Extracting cosmological information from the shape of cosmic voids

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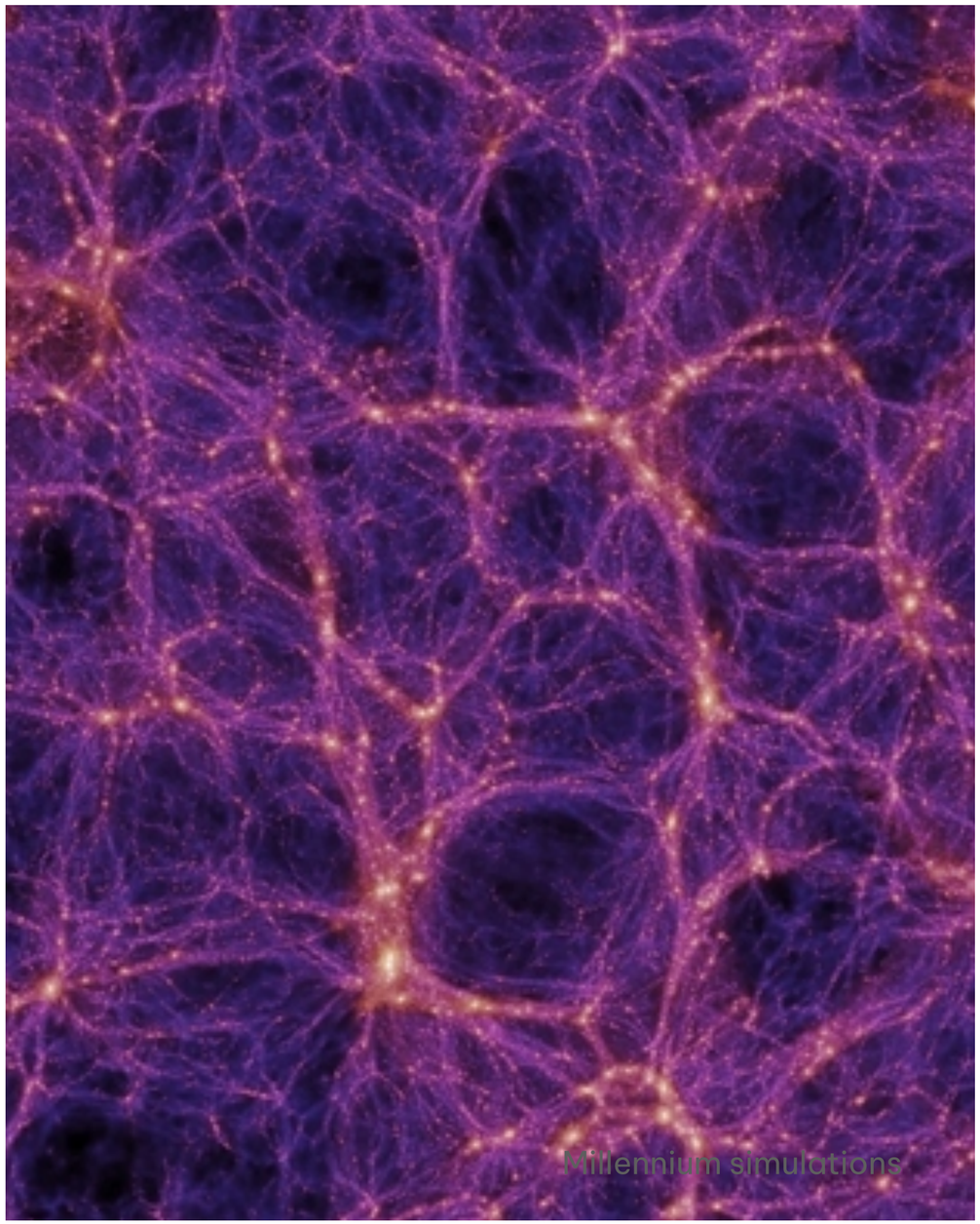
DARK ENERGY SPECTROSCOPIC INSTRUMENT

Cosmic voids

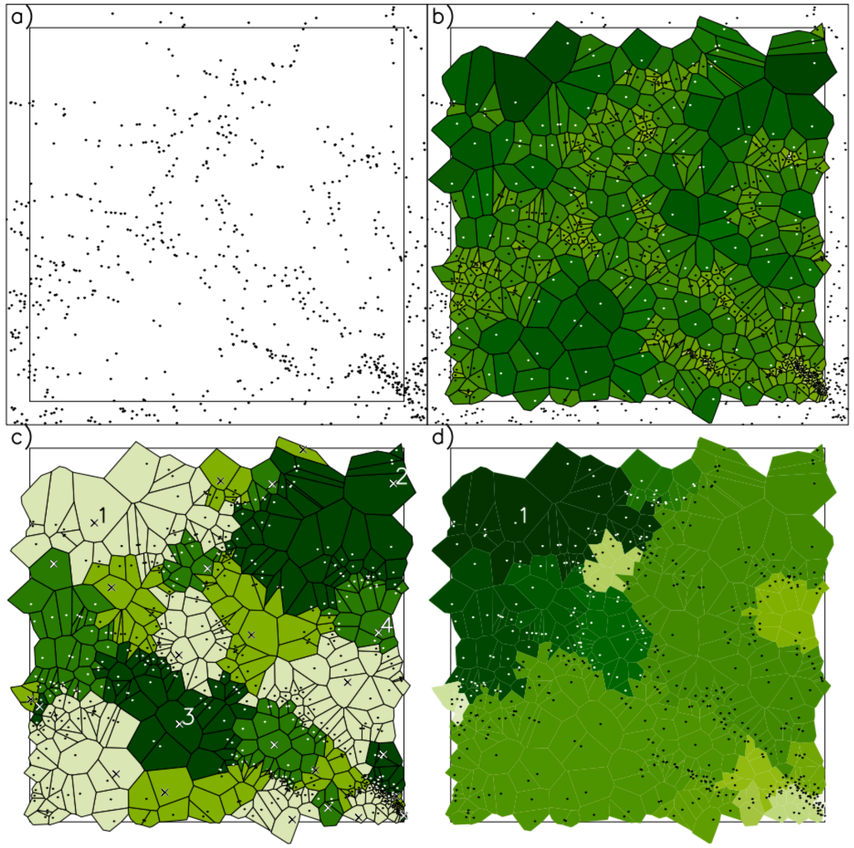
- Large underdense structures in the Universe
- Multiscale sensitivity: $10 - 100\ h^{-1}$Mpc
- Interpretable as spatially distinct components of the cosmic web
- Most linear structures in the Universe: simple dynamic
- Dominated by dark energy
- Sensitive to diffuse components
- Sensitive to theories of relativity



Void identification

VIDE : Void IDentification and Examination toolkit

Sutter et al. 2014



Neyrinck 2008

- Based only on **topological criterium**: finding voids in the 3D distribution of tracers

  a) Voronoi tessellation

  b) Zones division (finding minima)

  c) Watershed algorithm

➡ Void catalog

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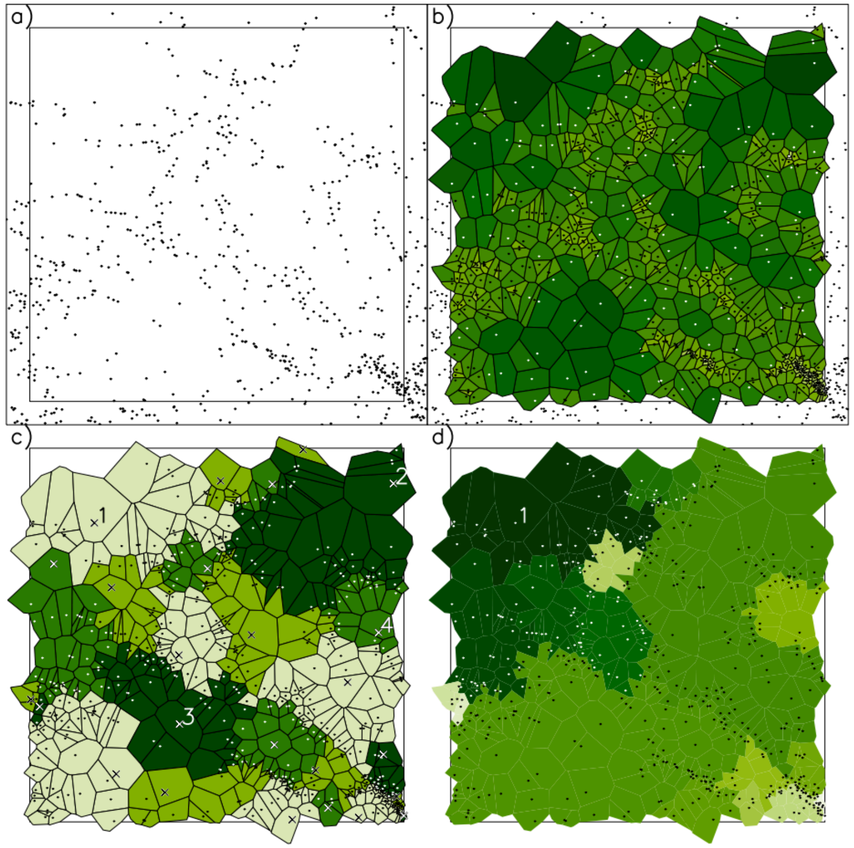

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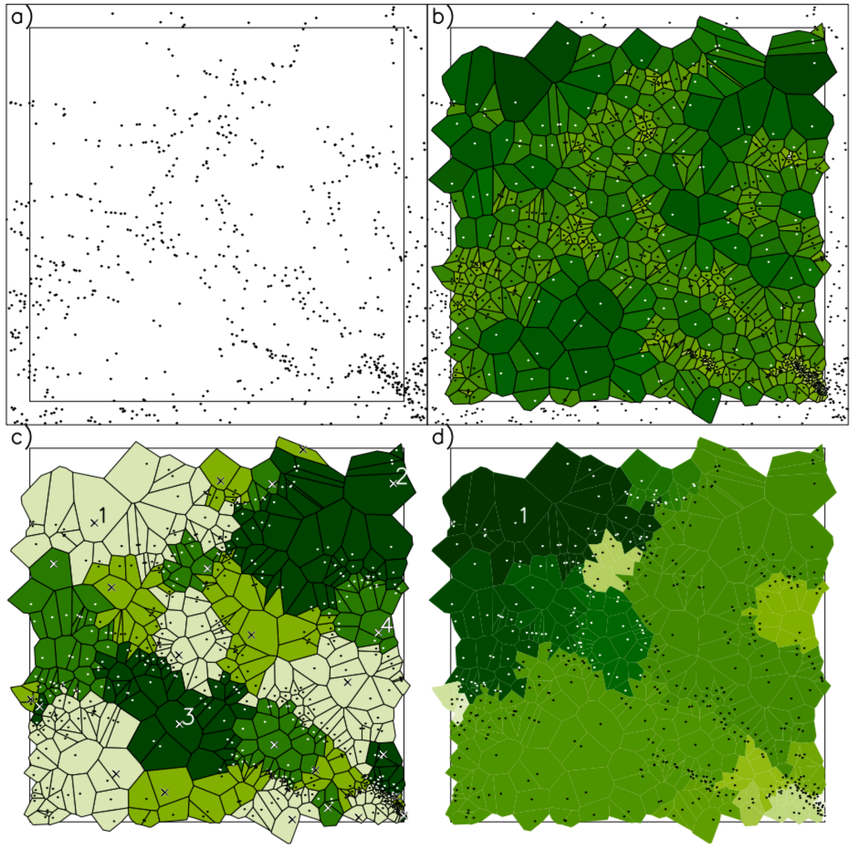

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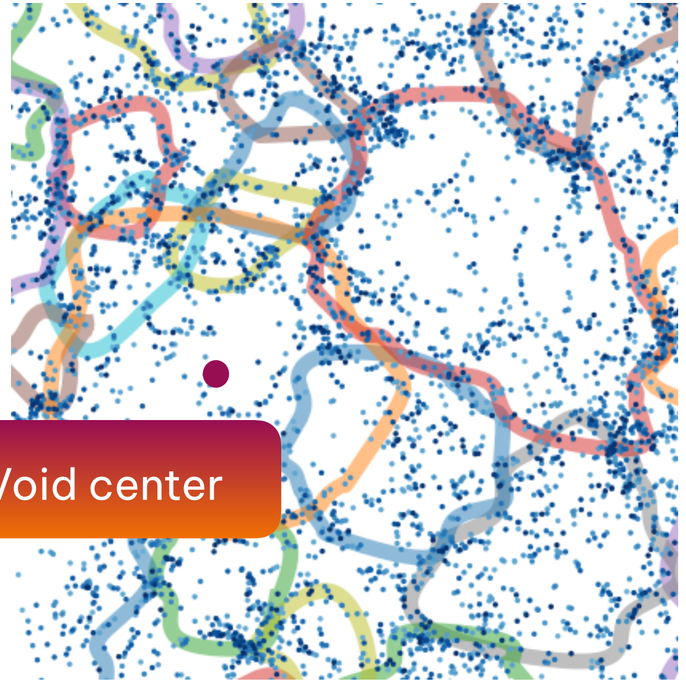

Verza et al. 2019

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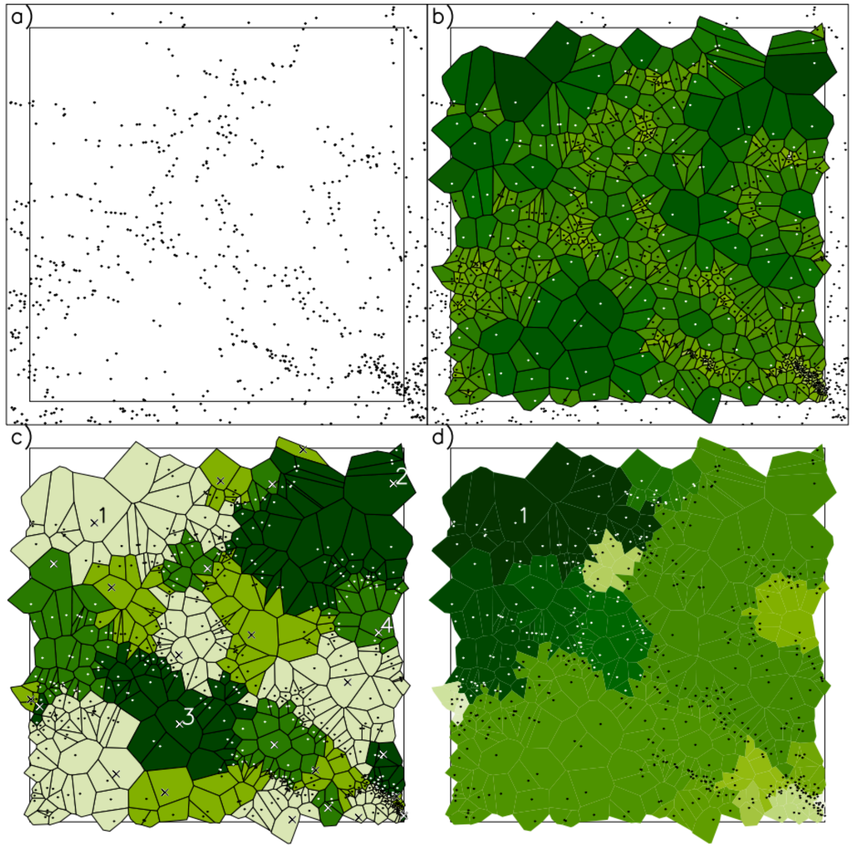

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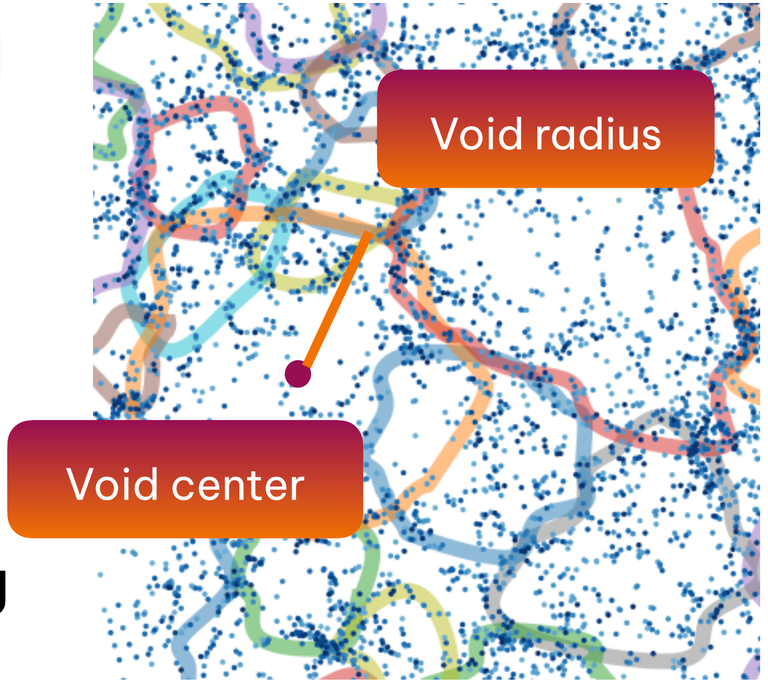

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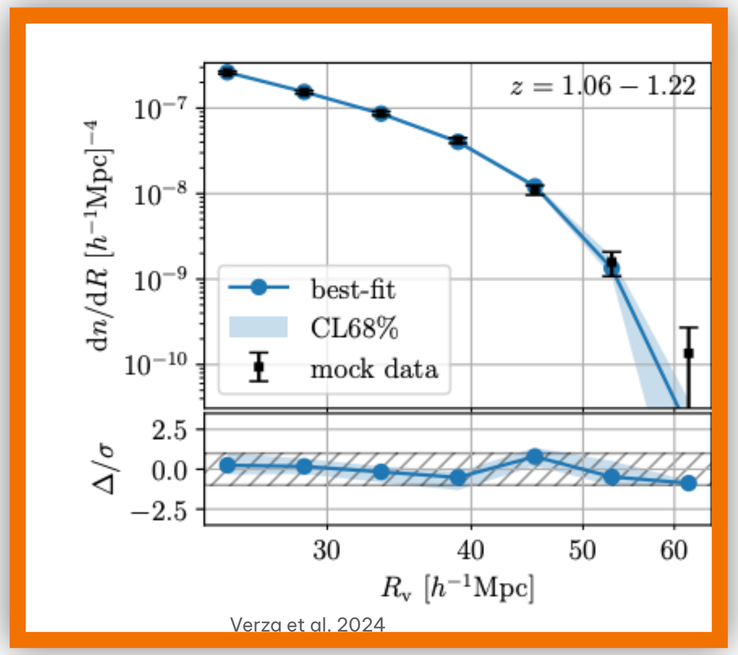
Void observables

Void observables

Void abundance: *void size function (VSF)*

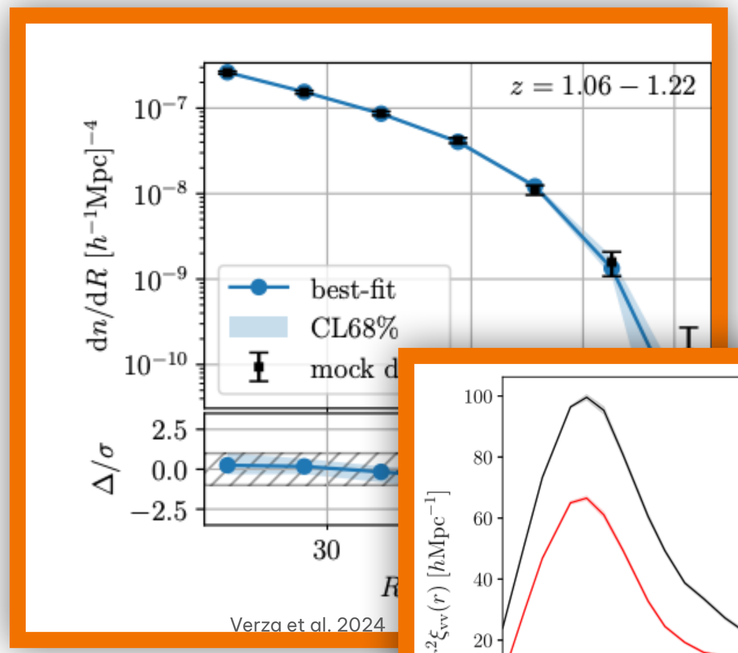


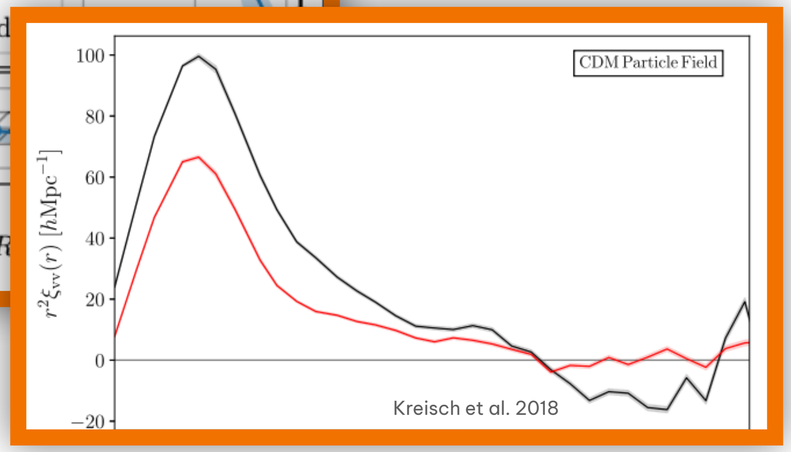
Verza et al. 2024

Void observables

Void abundance: *void size function (VSF)*

Void clustering: *void-void auto-correlation function*



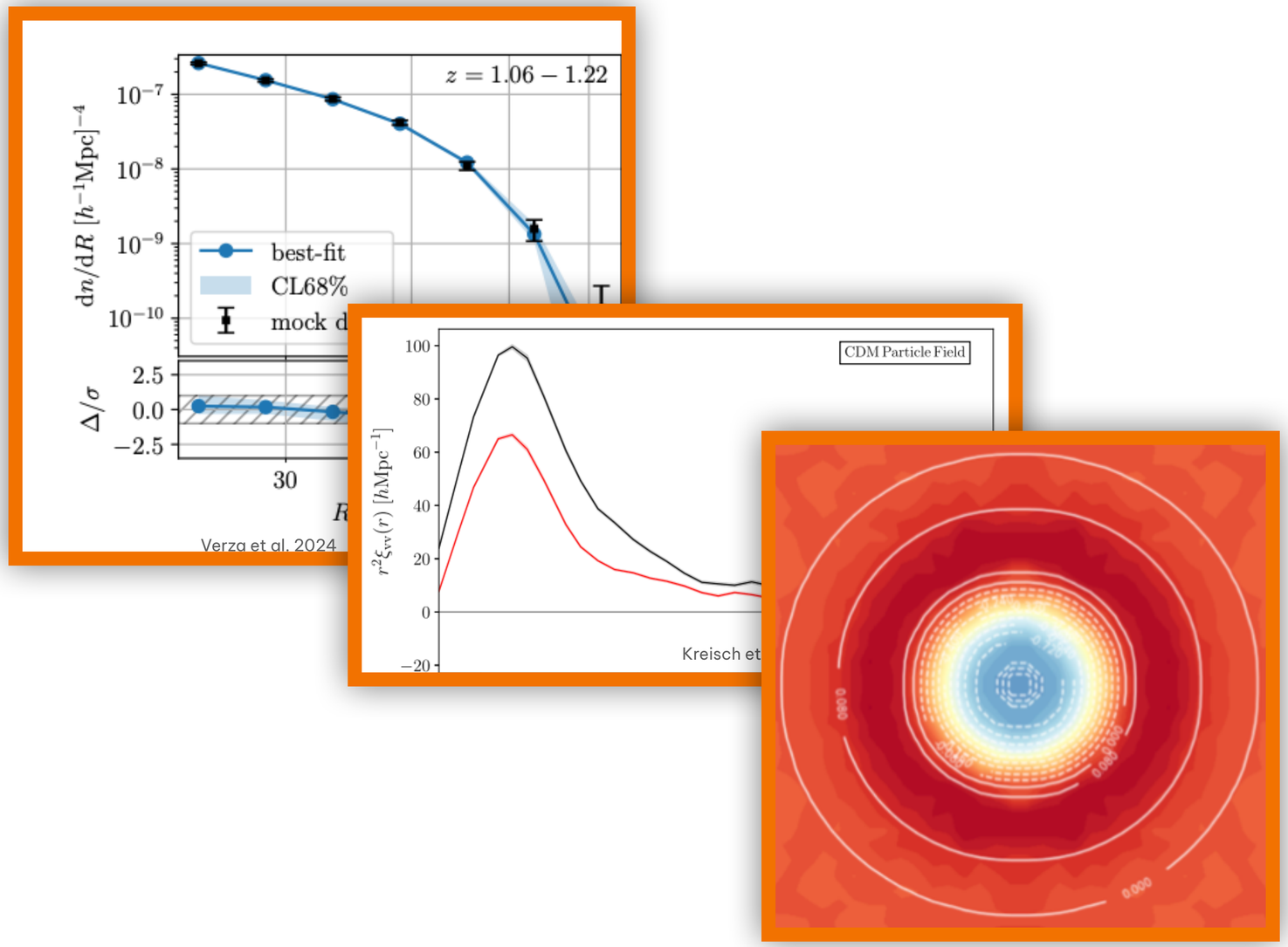


Void observables

Void abundance: *void size function (VSF)*

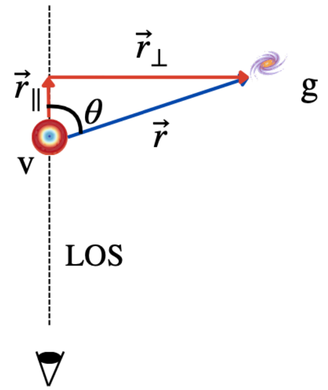
Void clustering: *void-void auto-correlation function*

Void shape: *void-galaxy cross-correlation function (VGCF)*



Void-galaxy cross-correlation function

- Probability to find a galaxy at a certain distance r and angle $\mu \equiv \cos\theta$ from the center of a void (respect to a random distribution of galaxies)
- Probing the density profile of tracers inside the void region

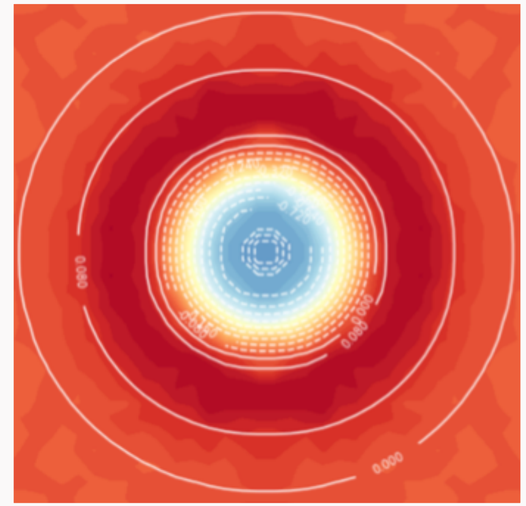


Davis-Peebles estimator:

$$\xi_{vg}^{DP}(r,\mu) = \frac{n_R}{n}\frac{D_v D_g(r,\mu)}{D_v R_g(r,\mu)} - 1$$

Multipoles:

$$\xi_\ell(r) = (2\ell+1)\int_0^1 \xi(r,\mu)P_\ell(\mu)d\mu$$



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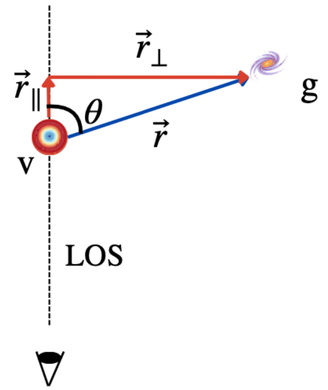

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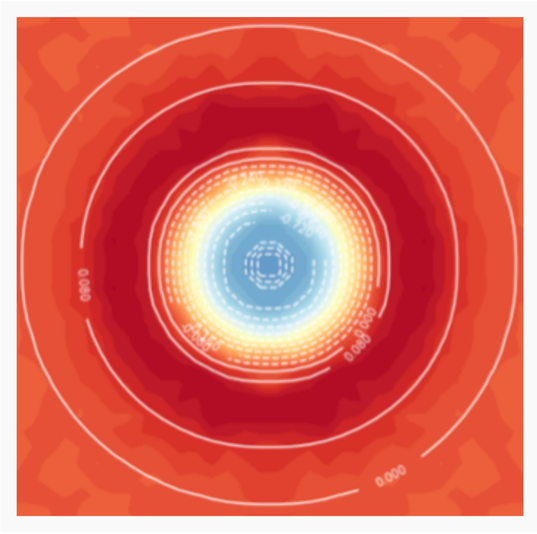


Important property : void are on average spherical !

Alcock-Paczynski test

A key ingredient to cosmological inference

- Distances estimated from measured redshift

$$d(z) = \int_0^z \frac{c dz'}{H(z')}$$

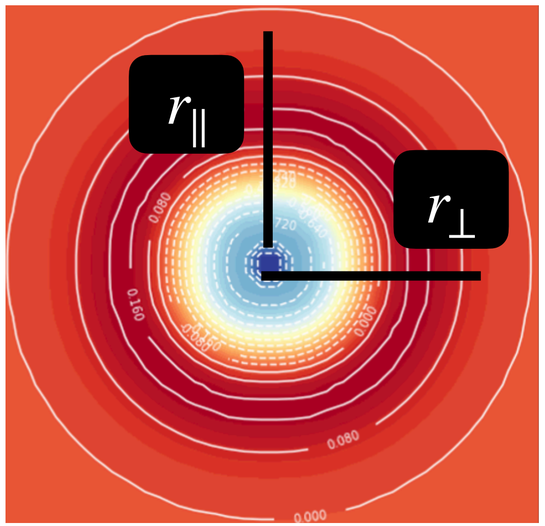
Assuming a flat Universe

- ΛCDM : $H(z) = H_0\sqrt{\Omega_{\rm m}(1+z)^3 + \Omega_\Lambda}$
- $w_0 w_a$CDM : $H(z) = H_0\sqrt{\Omega_{\rm m}(1+z)^3 + \Omega_{\rm de}(1+z)^{3(1+w_0+w_a)} e^{-3w_a z/(1+z)}}$

True cosmology

$r_\parallel \quad r_\perp$

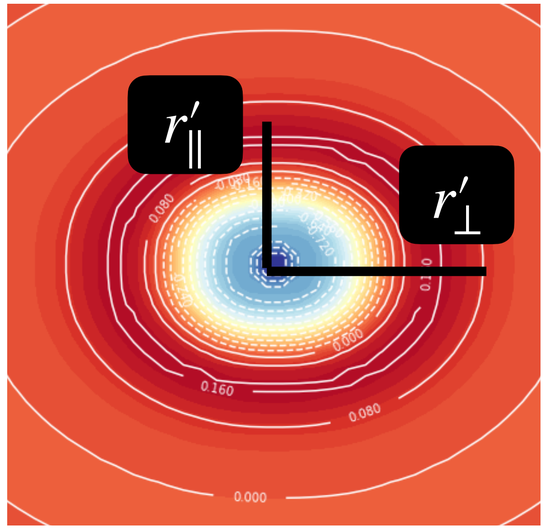
Real Space



Fiducial cosmology

$r_\parallel = q_\parallel r'_\parallel \quad r_\perp = q_\perp r'_\perp$

AP distortions



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Real Space

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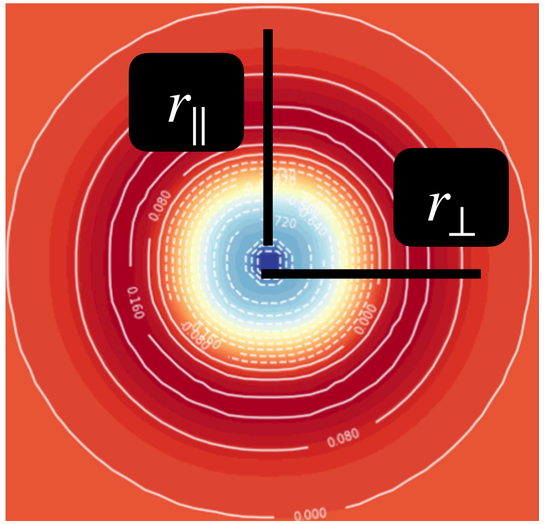
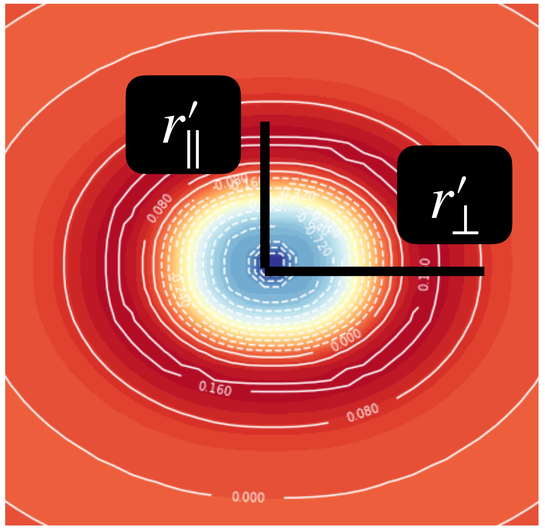


AP distortions

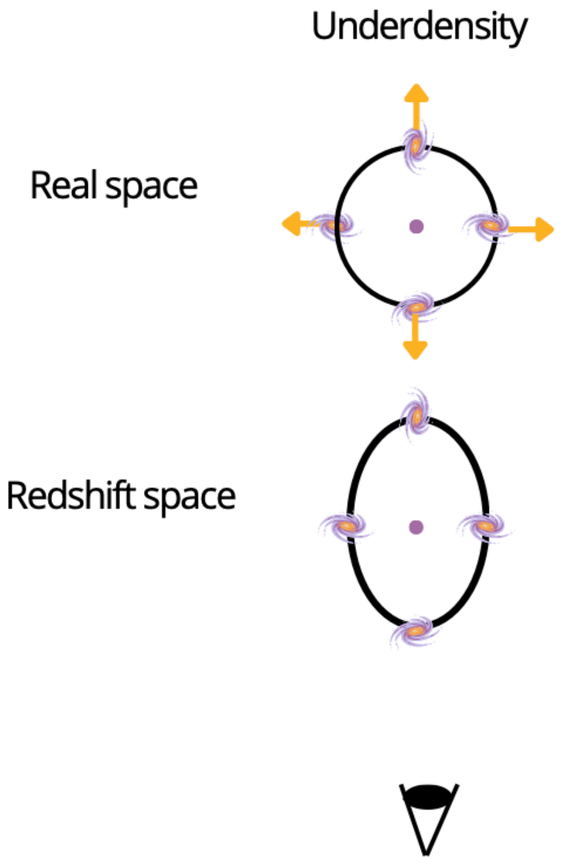
Fiducial cosmology

$r_\parallel = q_\parallel r'_\parallel \quad r_\perp = q_\perp r'_\perp$

$$\varepsilon = \frac{q_\perp}{q_\parallel} = \frac{D_A(z)H(z)}{D'_A(z)H'(z)}$$



Redshift Space Distortions



$$\beta = \frac{f}{b}$$

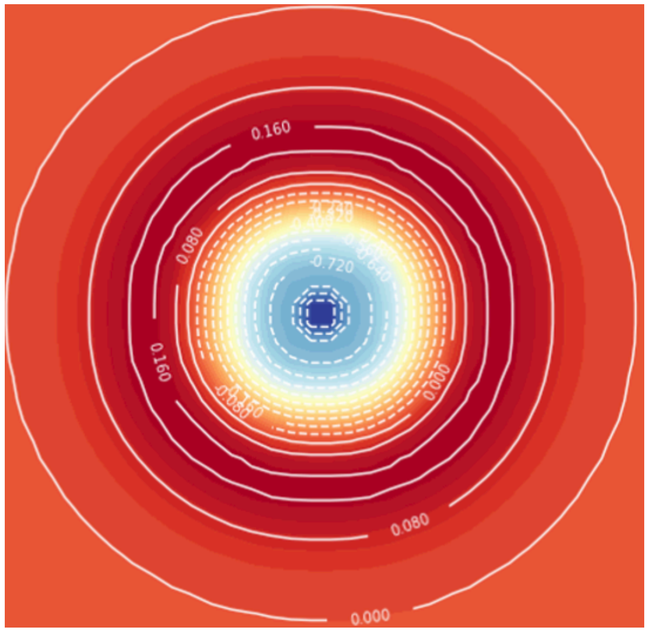
$$1 + z_{\text{obs}} = \left(\frac{v_{\text{pec}}}{c} + 1\right)(z_h + 1)$$

Peculiar velocity contribution

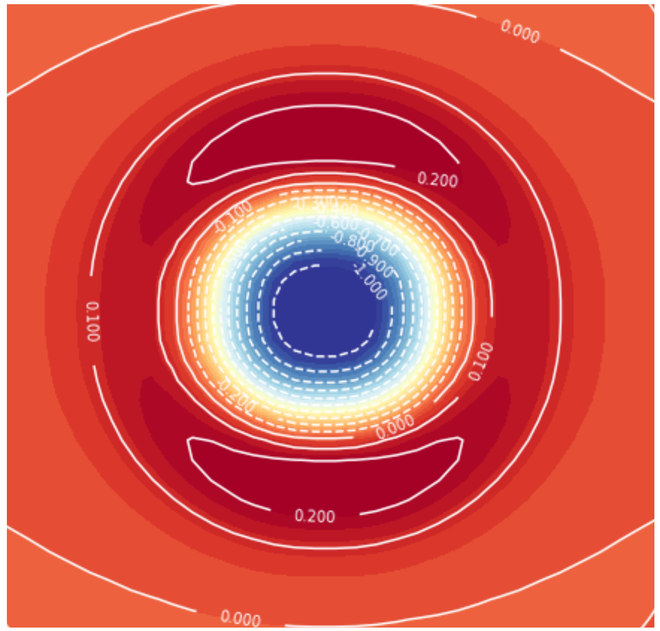
Cosmological expansion

- Dynamical distortions caused by the Doppler effect of galaxy peculiar velocities (PV)
- Degenerate with geometric distortions (AP)
- Measuring PV is extremely difficult! PV term neglected z_{obs}

Real Space
(no distortions)



Redshift space RSD



How to deal with RSD in the VGCF?

Standard approach - analytically modeling RSD in voids:

Assume local mass conservation at linear order in density fluctuations with growth rate f

Model Real-Space ccf $\xi(r)$

+

Add RSD

1. Linear model *Cai et al. 2016*
2. Empirical modification (nuisance parameters)

+

Add AP distortions

Expressing true coordinates as functions of the fiducial coordinates

$$\xi^s(s,\mu) = \mathscr{M}\left\{\xi(r) + \beta\bar{\xi}(r) + 2\mathcal{Q}\beta\mu^2[\xi(r) - \bar{\xi}(r)]\right\}$$

Hamaus et al. 2022

AP and RSD modeled together

Issues with this approach:

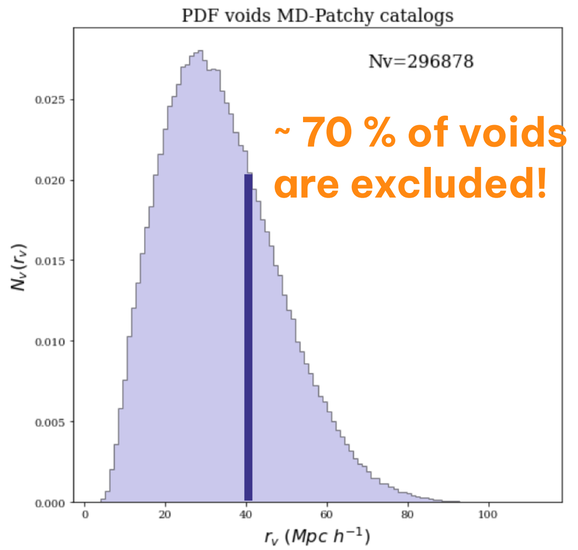
Smaller voids are difficult to model

Difficult to include systematics from the void identification – see Selection Effect in *Correa et al. 2023*

Solutions and alternative methods :

Eliminating voids at smaller scales

Standard



Voids radii distribution in BOSS Patchy mocks

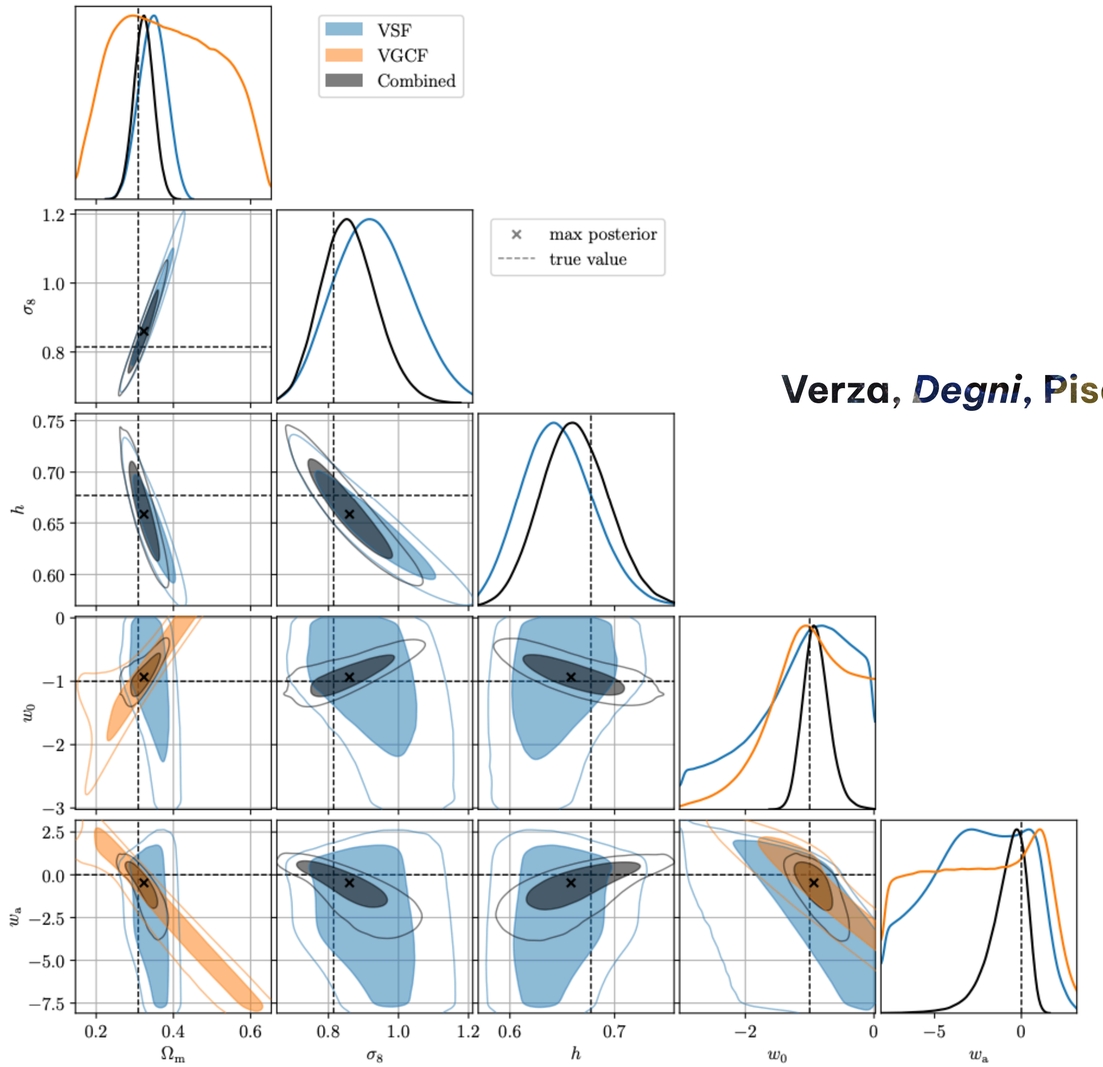
Cosmological constraints with standard approach

- Forecast analysis for the High Latitude Spectroscopic Survey for the Roman Telescope (*Wang et al. 2022*) using mock catalog with galaxies in the redshift range $z \sim 1 - 2$

Constraining cosmological parameters from the VGCF with the Standard approach

+

Combining constrains from VGCF and VSF



Verza, *Degni*, Pisani et al. 2024

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Investigating the impact of void finding systematics
Carlos Correa (MPE)

In progress

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Dynamical criteria to identify voids
See Simone's talk!

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Investigating the impact of void finding systematics *Carlos Correa (MPE)*

In progress

Dynamical criteria to identify voids *See Simone's talk!*

In progress

Removing RSD in the void finding process by reconstructing velocities

Nadathur et al. 2019

New approach : THIS WORK !

Degni et al. in prep (out soon!)

- Apply a velocity reconstruction technique to eliminate RSD from the position of galaxies creating the **reconstructed space**
- **Perform the AP test in reconstructed space**
- Goal: improve the statistical signal by including all the voids in the sample, reduce the impact of systematics introduced by the void finding process when finding voids in redshift space

In this work: reconstruction based on Zel'dovich approximation, implemented by Elena Sarpa

Strategy

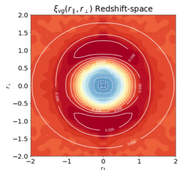
Tracers in z-space*

Void Finder

Void Catalog in z-space

VGCF

+



Likelihood Analysis

Extract ε and β

Velocity Reconstruction

Comparing ε

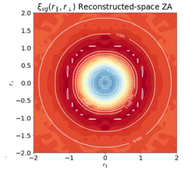
Tracers in r-space*

Void Finder

Void Catalog in r-space

VGCF

+



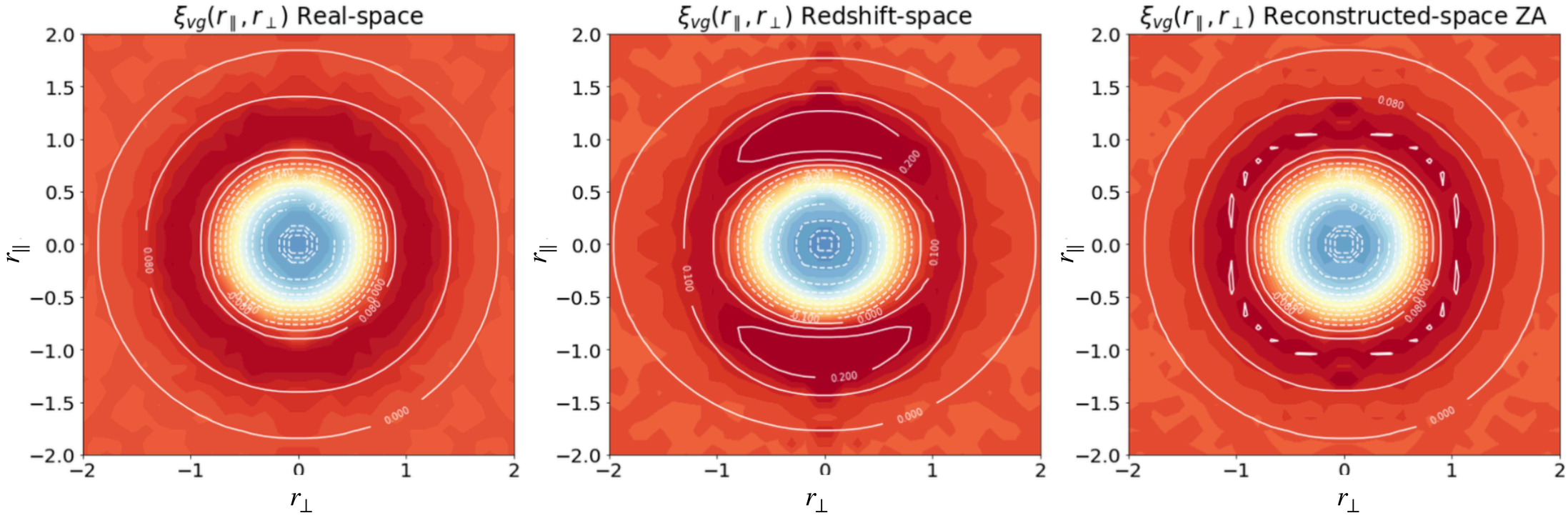
Likelihood Analysis

Extract ε and β

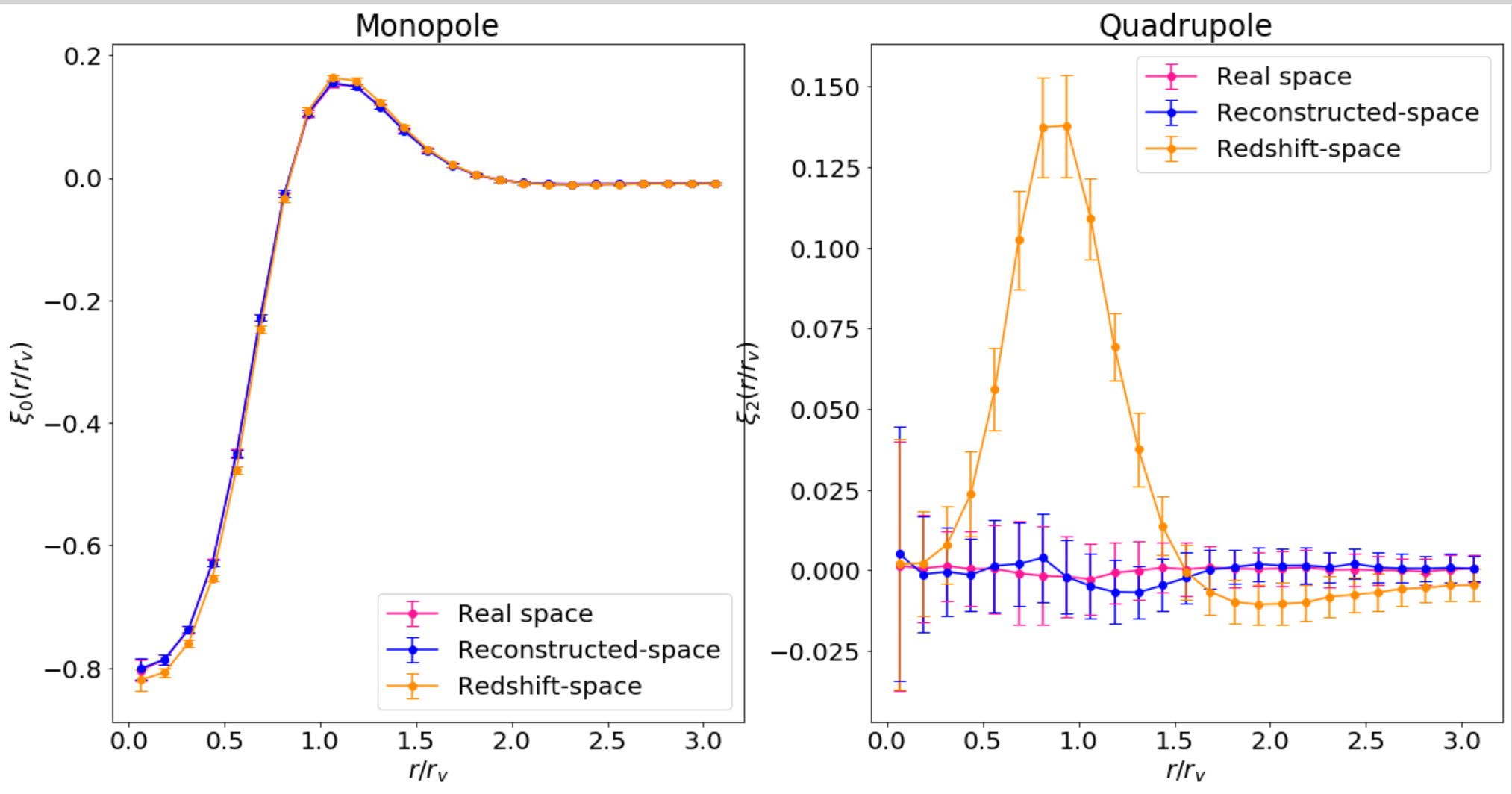
*z-space = redshift-space
*r-space = reconstructed-(real)-space

Data: Halos, Cubic Box, $L_{box} = 1000\ h^{-1}Mpc$, from Quijote Simulation High Resolution, $\bar{z} = 0.5$

Redshift-space: **anisotropies (only RSD)** Reconstructed-space : **no anisotropies**

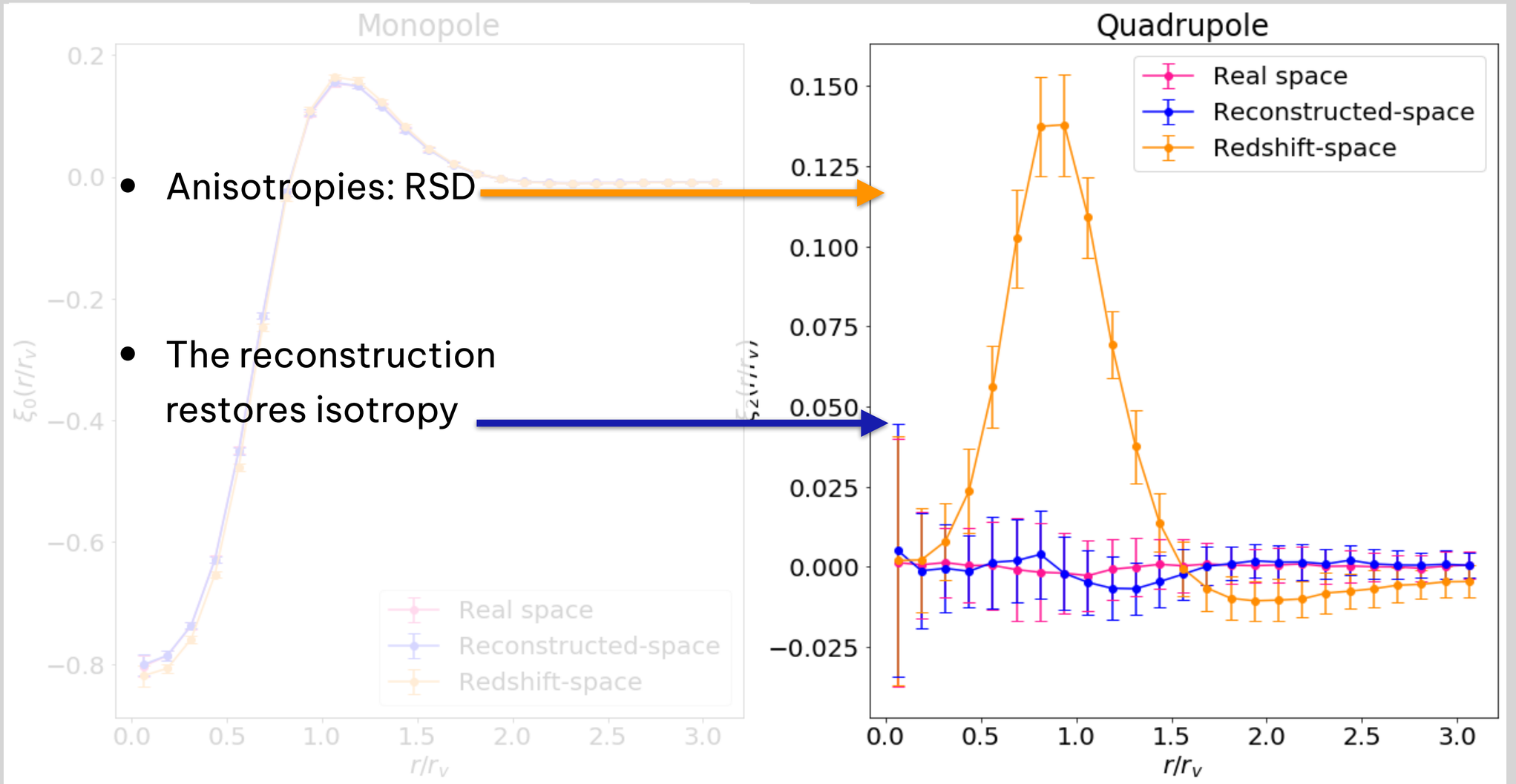


Void-galaxy cross-correlation function multipoles



Void-galaxy cross-correlation function multipoles

- Anisotropies: RSD
- The reconstruction restores isotropy



Results

Redshift space - Standard approach

$$\varepsilon = 1.007 \pm 0.019$$
$$\beta = 0.238 \pm 0.036$$

Redshift space $R_v > 3$ mps

Precision $\sigma_\varepsilon/\varepsilon$:

$1.9\,\%$

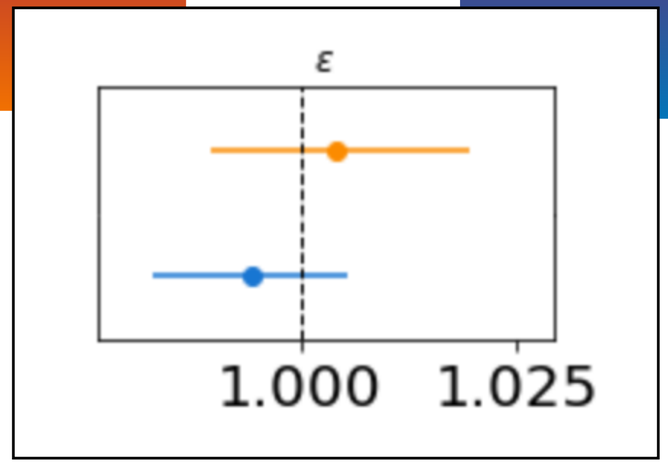
Reconstructed space - New approach

$$\varepsilon = 0.995 \pm 0.011$$
$$\beta = -0.004 \pm 0.010$$

Reconstructed space all voids

Precision $\sigma_\varepsilon/\varepsilon$:

$1.1\,\%$



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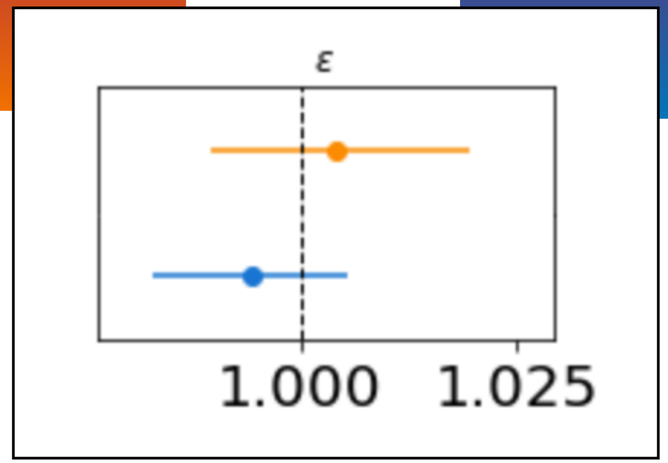


Sensitivity to the void size

Reconstructed space all voids

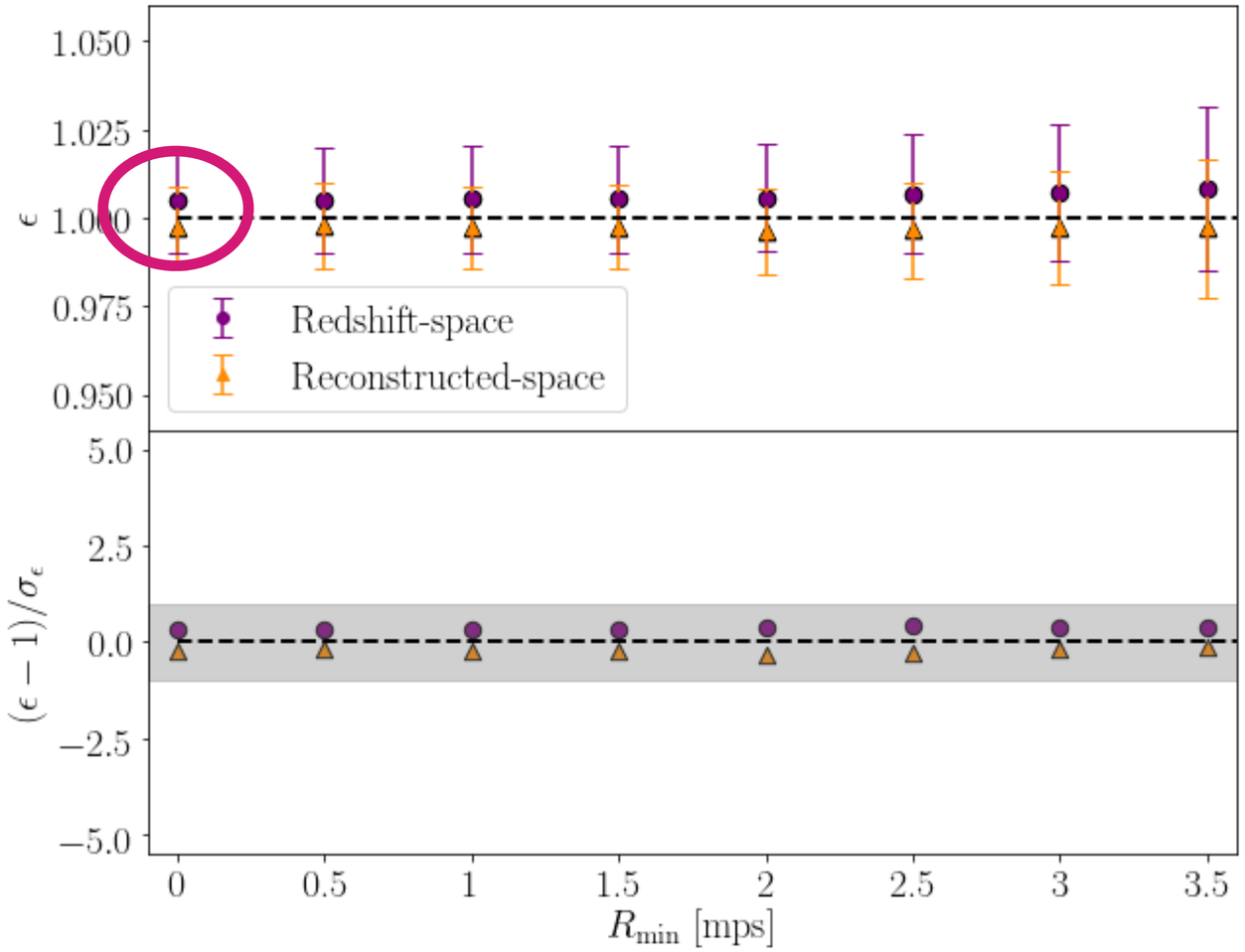
Precision $\sigma_\varepsilon/\varepsilon$:

1.1 %

Redshift space all voids

Precision $\sigma_\varepsilon/\varepsilon$:

1.5 %



Conclusions and Future perspectives

- ☑ Studied the impact of reconstruction in cosmic voids
- ☑ First analysis correlating galaxies and voids in reconstructed space
- ☐ Conduct an AP test varying the value of ε
- ☐ Apply the method to real data with the possibility to increase drastically the statistical signal
- ☑ Investigating the role of different reconstruction algorithms (see E. Maragliano's paper)

Take home message :

Reconstructed space analysis : more precise in recovering the AP parameter ε

Thank you for the attention :)

Giulia Degni

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