Probing the growth rate of structure with voids in VIPERS

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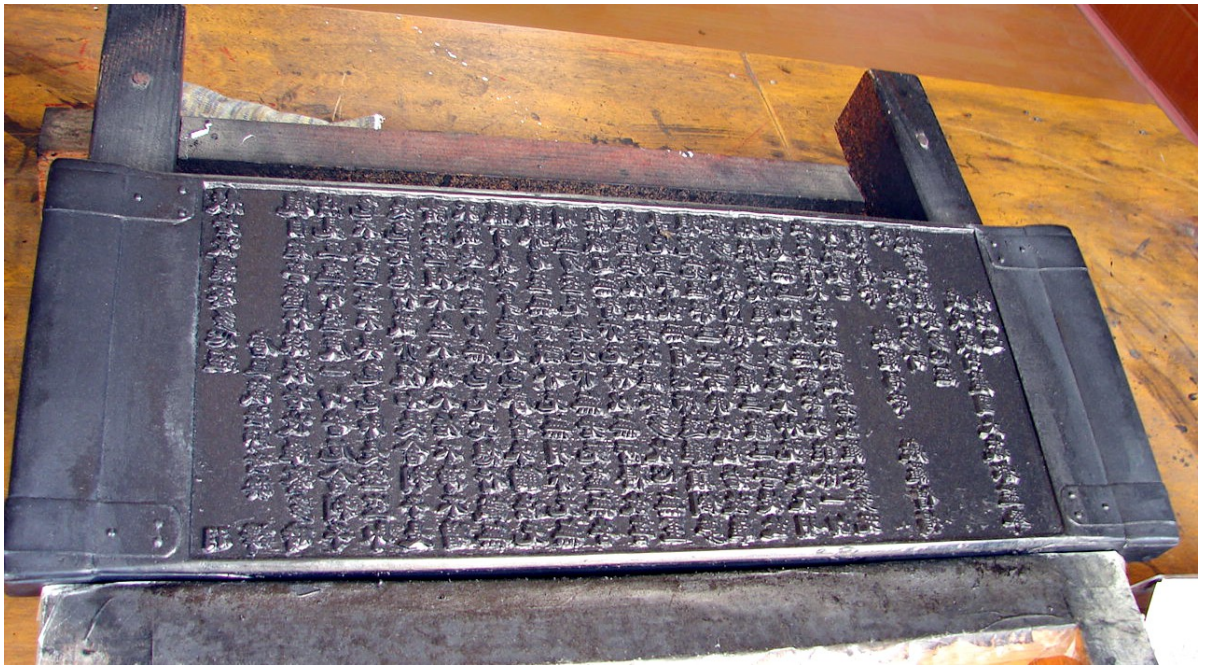
“Form is the void and the void is form...”
- *The Heart Sutra*

The nature of cosmic voids has been the subject of debate in Korea for many centuries!

Haeinsa Temple, South Gyeongsang Province, UNESCO World Heritage site.



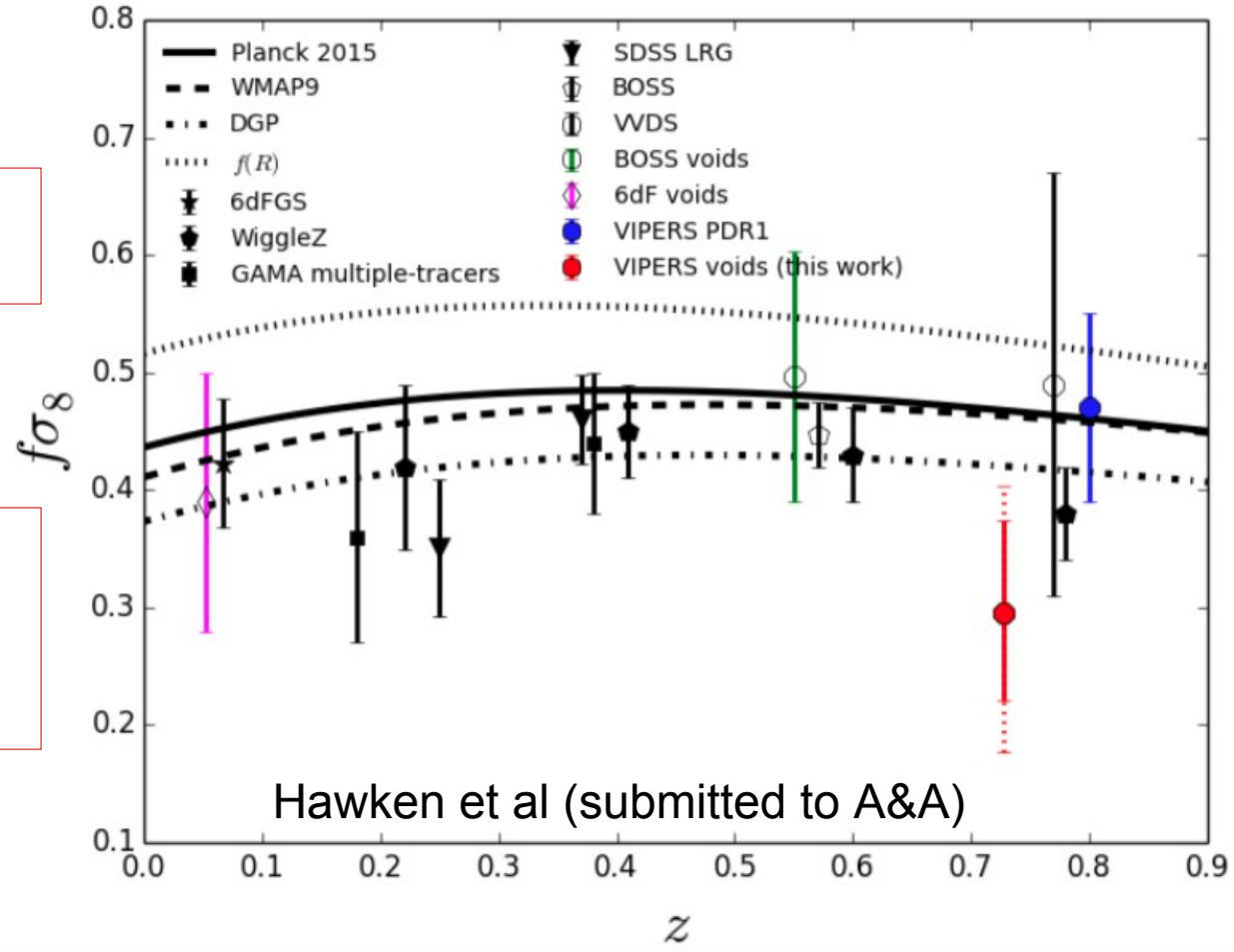
Wood carving of the Heart Sutra (c. 13th century).

Outline and key results

- VIPERS final public data release!
- Model for linear RSD around voids
- Application to VIPERS

$$\beta_{\rm VIPERS} = 0.423^{+0.104}_{-0.108}$$

$$f\sigma_8 = 0.296^{+0.075}_{-0.078}.$$

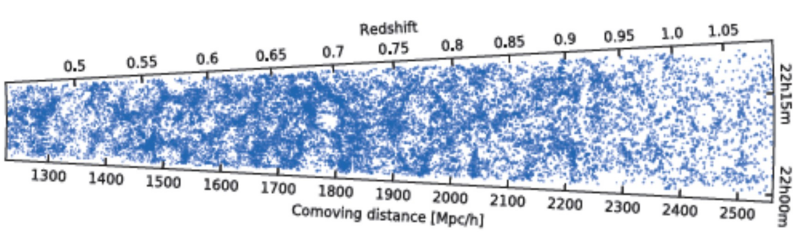


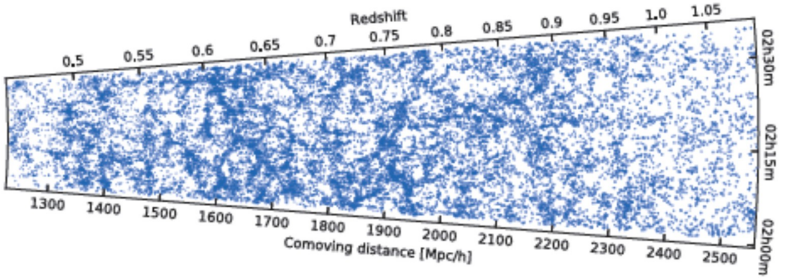
Hawken et al (submitted to A&A)

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)



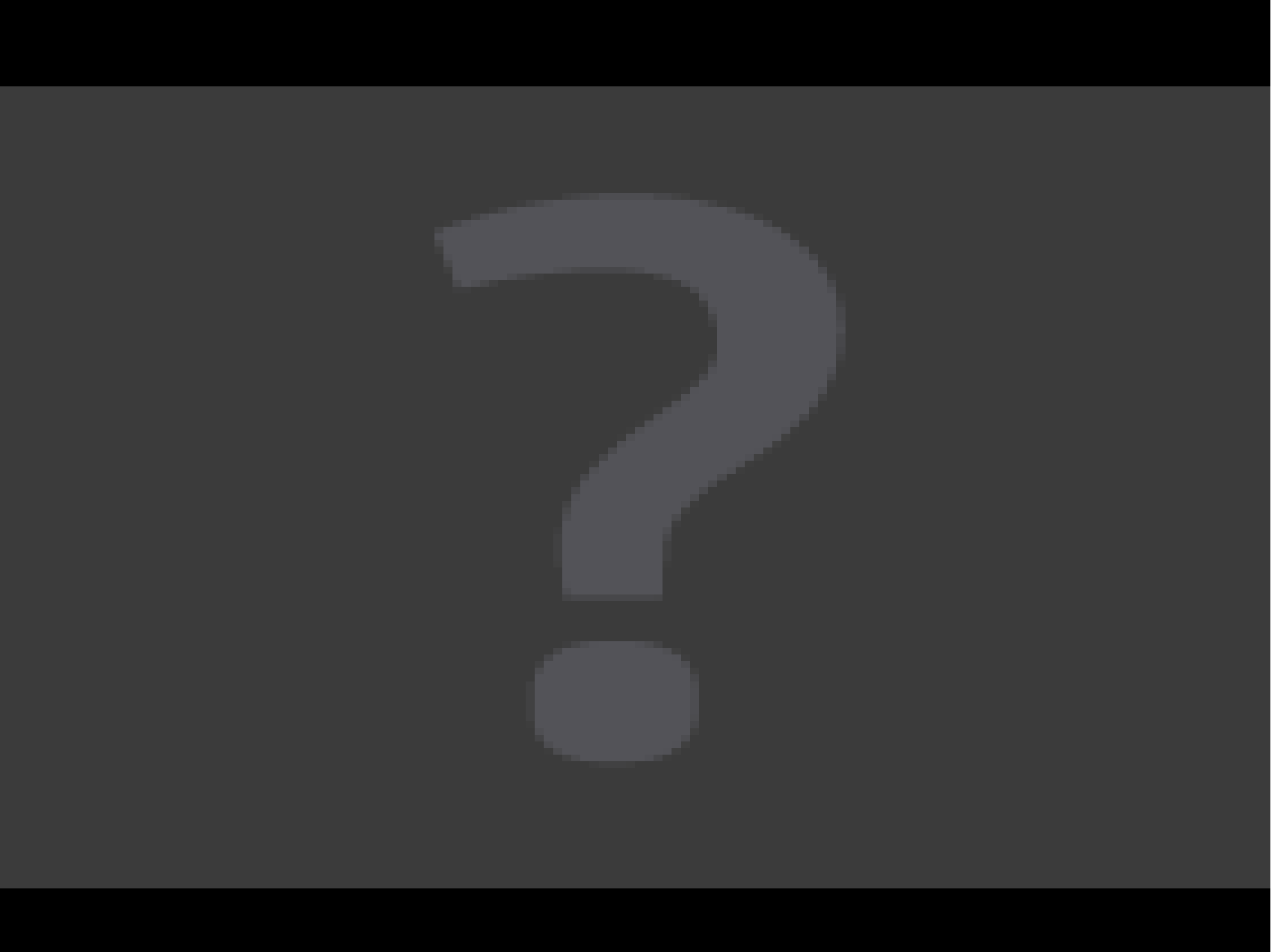


close to 100,000 redshifts in the range 0.5<z<1.2

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

High effective spectroscopic sampling > 40%

http://vipers.inaf.it/

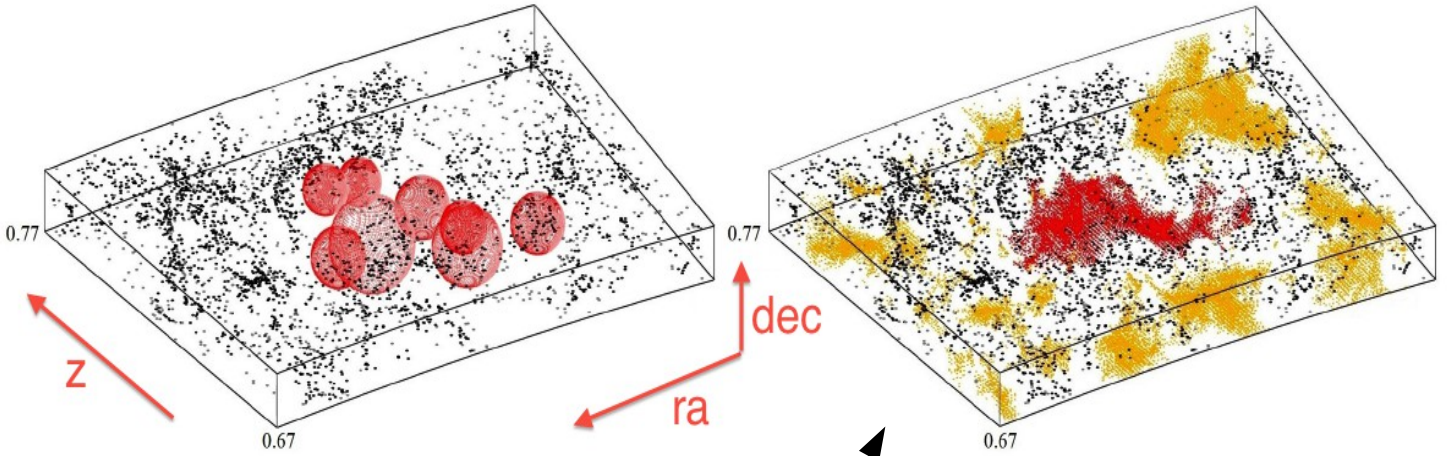


VIPERS Public Data Release 2

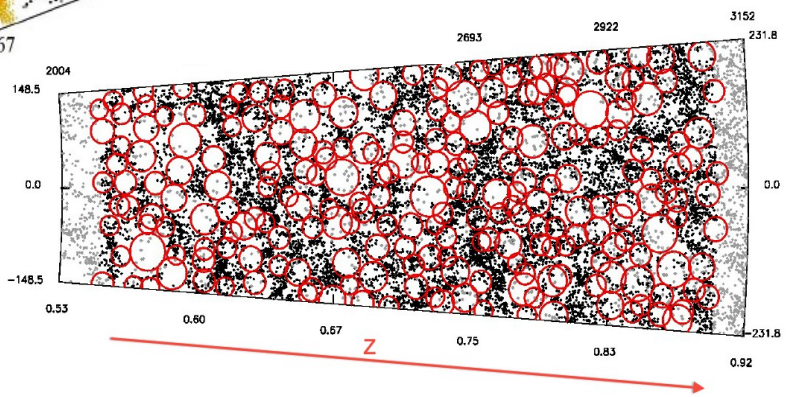
Friday 18th November

- Hawken et al, RSD from voids (this work)
- De la Torre et al, RSD + WL
- Wilson et al, RSD from clipped field in Fourier space
- Pezzotta et al, RSD in configuration space
- Malavasi et al, Galaxy segregation in filaments
- Rota et al, Power spectrum
- Cucciati et al, SFR vs density
- Marchetti et al, PCA spectral cleaning and repairing
- Scodeggio et al, PDR2 data paper

The search for voids in VIPERS



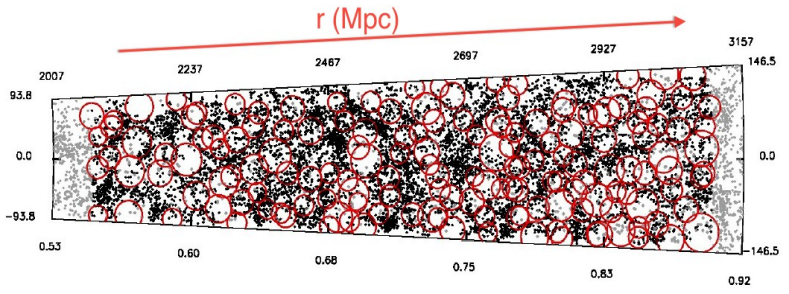
Find empty spheres on a fine regular grid in a volume limited catalogue



Topologically voids are aspherical

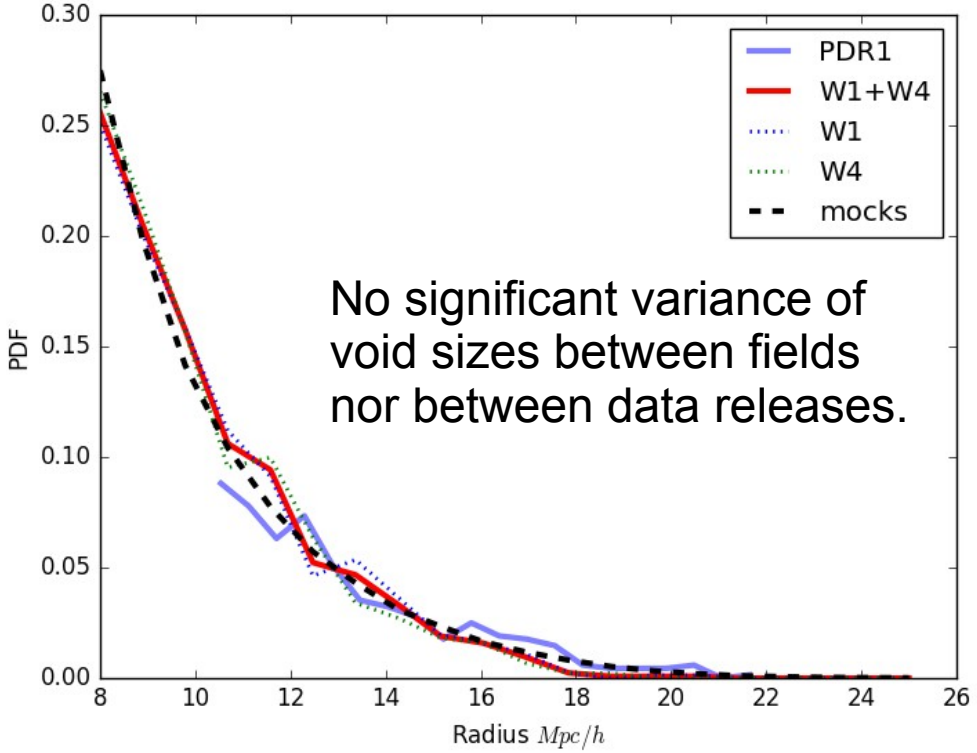
But here we assume them to be spheres...

See Micheletti et al 2014 for more info



Some basic VIPERS void statistics

Size distribution



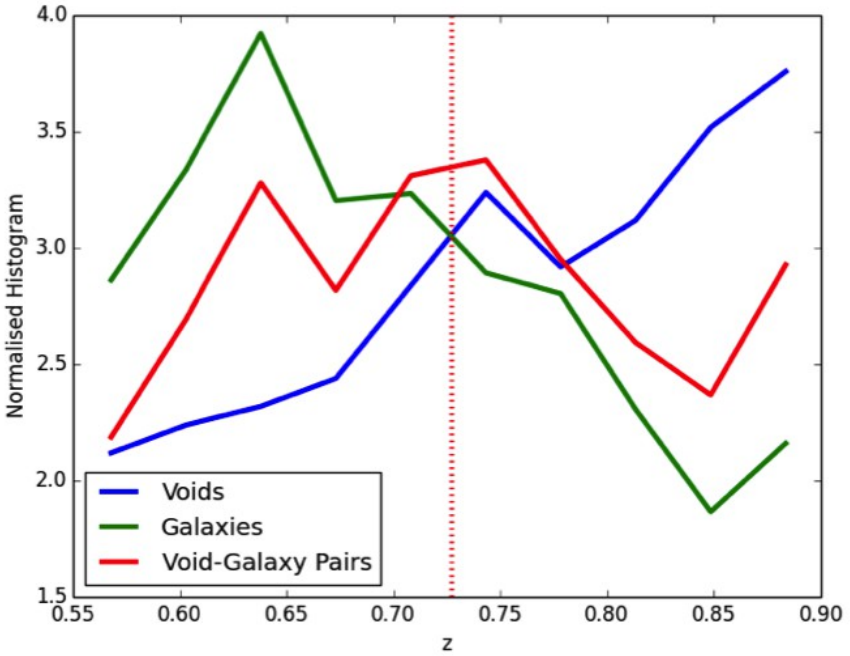
No significant variance of void sizes between fields nor between data releases.

How many voids?

822 voids in W1
441 voids in W4

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

Redshift distribution

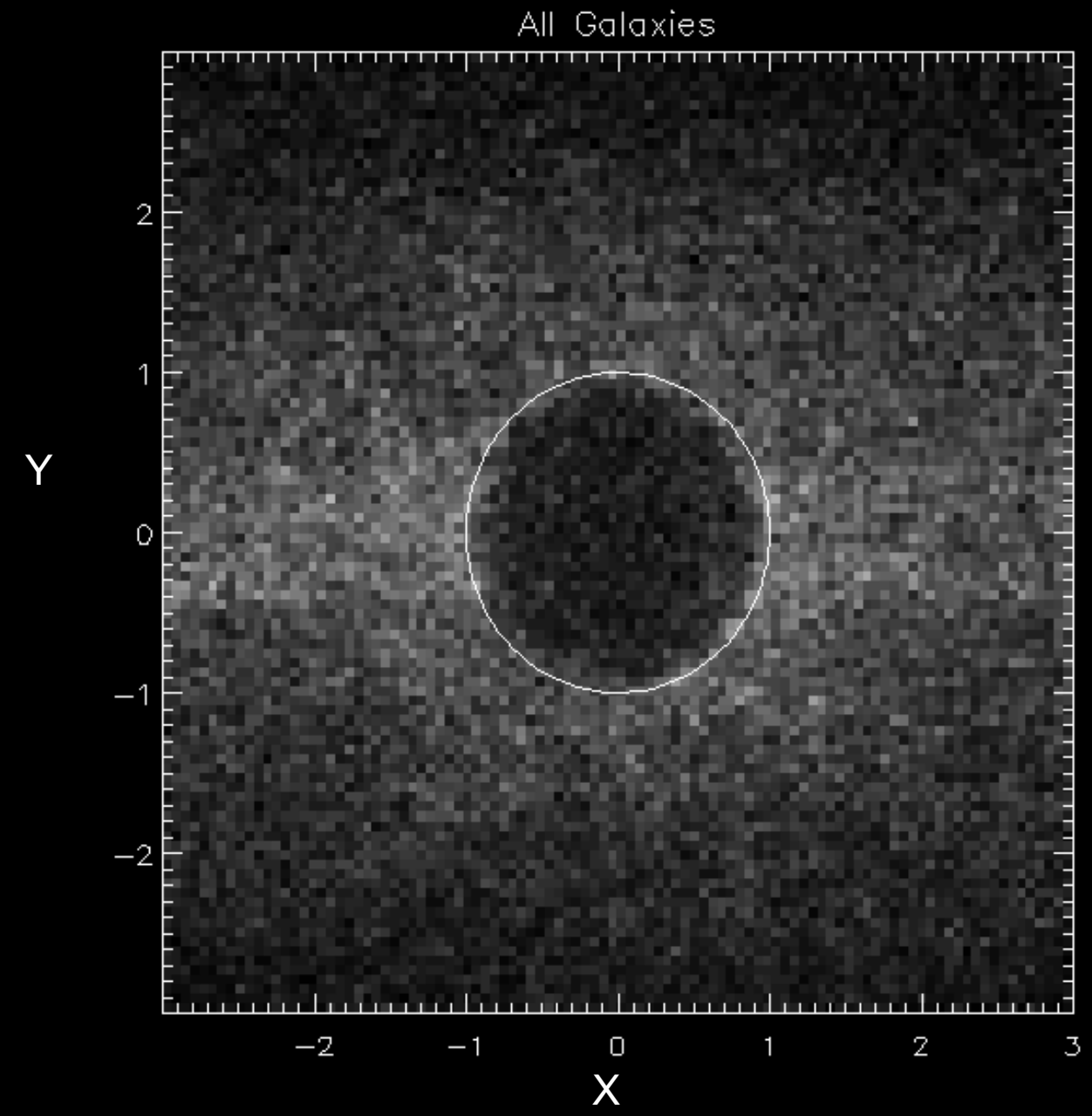


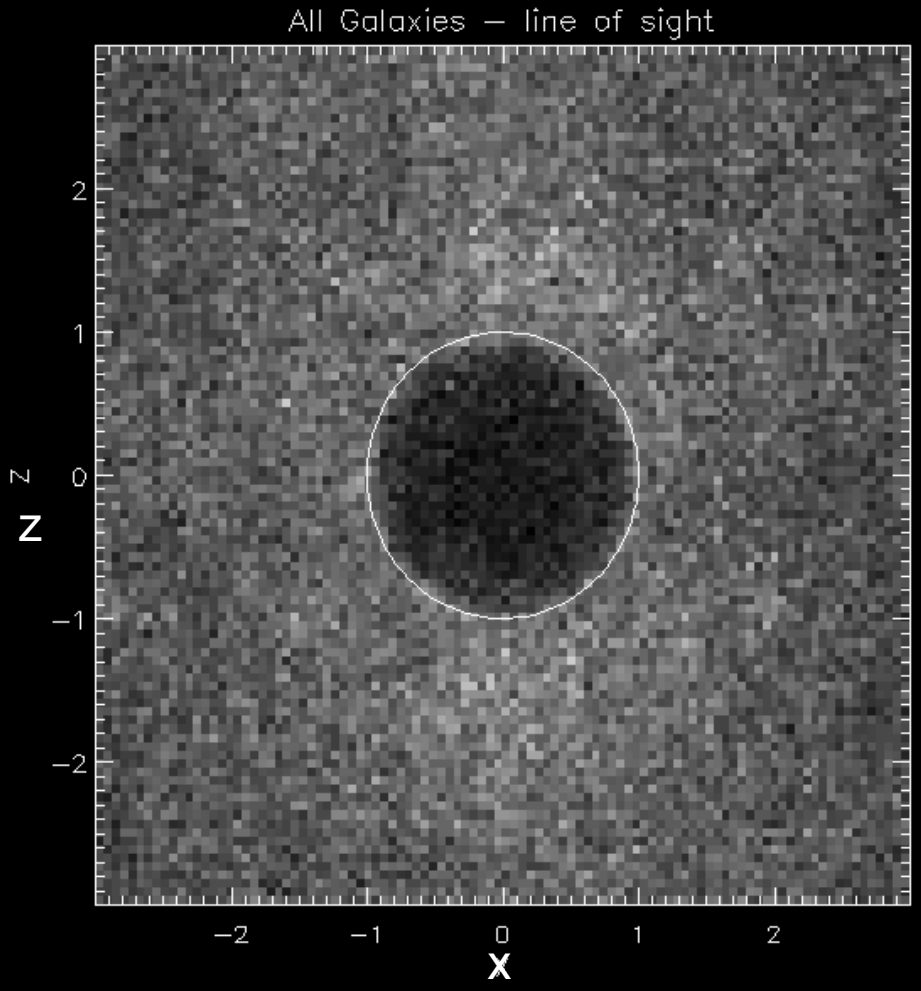
Stacked voids

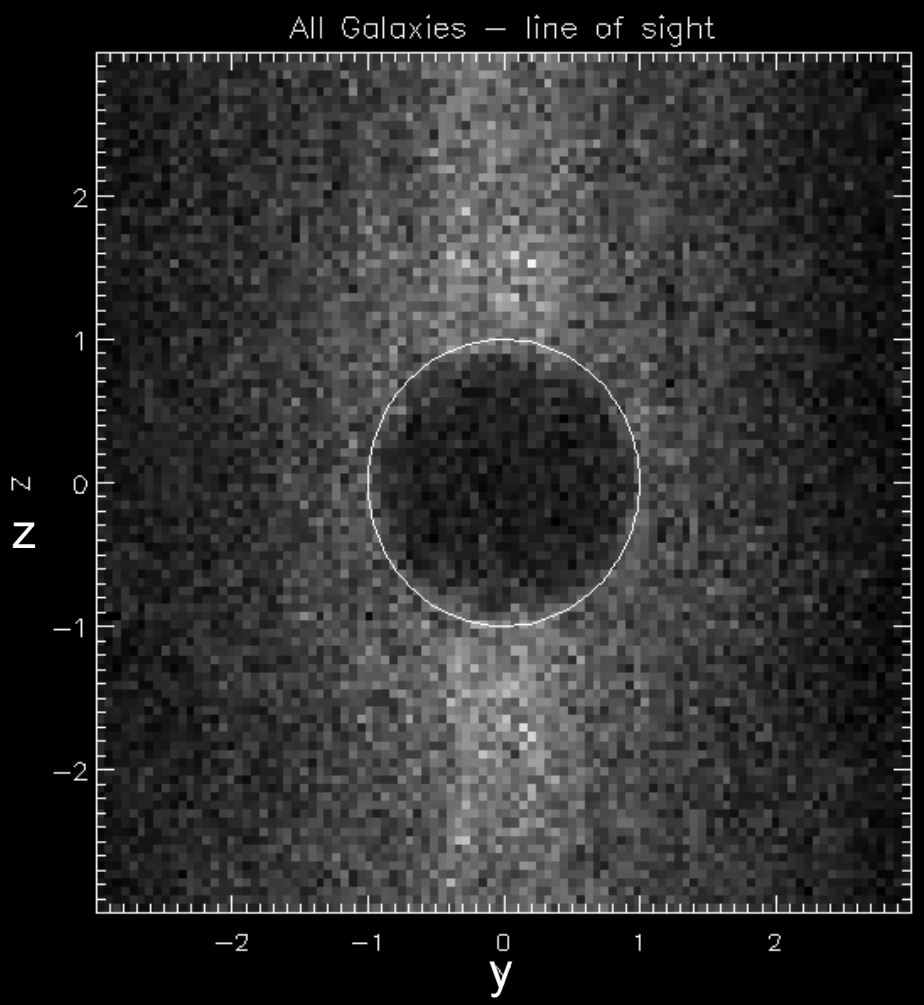
Thickness of 0.25 void radii

Galaxy positions rescaled

Systematic effects of survey geometry become apparent.

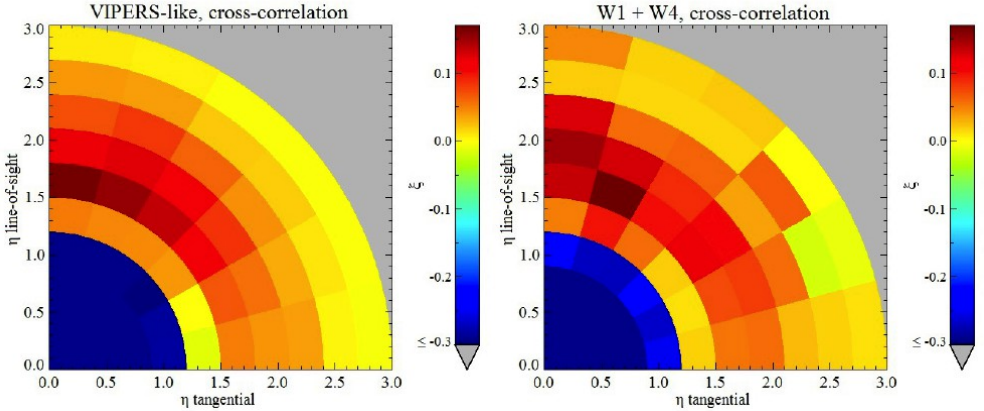




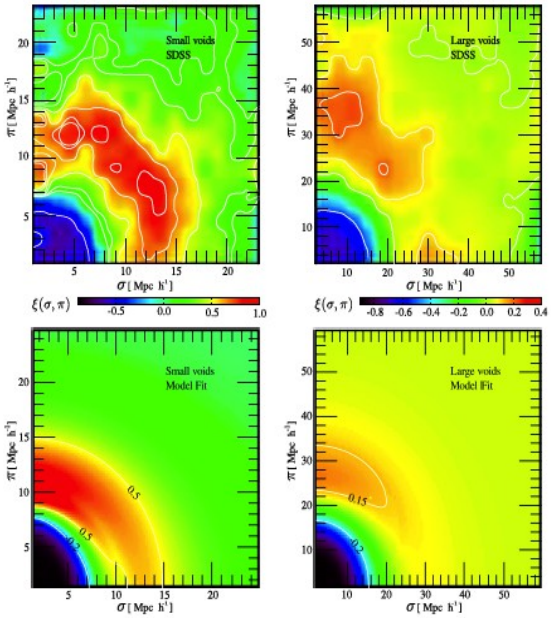


Euclid should be immune to border effects such as these!

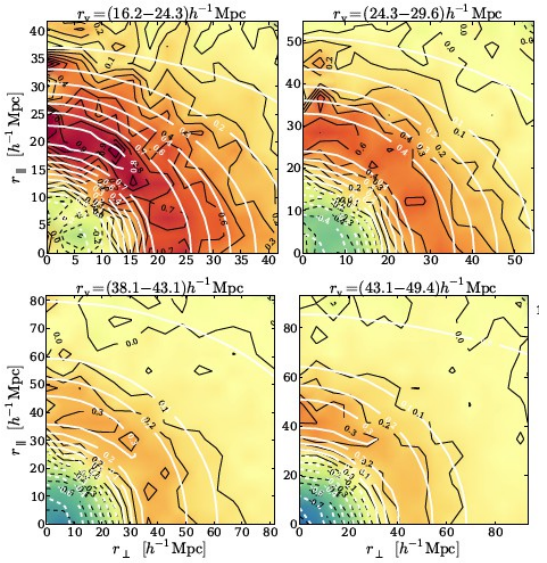
Why are RSD around voids interesting?



Micheletti, Iovino, AJH, Granett et al '14



Paz et al '13



Hamaus et al '16

Plenty of evidence for RSD around voids.

Largest component by volume of the cosmic web.

Dark Energy lives in voids.

Some modified gravity theories, like f(R), predict that the growth rate of structure should deviate from GR in low density environments.

Less affected by non-linearities.

A complimentary probe of the growth of structure.

Linear redshift space distortion model

Gaussian streaming model:

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

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

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. →

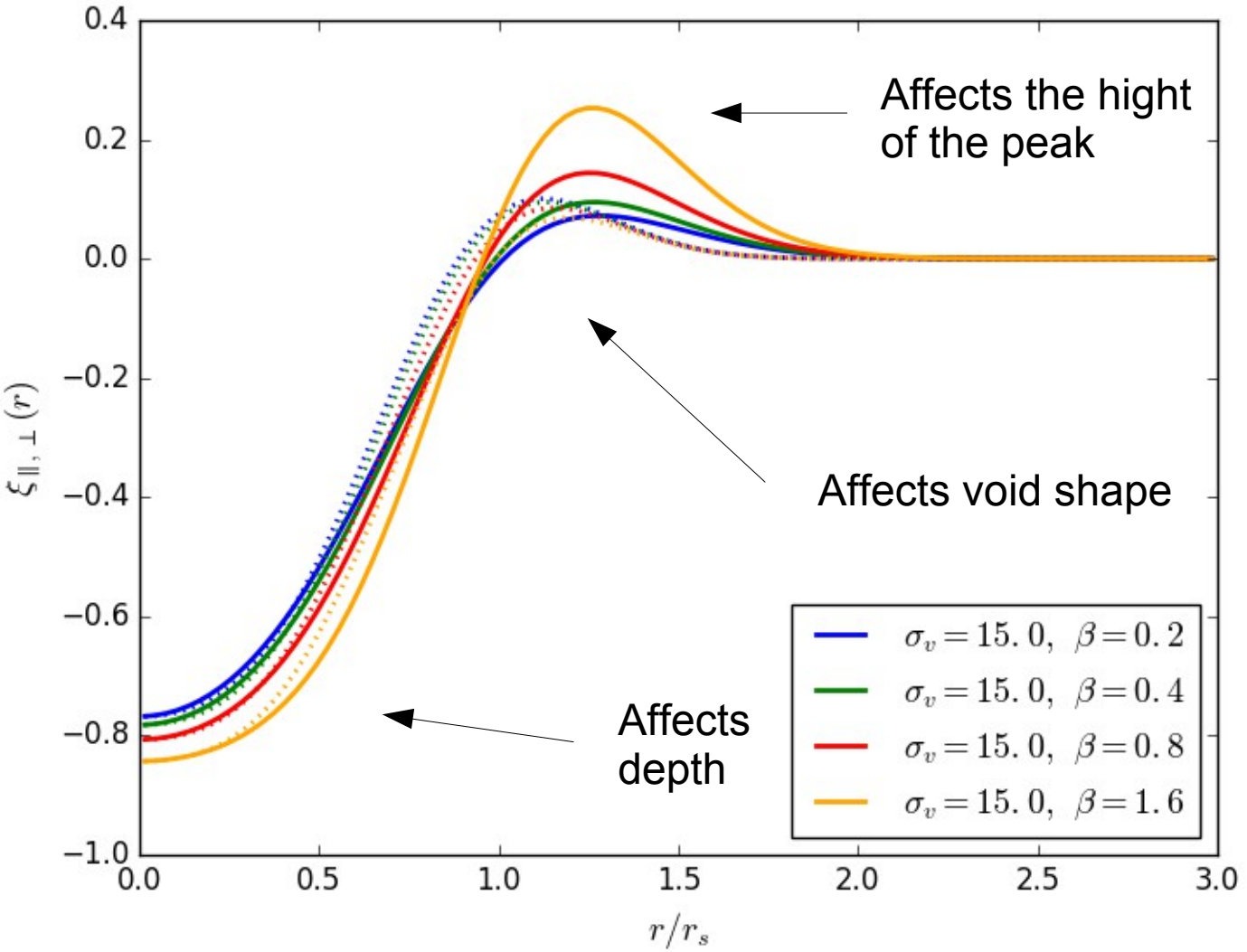
$$\beta = f(z)/b$$

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

In standard GR γ ≈ 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.

Undistorted profile is a stretched exponential toy model.

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

Velocity dispersion parameter

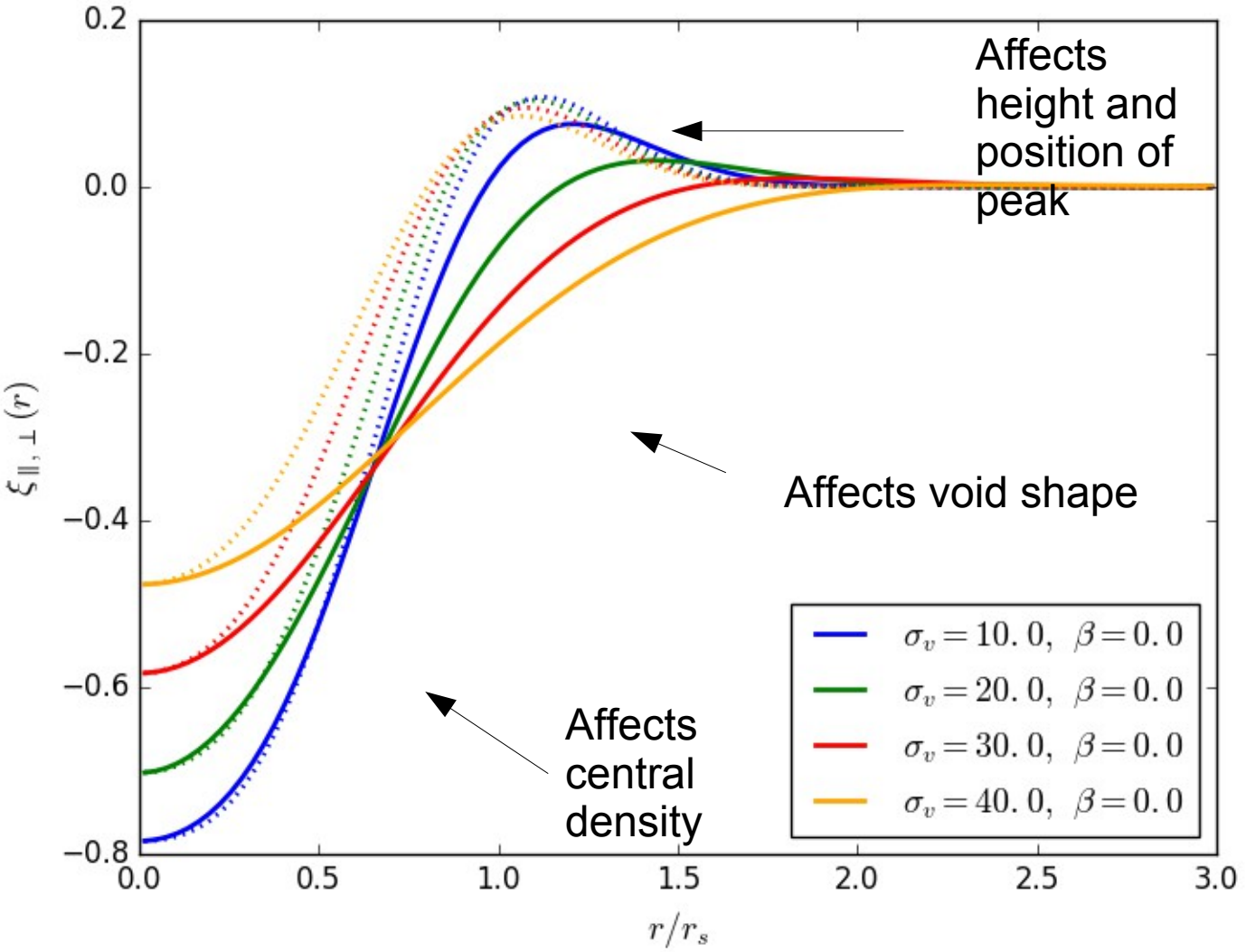
Redshift measurement error is a known and quantifiable source of uncertainty.

$$\sigma_z \approx 140\,\mathrm{km}\,s^{-1}$$

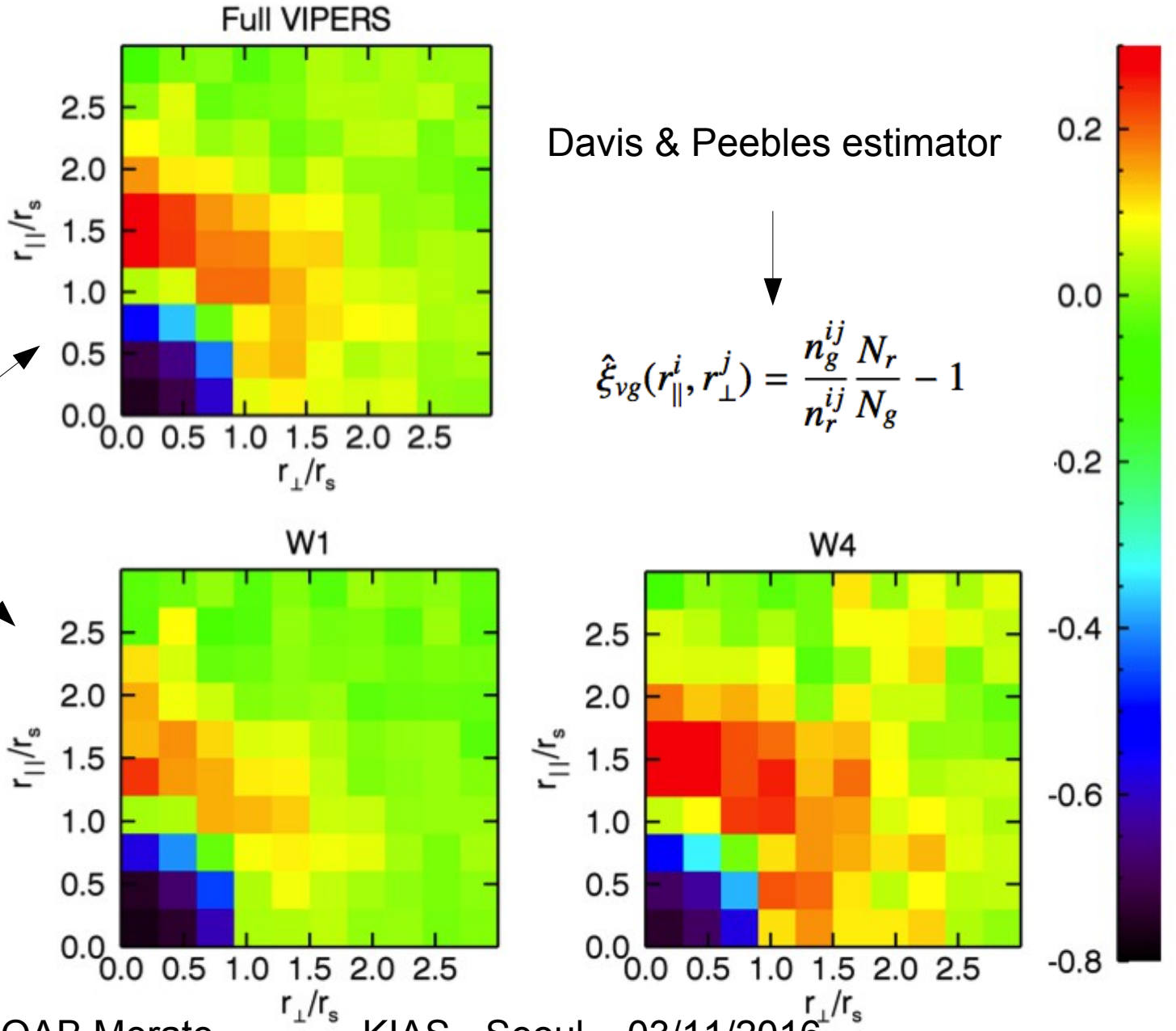
The dispersion has an effect on the apparent central density, and on the hight and position of the peak.

The peculiar velocities of galaxies around should have some intrinsic dispersion.

However, this function is poorly constrained.



Measuring the void-galaxy cross correlation



Davis & Peebles estimator

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

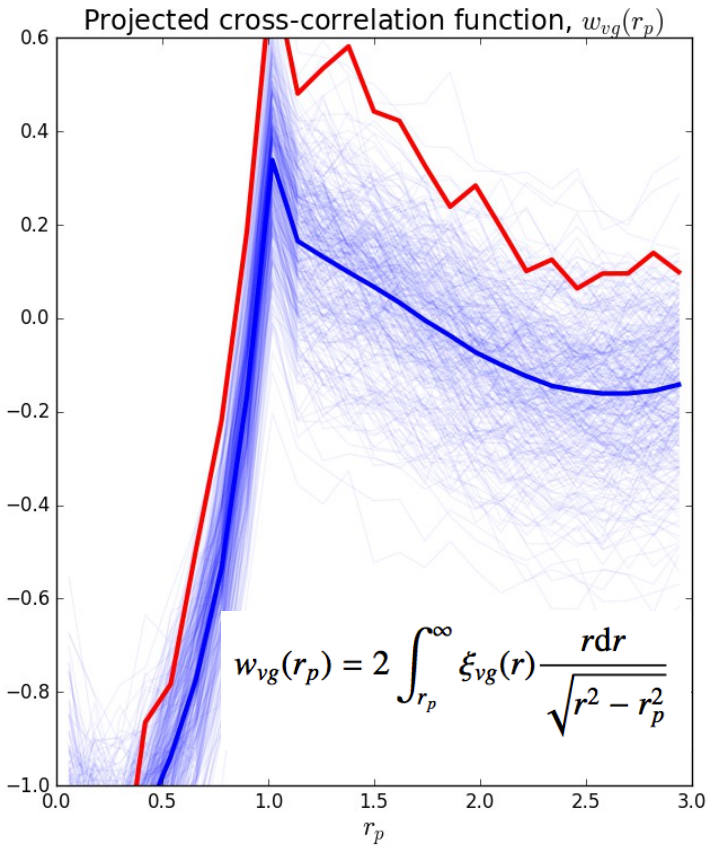
Anistropy due to RSD clearly visible

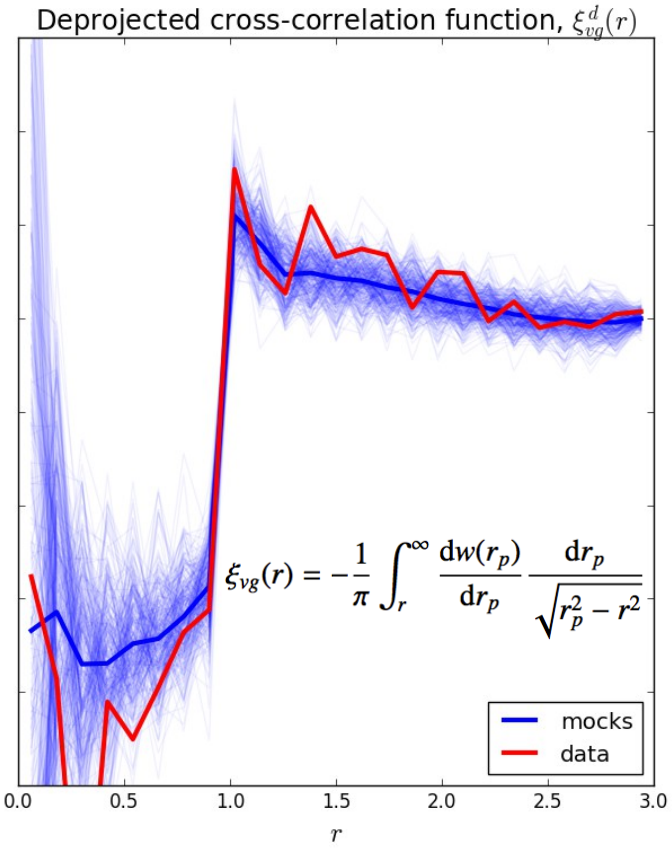
Deprojecting the projected cross correlation

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 (e.g. Pissani et al 2014).

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

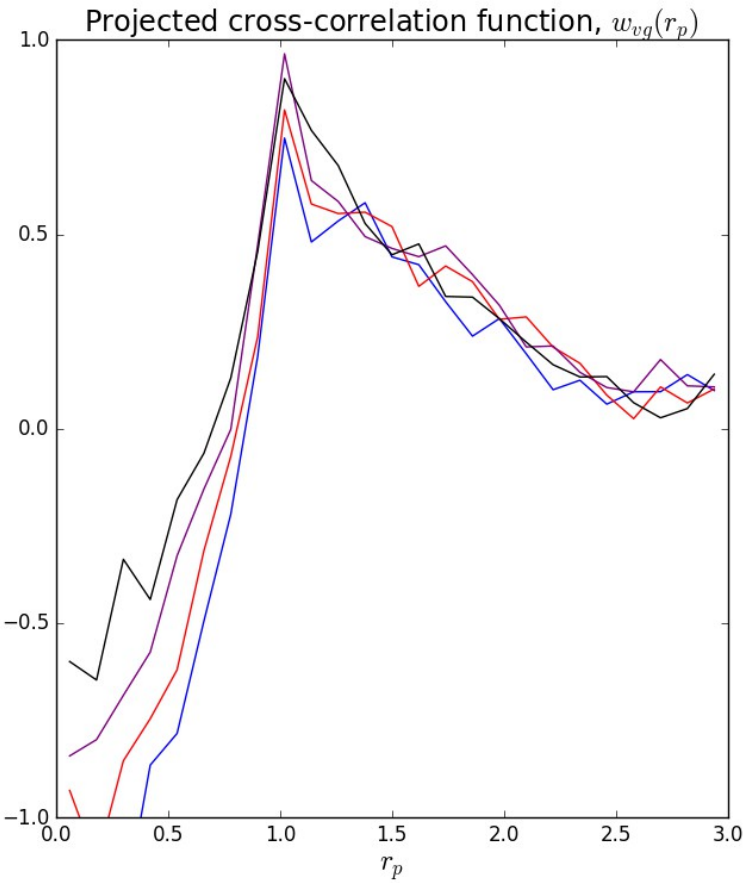
This should be the same as the undistorted realspace cross correlation. However the discrete transformation can introduce a bias if too few bins are used.

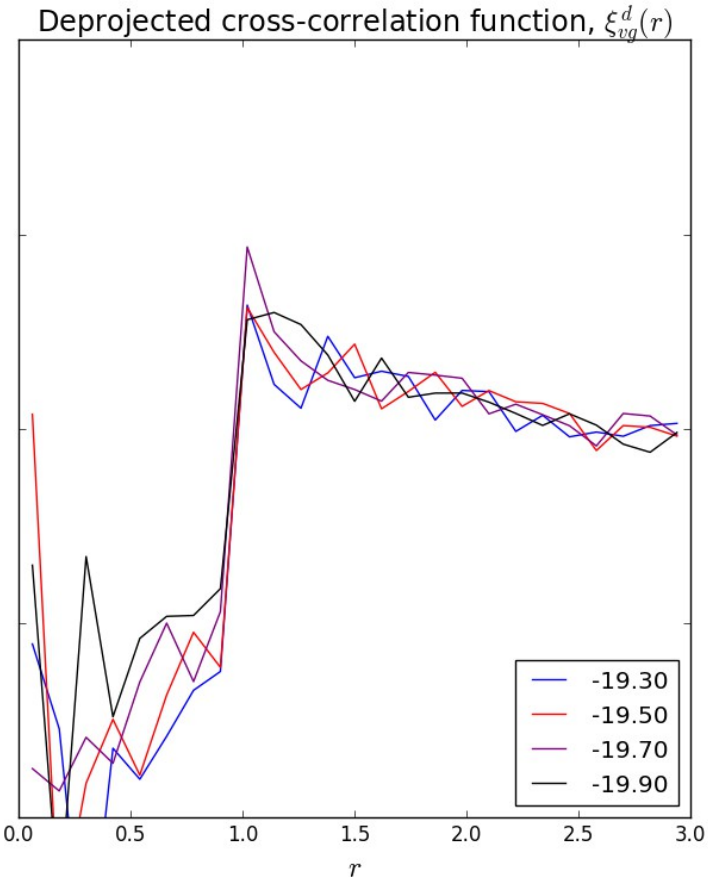
Different void tracers define voids with (slightly) different properties

We varied the magnitude cut of the volume limited catalogue within which we searched for voids.

Brighter catalogues define larger less underdense voids.

But the deprojected profiles are not that different.

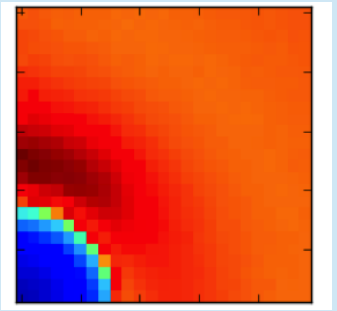




Euclid will enable us to learn more about the density profiles of void interiors.

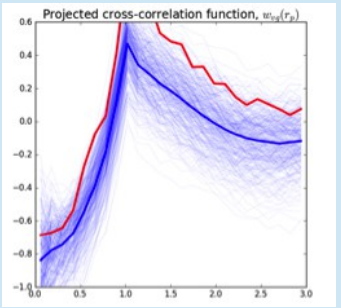
Estimating the growth rate

Anisotropic void-galaxy cross correlation function



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

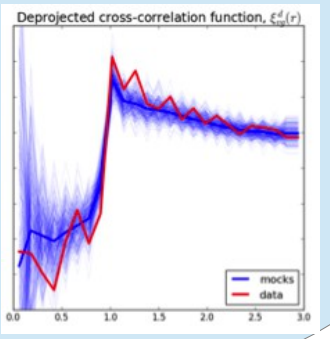
Projected void-galaxy cross correlation function



Redshift space distortion model

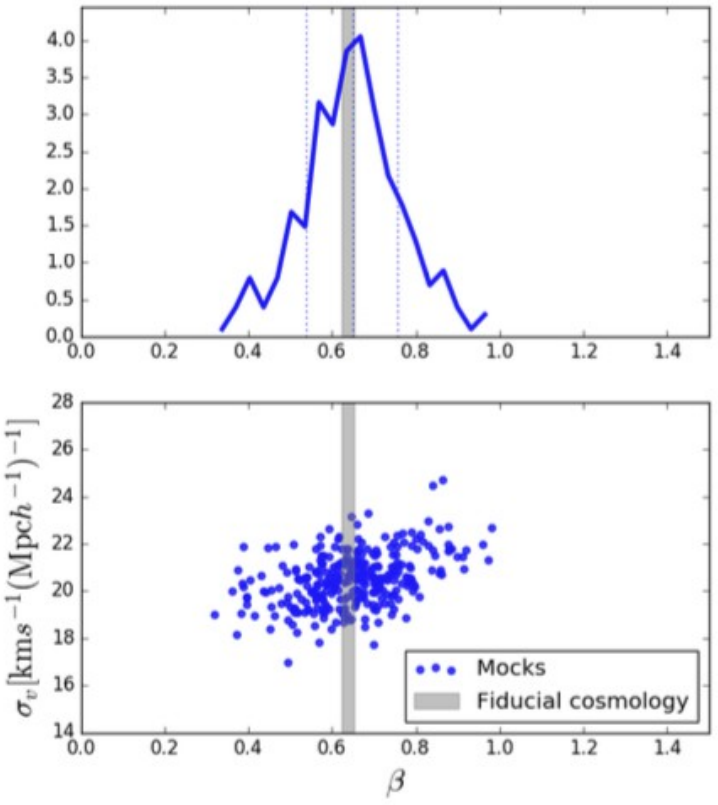
$$1+\xi_{vg}(r_{\parallel}, r_{\perp}) = \int_{-\infty}^{+\infty} \frac{\mathrm{d}w_3}{\sqrt{2\pi}\sigma_v} \exp\left(-\frac{(w_3 - v(r)\frac{r_3}{r})^2}{2\sigma_v^2}\right)[1+\xi_{vg}(r)]$$

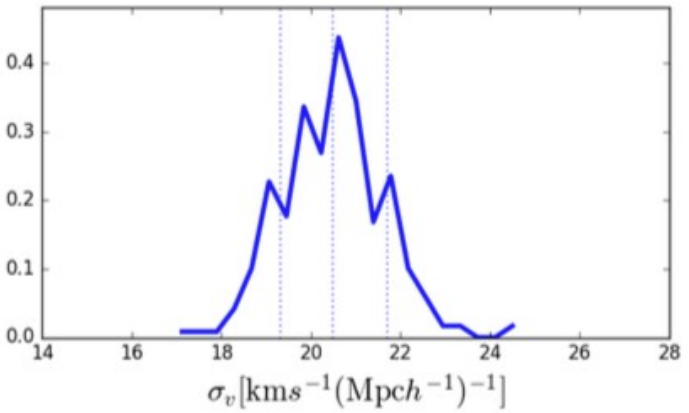
Deprojected cross correlation function



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

Analysis of mock catalogues



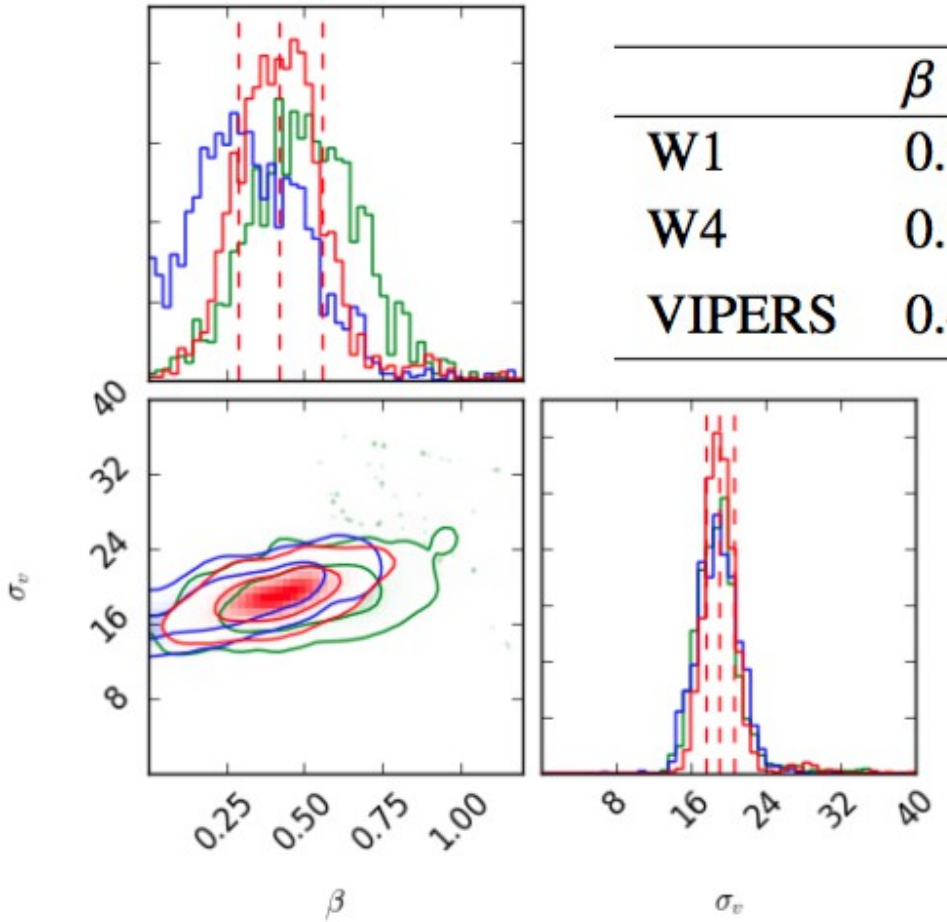


We estimated the values of β and σ in 306 VIPERS like mocks.

Recovered values are approximately Gaussian distributed about the fiducial value.

Hawken et al (submitted to A&A)

Application to VIPERS



	β	σ_v [km s^{-1} (h^{-1}Mpc)$^{-1}$]
W1	$0.315^{+0.202}_{-0.162}$	$18.9^{+2.2}_{-2.1}$
W4	$0.505^{+0.181}_{-0.175}$	$18.8^{+2.0}_{-2.0}$
VIPERS	$0.423^{+0.134\,(+0.104)}_{-0.135\,(-0.108)}$	$19.1^{+1.6}_{-1.5}$

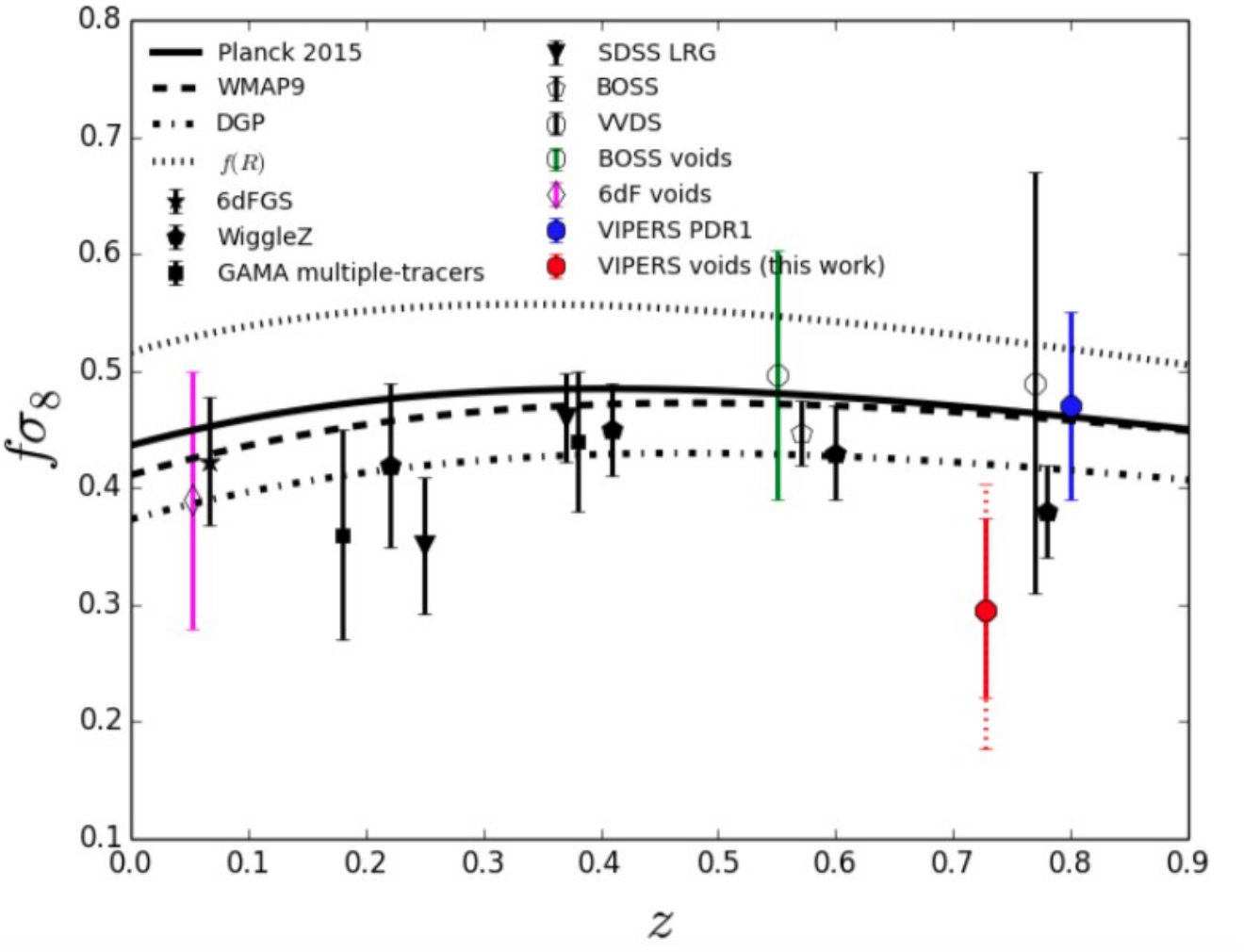
$$\beta_{\rm VIPERS} = 0.423^{+0.104}_{-0.108}$$

By measuring the bias we can convert this to fσ8

$$f\sigma_8 = 0.296^{+0.075}_{-0.078}.$$

Hawken et al (submitted to A&A)

Comparison to other measurements



Hawken et al (submitted to A&A)

Our result is not in tension with other measurements of the growth rate.

However, nor can it rule out any non-standard cosmologies.

The uncertainties are large but are comparable to Hamaus et al 2016 (SDSS) and Achitouv et al 2016 (6DF), but at higher redshift.

Summary

- VIPERS public data release on 18th of November
- Searched for voids in final VIPERS data
- Measured void-galaxy cross correlation function
- Estimated density profile from projected cross correlation
- Described RSD using a linear streaming model
- Fit this to mocks then to data

고맙습니다

What next for VIPERS voids?

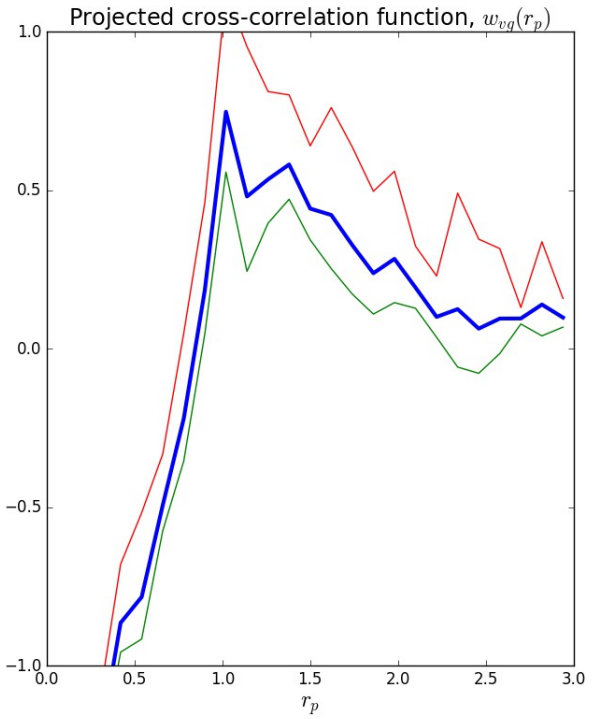
- Properties of galaxies in voids (Chris Haynes et al in prep)
- Better use of void shapes, not just spheres
- Relationship with other structures, clusters, filaments, etc.

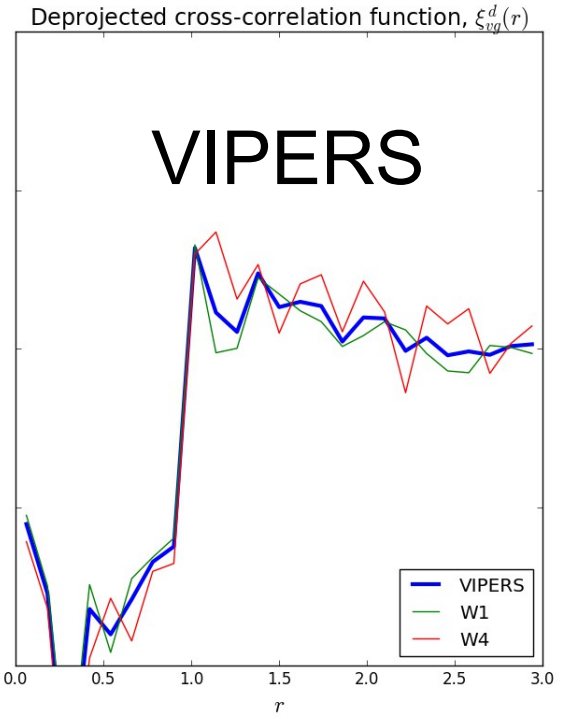
What next for void RSD?

- Better theoretical modelling of RSD and velocity dispersion
- Improved understanding of covariance

What about Euclid?

- Euclid should be good for void RSD experiments
- Need n(z), bias of galaxies, covariance matrix to make forecasts
- Integration of void codes with OU-LE3





We can study the redshift evolution of void properties.

GAMA has similar geometric properties to VIPERS, so a direct comparison is straightforward