GDR CoPhy Episode 4, June 2nd 2026

The Secret Life of Voids: Unifying Density Profiles and their Evolution

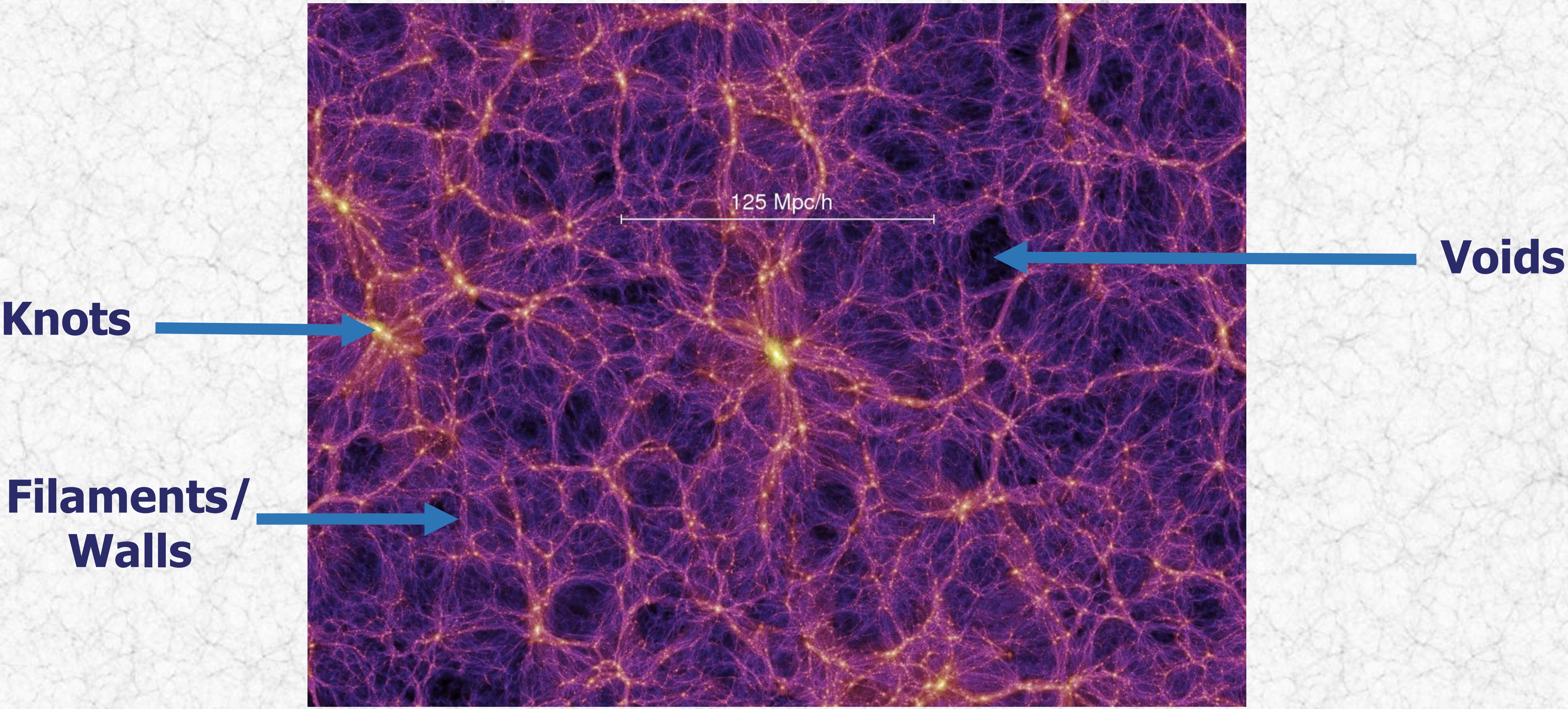
Based on arxiv:2210.02457, arxiv:2312.11241 and arxiv:2509.07092

Nico Schuster

+ collaborators

Nico Hamaus, Alice Pisani, Klaus Dolag, Jochen Weller and more

Large-Scale Structure



The Millenium Simulation Project

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What are Cosmic Voids?

Galaxies/Halos

- **Overdensities over hundreds times the mean density**
- **Baryonic physics of great relevance**
- **Complicated dynamics**
- **Complicated evolution**

Voids

- **Underdensities down to around 20% of the mean density**
- **Impact of baryonic physics almost irrelevant**
  - ⇨ N. Schuster et al. (2024)
- **Simpler linear dynamics**
  - ⇨ N. Schuster et al. (2023)
- **More predictable evolution**
  - ⇨ N. Schuster et al. (2026a)
  - ⇨ N. Schuster et al. in prep.

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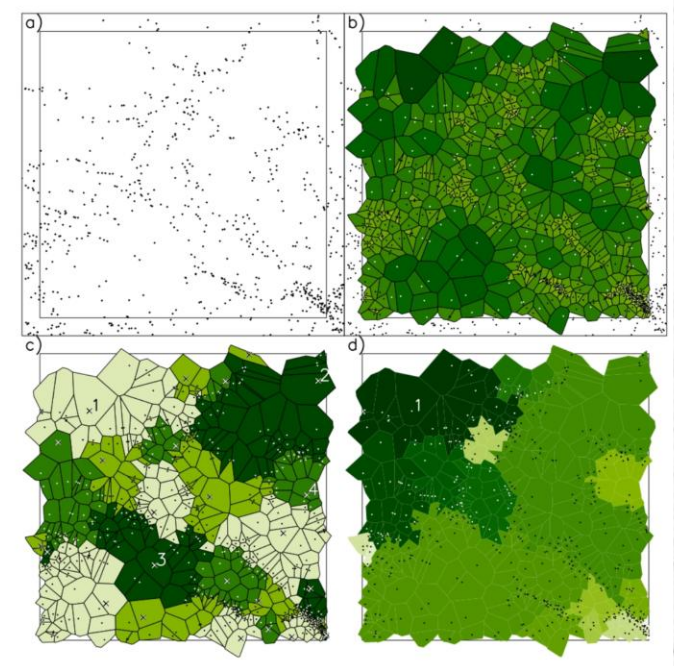
Void Identification

Free in surveys

How do we find Cosmic Voids?

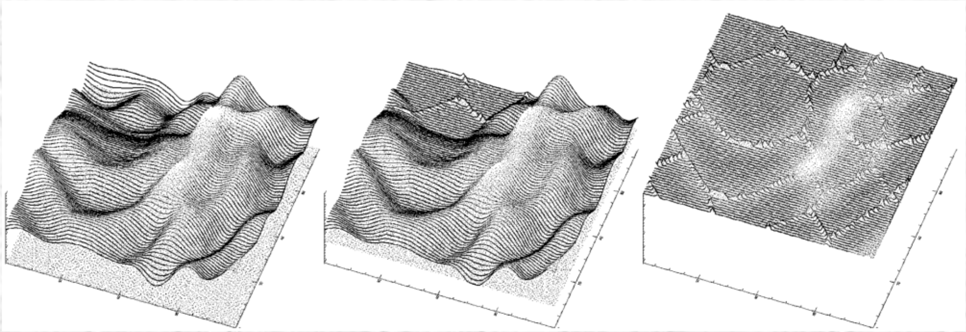


M. C. Neyrinck (2008)

Density field is estimated from tracers via Voronoi Tesselation (subdivision of space into cells with volumes closest to one particle)

+

Watershed

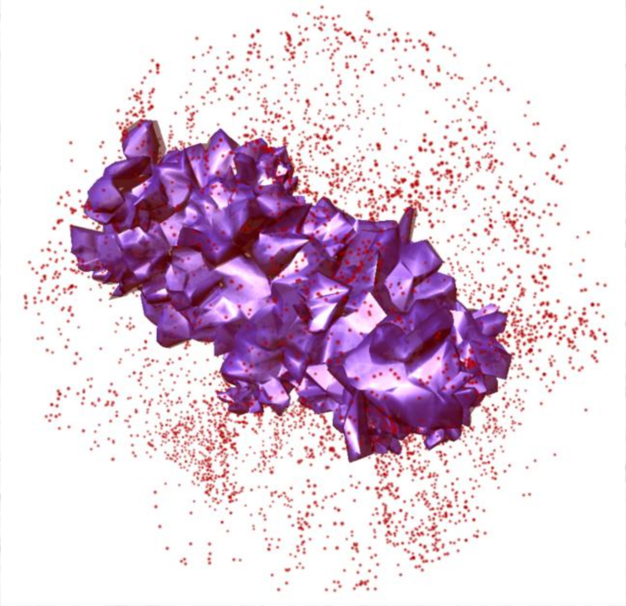


Platen (2007)

Starting from the cells of lowest density, we continually raise the density level until it drops again, defining our void boundaries

=

Voids



Sutter et al. (2015)

Depending on density between voids, they can be merged into larger ones

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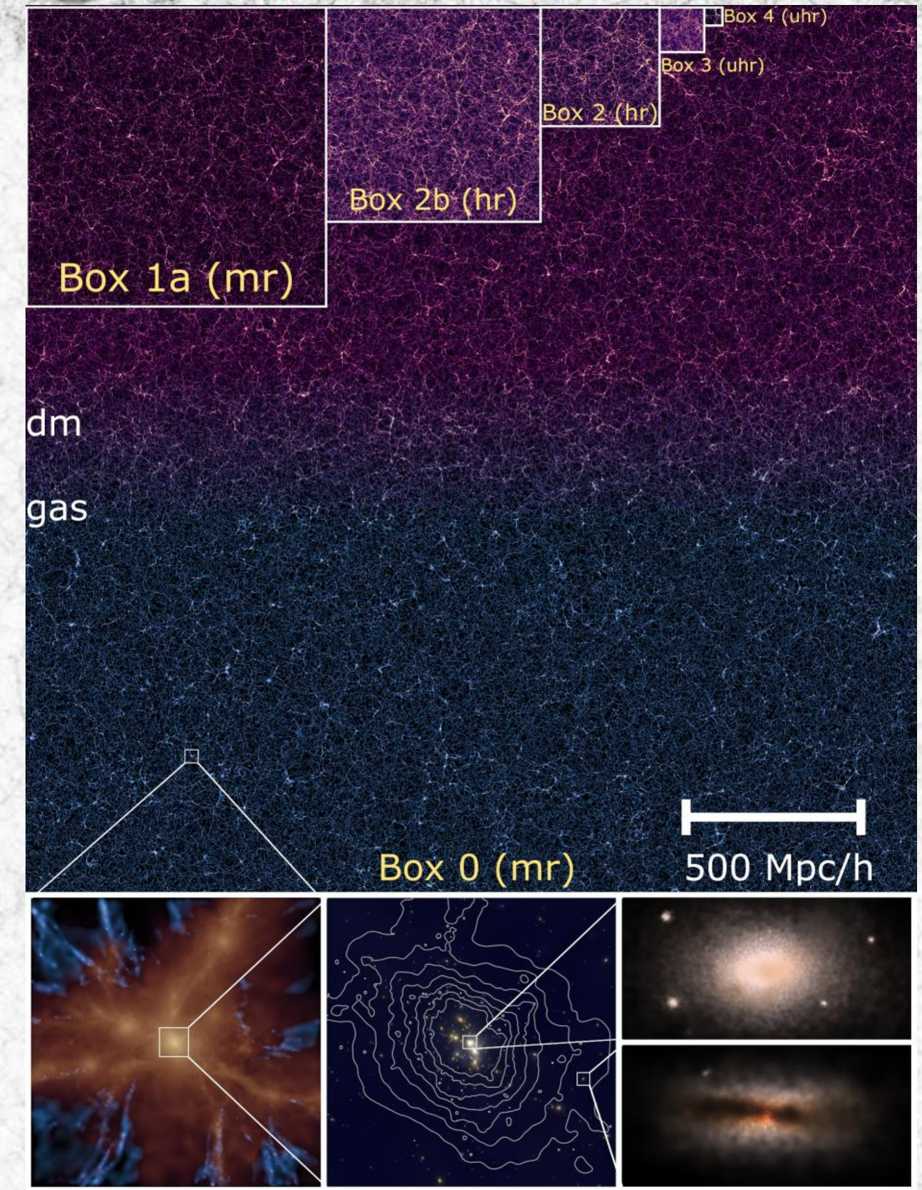
Magneticum Simulations



Credit: Benjamin Seidel
(see: Dolag et al. 2025)

Hydrodynamical simulations with dark matter only (DMo) counterparts, assuming a WMAP7 cosmology:

$\Omega_\Lambda = 0.728$ $\Omega_m = 0.272$

$\Omega_b = 0.0456$ $\sigma_8 = 0.809$

$n_s = 0.963$ $h = 0.704$

Name	Box	L_{Box}	$N_{particles}$	m_{CDM}	m_{baryon}	z
midres (mr)	0	2688	2×4536^3	1.3×10^{10}	2.6×10^9	0.29
highres (hr)	2b	640	2×2880^3	6.9×10^8	1.4×10^8	0.29
ultra-hr (uhr)	4	48	2×576^3	3.6×10^7	7.3×10^6	0.29

Name	M_{cut} $[M_\odot/h]$	N_h $[\times 10^6]$	$\bar{r}_t$ [Mpc/h]	N_v in halos	N_v in CDM
midres	1.0×10^{12}	62.1	6.8	356 597	600 273
highres	1.0×10^{11}	8.21	3.2	33 324	52 951
ultra-hr	1.3×10^9	0.136	0.93	346	424

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What makes Voids interesting for current and upcoming Surveys?

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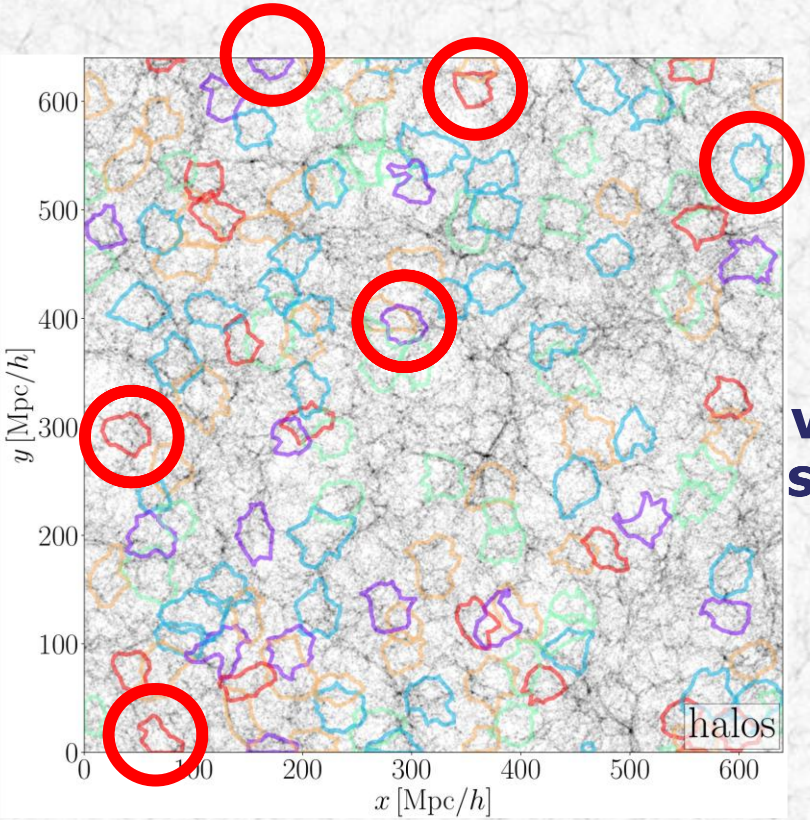
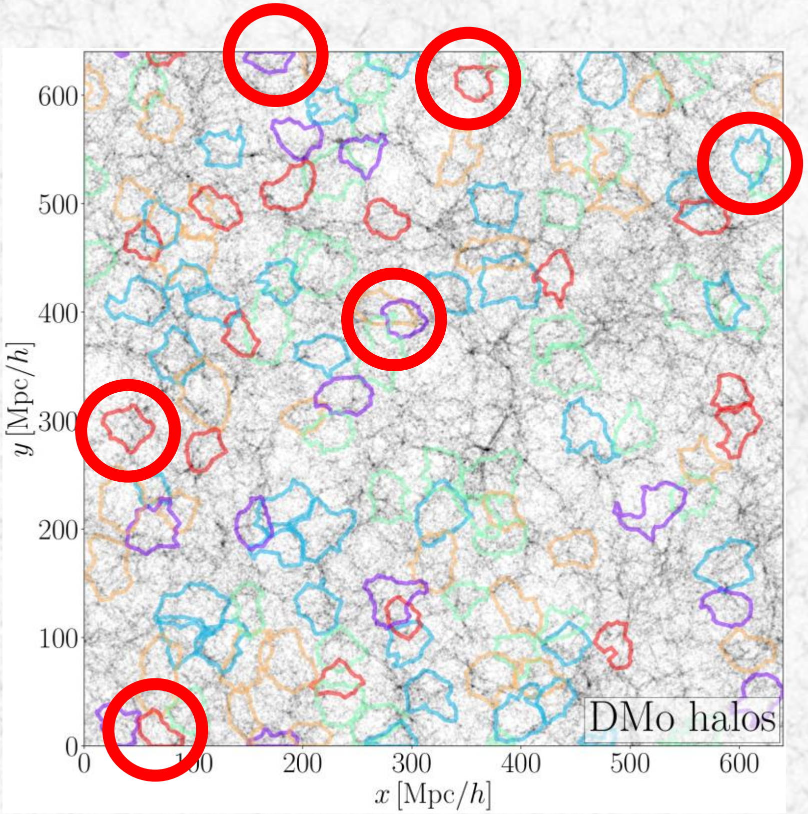
Baryonic Sensitivity

Due to different numbers of halos between hydro and DMo simulations at a given mass cut, void numbers differ as well.

To imitate observations, statistics from matched halo density catalogs are analyzed



Some individual voids match between simulations, but most do not



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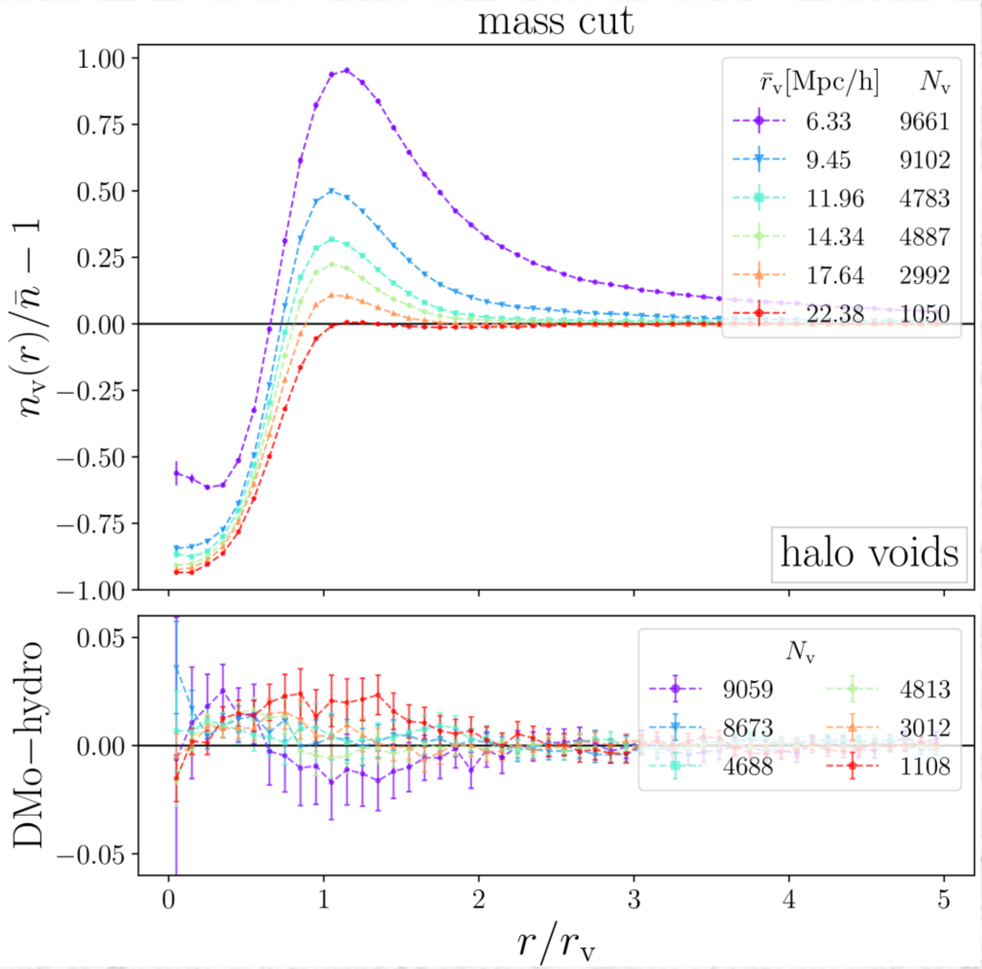
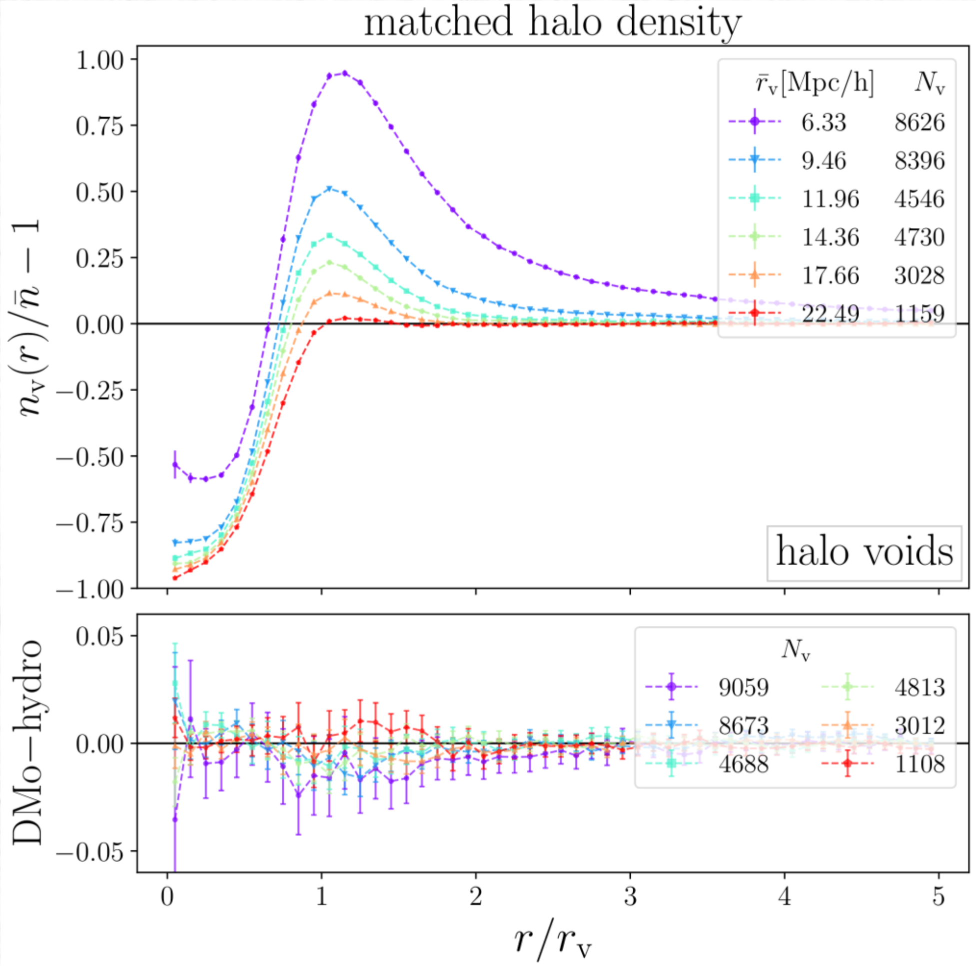
Baryonic Sensitivity - Halo Density

→ Matching halo densities reduces potential effects in halo defined voids





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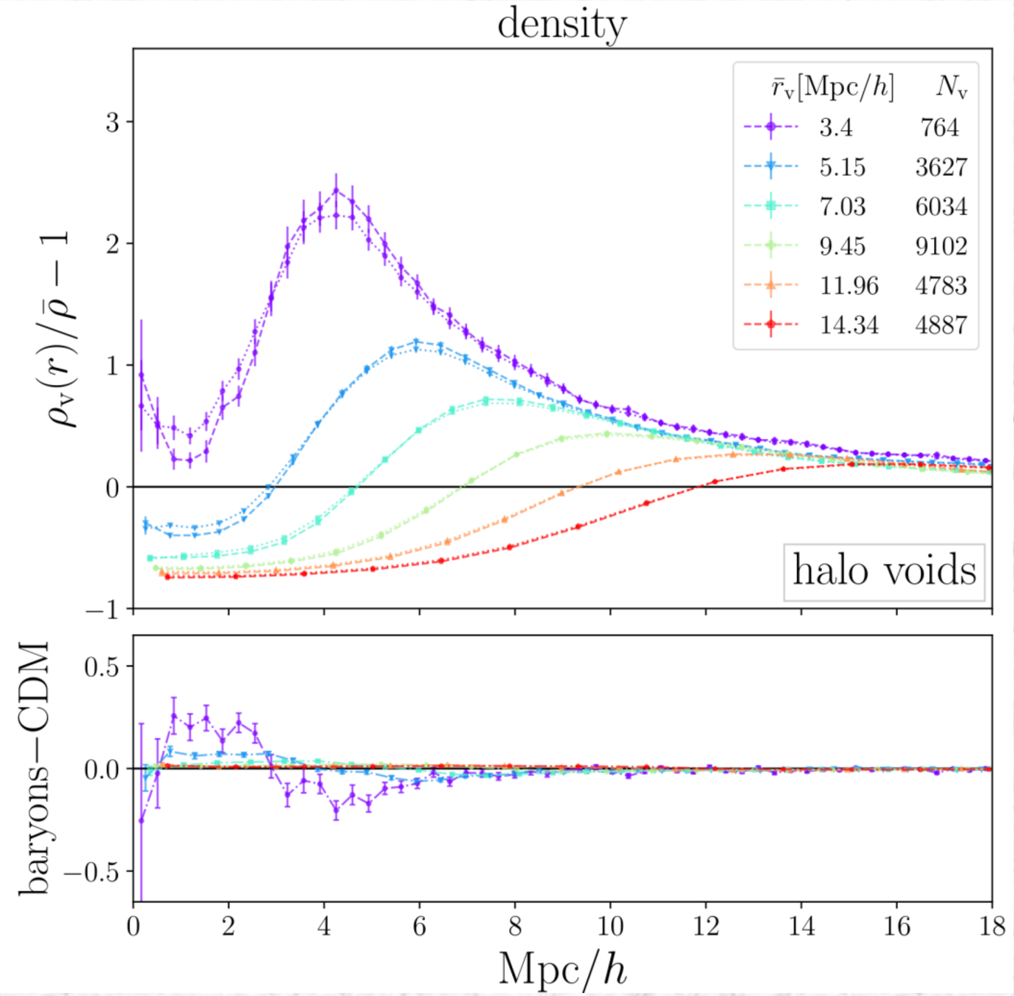
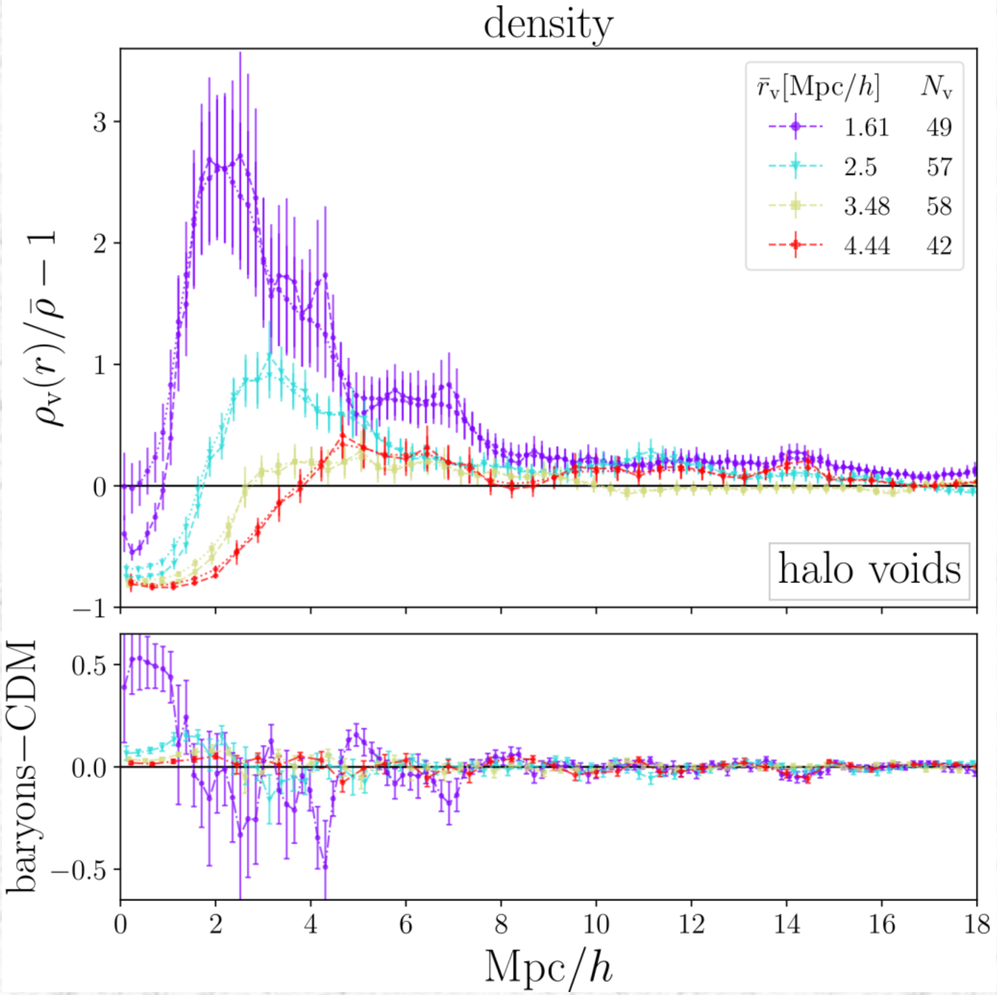
Baryons and CDM around voids

Density profiles of CDM (dashed) and baryons (dotted) in comoving scales



→ Limit on maximal differences and scale



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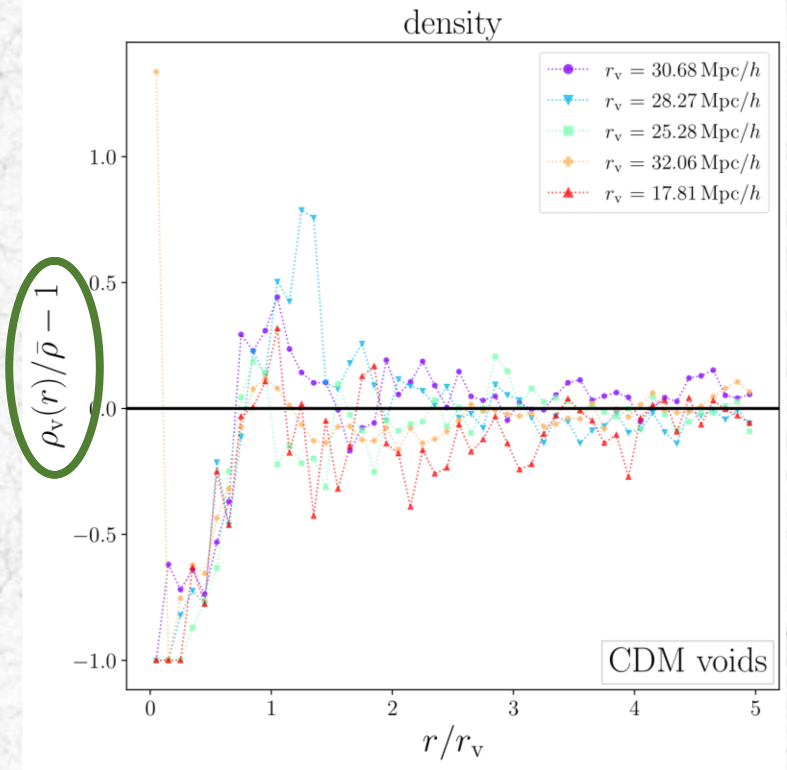
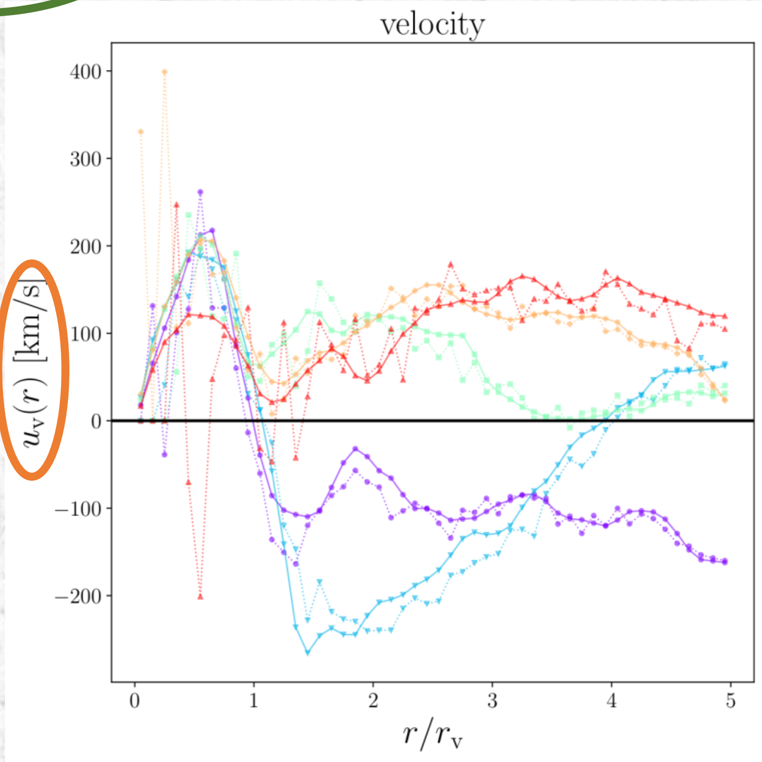
Modeling dynamics - Individual Voids

Application of linear mass conservation on the individual density profiles of **CDM** voids, the resulting velocity profiles (solid lines) and „measured" velocity profiles (dashed), $\boldsymbol{b_\mathrm{t}}$ is fixed to 1:

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

cosmology





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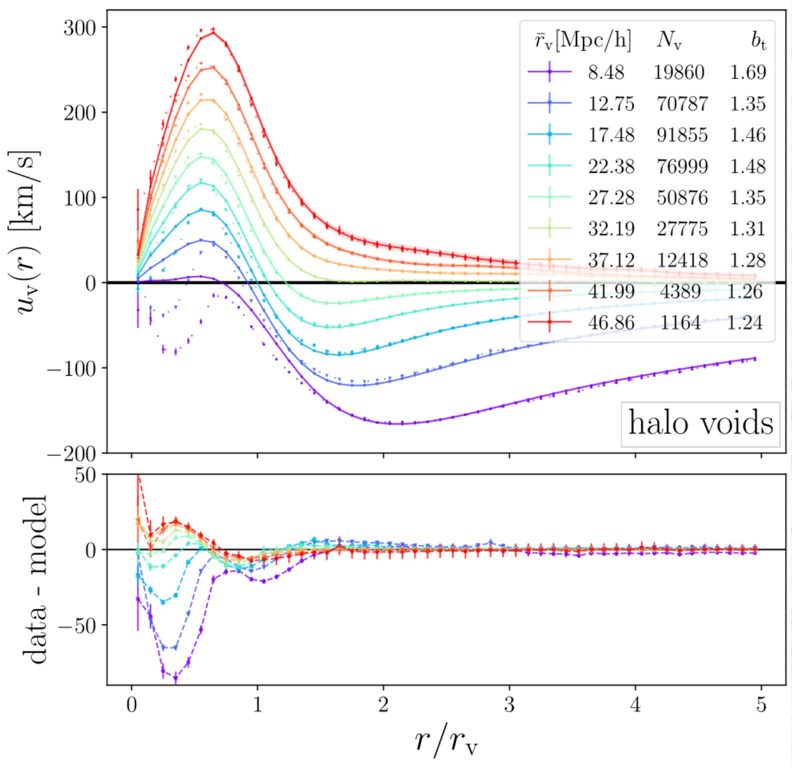
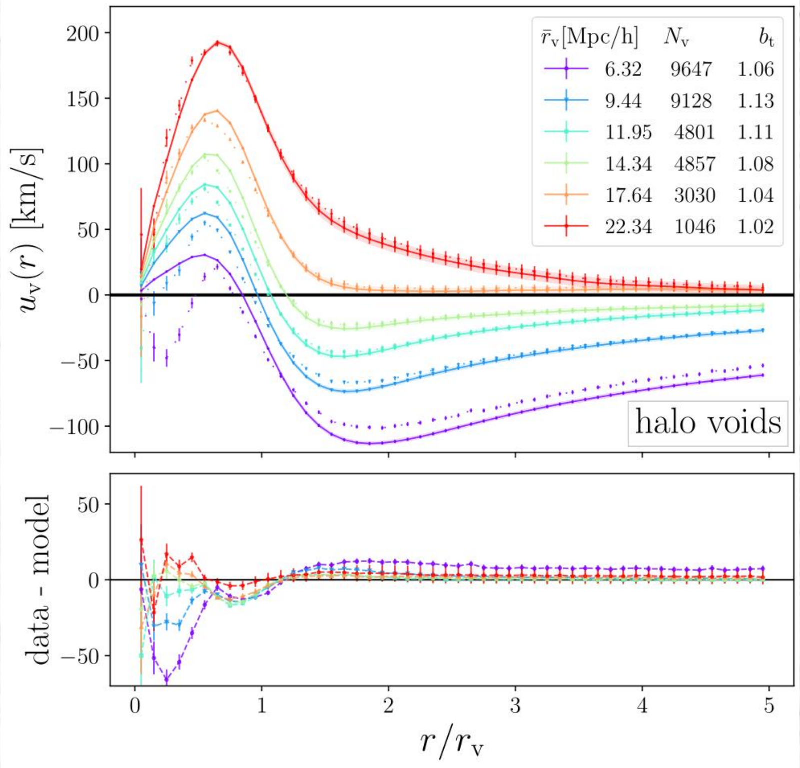
Modeling dynamics - Stacked Voids

midres



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 and sampling effects, not onset of nonlinearity around voids**

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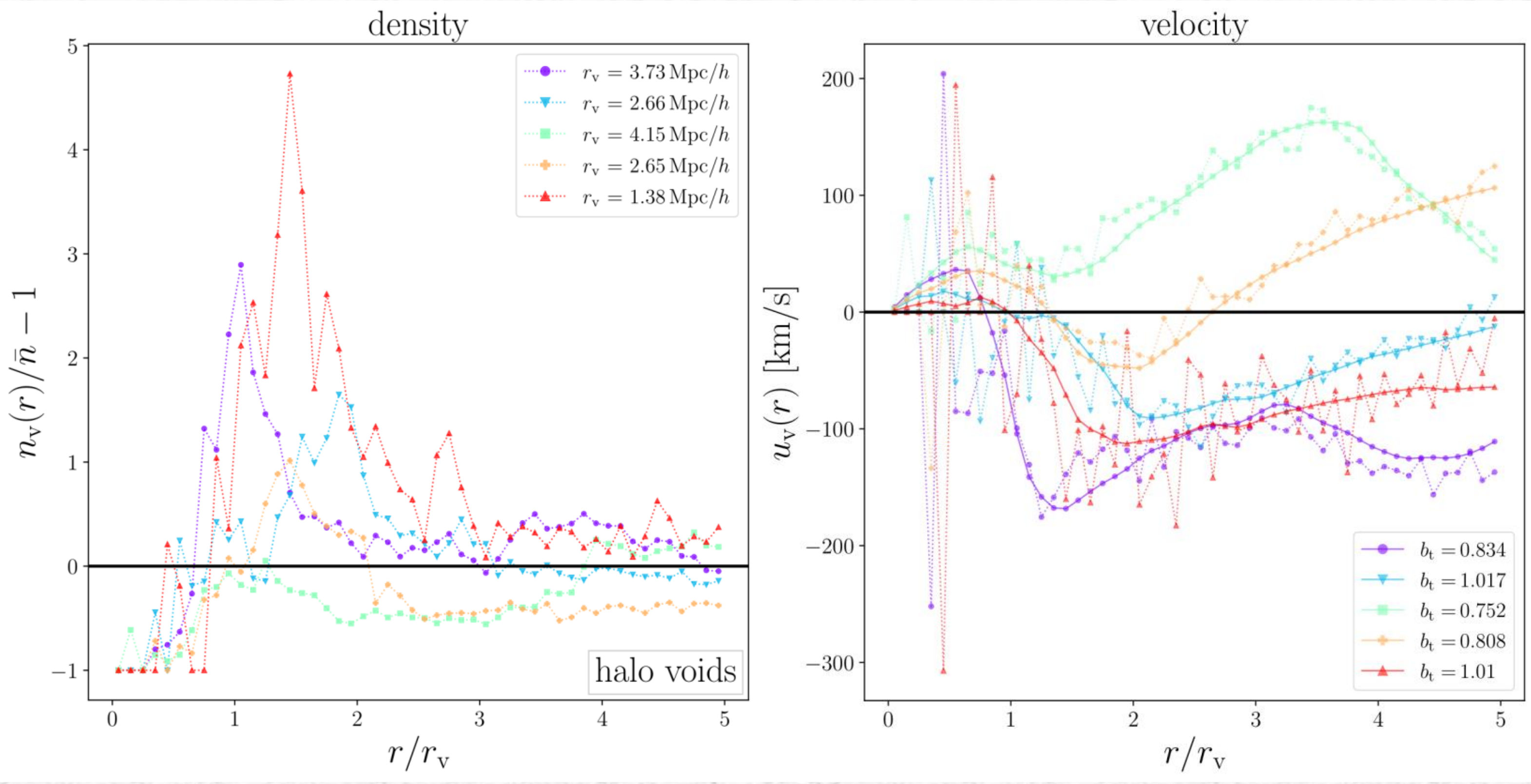
Modeling dynamics - Small Scale Limit?

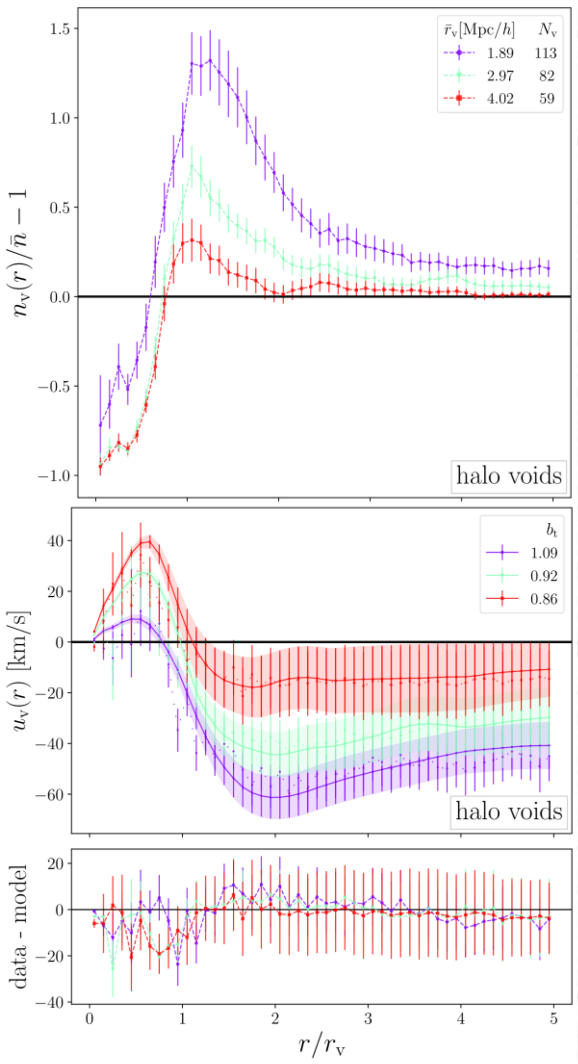
ultra-hr: $48\ \mathrm{Mpc}/h$ box with 346 halo voids

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

individual profiles:



stacked profiles:



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How do voids evolve?

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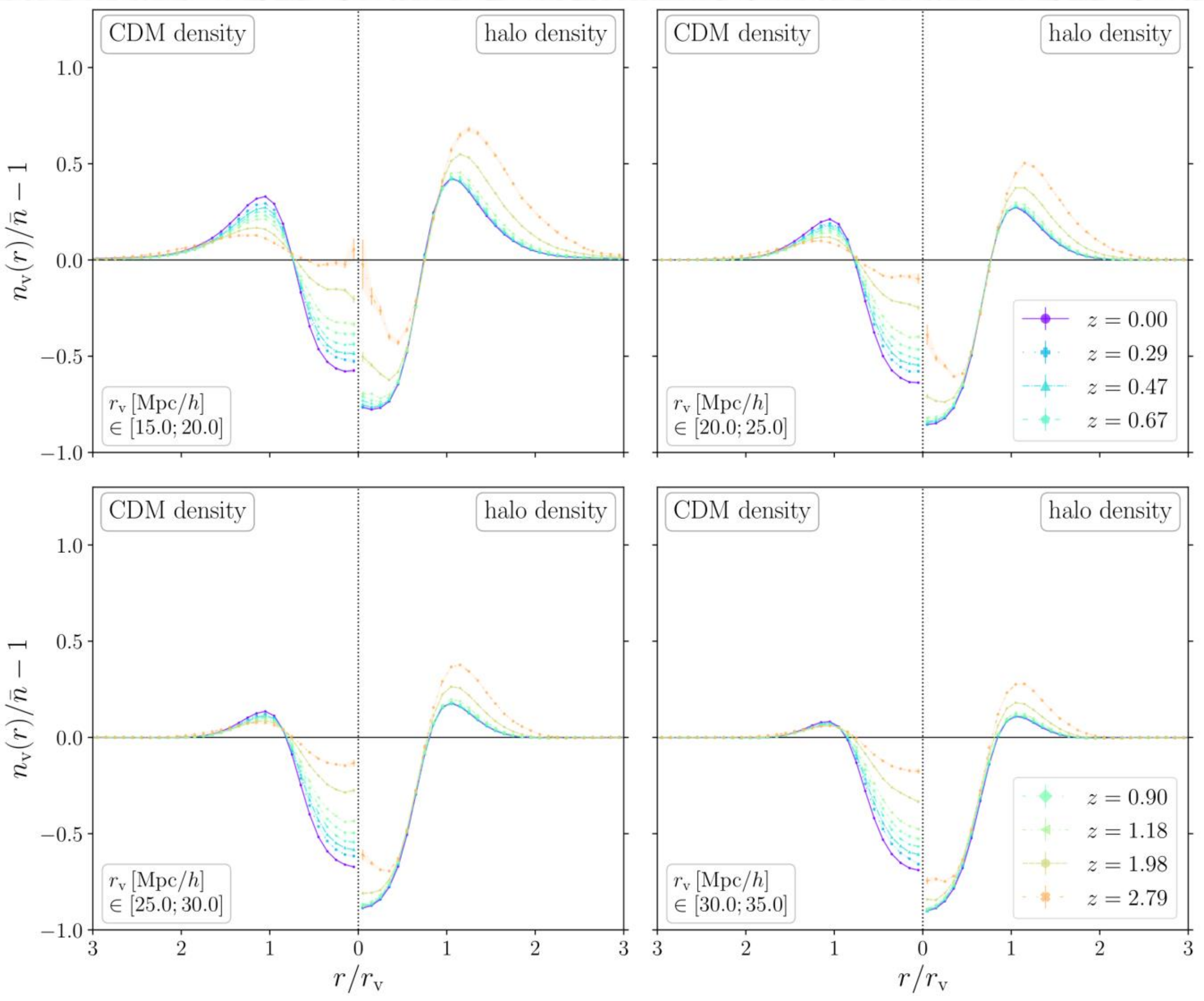
Densities around halo-defined voids

midres:

Left panels depict
CDM density
around halo voids



Right panels depict
halo density
around halo voids

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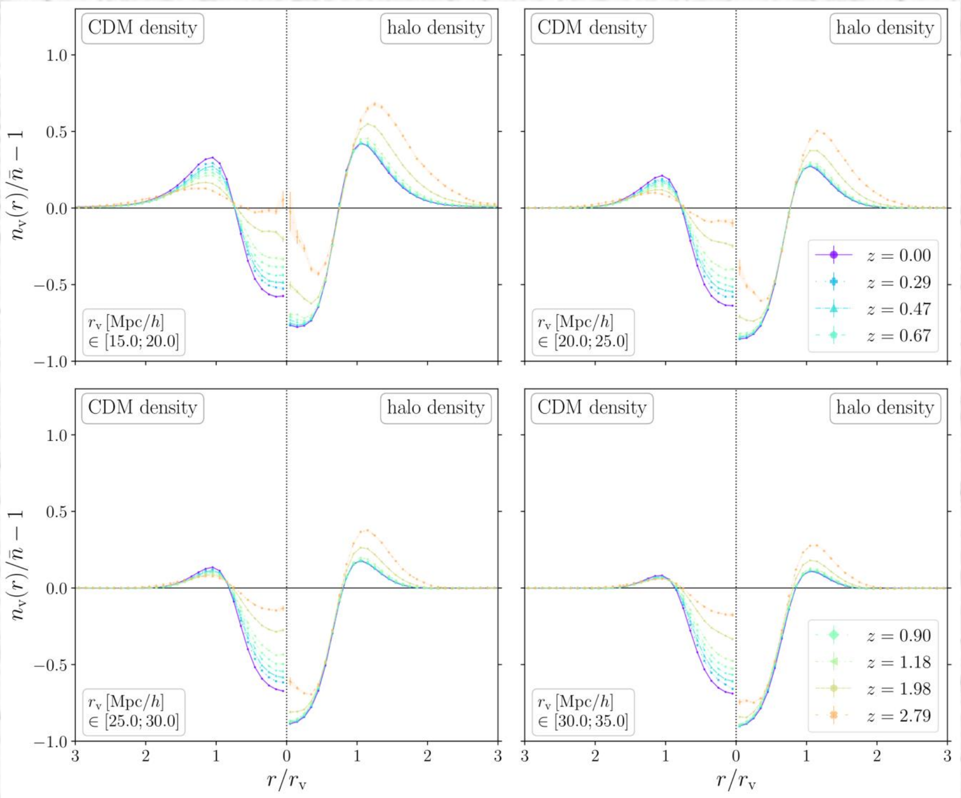
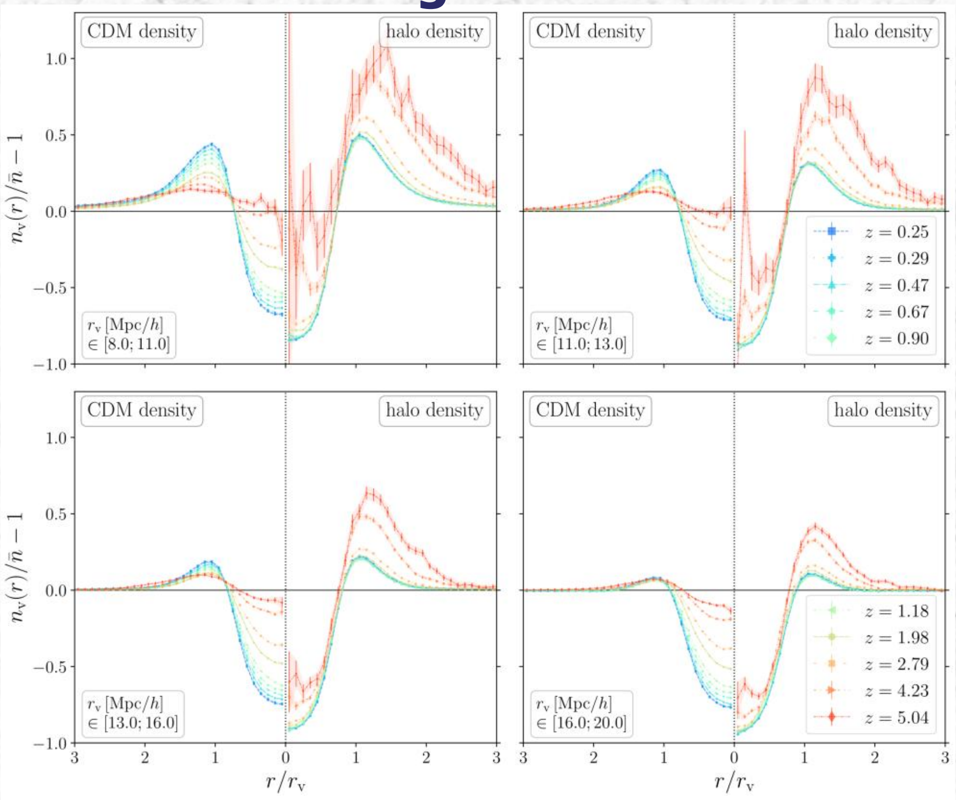
Densities around halo-defined voids

midres:



highres:



What causes this uncharacteristic evolution and how can we remedy it?

CDM densities evolve as expected:

Void interiours become emptier as CDM streams outwards and clusters at their boundary to form pronounced compensation walls.

Halo densities around voids of fixed size have a counterintuitive apparent evolution:

Their compensation walls are most pronounced at high redshift and decrease with time.

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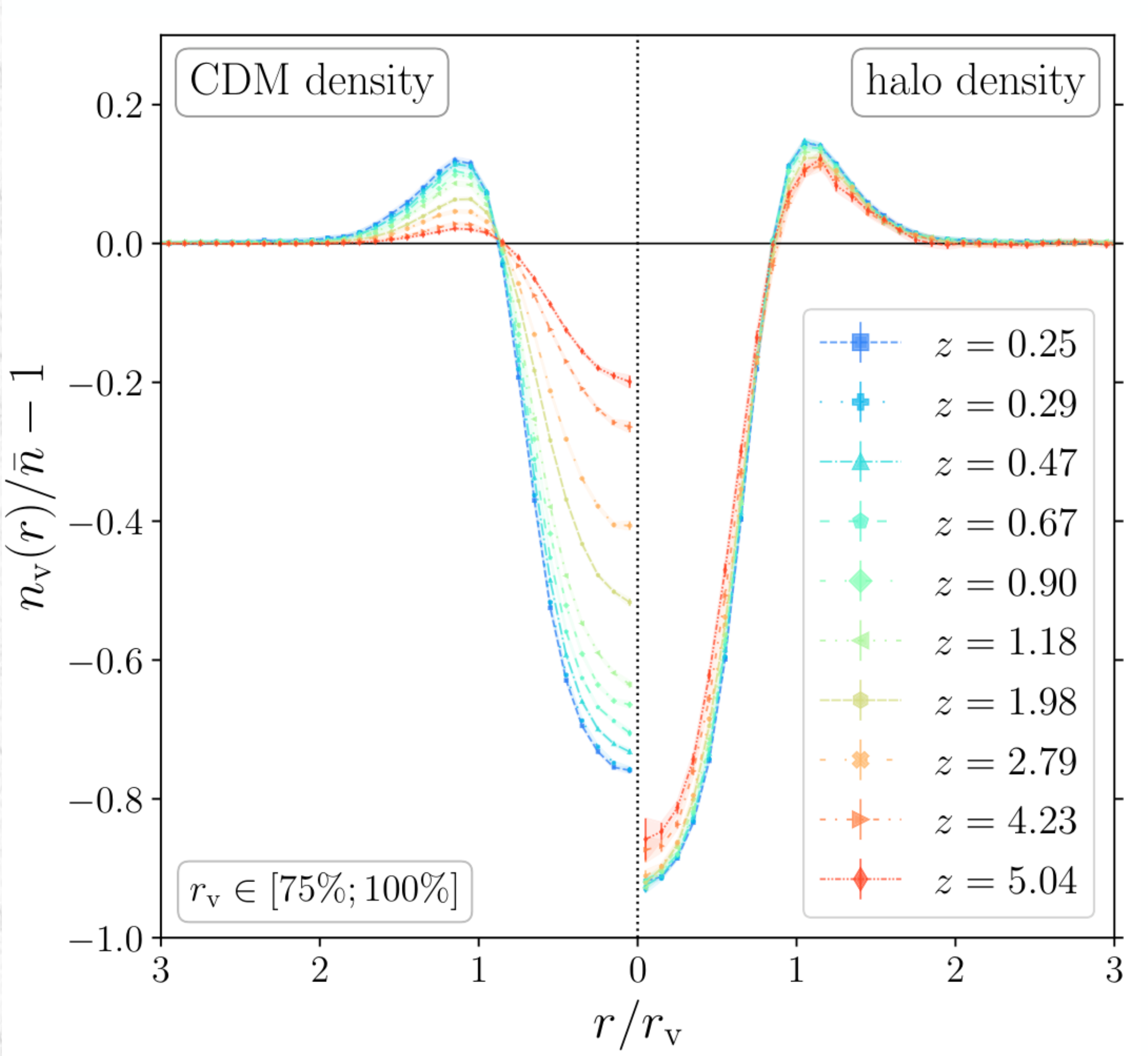
Densities in a relative-size framework

CDM densities evolve as expected.

Halo densities now evolve similiarly to CDM. Compensation walls grow with time as halos evacuate void centers.

A late-time stabilization of halo voids can be observed, similarly in the size evolution.



With this relative-size framework we follow the evolution of certain void populaions, capturing their density and size evolution at the same time

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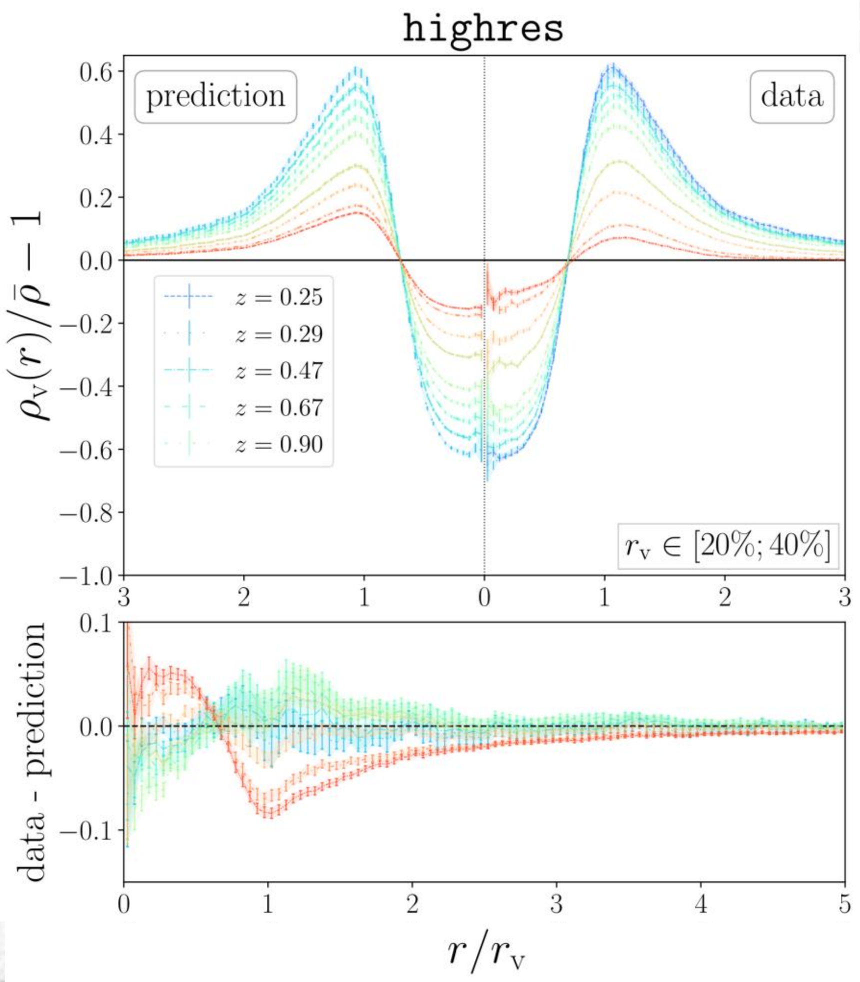
Linear predictions around evolving voids

We predict for bins in relative size using the growth factor

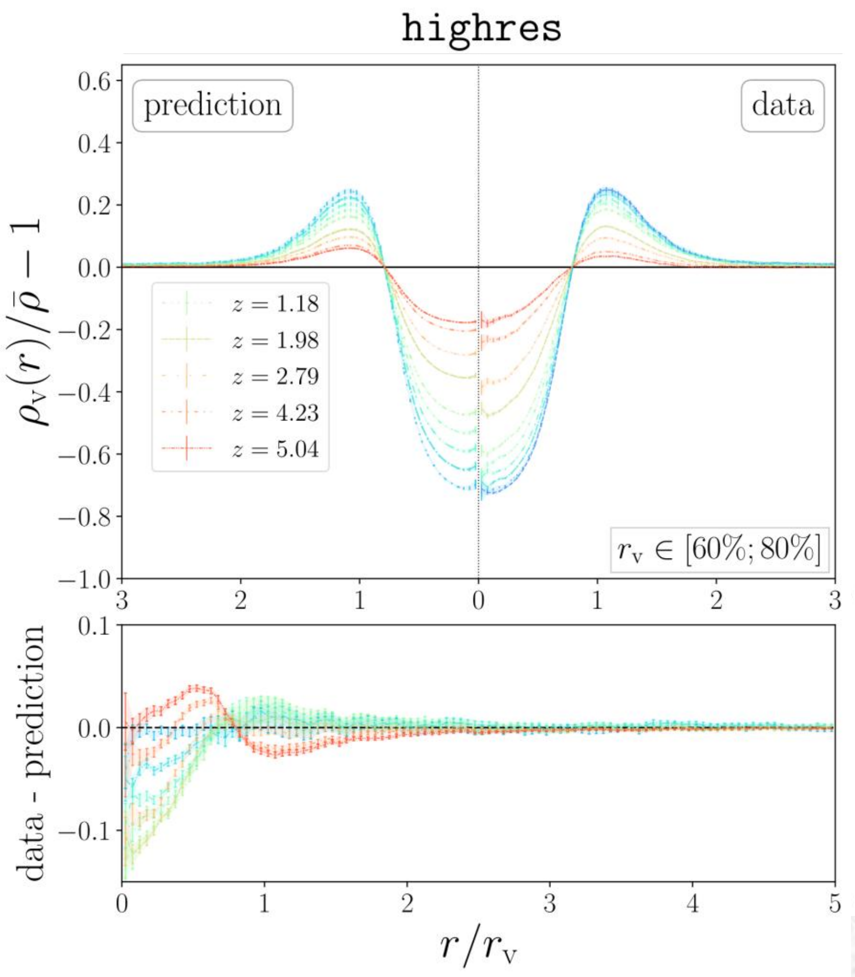


$$D_+(a) = \frac{5\,\Omega_\mathrm{m}}{2}\,\frac{H(a)}{H_0}\int_0^a \frac{\mathrm{d}\tilde{a}}{(\tilde{a}\,H(\tilde{a})/H_0)^3}$$

Two regimes where the linear model deviates from the data:

Small voids (left): compensation walls predicted too high, as linear model does not account for non-linear clustering

Large voids (right): interior densities overestimated at ~z = 1-2, implying **suppressed late-time structure growth**, potentially due to local impact of dark energy.



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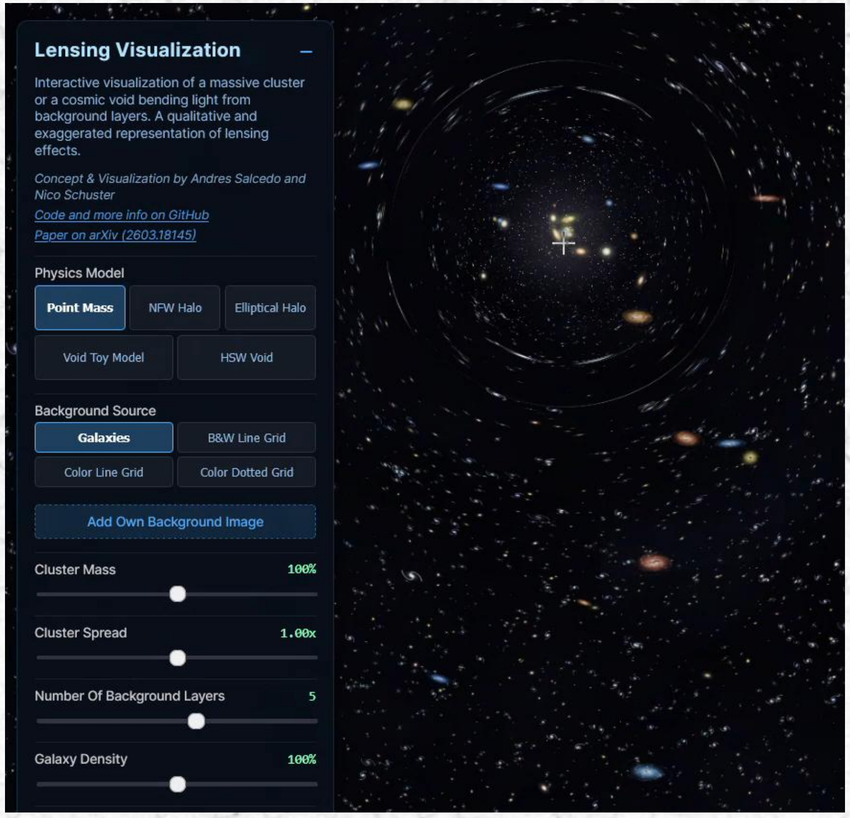
Visualizing and Communicating Science

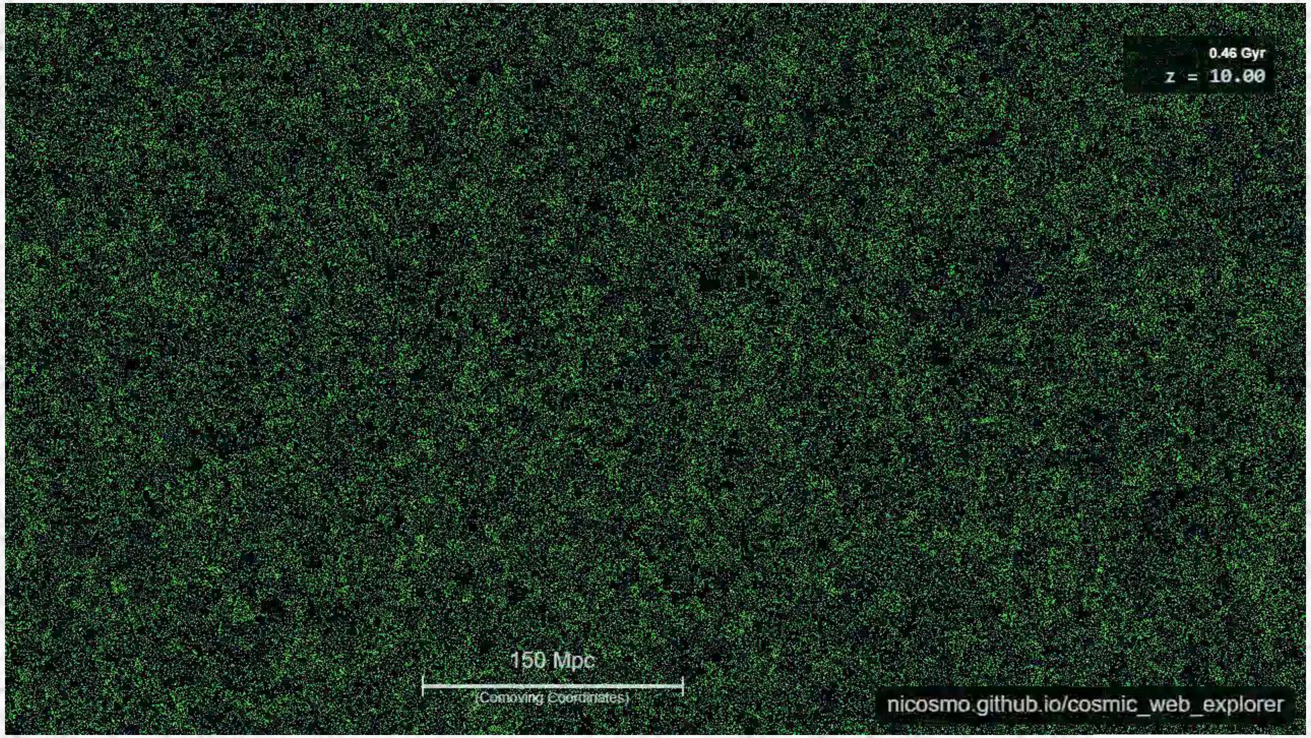
Real-time interactive browser tools with accurate science

On the method for such tools:

[Schuster et al. (2026b): arxiv:2603.18145](arxiv:2603.18145)



tinyurl.com/lensing-visualization or nicosmo.github.io/lensing_visualization



tinyurl.com/cosmic-web-explorer or nicosmo.github.io/cosmic_web_explorer

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Conclusions

- **Clean physics:** Baryons have negligible effect on voids, especially if tracer densities are matched. Baryons are more evenly distributed around them than CDM
- **Simplified dynamics:** CDM and halos have identical dynamics around voids, which can be modeled even around individual voids down to the smallest scales.
- **Halo voids stabilize:** At late times ($z \approx 1$ and below), they "freeze" and become passive tracers of cosmic expansion as their comoving sizes and densities reach a plateau.
- **Relative-size framework:** Essential for correctly tracking the evolution of void populations by simultaneously capturing their size and density evolution.
- **Pristine density evolution:** Linear growth accurately predicts CDM density evolution, but reveals potential dark energy effects around large voids

Papers:

Lensing tool:

Cosmic Web:

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