THE SPATIAL CLUSTERING OF ROSAT ALL-SKY SURVEY ACTIVE GALACTIC NUCLEI. III. EXPANDED SAMPLE AND COMPARISON WITH OPTICAL ACTIVE GALACTIC NUCLEI

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ABSTRACT

This is the third 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 (RASS) and the Sloan Digital Sky Survey (SDSS). In this paper, we extend the redshift range to 0.07 < z < 0.50 and measure the clustering amplitudes of both X-ray-selected and optically selected SDSS broad-line AGNs with and without radio detections as well as for X-ray-selected narrow-line RASS/SDSS AGNs. We measure the clustering amplitude through cross-correlation functions (CCFs) with SDSS galaxies and derive the bias by applying a halo occupation distribution model directly to the CCFs. We find no statistically convincing difference in the clustering of X-ray-selected and optically selected broad-line AGNs, as well as with samples in which radio-detected AGNs are excluded. This is in contrast to low-redshift optically selected narrow-line AGNs, where radio-loud AGNs are found in more massive halos than optical AGNs without a radio detection. The typical dark matter halo masses of our broad-line AGNs are log (M_{DMH}/[h^{-1} M_\odot]) ∼ 12.4–13.4, consistent with the halo mass range of typical non-AGN galaxies at low redshifts. We find no significant difference between the clustering of X-ray-selected narrow-line AGNs and broad-line AGNs. We confirm the weak dependence of the clustering strength on AGN X-ray luminosity at a ~2σ level. Finally, we summarize the current picture of AGN clustering to z ∼ 1.5 based on three-dimensional clustering measurements.

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

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1. INTRODUCTION

Galaxy clustering measurements of large area surveys, such as the 2dF Galaxy Redshift Survey (2dFGRS; Colless et al. 2001), Sloan Digital Sky Survey (SDSS; Abazajian et al. 2009), Deep Extragalactic Evolutionary Probe 2 Redshift Survey (Davis et al. 2003), Active Galactic Nucleus and Galaxy Evolution Survey (AGES; Kochanek et al. 2004), and VIMOS-VLT Deep Survey (Le Fèvre et al. 2005), with many thousands of galaxies have recently allowed narrow-line AGN clustering measurements for samples of up to 90,000 AGNs (Li et al. 2006). Studies, such as Wake et al. (2004), Li et al. (2006), Magliocchetti et al. (2004), and Mandelbaum et al. (2009), explore the clustering strength of low-redshift (z < 0.3) narrow-line AGN samples with respect to various AGN properties (e.g., black hole mass, radio emission). Optically selected narrow-line AGNs have a clustering strength similar to all galaxies (both blue and red). Narrow-line radio-loud AGNs cluster more strongly than AGNs without radio emission and identical samples of quiescent galaxies. Consequently, a denser environment of galaxies increases the probability of hosting a narrow-line radio-loud AGN.
Broad-line AGNs are, in general, more luminous than narrow-line AGNs. Moreover, their energy production dominates over the host galaxy starlight. Large area optical surveys have spectroscopically identified tens of thousands of broad-line AGNs (e.g., Schneider et al. 2010; Croom et al. 2001). The co-moving number density of broad-line AGNs is very low in the low-redshift universe ($z < 0.5$). The situation improves at higher redshifts as the co-moving AGN number distribution peaks at $z \sim 2$. Furthermore, a given observed area corresponds at higher redshift to a larger observed co-moving volume. These two facts favor broad-line AGN clustering measurements at $z \gtrsim 0.5$ (e.g., Porciani et al. 2004; Croom et al. 2005; Ross et al. 2009).

X-ray surveys have also been used to select AGNs. These surveys cover much less sky area, e.g., $\sim 0.1–10$ deg$^2$, than optical surveys. Further, they sample lower AGN luminosities than optical surveys and contain a significant fraction of obscured AGNs. In order to probe the required large observed co-moving volume needed for clustering measurements using these relatively small sky areas; 3D clustering measurements of X-ray-selected AGNs have mainly been conducted at $z \gtrsim 0.8$ (e.g., Gilli et al. 2005, 2009; Yang et al. 2006; Coil et al. 2007).

Optically selected AGNs at redshifts of $z \sim 1.0–1.5$ appear to reside in somewhat lower host DMH masses ($M_{\text{DMH}} \sim 10^{12–13} h^{-1} M_{\odot}$, e.g., Porciani et al. 2004; Coil et al. 2007; Ross et al. 2009) than XMM-Newton- and Chandra-selected AGN samples ($M_{\text{DMH}} \sim 10^{13–13.5} h^{-1} M_{\odot}$, e.g., Yang et al. 2006; Gilli et al. 2005, 2009; Coil et al. 2009; Allevato et al. 2011). Possible explanations of the differences in the clustering signals include either the presence of a large fraction of X-ray-absorbed narrow-line type II AGNs in the XMM-Newton and Chandra samples or the different luminosities of the AGN samples. At lower redshifts 3D broad-line X-ray AGN clustering measurements have been associated with large uncertainties, due to small sample sizes (e.g., Mullis et al. 2004).

To achieve smaller uncertainties in AGN clustering measurements, Coil et al. (2009) use the cross-correlation function (CCF) of AGNs with a tracer set of galaxies that contains a large number of objects. The AGN ACF is then inferred from the CCF, which has many more pairs at a given separation and hence significantly reduces the uncertainties in the spatial correlation function compared with the direct measurements of the AGN ACF.

In Krumpe et al. (2010b, hereafter Paper I) we use the cross-correlation technique to calculate the CCF between broad-line X-ray-selected AGNs from the ROSAT All-Sky Survey (RASS) and SDSS luminous red galaxies (LRGs) in the redshift range $0.16 < z < 0.36$. The potential of RASS, which is currently the most sensitive X-ray all-sky survey, can only be maximally exploited when it is combined with other large area surveys such as SDSS. The unprecedented low uncertainties of the inferred broad-line AGN ACF from the RASS/SDSS combination allows us to split our sample into subsamples according to their X-ray luminosities. From this work, for the first time, we report an X-ray luminosity dependence of broad-line AGN clustering in that higher luminosity AGNs cluster more strongly than their lower luminosity counterparts. We conclude that low-luminosity broad-line RASS/SDSS AGNs cluster similarly to blue galaxies at the same redshift, while high-luminosity RASS/SDSS AGNs cluster similarly to red galaxies.

In our second paper (Miyaji et al. 2011, hereafter Paper II), we apply an HOD modeling technique to the AGN–LRG CCF in order to move beyond determining the typical DMH mass based on the clustering signal strength and instead constrain the full distribution of AGNs as a function of DMH mass. To do this, we develop a novel method of applying the HOD model directly to the CCF. The HOD modeling significantly improves the analysis of the CCF because it properly uses the Fourier-transformed linear power spectrum in the “two-halo term” as well as the nonlinear growth of matter in the “one-halo term” through the formation and growth of DMHs. This results in significant improvements over the standard method, which is used in Paper I, of fitting both regimes with a phenomenological power law. One of the important results of this analysis is that at $0.16 < z < 0.36$ the mean number of satellite AGNs in a DMH does not proportionally increase with halo mass, as is found for satellite galaxies. The AGN fraction among satellite galaxies actually decreases with increasing DMH mass beyond $M_{\text{DMH}} \sim 10^{12} h^{-1} M_{\odot}$.

In this paper, we extend the scope of our previous papers to both somewhat lower and higher redshifts to obtain broad-line AGN clustering results at $z < 0.5$, where very precise narrow-line AGN clustering measurements exist but broad-line AGN clustering is poorly constrained. This is crucial for studying the possible evolution and luminosity dependence of broad-line AGN clustering from low to high redshifts. The dominant process that triggers AGN activity could be a function of redshift and/or halo mass, which may be reflected in the clustering properties. We also study the clustering signal of both X-ray- and optically selected broad-line AGN samples, and test whether the exclusion of radio-detected broad-line AGNs changes our results. As the same statistical method and galaxy tracer sets are used to infer the clustering signal for X-ray-selected and optically selected broad-line AGNs, we can explore differences in the clustering among the different selection techniques with low systematic uncertainties. Furthermore, we derive bias parameters by applying the HOD modeling directly to all CCFs. In Paper II, we show that using a power-law fit results even in the nonlinear regime, as is commonly done in the literature, is appropriate to detect differences in the clustering properties between different samples. However, the derived bias parameters and DMH masses based on these fits should be interpreted with caution as the fit not only considers the linear regime (two-halo term), but also the nonlinear regime (one-halo term). Consequently, here we derive the bias for each AGN sample using HOD modeling of the CCF. Full detailed results of the HOD modeling of the CCFs presented in this paper will be given in a future paper (T. Miyaji et al. 2012, in preparation).

This paper is organized as follows. In Section 2, we describe the properties of the different galaxy tracer sets used at different redshifts, while Section 3 gives the details of our different AGN samples. In Section 4, we briefly summarize the cross-correlation technique, how the AGN ACF is inferred from this, and present our results. We apply the HOD modeling in Section 5. Our results are discussed in Section 6 and we conclude in Section 7. Throughout the paper, all distances are measured in co-moving coordinates and given in units of $h^{-1}$ Mpc, where $h = H_0/100$ km s$^{-1}$ Mpc$^{-1}$, unless otherwise stated. We use a cosmology of $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$, and $\sigma_8(z = 0) = 0.8$, which is consistent with the Wilkinson Microwave Anisotropy Probe data release 7 (Larson et al. 2011, Table 3). The same cosmology is used in Papers I and II. Luminosities and absolute magnitudes are calculated for $h = 0.7$. We use AB magnitudes throughout the paper. All uncertainties represent to a 1σ (68.3%) confidence interval unless otherwise stated.
2. GALAXY TRACER SETS

The crucial ingredient in the cross-correlation method is the tracer set, a sample with a large number of objects that traces the underlying dark matter density distribution. The properties of the tracer set determine the redshift range over which the method can be applied. The AGN samples of interest are necessarily limited to the same redshift range and geometry as the corresponding tracer set. As the RASS/SDSS-selected AGNs (Anderson et al. 2007) are based on the SDSS data release 5 (DR5), we consequently limit the tracer sets to the same survey geometry when we compute the clustering measurements of the X-ray-selected AGN sample. The SDSS geometry and completeness are expressed in terms of spherical polygons (Hamilton & Tegmark 2004). This file is not publicly available for DR5; therefore, we use the latest version available prior to DR5: the DR4+ geometry file.7 However, optically selected SDSS AGNs (Schneider et al. 2010) make use of the full SDSS survey (DR7). Consequently, we consider tracer sets from the DR7 geometry whenever we compute CCFs of optically selected SDSS AGNs.

In the redshift range of 0.07 < z < 0.16, we use SDSS main galaxies for the tracer set, while SDSS LRGs (Eisenstein et al. 2001) are used for the corresponding cross-correlation sample at 0.16 < z < 0.36 (same as for Paper I). Very luminous red galaxies are used as a tracer set at 0.36 < z < 0.50. We will refer to the latter sample as the “extended LRG sample.” Above z ∼ 0.5 the number of galaxies with spectroscopic redshifts in SDSS decreases dramatically and does not allow the selection of further tracer sets with a sufficient density of objects. In the following subsections, we describe in detail the extraction of the various tracer sets and how we account for SDSS fiber collisions.

2.1. SDSS Main Galaxy Sample

The SDSS main galaxy sample (Strauss et al. 2002) is drawn from the New York University Value-Added Galaxy catalog9 (NYU VAGC; Blanton et al. 2005; Padmanabhan et al. 2008), based on SDSS DR7 (Abazajian et al. 2009).

The photometric data cover an area of 10,417 deg², while the spectroscopic data cover 7966 deg². Absolute magnitudes, based on Petrosian fluxes, are K-corrected to z = 0.1 (Blanton et al. 2003; Blanton & Roweis 2007), which is close to the median redshift of our sample. We follow a scheme similar to Zehavi et al. (2005b), who use the NYU VAGC to measure the clustering of various luminosity and color-selected galaxy subsamples. Similarly, we limit our sample to 14.5 < r < 17.5. The bright limit avoids incompleteness due to galaxy deblending, and the faint limit accounts for the slightly varying r-band magnitude limit over the SDSS area (nominal value r ∼ 17.7). The restriction of r < 17.5 ensures a uniform flux limit throughout the whole SDSS survey. In addition, we create a volume-limited galaxy sample by selecting objects with an absolute magnitude of −21.1 < M_r = -21.1. Finally, we limit the redshift range to 0.07 < z < 0.16.

Applying the above-mentioned selection criteria and considering only SDSS DR7 areas with a spectroscopic completeness ratio of >0.8, we select 68,273 galaxies with spectroscopic redshifts from the corresponding NYU VAGC. The DR7 area covered by restricting the spectroscopic comp-

pleteness ratio to >0.8 is 7670 deg². The properties of this DR7 SDSS main galaxy sample are summarized in Table 1.

As described above, the X-ray-selected RASS/SDSS AGN samples are based on DR5. Therefore, we further reconfigure the DR7 tracer sets (in this case the SDSS main galaxy sample) to the DR4+ geometry to define a common survey geometry to use when measuring the clustering of X-ray-selected AGNs. The restriction to the DR4+ survey area with a DR7 spectroscopic completeness ratio of >0.8 corresponds to an area of 5468 deg².

Table 1 lists the properties of the DR4+ SDSS main galaxy sample.

2.1.1. Accounting for the SDSS Fiber Collision

An operational constraint of the SDSS spectroscopic program is that two fibers cannot be placed closer than 55" on a single plate. Overlapping spectroscopic plates compensate partially for the effect. However, ~7% of the target galaxies cannot be spectroscopically observed because of fiber collisions. This observational bias is corrected by assigning to each galaxy that has not been observed the redshift of their nearest neighbor with a spectroscopic SDSS redshift (Blanton et al. 2005).

Although one might be concerned that this simple method could overcorrect and result in too many close galaxy pairs at the same redshift, which would then distort clustering measurements, Zehavi et al. (2005b) demonstrate that this correction procedure works very well. They use ΛCDM N-body simulations and design three galaxy samples and measure the correlation function for three samples: (1) from the full simulated galaxy distribution, (2) from simulated SDSS data including fiber collision losses and not correcting for it, and (3) from simulated SDSS data that correct for the fiber collision by assigning the redshift of their nearest spectroscopic neighbor. They verify that the differences between (1) and (3) are much smaller than the statistical uncertainties down to scales of r_p ∼ 0.1 h⁻¹ Mpc, while (2) underestimates the correlation function at scales r_p < 1 h⁻¹ Mpc. Therefore, we use the same fiber correction procedure for our main galaxy sample. The NYU VAGC10 provides this information through an SDSS fiber collision-corrected galaxy sample.

2.1.2. Construction of the Random Main Galaxy Sample

The random sample is another crucial ingredient required for measuring the correlation function. The purpose is to create a randomly distributed sample of objects that exactly matches all observational biases (window function, redshift distribution, etc.) of the observed sample. We follow the procedure of Paper I (for details see Section 3.1 of Paper I) and generate a set of random R.A. and decl. values within DR7 areas with a spectroscopic completeness ratio of >0.8, populate areas with higher completeness ratios more than areas with lower completeness ratios, smooth the observed redshift distribution by applying a least-square (Savitzky & Golay 1964) low-pass filter, and use this smoothed redshift profile to randomly assign redshifts to the objects in the sample.

The number of objects in a random catalog is chosen to have an adequate number of pairs in the CCF at the smallest scales measured here. For clustering measurements with the main galaxy sample the random catalog contains 100 times as many objects as the observed sample. The random catalog of the DR4+ SDSS main galaxy sample also contains 100 times as many objects in a random catalog as in the observed sample.

\footnote{9 http://sdss.physics.nyu.edu/vagc-dr7/vagc2/kcorrect/kcorrect.nearest.petro.z0.10.fits}

\footnote{10 http://sdss.physics.nyu.edu/vagc-dr7/vagc2/kcorrect/kcorrect.nearest.petro.z0.10.fits}
Table 1

Properties of the SDSS Galaxy Tracer Sets and the AGN Samples

| Sample Name                  | SDSS Geometry | M. log L\(_X\) Range (mag, erg s\(^{-1}\)) | Sample Size | (n) (b\(^3\) Mpc\(^{-3}\)) | (z) | (M. log L\(_X\)) (mag, erg s\(^{-1}\)) |
|------------------------------|---------------|------------------------------------------|-------------|----------------------------|-----|---------------------------------------|
| Main galaxy sample           | DR7           | 0.07 < z < 0.16, −22.1 < M\(_b\) < −21.1 | 68273       | 9.8 × 10\(^{-4}\)    | 0.13 | −21.41                                |
| LRG sample                   | DR7+          | 0.16 < z < 0.36, −23.2 < M\(_b\) < −21.0 | 65802       | 9.8 × 10\(^{-5}\)    | 0.28 | −21.71                                |
| Extended LRG sample          | DR7           | 0.36 < z < 0.50, −23.2 < M\(_b\) < −21.7 | 28781       | 3.9 × 10\(^{-5}\)    | 0.42 | −22.04                                |

**Note:** The selection criteria are described in Section 2.1 of Paper I. Here, we briefly summarize the sample selection. We extract LRGs from the Web-based SDSS Catalog Archive Server Jobs System\(^{11}\) 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 < M\(_b\) < −21.2, where M\(_b\) is based on the extinction-corrected r\(_{petro}\) magnitude.

11 http://casjobs.sdss.org/CasJobs/
to construct the $k$-corrected and passively evolved rest-frame $g_{\text{photo}}$ magnitudes at $z = 0.3$. We consider only LRGs that fall into the SDSS area with a DR7 spectroscopic completeness ratio of $>0.8$ and have a redshift confidence level of $>0.95$. The correction for the SDSS fiber collision in the SDSS LRG sample is slightly different from that for the SDSS main galaxy sample. LRGs exhibit very well-defined spectra dominated by an old stellar population that evolves very slowly. The reduced scatter in the spectral energy distribution (SED) of LRGs results in much lower photometric redshift uncertainties than the estimates for main galaxies, which can have ongoing star formation and therefore have a wider distribution of SEDs. We make use of the precise LRG photometric redshifts to correct for the SDSS fiber collision in the following manner. We select from the SDSS archive all LRGs that pass the pure photometric-based LRG selection criteria. We identify photometric LRGs that are closer than $55''$ to a spectroscopic-observed LRG in our redshift and absolute magnitude range. We then assign a redshift using the following steps: we accept the spectroscopic redshift of the LRG even if its redshift confidence level is $\leq 0.95$. If there is no spectroscopic redshift available for the object, we give the photometric LRG the same redshift as the spectroscopic neighbor LRG (within a $55''$ radius) if

$$|\delta z_{\text{spec,j}} - \delta z_{\text{photo,i}}| \leq \delta z_{\text{photo,i,1r}}.$$

If Equation (1) is not fulfilled, we assume that the photometric redshift of the LRG is the correct redshift. A redshift is assigned only if the object meets the selection criteria to construct a volume-limited sample: $0.16 < z < 0.36$ and $-23.2 < M_{g}^{0.3} < -21.2$. Approximately $2\%$ of the all LRGs in our sample are assigned redshifts. The properties of the sample are shown in Table 1.

The construction of the random catalogs is identical to the procedure described in Section 2.1.2 (for details see Section 3.1 of Paper I), except that the LRG random catalogs contain 200 times as many objects as the real DR7 and DR4+ LRG samples. This is a compromise between the required computation time to calculate the correlation functions and having sufficient counts on the smallest scales to avoid introducing noise. More objects are required at higher redshift for a given sky area to account for the fact that with increasing redshift the same angular distance on the sky corresponds to larger physical co-moving separations.

2.3. Extended SDSS Luminous Red Galaxy Sample

In order to extend our clustering measurements to higher redshifts, we create an "extended SDSS LRG sample" over the redshift range of $0.36 < z < 0.50$. The extraction of the sample and the correction for the SDSS fiber collision problem is identical to the SDSS LRG sample (see Section 2.2). Ideally this sample would also be volume-limited. However, that would require an absolute magnitude cut of $M_{g}^{0.3} = -22.2$ mag, which results in only 6292 objects. Because such a relatively low number of objects would yield a measured ACF with very large uncertainties, we use a non-volume-limited sample with $-23.2 < M_{g}^{0.3} < -21.7$. This is a compromise between making the sample volume-limited and retaining accuracy when computing the ACF and CCFs (see Table 1). We plot the absolute magnitude versus redshift for the 28,781 objects (DR7) in the extended LRG sample in Figure 1.

The co-moving number density for this sample given in Table 1 is computed over the redshift range $0.36 < z < 0.42$ and magnitude range $-23.2 < M_{g}^{0.3} < -21.7$, where the sample is volume-limited. Furthermore, it assumes that there is no number density evolution at higher redshifts ($0.36 < z < 0.42$) and in the range $-23.2 < M_{g}^{0.3} < -21.7$. In principle, we can derive the co-moving number density by integrating the LRG luminosity function. However, the different selection functions for low- and high-redshift LRGs are visible in the upper right corner (cut I and cut II; see Eisenstein et al. 2001).

![Figure 1. Absolute magnitude vs. redshift for the extended SDSS LRG sample (0.36 < z < 0.50). The absolute magnitude is based on the extinction-corrected $g_{\text{photo}}$, magnitude, passively evolved to $z = 0.3$. The different selection criteria for low- and high-redshift LRGs are visible in the upper right corner (cut I and cut II; see Eisenstein et al. 2001).](image_url)
Radio-loud AGNs are known to be more clustered than radio-quiet AGNs and reside in very massive DMHs (e.g., Magliocchetti et al. 2004; Hickox et al. 2009; Mandelbaum et al. 2009). Radio-loud AGNs are also more luminous in the X-rays than radio-quiet AGNs (Wilkes et al. 1994; Krumpe et al. 2010a).

In Paper I, we find an X-ray luminosity dependence in the AGN clustering amplitude. One possible explanation is that the high $L_X$ sample contains more radio-loud AGNs than the low $L_X$ sample, and therefore the relative overabundance of radio-loud AGNs in the high $L_X$ sample is causing the increase of the clustering amplitude. To test this hypothesis, we construct radio-quiet RASS/SDSS AGN samples. Anderson et al. (2003, 2007) list in their table of broad-line RASS/SDSS AGNs if an object is also detected as a radio source. The radio information is taken from the Faint Images of the Radio Sky at Twenty centimeters (FIRST; Becker et al. 1995; White et al. 1997) using the NRAO Very Large Array. We therefore create new AGN subsamples by restricting all samples to the area covered by FIRST and excluding all FIRST-detected sources, and refer to these subsamples as radio-quiet X-ray-selected AGN samples.

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In Tables 1–3, we label these subsamples with the entry “(rq).” Note that our approach is conservative, in that we do not apply the usual radio-to-optical flux density criteria of $R > 10$ (Kellermann et al. 1989). Instead we remove all radio-detected AGNs, which removes more objects than just those that are technically defined as radio-loud. Our definition of radio-quiet is that the AGNs are not detected by FIRST. However, for our goal of removing all radio-loud AGNs from the samples, the chosen procedure is adequate and the loss in a few additional AGNs will not significantly affect the clustering measurements and their uncertainties.

In the redshift range of $0.07 < z < 0.16$, 127 out of 504 objects are classified as radio-quiet RASS/SDSS AGNs and SDSS main galaxies. Since we find no significant difference in the CCF of samples that include or exclude these objects, we use the full sample. No overlap is found between radio-quiet RASS/SDSS AGNs and tracer set objects at higher redshifts.

In Figure 3, we show the distribution of the RASS/SDSS AGNs which are flagged as radio sources by Anderson et al. (2003, 2007), which we remove to create the “radio-quiet” samples. Considering only objects that fall in regions covered
by SDSS and FIRST, 17% of all RASS/SDSS AGN have radio detections in the $0.07 \leq z < 0.16$ range, 10% at $0.16 < z < 0.36$, and 14% at $0.36 < z < 0.50$. We also report the radio-detected AGN fraction in the corresponding lower and higher $l_X$ samples as the percentage values listed in Figure 3.

### 3.1.2. Narrow-line RASS/SDSS AGN Clustering

In order to test narrow-line versus broad-line AGN clustering, we construct X-ray-selected narrow-line AGN samples. In addition to the predominant broad-line AGNs, Anderson et al. (2007) classified ~7% of all RASS/SDSS AGNs as X-ray-emitting AGNs having narrower permitted emission lines. These 515 objects consist of X-ray-emitting AGN subclasses such as narrow-line Seyfert 1 galaxies (NLS1s) (10%), Seyfert 1.5 (29%), Seyfert 1.8 (18%), Seyfert 1.9 galaxies (22%), and Seyfert 2 candidates (21%). In total, 22% of these objects also have a FIRST radio detection. NLS1s, Seyfert 1.5, 1.8, and 1.9 AGNs show a mix of narrow and broad permitted typical AGN line components, while Seyfert 2 candidates have only narrow permitted emission lines. The latter are called candidates because it is well known that a fair fraction of them turn out to be reclassified as NLS1, Seyfert 1.8, or Seyfert 1.9 when re-observed with significantly improved spectroscopy (e.g., Halpern et al. 1999). Seyfert 1.5 and 1.8 galaxies have optical spectra with a broad-line Hβ component (exceeding FWHM values of 2500 km s$^{-1}$) at a very low flux level. For more details about the different narrow-line AGN subclasses in this sample see Anderson et al. (2003, 2007). Figure 4 shows that the narrow-line RASS/SDSS AGNs are mainly identified only at lower redshifts, to $z \sim 0.35$. Therefore, their classification as narrow-line AGNs is based on the permitted Hβ and Hα lines.

The studied narrow-line RASS/SDSS AGNs are found to have, on average, lower observed X-ray luminosities than broad-line RASS/SDSS AGNs. However, the vast majority of broad-line RASS/SDSS AGNs are known to be unabsorbed X-ray sources; therefore, their observed X-ray luminosity is equal to their intrinsic X-ray luminosity. On the other hand, narrow-line RASS/SDSS AGNs may be absorbed AGNs, and their intrinsic X-ray luminosities could be higher than the observed ones given in Figure 4. Consequently, both classes of RASS/SDSS AGN samples may be very similar with respect to intrinsic X-ray luminosity.

Due to ROSAT’s soft energy range of 0.1–2.4 keV, narrow-line RASS/SDSS AGNs can be absorbed only by moderate column densities ($N_H$). We simulate an X-ray spectrum with a photon index of $\Gamma = 2.5$, Galactic absorption of $N_{H, gal} = 2 \times 10^{20}$ cm$^{-2}$, and a typical redshift of $z = 0.15$, in order to estimate which intrinsic $N_H$ values are detectable with ROSAT. Compared to an unabsorbed source, the flux in the 0.1–2.4 keV ROSAT band drops down to 61% when an intrinsic column density of $N_H = 10^{21}$ cm$^{-2}$ is used (21% for $N_H = 10^{22}$ cm$^{-2}$). We conclude that only objects with $N_H \lesssim 10^{22}$ cm$^{-2}$ are detected in the RASS. Most likely the narrow-line RASS/SDSS AGN sample consists mainly of a mixture of unabsorbed and only moderately absorbed (a few $N_H = 10^{20}$ cm$^{-2}$) AGNs.

Although broad-line AGNs have a much lower projected space density than narrow-line AGNs and therefore yield, in general, more reliable identification with the RASS counterpart, Anderson et al. (2003, 2007) successfully demonstrate that the narrow-line RASS/SDSS AGNs are statistically very reliable identifications as well. They estimate that less than 5% of the counterparts are spurious random chance positional coincidences. Convincing evidence derives from the distribution of positional offsets relative to the X-ray positional error and equal area annuli. Furthermore, the observed distribution of the ratios of RASS/SDSS X-ray-to-optical flux matches expectations for typical X-ray-emitting AGNs. For details see Anderson et al. (2003, 2007). We conclude that the narrow-line RASS/SDSS AGNs have a comparable high counterpart reliability as the broad-line RASS/SDSS AGNs.

In the redshift range of $0.07 < z < 0.16$, 31 out of 194 narrow-line RASS/SDSS AGNs are also classified as SDSS main galaxies, while at $0.16 < z < 0.36$ only one object belongs to the narrow-line RASS/SDSS AGN sample and the LRG tracer set. As for the broad-line RASS/SDSS AGNs, we create an SDSS main galaxy sample that does not include galaxies that have been also classified as narrow-line RASS/SDSS AGNs and compute the corresponding CCF. On scales greater than $5 h^{-1}$ Mpc, the pair counts differ by less than 0.1% from the
original CCF. Therefore, the overlap in the samples does not affect the clustering results for the narrow-line RASS/SDSS AGNs.

3.2. Optically Selected SDSS Samples

All of our optically selected SDSS AGNs (called “quasars” in the SDSS literature) are drawn from Schneider et al. (2010) and use the full SDSS survey (DR7). The AGN candidate selection is described in detail in Richards et al. (2002) and can be summarized as follows. The highest priority is given to FIRST-detected optical point sources. Then sources with non-stellar colors in the ugriz photometry data are considered. Objects with photometric redshifts of $z \lesssim 3$ are targeted even if they are spatially resolved. FIRST-detected optical point sources and $z \lesssim 3$ AGN candidates are required to have a Galactic extinction-corrected $i$ magnitude of 19.1. This selection method picks $\sim 18$ objects per square degree which are followed up with the SDSS spectrograph. The resulting “primary” SDSS AGN sample is then supplemented by objects targeted by other SDSS spectroscopic selections (main galaxies, LRGs, RASS, stars, and serendipitous sources) that turned out to be AGNs. In the redshift range of interest (0.07 < $z$ < 0.50), these secondary channels account for $\sim 9\%$ of the total SDSS AGN sample (vast majority from the galaxy target selection). If a significant number of SDSS AGNs from these secondary channels were originally selected from the LRG sample, which is known to be strongly clustered, it could bias the AGN clustering. We verified that there is no overlap between the SDSS AGN and the LRG sample. Therefore, we do not expect any influences on our AGN clustering measurements caused by the secondary selection channel.

Schneider et al. (2010 and references within) have constructed AGN catalogs based on different SDSS data releases. They apply a luminosity selection of $M_i \leq -22$ mag and require that objects have at least one emission line exceeding a FWHM of 1000 km s$^{-1}$. Objects that have a spectrum with only narrow permitted AGN-typical emission lines are removed. The absolute magnitude $M_i$ is computed by using the $i$ point-spread function (PSF) Galactic extinction-corrected magnitude measurement and assuming a typical AGN spectral energy slope.

Historically, quasars are defined as objects at the high end of the AGN luminosity function having $M_B \leq -23$ mag (e.g., Schmidt & Green 1983). $M_i = -22$ mag corresponds to $M_B = -22.4$ mag for a typical AGN at $z = 0$. The Schneider et al. SDSS AGN catalog papers use the $i$ band instead of the $B$ band in part because the $i$-filter is less affected by Galactic absorption. However, a significant disadvantage of this is that the host galaxy light may represent a larger contribution to the total flux then the AGN. AGNs near the $M_i = -22$ mag cut can be equally bright as the host galaxy, e.g., host galaxies at $z \sim 0.4$ with $i = 19.1$ mag (within the detection limit of the SDSS AGN selection method) have $M_i = -22$ mag. Consequently, these AGNs may be less luminous than their quoted optical magnitude. This effect is somewhat mitigated by the use of the PSF photometric data in the AGN selection but should be kept in mind when interpreting our results.

The AGN candidate selection by Richards et al. (2002) has undergone constant modification to improve the efficiency. Schneider et al. (2010, 2007) use the final selection algorithm. AGNs in these catalogs have two spectroscopic target selection flags: BEST (final algorithm) and TARGET (actual algorithm during targeting). BEST uses the latest photometric software and has the highest quality data. The continuous modification of the AGN selection method and the inclusion of AGNs not selected by the standard selection means that the AGN catalogs are not statistically clean samples. The catalog of Schneider et al. (2010) contains 105,783 spectroscopically confirmed AGNs which have luminosities of $M_i \leq -22$, have at least one emission line exceeding an FWHM of 1000 km s$^{-1}$, have highly reliable redshifts, and are fainter than $i \sim 15$. We extract only objects that have a MODE flag of “PRIMARY.” This procedure applies to $99\%$ of all objects and limits our sample to objects that have been spectroscopically followed up based on a target selection and are not blended. We use the BEST flags whenever TARGET and BEST are available. We use optically selected SDSS AGNs in the redshift ranges of the corresponding tracer sets (0.07 < $z$ < 0.16, 0.16 < $z$ < 0.36, 0.36 < $z$ < 0.50). Except for the 0.07 < $z$ < 0.16 AGN sample, where the number of objects is very low, we further subdivide the samples into lower and higher $M_i$ subsamples (see Table 1). The $M_i$ cuts are chosen to yield approximately the same number of objects in the different luminosity subsamples. We use $M_i = -22.4$ for the 0.16 < $z$ < 0.36 sample and $M_i = -22.9$ for the 0.36 < $z$ < 0.50 sample (Figure 5).

In the 0.07 < $z$ < 0.16 redshift range, we find a high overlap between objects derived from the Schneider et al. (2010) AGN sample and the SDSS main galaxy sample. One hundred thirty-three out of 177 SDSS AGNs are also classified as SDSS main galaxies. As with the RASS/SDSS AGNs, we exclude these objects from the SDSS main galaxy sample and compute the CCF. The difference in the CCF occurs only on the larger scales and is less than 1%; therefore the overlap affects the clustering measurements very little. At higher redshifts, there is no overlap between optically selected SDSS AGN samples and SDSS LRGs used as our tracer sets. For the optically selected SDSS AGNs we do not estimate the co-moving number densities in Table 1. Their selection function is very complex and requires a sophisticated modeling method, which is beyond the scope of this paper.

3.2.1. Radio-quiet Optically Selected SDSS AGN Samples

To test the impact of radio-loud AGNs on the clustering signal of optically selected AGN samples, we further exclude FIRST radio-detected objects in the Schneider et al. (2010)
AGN samples. An AGN has a radio detection if its position coincidences with a FIRST catalog entry within 2\arcsec. We restrict all samples to the FIRST area to ensure that no radio-loud AGN is selected for the radio-quiet samples. Then we remove objects that have a measured FIRST radio flux in the AGN catalog. This is the same conservative approach of excluding all FIRST-detected AGNs as we do in Section 3.1.1 for the radio-quiet RASS/SDSS AGN subsamples. Here, we also use our definition of radio-quiet AGN samples for the optically selected AGNs, namely, that radio-to-optical flux density R based on the FIRST is R = 0. We also account for the restriction to the FIRST geometry in the corresponding tracer sets when we derive the ACF of the radio-quiet optically selected AGN samples. The resulting samples are labeled with the subsequent entry “(rq)” in Tables 1–3.

Figure 6 (top panel) shows the distribution of optically selected FIRST-detected AGNs within the larger optically selected AGN sample. A fraction of 44% of the 0.07 < z < 0.16 AGNs, 13% of 0.16 < z < 0.36 AGNs, and 9% of the 0.36 < z < 0.50 AGNs are detected by FIRST (considering only regions that are covered by FIRST and SDSS). The fraction is a sensitive function of redshift, as it depends on luminosity. The higher M∗ subsamples contain more FIRST radio detections (17% in 0.16 < z < 0.36 and 12% in 0.36 < z < 0.50) than the lower M∗ subsamples (8% in 0.16 < z < 0.36 and 5% in 0.36 < z < 0.50). Of the 96 radio-quiet SDSS AGNs in the redshift range 0.07 < z < 0.16, 78 are also classified as SDSS main galaxies.

3.2.2. X-Ray-selected Optical AGN Samples

The large number of X-ray-detected optically selected SDSS AGNs at redshifts above z = 0.16 allows us to test how different selections of AGNs affect the clustering signal of broad-line AGNs. The catalog paper by Schneider et al. (2010) lists for each individual AGN the relevant information if the object has a detection in the RASS faint or bright source catalog. Beside the construction of a radio-quiet optically selected SDSS AGN sample (Section 3.2.1), we create a sample that contains only optically selected broad-line SDSS AGNs that are not detected in RASS. This sample has the subsequent entry “(noX)” in the corresponding tables. Figure 6 (panel (b)) shows the distribution of objects with RASS detections among the optically selected SDSS AGN sample. A fraction of 70% of the optically selected SDSS AGNs are also detected by RASS in the redshift range of 0.07 < z < 0.16. At higher redshifts, RASS detects 32% (0.16 < z < 0.36) and 22% (0.36 < z < 0.50) of the optically selected broad-line SDSS AGNs. This is not surprising, as the low ROSAT sensitivity results in the RASS redshift distribution rising quickly to z ∼ 0.15 and strongly decreasing at higher redshift.

The optical and X-ray luminosities of broad emission line AGNs are known to be strongly correlated, the ratio of which is often expressed by the optical-to-X-ray spectral energy index αox (e.g., Avni & Tananbaum 1986; Green et al. 1995; Steffen et al. 2006; Krumpe et al. 2007; Anderson et al. 2007). Therefore, RASS detects 44% of the AGNs in the higher M∗ sample at 0.16 < z < 0.36 (29% at 0.36 < z < 0.50), but only 24% of the AGNs in the lower M∗ sample at 0.16 < z < 0.36 (17% at 0.36 < z < 0.50).

RASS contains only the highest-flux X-ray-emitting AGNs but has the complementary advantage of detecting lower AGN activity compared to the optically selected broad-line SDSS AGNs. X-ray luminosities of log (Lx/[erg s −1]) > 42 are a clear indicator of AGN activity, while in the optical a strong starlight component from the host galaxy can make it difficult to detect broad-line AGNs. The location of the RASS-detected AGNs in Figure 6 (panel (b)) indicates that RASS extends the detections of broad-line AGNs below the optical cut of M∗ = −22 mag used by Schneider et al. (2010) at z ≲ 0.35.

Furthermore, we also create AGN samples that contain only optically selected SDSS AGNs that are also detected as RASS sources (Figure 6, panel (b)). The samples are labeled with the subsequent entry “(onlyX)” for these objects we have both the X-ray and optical luminosities (Lx, M∗). In general, as expected by the αox connection, high/low M∗ corresponds to high/low Lx. The fraction of FIRST-detected AGNs increases more with M∗ than with Lx.

Finally, we design samples of optically selected SDSS AGNs that are neither FIRST nor RASS detections. These samples only cover the FIRST area. This selection results in 56% of the 0.16 < z < 0.36 and 67% of the 0.36 < z < 0.50 optically selected SDSS AGNs. We refer to these samples by the subsequent entry “(rq+noX).”

4. CLUSTERING ANALYSIS

We measure the two-point correlation function ξ(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. Here, we reiterate the essential elements of our method.

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

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

(2)
where DD(r) is the number of data–data pairs with a separation r, and DR(r) is the number data–random pairs; both pair counts have been normalized by the number density of data and random points. We measure $\xi$ on a two-dimensional grid of separations $r_p$, perpendicular to the line of sight, and $\pi$, along the line of sight, to separate the effects of redshift space distortion due to peculiar velocities along the line of sight. We obtain the projected correlation function $w_p(r_p)$ by integrating $\xi(r_p, \pi)$ along the $\pi$-direction.

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

$$w_p(\text{AGN}|\text{AGN}) = \frac{[w_p(\text{AGN}|\text{TRACE})]^2}{w_p(\text{TRACE}|\text{TRACE})},$$ (3)

where $w_p(\text{AGN}|\text{AGN})$, $w_p(\text{TRACE}|\text{TRACE})$ are the ACFs of the AGN and the corresponding tracer set, respectively, and $w_p(\text{AGN}|\text{TRACE})$ is the CCF of the AGNs with the tracer set. In other words, we assume that the CCF is the geometric mean of two ACFs, which has been verified to be valid by Zehavi et al. (2011, their Appendix A).

The CCF is computed by applying Equation (2)

$$\bar{\xi}_{\text{AGN}--\text{TRACE}} = \frac{D_{\text{AGN}} D_{\text{TRACE}}}{D_{\text{AGN}} R_{\text{TRACE}}} - 1.\quad (4)$$

For our purposes, the use of this simple estimator has several major advantages and results in only a marginal loss in the signal-to-noise ratio when compared to more advanced estimators (e.g., Landy & Szalay 1993). The estimator in Equation (4) requires the generation of a random catalog only for the tracer set. The tracer sets have well-defined selection functions and are, except for the extended LRG sample, volume-limited. Since the random catalog should exactly match all observational biases to minimize the systematic uncertainties, well-understood selection effects are a key to generation proper random samples. The AGN samples suffer from very complex and hard-to-model selection functions. Therefore, a random catalog of X-ray-selected RASS/SDSS AGN is subject to large systematic uncertainties due to the difficulty in accurately modeling the position-dependent sensitivity limit and the variation in the flux limit of the sources (caused by changing Galactic absorption over the sky- and spectrum-dependent corrections). Optically selected SDSS AGNs (see Section 3.2) rely on constantly modified selection algorithms and the acceptance of additional incomplete AGN selection methods. Consequently, the modeling of their selection function for the generation of a random catalog would be very challenging.

The errors in the adjacent bins in correlation measurements 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 as well as the covariance matrix $M_{ij}$, which reflects the degree to which bin $i$ is correlated with bin $j$. The covariance matrix is used to obtain reliable power-law fits to $w_p(r_p)$ by minimizing the correlated $\chi^2$ values. In our jackknife resampling, we divide the survey area into $N_T = 100$ subsection for the DR4+ geometry and 131 subsections for DR7, each of which is $50\text{--}60\text{deg}^2$. These $N_T$ jackknife-resampled correlation functions define the covariance matrix (Equation (5)):

$$M_{ij} = \frac{N_T - 1}{N_T} \sum_{k=1}^{N_T} \left[ w_k(r_{p,i}) - \langle w(r_{p,j}) \rangle \right] \times \left[ w_k(r_{p,j}) - \langle w(r_{p,j}) \rangle \right].$$ (5)

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

The generation of 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 CCF. For each jackknife sample, we calculate the inferred AGN ACF by using Equation (3). 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.

### 4.1. Inferring the AGN Auto-correlation Function

To infer the AGN ACF, we measure the CCF of the AGN sample with the tracer set and the ACF of the tracer set. In both cases we measure $r_p$ in a range of 0.05–40 $h^{-1}$ Mpc in 15 bins in a logarithmic scale. The upper 11 bins are identical with the bins used in Paper I and cover the $r_p$ range of 0.3–40 $h^{-1}$ Mpc. Consequently, we extend the measurements by four additional bins to smaller scales. We compute $\pi$ in steps of 5 $h^{-1}$ Mpc in a range of $\pi = 0–200 h^{-1}$ Mpc. The resulting $\xi(r_p, \pi)$ are shown in Figure 7 for the ACF of the tracer sets and for the CCF of the total AGN samples (X-ray-selected and optically selected) with the corresponding tracer sets.

Although the projected correlation function is computed by integrating over $\pi$ to infinity (see Equations (5) and (11) in Paper I), in practice an upper bound of the integration ($\pi_{\text{max}}$) is used to include most of the correlated pairs, give stable solutions, and suppress the noise introduced by distant, uncorrelated pairs. 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 Paper I, we find that the LRG ACFs (LRG sample and extended LRG sample) saturate at $\pi_{\text{max}} = 80 h^{-1}$ Mpc. All CCFs and the main galaxy sample ACFs saturate at $\pi_{\text{max}} = 40 h^{-1}$ Mpc. In addition, above these values the corresponding correlation lengths do not change by more than $1\sigma$, considering the increased uncertainties with increasing $\pi_{\text{max}}$ values. The use of $\pi_{\text{max}} = 80 h^{-1}$ Mpc for the LRG ACFs and $\pi_{\text{max}} = 40 h^{-1}$ Mpc for the main galaxy ACFs and all CCFs matches the $\pi_{\text{max}}$ values used for these samples by other studies, e.g., Zehavi et al. (2005a, LRG) and Zehavi et al. (2005b, SDSS galaxies). The $w_p(r_p)$ CCFs for the different total AGN samples with the corresponding tracer sets are shown in Figure 8, while the resulting power-law fits for the ACFs and CCFs based on

$$w_p(r_p) = r_p^\gamma \frac{\Gamma(1/2)\Gamma((\gamma - 1)/2)}{\Gamma(\gamma/2)},$$ (6)

where $\Gamma(x)$ is the Gamma function, are listed in Table 2.
Table 2
Power-law Fits to the ACFs of the Tracer Sets and the CCFs of the AGN—Tracer Sets

| Sample                        | Redshift | $r_0$   | Y  |
|-------------------------------|----------|---------|----|
|                               | (h⁻¹ Mpc)|         |    |
| SDSS tracer sets              |          |         |    |
| Main galaxy (DR4+)            | 0.07–0.16| 6.30⁺⁰⁻¹²| 1.85⁺⁰⁻⁰²|
| Main galaxy (DR7)             | 0.07–0.16| 6.27⁺⁰⁻¹²| 1.84⁺⁰⁻⁰²|
| LRG (DR4+)                    | 0.16–0.36| 9.63⁺⁰⁻¹⁴| 1.90⁺⁰⁻⁰³|
| LRG (DR7)                     | 0.16–0.36| 9.54⁺⁰⁻¹³| 1.90⁺⁰⁻⁰²|
| Extended LRG (DR4+)           | 0.36–0.50| 10.90⁺⁰⁻²⁶| 1.91⁺⁰⁻⁰³|
| Extended LRG (DR7)            | 0.36–0.50| 10.87⁺⁰⁻¹⁰| 1.89⁺⁰⁻⁰³|
| Total RASS-AGN                |          | 5.79⁺⁰⁻⁰⁴| 1.84⁺⁰⁻⁰⁵|
| Total SDSS-AGN (rq)           | 0.07–0.16| 5.85⁺⁰⁻¹²| 1.80⁺⁰⁻¹¹|
| Low Lz RASS-AGN               | 0.07–0.16| 5.19⁺⁰⁻⁰⁶| 1.90⁺⁰⁻¹⁰|
| High Lz RASS-AGN              | 0.07–0.16| 6.07⁺⁰⁻⁰⁵| 1.79⁺⁰⁻⁰⁶|
| Low Lz RASS-AGN (rq)          | 0.07–0.16| 5.49⁺⁰⁻⁰⁵| 1.94⁺⁰⁻⁰⁹|
| Low Lz RASS-AGN (rq)          | 0.07–0.16| 6.06⁺⁰⁻⁰⁴| 1.79⁺⁰⁻⁰⁶|
| Narrow-line RASS-AGN          | 0.07–0.16| 4.99⁺⁰⁻⁰⁴| 1.82⁺⁰⁻¹⁰|
| Total RASS-AGN (rq)           | 0.16–0.36| 6.88⁺⁰⁻¹⁷| 1.85⁺⁰⁻⁰⁴|
| Low Lz RASS-AGN               | 0.16–0.36| 7.01⁺⁰⁻¹⁸| 1.80⁺⁰⁻¹⁰|
| Low Lz RASS-AGN (rq)          | 0.16–0.36| 6.2⁺⁻⁰⁻³⁸| 1.82⁺⁰⁻⁰⁷|
| Low Lz RASS-AGN (rq)          | 0.16–0.36| 7.50⁺⁰⁻⁰⁴| 1.90⁺⁰⁻⁰⁷|
| Low Lz RASS-AGN (rq)          | 0.16–0.36| 6.09⁺⁰⁻⁰⁷| 1.85⁺⁰⁻⁰⁷|
| Narrow-line RASS-AGN          | 0.16–0.36| 7.83⁺⁰⁻⁰⁴| 1.94⁺⁰⁻⁰⁸|
| Total RASS-AGN (rq)           | 0.16–0.36| 5.78⁺⁰⁻⁰⁴| 1.79⁺⁰⁻¹⁴|
| Total RASS-AGN(q)             | 0.36–0.50| 6.8⁺⁻⁰⁻⁰⁴| 1.97⁺⁰⁻¹⁰|
| Total RASS-AGN (rq)           | 0.36–0.50| 6.67⁺⁰⁻⁰⁹| 2.08⁺⁰⁻⁰¹|

Optically selected AGN—SDSS AGN

| Sample                        | Redshift | $r_0$   | Y  |
|-------------------------------|----------|---------|----|
|                               | (h⁻¹ Mpc)|         |    |
| Total SDSS-AGN                | 0.07–0.16| 4.93⁺⁰⁻¹⁴| 1.96⁺⁰⁻¹²|
| Total SDSS-AGN (rq)           | 0.07–0.16| 4.70⁺⁰⁻⁰⁵| 2.11⁺⁰⁻¹⁷|
| Total SDSS-AGN                | 0.16–0.36| 6.9₁⁺⁰⁻⁰⁸| 1.91⁺⁰⁻⁰⁴|
| Total SDSS-AGN (rq)           | 0.16–0.36| 6.9₂⁺⁰⁻⁰⁸| 1.91⁺⁰⁻⁰⁴|
| Total SDSS-AGN (noX)          | 0.16–0.36| 6.9₂⁺⁰⁻⁰⁸| 1.91⁺⁰⁻⁰⁴|
| Total SDSS-AGN (rq+noX)       | 0.16–0.36| 6.9₂⁺⁰⁻⁰⁸| 1.91⁺⁰⁻⁰⁴|
| Total SDSS-AGN (onlyX)        | 0.16–0.36| 7.1₁⁺⁰⁻³³| 1.85⁺⁰⁻⁰⁵|
| Low M, SDSS-AGN               | 0.16–0.36| 6.9₁⁺⁰⁻⁰⁵| 1.91⁺⁰⁻⁰⁵|
| High M, SDSS-AGN              | 0.16–0.36| 6.7₉⁺⁰⁻⁰⁵| 1.90⁺⁰⁻⁰⁵|
| Low M, SDSS-AGN (rq)          | 0.16–0.36| 6.8₉⁺⁰⁻⁰⁵| 1.90⁺⁰⁻⁰⁵|
| High M, SDSS-AGN (rq)         | 0.16–0.36| 6.9₁⁺⁰⁻⁰⁵| 1.91⁺⁰⁻⁰⁵|
| Total SDSS-AGN                | 0.36–0.50| 7.₂₁⁺⁰⁻⁰⁵| 1.87⁺⁰⁻⁰⁴|
| Total SDSS-AGN (rq)           | 0.36–0.50| 7.₂₂⁺⁰⁻⁰⁵| 1.87⁺⁰⁻⁰⁴|
| Total SDSS-AGN (noX)          | 0.36–0.50| 7.₂₂⁺⁰⁻⁰⁵| 1.87⁺⁰⁻⁰⁴|
| Total SDSS-AGN (rq+noX)       | 0.36–0.50| 7.₂₂⁺⁰⁻⁰⁵| 1.87⁺⁰⁻⁰⁴|
| Low M, SDSS-AGN               | 0.36–0.50| 7.₁₂⁺⁰⁻⁰⁷| 1.95⁺⁰⁻⁰⁶|
| Low M, SDSS-AGN (rq)          | 0.36–0.50| 7.₁₂⁺⁰⁻⁰⁷| 1.95⁺⁰⁻⁰⁶|
| High M, SDSS-AGN (rq)         | 0.36–0.50| 7.₁₂⁺⁰⁻⁰⁷| 1.95⁺⁰⁻⁰⁶|

Notes. Values of $r_0$ and Y obtained from a power-law fit to $u(r_p)$ over the range $r_p = 0.3–40 h^{-1}$ Mpc for all samples using the full covariance matrix. For the LRG and extended LRG ACFs, we use $\pi_{\text{max}} = 80 h^{-1}$ Mpc, while for all other ACFs and CCFs we use $\pi_{\text{max}} = 40 h^{-1}$ Mpc. See Table 1 for the definition of the samples.

Our values for the ACFs of the tracer sets agree well with measurements from other studies. Using a slightly different magnitude cut of $-22 < M_r < -21$ in the redshift range 0.07 < z < 0.16, Zehavi et al. (2005b) find for the SDSS DR2 main galaxy sample a correlation length of $r_0 = 6.16 \pm 0.17 h^{-1}$ Mpc and a slope of $\gamma = 1.85 \pm 0.03$, fitting over the range $r_p = 0.13–20 h^{-1}$ Mpc. Zehavi et al. (2005a) study the clustering of ~30,000 LRGs with $-23.2 < M_r < -21.2$ and measure $r_0 = 9.80 \pm 0.20 h^{-1}$ Mpc and a slope of $\gamma = 1.94 \pm 0.02$, fitting over the range $r_p = 0.3–30 h^{-1}$ Mpc. Their clustering measurement in a sample of high-luminosity LRGs ($-23.2 < M_r < -21.8$, 0.16 < z < 0.44) yields $r_0 = 11.21 \pm 0.24 h^{-1}$ Mpc and $\gamma = 1.92 \pm 0.03$.

Table 3, we list the redshift range, the median effective redshift of $N_{\text{CFF}}(z)$ for the corresponding AGN samples, the derived best $r_0$ and $Y$ values based on power-law fits, and $r_0$ for a power-law fit with a fixed slope of $\gamma = 1.9$. The data are fitted over the range $r_p = 0.3–15 h^{-1}$ Mpc to be consistent with Paper I. 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: $N_{\text{CFF}}(z) = N_{\text{tracer}}(z) \times N_{\text{AGN}}(z)$.

The clustering strength is commonly expressed in terms of the rms fluctuations within a sphere with a co-moving radius of $8 h^{-1}$ Mpc ($\sigma_{8, \text{AGN}}$; see Equation (13) in Paper I). We derive $\sigma_{8, \text{AGN}}$ from the best-fit parameters of the power-law...
fits. The uncertainties on $\sigma_{\text{AGN}}$ are derived from the $r_0$–versus-$\gamma$ confidence contours of the one-parameter fit based on a correlated $\chi^2 = X_{\text{min}}^2 + 1.0$. Using $\sigma_{\text{AGN}}$, we further derive the bias parameter $b = \sigma_{\text{AGN}}(z)/\sigma(z)$ based on our power-law fits and give these values in column "b(z) PL fits" of Table 3. The parameter $b$ indicates the clustering strength by comparing the observed AGN clustering to that of the underlying mass distribution from linear growth theory (Hamilton 2001), with $\sigma(z) = D(z)\sigma_\odot(z = 0)$, where $D(z) = D_L(z)/D_L(z = 0)$ is the linear growth factor (Section 7.5 in Dodelson 2003). We use $\sigma(z = 0) = 0.8$ (see Section 1). The bias quantifies the amplification factor of the contrast of the object distribution with respect to that of the dark matter density distribution. The uncertainties of $b$ are derived from the standard deviation of $\sigma_{\text{AGN}}$.

Column "b(z) HOD" of Table 3 lists the bias parameter derived using HOD modeling, which is described below in Section 5. 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 ($b_{\text{HOD}}(M_{\text{DMH}}) = b_{\text{HOD}}(M_{\text{DMH}})$) in which the different AGN samples reside, listed in the last column of Table 3.
4.2. Robustness of the Clustering Measurements

In this section, we verify the stability of our result against possible observational biases and systematic effects. As shown in Paper I, the somewhat non-contiguous coverage of the SDSS DR4+ survey does not influence the clustering results significantly, given the uncertainties. For DR7 the situations improve as the SDSS geometry is much more contiguous. We verify that the number of random points is large enough to lead to a high number of pair counts at the smallest scales measured and not introduce noise.

Zehavi et al. (2005b) note that the largest structure detected in SDSS (the Sloan Great Wall) influences the galaxy clustering significantly for samples with $M_r < -21$ and $z < 0.1$. Therefore, we explore this effect on our SDSS main galaxy sample. We measure the ACF for a main galaxy sample that excludes the Sloan Great Wall ($165 < R.A. < 210$ and $-5 < \text{decl.} < 5$). We find a correlation length of $r_0 = 6.35 \pm 0.12$ h$^{-1}$ Mpc and $\gamma = 1.83 \pm 0.02$, which agrees well with the clustering measurements in which the Sloan Great Wall is included (see Table 2). We conclude that our main galaxy ACFs and the CCFs using the main galaxy sample as a tracer set are not affected by this supercluster at $z \sim 0.08$.

For several of the AGN subsamples split by luminosity, we have tested that slightly changing the luminosity cuts by up to $\pm 0.2$ mag (both brighter and fainter) does not significantly change the measured CCFs. The combination of the different tests listed above provides convincing evidence that our results are not significantly influenced by systematic effects and demonstrates their robustness.

5. BIAS FROM THE 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. The results from Paper II show that the linear bias parameters and typical DMH masses derived from the best power-law fits down to $r_p \approx 0.3$ h$^{-1}$ Mpc.
are subject to systematic errors. This is mainly because the power-law fits include scales in the nonlinear regime \( (r_p \lesssim 1.5 \ h^{-1} \text{ Mpc}) \), where the contribution from pairs of objects that belong to the same DMH (the one-halo term) is substantial. In this nonlinear regime the bias–DMH mass relation based on linear theory, in principle, should not be applied. Another, less significant source of systematic error is that even in the linear regime \( (r_p \gtrsim 1.5 \ h^{-1} \text{ Mpc}) \), the underlying matter correlation function deviates from a power law. In order to avoid these issues, Allevato et al. (2011) derive the bias parameters of their AGN samples in the XMM-Newton COSMOS survey by modeling their AGN ACFs at \( r_p \gtrsim 1.5 \ h^{-1} \text{ Mpc} \) with \( b_{\text{AGN}}^{2-h} \), where \( b_{\text{AGN}} \) is the AGN bias parameter and \( \xi_{\text{DM}}^{2-h} \) is the two-halo term of the dark matter correlation function modeled as the Fourier transform of the linear power spectrum.

In this paper, instead, we use the HOD modeling developed in Paper II to derive the bias parameter down to \( r_p \gtrsim 0.7 \ h^{-1} \text{ Mpc} \), instead of limiting ourselves to \( r_p \gtrsim 1.5 \ h^{-1} \text{ Mpc} \). This allows for better constraints on \( b_A \), especially in cases where the two-halo dominated (linear) regime extends below \( r_p \approx 1.5 \ h^{-1} \text{ Mpc} \), and a better treatment of the cases where the one-halo term contribution is still important at \( r_p \gtrsim 1.5 \ h^{-1} \text{ Mpc} \). Thus, in our approach, the main constraints are derived from the two-halo term, while including the one-halo term contribution in the model serves as a first-order perturbation from linear theory.

Paper II discusses the HOD modeling of the CCF between RASS/SDSS AGNs and LRGs at \( 0.16 < z < 0.36 \) for three different models: in model A all AGNs are satellites within the same DMH as the LRGs, while models B and C include different realizations of the cases where central and satellite AGNs are included and explicitly parameterized. See Paper II for details of these models. We repeat this exercise here for the AGN samples used in this paper to derive their bias parameters. The detailed results of the extensive HOD modeling will be presented in a separate paper (T. Miyaji et al. 2012, in preparation), where a number of new improvements in the modeling over that presented in Paper II will be included. In this paper, we follow exactly the method presented in Paper II. Here, we reiterate the main procedure.

1. Determine the central and satellite HODs of the tracer set galaxies \( \langle N_{\text{G},c}(M_h) \rangle \) and \( \langle N_{\text{G},s}(M_h) \rangle \) from their ACF. The space density constraint is additionally used for volume-limited samples (the SDSS main galaxy and the LRG sample).
2. Using the derived tracer set HODs \( \langle N_{\text{A},c}(M_h) \rangle \) and \( \langle N_{\text{A},s}(M_h) \rangle \) and using a parameterized model of the AGN central and satellite HODs \( \langle N_{\text{A},c}(M_h) \rangle \) and \( \langle N_{\text{A},s}(M_h) \rangle \), we fit the measured CCF between the AGN sample and the tracer set to constrain the AGN HODs. Since the galaxy ACFs have much higher statistical accuracy, the uncertainties in the tracer set HODs are negligible compared to the AGN HOD constraints.
3. Derive the bias parameter of the AGN sample using

\[
b_A = \frac{\int b_A(M_h) (N_{\text{A},c}(M_h) \phi(M_h) dM_h)}{\int (N_{\text{A},c}(M_h) \phi(M_h) dM_h), \tag{7}\]

where \( \langle N_{\text{A},c}(M_h) \rangle = \langle N_{\text{A},s}(M_h) \rangle + \langle N_{\text{A},c}(M_h) \rangle \), \( b_A(M_h) \) is the bias of DMHs with a mass \( M_h \), and \( \phi(M_h) \) is the DMH mass function. We use Equation (8) of Sheth et al. (2001) with parameters from Tinker et al. (2005) for \( b_A(M_h) \). The 1σ uncertainties of \( b_A \) corresponds to the \( 1 \times \Delta \chi^2 \leq 1 \) region in the parameter space of the \( \langle N_{\text{A},c}(M_h) \rangle \) model.

5.1. The HODs of the Tracer Sets

5.1.1. SDSS Main Galaxies \( (0.07 < z < 0.16) \)

As explained above in Section 2.1, the tracer set for the low-redshift AGN samples is selected from the SDSS main galaxy sample with an absolute magnitude range of \(-22.1 < M_{r}^{0.1} < -21.1\). The number density of this sample is \((9.77 \pm 0.16) \times 10^{-4} \ h^3 \text{ Mpc}^{-3}\). We use the five-parameter model by Zheng et al. (2007) to represent the central and satellite HODs of our low-redshift tracer set:

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

\[
\langle N_{\text{G},s}(M_h) \rangle = \langle N_{\text{G},c}(M_h) \rangle \left( \frac{M_h - M_0}{M_1'} \right)^{\alpha_s}.
\] (8)

This form involves a step function with a lower mass cutoff \( M_{\text{min}} \) which is smoothed by incorporating the error function (erf) with the width of the cutoff profile \( \sigma_{\log M} \). For the detailed description of the different parameters, see Section 3.2 of Zheng et al. (2007). A limitation of our current fitting software is that it allows a maximum of two simultaneous variable parameters. Thus, we search for acceptable fits in a two-parameter space, while fixing other parameters to reasonable values. We note that, for our current purposes in this paper of obtaining correct \( b_A \) values, which is mainly constrained by the two-halo term, the detail of the HOD is not critical (see discussions below in Section 5.2). A code that searches for the best-fit values and confidence ranges of model parameters in a many-parameter space using the Markov Chain Monte Carlo is under development and will be used in a future paper.

Zheng et al. (2007) perform fits to the full five-parameter space for several luminosity-threshold subsets of the SDSS main galaxy sample. We take advantage of the results of their \( M_r < 21.0 \) sample, which has a similar selection criteria to our SDSS main galaxy sample, and use their results to fix three parameters: \( \log(M_0/[h^{-1} \text{ Mpc}]) = 11.92, \log(M_1'/[h^{-1} \text{ Mpc}]) = 13.94, \) and \( \sigma_{\log M} = 0.39 \). We then search for the best-fit model for our measurement of the SDSS main galaxy ACF in the remaining two parameters \( (\log M_{\text{min}} \text{ and } \alpha_s) \) by minimizing the correlated \( \chi^2 \), taking into account the density constraint (see Equation (18) of Paper II). We find an excellent fit to the data with the best-fit values and 1σ uncertainties of \( \log(M_{\text{min}}/[h^{-1} \text{ Mpc}]) = 12.81 \pm 0.01 \) and \( \alpha_s = 1.16 \pm 0.02 \), with an associated bias parameter of \( b_A = 1.43 \pm 0.01 \). The uncertainties in these values are lower than those in Zheng et al. (2007) as we perform the fit with only two free parameters instead of five. For the fit, we use \( w_{\phi}(r_p) \) measurements in the range \( 0.2 < r_p [h^{-1} \text{ Mpc}] < 40 \).

First, we follow our HOD modeling described in Paper II and exclude data points that fall in the transition region between the one-halo-dominated and two-halo-dominated regimes. In the case of the SDSS main galaxy sample, using scales of \( 0.4 \ g [h^{-1} \text{ Mpc}] \) results in essentially the identical best-fit HOD. The SDSS main galaxy ACF and the best-fit model are shown in Figure 8 (upper left panel).

5.1.2. Luminous Red Galaxies \( (0.16 < z < 0.36) \)

The tracer set in the intermediate redshift range is the LRG sample with \(-23.2 < M_{r}^{0.3} < -22.1\) (Section 2.2). The derivation of central and satellite HODs of this sample is described in detail in Paper II. In summary, we start from
the results of Zheng et al. (2009) and make a two-parameter adjustment to find the HOD that fits best to our LRG ACF, including the number density constraint. For satellite LRGs, we interpolate between the \(\Delta x^2 = 4\) upper and lower bounds of the satellite HOD by Zheng et al. (2009), while for the central LRG HOD we shift their central HOD horizontally along the \(\log M_h\) axis. First, we fit \(w_p(r_p)\) measurements in the 0.2 \(< r_p [h^{-1}\text{Mpc}] < 40\) range. Significant residuals remain in the transition region between the one-halo- and two-halo-term-dominated regimes, due to the fact that our HOD modeling neglects the effects of halo–halo collisions in the two-halo term. Unlike with the main galaxy sample, this effect is not negligible with the LRG sample, due to a larger transition region. We therefore neglect data points in a range of 0.46 \(< r_p [h^{-1}\text{Mpc}] < 2.8\) and find a good fit to the data (Figure 8, middle left panel). The associated LRG bias parameter is \(b_G = 2.20 \pm 0.01\), where this error includes only the statistical 1\(\sigma\) uncertainty of the fit.

5.1.3. Extended LRGs (0.36 \(< z < 0.50\))

Unlike for the cases of the SDSS main galaxy and LRG samples, there is no template HOD model in the literature for a sample with almost identical selection criteria to those for our extended LRG sample, i.e., a non-volume-limited sample of LRGs with \(-23.2 < M_b^{1/3} < -21.7\) at 0.36 \(< z < 0.50\).

The closest sample that we can use as our template is the \(-23.2 < M_b^{1/3} < -21.8\), \(z \sim 0.3\) LRG sample, for which Zheng et al. (2009) made a detailed HOD investigation, in addition to the \(-23.2 < M_b^{1/3} < -21.2\) LRG sample. Thus, we follow the approach in Paper II for the LRG sample and search for the best-fit HOD model of the ACF of our extended LRG sample by adjusting Zheng et al. (2009) HOD results for the \(-23.2 < M_b^{1/3} < -21.8\) LRG sample.

In short, we take the central and satellite HODs from Figure 1(b) of Zheng et al. (2009) and search for the best-fit HOD by tweaking the template. We shift their central HOD horizontally by \(d\) in \(\log M_h\) and interpolate between their upper and lower bounds (\(\Delta x^2\)) of their satellite HOD, with the dividing ratio of \(f:(1-f)\), where \(f = 0\) \((f = 1)\) represents their lower (upper) bound on the satellite HOD (see Paper II for details). We search for the best-fit HOD model in the \((f, d)\) space, where the HOD-model-predicted \(w_p(r_p)\) function is calculated at \(z = 0.42\). As with the LRGs, we exclude the 0.46 \(< r_p [h^{-1}\text{Mpc}] < 2.8\) range from the fit. We fix the best-fit with \(f = 4.2 \pm 0.8\) and \(d = -0.29 \pm 0.04\). We do not use the density constraint in the fit, because the extended LRG sample is not volume-limited and therefore the number density is not accurately determined. However, the best-fit model gives a density of \(4.3 \times 10^{-5} [\text{h}^3 \text{Mpc}^{-3}]\), which is close to the number density of the extended LRGs calculated in the volume-limited portion of the sample (see Table 1).

5.2. AGN Biases and Typical Halo Masses

For the AGN HOD model, we use model B of Paper II, which parameterizes the number of central \((N_{A,c})\) and satellite \((N_{A,s})\) AGNs in a DMH:

\[
\begin{align*}
N_{A,c} &= f_A \Theta(M_h - M_{\text{min}}), \\
N_{A,s} &= f_s \Theta(M_h - M_{\text{min}})(M_h/M_1)^{\alpha_s},
\end{align*}
\]

where \(\Theta(x)\) is the step function (equal to 1 at \(x \geq 0\); 0 at \(x < 0\)) and \(f_A\) represents the AGN fraction (duty cycle) among central galaxies at \(M_h \geq M_{\text{min}}\). We use log \(M_1/M_{\text{min}} = 1.36\)

Equation (9), which Zehavi et al. (2005b) find to be a typical value at which a DMH hosts on average one satellite galaxy in addition to a central galaxy. We model the CCFs between our tracer sets and the AGNs using the same method as in Paper II:

\[
P_{AG,1h}(k) = \frac{1}{2\pi n_A} \int \phi(M_h) \{ N_{A,c} N_{G,s} + N_{A,s} N_{G,c}(M_h) y(k, M_h) + (N_{A,s} N_{G,s}(M_h) [y(k, M_h)]^2) dM_h, \}
\]

and

\[
w_p(r_p) = \int \frac{k}{2\pi} [P_{1h}(k) + P_{2h}(k)] J_0(kr_p) dk,
\]

where \(n_A(\Delta G)\) is the number density of AGNs (tracers), \(y(k, M_h)\) is the Fourier transform of the Navarro–Frenk–White profile (NFW; Navarro et al. 1997), \(P_{1h}(k)\) is the linear power spectrum of the density field with the transfer function by Eisenstein & Hu (1998), and \(J_0(x)\) is the zeroth-order Bessel function of the first kind.

Due to the low space density of AGNs, most CCFs do not have a signal-to-noise ratio on small scales that is sufficient for applying the \(\chi^2\) statistics. While a majority of CCFs contain \(\geq 16\) pairs per bin at \(r_p > 0.3 [h^{-1}\text{Mpc}]\), we have to exclude \(r_p < 0.7 [h^{-1}\text{Mpc}]\) bins for several CCFs in order to have at least 16 AGN–galaxy pairs per bin. To derive \(b_A\) in a consistent way for all CCFs, we use only \(r_p > 0.7 [h^{-1}\text{Mpc}]\) bins to derive column “b(z) HOD” for all of the AGN samples given in Table 3.

Since the purpose of using the HOD modeling in this paper is to derive reliable values of \(b_A\), we do not discuss detailed results using other models, which will presented in T. Miyaji et al. (2012, in preparation). The derived bias parameter, which is mainly constrained by the two-halo term, is not very sensitive to our particular choice of HOD model. To verify this, we repeat the HOD fits to the CCFs with different values of the parameter log \(M_1/M_{\text{min}}\) (Equation (9)). For various SDSS luminosity-threshold galaxy samples, Zehavi et al. (2005b) found the range of this parameter to be \(1.0 \leq \log M_1/M_{\text{min}} \leq 1.5\). Thus, we fix log \(M_1/M_{\text{min}}\) to 1.0, 1.36 (our default), and 1.6 and obtain \(b_A\) values in each case. The best-fit values of \(b_A\) typically vary only by \(\approx 0.01\) among these three cases, demonstrating the robustness of deriving the bias parameter using this method.

5.3. AGN HOD Bias Results

In Figure 9, we present the main results of our study. We show the HOD bias parameter for our different X-ray and optically selected AGN samples as a function of redshift. All AGN samples are consistent with a host DMH mass of log \((M_{DMH}/[h^{-1}\text{Mpc}^3]) = 12.4–13.4\) (see Table 3). Samples in which the radio-loud AGNs have been excluded have very similar clustering amplitudes as the total samples, in all three redshift ranges. The clustering signal of narrow-line RASS/SDSS AGNs at \(0.07 < z < 0.16\) is also very similar to broad-line RASS/SDSS AGNs at the same redshift. Furthermore, weak X-ray luminosity dependences on the broad-line AGN clustering amplitude are found at both \(0.07 < z < 0.16\) and \(0.16 < z < 0.36\).

5.4. Power-law versus HOD-derived Bias Parameters

The various AGN samples studied here allow us to compare the power-law-fit-derived bias parameters with those from HOD
Figures 9 and 10. Comparison between bias parameters derived from power-law fit vs. HOD modeling. We highlight the most important samples at the three redshift ranges: total X-ray-selected RASS/SDSS AGN samples (open triangles) and total optically selected SDSS AGN samples (filled triangles). The $1\sigma$ uncertainties for the different methods are plotted as error bars. The dotted line shows a 1:1 correspondence.

6. DISCUSSION

Our clustering measurements of luminous broad-line AGNs yield three independent data points in the poorly studied low-redshift range for both X-ray-selected and optically selected broad-line AGNs. In addition, we measure the clustering signal of X-ray-detected narrow-line AGNs. We derive the bias parameter of the different samples based on power-law fits and HOD modeling.

6.1. Comparison with X-Ray-selected Broad-line AGN Clustering Measurements

There are no published clustering measurements of X-ray-selected broad-line AGNs with comparable low uncertainties at low redshifts. For example, Mullis et al. (2004) measure the clustering strength of broad-line AGNs in the ROSAT North Ecliptic Pole Survey, for which we derive a bias parameter of $b = 1.83_{-0.61}^{+1.88}$ ($z = 0.22$, Paper I).

At higher redshift, Allevato et al. (2011) compute the clustering strength of X-ray (0.5–2 keV) unabsorbed and absorbed and narrow- and broad-line AGNs in the *XMM-Newton* COSMOS field in different bins where the median redshift of the subsamples varies from $z = 0.5$ to $z = 2.5$. They find that broad-line AGNs reside in DMH of log ($M_{DMH}/[h^{-1} M_\odot]$) $\sim 13.2$, independent of redshift. The average luminosity of their broad-line AGN sample is log ($L_{[0.1–2 keV]/[erg s^{-1}]}$) $\sim 44.1$ (intrinsic absorption-corrected luminosity; V. Allevato 2011, private communication), which corresponds to log ($L_{[0.1–2 keV]/[erg s^{-1}]}$)
Figure 11. Power-law bias parameter $b_{\text{AGN}} = \sigma_{b,\text{AGN}}(z)/\sigma_D(z)$ as a function of redshift for various X-ray-selected and optically selected AGN samples as well as blue and red galaxies. We plot our power-law fit bias parameters to compare different studies in a consistent manner. Black open symbols represent X-ray-selected AGN samples, while black filled symbols represent optically selected AGN samples. Clustering measurements for red and blue galaxies are shown as red and blue symbols at different redshifts. For the explanation of the dotted lines see Figure 9. For visualization purposes, we slightly offset the redshifts of the X-ray-selected and optically selected SDSS AGN samples.

(A color version of this figure is available in the online journal.)
X-ray-selected and optically selected AGNs at similar luminosities at low redshifts. Figure 11 compares our AGN clustering results to other X-ray-selected and optically selected AGN clustering studies. The properties of various clustering studies are given in Table 4 of Paper I. Hickox et al. (2009) study the clustering properties of AGNs in the AGES survey. As they publish only the AGN CCFs with galaxies, we use their best power-law fits (R. Hickox 2011, private communication) to infer their AGN ACF and the bias parameter, following our approach described in Section 4.1. From the redshift distributions presented in Hickox et al. (2009), we compute the effective median redshift for the CCFs (z_eff = 0.37) and derive a bias value of b <RM09 = 1.20^{+0.09}_{−0.08}.

Our finding of detecting no significant difference in the AGN clustering properties between X-ray-selected and optically selected AGNs at low redshifts may appear to be in contrast to AGN clustering measurements at higher redshifts (z > 0.7), where optically selected AGN samples have a lower clustering strength than X-ray-selected AGN samples (Figure 11). Furthermore, the clustering of X-ray-selected AGNs is roughly consistent with red galaxies at higher redshifts. However, some of the X-ray clustering studies significantly underestimate their uncertainties by using Poisson errors instead of jackknife errors. Moreover, X-ray-selected and optically selected AGN samples at these redshifts select AGNs with different intrinsic properties. While the optical AGNs are mainly drawn from large sky area surveys and sample luminous predominantly broad-line AGNs, the X-ray-selected AGN samples derive from very deep observations covering only a few square degrees on the sky. Consequently, the X-ray-selected AGNs have, on average, much lower luminosities. Additionally, the X-ray samples include absorbed AGNs, which results in a large fraction of narrow-line AGNs that are missed in the optical AGN samples at these redshifts.

6.3. Broad-line versus Narrow-line AGNs

The differences in the clustering signals between X-ray-selected and optically selected AGN samples at z > 0.7 can potentially be accounted for either because of a large luminosity difference between the samples or the large fraction of X-ray absorbed, optically narrow-line AGNs in the X-ray AGN samples.

To test the latter assumption, we measure the clustering properties of narrow-line RASS/SDSS AGNs classified by Anderson et al. (2007) in the redshift ranges of 0.07 < z < 0.16 and 0.16 < z < 0.36. The low number density of narrow-line RASS/SDSS AGNs at 0.16 < z < 0.36 forces us to use scales of r_p > 1.1 h^{-1} Mpc to apply the χ^2-statistics during the HOD modeling. The clustering strength of the narrow-line and total broad-line RASS/SDSS AGN samples at 0.07 < z < 0.16 agree well with each other (Table 3), although the uncertainty for the narrow-line AGN sample is large. The power-law fit bias parameter for the narrow-line RASS/SDSS AGN sample is significantly lower than the bias derived from the HOD model (see Figure 9) and would suggest a significantly lower clustering amplitude than the broad-line RASS/SDSS AGN sample. This is caused by differences between the samples on small scales where the one-halo term dominates. The power-law fits use these small scales, while the HOD modeling mainly relies on the two-halo term to determine the large-scale clustering.

At 0.16 < z < 0.36, the narrow-line AGN HOD bias parameter is too poorly constrained (b = 1.01^{+0.24}_{−0.17}) to allow for a detailed interpretation. While we cannot determine whether narrow-line RASS/SDSS AGNs cluster similarly or less than broad-line AGNs in that redshift range, we can rule out the conclusion that they are significantly more clustered. Two important points are worth noting: first, as ROSAT can detect only moderately X-ray-absorbed AGNs (log (N_{H}/cm^2) ≤ 22), while XMM-Newton and Chandra are sensitive to much more absorbed (and lower luminosity) AGNs, the narrow-line AGNs detected by RASS may not be as common. Second, the relative clustering strength of narrow-line AGNs could change with redshift if there is a difference in how AGN activity is triggered at different cosmological epochs. However, other studies confirm that low-redshift narrow-line (radio-quiet) AGNs are not strongly clustered and are hosted in galaxies that do not differ significantly from typical non-AGN galaxies (e.g., Mandelbaum et al. 2009; Li et al. 2006).

Allevato et al. (2011) find that X-ray-selected narrow-line AGNs in the XMM-Newton COSMOS field cluster slightly lower (2.3σ) than X-ray-selected broad-line AGNs and reside in DMVs of log (M_DM/h^{-1} M_{⊙}) ~ 13.0 in the redshift range z ~ 0.5–1.0. However, their narrow-line AGNs have an average intrinsic (absorption-corrected) log (L_{2-10 keV}/erg s^{-1}) = 43.1 (V. Allevato 2011, private communication), which is an order of magnitude lower than the average luminosity of their broad-line AGNs. When Allevato et al. (2011) consider only the X-ray properties of the sources to create X-ray-absorbed and X-ray-unabsorbed subsamples, in which both have an almost identical mean luminosity of log (L_{2-10 keV}/erg s^{-1}) ~ 43.65, they find that X-ray-absorbed AGNs cluster slightly less (2.6σ) than X-ray-unabsorbed AGNs.

To summarize, the difference between the AGN clustering properties between X-ray-selected and optically selected AGN samples at z > 0.7 is likely not due to a strongly clustered population of narrow-line AGNs in the X-ray samples. However, these objects do have significantly lower luminosities than optically selected broad-line AGNs.

6.4. Impact of Radio-loud Broad-line AGNs on the Clustering Signal

For each of the various broad-line AGN samples studied here, we create subsamples where we have excluded radio-detected AGNs to study the impact of radio-loud AGNs on the derived clustering strength. We do not find any significant differences between the AGN samples that include or exclude radio-detected AGNs. The HOD bias parameters for these samples agree well within their 1σ uncertainties in all three redshift ranges studied (see Figure 9). However, the samples are similar as only approximately 10%–20% of all broad-line AGNs have also radio (FIRST) detections, so this result may not be particularly constraining.

As mentioned in Section 3.2, the SDSS AGN target selection gives the highest priority to point sources that are detected in FIRST (above a certain flux limit) without considering their colors. We select all AGNs (n = 187) with 0.16 < z < 0.36 which have the SDSS FIRST target selection flag equal to 1. Hence, these objects were only selected on the basis of having a significant FIRST radio flux and can be understood as a well-defined radio-selected AGN sample ([z] = 0.28, ⟨M⟩ = −23.28). We compute the CCF of this AGN sample with the LRG tracer set. Due to the low number of AGNs in this sample, the HOD bias parameter has large uncertainties, with a value of b = 1.45^{+0.40}_{−0.26}. A sample of all 423 SDSS AGNs that have a radio detection (including the 187 radio-selected SDSS AGNs;
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**Figure 12.** Power-law bias vs. redshift (similar to Figure 9), comparing the clustering of differently selected AGN samples (radio and non-radio samples) and galaxies. Note that the HOD model bias parameter for the narrow-line RASS/SDSS AGN sample is significant higher ($b = 1.24^{+0.18}_{-0.19}$) than the power-law bias shown here.

(A color version of this figure is available in the online journal.)

\( z = 0.27, (M_i = -22.84) \) yields \( b = 0.97^{+0.18}_{-0.19} \). Furthermore, we compute the CCF of only the RASS/SDSS AGNs with \( 0.16 < z < 0.36 \) that are marked as radio sources in Anderson et al. (2007). The sample, which contains 144 objects and has \( (z = 0.25 \) and \( \log (L_{0.1-2.4kev} / [\text{erg s}^{-1}] ) \sim 44.36 \), yields an HOD bias parameter of \( b = 1.08^{+0.30}_{-0.32} \). No constraining results can be drawn by using only radio-detected SDSS AGN samples because these samples contain too few objects. However, all values are consistent with the clustering strengths of the other AGN samples in the same redshift range.

Many previous studies (e.g., Magliocchetti et al. 2004; Hickox et al. 2009; Mandelbaum et al. 2009) found that radio-loud AGNs cluster more strongly than AGNs without the presence of radio emission. At first glance our results may appear to be in contrast to these findings. However, those studies focus on the clustering properties of optical narrow-line (instead of broad-line) AGNs based on diagnostic emission-line ratios and radio luminosity. Moreover, when comparing the clustering strength of different samples it is essential to take into account the involved luminosities. Figure 12 shows the bias of various AGN and galaxy samples at lower redshift \( z \leq 0.6 \), focusing on comparing radio-selected AGN samples. For the radio (non-broad-line) AGN sample of Hickox et al. (2009), we derive a bias value of \( b_{\text{radio, 609}} = 2.07^{+0.14}_{-0.13} \) (\( z_{\text{eff}} = 0.47 \)) by following the description given in Section 6.2.

Magliocchetti et al. (2004) find that radio (FIRST) galaxies with AGN activity cluster more strongly than both radio-detected 2dFGRS galaxies without AGN activity and 2dFGRS galaxies without radio emission. It is not clear, however, whether the different galaxy samples have similar luminosities and colors. If the galaxy samples that are used for comparison are mainly blue, star-forming galaxies, one would expect a significant difference in the clustering strength based on the different host galaxy properties. Consequently, the clustering difference could reflect not by AGN activity but host galaxy type. The high bias parameter for radio-loud AGNs \( b = 2.07^{+0.14}_{-0.13} \) and moderate bias \( b = 1.20^{+0.09}_{-0.07} \) for X-ray-selected AGNs in Hickox et al. (2009) can also be explained by the different host galaxy populations (see their Figure 9).

Mandelbaum et al. (2009) compare the clustering strength of optically selected narrow-line AGNs \( (0.01 < z < 0.3 \) and \( -23 < M_i^{0.1} < -17 \)) with and without radio emission at fixed stellar mass, i.e., at fixed luminosity and color. They find that at fixed stellar mass radio-loud narrow-line AGNs cluster more strongly and hence reside in more massive DMHs than narrow-line AGNs without radio emission and galaxies without the presence of AGN activity (see Figure 12). Neither Magliocchetti et al. (2004) nor Mandelbaum et al. (2009) detect a difference in the clustering properties within the radio-loud narrow-line AGN sample as a function of radio luminosity.

Shen et al. (2009) compute the ACF of optical SDSS DR5 AGNs (from the Schneider et al. 2007 sample) in the redshift range \( 0.4 \lesssim z \lesssim 2.5 \). As we do here, they divide their samples into FIRST-detected and -undetected sources. Their fits (over the range \( 3-115 \) Mpc) suffer large uncertainties; therefore, they fix the slope of the power-law fit for all samples to \( y = 2 \). They compute the ACF of the FIRST-undetected SDSS AGNs. When they compare this result to the CCF between FIRST-detected and -undetected SDSS AGNs, they find a 2.5σ difference in \( r_0 \), only using the diagonal elements of the covariance matrix. Fixing the slope and not using the full covariance matrix likely increases the systematic uncertainties in their results. By contrast, our measurements test a much narrower redshift range, use the full covariance matrix, allow free \( r_0 \) and \( y \) values for the power-law fits, and use the HOD modeling approach. Shen et al. (2009) test much brighter AGN samples at higher redshifts than our samples here. The fact that they find a difference in the clustering of radio-detected versus non-detected AGNs and we do not may be a consequence of the samples having different luminosities or redshifts.

If broad-line AGNs at \( z < 0.5 \) indeed have no clustering dependence on radio emission, this may suggest that different physical mechanisms trigger radio emission in broad-line and narrow-line AGNs, as narrow-line AGNs do have a clustering dependence with radio emission (Mandelbaum et al. 2009) at fixed stellar mass. This would be somewhat surprising as significant radio emission in all AGNs is believed to be related to jet phenomena (e.g., Blandford & Payne 1982).

### 6.5. Luminosity Dependence of the Clustering Signal

In Papers I and II, we reported a possible X-ray luminosity dependence in the AGN clustering strength of RASS/SDSS AGNs in the redshift range \( 0.16 < z < 0.36 \) (see also Figure 9, green and yellow green symbols). The exclusion of radio-detected RASS/SDSS AGNs performed here tests whether the weak \( L_X \)-dependence of AGN clustering observed is due to the presence of radio-loud AGNs in the higher \( L_X \) sample (see Section 3.1.1).

As shown in Paper II, this luminosity-dependent clustering is more significant in the one-halo term than in the two-halo term. Using only larger scales of \( r_p > 0.7 \) Mpc for the HOD modeling in this paper (in order to derive bias parameter in a consistent way for all AGN samples) increases the error on the individual measurements. This results in a decrease in the significance of the luminosity-dependent clustering. We find that the 1.5σ (2.0σ using the power-law bias of this paper) clustering difference between the lower and higher \( L_X \) AGN samples remains roughly constant when we exclude radio-detected AGNs from both subsamples (1.7σ using the HOD bias; 2.4σ using the power-law bias of this paper).

The difference in the clustering strength of the lower and higher \( L_X \) RASS/SDSS AGN samples in the redshift range of
$0.07 < z < 0.16$ is $1.2\sigma$ (HOD model). The error bars on the bias of these samples are high, due to the low number of objects. The significance of the individual redshift measurements do not provide strong evidence for an X-ray luminosity dependence of the AGN clustering strength.

Other studies find similar weak trends at low redshifts (Figure 12). Cappelluti et al. (2010) compute the clustering signal for the Swift/Burst Alert Telescope 15–55 keV selected AGNs and find a clustering difference of $1.6\sigma$ for the higher $L_X$ AGNs relative to the lower $L_X$ AGNs. Comparing the photometric galaxy density around spectroscopic SDSS AGNs, Serber et al. (2006) and Strand et al. (2008) find that higher luminosity AGNs have more overdense galaxy environments compared to lower luminosity AGNs at scales smaller than 0.5 Mpc. These studies are not directly measuring AGN clustering; rather, they focus on the immediate environments of AGNs.

We do not detect an optical luminosity dependence of the SDSS AGN clustering. Given the large sample size and low resulting errors in these samples, this is a constraining result. Previous clustering measurements of optically selected AGNs using the 2dF QSO Redshift Survey (2QZ; Boyle et al. 2000), 2dF-SDSS LRG and QSO (2SLAQ; Cannon et al. 2006), and SDSS also find little evidence for an optical luminosity dependence of the AGN clustering strength (e.g., Croom et al. 2002; da Ângela et al. 2008; Mountrichas et al. 2009). Mountrichas et al. (2009) use CCFs between AGNs and LRGs and find some indication that bright SDSS AGNs cluster less than faint 2SLAQ QSOs, although the result is only marginally significant ($1.6\sigma$). On the other hand, Shen et al. (2009) detect a stronger clustering strength for the $10\%$ most luminous SDSS DR5 AGNs ($0.4 < z < 2.5$) at the $\sim2\sigma$ level. However, they caution that the dynamical range in luminosity probed is narrow and the sample size in the luminosity subsamples is not large enough to yield constraining clustering measurements. Porciani & Norberg (2006) suggest that a luminosity dependence of the clustering may be more evident at $z > 1.3$, while da Ângela et al. (2008) find hints that the lower redshift ranges ($z < 1.3$) may show more dependence with luminosity.

The optical and X-ray luminosities of broad-line AGNs are connected via the optical-to-X-ray spectral index, which measures the ratio of the rest-frame luminosity density at 2500 Å to 2 keV. Although the relation has some scatter (see Anderson et al. 2007 for the optical-to-X-ray spectral index for RASS/SDSS AGNs), more X-ray luminous AGNs are, on average, also intrinsically brighter in the optical. If indeed there is a weak X-ray luminosity dependence of the AGN clustering strength, the very narrow $M_r$ range that the optical SDSS AGNs span would hamper a detection. Identifying AGN activity using X-ray emission allows us to identify low-luminosity AGNs, where the optical light is dominated by the host galaxy. This results in a wider luminosity range in X-ray emission than in the optical (Figure 6, lower panel) in the two lowest redshift ranges. At $0.16 < z < 0.36$, the mean optical luminosity of the high $M_r$ SDSS AGN sample is only a factor of 2 higher (0.75 mag) than the low $M_r$ SDSS AGN sample, while the X-ray luminosities between the high and low $L_X$ samples differ by a factor of 4.4. This is also seen when considering the luminosity difference between the 90th percentile in the high-luminosity samples and the 10th percentile in the low-luminosity samples (factor $f = 4.3$ for optical SDSS AGNs, $f = 17.8$ for RASS/SDSS AGNs) and covered luminosity range ($f = 30$ for optical SDSS AGNs, $f = 310$ for RASS/SDSS AGNs).

Hence, to detect a possible optical luminosity dependence in the broad-line AGN clustering strength, as might be expected if there is a weak X-ray luminosity dependence, considering the optical-to-X-ray luminosity relation, a wider optical luminosity range has to be tested. As these samples already include the brightest objects, this is only possible if one can include lower optical luminosities where broad-line AGNs are not effectively selected due to an increase in the host galaxy starlight fraction. Only much deeper surveys at larger redshifts may yield the dynamical range to test the luminosity dependence for optically selected broad-line AGNs.

The possible X-ray luminosity dependence of broad-line AGN clustering detected at low redshifts (in that more X-ray luminous AGNs are more clustered than less X-ray luminous AGNs) may be difficult to reconcile with the result that, on average, low-luminosity (mainly narrow-line) X-ray-selected AGNs at higher redshifts are more clustered than luminous optically selected broad-line AGNs (see figure 11). If the X-ray luminosity dependence is real, this may suggest that different physical processes trigger AGN activity at different cosmological times or at different luminosities.

6.6. Current Picture of AGN Clustering

Although AGN clustering measurements are currently not as constraining and the interpretation of the results is not as clear as for galaxy clustering measurements, some general findings have emerged in the last few years.

At low redshifts ($z < 0.5$), broad- and narrow-line AGNs cluster similarly to inactive galaxies, occupying DMH masses of $\log (M_{DMH}/h^{-1} M_\odot) \sim 12.0–13.5$. This DMH mass range includes cases where the DMH is dominated by one $L^*$ galaxy or a small galaxy group composed of multiple such galaxies (Zehavi et al. 2005b, 2011).

Independent of the selection method, the clustering strength of broad-line AGNs does not significantly change, while narrow-line AGNs show a significant increase in the clustering amplitude when radio-selected narrow-line AGNs are studied. Finally, more X-ray luminous broad-line AGNs may cluster more strongly than their lower luminosity counterparts. Although the various AGN samples have different luminosities, radio-loud, optically selected narrow-line AGNs, very luminous X-ray AGNs, and red galaxies reside in somewhat similar high DMH masses. Lower luminosity X-ray AGNs, optical narrow-line AGNs with no radio emission, and blue galaxies tend to be found in lower DMH masses.

At high redshifts ($z \gtrsim 0.7$), X-ray-selected AGN samples appear to cluster more strongly than optically selected AGNs. The reason for this remains unclear. Possibly either low-luminosity or narrow-line (X-ray-absorbed) AGNs cluster more strongly than very luminous broad-line optical AGNs. Additionally, as some of the X-ray clustering studies significantly underestimate their systematic uncertainties it may turn out that these measurements are consistent with optical AGN clustering measurements. More high-$z$ AGN clustering measurements based on larger samples are needed to gain a clearer picture.

In this paper, we use AGN samples based on SDSS. In the very near future there is not another planned survey that includes photometry and a dedicated extensive spectroscopic follow-up program for AGNs over such large areas as that covered by SDSS. As both large co-moving volumes and spectroscopic redshifts are essential for precise AGN clustering measurements, major improvement in our X-ray-selected and optically selected low-redshift AGNs are therefore not expected in the very near
future. BOSS (Eisenstein et al. 2011) and BigBOSS (Schlegel et al. 2011) will detect high-redshift AGNs at $z \sim 2.2$, which will improve AGN clustering measurements at higher redshifts.

In the coming years, the ROSAT successor eROSITA (Predehl et al. 2007) will perform an all-sky survey in the hard and soft X-rays, probing much fainter than RASS, which is expected to detect up to $\sim 3$ million AGNs. Additionally, the Large Synoptic Survey Telescope (LSST; Ivezić et al. 2008) is expected to identify $\sim 2$ million AGNs in optical bands. eROSITA and LSST have the potential to significantly improve AGN clustering measurements at low and high redshifts, though only if there are dedicated large spectroscopic follow-up programs.

7. CONCLUSIONS

This work presents AGN clustering measurements at low redshifts in three independent redshift ranges: $0.07 < z < 0.16$, $0.16 < z < 0.36$, and $0.36 < z < 0.50$. Extending the use of the cross-correlation method of Krumpe et al. (2010b), we infer the auto-correlation for both X-ray-selected RASS and optically selected SDSS broad-line AGNs. As tracer sets we use SDSS main galaxies, SDSS LRGs, and very LRGs (extended LRG sample). We apply the HOD model method (Miyaji et al. 2011) directly to the measured CCFs to derive the bias parameter. We study the impact of different AGN selections on the clustering signal of broad-line AGNs, i.e., by excluding radio-detected AGNs. Furthermore, we compute the clustering strength for RASS-selected narrow-line AGNs.

We find no statistically convincing difference in the clustering of X-ray-selected and optically selected broad-line SDSS AGNs at low redshifts ($z < 0.5$). Different AGN selections based on either X-ray (RASS), optical (SDSS), or radio (FIRST), and combinations of these, do not significantly change the clustering signal for broad-line AGNs. This appears to be in contrast to other studies that find stronger clustering for radio-loud AGNs (e.g., Mandelbaum et al. 2009). However, these results are based on narrow-line, low-luminosity AGNs, while our sample consists of more luminous broad-line AGNs. For the X-ray-selected broad-line RASS/SDSS AGNs, we find HOD bias values of $1.23^{+0.09}_{-0.08}$, $1.30^{+0.09}_{-0.08}$, and $1.02^{+0.14}_{-0.09}$ in the redshift ranges $0.07 < z < 0.16$, $0.16 < z < 0.36$, and $0.36 < z < 0.50$, respectively, while the HOD bias values for the optically selected broad-line SDSS AGNs are $0.95^{+0.17}_{-0.10}$, $1.29^{+0.05}_{-0.05}$, and $1.33^{+0.07}_{-0.08}$, respectively. The corresponding inferred typical DMH masses hosting our broad-line AGNs are in the range of $\log \left( \frac{M_{\text{DMH}}}{h^{-1} M_\odot} \right)$ ~ $12.5$–$13.2$ and are consistent with those occupied by $L^*$ galaxies at these redshifts.

We measure the clustering of RASS-selected narrow-line AGNs, which consists of a mix of NLS1s, Seyfert 1.5, 1.8, 1.9, and Seyfert 2 candidates. We do not find a significantly lower clustering amplitude of RASS narrow-line AGNs compared to broad-line AGNs, although these measurements are subject to large uncertainties. In addition, we rule out that RASS narrow-line AGNs cluster significantly more strongly than broad-line AGNs at low redshifts.

We show that the exclusion of radio-detected RASS/SDSS AGNs in $0.16 < z < 0.36$ does not change the weak X-ray luminosity dependence of the AGN clustering strength that we find in Paper I (in that higher $L_X$ AGNs cluster more strongly than lower $L_X$ AGNs at $\sim 2\sigma$). We do not detect an optical luminosity dependence of the broad-line AGN clustering in the same redshift range, though this result is not particularly constraining due to the narrow $M_r$ range that is covered.

We derive the bias parameter based on the best power-law fit, the standard method used in literature, as well as by using HOD modeling. Important differences between the two techniques are found for some AGN samples. In particular, using a power-law fit can underestimate the bias compared to HOD modeling. We show that HOD model bias parameters are more reliable and more accurately reflect the large-scale clustering strength. Larger AGN samples will be provided by future missions such as eROSITA. As these samples will have lower statistical uncertainties, HOD model bias parameters should be used to avoid introducing systematic errors that could exceed the statistical errors and thus possibly lead to a misinterpretation of clustering measurements.

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