Cosmic voids as cosmological laboratories

Carlos Mauricio Correa Fayn

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The “void” team

Carlos Correa

Dante Paz (PhD supervisor)

Ariel Sánchez

Nelson Padilla

Andrés Ruiz

Raúl Angulo
Introduction & goals
Era of high-precision Cosmology

The Universe is not only expanding, but it is also accelerating.

The standard model postulates a flat-$\Lambda$CDM 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.

we ignore the 95% true nature of the Universe!!
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

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

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

Padilla et al. 2005; Ruiz et al. 2015

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)

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**cosmological information!**
Distortions: RSD & AP effects

RSD (Kaiser 1987)

\[ 1 + z_{\text{obs}} = (1 + z_{\text{cos}})(1 + z_{\text{pec}}) \]
\[ s = r + v \frac{(1 + z)}{H(z)} \]

AP (Alcock & Paczyński 1979)

\[ D_M(z), H(z) \quad [\Omega_m, \Omega_\Lambda, h] \]
\[ (x_1, x_2, x_3) \quad [h^{-1}\text{Mpc}] \]

Dynamical effect

Geometrical effect

Figure credit: Brian C. Thomas
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 $\xi(r)$, **spherical symmetry**
- **Redshift-space**: 2D map $\xi(\sigma, \pi)$, **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)

Paz et al. 2013

Dynamical information!
Projected correlations

Correa et al. 2019

\[ \xi(\theta, \zeta) \rightarrow \xi_{\text{los}}(\zeta) \]

**line-of-sight** correlation function

\[ \xi(\theta, \zeta) \rightarrow \xi_{\text{pos}}(\theta) \]

**plane-of-sky** correlation function

★ **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

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

\[ \xi[m \times m] \rightarrow C[m^2 \times m^2] \]
\[ \xi[2m] \rightarrow C[m \times m] \]
Projected correlations: performance

Correa et al. 2019

Millennium XXL simulation data
Redshift-space effects in voids

- 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

<table>
<thead>
<tr>
<th>identification in r-space</th>
<th>identification in z-space</th>
</tr>
</thead>
<tbody>
<tr>
<td>physical connection</td>
<td>spherical void finder</td>
</tr>
</tbody>
</table>

- **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**

\[
s = r + v \frac{(1 + z)}{H(z)}
\]
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

- 1) Void number conservation: above the shot-noise level
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Millennium XXL simulation data
• 1) Void number conservation: above the shot-noise level

• 2) Expansion (t-RSD): classical RSD induced by tracer dynamics

• 3) Off-centring (v-RSD): new type of RSD induced by the global void dynamics

real-space identification
redshift-space identification

Millennium XXL simulation data
Redshift-space effects

1) Void number conservation: above the shot-noise level
2) Expansion (t-RSD): classical RSD induced by tracer dynamics
3) Off-centring (v-RSD): new type of RSD induced by the global void dynamics
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

1) Void number conservation: above the shot-noise level

2) Expansion (t-RSD): classical RSD induced by tracer dynamics

3) Off-centring (v-RSD): new type of RSD induced by the global void dynamics

4) AP volume effect: fiducial cosmology (expansion or contraction)

5) Independence of the effects

6) Intrinsic ellipticity (e-RSD)

\[ R_{V}^{ZS} = q_{AP} \, q_{RSD} \, R_{V}^{RS} \]

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

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

\[ q_{AP} = \frac{D_{M}^{fid}(z)}{D_{M}^{RS}(z)} \quad q_{AP} = \frac{H^{RS}(z)}{H^{fid}(z)} \]

\[ s_{V} = r_{V} + V_{V}^{\parallel} \left(1 + z\right) \frac{1}{H(z)} \]

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

\[ R_{V}^{ZS} = q_{RSD} R_{V}^{TS} \]

\[ s_{V} = r_{V} + V_{\parallel} \frac{(1 + z)}{H(z)} \]

**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

**PROJECTED CORRELATIONS**

References

- Present and modelled
- Present, model in process
- Absent

New effects not taken into account previously

Impact on the cosmological statistics

**VSF**

**PROJECTED CORRELATIONS**

- BOSS DR12 [POS]
- BOSS DR12 [LOS]
- Mean Patchy mocks [POS]
- Mean Patchy mocks [LOS]
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
Thank you for your attention!

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

contact: cmcorrea@unc.edu.ar
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.

- **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.

**VSF theory**: excursion set + spherical evolution

**VSF observations**: t-RSD + AP effects

- **Bias relation**
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: $8.46 \times 10^9 \, h^{-1} M_{\odot}$
  - Periodic box: $3000 \, h^{-1} Mpc$

- Standard cosmology **flat-ΛCDM**
  - $h = 0.73$
  - $\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$
  - $z_{box} = 0.51$, 0.99 and 1.50

- **Dark matter haloes**: lower mass cut: $5 \times 10^{11} \, h^{-1} M_{\odot}$
  ($\sim 140 \times 10^6$ haloes)
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

BOSS spectroscopic survey
Dawson et al. 2013

- 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 \((\theta, \zeta)\)
  - real space \((r_\perp, r_\parallel)\)
  - redshift space \((\sigma, \pi)\)

\[
\begin{align*}
  \sigma &= D_M(z) \theta \\
  \pi &= \frac{c}{H(z)} \zeta \\
  r_\perp &= \sigma_{tc} \\
  r_\parallel &= \pi_{tc} - v_{||} \frac{1 + z}{H(z)}
\end{align*}
\]
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

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

\[ \xi(\theta, \zeta) \rightarrow \xi_{\text{los}}(\zeta) \]

**line-of-sight** correlation function

\[ \xi(\theta, \zeta) \rightarrow \xi_{\text{pos}}(\theta) \]

**plane-of-sky** correlation function

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

![Graphs showing correlation functions](image-url)
Model

1. AP effect

\[ \{ \Omega_m, \beta \} \cup \{ \sigma_v, \xi_0, r_0, \alpha \} \]

2. Scale-mixing effect

AP RSD density

3. RSD:

Gaussian streaming model (Paz et al. 2013)

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

4. Real-space density profile:

Double power law (Correa et al. 2019)

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

5. Real-space velocity profile:

From linear perturbation theory (Paz et al. 2013)

\[ v(r) = -\frac{1}{3(1+z)} \frac{H(z)}{\beta(z)} r \Delta(r) \quad \beta(z) = \frac{f(z)}{b} \]

GR vs MoG
Covariance matrices

\[
\begin{align*}
\xi[m \times m] & \rightarrow C[m^2 \times m^2] \\
\xi[2m] & \rightarrow C[m \times m]
\end{align*}
\]

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

Parameters of the model

\[ \{ \Omega_m, \beta \} \cup \{ \sigma_v, \xi_0, r_0, \alpha \} \]

AP  RSD  density

Measurements
(POS and LOS projections)

Covariance matrix
(error information)

Likelihood analysis
(MCMC exploration)

Model

Cosmological constraints
(best parameters + confidence regions)

Test calibrated

Comparison with MXXL parameters

MXXL data
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 barriers**, one underdense (expansion, void-in-void) and one overdense (collapse, void-in-cloud)

\[ \Delta_v = -0.8 \quad 1.06 \leq \Delta_c \leq 1.686 \]

- **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)

\[
\frac{dn_v}{d\ln R_v} = \frac{f_{\ln\sigma}(\sigma)}{V(R_v)} \frac{d\ln\sigma^{-1}}{d\ln R_v}
\]

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

\[ D := |\Delta_v|/(\Delta_c + |\Delta_v|) \quad x := D\sigma/|\Delta_v| \quad \sigma^2(R) = \int \frac{k^2}{2\pi^2} P_m(k) |W(k, R)|^2 \, dk \]

\[
R_v = 1.7 \ R_v^L
\]

\[
\frac{dn_v}{d\ln R_v} = \frac{f_{\ln\sigma}(\sigma) \ d\ln\sigma^{-1}}{V(R_v)} \frac{d\ln R_v^L}{d\ln R_v}
\]
Extra slides IV: redshift-space effects: the void size function

Standard picture of distortions

- **Real space**
  - Low density
  - High density
  - Cluster

- **Redshift space**
  - Low density
  - High density
  - Cluster
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

\[ F_{AP} = \frac{D_M}{D_H} \]
Bijective mapping: void number conservation
Physical description

**dynamical**
- t-RSD expansion effect

\[ \nu(r) = -\frac{1}{3} \frac{H(z)}{(1 + z)} \beta(z) r \Delta(r) \]

**geometrical / cosmological**
- AP change of volume effect

**dynamical**
- v-RSD off-centring effect

\[ s_V = r_V + V_v \left[ \left( 1 + z \right) \right] \]

\[ \nu = 0.8 < r/R_v^{\text{RS}} < 1.2 \]

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

**volume / size**

\[ R_v^{ZS} = q_{AP} q_{RSD} R_v^{\text{RS}} \]

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

**LOS displacement**

\[ q_{AP} = \frac{H^{\text{RS}}(z)}{H^{\text{fid}}(z)} \]

\[ q^{\perp}_{AP} = \frac{D^{\text{fid}}_M(z)}{D^{\text{RS}}_M(z)} \]
Expansion effect (t-RSD)

\[ R^{zs}_V = q_{RSD} R^{rs}_V \]

\[ q_{RSD} = 1 - \frac{1}{3} \delta R_v \beta(z) \Delta_{id} \]

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

\[ q^l_{RSD} = 1 - \frac{1}{6} \beta(z) \Delta_{id} = 1.092 > 1 \]
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)

\[ s_v = r_v + V_v \frac{(1 + z)}{H(z)} \]
Off-centring effect (v-RSD)

\[ s_v = r_v + V_v \frac{(1 + z)}{H(z)} \]
Independence of the effects (t-RSD and v-RSD)
Statistical evidence

\[ R_{\nu}^{\text{ZS}} = q_{\text{RSD}} R_{\nu}^{\text{ZS}} \]

\[ s_{\nu} = r_{\nu} + V_{\nu} \left( \frac{1 + z}{H(z)} \right) \]

Number conservation

t-RSD expansion

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.)

[Diagram showing various lines and curves representing different void samples labeled as TC-rs-b, TC-zs-b, TC-zs-b (q_{RSD}), and TC-zs-b (q_{RSD}) on a logarithmic scale. The x-axis represents the void radius (h^{-1} Mpc) and the y-axis represents the derivative of the number density (dn/dlnRv) and the change in the number density ratio (ΔNv/Nv).]
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

\[ R_v^{zs} = q_{AP} q_{RSD} R_v^{rs} \]
Impact on the correlation function
Contribution due to off-centring (\(v\)-RSD)

\[
s_v = r_v + V_v \frac{(1 + z)}{H(z)}
\]
Void ellipticity (e-RSD)

The intrinsic ellipticity of voids plays a very significant role.
Void ellipticity (e-RSD)
BOSS DR12 analysis

![Histogram of BOSS DR12 voids](image)

![Normalised covariance matrix](image)
BOSS DR12 analysis

AP + t-RSD

POS projection

v-RSD + e-RSD

LOS projection