Cosmic voids as cosmological laboratories

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2021 ICTP-SAIFR Prize in Classical Gravity and Applications

CONICET
UNC Universidad Nacional de Córdoba
IATE
OAC Observatorio Astronómico de Córdoba

Workshop on Classical Gravity and Applications
August 29th - 31st 2022

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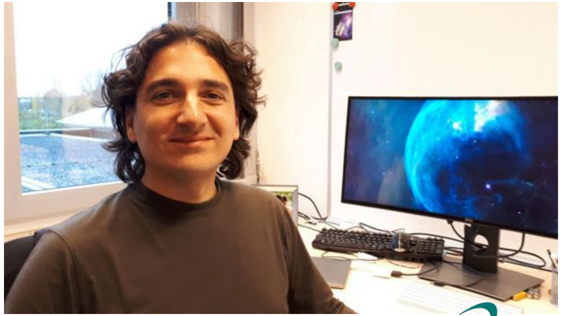

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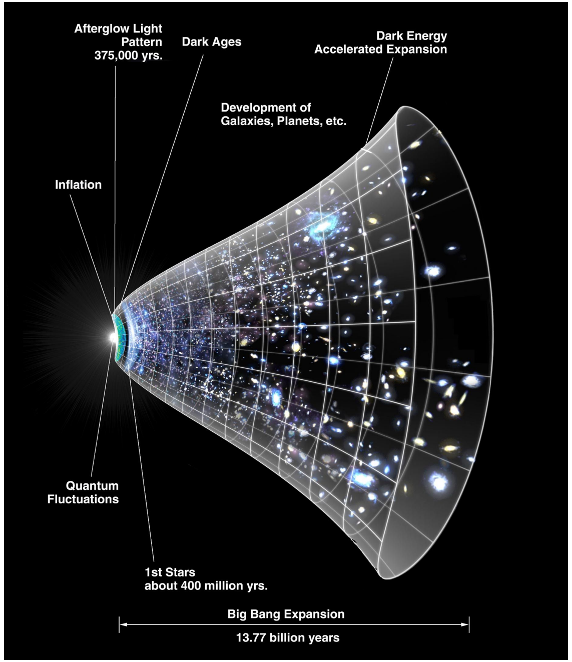
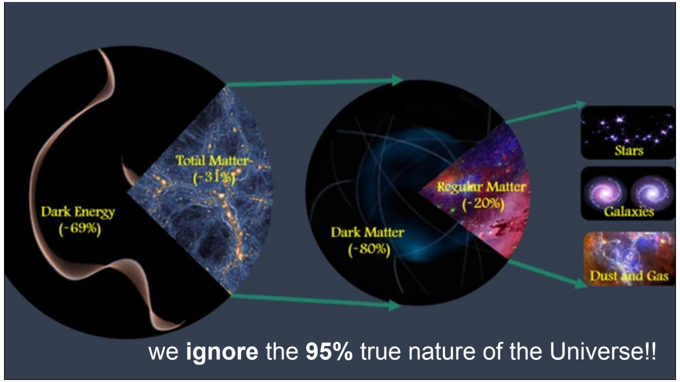
Introduction & goals

Dark-energy problem

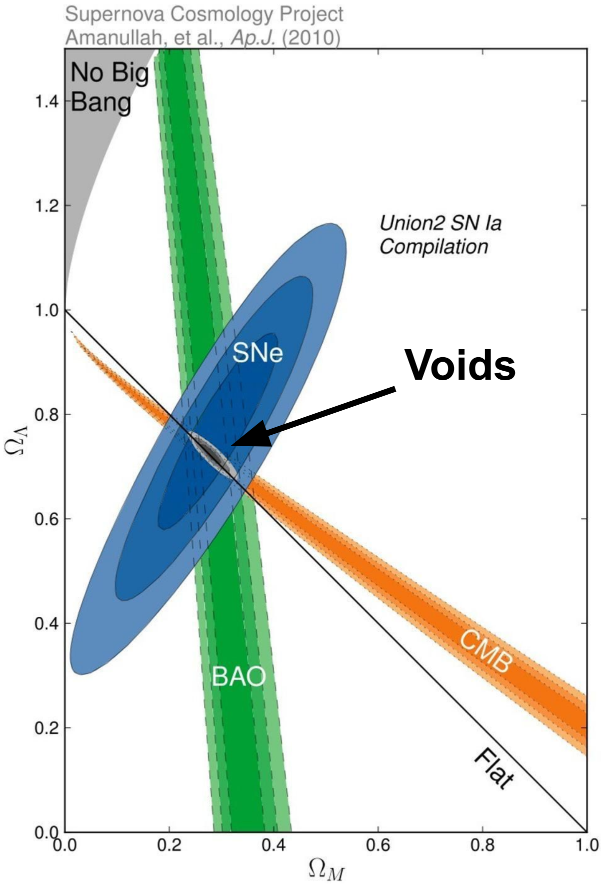
- Era of **high-precision Cosmology**
- The Universe is not only **expanding**, but it is also **accelerating**
- The standard model postulates a **flat-ΛCDM** Universe
- Cosmic acceleration is explained by a new component: **dark energy**
- **Cosmological constant** in Einstein equations?
- Review **General Relativity**?
- **Dominant** component: 70% energy budget
- One of the **major challenges** of modern Cosmology





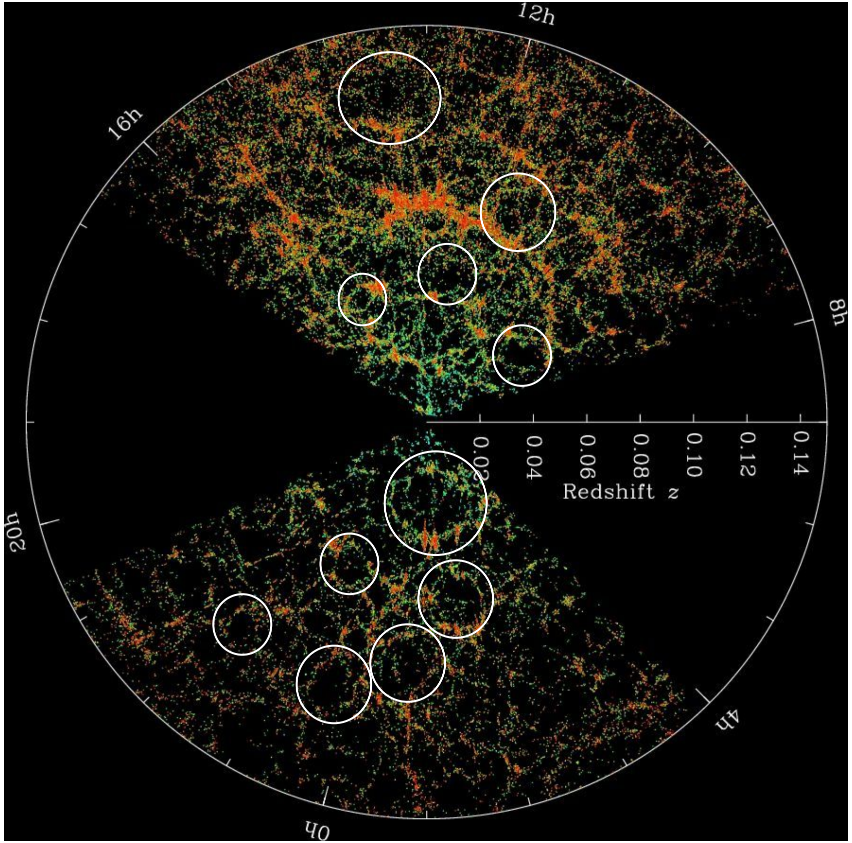
Dark-energy experiments

- ➢ Hubble diagram using distant **SNe Ia** as standard candles
- ➢ The study of **CMB anisotropies**
- ➢ **BAO scale** as a standard ruler
- ➢ **Cosmic voids**
  - ○ Standard ruler (stacking shape, spherical)
  - ○ Lensing
  - ○ **Abundance of voids** (size function)
  - ○ **Void-galaxy cross-correlations**



What are cosmic voids?

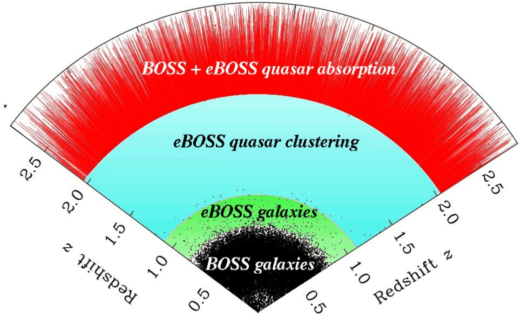
- Galaxies trace the **large-scale structure** of the Universe through the process of **gravitational instability**
- They form groups, clusters, filaments and walls
- Complementarily, they leave on their way vast underdense regions: **cosmic voids**
- Their statistical properties depend on:
  - **tracers** (galaxies, DM-haloes, DM-particles)
  - **void finder** (watershed, **spherical**)
- Consensus on basic properties:
  - **density**: 10-20% of the mean
  - **sizes**: tens of Mpc



https://www.sdss.org/science/

Cosmological relevance

- **Largest observable structures:** they encode key information about the **geometry** and **expansion history** of the Universe
- (Quasi) **linear dynamics:** simple theoretical description
- Ideal for testing **Modified Gravity** theories: unscreened environments
- **Modern spectroscopic surveys** (BOSS, eBOSS, DESI, HETDEX, Euclid)**:** rich sample of voids

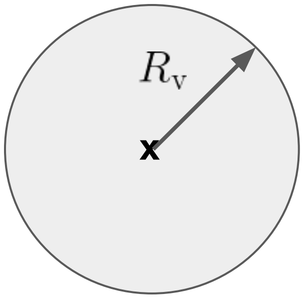


Cosmic voids

Spherical void finder

Padilla et al. 2005; Ruiz et al. 2015

Bases: integrated density contrast of underdense regions, assuming **spherical symmetry** with respect to underdense locations of space

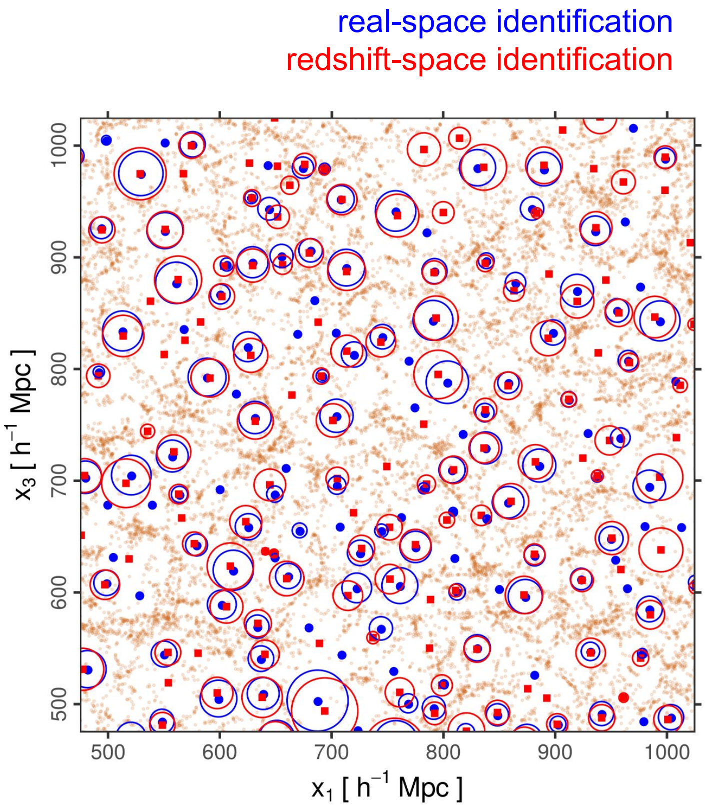


Steps:

1. Voronoi tessellation
2. Selection of candidates
3. Growth of spheres
4. Random walk
5. Overlap filtering

Catalogue of voids

- **Underdense spheres**
- **Non-overlapping**
- **Well defined radius and centre** $\Delta(R_v) = -0.9$
- **Isotropic outflow**

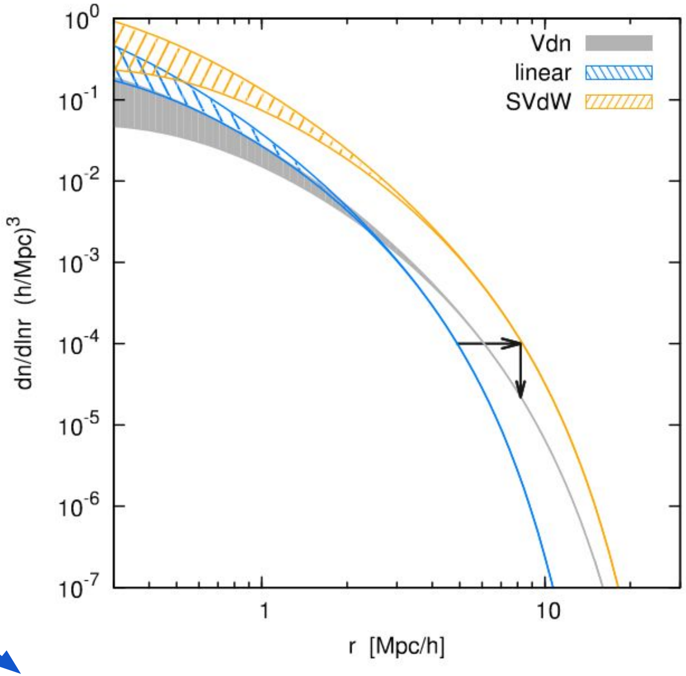


Correa et al. 2021
Millennium XXL simulation (Angulo et al. 2012)

Void size function (VSF)

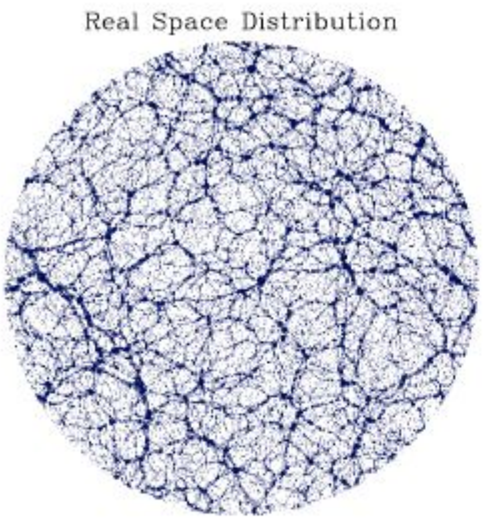
- **Void size function:** comoving number density of voids as a function of their size
- Characterises the **abundance** of voids
- Analogous to the DM halo mass function
- **Excursion set** theory + **spherical evolution** (expansion + collapse)
- Models:
  - **Linear** (Sheth & van de Weygaert 2004)
  - **SvdW** (Sheth & van de Weygaert 2004)
  - **Vdn** (Jennings et al. 2013)

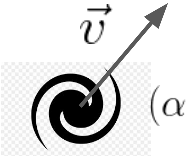
cosmological information!



Jennings et al. 2013

Distortions: RSD & AP effects

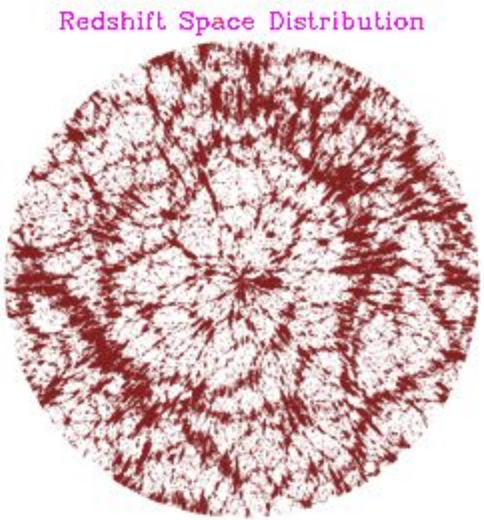




$\vec{v}$ (α, δ, z)

Figure credit: Brian C. Thomas

RSD (Kaiser 1987)



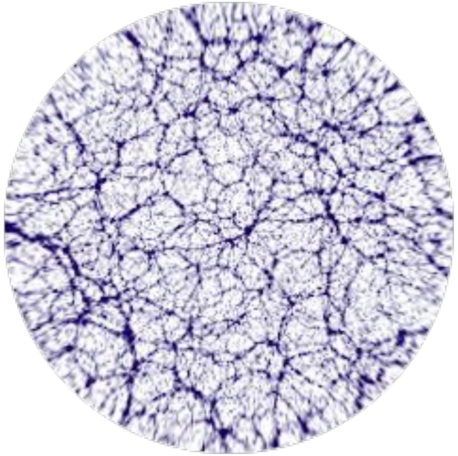
dynamical effect

$$1 + z_{\rm obs} = (1 + z_{\rm cos})(1 + z_{\rm pec})$$

$$s = r + v_{\parallel}\frac{(1+z)}{H(z)}$$

AP (Alcock & Paczyński 1979)

Fiducial space distribution



geometrical effect

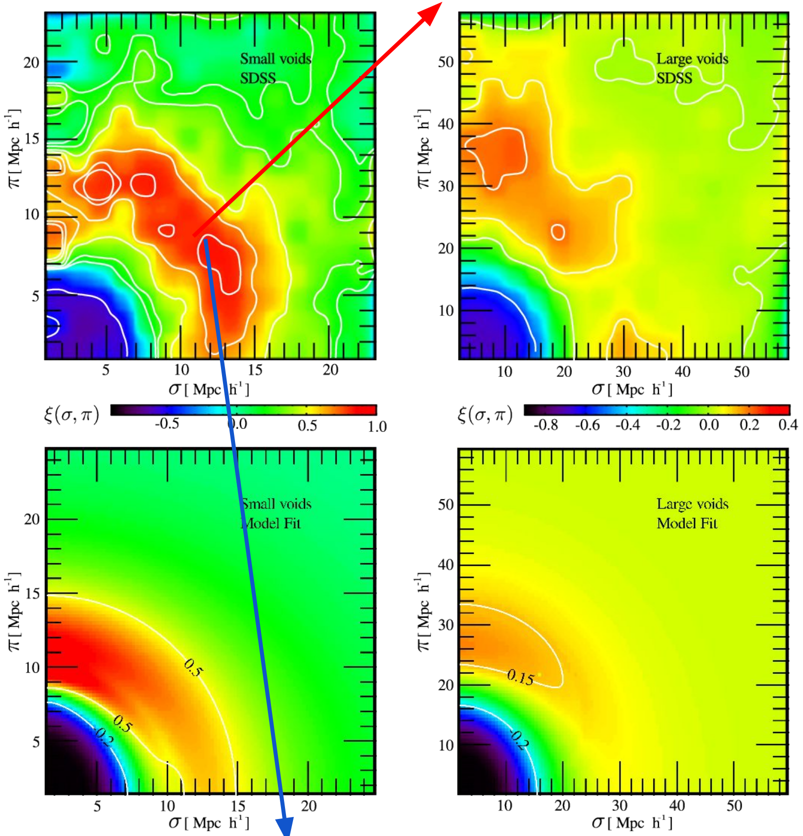
$$D_{\rm M}(z), H(z)\ [\Omega_m, \Omega_\Lambda, h]$$

$$(x_1, x_2, x_3)\ [h^{-1}{\rm Mpc}]$$

Void-galaxy cross-correlation function

- **Void-galaxy correlation function:** excess probability of finding void-galaxy pairs with respect to a homogeneous distribution
- Characterises the **density-fluctuation field** around voids
- **Real space:** 1D profile ξ(r), **spherical symmetry**
- **Redshift-space:** 2D map ξ(σ,π), **cylindrical symmetry**
- Modelling
  - **density profile:** empirical parametric models
  - **velocity profile:** linear perturbation theory
  - **AP:** cosmological scale transformations
  - **RSD:**
    - Linear model (Cai et al. 2016)
    - Gaussian streaming model (Paz et al. 2013)

dynamical information!



cosmological information!

Paz et al. 2013

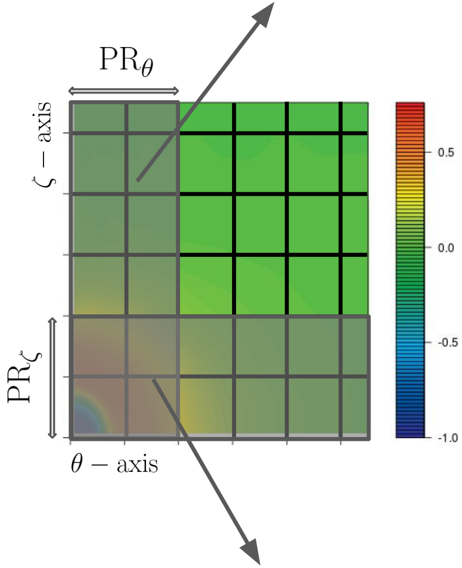
Projected correlations

Correa et al. 2019

Millennium XXL simulation data

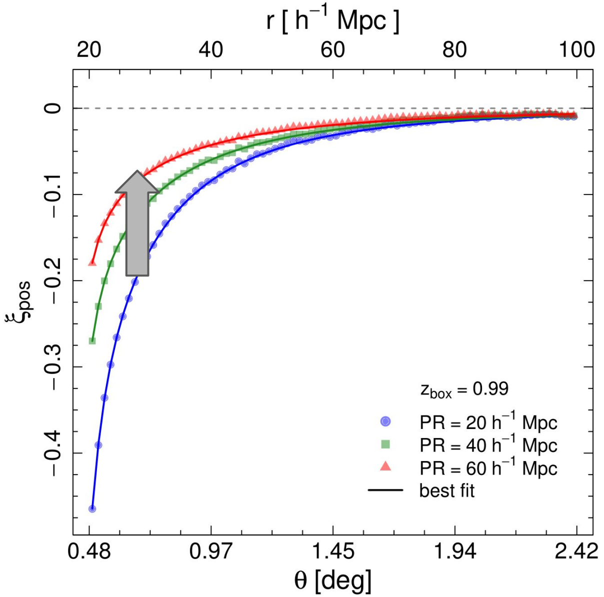
$$\xi(\theta, \zeta) \longrightarrow \xi_{\mathrm{los}}(\zeta)$$

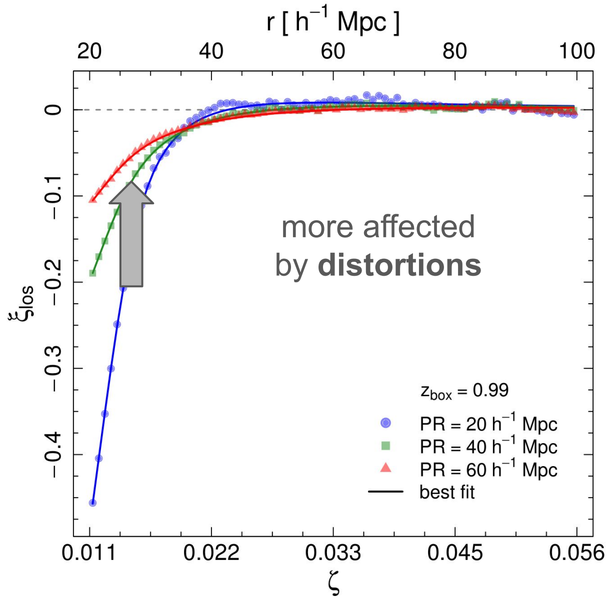
line-of-sight correlation function



plane-of-sky correlation function

$$\xi(\theta, \zeta) \longrightarrow \xi_{\mathrm{pos}}(\theta)$$





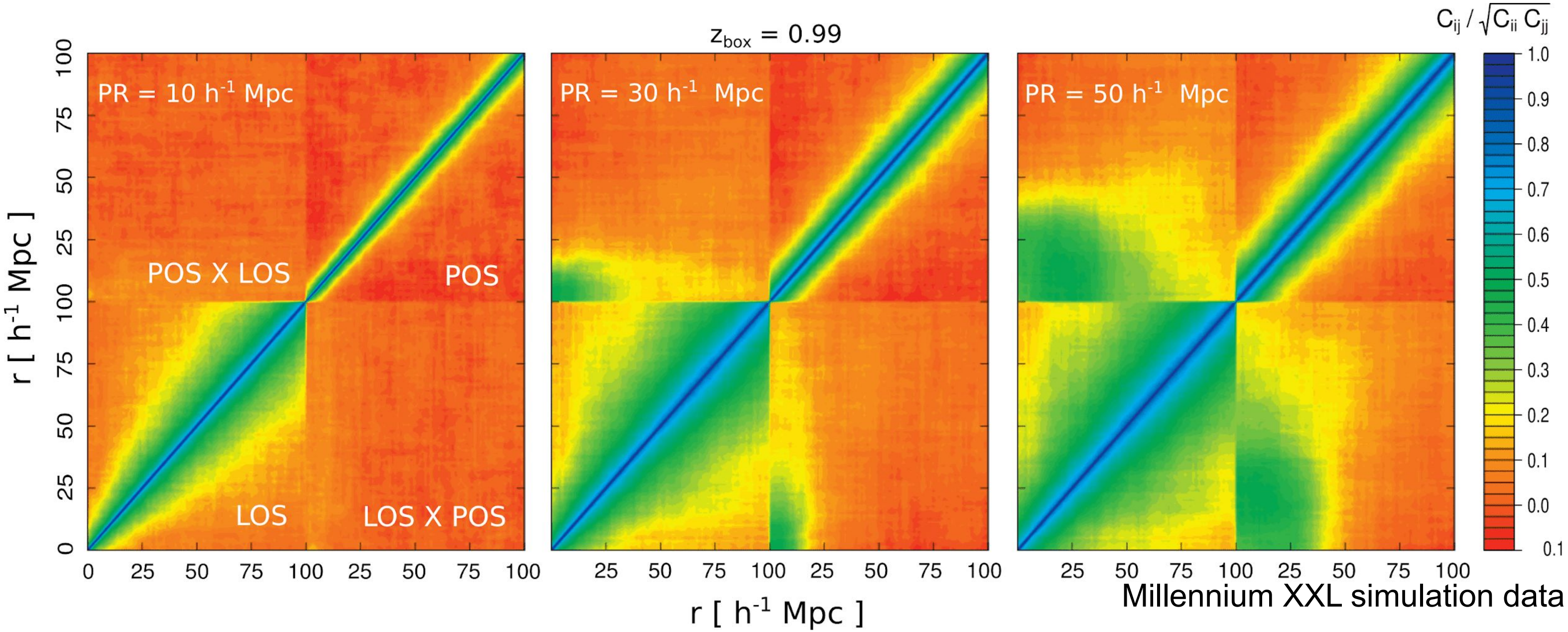
★ **Fiducial-free test**: correlations are directly measured in terms of void-centric **angles** and **redshifts** without assuming a distance scale

★ The combination of working on **observable space** and considering two **perpendicular projections** allows us to effectively **break** any possible **degeneracy** between the parameters due to **RSD** and **AP**

Projected correlations: covariance

Correa et al. 2019

$$\xi[m \times m] \longrightarrow C[m^2 \times m^2]$$
$$\xi[2m] \longrightarrow C[m \times m]$$

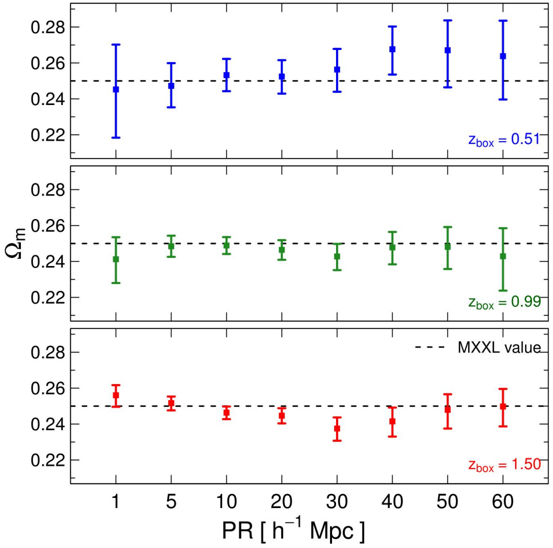


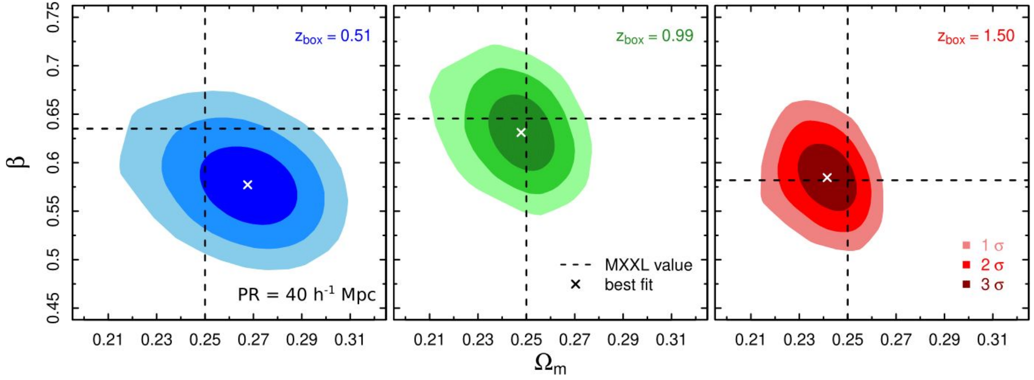
Millennium XXL simulation data

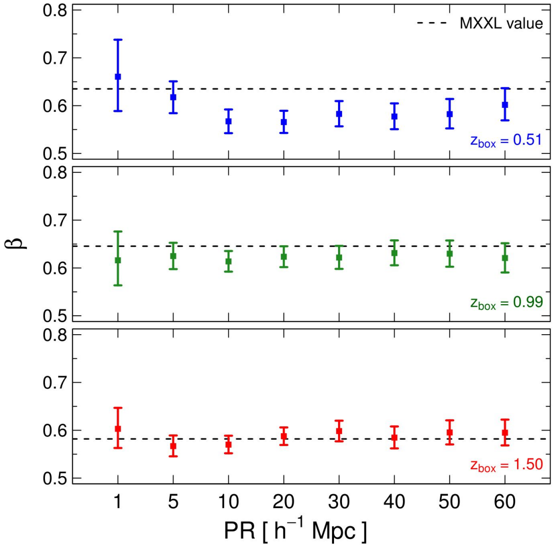
- Notably reduced **dimension**
- **Inversion** numerically more stable
- Propagation of **errors** substantially reduced
- Less **number of mocks** needed

Projected correlations: performance

Correa et al. 2019





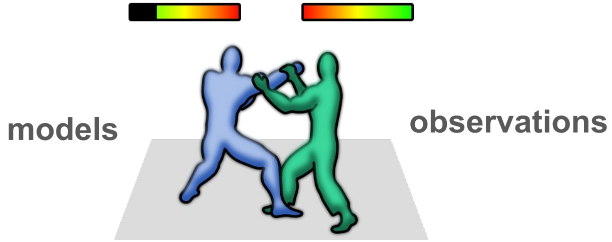


Millennium XXL simulation data

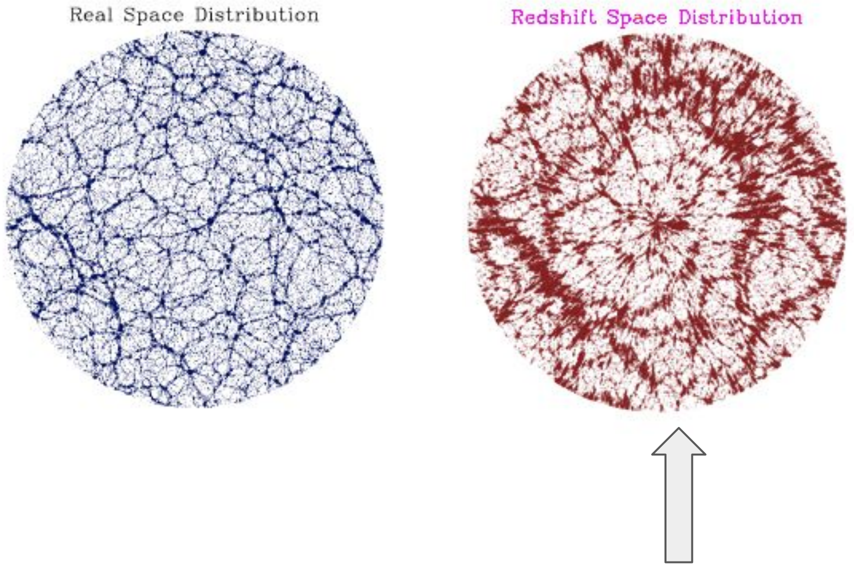
Redshift-space effects in voids

- **arXiv [2007.12064]** Redshift-space effects in voids and their impact on cosmological tests. Part I: the void size function
- **arXiv [2107.01314]** Redshift-space effects in voids and their impact on cosmological tests. Part II: the void-galaxy cross-correlation function
- **arXiv [2205.13604]** Cosmology with cosmic voids

An important drawback

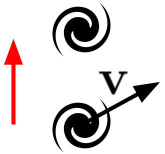


- **Tests fail** with **observational data**: model unable to reproduce the measurements and **biased cosmological constraints**
- **Void community** had the **same problem**
- Our standard picture of distortions around voids is **incomplete**
- **AP + RSD** also affect the previous step: the void identification process, affecting **intrinsic and global void properties**: **number**, **size** and **spatial distribution**
- **Additional distortion patterns** in observations



we identify voids here!!

Our approach to tackle this problem



$$s = r + v_{\parallel}\frac{(1+z)}{H(z)}$$

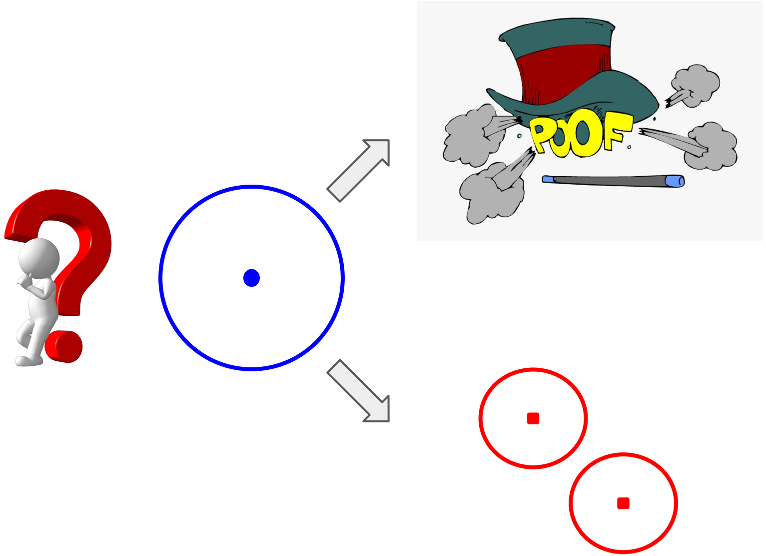
identification in r-space ⟺ **identification in z-space**

physical connection

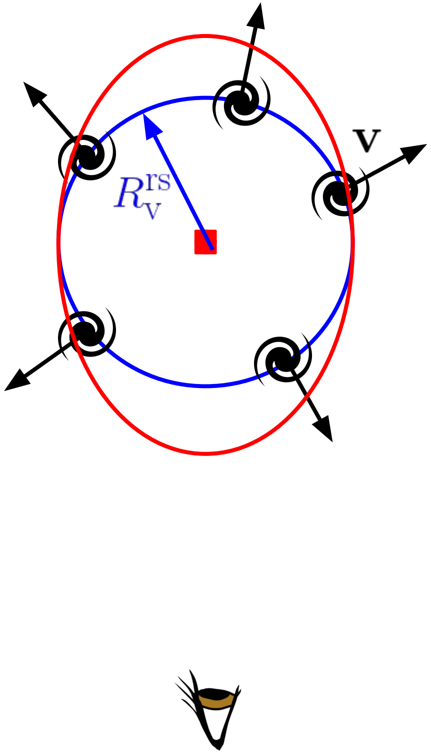
spherical void finder

- ❖ ***Galaxies*** can be considered **particles**
- ❖ They are **conserved**
- ❖ Only their **position** changes

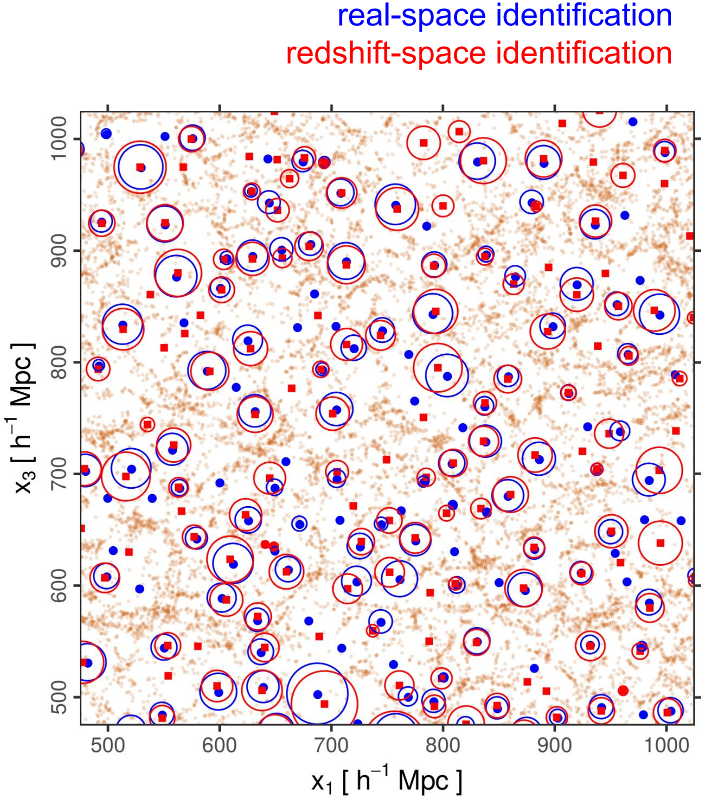
- ➢ ***Voids*** are **extensive** regions
- ➢ Some of them could be **destroyed**
- ➢ Artificial voids could be **created**
- ➢ Are the **same populations**?
- ➢ Different **statistical properties**



Redshift-space effects

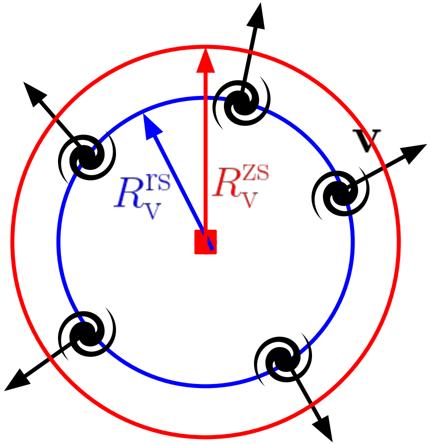


- **1) Void number conservation:** above the shot-noise level
- **2) Expansion (t-RSD):** classical RSD induced by **tracer dynamics**



Millennium XXL simulation data

Redshift-space effects



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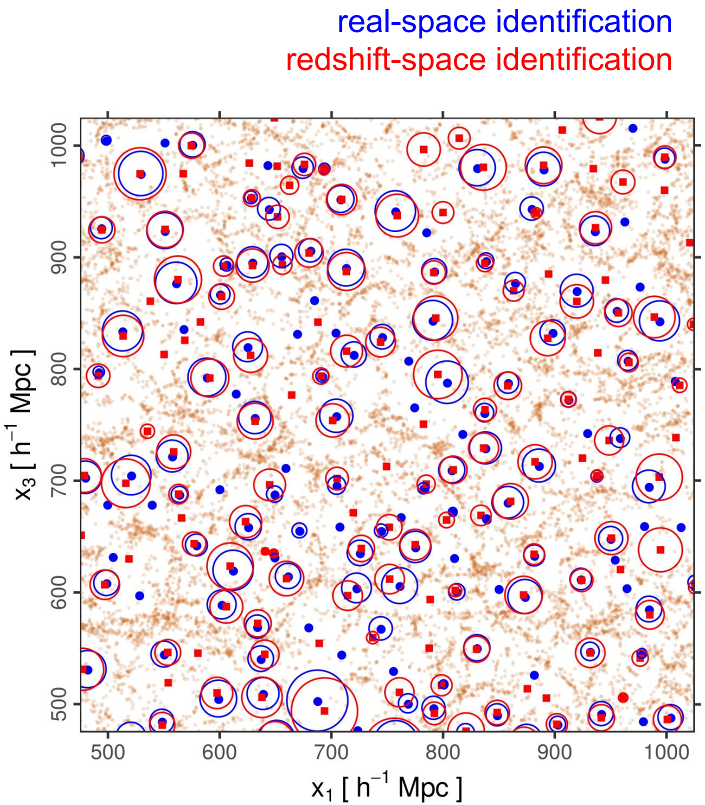

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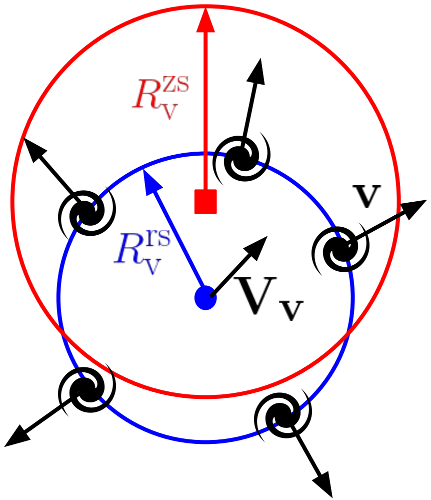
Redshift-space effects



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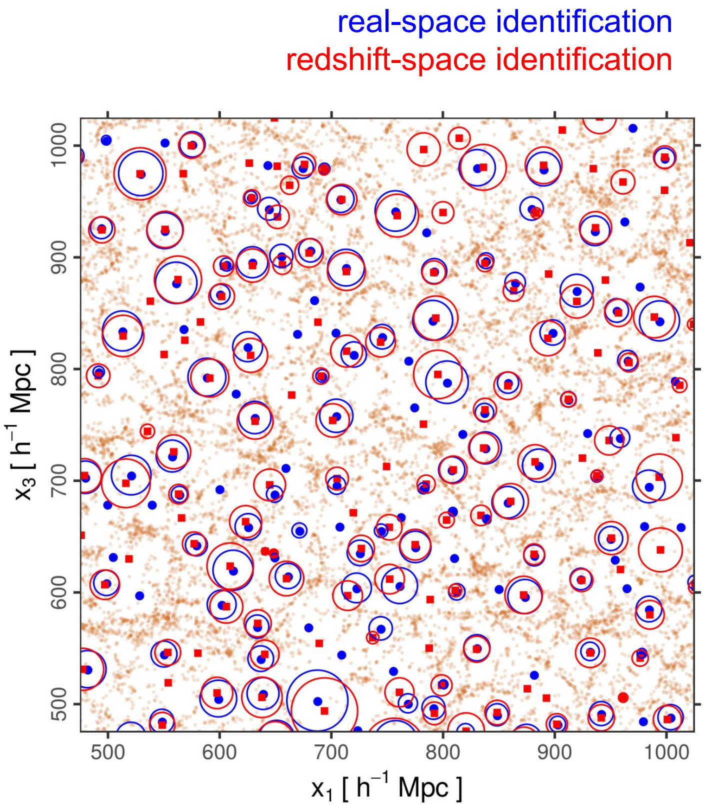

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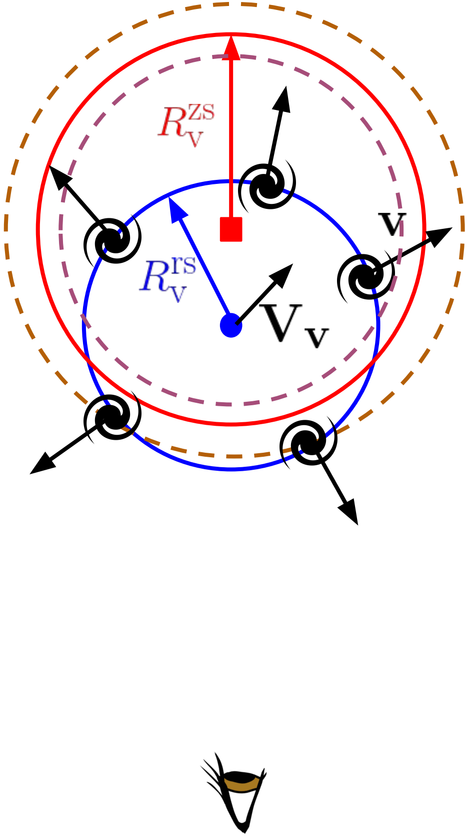

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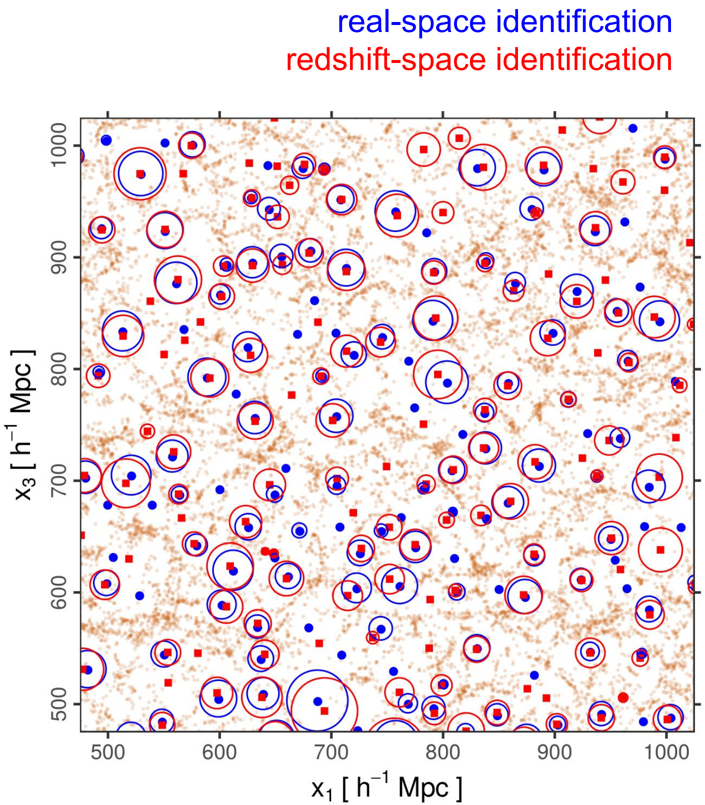
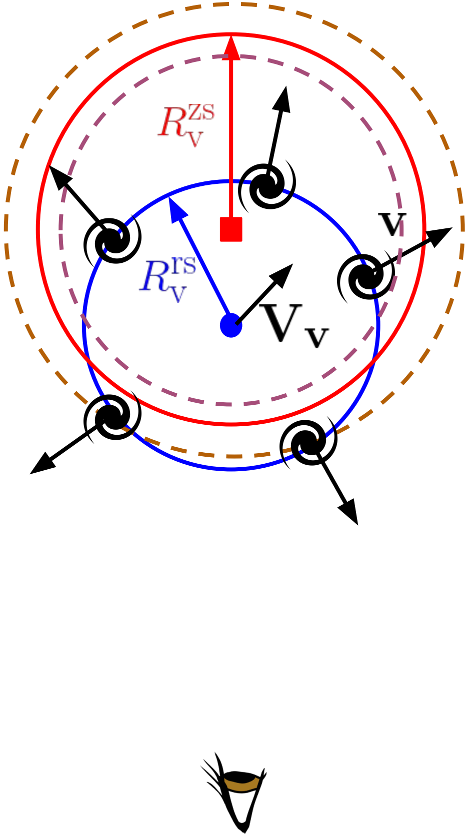
- **4) AP volume effect: fiducial cosmology** (expansion or contraction)
- **5) Independence of the effects**
- **6) Intrinsic ellipticity (e-RSD)**



Millennium XXL simulation data

Redshift-space effects



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$$
\begin{cases}
R_{\mathrm{V}}^{\mathrm{zs}} = q_{\mathrm{AP}}\ q_{\mathrm{RSD}}\ R_{\mathrm{V}}^{\mathrm{rs}} \\
q_{\mathrm{RSD}} = 1 - \frac{1}{6}\beta(z)\Delta_{\mathrm{id}} > 1 \\
q_{\mathrm{AP}} = \sqrt[3]{(q_{\mathrm{AP}}^{\perp})^2 q_{\mathrm{AP}}^{\parallel}} \\
q_{\mathrm{AP}}^{\perp} = \frac{D_{\mathrm{M}}^{\mathrm{fid}}(z)}{D_{\mathrm{M}}^{\mathrm{rs}}(z)} \qquad q_{\mathrm{AP}}^{\parallel} = \frac{H^{\mathrm{rs}}(z)}{H^{\mathrm{fid}}(z)}
\end{cases}
$$

$$s_{\mathrm{v}} = r_{\mathrm{v}} + V_{\mathrm{v}\parallel}\frac{(1+z)}{H(z)}$$

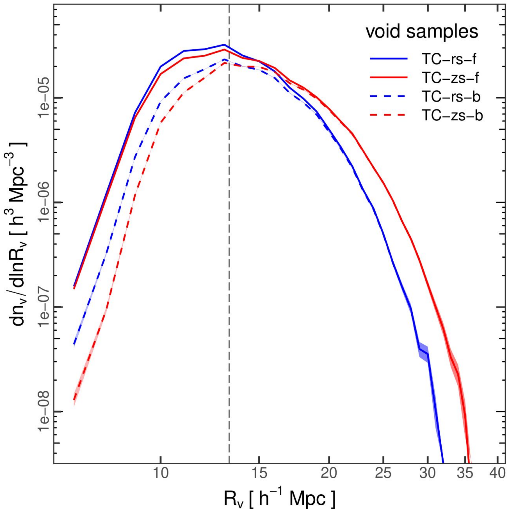
★ This formulation must be incorporated into models for the **void size function** and the **void-galaxy correlation function**

$$\{\Omega_m, \Omega_\Lambda, h, \beta = f/b\}$$

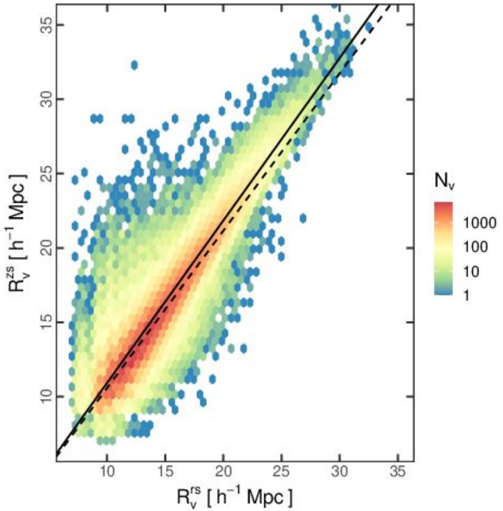
Statistical evidence

$$R_{\rm v}^{\rm zs} = q_{\rm RSD} R_{\rm v}^{\rm rs}$$

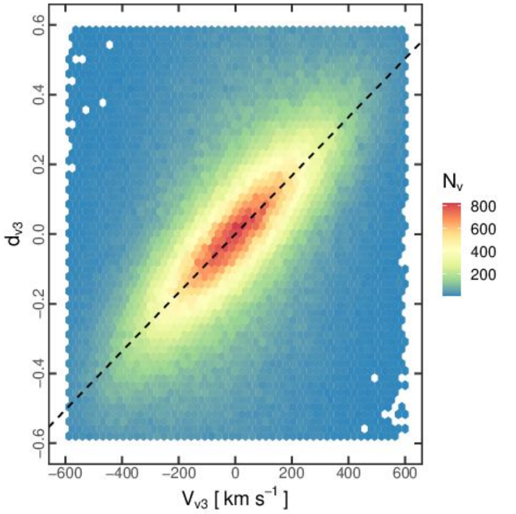
$$s_{\rm v} = r_{\rm v} + V_{\rm v\parallel}\frac{(1+z)}{H(z)}$$



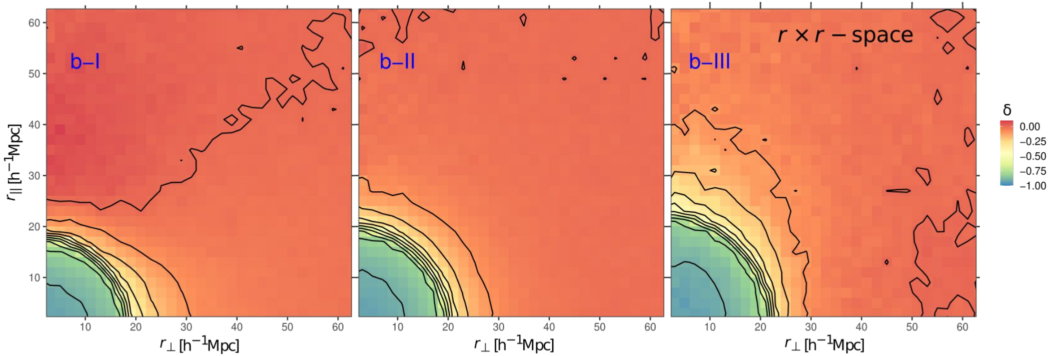
Number conservation



t-RSD expansion



v-RSD off-centring



e-RSD ellipticity

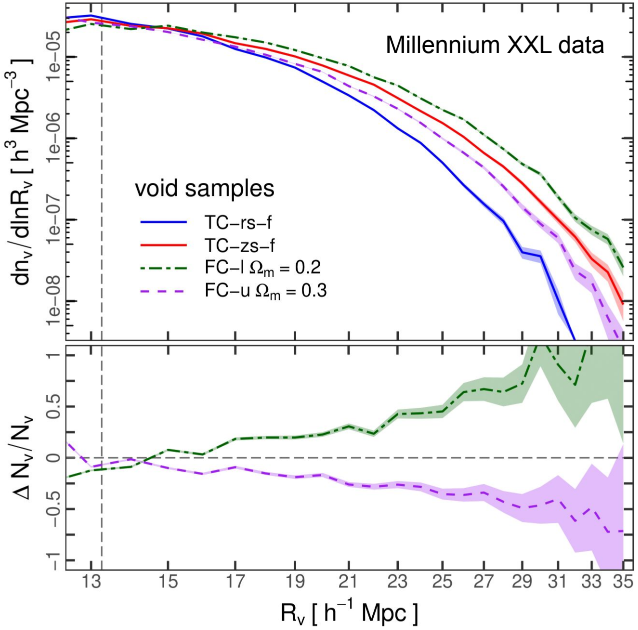
Millennium XXL simulation data

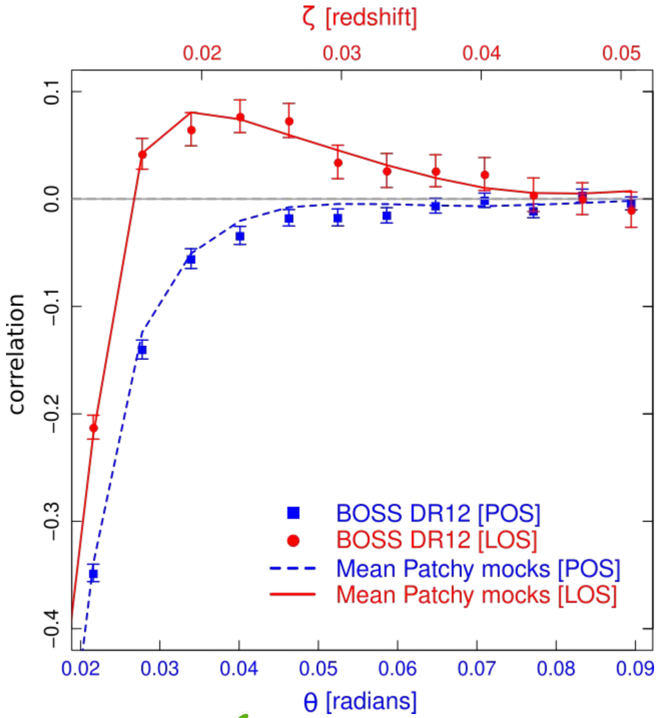
void in real-space

void in redshift-space

Impact on the cosmological statistics

VSF





PROJECTED CORRELATIONS

References

- present and modelled
- present, model in process
- absent

✓	❖	**AP effect**	✓
✓	❖	**t-RSD**	✓
FREE!	❖	**v-RSD**	✓
FREE!	❖	**e-RSD**	🛠

New effects not taken into account previously

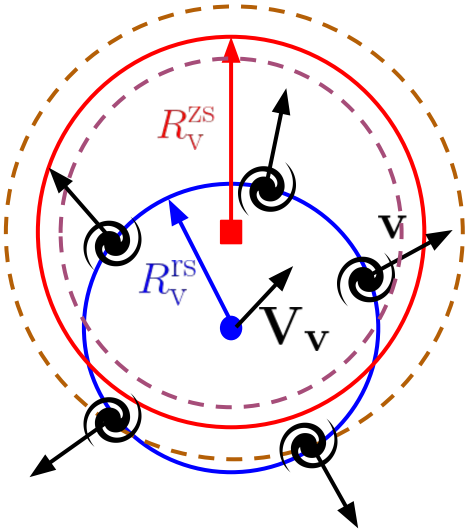
Conclusions

Conclusions

- In this era of high-precision cosmological measurements, cosmic voids are **promising cosmological probes** for testing the **dark-energy** problem and **alternative gravity theories**

- Our **standard picture of distortions** around voids is incomplete. Traditionally, we have focused only on the spatial distribution of galaxies. The truth is that the AP+RSD effects also affect **intrinsic void properties**, such as their number distribution, their size and their spatial distribution. This generates **additional distortion patterns** on observations, which lead to **biased cosmological constraints** if they are not treated properly.

- **Redshift-space effects** in voids
    - 1) Void number conservation
    - 2) **AP** volume effect
    - 3) Expansion effect **(t-RSD)**
    - 4) Off-centring effect **(v-RSD)**
    - 5) Void ellipticity **(e-RSD)**
    - 6) Independence of the effects



Conclusions

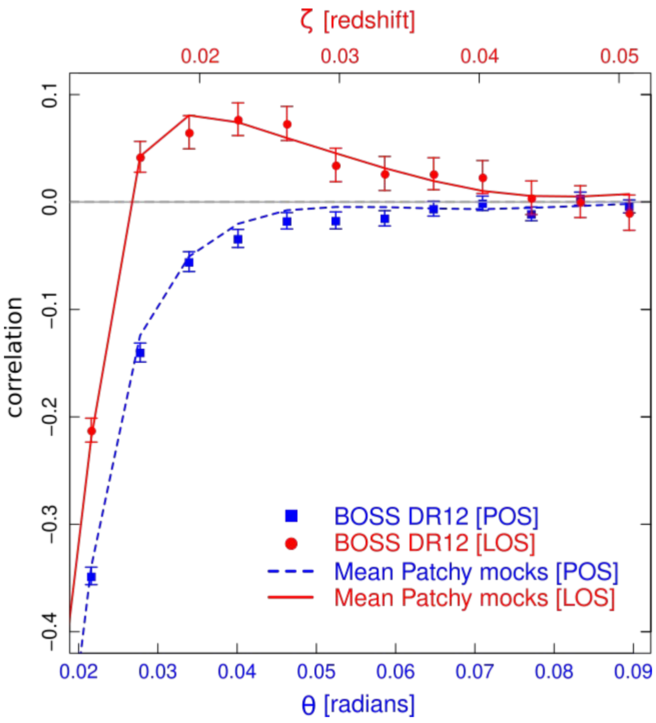
- A **new cosmological test** based on the **void-galaxy cross-correlation function**

1) **Projected correlation functions**

2) **Fiducial-cosmology-free test**

3) **Covariance** matrices associated with the method

- **Redshift-space effects** are detected with **high signal** in **modern surveys**



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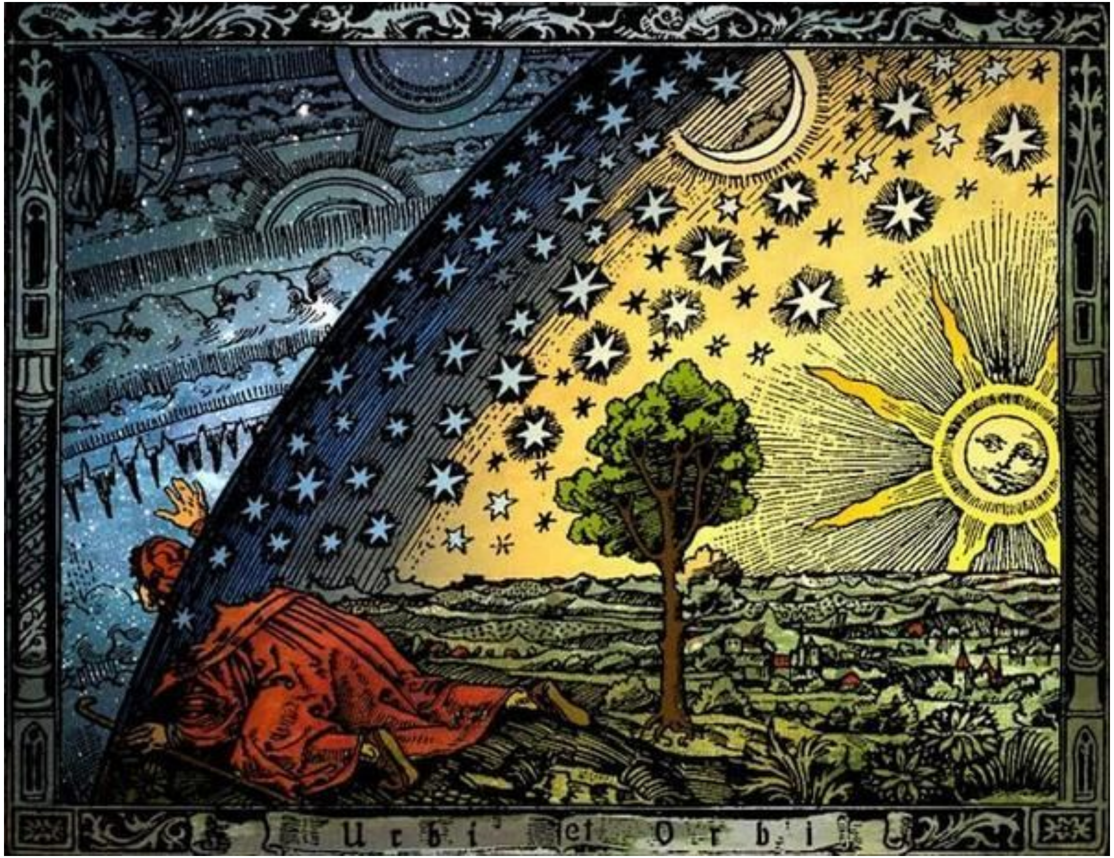

Main references [arXiv]:

- [1811.12251] (New test)
- [2007.12064] (z-space effects I)
- [2107.01314] (z-space effects II)
- [2205.13604] (BOSS preliminary analysis)

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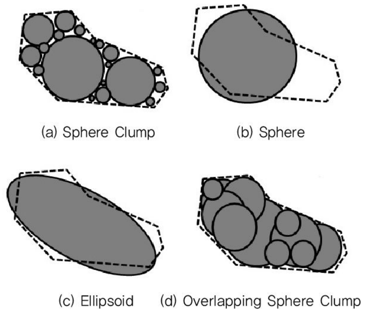
Future perspectives

- **Modelling the v-RSD and e-RSD effects:** improve our test based on the projected correlation functions by modelling the off-centring and ellipticity effects, not previously considered in the literature.

- **Popcorn void finder:** (Paz et al.) extension of the spherical void finder that in order to capture more realistic information about the shape of voids.



- **Bias relation in voids:** a proper bias relation constitutes the necessary link between both developments before the abundance of voids can be established as a reliable cosmological test.

VSF theory: excursion set + spherical evolution

VSF observations: t-RSD + AP effects

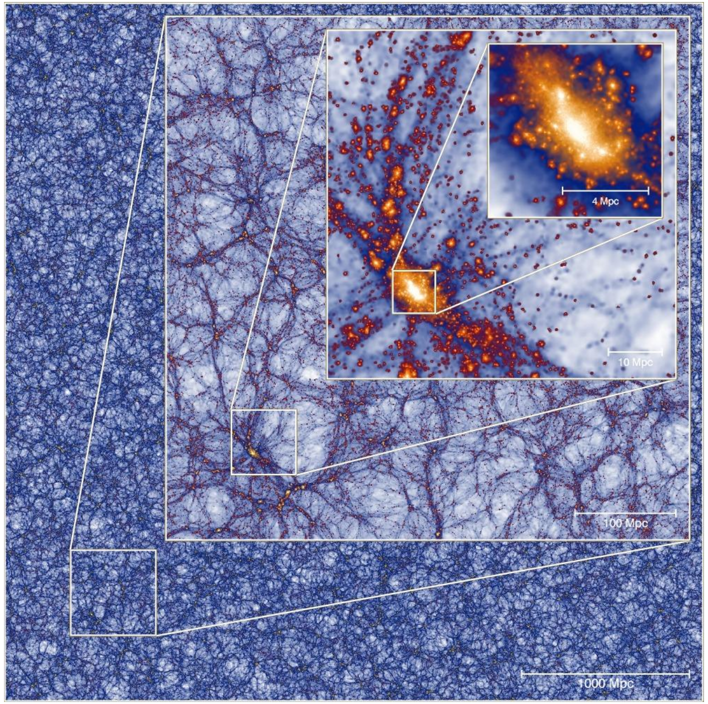
- **Cosmology with voids from BOSS data:** develop two robust and unbiased cosmological tests based on the void size function and the void-galaxy cross-correlation function to be applied on BOSS data.

Extra slides I: data set

Millennium XXL simulation

Angulo et al. 2012

- Calibration of **tests** and **models**
- Extension of *Millennium* (Springel et al. 2005)
- Great **resolution** and **volume:**
  - 6720^3 dark matter particles
  - Mass per particle: $8.46 \times 10^9\ h^{-1} M_{sun}$
  - Periodic box: $3000\ h^{-1} Mpc$
- Standard cosmology **flat-ΛCDM**
  - $h = 0.73$
  - $\boldsymbol{\Omega_m = 0.25}$, $\Omega_\Lambda = 0.75$
  - $\boldsymbol{z_{box}} = 0.51$, $\boldsymbol{0.99}$ and 1.50
- **Dark matter haloes**: lower mass cut: $5 \times 10^{11}\ h^{-1} M_{sun}$ ($\sim 140 \times 10^6$ haloes)

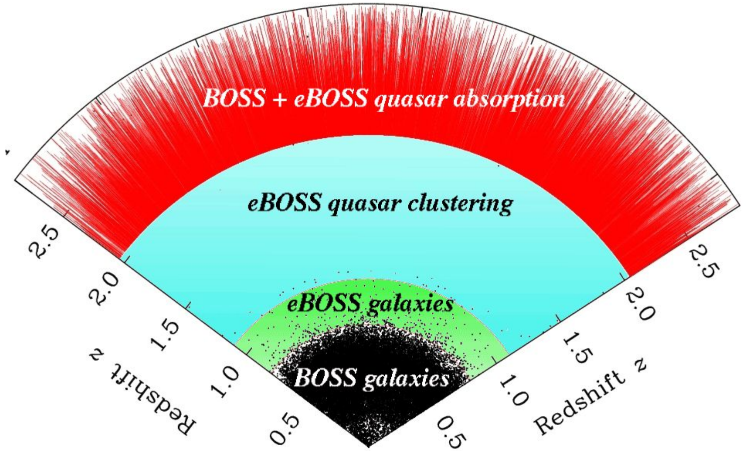


BOSS spectroscopic survey

Dawson et al. 2013

- Part of a six-year program of the **SDSS-III** designed for three scientific themes:
  - **dark energy** and **cosmological parameters**
  - structure, dynamics and chemical evolution of the Milky Way
  - architecture of planetary systems
- **1.5 million luminous red galaxies** (LRGs)
- Main scientific project: detect the **BAO characteristic scale**, use it as a physically calibrated ruler to determine the cosmic distance scale with **high precision**, achieving **tight constraints** on the eq. of state of dark energy
- Ideal for similar tests with cosmic **voids**

- **CMASS** and **LOWZ** samples of the **Data Release 12** (DR12).
- They contain **864,464** and **333,082 galaxies** in the northern and southern hemispheres
- **Mean redshift**: **0.48**
- **MultiDark Patchy mocks:** that reproduce the DR12 galaxy clustering catalogue with high fidelity on all relevant scales



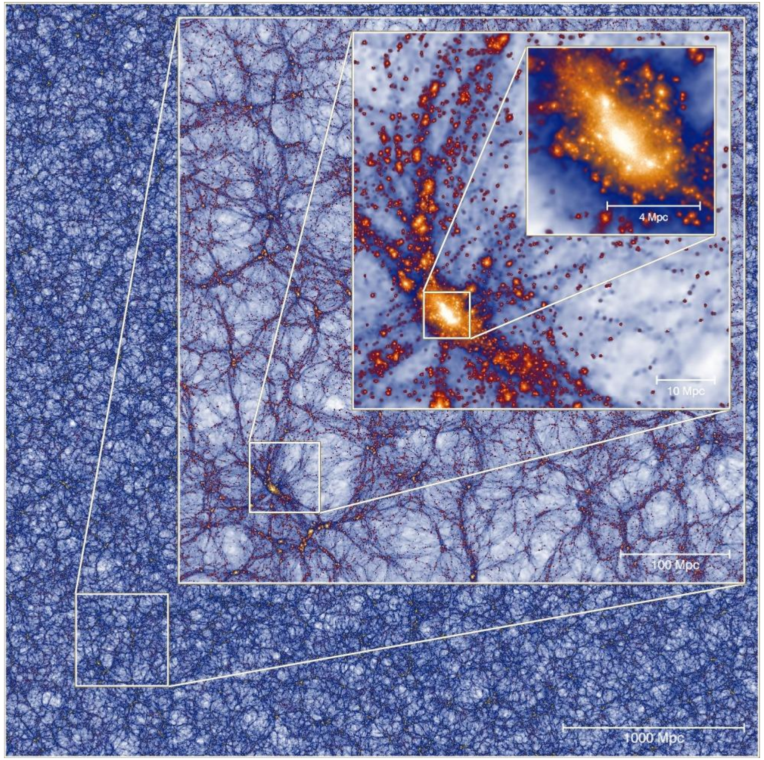
Extra slides II: a new cosmological test using cosmic voids

- [1811.12251] Non-fiducial cosmological test from geometrical and dynamical distortions around voids

Novel aspects

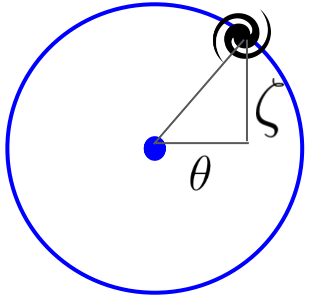
1. Fiducial-free test
2. Scale-mixing effect
3. Perpendicular projections of the void-galaxy correlation function
4. Covariance matrices

Calibration and evaluation: MXXL simulation



Millennium XXL simulation (Angulo et al. 2013)

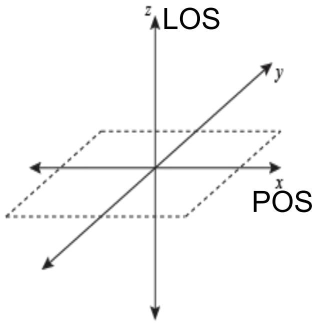
Fiducial-free test



- Surveys provide **angles (POS)** and **redshifts (LOS)**
- We treat correlations directly in terms of angular and redshift separations between void-galaxy pairs $\xi(\theta, \zeta)$
- It is not necessary to assume a **fiducial cosmology**
- The **AP effect** is taken into account naturally
- Coordinate systems:
  - **observable space** (θ, ζ)
  - **real space** $(r_\perp, r_\parallel)$
  - **redshift space** (σ, π)

$$\begin{cases} \sigma = D_{\mathrm{M}}(z)\theta \\ \pi = \dfrac{c}{H(z)}\zeta \end{cases}$$

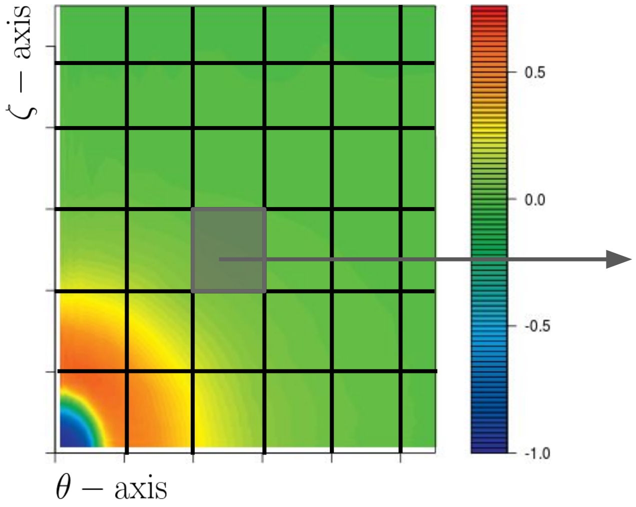
$$\begin{cases} r_\perp = \sigma_{\mathrm{tc}} \\ r_\parallel = \pi_{\mathrm{tc}} - v_\parallel \dfrac{(1+z)}{H(z)} \end{cases}$$

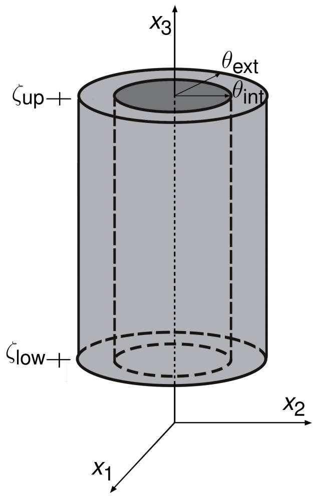


distant observer approximation

Scale-mixing effect

- Correlations can not be estimated **punctually**
- We must define a **binning scheme**
- Several **scales** are **mixed** in the measuring process
- Compare measurements with theoretical predictions of models





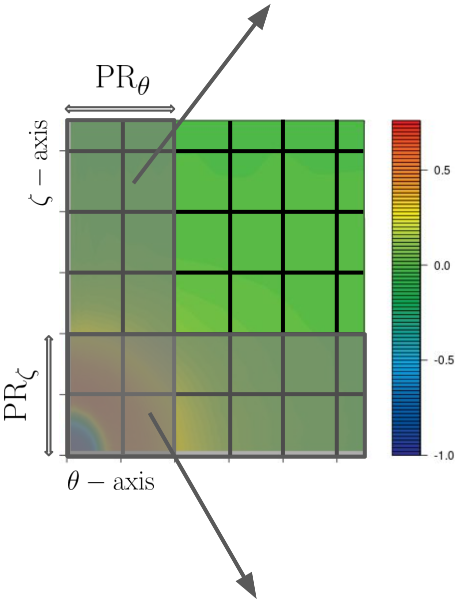
arbitrary bin: cylindrical shell oriented along the LOS

$$\xi_{\rm bin} = 2\frac{\int_{\pi_{\rm low}}^{\pi_{\rm up}} d\pi \int_{\sigma_{\rm int}}^{\sigma_{\rm ext}} \sigma[1+\xi(\sigma,\pi)]d\sigma}{(\sigma_{\rm ext}^2 - \sigma_{\rm int}^2)(\pi_{\rm up} - \pi_{\rm low})} - 1$$

Projected correlations

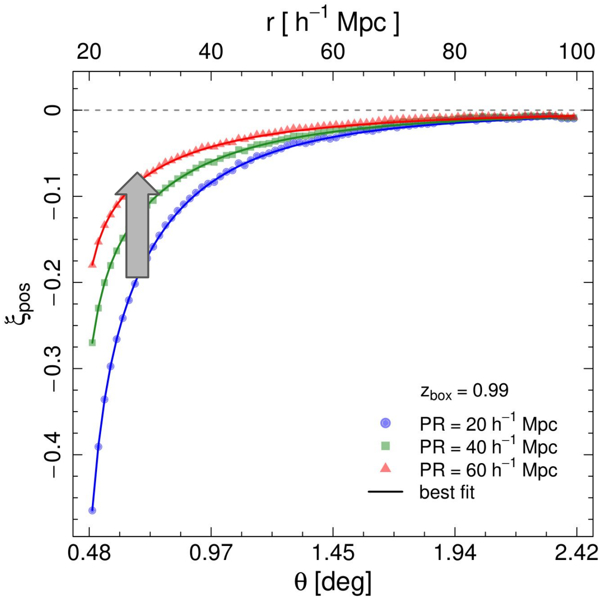
$$\xi(\theta,\zeta) \longrightarrow \xi_{\rm los}(\zeta)$$

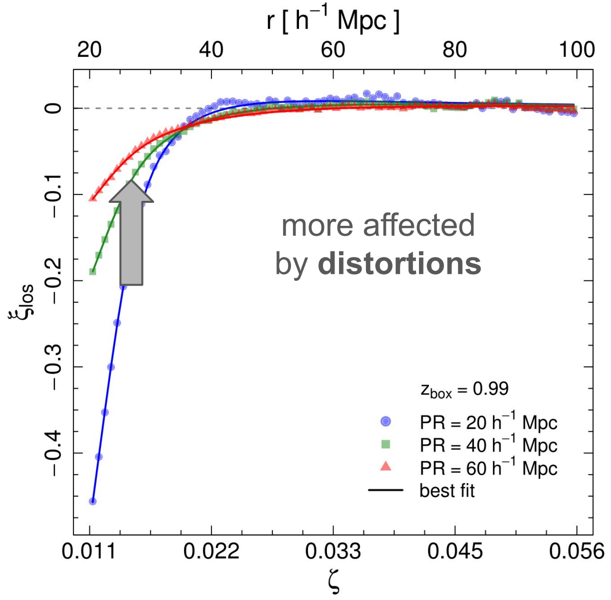
line-of-sight correlation function



plane-of-sky correlation function

$$\xi(\theta,\zeta) \longrightarrow \xi_{\rm pos}(\theta)$$





★ The combination of working on **observable space** and considering two **perpendicular projections** allows us to **break** effectively any possible **degeneracy** between the parameters

Model

1. **AP effect**
2. **Scale-mixing effect**

$$\{\Omega_m, \underbrace{\beta\} \cup \{\sigma_v}_{\text{RSD}}, \underbrace{\xi_0, r_0, \alpha}_{\text{density}}\}$$

AP

3. **RSD:**

   Gaussian streaming model (Paz et al. 2013)

$$1+\xi(\sigma,\pi) = \int_{-\infty}^{\infty} [1+\xi(r)] \frac{1}{\sqrt{2\hat{\pi}}\sigma_v} \exp\left[-\frac{(v_\parallel - v(r)\frac{r_\parallel}{r})^2}{2\sigma_v^2}\right] \mathrm{d}v_\parallel$$

4. **Real-space density profile:**

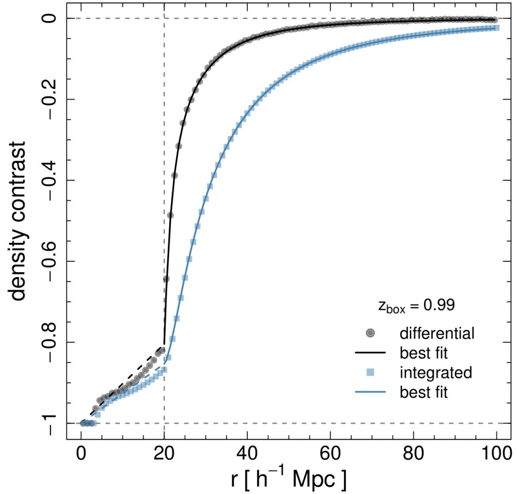
   Double power law (Correa et al. 2019)

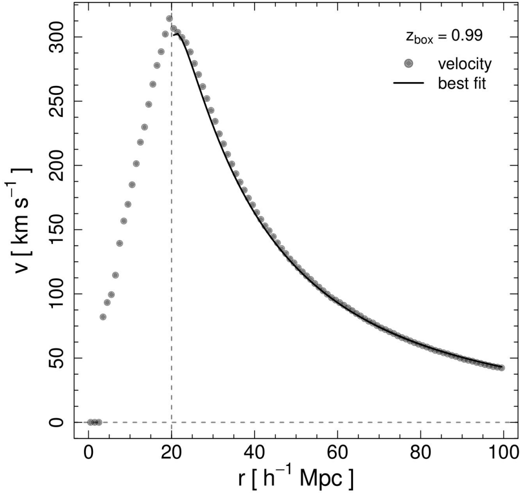
$$\xi(r) = -\xi_0 \left[\left(\frac{r}{r_0}\right)^{-3} + \left(\frac{r}{r_0}\right)^{-\alpha}\right]$$

5. **Real-space velocity profile:**

   From linear perturbation theory (Paz et al. 2013)

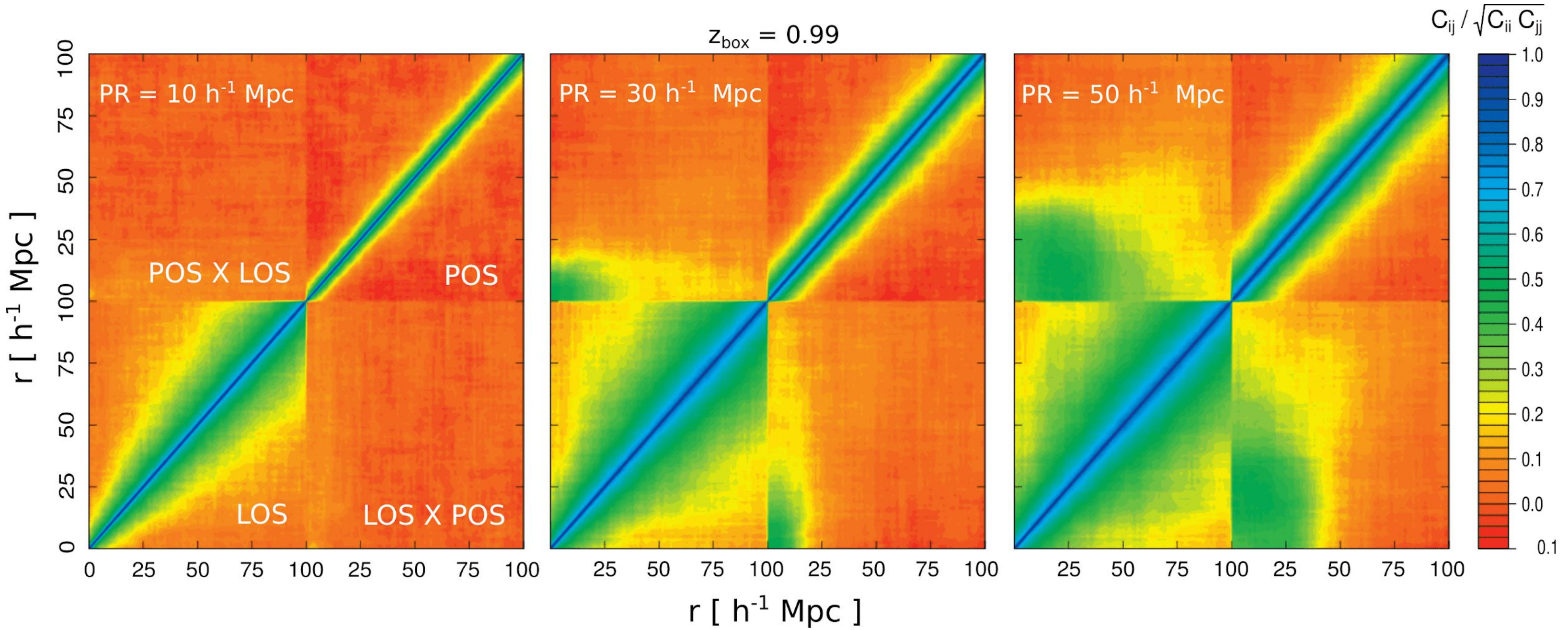
$$v(r) = -\frac{1}{3}\frac{H(z)}{(1+z)}\beta(z) r \Delta(r) \qquad \beta(z) = \frac{f(z)}{b} \longleftarrow \text{GR vs MoG}$$





Covariance matrices

$$\xi[m \times m] \longrightarrow C[m^2 \times m^2]$$
$$\xi[2m] \longrightarrow C[m \times m]$$

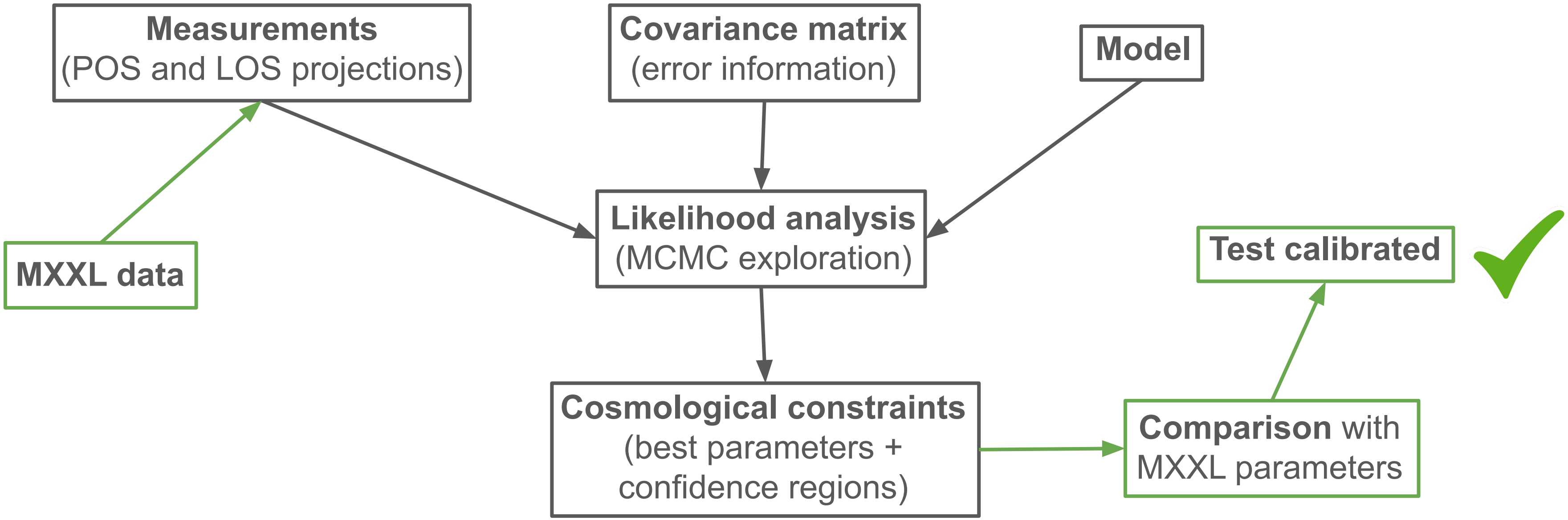


- Notably reduced **dimension**
- **Inversion** numerically more stable
- Propagation of **errors** substantially reduced
- Less **number of mocks** needed

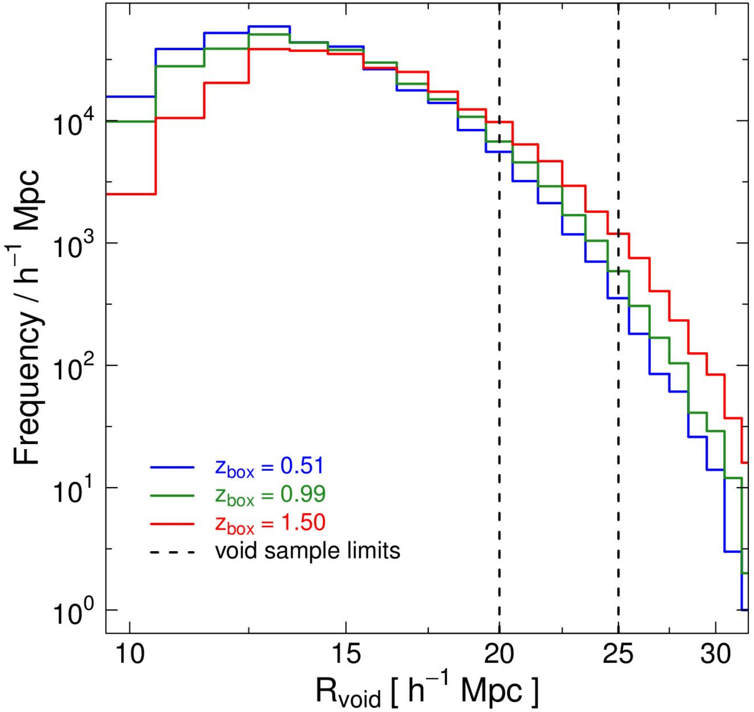
Test mechanism

Parameters of the model

$$\underset{\textbf{AP}}{\{\Omega_m,}\ \underbrace{\beta\} \cup \{\sigma_v,}_{\textbf{RSD}}\ \underbrace{\xi_0, r_0, \alpha\}}_{\textbf{density}}$$

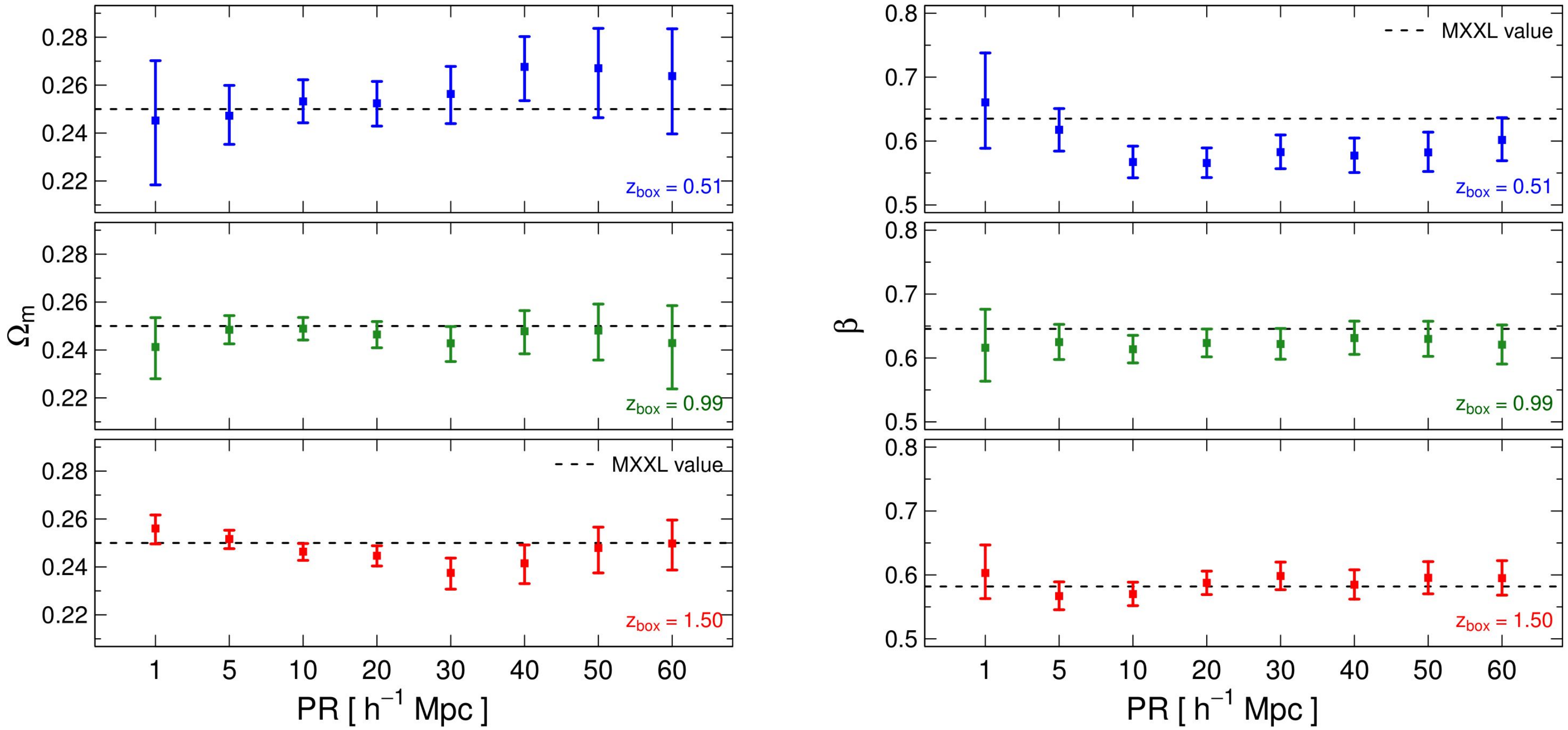


Void samples from the MXXL



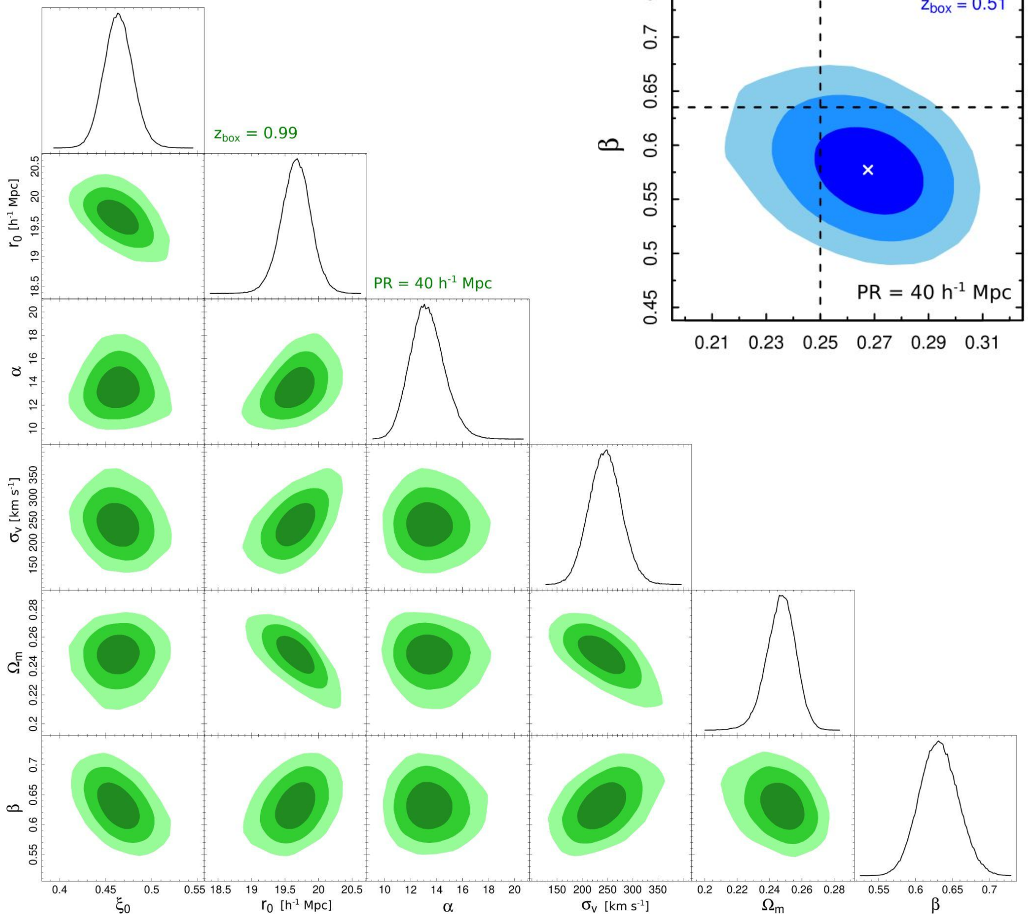
Performance

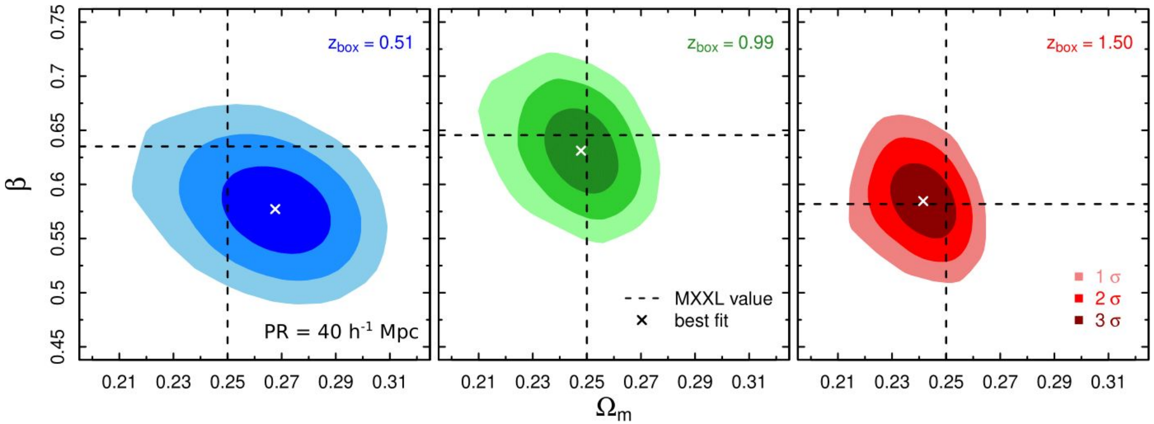
★ test **robust** with **redshifts** and **PRs**
★ **no degeneracies** among the parameters



★ tighter constraints at **higher redshifts**

Performance





Summary of the test

1. **Statistic:** void-galaxy cross-correlation function
    1.1. **Variant:** perpendicular projections with respect to the line of sight
2. **Fiducial free:** it is not necessary to assume a fiducial cosmology
3. **Model**
    3.1. **Density field:** own parametric model
    3.2. **Velocity field:** analytical model from linear perturbation theory
    3.3. **RSD:** Gaussian streaming model (Paz et al. 2013)
    3.4. **AP effect:** cosmological coordinate transformation
    3.5. **Scale mixing:** geometrical model that takes into the projection range
4. **Cosmological constraints**
    4.1. **Likelihood analysis:** MCMC exploration
    4.2. **Covariance matrices:** smaller, more stable inversion, reduction of noise, reduction of mocks needed
    4.3. **Calibration:** with the ***Millennium XXL simulation*** (Angulo et al. 2012). At $z=0.5$, *1.0* and *1.5*

Extra slides III: more about the VSF

Void evolution

Sheth & van de Weygaert 2004

Bases

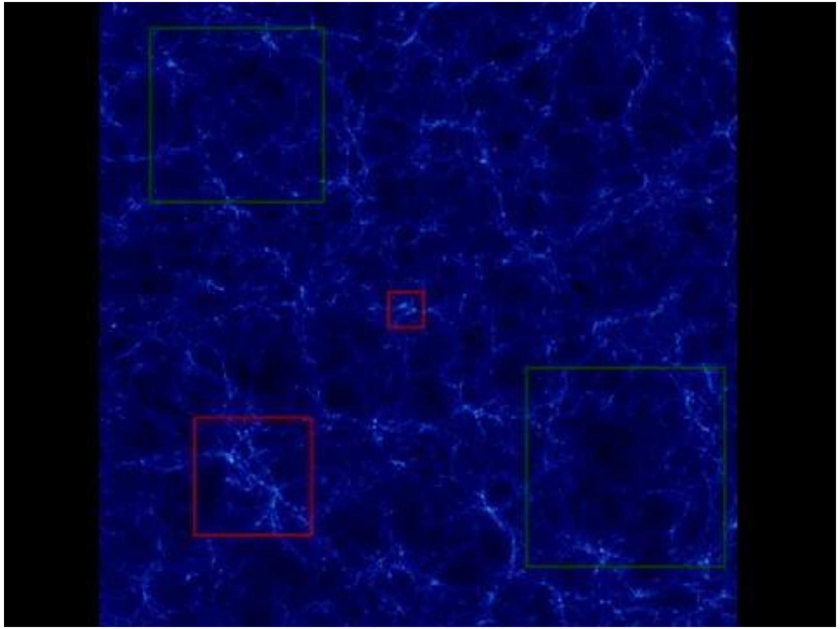
- ➢ Voids related to the small (under)density fluctuations in the **early Universe**
- ➢ **Isolated expansion** 

Characteristics

1. Expansion
2. Evacuation
3. Spherical geometry
4. Formation of a wall
5. Reverse top-hat density profile
6. Super-Hubble velocity
7. Suppression of growth structure
8. **Shell crossing**

Environment

- ➢ **void-in-void mode:** voids embedded in underdense environments, **expanding**
- ➢ **void-in-cloud mode:** voids surrounded by an overdense shell which will eventually **collapse**



Scorpio simulation (Sgró et al. 2010)

VSF modelling

- **Linear:** completely analogous to **Press-Schechter**, but with **two barrirers**, one underdense (expansion, void-in-void) and one overdense (collapse, void-in-cloud)

$$\Delta_{\rm v} = -0.8 \qquad\qquad 1.06 \leq \Delta_c \leq 1.686$$

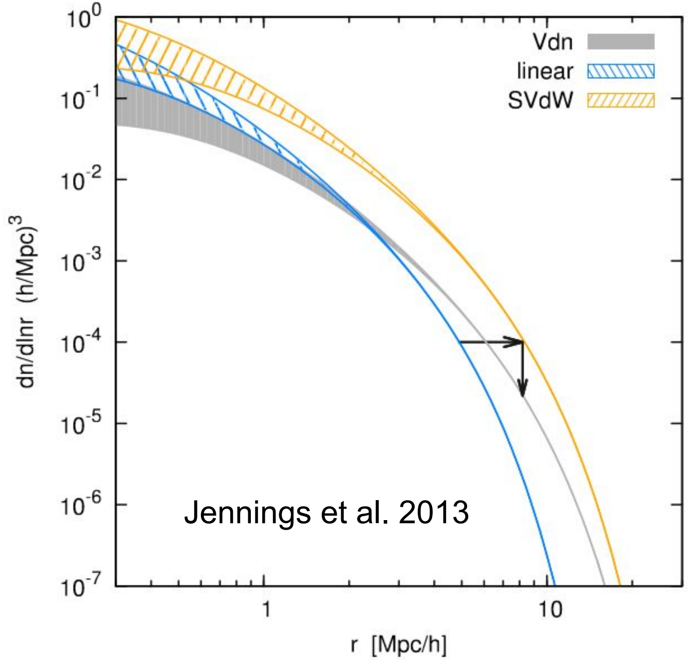
- **SvdW** (Sheth & van de Weygaert 2004): assumes **conservation of number density** through transition from linear to non-linear regime (**shell crossing**)

- **Vdn** (Jennings et al. 2013): assumes **conservation of comoving volume** fraction contained in voids (allows **mergers**)

$$\frac{dn_{\rm v}}{d\ln R_{\rm v}} = \frac{f_{\ln\sigma}(\sigma)}{V(R_{\rm v})}\frac{d\ln\sigma^{-1}}{d\ln R_{\rm v}}$$

$$f_{\ln\sigma}(\sigma) = 2\sum_{j=1}^{\infty}\exp\left[-\frac{(j\pi x)^2}{2}\right] j\pi x^2 \sin(j\pi\mathcal{D})$$

$$\mathcal{D} := |\Delta_{\rm v}|/(\Delta_c + |\Delta_{\rm v}|) \quad x := \mathcal{D}\sigma/|\Delta_{\rm v}| \qquad \sigma^2(\mathcal{R}) = \int \frac{k^2}{2\pi^2} P_m(k)|W(k,\mathcal{R})|^2\, dk$$



$$\frac{dn_{\rm v}}{d\ln R_{\rm v}} = \frac{f_{\ln\sigma}(\sigma)}{V(R_{\rm v})}\frac{d\ln\sigma^{-1}}{d\ln R_{\rm v}}$$

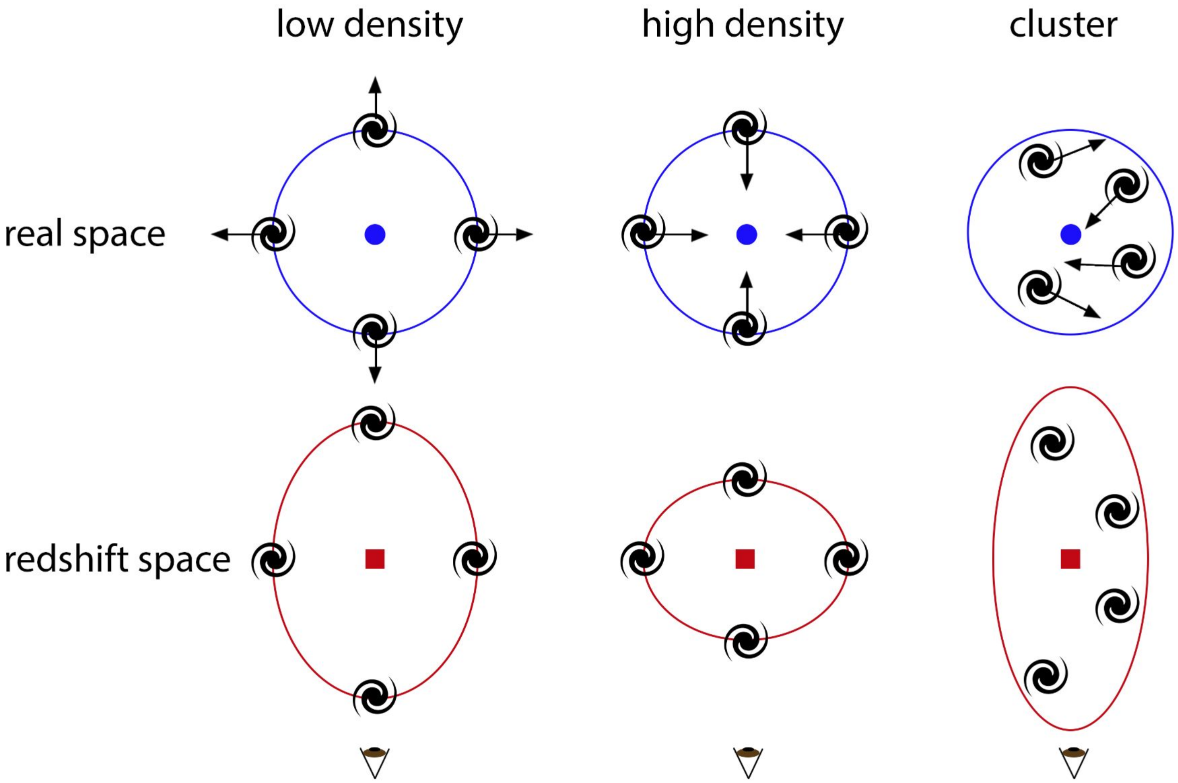
$$R_{\rm v} = 1.7\ R_{\rm v}^{\rm L}$$

$$\frac{dn_{\rm v}}{d\ln R_{\rm v}} = \frac{f_{\ln\sigma}(\sigma)}{V(R_{\rm v})}\frac{d\ln\sigma^{-1}}{d\ln R_{\rm v}^L}\frac{d\ln R_{\rm v}^L}{d\ln R_{\rm v}}$$

Extra slides IV: redshift-space effects: the void size function

- **arXiv [2007.12064]** Redshift-space effects in voids and their impact on cosmological tests. Part I: the void size function

Standard picture of distortions

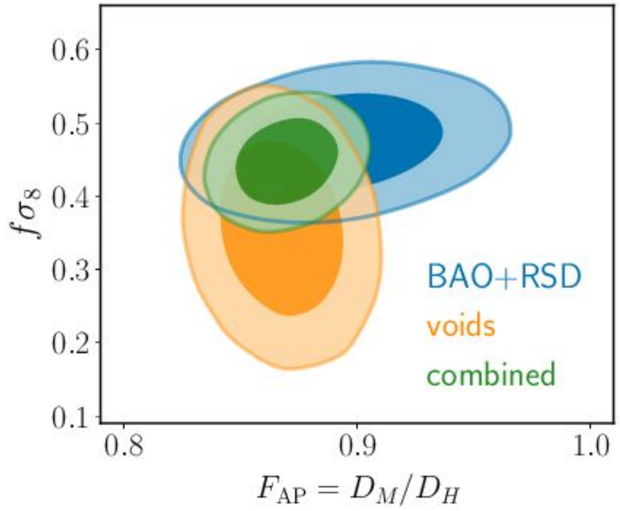


Reconstruction technique

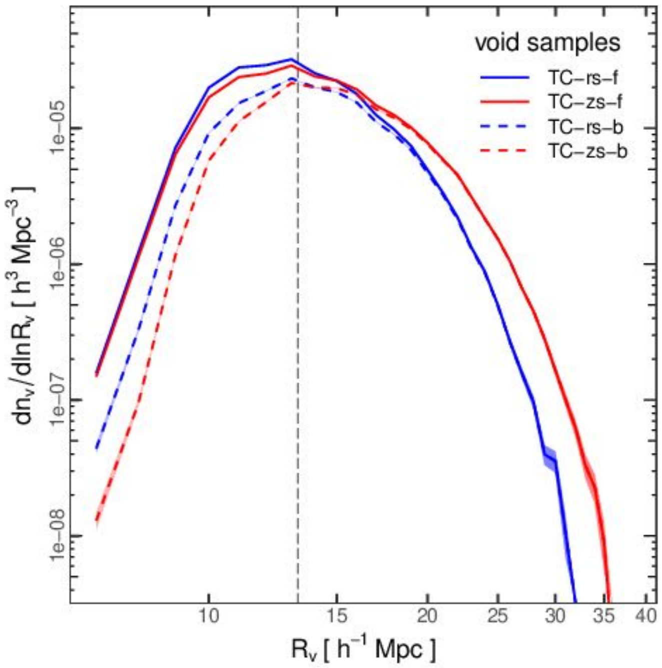
Nadathur et al. 2019

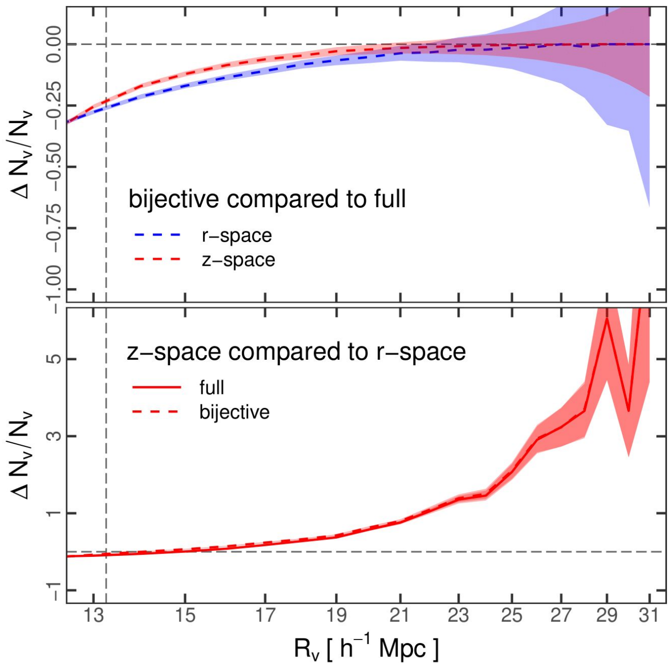
Recover the real-space position of galaxies using the Zeldovich approximation

- ✓ Recover statistical properties of voids
- ✓ Unbiased constraints
- ⚠️ **Computational expensive:** iterative process
- ⚠️ **Redundant:** removes RSD, then adds RSD
- ⚠️ **Hidden physics:** key information about the structural and dynamical nature of voids



Bijective mapping: void number conservation





Physical description

$\mathbf{V}_\mathrm{v}$

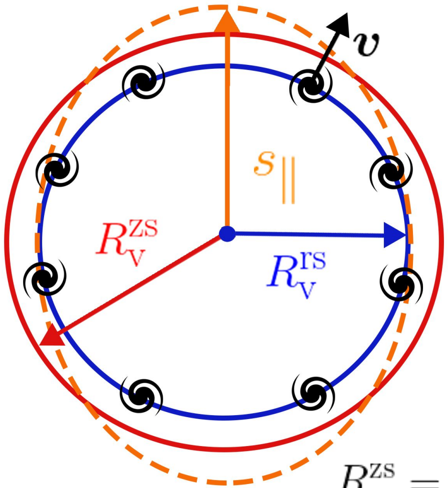
$0.8 < r/R_\mathrm{v}^\mathrm{rs} < 1.2$

Lambas et al. 2016;
Ceccarelli et al. 2016;
Lares et al. 2017

dynamical

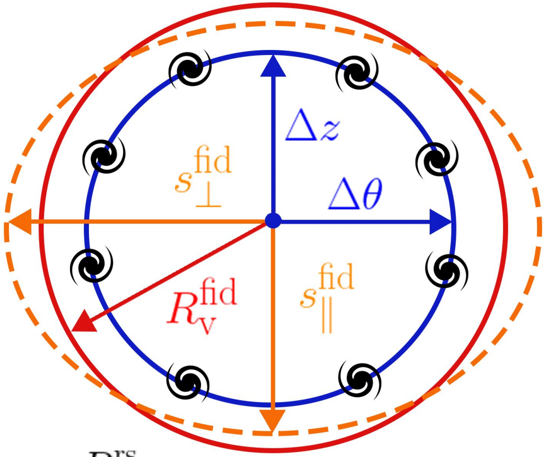
$\boxed{\text{t-RSD}}$ expansion effect

$$v(r) = -\frac{1}{3}\frac{H(z)}{(1+z)}\beta(z) r\,\Delta(r)$$



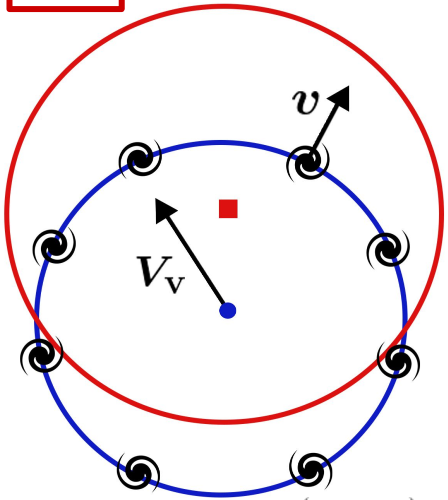
geometrical / cosmological

$\boxed{\text{AP}}$ change of volume effect



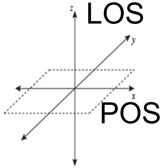
dynamical

$\boxed{\text{v-RSD}}$ off-centring effect



$$R_\mathrm{v}^\mathrm{zs} = q_\mathrm{AP}\; q_\mathrm{RSD}\; R_\mathrm{v}^\mathrm{rs}$$

$$s_\mathrm{v} = r_\mathrm{v} + V_{\mathrm{v}\parallel}\frac{(1+z)}{H(z)}$$



$$R_\mathrm{v}^\mathrm{zs} = q_\mathrm{RSD} R_\mathrm{v}^\mathrm{rs}$$

$$q_\mathrm{RSD} = 1 - \frac{1}{6}\beta(z)\Delta_\mathrm{id} > 1$$

volume / size

$$R_\mathrm{v}^\mathrm{fid} = q_\mathrm{AP} R_\mathrm{v}^\mathrm{rs}$$

$$q_\mathrm{AP} = \sqrt[3]{(q_\mathrm{AP}^\perp)^2 q_\mathrm{AP}^\parallel}$$

$$q_\mathrm{AP}^\parallel = \frac{H^\mathrm{rs}(z)}{H^\mathrm{fid}(z)}$$

$$q_\mathrm{AP}^\perp = \frac{D_\mathrm{M}^\mathrm{fid}(z)}{D_\mathrm{M}^\mathrm{rs}(z)}$$

LOS displacement

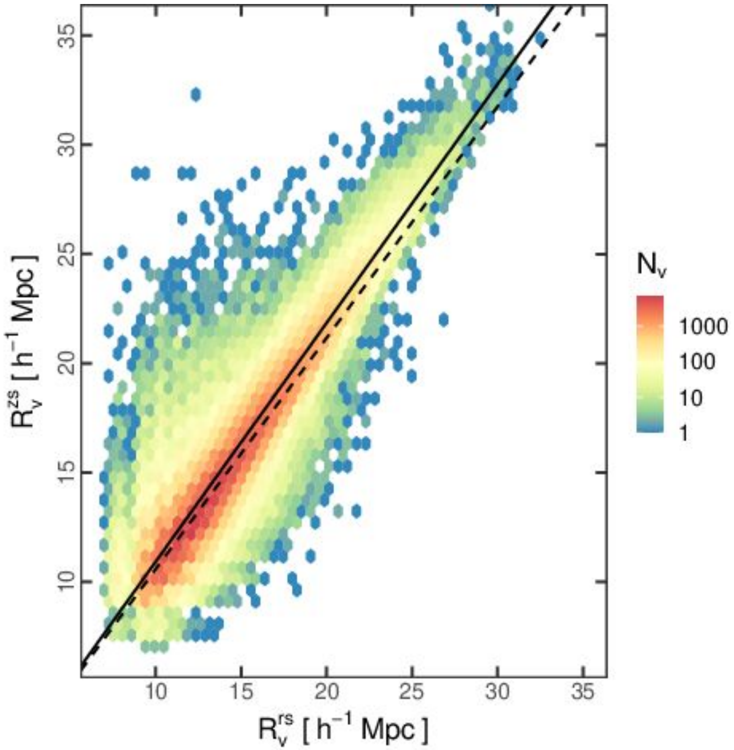
Expansion effect (t-RSD)

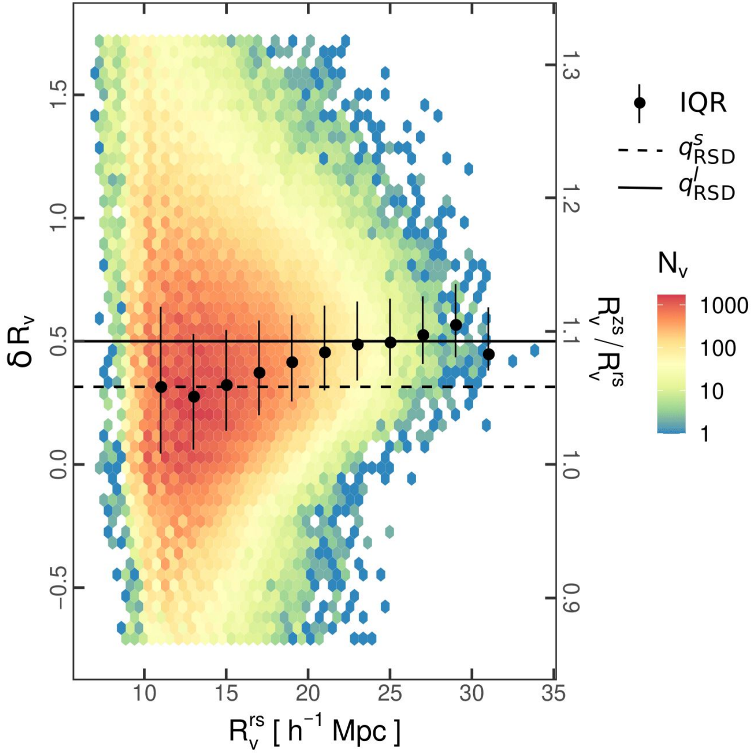
$$R_{\rm v}^{\rm zs} = q_{\rm RSD} R_{\rm v}^{\rm rs}$$

$$q_{RSD} = 1 - \frac{1}{3}\delta R_{\rm v}\beta(z)\Delta_{\rm id}$$

$$q^{s}_{RSD} = \sqrt[3]{1 - \frac{1}{3}\beta(z)\Delta_{\rm id}} = 1.058 > 1$$

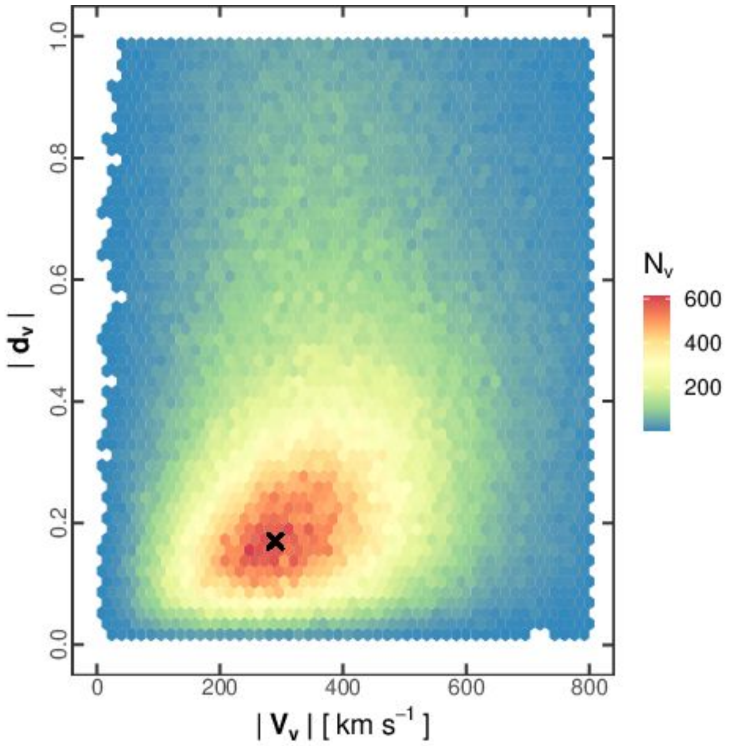
$$q^{l}_{RSD} = 1 - \frac{1}{6}\beta(z)\Delta_{\rm id} = 1.092 > 1$$

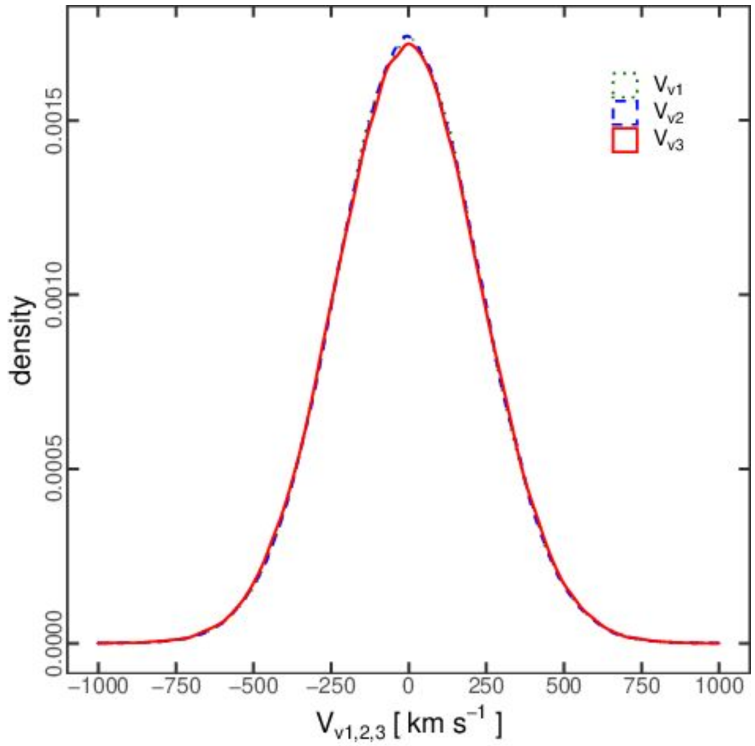




Void dynamics

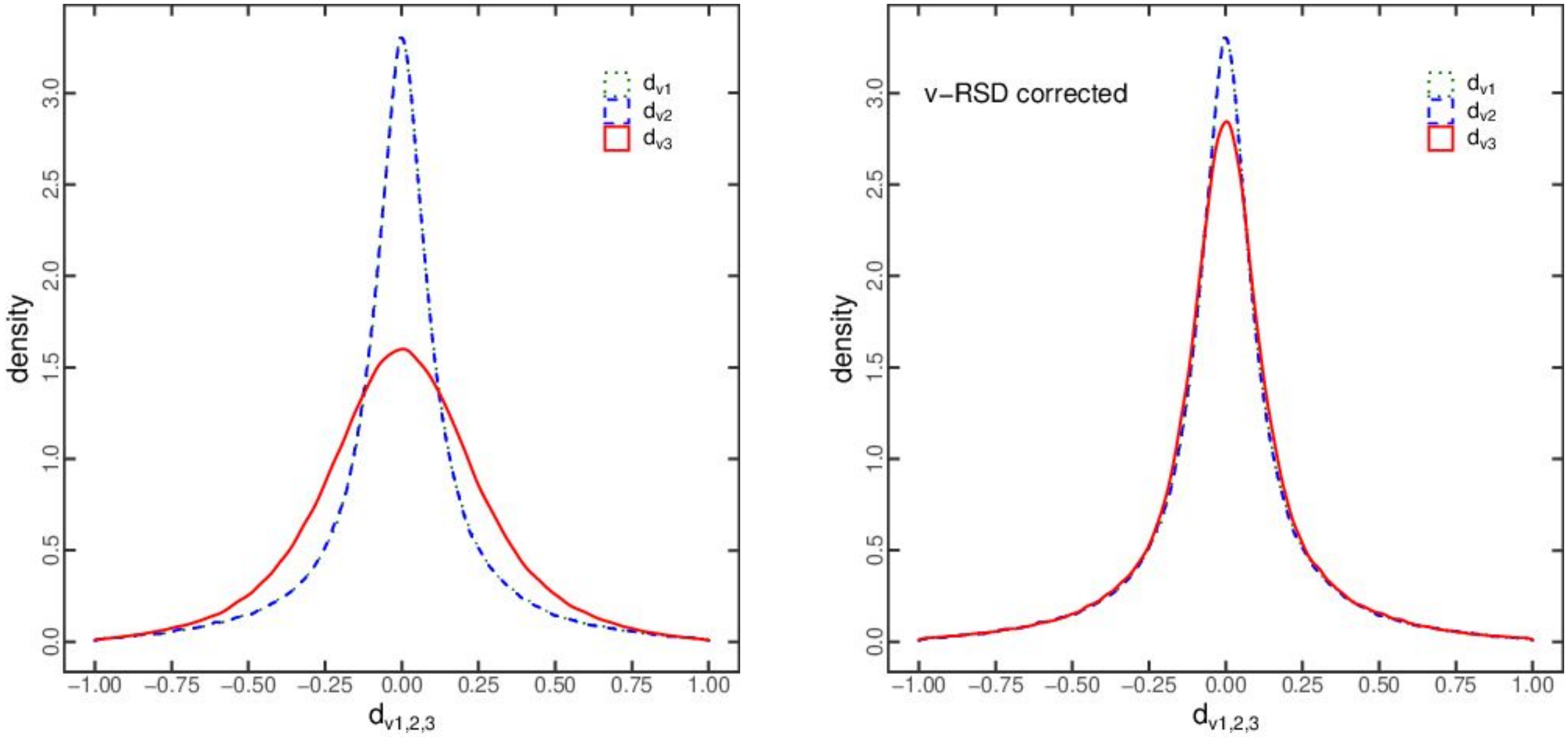
- Voids typically move with a velocity of **290 km/s**
- Voids typically displace an amount of **0.17 Rv**





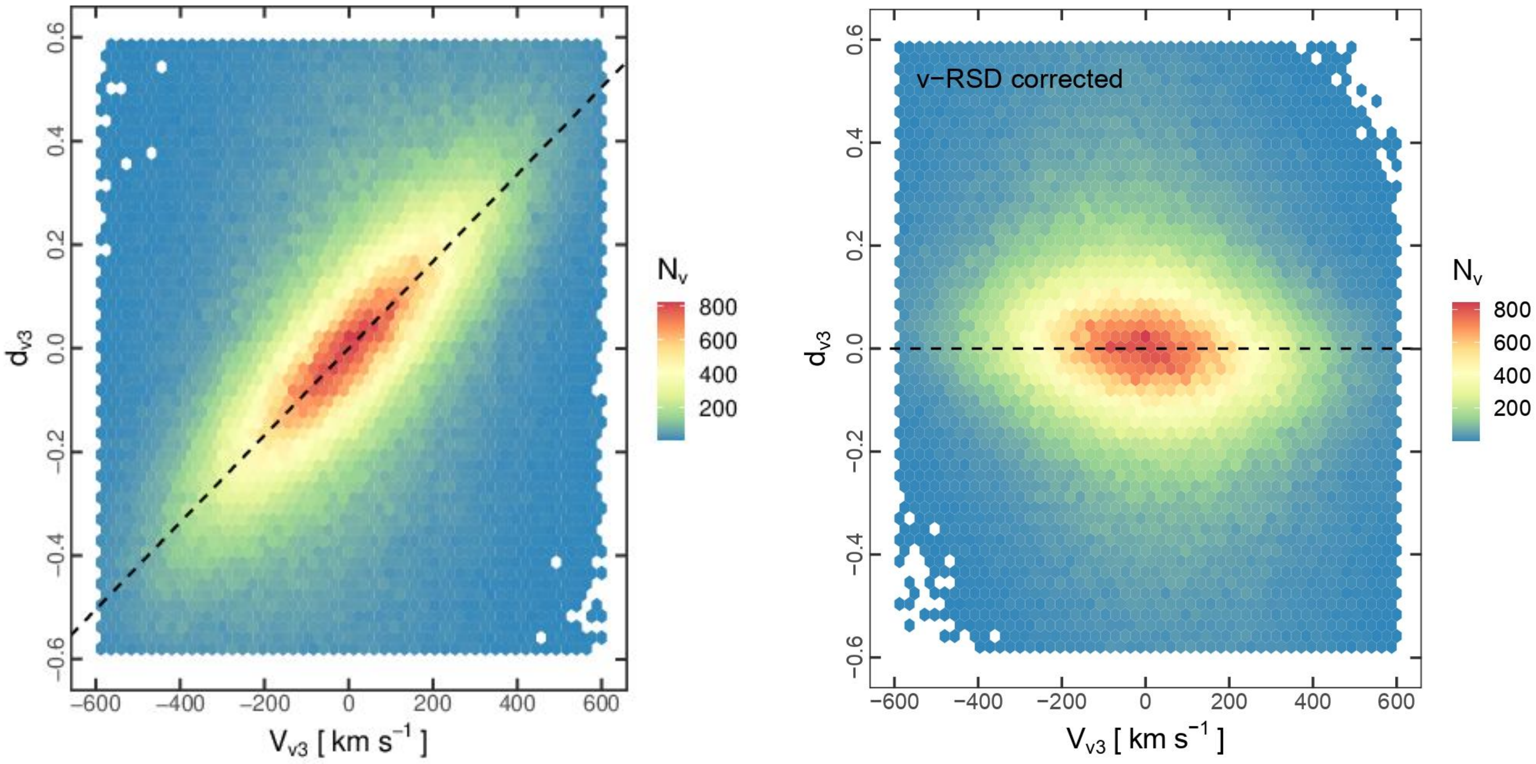
Off-centring effect (v-RSD)

$$s_{\mathrm{v}} = r_{\mathrm{v}} + V_{\mathrm{v}\parallel}\frac{(1+z)}{H(z)}$$

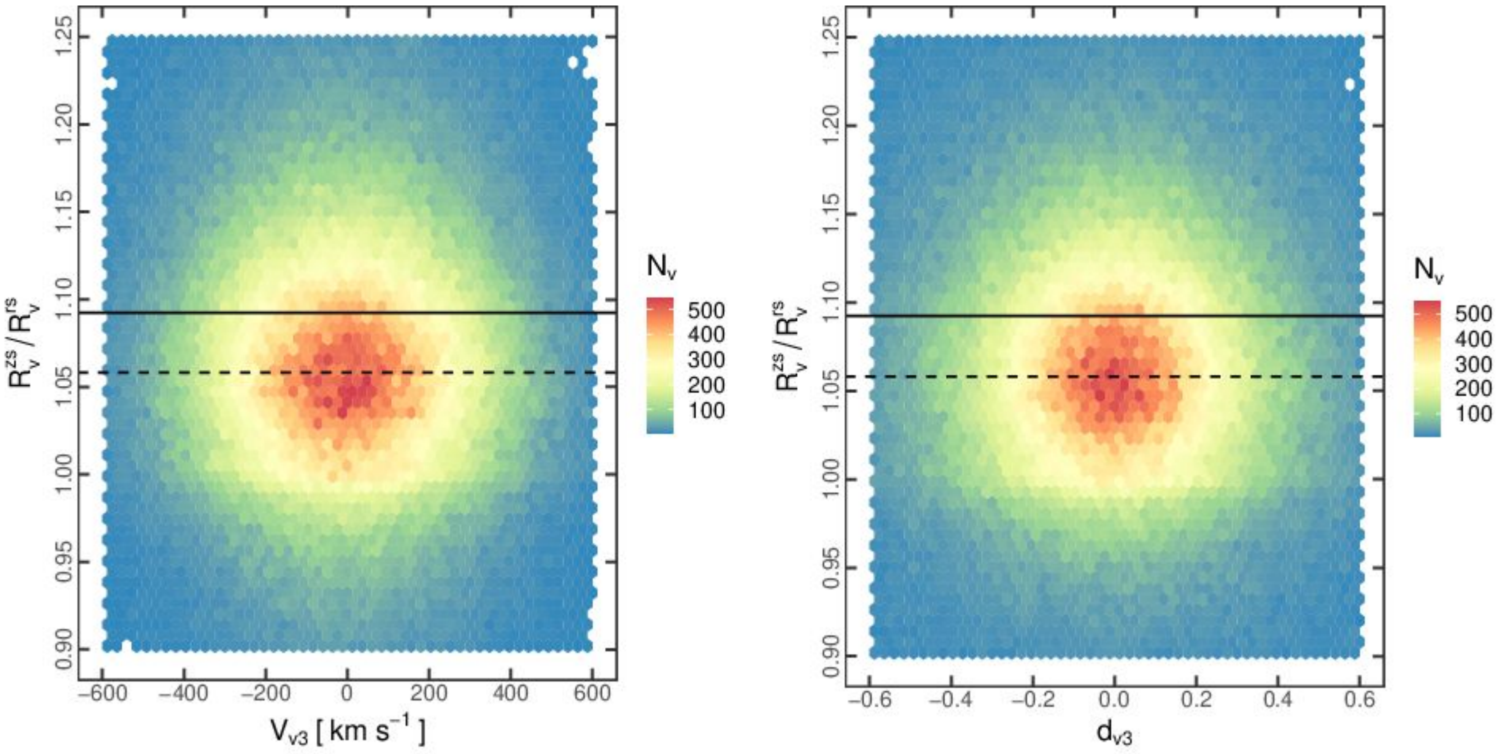


Off-centring effect (v-RSD)

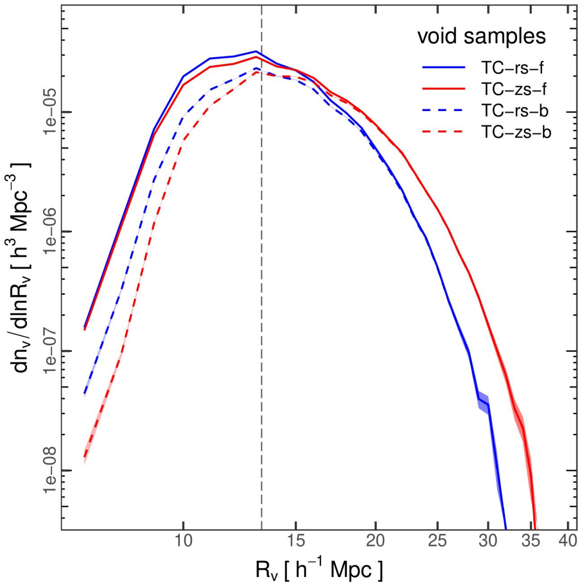
$$s_{\rm v} = r_{\rm v} + V_{{\rm v}\parallel}\frac{(1+z)}{H(z)}$$



Independence of the effects (t-RSD and v-RSD)

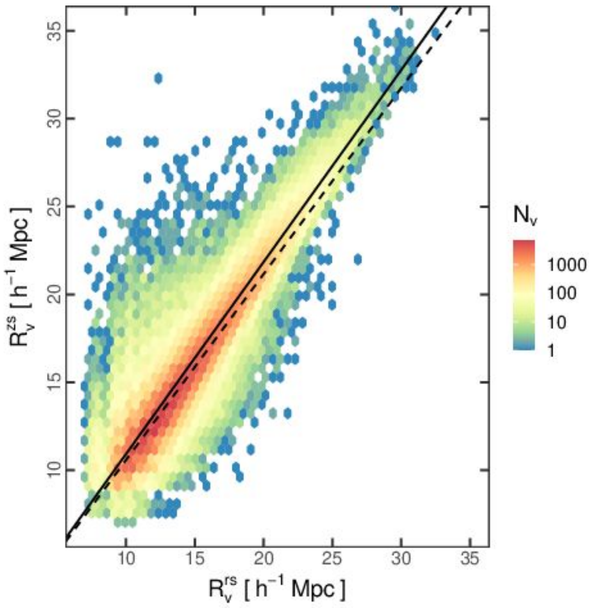


Statistical evidence



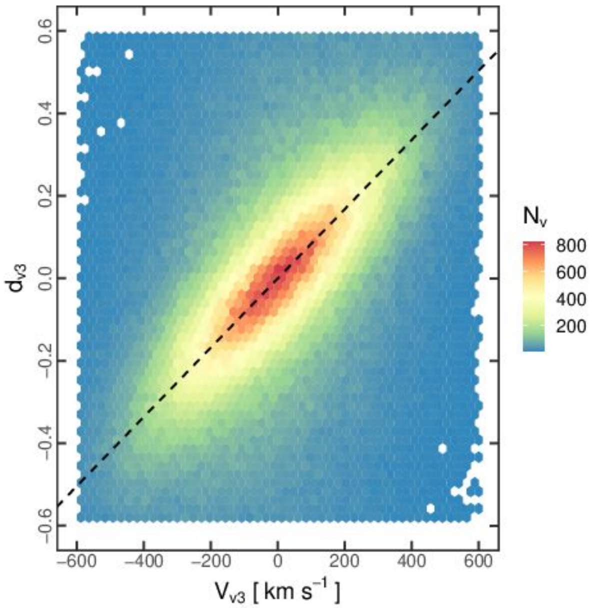
Number conservation

$$R_{\mathrm{v}}^{\mathrm{zs}} = q_{\mathrm{RSD}} R_{\mathrm{v}}^{\mathrm{rs}}$$



t-RSD expansion

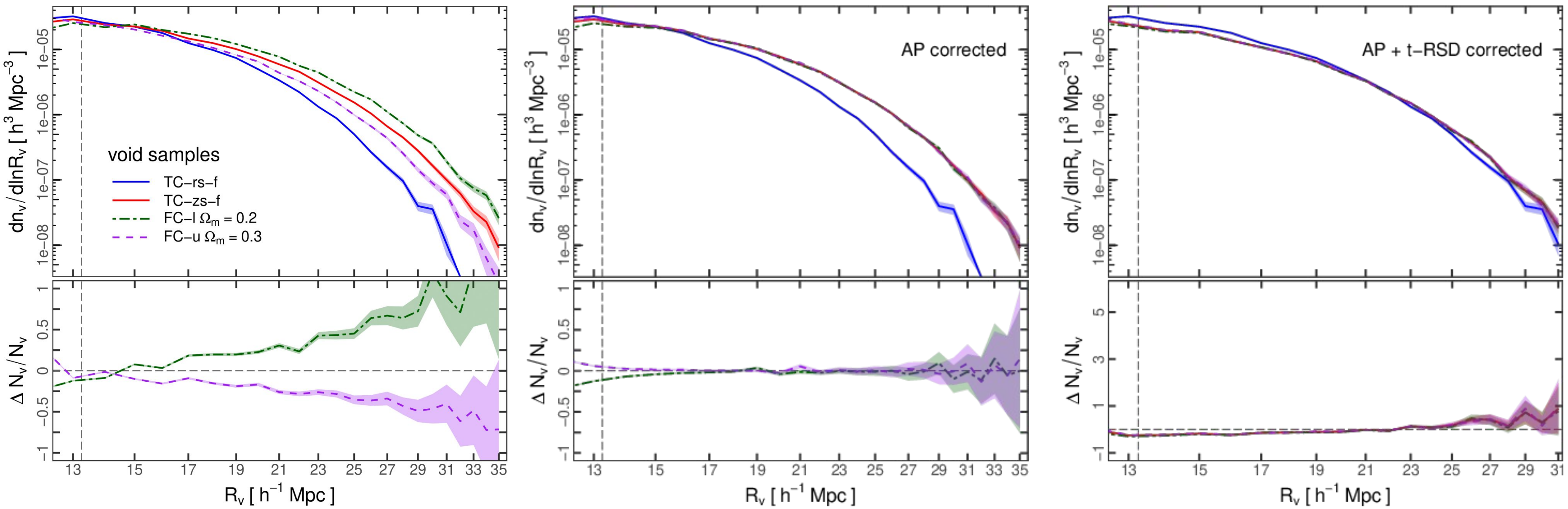
$$s_{\mathrm{v}} = r_{\mathrm{v}} + V_{\mathrm{v}\parallel} \frac{(1+z)}{H(z)}$$



v-RSD off-centring

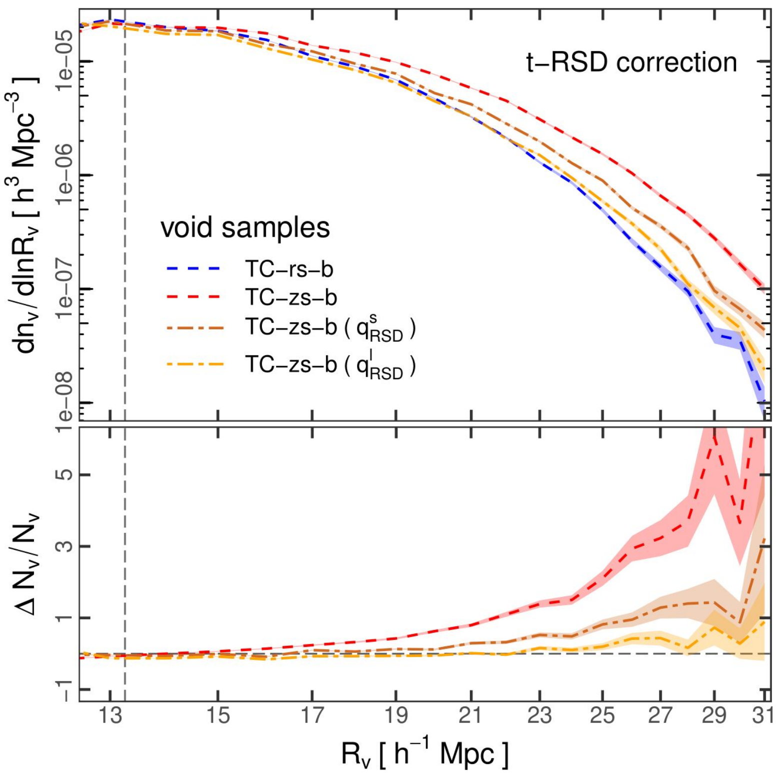
Millennium XXL simulation data

Impact on the void size function



$$R_V^{zs} = q_{AP}\ q_{RSD}\ R_V^{rs}$$

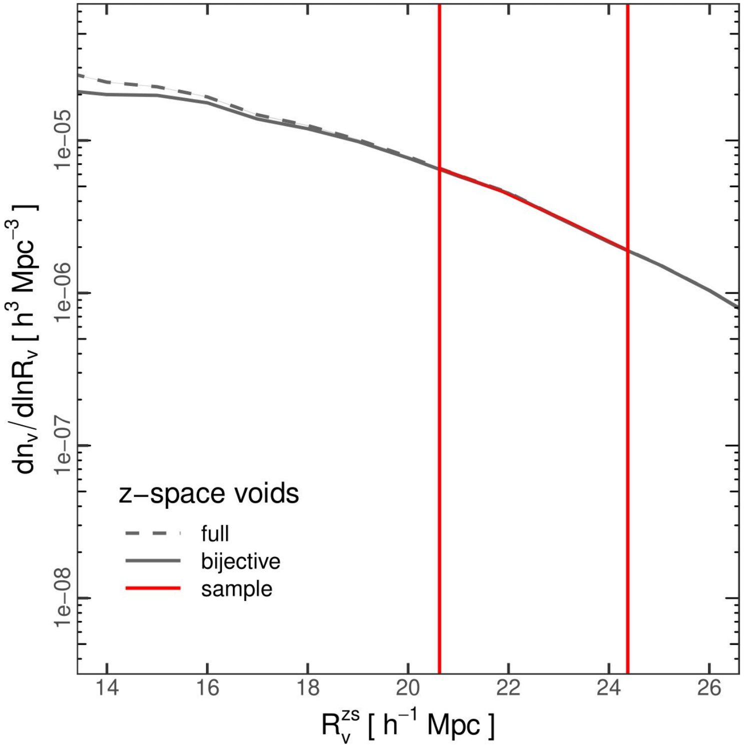
Impact on the void size function (cont.)



Extra slides V: redshift-space effects: the void-galaxy correlation function

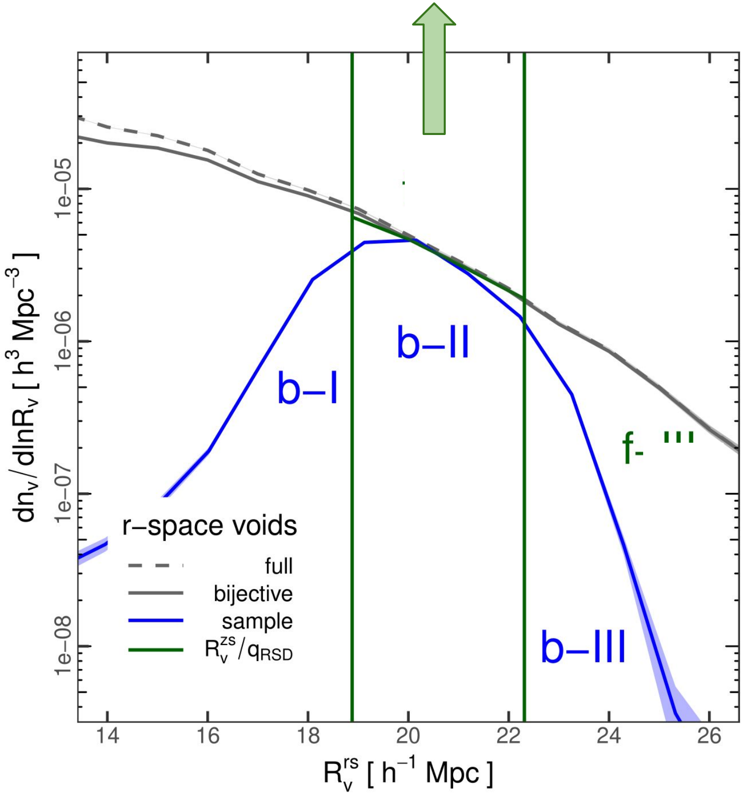
- **arXiv [2107.01314]** Redshift-space effects in voids and their impact on cosmological tests. Part II: the void-galaxy cross-correlation function
- **arXiv [2205.13604]** Cosmology with cosmic voids

Void samples



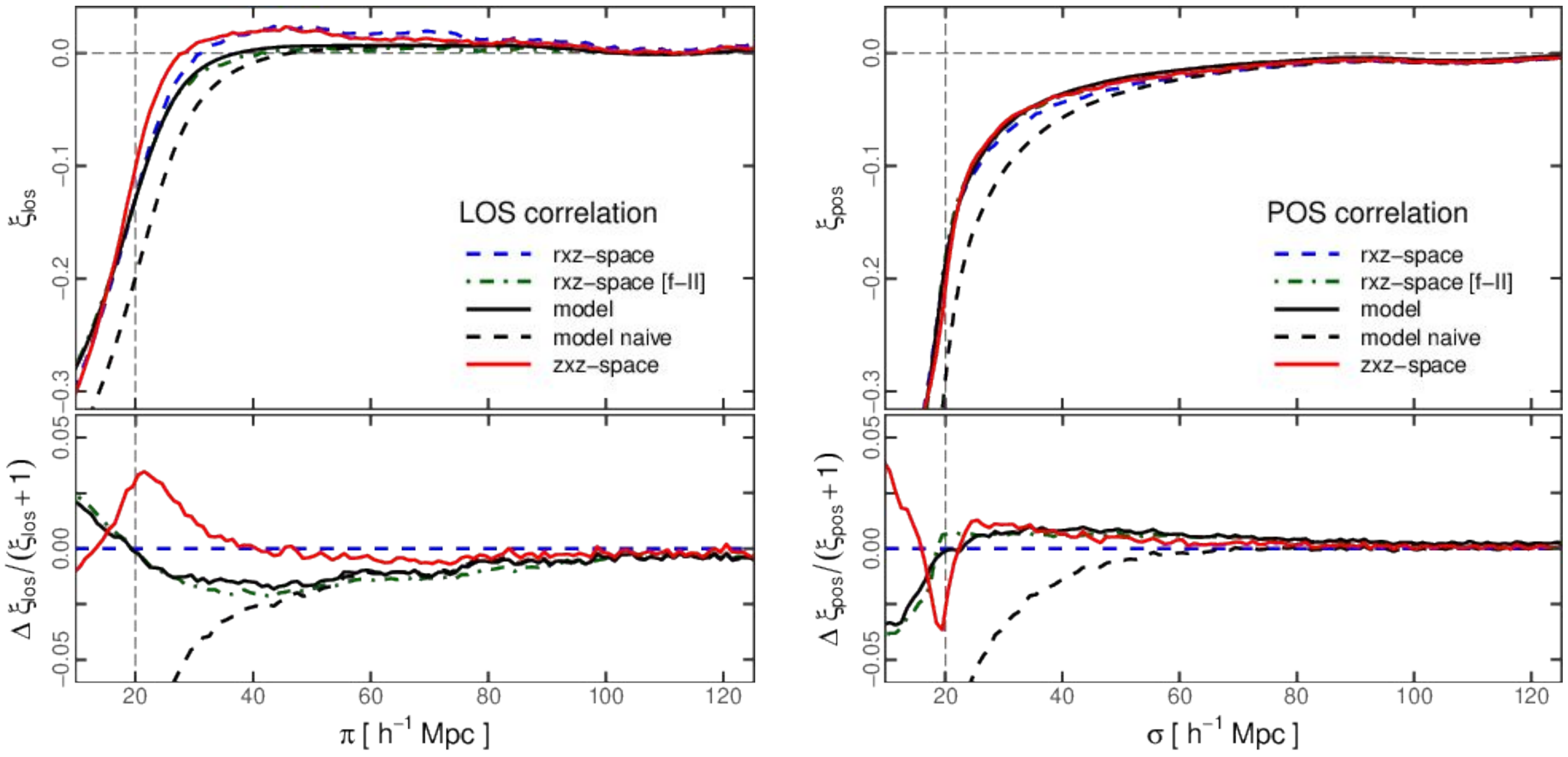
volume correction

$$R_v^{zs} = q_{AP}\ q_{RSD}\ R_v^{rs}$$

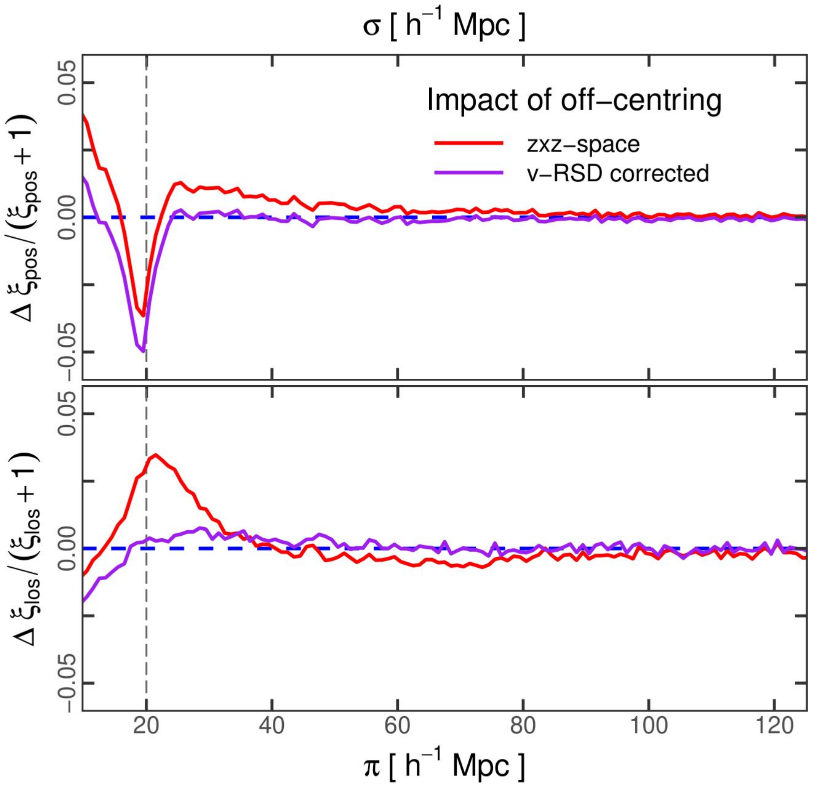


Millennium XXL Simulation data

Impact on the correlation function

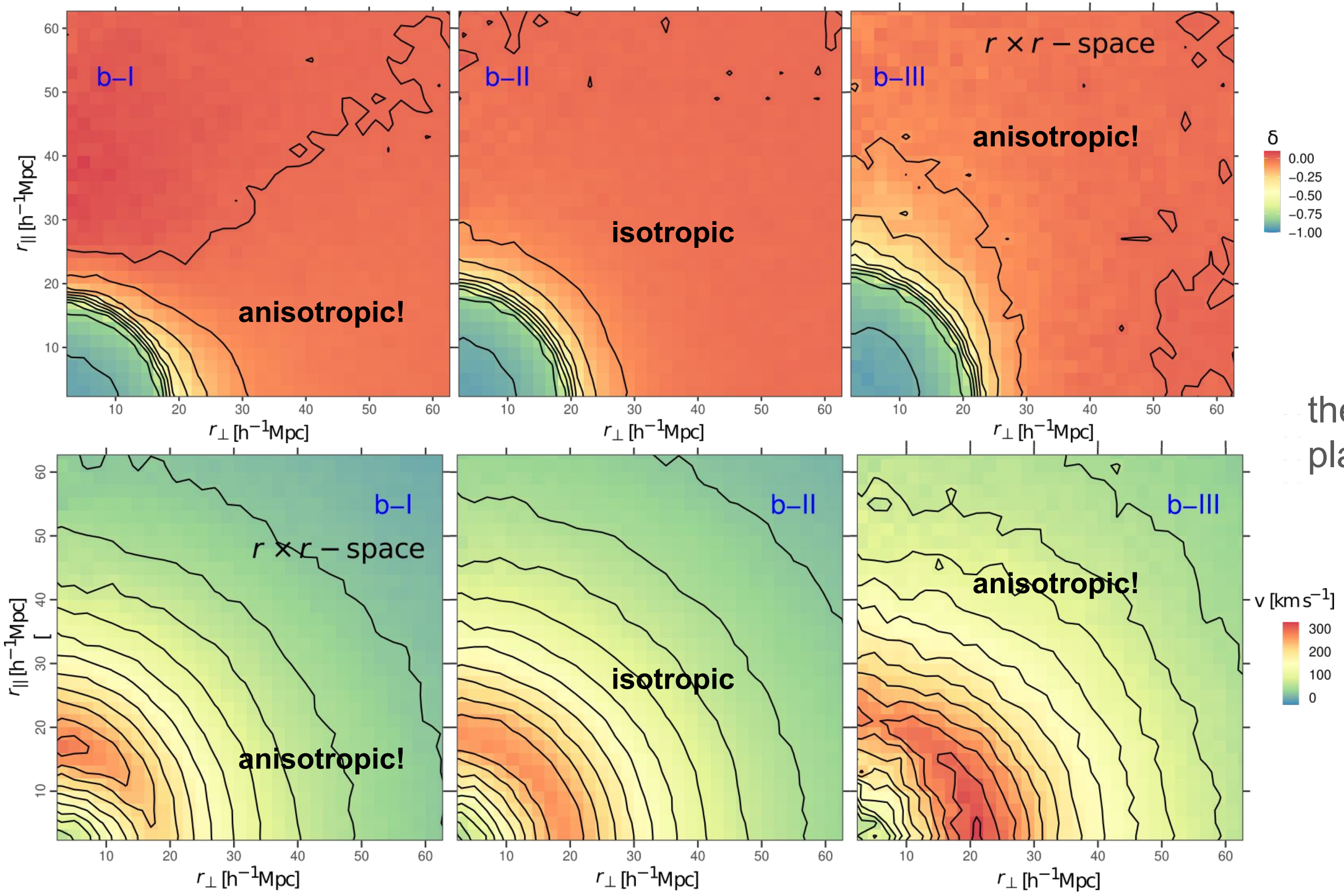


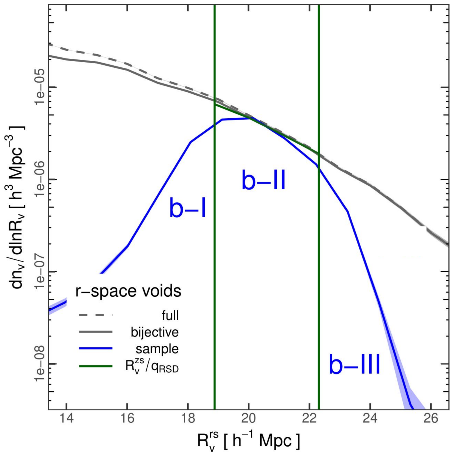
Contribution due to off-centring (v-RSD)



$$s_{\rm v} = r_{\rm v} + V_{\rm v\parallel}\frac{(1+z)}{H(z)}$$

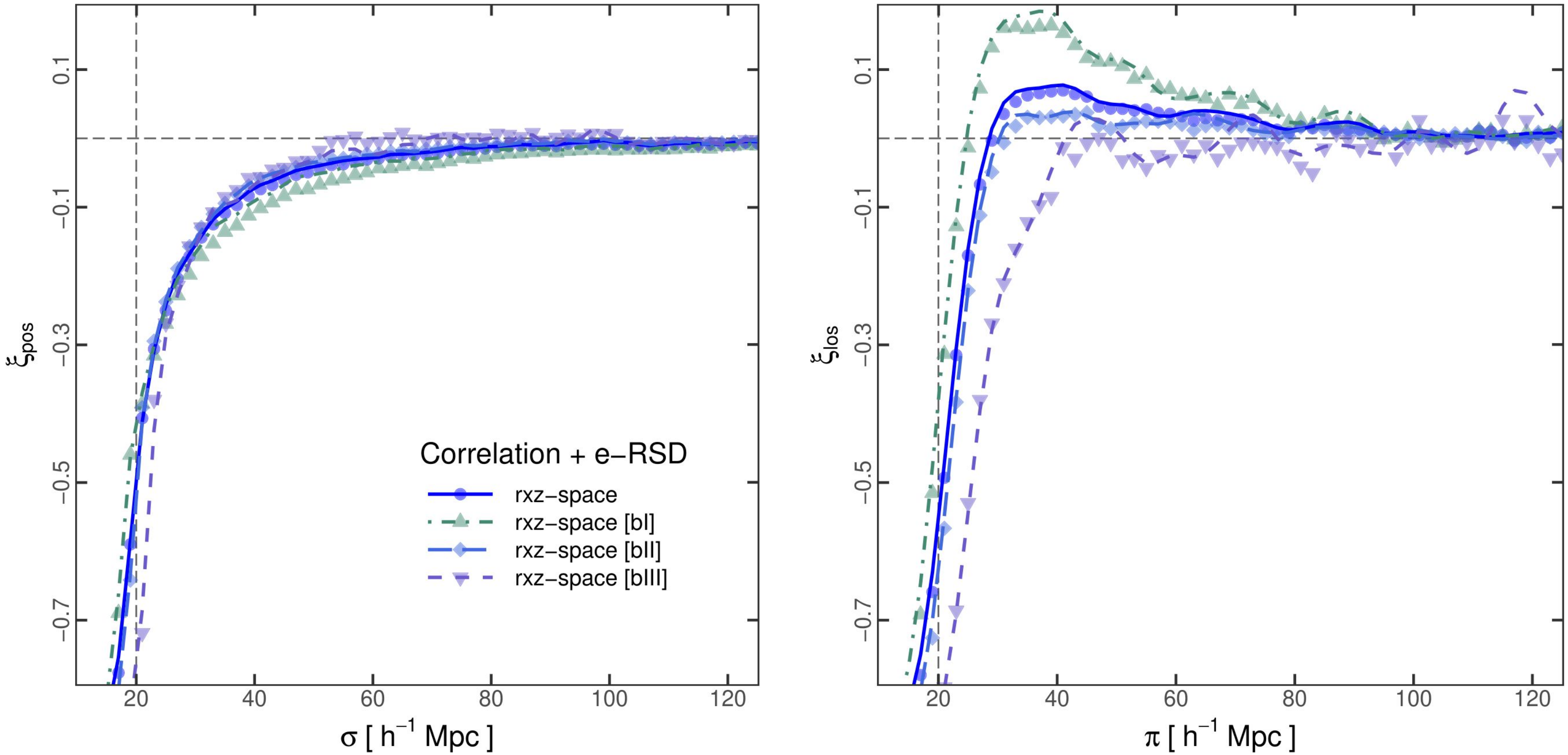
Void ellipticity (e-RSD)



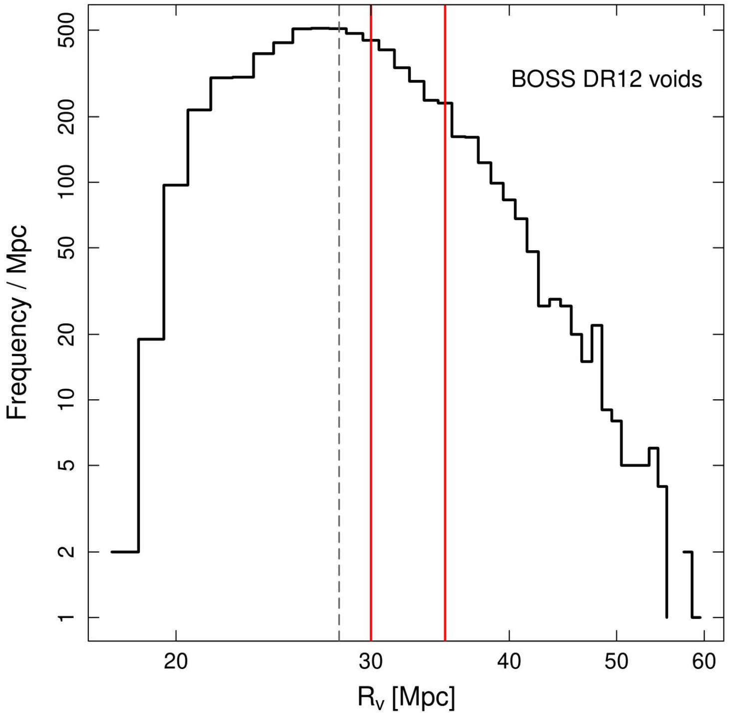


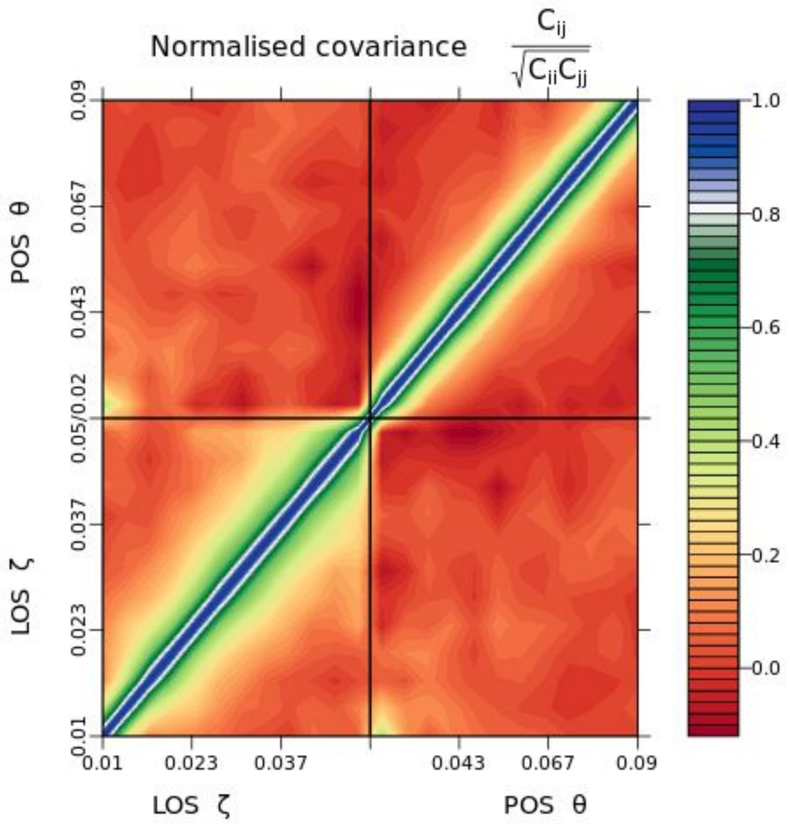
the intrinsic **ellipticity** of voids plays a very significant role

Void ellipticity (e-RSD)

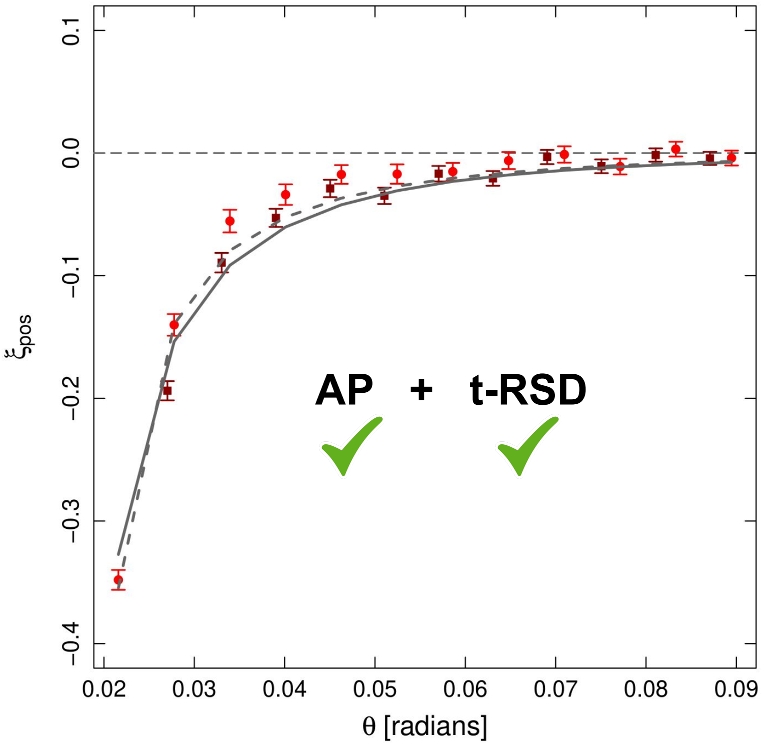


BOSS DR12 analysis

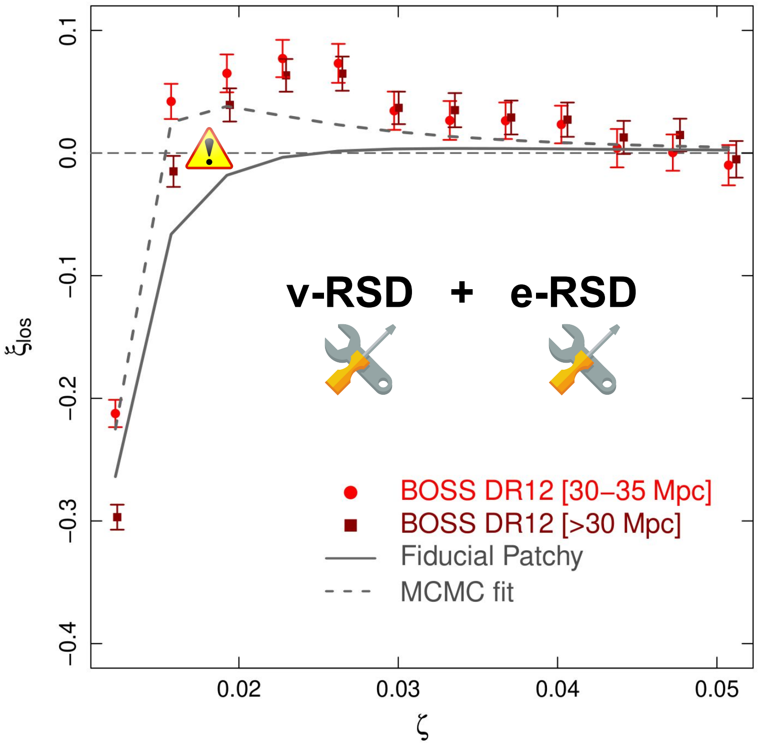




BOSS DR12 analysis



POS projection



LOS projection