Study of the Nature of Cosmological Voids: A Thorough Statistical Analysis

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Outline

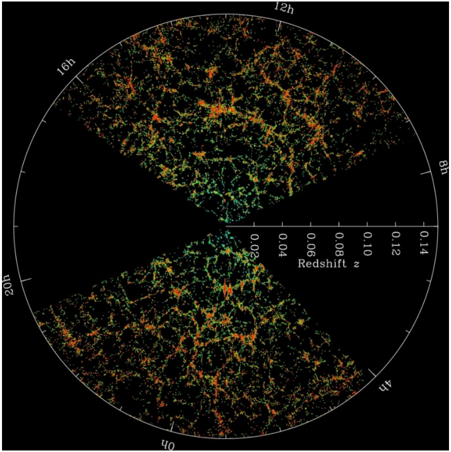
What Are Cosmological Voids?

Voids: Vast, underdense regions that occupy a significant fraction of the universe. They are important because:

- Help us understand the large-scale structure of the universe [Peebles, 1980].
- Provide insight into cosmological parameters like dark energy and dark matter [Sutter et al., 2015].
- Offer unique constraints on models of cosmic evolution [Ryden, 1995].

Key Characteristics of Voids

- **Size**: Voids can be 10s to 100s of megaparsecs in diameter.
- **Shape**: Voids are typically non-spherical and can be ellipsoidal due to gravitational influences [Lavaux & Wandelt, 2012].
- **Location**: Found between galaxy clusters and filaments in the cosmic web [Kirshner et al., 1981].



Visualization of cosmic voids in the

Why Study Voids?

Research Motivation:

- While clusters and filaments have been extensively studied, voids offer new insights into the low-density regions of the universe.
- Studying voids provides a different angle for understanding dark energy and cosmic expansion [Lavaux & Wandelt, 2012].
- Voids are naturally simpler environments, making them ideal for testing theories of cosmic evolution [Ryden, 1995].

Objective of this Research

- **Goal**: Perform a statistical analysis of voids using SDSS DR7 data and Planck 2018 cosmological parameters.
- Analyze:
  - Void size distribution.
  - Spatial distribution and clustering of voids.
  - Correlation with redshift.
  - Higher-order anisotropy in voids

History of Void Research

Early Discoveries:

- First observations of voids in galaxy redshift surveys in 1977 by *Gregory & Thompson* and *Joseph & Tully* [Gregory & Thompson, 1977].
- *Kirshner et al.* discovered the Boötes void, one of the largest known voids, in 1981 [Kirshner et al., 1981].
- Initial skepticism regarding the existence of voids due to survey limitations.

Voids in the 1980s and 1990s

Key Developments:

- *Melott* (1987) explored the relationship between void size and the dominant type of matter in the universe (hot vs. cold dark matter) [Melott, 1987].
- *Ryden* (1995) investigated the structure of voids and proposed their use as cosmological tools [Ryden, 1995].
- *Dekel & Rees* (1993) studied void formation and properties in the context of different cosmological models [Dekel & Rees, 1993].

Challenges and Recent Advances

Challenges in Void Research:

- Systematic errors from irregular void shapes and peculiar velocities [Ryden, 1995].
- Difficulty in void detection due to sparse observational data.

Recent Breakthroughs:

- *Lavaux & Wandelt* (2012) introduced the concept of stacked voids, minimizing irregularities by averaging over many voids [Lavaux & Wandelt, 2012].
- The use of voids for cosmological parameter estimation using the Alcock-Paczynski test [Lavaux & Wandelt, 2012].

Void Detection Algorithms

Void Identification and Detection:

- Early void detection was manually intensive.
- Modern methods, like *VIDE* (Void IDentification and Examination), utilize sophisticated algorithms for void detection from large galaxy surveys [Sutter et al., 2015].

Data: SDSS DR7 Voids

Void Catalog: We utilized the void catalog developed by Douglass et al. (2024) from the SDSS DR7 dataset, which assumes Planck 2018 cosmology [Douglass et al., 2024]. Catalogs here

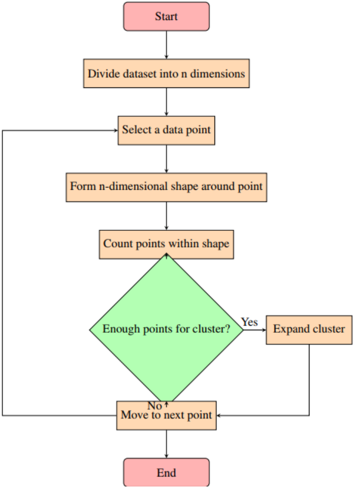
- Redshifts: $z = 0.015 - 0.110$.
- To put this redshift into perspective: Redshift of 0.110 means that the object is far away, approximately 1.5 billion light-years from us and Redshift of 0.015 means that the object is not too far from us on a cosmic scale, this corresponds to a distance of about 200 million light-years.
- Columns: Cartesian coordinates (x, y, z), radius, redshift, right ascension, declination, ellipsoid axes, surface area, and volume.

Void Size Distribution Analysis

- Examining the size distribution of voids based on effective radius.
- Detecting any evolutionary trends by correlating void size with redshift.
- Histogram of void size to identify the typical void sizes within the dataset.

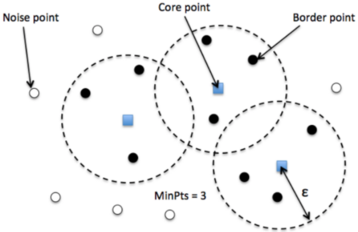
Void Clustering and Spatial Distribution

- Applying DBSCAN to identify distinct void populations based on their properties.
- Clustering voids to detect groupings or patterns in the large-scale structure.



Flowchart for DBSCAN

DBSCAN Algorithm visualisation

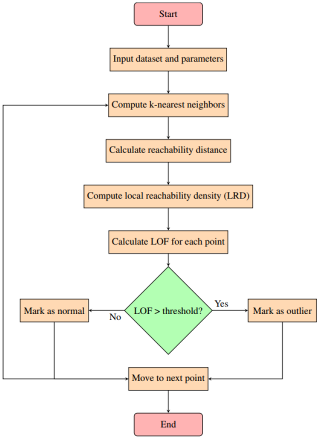


DBSCAN

Outlier Detection Using LOF

Local Outlier Factor (LOF) Algorithm:

- Used to detect voids with unusual properties (supervoids).
- Compares the local density of each void with its neighbors to flag outliers.

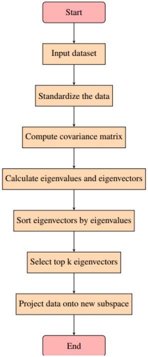


Flowchart of outlier detection using LOF

Principal Component Analysis (PCA)

PCA for Dimensionality Reduction:

- Applied PCA to reduce the complexity of the void dataset.
- Two main principal components capture the majority of the variance.

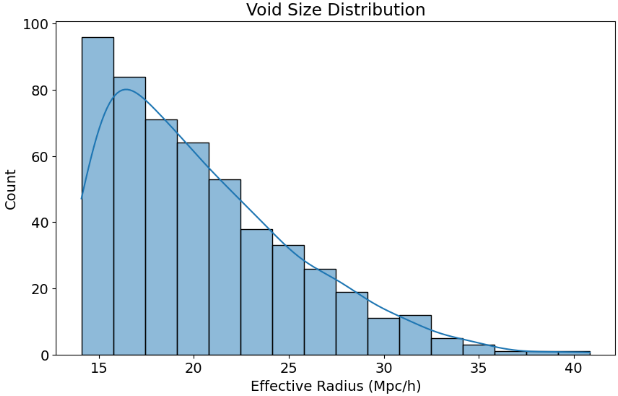


PCA algorithm .

Void Size Distribution

Key Findings:

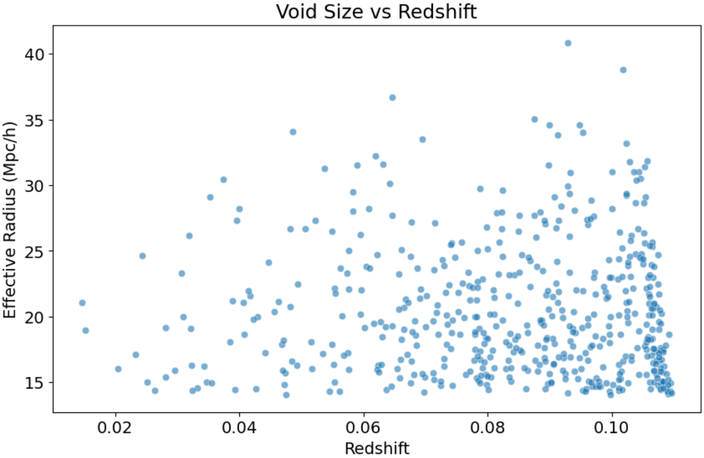
- Void sizes range from 14 to 41 Mpc/h.
- The distribution is right-skewed, peaking at 16-18 Mpc/h.
- Larger voids (>30 Mpc/h) represent supervoids.
- Shows hierarchical structure of cosmic voids



Redshift Dependence of Void Size

Key Findings:

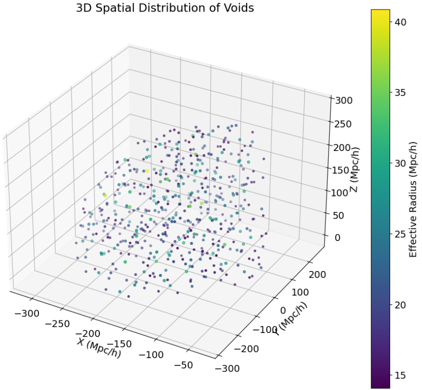
- No strong correlation between void size and redshift.
- Voids are relatively stable in size over the redshift range of 0.015 to 0.110.



Void Spatial Distribution

Key Findings:

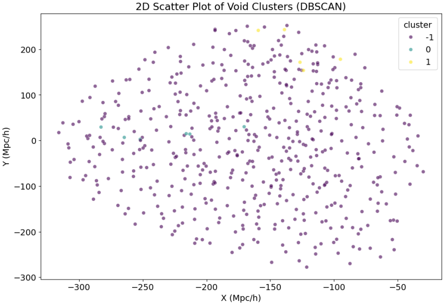
- Voids are non-uniformly distributed in 3D space.
- Clustering of voids in certain regions, which correspond to low-density areas in the cosmic web.



Void Clustering Results

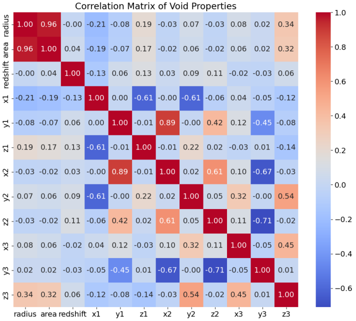
DBSCAN Clustering:

- Three void clusters identified using DBSCAN.
- Largest voids form distinct populations (noise cluster in DBSCAN).
- All means different formation histories, varying enviromental influences and distinct stages of void evolution.



Correlation analysis of void properties

- Potential anisotropy: The moderate correlation between radius and z3 indicate a subtle preferred direction in void shapes or sizes.
- Independence of void properties: Most void characteristics are not strongly influenced by their spatial location or orientation.
- The lack of strong correlations between different orientation components means that voids have complex, non-spherical shapes.

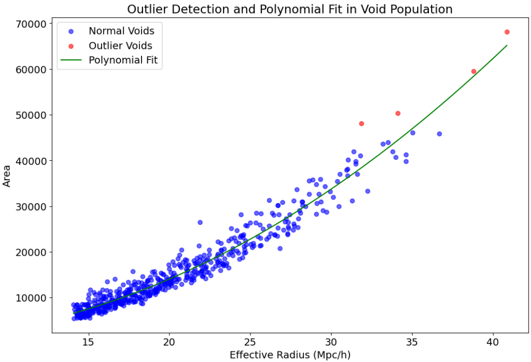


Void Outlier Detection

Key Findings:

- Outliers detected using LOF have significantly larger radii (> 30 Mpc/h).
- These outliers represents rare supervoids.
- We also fitted a second order polynomial to this plot and found out the equation:

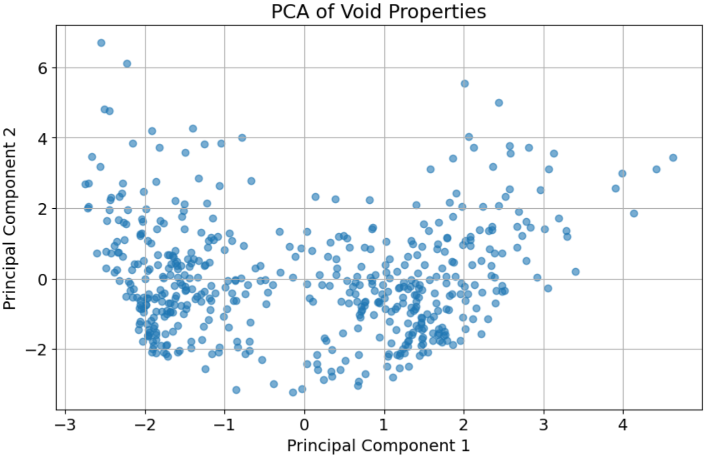
$$y = 44.391110x^2 - 251.988213x + 1343.898984 \tag{1}$$



Principal Component Analysis (PCA) Results

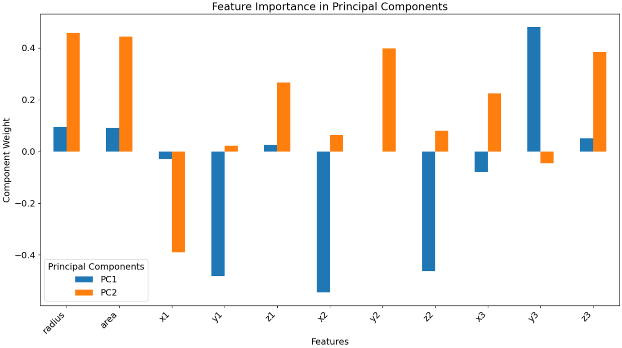
Key Findings:

- Two principal components explain 50% of the variance in void properties.
- Void size and surface area are the most significant features in clustering.



PCA continued

- **Feature Importance**: The loadings shows that both spatial distribution (captured mainly in PC1) and void size (captured mainly in PC2) are important factors in describing the variation among voids.
- **Size-Location Relationships**: The combination of size-related features (radius, area) with spatial coordinates in both PCs suggests a complex relationship between void sizes and their locations in space.



PCA loading scores

Feature	PC1	PC2
radius	0.094891	0.457697
area	0.091268	0.444144
x1	-0.029742	-0.391106
y1	-0.481475	0.022846
z1	0.025748	0.266112
x2	-0.544064	0.061766
y2	-0.000453	0.398024
z2	-0.463175	0.079633
x3	-0.080541	0.224692
y3	0.479335	-0.045821
z3	0.050146	0.384424

Void Anisotropy Correlation Function

Discussion

- The correlation function is given by:

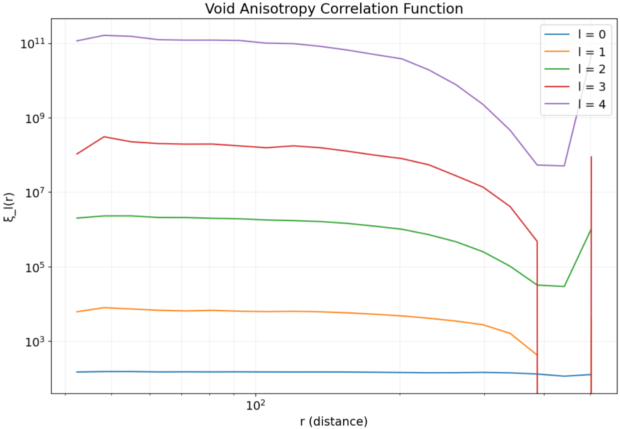
$$\xi(\mathbf{r}) = \sum_{l} \xi_l(r)\mathcal{P}_l(\cos\theta), \tag{2}$$

- The easier way to see this is to decompose into multipoles.
- **Monopole ($l = 0$)**: Represents the isotropic part of the correlation function, giving the average correlation independent of direction.
- **Dipole ($l = 1$)**: Captures the linear anisotropy, which can arise due to peculiar velocities or other directional dependencies.
- **Quadrupole ($l = 2$)**: Indicates more complex anisotropy, often linked to redshift-space distortions or gravitational lensing effects.
- **Higher Moments ($l \geq 3$)**: Represent increasingly subtle anisotropies that can be indicative of intricate cosmic phenomena or observational artifacts.

Void Anisotropy Correlation Function

Key Findings:

- Anisotropy detected in higher-order multipole moments ($l = 2, 4$).
- Higher-order correlations suggest that cosmic voids are not entirely isotropic.
- Possible influences include large-scale tidal fields and redshift-space distortions.



Void Anisotropy: Interpretation

- The void correlation function shows deviations from isotropy.
- Higher multipoles ($l \geq 2$) reveal directional dependencies.
- These anisotropies may be linked to environmental factors like neighboring clusters and filaments.

Scale dependence of void correlation function

- r<10 Mpc/h : Strong correlation at all moments, Reason: Due to size of voids and their immediate enviroments.
- 10<r<100 Mpc/h : Multiple bumps and dips, Reason: Due to void in void void and void in cloud processes described in exursion set theory
- r>100 Mpc/h : Correlation function tends to converge towards zero but aninotropy still persist
- Subtle bump is observed at 100-150 Mpc/h for monopole and quadrupole moments, Reason: Imprint of BAO in the void

Concluding Remarks

Key Ideas:

- Comprehensive analysis of void properties using SDSS DR7 and Planck 2018 data.
- Statistical analysis of void size, spatial distribution, and redshift dependence.
- Application of machine learning techniques (DBSCAN, LOF, PCA) to identify void clusters and outliers.
- Detection of void anisotropies using the correlation function, revealing higher-order moments.

Significance of the Results

- Voids provide new insights into the cosmic web and large-scale structure of the universe.
- The absence of a redshift-size correlation challenges simple void evolution models.
- Outliers (supervoids) may hold clues to early universe dynamics and the role of dark energy in cosmic expansion.

Future Research Directions

- Investigate the impact of dark energy on void expansion.
- Further explore the significance of void anisotropies.
- Utilize larger datasets (e.g., Euclid survey) to enhance statistical analysis.
- Extend the analysis of supervoids and their connection to cosmic microwave background anomalies.

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