Constraining cosmology with the dynamics of voids

Adam J. Hawken

Osservatorio Astronomico di Brera, INAF, Merate/Milano

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Summary

I shall give an overview of how we can model void density profiles.

I shall show how we can use our model to characterise super structures in BOSS.

I shall illustrate how measurements of the void-galaxy cross correlation function exhibit an anisotropy indicative of linear RSD.

I shall demonstrate how by deprojecting the cross-correlation we can remove the RSD.

I shall also demonstrate that a linear model for the RSD is sufficient to measure the growth rate of structure in simulations.

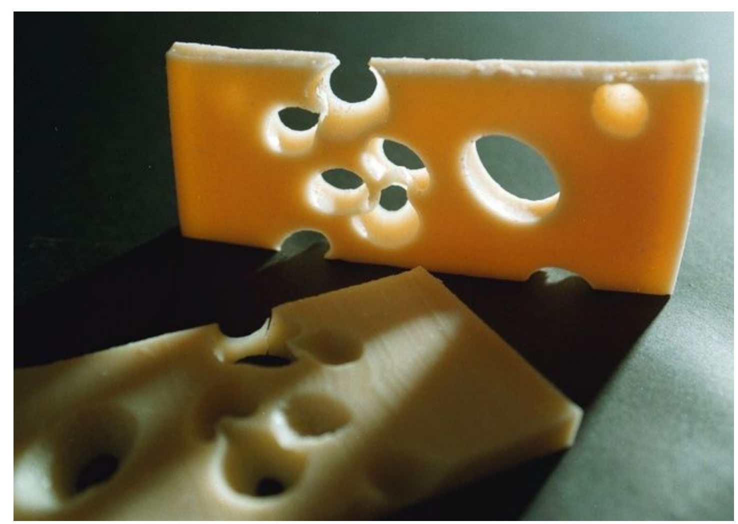
I shall apply the same technique to data from VIPERS and compare the result to other measurements.

What are cosmic voids? Are voids interesting?

- Voids are an important structural and dynamical component of the cosmic web.
  - Occupy most of the volume of the Universe
  - Drive the expansion of the Universe

- Cosmological information is encoded in their structural and dynamical properties:
  - Substructure
  - Evacuation
  - Expansion
  - Morphology
  - Topology

- Pristine low density environments in which to study galaxy evolution.

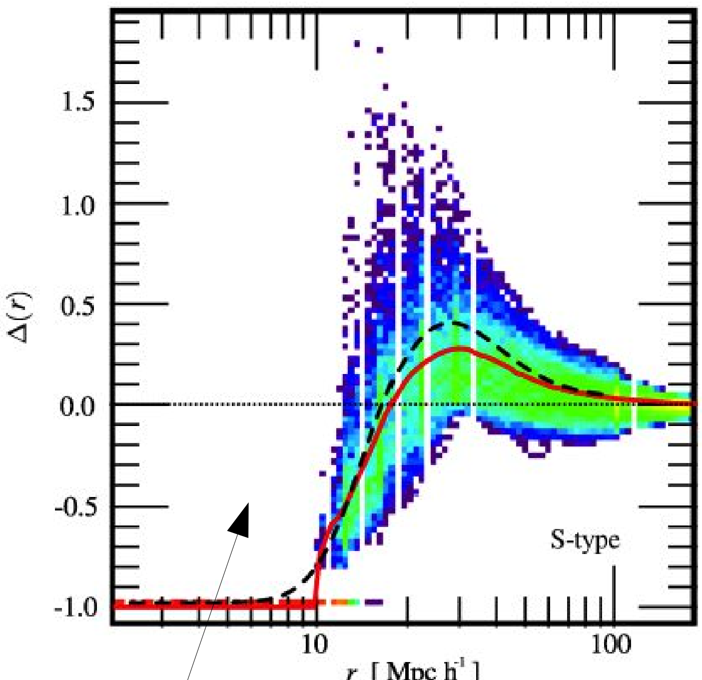


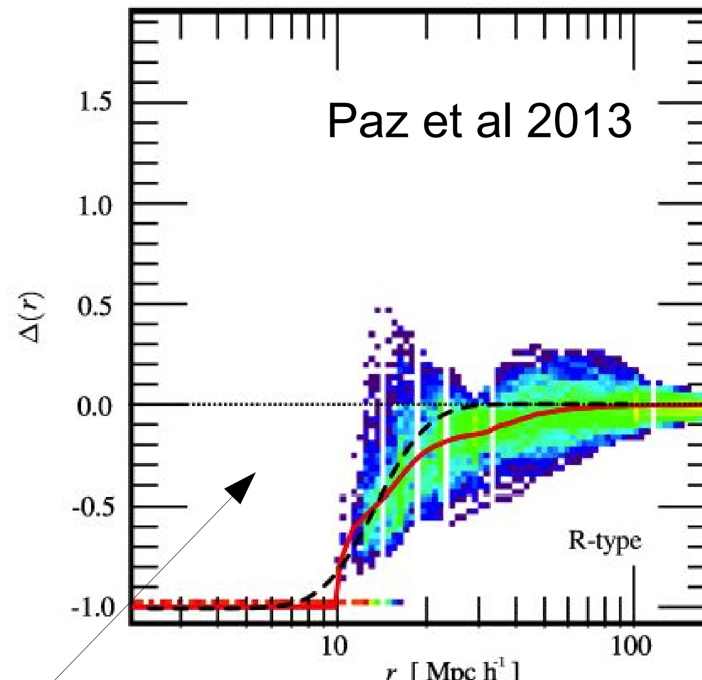
Modelling void density profiles

Understanding how material is distributed in and around voids is an essential step in understanding their dynamical properties.

Some voids are surrounded by a compensating overdense ridge, others are not (Sheth & van de Weygaert 2004).

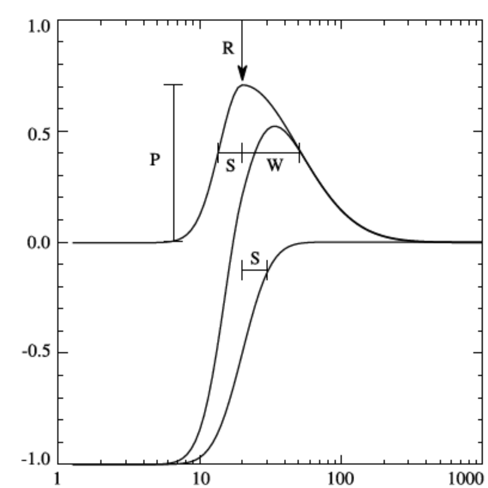
Paz et al 2013 break down void profiles into different parts.





$$\Delta_R(r) = \frac{1}{2}\left[\mathrm{erf}\left(S\log(r/R)\right) - 1\right]$$

$$\Delta_S(r) = \frac{1}{2}\left[\mathrm{erf}\left(S\log(r/R)\right) - 1\right] + P\exp\left(-\frac{\log^2(r/R)}{2\Theta^2(r)}\right)$$



Modelling void density profiles

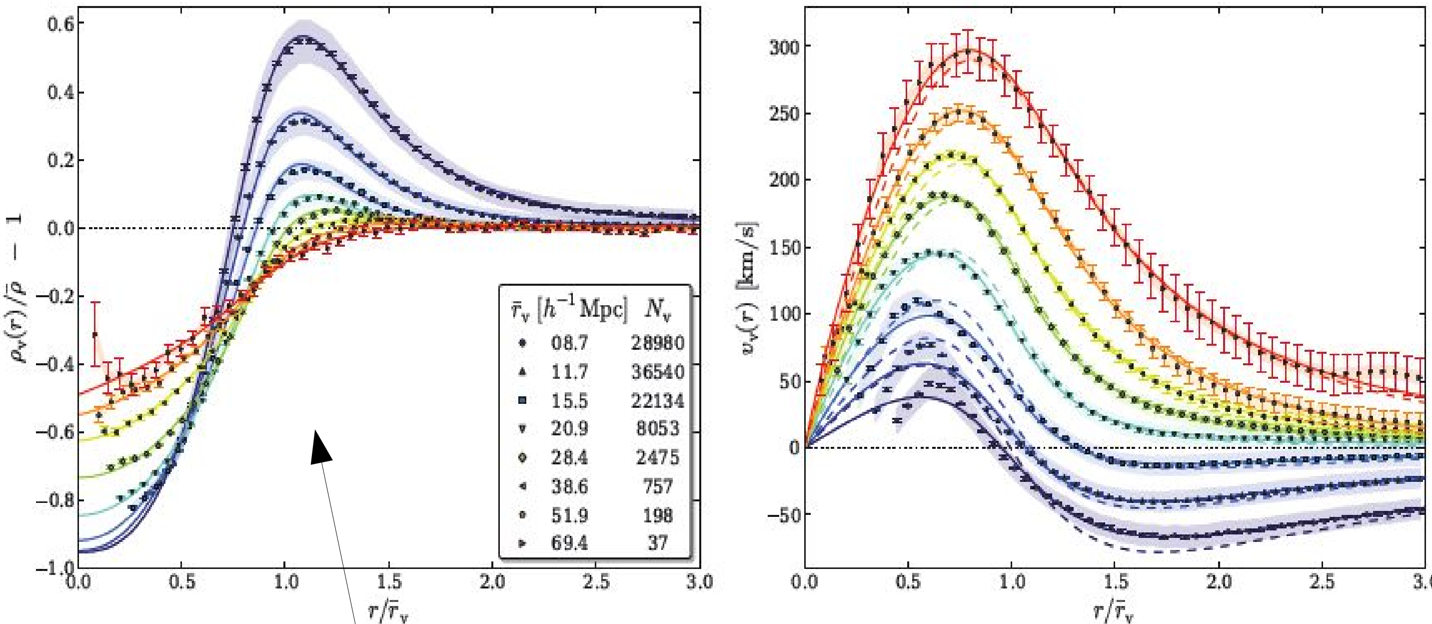
Hamaus et al 2014 suggest a universal density profile for voids.

$$\frac{\rho_{\rm v}(r)}{\bar{\rho}} - 1 = \delta_c \frac{1-(r/r_s)^\alpha}{1+(r/r_{\rm v})^\beta}$$

Their description works well for a variety of tracers and void sizes in simulations.

However, the integrated density contrast can be complicated to write down.

$$\Delta(r) = \delta_c\, {}_2F_1\left[1, \frac{3}{\beta}, \frac{3}{\beta}+1, -(r/r_{\rm v})^\beta\right] - \frac{3\delta_c(r/r_s)^\alpha}{\alpha+3}\, {}_2F_1\left[1, \frac{\alpha+3}{\beta}, \frac{\alpha+3}{\beta}+1, -(r/r_{\rm v})^\beta\right]$$



The assumption of linear velocities is a good description

(see also Padilla et al '05, Dubinski '93)

Our model for the void density profile

We propose a simple stretched exponential form for the cumulative void density profile (generalised Gaussian).

$$\Delta(r) = \delta_c \exp\left(- \left(\frac{r}{r_v} \right)^{\alpha} \right)$$

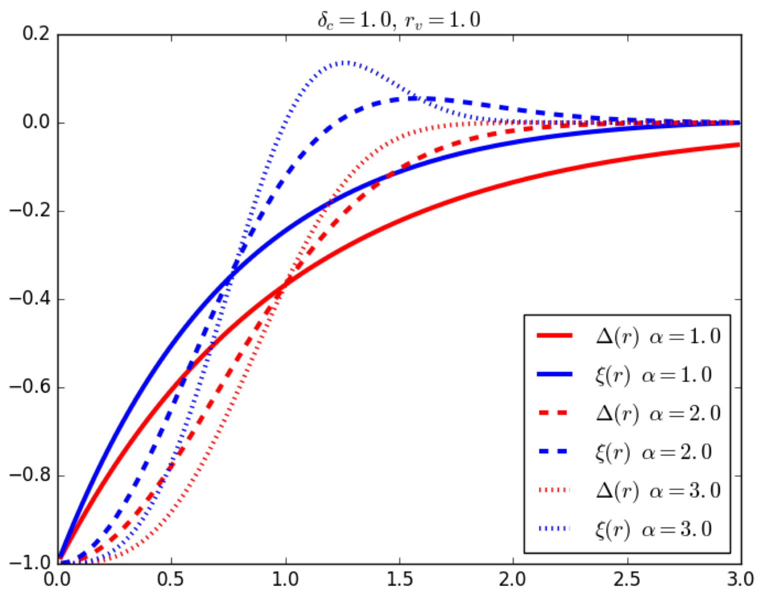
Shape parameter

Scale radius

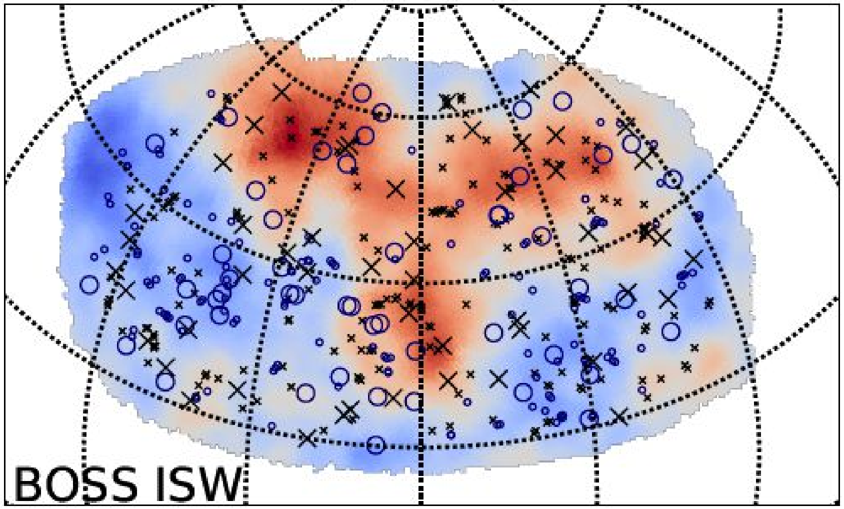
Central density parameter

$$\xi_{vg}(r) = \delta_c \left(1 - \frac{\alpha}{3} \left(\frac{r}{r_v} \right)^{\alpha} \right) \exp\left(- \left(\frac{r}{r_v} \right)^{\alpha} \right)$$

The cross correlation function is very easy to write down.



Characterising BOSS Super-Structures

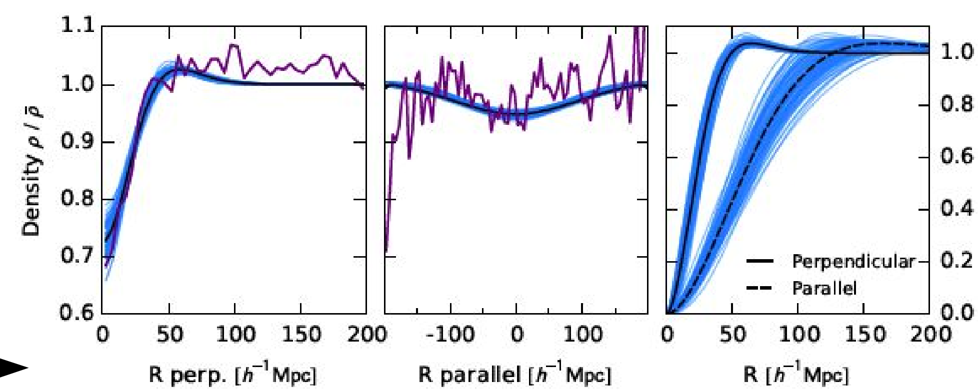


Super voids have been found in SDSS photometric redshift catalogues (Granett, Neyrinck, Szapudi 2008). Using a Voronoi void finder.

Furthermore there is evidence that such superstructures may be connected to features on the CMB (Szapudi et al 2015).

Spectroscopic information from BOSS allows us to characterise the density profiles of these objects and to test to see if they are significant.

We separate the line of sight and tangential profiles.

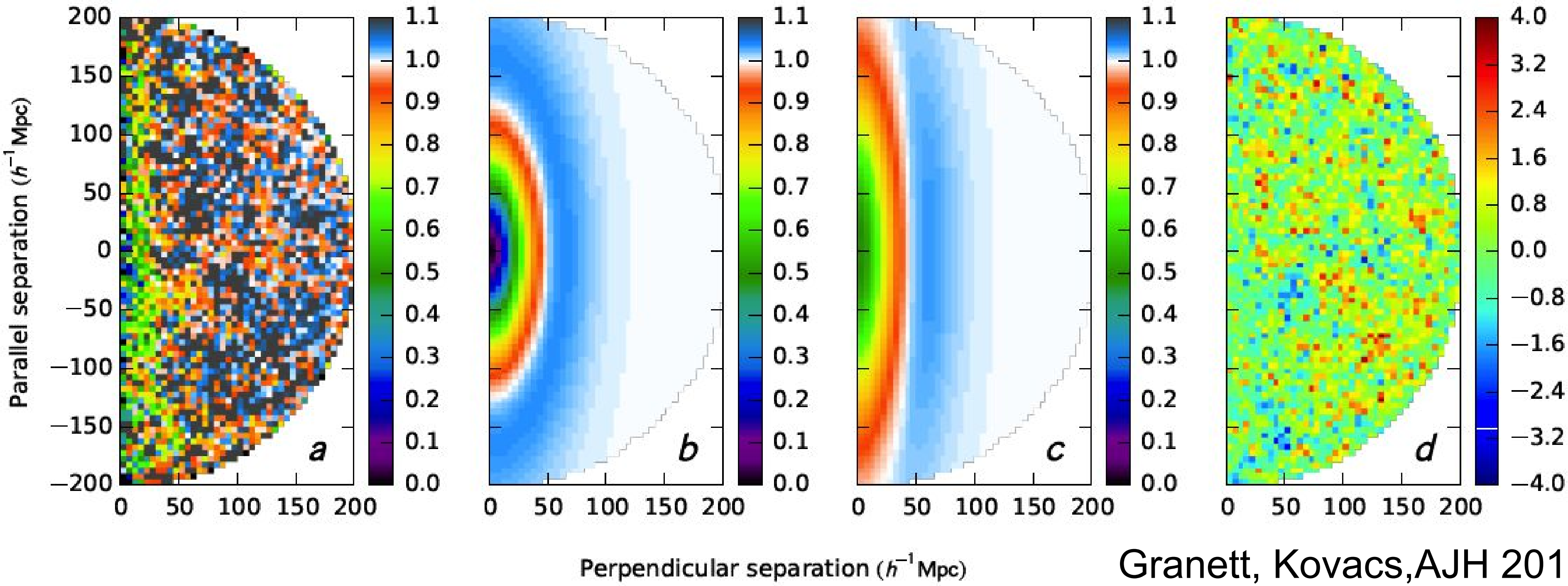


Our model can be easily extended to allow for elliptical void profiles.

$$\tilde{r}^2 = r_{perp}^2 + r_{par}^2/q^2.$$

Granett, Kovacs,AJH 2015

Characterising BOSS Super-Voids



Granett, Kovacs,AJH 2015

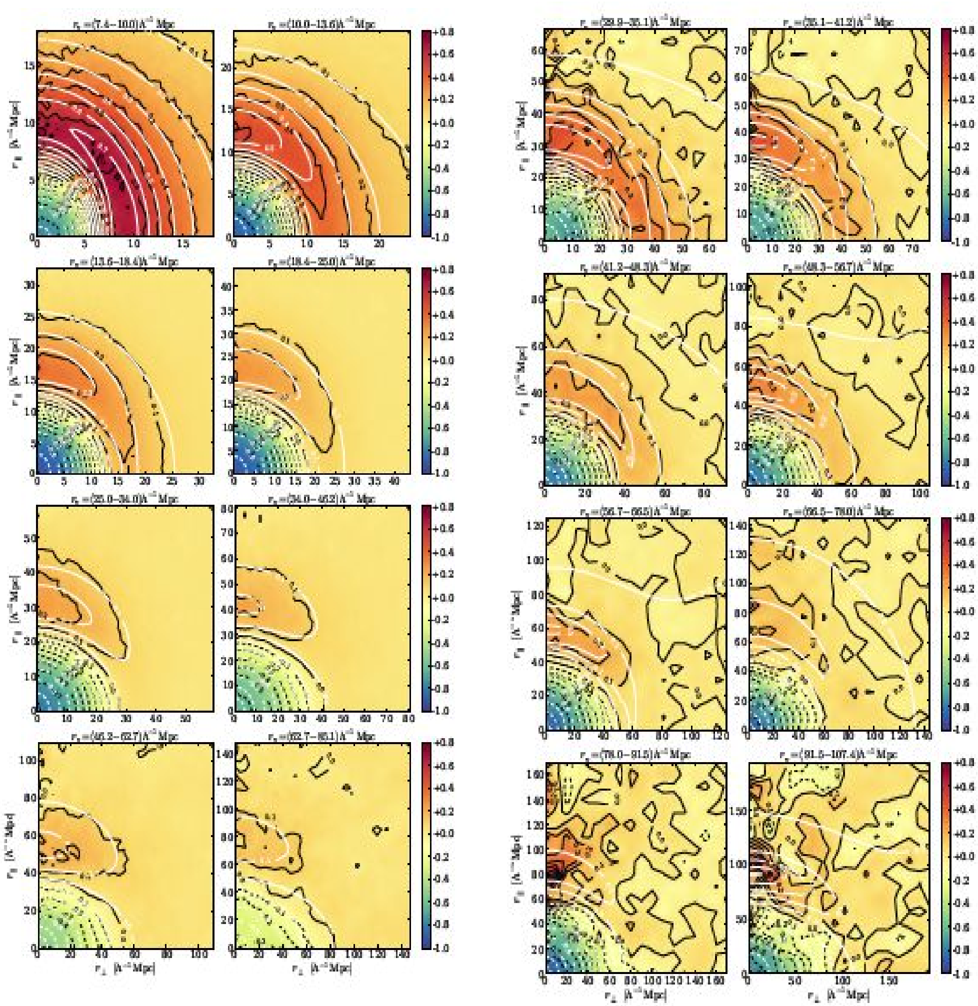
Convolve profile with a Gaussian kernel to account for photometric redshift errors.

$$\rho_z(r_{perp}, r_{par}) = \frac{1}{\sqrt{2\pi\sigma_{los}^2}} \int e^{-\frac{(y-r_{par})^2}{2\sigma_{los}^2}} \rho(r_{perp}, y) dy.$$

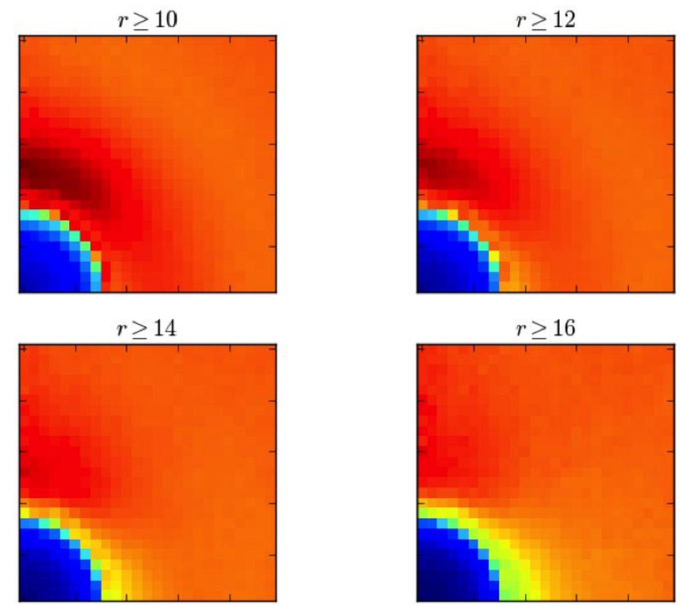
We find that these super voids are significantly elongated along the line of sight.

We believe that this is a selection effect of the void finder in photometric redshift space.

Evidence of redshift space distortions (in simulations)

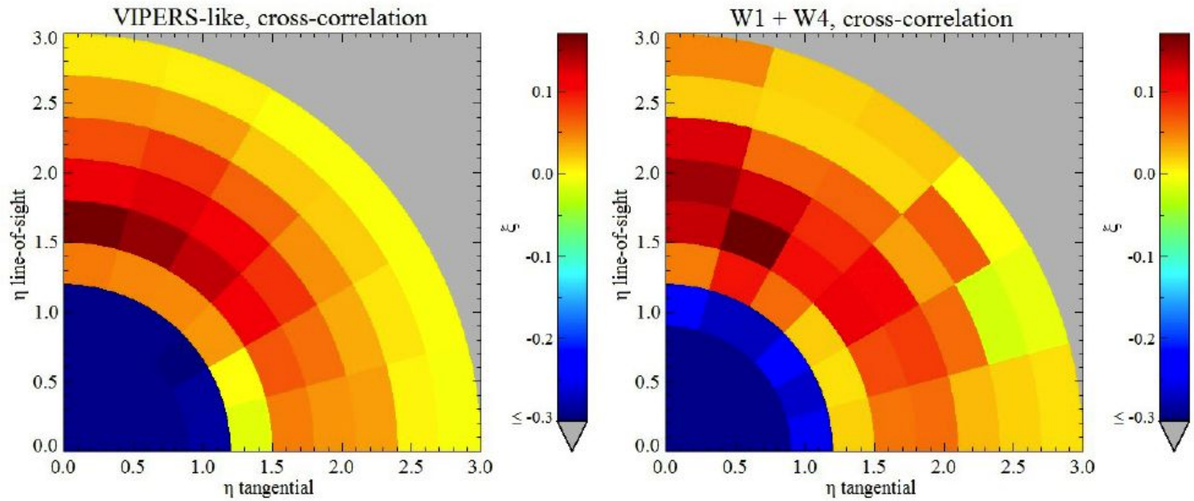


Hamaus et al '15

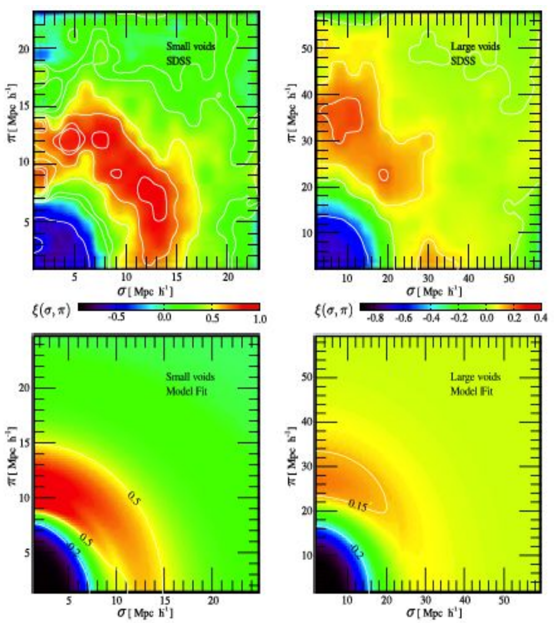


AJH, Granett, Guzzo, Iovino et al in prep

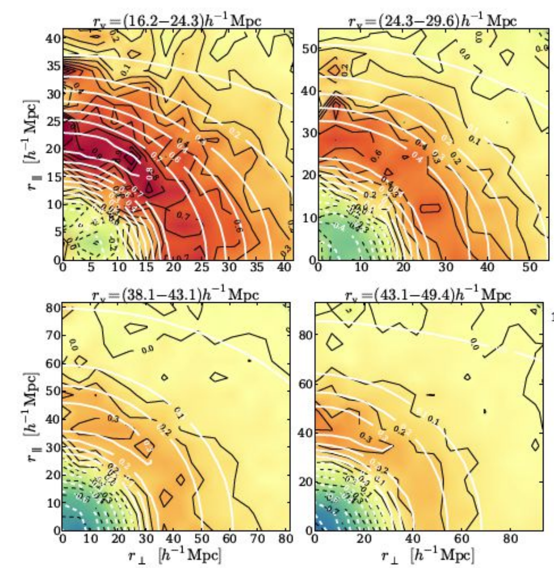
Evidence of redshift space distortions (in observations)



Micheletti, Iovino, AJH, Granett et al '14



Paz et al '13



Hamaus et al 2016

Linear redshift space distortion model

Gaussian streaming model:

$$1+\xi_{vg}(r_{\|}, r_{\perp}) = \int_{-\infty}^{+\infty} \frac{\mathrm{d}w_3}{\sqrt{2\pi}\sigma_v} \exp\left(-\frac{(w_3 - v(r)\frac{r_3}{r})^2}{2\sigma_v^2}\right)[1+\xi_{vg}(r)]$$

$$r_3 = r_{\|} - \frac{w_3}{H_0},\ r^2 = r_{\perp}^2 + r_3^2$$

Assume that all anisotropy is caused by RSD (i.e. no Alcock-Paczynski and no ellipticity)

$$v(r) = -\frac{H(z)}{1+z} r\Delta(r)\frac{\beta}{3}$$

Linear velocities

β is proportional to the growth rate of structure.

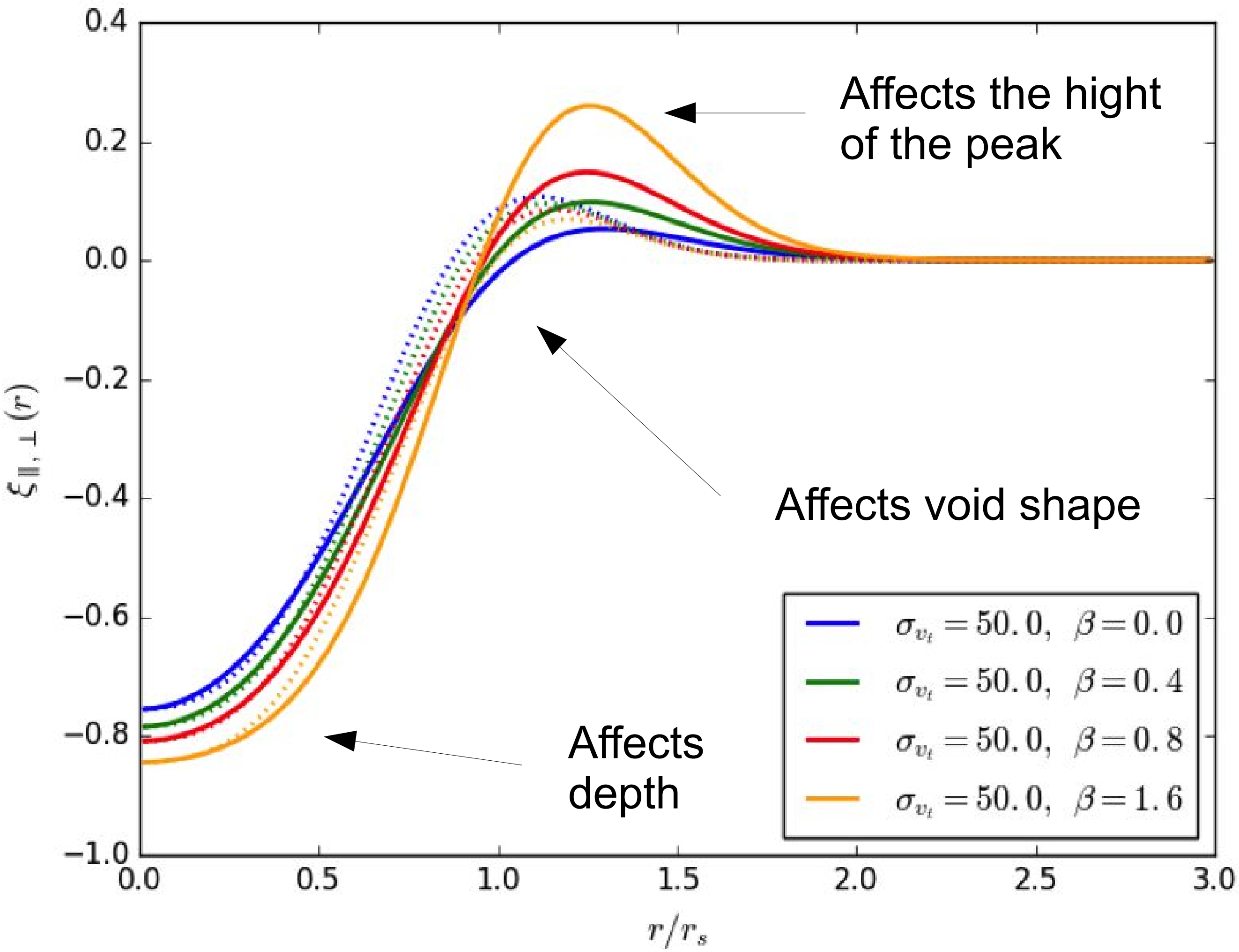
$$\beta = f(z)/b$$

$$f = \frac{d\ln D}{d\ln a}$$

In standard GR $\gamma \approx 0.55$

$$f(z) = \Omega_m^{\gamma}(z)$$

Growth parameter



$$v(r) = -\frac{H(z)}{1+z} r \Delta(r) \frac{\beta}{3}$$

$$\beta = f(z)/b$$

Solid lines show line of sight component.

Dotted lines show tangential component.

Velocity dispersion parameter

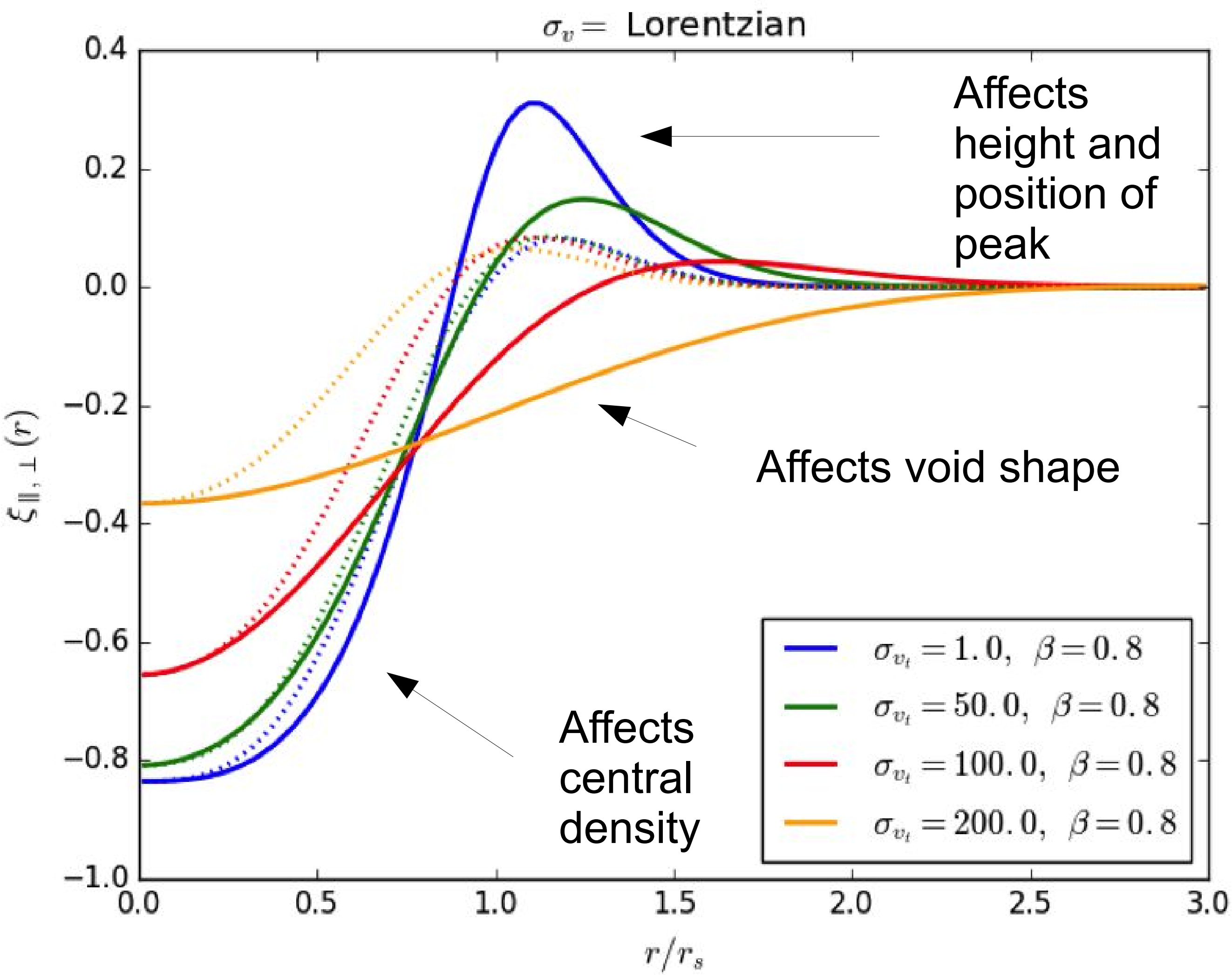
The peculiar velocities of galaxies around should have some dispersion.

This dispersion should be a function of distance from the void centre.

$$\sigma_v(r) = \sigma_{v'}\left(1 - \frac{1}{\sqrt{2}(1 + \frac{r^2}{\omega})}\right)$$

We find that a Lorentzian dispersion is a better fit than a constant dispersion.

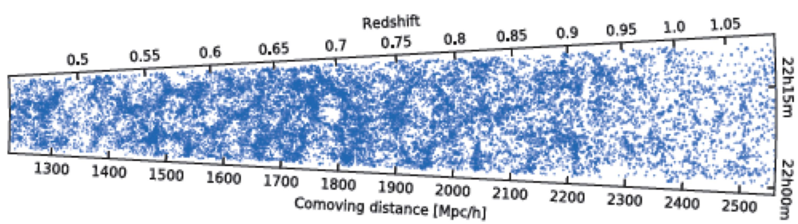
The dispersion has an effect on the apparent central density, and on the hight and position of the peak.

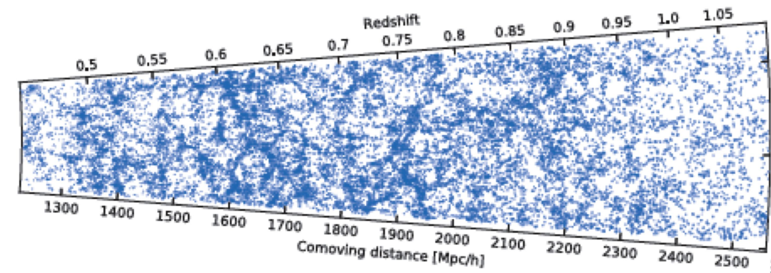


The VIMOS Public Extragalactic Redshift Survey

VIPERS (now complete) is an ESO large program, started at the end of 2008, to map in detail the spatial distribution of galaxies down to $i_{AB} < 22.5$

VIPERS is split over two CFHTLS fields (W1 and W4)





close to 100,000 redshifts in the range 0.5<z<1.2

Large volume ~5x10^7 h^3/Mpc^3

High effective spectroscopic sampling > 40%

What can we do with VIPERS?

VIPERS has a large volume, is at a high redshift and has a high density, s would be close to being the optimal void survey were it not for the unfortunate geometry.

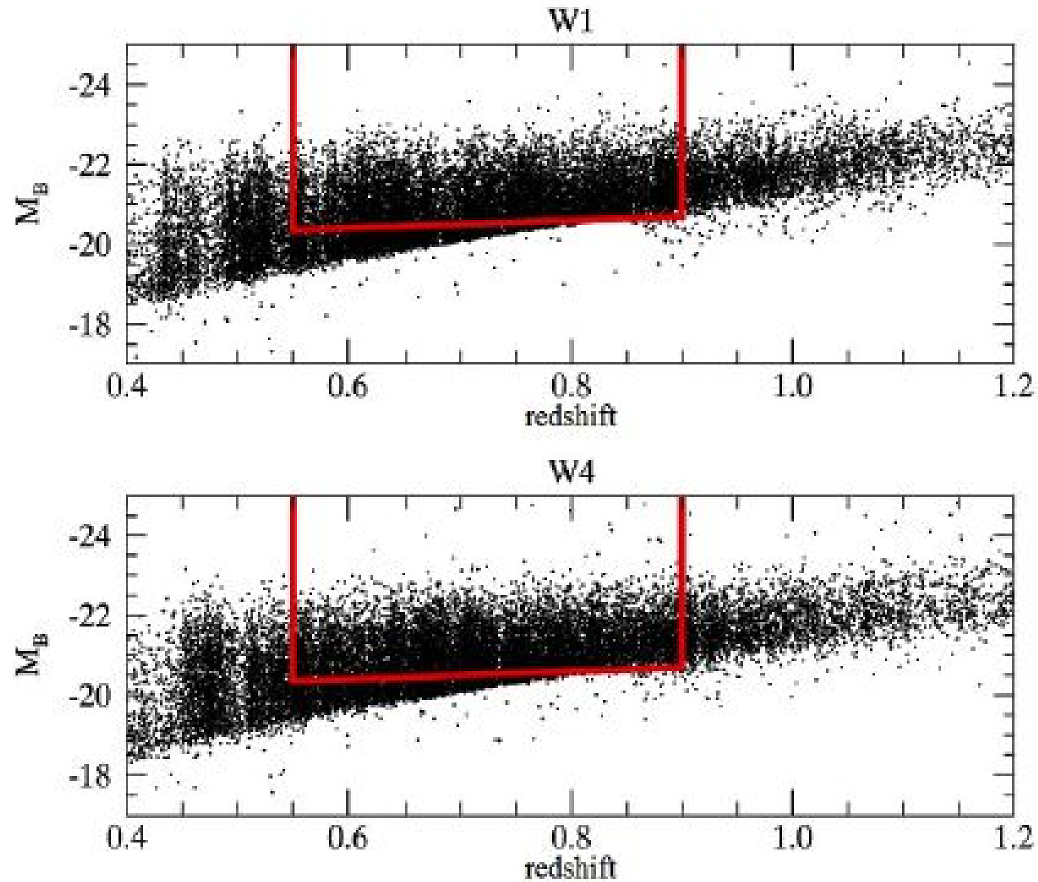
The flatness of VIPERS prevents us from using popular watershed void finding algorithms.

We developed a void finding algorithm based on empty spheres.

We carry out our search in a volume limited catalogue, selecting galaxies with an absolute magnitude:

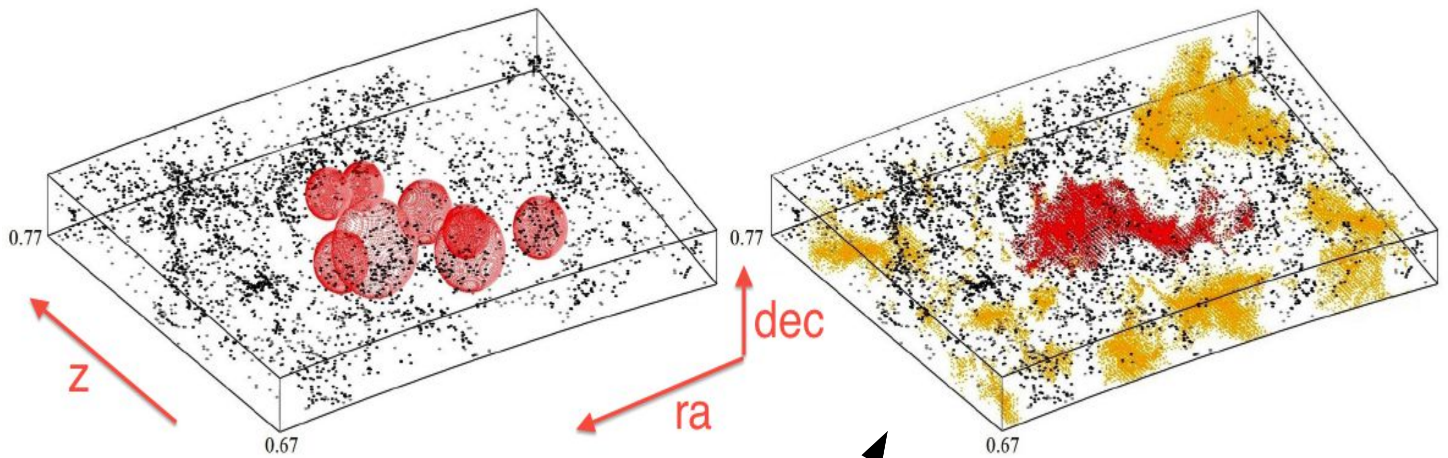
M_B < -19.5 – z

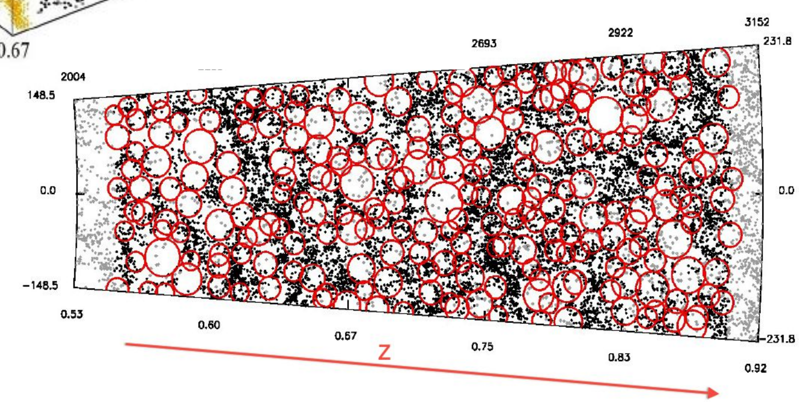
within the redshift range 0.55 < z < 0.9.



Micheletti, Iovino, AJH, Granett et al '14

The search for voids in VIPERS

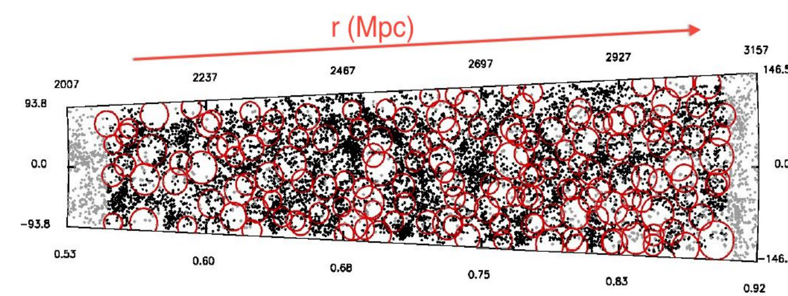




Find empty spheres on a fine regular grid in a pruned volume limited catalogue

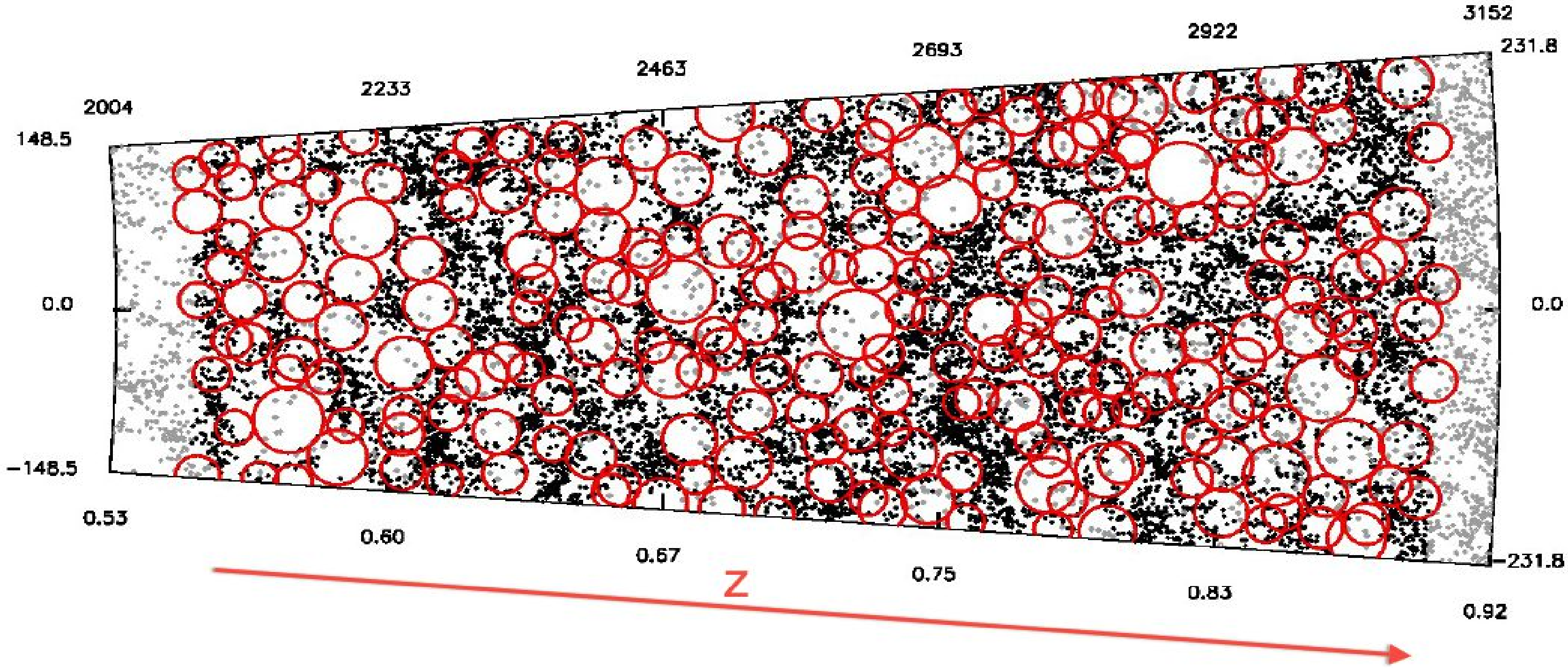
Topologically voids are aspherical

But here we assume them to be spheres...

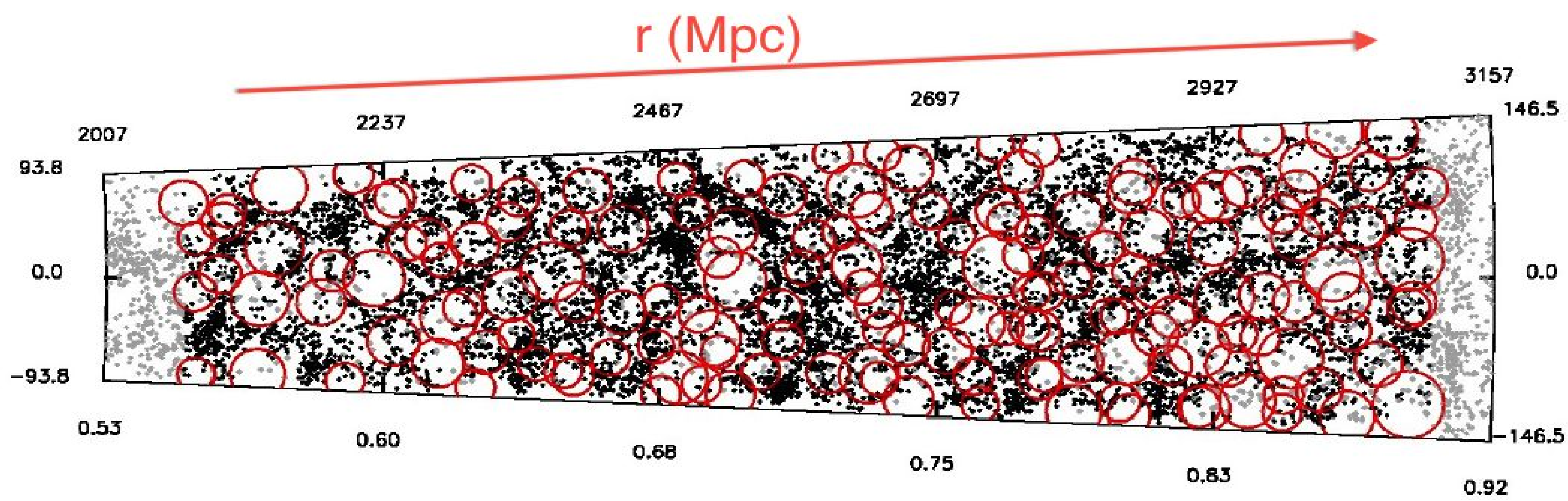


Micheletti, Iovino, AJH, Granett et al '14

W1 : 473 voids



W4 : 240 voids



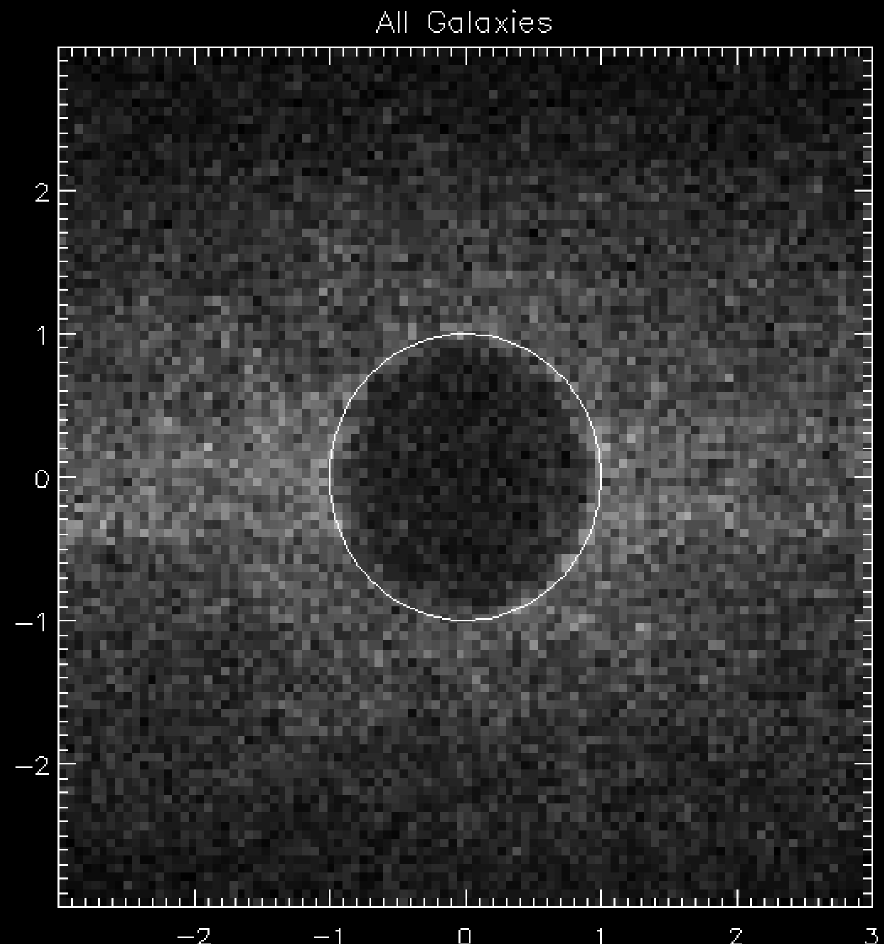
Micheletti, Iovino, AJH, Granett et al '14

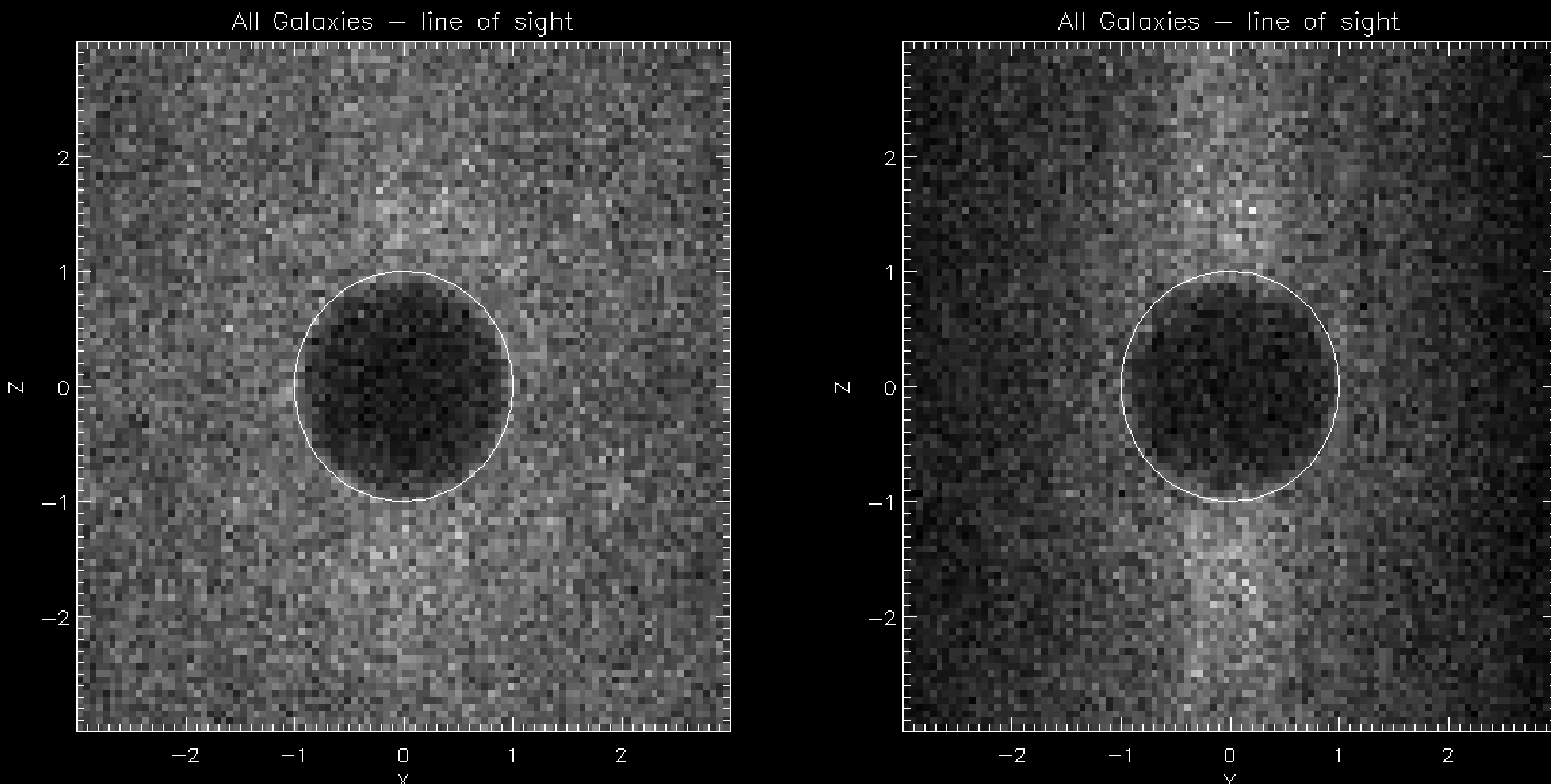
Stacked voids

Thickness of 0.25 void radii

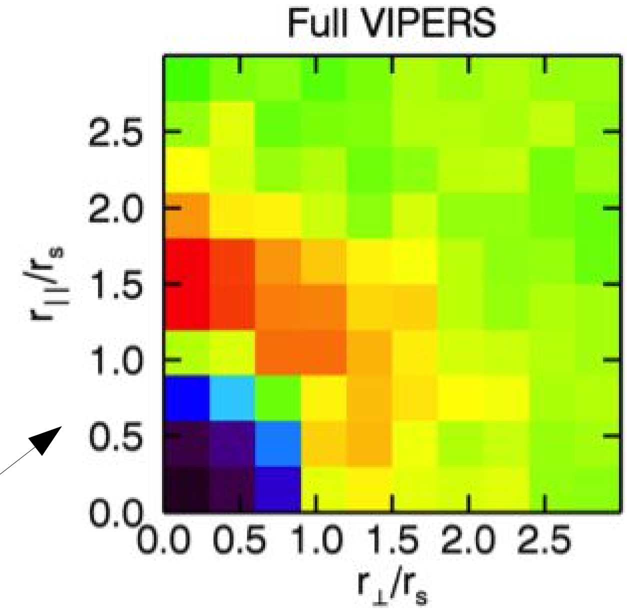
Galaxy positions rescaled

Systematic effects of survey geometry become apparent.




All Galaxies – line of sight
Z
X
All Galaxies – line of sight
Z
Y

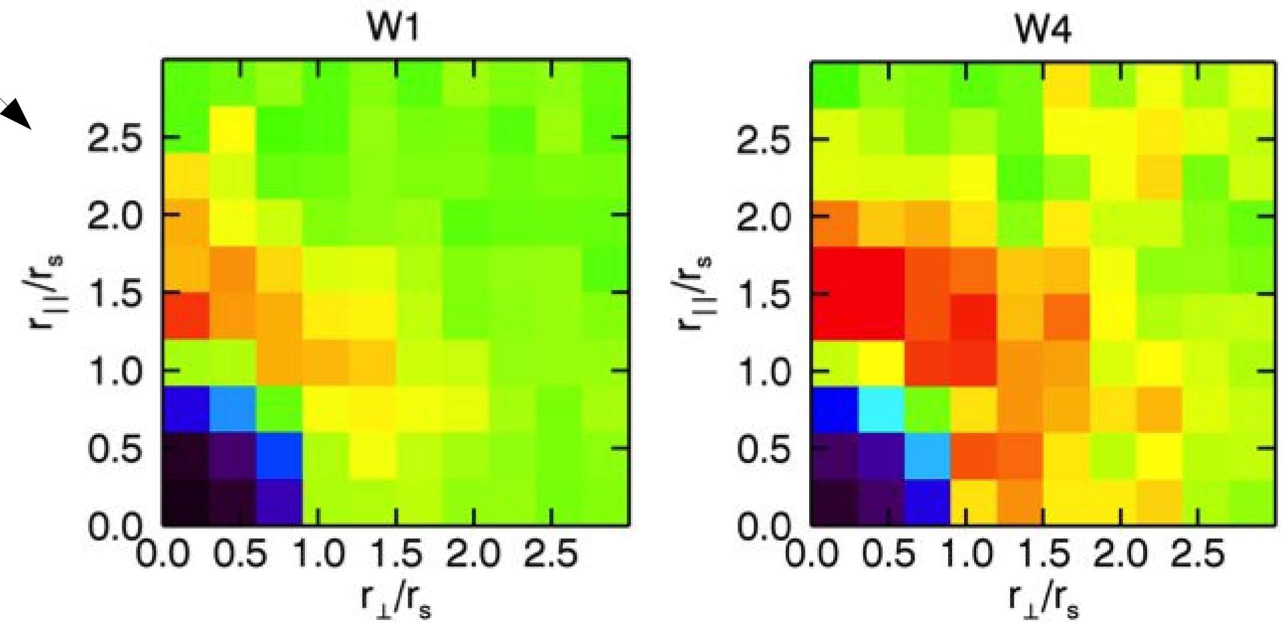
Measuring the void-galaxy cross correlation

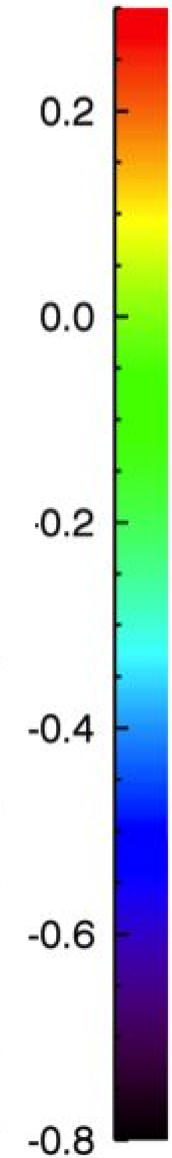


Davis & Peebles estimator

$$\hat{\xi}_{vg}(r_{||}^i, r_\perp^j) = \frac{n_g^{ij}}{n_r^{ij}} \frac{N_r}{N_g} - 1$$

Anistropy due to RSD clearly visible





Mock galaxy catalogues

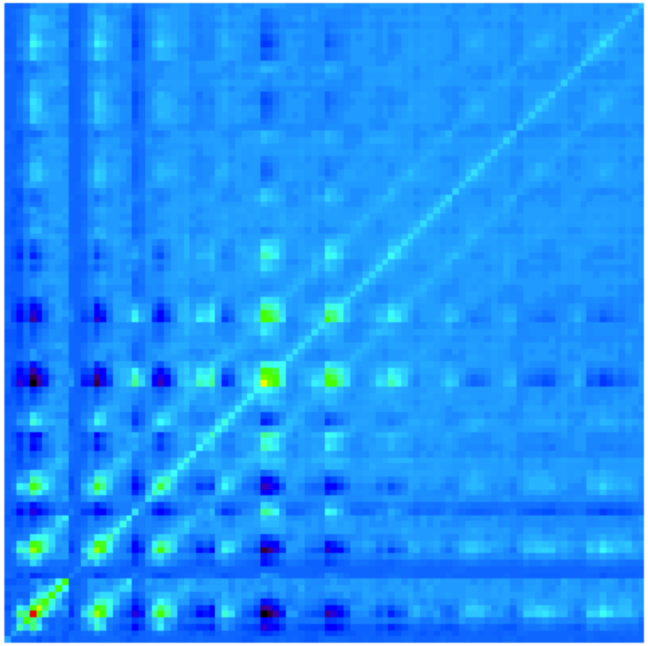
We use 306 mock galaxy catalogues built from MultiDark simulations populated with an HOD (de la Torre et al 2013).

The mocks have a Planck 2013 like cosmology:

$\Omega m = 0.31$, $\Omega de = 0.69$, $h=0.7$

We run our void finder on each catalogue, measured the void-galaxy cross correlations, and built covariance matrices for each field.

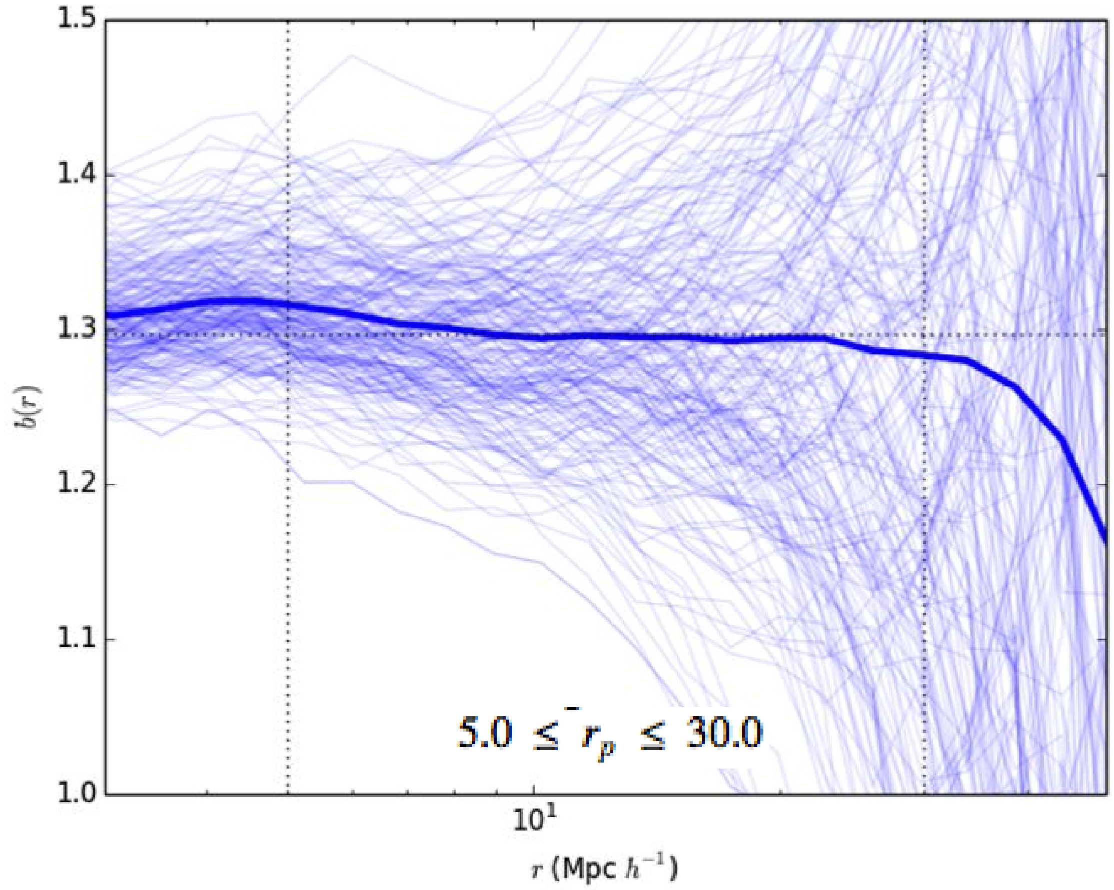
$$C_{ij,mn} = \frac{1}{N_{\mathrm{mock}} - 1} \sum_{N} (\xi_{ij} - \bar{\xi}_{ij})(\xi_{mn} - \bar{\xi}_{mn})$$



Galaxy bias in the mocks

We measure the projected correlation function in the mocks to estimate the bias.

$$b = 1.29 \pm 0.015.$$



From this we can say what we expect β to be measured as

β = 0.636 +/- 0.015

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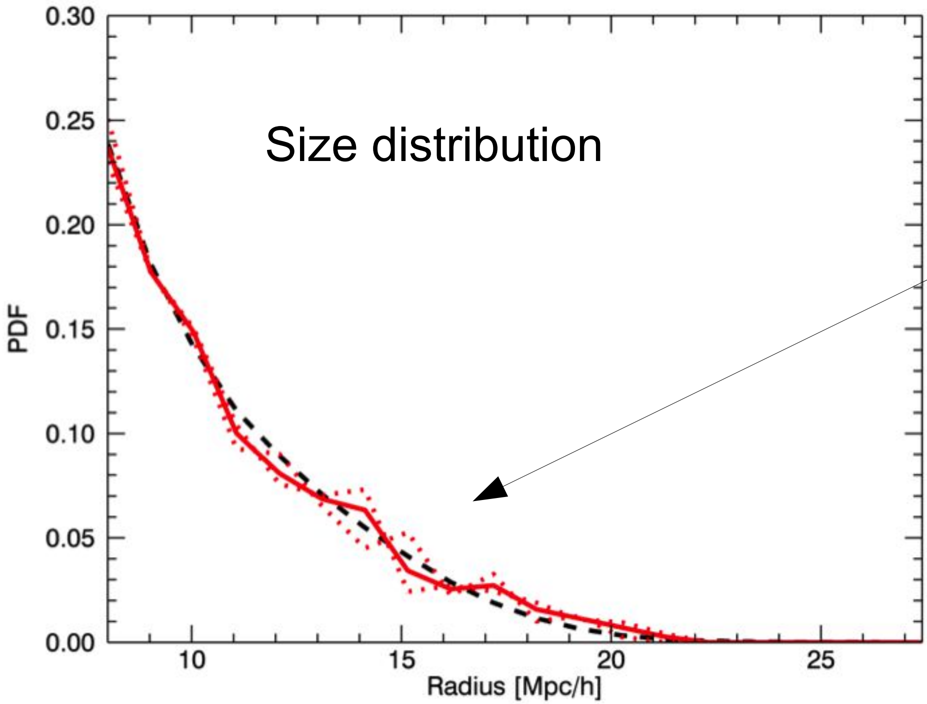
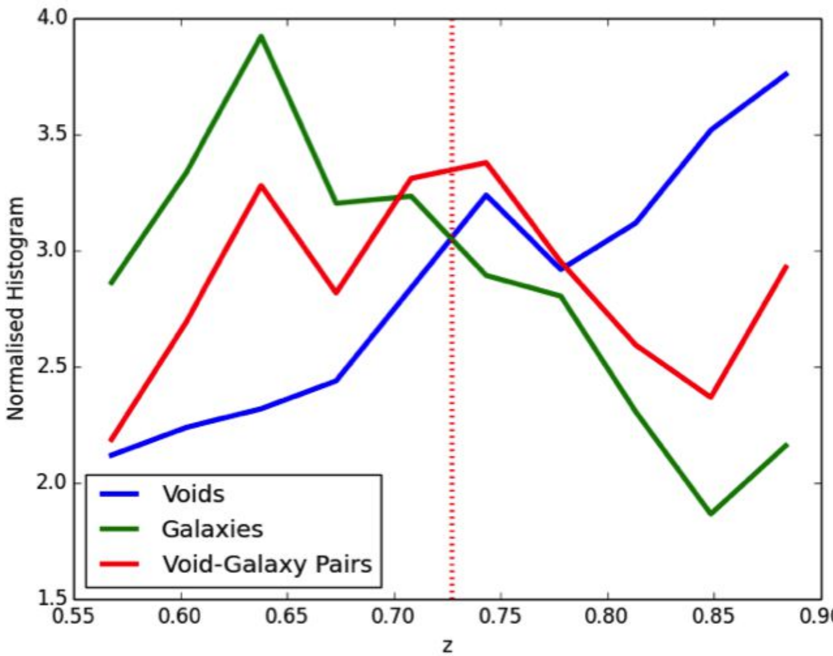
Some basic void statistics



No significant variance of void sizes between fields.

Redshift distribution



The number of voids increases with redshift, because the volume of the survey increases.

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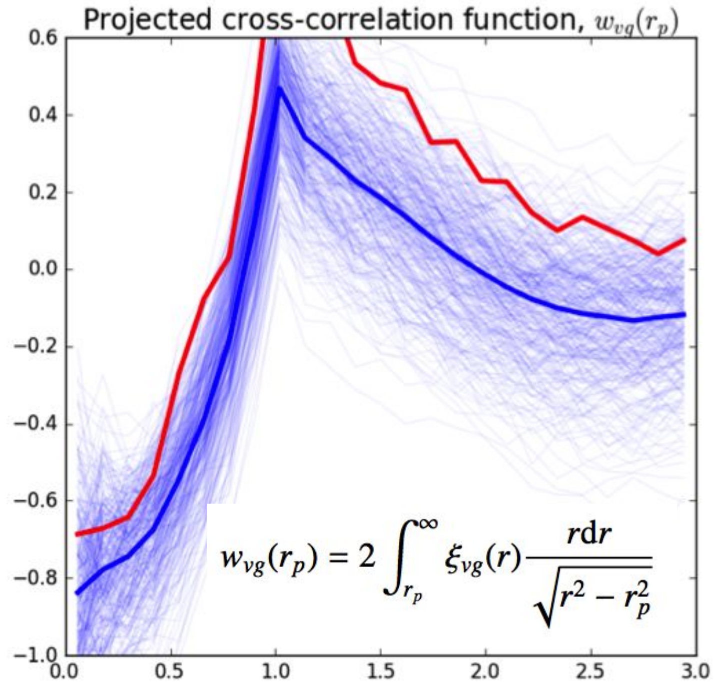
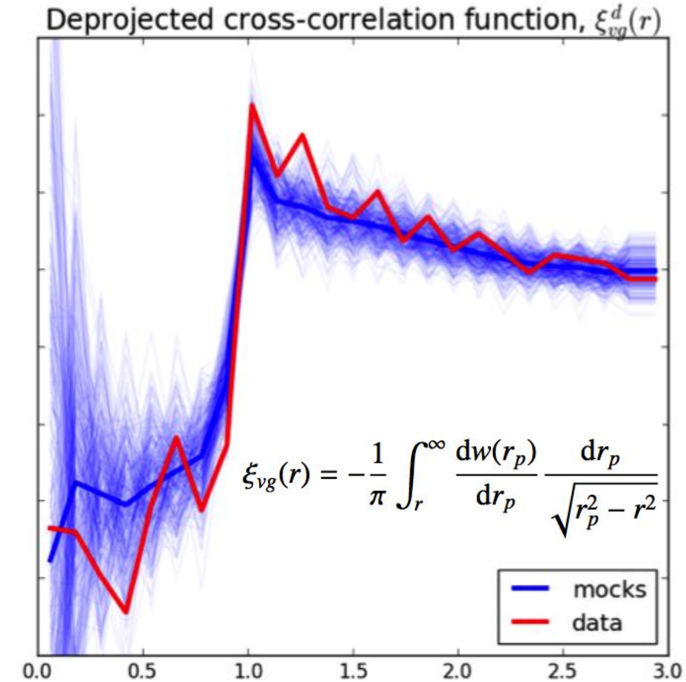
Deprojecting the projected cross correlation

We wish to recover the void-galaxy cross correlation function without RSD.

To do this we first integrate along the line of sight to get the projected cross correlation.

$$w_{vg} = 2\int_0^{\infty} \xi_{vg}(r_\perp, r_\parallel)\mathrm{d}r_\parallel$$





We then invert this integral using an Abel transform to get the deprojected cross correlation.

$$\xi_{vg}(r_i) = -\frac{1}{\pi}\sum_{j\geq i} \frac{w_{vg,j+1} - w_{vg,j}}{r_{p,j+1} - r_{p,j}} \ln\left(\frac{r_{p,j+1} + \sqrt{r_{p,j+1}^2 - r_i^2}}{r_{p,j} + \sqrt{r_{p,j}^2 - r_i^2}}\right)$$

This should be the same as the undistorted realspace cross correlation. However the discrete transformation can introduce a bias if too few bins are used.

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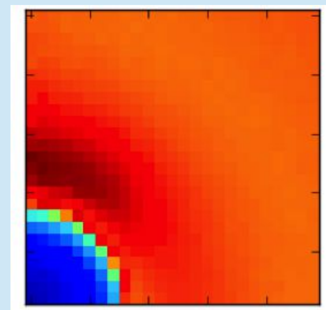
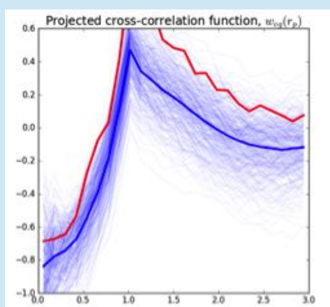
Estimating the growth rate

Anisotropic void-galaxy cross correlation function



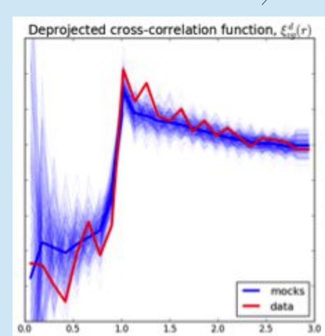
$$w_{vg}(r_p) = 2\int_{r_p}^{\infty} \xi_{vg}(r)\frac{r\mathrm{d}r}{\sqrt{r^2 - r_p^2}}$$

Projected void-galaxy cross correlation function



$$\xi_{vg}(r) = -\frac{1}{\pi}\int_{r}^{\infty} \frac{\mathrm{d}w(r_p)}{\mathrm{d}r_p}\frac{\mathrm{d}r_p}{\sqrt{r_p^2 - r^2}}$$

Deprojected cross correlation function



Redshift space distortion model

$$1+\xi_{vg}(r_{\parallel}, r_{\perp}) = \int_{-\infty}^{+\infty} \frac{\mathrm{d}w_3}{\sqrt{2\pi}\sigma_v} \exp\left(-\frac{(w_3 - v(r)\frac{r_3}{r})^2}{2\sigma_v^2}\right)[1+\xi_{vg}(r)]$$

MCMC on the toy model

We apply this method first to the toy model introduced earlier.

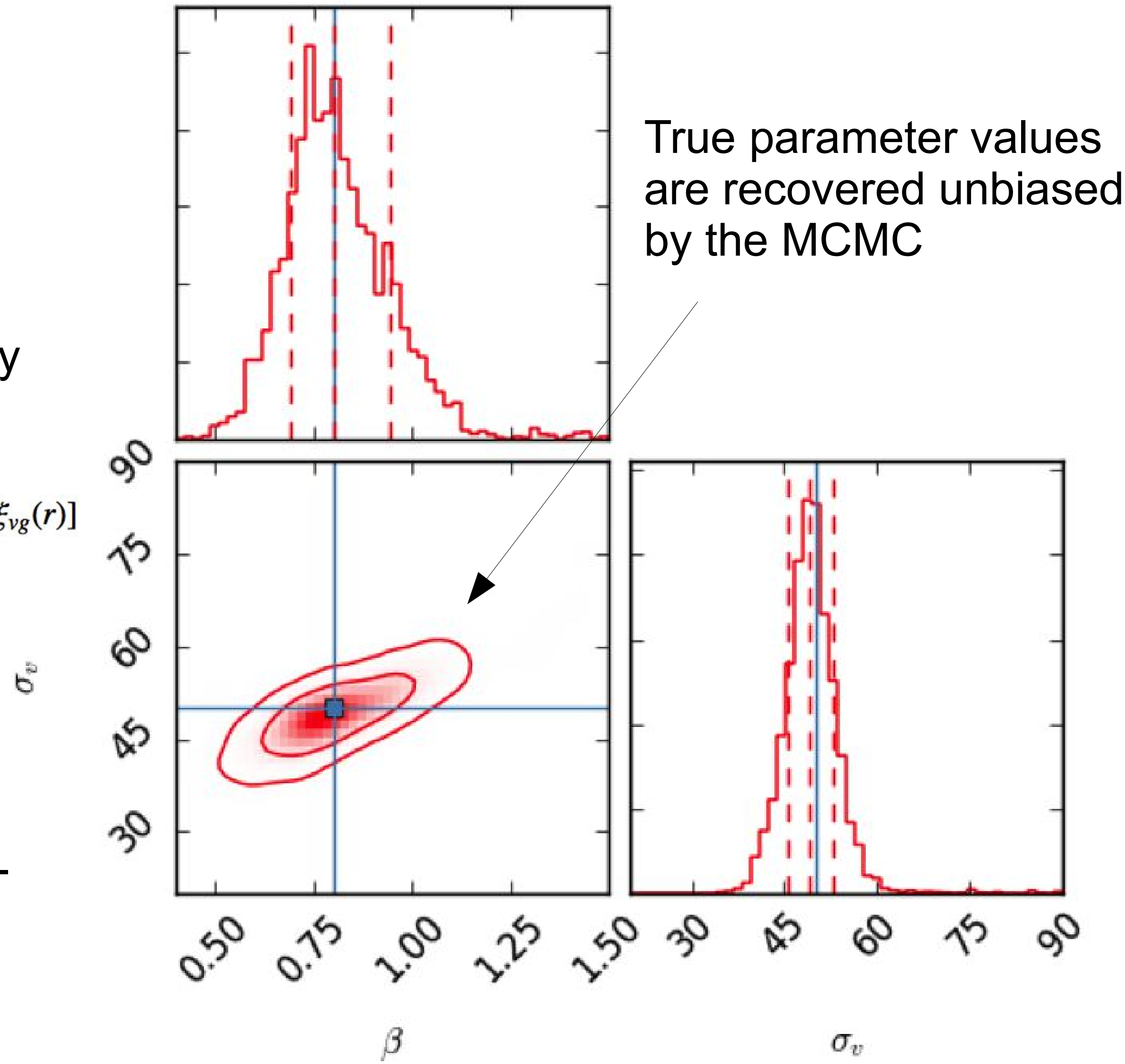
$$\xi_{vg}(r) = \delta_c\left(1 - \frac{\alpha}{3}\left(\frac{r}{r_v}\right)^{\alpha}\right)\exp\left(-\left(\frac{r}{r_v}\right)^{\alpha}\right)$$

We know that the redshift space distortions in this case are completely linear.

$$1+\xi_{vg}(r_{\parallel}, r_{\perp}) = \int_{-\infty}^{+\infty} \frac{\mathrm{d}w_3}{\sqrt{2\pi}\sigma_v} \exp\left(-\frac{(w_3 - v(r)\frac{r_3}{r})^2}{2\sigma_v^2}\right)[1+\xi_{vg}(r)]$$

Any bias in the measurement is then due to the method and not to the model.

We used MCMC Hammer (Foreman-Mackay et al 2012)



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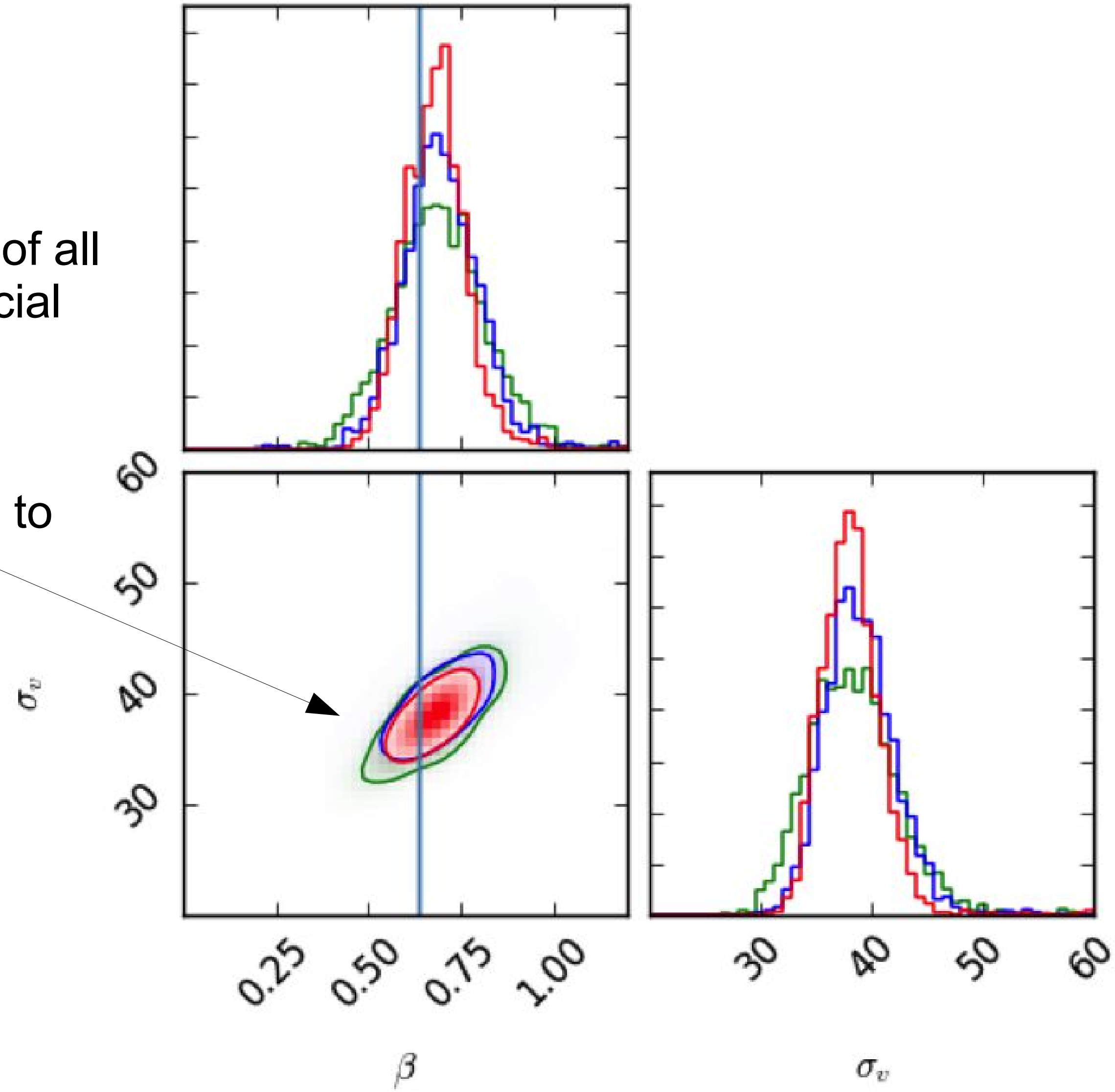
MCMC on the mean of the mocks

Using the mean cross correlations of all the mocks we can recover the fiducial cosmology to within one sigma.

bias introduced by the method is minimal, any offset is probably due to inaccuracies in the RSD model.



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MCMC on data

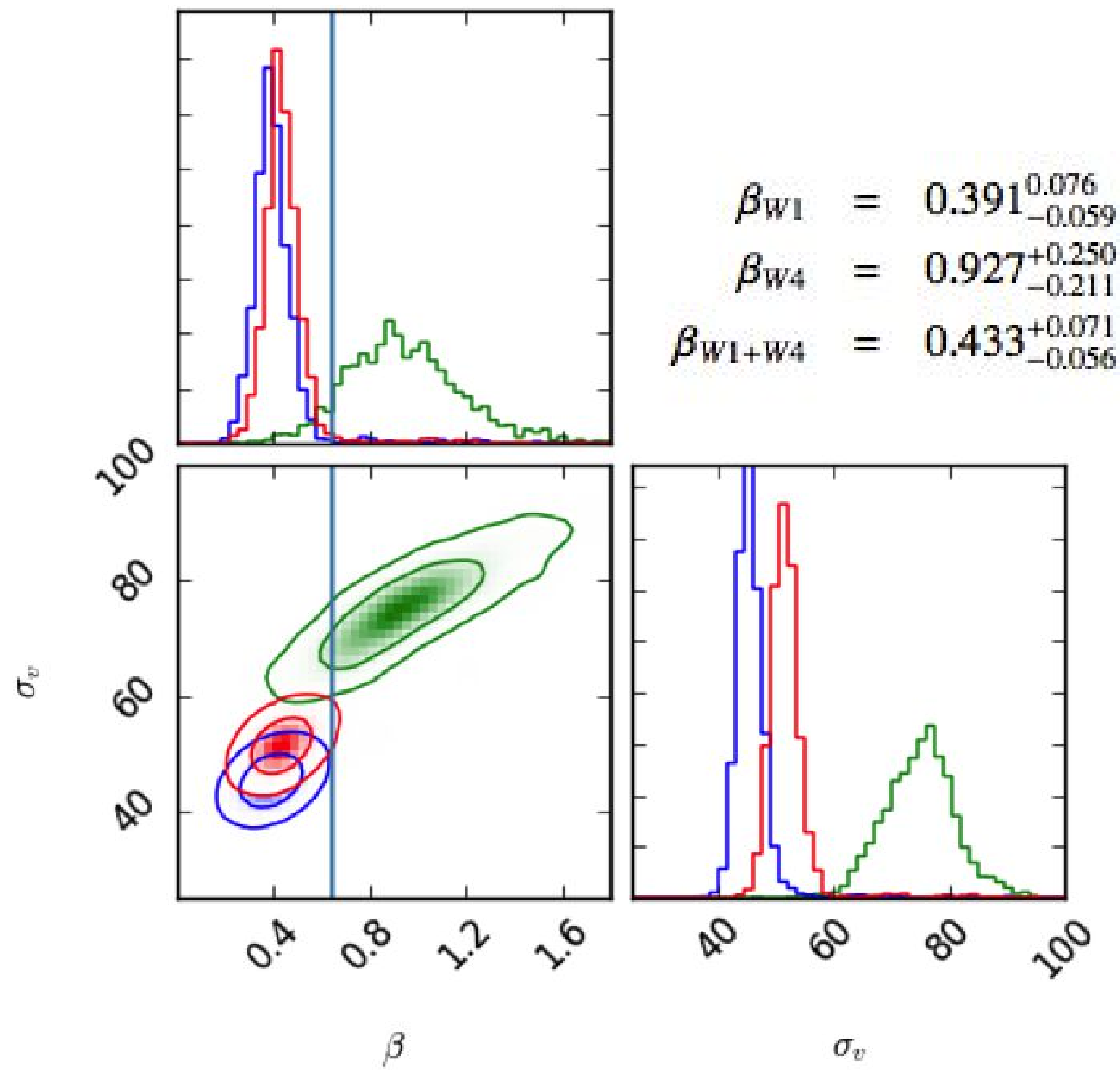
Fit deprojection of mean cross correlation of the two fields, this reduces noise.

$$\xi_{W1+W4} = \xi_{W1}\frac{N^{W1}_{\rm voids}}{N^{\rm tot}_{\rm voids}} + \xi_{W4}\frac{N^{W4}_{\rm voids}}{N^{\rm tot}_{\rm voids}}$$

Treat the two fields as independent

$$\chi^2_{W1+W4} = \Delta^T_{W1}C^{-1}_{W1}\Delta_{W1} + \Delta^T_{W4}C^{-1}_{W4}\Delta_{W4}$$

The fields agree with each other to within two sigma.



AJH, Granett, Guzzo, Iovino et al in prep

Sigma8 of galaxies

The growth rate of structure is often quantified in terms of f multiplied by the normalisation sigma8.

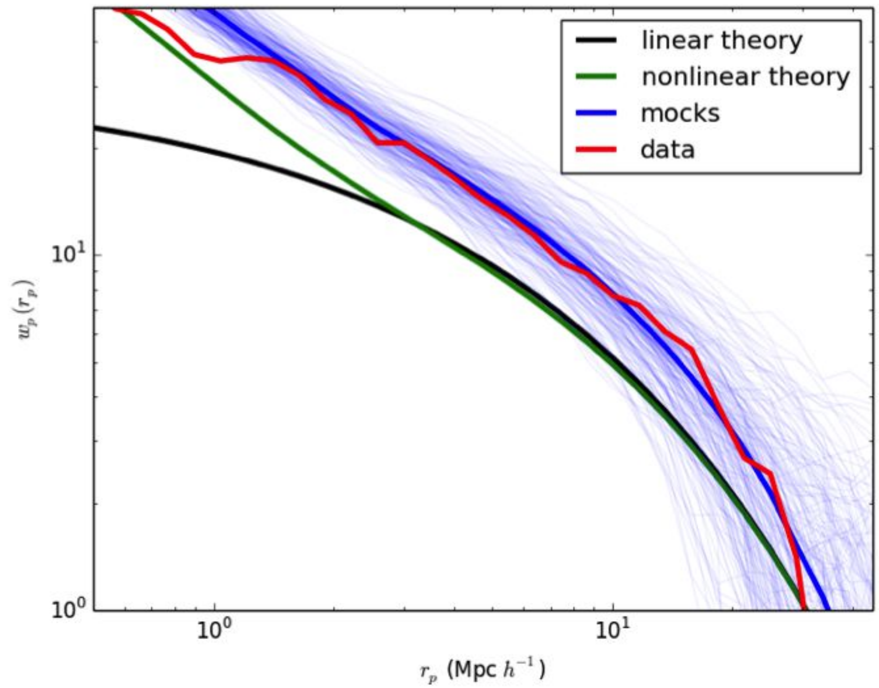
$$f\sigma_8 = \beta\sigma_8^{\text{galaxies}}$$

We can calculate sigma8 of galaxies directly from the projected galaxy autocorrelation function.

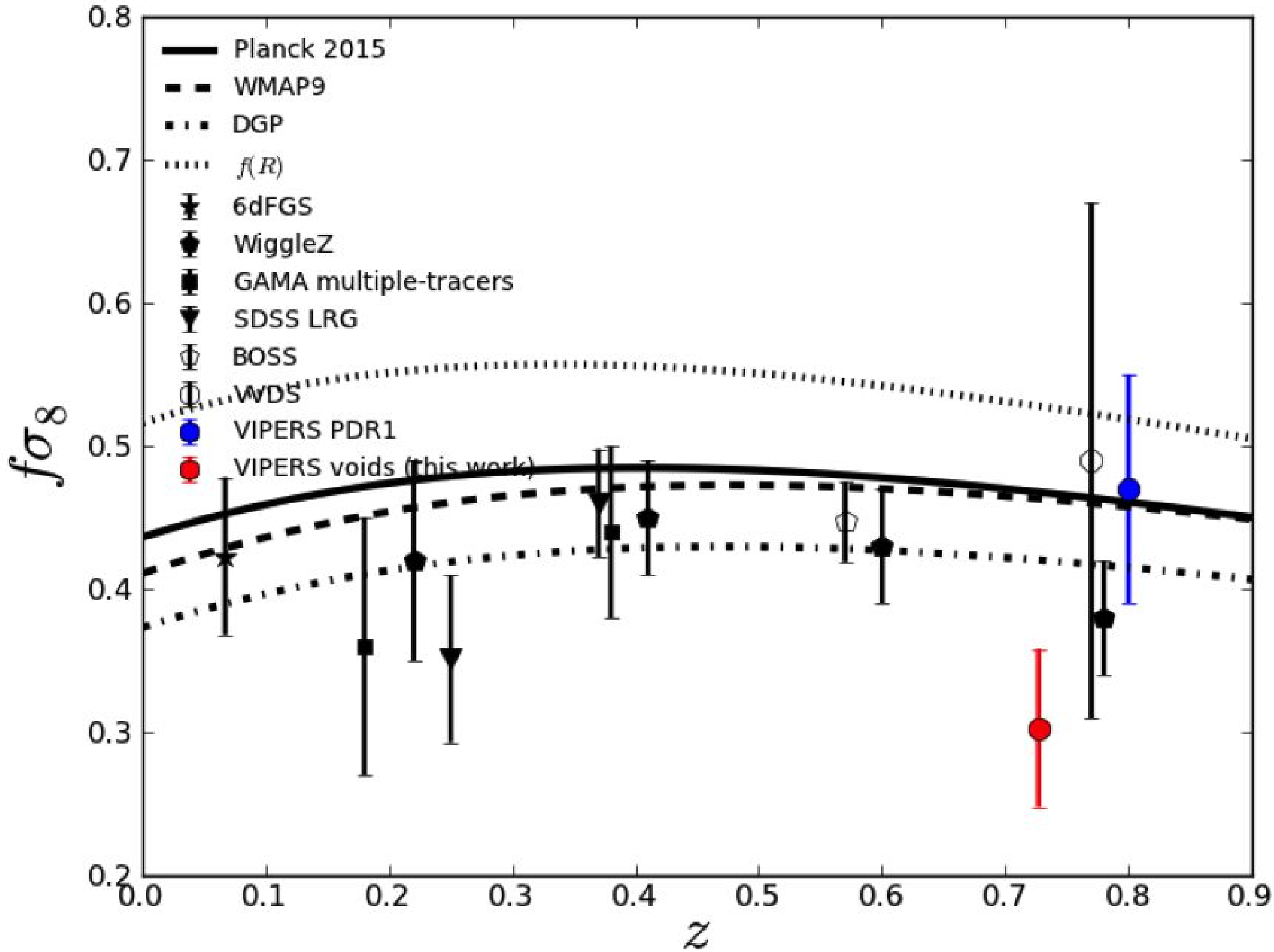
$$\sigma_R^2 = \frac{1}{R^3}\int_0^\infty r_p w_p(r_p) g(r_p/R) \mathrm{d}r_p,$$

where $R = 8\mathrm{Mpc}h^{-1}$ and

$$g(x) = \begin{cases} \frac{1}{2\pi}[3\pi - 9x + x^3] & \text{if } x \leq 2 \\ \frac{1}{2\pi}\left[\frac{-x^4+11x^2-28}{\sqrt{x^2-4}} + x^3 - 9x + 6\sin^{-1}\left(\frac{2}{x}\right)\right] & \text{if } x > 2. \end{cases}$$



Comparison to other measurements



AJH, Granett, Guzzo, Iovino et al in prep

Summary

I gave an overview of how we can model void density profiles.

I showed how we can use our model to characterise super structures in BOSS.

I illustrated how measurements of the void-galaxy cross correlation function exhibit an anisotropy indicative of linear RSD.

I demonstrated how by deprojecting the cross-correlation we can remove the RSD.

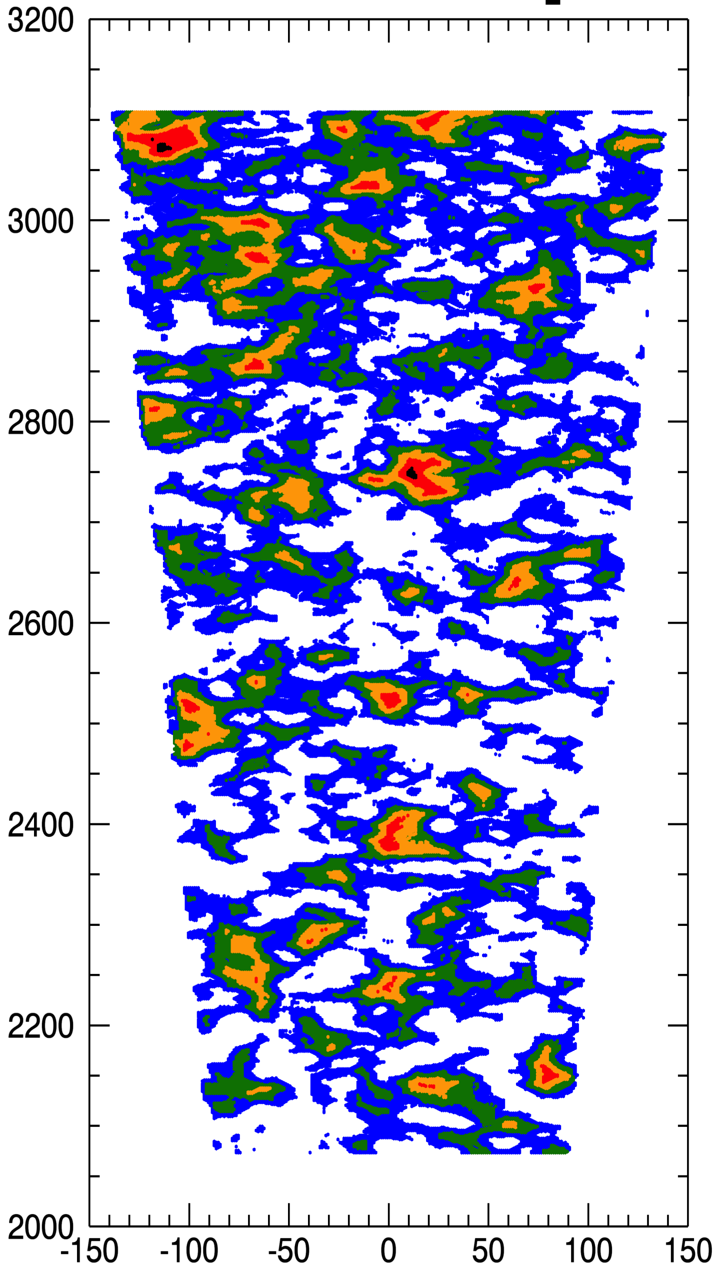
I also demonstrated that a linear model for the RSD is sufficient to measure the growth rate of structure in simulations.

I applied the same technique to data from VIPERS and compared the result to other measurements.

GRAZIE!!!

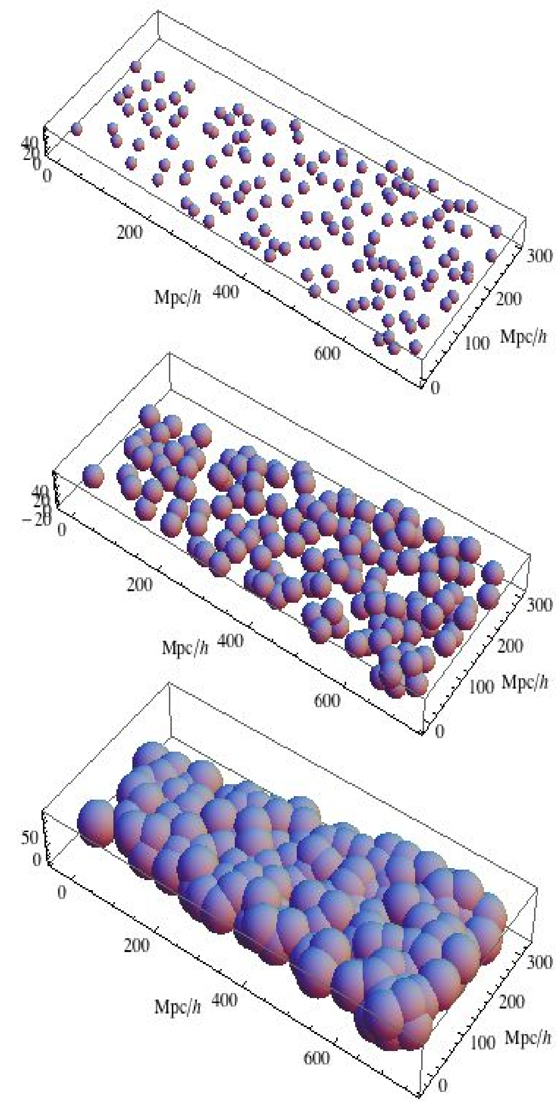
Domande?

Lots of potentially interesting things



Topology?

- Voids in the reconstructed density field
- Cross-correlation with clusters
- How pristine are the interiors of voids?
- Are void galaxies any different from galaxies in other low density environments?



Schimd

How mobile are void centres?

There is some disagreement in the literature as to how stable void centres are.

Some authors claim that they hardly move at all as voids evolve.

Others claim that they have significant peculiar velocities, depending on the type of void (Lambas et al 2015).

Modelling void density profiles

$$\Delta(r) = \frac{1}{V}\int_V \left(\frac{\rho(r)}{\bar{\rho}} - 1\right) \mathrm{d}V.$$

$$\xi_{vg}(r) = \frac{1}{3r^2}\frac{\mathrm{d}}{\mathrm{d}r}(r^3\Delta(r))$$

$$\Delta(r) = \delta_c \exp\left(-\left(\frac{r}{r_v}\right)^{\alpha}\right)$$

$$\xi_{vg}(r) = \delta_c\left(1 - \frac{\alpha}{3}\left(\frac{r}{r_v}\right)^{\alpha}\right)\exp\left(-\left(\frac{r}{r_v}\right)^{\alpha}\right)$$

$$\xi_{vg}(r) \quad = \quad \frac{\rho(r)}{\bar{\rho}} - 1$$