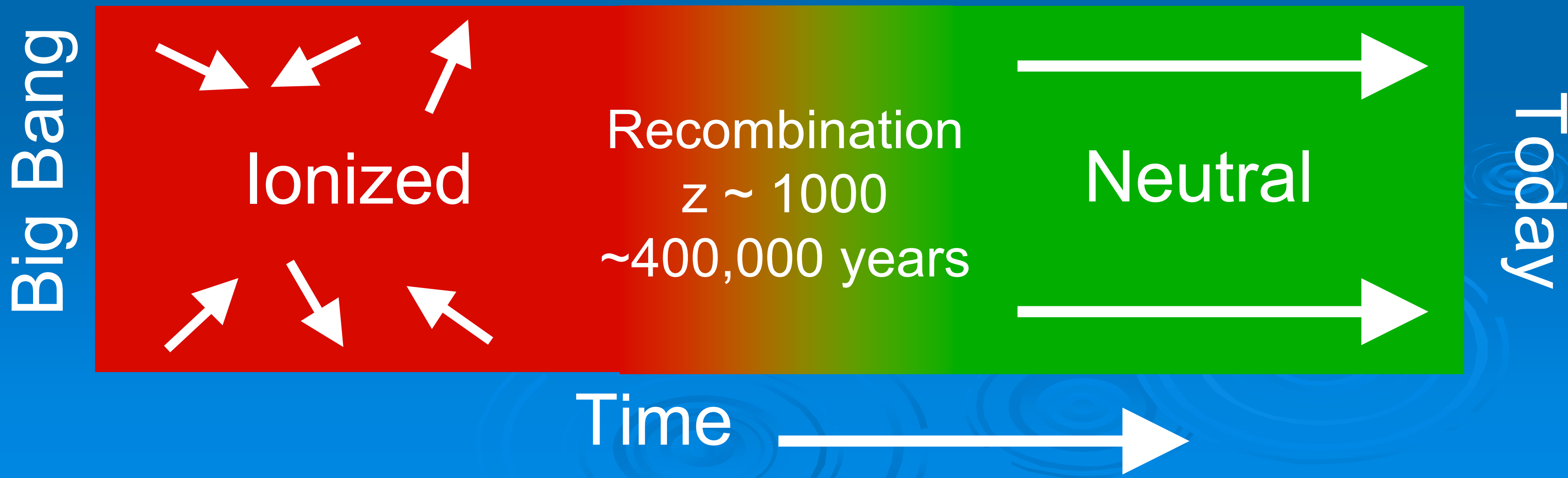
Sound Waves in the Early Universe

Before recombination:

- Universe is ionized.
- Photons provide enormous pressure and restoring force.
- Perturbations oscillate as acoustic waves.

After recombination:

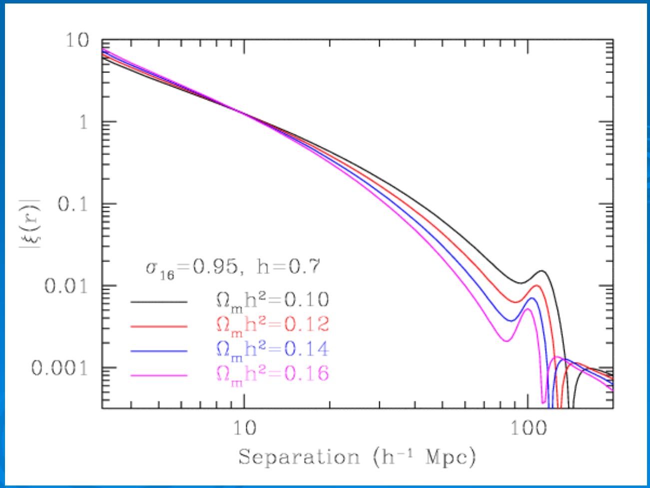
- Universe is neutral.
- Photons can travel freely past the baryons.
- Phase of oscillation at t_{rec} affects late-time amplitude.



Sound Waves

- Each initial overdensity (in DM & gas) is an overpressure that launches a spherical sound wave.
- This wave travels outwards at 57% of the speed of light.
- Pressure-providing photons decouple at recombination. CMB travels to us from these spheres.
- Sound speed plummets. Wave stalls at a radius of 150 Mpc.
- Overdensity in shell (gas) and in the original center (DM) both seed the formation of galaxies. Preferred separation of 150 Mpc.

QuickTime™ and a
GIF decompressor
are needed to see this picture.



A Statistical Signal

- The Universe is a super-position of these shells.
- The shell is weaker than displayed.
- Hence, you do not expect to see bullseyes in the galaxy distribution.
- Instead, we get a 1% bump in the correlation function.

QuickTime™ and a
GIF decompressor
are needed to see this picture.

Response of a point perturbation

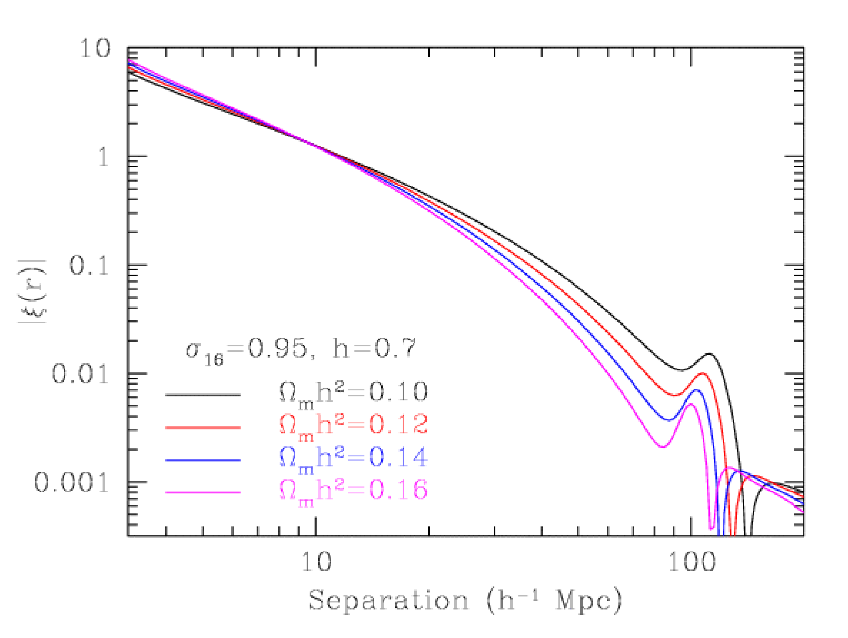
QuickTime™ and a
GIF decompressor
are needed to see this picture.

Remember: This is a tiny ripple on a big background.

Based on CMBfast outputs (Seljak & Zaldarriaga). Green's function view from Bashinsky & Bertschinger 2001.

Theory and Observables

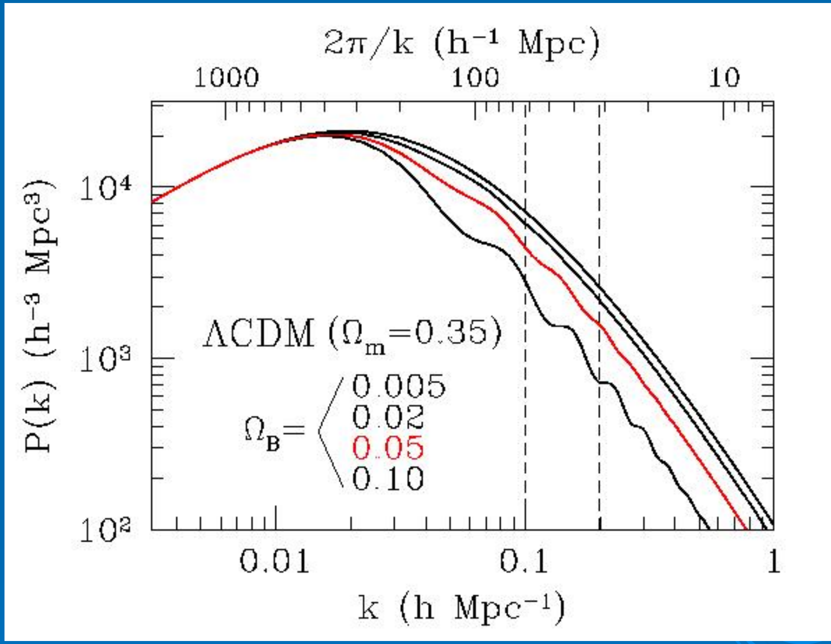
- Linear clustering is specified in proper distance by $\Omega_m h^2$, $\Omega_b h^2$, and n.
- Two scales: acoustic scale and M-R equality horizon scale.
- Measuring both breaks degeneracy between $\Omega_m h^2$ and distance to z=0.35.



$\Omega_m h^2$ shifts ratio of large to small-scale clustering, but doesn't move the acoustic scale much.

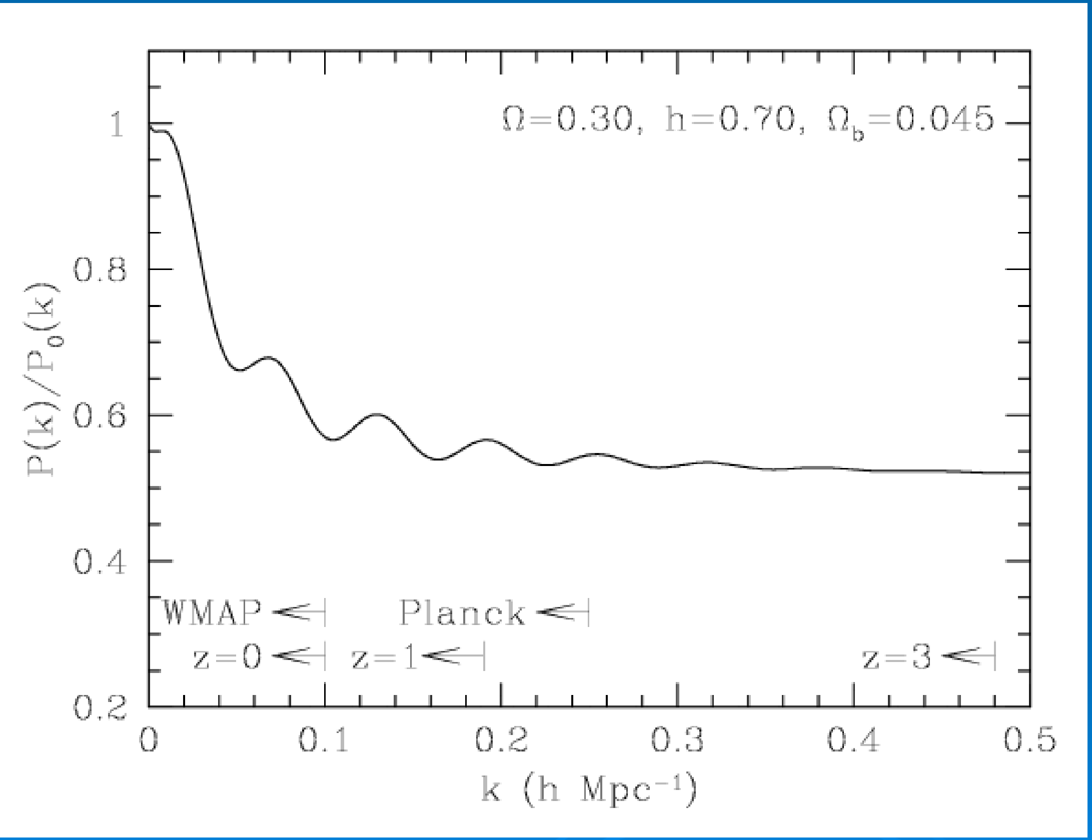
Acoustic Oscillations in Fourier Space

- A crest launches a planar sound wave, which at recombination may or may not be in phase with the next crest.
- Get a sequence of constructive and destructive interferences as a function of wavenumber.
- Peaks are weak — suppressed by the baryon fraction.
- Higher harmonics suffer from Silk damping.



Linear regime matter power spectrum

Acoustic Oscillations, Reprise

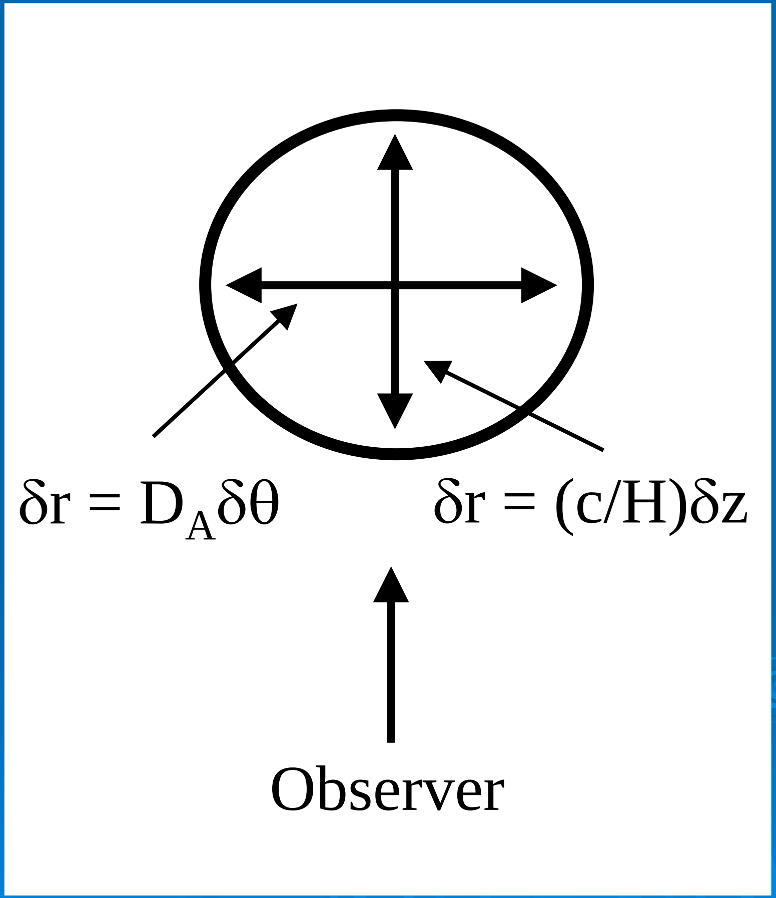


Linear regime matter power spectrum

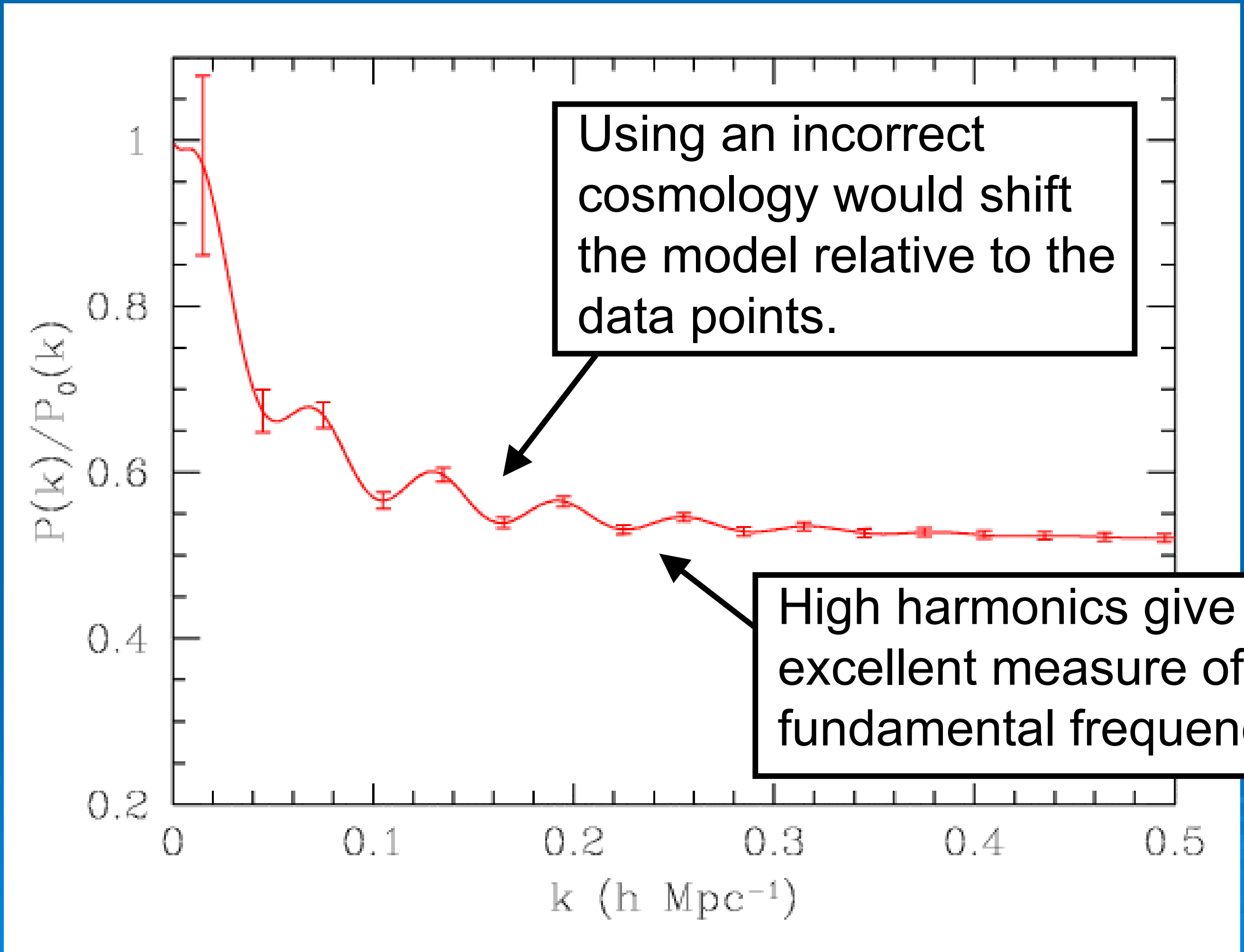
- Divide by zero-baryon reference model.
- Acoustic peaks are 10% modulations.
- Requires large surveys to detect!

A Standard Ruler

- The acoustic oscillation scale depends on the sound speed and the propagation time.
  - These depend on the matter-to-radiation ratio ($\Omega_m h^2$) and the baryon-to-photon ratio ($\Omega_b h^2$).
- The CMB anisotropies measure these and fix the oscillation scale.
- In a redshift survey, we can measure this along and across the line of sight.
- Yields $H(z)$ and $D_A(z)$!

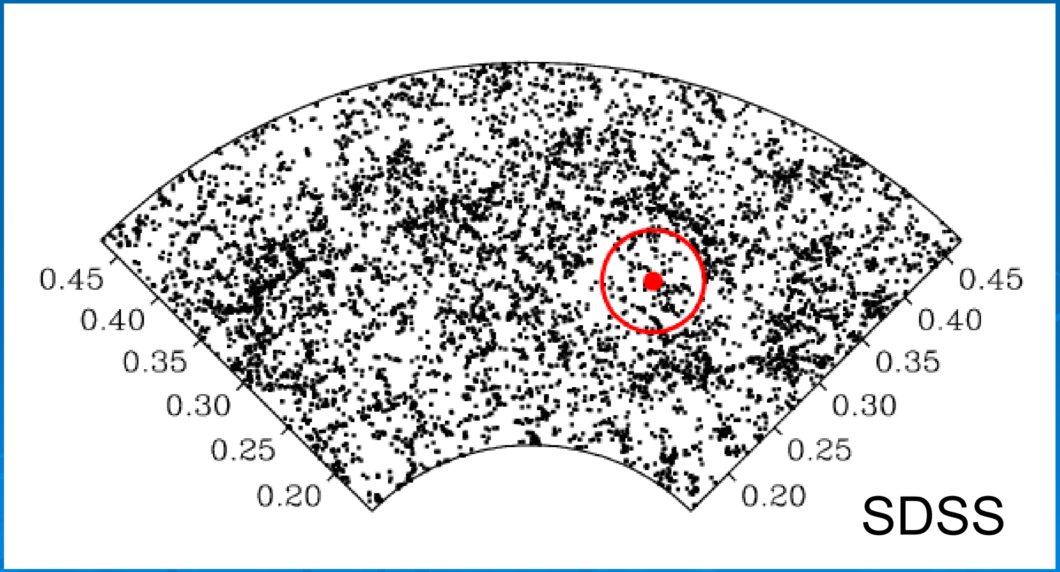


Measuring the Acoustic Scale



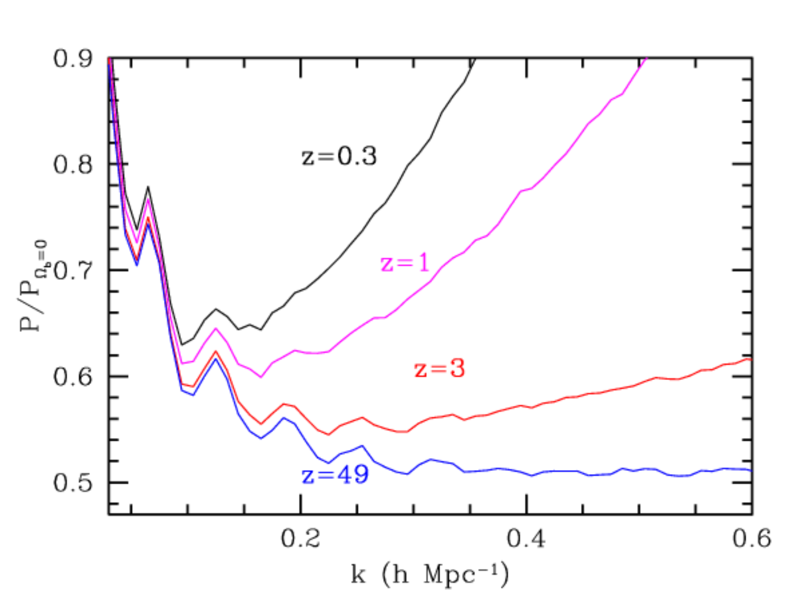
Galaxy Redshift Surveys

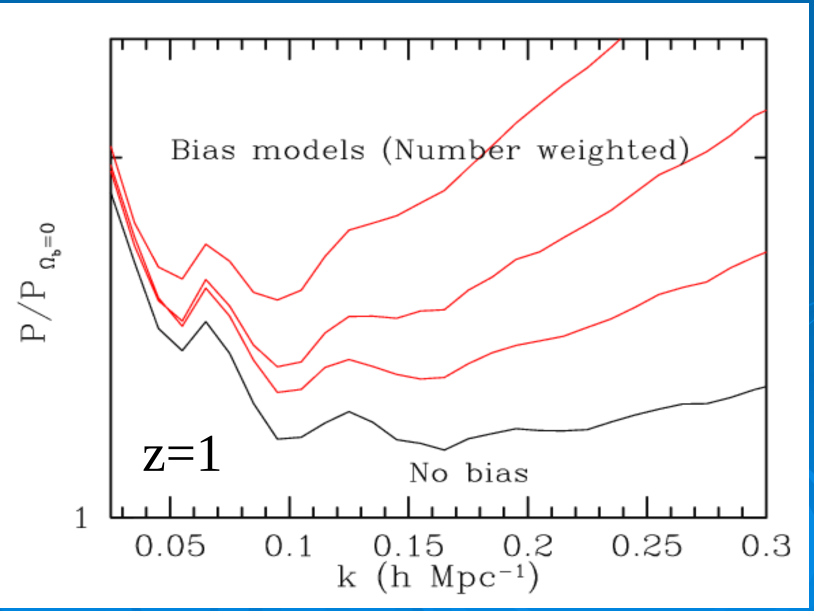
- Redshift surveys are a popular way to measure the 3-dimensional clustering of matter.
- But there are complications from:
  - Non-linear structure formation
  - Bias (light ≠ mass)
  - Redshift distortions
- Do these affect the acoustic signatures?



Nonlinearities & Bias

- Non-linear gravitational collapse erases acoustic oscillations on small scales. However, large scale features are preserved.
- Clustering bias and redshift distortions alter the power spectrum, but they don't create preferred scales at 100h^{-1} Mpc!
- Acoustic peaks expected to survive in the linear regime.





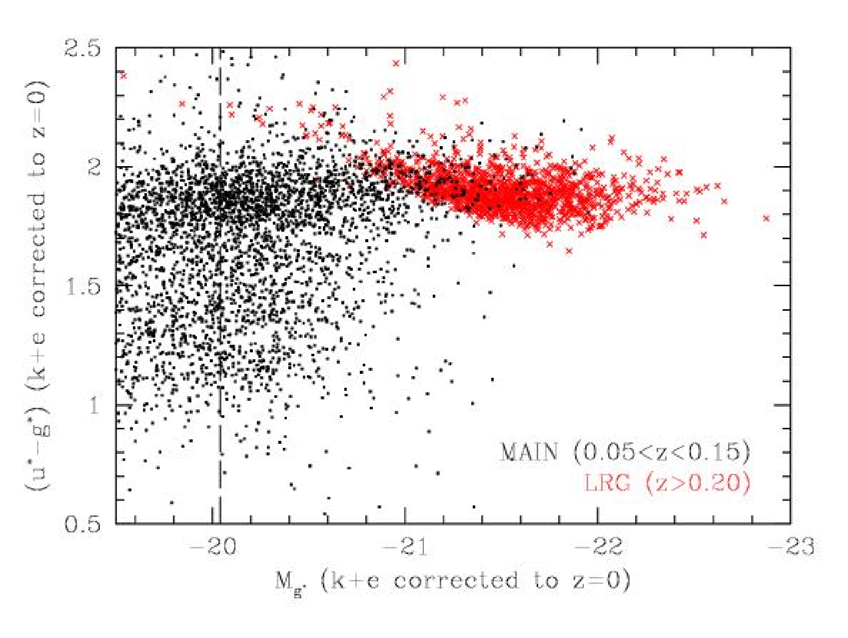
Meiksen & White (1997), Seo & DJE (2005)

Virtues of the Acoustic Peaks

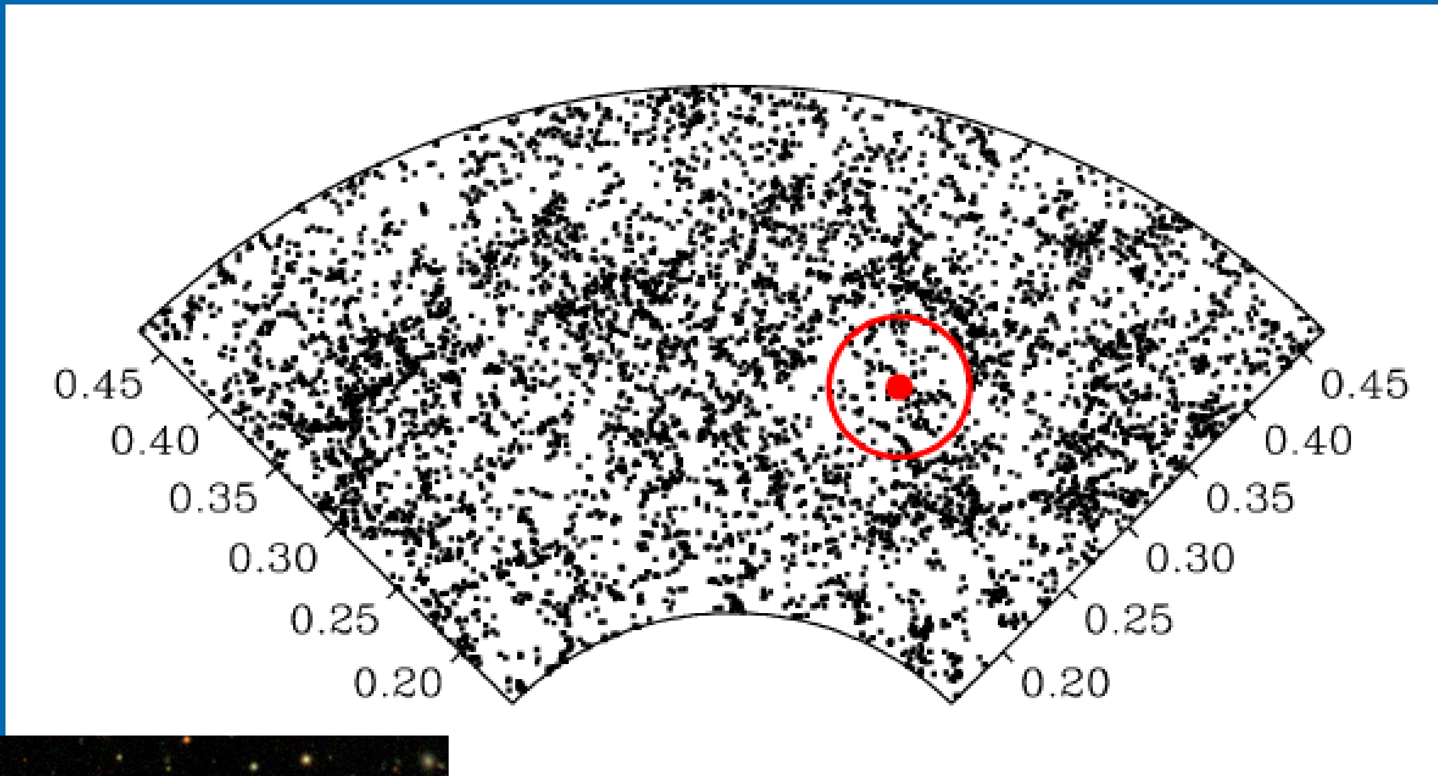
- Measuring the acoustic peaks across redshift gives a purely geometrical measurement of cosmological distance.
- The acoustic peaks are a manifestation of a preferred scale.
  - Non-linearity, bias, redshift distortions shouldn't produce such preferred scales, certainly not at 100 Mpc.
  - Method should be robust, but in any case the systematic errors will be very different from SNe.
- However, the peaks are weak in amplitude and are only available on large scales (30 Mpc and up). Require huge survey volumes.

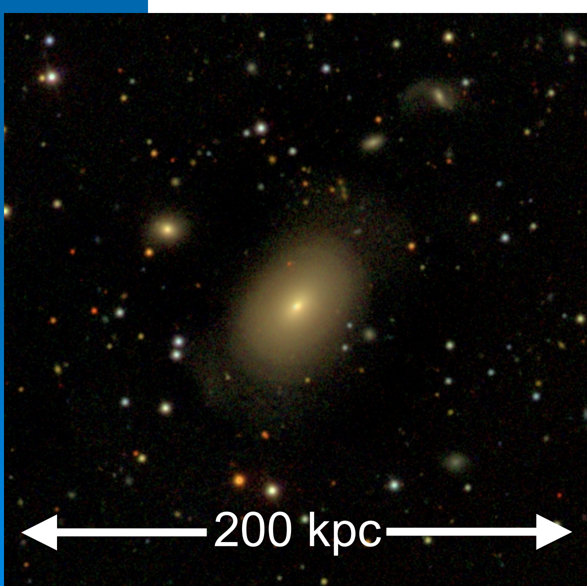
Introduction to SDSS LRGs

- SDSS uses color to target luminous, early-type galaxies at $0.2<z<0.5$.
  - Fainter than MAIN ($r<19.5$)
  - About 15/sq deg
  - Excellent redshift success rate
- The sample is close to mass-limited at $z<0.38$. Number density ~ $10^{-4}\ h^3$ Mpc^{-3}.



- Science Goals:
  - Clustering on largest scales
  - Galaxy clusters to z~0.5
  - Evolution of massive galaxies





QuickTime™ and a
GIF decompressor
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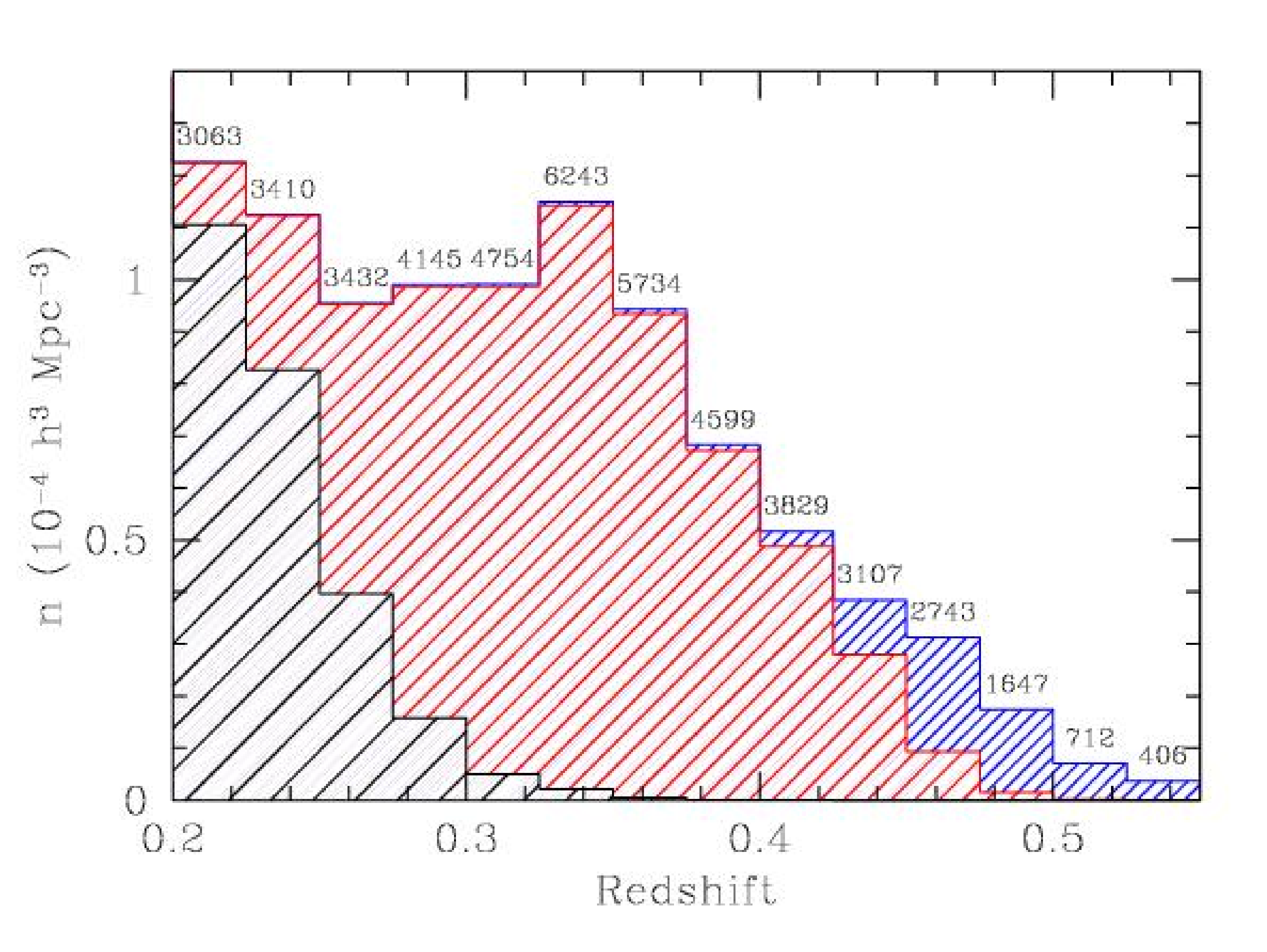
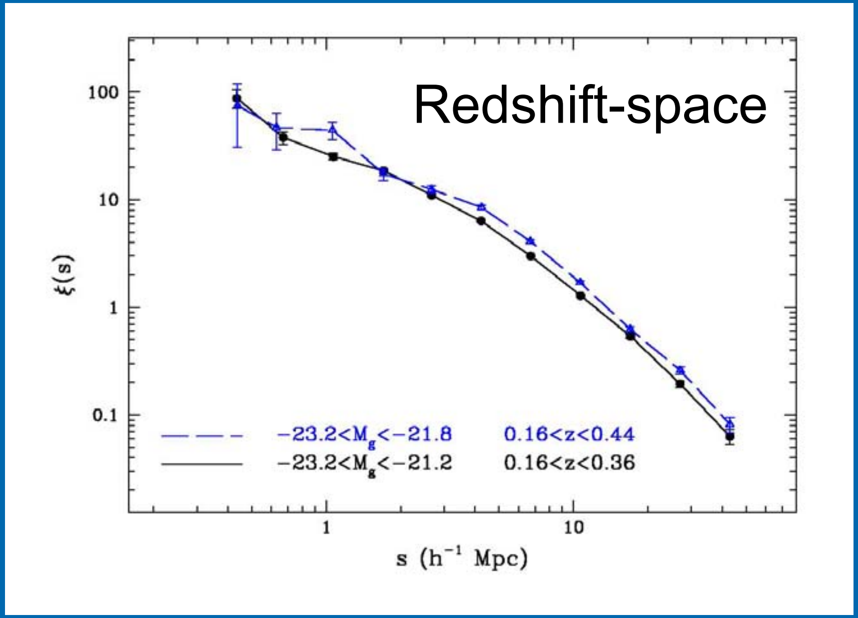
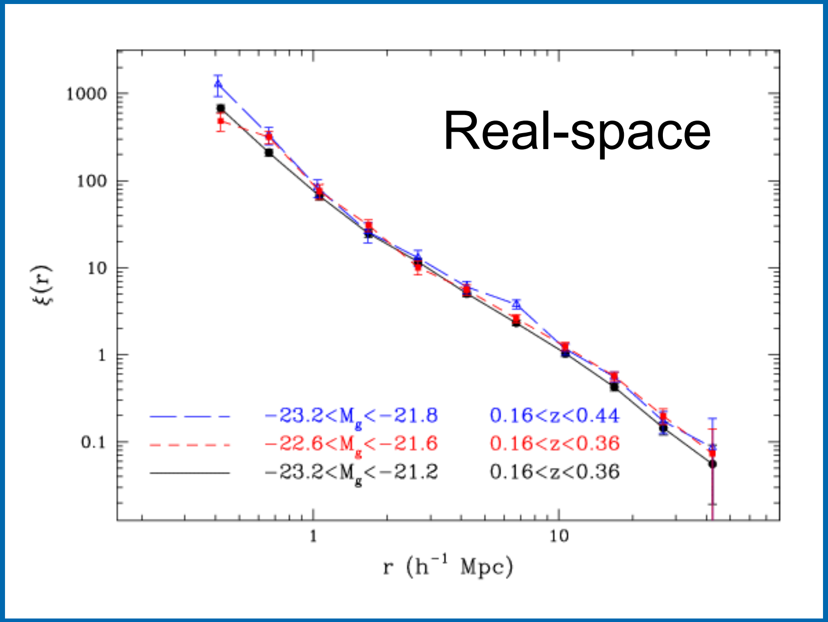
55,000 Spectra



Intermediate-scale Correlations



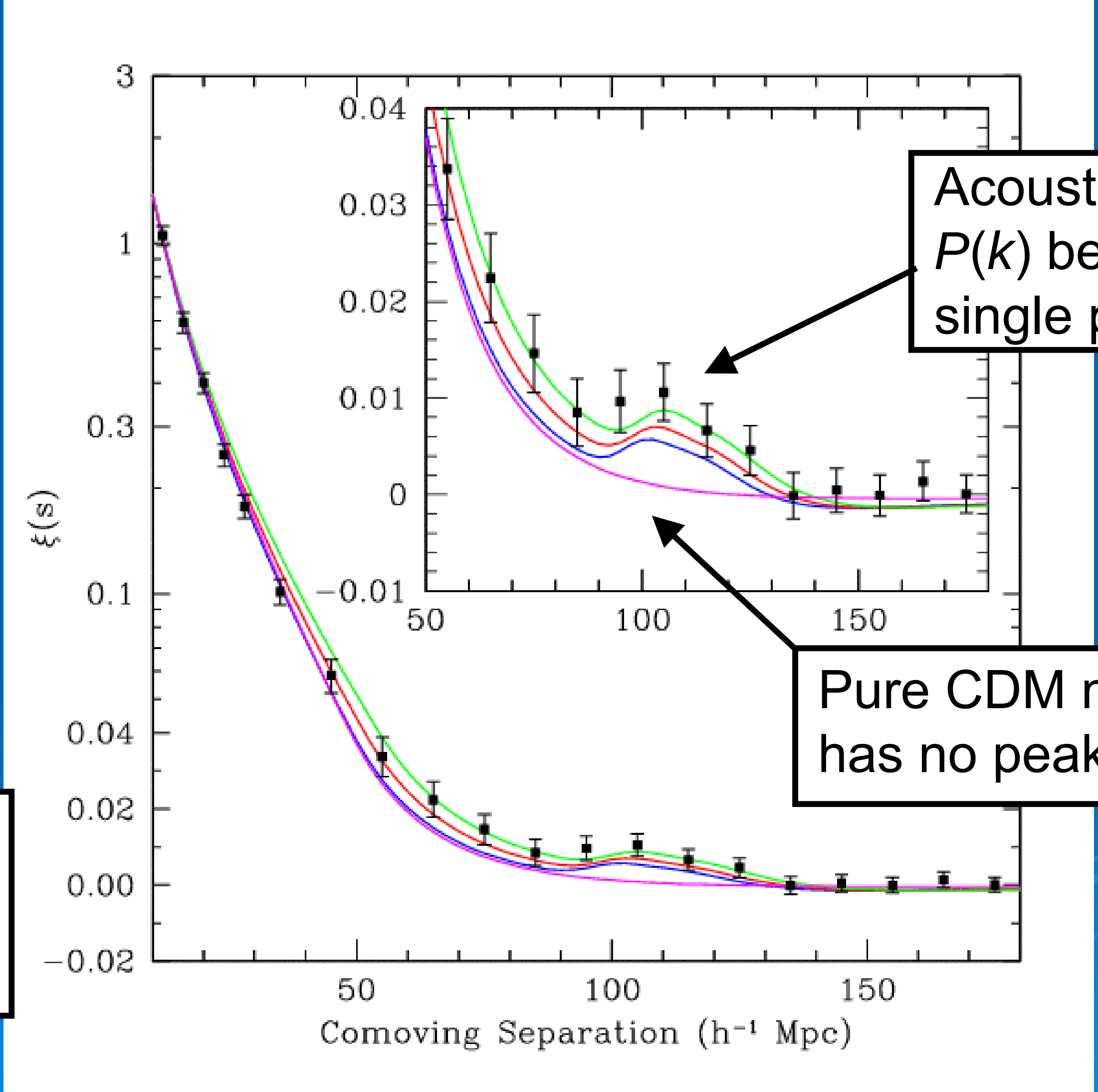


Zehavi et al. (2004)

- Subtle luminosity dependence in amplitude.
  - σ_8 = 1.80±0.03 up to 2.06±0.06 across samples
  - $r_0 = 9.8h^{-1}$ up to $11.2h^{-1}$ Mpc
- Real-space correlation function is not a power-law.

On to Larger Scales....

Large-scale Correlations

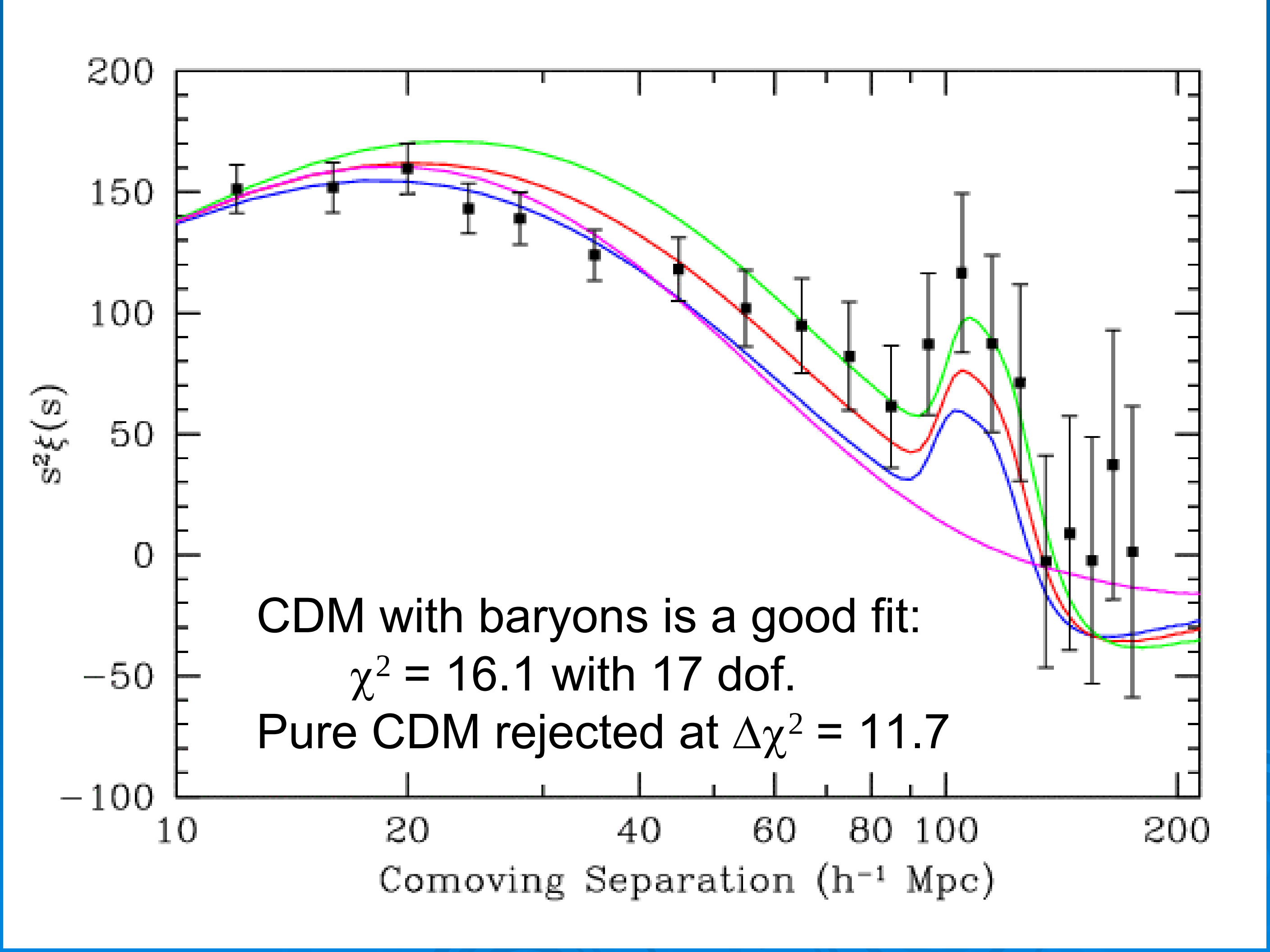


Acoustic series in *P*(*k*) becomes a single peak in $\xi(r)$!

Pure CDM model has no peak.

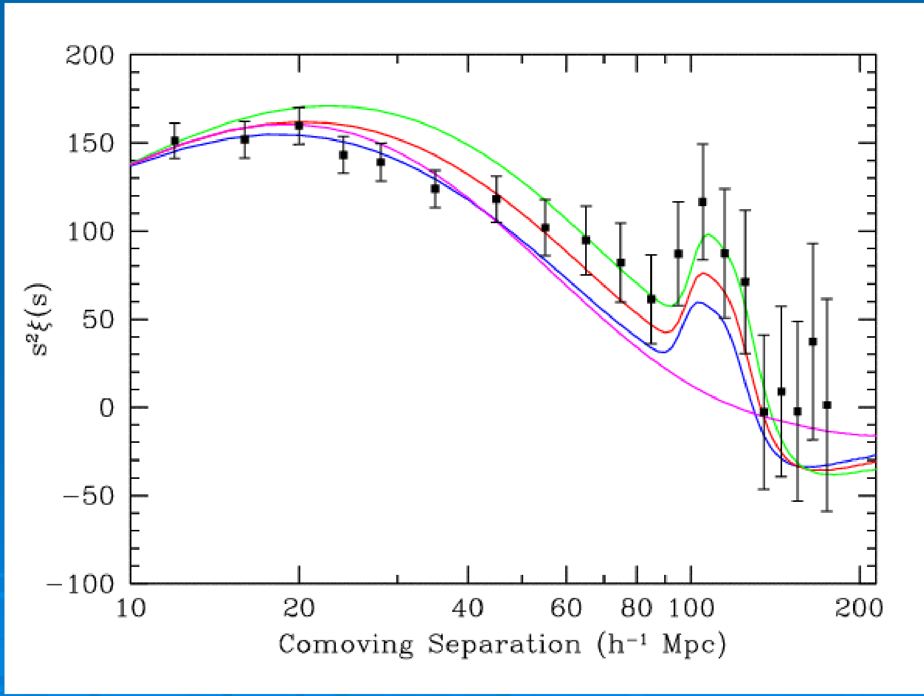
Warning: Correlated Error Bars

Another View

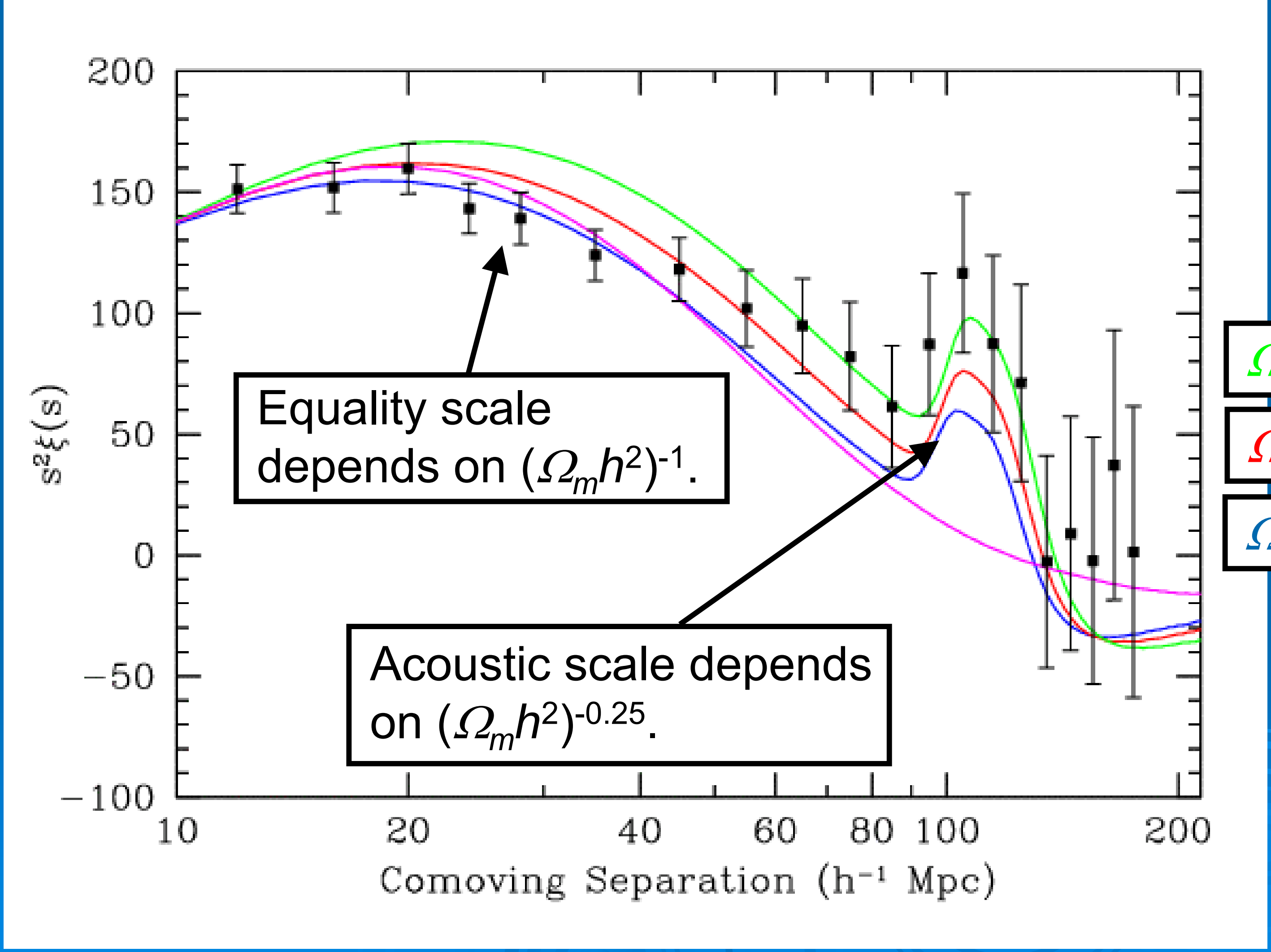


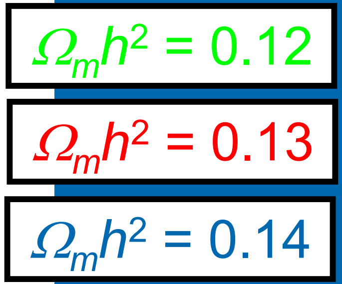
A Prediction Confirmed!

- Standard inflationary CDM model requires acoustic peaks.
  - Important confirmation of basic prediction of the model.
- This demonstrates that structure grows from z=1000 to z=0 by linear theory.
  - Survival of narrow feature means no mode coupling.



Two Scales in Action

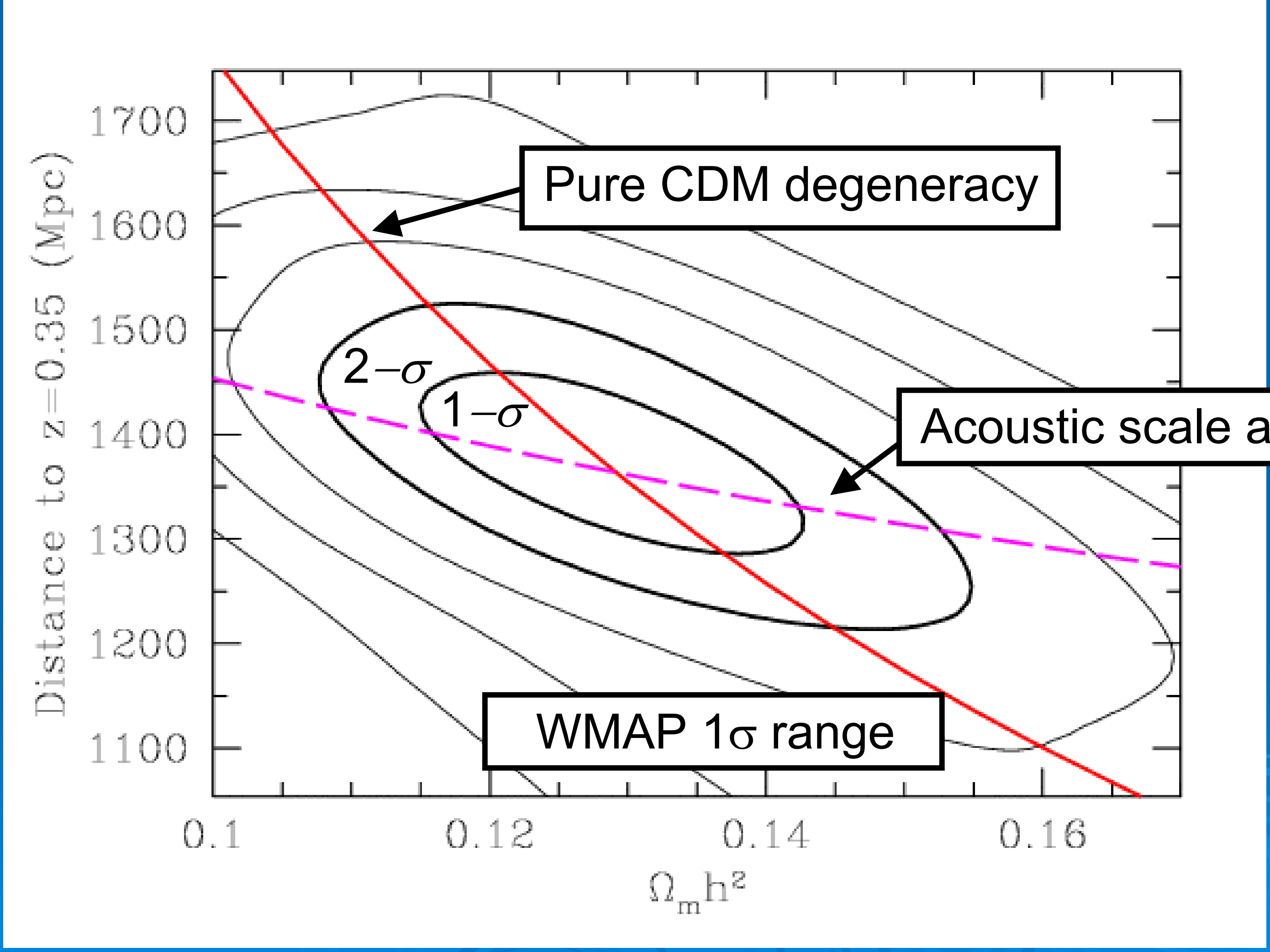




Parameter Estimation

- Vary $\Omega_m h^2$ and the distance to $z = 0.35$, the mean redshift of the sample.
  - Dilate transverse and radial distances together, i.e., treat $D_A(z)$ and $H(z)$ similarly.
- Hold $\Omega_b h^2 = 0.024$, $n = 0.98$ fixed (WMAP).
  - Neglect info from CMB regarding $\Omega_m h^2$, ISW, and angular scale of CMB acoustic peaks.
- Use only $r>10h^{-1}$ Mpc.
  - Minimize uncertainties from non-linear gravity, redshift distortions, and scale-dependent bias.
- Covariance matrix derived from 1200 PTHalos mock catalogs, validated by jack-knife testing.

Cosmological Constraints



Measuring a Known Scale

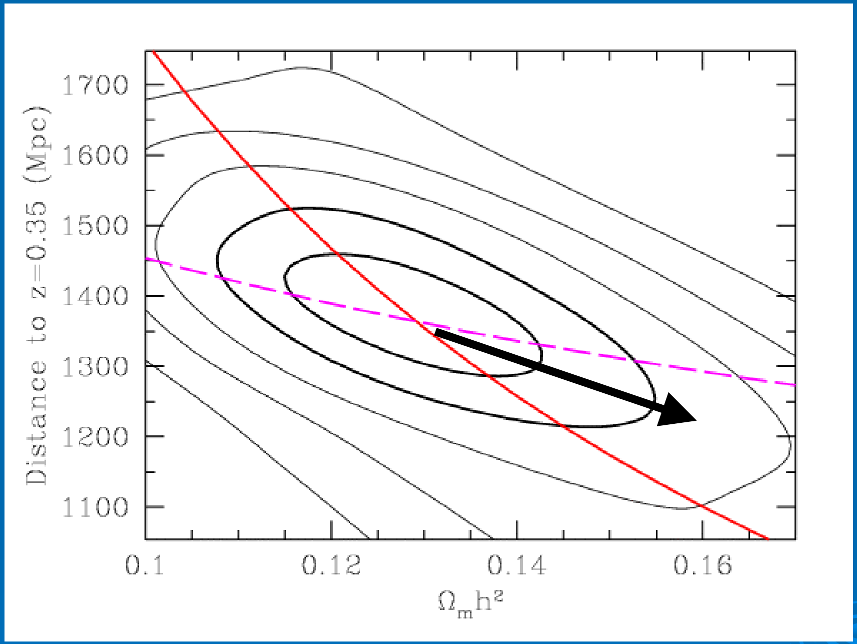
- For a given $\Omega_m h^2$, the acoustic scale is known.
- We measure it in the CMB at z=1000 to 1% and in SDSS at z=0.35 to 4%.
- This constrains Ω_m, Ω_K, and dark energy in two separate redshift ranges: $0<z<0.35$ and $0.35<z<1000$.

$$\int_0^{1000} \frac{c\,dz}{H(z)} - \int_0^{0.35} \frac{c\,dz}{H(z)} = \int_{0.35}^{1000} \frac{c\,dz}{H(z)}$$

(Flat)

A Standard Ruler

- If the LRG sample were at z=0, then we would measure H_0 directly (and hence Ω_m from $\Omega_m h^2$).
- Instead, there are small corrections from w and Ω_K to get to z=0.35.
- The uncertainty in $\Omega_m h^2$ makes it better to measure $(\Omega_m h^2)^{1/2} D$. This is independent of H_0.



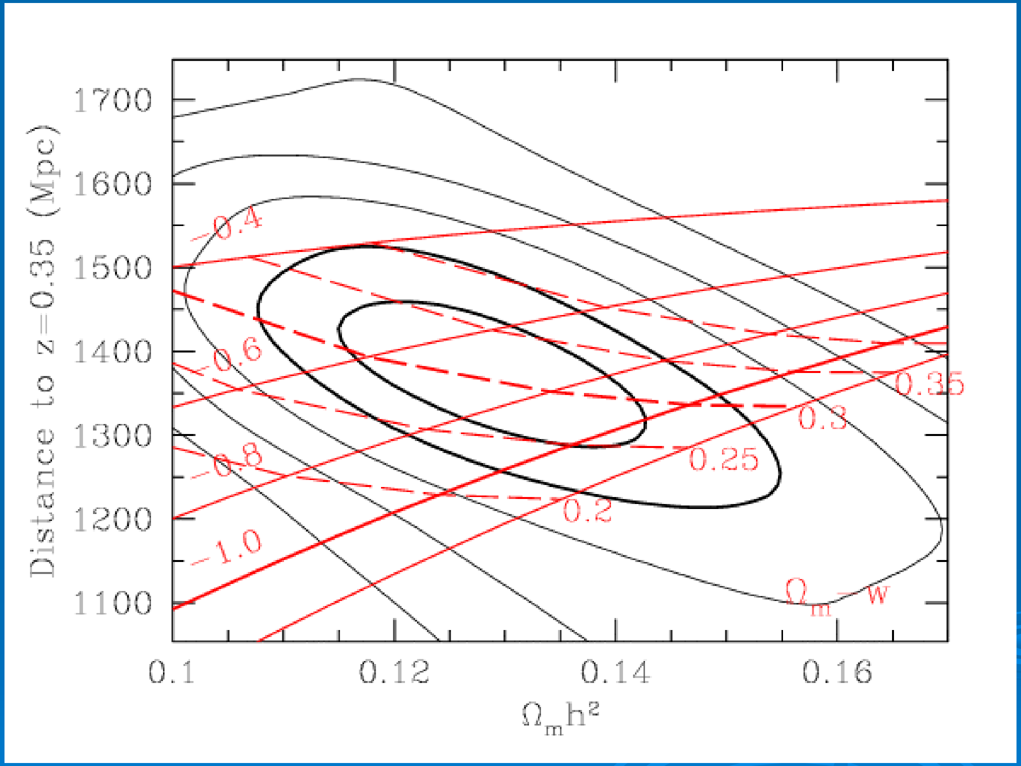
- We find $\Omega_m = 0.273 \pm 0.025 + 0.123(1+w_0) + 0.137\Omega_K$.

Essential Conclusions

- SDSS LRG correlation function does show a plausible acoustic peak.
- Ratio of $D(z=0.35)$ to $D(z=1000)$ measured to 4%.
  - This measurement is insensitive to variations in spectral tilt and small-scale modeling. We are measuring the same physical feature at low and high redshift.
- $\Omega_m h^2$ from SDSS LRG and from CMB agree. Roughly 10% precision.
  - This will improve rapidly from better CMB data and from better modeling of LRG sample.
- $\Omega_\mathrm{m} = 0.273 \pm 0.025 + 0.123(1+w_0) + 0.137\Omega_K$.

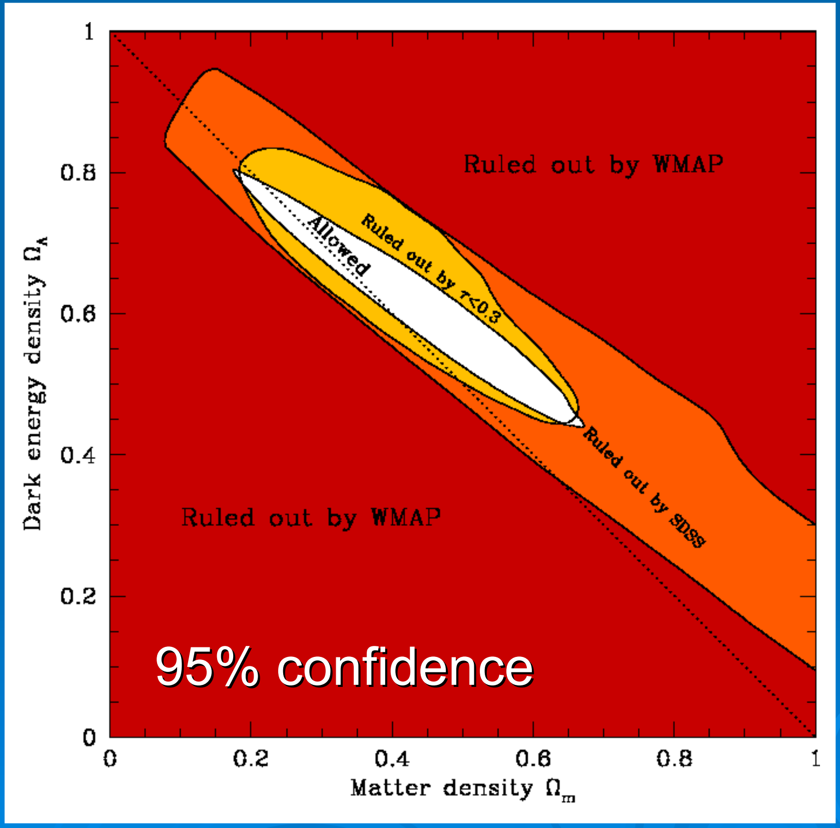
Constant *w* Models

- For a given *w* and $\Omega_m h^2$, the angular location of the CMB acoustic peaks constrains Ω_m (or H_0), so the model predicts $D_A(z=0.35)$.
- Good constraint on Ω_m, less so on *w* (–0.8±0.2).



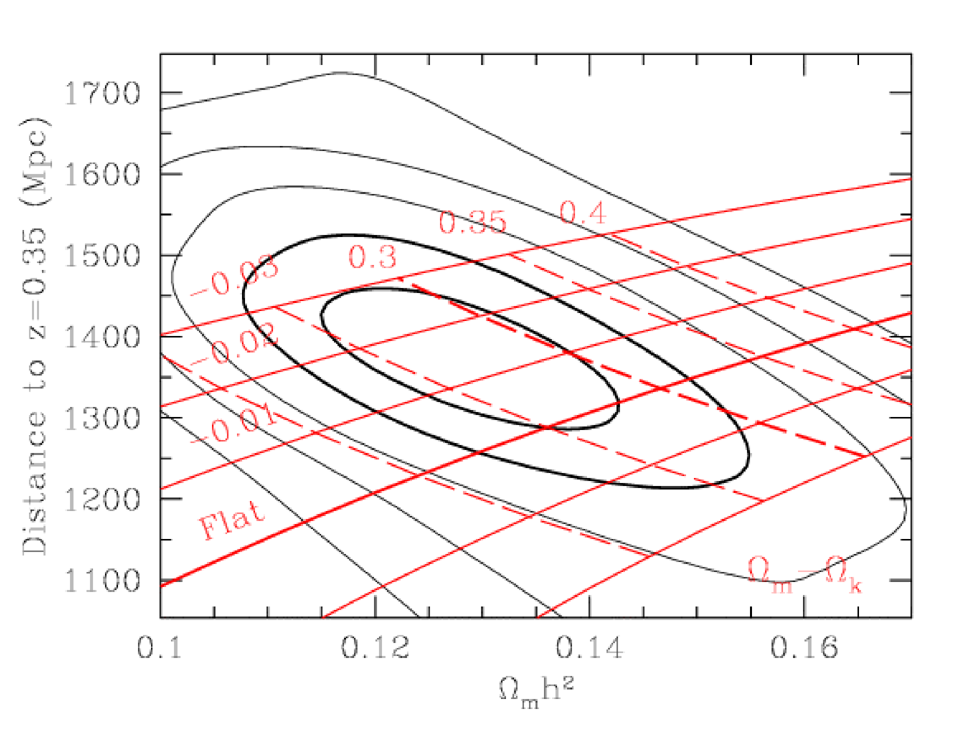
Λ + Curvature

- Consider models with $w = -1$ (aka, Λ) but with non-zero curvature.



Tegmark et al. (2004)

Λ + Curvature



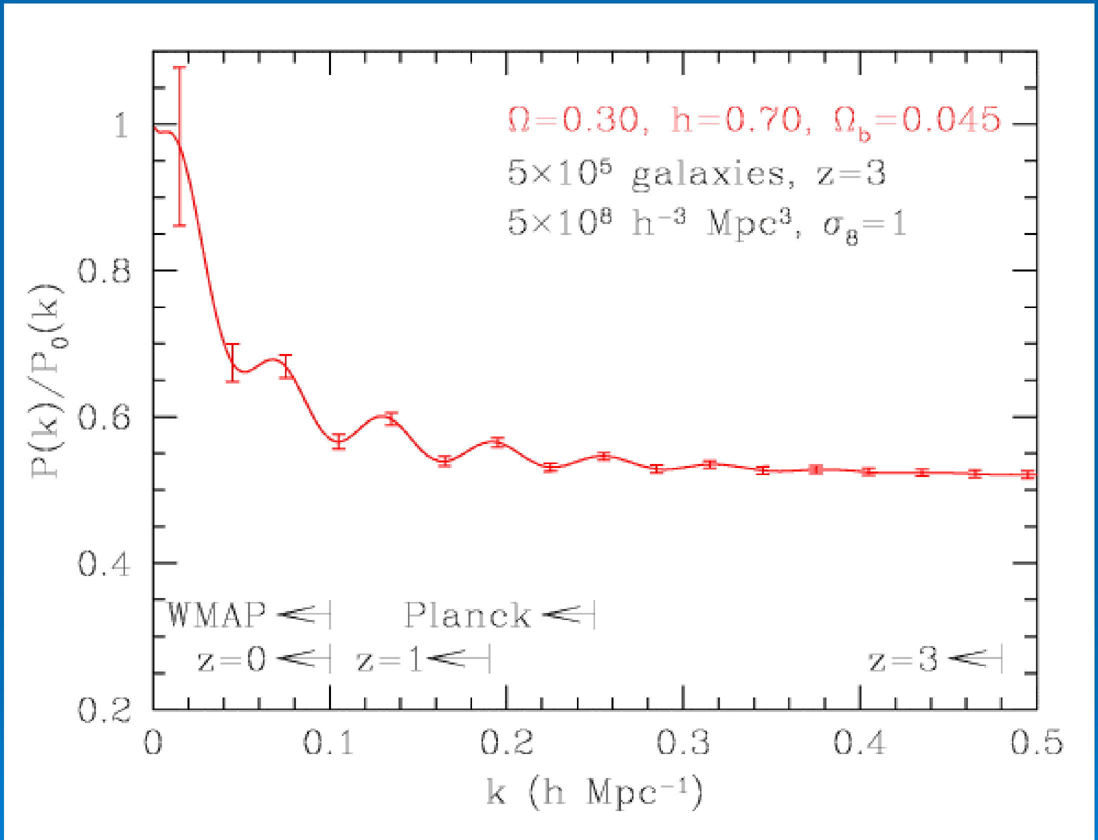
- Common distance scale to low and high redshift yields a powerful constraint on spatial curvature:

$$\Omega_K = -0.010 \pm 0.009 \quad (w = -1)$$

Beyond SDSS

- By performing large spectroscopic surveys at higher redshifts, we can measure the acoustic oscillation standard ruler across cosmic time.
- Higher harmonics are at $k \sim 0.2h$ Mpc^{-1} (λ=30 Mpc)
- Measuring 1% bandpowers in the peaks and troughs requires about 1 Gpc^3 of survey volume with number density $\sim 10^{-3}$ comoving h^3 Mpc^{-3} = ~1 million galaxies!
- We have considered surveys at z=1 and z=3.
  - Hee-Jong Seo & DJE (2003, ApJ, 598, 720)
  - Also: Blake & Glazebrook (2003), Linder (2003), Hu & Haiman (2003).

A Baseline Survey at $z = 3$

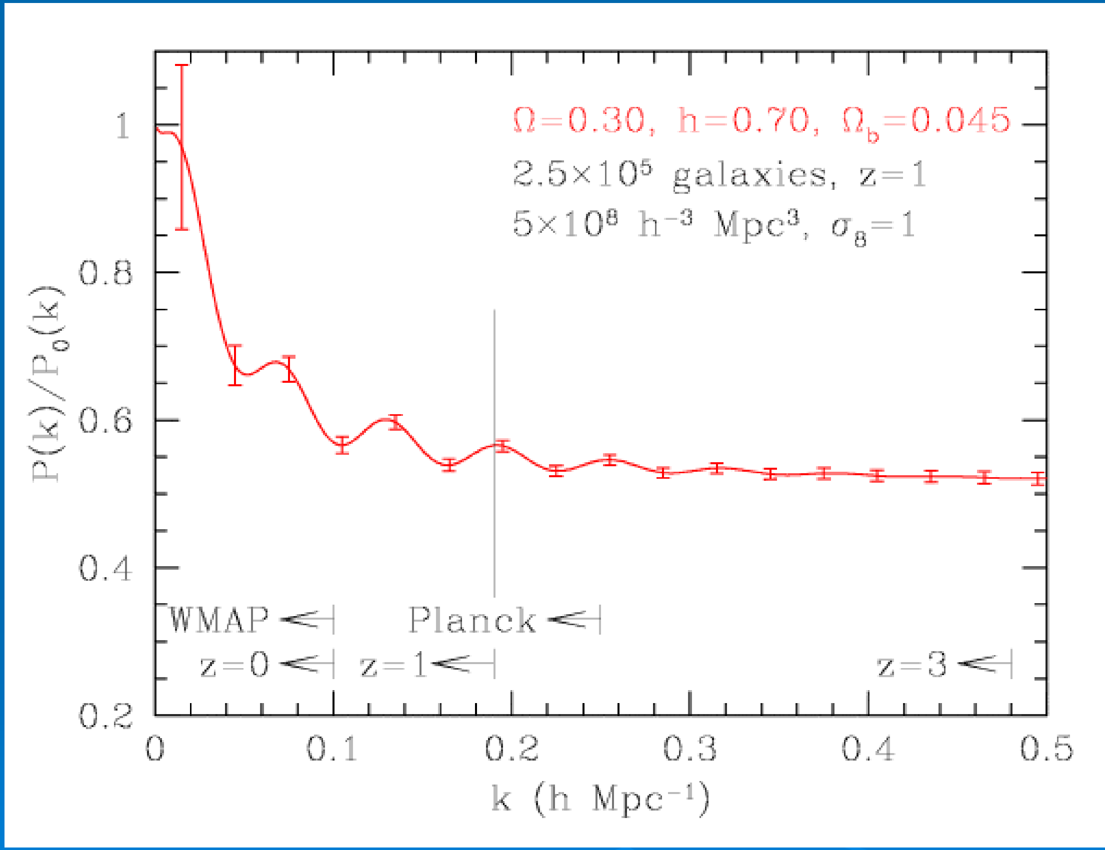


Statistical Errors from the z=3 Survey

- 600,000 gal.
- ~300 sq. deg.
- 10^9 Mpc^3
- 0.6/sq. arcmin

- Linear regime k<0.3h Mpc^{-1}
- 4 oscillations

A Baseline Survey at $z = 1$



Statistical Errors from the z=1 Survey

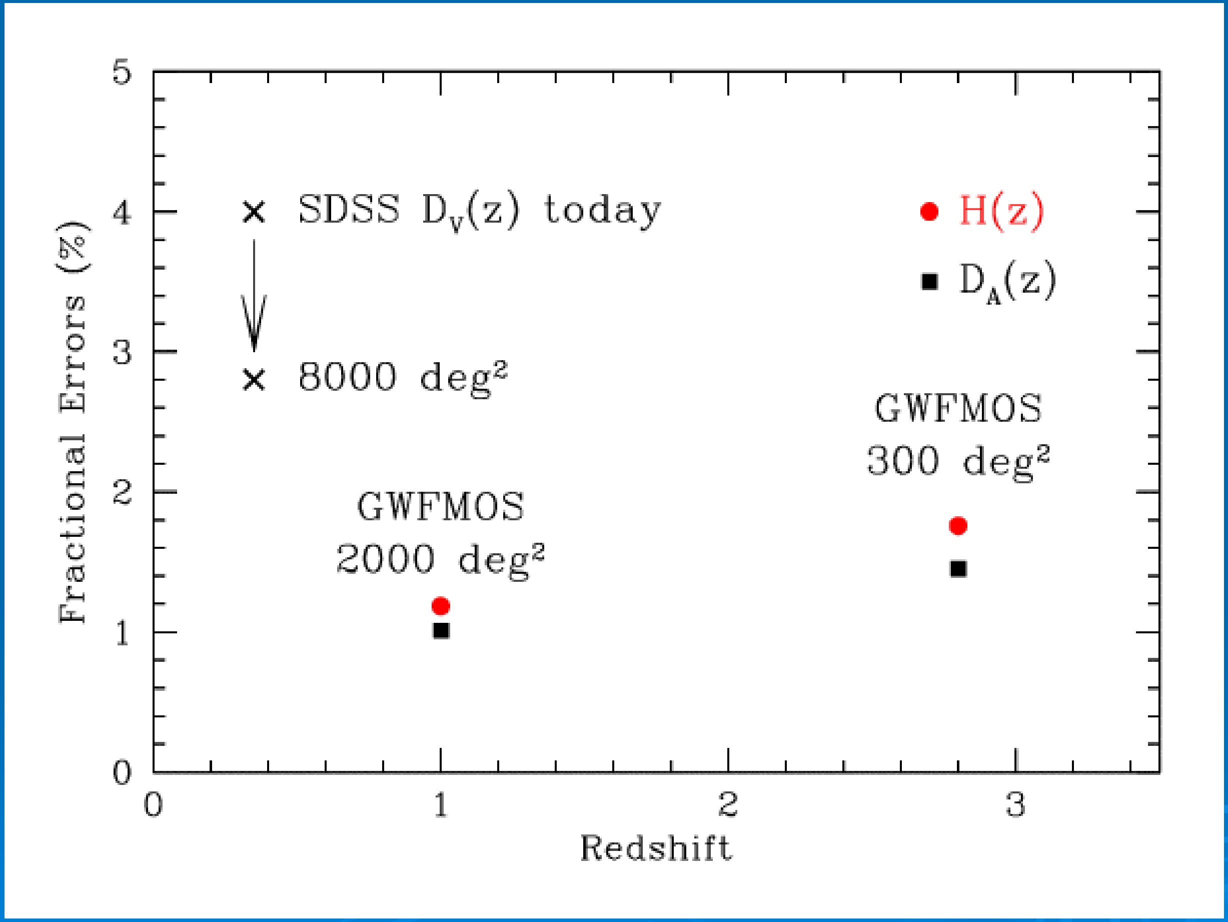
- 2,000,000 gal., z = 0.5 to 1.3
- 2000 sq. deg.
- 4x10^9 Mpc^3
- 0.3/sq. arcmin
- Linear regime k<0.2h Mpc^{-1}
- 2-3 oscillations

Methodology

Hee-Jong Seo & DJE (2003)

- Fisher matrix treatment of statistical errors.
  - Full three-dimensional modes including redshift and cosmological distortions.
  - Flat-sky and Tegmark (1997) approximations.
  - Large CDM parameter space: $\Omega_m h^2$, $\Omega_b h^2$, n, T/S, Ω_m, plus separate distances, growth functions, β, and anomalous shot noises for all redshift slices.
- Planck-level CMB data
- Combine data to predict statistical errors on $w(z) = w_0 + w_1 z$.

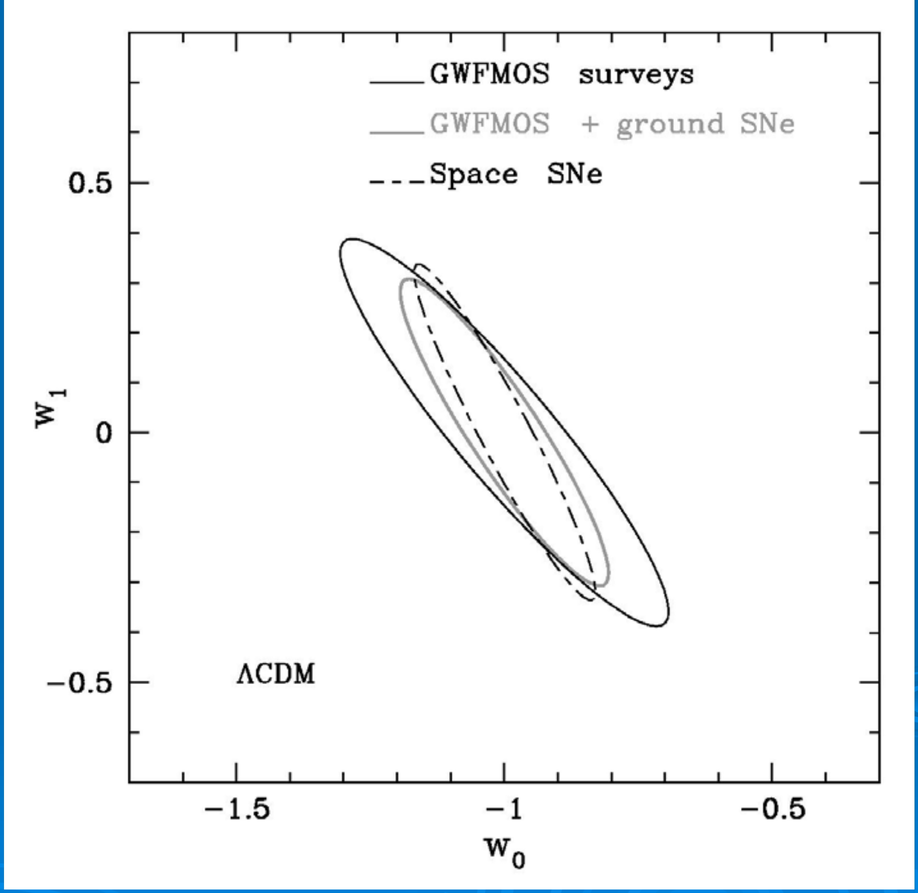
Baseline Performance



Distance Errors versus Redshift

Results for ΛCDM

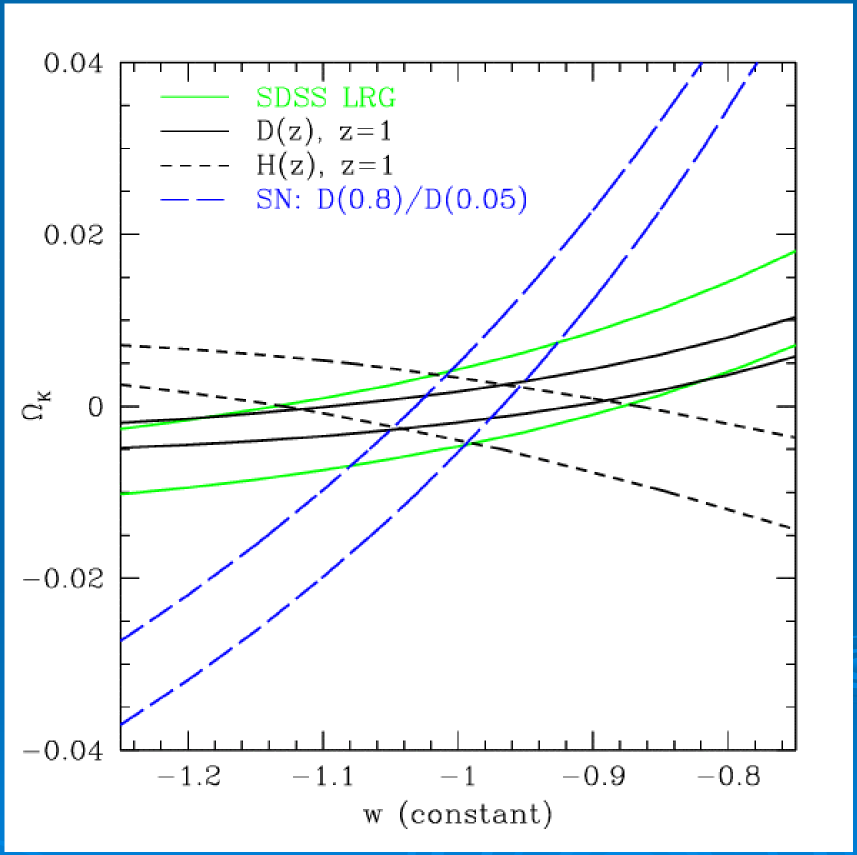
- Data sets:
  - CMB (*Planck*)
  - SDSS LRG (z=0.35)
  - Baseline *z*=1
  - Baseline *z*=3
  - SNe (1% in Δ*z*=0.1 bins to *z*=1 for ground, 1.7 for space)
- $\sigma(\Omega_m) = 0.027$
  $\sigma(w) = 0.08$ at $z=0.7$
  $\sigma(dw/dz) = 0.26$
- $\sigma(w) = 0.05$ with ground SNe



Dark Energy Constraints in ΛCDM

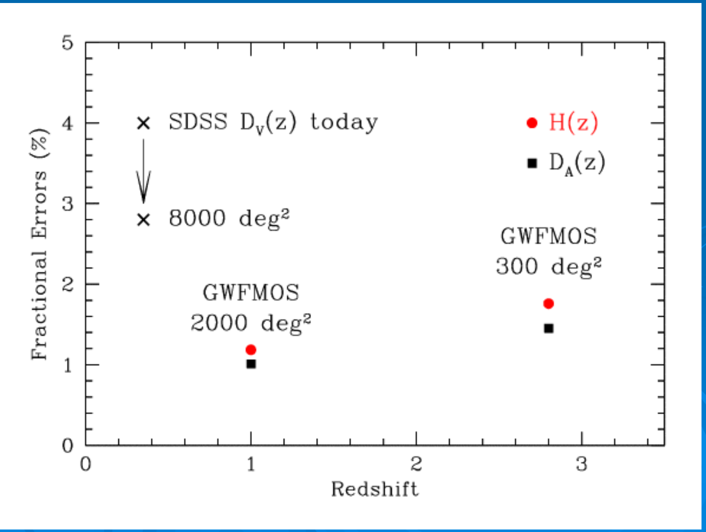
Breaking the *w*-Curvature Degeneracy

- To prove $w \neq -1$, we should exclude the possibility of a small spatial curvature.
- SNe alone, even with space, do not do this well.
- SNe plus acoustic oscillations do very well, because the acoustic oscillations connect the distance scale to z=1000.



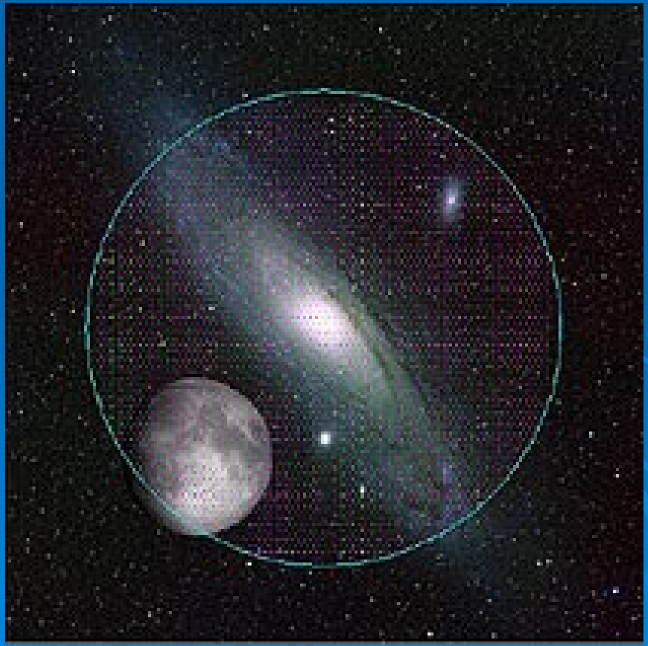
Opening Discovery Spaces

- With 3 redshift surveys, we actually measure dark energy in 4 redshift ranges: $0<z<0.35$, $0.35<z<1$, $1<z<3$, and $3<z<1000$.
- SNe should do better at pinning down $D(z)$ at $z<1$. But acoustic method opens up $z>1$ and H(z) to find the unexpected.
- Weak lensing, clusters also focus on $z<1$. These depend on growth of structure. We would like both a growth and a kinematic probe to look for changes in gravity.



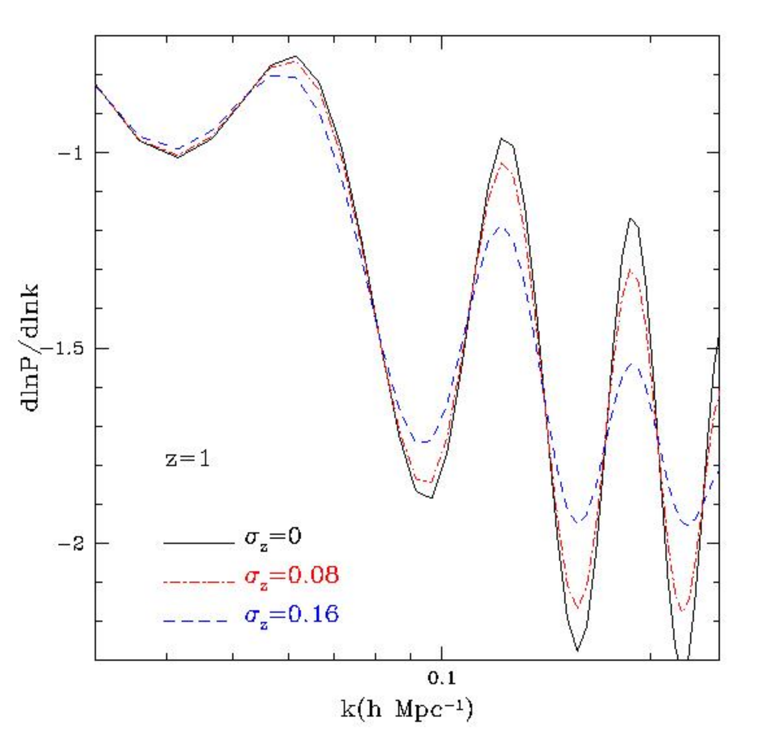
A Better Mousetrap

- How to survey a million galaxies at $z = 1$ over 1000 sq. deg? Or half a million at $z = 3$ over 300 sq. deg?
- This is a large step over on-going surveys, but it is a reasonable goal for the coming decade.
- KAOS spectrograph concept for Gemini (GWFMOS) could do these surveys in a year.
  - 4000-5000 fibers, using Echidna technology, feeding multiple bench spectrographs.
  - 1.5 degree diameter FOV
  - http://www.noao.edu/kaos
  - Well ranked in Aspen process.
  - Also high-res for Galactic studies.
  - Currently finishing feasibility study.



Photometric Redshifts?

- Can we do this without spectroscopy?
- Measuring H(z) requires detection of acoustic oscillation scale along the line of sight.
  - Need ~10 Mpc accuracy. σ_z~0.003(1+z).
- But measuring $D_A(z)$ from transverse clustering requires only 4% in 1+z.
- Need ~half-sky survey to match 1000 sq. deg. of spectra.
- Less robust, but likely feasible.



4% photo-z's don't smear the acoustic oscillations.

What about H_0?

- Does the CMB+LSS+SNe really measure the Hubble constant? What sets the scale in the model?
  - The energy density of the CMB photons plus the assumed a neutrino background gives the radiation density.
  - The redshift of matter-radiation equality then sets the matter density ($\Omega_m h^2$).
  - Measurements of Ω_m (e.g., from distance ratios) then imply H_0.
- Is this good enough?

What about H_0?

- What if the radiation density were different, (more/fewer neutrinos or something new)?
  - Sound horizon would be shifted in scale. LSS inferences of Ω_m, Ω_k, $w(z)$, etc, would be correct, but $\Omega_m h^2$ and H_0 would be shifted.
  - Baryon fraction would be changed ($\Omega_b h^2$ is fixed).
  - Anisotropic stress effects in the CMB would be different. This is detectable with Planck.
- So H_0 is either a probe of "dark radiation" or dark energy (assuming radiation sector is simple).
  - 1 neutrino species is roughly 5% in H_0.
  - We could get to ~1%.

DJE & White (2004)

Pros and Cons
of the Acoustic Peak Method

Advantages:

- Geometric measure of distance.
- Robust to systematics.
- Individual measurements are not hard (but you need a lot of them!).
- Can probe $z>2$.
- Can measure $H(z)$ directly (with spectra).

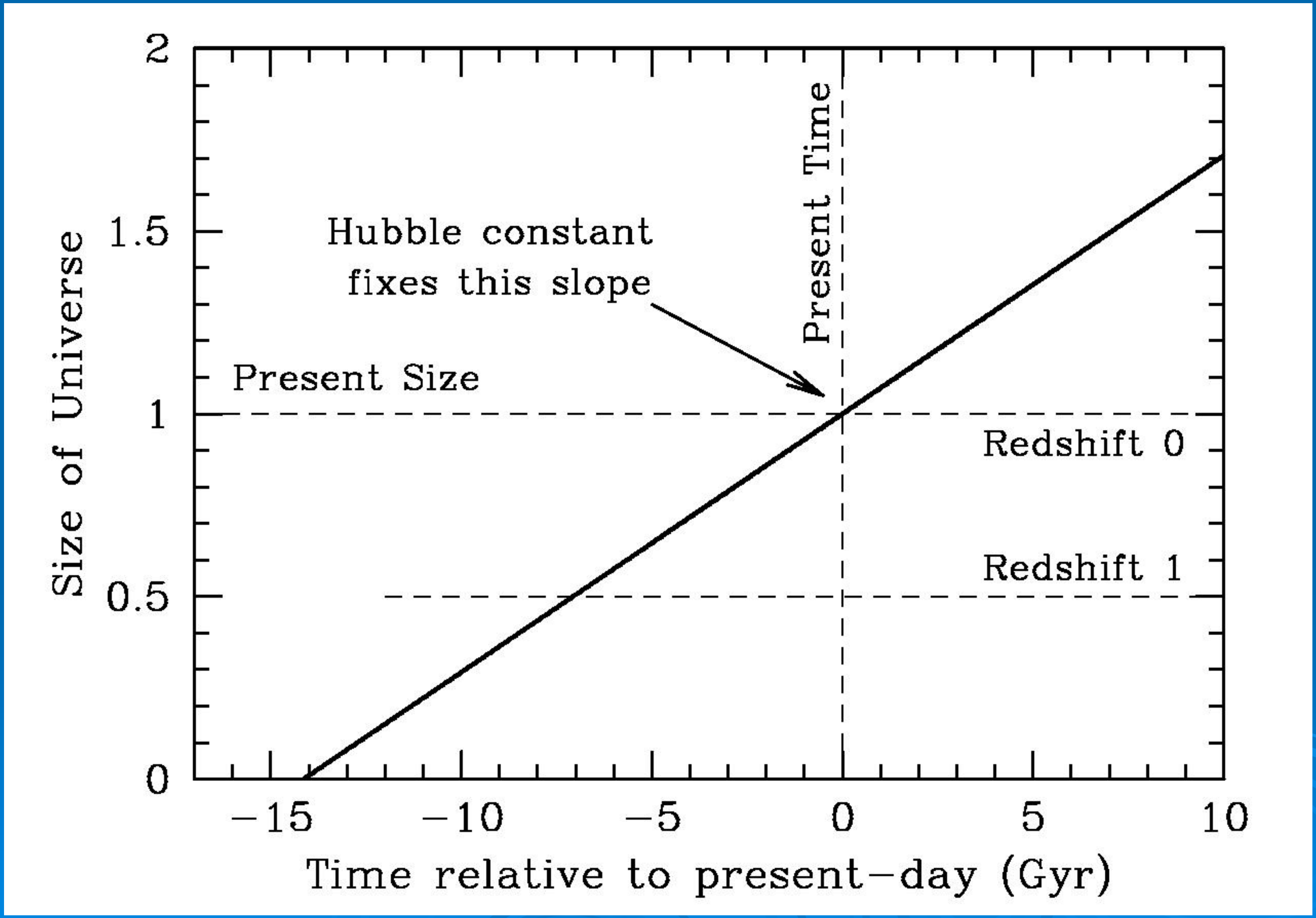
Disadvantages:

- Raw statistical precision at $z<1$ lags SNe and lensing/clusters.
  - Full sky would help.
- If dark energy is close to Λ, then $z<1$ is more interesting.
- Some model dependence as regards inferences from CMB.

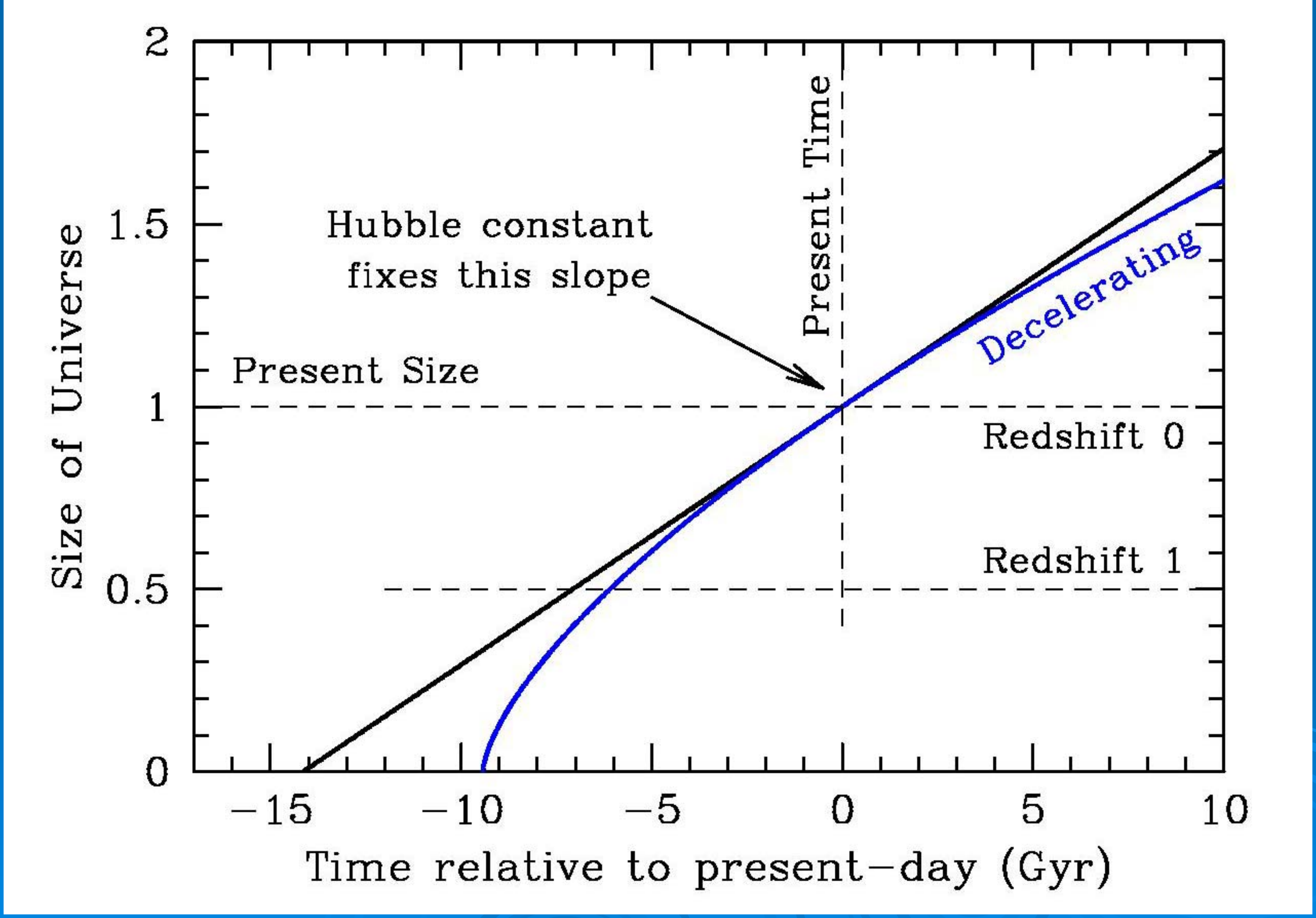
Conclusions

- Acoustic oscillations provide a robust way to measure H(z) and $D_A(z)$.
  - Clean signature in the galaxy power spectrum.
  - Can probe high redshift.
  - Can probe H(z) directly.
  - Independent method with similar precision to SNe.
- SDSS LRG sample uses the acoustic signature to measure $D_A(z=0.35)/D_A(z=1000)$ to 4%.
- Large high-*z* galaxy surveys are feasible in the coming decade.
- Order from KAOS! http://www.noao.edu/kaos

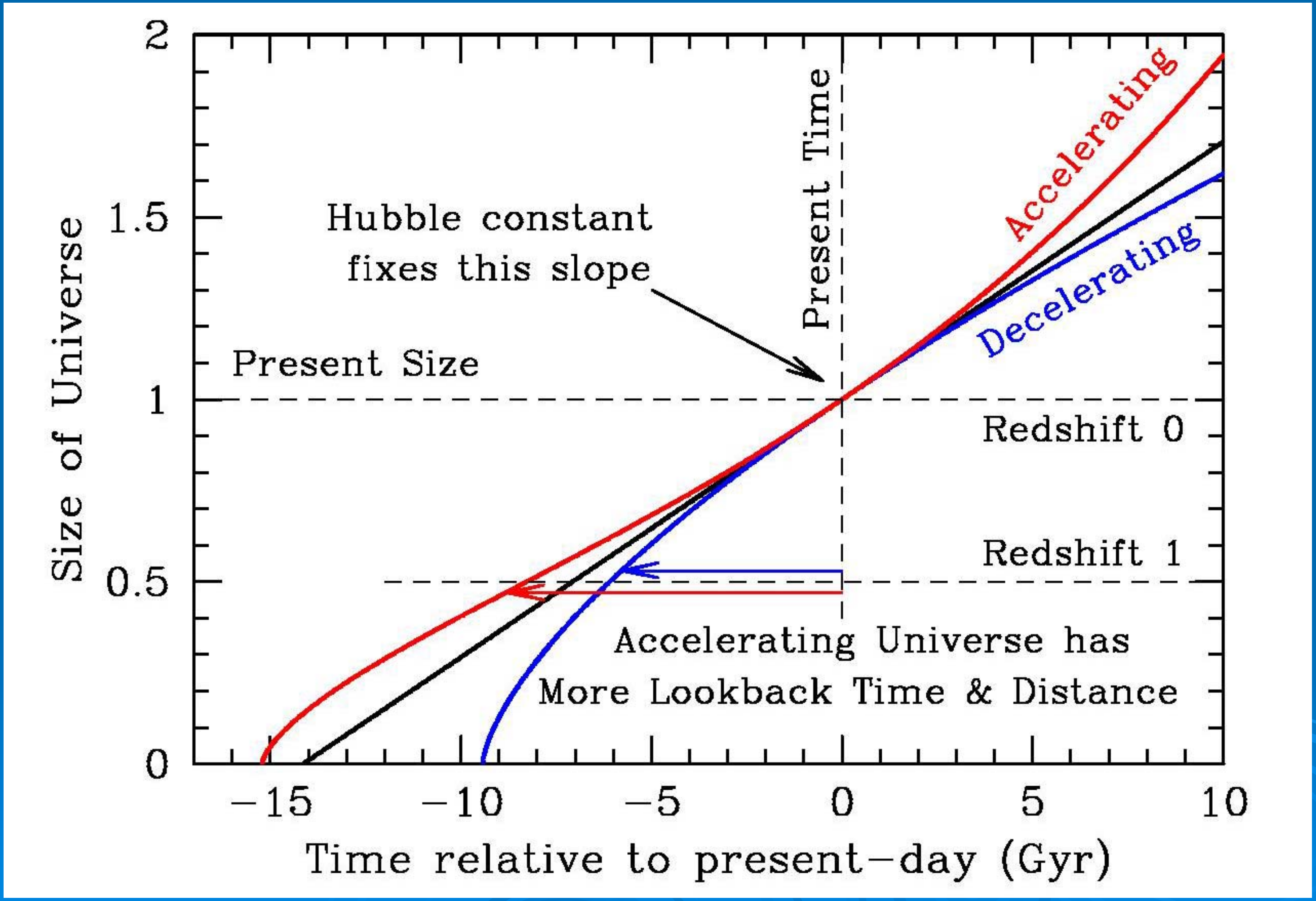
Distances to Acceleration



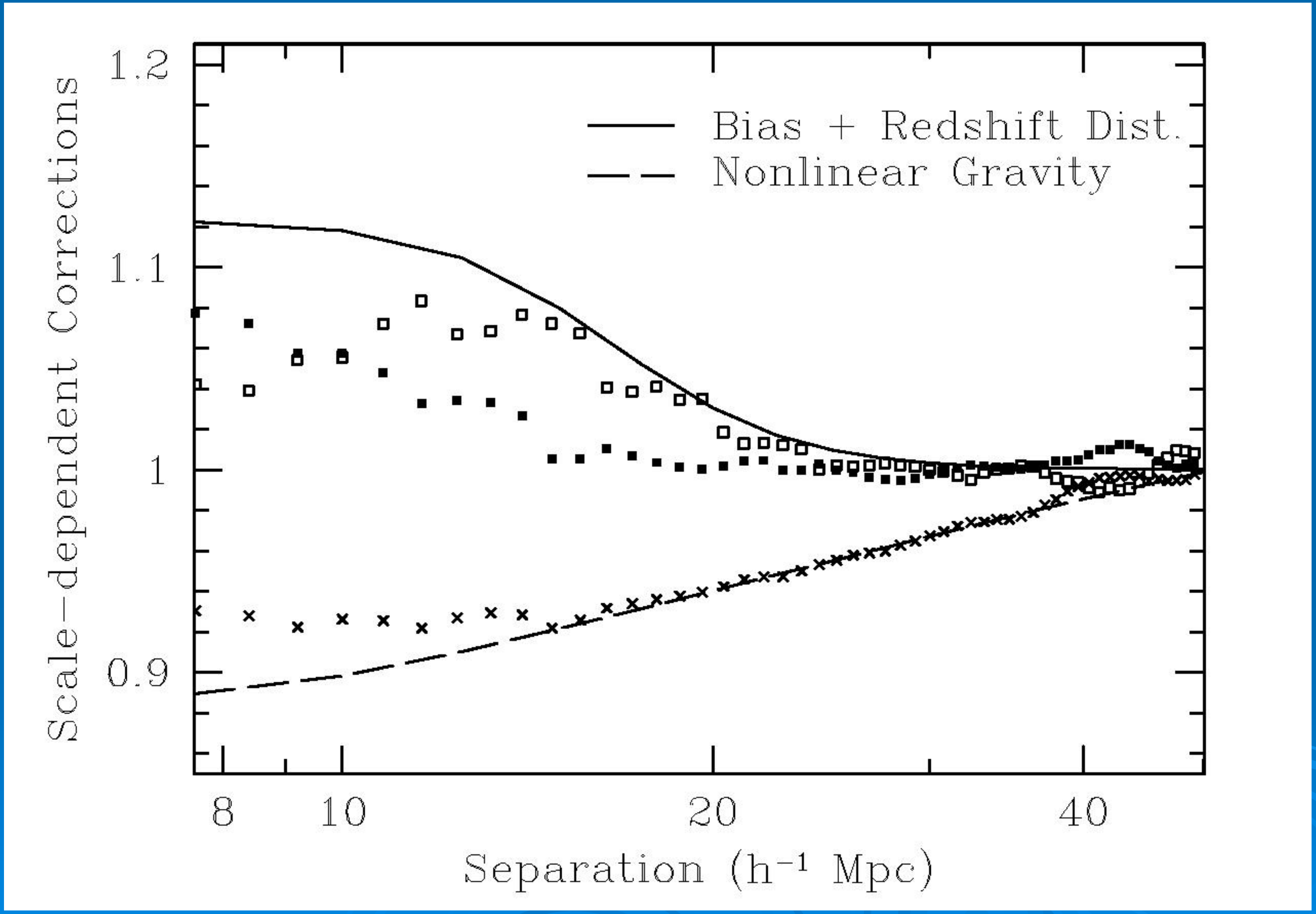
Distances to Acceleration



Distances to Acceleration



Nonlinear Corrections

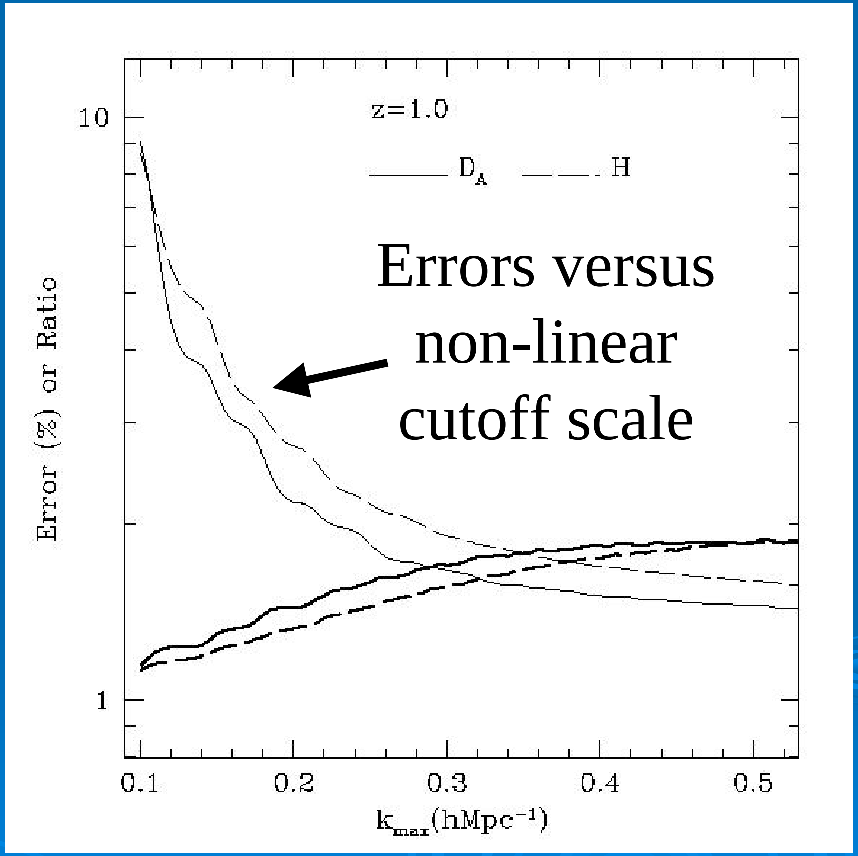


An Optimal Number Density

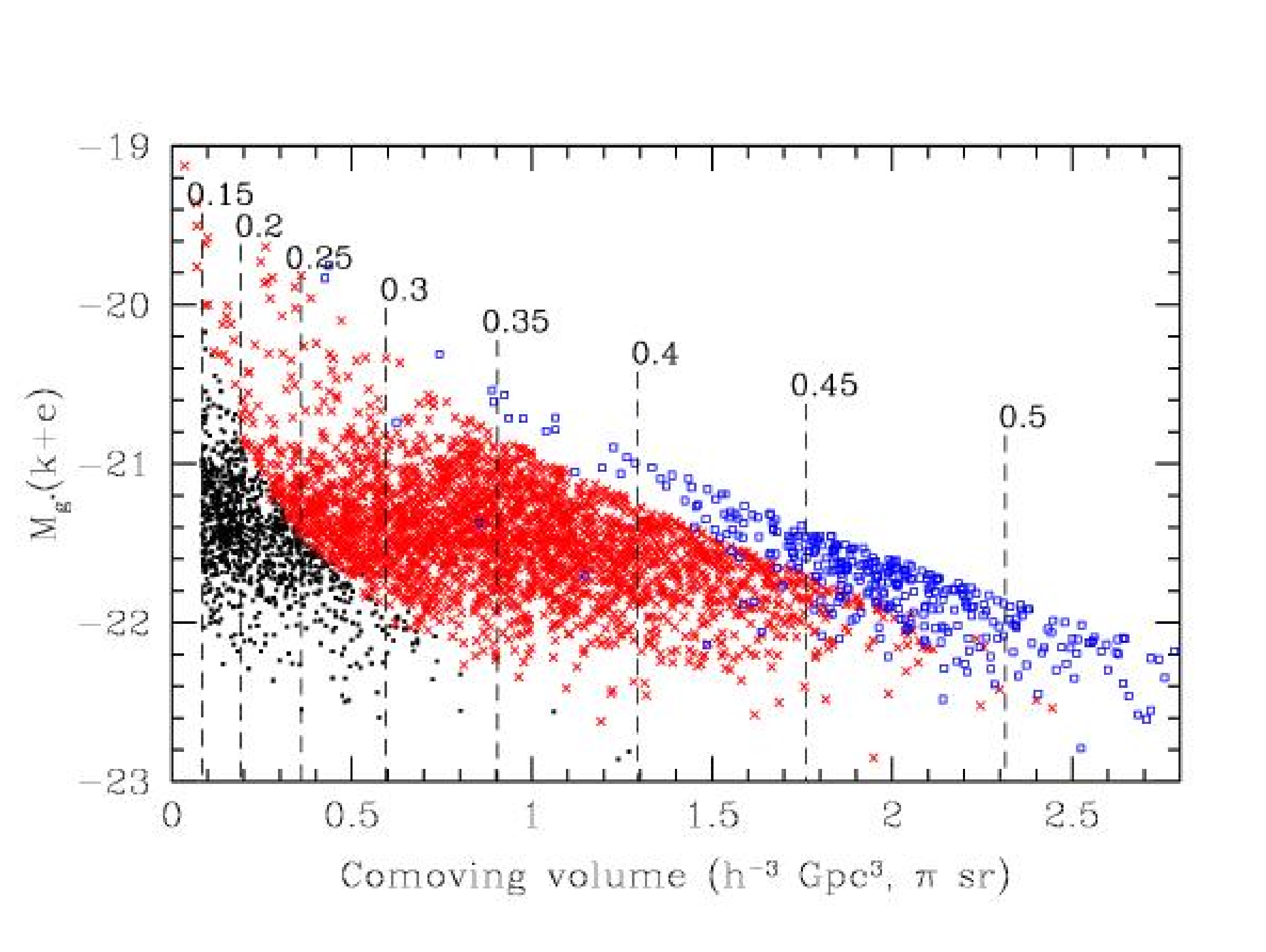
- Since survey size is at a premium, one wants to design for maximum performance.
- Statistical errors on large-scale correlations are a competition between sample variance and Poisson noise.
  - Sample variance: How many independent samples of a given scale one has.
  - Poisson noise: How many objects per sample one has.
- Given a fixed number of objects, the optimal choice for measuring the power spectrum is an intermediate density.
  - Number density roughly the inverse of the power spectrum.
    - $10^{-4}\ h^3\ \mathrm{Mpc}^{-3}$ at low redshift; a little higher at high redshift.
  - Most flux-limited surveys do not and are therefore inefficient for this task.

Higher Redshifts Perform Better

- Nonlinear gravitational clustering erases the acoustic oscillations.
- This is less advanced at higher redshifts.
- Recovering higher harmonics improves the precision on distances.
- Leverage improves from *z*=0 to *z*=1.5, then saturates.

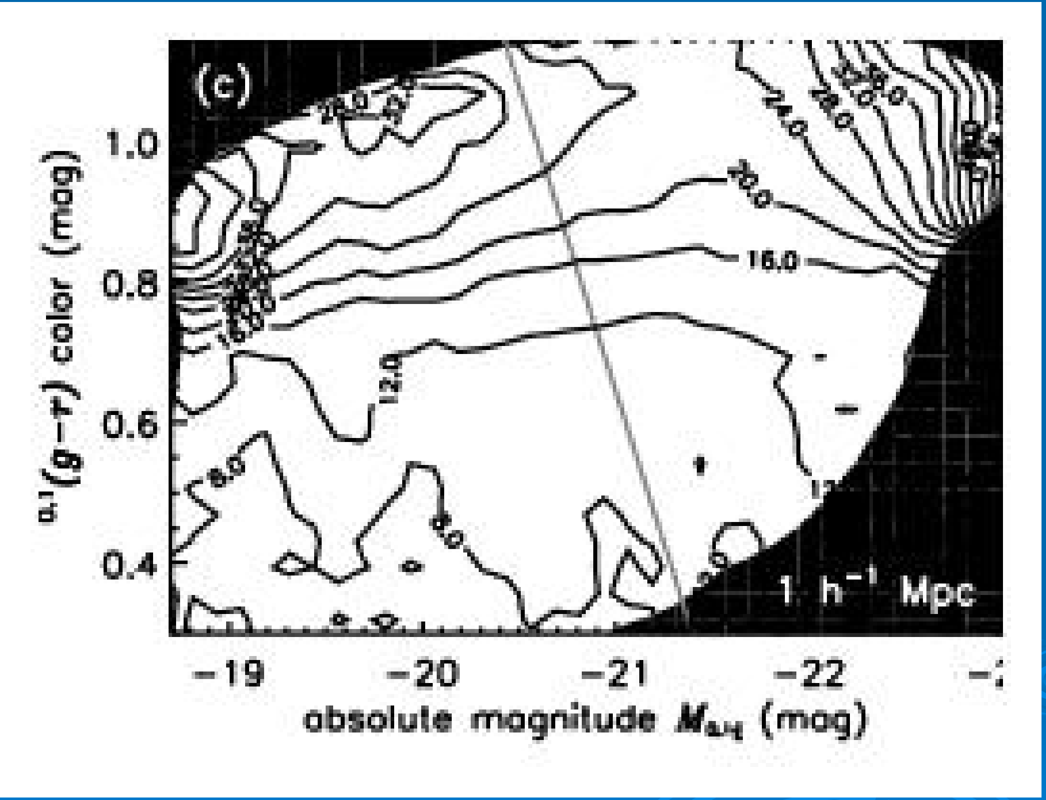


A Volume-Limited Sample



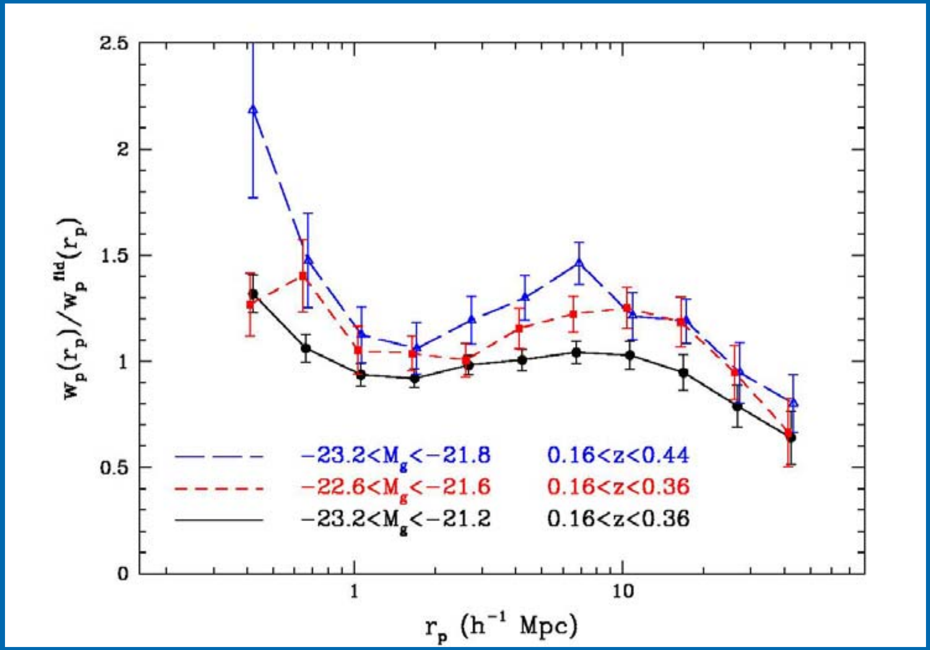
Luminosity-dependent Bias

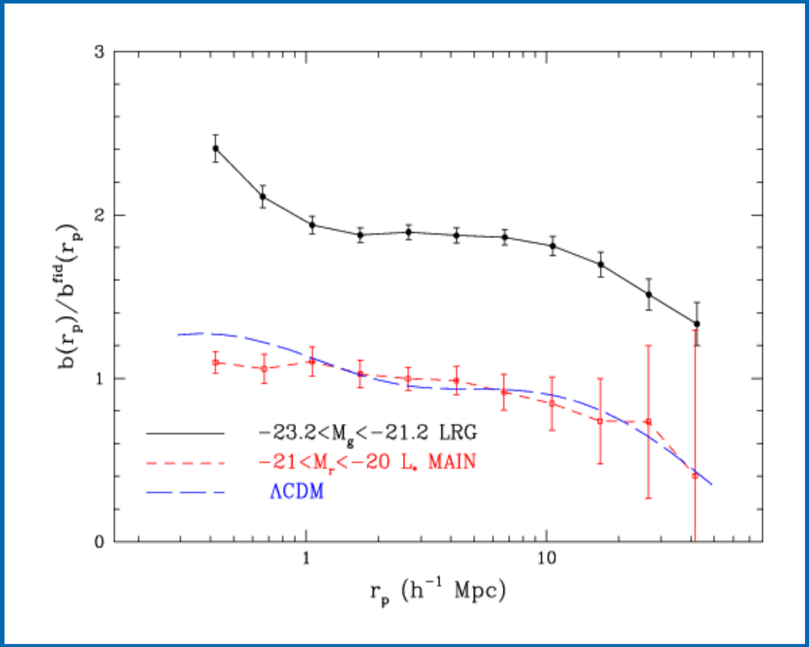
- Bias appears to change noticeably (40%?) at the luminous end, even within the narrow LRG range.
- We will need to be careful when combining $z>0.4$ and $z<0.4$.



Hogg et al. (2002)

Real-space Correlations



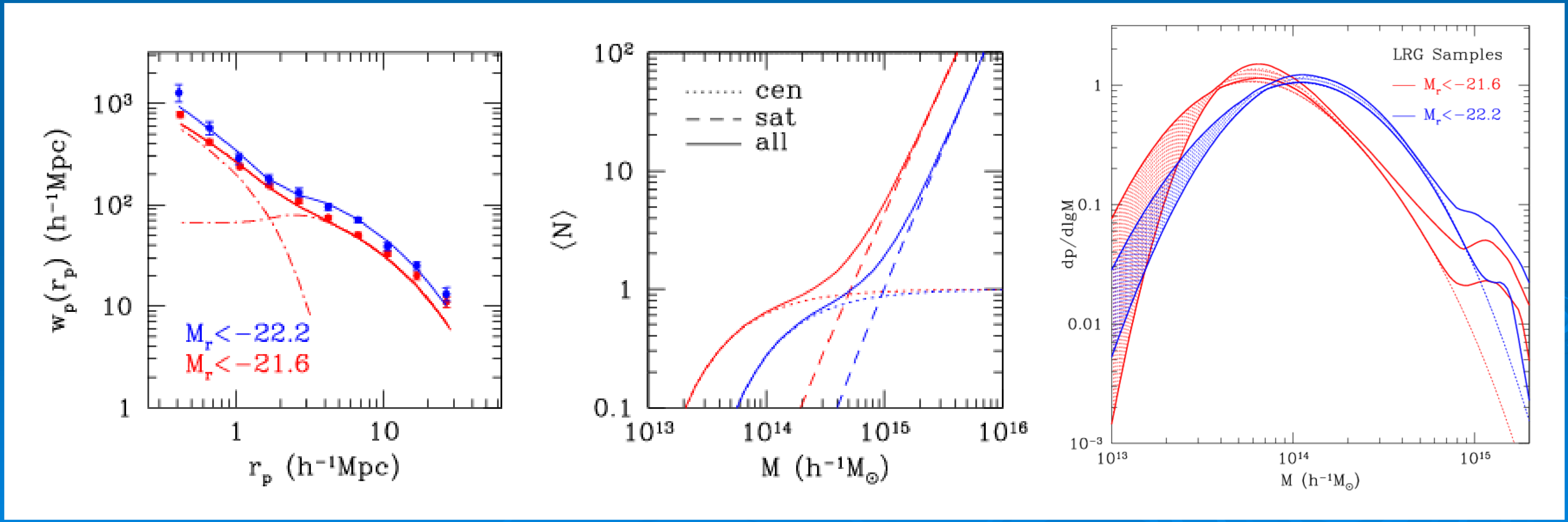


Zehavi et al. (2004)

- Obvious deviations from power laws!
- σ_8 = 1.80±0.03 up to 2.06±0.06 across samples
- r_0 = 9.8h^{-1} up to 11.2h^{-1} Mpc

Halo Occupation Modeling

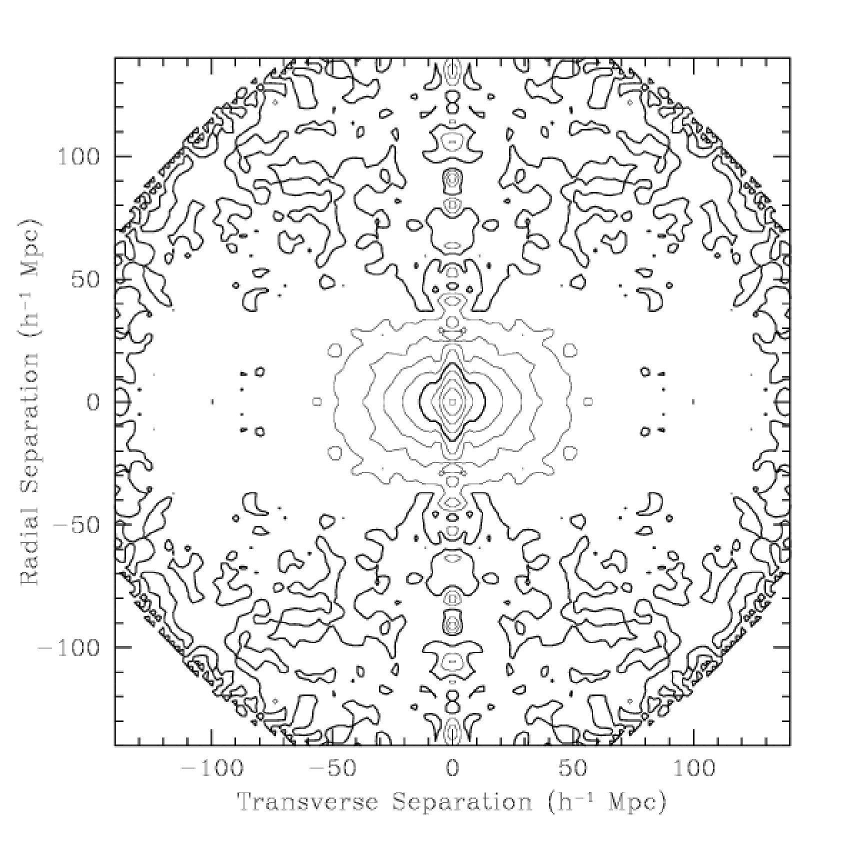
- The distribution of dark matter halo masses for the galaxies determines their clustering.
- Generically predict an inflection in $\xi(r)$.



From Zheng Zheng; similar to Zehavi et al. (2004)

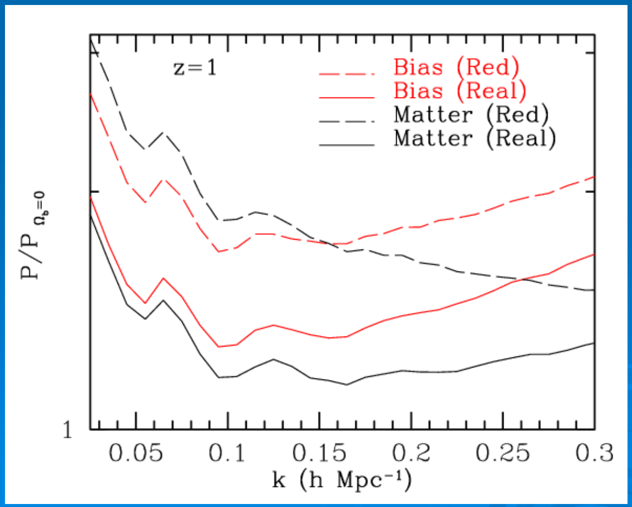
Redshift Distortions

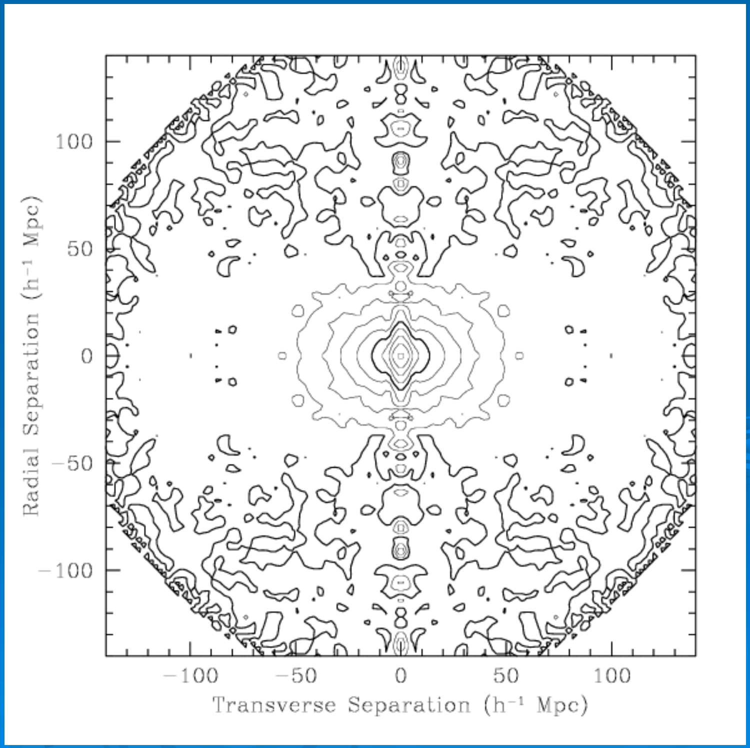
- Redshift distortions will be interesting for the study of the host halos of LRGs, but are a nuisance for the extraction of Alcock-Paczynski distortions of the isotropic power.



Redshift Distortions

- Redshift surveys are sensitive to peculiar velocities.
- Since velocity and density are correlated, there is a distortion even on large scales.
- Correlations are squashed along the line of sight (opposite of finger of god effect).





Measuring a Known Scale

- For a given $\Omega_m h^2$, the acoustic scale is known.
- We measure it in the CMB at z=1000 to 1% and in SDSS at z=0.35 to 4%.
- This constrains Ω_m, Ω_K, and dark energy in two separate redshift ranges: $0<z<0.35$ and $0.35<z<1000$.

Constant *w* Models

- As before, but now overlaid with grid of H_0 and *w*.