Higher Order Clustering Statistics
Towards the generalised BAO structure

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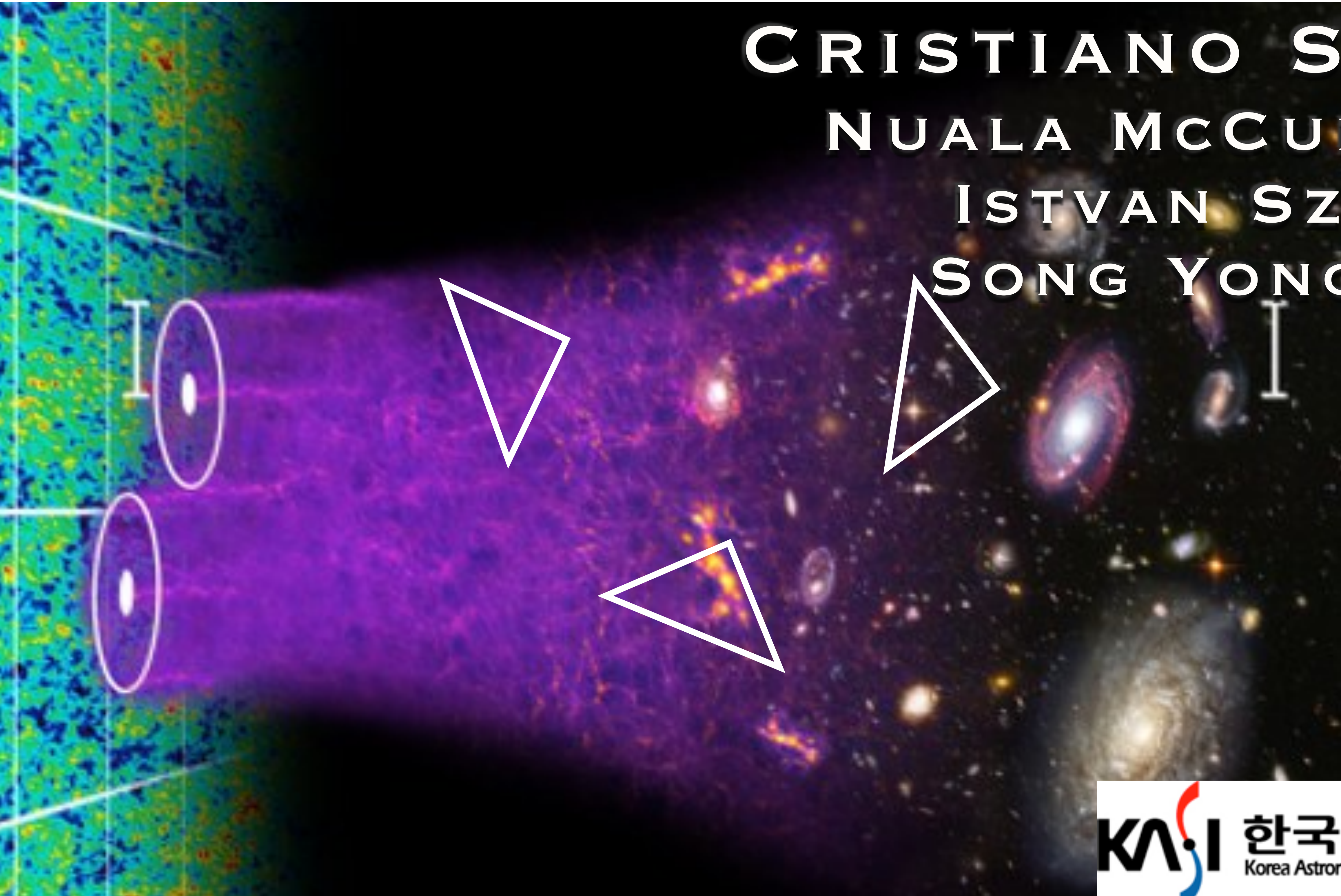

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Outline

- Background
  - Cosmic distances
  - Statistics
  - Theory and Systematics

- Model-independent estimates of cosmic distances
  - mitigating BAO systematics
  - utilizing the Alcock-Paczynski effect
  - The BAO ring
  - Higher dimensional BAO

Background

Key observables in spectroscopic galaxy surveys:

(1) 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.

(2) 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.

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

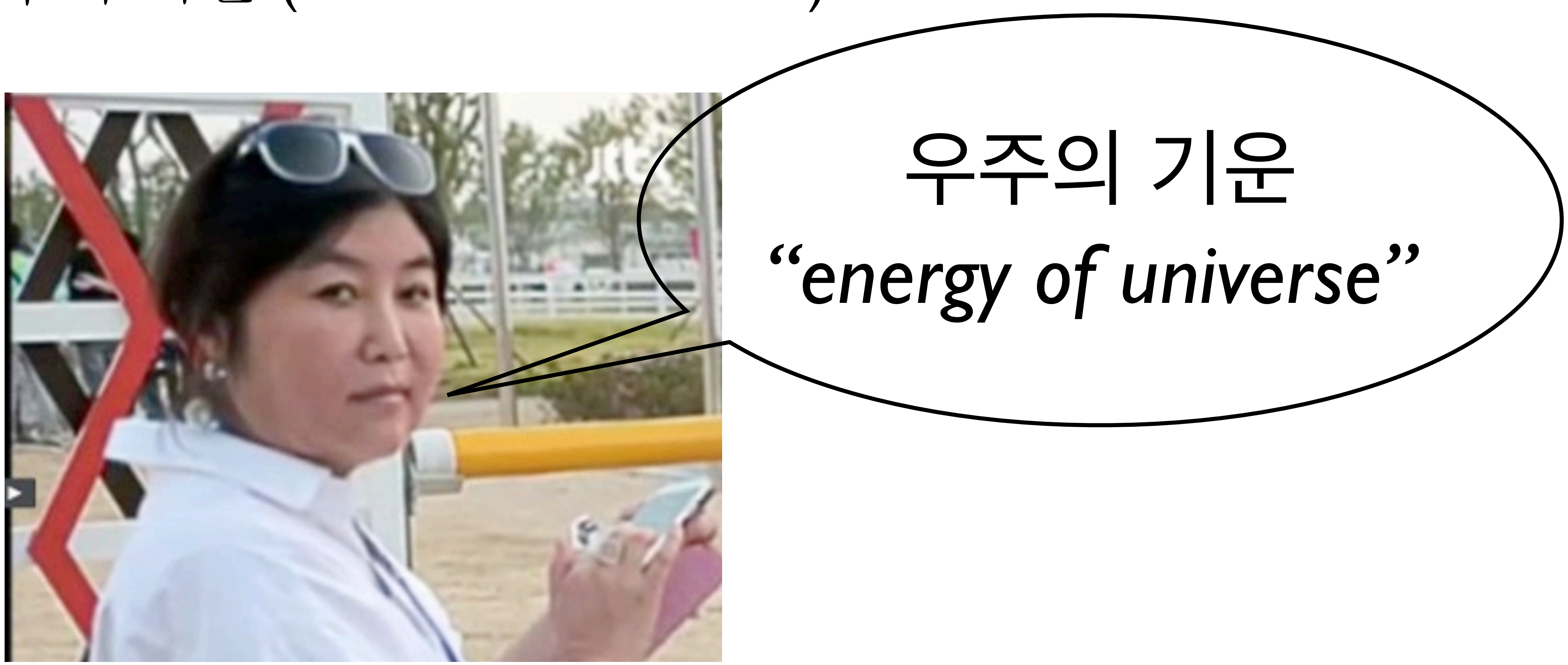
$$D_A(z) = \frac{1}{1+z} r(z) = \frac{1}{1+z}\int_0^z \frac{dz'}{H(z')},$$

(3) Growth Rate, f **(dδ/d ln a)**
- 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.

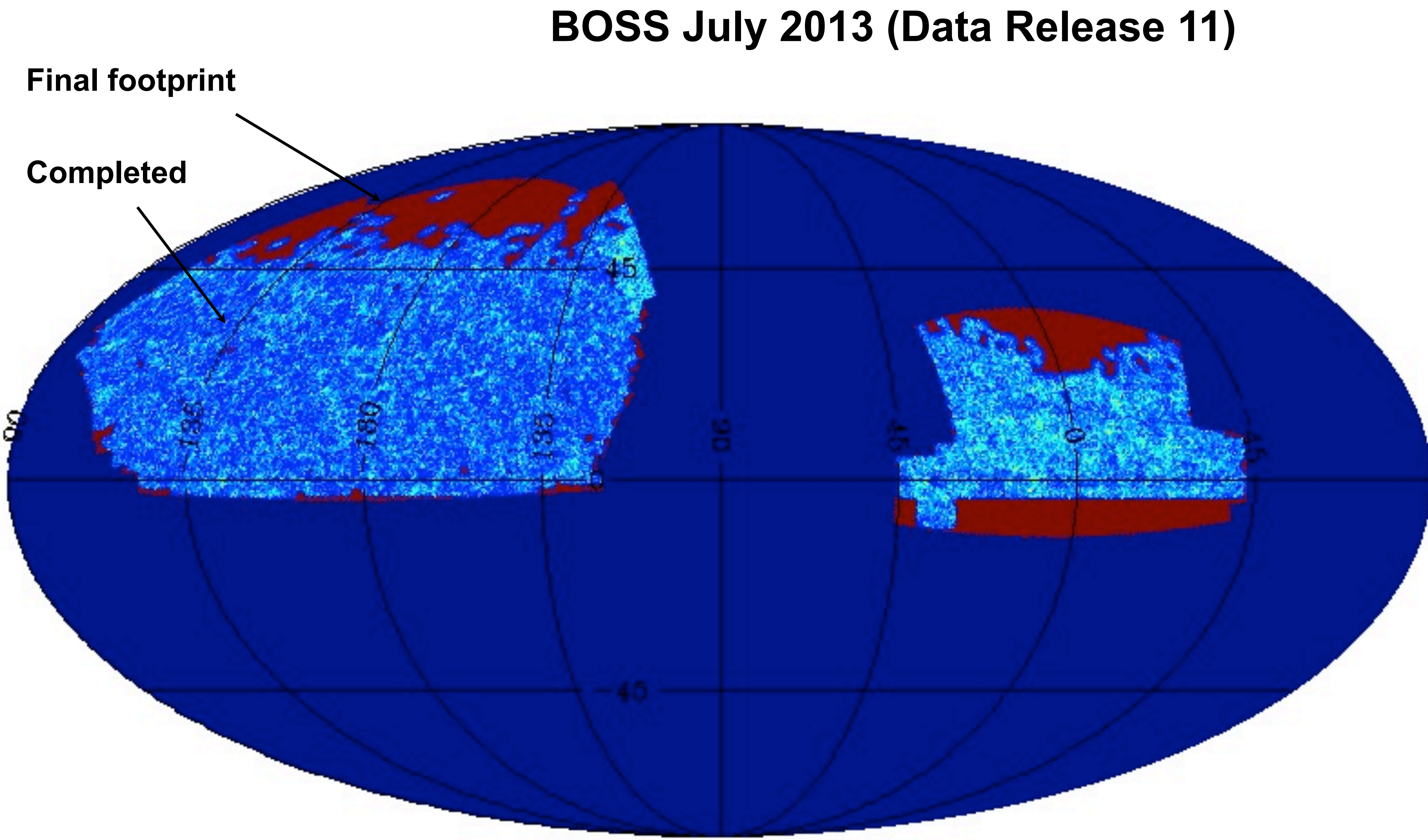
Background

Distances are essential to test theoretical models explaining cosmic acceleration;

- **ΛCDM**
- **Dynamical DE**
- **Non-Einsteinian gravity**
- **Holographic arguments**
- **.......**
- 우주의 기운 (Choi Sun-Sil etal 2015)



BOSS: Survey Progress



Statistics: Correlation Functions

We want to evaluate the 2-point statistics of the over-density field, **δ**

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

We call this the two-point correlation function

$$\xi(r) = \sum_i \frac{n_i(r)}{\bar{n} dV} - 1$$

Algorithmically calculate pair counts according to Landy-Szalay estimator

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

The probability of finding a galaxy in 2 volume elements separated by r

$$dP = n^2 \left[1 + \xi(r)\right] dV_1 dV_2$$

Statistics: Correlation Functions

We want to evaluate the
2-point statisti
over-density

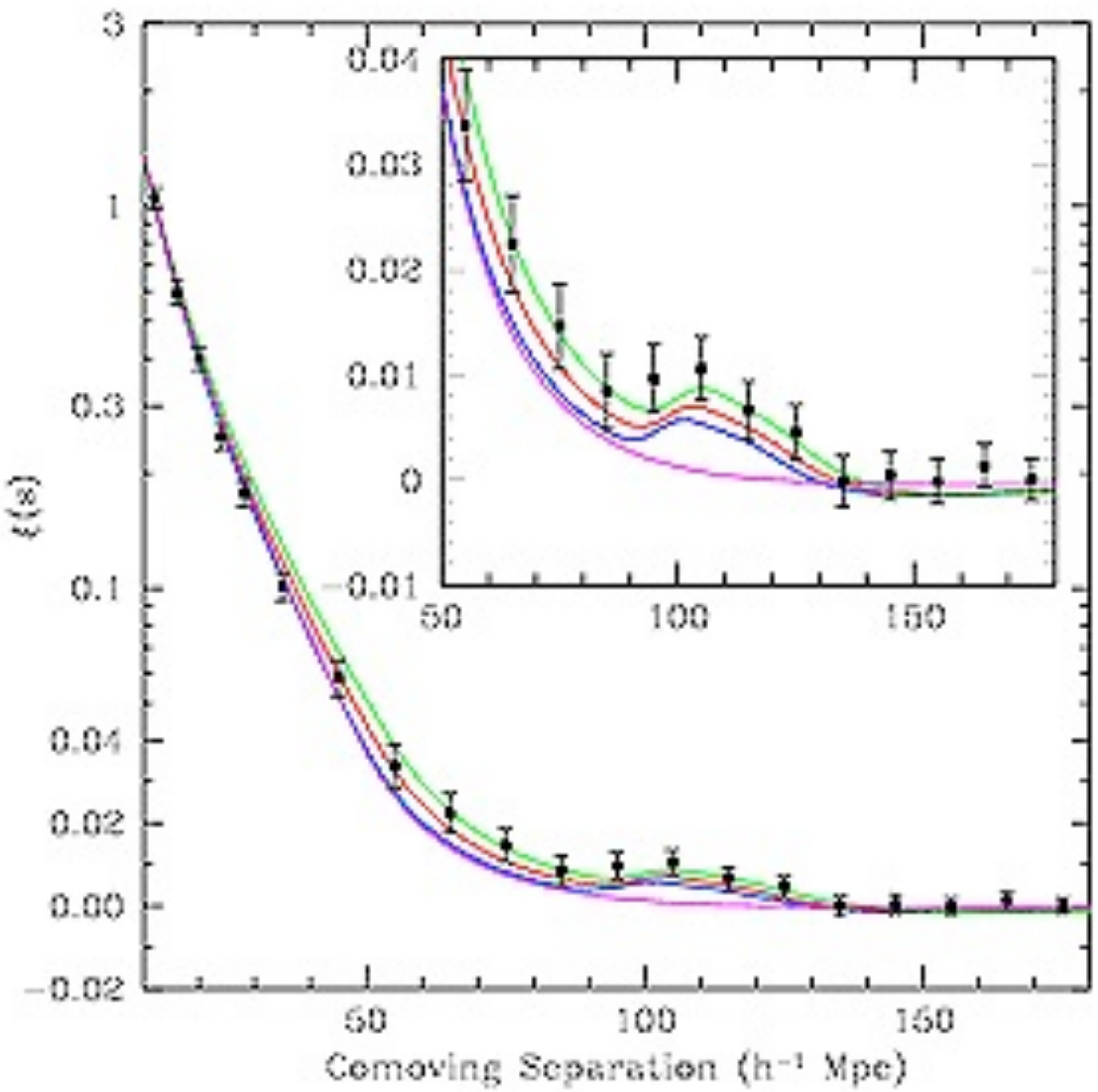
$$x + r))\rangle_x$$

We call this the
correlation f

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

Algorithmically
pair counts acc
Landy-Szalay e

$$- 2DR + RR \over RR$$



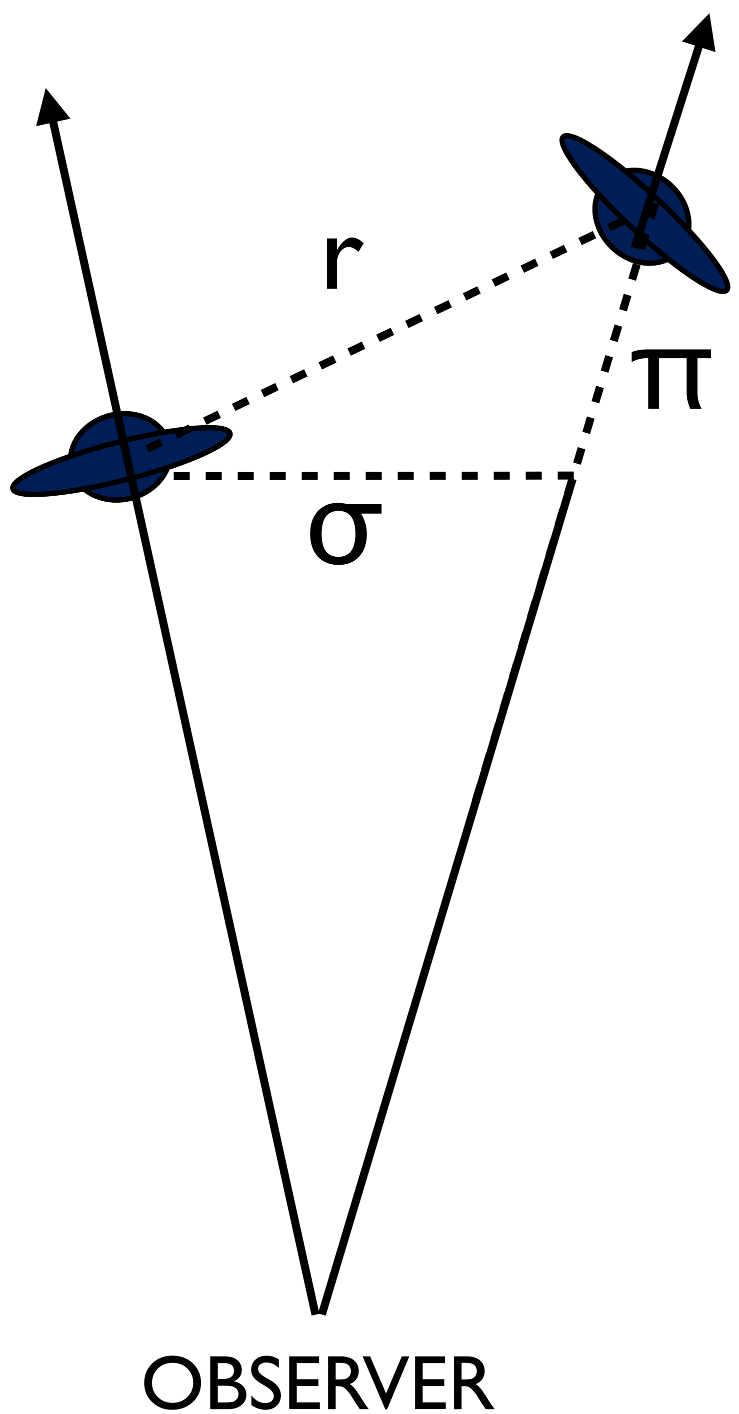
(www.sdss3.org)

The probability
a galaxy in 2 volume
elements separated by r

$$+ \xi(r)]\, dV_1 dV_2$$

Statistics: Anisotropic 2PCF

From 1D -> 2D



Bin pairs of galaxies into distances (σ, π) rather than just one distance, r.

Apart from the binning scheme the statistic is computed in the same way....

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

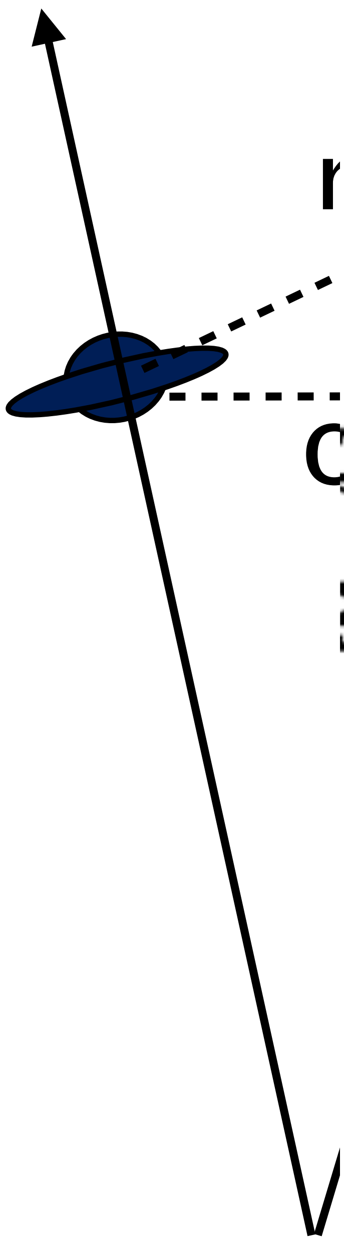
If there are no preferred directions then the result would be perfectly circular iso-clustering contours in (σ, π)-space

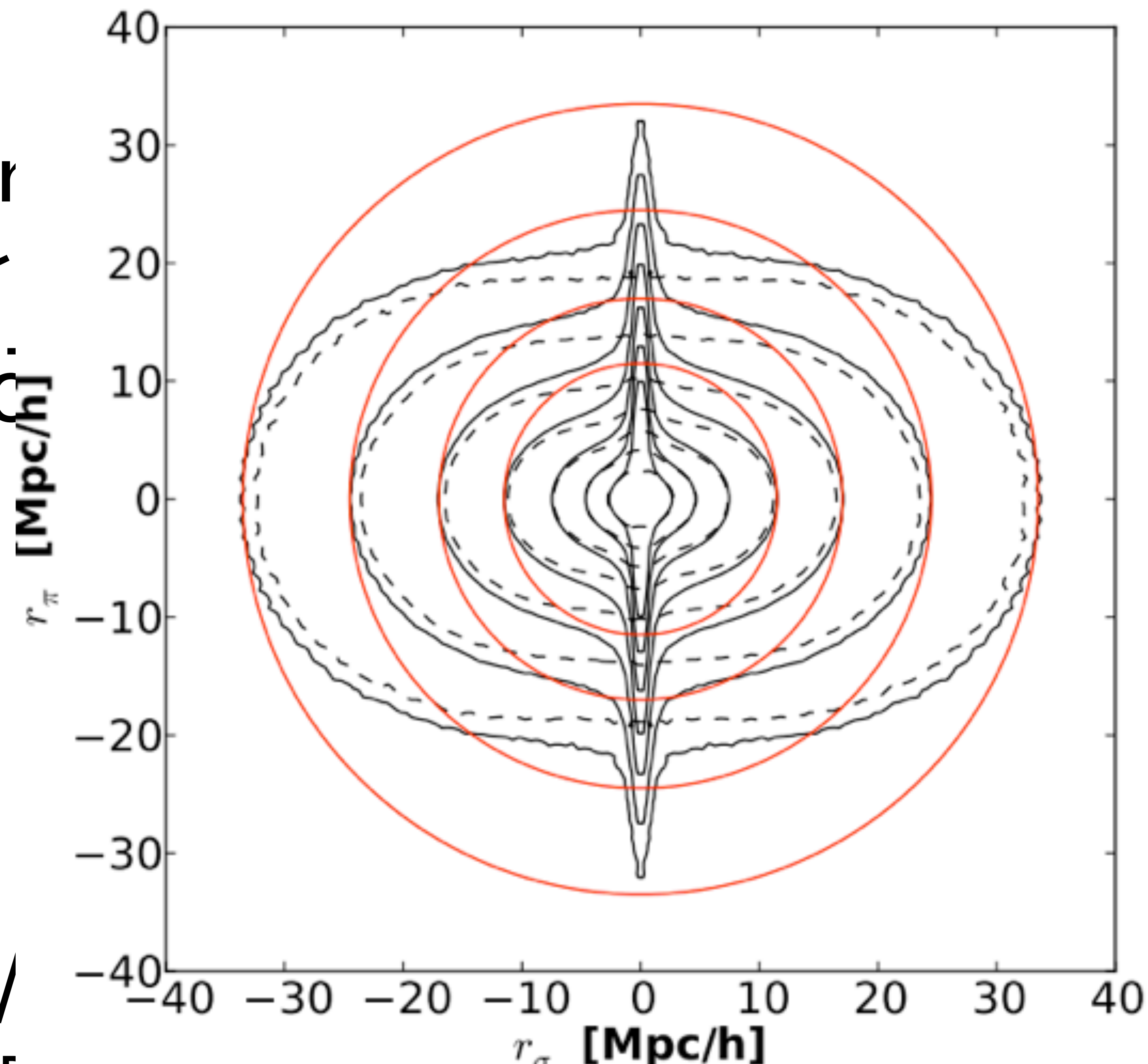
Statistics: Anisotropic 2PCF

From 1D -> 2D

Bin pairs of galaxies into distances

one





g scheme

ed in the

$+ RR$

ed

sult would

o-clustering

OBSERVER

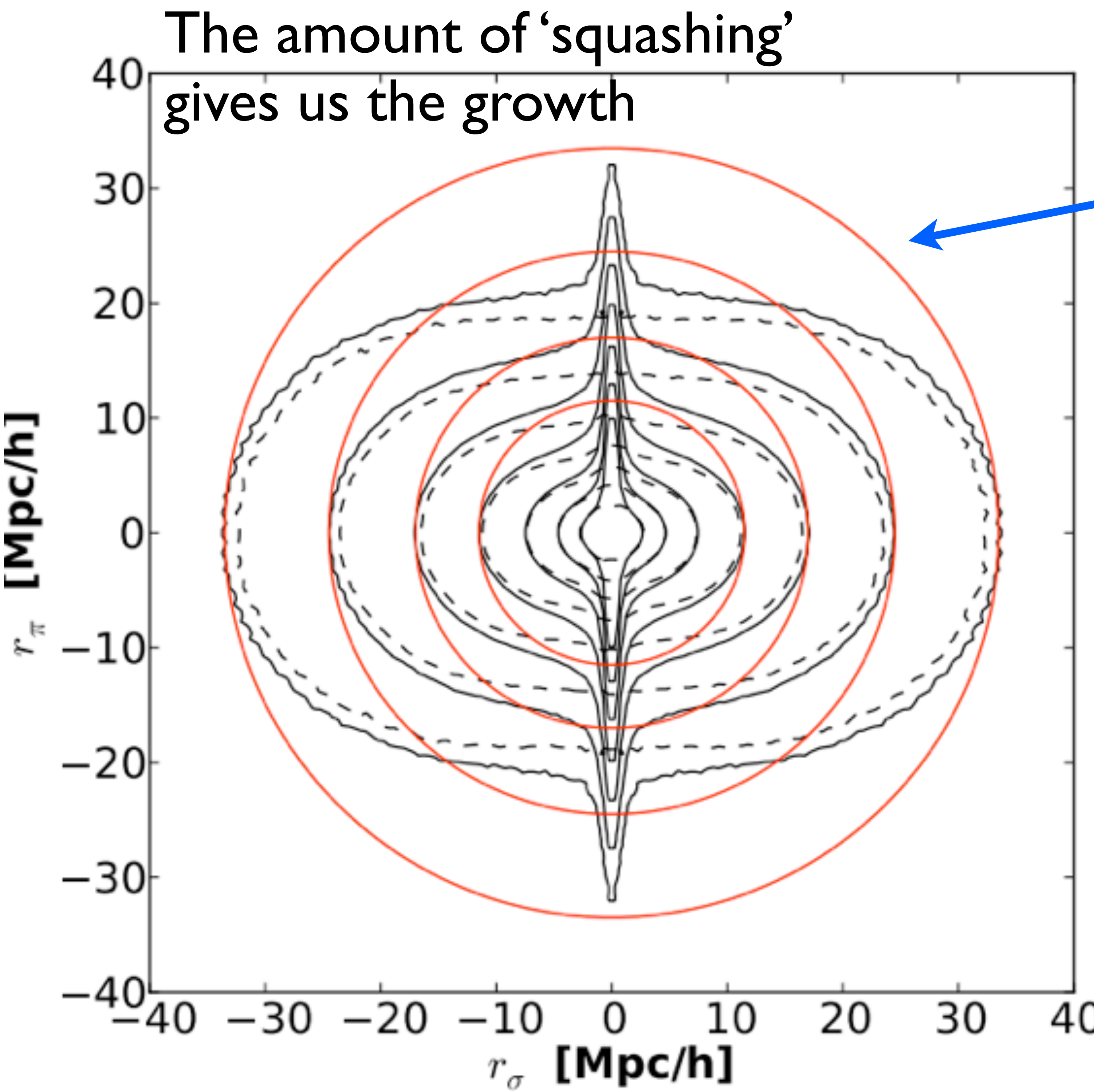
contours in (σ, π)-space

Anisotropic 2PCF

3 main contributions to anisotropic clustering:

- Non-linear, Fingers of God (FoG)
- Linear, Large Scale Velocities (Kaiser)
- Incorrect cosmological parameters
  - i.e. Alcock-Paczynski effect (AP)

Anisotropic 2PCF



Red - No RSD

Dashed - Linear

Solid - Linear + FoG

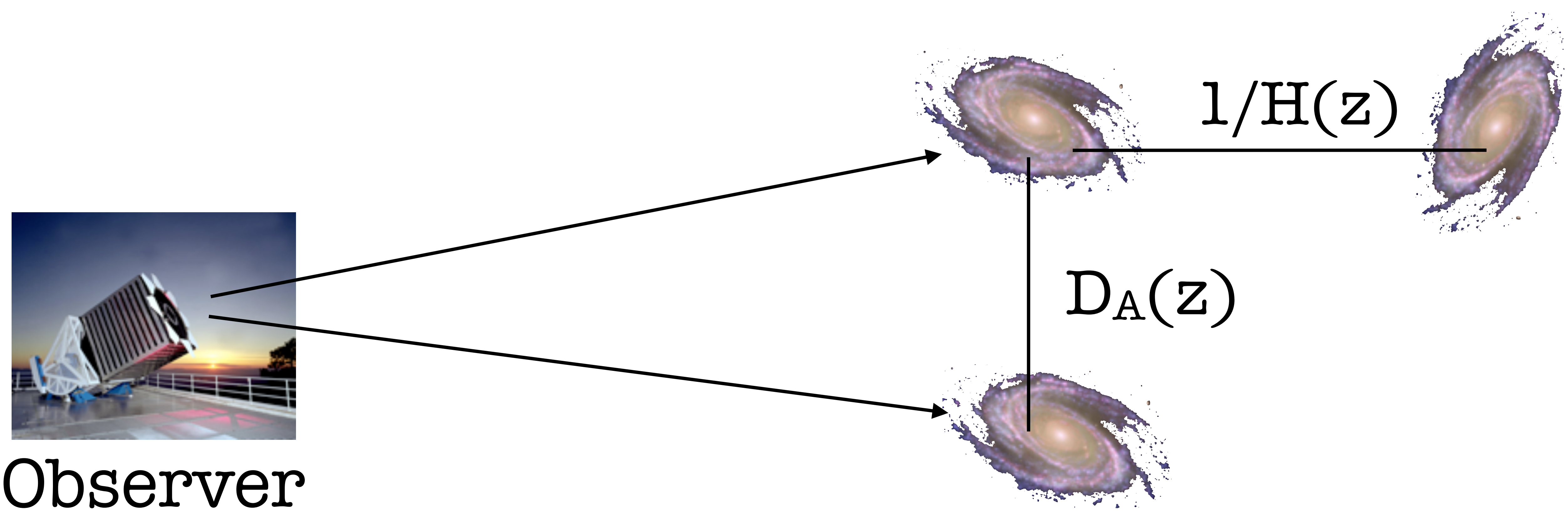
Nonlinear regime theoretically difficult to model

M. White et al (2011)

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

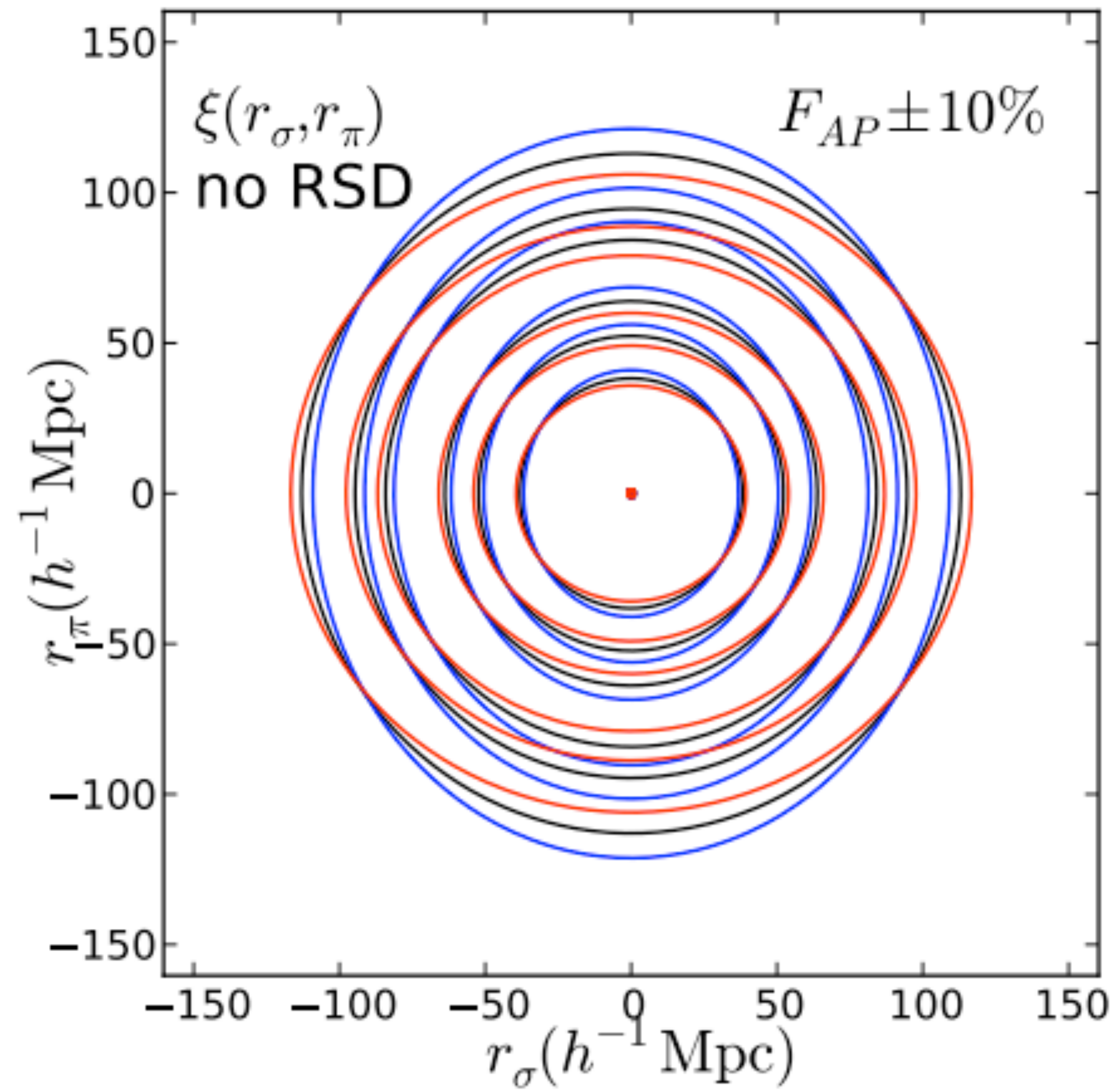


Alcock-Paczynski Effect

$\xi(r_p, \pi)$ appears anisotropic if you assume the wrong cosmology;

constrains the combination:
$F(z) \equiv (1+z)\, D_A(z)\, H(z)/c$

However geometric distortions can be modeled exactly:



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

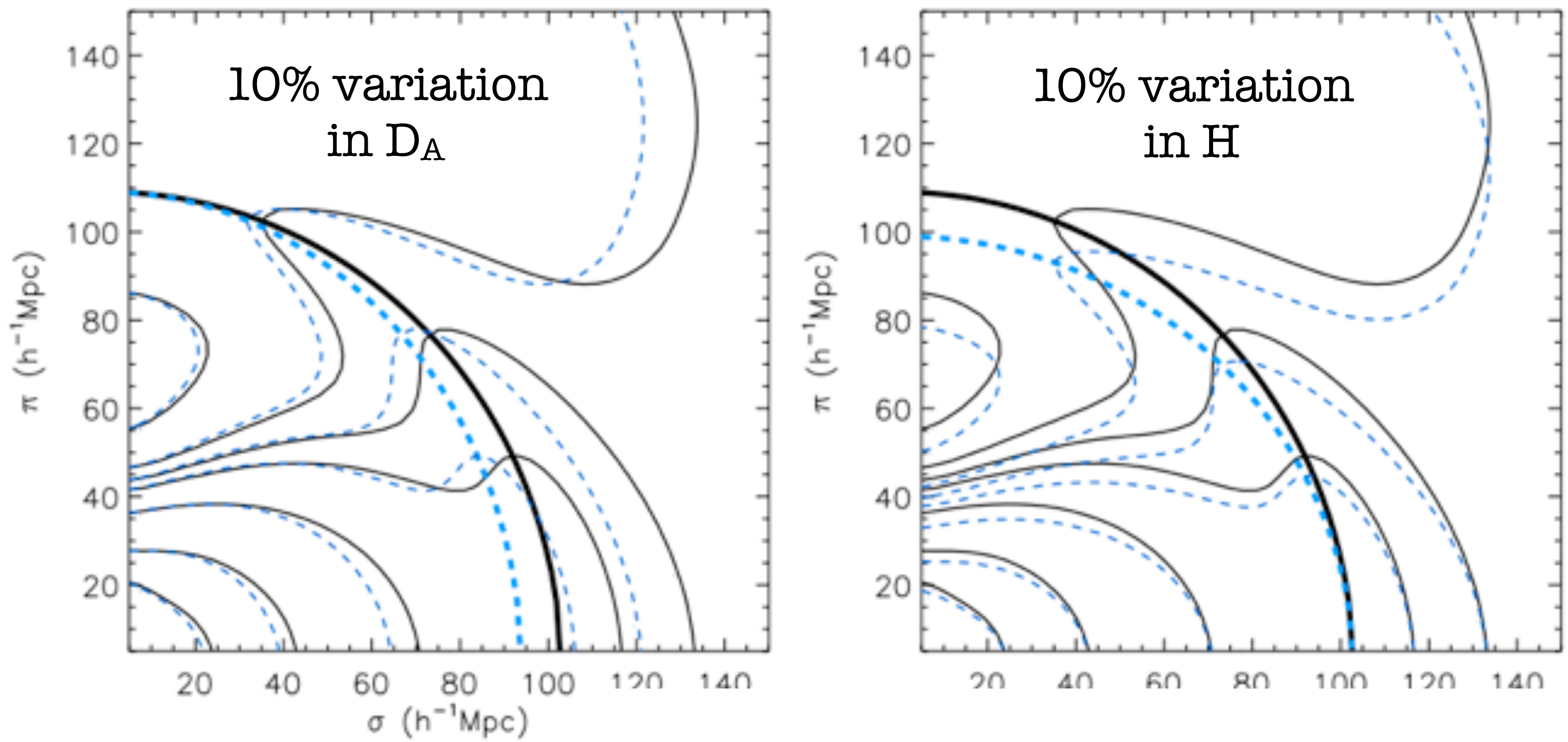
$$\alpha_\perp = \frac{D_A^{\mathrm{fid}}(z_{\mathrm{eff}})}{D_A^{\mathrm{true}}(z_{\mathrm{eff}})}, \qquad \alpha_\parallel = \frac{H^{\mathrm{true}}(z_{\mathrm{eff}})}{H^{\mathrm{fid}}(z_{\mathrm{eff}})},$$

Pure Alcock-Paczynski Measure

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

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

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

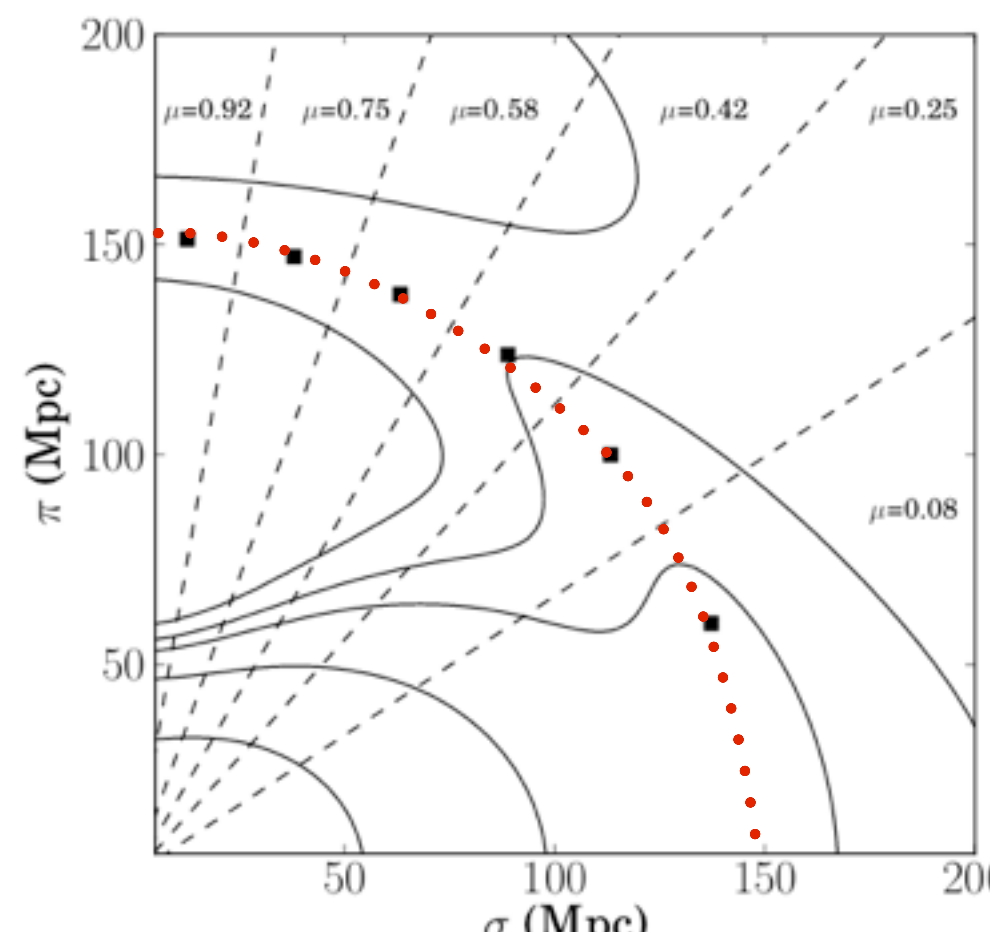


D_A, H vary peak positions off the BAO ring.

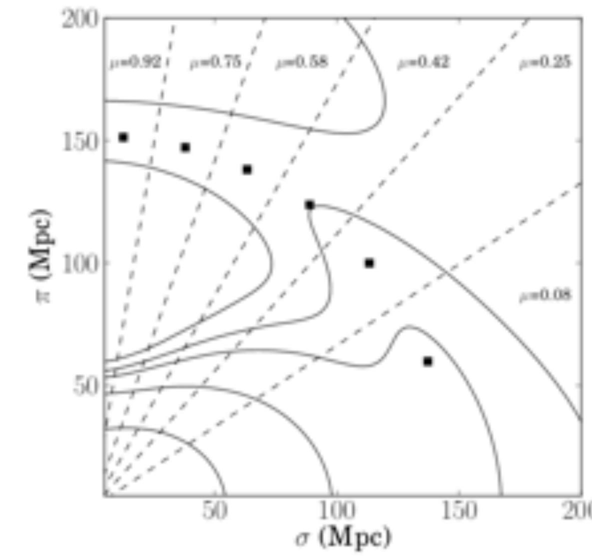
We want to avoid fitting the full shape of the anisotropic correlation function, as it depends on unknown systematic and physics, like scale dependent bias, etc.

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

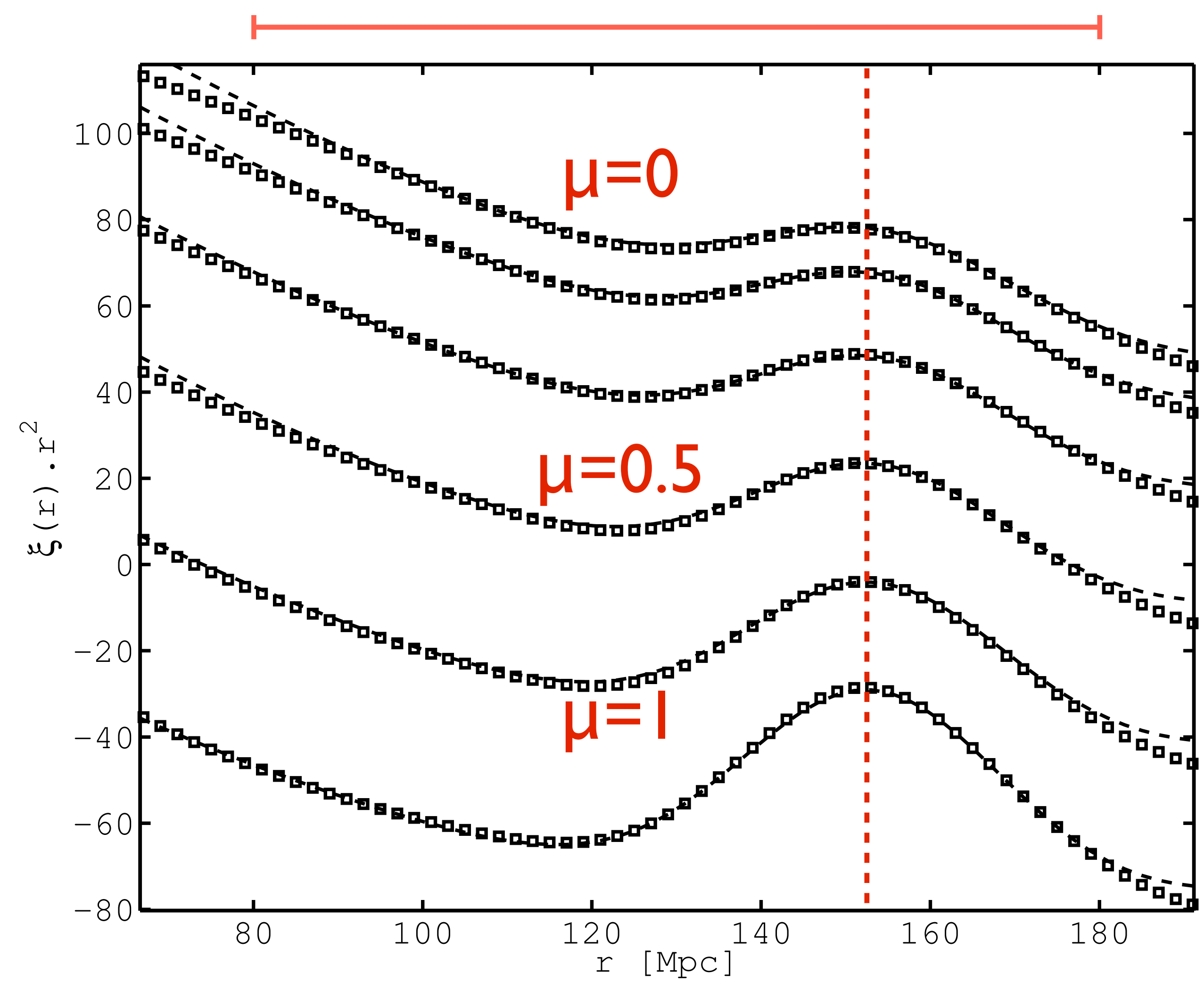


$$\xi_{\mu}(s) \times s^2 = A.s^2 + B.s + Ee^{-(s-D)^2/C} + F,$$

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.

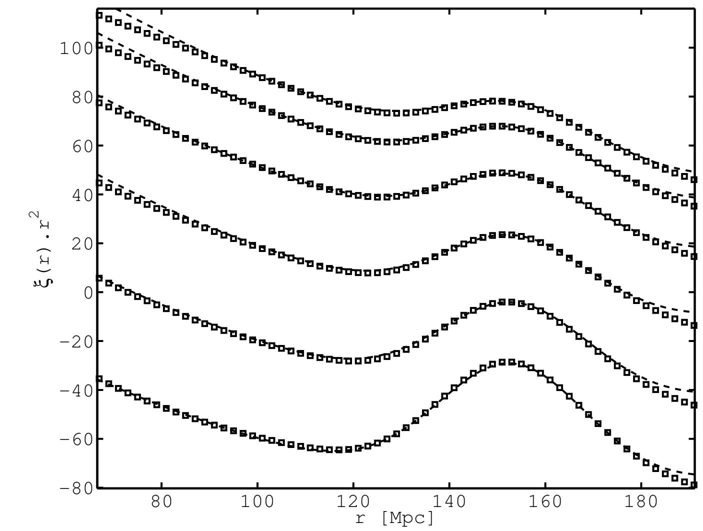


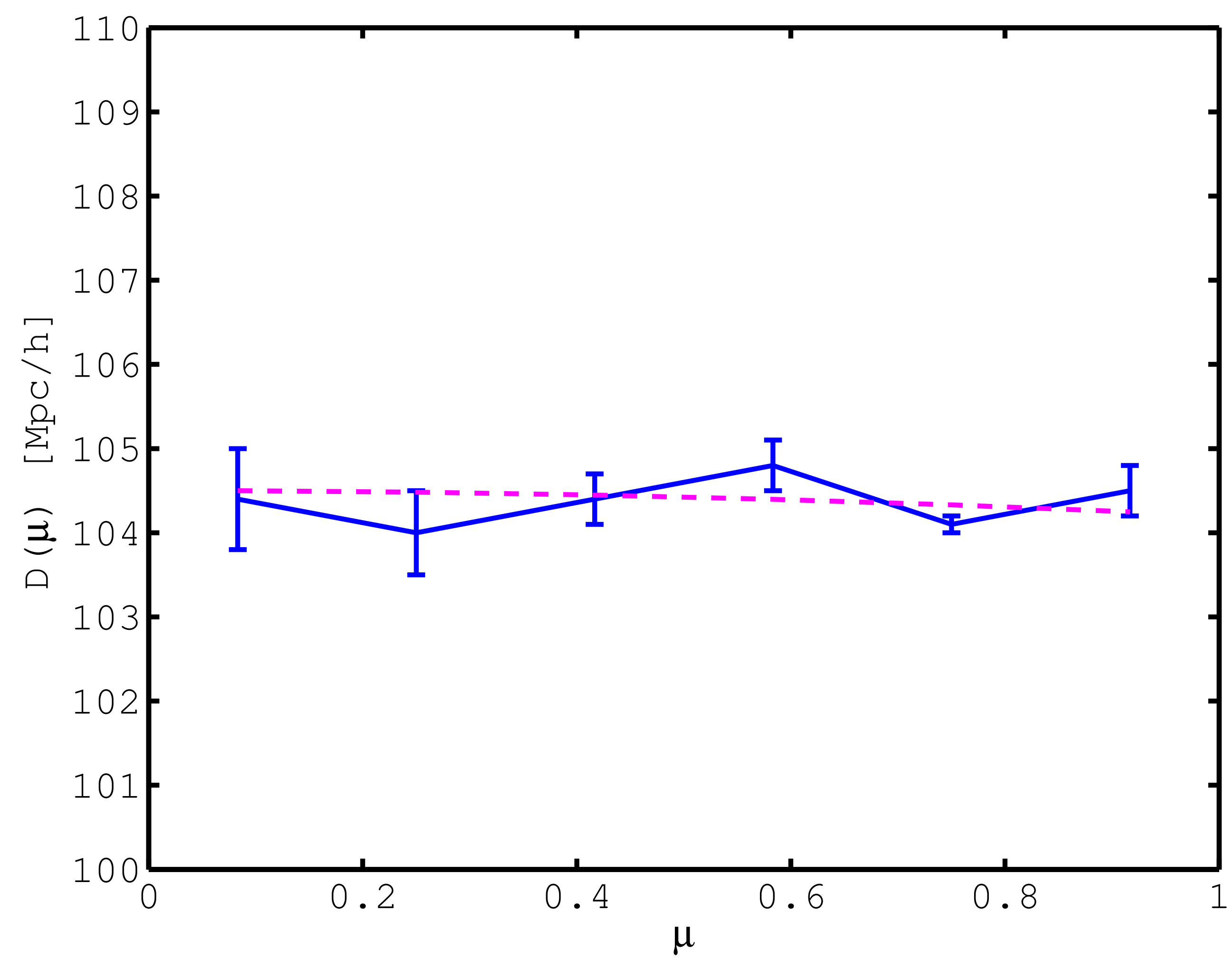
Anisotropic BAO Peaks

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

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

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

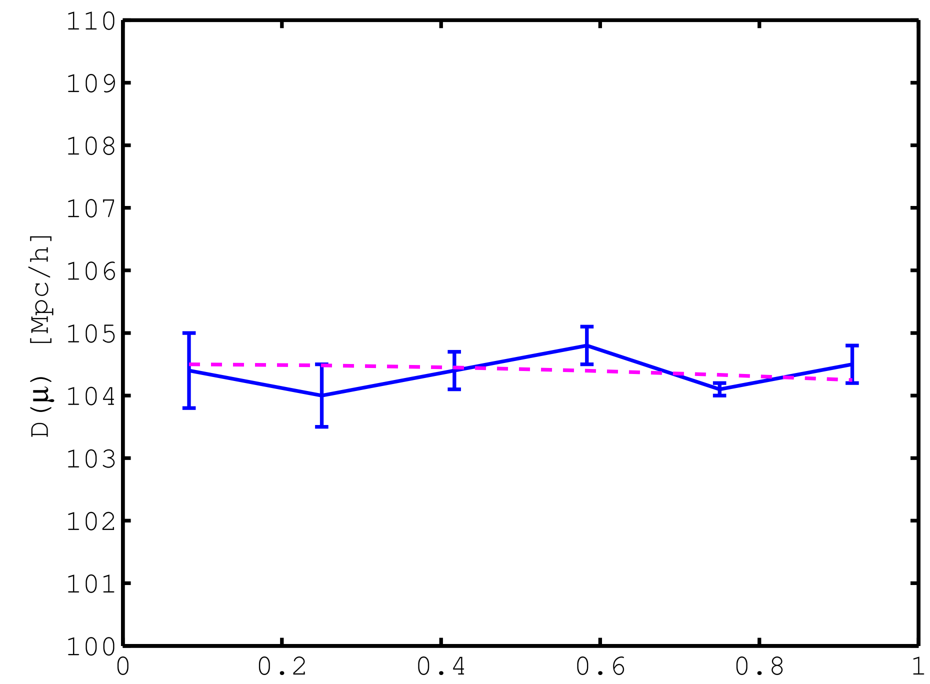




Anisotropic BAO Peaks

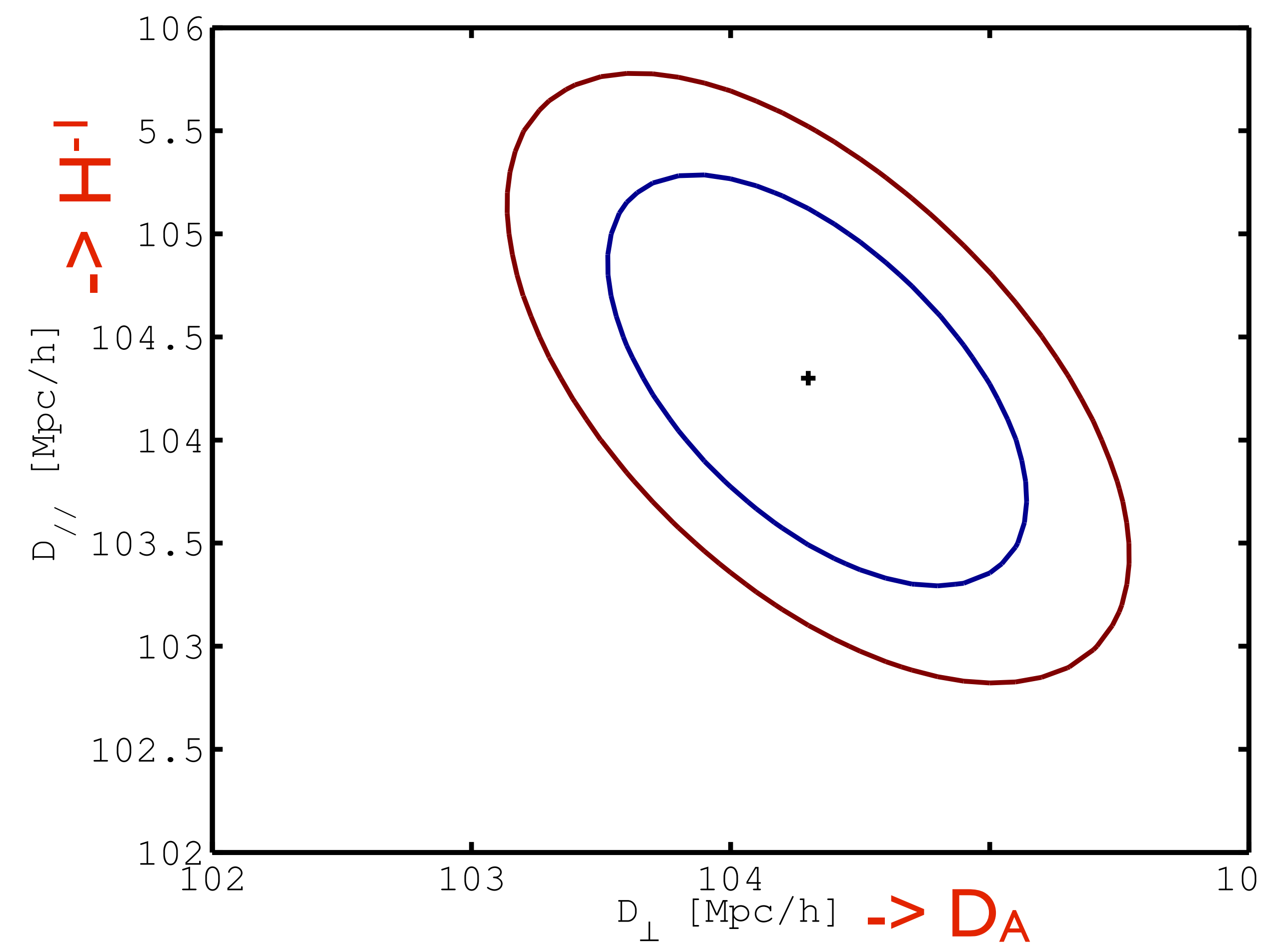
$$D(\mu) = \frac{D_\perp . D_{||}}{\sqrt{(D_\perp.\mu)^2 + D_{||}^2(1-\mu^2)}}$$

$$\begin{aligned} H_{obs}^{-1} &= H_{fid}^{-1}\frac{D_{||,fid}}{D_{||,obs}}, \\ D_{A,obs} &= D_{A,fid}\frac{D_{\perp,fid}}{D_{\perp,obs}}. \end{aligned}$$



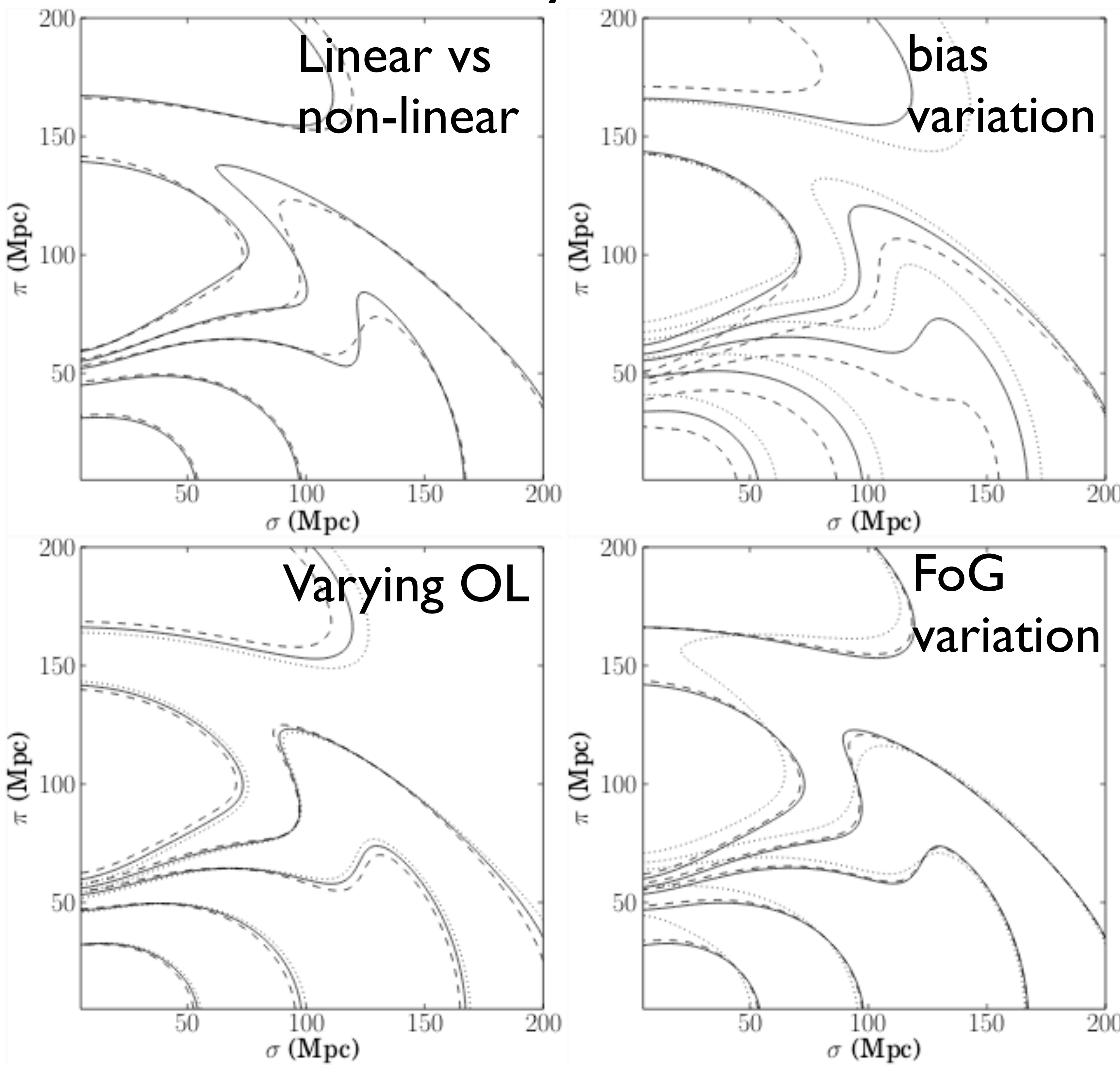
Next we create theoretical models that include different systematics and and observational effects.

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



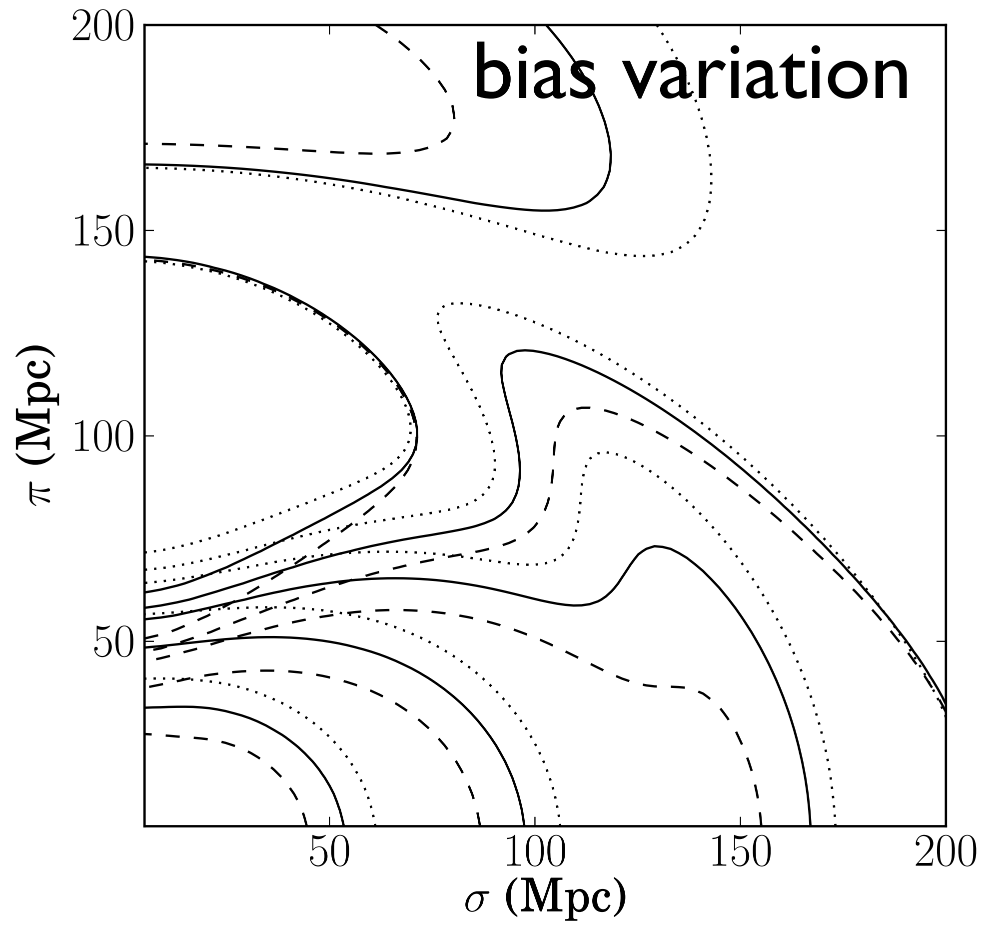
Anisotropic BAO Peaks

Check systematics

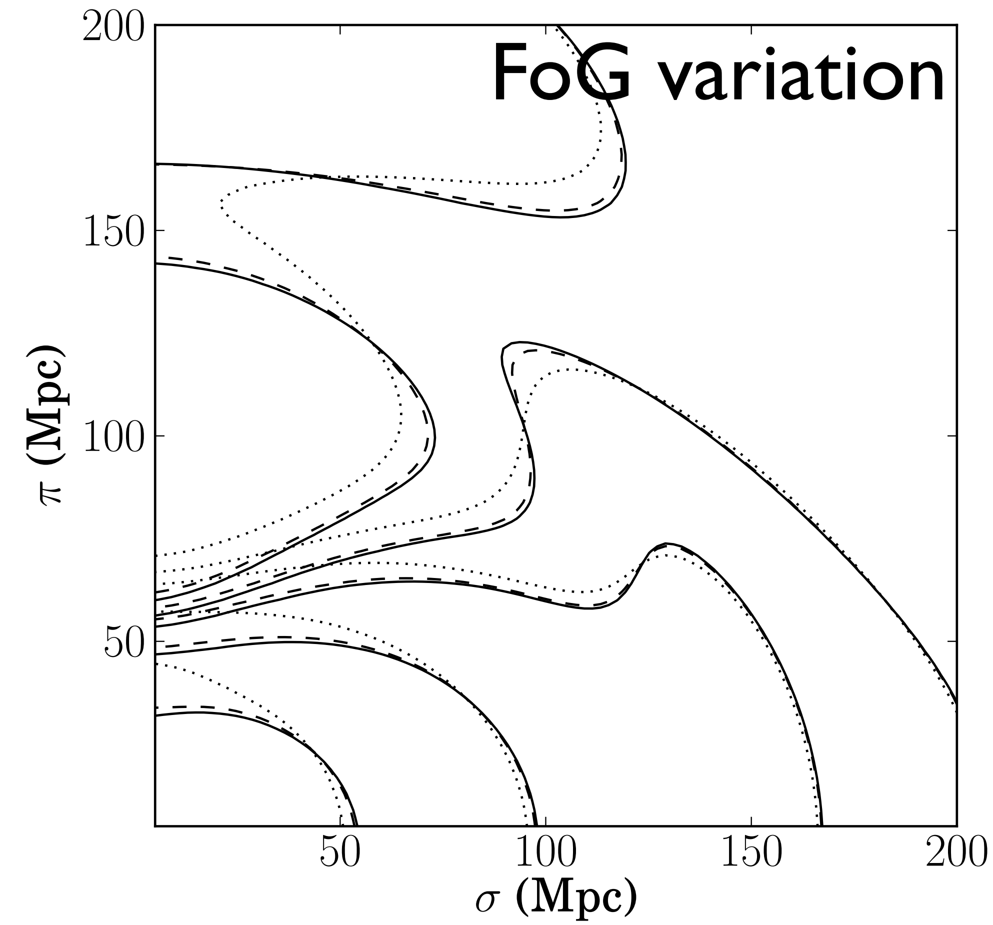


Anisotropic BAO Peaks

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



bias	D_A(Mpc)	H^{-1}(Mpc)
1.5	1395.18 (0.00 %)	3241.28 (0.20%)
2.0 (fid)	1395.18 (0.00 %)	3234.76 (0.00 %)
2.5	1384.29 (-0.78%)	3234.76 (0.00%)



σ_v(Mpc)	D_A (Mpc)	H^{-1} (Mpc)
2	1392.47 (-0.19 %)	3253.96 (0.59%)
5 (fid)	1395.18 (0.00 %)	3234.76 (0.00 %)
8	1395.18 (0.00 %)	3234.76 (0.00 %)
11	1397.99 (0.20 %)	3166.40 (-2.11%)
15	1397.99 (0.20 %)	3077.53 (-4.86%)

Anisotropic BAO Peaks

Modeling the RSD effect

We show the derived distance measurements using models with various σv choices, of 0, 2, 4, 6, 8 Mpc/h. We find a significant trend with these values of σv with either D// and D⊥

But as we can see both D// and D⊥ can be modelled using a simple function:

$$D(\mu) = D^{fid}(\mu) + \alpha(\mu) + \beta(\mu)\sigma_v^2,$$

Although the dashed lines show 1% and 4% increase in H-1 which follows closely the σv induced anisotropy, so there will be some degeneracy.

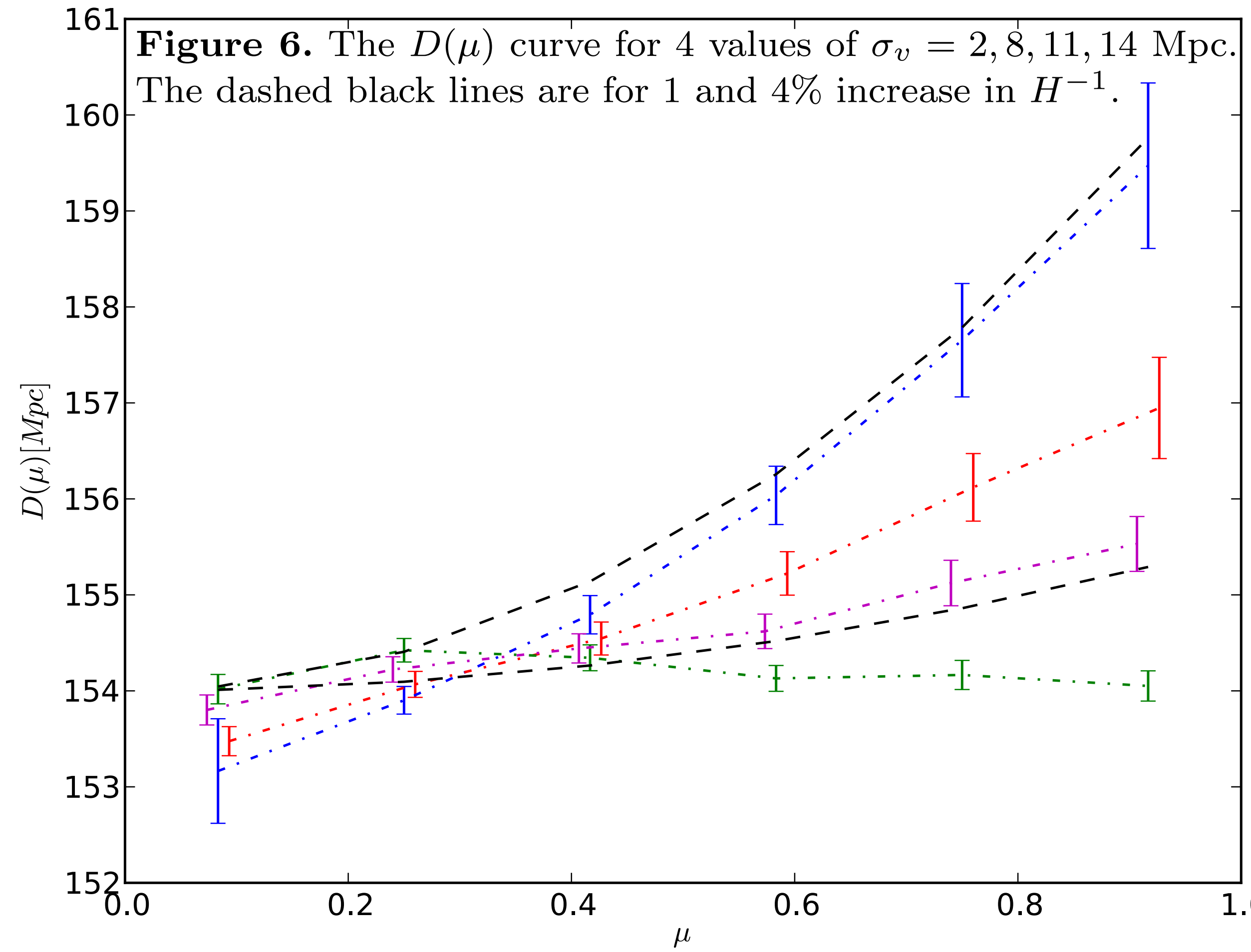


Figure 6. The $D(\mu)$ curve for 4 values of $\sigma_v = 2, 8, 11, 14$ Mpc. The dashed black lines are for 1 and 4% increase in H^{-1}.

	Ω_Λ	0.62		0.68		0.73	
		α_i	β_i	α_i	β_i	α_i	β_i
	0.08	-0.18	-0.004	-0.15	-0.004	-0.21	-0.004
	0.25	0.21	-0.003	0.07	-0.002	0.10	-0.002
μ_i	0.42	-0.17	0.002	-0.10	0.002	-0.09	0.002
	0.58	-0.51	0.009	-0.47	0.010	-0.42	0.009
	0.75	-0.77	0.018	-0.68	0.018	-0.65	0.018
	0.92	-1.07	0.027	-0.88	0.026	-0.89	0.027

<u>minimal cosmological dependance</u>

Anisotropic BAO Peaks

Modeling the RSD effect

Modeling the RSD effect allows us to make percent level predictions of Da, H for future surveys, like DESI

Firstly we fit the case without RSD. If we do not correct for the RSD effect we know from previous tests that our results on H^{-1} will be necessarily biased. We find $D_{||} = 155.15 \pm 0.51$ Mpc and $D_{\perp} = 154.04 \pm 0.30$ Mpc that results in the following constraints; $D_A = 1399.71^{+2.71}_{-2.74} (0.32^{-0.20}_{+0.19}\%)$ and $H^{-1} = 3196.79^{+10.57}_{-10.44} (-1.17 \pm 0.32\%)$, where the percentage denotes the deviation from fiducial model.

$D_{||} = 154.92^{+0.51}_{-2.29}$ Mpc and $D_{\perp} = 153.90^{+0.25}_{-0.25}$ Mpc with $\sigma_v = 6.8^{+2.0}_{-6.8}$ Mpc, which leads to $D_A = 1401.01^{+2.29}_{-2.26} (0.42^{-0.17}_{+0.16}\%)$ and $H^{-1} = 3201.66^{+47.94}_{-10.39} (-1.02^{+1.48}_{-0.32}\%)$.

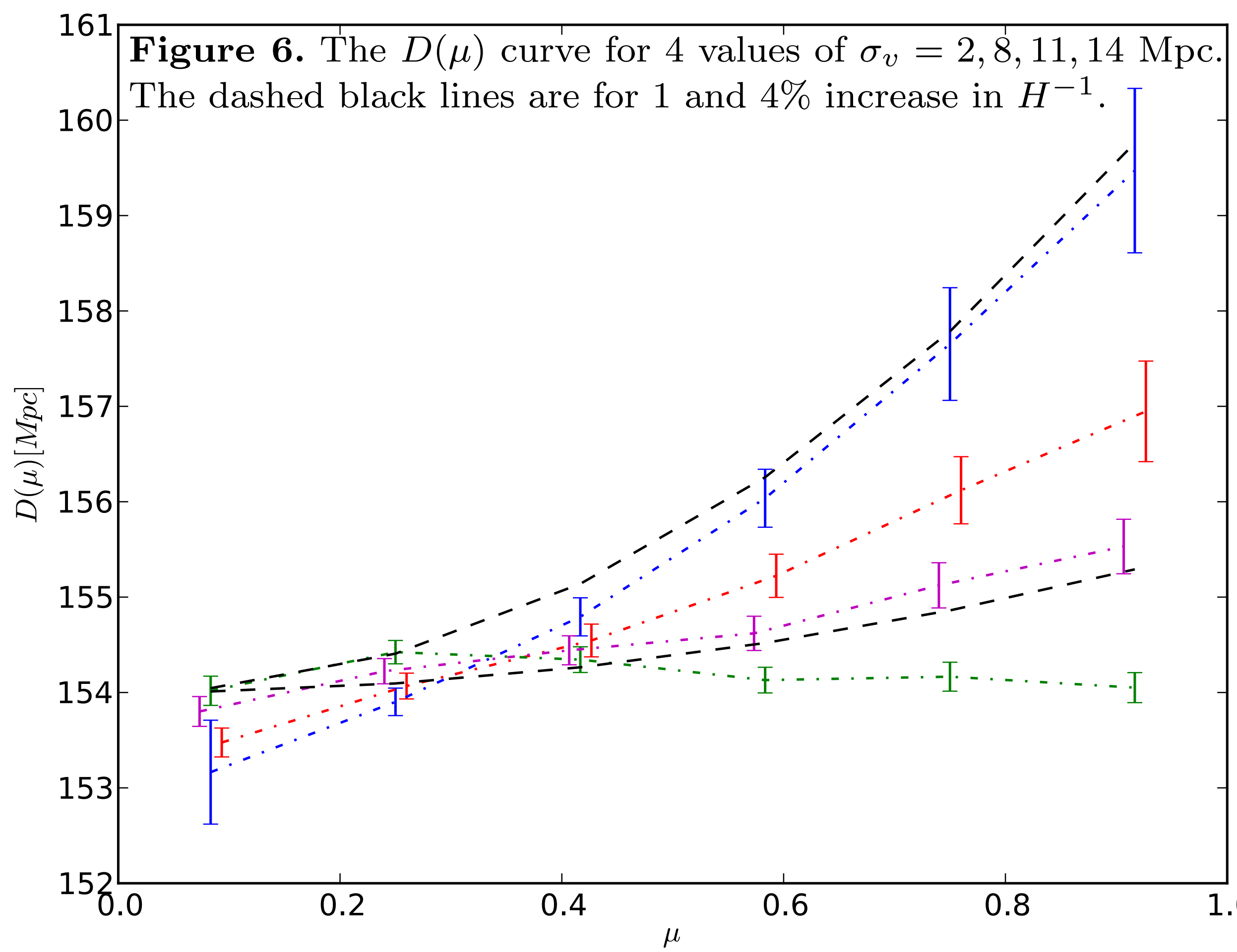


Figure 6. The $D(\mu)$ curve for 4 values of $\sigma_v = 2, 8, 11, 14$ Mpc. The dashed black lines are for 1 and 4% increase in H^{-1}.

Ω_Λ	0.62		0.68		0.73	
	α_i	β_i	α_i	β_i	α_i	β_i
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0.92	-1.07	0.027	-0.88	0.026	-0.89	0.027

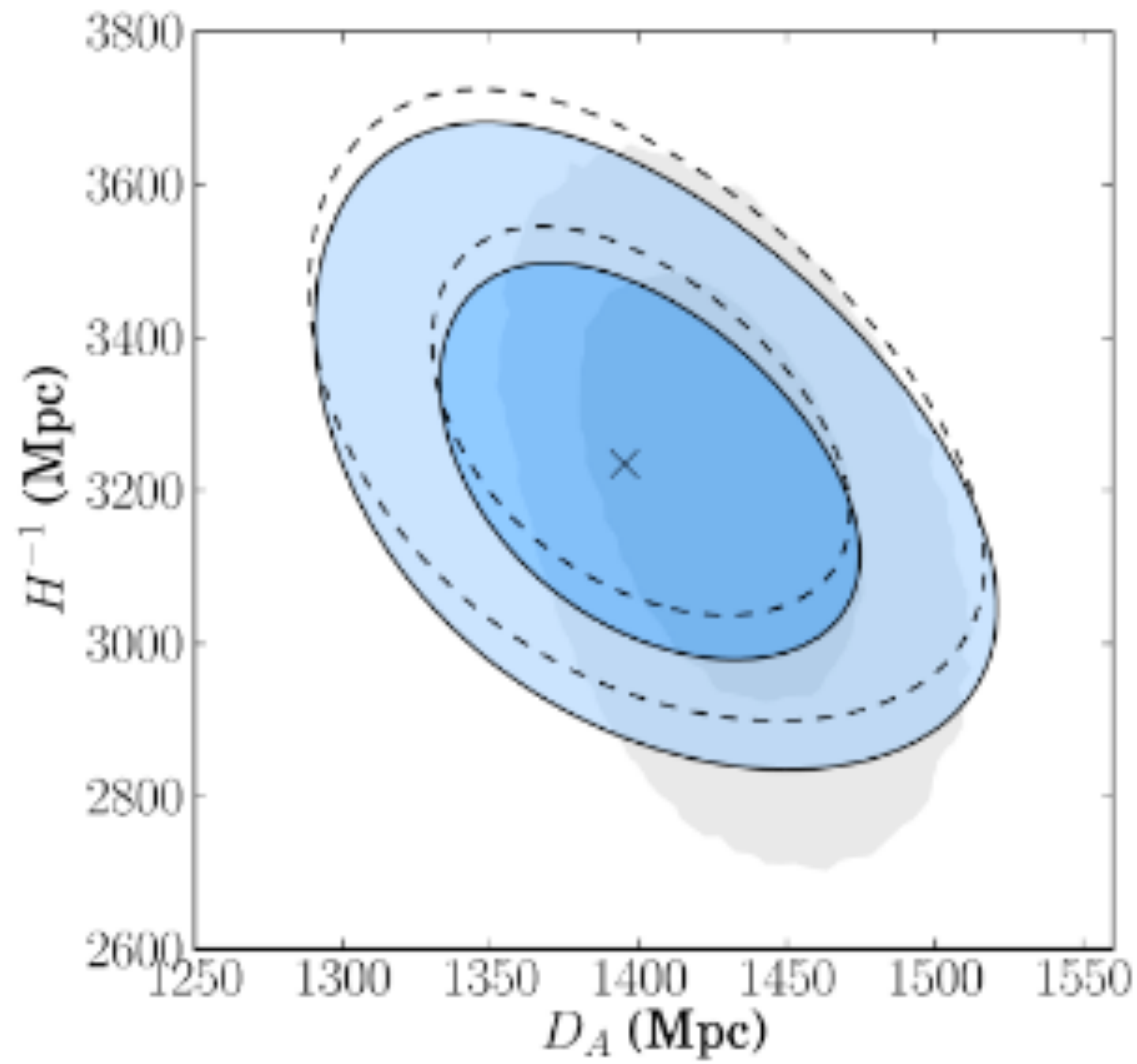
minimal cosmo dependance

Anisotropic BAO Peaks

Using 600 mock catalogues mimicking the BOSS survey

Modeling and marginalizing out the FoG systematic degrades the los BAO distance and hence H^{-1}. However is provides a less biased result.

obtain constraints on D_A & H^{-1} at the level of 2% and 5% resp.



Sabiu & Song (2016)
arxiv:1603.02389

Anisotropic BAO Peaks

Can we squeeze any more information from the BAO?

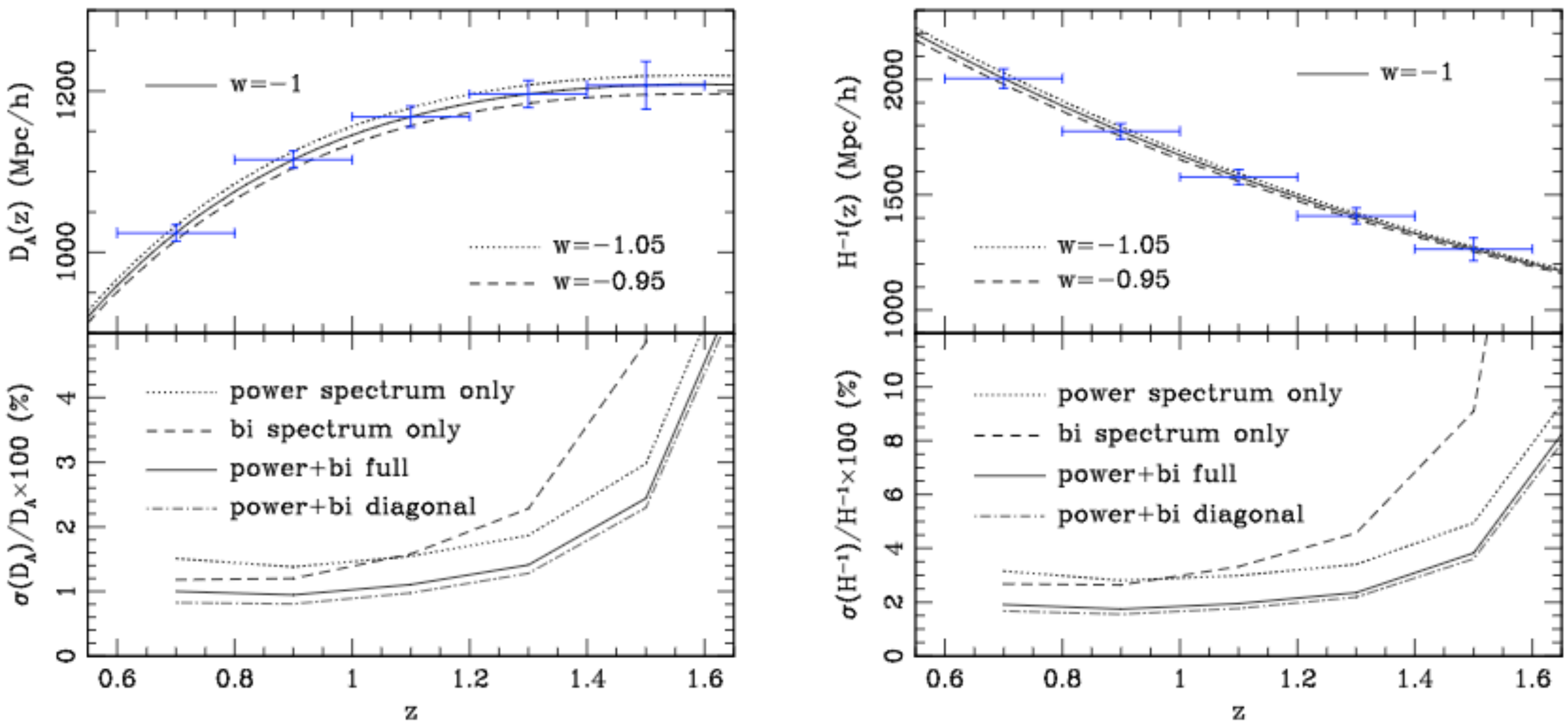


Figure from **(Song etal arxiv:1502.03099),** showing the expected constraints from using the power spectrum and bispectrum alone and in combination.

Slepian, Eisenstein etal detected the BAO structure in the isotropic 'averaged' 3PCF (arxiv:1607.06097)

The AP effect in the 3PCF

$$\tilde{B}^{\rm obs}(k_1,k_2,k_3,\mu_1,\mu_2) = \left(\frac{H^{\rm true}}{H^{\rm fid}}\right)^2\left(\frac{D_A^{\rm fid}}{D_A^{\rm true}}\right)^4 \times \tilde{B}(q_1,q_2,q_3,\nu_1,\nu_2)\,.$$

The relations between two coordinates are give by,

$$q_i = \alpha(\mu_i)k_i\,,$$

and

$$\nu_i = \frac{\mu_i}{\alpha(\mu_i)}\frac{H^{\rm true}}{H^{\rm fid}}\,, \qquad (15)$$

where $\alpha(\mu_i)$ is defined by,

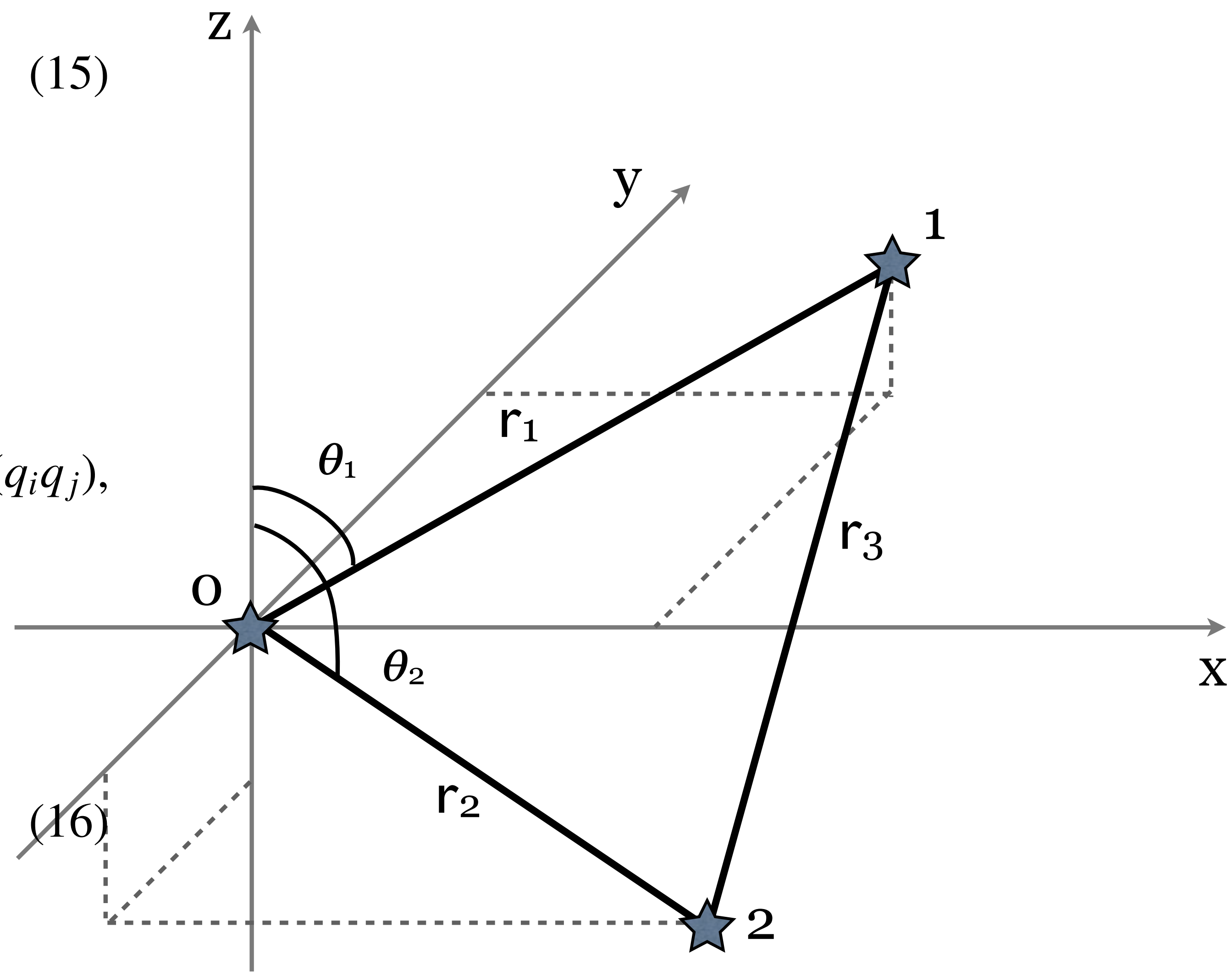
$$\alpha(\mu_i) \equiv \left\{\left(\frac{D_A^{\rm fid}}{D_A^{\rm true}}\right)^2 + \left[\left(\frac{H^{\rm true}}{H^{\rm fid}}\right)^2 - \left(\frac{D_A^{\rm fid}}{D_A^{\rm true}}\right)^2\right]\mu_i^2\right\}^{1/2}\,.$$

The cosine of angle between two vectors, $\nu_{ij} = (\mathbf{q}_i\cdot\mathbf{q}_j)/(q_iq_j)$, is given by,

$$\nu_{ij} = \left(\frac{D_A^{\rm fid}}{D_A^{\rm true}}\right)^2\frac{\eta_{ij}}{\alpha(\mu_i)\alpha(\mu_j)} + \left[\left(\frac{H^{\rm true}}{H^{\rm fid}}\right)^2 - \left(\frac{D_A^{\rm fid}}{D_A^{\rm true}}\right)^2\right]\frac{\mu_i\mu_j}{\alpha(\mu_i)\alpha(\mu_j)}\,. \qquad (16)$$

Here, we define $\eta_{ij} = (\mathbf{k}_i\cdot\mathbf{k}_j)/(k_ik_j)$.

Triangular configuration for the 3PCF.



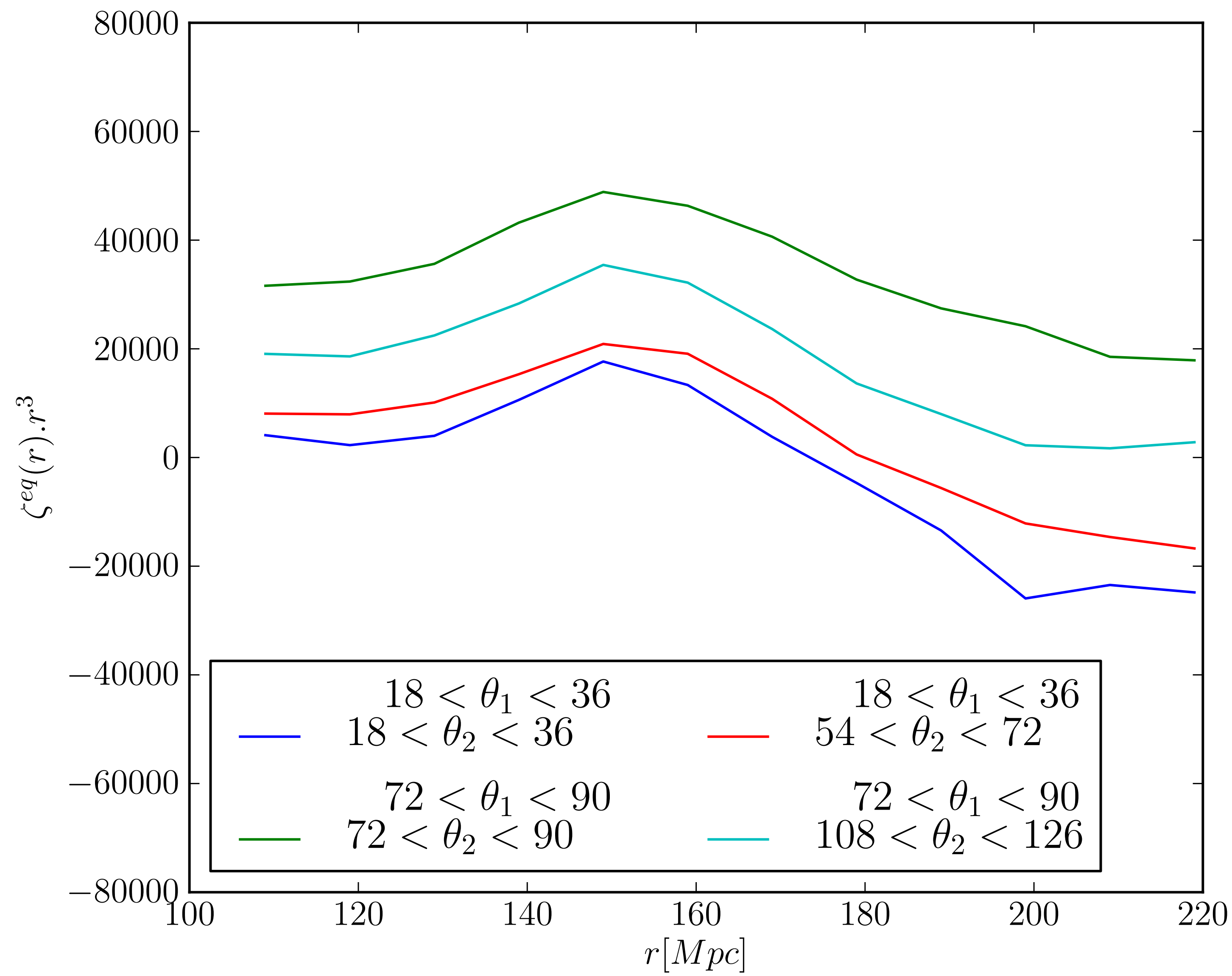
The anisotropic 3PCF

Using 400 Quick-Particle-Mesh (QPM) mock catalogues mimicking the BOSS DR12 CMASS survey

We calculate the 3PCF for equilateral configurations at different angles to the line-of-sight

When one side of the triangle lies close to the los we see the usual kaiser suppression.

This suppression disappears when looking at triangles that lie flat on the plane of the sky.

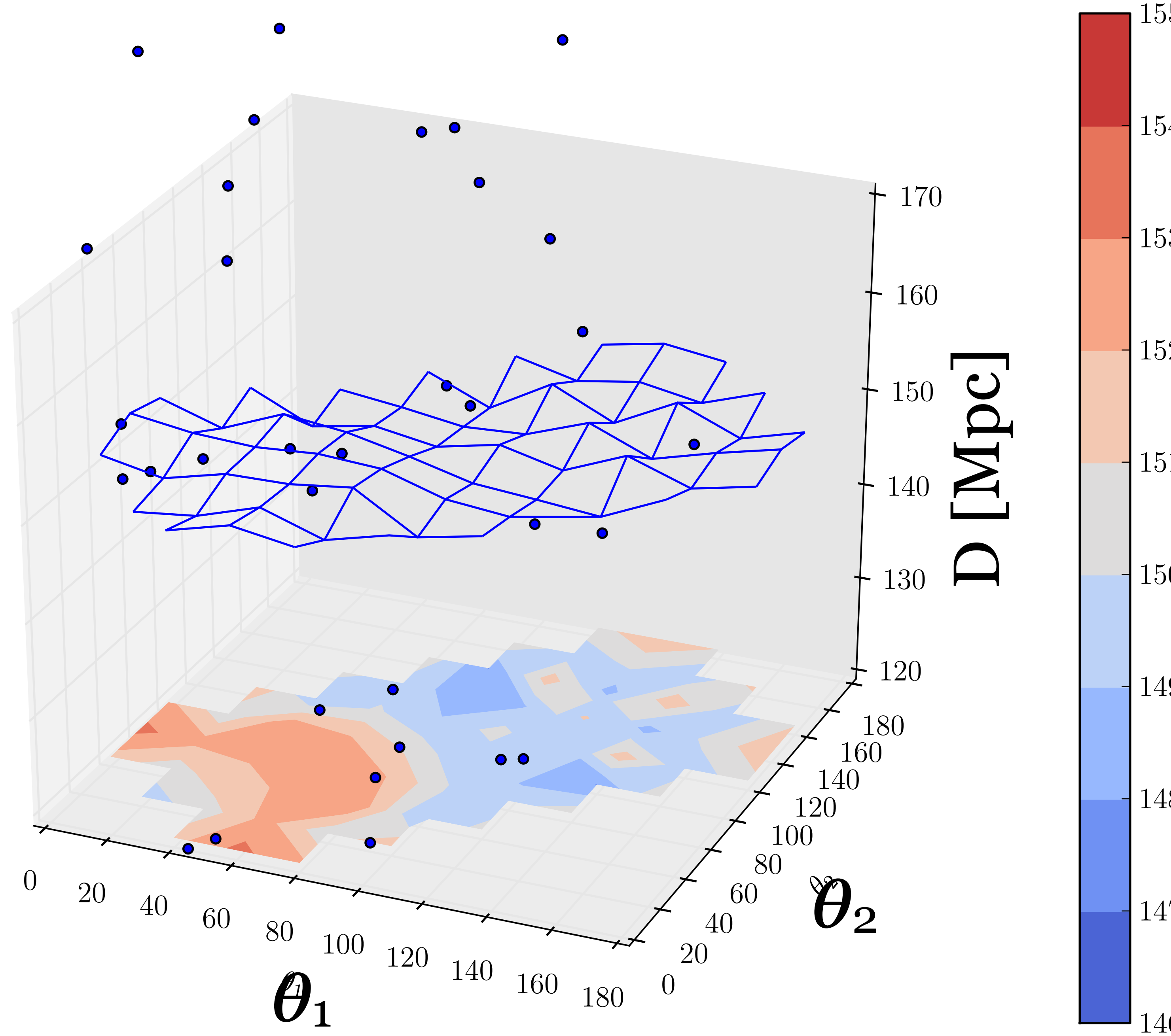


The generalized BAO membrane

From the mean of the mock catalogues we determine the peak location as a function of angle

This forms a membrane in the (D, θ_1, θ_2) space

Distortions or warpings of the BAO membrane will inform us on about D_A & H^{-1}



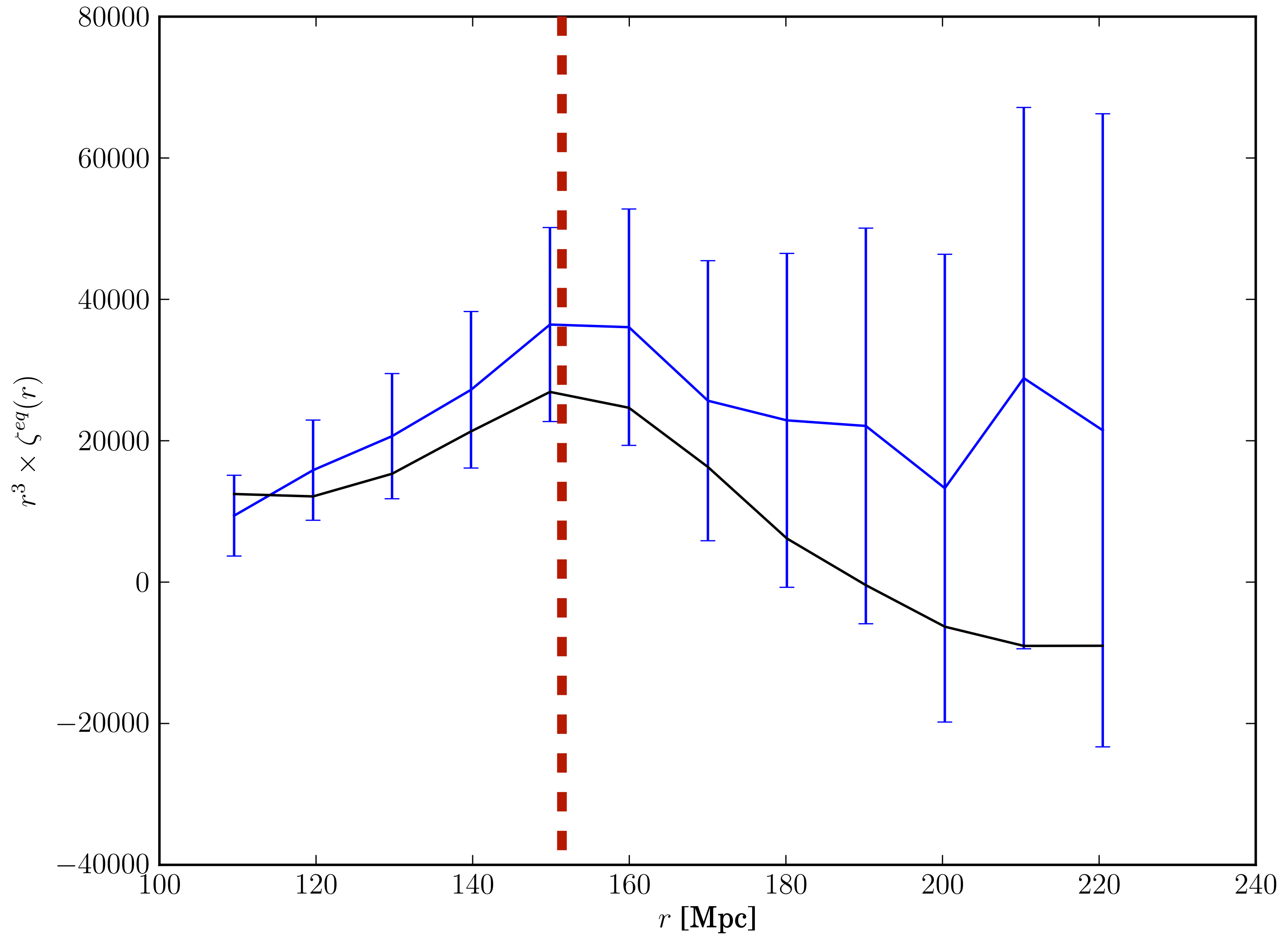
The 3-point BAO

Isotropic (angle averaged) equilateral 3PCF

Using SDSS DR12 CMASS North and South patches combined

We measure the isotropic 3PCF and determine the peak location

Error are from 400 QPM mocks



The 3-point BAO

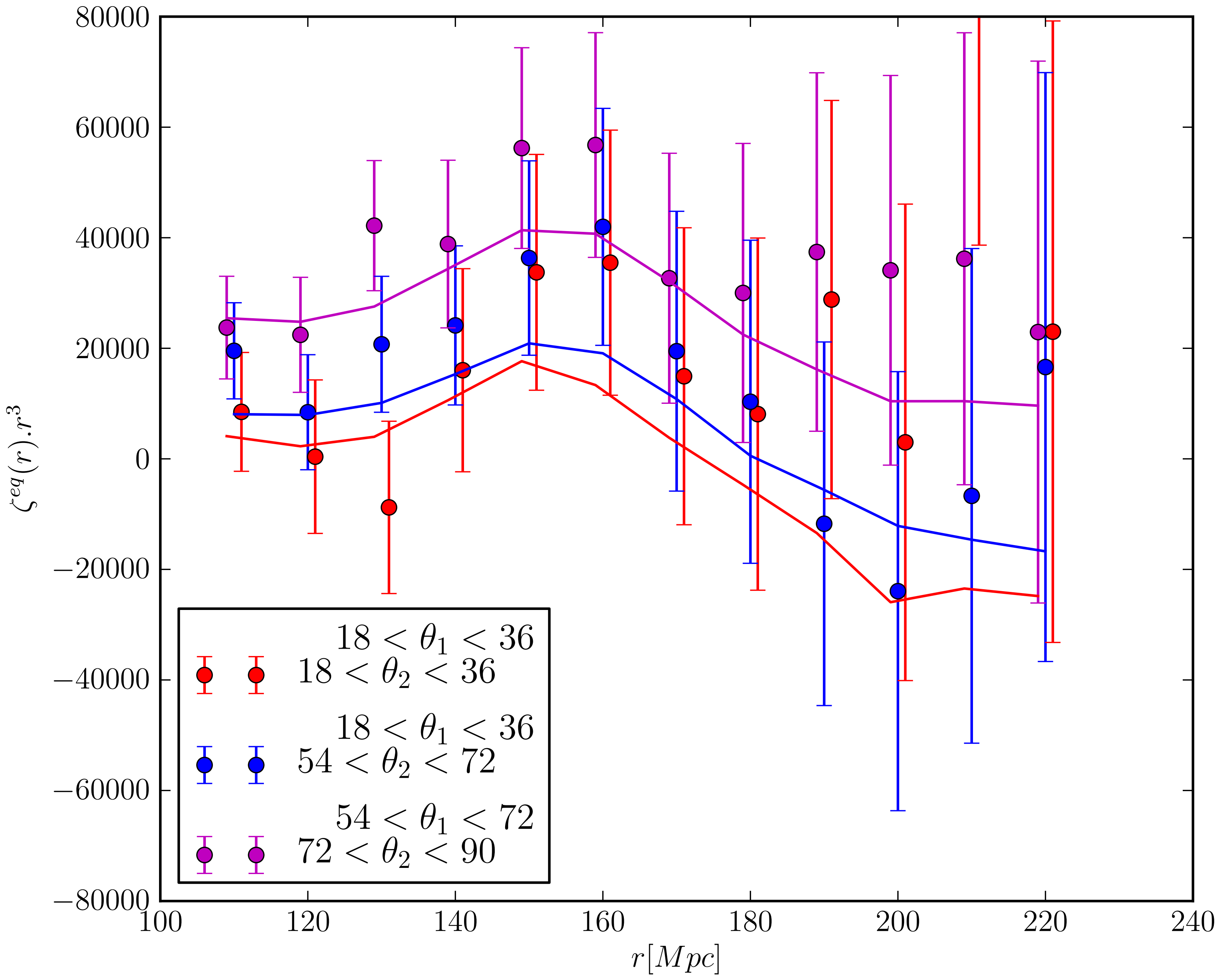
Again using the DR12 CMASS Galaxies

I measure the anisotropic equilateral 3PCF

We again see a clear peak structure for various angular configurations

A first detection of the BAO structure in the anisotropic redshift-space 3-point correlation function

Anisotropic equilateral 3PCF



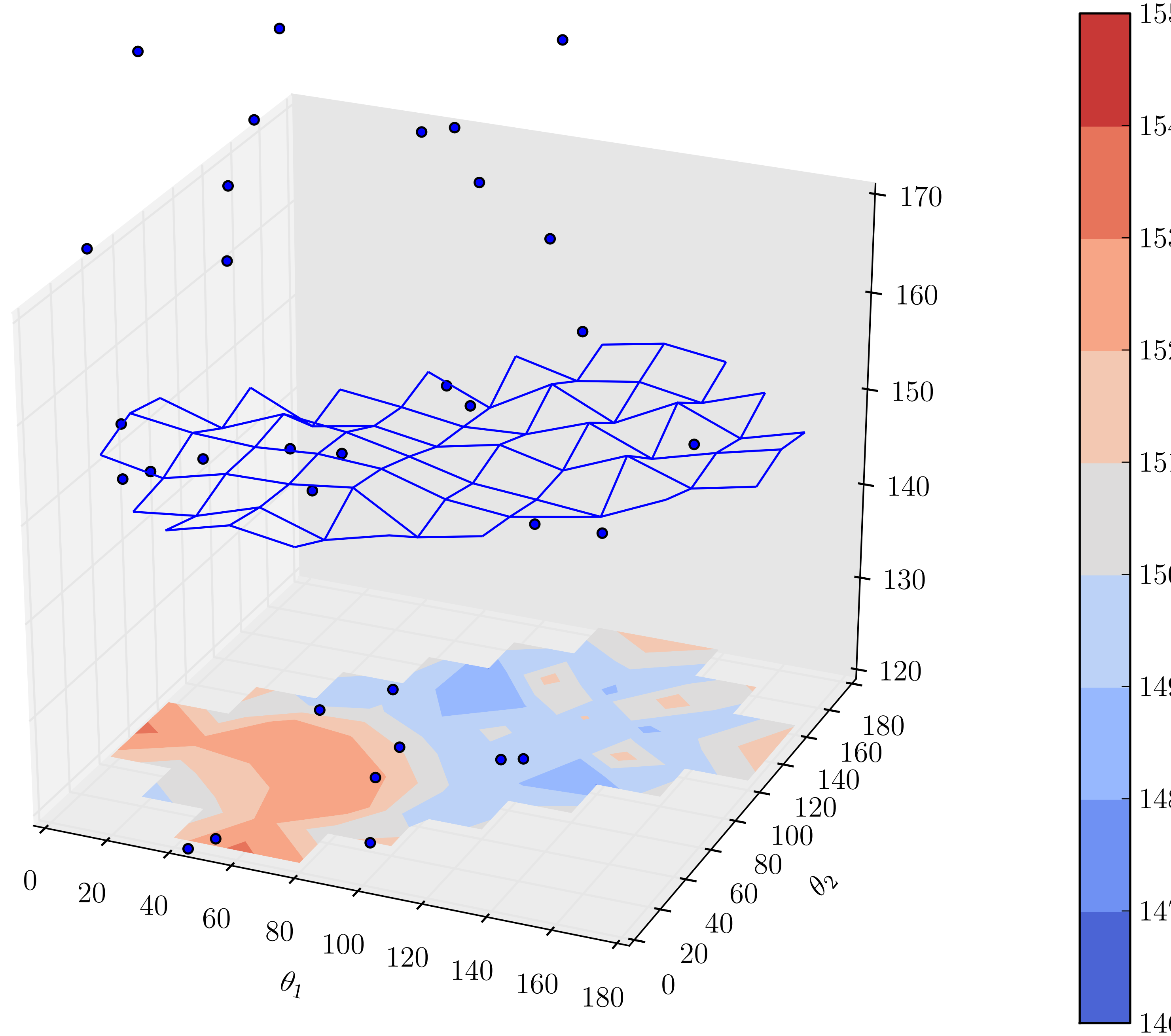
The BAO membrane

This is work in progress and will be completed soon.

Only thing left to do is fit the D_A & H^{-1} by varying the peak points measured in DR12 to the simulated membrane structure.

Originally I thought that I could fit to a simulation template, however the 'off-peak' shifts must be modeled....

So I have to go to perturbation theory. Nuala McCullagh (Durham) is helping me on this



Conclusions

We wanted clean measurements of $D_A(z)$ & $H^{-1}(z)$ as they are fundamental quantities that describe the geometry and evolution of the background universe.

- we have measured the higher order BAO structure in the 3PCF of BOSS DR12 galaxies
- soon we will extract $D_A(z)$ & $H^{-1}(z)$ measurements

Things to do......

- Covariance estimation - large number of measurement bins

P(k,mu)

Bi(k1, k2, k3, mu1, mu2)

- Theory - must model off-peak shifts for $D_A(z)$ & $H^{-1}(z)$. Maybe tree level is ok for BAO scales.
- Systematics - may be more severe than for 2-point statistics. Will same procedure as Ashley Ross etal work for 3PCF?

Extra slides……………