Cosmic voids identification through tracer dynamics: a novel (?) approach for large-scale structure analyses

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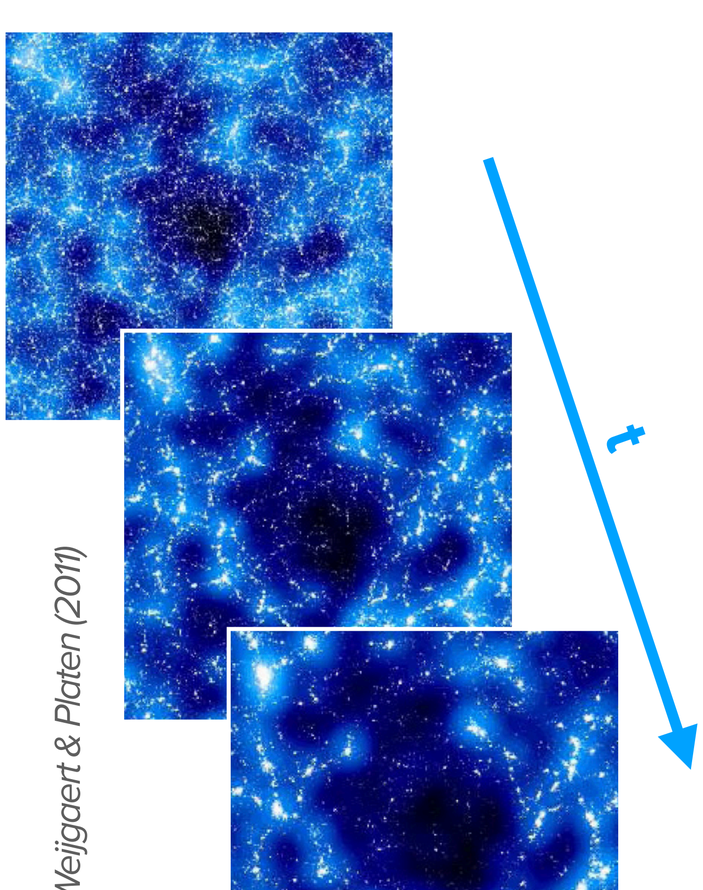
17th JULY 2025

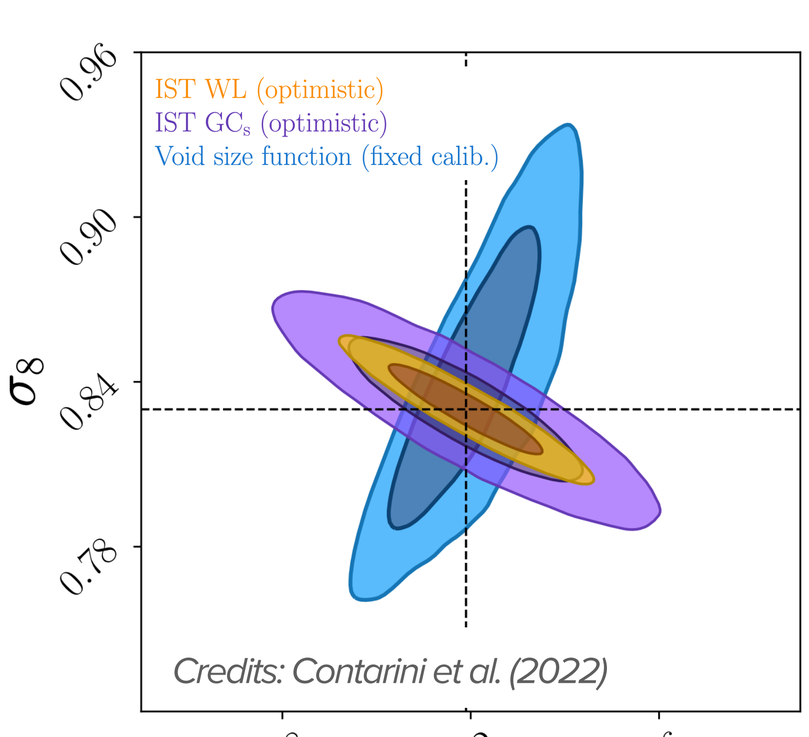
OPTIMIZING THE EXTRACTION OF COSMOLOGICAL INFORMATION FROM THE LATEST SPECTROSCOPIC REDSHIFT SURVEYS @ SESTO, ITALY

COSMIC VOIDS: A SUMMARY (AGAIN...)



Credits:
van de Weijgaert & Platen (2011)

Voids provide a variety of cosmological probes...



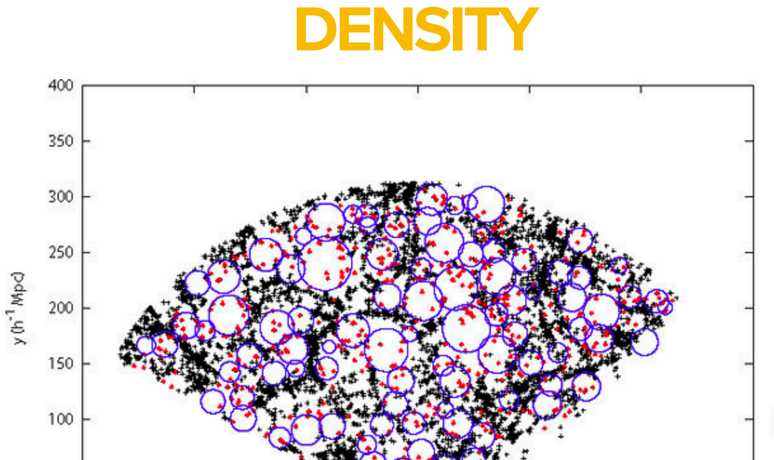
...Complementary with standard ones!

VOID IDENTIFICATION

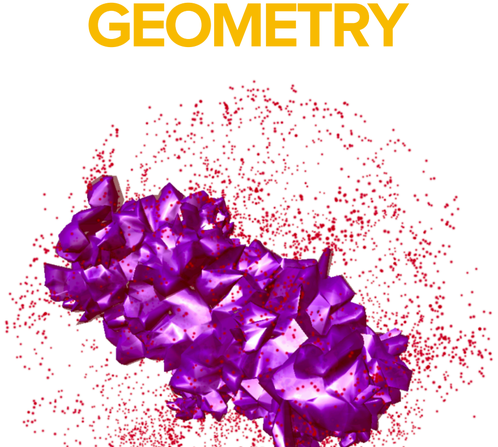
No unique definition of cosmic void *(Real issue?)*

Three different classes of methods (according to *Lavaux & Wandelt, 2009*)

DENSITY



GEOMETRY



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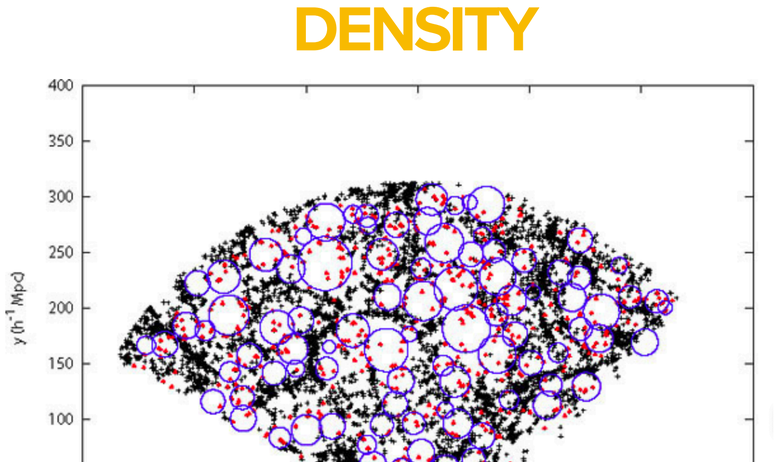
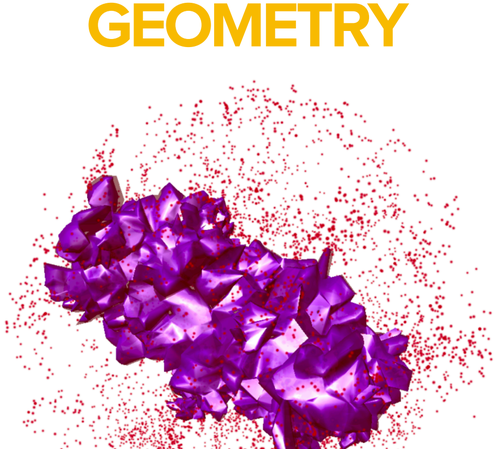
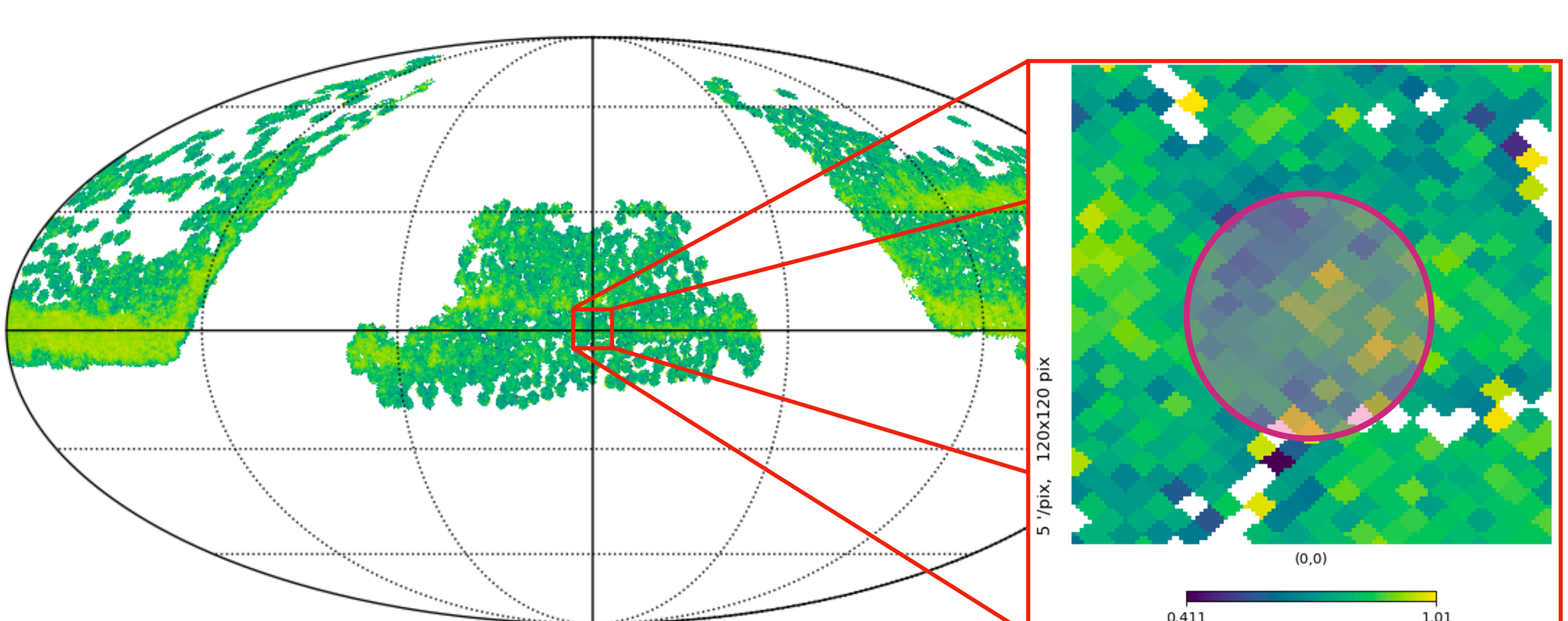


GEOMETRY



SHOT NOISE!

And huge impact of mask & systematics…



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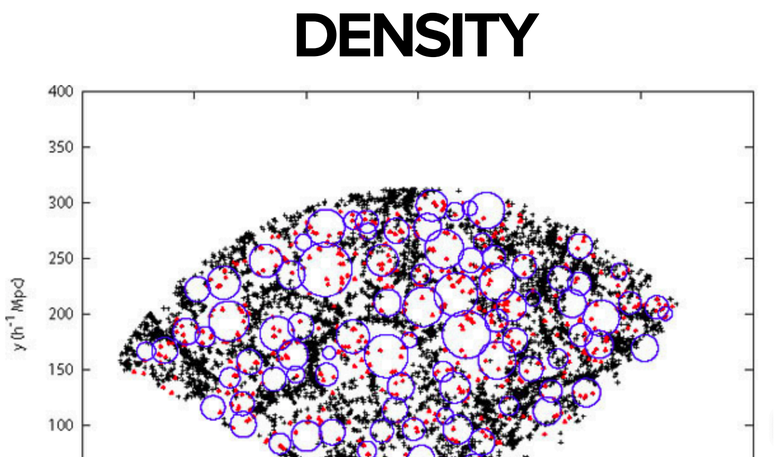
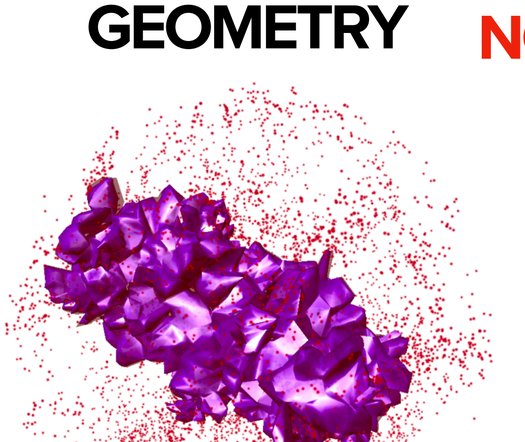
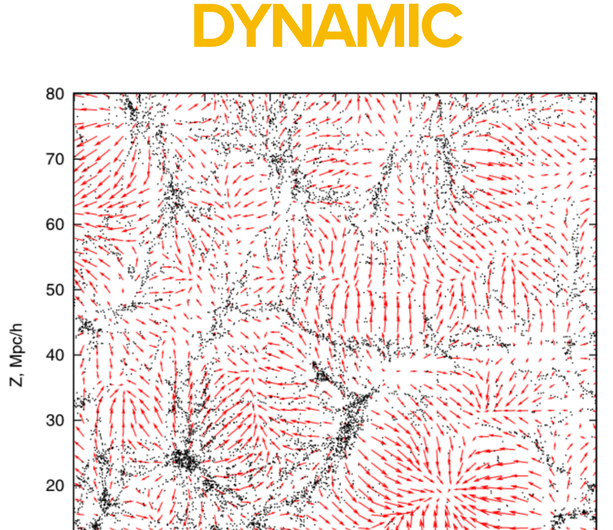


GEOMETRY



SHOT NOISE!

DYNAMIC



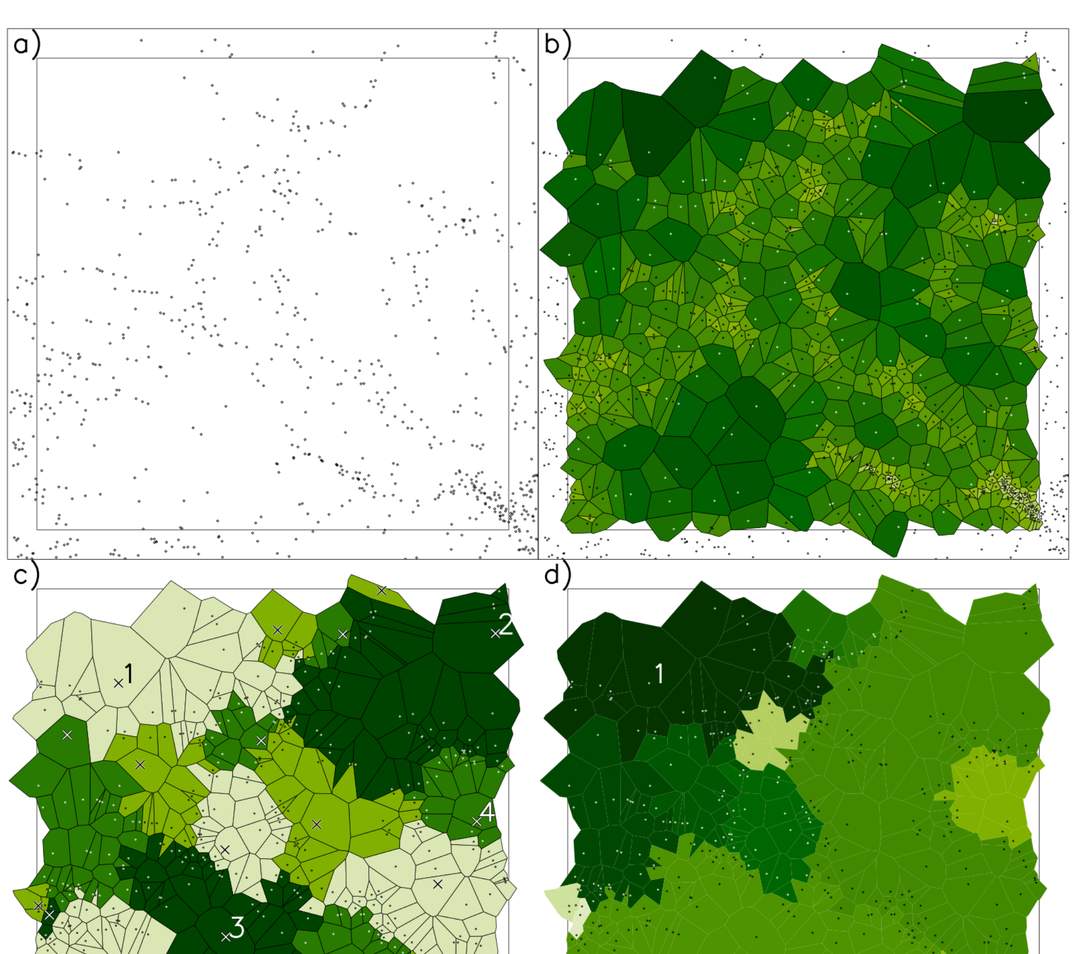
VOID IDENTIFICATION: GEOMETRICAL METHODS

ZOBOV-BASED: (Neyrinck et al. 2007)

VIDE (Sutter et al. 2014), REVOLVER (Nadathur et al. 2019) …

3D Geometrical method:

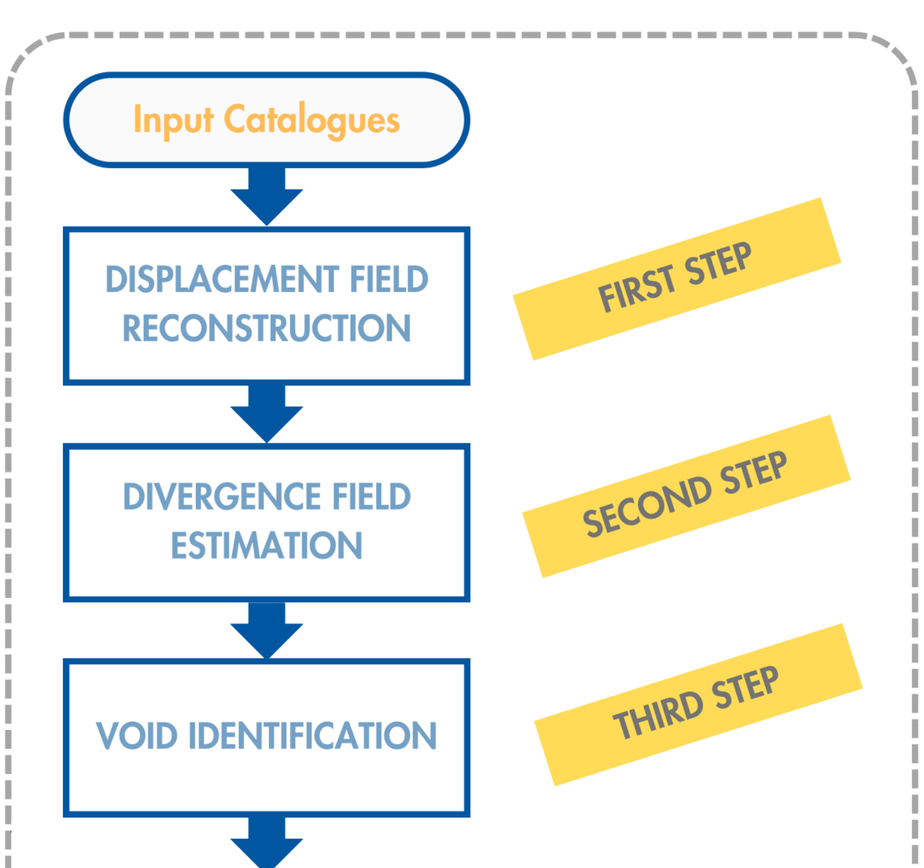
- Voronoi tessellation
- Identification of local density minima
- Void formation (watershed)
- Radius assignation



Credits: Neyrinck et al. (2007)

BACK-IN-TIME VOID FINDER

- **Based on dynamical criteria,** overcoming the typical issues associated with geometry- and density-based methods
- Use of cosmic tracers to sample the displacement (velocity) field instead of the density field (Optimal transport)
- Three main steps
- New generation surveys friendly (random used by default, masks, weights…)



DISPLACEMENT FIELD RECONSTRUCTION

- **«Back-in-time» optimal transport**

$$\mathbf{x}(\mathbf{q}, t) = \mathbf{q} + \boldsymbol{\Psi}(\mathbf{q}, t)$$

- No cosmological assumption for displacement calculation
- Assumption of a random catalogue

DISPLACEMENT FIELD RECONSTRUCTION

- **«Back-in-time» optimal transport**

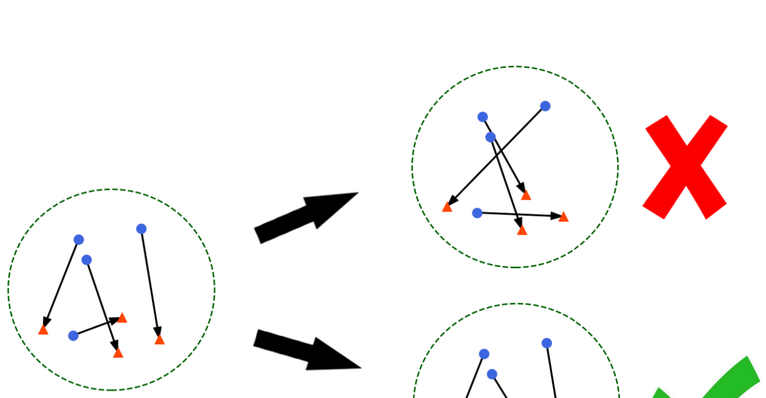
$$\mathbf{x}(\mathbf{q}, t) = \mathbf{q} + \mathbf{\Psi}(\mathbf{q}, t)$$

- No cosmological assumption for displacement calculation
- Assumption of a random catalogue
- Formally, minimisation of the cost function:

$$\int_{\mathbb{R}^3} \|T(\boldsymbol{q}) - \boldsymbol{q}\|^2 \, \mathrm{d}^3\boldsymbol{q}$$

- In practise: *discrete* action minimisation

(PIZA-like, Croft & Gaztanaga 1997)



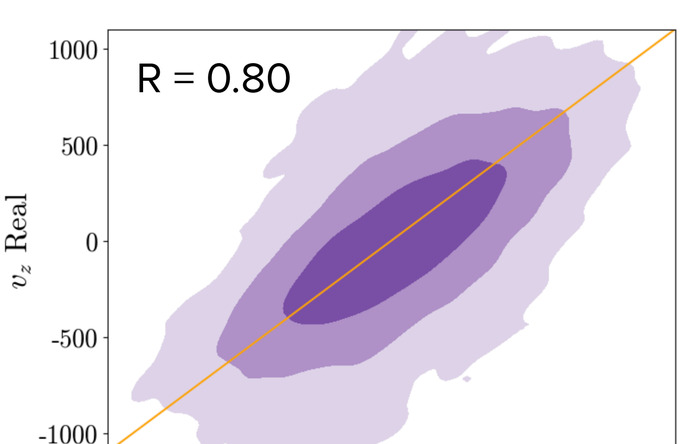
Limited by shell-crossing (but just fine in void regimes)

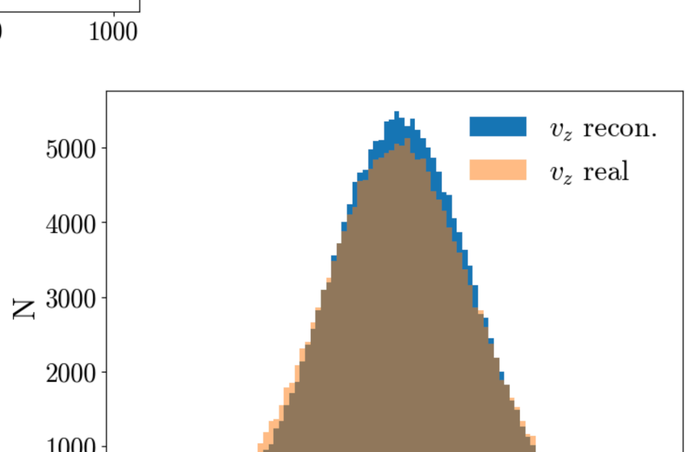
- Scaling $\sim n^{1.1}$ (cpu-time reconstruction dominated)

DISPLACEMENT FIELD RECONSTRUCTION

- Real space reconstruction ($\Psi_{\rm BT} \neq \Psi$ if we deal with biased tracers… a little of Math is required), assuming (now) a fiducial cosmology

$$v_{//} = a(z)H(z)\frac{f(z)}{(b(z)+f(z))}\Psi_{\rm BT,//}$$





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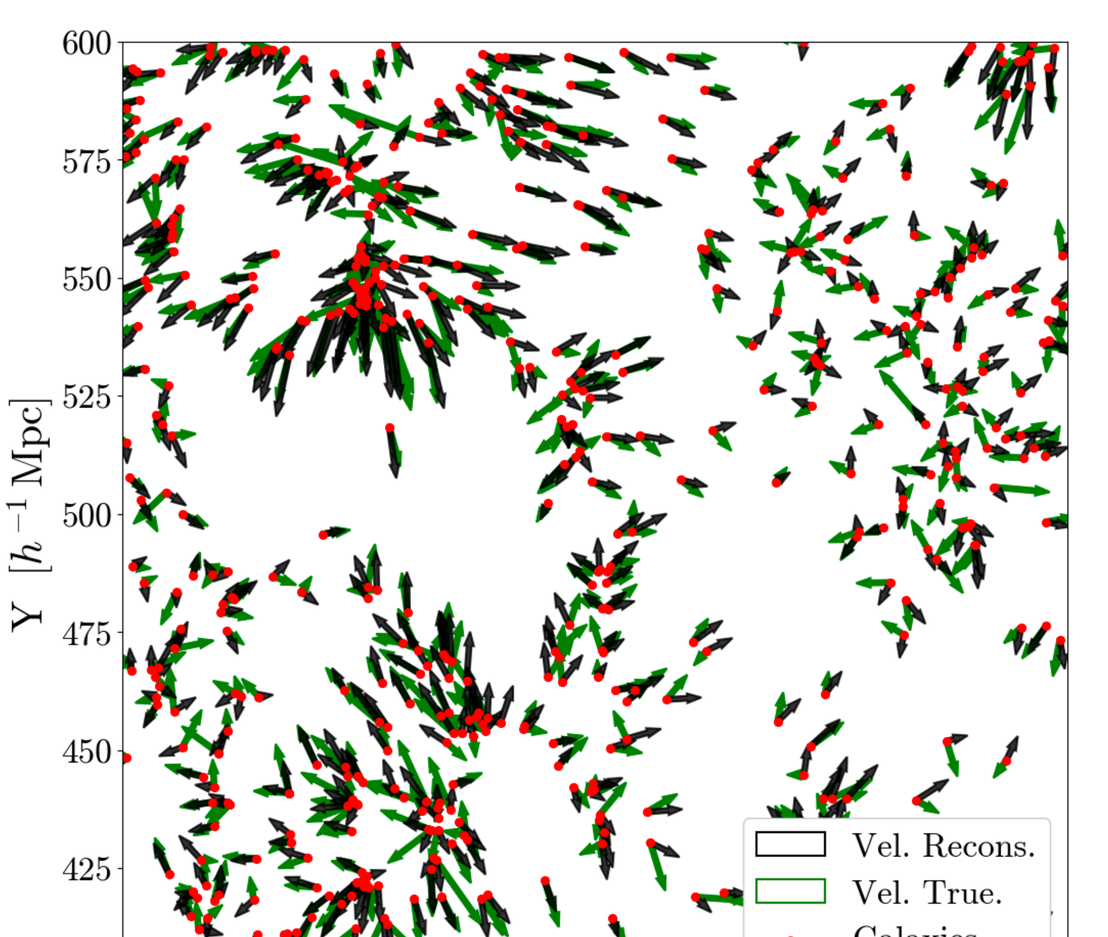
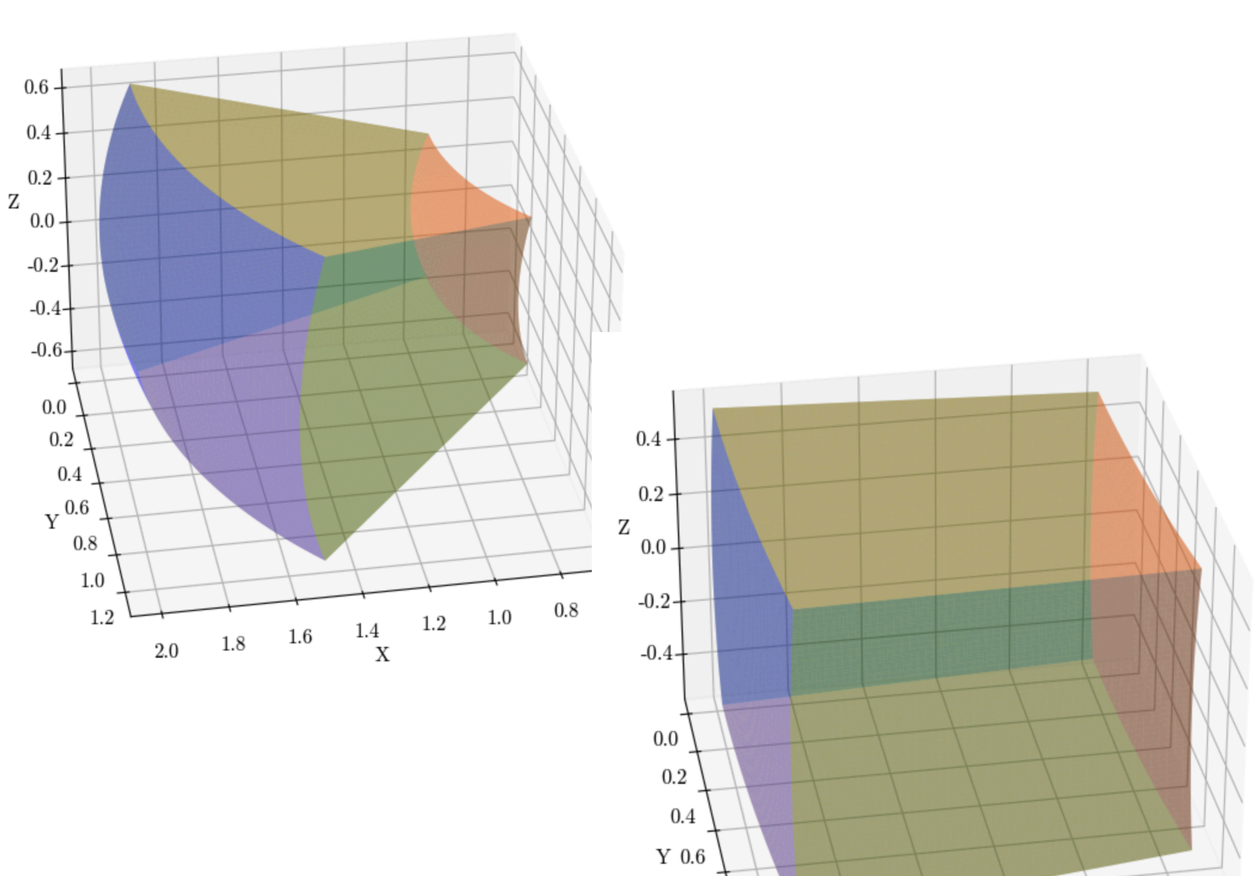


DIVERGENCE FIELD CALCULATION

- Divergence calculated as the flux of Ψ_{BT} through surfaces of cells of **complex geometry**, fundamental to correctly account for $n(z)$!
- Under Zel'dovich approximation:

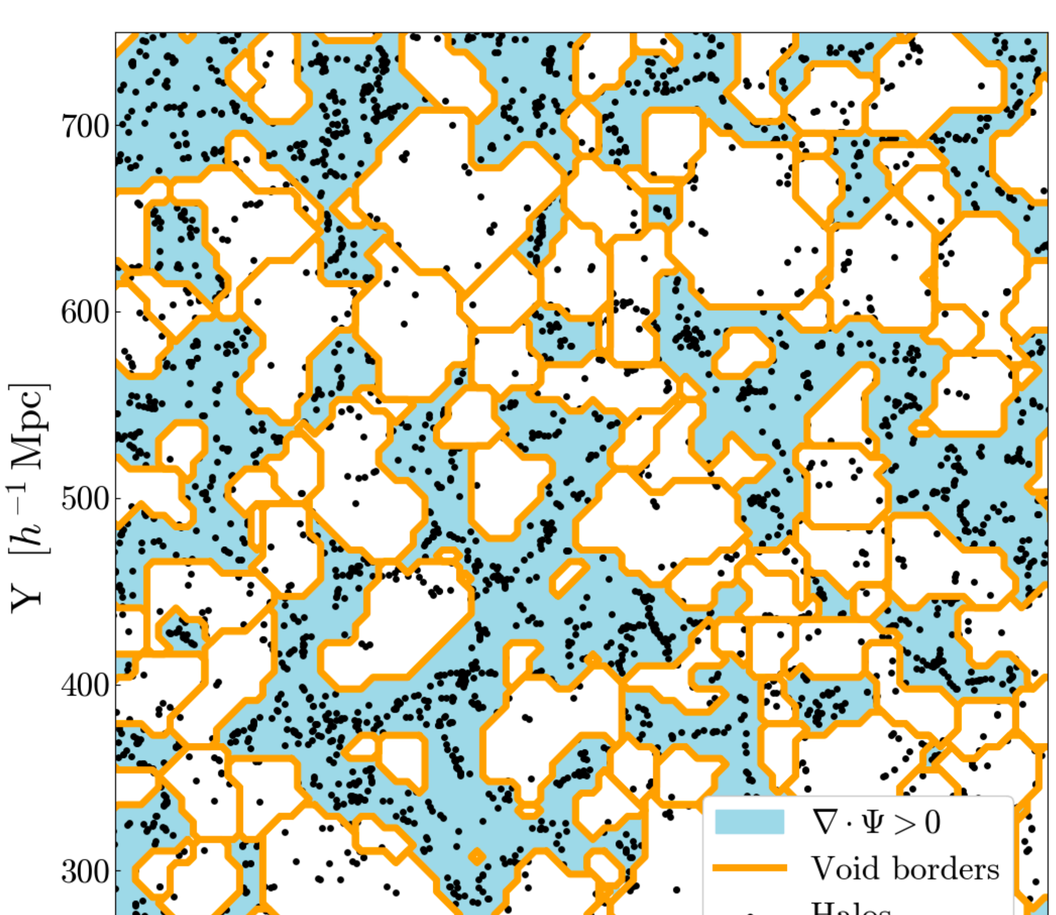
$$\delta(\mathbf{x}) \approx -\nabla_{\mathbf{q}} \cdot \mathbf{\Psi}$$

- Divergence field is filtered at a given scale



VOID IDENTIFICATION

- Identification of the local minima
- Watershed algorithm over divergence cells
- **Creation of non overlapping regions of the space with negative divergence**



SIMPLE BOX APPLICATION

Aletheia Simulations (Esposito et al. 2024)

Planck cosmology

$$z = 0$$

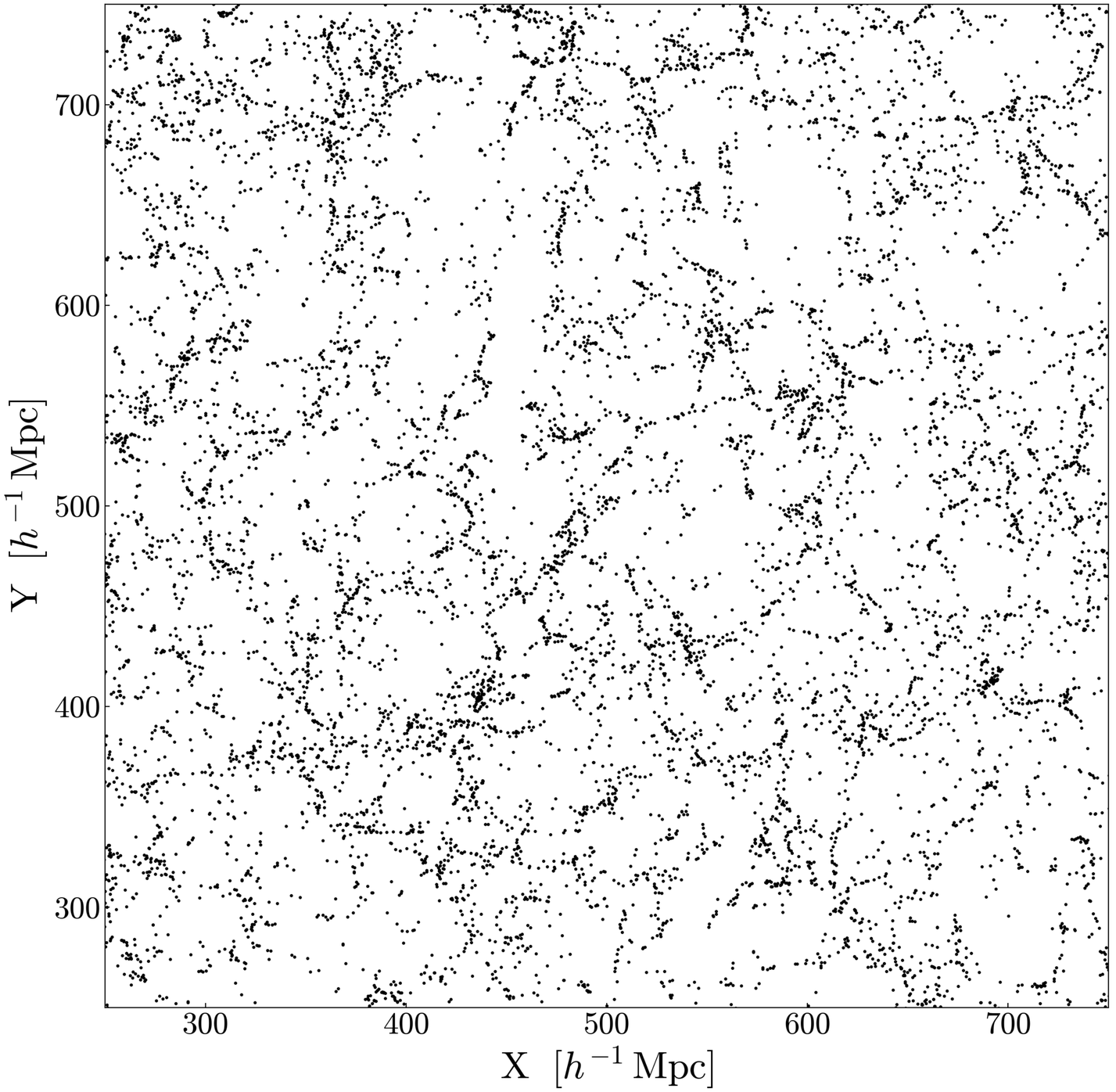
$$\sim 2.1 \times 10^6 \text{ halos with } M \geq 2.62 \times 10^{12} M_\odot$$

$$b = 1.146$$

Validation against REVOLVER (Nadathur et al 2019)

Stability test on DM

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE CPPM



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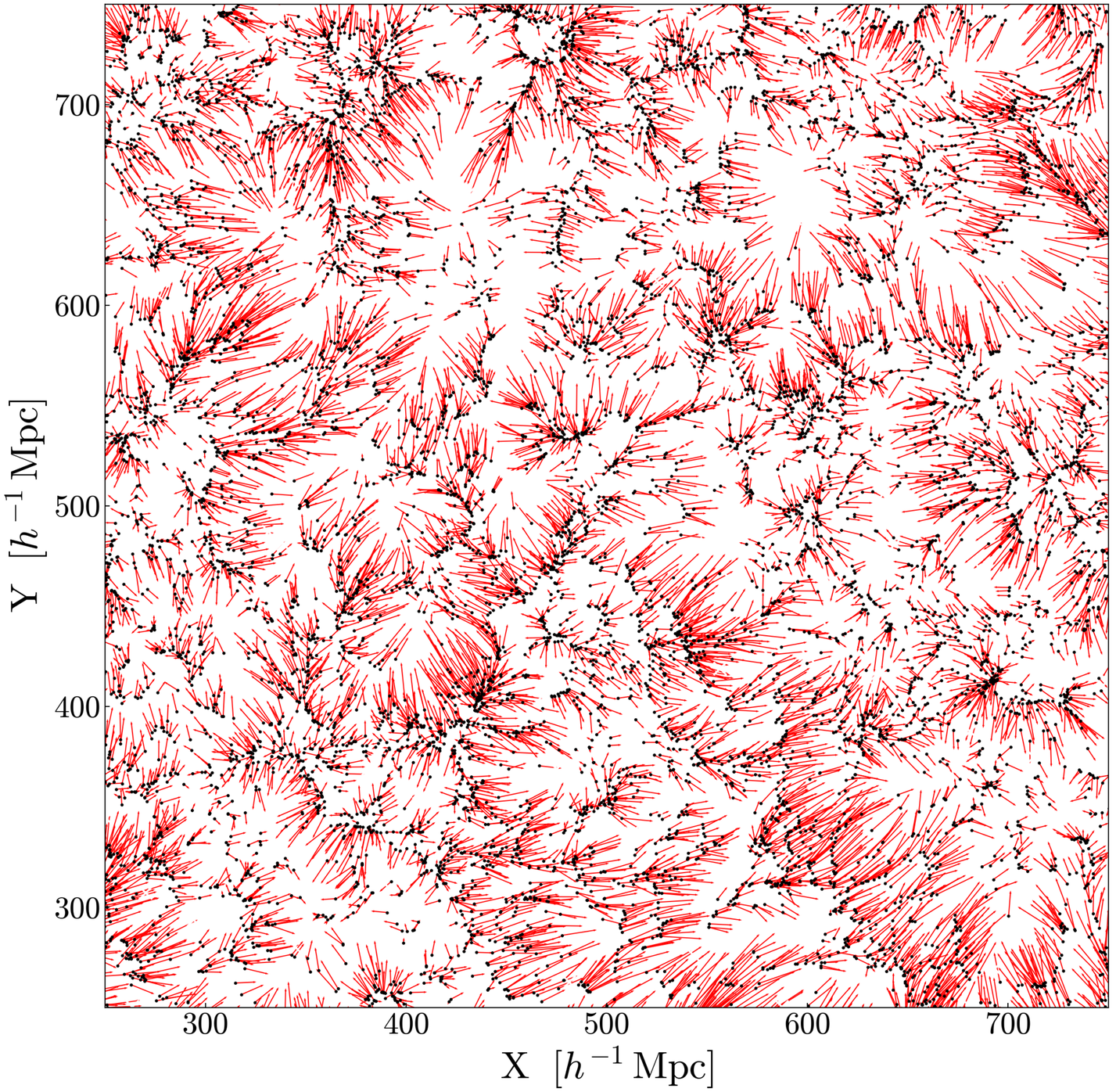

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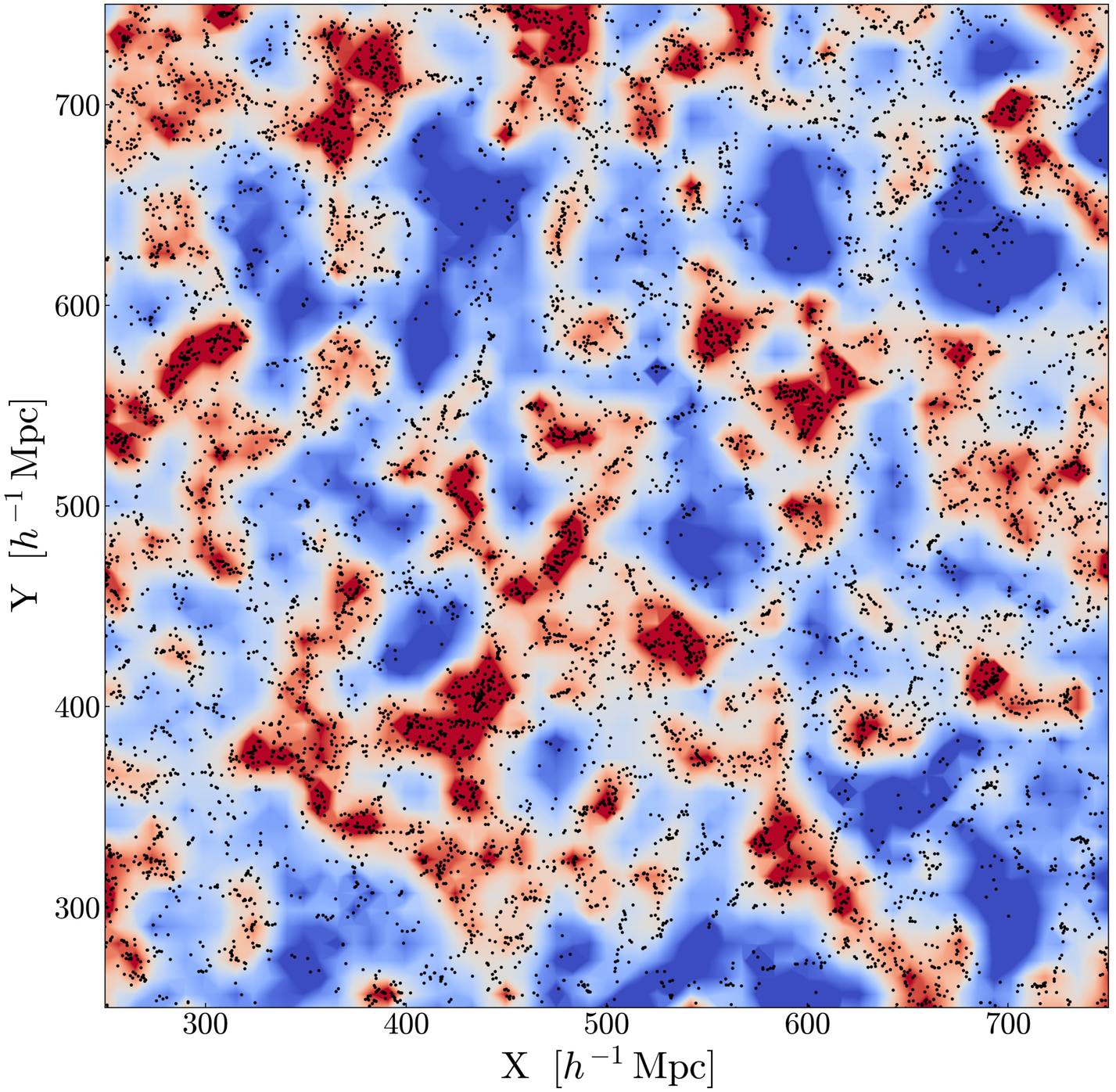

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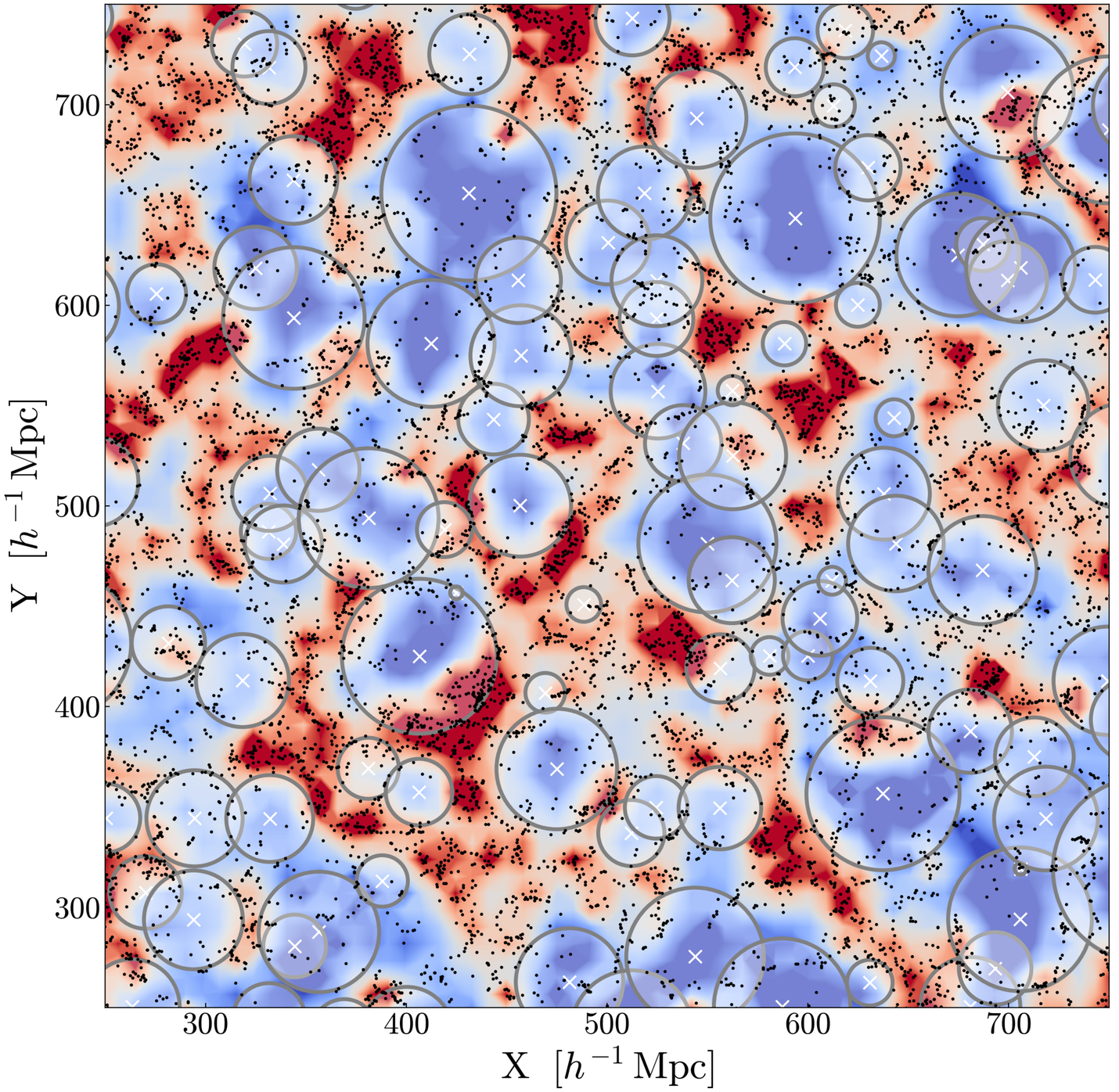

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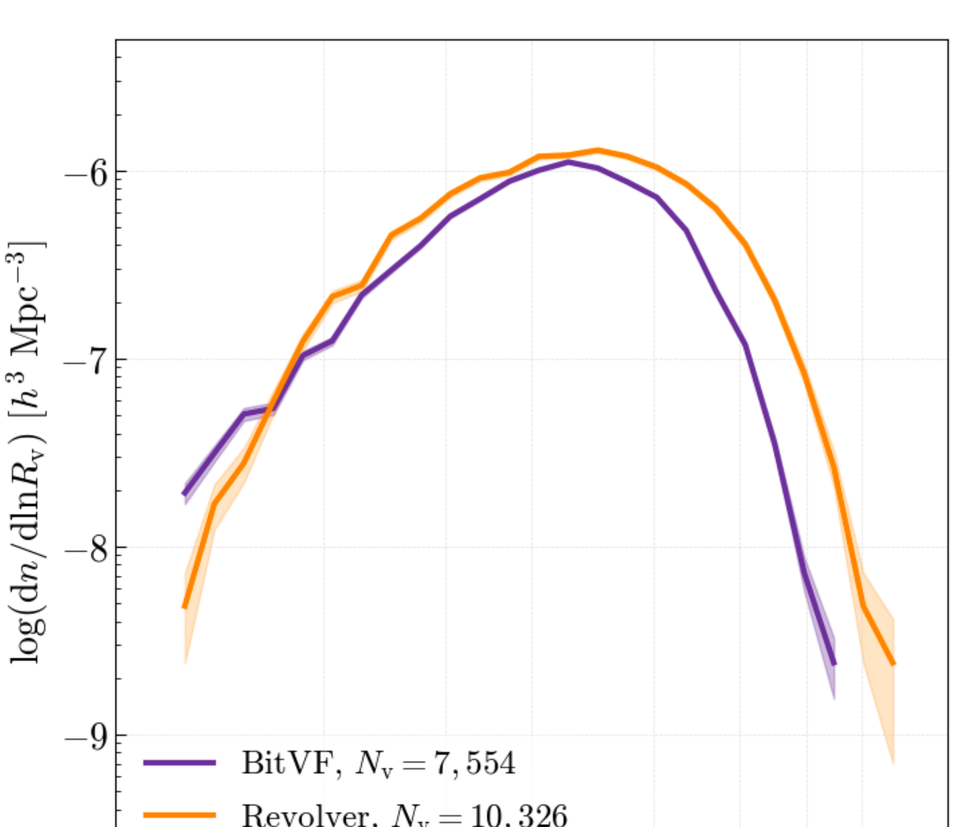
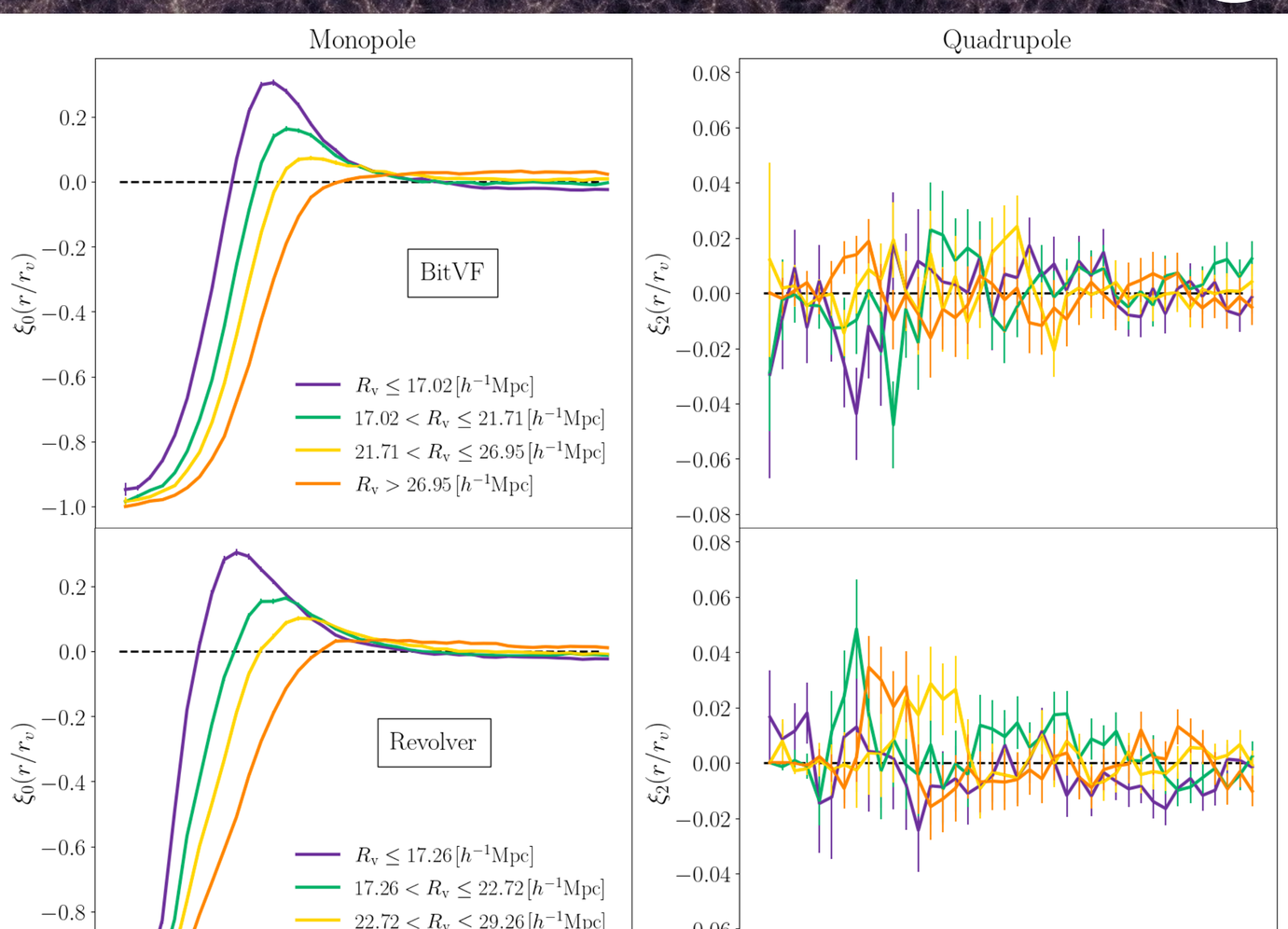




SIMPLE BOX APPLICATION: STABILITY TEST

Evaluation of model-like VSF (Excursion-set based)

Assumption of initial gaussianity

Filtered density field at scale $S = \sigma^2(M) = \sigma^2(R)$

Perturbations described by Brownian random walks in $\delta - S$ space

Halo formation given by random walk crossing of the linear barrier $\delta_c = 1.686$

Cloud-in-cloud problem

→

HALO MASS FUNCTION

(e.g Bond 1991, Sheth & Tormen 1999)

→

Size instead of mass

Second linear barrier: $\delta_v = -2.7$

Conversion to eulerian space

Void-in-cloud, cloud-in-void, void-in-void structures added!

→

VOID SIZE FUNCTION

(e.g , Sheth & van de Weygaert 2004, Jennings et al. 2013, Verza et al. 2024)

SIMPLE BOX APPLICATION: STABILITY TEST

VOID SIZE FUNCTION

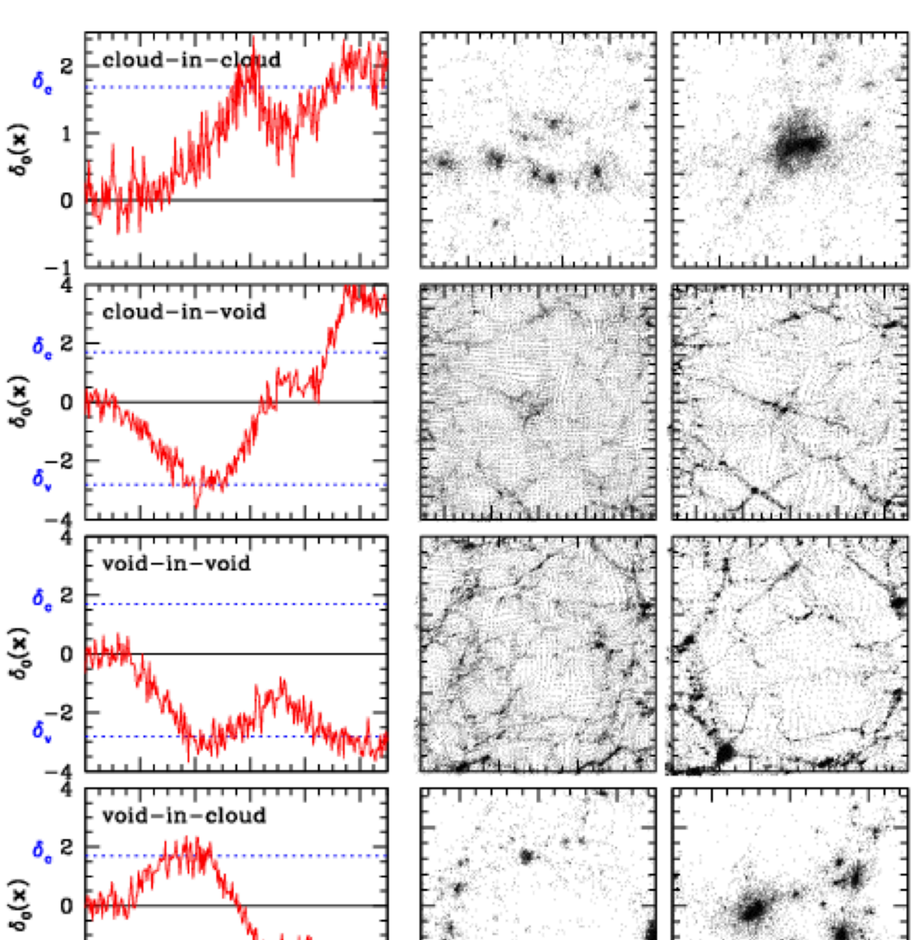
~~Filtered density field~~

Void formation barrier

Overlap criteria

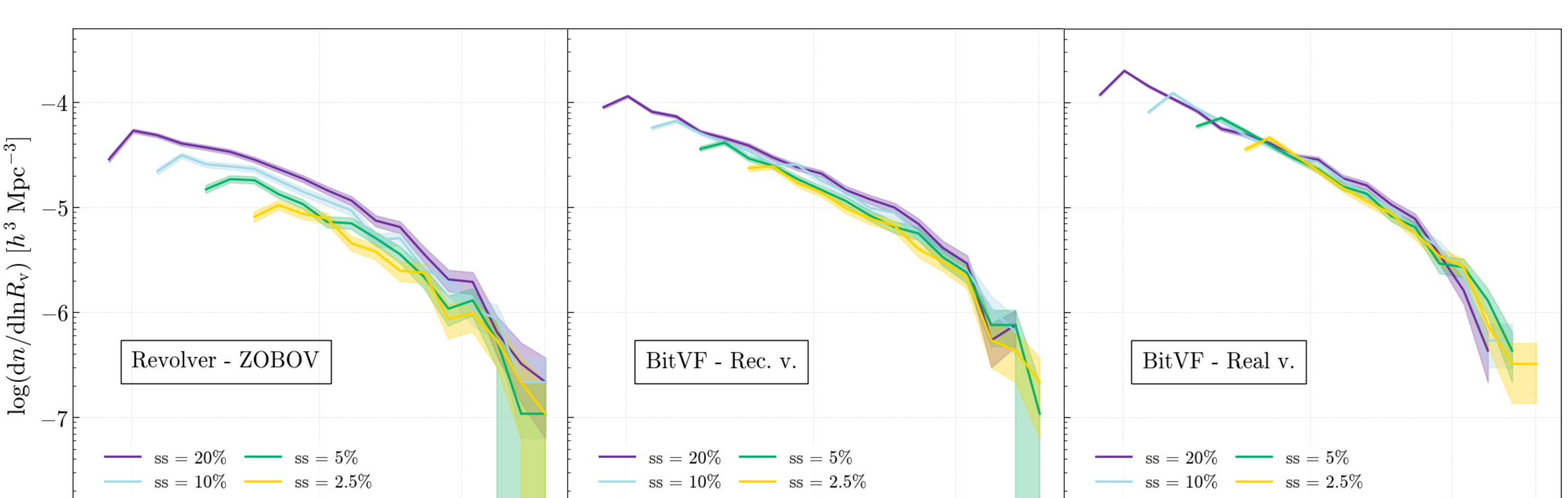
Void-in-void

~~Void-in-cloud~~



Credits: Sheth & van de Weygaert 2004

SIMPLE BOX APPLICATION: STABILITY TEST



LIGHT-CONE APPLICATION

BUZZARD Mocks (DeRose et al. 2019)

DESI-like mock

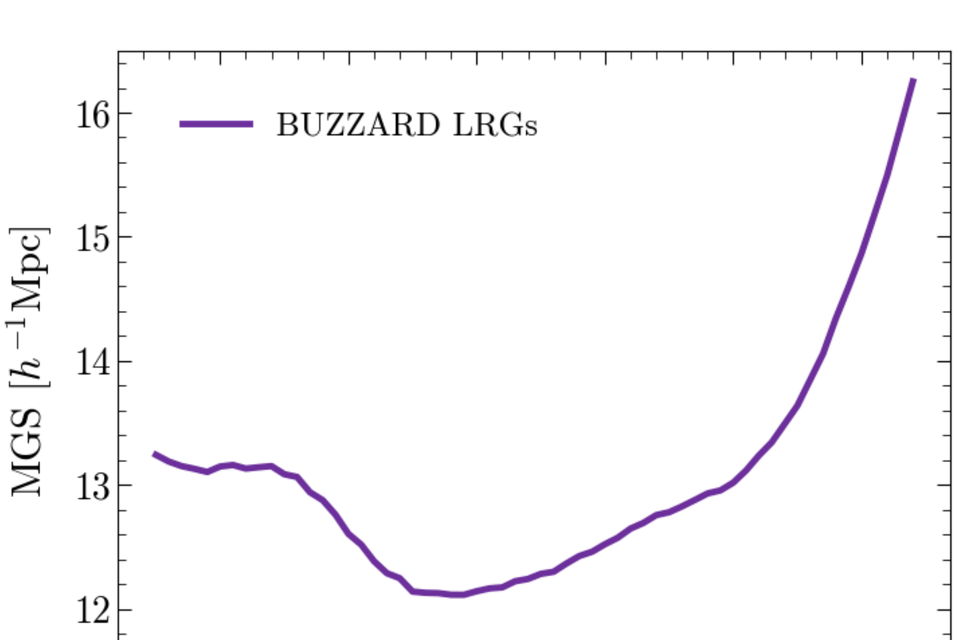
Full LRG sample, $0.25 < z < 1.15$

$\sim 6.1 \times 10^6$ galaxies

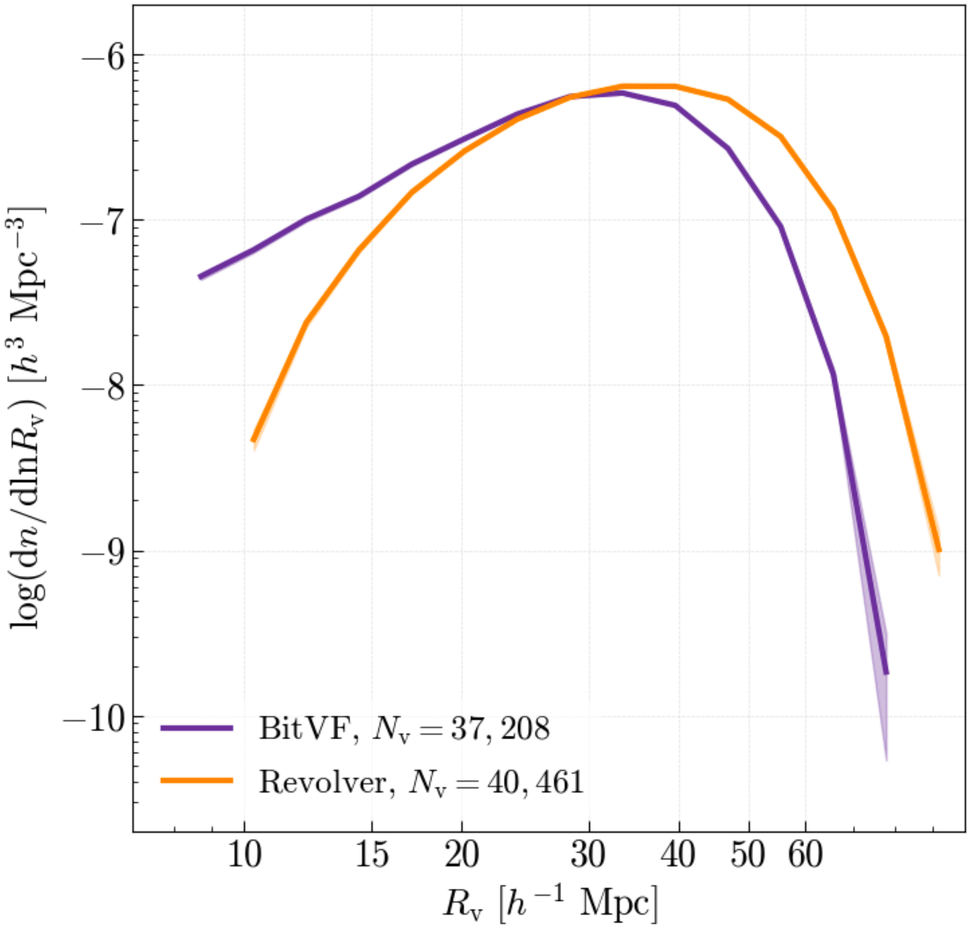
Analysis performed at $0.35 < z < 0.95$

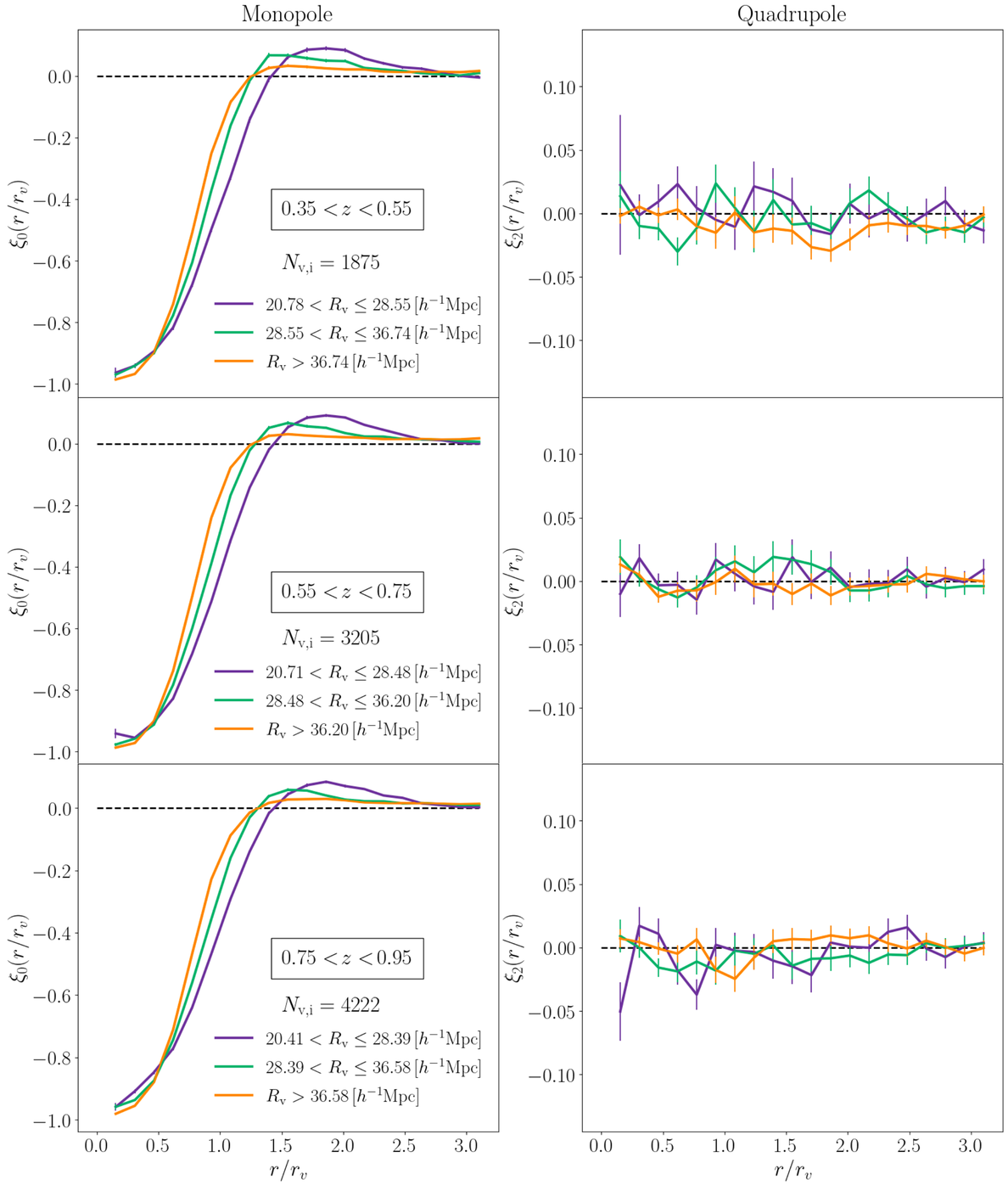
One quarter of the sky

Real-, redshift-,reconstructed-space



LIGHT-CONE APPLICATION: REAL SPACE





LIGHT-CONE APPLICATION: REDSHIFT-SPACE

Voids elongated: RSD

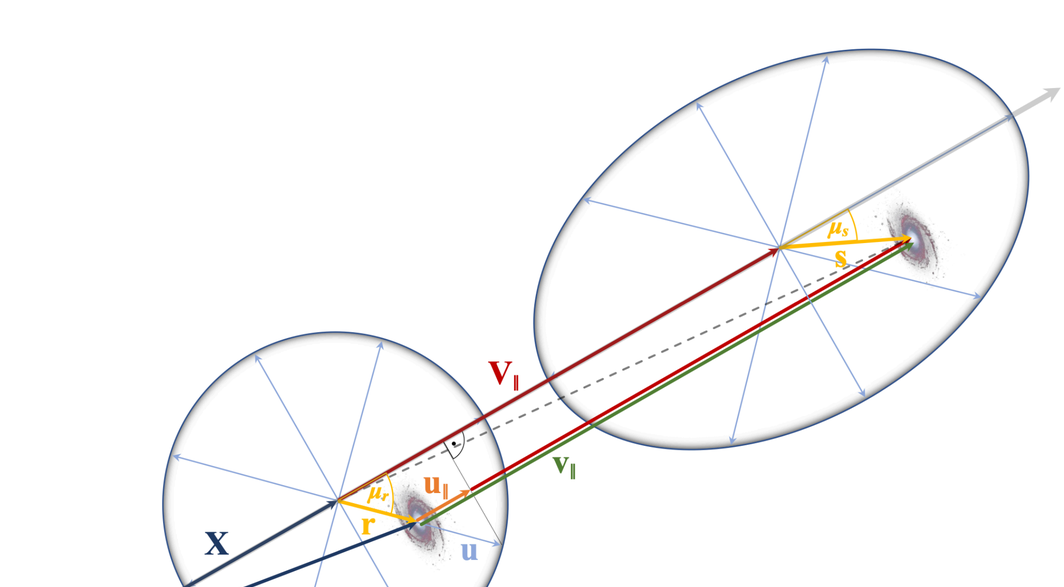
Change in radius

Lost of small voids

Big voids break down in smaller structures

Shifting of the center

Selection effect



Credits: Hamaus et al. 2020

LIGHT-CONE APPLICATION: REDSHIFT-SPACE

Voids elongated: RSD

Change in radius

Lost of small voids

Big voids break down in smaller structures

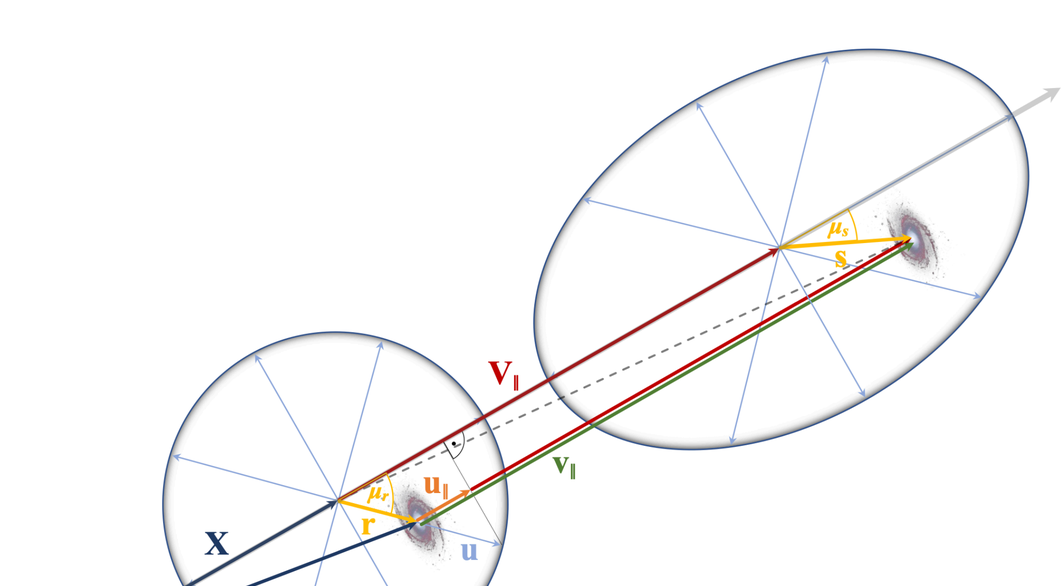
Shifting of the center

Selection effect

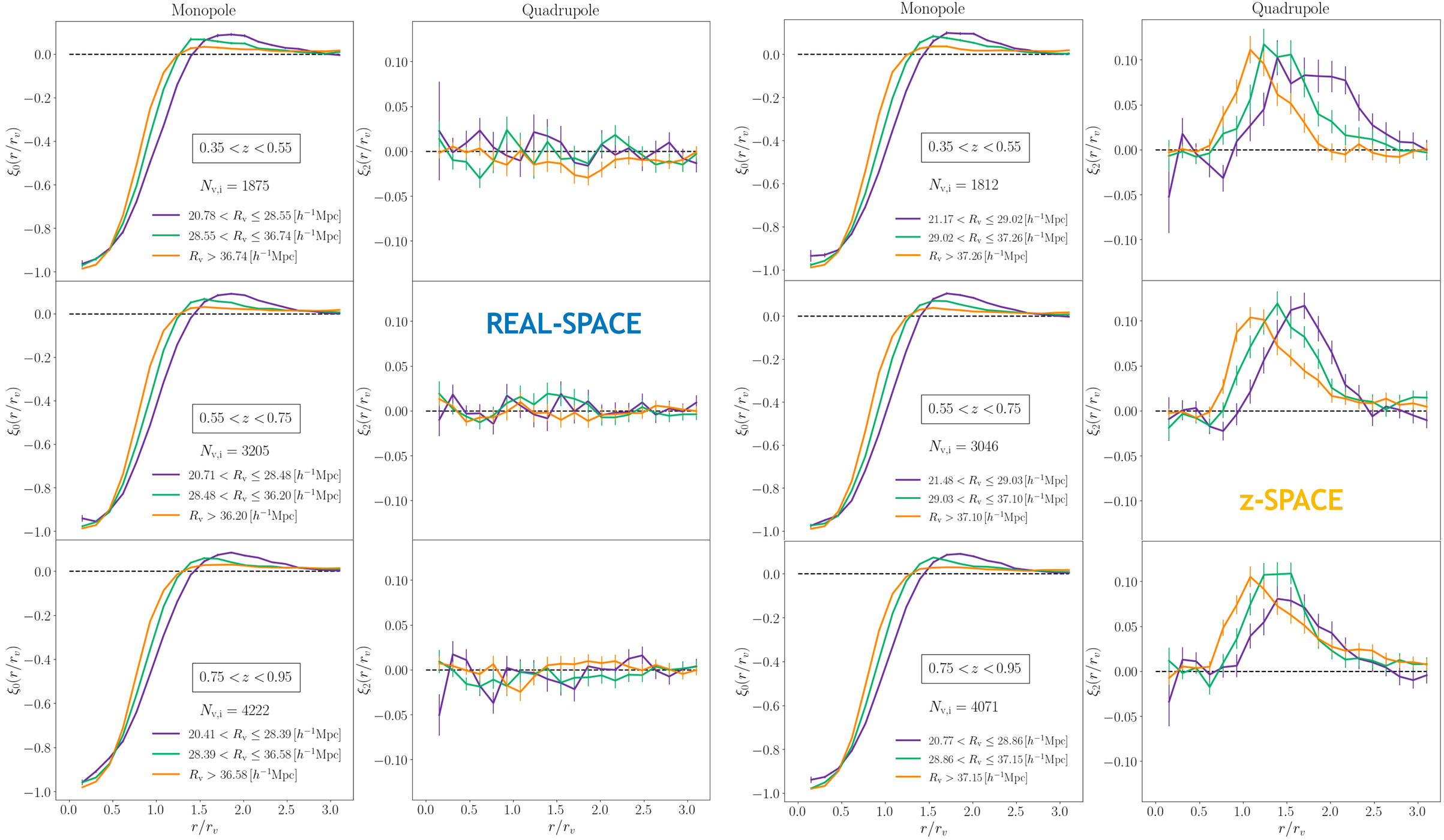
If the method works…

Small impact on the void number

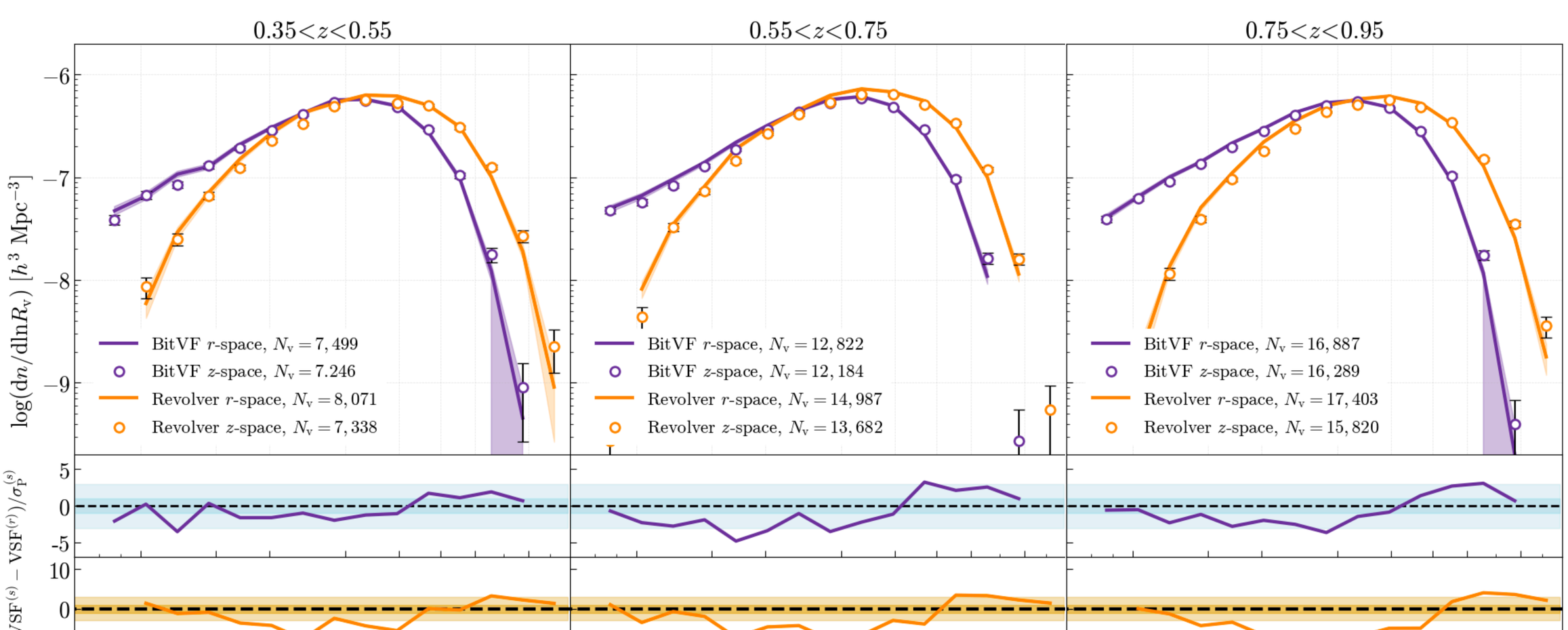
Similar VSF between real- and z-space



Credits: Hamaus et al. 2020


Monopole
Quadrupole
Monopole
Quadrupole
$0.35 < z < 0.55$
$N_{\rm v,i} = 1875$
$20.78 < R_{\rm v} \leq 28.55\,[h^{-1}{\rm Mpc}]$
$28.55 < R_{\rm v} \leq 36.74\,[h^{-1}{\rm Mpc}]$
$R_{\rm v} > 36.74\,[h^{-1}{\rm Mpc}]$
$0.35 < z < 0.55$
$N_{\rm v,i} = 1812$
$21.17 < R_{\rm v} \leq 29.02\,[h^{-1}{\rm Mpc}]$
$29.02 < R_{\rm v} \leq 37.26\,[h^{-1}{\rm Mpc}]$
$R_{\rm v} > 37.26\,[h^{-1}{\rm Mpc}]$
REAL-SPACE
z-SPACE
$0.55 < z < 0.75$
$N_{\rm v,i} = 3205$
$20.71 < R_{\rm v} \leq 28.48\,[h^{-1}{\rm Mpc}]$
$28.48 < R_{\rm v} \leq 36.20\,[h^{-1}{\rm Mpc}]$
$R_{\rm v} > 36.20\,[h^{-1}{\rm Mpc}]$
$0.55 < z < 0.75$
$N_{\rm v,i} = 3046$
$21.48 < R_{\rm v} \leq 29.03\,[h^{-1}{\rm Mpc}]$
$29.03 < R_{\rm v} \leq 37.10\,[h^{-1}{\rm Mpc}]$
$R_{\rm v} > 37.10\,[h^{-1}{\rm Mpc}]$
$0.75 < z < 0.95$
$N_{\rm v,i} = 4222$
$20.41 < R_{\rm v} \leq 28.39\,[h^{-1}{\rm Mpc}]$
$28.39 < R_{\rm v} \leq 36.58\,[h^{-1}{\rm Mpc}]$
$R_{\rm v} > 36.58\,[h^{-1}{\rm Mpc}]$
$0.75 < z < 0.95$
$N_{\rm v,i} = 4071$
$20.77 < R_{\rm v} \leq 28.86\,[h^{-1}{\rm Mpc}]$
$28.86 < R_{\rm v} \leq 37.15\,[h^{-1}{\rm Mpc}]$
$R_{\rm v} > 37.15\,[h^{-1}{\rm Mpc}]$
$\xi_0(r/r_v)$
$\xi_2(r/r_v)$
r/r_v

LIGHT-CONE APPLICATION: REDSHIFT-SPACE



LIGHT-CONE APPLICATION: RECONSTRUCTED-SPACE

Back-in-time!

$$\vec{r} = \vec{s} + \frac{f(z)}{(b(z) + f(z))} \Psi^{\parallel}_{\mathrm{BT}}$$

Correction to Nusser&Davis 1994 (Biased displacement)

Done in 2 steps (for now)

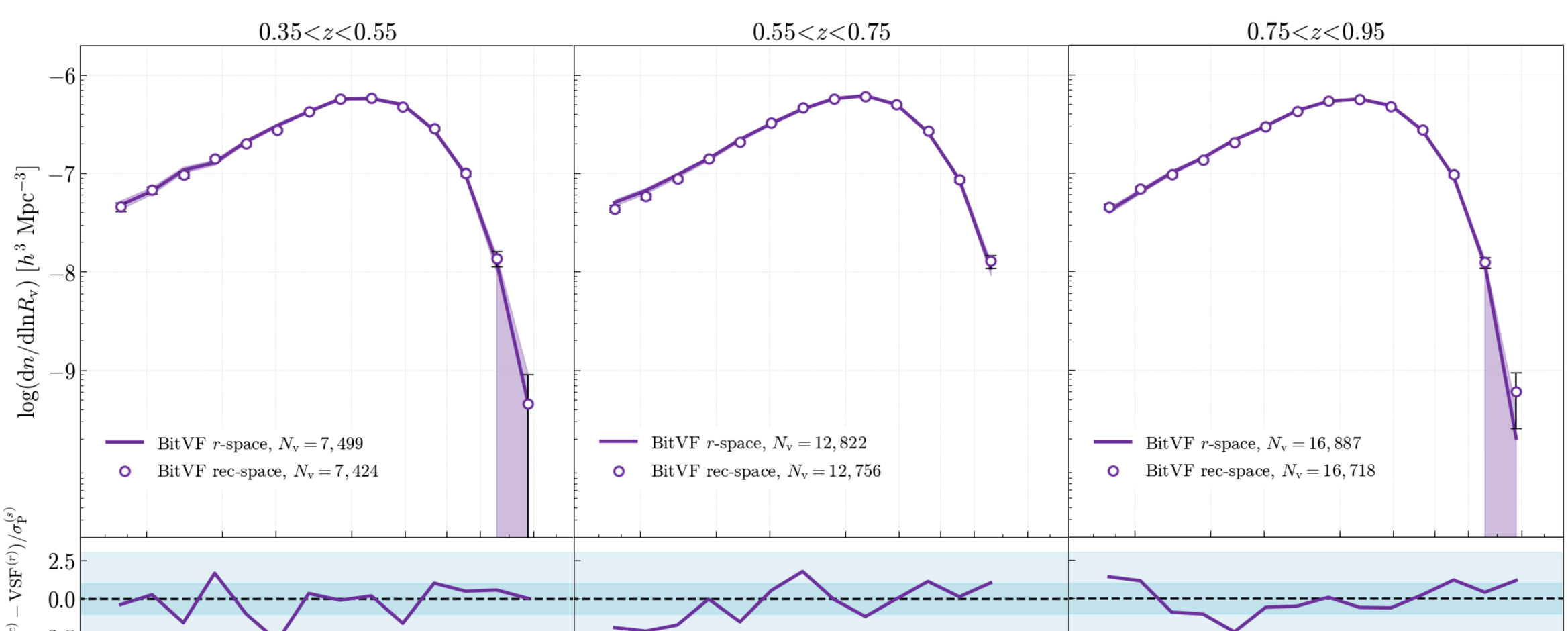
Goal: recovering of real-space

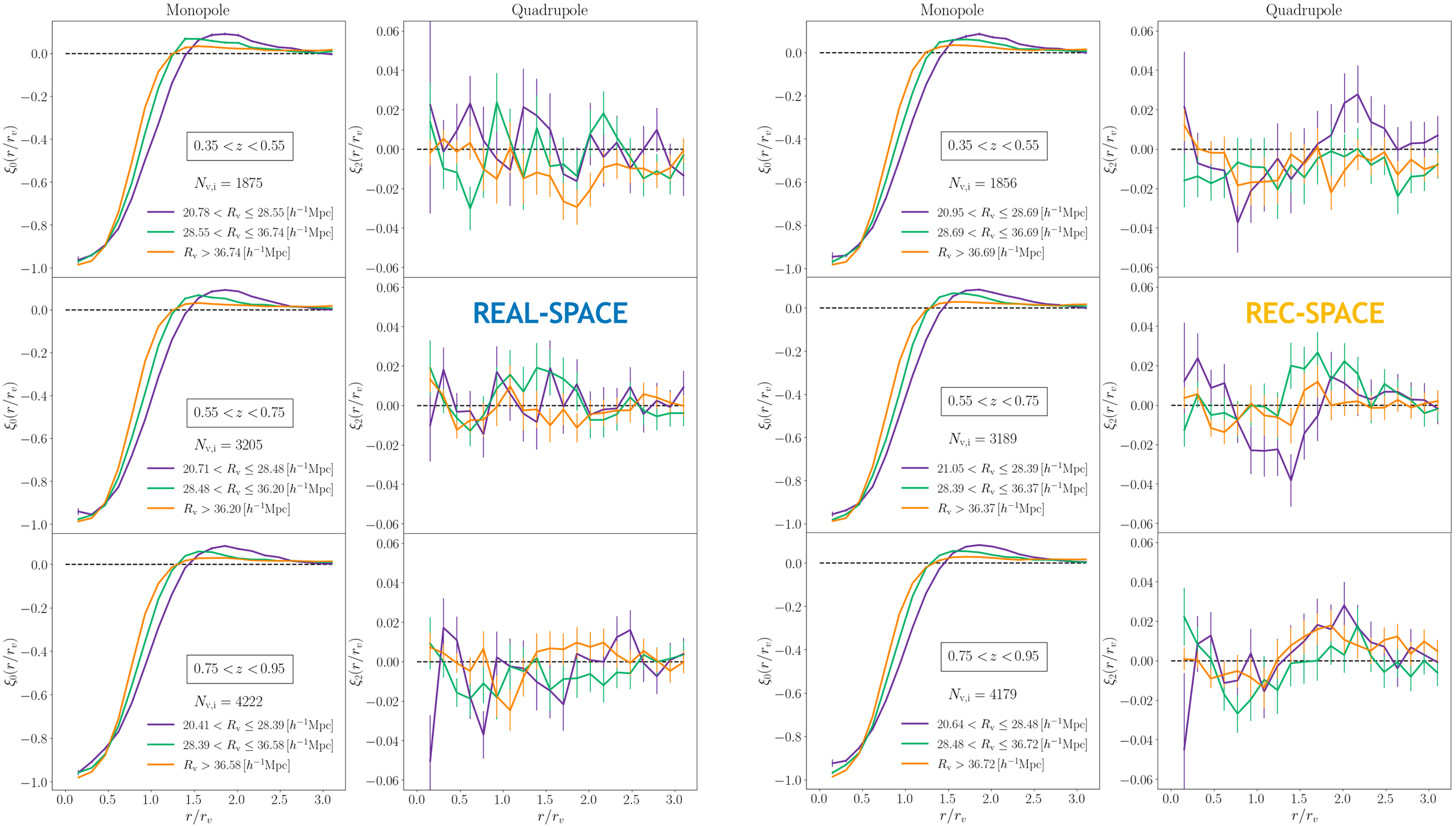
Strong indicator: zero VGCF quadrupole

Very preliminary results

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE CPPM

LIGHT-CONE APPLICATION: RECONSTRUCTED-SPACE




Monopole
Quadrupole
Monopole
Quadrupole
$0.35 < z < 0.55$
$N_{\rm v,i} = 1875$
$20.78 < R_{\rm v} \leq 28.55\,[h^{-1}{\rm Mpc}]$
$28.55 < R_{\rm v} \leq 36.74\,[h^{-1}{\rm Mpc}]$
$R_{\rm v} > 36.74\,[h^{-1}{\rm Mpc}]$
$0.35 < z < 0.55$
$N_{\rm v,i} = 1856$
$20.95 < R_{\rm v} \leq 28.69\,[h^{-1}{\rm Mpc}]$
$28.69 < R_{\rm v} \leq 36.69\,[h^{-1}{\rm Mpc}]$
$R_{\rm v} > 36.69\,[h^{-1}{\rm Mpc}]$
REAL-SPACE
REC-SPACE
$0.55 < z < 0.75$
$N_{\rm v,i} = 3205$
$20.71 < R_{\rm v} \leq 28.48\,[h^{-1}{\rm Mpc}]$
$28.48 < R_{\rm v} \leq 36.20\,[h^{-1}{\rm Mpc}]$
$R_{\rm v} > 36.20\,[h^{-1}{\rm Mpc}]$
$0.55 < z < 0.75$
$N_{\rm v,i} = 3189$
$21.05 < R_{\rm v} \leq 28.39\,[h^{-1}{\rm Mpc}]$
$28.39 < R_{\rm v} \leq 36.37\,[h^{-1}{\rm Mpc}]$
$R_{\rm v} > 36.37\,[h^{-1}{\rm Mpc}]$
$0.75 < z < 0.95$
$N_{\rm v,i} = 4222$
$20.41 < R_{\rm v} \leq 28.39\,[h^{-1}{\rm Mpc}]$
$28.39 < R_{\rm v} \leq 36.58\,[h^{-1}{\rm Mpc}]$
$R_{\rm v} > 36.58\,[h^{-1}{\rm Mpc}]$
$0.75 < z < 0.95$
$N_{\rm v,i} = 4179$
$20.64 < R_{\rm v} \leq 28.48\,[h^{-1}{\rm Mpc}]$
$28.48 < R_{\rm v} \leq 36.72\,[h^{-1}{\rm Mpc}]$
$R_{\rm v} > 36.72\,[h^{-1}{\rm Mpc}]$
$\xi_0(r/r_v)$
$\xi_2(r/r_v)$
r/r_v

SUMMARY

BitVF: New dynamical method for cosmic void identification

New fast (and simple) OT algorithm

Validated on boxes against Revolver

RSD impact on LRG-voids mitigated by a factor of 2

Successful real-space reconstruction

To do:

Play with different configurations

Application at scenarios with complex selection function (Antonio catalogs!) and footprints

Application to real data

Out soon in GitHub and as part of the CosmoBolognaLib (Marulli et al. 2016)

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE CPPM