AstroParticle Symposium 2022, November 8th

Nonlinear Structure and Linear Dynamics of Voids

arxiv:2210.02457

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in collaboration with

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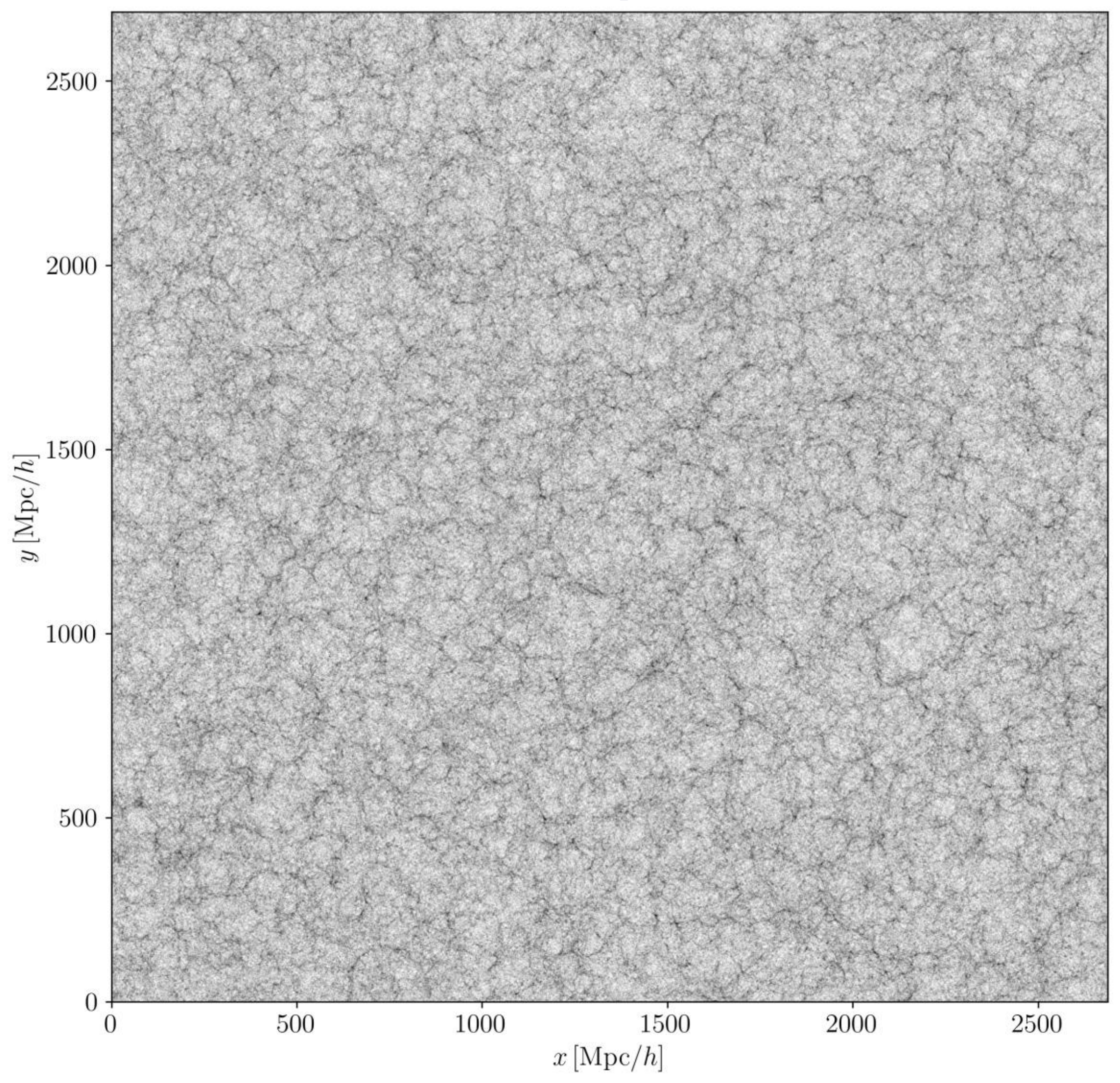
Outline

- Magneticum Simulations
- Void Distributions
- Density Profiles
- Velocity Profiles
- Linear Mass Conservation
- Conclusions

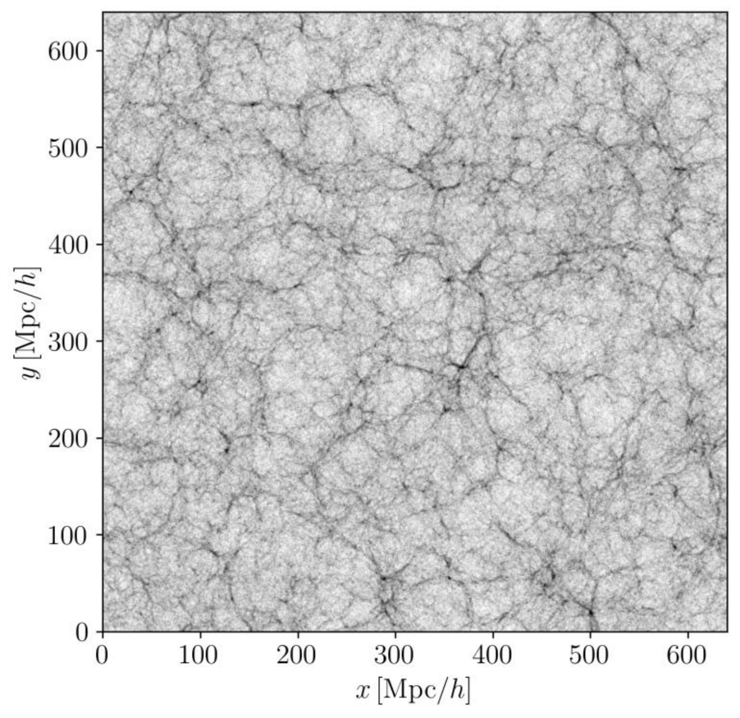
Magneticum Simulations - CDM

midres / mr

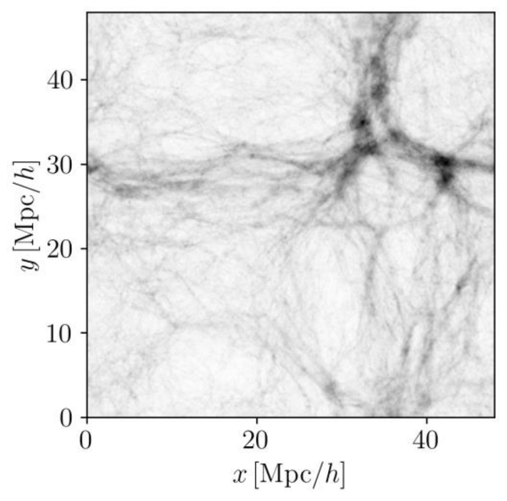


Hydrodynamical simulations with WMAP7 cosmology at different resolutions and scales, in this work at redshift $z = 0.29$.

highres / hr



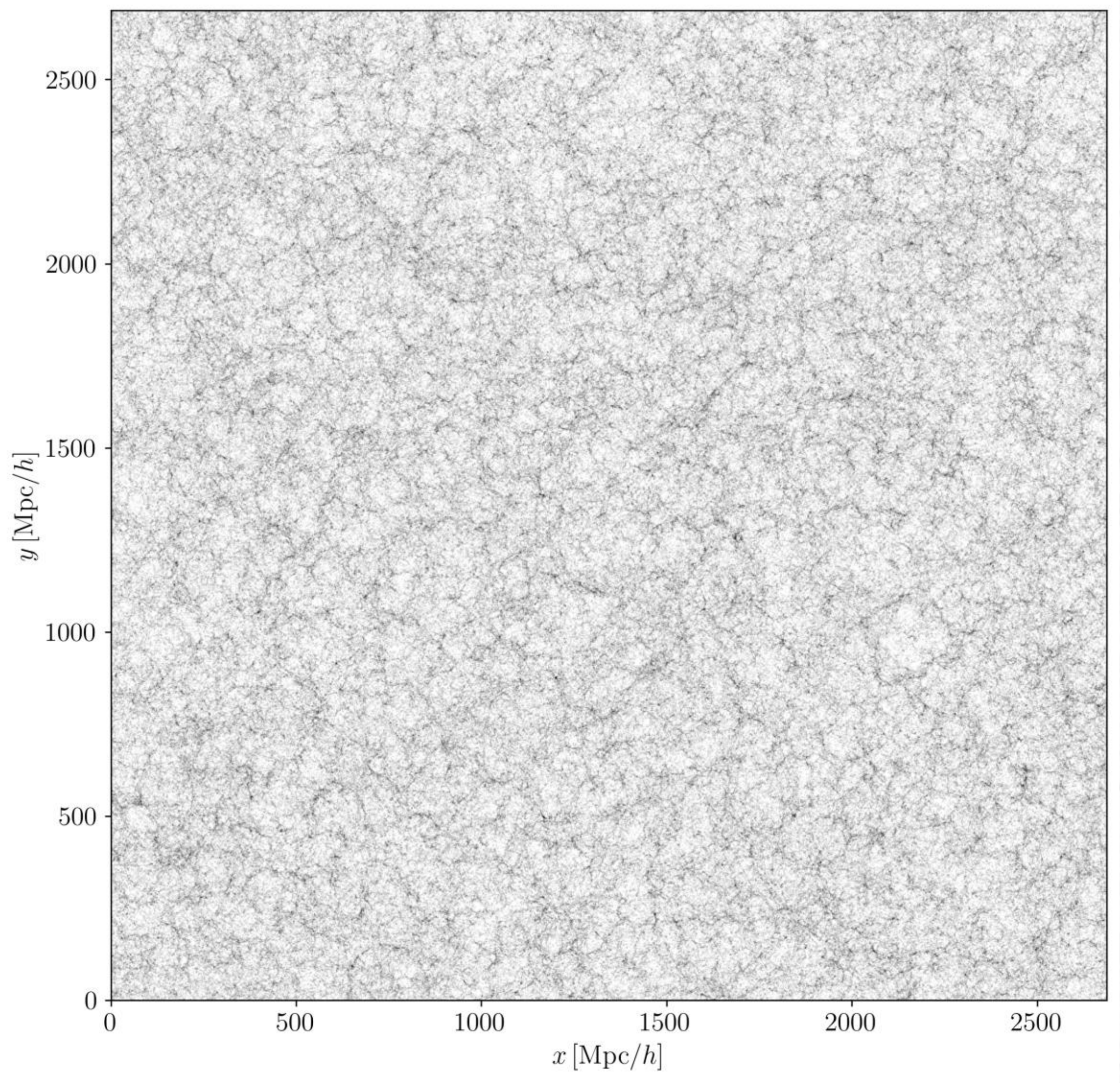
ultra-hr / uhr



magneticum.org

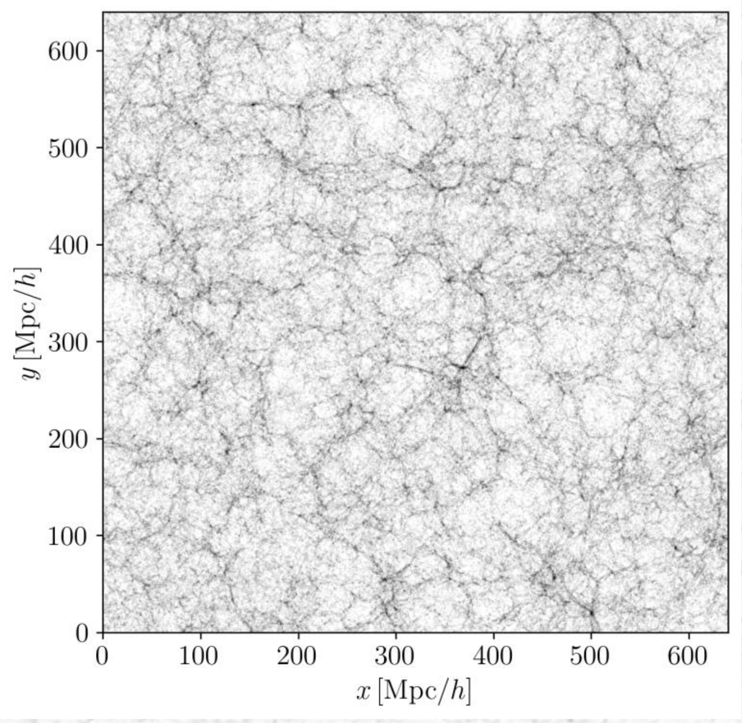
Magneticum Simulations - Halos

midres / mr

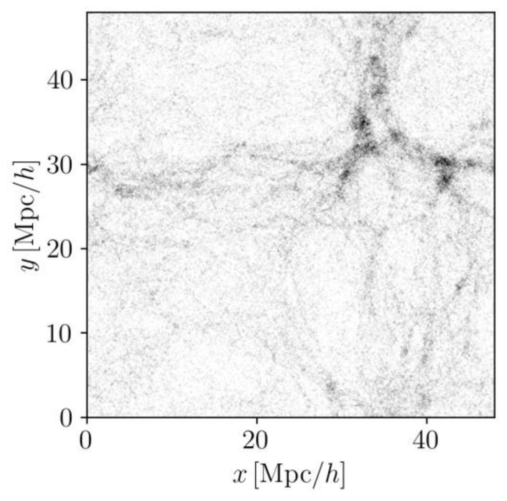


(Sub-) halo selection at different masses, depending on resolution limit of the simulations. For void finding both halos & CDM possible.

highres / hr



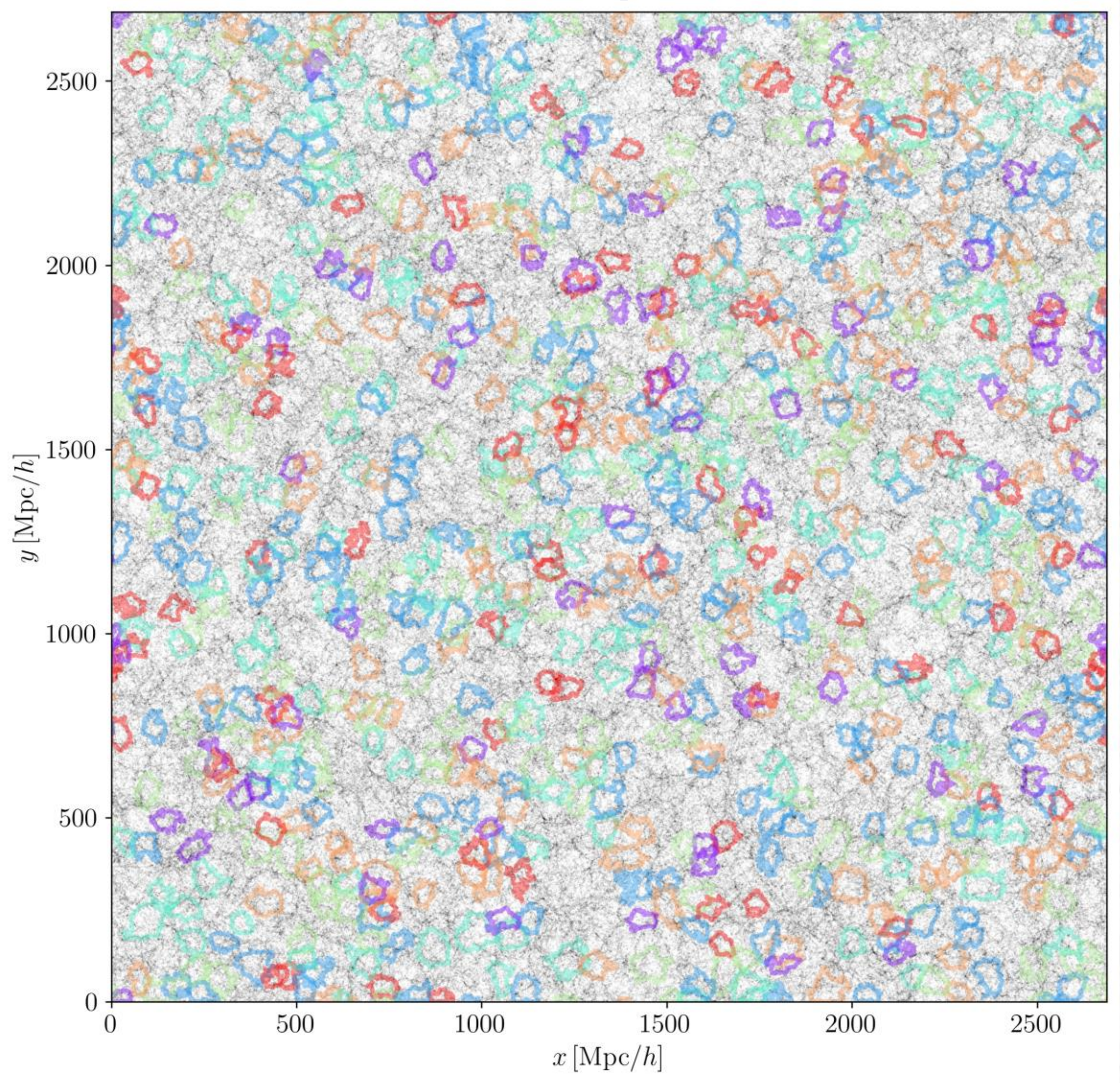
ultra-hr / uhr



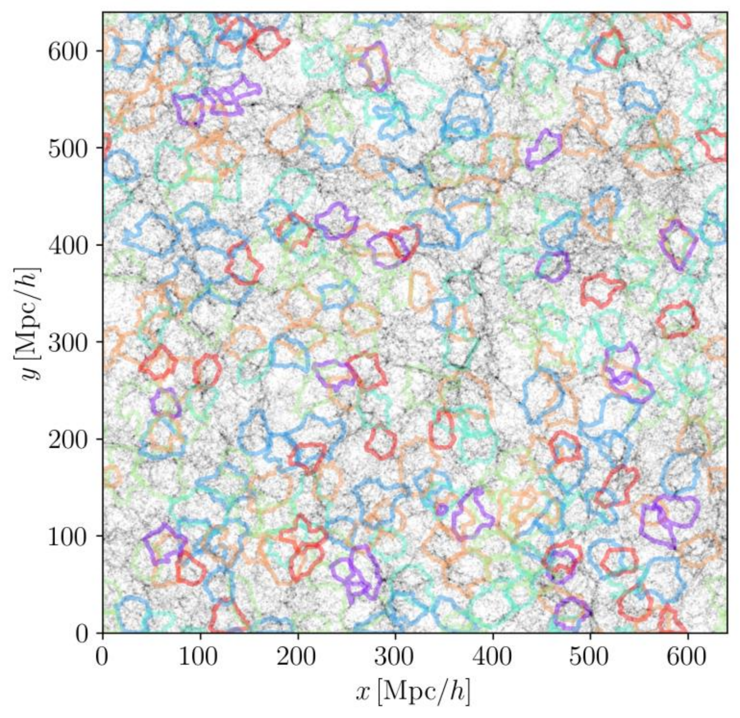
Magneticum Simulations - Voids

Voids identified using VIDE, via Voronoi tesselation and watershed algorithm. Voids can be merged, depending on density between shared wall.

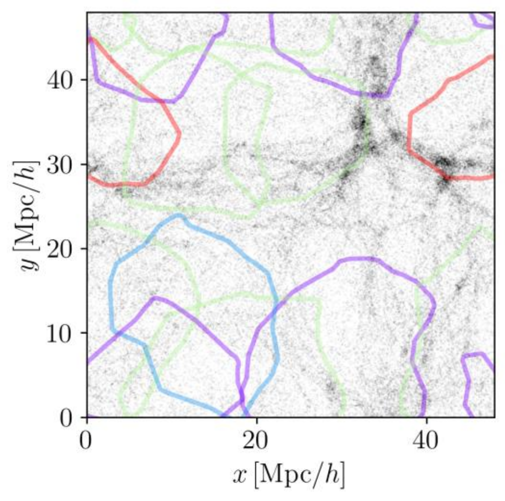
midres / mr



highres / hr

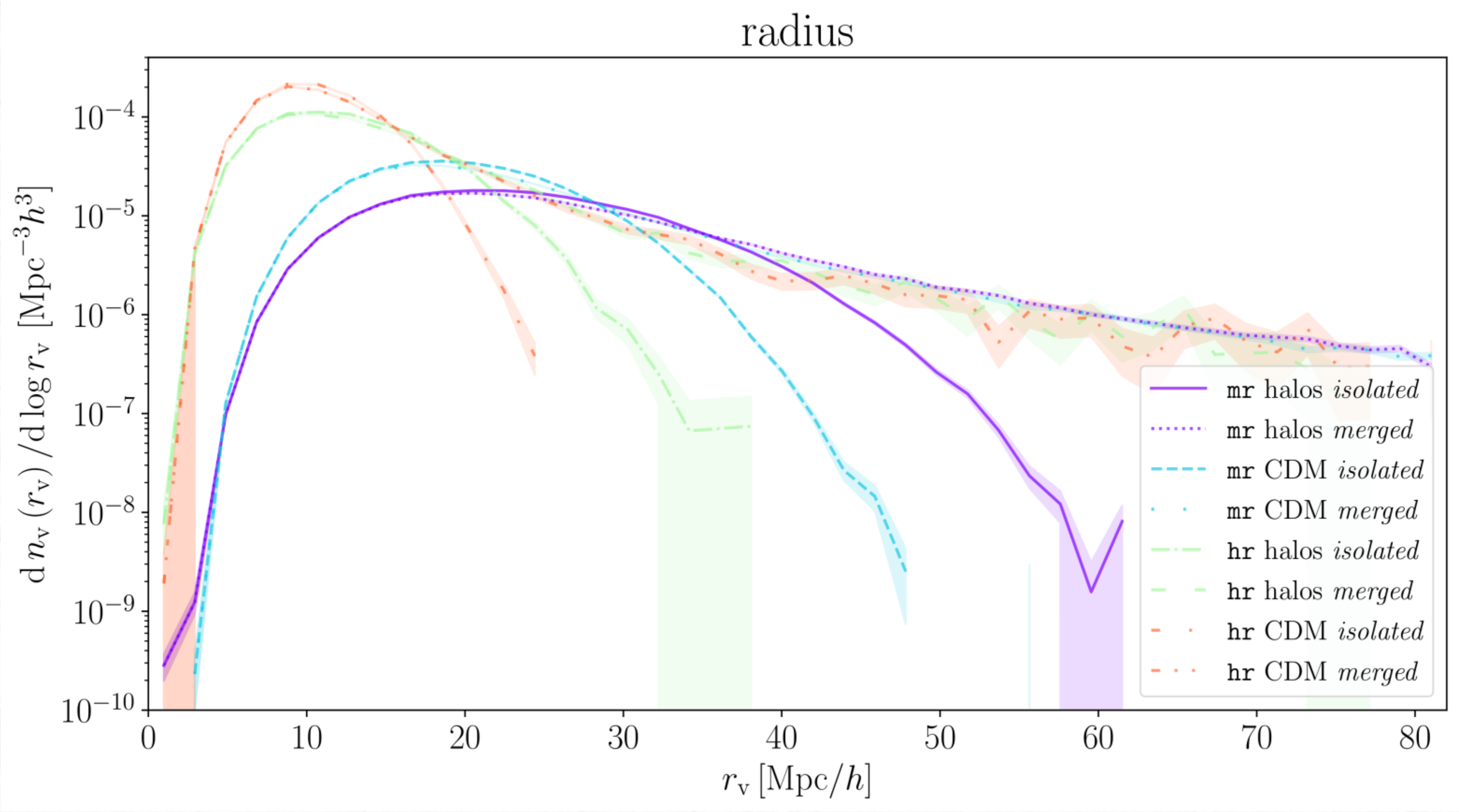


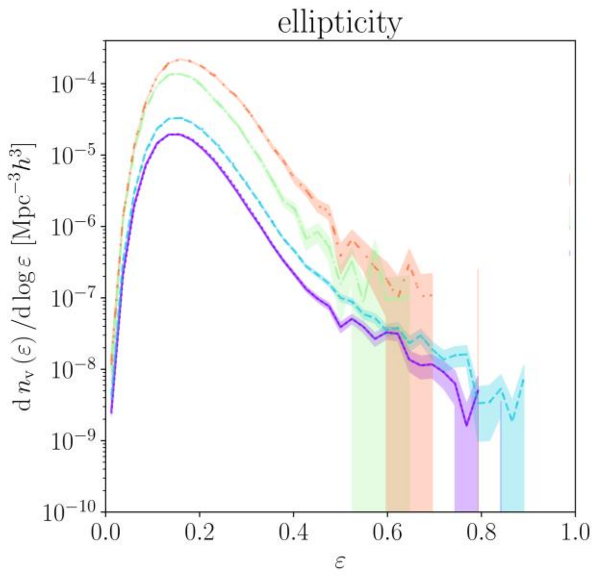
ultra-hr / uhr

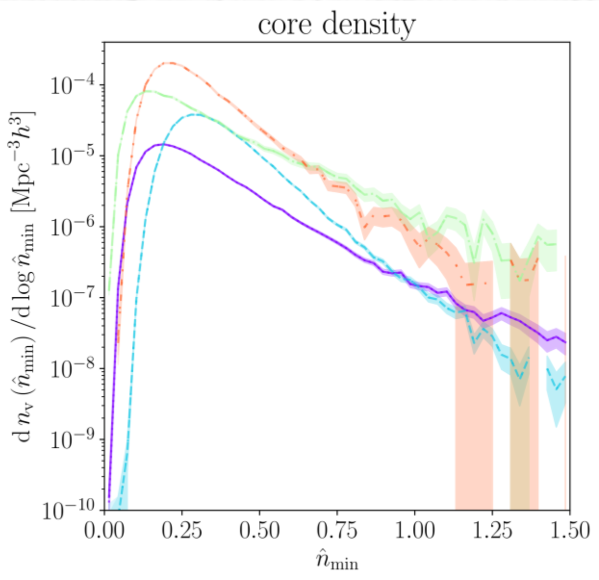


Void Distributions

Void size function in **midres** & **highres** for CDM and halo defined voids. More CDM voids than halo voids at identical n_t. Void size function of **merged** voids converges on large scales.

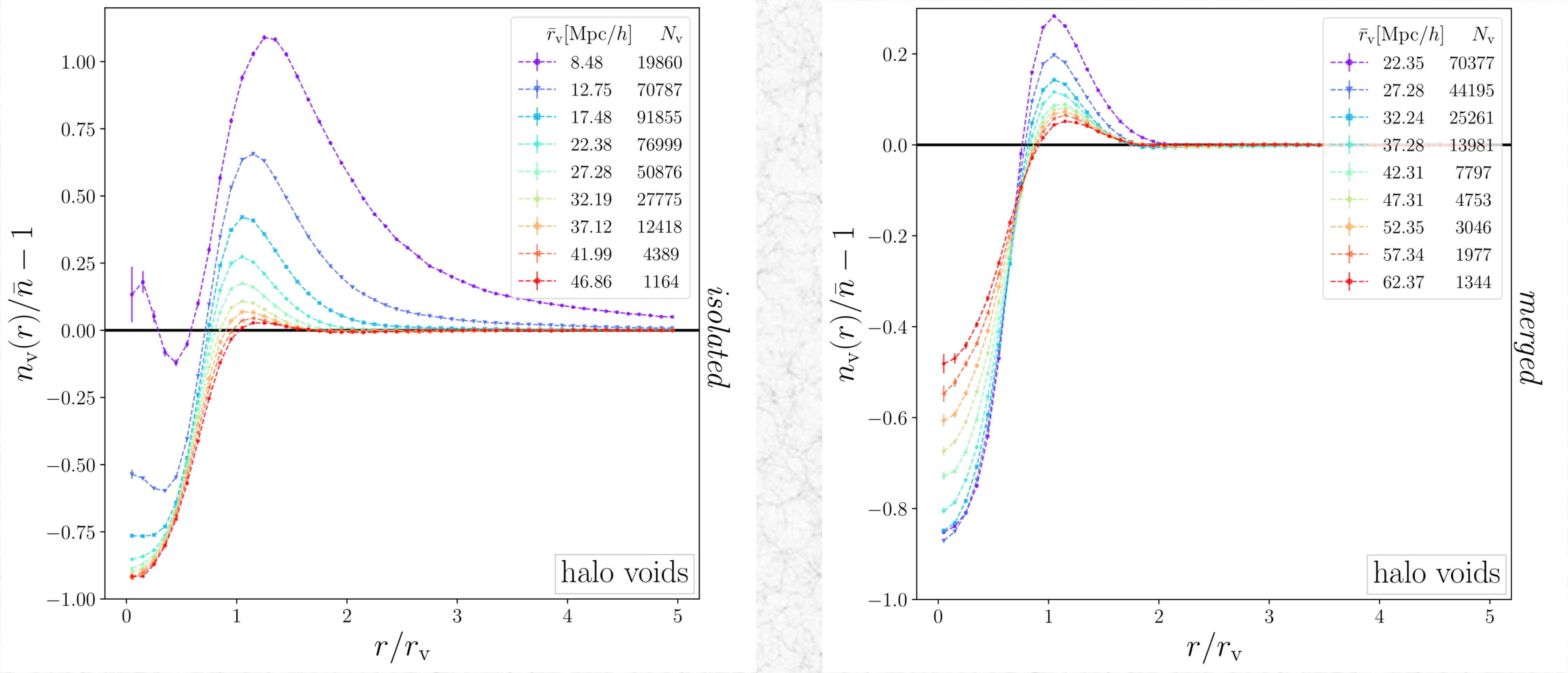






Density Profiles

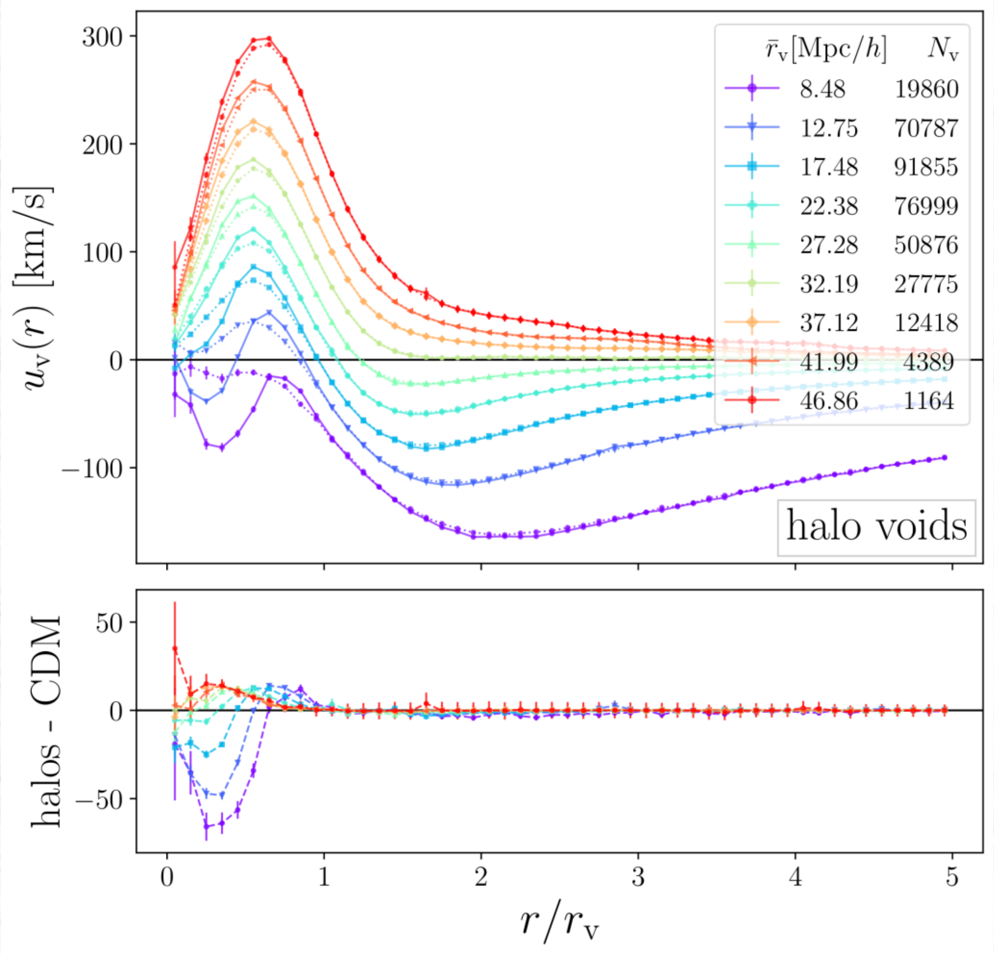
Density profiles of halo voids in **midres**, presented in stacked bins of their radii:



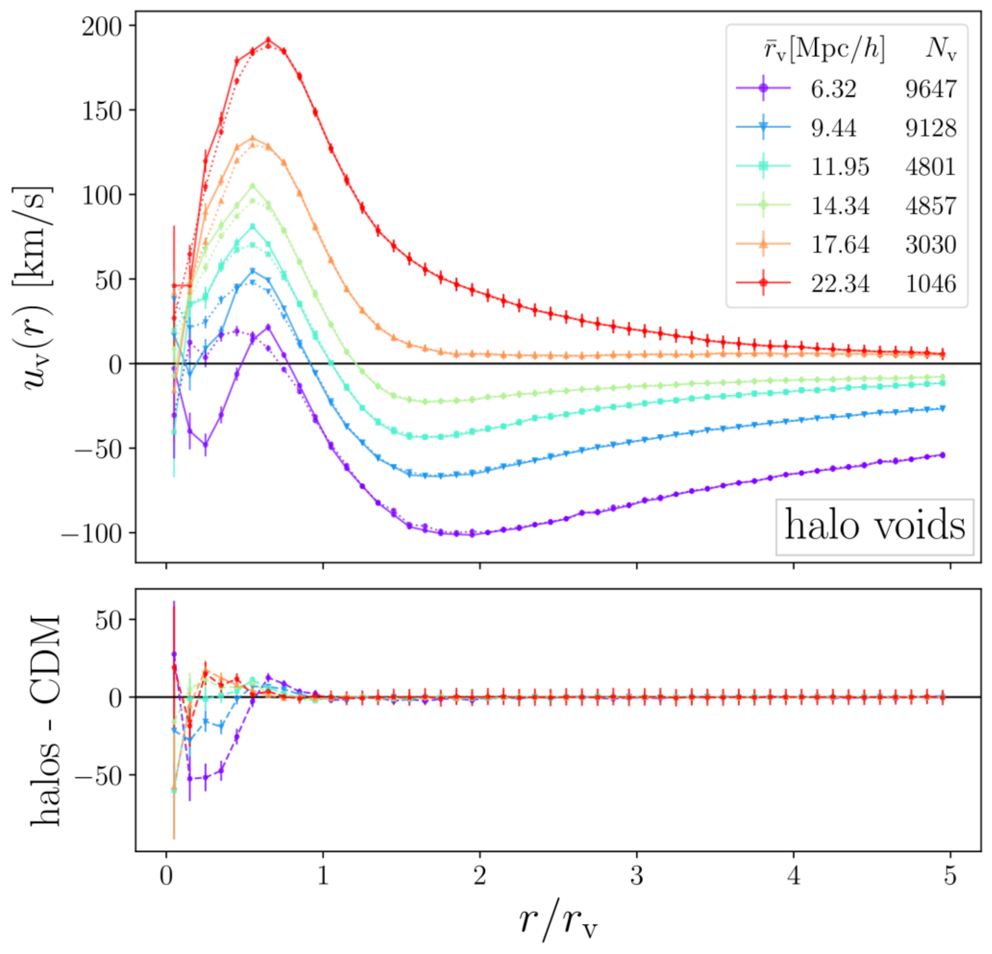
Velocity Profiles

Velocity of CDM & halos around isolated halo voids → high agreement in both simulations

midres



highres

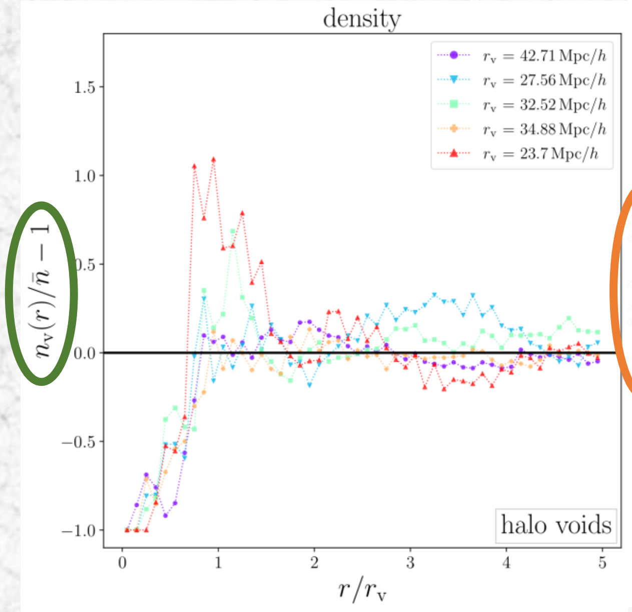


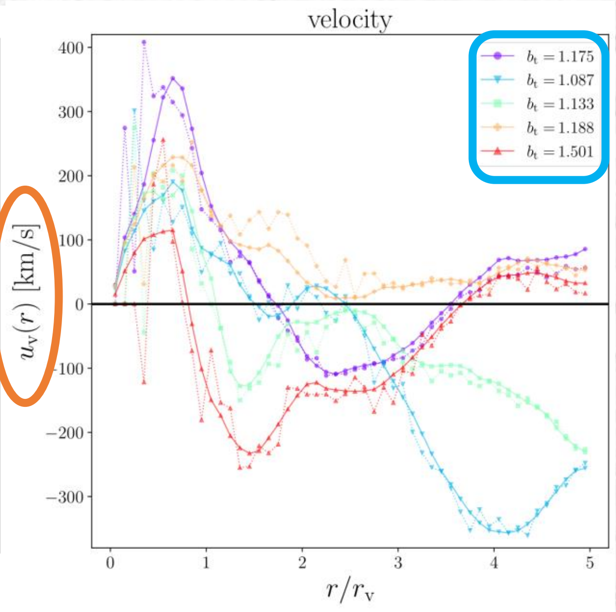
Linear Mass Conservation - Individual Voids

Application of linear mass conservation on the individual density profiles of halo voids, the resulting velocity profiles (solid lines) and „measured“ velocity profiles (dashed), b_t is fitted for each profile:

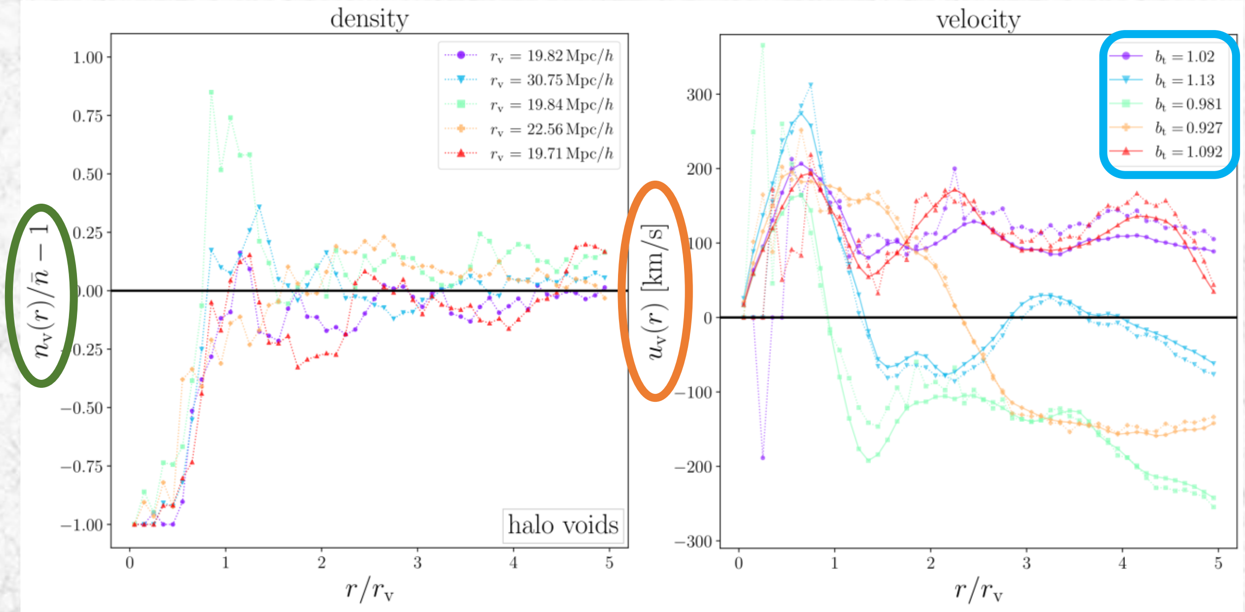
$$u_\mathrm{v}(r,z) = -\frac{\Omega_\mathrm{m}^\gamma(z)}{\boxed{b_\mathrm{t}}}\frac{H(z)}{1+z}\frac{1}{r^2}\int_0^r\left(\frac{n_\mathrm{v}(q)}{\bar{n}}-1\right)q^2\,\mathrm{d}q$$

midres



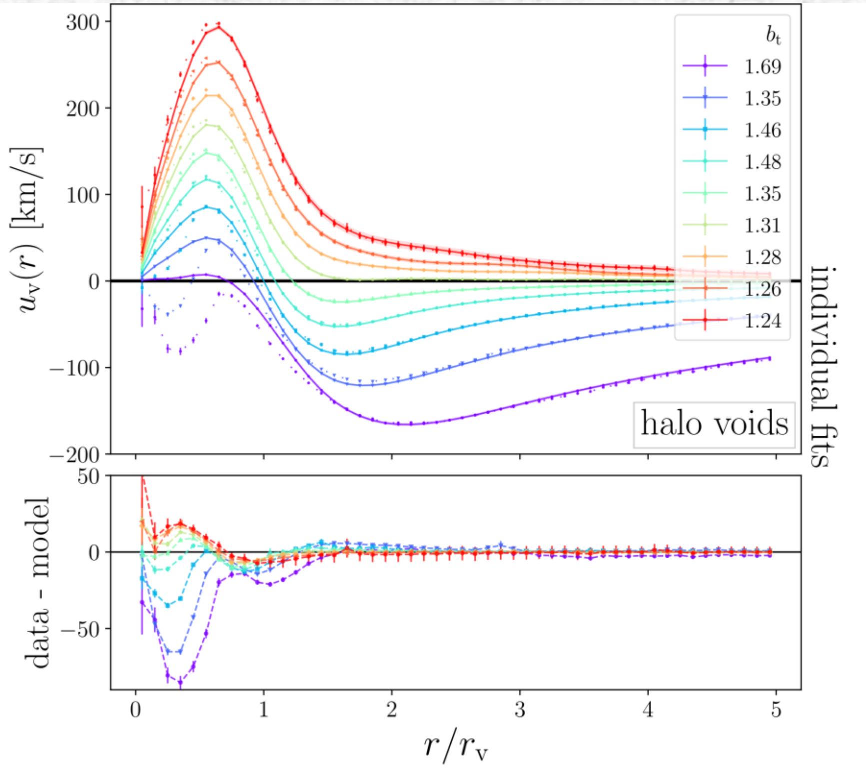


highres



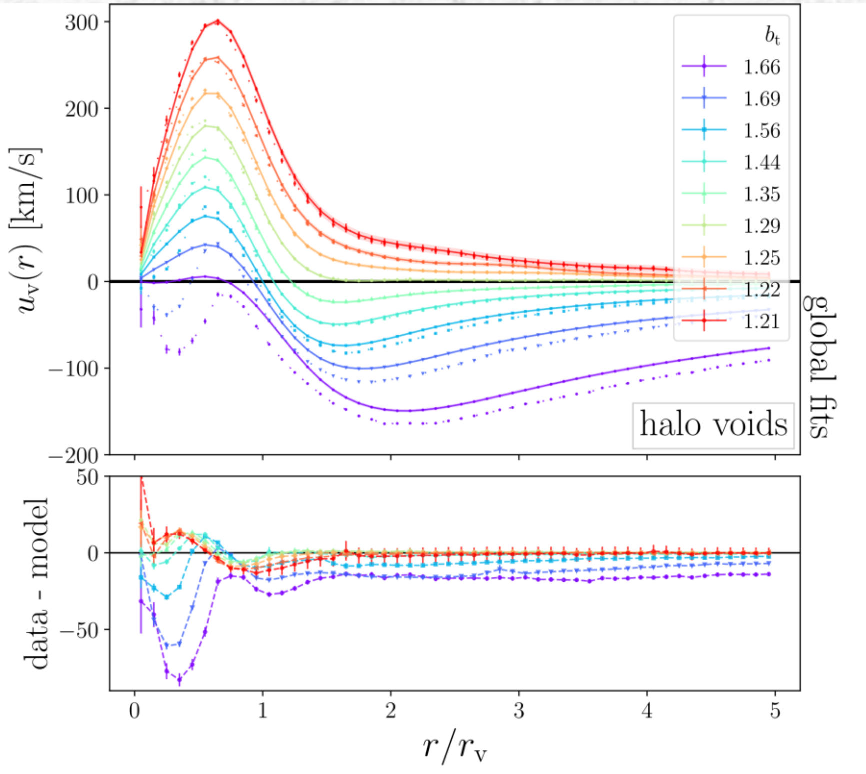
Linear Mass Conservation - Stacked Voids

midres



Individual fits: use linear theory on each individual profile and fit $b_{\rm t}$, then stack the resulting linear theory. Indicated $b_{\rm t}$ is the mean value

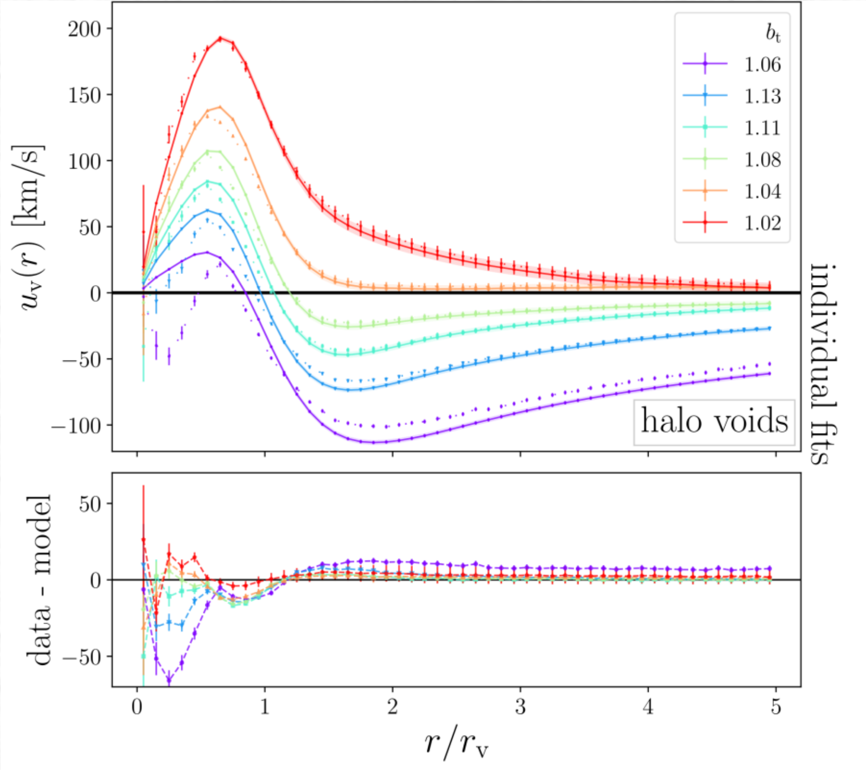
midres



Global fits: use linear theory on each individual profile with $b_{\rm t} = 1$, stack the resulting linear theory profiles and then fit for a global $b_{\rm t}$ to stacks of measured velocity profiles (data)

Linear Mass Conservation - Stacked Voids

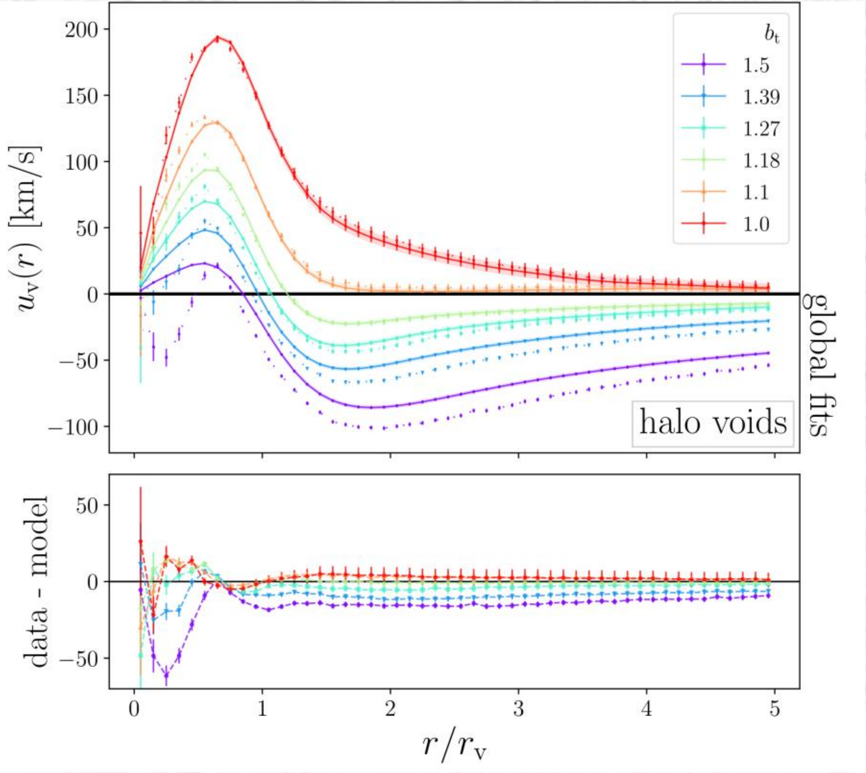
highres



Similar agreement between (simulation) data and model in **highres** at smaller scales than in **midres**, e.g. $22\ \mathrm{Mpc}/h$ in **mr** and $12\ \mathrm{Mpc}/h$ in **hr**

→ resolution effect and not onset of nonlinearity around voids

highres



Differences decrease with increasing radius.

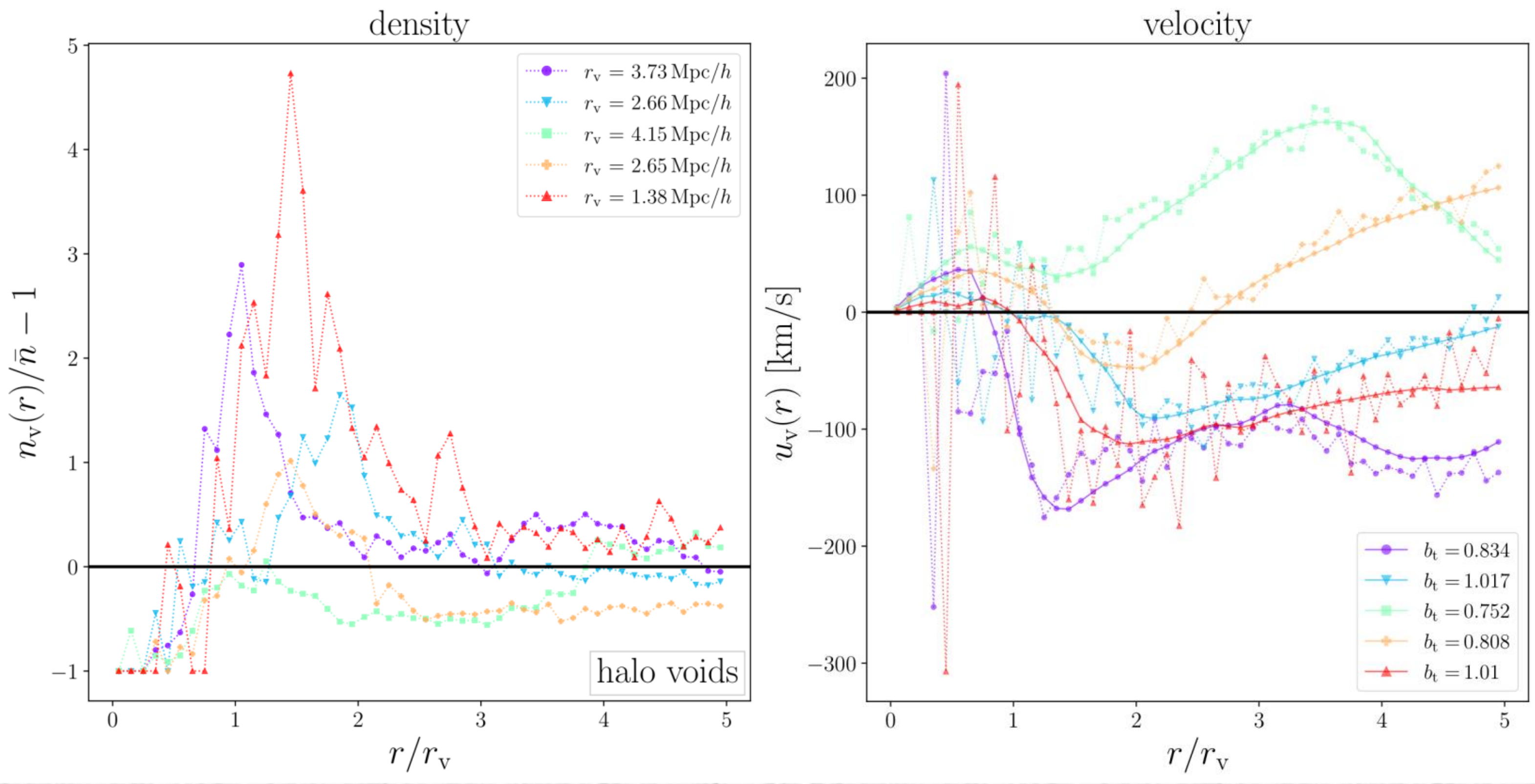
Slightly smaller differences in individual fits near the void centers.

Linear Mass Conservation - Resolution Study

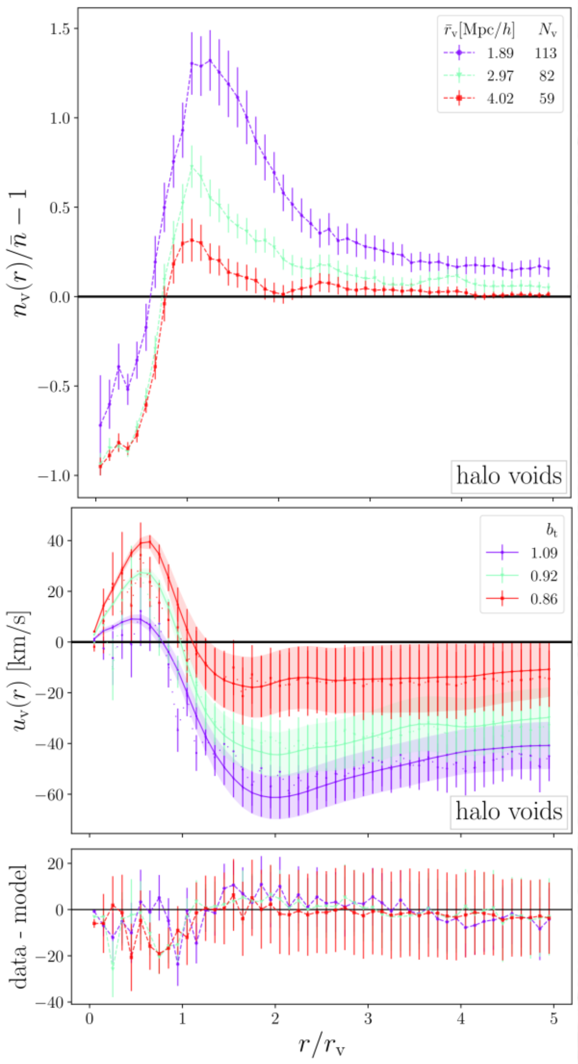
ultra-hr: $48\ \mathrm{Mpc}/h$ box with 346 halo voids

→ linear mass conservation still holds up around voids with radii of a few Mpc/h.

individual profiles:



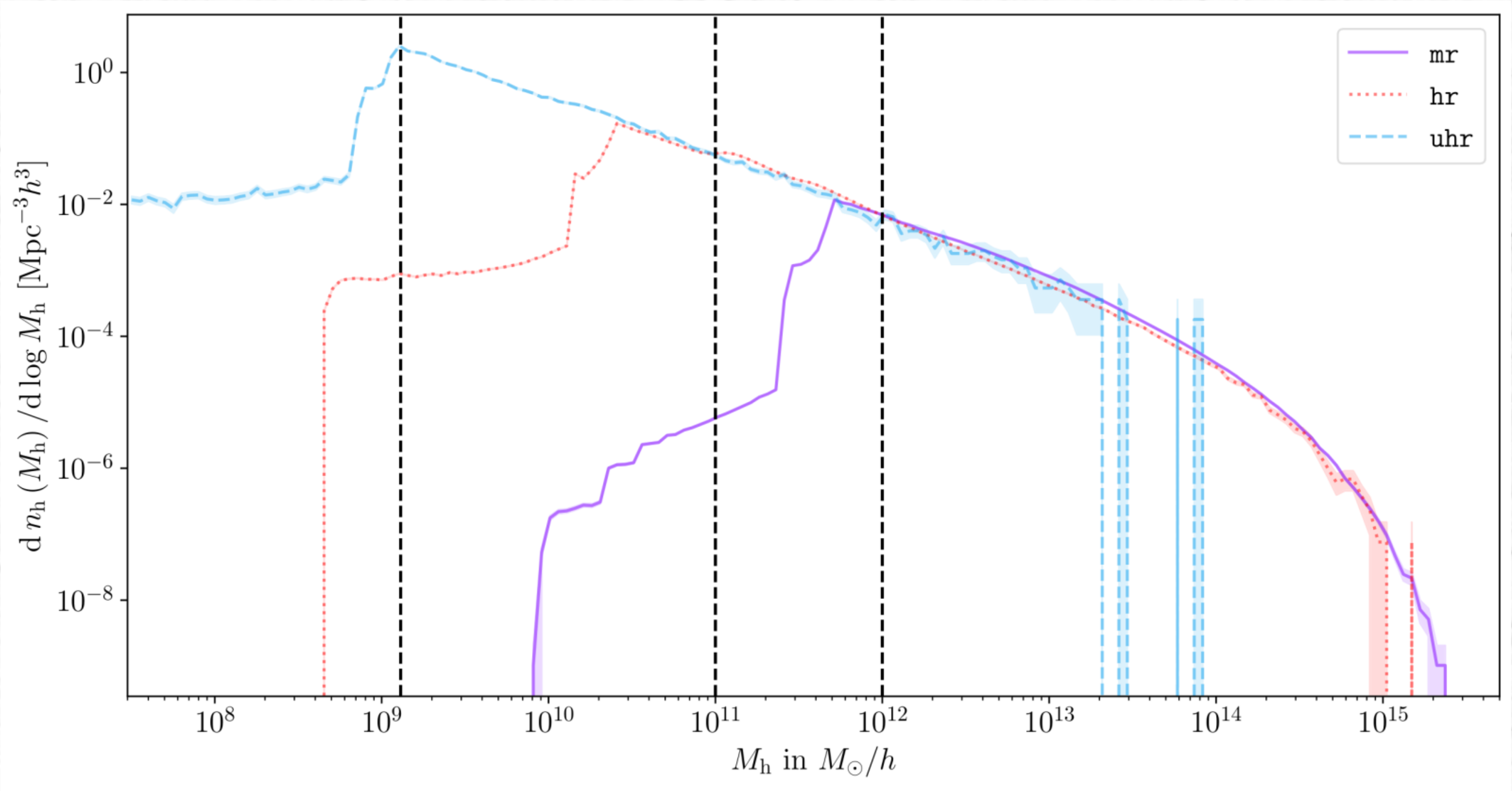
stacked profiles:



Conclusions

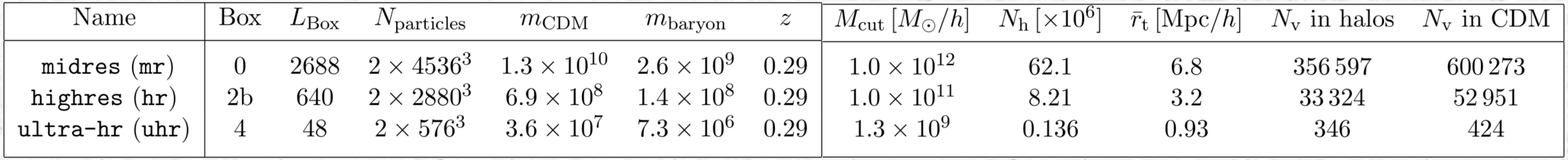
- Merged voids have shallower density profiles due to substructure inside voids and their **void size functions converge** on large scales
- CDM & halo move at same speed around halo defined voids
- Large voids dominated by outflow, small ones by infall towards compensation wall
- **Individual** & **stacked** voids accurately obey **linear** mass conservation, down to scales of order $\mathbf{1\ Mpc}/\boldsymbol{h}$.
- More results on non-radial stacks, mass weights, different velocity estimators, sampling effects in void profiles and linear mass conservation around CDM voids: arxiv:2210.02457

Simulation Details, Halo Mass Function & Void Numbers



WMAP7 cosmology:

$$h = 0.704$$
$$\Omega_\Lambda = 0.728$$
$$\Omega_\mathrm{m} = 0.272$$
$$\Omega_\mathrm{b} = 0.0456$$
$$\sigma_8 = 0.809$$
$$n_s = 0.963$$



Name	Box	L_Box	$N_\mathrm{particles}$	m_CDM	m_baryon	z	$M_\mathrm{cut}\ [M_\odot/h]$	$N_\mathrm{h}\ [\times 10^6]$	$\bar{r}_\mathrm{t}\ [\mathrm{Mpc}/h]$	N_v in halos	N_v in CDM
`midres` (`mr`)	0	2688	2×4536^3	1.3×10^{10}	2.6×10^9	0.29	1.0×10^{12}	62.1	6.8	356 597	600 273
`highres` (`hr`)	2b	640	2×2880^3	6.9×10^8	1.4×10^8	0.29	1.0×10^{11}	8.21	3.2	33 324	52 951
`ultra-hr` (`uhr`)	4	48	2×576^3	3.6×10^7	7.3×10^6	0.29	1.3×10^9	0.136	0.93	346	424

magneticum.org

Void Properties

center (volume-weighted barycenter): $$\mathbf{X}_\mathrm{v} = \frac{\sum_j \boldsymbol{x}_j \, V_j}{\sum_j V_j}$$

radius: $$r_\mathrm{v} = \left(\frac{3}{4\pi} \sum_j V_j \right)^{1/3}$$

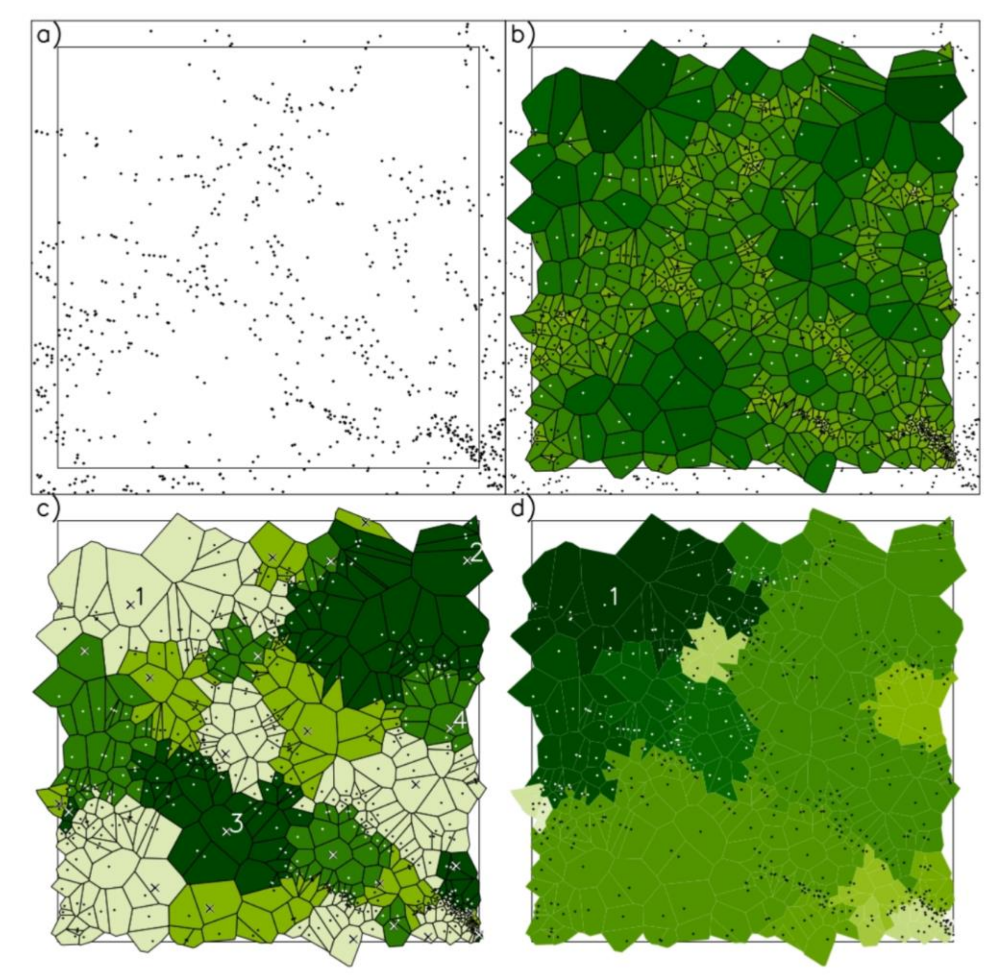
core density: $$\hat{n}_\mathrm{min} = \frac{n_\mathrm{min}}{\bar{n}}$$

inertia tensor: $$M_{xy} = -\sum_j x_j \, y_j \qquad M_{xx} = \sum_j \left(y_j^2 + z_j^2 \right)$$

ellipticity: $$\varepsilon = 1 - \left(\frac{J_1}{J_3} \right)^{1/4}$$

compensation: $$\Delta_\mathrm{t} \equiv \frac{N_\mathrm{t}/V}{\bar{n}} - 1 = \hat{n}_\mathrm{avg} - 1$$

Void Finding



M. C. Neyrinck (2008)

Void finding done by using VIDE in both CDM and halos.

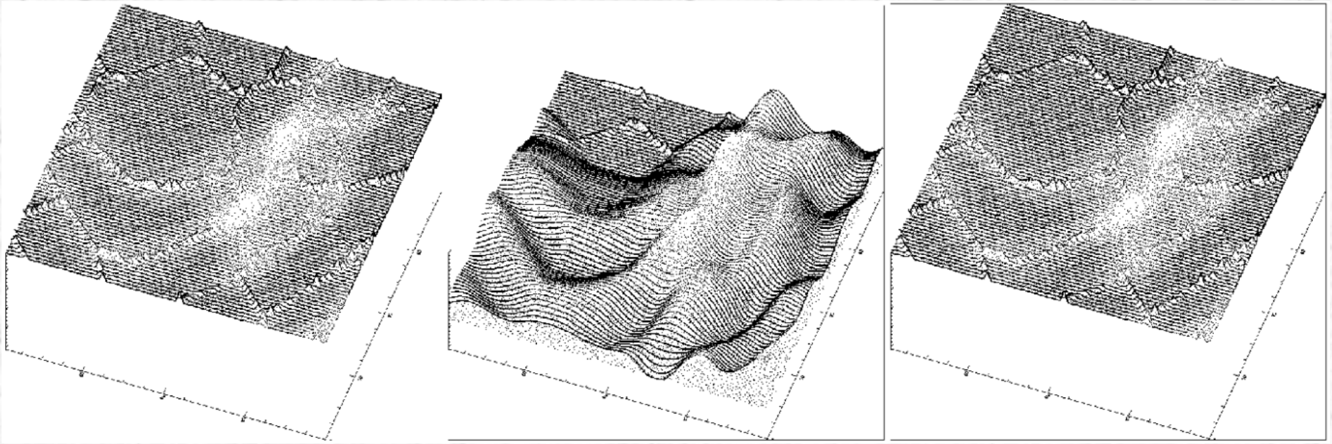
a) tracer positions

b) Voronoi tesselation

c) zoning

d) watershed

Voids can be merged, depending on the density of the rigdes between them

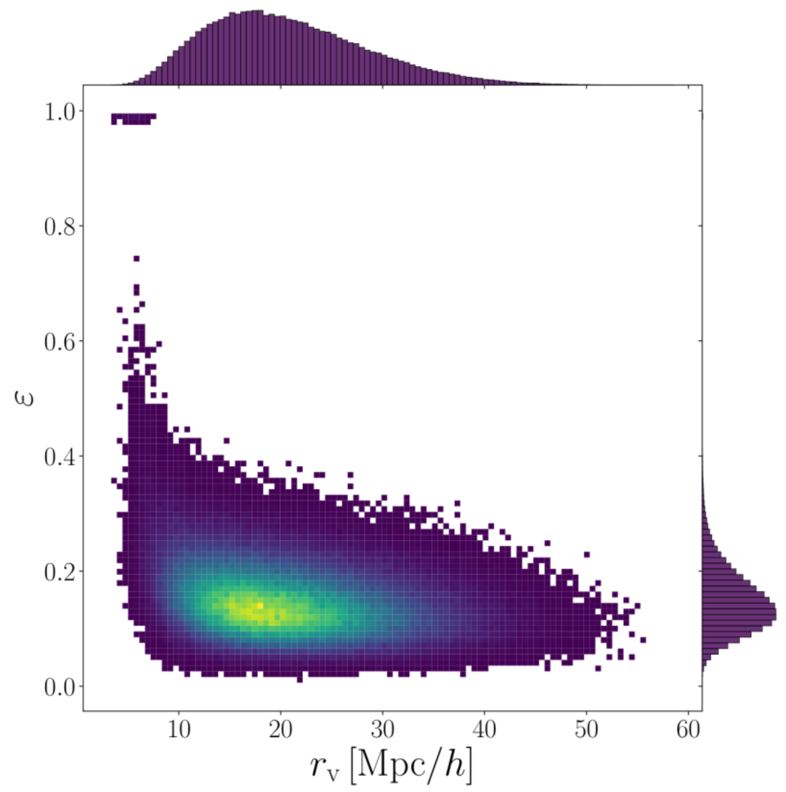


Platen (2007)

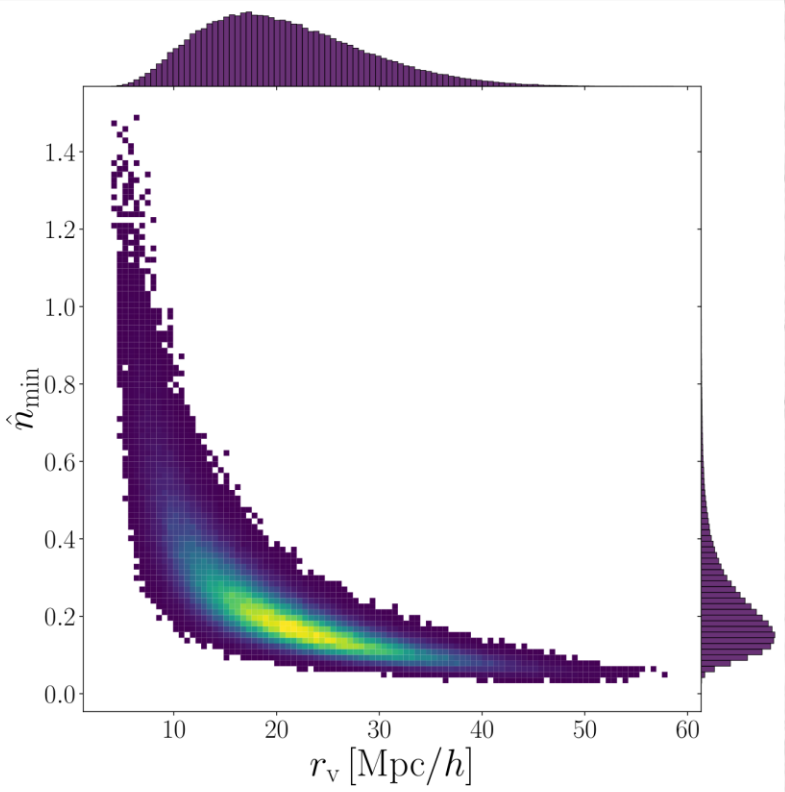
Void Distributions II

Two-dimensional distributions of voids in **midres** in radius and..

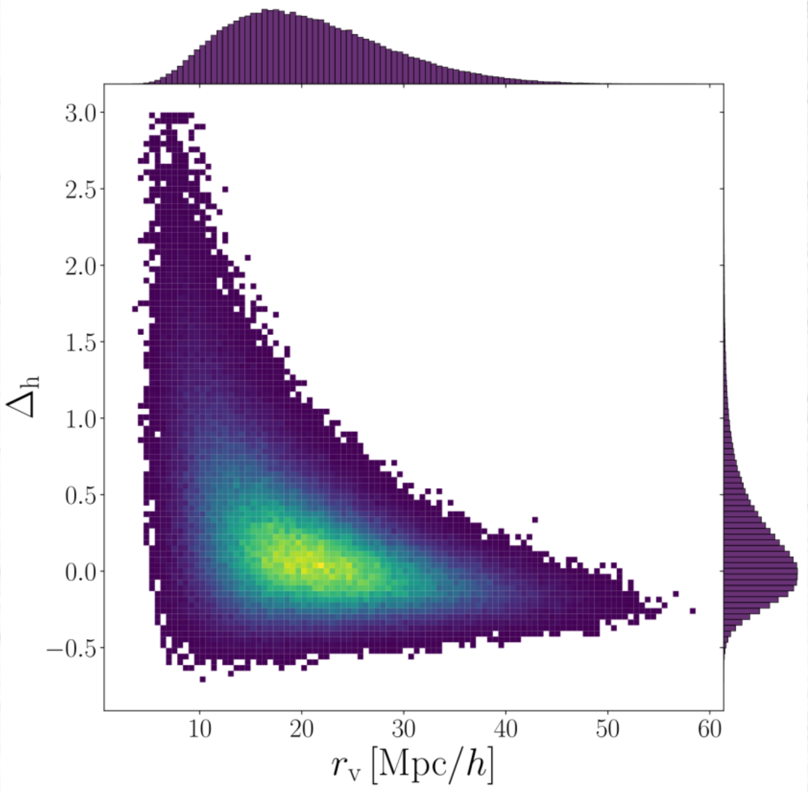
ellipticity



core density



compensation



Void Profiles

Individual profiles:

Density: $n_{\mathrm{v}}^{(i)}(r) = \frac{3}{4\pi\,\bar{w}} \sum_j \frac{w_j\ \Theta(\mathrm{r_j})}{(r+\delta r)^3\ -\ (r\ -\delta r)^3}$

w_j (optional) weights, $\bar{w}$ mean weight and $\Theta(\mathrm{r_j}) \equiv\ \vartheta[r_j\ - (r-\delta r)]\,\vartheta[-r_j + (r+\delta r)]$
with Heaviside step function ϑ

Velocity: $u_{\mathrm{v}}^{(i)}(r) = \frac{\sum_j \boldsymbol{u}_j \cdot \hat{\boldsymbol{r}}_j\ V_j\,\Theta(r_j)}{\sum_j V_j\,\Theta(r_j)}$

Stacked profiles:

$$n_{\mathrm{v}}(\mathrm{r}) = \frac{1}{N_{\mathrm{v}}}\sum_i n_{\mathrm{v}}^{(i)}(r)$$

individual stacks: $u_{\mathrm{v}}(r) = \frac{1}{N_{\mathrm{v}}}\sum_i u_{\mathrm{v}}^{(i)}\,(r)$

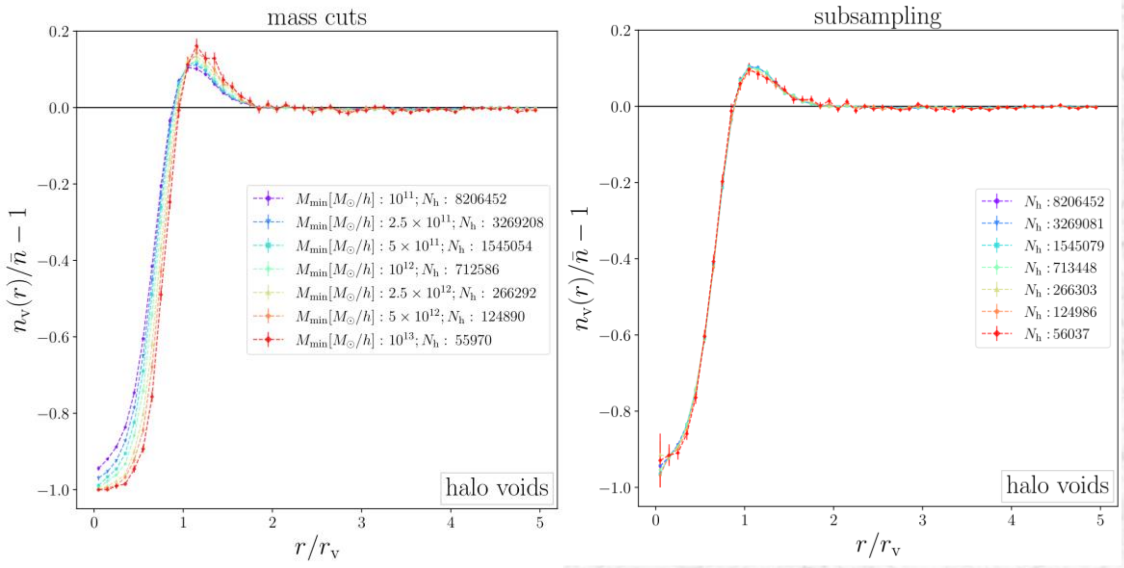
global stacks: $u_{\mathrm{v}}(r) = \frac{\sum_i\left[\sum_j \boldsymbol{u}_j \cdot \hat{\boldsymbol{r}}_j\ V_j\,\Theta(r_j)\right]^{(i)}}{\sum_i\left[\sum_j V_j\,\Theta(r_j)\right]^{(i)}}$

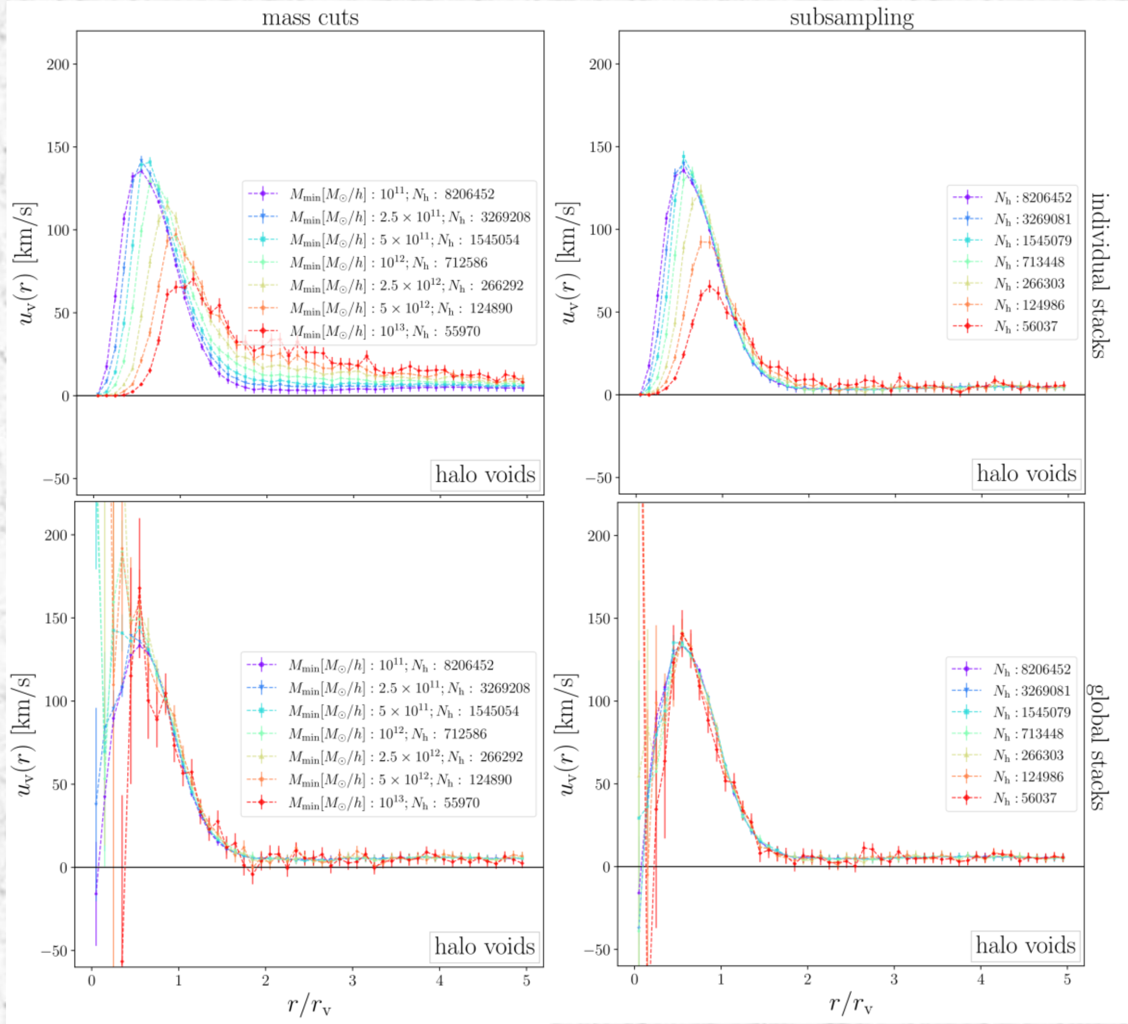
From local mass conservation
via linear continuity equation: $u_{\mathrm{v}}\,(r,z) = -\,\frac{\Omega_{\mathrm{m}}^{\gamma}(z)}{b_{\mathrm{t}}}\,\frac{H(z)}{1+z}\,\frac{1}{r^2}\int_0^r\left(\frac{n_{\mathrm{v}}(q)}{\bar{n}} - 1\right)q^2\,\mathrm{d}q$

Sampling Effects

Effects of mass cuts and subsamplings on density profiles (bottom) and velocity profiles (right) in both stacking methods for halo voids in exemplary bin with $r_\mathrm{v}[\mathrm{Mpc}/h] \in [16.0, 20.0]$ in **highres**

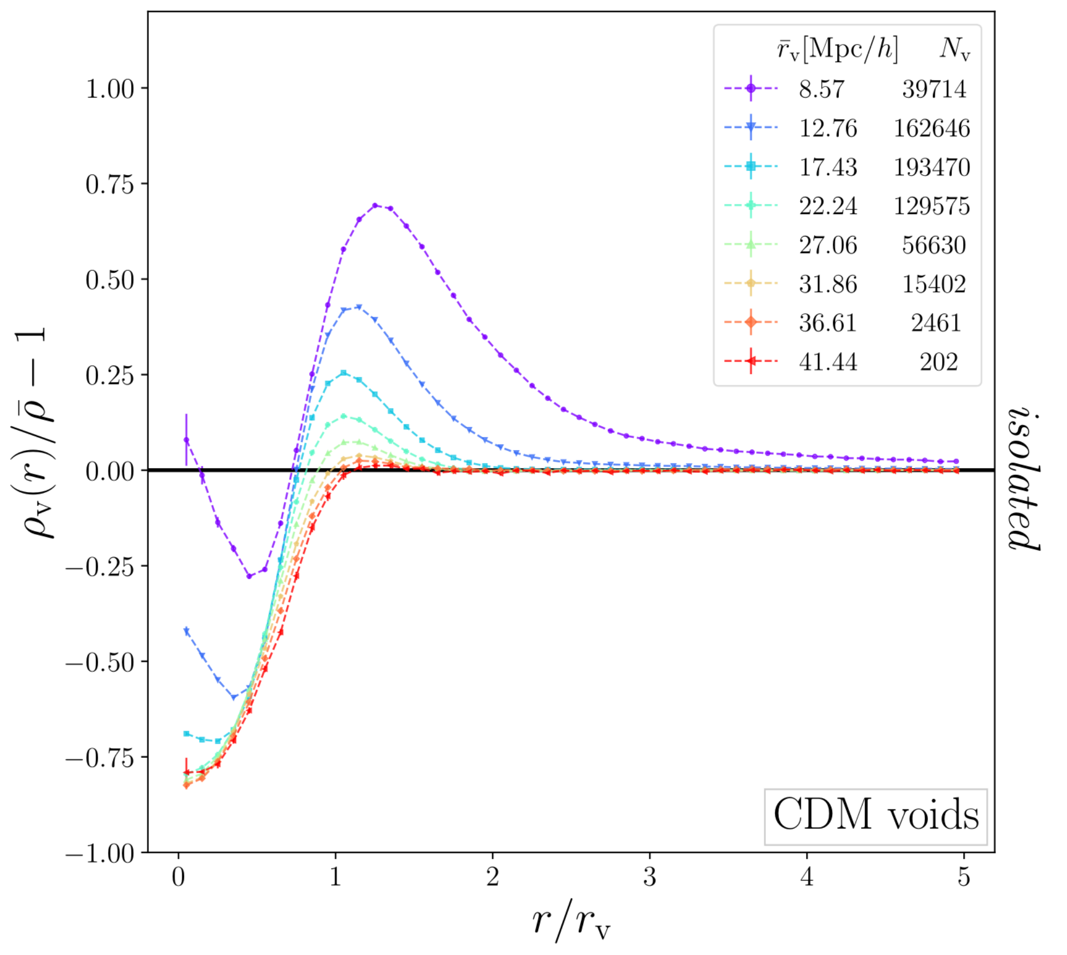
→ only density profiles and velocity profiles with global stacks give expected results

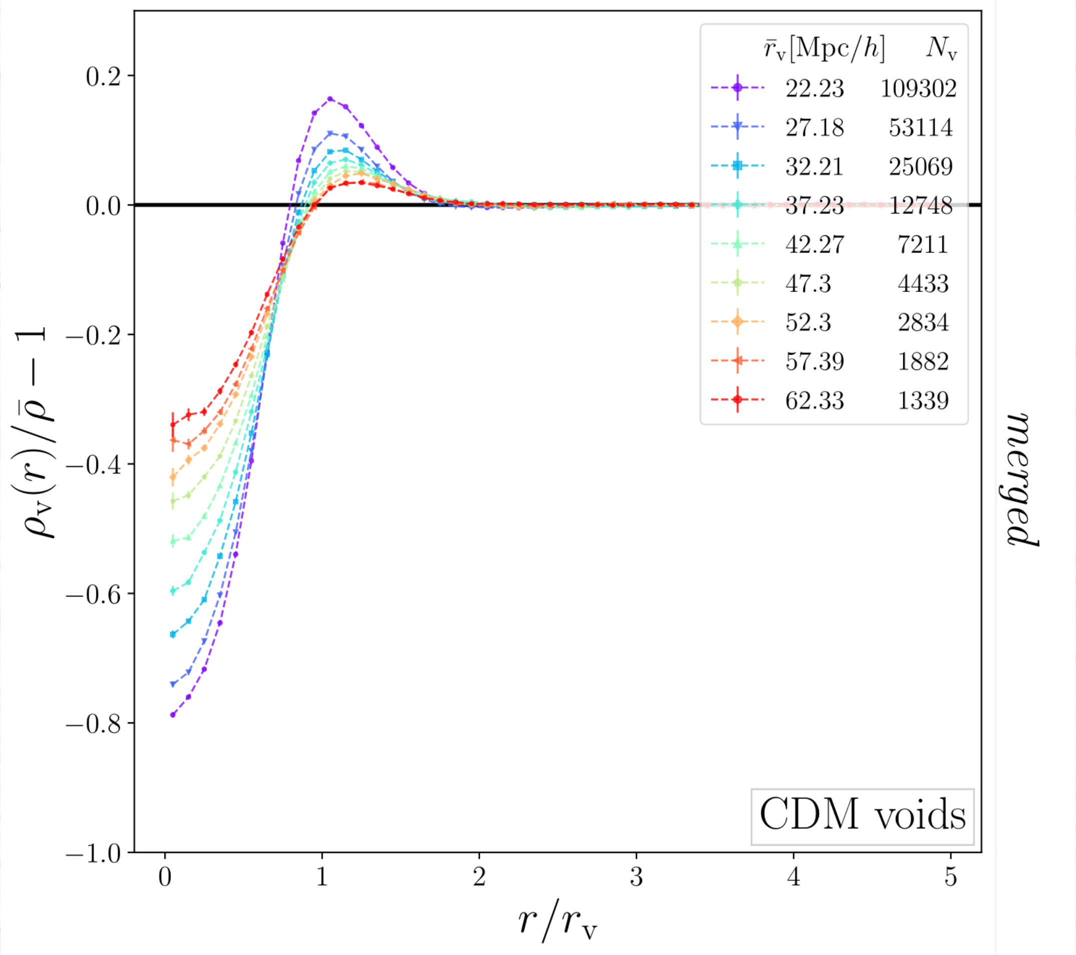




Density Profiles - CDM

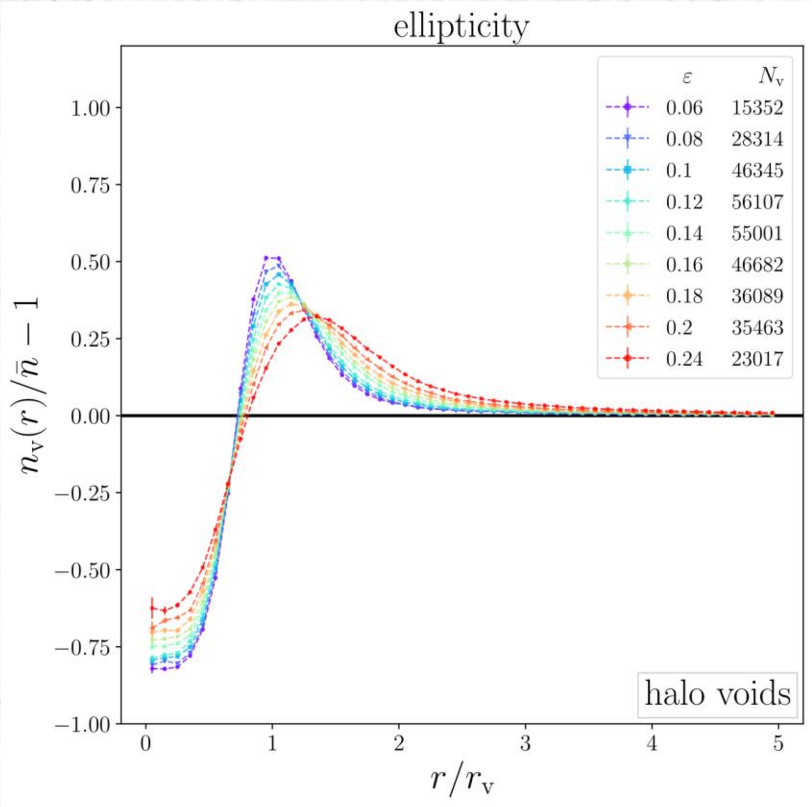
Density profiles of CDM voids in **midres**, presented in stacked bins of their radii:

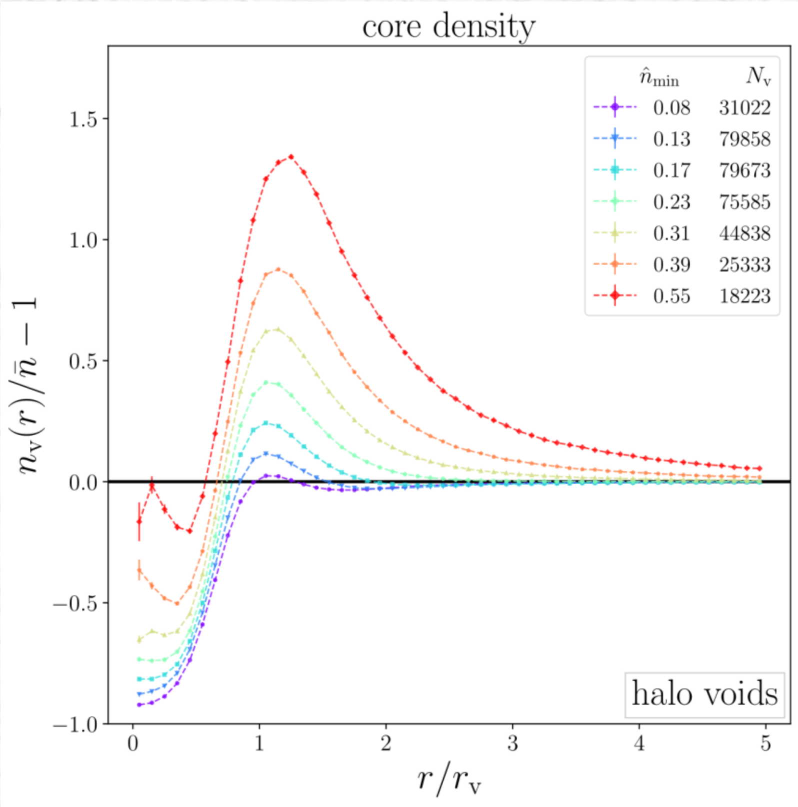


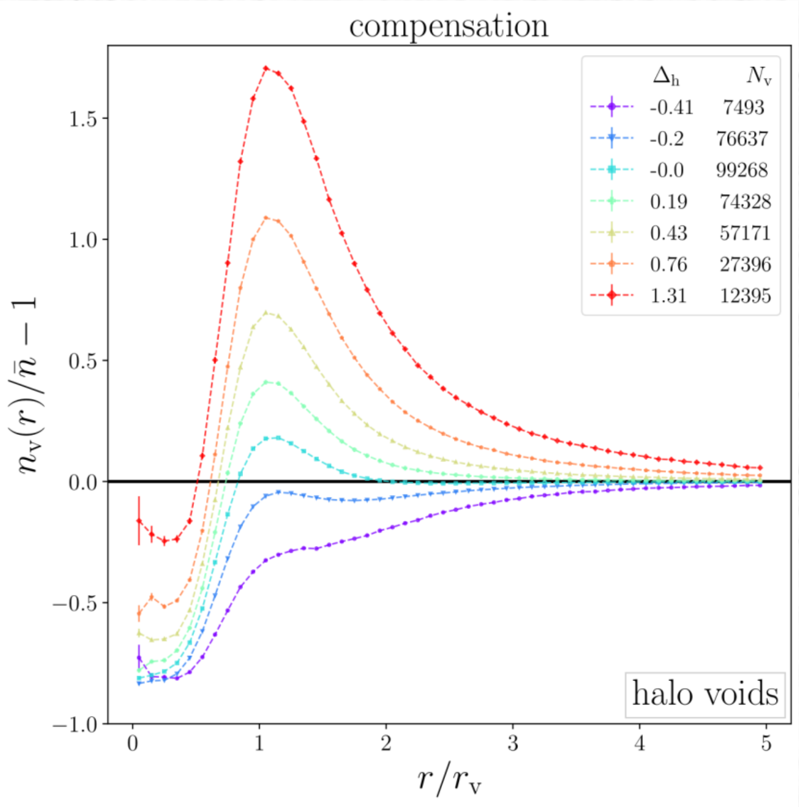


Density Profiles - Alternative Stacks

Density profiles of halo voids in **midres**, presented in stacked bins different void properties:

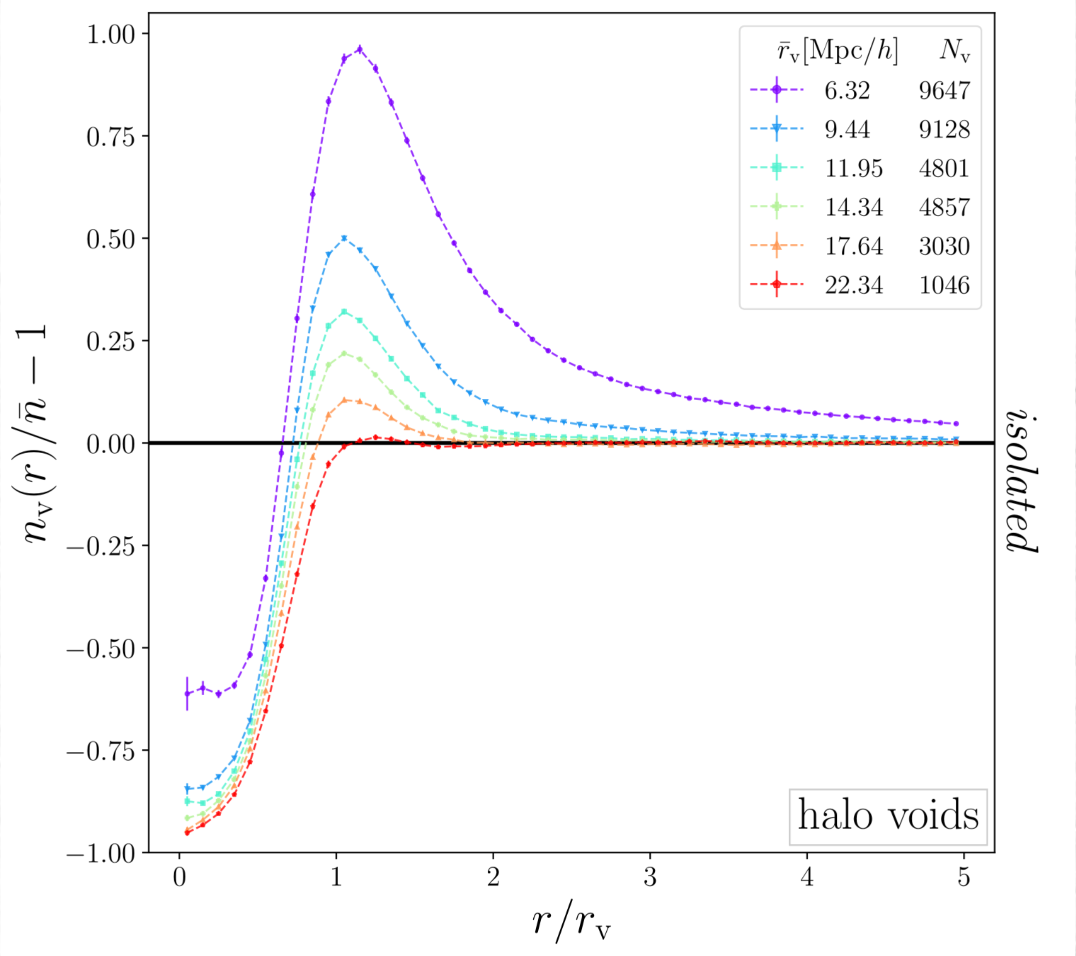


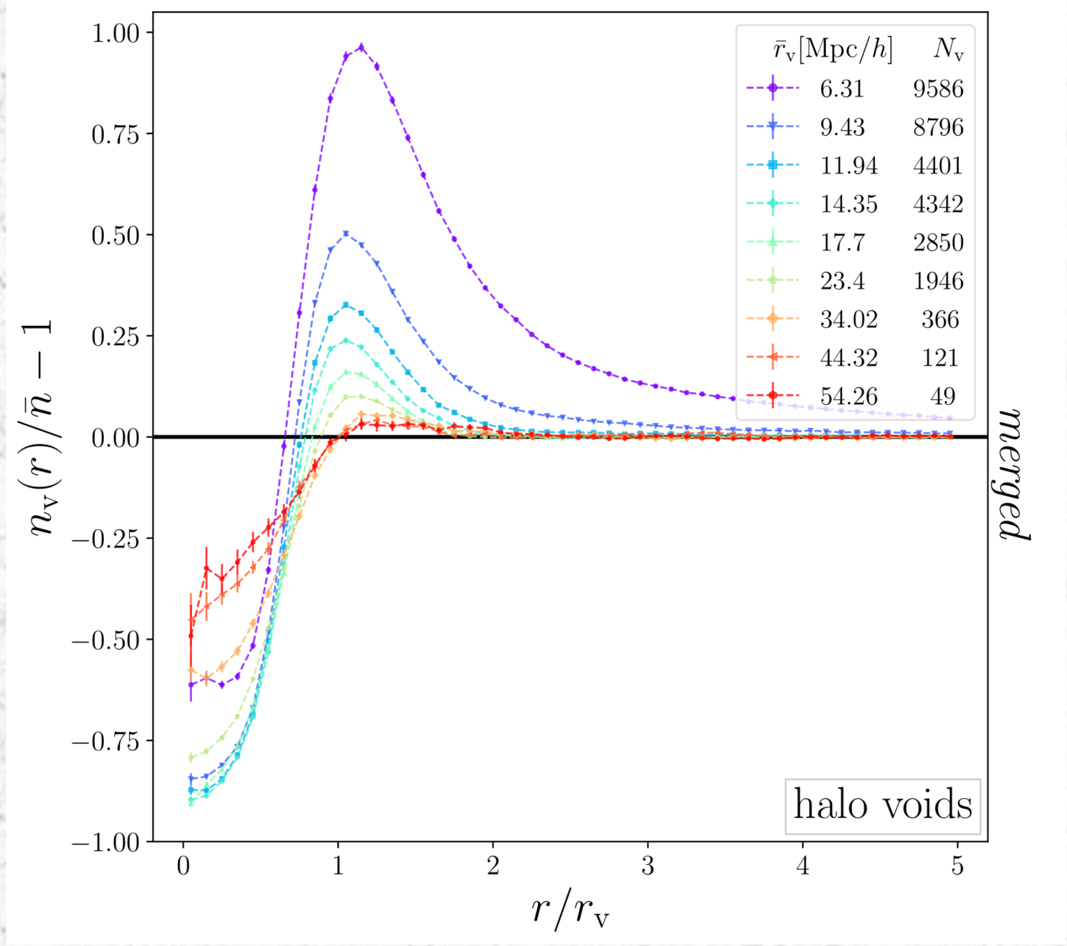




Density Profiles - HR

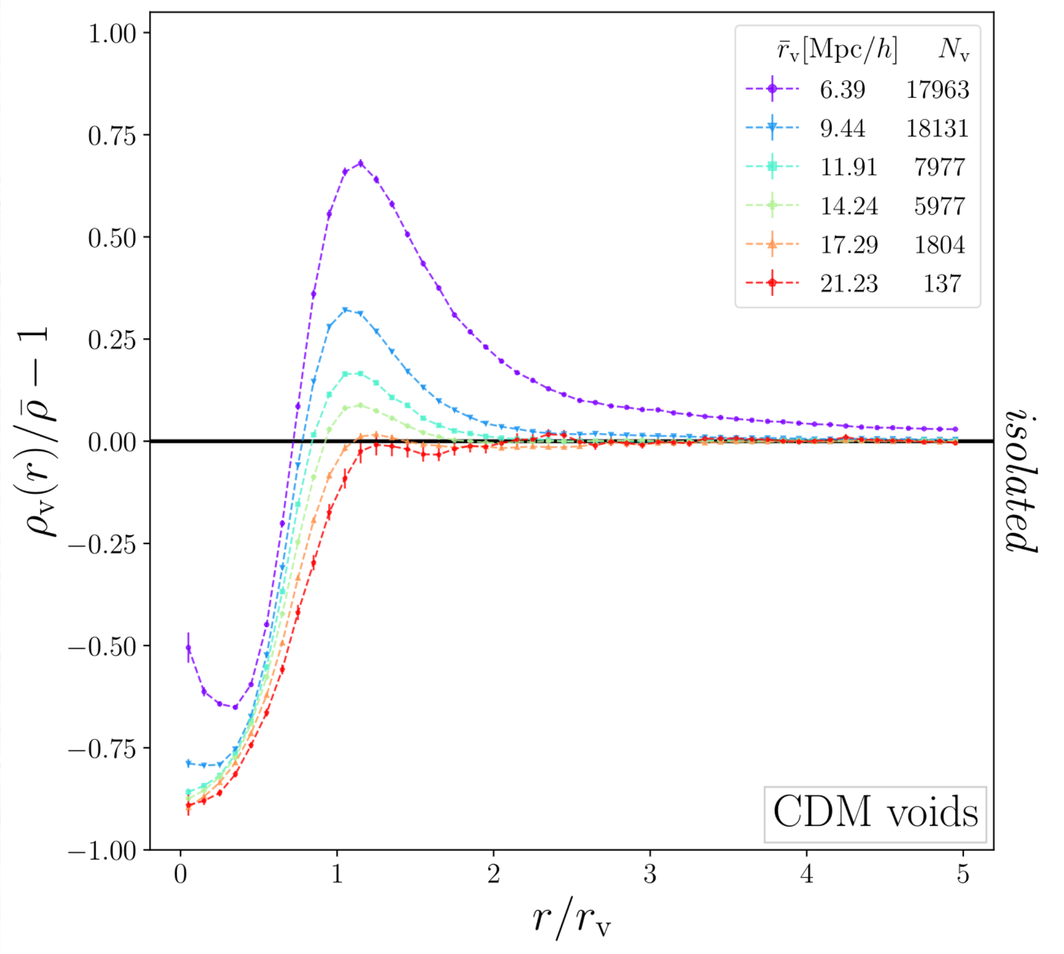
Density profiles of halo voids in **highres**, presented in stacked bins of their radii:

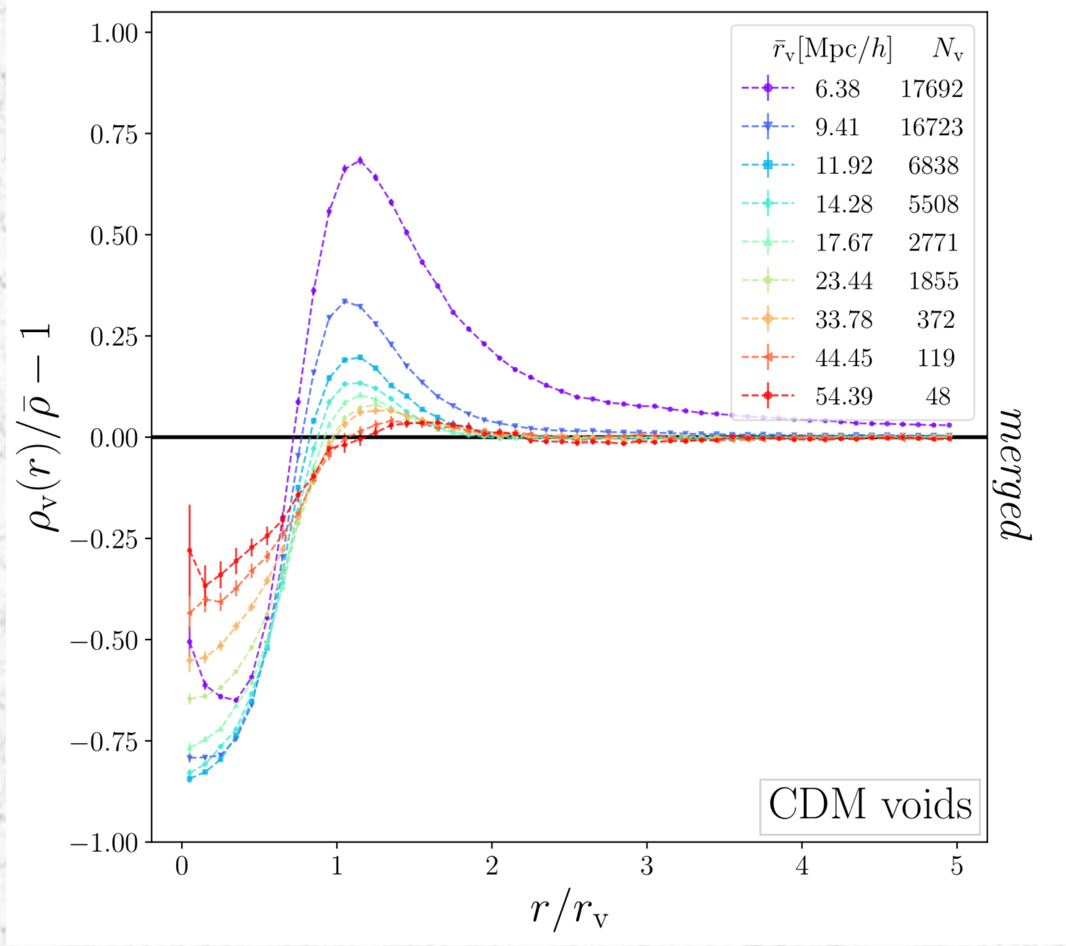




Density Profiles - HR CDM

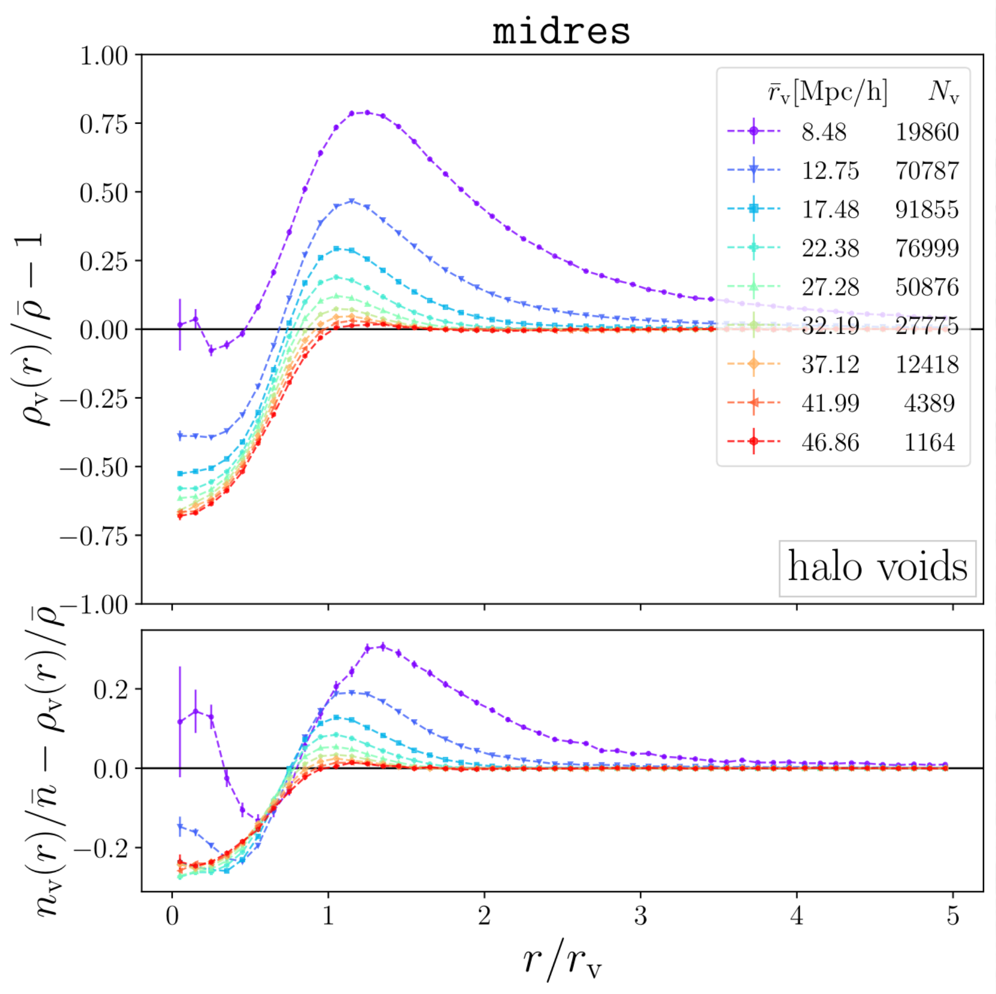
Density profiles of CDM voids in **highres**, presented in stacked bins of their radii:

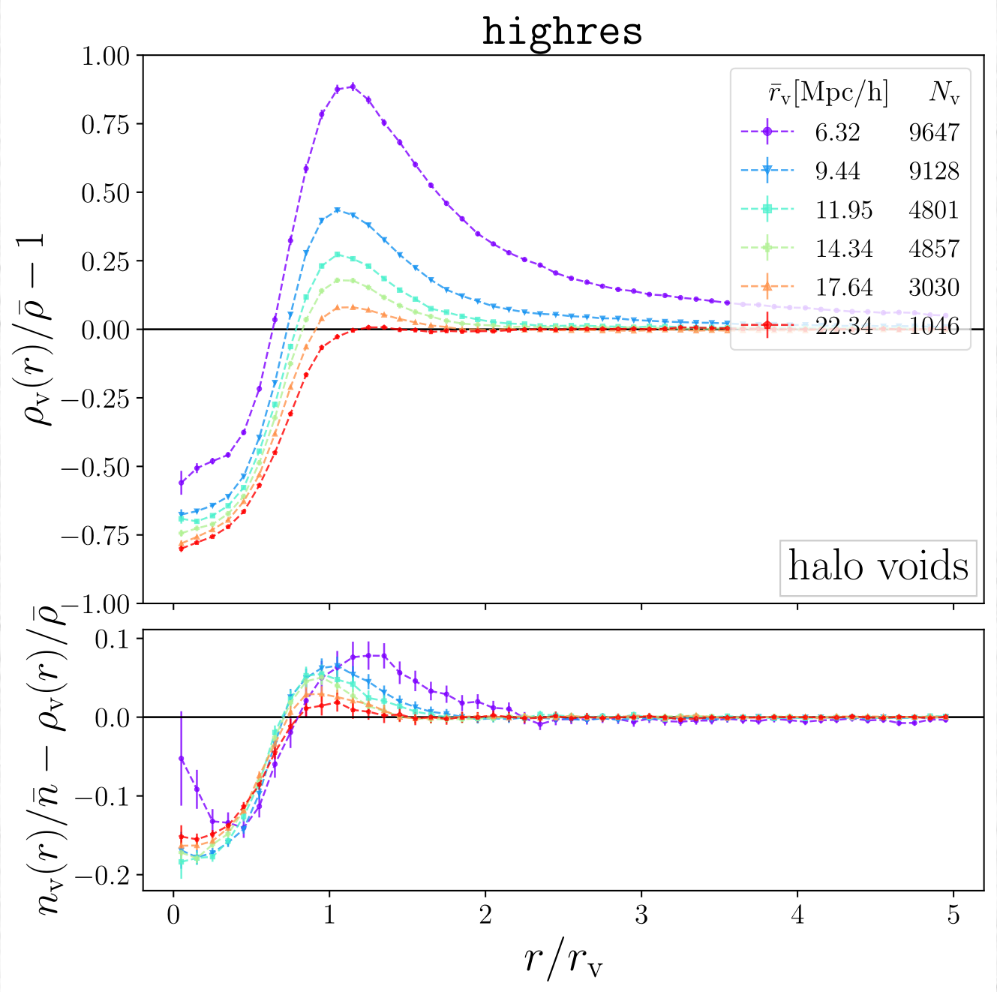




Matter Density Profiles

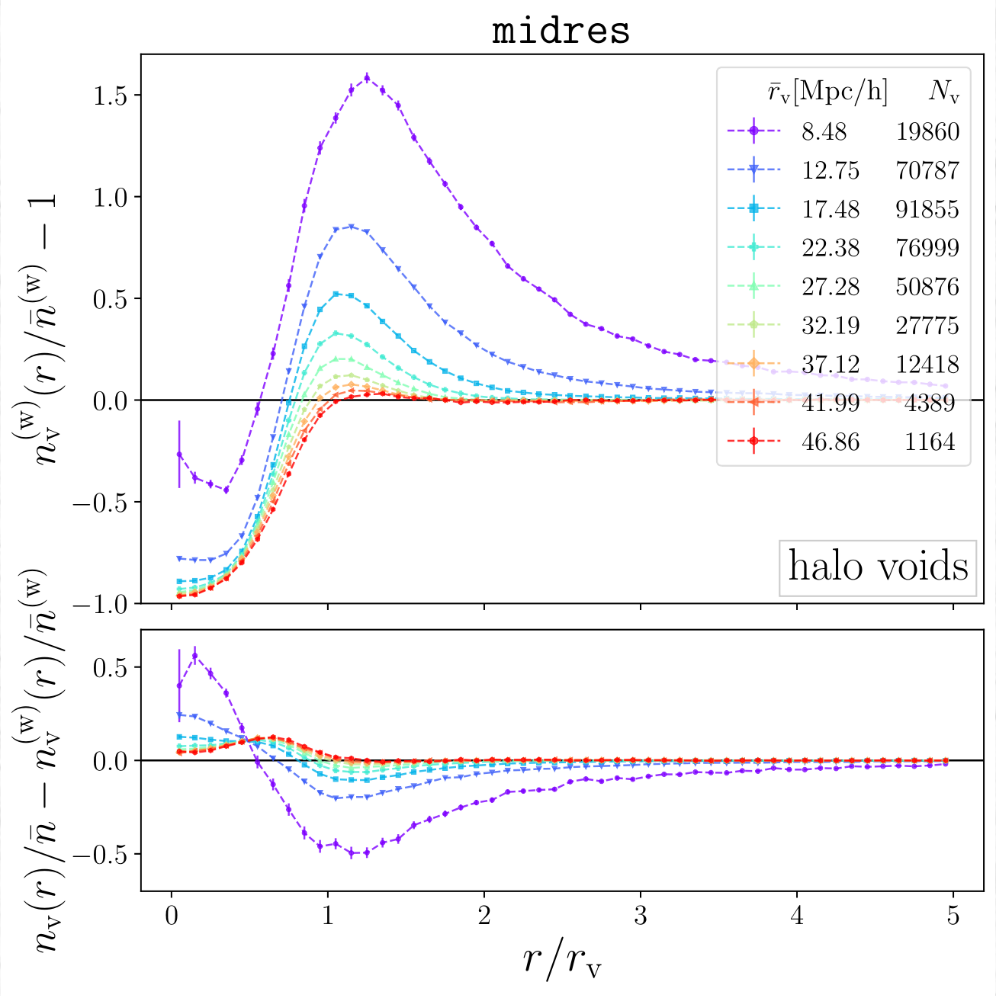
Matter density profiles of CDM around *isolated* halo voids in **midres**, in void radius bins:

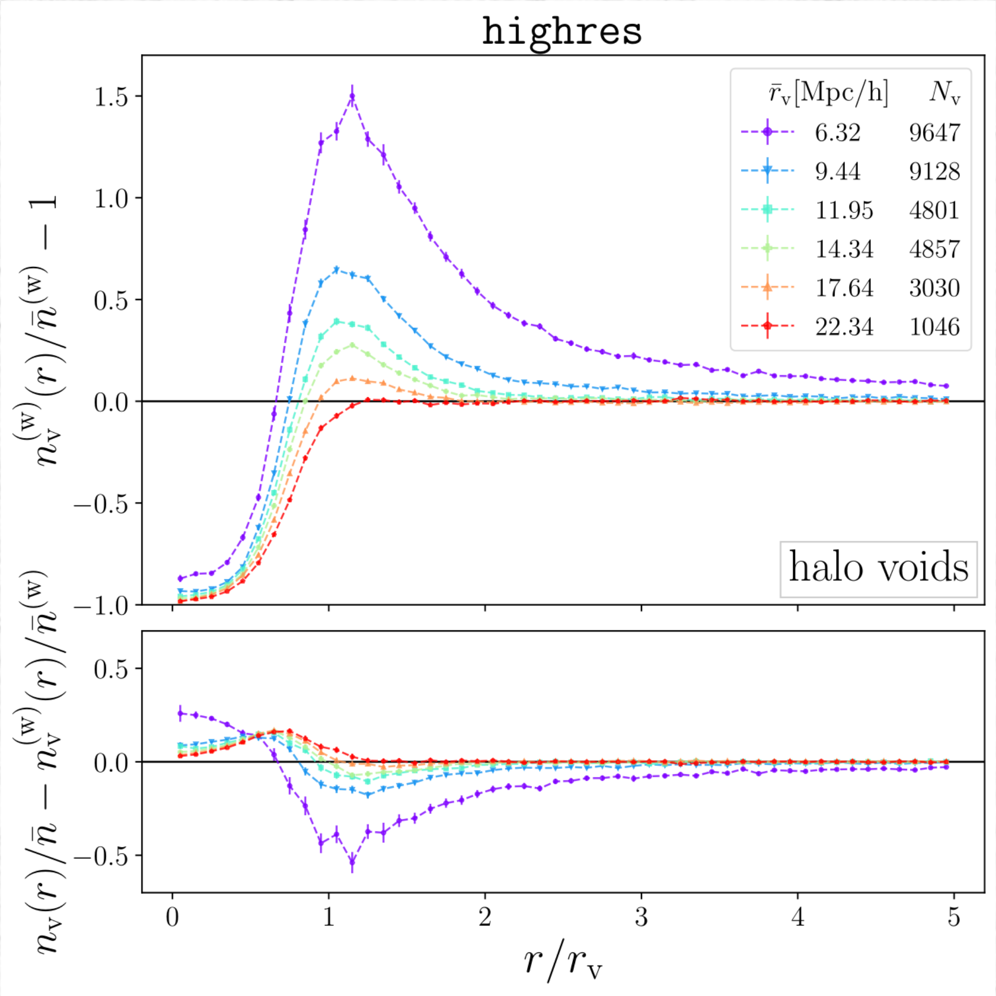




Mass-Weighted Density Profiles

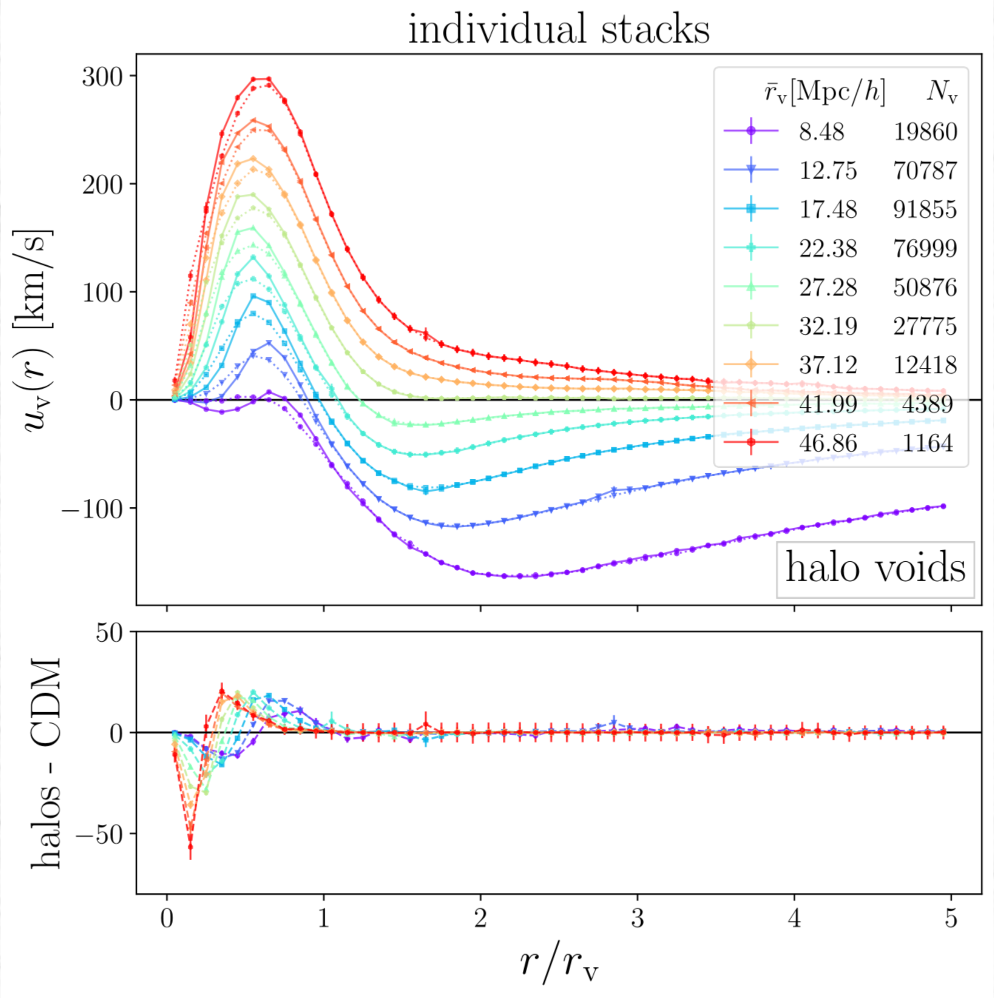
Mass-weighted density profiles *isolated* halo voids, in void radius bins:

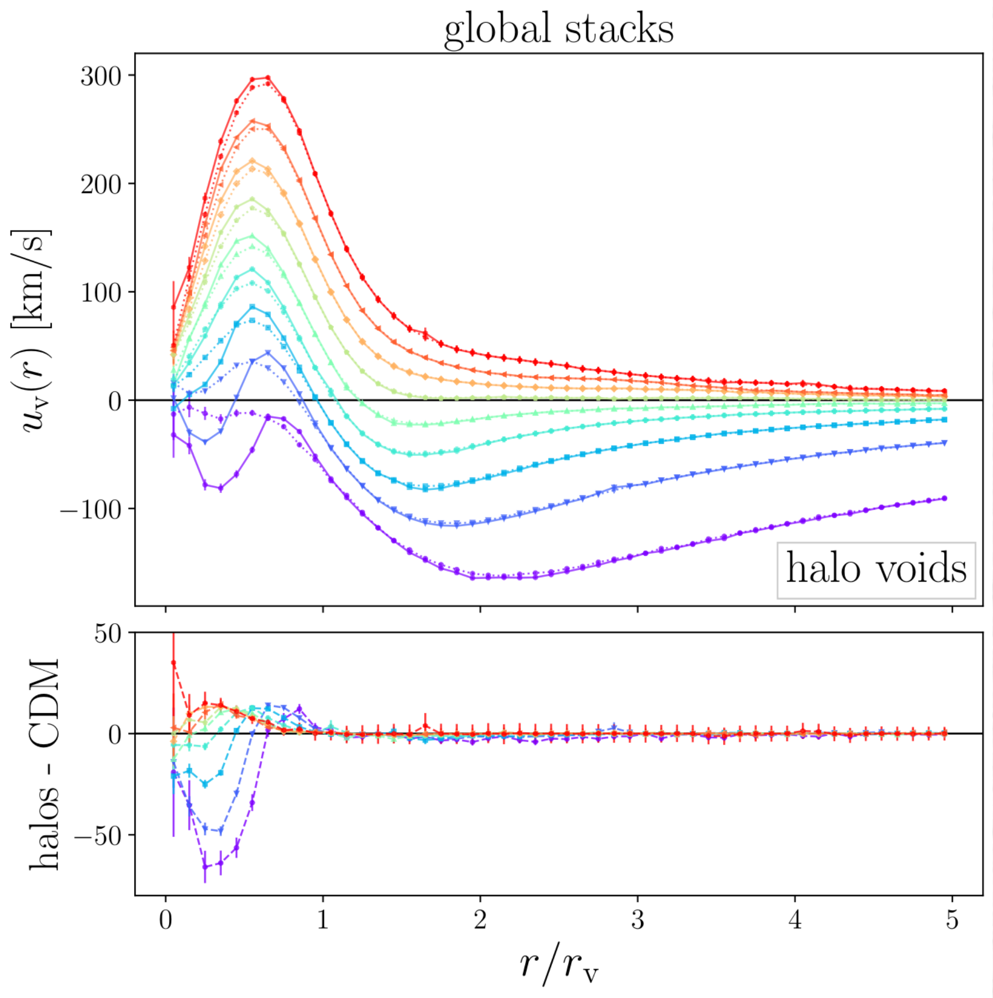




Velocity Profiles - Individual/Global Stacks

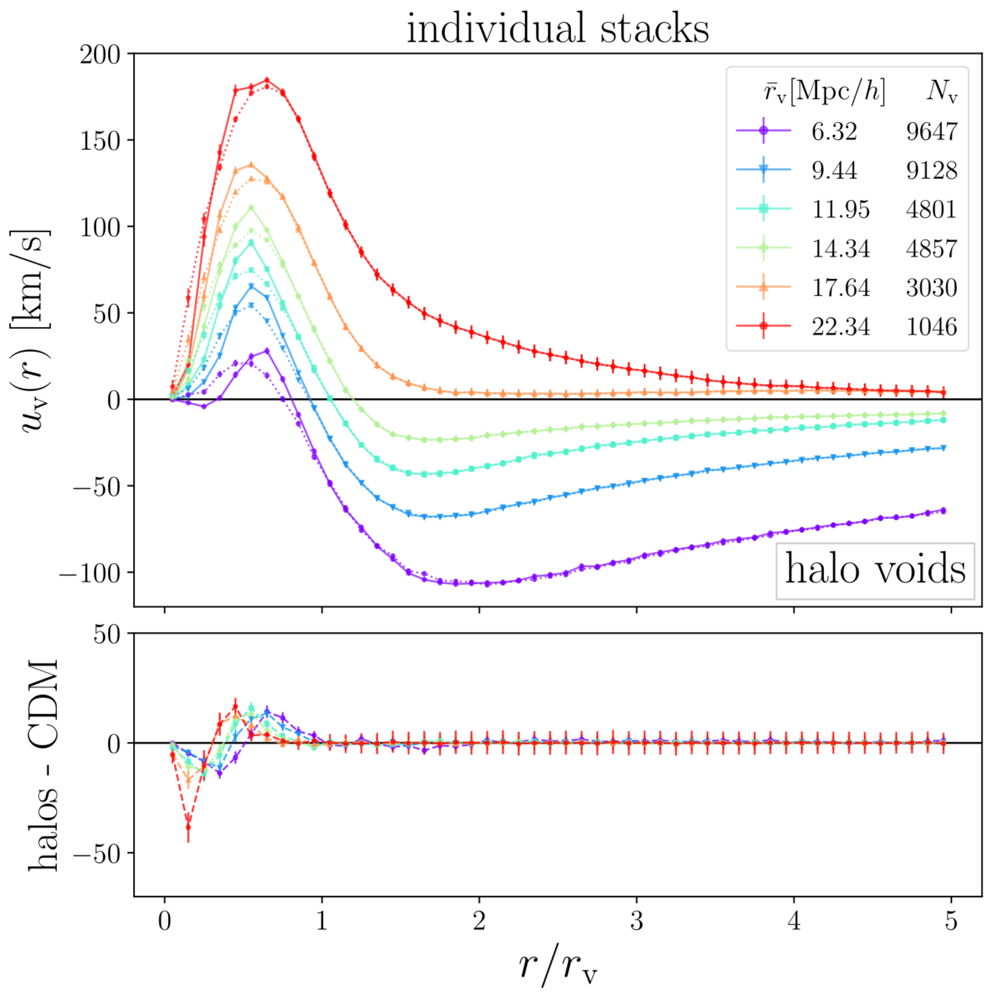
Velocity of CDM & halos around halo voids in **midres** → high agreement in both stacking methods

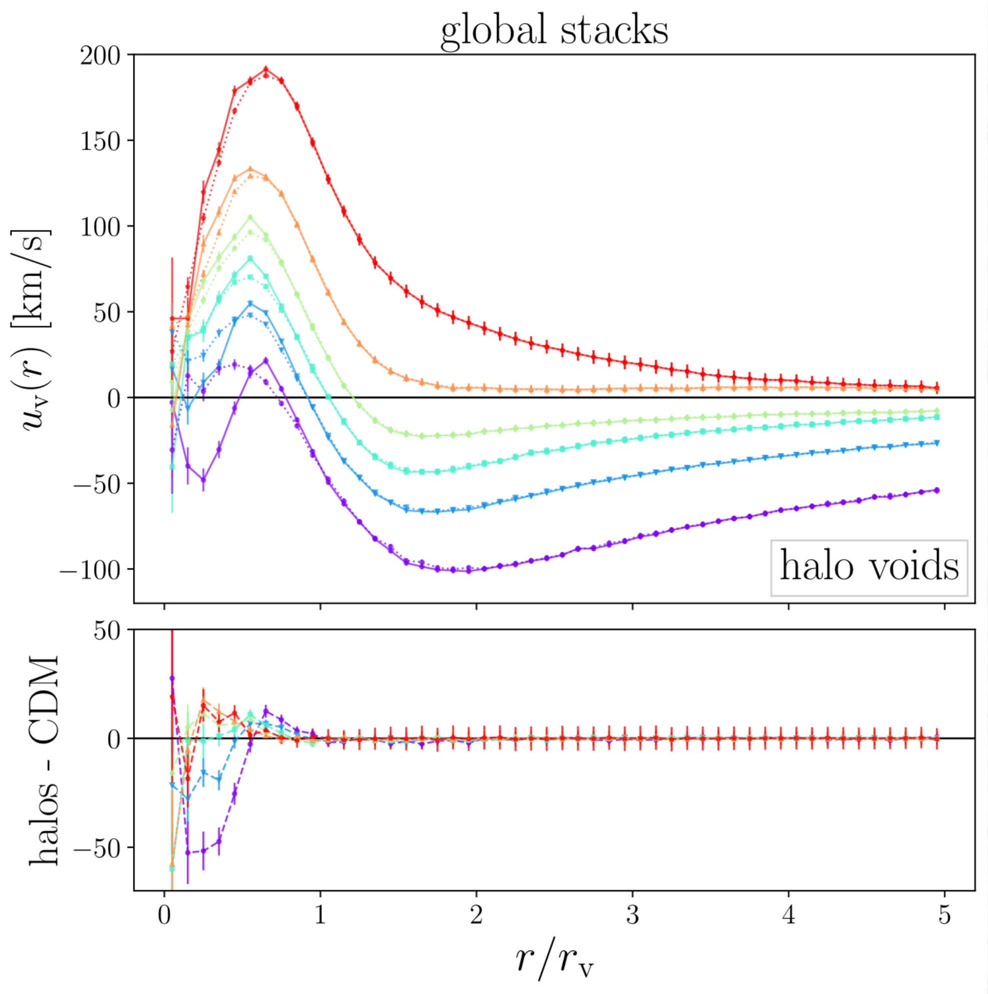




Velocity Profiles - HR

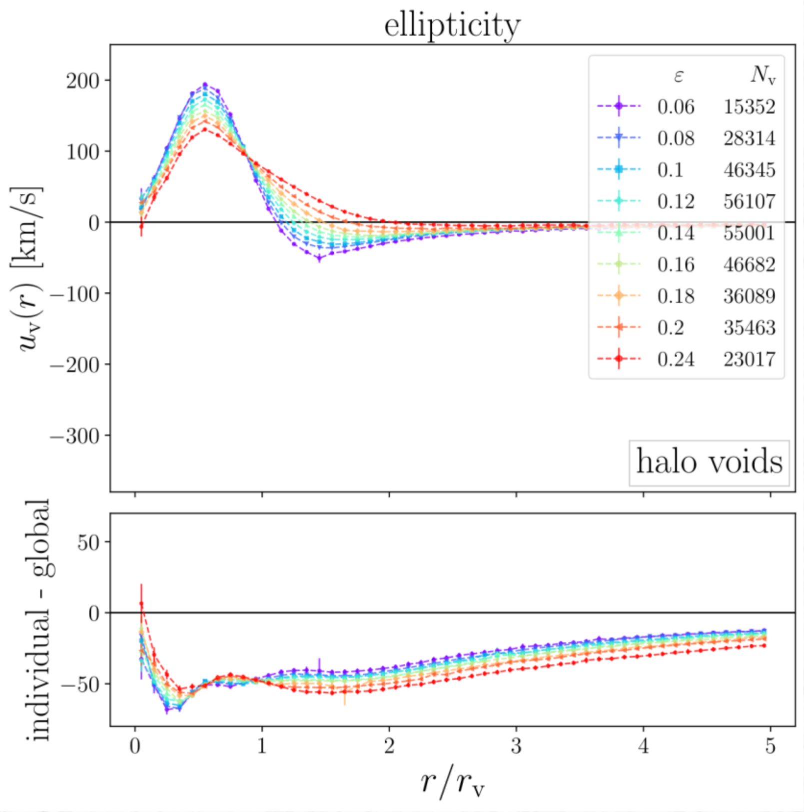
Velocity profiles CDM and halos around halo voids in **highres**, in void radius bins:

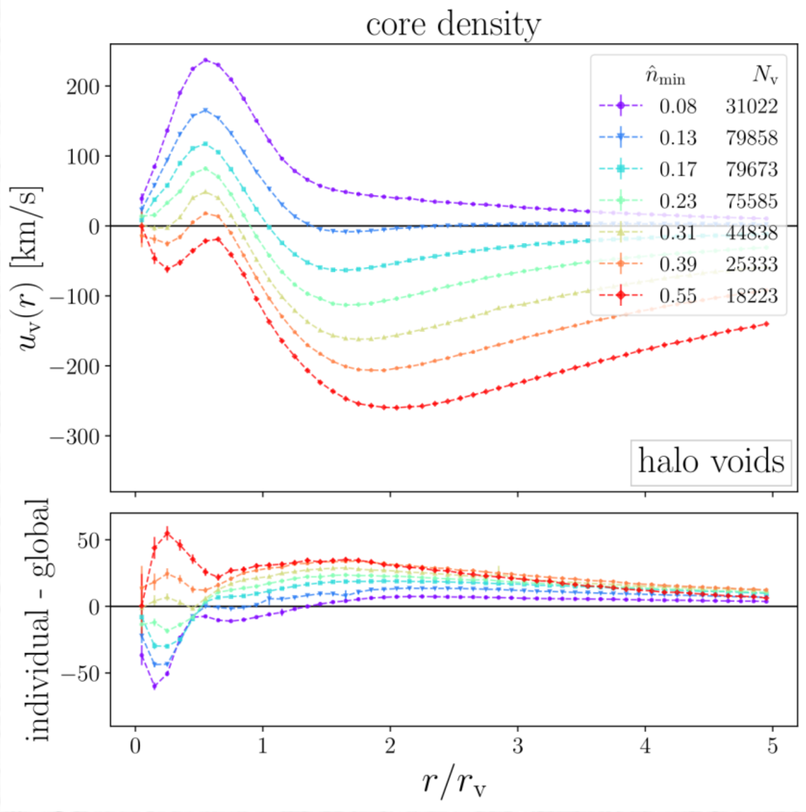


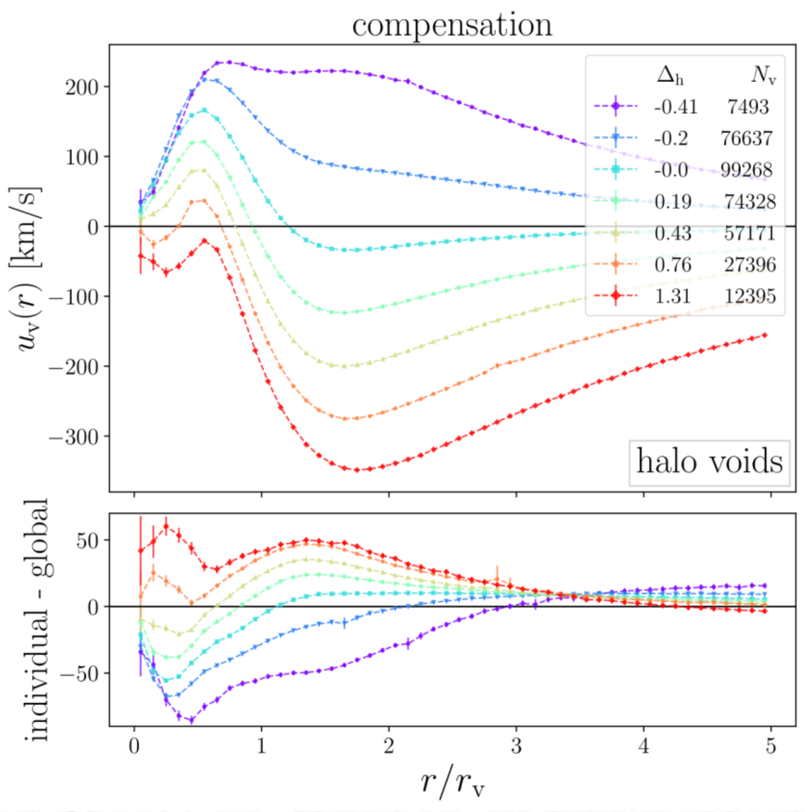


Velocity Profiles - Alternative Stacks

Velocity profiles of halo voids in **midres**, presented in stacked bins different void properties:

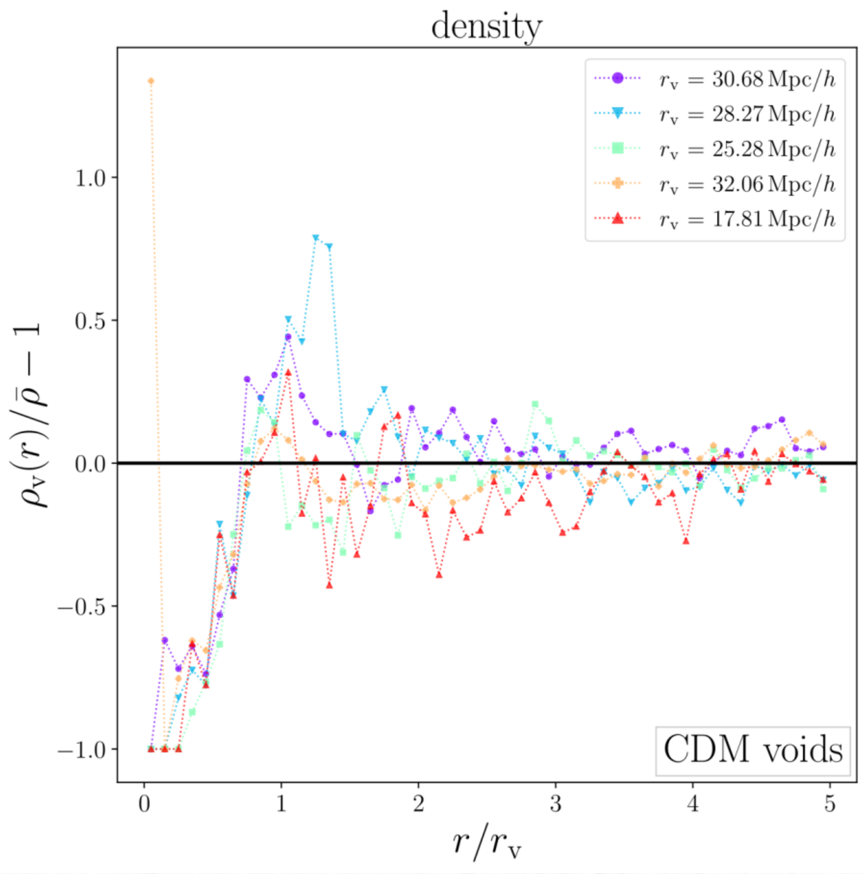

ellipticity

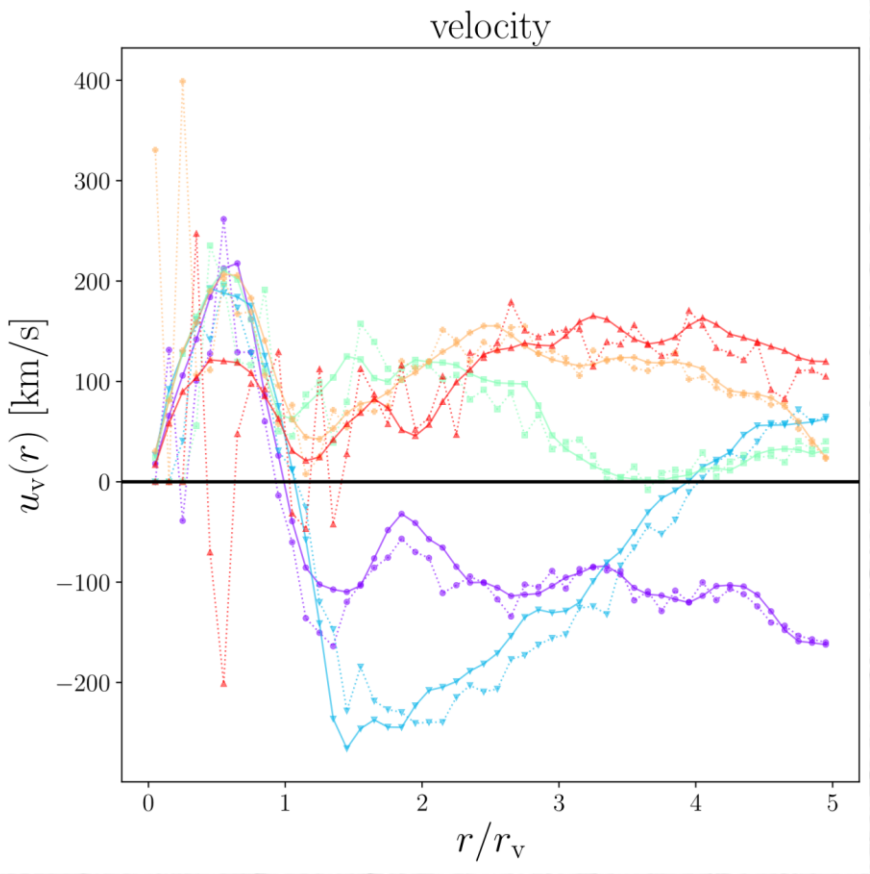

core density


compensation

Linear Mass Conservation - Individual CDM Voids

Application of linear mass conservation on the density profiles of **CDM** voids in **midres** and the resulting velocity profiles with $b_\mathrm{t} = 1$ (no fitting!).

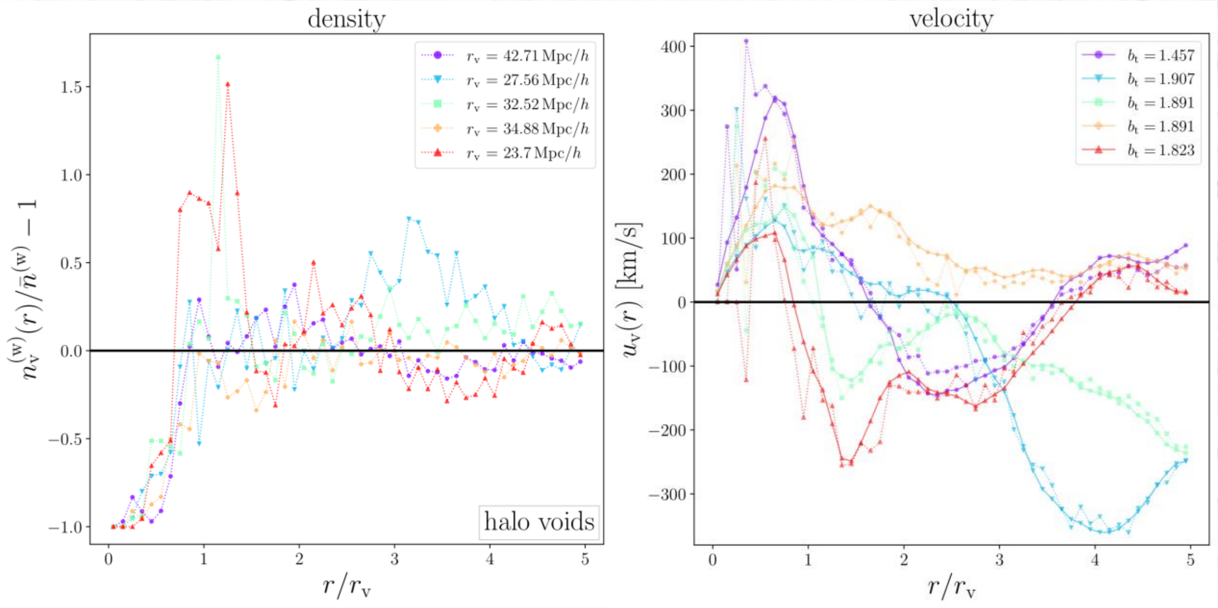




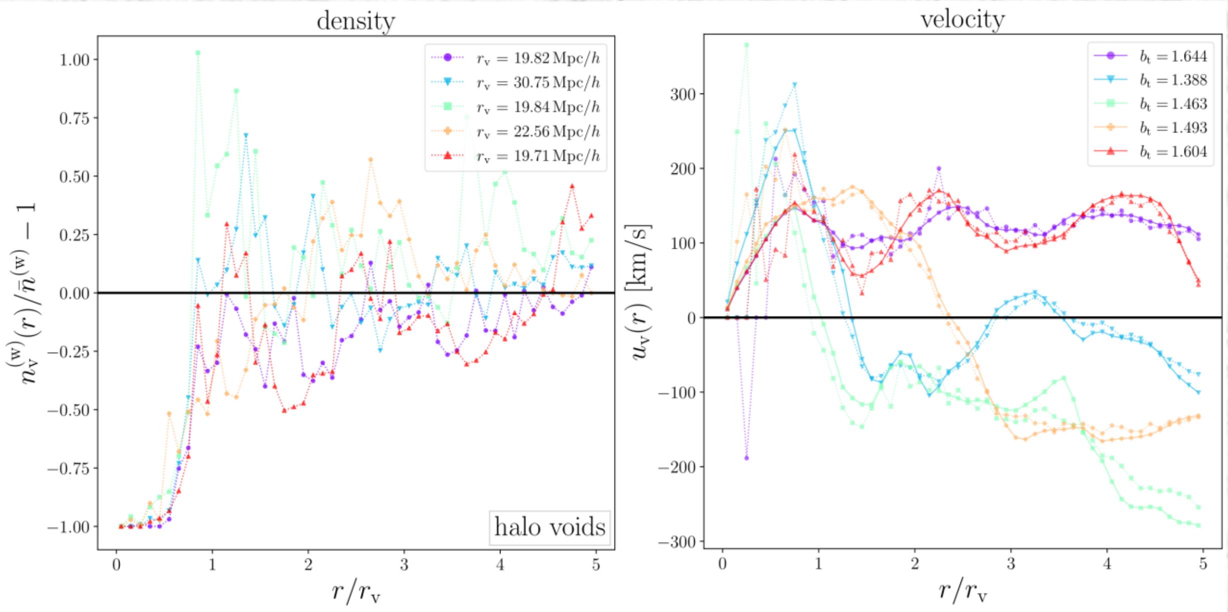
Linear Mass Conservation - Individual Voids ($w_i = M_i$)

Application of linear mass conservation on the individual **mass-weighted** density profiles of halo voids and the resulting velocity profiles, where b_t is fitted for each profile:

midres



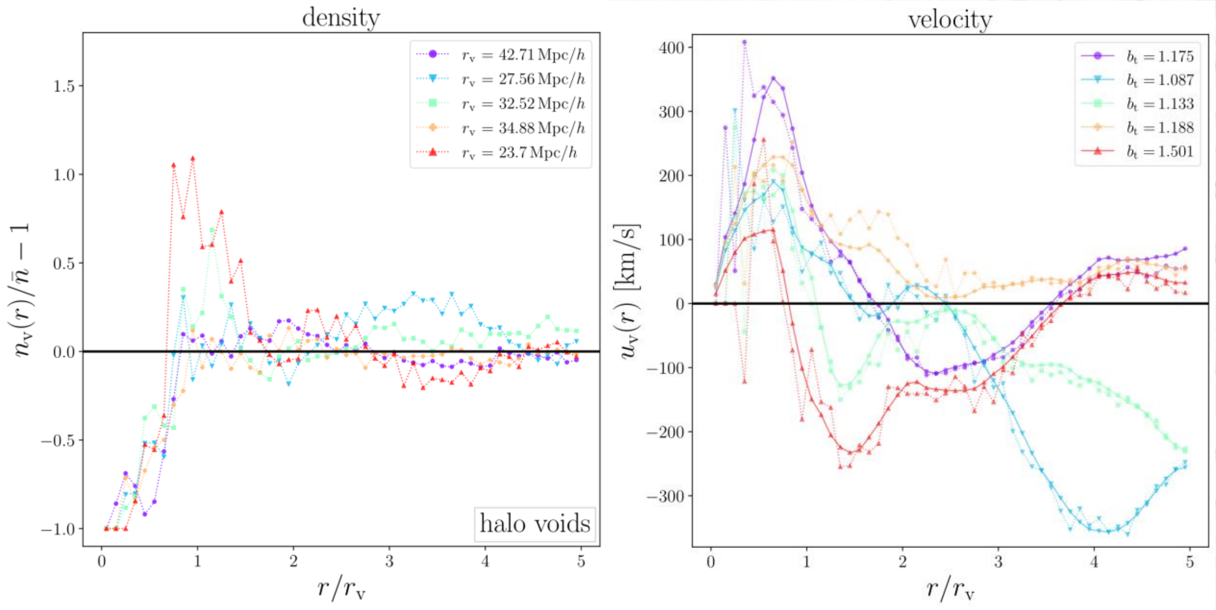
highres



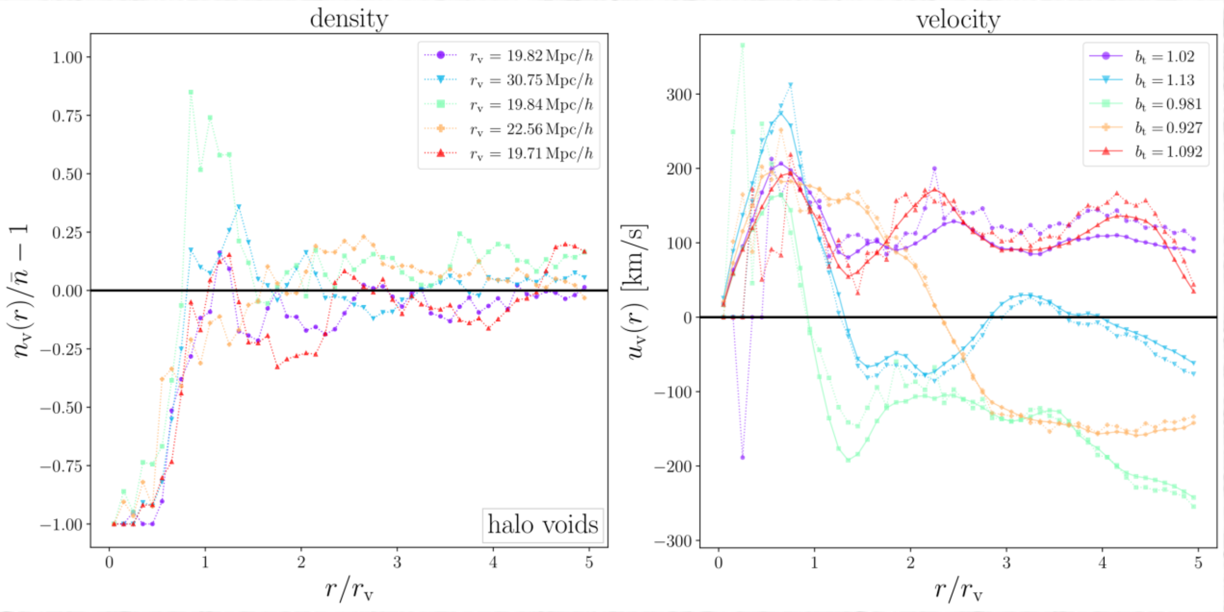
Linear Mass Conservation - Individual Voids ($w_i = 1$)

As in main slides, linear mass conservation on the individual density profiles of halo voids and the resulting velocity profiles, where b_t is fitted for each profile:

midres

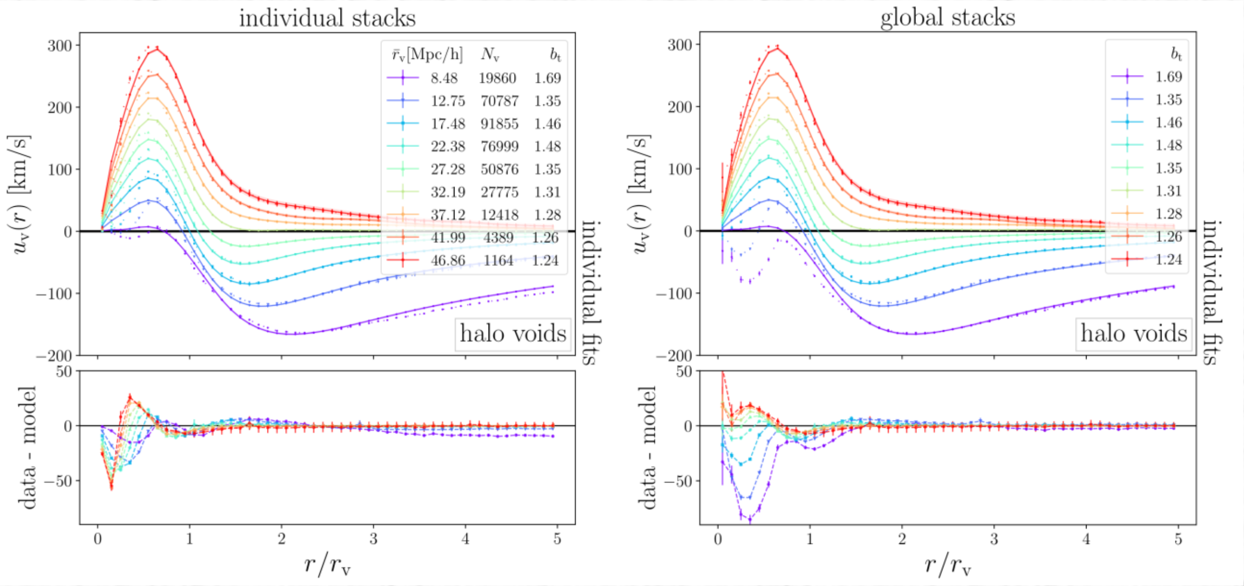


highres



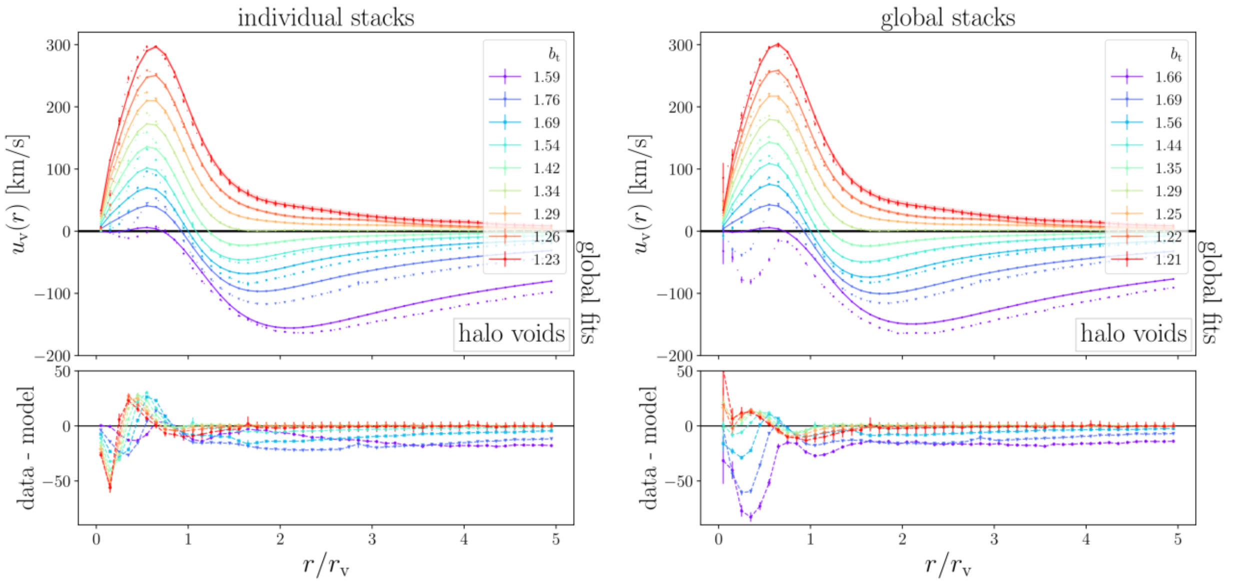
Linear Mass Conservation - Stacked Voids, both estimators

midres



Individual fits: use linear theory on each individual profile and fit b_t, then stack the resulting linear theory. Indicated b_t is the mean value

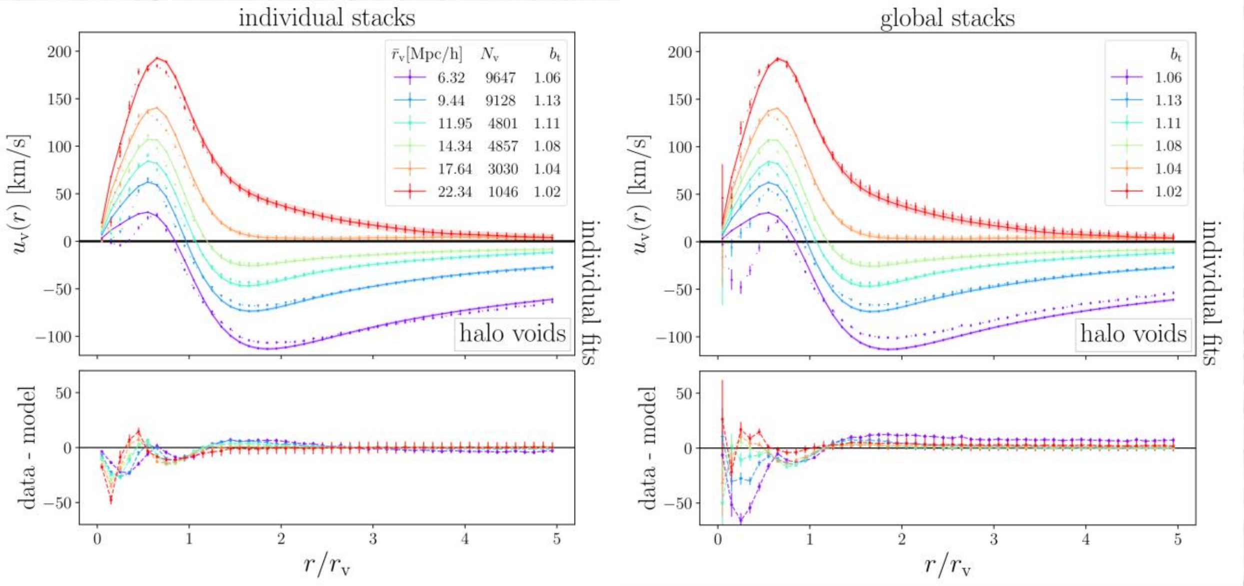
midres



Global fits: use linear theory on each individual profile with $b_\mathrm{t} = 1$, stack the resulting linear theory profiles and then fit for a global b_t to stacks of measured velocity profiles (data)

Linear Mass Conservation - Stacked Voids, both estimators

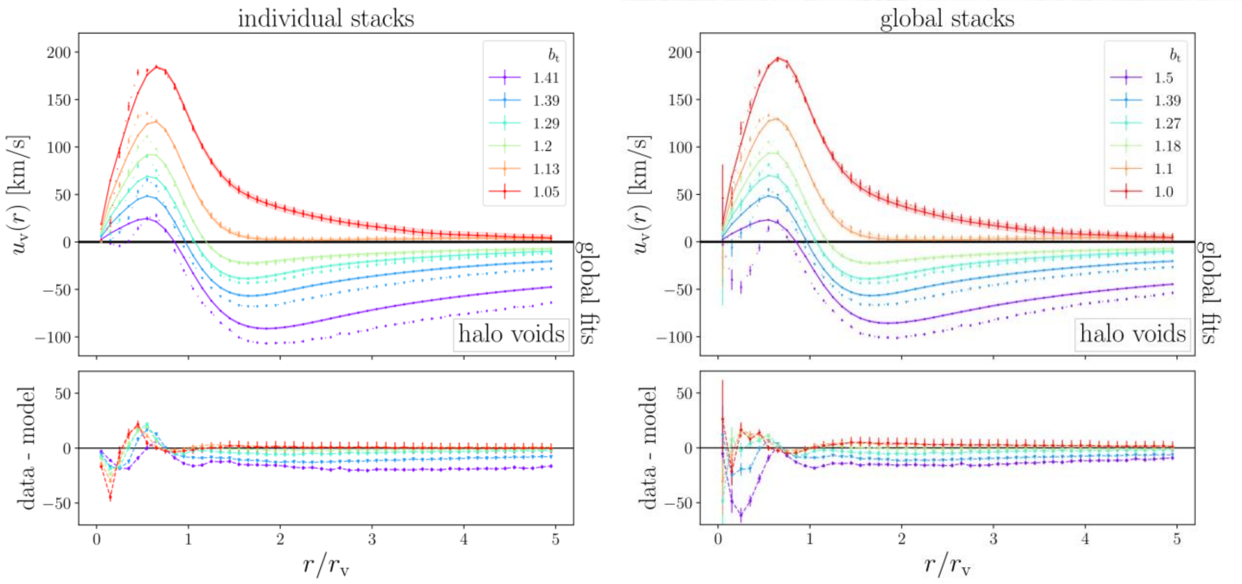
highres



Similar agreement between (simulation) data and model in **highres** at smaller scales than in **midres**, e.g. $22\ \mathrm{Mpc}/h$ in **mr** and $12\ \mathrm{Mpc}/h$ in **hr**

→ resolution effect and not onset of nonlinearity around voids

highres

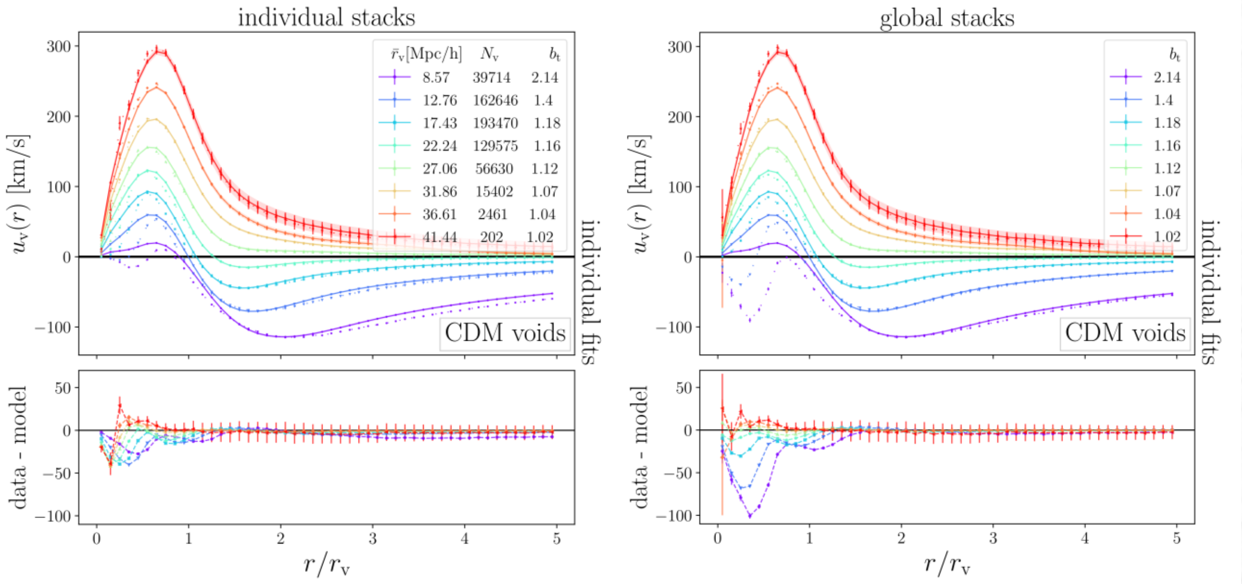


In global stacks differences decrease with increasing radius, in individual stacks same magnitude independent of r_v.

Slightly smaller differences in individual fits near the void centers.

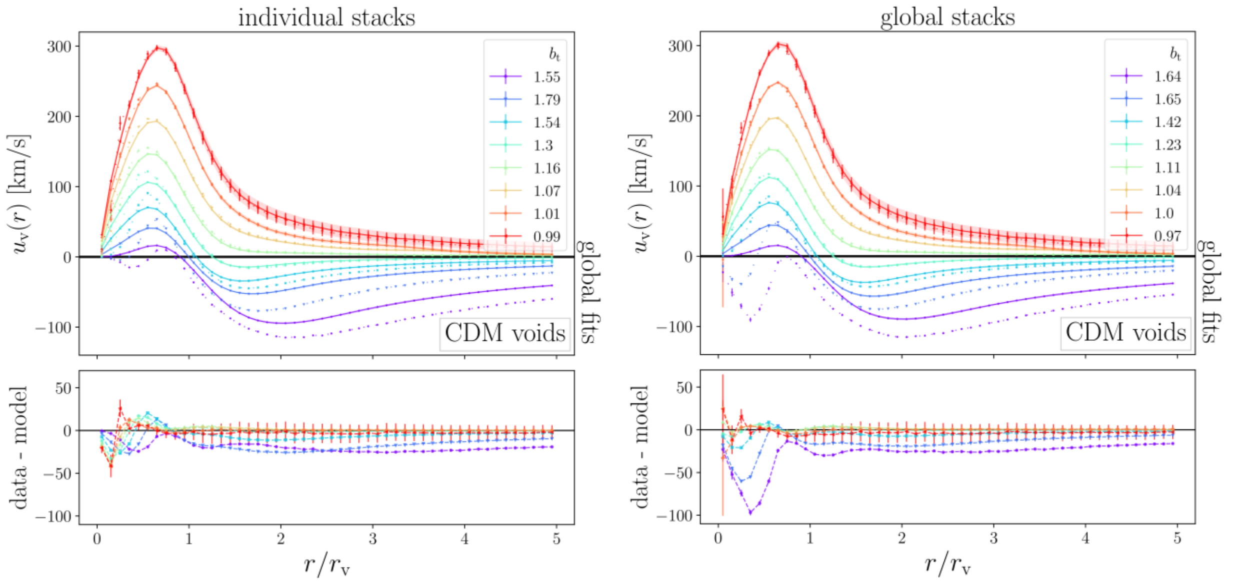
Linear Mass Conservation - Stacked Voids, CDM

midres, CDM



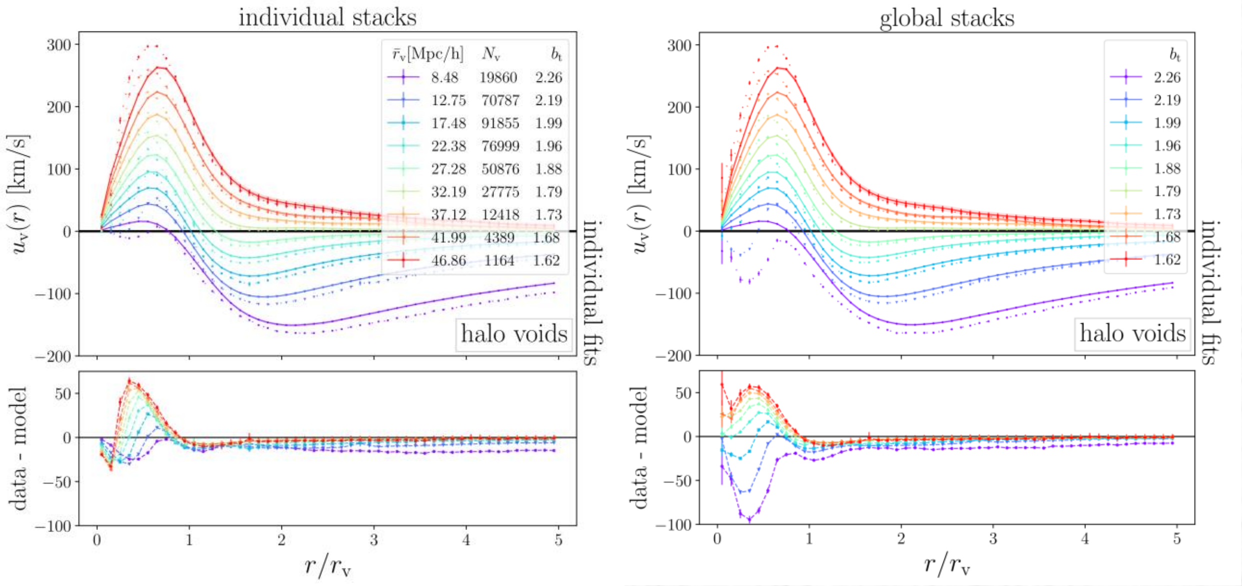
Even though CDM should have $b_{\rm t} = 1$, we choose to fit $b_{\rm t}$ in order to see which method results in bias values closest to unity.

midres, CDM



Linear Mass Conservation - Stacked Voids, mass weights

midres



Even though CDM should have $b_\mathrm{t} = 1$, we choose to fit b_t in order to see which method results in bias values closest to unity.

midres