Towards unbiased constraints on the expansion history from galaxy clustering

CosKASI
Cosmology Group at
Korea Astronomy and Space Science Institute

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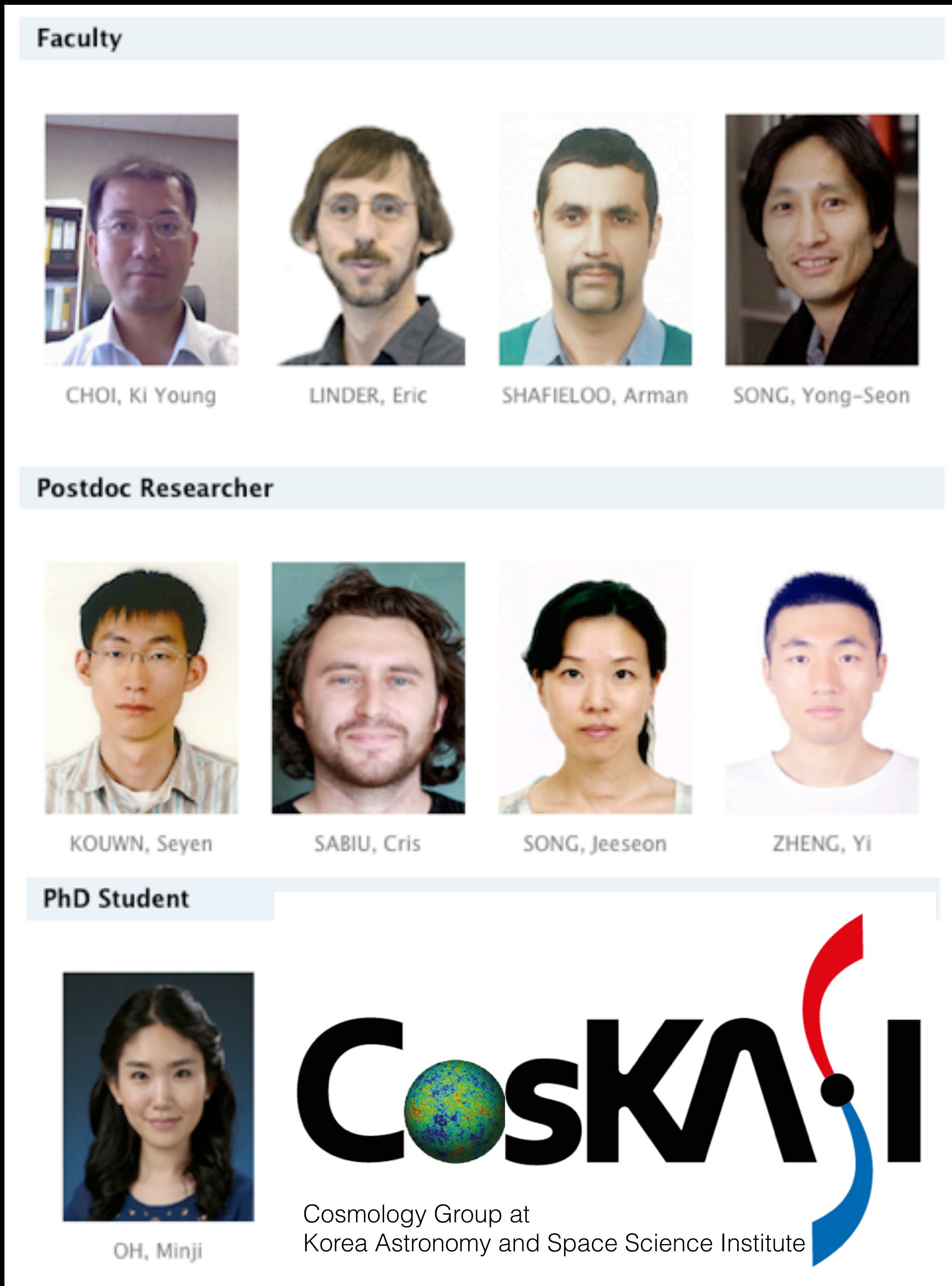
WITH YONGSEON SONG

JOINT WINTER CONFERENCE ON PARTICLE PHYSICS,
STRING AND COSMOLOGY - HIGH1- JAN 2015

CosKASI Group (KASI, Daejeon)



New and still expanding Cosmology group at KASI

Theoretical front:
Inflation
Dark Matter
Modified Gravity

Observational front:
Cosmology using Galaxy Clusters

Dark Energy from Galaxy Clustering in SDSS and future DESI (official member)

Testing GR and other cosmological assumptions using current and future data.

http://cosmology.kasi.re.kr

Outline

- 2-point Correlations (Anisotropic)
  - Baryon Oscillations (BAOs)
  - Alcock-Paczynski effect
  - Minimal theory approach (proof of concept)
  - Checking systematics

- Clustering Shells
  - Methodology
  - Forecasting constraints

- Conclusions

Background

Key observables in spectroscopic surveys:

Angular diameter distance $\mathbf{D_A}$
- Exploiting BAO as standard rulers which measure the angular diameter distance and expansion rate as a function of redshift.

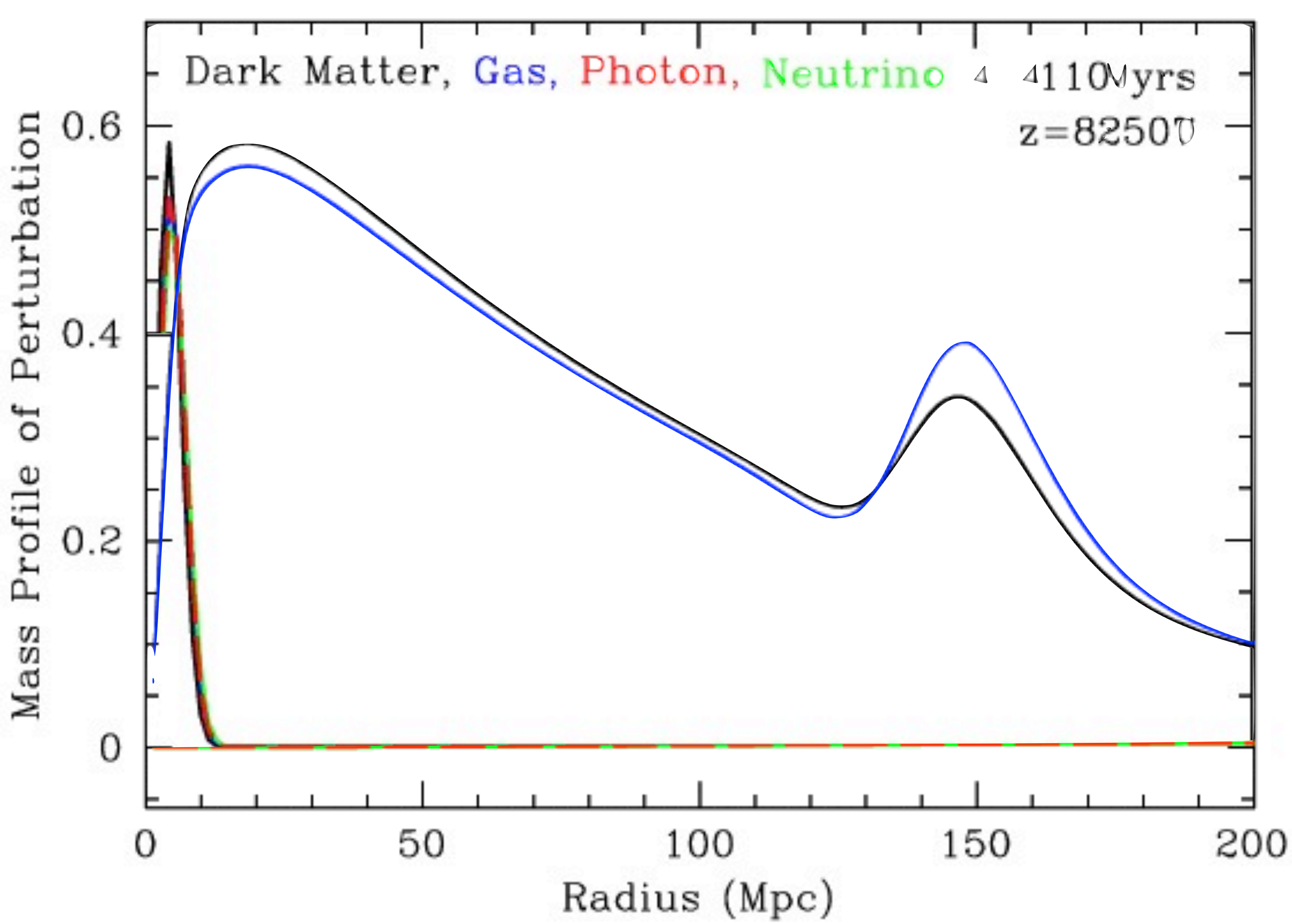
Radial distance $\mathbf{H^{-1}}$
- Exploiting redshift distortions as intrinsic anisotropy to decompose the radial distance represented by the inverse of Hubble rate as a function of redshift. (Useful for Arman's Om statistics, see his talk on web!)

Coherent motion $\mathbf{G_\Theta}$
- The coherent motion, or flow, of galaxies can be statistically estimated from their effect on the clustering measurements of large redshift surveys, or through the measurement of redshift space distortions.

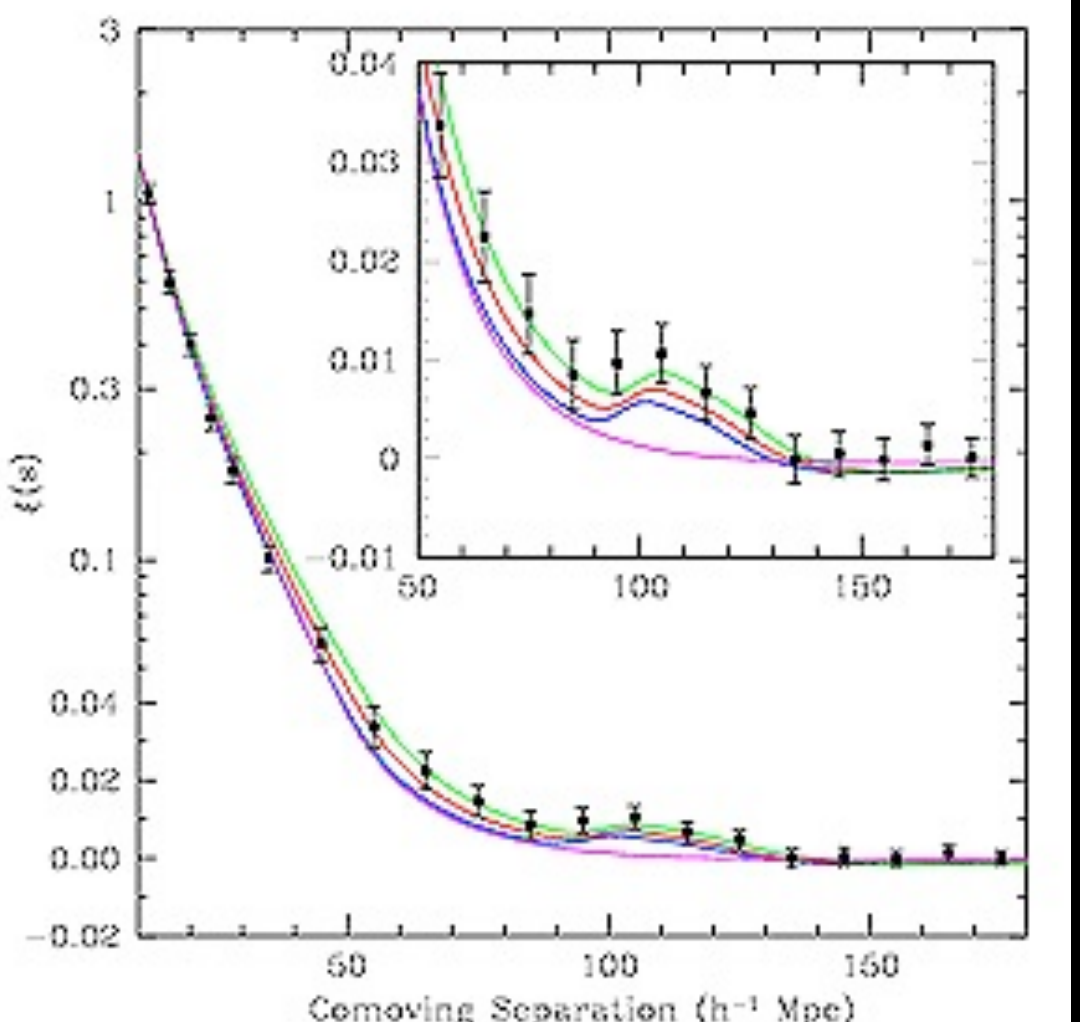
These are essential to test theoretical models explaining cosmic acceleration; **ΛCDM, Dynamical DE, Einstein's gravity**

BAO

- Imprint of the acoustic phenomena caused by the coupling of the photon and gas perturbations in the early-universe (< 0.4 Myr).
- The physical scale is well-understood, thus can be used as a standard ruler.
- It shows up as an enhanced overdensity with a characteristic scale of ~ 150 Mpc.

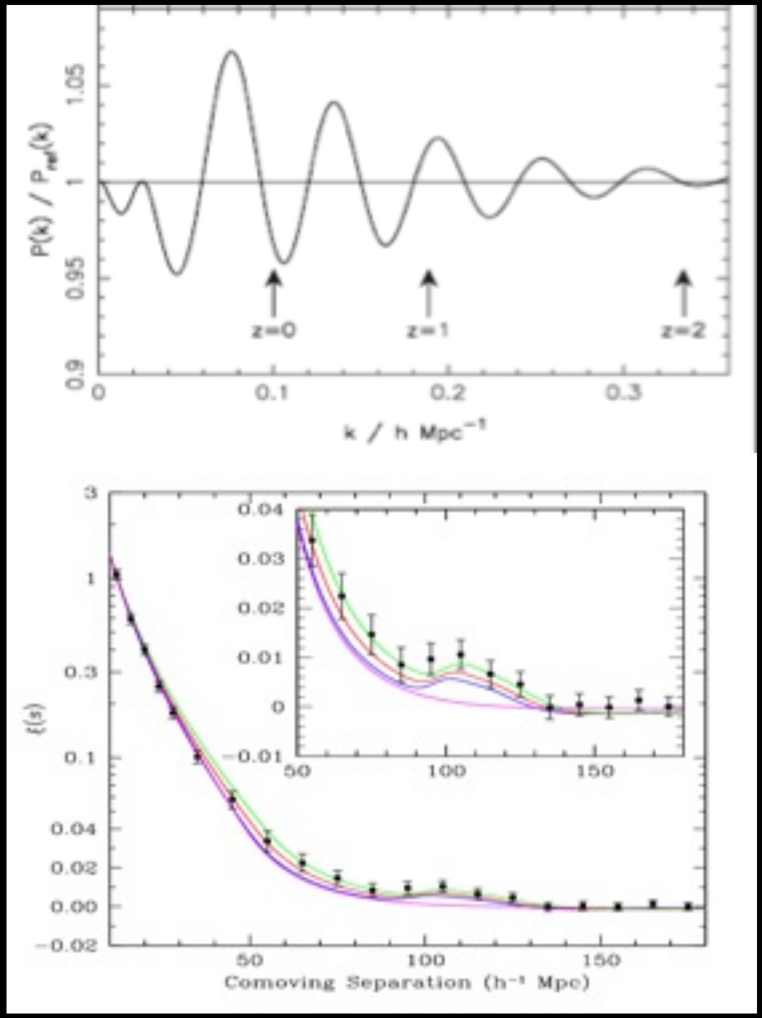


(From D. Eisenstein)



(www.sdss3.org)

BAOs to Dark Energy



- How can we use BAOs to arrive at the dark energy equation of state?
  - By analyzing matter power spectrum we can deduce the wavelength of the "wiggles" in k-space or the BAO 'peak' in configuration-space
  - We'll call this wavelength k_A

- k_A can be obtained through theory by the following steps:
- k_A can be related to sound horizon at last scattering through

$$k_A = 2\pi/s$$

- At high redshift, affects of dark energy can be neglected, and s is given by

$$s = \frac{1}{H_0\Omega_m^{1/2}} \int_0^{a_r} \frac{c_s}{(a + a_{eq})^{1/2}}\, da$$

- a_r and a_{eq} are scale factors at recombination and matter radiation equality
- c_s is sound speed ($\sim c/\sqrt{3}$)

Correlation Functions

- Galaxy catalogues show rich and complex structures in the spatial distribution, with filaments, walls, voids, etc.

- These structures encode a lot of info on the physics and underlying models of cosmology.

- We want to quantify the structure of our data. How do we condense this information into a manageable form?

We want to evaluate: where δ is the density contrast

$$\langle \delta(x)\delta(x+r)\rangle$$

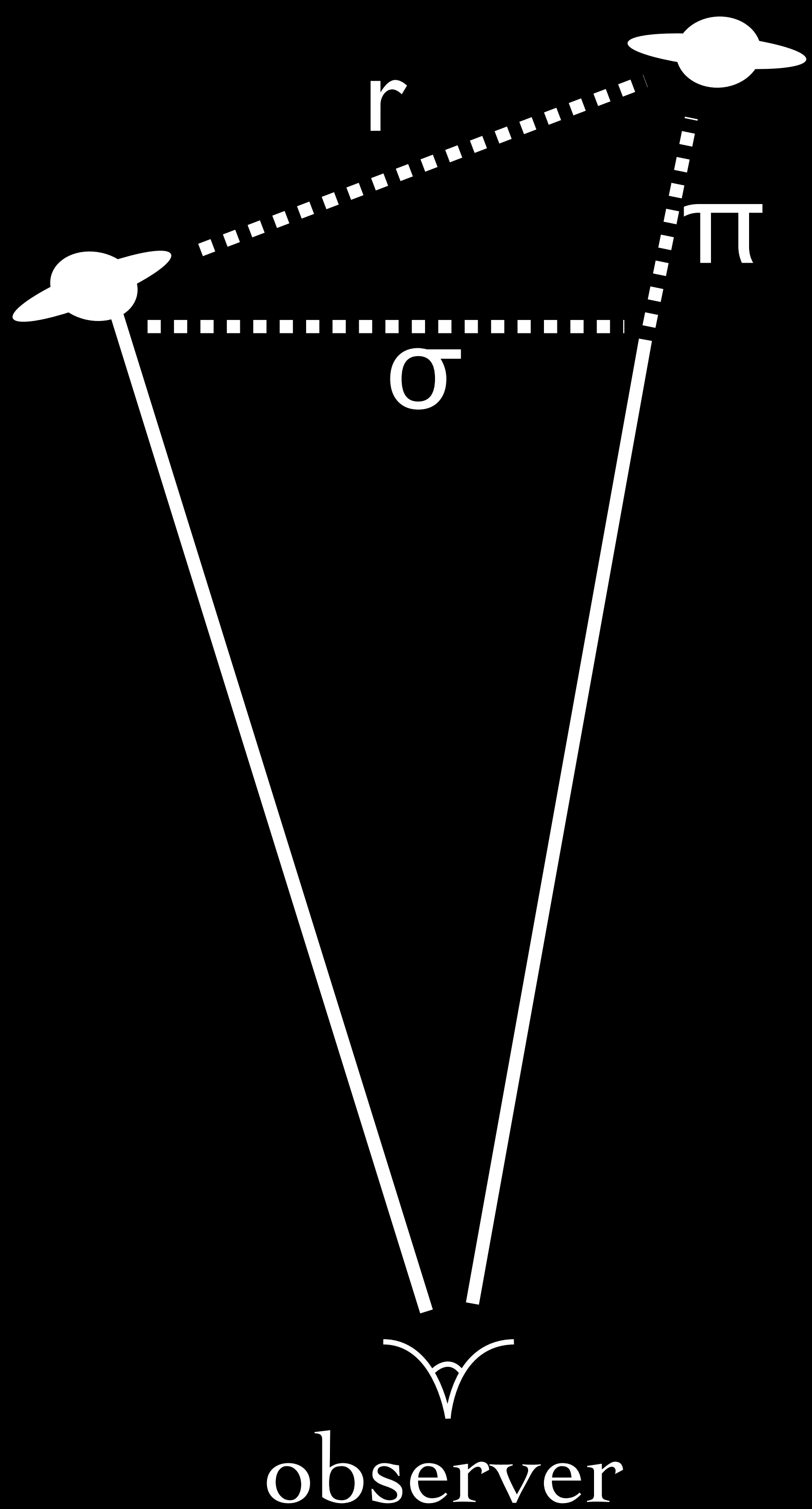
We call this the Two Point Correlation Function (2PCF)

$$\xi_i(r) = \frac{n_i(r)}{\bar{n}.dV} - 1$$

The estimator for this statistic is:

$$\xi(r) = \frac{DD - 2DR + RR}{RR}$$

Anisotropic 2PCF



Bin galaxy pairs in two distances (π,σ) instead of the single distance between pairs, r.

Apart from the binning this is the same as doing the 2PCF.

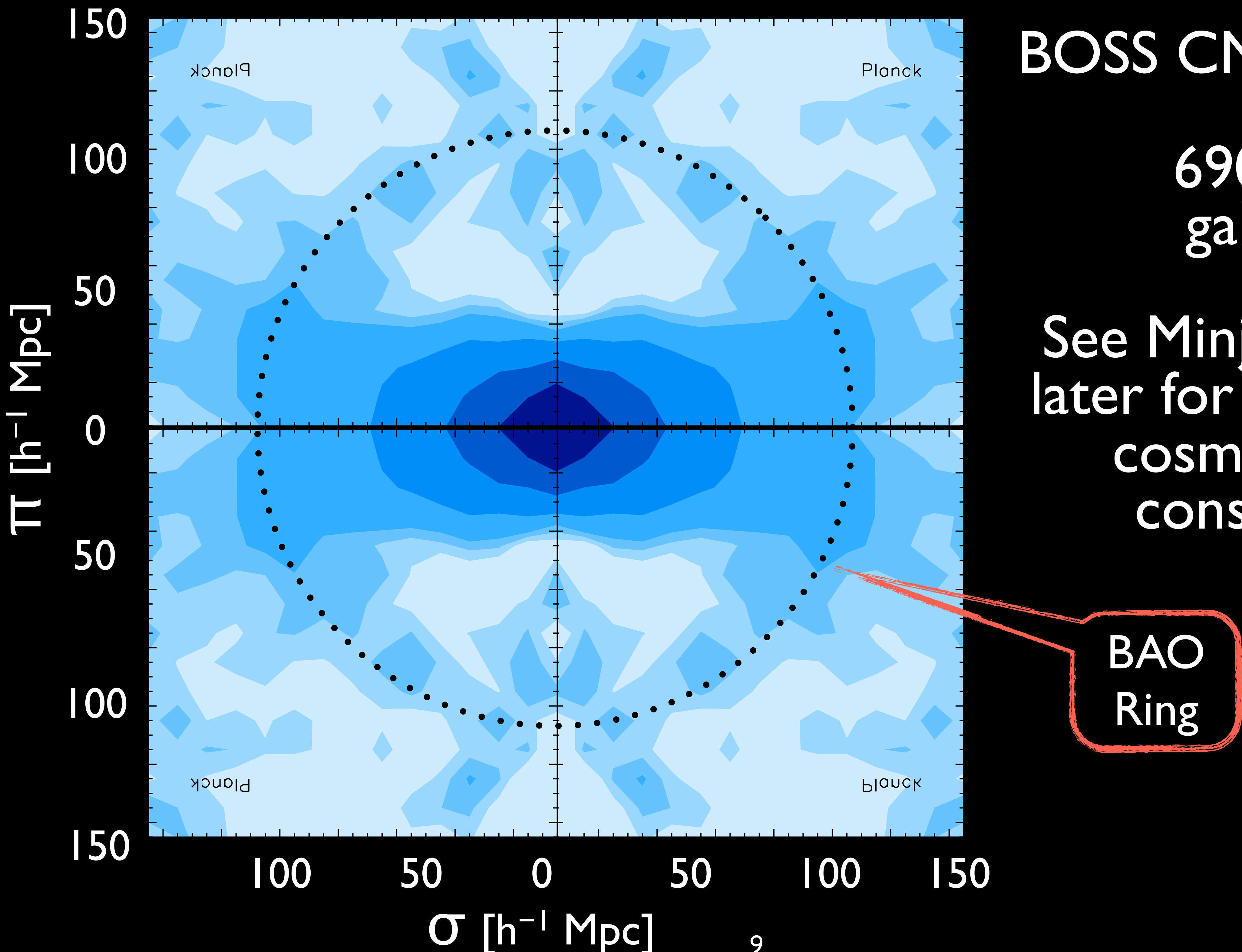
And if there are no preferred directions then the correlation function will give perfectly circular contours in (π,σ).

$$\xi(r) = \frac{DD - 2DR + RR}{RR}$$

2D clustering on large scale

Linder, Oh, Okumura, **Sabiu**, Song (2013) arXiv:1311.5226 (DR9 paper)

Song, **Sabiu,** Okumura, Oh, Linder (2014) arXiv:1407.2257 (DR11 paper)



BOSS CMASS DR11

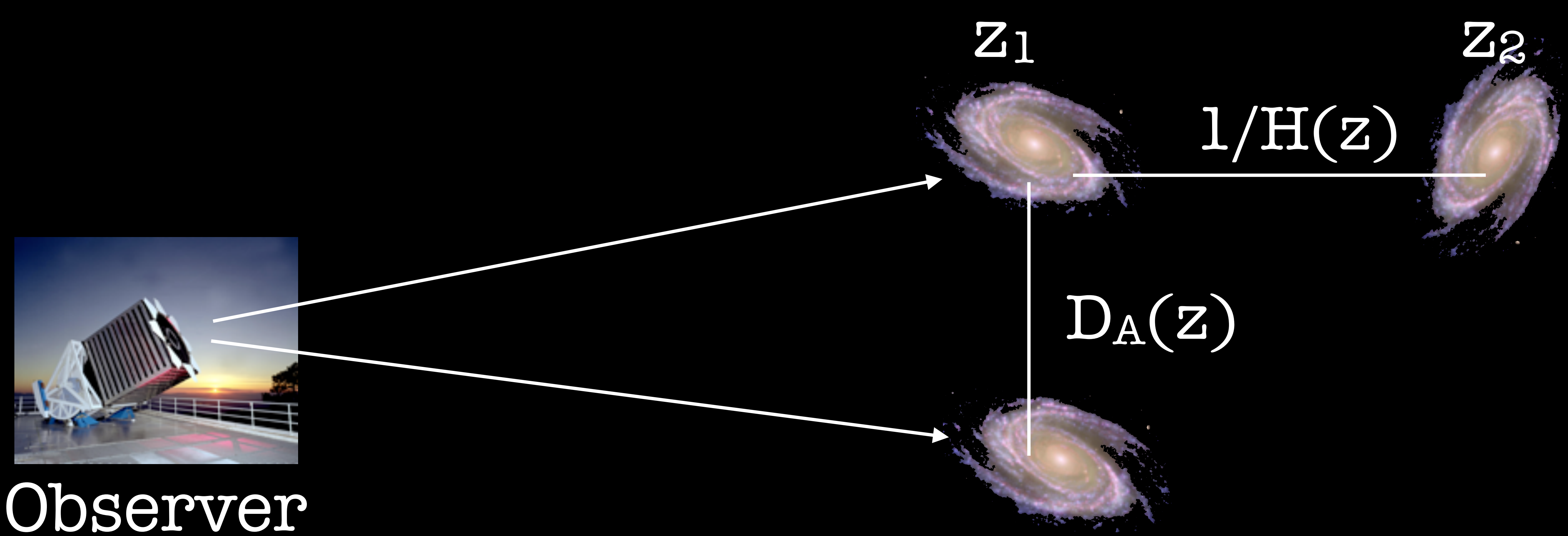
690,826 galaxies

See Minji Oh's talk later for details and cosmological constraints

Alcock-Paczynski Effect

We measure RA, Dec and Redshift for each galaxy. However we must choose a cosmological model to convert these positions into a cartesian comoving coordinate system.

Even without a standard ruler, we can measure the clustering along and perpendicular to the line of sight and thus constrain the combination of $D_A * H$



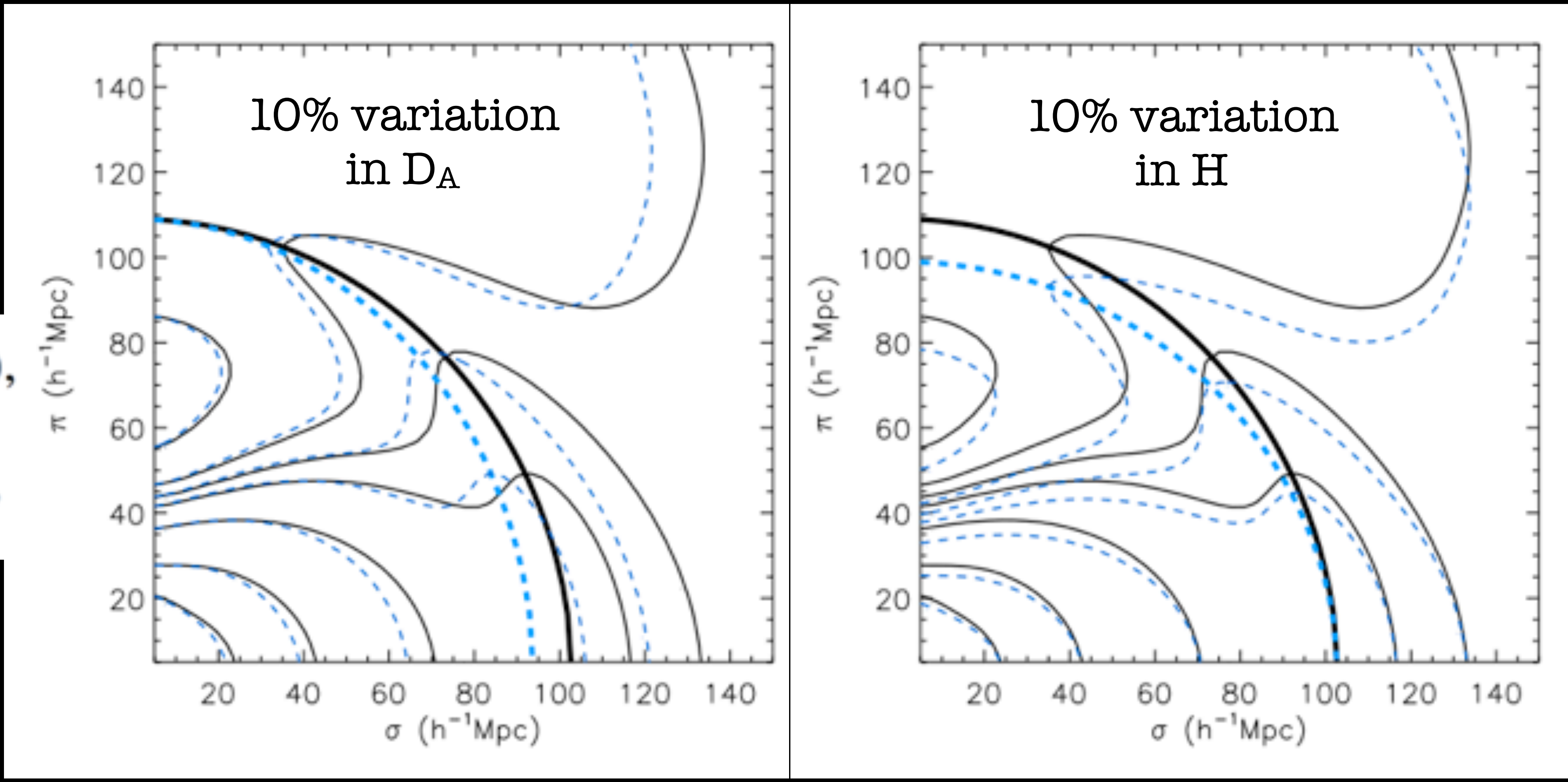
Alcock-Paczynski Effect

Theoretically the geometric distortions of the AP effect can be modeled exactly:

$$\xi^{\rm fid}(r_\sigma, r_\pi) = \xi^{\rm true}(\alpha_\perp r_\sigma, \alpha_\parallel r_\pi),$$

$$\alpha_\perp = \frac{D_A^{\rm fid}(z_{\rm eff})}{D_A^{\rm true}(z_{\rm eff})}, \qquad \alpha_\parallel = \frac{H^{\rm true}(z_{\rm eff})}{H^{\rm fid}(z_{\rm eff})},$$

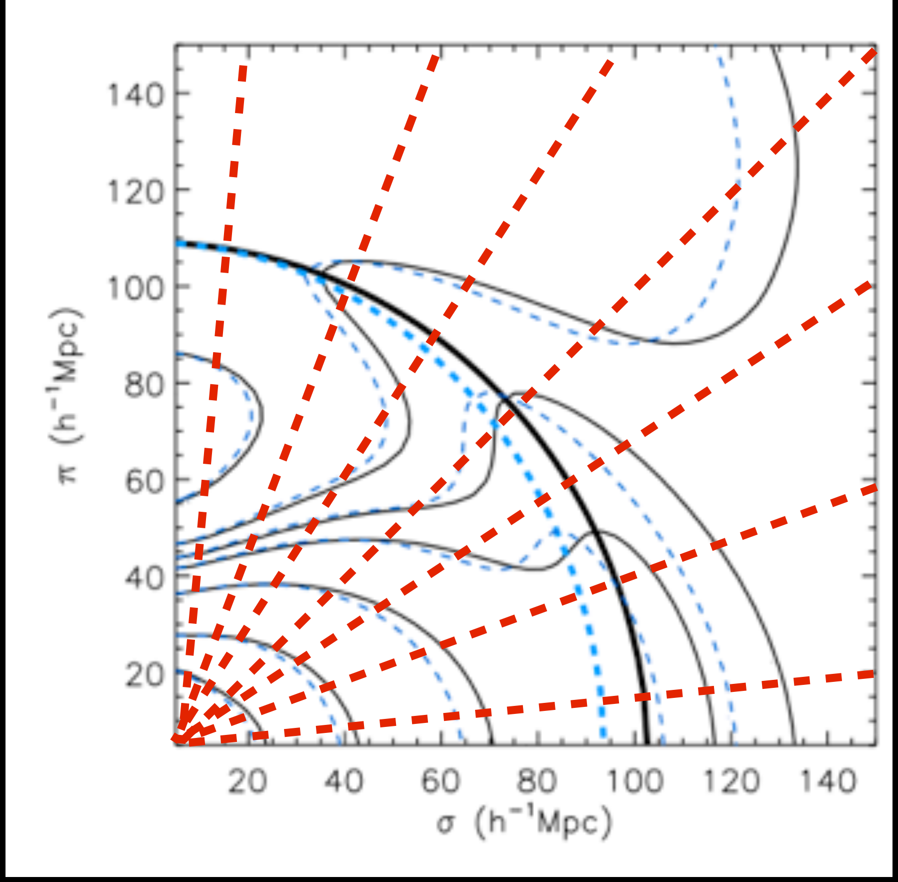
D_A, H vary peak positions off the BAO ring.



We want to avoid fitting the full shape of the anisotropic correlation function, as it depends on unknown systematic and physics, like scale dependent bias, etc.

A cleaner method would be to just measure the shape of the BAO ring.

We can do this by looking at many thin wedges in this 2D projection, i.e. many directionally constrained 1-D correlation functions.

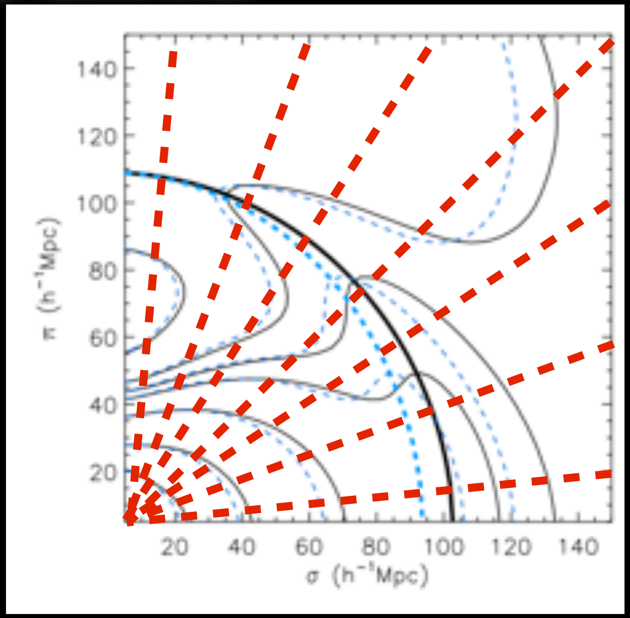


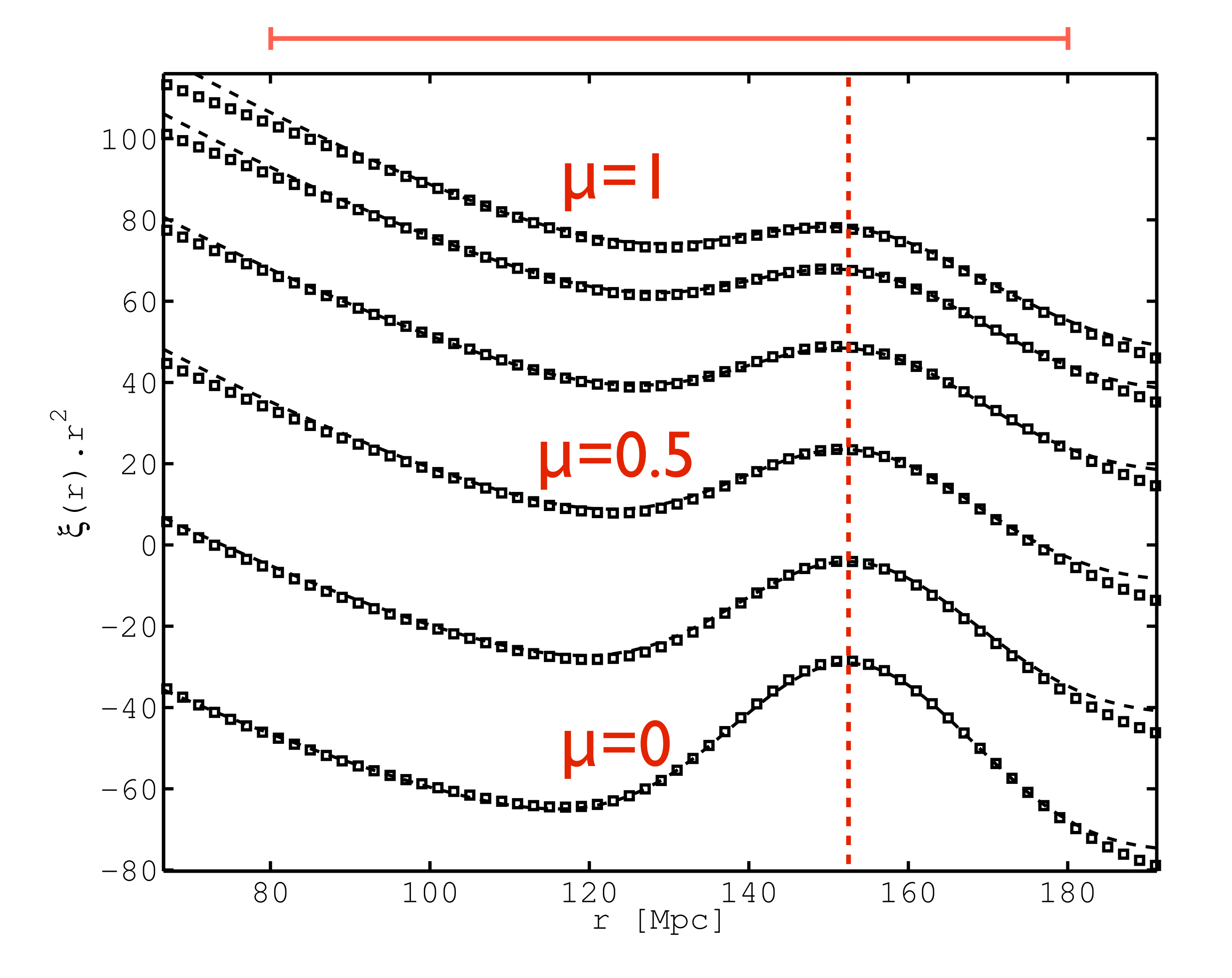
Anisotropic BAO Peaks

$$\xi_\mu(s) \times s^2 = A.s^2 + B.s + Ee^{-(s-D)^2/C} + F,$$

A simple function to approximate the shape of the correlation function
We use a quadratic plus a gaussian, fitted over the range 80<r<180 Mpc

We care only about locating the BAO peak position. The centre of the gaussian is controlled by D.



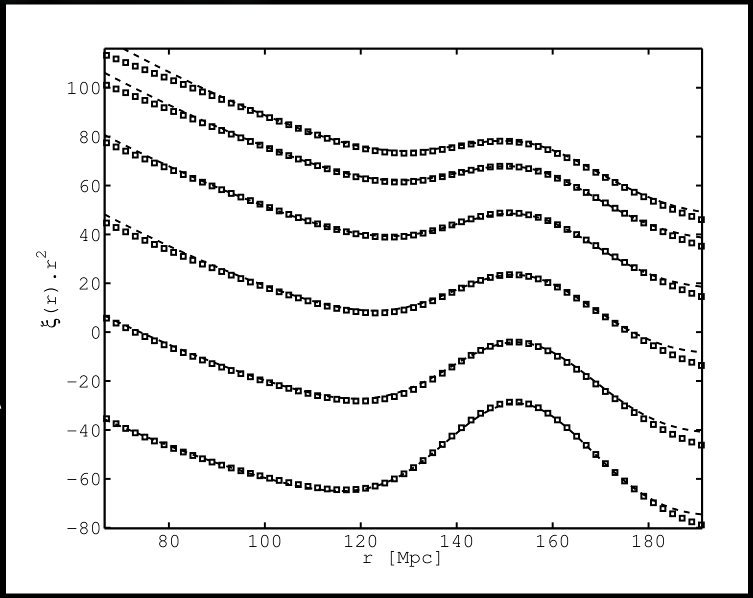


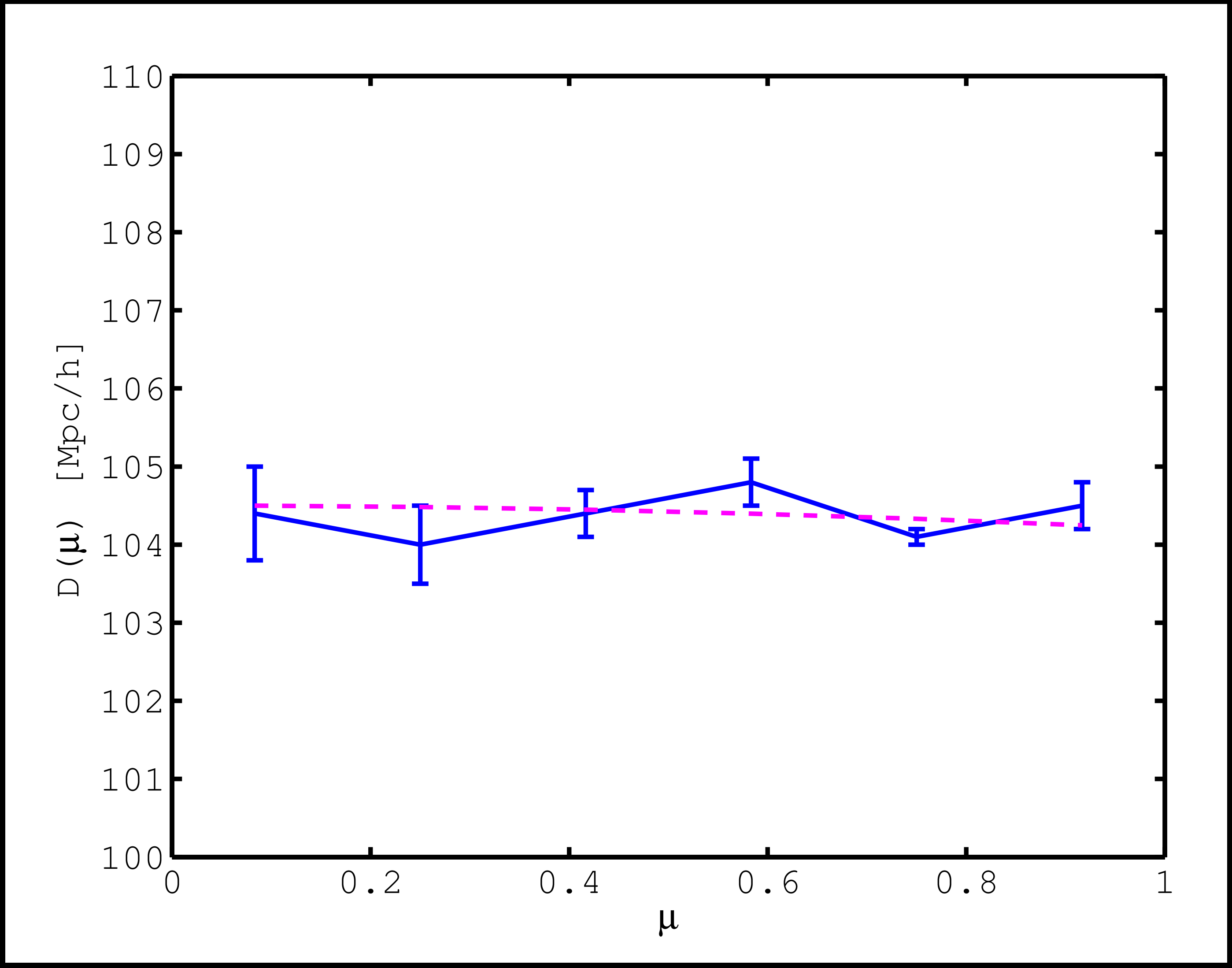
Anisotropic BAO Peaks

Simply we can fit an elliptic function to the obtained D(μ) and get a semi-major and minor distance defining an ellipse.

$$D(\theta) = \frac{D_{||} D_{\perp}}{\sqrt{(D_{||}\cos\theta)^2 + (D_{\perp}\sin\theta)^2}}$$

From this we constrain the two distances, $D_{//}$ along the line of sight and $D_{\perp}$ across the line of sight.





Anisotropic BAO Peaks

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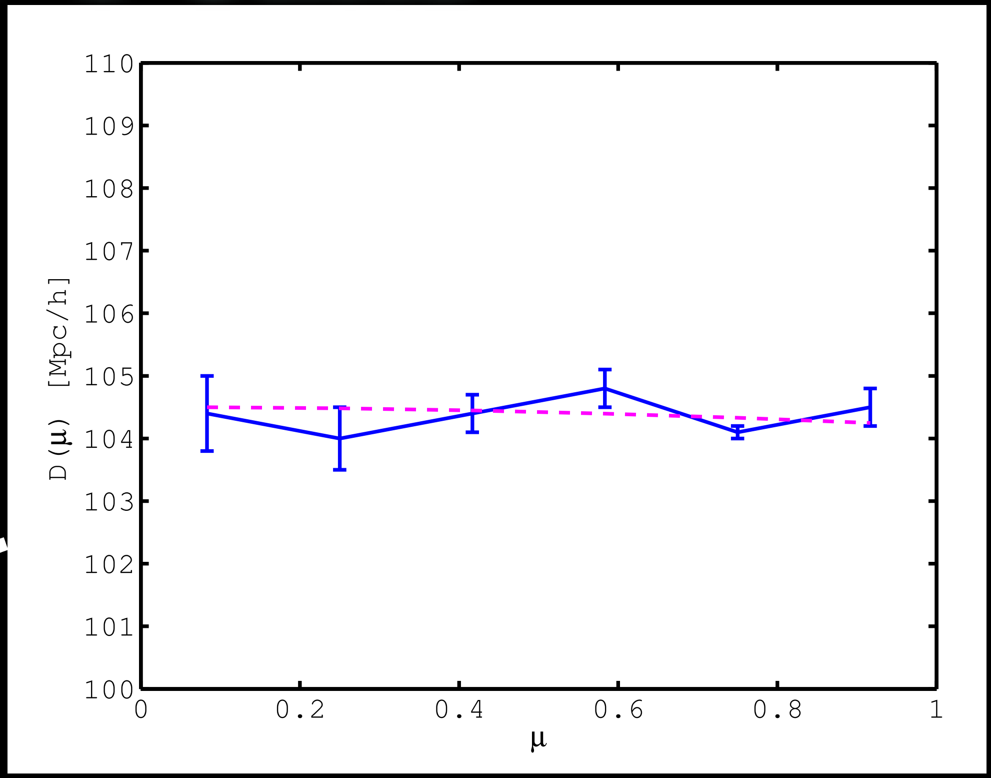
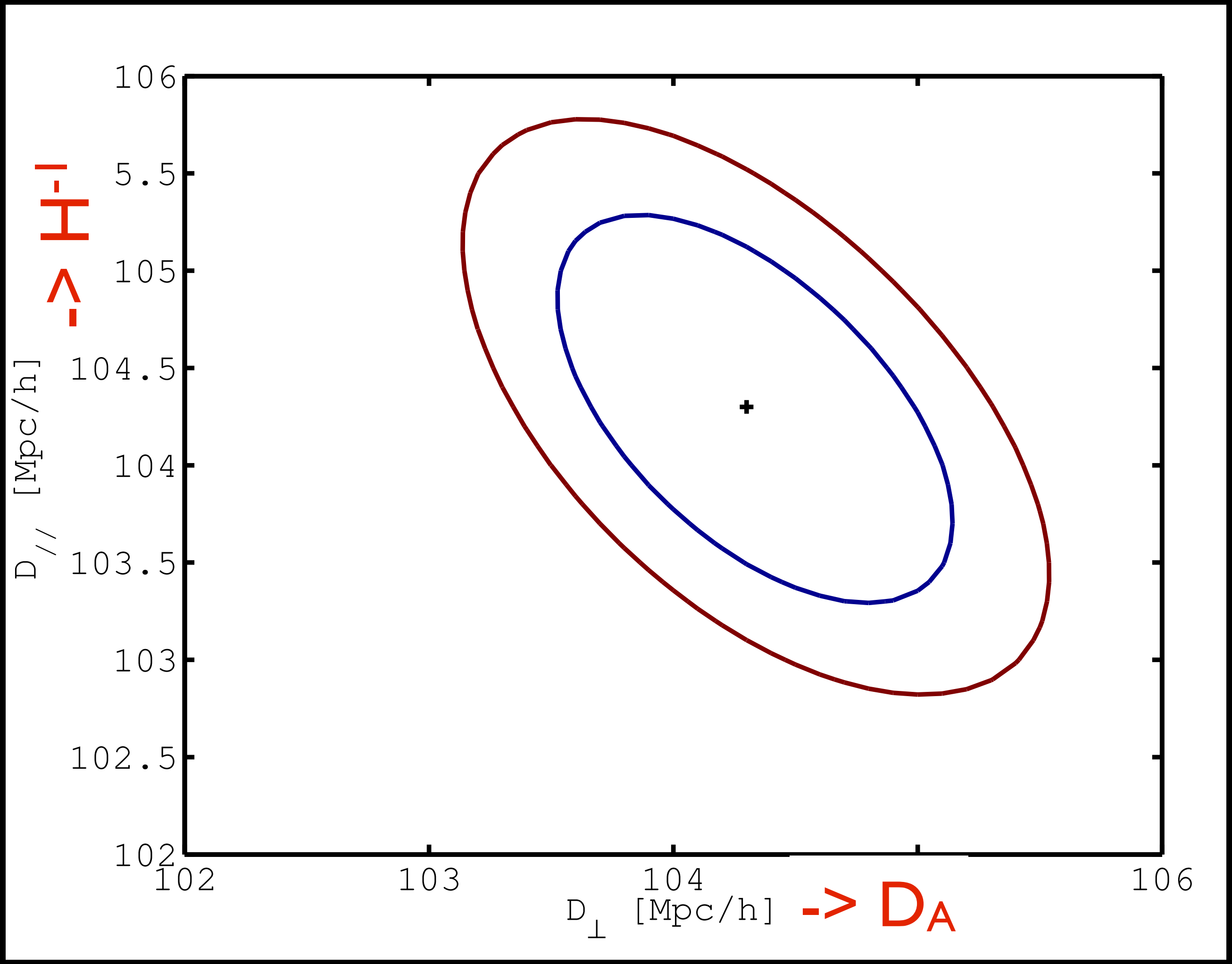


Next we create theoretical models that include different systematics and and observational effects.

In the fiducial case we obtain a simultaneous measurement of D_A and H^{-1}

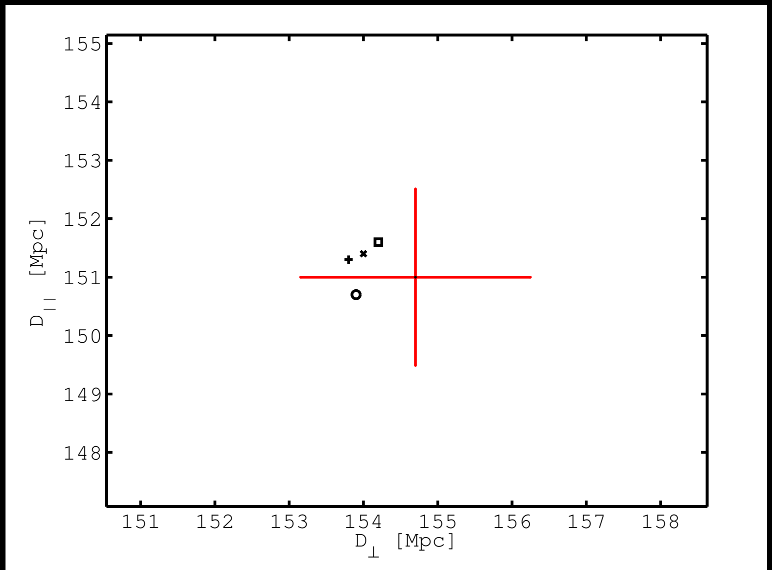
Assuming 1% error on the clustering measurements leads to ~1% error on the distances.



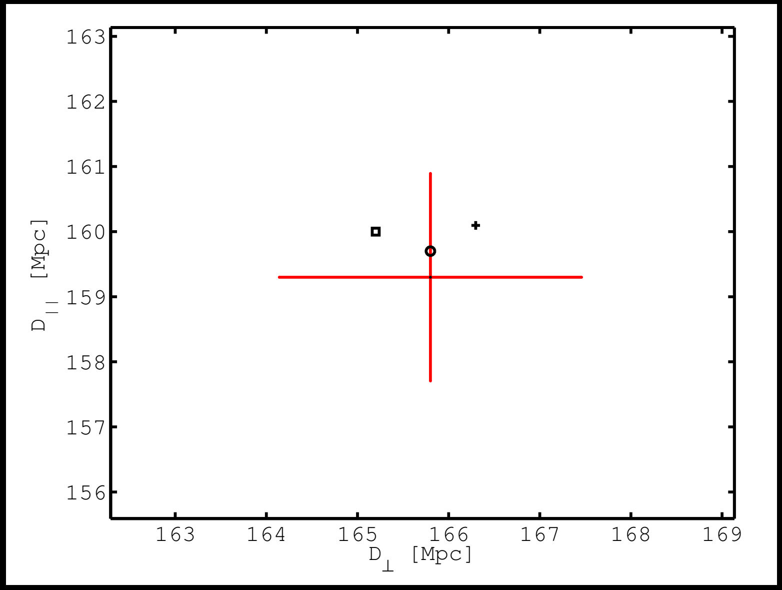
Anisotropic BAO Peaks

Will certain systematic uncertainties effect our methodology to reliably estimate the peak location?

We show the derived distance measurements using models with various σv choices, of 0, 2, 4, 6, 8 Mpc/h. No significant trend or deviation with these values of σv with either D// or D⊥ and all measurements lie within a 1% error margin.



we show the effect of changing the bias factor on the derived distance measures. We find that values of b = 1.2, 1.4,1.6, 1.8 all give consistent values of $D_{//}$ and $D_{\perp}$.



We also checked the effect of shifting the overall shape of the spectrum and looked at Linear vs NonLinear templates. However all give 1% level or less deviations on the distances. So our fitting function seems to have enough freedom to accommodate many unknown factors that, in the end, we don't want to deal with!

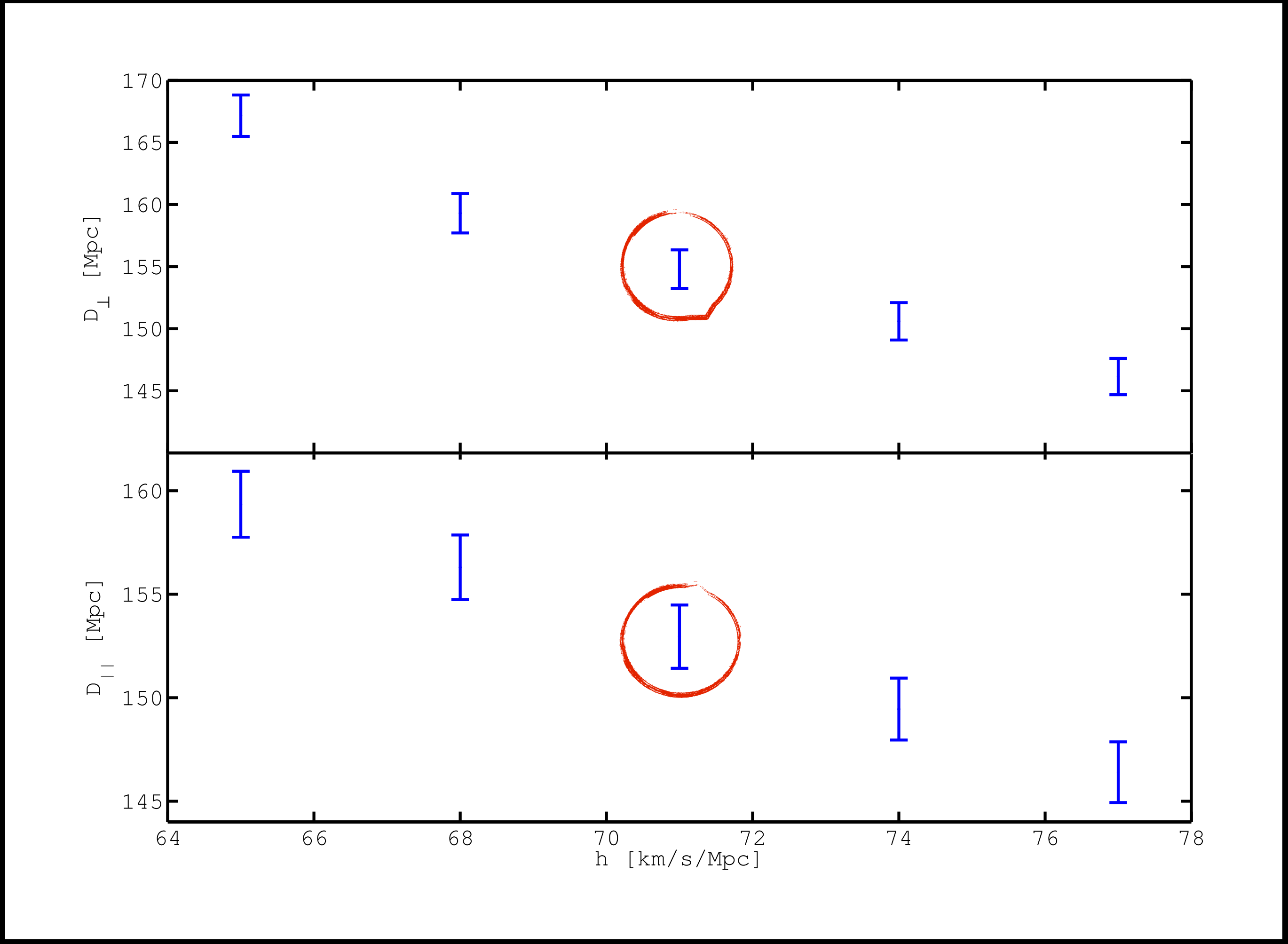
Anisotropic BAO Peaks

Will certain systematic uncertainties effect our methodology to reliably estimate the peak location?

changing little h changes the amount of dark matter ($O_m=w_m/h^2$) and O_{DE} if assuming flatness. This then effects D_A and H^{-1}

The Alcock-Paczynski geometrical distortions are large compared to the systematic variations we found previously.

We are currently working on this method to give us tight and unbiased constraints on D_A and H^{-1}



Clustering Shells

with Xiao-Dong Li & Changbom Park (KIAS)

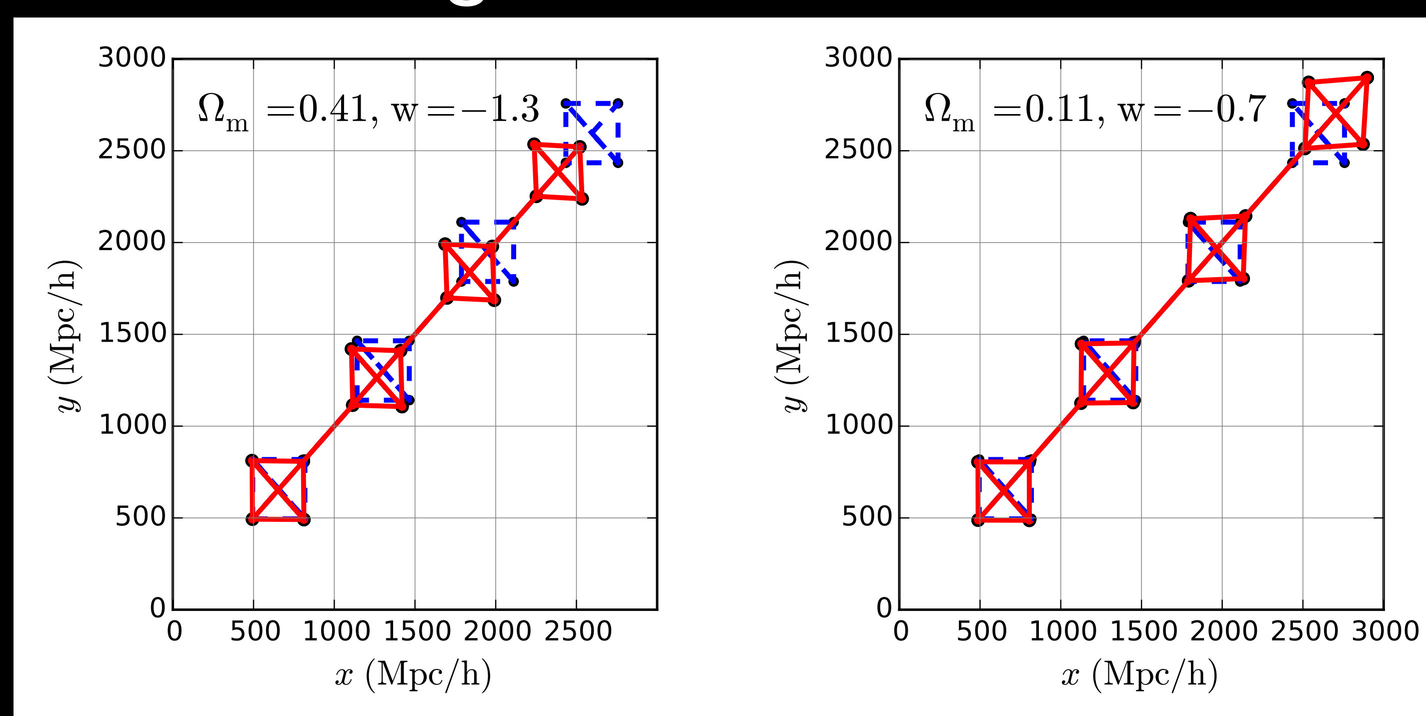
Even without a standard ruler, we can measure the clustering along and perpendicular to the line of sight and thus constrain the combination of D_A and H^{-1}

In this statistical analysis we aim to constrain the AP effect. Rather than using the BAO peak position, we use the integrated clustering signal in different directions.

$$\xi_{\Delta s}(\mu) \equiv \int_{s_{\min}}^{s_{\max}} \xi(s,\mu)\, ds.$$

Pictorially what happens to cosmological positions if translated using an incorrect cosmological model.

For Om=0.11, w=-0.7, we see a LOS shape compression and volume shrinkage.



For Om=0.41, w=-1.3, we see a stretch of the shape in the LOS direction and magnification of the volume

Clustering Shells

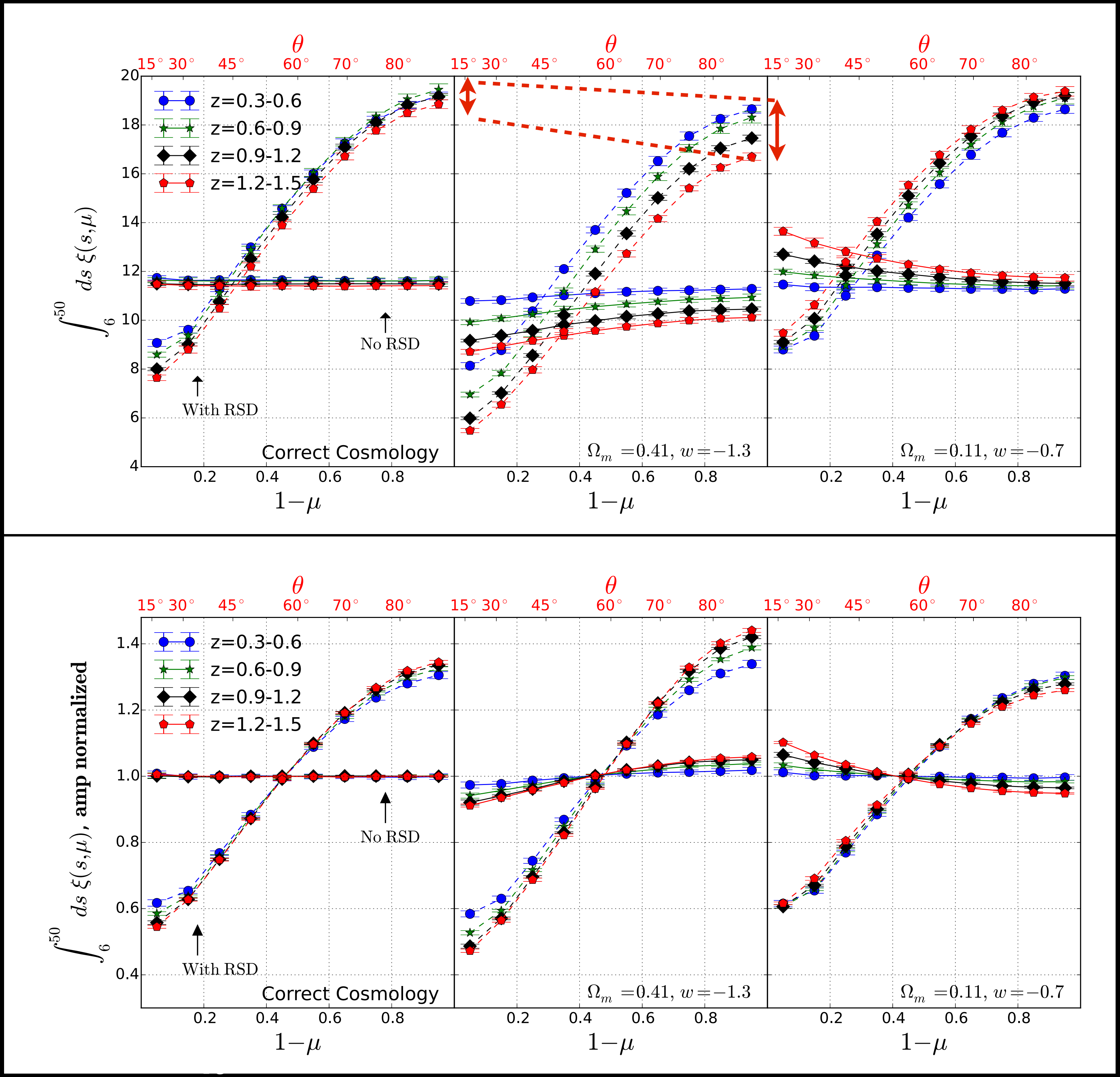
The integrated clustering strength as a function of angle at varies redshifts.

In the no RSD case in the correct cosmology the curves are flat. In the wrong cosmologies they are distorted.

With RSDs we see much more variation in shape and amplitude.

If we normalise the curves, then we remove amplitude information and minimise the volume effect thus focusing on a pure AP measurement.

Using mock many catalogues drawn from the Horizon Run simulations (from Juhan Kim, KIAS)



Clustering Shells

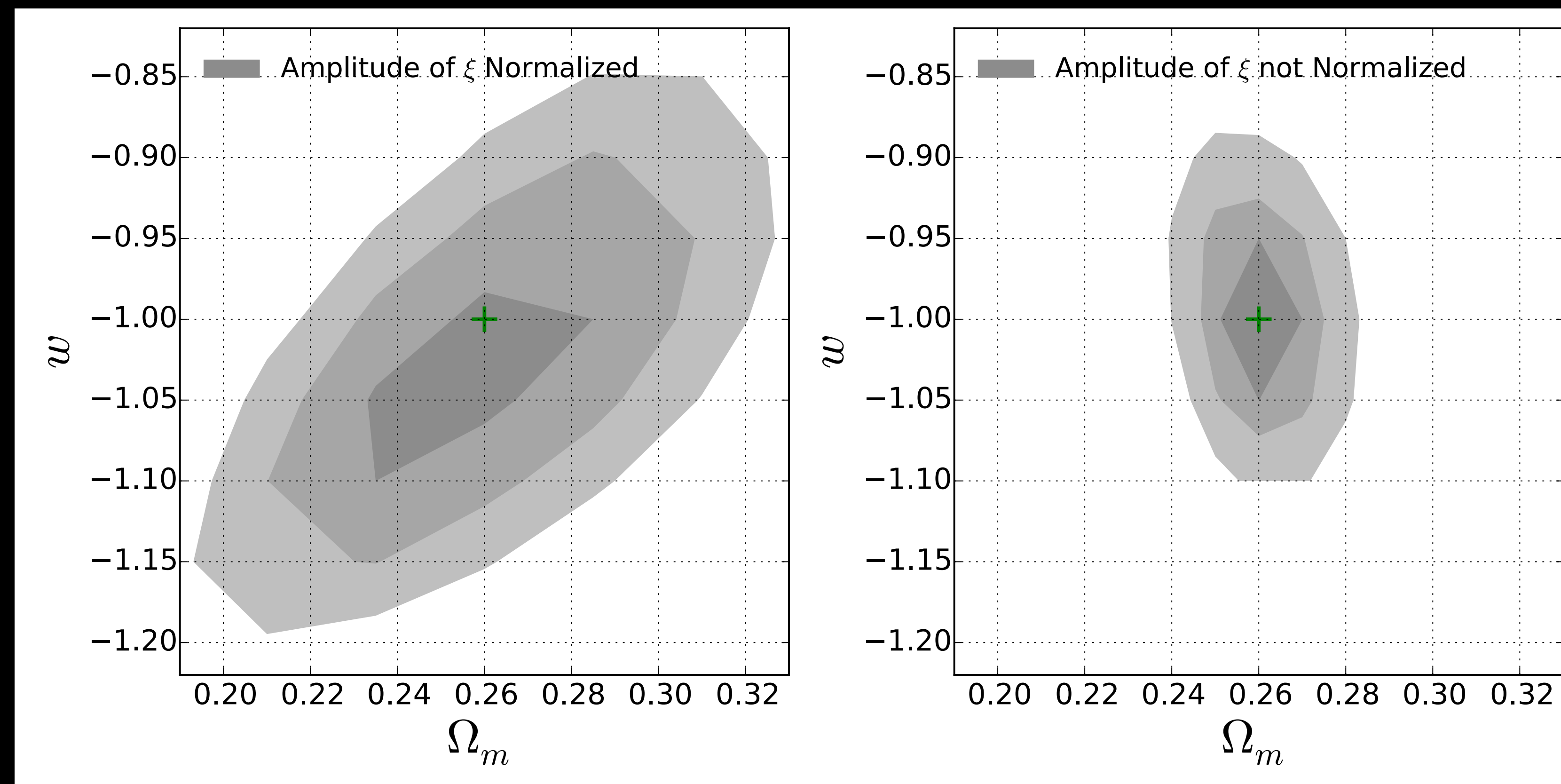
We construct a likelihood function by requiring that the shape change as a function of redshift is minimized. Of course there is a redshift evolution of the clustering, however this is modeled to first-order using N-body simulations.

$$H(z) = H_0\sqrt{\Omega_m a^{-3} + (1-\Omega_m)a^{-3(1+w)}},$$

$$D_A(z) = \frac{1}{1+z}r(z) = \frac{1}{1+z}\int_0^z \frac{dz'}{H(z')},$$

$$\frac{[\Delta r_{\parallel}/\Delta r_{\perp}]_{\rm wrong}}{[\Delta r_{\parallel}/\Delta r_{\perp}]_{\rm true}} = \frac{[D_A(z)H(z)]_{\rm true}}{[D_A(z)H(z)]_{\rm wrong}},$$

$$\frac{\rm Volume_{wrong}}{\rm Volume_{true}} = \frac{[D_A(z)^2/H(z)]_{\rm wrong}}{[D_A(z)^2/H(z)]_{\rm true}},$$



The clustering shells provide a similar constraints to those obtained from standard BAO analysis.

The volume effect, which causes redshift evolution in the amplitude of 2pCF, leads to very tight constraint on cosmological parameters. But it suffers from systematic effects of growth of clustering and the variation of galaxy sample with redshift.

Conclusions

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- we have shown that the anisotropic BAO peak positions are unaffected by the systematics we consider, namely bias, FoG, non-linear templates.

- this method therefore provides an unbiased constraints on $D_A(z)$ and $H^{-1}(z)$.

- we are working now on the constraining power of this method considering current and future data from SDSS BOSS -> DESI.

- The anisotropic 'clustering shells' provide unbiased and tight constraints on w and Om, considering flat LCDM model.

- However more generally this methodology can be used to track the expansion history.