Testing ΛCDM with Non-linear Pairwise Velocities

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WARP
Warsaw, 27th October 2026

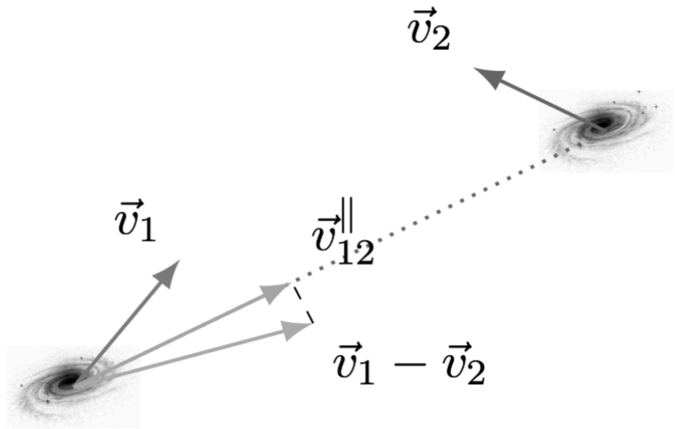
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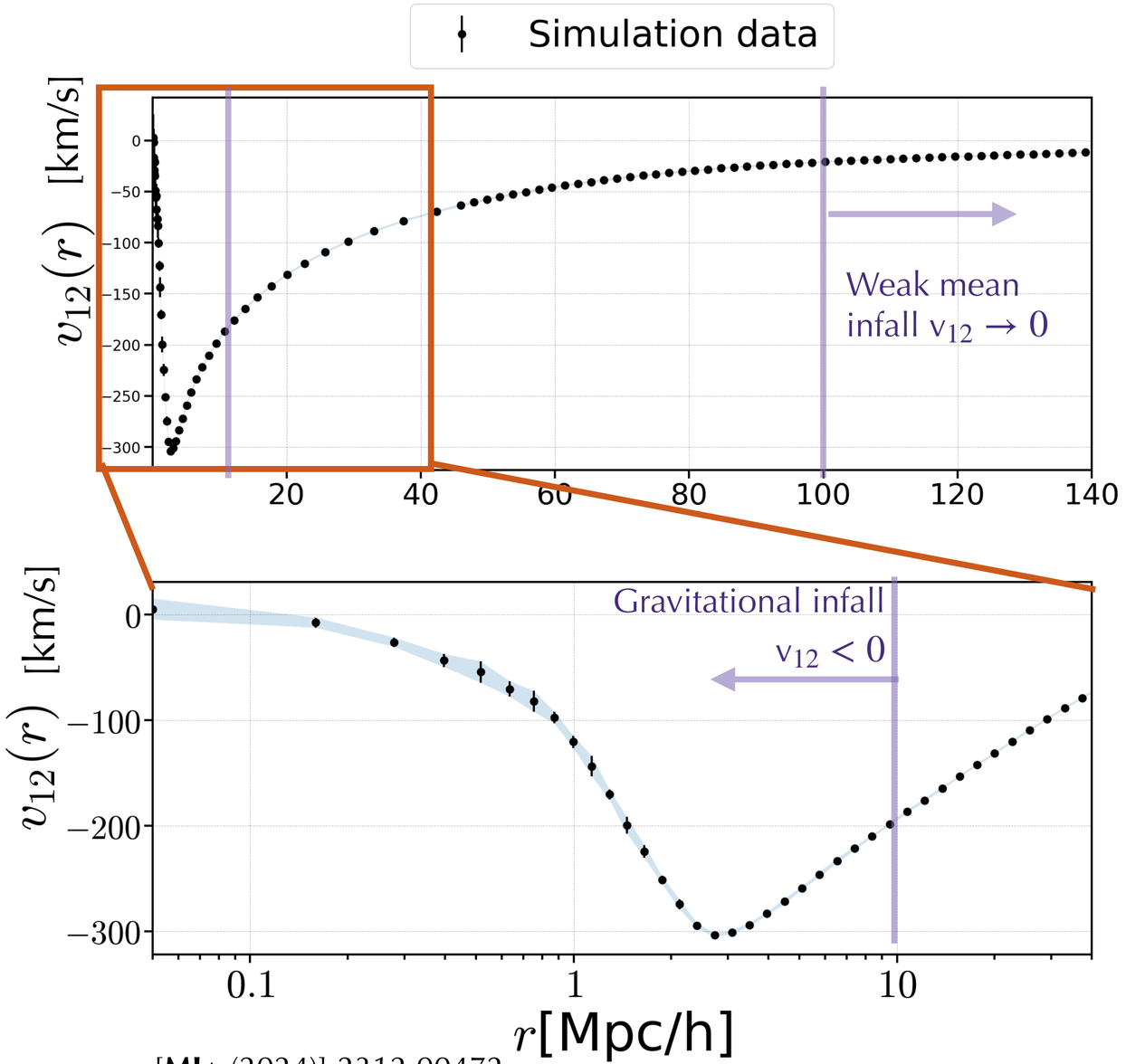
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Beyond Clustering: Probing Gravity Through Motion

The mean pairwise velocity for pairs separated by a distance r:

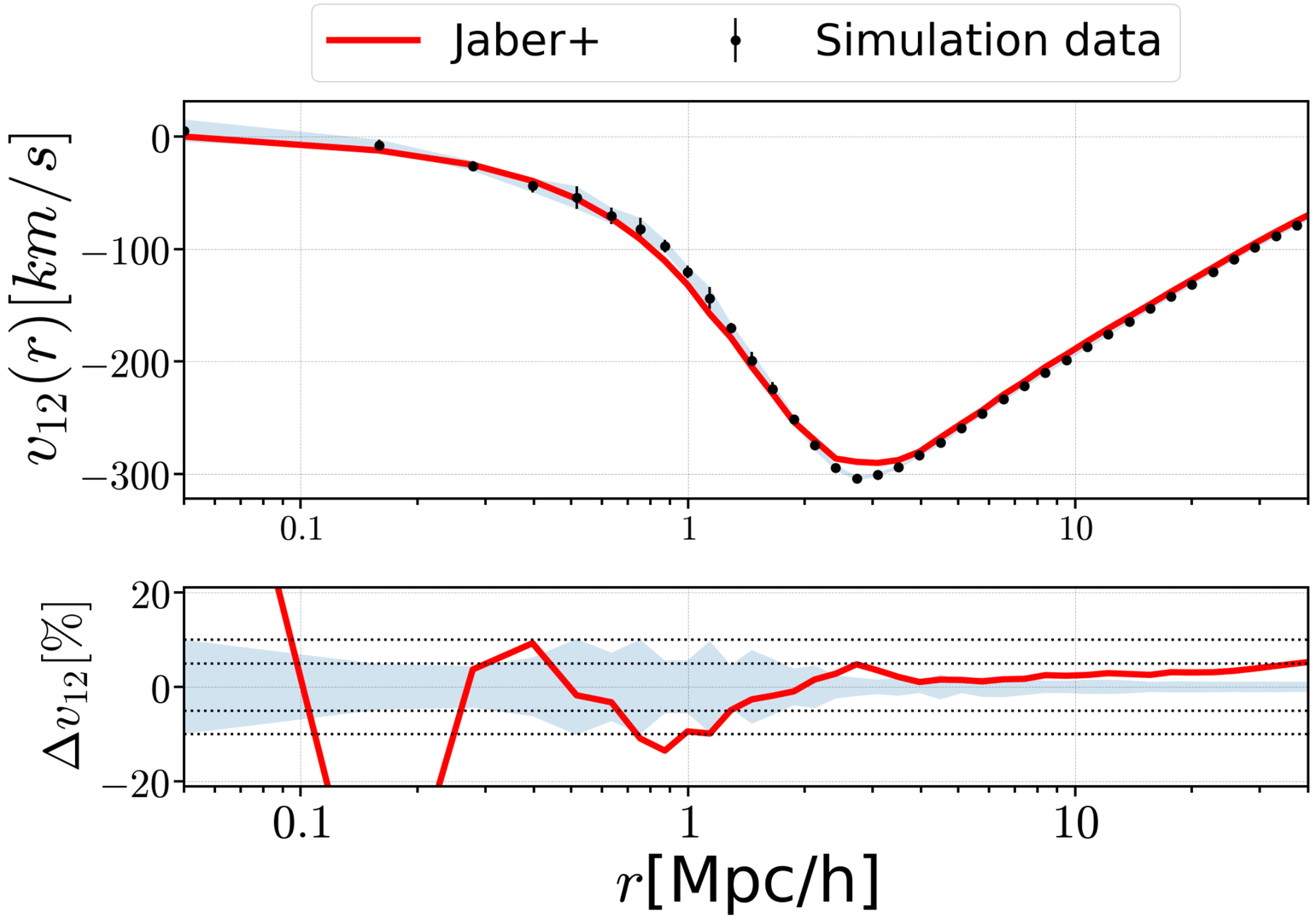
$$v_{12}(r) = \langle (\vec{v}_2 - \vec{v}_1) \cdot \frac{\vec{r}}{|\vec{r}|} \rangle$$





[**MJ**+ (2024)] 2312.00472

Unlocking the nonlinear regime



[**MJ**+ (2024)] 2312.00472

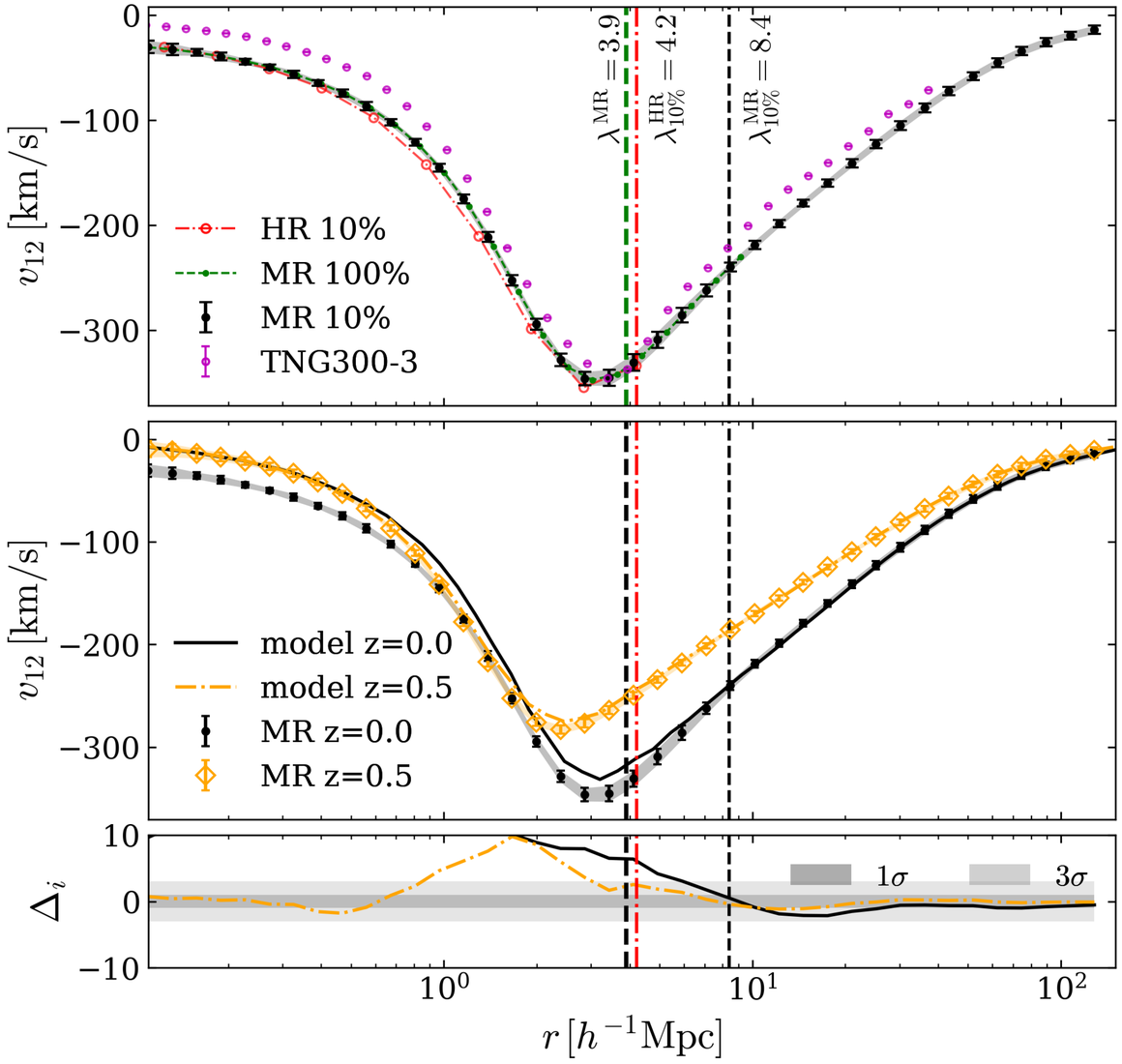
$$\frac{v_{12}}{aHr} = -\frac{1}{3(1+\xi_{12})}\frac{\partial \bar{\xi}_{12}}{\partial \ln a}$$

Exact pair conservation + nonlinear matter clustering —> Predictions beyond linear scales.

[Davis & Peebles (1977)]

[R. Juszkiewicz; V. Springer; R. Durrer (1999)]

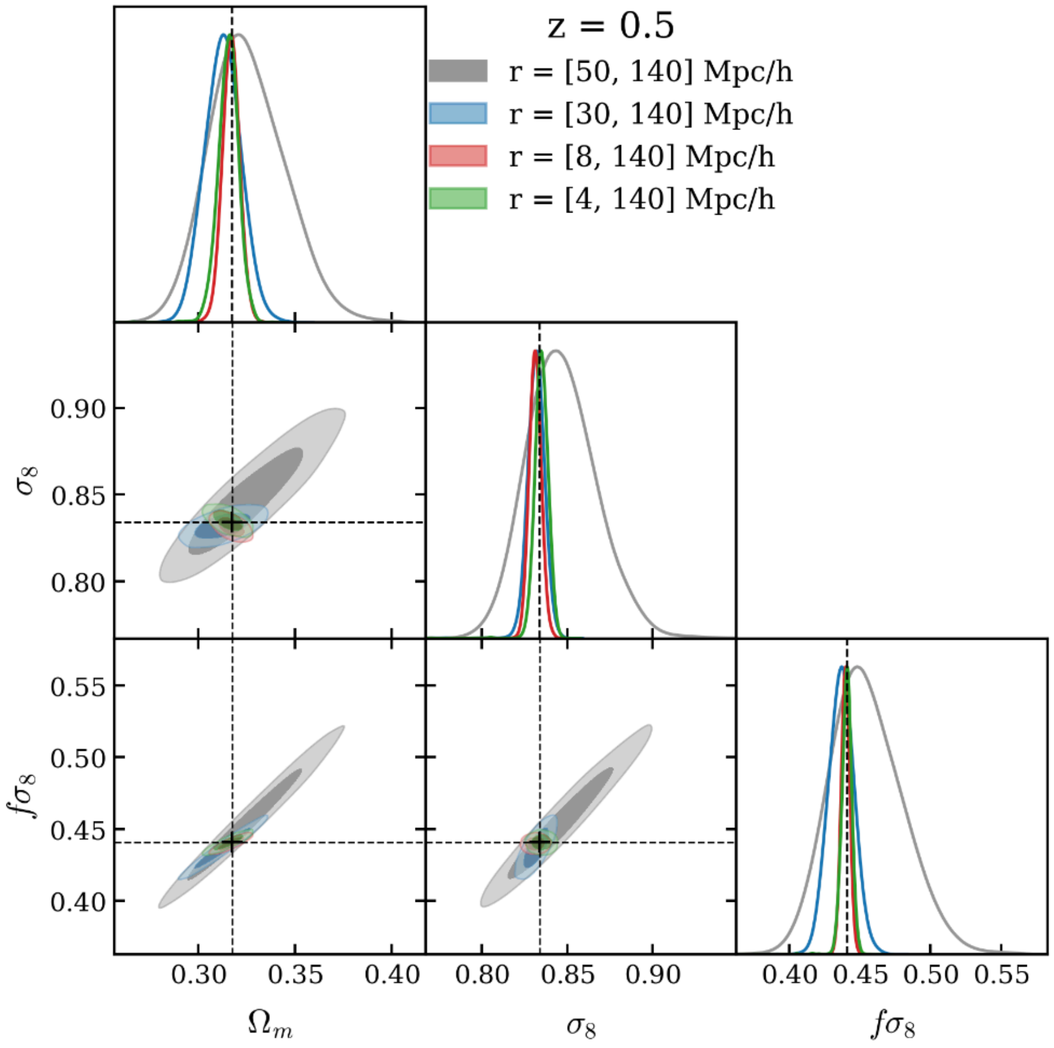
How Reliable Are Our Predictions?

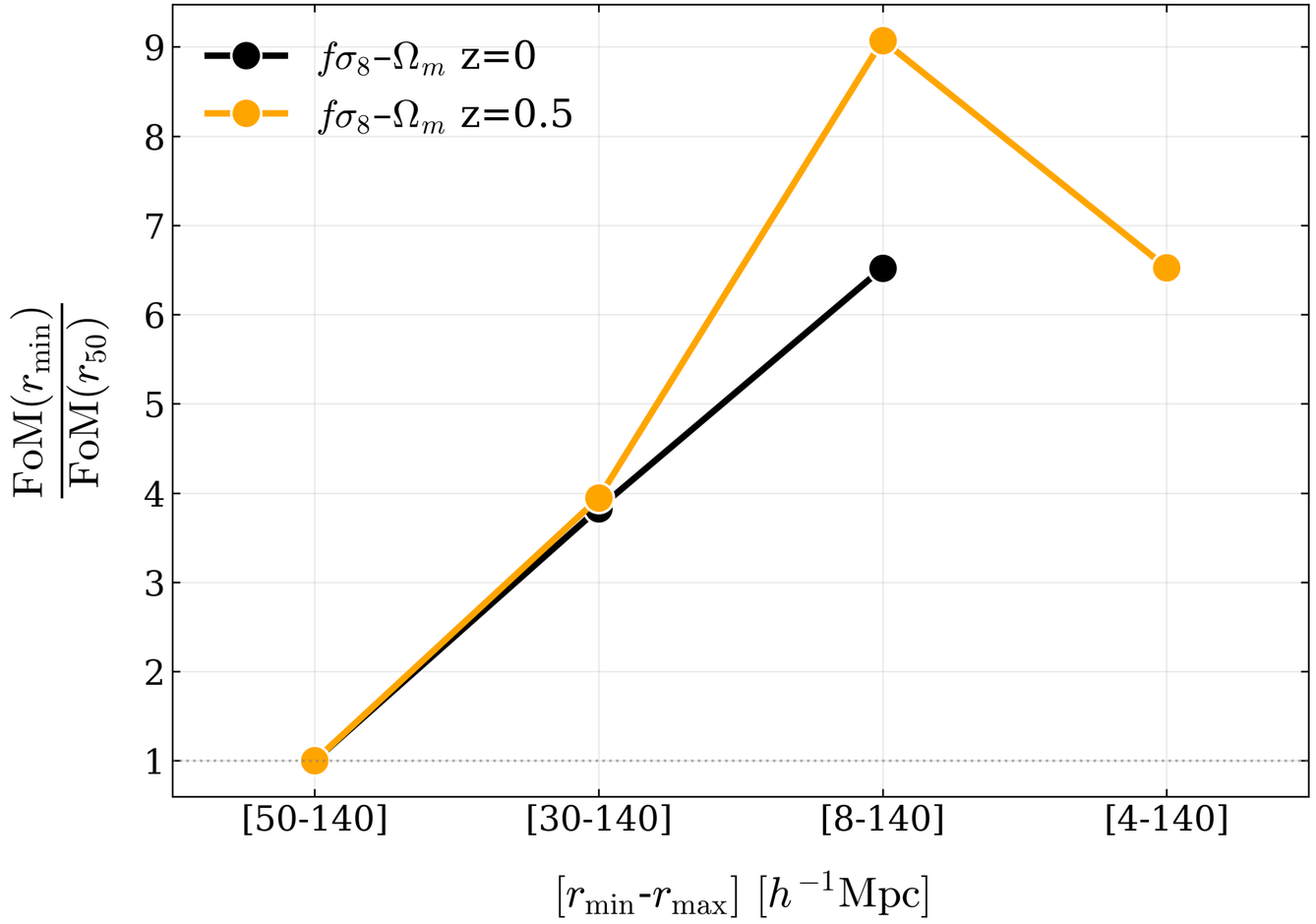


[**MJ,** A.Taverna, R.Strid, W Hellwing (2026) 2609.07976]

- Validated against Quijote and TNG300-3 simulations.
- Residuals determine the likelihood scale cuts
  - $z = 0: \quad r_{\rm min} = 8$Mpc/h
  - $z = 0.5: r_{\rm min} = 4$Mpc/h

Nonlinear Scales Sharpen Cosmological Constraints





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Towards Independent Tests of ΛCDM

Observer location: where we observe from

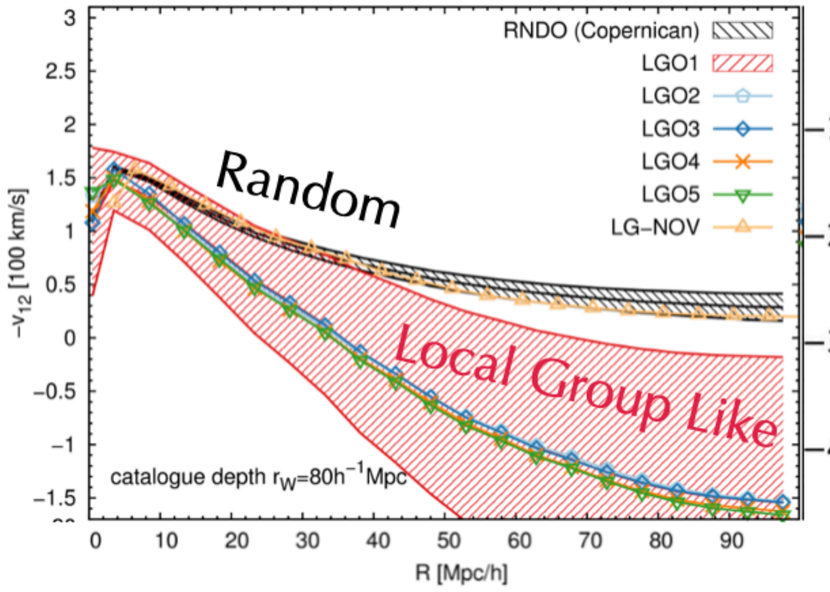
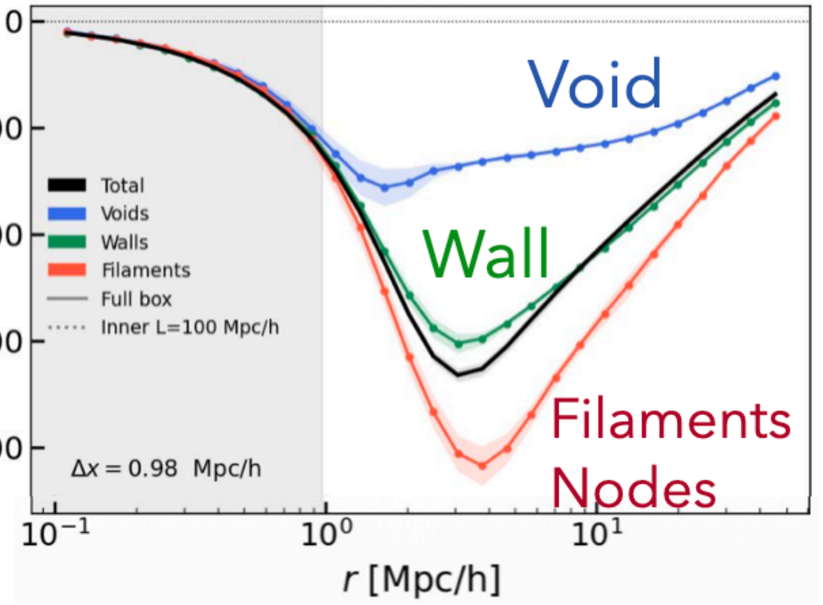


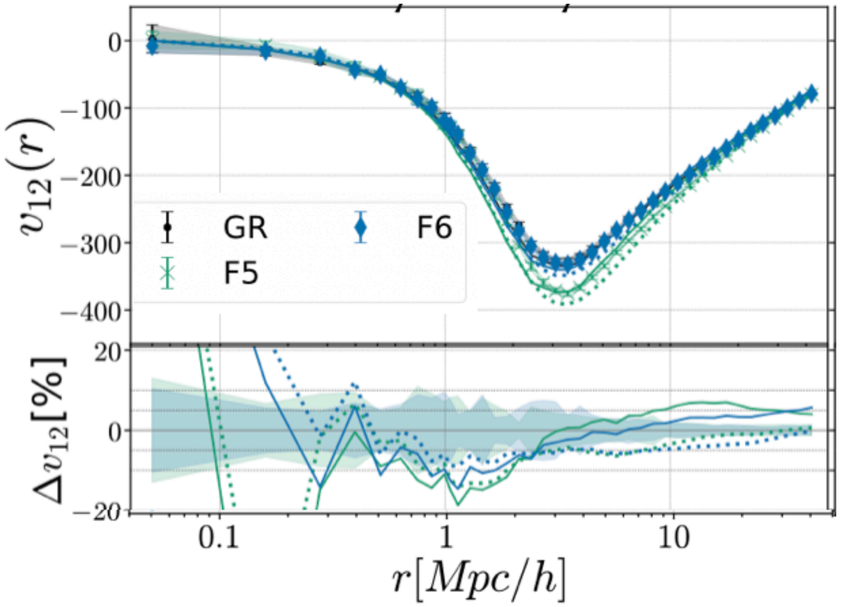
Fig. adapted from 1609.07120

Environment: which structures we observe



A. Taverna, **MJ**, + (in prep)

Gravity theory: what drives the motions



[**MJ**+ (2024), PRD (arXiv:2312.00472)]

Nonlinear pairwise velocities offer a promising independent test of cosmic growth, provided we understand both the dynamics and the tracers we observe.

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Mean Pairwise Velocities

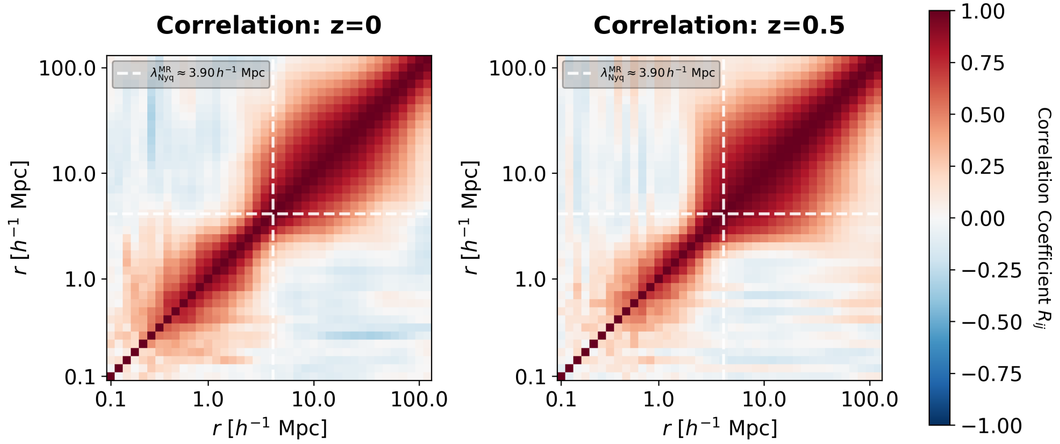
$$\frac{v_{12}}{Hr} = -\frac{1}{3(1+\xi_{12})}\frac{\partial \bar{\xi}_{12}}{\partial \ln a}$$

Sensitive to cosmology.

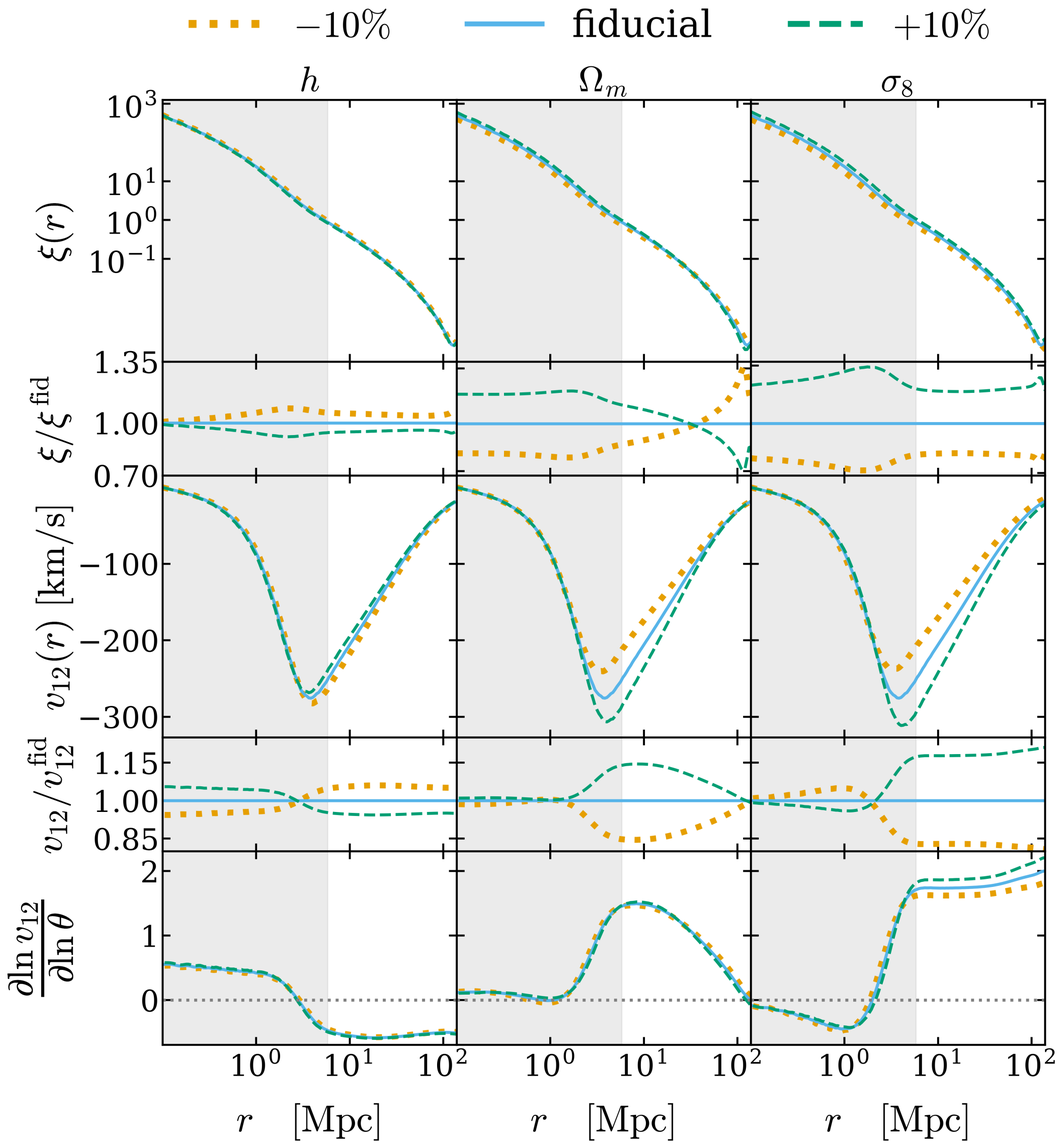
Constraining power?

Different separations?

Set of 100 QUIJOTE simulations [Villaescusa-Navarro+(2020)] to estimate the full covariance matrix.



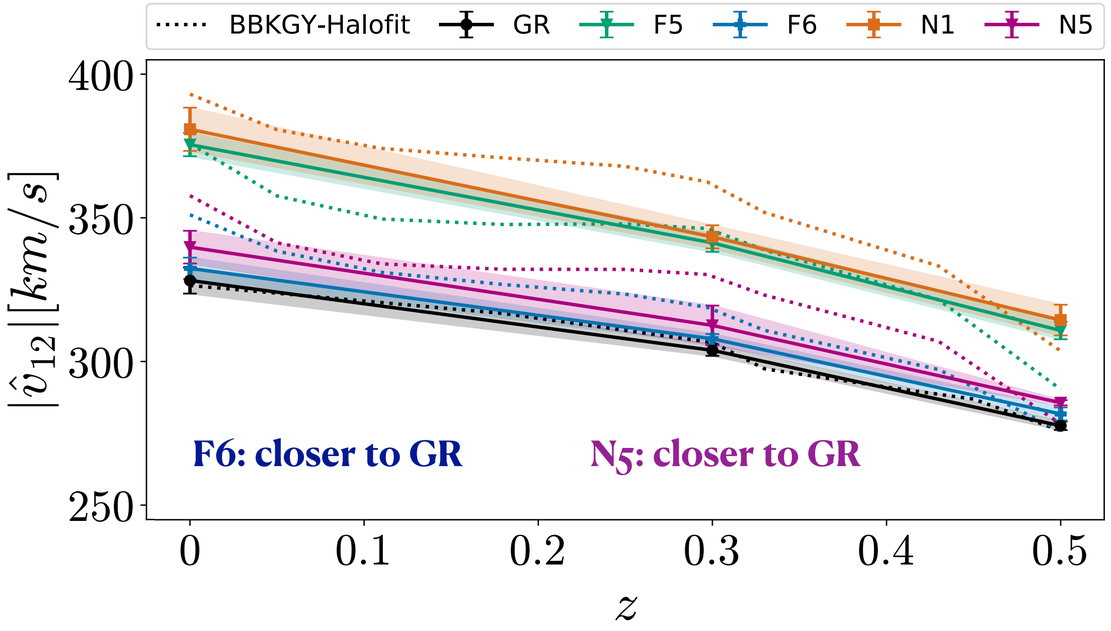
[**MJ,** A.Taverna, R.Strid, W Hellwing (2026) 2609.07976]

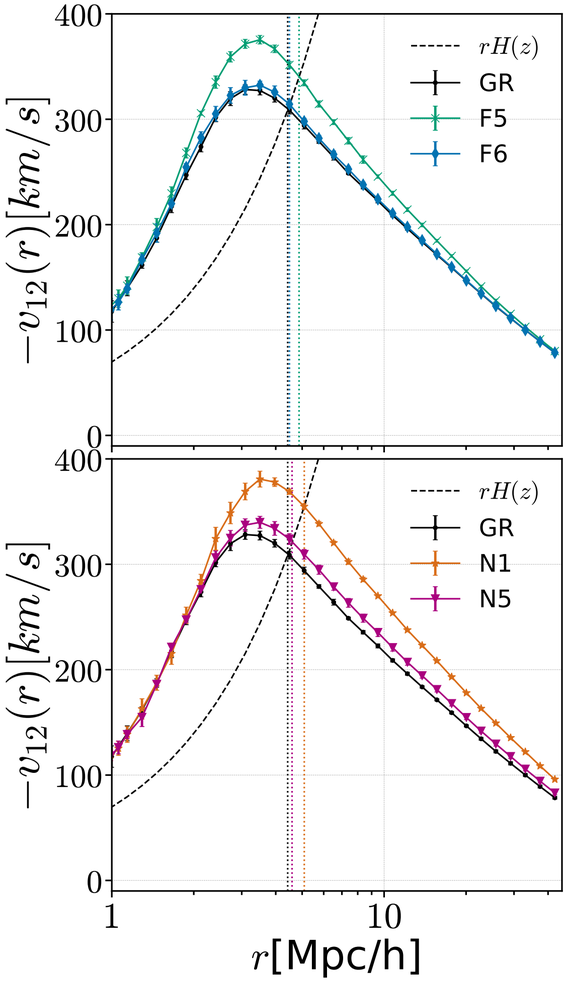


Signatures of MG in the MPV

$|\hat{v}_{12}|$: minimum value

- Function of redshift.
- Sensitive to the model of gravity: larger streaming velocities for stronger modifications of gravity, compared to GR.





[**MJ**+ (2024), PRD (arXiv:2312.00472)]

An ensemble of constrained simulations

CLUES Classic

Data

- Peculiar velocities (CF3)

Method

- Linear theory + Wiener filter

Ensemble

- 300 runs, randomised phases

Coverage

- Sparse, reliable to ~100 Mpc/h

Status

- Bias-free, traces total matter
- Baseline pipeline in current use

[Hoffman, Y., & Ribak, E. (1991); Nusser & Dekel (1992); Gottlöber, S., Hoffman, Y., & Yepes, G. (2010)]

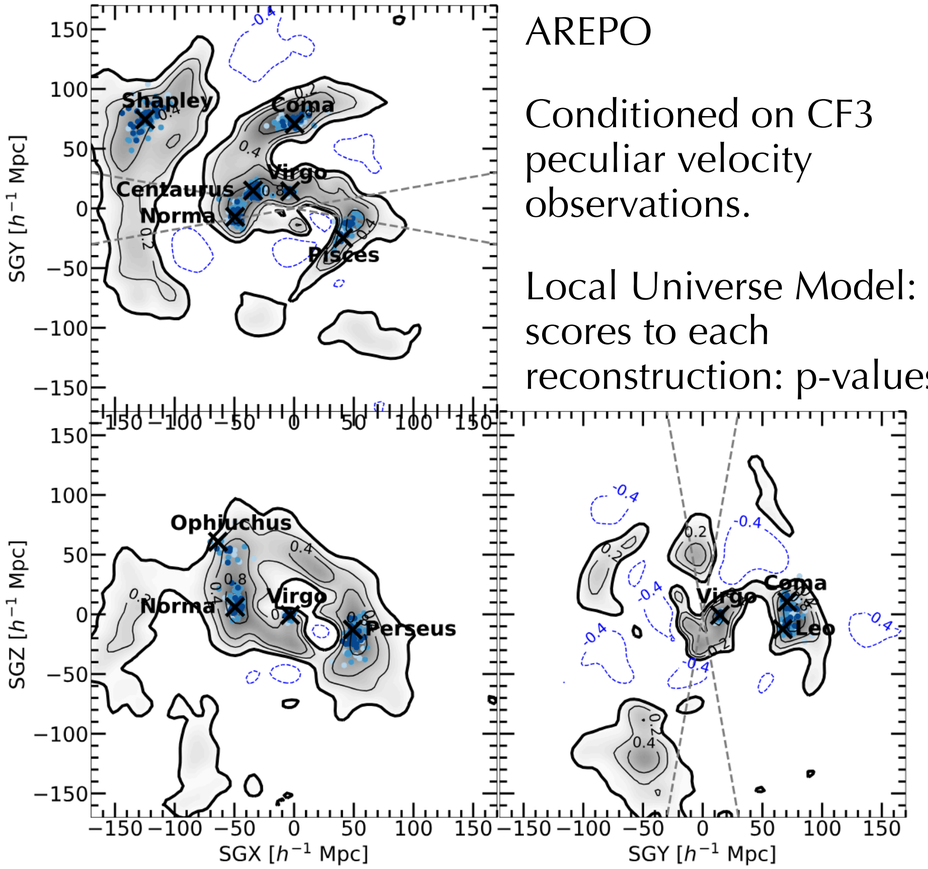
[Pfeifer +(2023) 2305.05694]

512^3 particles,
$m_p \approx 8 \times 10^{10} M_\odot/h$

AREPO

Conditioned on CF3 peculiar velocity observations.

Local Universe Model: scores to each reconstruction: p-values



[Pfeifer +(2023) 2305.05694]

Statistics over the ensemble

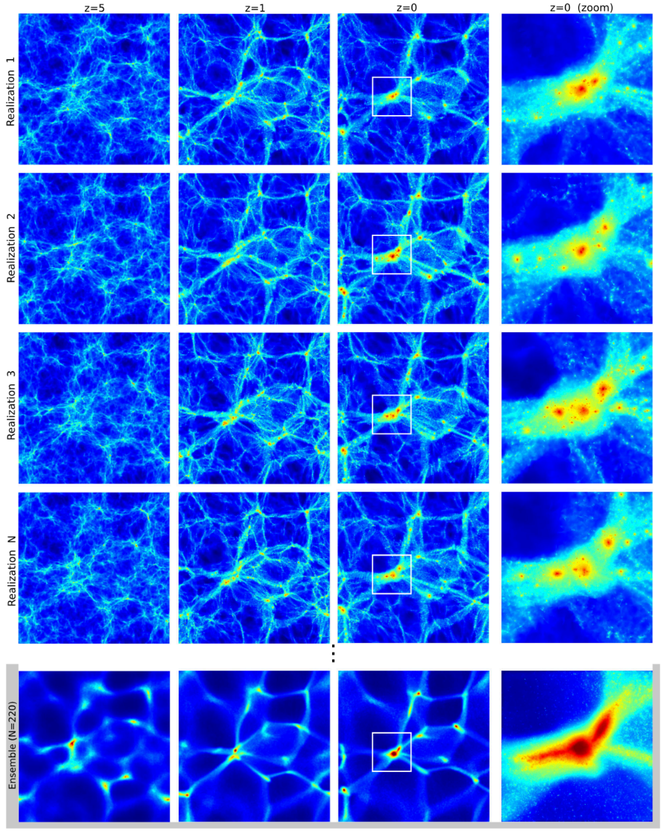
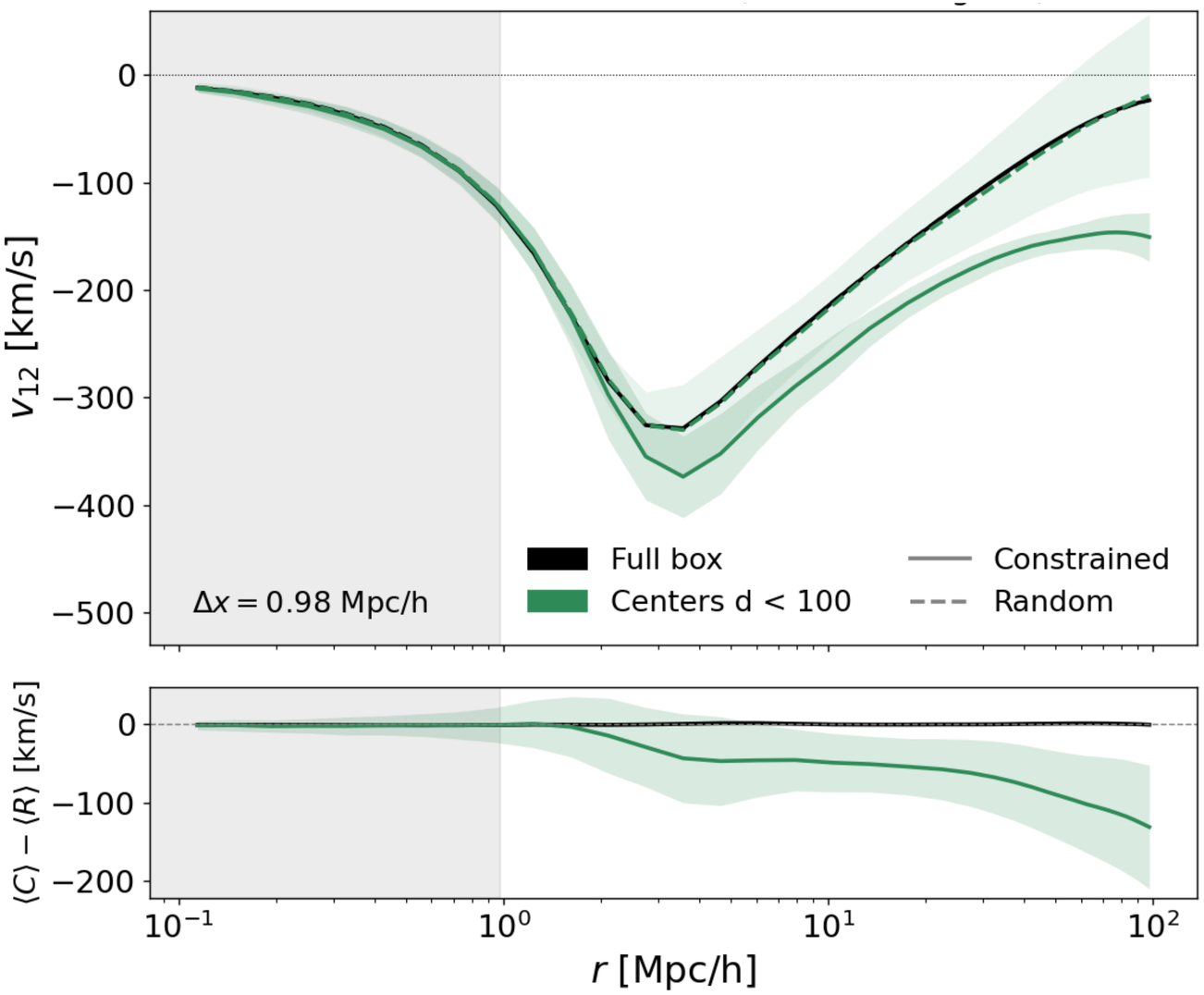


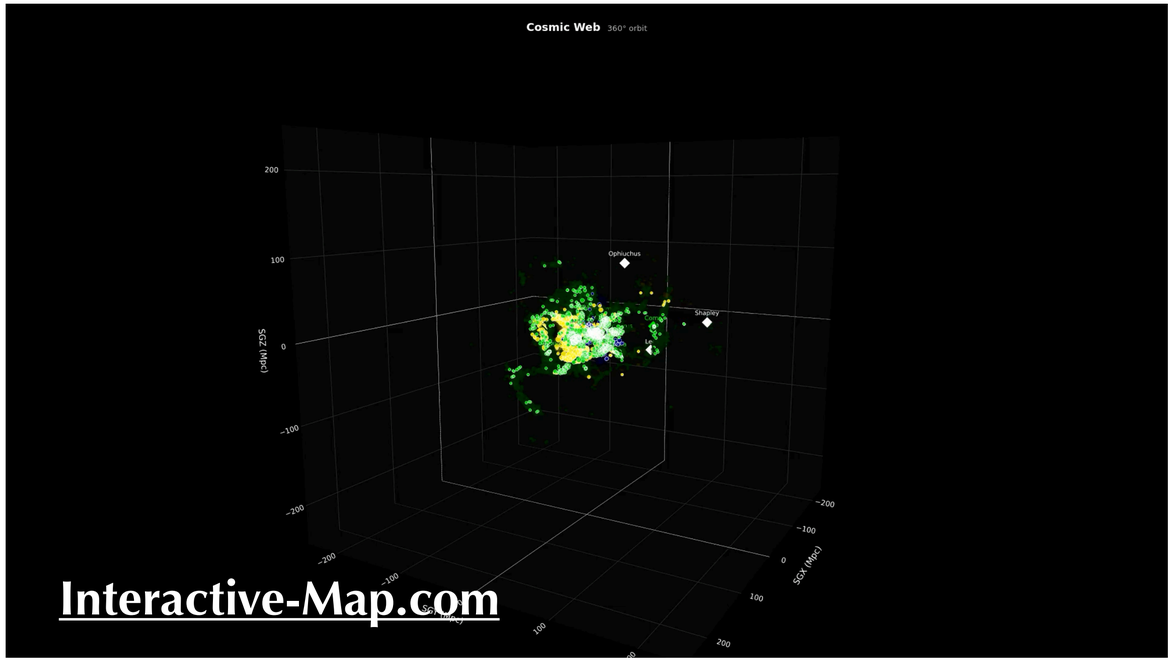
Figure for illustration purposes, from

[M.A. Aragón-Calvo (2016)]

Constrained Simulations: Testing Our Cosmic Perspective



[A. Taverna, **MJ**+ (in prep)]



MJ, + (in prep)

A local, observer-centred sample need not reproduce the velocity statistics of the full cosmological volume.