Dark Energy and Cosmic Sound

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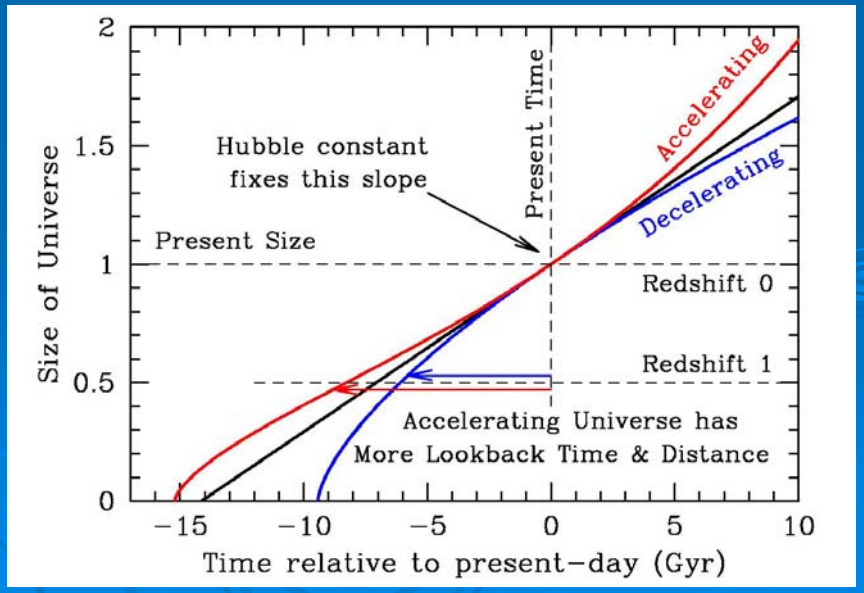
Michael Blanton, David Hogg, Bob Nichol, Roman Scoccimarro, Ryan Scranton, Hee-Jong Seo, Ed Sirko, David Spergel, Max Tegmark, Martin White, Idit Zehavi, Zheng Zheng, and the SDSS.

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.

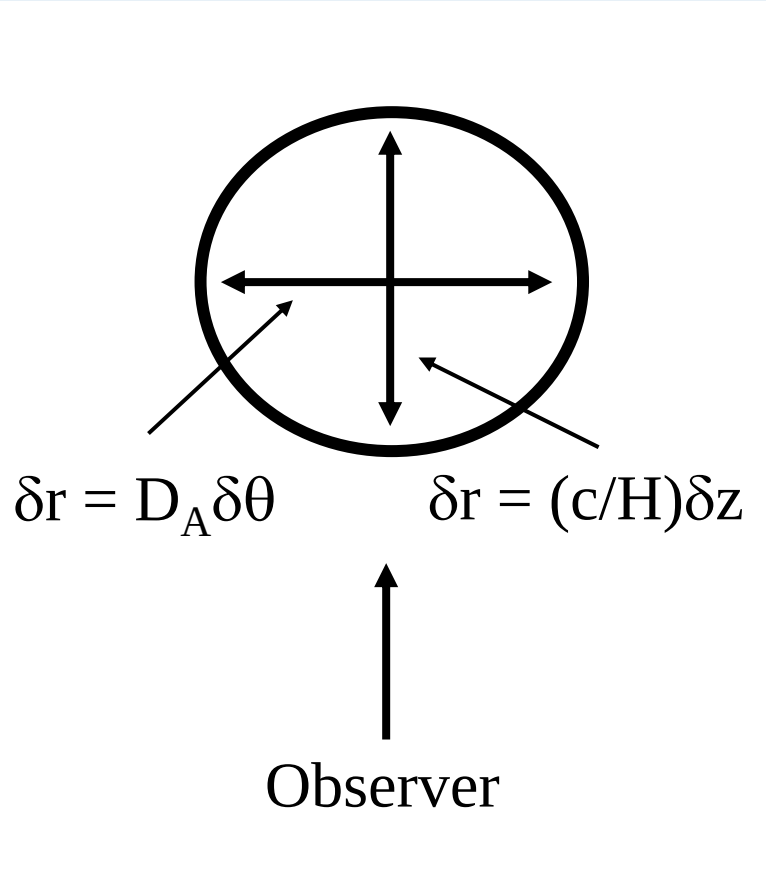


A Quick Distance Primer

- 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

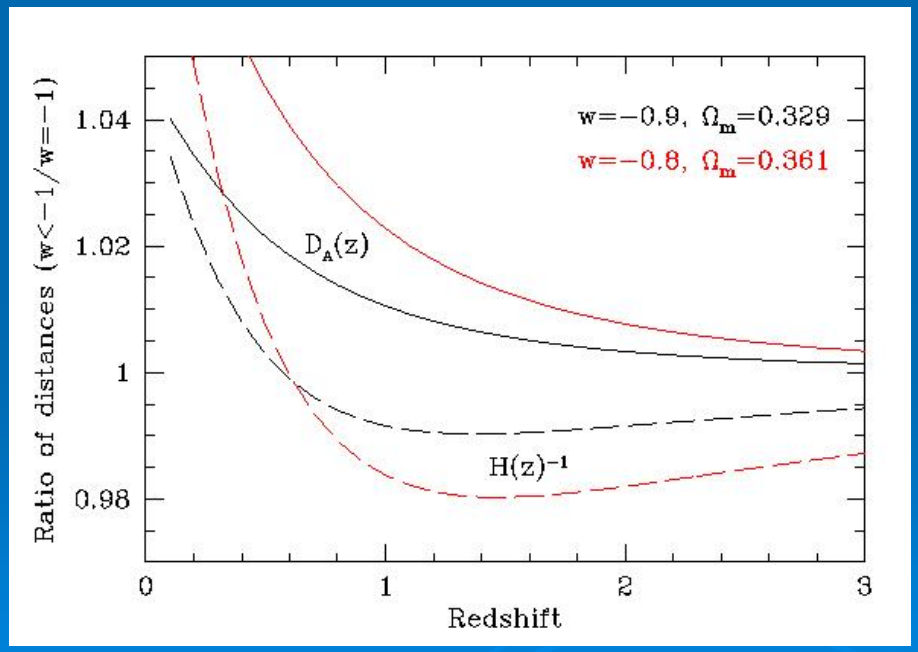
$$D = \int_0^z \frac{c\,dz}{H(z)} \quad \text{(flat)}$$

- $H(z)$ 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.



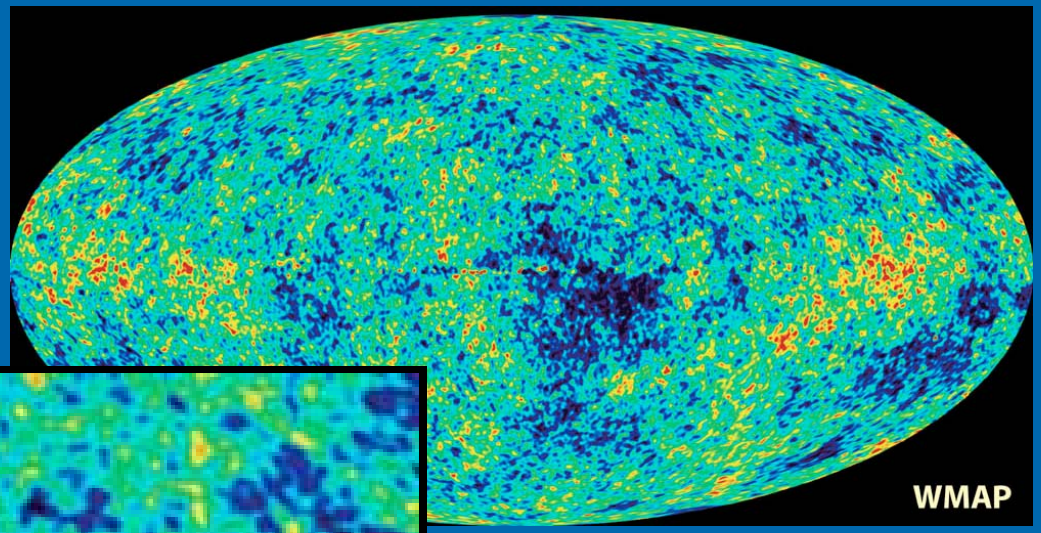
Comparing Cosmologies

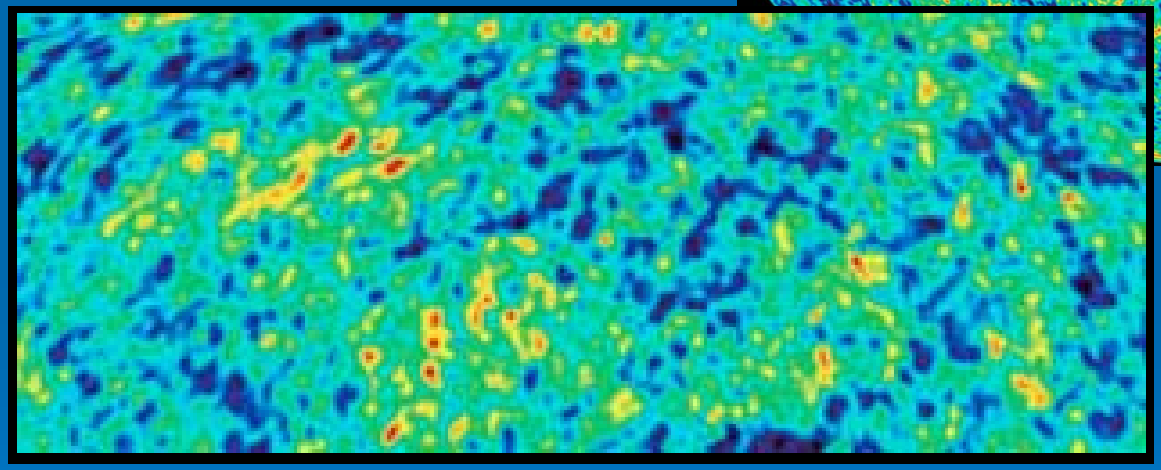
- Varying w assuming perfect CMB:
  - Fixed $\Omega_m h^2$
  - $D_A(z=1000)$
- dw/dz is even harder.
- Need precise, redundant observational probes!

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.

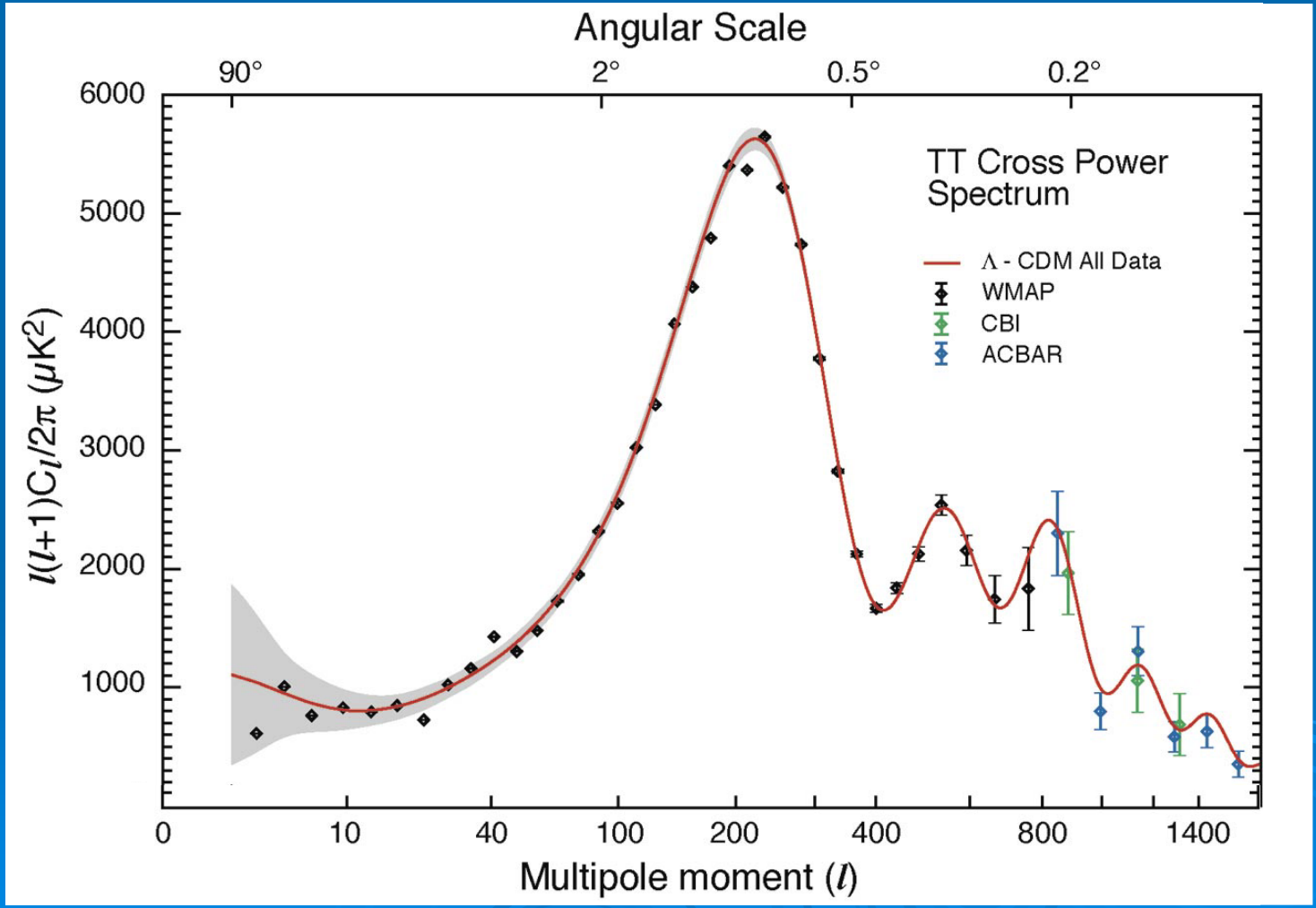
Acoustic Oscillations in the CMB





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

Acoustic Oscillations in the CMB



WMAP team (Bennett et al. 2003)

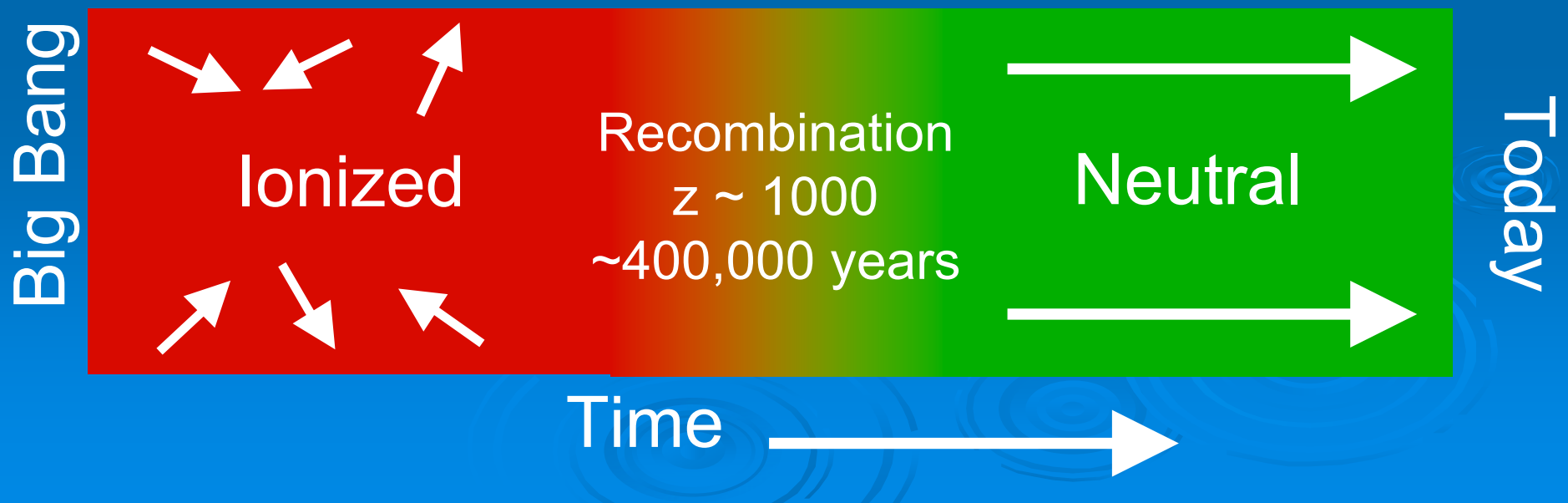
Sound Waves in the Early Universe

Before recombination:

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

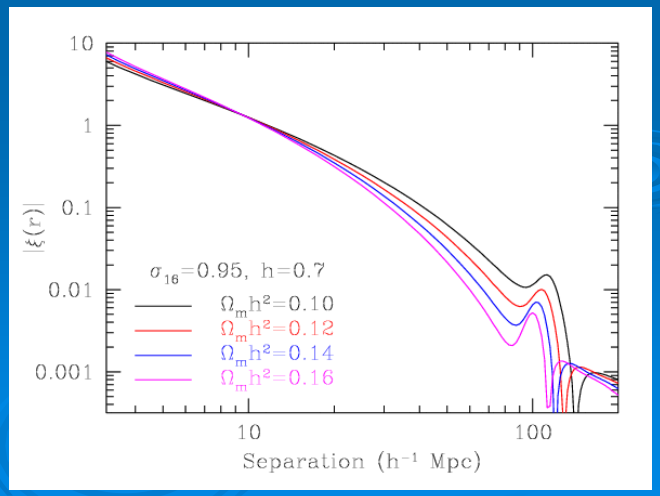
After recombination:

- 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.



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.

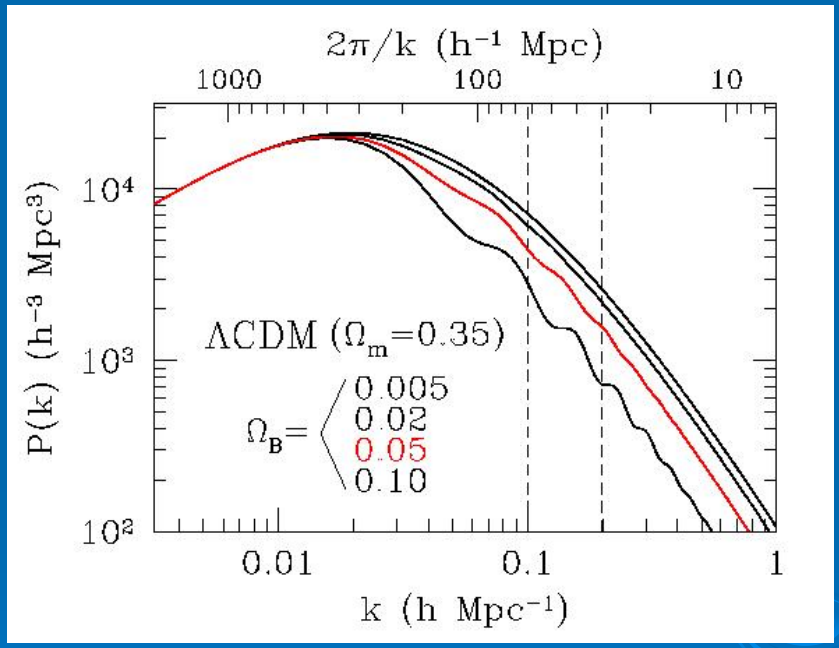
Response of a point perturbation

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

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

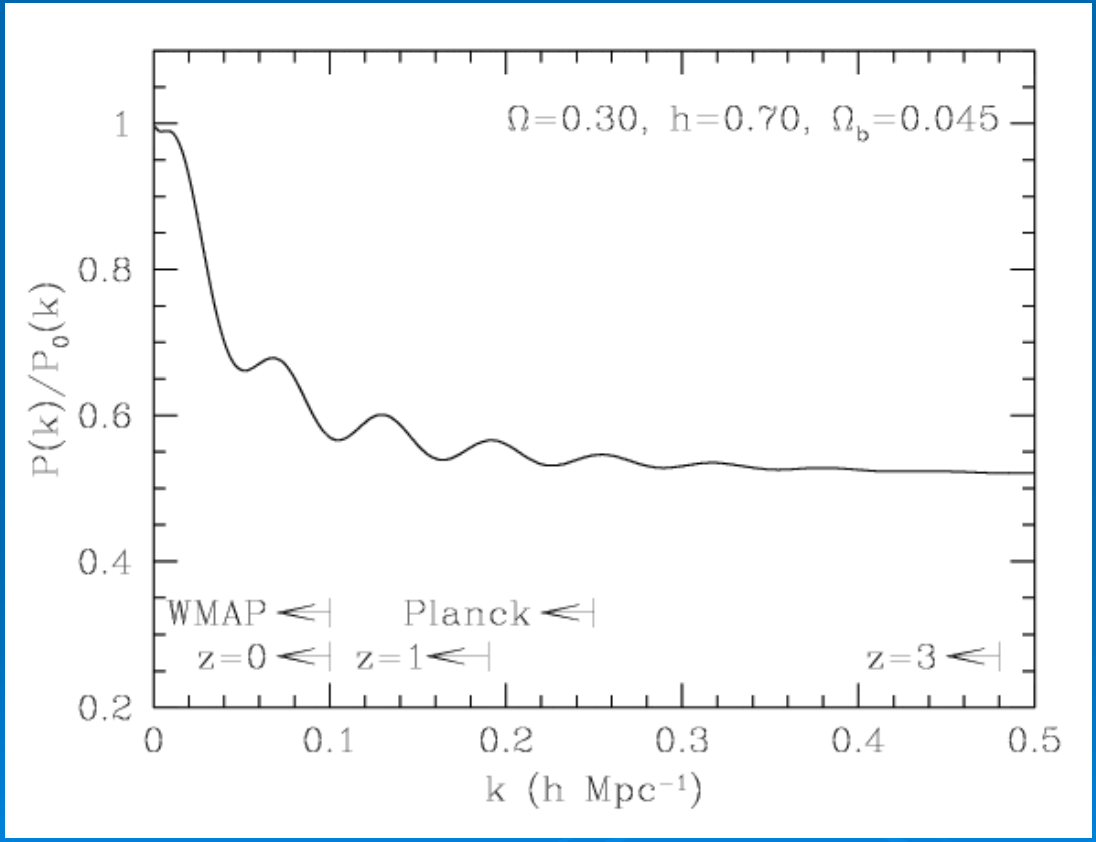
Acoustic Oscillations in Fourier Space

- 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

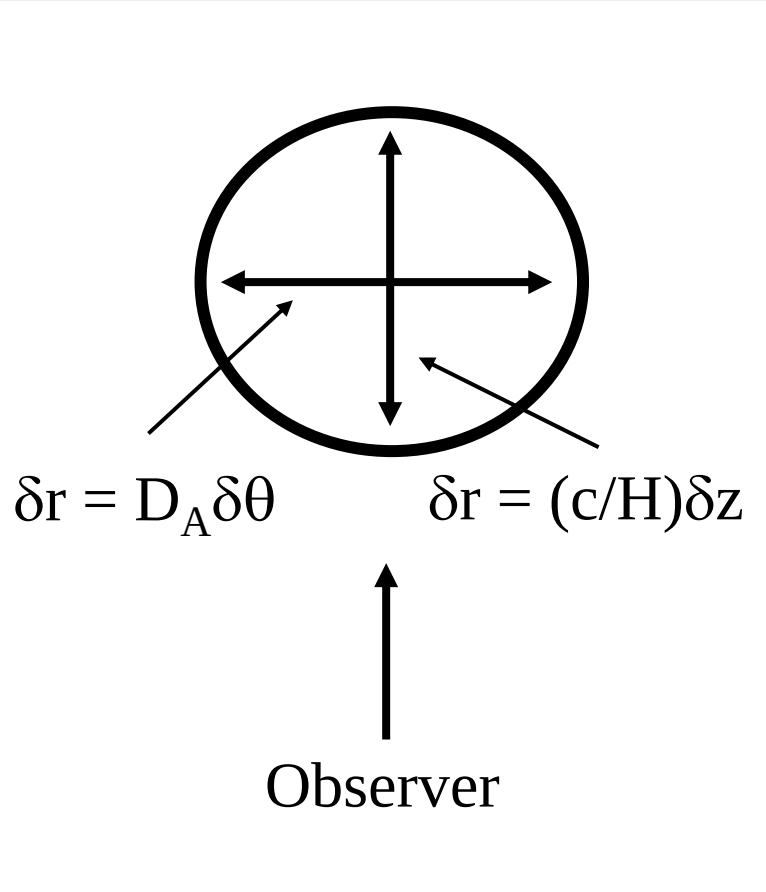


- Divide by zero-baryon reference model.
- Acoustic peaks are 10% modulations.
- Requires large surveys to detect!

Linear regime matter power spectrum

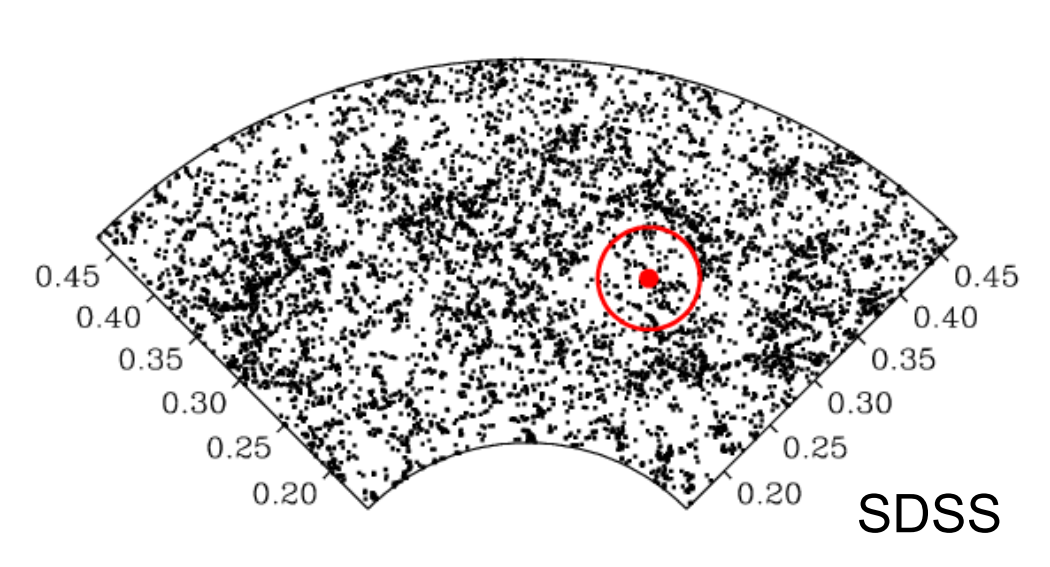
A Standard Ruler

- 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 $D_A(z)$!



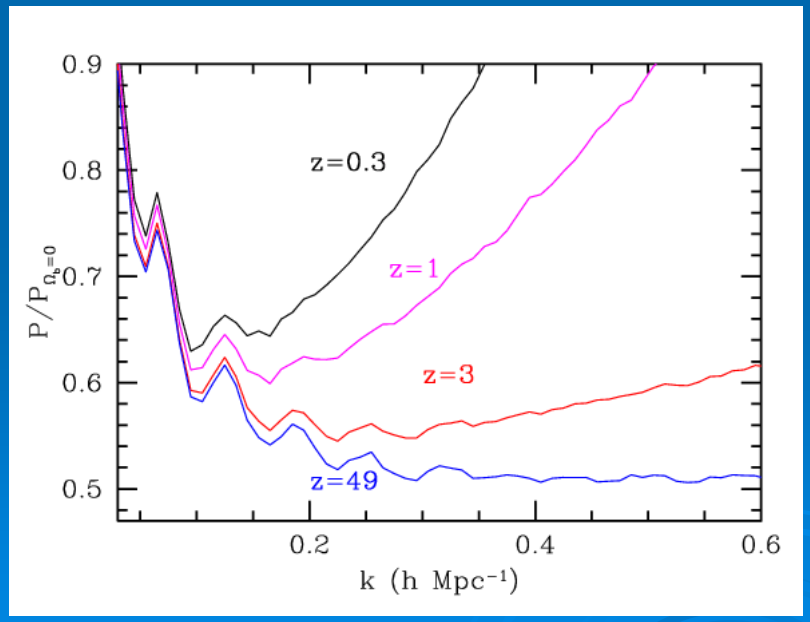
Galaxy Redshift Surveys

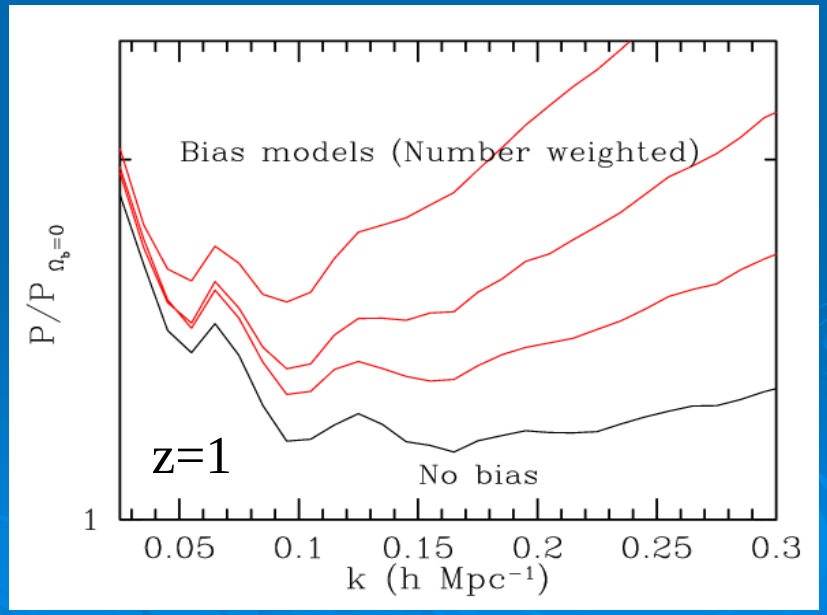
- Redshift surveys are a popular way to measure the 3-dimensional clustering of matter.
- But there are complications from:
  - Non-linear structure formation
  - Bias (light ≠ mass)
  - Redshift distortions
- Do these affect the acoustic signatures?



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.





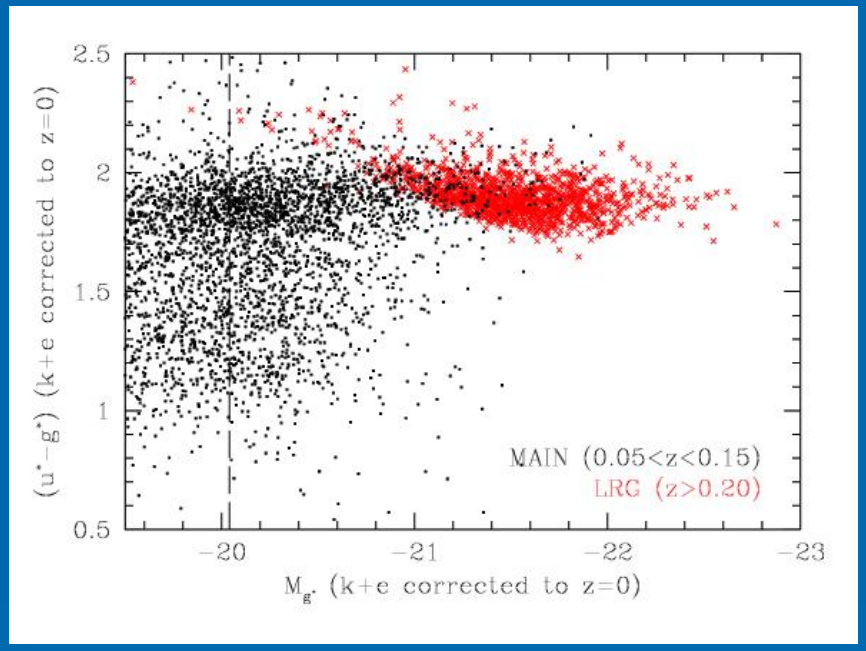
Meiksen & White (1997), Seo & DJE (2005)

Virtues of the Acoustic Peaks

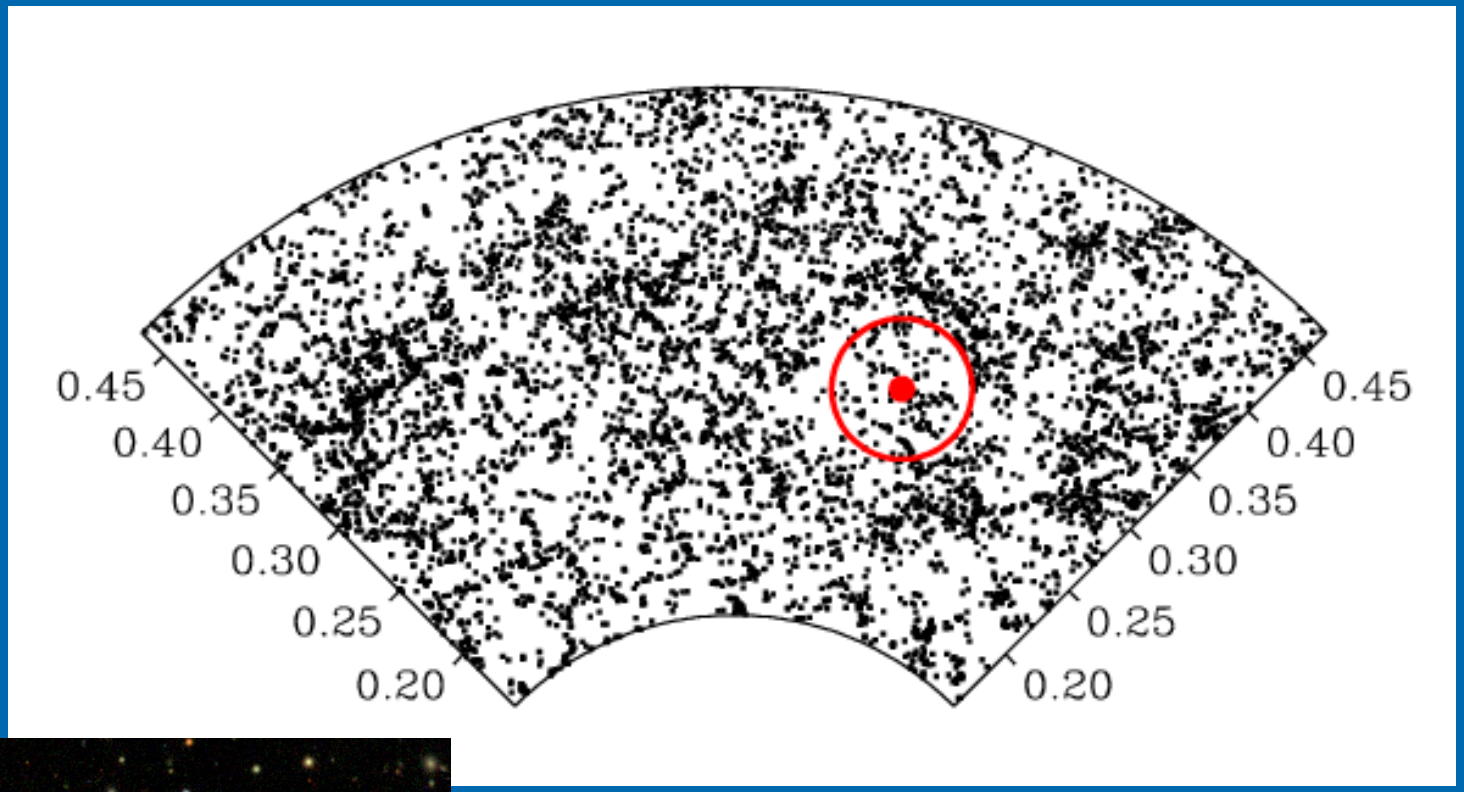
- Measuring the acoustic peaks across redshift gives a purely geometrical measurement of cosmological distance.
- The acoustic peaks are a manifestation of a preferred scale.
  - Non-linearity, bias, redshift distortions shouldn't produce such preferred scales, certainly not at 100 Mpc.
  - Method should be robust, but in any case the systematic errors will be very different from other schemes.
- 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


0.45
0.40
0.35
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0.25
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0.45
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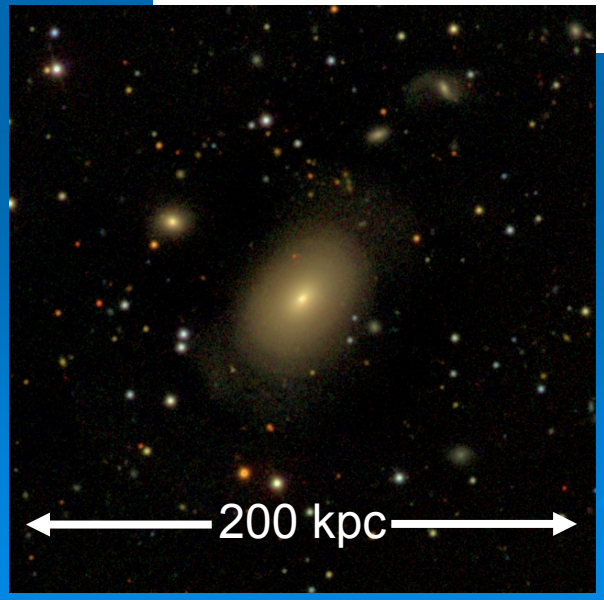
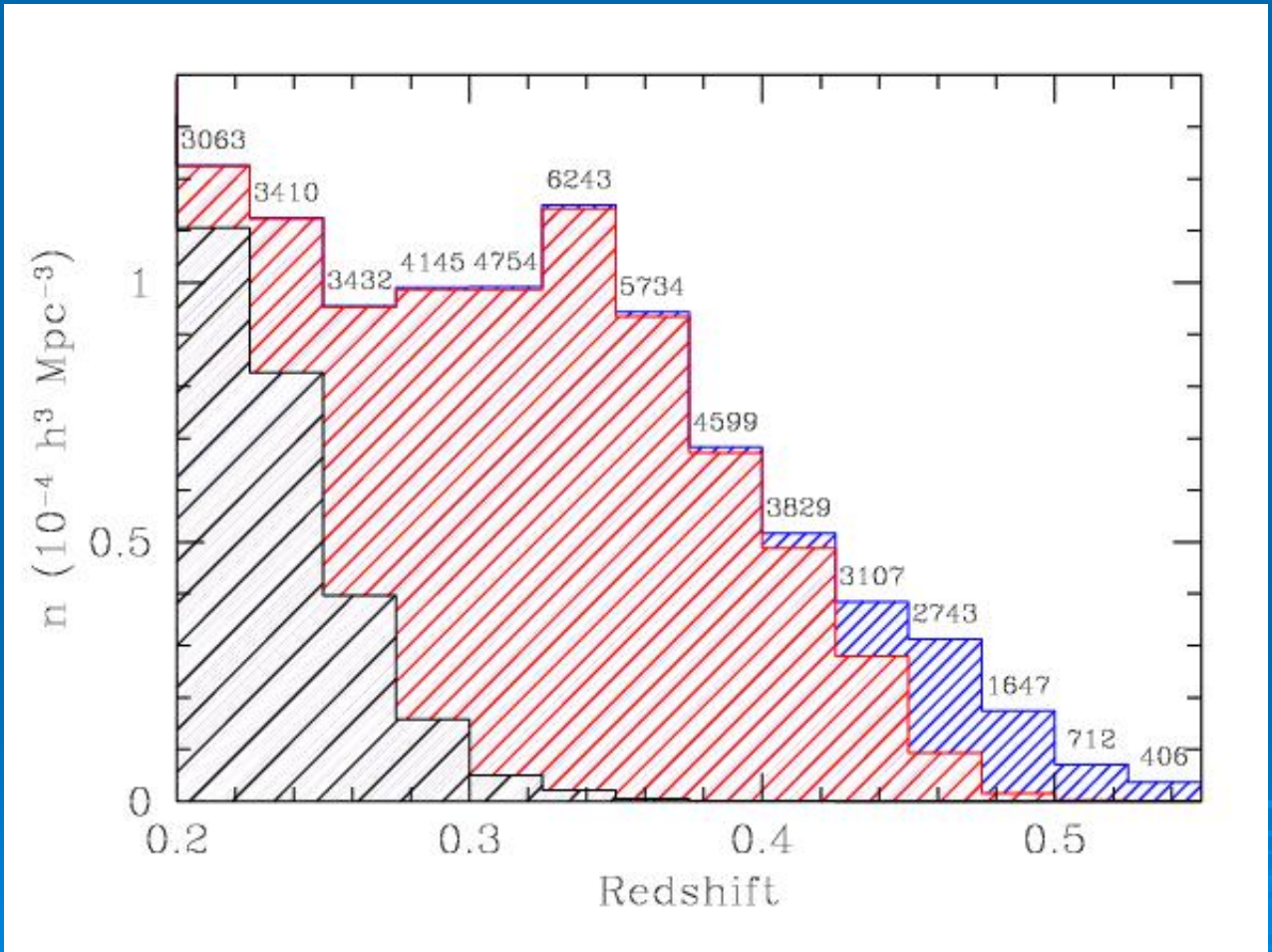
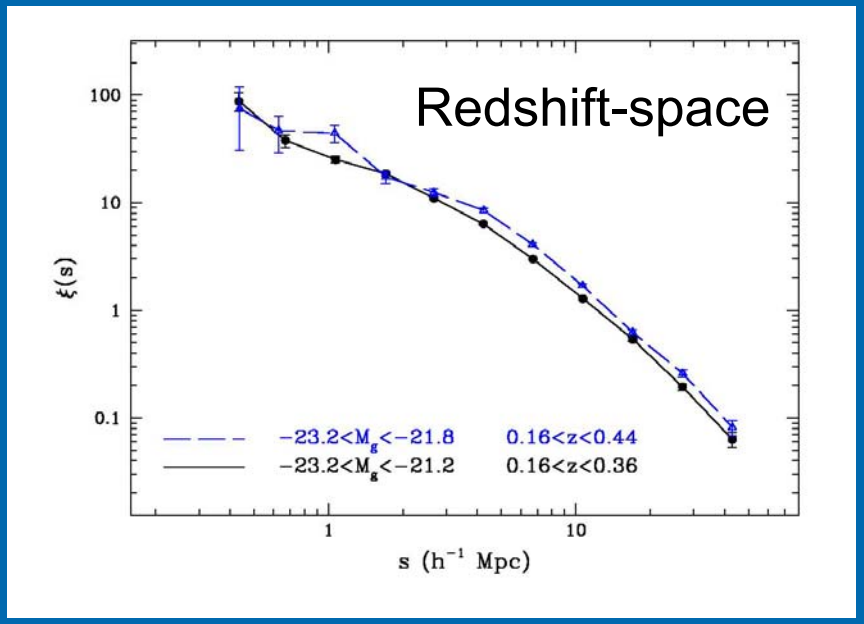
0.35
0.30
0.25
0.20

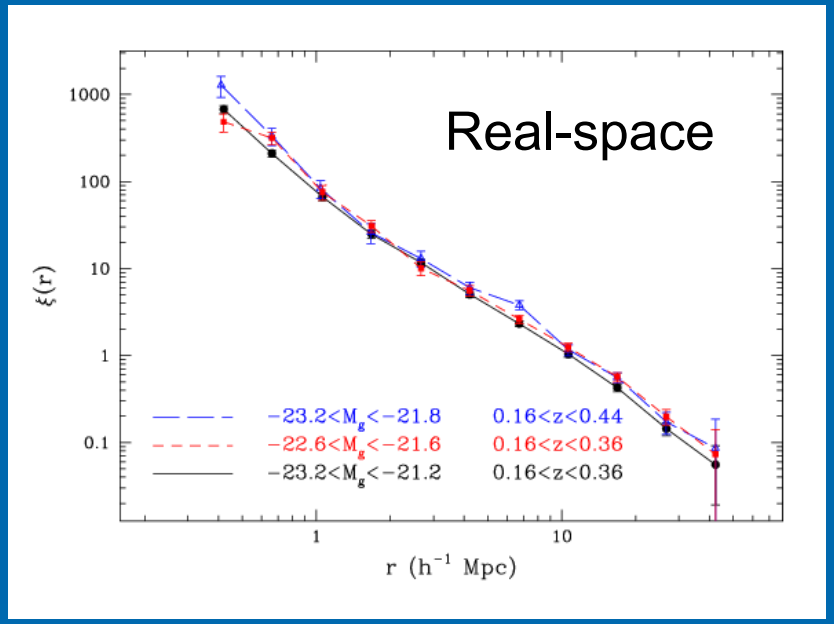

200 kpc

55,000 Spectra



Intermediate-scale Correlations



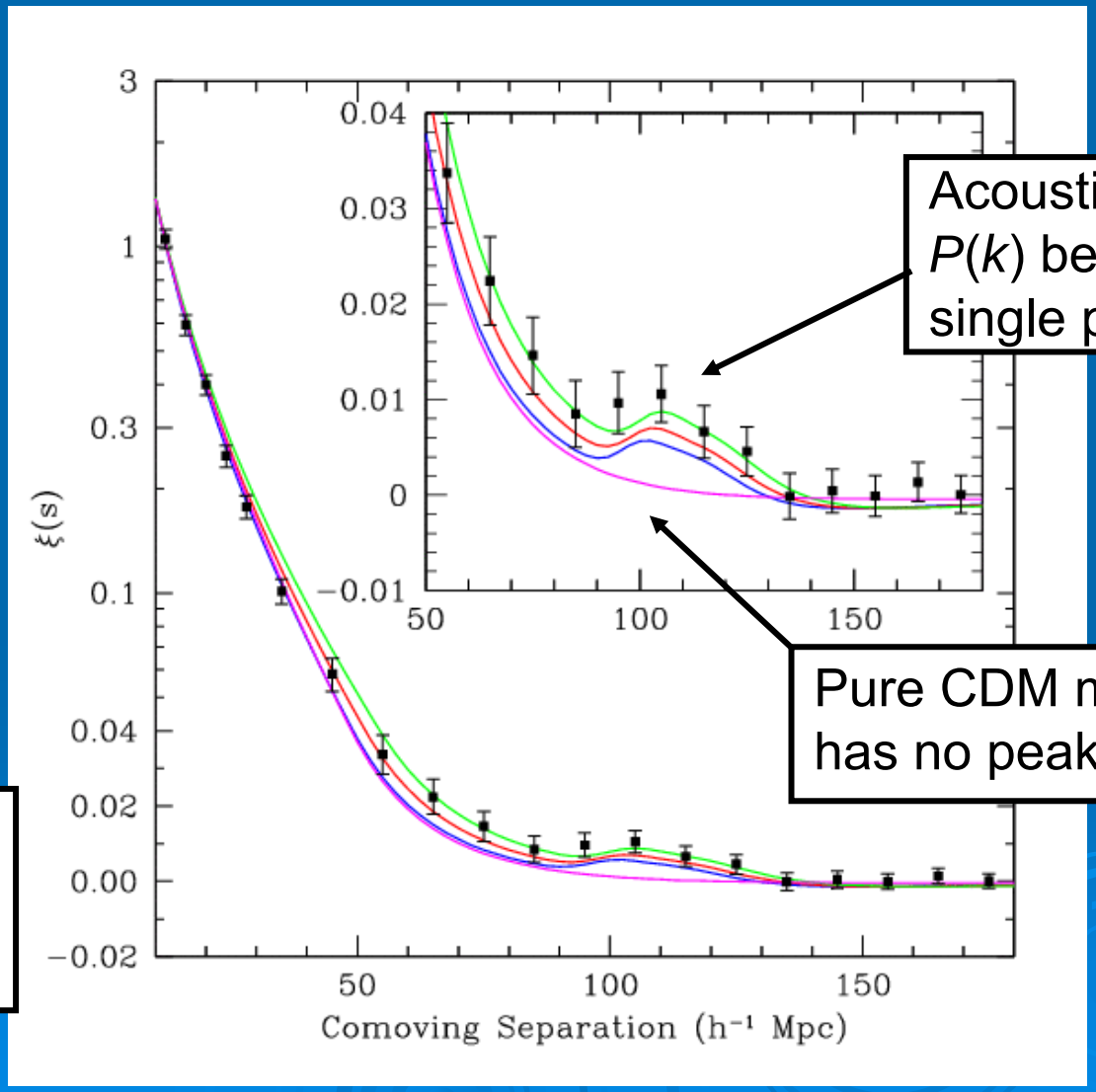


Zehavi et al. (2004)

- 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

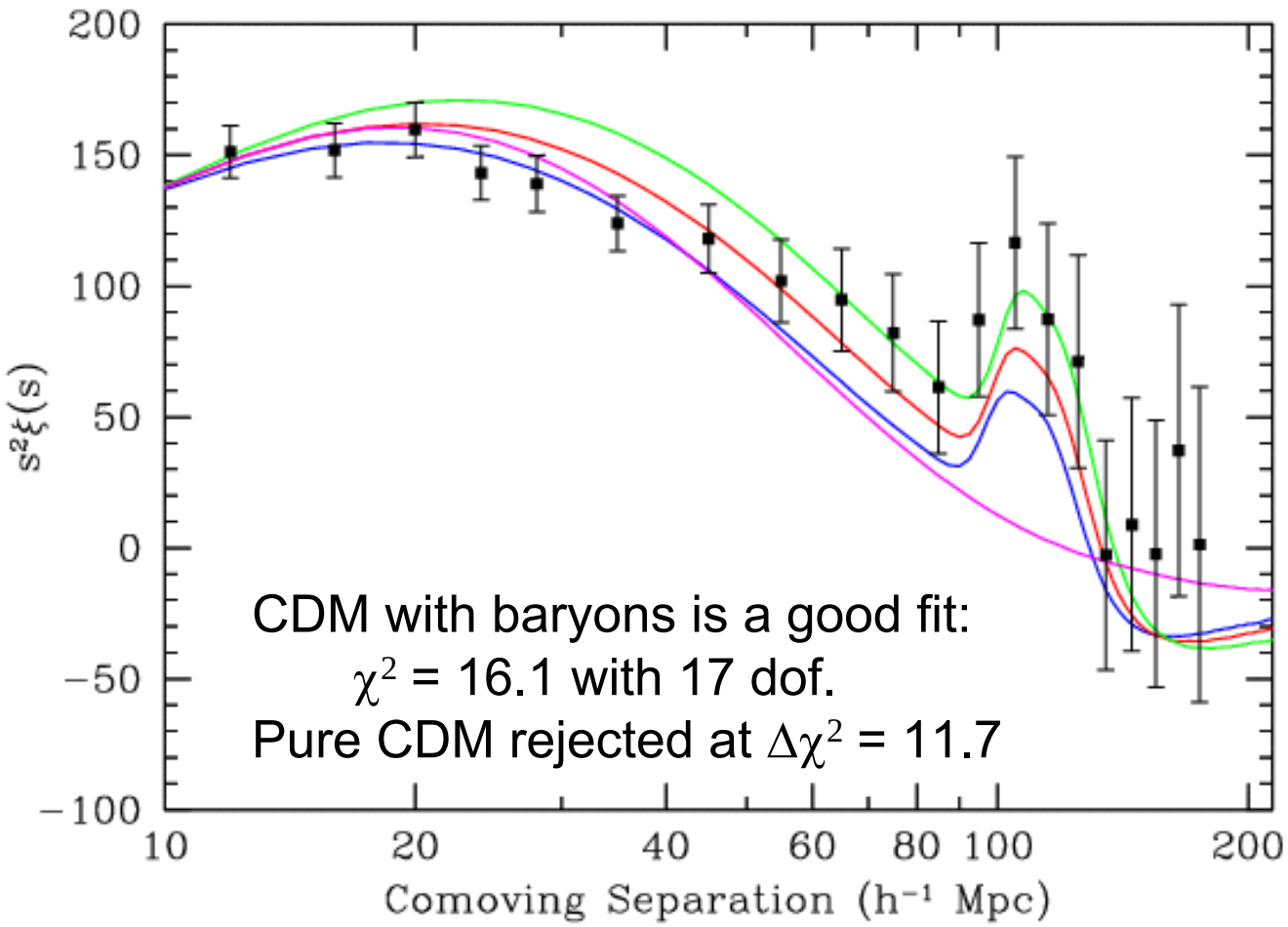


Acoustic series in $P(k)$ becomes a single peak in $\xi(r)$!

Pure CDM model has no peak.

Warning: Correlated Error Bars

Another View



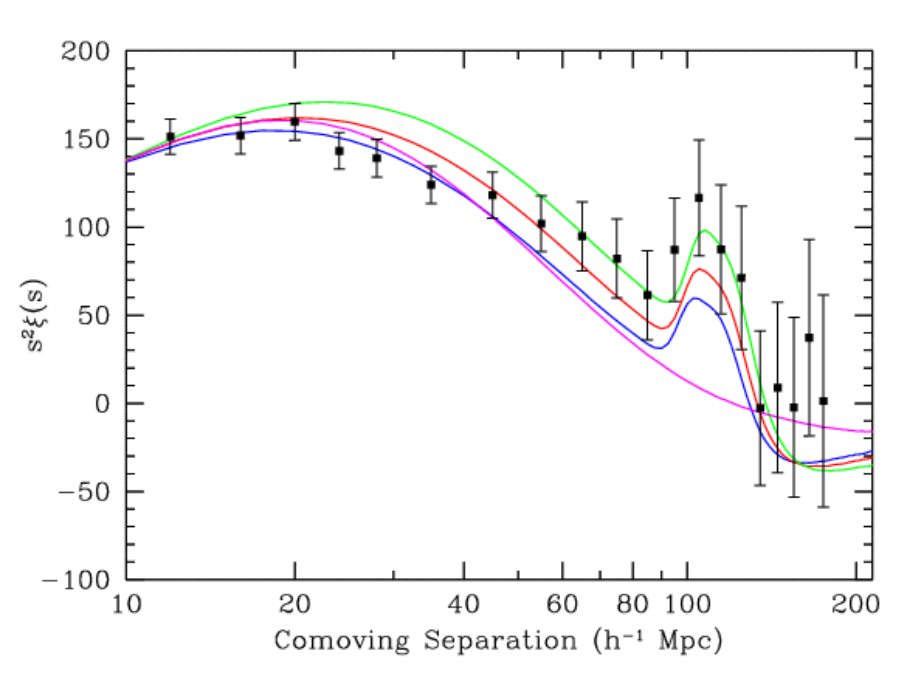
CDM with baryons is a good fit:

χ^2 = 16.1 with 17 dof.

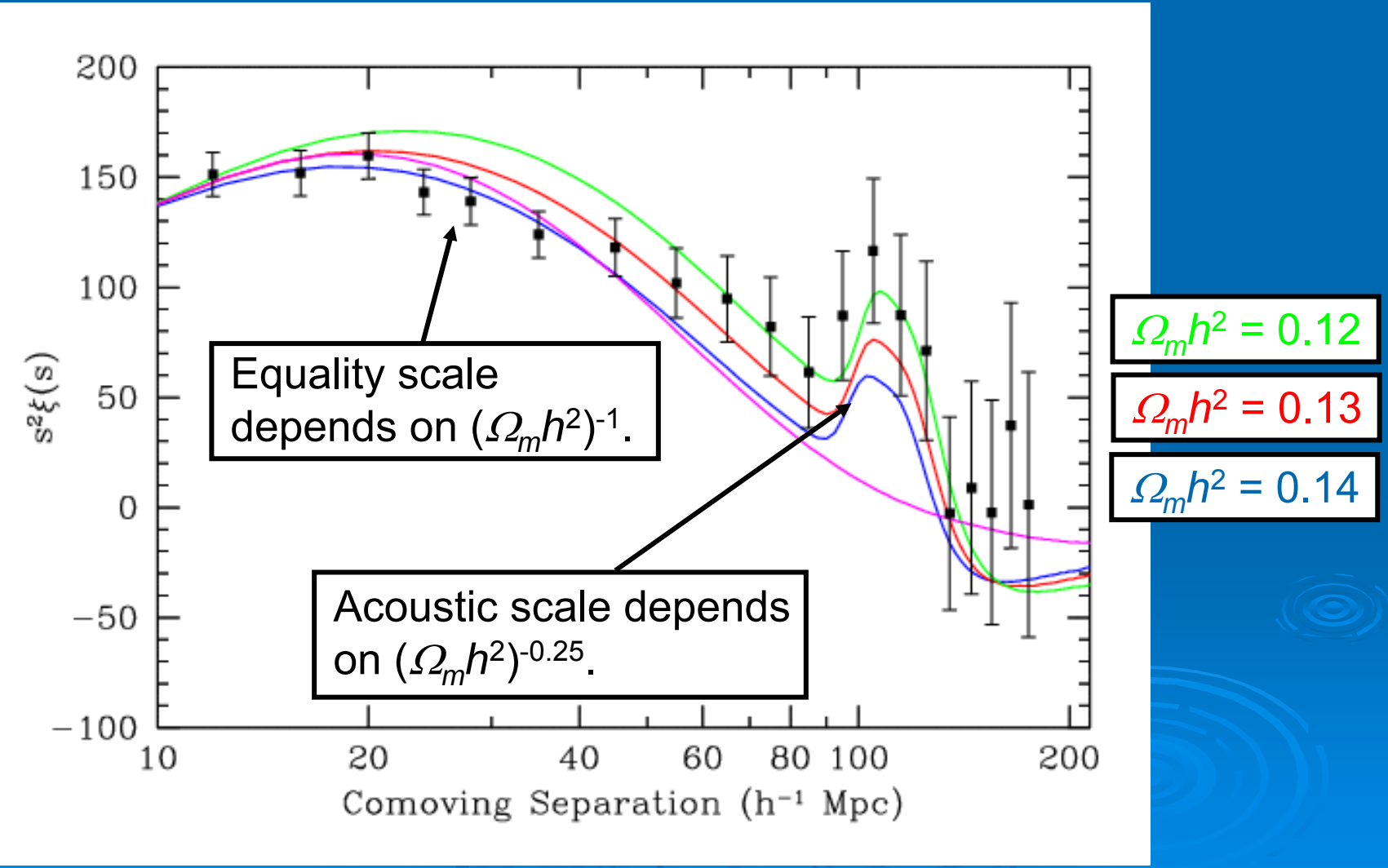
Pure CDM rejected at $\Delta\chi^2$ = 11.7

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.



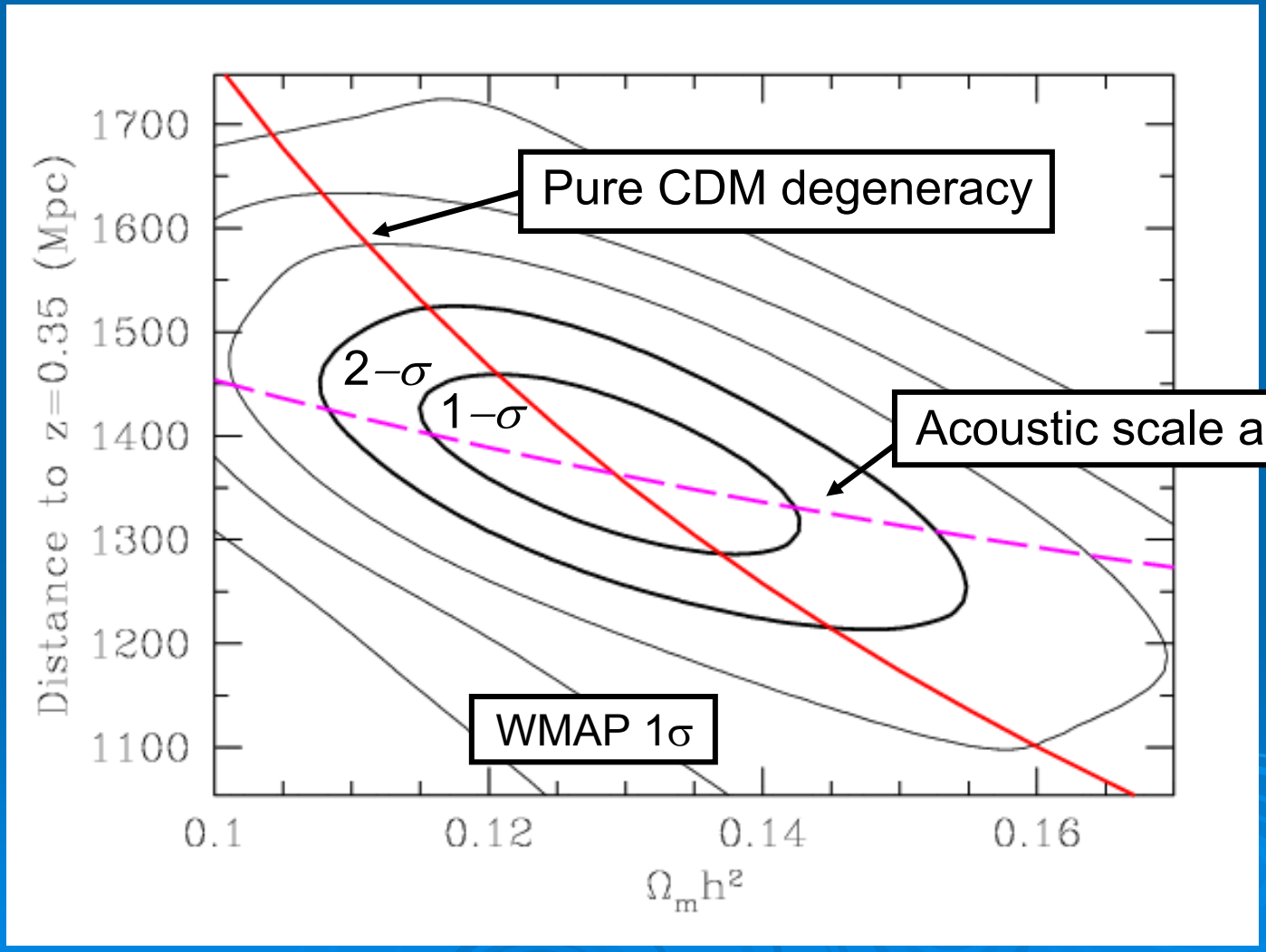
Two Scales in Action



Parameter Estimation

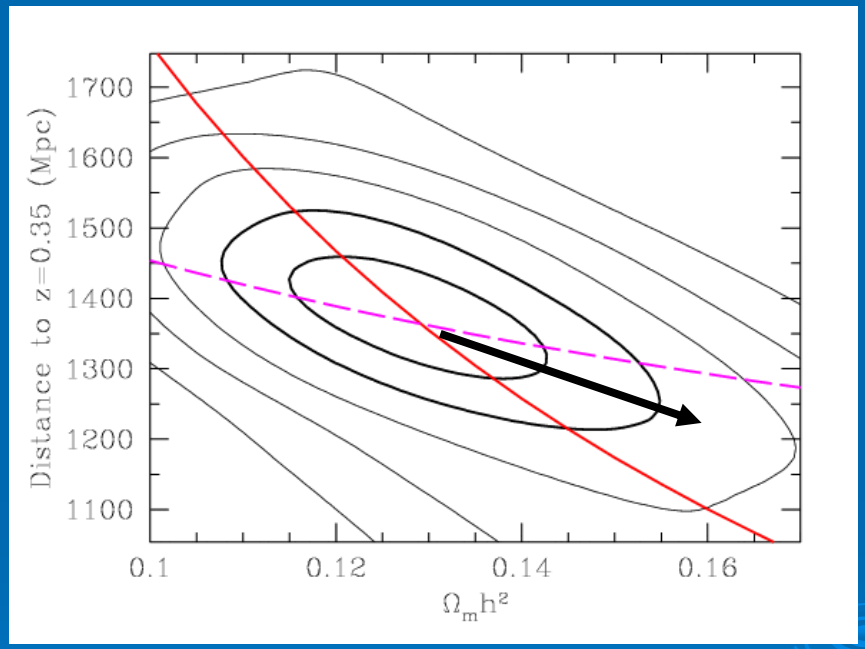
- Vary $\Omega_m h^2$ and the distance to z = 0.35, the mean redshift of the sample.
  - Dilate transverse and radial distances together, i.e., treat $D_A(z)$ and $H(z)$ similarly.
- Hold $\Omega_b h^2$ = 0.024, n = 0.98 fixed (WMAP).
  - Neglect info from CMB regarding $\Omega_m h^2$, ISW, and angular 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



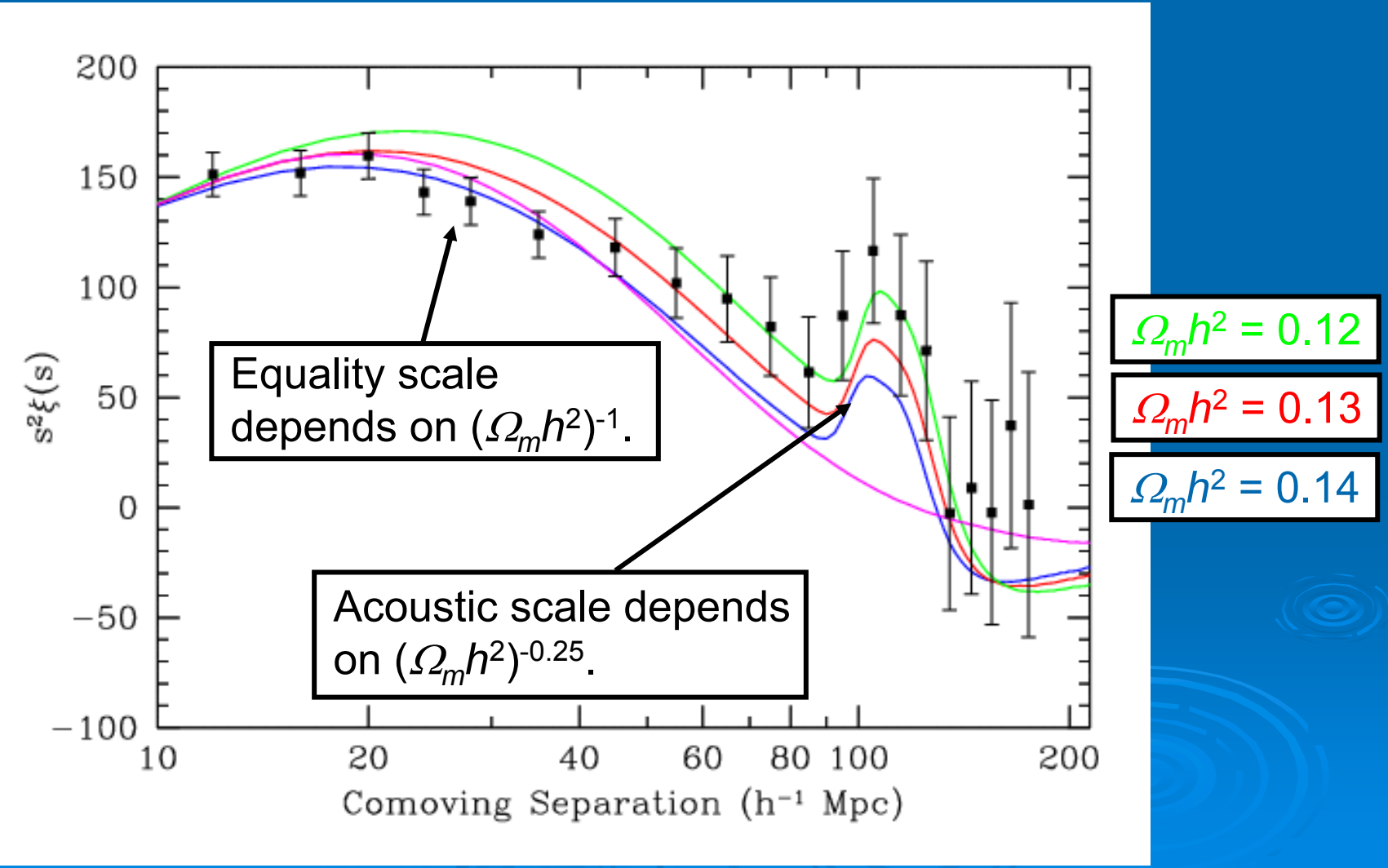
A Standard Ruler

- 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.

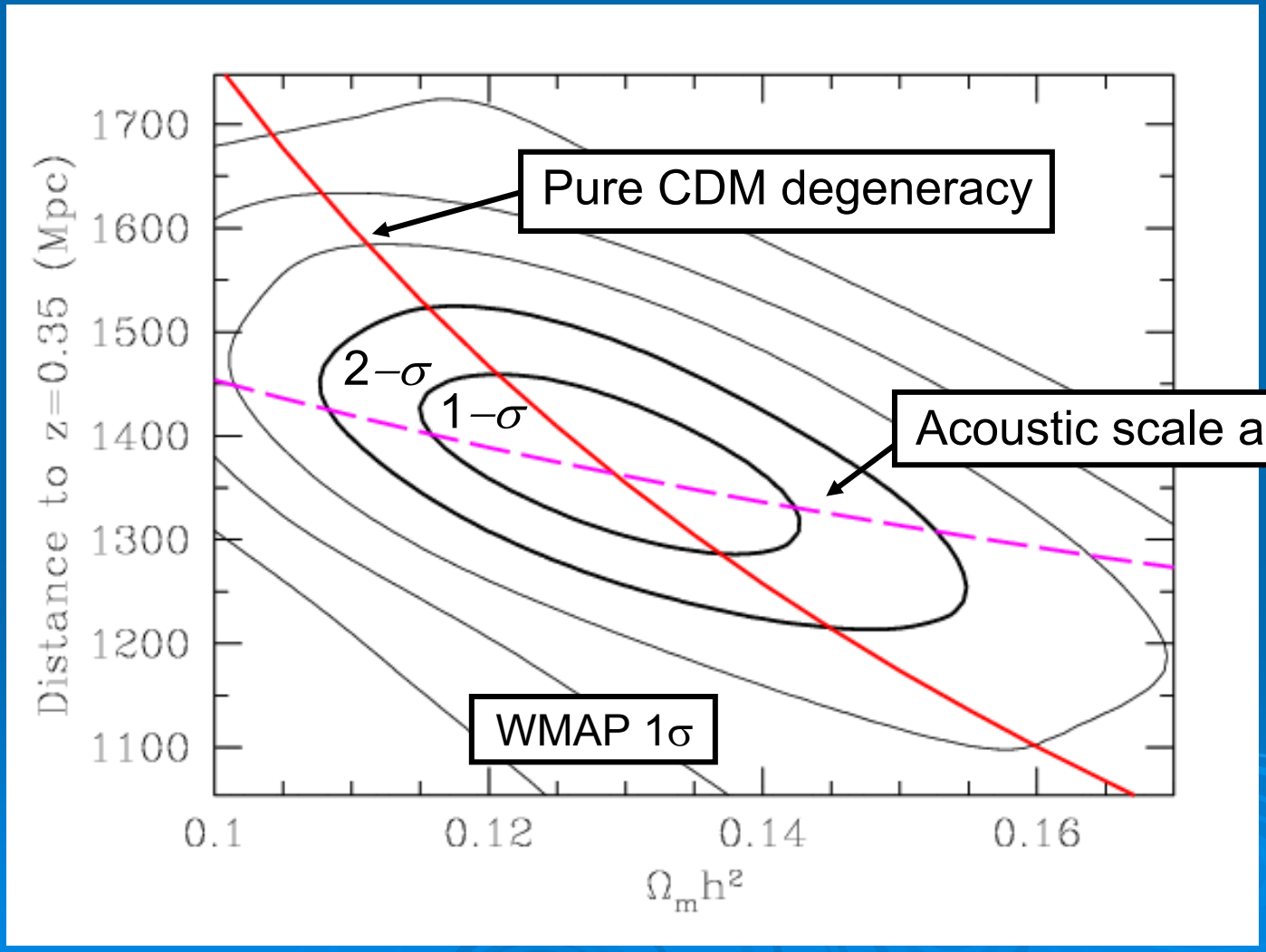


- We find $\Omega_m = 0.273 \pm 0.025 + 0.123(1+w_0) + 0.137\Omega_K$.

Two Scales in Action



Cosmological Constraints

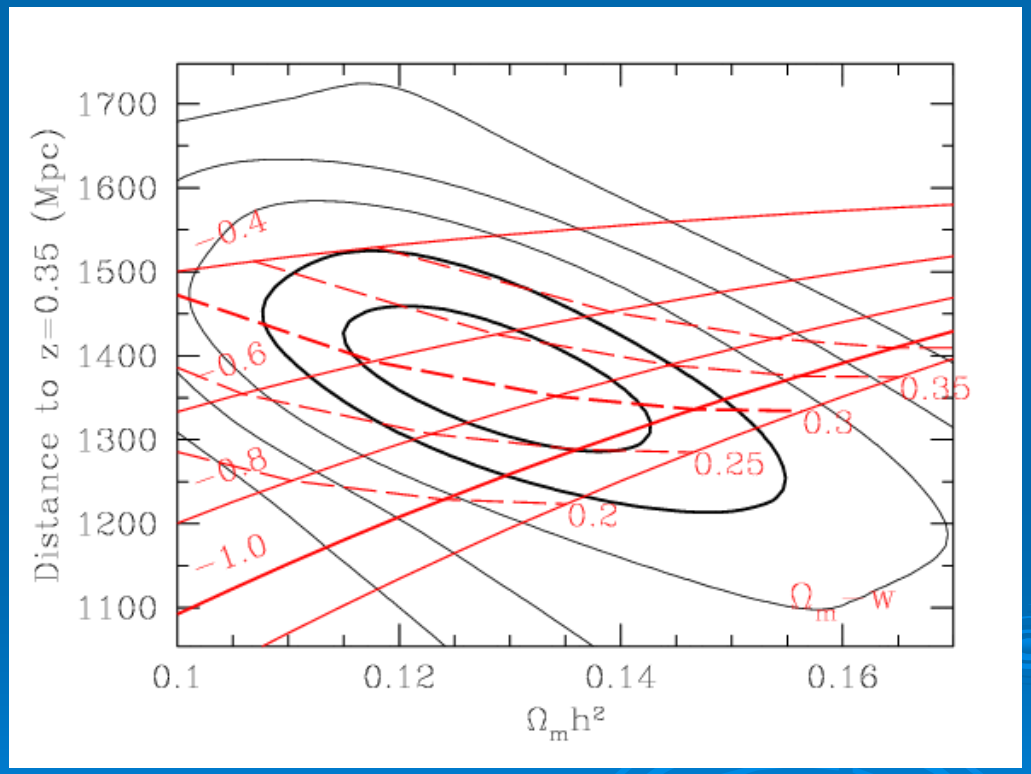


Essential Conclusions

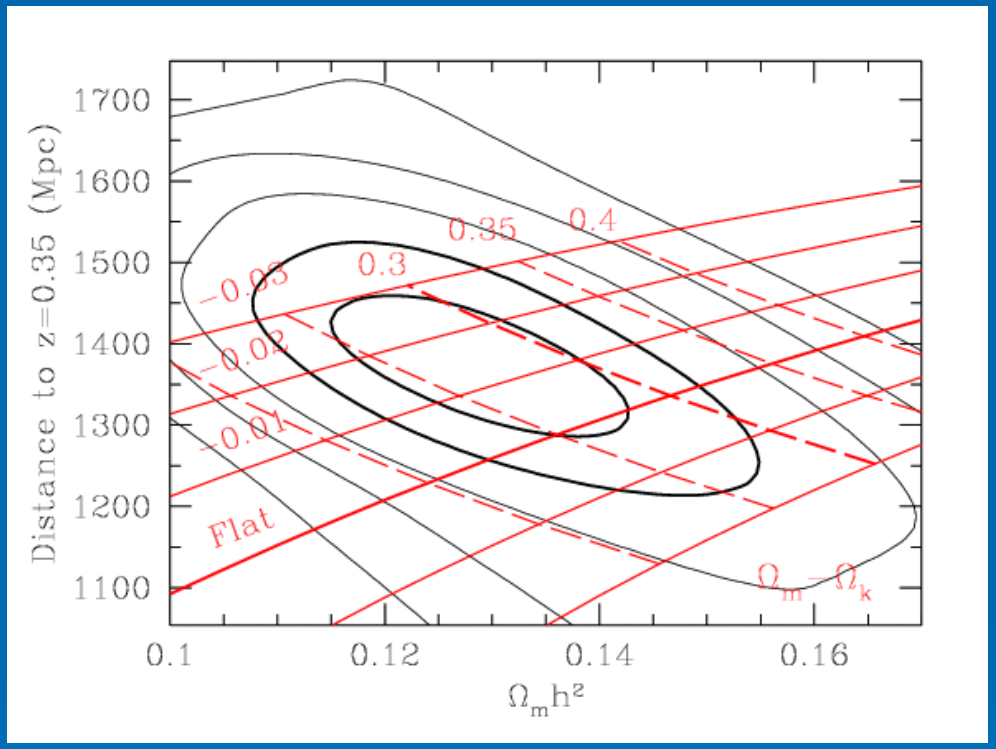
- SDSS LRG correlation function does show a plausible acoustic peak.
- Ratio of $D(z=0.35)$ to $D(z=1000)$ measured to 4%.
  - This measurement is insensitive to variations in spectral tilt and small-scale modeling. We are measuring the same physical feature at low and high redshift.
- $\Omega_m h^2$ 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.
- $\Omega_m = 0.273 \pm 0.025 + 0.123(1+w_0) + 0.137\Omega_K$.

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

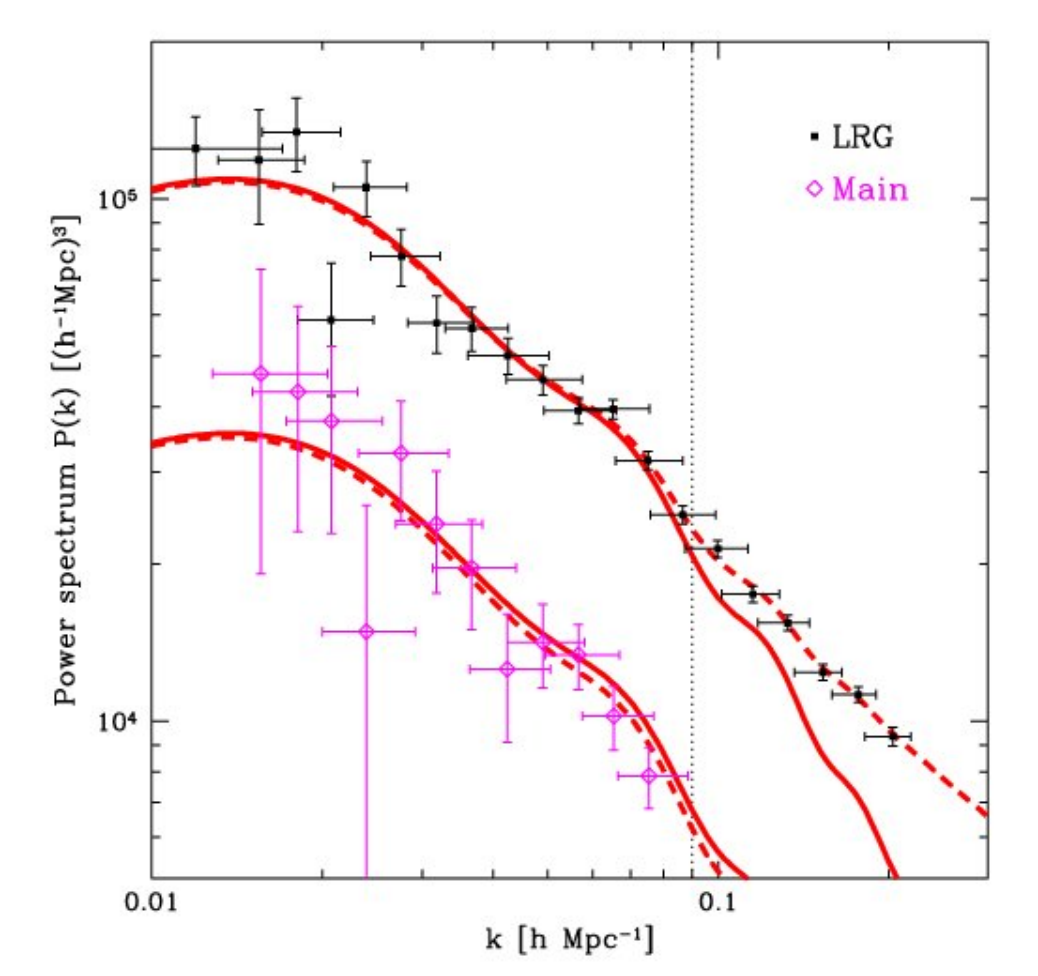


- Common distance scale to low and high redshift yields a powerful constraint on spatial curvature:

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

Power Spectrum

- We have also done the analysis in Fourier space with a quadratic estimator for the power spectrum.
- The results are highly consistent.
  - Ω_m = 0.25, in part due to WMAP-3 vs WMAP-1.
- Also FKP analysis in Percival et al. (2006).



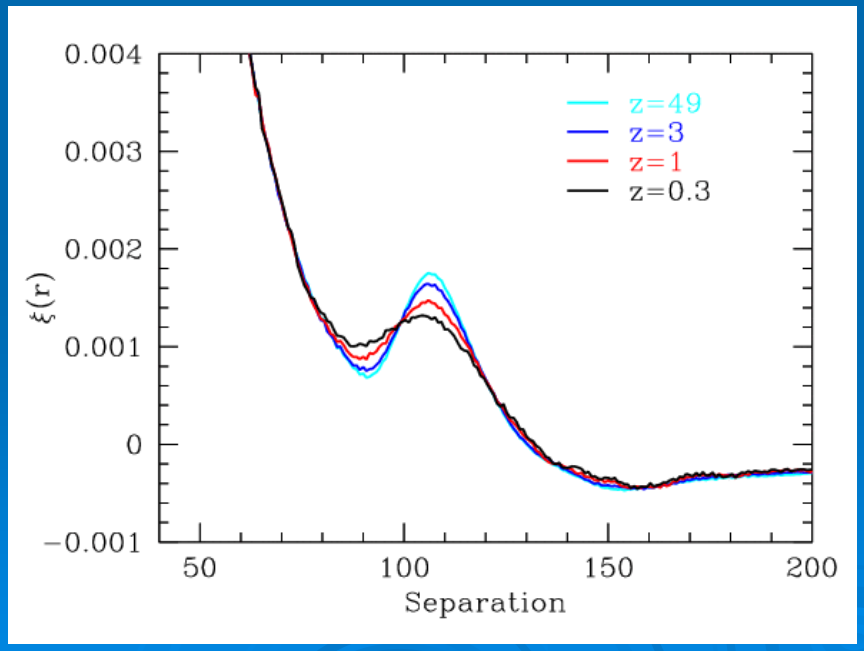
Tegmark et al. (2006)

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~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 ~10^{-3} comoving h^3 Mpc^{-3} = ~1 million galaxies!
- Discuss survey optimization then examples.

Non-linearities Revisited

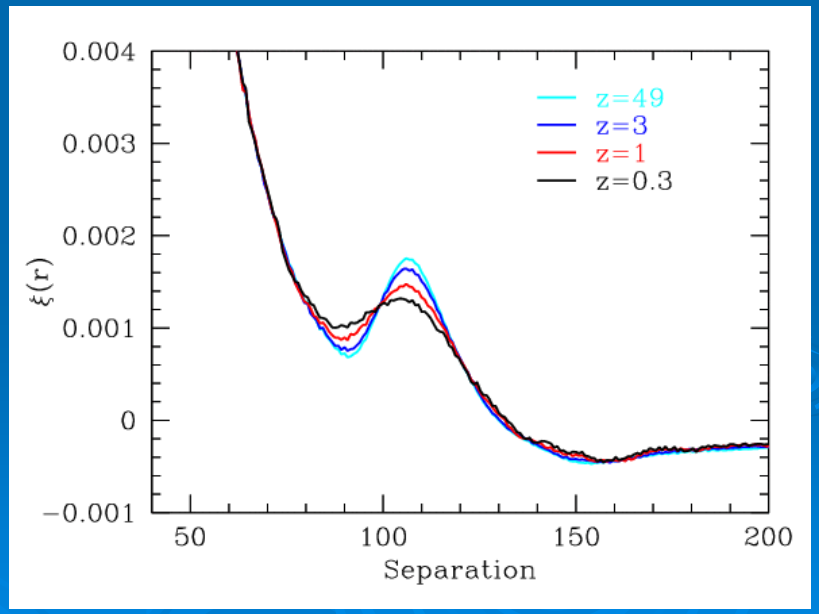
- Non-linear gravitational collapse and galaxy formation partially erases the acoustic signature.
- This limits our ability to centroid the peak and could in principle shift the peak to bias the answer.



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

Nonlinearities in $\xi(r)$

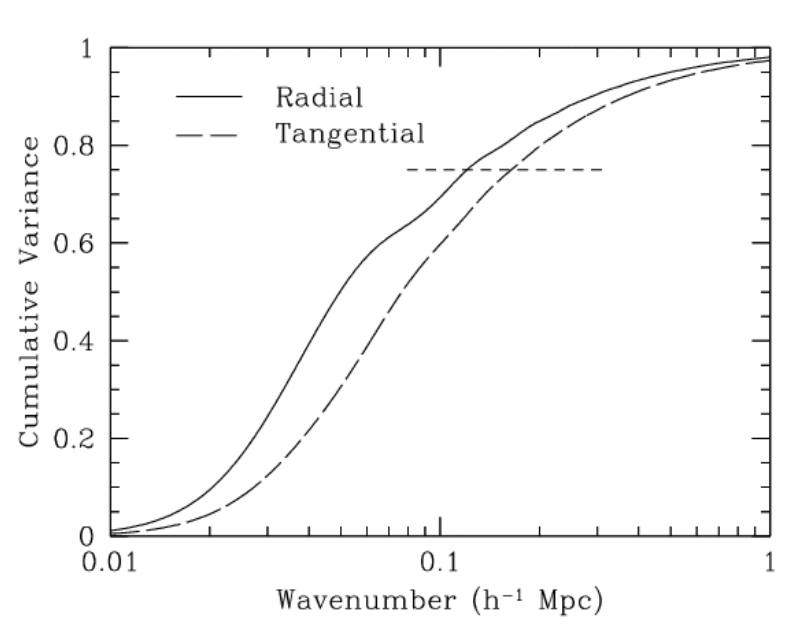
- The acoustic signature is carried by pairs of galaxies separated by 150 Mpc.
- Nonlinearities push galaxies around by 3-10 Mpc. Broadens peak, erasing higher harmonics.
- Moving the scale requires net infall on 100 h^{-1} Mpc scales.
  - This depends on the over-density inside the sphere, which is about $J_3(r) \sim 1\%$.
  - Over- and underdensities cancel, so mean shift is <<1%.
- Simulations show no evidence for any bias at 1% level.



Seo & DJE (2005); DJE, Seo, & White, in press

Where Does Displacement Come From?

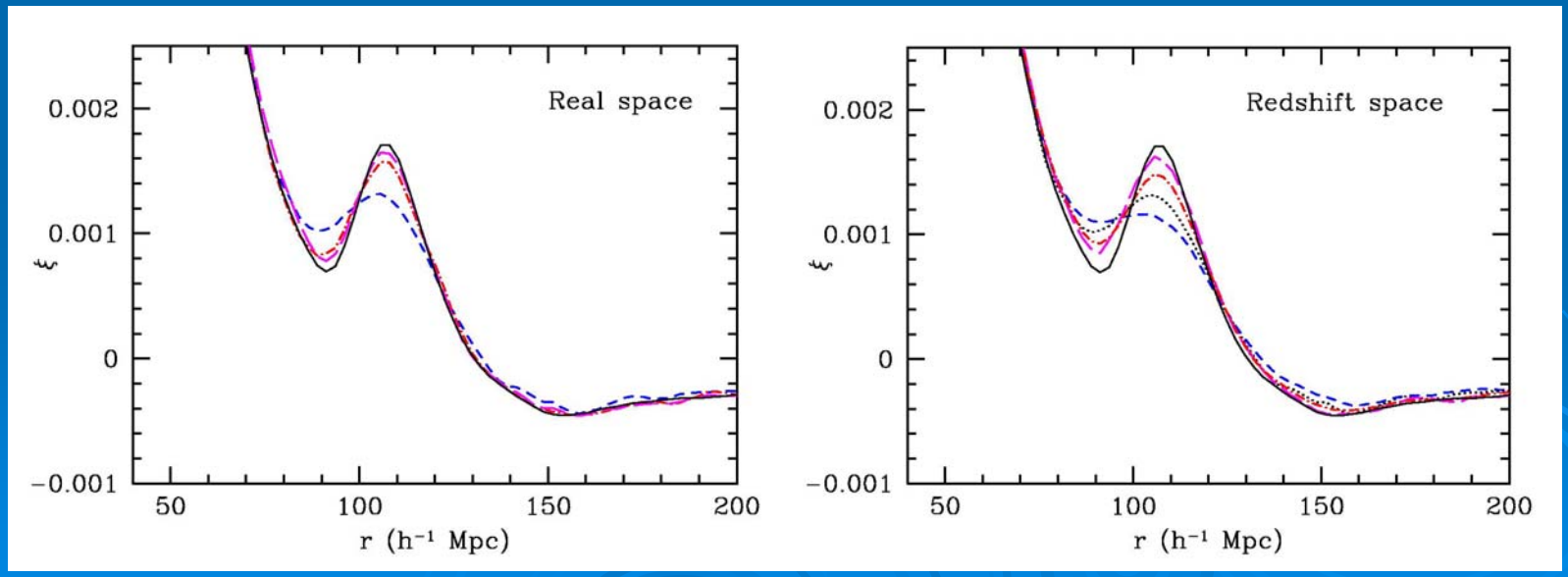
- Importantly, most of the displacement is due to bulk flows.
  - Non-linear infall into clusters "saturates". Zel'dovich approx. actually overshoots.
- Bulk flows in CDM are created on large scales.
  - Looking at pairwise motion cuts the very large scales.
- The scales generating the displacements are exactly the ones we're measuring for the acoustic oscillations.



DJE, Seo, Sirko, & Spergel, in press

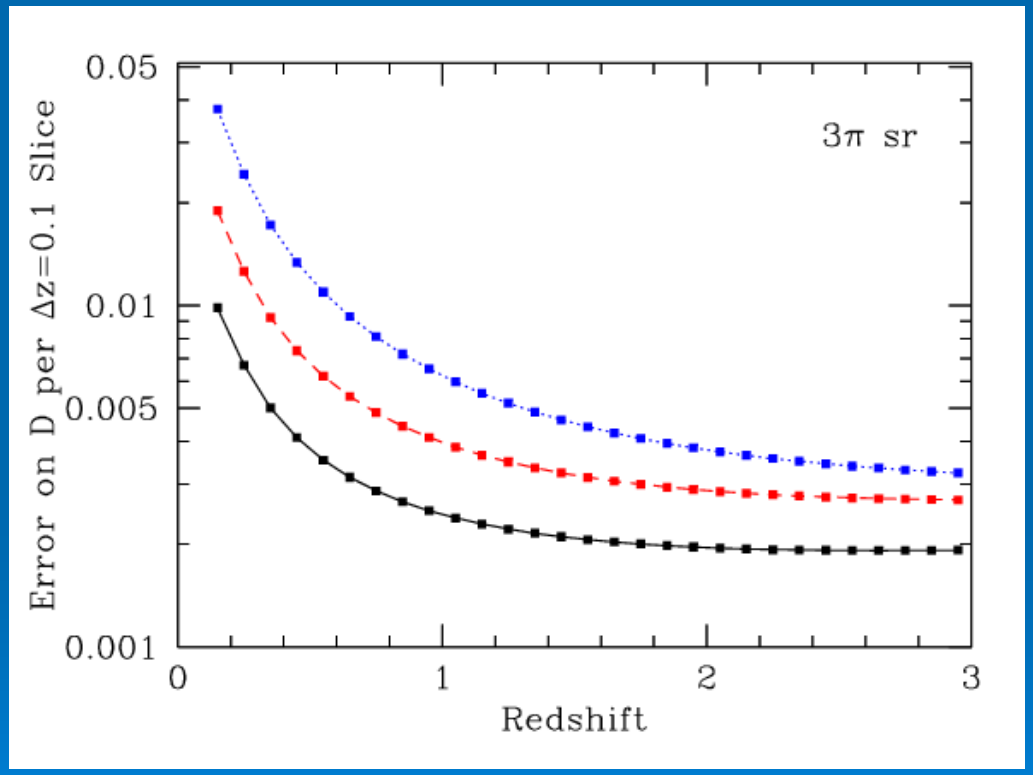
Fixing the Nonlinearities

- Because the nonlinear degradation is dominated by bulk flows, we can undo the effect.
- Map of galaxies tells us where the mass is that sources the gravitational forces that create the bulk flows.
- Can run this backwards.
- Restore the statistic precision available per unit volume!



DJE, Seo, Sirko, & Spergel, in press

Cosmic Variance Limits



Seo & DJE, submitted

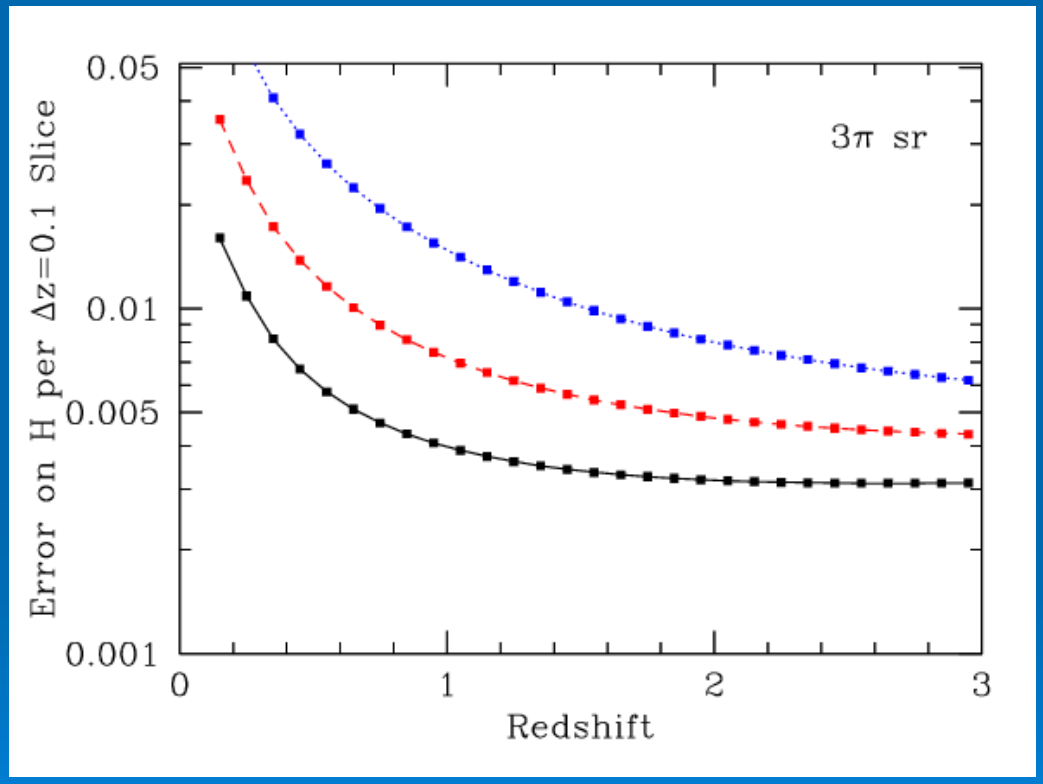
Errors on $D(z)$ in Δz=0.1 bins. Slices add in quadrature.

Black: Linear theory

Blue: Non-linear theory

Red: Reconstruction by 50% (reasonably easy)

Cosmic Variance Limits



Seo & DJE, submitted

Errors on $H(z)$ in Δz=0.1 bins. Slices add in quadrature.

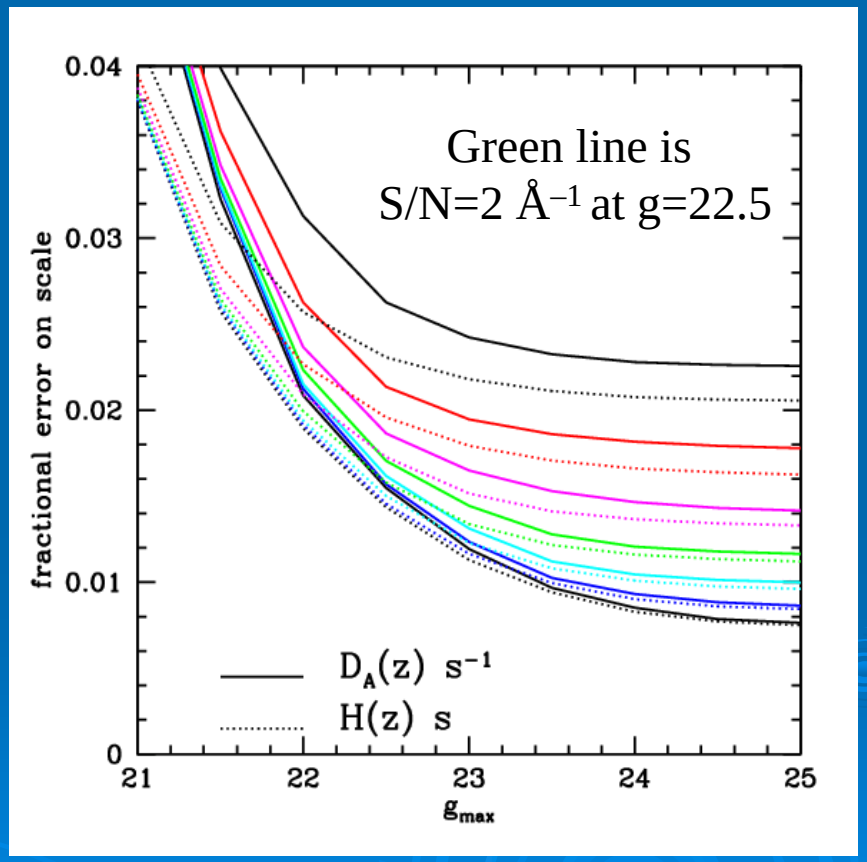
Black: Linear theory

Blue: Non-linear theory

Red: Reconstruction by 50% (reasonably easy)

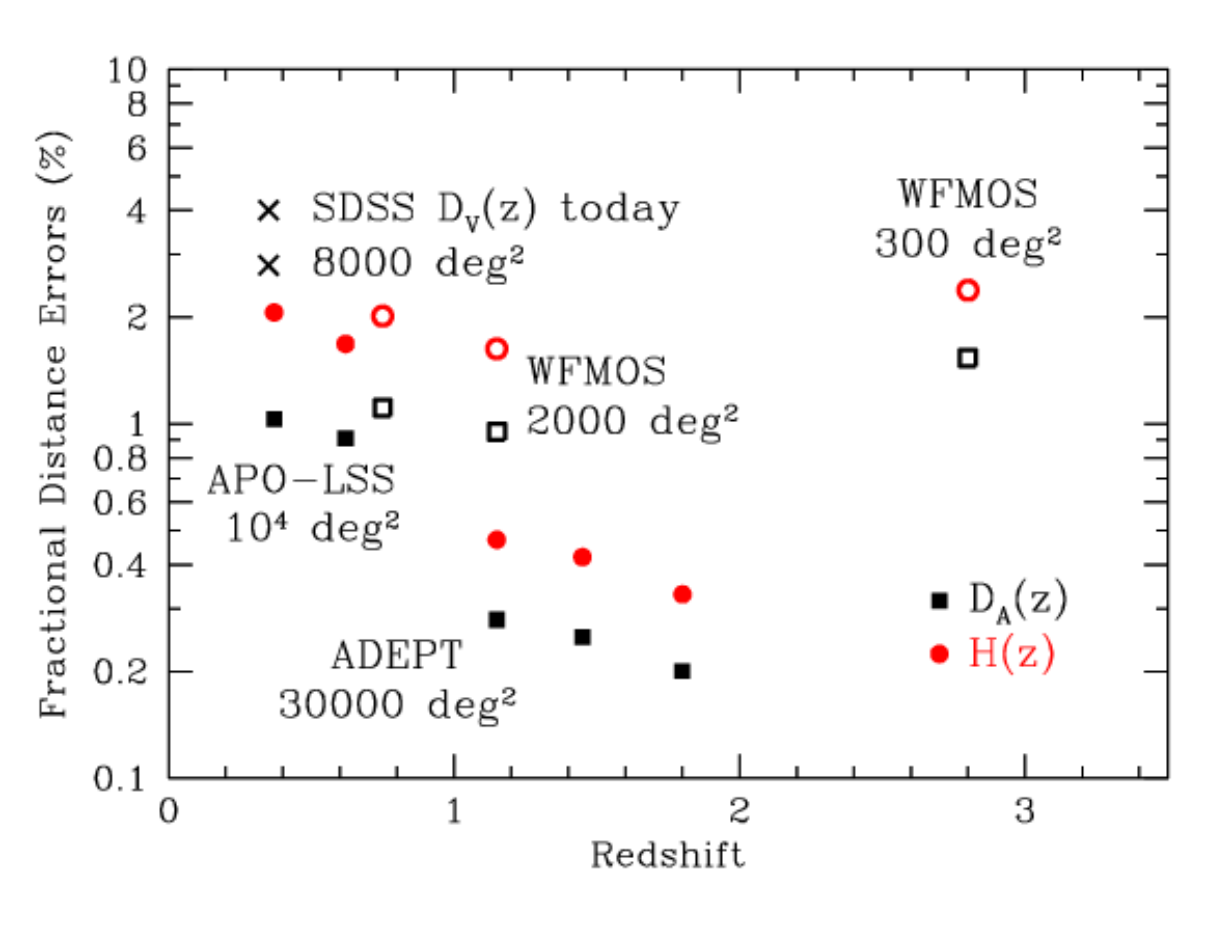
Seeing Sound in the Lyman α Forest

- The Lyα forest tracks the large-scale density field as well, so a grid of sightlines should show the acoustic peak.
- This may be a cheaper way to measure the acoustic scale at z>2.
  - Bonus: the sampling is better in the radial direction, so favors H(z).
- Require only modest resolution (R=250) and low S/N. UV coverage is a big plus.



White (2004); McDonald & DJE (2006)

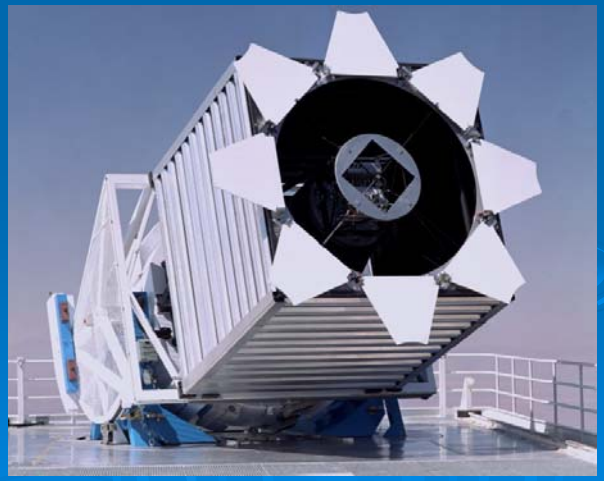
Chasing Sound Across Redshift



Distance Errors versus Redshift

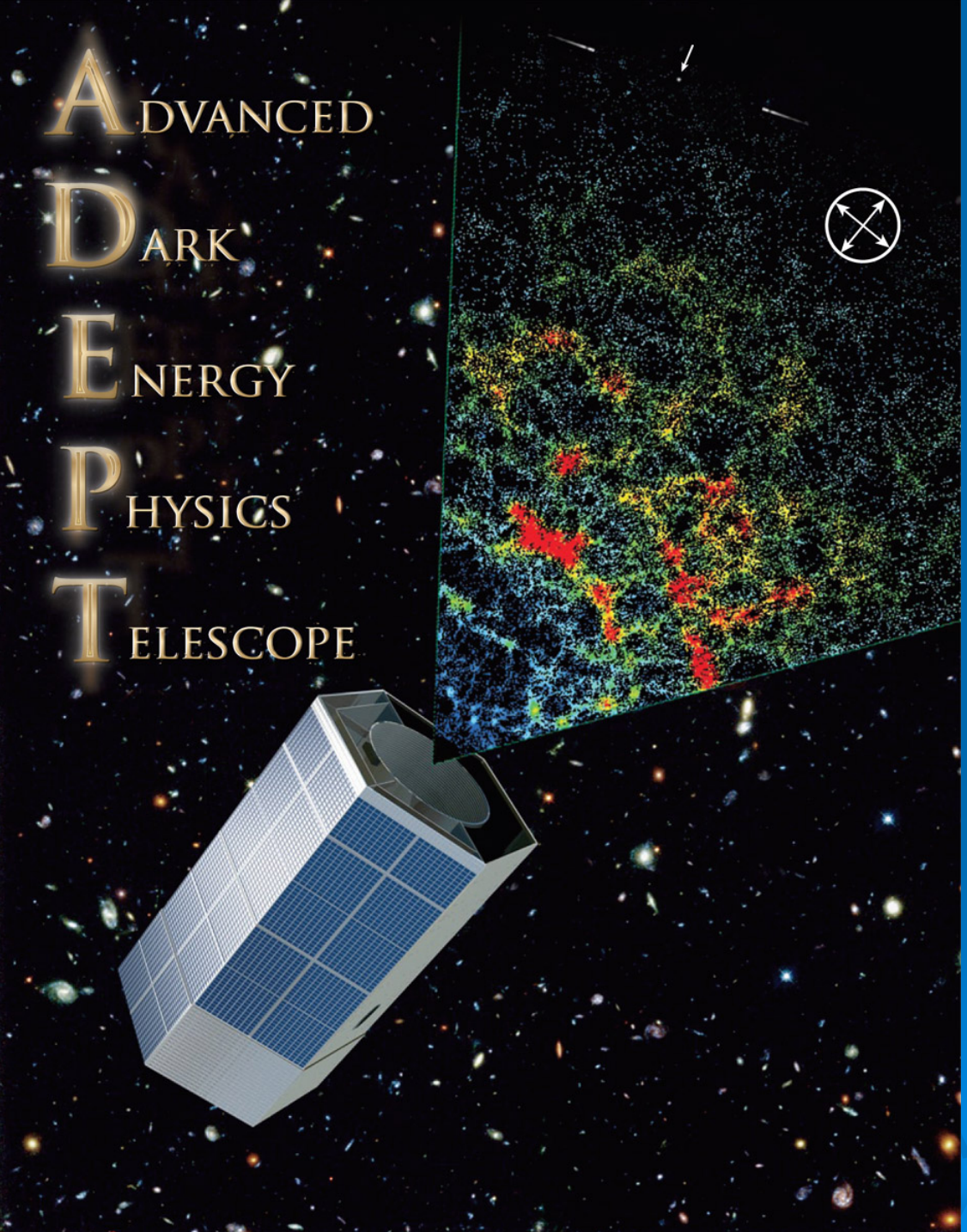
APO-LSS

- New program for the SDSS telescope for the period 2008–2014. 10,000 deg^2 of new spectroscopy from SDSS imaging.
  - 1.5 million LRGs to z=0.8, including 4x more density at z<0.5.
  - 7-fold improvement on large-scale structure data from entire SDSS survey, measure the distance scale to better than 1%.
  - Lyα forest from grid of 100,000 z>2.2 quasars.
  - Mild upgrades to the spectrographs to reach 1000 fibers per shot and more UV coverage.
- Other aspects of the program include stellar spectroscopic survey for galactic structure and a multi-fiber radial-velocity planet search.
- Collaboration now forming.



New Surveys

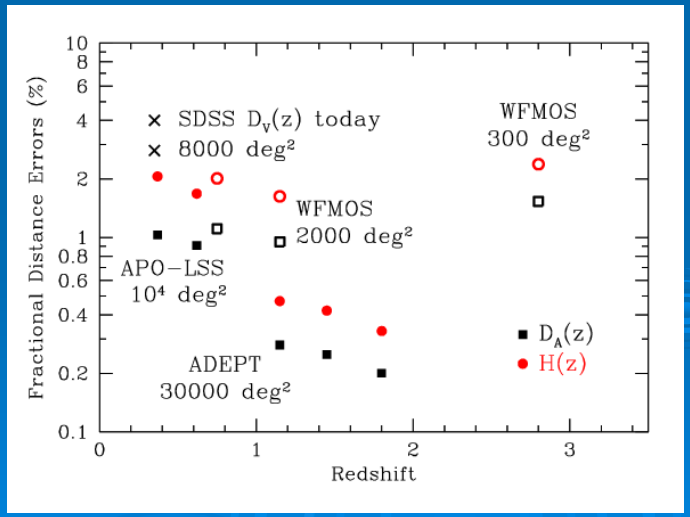
- WiggleZ: Survey of z~0.8 emission line galaxies at AAT with new AAOmega upgrade.
- FMOS: *z*~1.5 Subaru survey with IR spectroscopy for Hα.
- HETDeX: Lyα emission galaxy survey at 1.8<z<3.8 with new IFU on HET.
- New WFMOS spectrograph for Gemini/Subaru could do major *z*~1 and *z*~2.5 surveys in ~100 nights each.
  - Well ranked in Aspen second-generation instruments plan. Currently entering a competitive design study.
  - 1.5 degree diameter FOV, 4000-5000 fibers, using Echidna technology, feeding multiple bench spectrographs.
  - Also high-res for Galactic studies.



- Concept proposed for the Joint Dark Energy Mission (JDEM).
- 3/4-sky survey of $1<z<2$ from a small space telescope, using slitless IR spectroscopy of the Hα line.
  SNe Ia to z~1.4.
- 100 million redshifts; 20 times more effective volume than previous ground-based surveys.
- Designed for maximum synergy with ground-based dark energy programs.

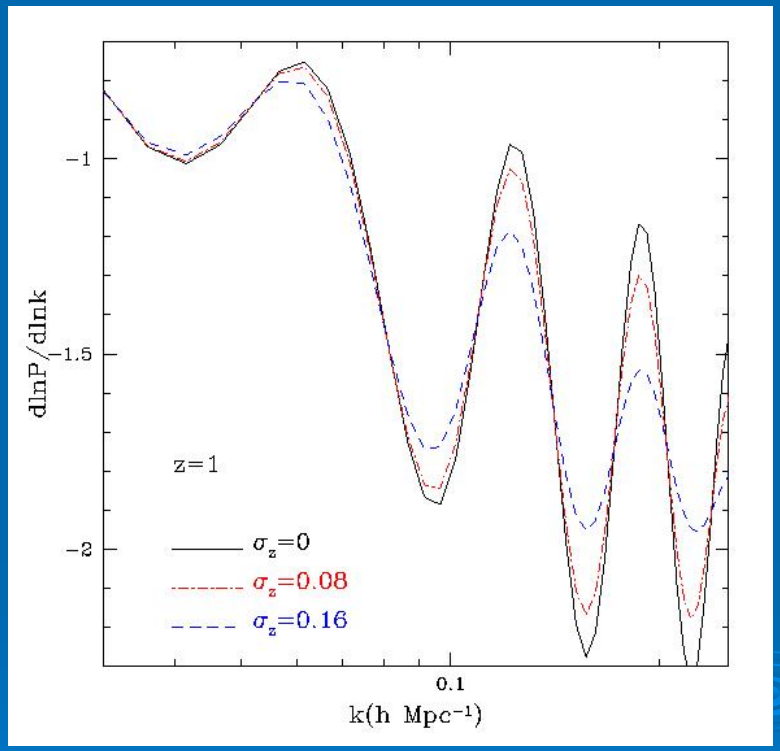
Opening Discovery Spaces

- With CMB and galaxy surveys, we can study dark energy out to 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.



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)

We've Only Just Begun

- SDSS LRG has only surveyed only 10^{-3} of the volume of the Universe out to z~5.
- Only 10^{-4} of the modes relevant to the acoustic oscillations.
- Fewer than 10^{-6} of the linear regime modes available.
- There is an immense amount more information about the early Universe available in large-scale structure.

Spergel

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.