THE GROWTH RATE OF STRUCTURE AROUND COSMIC VOIDS

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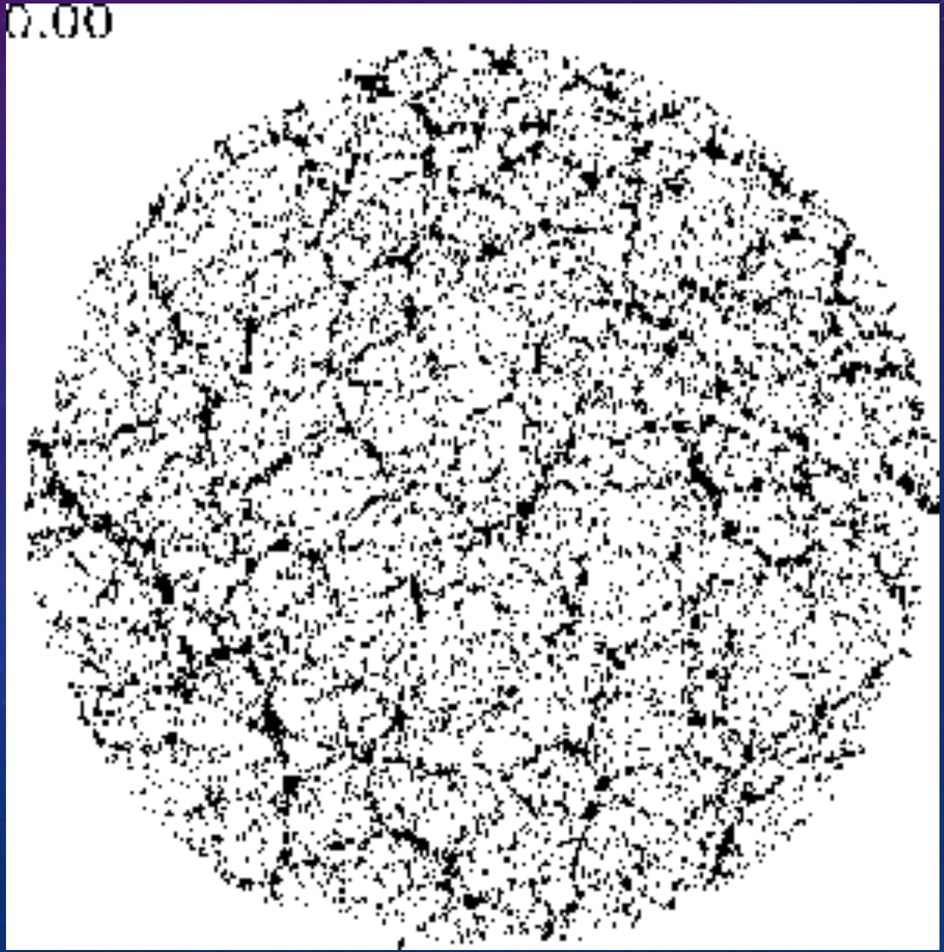
WHAT ARE REDSHIFT SPACE DISTORTIONS?

- Hubble demonstrated that there is a relationship between the recessional velocity of galaxies and their distance.
- We use the redshift of a galaxy as a proxy for it's distance from us.

- Galaxies have peculiar velocities due to gravitational interactions.
- These add an additional component to their apparent recessional velocity and thus their redshift.
- These redshift space distortions lead to anisotropies in the clustering pattern of galaxies (Kaiser 1987, Hamilton 1992 etc).

$$s = r + v_{\parallel} \frac{(1+z)}{H(z)}$$



Melott et al. (1998)

WHY DO WE WANT TO MEASURE RSD?

- In linear theory, the velocity field is a linear function of the local density field and the growth rate of structure
- β is our parameter of interest
- In general relativity $\gamma \approx 0.55$

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

$$\beta = \frac{f(z)}{b_g}$$

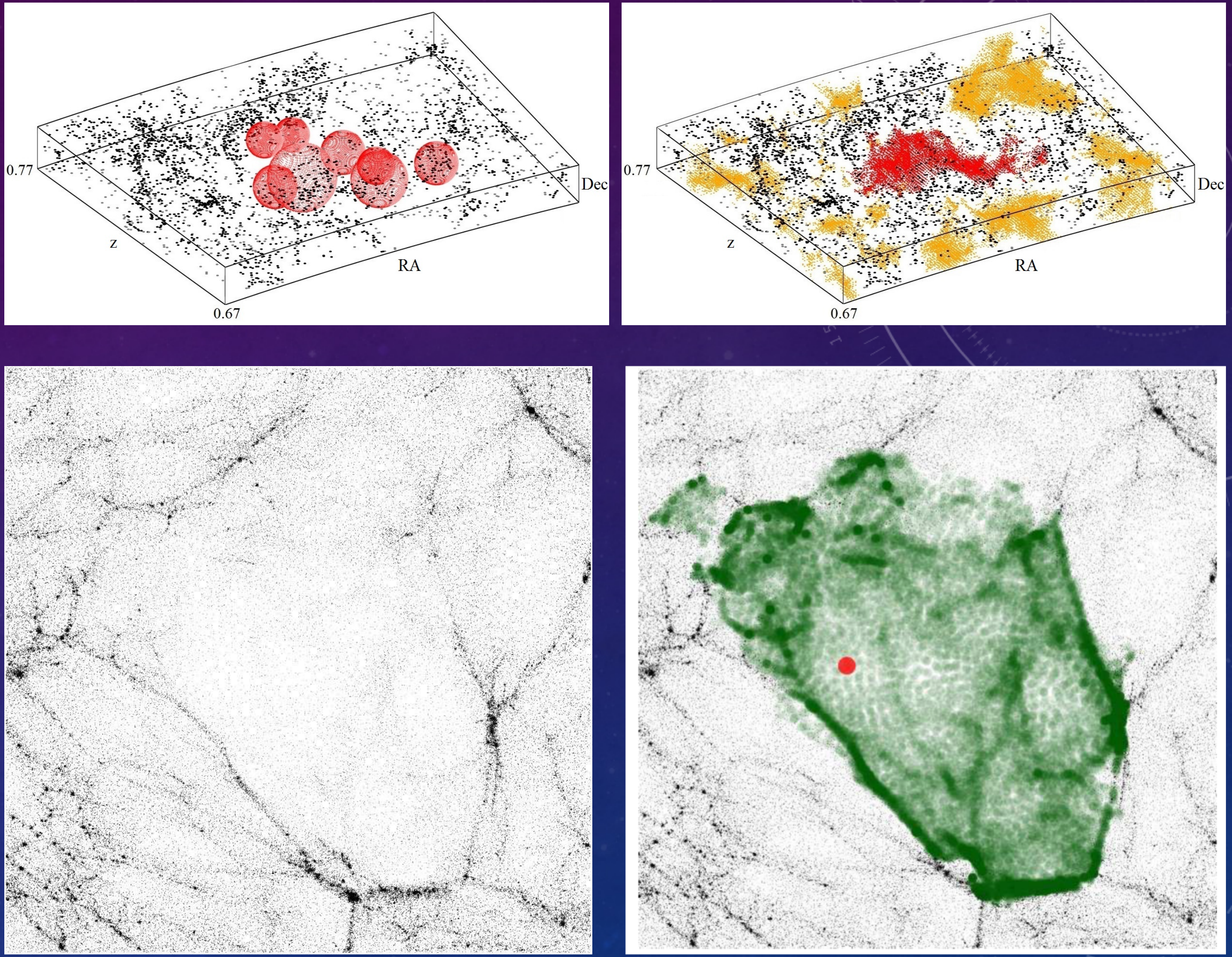
$$f(z) \approx \Omega_m^{\gamma}(z)$$

WHAT ARE COSMIC VOIDS?

- Voids are an important structural and dynamical component of the cosmic web.
  - They occupy most of the volume of the Universe
  - They drive the expansion of the Universe
- Seminal paper by Sheth & van der Weygaert 2004

HOW ARE VOIDS DEFINED?

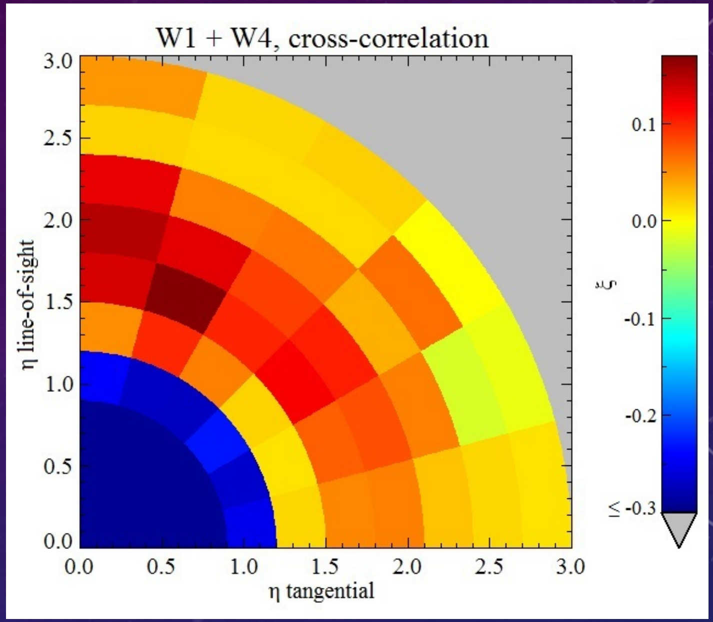
- Different void finding algorithms define voids in different ways.
- Which to use depends on a number of factors:
  - Survey geometry
  - What science do you want to do?
- There are two main types of void finders:
  - Spherical void finders
  - Watershed void finders (i.e. ZOBOV)



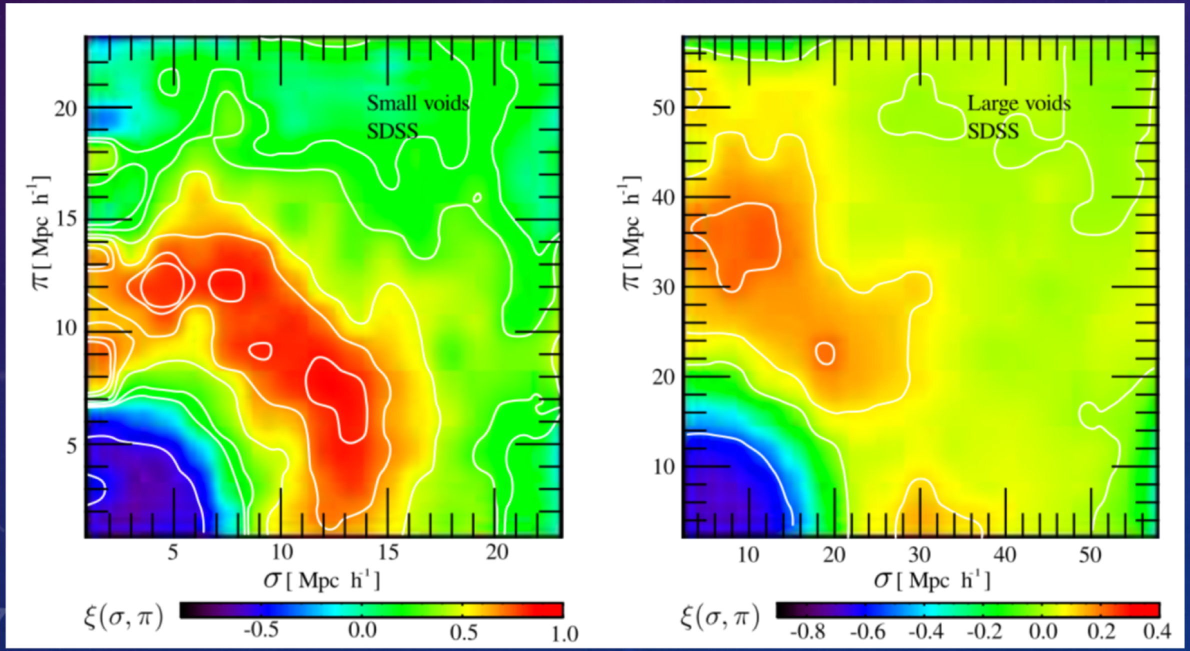
Top: Micheletti et al 2014. Bottom: Neyrinck 2008

WHY SHOULD WE BE INTERESTED IN RSD AROUND VOIDS?

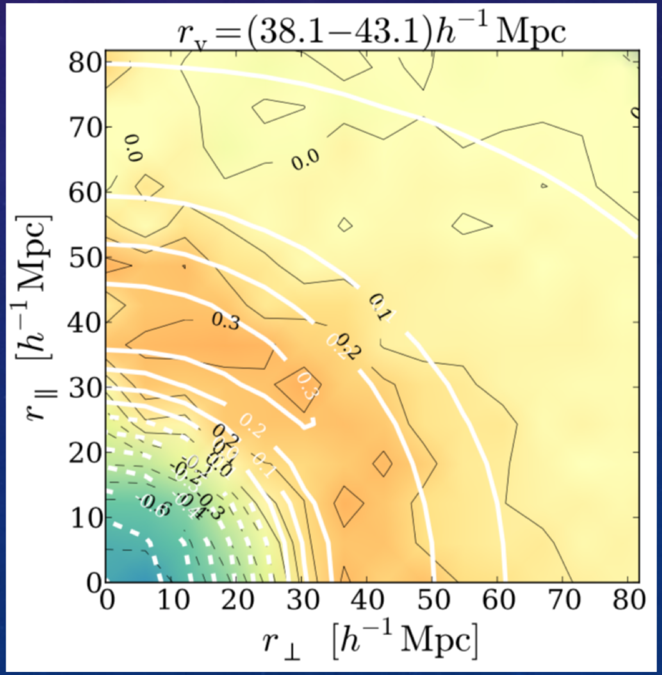
- Plenty of observational evidence for RSD around voids
- Complementary probe of the growth rate of structure



Micheletti et al 2014



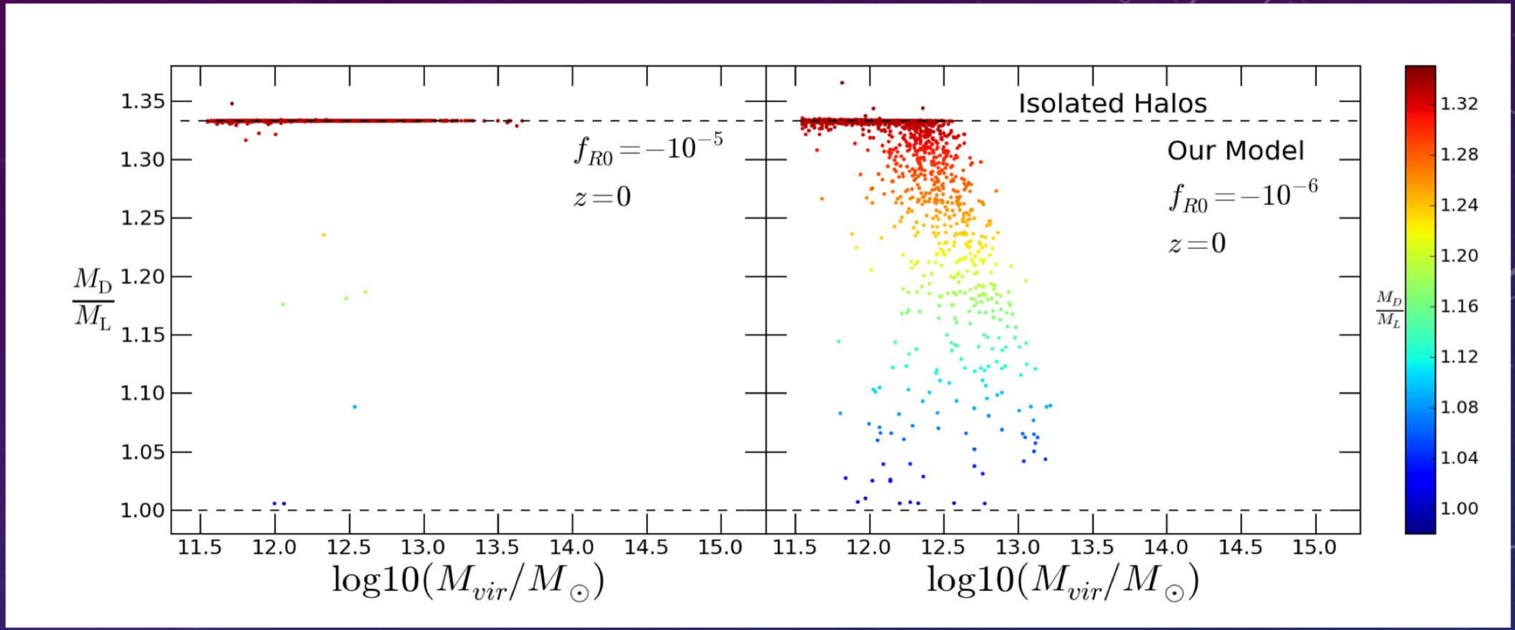
Paz et al 2013

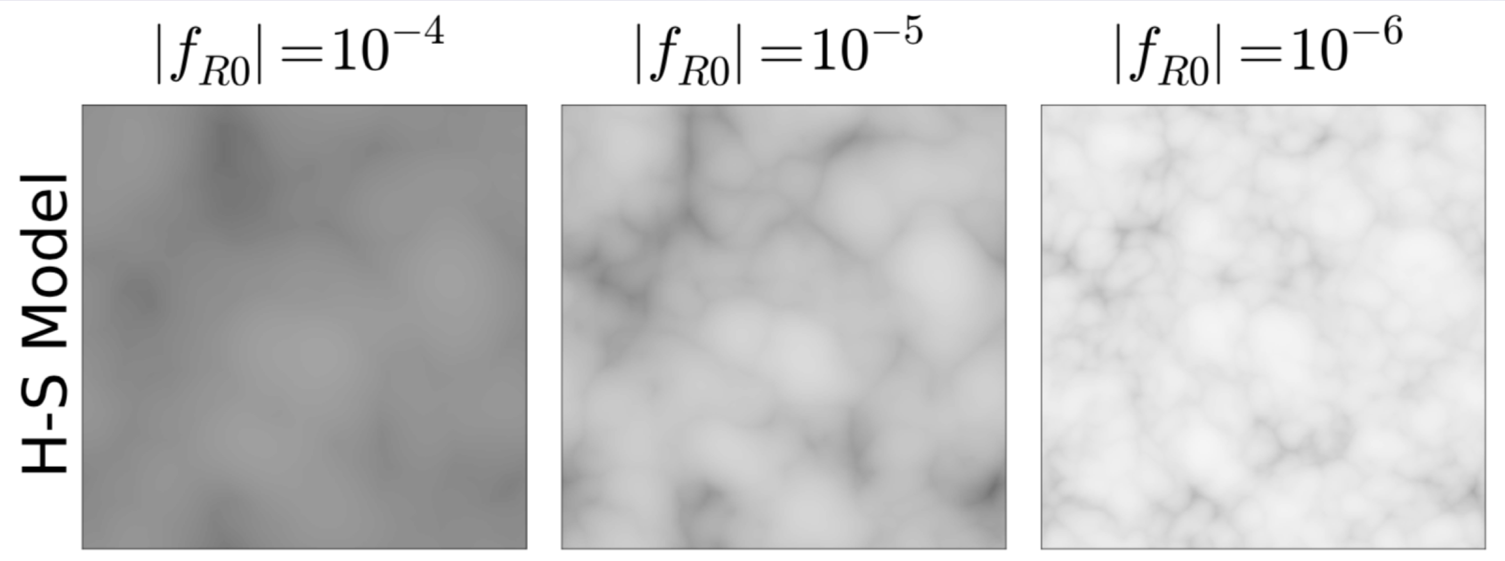


Hamaus et al 2016

WHY STUDY RSD AROUND VOIDS?

- Some modified gravity theories, like chameleon f (R), predict that the growth rate of structure should deviate from GR in low density environments.
- Thus the environmental dependence of the growth rate of structure is a test of GR.





He, Li, AJH, & Granett 2014

MULTIPOLES OF THE VOID-GALAXY CROSS CORRELATION

- The void-galaxy cross correlation can be decomposed into multipoles.
- Even multipoles higher than the monopole are a result of RSD
- See Nadathur and Percival 2017, Hamaus et al 2017, Cai et al 2016

$$\xi_{vg}(r,\mu) = \sum \mathcal{L}_\ell \xi_\ell(r),$$

where

$$\xi_\ell(r) = \int_0^1 \xi_{vg}(r,\mu)(1+2\ell)\mathcal{L}_\ell(\mu)\mathrm{d}\mu,$$

$$\begin{aligned}
\mathcal{L}_0(\mu) &= 1, \\
\mathcal{L}_2(\mu) &= \frac{3\mu^2-1}{2}, \\
\mathcal{L}_4(\mu) &= \frac{35\mu^4-30\mu^2+3}{8}
\end{aligned}$$

MULTIPOLES OF THE VOID-GALAXY CROSS CORRELATION

- Cai et al 2016 proposed a simple model for the void multipoles.
- Hamaus et al 2017 showed that it can be used to measure the growth rate in data.
- This model assumes that the void centres are invariant to RSD, i.e. they are stationary.

$$\xi_0(r) = \left(1 + \frac{\beta}{3}\right)\xi_{vg}(r),$$

$$\xi_2(r) = \frac{2\beta}{3}[\xi_{vg}(r) - \bar{\xi}(r)].$$

$$\xi_0(r) = \left(1 + \frac{1}{3}(\beta_g + \beta_v) + \frac{1}{5}\beta_g\beta_v\right)\xi_{vg}(r),$$
$$\xi_2(r) = \left(\frac{2}{3}(\beta_g + \beta_v) + \frac{4}{7}\beta_g\beta_v\right)[\xi_{vg} - \bar{\xi}_{vg}(r)],$$
$$\xi_4(r) = \left(\frac{8}{35}\beta_g\beta_v\right)[\xi_{vg}(r) + \frac{5}{2}\bar{\xi}_{vg}(r) - \frac{7}{2}\bar{\bar{\xi}}_{vg}(r)],$$

Linear multipoles for a general cross correlation.

Two β parameters.

Used in e.g. Mohammad + VIPERS 2017 to model group-galaxy cross correlations.

if $\beta_v = 0$

$$\xi_0(r) = \left(1 + \frac{\beta}{3}\right)\xi_{vg}(r),$$
$$\xi_2(r) = \frac{2\beta}{3}[\xi_{vg}(r) - \bar{\xi}(r)].$$

if $\beta_v = \beta_g$

$$\xi_0(r) = \left(1 + \frac{2}{3}\beta + \frac{1}{5}\beta^2\right)\xi(r),$$
$$\xi_2(r) = \left(\frac{4}{3}\beta + \frac{4}{7}\beta^2\right)[\xi - \bar{\xi}(r)],$$
$$\xi_4(r) = \left(\frac{8}{35}\beta^2\right)[\xi(r) + \frac{5}{2}\bar{\xi}(r) - \frac{7}{2}\bar{\bar{\xi}}(r)]$$

- In this model the higher multipoles are a function of the monopole.
- The two beta parameters are degenerate.
- We need prior knowledge of one in order to gain knowledge of the other.

$$\xi_2 = \frac{B}{A}[\xi_0 - \bar{\xi}_0],$$

$$\xi_4 = \frac{C}{A}[\xi_0 + \frac{5}{2}\bar{\xi}_0 - \frac{7}{2}\bar{\bar{\xi}}_0],$$

where

$$A = 1 + \frac{1}{3}(\beta_g + \beta_v) + \frac{1}{5}\beta_g\beta_v,$$

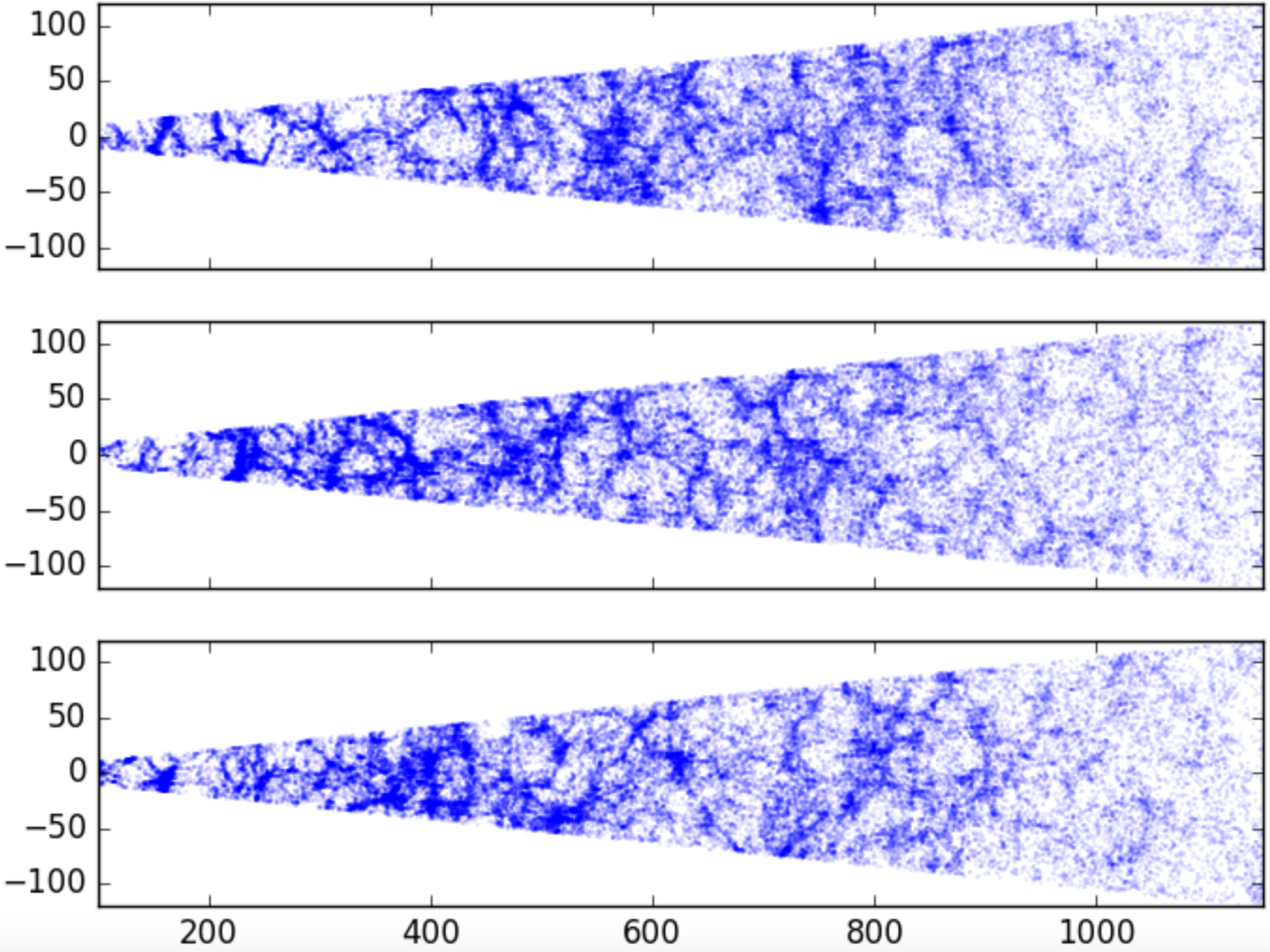
$$B = \frac{2}{3}(\beta_g + \beta_v) + \frac{4}{7}\beta_g\beta_v,$$

$$C = \frac{8}{35}\beta_g\beta_v.$$

THE GROWTH RATE OF STRUCTURE AROUND VOIDS IN GAMA

- We search for voids in GAMA using the same void finder as applied to VIPERS
  - Micheletti et al 2014, Hawken et al 2017
- We measure the void-galaxy cross correlation
- We fit our new model for the multipoles of the void-galaxy cross correlation
- This work is at a late stage of preparation (Hawken et al in prep.)

- The cosmic web is visible here in GAMA II data.
- r < 19.8
- Studied the three equatorial fields: G09, G12, G15

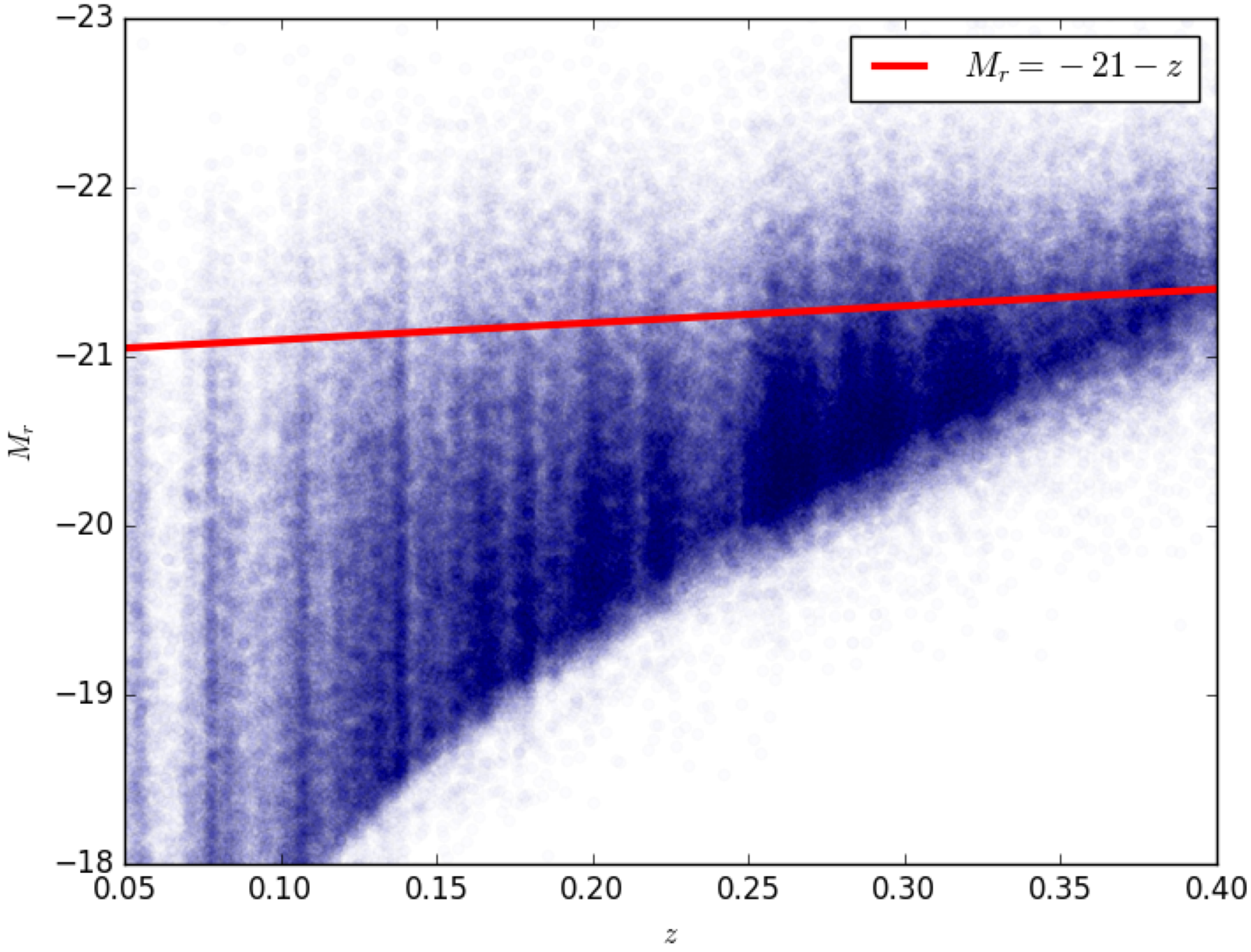


www.gama-survey.org

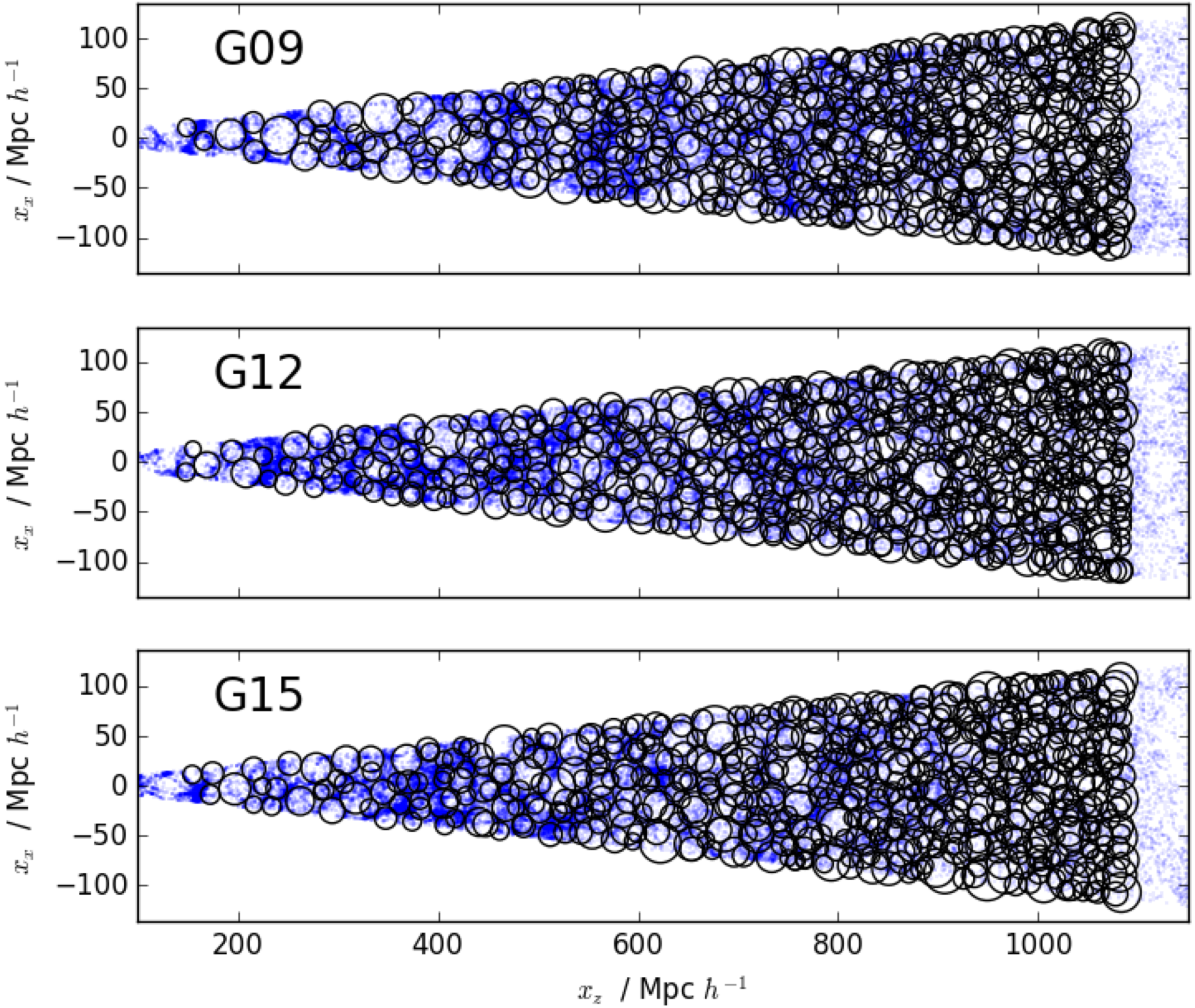
Baldry et al 2018

Baldry et al 2015

- Volume limited catalogue
- Number density constant as a function of redshift
- Highly biased sample gives high contrast between high and low density regions

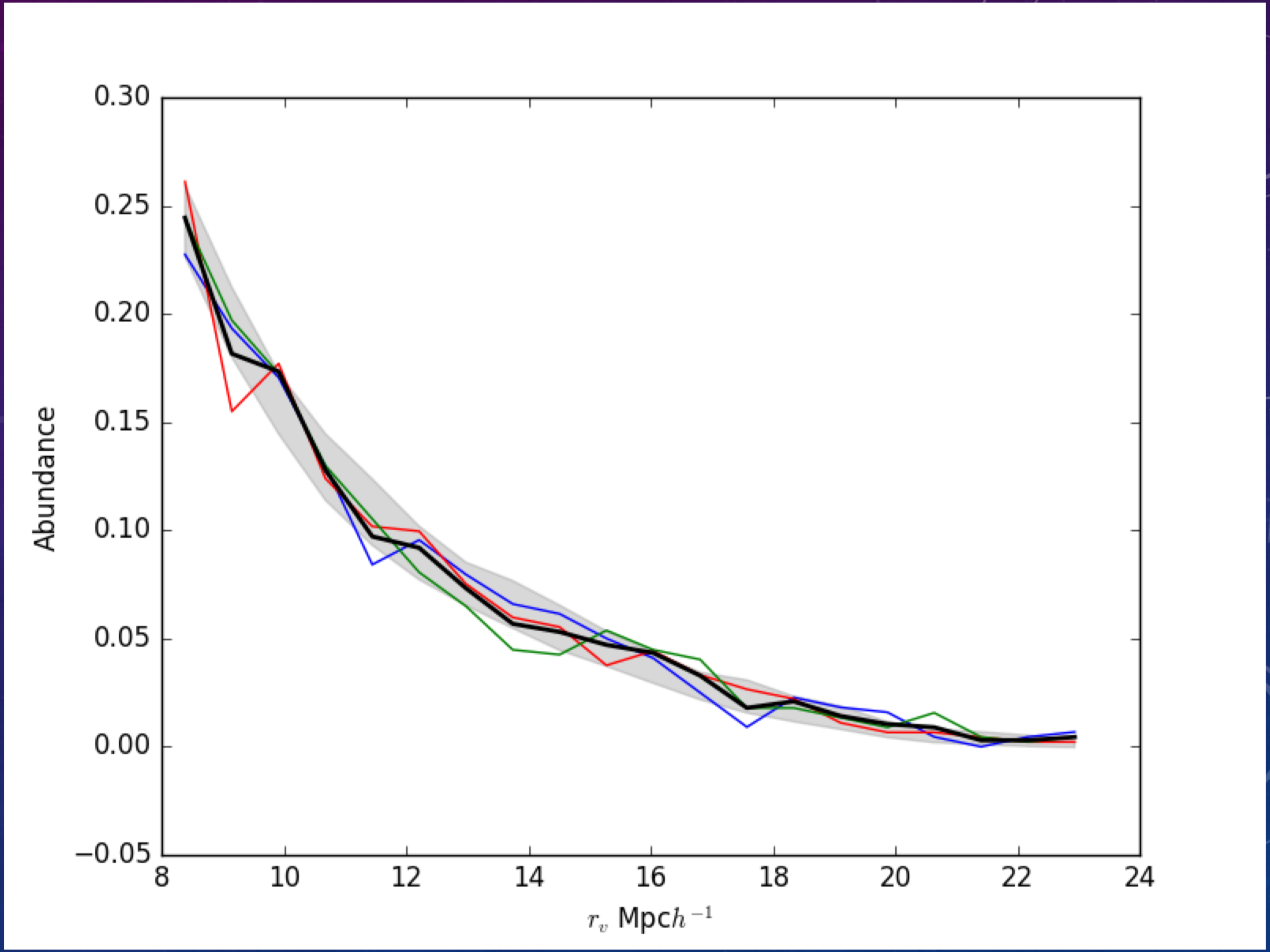


- There are many different algorithms to identify voids.
- Here voids have been identified using a spherical void finder.
- Maximal non-overlapping empty spheres.



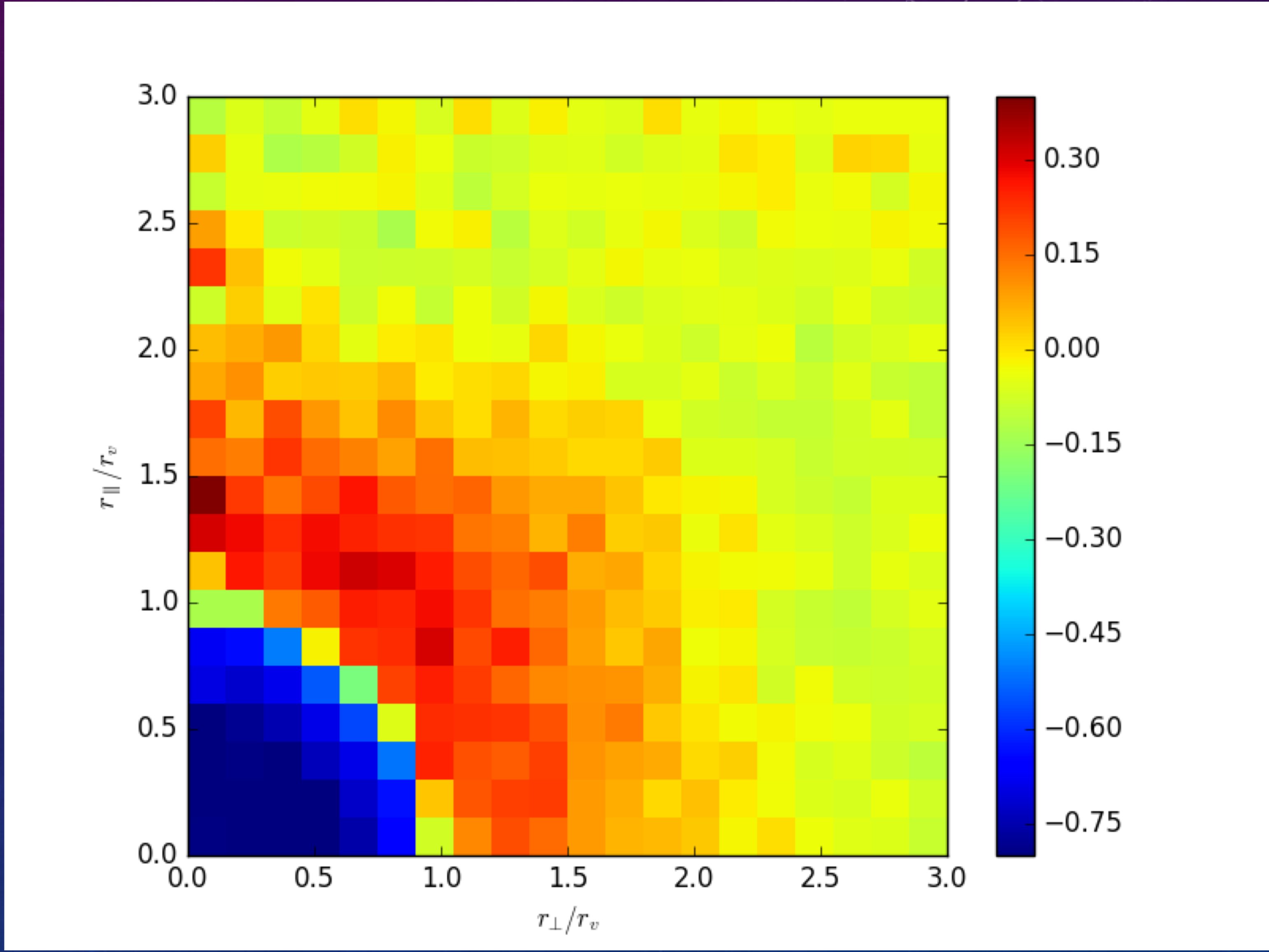
ABUNDANCE OF GAMA VOIDS

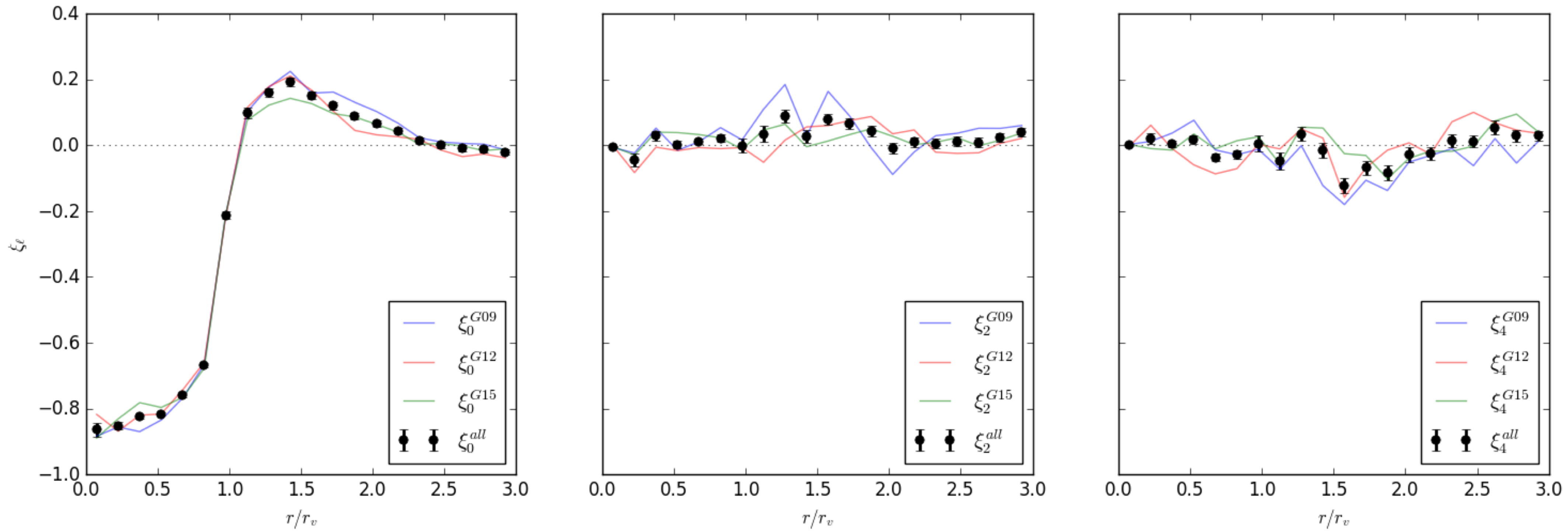
- Comparing the abundance of voids in the data to mock galaxy catalogues allows us to rule out gross deviations from LCDM



VOID-GALAXY CROSS-CORRELATION

- Anisotropy indicative of RSD



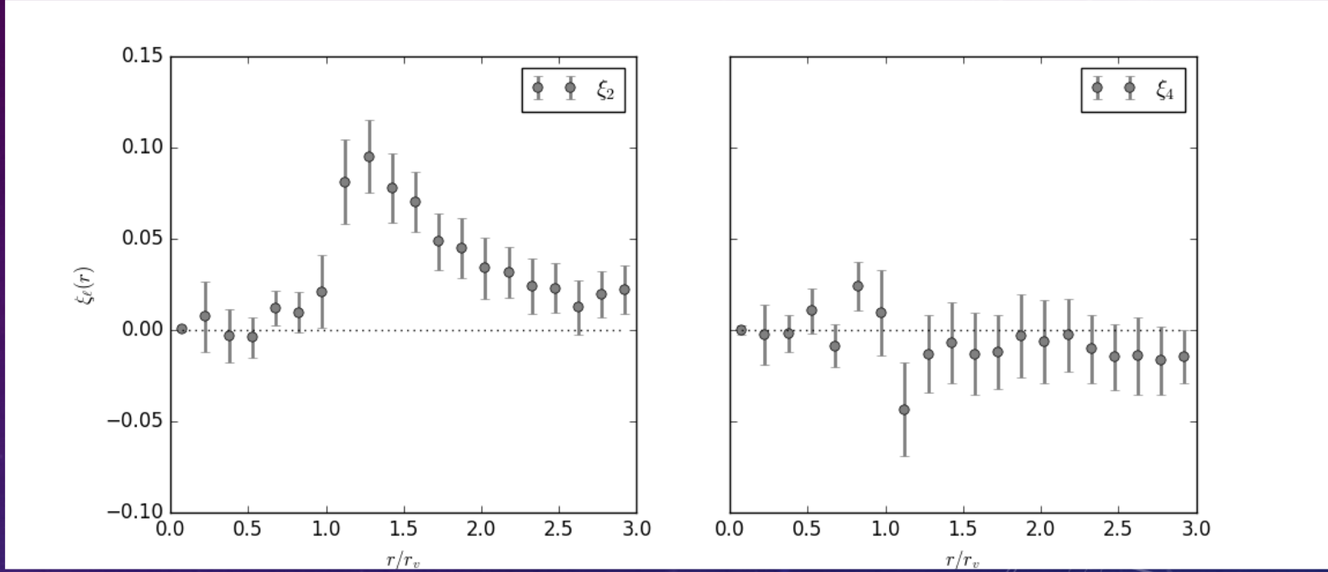


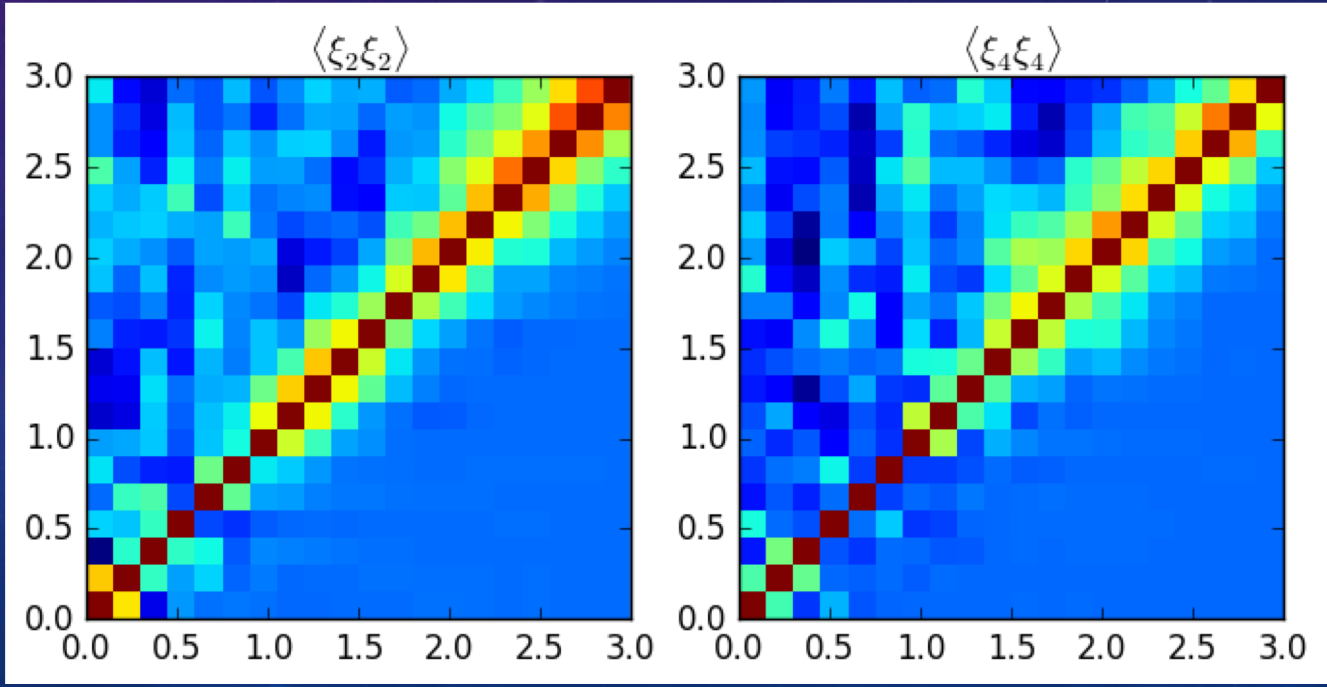
- GAMA multipoles
- Monopole shows shape of the void profile
- Quadrupole expected from linear galaxy motions
- Hexadecapole could be a result of non-zero void peculiar motions

$$\xi_\ell(r) = \int_0^1 \xi_{vg}(r,\mu)(1+2\ell)\mathcal{L}_\ell(\mu)\mathrm{d}\mu$$

MOCKS

- We used 26 realisations of the 3 equatorial GAMA fields
- Galaxy formation model of Gonzalez-Perez et al 2014
- Lightcone construction described in Merson et al 2013
- Applied the same magnitude cut
- Ran the void finder
- Measured void-galaxy cross correlation and multipoles
- Built covariance matrices (these are noisy so we applied tapering).





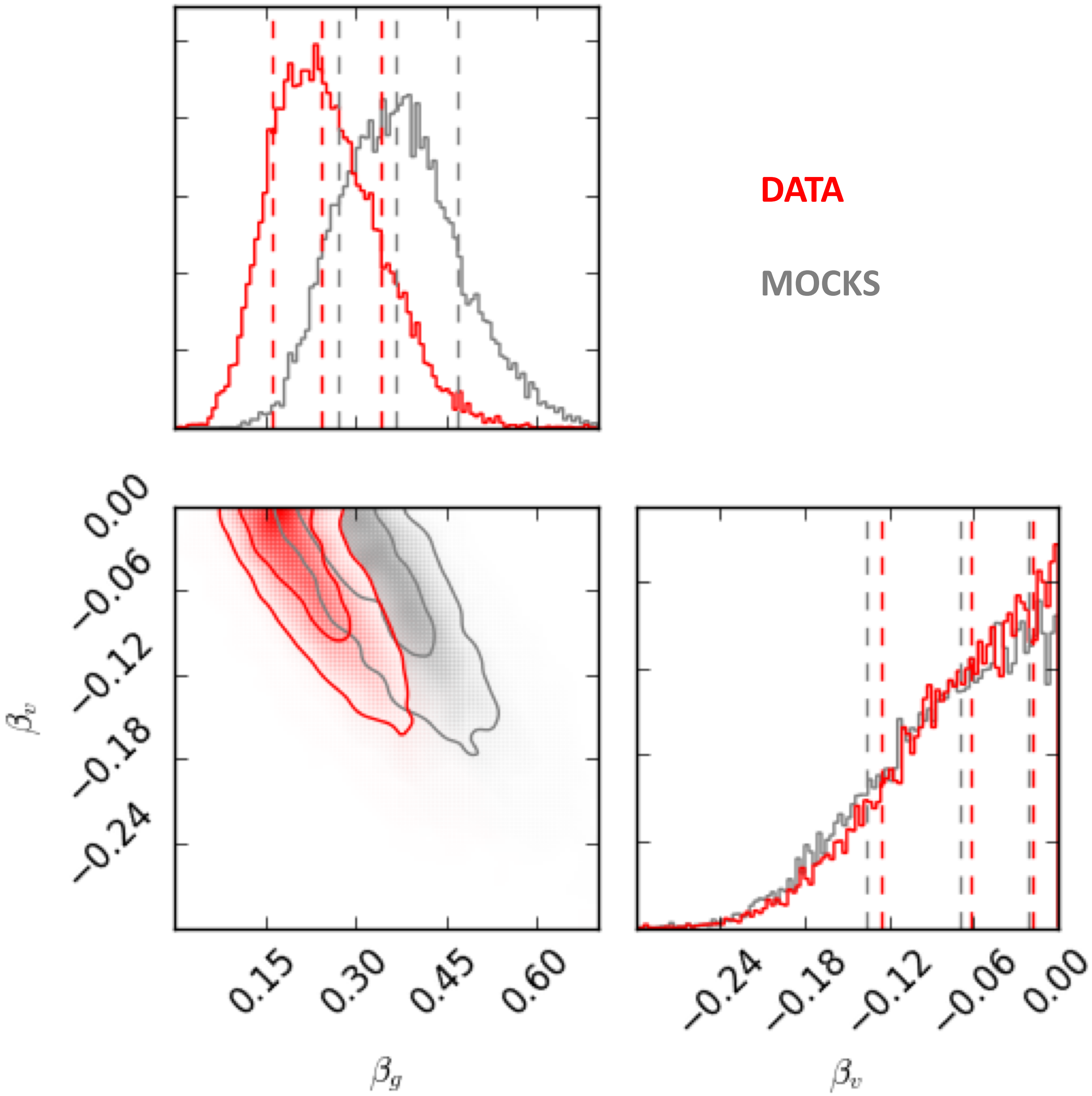
FLAT PRIORS

$$\chi^2_\ell(\theta) = \Delta^T_\ell C^{-1}_\ell \Delta_\ell,$$

$$\Delta_\ell = \xi^{\rm obs}_\ell - \xi^{\rm mod}_\ell(\theta)$$

$$\mathcal{L}(\theta) = \exp\left(-\frac{\chi^2_2 + \chi^2_4}{2}\right)$$

- We know that β_g is positive
- Assume that β_v must be negative
- MCMC hammer (Foreman-Mackay et al 2013)

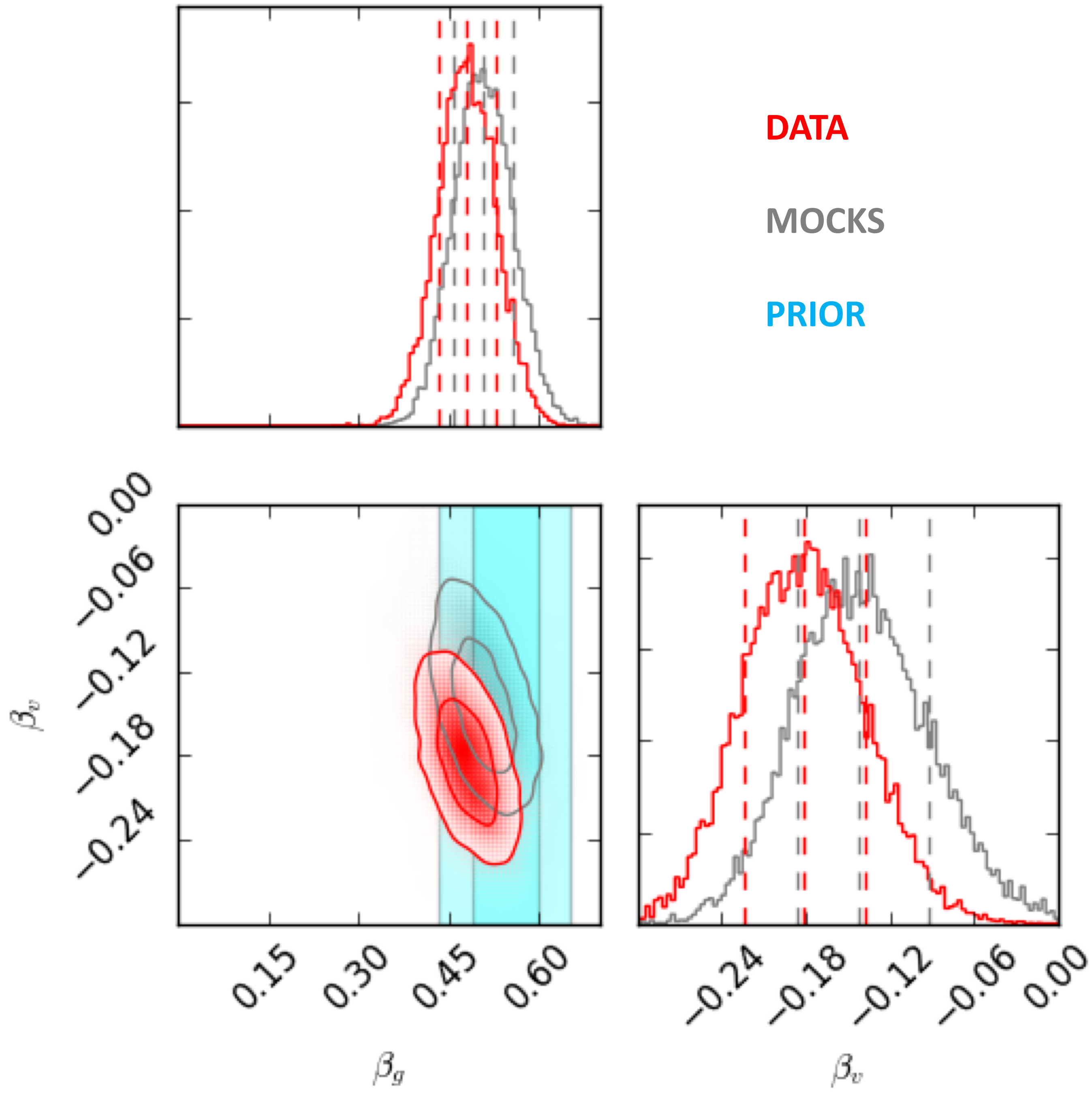


GAUSSIAN PRIOR ON β_g

- We know what the galaxy bias and growth rate are in the mocks.
- We can use this information to put a prior on β_g (with a 10% error bar).

$$\beta_g = 0.544$$

- This provides us with a measurement of β_v in the mocks.



CONCLUDING POINTS

- We have measured the multipoles of the void galaxy cross correlation function in mock galaxy catalogues and in GAMA.
- There appears to be a non-zero hexadecapole.
- There may be a growth rate and a bias associated with the void centres.
- This conclusion applies to spherical voids in small volume surveys.
- Void bias must be understood in order to get accurate measurements of the growth rate from voids.