# Cosmic Voids: Probing the Universe with Nothing

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Cosmic voids, the under dense regions of the cosmic web, make up a significant portion of the volume of the universe and are quickly becoming a promising cosmological probe as the volume and tracer density of surveys increases. Due to their unique, low density environment, cosmic voids are dominated by diffuse dynamical effects such as expansion due to Dark Energy and Neutrinos which makes them an ideal candidate for testing General Relativity and Modified Gravity models at cosmological scales in an environment that can be more easily modeled than the nonlinear scales of galaxy clusters. Void finding algorithms have become efficient at building void catalogues from a variety of tracers and have been able to build catalogues that accurately match the underlying void distribution. From these catalogues, techniques using void stacks, two point statistics and weak lensing offer avenues to constrain cosmological parameters. Results from SDSS catalogues have shown that voids provide competitive constraints and future surveys will meet the requirements for void cosmology to further extend the reach of modern cosmology.

## I. INTRODUCTION

Modern cosmology has become adept at extracting information from luminous matter. Clustering information extracted from Baryon Acoustic Oscillations (BAO), Redshift Space Distortions (RSD) and Weak Lensing (WL) have become pillars in cosmological analysis. All these probes rely on what is directly or indirectly visible. A major portion of the volume of the universe, however, is made of huge under-dense regions with little no matter at all known as cosmic voids. This makes them appealing candidate as as a cosmological probe.

It has been known since 1981 that as much as 40 percent of the universe is made up of large under-dense regions known as cosmic voids. Although more research is needed into the formation of these structures, it is generally thought that voids formed as comoving regions of under-density that formed due to the initial density perturbations in the primordial plasma [1]. As positive perturbations caused gravitational collapse into galaxies and clusters that formed the filaments of the cosmic web, so too did voids empty of matter. Thus, just as clustering of galaxies traces the evolution of the universe, so too must the clustering of voids (albeit with a lower signal-to-noise ratio (SNR)).

As a cosmological probe, voids offer several advantages as compared to other probes. Many recent surveys have relied on fitting models to power spectra and correlation functions. Such a method requires accurate modeling of the systematic effects such as RSD and galaxy bias. The accuracy of this modeling is limited by the nonlinear nature of RSD on small scales. The low density environments within and around voids are made up of galaxies that have not had the chance to virialize, making the effects of RSD easier to model.

Since the dynamical effects of neutrinos and dark energy are the dominant dynamics in voids, voids are the ideal laboratory for studying extended cosmological parameters such as the time-varying equation of state $w(z) = w_0 + w_a(z/(1+z))$ and the sum of the neutrino masses $\Sigma m_\nu$ [2].

Certain Modified Gravity (MG) models, such as the nDGPlens model differ from GR far from large gravitating objects and predict different properties in and around voids (see Section III) which provides an independent way of constraining such models.

Even without these inherent advantages, however, void statistics and constraints can be combined with other probes, such as BAO and RSD, to provide tighter constraints on cosmological parameters than those methods alone. Thus, the importance of voids in testing the $\Lambda CDM$ in the future can't be overstated.

In Section II, we discuss three methods for locating, identifying and constructing data catalogues: the computationally efficient method used by [3], the method used for the DR12 release ZOBOV algorithm [4] and the more recent DIVE algorithm described in [5]. In Section III, we discuss the various methods in which voids are used in cosmology. We define the two point void-void and void-galaxy correlation function and describe how they can be used for cosmological constraints and to test modified gravity models, specifically the DGPlens model. Finally in Section IV, we then discuss how the previous uses of voids have been applied to the latest galaxy catalogues and will be used in the near future.

## II. FINDING VOIDS

Cosmic voids come in a huge variety of shapes and sizes, but before they can be used reliably as a cosmological probe, a rigorous definition of what constitutes a void and a reliable way of identifying and locating them is required.

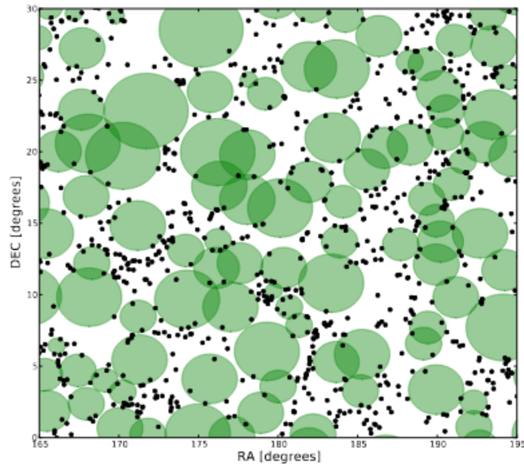


FIG. 1. Illustration of the Void-finding Algorithm from [3]. Each green circle represents a potential void (prior to quality cuts) and each black dot is a tracer LRG.

The definition of and the location in space of a cosmic void, however, is intrinsically tied together and varies depending on which algorithm is used. In this section, we review three popular algorithms which have been used in the literature. All these methods rely on galaxies as tracers, so that they are also affected by galaxy bias. One method to reduce the effect introduced by using a biased tracer is discussed in Section III.

### A. J. Clampitt 2015

A computationally efficient and illustrative way of locating voids is described in [3] and we will briefly describe the method here.

In order to locate voids, we need a luminous tracer to use to represent the underlying density field. [3] uses LRGs from the DR7 SDSS catalogue sliced into comoving sections of 20-100 Mpc/h. Each slice is treated as a 2D projection and we seek to identify the under-dense regions on this projection. The projection is split into pixels and a specified number of pixels $N_{pixels}$ is masked out around each tracer. An algorithm is then used to group together continuous, circular regions which contain less than a specified number of pixels $N_{threshold}$. These are labeled as voids and assigned a radius that depends on the density distribution of masked pixels around the center of each region. These voids then go through a series of quality cuts where the true under-densities in the dark matter are empirically separated from the under-densities due to the limitations of the survey. A visualization of this method is shown in Figure I.

This method, however, assumes a fiducial shape of cosmic voids which are known to be highly irregular. The method also has two free parameters, $N_{threshold}$ and $N_{pixels}$, which may wildly change the catalogue depending on their choice. Other, more computationally taxing, methods are able to obtain a shape that more accurately reflects the shape of each individual void.

### B. ZOBOV (Neyrinck 2008)

The ZOBOV (Zones Bordering on Voidness) algorithm developed in [6], was used in void finding in the BOSS DR12 catalogue [4]. This method is similar to the previous method where a suitable tracer is chosen, then used as the basis of locating under-densities, but uses a method which allows for irregularly shaped voids. The basis of this method relies on density estimation using Voroni Tessellation which we give a basic description of here (See [7] for a review).

The algorithm first divides the space around each tracer into cells where the edges around each tracer $p$ of the cell are defined as the points which are closer to $p$ than to any other particle. Each of these cells is then assigned a density $\rho = 1/V_p$ where $V_p$ is the volume of the cell. This is Voroni Tessellation.

The algorithm then searches for local minima, starting at one cell and comparing the densities of the surrounding cells before jumping to the lowest density cell. This continues until a minimum is found.

What follows is a similar quality cut step as the previously described algorithm, except the minima go through a process of elimination and joining. Each void is grown until it reaches a point where it crosses a deeper minima where it stops. A full description is provided in [6].

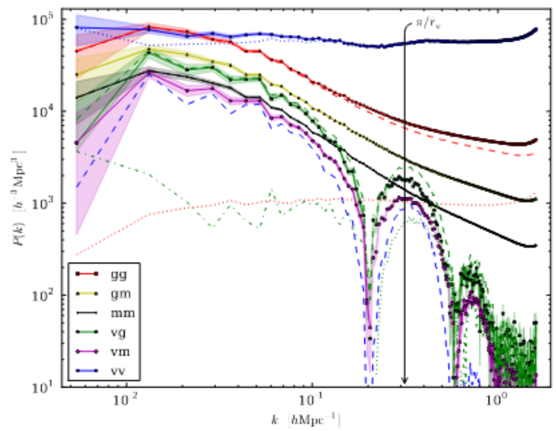


FIG. 2. Illustration of various power spectra from [9] from a simulation. The solid colored lines indicate the various power spectra with the fill indicating the error. The dashed lines indicate the power spectra minus shot noise and the arrow on the right side of the graph indicates the exclusion scale of the void sample used. The void-void power spectrum (blue line) is the poorest indicator of the underlying matter-matter power spectrum except at the largest of scales. The galaxy-galaxy spectrum (red line) is a much better indicator as is to be expected. The Void-Galaxy power spectrum (green line) is the closest match to the matter-matter spectrum.

Finally, a probability that each void is a true void is defined based on the density contrast and by comparing it to a Poisson particle distribution.

### C. DIVE (Zhao 2016)

Used more recently in [5] and described in [8], the DIVE algorithm relies on defining various tetrahedron that have the tracers at their vertices. A circle is then circumscribed within each tetrahedron. These regions are labeled as voids such that the circumscribed circle does not contain and tracers.

These potential voids then once again go through a process of quality cuts similar to the two previous methods.

## III. METHODS AND MODELS

Void cosmology is a developing area of research and there have been several methods introduced for extracting cosmological information. Some of the most promising is two-point void clustering statistics, Alcock-Paczynski (AP) test as applied to void stacks, and WL.

### A. Clustering Statistics

Just as there are clustering statistics with galaxies, there are two main types of void clustering statistics: Void-Void and Void-Galaxy. From the positions of voids and galaxies we can define a the Void-Void two point correlation function (and corresponding power spectrum) and also Void-Galaxy correlation function (and corresponding power spectrum). For the purposes of this review, we follow the definitions used in [9].

The Void-Galaxy power spectrum is

$$P_{vg}(k) = \frac{1}{n_v n_g} \int \int \frac{dn_v}{dr_v} \frac{dn_g}{dm_g} b_g b_v \rho_v P_{mm} dr_v dm_g$$

where $n_v$ and $n_g$ are the number distribution of the voids and galaxies, $\rho(r_v)$ is the density distribution of voids as a function of void radius $r_v$, $m_g$ is the mass of the dark matter halo, $P_{mm}$ is the linear matter power spectrum and $b_v$ and $b_g$ are the linear bias terms which reflect the fact that galaxies are poor tracers of the underlying true distribution.

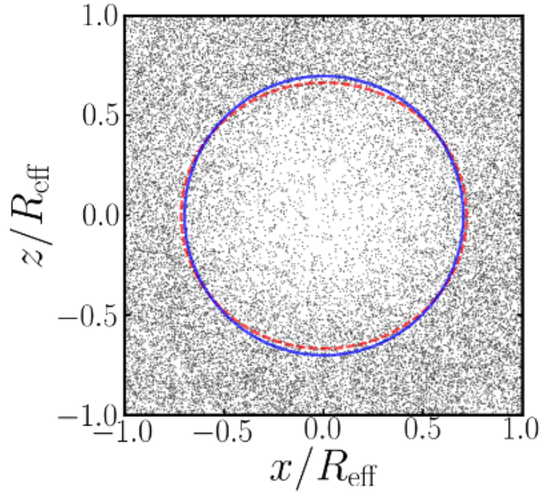


FIG. 3. Illustration of the AP test on a void stack created from BOSS DR12 CMASS catalogue from [4]. The blue line is the expected spherical shape and the red is the observed shape.

We can also define a Void-Void power spectrum $P_{vv}$. However, [9] has shown that the Void-Galaxy power spectrum is a better indicator of the underlying mater distribution as the clustering of voids suffers from higher shot-noise and lower number density as compared to galaxies. The Void-Galaxy power spectrum actually matches the underlying matter power spectrum better than the galaxy power spectrum (See Figure II). This means that voids can be used as a way to calibrate galaxy bias. We can also directly relate voids to cosmological parameters, using the correlation function for the separation between void centers and galaxies to get a constraint on $f\sigma_8$ and $H(z)D_A(z)$.

### B. Alcock-Paczynski Test

Besides two point statistics, another method we can apply to voids is the Alcock-Paczynski Test or AP test for short, which leverages the fact that the true cosmology of the universe differs from the assumed fiducial cosmology. Because we do not observe the true position of galaxies but rather their redshift, we must infer position by assuming a fiducial cosmology and converting redshift to position. However, since we do not know the true value of $H(z)$ or $D_A(z)$, there will be a difference between the true and measured positions. This is known as the AP effect. In normal clustering analysis, the AP test is typically used with a well known feature which can be accurately modeled such as the Baryon Acoustic Oscillation signal. We have a theoretical model for the power spectrum which we vary by a parameter, in this case alpha. This parameter is then directly related the Hubble parameter and angular diameter distance.

$$\alpha = \frac{D'_A(z)H'(z)r'_s}{D_A(z)H(z)r_s}$$

where $D_A(z)$ is the angular diameter distance and $H(z)$ is the Hubble parameter in the true cosmology, $D'_A(z)$ is the angular diameter distance and $H'(z)$ is the Hubble parameter in the fiducial cosmology, and $r'_s$ and $r_s$ are the radius of the BAO in the fiducial and true cosmologies respectively. We can then vary $\alpha$ until we have the best fit to the data and use this to infer the true cosmology. When performing an isotropic fit, $D_A(z)$ and $H(z)$ are degenerate, but anisotropic fits can break this degeneracy.

Now, we can perform the AP test with voids as well, but the method is a bit different. Instead of fitting a power spectrum, we can compare the observed shape of voids with the expected shape and vary our model by a similar parameter which is directly related to the cosmological parameters. Voids can have a variety of different shapes, but on average we expect that shape to be spherically symmetric. So voids are "stacked" in order to get an average shape which we can then perform the AP test with. Following [4], we define

$$\Delta l = \frac{c}{H(z)}\Delta z$$

and

$$\Delta r = (1+z)D_A(z)\Delta\theta$$

$$e(z) = \frac{\Delta l'/\Delta r'}{\Delta l/\Delta r} = \frac{D_A(Z)H(z)}{D'_A H'(z)}$$

where $e(z)$ is out AP parameter. Here $\Delta l$ is the void length along the line-of-sight and $\Delta r$ Is the length transverse to the line-of-sight for the fiducial and observed cosmologies and z is the redshift.

The AP test is performed in this case by comparing the observed length along and transverse to the line-of-sight to the expected spherical symmetry. See Figure 3 for an example of this test for the BOSS DR12 CMASS catalogue.

This can be a powerful cosmological probe. Since RSDs and other effects are more easily modeled in low density environments, we can potentially get a better constraint using the AP test with void stacks over BAO. The AP test can be used to constrain $H(z)D_A(z)$ directly, but has also been used directly to constrain $\Omega_m$ since

$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}$$

for $\Lambda CDM$.

### C. Weak Lensing in Voids

Weak Lensing (WL), refers to the weak gravitational lensing of galaxies due to the foreground galaxies between the source and the observer. Weak lensing is typically study in the 3x2 analysis. For voids, we look specifically at the convergence field defined in [10].

The convergence for an object is given by

$$\kappa = \frac{1}{2}\nabla^2\psi_{2D}$$

where $\psi_{2D}$ is the 2d lensing potential

$$\psi_{2D} = \frac{D_{ls}}{D_l D_s}\int \phi dz$$

where

As shown in [10], one can use the convergence field as a way to both locate voids, and test modifications to General Relativity known as Modified Gravity (MG). We discuss WL and MG in Section IV. Peaks in the convergence field correspond to peaks in the matter distribution and therefore can be used in a very similar way to the methods discussed in Section II to locate and identify voids. This has been show to result in less biases void catalogues.

### D. Modified Gravity in Voids

From the convergence field we can use voids to test MG models. Using the number of peaks as well as the number of voids, we can test MG models. For example, two MG models, the nDGP model and the nDGPlens model have different gravitational potentials. So the number of peaks in the convergence field should differ as well.

$$\nabla^2\phi_{GR} = 4Ga^2\delta\rho$$

where a is the scale factor and $\delta$ is the overdensity. This differs from the lensing potential in nDGPlens

$$\nabla^2\phi_{GR} = 4Ga^2\delta\rho + \frac{1}{2}\nabla^2\Psi$$

where $\Psi$ is a scalar field.

[10] has shown that for simulations a difference in peaks and in void count is apparent. There is also some evidence that the matter of content in voids differs in different cosmologies as well as from what is predicted for $\Lambda CDM$.

So now that we are familiar with the various methods of studying voids, let's take a look into what's already been done and what's yet to come for the future of this cosmological probe.

## IV. CONCLUSION

| Parameter | Voids | BAO + RSD | BAO + RSD + Voids |
|---|---|---|---|
| $H_0 r_s$ | - | 14.28 ± .34 | 14.05 ± .14 |
| $f\sigma_8$ | .501 ± .051 | .462 ± .032 | .453 ± .022 |
| $D_A/r_s$ | - | 9.44 ± .11 | 9.383 ± .077 |
| $D_A H_0/c$ | .4367 ± .0045 | .449 ± .014 | .4396 ± .0040 |

Table 1: Mean and $1\sigma$ with and without Voids [11] from the SDSS DR12 CMASS catalogue. Voids are able to provide competitive constraints on $f\sigma_8$, and when combined with BAO and RSD, provide a 30-60 percent improvement on the uncertainty.

Cosmic Voids promise to be a powerful cosmological tool in the coming decades, especially when combined with other cosmological probes such as BAO, RSD, and WL. Using the void-galaxy power spectrum, we are able to constrain parameters and calibrate galaxy bias.

Void stacks are a promising way to use the AP-Test to obtain better constraints on $\Omega_m$ than BAO. Recent work also shows the potential to recover the BAO peak using voids and galaxies [12].

Weak Lensing provides a way to both locate voids using the convergence field and also test Modified Gravity models such as nDGPlens. All these avenues describe a bright future for void cosmology, but there are some challenges left to overcome.

One of the reasons why voids haven't been more widely used is that they require both high tracer density and large survey volume. The SDSS was the first to provide a survey that met these requirements and competitive constraints were obtained solely from voids. The consensus results for SDSS BOSS DR12 obtained the tightest constraints combining voids with BAO and RSD. A summary of the results is given in Table 1. The latest results from eBOSS DR16 improved even further on this [13].

This problem is easier to overcome as current and future surveys such as DESI, EUCLID, WFIRST etc. will be able to exploit voids even further. Projections for EUCLID already show a promising constraint on the redshift dependent growth index $\gamma(z) = \gamma_0 + \gamma_1 z(1+z)$ [14].

Other challenges for void cosmology center around theoretical and computational issues. More work is needed to understand the dynamics and galaxy populations of voids. Accurate modeling of voids requires a firm understanding of the systematic effects such as RSD and void bias. Accurate and large simulations are required to enable this type of study. [2].

Should these issues be overcome, the next decade and beyond promises to see the addition of a relatively new and powerful cosmological probe.

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