Improving the signal from cosmic voids using reconstruction

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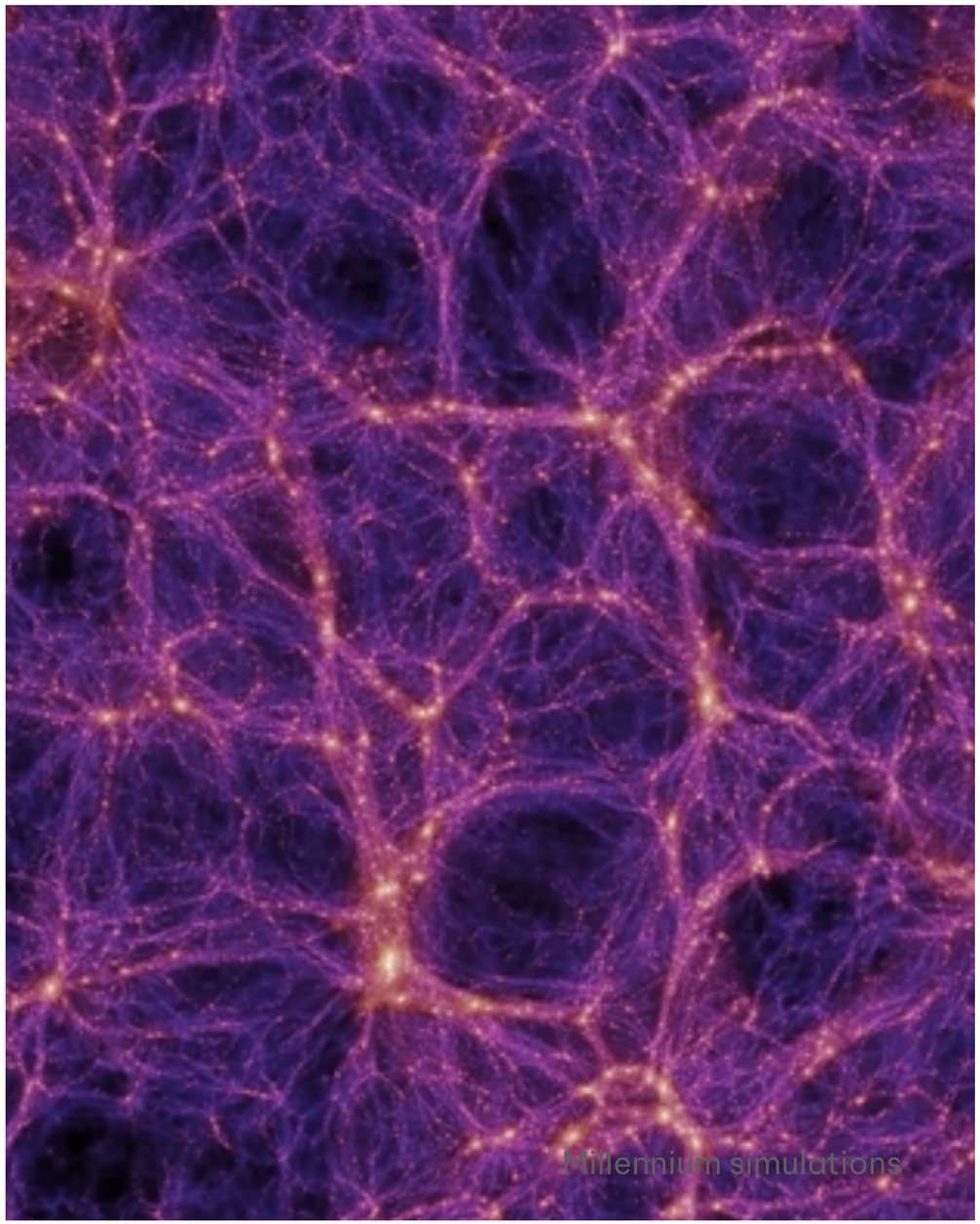
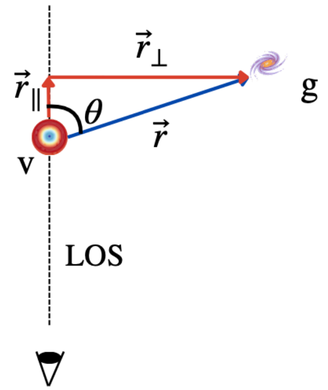
Cosmic voids

- 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-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

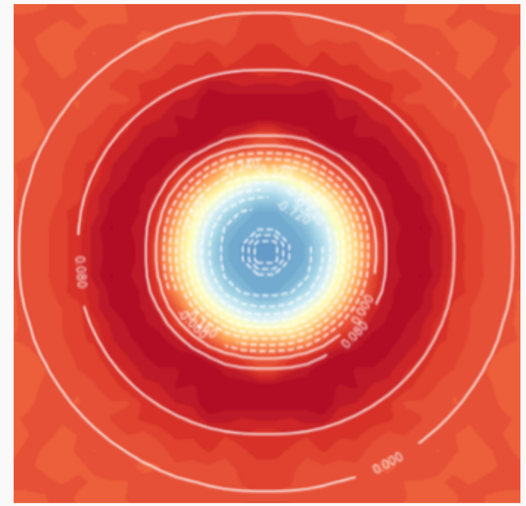


Davis-Peebles estimator:

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

Multipoles:

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



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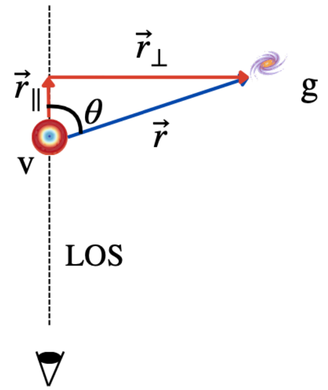

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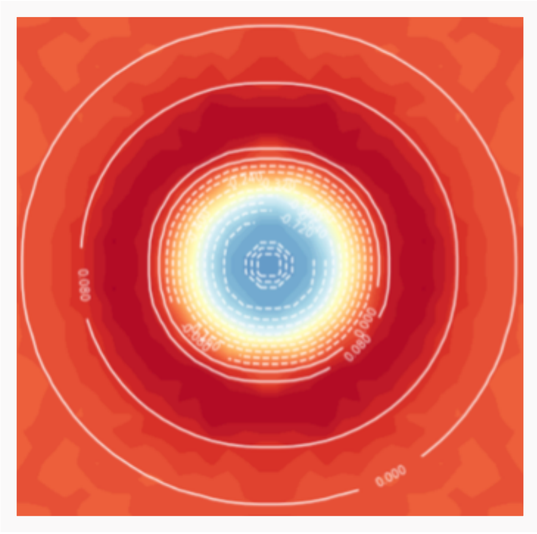
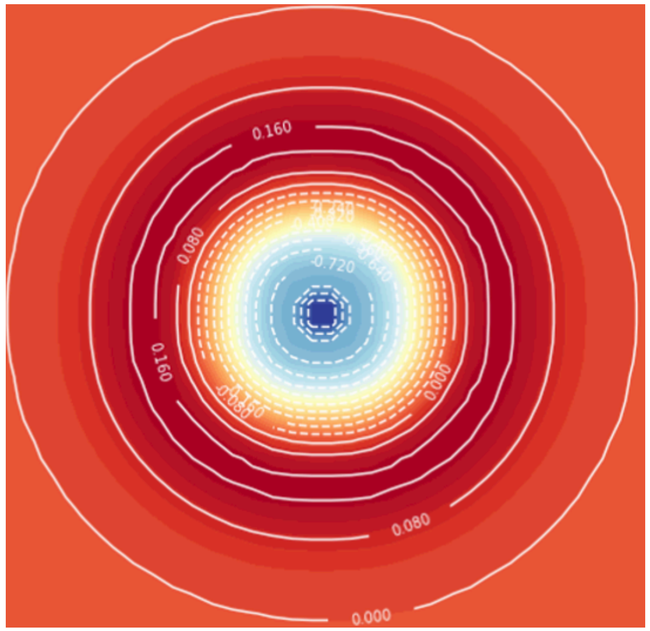
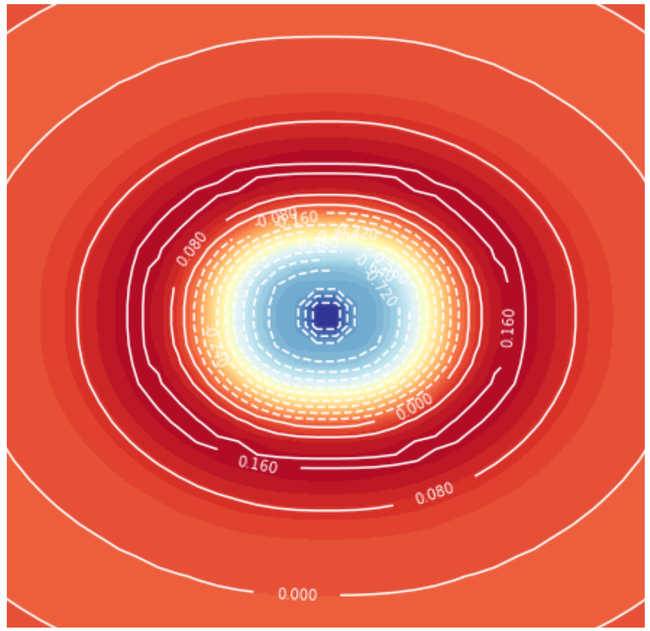


Important property : void are on average spherical !

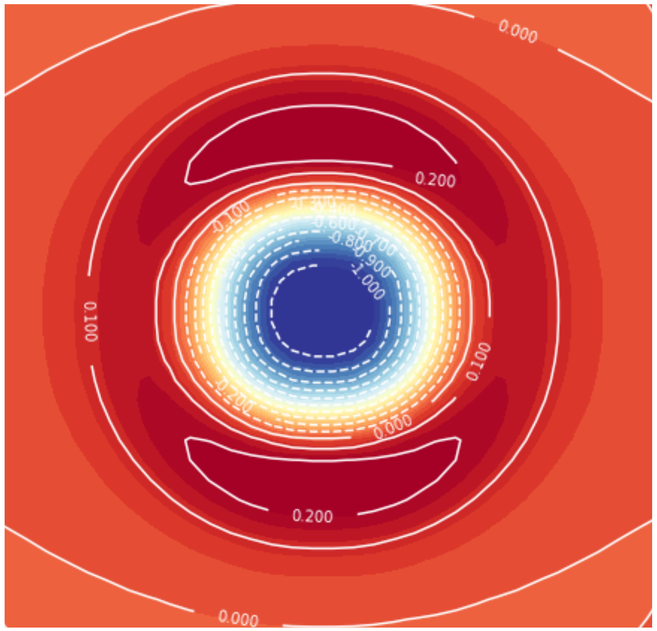
Real Space (no distortions)



AP distortions



Redshift space distortions



Alcock-Paczynski test

A key ingredient to cosmological inference

- Distances estimated from measured redshift

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

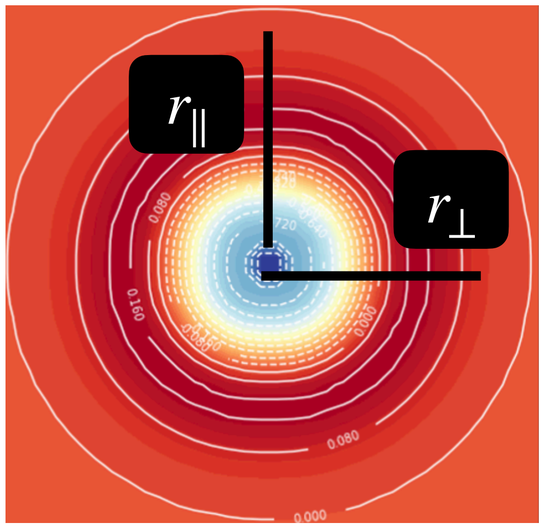
Assuming a flat Universe

- 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

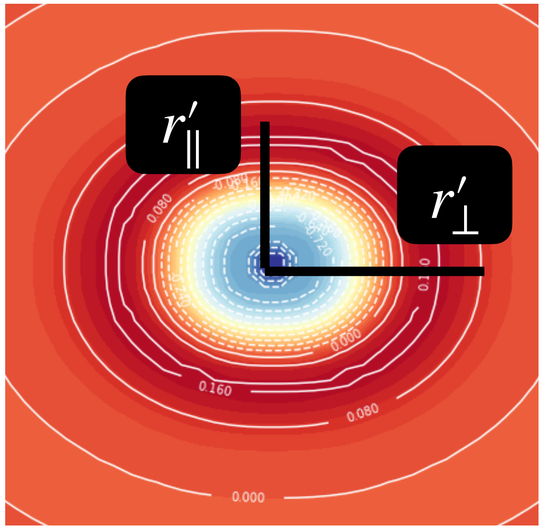


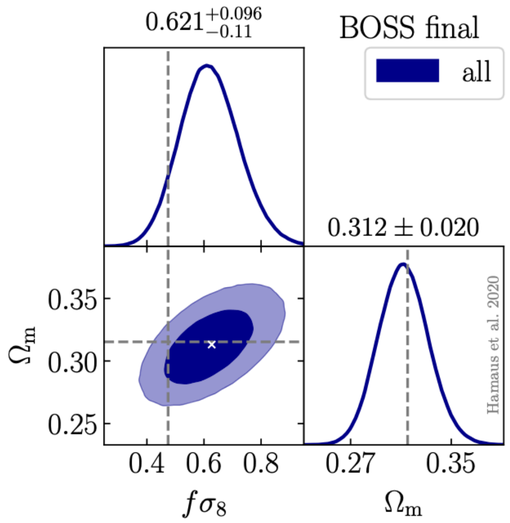
Fiducial cosmology

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

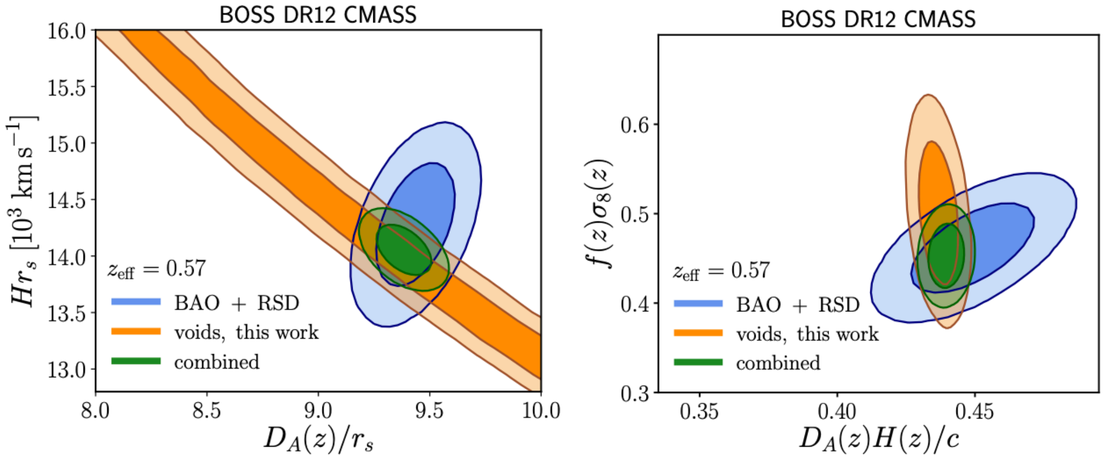
$$\varepsilon = \frac{q_\perp}{q_\parallel} = \frac{D_A(z)H(z)}{D'_A(z)H'(z)}$$

AP distortions

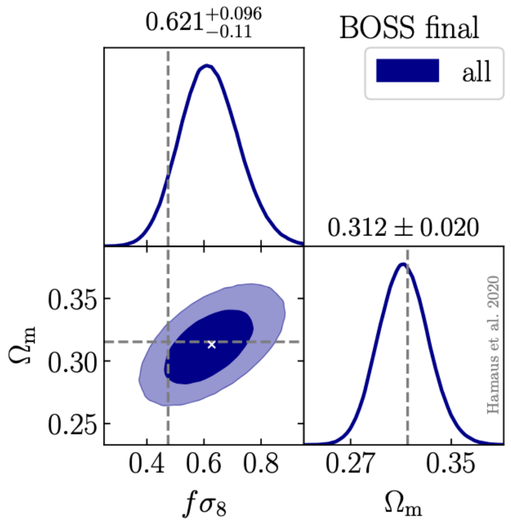




Hamaus et al. 2020



Nadathur et al. 2020



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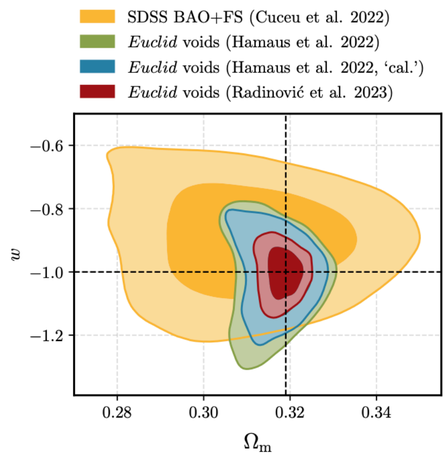
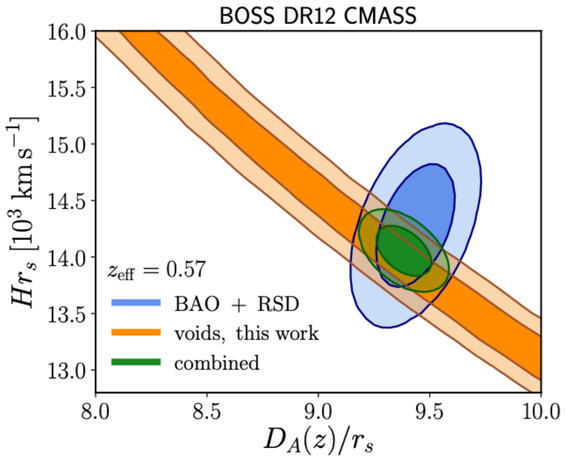
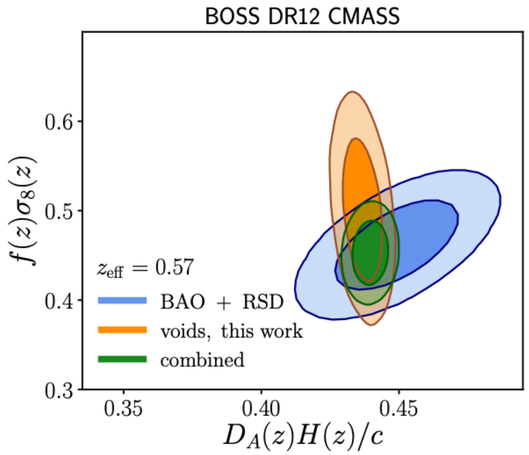


Radinovic et al. 2023





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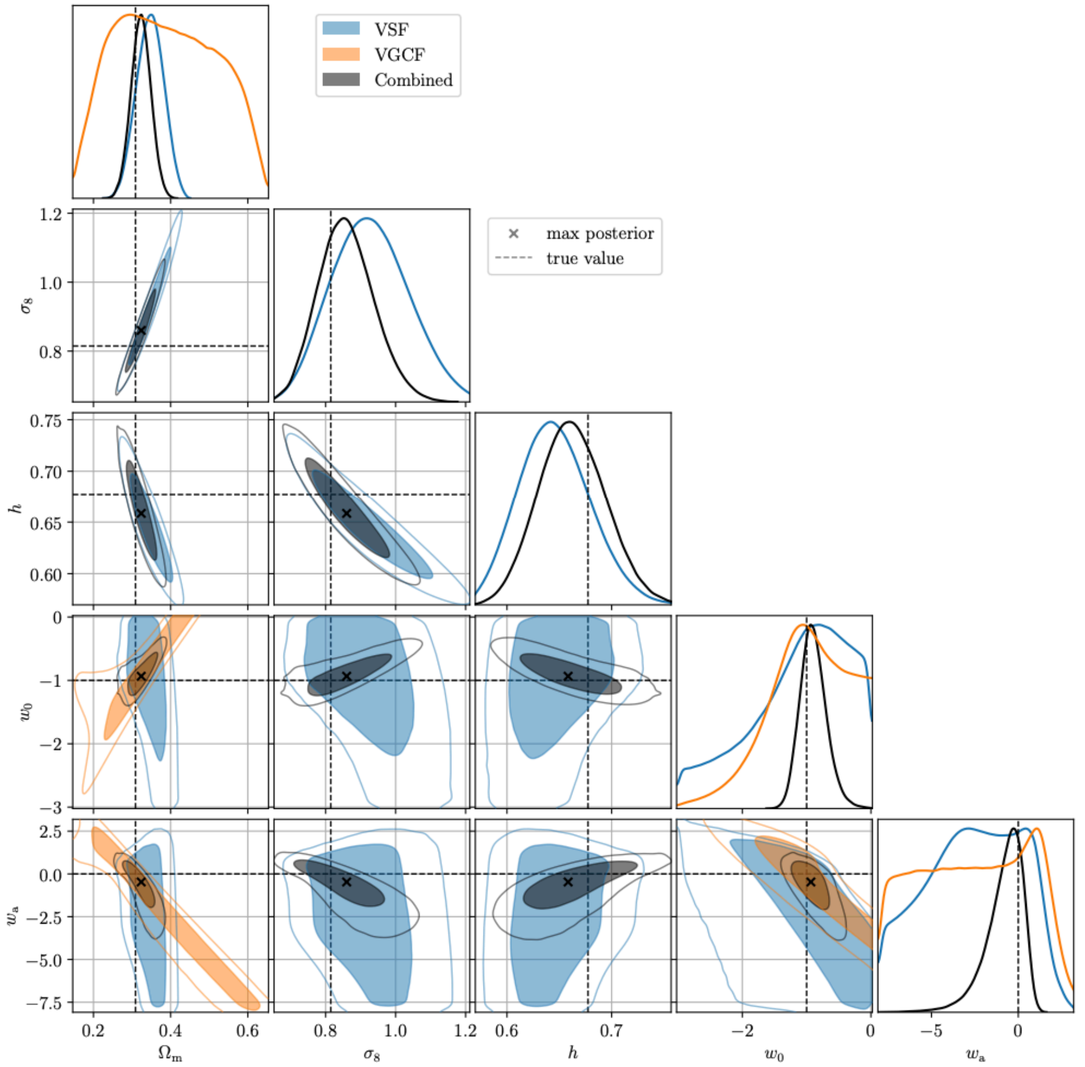


Verza, Degni et al. 2025

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:

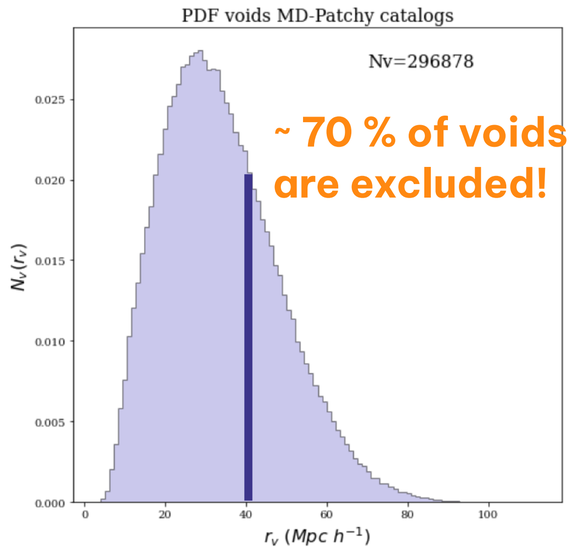
Smaller voids are difficult to model

Difficult to include systematics from the void identification – see Selection Effect in *Correa et al. 2022*

Solutions and alternative methods :

Eliminating voids at smaller scales

Standard



Voids radii distribution in BOSS Patchy mocks

Issues with this approach:

Smaller voids are difficult to model

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Solutions and alternative methods :

Eliminating voids at smaller scales

Standard

Investigating the impact of void finding systematics – selection effect

In progress

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Solutions and alternative methods :

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Standard

Investigating the impact of void finding systematics – selection effect

In progress

Dynamical criteria to identify voids

Sartori et al. 2026

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. 2022*

Solutions and alternative methods :

Eliminating voids at smaller scales	Investigating the impact of void finding systematics – selection effect	Dynamical criteria to identify voids	Removing RSD in the void finding process by reconstructing velocities
Standard	In progress	*Sartori et al. 2026*	*Nadathur et al. 2019*

New approach : THIS WORK !

Degni et al. 2026

- 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

Strategy

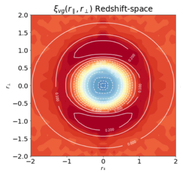
Tracers in z-space*

Void Finder

Void Catalog in z-space

VGCF

+



Likelihood Analysis

Extract ε and β

Velocity Reconstruction

Comparing ε

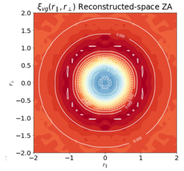
Tracers in r-space*

Void Finder

Void Catalog in r-space

VGCF

+

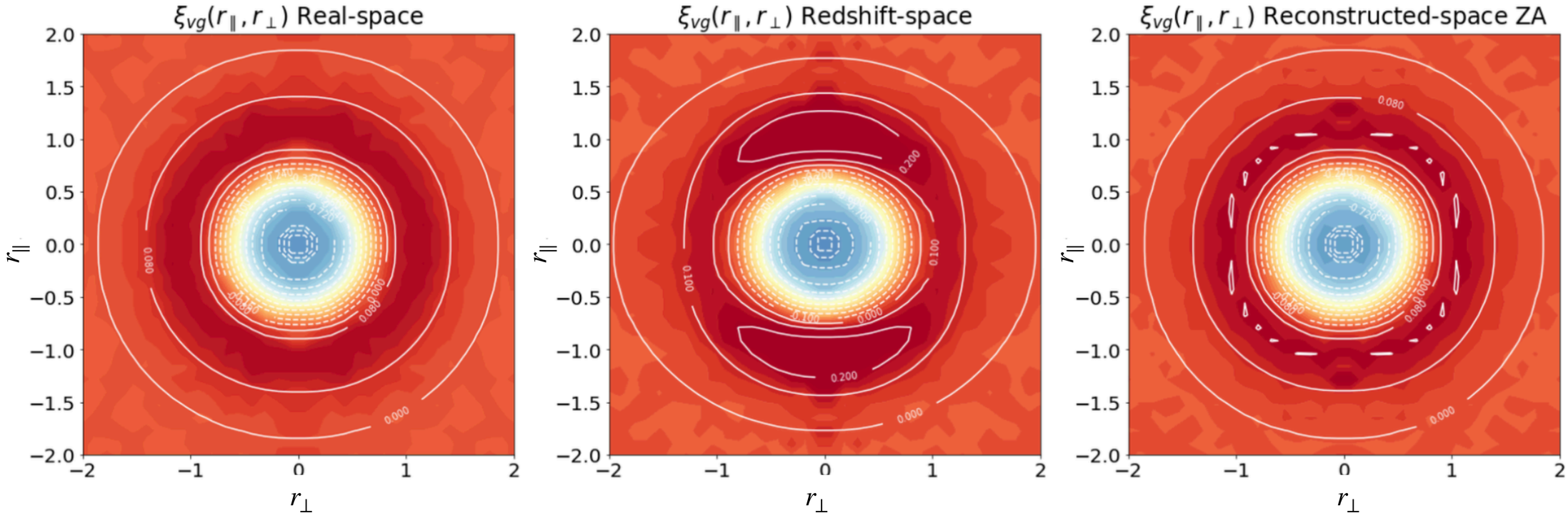


Likelihood Analysis

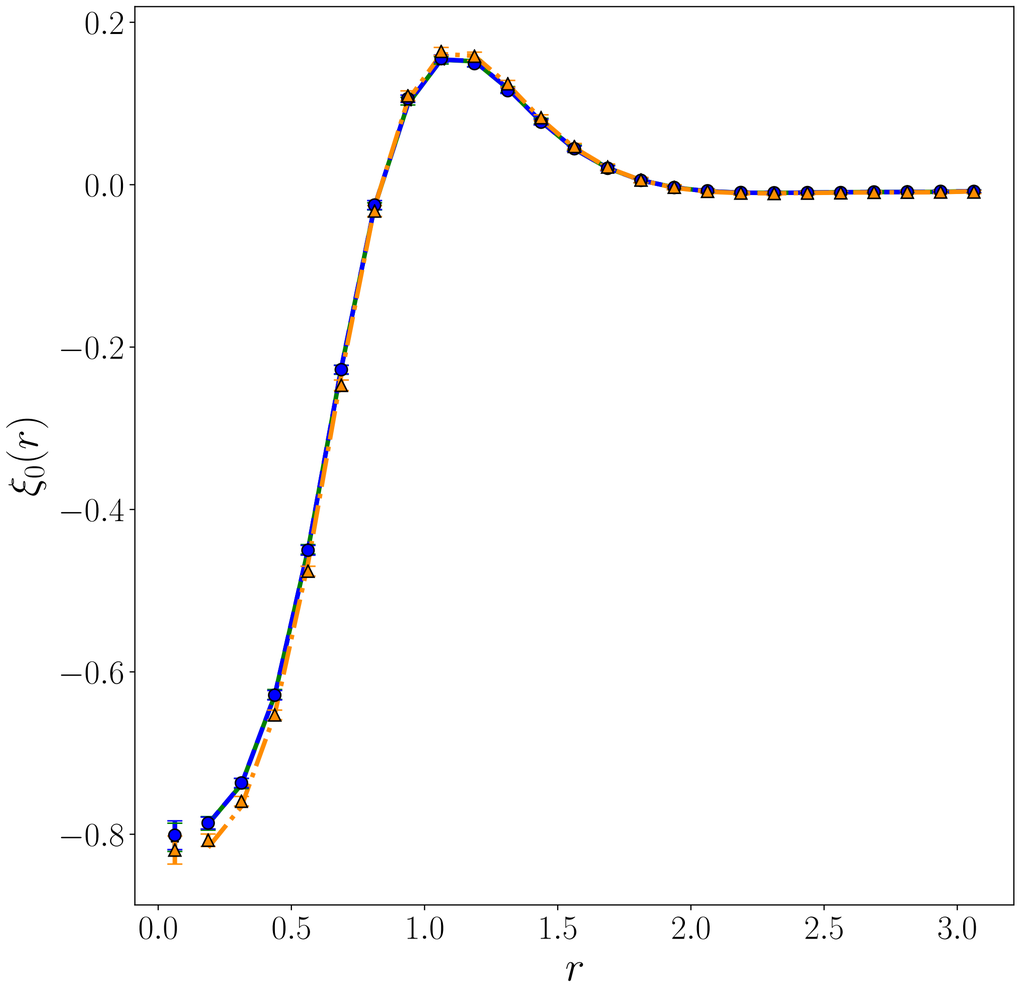
Extract ε and β

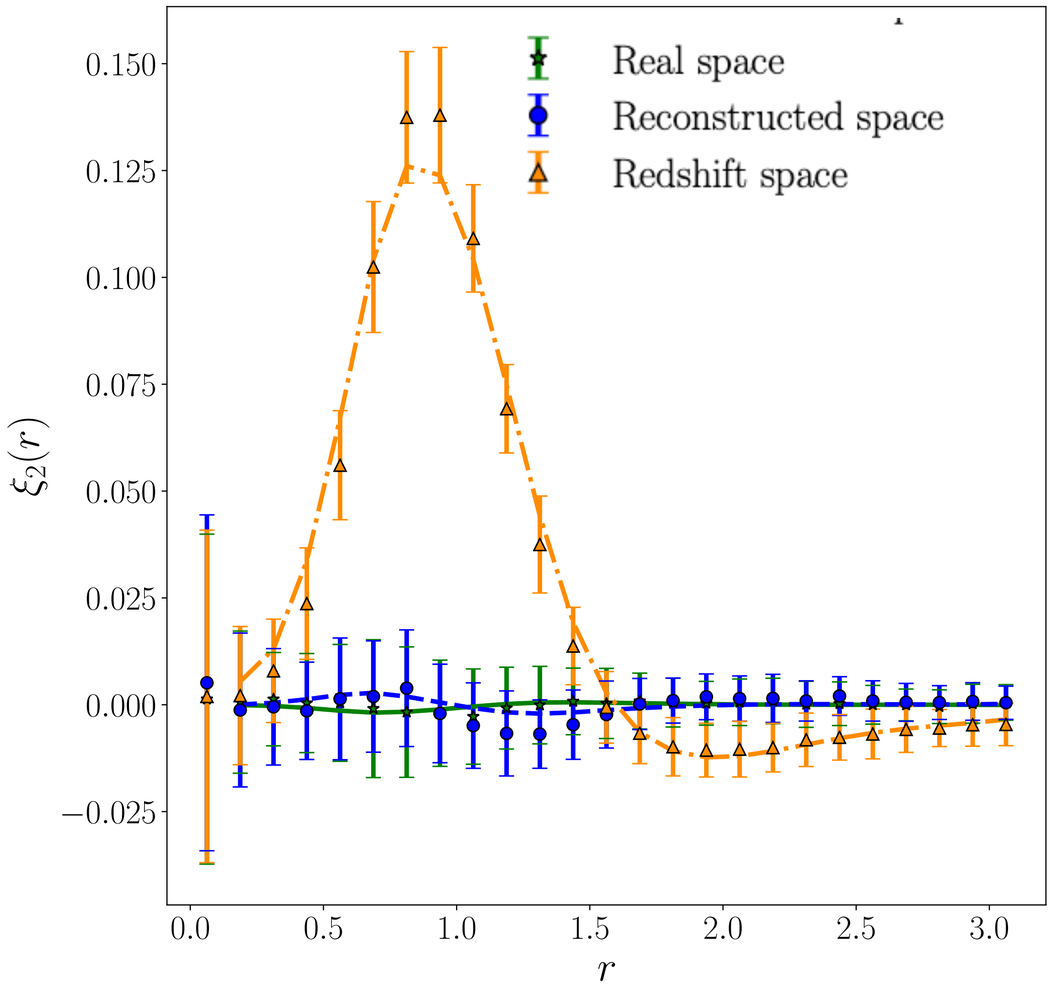
Data: Halos, Cubic Box, $L_{box} = 1000\ h^{-1}Mpc$, from Quijote Simulation High Resolution, $\bar{z} = 0.5$

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



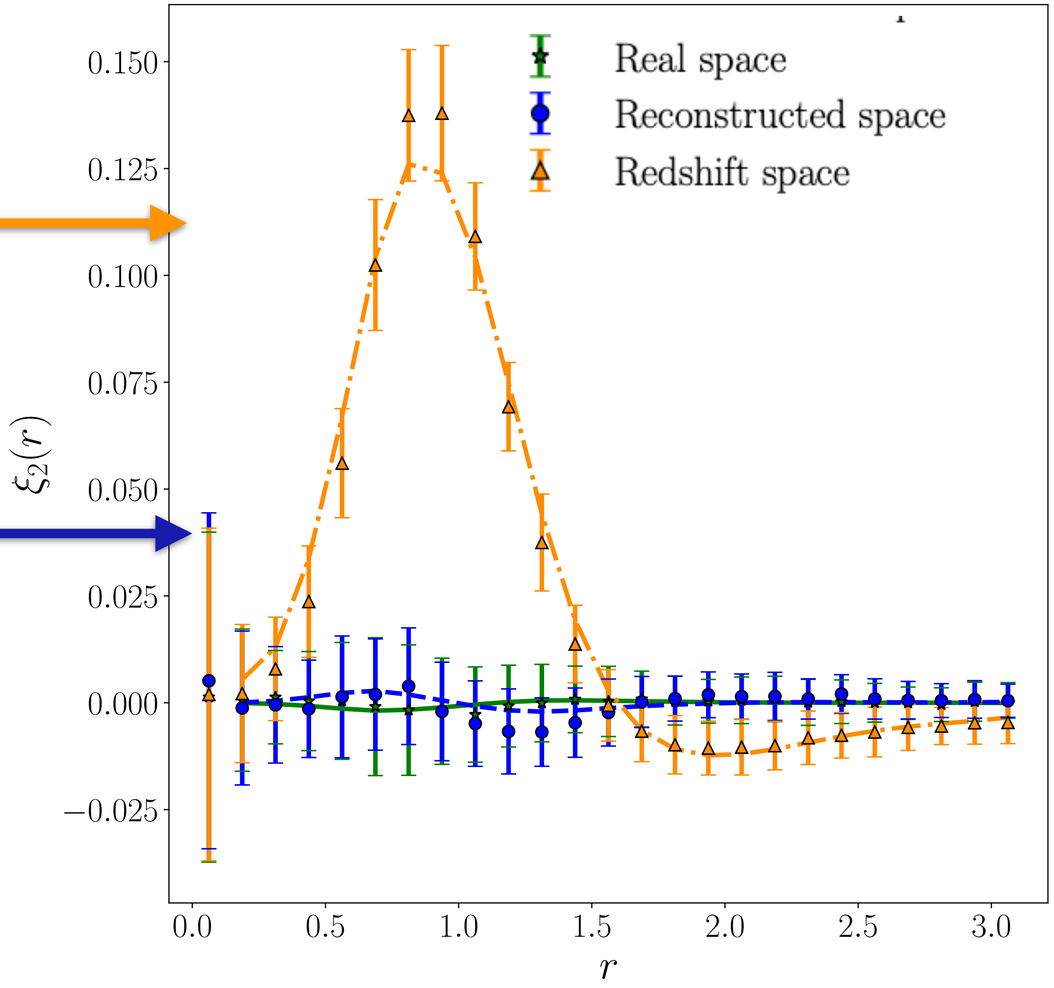
Void-galaxy cross-correlation function multipoles





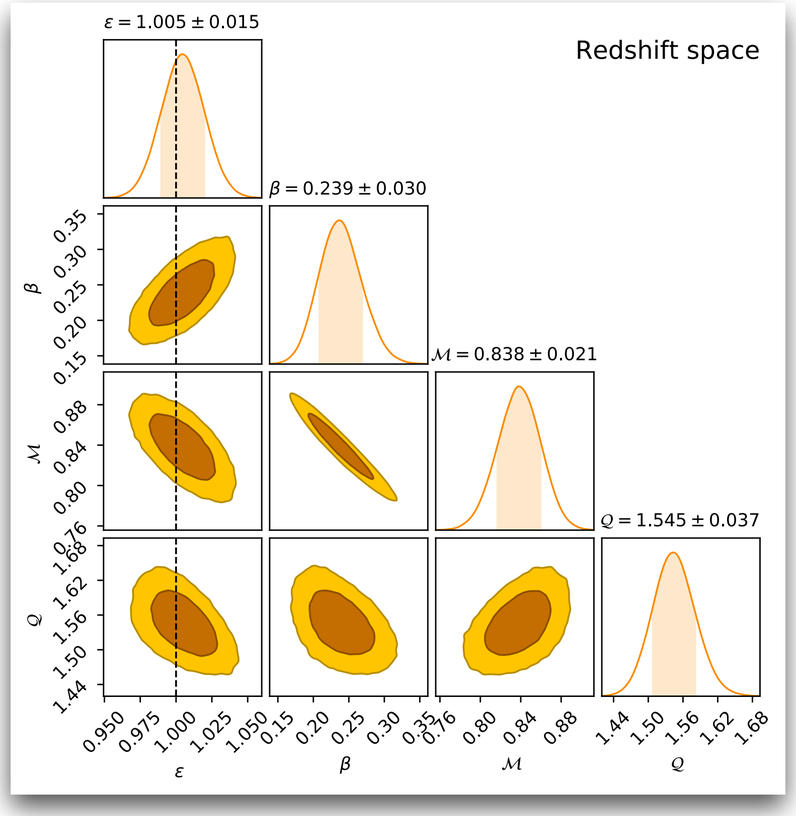
Void-galaxy cross-correlation function multipoles

- Anisotropies: RSD
- The reconstruction restores isotropy

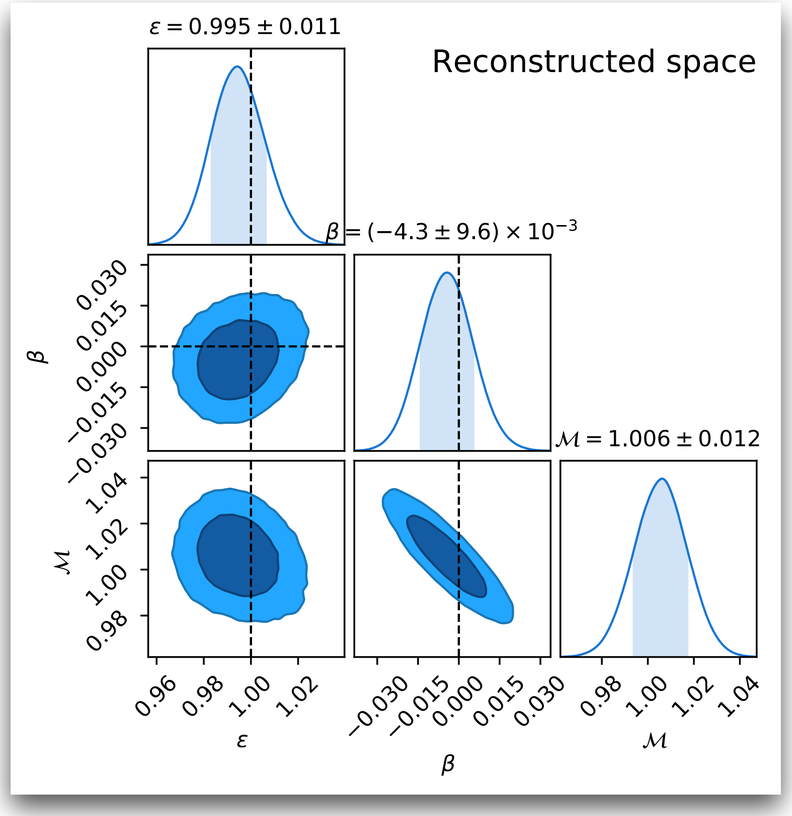


Results

Redshift space - Standard approach



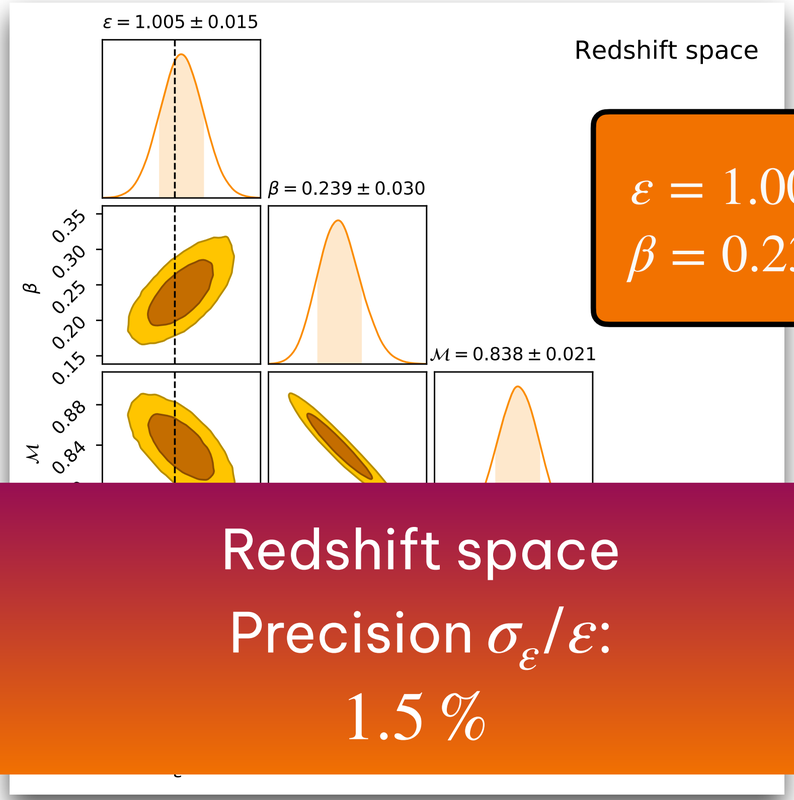
Reconstructed space - New approach



Results

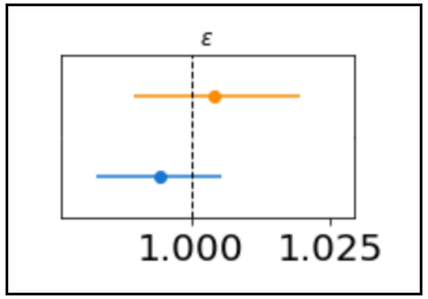
Redshift space - Standard approach

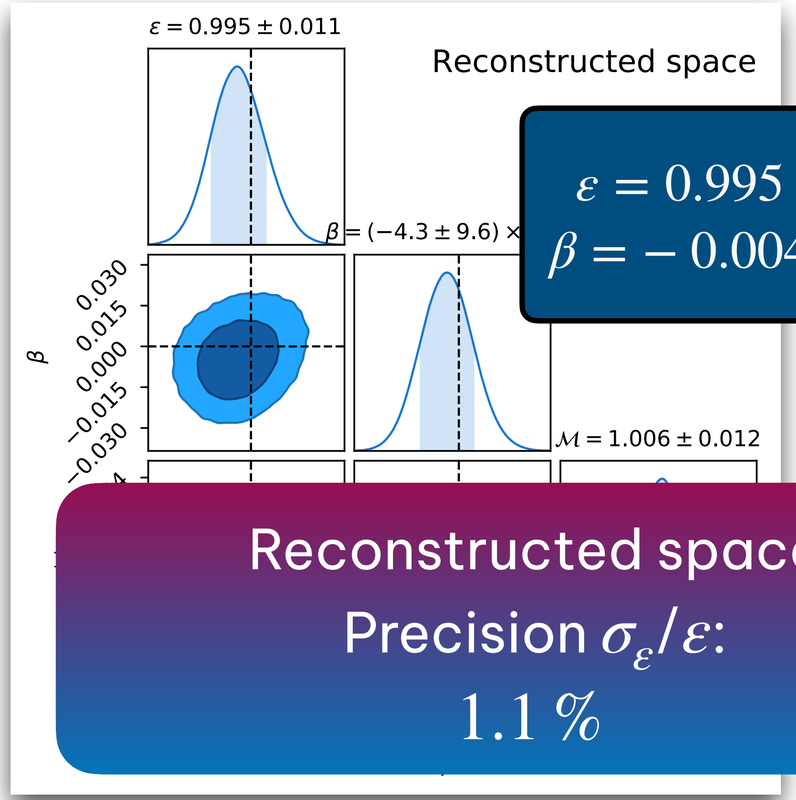
Reconstructed space - New approach



$\varepsilon = 1.005 \pm 0.015$

$\beta = 0.239 \pm 0.030$





$\varepsilon = 0.995 \pm 0.011$

$\beta = -0.004 \pm 0.010$

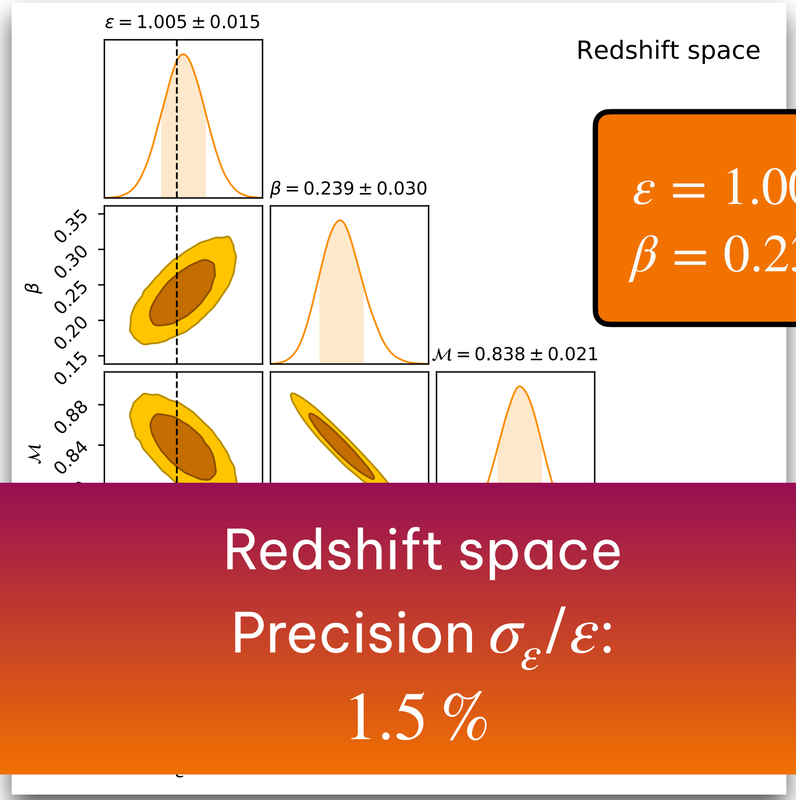
Redshift space
Precision $\sigma_\varepsilon/\varepsilon$:
1.5 %

Reconstructed space
Precision $\sigma_\varepsilon/\varepsilon$:
1.1 %

Results

Redshift space - Standard approach

Reconstructed space - New approach



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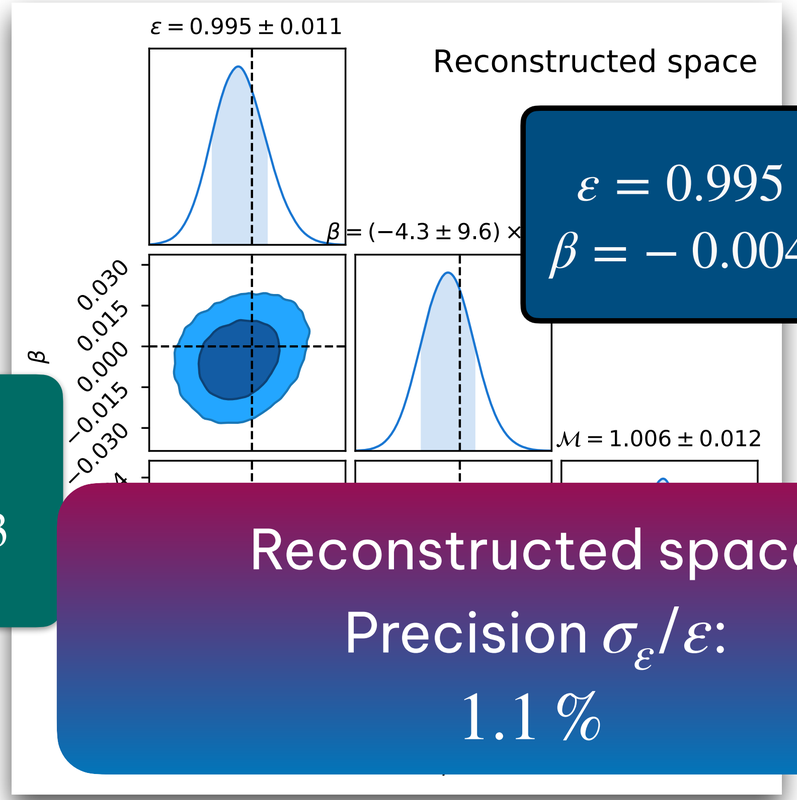

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Improvement factor

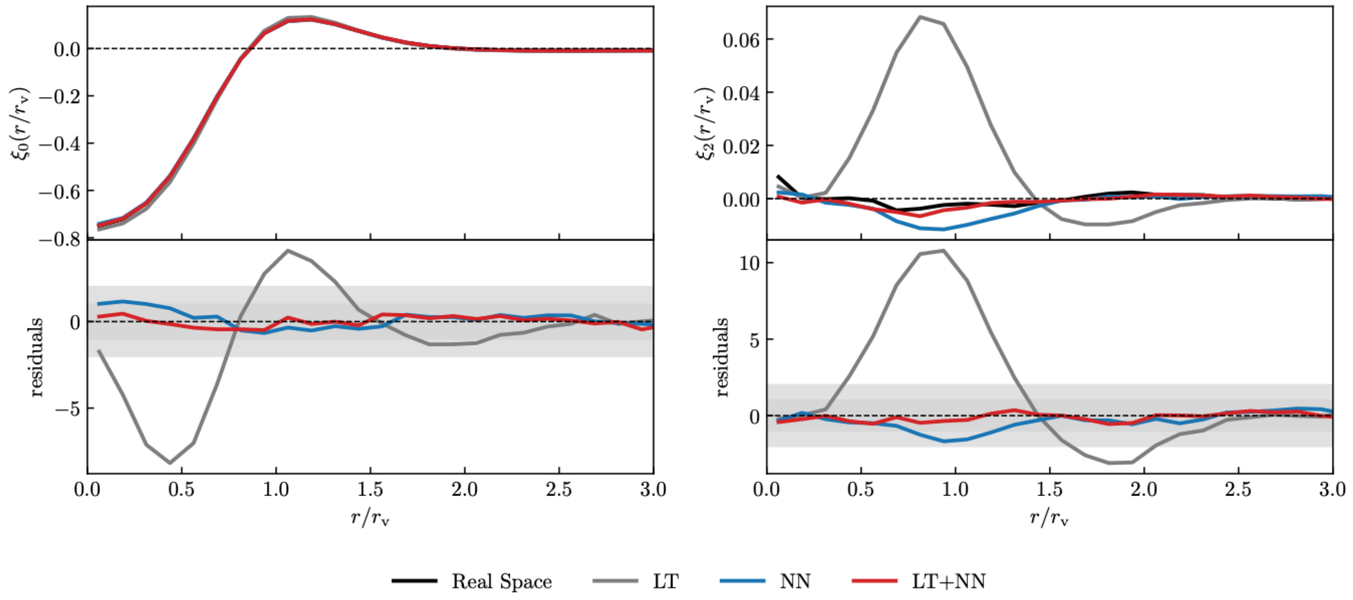
$$I = \sigma_{\mathrm{pre-rec}}/\sigma_{\mathrm{post-rec}} = 1.3$$

Redshift space
Precision $\sigma_\varepsilon/\varepsilon$:
1.5 %

Reconstructed space
Precision $\sigma_\varepsilon/\varepsilon$:
1.1 %

Qualitative study of the impact of different reconstruction algorithms

- Comparison between three reconstruction methods :
  - LT : Zel'dovich reconstruction - a direct application of linear perturbation theory
  - NN : Neural network reconstruction technique based on Ganeshaiah Veena et al. 2023
  - LT + NN : hybrid approach in which neural networks is trained on LT reconstructed fields



Maragliano et al. 2025

Conclusions and Future perspectives

- ☑ Studied the impact of reconstruction in cosmic voids
- ☑ First analysis correlating galaxies and voids in reconstructed space
- ☑ Investigating the role of different reconstruction algorithms (*Maragliano et al. 2025)*
- ☐ Apply the method to real data with the possibility to increase drastically the statistical signal

Take home message :

Reconstruction help to mitigate the degeneracy between ε and β

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

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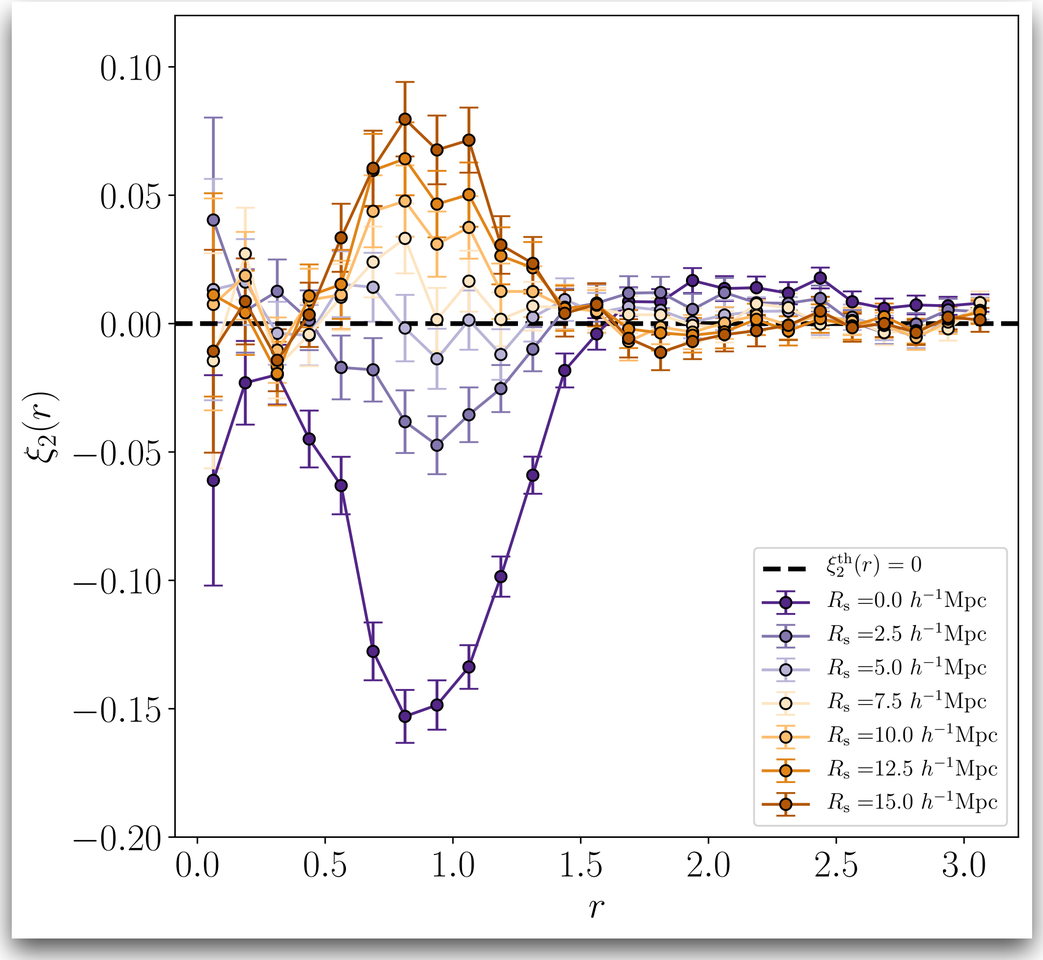
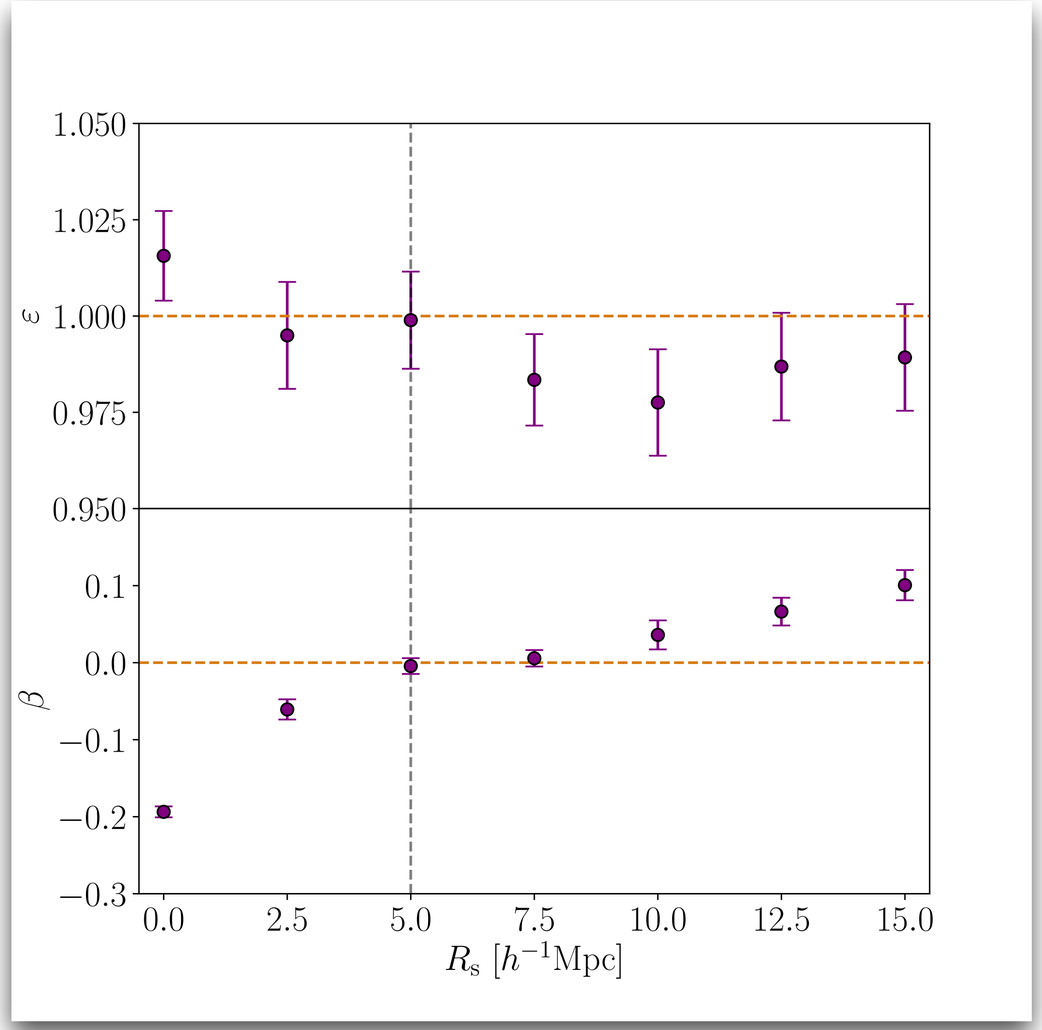
Backup slide: smoothing scale





Backup slide: sensitivity to the fiducial cosmology