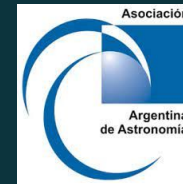


Cosmic voids as cosmological laboratories

Carlos M. Correa
OPINAS - MPE

Collaborators:

- ❖ Dante Paz
- ❖ Ariel Sánchez
- ❖ Nelson Padilla
- ❖ Andrés Ruiz
- ❖ Raúl Angulo



Cosmology from Home
3-14 July 2023

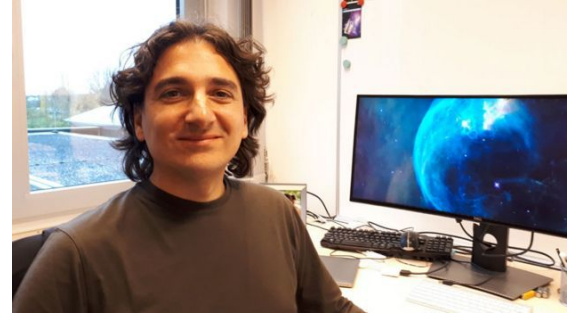
The “void” team



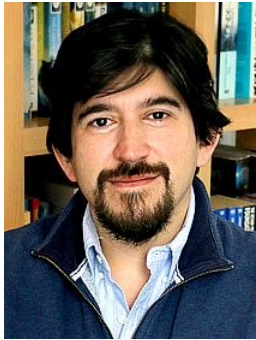
Carlos Correa



Dante Paz



Ariel Sánchez



Nelson Padilla



Andrés Ruiz



Raúl Angulo

Goals of my talk

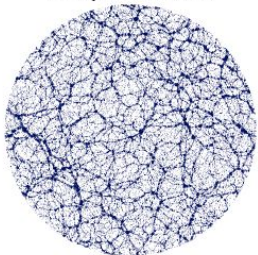
1) High precision cosmology with 2 void statistics:

- Void size function (void abundance)
- Void-galaxy correlation function

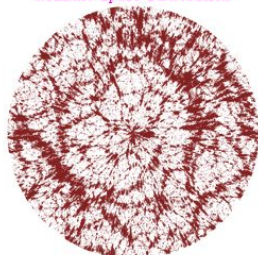
2) Impact of spatial distortions:

- **dynamical** (Kaiser effect, **RSD**)
- **geometrical** (Alcock-Paczynski effect, **AP**)

Real Space Distribution



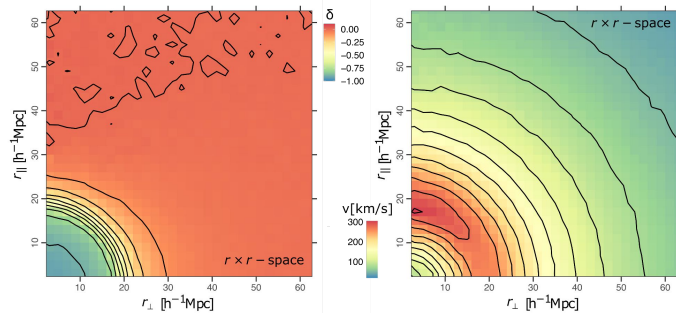
Redshift Space Distribution



we identify voids here!!

3) Redshift-space mapping of voids. New effects!:

- **dynamical** (Kaiser effect, **RSD**)
 - **tracer** dynamics (t-RSD)
 - **void** dynamics (v-RSD)
- **geometrical** (Alcock-Paczynski effect, **AP**)
- **structural** (ellipticity effect, **e-RSD**)



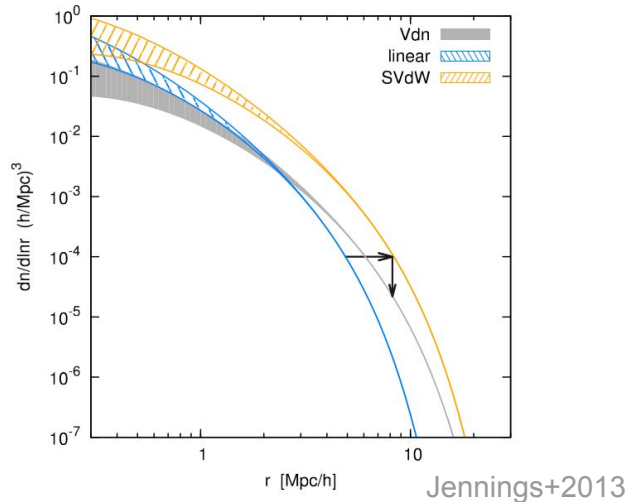
anisotropies in real space!!

Introduction

Statistical tools

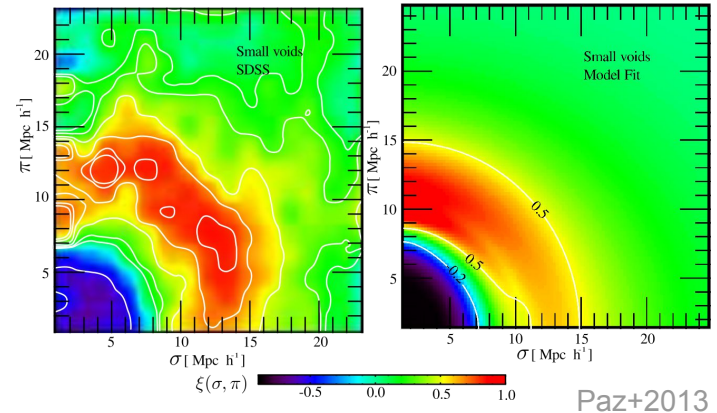
1) Void size function

- Characterises the **abundance** of voids.
- Analogous to the dark-matter halo mass function. It can be modelled by means of the **excursion set** theory + **spherical evolution** (expansion + collapse).



2) Void-galaxy correlation function

- Characterises the **density-fluctuation field** around voids.
- The **anisotropic patterns** observed on the 2D correlation maps are a valuable source of **dynamical** and **cosmological** information due to **spatial distortions (RSD, AP)**.



Pay attention to distortions!

⚠ It is extremely important to consider a **complete description** of the effects of **spatial distortions** (**dynamical** and **geometrical**) around voids in order to obtain **unbiased cosmological constraints**.

⚠ They do not only affect the galaxy positions! They also affect **global statistical properties** of voids. **New effects!**

⚠ They affect **both statistics**: VSF and vgCF!

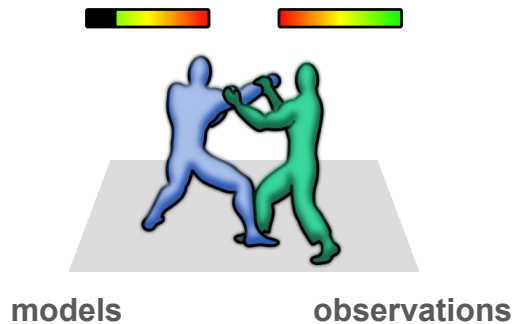
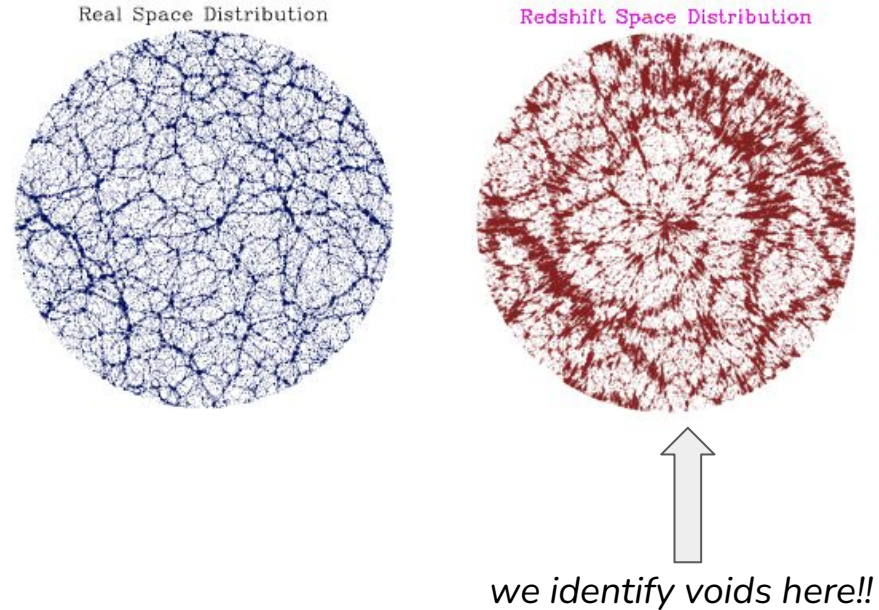


Fig. credit: Brian C. Thomas



Approaches [correlation function]

1) Reconstruction

- Nadathur+2019
- Recover approximately the real-space position of galaxies using the **Zeldovich equation** for the displacement field in redshift space.
- Prior to the void identification step. Iterative process.
- The analysis is performed with **real-space voids** (centres) and **redshift-space galaxies**.

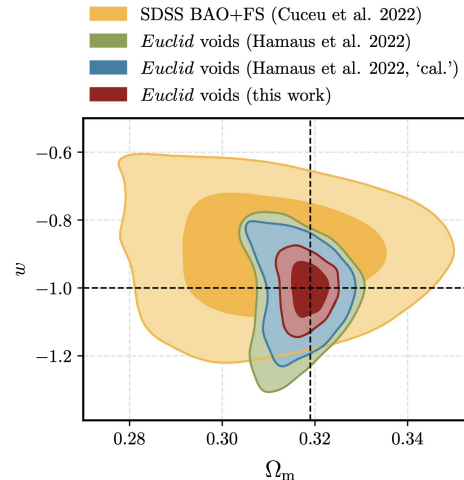
Why an **alternative** approach?

- **Hidden physics** in void systematics
- Learn more about **dynamics** and **structure** of voids
- **Physical models** enrich the tests

2) Parametric

- Hamaus+2020
- They include two additional **nuisance parameters** in the theoretical model to account for systematics: M (**monopole like**) and Q (**quadrupole like**).

$$\xi^S(s_{\perp}, s_{\parallel}) = \mathcal{M} \left\{ \xi(r) + \frac{f}{b} \bar{\xi}(r) + 2Q \frac{f}{b} \mu^2 [\xi(r) - \bar{\xi}(r)] \right\}$$

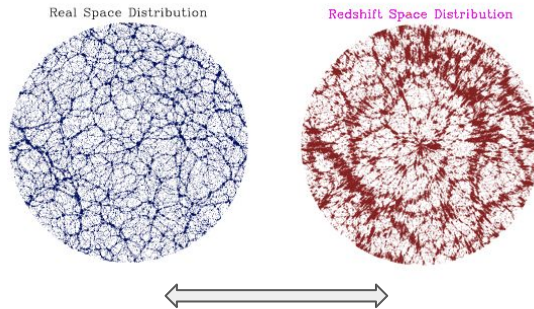


Radinović+2023
Euclid forecast

Approaches [correlation function]

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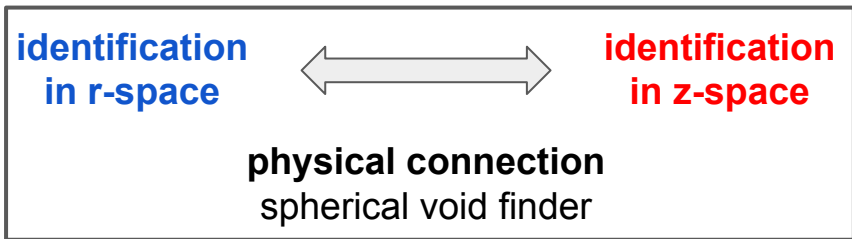
$$\xi^s(s_{\perp}, s_{\parallel}) = \mathcal{M} \left\{ \xi(r) + \frac{f}{b} \bar{\xi}(r) + 2Q \frac{f}{b} \mu^2 [\xi(r) - \bar{\xi}(r)] \right\}$$

3) Redshift-space mapping of voids

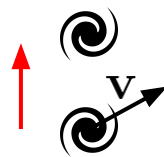
- Correa+2021
- Find a **physical connection** between the two void populations identified in **real space** and **redshift space**.
- We use the **spherical void finder**.
- Physically-motivated model based on **dynamical** and **cosmological** grounds.
- Applicable to **both statistics**: VSF and vgCF.

Redshift-space effects in voids

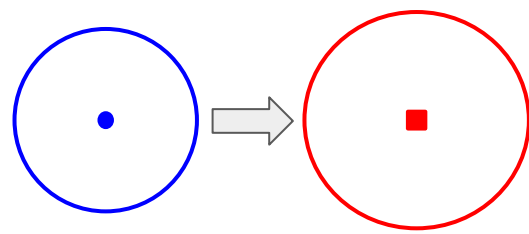
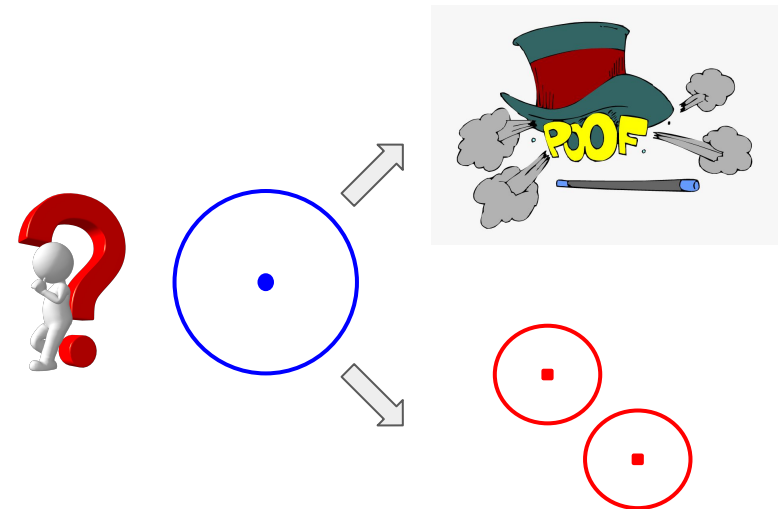
Redshift-space mapping of voids



- ❖ 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.



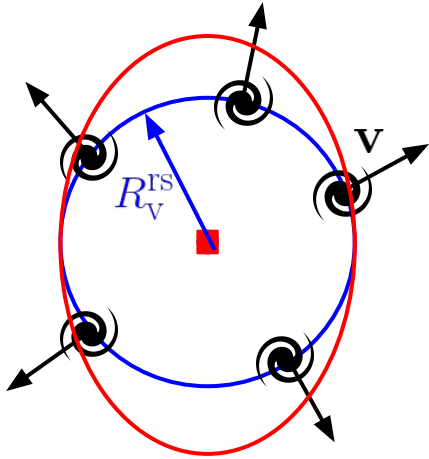
$$s = r + v_{\parallel} \frac{(1+z)}{H(z)}$$



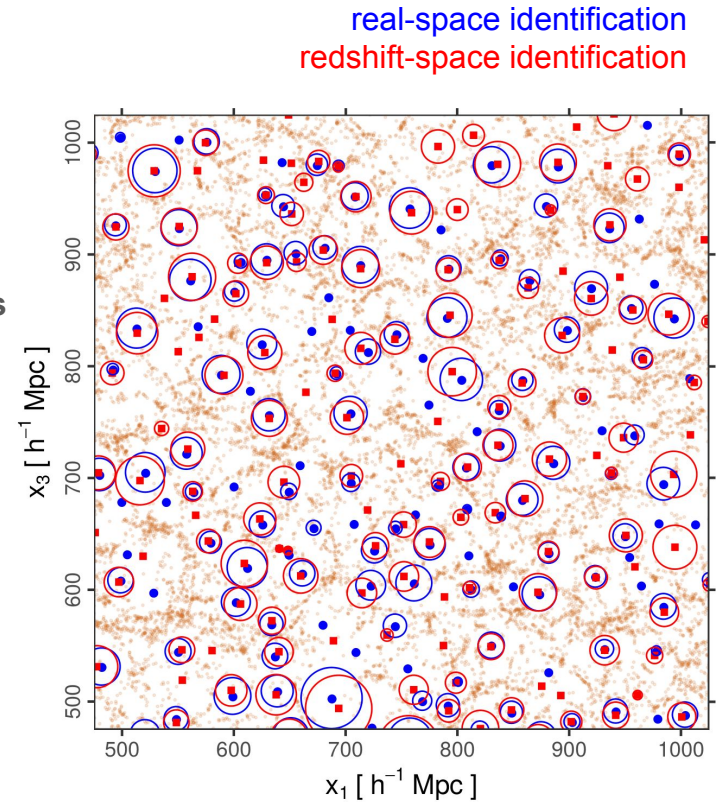
conserved above the shot noise level!

Redshift-space effects

Correa+2021 [arXiv:2007.12064]



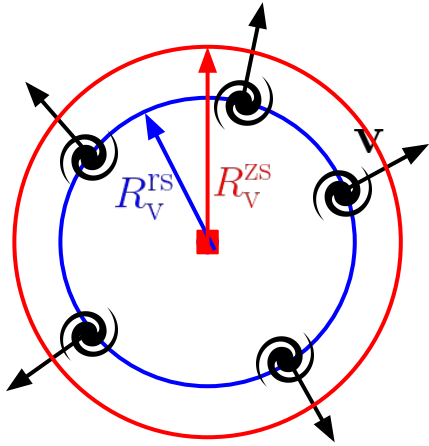
- **Void number conservation**
above the shot-noise level
- **1) Expansion (t-RSD)**
classical RSD induced by **tracer dynamics**



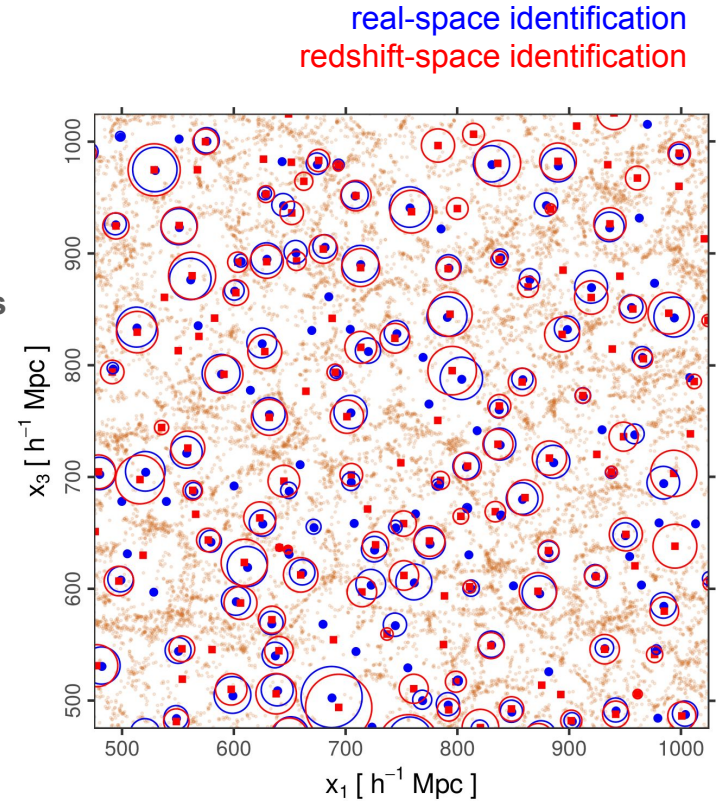
Correa+2021
Millennium XXL data

Redshift-space effects

Correa+2021 [arXiv:2007.12064]



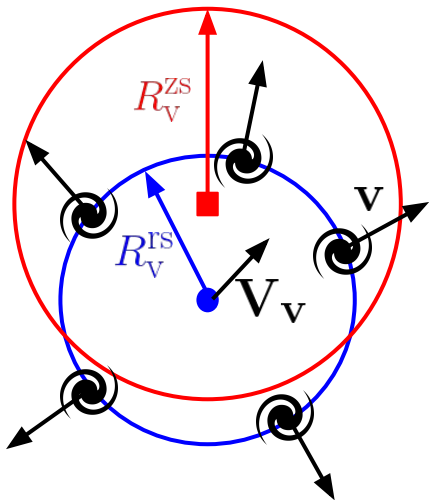
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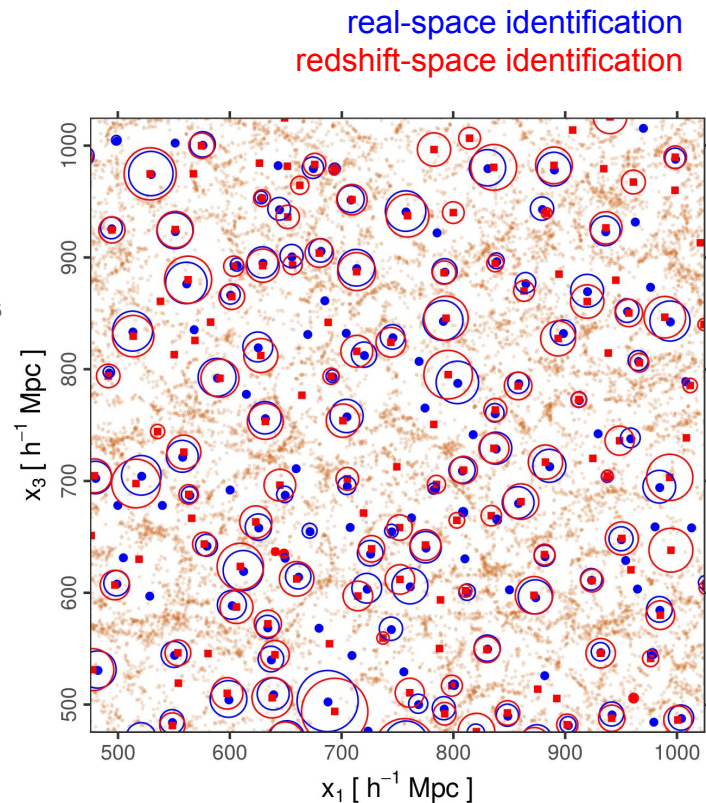
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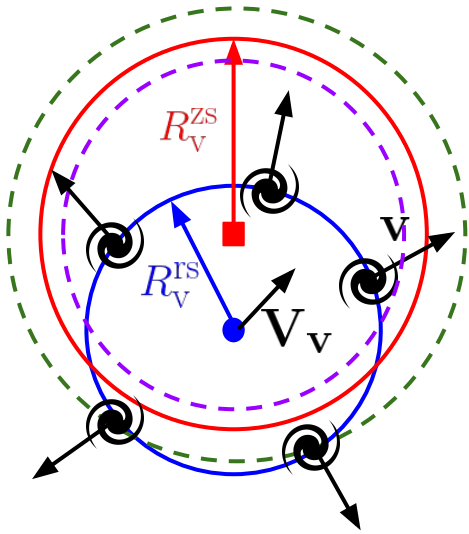
- **Void number conservation**
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- **2) Off-centring (v-RSD)**
new type of RSD induced by the global **void dynamics**



Correa+2021
Millennium XXL data

Redshift-space effects

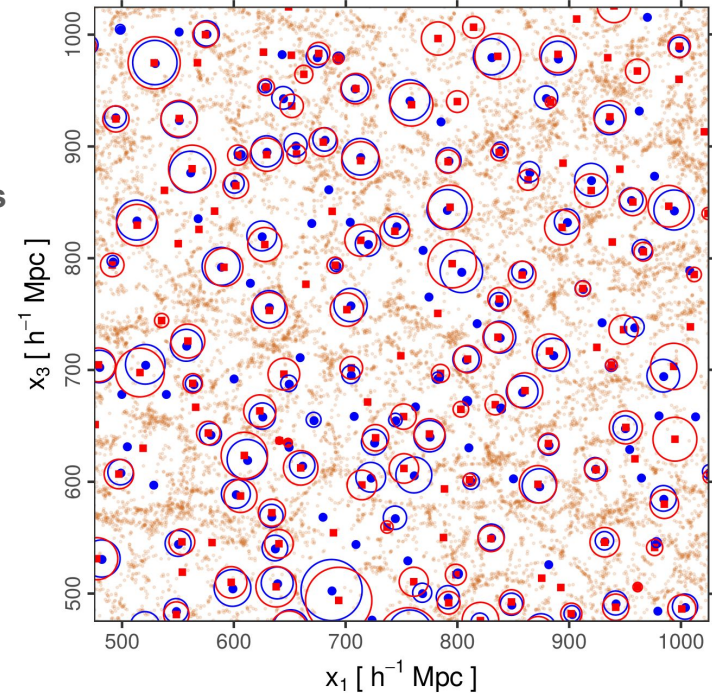
Correa+2021 [arXiv:2007.12064]



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- **3) AP volume effect**
fiducial cosmology (expansion or contraction)



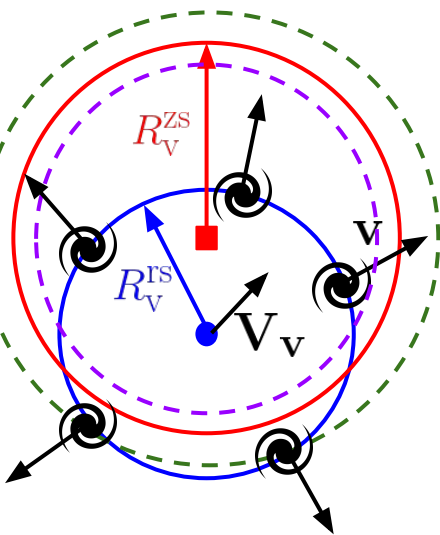
real-space identification
redshift-space identification



Correa+2021
Millennium XXL data

Redshift-space effects

Correa+2021 [arXiv:2007.12064]



- **Void number conservation**
above the shot-noise level
- **1) Expansion (t-RSD)**
classical RSD induced by **tracer dynamics**
- **2) Off-centring (v-RSD)**
new type of RSD induced by the global **void dynamics**
- **3) AP volume effect**
fiducial cosmology (expansion or contraction)

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

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

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

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

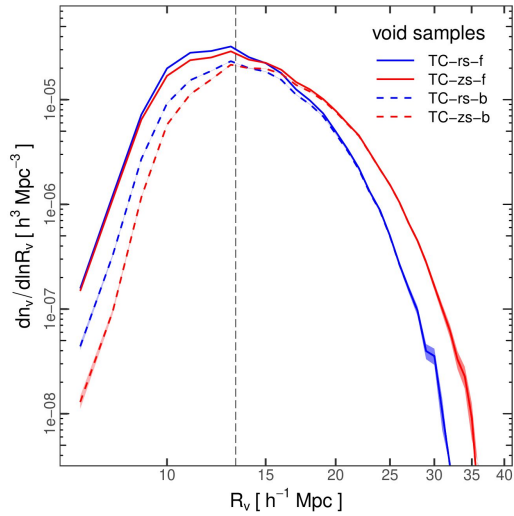
$$s_v = r_v + V_{v\parallel} \frac{(1+z)}{H(z)}$$

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

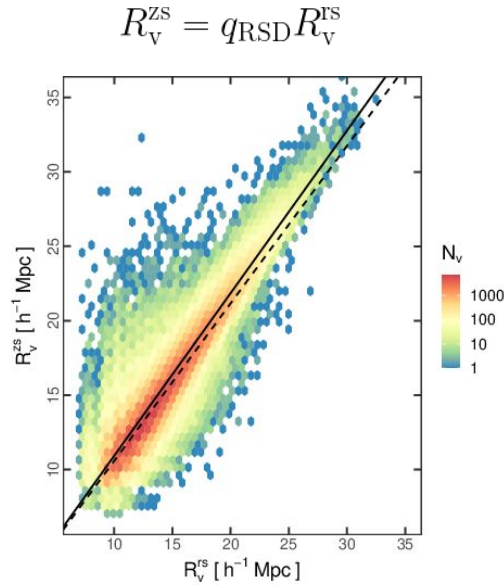
$$\{\Omega_m, \Omega_\Lambda, h, \beta = f/b\}$$

Redshift-space effects

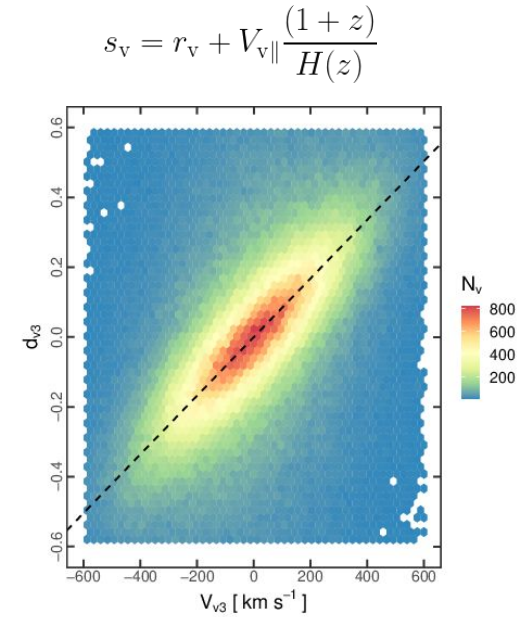
Correa+2021 [[arXiv:2007.12064](https://arxiv.org/abs/2007.12064)]



Number conservation



t-RSD expansion



v-RSD off-centring

Correa+2021
Millennium XXL data

Impact on the cosmological statistics:

- *the void size function*
- *the void-galaxy correlation function*

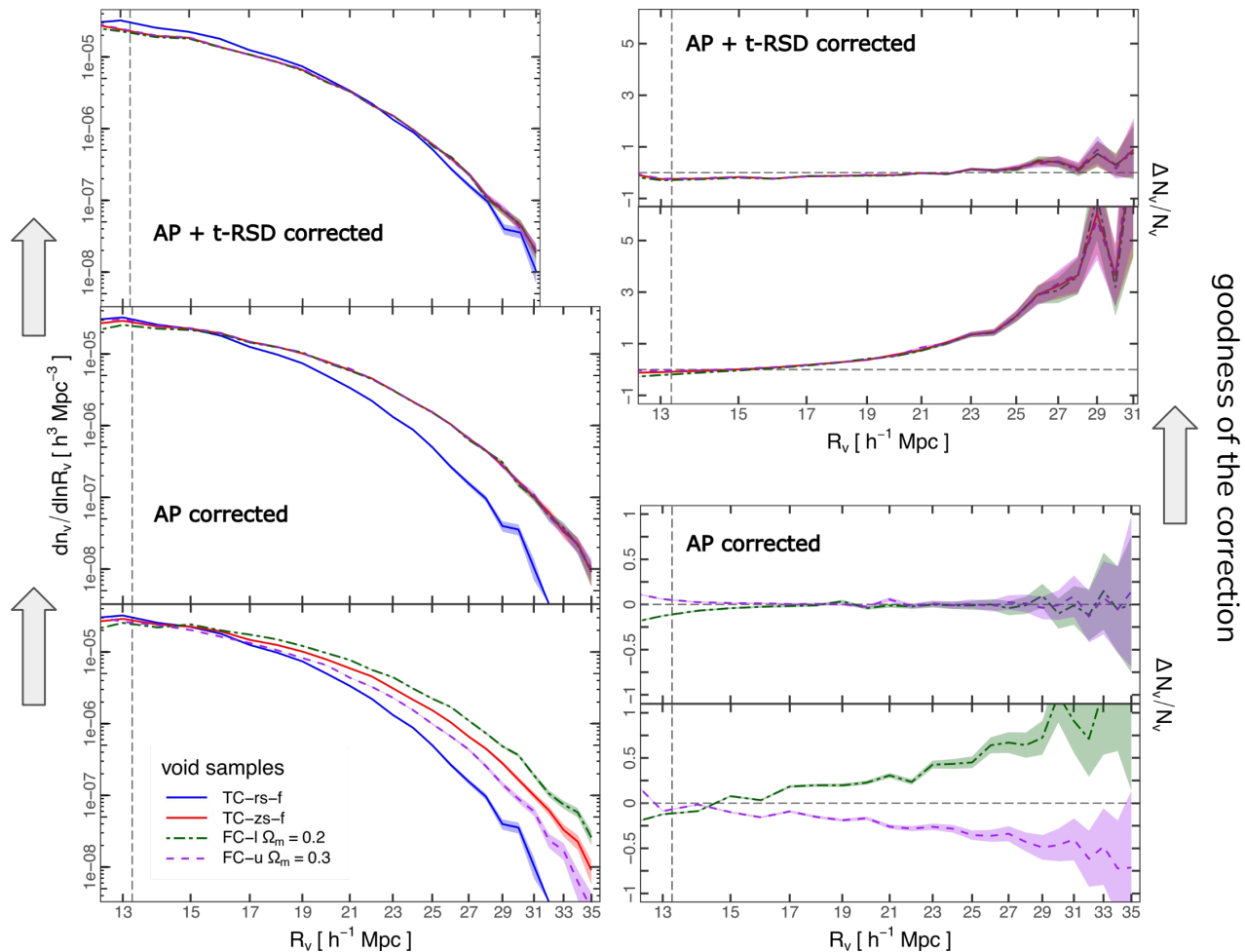
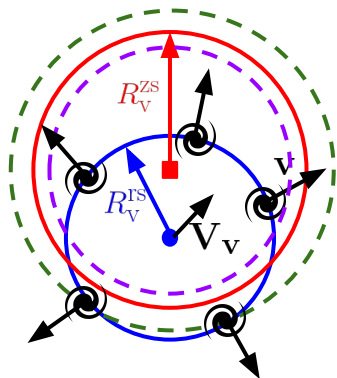
Void size function

Correa+2021 [arXiv:2007.12064]

AP + t-RSD + ~~v-RSD~~

$$R_V^{ZS} = q_{AP} q_{RSD} R_V^{RS}$$

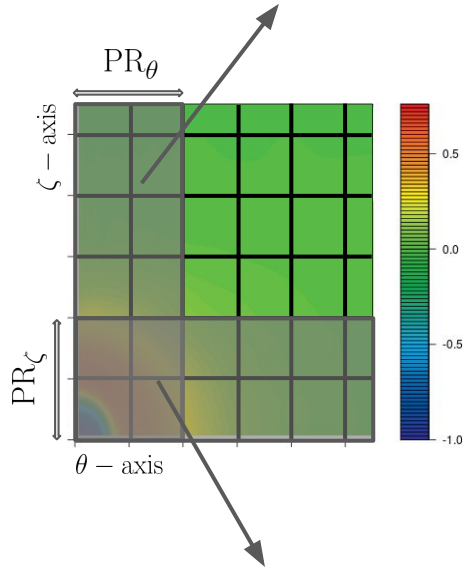
excursion set
+
spherical evolution



Projected correlations

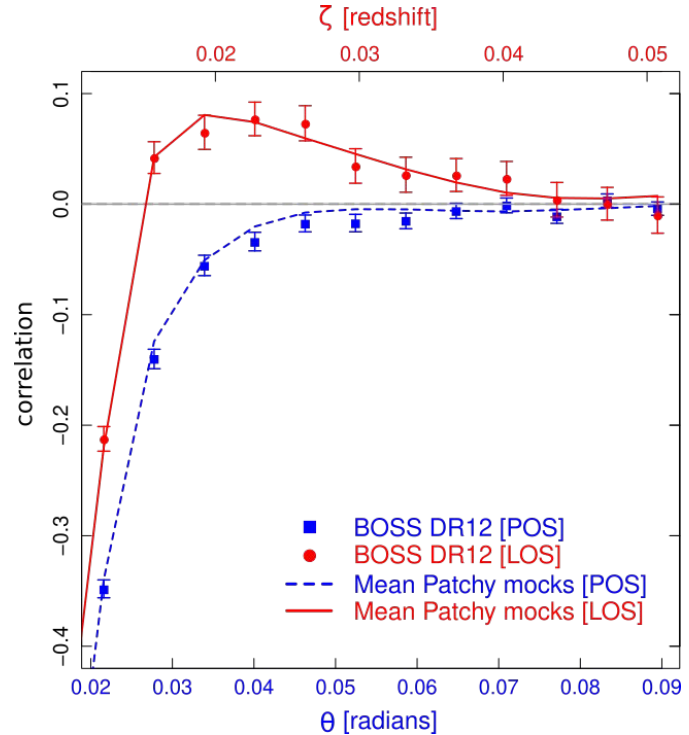
Correa+2019 [arXiv:1811.12251]; Correa & Paz 2022 [arXiv:2205.13604]

line-of-sight correlation function $\xi(\theta, \zeta) \longrightarrow \xi_{\text{los}}(\zeta)$



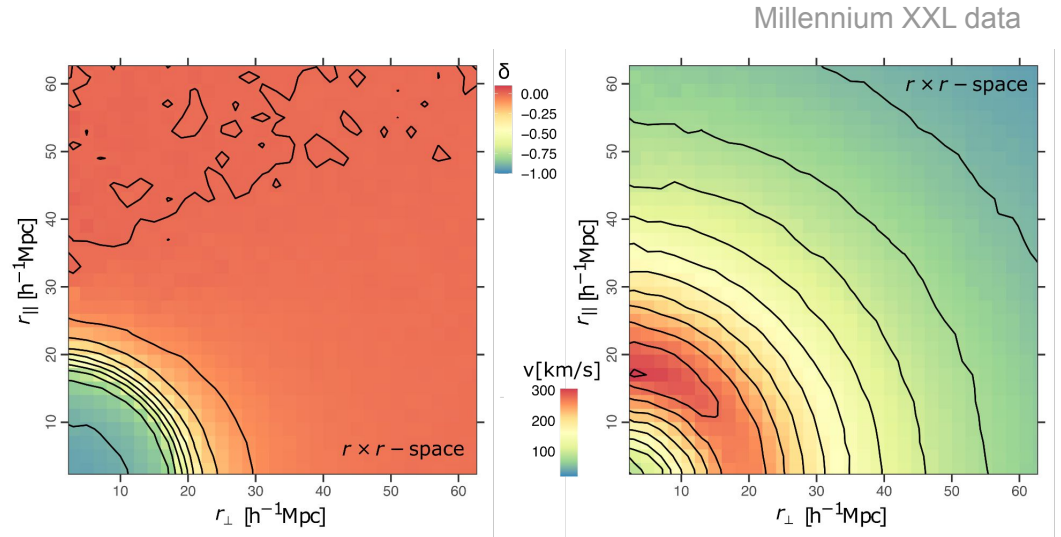
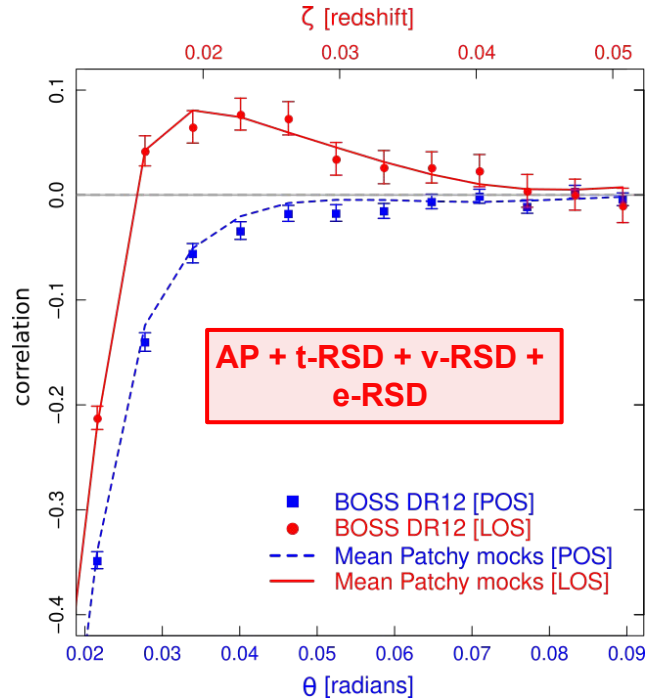
- **Maximise** the way in which we extract information from **anisotropic patterns** on correlation maps.
- **LOS projection** is very sensitive to the z-space effects in voids
- Excellent **signal-to-noise** ratio

plane-of-sky correlation function $\xi(\theta, \zeta) \longrightarrow \xi_{\text{pos}}(\theta)$



Anisotropies in real space!

Correa+2022 [arXiv:2107.01314]



- **Density and velocity maps** in of void samples show prominent **anisotropic patterns in real space!**
- Voids are ellipsoidal rather than spherical: **ellipticity effect (e-RSD)**

Conclusions

Conclusions

- **Cosmic voids** are promising cosmological probes for testing the **dark-energy** problem and **alternative gravity theories**.
- High precision cosmology with the **void size function** (abundance) and the **void-galaxy correlation function**.
- It is extremely important a **complete description** of the effects of **geometrical (AP)** and **dynamical (RSD)** distortions around voids in order to obtain **unbiased cosmological constraints**.
- **Redshift-space mapping of voids**: we developed a theoretical and statistical framework to address this problematic based on **cosmological** and **dynamical** grounds.
- New effects!: **AP-volume**, **expansion (t-RSD)**, **off-centring (v-RSD)**, **ellipticity (e-RSD)**.
- The **projected correlations** allow us to:
 - maximise the extraction of information from the **anisotropic patterns** on correlation maps.
 - significantly reduce the number of mock catalogues needed to estimate **covariances**.

Thank you for your attention!
contact: ccorrea@mpe.mpg.de

References to my work [arXiv]:



- [\[2210.17459\]](#) (PhD thesis)
- [\[1811.12251\]](#) (Projected correlations)
- [\[2007.12064\]](#) (Redshift-space effects I)
- [\[2107.01314\]](#) (Redshift-space effects II)
- [\[2205.13604\]](#) (Voids in a nutshell)