TOWARDS 1% DISTANCE MEASUREMENTS WITH COSMIC SOUND

Nikhil Padmanabhan, Yale

In collaboration with BOSS galaxy clustering WG

NP et al, 2012, Anderson et al 2012
plus many others

NASA Astrophysical Theory Program
DOE Office of Science

The clustering of galaxies in the SDSS-III Baryon Oscillation Spectroscopic Survey: Baryon Acoustic Oscillations in the Data Release 9 Spectroscopic Galaxy Sample

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Results

- It's been a busy year
  - First results from B(aryon) O(scillation) S(spectroscopic) S(urvey)
    - Galaxy BAO results at z=0.55
    - Lyman-alpha forest measurements at z=2.5
    - This talk will focus on the first.
  - Improvements in analysis techniques
  - Towards precision measurements
  - Lots of results expected over the next years

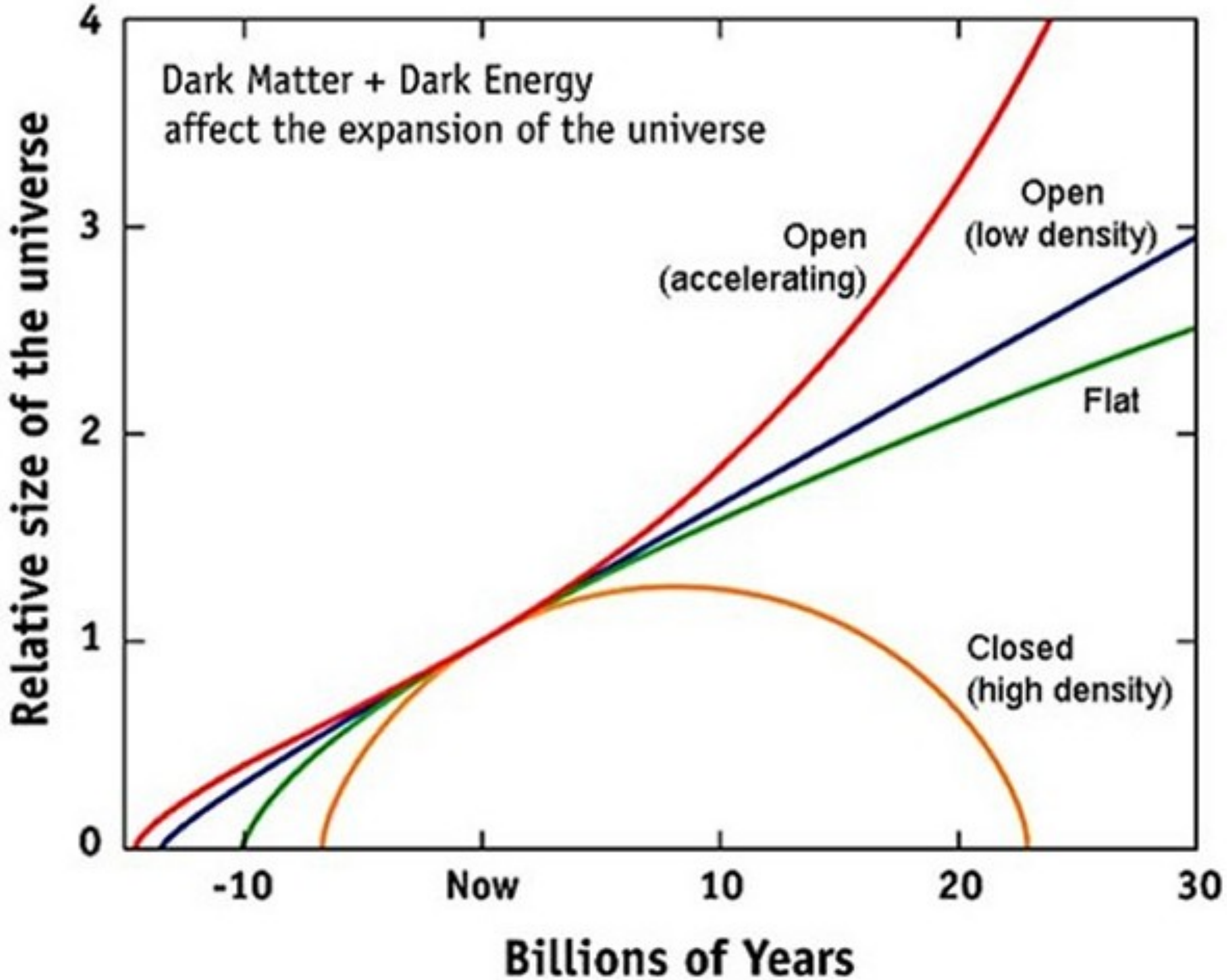
Outline

- Baryon Acoustic Oscillations, very quickly
- Recent Developments
  - How to build a better standard ruler?
  - First galaxy BAO results from BOSS
  - BigBOSS : BAO in the future

Outline

- Baryon Acoustic Oscillations, very quickly
  - Standard rulers
  - Building standard rulers
- Recent Developments
  - How to build a better standard ruler?
  - First galaxy BAO results from BOSS
  - BigBOSS : BAO in the future

What is the expansion history of the Universe?



Cosmology 101

Expansion rate of the Universe

$$H^2(a) = H_0^2 \left[\Omega_R a^{-4} + \Omega_M a^{-3} + \Omega_k a^{-2} + \Omega_{DE} \exp\left\{ 3 \int_a^1 \frac{da'}{a'} \left[1 + w(a')\right] \right\} \right].$$

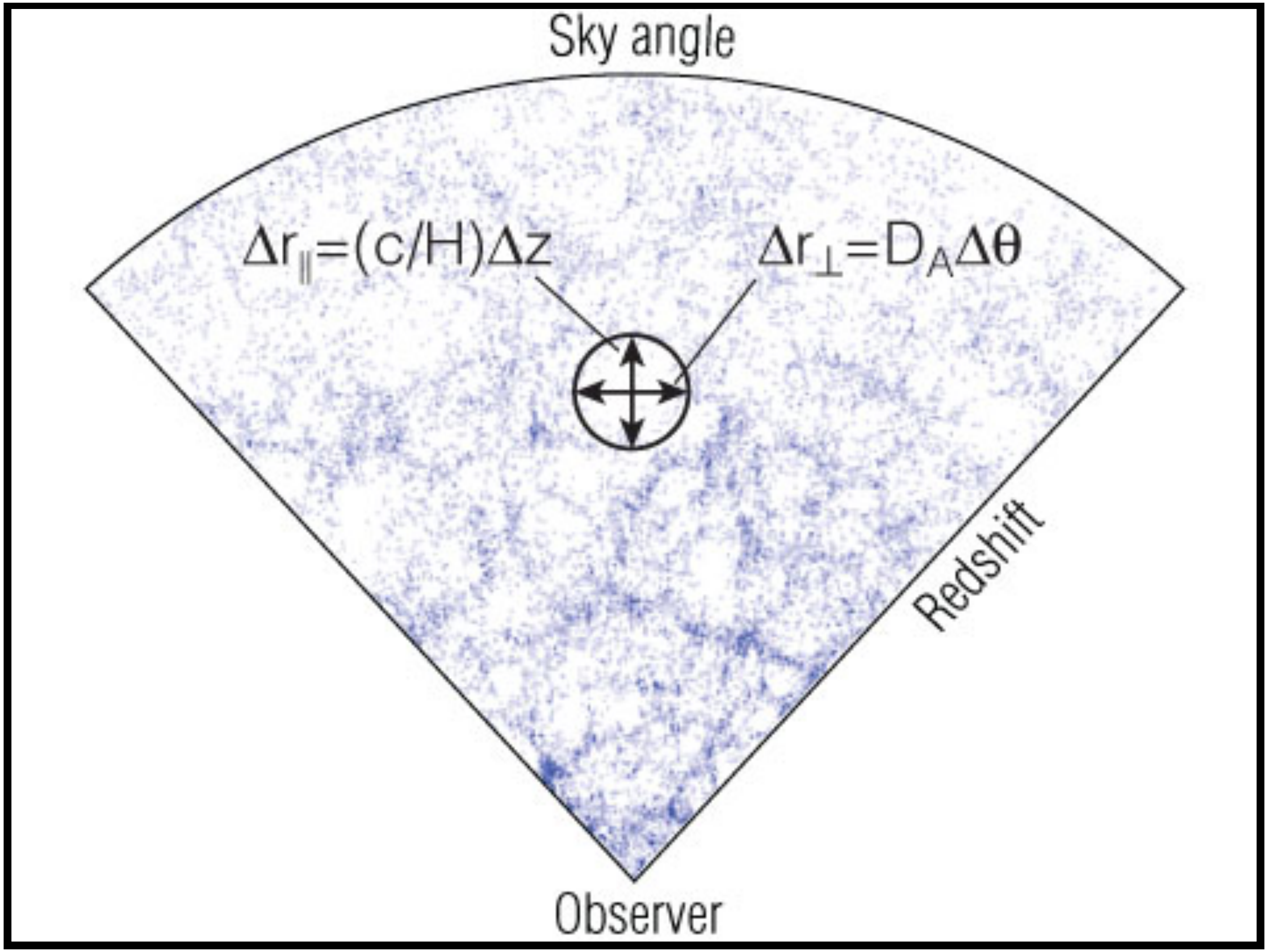
$$w(a) = w_0 + w_a(1 - a),$$

Distances (Comoving, and angular diameter)

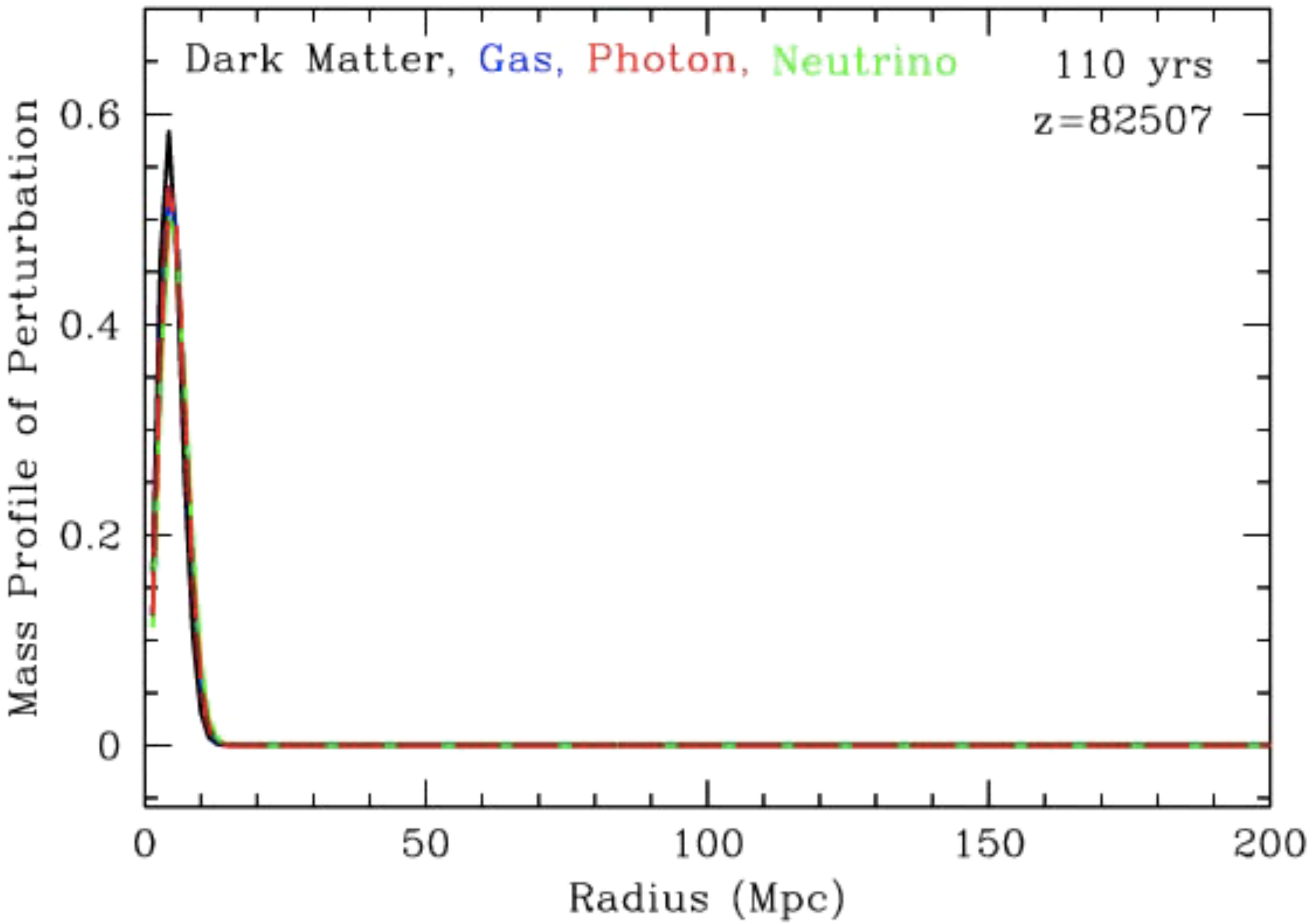
$$D_C(z) = \frac{c}{H_0} \int_0^z dz' \frac{H_0}{H(z')} \ .$$

$$D_A(z) = K^{-1/2} \sin\left(K^{1/2} D_C \right)$$

Measuring two distances with standard rulers



Sound Waves imprint a Standard Ruler



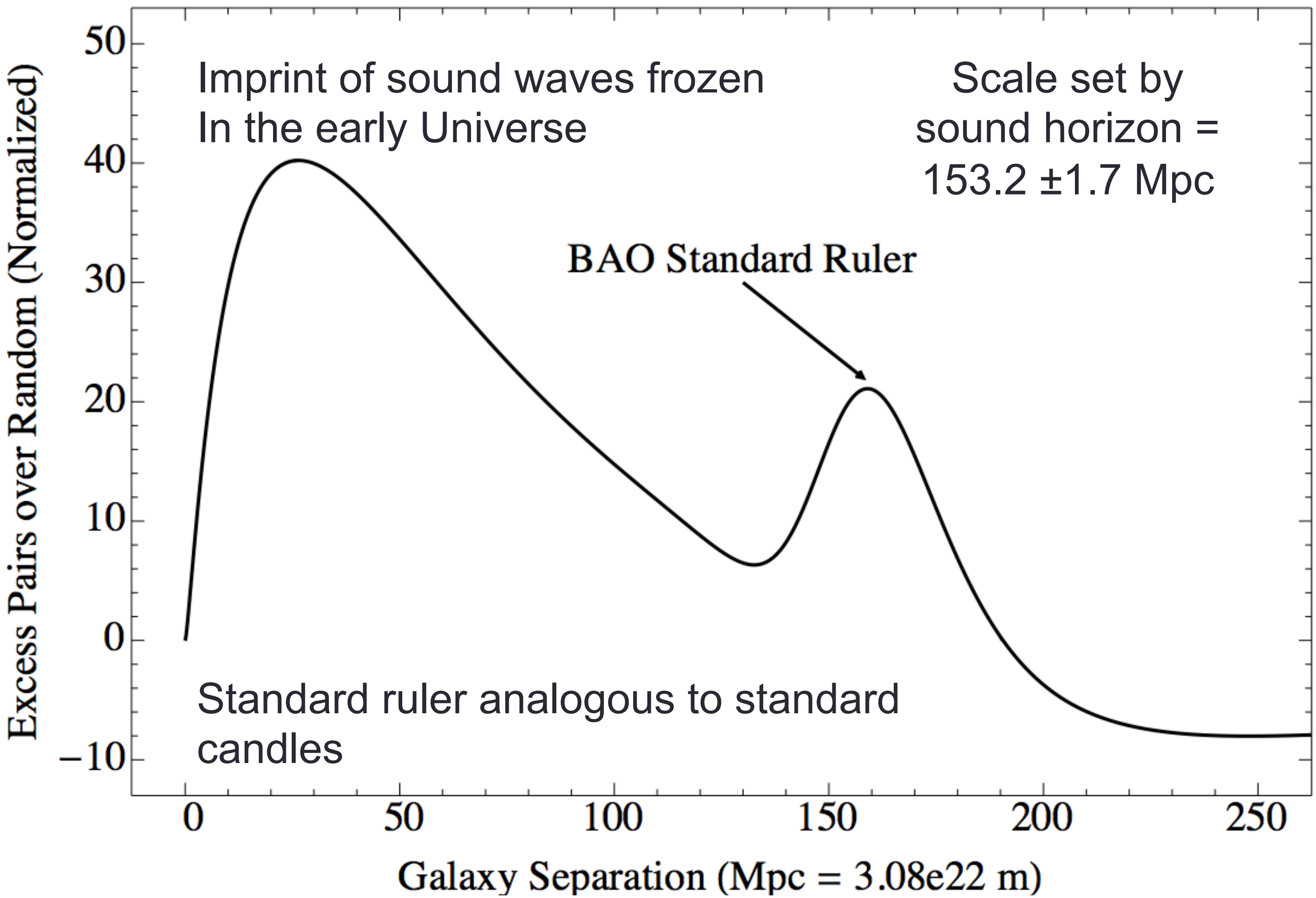
Daniel Eisenstein

Constructing a Standard Ruler

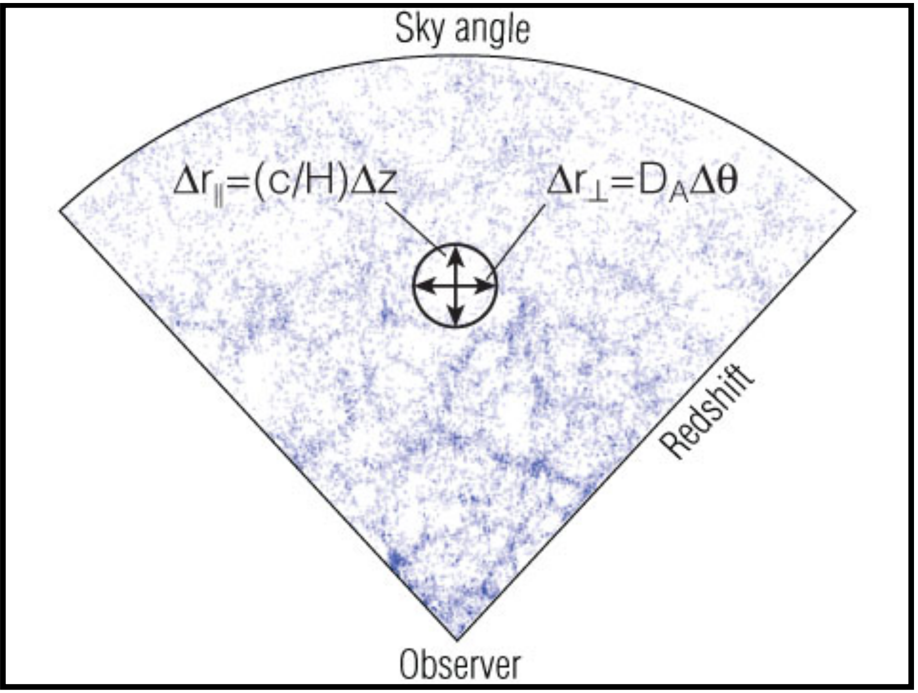
- The plasma of the early Universe supports sound waves
  - Compton scattering between electrons and photons
  - Coulomb interactions between electrons and protons
- Sound waves from the initial density perturbations expand outward
  - Speed of sound ~ $c/\sqrt{3}$
- When the Universe cools below 0.3 eV, electrons and protons "recombine"
  - Sound wave stalls, leaving imprint on density fluctuations.
  - Characteristic scale of 153.2 Mpc ~ 4.7e24 m

$$r_s = \int_0^{t_*} \frac{c_s(t)}{1+z} dt = \int_{z_*}^{\infty} \frac{c_s(z)}{H(z)} dz.$$

The Standard Ruler in the Galaxy Correlation Function



Measuring $d_A(z)$ and $H(z)$



- Transverse scale measures angular diameter distance
- Radial scale measures the Hubble constant
- Internal consistency tests
- H(z) unique amongst dark energy probes
- H(z) important to constrain dark energy at high redshifts
- Observationally, think about isotropic dilation and warping

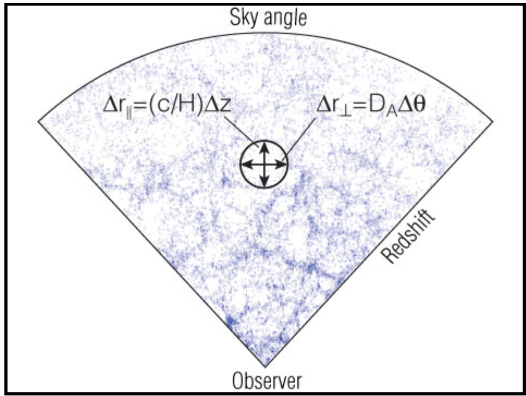
Why BAO?

- Simple measurement
  - Only requires positions
- Underlying theory is simple
  - Mostly linear physics (fluctuations are 1 part in 10^4)
  - Exquisitely calibrated by the CMB (~1% with WMAP, much better with Planck)
  - 3D feature (hard to mimic)
  - Very large scales >> scales of astrophysical complications
    - Can be treated perturbatively

Observables

- Positions on the sky and redshifts
  - 3D map of the Universe
  - Precision redshifts require a spectroscopic survey
- Need to convert angular separations to physical distances
  - Ruler oriented transverse to line of sight measures distance to the ruler.
  - Distance as a function of redshift
  - Integrated expansion rate
- Need to convert redshift separations to physical distances
  - Ruler oriented parallel to the line of sight

  measures rate of change of distance with redshift.
  - Expansion rate.
- Not possible with standard candles.



Constructing a BAO survey

Survey

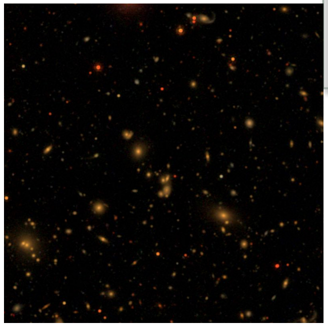
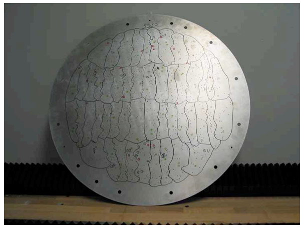


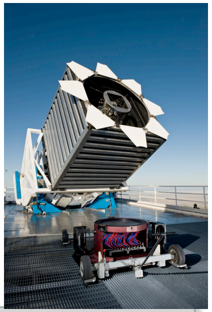
Image Sky

SDSS-I/II imaged 14K sq. deg (1/3 of sky)
~ billion objects detected

1.5M

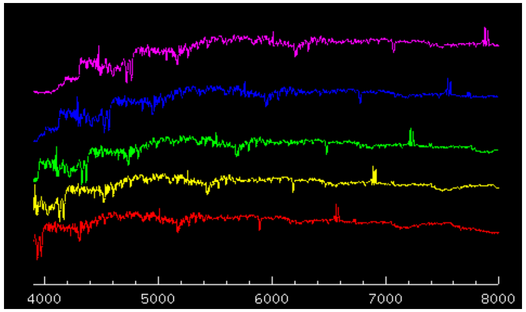
Select objects



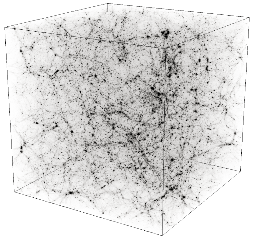


Get Spectra

1000 at a time



Measure redshifts



3D Map

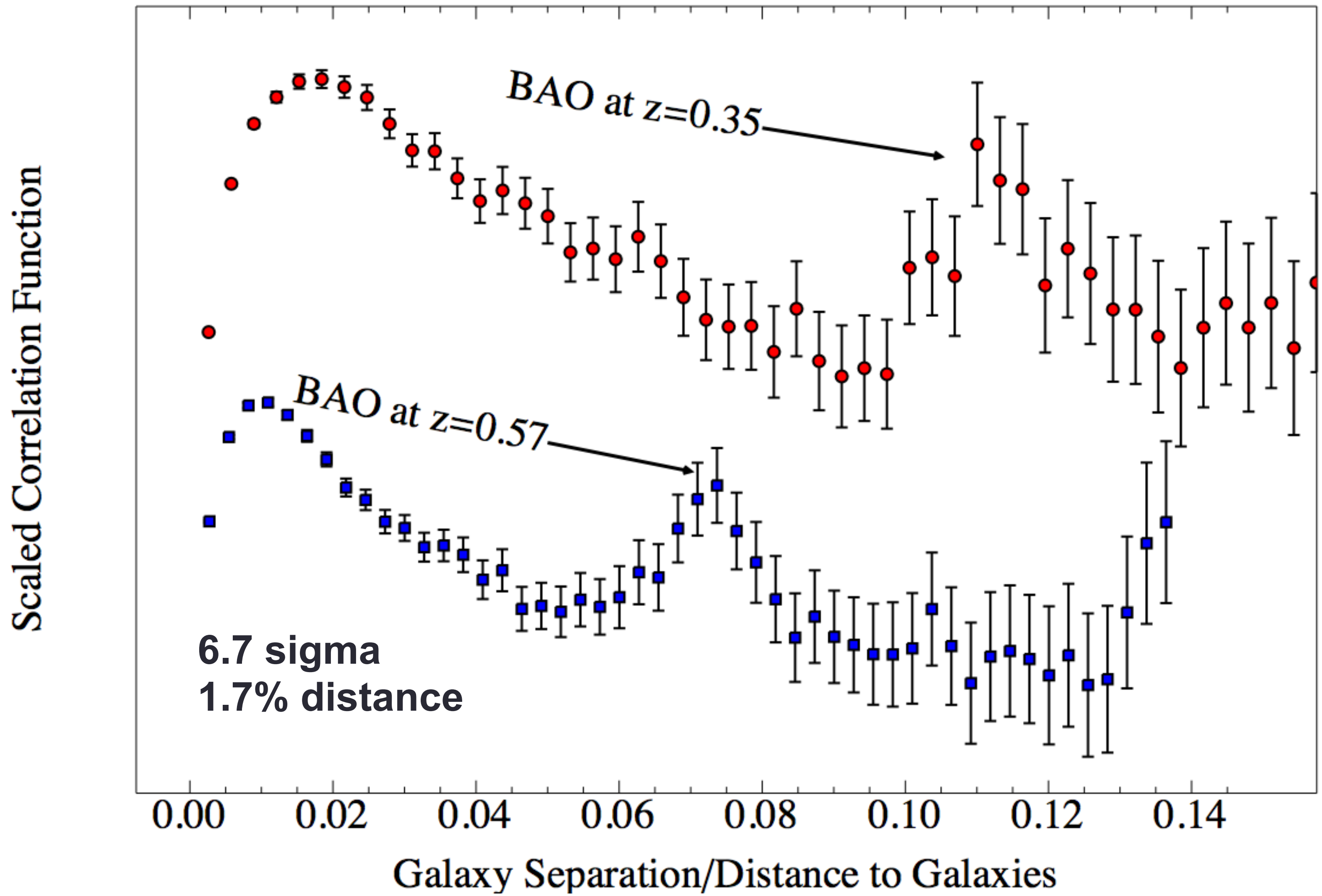
BAO Experiments : Past

Survey	Redshift	Years	Precision
2dFGRS	0.2	Completed (2005)	detection
SDSS-I/II	0.35	Completed (2005)	detection
SDSS-I/II	0.35	Completed	3.4%

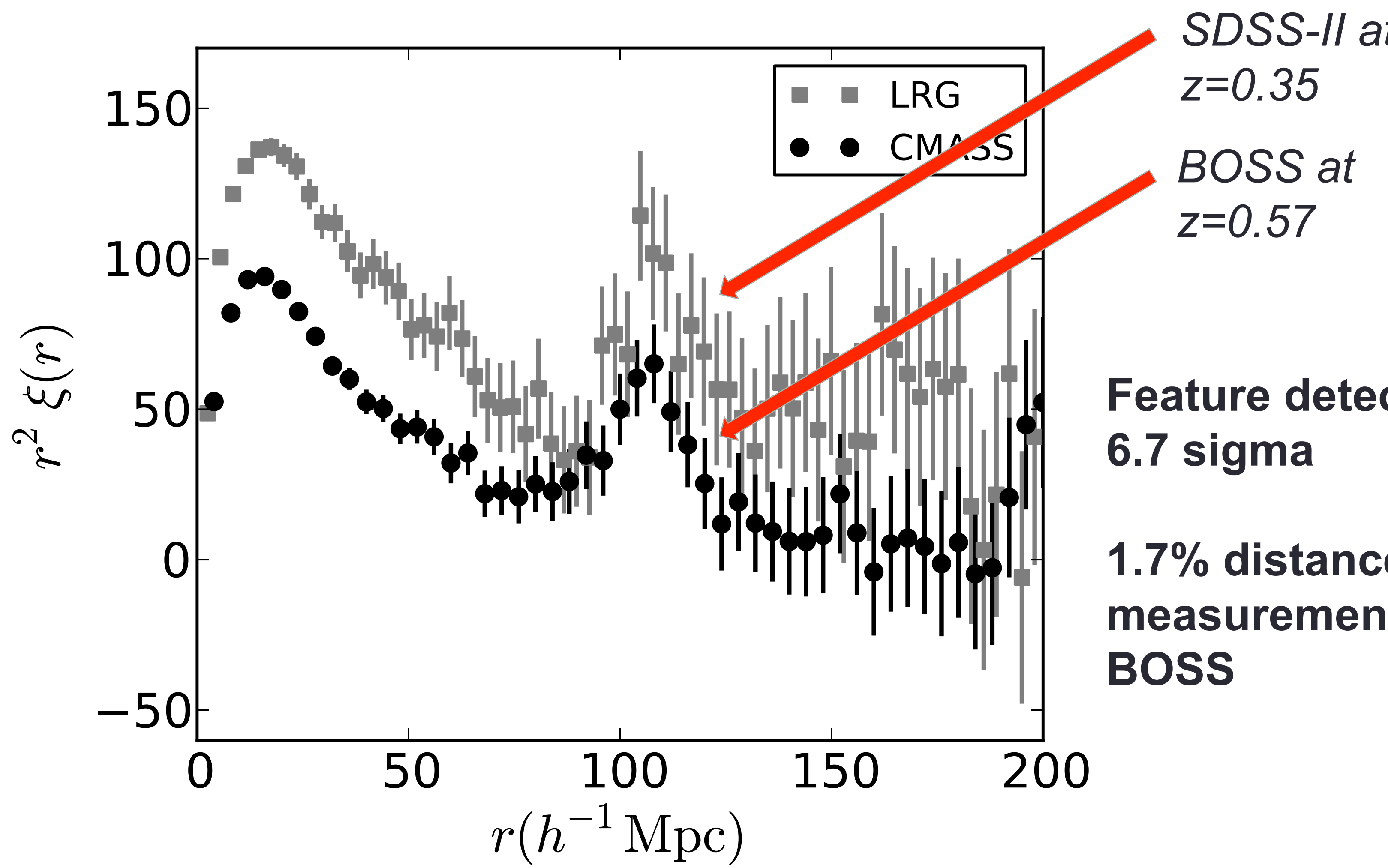
BAO Experiments : Past, Present

Survey	Redshift	Years	Precision
2dFGRS	0.2	Completed	detection
SDSS-I/II	**0.35**	**Completed**	**2%**
WiggleZ	0.7	Completed	4%
BOSS	**0.35, 0.55, 2.5**	**2009-2014**	**1.7% at z=0.55 today**
BOSS	0.35, 0.55, 2.5	2009-2014	1% (0.35, 0.55), 1.5% (2.5)
HETDEX	3.0	2013-2015	1%

The BAO feature clearly detected



The BAO Feature clearly detected



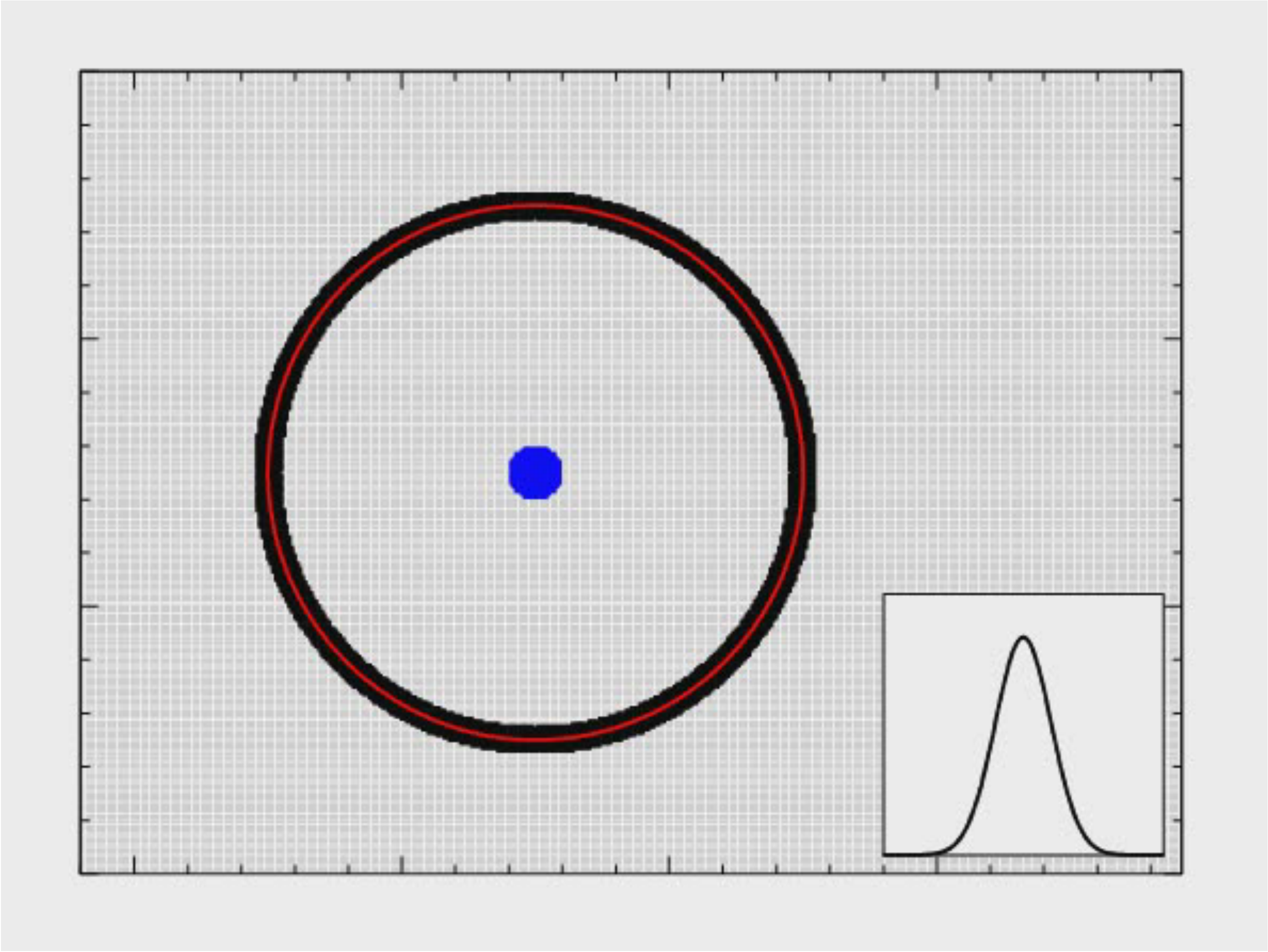
Feature detected at 6.7 sigma

1.7% distance measurement from BOSS

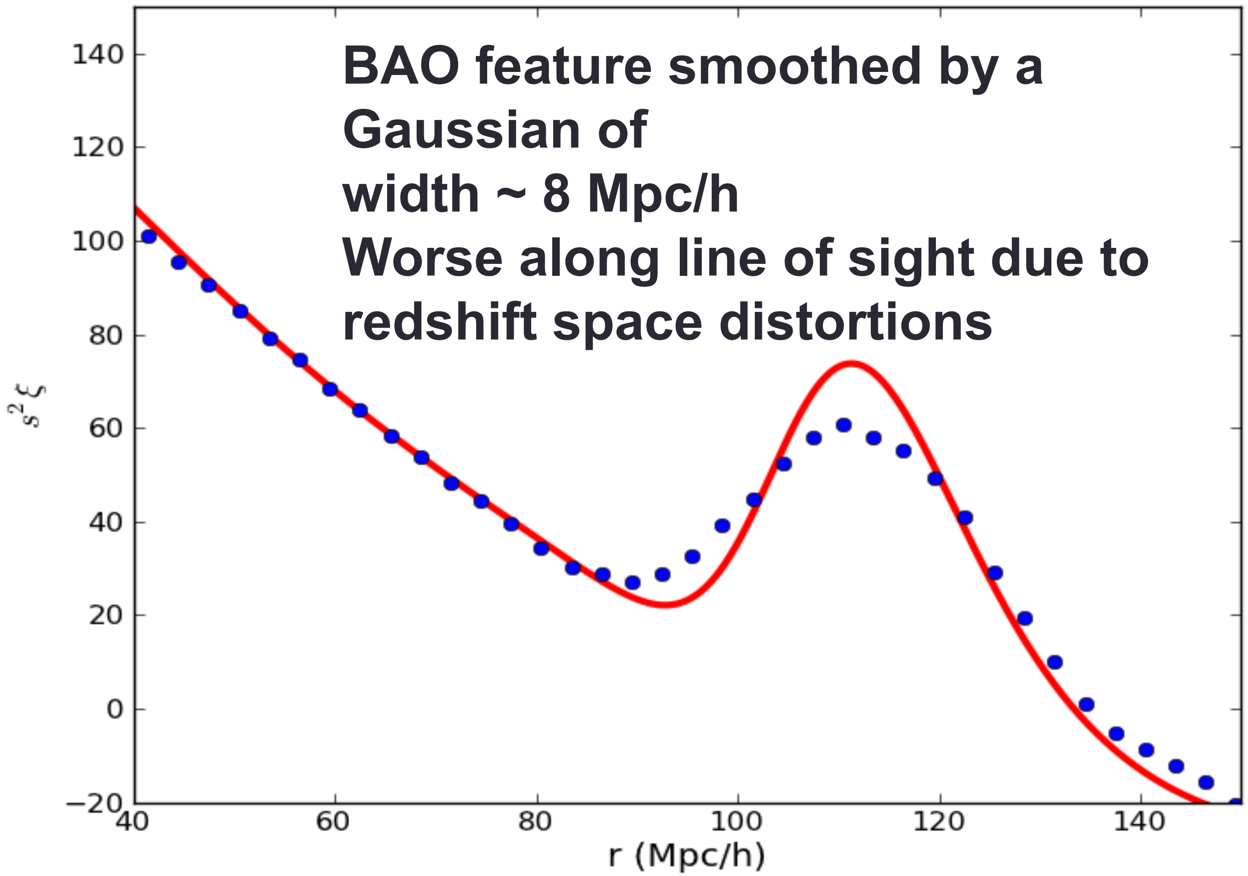
Outline

- Baryon Acoustic Oscillations, very quickly
- Recent Developments
  - How to build a better standard ruler?
    - The nonlinear evolution of the standard ruler
    - An application to DR7
  - First galaxy BAO results from BOSS
- BigBOSS : BAO in the future

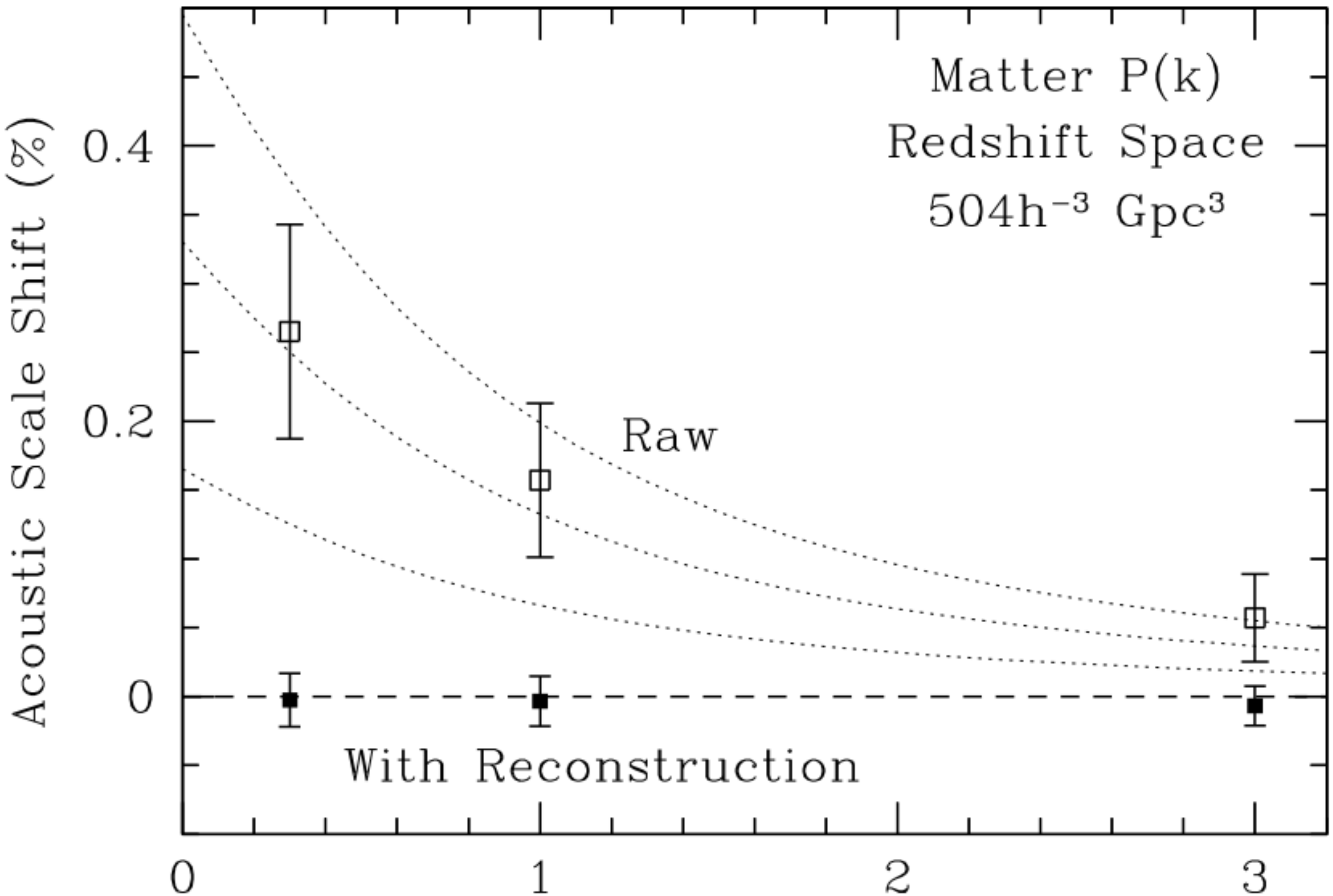
BAO and structure formation



Nonlinear evolution

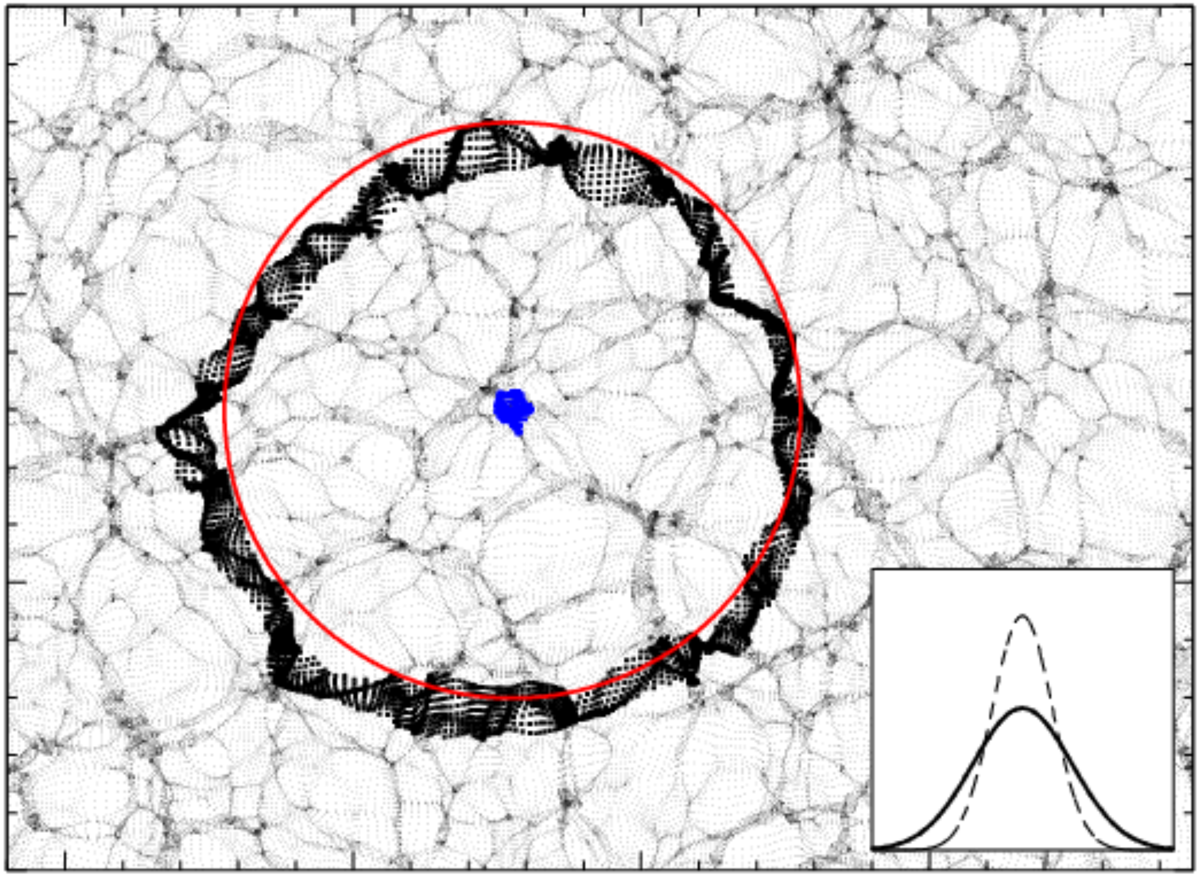


Nonlinear evolution

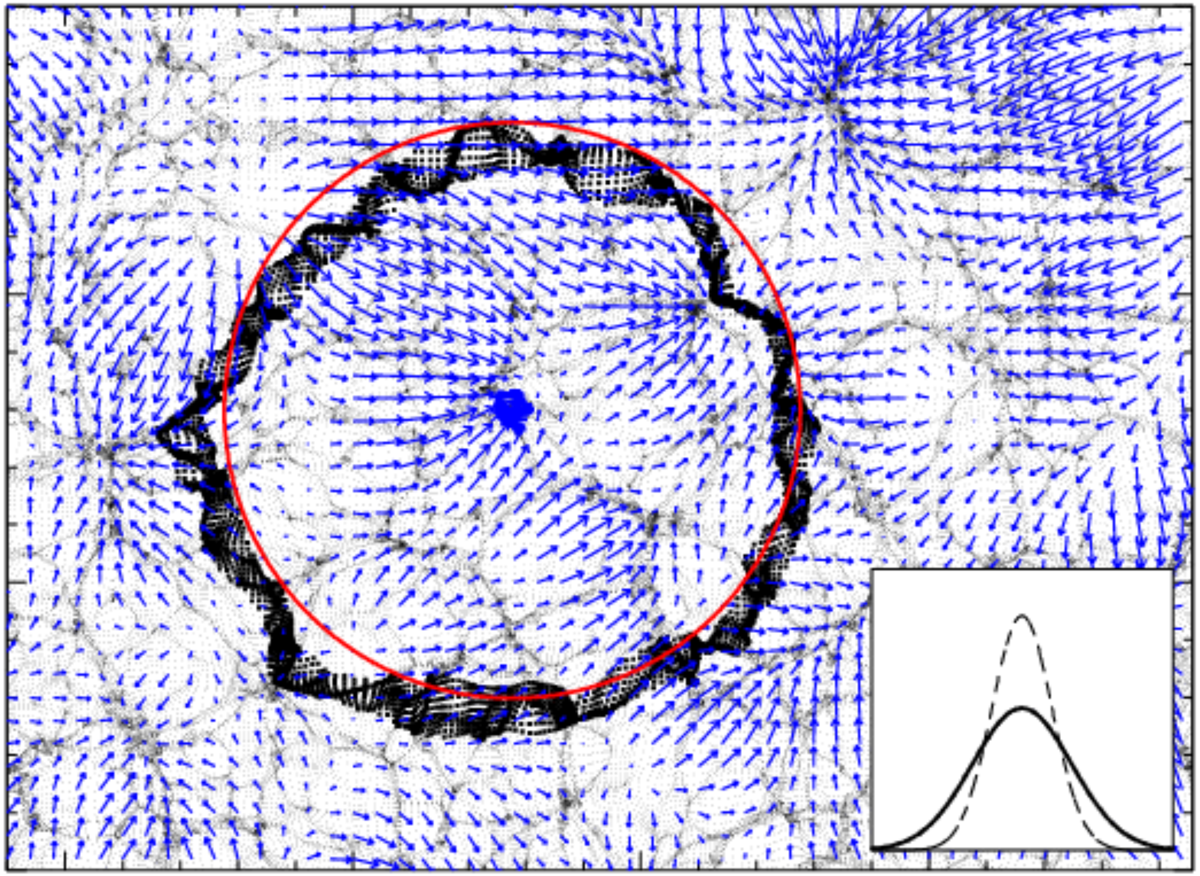


Seo et al, 2010

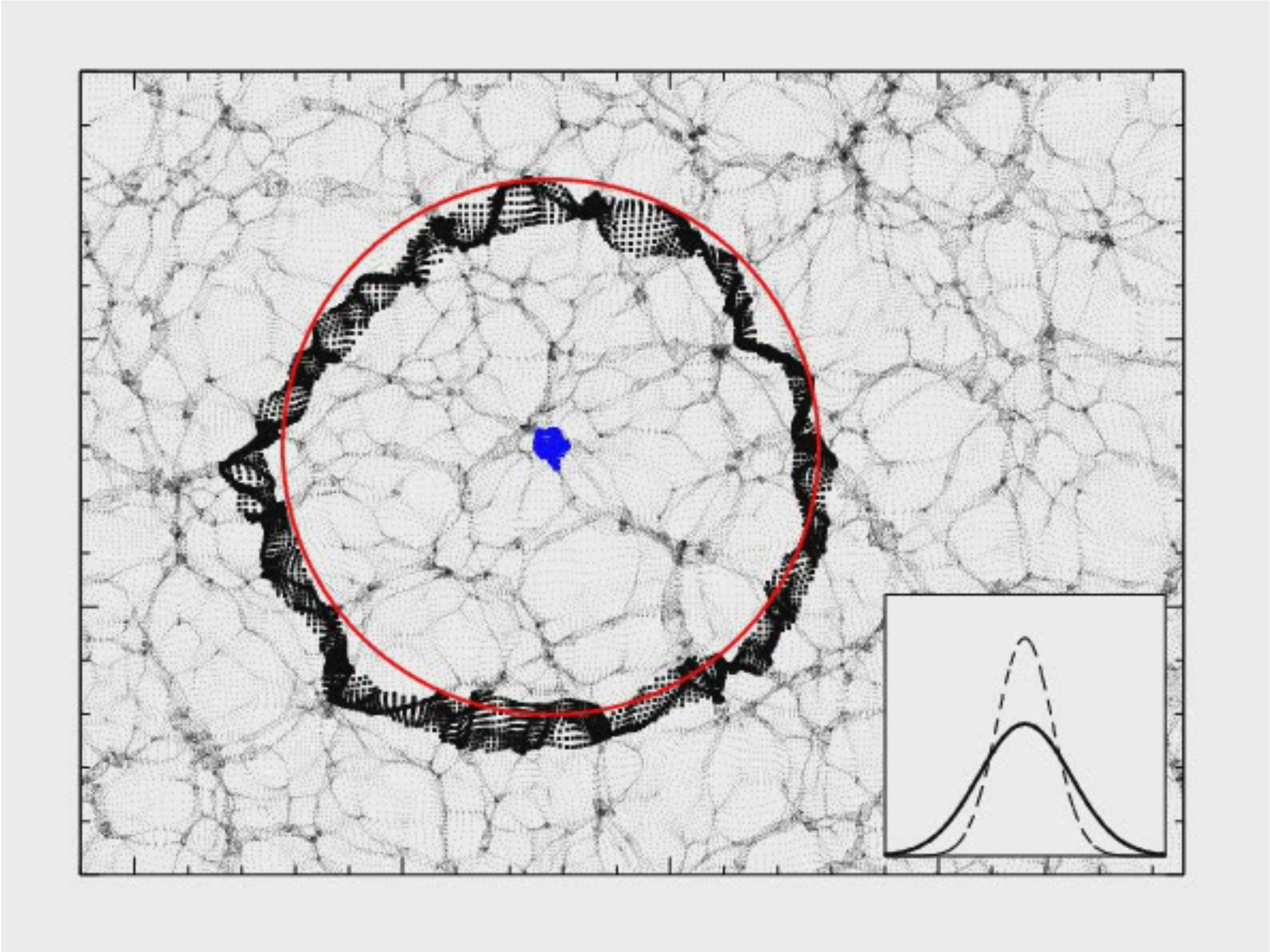
Reconstruction



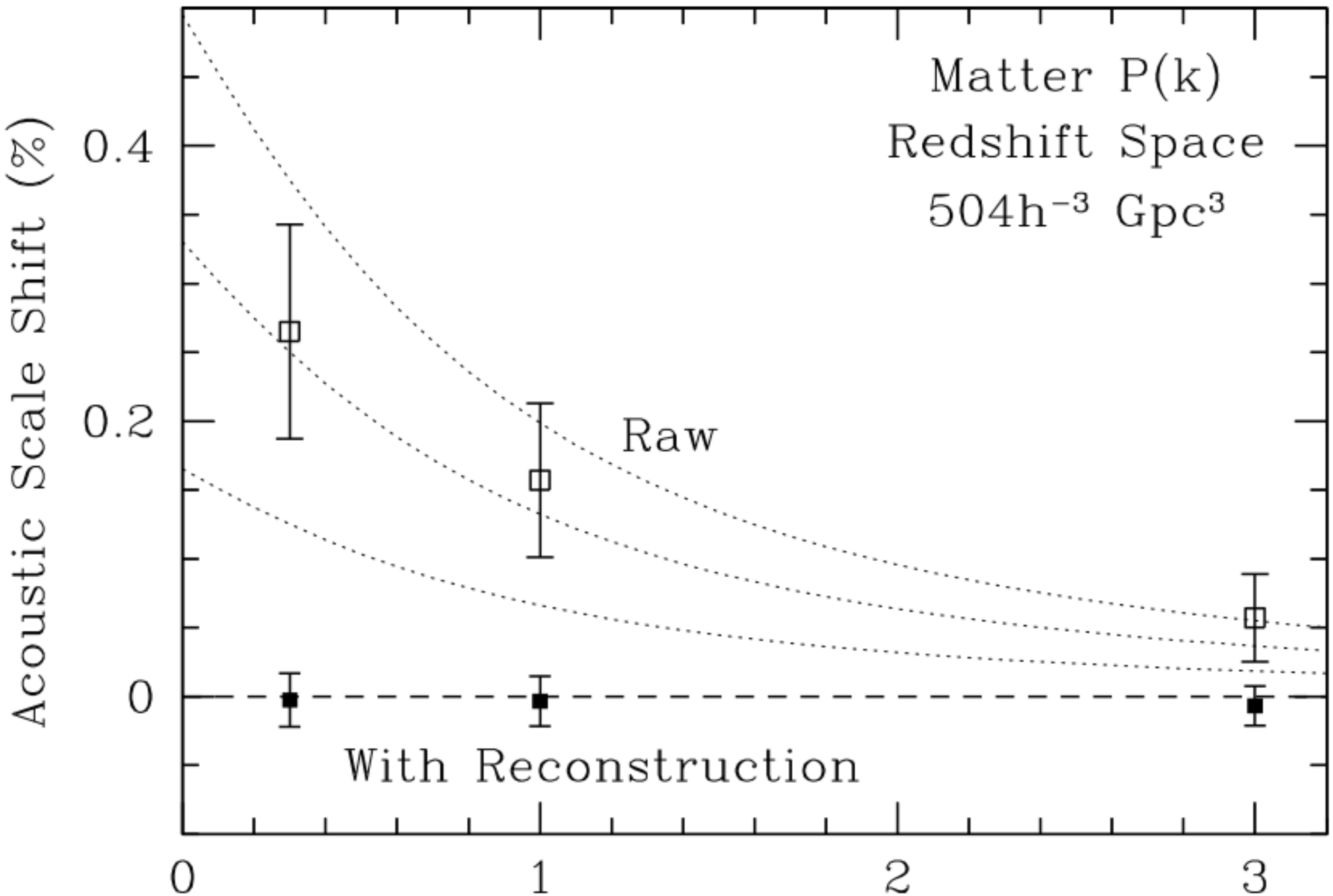
Reconstruction



Reconstruction

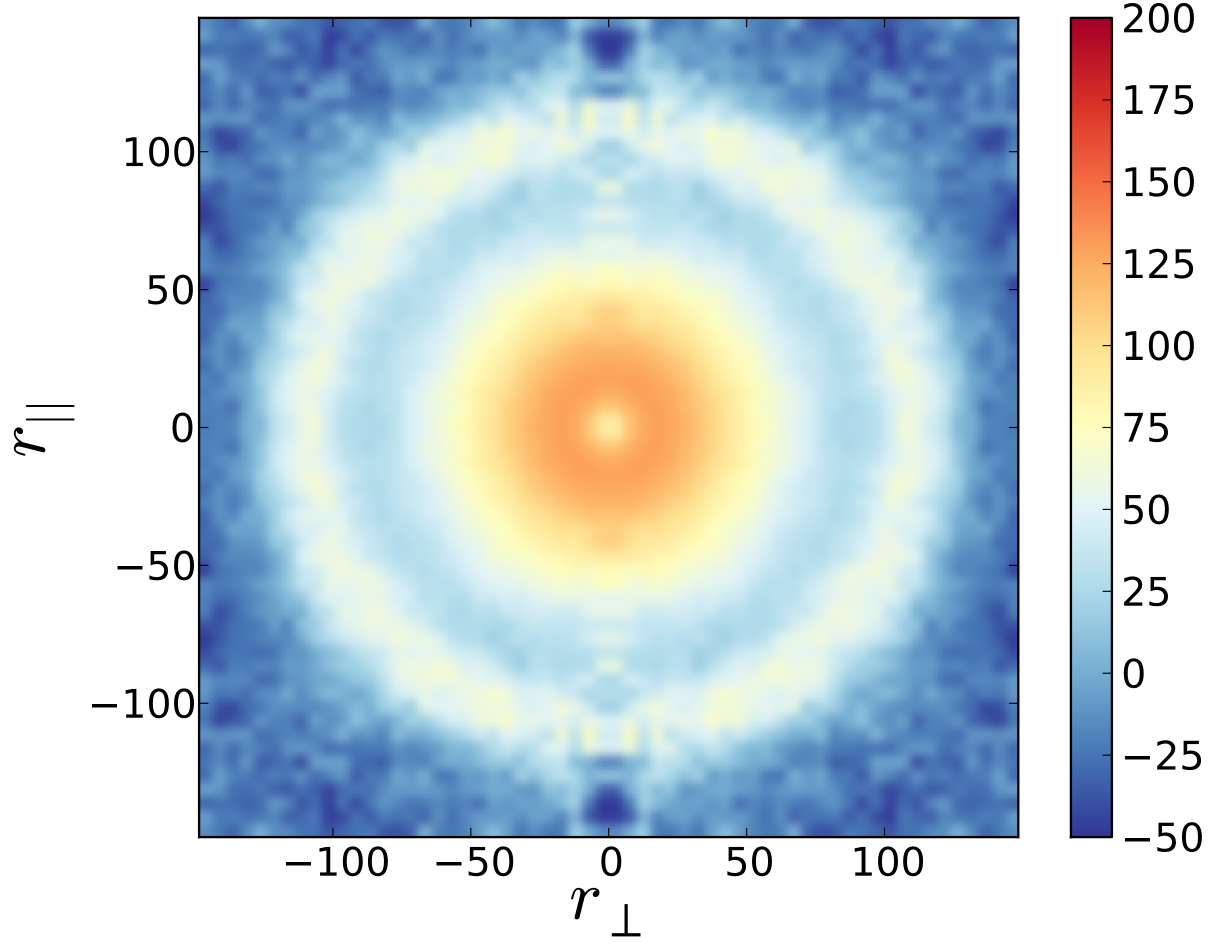


Towards a linear density field



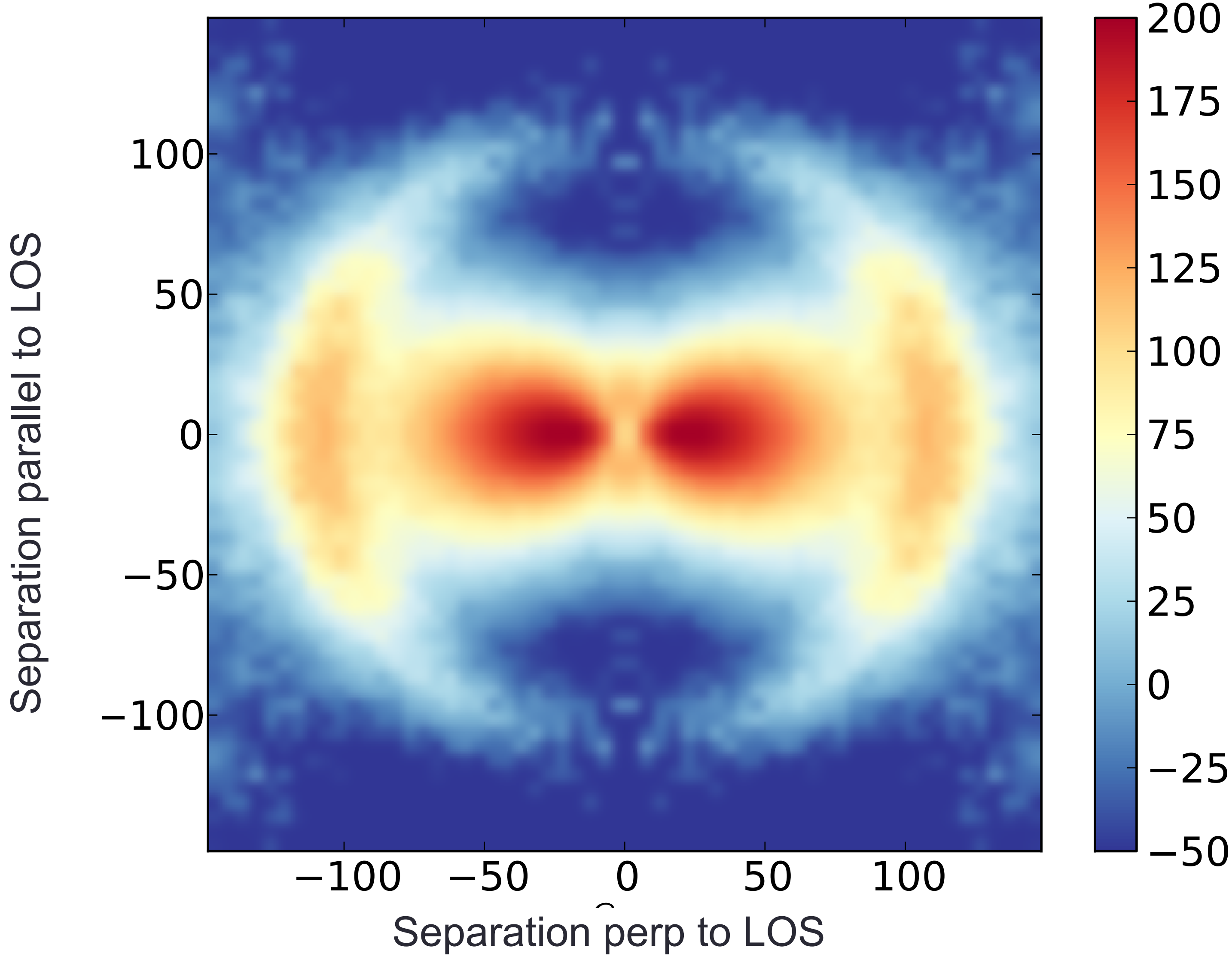
Seo et al, 2010

Simulations : Real Space



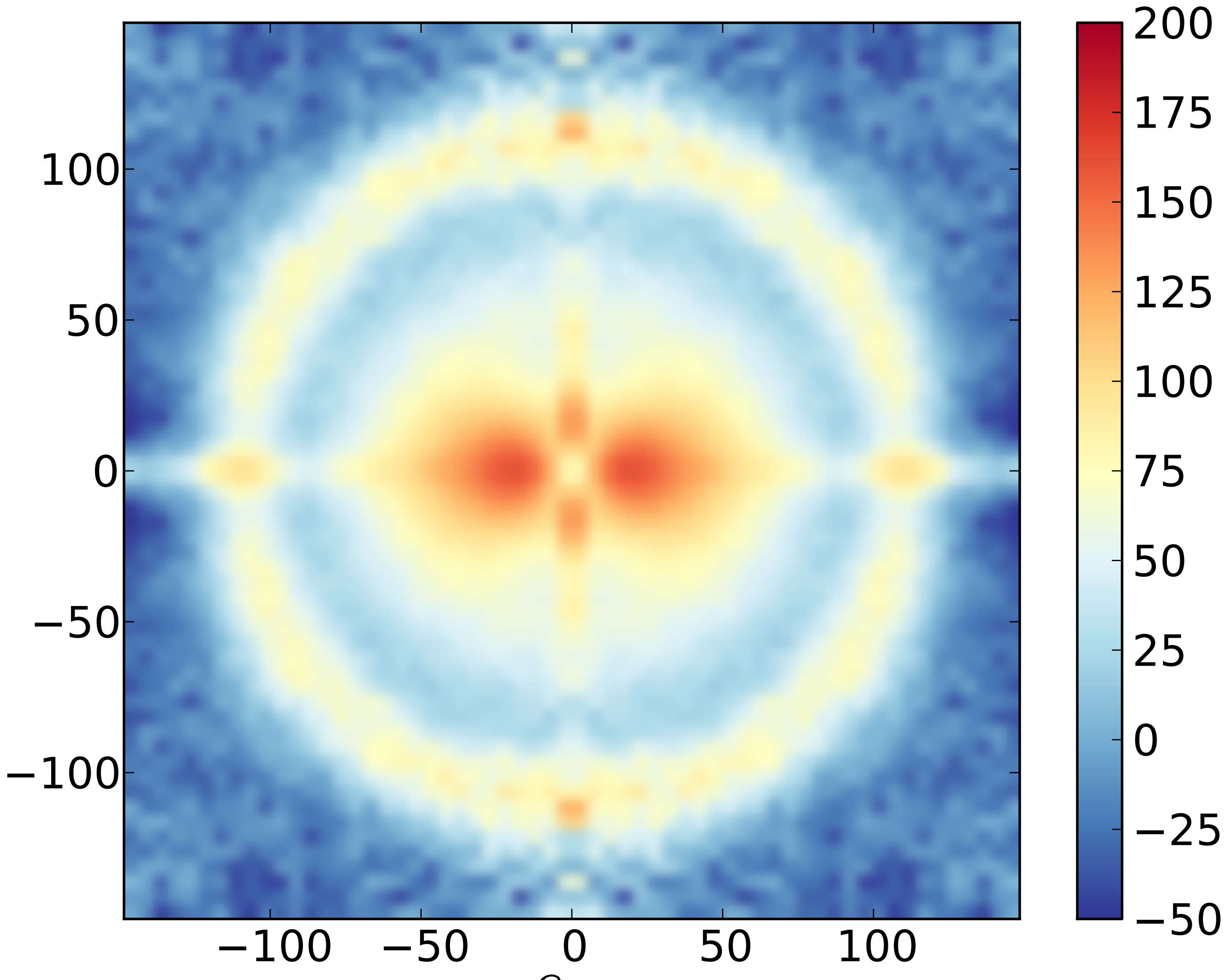
Simulations : Before

NP et al, 2012



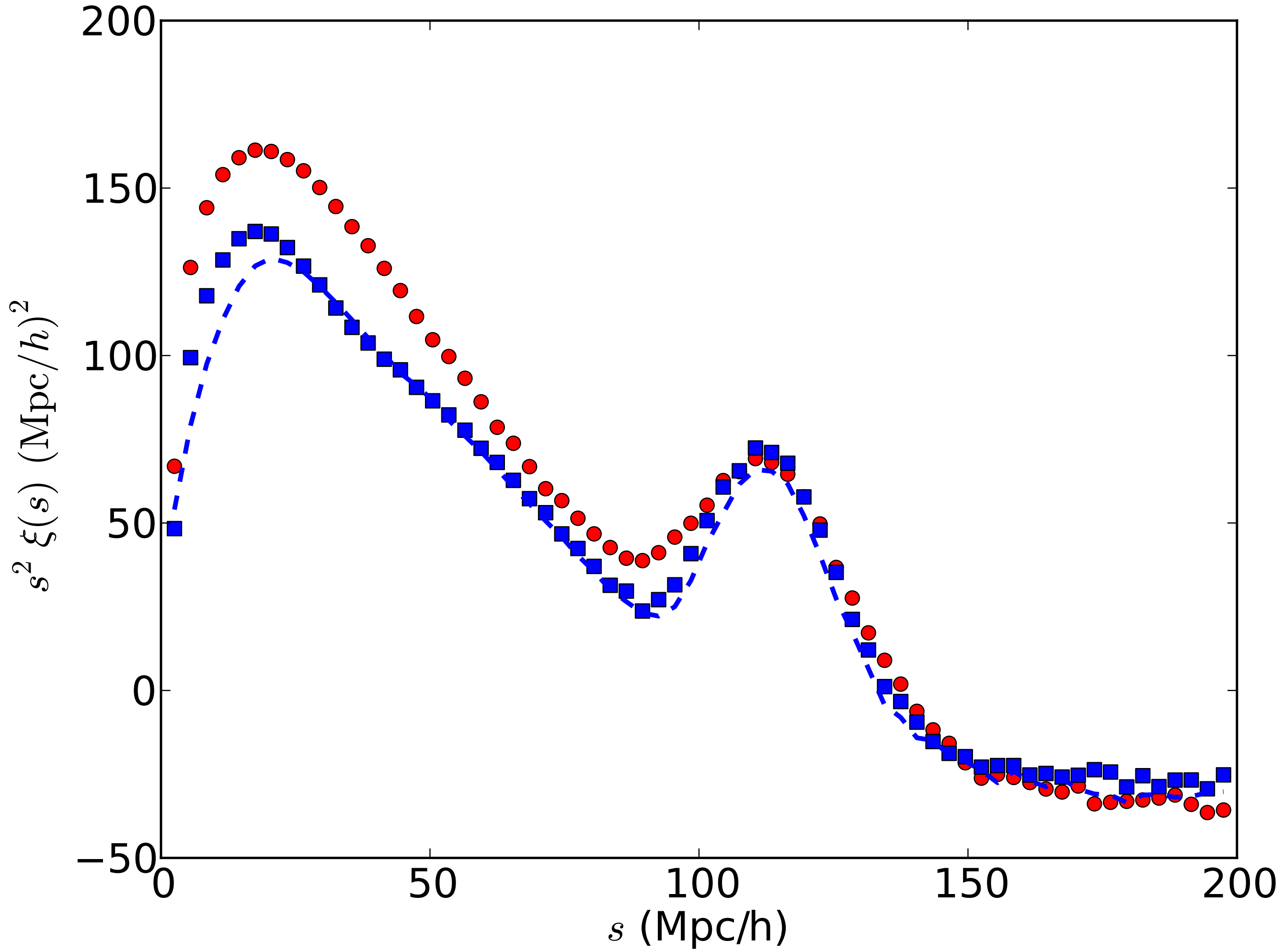
Simulations : After

NP et al, 2012

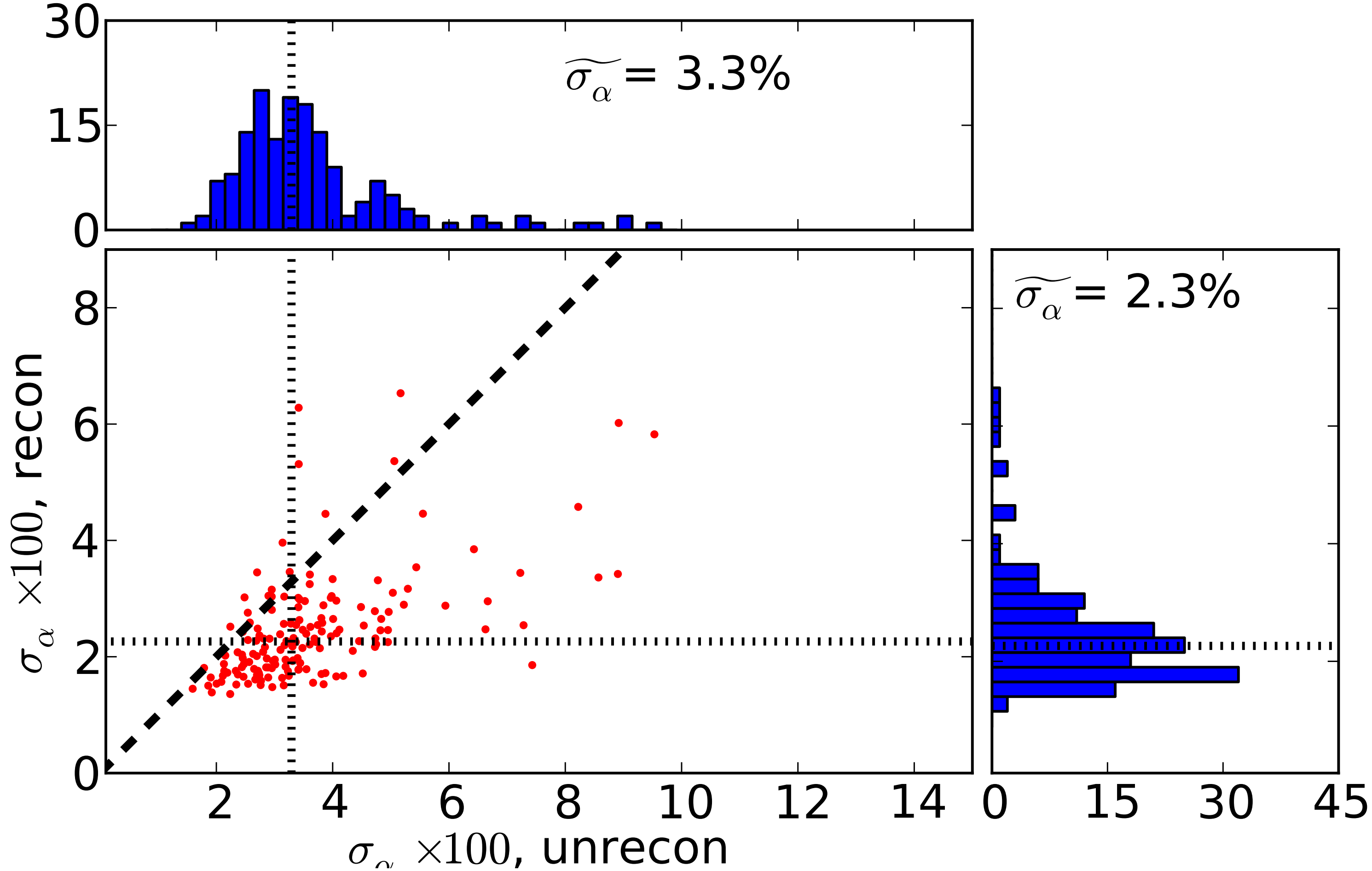


The two point correlations

NP et al, 2012



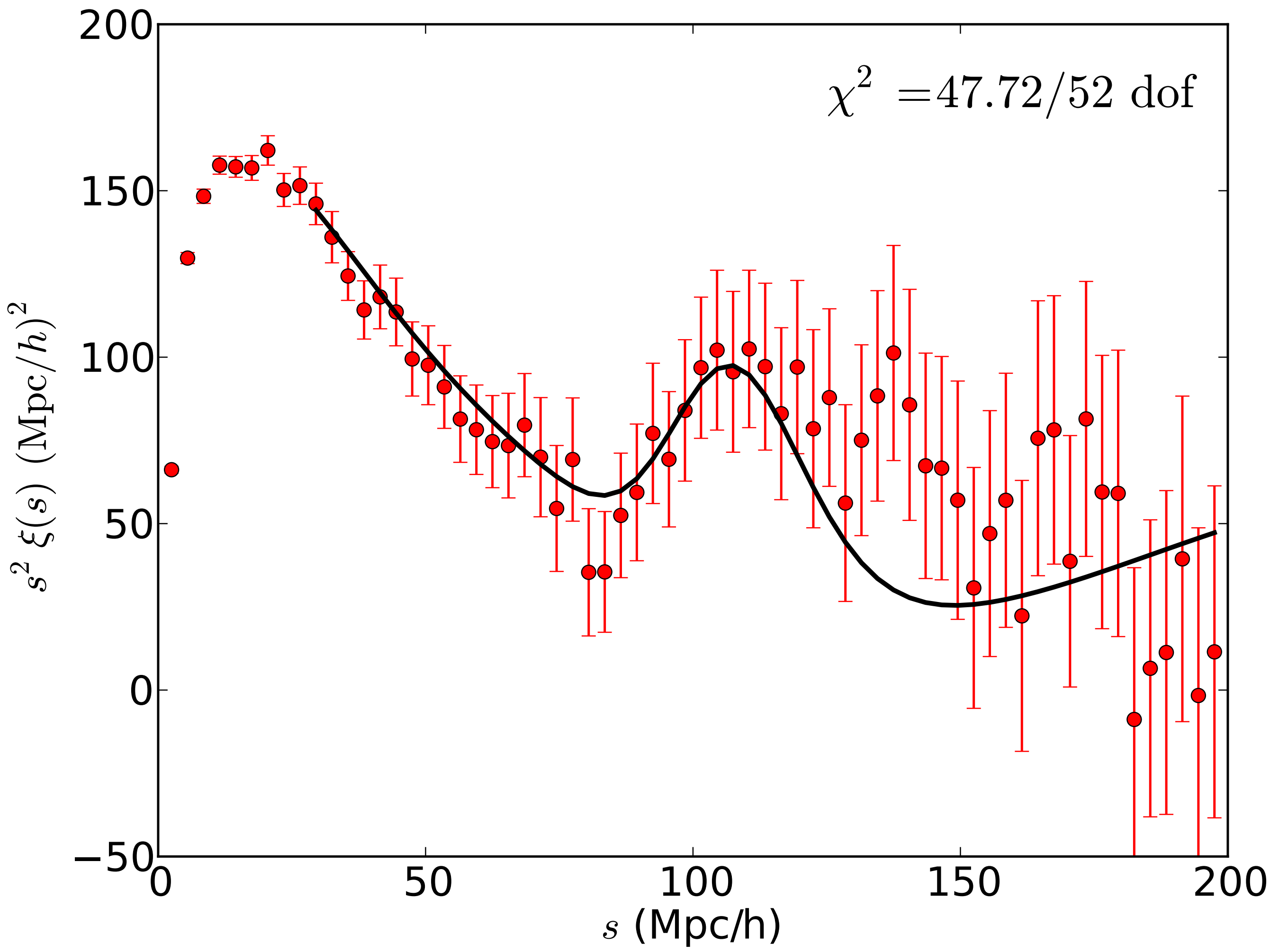
Errors



$\widetilde{\sigma_\alpha} = 3.3\%$
$\widetilde{\sigma_\alpha} = 2.3\%$
$\sigma_\alpha \times 100$, recon
$\sigma_\alpha \times 100$, unrecon
30
15
0
8
6
4
2
0
2
4
6
8
10
12
14
0
15
30
45

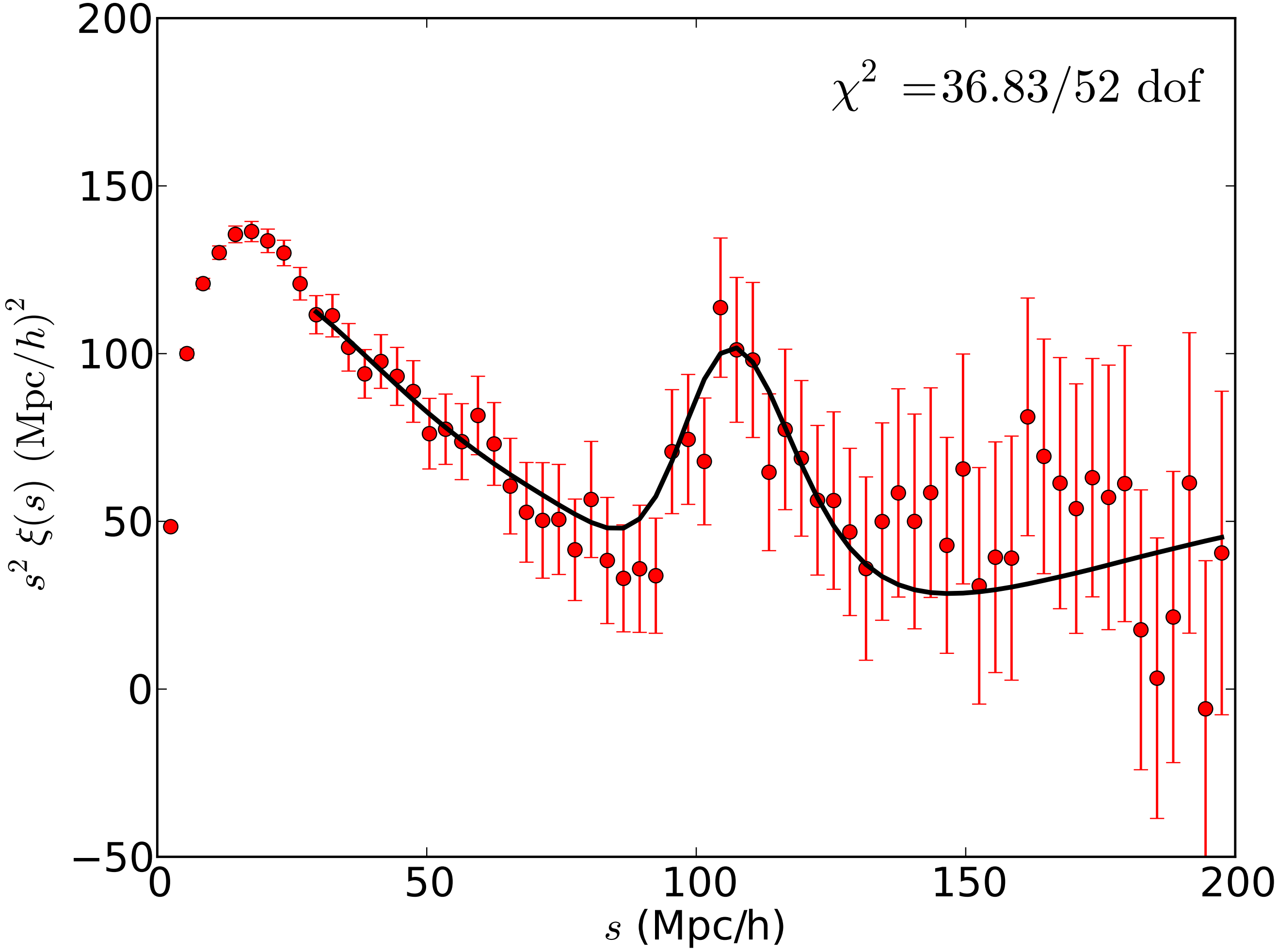
SDSS I/II : Before

NP et al, 2012



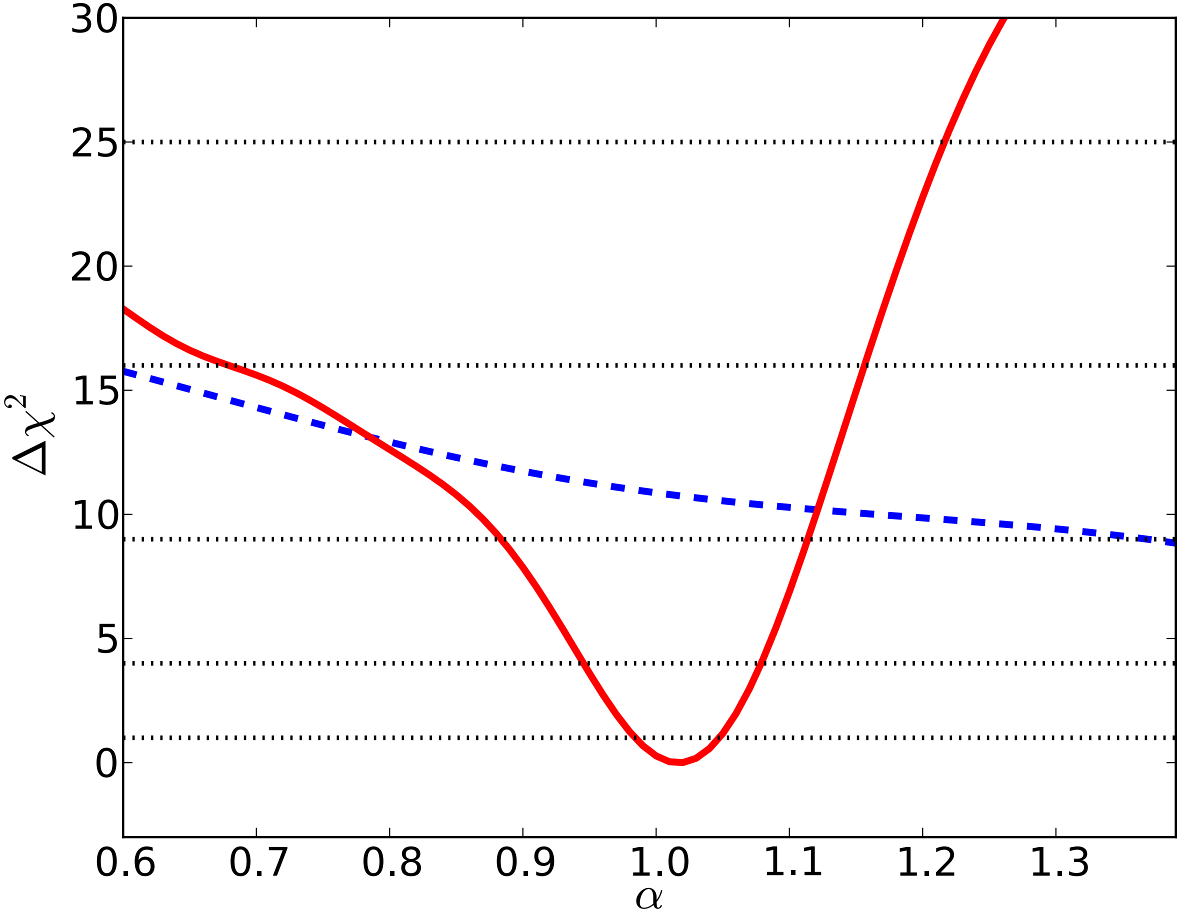
SDSS I/II : After

NP et al, 2012



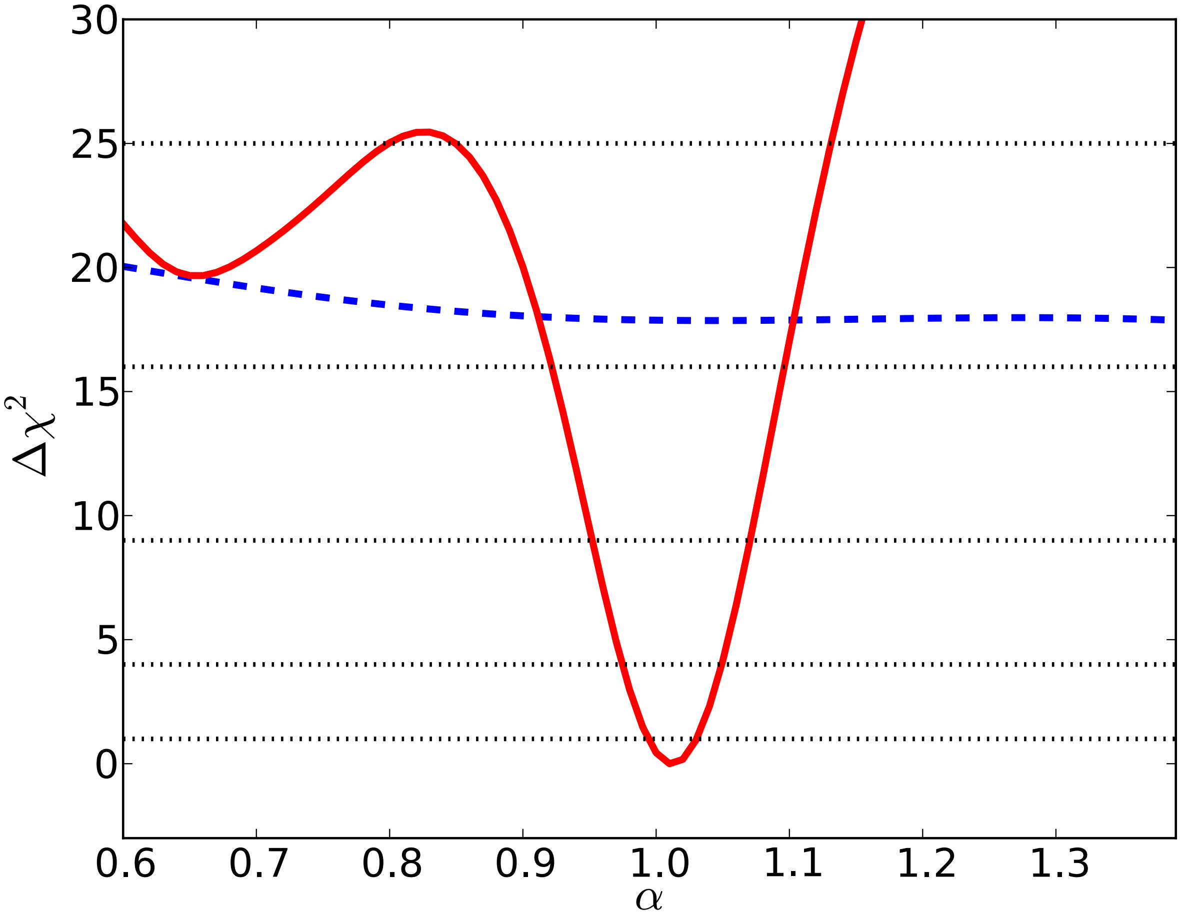
Significance : Before

3.3 sigma



Significance : After

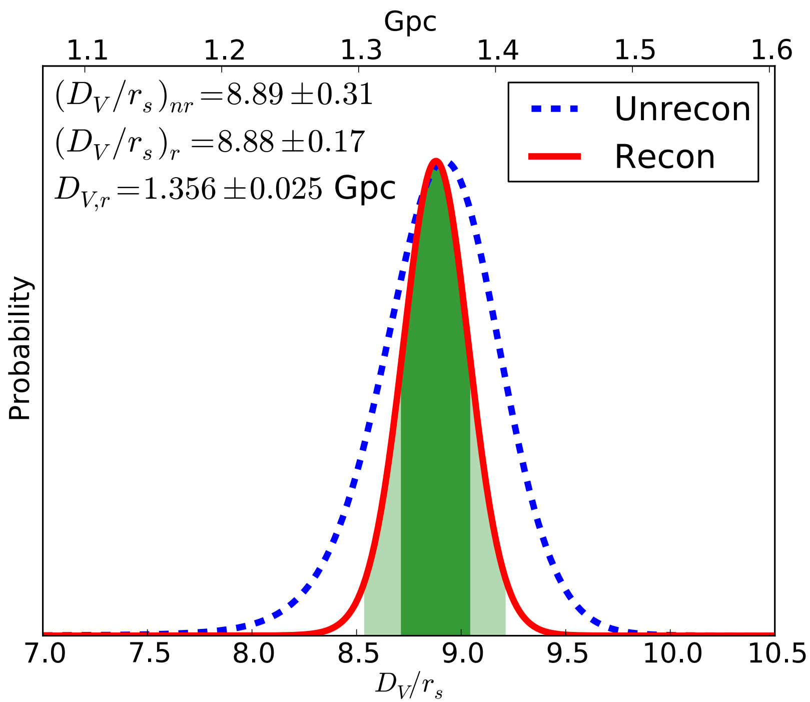
4.2 sigma



DR7 : Key Points

NP et al, 2012

- First application of reconstruction to data
- Error reduced by factor of 1.7
- BAO smoothing reduced by 50%



Outline

- Baryon Acoustic Oscillations, very quickly
- Recent Developments
  - How to build a better standard ruler?
  - First galaxy BAO results from BOSS
    - What is BOSS?
    - Galaxies in BOSS
    - First BAO results from BOSS
  - BigBOSS : BAO in the future

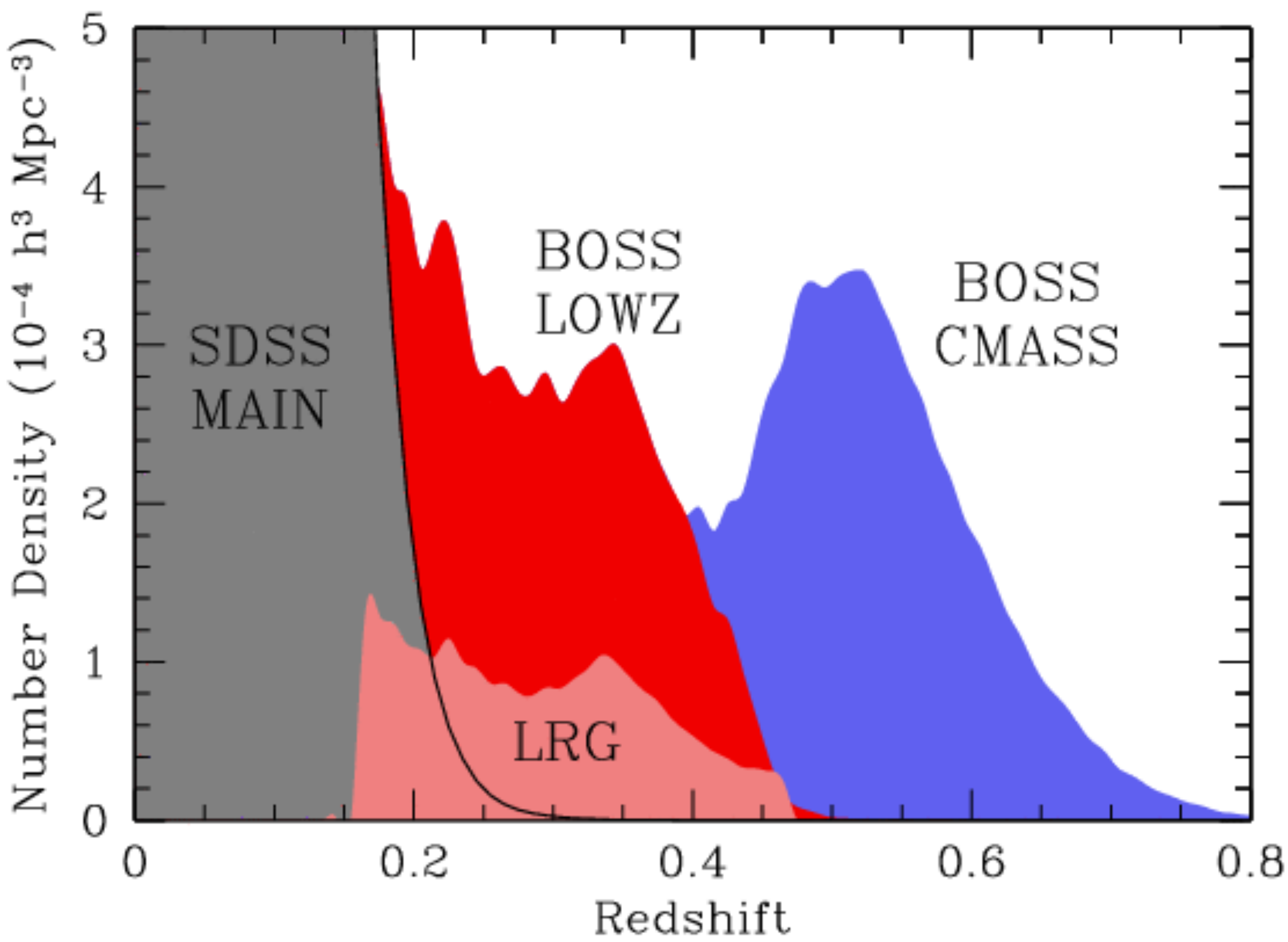
What is BOSS?

- Baryon Oscillation Spectroscopic Survey
- BAO with galaxies, Lyman-alpha forest
- On going dark energy experiment
  - Funded by DoE, NSF, Sloan Foundation and Participating Institutions
- The definitive low redshift BAO measurement
- 1% distance measurements at z=0.35, 0.6
- First results with 1/3 of the data out!

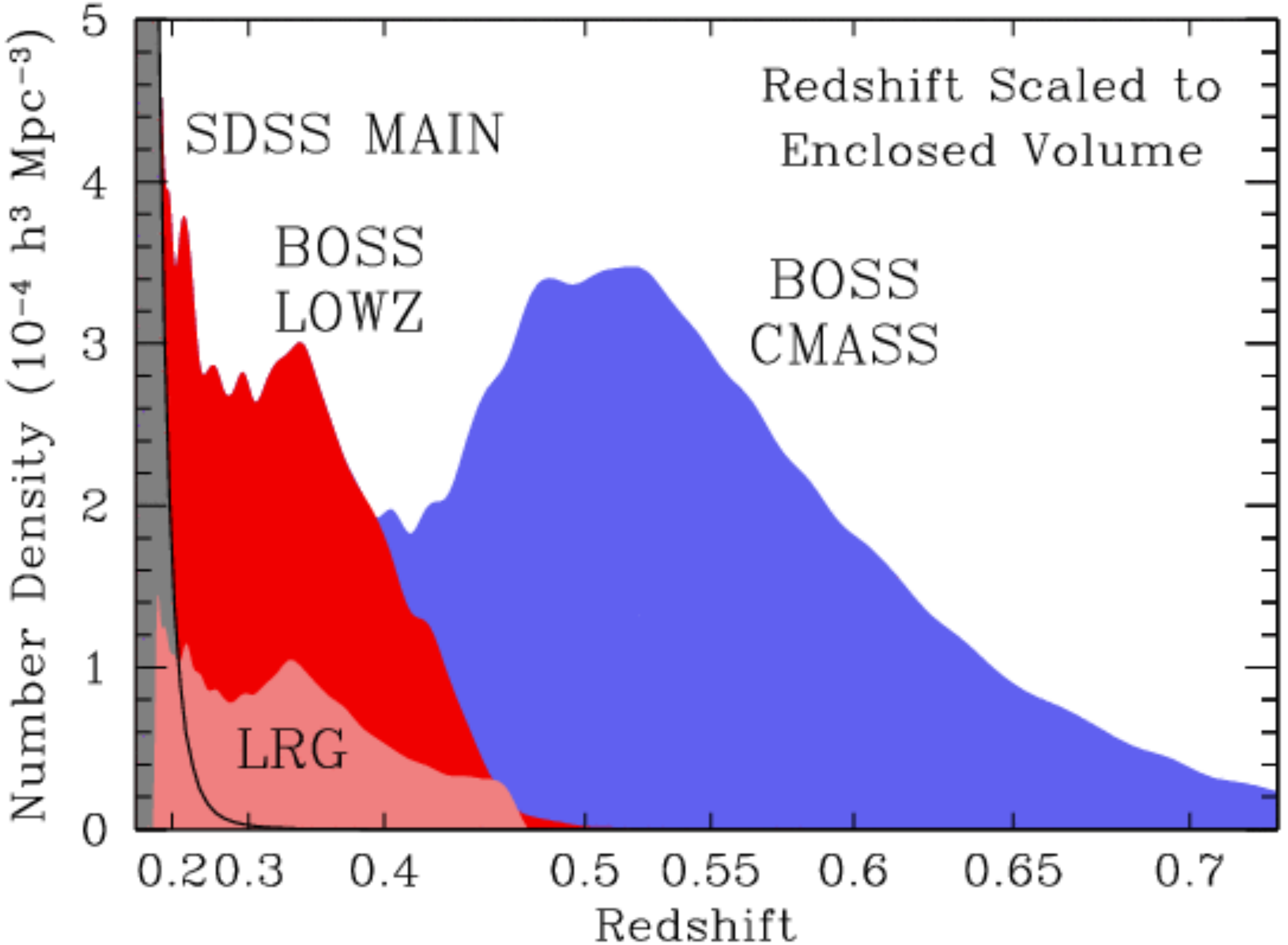
A BOSS Factsheet

	BOSS
Telescope	SDSS 2.5m
Number of simultaneous spectra	1000
Survey duration	2009-2014
Total number of galaxies	1.5 million
Distance precision from galaxy BAO	1% at z=0.35, z=0.6
Figure of Merit	11

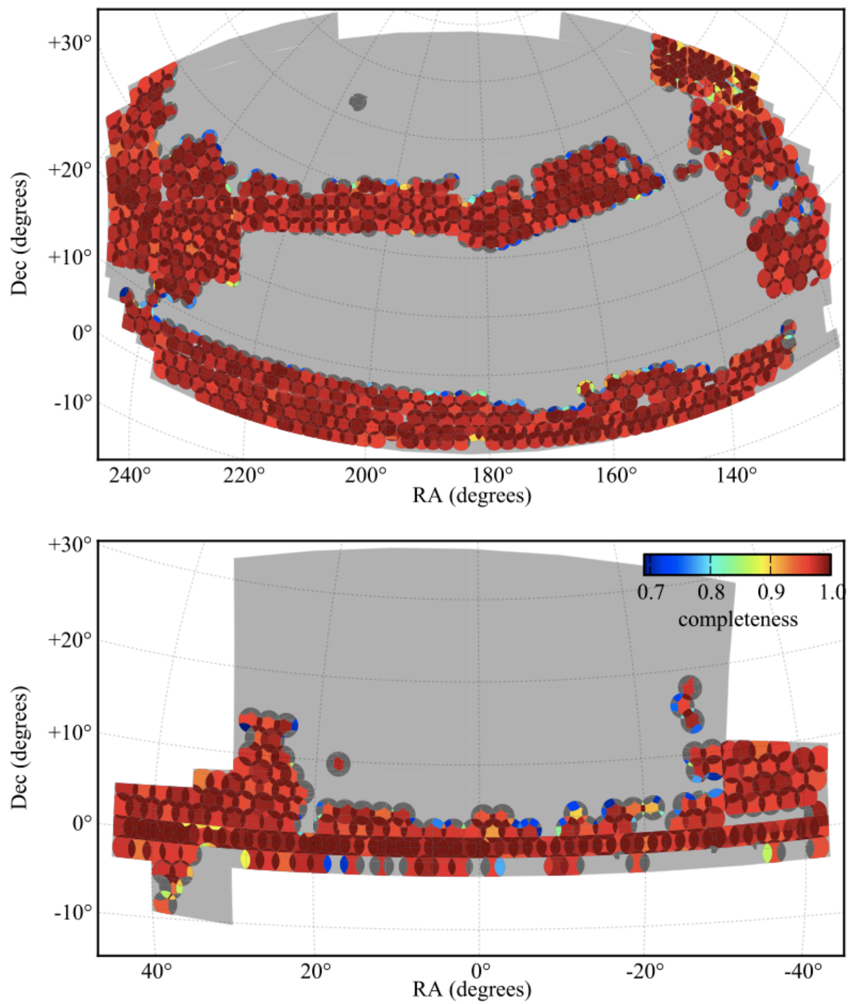
BOSS pushes out to higher redshift



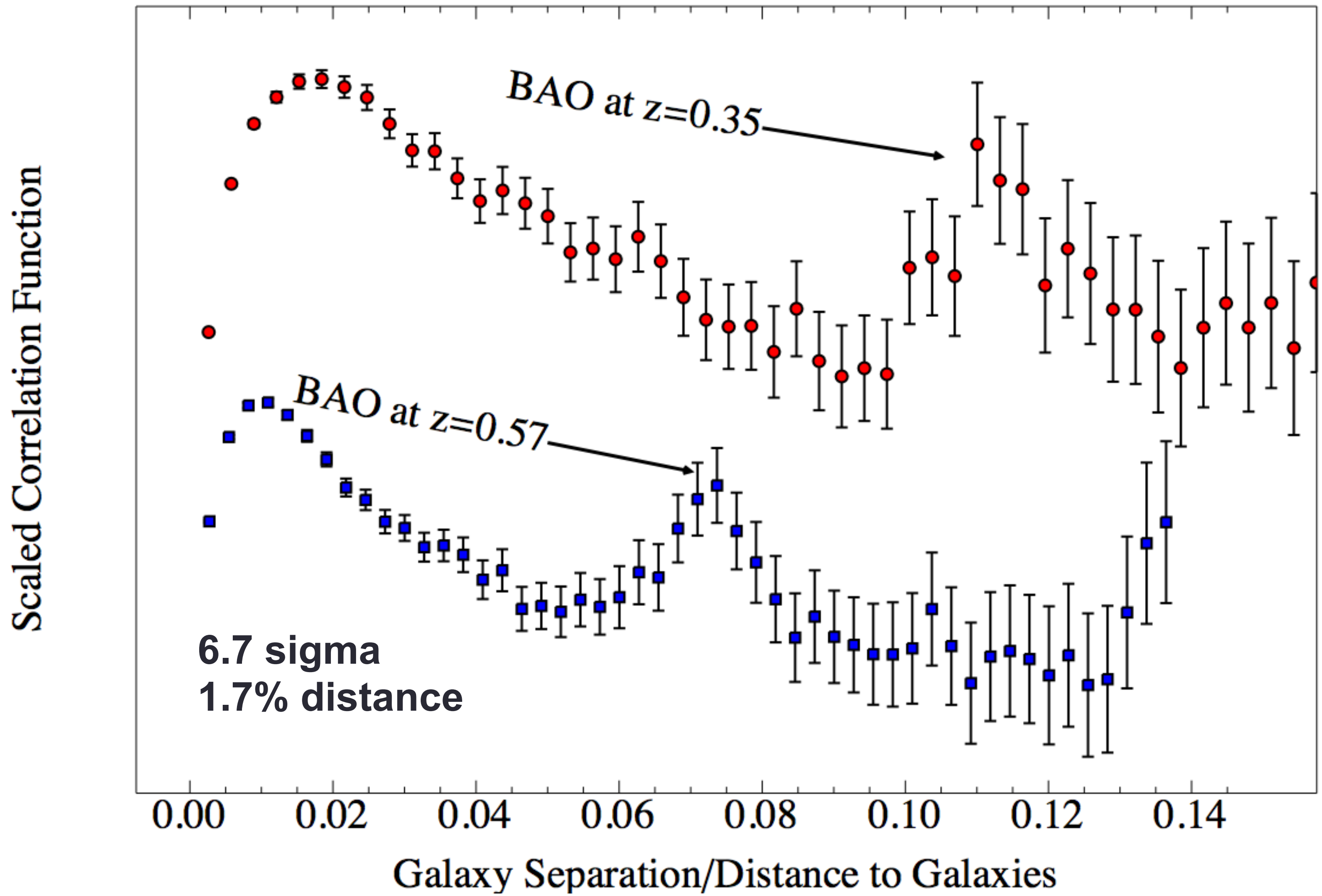
… and surveys a larger volume



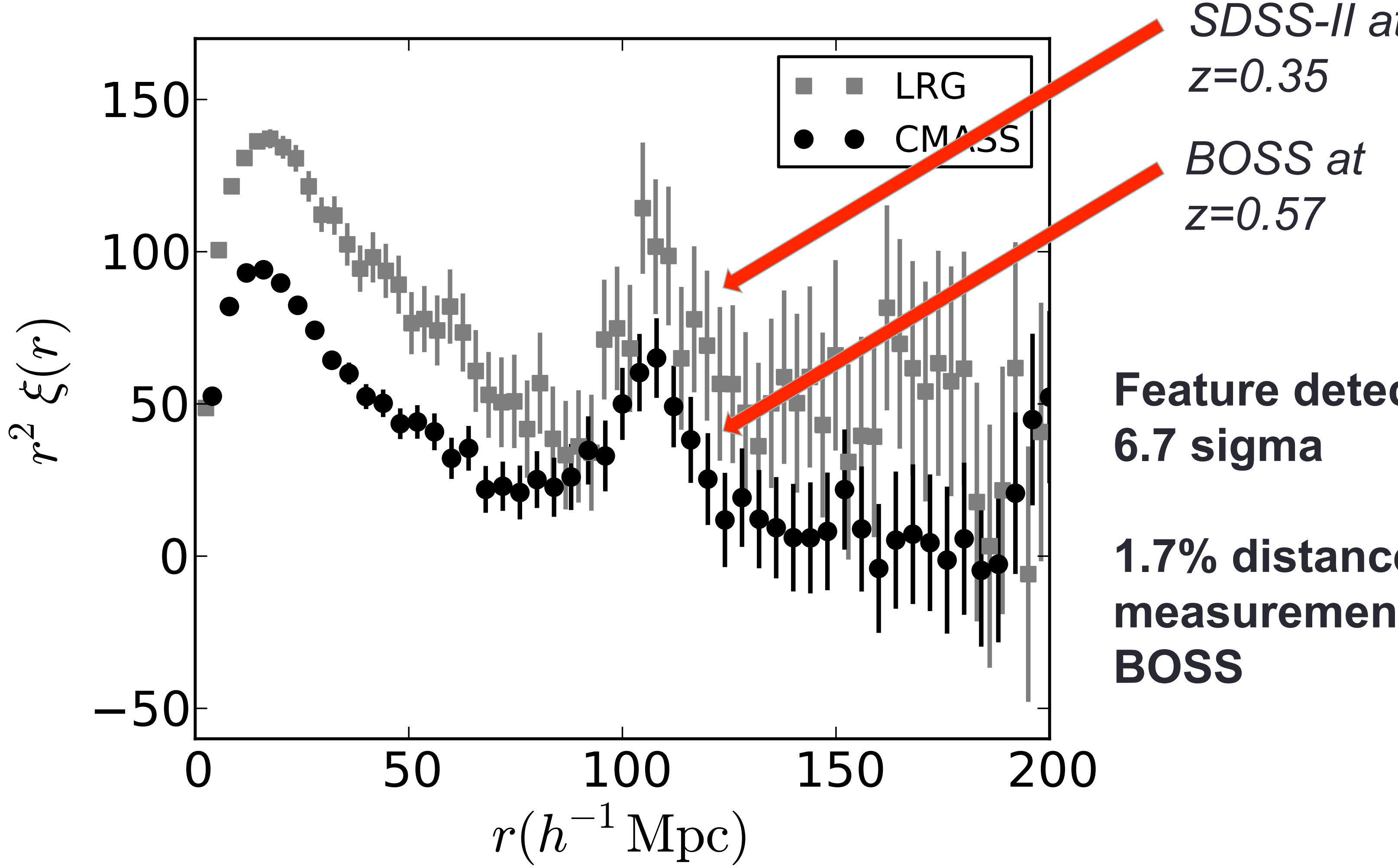
3200 deg^2 surveyed (of 10000)



BOSS measures the BAO standard ruler



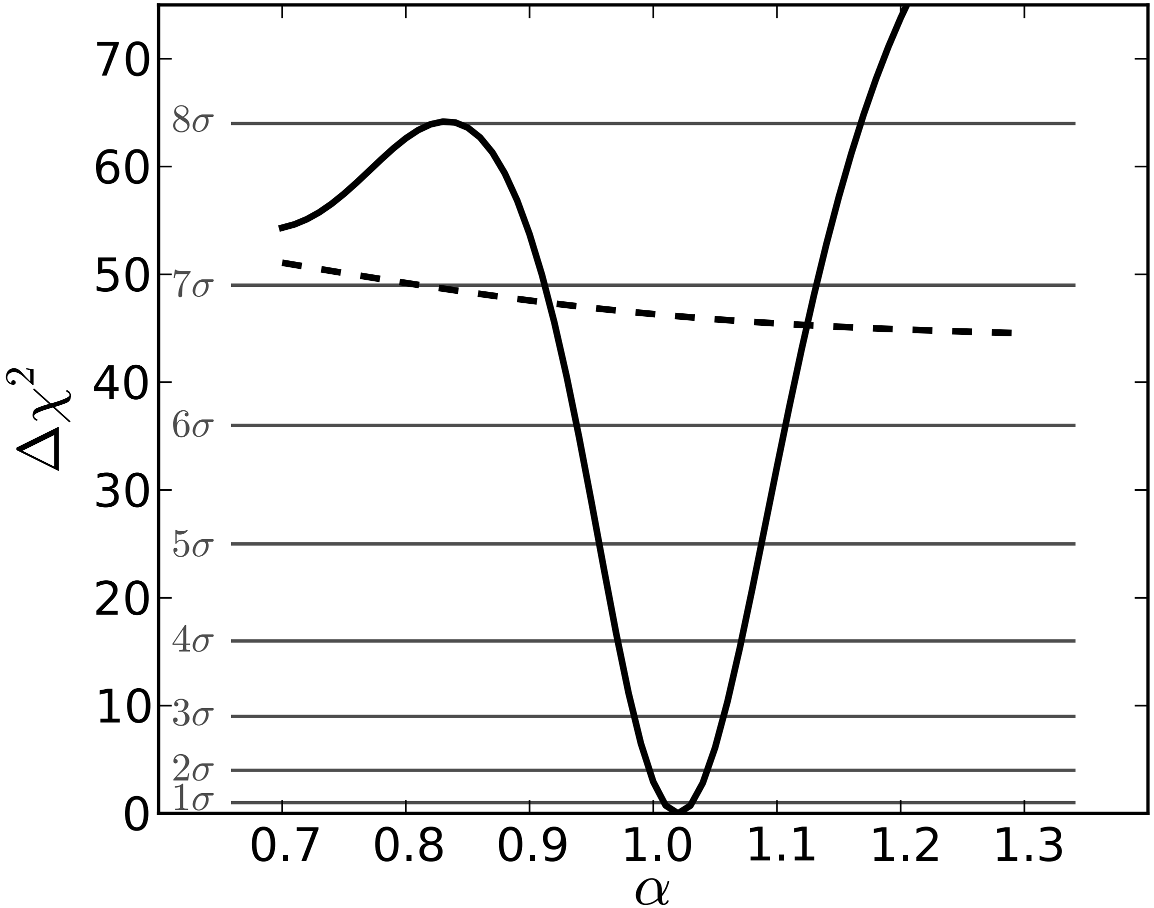
The BAO Feature clearly detected



Feature detected at 6.7 sigma

1.7% distance measurement from BOSS

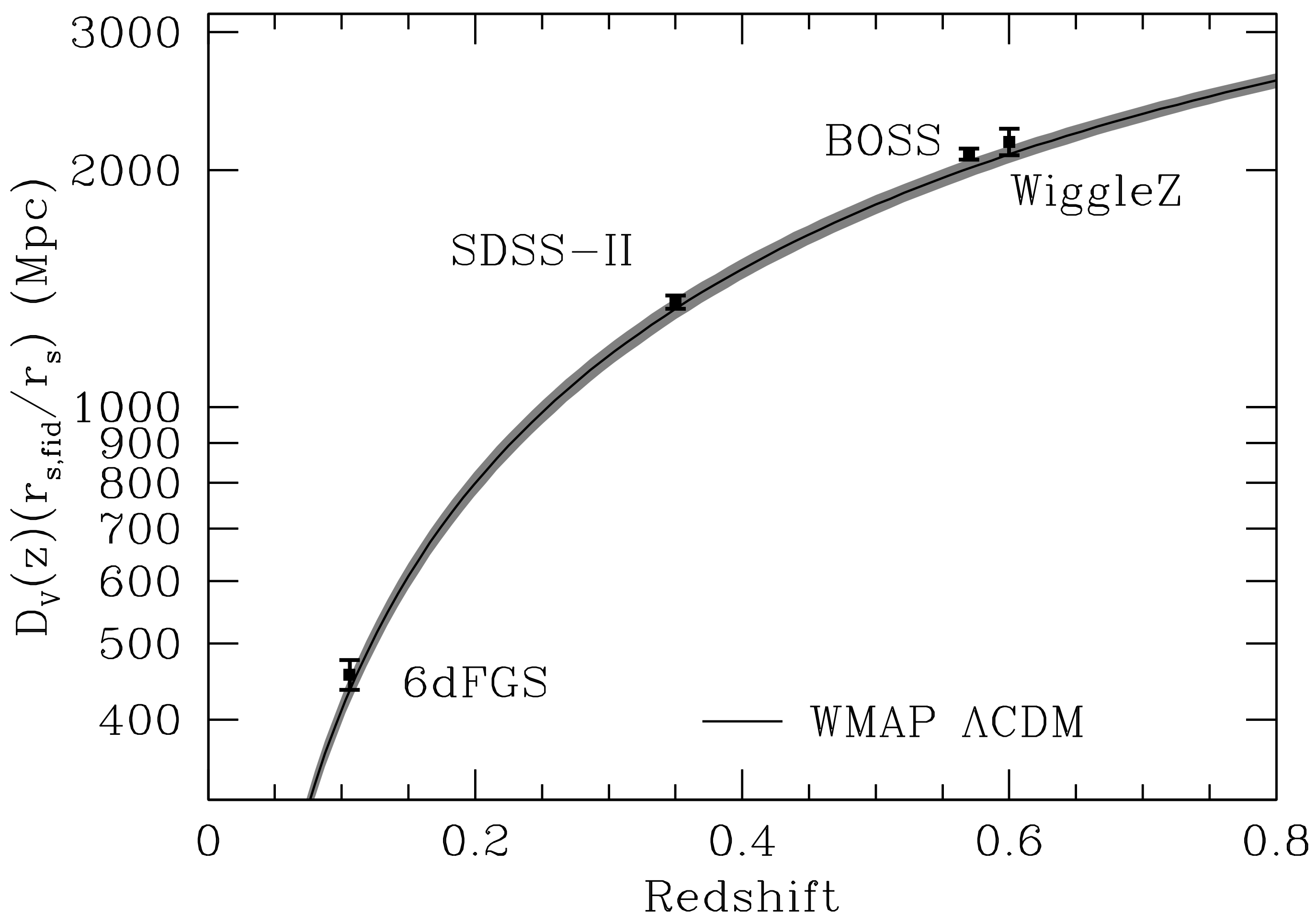
The BAO detection is highly significant!



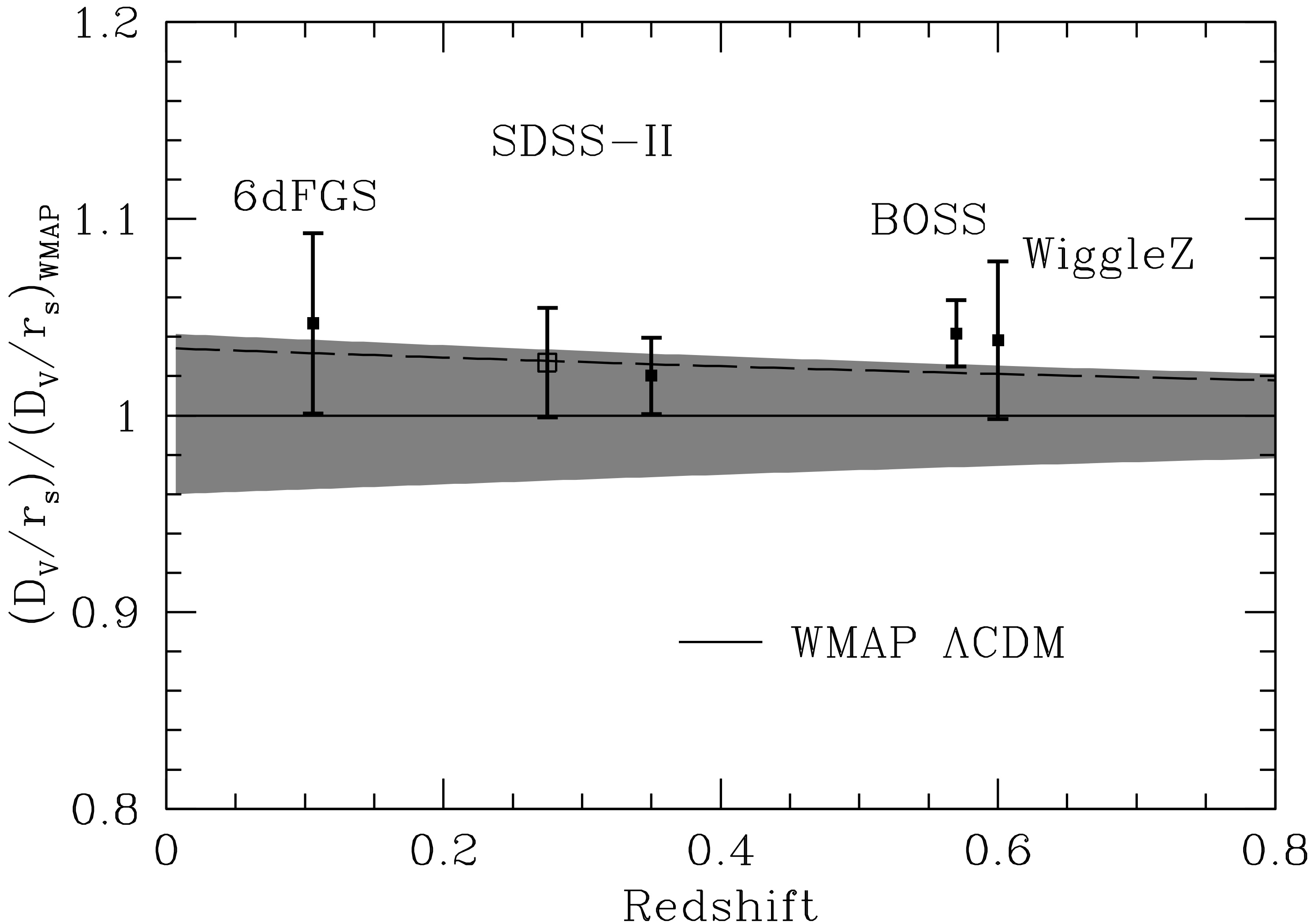
Highlights

- First BAO results from the Baryon Oscillation Spectroscopic Survey
- BAO feature seen more clearly than ever before (6.7 sigma detection)
- Most precise distance constraints from the BAO measurements to date (1.7%)
- A good year for SDSS!
  - Most precise BAO distance measurements!
  - 1.7% at z=0.57
  - 1.9% at z=0.35 (Feb 2012)

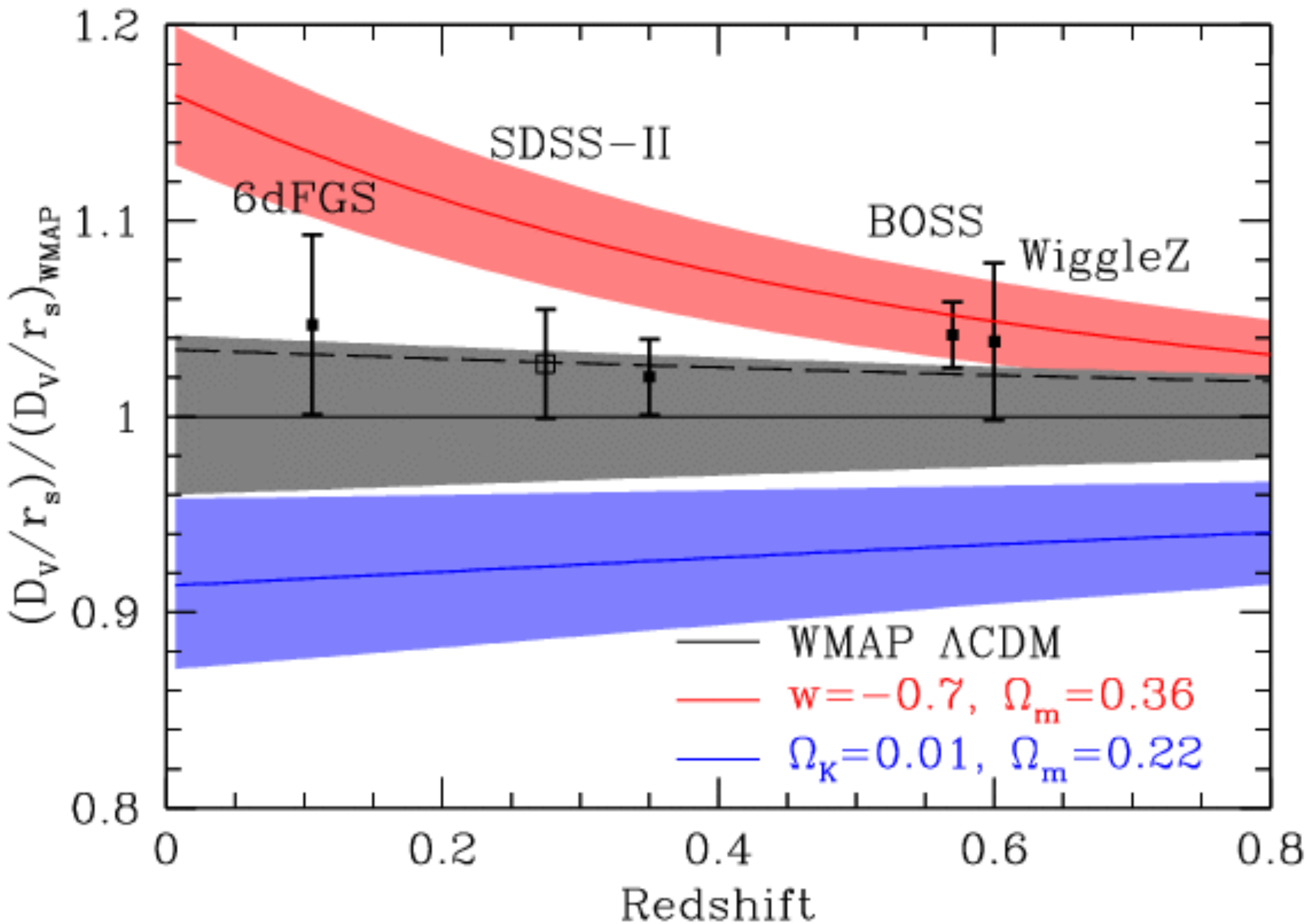
BAO measure the expansion history



The BAO Hubble Diagram



The BAO Hubble Diagram



Deconstructing the Friedmann Eqn.

$$H^2(a) = H_0^2 \left[\Omega_R a^{-4} + \Omega_M a^{-3} + \right.$$

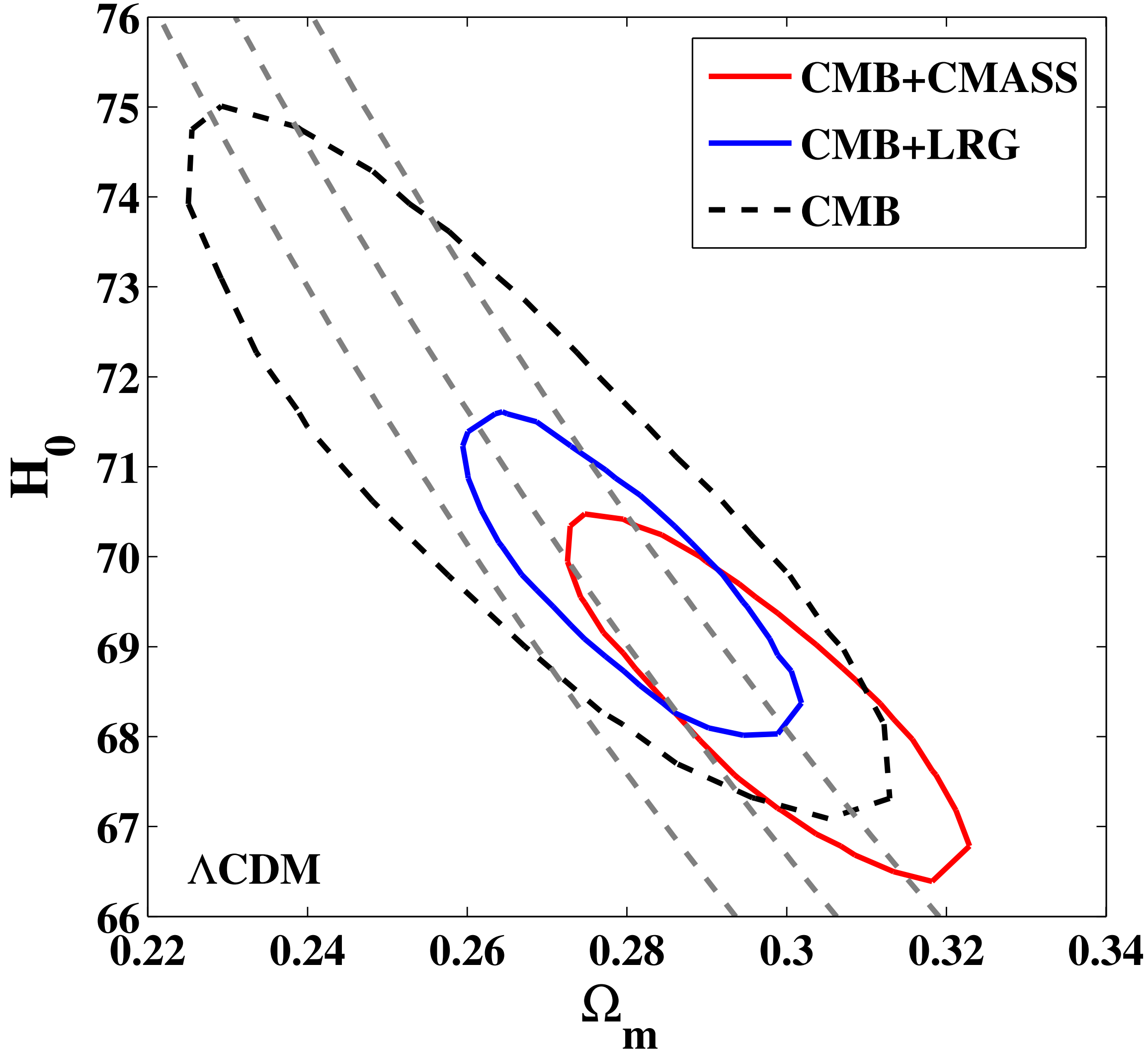
$$\left. \Omega_k a^{-2} + \Omega_{DE} \exp\left\{ 3 \int_a^1 \frac{da'}{a'} [1 + w(a')] \right\} \right]$$

The matter density

$$H^2(a) = H_0^2\left[\Omega_R a^{-4} + \Omega_M a^{-3} + \right.$$

$$\left.\Omega_k a^{-2} + \Omega_{DE}\exp\left\{3\int_a^1 \frac{da'}{a'}\,[1 + w(a')]\right\}\right]$$

Measuring H_0; consistency

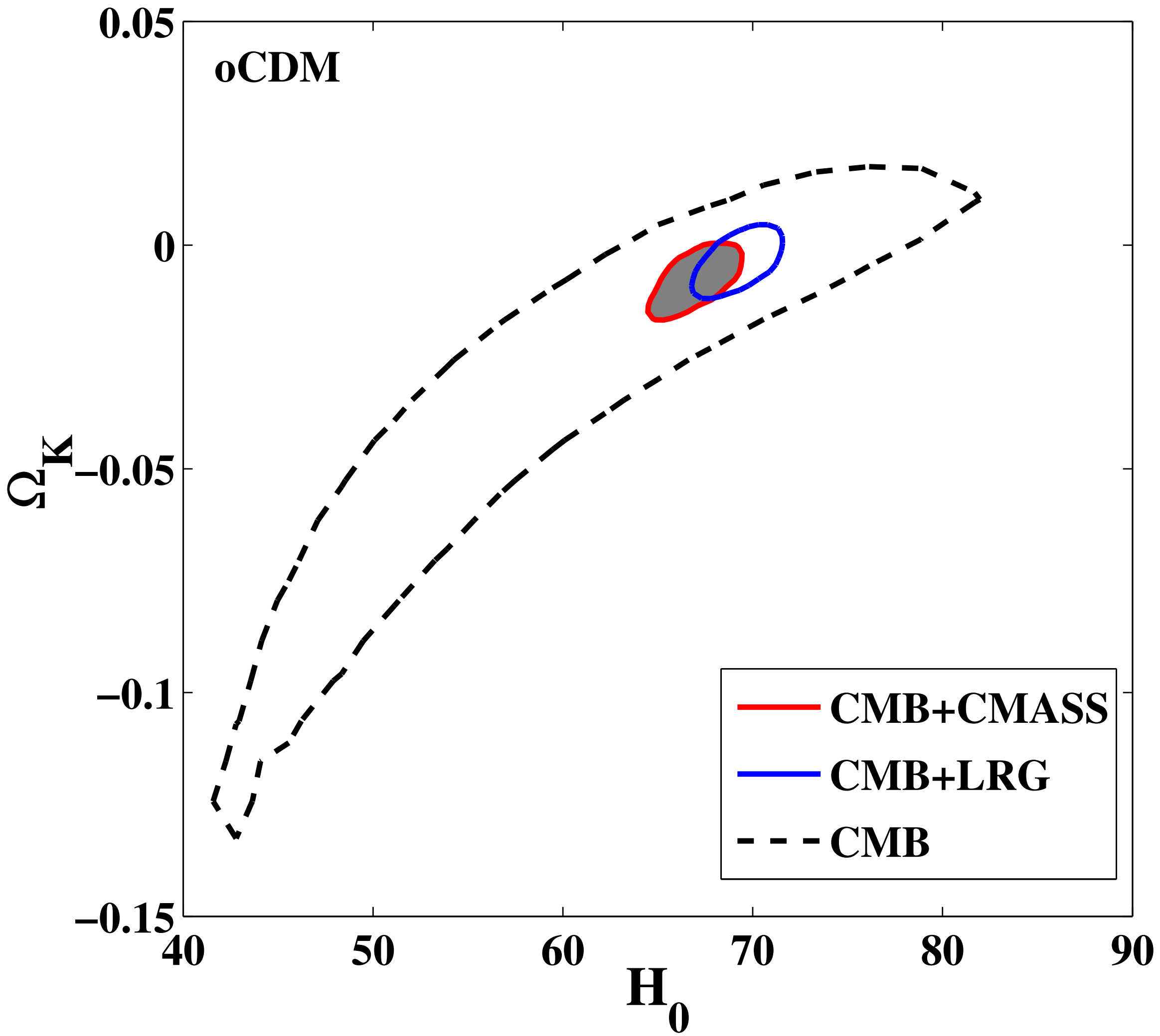


Measuring the curvature

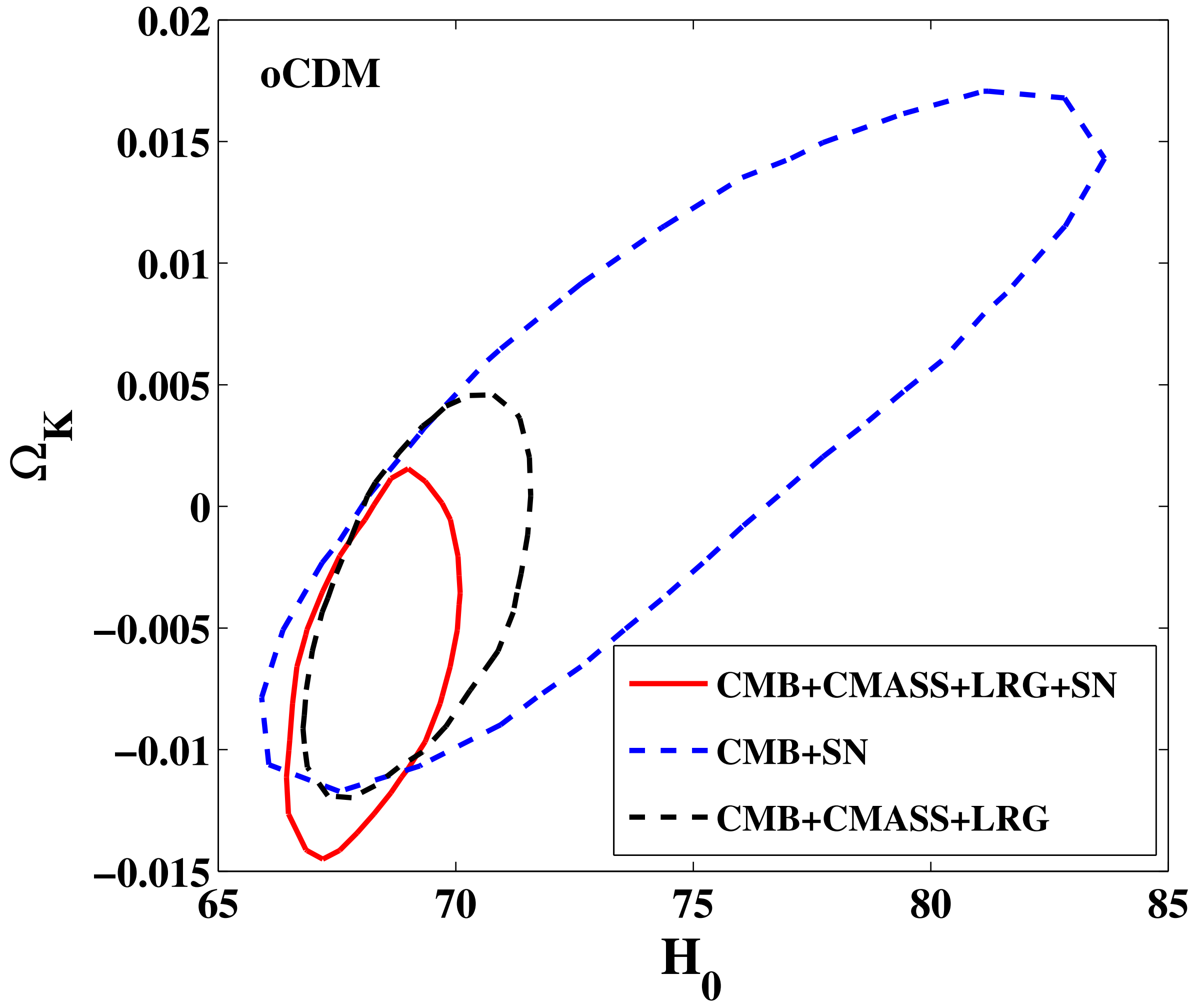
$$H^2(a) = H_0^2 \left[\Omega_R a^{-4} + \Omega_M a^{-3} + \right.$$

$$\left. \Omega_k a^{-2} + \Omega_{DE} \exp\left\{ 3 \int_a^1 \frac{da'}{a'} \left[1 + w(a') \right] \right\} \right]$$

Breaking the geometrical degeneracy



Comparing BAO to SN

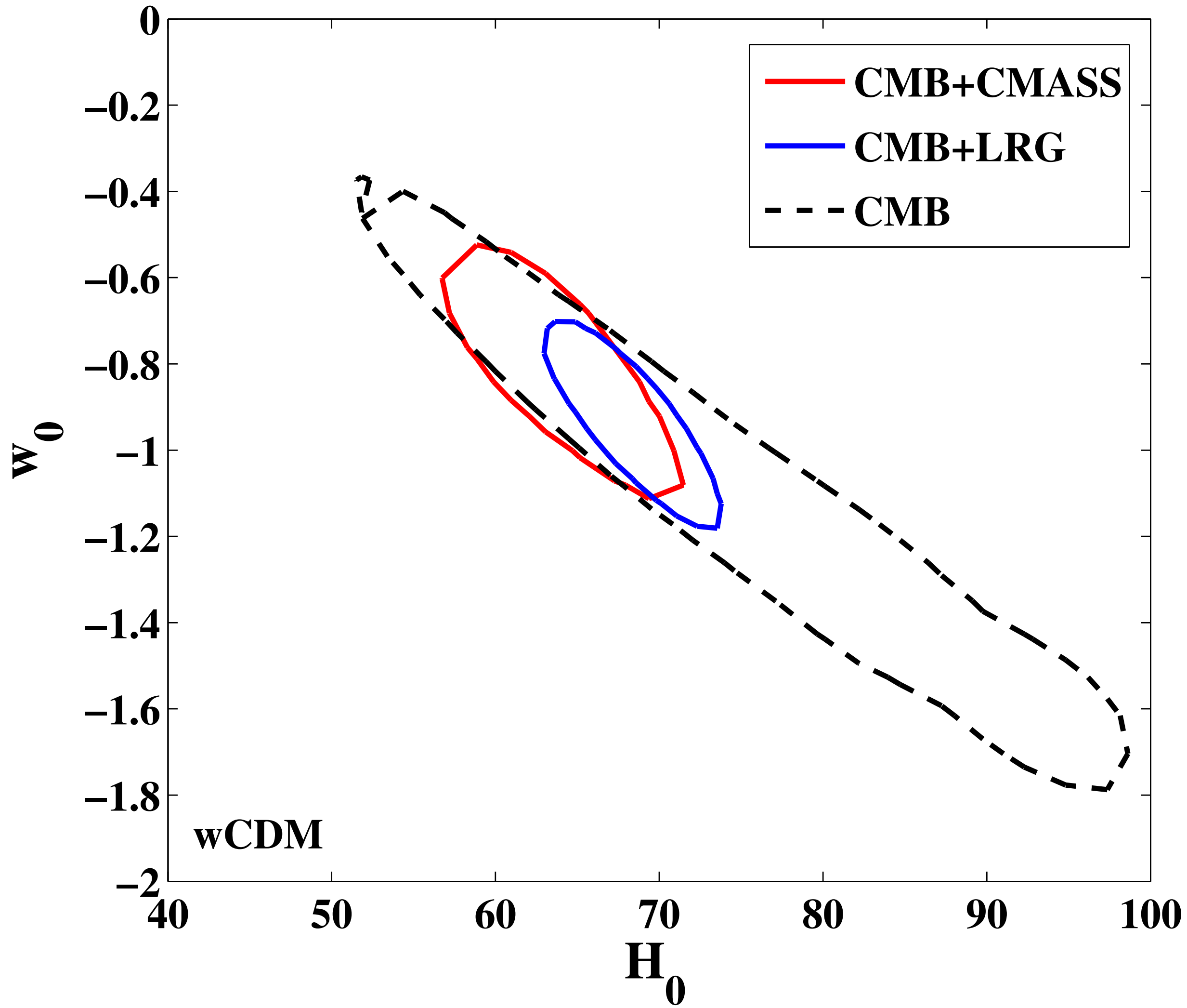


Measuring the eqn of state

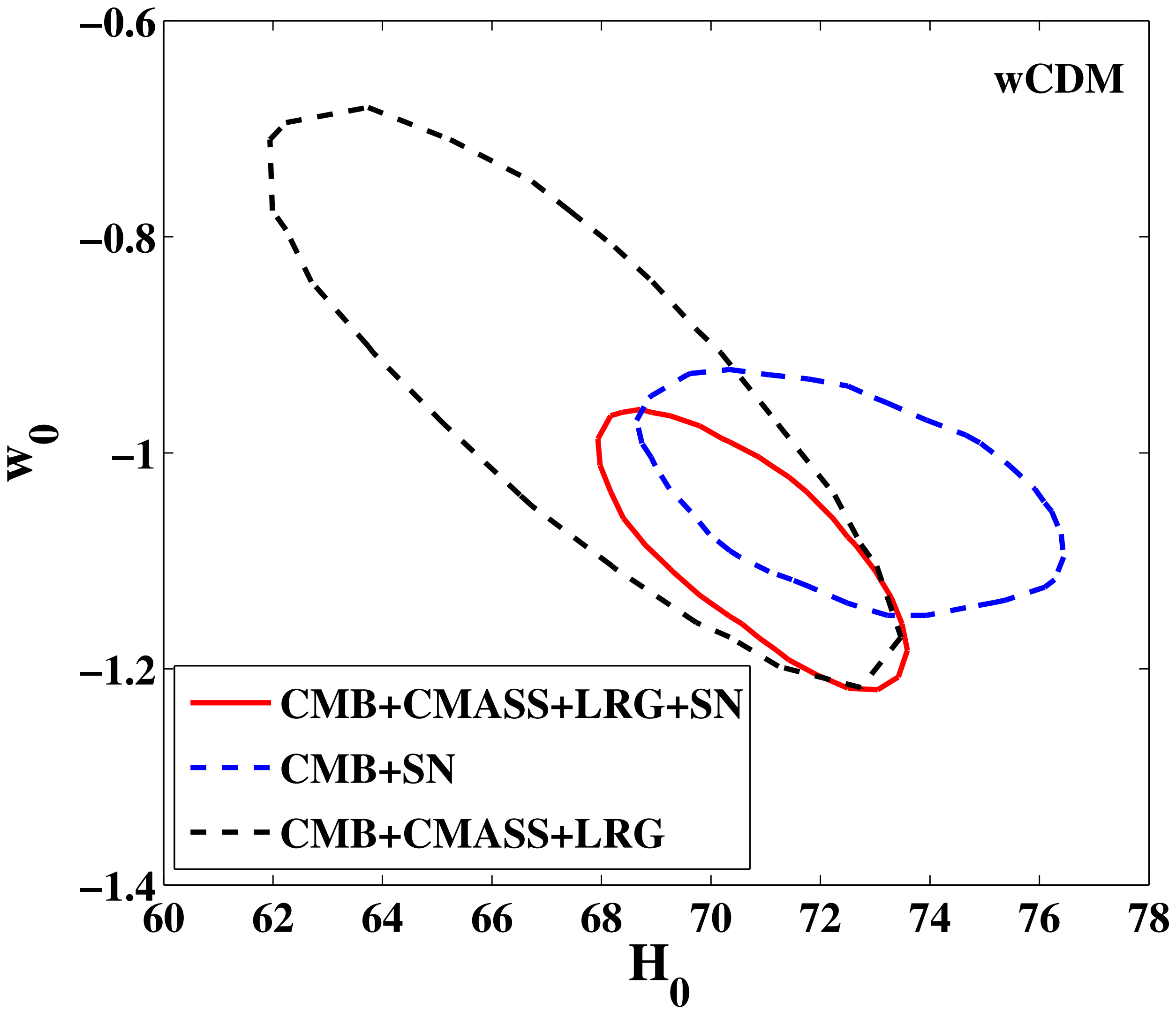
$$H^2(a) = H_0^2 \Big[\Omega_R a^{-4} + \Omega_M a^{-3} +$$

$$\Omega_k a^{-2} + \Omega_{DE} \exp\left\{ 3 \int_a^1 \frac{da'}{a'} [1 + w(a')] \right\} \Big]$$

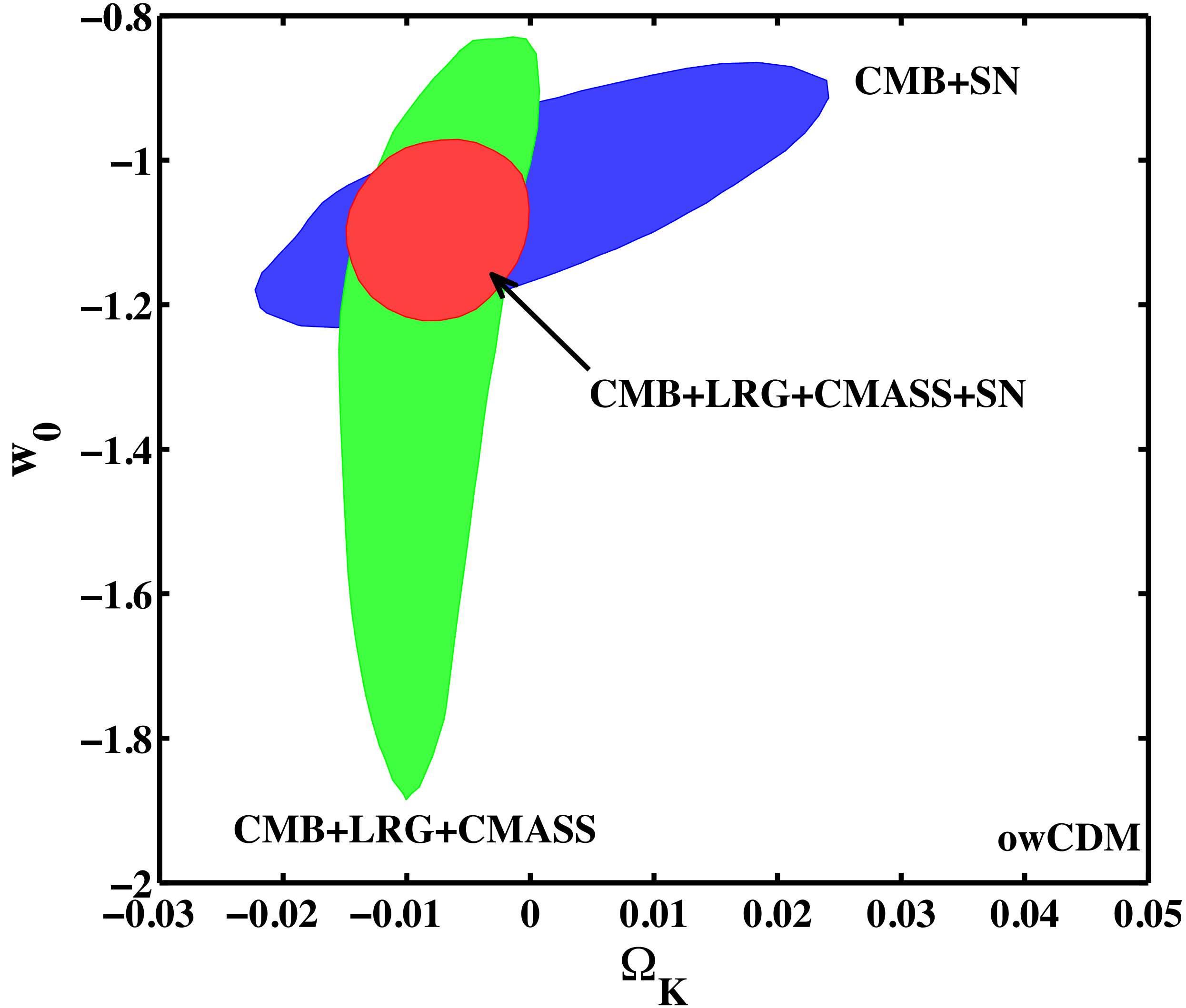
Measuring the eqn of state



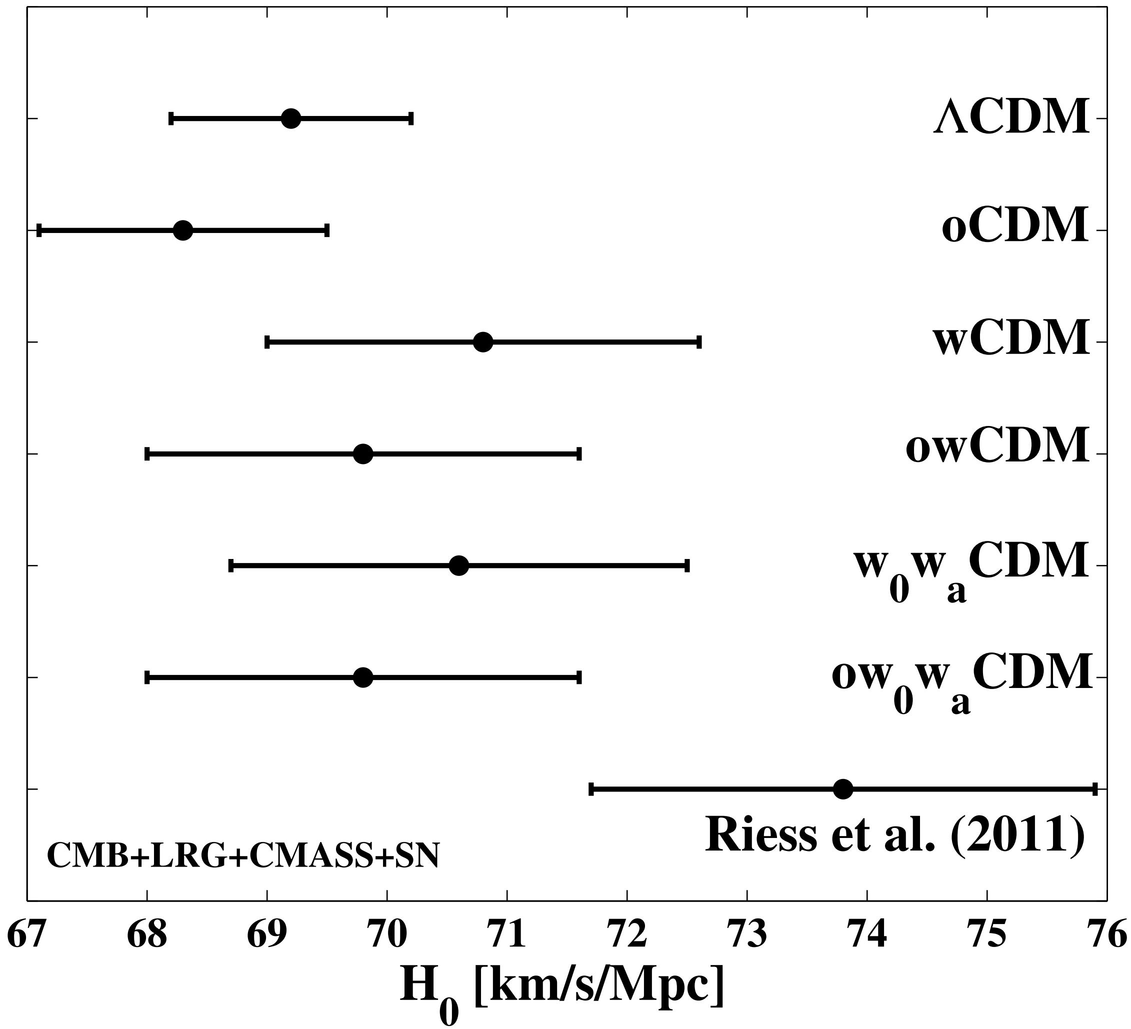
Comparing BAO to SN



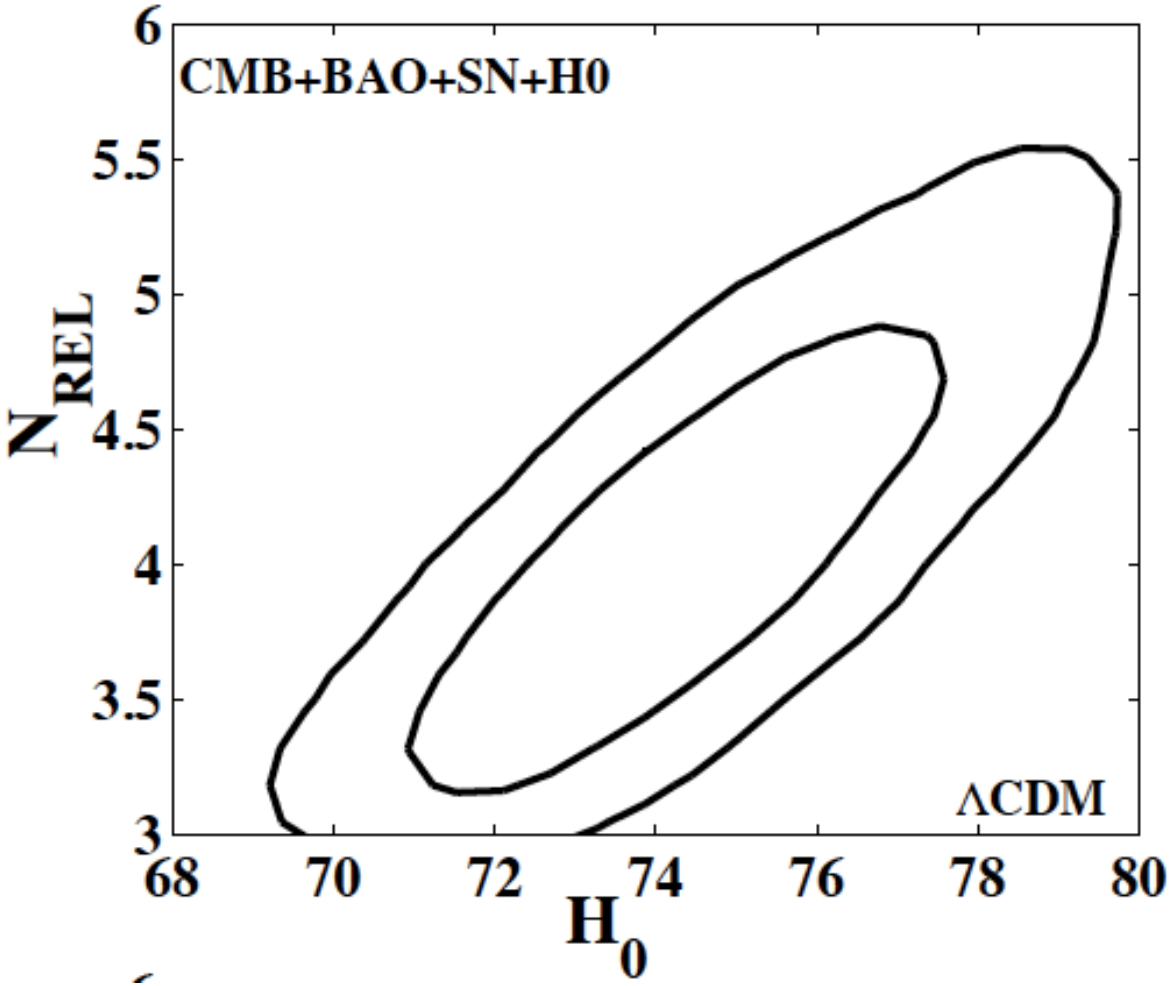
The complementarity of BAO and SN



Measuring the Hubble constant



Resolving this “discrepancy”

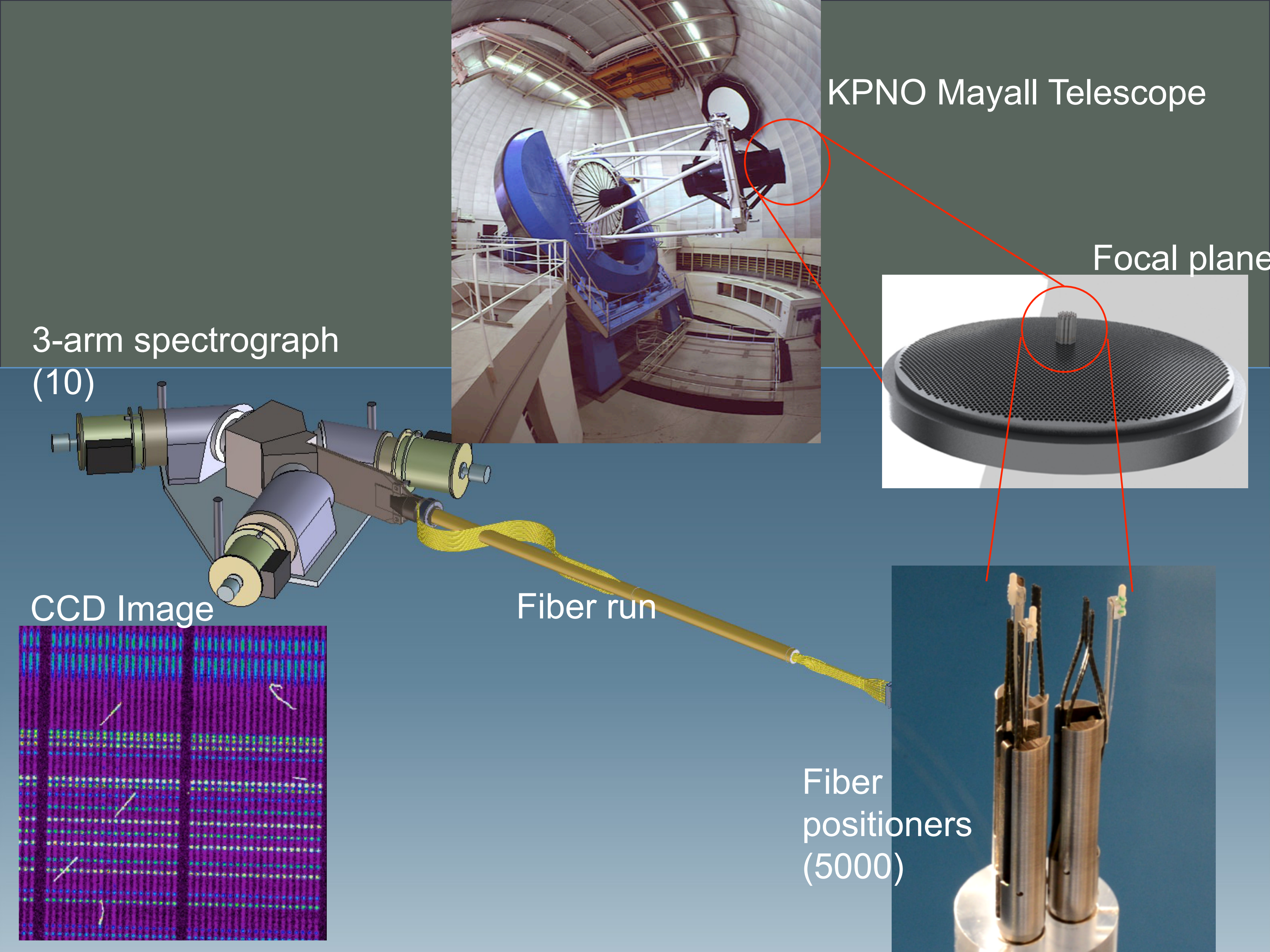


Outline

- Baryon Acoustic Oscillations, very quickly
- Recent Developments
  - How to build a better standard ruler?
  - First galaxy BAO results from BOSS
  - BigBOSS : BAO in the future

BAO Experiments : Past, Present and Future

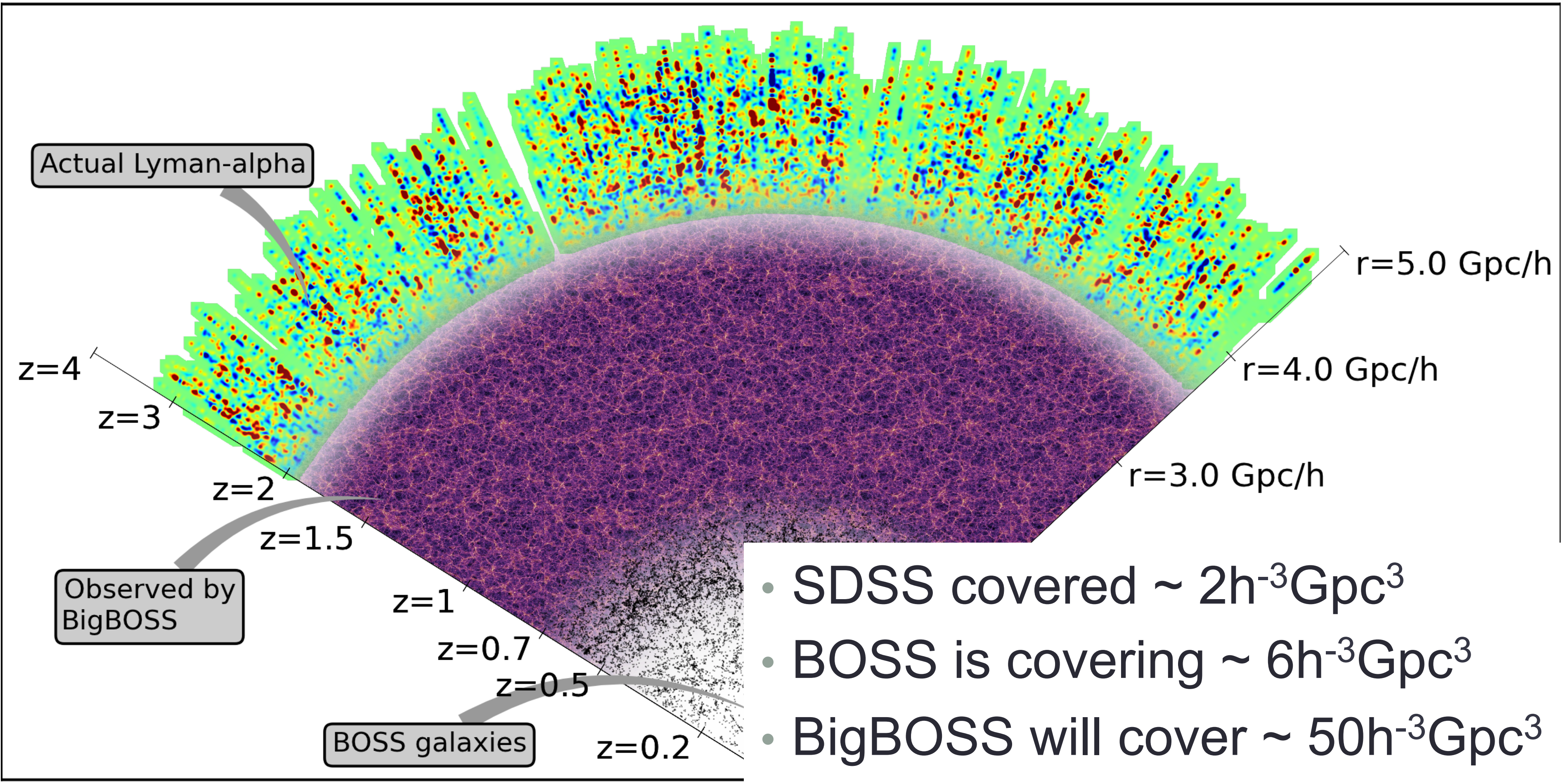
Survey	Redshift	Years	Precision
2dFGRS	0.2	Completed	detection
SDSS-I/II	**0.35**	**Completed**	**2%**
WiggleZ	0.7	Completed	4%
BOSS	**0.35, 0.55, 2.5**	**2009-2014**	**1.7% at z=0.55 today**
BOSS	0.35, 0.55, 2.5	2009-2014	1% (0.35, 0.55), 1.5% (2.5)
HETDEX	3.0	2013-2015	1%
eBOSS	1.0	2014-2018?	1%
BigBOSS	0.2-1.7	2017??	<1% in multiple bins
WFIRST	1.5 – 2.5?	??	<1% in multiple bins
Euclid	0.7 – 2.0	2020	<1% in multiple bins


KPNO Mayall Telescope
Focal plane
3-arm spectrograph (10)
CCD Image
Fiber run
Fiber positioners (5000)

BOSS v BigBOSS

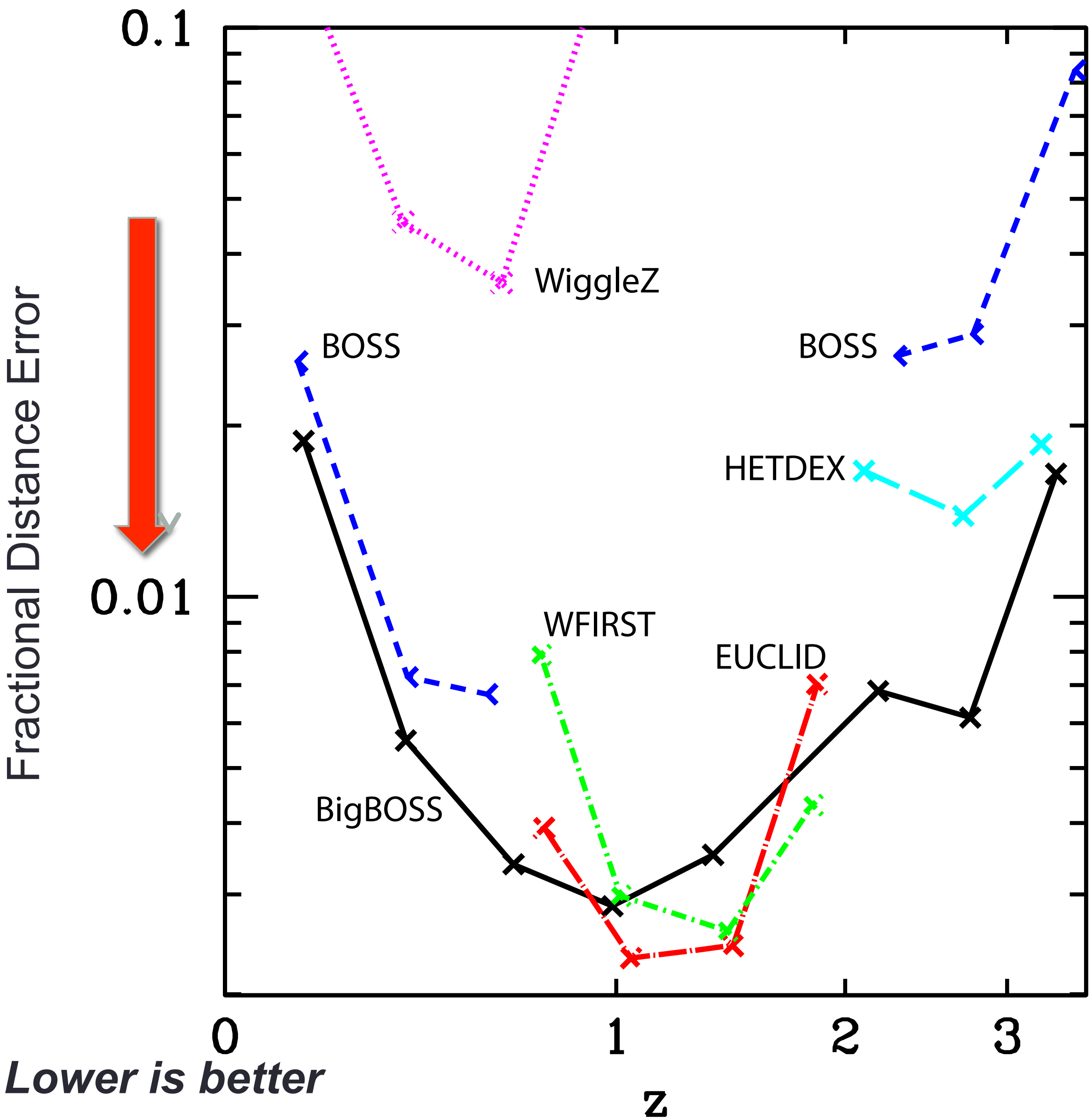
	BOSS	BigBOSS
Telescope	SDSS 2.5m	KPNO 4m
Number of simultaneous spectra	1000 (by hand)	5000 (by robot)
Survey duration	2009-2014	2017-2022
Total number of galaxies	1.5 million	20 million
Redshifts	$0.2 < z < 0.7$	$0.5 < z < 3.5$
Distance precision from galaxy BAO	~1% in 2 redshift bins	~1% in 35 bins
Figure of Merit	11	132

BigBOSS is BIG



- SDSS covered ~ $2h^{-3}Gpc^3$
- BOSS is covering ~ $6h^{-3}Gpc^3$
- BigBOSS will cover ~ $50h^{-3}Gpc^3$
- unprecedented volume

Distance constraints



Lower is better

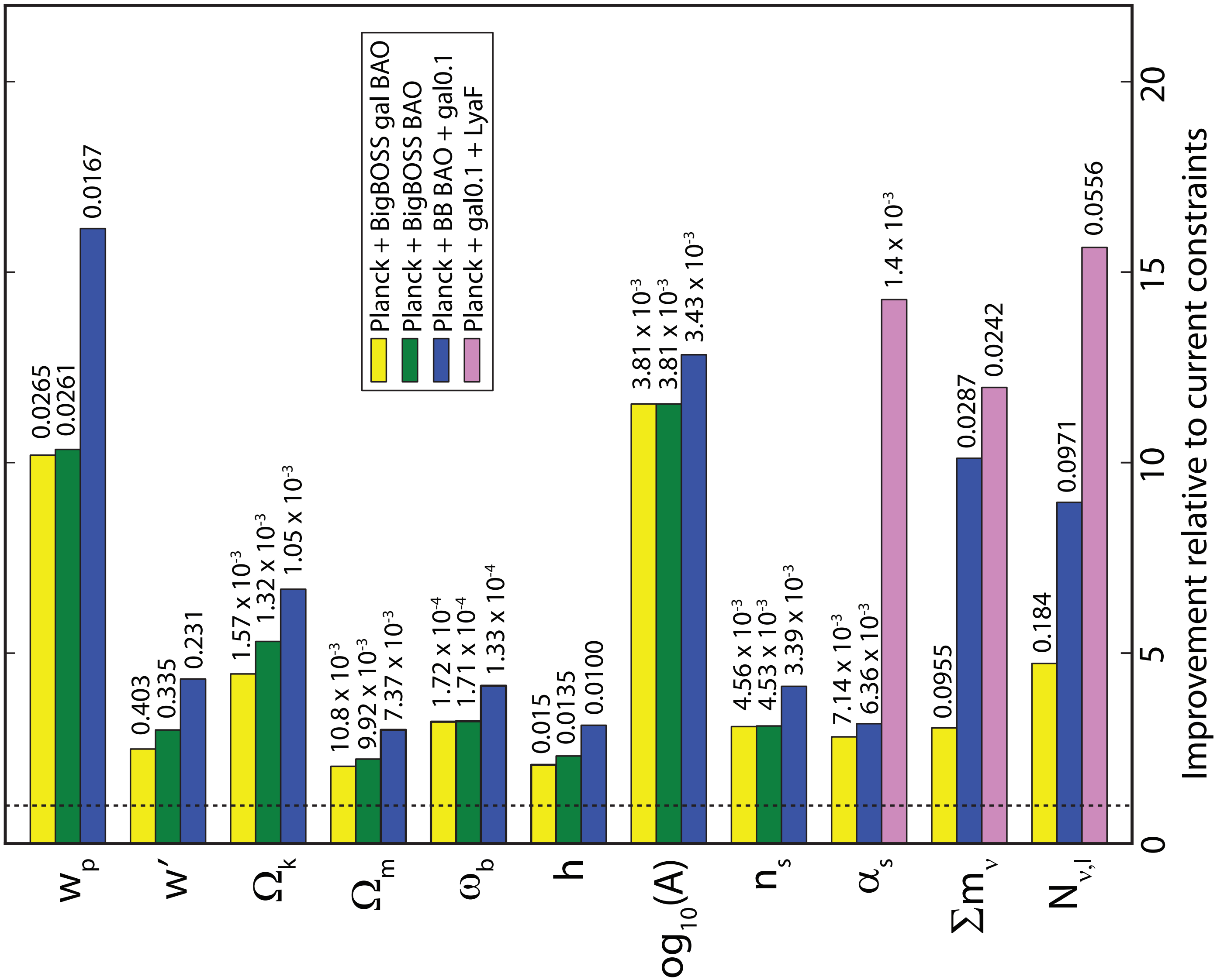
- BigBOSS has <1% distance errors over the widest redshift range
- Probe the expansion history over the widest redshift range

NASA WFIRST Science Definition Team

BigBOSS is competitive with space missions

	Figure of Merit
Today (* all probes *)	10
BOSS	11
BigBOSS	132
Space-based missions	126 (WFIRST), 145 (Euclid)

Beyond dark energy with BigBOSS



Results

- It's been a busy year
  - First results from B(aryon) O(scillation) S(spectroscopic) S(urvey)
    - Galaxy BAO results at z=0.55
    - Lyman-alpha forest measurements at z=2.5
    - This talk will focus on the first.
  - Improvements in analysis techniques
  - Towards precision measurements
  - Lots of results expected over the next years