Dark Energy and Cosmic Sound

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David Spergel, Max Tegmark, Martin White,
Xiaoying Xu, Idit Zehavi, and the SDSS.

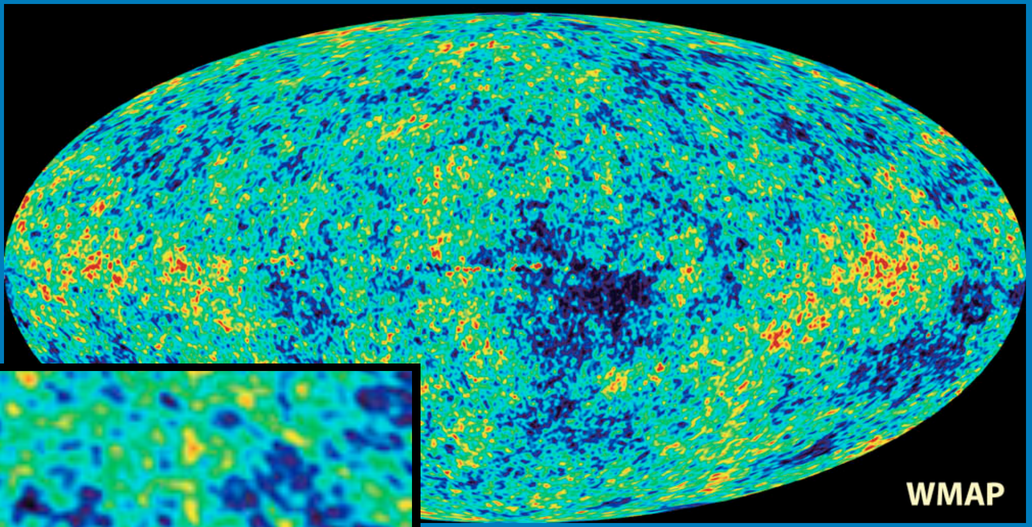
Dark Energy

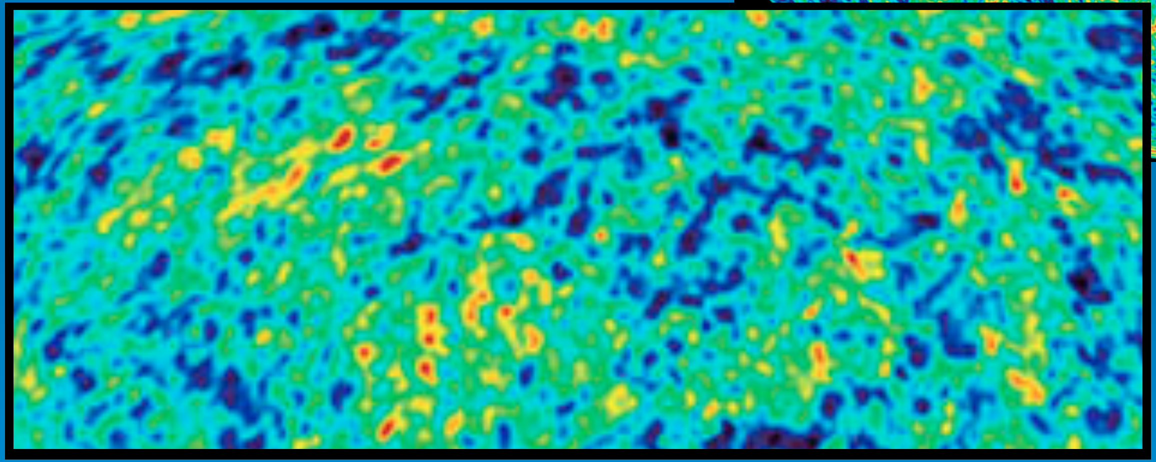
- In 1998, two groups argued from supernova data that the expansion rate of the Universe is accelerating!
- Many possible explanations have been advanced.
  - Cosmological constant
  - New low-mass field(s)
  - Modification to gravity
  - Extra dimensions
  - Your favorite here
- All are exotic, and none is so aesthetically compelling as to be the obvious preference.
- What more can we do observationally?
  - Main path is very accurate distance measurements, 1% and better!

Outline

- Baryon acoustic oscillations as a standard ruler.
  - Linear theory pedagogy.
  - Non-linear structure formation.
- Detection of the acoustic signature in the SDSS Luminous Red Galaxy sample.
  - Cosmological constraints therefrom, including a summary of the new DR7 results.
- Large galaxy surveys at higher redshifts as a route to 1% distances and better.
  - Introduce SDSS-III.

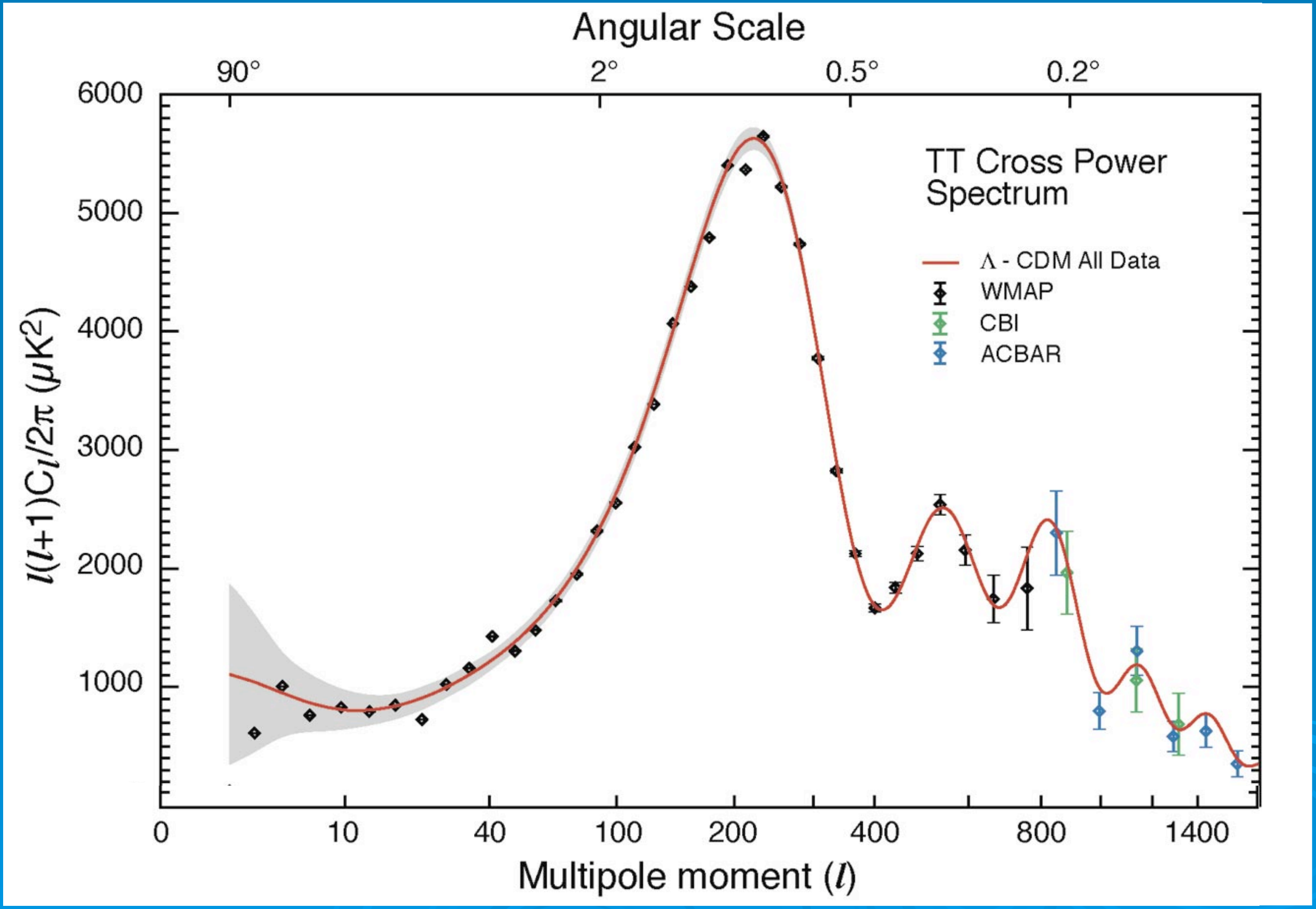
Acoustic Oscillations in the CMB





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

Acoustic Oscillations in the CMB



WMAP team (Bennett et al. 2003)

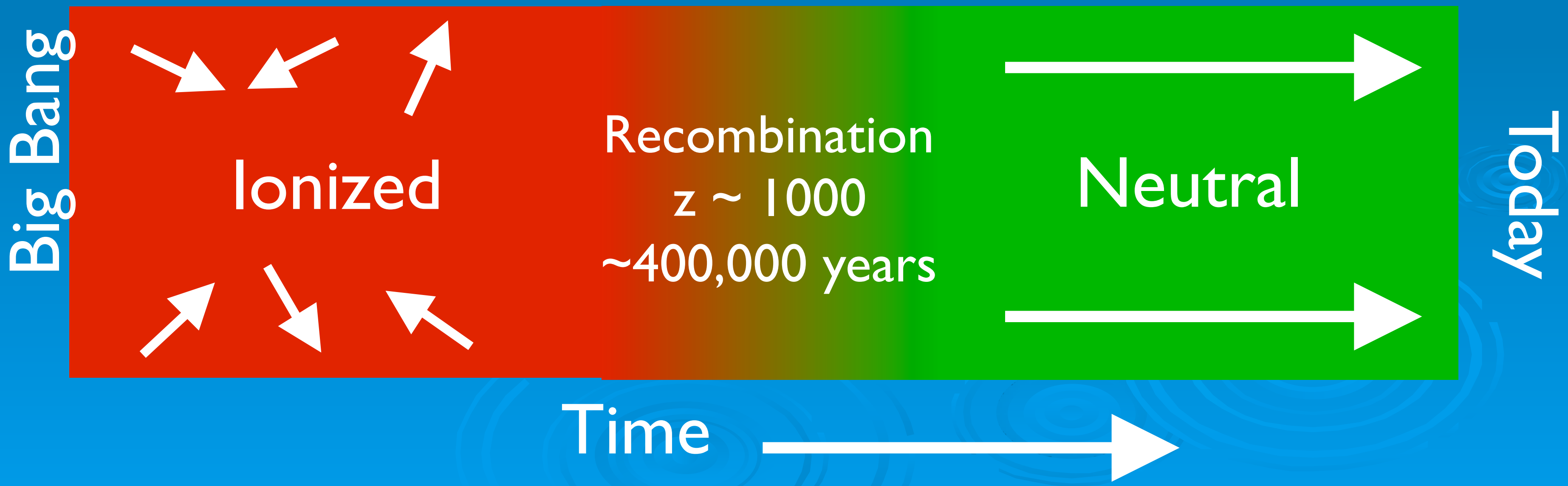
Sound Waves in the Early Universe

Before recombination:

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

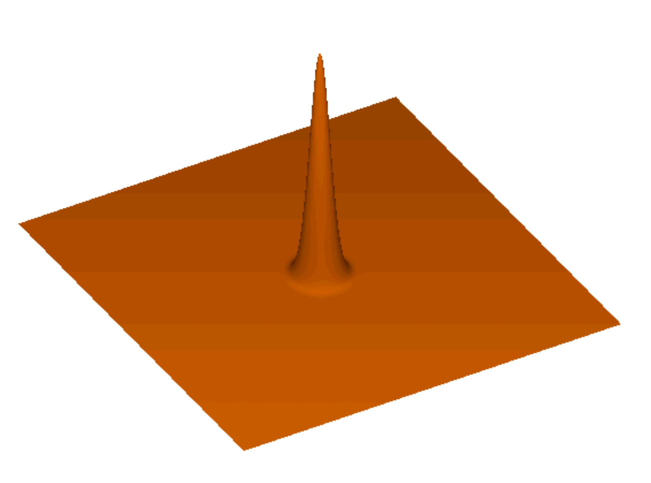
After recombination:

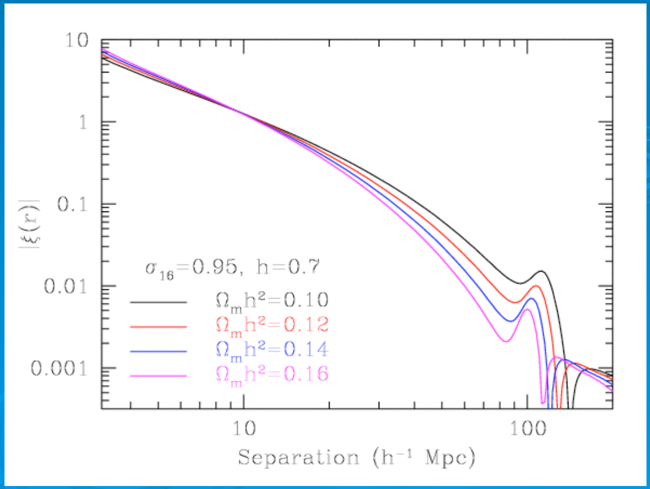
- Universe is neutral.
- Photons can travel freely past the baryons.
- Phase of oscillation at t_{rec} affects late-time amplitude.



Sound Waves

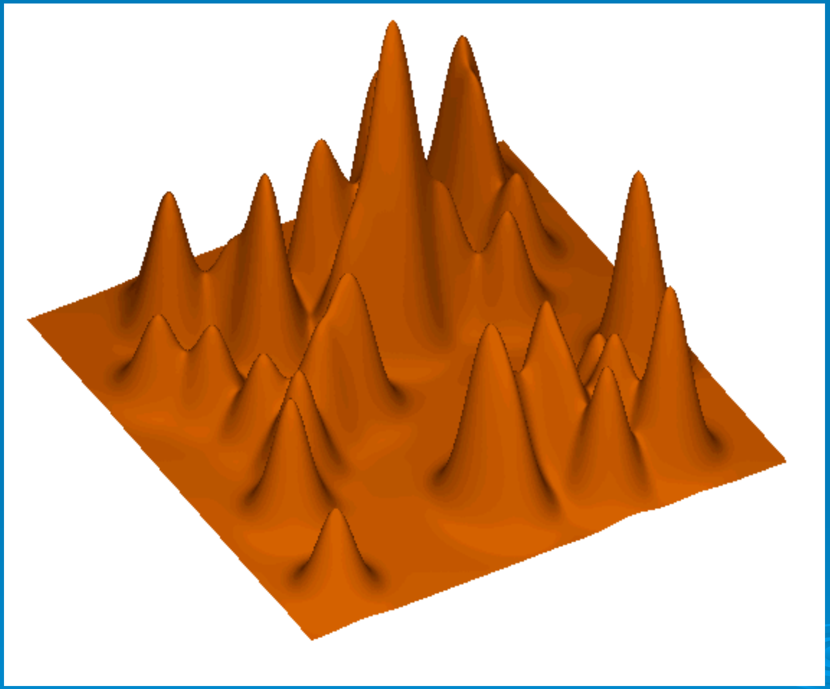
- Each initial overdensity (in DM & gas) is an overpressure that launches a spherical sound wave.
- This wave travels outwards at 57% of the speed of light.
- Pressure-providing photons decouple at recombination. CMB travels to us from these spheres.
- Sound speed plummets. Wave stalls at a radius of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



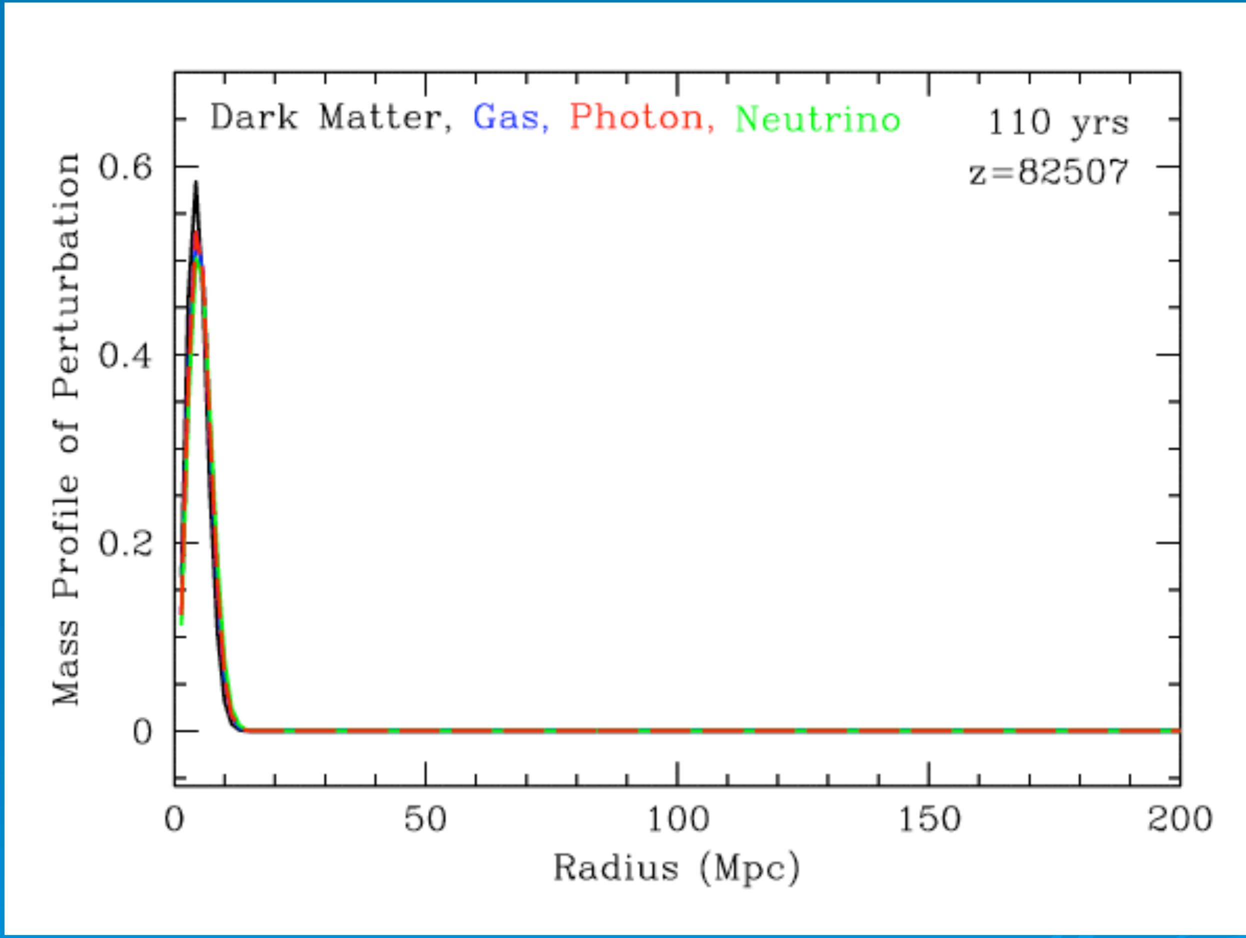


A Statistical Signal

- 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

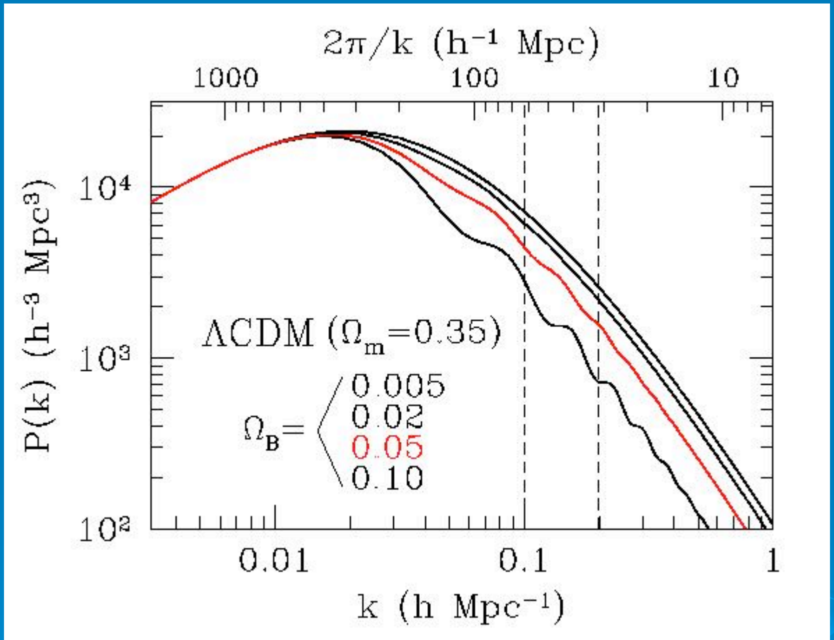


Remember: This is a tiny ripple on a big background.

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

Acoustic Oscillations in Fourier Space

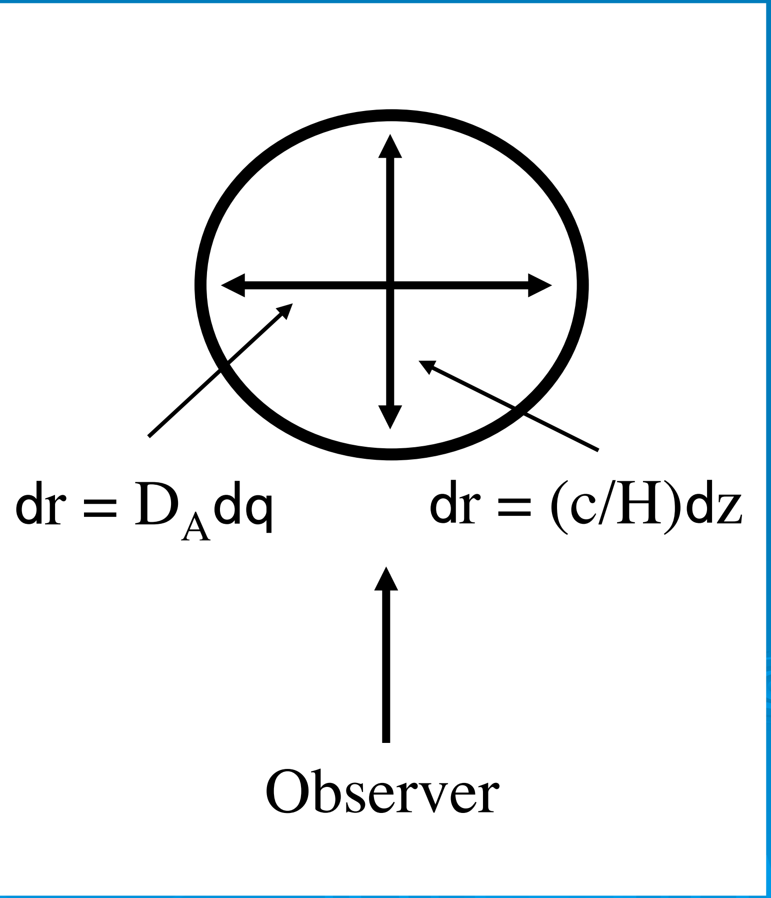
- A crest launches a planar sound wave, which at recombination may or may not be in phase with the next crest.
- Get a sequence of constructive and destructive interferences as a function of wavenumber.
- Peaks are weak — suppressed by the baryon fraction.
- Higher harmonics suffer from Silk damping.



Linear regime matter power spectrum

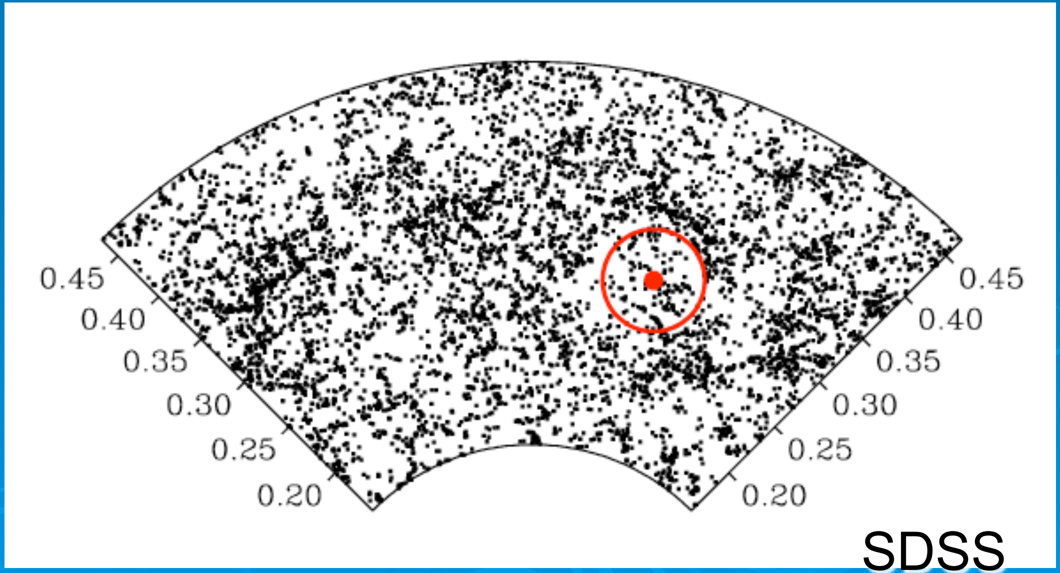
A Standard Ruler

- The acoustic oscillation scale depends on the sound speed and the propagation time.
  - These depend on the matter-to-radiation ratio ($W_m h^2$) and the baryon-to-photon ratio ($W_b h^2$).
- 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 $D_A(z)$!



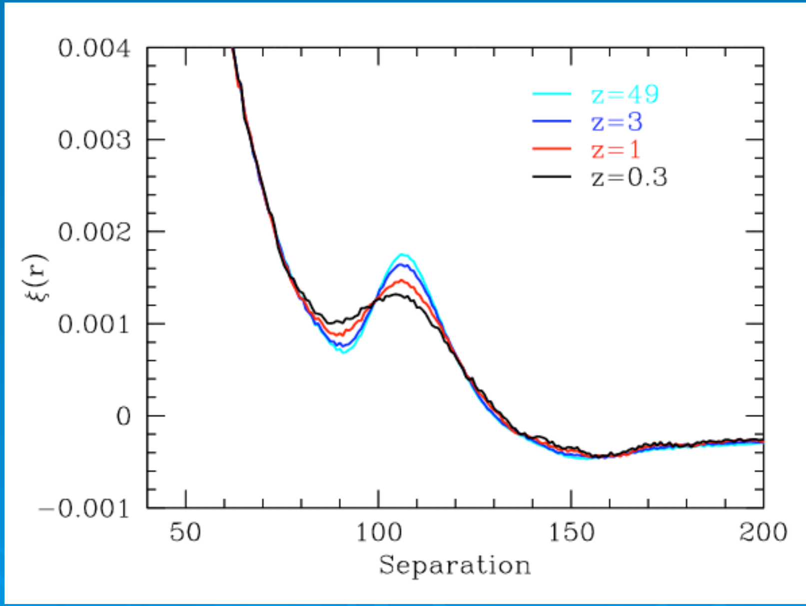
Galaxy Redshift Surveys

- 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
- Partially degrade the BAO peak, but systematics are small because this is a very large preferred scale.



Non-linear Structure Formation

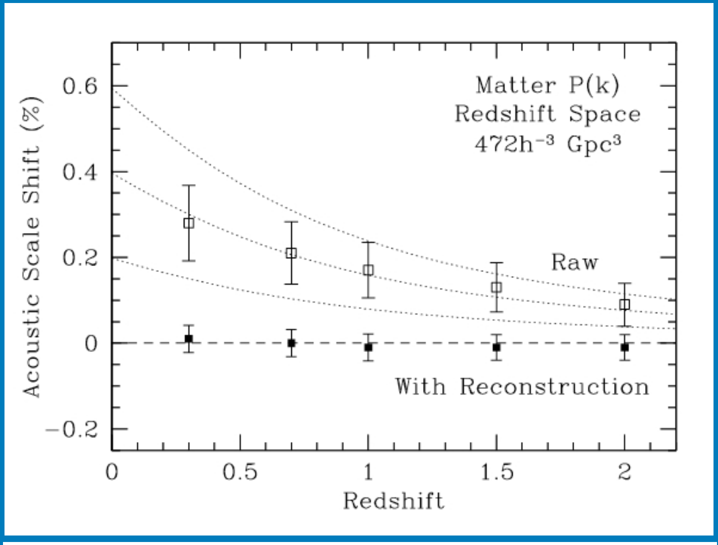
- The acoustic signature is carried by pairs of galaxies separated by 150 Mpc.
- Nonlinearities push galaxies around by 3-10 Mpc. Broadens peak, making it hard to measure the scale.
  - Non-linearities are increasingly negligible at z>1. Linear theory peak width dominates.
- Moving the scale requires net infall on 150 Mpc scales.
  - This depends on the over-density inside the sphere, which is about 1%.
  - Over- and underdensities cancel, so mean shift is <0.5%.
  - Simulations confirm that the shift is <0.5%.

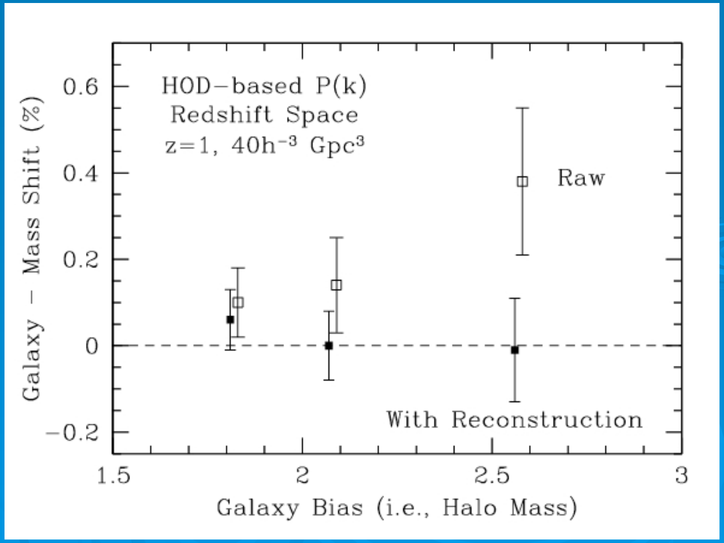


Seo & DJE (2005); DJE, Seo, & White (2007)

BAO in Simulations

- N-body simulations show the acoustic peak to be stable.
  - Shifts of 0.3% at z=0, highly predictable.
- Halo-based galaxy bias yields an additional shift, of order 0.5% for high biases.
- Effect is well matched to 2nd-order perturbation theory calculation of Padmanabhan & White (2009).
- These shifts can be predicted and removed, but we'll see a better way later in the talk.



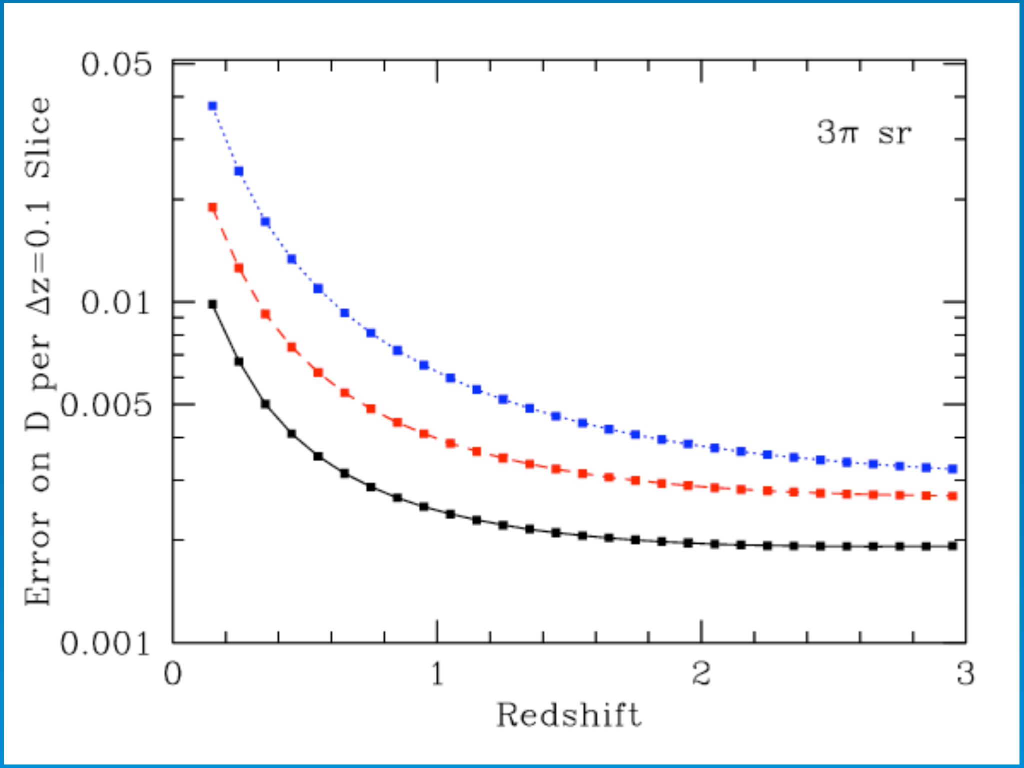


Seo et al. (2010); Mehta et al. (2011)

Virtues of the Acoustic Peaks

- The acoustic signature is created by physics at z=1000 when the perturbations are 1 in 10^4. Linear perturbation theory is excellent.
- Measuring the acoustic peaks across redshift gives a geometrical measurement of cosmological distance.
- The acoustic peaks are a manifestation of a preferred scale. Still a very large scale today, so non-linear effects are mild and dominated by gravitational flows that we can simulate accurately.
  - No known way to create a sharp scale at 150 Mpc with low-redshift astrophysics.
- Measures absolute distance, including that to z=1000.
- Method has intrinsic cross-check between $H(z)$ & $D_A(z)$, since D_A is an integral of H.

Cosmic Variance Limits



Seo & DJE (2008)

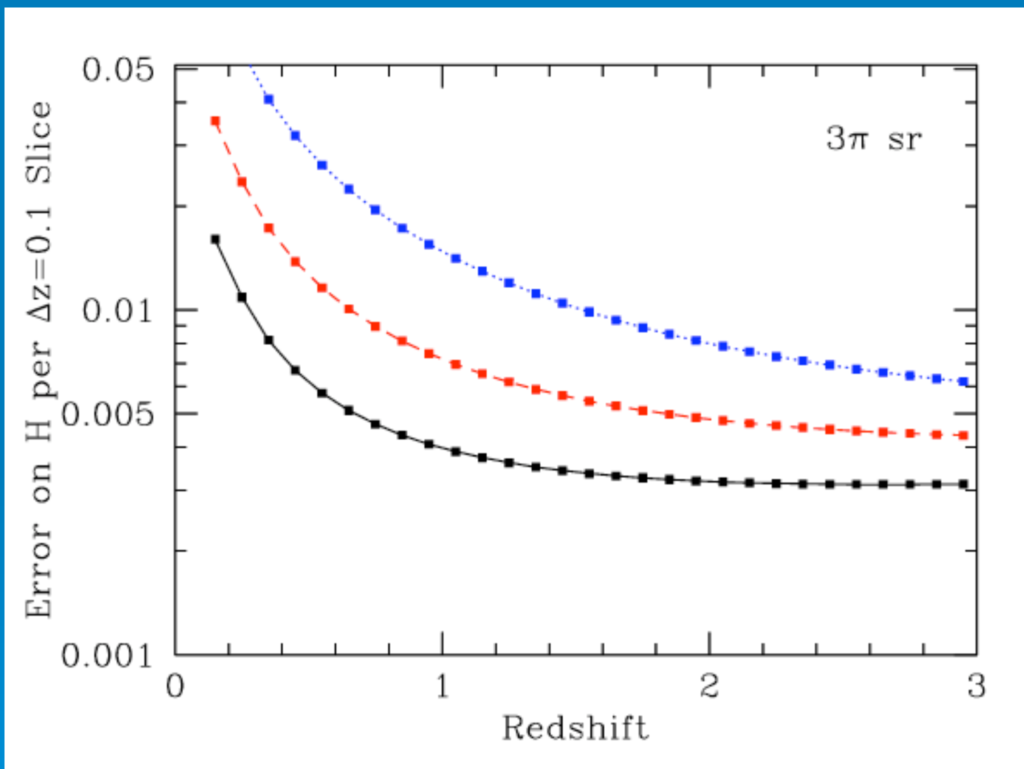
Errors on *D*(*z*) in Dz=0.1 bins. Slices add in quadrature.

Black: Linear theory

Blue: Non-linear theory

Red: Reconstruction by 50% (reasonably easy)

Cosmic Variance Limits



Seo & DJE (2008)

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

Black: Linear theory

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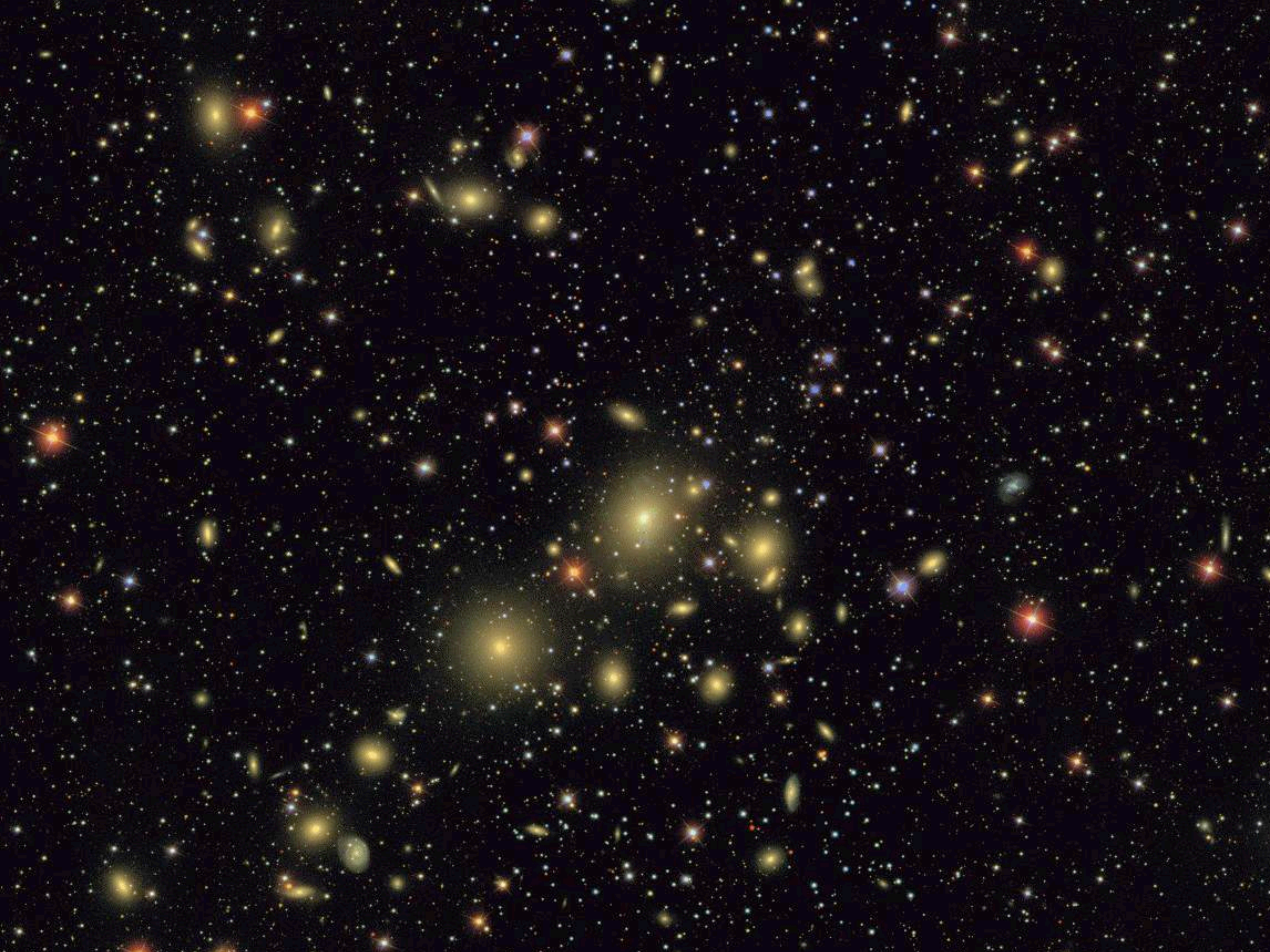
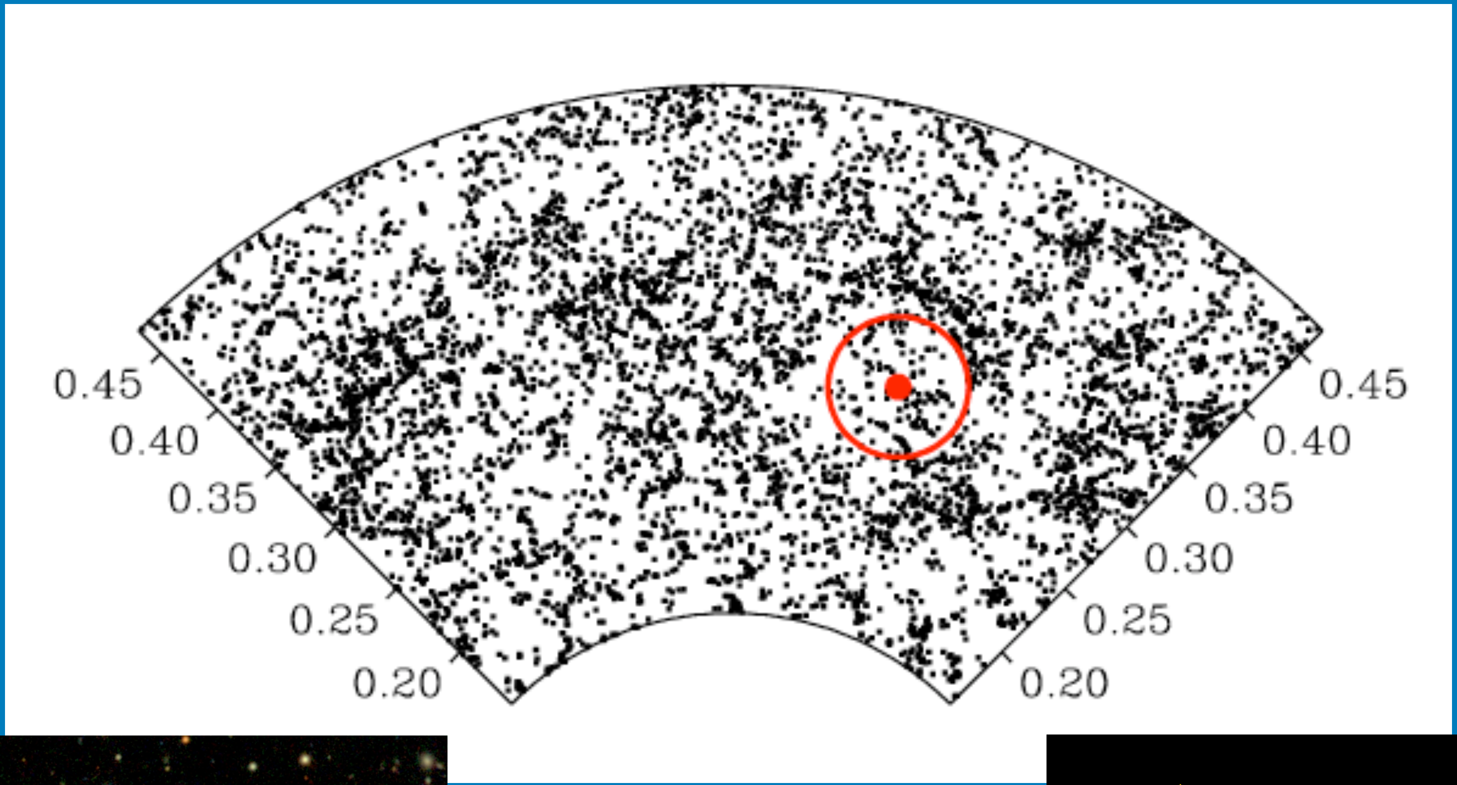
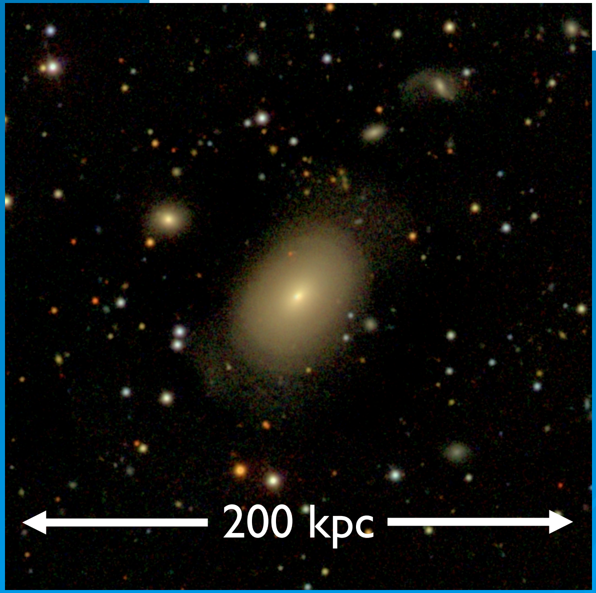
The Sloan Digital Sky Survey

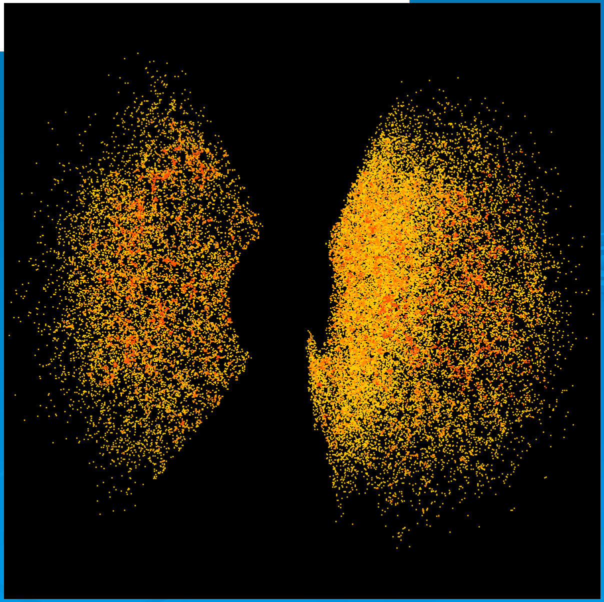
- The SDSS is the world's largest galaxy redshift survey.
- Took digital pictures of one quarter of the sky in 5 bandpasses.
  - Over 350 million objects.
- Then performed spectroscopy of 1.5 million objects, mostly galaxies.
- Project began in 1990, started taking data in 1998, finished in 2008.
- SDSS-III started in 2008; more on this later.



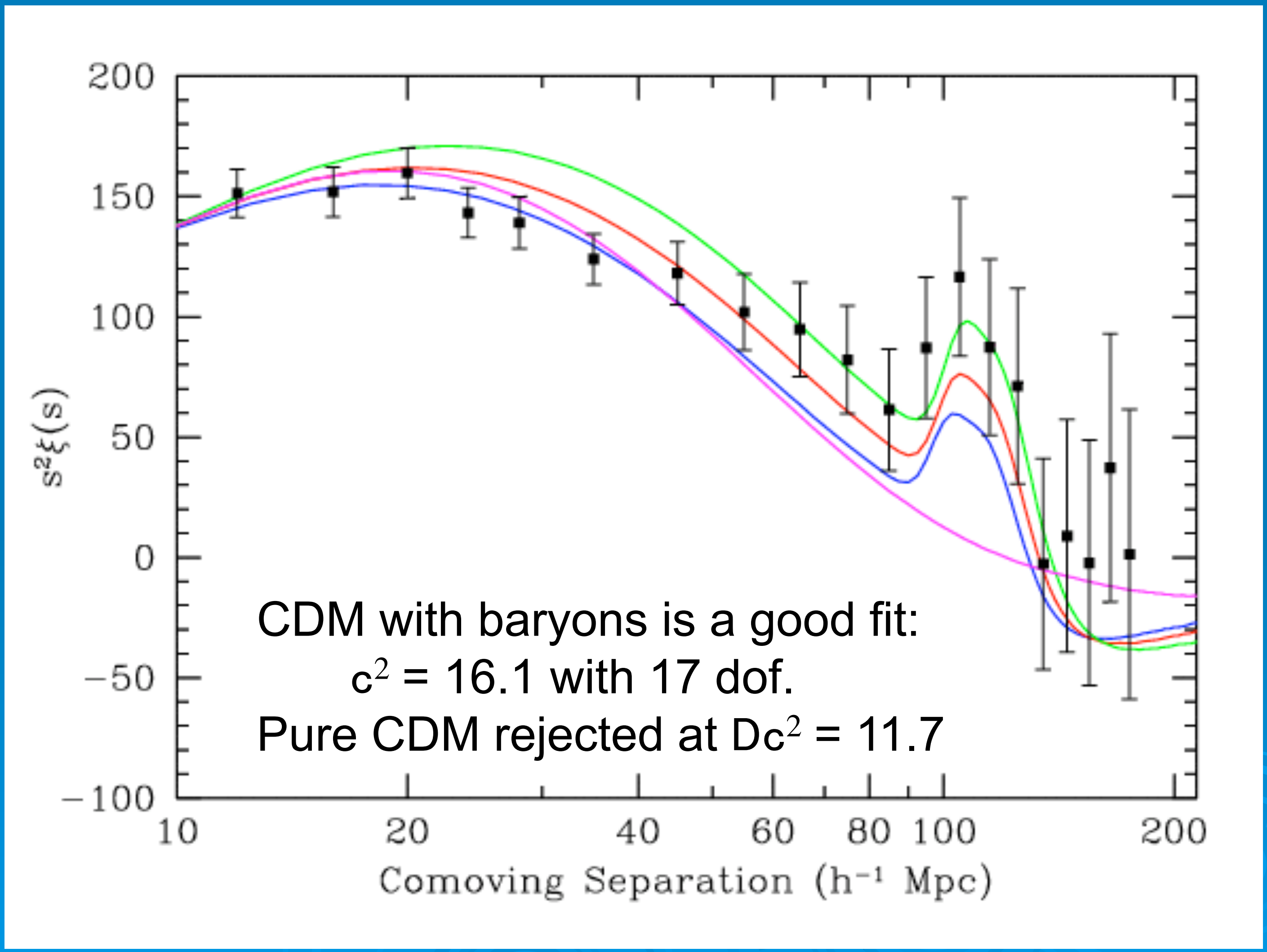




SDSS Luminous Red Galaxies

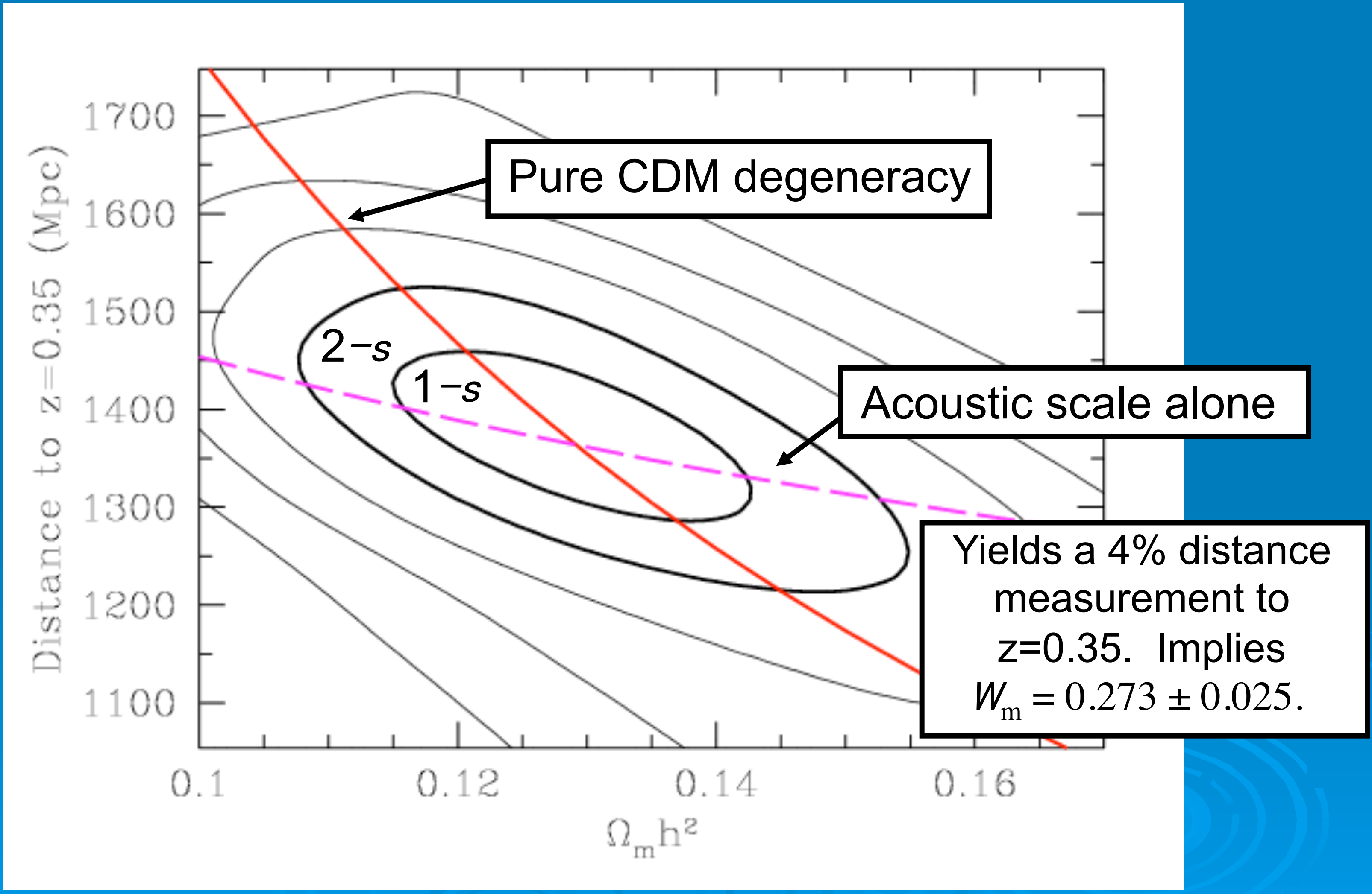


Detection of the Acoustic Peak



Eisenstein et al. (2005)

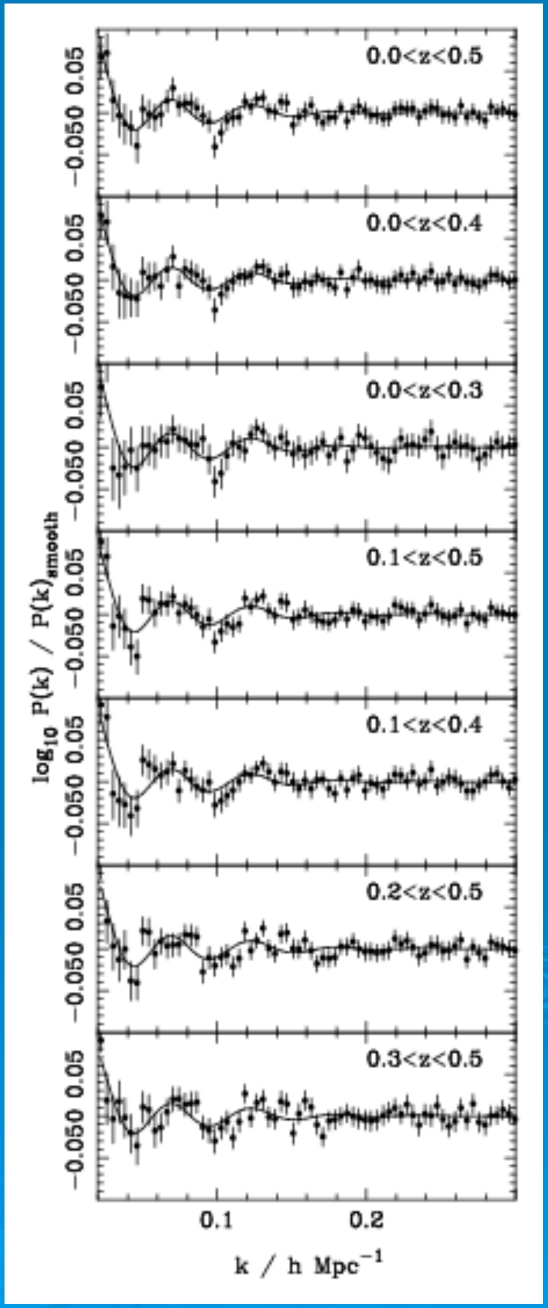
Cosmological Constraints



Eisenstein et al. (2005)

BAO in SDSS-II DR7

- We have also done several power spectrum analyses.
- Most recently, Percival et al. (2009) analysis of BAO signature in SDSS-II (LRG+MAIN) and 2dF GRS.
- Reid et al. (2009) analysis of LRG power spectrum, including halo compression and quasi-linear corrections to use the broadband power spectra.
- Both use FKP P(k) techniques.
- DR7 covers 7900 sq deg and has about 110K LRGs, about twice the Eisenstein et al. (2005) data set.



Percival et al. (2009)

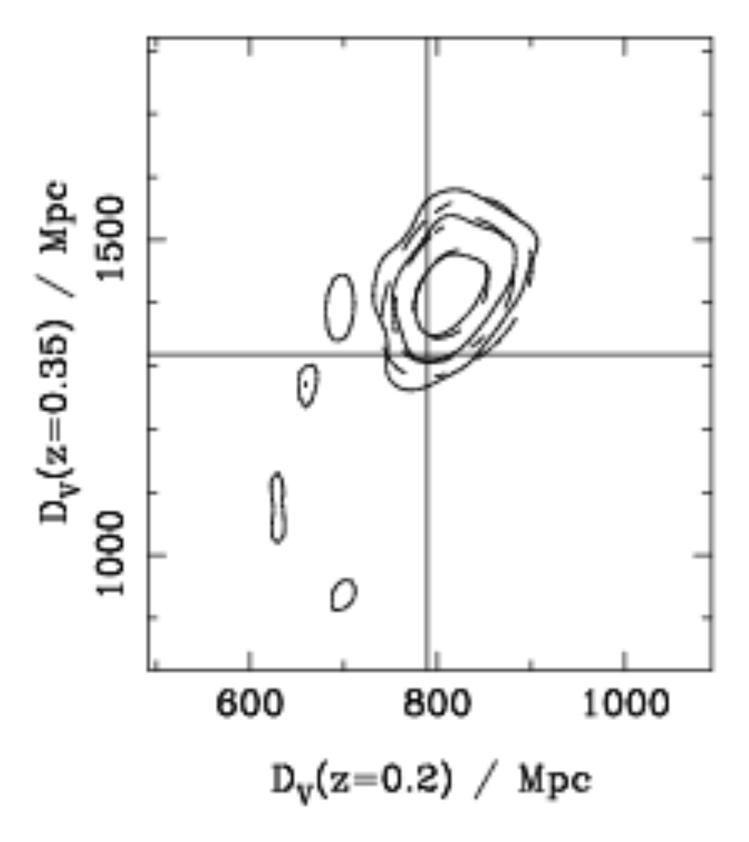
BAO Distance Measurements

- Percival et al. (2009) fits a distance-redshift relation held at z=0.2 and 0.35.
- Can express result as:

$D_V(0.275) = 1104 \pm 30$ Mpc (2.7%)
$\times(\Omega_m h^2/0.1326)^{-0.25}$
$\times(\Omega_b h^2/0.02273)^{-0.134}$, and

$D_V(0.35)/D_V(0.20) = 1.736 \pm 0.065$

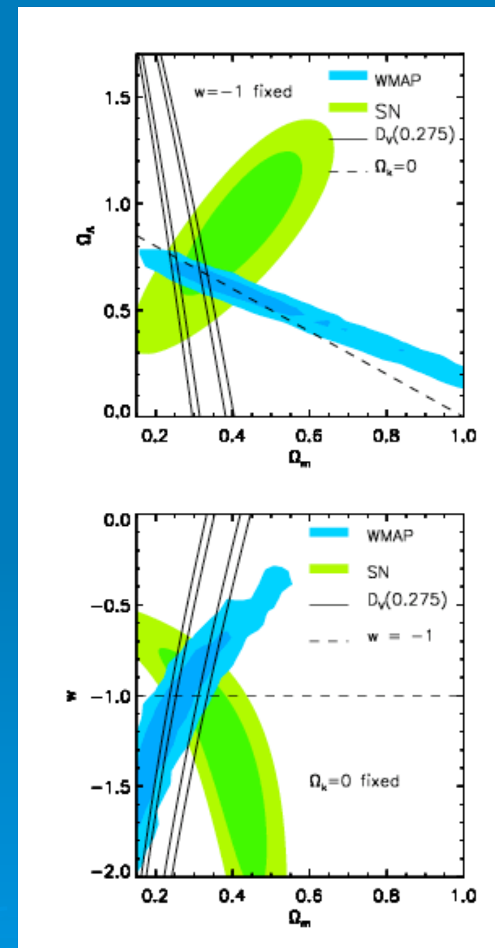
  - LCDM is 1.67, so only 1-sigma away; EdS is 1.55.



Percival et al. (2009)

Low-redshift constraints

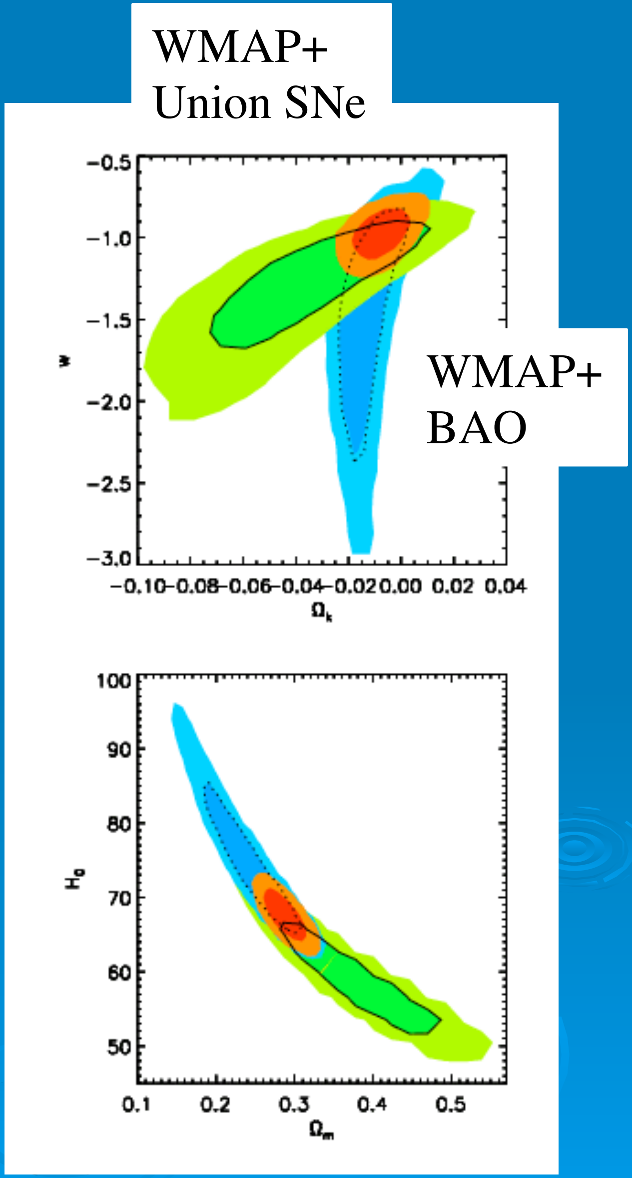
- Using this standard ruler and CMB constraints on the matter and baryon density, we can use the standard ruler to measure H_0 and hence W_m.
  - $W_m = (0.282 \pm 0.018)$
  - $H_0 = (68.6$ –+ 2.2 km/s/Mpc)
    - Both with small dependencies on $W_m h^2$, W_K, and w_0.
- This depends only the low-z distance scale.



Percival et al. (2009)

Combination with WMAP & SNe

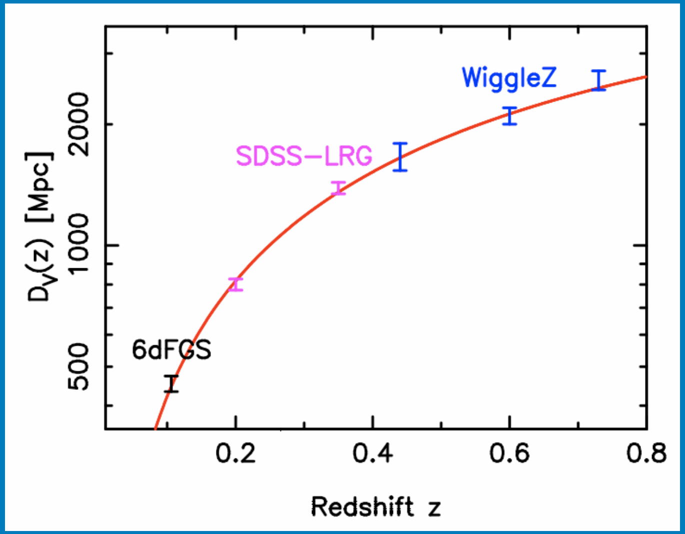
- Good consistency between the three data sets and between the two analyses. “Tensions” are not statistically significant.
- Models that are both non-flat and have constant *w* give overlap at flat LCDM.
  - $W_K = -0.006 \pm 0.008$
  - $w = -0.97 \pm 0.10$
  - $W_m = 0.290 \pm 0.019$
  - $H_0 = 67.6 \pm 2.2$ km/s/Mpc

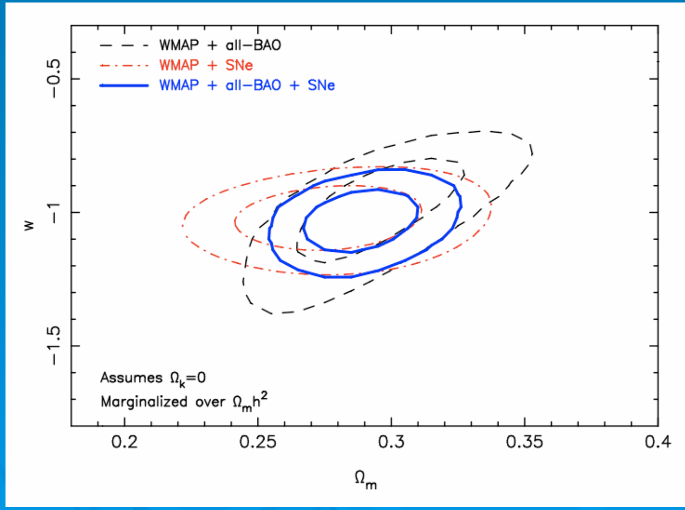


Percival et al. (2009)

New BAO Detections!

- Two new surveys published BAO detections in 2011.
- WiggleZ on the Anglo-Australian Telescope
  - 200k galaxies over 800 sq deg.
  - 3.8% measurement at z=0.6.
  - Blake et al. (2011)
- 6dF Galaxy Survey
  - 75k galaxies over 17,000 sq deg.
  - 4.5% measurement at z=0.1.
  - Beutler et al. (2011)
- We now have a BAO Hubble diagram!
  - Excellent agreement with SNe.

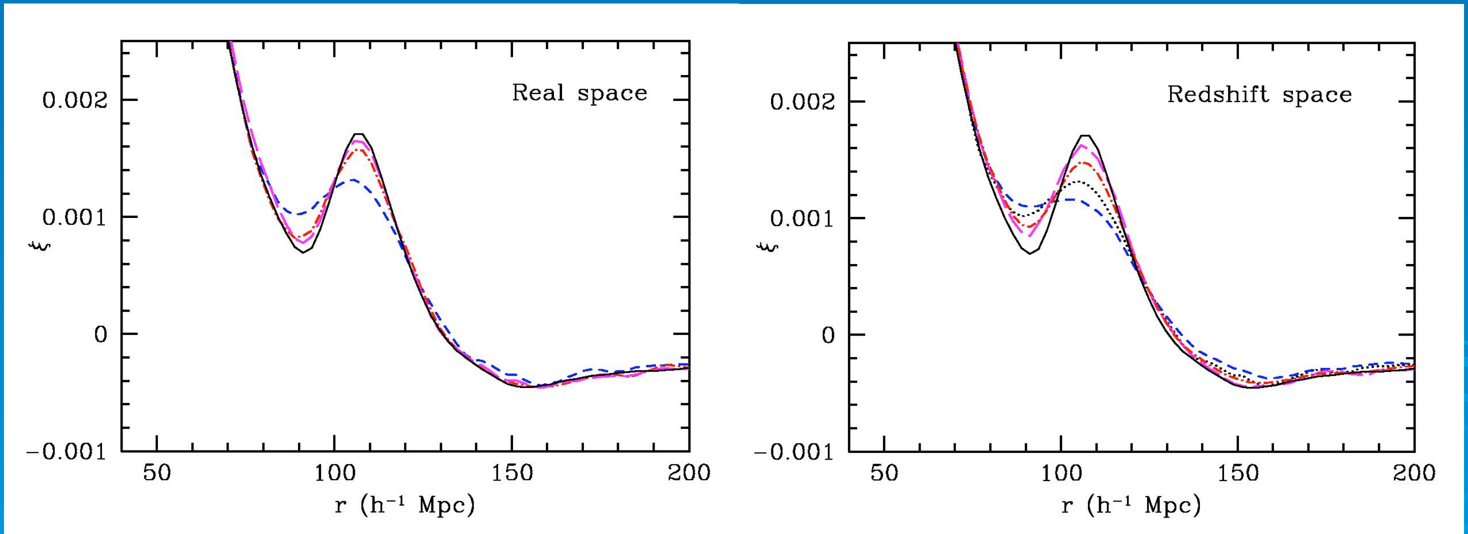




Blake et al. (2011)

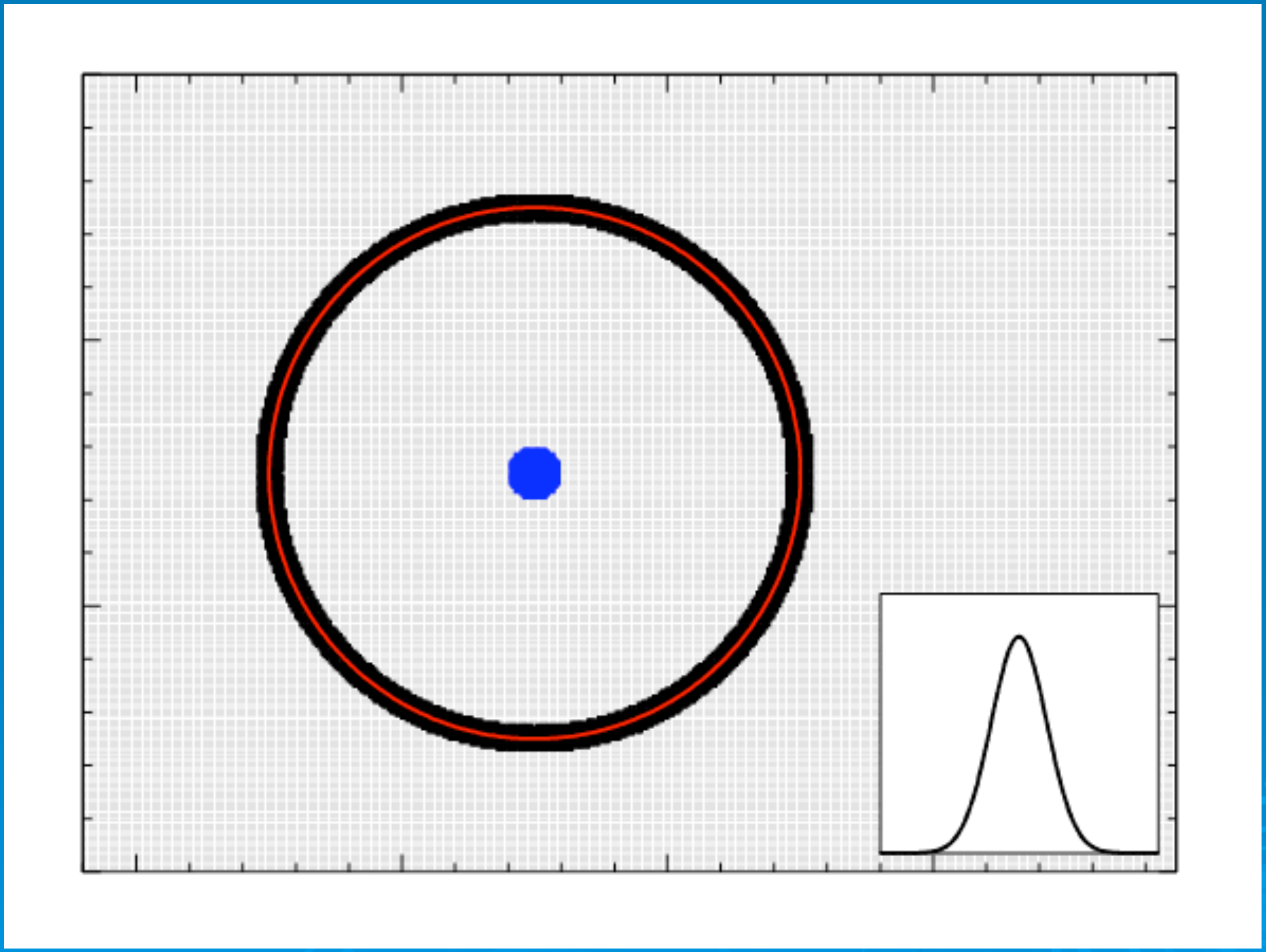
Improving the Acoustic Peak

- Most of the non-linear degradation is due to bulk flows. These are produced by the same large-scale structure that we are measuring for the BAO signature.
- Map of galaxies tells us where the mass is that sources the gravitational forces that create the bulk flows.
- Can run this backwards and undo most non-linearity.
- Restore the statistic precision available per unit volume!



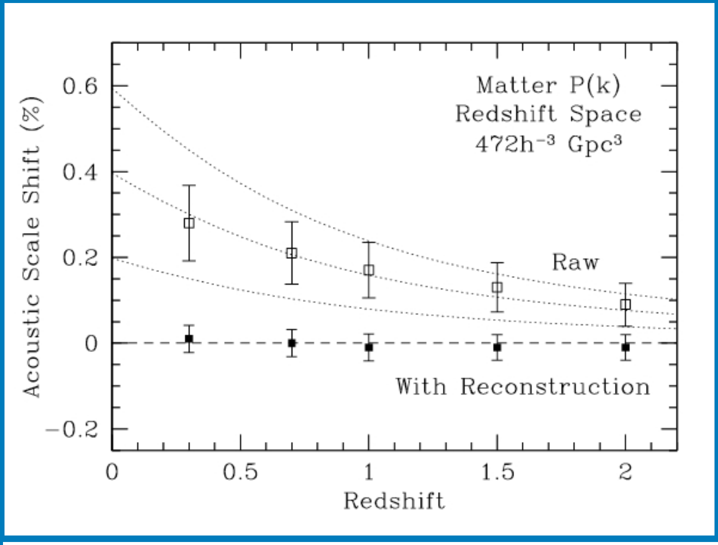
DJE, Seo, Sirko, & Spergel (2007)

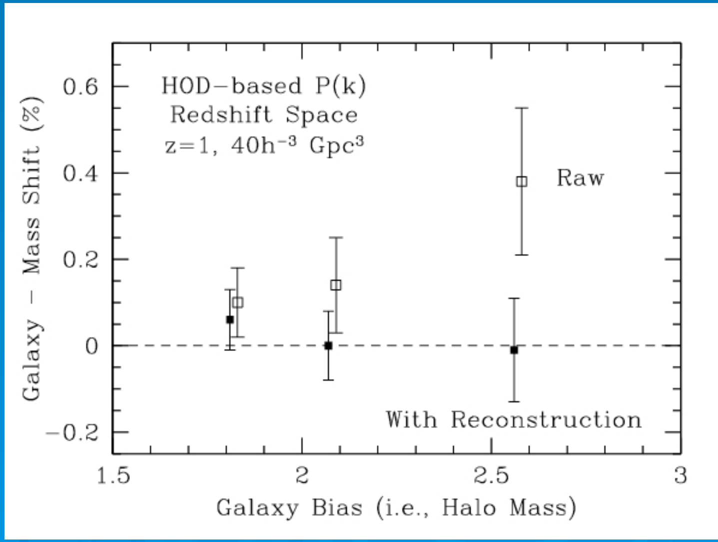
Reconstruction in Action



Reconstruction in Simulations

- In large sets of simulations, both periodic box and with a survey mask, reconstruction improves the precision of the measurement of the acoustic scale.
- But it also reduces the shift due to non-linear structure formation and galaxy bias.
  - Less than 0.02% in the matter power spectrum!
  - 0.1% for galaxy bias models.
- This is because we are correcting for the large-scale flows that create the shifts.



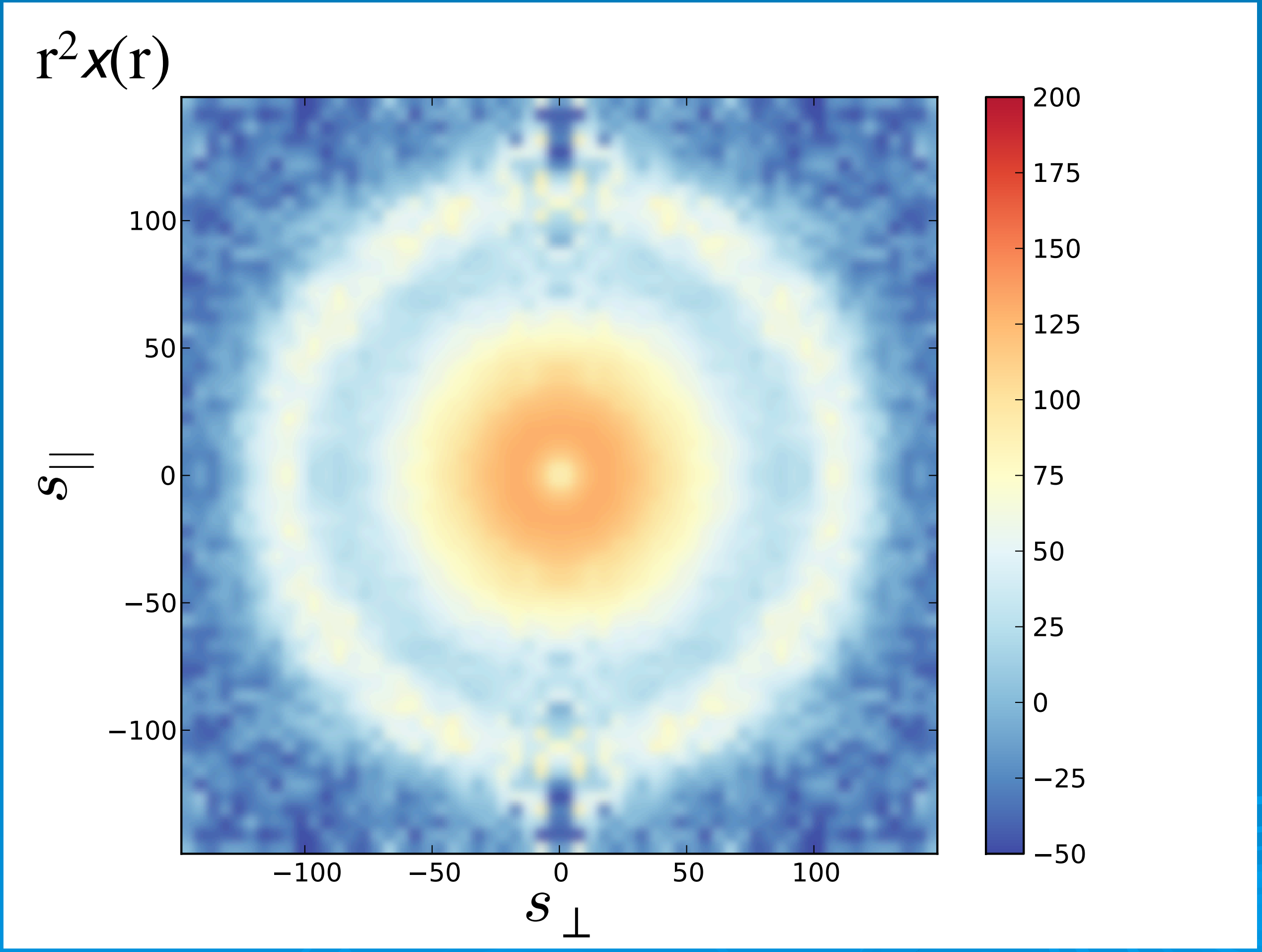


Seo et al. (2010); Mehta et al. (2011)

DR7 with Reconstruction

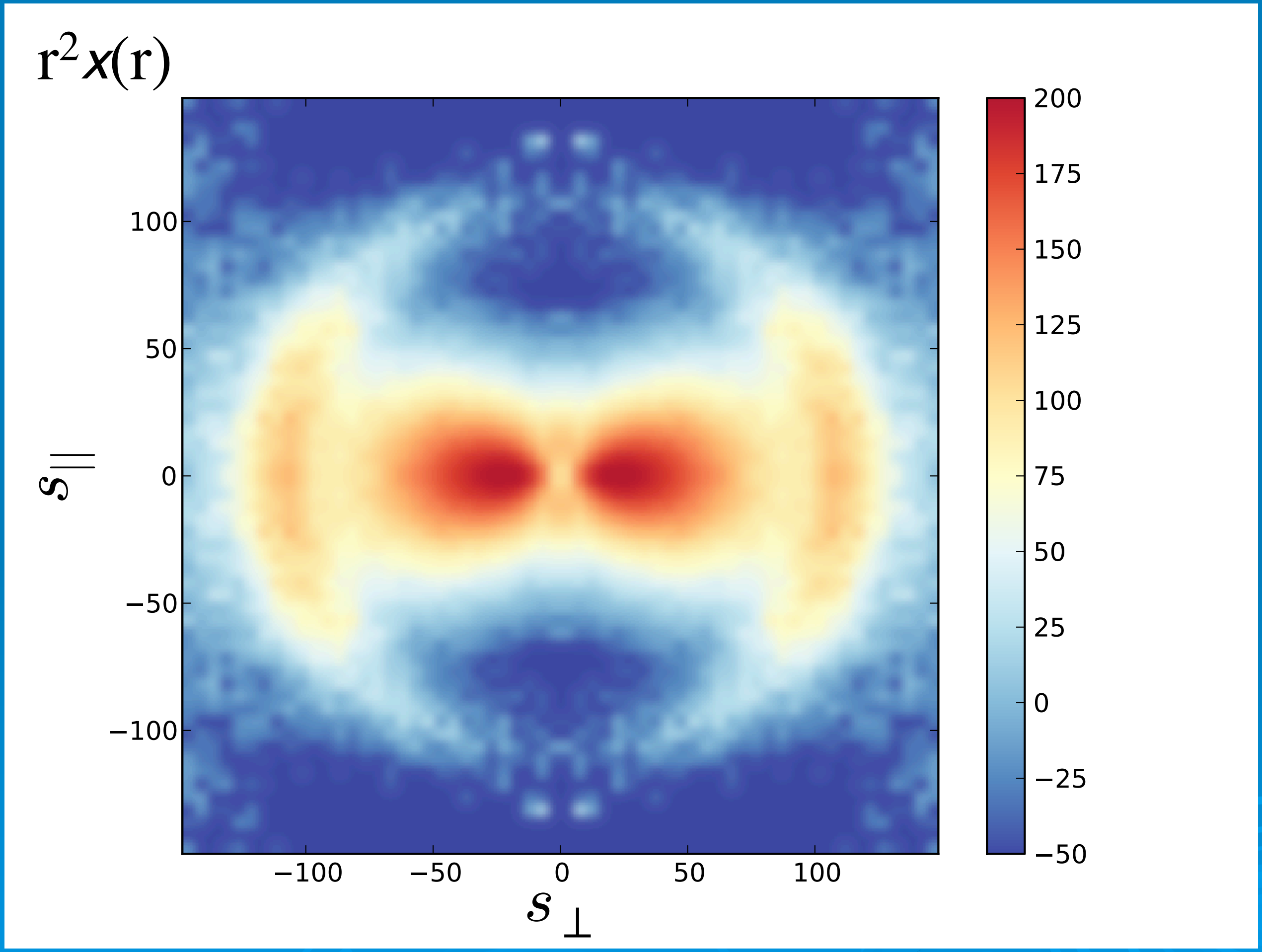
- Padmanabhan et al., Xu et al., and Mehta et al. (in final prep) will present a new analysis of the SDSS-II DR7 Luminous Red Galaxy sample.
  - 106k galaxies over 7200 sq deg.
- First analysis to include reconstruction.
- Improves errors as if we were tripling the survey volume.

Real-space Clustering



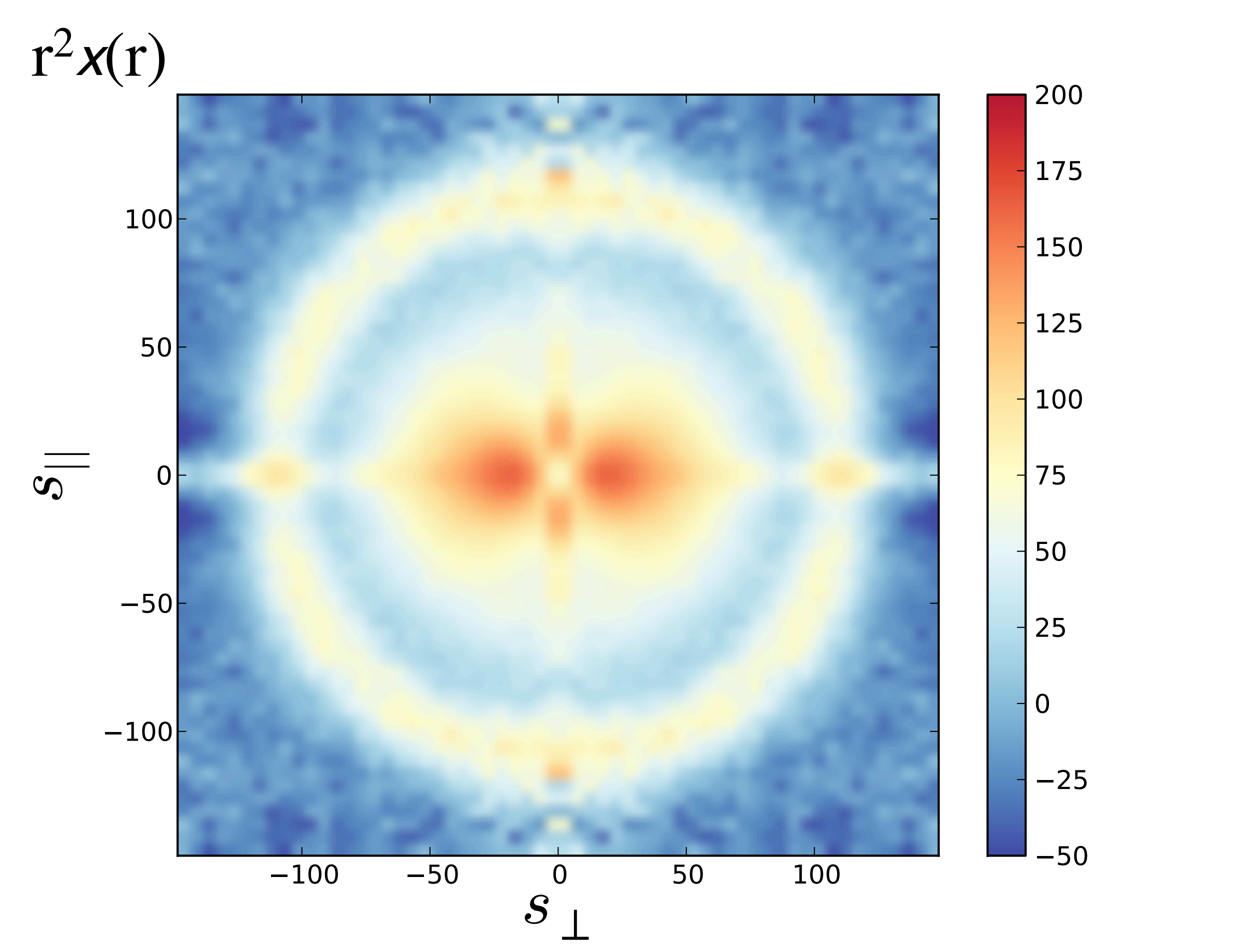
DR7 Mock Catalogs from Pamanabhan et al. (2012)

Redshift-space Clustering



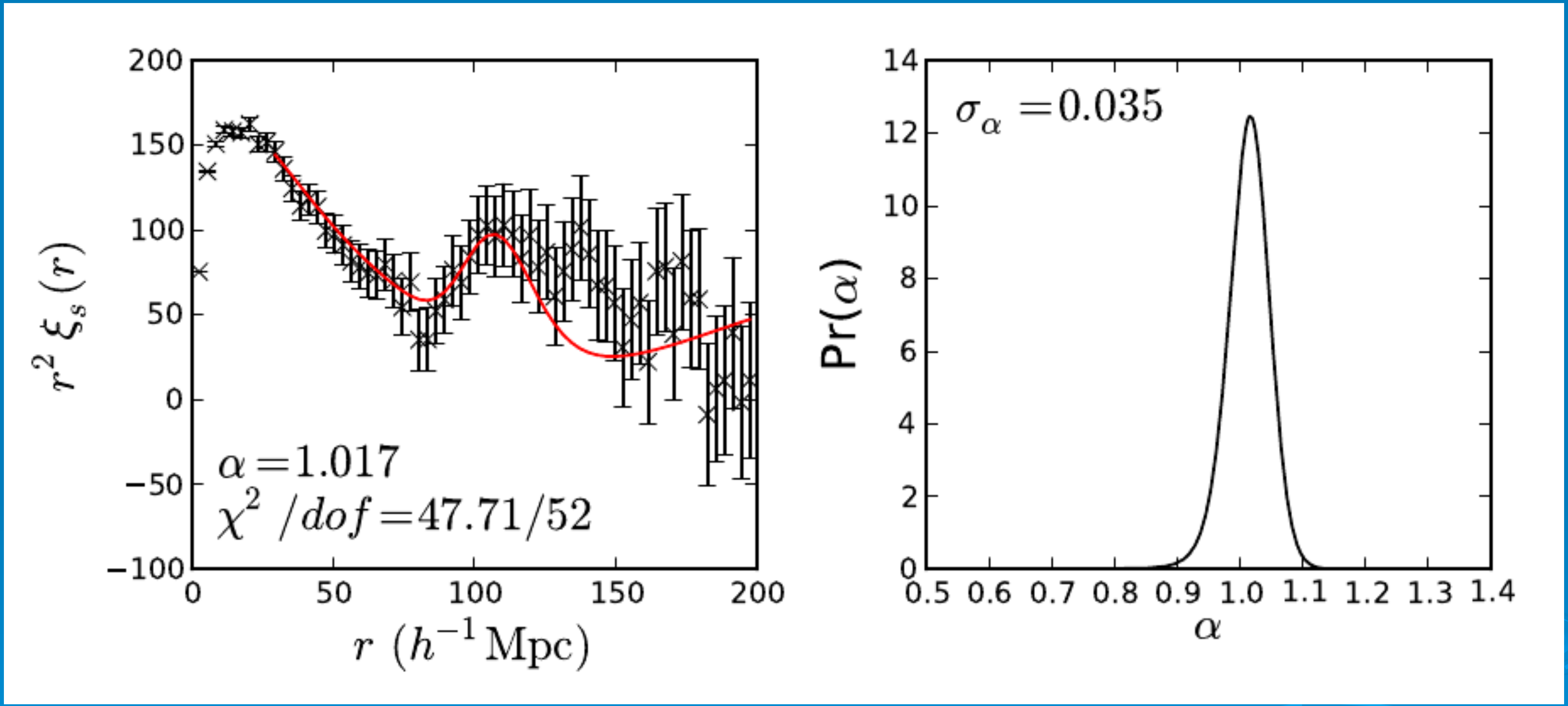
DR7 Mock Catalogs from Pamanabhan et al. (2012)

Redshift-Space Clustering after Reconstruction



DR7 Mock Catalogs from Pamanabhan et al. (2012)

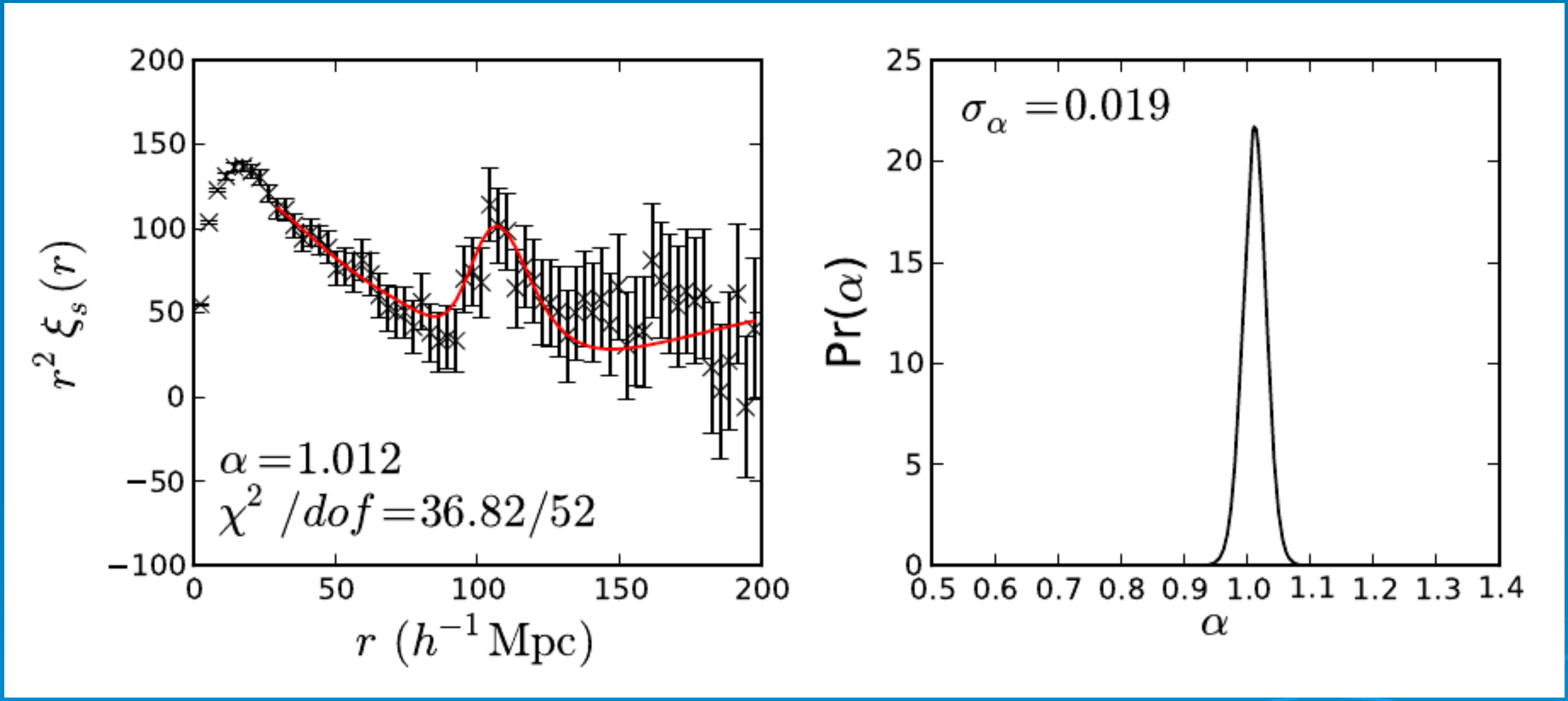
Before Reconstruction



- Large-scale correlation function and measurement of the acoustic scale.

Pamanabhan et al. (2012); Xu et al. (2012)

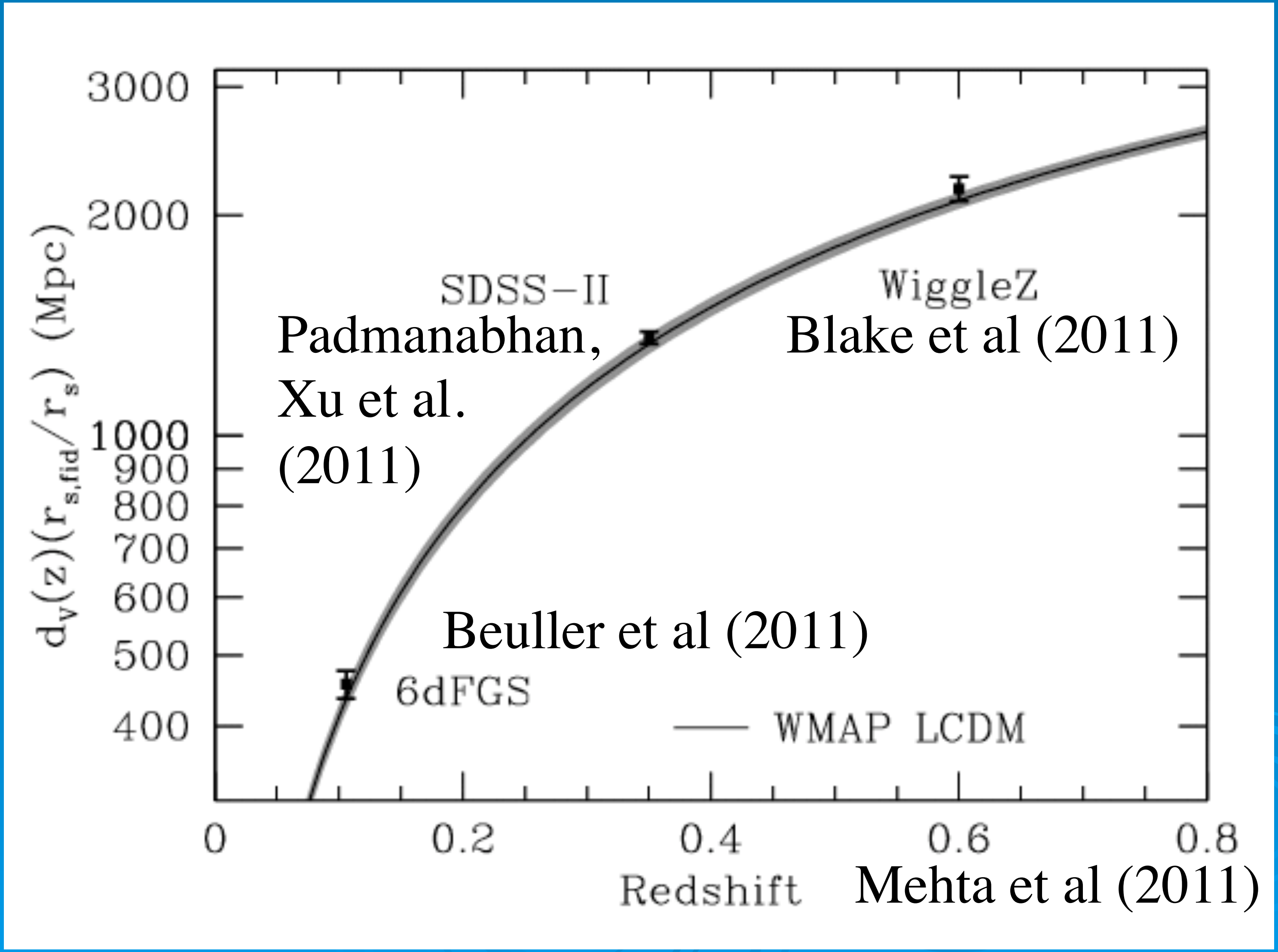
After Reconstruction

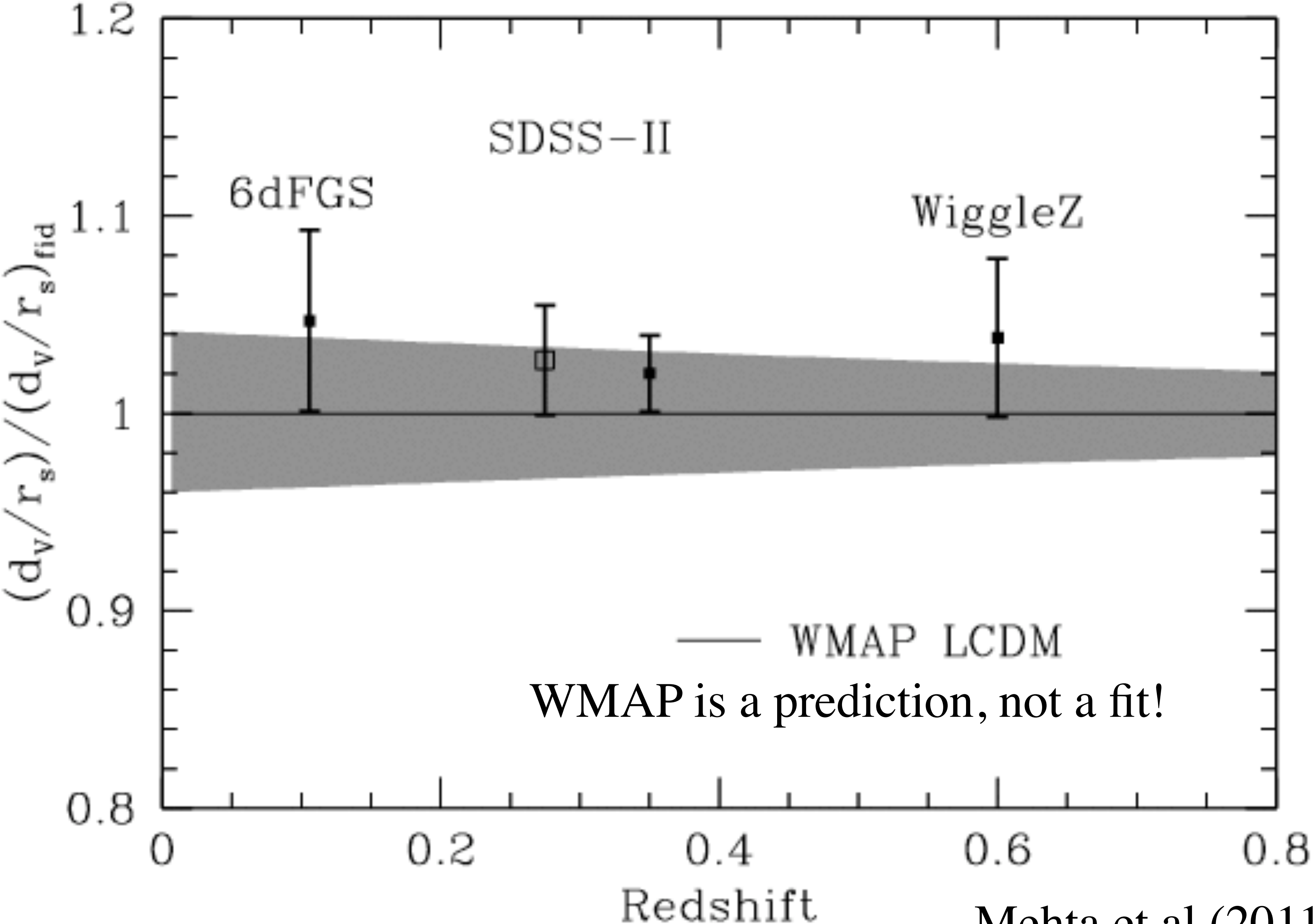


- Reconstruction sharpens the errors from 3.5% to 1.9%, equivalent to tripling the survey volume.

Pamanabhan et al. (2012); Xu et al. (2012)

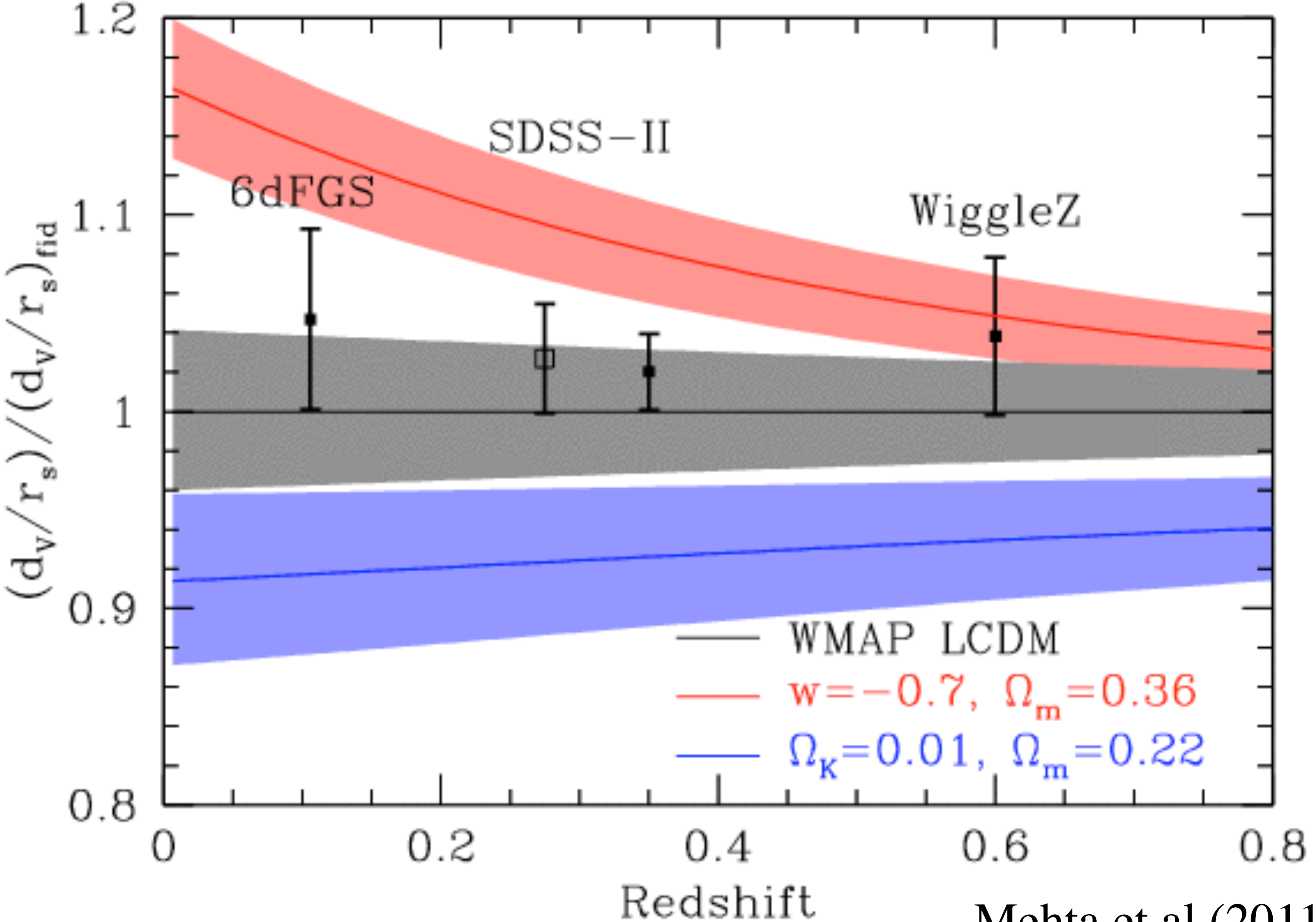
A BAO Hubble Diagram





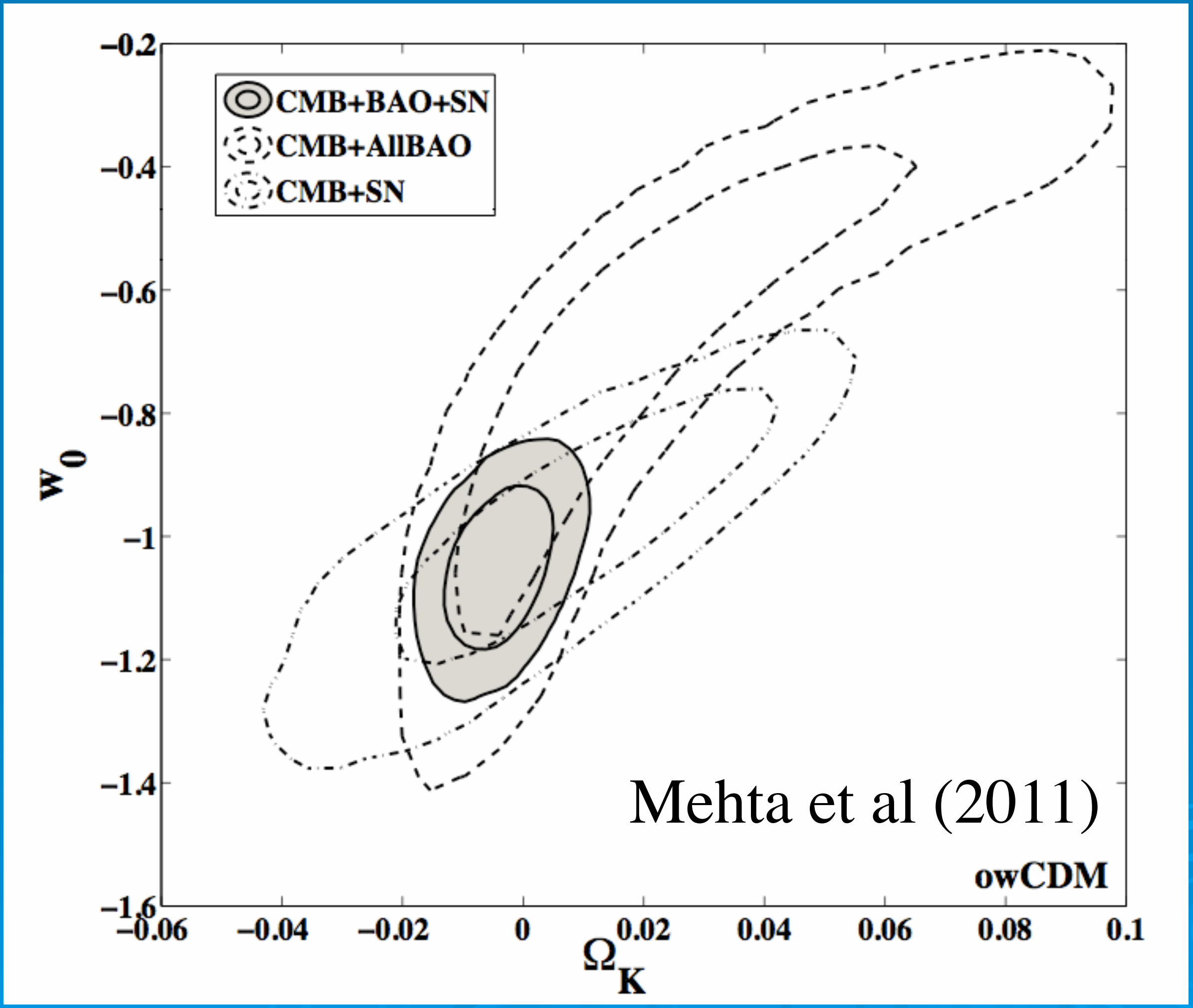
WMAP is a prediction, not a fit!

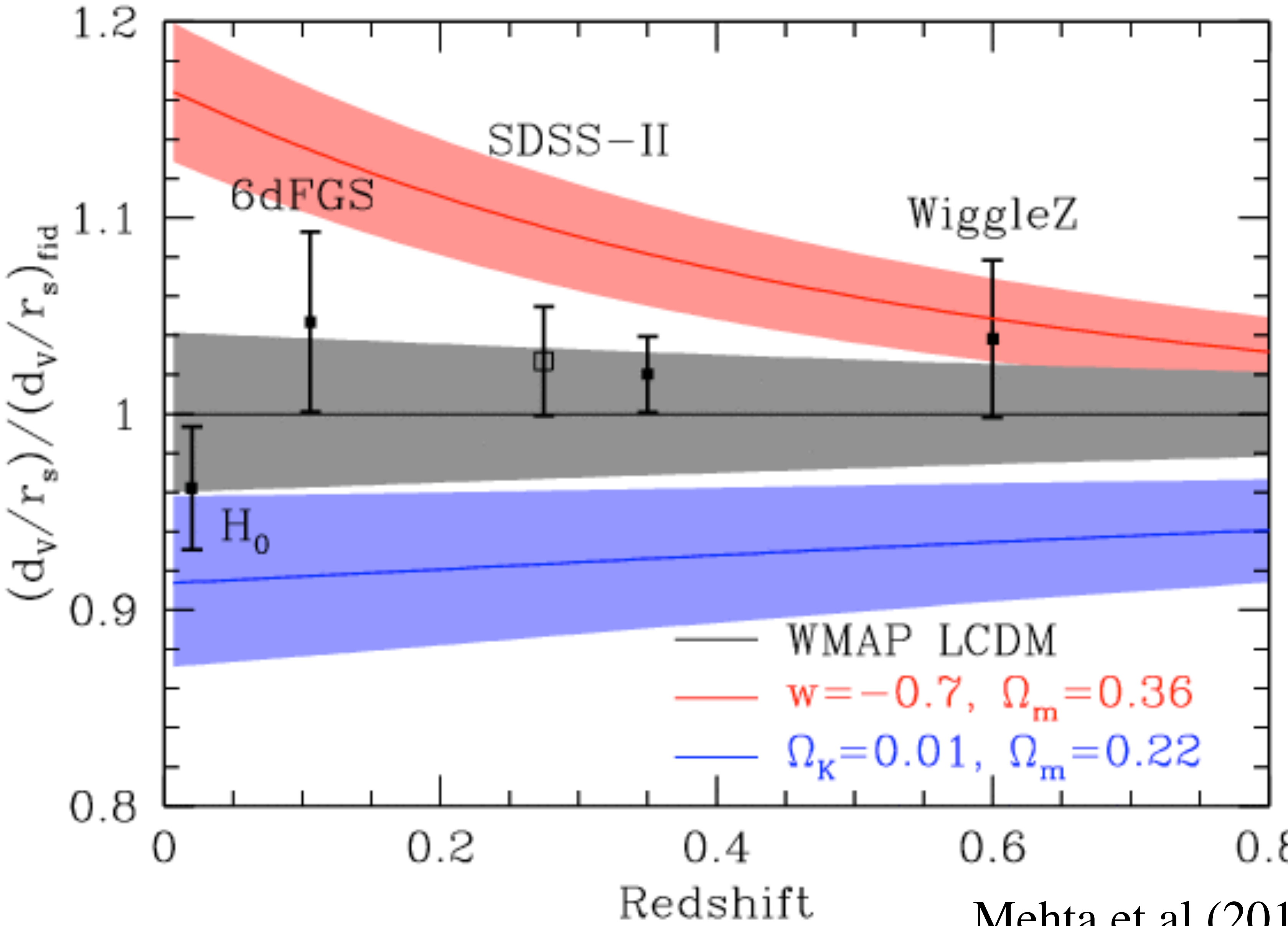
Mehta et al (2011)



Mehta et al (2011)

BAO & SNe Together





Mehta et al (2011)

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 ($W_m h^2$).
  - Measurements of W_m (e.g., from distance ratios) then imply H_0.
- What if the radiation density were different, i.e. more/ fewer neutrinos or something new?
  - Sound horizon would shift in scale. LSS inferences of W_m, W_k, $w(z)$, etc, would be correct, but $W_m h^2$ and H_0 would shift.
  - Minor changes in baryon fraction and CMB anisotropic stress.
- So comparison of H_0 from direct measures to CMB-based inferences are a probe of "dark radiation".
  - 1% in H_0 is 0.2 effective neutrino species.

DJE & White (2004)

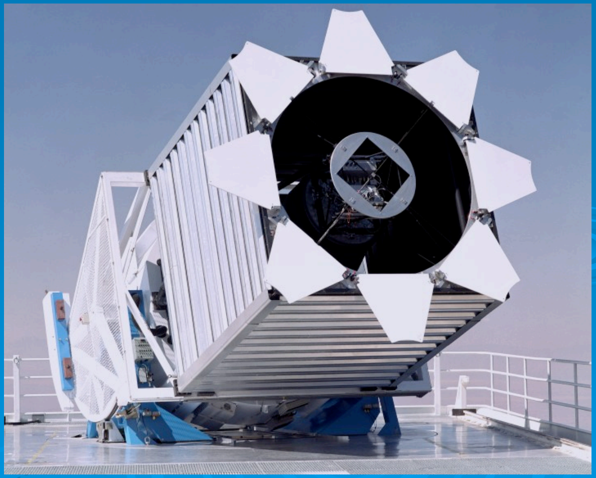
- Or can check BAO+SNe prediction.

Coming Soon....

- SDSS-III BOSS is underway.
  - Factor of 7 increase over SDSS-II.
  - First BAO results in 2012.
- HETDEX survey will start: 800k galaxies at $z>2$.
- Bold new surveys for the end of the decade.
  - Euclid mission will survey ~50M galaxies at $0.7<z<2$.
  - WFIRST to do deeper survey over smaller area.
  - BigBOSS, DESpec, 4MOST, SUMIRE concepts.
  - 21 cm instruments.
- We have only scratched the surface of what is possible with the study of large-scale structure!

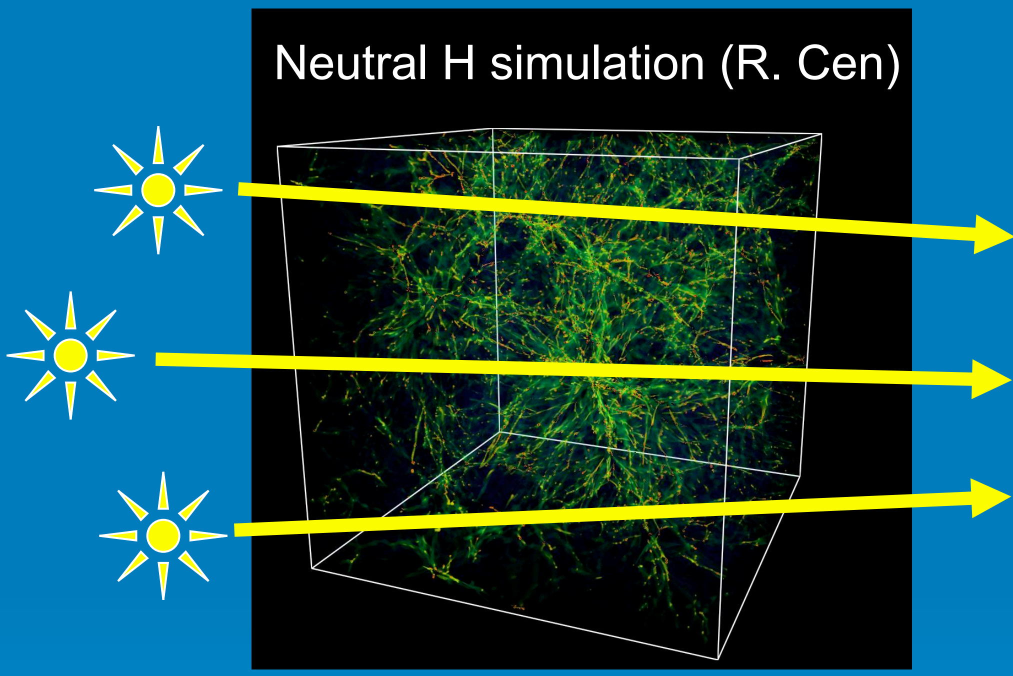
SDSS-III Baryon Oscillation Spectroscopic Survey (BOSS)

- New program for the SDSS telescope for 2008–2014.
- Definitive study of the low-redshift acoustic oscillations. 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 1% at z=0.35 and z=0.6.
  - Survey is now 40% complete!

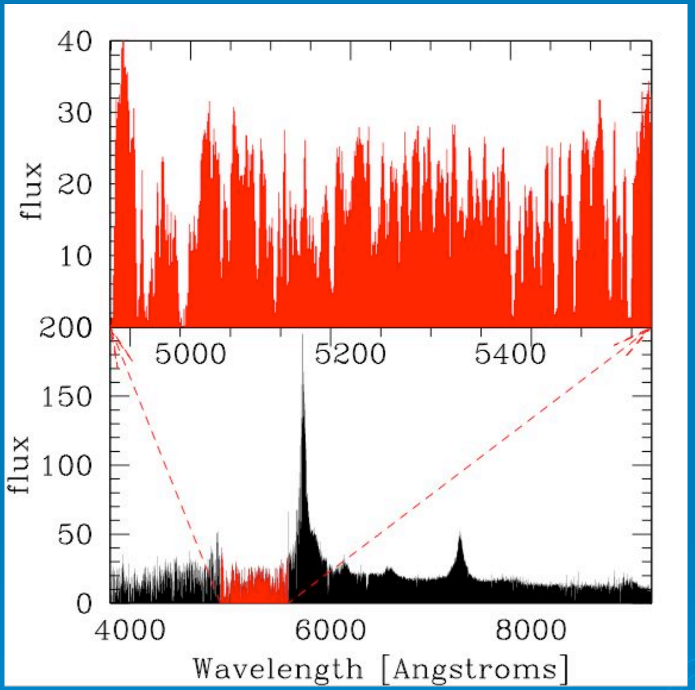


- Simultaneous project to discover the BAO in the Lyman α forest.
  - 160,000 quasars. 20% of fibers.
  - Few% measurement of D & H at z=2.3.
  - Higher risk but opportunity to open the high-redshift distance scale.
- More info at http://www.sdss3.org

Seeing Sound in the Lyman a Forest



Neutral H absorption observed
in quasar spectrum at z=3.7



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

White (2004); McDonald & DJE (2006)

BOSS Survey is Underway: 500,000 galaxies in the can!

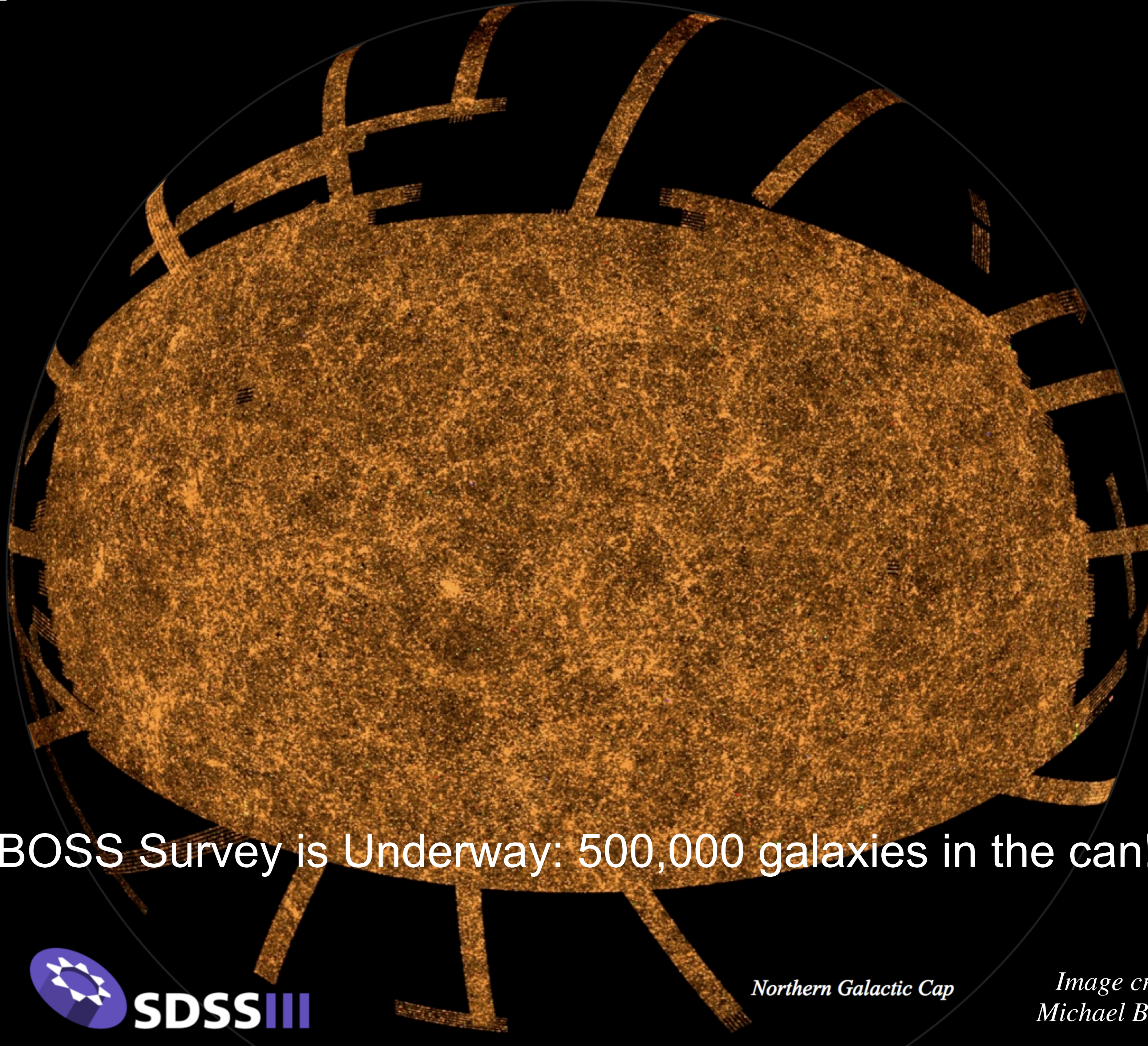


Image credit: Michael Blanton

Conclusions

- Acoustic oscillations provide a robust way to measure H(z) and $D_A(z)$.
  - Clean signature in galaxy clustering.
  - Can probe high redshift; can probe H(z) directly.
  - Independent method with good precision.
- SDSS uses the reconstructed acoustic signature to measure the distance to z=0.35 to 2%.
- Larger galaxy surveys such as SDSS-III/BOSS will push to 1% and below across a range of redshift.
- For those wanting much more info, our new review "Observational Probes of Cosmic Acceleration" by Weinberg, Mortonson, Eisenstein, Hirata, Riess, & Rozo, will be on arXiv within a week.