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Answers from the Void: VIDE and its Applications

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Abstract. We discuss various applications of VIDE, the Void IDentification and Examination toolkit, an open-source Python/C++ code for finding cosmic voids in galaxy redshift surveys and N-body simulations. Based on a substantially enhanced version of ZOBOV, VIDE not only finds voids, but also summarizes their properties, extracts statistical information, and provides a Python-based platform for more detailed analysis, such as manipulating void catalogs and particle members, filtering, plotting, computing clustering statistics, stacking, comparing catalogs, and fitting density profiles. VIDE also provides significant additional functionality for pre-processing inputs: for example, VIDE can work with volume- or magnitude-limited galaxy samples with arbitrary survey geometries, or dark matter particles or halo catalogs in a variety of common formats. It can also randomly subsample inputs and includes a Halo Occupation Distribution model for constructing mock galaxy populations. VIDE has been used for a wide variety of applications, from discovering a universal density profile to estimating primordial magnetic fields, and is publicly available at http://bitbucket.org/cosmicvoids/vide_public and http://www.cosmicvoids.net.

Keywords. cosmology: large-scale structure of universe, methods: data analysis, methods: n-body simulations, dark matter

1. Introduction

First discovered over thirty years ago (e.g., Gregory & Thompson 1978), cosmic voids are emerging as a novel and innovative probe of both cosmology and astrophysics through their intrinsic properties (e.g., Bos *et al.* 2012), exploitation of their statistical isotropy via the Alcock-Paczyński test (Sutter et al. 2014), or cross-correlation with the cosmic microwave background (Ilić et al. 2013; Planck Collaboration 2013; Cai *et al.* 2014). Additionally, fifth forces and modified gravity are unscreened in void environments, making them singular probes of exotic physics (e.g., Li et al. 2012; Clampitt et al. 2013; Carlesi *et al.* 2014).

Voids are also fascinating objects to study by themselves. For example, there appears to be a self-similar relationship between voids in dark matter distributions and voids in galaxies (Sutter *et al.* 2014) via a universal density profile (Hamaus et al. 2014) (hereafter HSW). Observationally, the anti-lensing shear signal (Melchior *et al.* 2014; Clampitt & Jain 2014) and Ly-alpha absorption measurements (Tejos *et al.* 2012) have illuminated the dark matter properties in voids.

However, there are only a few public catalogs of voids identified in galaxy redshift surveys, primarily the SDSS (e.g., Pan *et al.* 2012; Sutter *et al.* 2012). And while there are many published methods for finding voids based on a variety of techniques, most codes remain private. In order

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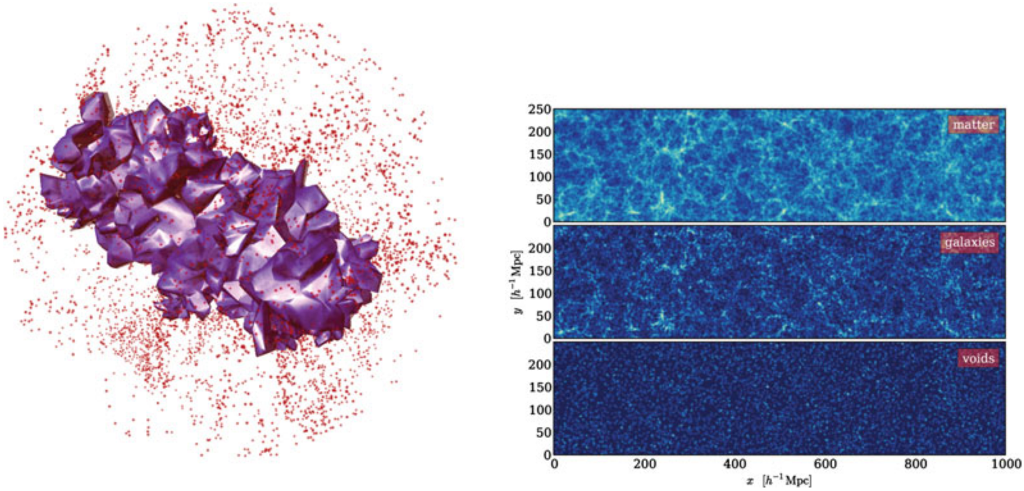

Figure 1. Watershed void finding in VIDE. The left panel shows the Voronoi cells belonging to a void embedded in an observed galaxy population. *Reproduced from Sutter et al. (2012).* The right panel shows projections of dark matter, mock galaxies, and void positions in a simulation. *Reproduced from Hamaus et al. (2014).*

to accelerate the application of voids, it is essential to provide easy-to-use, flexible, and strongly supported void-finding codes.

In this work we discuss VIDE, for Void IDentification and Examination, a toolkit based on the publicly-available watershed code ZOBOV (Neyrinck 2008) for finding voids but considerably enhanced and extended to handle a variety of simulations and observations (Sutter et al. 2014). VIDE also provides an extensive interface for analyzing void catalogs.

2. Void Finding

VIDE is able to identify voids in N-body simulation snapshots produced by GADGET (Springel 2005), FLASH (Dubey et al. 2008), RAMSES (Teyssier 2002) 2HOT (Warren 2013), and generic ASCII files. VIDE can either find voids directly in the full simulation, or randomly subsampled populations, as well as halo catalogs and mock galaxy samples using the Halo Occupation Distribution formalism (Berlind & Weinberg 2002). For observational datasets, to find voids in galaxy surveys the user must provide a list of galaxy positions and a pixelization of the survey mask using HEALPIX (Gorski et al. 2005)†.

The core of our void finding algorithm is ZOBOV (Neyrinck 2008), which creates a Voronoi tessellation of the tracer particle population and uses the watershed transform to group Voronoi cells into zones and subsequently voids (Platen et al. 2007). The Voronoi tessellation provides a density field estimator based on the underlying particle positions.

ZOBOV first groups nearby Voronoi cells into *zones*, then merges adjacent zones into voids by finding minimum-density barriers between them. We impose a density-based threshold within ZOBOV where adjacent zones are only added to a void if the density of the wall between them is less than 0.2 times the mean particle density $\bar{n}$. This density criterion prevents voids from expanding deeply into overdense structures and limits the depth of the void hierarchy (Neyrinck 2008).

In this picture, a void is simply a basin in the Voronoi density field bounded by a common set of higher-density ridgelines, as demonstrated by Figure 1, which shows a typical 20 h^{-1}Mpc void identified in the SDSS DR7 galaxy survey (Sutter *et al.* 2012). This also means that voids may

† http://healpix.jpl.nasa.gov

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have any *mean* density, since the watershed includes in the void definition all wall particles all the way up to the very highest-density separating ridgeline.

We have made several modifications and improvements to the original ZOBOV algorithm. First, we have strengthened the algorithm with respect to numerical precision by rewriting large portions in a templated C++ framework. We enforce bijectivity in the Voronoi graph, so that the tessellation is self-consistent, and use an improved volume-splitting technique to minimize the number of difference operators at the edge of the box when joining subregions. Finally, we have optimized several portions of the central watershed algorithm, enabling the identification of voids in simulations with up to 1024^3 particles in ~ 10 hours using 16 cores.

To prevent the growth of voids outside survey boundaries in observational datasets, we place a large number of mock particles along any identified edge and along the redshift caps. We assign essentially infinite density to these mock particles, preventing the watershed from including zones external to the survey. Since the local volumes of the edge galaxies are arbitrary, we prevent these mock particles from participating in any void by disconnecting their adjacency links in the Voronoi graph.

We use the mean particle spacing to set a lower size limit for voids because of Poisson shot noise. VIDE does not include any void with effective radius smaller than $\bar{n}^{-1/3}$, where $\bar{n}$ is the mean number density of the sample. We define the effective radius as as the radius of a sphere with the same total volume of all the Voronoi cells that make up the void.

Figure 1 shows an example void population with VIDE, taken from the analysis of Hamaus *et al.* (2014). In this figure we show a slice from an N-body simulation, a set of mock galaxies painted onto the simulation using the HOD formalism discussed above, and the distribution of voids identified in the mock galaxies.

VIDE automatically provides some basic derived void information, such as the *macrocenter*, or volume-weighted center of all the Voronoi cells in the void, and the ellipticity.

3. Post-Processing & Analysis

VIDE provides a Python-based application programming interface (API) for loading and manipulating the void catalog and performing analysis and plotting.

Via the API the user has immediate access to all basic and derived void properties (ID, macrocenter, radius, density contrast, RA, Dec, hierarchy level, ellipticity, etc.) as well as the positions (x, y, z, RA, Dec, redshift), velocities (if known), and local Voronoi volumes of all void member particles. The user can also access all particle and galaxy sample information, such as redshift extents, the mask, simulation extents and cosmological parameters. Upon request the user can also load all particles in the simulation or observation.

VIDE includes several built-in plotting routines. First, users may plot cumulative number functions of multiple catalogs on a logarithmic scale. Volume normalizations are handled automatically, and 1σ Poisson uncertainties are shown as shaded regions, as demonstrated in Figure 3. Secondly, users may plot a slice from a single void and its surrounding environment. In these plots we bin the background particles onto a two-dimensional grid and plot the density on a logarithmic scale. We draw the void member galaxies as small semi-transparent disks with radii equal to the effective radii of their corresponding Voronoi cells.

The user can directly compare two void catalogs by using a built-in function for computing the overlap. This function attempts to find a one-to-one match between voids in one catalog and another and reports the relative properties (size, ellipticity, etc.) between them. It also records which voids cannot find a reliable match and how many potential matches a void may have. A more detailed discussion of the matching process can be found in Sutter *et al.* (2014).

VIDE allows the user to compute simple two-point clustering statistics, i.e. power spectra and correlation functions.

Three-dimensional stacks of voids are useful in a variety of scenarios, and the user may construct these with built-in functions. The stacked void may optionally contain only void member particles or all particles within a certain radius. With this stacked profile VIDE can build a spherically averaged radial density profile and fit the universal HSW void profile to it.

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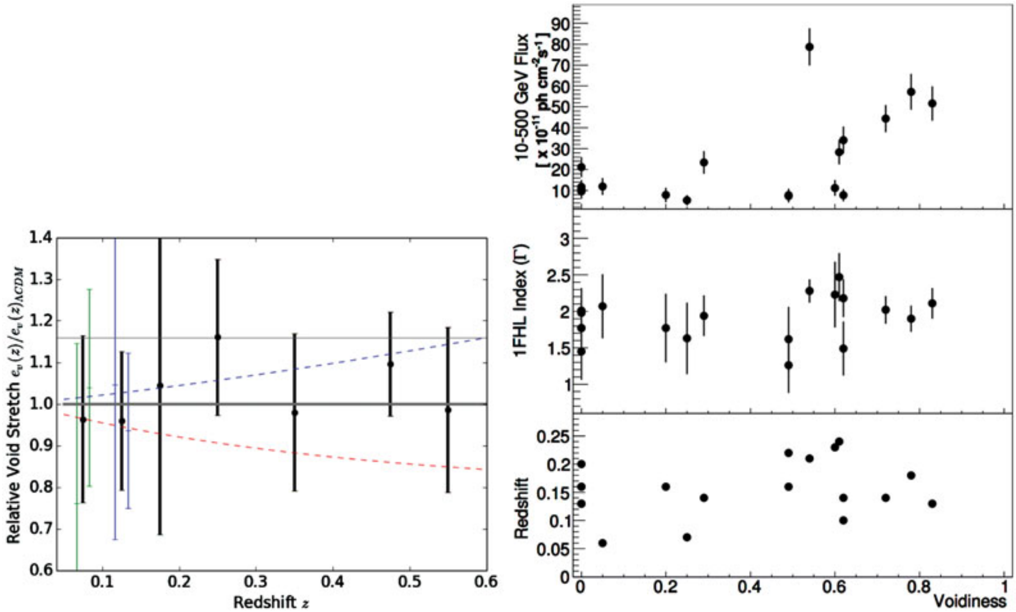

Figure 2. Left panel: a detection of the Alcock-Paczyński effect using stacked cosmic voids in the SDSS DR7 and DR10. The slight deviation from unity in the expected void stretch can be used to extract cosmological parameters. *Reproduced from Sutter et al. (2014).* Right panel: GeV luminosity versus void fraction along the line of sight for Fermi-detected blazars. *Reproduced from Furniss et al. (2014).*

All proper normalizations are handled internally. Figure 3 shows an example of VIDE-produced density profiles and best-fit HSW profile curves.

4. Applications

Throughout its development VIDE has been used in a variety of applications. Initially, the enhancements to ZOBOV were used to create a set of public catalogs from both observations (Sutter *et al.* 2012, 2014) and simulations (Sutter *et al.* 2014). The toolkit presented in this work is fully compatible with those public releases.

The publication of simple void properties, such as sky position and effective radius, enabled direct cross correlations with other datasets leading to several interesting results. Examples of such correlations include: galaxy shear maps leading to a detection of a weak lensing effect inside voids (Melchior *et al.* 2014), the cosmic microwave background giving rise to a detection of the integrated Sachs-Wolfe effect (Planck Collaboration 2013; Ilić et al. 2013), and positions of high-energy blazars putting limits on the intergalactic magnetic field (Furniss *et al.* 2014). The latter correlation is shown in the right panel of Figure 2. Additionally, cross-correlations of void centers with galaxy positions have recently been demonstrated to allow the construction of a static ruler (Hamaus *et al.* 2014), and the three-dimensional arrangement of galaxies around stacked voids has been exploited for an Alcock-Paczyński test (Sutter et al. 2014), as shown in the left-hand panel of Figure 2.

Derived void statistical information, such as radial density profiles (as shown in Figure 3), have led to the discovery of a universal density profile (Hamaus et al. 2014; Sutter *et al.* 2014) and a method for constructing real-space profiles in a parameter-independent manner (Pisani *et al.* 2013). The abundance of voids is potentially a very powerful probe of cosmology, as shown in Sutter *et al.* (2014) and highlighted in Figure 3.

Lastly, the ability to match and compare void properties from one catalog to another (a built-in feature of VIDE) has been used to examine the relationship of voids identified in sparse,

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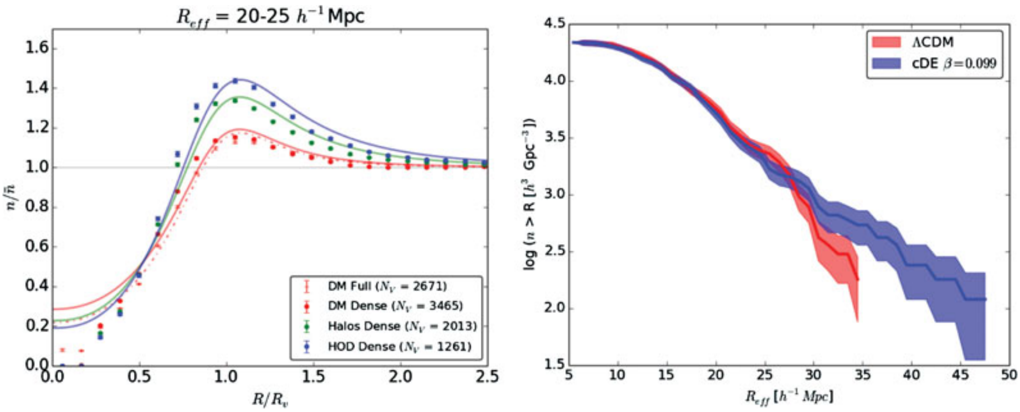

Figure 3. Left panel: example one-dimensional radial density profiles of stacked voids (points with error bars) and best-fit curves (thin lines) using the HSW profile. *Reproduced from Sutter et al. (2014)*. Right panel: example cumulative void number functions from simulations. *Reproduced from Sutter et al. (2014)*.

biased galaxy samples to dark matter underdensities (Sutter *et al.* 2014) and to reconstruct the life history of voids using merger trees (Sutter et al. 2014).

5. Conclusions

We have presented and discussed the capabilities of VIDE, a new Python/C++ toolkit for identifying cosmic voids in cosmological simulations and galaxy redshift surveys, as well as a brief overview of its current applications. VIDE performs void identification using a substantially modified and enhanced version of the watershed code ZOBOV. Furthermore, VIDE is able to support a variety of mock and real datasets, and provides extensive and flexible tools for loading and analyzing void catalogs. We have highlighted these analysis tools (e.g., filtering, plotting, clustering statistics, stacking, profile fitting) using examples from previous and current research using VIDE.

The analysis toolkit bundled in VIDE enables a wide variety of both theoretical and observational void research. As its most basic, the void properties made available to the user, such as sky positions, shapes, and sizes, permit simple explorations of void properties and cross-correlation with other datasets. The user may also use void member particles and their associated volumes for examining galaxy properties in low-density environments. Cross-matching by overlapping catalogs can be useful for understanding the impacts of peculiar velocities or galaxy bias, as well as providing a platform for studying the effects of modified gravity or fifth forces on a void-by-void basis. Void power spectra, shape distributions, number functions, and density profiles, easily accessible via VIDE, are sensitive probes of cosmology. Users may also access HSW density profiles, enabling theoretical predictions of the ISW or gravitational lensing signals.

The past few years have seen an enormous growth in void interest and research. This research includes new void-finding algorithms, studies of void properties, investigations and forecasts of cosmological probes, and explorations into the nature of void themselves from theoretical and numerical viewpoints. Put simply, VIDE is designed to meet the growing demand of next-generation void science.

The VIDE code and documentation is currently hosted at `http://bitbucket.org/cosmicvoids/vide_public`, with links to numbered versions at `http://www.cosmicvoids.net`.

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