CONSTRAINING COSMIC ACCELERATION

(AND GRAVITY ON COSMIC SCALES)

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in collaboration with

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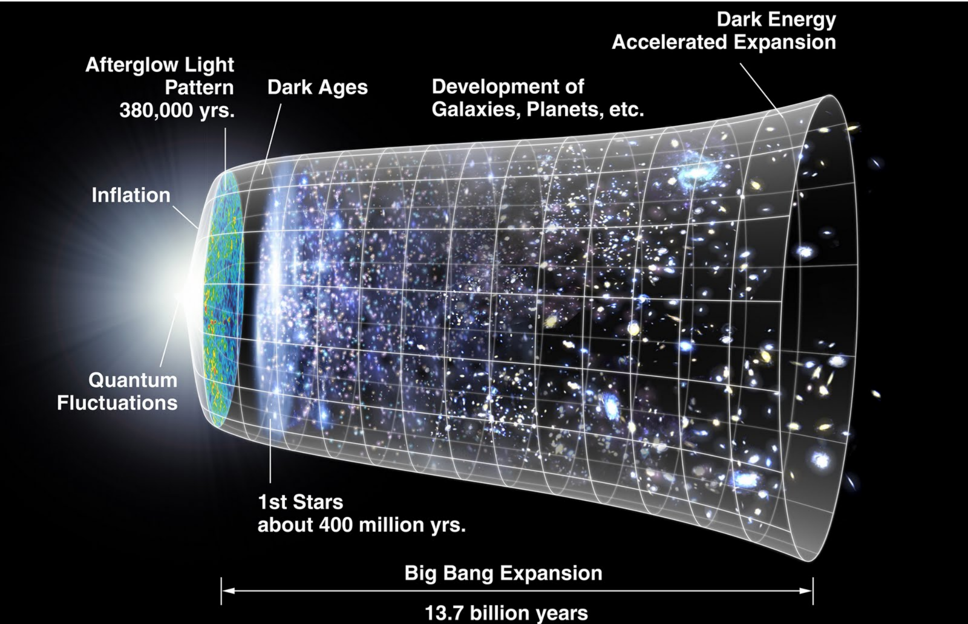
BEN HOYLE, JOCHEN WELLER

From the Vacuum to the Universe — Humboldt Kolleg, Kitzbühel, June 30, 2016

Standard Model of Cosmology



Standard Model of Cosmology

Galaxies trace the expansion of cosmic spacetime, described by

FLRW-metric

$$\mathrm{d}s^2 = c^2\mathrm{d}t^2 - a^2(t)\left(\frac{\mathrm{d}r^2}{1-kr^2} + r^2\mathrm{d}\Omega^2\right)$$

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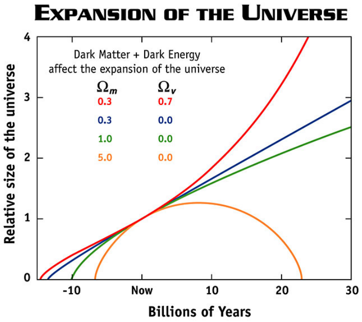
Observational evidence for $\ddot{a} > 0 \Rightarrow \Lambda\text{CDM}$



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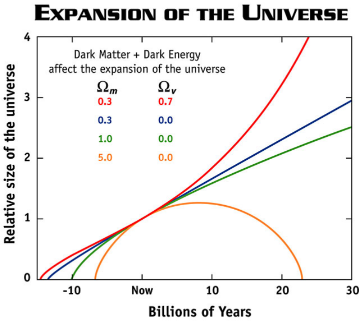

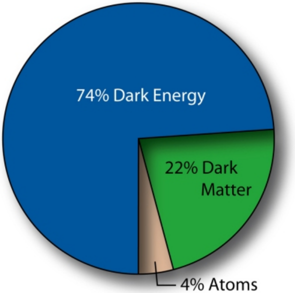

Standard Model of Cosmology

Friedman Equations

$$\dot{a}/a \equiv H = H_0\sqrt{\Omega_{\mathrm{r},0}a^{-4} + \Omega_{\mathrm{m},0}a^{-3} + \Omega_{k,0}a^{-2} + \Omega_{\Lambda,0}}$$

$$-\ddot{a}a/\dot{a}^2 \equiv q = 1/2\sum\Omega_i(1+3w_i), \quad w_i = p_i/\rho_i$$

Components of the Universe: $\Omega_i = \rho_i/\rho_{\mathrm{crit}}$ with $\sum\Omega_i + \Omega_k = 1$

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STANDARD MODEL OF COSMOLOGY

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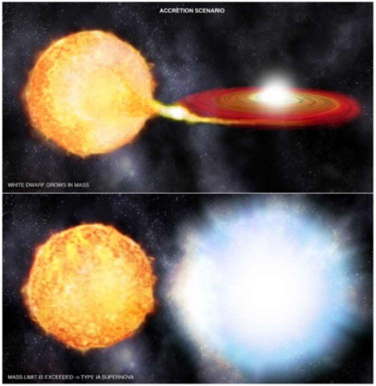
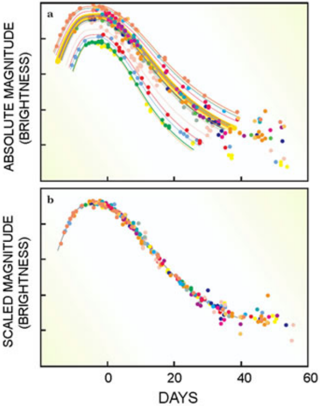
Equation of state:

- Radiation $w_\mathrm{r} = 1/3$
- Matter $w_\mathrm{m} = 0$
- Curvature $w_k = -1/3$
- Cosmological constant $w_\Lambda = -1$

Supernovae as Standard Candles





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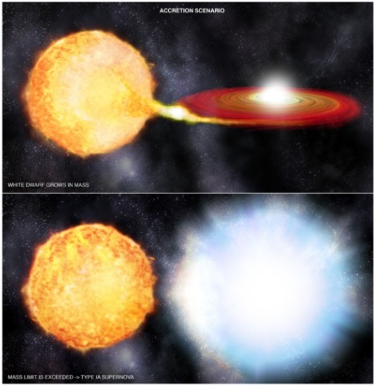

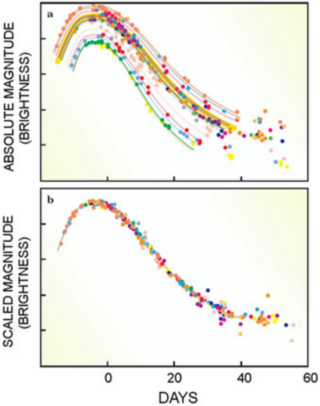

Luminosity Distance

$$\sqrt{L/4\pi F} \equiv D_L(z) = \frac{(1+z)c}{H_0\sqrt{-\Omega_{k,0}}} \sin\left(H_0\sqrt{-\Omega_{k,0}} \int_0^z \frac{1}{H(z')}\,\mathrm{d}z'\right)$$

Redshifts $z = 1/a - 1$ from spectra of host galaxies

Supernovae as Standard Candles

Distance Modulus: apparent vs. absolute magnitude

$$\begin{aligned} \mu &\equiv m(F) - M(L) = 5\log_{10}\left(\frac{D_L(z)}{\mathrm{Mpc}}\right) + 25 \\ &\simeq 43.17 + 5\log_{10} z + 1.086(1-q_0)z - 5\log_{10}\left(\frac{H_0}{70\,\mathrm{km/s/Mpc}}\right) \end{aligned}$$

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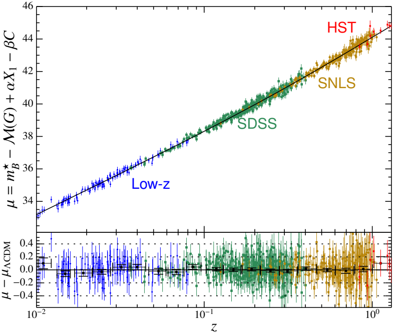
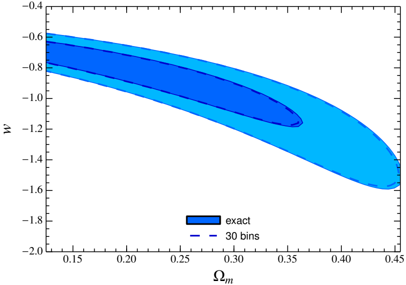
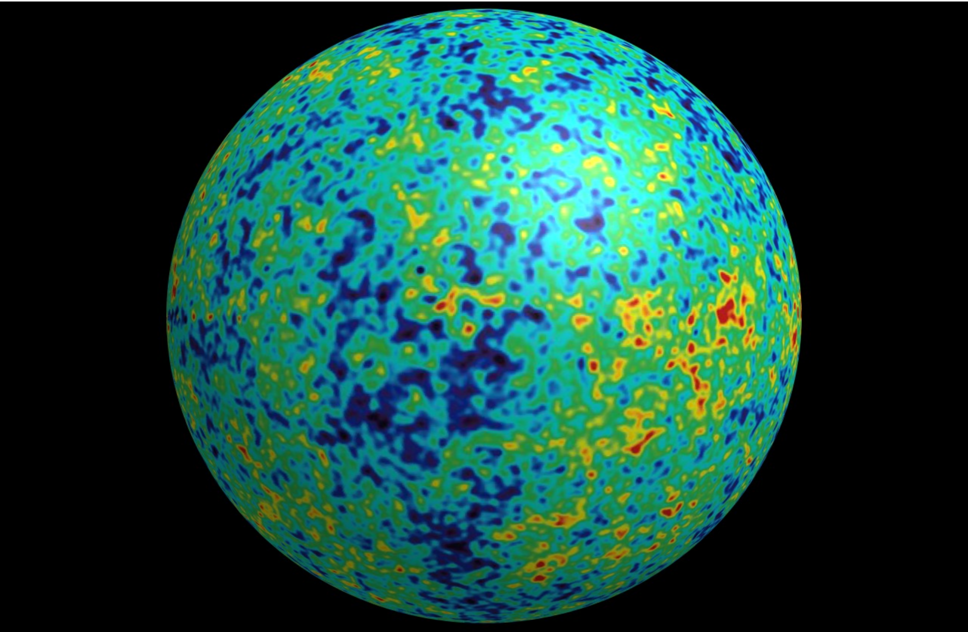




Betoule et al. 2014

CMB as Standard Ruler



CMB as Standard Ruler

Baryon acoustic oscillations (BAO) due to sound horizon $r_s \simeq 150$ Mpc of primordial plasma at $z \sim 1100$ with apparent angular size $\theta_s \simeq 1°$

Angular Diameter Distance

$$r_s/\theta_s \equiv D_A(z) = \frac{c}{(1+z)H_0\sqrt{-\Omega_{k,0}}} \sin\left(H_0\sqrt{-\Omega_{k,0}} \int_0^z \frac{1}{H(z')}\, \mathrm{d}z' \right)$$

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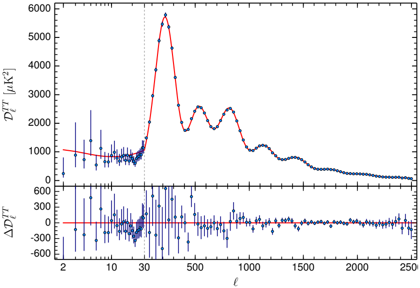
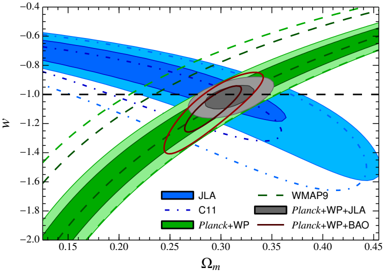
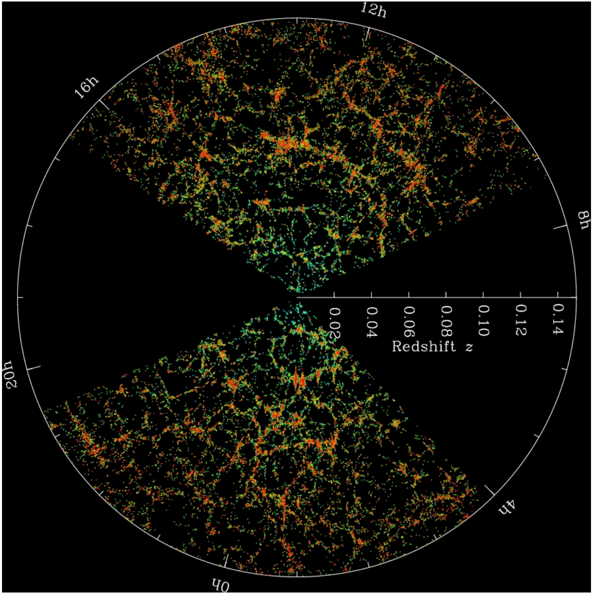


Planck 2015



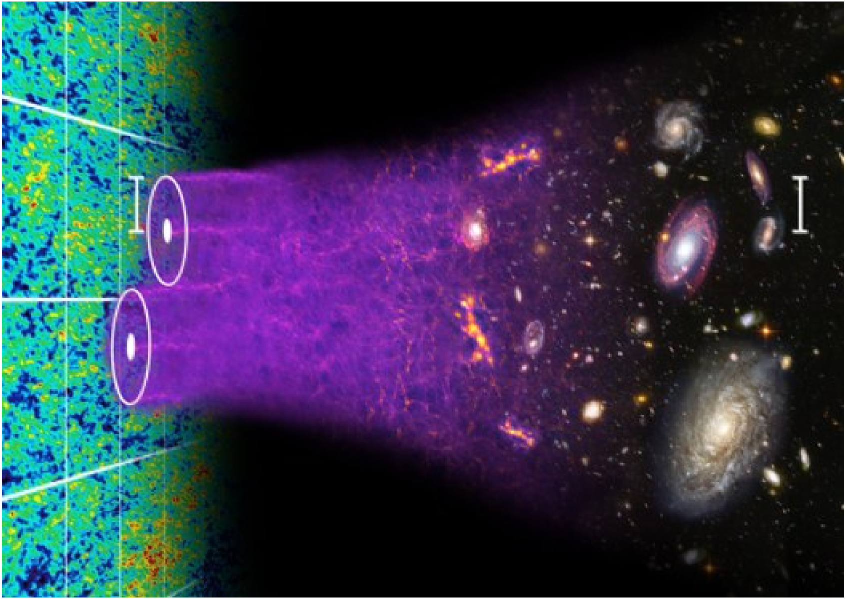
Betoule et al. 2014

Large-Scale Structure (LSS)



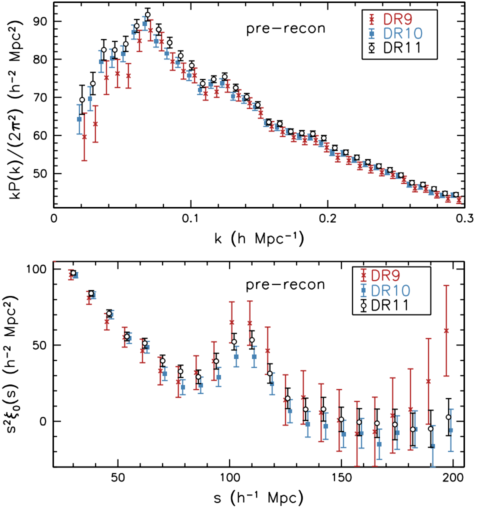
SDSS

LSS as Standard Ruler



LSS AS STANDARD RULER

Anderson et al. 2014



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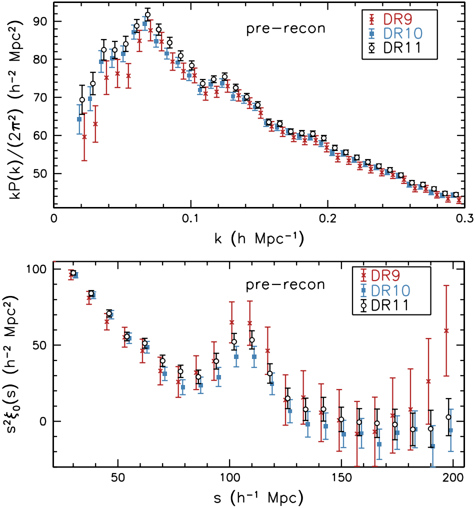

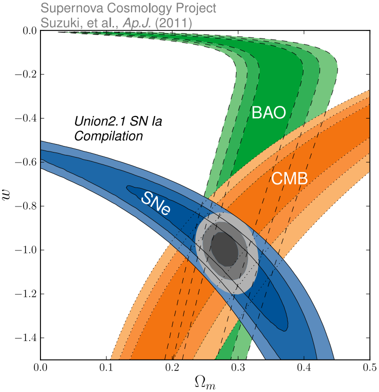

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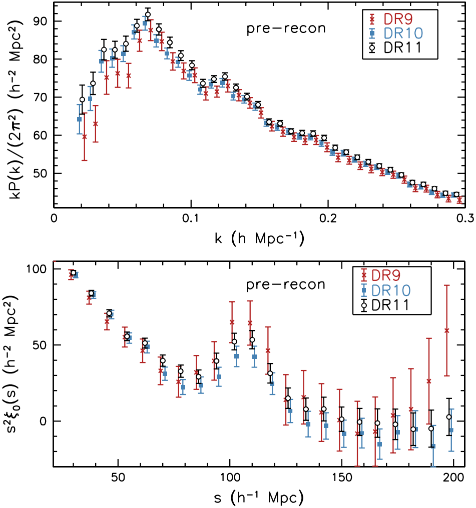
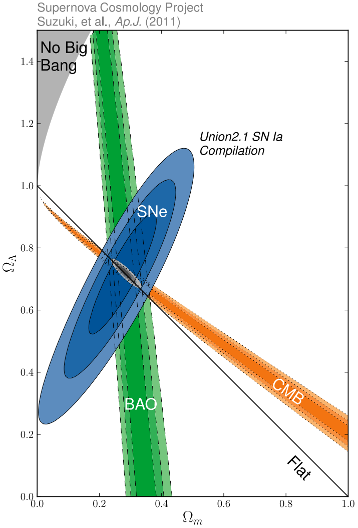
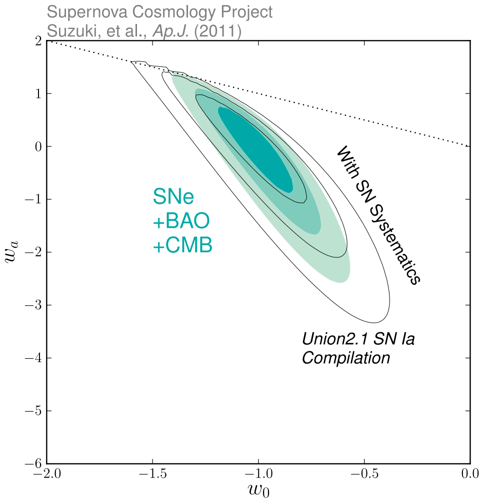


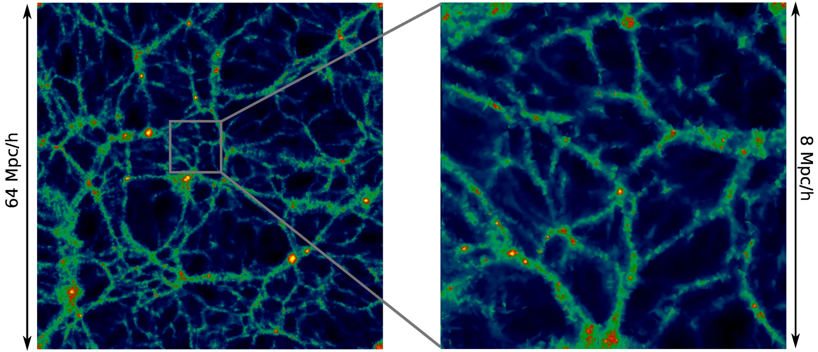


LSS as Standard Ruler

Evolution of dark energy: $w(z) = w_0 + w_a \frac{z}{1+z}$

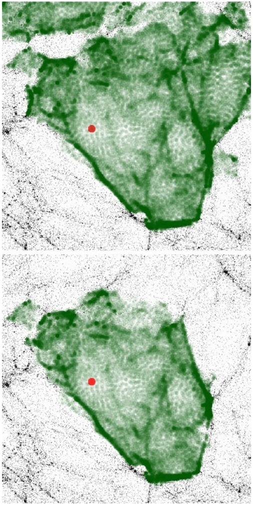


The Cosmic Web

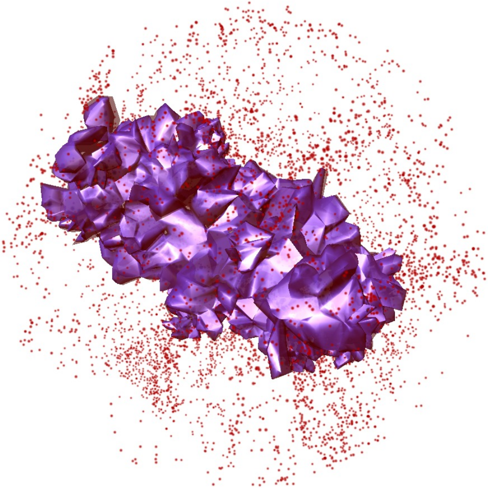


Aragon-Calvo, Szalay (2013)

Cosmic Voids as Standard Spheres

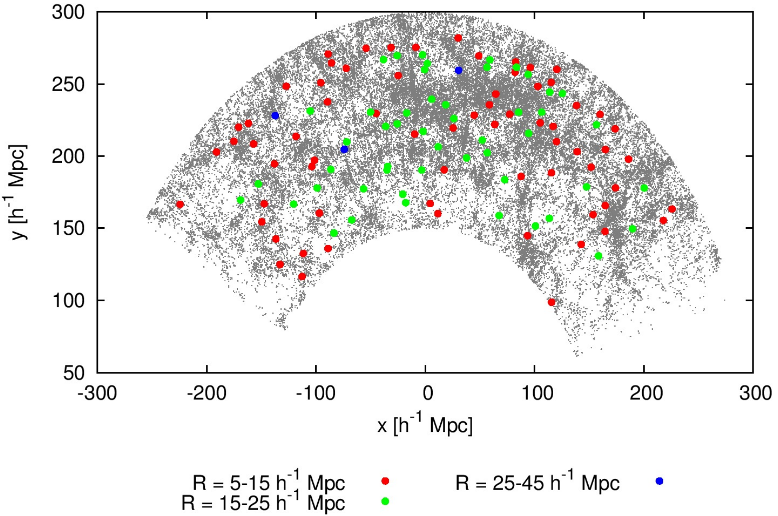


Neyrinck (2008)



Sutter, Lavaux, Wandelt, Weinberg (2012)

Observed Cosmic Voids (SDSS)

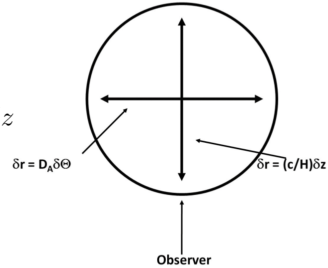


Sutter et al. (2012)

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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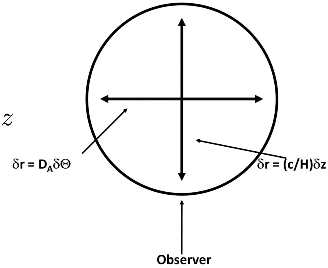


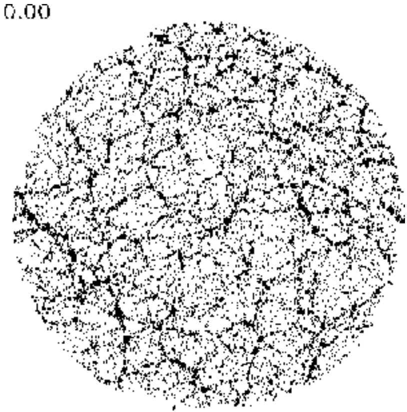
Any deviation from the fiducial cosmology causes geometric distortions. ⇒ Determine ellipticity ε via

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

Cosmic Voids in Redshift Space

Peculiar motions of galaxies cause redshift-space distortions:

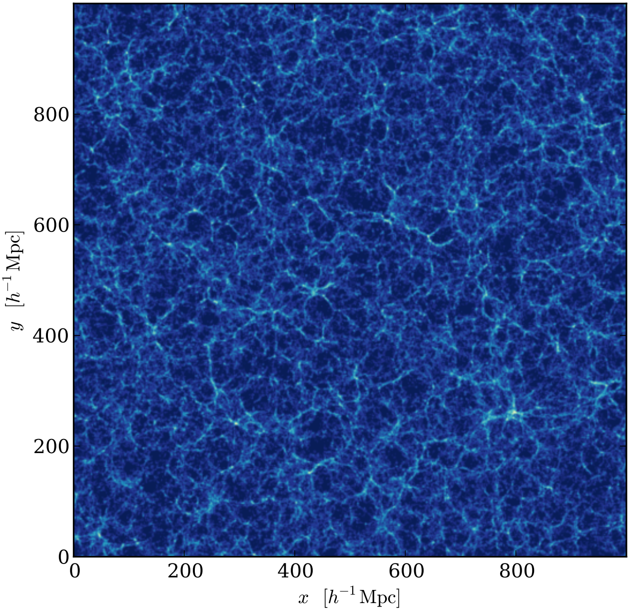
$$\tilde{\mathbf{r}} = \mathbf{r} + \mathbf{v}_{\parallel} H^{-1}(z)$$



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?

Cosmic Voids in Redshift Space



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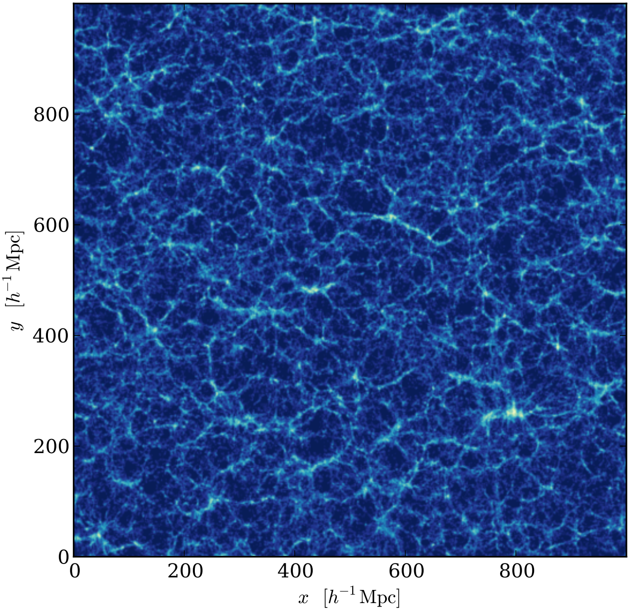

Model

Void-galaxy cross-correlation function in redshift space:

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

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

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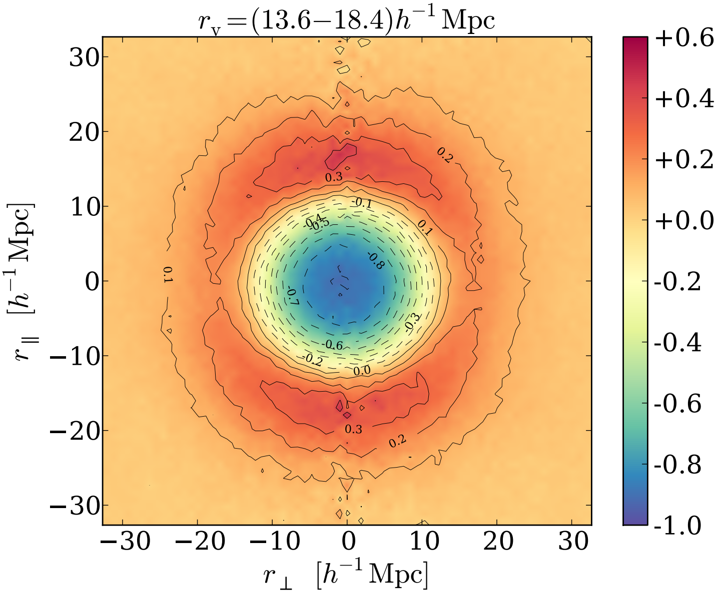
Linear growth rate: $f(z) = \Omega_{\mathrm{m}}^{0.55}(z)$ in General Relativity

Analysis: Dense Mock Galaxies



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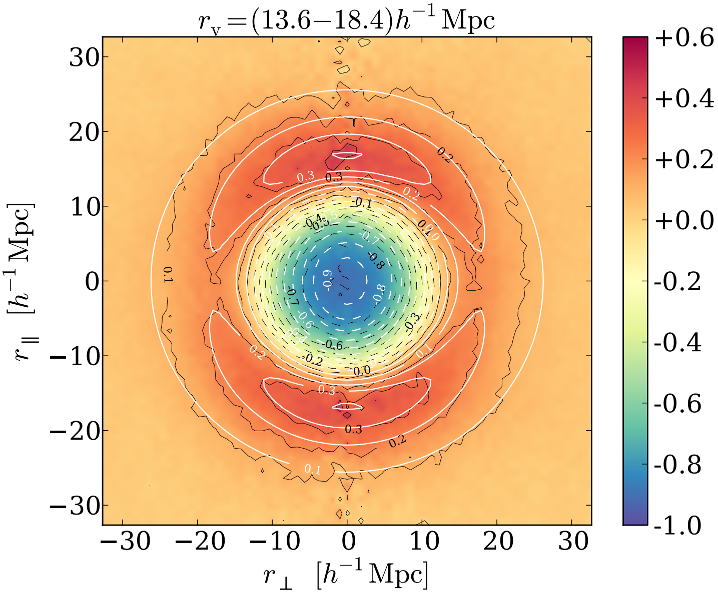
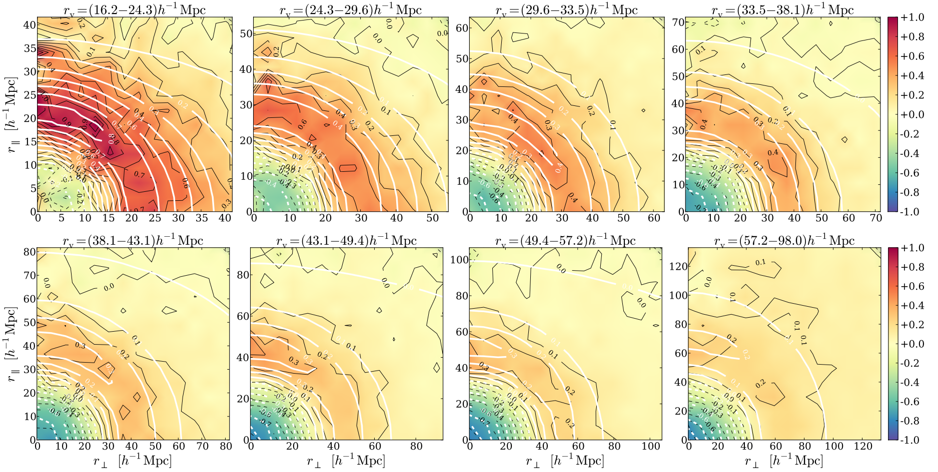


Analysis: SDSS CMASS DR11 Galaxies



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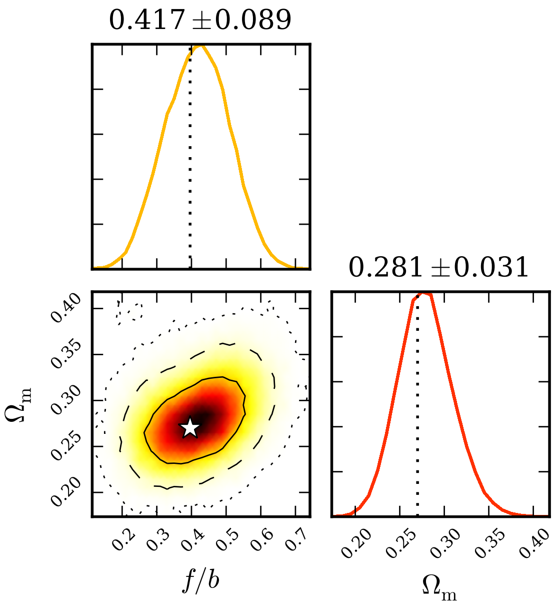

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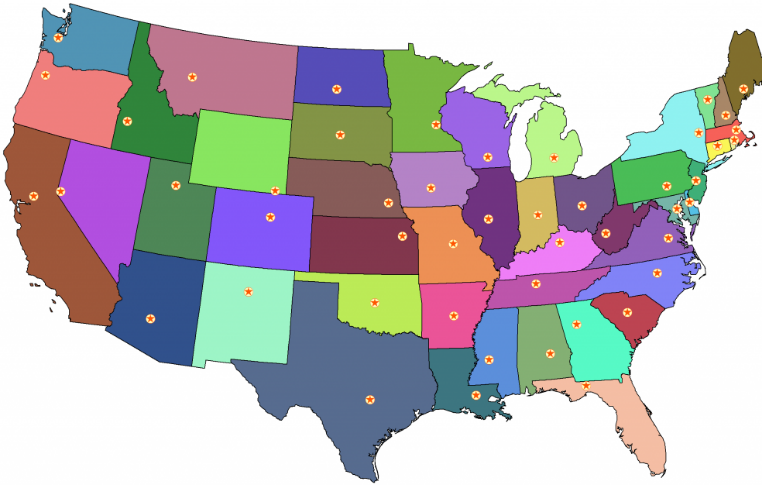
- This can help to test modified gravity theories (alternatives for dark energy) in their unscreened regime.

Questions ? Thank you !

Definition of voids

Define density field via Voronoi tessellation of tracer particles



Definition of voids

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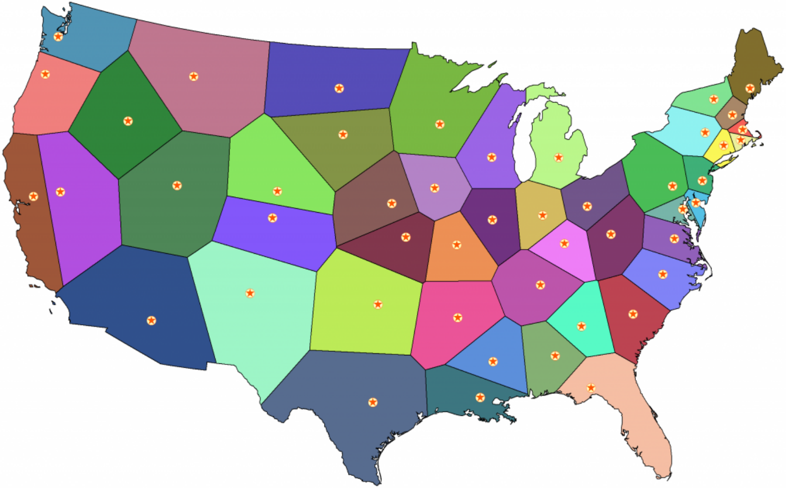
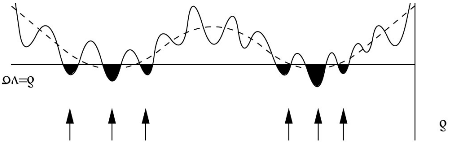


Cosmic Voids as Standard Spheres

Search for local minima in density field



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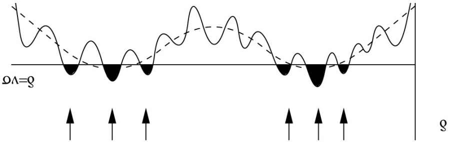
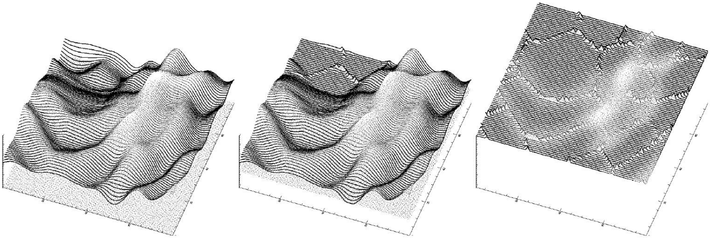


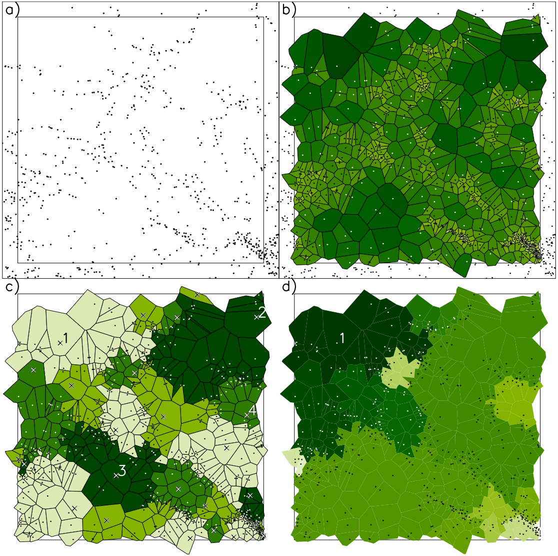
and raise a density threshold until a ridge is reached



Watershed algorithm, Platen et al. (2007)

Definition of voids

ZOBOV, Neyrinck (2008)



Void profile

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

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

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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

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

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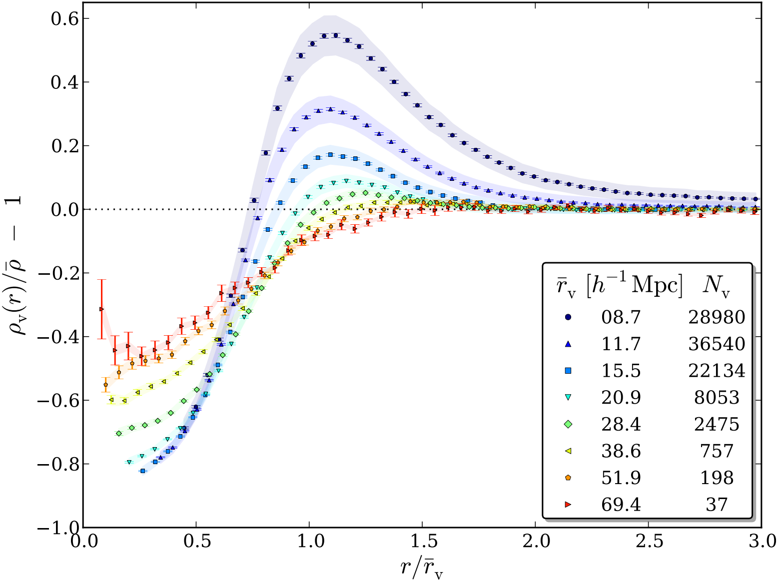
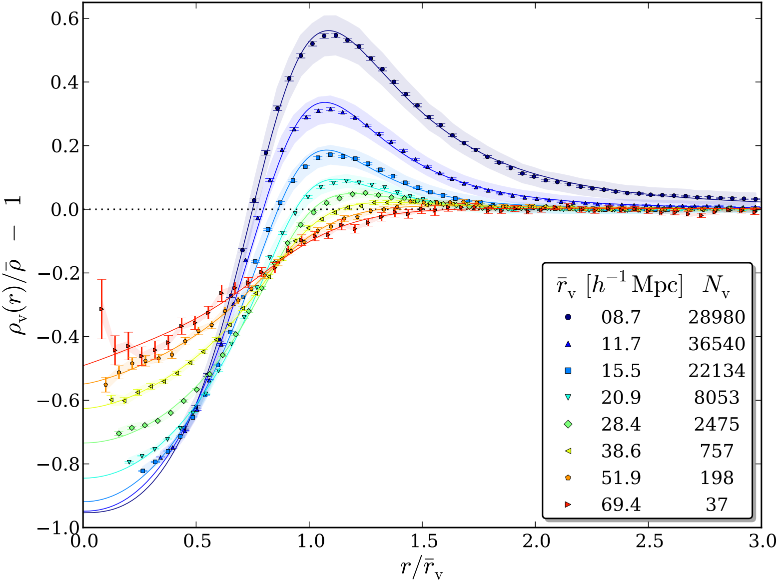
In General Relativity: $f(z) = \Omega_{\mathrm{m}}^{0.55}(z)$

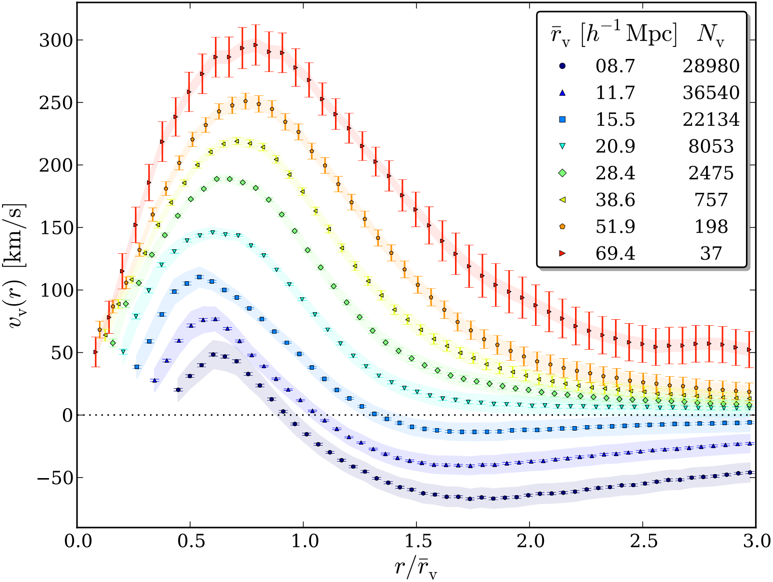
Void profile: density



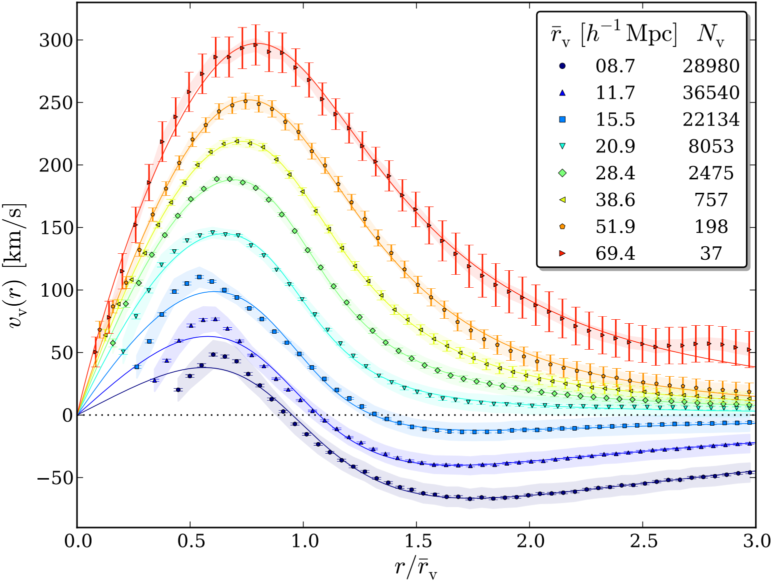
Void profile: density



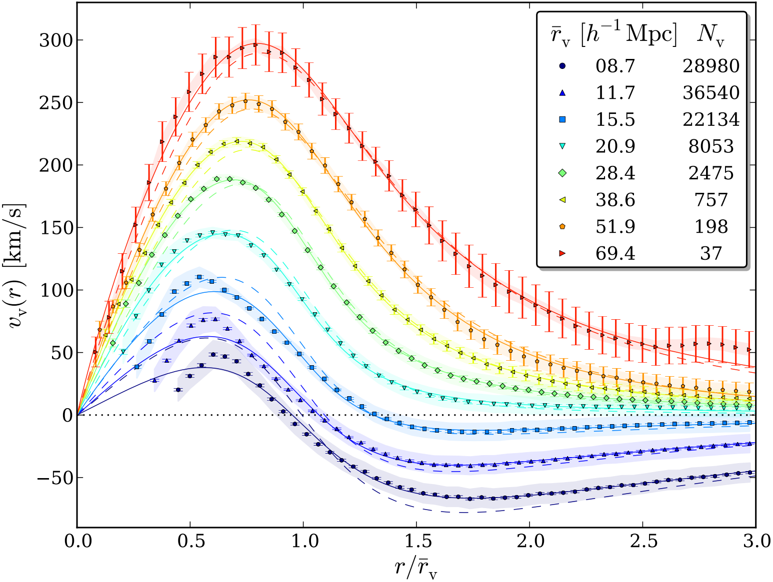
Void profile: velocity



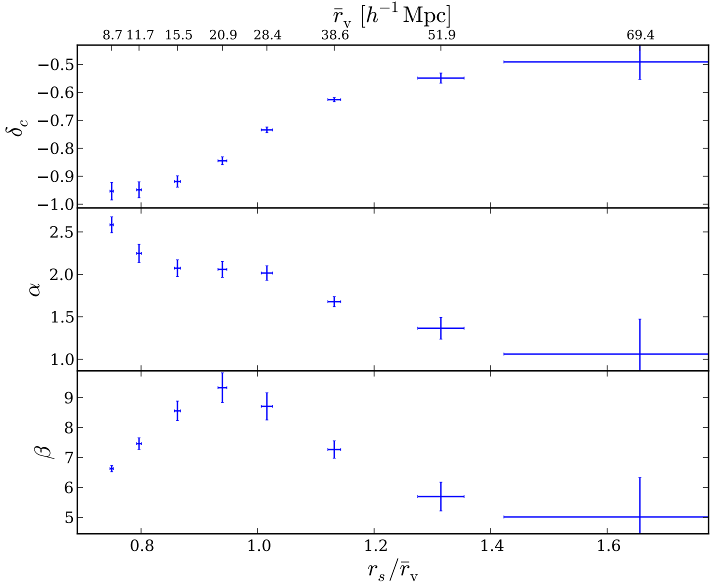
Void profile: velocity



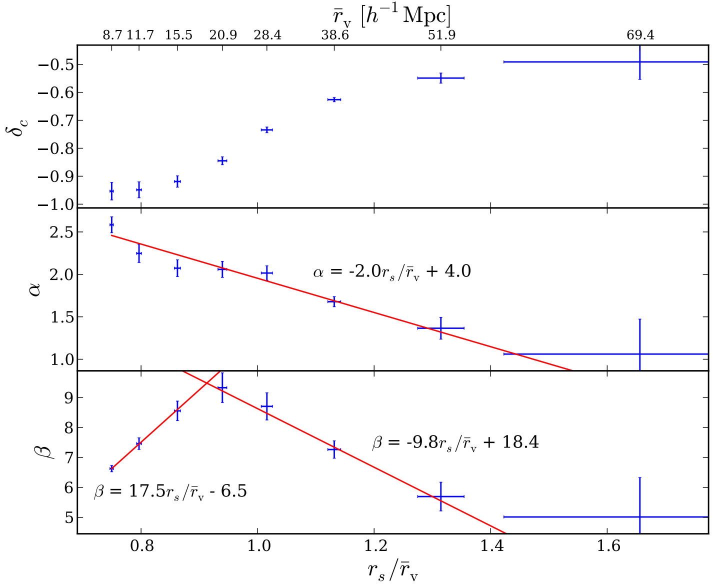
VOID PROFILE: VELOCITY



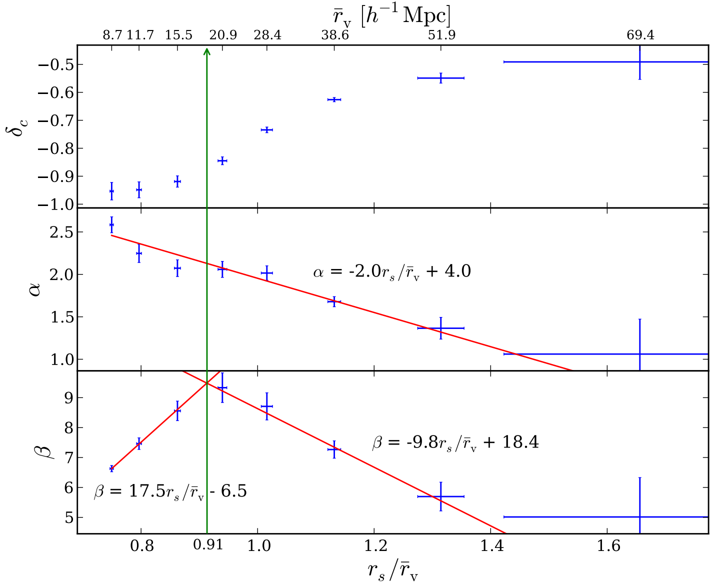
Void profile: parameters



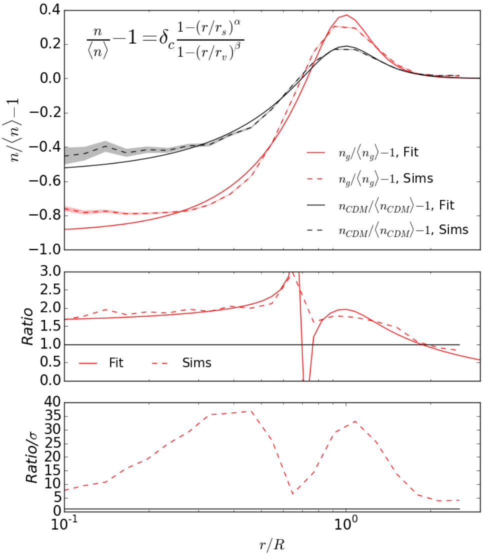
VOID PROFILE: PARAMETERS



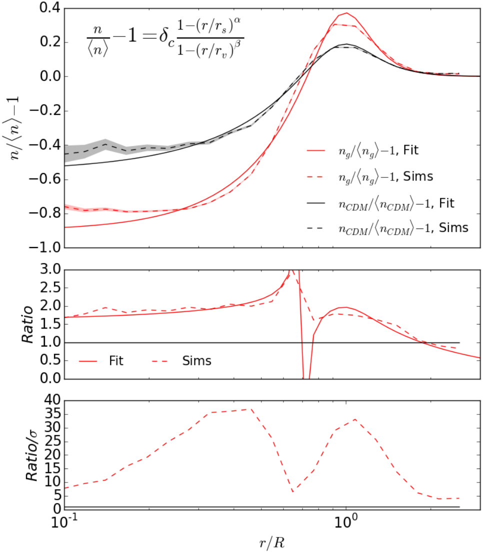
Void profile: parameters

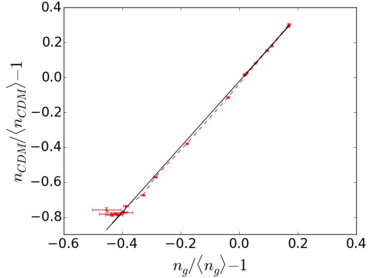


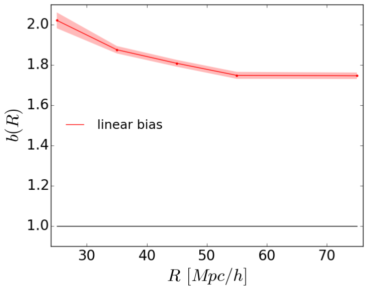
Void profile: galaxies vs. dark matter



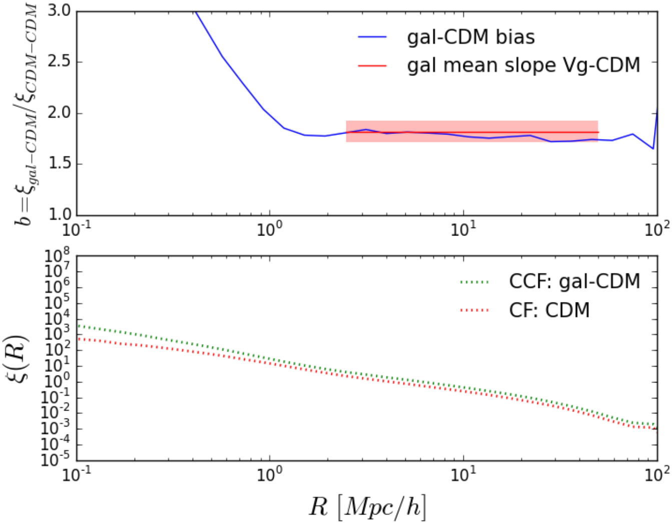
Void profile: galaxies vs. dark matter





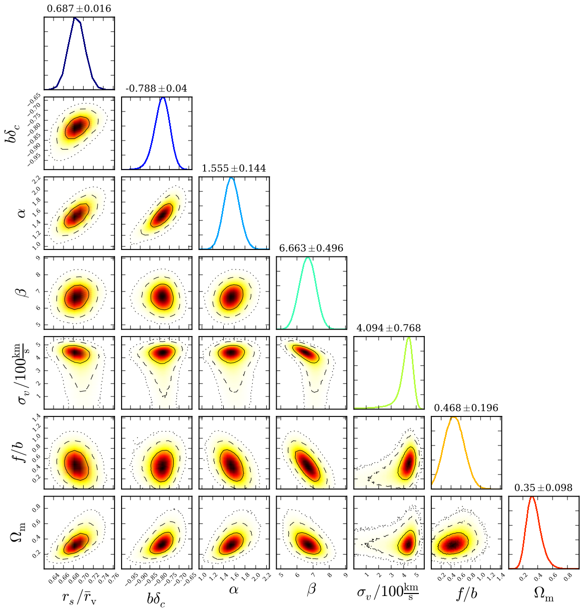


Void profile: galaxies vs. dark matter

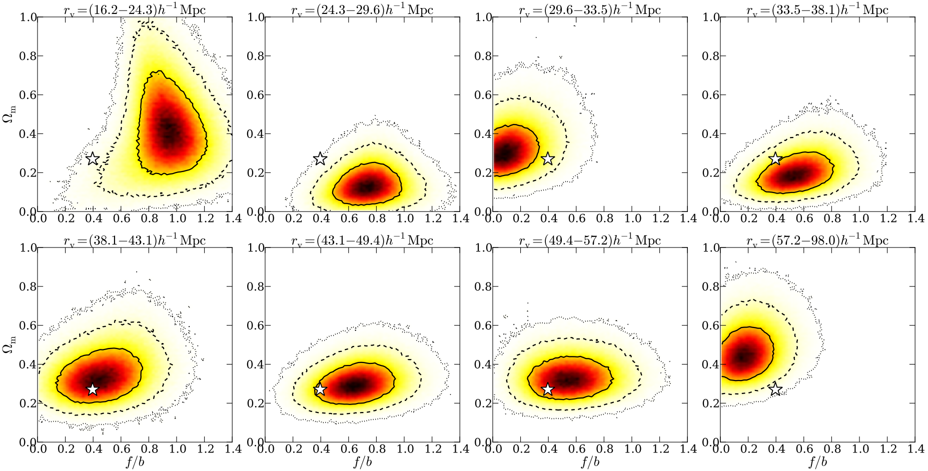


Pollina et al. 2016 (in prep.)

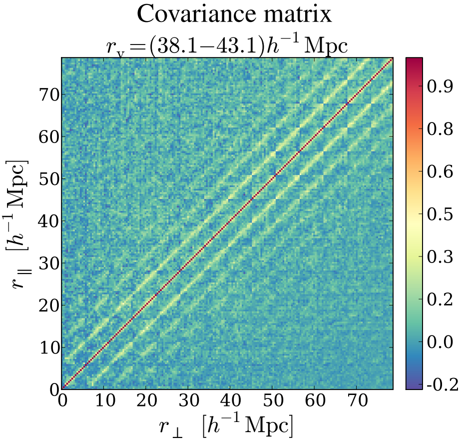
RSD analysis: SDSS CMASS DR11 galaxies

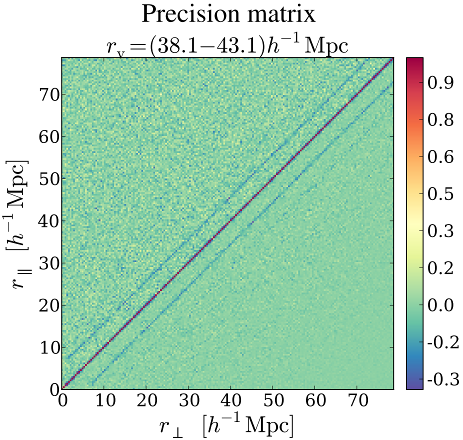


Analysis: SDSS CMASS DR11 Galaxies



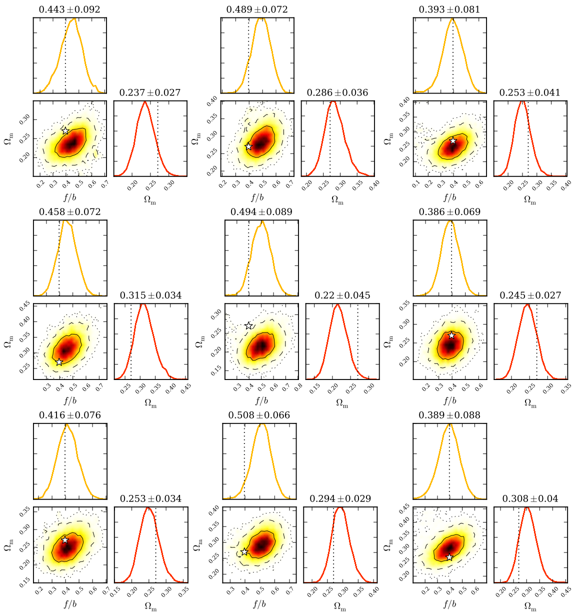
RSD analysis: SDSS CMASS DR11 galaxies



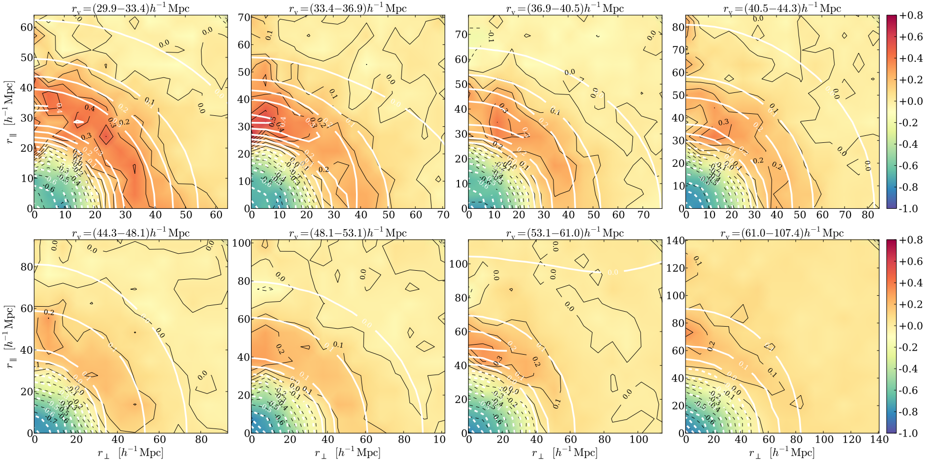


$$\mathcal{L}(\hat{\xi}_{\mathrm{vg}}|\boldsymbol{\theta}) \propto \exp\left[-\frac{1}{2}(\hat{\xi}_{\mathrm{vg}} - \xi_{\mathrm{vg}})^{\intercal}\mathbf{C}^{-1}(\hat{\xi}_{\mathrm{vg}} - \xi_{\mathrm{vg}})\right]$$

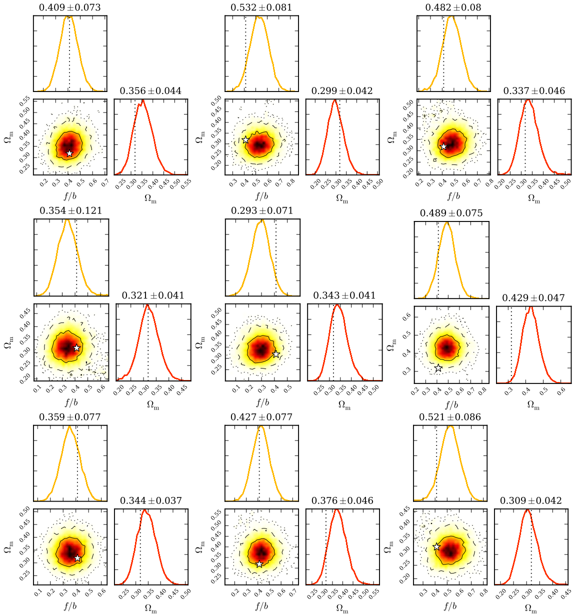
RSD analysis: SDSS CMASS DR11 bootstraps



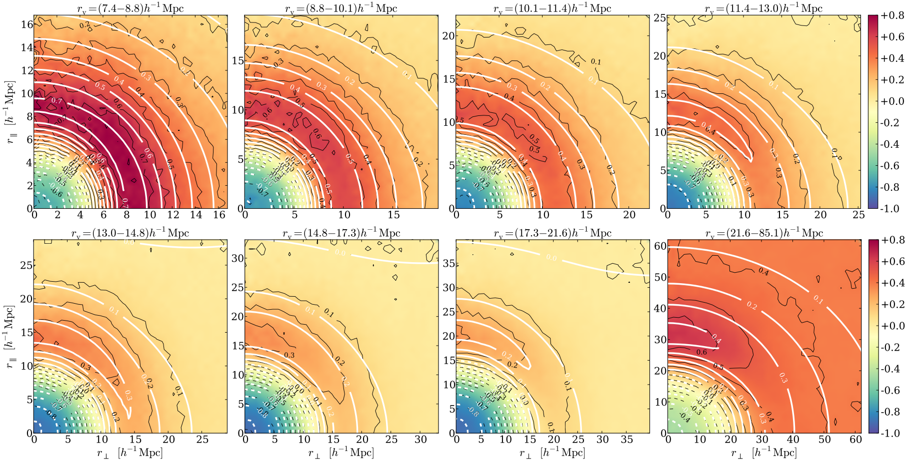
RSD analysis: SDSS CMASS DR11 mocks



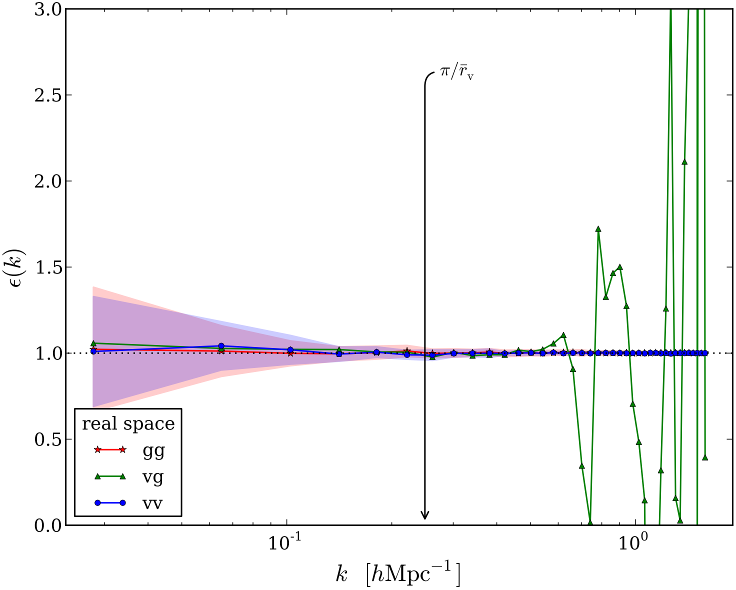
RSD analysis: SDSS CMASS DR11 mocks



RSD analysis: SDSS MAIN mocks



Alcock-Paczynski test



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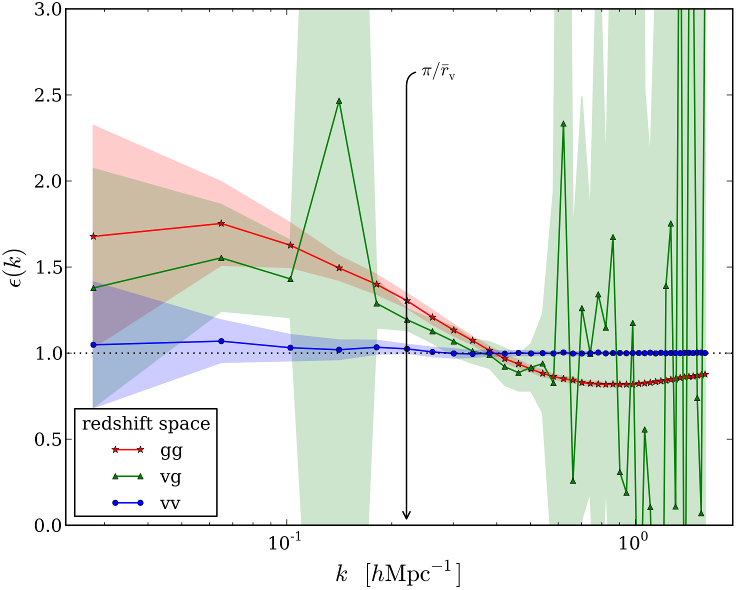
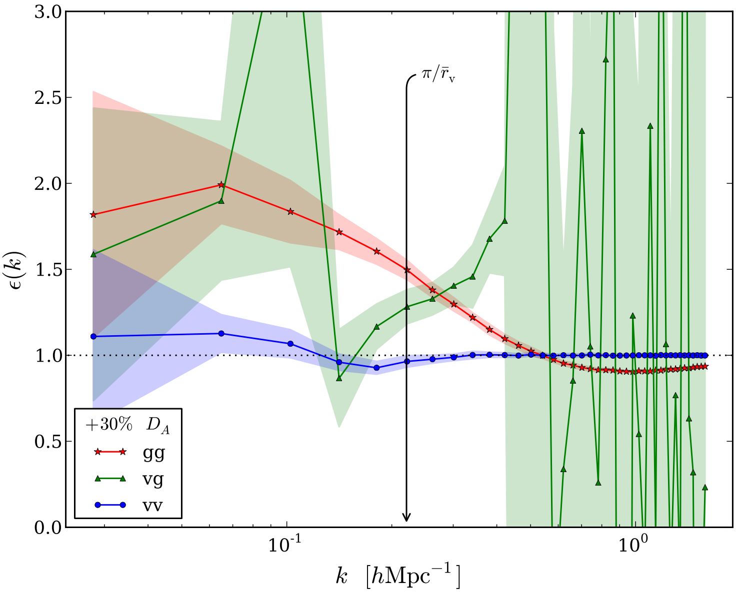


Alcock-Paczynski test



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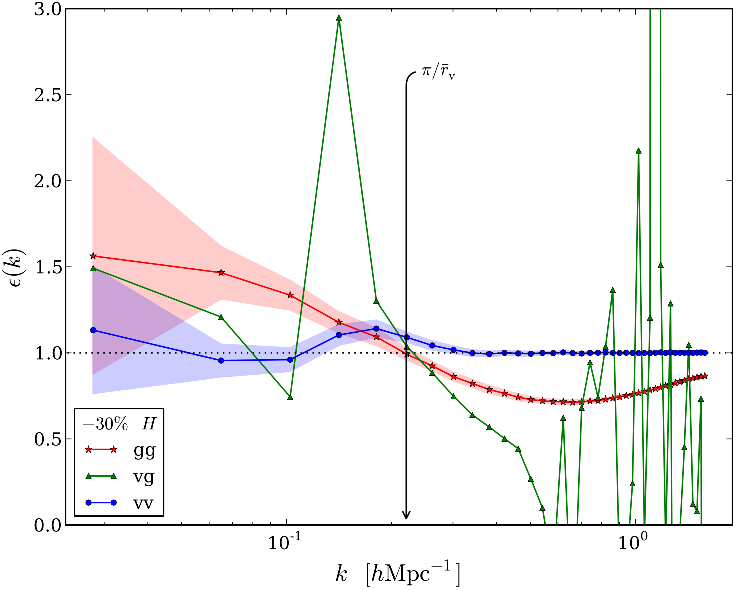

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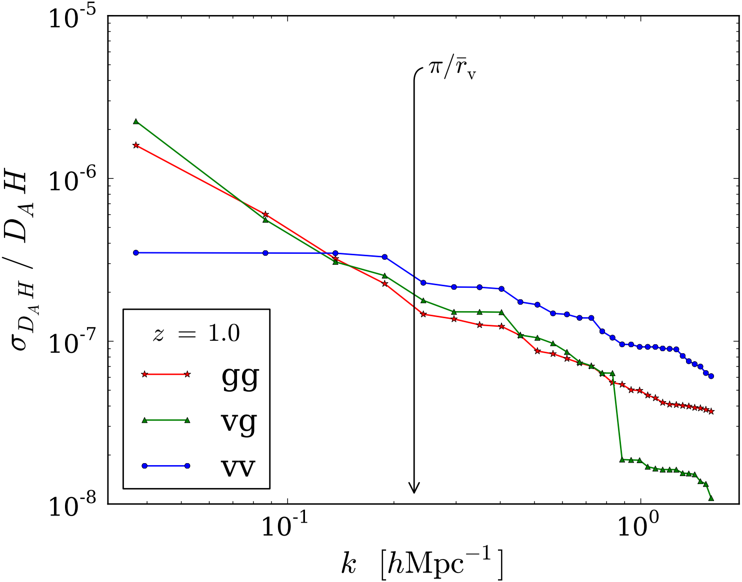
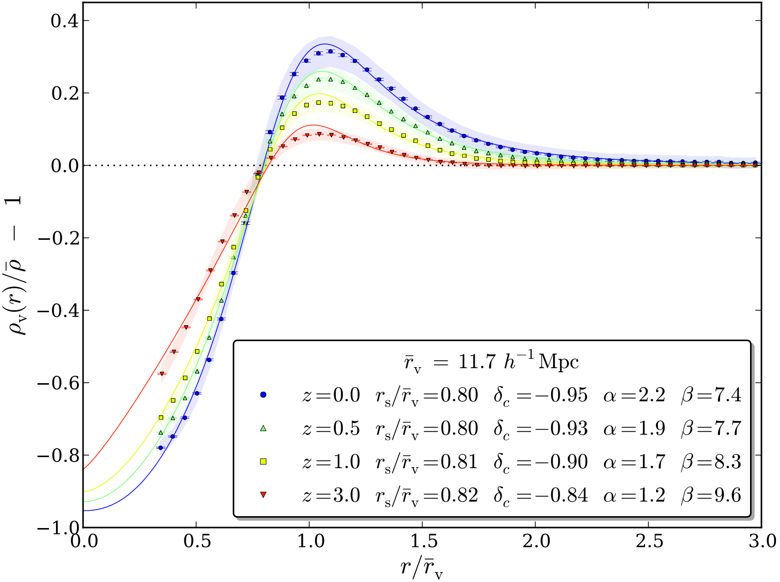


Void profile: universality



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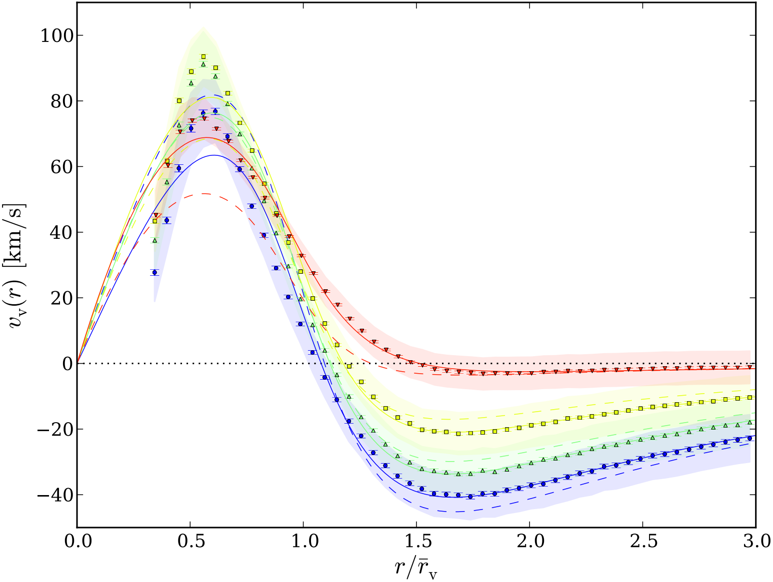
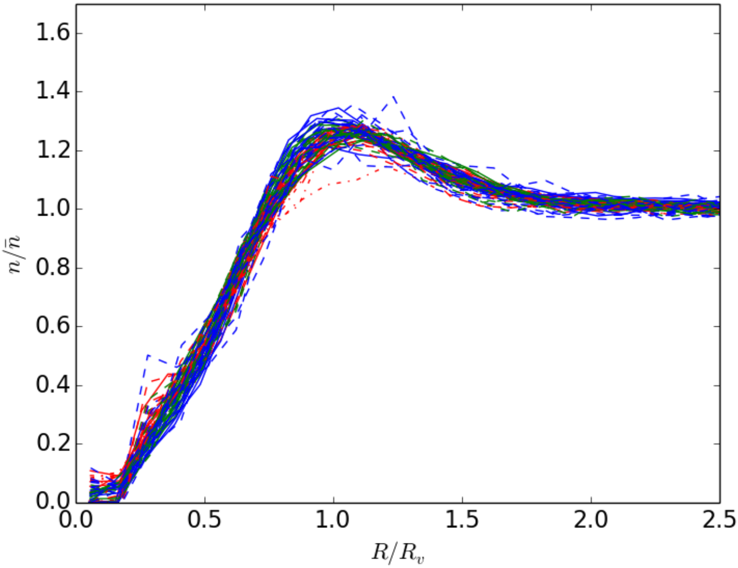
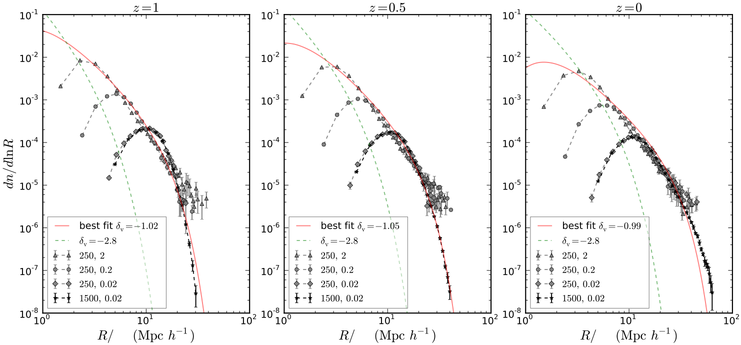


Void profile: universality

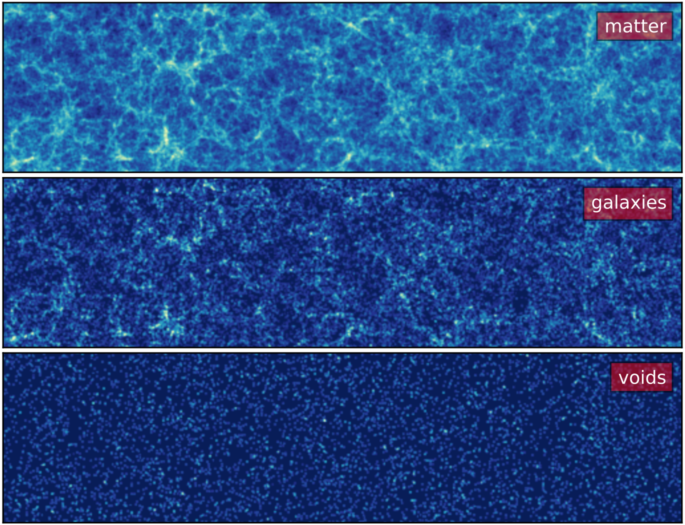


Void abundance

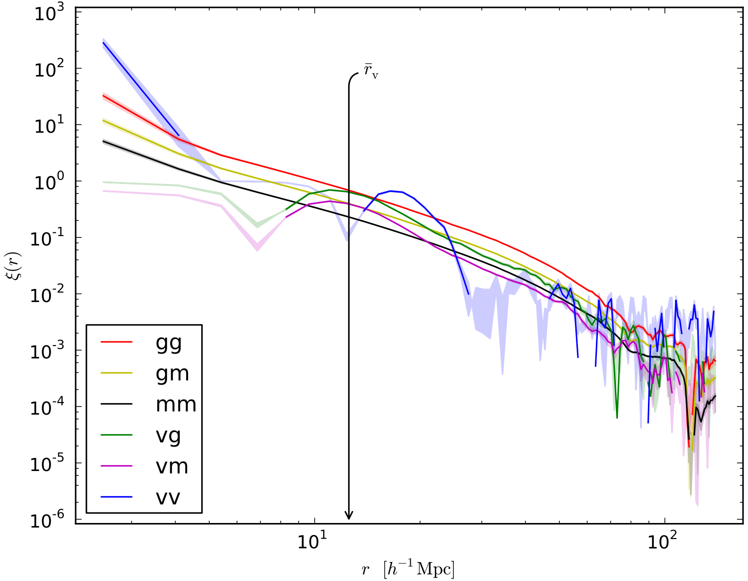


DENSITY FIELDS

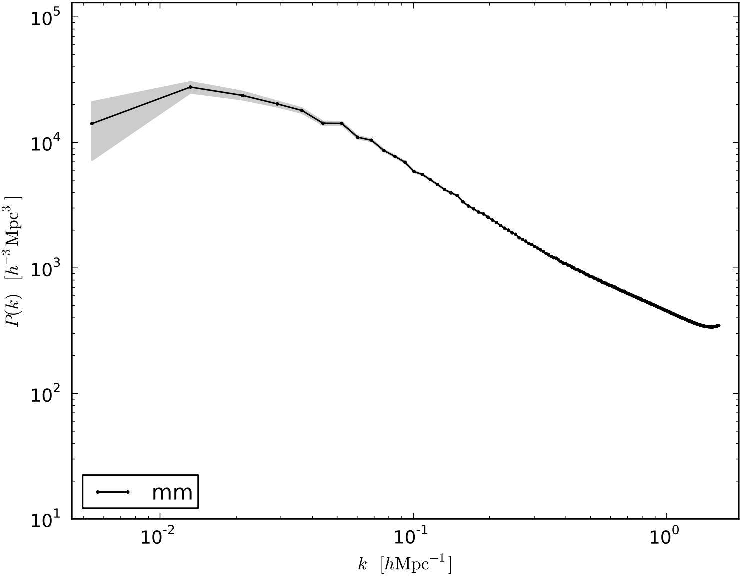
Voids are less clustered and more sparse than galaxies:



Correlation function



Power spectrum



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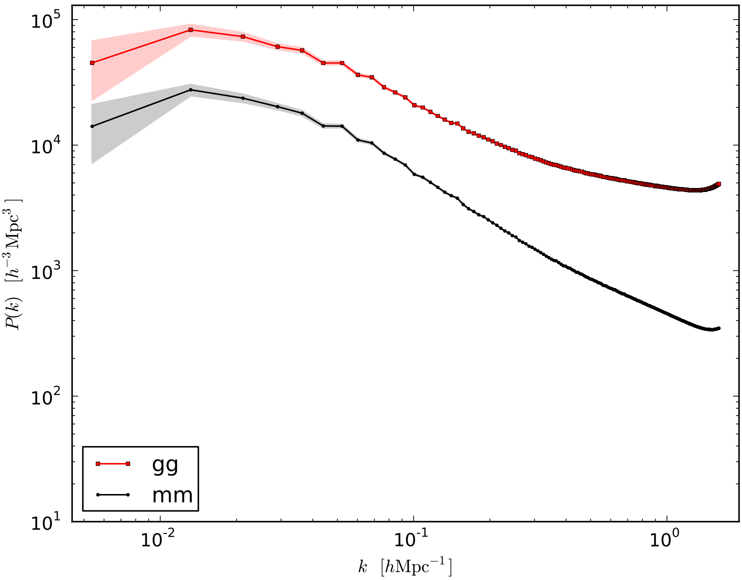

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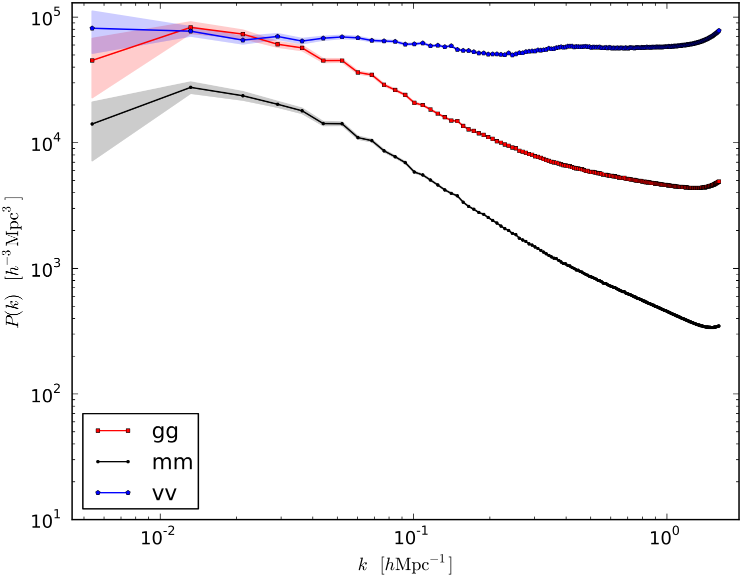

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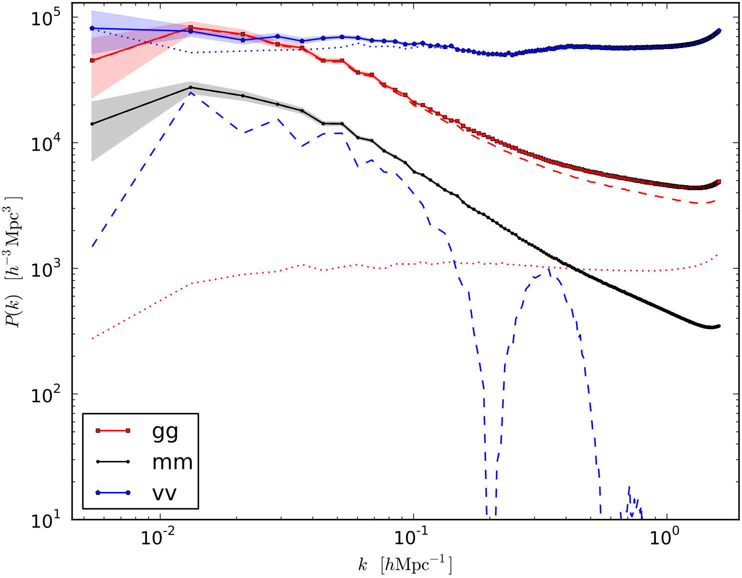

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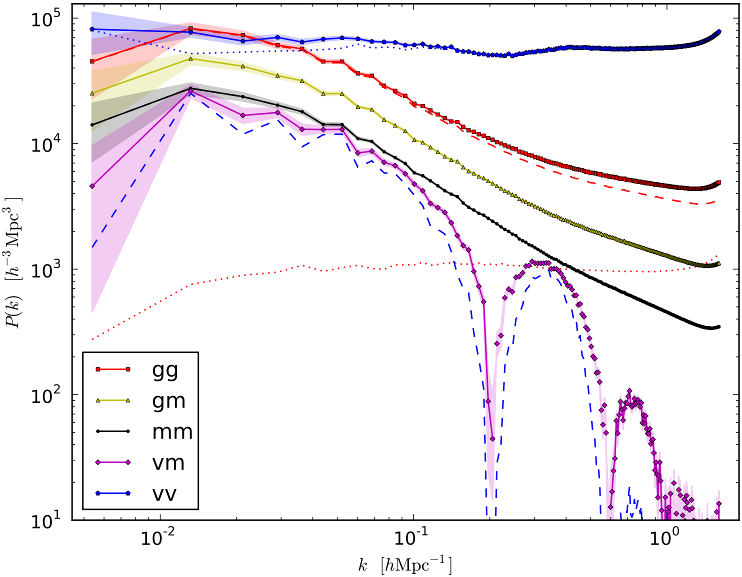
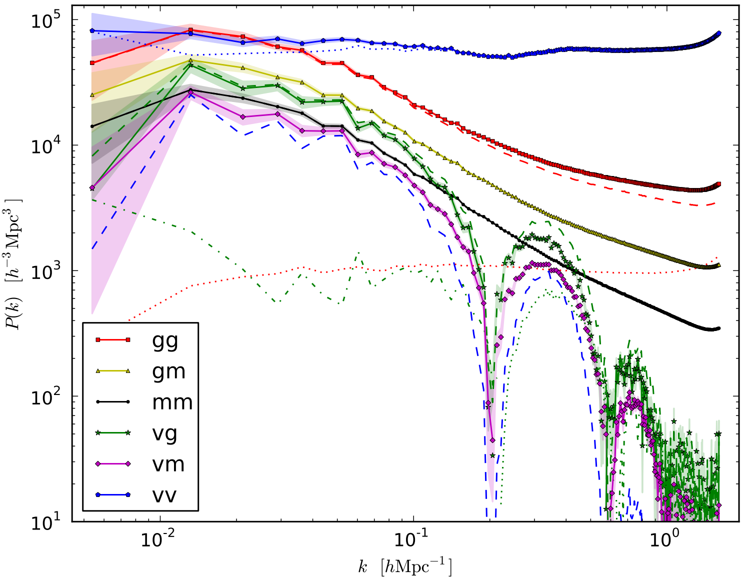
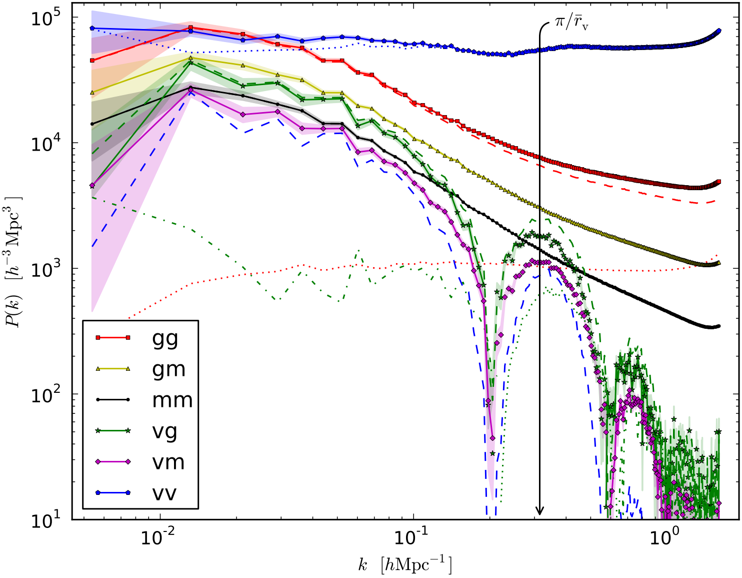


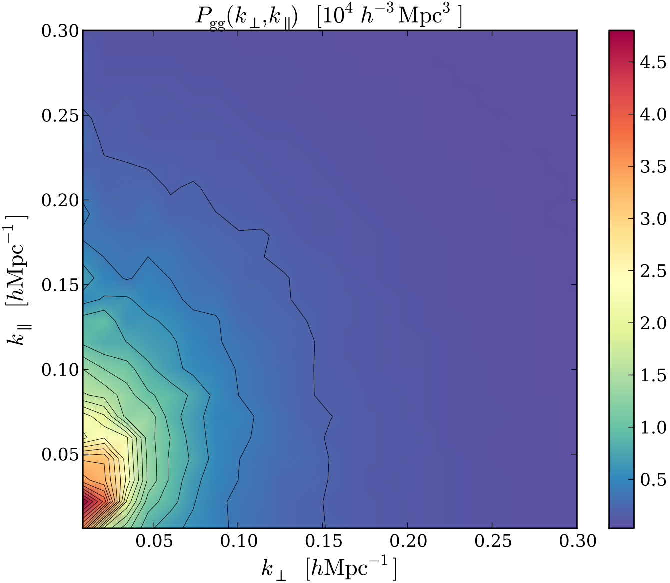
Power spectrum



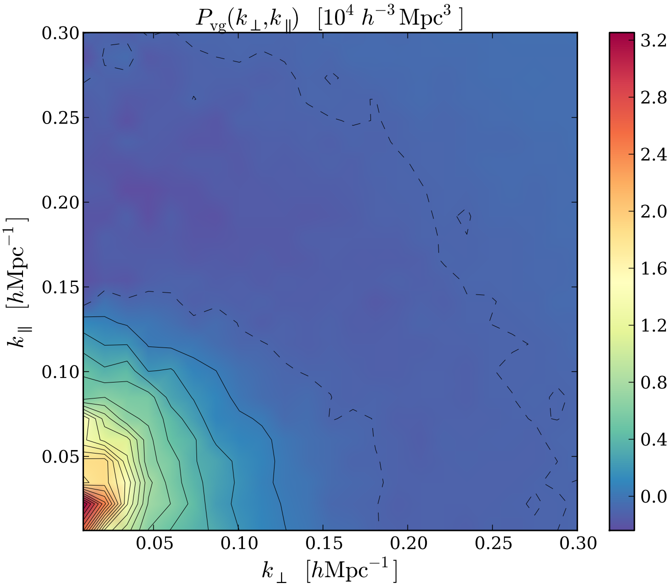
Power spectrum



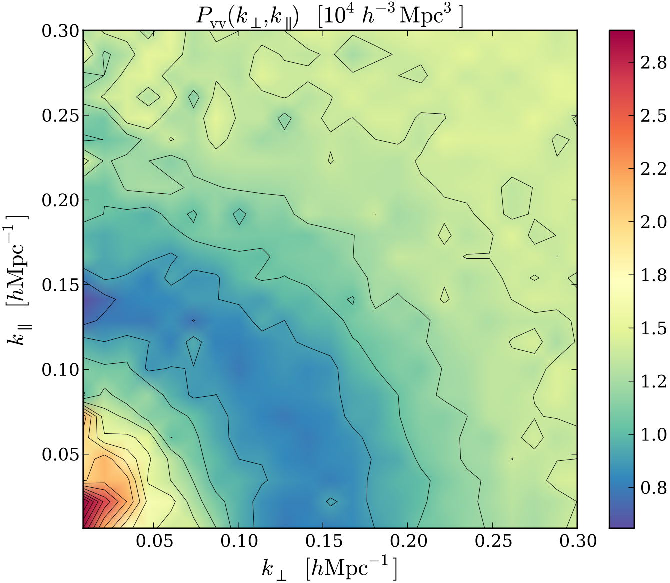
2D power spectrum



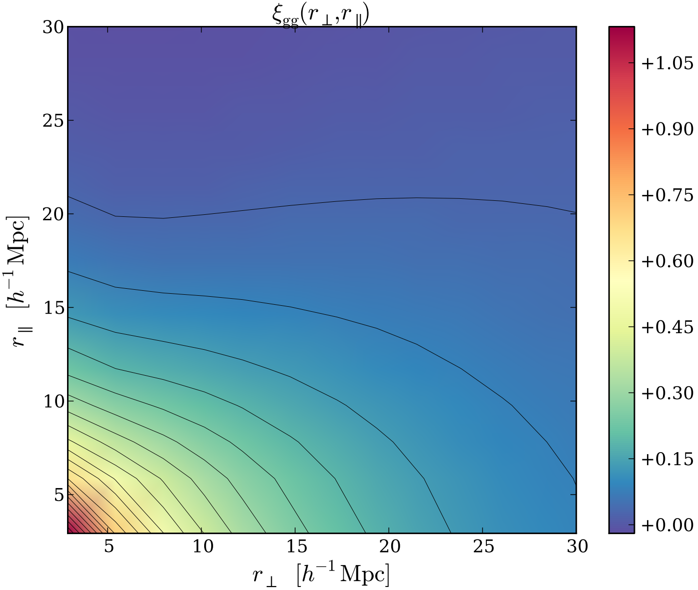
2D power spectrum



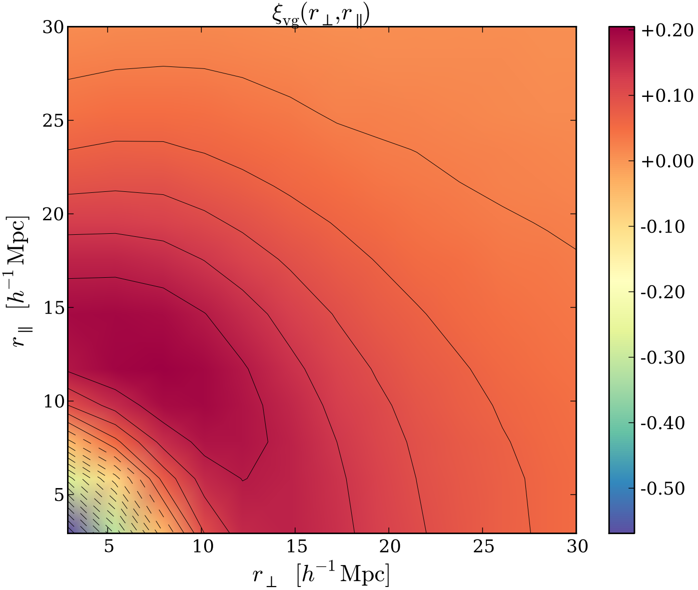
2D power spectrum



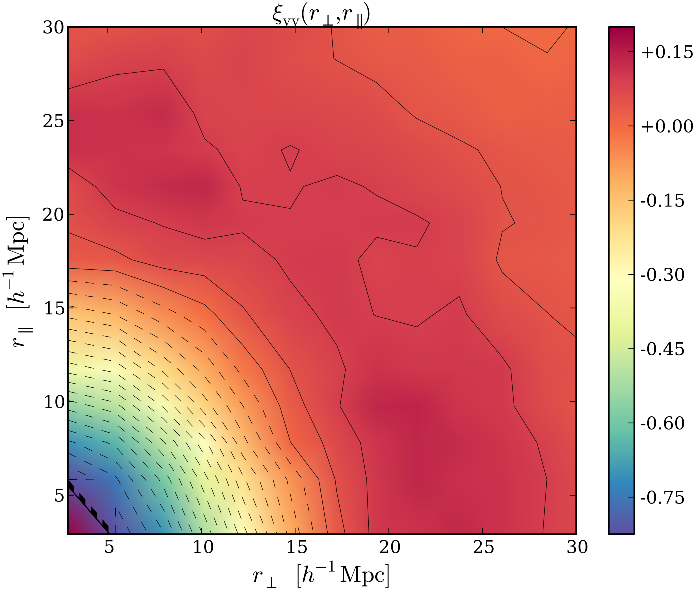
2D correlation function



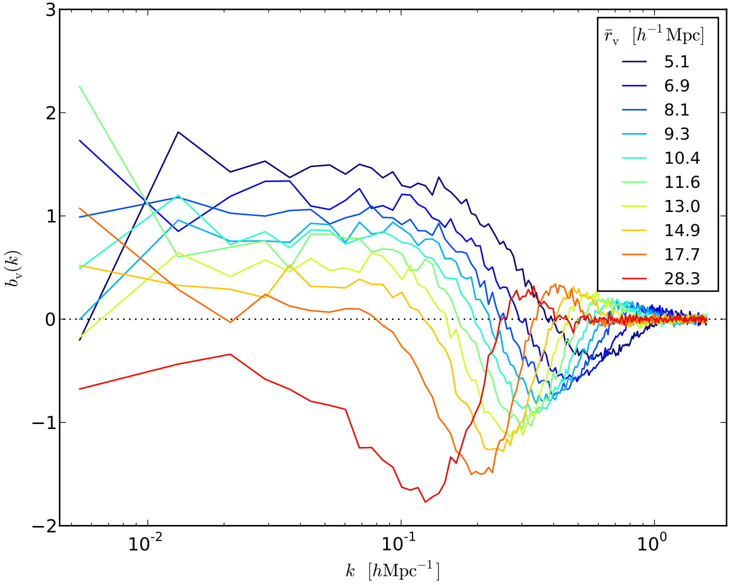
2D correlation function



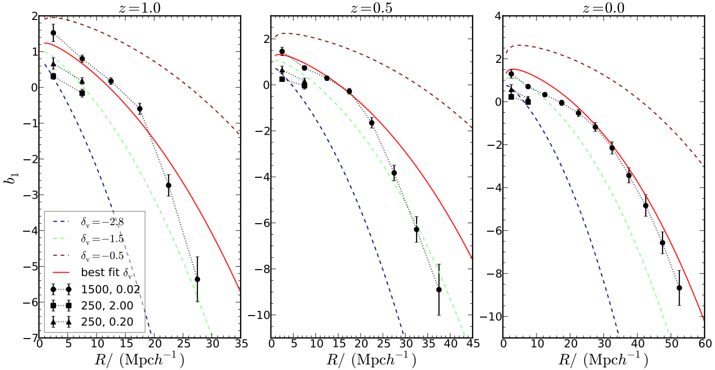
2D correlation function



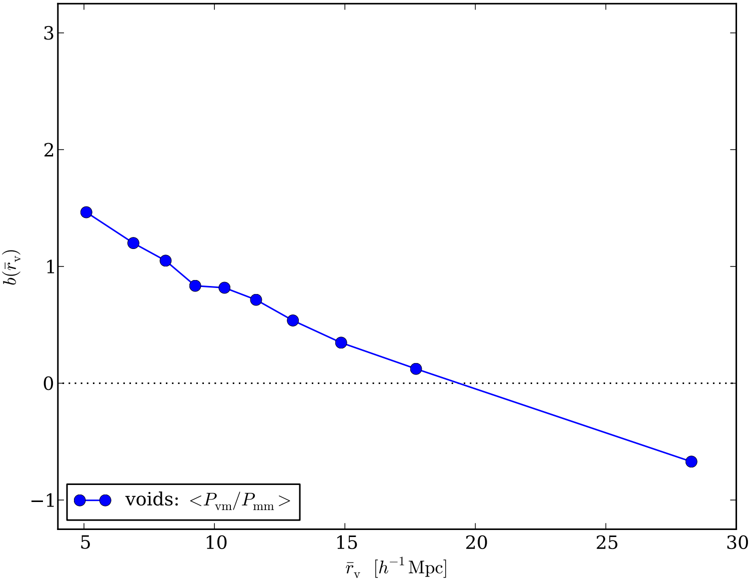
Void bias


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

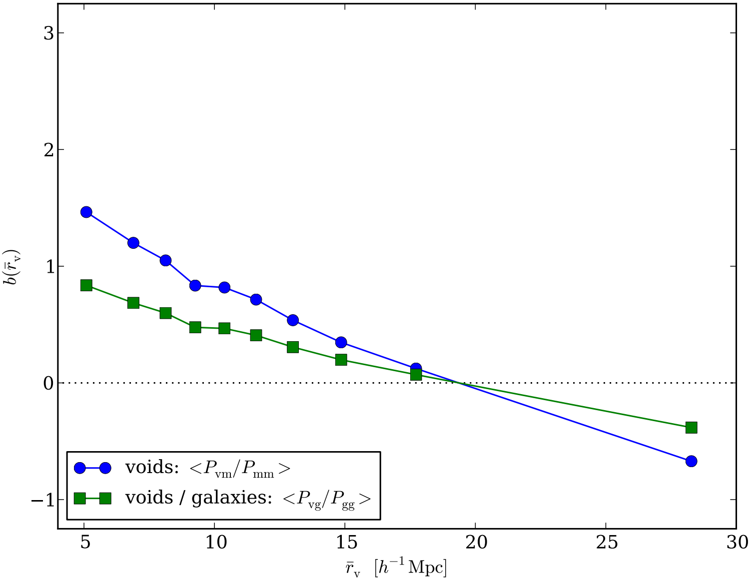
Linear void bias



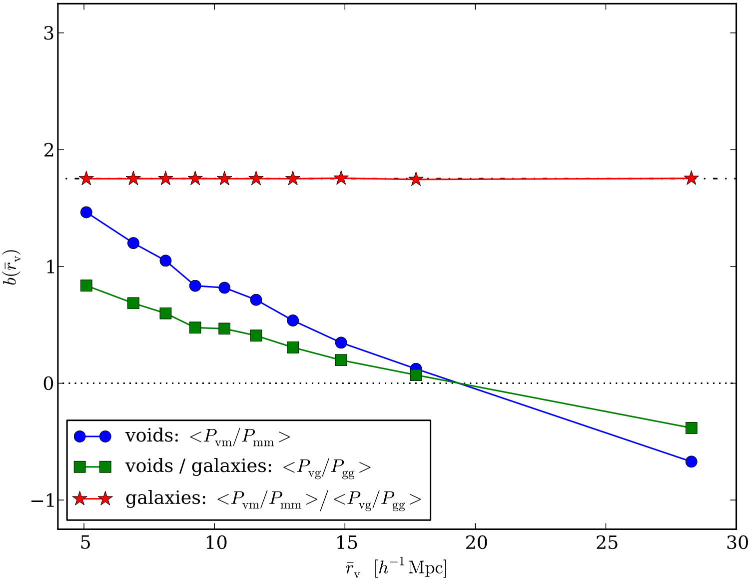
Linear void bias



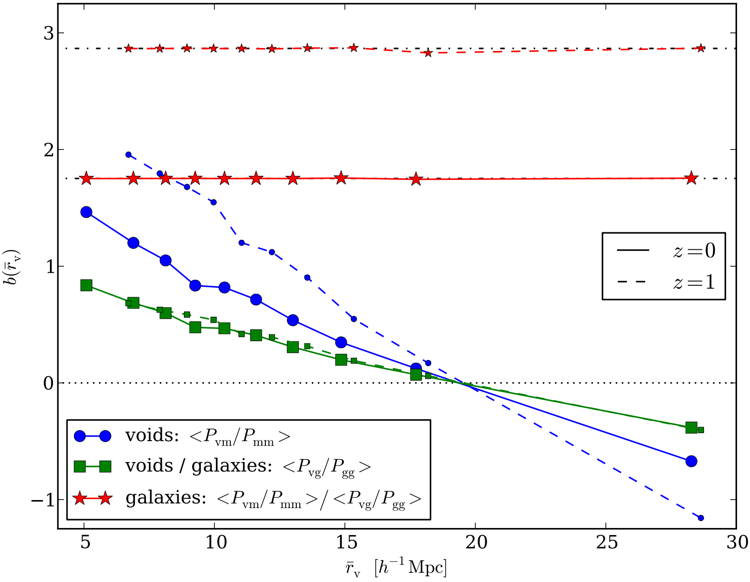
Linear void bias



Linear void bias



Linear void bias



Linear void bias