THE SPATIAL CLUSTERING OF ROSAT ALL-SKY SURVEY ACTIVE GALACTIC NUCLEI IV. MORE MASSIVE BLACK HOLES RESIDE IN MORE MASSIVE DARK MATTER HALOS

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ABSTRACT

This is the fourth paper in a series that reports on our investigation of the clustering properties of active galactic nuclei (AGNs) identified in the ROSAT All-Sky Survey and Sloan Digital Sky Survey (SDSS). In this paper we investigate the cause of the X-ray luminosity dependence of the clustering of broad-line, luminous AGNs at 0.16 < z < 0.36. We fit the Hα line profile in the SDSS spectra for all X-ray and optically selected broad-line AGNs, determine the mass of the supermassive black hole (SMBH), M_BH, and infer the accretion rate relative to Eddington (L/L_EDD). Since M_BH and L/L_EDD are correlated, we create AGN subsamples in one parameter while maintaining the same distribution in the other parameter. In both the X-ray and optically selected AGN samples, we detect a weak clustering dependence with M_BH and no statistically significant dependence on L/L_EDD. We find a difference of up to 2.7σ when comparing the objects that belong to the 30% least and 30% most massive M_BH subsamples, in that luminous broad-line AGNs with more massive black holes reside in more massive parent dark matter halos at these redshifts. These results provide evidence that higher accretion rates in AGNs do not necessarily require dense galaxy environments, in which more galaxy mergers and interactions are expected to channel large amounts of gas onto the SMBH. We also present semianalytic models that predict a positive M_{DMH} dependence on M_BH, which is most prominent at M_BH ~ 10^{8−9} M_☉.

Key words: galaxies: active – large-scale structure of universe – X-rays: galaxies

1. INTRODUCTION

There has been increasing interest in large-scale clustering measurements of active galactic nuclei (AGNs) in recent years. Such measurements (see review by Krumpe et al. 2014) not only allow one to study the distribution of matter in the universe out to redshifts where it becomes very challenging and observationally expensive to detect galaxies in large numbers, but they also can be used to constrain theoretical models of AGN/galaxy coevolution, feedback mechanisms, AGN host-galaxy properties, the distribution of AGNs with dark matter halo (DMH) mass, and the fueling process(es) of supermassive black holes (SMBH) (e.g., Porciani et al. 2004; Gilli et al. 2005, 2009; Yang et al. 2006; Coil et al. 2009; Ross et al. 2009; Cappelluti et al. 2010; Krumpe et al. 2010b, 2012; Allevato et al. 2011; Miyaji et al. 2011; Mountrichas & Georgakakis 2012; Koutoulidis et al. 2013).

Spatial correlation measurements with several tens of thousands of galaxies yield significant clustering dependences on galaxy properties such as luminosity, morphological type, spectral type, and redshift (e.g., Norberg et al. 2002; Madgwick et al. 2003; Zehavi et al. 2005, 2010; Meneux et al. 2006, 2009; Coil et al. 2008). These findings confirm the hierarchical model of structure formation in which more massive, and hence more luminous, galaxies reside in more massive DMHs and are therefore clustered more strongly (e.g., Zehavi et al. 2005, 2010; Coil et al. 2006). Whether this relation should also apply to AGN luminosity is not trivial. Since the AGN luminosity depends primarily on the mass of the SMBH (M_BH), the accretion rate relative to Eddington (L/L_EDD), and the radiative accretion efficiency, a relation between clustering and AGN luminosity should ultimately be due to a connection between DMH mass and one or more of these physical parameters.

Based on smoothed-particle hydrodynamic simulations using GADGET (Springel 2005), Booth & Schaye (2010) explore the correlation between SMBH mass and the mass of the hosting DMH. In the simulations, the black holes grow either by the accretion of ambient gas or mergers. The black holes also inject a fixed fraction of the rest mass energy of the gas into the surrounding medium. A self-regulating black hole injects enough energy to displace gas from the host galaxy on longer timescales. The binding energy of the gas is determined by the DMH potential. Thus, Booth & Schaye (2010) conclude that the mass of the SMBH is regulated primarily by the DMH mass and not the stellar mass of the galaxy. Fanidakis et al. (2012) use the semianalytical galaxy-formation model GALFORM (Cole et al. 2000; more details on their simulations are given in Section 6.4) and find a correlation between SMBH mass and DMH mass at almost all cosmic times (z = 0.0–6.2). Volonteri et al. (2011) use the measured black hole mass, velocity dispersion σ, and asymptotic circular velocity of 25 local galaxies from Kormendy et al. (2011) to show that, although with some scatter, the black hole masses correlate well with the parent DMH masses.

AGN clustering studies can be used to observationally test such predictions. Several studies have measured the large-scale clustering dependence on AGN properties such as X-ray luminosity, with varying results. Coil et al. (2009) find no correlation between the AGN X-ray luminosity and the clustering strength at z = 0.7–1.4. At z ~ 0.1, Mountrichas & Georgakakis (2012) also detect no significant correlation in their sample of XMM-Newton-selected AGNs. Yang et al.
reports a tentative (∼1σ) dependence of the clustering signal, such that the brighter sample is more clustered than the fainter sample. Cappelluti et al. (2010) and Koutoulidis et al. (2013) verify this finding using different AGN samples at different redshifts. Koutoulidis et al. (2013) use a large sample of ∼1500 AGNs from the Chandra Deep Field (CDF) North and South, the extended CDF South, COSMOS, and AEGIS. The median redshifts of their low and high Lx AGN samples are (z) ∼ 0.8–1.1. Except for the CDF South survey, they find weak X-ray luminosity dependences at a level up to ∼2σ.

One way to reduce the uncertainties involved in clustering measurements—beyond using larger AGN samples—is to compute the cross-correlation function (CCF) with a dense galaxy sample instead of computing the autocorrelation function (ACF) of the AGNs. Several studies (e.g., Li et al. 2006; Coil et al. 2007, 2009; Wake et al. 2008; Hickox et al. 2009; Mountrichas et al. 2013; Georgakakis et al. 2014) demonstrate the potential of this approach and compute the CCF between AGNs and a large sample of galaxies to infer the ACF of the AGNs. The significant increase in the number of pairs at a given separation, used to measure the clustering strength, reduces the uncertainties in the spatial correlation function compared to the direct measurements of the AGN ACF.

In Krumpe et al. (2010a, hereafter Paper I), we use the same technique as Coil et al. (2009) to measure the CCF between ROSAT All-Sky Survey (RASS) AGNs identified in the Sloan Digital Sky Survey (SDSS) and a large set of SDSS luminous red galaxies (LRGs) at 0.16 < z < 0.36. The study is based on SDSS data release 4+ (DR4+). The unprecedented low uncertainties of the inferred broad-line AGN ACF allow us to split the sample into low and high X-ray luminosity subsamples and to report a ∼2.5σ X-ray luminosity dependence of broad-line AGN clustering. We find that higher luminosity AGNs cluster more strongly than their lower luminosity counterparts. Consequently, higher luminosity X-ray AGNs reside, on average, in more massive DMHs than do lower luminosity X-ray AGNs.

In the second paper of this series (Miyaji et al. 2011, hereafter Paper II), we describe a novel method of applying the halo occupation distribution (HOD) modeling technique directly to the precise measured CCF between RASS/SDSS AGNs and SDSS LRGs to constrain the distribution of AGNs as a function of DMH mass. This method also allows us to derive the large-scale bias parameter of the AGN sample with much lower systematic uncertainties than using a phenomenological power-law fit, as is often done. As shown in Paper II, the X-ray luminosity dependence is more prominent in the one-halo term (ρc < 1 h⁻¹ Mpc). The HOD-based typical DMH masses derived from the two-halo term for the high- and low-luminosity RASS/SDSS AGN subsamples differ by ∼1.8σ. In addition, we find that models where the AGN fraction among satellites decreases with DMH mass beyond MDMH ∼ 10¹² h⁻¹ M⊙ are preferred. This is in contrast to what is found for satellite galaxies without AGNs (Zheng et al. 2009; Zehavi et al. 2010).

In the third paper (Krumpe et al. 2012, hereafter Paper III), we extend the cross-correlation measurements to lower and higher redshifts, covering a redshift range of z = 0.07–0.50. We show that the weak X-ray luminosity dependence of broad-line AGN clustering is also found if radio-detected AGNs are excluded. Furthermore, we compute the large-scale clustering for optically selected broad-line SDSS AGNs using the final SDSS DR7, but we detect no optical luminosity dependence on the clustering strength, although the optical broad-line SDSS AGN sample in 0.16 < z < 0.36 contains more than twice as many objects as the RASS/SDSS AGN sample. We conclude that the most likely explanation for this result is the smaller dynamic range probed in optical luminosities compared to X-ray luminosities.

In this paper we focus on the redshift range 0.16 < z < 0.36, where the CCF of RASS/SDSS AGNs and LRGs has the highest signal-to-noise ratio (S/N). We fit the H0 line profile in the SDSS spectra of broad-line AGN to infer the Mbh and the L/EDD. Dividing the AGN sample into low and high Mbh mass, as well as low and high L/EDD, provides insights into the main physical driver of the weak detected X-ray luminosity dependence of broad-line AGN clustering.

This paper is organized as follows. In Section 2, we describe the properties of the LRG tracer set and the AGN samples. Section 3 provides details on how we fit the H0 line profile in the optical SDSS AGN spectra, derive the Mbh, estimate L/EDD, and define our AGN subsamples. In Section 4, we briefly summarize the cross-correlation technique, how the AGN ACF is inferred from this, and how we derive the large-scale bias parameters using HOD modeling. Section 5 provides the results of our clustering measurements. The detailed results of the HOD modeling of the CCFs presented in this paper and in Paper III will be included in a future paper (T. Miyaji et al., in preparation). Our results are discussed in Section 6, and we present our conclusions in Section 7. Throughout the paper, all distances are measured in comoving coordinates and given in units of h⁻¹ Mpc, where h = H₀/100 km s⁻¹ Mpc⁻¹, unless otherwise stated. We use a cosmology of Ωm = 0.3, ΩΛ = 0.7, and σ₈(z = 0) = 0.8, which is consistent with the WMAP data release 7 (Table 3 of Larson et al. 2011). The same cosmology is used in Papers I–III. Luminosities and absolute magnitudes are calculated for h = 0.7. We use AB magnitudes throughout the paper. All uncertainties represent 1σ (68.3%) confidence intervals unless otherwise stated.

2. DATA

The data sets used in this study are drawn from the SDSS, which consists of an imaging survey in five bands and an extensive spectroscopic follow-up survey with a fiber spectrograph. The selection of the optically selected AGN candidates is described in Richards et al. (2002). LRGs are chosen by following Eisenstein et al. (2001).

2.1. SDSS Luminous Red Galaxy Sample

The selection of SDSS LRGs follows the procedure described in Section 2.1 of Paper I and Section 2.2 of Paper III. Here we briefly summarize the sample selection. We extract LRGs from the web-based SDSS Catalog Archive Server Jobs System7 using the flag “galaxy_red,” which is based on the selection criteria defined in Eisenstein et al. (2001). We verify that the extracted objects meet all LRG selection criteria and create a volume-limited sample with 0.16 < z < 0.36 and −23.2 < Mg0.3 < −21.2, where Mg0.3 is based on the extinction-corrected rpetro magnitude, k-corrected, and passively evolved to rest-frame gpetro magnitudes at

7 http://casjobs.sdss.org/CasJobs/
z = 0.3. We consider only LRGs that fall into the SDSS area with a DR7 spectroscopic completeness ratio of greater than 0.8 and that have a redshift confidence level of greater than 0.95. The SDSS geometry and completeness ratio are expressed in terms of spherical polygons (Hamilton & Tegmark 2004). The file is publicly available through the New York University Value-Added Galaxy Catalog (NYU-VAGC) website (Blanton et al. 2005).

We correct for the SDSS fiber collision as described in detail in Krumpe et al. (2010b, 2012). We have to assign to approximately 2% of all LRGs in our sample a redshift due to the fiber collision problem.

The construction of the random LRG sample is identical to the procedure described in Section 3.1 of Paper I. Our LRG random sample contains 200 times as many objects as the real LRG sample. We generate a set of random R.A. and decl. values within DR7 areas with spectroscopic completeness ratios of greater than 0.8, populate areas with higher completeness ratios more than ones with lower completeness ratios, and randomly assign redshifts to the objects in the sample by using the smoothed redshift profile of the observed redshift distribution.

2.2. RASS/SDSS AGN Samples

The RASS (Voges et al. 1999) is currently still the most sensitive all-sky survey in the soft (0.1–2.4 keV) X-ray regime. Anderson et al. (2003, 2007) positionally cross-correlate RASS sources with SDSS spectroscopic objects and classify RASS- and SDSS-detected AGNs based on SDSS DR5. They find 6224 AGNs with broad permitted emission lines in excess of 1000 km s\(^{-1}\) FWHM and 515 narrow, permitted emission line AGN matching RASS sources within 1 arcmin. More details on the sample selection are given in Section 2.2 of Paper I and Anderson et al. (2003, 2007). Since ROSAT observed the sky in the soft energy band (0.1–2.4 keV), the RASS/SDSS AGN sample is biased toward AGNs with little to no X-ray absorption. The vast majority of the optical counterparts are therefore AGNs with broad emission lines and UV excess. There is no overlap between the RASS/SDSS AGNs and the LRG sample.

To study the X-ray luminosity dependence of the clustering of these AGNs, we have to limit the SDSS footprint to the publicly available DR4+ geometry. We split our sample in the redshift range 0.16 < z < 0.36 into subsamples according to X-ray luminosity. We use a 0.1–2.4 keV observed luminosity cut (assuming a photon index $\Gamma = 2.5$, corrected for Galactic absorption) of $L_X/\text{erg s}^{-1} = 44.29$. The observed flux in the 0.1–2.4 keV band has a large soft-excess contribution that is not representative of the underlying intrinsic, hard power-law X-ray spectrum. Thus, we use the template XMM-Newton spectrum of powerful radio-quiet ROSAT QSOs from Krumpe et al. (2010a) to estimate the corresponding flux in the 0.5–10 keV and 2–10 keV energy ranges. Using the median redshift of the sample ($z = 0.27$), the cut at 0.1–2.4 keV corresponds to a cut at $L_X/\text{erg s}^{-1} = 43.7$ and log $(L_{2-10keV}/\text{erg s}^{-1}) = 43.4$.

As an alternative estimate, we match our RASS AGN sample with the 3XMM-DR5 catalog (Rosen et al. 2015). We fit a regression line between the RASS 0.1–2.4 keV fluxes and the XMM-Newton 2–12 keV fluxes. Using Xspec (Arnaud 1996), we model the same ratio with a broken power law and determine the luminosity ratios in the ranges 0.1–2.4 keV, 0.5–10 keV, and 2–10 keV. We find somewhat smaller corrections: log $(L_X/\text{erg s}^{-1}) = 44.29$ corresponds to log $(L_{0.5-10keV}/\text{erg s}^{-1}) = 43.9$ and log $(L_{2-10keV}/\text{erg s}^{-1}) = 43.7$. This approach has the disadvantage that the observations were taken over a decade apart, and temporal variation in the X-ray luminosity/flux of the objects will affect the estimate. However, one could argue that such variations are effectively averaged over a large sample of X-ray objects as used here. Fits to the 0.5–10 keV XMM-Newton spectra verified that the vast majority ($\sim 95\%$) of the cross-matched RASS/XMM AGNs are unabsorbed in the X-rays ($N_H < 10^{21}$ cm\(^{-2}\)), while the remaining sources show absorption at a level of only a few $10^{21}$ cm\(^{-2}\).

We calculate the comoving number densities as described in detail in Paper I. For a given R.A. and decl., we compute the limiting observable RASS count rate and infer the absorption-corrected flux limit versus survey area for RASS/SDSS AGNs. We then compute the comoving volume available to each object ($V_0$) to be included in the sample (Avni & Bahcall 1980). The comoving number density follows by computing the sum of the available volume over each object, $n_{\text{AGN}} = \sum_i 1/V_0,i$. The comoving number densities for the total, high $L_X$, and low $L_X$ subsamples are 6.0, 0.12, and $5.8 \times 10^{-3}$ h\(^3\) Mpc\(^{-3}\), respectively.

3. DERIVING $M_{BH}$ AND $L/L_{edd}$ THROUGH $\Halpha$ LINE PROFILE FITS

The so-called virial method is routinely employed to estimate $M_{BH}$ from single-epoch spectra based solely on the width of broad emission lines together with an appropriate continuum luminosity (Kaspi et al. 2000; Peterson & Wandel 2000; Vestergaard 2002). The FWHM of $\Halpha$ (FWHM\(_{\Halpha}\)) and the rest-frame continuum luminosity at 5100 Å ($L_{5100}$) are most commonly used to compute $M_{BH}$ for low-redshift AGNs because the corresponding calibrations are the best-studied ones to date. On the other hand, the H\(_\alpha\) line offers a higher S/N than H\(_\beta\) and tight relations between FWHM\(_{\Halpha}\) and FWHM\(_{H\beta}\), as well as between $L_{5100}$ and $L_{H\beta}$, have been established (Greene & Ho 2005; Schulze & Wisotzki 2010). Consequently, accurate $M_{BH}$ estimates can also be obtained from the broad H\(_\alpha\) line.

The simultaneous use of the broad H\(_\alpha\) line as a proxy for the velocity dispersion in the broad-line region (BLR) and for the AGN luminosity has two major advantages. First, we avoid any potential contamination of $L_{5100}$ by host galaxy light and the influence of the broad Fe\(_\alpha\) emission in type I AGNs on the broad H\(_\beta\) FWHM measurement (Greene & Ho 2005). Second, we obtain reliable BH mass estimates even for those objects where the S/N of H\(_\beta\) would be too low.

3.1. Fitting the $\Halpha$ Line Profile

We retrieve the individual SDSS DR7 optical spectra for our entire RASS/SDSS AGN sample in order to measure the luminosity and FWHM of $\Halpha$ for each AGN. Although the FWHM and integrated flux of $\Halpha$ could in principle be measured directly from the spectra, the narrow $\Halpha$ and [N\(_\II\)] lines on top of the broad H\(_\alpha\) line have a significant impact on the estimated $M_{BH}$ and $L/L_{edd}$ values (Figure 1, left panels), as
Previous studies have used multiple Gaussian components (e.g., Brotherthom et al. 1994; Sulentic et al. 2002; Shen et al. 2008; Schulze et al. 2009) or high-order Gauss-Hermite polynomials (e.g., Salviander et al. 2007; McGill et al. 2008; Stern & Laor 2012) to describe the asymmetries of the line. We test both approaches to fit the SDSS spectra and conclude that the latter is more robust against the choice of initial parameter estimates.

We simultaneously model the broad H\(\beta\) and H\(\alpha\) lines together with the narrow H\(\beta\), [O \(\text{iii}\)] \(\lambda\)4960, \(\lambda\)5007, H\(\alpha\), and [N \(\text{ii}\)] \(\lambda\)6548, \(\lambda\)6583 emission lines. We briefly describe our algorithm of modeling the broad H\(\alpha\) line below and follow an approach similar to Stern & Laor (2012). The model of the H\(\beta\) region (left panels in Figure 1) is only used to better constrain the parameters of narrow lines. The well-isolated narrow [O \(\text{iii}\)] line in the H\(\beta\) region gives parameter restrictions that are superior to the narrow-line profiles in the H\(\alpha\) region, where the narrow and broad lines can be strongly blended.

As a first step, the approximate underlying continua are independently subtracted from the H\(\beta\) and H\(\alpha\) lines by linear interpolation between the adjacent rest-frame spectral regions 4720–4760 \(\text{Å}\) and 5070–5130 \(\text{Å}\), as well as 6150–6230 \(\text{Å}\) and 6750–6950 \(\text{Å}\), respectively. The fit requires initial guesses for the broad and narrow line components. The initial guesses for the FWHM and line flux of the broad lines are determined by a fourth-order Gauss-Hermite polynomial of the entire H\(\alpha\) line and assuming standard H\(\alpha\) and H\(\beta\) ratios. The initial guesses of the narrow line components are based on the total flux of the observed [O \(\text{iii}\)] line and typical narrow-line AGN ratios. An eighth-order Gauss-Hermite polynomial provides a good fit for the full model of complex broad H\(\beta\) and H\(\alpha\) line shapes in almost all cases. All narrow emission lines are assumed to have ordinary Gaussian profiles that are coupled in redshift, velocity dispersion, and line ratios for doublets. While [O \(\text{iii}\)] can exhibit a blueshifted wing in cases with an outflow (e.g., Mullaney et al. 2013), the narrow component usually strongly dominates the line flux, and therefore a single-component line fit is generally robust when coupled to lower ionization lines like [N \(\text{ii}\)]. In cases where the outflow component dominates, we decouple [O \(\text{iii}\)] from the fit to other narrow lines, as described below. We also add the two dominant Fe \(\text{ii}\) lines in the H\(\beta\) wavelength range as Gaussians to our model. The best-fit model is determined by using a Levenberg–Marquardt minimization algorithm, where spectral regions of unconsidered weak narrow emission lines, e.g., [O \(\text{iii}\)]\(\lambda\)6300 and [S \(\text{ii}\)] \(\lambda\)6718, \(\lambda\)6732, have been masked out along with pixels assigned as bad by the SDSS spectroscopic pipeline.

We deviate slightly from the scheme above in the following three cases: (1) the broad H\(\beta\) line is too weak to be modeled, (2) the [O \(\text{iii}\)] line exceeds a width of 600 km s\(^{-1}\), or (3) the narrow H\(\alpha\) line flux is negative in the initial best-fit model. In the first case, we repeat the model without any broad H\(\beta\) and Fe \(\text{ii}\) components. In the second and third case, the [O \(\text{iii}\)] line is likely to be affected by outflows and may not match the line profile of the other narrow lines. Therefore, we allow the [O \(\text{iii}\)] line to have an independent redshift and velocity dispersion with respect to the other narrow lines.

One percent of the RASS/SDSS spectra do not allow such an analysis because significant parts of the spectral range around H\(\alpha\) or [O \(\text{iii}\)] are masked out. We do not expect any significant impact on our study, due to the low number of objects for which this is the case (see also Section 5.1 below).
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Examples of the best-fit models for typical S/N AGN spectra are shown in Figure 1. From those best-fit models we measure the FWHM and integrated flux of the broad-line Hα component, as these are the parameters required to estimate \( \dot{M}_\text{BH} \) and \( L/L_{\text{edd}} \). Our model is not designed to provide a perfect fit to Hα line profiles for the most complex cases. However, the model deviations concerning the Hα width and flux are much smaller than the systematics of virial \( \dot{M}_\text{BH} \) estimates (see discussion in Denney et al. 2009). To assess the uncertainties of the derived parameters and to identify unreliable models, we generate 100 realizations of the same spectrum by replacing each pixel within its 1σ variance given by the SDSS error spectrum and analyze the artificial spectra in the same manner. The uncertainty for each quantity is then taken as the dispersion (1σ error corresponding to 68.3%) in the best-fit value of all 100 measurements.

We compared our measurements with those of Stern & Laor (2012) to cross-check our results with a completely independent algorithm (Figure 2) and to provide an estimate of the systematic uncertainties. In contrast to our study, their sample contains lower luminosity AGNs at a slightly different redshift range. Thus, the samples only overlap partially. For the broad Hα FWHM and luminosity, we find relatively tight correlations around the unity relation. The measurements of the broad Hα FWHM exhibit a larger scatter and are slightly skewed toward lower values using our method. We inspected those spectra and identify a common characteristic in these cases: the narrow lines are broader and weaker than for the other AGNs in the sample. Thus, deblending the narrow [N II]+Hα from the broad Hα line can be challenging. This is particularly true for broad Hα lines with an FWHM less than 4000 km s\(^{-1}\). In summary, our line-profile fitting method provides robust estimates for the FWHM and line flux within their systematic uncertainties and without the need for human interaction.

3.2. Estimating \( \dot{M}_\text{BH} \)

The virial black hole mass is estimated by combining the empirically calibrated BLR size–luminosity relation, derived from reverberation mapping monitoring of nearby AGNs, and assuming virialized BLR motions, \( \dot{M}_\text{BH} = f_{\text{vir}} v^2 R_{\text{BLR}} G^{-1} \), where \( v \) is the FWHM of broad lines in the AGN spectrum and \( f_{\text{vir}} \) is the virial factor representing the BLR kinematics. Several different estimators for \( \dot{M}_\text{BH} \) have independently been reported in the literature using different BLR size–luminosity relations and virial factors based on different assumptions. Here we employ two different calibrations to check their potential impact on our results. The first is from McLure & Dunlop (2004):

\[
\frac{\dot{M}_\text{BH}}{M_\odot} = 4.7 \left( \frac{L_{5100}}{10^{44} \text{ erg s}^{-1}} \right)^{0.61} \left( \frac{\text{FWHM}_{\text{H}α}}{\text{km s}^{-1}} \right)^2
\]

which is also used by Shen et al. (2009) to estimate \( \dot{M}_\text{BH} \) for all unobscured, optically selected SDSS AGN. The second calibration is based on the most recent BLR size–luminosity relation of Bentz et al. (2009), assuming a virial factor of \( f_{\text{vir}} = 5.5 \), which is empirically determined by Onken et al. (2004):

\[
\frac{\dot{M}_\text{BH}}{M_\odot} = 8.13 \left( \frac{L_{5100}}{10^{44} \text{ erg s}^{-1}} \right)^{0.52} \left( \frac{\text{FWHM}_{\text{H}α}}{\text{km s}^{-1}} \right)^2.
\]

Throughout the paper, we use the second calibration (Bentz et al. 2009) for the estimates of the black hole masses. In Section 5.1 we test the robustness of our clustering results if the first calibration method is used instead. As we demonstrate below, we find very similar results using either calibration.

In order to use our measurements from the Hα line to estimate \( \dot{M}_\text{BH} \), we have to replace \( L_{5100} \) by \( L_{\text{H}α} \) and FWHM\(_{\text{H}α} \) by FWHM\(_{\text{H}α} \) in Equations (1) and (2), following Greene & Ho (2005) (their Equations (1) and (3)).

Denney et al. (2009) point out that the inclusion of low S/N spectra adds a systematic offset in \( \dot{M}_\text{BH} \) estimates because the line width is systematically underestimated. Therefore, we enforce a lower cutoff in the measured S/N level of the broad Hα line flux. We determine the cutoff S/N by selecting the five AGN spectra with the highest S/N. Then, we artificially degrade the S/N gradually down to a continuum S/N of 1. For each S/N level, we generate 250 spectra and model these individual spectra with our line-profile fitting method.

At an Hα FWHM uncertainty level of greater than 40%, the measurement uncertainties exceed the commonly assumed systematic uncertainties for virial \( \dot{M}_\text{BH} \) estimates of ~0.3 dex. More than 90% of all of our generated spectra have FWHM uncertainties of less than 40% if we restrict the Hα S/N to values greater than 10 (Figure 3). Consequently, we adapt this S/N threshold as a limit for selecting objects that yield reliable \( \dot{M}_\text{BH} \) estimates. This cutoff leads to a removal of 189 out of 1538 objects (12% of the sample). We apply this S/N cut and compare our measured FWHM values to the ones from Stern & Laor (2012). The observed scatter in FWHM between both methods is 0.08 dex, which corresponds to an \( \dot{M}_\text{BH} \) error of 0.16. This can be interpreted as a simple estimate of the minimum systematic uncertainty in the \( \dot{M}_\text{BH} \) determination, which is reflected in the commonly assumed total ~0.3 dex systematic uncertainty of this method.

The main purpose of this paper is to study the clustering of AGN samples with low and high \( \dot{M}_\text{BH} \) and \( L/L_{\text{edd}} \), respectively. Any uncertainty in the calibration of \( \dot{M}_\text{BH} \) will affect our entire sample similarly. Thus, our results will not depend on the absolute accuracy of the \( \dot{M}_\text{BH} \) calibration because we are interested only in relative \( \dot{M}_\text{BH} \) values such that we can divide the full sample into low and high \( \dot{M}_\text{BH} \) subsamples.
and (\ldots) \text{bol}.X vs. = SN 10.

spectrum (various degraded S of spectra for which the FWHM is within 40\% of the original high S indicated by different symbols.

function of the signal-to-noise ratio (S/N) of the integrated flux of the broad Hα line. We use high S/N spectra to simulate 250 realizations at various degraded S/N levels. Within each S/N bin, we determine the fraction of spectra for which the FWHM is within 40\% of the original high S/N spectrum (see text for details). We show the results for five different objects indicated by different symbols.

3.3. Estimating $L/L_{\text{EDD}}$

The Eddington ratio $L/L_{\text{EDD}}$ is the ratio between the bolometric and the Eddington luminosity ($L_{\text{edd}} = 1.26 \times 10^{38} M_{\text{BH}}/M_\odot$ erg s$^{-1}$). The quantity is commonly derived by using the inferred $M_{\text{BH}}$ and the optical continuum luminosity at 5100 Å, adopting a certain bolometric correction factor. Different bolometric correction factors used to estimate the bolometric luminosity $L_{\text{bol}}$ from $L_{5100}$ are quoted in the literature (Kaspi et al. 2000; McLure & Dunlop 2004; Richards et al. 2006a). While these correction factors are subject to uncertainties, they are required to estimate the bolometric luminosity if only a single-epoch optical spectrum is available.

We use a correction factor of $\delta = 10.3$ (Richards et al. 2006a), which is consistent with values used by other studies. Again, we use the relation from Greene & Ho (2005) to estimate $L_{5100}$ from $L_{\text{H}α}$ for the computation of $L_{\text{bol}}$.

3.4. Defining X-Ray-selected AGN Subsamples

The RASS/SDSS AGNs in our sample do not uniformly populate the $M_{\text{BH}}$–$L/L_{\text{EDD}}$ plane (Figure 4). Although there is substantial scatter, on average, higher $L/L_{\text{EDD}}$ are found in AGNs with lower $M_{\text{BH}}$. While the absence of objects in the upper right corner of this plane is not an observational bias, but reflects the nonexistence of (unabsorbed) RASS/SDSS AGNs with both high $M_{\text{BH}}$ and high $L/L_{\text{EDD}}$ in the redshift range studied here, the lack of objects in the lower left corner reflects an observational bias. AGNs with low $L/L_{\text{EDD}}$ and low $M_{\text{BH}}$ are too weak to produce a significant broad Hα line relative to the host galaxy continuum. The Hα flux S/N cutoff used here primarily removes objects with log ($M_{\text{BH}}/M_\odot$) $\sim$ 7–8.

Since $M_{\text{BH}}$ and $L/L_{\text{EDD}}$ are correlated in our full sample, and we aim to reveal which of these quantities drives the observed X-ray luminosity dependence of AGN clustering, doing a simple cut of the full sample into low and high $M_{\text{BH}}$ subsamples, as well as high and low $L/L_{\text{EDD}}$ subsamples, will not be useful. When creating subsamples that depend on one parameter, the distribution of the second parameter in both subsamples must be the same. This “matching” of the subsamples is a commonly used method in clustering measurements (e.g., Coil et al. 2009). However, one has to test that the procedure of creating matched subsamples is not introducing a bias to the clustering results. We will do so below by testing different methods to produce matched subsamples (see Section 5.1).

Before creating low and high $M_{\text{BH}}$ subsamples, objects that lie outside the range $–2.2 < \log(L/L_{\text{EDD}}) < –0.2$ are removed. We then determine the number of objects in each $L/L_{\text{EDD}}$ bin, using a bin width of 0.2 (logarithmic scale). In each $L/L_{\text{EDD}}$ bin, we create three subsamples: 30\% of objects with the lowest $M_{\text{BH}}$, 40\% with medium $M_{\text{BH}}$, and 30\% of objects with the highest $M_{\text{BH}}$ (Figure 5). The procedure creates low, medium, and high $M_{\text{BH}}$ AGN subsamples with extremely similar (“matched”) $L/L_{\text{EDD}}$ distributions but different median $M_{\text{BH}}$ (see Table 1). All $M_{\text{BH}}$ AGN subsamples have median log ($L/L_{\text{EDD}}) = –1.00$.

The low (30\%), medium (40\%), and high (30\%) $L/L_{\text{EDD}}$ RASS/SDSS AGN subsamples with matched $M_{\text{BH}}$ distributions are created by first applying a cut of $6.7 < \log(M_{\text{BH}}/M_\odot) < 9.5$ to remove extreme sources and then following the same approach as described above, using bins of $M_{\text{BH}}$ with a bin width of 0.2 (logarithmic scale). All $L/L_{\text{EDD}}$ AGN subsamples have median log ($M_{\text{BH}}/M_\odot) = 7.92–7.93$.

Figures 4 and 5 show that divisions into low, medium, and high $M_{\text{BH}}$ as well as $L/L_{\text{EDD}}$ are very similar to divisions into low, medium, and high $L_X$. Thus, one cannot anticipate if the X-ray luminosity clustering dependence is related to $L/L_{\text{EDD}}$ or $M_{\text{BH}}$, as we aim to test here.

The directly observed parameters FWHM and $L_{\text{H}α}$ do not correlate with each other as strongly as $M_{\text{BH}}$ and $L/L_{\text{EDD}}$ (see Figure 6). However, we decide to use the same method to create subsamples defined by FWHM and $L_{\text{H}α}$ as well. Thus, we again split the full sample into three subsamples defined using one parameter, while maintaining the same distribution in the other parameter of interest. To create subsamples in FWHM, we first limit to objects with $41.7 < \log(L_{\text{H}α}/\text{erg s}^{-1}) < 44.1$ and then use a bin width
3.5. Defining the Optically Selected AGN Subsamples

The optically selected SDSS AGNs (called “quasars” in the SDSS literature) are drawn from the catalog provided by Schneider et al. (2010). Instead of using the classic selection in the B-band, Schneider et al. (2010) use the SDSS i-band because it is less affected by Galactic absorption. However, this comes with the significant disadvantage that host-galaxy light might represent a significant fraction of the total flux in the i-filter. Schneider et al. (2010) apply an apparent magnitude cut of $M_i \leq -22$ and require that objects have at least one emission line exceeding an FWHM of 1000 km s$^{-1}$. Unlike our RASS/SDSS AGN sample, this sample of 3500 objects (0.16 $\leq z \leq 0.36$) has the footprint of SDSS Data Release 7. The DR4+ and DR7 areas are 5468 deg$^2$ and 7670 deg$^2$, respectively, when we consider only the area that has a DR7 completeness ratio of $f_{\text{comp}} > 0.8$. Thus the area occupied by the optically selected AGN sample is 1.4 times larger than the area covered by the X-ray-selected AGN sample. Additionally, the number density (per square degree) of optically selected AGNs is 1.6 times higher than for the X-ray-selected AGNs.

We retrieve the individual SDSS spectra of the optically selected SDSS AGNs and derive the FWHM of the broad Hα line and the $L_{\text{Hα}}$, through spectral fits (see Section 3). This procedure is identical to the one used for the RASS/SDSS AGN sample (see Section 3.1). We select only objects with $S/N > 10$ in the flux of the broad Hα line. We derive the individual black hole masses and $L/L_{\text{edd}}$ for the remaining 2831 AGNs. The X-ray and optically selected AGN samples have 807 objects in common, which is 29% of the total optically selected AGN sample. Thus, there is substantial difference between the X-ray and optically selected AGN samples.

Figure 6 compares how the X-ray-selected RASS/SDSS AGN sample and the optically selected SDSS AGN sample span the observed parameter space of $L_{\text{Hα}}$ and FWHM (left panel) and the derived parameter space of $L/L_{\text{edd}}$ and $M_{\text{BH}}$ (right panel). In the observed parameter space, there are two obvious differences between these samples. First, the RASS/SDSS AGN sample extends to lower $L_{\text{Hα}}$. This is likely a consequence of rejecting AGNs with $M_i > -22$ in order to exclude objects with a strong starlight component from the host galaxy because an AGN has to have a certain luminosity to outshine its host galaxy. Clearly, X-ray selection of AGNs (RASS/SDSS) allows us to extend to fainter AGN luminosities, below the optical cut. Thus, at X-ray wavelengths we are able to detect AGNs that might not outshine their host galaxy in the optical (see, e.g., Hopkins et al. 2009). At log $(L_{\text{Hα}}/[\text{erg s}^{-1}]) > 42.5$, both samples span a similar parameter space, and the dynamic range in FWHM is almost identical in both samples.

Differences in the observed parameter space naturally translate into differences in the derived $M_{\text{BH}}-L/L_{\text{edd}}$ space (Figure 6, right panel). Compared with the X-ray-selected AGN sample, the optical AGN sample has a deficiency of AGNs with low $M_{\text{BH}}$. The optically selected sample also extends marginally to higher $M_{\text{BH}}$ and lower $L/L_{\text{edd}}$.

We create optically selected AGN subsamples with respect to $M_{\text{BH}}$, $L/L_{\text{edd}}$, FWHM, and $L_{\text{Hα}}$ (with matched distribution in the other parameter of interest; see Section 3.4). We have to use slightly different limits for some of the parameters because the X-ray and optically selected AGN samples cover slightly different parameter spaces. Thus, when we create the low, medium, and high $M_{\text{BH}}$ subsamples with matched $L/L_{\text{edd}}$ distributions, we use an $L/L_{\text{edd}}$ limit of $-2.3 < \log(L/L_{\text{edd}}) < 0.1$. The optical $M_{\text{BH}}$ subsamples...
### Table 1
Properties of Inferred AGN ACFs and Derived Quantities

| AGN Sample Name | Number of Objects | Median $z_{\text{eff}}$ | 10th, 50th, 90th Percentiles | \( r_{\text{0.57 \ h^{-1} Mpc}} \) | \( r_{\text{0.3 \ h^{-1} Mpc}} \) | \( b(2) \) | \( \log M_{\text{dyn}}^{500} \) |
|-----------------|-------------------|------------------------|-----------------------------|--------------------------|--------------------------|----------------|--------------------------|
| total RASS AGN  | 1349              | 0.27                   | 43.70, 44.17, 44.68         | 4.02±0.45                | 1.62±0.15                | 4.09±0.35       | 1.32±0.11                |
| low \( L_{\text{X}} \) RASS | 858              | 0.25                   | 43.63, 43.99, 44.23         | 3.12±0.41                | 1.55±0.19                | 3.28±0.16       | 1.22±0.12                |
| high \( L_{\text{X}} \) RASS  | 491              | 0.29                   | 44.34, 44.53, 44.87         | 5.38±0.68                | 1.88±0.13                | 5.41±0.73       | 1.53±0.17                |
| low \( M_{\text{MB}} \) RASS  | 410              | 0.22                   | 7.07, 7.54, 8.01            | 2.71±0.53                | 2.07±0.46                | 2.65±0.56       | 0.96±0.24                |
| medium \( M_{\text{MB}} \) RASS | 525              | 0.27                   | 7.55, 7.92, 8.36            | 4.34±0.44                | 1.61±0.11                | 4.32±0.15       | 1.38±0.13                |
| high \( M_{\text{MB}} \) RASS  | 400              | 0.29                   | 7.92, 8.38, 8.91            | 4.60±0.21                | 1.85±0.11                | 4.67±0.12       | 1.62±0.20                |
| low \( L/L_{\text{Edd}} \) RASS | 418              | 0.23                   | –1.79, –1.36, –0.98         | 3.00±0.78                | 1.45±0.21                | 3.17±0.54       | 1.30±0.18                |
| medium \( L/L_{\text{Edd}} \) RASS | 522              | 0.27                   | –1.36, –1.00, –0.71         | 2.87±1.97                | 1.59±0.40                | 2.89±0.46       | 1.29±0.13                |
| high \( L/L_{\text{Edd}} \) RASS | 404              | 0.29                   | –1.01, –0.68, –0.35         | 4.36±0.67                | 2.14±0.22                | 3.92±0.74       | 1.18±0.15                |
| low \( \text{FWHM} \) RASS  | 415              | 0.27                   | 1280, 1910, 2470            | 2.69±0.60                | 2.30±0.40                | 2.32±0.71       | 1.09±0.12                |
| medium \( \text{FWHM} \) RASS | 525              | 0.26                   | 2340, 2890, 3690            | 2.90±0.35                | 1.35±0.24                | 3.70±0.64       | 1.47±0.17                |
| high \( \text{FWHM} \) RASS  | 404              | 0.27                   | 3650, 4840, 7920            | 3.52±0.57                | 1.53±0.26                | 3.82±0.77       | 1.53±0.18                |
| low \( L_{\text{IR}} \) RASS  | 414              | 0.22                   | 41.99, 42.29, 42.53         | 2.14±0.06                | 1.93±0.06                | 2.69±0.54       | 1.21±0.18                |
| medium \( L_{\text{IR}} \) RASS | 526              | 0.27                   | 42.52, 42.74, 42.96         | 1.96±1.00                | 1.83±1.32                | 2.13±0.64       | 1.31±0.16                |
| high \( L_{\text{IR}} \) RASS  | 403              | 0.29                   | 42.93, 43.24, 43.63         | 3.52±0.39                | 1.53±0.26                | 3.82±0.78       | 1.36±0.20                |
| faint \( M_{\text{RASS}} \)  | 443              | 0.23                   | –21.26, –21.80, –22.04      | 3.21±0.69                | 1.69±0.69                | 3.32±0.58       | 1.10±0.26                |
| medium \( M_{\text{RASS}} \)  | 460              | 0.27                   | –22.15, –22.39, –22.63      | 3.51±0.71                | 1.71±0.76                | 3.65±0.81       | 1.21±0.19                |
| luminous \( M_{\text{RASS}} \) | 445              | 0.29                   | –22.76, –23.13, –23.96      | 3.04±0.76                | 1.47±0.17                | 2.94±0.54       | 1.48±0.17                |
| faint \( M_{\text{rest}} \)  | 444              | 0.22                   | –20.84, –21.39, –21.66      | 3.18±0.63                | 1.79±0.56                | 3.19±0.59       | 1.13±0.23                |
| med. \( M_{\text{5500}–6800 \ h} \) RASS | 460              | 0.27                   | –21.79, –22.02, –22.27      | 2.44±1.94                | 1.36±0.28                | 3.39±0.67       | 1.25±0.17                |
| lum. \( M_{\text{5500}–6800 \ h} \) RASS | 445              | 0.30                   | –22.42, –22.81, –23.67      | 4.23±1.06                | 1.70±0.15                | 4.20±0.79       | 1.49±0.17                |

**Note:** Samples displayed in italics are those that are created to match distributions in the other parameter of interest (e.g., samples split in \( M_{\text{MB}} \) have matched distributions in \( L/L_{\text{Edd}} \) and vice versa; samples split in FWHM have matched distributions in \( L_{\text{IR}} \). The fourth column lists the median value. For the total samples, we state in this column the \( L_{\text{X}} \) or \( M_{\text{RASS}} \) value. All samples cover a redshift range of \( 0.16 < z < 0.36 \) and contain only objects with \( S/N > 10 \) in Hs flux. Values of \( r_{\text{0.57 \ h^{-1} Mpc}} \) and \( r_{\text{0.3 \ h^{-1} Mpc}} \) are obtained from a power-law fit to \( n_{\text{r}}(r_{\text{p}}) \) over the range \( r_{\text{p}} = 0.3–15 \ h^{-1} \text{Mpc} \), using the full error covariance matrix and minimizing the correlated \( \chi^2 \) values.
have median $\langle \log (L/L_{\text{edd}}) \rangle = -1.04$ to $-1.00$, while the $L/L_{\text{edd}}$ subsamples have $\langle \log (M_{\text{BH}}/M_\odot) \rangle = 8.12$–$8.13$.

When we create three subsamples in FWHM, we limit $L_{\text{H}a}$ to $42.1 < \log(L_{\text{H}a}/[\text{erg s}^{-1}]) < 44.1$. The FWHM subsamples have $\langle \log (L_{\text{H}a}/[\text{erg s}^{-1}]) \rangle = 42.88$. For the $L_{\text{H}a}$ subsamples, we apply a limit of $2.8 < \log($FWHM$/[\text{km s}^{-1}]) < 4.2$. We find $\langle \text{FWHM} \rangle = 3240$–$3280$ km s$^{-1}$ for the low, medium, and high $L_{\text{H}a}$ subsamples. All bin widths are identical to the ones used for defining the X-ray-selected AGN subsamples.

We produce optical AGN subsamples divided by $M_i$. We use simple $M_i$ cuts of $M_i = -22.27$ and $M_i = -22.67$ to construct faint, medium, and luminous $M_i$ subsamples with similar numbers of sources. Finally, we create $M_{\text{rest}}^{22.53\text{mag}}$–$6800$ subsamples of the optically selected AGNs. We use cuts at $M_{\text{rest}}^{22.53\text{mag}} = -22.13$ mag and $M_{\text{rest}}^{22.53\text{mag}} = -22.53$ mag. As with the X-ray-selected AGNs, we do not match the distribution of any other parameter when creating the subsamples defined by $M_i$ and $M_{\text{rest}}^{22.53\text{mag}}$–$6800$. All samples are presented in Table 1.

4. METHODOLOGY

4.1. Clustering Measurements

We measure the two-point correlation function $\xi(r)$ (Peebles 1980), which measures the excess probability $dP$ above a Poisson distribution of finding an object in a volume element $dV$ at a distance $r$ from another randomly chosen object. The ACF measures the spatial clustering of objects in the same sample, while the CCF measures the clustering of objects in two different samples. We use the same approach as described in detail in Section 3 of Paper I and Section 4 in Paper III. Here we explain the essential elements of our method.

We use the correlation estimator of Davis & Peebles (1983) in the form

$$\xi(r) = \frac{DD(r)}{DR(r)} - 1,$$

where $DD(r)$ is the number of data–data pairs with a separation $r$, and $DR(r)$ is the number of data–random pairs. Both pair counts have been normalized by the number density of data and random points. To separate the effect of redshift distortions, the correlation function is measured as a function of two components of the separation vector between two objects, that is, one perpendicular to $(r_\parallel)$ and the other along $(\pi)$ the line of sight. The parameter $\xi(r_\parallel, \pi)$ is thus extracted by counting pairs on a two-dimensional grid of separations $r_\parallel$ and $\pi$. We obtain the projected correlation function $w_\parallel(r_\parallel)$ by integrating $\xi(r_\parallel, \pi)$ along the $\pi$ direction.

As in Paper I, we infer the AGN ACF from the CCF between the AGN sample and the corresponding galaxy tracer set and the ACF of the tracer set following Coil et al. (2009):

$$w_\parallel(\text{AGN}|\text{AGN}) = \frac{[w_\parallel(\text{AGN}|\text{trace})]^2}{w_\parallel(\text{trace}|\text{trace})},$$

where $w_\parallel(\text{AGN}|\text{AGN})$ and $w_\parallel(\text{trace}|\text{trace})$ are the ACFs of the AGN and the corresponding tracer set, respectively, and $w_\parallel(\text{AGN}|\text{trace})$ is the CCF between the AGN and the tracer set (i.e., a galaxy sample).

The CCF is computed using

$$\xi_{\text{AGN}–\text{trace}} = \frac{D_{\text{AGN}} D_{\text{trace}}}{D_{\text{AGN}} R_{\text{trace}}} - 1.$$

For our purposes, the use of this simple estimator has several major advantages and results in only a marginal loss in the $S/N$ when compared to more advanced estimators (e.g., Landy & Szalay 1993). The estimator in Equation (5) requires the generation of a random catalog only for the tracer set. Since the random catalog should exactly match all observational biases to minimize the systematic uncertainties, well-understood selection effects are key to creating proper random samples. The tracer sets have well-defined selection functions, while the AGN samples suffer from selection functions that are very complex and difficult to model.

4.2. Error Analysis

The measurements in the adjacent bins of the correlation function are not independent. Poisson errors will significantly underestimate the uncertainties and should not be used for error
calculations. Instead, we use the jackknife resampling technique to estimate the measurement errors based on the covariance matrix \( M_{ij} \), which reflects the degree to which bin \( i \) is correlated with bin \( j \).

In our jackknife resampling, we divide the survey area into \( N_T = 100 \) subsections for the DR4+ geometry (X-ray-selected AGN sample), each of which is \( \sim 50-60 \) deg\(^2\). Since the optically selected AGN sample uses the DR7 geometry, we divide this area into \( N_T = 131 \) subsections of roughly equal area. These \( N_T \) jackknife-resampled correlation functions define the covariance matrix:

\[
M_{ij} = \frac{N_T - 1}{N_T} \left[ \sum_{k=1}^{N_T} \left( w_k(r_{pi}) - \left\langle w(r_{pi}) \right\rangle \right) \right] \times \left( w_k(r_{pj}) - \left\langle w(r_{pj}) \right\rangle \right).
\]

(6)

We calculate \( w_p(r_p) \) \( N_T \) times, where each jackknife sample excludes one section and \( w_k(r_{pi}) \) and \( w_k(r_{pj}) \) are from the \( k \)th jackknife samples of the AGN ACF and \( \left\langle w(r_{pi}) \right\rangle \), \( \left\langle w(r_{pj}) \right\rangle \) are the averages over all of the jackknife samples. The uncertainties represent 1\( \sigma \) (68.3\%) confidence intervals.

The generation of the covariance matrix for the inferred AGN ACF considers the \( N_T \) jackknife-resampled correlation functions of the CCF (AGN and corresponding tracer set) and the tracer set ACF. For each jackknife sample, we calculate the inferred AGN ACF by using Equation (4). The resulting \( N_T \) \( w_p(r_p) \) jackknife-resampled projected correlation functions of the inferred ACFs are then used to compute the covariance matrix of the inferred AGN ACF.

5. RESULTS

We measure high-accuracy CCFs of the different AGN samples with the LRG tracer set (see Figure 7). In addition, we compute the high-precision ACF of the LRG sample. In both cases, we measure \( r_p \) in the range 0.05–40 \( h^{-1} \) Mpc in 15 logarithmic bins, identical to those used in Paper III. We compute \( \pi \) in steps of 5 \( h^{-1} \) Mpc in the range \( \pi = 0-200 \) \( h^{-1} \) Mpc.

To derive \( \pi_{\text{max}} \), we compute \( w_p(r_p) \) for a set of \( \pi_{\text{max}} \) ranging from 10 to 160 \( h^{-1} \) Mpc in steps of 10 \( h^{-1} \) Mpc. We then fit \( w_p(r_p) \) over an \( r_p \) range of 0.3–40 \( h^{-1} \) Mpc with a fixed \( \gamma = 1.9 \) and determine the correlation length \( r_0 \) for the individual \( \pi_{\text{max}} \) measurements. As in Papers I–III, we find that the LRG ACF sample saturates at \( \pi_{\text{max}} = 80 \) \( h^{-1} \) Mpc. All CCFs saturate at \( \pi_{\text{max}} = 40 \) \( h^{-1} \) Mpc. Power-law fits for the ACFs and CCFs are based on

\[
w_p(r_p) = r_p \left( \frac{r_0}{r_p} \right)^\gamma \frac{\Gamma(1/2)\Gamma((\gamma - 1)/2)}{\Gamma(\gamma/2)},
\]

(7)

where \( \Gamma(x) \) is the gamma function.

To derive the clustering properties of the AGN samples, we follow two different approaches:

1) Power-law fits to the inferred AGN ACF: We use Equation (4) to infer the ACF for the individual AGN sample from the CCF of this sample with the LRG tracer set and the ACF of the LRG sample. We fit the data points of the inferred AGN ACFs with the expression given in Equation (7) and derive best-fit \( r_0 \) and \( \gamma \) values. The data are fitted over the range \( r_p = 0.3-15 \) \( h^{-1} \) Mpc to be consistent with Papers I–III. Since we measure the CCF to infer the ACF, the resulting effective
redshift distribution for the clustering signal is determined by both the redshift distribution of the tracer set and the AGN sample: 
\[ N_{\text{CCF}}(z) = N_{\text{tracer}}(z) * N_{\text{AGN}}(z). \]

In Table 1 we list the redshift range, the median effective redshift of \( N_{\text{CCF}}(z) \) for the corresponding AGN samples, the derived best \( r_p \) and \( \gamma \) values based on power-law fits, and \( r_p \) for a power-law fit with a fixed slope of \( \gamma = 1.9 \) (for ease of comparison).

(2) Bias from HOD modeling: In Paper II we develop a novel method to infer the HOD of RASS/SDSS AGNs directly from the well-constrained CCF of RASS/SDSS AGNs with LRGs. In performing the HOD modeling, we consider that galaxies and AGNs are associated with DMHs. A DMH may contain one or more galaxies or AGNs that are included in our samples. Using the HOD of the LRGs as a template, we constrain the HOD of the AGN by fitting the CCF between AGNs and LRGs. A few of the CCFs do not have enough pairs on small scales for applying \( \chi^2 \) statistics. Thus to derive consistent constraints for all CCF, we consider only bins with \( r_p > 0.7 \ h^{-1} \text{Mpc} \) for all CCF fits (as in Paper III).

Using the best-fit model of the AGN HODs, we derive the bias parameter of the AGN sample by applying
\[
b_{\text{AGN}} = \frac{\langle b_h(M_h) \rangle \langle N_{\text{AGN}}(M_h) \phi(M_h) dM_h \rangle}{\langle N_{\text{AGN}}(M_h) \phi(M_h) dM_h \rangle}, \tag{8}
\]
where \( b_h(M_h) \) is the bias of DMHs with a mass \( M_h \), and \( \phi(M_h) \) is the DMH mass function. In Paper II, we discuss different realizations of the HOD modeling depending on how central and satellite AGNs in DMHs are included or excluded. Here, we apply only “Model A,” assuming that, at low redshifts, black hole accretion occurs more frequently in galaxies with lower stellar mass than in typical LRGs. Thus, we assume that (1) the LRG (highest stellar mass) occupies the center of the DMH and (2) all AGNs are satellites within the same DMH. This is motivated by observations of AGN “downsizing” (Ueda et al. 2003; Hasinger 2008; Miyaji et al. 2015).

As we are interested here (and in Paper III) only in the large-scale bias values and the estimate of the typical halo mass, our results do not depend significantly on the choice of the one-halo term model (model A, B, or C). For example, in the case of the total RASS AGN sample, the best-fit HOD-derived bias values change by less than 0.02 among models A, B, and C. This is a minor fraction of the statistical uncertainty in the bias measurement (±0.09).

The bias parameters derived by power-law fits and HOD modeling can deviate significantly. As discussed in Paper III (see Section 5.4 of Paper III for more details), HOD-derived bias parameters are strongly preferred over those from power-law fits for various reasons.

Inconsistencies between the HOD-derived \( b(z) \) and the results from power-law fits are caused by (1) obtaining power-law fits to the inferred AGN ACFs, which have much larger uncertainties than the directly measured CCFs between AGNs and LRGs (the HOD uses CCFs instead of the AGN ACFs), and (2) fitting the inferred AGN ACF in a range \( r_p = 0.3-15 \ h^{-1} \text{Mpc} \). The latter is also applied by other studies because the clustering signal is not well constrained above \( r_p \sim 15 \ h^{-1} \text{Mpc} \). However, such a fit includes scales in the nonlinear region in which the bias-DMH mass relation, based on linear theory, should not be applied. We decide to do so nevertheless to be consistent with Papers I and III, as well to allow the reader to perform a direct comparison to other studies.

Based on the HOD-derived bias parameter \( b(z) \) (HOD), we derive the typical DMH mass occupied by the AGN sample. Using Equation (8) of Sheth et al. (2001) and the improved fit for this equation given by Tinker et al. (2005), we compute the expected large-scale Eulerian bias factor for different DMH masses at different redshifts. Comparing the observed \( b \) value from HOD modeling with the DMH bias factor from \( \Lambda \)CDM cosmological simulations provides an estimate of the typical DMH mass \( (M_{\text{DMH}}^{\text{typ}}) = b_{\text{obs}}(z, h, M_{\text{DMH}}) \) in which the different AGN samples reside, as listed in the last column of Table 1. Small differences in the median effective redshift between different subsamples do not significantly change the derived typical DMH mass. The low and high \( M_{\text{BH}} \) samples of the X-ray-selected AGN sample have the largest difference in median effective redshift when we consider only samples that have matched distributions in the other parameter of interest. Computing the typical DMH mass at these different redshifts leads to a difference of only \( \Delta \log (M_{\text{DMH}}^{\text{typ}}) = 0.08 \) (e.g., for a bias value of 1.20, log \( (M_{\text{DMH}}^{\text{typ}})_{\text{z}=0.22} \) = 12.83 and log \( (M_{\text{DMH}}^{\text{typ}})_{\text{z}=0.30} \) = 12.75).

We emphasize that \( M_{\text{DMH}}^{\text{typ}} \) should not be compared between different studies. Various conversions are used in the literature to derive \( M_{\text{DMH}}^{\text{typ}} \) from \( b_{\text{DMH}} \). In particular, for the same bias parameter, studies based on optically selected AGN samples derive \( M_{\text{DMH}}^{\text{typ}} \) values up to ~0.6 dex lower than studies using X-ray-selected AGN samples (depending on the actual bias factor and redshift of the sample). The use of the improved fit from Tinker et al. (2005) compared to Equation (8) of Sheth et al. (2001) alone can account for an \( M_{\text{DMH}}^{\text{typ}} \) difference of ~0.3 dex. Thus, instead of blindly using the derived \( M_{\text{DMH}}^{\text{typ}} \) values from different studies, one should recompute these values from the bias parameters in the same manner.

For the X-ray and optically selected AGN samples, we find a clustering dependence on \( M_{\text{BH}} \); in that subsamples with high \( M_{\text{BH}} \) cluster more strongly than their low \( M_{\text{BH}} \) counterparts. No significant clustering dependence on \( L/L_{\text{edd}} \) is observed. We also detect a weak \( FWHM_{\text{Hb}} \), clustering dependence, in that AGN with low \( FWHM_{\text{Hb}} \) are less clustered than their high \( FWHM_{\text{Hb}} \) counterparts. For the X-ray AGN sample, which has a larger dynamical range in \( L_{\text{Hb}} \) than the optical sample, we do not find a significant dependence on \( L_{\text{Hb}} \).

5.1. Robustness of the Clustering Measurements

In this section we verify the reliability of our clustering results by altering the selection of the different AGN subsamples with respect to different parameters. Moderate changes should not influence the clustering results significantly. Therefore this should serve as a test of the robustness of our results.

In Section 3.2, we clarify why we do not use black hole mass estimates from objects with H\( \alpha \) luminosity \( S/N < 10 \). For the first check, we lower this threshold to \( S/N = 5 \), generate the various AGN subsamples, and compute their clustering. Comparing the subsamples with respect to the same parameter (e.g., X-ray luminosity, \( M_{\text{BH}} \), \( L/L_{\text{edd}} \), the newly derived constraints agree well within their 1\( \sigma \) uncertainties with the findings of the \( S/N = 10 \) samples. The same applies when we apply a very conservative threshold of \( S/N = 20 \).
The intrinsic scatter of approximately 0.3 dex in the SMBH mass estimate could have a substantial effect on the observed correlations between \(M_{\text{BH}}\) and \(L_{\text{BH}}\) as well as \(L/L_{\text{EDD}}\). In Section 6.4, we use simulations to explore the impact of SMBH mass errors on the clustering correlations and show that the expected modification of the correlations is very mild.

In this section, we investigate possible effects of the scatter in the SMBH mass estimates from the observational point of view. Two different approaches for estimating \(M_{\text{BH}}\) based on the optical spectra were discussed in Section 3.2. Throughout the paper, we use the relation given in Bentz et al. (2009) (see Equation (2)). Here we recompute \(M_{\text{BH}}\) based on McLure & Dunlop (2004) (see Equation (1)). For the X-ray and optically selected AGN samples, the \(M_{\text{BH}}\) values estimated from McLure & Dunlop (2004) are on average 0.2 dex smaller than the ones from Bentz et al. (2009). We repeat the clustering measurement of low and high \(M_{\text{BH}}\) and \(L/L_{\text{EDD}}\) AGN subsamples, respectively. We find trends identical to those reported in Table 1. The results for all subsamples based on McLure & Dunlop (2004) agree well with their corresponding subsamples based on Bentz et al. (2009), within the 1σ uncertainties. Thus, different estimators for the SMBH mass, which are subject to different systematic errors, give extremely similar results. We conclude that, in our study, uncertainties related to the clustering measurement itself (i.e., the moderate number of AGNs) dominate over systematic SMBH mass errors.

A key ingredient of our paper is that we split the AGN sample in such a way that we match the distribution of another parameter of interest (see Section 3.4). To test this, we alter the procedure of creating the different subsamples. First, we fit a regression line to the data and split the sample into objects above and below the regression line. The resulting subsamples have moderately deviating distributions in the other parameter of interest. This approach yields consistent clustering results with respect to our final results presented in Table 1.

Second, we repeat the generation of low, medium, and high \(M_{\text{BH}}\) and \(L/L_{\text{EDD}}\) samples with matched distributions in the other parameter of interest. This time, we split the sample into 40% (low), 20% (medium), and 40% (high). All corresponding samples agree with the original samples, within the combined 1σ uncertainties. Except for the optical \(L/L_{\text{EDD}}\) subsamples, we also find identical trends for all other parameters in the X-ray and optically selected AGN samples. For the optical \(L/L_{\text{EDD}}\) subsamples, the split into 30% (low), 40% (medium), and 30% (high) suggests a weak and tentative positive \(L/L_{\text{EDD}}\) clustering dependence (\(\sim 1.7\sigma\) between the low and high \(L/L_{\text{EDD}}\) subsamples; see Table 1). When we split the same sample into 40% (low), 20% (medium), and 40% (high), we find \(b_{\text{low}} = 1.35^{+0.14}_{-0.10}\), \(b_{\text{medium}} = 1.33^{+0.17}_{-0.16}\), and \(b_{\text{high}} = 1.35^{+0.14}_{-0.11}\). Thus, we find no evidence for an \(L/L_{\text{EDD}}\) clustering dependence.

Third, we generate subsamples that have perfectly identical distributions in the other parameter of interest (instead of very similar distributions). To do so, we compute in each bin which of the subsamples (low, medium, or high) contains the most objects. We then randomly select and add again objects from the subsamples with the lower number of objects until all three subsamples contain an equal number of objects in this bin. In other words, we scale up the number of objects in a subsample to that of the subsample with the highest number of objects. This method allows multiple entries of single objects in a given subsample. Ultimately, in each bin only one or two objects are added to subsamples. Thus, these subsamples are extremely similar to the matched samples that we use throughout the paper. Consequently, it is not surprising that both methods result in virtually identical clustering signals.

In Figure 5 (right panel histogram) the low, medium, and high \(M_{\text{BH}}\) subsamples overlap considerably. As a fourth test, we now create low and high \(M_{\text{BH}}\) and \(L/L_{\text{EDD}}\) subsamples that have completely separated distributions, but still match in the \(L/L_{\text{EDD}}\) and \(M_{\text{BH}}\) distribution, respectively. We divide the X-ray and optical AGN samples at \(M_{\text{BH}} = 10^{8}\ M_{\odot}\) and \(\log (L/L_{\text{EDD}}) = -1\). We weight the samples by adding sources in a subsample multiple times until a matched distribution is created. One major disadvantage of this approach is that we have to limit substantially the parameter space of the other parameter to match its distribution in both subsamples (see Figures 4, 5). For the X-ray-selected RASS/SDSS AGN samples, we find \(b_{\text{low}} = 1.05^{+0.18}_{-0.16}\), \(b_{\text{high}} = 1.26^{+0.21}_{-0.20}\), \(b_{\text{low}}/L_{\text{edd}} = 1.13^{+0.18}_{-0.18}\), and \(b_{\text{high}}/L_{\text{edd}} = 1.17^{+0.16}_{-0.14}\). The bias values for the optically selected SDSS AGN samples are \(b_{\text{low}} = 1.26^{+0.17}_{-0.16}\), \(b_{\text{high}} = 1.38^{+0.16}_{-0.15}\), \(b_{\text{low}}/L_{\text{edd}} = 1.32^{+0.15}_{-0.13}\), and \(b_{\text{high}}/L_{\text{edd}} = 1.28^{+0.21}_{-0.21}\). Due to significant restriction of the parameter space and thus a substantial decrease in the number of AGN, this approach leads to less significant results.

Fifth, we combine the X-ray and optically selected AGN samples. We divide the combined sample into the highest 30%, middle 40%, and lowest 30% with respect to the corresponding parameter. We also combine the middle and lowest samples (70%). Again, the different subsamples have matched distributions in the other parameter of interest. We find a 2.6σ difference when comparing the AGNs with the 30% highest to the 70% lowest SMBH masses (\(b_{70\% \text{low}} = 1.19^{+0.07}_{-0.08}\), \(b_{70\% \text{high}} = 1.50^{+0.14}_{-0.13}\)).

Last, we drop the requirement of having subsamples with matched distributions in the other parameter of interest. We naively create samples of low, medium, and high \(M_{\text{BH}}\), \(L/L_{\text{EDD}}\), FWHM, and \(L_{\text{H} \alpha}\) simply by dividing the samples into the highest 30%, medium 40%, and lowest 30% with

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**Table 2**

Clustering Properties with Respect to \(M_{\text{BH}}\) and \(L/L_{\text{EDD}}\) When Using Unmatched Distributions in the Other Parameter of Interest

| AGN Sample Name | Median log \(M_{\text{BH}}/M_{\odot}\) | Median log \(L/L_{\text{EDD}}\) | \(b(z)\) | HOD |
|----------------|----------------------------------|-------------------------------|---------|-----|
| X-ray-selected RASS/SDSS AGN—Data Release 4+ | | | | |
| low \(M_{\text{BH}}\) RASS | 7.49 | -0.76 | 1.00^{+0.18}_{-0.15} | |
| medium \(M_{\text{BH}}\) RASS | 7.92 | -1.01 | 1.36^{+0.20}_{-0.18} | |
| high \(M_{\text{BH}}\) RASS | 8.46 | -1.33 | 1.49^{+0.15}_{-0.16} | |
| low \(L/L_{\text{EDD}}\) RASS | 8.29 | -1.42 | 1.41^{+0.17}_{-0.16} | |
| medium \(L/L_{\text{EDD}}\) RASS | 7.92 | -1.00 | 1.49^{+0.20}_{-0.15} | |
| high \(L/L_{\text{EDD}}\) RASS | 7.62 | -0.64 | 1.09^{+0.12}_{-0.10} | |

Optically Selected AGN—SDSS AGN—SDSS Data Release 7

| AGN Sample Name | Median log \(M_{\text{BH}}/M_{\odot}\) | Median log \(L/L_{\text{EDD}}\) | \(b(z)\) | HOD |
|----------------|----------------------------------|-------------------------------|---------|-----|
| low \(M_{\text{BH}}\) SDSS | 7.72 | -0.72 | 1.28^{+0.16}_{-0.16} | |
| medium \(M_{\text{BH}}\) SDSS | 8.12 | -1.04 | 1.15^{+0.08}_{-0.07} | |
| high \(M_{\text{BH}}\) SDSS | 8.58 | -1.42 | 1.58^{+0.07}_{-0.06} | |
| low \(L/L_{\text{EDD}}\) SDSS | 8.51 | -1.46 | 1.43^{+0.11}_{-0.10} | |
| medium \(L/L_{\text{EDD}}\) SDSS | 8.08 | -1.03 | 1.42^{+0.11}_{-0.12} | |
| high \(L/L_{\text{EDD}}\) SDSS | 7.76 | -0.65 | 1.12^{+0.15}_{-0.06} | |

Note. An explanation of the columns is given in Table 1.
respect to the corresponding parameter. Dividing the sample according to $M_{BH}$, for example, in this manner leads to subsamples with very different median $L/L_{EDD}$ values. We present the results for subsamples in $M_{BH}$ and $L/L_{EDD}$ with unmatched distributions in the other parameter (for X-ray and optical AGN) in Table 2. Despite the “mixing” of the two parameters, $M_{BH}$ and $L/L_{EDD}$, the trends seen in the HOD-based bias parameters are similar, though not identical, to the subsamples with matched distributions. We will discuss these results below in Section 6.1 in more detail.

As described above, we consider only data bins for all CCFs with $r_p > 0.7 \, h^{-1} \, \text{Mpc}$ for the computation of the HOD-based bias parameter. As a last test, we recompute the HOD bias parameter using bins with $r_p > 0.5 \, h^{-1} \, \text{Mpc}$. Again, the results agree well within the 1σ uncertainties. The few exceptions are caused by a very low data point at $r_p \sim 0.6 \, h^{-1} \, \text{Mpc}$. In all of these cases, there are at most 10 pairs that contribute to this data point. Thus, $\chi^2$ statistics, as mentioned before, should not be applied. The combination of the various tests listed here provides convincing evidence that our results are not significantly influenced by systematic effects and demonstrates their robustness with respect to moderate changes in our methodology and sample selection.

5.2. Exploring the One-halo Term Dependence of Different AGN Parameters

The HOD modeling introduced in Paper II of this series allows us to explore properties of the one-halo term, that is, at small separations where two objects occupy the same DMH. More importantly, we are able to provide the full distribution of the number of AGNs as a function of $M_{DMH}$, instead of quoting only a typical value. As a parameterization of the AGN HOD, we use a simple truncated power law, assuming that all AGNs are in satellites (“Model A” in Paper II, for more details see Paper II):

\[
\langle N_{AGN,s} \rangle \propto M_{DMH}^{\alpha} \Theta(M_{DMH} - M_c) \tag{9}
\]

where $\Theta(x)$ is the step function (=1 at $x \geq 0$; =0 at $x < 0$), $M_c$ is a critical (minimum) DMH mass below which the HOD is zero (where the DMH does not contain an AGN), $\alpha$ is the power-law slope of the HOD above $M_c$, and $N_{AGN,s}$ the number of (satellite) AGNs in the same DMH.

While a model with an adequate mix of central and satellite AGNs is more realistic (models B and C in Paper II), we here show the results of our simplest model because the purpose of this section is to highlight the differences between samples, including the constraints from both the one- and two-halo terms, while the constraints on bias values come only from the two-halo term.

To achieve adequate constraints, we divide the full AGN sample into only two subsamples (instead of three, as above) for each parameter of interest. We follow the description of Section 3.4 and create low and high samples for $M_{BH}$, $L/L_{EDD}$, FWHM, and $L_{H\alpha}$ with matched distributions in $L/L_{EDD}$, $M_{BH}$, $L_{H\alpha}$, and FWHM, respectively. We list their clustering properties in Table 3. The low and high $L_X$ and $M_i$ samples use a simple cut (log $(L_{0.1-2.4\,\text{keV}}/[\text{erg s}^{-1}]) = 44.29$, $M_i = -22.4$). For the faint $M_i$ sample ($\langle M_i \rangle = -22.18$), we find $b_{\text{linfit}} = 1.45^{+0.10}_{-0.12}$, while the luminous $M_i$ sample ($\langle M_i \rangle = -22.79$) yields $b_{\text{lin}} = 1.29^{+0.07}_{-0.10}$ (1.2σ difference).

The $M_i$ clustering dependence will be discussed in detail in Section 6.3.

We run the HOD modeling for all low and high AGN subsamples using bins with $r_p > 0.5 \, h^{-1} \, \text{Mpc}$. To do so, we assume that $\chi^2$ statistics can be applied if a data point contains at least 15 pairs. Lowering the $r_p$ limit allows us to explore the one-halo term via HOD modeling in more detail. We derive the best fit for all of the low and high parameters individually and show their results in Figures 8 and 9. These two-dimensional plots show a clearer difference between the subsamples than collapsing the information into one dimension such as the bias parameter.

All low and high subsamples (independent of the studied parameter) are consistent with $\alpha < 1$. As pointed out in Paper II, HOD analyses of galaxies over a wide range of absolute magnitudes and redshifts find $\alpha \sim 1.0 - 1.2$. Comparing the AGN and galaxy results implies that models are preferred in which the fraction of satellite AGNs to satellite galaxies decreases with increasing DMH mass. Figure 8 shows evidence that high FWHM and broad-line $L_{H\alpha}$ AGNs show an even steeper decrease with DMH mass (i.e., lower $\alpha$).

The confidence contours of the optically selected AGN subsamples (Figure 9) are narrower than for the X-ray-selected
sample. This is due to the larger number of optical AGNs than X-ray-selected AGNs. However, the general two-dimensional appearance of the confidence contours are very similar between the X-ray and optically selected AGN samples. We note that, for the $M_{\text{BH}}$ subsamples, the low and high optically selected AGNs have different $\alpha$ and $M_{\text{cr}}$ values, while the low and high $M_{\text{BH}}$ X-ray-selected AGN subsamples have consistent $\alpha$ and different $M_{\text{cr}}$ values.

6. DISCUSSION

In this section, we use our results to discuss the physical origin of the observed $L_X$ clustering dependence. We also compare our results to other studies and discuss why we do not detect an $M_{\text{BH}}$ clustering dependence when the clustering results between the X-ray and optical AGN samples are so similar. Finally, we compare our results to predictions from state-of-the-art semianalytic cosmological simulations.

6.1. $M_{\text{BH}}$ as the Origin of the $L_X$ Clustering Dependence

We first verify that the weak X-ray luminosity dependence of the clustering strength found in Paper I is still present in the reduced AGN sample when we exclude $\sim 13\%$ of all objects to reliably estimate $M_{\text{BH}}$. The dependence is detected at the $1.4\sigma$ level when considering “b(z) HOD” in Table 1 (and is $2.5\sigma$ comparing the $r_0$ values at fixed $\gamma$). Using the full X-ray sample, we reported a $1.8\sigma$ detection in Paper II using HOD-derived bias values.

We split the X-ray-selected AGN sample into three subsamples with respect to $M_{\text{BH}}$ (with matched $L/L_{\text{edd}}$ distributions) and show the results in Figure 10 (left) as a blue line. The X-ray sample shows a steady increase of the bias parameter with $M_{\text{BH}}$. The difference between the lowest and highest $M_{\text{BH}}$ subsamples in the X-ray-selected AGN sample is $2.3\sigma$.

For the X-ray and optically selected AGN sample (red line), we detect the highest clustering in the subsample that contains...
the 30% most massive black holes. For both AGN populations, we combine the low and the medium subsamples and compute their combined clustering strength. As a result of the increased sample size, the uncertainties decrease. The bias difference compared to the high $M_{\text{BH}}$ subsample is $2.0\sigma$ and $2.7\sigma$ for the X-ray and optical AGN samples, respectively. We show these data points at the median $M_{\text{BH}}$ values of each subsample in Figure 10.

The X-ray AGN sample shows no hints of a correlation between clustering strength and $L_{\text{EDD}}$ (Figure 10, right panel). The optical AGN sample has a slight positive correlation in that AGNs with higher $L_{\text{EDD}}$ are slightly more clustered than their lower $L_{\text{EDD}}$ counterparts. However, this $\sim 1.7\sigma$ difference disappears when we split the sample into 40% (low), 20% (medium), and 40% (high) bins in $L_{\text{EDD}}$ (see Figure 10, right panel). In Section 6.3 we discuss the nonnegligible selection biases of the optical SDSS AGN sample; as a result, we regard the X-ray-selected AGN sample as less contaminated by observational selection effects. Thus, we do not find convincing statistical evidence for a clustering dependence with $L_{\text{EDD}}$.

For the X-ray-selected AGNs, we still detect a $2.0\sigma$ difference between the low and high $M_{\text{BH}}$ samples when we do not require that the subsamples have matched distributions in $L_{\text{EDD}}$. Using simple cuts in $L_{\text{EDD}}$ without required matched distributions in $M_{\text{BH}}$ yields a $2.2\sigma$ difference in that low and medium $L_{\text{EDD}}$ AGNs cluster more strongly than high $L_{\text{EDD}}$ AGNs. If we assume that this $L_{\text{EDD}}$ AGN clustering dependence is real and that there is no clustering dependence on $M_{\text{BH}}$, this finding would contradict the observed X-ray luminosity clustering dependence that high $L_X$ AGNs (and thus high $L_{\text{EDD}}$) are more strongly clustered than low $L_X$ AGNs. Figures 4 and 5 show that the AGNs with the lowest $L_{\text{EDD}}$ also have high $M_{\text{BH}}$. Thus, we conclude that differences in $M_{\text{BH}}$ (in these naively defined subsamples) are responsible for the observed differences in the clustering of the...
low and high $L/L_{\text{edd}}$ AGN subsamples. Similar results are found for the optically selected AGN sample when we do simple divisions of the full sample without matching the distributions in the other parameter of interest.

Since $M_{\text{BH}}$ is estimated from the observed parameters FWHM and $L_{\text{H\alpha}}$, we also investigate the dependence of the clustering strength when we divide the full samples according to these parameters (see Table 1). As before, we divide the sample in one parameter in such a way that we conserve the distribution in the other parameter in all subsamples. In our sample of luminous broad-line (X-ray-selected) RASS/SDSS AGNs, we find a 2.0σ clustering difference between the lowest and highest FWHM samples and only a 0.6σ difference between the lowest and highest $H\alpha$ luminosity samples. For the optical AGN sample, we find a 1.9σ difference for the low and high FWHM samples and a 1.5σ difference for the low and high $H\alpha$ luminosity samples. Both parameters are used to estimate $M_{\text{BH}}$, though the scaling is much stronger with FWHM than with $L_{\text{H\alpha}}$, (converted to $L_{5100}$, see Equations (1) and (2)).

The similar FWHM clustering dependence in the X-ray and optical AGN samples provides further evidence that $M_{\text{BH}}$ is the key parameter driving the observed $L_X$ dependence of the clustering strength.

Analysis of the two-dimensional parameter space in Figure 8 further supports our claim that the $L_X$ dependence of the clustering strength originates from an $M_{\text{BH}}$ dependence. For the X-ray-selected sample (Figure 8), the contours of the low and high $M_{\text{BH}}$ samples are extremely similar to the $L_X$ contours, while the $L/L_{\text{edd}}$ contours differ significantly from the $L_X$ contours. We therefore conclude that only the black hole mass, and not a combination of $M_{\text{BH}}$ and $L/L_{\text{edd}}$, is responsible for the observed weak X-ray luminosity dependence of the clustering. Within the explored $M_{\text{BH}}$ range, we estimate an average increase of the bias parameter of $\Delta b \sim 0.7$ per dex $M_{\text{BH}}$. This corresponds to approximately one dex increase in $M_{\text{DMH}}$ per dex $M_{\text{BH}}$.

If our studies had shown that the clustering strength correlates directly with $L/L_{\text{edd}}$ but not with $M_{\text{BH}}$, then more strongly clustered AGNs would accrete more material. In this scenario, because highly accreting AGNs would lie in environments with a high density of galaxies, galaxy mergers and galaxy–galaxy interactions would likely be the main triggers of AGN activity. However, we find that the clustering strength depends mainly on $M_{\text{BH}}$ and not on $L/L_{\text{edd}}$. Thus, high X-ray luminosity AGNs do not necessarily require dense environments to accrete more matter. We find that, on average, AGNs in dense environments have higher $M_{\text{BH}}$ than their counterparts in lower density environments. The higher $L_X$ that are observed are then a direct consequence of having higher $M_{\text{BH}}$.

Our findings are also consistent with a scenario in which the AGN luminosity can vary on short timescales (e.g., Hickox et al. 2014), due to a variability in the black hole accretion rate ($L/L_{\text{edd}}$). In this view, the instantaneous luminosity of an AGN is only a weak indicator of the time-averaged black hole accretion rate. Since $L/L_{\text{edd}}$ (which reflects the amount of accreted gas) can rapidly fluctuate, it will not necessarily show a correlation with the properties of the host galaxy or DMH mass. On the other hand, $M_{\text{BH}}$ cannot fluctuate on short timescales as it stays nearly constant or grows slowly. Therefore, the black hole mass is not subject to stochastic variability and correlates more tightly with host-galaxy properties and the host DMH mass.

In the hierarchical model of structure formation, more massive galaxies reside in more massive DMHs (e.g., Mostek et al. 2013; Skibba et al. 2015). More massive galaxies are also more luminous (e.g., Tully & Fisher 1977; McGaugh et al. 2000). This leads to the well-observed luminosity dependence of the clustering signal for galaxies (e.g., Zehavi et al. 2010; Skibba et al. 2014). If more massive galaxies also had more massive bulges, the relationship between the $M_{\text{BH}}$ and stellar velocity dispersion of the surrounding galactic bulge (e.g., Ferrarese & Merritt 2000; Gebhardt et al. 2000; Kormendy & Ho 2013) should then also lead to a correlation of $M_{\text{BH}}$ and $M_{\text{DMH}}$.

We first compare our results with a simple empirically motivated model, rather than a full semianalytic model. We take the relations between galaxy stellar mass and DMH mass at $z \sim 0.3$ from Behroozi et al. (2013). Next, we assign each galaxy a black hole with a mass that is determined by the stellar mass of the host galaxy, following Conroy & White (2013) (their Equation (1)). No scatter in the stellar mass to $M_{\text{BH}}$ relationship is included in our treatment.

The result of this simple model is shown in Figure 12, along with our measurements. There are discrepancies between the model prediction and measurements: at $M_{\text{BH}} < 10^8 M_\odot$ the model predicts a lower $M_{\text{DMH}}$ than we find, though the difference is within 3σ. At higher $M_{\text{BH}}$, the model predicts a stronger relationship between $M_{\text{BH}}$ and $M_{\text{DMH}}$ than we find. While it is understandable how our measurements could lie about the predicted line, in that we measure the mass of the parent halo from the large-scale bias while the model predicts the mass of the subhalo hosting the AGN, our measurement at $M_{\text{BH}} \sim 10^{8.4} M_\odot$, falls below the prediction (a 3.7σ difference).

The shallower slope seen in the data compared to the model here could be caused by the cumulative scatter in each of the correlations in the logical chain ($M_{\text{DMH}} \rightarrow M_{\text{stellar}} \rightarrow M_{\text{bulge}} \rightarrow M_{\text{BH}}$). We will evaluate the predictions of semianalytic models.
in Section 6.4 and will show that they describe our findings better than the simple model does.

6.2. Comparing Our Results to Other Studies

Zhang et al. (2013) and Komiya et al. (2013) study the projected quasar number density around galaxies. Both find evidence that the clustering scale length \( r_0 \) depends on \( M_{BH} \). Zhang et al. (2013) detects this trend, however, at a significance level of only \( \sim 1\sigma \). They also note that there is no clustering dependence on optical quasar luminosity. Based on SDSS AGN data, Komiya et al. (2013) find a trend that \( r_0 \) increases with \( M_{BH} > 10^8 M_\odot \). Our \( r_0 \) measurements for the \( M_{BH} \) subsamples (although at moderately different redshift ranges) agree with their results when we consider the \( 1\sigma \) uncertainties. At lower black hole masses, Komiya et al. (2013) do not find an \( r_0 \) dependence. This might be due to selection biases of the AGN population, as we will show in Section 6.4. Additionally, Komiya et al. (2013) do not find significant \( r_0 \) dependences on AGN luminosity \( (L_{5100}) \). However, the dynamic range in their study is less than a magnitude.

Shen et al. (2009) compute the ACF of optically selected broad-line SDSS AGNs (DR5) at \( 0.4 < z < 2.5 \). They detect a \( \sim 2\sigma \) difference in the clustering strength when they split the AGN sample into the 10% most massive \( M_{BH} \) and the remaining 90%, in that AGNs with the highest \( M_{BH} \) are more strongly clustered. Their results are consistent with our findings, although their sample extends up to \( z = 2.5 \) and contains more massive black holes at higher redshifts. When Shen et al. (2009) split their sample into luminous and faint quasars, they found that both correlation functions agree with each other. Only the 10% most luminous quasars show a larger clustering strength (at the \( \sim 2\sigma \) level) than the remaining 90% of the sample. This result is also consistent with our findings, which we will discuss in the next subsection (see also Figure 11, left).

6.3. Why Do We Not Detect an \( M_i \) Clustering Dependence in the Optically Selected AGN Sample?

Interestingly, we find very similar clustering dependences for the X-ray and the optically selected AGN samples. However, an important question remains: if there are such similar dependences in the clustering strength with \( M_{BH} \), \( L/L_{EDD} \), FWHM, and \( L_{H\alpha} \), why do we not see a clustering dependence with \( M_i \) when we see a dependence with \( L_X \)? Within the X-ray-selected sample, we detect a very weak \( M_i \) clustering dependence, in that the faint and luminous \( M_i \) RASS AGN samples (see Table 1) differ by \( 1.2\sigma \). The direct comparison between the \( M_i \) clustering dependence of the X-ray and optically selected sample in Figure 11 (left) shows that only the faint optical \( M_i \) subsamples deviate from the trend detected in the X-ray-selected sample. However, the difference is not significant considering the uncertainties of the measurements.

Above \( z \sim 0.28 \) the \( H\alpha \) line is shifted outside the SDSS \( i\)-band filter. The redshift range studied here includes sources above and below this redshift. Thus, below \( z \sim 0.28 \) the broadline \( H\alpha \) line contributes flux to the \( M_i \) band, while above \( z \sim 0.28 \) this direct AGN luminosity indicator is not contributing to the \( M_i \) band flux. To explore if this difference in \( M_i \) contribution is responsible for the observed clustering difference in X-ray and optically selected AGN samples, we derive the absolute 5500–6800 Å rest-frame magnitude for all X-ray and optically selected AGNs. The band pass of this rest-frame magnitude is chosen in such a way that it includes the \( H\alpha \) line for all objects in our samples. We compute the clustering dependence as a function of this rest-frame absolute magnitude (Figure 11, right) and find trends very similar to those as a function of \( M_i \) (Figure 11, left). Thus, shifting the \( H\alpha \) line outside the \( M_i \) band does not explain the difference in the clustering signals.

Figure 13 shows that the luminous absolute magnitude subsamples for the X-ray and optically selected AGNs cover a similar parameter space in the \( M_{BH} \) versus absolute 5500–6800 Å rest-frame magnitude plane. The median values of the samples are almost identical. Thus, it is not very surprising that these samples have similar clustering strengths given their similar values of \( M_i \), \( H\alpha \) and absolute 5500–6800 Å rest-frame magnitude. On the other hand, Figure 13 demonstrates that the faint absolute magnitude subsamples for the X-ray and optically selected AGN samples are substantially different. The X-ray sample extends (as in all other parameters) to much lower magnitudes. Thus, the dynamic range of the X-ray-selected RASS/SDSS sample is wider than that of the optical AGN sample. As a consequence, the medium absolute magnitude subsample of the X-ray-selected AGN sample includes the vast majority of the optical AGNs in the faint absolute magnitude subsample. If one combines the faint and medium absolute magnitude subsamples in the optical to roughly match the medium X-ray subsample, the clustering strength between both AGN populations agrees very well (\( b_{\text{opt, faint + med.}} = 1.29^{+0.07}_{-0.07} \); see Figure 11).

Finally, we explore the selection of the X-ray and optical AGNs in more detail. The RASS/SDSS sample is an X-ray flux-limited sample. ROSAT’s soft energy range significantly biases the sample toward broad-line AGNs as these sources are unabsorbed (or only mildly absorbed) in the X-rays. In addition to the X-ray flux limit, the sample is also subject to an optical flux limit because an SDSS spectrum is required for the characterization of a source. However, the X-ray and optical luminosities of broad-line AGNs correlate well (e.g., Tananbaum et al. 1979; Grupe et al. 2010; Lusso et al. 2010). Since ROSAT has limited sensitivity, it is able to detect only the X-ray-brightest AGNs. These objects are typically also bright in the optical. Thus, the impact of the optical flux limit on the sample selection is moderate.

The optical SDSS AGN selection, on the other hand, is much more complex. The target selection relies on several different selection techniques. The main criterion is a color cut and an optical flux limit. Broad-line AGNs with a certain amount of extinction will not meet the color-cut criterion. Additional objects are included in the sample due to their radio emission. Most importantly, an absolute magnitude cut is applied.

Figure 14 (left) shows that the optically selected AGN sample is not a flux-limited sample, although the sample selection considers only objects with \( 15.0 < i < 19.1 \). The absolute \( M_i \) cut (applied to prevent substantial contamination by host galaxy light) causes a serious deficiency of objects above the lower \( i\)-band limit of \( i < 19.1 \). The X-ray-selected AGN sample (Figure 14, right) includes objects down to almost the same apparent \( i\)-band magnitude, independent of redshift. Various SDSS papers discuss how the optical SDSS AGN sample is not a uniformly selected sample (e.g., Richards et al. 2006b). We conclude that the complex optical AGN
selection might be the origin of the clustering differences between the X-ray and optically selected AGN samples. The strongest differences are detected between the samples of the lowest median redshift; this is also the range in which the optical AGN sample deviates most from a clean, flux-limited sample. We therefore consider the X-ray-selected RASS/SDSS AGN sample as the more complete sample and use only their clustering properties in the next section.

6.4. Comparison to Cosmological Simulations

Hydrodynamical (e.g., Bryan et al. 2014; Hirschmann et al. 2014; Steinborn et al. 2015) and semianalytical (e.g., Malbon et al. 2007; Marulli et al. 2008; Fanidakis et al. 2011; Benson 2012) state-of-the-art simulations have reached a level of complexity such that they can well predict observed quantities such as luminosity and stellar mass functions (e.g., Hopkins et al. 2006; Degraf et al. 2010; Fanidakis et al. 2012). The observed clustering properties of galaxies and AGNs provide additional important constraints for such models (e.g., Bonoli et al. 2009).

Theoretical models of galaxy formation that include prescriptions for modeling BH growth can provide important constraints on the fueling modes of AGN. For example, models in which AGN activity is triggered by major mergers between galaxies or secular processes within the host galaxy (e.g., disk instabilities) predict a well-defined correlation function for luminous quasars, with an average DMH mass of $M_{\text{DMH}} \sim 10^{12} h^{-1} M_\odot$ (Bonoli et al. 2009, 2010; Fanidakis et al. 2013). However, the inclusion of an additional mode of growth that is linked to diffuse gas accretion in massive halos (Fanidakis et al. 2012) predicts a much higher average halo mass for moderate-luminosity AGNs, in contrast to their luminous counterparts (Fanidakis et al. 2013). Comparing this specific picture of AGN clustering with the available observations could potentially provide important insights into the correct modeling of the growth of black holes in galaxy-formation models.

Cosmological simulations and their predicted clustering properties can also be used to test the impact of sample selection biases for observed samples. As an example, let us assume that in an unbiased sample there is no clustering dependence as a function of a certain AGN parameter. A
particular observational selection bias might cause a clustering
dependence to be measured. As selection biases can be
included in the cosmological simulation, one can therefore
compare the predictions for the unbiased and observed
(including selection biases) AGN samples. Such knowledge
is crucial to avoid wrong interpretations about the underlying
physics when using clustering studies. Thus cosmological
simulations are not only important to test our theoretical
understanding of the observed universe but also to explore the
impact of observational sample biases.

Here we use the semianalytical galaxy-formation model
GALFORM (Cole et al. 2000) to compare with our observed
AGN clustering signals. Fanidakis et al. (2011, 2012, 2013)
modeled SMBH in these simulations, using an identical model
in all three papers. Only the cosmology has changed from
WMAP1 (in the first two papers) to WMAP7 (Fanidakis
et al. 2013). In Fanidakis et al. (2013), the authors incorporate
two modes of AGN accretion in the GALFORM model. The first
is the starburst mode (cold accretion), in which accretion onto
the BH is tightly coupled to the mass of the cold gas available
in the galaxy, which also contributes to star formation. This
mode occurs when the host galaxy encounters a major galaxy
merger, a minor merger, or a disk instability. These phenomena
can take place in a wide range of halo masses. However,
observable AGN luminosities within the range defined in this
study are typically produced in DMHs with
\[ M_{\text{DMH}} < 10^{12.5} h^{-1} M_\odot \]
(Fanidakis et al. 2013).

The second is the hot-halo mode (hot accretion), which
occurs in DMHs with higher masses. A fraction of the AGN
energy output is used to heat the gas in the DMH and suppress
cooling of the gas. The SMBH accretes directly from the
diffuse gas in the DMH. This mode regulates the black hole
accretion in very massive halos with \( M_{\text{DMH}} \gtrsim 10^{13} h^{-1} M_\odot \).
For more details on both modes and their modeling, we refer
the reader to Fanidakis et al. (2013) and the references within.

The model of Fanidakis et al. (2013) is successful in
reproducing several observational constraints, including the
observed luminosity functions of galaxies and AGNs over a
wide range of redshifts (Fanidakis et al. 2011, 2012). In
addition, they can reproduce reasonably well the observed
mass relationship and the global and active black hole
mass functions.

The primary motivation for running the simulation is to
explore how AGN clustering depends on the mode of AGN
accretion, as described in the two modes mentioned above.
Here we can thus compare our observational results directly to
theoretical predictions. In addition, we can explore the effect of
the RASS flux limit selection on our observational sample.

Fanidakis et al. (2013) present the typical DMH masses for
AGNs observed in a redshift range of \( z = 0–1.3 \). Here we
repeat this simulation in a redshift range of \( z = 0.16–0.36 \),
equal to the redshift range used for the observed X-ray and
optically selected AGN samples. For each galaxy, the
simulation allows one to identify when the AGN is active.
An object is included in the AGN sample if its central engine is
active in at least one of the five logarithmically spaced
snapshots output between \( z = 0.16–0.36 \). AGN properties such
as \( M_{\text{BH}}, L_{\text{bol}}, L/L_{\text{edd}} \), and redshift are available for each of
the different snapshots. The parameter \( L_{\text{bol}} \) is calculated assuming
that the accretion flow forms a geometrically thick disk for
relatively high accretion rates (Shakura & Sunyaev 1973). At
lower accretion rates, a geometrically thick disk or an
advection-dominated accretion flow is modeled (ADAF,
Narayan & Yi 1994).

X-ray luminosities are calculated directly from \( L_{\text{bol}} \) by
applying the bolometric correction from Marconi et al. (2004).
We consider an object to be an AGN if its intrinsic 2–10 keV
rest-frame luminosity is \( L_{2–10\text{keV}} \gtrsim 10^{41.5} \text{erg s}^{-1} \). The sample
contains X-ray unabsorbed and absorbed AGNs. Based on the
luminosity, we use the empirical formula of Hasinger (2008)
to determine the probability that the object is absorbed. We then
classify statistically if an object is unabsorbed or absorbed.
Below, we will refer to this AGN sample as the “all-simulated
AGN” sample. More recent estimates of the obscured fraction
of AGNs as a function of luminosity have been presented by
Merloni et al. (2014), who show that the probability that an
AGN at high luminosities is absorbed is higher than that
suggested by Hasinger (2008). We test the impact of a higher
obscured fraction at high luminosities and find insignificant
differences as far as clustering measurements are concerned.
We therefore retain the empirical obscuration relation of
Hasinger (2008) as presented in Fanidakis et al. (2013).

Since RASS is essentially a flux-limited survey (see also
Figure 14, right), only AGNs above a certain X-ray flux are
contained in the RASS AGN catalog. However, due to the
characteristics of the RASS, different regions of the sky have
different exposure times. To mimic the RASS flux selection,
we also apply an average flux cut to the simulated AGN sample
by using the X-ray luminosities and redshifts of objects in the
simulation. We refer to this sample as the “RASS-selected
AGN sample.” Its location in the \( M_{\text{BH}} \) versus \( L/L_{\text{edd}} \) plane
is shown in Figure 15 (colored grid points). This sample also
includes the effect that RASS is sensitive only to unabsorbed
X-ray AGNs. However, since the luminosities of the RASS
AGNs are high, the simulation classifies the vast majority of
the objects as X-ray unabsorbed.
In the same plane, we also show the observed X-ray-selected broad-line RASS/SDSS AGN sample. In general, the simulation agrees well with the observations, in that sources lie in a similar region of this space. However, the simulation slightly overestimates the number of AGNs with \( M_{\text{BH}} > 10^{8.5} M_\odot \) and \( \log (L/L_{\text{edd}}) < -2 \). Such objects should be detectable given the RASS flux limit, but they do not exist in large numbers (at the observed redshift range). However, these are the objects in the simulation for which the accretion flow is modeled with an ADAF. These AGNs are observationally associated with radio-bright, mechanical feedback-dominated SMBHs (e.g., Churazov et al. 2005; Hickox et al. 2009; Smolcic 2009). The optical spectra of these objects do not contain any high excitation lines typical of AGNs (e.g., Best & Heckman 2012). Thus, one might argue that these objects would not be classified as AGNs in an SDSS spectrum. We therefore limit the simulated RASS-selected AGN sample (and the predictions in the following paragraphs) to those sources with log \( (L/L_{\text{edd}}) > -2 \). Despite these minor differences, we calculate the bias parameter for the simulated AGNs and the observed RASS-selected AGN sample. The bias is calculated in bins of 0.2 in log \( (M_{\text{BH}}/M_\odot) \) and log \( (L/L_{\text{edd}}) \) using Equation (4) given in Fanidakis et al. (2013) (see also Equation (8) in this paper). We follow the same procedure as for the observed AGN samples. Thus, the bias values are converted into typical DMH masses (log \( M_{\text{DMH}}^{\text{typ}} \)). Since the simulation uses the conversion given by Sheth et al. (2001) without applying the improved fitting formula by Tinker et al. (2005), we recompute for the observed \( L_X, M_{\text{BH}}, \) and \( L/L_{\text{edd}} \) AGN subsamples in Table 1 \( M_{\text{DMH}}^{\text{typ}} \) based only on the ellipsoidal collapse model of Sheth et al. (2001). This allows us to directly compare the predictions with the observations, as shown in Figure 16.

In the case of the simulated RASS-selected AGN sample, we also assign to every BH mass a random error from a Gaussian distribution with \( \sigma = 0.3 \) dex. We recalculate all of the relations (red lines) shown in Figure 16 for 50 realizations and show a subset of these as orange lines. This exercise not only allows for a more realistic comparison to the data, but also allows us to explore the impact of the intrinsic scatter of approximately 0.3 dex in the \( M_{\text{BH}} \) estimate of the observed sample. Figure 16 shows that the 0.3 dex uncertainty in the BH mass estimates has no significant impact on the prediction of the correlations shown. Only at very low \( M_{\text{BH}} \) and high \( L/L_{\text{edd}} \) does the scatter between different realizations increase. However, this is caused by the low number of objects with such properties in the simulations.

For the all-simulated AGN sample (black line), the simulation predicts a positive clustering dependence on X-ray luminosity only above log \( (L_{2-10}/\text{erg s}^{-1}) \approx 44 \). This might explain why studies of moderate X-ray luminosity do not see a clustering dependence on luminosity and conflicting results are presented in the literature. The RASS selection results in a luminosity dependence that extends down to log \( (L_{2-10}/\text{erg s}^{-1}) \approx 43 \) (red line). The data and the predictions for the RASS sample agree remarkably well.

For the \( M_{\text{BH}} \) clustering dependence (Figure 16, middle), the simulation predicts a strong clustering dependence with \( M_{\text{BH}} \) for the all-simulated AGN sample; a steady increase of typical DMH mass with \( M_{\text{BH}} \) is found (see also Figure 7 in Fanidakis et al. 2012). Above \( M_{\text{BH}} \approx 10^8 M_\odot \), the correlation is even stronger. The RASS flux limit selection of the all-simulated AGN sample has a moderate impact on the \( M_{\text{BH}} \) clustering dependence. It amplifies the correlation at \( M_{\text{BH}} \gtrsim 10^8 M_\odot \) and weakens it below \( M_{\text{BH}} \approx 10^8 M_\odot \) compared to an unbiased AGN sample. The model shows that, in flux-limited samples below \( M_{\text{BH}} \approx 10^8 M_\odot \), no clustering correlation with \( M_{\text{BH}} \) should be detectable, although an unbiased AGN sample will still show a very weak \( M_{\text{BH}} \) clustering dependence in this \( M_{\text{BH}} \) range. This is consistent with the result found by Komiyama et al. (2013).

The observed \( M_{\text{BH}} \) clustering dependence agrees reasonably well with the model prediction, as shown in Figure 16. The data hint that the observed clustering dependence might not be as strong as predicted by the simulated RASS-selected AGN sample.

The predicted \( L/L_{\text{edd}} \) clustering dependence also matches the observations well (Figure 16, right). Below \( L/L_{\text{edd}} \approx 10^{-2} \) the model predicts higher DMH masses than are currently detected for AGNs, but our data do not probe Eddington ratios that low. The model predicts that, at low
$L/L_{\text{edd}}$ values, the RASS flux limit selection should cause a very strong negative $L/L_{\text{edd}}$ dependence to the clustering amplitude. The data point with the lowest $L/L_{\text{edd}}$ in the RASS/SDSS AGN sample does not allow us to verify or reject this prediction. Although our samples contain objects down to $L/L_{\text{edd}} \sim 10^{-2}$ (see Figure 4), AGN samples with even lower $L/L_{\text{edd}}$ are needed to critically test the prediction of high $M_{\text{DMH}}$ at low $L/L_{\text{edd}}$.

Such tests between observations and state-of-the-art simulations offer a unique opportunity to constrain the physical mechanisms included in galaxy and AGN formation models. For example, a mechanism for the hot-halo mode in which black holes with low $L/L_{\text{edd}}$ and high $M_{\text{BH}}$ reproduce the real RASS-selected sample might agree better with the observed AGN clustering dependences. Thus, a channel has to be found to remove the simulated objects with $M_{\text{BH}} \gtrsim 10^{8.5} M_\odot$ and $L/L_{\text{edd}} \lesssim -2$. In the current model, the hot-halo AGNs arise from the necessity for AGN feedback in massive DMHs. The accretion rate in this mode is calculated indirectly from the cooling properties of the host halo and corresponds to an accretion flow that is able to reproduce powerful AGN outflows that suppress gas cooling and star formation. The tuning of the free parameters in this calculation is done by fitting the model to the observed galaxy luminosity function at $z=0$. Obviously, more observational data are needed to constrain the model. The comparison between the simulated and real RASS-selected AGN samples in Figures 15 and 16 could be used as additional constraints for constraining the free parameters in the model.

When cosmological simulations such as the one presented here are adjusted to match the observed AGN clustering properties, to be considered successful they still have to match other observational constraints, such as the luminosity function of galaxies and AGNs at different redshifts. Changes in the physical treatment of AGN accretion might also solve other challenges, such as the observed deficiency of low-luminosity AGNs at high redshifts when compared to predictions from simulations (e.g., Miyaji et al. 2015). Including various constraints from galaxy and AGN clustering measurements has thus the power not only to improve the simulations but also to enhance our general understanding of AGN physics and AGN and galaxy coevolution.

7. CONCLUSIONS

Motivated by the detection of a weak X-ray luminosity dependence of the clustering strength of AGNs in the first paper of this series, here we explore the physical origin of this dependence. Using the optical spectra of our soft X-ray-selected (RASS/SDSS) luminous, broad-line AGN sample at $0.16 < z < 0.36$, we estimate black hole masses and Eddington ratios and calculate the clustering dependence on each.

Since $M_{\text{BH}}$ and $L/L_{\text{edd}}$ are correlated, we create subsamples in $M_{\text{BH}}$ and $L/L_{\text{edd}}$ that have matched distributions in the other parameter of interest. We compute the clustering strength for the subsamples and find a weak clustering dependence with $M_{\text{BH}}$ and no significant correlation with $L/L_{\text{edd}}$. Various adjustments in how the subsamples are created do not change the results. We also study the clustering of the observed parameters (luminosity and FWHM of the broad Hβ line) that are used to derive $M_{\text{BH}}$. We find a weak FWHM$_{\text{Hβ}}$ clustering correlation in that AGNs with low FWHM$_{\text{Hβ}}$ are less clustered than their high FWHM$_{\text{Hβ}}$ counterparts.

We also study the clustering properties of an optically selected SDSS AGN sample. This sample has 29% of its objects in common with the X-ray-selected RASS/SDSS AGN sample. We detect the same trends as found for the X-ray AGN sample with respect to $M_{\text{BH}}$, $L/L_{\text{edd}}$, $L_{\text{X}}$, and FWHM$_{\text{Hβ}}$. The X-ray and optically selected AGN samples show divergent clustering signals for the lowest $M_{\text{BH}}$ (absolute i-band magnitude) samples. We argue that this is caused by various complex selection effects in the optical sample and that the X-ray-selected RASS/SDSS AGN sample is more uniformly selected.

From our correlation function measurements, we conclude that $M_{\text{BH}}$ is the origin of the observed weak X-ray luminosity clustering dependence. The confidence contours of our AGN HOD modeling parameters further support this finding, as low and high $M_{\text{BH}}$ and $L_{\text{X}}$ samples show extremely similar contours, while the low and high $L/L_{\text{edd}}$ sample contours differ significantly from the $L_{\text{X}}$ contours.

The $M_{\text{BH}}$ clustering dependence is detected at a significance level of $2.7\sigma$. In both the X-ray and optical AGN samples, the highest clustering strength is found for AGNs with the 30% highest $M_{\text{BH}}$. Thus, at a redshift range of $0.16 < z < 0.36$, luminous broad-line AGNs with more massive $M_{\text{BH}}$ reside, on average, in more massive DMHs. In this context, the DMH mass refers to the single largest (parent) halo mass.

Since the observed clustering strength does not depend on $L/L_{\text{edd}}$ in a statistically significant way, AGNs with high accretion rates do not require large-scale dense environments with high galaxy density. This provides evidence that major or minor mergers play only a limited role in the AGN accretion processes in the low-redshift universe. Internal processes such as disk instabilities could be the dominant AGN triggering mechanism at late cosmic times.

Empirically motivated models that include simple monotonic relationships between $M_{\text{DMH}}$, $M_{\text{stellar}}$, and $M_{\text{BH}}$ and without AGN feedback or treatments of AGN triggering do not match well the observed relationships between $M_{\text{BH}}$ and $M_{\text{DMH}}$ derived from clustering. Thus, we use a semianalytical model to study the predicted clustering dependences as a function of $L_{\text{X}}$, $M_{\text{BH}}$, and $L/L_{\text{edd}}$. This model included AGN feedback and two modes of AGN accretion and fits the observed $M_{\text{BH}}$ versus $M_{\text{DMH}}$ relation better than the simple model. Comparing the simulated full AGN sample with a simulated RASS flux-limited AGN sample, we show that observational selection effects moderately change the expected clustering dependences. The simulation predicts that higher $M_{\text{BH}}$ are found in more massive halos, and the predicted correlations with $L_{\text{X}}$, $M_{\text{BH}}$, and $L/L_{\text{edd}}$ agree reasonably well with our observations presented here.

Clustering measurements with small uncertainties offer a unique opportunity, after considering the effects of selection biases, to identify missing physics in our current understanding of the galaxy and AGN evolution by comparing theoretical predictions with observations. Thus, future clustering measurements as a function of various galaxy and AGN parameters will deliver needed additional constraints that will improve upon and distinguish between current theoretical models.

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