Clustering and Bias Measurements of SDSS Voids

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\textbf{ABSTRACT}

Using a void catalog from the SDSS survey, we present the first measurements of void clustering and the corresponding void bias. Over the range $30 - 200 \text{ Mpc}/h$ the void auto-correlation is detected at $5\sigma$ significance for voids of radius $15 - 20 \text{ Mpc}/h$. We also measure the void-galaxy cross-correlation at higher signal-to-noise and compare the inferred void bias with the autocorrelation results. Void bias is constant with scale for voids of a given size, but its value falls from $5.6 \pm 1.0$ to below zero as the void radius increases from 15 to 30 Mpc/$h$. The comparison of our measurements with carefully matched galaxy mock catalogs, with no free parameters related to the voids, shows that model predictions can be reliably made for void correlations. We study the dependence of void bias on tracer density and void size with a view to future applications. In combination with our previous lensing measurements of void mass profiles, these clustering measurements provide another step towards using voids as cosmological tracers.

\textbf{Key words:} cosmology: observations – dark matter – large scale structure of Universe

\section{INTRODUCTION}

The clustering of galaxies was first detected over 60 years ago (Limber 1954; Rubin 1954), and since then this observable has developed into one of the cornerstones of modern cosmology. While the abundance and other properties of voids have been measured in the past, this paper is the first successful attempt to detect their clustering in survey data. Galaxy clustering is strongest on nonlinear scales less than 10 Mpc/$h$, but these scales are smaller than the radius of a typical void, so that meaningful void-void correlations are impossible to measure at such scales. Only the large scale regime where the magnitude of 2-point correlations has fallen to the $\sim 0.1$ level and below is available for void clustering measurements. Not only is the available signal smaller, but the noise in void correlation functions is greater since voids are far less numerous than galaxies. Voids are much larger and finding even one requires many galaxies to trace its shape.

Theoretical work on modeling the bias of dark matter halos (Cole & Kaiser 1989; Mo & White 1996; Sheth & Tormen 1999) was extended to voids by Sheth & van de Weygaert (2004). The resulting bias function starts out positive for the smallest voids but eventually transitions to negative values for the largest objects. Hamaus et al. (2014) measured the void-void and void-galaxy power spectrum in simulations, recovering this transition to negative bias for larger voids. (See also Padilla et al. (2005) for an earlier study of void-void correlations in simulations.) Using voids traced by simulated dark matter particles, Chuen Chan et al. (2014) showed that this transition scale also depends on void tracer density. On the observational side, the focus has been on the size distribution of voids and the distribution and properties of galaxies within the voids, not on large scale clustering and void bias. One exception is the void-galaxy cross-correlation measurements of Paz et al. (2013), whose main aim was to understand the dynamics of voids.

In Clampitt & Jain (2015), henceforth CJ15, we presented a new void finder and void catalog using Sloan Digital Sky Survey (SDSS) data. In addition, we measured the density profiles of these voids using weak lensing, finding an average central density $\delta \lesssim -0.5$. Complementing previous void profiles assumed from visible galaxies (Hoyle & Vogeley 2004; Pan et al. 2014; Ceccarelli et al. 2013; Sutter et al. 2014; Nadathur et al. 2015), our lensing measurements showed directly that these objects are voids in the dark matter. In this work, we use the same set of voids to measure void clustering and bias. In Sec 2, we describe our SDSS and mock data sets. In Sec. 3 we present high-significance measurements of void-void clustering, void-galaxy clustering, and void bias, and make comparison with mock mea-
measurements of the same. Finally, in Sec. 4 we discuss the implications of the measurements and possible future directions for void clustering studies.

2 SDSS AND MOCK DATA SETS

2.1 SDSS void catalog

For void tracers in SDSS we use the Luminous Red Galaxy (LRG) sample of Kazin et al. (2010), specifically the volume limited sample at 0.16 < z < 0.36. We use the largest contiguous patch (∼ 7,000 square degrees) of the available data. This sample has ∼ 56,000 LRGs and covers a comoving volume ∼ 0.6 (Gpc/h)³. See Table 1 for more details on this sample.

The void finder of CJ15 begins by dividing the SDSS LRG sample into redshift slices of various thickness. Within each of these slices, all LRGs are projected onto a 2D spherical space and holes in the LRG distribution are found within each slice. These potential void centers are then culled with several quality cuts on the void axis ratio, location (required to be well within the survey edges), and volume overlap between voids. CJ15 showed that the density profiles derived from weak lensing were consistent between samples with volume overlap cutoffs of 50% and 90%. For most of our results, we require that each void has an overlapping volume fraction of 50% or less; this simplifies somewhat the interpretation of the clustering measurements as coming from unique voids.

This fiducial sample has ∼11,000 voids. In Sec. 3.4 we briefly compare the void-galaxy correlation using the 90% overlap sample, with 19,000 objects this sample increases the number of voids by about a factor of 2.

The void finder outputs two sizes for each void: a projected radius in the plane of the sky (Rv) and a size in the line-of-sight direction (sv). We expect voids with the same clustering amplitude and bias to have comparable total volume. Thus we define an effective radius which is the radius of the sphere with the same volume as the ellipsoid output by the void finder:

\[ r_{\text{eff}} \equiv (R_v^2 s_v)^{1/3}. \]  

For all measurements, we group the voids in three size bins: \( r_{\text{eff}} = 15 - 20 \text{ Mpc}/h \), 20 - 25 Mpc/h, and 25 - 30 Mpc/h.

2.2 Horizon Run mocks

For mock void samples, we use one of the eight public full-sky mock surveys from the Horizon Run Simulation (Kim et al. 2009) with cosmology \( \Omega_m = 0.26, \Omega_\Lambda = 0.74, \) and \( \sigma_8 = 0.79. \) Restricting to the same redshift range as the data, this gives us ∼ 6 times the volume. We make use of four different simulated halo samples as void tracers. First, the Matched sample is chosen to have the same density and halo bias as the LRGs in the data. The other three halo samples are chosen by setting minimum mass thresholds such that, in comparison to the data, they have: exactly the same density (Sparse), 2× the density (Medium), and 4× the density (Dense). The result is that the tracer bias varies by ∼ 15 – 30% along with the larger variation in tracer density. We summarize the tracer densities, inter-particle spacing, halo mass thresholds, and halo bias of these samples in Table 1.

Note that our Sparse and Matched sample voids have an average inter-particle spacing of 21.5 Mpc/h, which is larger than our smallest measured bin of void sizes, 15 Mpc/h < \( r_{\text{eff}} < 20 \) Mpc/h. Although this bin may therefore have some contamination from chance gaps between galaxies (“Poisson” voids), the lensing measurements of CJ15 indicate that voids in this sample are on average significantly underdense in the dark matter. Furthermore, for these smaller voids we see a smooth change in void bias (see Sec. 3.3 and Fig. 4) as tracer density is increased from the Sparse to Medium, and finally to the Dense sample (for which all voids are larger than the inter-particle spacing). This provides further evidence that we do not see a qualitative change from true voids to spurious voids as the tracer inter-particle spacing is increased to be slightly larger than the void size.

3 RESULTS

We measure the 2-point correlation function \( \xi(r) \) using the estimator of Landy & Szalay (1993):

\[ \xi(r) = \frac{DD(r) - DR(r) - RD(r) + RR(r)}{RR(r)}, \]  

where, e.g., for void-void clustering \( DD(r) \) denotes the number of void-void pairs, \( DR(r) \) and \( RD(r) \) the number of void-random pairs, and \( RR(r) \) the number of random-random pairs with comoving separation \( r \). We use TreeCorr (Jarvis et al. 2004) to compute all correlation functions. We obtain the covariance by splitting the survey into 128 patches and using the jackknife method described in Norberg et al. (2009). Likewise for the whole-sky simulation covariance, but in that case we use 192 patches, each 4x larger than the data jackknife patches. We make use of HEALpix (Görski et al. 2005) for defining equal-area jackknife patches. We checked that our error bars are not sensitive to this difference between the size of mock and data patches by repeating the measurements using a set of data patches with comparable size to the mock patches. For both voids and galaxies, we use corresponding random catalogs with 20 times as many points.

3.1 Void-void clustering

In Fig. 1 we show the void-void clustering measurement, \( \xi_{vv} \), in data and mocks. Outside \( 2r_{\text{eff}} \) all correlations involve distinct voids, and in this regime the data and mocks are in qualitative agreement. To obtain the significance of detection, we use a likelihood ratio test comparing two hypotheses: the null hypothesis of no clustering and the simulation hypothesis that the data was generated from a model with central values and covariance matching the simulation measurements. Considering only the data on scales \( 2r_{\text{eff}} < r < 200 \) Mpc/h, the detection significance for the

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2 http://sdss.kias.re.kr/astro/Horizon-Run/

3 https://github.com/rmjarvis/TreeCorr

4 http://healpix.sf.net
**Void Clustering in SDSS**

Void Tracer Properties of SDSS LRGs and Simulation Halos

| sample name | dataset | density | inter-particle spacing | halo mass threshold | halo bias |
|-------------|---------|---------|------------------------|---------------------|----------|
| Data        | SDSS    | $1 \times 10^{-4}$ (Mpc/h)$^{-3}$ | 21.5 Mpc/h          | -                   | 2.1      |
| Matched     | HR simulation | $1 \times 10^{-4}$ (Mpc/h)$^{-3}$ | 21.5 Mpc/h          | $1.3 \times 10^{13} M_{\odot}/h$ | 2.1      |
| Sparse      | HR simulation | $1 \times 10^{-4}$ (Mpc/h)$^{-3}$ | 21.5 Mpc/h          | $1.3 \times 10^{13} M_{\odot}/h$ | 1.8      |
| Medium      | HR simulation | $2 \times 10^{-4}$ (Mpc/h)$^{-3}$ | 17.1 Mpc/h          | $1.3 \times 10^{13} M_{\odot}/h$ | 2.1      |
| Dense       | HR simulation | $4 \times 10^{-4}$ (Mpc/h)$^{-3}$ | 13.5 Mpc/h          | $0.7 \times 10^{13} M_{\odot}/h$ | 2.4      |

Table 1. Description of the SDSS galaxies and HR simulated halos used to define voids. The halo mass threshold of the mock samples indicates the minimum halo mass included. The Matched sample of simulated halos is our primary sample for comparison to the Data.

$r_{eff} = 15 - 20$ Mpc/h bin is slightly larger than 5σ, corresponding to a p-value $\sim 2 \times 10^{-7}$. For the 20 – 25 Mpc/h bin we obtain a 3σ measurement, corresponding to a p-value 0.0014. The largest radius voids are fewest in number, leading to a measurement consistent with both the null hypothesis and the simulations.

The data is strong enough to discern a decrease in the correlation strength with void size, and the mocks show this trend even more clearly. In § 3.2 we comment more on these trends, and quantify the variation further with fits to the void bias $b_v$. In Fig. 1 we also plot our best fit model of the void-void correlation, $\xi_{vv} = b_v^2 \xi_{mv}$, for both data and mocks. These theoretical curves match the measurement very well, as expected if voids are biased tracers of the dark matter density field. In addition to comparing this single-parameter model to the data, it is useful to directly compare the data to the Matched sample of simulated voids. The reduced chi-square (using radial bins $2r_{eff} < r < 200$ Mpc/h) is 8/6, 4/5, and 2/5 for the three size bins, all acceptable fits. However, the more sensitive likelihood ratio test shows tension at the 1 to 2σ level for the 15 – 20 Mpc/h and 20 – 25 Mpc/h bins. Although this tension is relatively small, it may be pointing to a slight mismatch between our Data and Matched simulation samples (see Sec. 4 for further discussion).

3.2 Void-galaxy clustering

The void-galaxy clustering measurement, $\xi_{vg}$, is shown in Fig. 2. Due to the much larger number of galaxies compared to voids ($\sim 10$ times more), the signal to noise (S/N) is much higher in this measurement compared to the autocorrelation. It thus yields more precise values for void bias (see § 3.3). We plot our best fit model, $\xi_{vg} = b_v b_g \xi_{mg}$ for both data and mocks. The galaxy bias, defined as $b_g = \sqrt{\xi_{gg}/\xi_{mm}}$, is $b_g = 2.1$ for the Data LRGs, and $b_g = 2.1$ for our Matched halo sample. As with $\xi_{vv}$, the goodness-of-fit of the simulation model is acceptable for all three void radius bins: in order of increasing void size the reduced $\chi^2$ is 4/6, 6/5, and 7/5. The tension between mocks and data in $\xi_{vv}$ based on the likelihood ratio statistic is not present in the measurement of $\xi_{vg}$. In all three $r_{eff}$ bins, mocks and data are consistent within $\sim 1\sigma$ using the likelihood ratio test (see Sec. 3.1 for details).

In Fig. 3 we show the entire range of the void-galaxy clustering measurement: (i) the innermost scales $r < r_{eff}/2$ where $\xi_{vg} = -1$ by definition, (ii) the void profile regime between $r_{eff}/2$ and $2r_{eff}$, and (iii) the linear regime $r > 2r_{eff}$ (the subject of Fig. 2). Regarding (i), we note simply that both the data and mock measurements are indeed equal to 1 at small scales, a reassuring check of the measurement and random point catalogs. The void profile in (ii) shows more structure: the smallest voids display a clear positive bump which becomes less prominent as void size $r_{eff}$ increases.
and disappears entirely for voids with $r_{\text{eff}} > 25$ Mpc/h. Thus the largest voids are the only ones that dominate their environments and are underdense out to very large scales. These results are qualitatively consistent with those of Ceccarelli et al. [2013] and Hamaus et al. [2014], who find that larger voids lack the compensatory ridge that surrounds many smaller voids. (Although see also Nadathur et al. [2015], on void profiles that show less significant differences as a function of size.) Due to the sharply rising profile and good signal-to-noise in this regime, even slight differences between data and mocks are easy to see. Fig. 3 shows that for all three void size bins, the mock profiles have a denser and somewhat sharper ridge of galaxies around the void. In Sec. 4, we discuss possible differences between data and mocks that could be the cause. In the following section, we discuss in more detail the linear regime results and implications for void bias.

### 3.3 Void bias

For both data and mocks we obtain two values for the best fit bias of each void size bin: one via the void-galaxy correlation,\
\[
b_{v}^{\text{cross}} = \frac{\xi_{vg}}{b_{g}^{\text{mm}}},
\]
and one via the void-void correlation,\
\[
b_{v}^{\text{auto}} = \pm \sqrt{\frac{\xi_{vv}}{\xi_{\text{mm}}^{\text{mm}}}},
\]
where $\xi_{\text{mm}}$ is the matter-matter correlation function measured from the simulations. With the auto-correlation we actually measure bias squared, then take the square root and choose the sign of bias that matches the sign of $\xi_{vg}/(\xi_{\text{mm}} b_{g})$. Both fits use only the data between $2 r_{\text{eff}} < r < 80$ Mpc/h: the lower limit assures we use only pairs of distinct voids in the bias measurement, while the upper limit keeps us from dividing by the value of $\xi_{\text{mm}}$ where it is falling rapidly and approaching the Baryon Acoustic Oscillations (BAO) scale.
(and thus more strongly dependent on cosmology). The noise on $b_{\text{auto}}^\text{cross}$ for the largest voids in the data is very large and thus we were unable to obtain a bias fit for that sample.

The resulting bias values are shown in Fig. 4. The SDSS Data voids clearly show decreasing bias with void radius. In the left panel, the bias falls from $5.6 \pm 1.0$ to $-0.4 \pm 1.1$ between $r_{\text{eff}} = 15 - 20 \, \text{Mpc}/h$ and $25 - 30 \, \text{Mpc}/h$, an $\sim 5\sigma$ detection of a decreasing trend with radius. Comparing between the Data and Matched mock samples, the fitted void bias values are consistent for both $b_{\text{auto}}^\text{cross}$ and $b_{\text{cross}}^\text{auto}$. Similarly, comparing between the two estimates of bias, both provide reassuringly consistent results in both data and mocks.

The mocks allow us to use higher tracer densities compared to the SDSS LRG sample and explore the effect on void bias. In all cases, the same galaxies (the Matched sample) are used in the cross-correlation measurement, to isolate the effect of tracer density on void bias. It is evident that there is a range of bias values, with the maximum positive and negative bias suggesting objects that are as rare as large galaxy clusters. For the Dense and Medium samples we find an interesting transition of the void bias from positive to negative values with increasing radius. The void radius at which bias crosses zero depends on tracer density: it occurs at $\sim 21 \, \text{Mpc}/h$, $25 \, \text{Mpc}/h$, and above $30 \, \text{Mpc}/h$ for our three samples of decreasing density. This trend has been studied before in simulations by Hamaus et al. (2014) and Chuen Chan et al. (2014). Those works used tracer densities of $0.02 \, (\text{Mpc}/h)^{-3}$ and larger, at least 50 times denser than our samples. The qualitative dependence of void bias on radius is the same between our voids and those of Hamaus et al. (2014) and Chuen Chan et al. (2014). However, the detailed values of the bias depend on the void finder, and the fact that our bias zero crossing for the Dense sample is similar to that of Hamaus et al. (2014) (at 19.5 Mpc/h) is a coincidence.

Fixing the void size, Chuen Chan et al. (2014) showed that simulated voids found using denser tracer samples have lower bias. Here we extend those results to observationally interesting tracer densities and find the same qualitative trends. Our Matched sample with density $10^{-4} \, (\text{Mpc}/h)^{-3}$ has higher bias at all void sizes than the $2 \times 10^{-4} \, (\text{Mpc}/h)^{-3}$ sample, which in turn has higher bias than the $4 \times 10^{-4} \, (\text{Mpc}/h)^{-3}$ sample. The difference in bias between samples is greatest for the voids with larger radii. Note that this densest sample is comparable to the density of the CMASS (Anderson et al. 2014) and LOWZ (Tojeiro et al. 2014) galaxy samples of the Baryon Oscillation Spectroscopic Survey (BOSS) (Alam et al. 2015).

Finally, we find that the void bias depends on the tracer bias. The Matched sample has the same tracer density as the Sparse sample, but with an average halo bias that is $15\%$ smaller. This smaller halo bias causes the void bias to drop by $5\%$, $15\%$, and $50\%$ for the three increasing void radius bins (see Fig. 4). Thus, even a small change in tracer bias makes a substantial difference in the void bias for larger voids. The importance of tracer bias on simulated void properties was also recently studied by Pollina et al. (2016). This work points out that due to this dependence on tracer bias, simply subsampling dark matter particles of a simulation to the appropriate density is not sufficient to match observed galaxy-defined void samples. An explanation for the trends described above is discussed in Sec. 4.

### 3.4 Volume overlap

The void finder of CJ15 allows us to choose the maximum amount of overlap allowed between neighboring voids. In Fig. 4 we study the effect of this parameter by comparing the measured SDSS void-galaxy correlations using both 90% maximum overlap between voids and 50% (our fiducial sample). The results are consistent for the smallest void sample.
but for the medium and largest voids there is a significant
difference. Correlations, and therefore void bias, are more
negative for the sample which allows more overlap. For the
$r_{\text{eff}} = 20 - 25$ Mpc/$h$ sample the void bias is 30-40% smaller.
The effect on the $r_{\text{eff}} = 25 - 30$ Mpc/$h$ sample is even more
striking; the measured bias is clearly negative for the 90% overlap
sample. This is our first clear detection of a negative void
bias in survey data. While there is a difference in the
bias of the two void samples, further study will be needed to
verify conclusively whether this is due to the differing void
overlap. The two samples also differ in their statistics: the
90% overlap sample has a factor of 2 more voids, and hence
the error bars are significantly tighter. We have not ruled
out the possibility that the differences above are simply due
to better signal-to-noise, and leave further study of volume
overlap trends for future work.

There is also some effect in the transition region (not
pictured) from $\xi_{\text{VG}} \sim -1$ to its peak around $r \sim r_{\text{eff}}$, with
the direction of the effect such that the 90% overlap sample
has a denser and somewhat sharper ridge of galaxies around
the void. Note that the results shown in Fig. 7 of CJ15 for
the lensing mass profiles of these two void samples were
consistent. The higher S/N void-galaxy cross-correlations are
required in order to pick up this slight difference in the profiles.
Finally, we also compared the two samples’ void-void cor-
relations, but again in this case the errors are too large to
discrim a difference.

4 DISCUSSION

We have presented a 5$\sigma$ detection of the void auto-
correlation function (Fig. 1) over $30 - 200$ Mpc/$h$ using the
SDSS void sample of [Clampitt & Jain 2015]. The higher
signal-to-noise void-galaxy cross-correlations (Fig. 2) yield
even more precise measurements of the void bias. Void bias
is constant over the range of scales we measure, outside twice
the void radius. Bias results (Fig. 3) comparing auto- and
cross-correlations are consistent in all size bins, spanning
void radii over the range $15 - 30$ Mpc/$h$. Using the cross-
correlation, we find that void bias falls from $5.6 \pm 1.0$ to
$-0.4 \pm 1.1$ over this range of radii, a $\sim 5\sigma$ detection of the
trend. In addition, we made a careful comparison with corre-
lations in mock catalogs. We match the galaxy tracer density
and bias and use the same void finder on the mocks. The
void bias using both methods is consistent between data and
mocks. Our results are promising for void cosmology with
future surveys: based solely on the properties of tracer galax-
ies, mock catalogs provide predictions of large-scale void cor-
relations that can be compared to measurements.

With these mock voids, we choose different halo tracers
to confirm previous results that void bias decreases with
(i) increasing void size and (ii) increasing tracer density.
The large, positive bias observed for small voids transitions
through zero to increasingly negative values for large,
densely sampled voids. Fig. 4 shows a third trend: void sam-
pies defined from less biased halos show the same trend as
with increasing tracer density. The trends with higher den-
sity or lower bias can be understood by noting that voids
are defined at fixed underdensity threshold. So as the tracer
density increases, we expect that the true mass density is
lower for a region to be identified as a void. In summary:

| High Density/Low bias of galaxy tracer |
|---------------------------------------|
| → Emptier voids                       |
| → Smaller amplitude positive bias for small voids |
| → Higher amplitude negative bias for large voids |

In future work, these trends can be tested and studied
in more detail [Sutter et al. 2014] have shown that voids
defined using denser tracer samples are more likely to ac-
curately trace the dark matter field. Similarly, it would be
interesting to confirm whether or not our voids defined from
less biased tracers are also more empty of dark matter [Na-
dathur & Hotchkiss 2015]. In addition, higher order effects
such as the detailed bias distribution of the void tracers
may make a difference to the resulting void properties. For
example, as discussed in Sec. 3.1, there is a slight $1 - 2\sigma$
discrepancy in the auto-correlation for some void size bins.
In future work we can explore whether using a mock sample
with realistic mass-luminosity scatter and satellite fraction
will remove any remaining differences between mock and
data voids. Another possible source of discrepancy is due
to the different cosmologies: the Planck Collaboration et al. (2015) best-fit value of \( \Omega_m \) is \( \sim 0.31 \pm 0.01 \), whereas the simulations use 0.26.

We checked that differing treatments of redshift space distortions (RSD) in mocks and data is not the source of this discrepancy. When analyzing the mock catalogs, the preceding results involve running the void finder and all measurements using real space coordinates. However, we have separately analyzed the mocks after converting galaxy positions to redshift space using peculiar velocity information. The correlation functions change by a negligible amount within our errors, as might be anticipated from Lambas et al. (2016). This work finds that void pairwise velocities are small, usually below 100 km/s, which would cause an ~1 Mpc/h shift along the x-axis of correlation function plots. See also Sutter et al. (2014b) which finds that individual void macrocenters move very little over the course of the void’s lifetime.

Galaxy samples in current surveys can be used for additional void clustering measurements. These include the higher density LOWZ and CMASS galaxy samples of BOSS discussed in Section 3.3. In the future, much larger surveys will be available. The majority of these surveys are imaging surveys that provide photometric redshifts, from which void samples can be created, but must be interpreted keeping in mind the uncertainty in the position along the line of sight. Three dimensional galaxy surveys from the Prime Focus Spectrograph on the Subaru telescope, and the Euclid and WFIRST satellites in the next decade will enable void studies over larger volumes and higher redshifts (Krause et al. 2013).

A new approach to void cosmology involves the joint analysis of observables described in this paper and Clampitt & Jain (2015): void-galaxy, void-void, and void-mass correlations from weak lensing, as well as void abundances. These observables are analogous to cluster cosmology. By running the same void finder on data and realistic void samples from simulations with varying cosmology, detailed comparisons between survey data and theoretical predictions can be made. The pros and cons of using voids as cosmological probes have been discussed in the literature. One obvious limitation is the lower statistical precision of void measurements. However there are theoretical reasons to expect a stronger signal for some cosmological tests, in particular modified gravity effects discussed below. For clustering measurements, more study is needed to understand the requirements for voids to provide useful tests. Improvements to void finder algorithms and increasing amounts of data from ongoing surveys will only improve the signal-to-noise of these initial measurements of void-void, void-galaxy, and void-mass correlations. A different cosmological test relies on the insensitivity of voids to nonlinear redshift space distortions. The varying bias levels studied here are relevant for redshift space distortions; in particular, the nearly unbiased void population may be useful in performing the Alcock-Paczyński test (Alcock & Paczynski 1979) to constrain cosmology (Hamaus et al. 2014, 2015).

Void lensing and clustering may be particularly useful for applications such as constraining modified gravity theories. Barreira et al. (2015) have shown Galileon models have a large effect on void lensing predictions. It would be interesting to test whether such theories also give significantly different results for void bias. In addition, the changes to void number functions in chameleon theories (Clampitt, Cai & Li 2013; Lam et al. 2015; Zivick et al. 2015) Cai et al. (2015) may cause changes in the void bias as a function of void size.

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REFERENCES

Alam, S., Albareti, F. D., Allende Prieto, C., et al. 2015, arXiv:1501.00963
Alcock, C., & Paczynski, B. 1979, Nature (London), 281, 358
Anderson, L., Aubourg, É., Bailey, S., et al. 2014, MNRAS, 441, 24
Barreira, A., Cautun, M., Li, B., Baugh, C., & Pascoli, S. 2015, arXiv:1505.05809
Cai, Y.-C., Padilla, N., & Li, B. 2015, MNRAS, 451, 1036
Ceccarelli, L., Paz, D., Lares, M., Padilla, N., & Lambas, D. G. 2013, MNRAS, 434, 1435
Clampitt J., Cai Y.-C., Li B., 2013, MNRAS, 431, 749
Clampitt J., & Jain, B. 2015, MNRAS, 454, 3357
Chuen Chan, K., Hamaus, N., & Desjacques, V. 2014, arXiv:1409.3849
Cole, S., & Kaiser, N. 1989, MNRAS, 237, 1127
Górski, K. M., Hivon, E., Banday, A. J., et al. 2005, ApJ, 622, 759
Hamaus, N., Wandelt, B. D., Sutter, P. M., Lavaux, G., & Warren, M. S. 2014, Physical Review Letters, 112, 041304
Hamaus, N., Sutter, P. M., & Wandelt, B. D. 2014, Physical Review Letters, 112, 251302
Hamaus, N., Sutter, P. M., Lavaux, G., & Wandelt, B. D. 2014, JCAP, 12, 013
Hamaus, N., Sutter, P. M., Lavaux, G., & Wandelt, B. D. 2015, arXiv:1507.04363
Hoyle, F., & Vogeley, M. S. 2004, ApJ, 607, 751
Jarvis, M., Bernstein, G., & Jain, B. 2004, MNRAS, 352, 338
Kazin, E. A., Blanton, M. R., Scoccimarro, R., et al. 2010, ApJ, 710, 1444
Krause, E., Chang, T.-C., Doré, O., & Umeda, K. 2013, ApJL, 762, L20
Kim, J., Park, C., Gott, J. R., III, & Dubinski, J. 2009, ApJ, 701, 1547
Lam, T. Y., Clampitt, J., Cai, Y.-C., & Li, B. 2015, MNRAS, 450, 3319
Lambas, D. G., Lares, M., Ceccarelli, L., et al. 2016, MNRAS, 455, L99
Landy, S. D., & Szalay, A. S. 1993, ApJ, 412, 64
Limber, D. N. 1954, ApJ, 119, 655
Mo, H. J., & White, S. D. M. 1996, MNRAS, 282, 347
Nadathur, S., Hotchkiss, S., Diego, J. M., et al. 2015, MNRAS, 449, 3997
Nadathur, S., & Hotchkiss, S. 2015, arXiv:1507.00197
Norberg, P., Baugh, C. M., Gaztañaga, E., & Croton, D. J. 2009, MNRAS, 396, 19
Padilla, N. D., Ceccarelli, L., & Lambas, D. G. 2005, MNRAS, 363, 977
Pan, D. C., Vogeley, M. S., Hoyle, F., Choi, Y.-Y., & Park, C. 2012, MNRAS, 421, 926
Paz, D., Lares, M., Ceccarelli, L., Padilla, N., & Lambas, D. G. 2013, MNRAS, 436, 3480
Planck Collaboration XIII 2015, arXiv:1502.01589
Pollina, G., Baldi, M., Marulli, F., & Moscardini, L. 2016, MNRAS, 455, 3075
Rubin, V. C. 1954, Proceedings of the National Academy of Science, 40, 541
Sheth, R. K., & Tormen, G. 1999, MNRAS, 308, 119
Sheth, R. K., & van de Weygaert, R. 2004, MNRAS, 350, 517
Sutter, P. M., Lavaux, G., Hamaus, N., et al. 2014, MNRAS, 442, 462
Sutter, P. M., Elahi, P., Falck, B., et al. 2014, MNRAS, 445, 1235
Tojeiro, R., Ross, A. J., Burden, A., et al. 2014, MNRAS, 440, 2222
Zivick, P., Sutter, P. M., Wandelt, B. D., Li, B., & Lam, T. Y. 2015, MNRAS, 451, 4215