Measuring the Cosmic Distance Scale with SDSS-III

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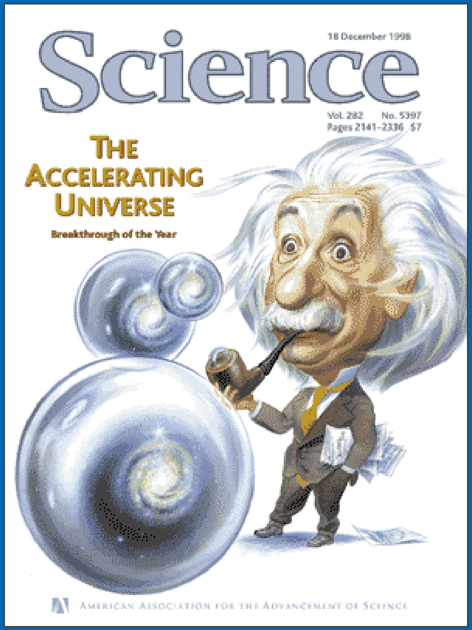
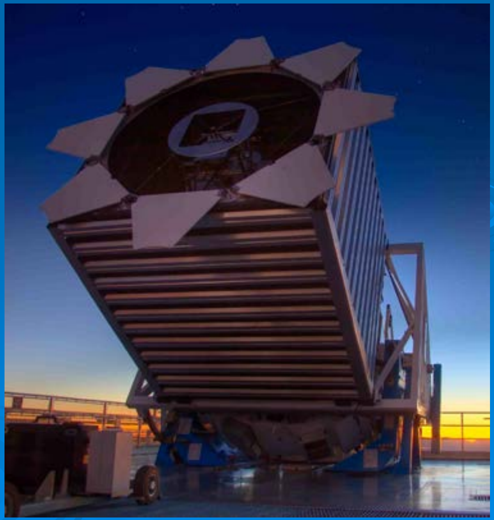
Motivation & Outline

- Dark Energy pushes us to measure the cosmic distance scale and the behavior of gravity to high precision.

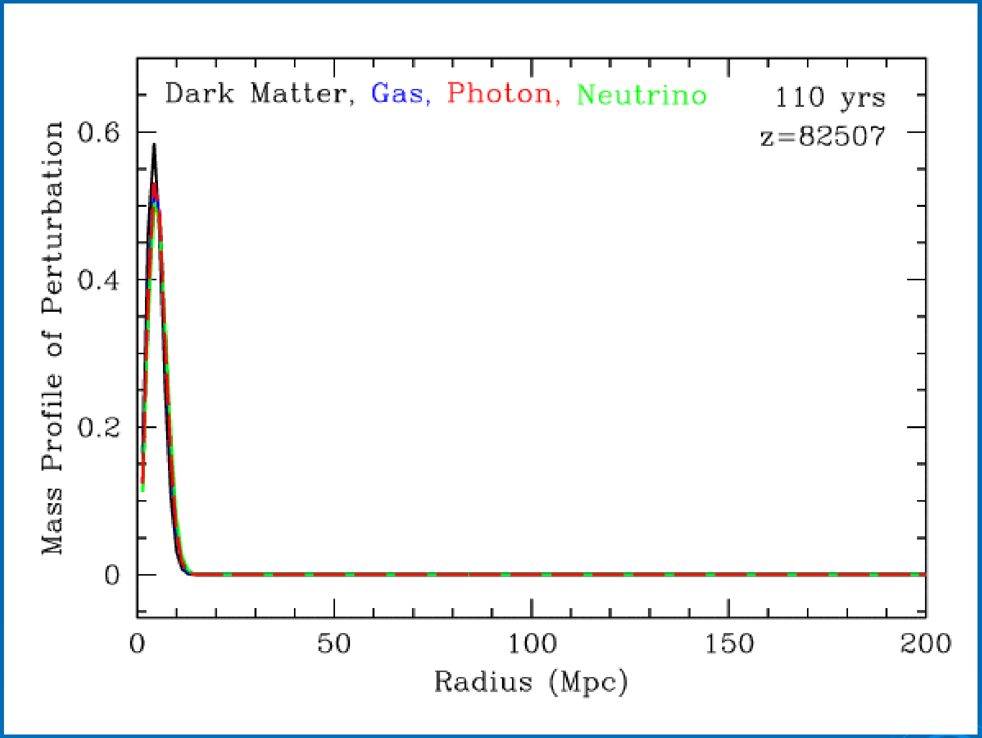
- I will introduce baryon acoustic oscillations as a standard ruler.
  - Linear theory pedagogy.
  - Non-linear structure formation.
- Reconstruction & BAO in SDSS-II DR7.
- Cosmology results from SDSS-III DR9.
  - BAO and growth of structure measurements in the BOSS galaxy sample.
  - BAO in the Lyman α forest.
- A path to 1% distances and better.





Sound Waves in the Early Universe

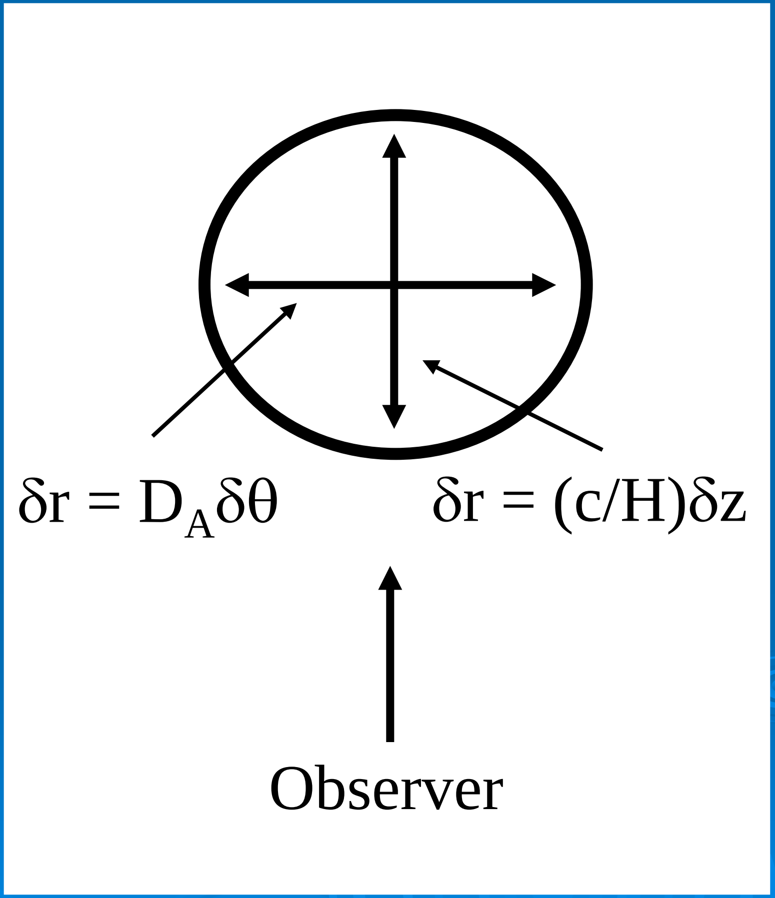
- Each initial overdensity (in DM & gas) is an overpressure that launches a spherical sound wave.
- This wave travels outwards at 57% of the speed of light.
- Pressure-providing photons decouple at recombination. We see this as the CMB.
- Sound speed plummets. Wave stalls at a radius of 150 Mpc.



- Overdensity in shell (gas) and in the original center (DM) both seed the formation of galaxies. Preferred separation of 150 Mpc.

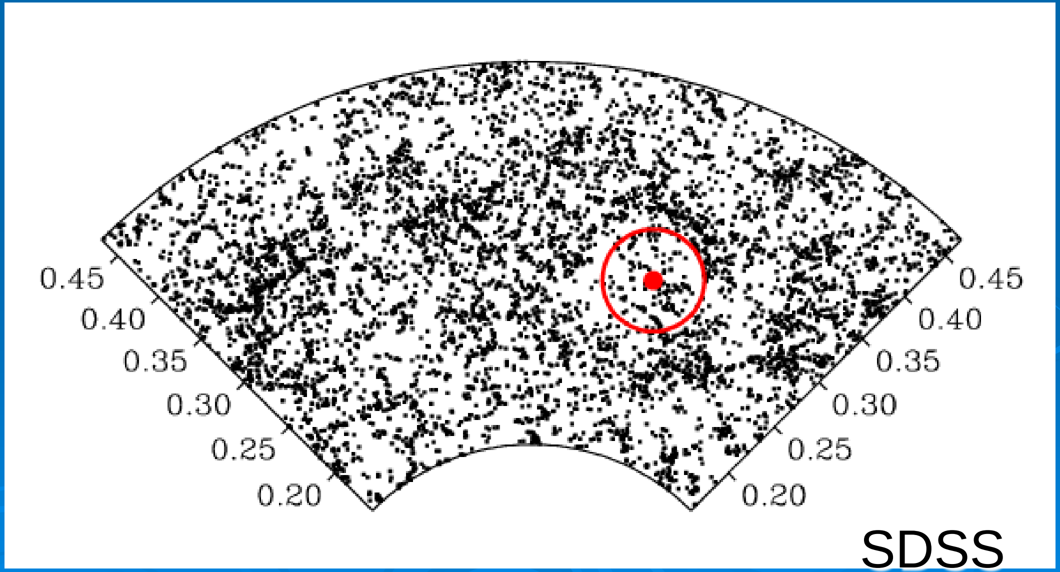
A Standard Ruler

- 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 $D_A(z)$!



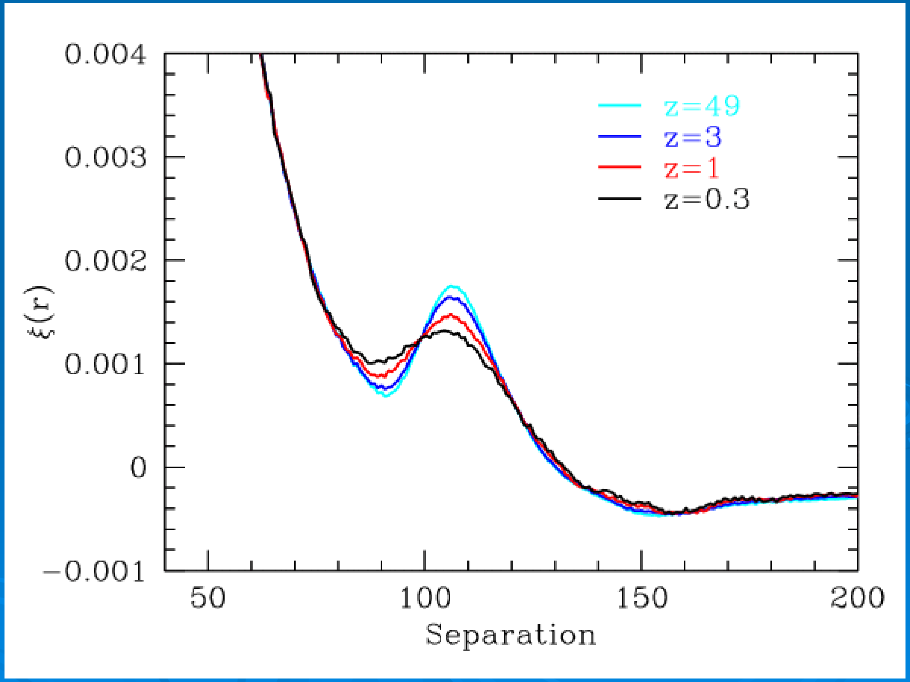
Galaxy Redshift Surveys

- Redshift surveys are a popular way to measure the three-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

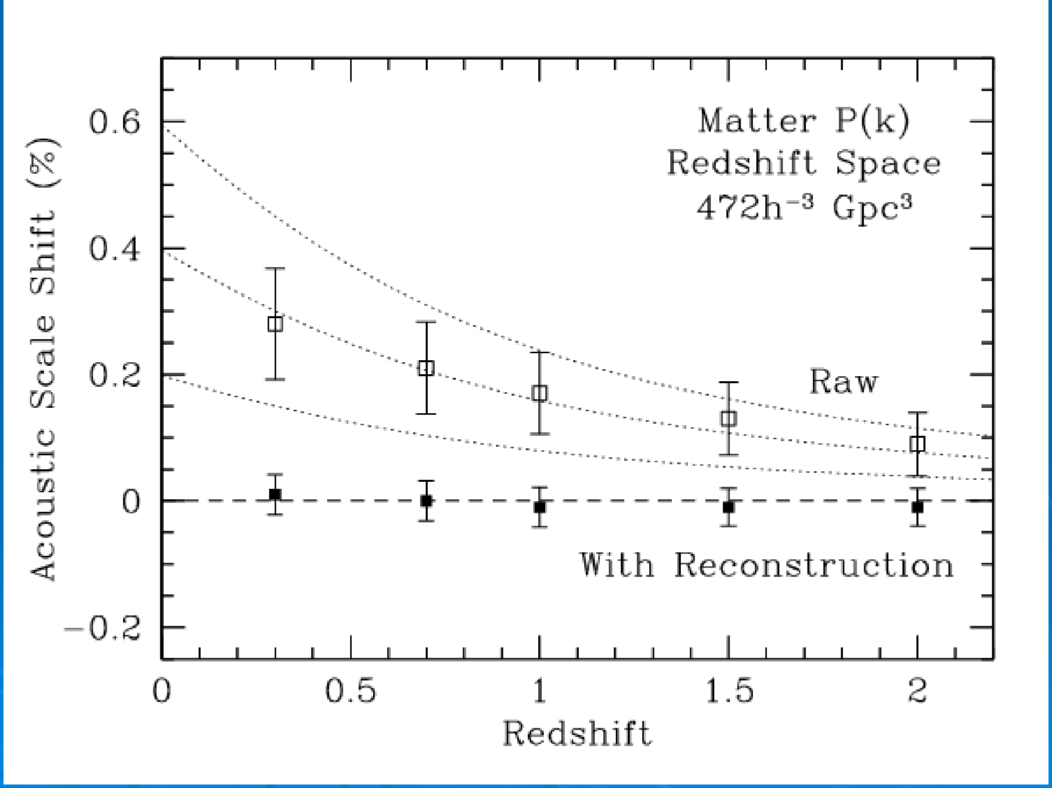
- The acoustic signature is carried by pairs of galaxies separated by 150 Mpc.
- Nonlinearities push galaxies around by 3-10 Mpc. Broadens peak, making it hard to measure the scale.
  - Non-linearities are increasingly negligible at z>1. Linear theory peak width dominates.
- Moving the scale requires net infall on 150 Mpc scale.
  - This depends on the over-density inside the sphere, which is or order1%.
  - Over- and underdensities partially cancel, so mean shift is <0.5%.



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

BAO in Simulations

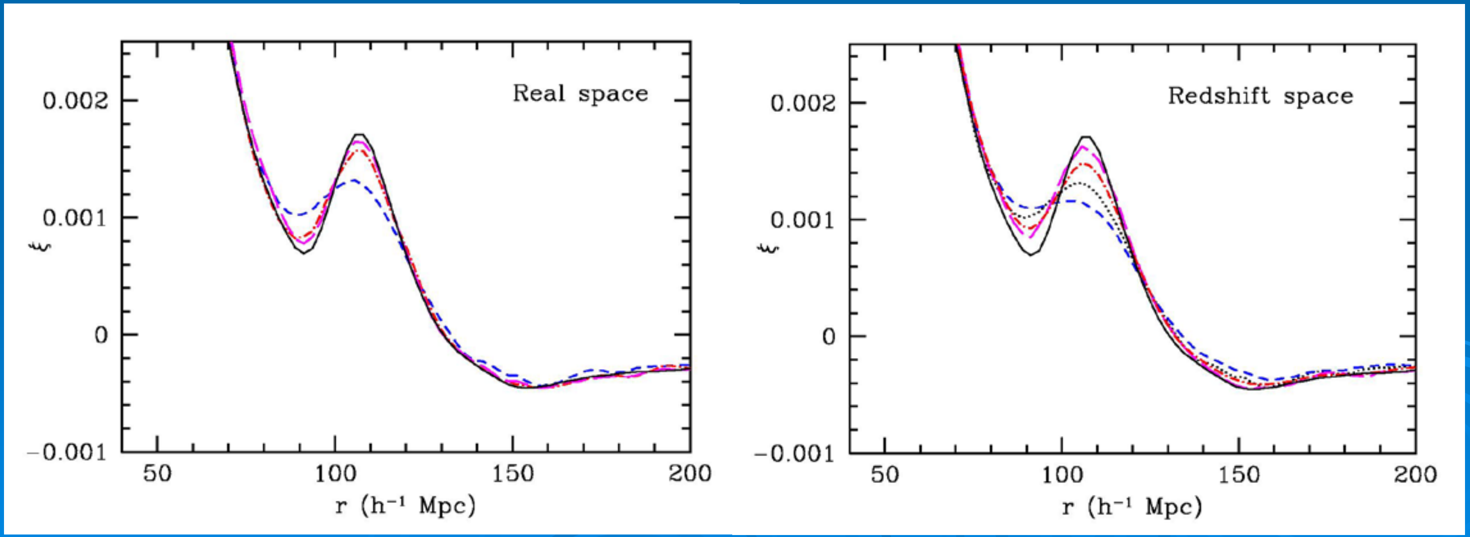
- N-body simulations show the acoustic peak to be preserved.
  - Shifts of 0.3% at z=0, highly predictable.
- Halo-based galaxy bias yields an additional shift, of order 0.5% for high biases.
- Effect is well matched to 2nd-order perturbation theory calculation of Padmanabhan & White (2009).
- These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



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

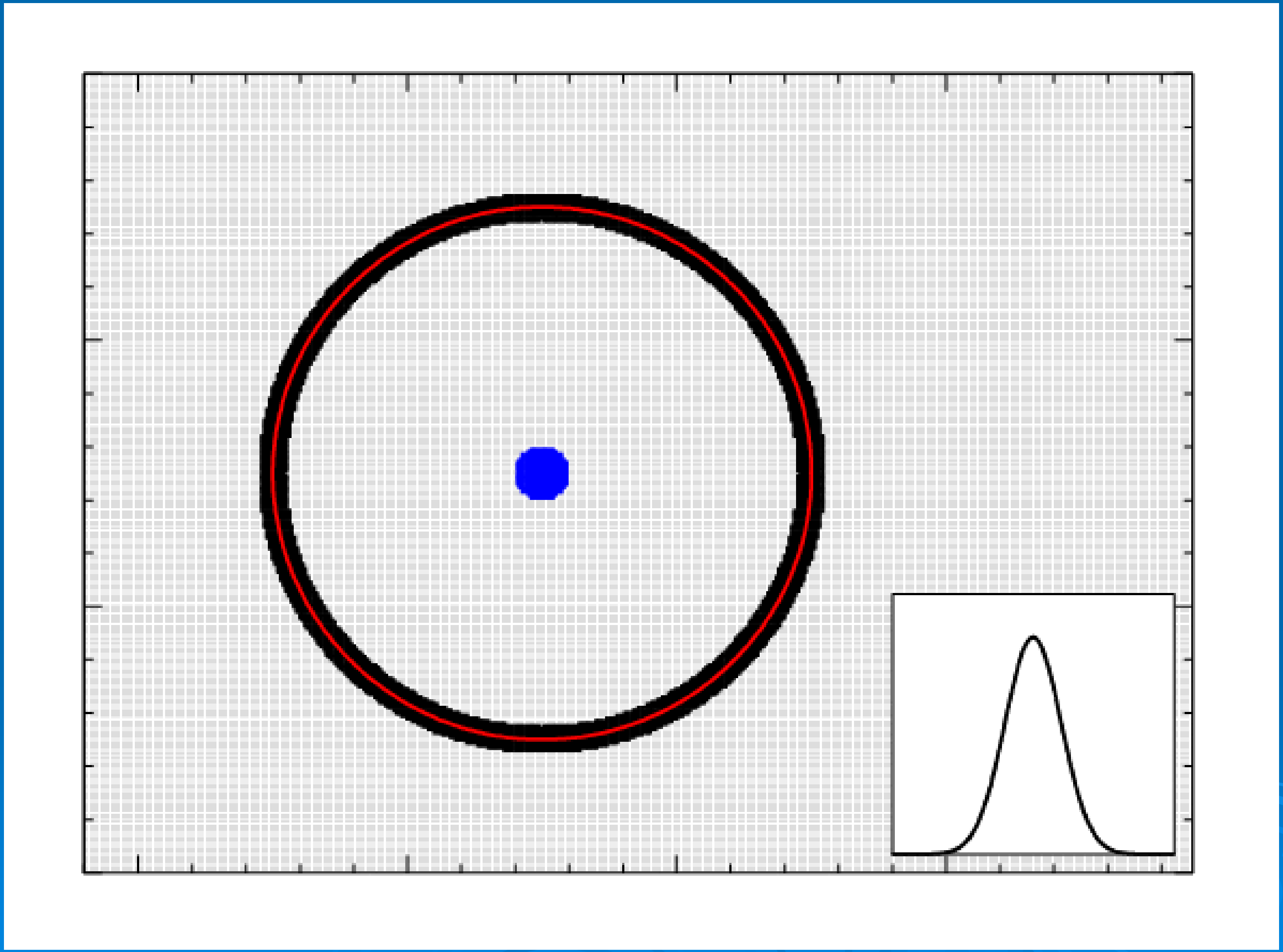
Improving the Acoustic Peak

- Most of the non-linear degradation is due to large-scale 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)

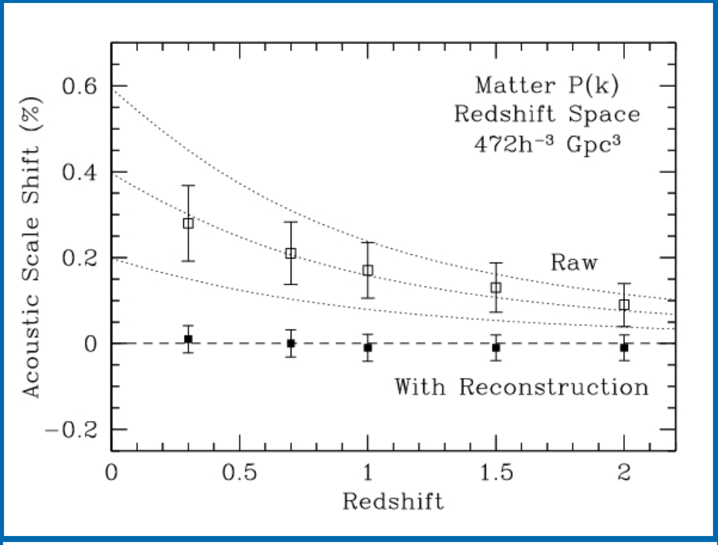
Reconstruction Illustrated

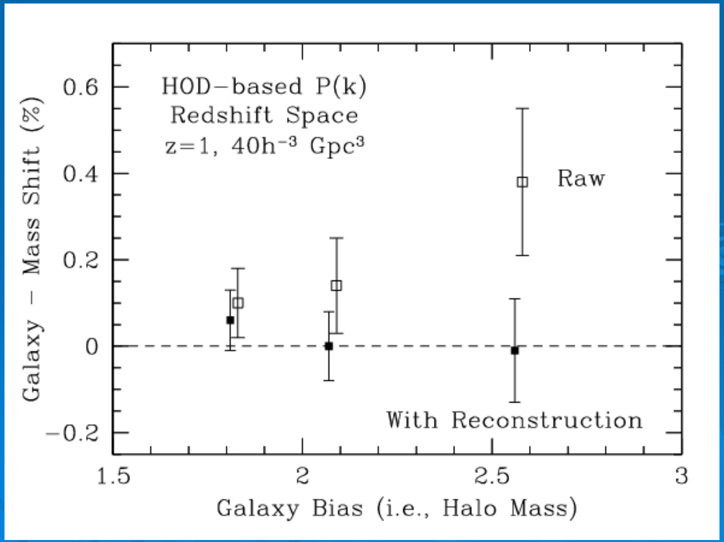


Padmanabhan et al. (2012)

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 case!
  - 0.1% for galaxy bias models.
  - Xu et al. (2012) finds 0.1±0.15% on SDSS-II N-body mock catalogs.
- We are correcting for the large-scale flows that create the shifts.

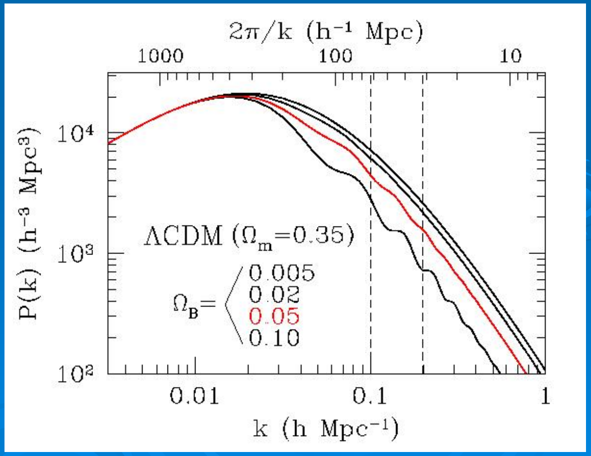




Seo et al. (2010); Mehta et al. (2011)

Observing the BAO

- Study of observational systematic errors in the clustering analysis of galaxy surveys is an old topic.
  - Extensive work over the last several decades, with many methods for diagnosing, removing, and avoiding systematic effects.
- The BAO application is much easier than general P(k) because the BAO signature is oscillatory and hence strongly differential in scale.
  - Observational effects are nearly always broadband, and we simply marginalize against general broadband terms.
- Length scale is tied directly to measurement of angles and redshifts, which are much better than 10^{-3}.

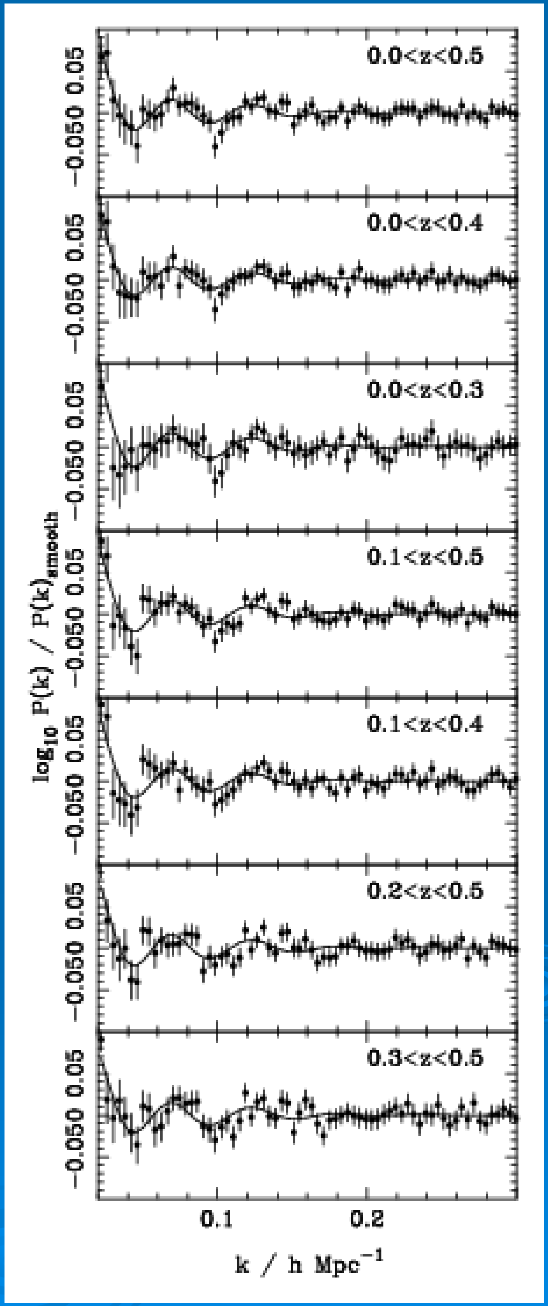


The Sloan Digital Sky Survey

- The SDSS is the world's largest galaxy redshift survey.
- Wide-field imaging and spectroscopy of galaxies, quasars, and stars.
- Data Release 7: full data set from the original Legacy survey, including galaxies to z~0.5.
- Data Release 9: latest release from SDSS-III, including galaxies to z~0.7.

BAO in SDSS-II DR7

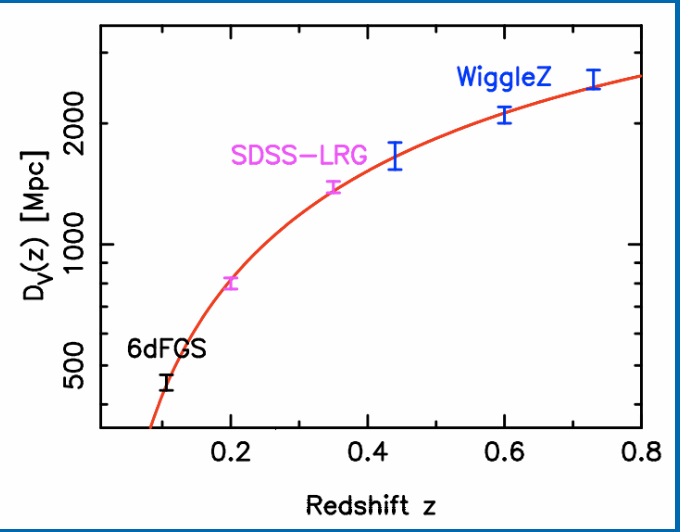
- SDSS-I and II produced several analyses of the BAO, culminating in Percival et al. (2009) and Reid et al. (2009) analysis of the power spectrum of the final SDSS-II (LRG+MAIN) and 2dF GRS.
- Average signal produced a 2.7% measurement of the distance to z=0.275.
- Good agreement with LCDM model. WMAP5+BAO+SN yields:
  - $H_0 = 68 \pm 2$ km/s/Mpc and
  - $\Omega_m = 0.29 \pm 0.02$
    in both LCDM and owCDM.

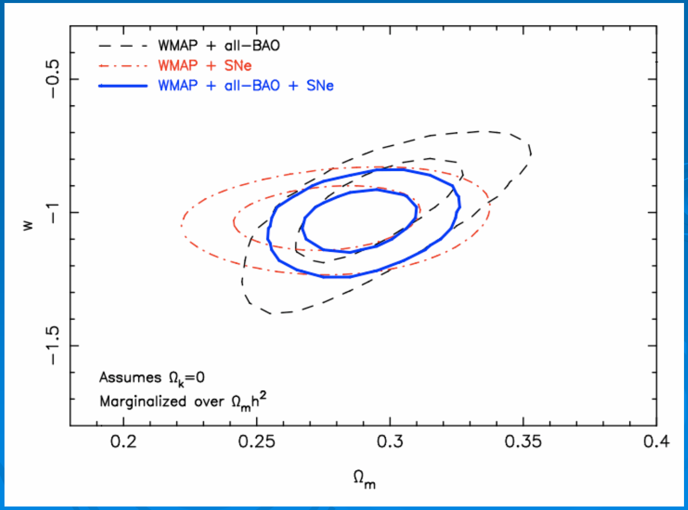


Percival et al. (2009)

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.



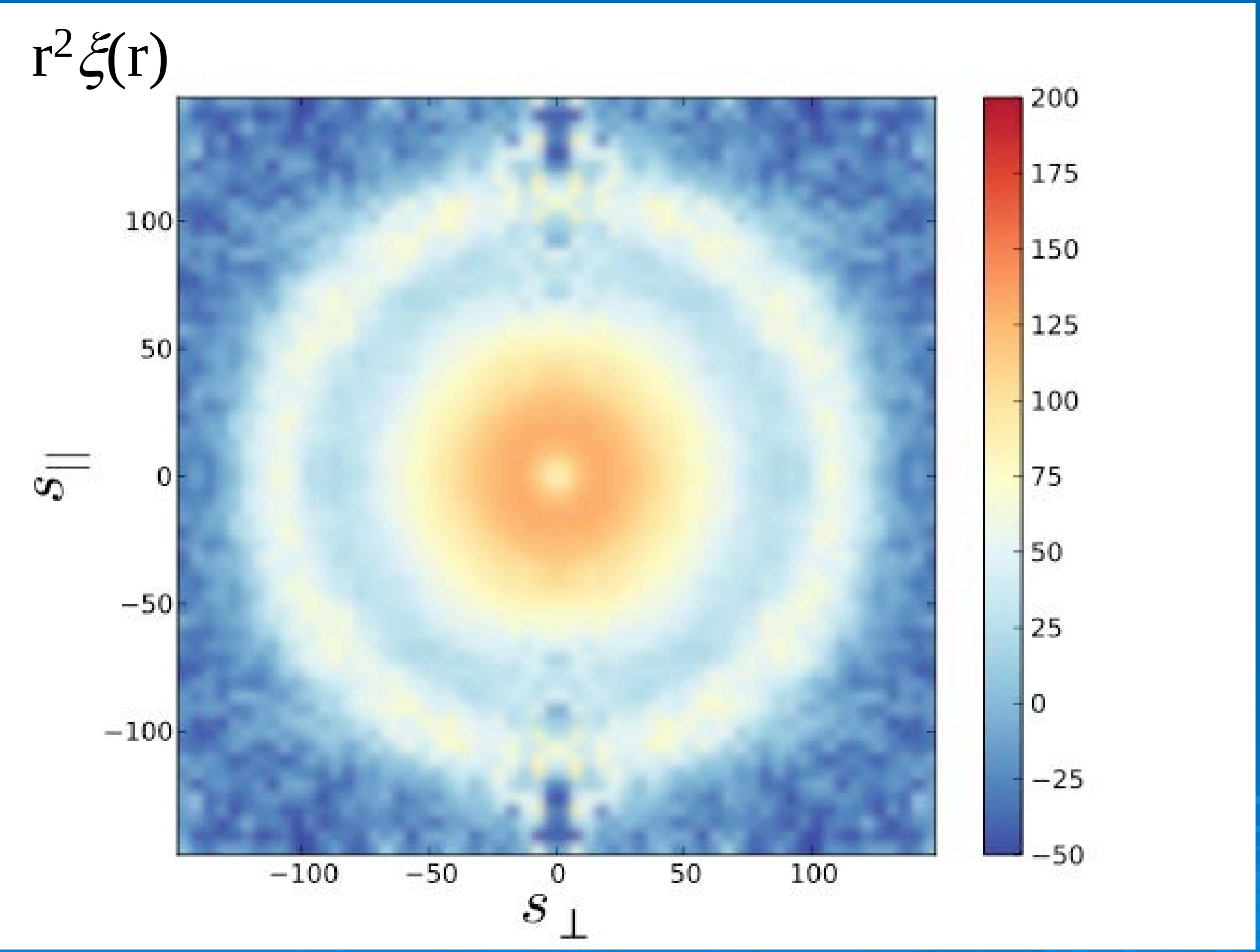


Blake et al. (2011)

DR7 with Reconstruction

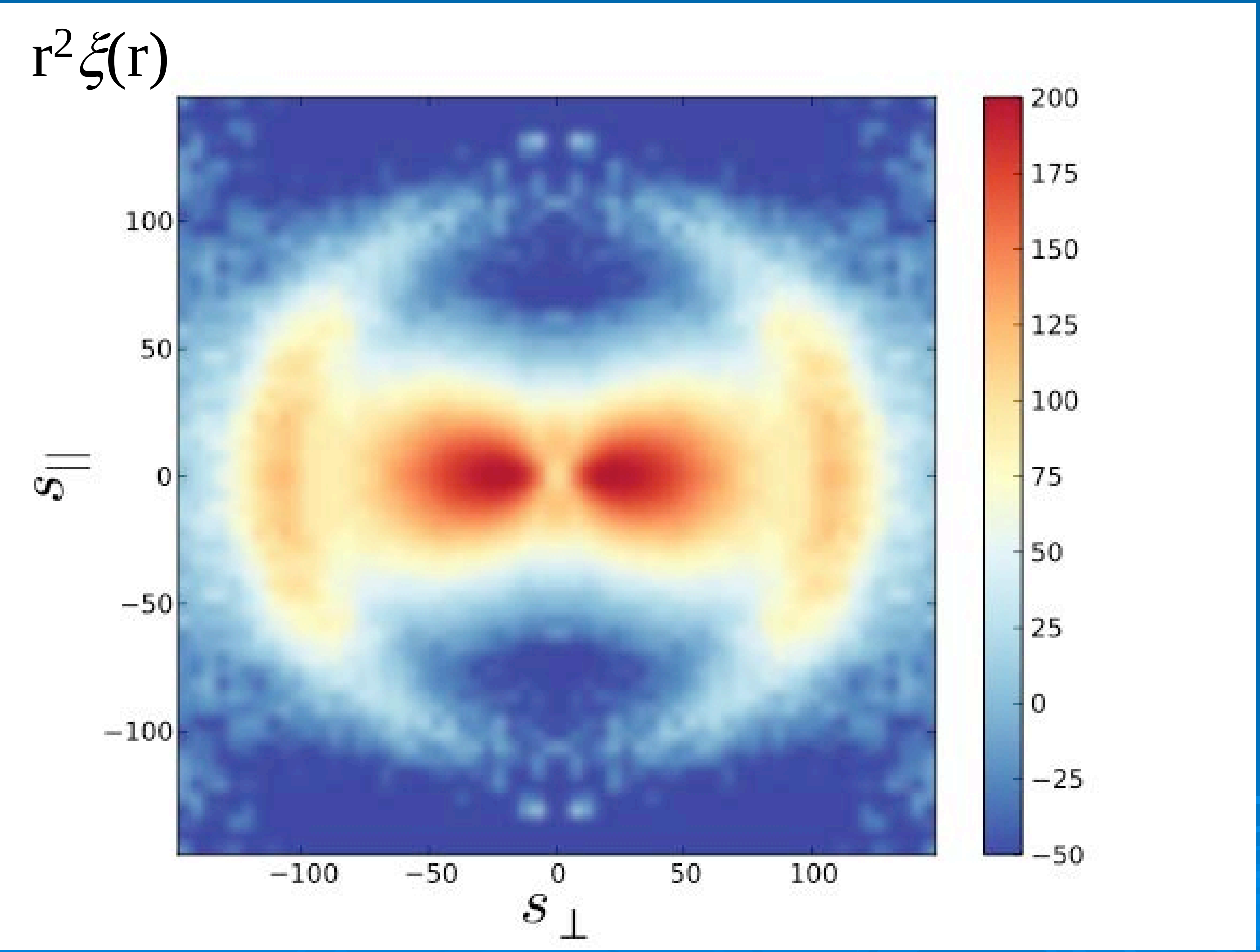
- Padmanabhan et al., Xu et al., and Mehta et al. (2012) present a new analysis of the SDSS-II DR7 Luminous Red Galaxy sample.
  - 106k galaxies over 7200 sq deg.
- First analysis to include reconstruction.
- Improves errors as if we were tripling the survey volume.

Real-space Clustering



DR7 Mock Catalogs Padmanabhan et al. (2012)

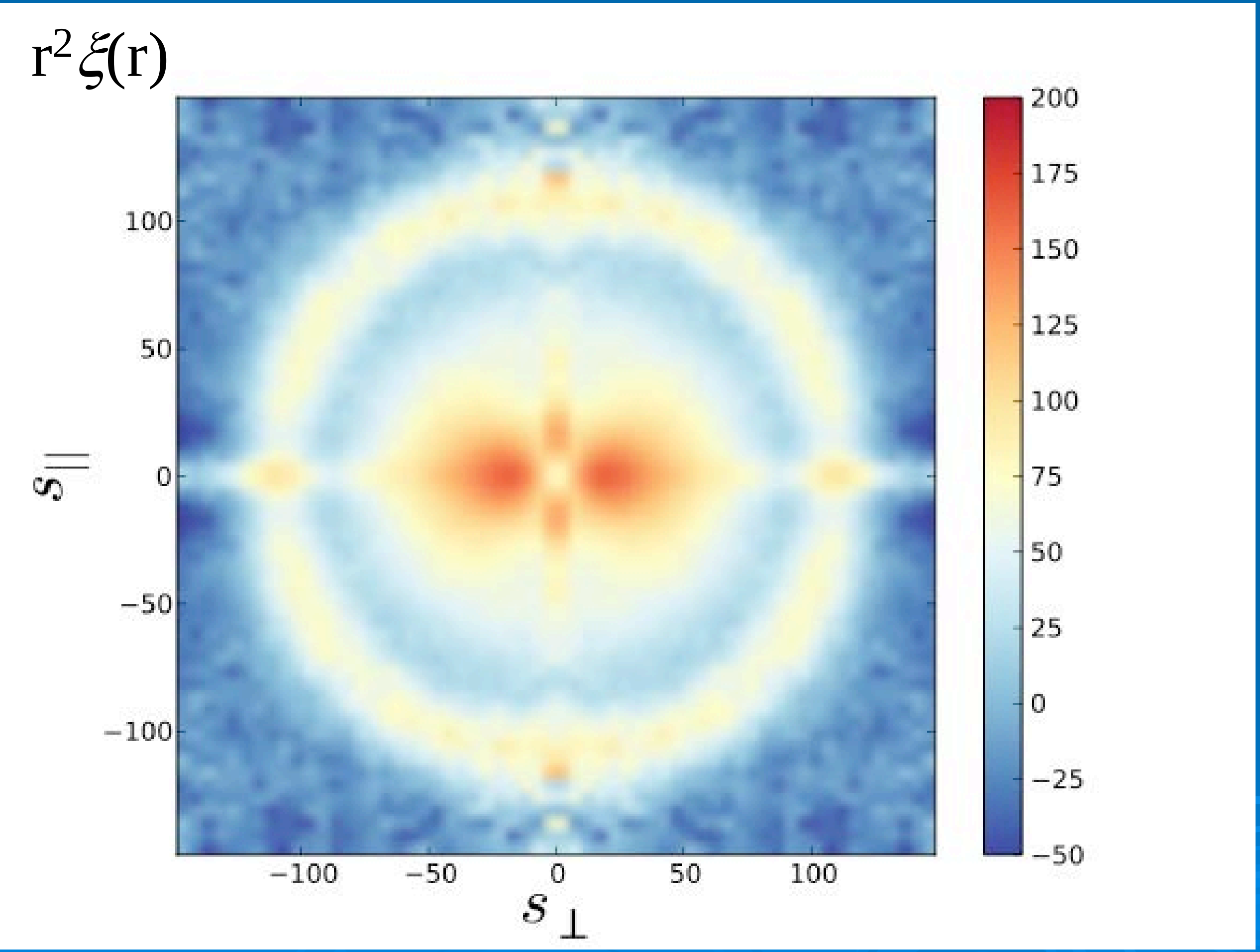
Redshift-space Clustering



DR7 Mock Catalogs

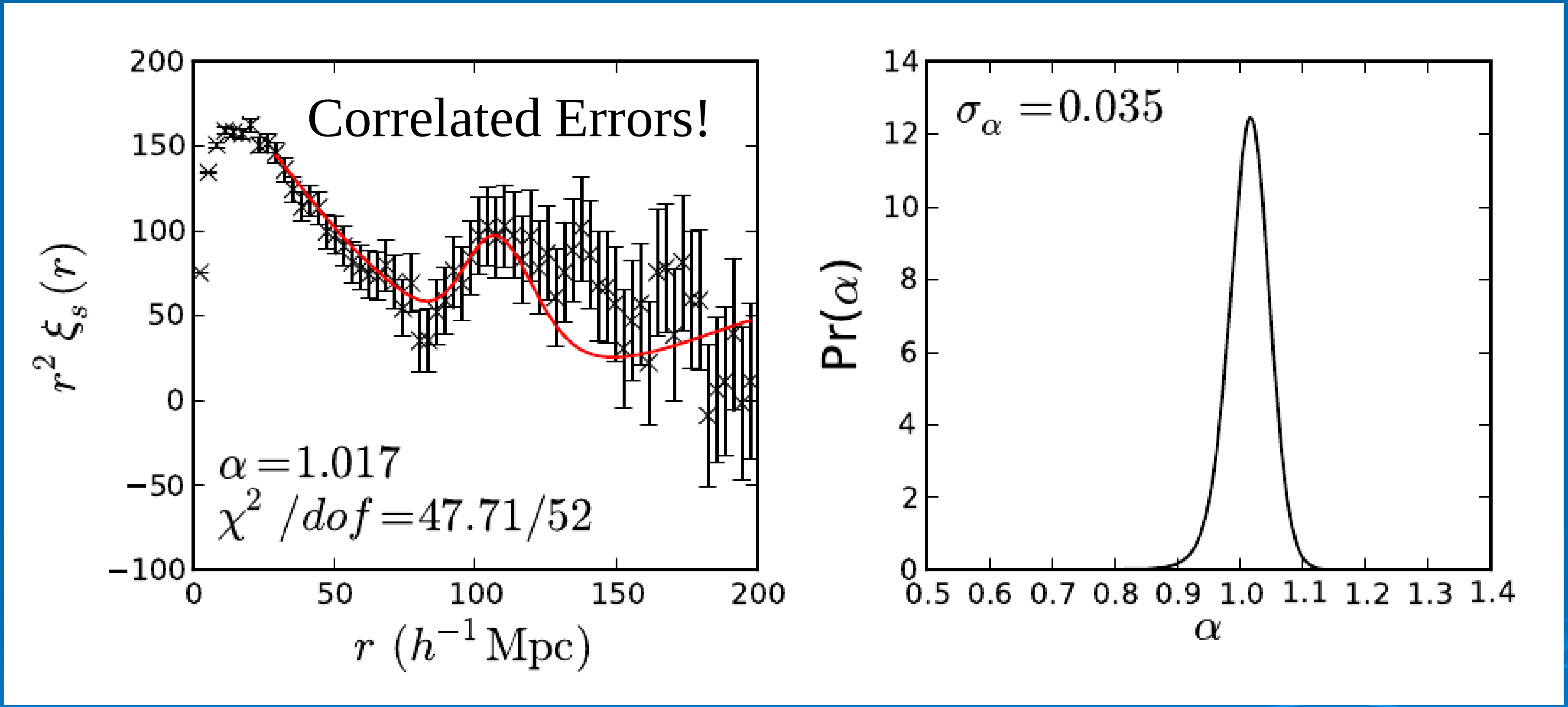
Padmanabhan et al. (2012)

Redshift-Space Clustering after Reconstruction



DR7 Mock Catalogs   Padmanabhan et al. (2012)

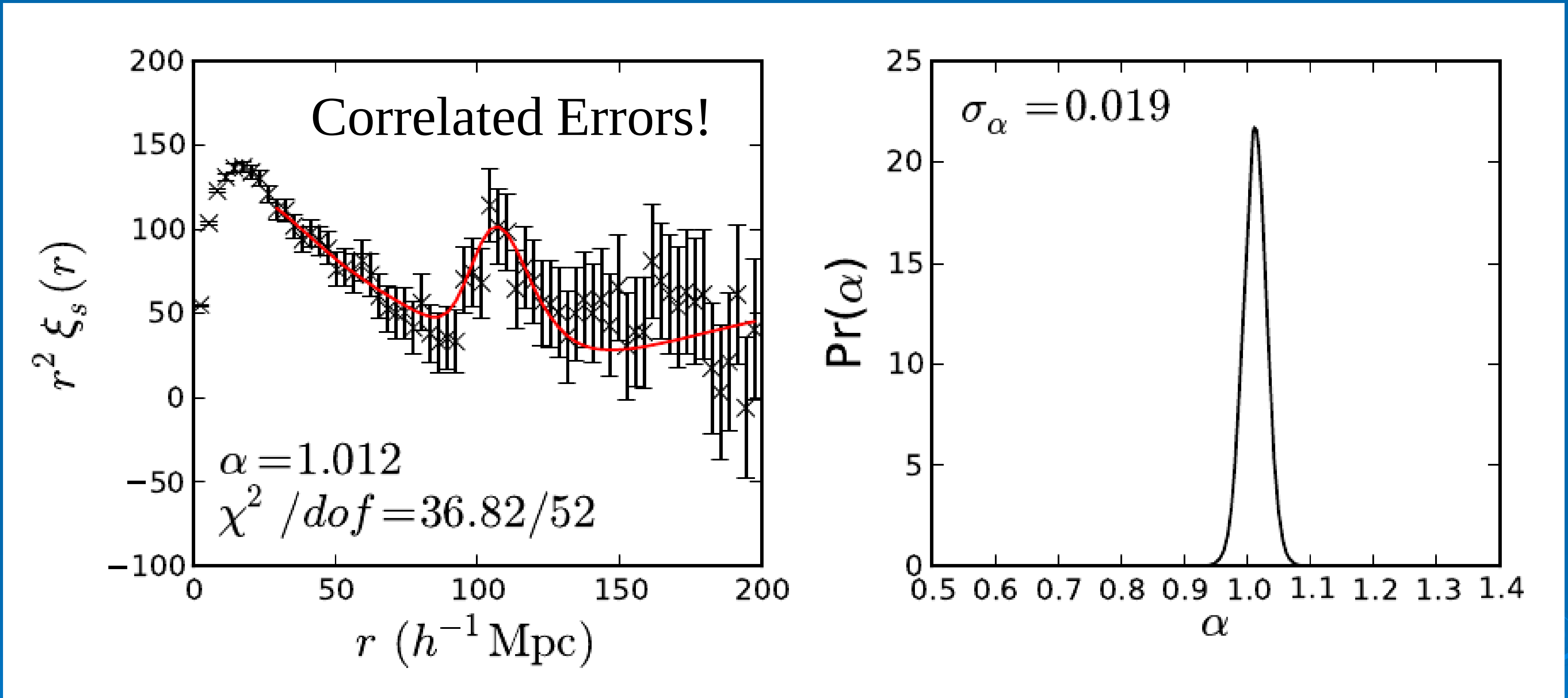
Before Reconstruction



- 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)

SDSS-III

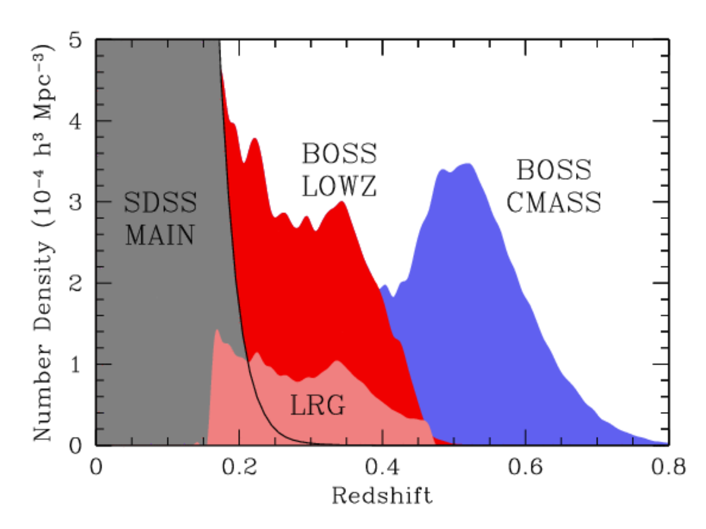
- SDSS-III is the next phase of the SDSS project, operating from summer 2008 to summer 2014.
- SDSS-III has 4 surveys on 3 major themes.
  - BOSS: Largest yet redshift survey for large-scale structure.
  - SEGUE-2: Optical spectroscopic survey of stars, aimed at structure and nucleosynthetic enrichment of the outer Milky Way.
  - APOGEE: Infrared spectroscopic survey of stars, to study the enrichment and dynamics of the whole Milky Way.
  - MARVELS: Multi-object radial velocity planet search.
- Extensive re-use of existing facility and software.
- Strong commitment to public data releases.
- Support from Sloan Foundation, Dept of Energy, National Science Foundation, and over 50 member institutions from around the world.

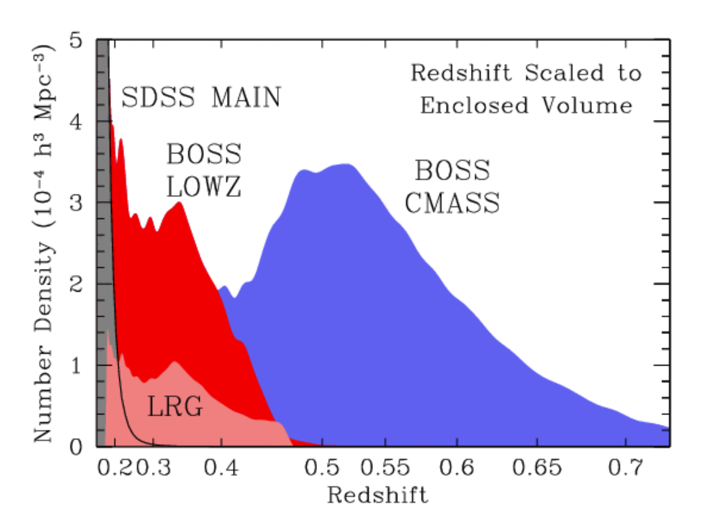
SDSS-III Collaboration

- Univ. of Arizona
- Brazilian Participation Group (ON and 4 universities)
- Brookhaven National Lab
- Cambridge Univ.
- Carnegie-Mellon Univ.
- *Case Western Univ.*
- *Fermilab*
- Univ. of Florida
- French Participation Group (APC, CEA, IAP, LAM, Besancon)
- German Participation Group (AIP, MPIA, ZAH)
- Harvard University
- Instituto de Astrofisica de Canarias
- *Instituto de Astrofisica de Andalucia, Granada* *
- *IFIC Valencia*
- *ICREA Barcelona*
- *INAF Treiste*
- Johns Hopkins Univ.
- *UC Irvine*
- *Korean Institute for Advanced Study*
- Lawrence Berkeley National Lab
- MPA Garching
- MPE Garching
- Michigan St Univ/Notre Dame/JINA
- New Mexico State Univ.
- New York Univ.
- Ohio State Univ.
- Penn State Univ.
- *Univ. of Pittsburgh*
- Univ. of Portsmouth
- Princeton Univ.
- *UC Santa Cruz*
- *Texas Christian University*
- Univ. of Tokyo
- Univ. of Utah
- Vanderbilt University
- Univ. of Virginia
- Univ. of Washington
- *University of Wisconsin*
- Yale University
- Italics indicate smaller members

SDSS-III Baryon Oscillation Spectroscopic Survey

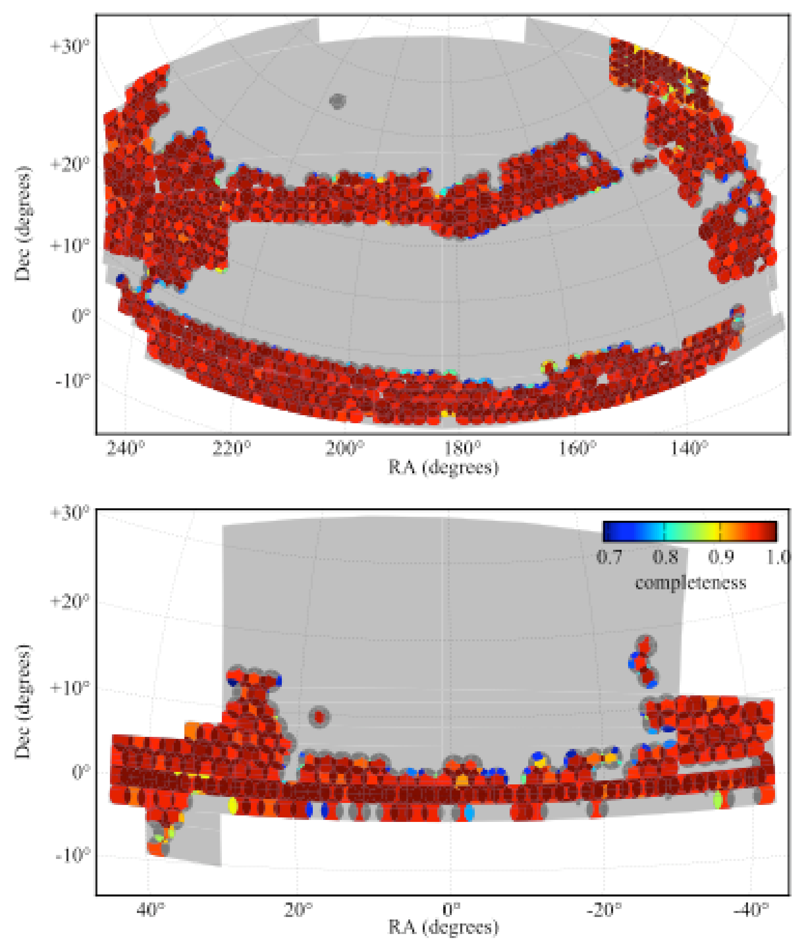
- BOSS is a comprehensive study of the low-redshift BAO and the best large-scale structure sample yet.
- 10,000 deg^2 and 1.5 million spectra of massive galaxies out to z=0.75.
  - Plus z>2 quasars to look for BAO in the Lyman α forest.
  - Intends to achieve 1% distance to z=0.35 and z=0.6.
- Survey is now 80+% complete, over 1 million spectra in hand.





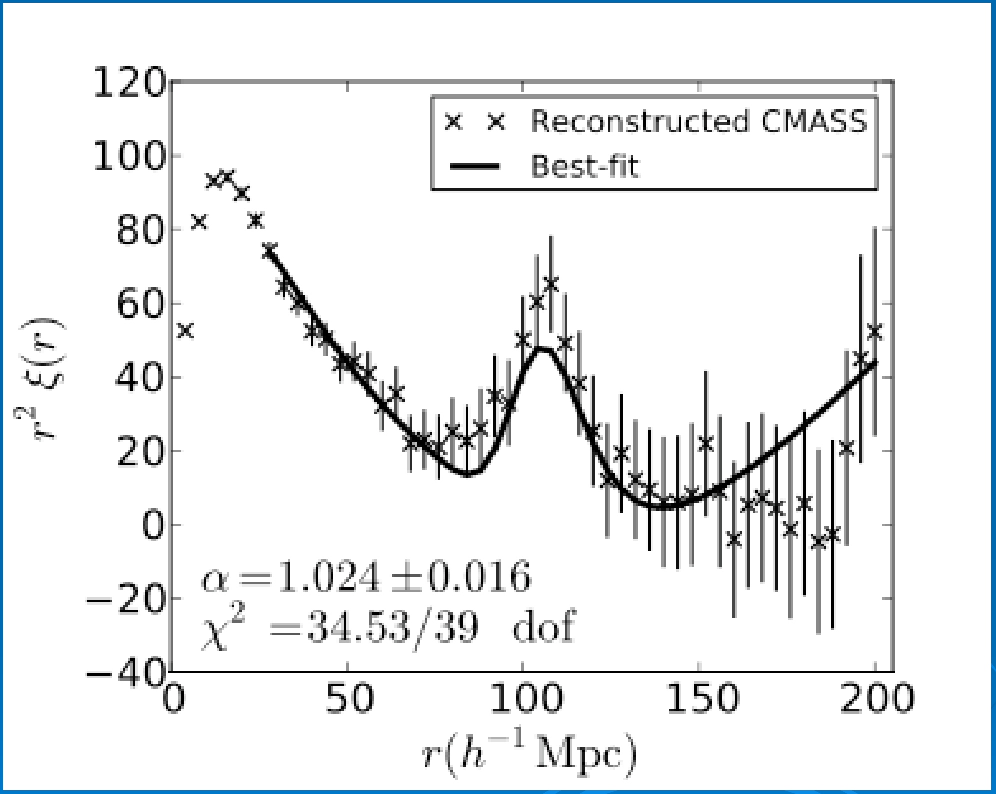
Data Release 9

- In July 2012, we released the first 20 months of BOSS spectroscopic data!
  - 700,000 BOSS spectra
  - Plus the previous 1.5M spectra from SDSS, and all of the imaging.
- Our first BAO analysis uses only the higher redshift portion of the sample.
- 264k galaxies over 3275 deg^2 with a median redshift of 0.57.



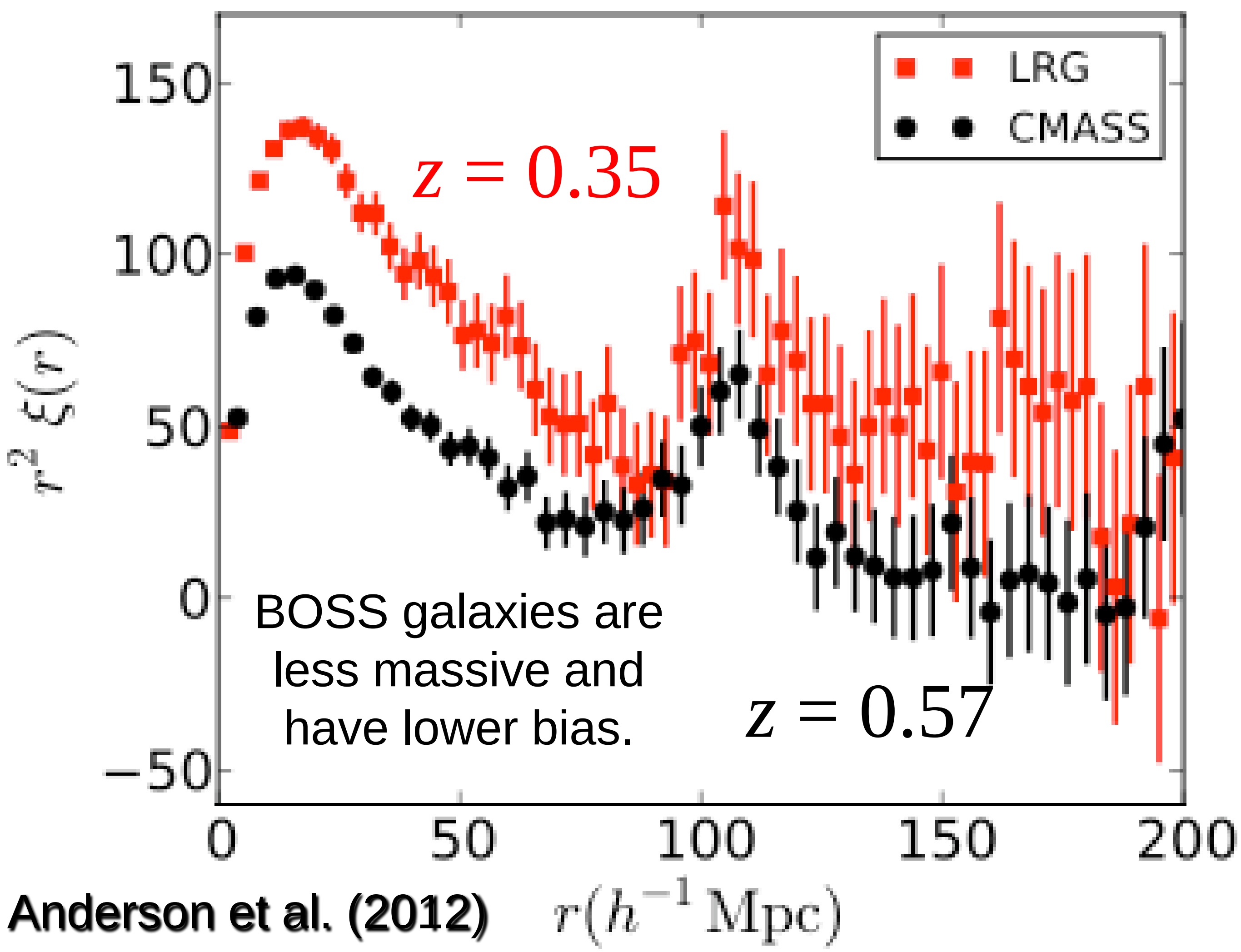
BAO in SDSS-III

- We find a very clear detection of the acoustic peak.
- Comprehensive analysis performed in both correlation function and power spectrum.
- We measure the distance to z=0.57 to 1.7% precision.
  - $D_V(0.57) = 2094 \pm 34$ Mpc



Anderson et al. (2012)

Comparison to *z*=0.35

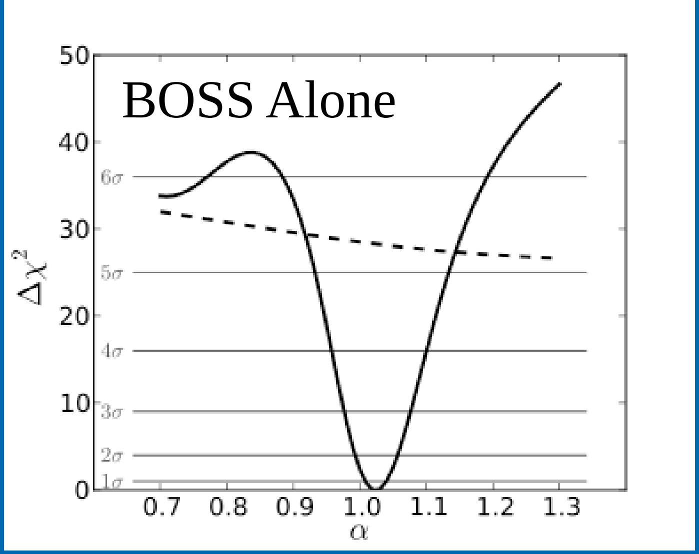


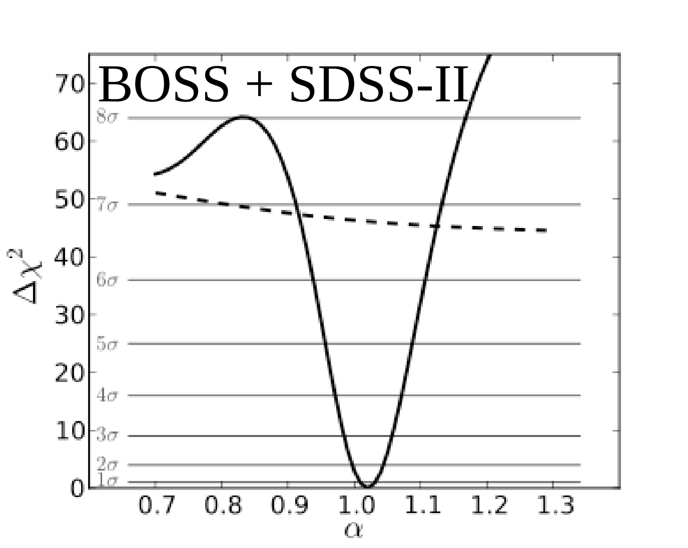
Anderson et al. (2012)

Detection Significance

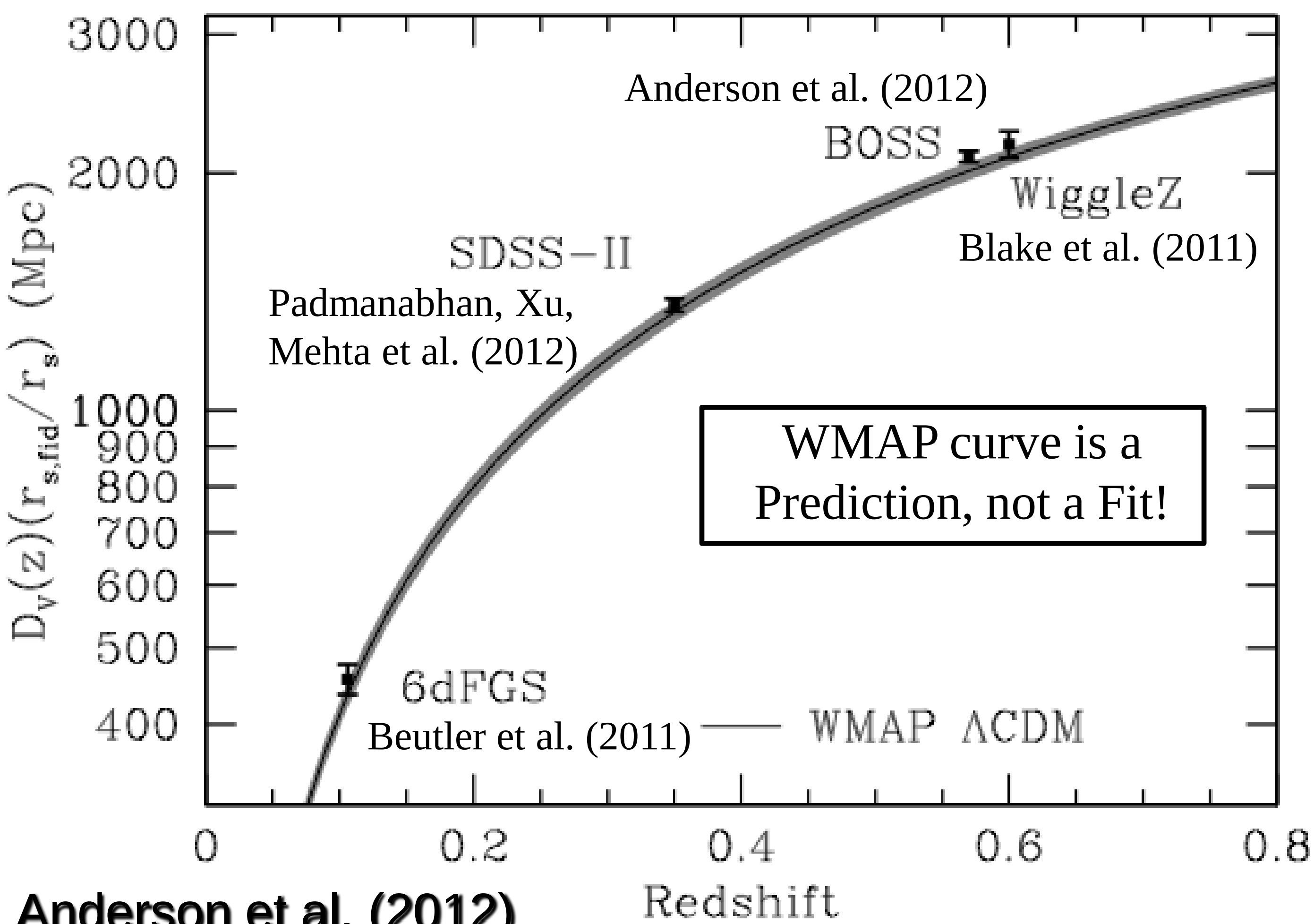
- The BOSS z=0.57 acoustic peak detection is itself over 5σ, a first for a single dataset.
- Combined with the SDSS-II z=0.35 result, detection is over 6.5σ.
- However, with the strong detection in the CMB, the interesting question is not so much whether the BAO exists but rather what distance scale it implies.

Anderson et al. (2012)



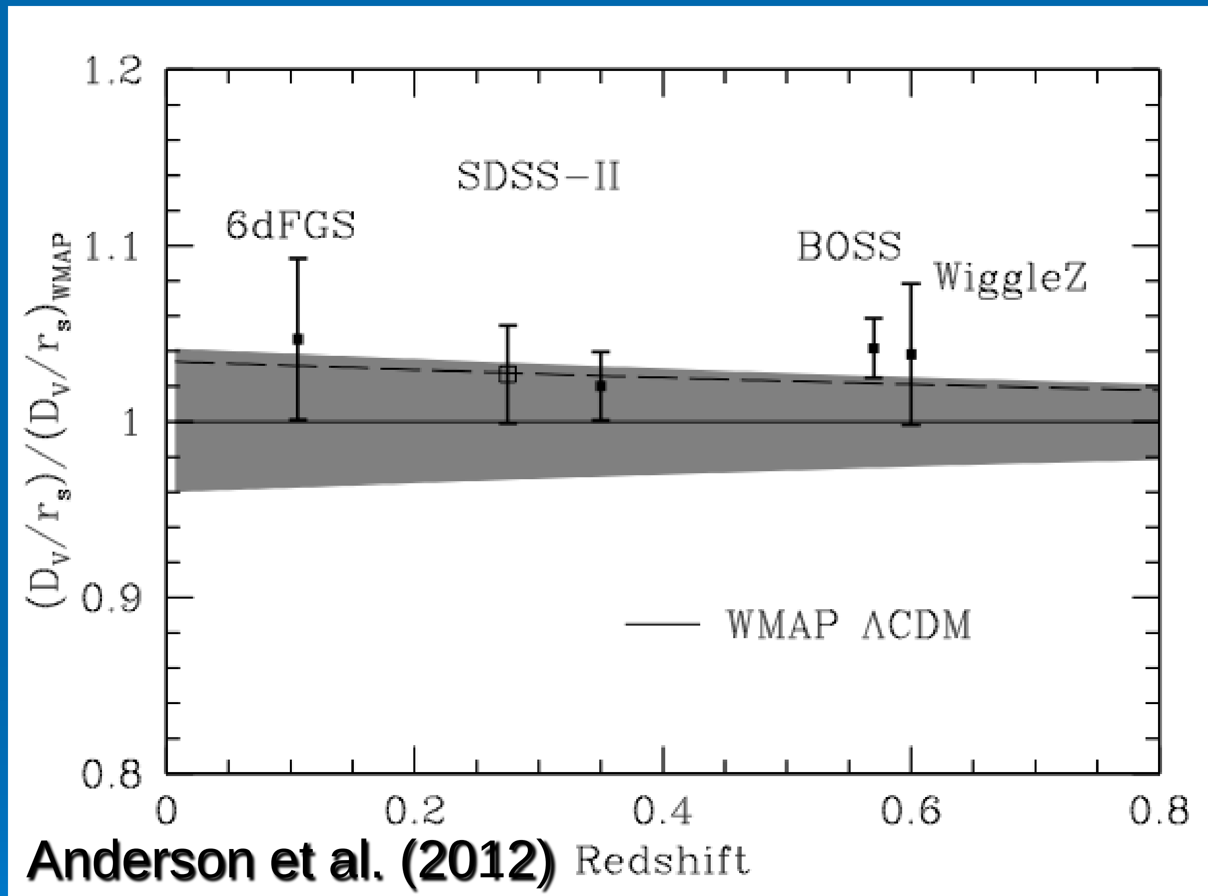


BAO Hubble Diagram



Anderson et al. (2012)

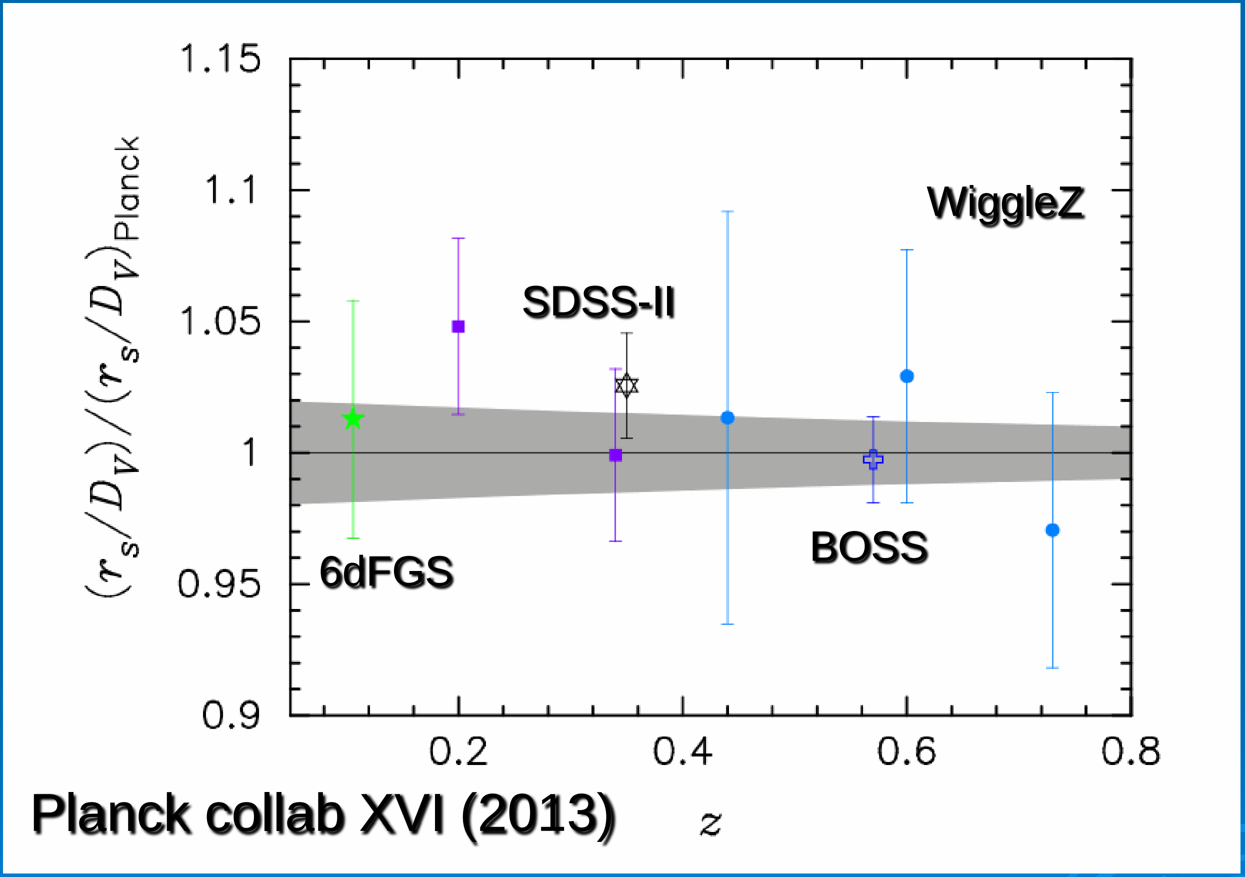
Finer Comparison



Anderson et al. (2012)

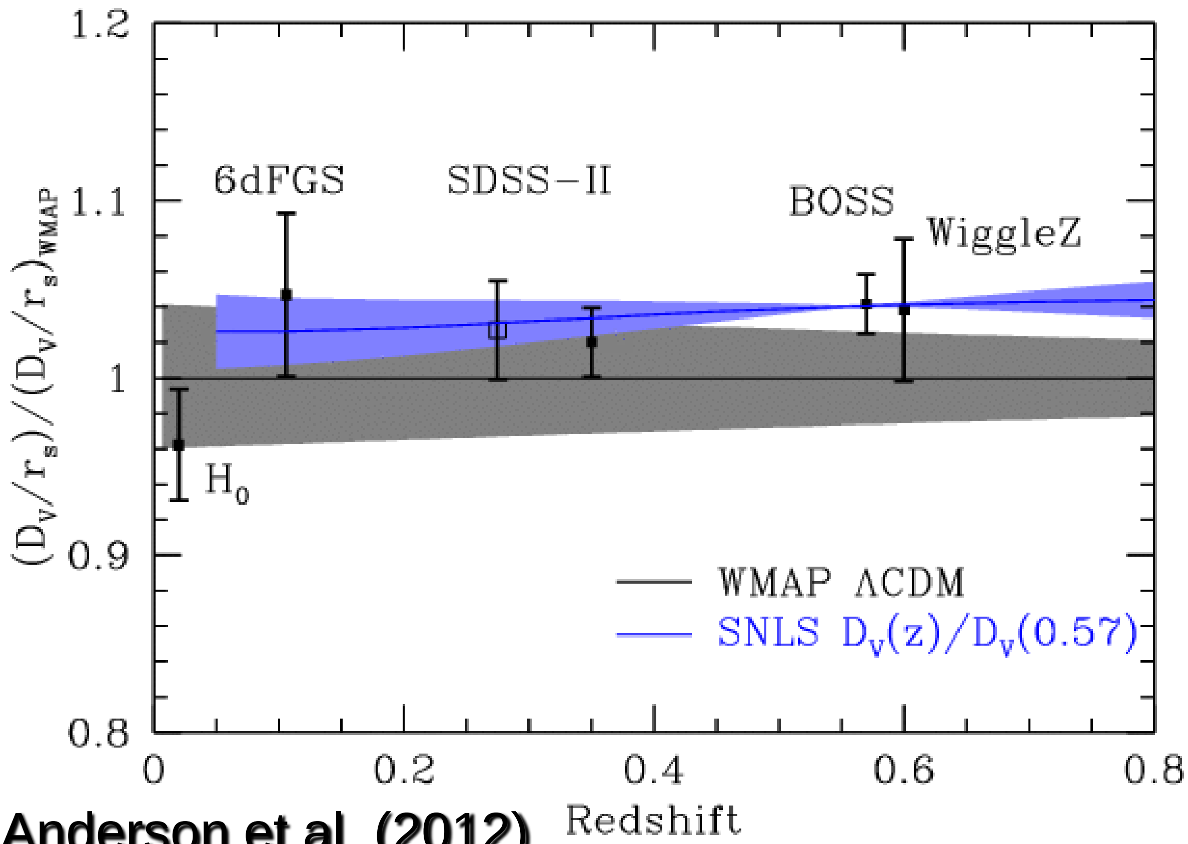
- WMAP+SDSS data sets consistent with flat, cosmological constant model.

Comparison to Planck



- Planck error range is half the size. Shifts in the direction of the BOSS measurement.

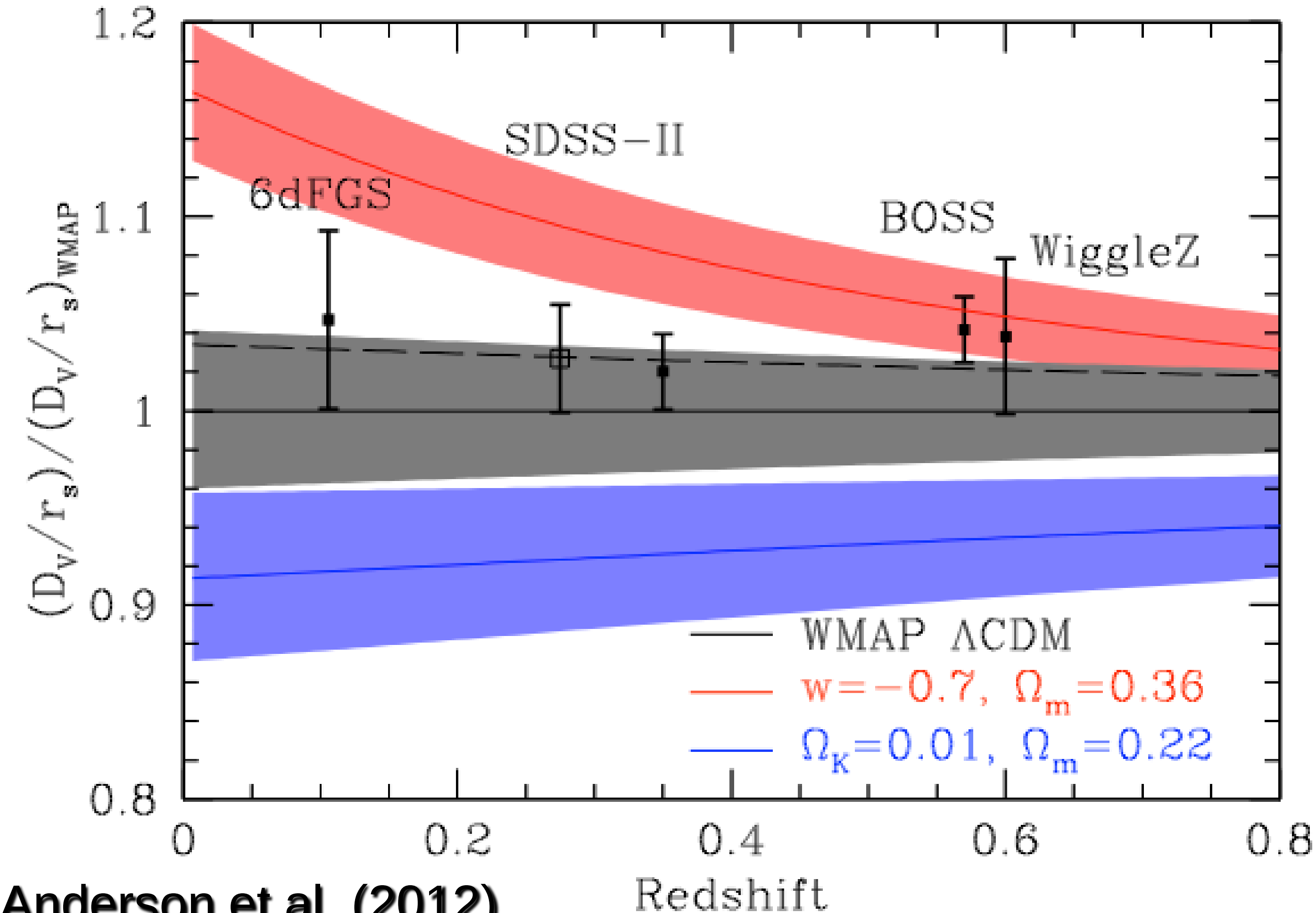
Consistency with SNe



Anderson et al. (2012)

- BAO matches well to the SNe relative distance scale.

Cosmological Leverage

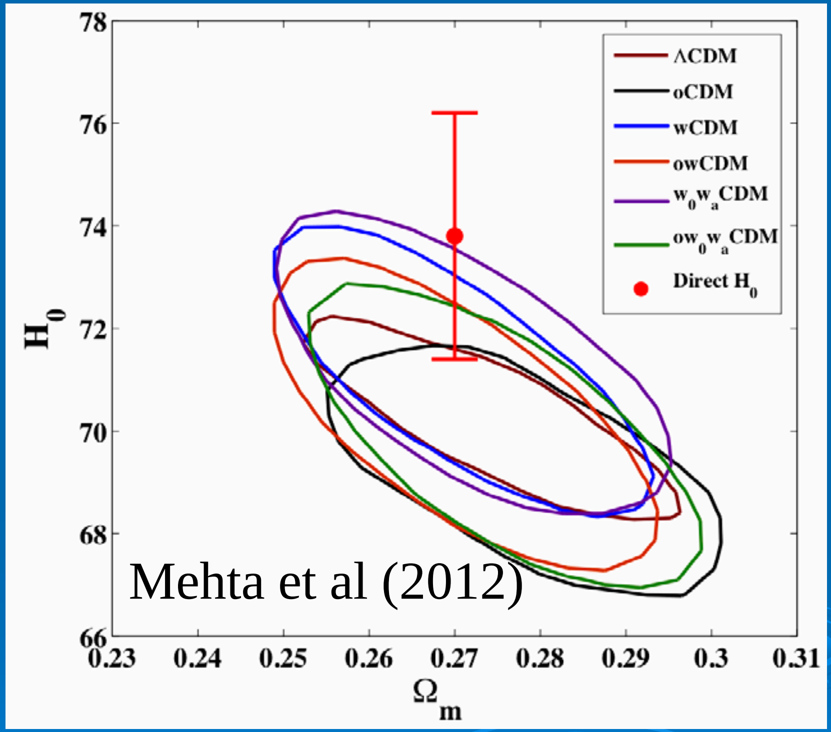


Anderson et al. (2012)

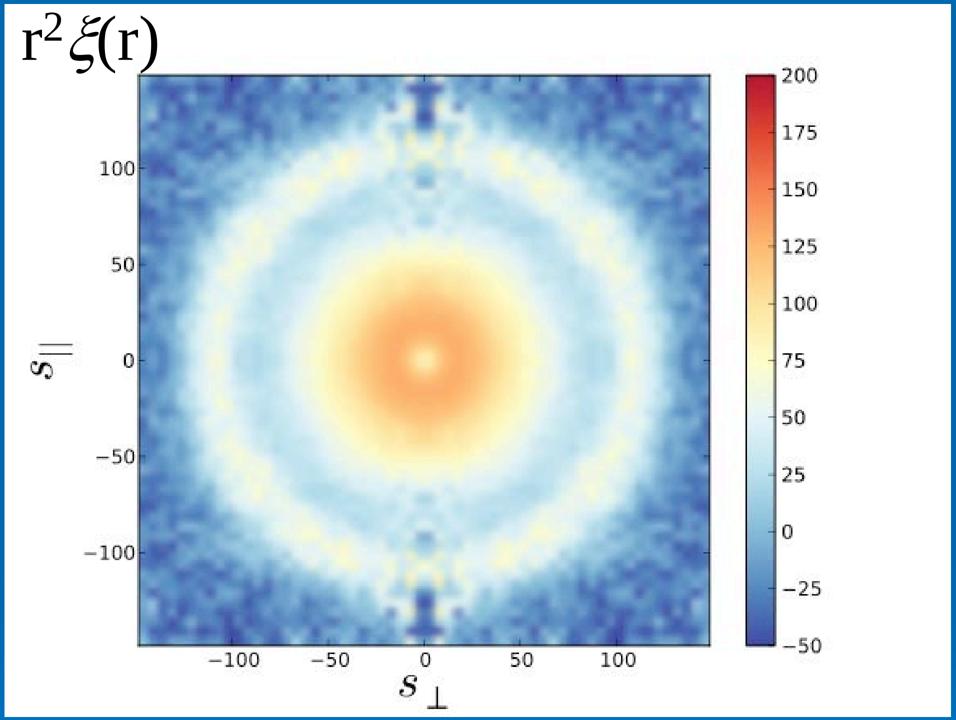
- Excellent agreement with flat LCDM cosmology.

Measuring the Expansion and Density of the Universe

- The combination of CMB, BAO, and Supernova produces a reverse distance ladder:
  - CMB calibrates z=1000.
  - BAO transfers to z=0.35.
  - SNe carries to z=0.
- Get strong constraints on H_0 and Ω_m independent of curvature and expansion history. With WMAP-7:
  - H_0 = 69.8 ± 1.8 km/s/Mpc
  - Ω_m = 0.277 ± 0.014



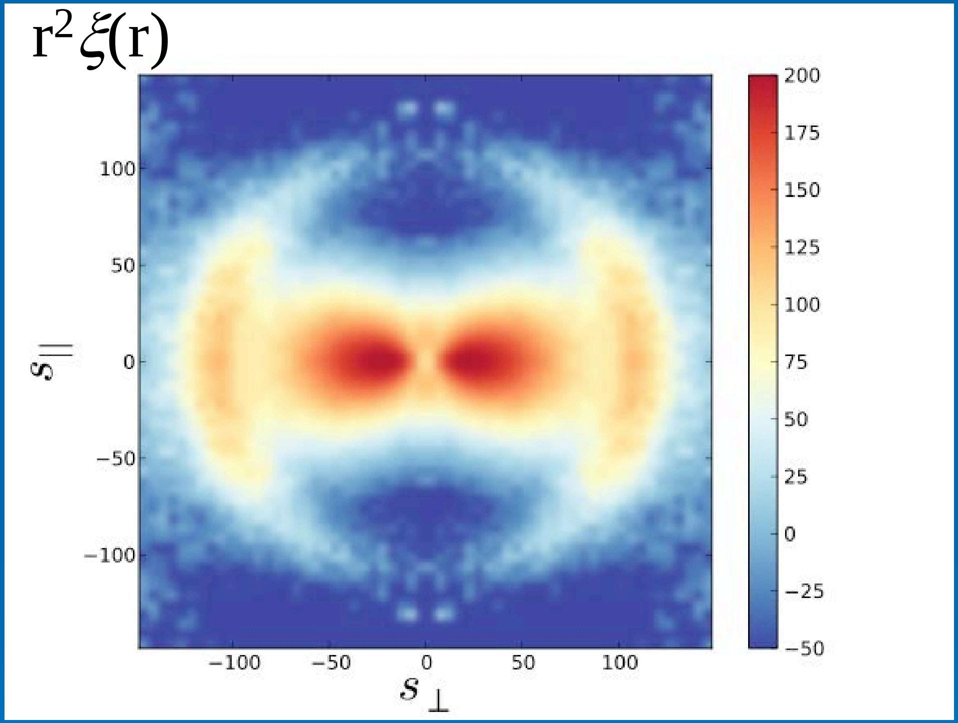
Anisotropic Clustering



SDSS-II DR7 Mock Catalogs
Padmanabhan et al. (2012)

- Clustering should be isotropic in real space. Using the wrong cosmology creates anisotropy (Alcock-Paczynski effect).
  - Measure F ~ $D_A H(z)$
- The BAO ring can be distorted.
- But there is much more information on smaller scales, if one can model accurately.

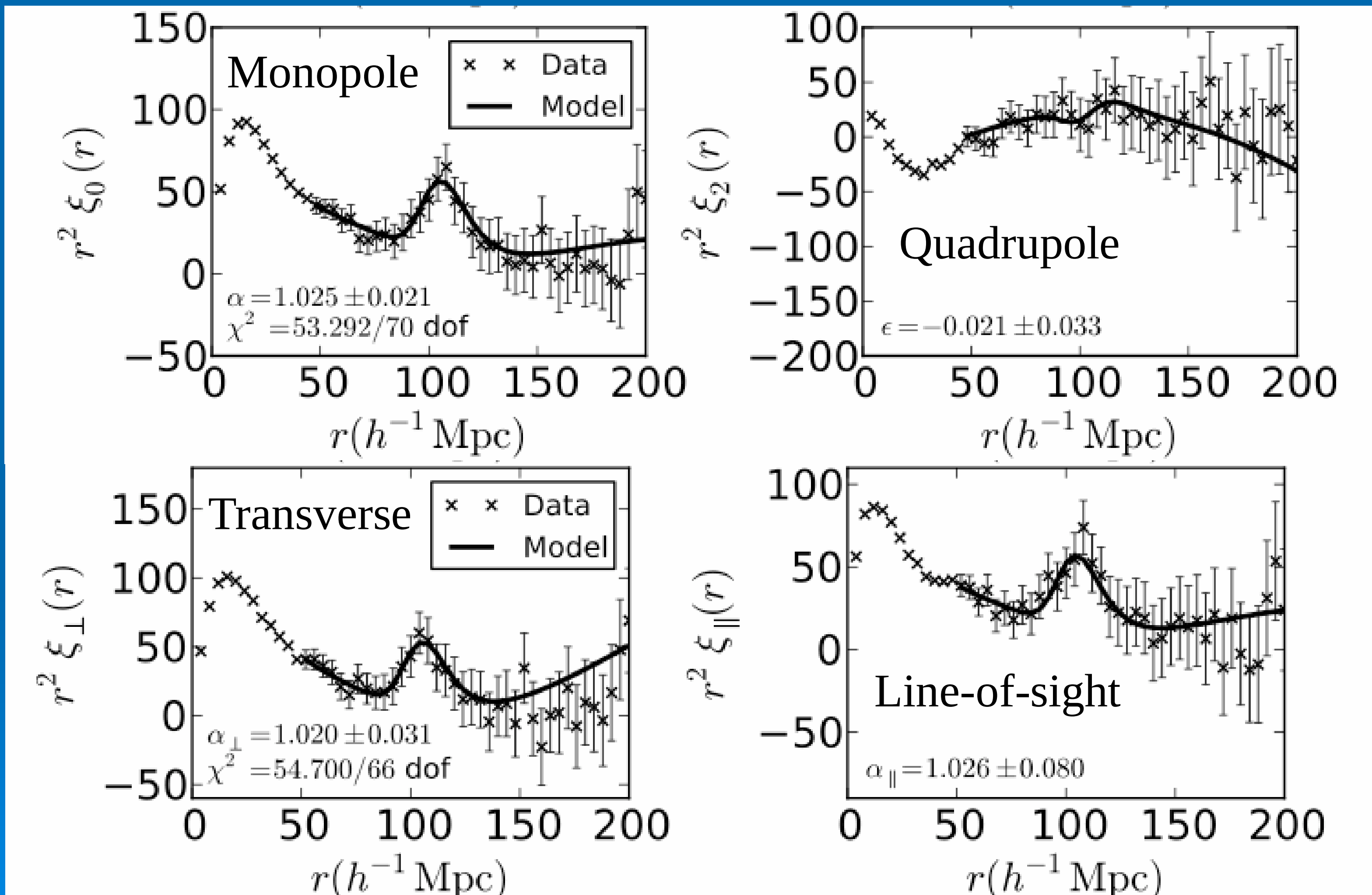
Redshift Distortions



SDSS-II DR7 Mock Catalogs
Padmanabhan et al. (2012)

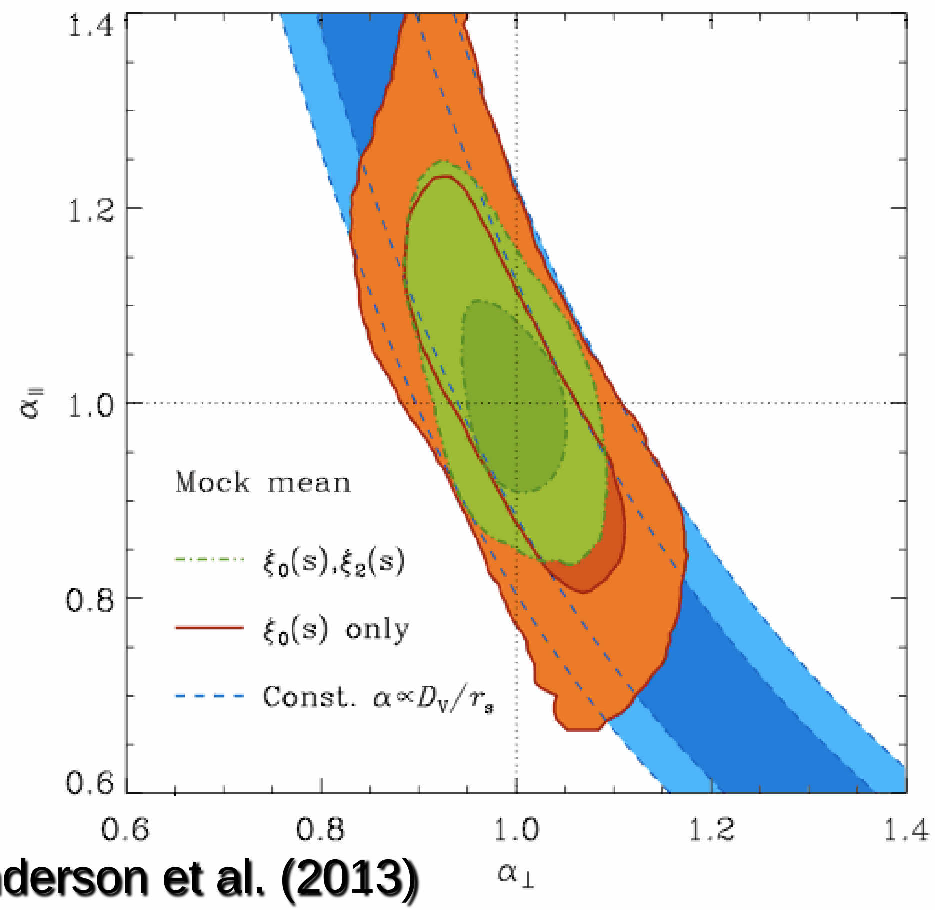
- Peculiar velocities create redshift distortions in clustering.
- This is an order unity anisotropy, compared to our 1% interest in the A-P effect.
- Redshift distortions are of great interest: the large-scale velocity field is a test of gravity.
- We want to separate the two!

Anisotropic BAO in DR9



Anderson et al. (2013), Kazin et al. (2013)

From Anisotropic to Isotropic

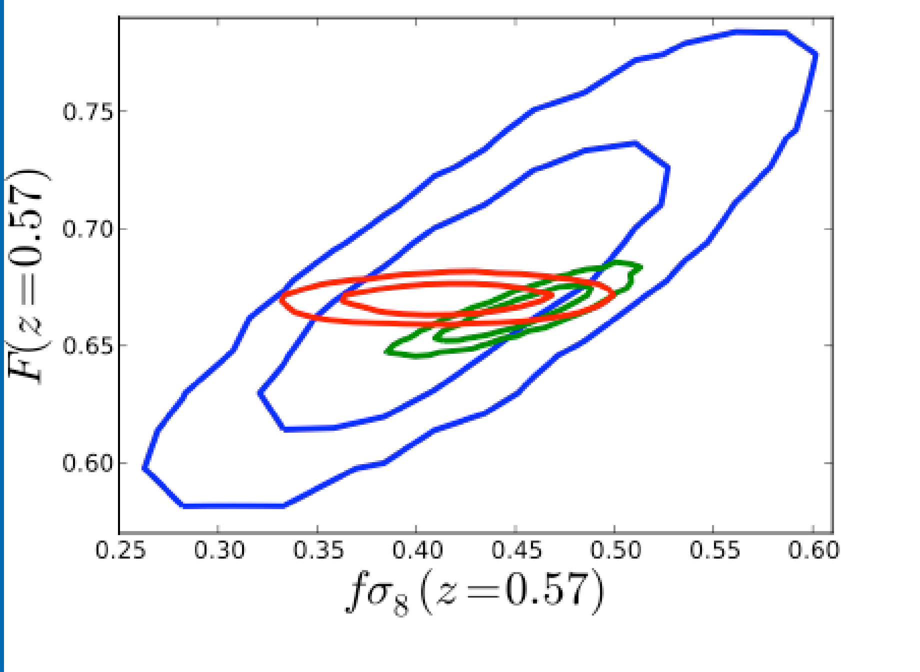


Anderson et al. (2013)

- At low redshift, D_V is a good compression of current data.

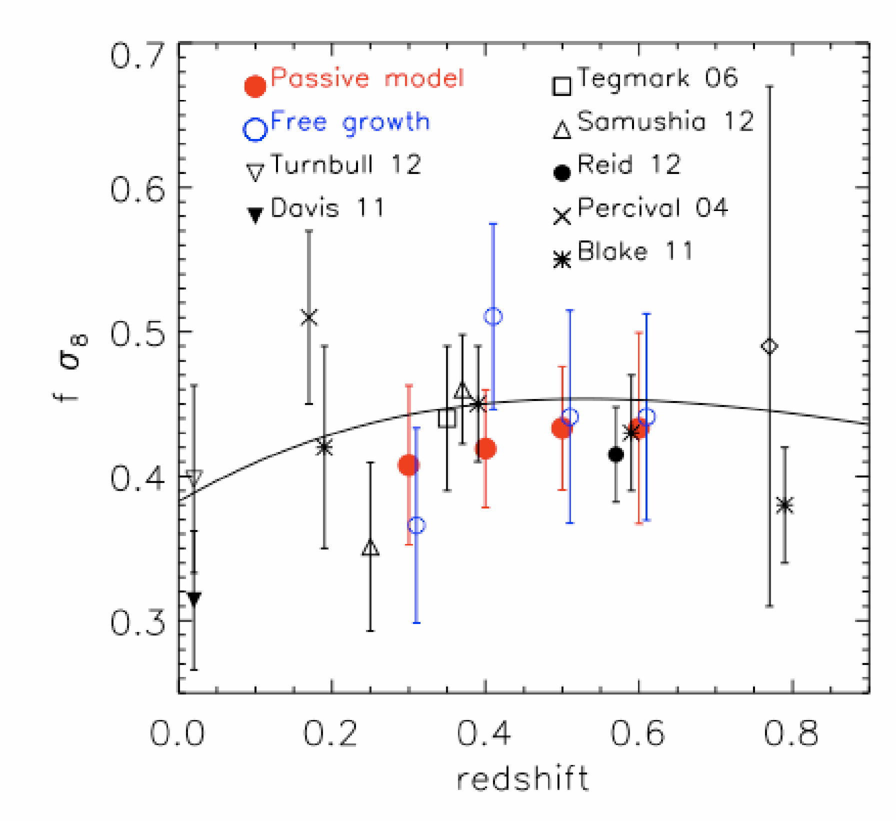
Broadband Anisotropies

- Several analyses have used BOSS DR9 data to study the and the Alcock-Paczynski effect and the growth of structure from large-scale redshift distortions.
- Variations in methodology; similar results obtained.

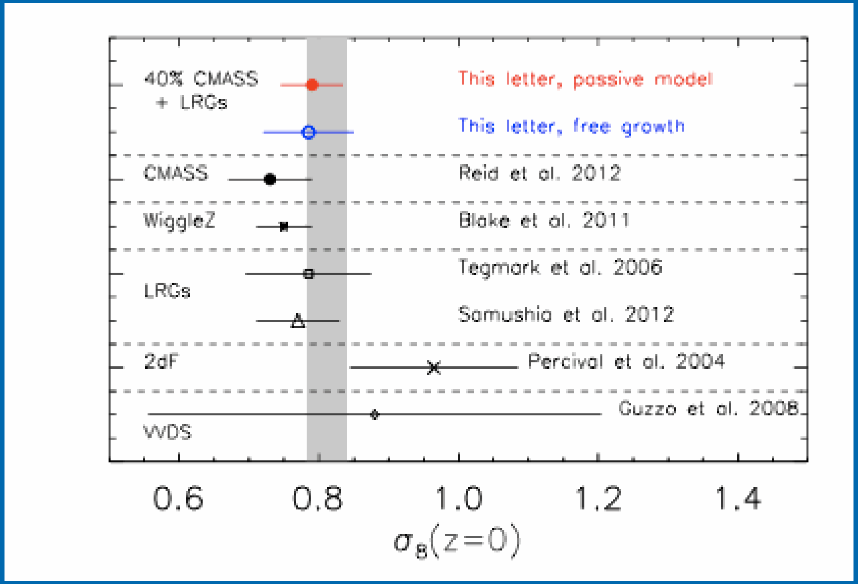


- Figure from Reid et al. (2012). See also Tojeiro et al. (2012), Samushi et al. (2012), Sanchez et al. (2013), Chuang et al. (2012)

Measuring Velocities over Cosmic Time



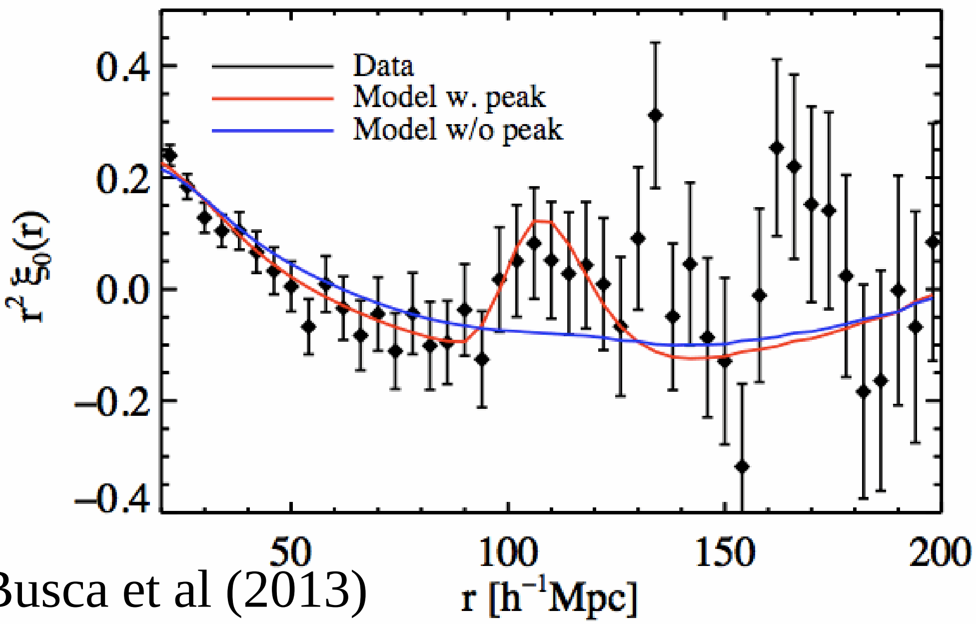
Tojeiro et al. (2012)



- Constraints on $f\sigma_8$ and σ_8 are nicely consistent with GR and the LCDM model.
- Precision on σ_8 is currently O(0.05).

BAO in the Lyman α Forest

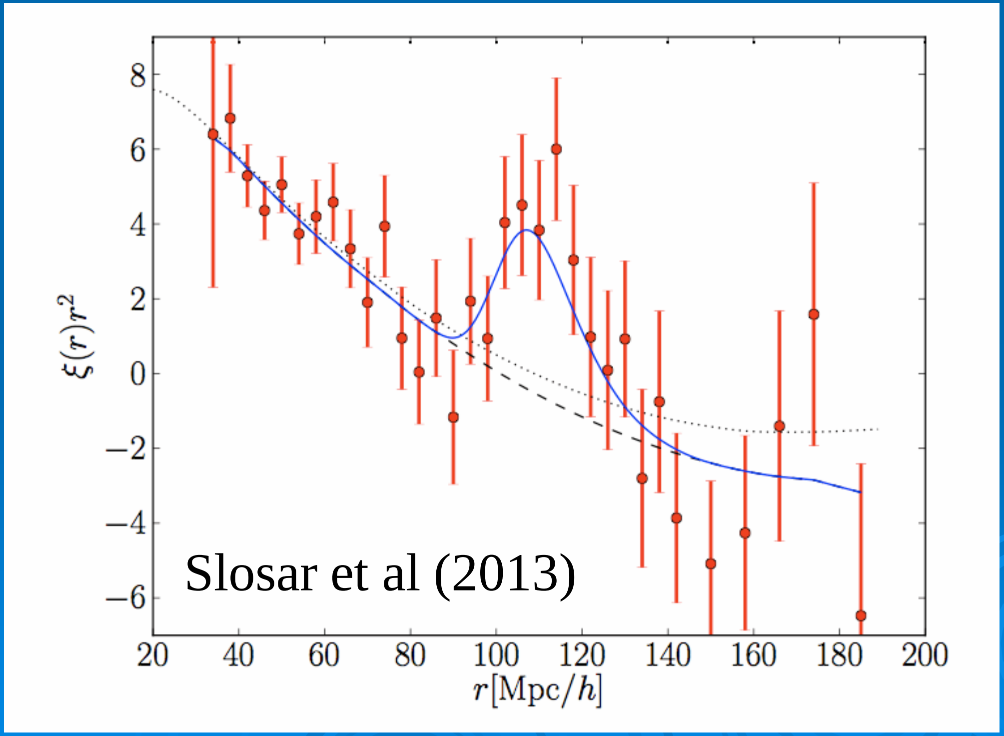
- Bucsa et al. (2012) reports a first detection of the acoustic peak in the Lyman α Forest.
- This uses a set of 48,600 quasars at z>2.1.
- Measures H at z=2.3 to <4%!



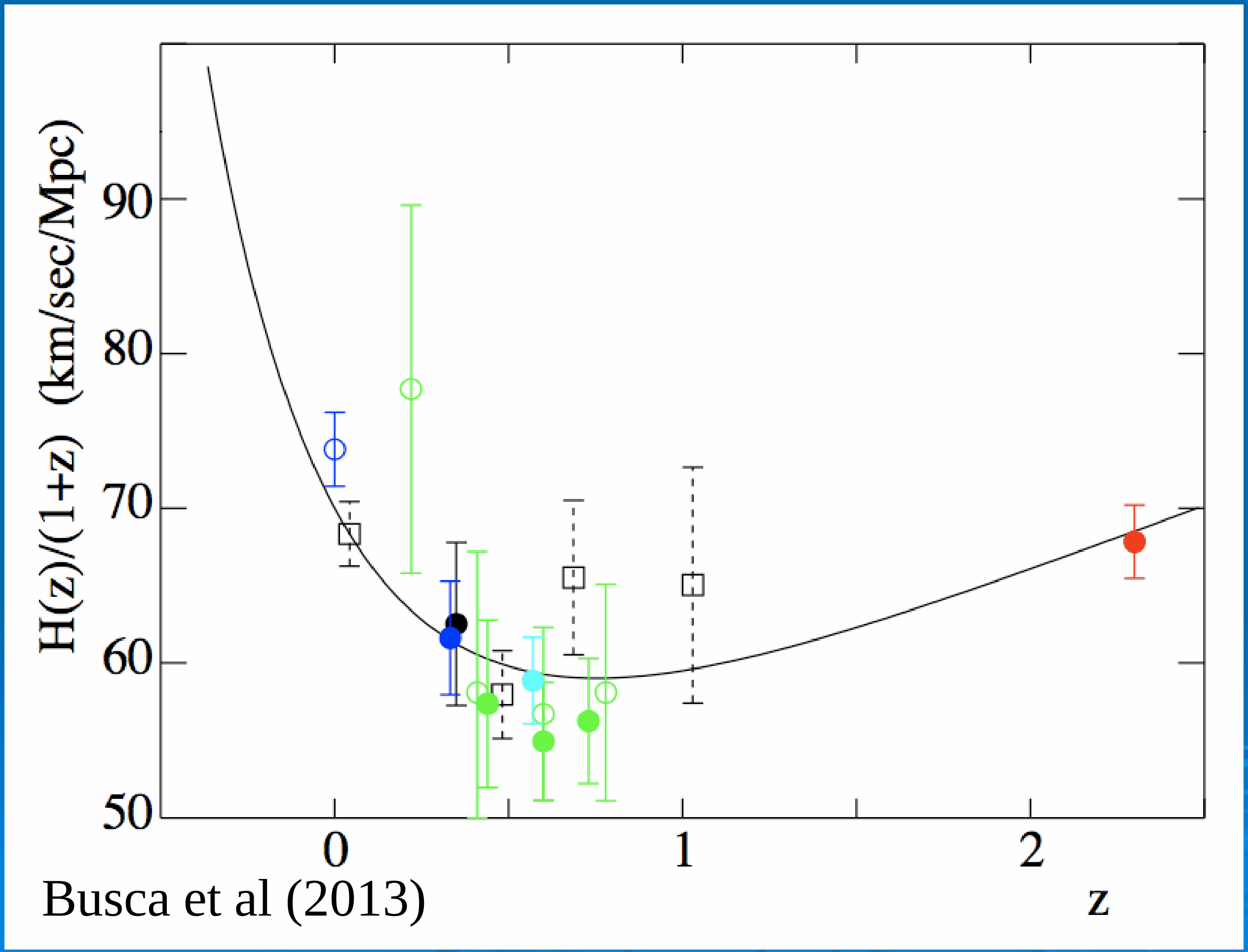
Busca et al (2013)

BAO in the Lyman α Forest

- Slosar et al. (2013) & Kirkby et al. (2013) get similar results with different analysis. First highly precise measurement of the Hubble parameter at z~2.



Detection of Cosmic Decelleration from z=2.3 to z=0.6



Coming Soon....

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

Observing Dark Energy

- Weinberg et al. (2012; arXiv:1201.2434) provides a review of the observational methods for the study of dark energy.

arXiv:1201.2434v1 [astro-ph.CO] 11 Jan 2012

Observational Probes of Cosmic Acceleration☆

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Abstract

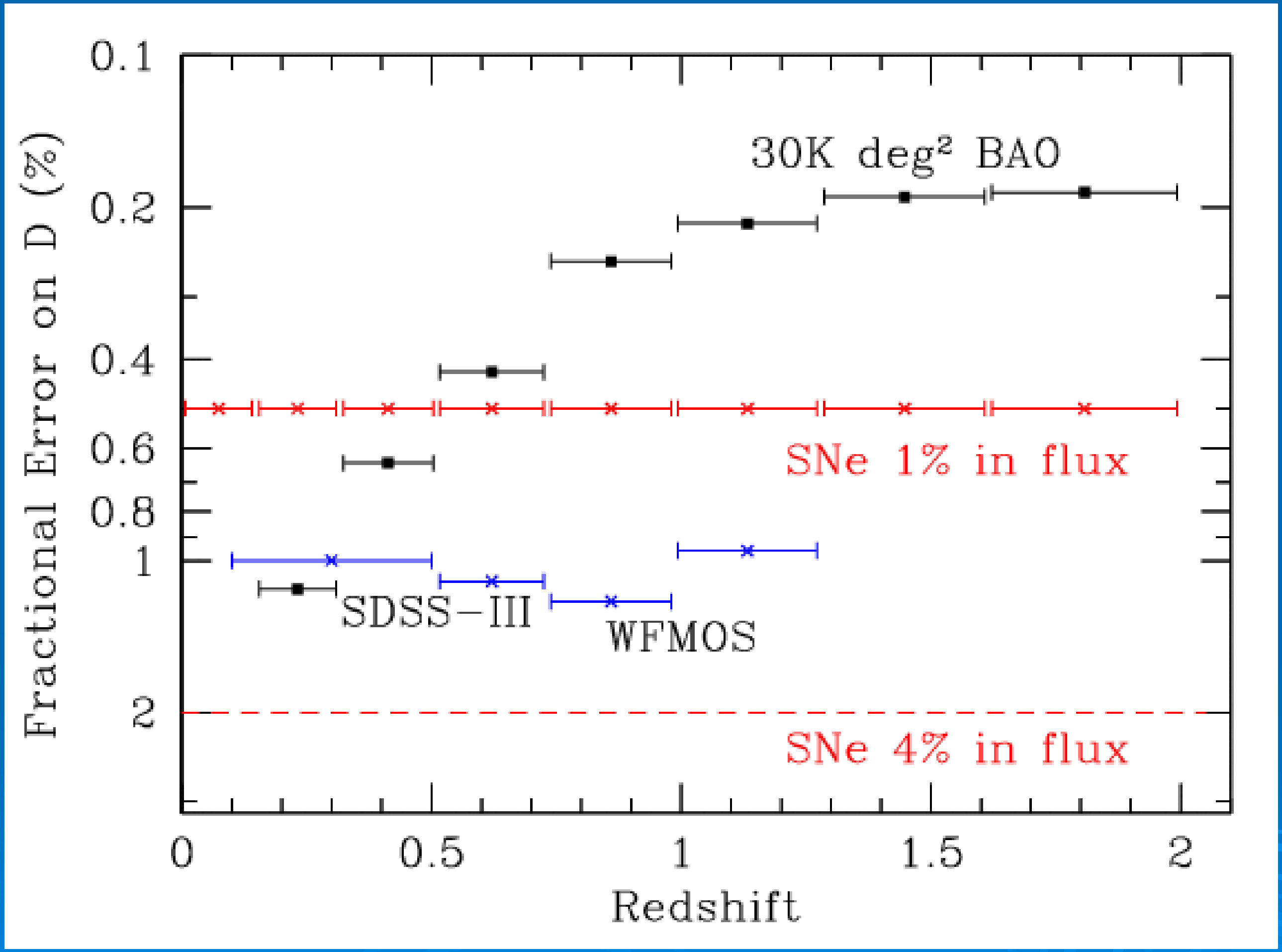
The accelerating expansion of the universe is the most surprising cosmological discovery in many decades, implying that the universe is dominated by some form of "dark energy" with exotic physical properties, or that Einstein's theory of gravity breaks down on cosmological scales. The profound implications of cosmic acceleration have inspired ambitious efforts to understand its origin, with experiments that aim to measure the history of expansion and growth of structure with percent-level precision or higher. We review in detail the four most well established methods for making such measurements: Type Ia supernovae, baryon acoustic oscillations (BAO), weak gravitational lensing, and the abundance of galaxy clusters. We pay particular attention to the systematic uncertainties in these techniques and to strategies for controlling them at the level needed to exploit "Stage IV" dark energy facilities such as BigBOSS, LSST, *Euclid*, and *WFIRST*. We briefly review a number of other approaches including redshift-space distortions, the Alcock-Paczynski effect, and direct measurements of the Hubble constant H_0. We present extensive forecasts for constraints on the dark energy equation of state and parameterized deviations from General Relativity, achievable with Stage III and Stage IV experimental programs that incorporate supernovae, BAO, weak lensing, and cosmic microwave background data. We also show the level of precision required for clusters or other methods to provide constraints competitive with those of these fiducial programs. We emphasize the value of a balanced program that employs several of the most powerful methods in combination, both to cross-check systematic uncertainties and to take advantage of complementary information. Surveys to probe cosmic acceleration produce data sets that support a wide range of scientific investigations, and they continue the longstanding astronomical tradition of mapping the universe in ever greater detail over ever larger scales.

Keywords:

Conclusions

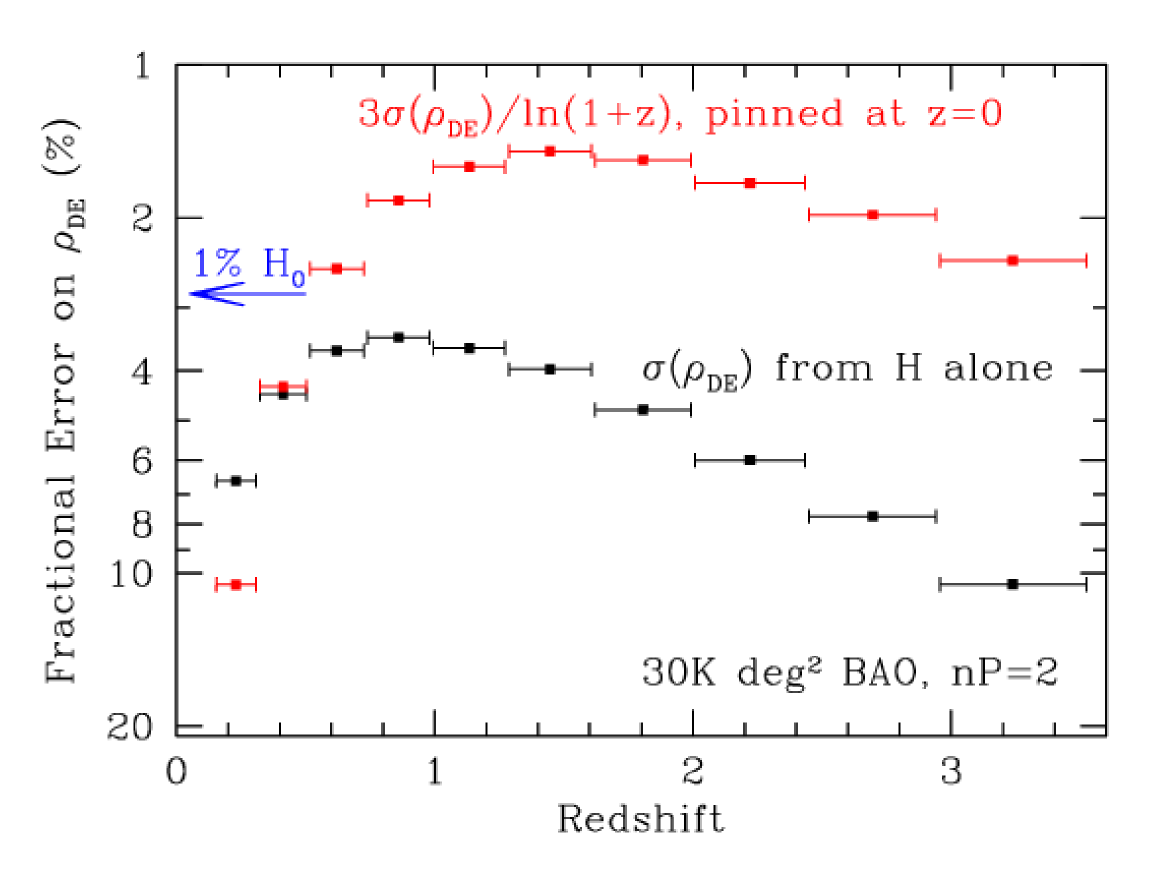
- Acoustic oscillations provide a robust way to measure H(z) and $D_A(z)$.
  - Clean signature in the clustering of galaxies.
  - Can probe high redshift; can probe H(z) directly.
  - Well protected from low redshift systematics.
- SDSS uses the acoustic signature to measure the distance to z=0.35 to 1.9% and to z=0.57 to 1.7%. Plus a first detection at z=2.3.
  - Excellent consistency with flat ΛCDM.
- Larger galaxy surveys such as SDSS-III/BOSS will push to 1% and below in this decade.

Building the Distance Scale



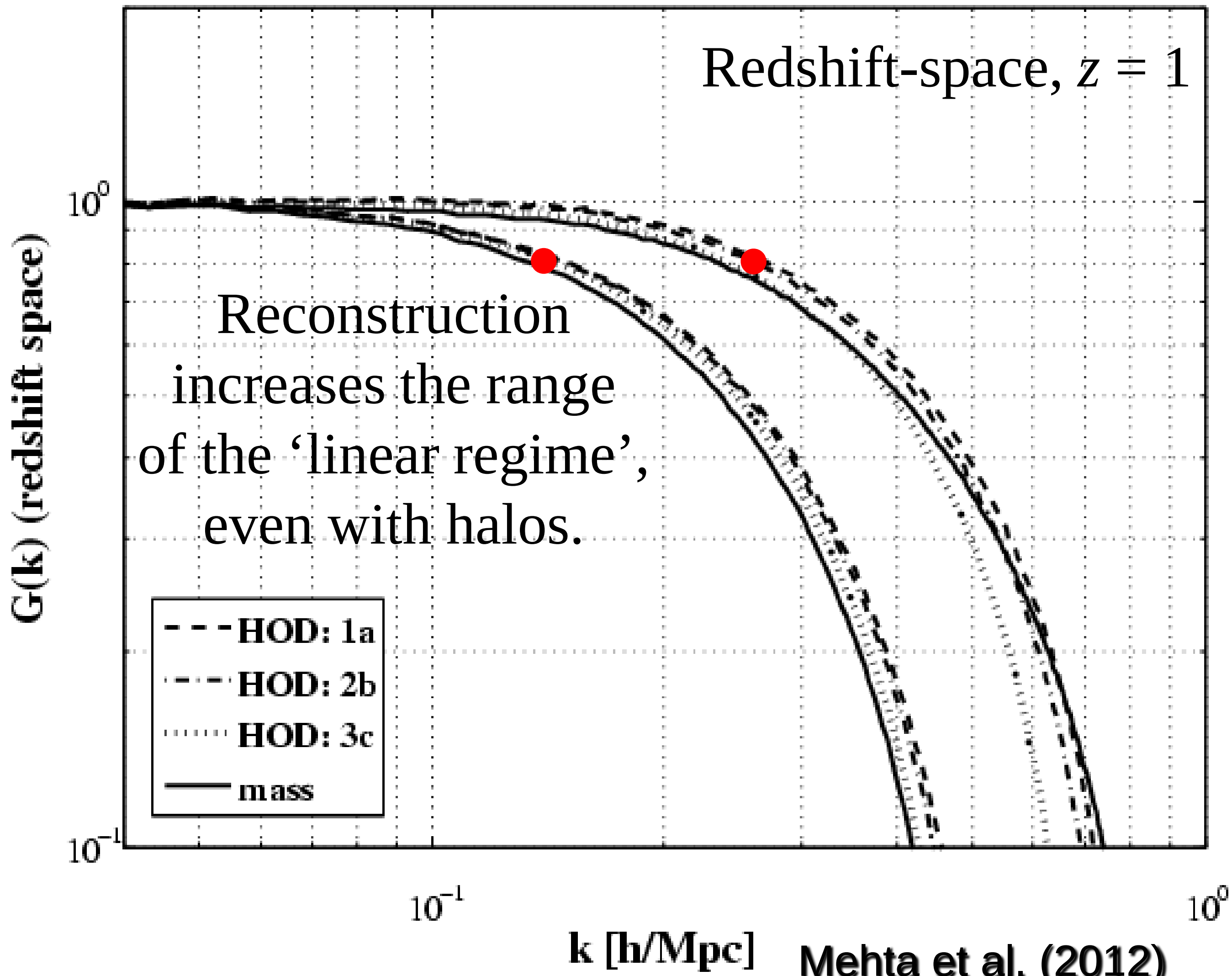
- SNe and BAO are highly complementary in z!

Measuring Dark Energy at z>1



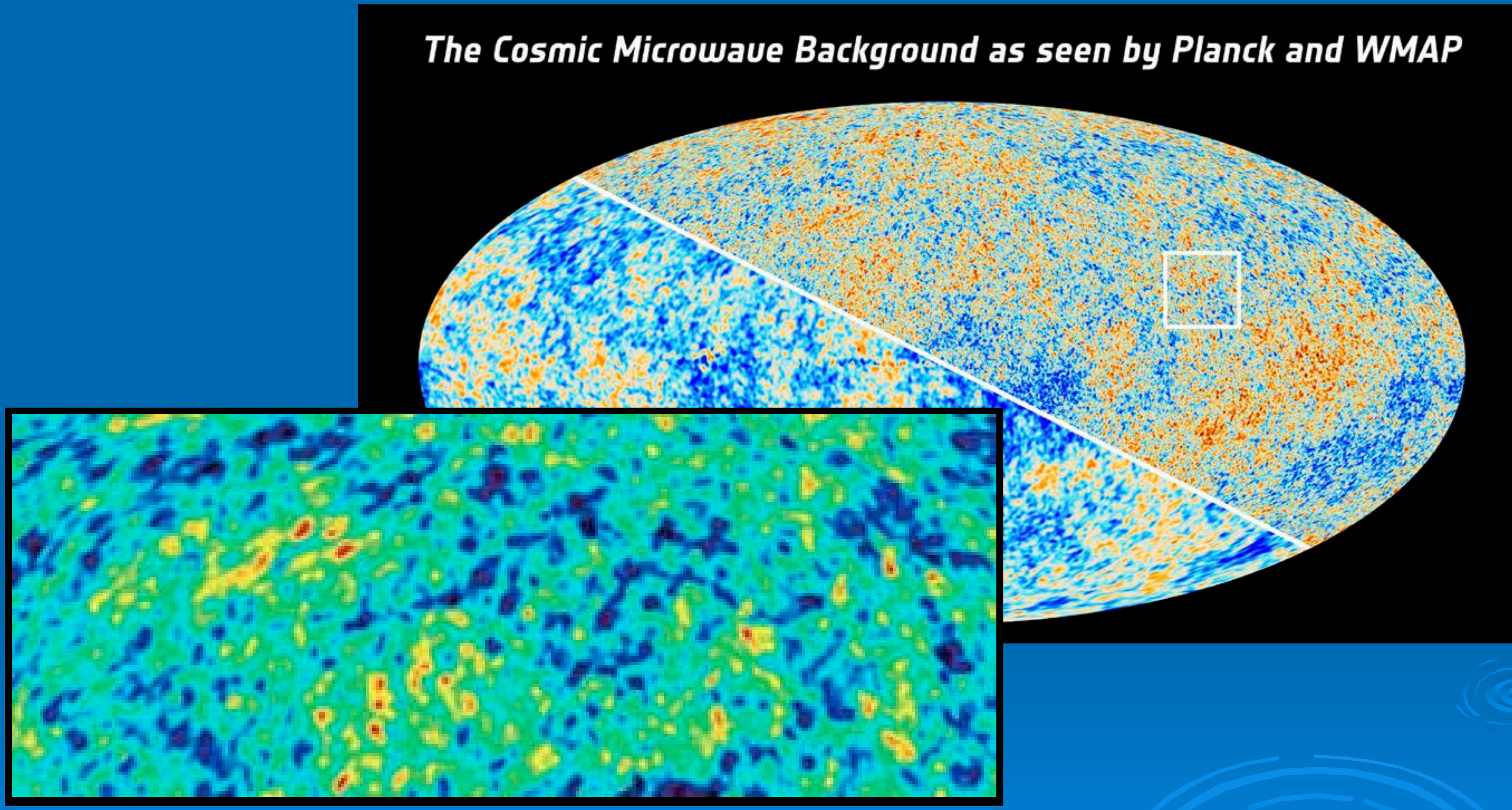
- Precise H(z) at z>1 can achieve excellent constraints on dark energy.

Assessing Reconstruction



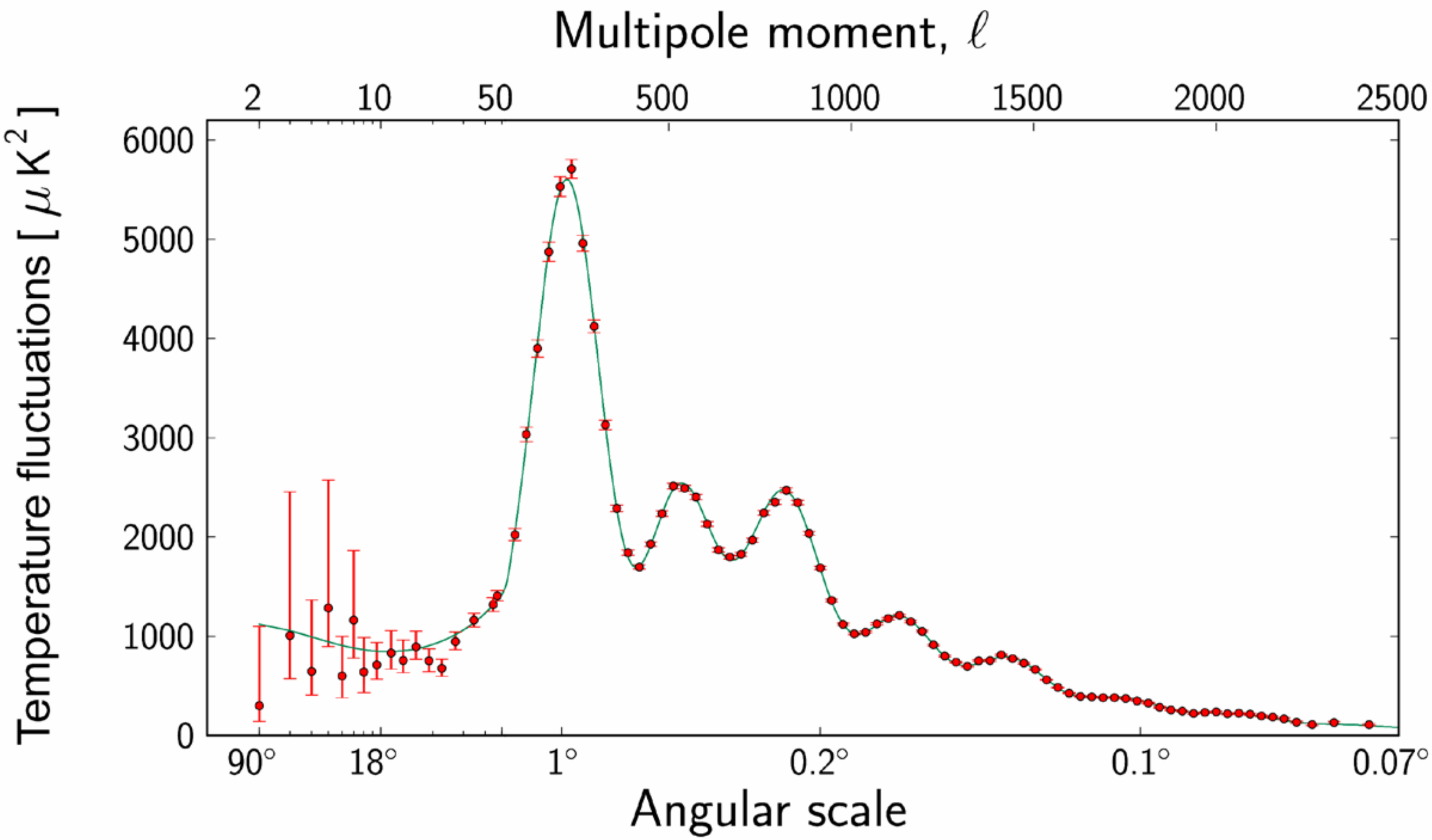
Mehta et al. (2012)

Acoustic Oscillations in the CMB



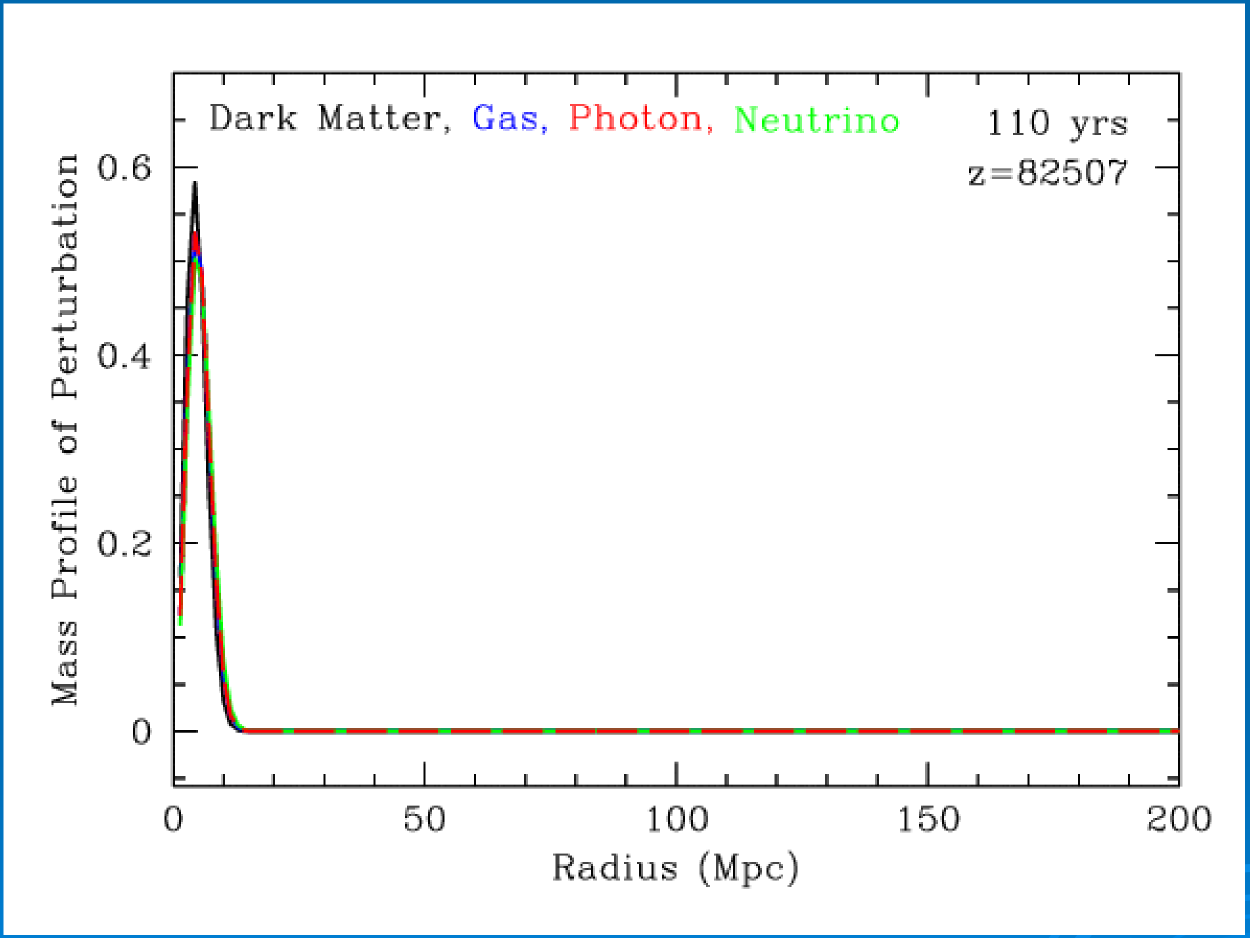
- Although there are fluctuations on all scales, there is a characteristic angular scale.

Acoustic Oscillations in the CMB



Planck Collaboration (2013)

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.