Measuring the Cosmic Distance Scale with SDSS-III

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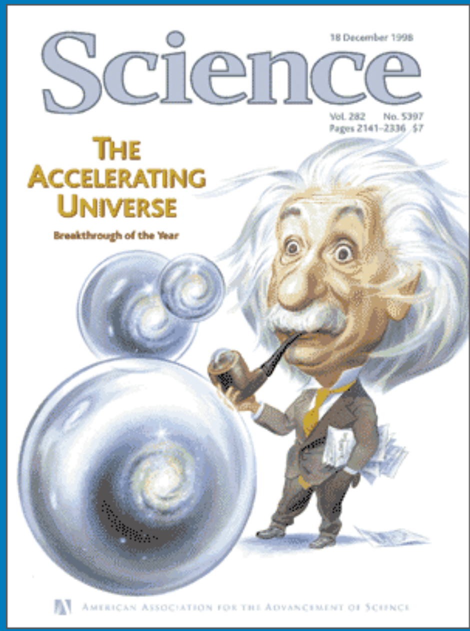
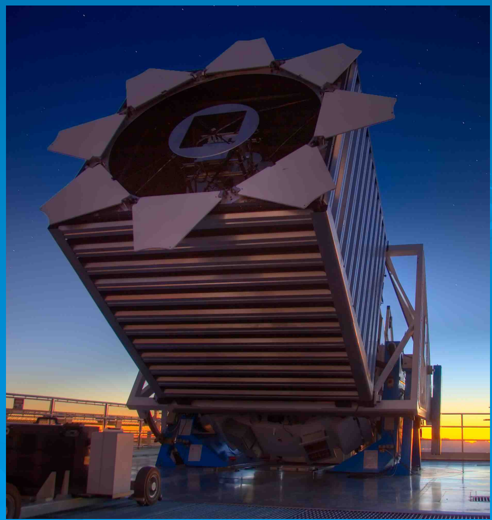
Motivation & Outline

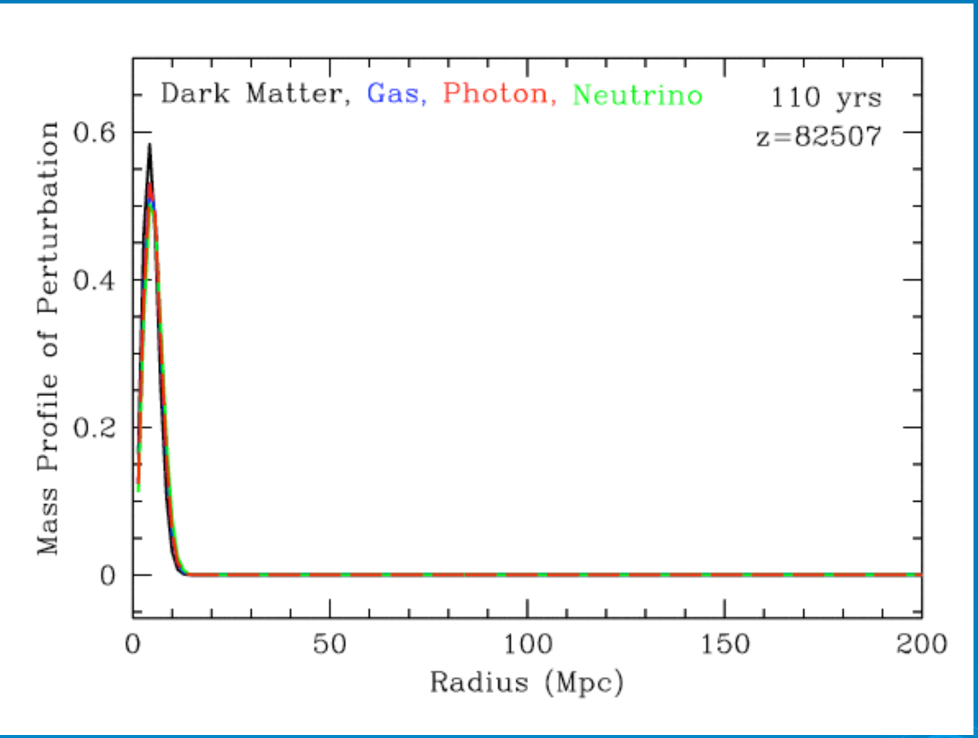
- Dark Energy pushes us to measure the cosmic distance scale and the behavior of gravity to high precision.
- I will introduce baryon acoustic oscillations as a standard ruler.
  - Linear theory pedagogy.
  - Non-linear structure formation.
- Reconstruction & BAO in SDSS-II DR7.
- Cosmology results from SDSS-III DR9.
  - BAO from galaxies and Lyman α forest.
  - Many other results and details in other talks and posters.
- A path to 1% distances and better.





Sound Waves in the Early Universe

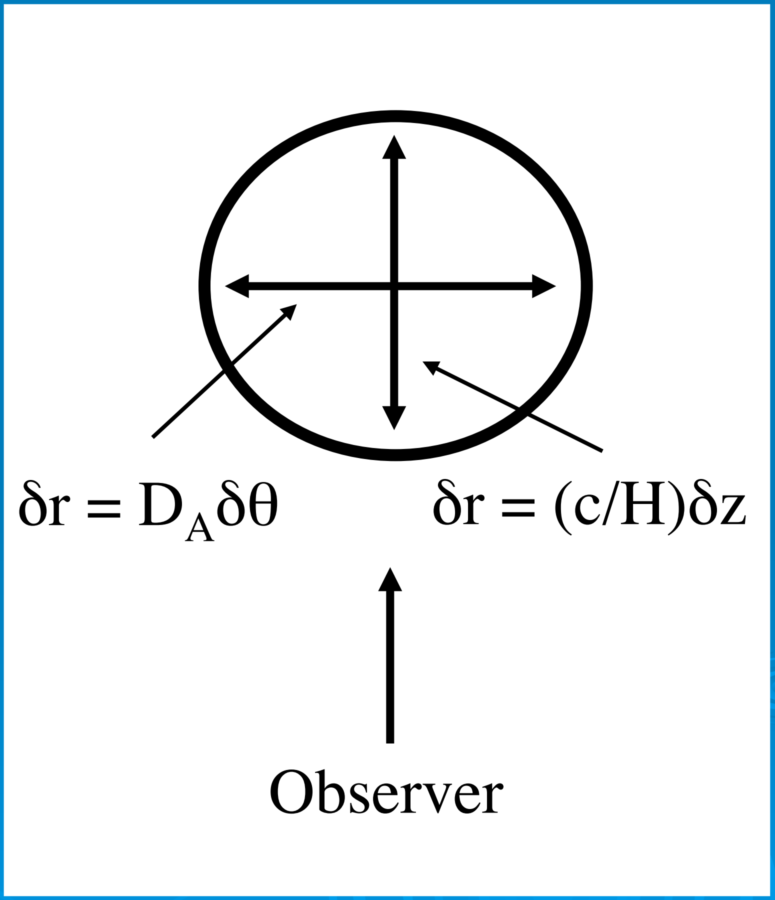
- Each initial overdensity (in DM & gas) is an overpressure that launches a spherical sound wave.
- This wave travels outwards at 57% of the speed of light.
- Pressure-providing photons decouple at recombination. We see this as the CMB.
- Sound speed plummets. Wave stalls at a radius of 150 Mpc.



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

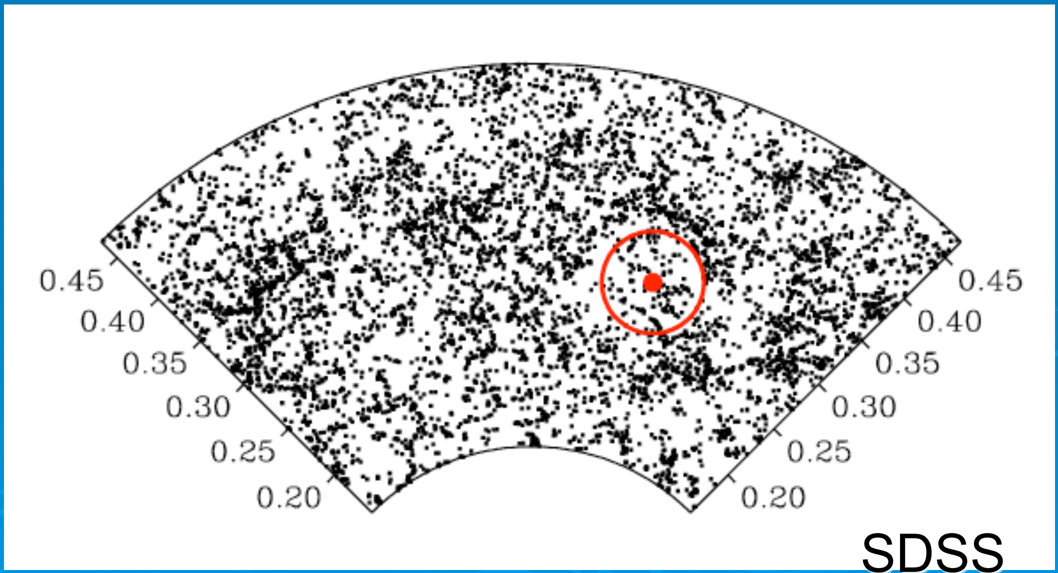
A Standard Ruler

- 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 $D_A(z)$!



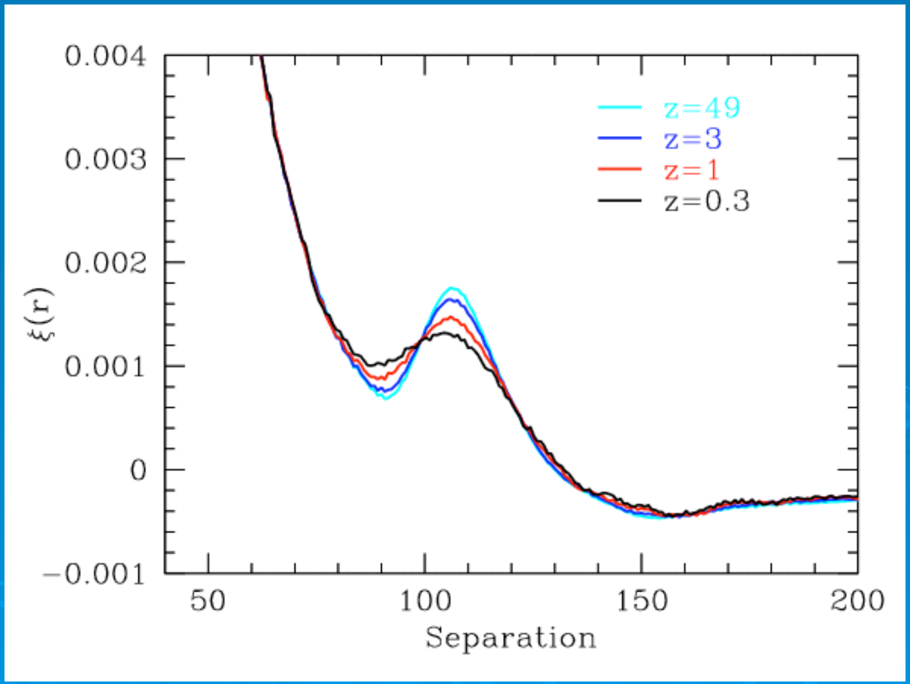
Galaxy Redshift Surveys

- 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

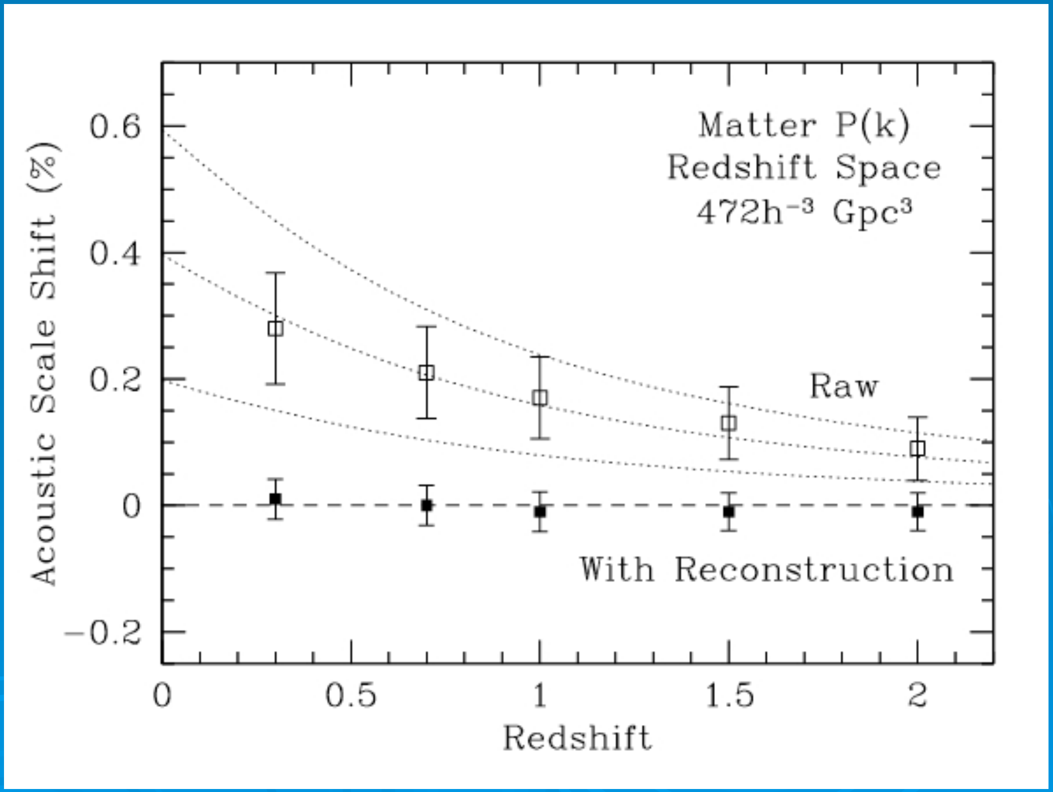
- The acoustic signature is carried by pairs of galaxies separated by 150 Mpc.
- Nonlinearities push galaxies around by 3-10 Mpc. Broadens peak, making it hard to measure the scale.
  - Non-linearities are increasingly negligible at z>1. Linear theory peak width dominates.
- Moving the scale requires 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

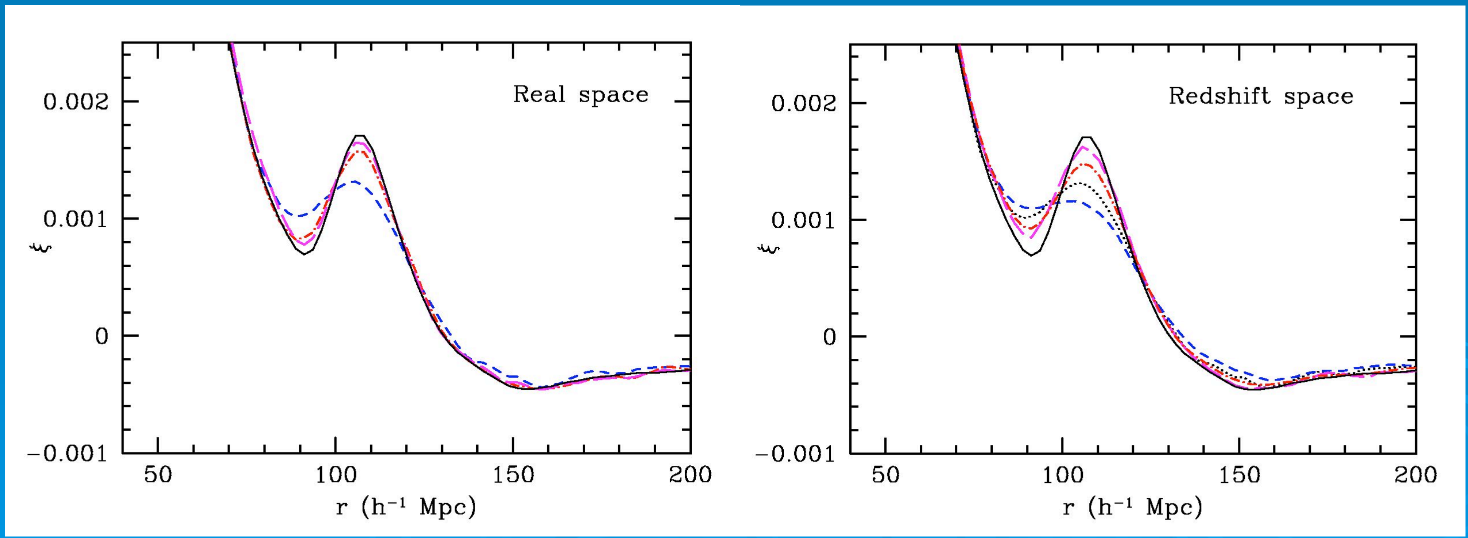
- N-body simulations show the acoustic peak to be preserved.
  - Shifts of 0.3% at z=0, highly predictable.
- Halo-based galaxy bias yields an additional shift, of order 0.5% for high biases.
- Effect is well matched to 2nd-order perturbation theory calculation of Padmanabhan & White (2009).
- These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



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

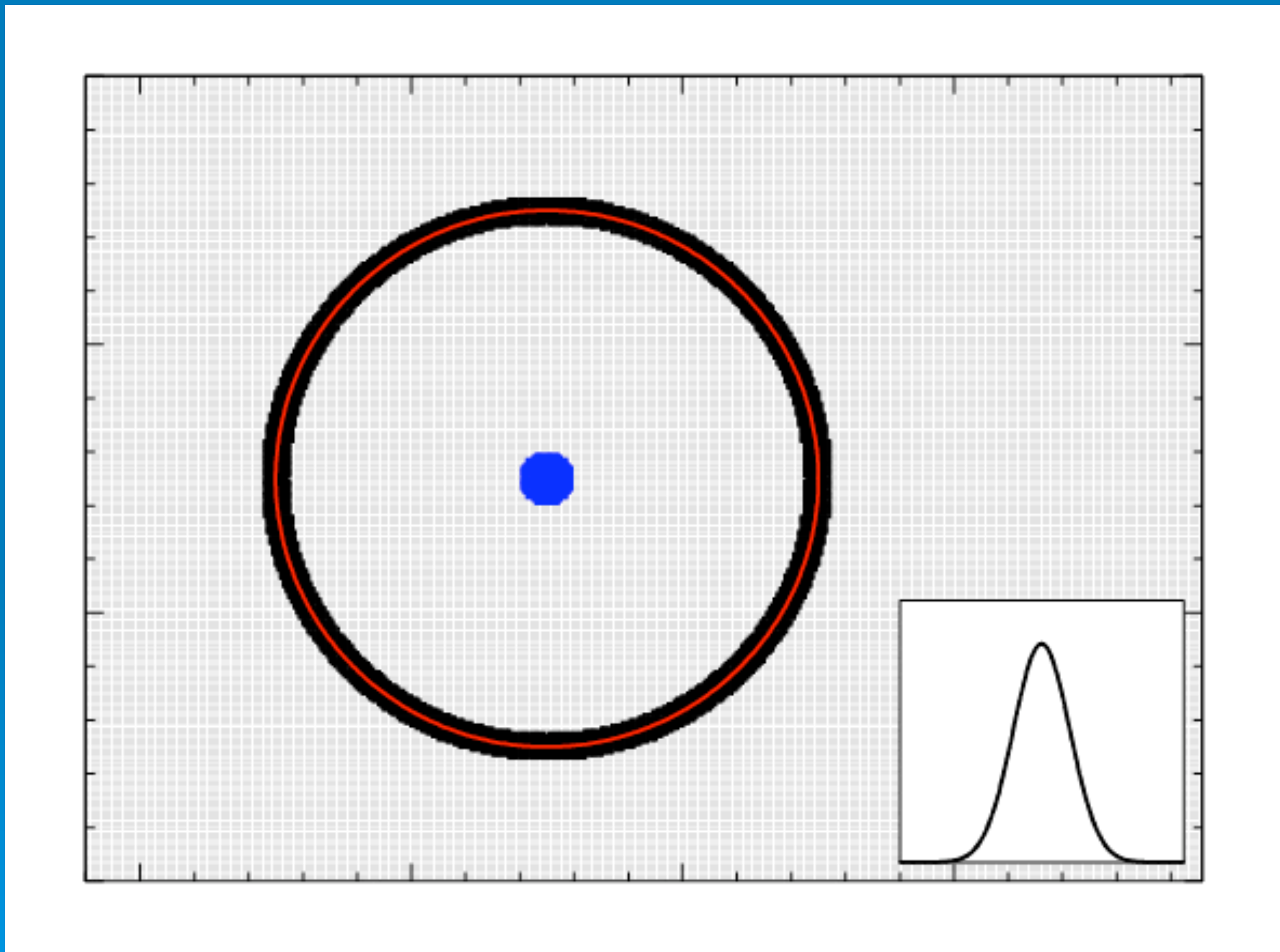
Improving the Acoustic Peak

- 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)

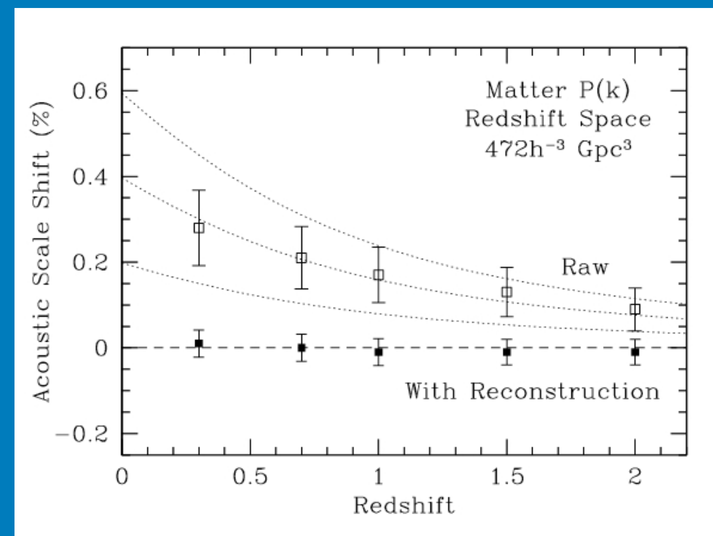
Reconstruction Illustrated

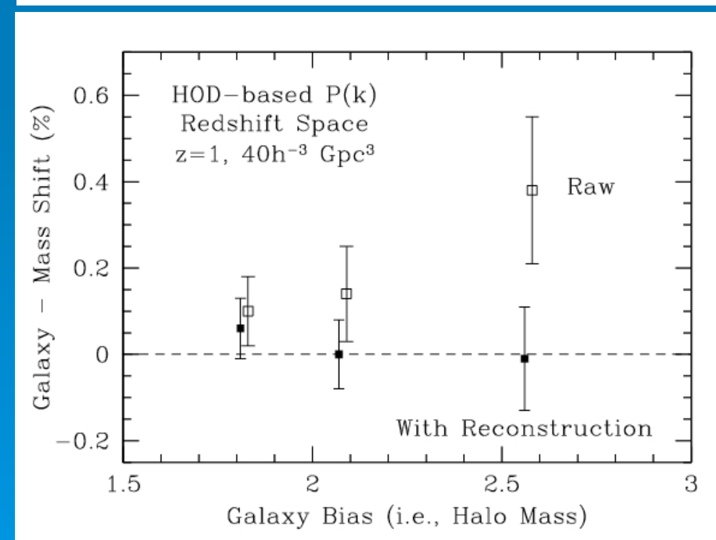


Padmanabhan et al. (2012)

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.





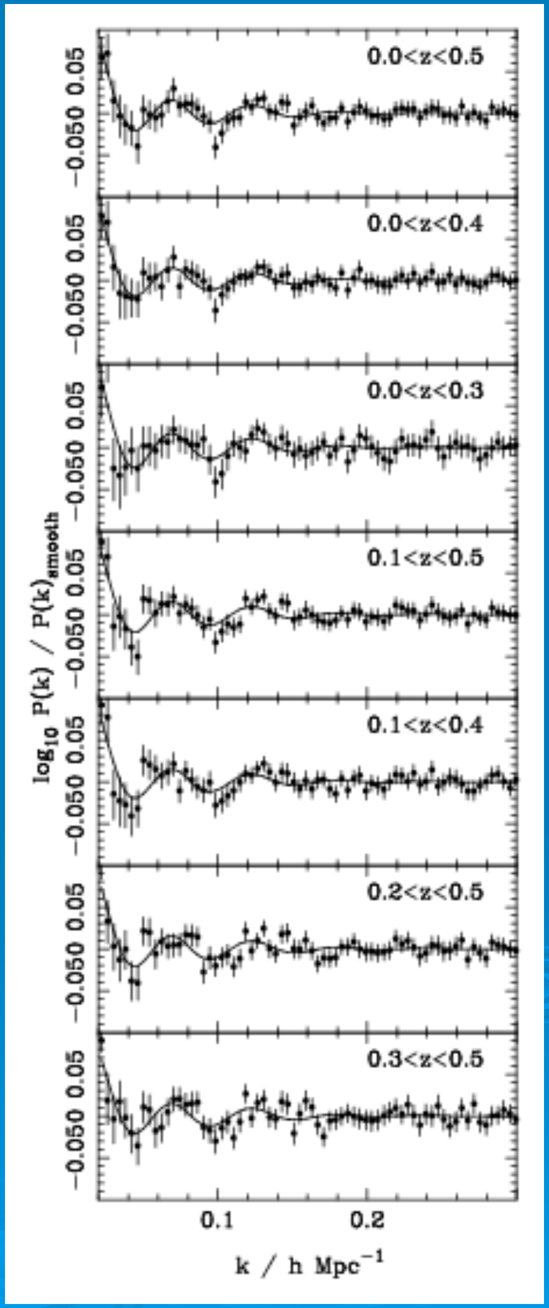
Seo et al. (2010); Mehta et al. (2011)

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.
- Data Release 10: Coming next week.

BAO in SDSS-II DR7

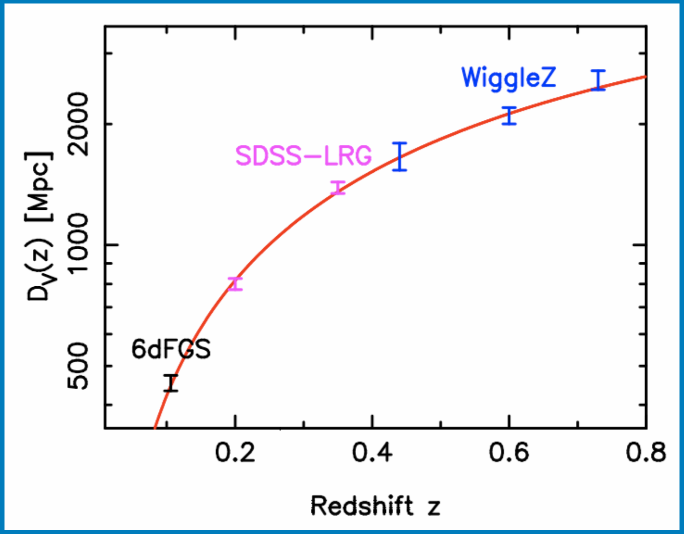
- SDSS-I and II produced several analyses of the BAO, culminating in Percival et al. (2009) and Reid et al. (2009) analysis of the power spectrum of the final SDSS-II (LRG +MAIN) and 2dF GRS.
- Average signal produced a 2.7% measurement of the distance to z=0.275.
- Good agreement with LCDM model. WMAP5+BAO+SN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

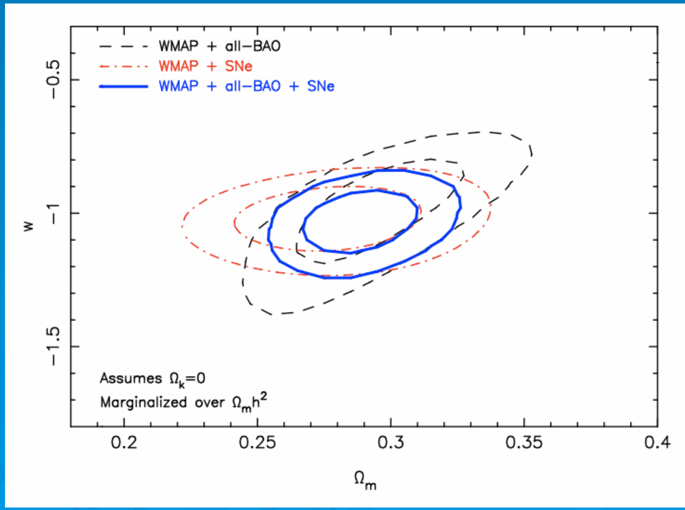


Percival et al. (2009)

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.



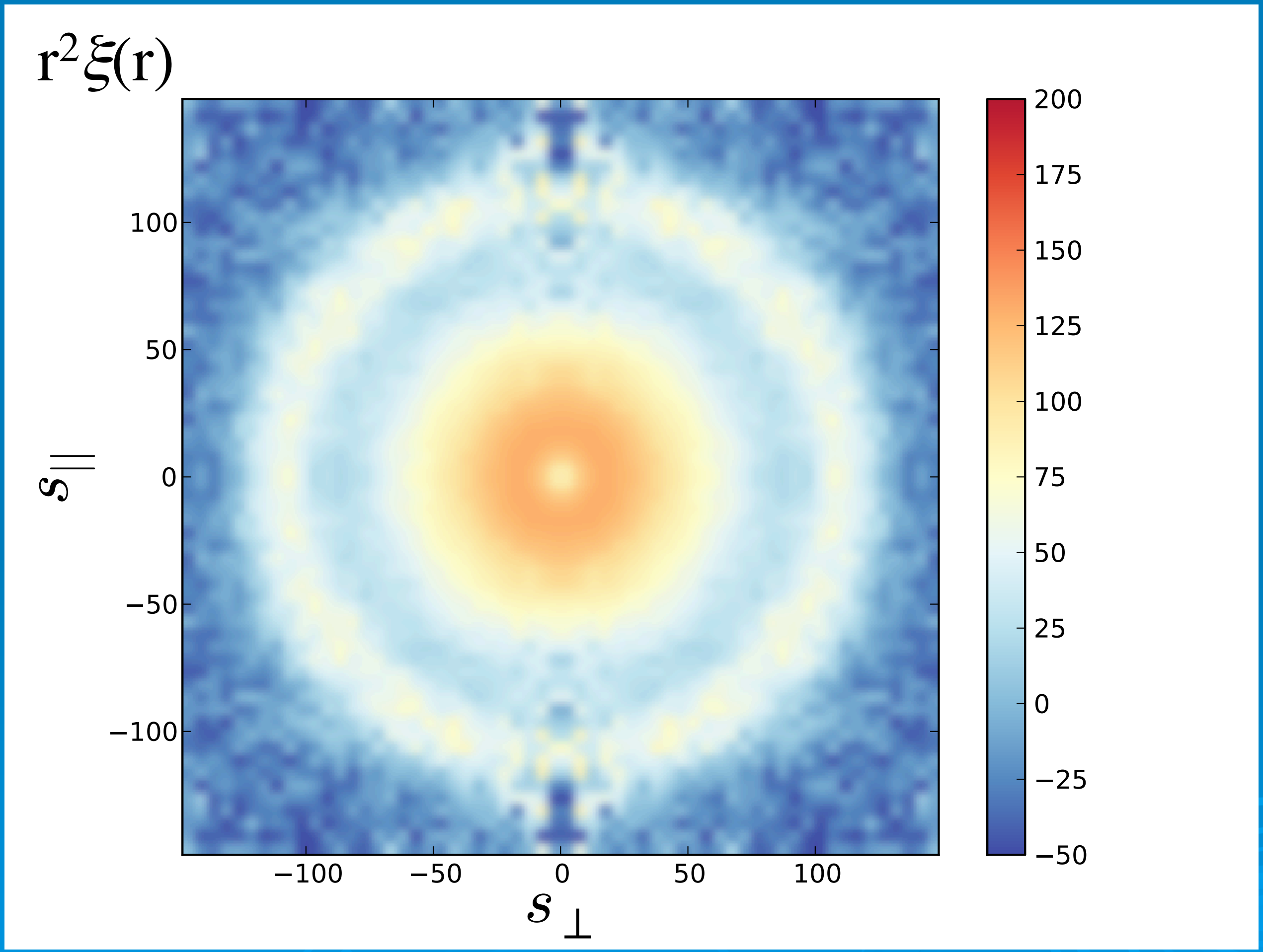


Blake et al. (2011)

DR7 with Reconstruction

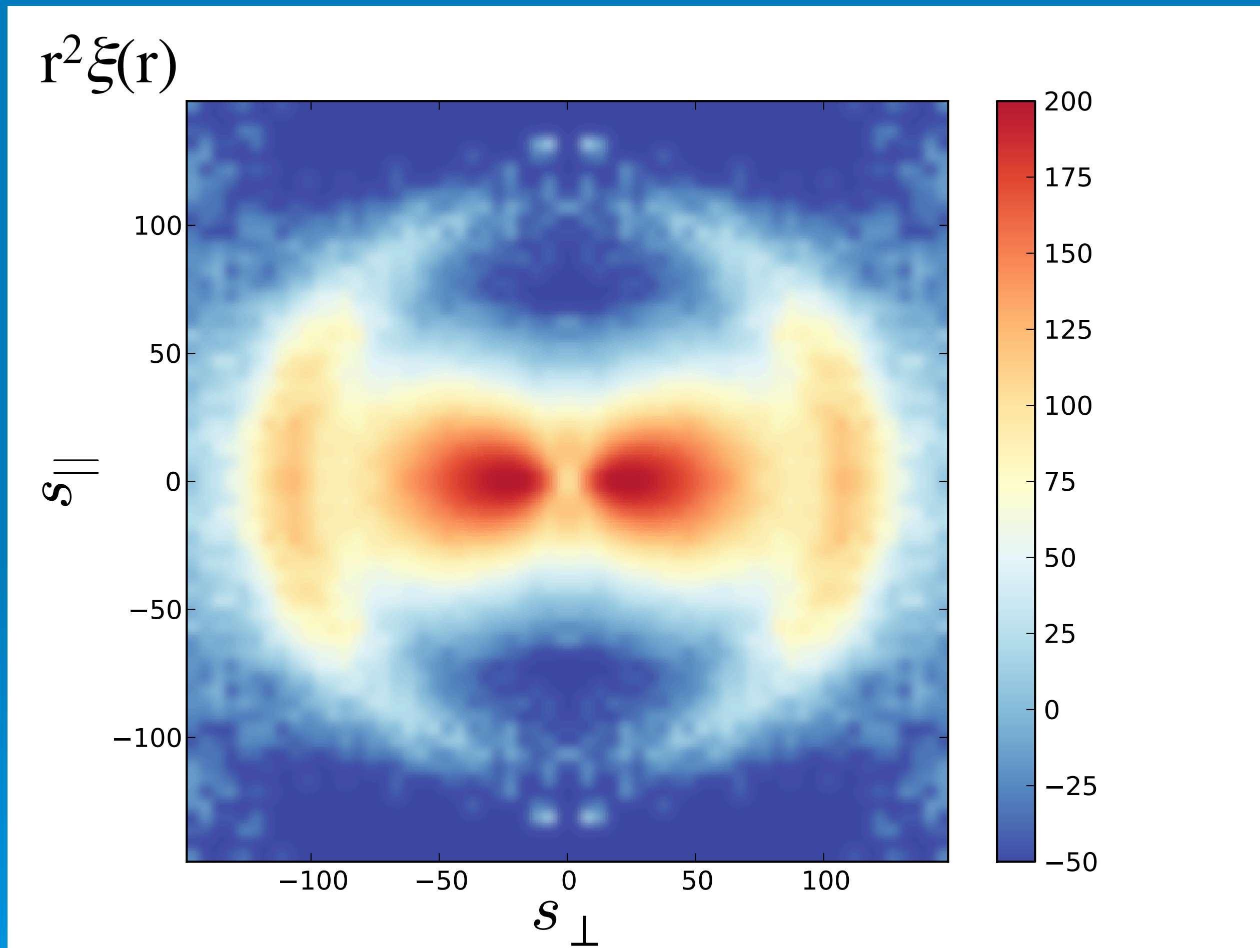
- Padmanabhan et al., Xu et al., and Mehta et al. (2012) present a new analysis of the SDSS-II DR7 Luminous Red Galaxy sample.
  - 106k galaxies over 7200 sq deg.
- First analysis to include reconstruction.
- Improves errors as if we were tripling the survey volume.

Real-space Clustering



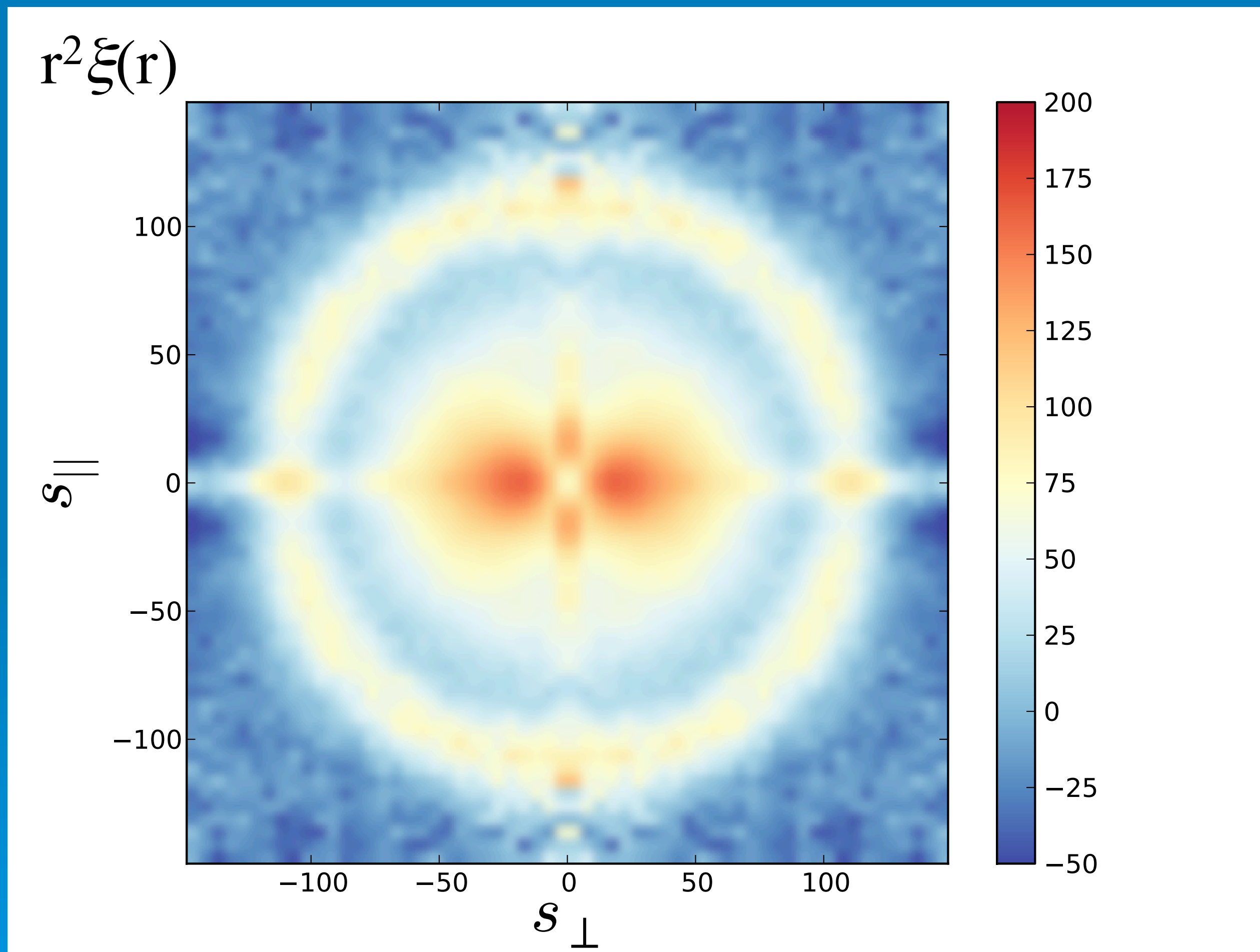
DR7 Mock Catalogs   Padmanabhan et al. (2012)

Redshift-space Clustering



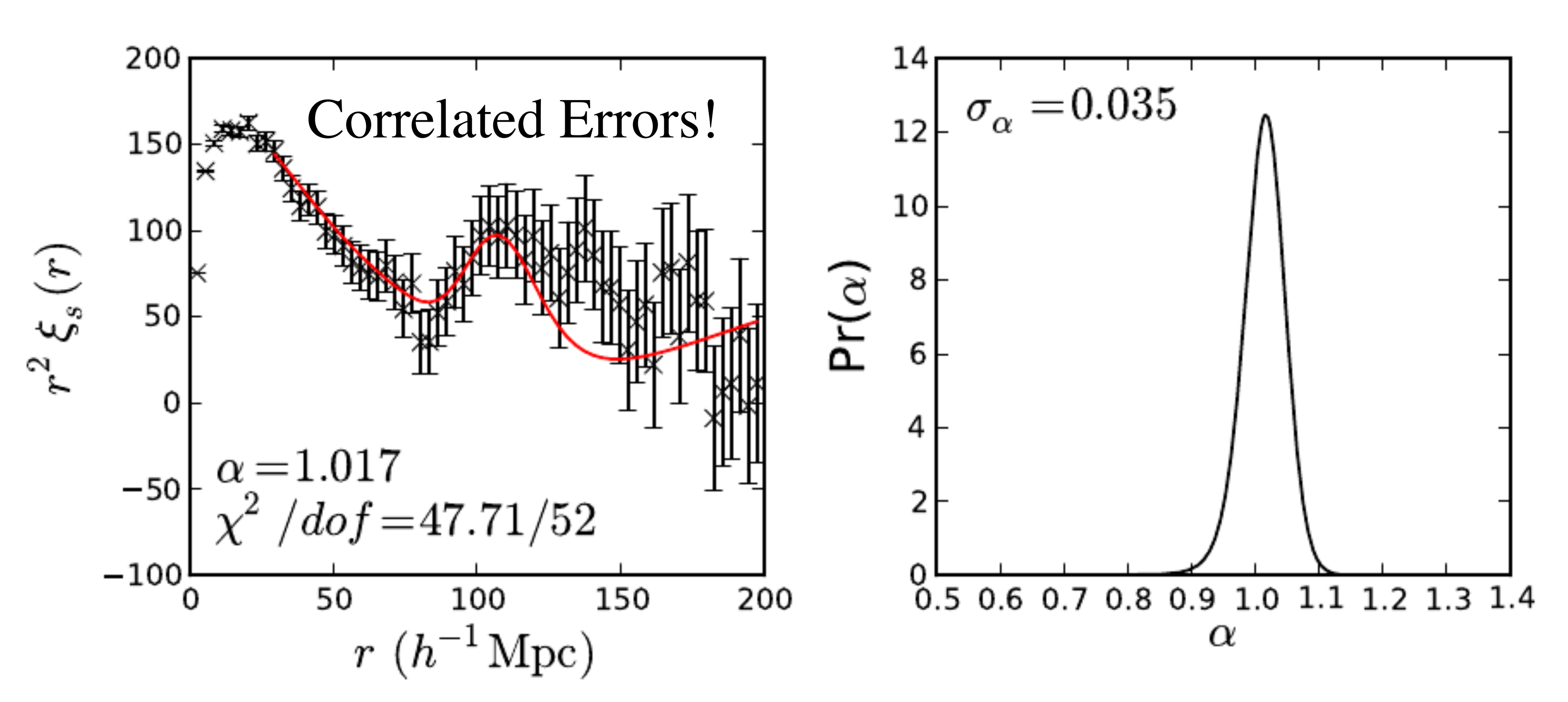
DR7 Mock Catalogs Padmanabhan et al. (2012)

Redshift-Space Clustering after Reconstruction



DR7 Mock Catalogs Padmanabhan et al. (2012)

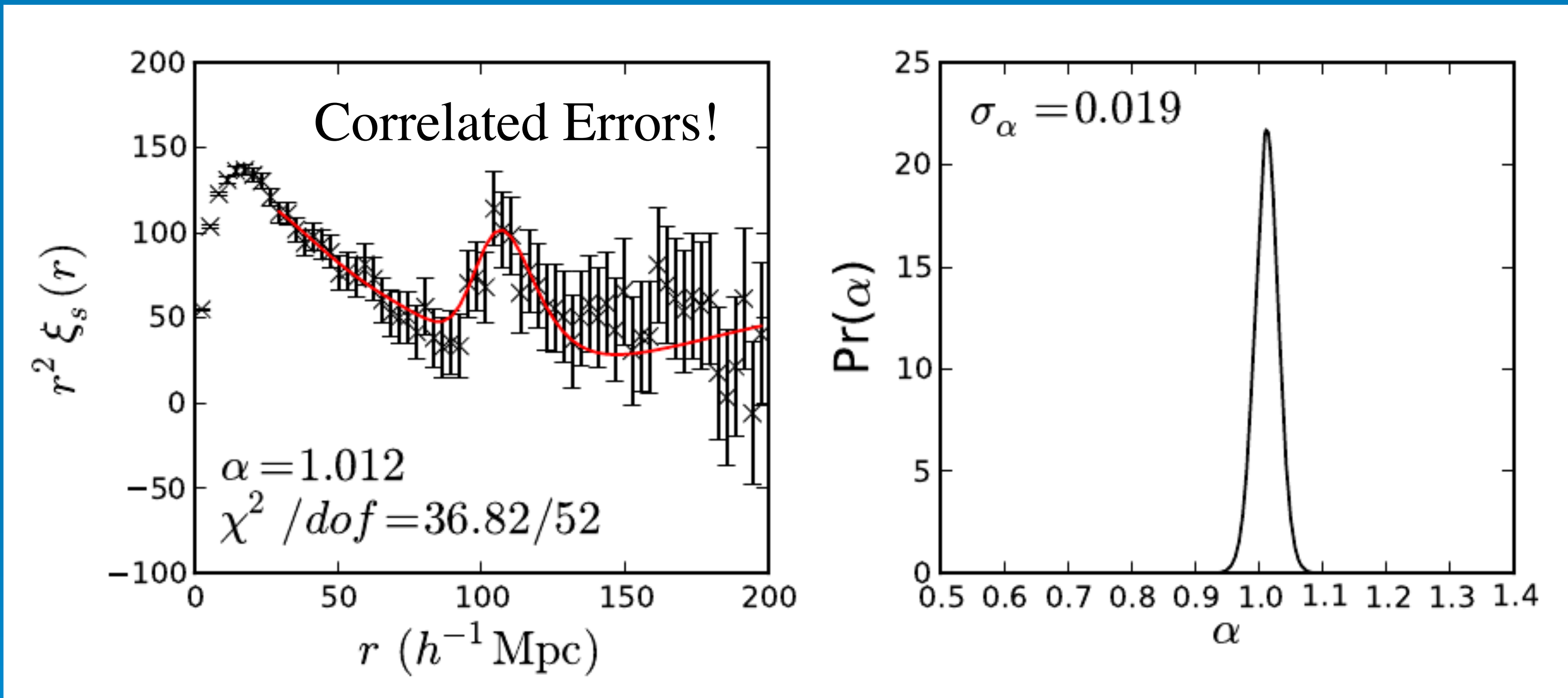
Before Reconstruction



- 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

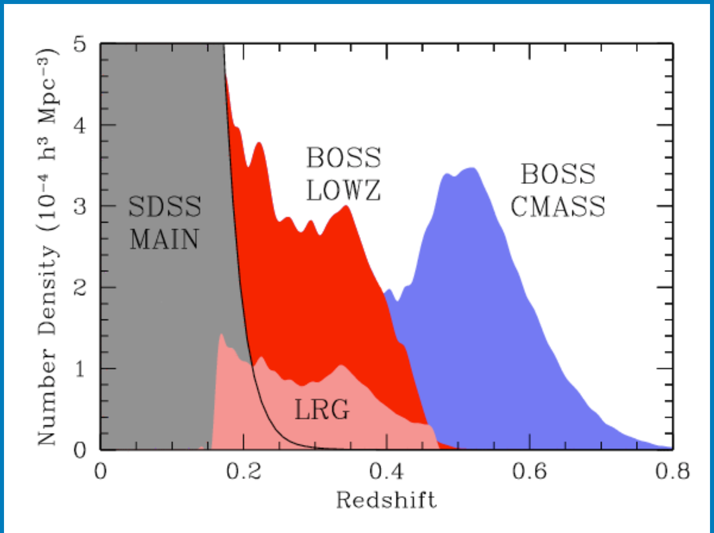
- SDSS-III is the next phase of the SDSS project, operating from summer 2008 to summer 2014.
- SDSS-III has 4 surveys on 3 major themes.
  - BOSS: Largest yet redshift survey for large-scale structure.
  - SEGUE-2: Optical spectroscopic survey of stars, aimed at structure and nucleosynthetic enrichment 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.

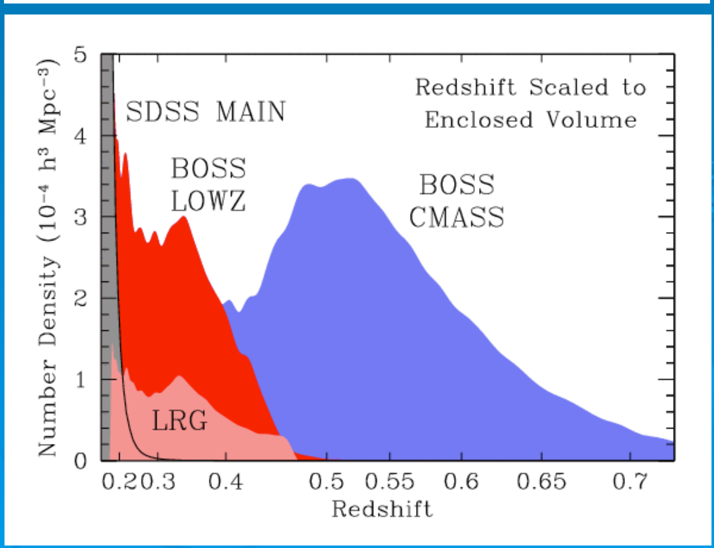
SDSS-III Collaboration

- 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

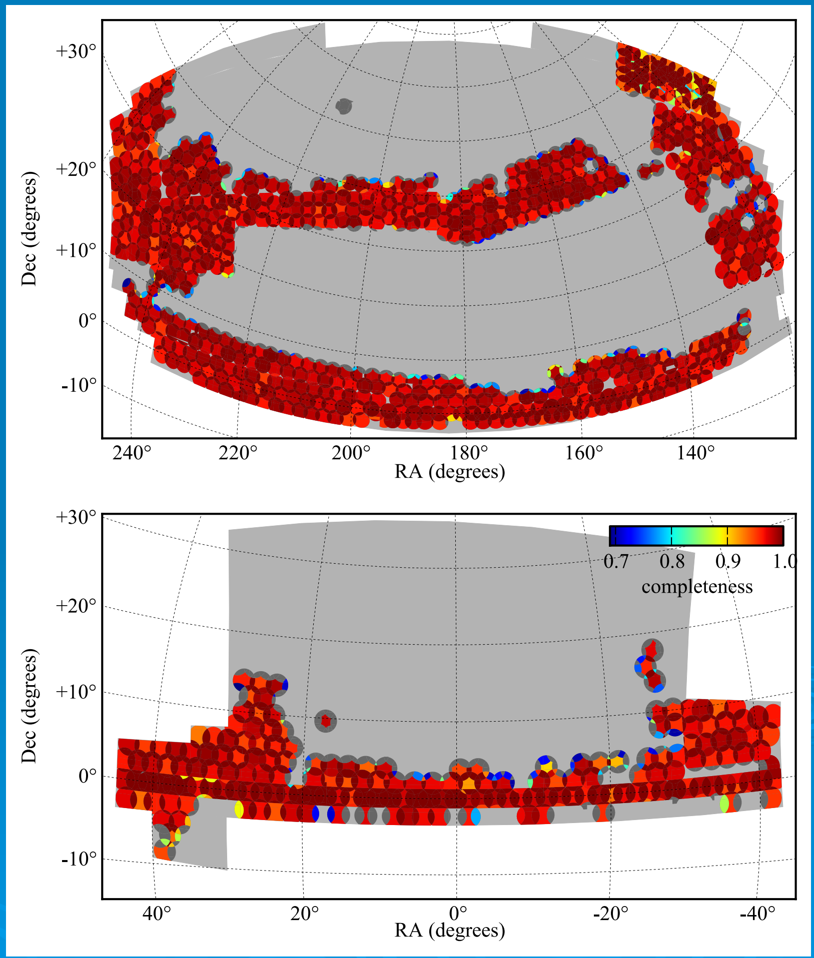
- BOSS is a comprehensive study of the low-redshift BAO and the best large-scale structure sample yet.
- 10,000 deg^2 and 1.5 million spectra of massive galaxies out to z=0.75.
  - Plus z>2 quasars to look for BAO in the Lyman α forest.
  - Intends to achieve 1% distance to z=0.35 and z=0.6.
- Survey is now 90% complete, over 1 million spectra in hand.





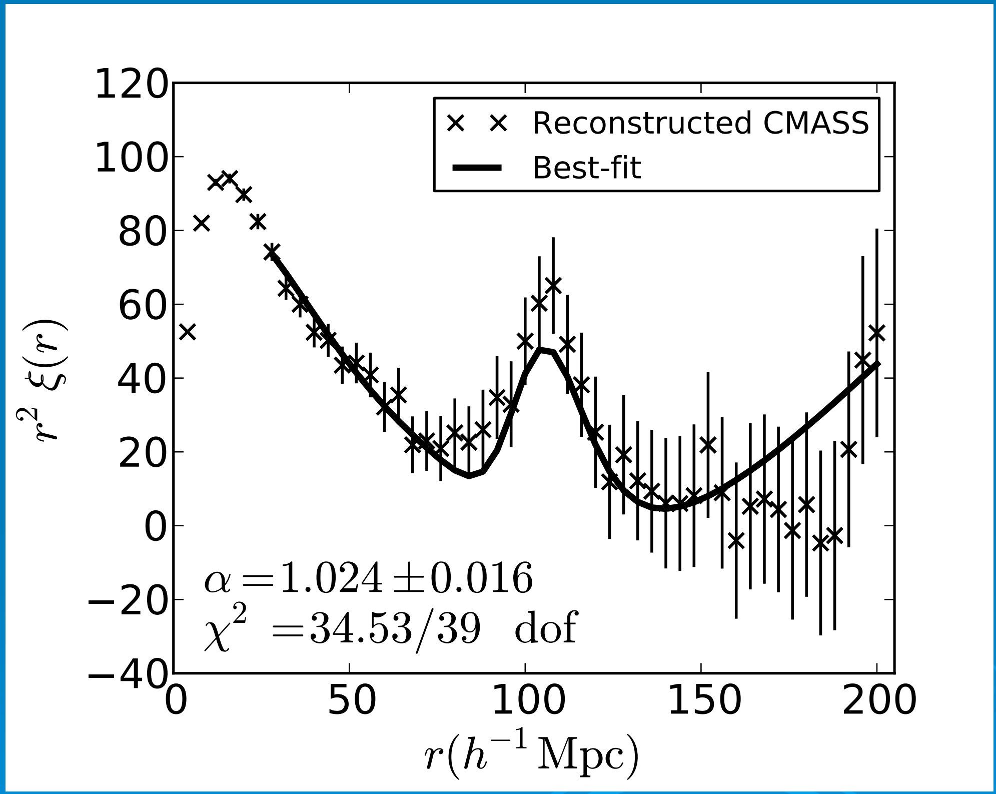
Data Release 9

- In July 2012, we released the first 20 months of BOSS spectroscopic data.
  - 700,000 BOSS spectra, 1/3 of the footprint.
  - 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 (known as CMASS).
- 264k galaxies over 3275 deg^2 with a median redshift of 0.57.



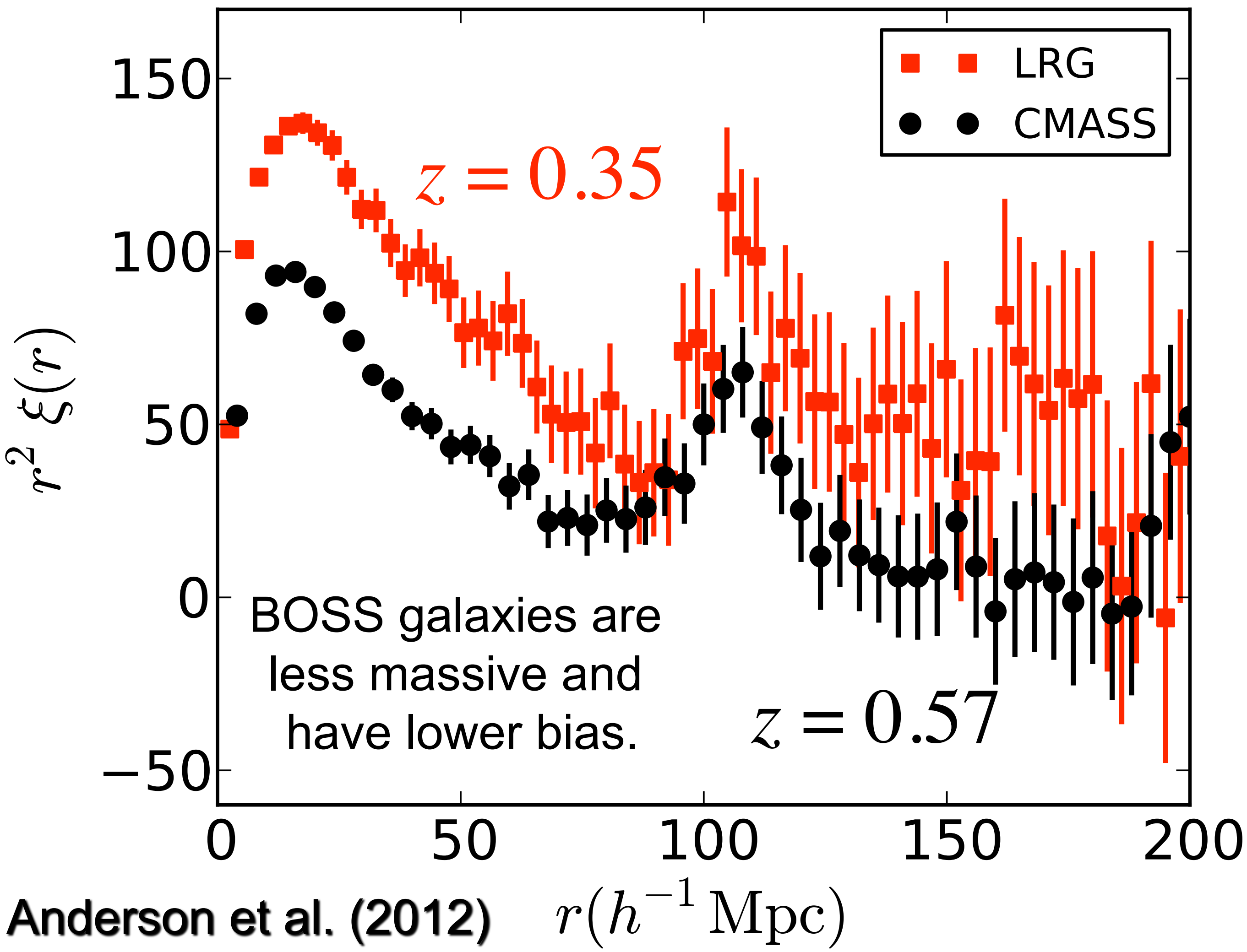
BAO in SDSS-III

- 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)

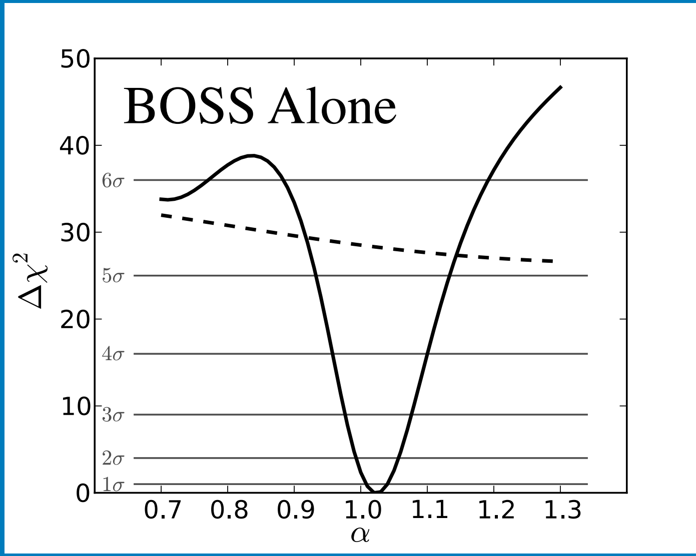
Comparison to *z*=0.35

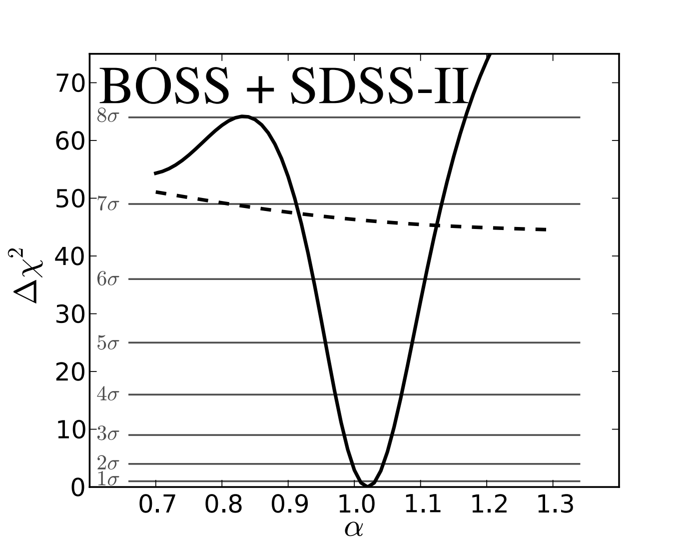


Anderson et al. (2012)

Detection Significance

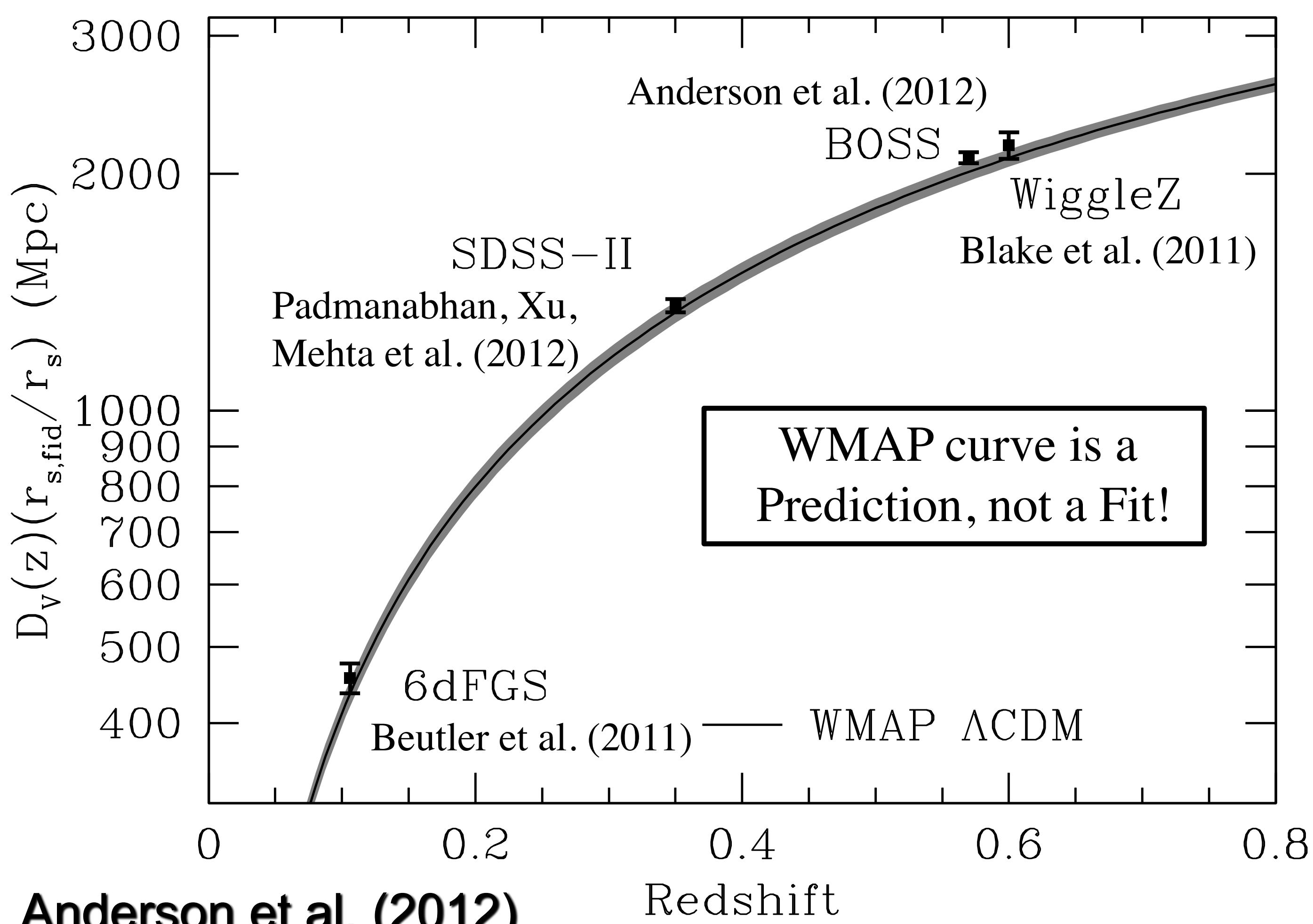
- The BOSS z=0.57 acoustic peak detection is itself over 5σ, a first for a single dataset.
- Combined with the SDSS-II z=0.35 result, detection is over 6.5σ.
- However, with the strong detection in the CMB, the interesting question is not so much whether the BAO exists but rather what distance scale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





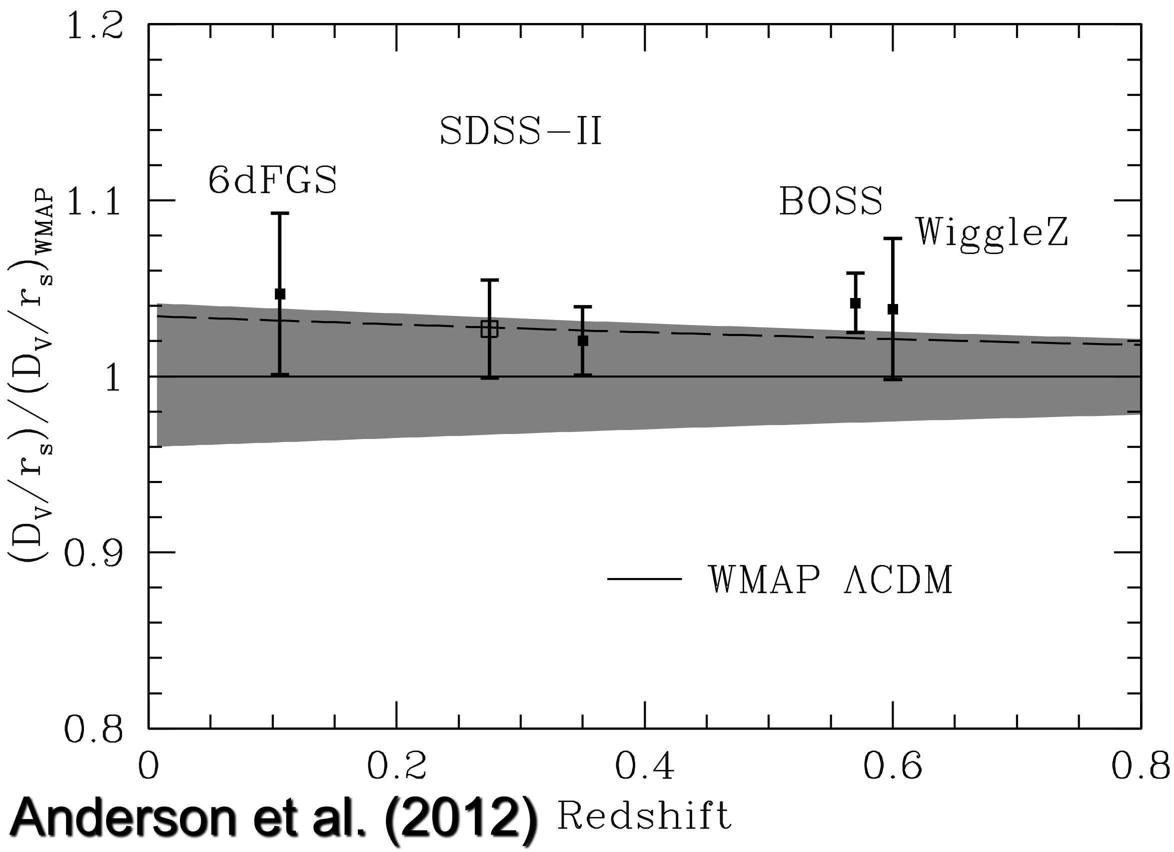
Anderson et al. (2012)

BAO Hubble Diagram



Anderson et al. (2012)

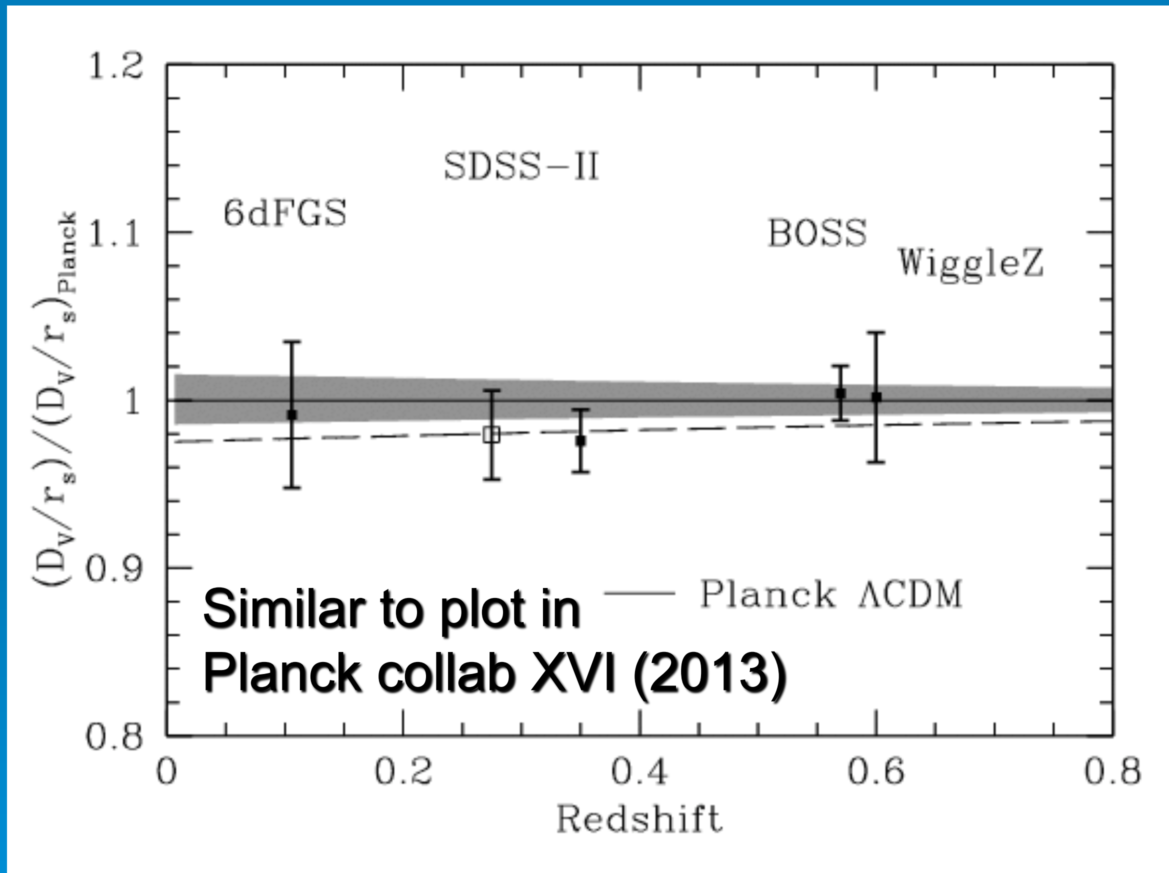
Finer Comparison



Anderson et al. (2012)

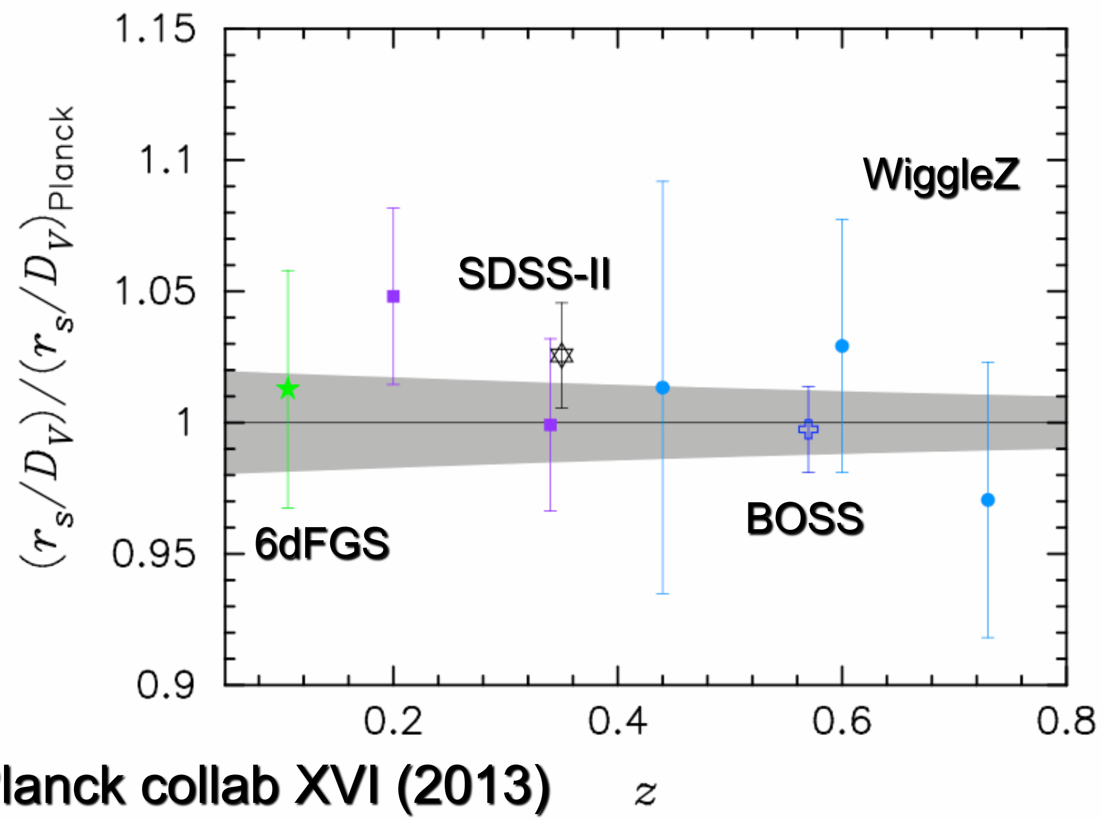
- WMAP+SDSS data sets consistent with flat, cosmological constant model.

Comparison to Planck



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

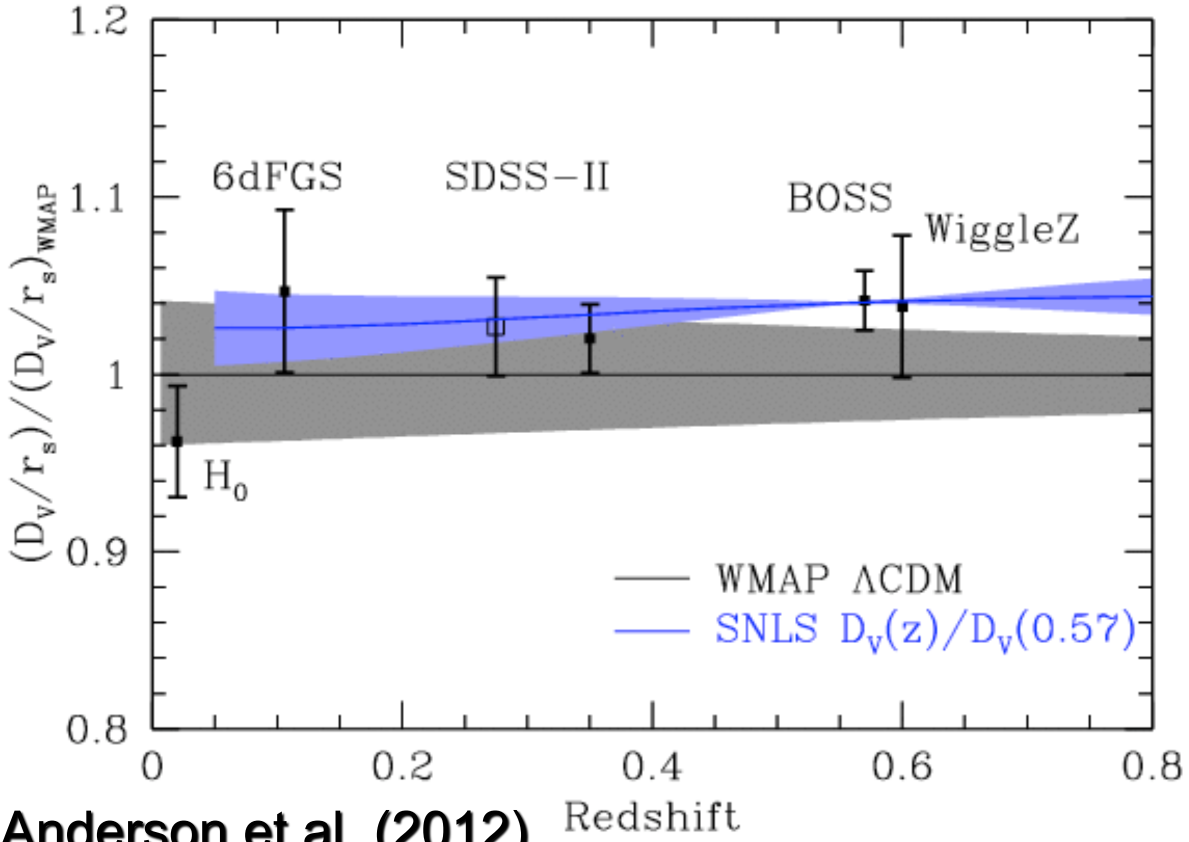
Comparison to Planck



Planck collab XVI (2013)

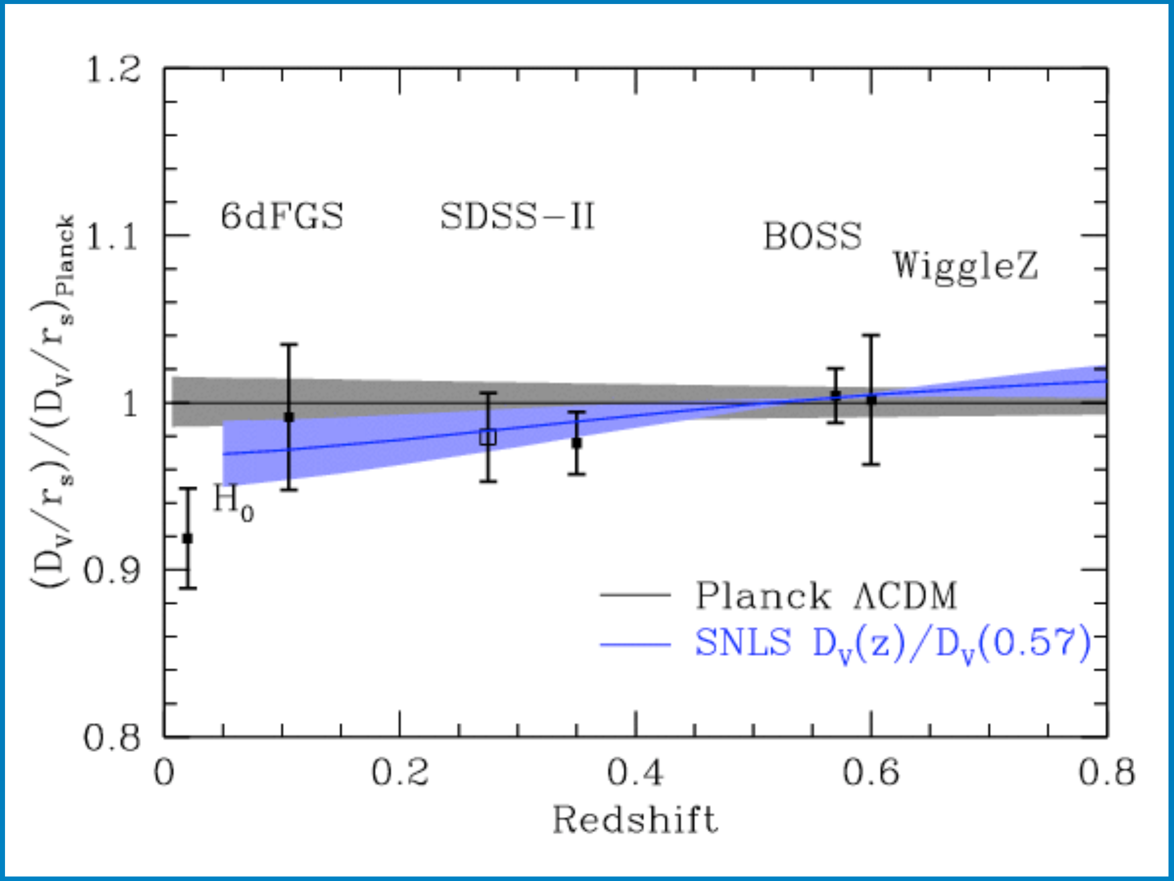
- Planck error range is half the size. Shifts in the direction of the BOSS measurement.

Consistency with SNe



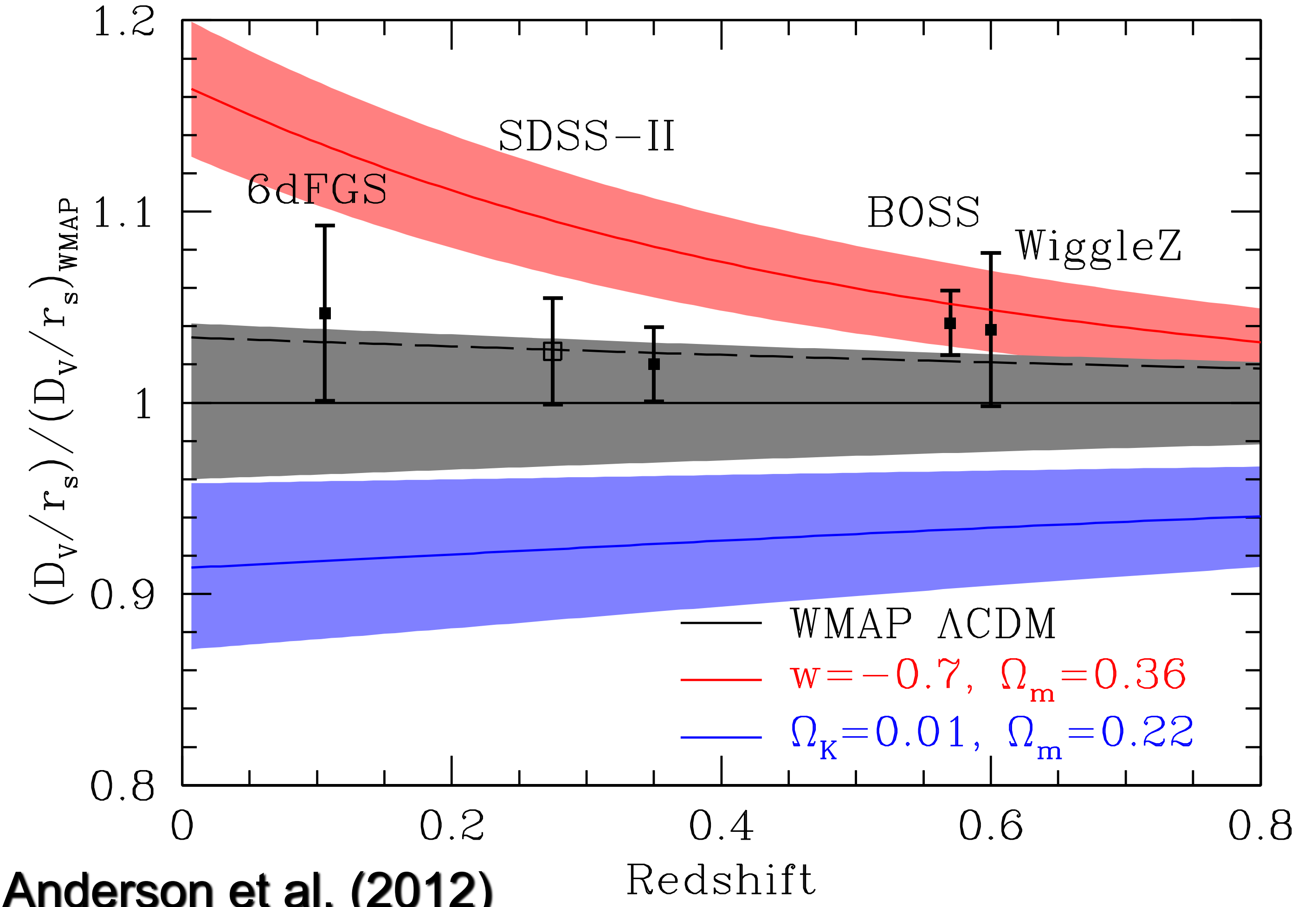
Anderson et al. (2012)

- BAO matches well to the SNe relative distance scale.



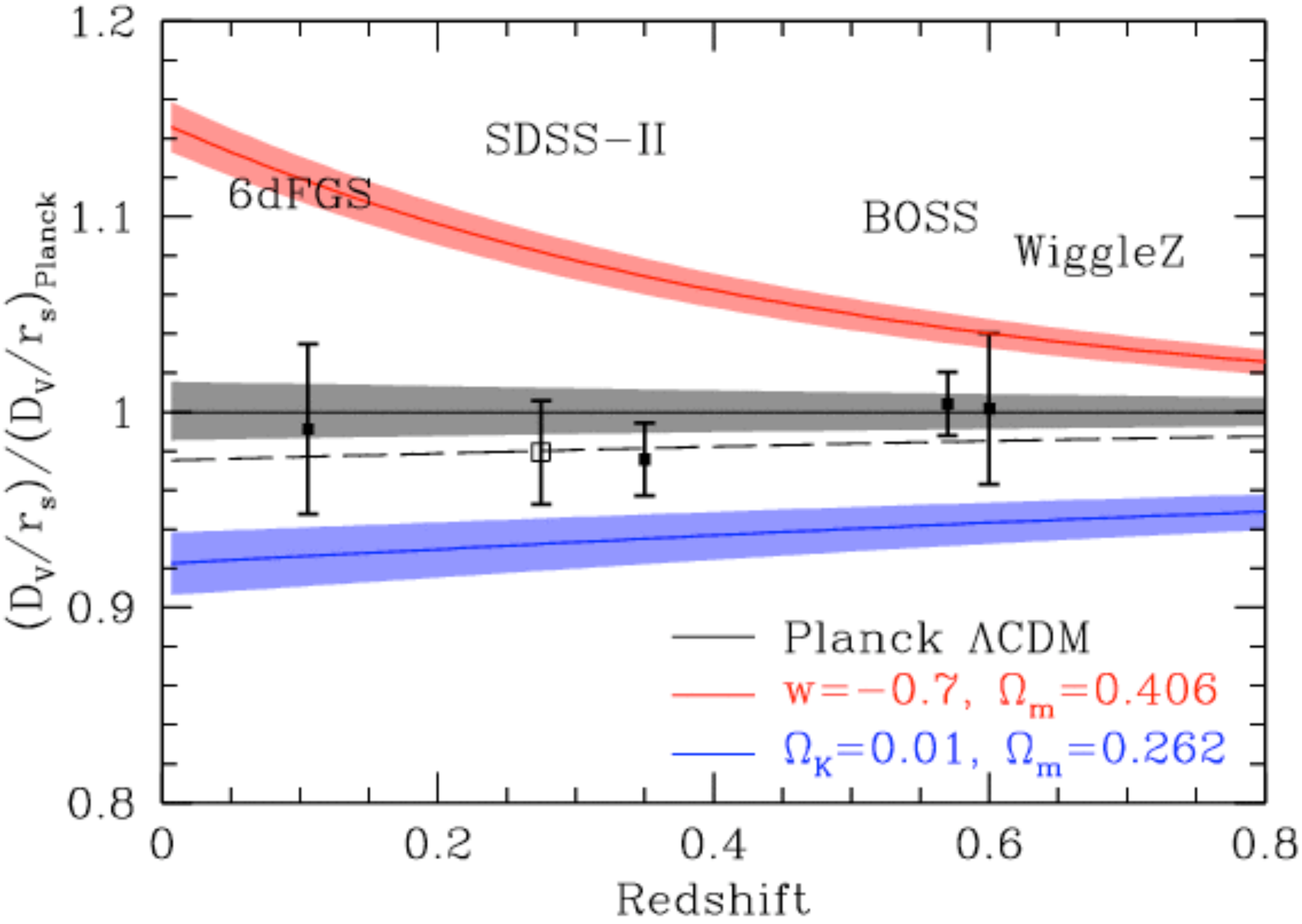
- One can see why Planck + SNe pulls *w* slightly away from –1.
- Planck data with flat LCDM pulls away from H_0.

Cosmological Leverage



Anderson et al. (2012)

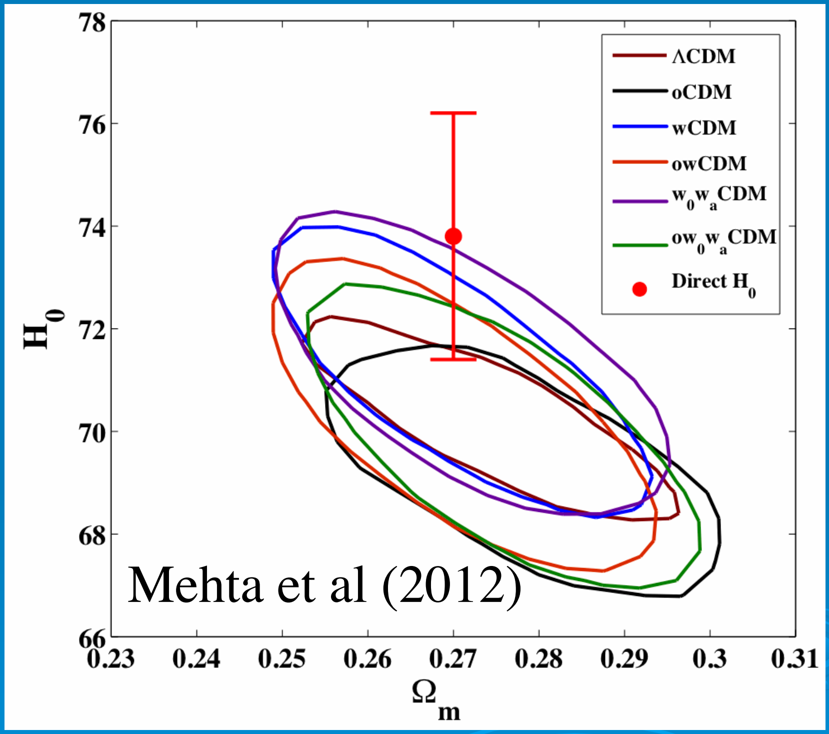
- Excellent agreement with flat LCDM cosmology.



1.2
1.1
1
0.9
0.8
0
0.2
0.4
0.6
0.8
Redshift
$(D_V/r_s)/(D_V/r_s)_{Planck}$
SDSS-II
6dFGS
BOSS
WiggleZ
Planck ΛCDM
$w=-0.7,\ \Omega_m=0.406$
$\Omega_K=0.01,\ \Omega_m=0.262$

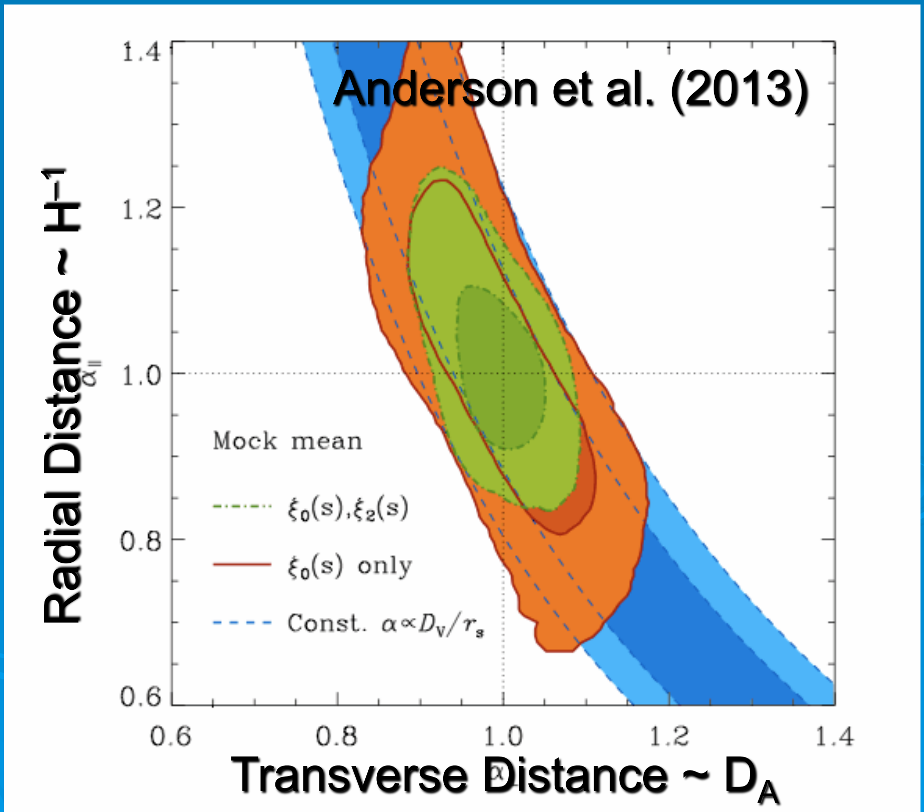
Measuring the Expansion and Density of the Universe

- 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+SNLS3:
  - H_0 = 69.8 ± 1.8 km/s/Mpc
  - Ω_m = 0.277 ± 0.014



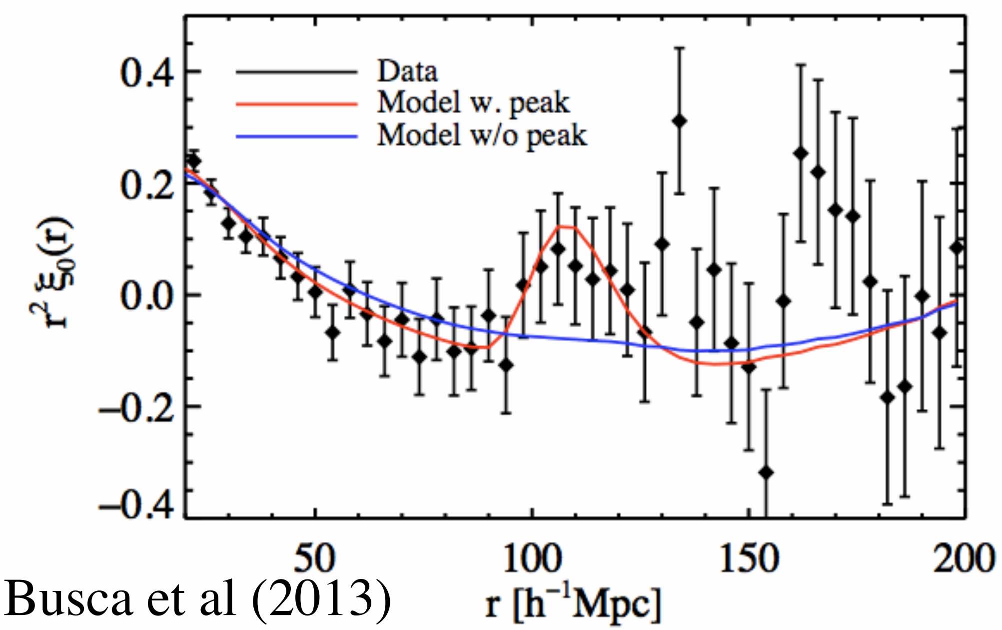
Measuring Anisotropic BAO

- In 2012 & 2013, we produced a set of papers analyzing the anisotropic clustering to measure D_A and H at z=0.57 from the BAO, as well as measures of $f\sigma_8$.
- One important result is that at low redshift, D_V is an efficient compression of the current data.



BAO in the Lyman α Forest

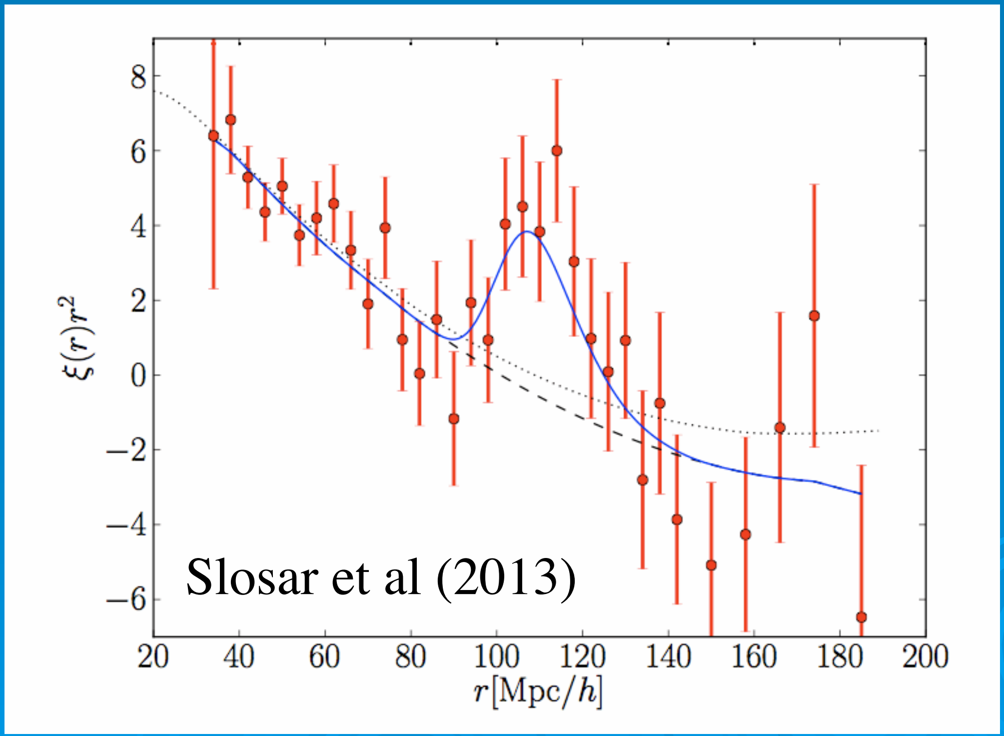
- Bucsa et al. (2012) reports a first detection of the acoustic peak in the Lyman α Forest.
- This uses a set of 48,600 quasars at $z>2.1$.
- Measures H at $z=2.3$ to <4%!



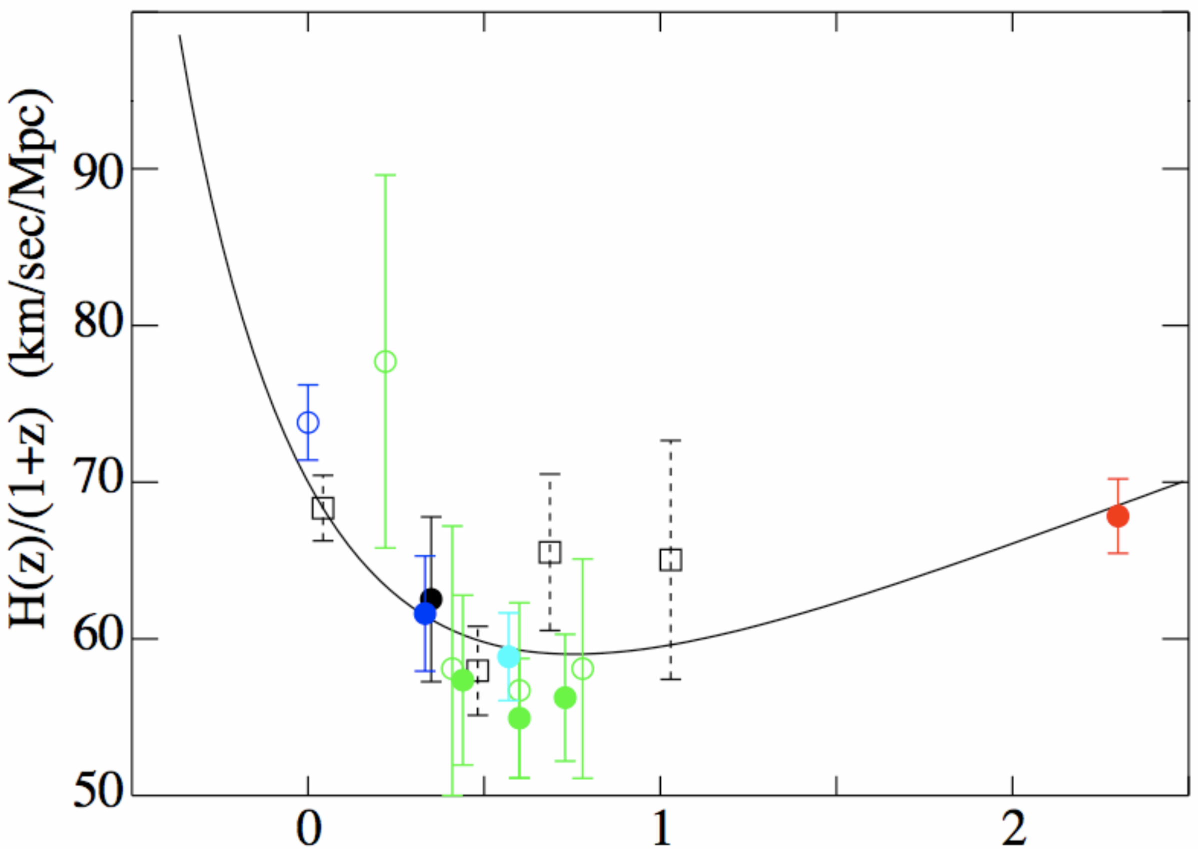
Busca et al (2013)

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.



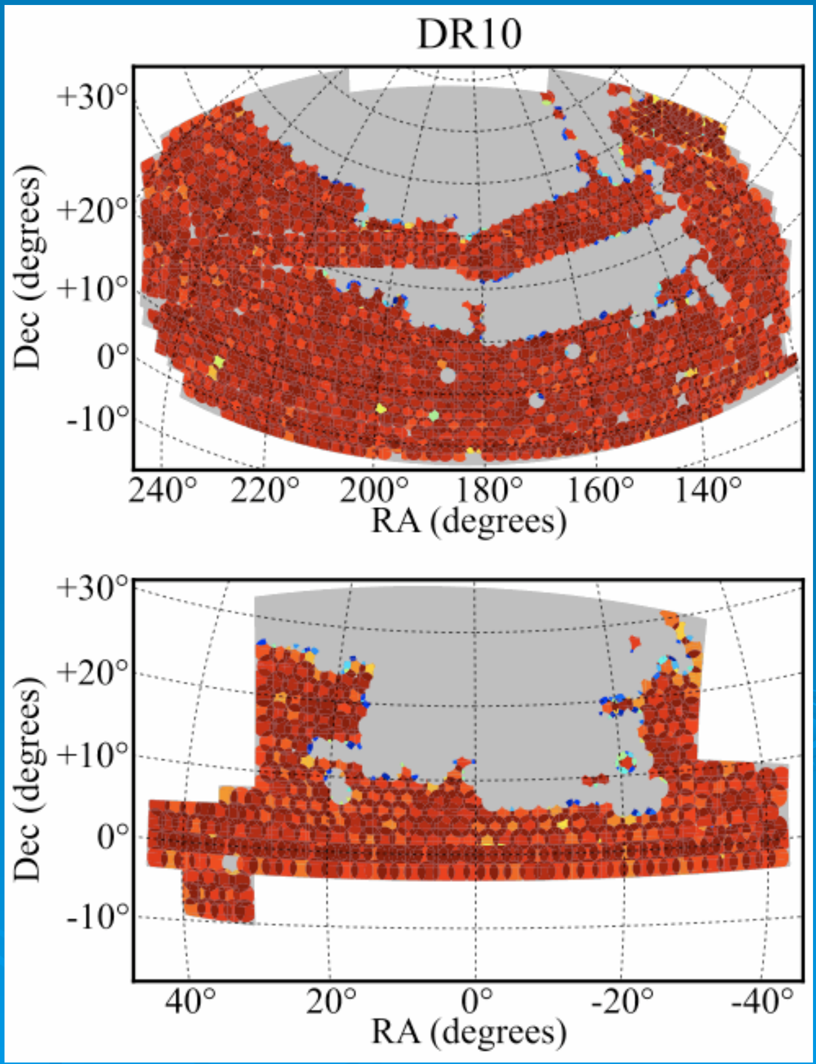
Detection of Cosmic Decelleration from z=2.3 to z=0.6



Busca et al (2013)

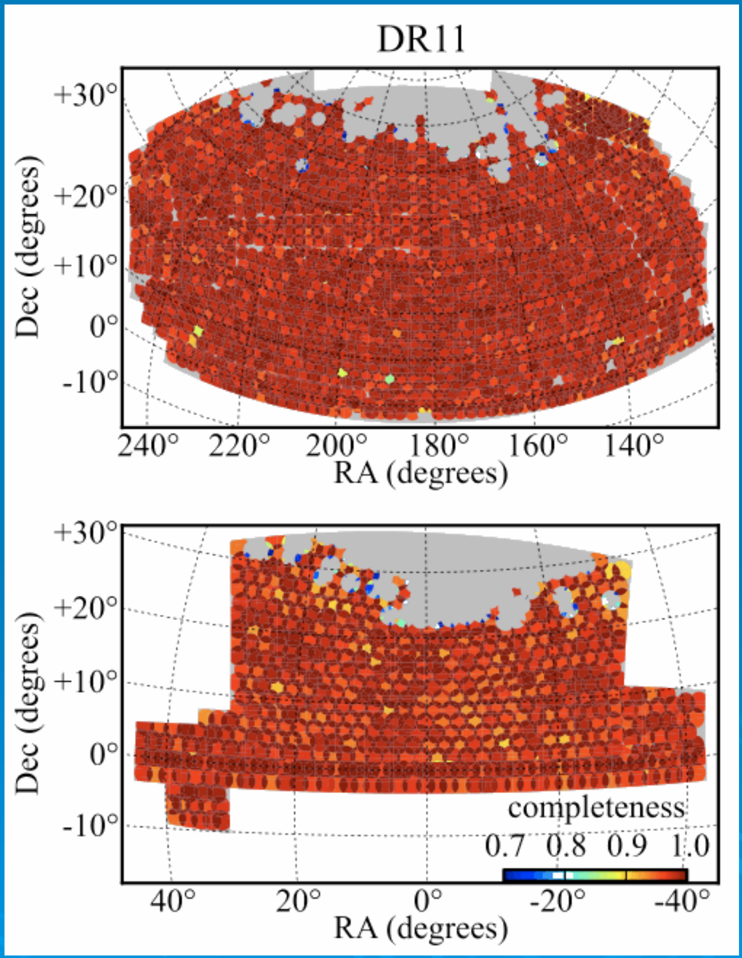
Data Release 10

- SDSS-III Data Release 10 will occur next week.
- Contains about 2/3 of the BOSS footprint, through July 2012.
- First release of APOGEE data: 60,000 high-resolution H-band spectra of stars across the Milky Way.
- All past SDSS data.



Data Release 11

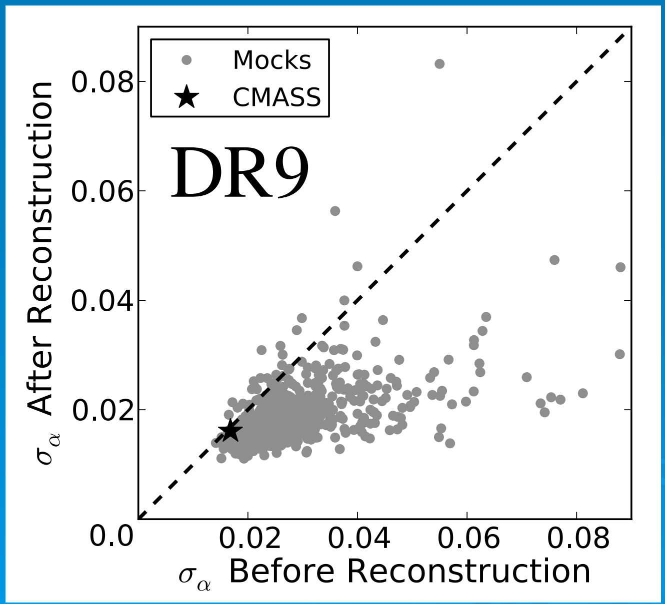
- However, the BOSS team is preparing analyses of all data through May 2013.
- This is known as Data Release 11, which will occur at the end of 2014.
- Contains 8500 deg^2, over 1M galaxy spectra.

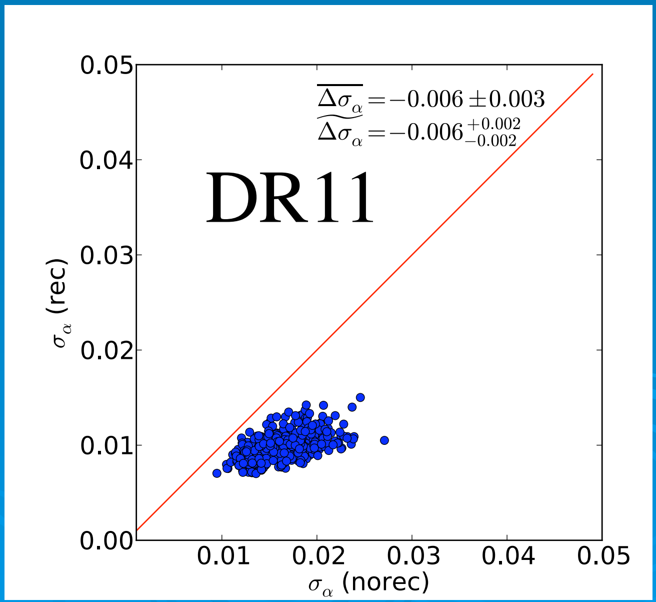


SDSS Collab, in prep (2013)

Reconstruction in DR11

- In DR9, reconstruction didn't improve our BAO measurement.
- This was due to the poor survey window: too much area within 150 Mpc (5 deg) of a boundary.
- DR11 has a filled geometry. Reconstruction improves mocks substantially, from 1.7% to 1.1%. BAO at >8 sigma.





Anderson et al. (2012)

SDSS Collab, in prep (2013)

SDSS-IV

- SDSS-IV will start in July 2014. It includes three surveys:
  - eBOSS: A survey of galaxies and quasars at z>0.7, featuring 7500 sq deg of higher redshift LRGs and quasars plus 1500 sq deg of emission-line galaxies.
  - MaNGA: A multi-object integral-field-unit spectroscopic survey of 10^4 nearby galaxies.
  - APOGEE-II: A high-resolution IR survey of the Milky Way, including observations of the southern hemisphere from Las Campanas.
- SDSS-IV collaboration is now forming.

Coming Soon....

- SDSS-III BOSS is underway.
  - Factor of 7 increase over SDSS-II.
  - DR9 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!

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 and BOSS use 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-IV/eBOSS will push to 1% and below in this decade.