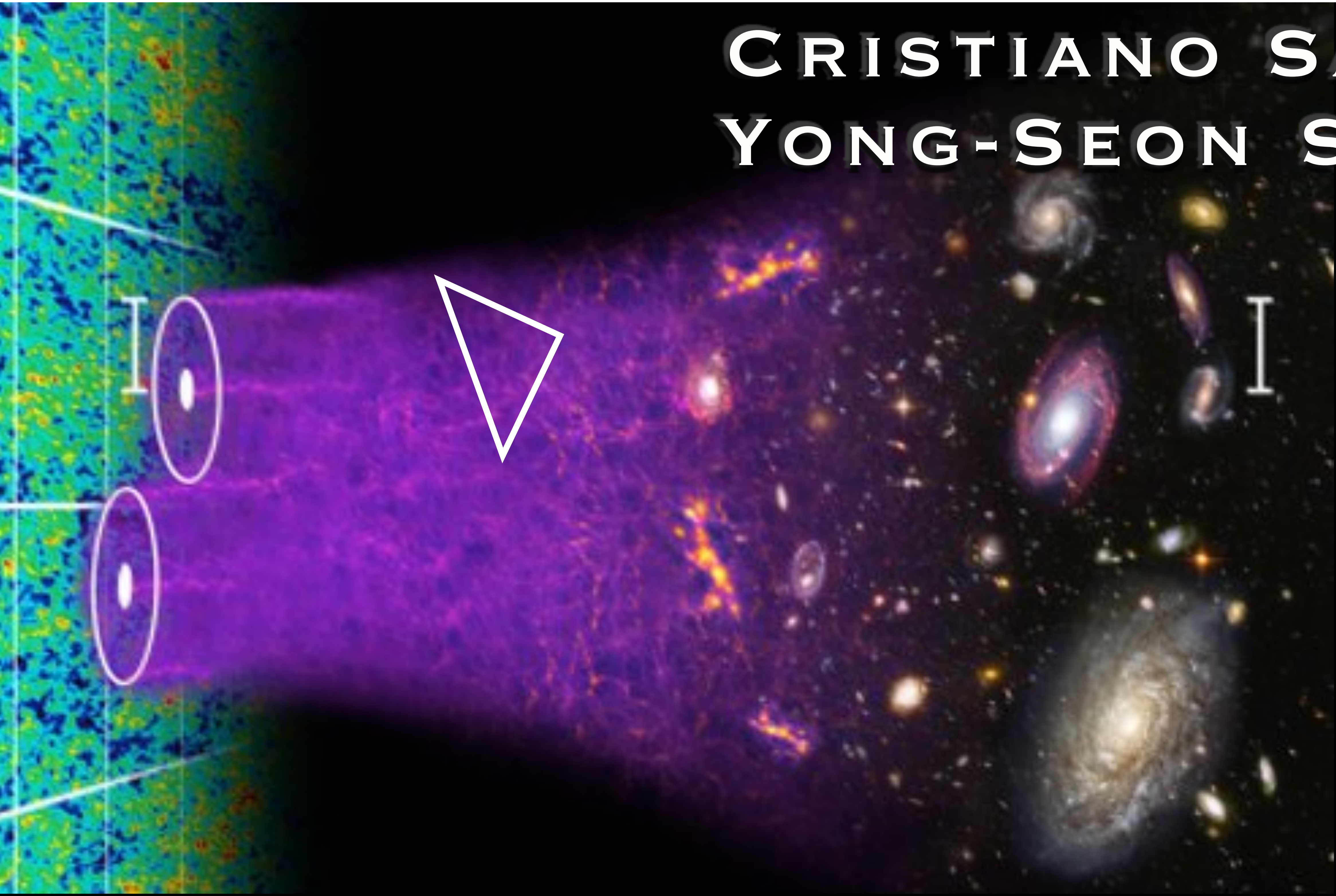
Higher Order Clustering Statistics
Towards the generalised BAO structure

Cosmology Group at
Korea Astronomy and Space Science Institute

CRISTIANO SABIU
YONG-SEON SONG



DAEJEON - SEPT 8 - 2016

Outline

- Constraining Compensated Isocurvature
  - luminosity weighted clustering
    (w/ Maayane Soumagnac, Rennan Barkana, Avi Loeb ++)

- Testing gravity
  - Higher Order Statistics
  - can we distinguish GR+LCDM from others?
    (w/ Changbom Park, David Mota, Claudio Llinares)

- Model-independent estimates of cosmic observables
  - utilizing the Alcock-Paczynski effect
  - Higher dimensional BAO

don't see what has been done;
see what remains to be done.
- Buddha

Isocurvature from LSS

CosKASI

Scale-Dependent Bias of Galaxies from Baryonic Acoustic Oscillations

arxiv: 1009.1393

Rennan Barkana[1] and Abraham Loeb[2⋆]
[1] Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv 69978, Israel
[2] Astronomy Department, Harvard University, 60 Garden Street, Cambridge, MA 02138, USA

Following up the theoretical prediction of Barkana & Loeb (2010) we looked for the scale dependent bias of the luminosity weighted correlation function using BOSS DR10

The initial BAO density enhancement leads to extra clustering of baryons on large scales.

However the large scale different between the clustering of galaxies and of luminosity weighted galaxies could also have a more significant primordial origin....

Isocurvature from LSS

Standard Inflationary scenario: primordial perturbations are adiabatic (all particle species are in phase)

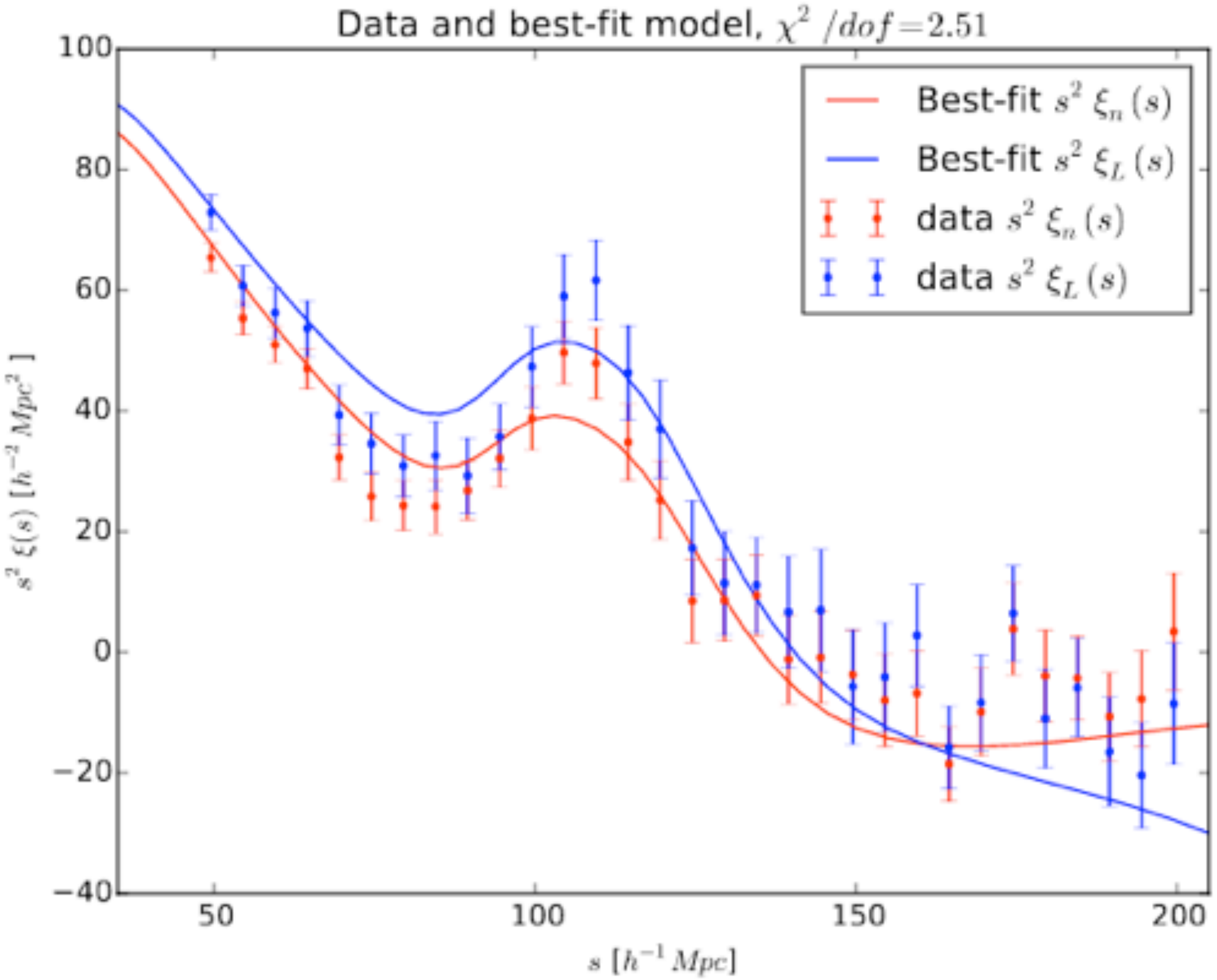
More complex scenarios: could have isocurvature fluctuations in relative number density of different spices (out of phase)

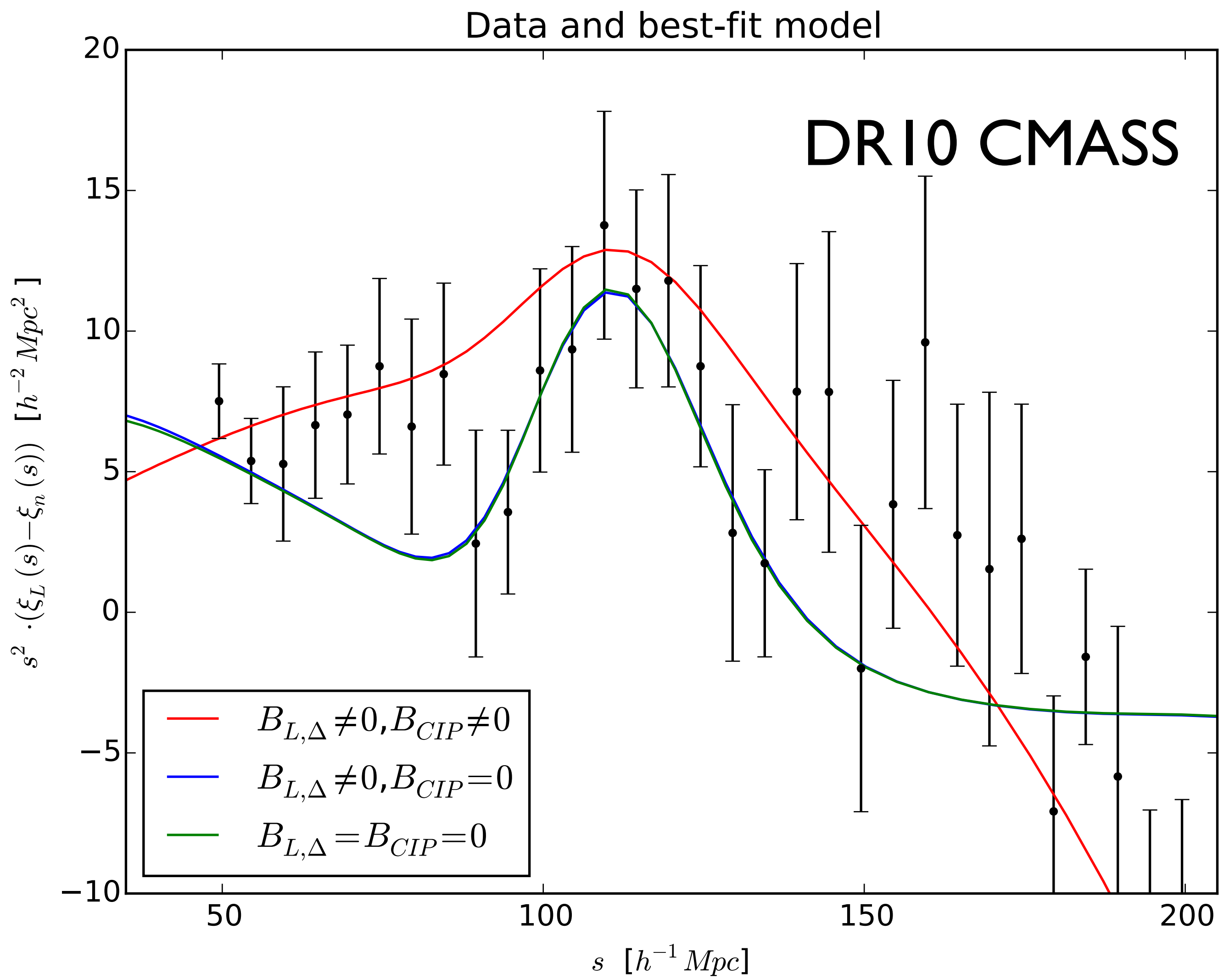
isocurvature is not favored by CMB experiment. However there could exist a primordial, compensated isocurvature component (CIP) to the overall fluctuations between DM and baryons.

$$\xi_n = B_{n,t}^2 \xi_{\rm tot} + 2B_{n,t}B_{n,\Delta}\xi_{\rm add} + B_{n,\Delta}^2 B_{\rm CIP}\hat{\xi}_{\rm CIP},$$

$$\xi_L = B_{L,t}^2 \xi_{\rm tot} + 2B_{L,t}B_{L,\Delta}\xi_{\rm add} + B_{L,\Delta}^2 B_{\rm CIP}\hat{\xi}_{\rm CIP},$$

Isocurvature from LSS





M. Soumagnac et al. PRL, Vol 116, Issue 20
arXiv:1602.01839

At the moment the data cannot give strong constraints on either the large scale bias induced by extra baryon clumping or by primordial CIP....

We are currently updating this work with DR12 CMASS + LOWZ

Probing Scalar Field Theories

Light scalar fields coupled to matter (baryons) are predicted by many theories beyond the standard model.

•

Coupled means we have a fifth−force in nature. If it exists, is there any room for cosmological signatures (of the fifth−force)?

•

A fifth−force is strongly constrained from local gravity experiments (inverse square law, solar--system tests, EP).

•

Naive conclusion: Either very short range or very weakly coupled, in other words: no cosmological effects of the fifth−force!

•

Not the case if the field has a screening mechanism. The fifth−force can remain ’hidden’ to local experiments!

•

We consider two models that have this property: Chameleon & Symmetron

Probing Scalar Field Theories in redshift-space

with Changbom Park & David Mota
arxiv:1603.05750

We focus our analysis in two specific scalar tensor models: the symmetron model and a particular case of f(R) theories.

Both models include screening mechanisms, which reduce them to general relativity in high density regions and thus pass solar system tests.

N-body simulations from Llinares, Mota etal (2013) arXiv:1307.6748

Npart=512^3
Side=256Mpc/h
at z=0.0
Dark matter and FoF halos

Model	λ_0	z_{SSB}	β
Symm A	1	1	1
Symm B	1	2	1
Symm C	1	1	2
Symm D	1	3	1

Model	n	$\lvert f_{R0}\rvert$	λ_0
fofr4	1	10^{-4}	23.7
fofr5	1	10^{-5}	7.5
fofr6	1	10^{-6}	2.4

Symmetron Model
Hinterbichler & Khoury (2010)

f(R) Gravity Model
Hu & Sawicki (2007)

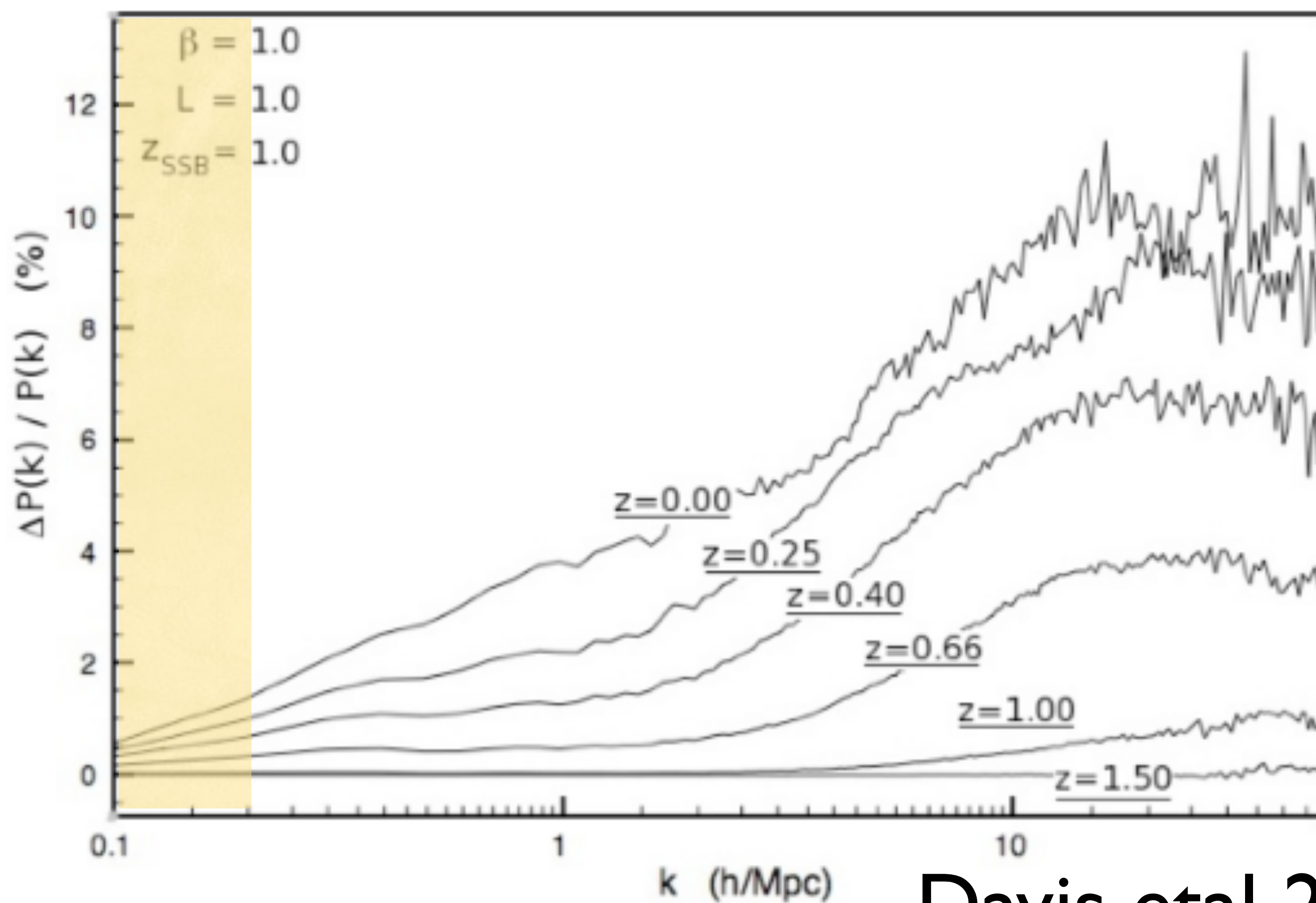
Probing Scalar Field Theories in redshift-space

Percent level difference at relevant scales and redshifts

Isotropic Power Spectrum not very sensitive to information in the velocity field

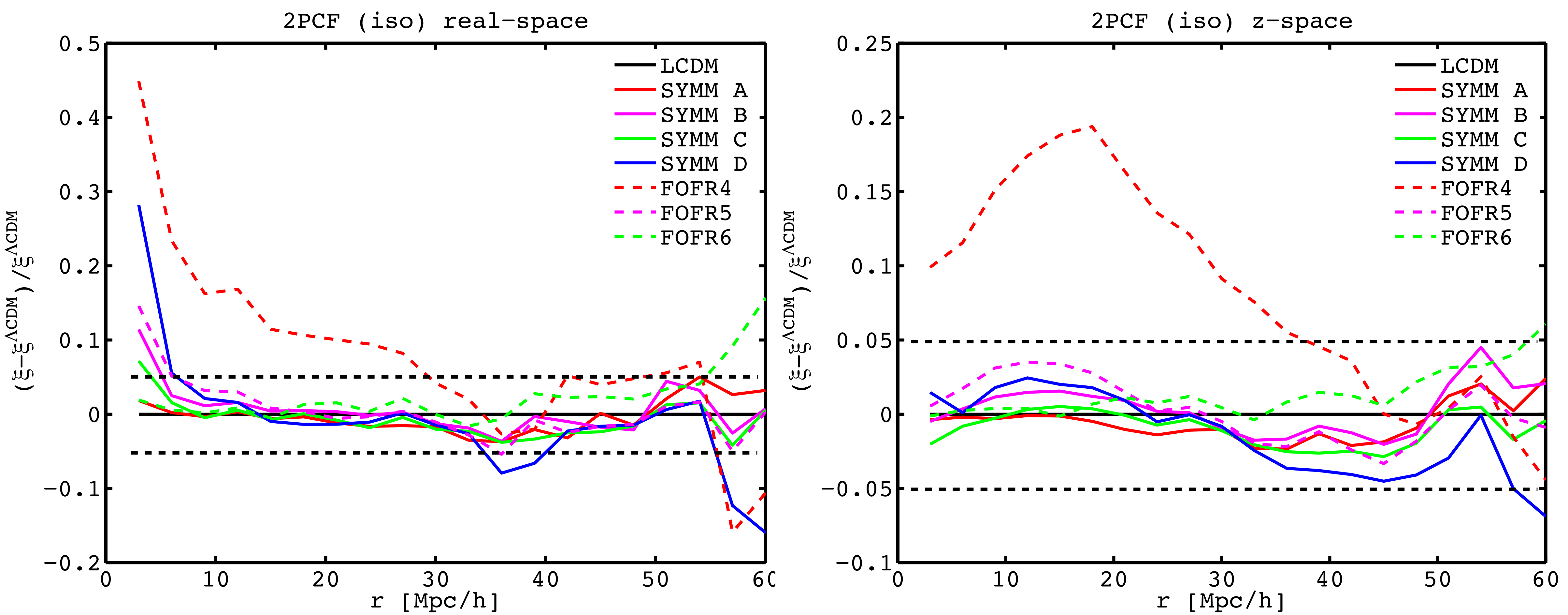
Look in redshift-space using anisotropic statistics?

Symmetron Power Spectrum



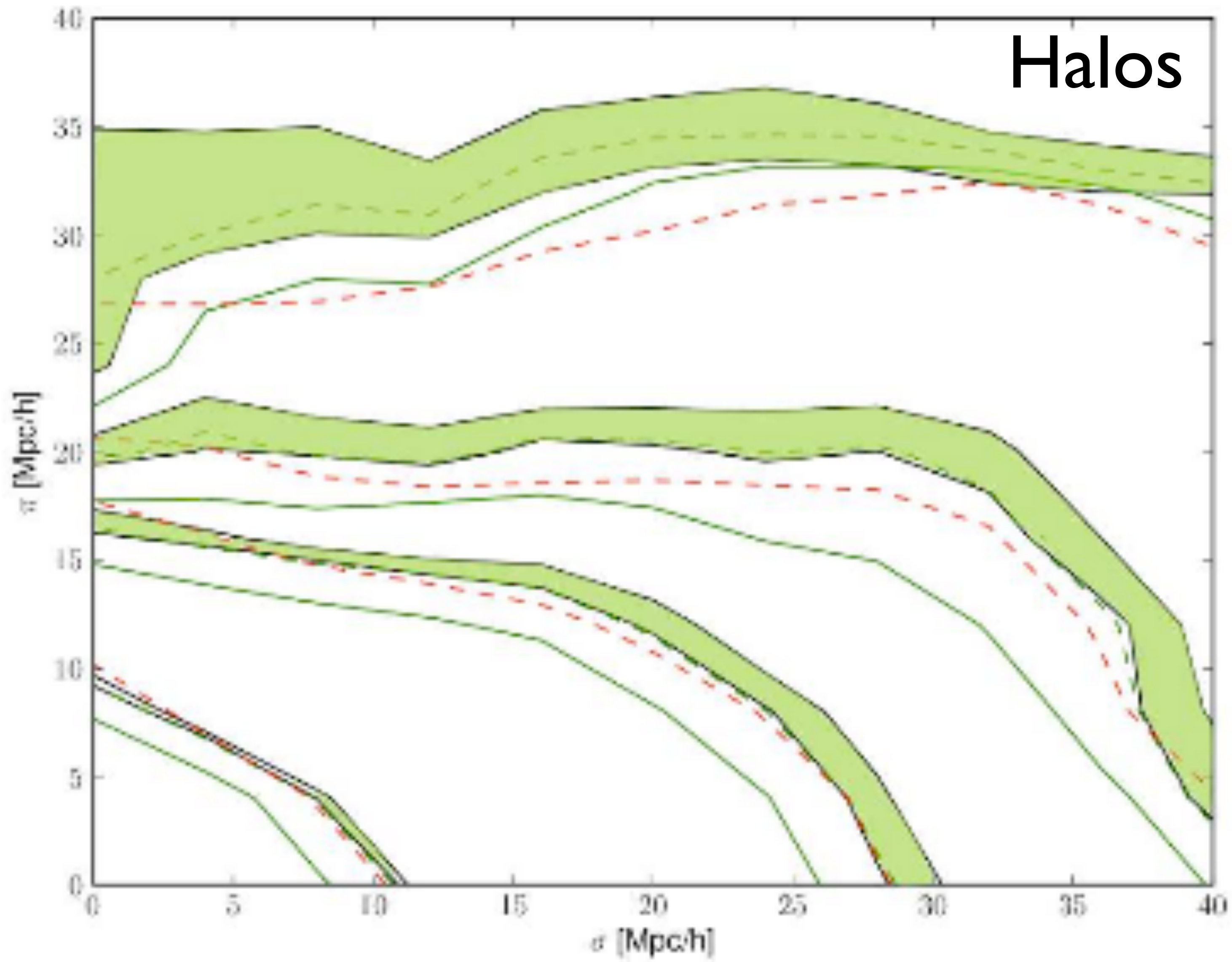
Davis etal 2011

Probing Scalar Field Theories in redshift-space



- Using iso-2PCF, more deviation from LCDM in redshift-space
- FOFR4 and SymmD models show largest difference > ~5%
- Maybe we can investigate velocity effect more specifically....

Probing Scalar Field Theories in redshift-space



- In anisotropic proj again FOFR4 shows large variation in DM
- Halo clustering exhibits wider dispersion amongst models
- So what? Can we construct a smoking gun test? maybe...

Probing Scalar Field Theories in redshift-space

3-Point correlations (Fourier Dual of Bispectrum)

The complete statistical description of a field may require higher-order statistics,

$$\zeta(r_1, r_2, r_3) = \langle \delta_{gal}(r_1)\delta_{gal}(r_2)\delta_{gal}(r_3) \rangle$$

Probability of finding pairs/triplets of objects:

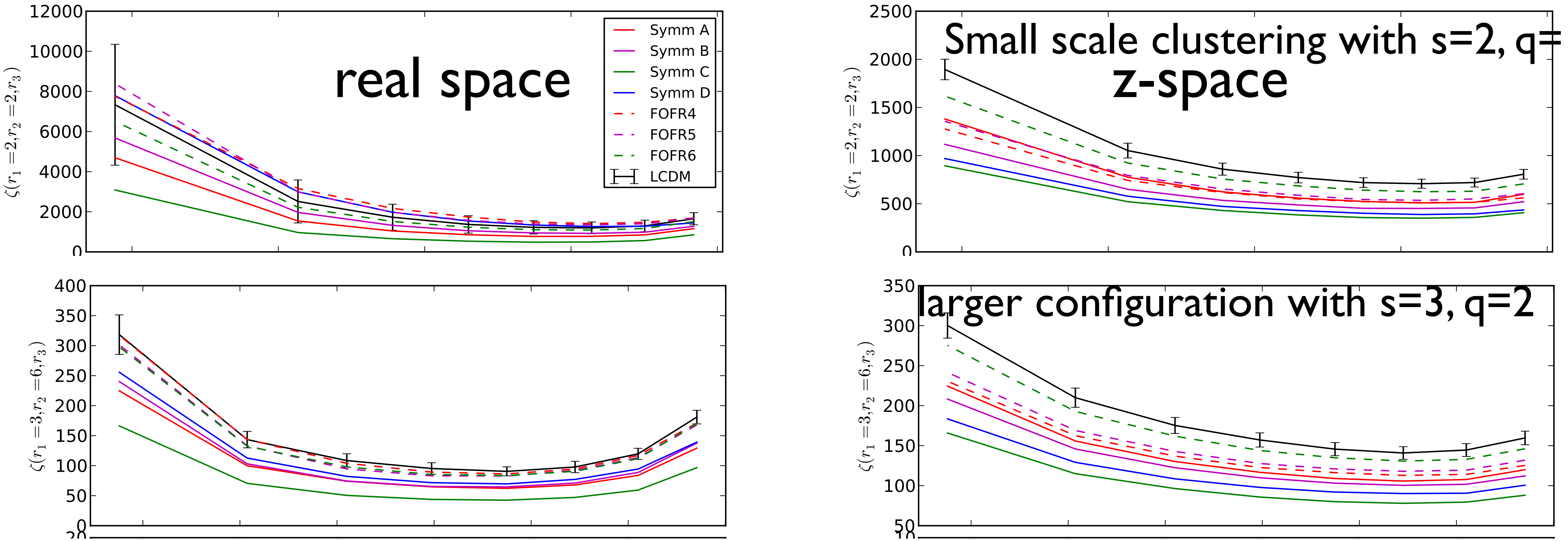
$$dP = n^3(1 + \xi(r_1) + \xi(r_2) + \xi(r_3) + \zeta(r_1, r_2, r_3))dV_1 dV_2 dV_3$$

random — correlated pairs — correlated triplets

It's difficult to compute and cpu intensive...
Im developing a code to do this using MPI, kd-trees, and some other tricks: https://bitbucket.org/csabiu/kstat

Probing Scalar Field Theories in redshift-space

The 3pcf in various modified gravity simulations



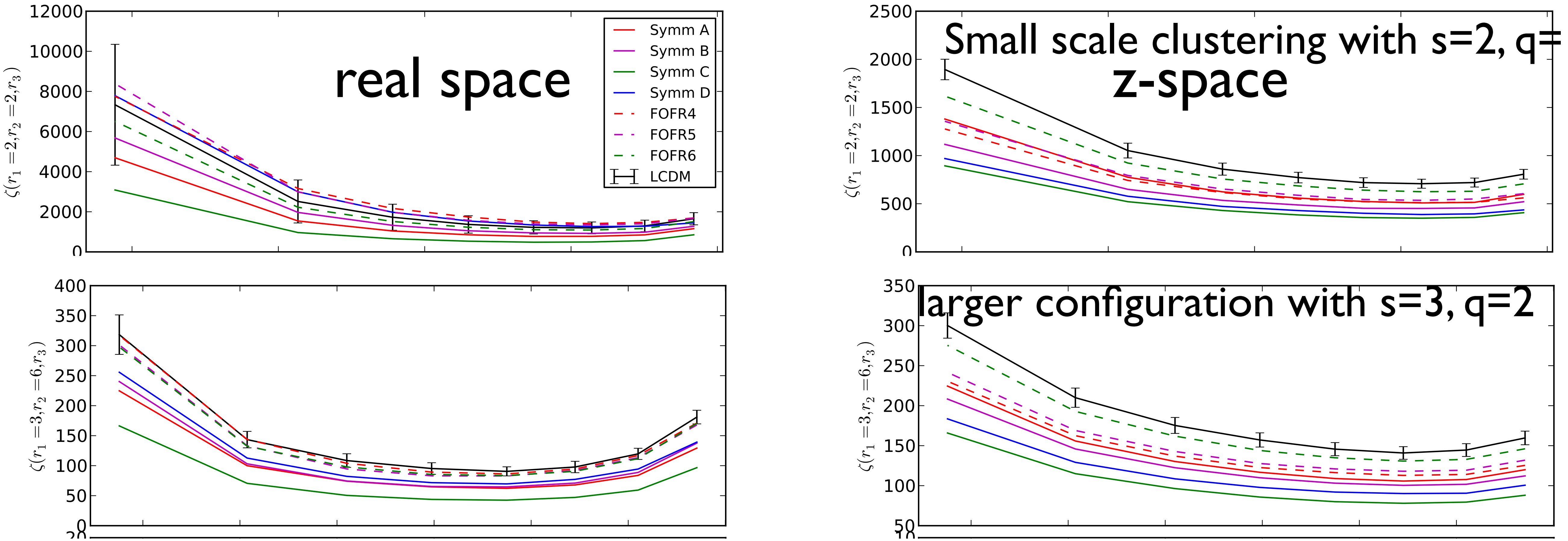
A&A Vol. 592 (2016/07)
arxiv:1603.05750

there is significant dispersion between models which suggest that the 3PCF is a more powerful probe of modified gravitational clustering.

The redshift space clustering tends to flatten the 3PCF, with FOFR4 displaying an extreme case of this.

Probing Scalar Field Theories in redshift-space

The 3pcf in various modified gravity simulations



A&A Vol. 592 (2016/07)
arxiv:1603.05750

I hope to update this work using other modified gravity models and larger simulations. Let me know if you are interested!

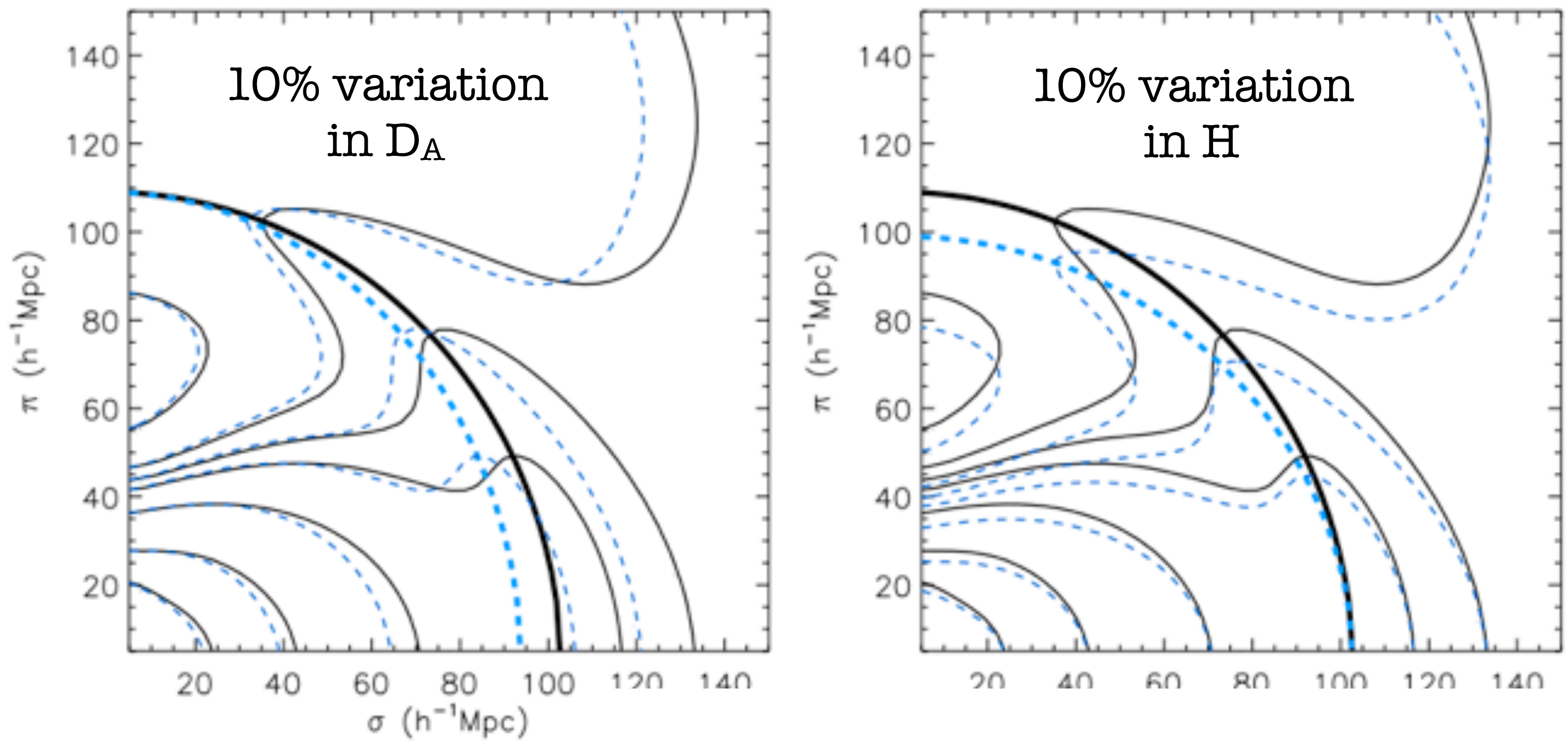
"You only lose what you cling to." - Buddha

Pure Alcock-Paczynski Measure

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

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

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

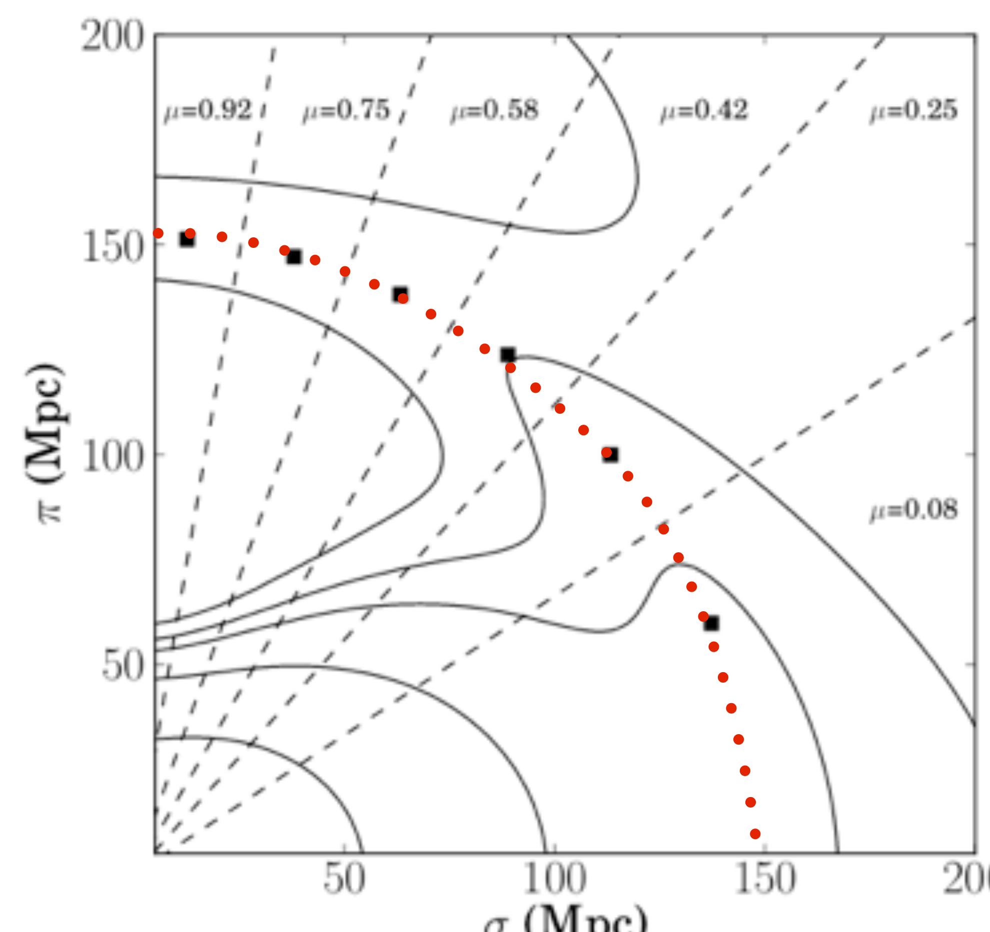


D_A, H vary peak positions off the BAO ring.

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.

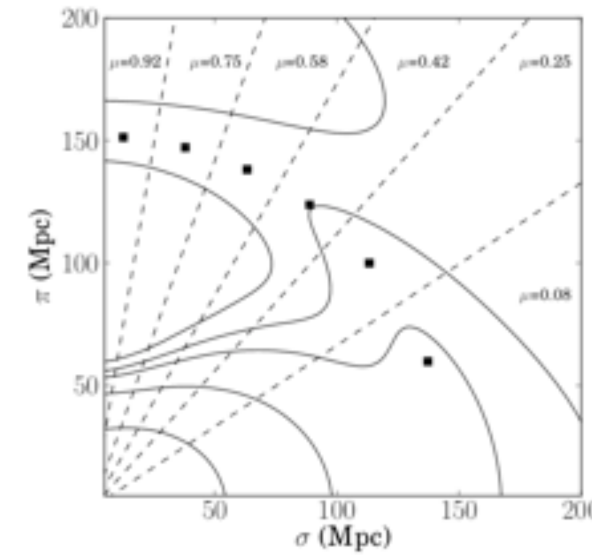


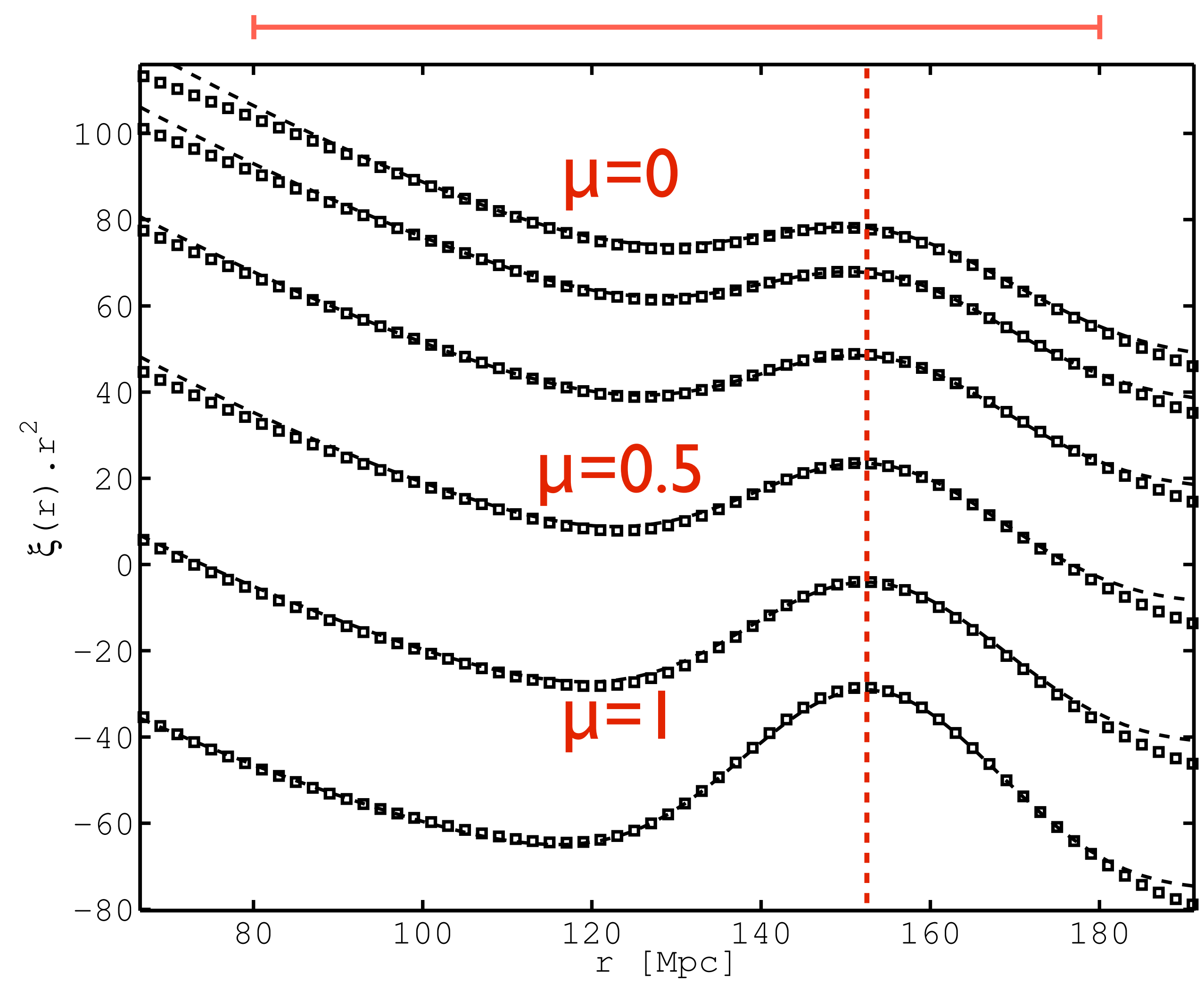
Anisotropic BAO Peaks

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

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.



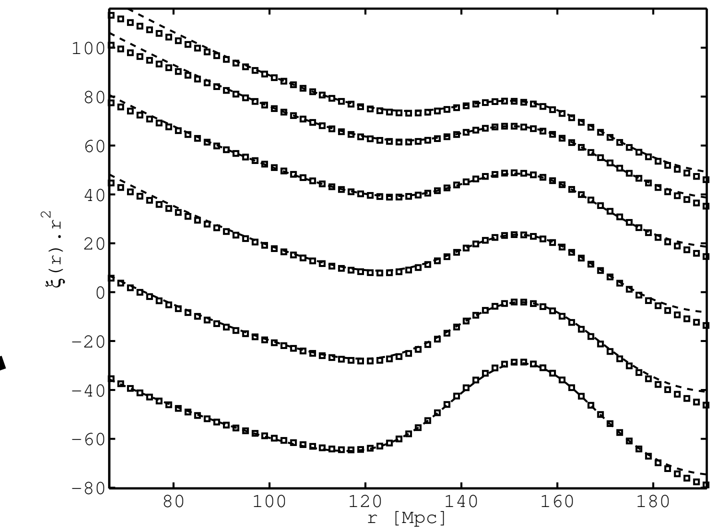


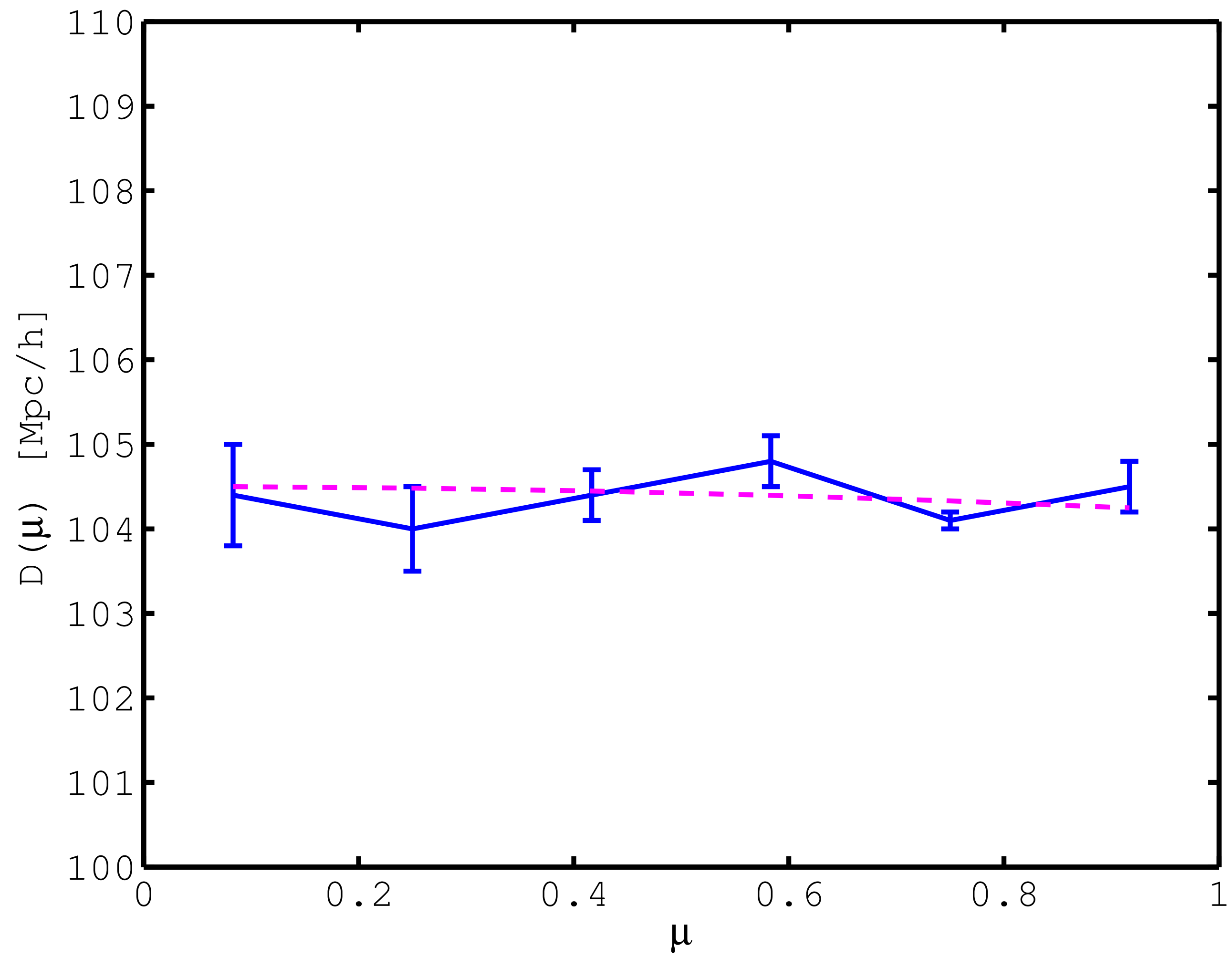
Anisotropic BAO Peaks

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.



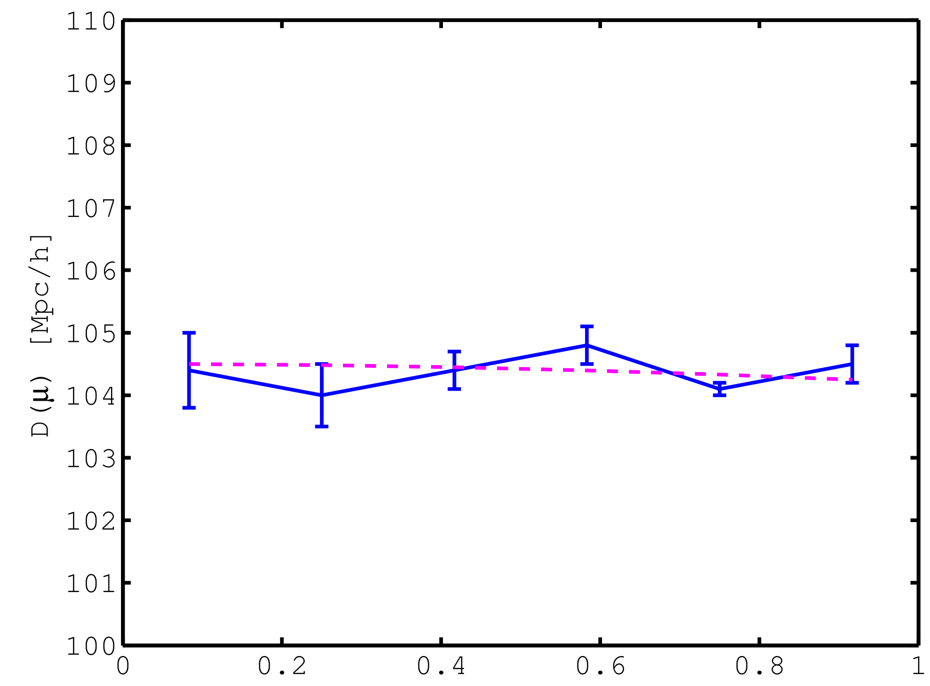


Anisotropic BAO Peaks

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

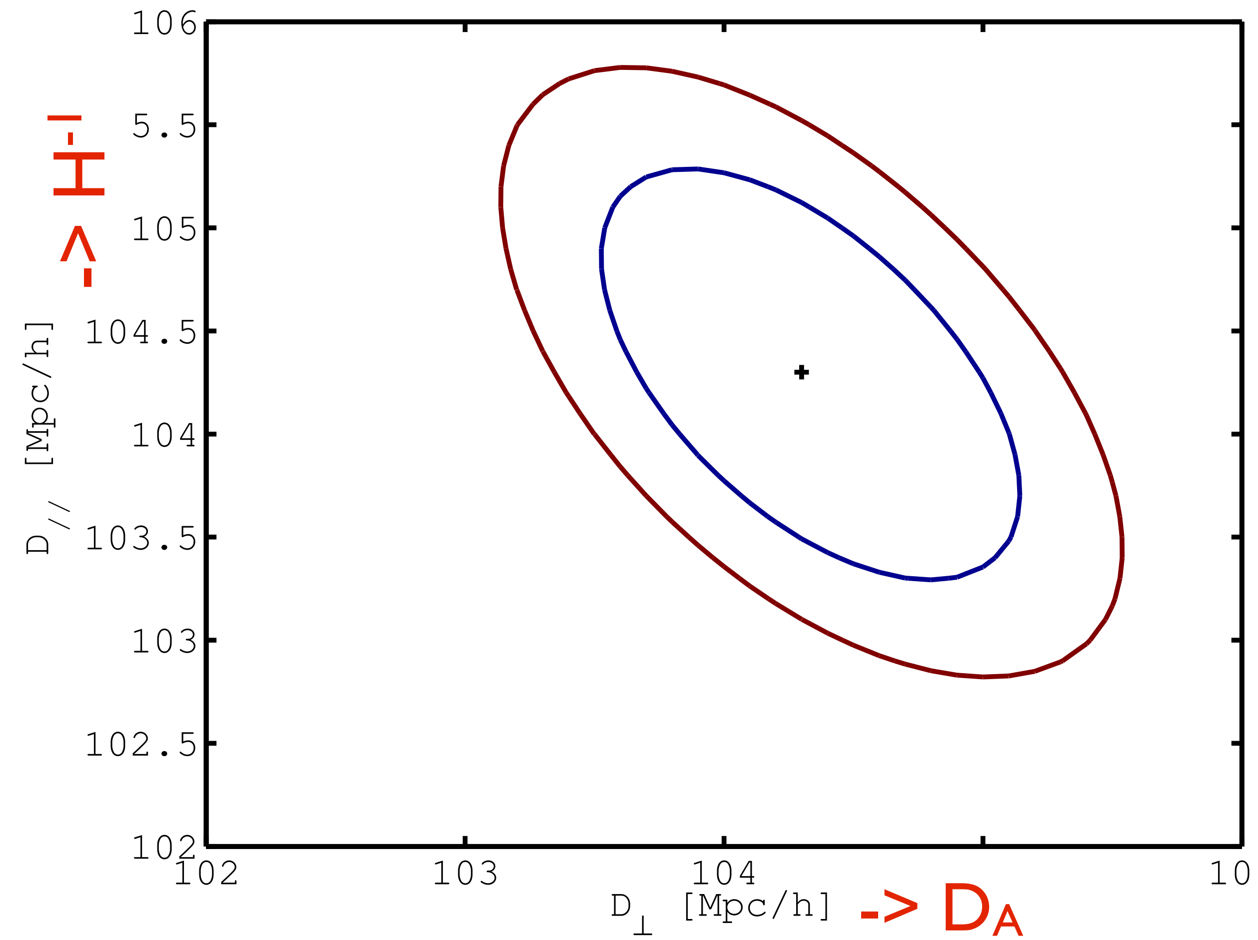
$$H_{obs}^{-1} = H_{fid}^{-1}\frac{D_{||,fid}}{D_{||,obs}},$$

$$D_{A,obs} = D_{A,fid}\frac{D_{\perp,fid}}{D_{\perp,obs}}.$$



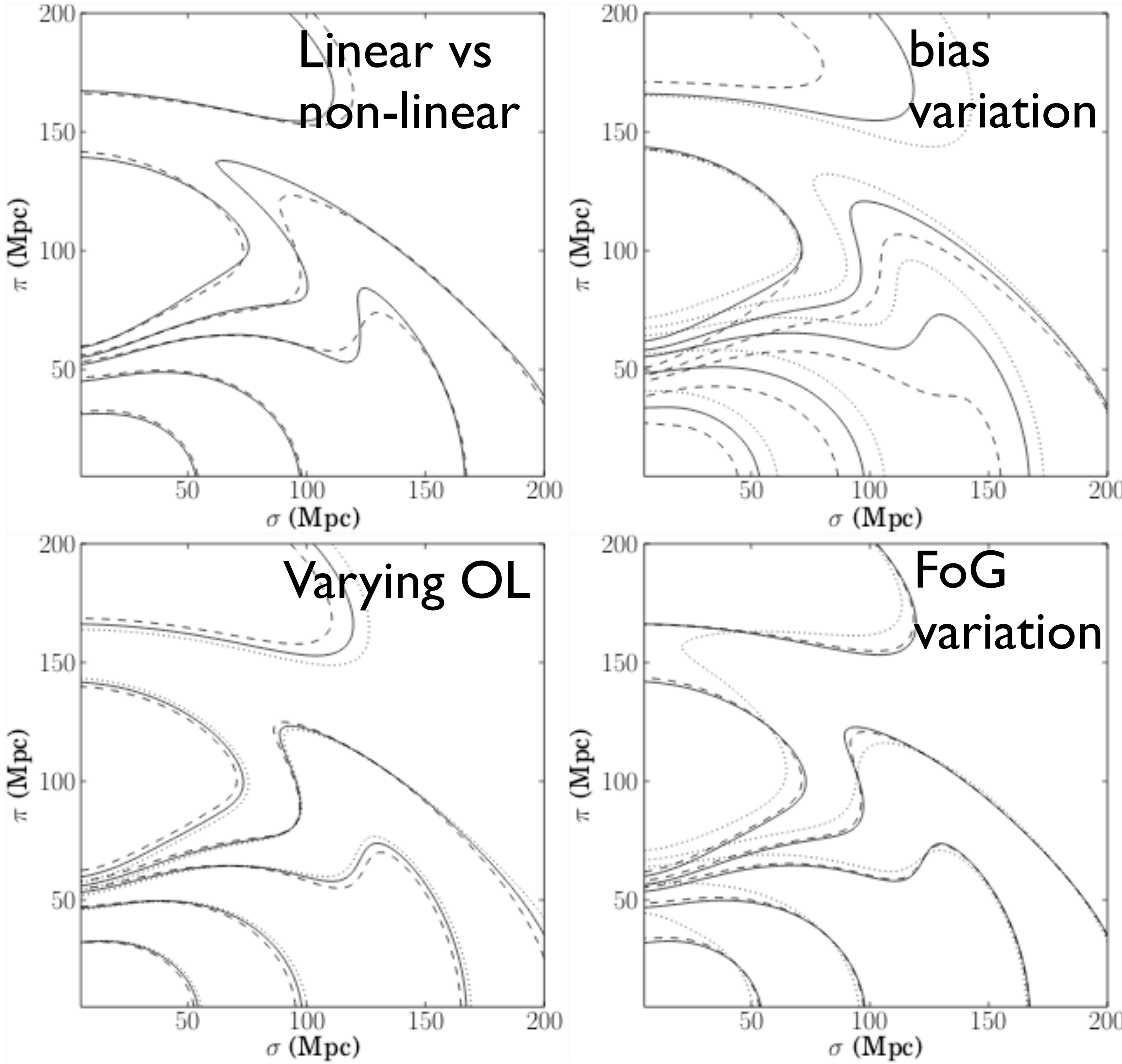
Next we create theoretical models that include different systematics and and observational effects.

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



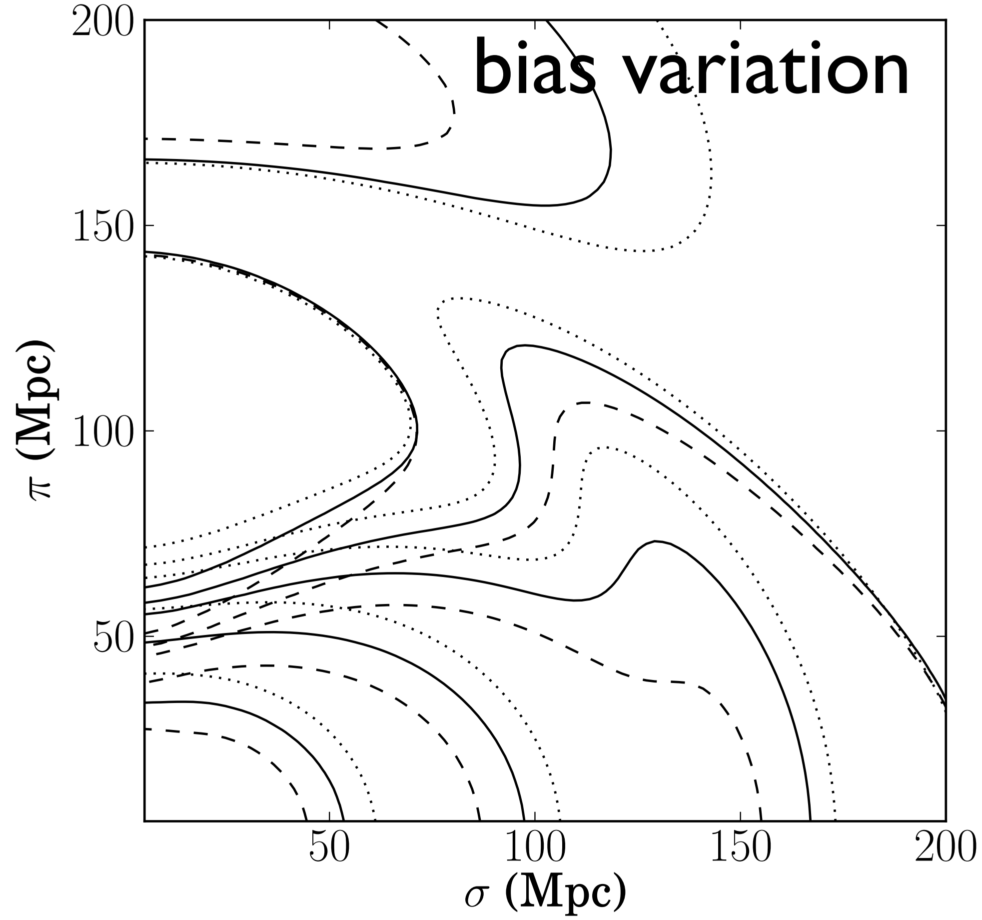
Anisotropic BAO Peaks

Check systematics

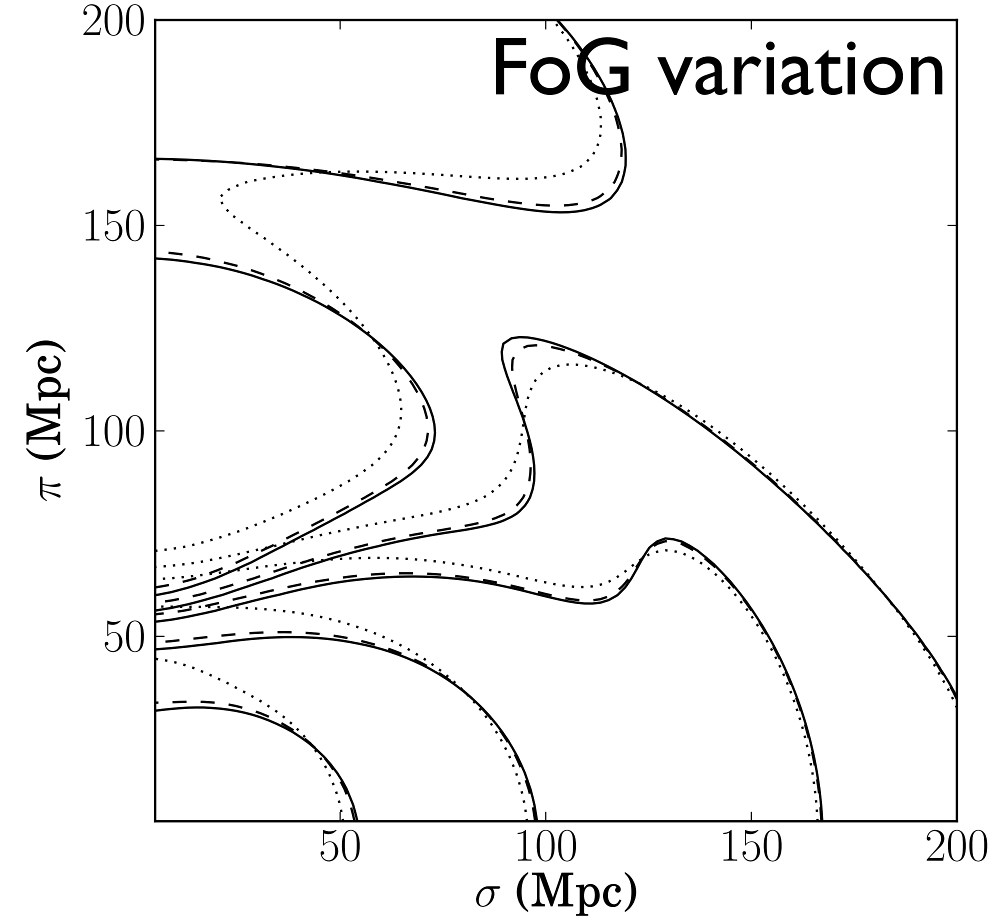


Anisotropic BAO Peaks

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.

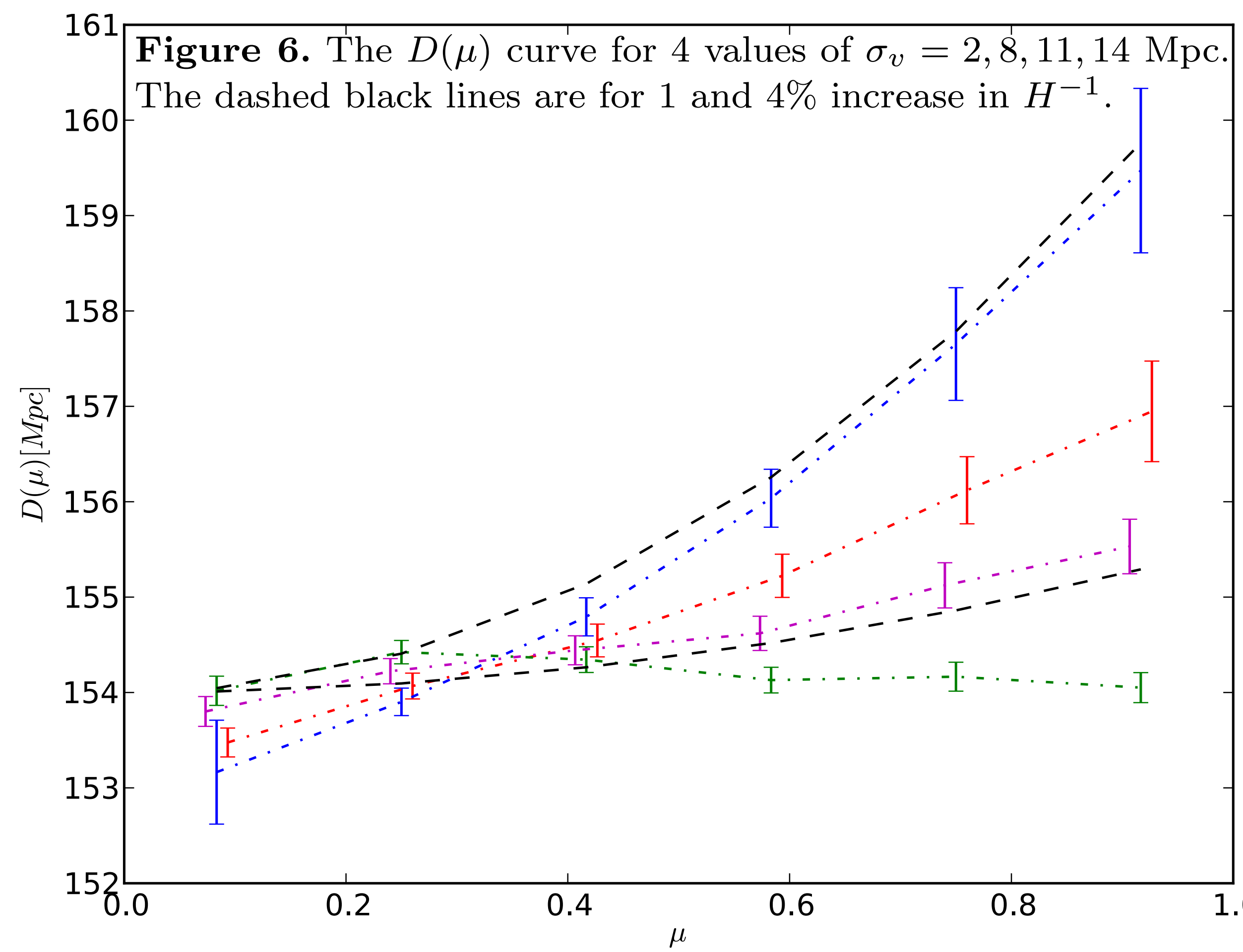


Figure 6. The $D(\mu)$ curve for 4 values of $\sigma_v = 2, 8, 11, 14$ Mpc. The dashed black lines are for 1 and 4% increase in H^{-1}.

	Ω_Λ	0.62		0.68		0.73	
		α_i	β_i	α_i	β_i	α_i	β_i
μ_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
	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

minimal cosmological dependance

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.

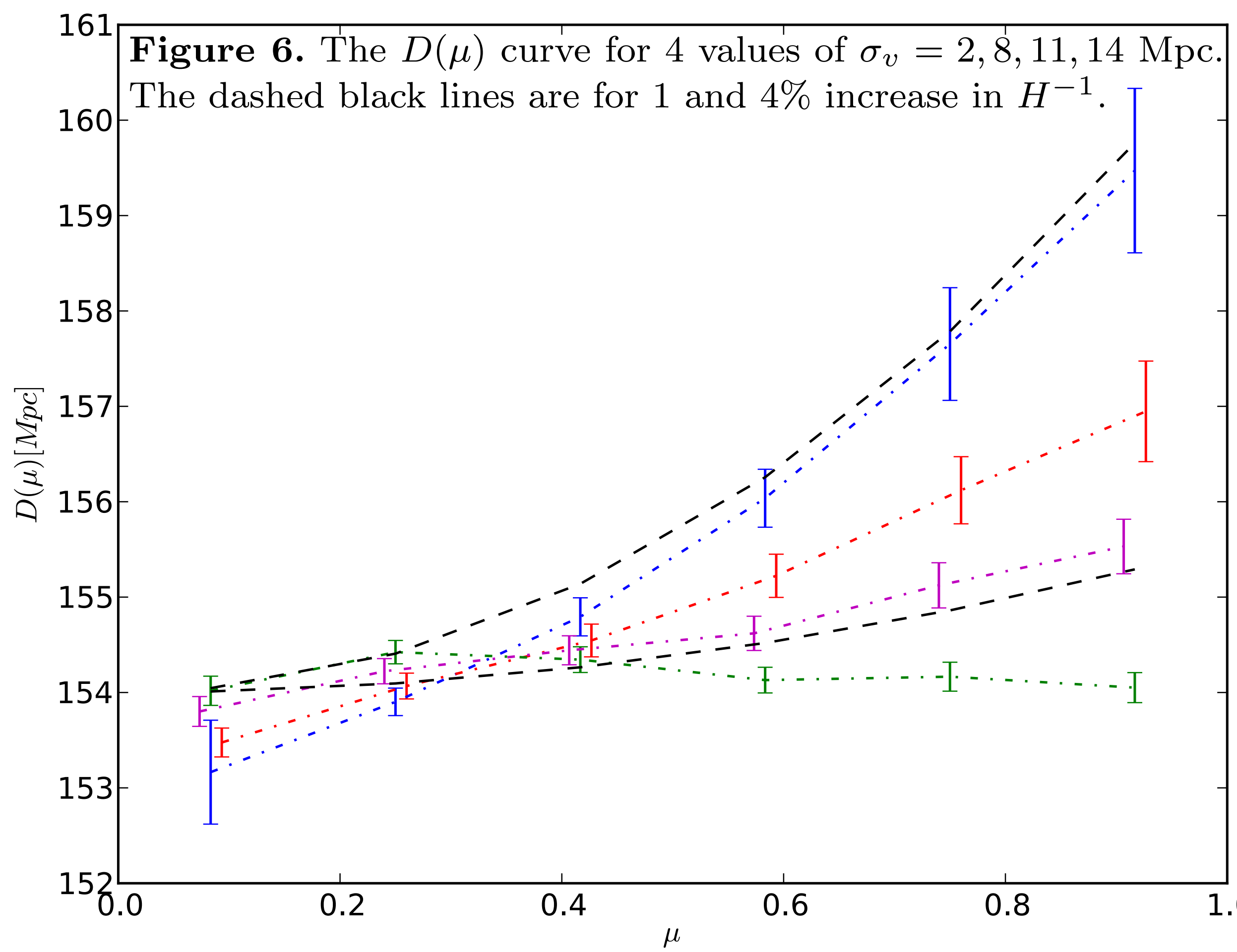


Figure 6. The $D(\mu)$ curve for 4 values of $\sigma_v = 2, 8, 11, 14$ Mpc. The dashed black lines are for 1 and 4% increase in H^{-1}.

$D_{||} = 154.92^{+0.51}_{-2.29}$ 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 $H^{-1} = 3201.66^{+47.94}_{-10.39} (-1.02^{+1.48}_{-0.32}\%)$.

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
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

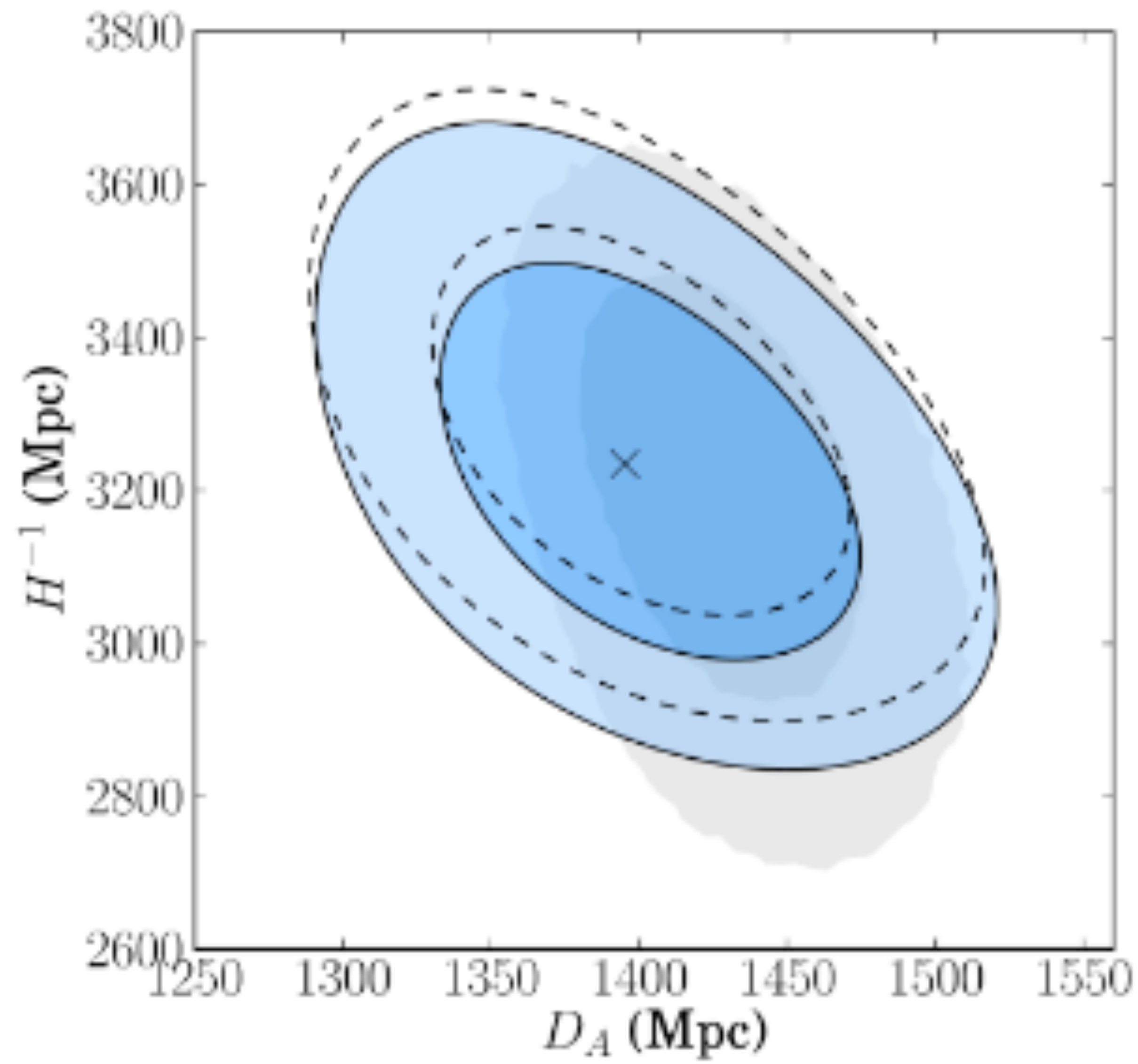
minimal cosmo dependance

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. However is provides a less biased result.

obtain constraints on DA & H at the level of 2% and 5% resp.



Sabiu & Song (2016)
arxiv:1603.02389

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

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

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

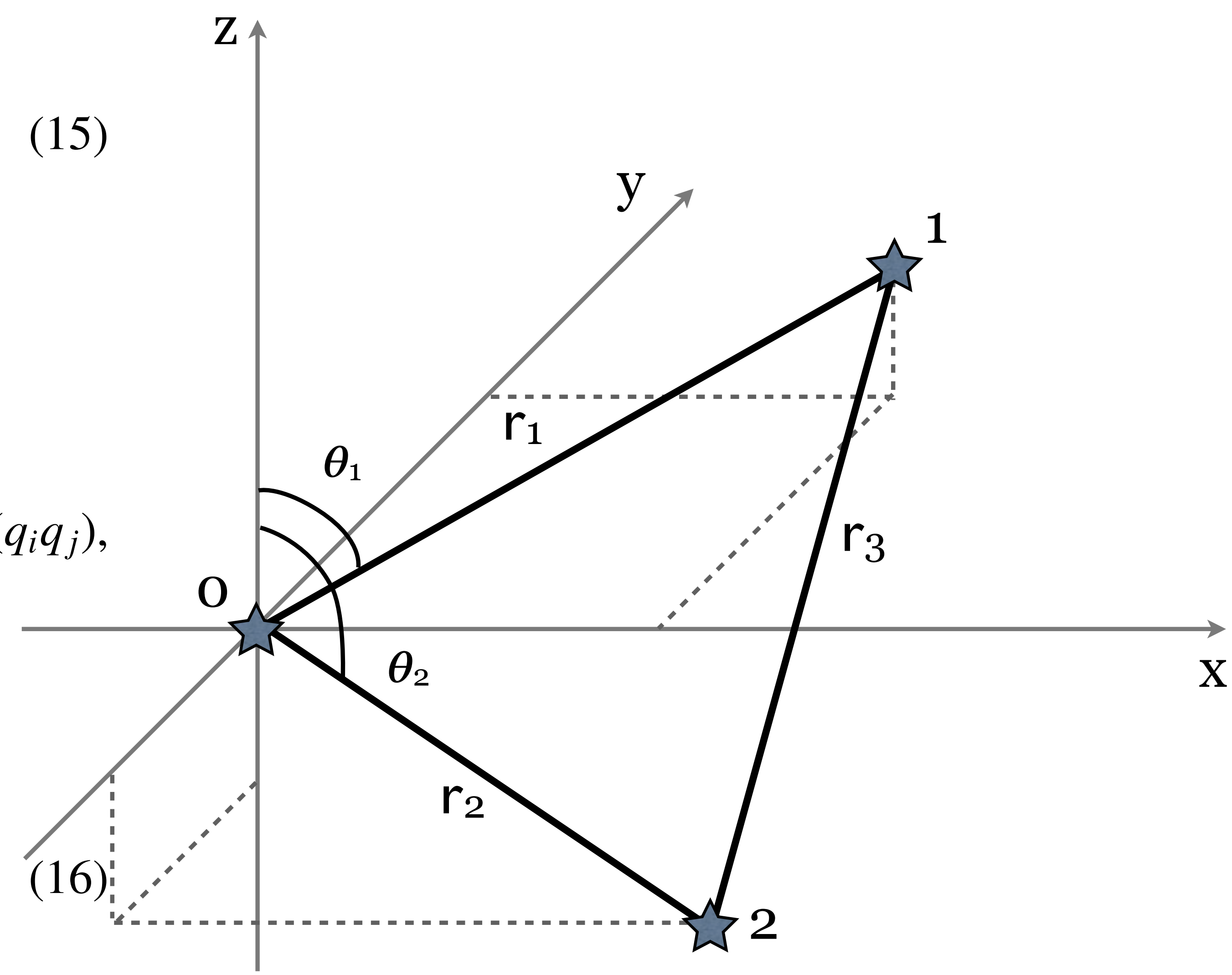
$$\alpha(\mu_i) \equiv \left\{\left(\frac{D_A^{\rm fid}}{D_A^{\rm true}}\right)^2 + \left[\left(\frac{H^{\rm true}}{H^{\rm fid}}\right)^2 - \left(\frac{D_A^{\rm fid}}{D_A^{\rm true}}\right)^2\right]\mu_i^2\right\}^{1/2}.$$

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

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

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

Triangular configuration for the 3PCF.



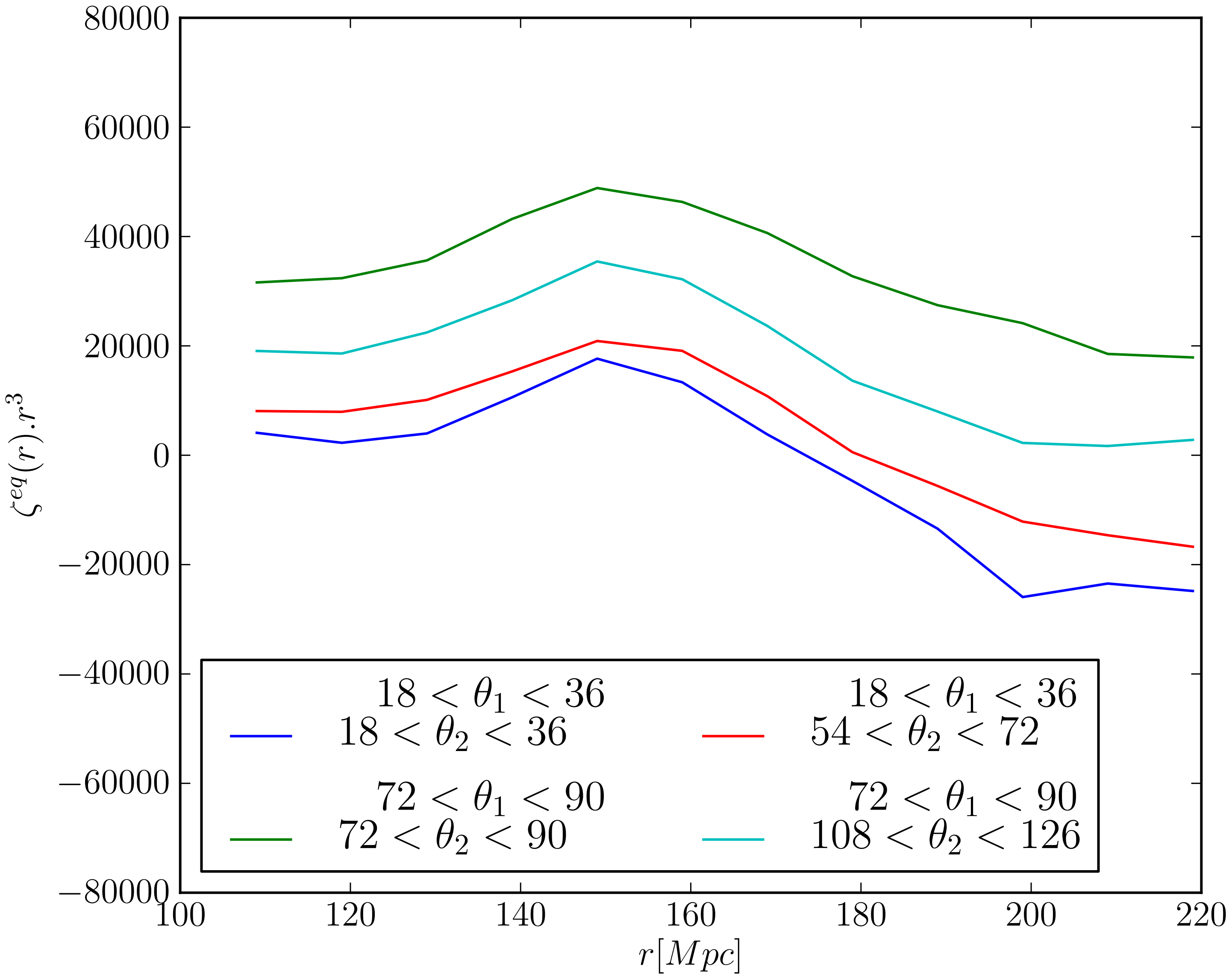
The anisotropic 3PCF

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.

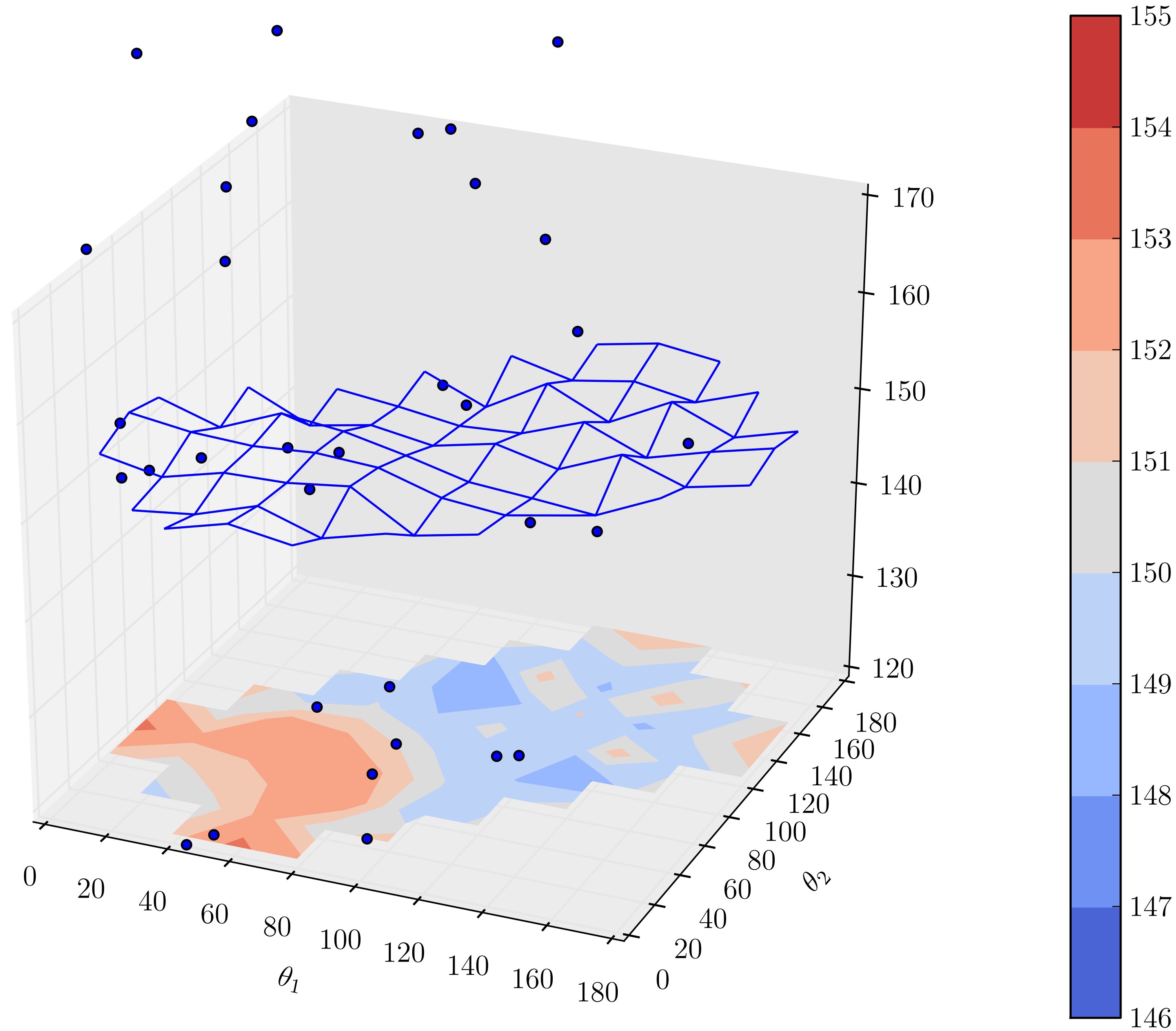
This suppression disappears when looking at triangles that lie flat on the plane of the sky.



The 3-point BAO

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

This forms a membrane in the D, theta1, theta2 space



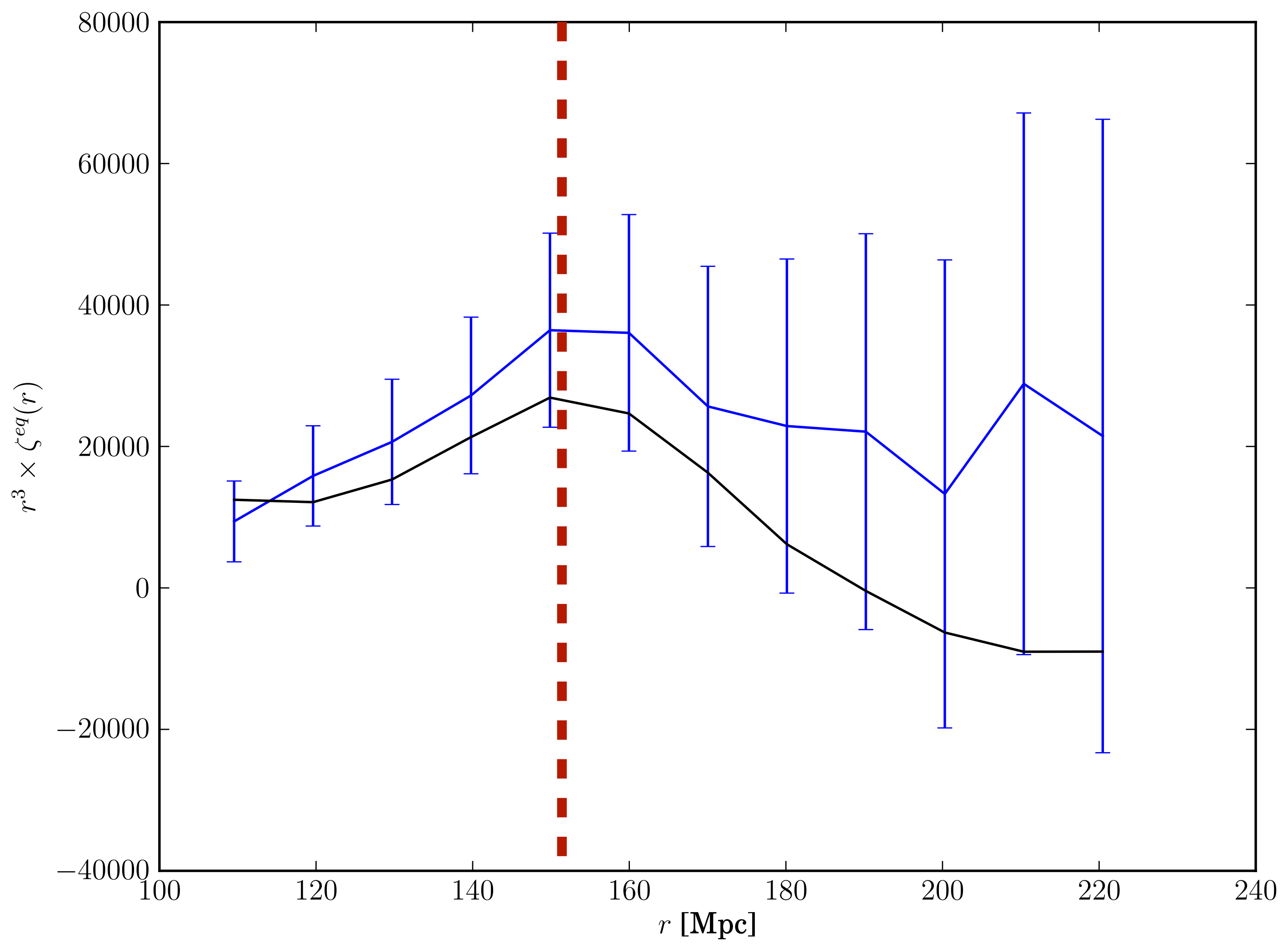
The 3-point BAO

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



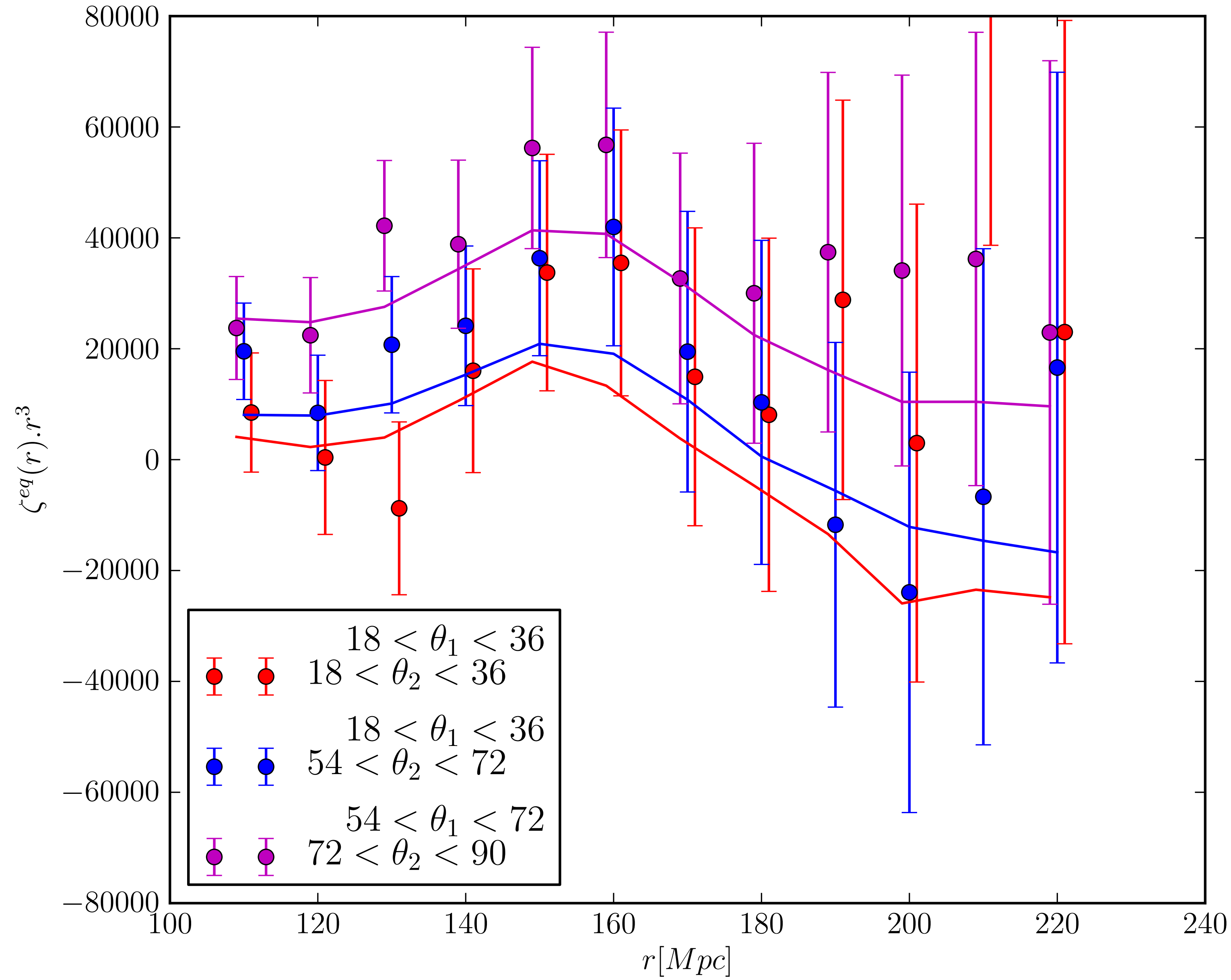
The 3-point BAO

Again using the DR12 Galaxies

we measure the anisotropic equilateral 3PCF

We again see a clear peak structure for various angular configurations

Anisotropic equilateral 3PCF

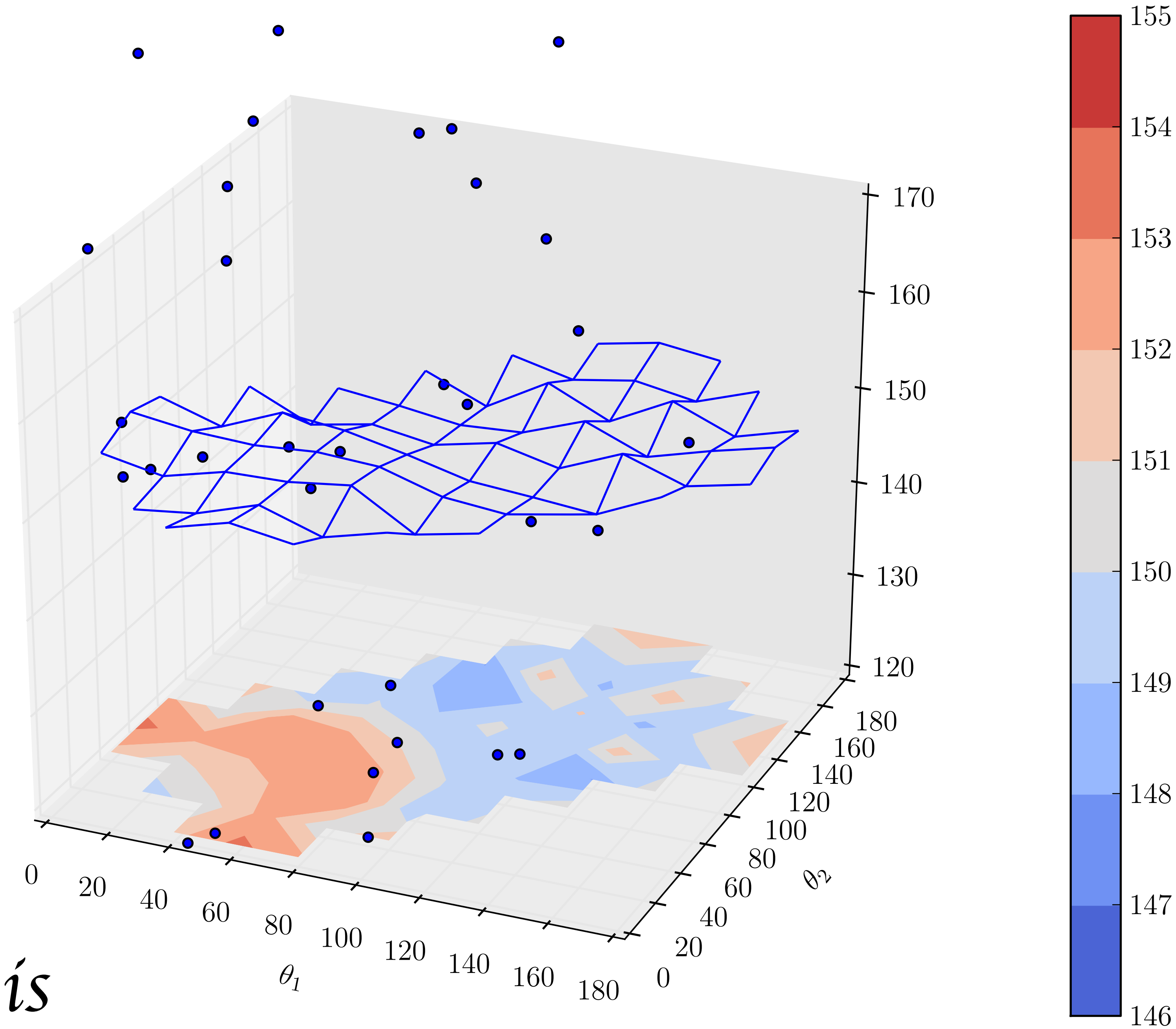


The 3-point BAO

This is work in progress and will be completed soon.

Only thing left to do is fit the DA and H 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....



"Pain is certain, suffering is optional." - Buddha

Conclusions

"To understand everything is to forgive everything" - Buddha

CosKASI

We used the luminosity correlation function to put limits on compensated isocurvature.
- Soon hope to update this work with DR12 CMASS+LOWZ

We hunted for mod. grav. induced variations in the velocity field and the local environment density...
- Measured the redshift-space clustering statistics
- Although this is only a qualitative study so far, it is the 1st regarding redshift-space bispectra/3PCF in modified gravity.

We wanted clean measurements of Da and H(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 Da and H measurements