VOID DYNAMICS

CONSTRAINTS ON COSMOLOGY AND GRAVITY

NICO HAMAUS

in collaboration with

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INPA Seminar

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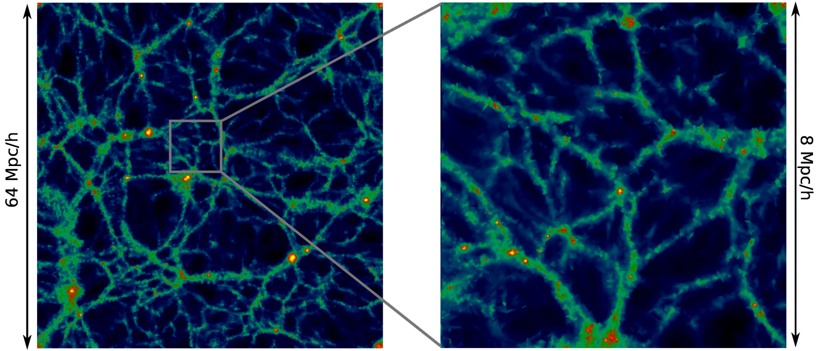
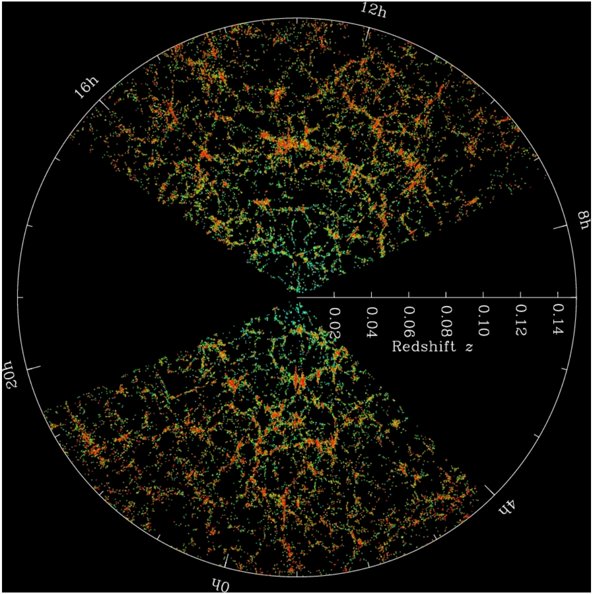
1. Voids in theory
2. Voids in simulations
   arXiv: 1307.2571, 1403.5499, 1409.3580, 1507.04363
3. Voids in observations
   arXiv: 1602.01784
4. Conclusions

The cosmic web



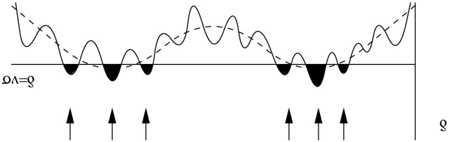
Aragon-Calvo, Szalay (2013)

SDSS galaxies



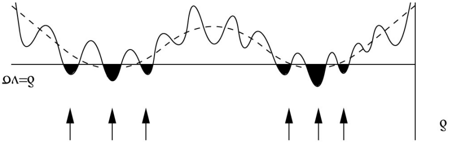
DEFINITION OF VOIDS

Search for local minima in density field

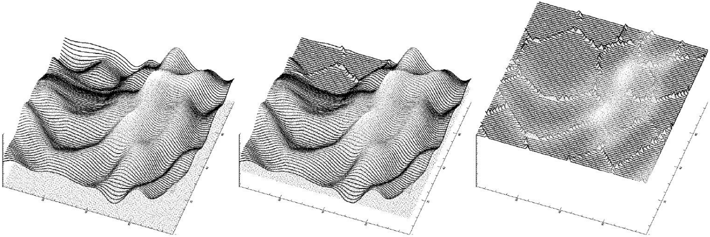


Definition of voids

Search for local minima in density field



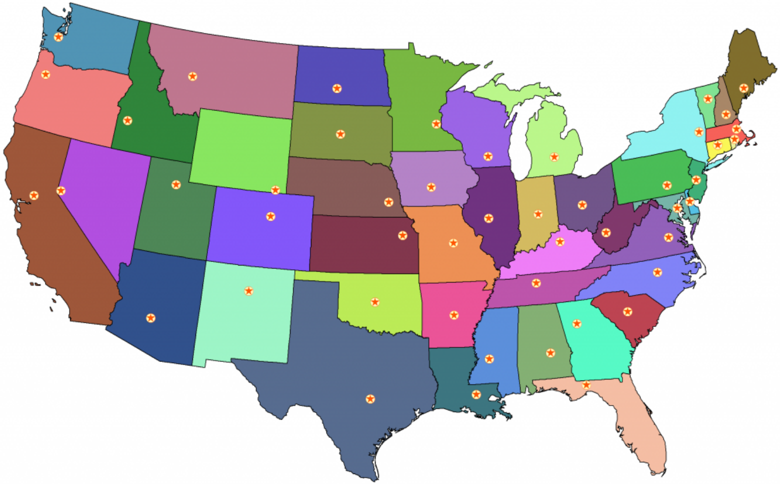
and raise a density threshold until a ridge is reached



Watershed algorithm, Platen et al. (2007)

Definition of voids

Define density field via Voronoi tessellation of tracer particles



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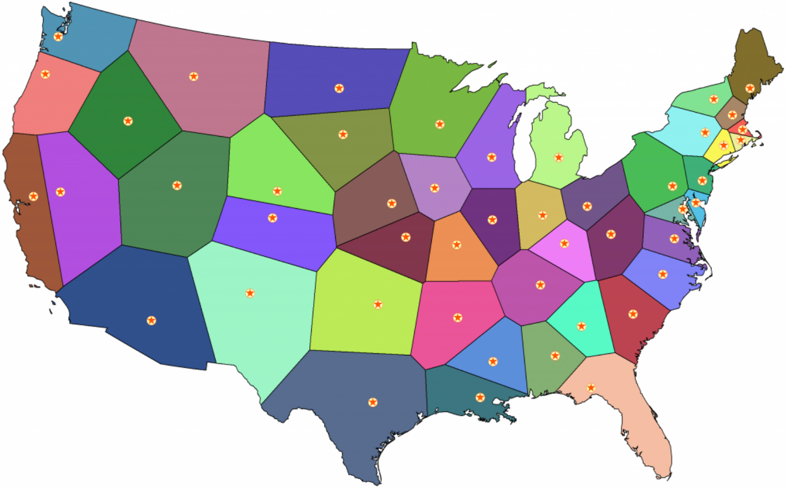
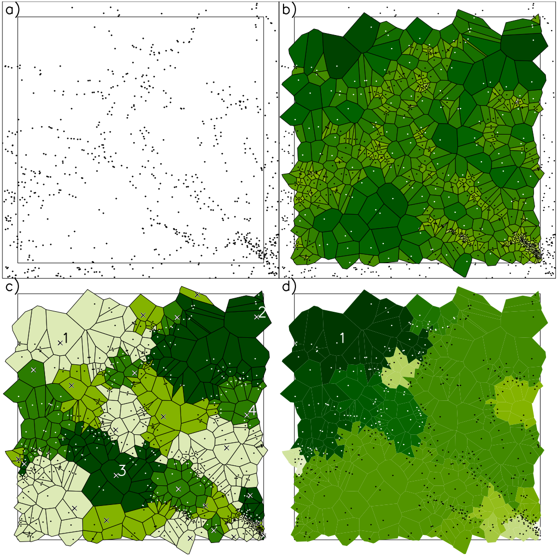


Definition of voids

ZOBOV, Neyrinck (2008)



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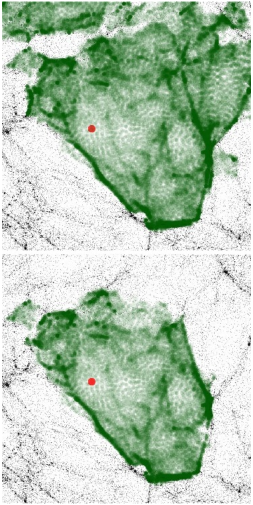
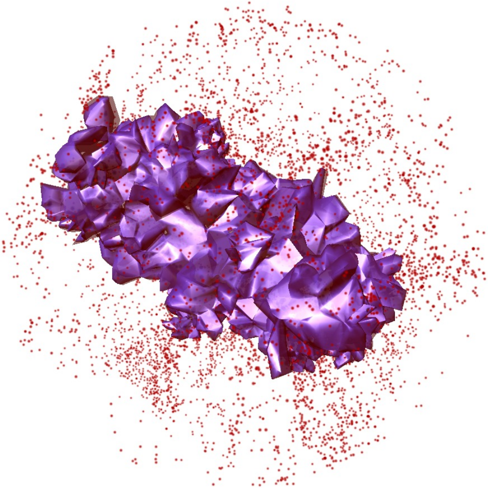
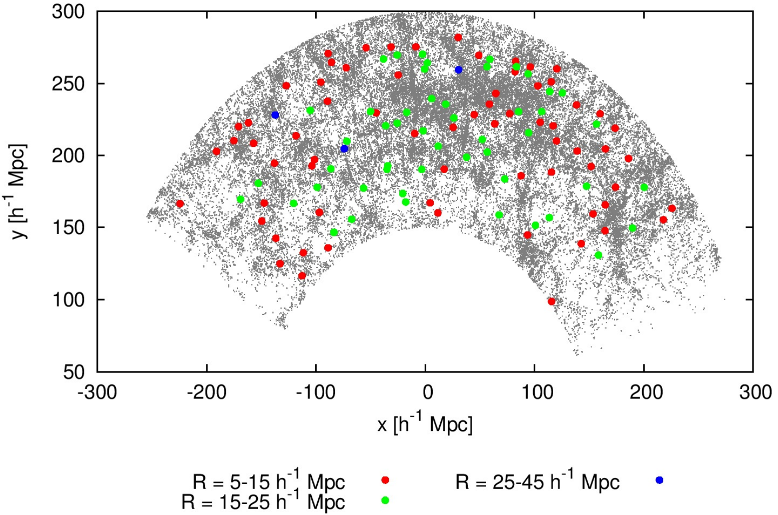


Neyrinck (2008)



Sutter, Lavaux, Wandelt, Weinberg (2012)

Observed voids (SDSS)



Sutter et al. (2012)

Void profile

Estimate density and velocity profile by “stacking” tracer particles around void centers

$$\rho_{\mathrm{v}}(r) = \frac{3}{4\pi} \sum_i \frac{m_i(\boldsymbol{r}_i)}{(r+\delta r)^3 - (r-\delta r)^3}$$

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Empirical best-fit model (4 parameters)

$$\frac{\rho_{\mathrm{v}}(r)}{\bar{\rho}} - 1 = \delta_c \frac{1-(r/r_s)^{\alpha}}{1+(r/r_{\mathrm{v}})^{\beta}}\,, \qquad r_{\mathrm{v}} \equiv (3V_{\mathrm{v}}/4\pi)^{1/3}$$

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Mass conservation to linear order

$$v_{\mathrm{v}}(r) = -\frac{1}{3}\frac{f(z)H(z)}{1+z} r\Delta_{\mathrm{v}}(r) \,, \quad \Delta_{\mathrm{v}}(r) \equiv \frac{3}{r^3}\int_0^r \left(\frac{\rho_{\mathrm{v}}(s)}{\bar{\rho}} - 1\right) s^2 \mathrm{d}s$$

VOID PROFILE

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EMPIRICAL BEST-FIT MODEL (4 PARAMETERS)

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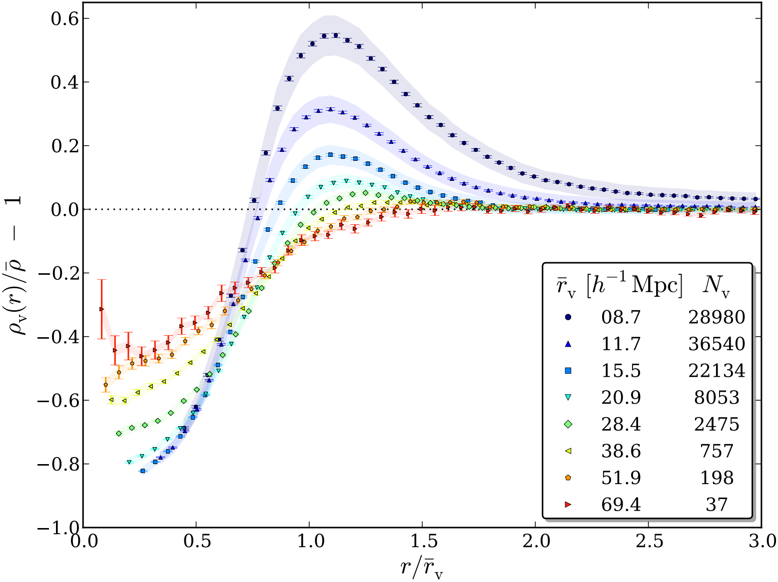
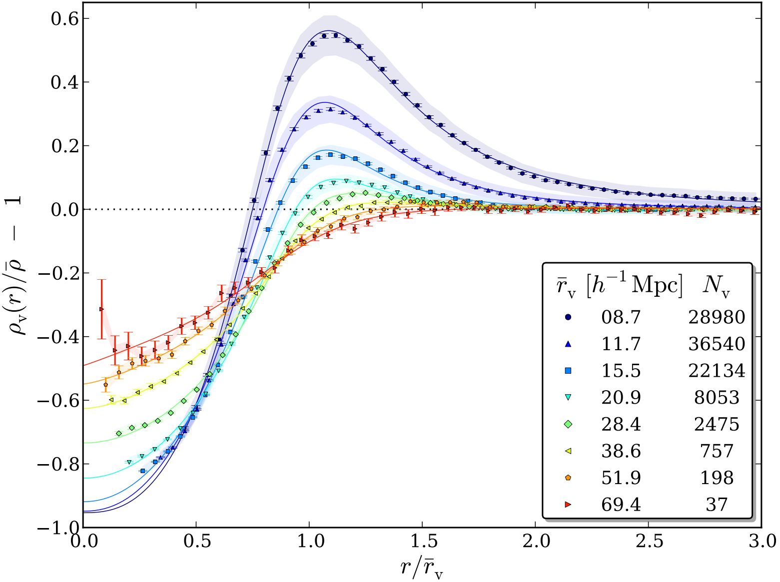
In General Relativity: $f(z) = \Omega_{\rm m}^{0.55}(z)$

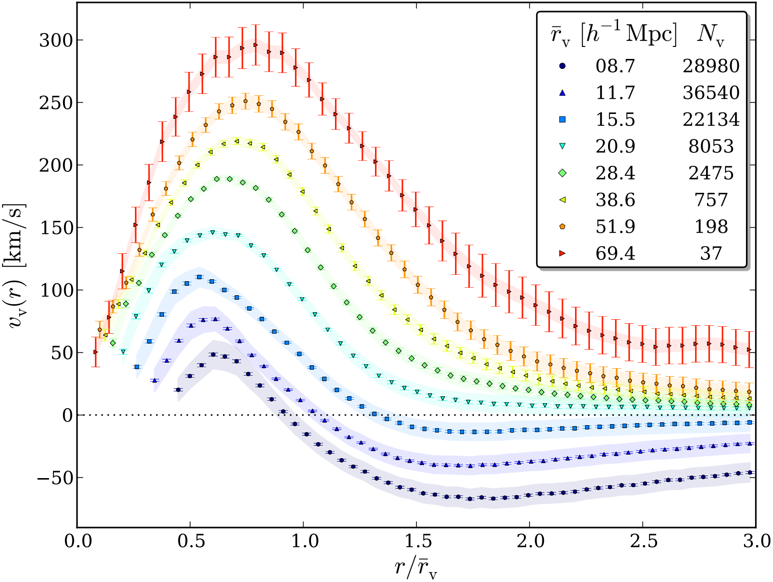
Void profile: density



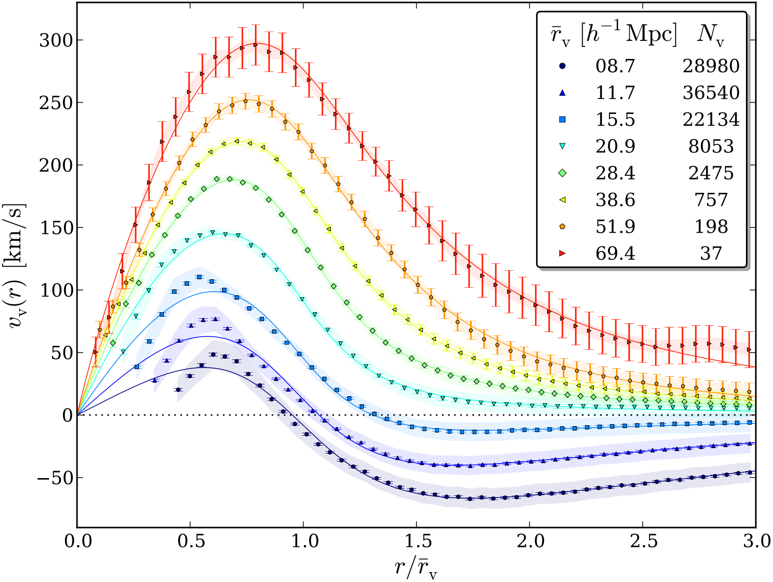
VOID PROFILE: DENSITY



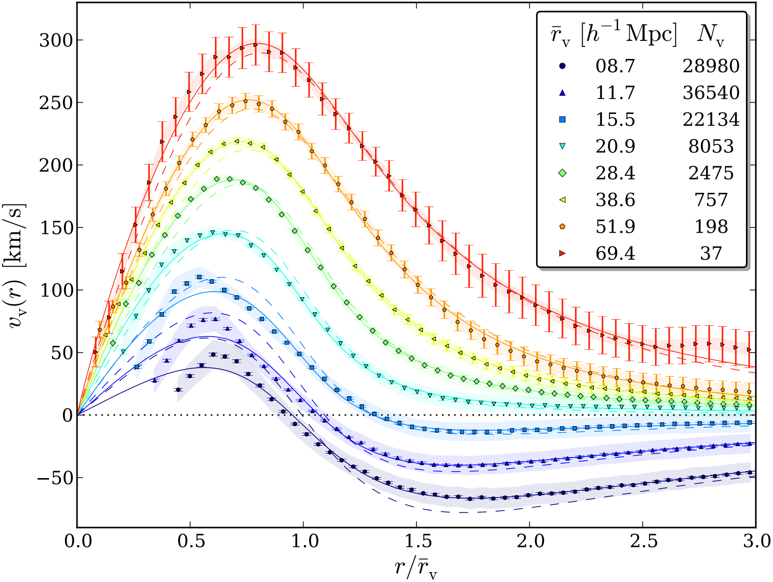
Void profile: velocity



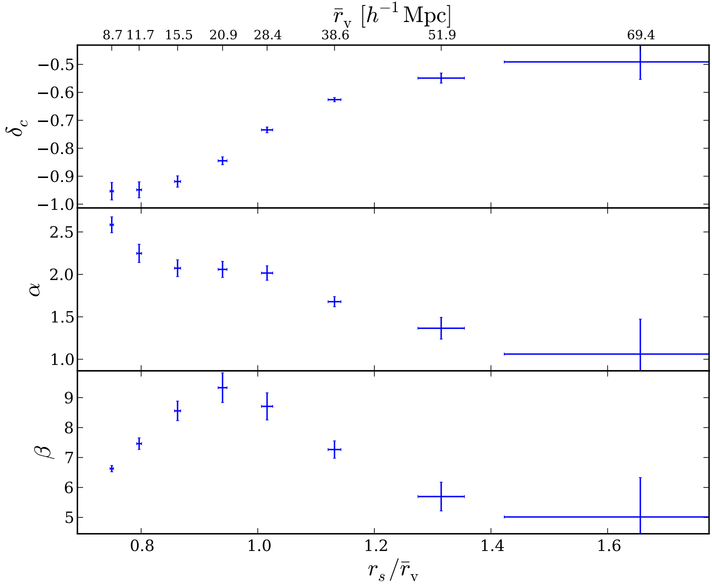
Void profile: velocity



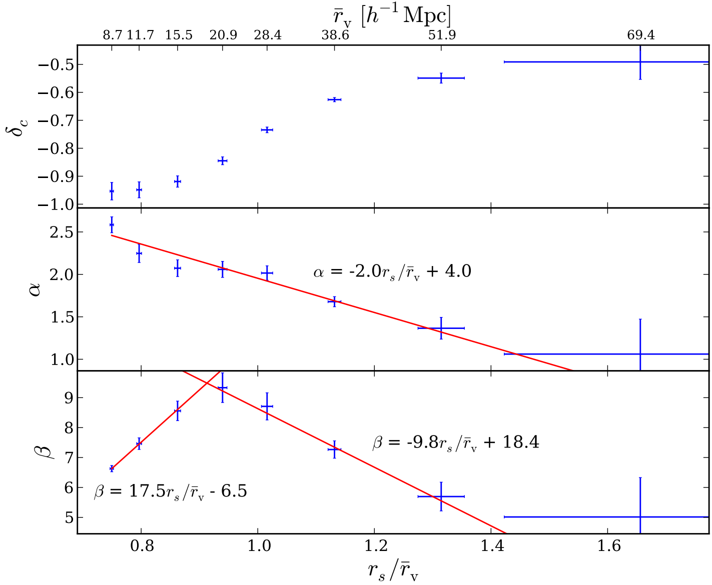
Void profile: velocity



VOID PROFILE: PARAMETERS



Void profile: parameters



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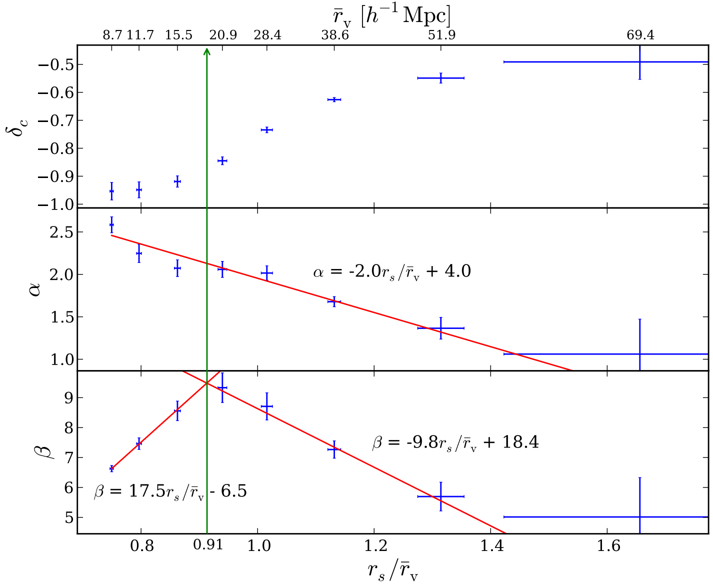
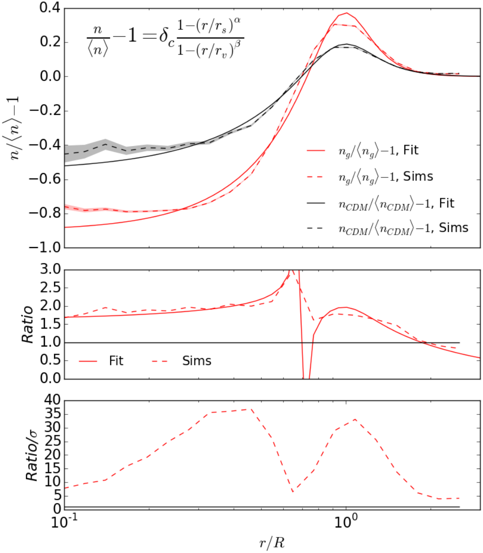
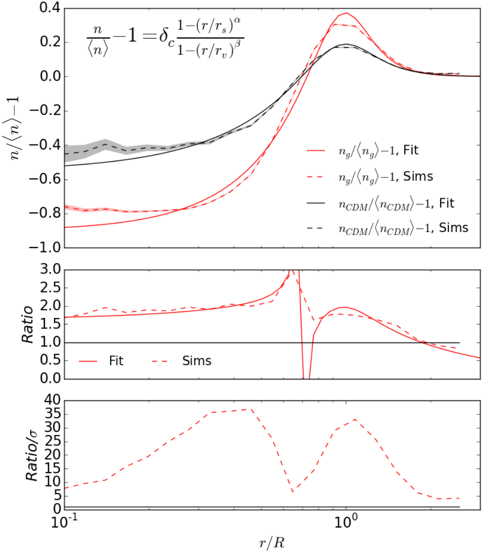
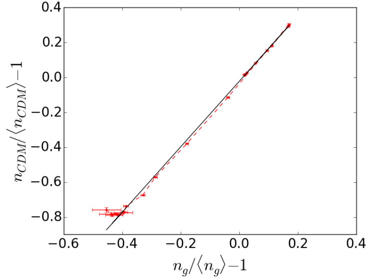


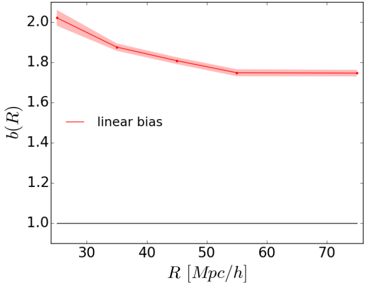
Void profile: galaxies vs. dark matter



VOID PROFILE: GALAXIES VS. DARK MATTER







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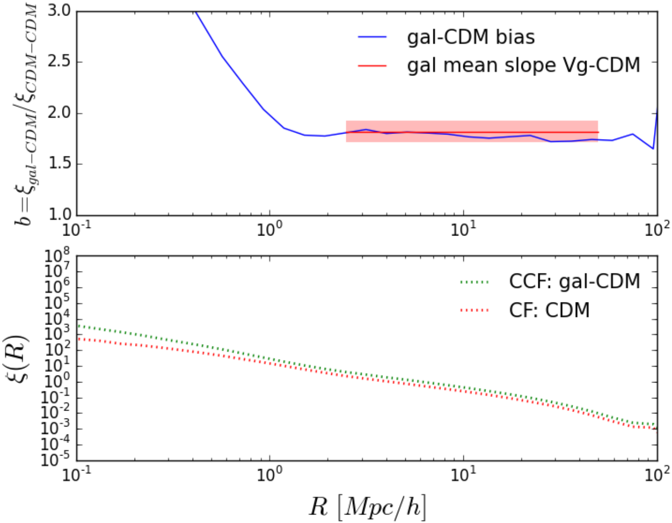
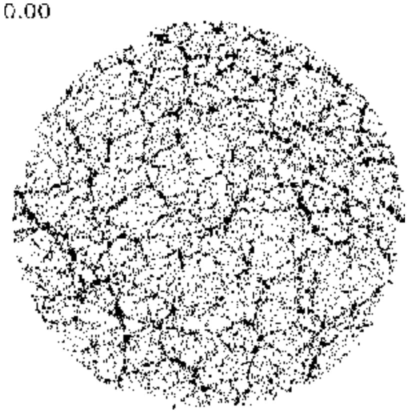


Pollina et al. 2016 (in prep.)

VOIDS IN REDSHIFT SPACE

Peculiar motions of galaxies cause redshift-space distortions:

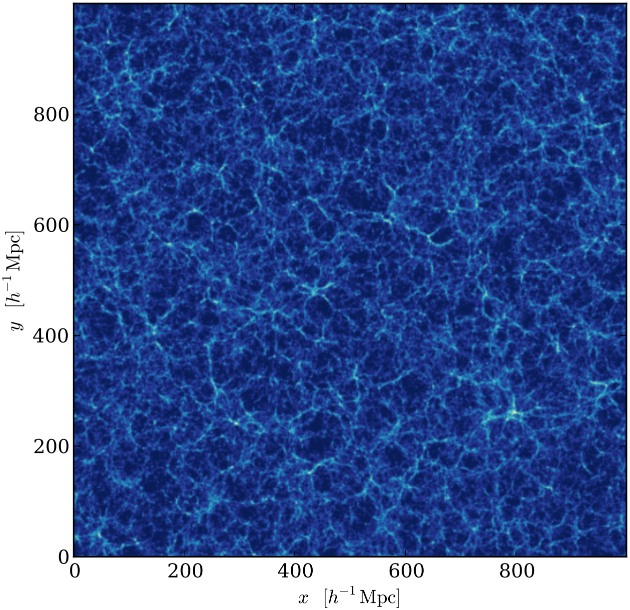
$$\tilde{\mathbf{r}} = \mathbf{r} + \mathbf{v}_{\|} H^{-1}(z)$$



Melott et al. (1998)

- $\perp$ to line of sight: *Pancakes of God* from linear growth
- $\|$ to line of sight: *Fingers of God* from nonlinear collapse
- Galaxy correlation function no longer isotropic, what about voids?

Voids in redshift space



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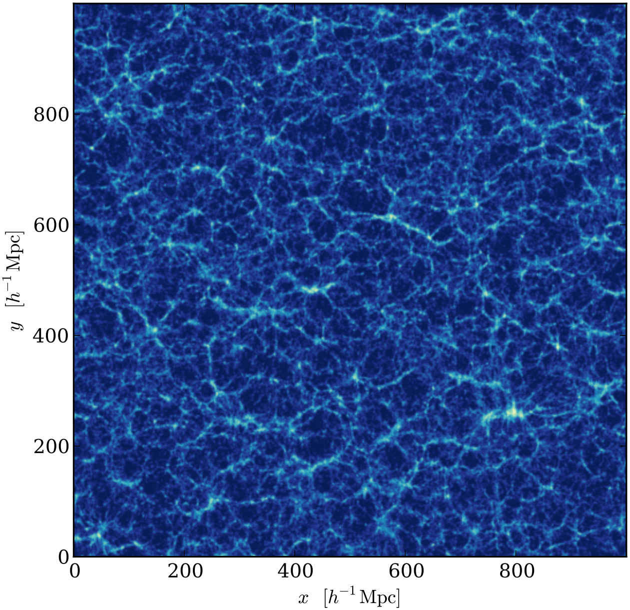

Model

Void-galaxy cross-correlation function in redshift space:

$$1 + \tilde{\xi}_{\mathrm{vg}}(\tilde{\mathbf{r}}) = \int \mathcal{P}\left(\mathbf{v}, \mathbf{r}\right) \left[1 + \xi_{\mathrm{vg}}(\mathbf{r})\right] \, \mathrm{d}^3 v = \int_{-\infty}^{\infty} \mathcal{P}\left(v_{\parallel}, \mathbf{r}\right) \frac{\rho_{\mathrm{v}}(r)}{\bar{\rho}} \, \mathrm{d} v_{\parallel}$$

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Assume a Gaussian pairwise velocity distribution with mean $v_{\mathrm{v}}(r)\frac{r_{\parallel}}{r}$

$$\mathcal{P}\left(v_{\parallel}, \mathbf{r}\right) = \frac{1}{\sqrt{2\pi}\sigma_v(\mathbf{r})} \exp\left[-\frac{\left(v_{\parallel} - v_{\mathrm{v}}(r)\frac{r_{\parallel}}{r}\right)^2}{2\sigma_v^2(\mathbf{r})}\right]$$

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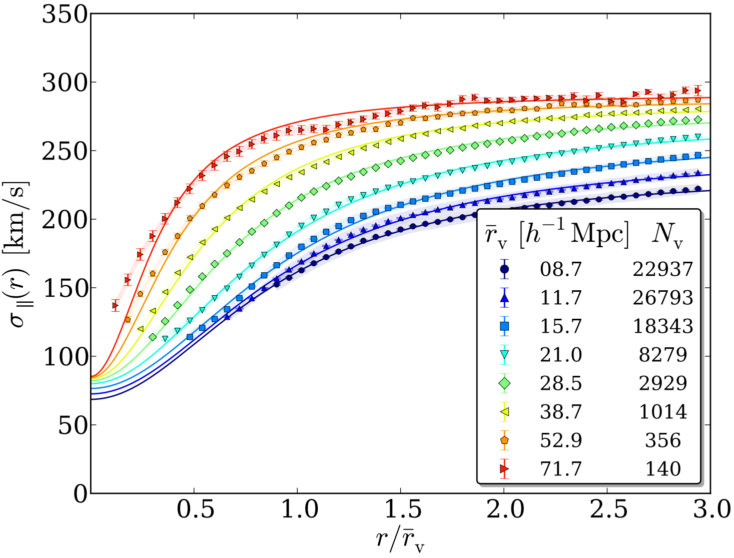
and with velocity dispersion

$$\sigma_v^2(\mathbf{r}) = \sigma_{\|}^2(r)\frac{r_{\|}^2}{r^2} + \sigma_{\perp}^2(r)\left(1 - \frac{r_{\|}^2}{r^2}\right)$$

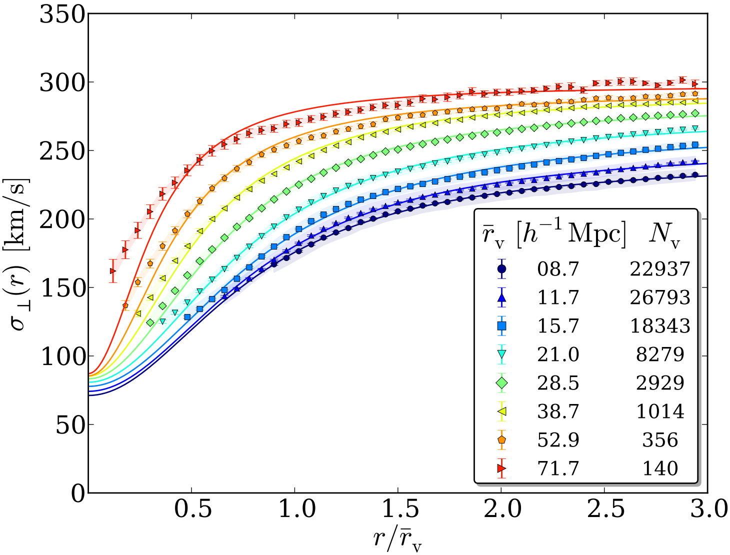
Assume:

$$\sigma_{\|,\perp}(r) \equiv \sigma_v = \mathrm{const.}$$

Velocity dispersion



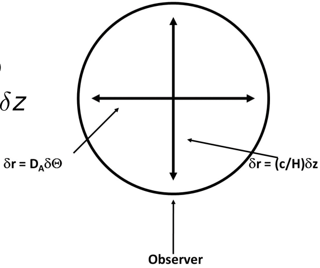
Velocity dispersion



Alcock-Paczynski test

Perform *Alcock-Paczynski test* to constrain cosmological parameters:

- Angular separation $\delta r_{\perp} = D_A(z)\,\delta\Theta$
- Radial separation $\delta r_{\parallel} = cH^{-1}(z)\,\delta z$



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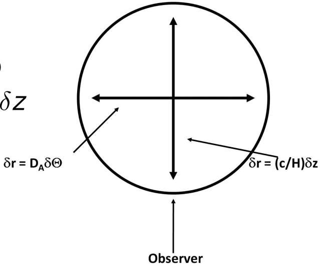

ANGULAR DIAMETER DISTANCE & HUBBLE RATE

$$D_A(z) = c\int_0^z H^{-1}(z')\,\mathrm{d}z' \quad , \quad H(z) = H_0\sqrt{\Omega_\mathrm{m}(1+z)^3 + \Omega_\Lambda}$$

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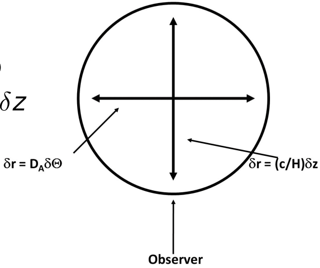


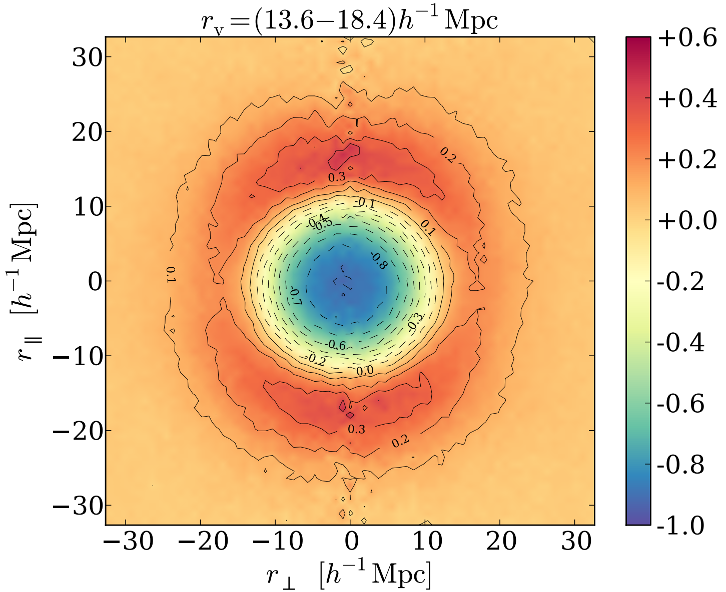
Angular diameter distance & Hubble rate

$$D_A(z) = c \int_0^z H^{-1}(z')\, \mathrm{d}z' \quad , \quad H(z) = H_0 \sqrt{\Omega_\mathrm{m}(1+z)^3 + \Omega_\Lambda}$$

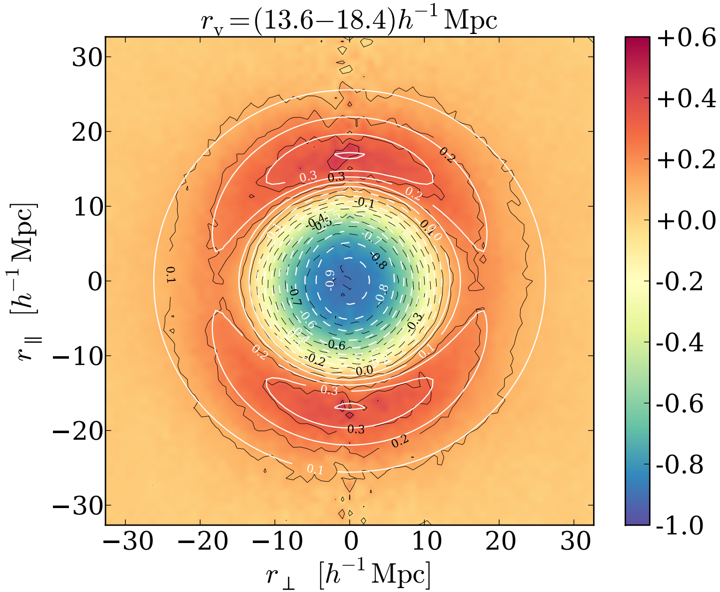
Any deviation from the fiducial cosmology causes geometric distortions. $\Rightarrow$ Determine ellipticity ε via

$$\varepsilon = \frac{\delta r_\parallel}{\delta r_\perp} = \frac{D_A^{\mathrm{true}}(z) H^{\mathrm{true}}(z)}{D_A^{\mathrm{fid}}(z) H^{\mathrm{fid}}(z)}$$

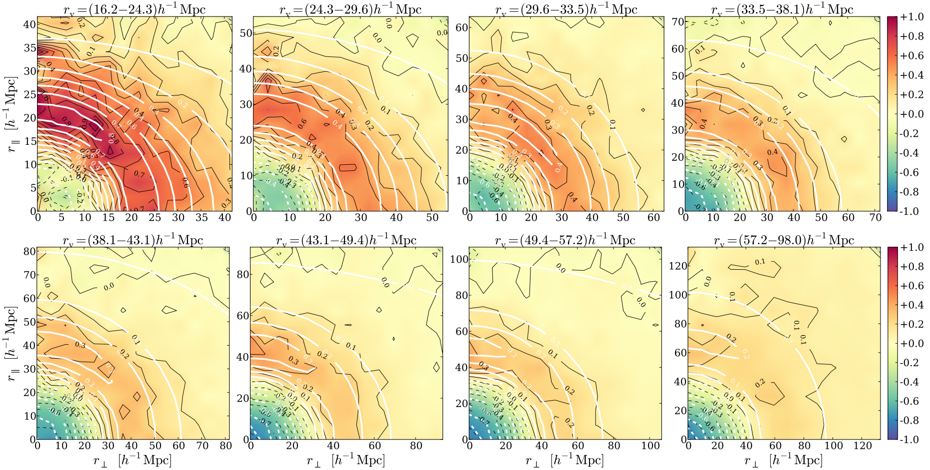
RSD ANALYSIS: DENSE MOCK GALAXIES



RSD analysis: dense mock galaxies



RSD analysis: SDSS CMASS DR11 galaxies



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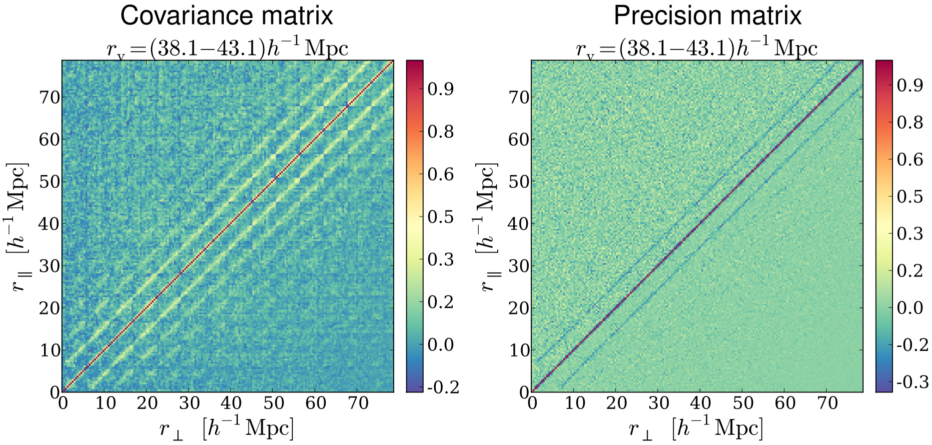
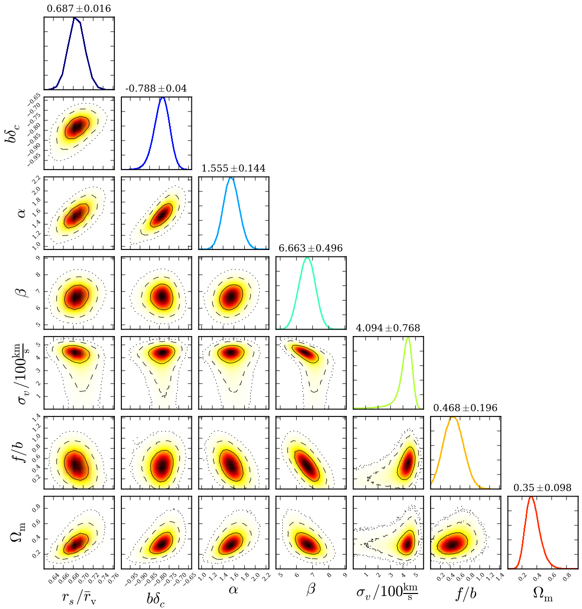


$$\mathcal{L}(\hat{\xi}_{\mathrm{vg}}|\boldsymbol{\theta}) \propto \exp\left[-\frac{1}{2}(\hat{\xi}_{\mathrm{vg}} - \xi_{\mathrm{vg}})^{\mathsf{T}}\mathbf{C}^{-1}(\hat{\xi}_{\mathrm{vg}} - \xi_{\mathrm{vg}})\right]$$

RSD analysis: SDSS CMASS DR11 galaxies



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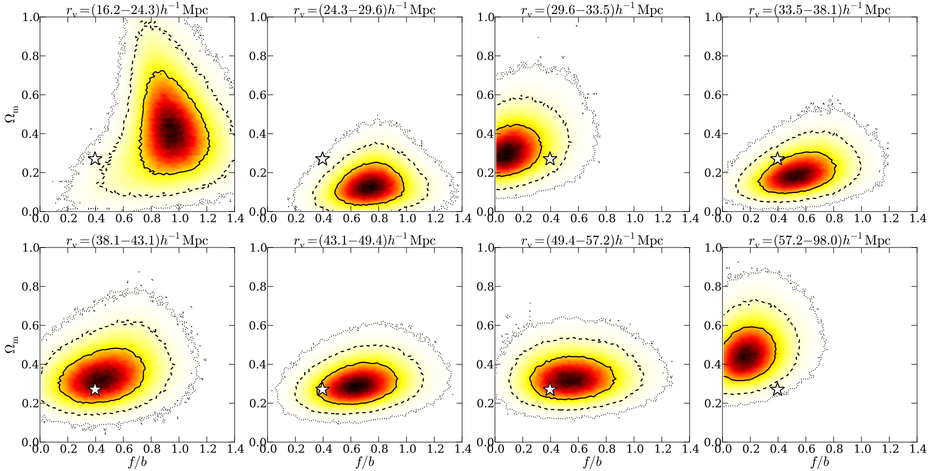

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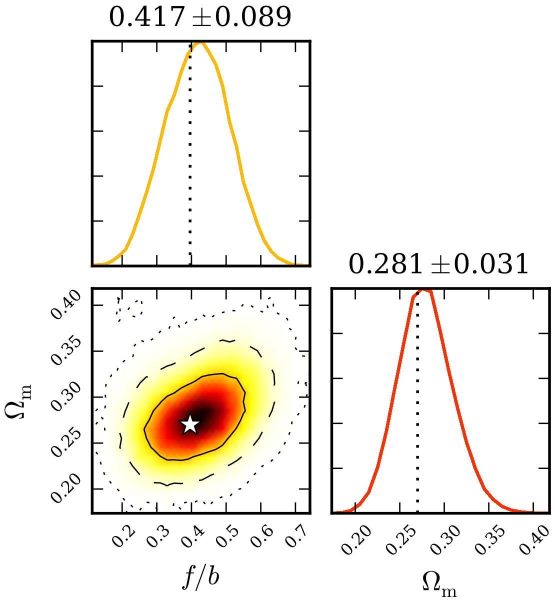
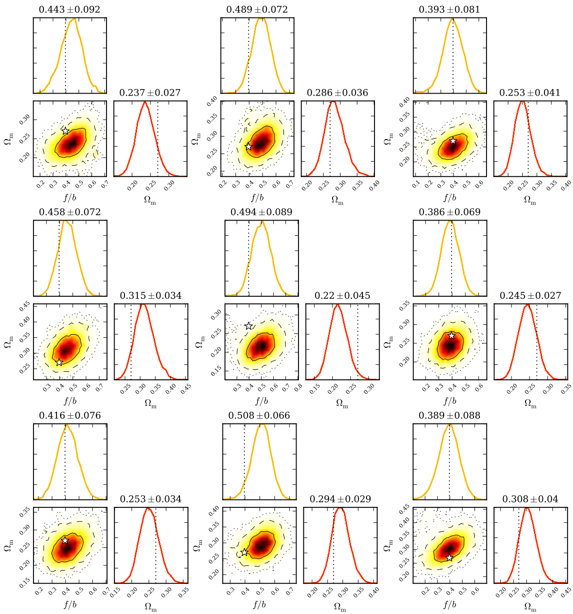
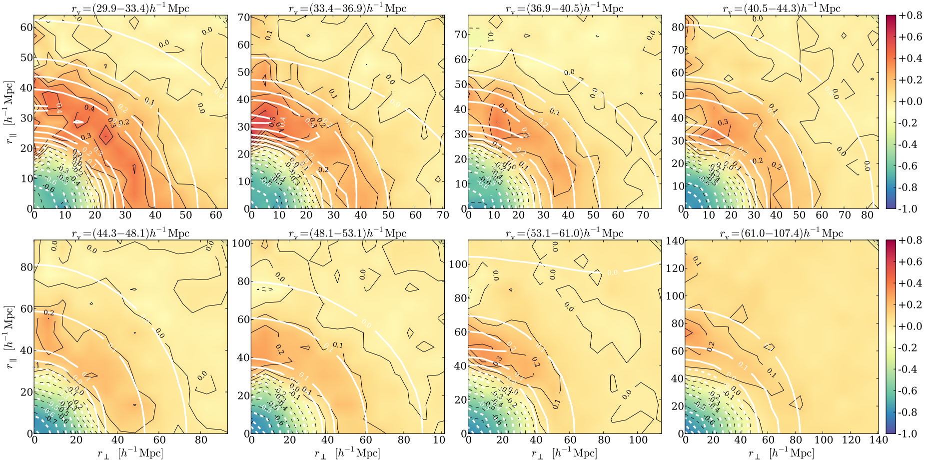


RSD analysis: SDSS CMASS DR11 bootstraps



RSD analysis: SDSS CMASS DR11 mocks



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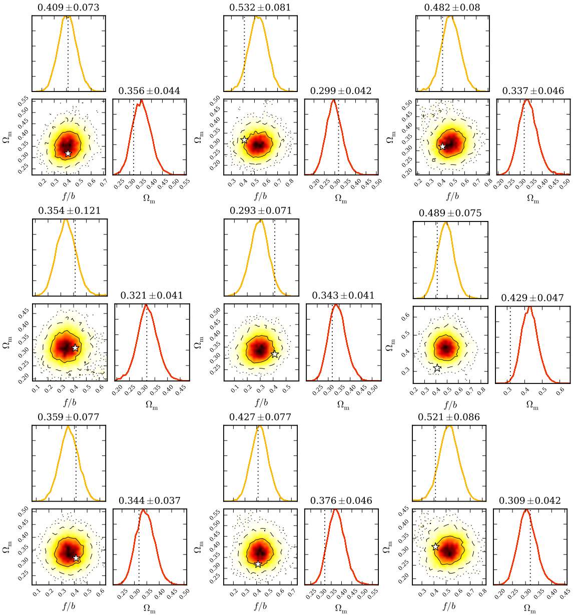

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Conclusions

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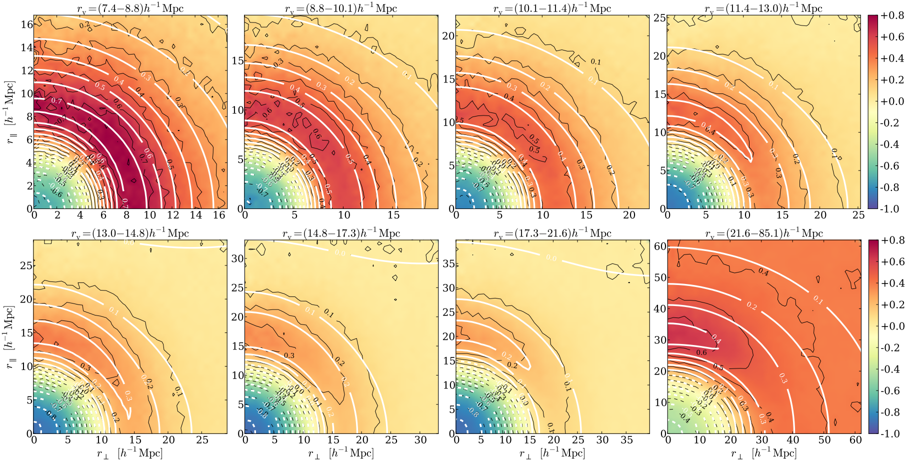
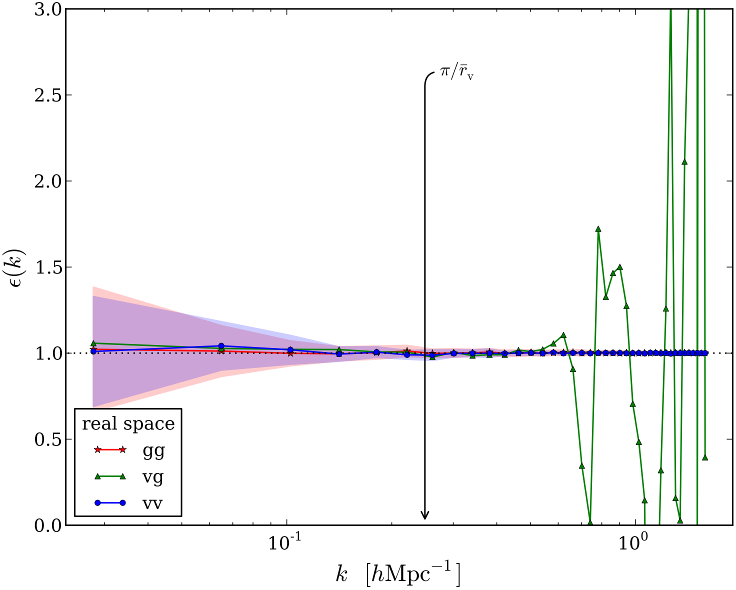
- Further improvements possible with SDSS DR12 CMASS & LOWZ samples.
- Possibility to combine with void lensing (e.g. DES, see arXiv:1605.03982) and void BAO (arXiv:1511.04405).

Questions ? Thank you !

RSD analysis: SDSS MAIN mocks



Alcock-Paczynski test



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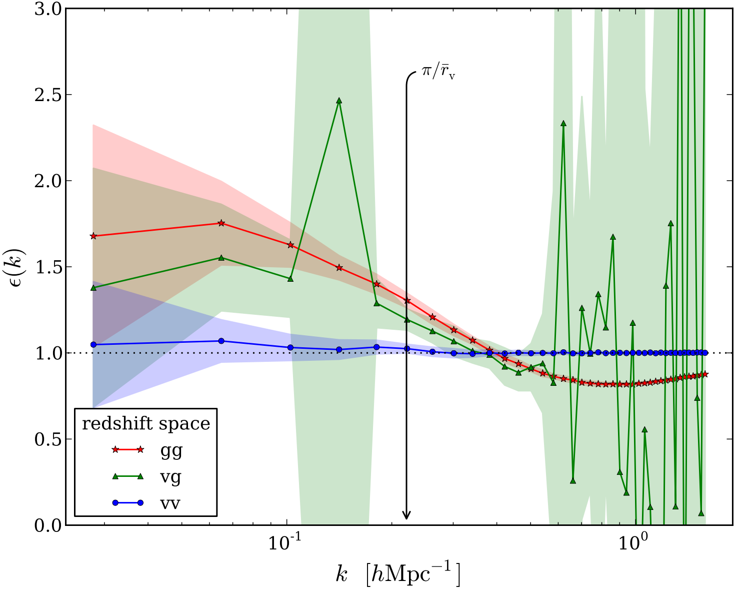

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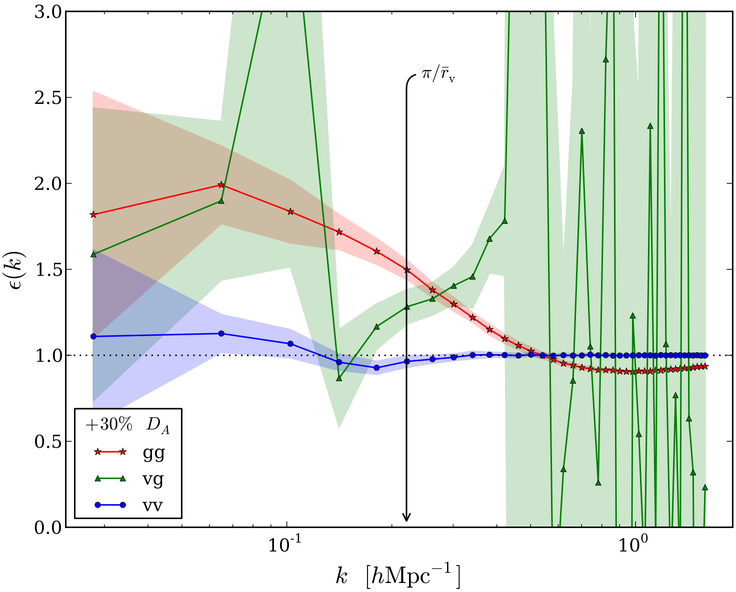

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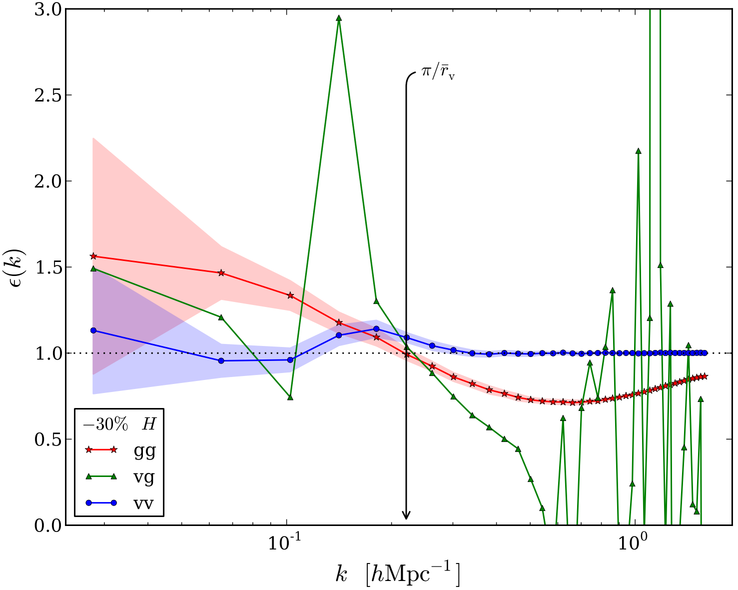

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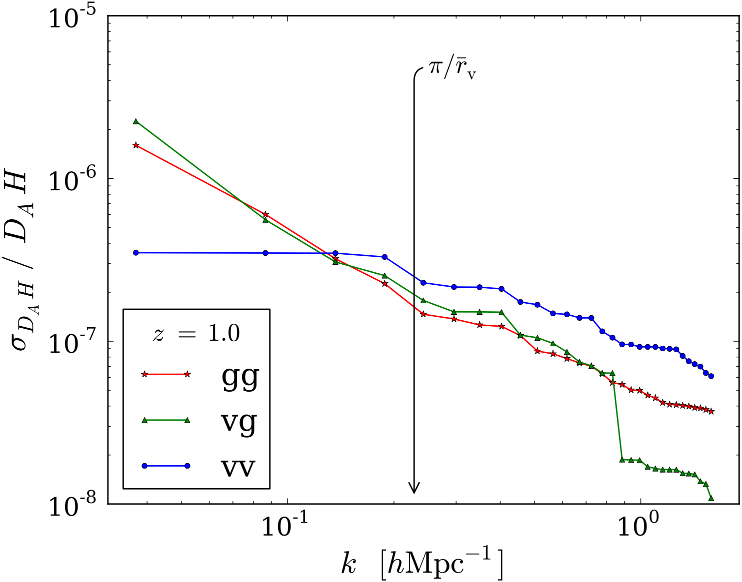
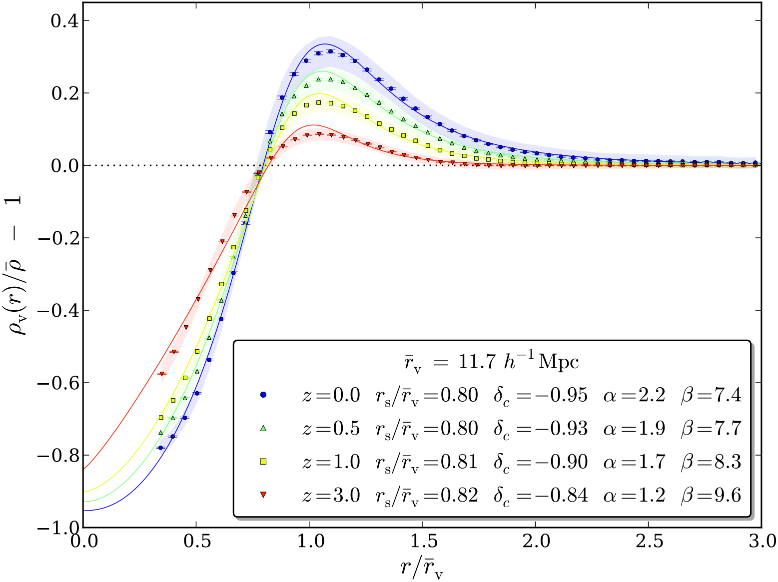


Void profile: universality



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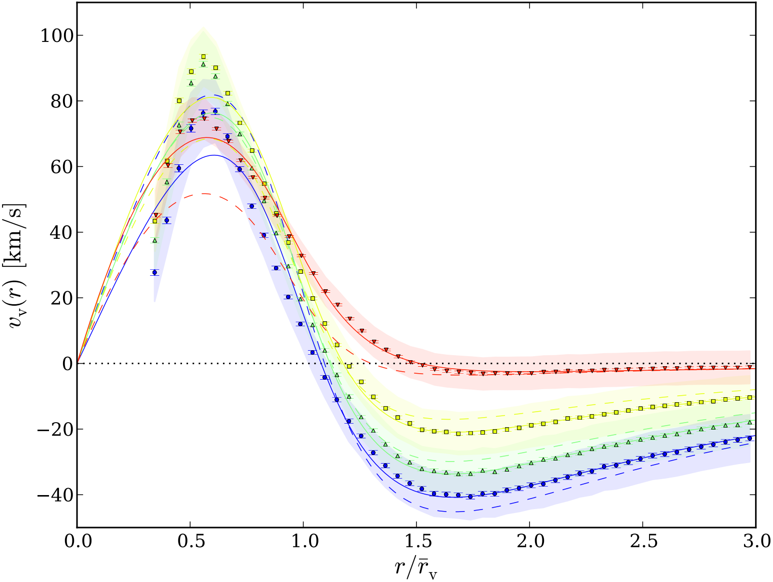

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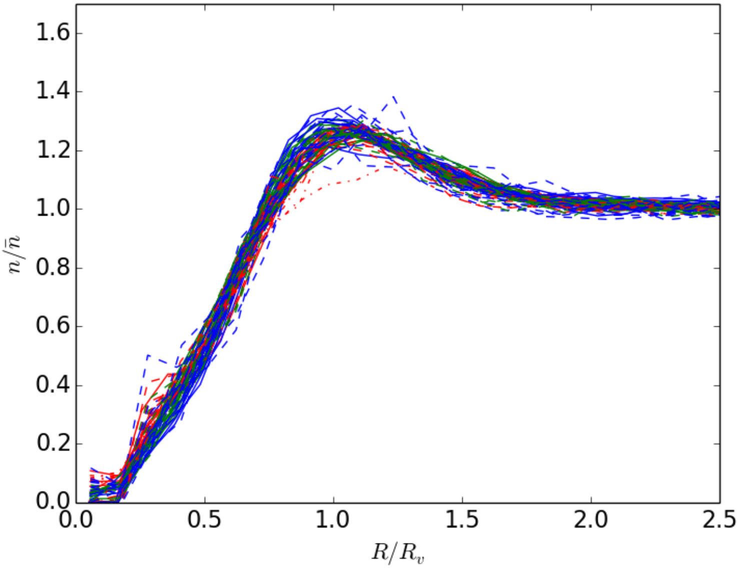
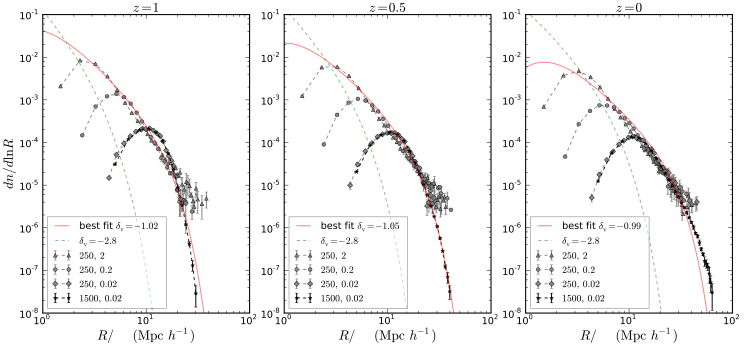
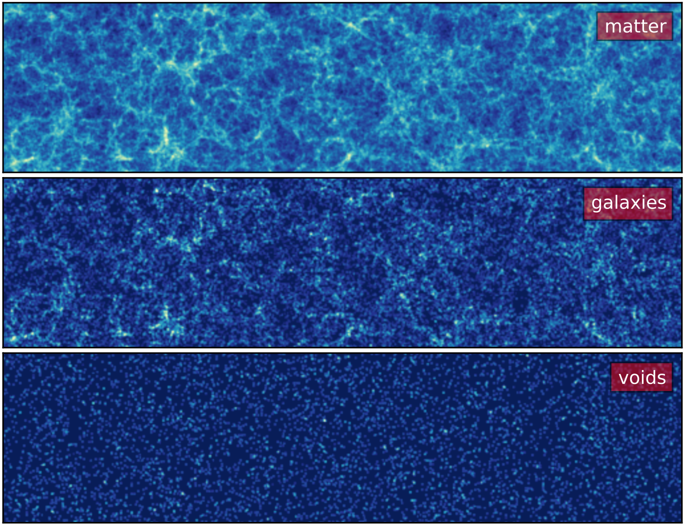


Void abundance

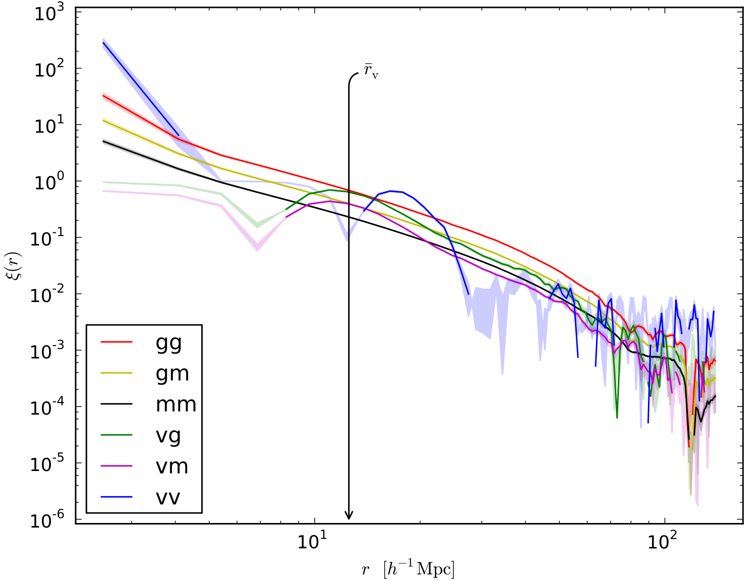


Density fields

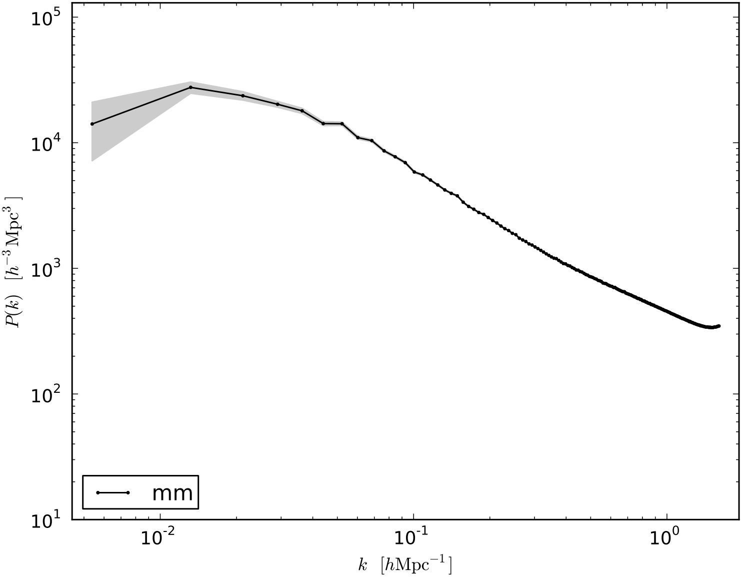
Voids are less clustered and more sparse than galaxies:



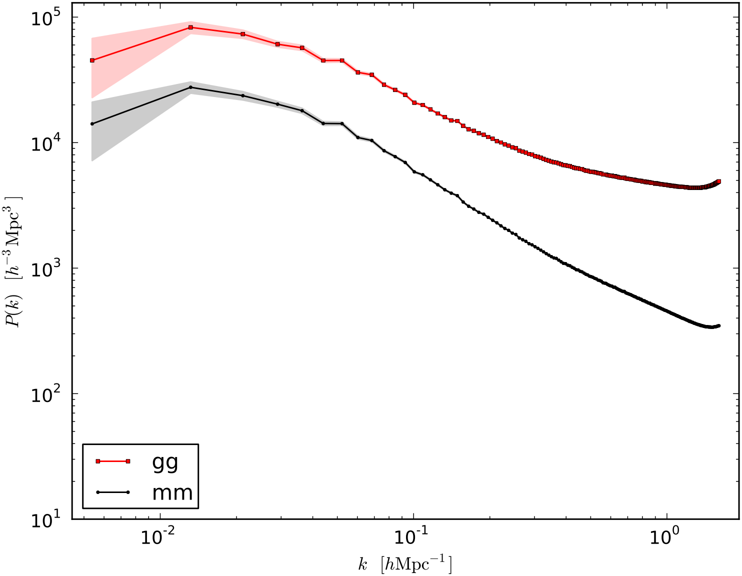
CORRELATION FUNCTION



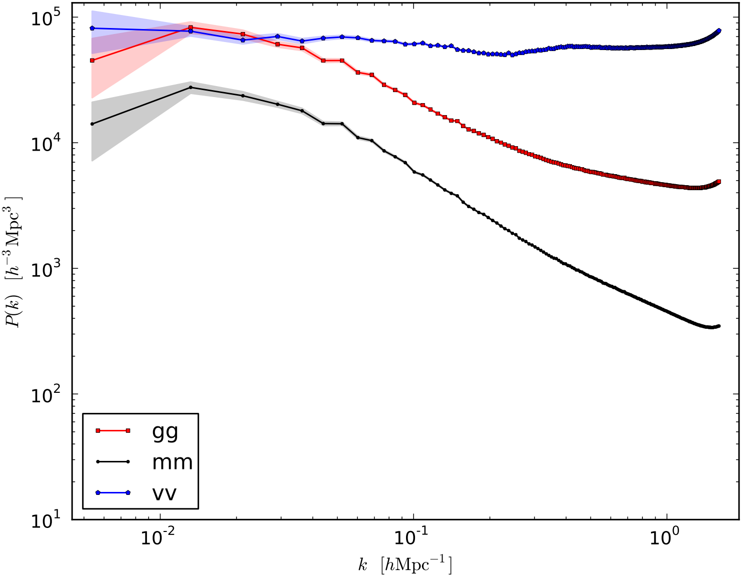
Power spectrum



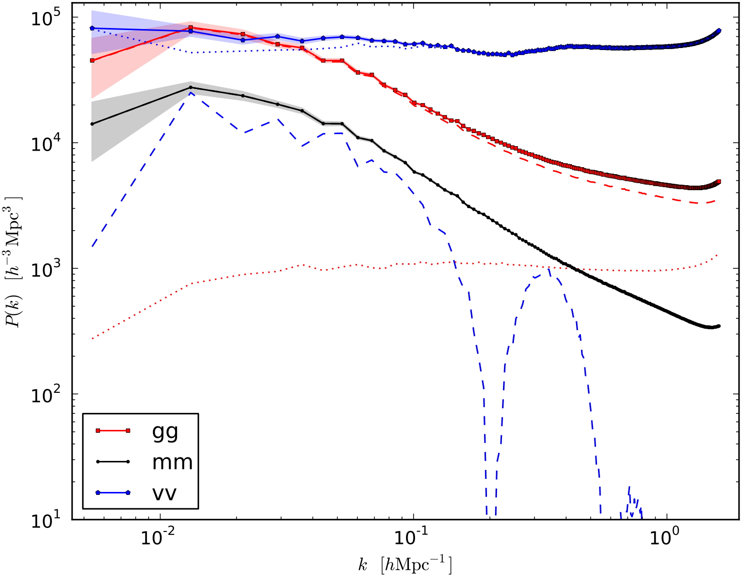
POWER SPECTRUM



POWER SPECTRUM



Power spectrum



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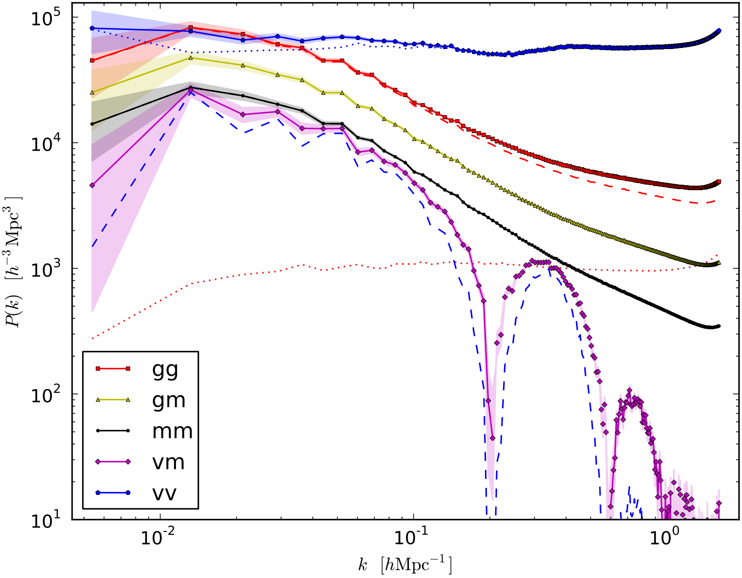
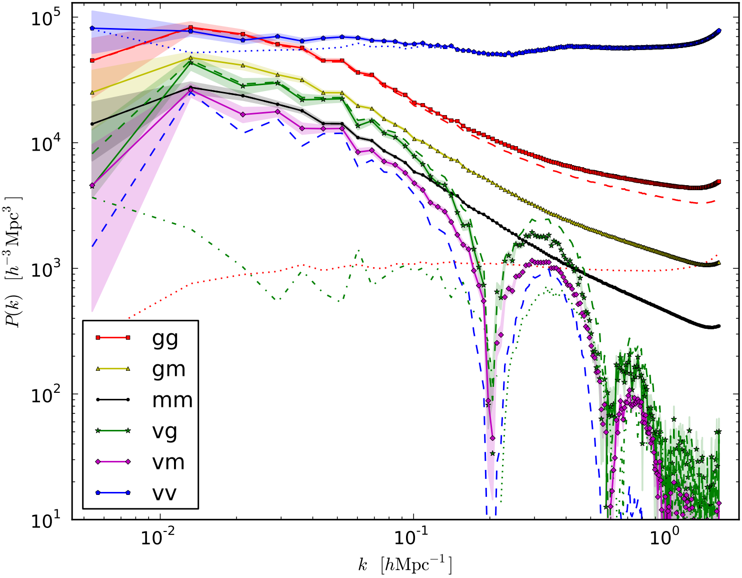
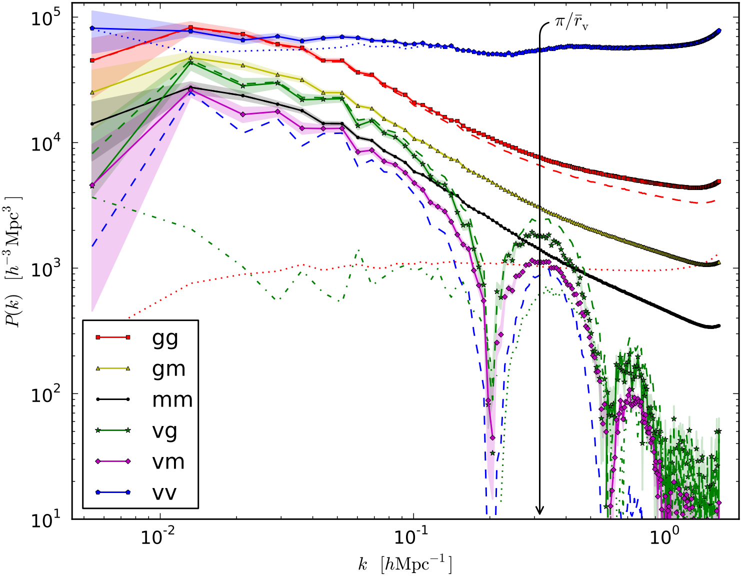


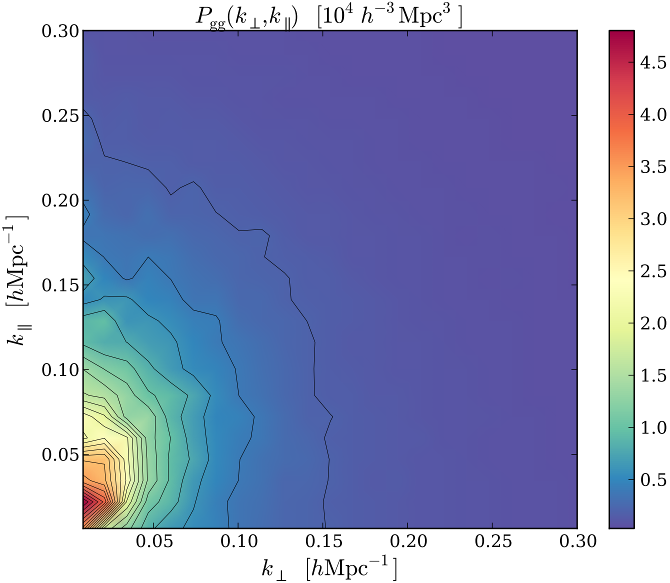
Power spectrum



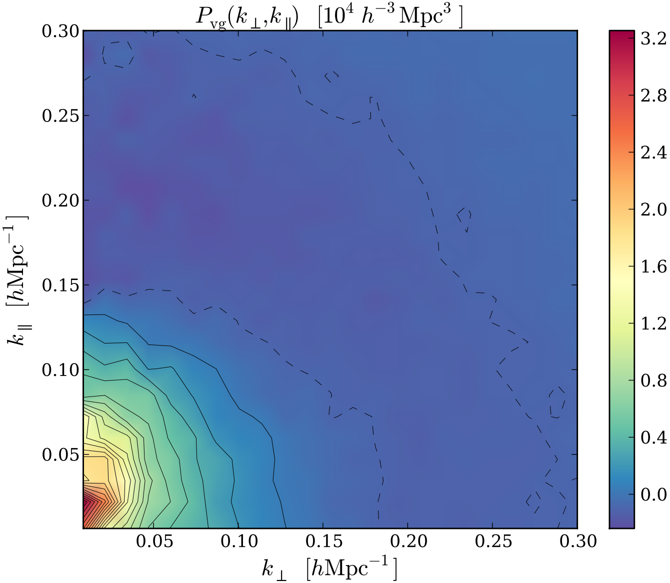
Power spectrum



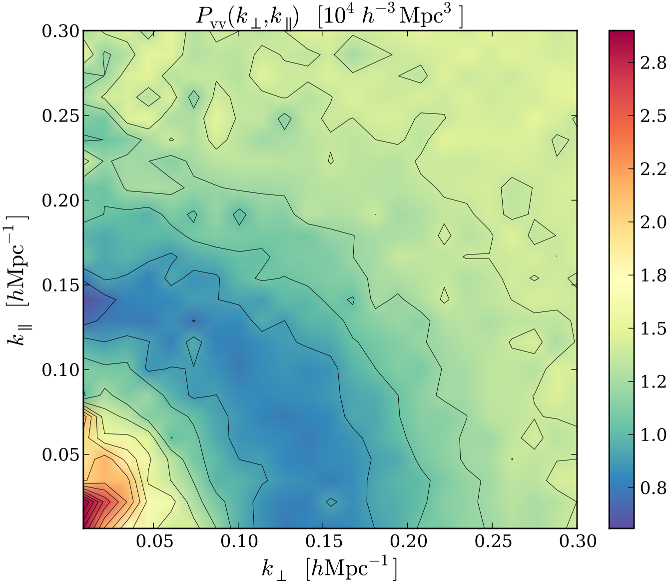
2D POWER SPECTRUM



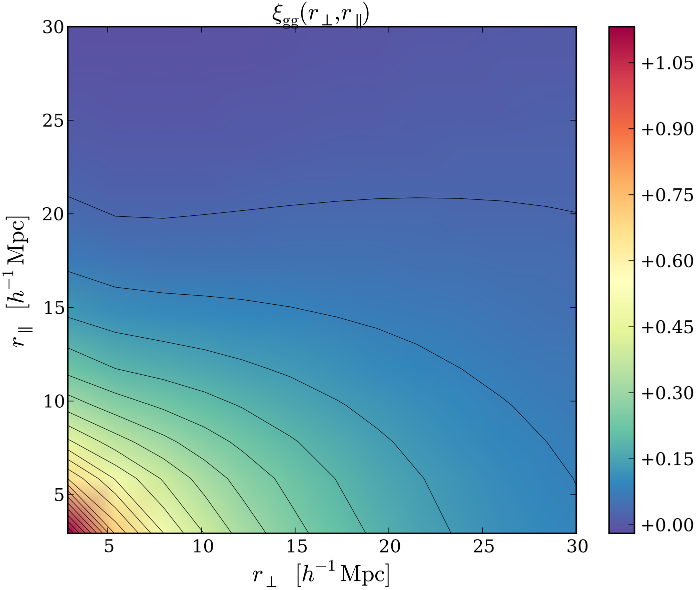
2D power spectrum



2D power spectrum



2D correlation function



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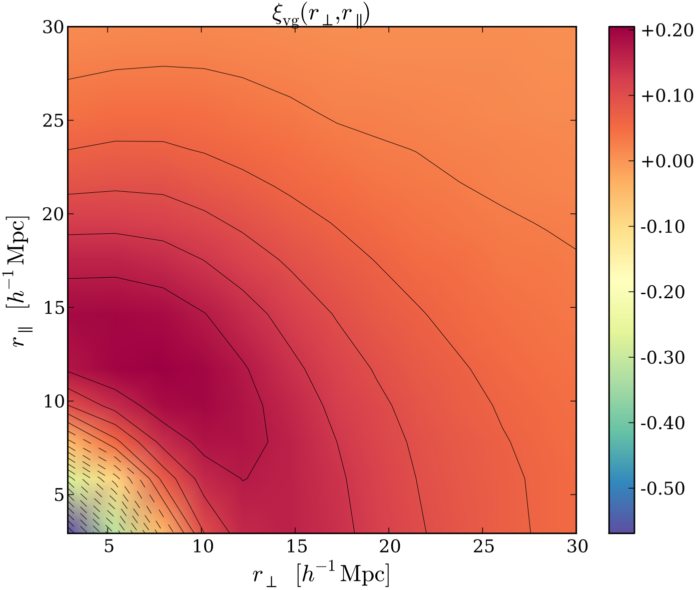
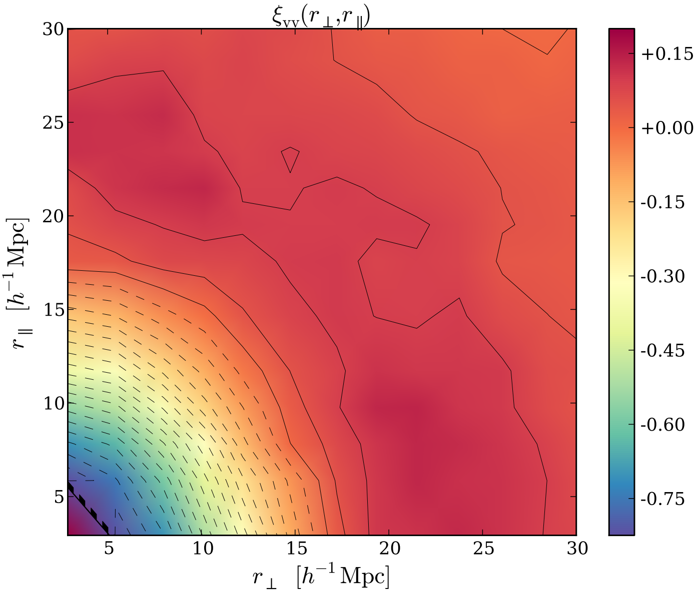
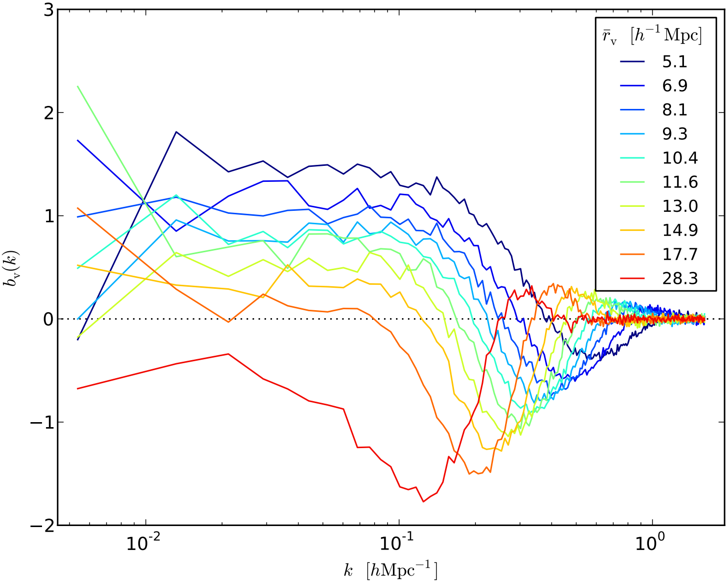


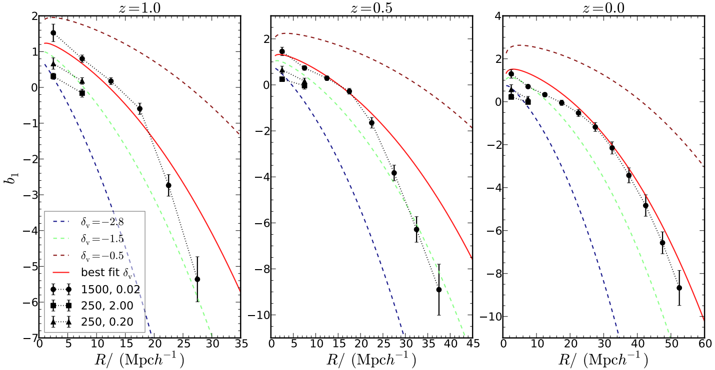
2D correlation function



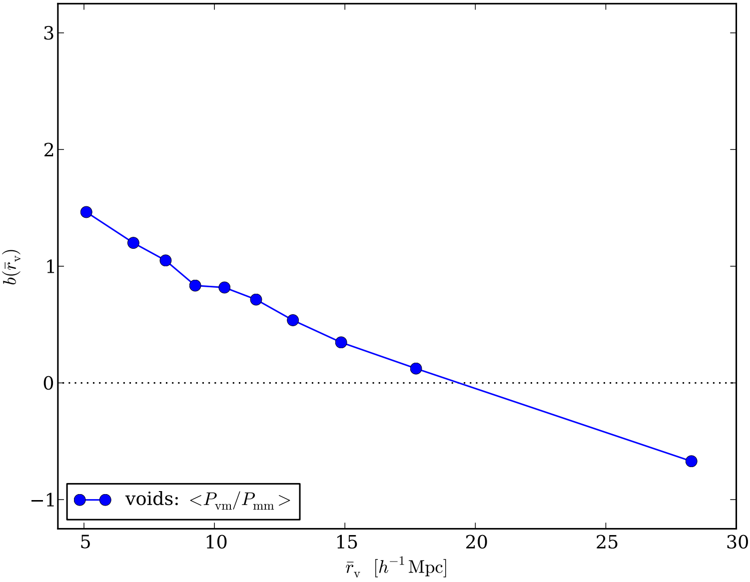
Void bias


$\bar{r}_v$ $[h^{-1}\,\mathrm{Mpc}]$
5.1
6.9
8.1
9.3
10.4
11.6
13.0
14.9
17.7
28.3
$b_v(k)$
k $[h\mathrm{Mpc}^{-1}]$
3
2
1
0
−1
−2
10^{-2}
10^{-1}
10^{0}

Linear void bias



Linear void bias



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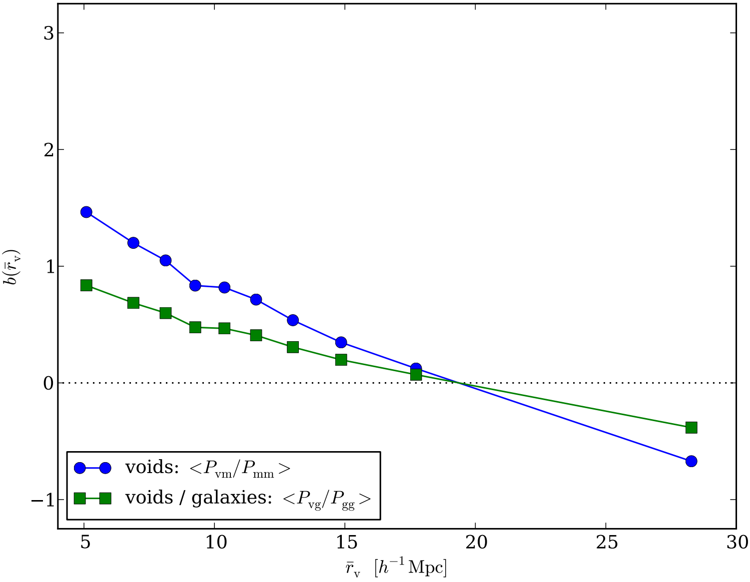
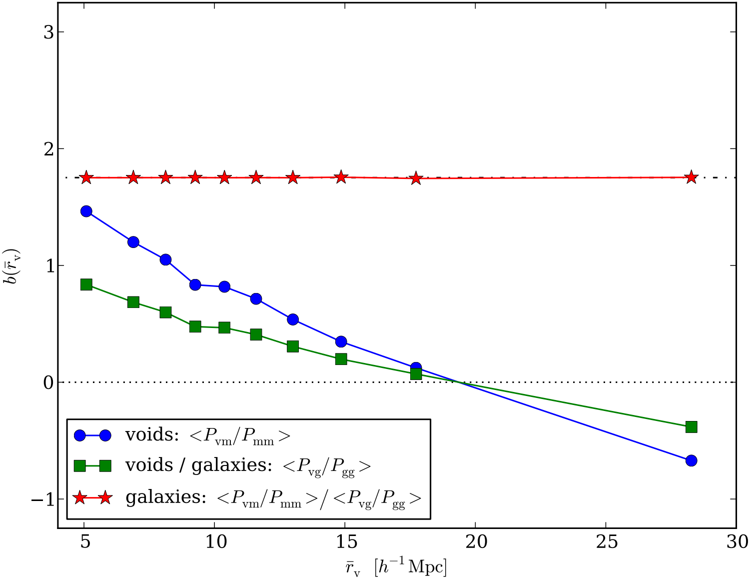
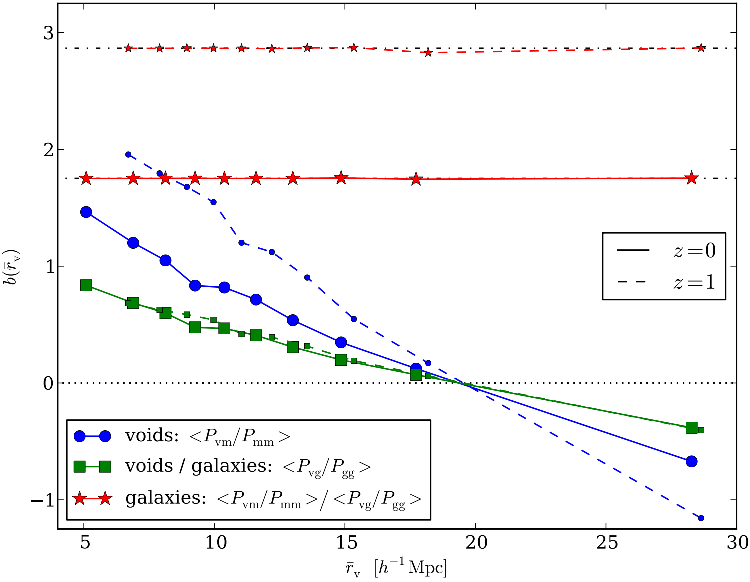


Linear void bias



LINEAR VOID BIAS



Linear void bias