A 2% Measurement of the BAO in SDSS DR7 using Reconstruction

Berkeley Cosmology Group Seminar

Tuesday October 25, 2011

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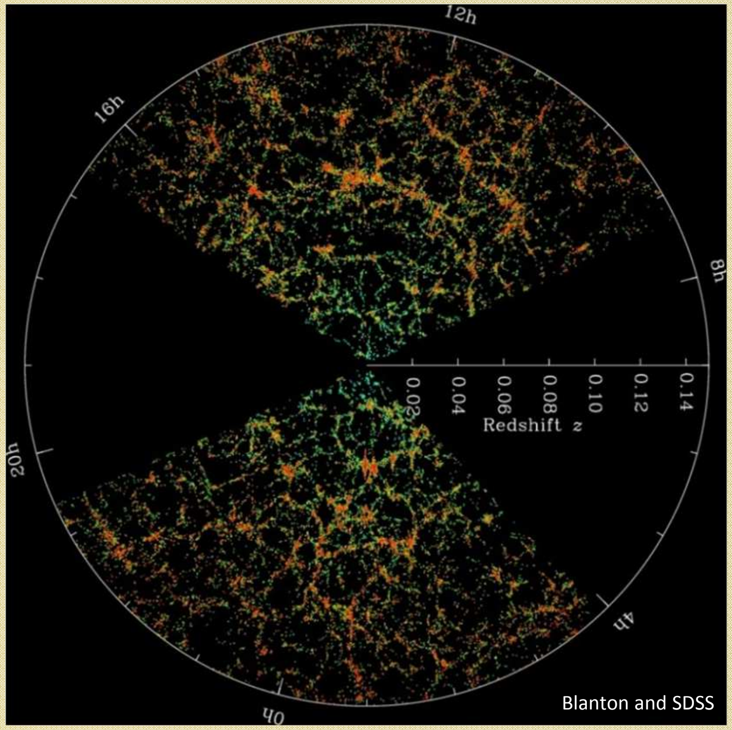

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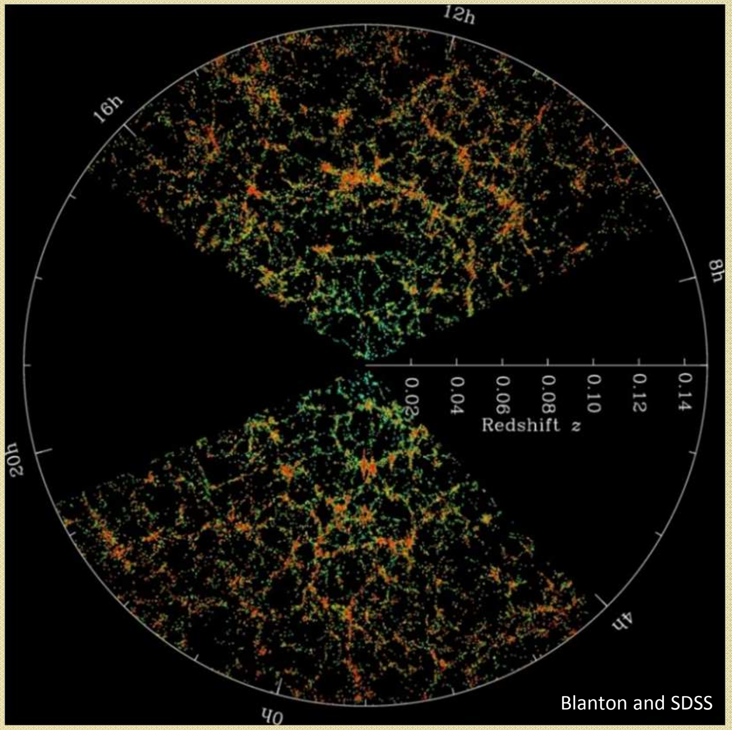
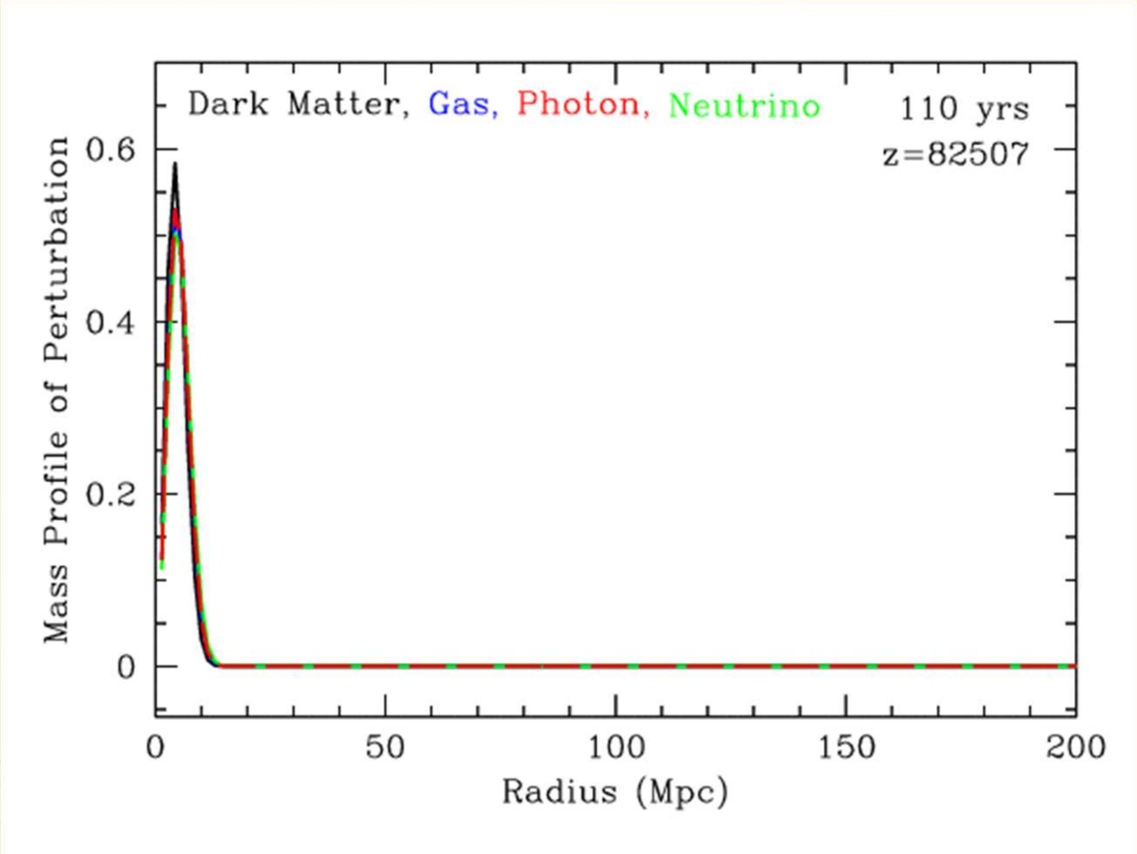


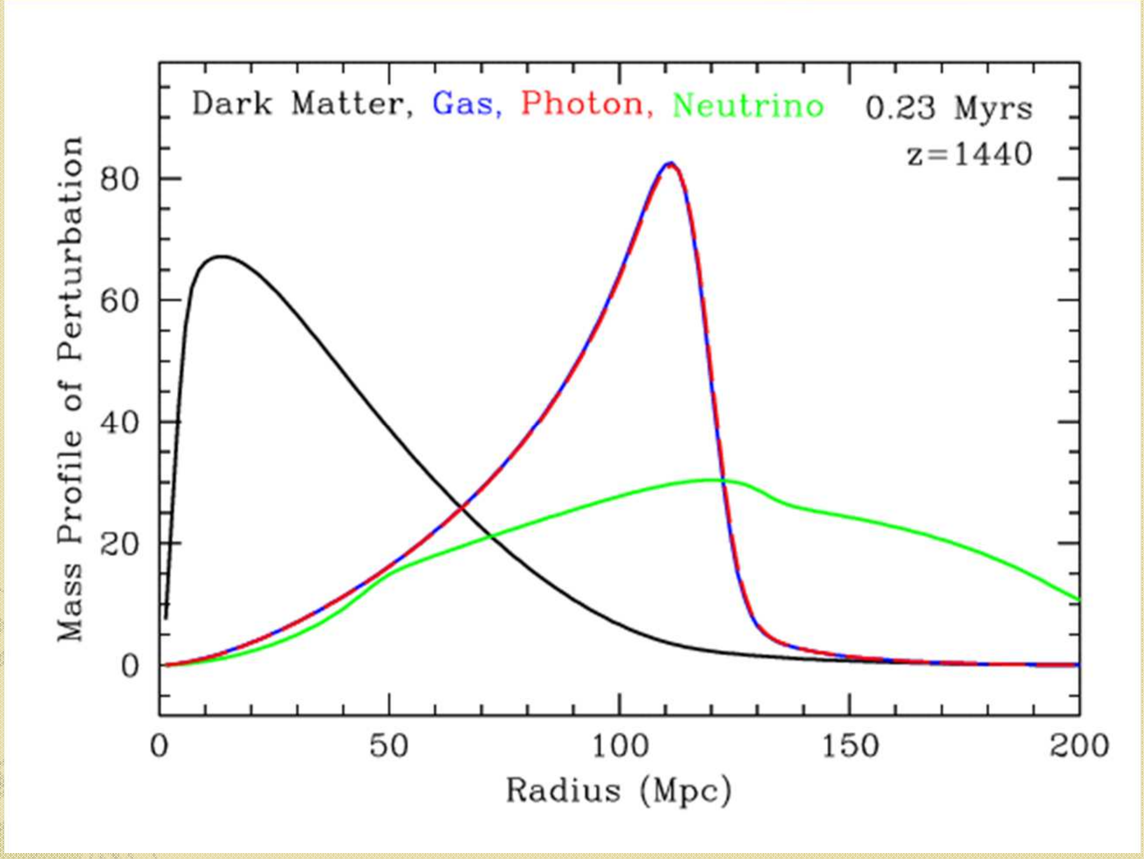
What are BAOs?



We start with a tiny overdensity in the primordial universe…

http://cmb.as.arizona.edu/~eisenste/acousticpeak/acoustic_physics.html

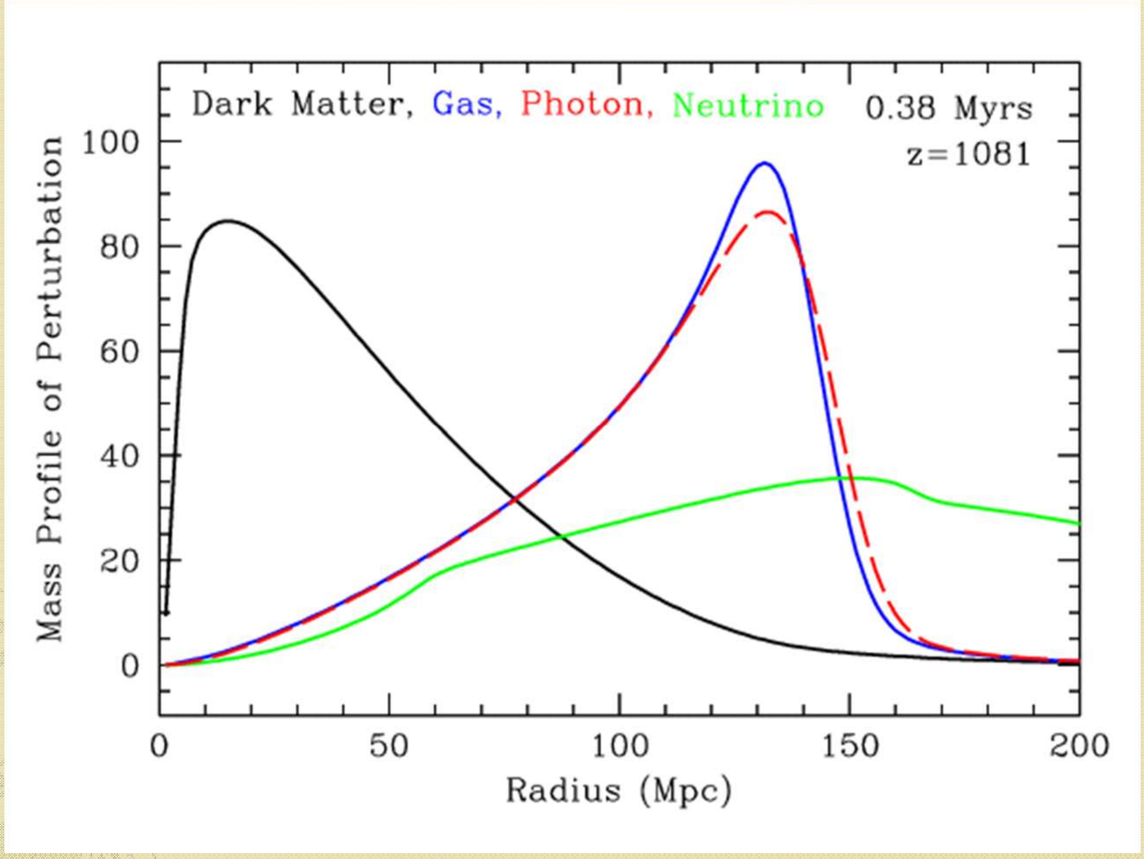
What are BAOs? (cont'd)



Photons and baryons push out in a spherical sound wave.

Dark matter tries to pull material back in.

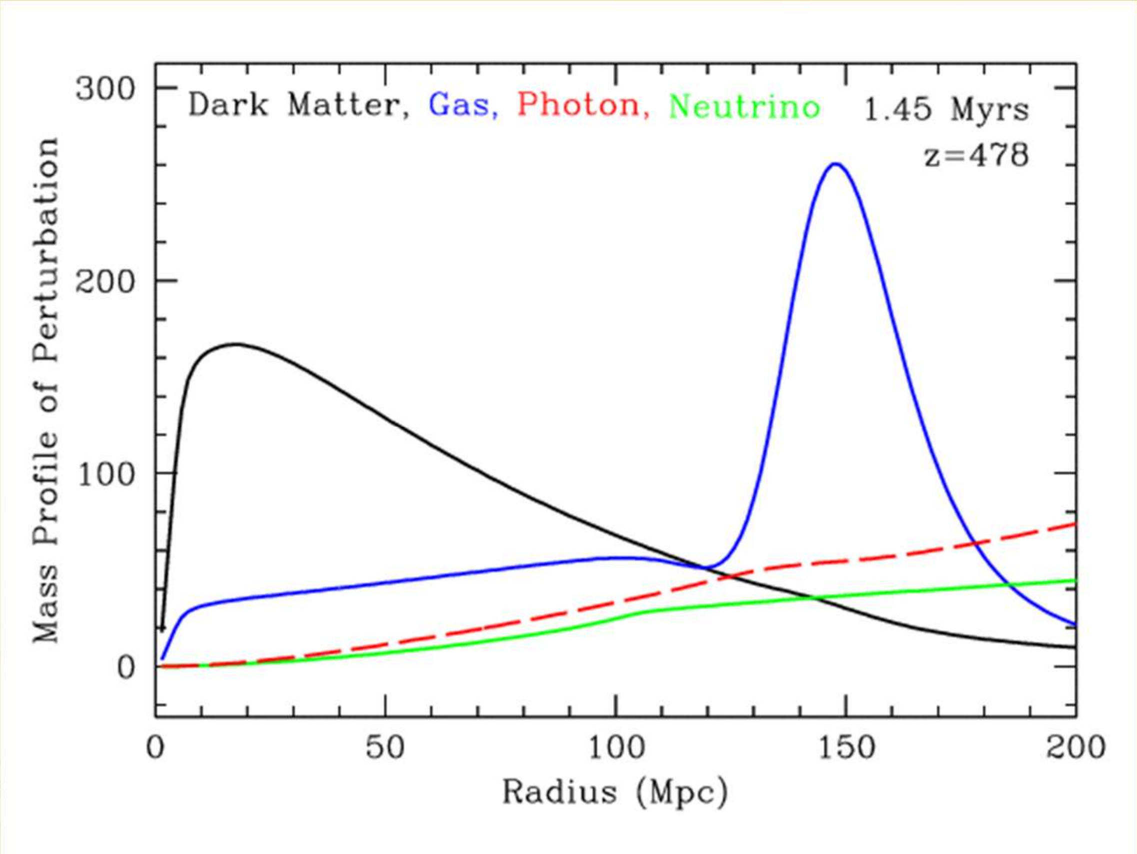
What are BAOs? (con’td)



Standing waves form in the fluid.

At recombination, their phases are imprinted on the photon and baryon distributions; these are the **baryon acoustic oscillations**.

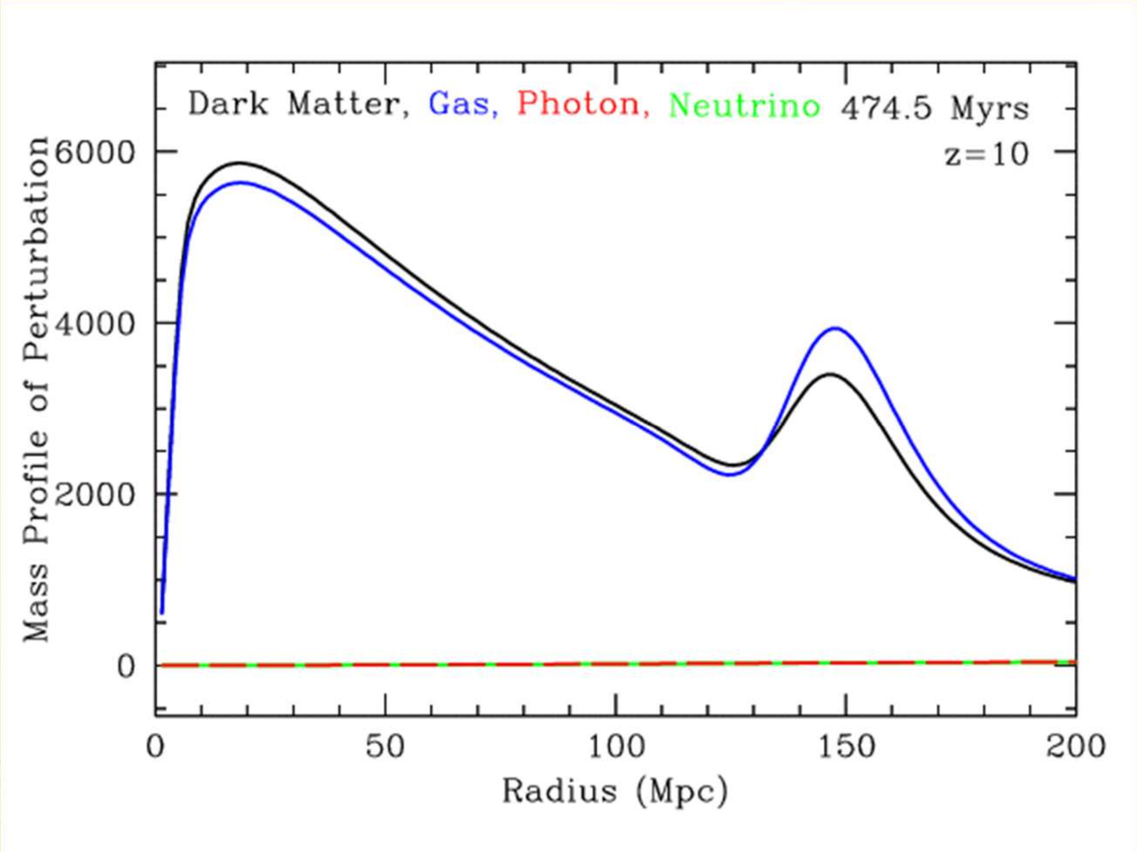
What are BAOs? (cont'd)



Before recombination, photon-baryon fluid travelled 150 comoving Mpc.

Baryons deposited at this distance.

What are BAOs? (cont'd)



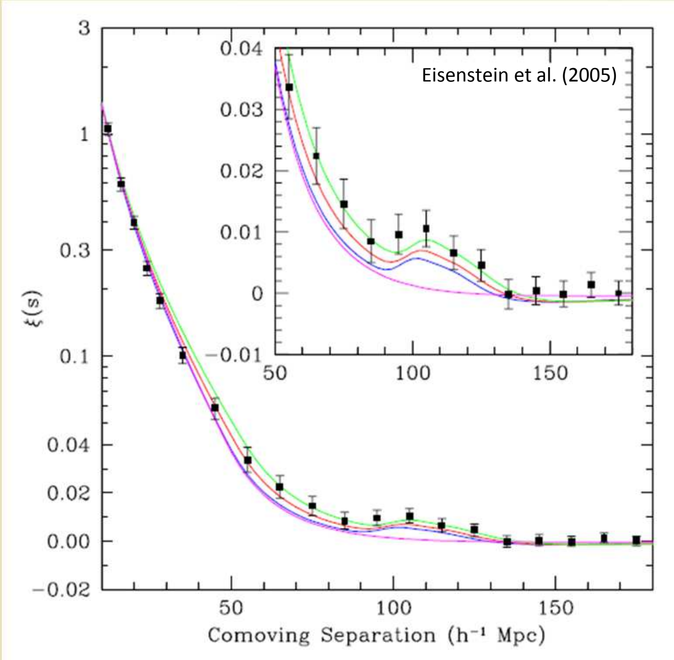
Gravity equilibrates distributions of dark matter and baryons.

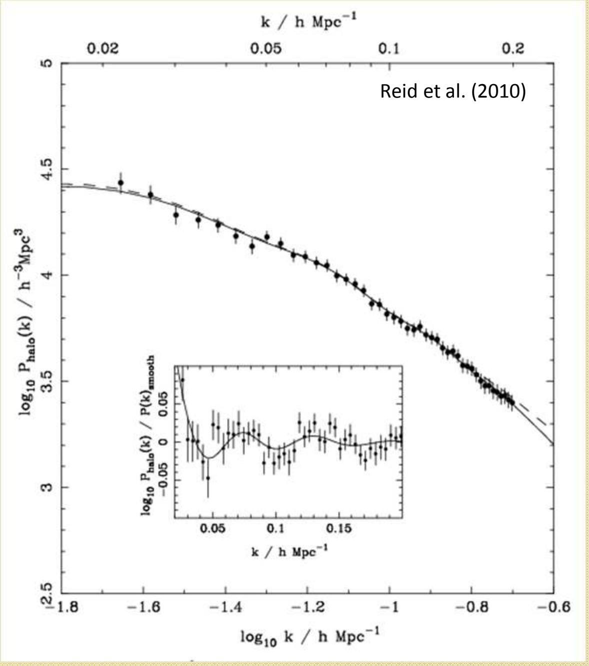
A tiny excess is left at 150 Mpc; this is known as the **acoustic peak**.

The Acoustic Peak

- The 150Mpc scale marked by the location of the acoustic peak is known as the **acoustic scale** or sound horizon.
- The magnitude of this scale in linear theory is only affected by two factors: 1) the time of matter-radiation equality (set by $\Omega_m h^2$), 2) the value of $\Omega_b h^2$. Both of these can be measured to sufficient accuracy from CMB data.
- WMAP5 has measured the acoustic scale to 1.3% accuracy.
- Hence, it can be used as a **standard ruler** for measuring cosmological distances which can then be used to constrain various cosmological parameters.

Clustering Statistics

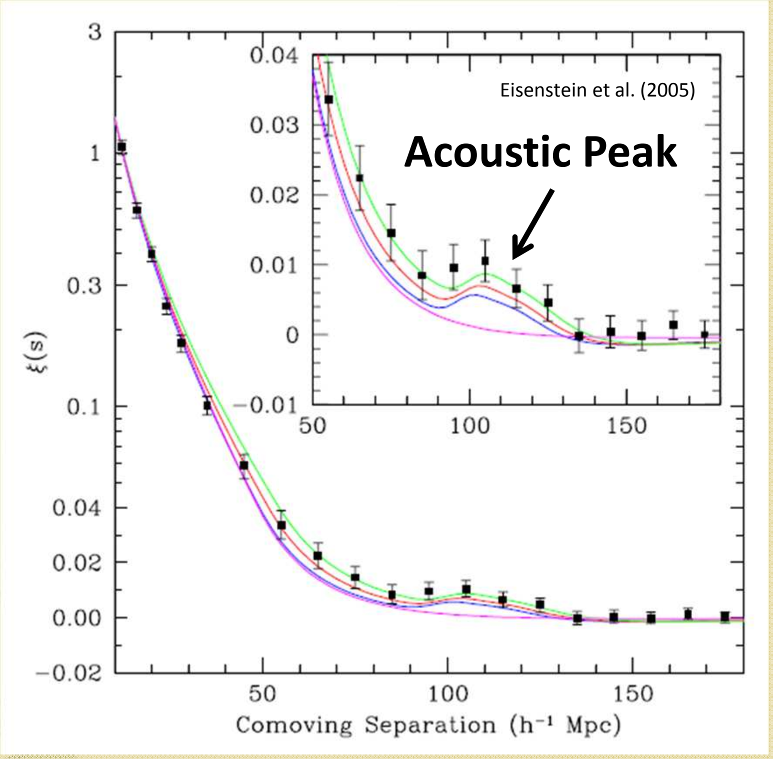




Correlation function ξ(r)

Power spectrum P(k)

The Correlation Function



- ξ(r) = excess probability over a random distribution of finding two galaxies with a separation *r*.
- ξ(r) has a small peak at separations corresponding to the acoustic scale.
- To measure acoustic scale, fit model for ξ(r) to data.

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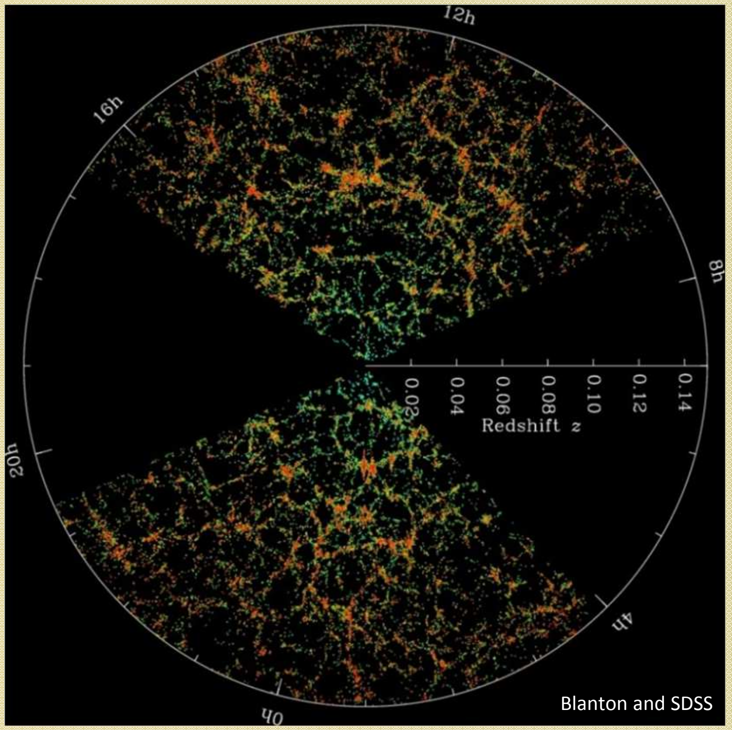
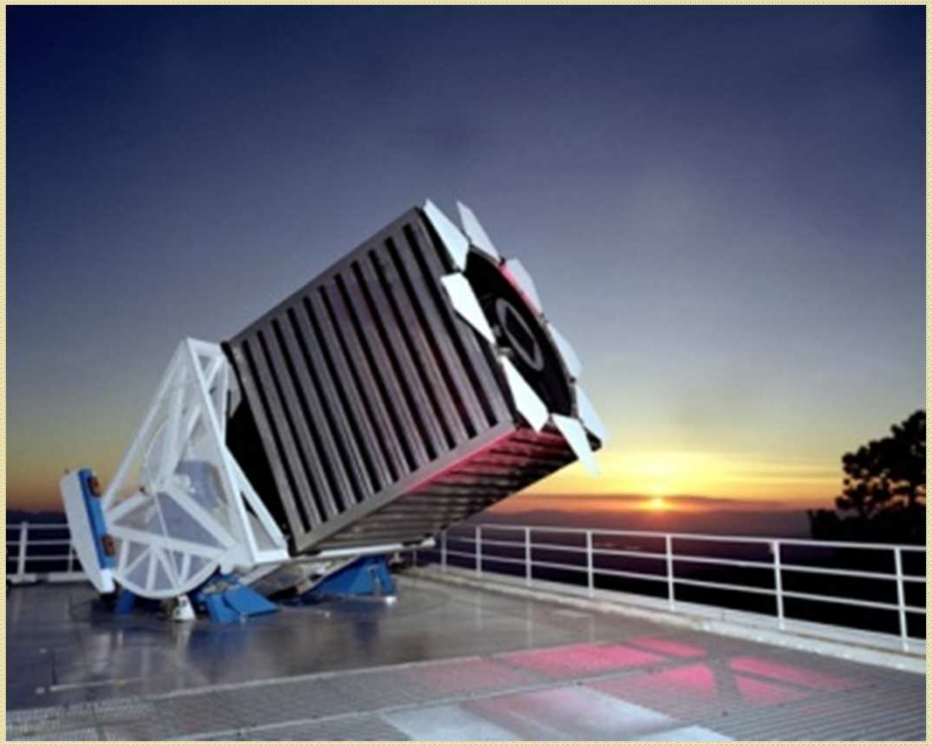


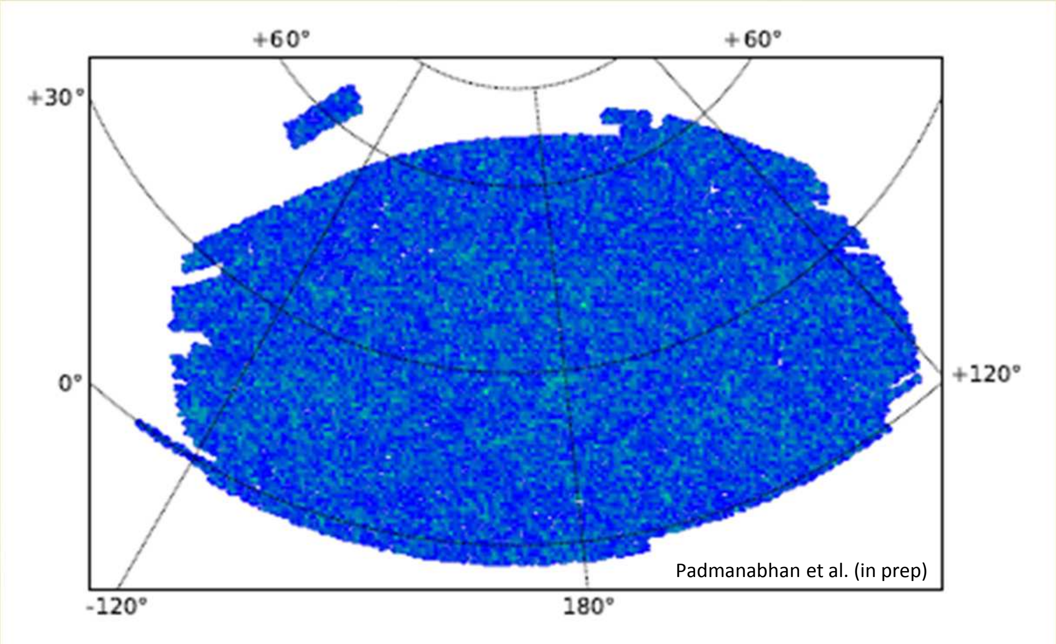
Blanton and SDSS

SDSS Survey

- Currently, one of the largest galaxy surveys in operation.
- Dedicated 2.5m telescope.
- SDSS II used a pair of spectrographs that could observe more than 600 objects simultaneously.



Luminous Red Galaxy Sample



Sky coverage: 7124 square degrees

The DR7 luminous red galaxy (LRG) sample:

- Redshift range: z=0.16-0.47 (1.4Gpc^3/h^3).
- Number density: approximately 20 objects per square degree.

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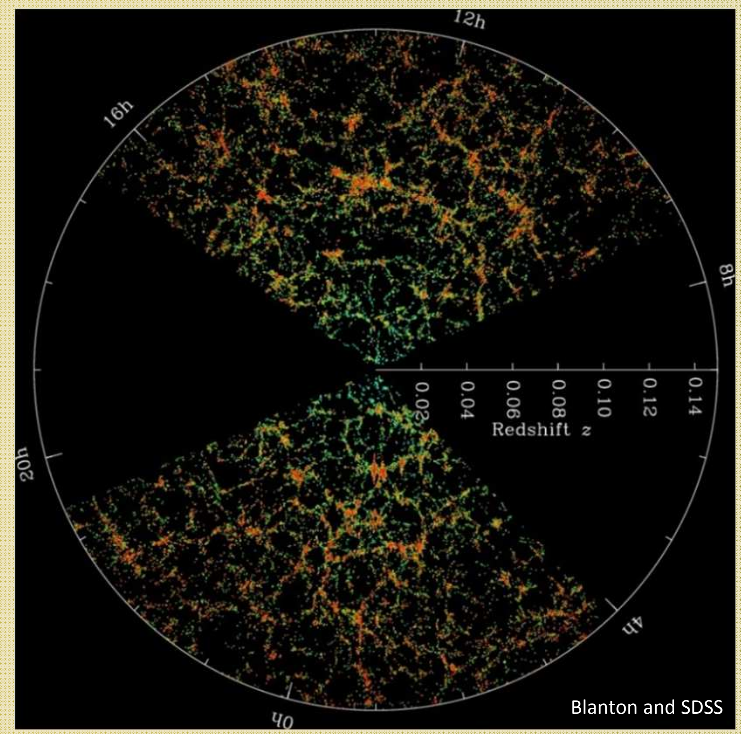
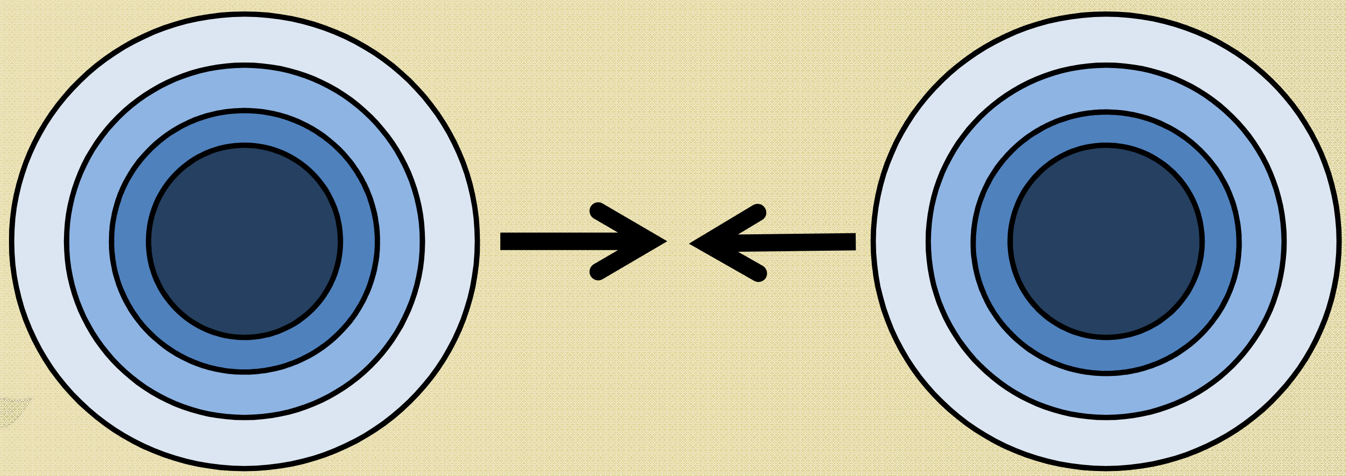
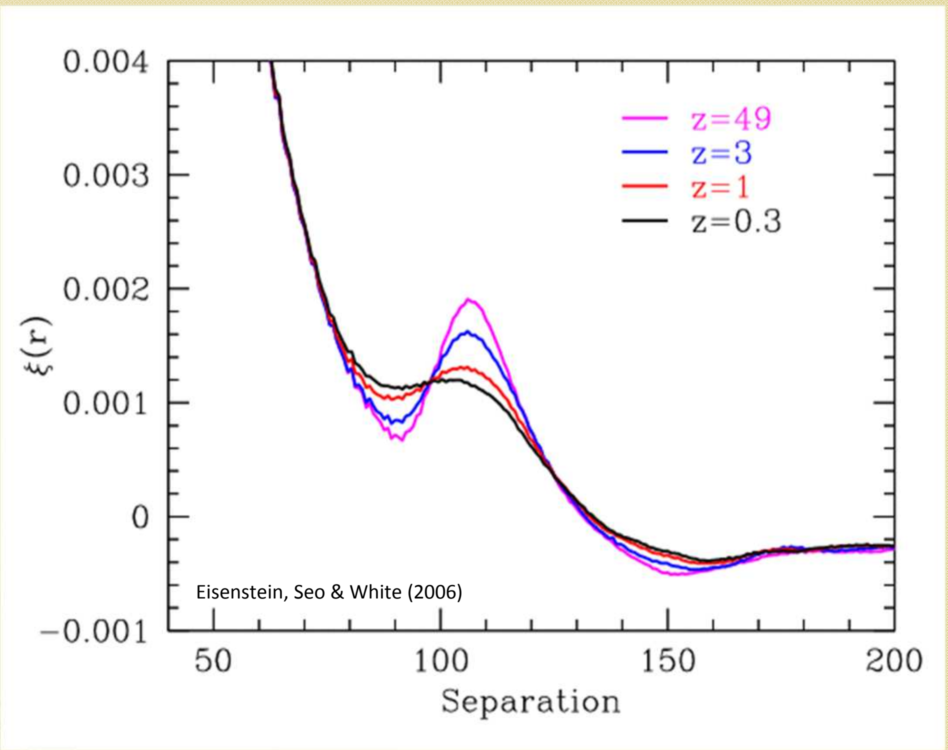


Non-linear Evolution



Non-linear Evolution (cont'd)

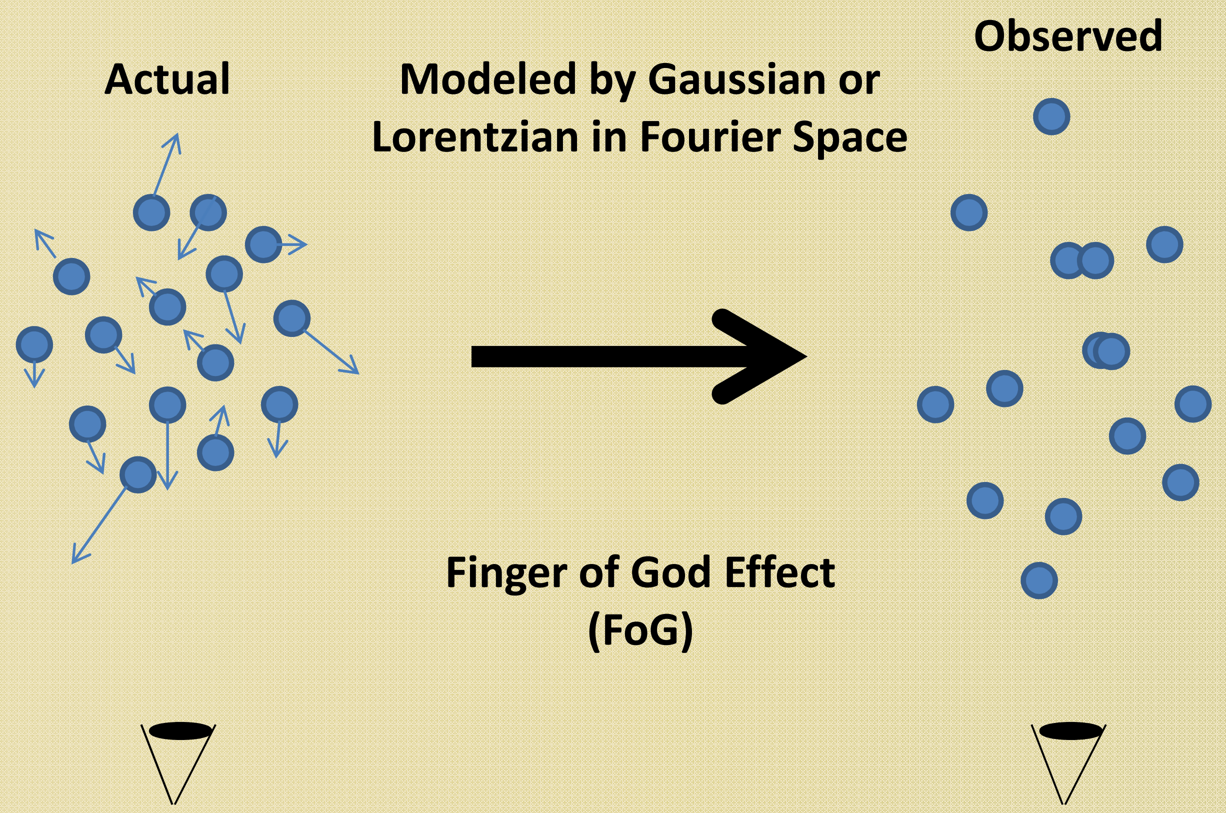


- Non-linear growth:
  - Smears the BAO.
  - Shifts the BAO.
- These make it harder to measure the acoustic scale.
- **Reconstruction** can partially undo these effects.

Redshift Space Distortions

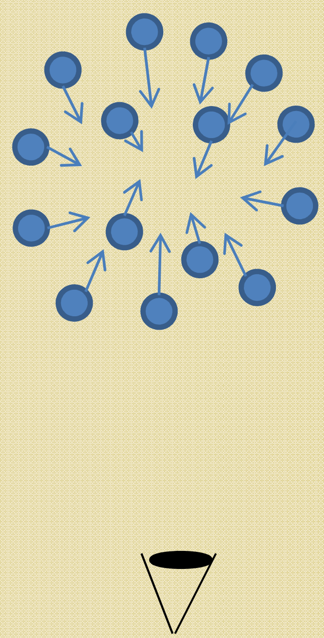
- We use redshifts to measure the positions of galaxies along the line-of-sight.
- The measured redshifts are affected by the motions of the galaxies.
- Hence, the measured redshift of any galaxy is the combination of cosmological redshift and an additional component due to the galaxy's line-of-sight velocity.
- This "extra" redshift gives rise to redshift space distortions which make the clustering of galaxies appear anisotropic.

Distortions (cont'd)



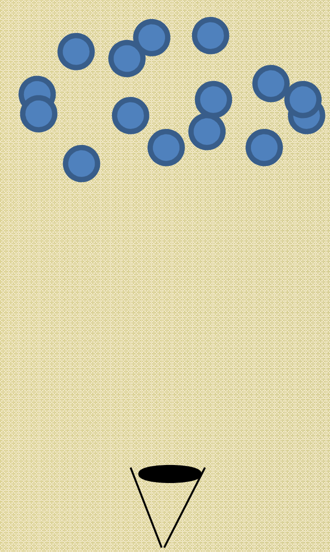
Distortions (cont'd)

Actual



Modeled by $(1+f\mu^2/b)^2$ in Fourier Space

Observed



Coherent Infall (Kaiser Effect)

Scale Dependent Bias

- We use galaxies as tracers of the underlying distribution of dark matter.
- However, galaxies only form in the most massive halos, so they are biased tracers.
- This bias is apparent as an offset between the matter correlation function and the galaxy correlation function.
- At large r, this offset is roughly constant; at small r, it has a scale dependence due to non-linear evolution.
- This scale dependence can be marginalized out from data using an appropriate fitting model.

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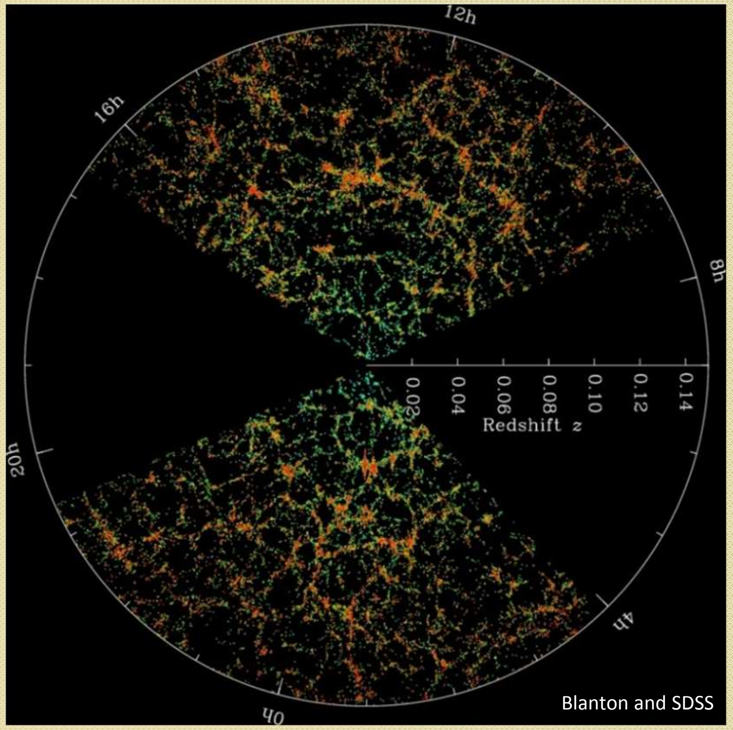


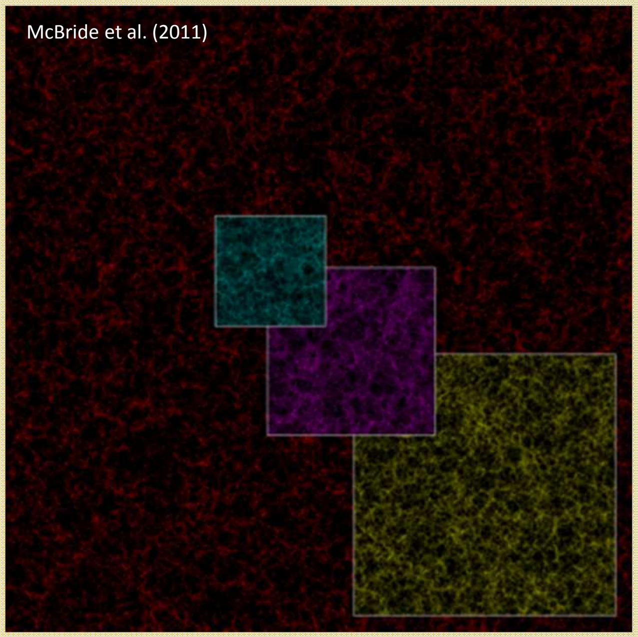
Blanton and SDSS

Tool Inventory

- **Reconstruction**:
  - Deals with non-linear structure growth.
- **Covariance matrix**:
  - Approximates errors on the correlation function when we perform our fits.
- **Fitting model and algorithm**:
  - Deals with other uncertainties.
  - Measures the acoustic scale.
- These require **mock catalogues** to:
  - Validate fitting model and reconstruction technique.
  - Serve as a basis for our covariance matrix algorithm.

LasDamas Mocks

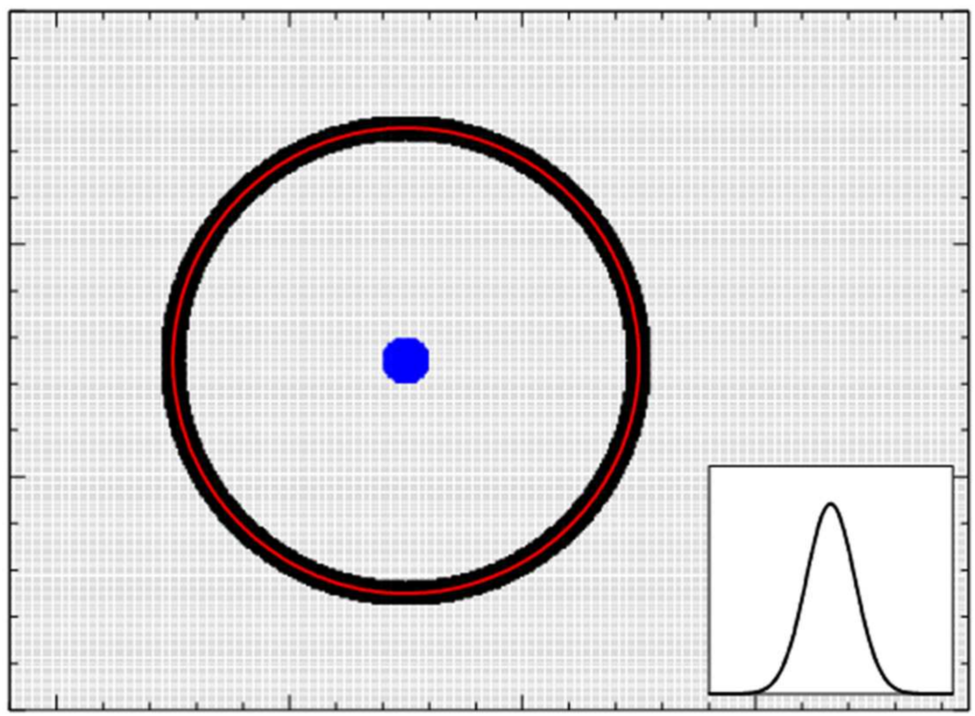
- Simulation cosmology (at z = 0): $\Omega_m = 0.25$, $\Omega_b = 0.04$, $h = 0.7$, $n_s = 1.0$, $\sigma_8 = 0.8$
- 40 simulations of 1280^3 particles in 2.4Gpc/h boxes
- Simulation halos populated according to LRG parameters =>160 mocks generated.



Reconstruction

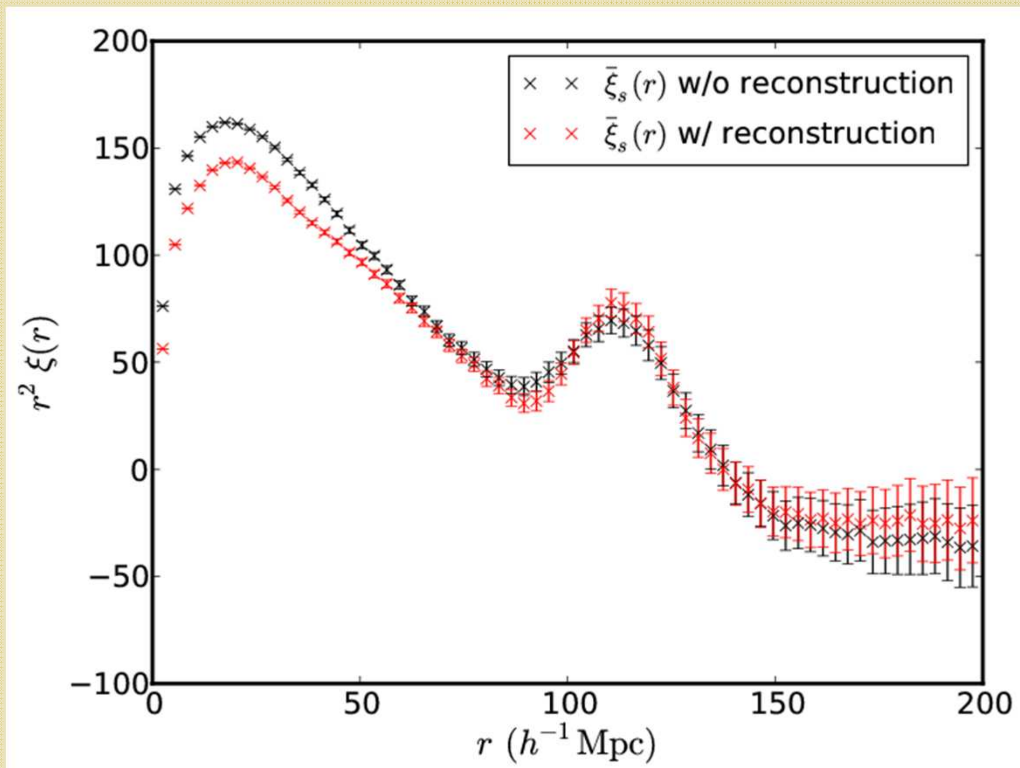
- Non-linear structure growth smears the BAO peak and reduces its amplitude.
- Apply reconstruction to partially undo these effects.
- To apply reconstruction:
  - Estimate the matter density field from observations.
  - Use Zel'dovich approximation to calculate 1^{st} order displacement field using this density field.
  - Shift galaxies back along these displacement vectors, this should place them back near their linear theory positions.

Reconstruction (cont'd)

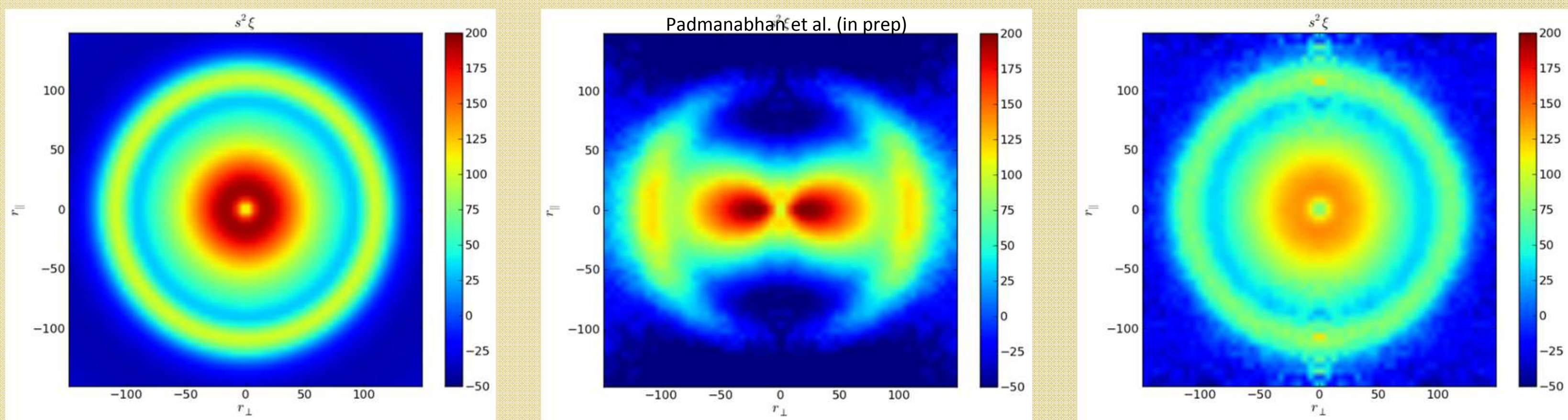


Courtesy D. Eisenstein

Reconstruction on LD

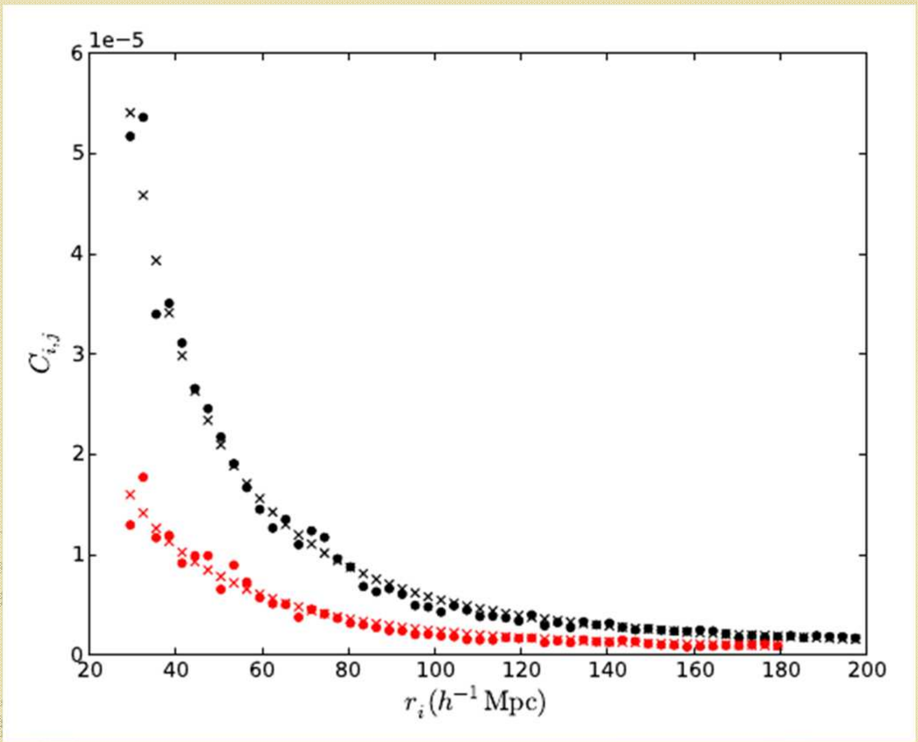


Reconstruction on LD $\xi(r_p,\pi)$



Linear Theory (Real space)	Mocks without reconstruction	Mocks with reconstruction

Covariance Matrices



- The covariance matrix calculated from the mocks is noisy, despite having 160 realizations.
- In a well-measured covariance matrix, these curves should be smooth.

Covariance Matrices (cont'd)

- Analytic Gaussian covariance matrix:

$$C_{ij} = \frac{2}{V} \int j_0(kr_i) j_0(kr_j) \left(P(k) + \frac{1}{n} \right)^2 \frac{k^2 dk}{2\pi^2}$$

$$P(k) = \frac{1}{2} \int_{-1}^{1} \underbrace{\left(1 + \frac{f}{b} \mu^2 \right)^2}_{\text{Kaiser}} \underbrace{F(\mu, k)}_{\text{FoG}} P_m(k) d\mu$$

$$P_m(k) = \left(P_{lin}(k) - Pn_w(k) \right) \underbrace{\exp\left(-\frac{k^2 {\Sigma_{nl}}^2}{2} \right)}_{\text{Acoustic Peak Smearing due to Non-linear Evolution}} + Pn_w(k)$$

Covariance Matrices (cont'd)

- Analytic Gaussian covariance matrix:

$$C_{ij} = \frac{2}{V} \int j_0(kr_i) j_0(kr_j) \left(P(k) + \frac{1}{n} \right)^2 \frac{k^2 dk}{2\pi^2}$$

c_0 c_1 $+ c_2$

- Modified Gaussian covariance matrix:

$$C_{ij} = \frac{2}{V} \int j_0(kr_i) j_0(kr_j) \left(c_0 P(k) + c_1 \frac{1}{n} \right)^2 \frac{k^2 dk}{2\pi^2} + c_2$$

- Modified Gaussian covariance matrix is smooth and fits mock covariances well => use it to fit the data.

Fitting Form

- To measure the BAO scale, we fit using the model:

$$\xi_{fit}(r) = B^2\, \xi_{m}(\alpha r) + A(r)$$

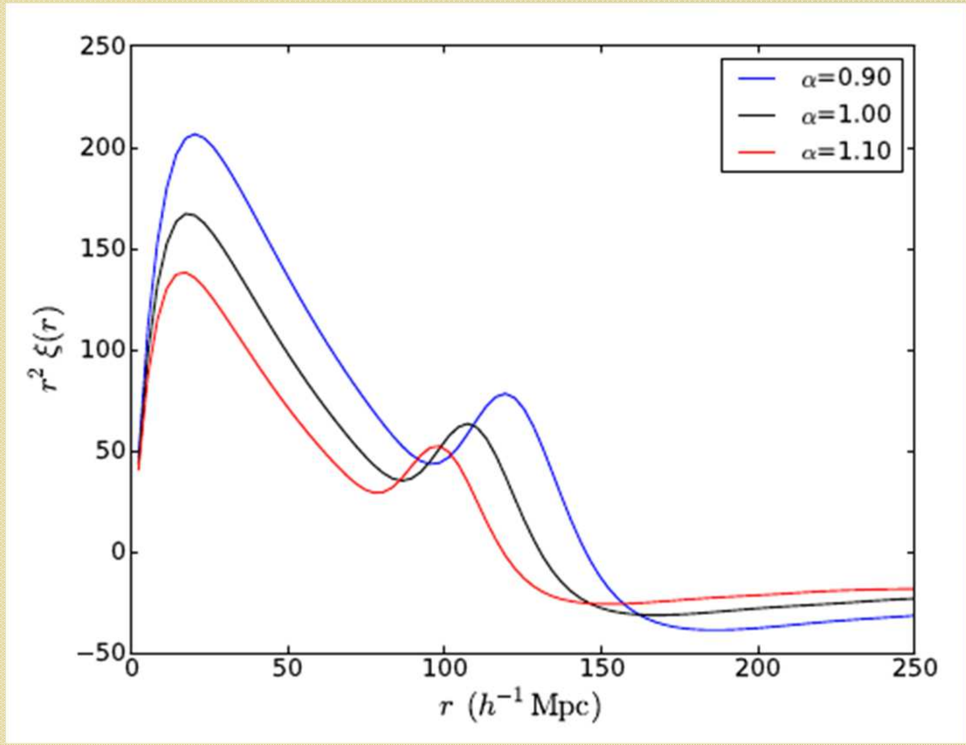
- Model acoustic peak smearing by applying a Gaussian smoothing to the power spectrum in Fourier space:

$$P_{m}(k) = [P_{lin}(k) - Pn_{w}(k)] \exp\left(-\frac{k^2 {\Sigma_{nl}}^2}{2}\right) + Pn_{w}(k)$$

- $A(r)$ is used to marginalize out broadband effects such as scale-dependent bias and redshift space distortions, it can also account for errors in the model cosmology.

Fitting Form (cont'd)

- We use α to parameterize the BAO scale.
- α>1 implies the BAO is shifted to smaller scales.
- α<1 implies the BAO is shifted to larger scales.



Fitting

- Minimize χ^2 goodness of fit indicator to determine the α that gives the best-fit model:

  $$\chi^2(\alpha) = [\xi_{fit}(r;\alpha) - \xi_{data}(r)]^T C^{-1} [\xi_{fit}(r;\alpha) - \xi_{data}(r)]$$

- Can also measure the probability distribution of α, $\Pr(\alpha)$ as:

  $$\Pr(\alpha) \propto \exp\left(-\frac{\chi^2(\alpha)}{2}\right)$$

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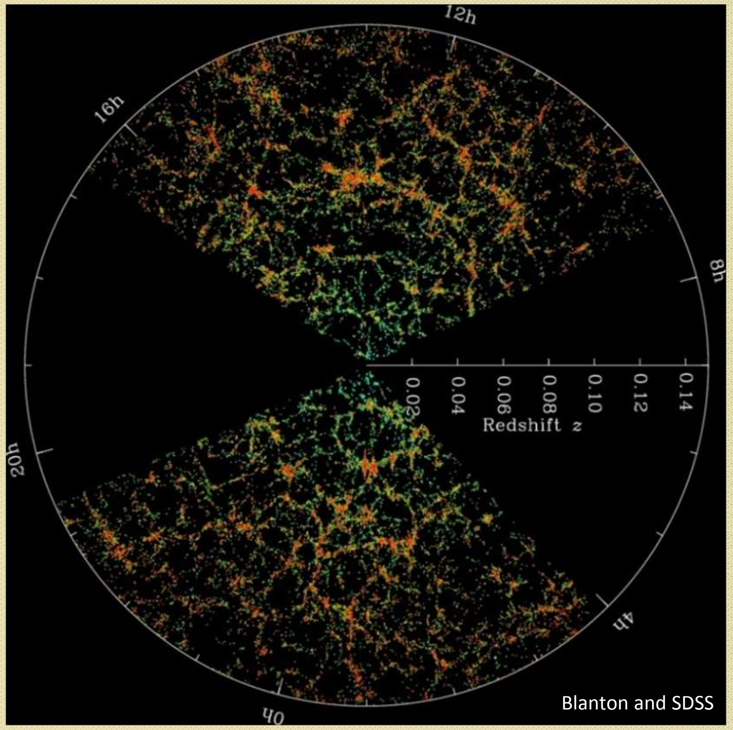


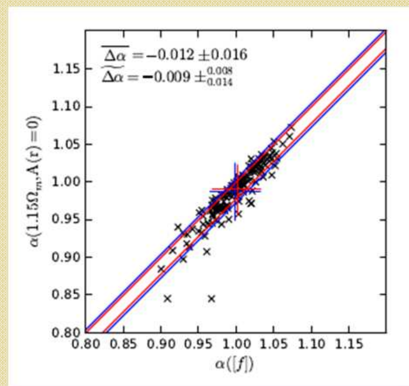
Fiducial Model

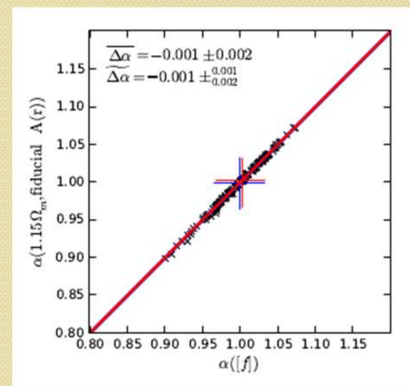
$$\xi_{fit}(r) = B^2\, \xi_m(\alpha r) + A(r)$$

- Model parameters:
  - True LasDamas cosmology.
  - $A(r) = \frac{a_1}{r^2} + \frac{a_2}{r} + a_3.$
  - BAO smoothing scale (Σ_{nl}) = 8Mpc/h before reconstruction, 4Mpc/h after reconstruction.
  - Fitting range of 30-200Mpc.
- Need to make sure that if we change any of the above parameters, we still obtain consistent measures of α.

Robust Fitting of the BAO Scale

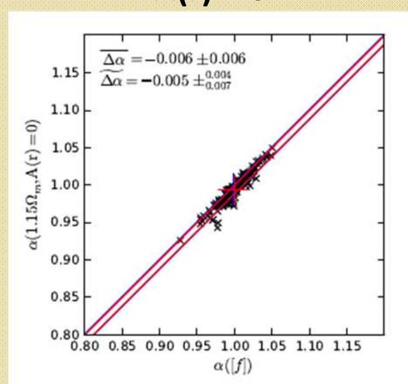
Before Reconstruction

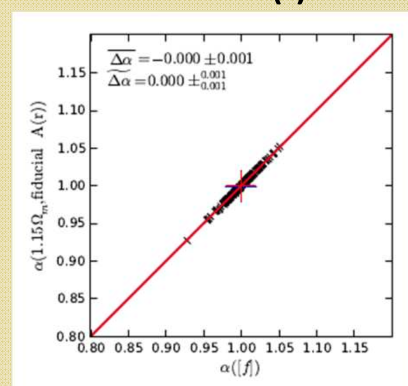




A(r) = 0 **Fiducial A(r)**

After Reconstruction

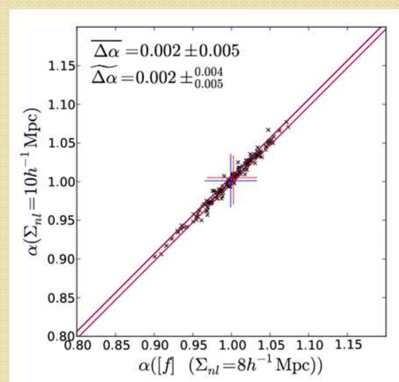


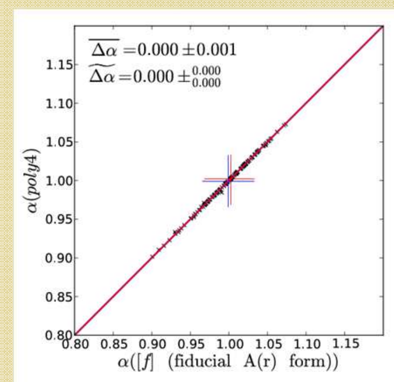


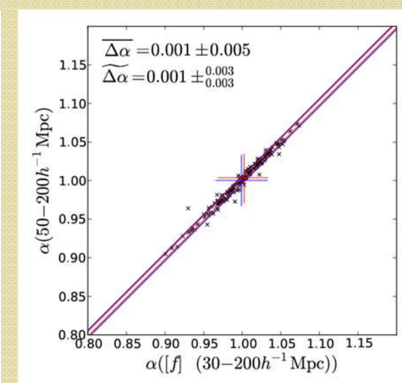
α measured using the Fiducial Model versus α measured using a cosmology with 15% larger Ω_m than LasDamas

Robust Fitting (cont'd)

Before Reconstruction

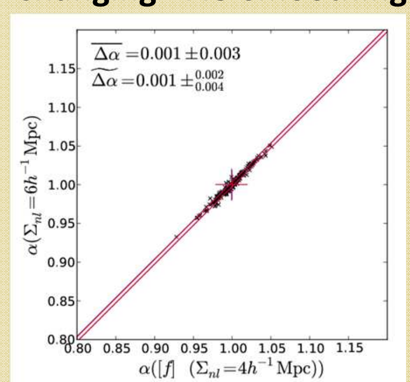


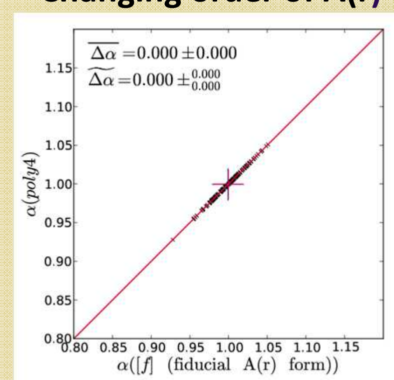


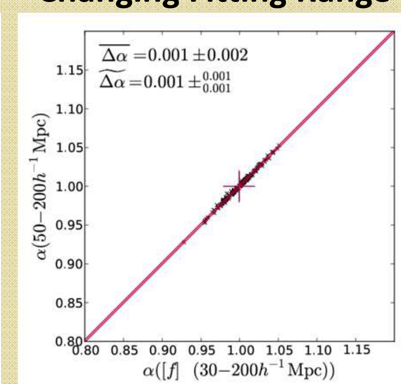


Changing BAO smoothing | **Changing order of A(r)** | **Changing Fitting Range**

After Reconstruction







LasDamas Results

- Before reconstruction:
  - Mean $\alpha = 0.999 \pm 0.033$
  - Median $\alpha = 1.003 \pm^{0.030}_{0.034}$
- After reconstruction:
  - Mean $\alpha = 0.999 \pm 0.020$
  - Median $\alpha = 1.000 \pm^{0.019}_{0.020}$
- Error on acoustic scale decreases from 3.3% to 2.0%, equivalent to increasing the survey volume by a factor of 2.7 ($V \propto \sigma^{-2}$)!

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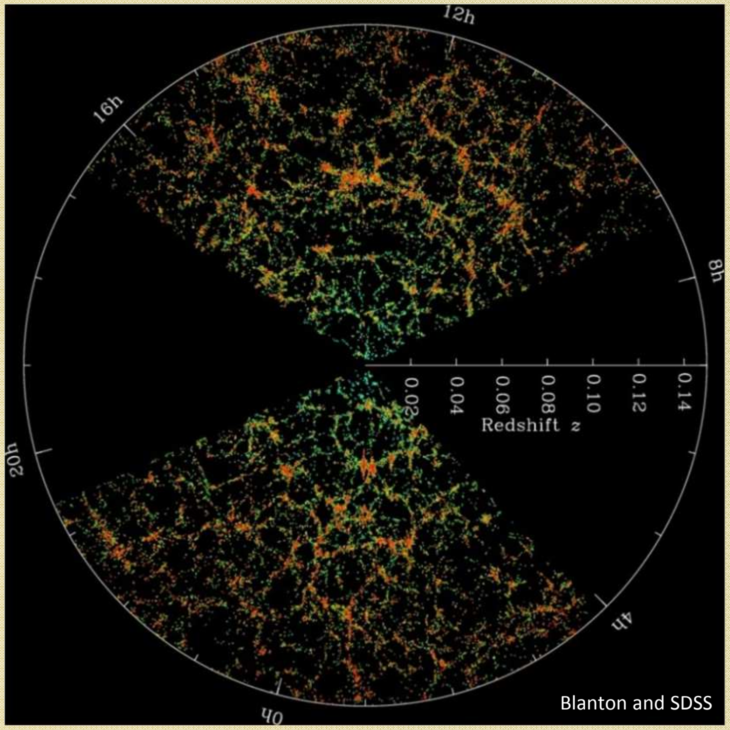
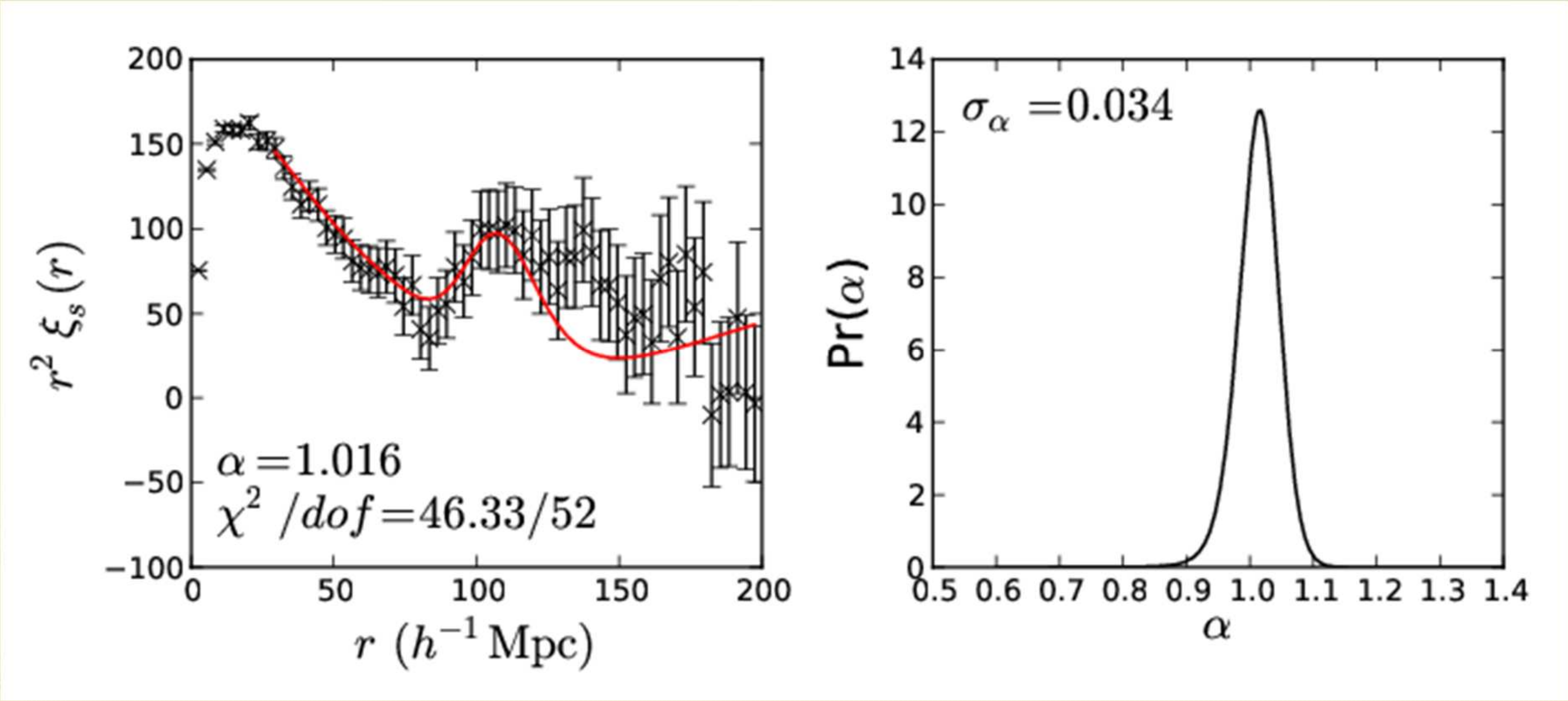
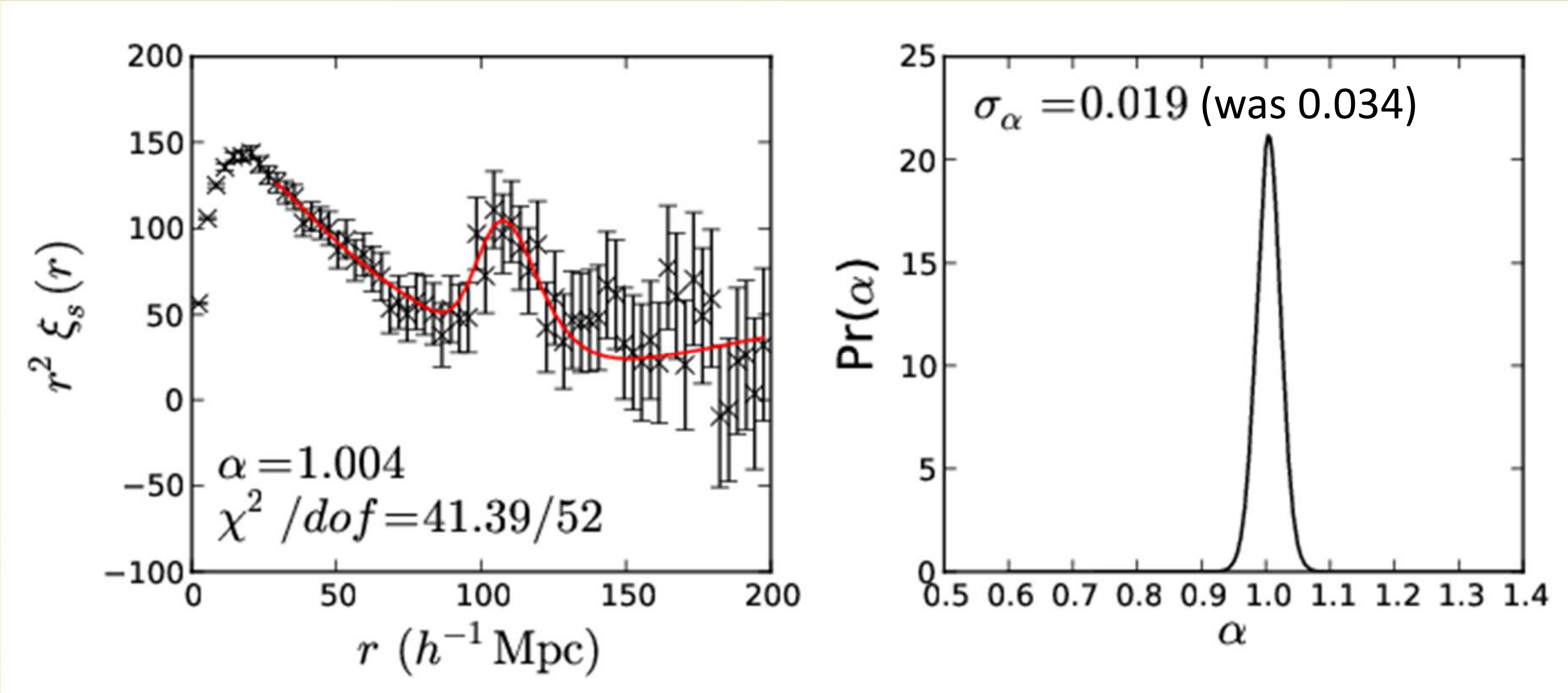


Blanton and SDSS

DR7 Pre-Reconstruction



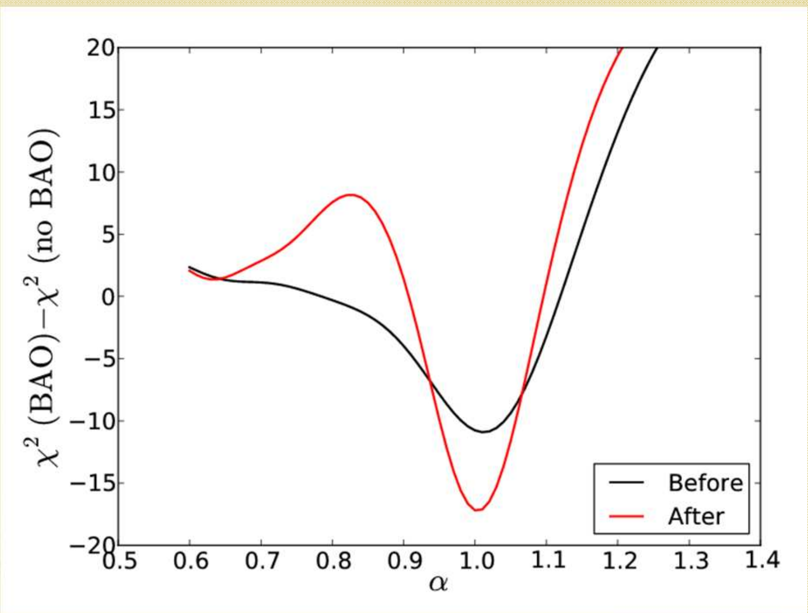
DR7 Post-Reconstruction



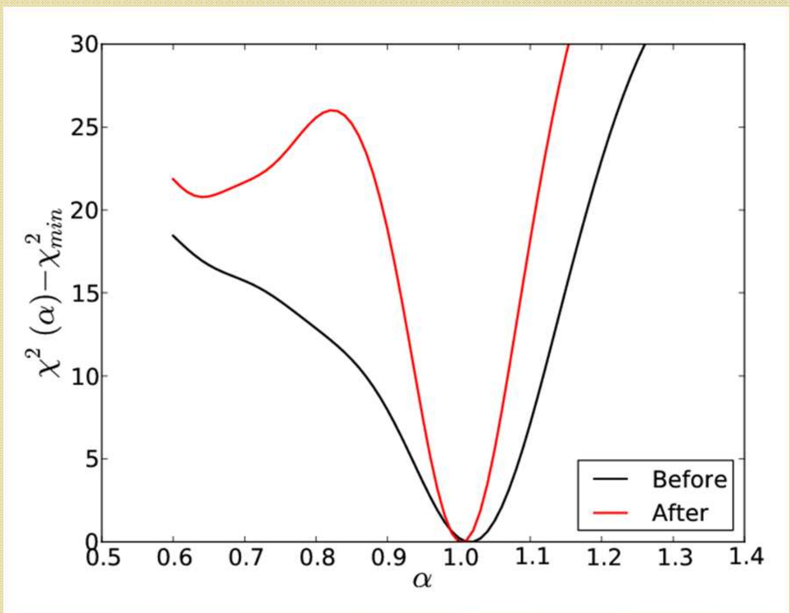
DR7 Results

- Before reconstruction:
  - $\alpha = 1.016 \pm 0.034$
- After reconstruction:
  - $\alpha = 1.004 \pm 0.019$
- Error on acoustic scale decreases from 3.4% to 1.9%, this is a 44% decrease (similar to LasDamas).
- Again, this is equivalent to the effects of tripling the survey volume, but reconstruction gives us this extra help for free!

Significance of Detection



Does the BAO exist?



How well have we measured it?

DR7 Results (cont'd)

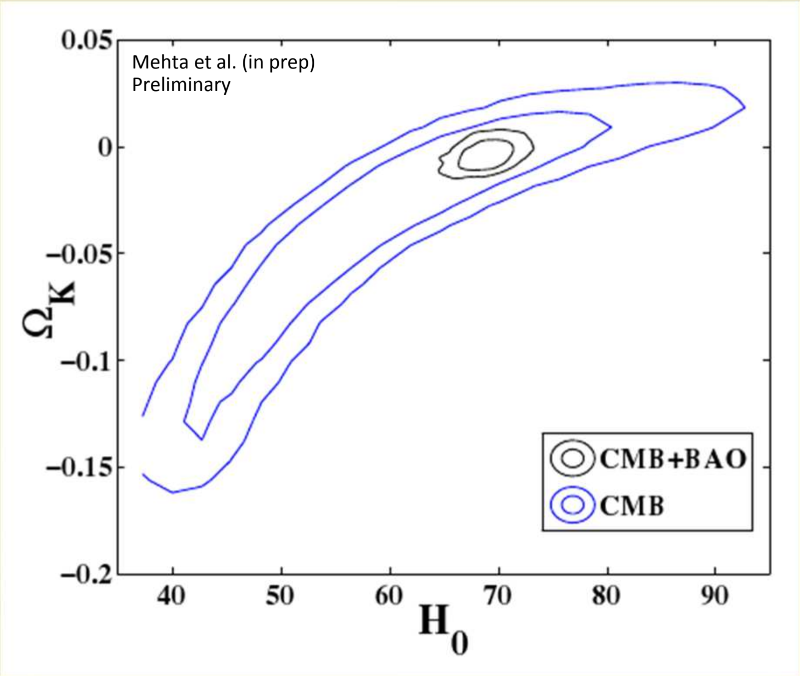
$$\alpha = \frac{D_v(z)/s}{D_{v,fid}(z)/s_{fid}}$$

- For z_{med} = 0.35 and a WMAP7 fiducial cosmology:
  - $D_{v,fid}(z_{med})$ = 1340.2 Mpc (spherically averaged distance to z_{med})
  - s_{fid} = 152.8 Mpc
- Before reconstruction:
  - $\alpha = 1.016 \pm 0.034 \Rightarrow D_v(z_{med}=0.35)/s = 8.86 \pm 0.30$
- After reconstruction:
  - $\alpha = 1.004 \pm 0.019 \Rightarrow D_v(z_{med}=0.35)/s = 8.76 \pm 0.17$

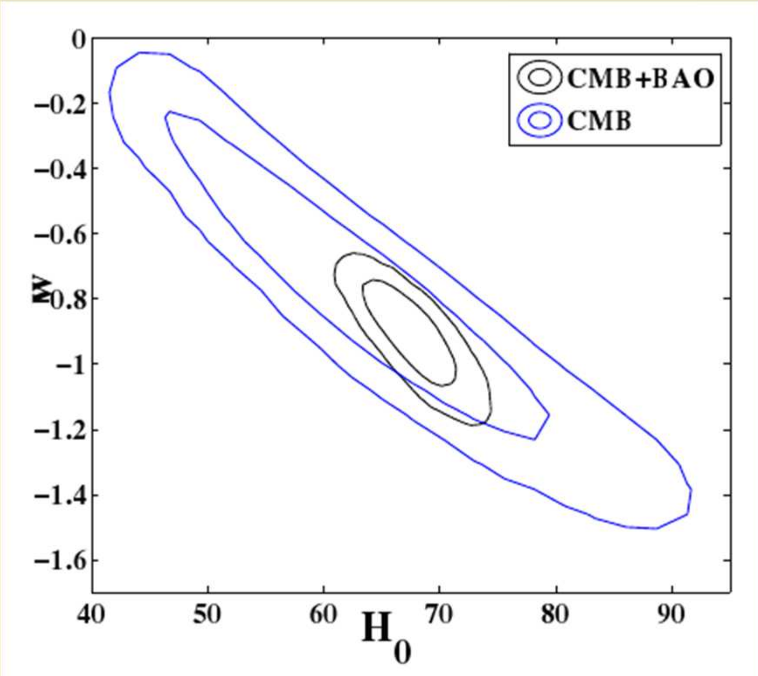
Cosmology with BAO

- The MCMC algorithm:
  - Select cosmology of interest and initial guesses for cosmological parameters.
  - Calculate observables, such as α, using these parameters .
  - Determine $P_{current}$(observables) using the probability distributions measured from data.
  - Select candidate values for cosmological parameters in next step of chain, calculate $P_{candidate}$(observables).
  - Use the ratio of $P_{candidate}/P_{current}$ to determine if candidate parameters are a suitable next step.
  - Continue until values for cosmological parameters converge.

Cosmology (cont'd)

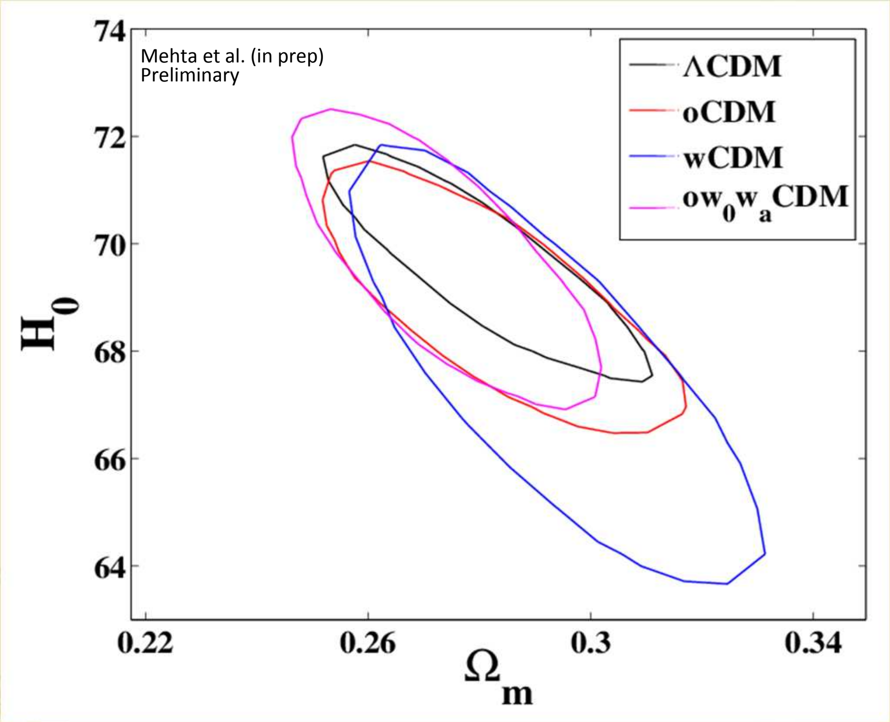


Open Universe



Varying Dark Energy

Cosmology (cont'd)

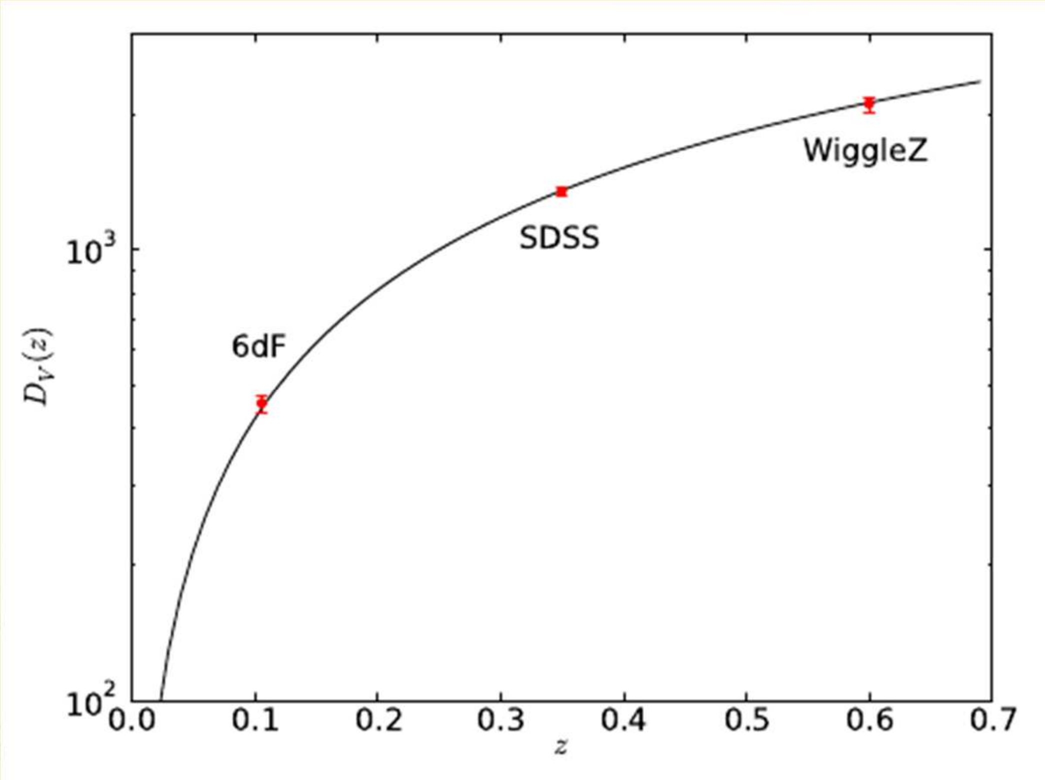


- ΛCDM (CMB+BAO):
  - $\Omega_m = 0.281 \pm 0.019$
  - $H_0 = 69.6 \pm 1.5$
- ow_0w_aCDM (CMB+BAO+SNLS):
  - $\Omega_m = 0.274 \pm 0.017$
  - $H_0 = 69.7 \pm 1.8$
  - $\Omega_k = -0.011 \pm 0.007$
  - $w_0 = -0.927 \pm 0.165$

Cosmology (cont'd)

- ow_0w_aCDM without reconstruction:
  - $\Omega_m = 0.281 \pm 0.023$
  - $H_0 = 69.0 \pm 2.5$ km/s/Mpc
- ow_0w_aCDM with reconstruction:
  - $\Omega_m = 0.274 \pm 0.017$
  - $H_0 = 69.7 \pm 1.8$ km/s/Mpc
- 28% decrease in error on H_0, 26% decrease in error on Ω_m.
- Decreases also seen for exotic cosmologies => reconstruction helps improve constraints on cosmological parameters!

Cosmology (cont'd)



From SDSS:

- $D_v(z_{med}=0.35)/s = 8.76 \pm 0.17$
- ΛCDM (BAO+CMB) :
  - $\Omega_m = 0.281 \pm 0.019$
  - $H_0 = 69.6 \pm 1.5$ km/s/Mpc
  - s = 152.8 Mpc.

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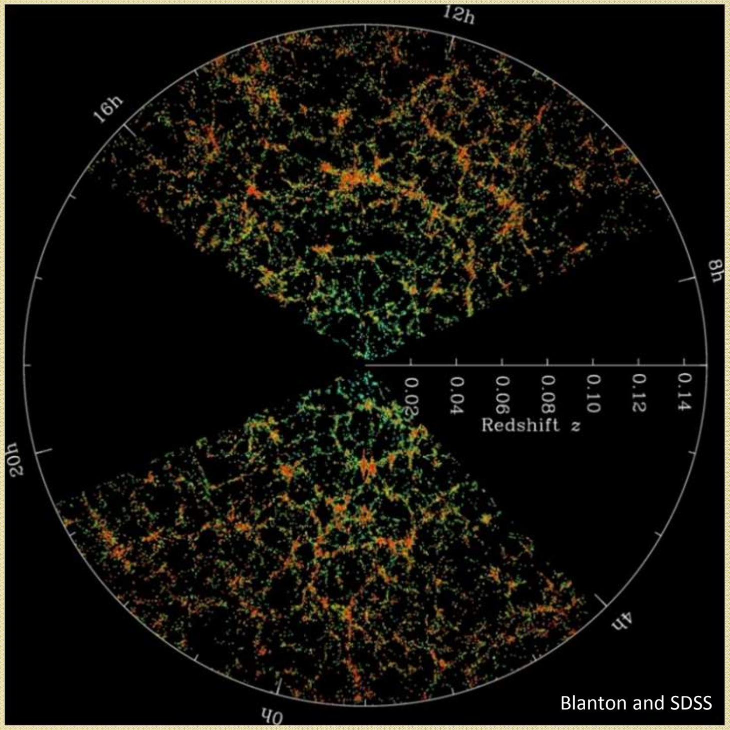

Blanton and SDSS

Future Surveys

BOSS (SDSS III)	DES	LSST	WFIRST	BigBOSS
Spectroscopic	Photometric	Photometric	Spectroscopic (space-based)	Spectroscopic
Mainly BAO	BAO, SN, WL and clusters	BAO, SN, WL and clusters	BAO, SN and WL	Mainly BAO
2.5m	4.0m	8.4m	1.3m	4.0m
2009-2014	Start 2012	Start 2020	Start 2020	????
1.5 million LRGs	300 million galaxies	Billions of galaxies	120 million galaxies	20 million galaxies
10,000 sq deg	5000 sq deg	20,000 sq deg	11,000 sq deg	14,000 sq deg
$0.2<z<0.7$	$0.2<z<1.3$	$0.5<z<3.0$	$0.7<z<2.0$	$0.2<z<1.7$

Conclusions

- We presented the first application of reconstruction to real galaxy data.
- We applied a more careful treatment of the covariances.
- We showed that our fiducial model is robust against small changes in model parameters.
- We measured the DR7 BAO scale to 3.4% accuracy before reconstruction and **1.9% accuracy after reconstruction**
- Our BAO detection is more significant after reconstruction.
- BAO can improve constraints on cosmological parameters. Our cosmology results are consistent with ΛCDM.