Measuring D_A and H at z=0.35 from the SDSS DR7 LRGs using Baryon Acoustic Oscillations

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Xiaoying Xu

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Carnegie Mellon Univeristy

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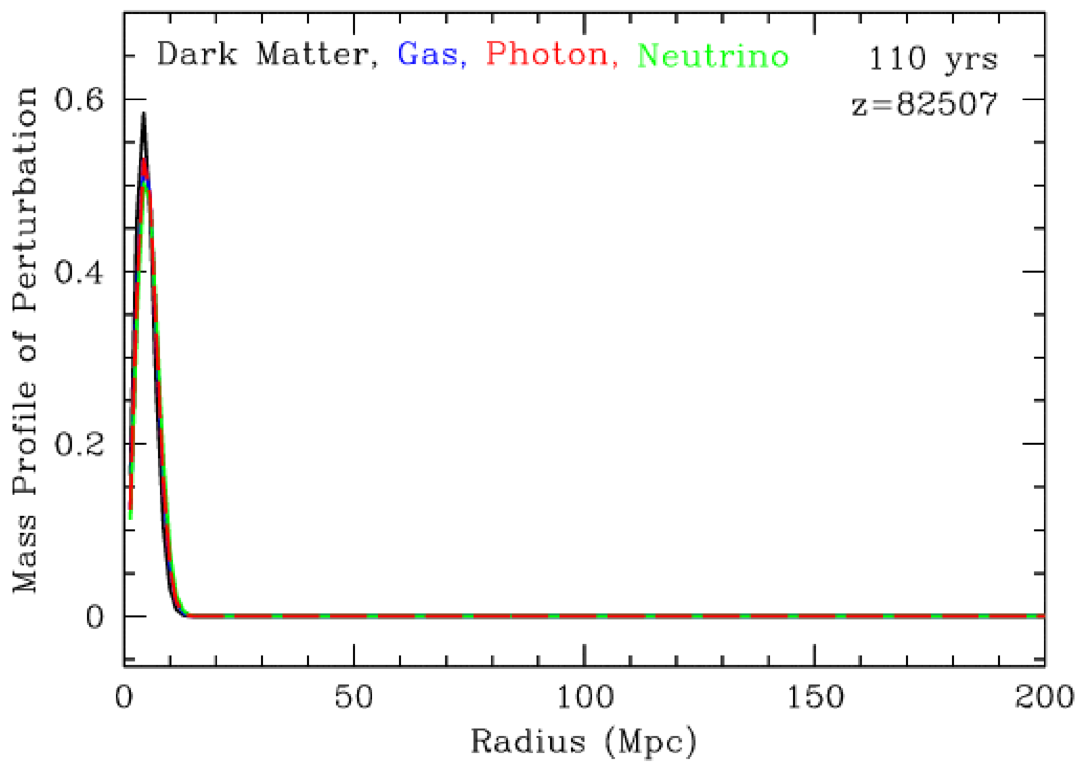
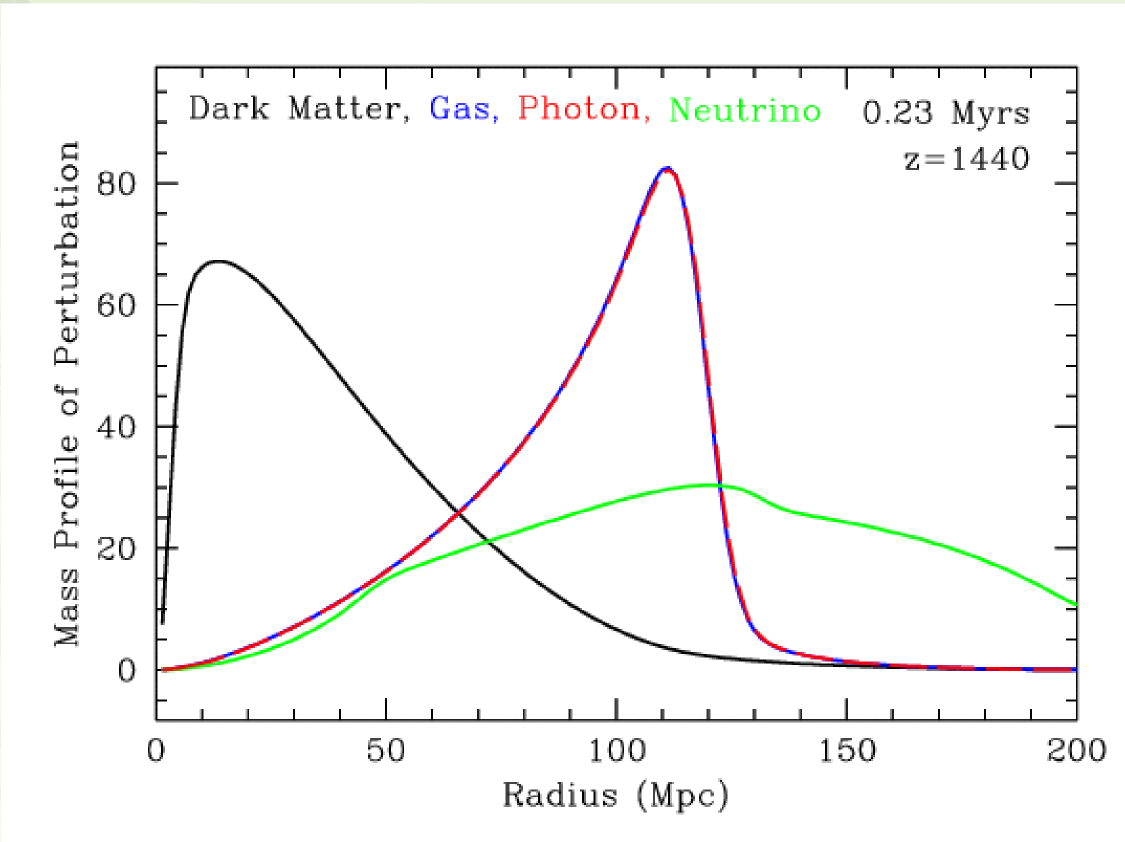
What are BAO?



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

We start with a tiny overdensity in the primordial universe…

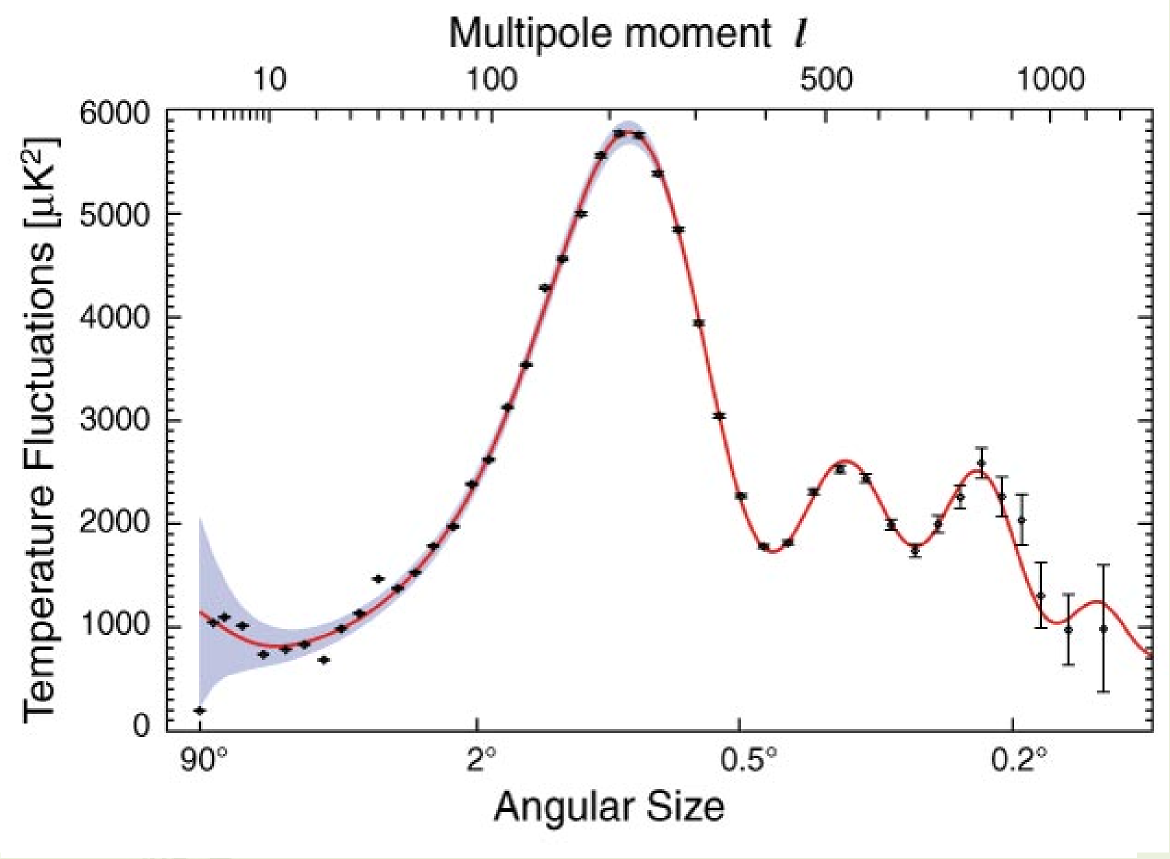
What are BAO?



Photons and baryons push out in a spherical sound wave.

Dark matter tries to pull material back in.

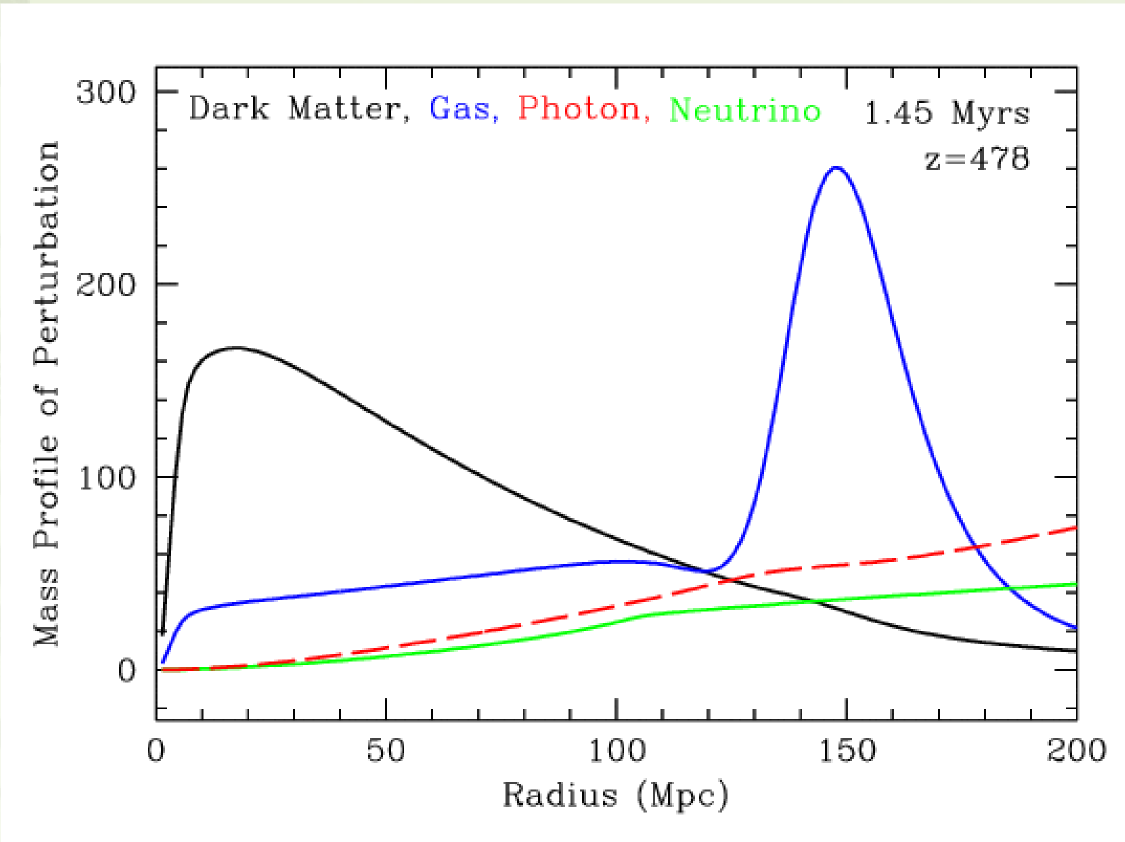
What are BAO?



Standing waves form in the fluid.

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

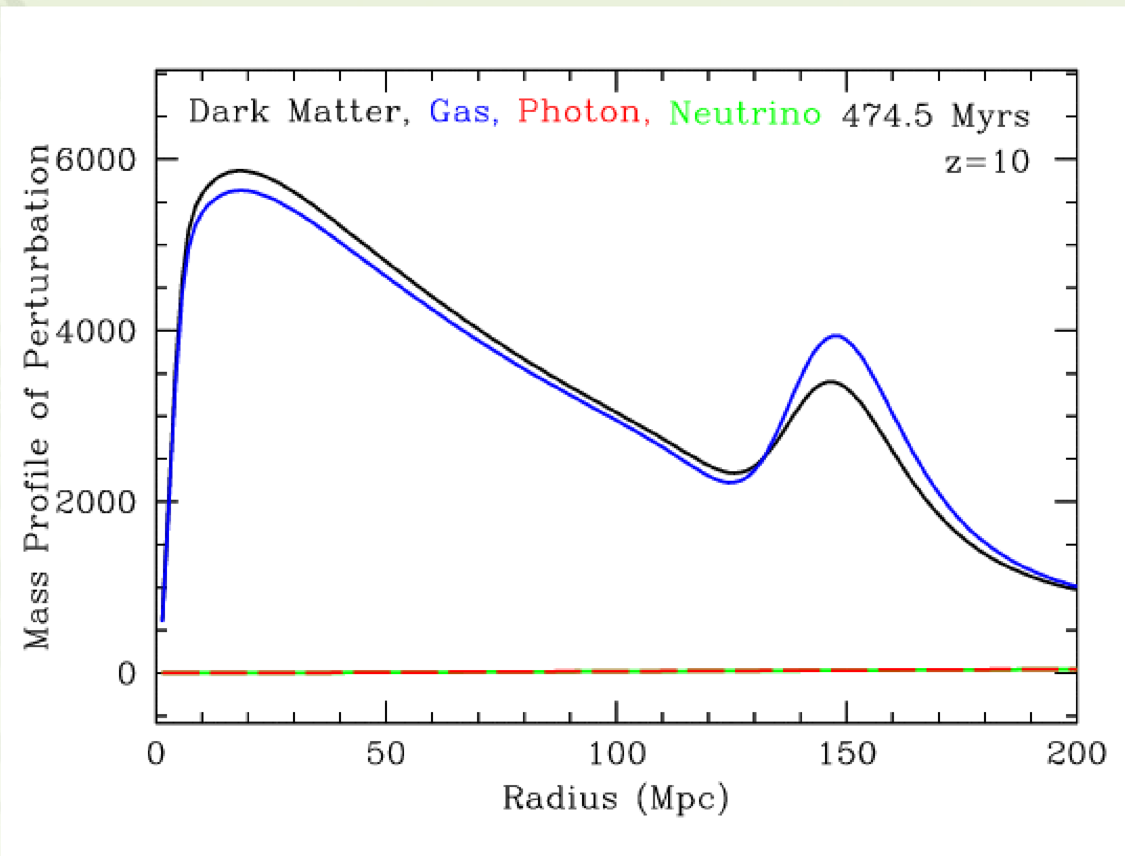
What are BAO?



The sound waves travel about **150 comoving Mpc** prior to recombination.

Baryons deposited at this distance.

What are BAO?



Gravity equilibrates the distributions of dark matter and baryons.

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

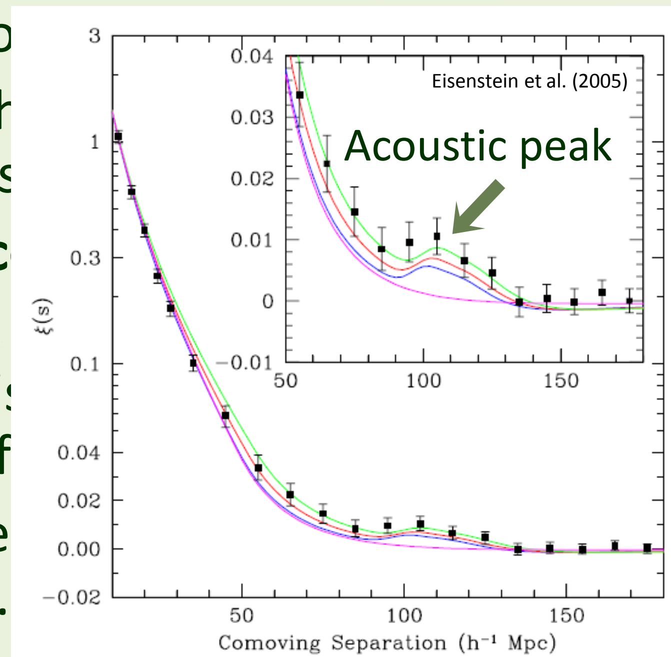
The BAO as a Standard Ruler

- The position of the acoustic peak marks a characteristic scale that is about 150 comoving Mpc.
- This scale is known as the **acoustic scale** or the **sound horizon**.
- Its magnitude only depends on 2 factors:
  – Time of matter radiation equality (depends on $\Omega_m h^2$).
  – Value of $\Omega_b h^2$.
- The sound horizon has been measured to 1.1% accuracy by WMAP7 → it can be used as a very accurate **standard ruler**.

The BAO as a Standard Ruler

- Start with a set of galaxy observations covering a large volume.
- Compute the spherically-averaged correlation function assuming some fiducial cosmology.
- **If the assumed cosmology is wrong, the BAO will appear slightly shifted.**
- Parameterize this shift in a model and fit model to data to measure the shift.
- Repeat at different redshifts => spherically-averaged distance-redshift relation.

The BAO as a Standard Ruler

- Start with a set o 

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$$\alpha = \frac{D_V(z)/r_s}{D_{V,f}(z)/r_{s,f}} = \left[\frac{D_A^2(z)}{D_{A,f}^2(z)}\frac{H_f(z)}{H(z)}\right]^{1/3}\frac{r_{s,f}}{r_s}$$

Anisotropic BAO

- Anisotropies in the BAO can help us separate D_A and H.
- Anisotropic clustering arises from 2 sources:
  - **Redshift space distortions:** Cause changes to the broadband, does not affect the BAO in particular.
  - **Assuming the wrong cosmology:** Shifts the BAO such that it appears in slightly different positions along different directions.
- The second of these can be used to separately constrain $D_A(z)$ and H(z), allowing us to directly probe the cosmic expansion history.

Anisotropic BAO

- Anisotropi … and H.
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  - **Redshi…** … the broadband, does no…
  - **Assumi…** … BAO such that it appears … different directio…
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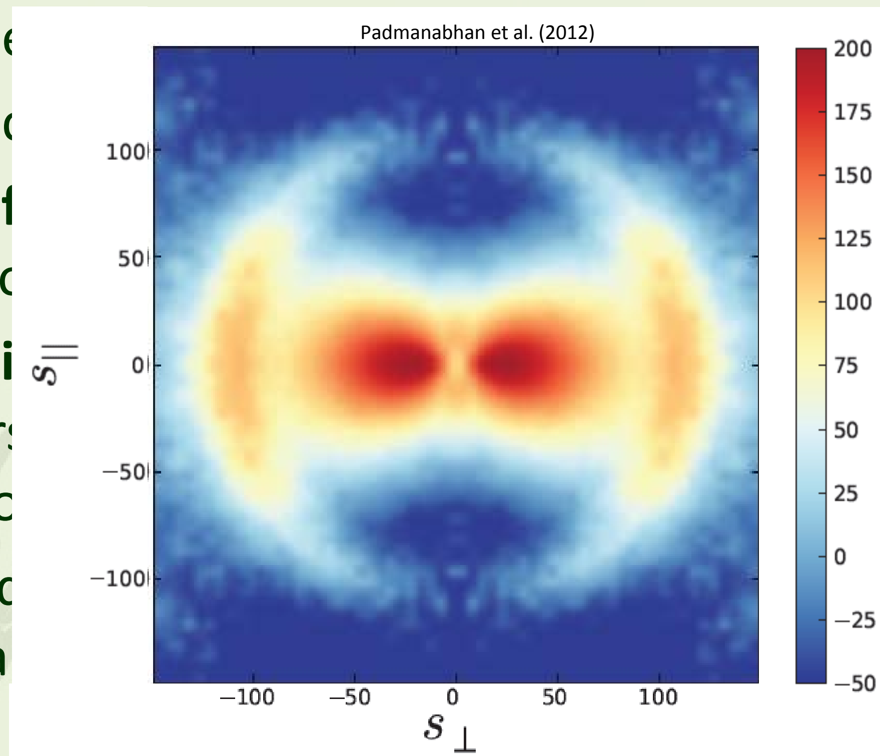

Anisotropic BAO

- Anisotropic clustering introduces power into the higher order even multipoles of the correlation function.
- Hence, to measure the anisotropy in the BAO, we can use the l=2 quadrupole (we will still assume that l>2 moments are 0).
- We fit models of the monopole and quadrupole to the data; these models contain terms that parameterize the BAO shift:

$$1 + \varepsilon = \sqrt[3]{\frac{H_f(z) D_{A,f}(z)}{H(z) D_A(z)}}$$

- We then simultaneously fit the monopole and quadrupole for α and ε → D_A and H.

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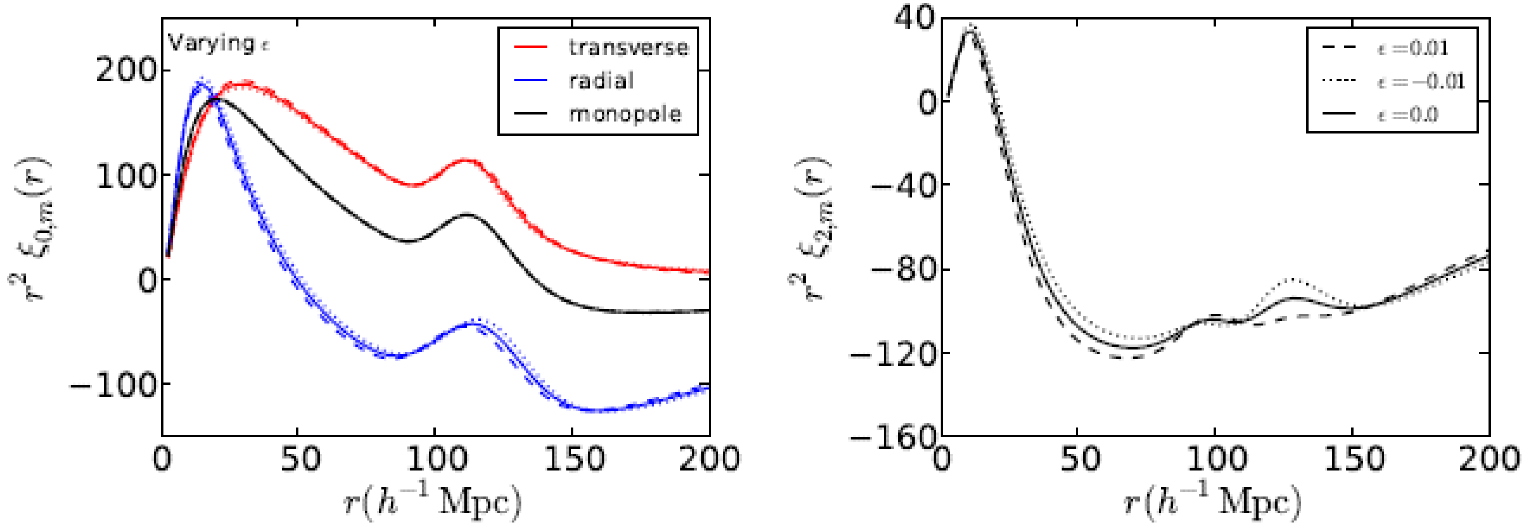
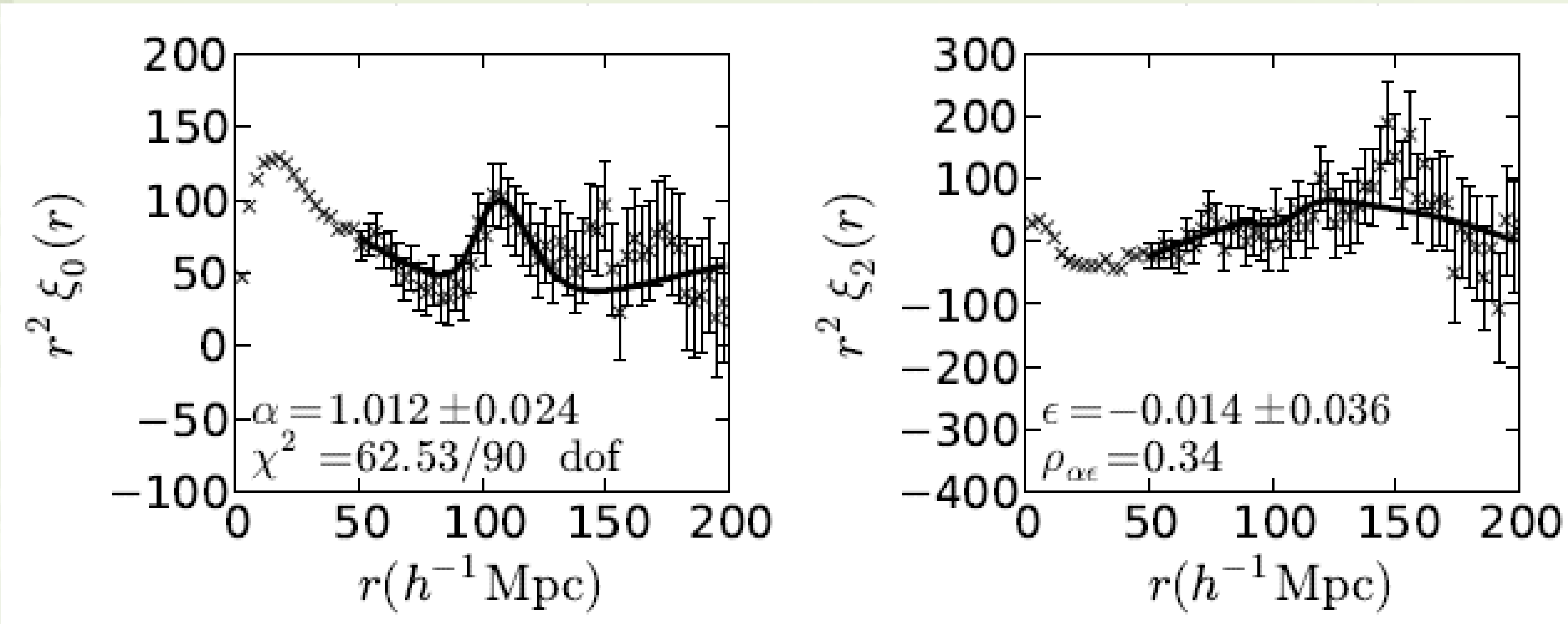
The Quadrupole



Our Data

- We use data from the Sloan Digital Sky Survey (SDSS).
- Data taken by 2.5m telescope at Apache Point Observatory.
- SDSS is currently in its 3rd generation; we use the final data release from the 2nd generation (SDSS-II DR7).
- **DR7 LRG sample** (2 spectrographs, 600 fibers per):
  - $0.16 < z < 0.47$ (median $z=0.35$), about 7000 deg^2 sky coverage, $1 \times 10^{-4} h^3/Mpc^3$ number density

DR7 Results



H(z) = 84.4±7.1 km/s/Mpc (8.4% measurement)

$D_A(z)$ = 1050±38 Mpc (3.6% measurement)

Conclusions

- We present methods for anisotropic BAO analysis and use it to separately constrain $D_A(z)$ and $H(z)$ using SDSS DR7.
- We obtain an 8.4% measurement of $H(z)$ and a 3.6% measurement of D_A (z).
- Future BAO surveys will be able to improve the precision of these measurements; the methods presented here will be directly applicable to future analyses.