$f_{\rm NL}$ & $\sum m_\nu$
FROM THE CLUSTERING OF VOIDS

NICO HAMAUS

in collaboration with

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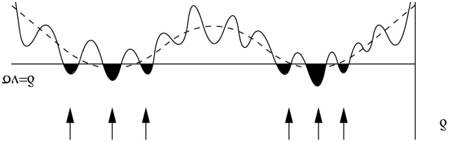
Outline

Definition of voids

Search for local minima in density field



Definition of voids

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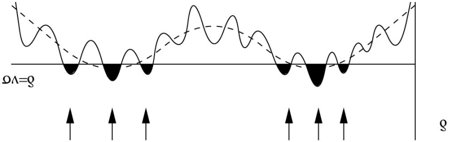
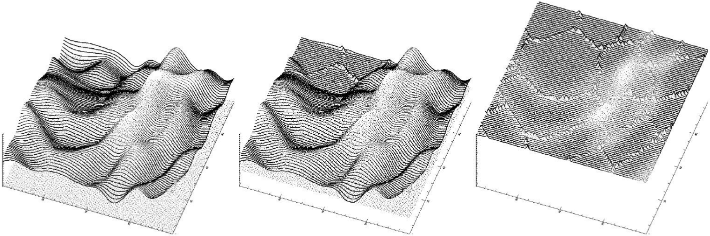
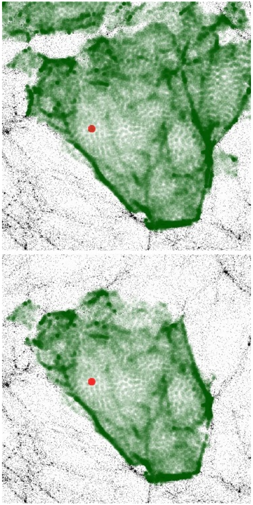


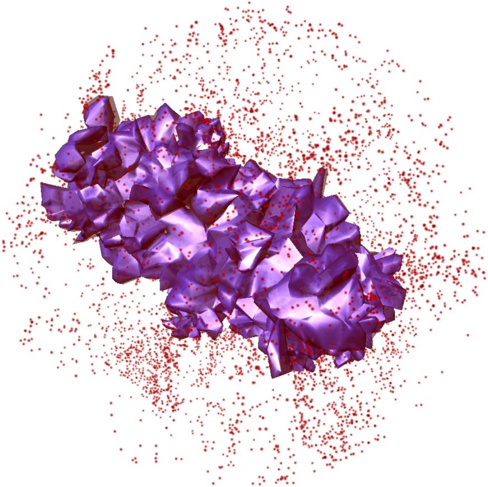
and raise a density threshold until a saddle point is reached



Watershed algorithm: Platen et al. (2007, MNRAS 380, 551)

Definition of voids

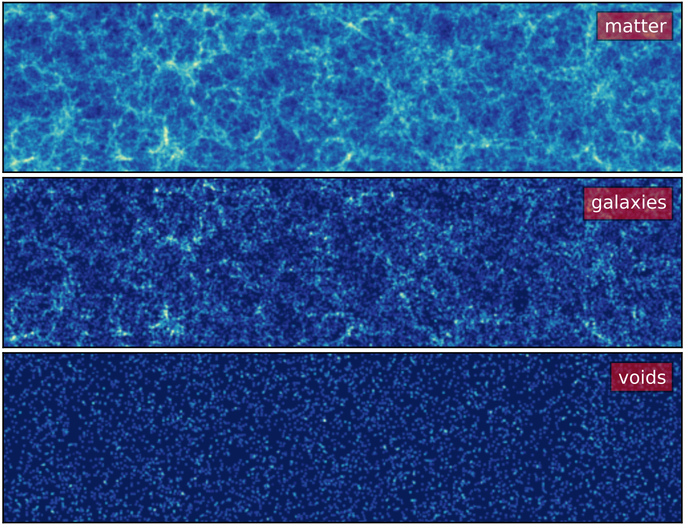




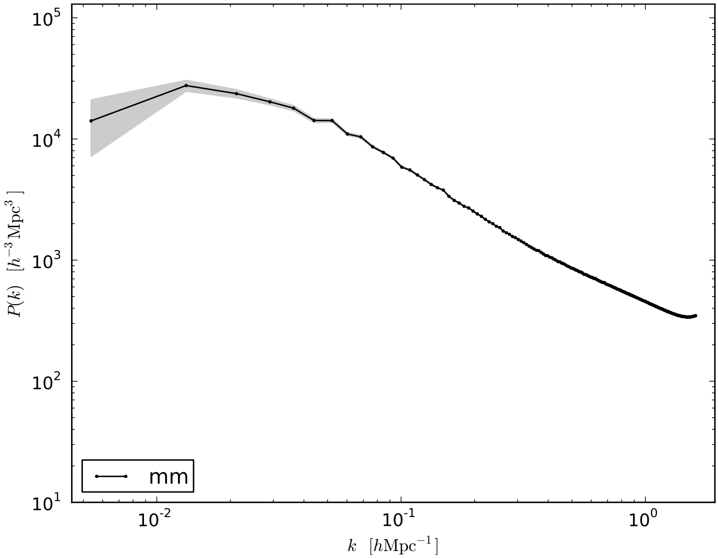
ZOBOV: Neyrinck (2008, MNRAS 386, 4) VIDE: Sutter, Lavaux, Hamaus et al. (2015, A&C 9, 1)

Density fields

Voids are biased tracers of LSS (less clustered and sparser than galaxies)

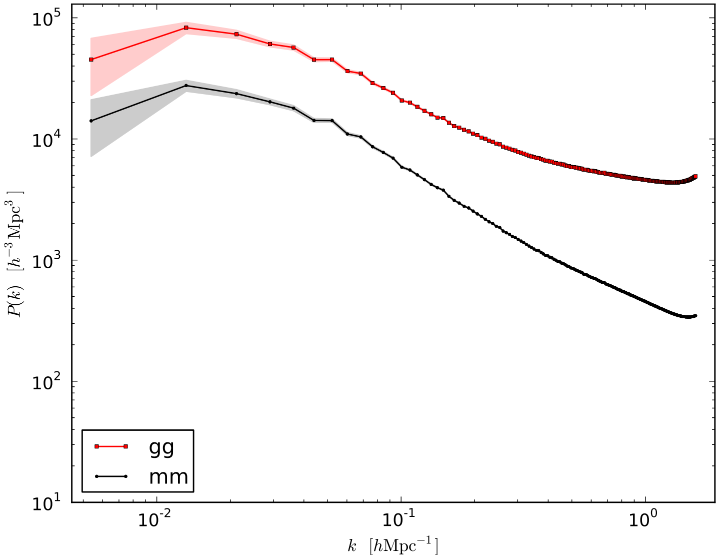


POWER SPECTRUM



Hamaus et al. (2014, PRL 112, 041304)

Power spectrum



Hamaus et al. (2014, PRL 112, 041304)

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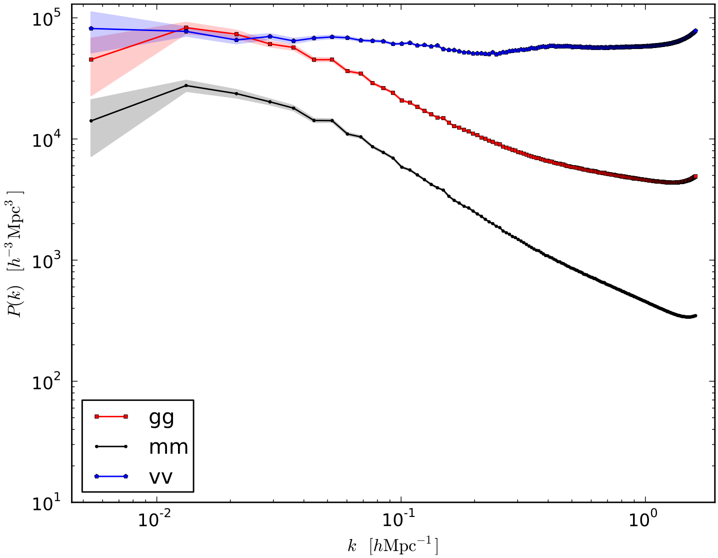

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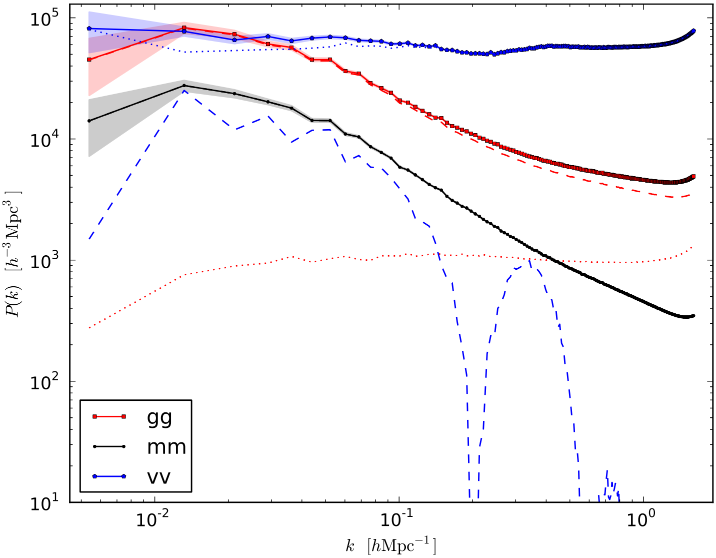
Power spectrum



Hamaus et al. (2014, PRL 112, 041304)

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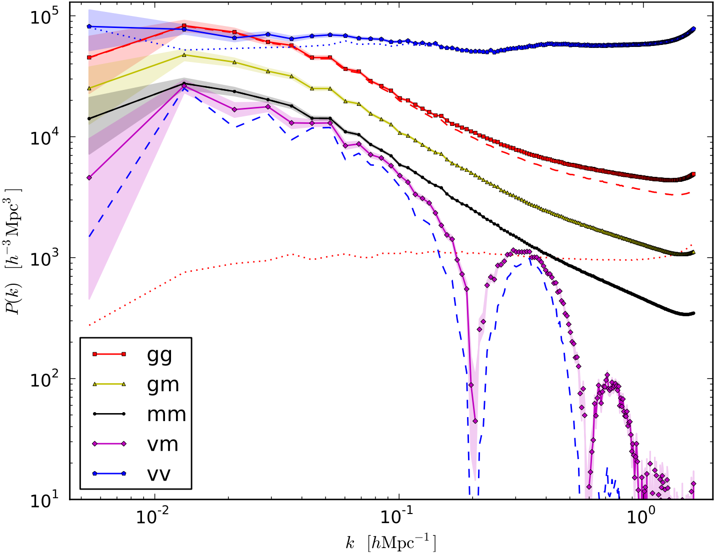

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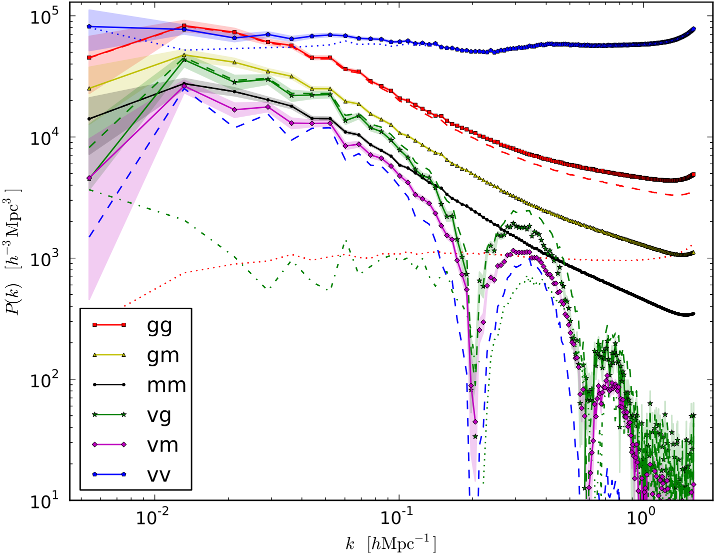

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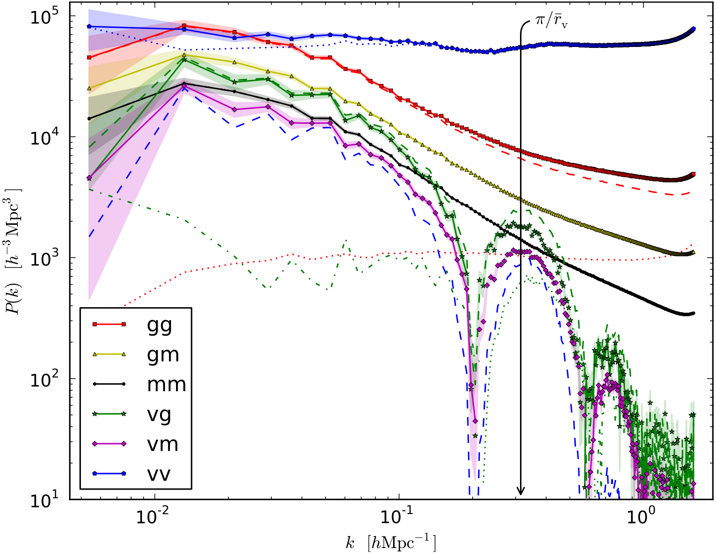
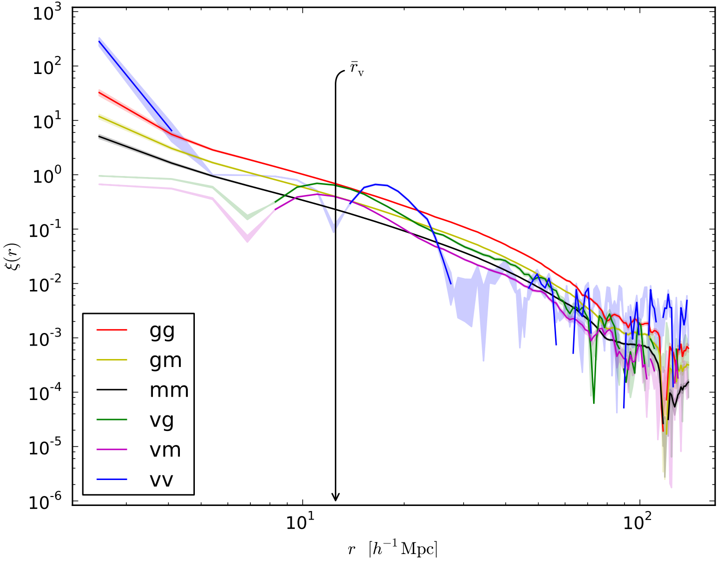


Hamaus et al. (2014, PRL 112, 041304)

Correlation function



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"Void model"

$$P_{\rm vg}^{(1\mathcal{V})}(k) = \frac{1}{\bar{n}_{\rm v}\bar{n}_{\rm g}} \int \frac{\mathrm{d}n_{\rm v}(r_{\rm v})}{\mathrm{d}r_{\rm v}} N_{\rm g}(r_{\rm v})\; u_{\rm v}(k|r_{\rm v})\; \mathrm{d}r_{\rm v}$$

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Model for voids of given radius

$$P_{\rm vg}(k) \simeq b_{\rm v} b_{\rm g} u_{\rm v}(k) P(k) + \bar{n}_{\rm v}^{-1} u_{\rm v}(k)$$

$$P_{\rm vv}(k) \simeq b_{\rm v}^2 P(k) + \bar{n}_{\rm v}^{-1}$$

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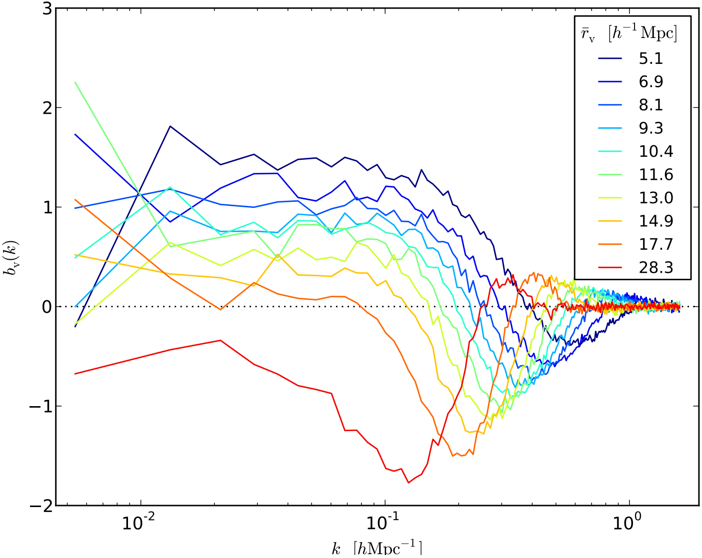
- Void density profile is normalized to $u_{\rm v}(k \to 0) = 1$
- Large scales: linearly biased tracers of dark matter
- Small scales: dominated by internal void structure

Void bias



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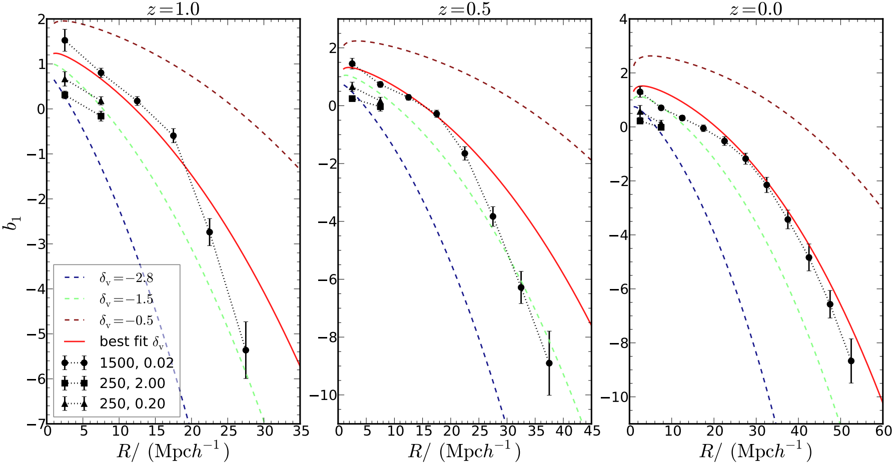
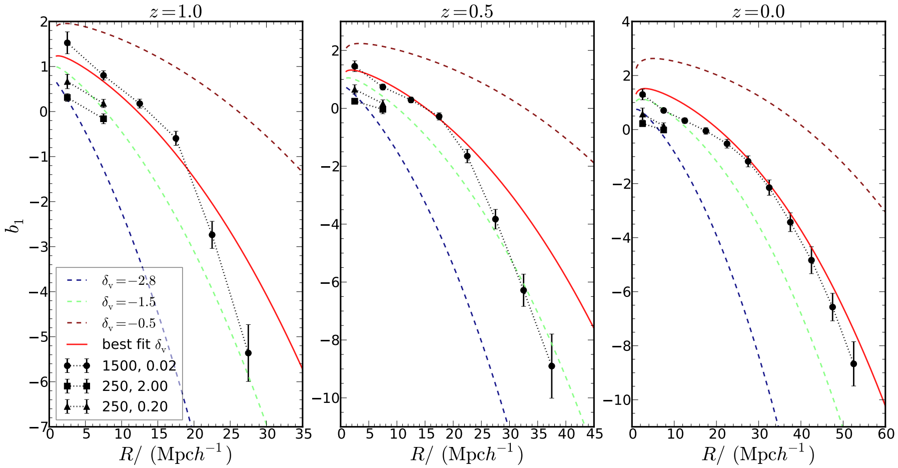
Linear void bias



Chan, Hamaus, Desjacques (2014, PRD 90, 103521)

Linear void bias



Chan, Hamaus, Desjacques (2014, PRD 90, 103521)

Separate Universe Simulations: Chan, Li, Biagetti, Hamaus (2019, arXiv:1909.03736)

Primordial Non-Gaussianity

Expand primordial potential locally around Gaussian to first order

$$\Phi(\mathbf{x}) = \Phi_{\mathrm{G}}(\mathbf{x}) + f_{\mathrm{NL}} \left[\Phi_{\mathrm{G}}^2(\mathbf{x}) - \langle \Phi_{\mathrm{G}}^2 \rangle\right]$$

Coupling between short- and long-wavelength modes effectively causes local rescaling in the amplitude of matter fluctuations σ_8.

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Additional *scale-dependent* contribution to linear bias

$$b_{\rm NG} = 2f_{\rm NL}\mathcal{M}^{-1}\frac{\partial\ln n}{\partial\ln\sigma_8}\,, \qquad \mathcal{M}(k) = \frac{2}{3}\frac{k^2T(k)D(z)}{\Omega_{\rm m}H_0^2}$$

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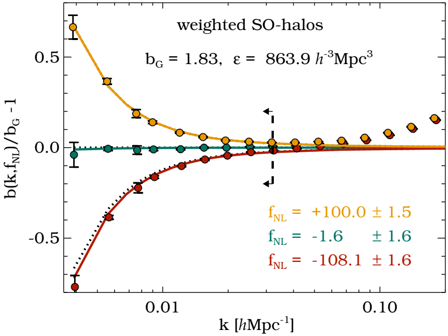
With a *universal* halo-mass function / void-size function:

$$b(k, f_{\rm NL}) = b_{\rm G} + f_{\rm NL}(b_{\rm G}-1)\delta_c\frac{3\Omega_{\rm m}H_0^2}{k^2T(k)D(z)}$$

Dalal et al. (2008, PRD 77, 123514); Slosar et al. (2008, JCAP 08, 031)

Scale-dependent bias



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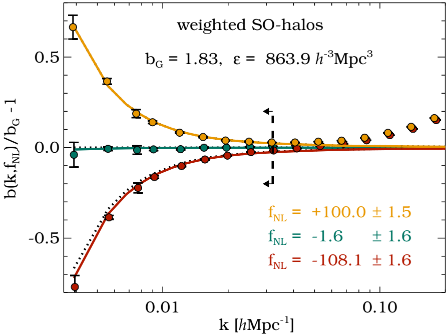
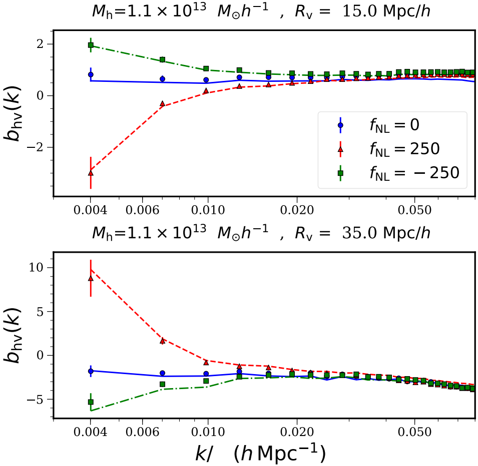
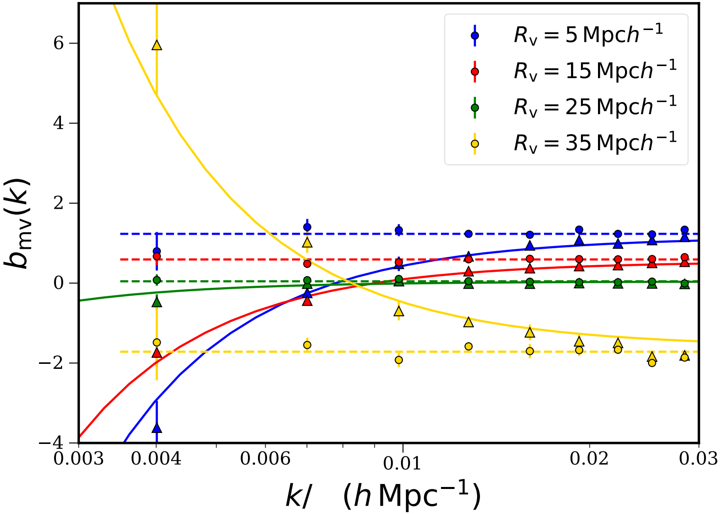


Hamaus, Seljak, Desjacques (2011, PRD 84, 083509)



Chan, Hamaus, Biagetti (2019, PRD 99, 121304)

Scale-dependent void bias



Chan, Hamaus, Biagetti (2019, PRD 99, 121304)

Fisher forecast

Perform *multi-tracer* analysis (5 halo-mass bins, 3 void-size bins):

$$F_{f_{\mathrm{NL}}f_{\mathrm{NL}}} = V \int \frac{\mathrm{d}^3k}{(2\pi)^3} \frac{1}{2} \mathrm{Tr}\left(\Sigma^{-1} \frac{\partial \Sigma}{\partial f_{\mathrm{NL}}} \Sigma^{-1} \frac{\partial \Sigma}{\partial f_{\mathrm{NL}}} \right) , \quad \Sigma_{ij} \equiv \langle \delta_i(\boldsymbol{k}) \delta_j(\boldsymbol{k}) \rangle$$

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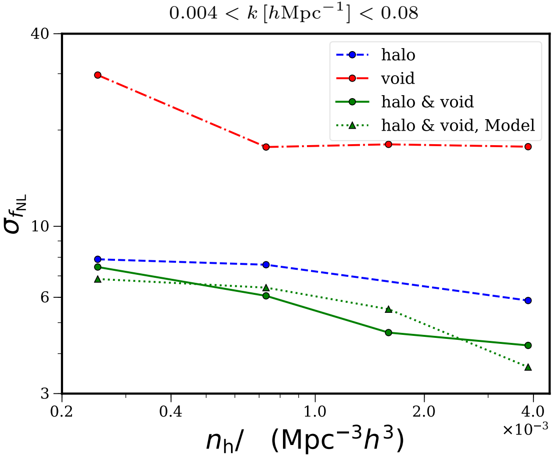
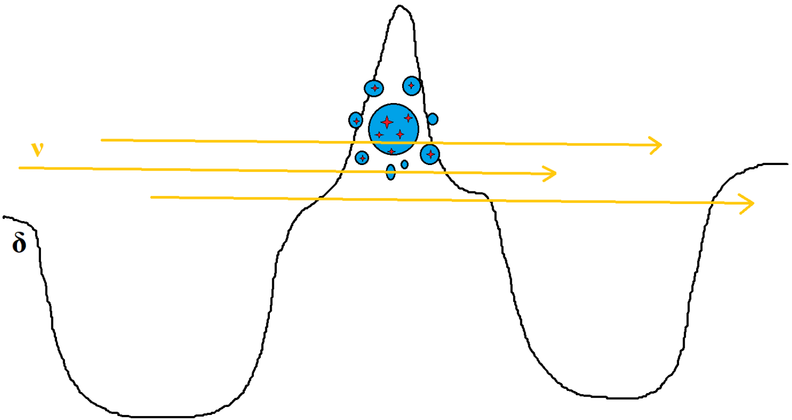


Neutrinos and voids

Neutrinos freely stream into voids

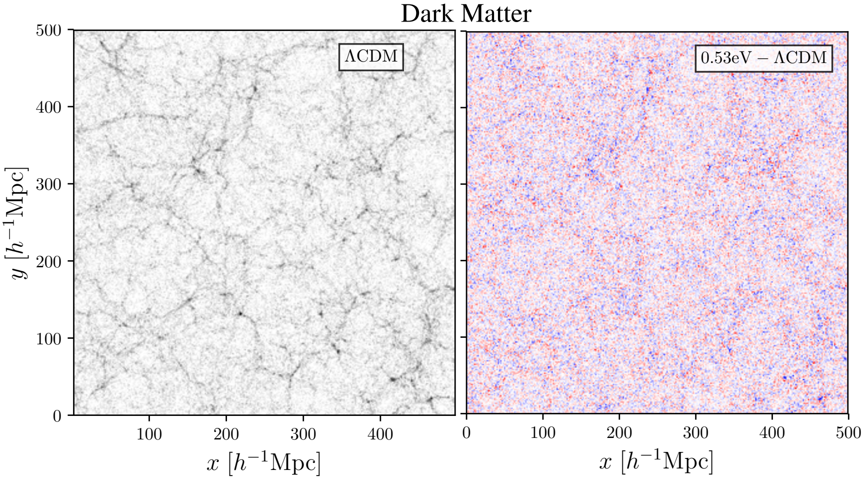


Massara et al. (2015, JCAP 11, 018)

Banerjee & Dalal (2016, JCAP 11, 015)

Kreisch et al. (2019, MNRAS 488, 4413)

DEMNUni Simulations



$$L_{\mathrm{box}} = 2h^{-1}\mathrm{Gpc},\ N_{\mathrm{cdm}} = 2048^3,\ N_{\nu} = 2048^3,\ \sum m_{\nu}[eV] = 0.17, 0.30, 0.53$$

Castorina et al. (2015, JCAP 7, 043); Carbone, Petkova, Dolag (2016, JCAP 7, 034)

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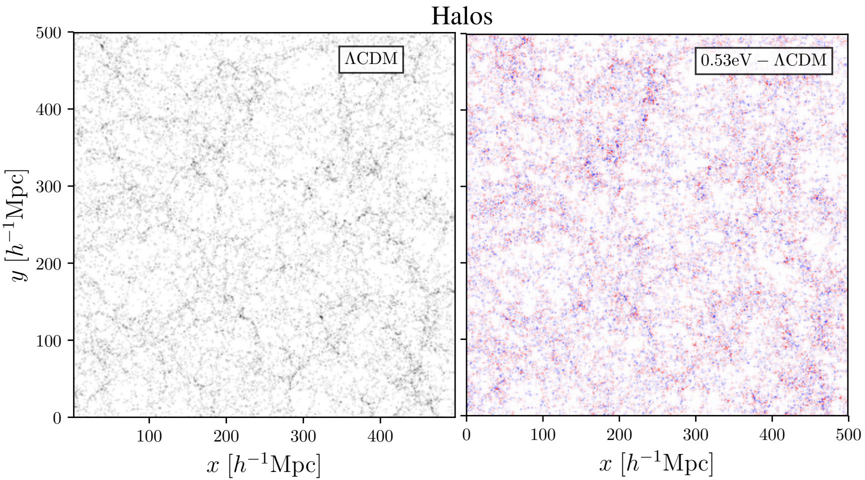

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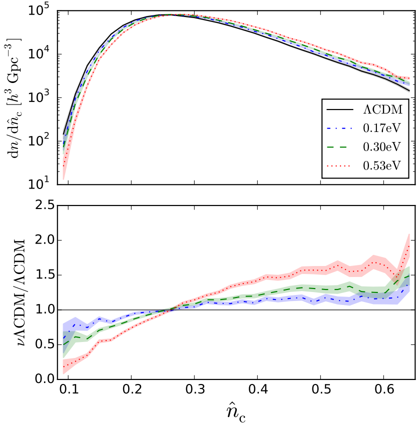
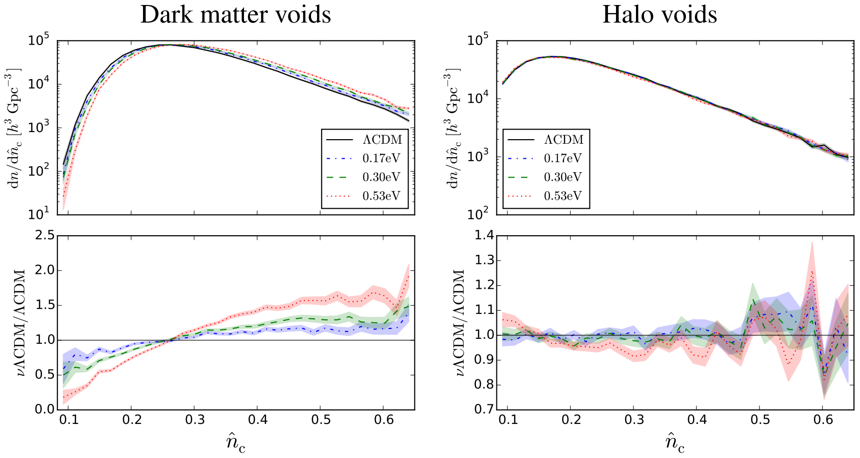
Void abundance

Dark matter voids

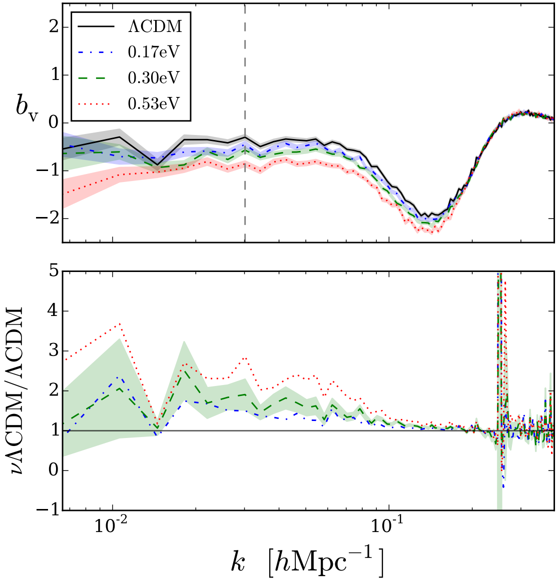


Halo voids

Void abundance

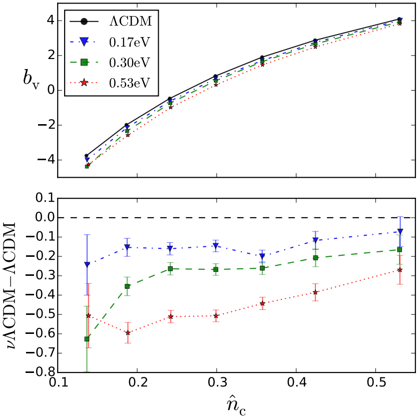


Void bias



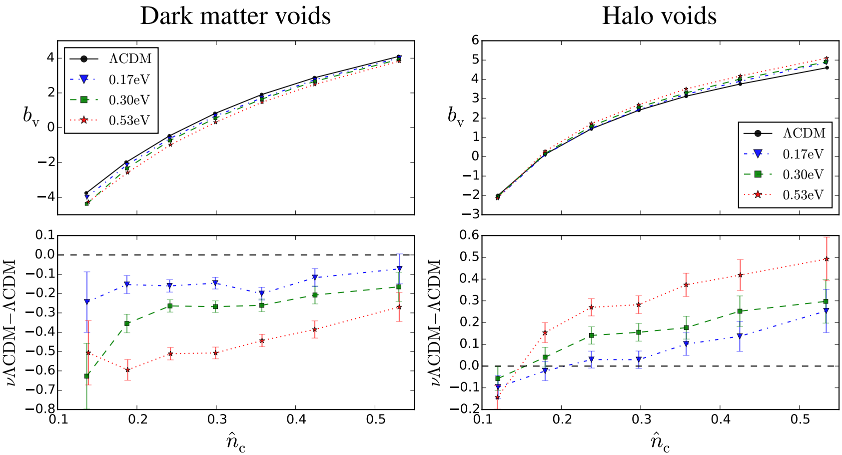
Linear void bias

Dark matter voids



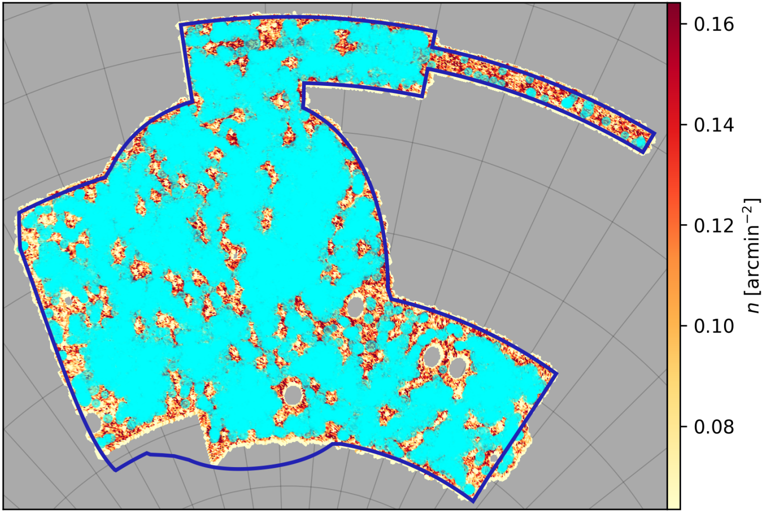
Halo voids

Linear void bias



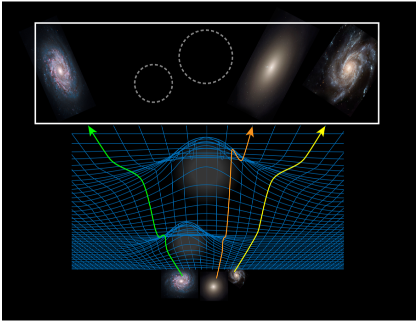
Schuster, Hamaus et al. (2019, JCAP in press, arXiv:1905.00436)

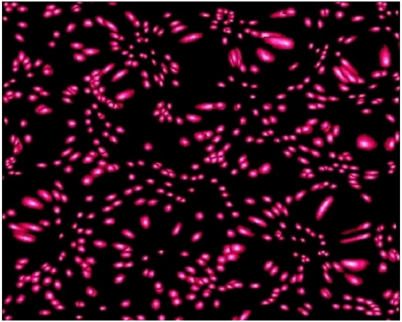
Voids in the Dark Energy Survey



Pollina, Hamaus et al. (in prep. for DES)

Void lensing





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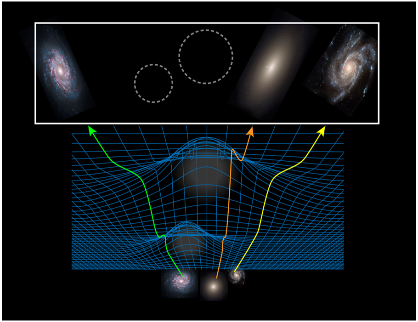

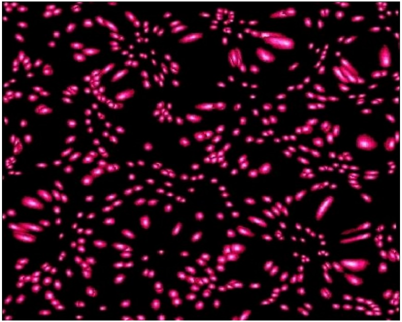

$$\Delta\Sigma(r_p) \equiv \bar{\Sigma}(< r_p) - \Sigma(r_p) = \Sigma_{\rm crit}\gamma_+(r_p) \ , \quad \Sigma_{\rm crit} = \frac{c^2}{4\pi G}\frac{D_A(z_{\rm s})}{D_A(z_{\rm l})D_A(z_{\rm l}, z_{\rm s})}$$

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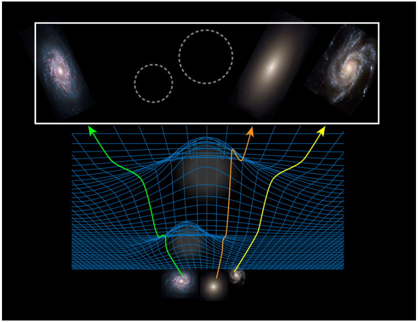

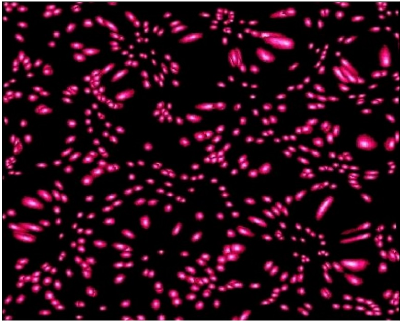

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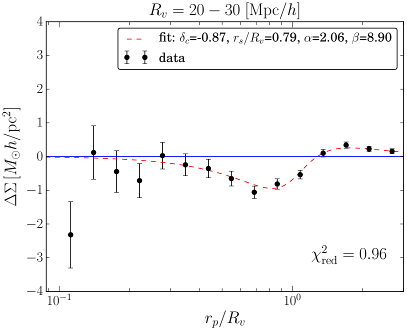
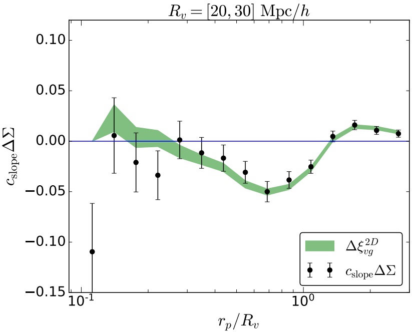
$$\Sigma(r_p) = \int \rho\left(\sqrt{[r_z - D_A(z_{\rm l})]^2 + r_p^2}\right)\mathrm{d}r_z$$

Void lensing: DES Y1





Fang, Hamaus et al. (2019, MNRAS 490, 3573)

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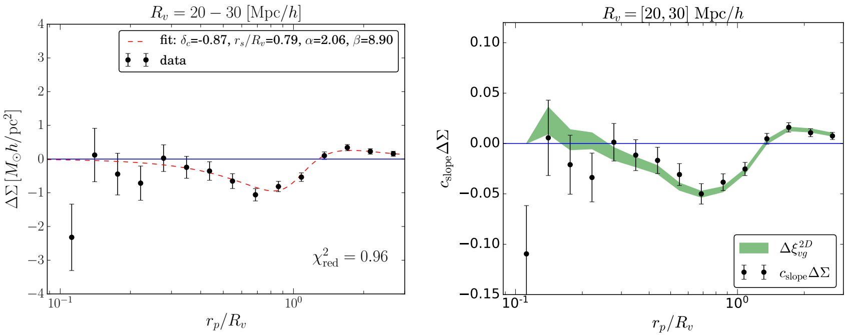

Fang, Hamaus et al. (2019, MNRAS 490, 3573)

Mass (dark matter + baryons) vs. Light (baryons)

$$\left.\begin{aligned}\Delta\Sigma(r_p) &\equiv \bar{\Sigma}(<r_p) - \Sigma(r_p)\\ \Delta\xi^{\mathrm{2D}}_{\mathrm{vg}}(r_p) &\equiv \bar{\xi}^{\mathrm{2D}}_{\mathrm{vg}}(<r_p) - \xi^{\mathrm{2D}}_{\mathrm{vg}}(r_p)\end{aligned}\right\} \Rightarrow \Delta\xi^{\mathrm{2D}}_{\mathrm{vg}}(r_p) = \frac{b_{\mathrm{g}}}{\langle\Sigma_{\mathrm{m}}\rangle}\Delta\Sigma(r_p)$$

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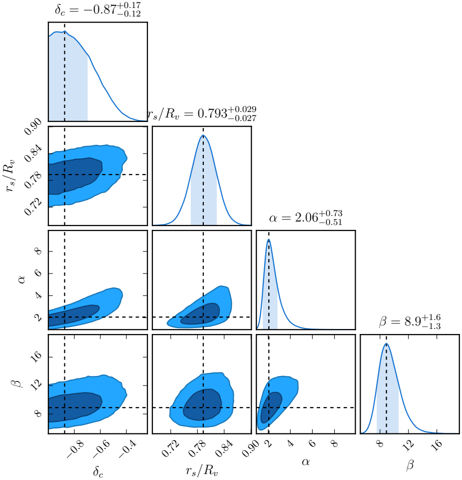

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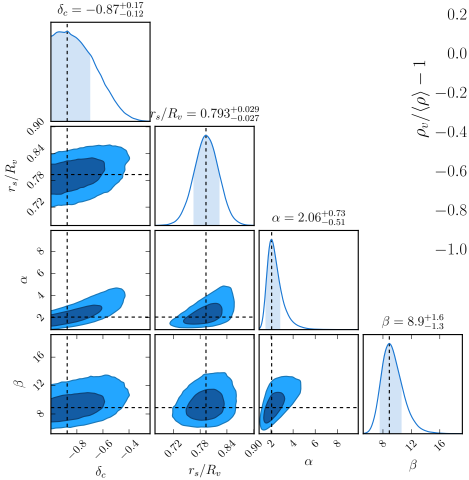

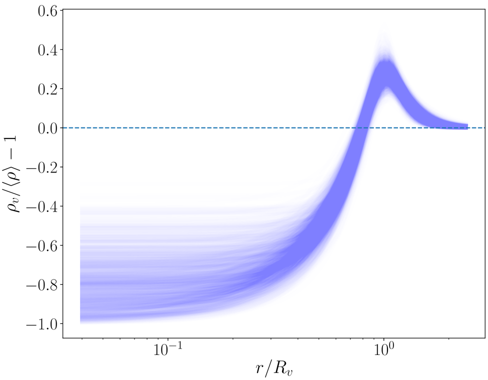

$$\frac{\rho_{\rm v}(r)}{\bar{\rho}} - 1 = \delta_c \frac{1-(r/r_s)^\alpha}{1+(r/r_{\rm v})^\beta}$$

Fang, Hamaus et al. (2019, MNRAS 490, 3573)

Conclusions

- Voids are biased tracers of the LSS, like galaxies / 21cm / Ly-α, etc.

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- Their linear bias extends far into the negative regime.

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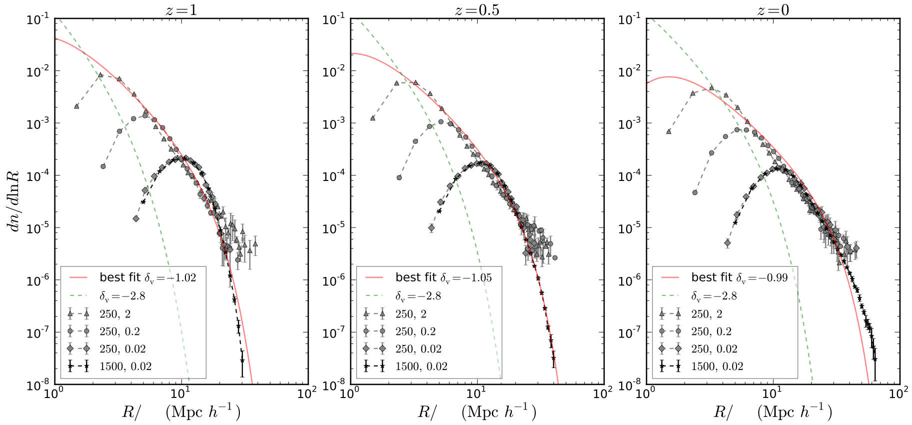
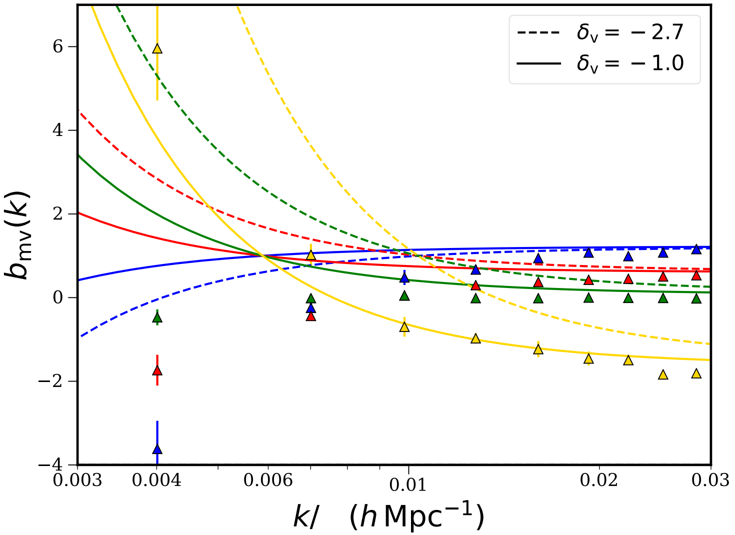
Thank you !

Void abundance



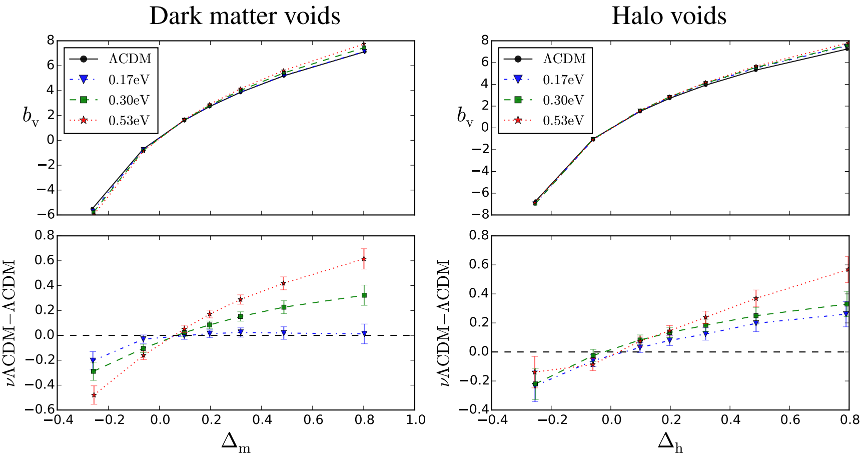
Chan, Hamaus, Desjacques (2014, PRD 90, 103521)

Scale-dependent void bias



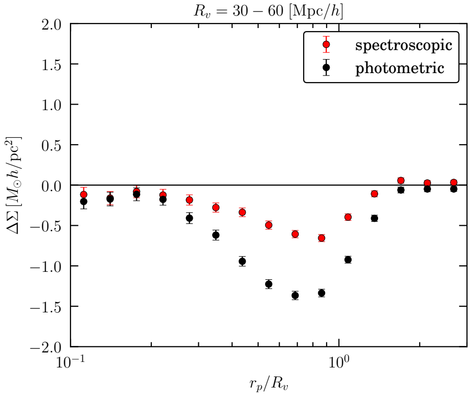
Chan, Hamaus, Biagetti (2019, PRD 99, 121304)

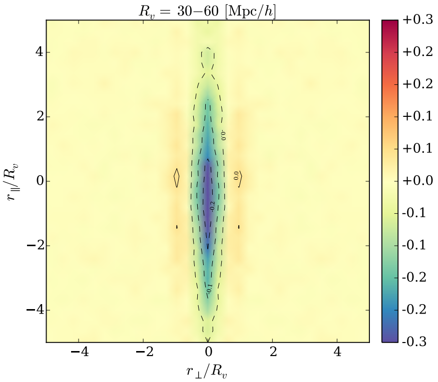
Linear void bias



Schuster, Hamaus et al. (2019, JCAP in press, arXiv:1905.00436)

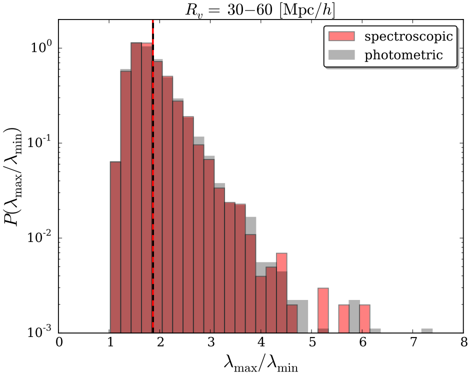
Void lensing: DES Y1 mocks

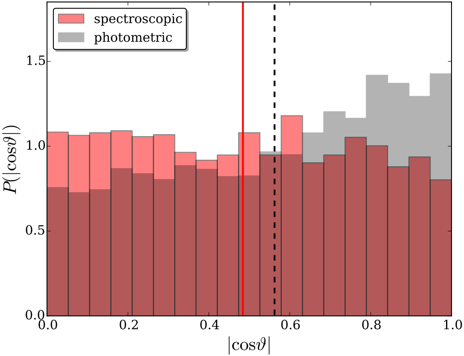




Fang, Hamaus et al. (2019, MNRAS 490, 3573)

Void lensing: DES Y1 mocks





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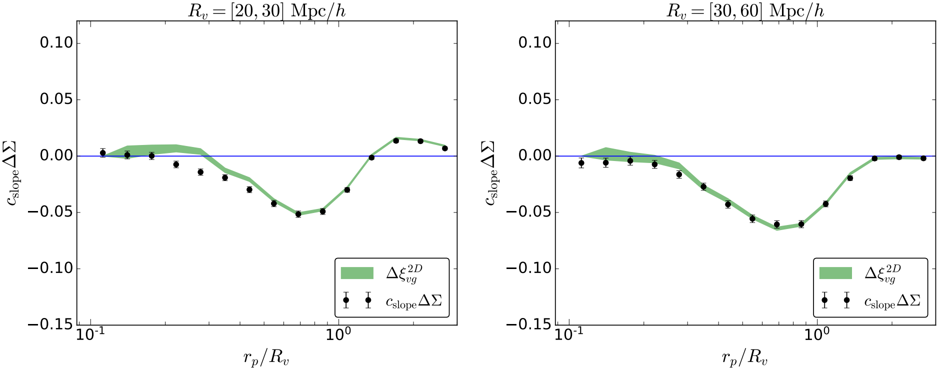

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