The dark matter of galaxy voids

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6 January 2014

ABSTRACT

How do observed voids relate to the underlying dark matter distribution? To examine the spatial distribution of dark matter contained within voids identified in galaxy surveys, we apply Halo Occupation Distribution models representing sparsely and densely sampled galaxy surveys to a high-resolution \( N \)-body simulation. We compare these galaxy voids to voids found in the halo distribution, low-resolution dark matter, and high-resolution dark matter. We find that voids at all scales in densely sampled surveys — and medium- to large-scale voids in sparse surveys — trace the same underdensities as dark matter, but they are larger in radius by \( \sim 20\% \), they have somewhat shallower density profiles, and they have centers offset by \( \sim 0.4 \) \( R_{\text{rms}} \). However, in void-to-void comparison we find that shape estimators are less robust to sampling, and the largest voids in sparsely sampled surveys suffer fragmentation at their edges. We find that voids in galaxy surveys always correspond to underdensities in the dark matter, though the centers may be offset. When this offset is taken into account, we recover almost identical radial density profiles between galaxies and dark matter. All mock catalogs used in this work are available at http://www.cosmicvoids.net.

Key words: cosmology: simulations, cosmology: large-scale structure of universe

1 INTRODUCTION

Current and future large-scale galaxy redshift survey programs map out large volumes of the cosmic web (e.g., Laureijs et al. 2011; Ahn et al. 2012; Parkinson et al. 2012). Since galaxies trace the underlying dark matter distribution, albeit in a sparse and biased fashion (Baugh 2013), we can use statistics of the galaxy population (i.e., the overdensities) to understand the growth and present-day structure of the Universe and its relation to dark energy (Weinberg et al. 2013). Surveys typically focus on two-point statistics of the galaxy distribution, such as the galaxy autocorrelation function (Sánchez et al. 2012; Marín et al. 2013) or the baryon acoustic oscillation feature (Bassett & Hlozek 2010), both of which are sensitive probes of cosmology.

A complementary approach to using the structure of matter to understand cosmology is to examine the underdense regions of the cosmic web, namely cosmic voids (Gregory & Thompson 1978). Voids offer several advantages over traditional measures of large-scale structure: they have a wide range of sizes (Hoyle & Vogeley 2004; Pan et al. 2012; Sutter et al. 2012b), allowing a study of multiple length scales simultaneously; they fill up most of the volume of the universe (Hoffman & Shaham 1982), giving a large statistical weight; they are nearly empty of matter (by definition), so fifth forces from modified gravity and coupled dark matter-dark energy remain unscreened inside them (Li & Zhao 2009; Li et al. 2012; Clampitt et al. 2013; Spolyar et al. 2013); they can potentially serve as standard rulers (Hamaus et al. 2013); and their statistical isotropy can be leveraged to perform an Alcock-Paczynski test (Alcock & Paczynski 1979; Ryden 1995; Lavaux & Wandelt 2011; Sutter et al. 2012a).

However, the statistical properties of voids in galaxy populations are not the same as those in dark matter distri-
butions (Little & Weinberg 1994; Benson et al. 2003; Sutter et al. 2013). Since voids are defined by the lack of tracers (whether galaxies in a survey or particles in an N-body simulation), void sizes and shapes will necessarily be sensitive to the sampling density and biasing of the tracers. Additionally, voids exhibit a complex internal hierarchy of structure (Gottlober et al. 2003; Goldberg & Vogeley 2004; Aragon-Calvo & Szalay 2012) that is imperfectly sampled by galaxies.

While we can empirically model the changes to void statistics when transitioning from dark matter to galaxy voids (as we do in Sutter et al. 2013), we must ensure that galaxy surveys really are capable of robustly identifying voids. We must determine if a void traced by a galaxy survey of a given sampling density corresponds to a single dark matter void. If it does, we must establish the relationship between the galaxy void and the dark matter underdensity. The nature of this relationship will depend on survey density, so we must also estimate the minimum galaxy density necessary to faithfully capture the portion of the cosmic web represented by voids. This is necessary to interpret recent work such as Melchior et al. (2013), which probe the underlying dark matter potential with galaxy lensing.

There have been some previous efforts to examine the interiors of voids, but these works focused on a single or very few voids at limited scales (Schmidt et al. 2001; Benson et al. 2003; Gottlober et al. 2003; Goldberg & Vogeley 2004). Most authors attempt to make contact with observations by using mock galaxy populations within simulations (Benson et al. 2003; Ceccarelli et al. 2006; Pan et al. 2012; Tavasoli et al. 2013; Sutter et al. 2013). Instead, in this work we examine in detail the interior dark matter contents of galaxy voids. We use a Halo Occupation Distribution model (Berlind & Weinberg 2002) to generate two mock galaxy surveys: a representative sparsely sampled survey and a representative densely sampled survey. Drawing these mock surveys from a single high-resolution simulation, we compare on a void-by-void basis to voids in the halo distribution, low-resolution dark matter matched to the mean survey density, and high-resolution dark matter.

In the following section, we summarize our simulation, dark matter samples, mock galaxy catalogs, void finding technique, and method for matching galaxy voids to dark matter voids. In Section 3 we examine visually projected densities inside galaxy voids, trace the radial density profiles of dark matter within galaxy voids, and examine the correlations between underdensities in the galaxies and the dark matter at various radii. Section 3 focuses on comparing galaxy voids and dark matter voids on an individual basis by examining relative positions, sizes, profiles, and ellipticities. Finally, in Section 4 we offer concluding comments and discussions regarding prospects for upcoming galaxy redshift surveys.

2 NUMERICAL APPROACH

2.1 Simulations & Mocks

We source all samples and mock catalogs in this work from a single ΛCDM dark matter N-body simulation. We use the 2HOT code, an adaptive treecode N-body method whose operation count scales as $N \log N$ in the number of particles (Warren 2013). Accuracy and error behavior have been improved significantly for cosmological volumes through the use of a technique to subtract the uniform background density, as well as using a compensating smoothing kernel for small-scale force softening (Dehnen 2001). We use a standard symplectic integrator (Quinn et al. 1997) and an efficient implementation of periodic boundary conditions using a high-order ($p = 8$) multipole local expansion. We adjust the error tolerance parameter to limit absolute errors to 0.1% of the rms peculiar acceleration. Initial conditions were generated using a power spectrum calculated with CLASS (Blas et al. 2011) and realized with a modified version of 2LPTIC (Crocce et al. 2006).

This particular simulation assumed WMAP 7-year cosmological parameters (Komatsu et al. 2011). The box size was 1 h⁻¹Gpc on a side and contained 1024³ particles, giving a particle mass resolution of 7.36 × 10¹¹ h⁻¹ M⊙. All analysis in this work used a single real-space snapshot at z = 0. For the dark matter analysis, we take successive random subsamples of the particles to achieve tracer densities of 10⁻², 4 × 10⁻³, and 3 × 10⁻⁴ particles per cubic h⁻¹Mpc. These samples as labeled as DM Full, DM Dense, and DM Sparse, respectively. We chose the latter values to roughly match the mean number densities of the mock galaxy populations, which we will discuss below.

We use the Rockstar halo finder (Behroozi et al. 2013), a six-dimensional phase-space plus time halo finder, to identify spherical overdensity (SO) halos at 200 times the background density. We use the default Rockstar parameters, except for requiring strict SO masses that include unbound particles and particles that may exist outside of the FOF group for the halo. We use the halo catalog both as a direct source of tracers for void finding and as inputs for the HOD modeling. We take two halo populations, one labeled Halos Dense that includes all halos down to the minimum resolvable halo mass of 1.47 × 10¹² h⁻¹ M⊙ (20 particles), and one labeled Halos Sparse that only includes halos above 1.2 × 10¹³ h⁻¹ M⊙. We use these two thresholds to approximate the minimum mass used in the HOD distribution, thereby allowing us to compare voids found in halos to those found in galaxy populations.

We produce galaxy catalogs from the above halo population using the code described in (Tinker et al. 2006) and the HOD model described in (Zheng et al. 2007). HOD modeling assigns central and satellite galaxies to a dark matter halo of mass $M$ according to a parametrized distribution. In the case of the Zheng et al. (2007) parametrization, the mean number of central galaxies is given by

$$\langle N_{\text{cen}}(M) \rangle = \frac{1}{2} \left[ 1 + \text{erf} \left( \frac{\log M - \log M_{\text{min}}}{\sigma_{\log M}} \right) \right]$$

(1)

and the mean number of satellites is given by

$$\langle N_{\text{sat}}(M) \rangle = \langle N_{\text{cen}}(M) \rangle \left( \frac{M - M_0}{M_0'} \right)^{\alpha},$$

(2)

where $M_{\text{min}}$, $\sigma_{\log M}$, $M_0$, $M_0'$, and $\alpha$ are free parameters that can be inferred by fitting the observed space density and clustering of a given galaxy population. The probability distribution of central galaxies $P(N_{\text{cen}} \mid \langle N_{\text{cen}} \rangle)$ is a nearest-integer distribution, and satellites follow a Poisson $P(N_{\text{sat}} \mid \langle N_{\text{sat}} \rangle)$. © 0000 RAS, MNRAS 000, 000–000
Using the above model we generate two mock catalogs. The first is matched to the SDSS DR9 CMASS galaxy sample (Ahn et al. 2012) using the parameters found by Manera et al. (2013) ($\sigma_{\text{log } M} = 0.596$, $M_0 = 1.2 \times 10^{13} \, h^{-1} M_\odot$, $M'_0 = 10^{14} \, h^{-1} M_\odot$, $\alpha = 1.0127$, and $M_{\text{min}}$ chosen to fit the mean number density). We call this sample HOD Sparse, since we are using it to represent a relatively low-resolution galaxy sample. We use the full resolved halo population to create this sample, which contains many galaxies in halos with $M < M_0$ because of the large scatter parameter $\sigma_{\text{log } M}$. Our second catalog, named HOD Dense, is matched to the SDSS DR7 main sample (Strauss et al. 2002) at $z < 0.1$ using the parameters found by Zehavi et al. (2011) for galaxies with $M_* < -21 + 5 \log h \, (\sigma_{\text{log } M} = 0.21$, $M_0 = 6.7 \times 10^{13} \, h^{-1} M_\odot$, $M'_0 = 2.8 \times 10^{13} \, h^{-1} M_\odot$, $\alpha = 1.12$). Our simulation only resolves halos down to $M \approx 2M_0$, so we cannot fully represent the HOD, but adopting these parameters and a cutoff at the 20-party minimum halo mass produces a high density galaxy catalog with reasonably realistic clustering properties.

### 2.2 Void Finding

We identify voids with a modified version of ZOBOTV (Neyrinck 2008, Lavaux & Wandelt 2011, Sutter et al. 2012). These modifications include handling of survey masks, performance enhancements, enforcement of bijectivity in the construction of the Voronoi graph in high-density regimes, and the development of a fully-pipelined environment that handles input preparation and post-processing filtering.

ZOBOTV creates a Voronoi tessellation of the tracer particle population and uses the watershed transform to group Voronoi cells into zones and voids (Platen et al. 2007). The watershed transform identifies catchment basins as the cores of voids, and ridgelines, which separate the flow of water, as the boundaries of voids. The watershed transform naturally builds a nested hierarchy of voids (Lavaux & Wandelt 2011, Bos et al. 2012), and for the purposes of this work we only examine root voids, which are voids at the base of the tree hierarchy and hence have no parents. We also impose two density-based criteria on our void catalog. The first is a threshold cut within ZOBOTV itself where voids only include as additional members Voronoi zones with density less than 0.2 the mean particle density. If a void consists of only a single zone (as they often do in sparse populations) then this restriction does not apply. We apply the second density criterion as a post-processing step: we only include voids with mean central densities below 0.2 times the mean particle density. We measure this central density within a sphere of radius $R = R_{\text{eff}} / A$, where

$$R_{\text{eff}} \equiv \left( \frac{3}{4 \pi V} \right)^{1/3} ,$$

where $V$ is the total volume of the Voronoi cells that contribute to the void. We also ignore voids with $R_{\text{eff}}$ below the mean particle spacing $\bar{n}^{-1/3}$ of the tracer population, as these will arise simply from Poisson fluctuations. In sum, we identify voids as depressions in the tracer density (of dark matter particles, halos, or galaxies); voids are non-spherical aggregations of Voronoi cells that share a common basin and are bounded by a common set of higher-density walls.

Additionally, for the analysis below we need to define a center for the void. For our work, we take the barycenter, or volume-weighted center of all the Voronoi cells in the void:

$$X_i = \frac{1}{\sum_i V_i} \sum_i x_i V_i ,$$

where $x_i$ and $V_i$ are the positions and Voronoi volumes of each tracer $i$, respectively.

Table 1 summarizes the samples used in this work, their minimum effective void radius ($R_{\text{eff}, \min} \equiv \bar{n}^{-1/3}$), and the number of voids identified in the simulation volume.

### 2.3 Void Matching

We use the amount of volume overlap to find matches between galaxy voids and voids in other samples. For each galaxy void, we first make a list of potential matches by considering all voids in the matched void catalog whose centers lie within the watershed volume of the galaxy void. Then for each potential matched void, we sum the volumes of each particle whose Voronoi cell overlaps any Voronoi cell of the galaxy void. We take the potential matched void with the greatest amount of volume overlap as the match.

To simplify the measurement of overlap between two Voronoi cells, we place each particle at the center of a sphere whose volume is the same as its respective cell. We measure the distance between particles and assume they overlap if their distances meet the criterion

$$d \leq 0.25(R_1 + R_2) ,$$

where $d$ is the distance and $R_1$ and $R_2$ are the radii of the spheres assigned to particles 1 and 2, respectively. This procedure is approximate, but adequate for our purposes in this paper. We found the factor of 0.25 to strike the best balance between conservatively estimating overlap while still accounting for our rough estimate of the Voronoi volume of each particle.

To account for the possibility that dark matter voids may be less underdense (in terms of central density) than galaxy voids, we allow matching between galaxy voids and any void in the matched catalog, including voids that would normally be removed by the central density threshold discussed in the previous section.

### 3 Void Interiors

In Figure 1 we compare the radial density profiles of voids identified in the HOD mock galaxy samples to the radial profiles of halos and dark matter about the same centers. To
stack voids we align the barycenters of all voids in a given size range. We keep the void positions fixed as we build profiles in the halo and dark matter samples. For the dark matter we only show the DM Full sample, as the sparsely sampled dark matter would necessarily yield the same average result but with greater noise.

Beginning with the HOD Dense voids (top row), we see that the radial density profiles of HOD galaxies and halos are virtually identical. In the smallest radius bin ($R_{\text{eff}} = 20 - 25 \ h^{-1}\text{Mpc}$) these spherically averaged profiles rise from $n/\bar{n} \approx 0$ at $R = 0$ to a maximum of $n/\bar{n} \approx 1.4$ at $R = 0.9R_{\text{eff}}$, with a clear compensation shell surrounding the central underdensity. For the larger size sample the compensation is much weaker and the slope is shallower. The central dark matter densities are $n/\bar{n} \approx 0.3$ for all void radii, indicating that a combination of galaxy bias and shot noise has allowed the watershed approach to identify regions that are more underdense in galaxies than in dark matter. However, the dark matter profiles match the galaxy and halo profiles past $R \approx 0.4R_{\text{eff}}$. Importantly, the voids that are large in galaxies are also large in dark matter.

Turning to the HOD Sparse sample (bottom row), the galaxy central densities are now lower than the halo central densities, which suggests that the watershed algorithm is taking advantage of sampling fluctuations to find deep minima in the galaxy distribution. The central dark matter densities are higher than in the Dense case ($n/\bar{n} \approx 0.5$), and the dark matter profiles are shallower than the galaxy profiles. The compensation effect is also weaker. Not surprisingly, voids in this much sparser, more highly biased galaxy population are less effective (relative to HOD Dense) at corresponding to deep minima in the dark matter distribution.

Nonetheless, the voids in the galaxy distribution are indeed underdense in the halos and dark matter, with similar radial extents, demonstrating the ability of a BOSS-like galaxy survey to reveal large-scale matter underdensities.

To further quantify this relationship, in Figure 2 we correlate densities measured within various radii in the galaxy voids to densities measured in the high-resolution dark matter. That is, we compute $n/\bar{n}(< R/R_{\text{eff}})$, spherically averaged, for each galaxy void. We then compute $n/\bar{n}$ in the DM Full sample within those same spheres, and plot the correlations between the pairs of densities. We measure the densities at 0.5, 0.75, and 1.0 times the effective radius $R_{\text{eff}}$ of each galaxy void, considering all voids above the minimum $R_{\text{eff}}$ threshold.

In Figure 2 we see that even the most underdense cores of HOD Dense galaxy voids correlate with higher densities ($\sim 0.3 \ n/\bar{n}$) in the dark matter. Within $R \approx 0.75R_{\text{eff}}$, a strong correlation appears, and the densities in the galaxies and the dark matter are nearly identical, modulated by a slight offset. Within the full void effective radius, however, the galaxy and dark matter densities match excellently. At this radius, a density in the galaxies corresponds to an equivalent density in the dark matter but with $\sim 10\%$ rms scatter.

The correlations to HOD Sparse galaxy voids show similar trends, but with larger systematic offsets, even at the void effective radius. Overall, voids with low densities at $R = 0.5-1.0R_{\text{eff}}$ correlate most strongly with high-resolution dark matter densities of $0.5-0.8 \ n/\bar{n}$.

We finally turn to slices of the tracer density maps to give a visual impression of the behavior of the dark matter inside galaxy voids. Figures 3 and 4 show such slices, which we have centered on four voids from the HOD Dense and HOD Sparse samples. We chose the particular voids randomly but selected a representative sample from the range of scales in the void catalog. We overplot each void on its host sample density map, as well as density maps from the halo catalog corresponding to the mock galaxy sample (Halos Dense for HOD Dense and Halos Sparse for HOD Sparse), the low-resolution dark matter sample with an equivalent mean number density (DM Dense for HOD Dense and DM Sparse for HOD Sparse), and the high-resolution dark matter sample DM Full. We also show any nearby voids that happen to lie in the slice, and the void chosen to be the best match using the procedure described in the section above. We represent each void as a circle with radius $R_{\text{eff}}$.

While the plotted circles only crudely represent the complex shape of each void (see, for example, Figure 2 of Sutter et al. [2012]), they do give us a useful base for examining void contents.

The voids traced by the HOD Dense sample tend to remain in the dark matter at all void scales, as we see in Figure 3. While there is modest fragmentation (i.e., the breakup of a single galaxy void into many smaller dark matter substructures) in the dark matter, it is much less severe than in the HOD Sparse case and does not strongly affect the void interiors. Matched voids in the halo, low-resolution dark matter, and high-resolution dark matter are smaller, but still correspond to the same fundamental structure identified in the galaxies. For the smallest voids there is an almost perfect match between the galaxy voids and their dark matter counterparts. We see the surrounding and internal structures thicken in the dark matter, but since the galaxies in this case already faithfully represent the cosmic web, it does not lead to large distortions of the voids.

In the case of the HOD LowRes sample shown in Figure 4 we see that while large voids are situated in clear underdense regions, the galaxies are so sparse that it is difficult to visually separate the void and wall regions. The largest voids begin to fragment into smaller structures even in the halo and low-resolution dark matter populations, while we have difficulty finding appropriate matches for the smallest voids. The walls surrounding the underdense regions marked by the large voids grow thicker as we increase the sampling density. We see an extreme amount of fragmentation as the dark matter particles fill in structure marked by the large HOD voids. However, this fragmentation is limited to the edges of the voids, where the dark matter reveals additional substructure in the wall and filament networks surrounding each void; there is still a clear underdensity in the center. For medium-scale voids ($\sim 45h^{-1}\text{Mpc}$), there is much less fragmentation in the dark matter.

4 RELATIONSHIPS TO MATCHED VOIDS

We now directly compare voids in the two mock galaxy samples to their matched counterparts in the halo, low-resolution dark matter, and high-resolution dark matter populations. While this matching cannot be done in observations (where we do not have access to the dark matter distribution), it provides insight about the physical relationship of (simulated) galaxy and dark matter voids when reliable
matches can be found. We use the matching technique described in Section 2 for each pair of catalogs. Additionally, to assess the significance of our results we ran another simulation with identical cosmology and simulation parameters but with a different realization of the initial conditions. Thus for every matched void we also have a matched void from the alternate simulation.

We are unable to find matches for most of the smallest HOD Sparse voids to the halo or low-resolution dark matter voids. Conversely, we are able to find matches for nearly all HOD Dense voids at all scales. We are always able to find a match between galaxy voids at either density to the high-density dark matter voids, since the higher resolution uncovers significant substructure, as we have seen above. Unsurprisingly, for both galaxy samples the smallest voids share little common volume with matches and match just as readily to voids in an alternate realization.

We construct the stacked radial profiles of Figure 5 in a similar fashion as in Figure 1 with one major difference: instead of keeping the centers fixed on the galaxy voids, we shift the centers to the barycenter of each matched void in the stack. Thus, for each galaxy void in the given size range, we find the best match (based on volume overlap as described in Section 2), build the radial profile around that matched void, normalize the profile to the mean number density of that sample, and add that profile to the stack, regardless of its size. We do not rescale the voids as we add them to the stack.

In contrast with Figure 1 these profiles lack any strong differences between the galaxy voids and the dark matter voids. While there is still some residual difference in the densities at the very central regions of each profile, the compensation in the dark matter is not as high as in the galaxies, there are no significant changes to the slope. The profiles in the dark matter appear slightly broader and have lower compensations because we are including voids of a
Figure 2. Correlations between dark matter and galaxy densities with various radii for the HOD Dense (top row) and HOD Sparse (bottom row) void samples. We compute mean densities in spheres of radius $0.5R_{\text{eff}}$ (left), $0.75R_{\text{eff}}$ (middle), and $1.0R_{\text{eff}}$ (right). Densities in each sample are relative to the mean number density $\bar{n}$ of that sample. Each histogram bin has width $0.05n/\bar{n}$. Correlation values are the fraction of all voids in each bin, and the thin grey line indicating equal densities is to guide the eye.

much wider radius range due to the matching (i.e., a single $25 \, h^{-1}$Mpc galaxy void can match to voids of many sizes in the dark matter) than in the galaxy voids themselves. This broadening is not surprising; contrast, for example, the profiles from narrow stacks in Sutter et al. (2012b) to the profile from all voids in Pan et al. (2012). As with the profiles above, the HOD Dense profiles are much more similar to the dark matter profiles than those from the HOD Sparse sample.

Since the matched voids only include voids inside the galaxy voids, these profiles show that each galaxy void corresponds to a deep underdensity in the dark matter, but that the centers are shifted. Once this shift in position is taken into account, we can recover the expected universal density profile (Lavaux & Wandelt 2011).

The fraction of the volume of galaxy void shared between it and the matched voids tells a similar story. Smaller voids in both galaxy samples share a significant fraction of their volume — around 40% — with high-resolution dark matter voids, with larger voids sharing ~ 20% of their volume. For both galaxy mocks we see a clear distinction between matches to the same realization and matches to the alternate realization for all halo and dark matter samples. Indeed, we find that even though we are able to find matches in the alterate realization, and they may happen to be nearby the galaxy void, there is very little common volume, even for the HOD Sparse voids at all radii, meaning that there is still significant correspondence to the dark matter in the low-resolution galaxy voids.

Figure 6 shows the relative distance $d/R_{\text{eff}}$ (where $R_{\text{eff}}$ is the effective radius of the galaxy void) between the best-match void in each halo and dark matter sample and the HOD Dense and HOD Sparse galaxy voids. We also plot the relative distance to the best match void in the alternate realization. Both the HOD Dense and HOD Sparse matches follow similar trends: while some matched voids are no further than $0.3R_{\text{eff}}$, most have a relative distance of ~ 0.6, while a few of the smallest voids are further than the galaxy void effective radius (due to the ellipticity of the galaxy void). There are no significant differences between the distances to matches in the halo population and the dark matter population. Finally, the mean distances to matches in the same realization are always shorter than matches to the alternate realization. This suggests that there is a clear correspondence between galaxy and dark matter voids at almost all scales.

In Figure 7 we show the relative size, which we define as $R_{\text{eff,match}}/R_{\text{eff}}$ of the void matched in the halo and dark matter populations to the galaxy voids. For both the HOD Sparse and HOD Dense the match relative radius is roughly unity for the halos and low-resolution dark matter, and somewhat less than that (0.5 for HOD Sparse and 0.75 for HOD Dense) for the high-resolution dark matter. For both types of galaxy voids, the relative radius decreases for larger voids. This is because the larger voids in galaxies are more likely to contain substructure and more likely have wider walls in the dark matter, so the matched voids will necessarily be smaller. There is only of order~ 10% scatter in these relations for both galaxy samples.

However, the relationship between the shapes of the galaxy and matched voids is more complicated. To roughly measure the void shapes we compute the ellipticity. For a
Figure 3. Voids in the HOD Dense sample and projected density slices of various tracer populations. We select four voids at random but chosen to fairly represent the size ranges in this sample. We list the size of each void in the top row. We represent the selected void as an orange circle with radius equal to its effective radius $R_{\text{eff}}$. Other unrelated voids in the slice are plotted as grey circles. We project each HOD Dense void on other tracer populations in the next three rows. The second row is the Halos Dense sample, the third is DM Dense, and the bottom row is DM Full. Within each sample, the void identified as the best match using the procedure discussed in Section 2.3 is plotted in red. The size of the best-match void and the name of the sample is given on the top of each plot. Note that in some cases there is no match found, which we indicate by “No match”, and in others there is a perfect correspondence, so that the orange circle is not visible. The width of each slice along the line of sight is 50 $h^{-1}$Mpc. The tracer densities are given in units of $\bar{n}$, the mean number density of each sample, and colored from 0 (dark blue) to 1.5 (white). The axes are marked in units of $h^{-1}$Mpc.

Given a set of tracers within a void we first construct the inertia tensor:

$$M_{xx} = \sum_{i=1}^{N_p} (y_i^2 + z_i^2)$$

$$M_{xy} = -\sum_{i=1}^{N_p} x_i y_i.$$
where $N_p$ is the number of particles in the void, and $x_i$, $y_i$, and $z_i$ are coordinates of the particle $i$ relative to the void barycenter. The other components of the tensor are obtained by cyclic permutations. Given the inertia tensor, we compute the eigenvalues and form the ellipticity:

$$
\epsilon = 1 - \left( \frac{J_1}{J_3} \right)^{1/4},
$$

where $J_1$ and $J_3$ are the smallest and largest eigenvalues, respectively. Figure 4 shows the relative ellipticity between the galaxy voids and the halo and dark matter voids.

For both galaxy samples, the relative ellipticity is centered on unity for matches to voids in the halo populations, suggesting that we are roughly capturing the void shape information with the galaxies. The mean relative ellipticity increases for matches to the dark matter voids, since generally voids are more elliptical in dark matter than galaxies. However, there is also high variance in matches to the dark matter, and there is no clear distinction between matches to the same realization and matches to the alternate realization. This is not surprising, since ellipticity measurements of individual voids are very noisy due to the relatively few number of tracers within a void (Bos et al., 2012; Sutter et al., 2013), and small changes in the barycenter can greatly influence the resulting ellipticity measurement. This emphasizes the importance of void stacking to improve the overall signal-to-noise and obtain reliable shape information (Lavaux & Wandelt, 2011).
The dark matter of galaxy voids

Figure 5. Radial density profiles of stacked voids in the HOD Dense (top row) and HOD Sparse (bottom row) samples. For the other samples listed, we build the profiles around the centers of the best match voids to the galaxy voids in that stack, in contrast to Figure 1 where we keep the center fixed. We choose stacks to highlight overcompensated (left column) and undercompensated (right column) void scales, and we indicate the void size ranges used in each stack at the top of each plot. We normalize each profile to the mean number density $\bar{n}$ of its corresponding sample.

5 CONCLUSIONS

We have performed the most comprehensive analysis to date of the relationship between voids in galaxy surveys and underdensities in dark matter. We have examined this relationship by building HOD mock galaxy populations within a high-resolution $N$-body simulation, finding voids in the galaxy distribution, and examining their radial density profiles of galaxies, halos, and dark matter. We have further elucidated this relationship by matching each identified galaxy void to an individual dark matter void. We have contrasted sparsely sampled and densely sampled galaxy surveys to assess the ability of current and future surveys to accurately identify and characterize voids in the cosmic web. We have also provided further examination of the common use of halo positions to represent a galaxy survey, as previously studied in works such as Padilla et al. (2005).

Most importantly, we found that voids identified in both high- and low-resolution galaxy surveys correspond to physical underdensities in the dark matter. While the core densities in the corresponding dark matter tend to be higher than in the galaxy survey, at radii larger than roughly half the effective void radius the profiles are nearly identical. Also, we have found that each galaxy void does contain a deep underdensity, but the location of that underdensity is usually offset from the galaxy void barycenter. When this offset is taken into account, we recover a nearly universal density profile. Measured at the void effective radius, mean densities in the galaxies are within 10% of the mean densities in the dark matter.

We have determined the capability of a particular survey to robustly identify given classes of voids. For high-resolution surveys, the smallest galaxy voids are most suspect, since they share little common volume with matches, tend to have highly displaced centers, and have large scatter in the relative radius to dark matter voids. They are also easily confused by matches to alternate realizations. However, above $\sim 25-30 \ h^{-1}\text{Mpc}$, galaxy voids form a much...
Figure 6. Relative distance ($d/R_{\text{eff}}$) between the centers of matched voids to the HOD Dense (left) and HOD Sparse (right) voids as a function of HOD void effective radius. The solid lines indicate mean values in $5 \, h^{-1}\text{Mpc}$ bins and shaded regions represent one standard deviation in that bin. The red line and light red shaded area are for matched to the same simulation, and the blue line and light blue shaded area are for matches to a simulation with a different realization of an identical cosmology.

Figure 7. Relative radius ($R_{\text{eff,match}}/R_{\text{eff}}$) between the centers of matched voids and the HOD Dense (left) and HOD Sparse (right) voids as a function of HOD void effective radius. The solid lines indicate mean values in $5 \, h^{-1}\text{Mpc}$ bins and shaded regions represent one standard deviation in that bin. The red line and light red shaded area are for matched to the same simulation, and the blue line and light blue shaded area are for matches to a simulation with a different realization of an identical cosmology.

tighter correspondence to dark matter voids. We also see ranges of void sizes in low-resolution surveys that appear reasonably well-matched to dark matter voids. While larger voids here tend to host significant dark matter substructure (i.e., fragmentation), this substructure is largely limited to the void edges; the interiors usually contain a single deep underdensity. Medium-scale voids, in the range $\sim 25 - 55 \, h^{-1}\text{Mpc}$, trace relatively the same structures as the dark matter. These results confirm the statistical interpretation of Hamaus et al. (2013): the cross-spectra of void and matter distributions indicate that void identified with the watershed approach do indeed inhabit underdense regions of the universe.

Voids at all scales in both high- and low-resolution surveys appear to map the same shapes as the dark matter voids, as we have seen in our ellipticity measurements. However, the noisiness of the ellipticity measurement leads to matches of the same significance to alternate realizations. Stacking procedures, which trade some loss of shape information for increased signal-to-noise and smoothening of the remaining shape, offer a promising alternative to this difficult situation (Lavaux & Wandelt 2011; Sutter et al. 2012a).

While we have utilized the matching procedure to gain insights into the relationship between galaxy voids and dark matter underdensities, we do not offer this as a prescription for inferring dark matter characteristics from an individual observed void. Instead, this analysis informs us on the relative uncertainty of void properties. For example, if we use
the center of a galaxy void as a starting place for calculating the integrated Sachs-Wolfe effect \cite{PlanckCollaboration13} or the lensing potential \cite{Melchior13}, and assume that this galaxy void corresponds to a single dark matter void, then this analysis indicates that the true center in the dark matter is likely within $\sim 50\%$ of the void radius.

We have targeted our mock galaxy populations to two specific surveys: the SDSS DR7 main sample ($M_r < -21$) and the SDSS DR9 CMASS sample, which we have taken to generally represent densely and sparsely sampled surveys, respectively. Even though a full analysis should be undertaken to examine the quality of voids in future surveys such as BigBOSS \cite{Schlegel11} or Euclid \cite{Laureijs11}, this work provides some guidelines on the robustness of identified voids. While we have focused on the interior contents of voids in this paper, \cite{Sutter13} examines the statistical properties of galaxy void populations from realistic surveys.

We conclude that cosmological analyses that rest on the properties of voids such as size distributions or radial profiles are generally reliable when high-resolution galaxy surveys are used, as there is a clear correspondence between these voids and their dark matter counterparts. This correspondence is weakened for sparsely sampled surveys. However, it is not removed: there is a range of void scales that match reliably to dark matter. Shape measurements with voids appear problematic in all surveys, but there are avenues available to address this such as statistical shape measurements in stacks of voids. Most importantly, galaxy voids at all scales in all kinds of surveys still remain as underdensities in the dark matter and can still be considered as voids in the general sense. This is vitally important, since voids identified in galaxy surveys are a potentially rich source of astrophysical and cosmological information.

\section*{Acknowledgments}

The authors would like to thank Nico Hamaus for useful comments. PMS and BDW acknowledge support from NSF Grant AST-0908902. BDW acknowledges funding from an ANR Chaire d’Excellence, the UPMC Chaire Internationale in Theoretical Cosmology, and NSF grants AST-0908902 and AST-0708849. GL acknowledges support from CITI National Fellowship and financial support from the Government of Canada Post-Doctoral Research Fellowship. Research at Perimeter Institute is supported by the Government of Canada through Industry Canada and by the Province of Ontario through the Ministry of Research and Innovation. DW acknowledges support from NSF Grant AST-1009505.

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