A Unique Composition of Emptiness

Cosmic Voids as Cosmological Probes

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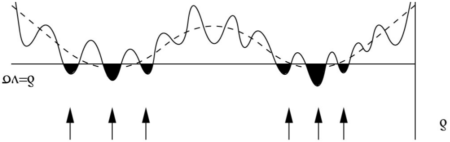
in collaboration with

Guilhem Lavaux, Alice Pisani, Paul Sutter, Benjamin Wandelt

Theoretical and Observational Progress on LSS of the Universe — ESO, Garching, July 23, 2015

DEFINITION OF VOIDS

Search for local minima in density field



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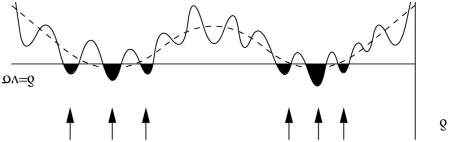
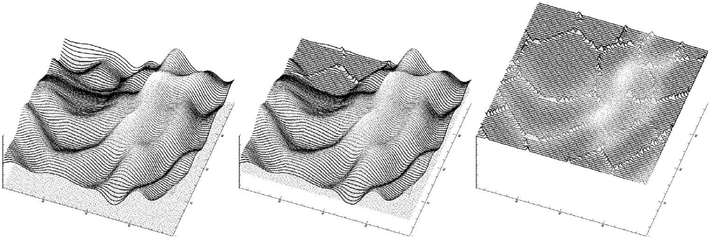
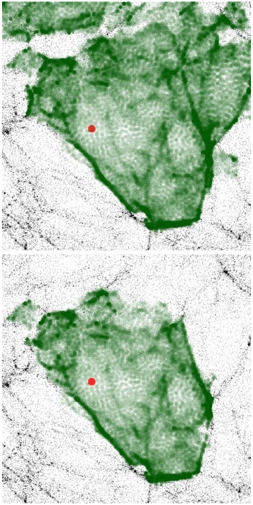


and raise a density threshold until a ridge is reached

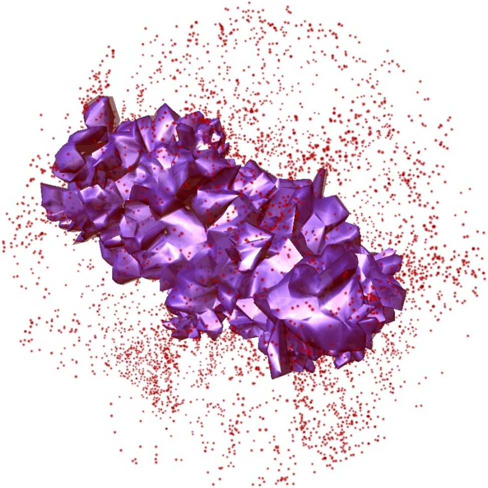


Watershed algorithm, Platen et al. (2007)

Definition of voids

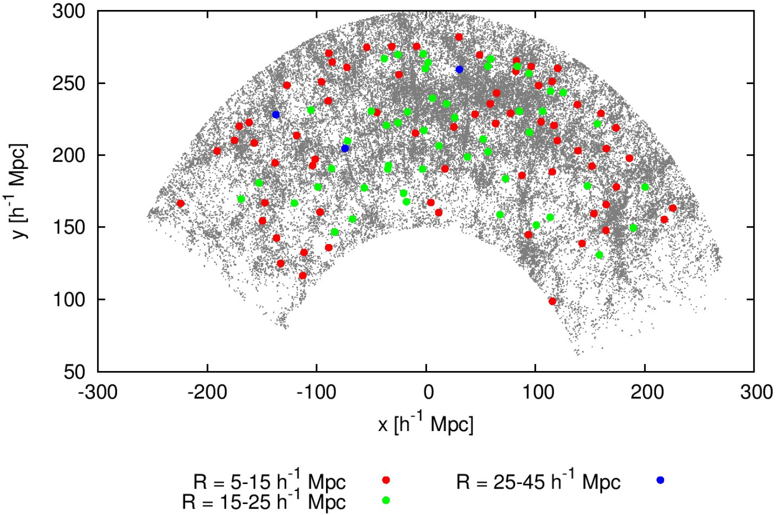


Zobov: Neyrinck (2008)



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

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

$$v_{\mathrm{v}}(r) = \frac{1}{N(r)} \sum_i \boldsymbol{v}_i(\boldsymbol{r}_i) \cdot \frac{\boldsymbol{r}_i}{r_i}$$

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With linear theory

$$v_{\rm v}(r) = -\frac{1}{3}\frac{f(z)H(z)}{1+z} r\Delta_{\rm v}(r)$$

where $f(z) = \Omega_{\rm m}^{0.55}(z)\ ,$ $\Delta_{\rm v}(r) = \frac{3}{r^3}\int_0^r\left(\frac{\rho_{\rm v}(q)}{\bar\rho} - 1\right) q^2{\rm d}q$

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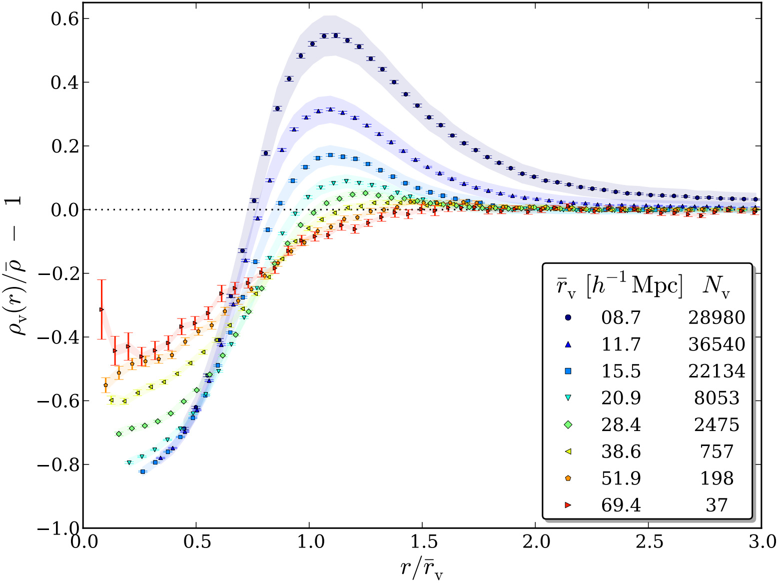
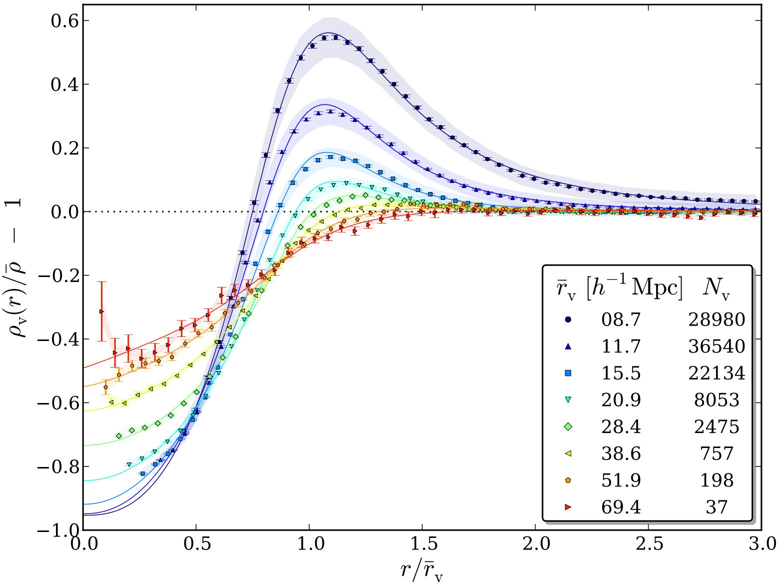
Empirical best-fit model (4 parameters)

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

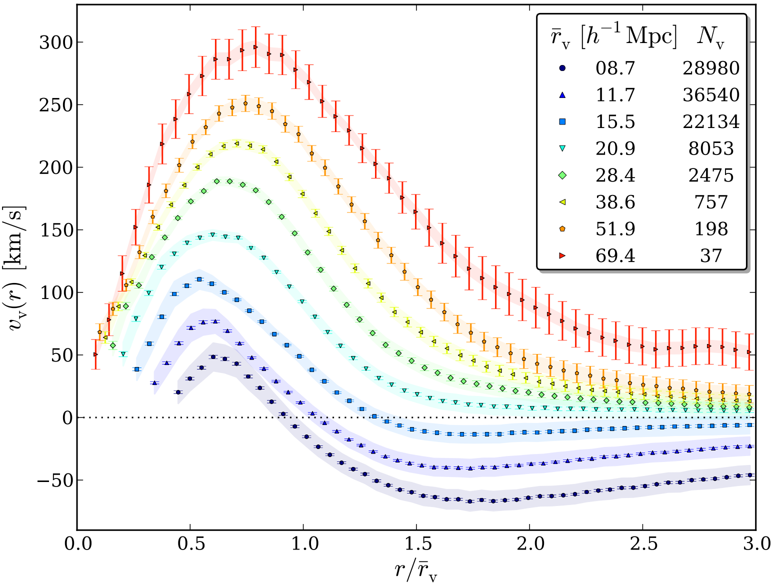
VOID PROFILE: DENSITY



Void profile: density



Void profile: velocity



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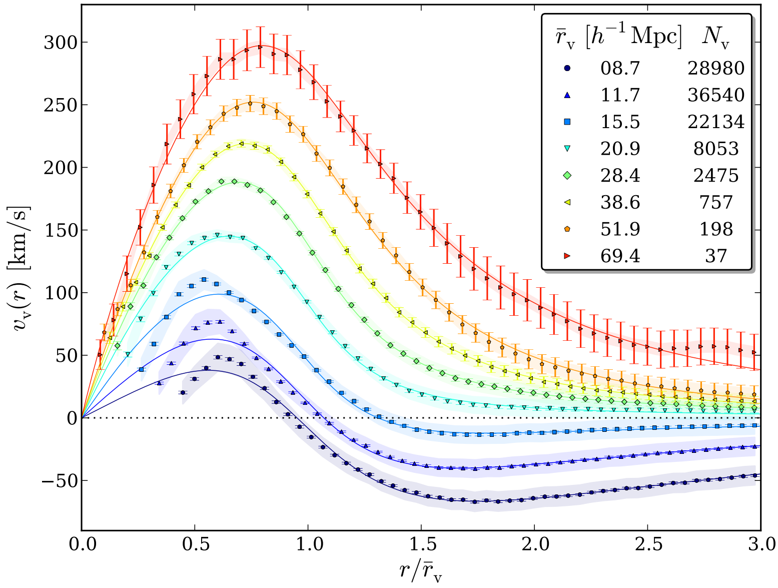
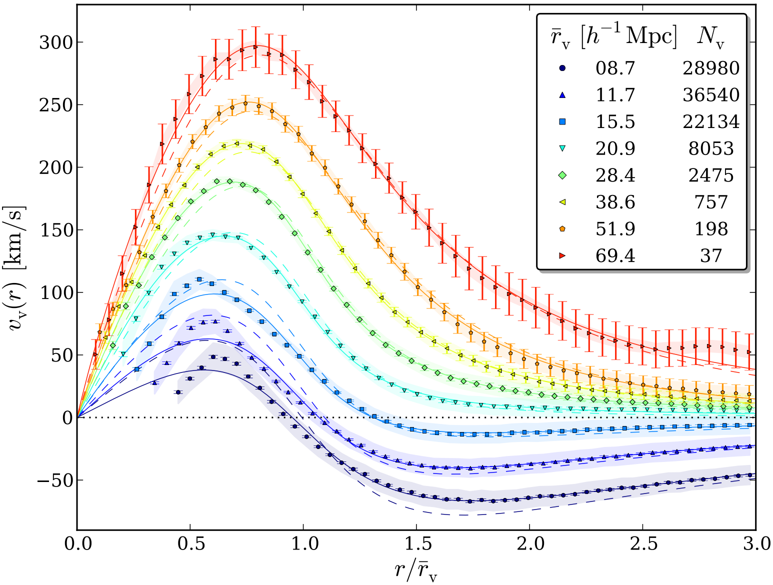


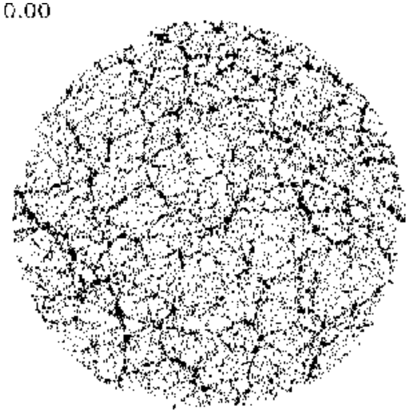
VOID PROFILE: VELOCITY



VOIDS IN REDSHIFT SPACE

Peculiar motions of galaxies cause redshift-space distortions:

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



Melott et al. (1998)

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

MODEL

Void-galaxy cross-correlation function in redshift space:

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

MODEL

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

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

and with velocity dispersion

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

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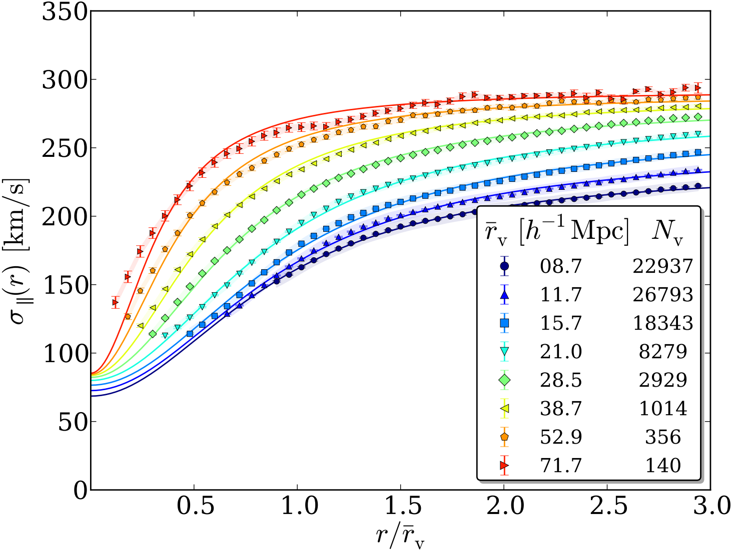
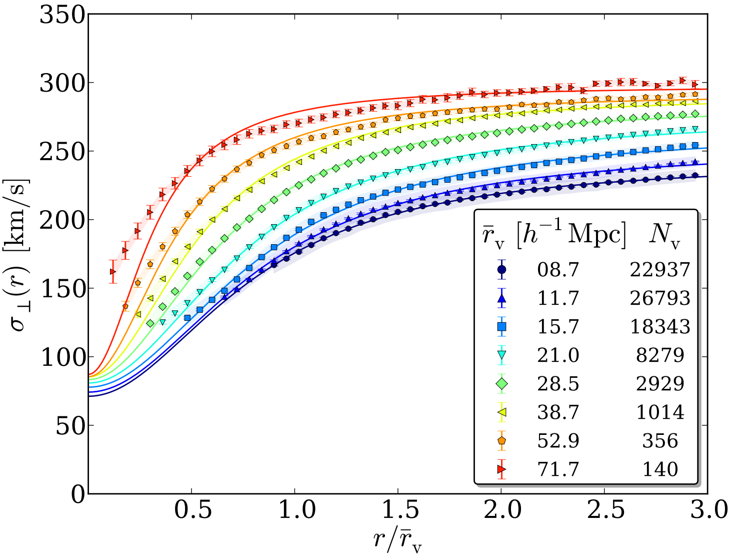
Model:

$$\sigma_{\parallel,\perp}(r) = \sigma_v\left(1-\frac{1/\sqrt{2}}{1+r^2/\omega^2}\right)$$

VELOCITY DISPERSION



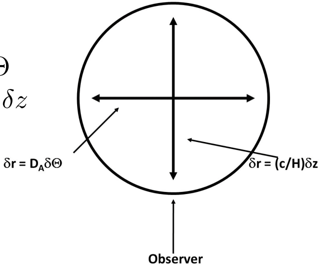
Velocity dispersion



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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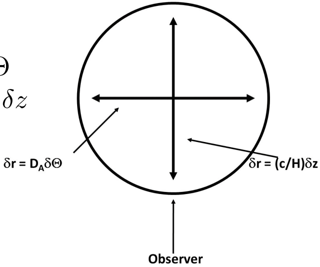


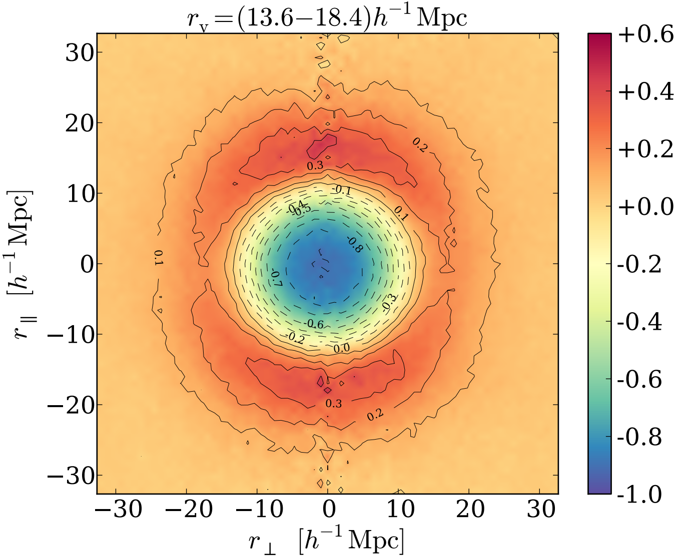
Angular diameter distance & Hubble rate (assumed values)

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

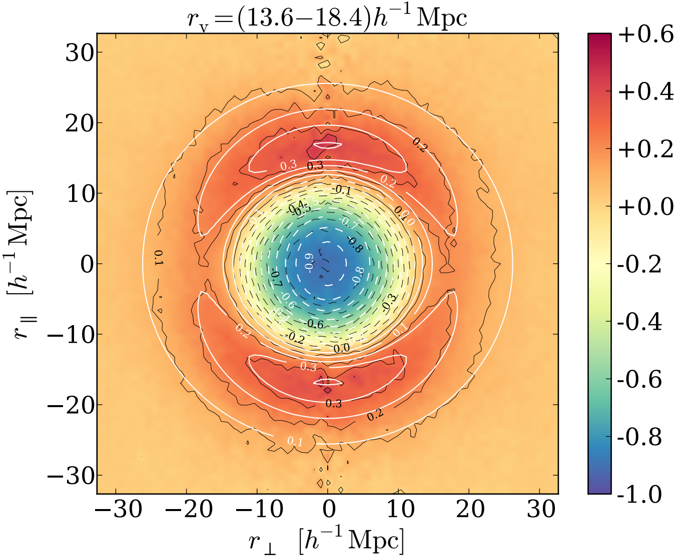
Any deviation from the fiducial cosmology causes geometric distortions. $\Rightarrow$ Determine ellipticity ε via

$$\frac{\delta r_\parallel}{\delta r_\perp} \propto \frac{\varepsilon}{D_A(z)H(z)}$$

RSD analysis: dense mock galaxies



RSD ANALYSIS: DENSE MOCK GALAXIES



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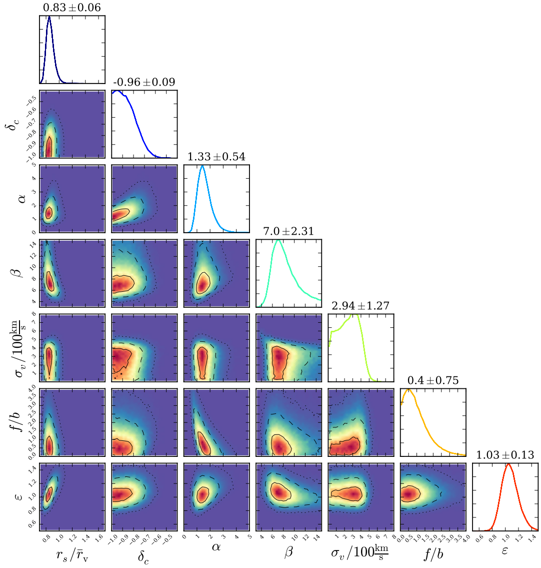
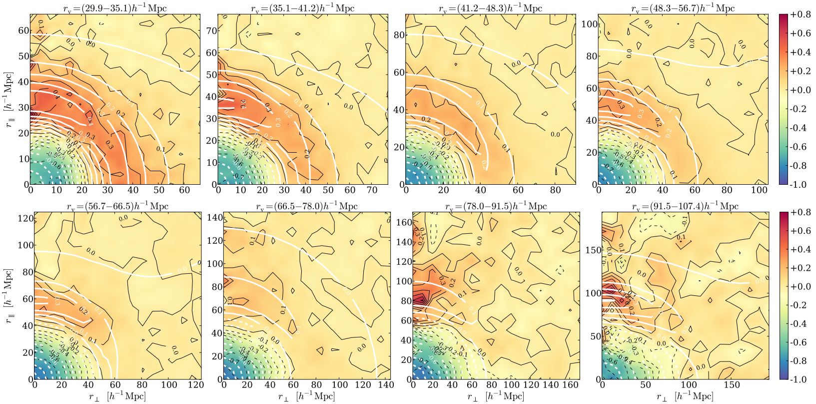


RSD ANALYSIS: SDSS CMASS MOCKS



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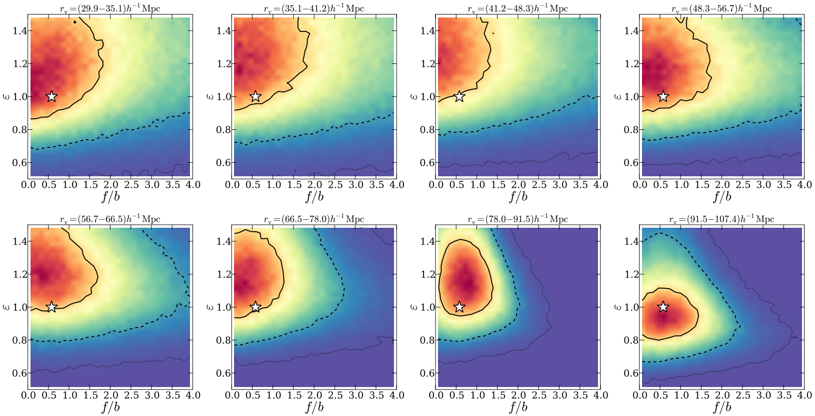
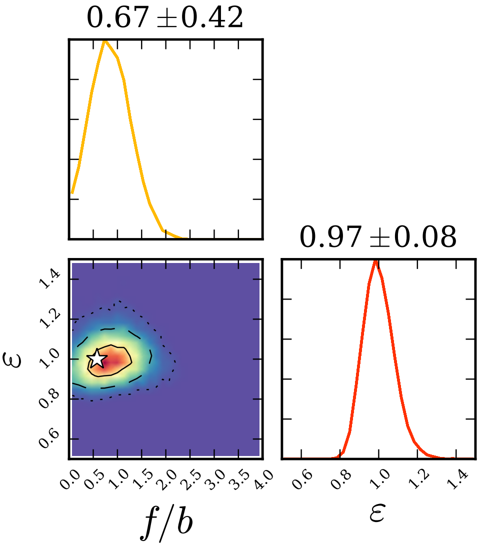


RSD ANALYSIS: SDSS CMASS MOCKS COMBINED



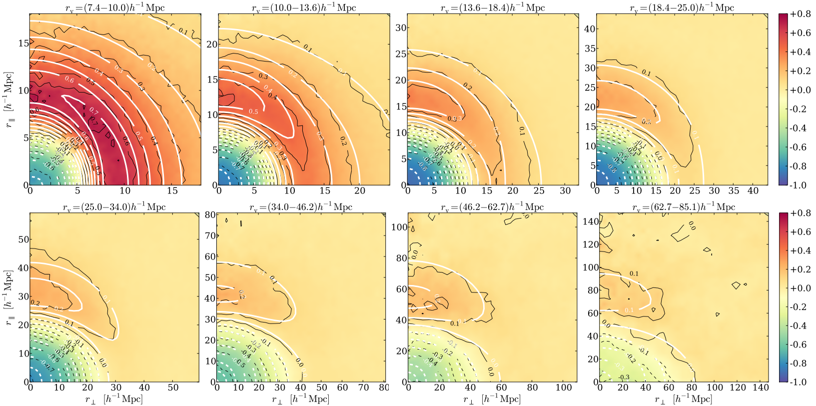
CONCLUSIONS

- The best-fit void density profile parameters $(r_s, \delta_c, \alpha, \beta)$ inferred from $\tilde{\xi}_{\mathrm{vg}}(\tilde{r}_\parallel, \tilde{r}_\perp)$ are consistent with the 1D-analysis of the real-space density profile $\rho_{\mathrm{v}}(r)$.
- Void density profile parameters $(r_s, \delta_c, \alpha, \beta)$ and cosmological parameters $(\sigma_v, f/b, \varepsilon)$ show no strong degeneracies, as they separately describe the isotropic / anisotropic part of $\tilde{\xi}_{\mathrm{vg}}(\tilde{r}_\parallel, \tilde{r}_\perp)$.
- Growth rate f/b and AP parameter ε do not depend on r_{v}. This allows to place joint constraints from the entire range of void sizes, yielding improvements by factors of a few.
- The low number of sparse galaxies at high redshift can be partly compensated by their higher galaxy bias to yield comparable constraints on f/b and ε.
- The relative uncertainties on f/b and ε achievable in a survey volume of $V = 1h^{-3}\mathrm{Gpc}^3$ range between $\sigma_{f/b}/(f/b) \sim 0.4 - 0.6$ and $\sigma_\varepsilon/\varepsilon = \sigma_{D_A H}/D_A H \sim 0.05 - 0.08$.

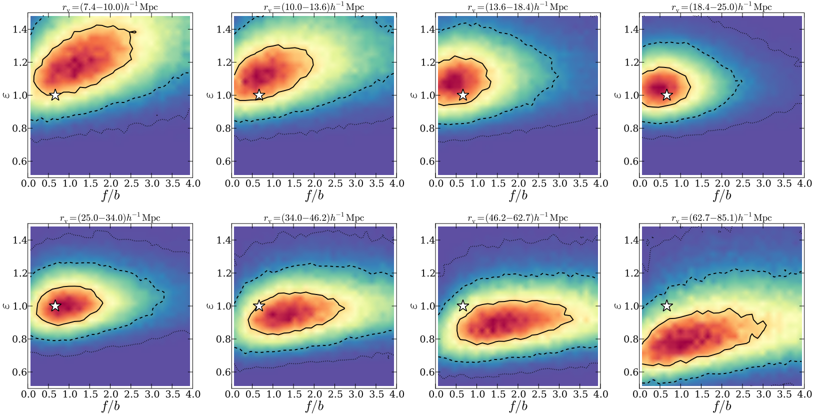
Questions ?

Thank you !

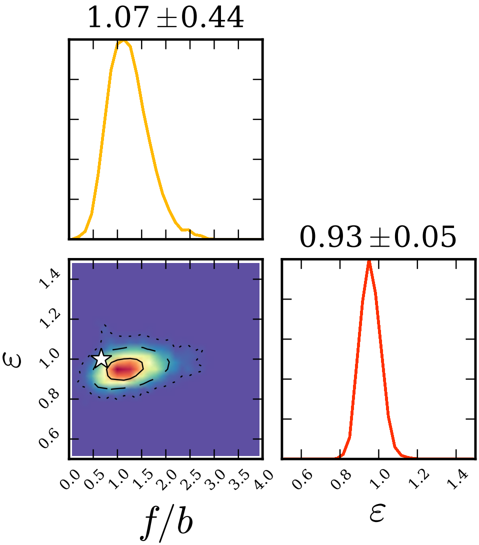
RSD ANALYSIS: SDSS MAIN MOCKS



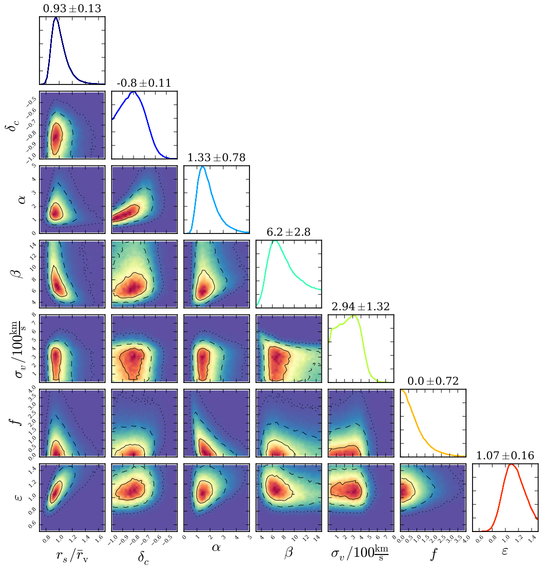
RSD ANALYSIS: SDSS MAIN MOCKS



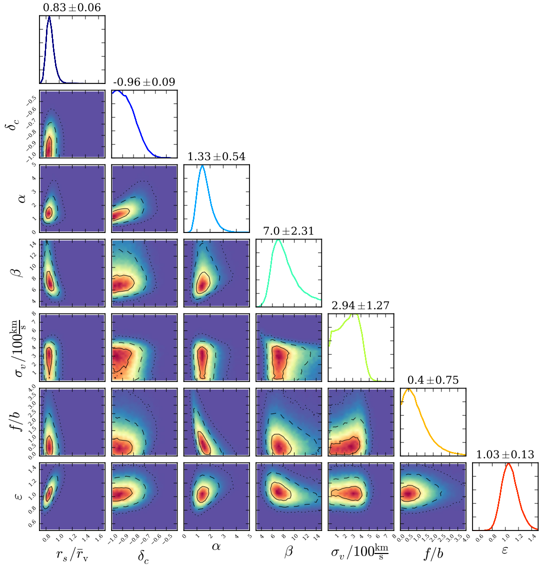
RSD analysis: SDSS MAIN mocks combined



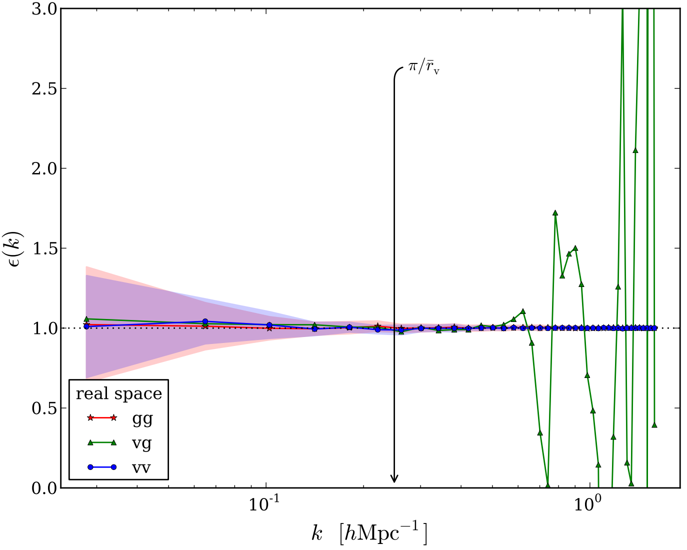
RSD analysis: dark matter vs. dense mocks



RSD ANALYSIS: DARK MATTER VS. DENSE MOCKS



Alcock-Paczynski test



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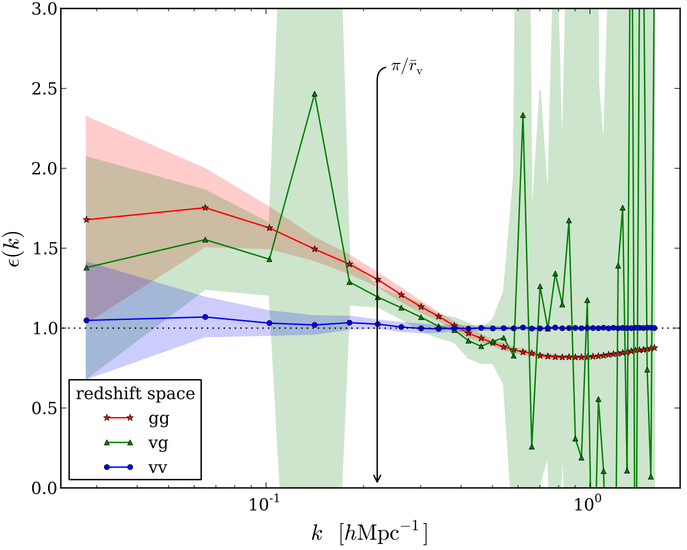

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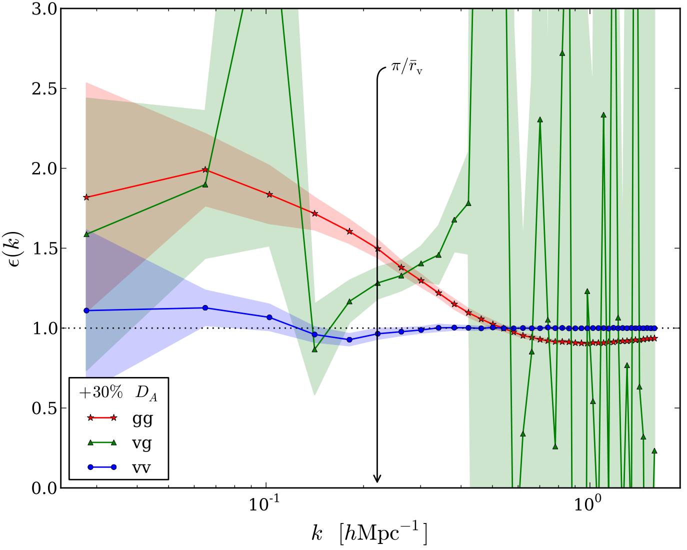

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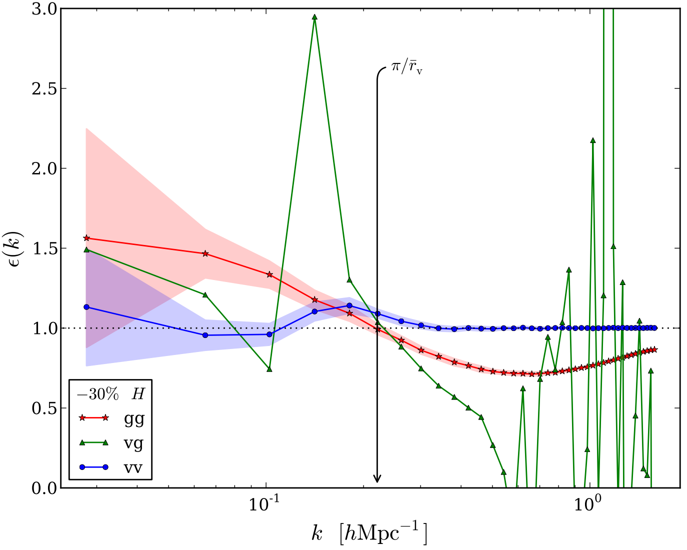

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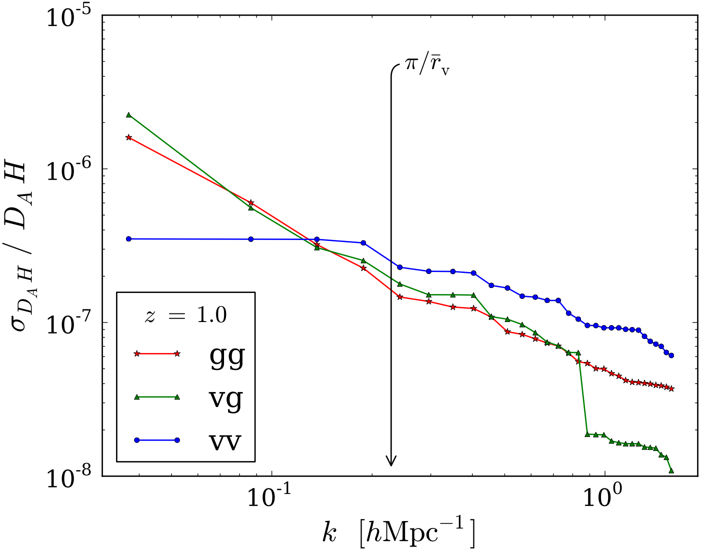
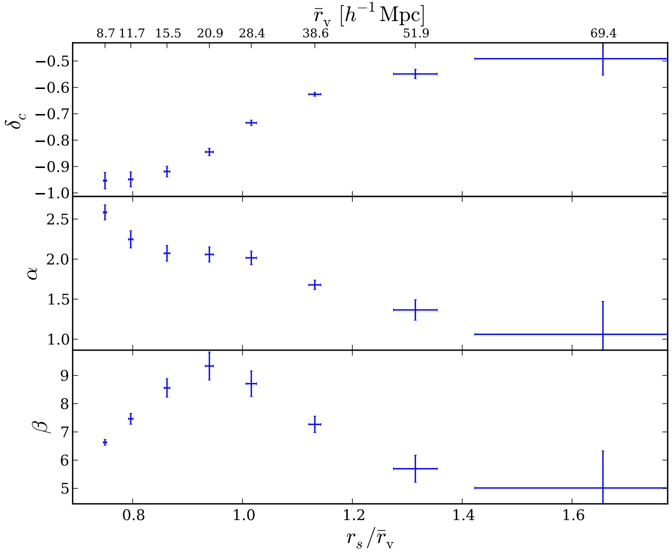


VOID PROFILE: PARAMETERS



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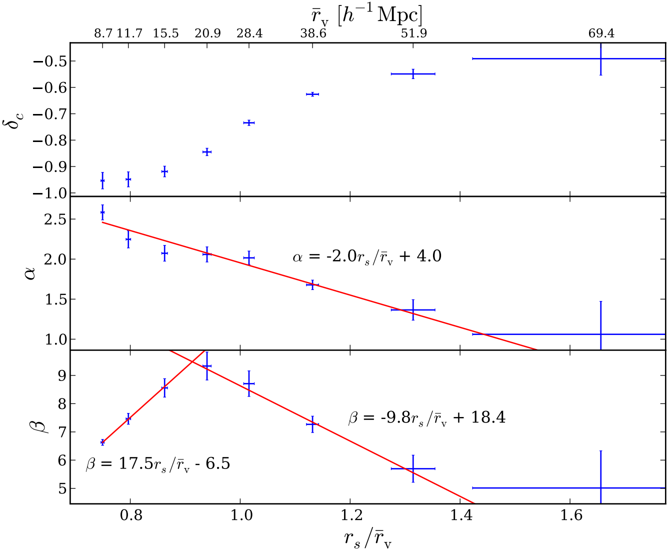

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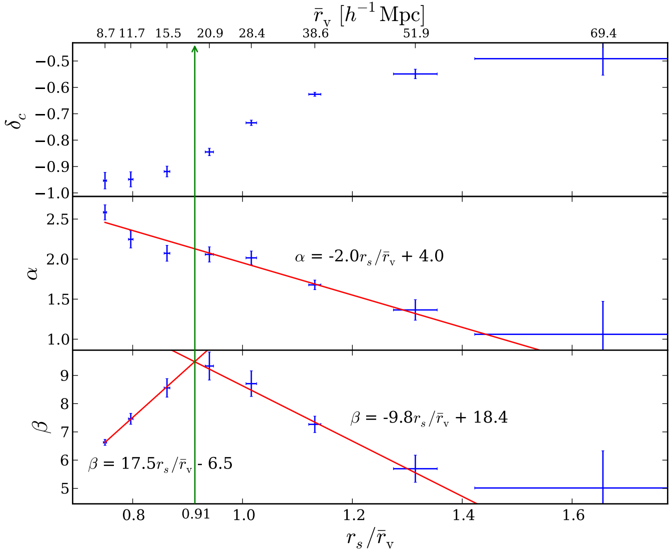
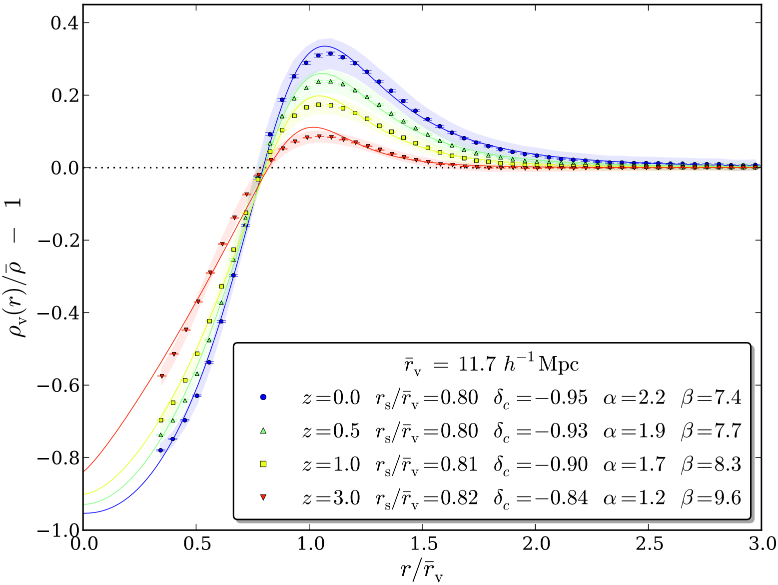
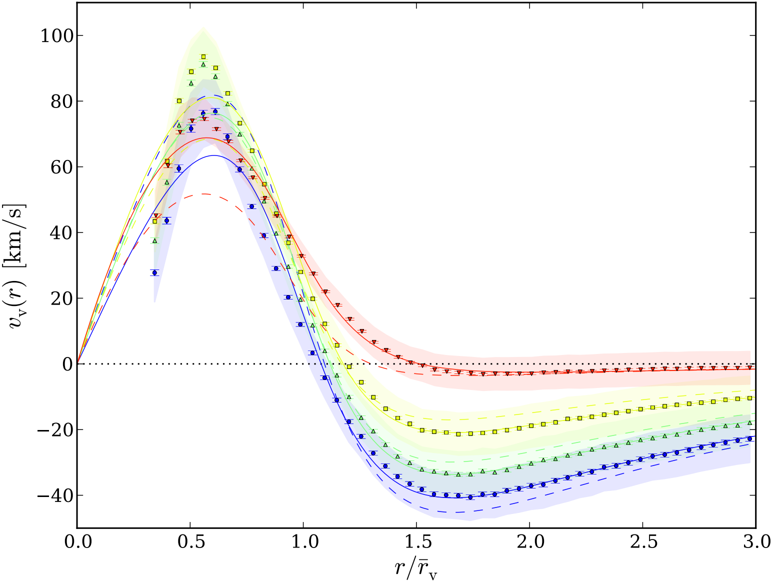


Void profile: universality



VOID PROFILE: UNIVERSALITY



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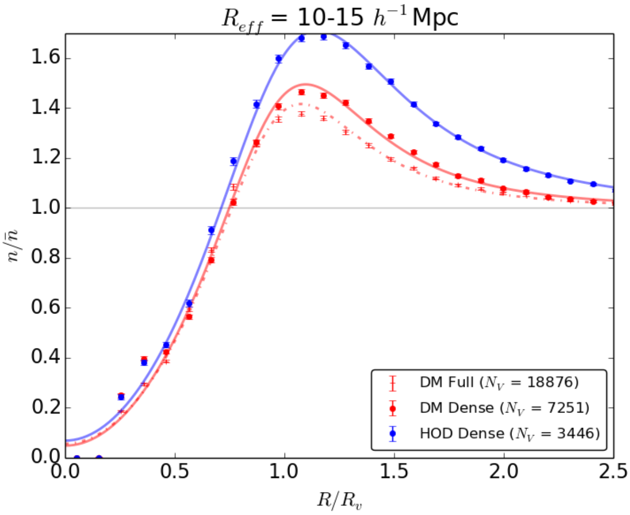

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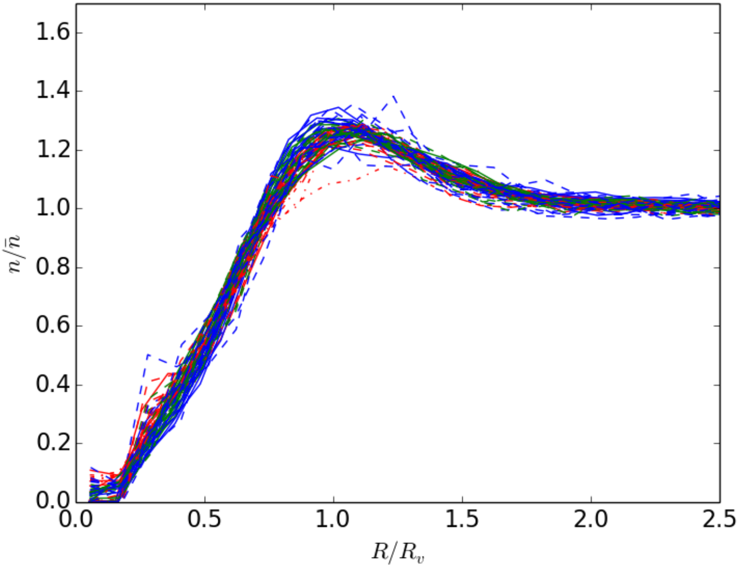
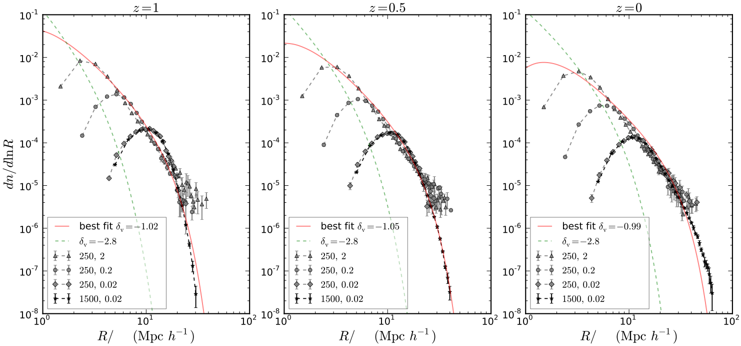
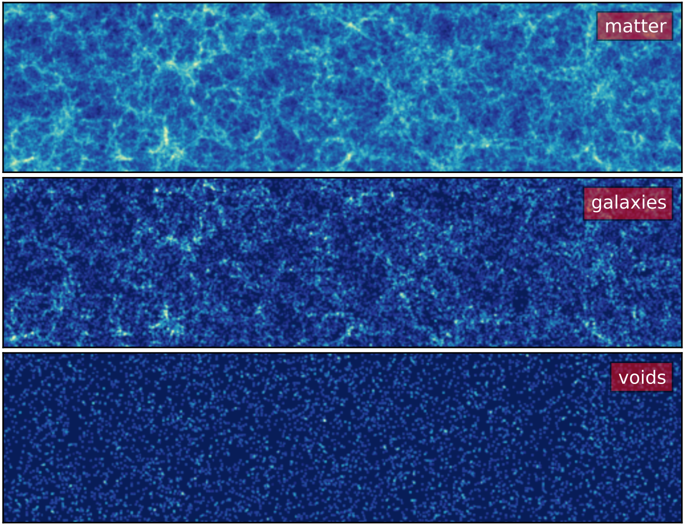


VOID ABUNDANCE

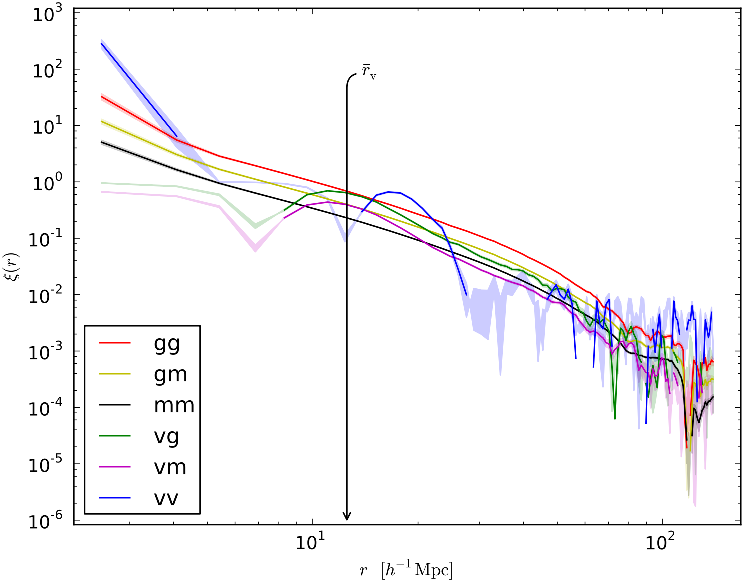


Density fields

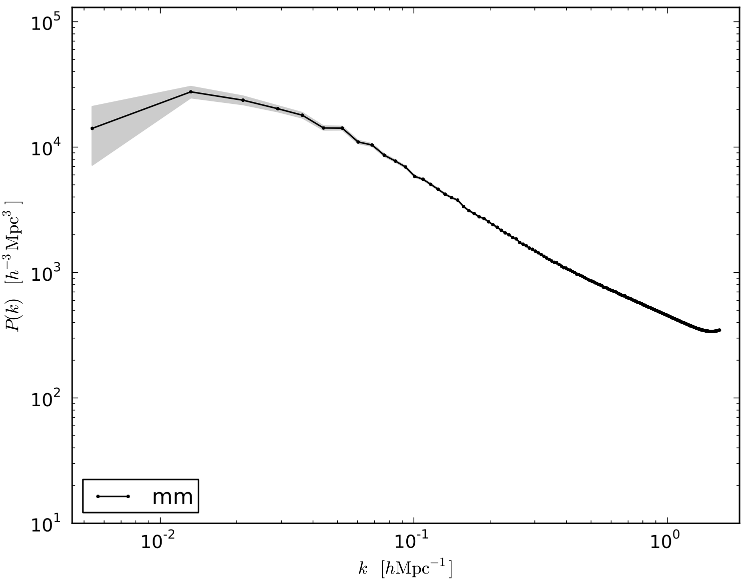
Voids are less clustered and more sparse than galaxies:



CORRELATION FUNCTION



POWER SPECTRUM



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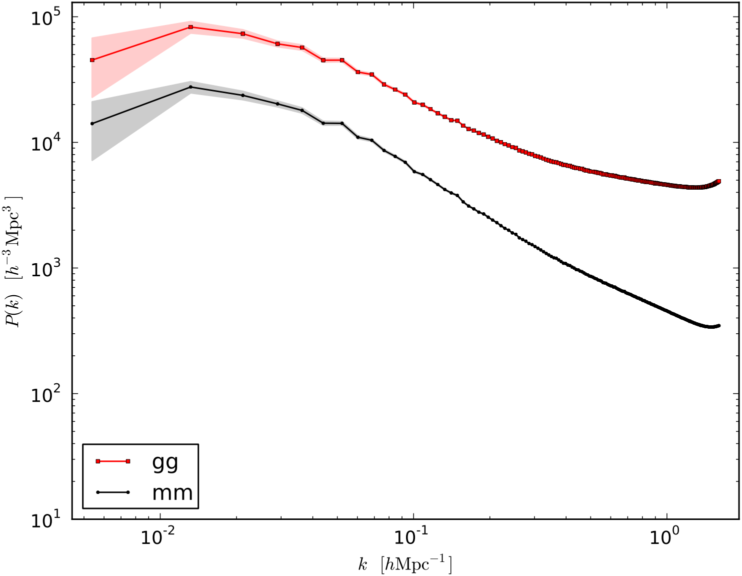
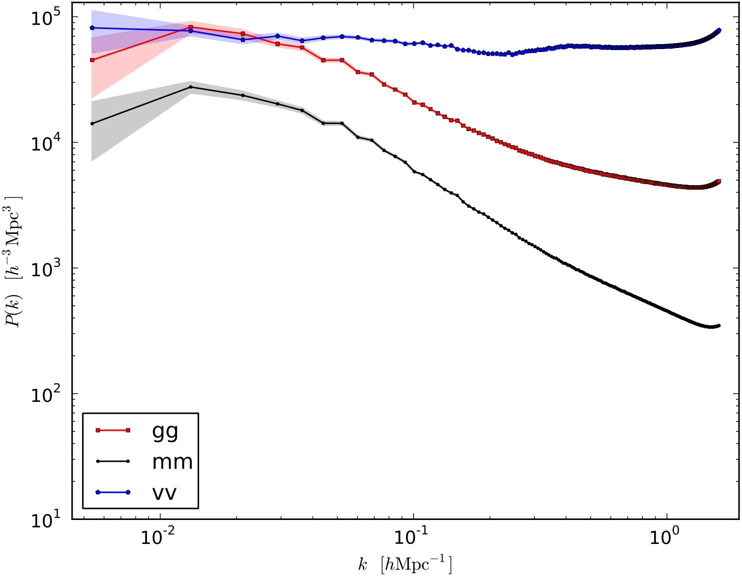


Power spectrum



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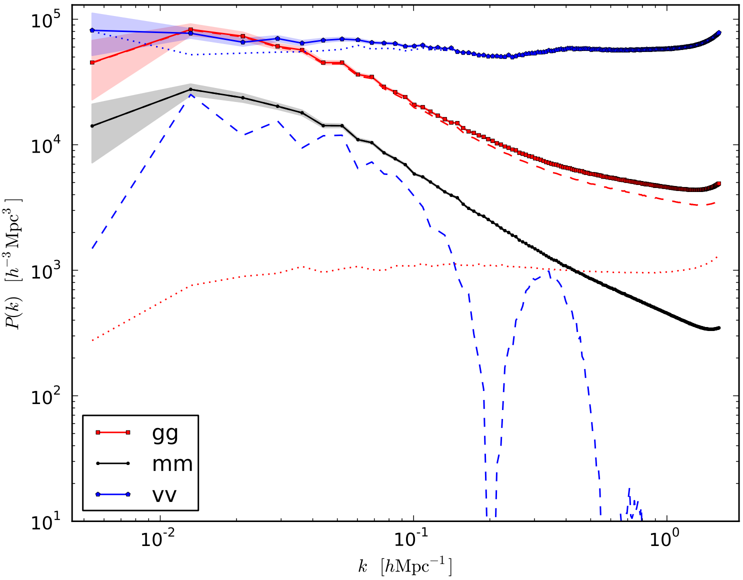

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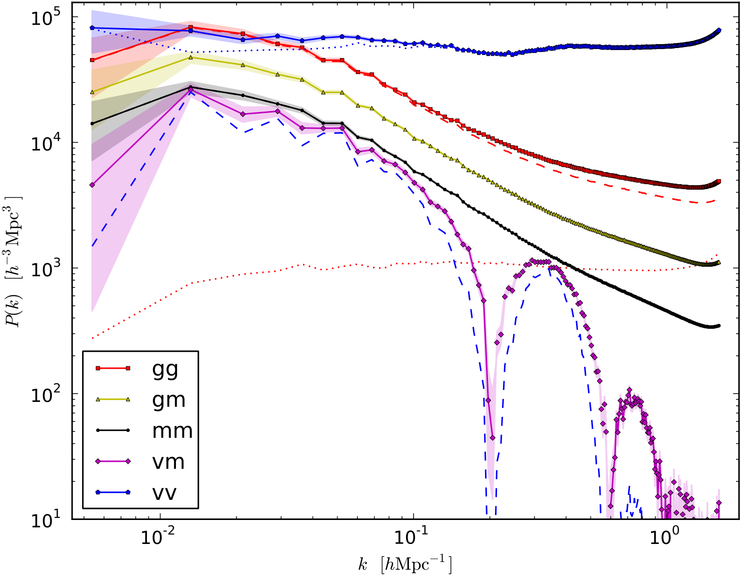

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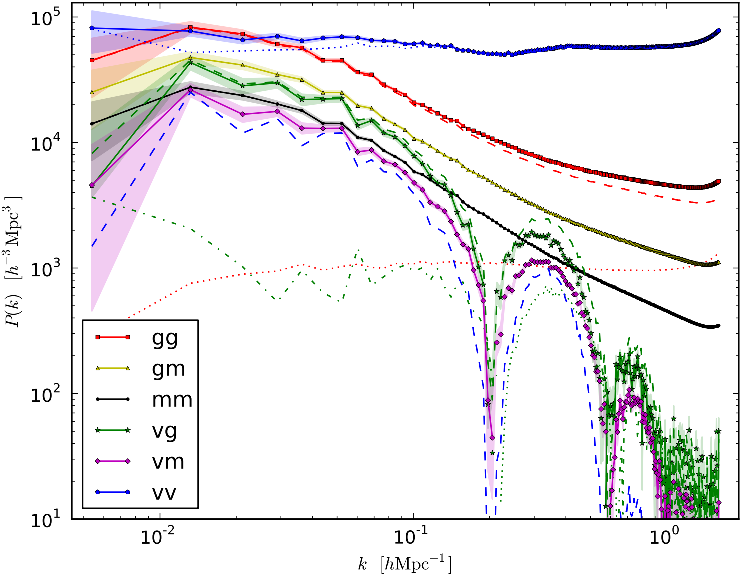

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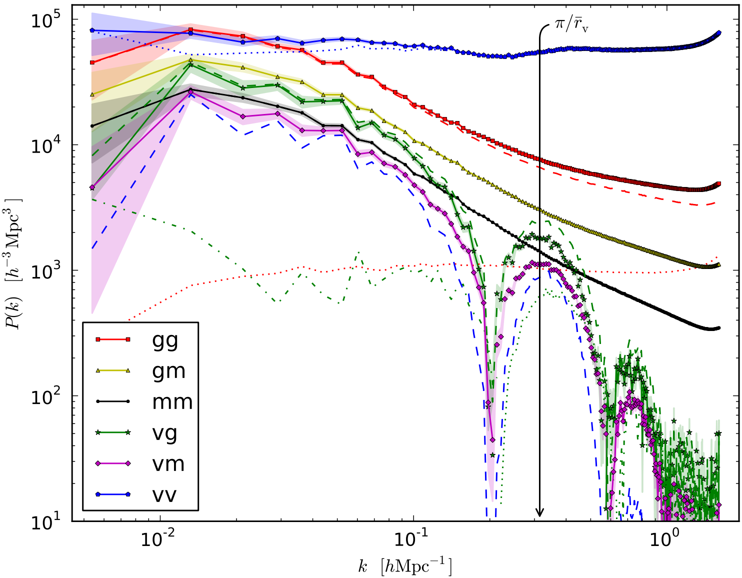
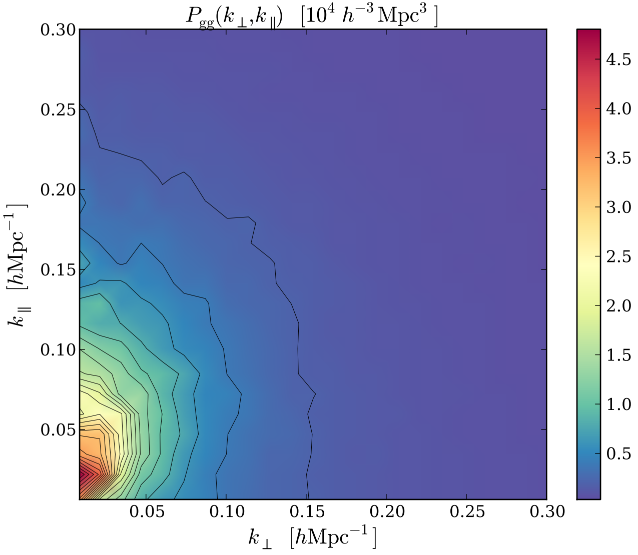
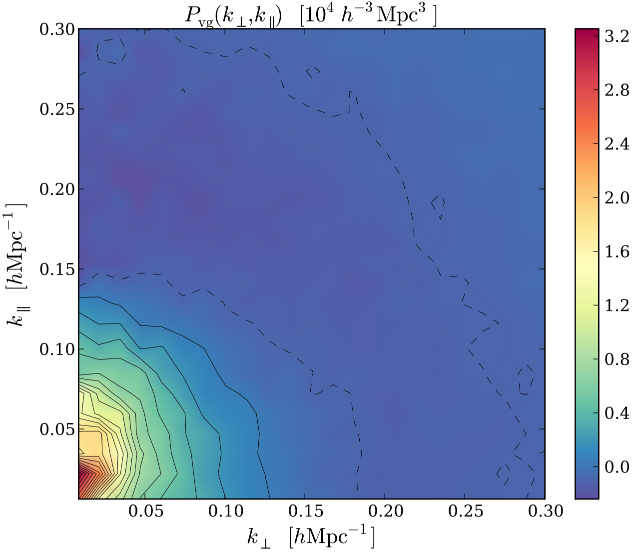


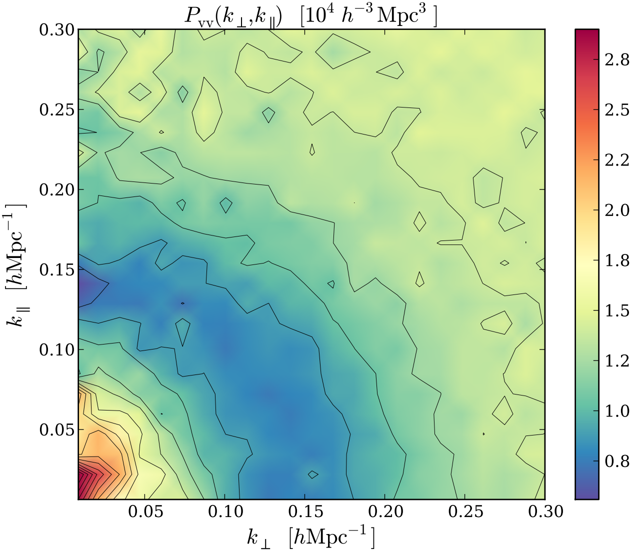
2D power spectrum



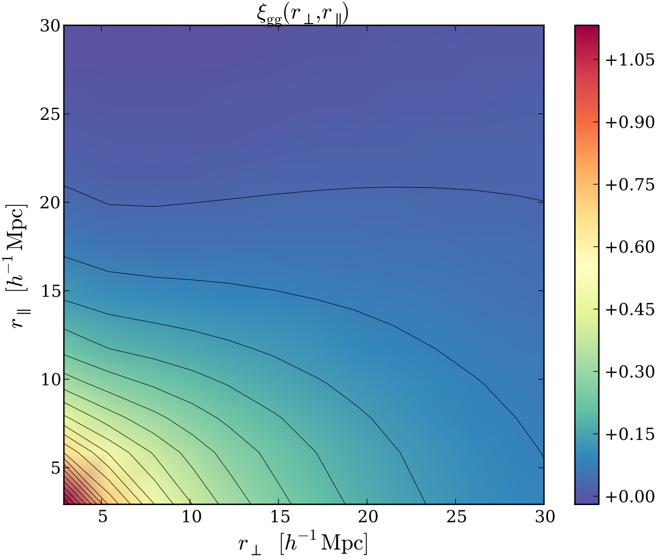
2D POWER SPECTRUM



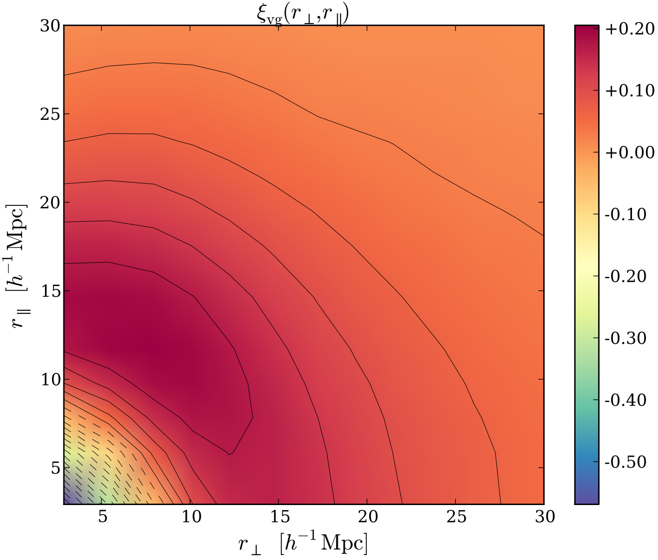
2D POWER SPECTRUM



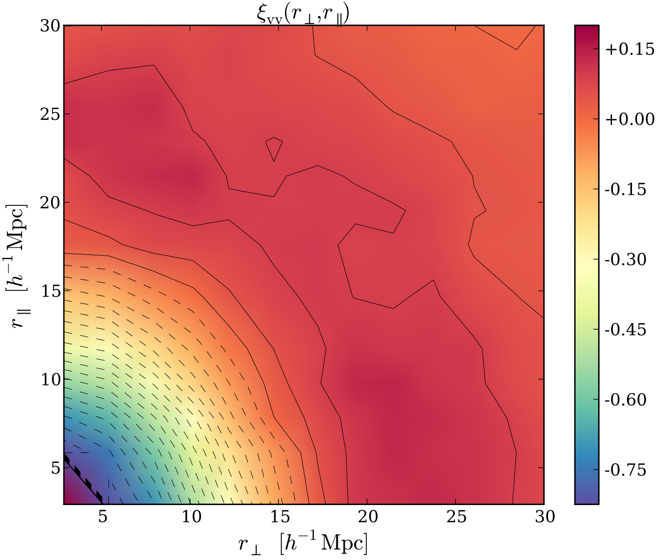
2D CORRELATION FUNCTION



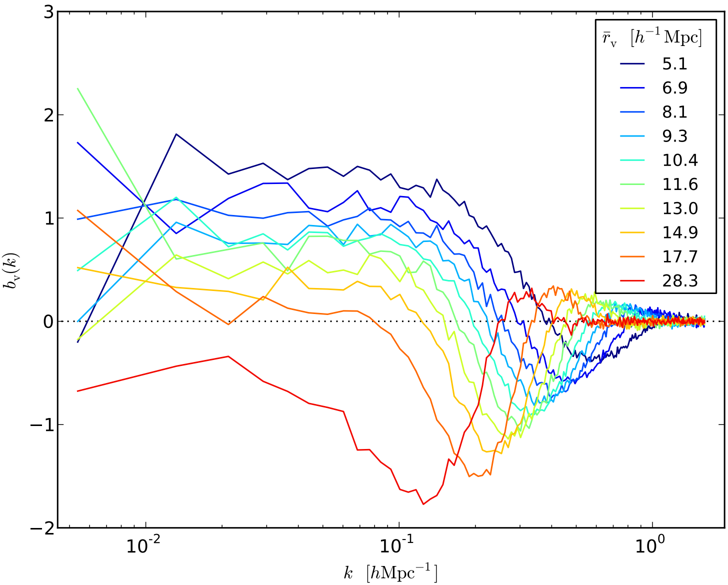
2D CORRELATION FUNCTION



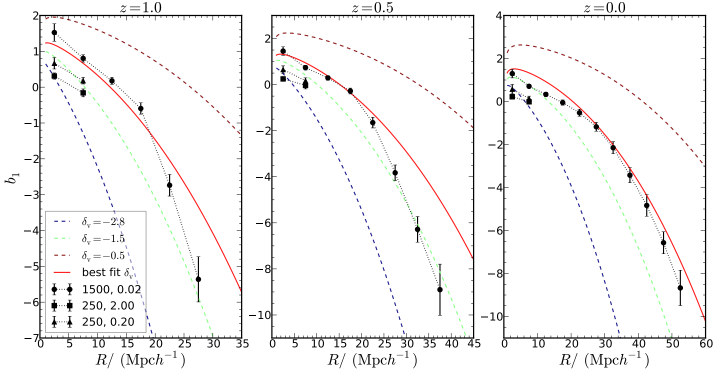
2D correlation function



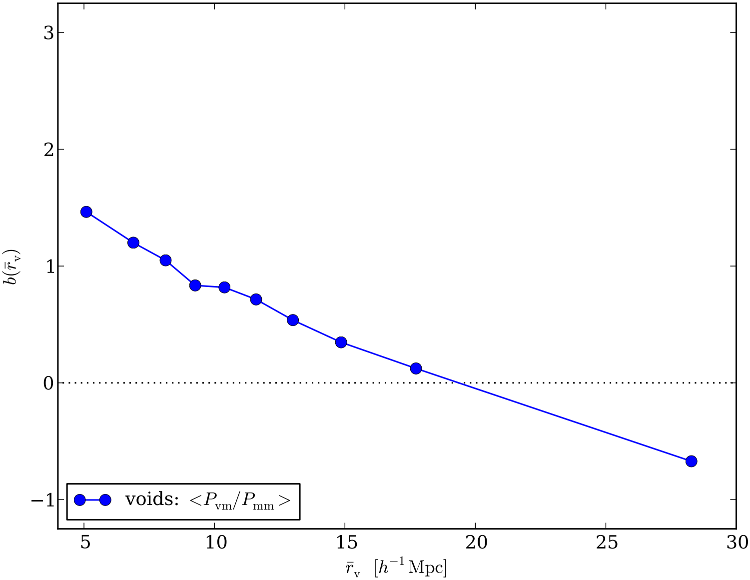
Void bias


$\bar{r}_v$ [h^{-1}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 [hMpc^{-1}]
3
2
1
0
−1
−2
10^{-2}
10^{-1}
10^{0}

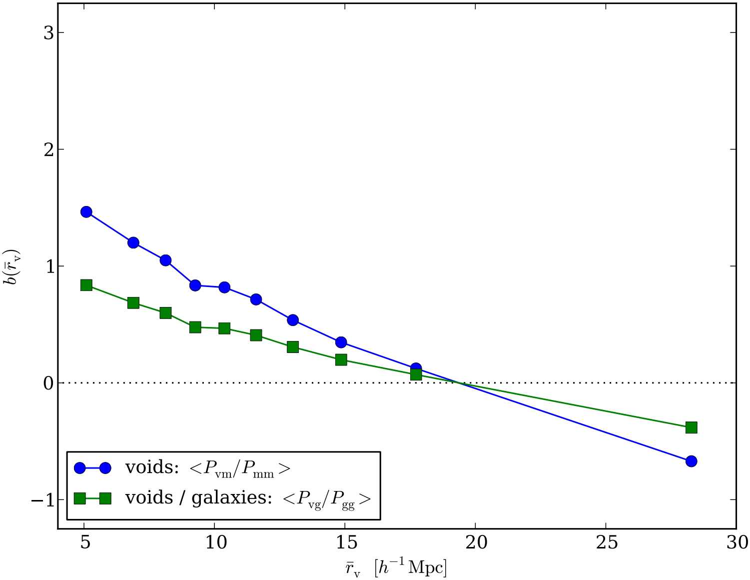
Linear void bias



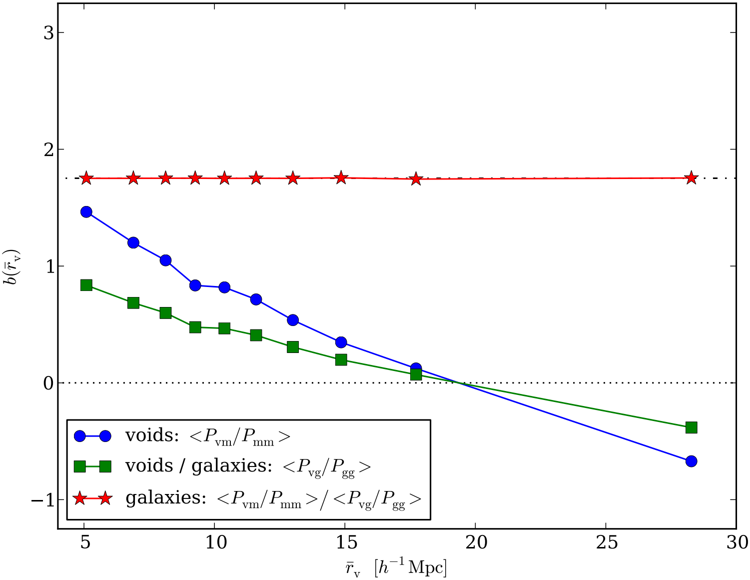
Linear void bias



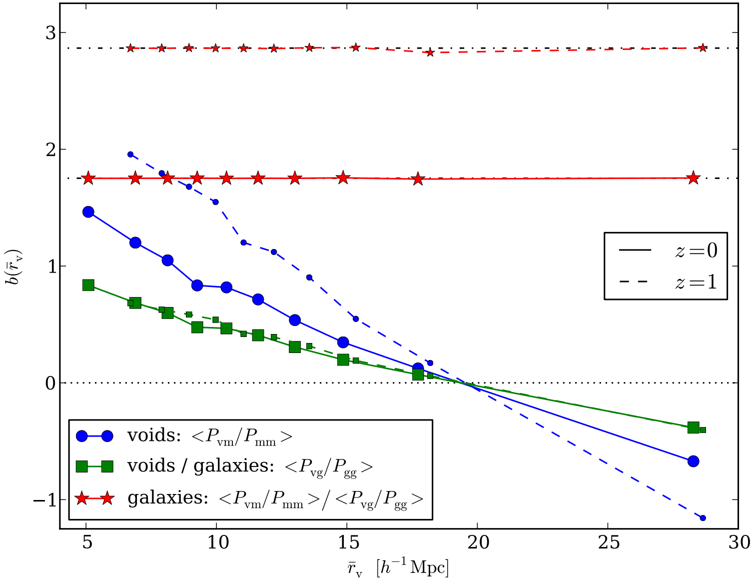
LINEAR VOID BIAS



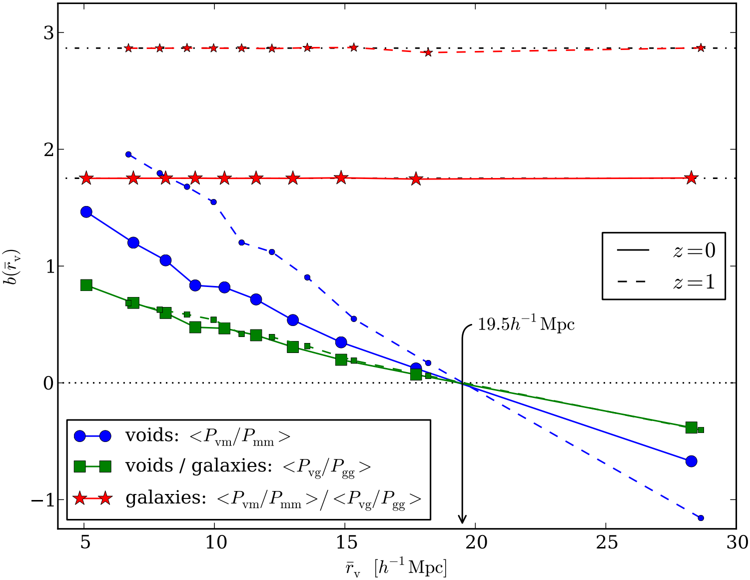
Linear void bias



LINEAR VOID BIAS

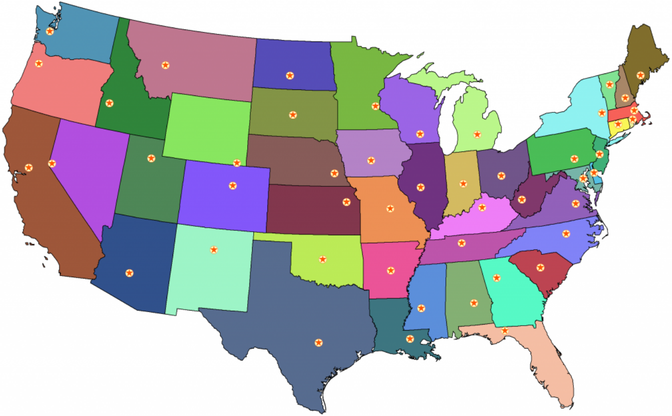


Linear void bias



DEFINITION OF VOIDS

Define density field via Voronoi tessellation of tracer particles



DEFINITION OF VOIDS

Define density field via Voronoi tessellation of tracer particles