Properties of Galaxies around AGNs with Most Massive Supermassive Black Hole Revealed by the Clustering Analysis

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ABSTRACT

We present results of the clustering analysis between active galactic nuclei (AGNs) and galaxies at redshift 0.1–1.0 for investigating properties of galaxies associated with the AGNs, revealing the nature of fueling mechanism of supermassive black holes (SMBHs). We used 7916 SDSS AGNs/QSOs for which virial masses of individual SMBHs were measured, and divided them into four mass groups. Cross-correlation analysis was performed to reconfirm our previous result that cross-correlation length increases with SMBH mass $M_{\text{BH}}$; we obtained consistent results. The dark matter halo mass for each mass group was measured as $\sim 10^{13.1} h^{-1} M_\odot$ for $M_{\text{BH}} = 10^{7.5} – 10^{8.2} M_\odot$ and $\sim 10^{14.0} h^{-1} M_\odot$ for $M_{\text{BH}} = 10^9 – 10^{10} M_\odot$. The averaged color and luminosity distributions of galaxies around the AGNs/QSOs were also derived for each mass group. The galaxy color $D_{\text{opt–IR}}$ was estimated for SED constructed from a merged SDSS and UKIDSS catalog. The distributions of color and luminosity were derived by the subtraction method, which does not require redshift information of galaxies. The main results of this work are: (1) dark matter halo mass increases by one order of magnitude from...
the lower mass group to the highest mass group; (2) the environment around AGNs with the most massive SMBH ($M_{\text{BH}} > 10^9 M_\odot$) is dominated by red sequence galaxies; (3) marginal indication of decline in luminosity function at dimmer side of $M_{\text{IR}} > -19.5$ is found for galaxies around AGNs with $M_{\text{BH}} = 10^{8.2} - 10^9 M_\odot$ and nearest redshift group ($z = 0.1 - 0.3$). These results indicate that AGNs with the most massive SMBHs reside in haloes where large fraction of galaxies have been transited to the red sequence probably due to the AGN feedback in each galaxy. The accretion of hot halo gas can be the most plausible mechanism to fuel the SMBHs above $\sim 10^9 M_\odot$.

Subject headings: astronomical databases: miscellaneous, galaxies: active, large-scale structure of universe, quasars: general, virtual observatory tools

1. Introduction

There are a lot of observational evidences that a Supermassive Black Hole (hereafter SMBH) is located in the center of all but the smallest galaxies (Richstone et al. 1998). Although the evolution mechanism of SMBH is still not well known, a recent growing evidence suggests that there is a strong link between the growth of SMBH and the star formation in the host galaxy. One of the observational evidence is the similarity between the evolutions of black hole accretion rate and the star formation rate of galaxies (e.g., Madau et al. 1996; Boyle et al. 1998; Ueda et al. 2003; Zheng et al. 2009). Another important evidence is the correlation between mass of the SMBH ($M_{\text{BH}}$) and mass ($M_b$) / velocity dispersion ($\sigma$) of the bulge component of its host galaxy (Magorrian et al. 1998; Ferrarese & Merritt 2000; Gebhardt et al. 2000; Ho 2007). These relations indicate that BHs and bulges coevolve by regulating each other’s growth.

According to the theoretical works (e.g., King 2014), mass of a SMBH can be regulated by its own outflow from an active galactic nucleus (AGN) in a way that the interstellar gas is expelled far away from the host galaxy once $M_{\text{BH}}$ reaches to the critical mass given by the $M_{\text{BH}}$-$\sigma$ relation. As a result both the star formation in the bulge and mass accretion onto the SMBH are terminated. Therefore understanding the evolution mechanism of SMBHs and AGN phenomenon is crucial to shed light on the evolution of galaxies.

The most important open questions are the nature of the fueling of SMBHs and triggering mechanisms of AGNs. The following three modes have been proposed for transferring gas onto the center of galaxy (e.g., Croton et al. 2006; Lagos et al. 2008; Keres et al. 2009; Panidaki et al. 2013): First one is a secular mode which arise through internal dynamical processes in the disk such as a bar instability or external processes of galaxy interactions. Most of AGNs with lower luminosity are believed to be caused by this mode (e.g., Pentericci et al. 2013; Sabater et al. 2013).

Second one is a merger mode in which gravitational torques induced by galaxy-galaxy ma-
JOR/Minor mergers drive inflows of cold gas toward the center of galaxies, triggering the central starbursts and also accretion on to the SMBH, i.e. AGN (e.g., Hopkins et al. 2008). This mode can be the major mechanism for the most luminous AGNs, i.e. QSOs.

There has been an observational evidence that AGN activity is enhanced for close companion galaxies which are assumed to be undergoing early stage of interaction (Silverman et al. 2011). However, the fraction of such close pairs is only $\sim 18\%$, and visual inspection of HST image revealed that $\sim 85\%$ of AGN host galaxies show no strong distortions on their morphologies (Cisternas et al. 2011). Thus galaxy interaction including major merger cannot be the only mechanism for fueling SMBHs, at least for AGNs with moderate luminosity sampled by Silverman et al. (2011) and Cisternas et al. (2011). Kaviraj (2014) analyzed SDSS data to probe the role of minor mergers in driving stellar mass and BH growth in galaxies, and suggest that around half of the star formation activity is triggered by the minor-merger process.

Third one is a hot halo mode which is characterized by quiescent accretion of gas from the hot halo (Keres et al. 2009; Fanidiakis et al. 2013). In this mode the accretion rate is lower than the other two modes. However it can be the most effective accretion in a massive dark matter halo with $M_h > 10^{12.5} \, M_\odot$, as the accretion by the other two modes is inhibited due to AGN feedback. Thus SMBHs in massive haloes with $M_h > 10^{12.5} \, M_\odot$ are expected to evolve through the hot halo mode, and the corresponding mass of SMBH is $> 10^9 \, M_\odot$ (Fanidiakis et al. 2013b). Due to the lower accretion rate, the expected AGN luminosity in this mode is typically lower than those of the other two modes.

Kauffmann et al. (2009) observationally found that there are two distinct modes in BH growth. One is associated with galaxy bulges that are undergoing significant star formation, and the other is associated with those with little or no on-going star formation. The former one could be related with the star formation induced by secular and/or merger mode, and the latter with the hot halo mode.

The mass of dark matter halo in which SMBH resides can be estimated through the large-scale environments. As an estimator of large-scale environments, cross-correlation length and/or a bias parameter are usually used. The absolute bias of AGNs distribution relative to that of the dark matter can be derived from the observed two point correlation function, which is then used to estimate mass of the dark matter halo.

Ross et al. (2009) performed correlation analysis for SDSS QSOs with redshift from 0.3 to 2.2, and obtained a result that the QSOs inhabit dark matter haloes of constant mass of $\sim 2 \times 10^{12} h^{-1} M_\odot$ at any redshifts. Combining this observational result with the theoretical work by Fanidiakis et al. (2013), the optical AGNs/QSOs are expected to be mostly powered by either secular or merger mode. It is also inferred that they appear only in the dark matter halo of which the mass does not exceed a critical mass that is determined by the AGN feedback.

Hickox et al. (2009) analyzed the data of radio, X-ray, and IR detected AGN samples, and found that the corresponding masses of dark matter haloes are $\sim 10^{13.5} h^{-1} M_\odot$, $\sim 10^{13.9} h^{-1} M_\odot$,
and $\sim 10^{12.0}h^{-1}M_\odot$, respectively. Krumpe et al. (2012) also derived the halo mass for the X-ray selected ROSAT AGNs and the optically selected SDSS AGNs, and they obtained $\sim 10^{13.2}M_\odot$ and $\sim 10^{12.7}M_\odot$, respectively. The larger halo mass for the radio and X-ray AGNs may indicate that they are powered through the hot halo mode. Many other studies on clustering and/or environment of AGNs/QSOs have been reported elsewhere (e.g., Croom et al. 2005; Coil et al. 2009; Silverman et al. 2009; Donoso et al. 2010; Allevato et al. 2011; Bradshaw et al. 2011; Shaohua et al. 2013; Georgakakis et al. 2014).

As shown here, the large-scale environment can provide a clue to the nature of fueling mechanism of SMBHs, and it especially reflect intrinsic properties such as BH mass rather than temporal properties such as AGN luminosity. Shen et al. (2011) studied the dependence of quasar clustering on luminosity, mass of SMBH, quasar color, and radio loudness. They did not find significant dependence on either luminosity, mass, or color, while they marginally found that the most luminous and most massive QSOs are more strongly clustered than the remainder of the sample at $\sim 2$ sigma level, and radio-loud QSOs are more strongly clustered than radio-quiet QSOs.

To investigate the relation between the environment and intrinsic properties of AGNs with better accuracy, we have developed a clustering analysis method which does not require measurements of galaxy redshift and thus can utilize all the galaxies detected in the imaging data (Shirasaki et al. 2011; Komiya et al. 2013). Komiya et al. (2013) examined dependence of AGN-galaxy clustering on BH mass, and found an indication of an increasing trend of cross-correlation length above $10^{8.2}M_\odot$.

In this paper, following the result of Komiya et al. (2013), we study the properties of galaxies around AGNs and its dependence on BH mass by combining optical and near infrared dataset of SDSS and UKIDSS survey. It is expected that, if the increase of clustering strength for AGNs with higher BH mass is due to the prominence of hot halo mode, most of the galaxies around the AGNs are in red sequence since they reside in haloes where gas cooling and star formation have been shut off by AGN feedback.

Throughout this paper, we assume a cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $h = 0.7$ and $\sigma_8 = 0.8$. All magnitudes are given in the AB system. All the distances are measured in comoving coordinates. The correlation length is presented in unit of $h^{-1}\text{Mpc}$.

2. Datasets

2.1. AGNs

The AGN samples were extracted from two AGN properties catalogs created by Shen et al. (2011) and Greene et al. (2007a). These catalog contains virial mass estimates of SMBHs, which were measured from the FWHM of an emission line and continuum flux density. We examined systematic difference of the mass estimates between the two catalogs by extracting AGNs which are contained in both of the catalogs. As shown in Figure 1, the mass estimates of Greene et al.
MG07 is relatively lower than the estimates of Shen et al. (2011) by 0.5 dex. We therefore calibrated MG07 with MS11 using the following formula:

\[ M'_{G07} = \frac{M_{G07} - 1.06}{0.806}. \]  

We used \( M'_{G07} \) as mass estimates of AGNs which are included only in the catalog of Greene et al. (2007a). For the other AGNs, we used \( M_{S11} \) as their mass estimates.

In this work the range of redshift is restricted to 0.1–1.0, and mass of SMBH is restricted to the range of \( 10^{6.5}–10^{10} M_\odot \). The redshift and mass distributions of AGNs used in this work are shown in Figures 2 and 4. The AGN samples from Greene et al. (2007a) mostly comprise lower redshift and lower mass samples. All the samples are divided into nine groups shown in Figure 2 and sample selection is applied following the criteria described in section 2.3. The samples outside of the nine groups are not used in this work. The number of analyzed AGNs is 959 from Greene et al. (2007a), 6957 from Shen et al. (2011), and 7916 in total.

### 2.2. Galaxies

The galaxy samples were retrieved from Virtual Observatory (VO) services of SDSS DR8 (Aihara et al. 2011) and UKIDSS DR9 LAS catalog. The UKIDSS project is defined in Lawrence et al. (2007). The data retrieval and creation of the merged catalog were performed for each AGN. The JVO command line tool (jc client 1) was used to automate the data retrieval. The following criteria are used to retrieve the galaxy sample: For SDSS catalog data of which resolveStatus attribute equals to 257 or 258, which corresponds to select unique objects, are retrieved. For UKIDSS LAS catalog data of which mergedClass attribute equals to 1 or −3, which corresponds to select objects flagged as “Galaxy” or “Probable galaxy”, are retrieved. For both catalog data within 1 degree from the AGN coordinates are retrieved. Photometric magnitude used in this work is an aperture magnitude in 2 arcsec diameter for both SDSS and UKIDSS.

The two catalogs were merged into a single one. In creating the merged catalog, UKIDSS objects detected in the K band data were used as a reference, and a nearest neighbor was selected from the SDSS catalog within 2 arcsec distance for each UKIDSS object. The UKIDSS objects for which SDSS counterpart was not found were preserved in the merged catalog, while the SDSS objects which were not selected as a counterpart were not included in the merged catalog. Thus our galaxy samples are K-band selected ones.

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1 [http://jvo.nao.ac.jp/jc_clinet/](http://jvo.nao.ac.jp/jc_clinet/)
2.3. Data selection

Data selection was applied to the AGN datasets to ensure their quality as follows: at first, coverage of the SDSS and UKIDSS galaxy samples were investigated. The region around the AGN was divided into small areas of $100'' \times 100''$. The number of galaxies was counted for every small areas, and the area of zero count was taken as a dead region. The dead regions correspond to the region where the survey was not conducted or the region masked in source extraction to avoid bright star or for some other reasons. We found that some of the UKIDSS galaxy samples were spurious events caused by cosmic rays or bright stars. The area that contains the spurious events was identified by looking for a high density region in the count map of the samples detected in the K-band and not detected in SDSS. Those areas were taken as dead regions as well. The fractions of the dead region were calculated as a function of projected distance from the AGN position with 0.2 Mpc bin width. If the fraction exceeds 0.2 at a projected distance less than 5 Mpc, the AGN dataset was removed from the samples. Otherwise the fractions are used to correct the effective area in deriving the number density of galaxies.

Next we examined the uniformity of the galaxy number density around AGN. Since the number of galaxies associated with the AGNs is much smaller than the total number of background/foreground galaxies, a flat distribution is expected for the number density as a function of distance from AGN. If there exist a cluster/group of galaxies or stars in front of the AGN field, it can produce strong fluctuation in the distribution of number density. Inhomogeneity of the depth of observations can also produce discontinuous density distribution.

To reduce the effect producing a false signal, we calculated three parameters, $\chi^2$, $\sigma_{\text{max}}$, and $B_{\text{QG}}$, and they were used to filter the datasets showing non-uniformity in number density. The parameter $\chi^2$ is a square sum of the deviation from a flat distribution, and the parameter $\sigma_{\text{max}}$ is a maximum deviation from the average density calculated at a distance range from 2 to 5 Mpc. The adapted criteria are $\chi^2/(n-1) \leq 3.0$ and $\sigma_{\text{max}} \leq 5$, where $n$ is the number of data points in the galaxy number density distribution. $B_{\text{QG}}$ was calculated as (Longair & Seldner 1979),

$$B_{\text{QG}} = \frac{3 - \gamma}{2\pi} \frac{N_{\text{total}} - N_{\text{bg}}}{\rho_0},$$

where $N_{\text{total}}$ is the total number of galaxies at projected distance less than 1 Mpc from AGN, $N_{\text{bg}}$ is the expected number of background/foreground galaxies which are not associated with the AGN and is estimated from the number density at $r_p = 3.0-5.0$ Mpc, $\rho_0$ is the average number density of observed galaxy at the AGN redshift. This parameter is usually used to estimate the clustering strength, but here it is used to remove datasets showing extraordinary large positive/negative excess density around AGNs. The criterion adapted is $-10000 \leq B_{\text{QG}} \leq 10000$. Only two samples were discarded with this selection.

To maximize the signal-to-noise ratio, we removed datasets of shallow observations based on the parameter $\rho_0$, which is an average number density of galaxies at the AGN redshift; $\rho_0$ is calculated from the luminosity function which is parametrized as a function of redshift $z$ and rest-frame
wavelength $\lambda$ as discussed in Komiya et al. (2013). We adapted a criteria of $\rho_0 \geq 10^{-4}$ Mpc$^{-3}$.

The total number of AGN datasets that have passed above criteria is 7916 out of the original number of 9944. About 20% of datasets are discarded. Among the 7916 samples, $\sim$82% of the samples overlap with the Komiya et al. (2013) samples.

3. Analysis Method

3.1. Correlation length

The analysis method used for calculating the AGN-galaxy cross-correlation function is completely the same as that used in Komiya et al. (2013), which is briefly described here.

The cross-correlation function of AGNs and galaxies $\xi(r)$ can be expressed as an excess in number density of galaxies $\rho(r)$ relative to the average density $\rho_0$ at the AGN redshift,

$$\xi(r) = \frac{\rho(r)}{\rho_0} - 1,$$

where $r$ represents the distance from an AGN. We assume the power-law form for the cross-correlation function,

$$\xi(r) = \left(\frac{r}{r_0}\right)^{-\gamma},$$

where $r_0$ is the correlation length and $\gamma$ is the power-law index fixed to 1.8, which is a canonical value measured by many other clustering study of galaxies and QSOs. The projected cross-correlation function $\omega(r_p)$ is calculated by integrating Equation (3) as

$$\omega(r_p) = 2 \int_0^{\infty} \xi(r, \pi)d\pi = 2 \int_{r_p}^{\infty} \frac{r\xi(r)}{\sqrt{r^2 - r_p^2}}dr = r_p \frac{r_0}{r_p} \frac{\Gamma(\frac{1}{2}) \Gamma(\frac{\gamma - 1}{2})}{\Gamma(\frac{\gamma}{2})},$$

where $\pi$ and $r_p$ are distance along and perpendicular to the line of sight, respectively, and $\Gamma$ is the gamma function. $\omega(r_p)$ can be derived observationally from the surface density of galaxies $n(r_p)$ as

$$\omega(r_p) = \frac{n(r_p) - n_{bg}}{\rho_0},$$

where $n_{bg}$ represents the surface density of background/foreground galaxies which are unassociated with the corresponding AGN. From Equations (5) and (6), the surface density of galaxies around an AGN can be modeled as

$$n(r_p) = C(\gamma) \cdot \rho_0 \cdot r_p \left(\frac{r_0}{r_p}\right)^\gamma + n_{bg},$$

where the term of the gamma function is represented by $C(\gamma)$. Fitting this model function to the observed surface density, we can obtain the best estimates of $r_0$ and $n_{bg}$. As already mentioned, $\gamma$
is fixed to 1.8 and $\rho_0$ is calculated from the empirical formula of galaxy luminosity function. Since the clustering signal is too weak to obtain meaningful parameter values for each AGN dataset, we applied the fitting to the average of $n(r_p)$ and $\rho_0$ for a given AGN group.

The uncertainty of $r_0$ is calculated as the square root of the square sum of the systematic error derived from the uncertainty of $\rho_0$ discussed in Komiya et al. (2013) and one sigma statistical error. It should be noted that the cross-correlation length obtained by this method is not a simple average for the AGN group, but an average weighted with $\rho_0$. Thus the result is biased to the low-$z$ AGN samples.

### 3.2. Dark matter halo mass

The mass $M_h$ of the dark matter halo where AGNs reside can be derived from the cross-correlation length between AGNs and galaxies as follows: Assuming linear bias, the autocorrelation function of AGNs $\xi_{AA}$ is related with the cross-correlation function between AGNs and galaxies $\xi_{AG}$ in the form,

$$\xi_{AA} = \frac{\xi_{AG}^2}{\xi_{GG}}, \quad (8)$$

where $\xi_{GG}$ is the autocorrelation function of galaxies. The autocorrelation function of SDSS galaxies measured by Zehavi et al. (2005) is $\xi_{GG} = (r/r_{GG})^{-\gamma}$ with $\gamma \sim 1.8$ and the galaxy autocorrelation length of $r_{GG} \sim 5 \: h^{-1} \text{Mpc}$. Thus, in case $\gamma$ of $\xi_{AG}$ and $\xi_{AA}$ are the same, $\xi_{AA}$ can be simply expressed as:

$$\xi_{AA} = \left(\frac{r}{r_{AA}}\right)^{-\gamma}, \quad (9)$$

where AGN autocorrelation length $r_{AA} = r_0^2/r_{GG}$.

The linear bias of AGNs $b$ is calculated as (Koutoulidis et al. 2013):

$$b = \frac{\sigma_{8,\text{AGN}}}{\sigma_{8,\text{DM}}}, \quad (10)$$

where $\sigma_{8,\text{AGN}}$ and $\sigma_{8,\text{DM}}$ is the rms fluctuations of the AGN and dark matter density distribution within spheres of a comoving radius of $8 \: h^{-1} \text{Mpc}$, respectively. $\sigma_{8,\text{AGN}}$ is given by

$$\sigma_{8,\text{AGN}} = J_2(\gamma)^{1/2} \left(\frac{r_{AA}}{8}\right)^{\gamma/2}, \quad (11)$$

$$J_2(\gamma) = \frac{72}{(3-\gamma)(4-\gamma)(6-\gamma)2^{\gamma}}, \quad (12)$$

and $\sigma_{8,\text{DM}}$ is

$$\sigma_{8,\text{DM}} = \sigma_8 \frac{D(z)}{D(0)}, \quad (13)$$

where $D(z)$ is the linear growth factor given as,

$$D(z) = \frac{5\Omega_m E(z)}{2} \int_z^{\infty} \frac{1 + y}{E^3(y)}dy, \quad (14)$$
\[ E(z)^2 = \Omega_m (1 + z)^3 + \Omega_\Lambda \]  

Using Equations (10), (11) and (13), bias is calculated from the AGN autocorrelation length as:

\[ b = \left( \frac{r AA}{8} \right)^{\gamma/2} J_{\gamma} \left( \frac{\sigma_8 D(z)}{D(0)} \right)^{-1} \]  

The relation between dark matter halo mass and bias parameter is derived by Sheth et al. (2001) as:

\[ b = 1 + \frac{1}{\sqrt{a \delta_{sc}(z)}} \left[ \sqrt{a\nu^2} + \sqrt{ab(\nu^2)^{1-c}} - \frac{(\nu 2)^c}{(\nu^2)^c + b(1-c)(1-c/2)} \right] \]  

where, \( a = 0.707 \), \( b = 0.5 \), \( c = 0.6 \), \( \nu = \delta_{sc}(z)/\sigma(M_h) \), \( \delta_{sc}(z) \) is a critical over density required for collapse in spherical model and given by:

\[ \delta_{sc}(z) = \frac{0.15(12\pi)^{2/3}\Omega(z)^p}{D(z)} \]  

\[ \Omega(z) = \frac{\Omega_m (1 + z)^3}{\Omega_\Lambda + \Omega_m (1 + z)^3} \]  

where \( p = 0.0055 \). \( \sigma(M_h) \) is rms density fluctuation of dark matter halo with mass \( M_h \), and is given by van den Bosch (2002):

\[ \sigma(M_h) = \sigma_8 \frac{f(u)}{f(u_8)} \]  

where \( u_8 = 32\Gamma \) with \( \Gamma = 0.173 \),

\[ u = 3.804 \times 10^{-4}\Gamma \left( \frac{M_h}{\Omega_m} \right)^{1/3} \]  

\[ f(u) = 64.087(1 + 1.074u^{0.3} - 1.581u^{0.4} + 0.954u^{0.5} - 0.185u^{0.6})^{-10} \]  

Thus the mass of dark matter halo can be estimated by using Equation (17) from the AGN bias parameter.

### 3.3. Red galaxy fraction and luminosity distribution

Using the UKIDSS/SDSS merged catalog obtained as described in section 2.2, color of each galaxy was calculated by performing the SED fitting. The SED fitting was performed by using EAZY software developed by Brammer et al. (2008). As we are interested only in the galaxies associated with the AGNs, the redshift was fixed to the AGN redshift in the SED fitting. Photometric redshift was not used since the expected error can be large and does not improve the statistics significantly. Instead of using the photometric redshift, we adapted filtering based on \( \chi^2 \) of the SED fitting to remove galaxies located at redshifts different from those of AGNs.
A color estimator $D_{\text{opt-IR}}$ is defined as

$$D_{\text{opt-IR}} = m_{\text{opt}} - m_{\text{IR}},$$

where $m_{\text{opt}}$ and $m_{\text{IR}}$ are magnitudes at wavelength range 3,000–3,500 Å and 10,000–12,000 Å in the rest frame, respectively. In this analysis, we used only the galaxy samples which were detected both in UKIDSS and SDSS and for which the reduced $\chi^2$ of the SED fitting is less than a given limit.

The $D_{\text{opt-IR}}$ distribution for galaxies associated with the AGNs can be derived by the subtraction method. $D_{\text{opt-IR}}$ distributions averaged over every AGNs in a group are calculated at a central and an offset region of AGN field. We defined the central region as the region within 1 Mpc from the AGN, and defined the offset region as an annulus region at a distance of 3 to 5 Mpc. Since most of the galaxy samples at the offset region are located at redshifts different from that of AGN, it can be regarded as background galaxies. By subtracting distribution at offset region from that at central region, we can obtain the $D_{\text{opt-IR}}$ distribution for galaxies associated with the AGNs.

The reduced $\chi^2$ of the SED fitting for galaxies at the offset region tends to be larger than that of galaxies at the central region, since the fitting is performed by assuming incorrect redshifts. We determined the limit of the reduced $\chi^2$ for selecting galaxies, by comparing the distributions for central and offset galaxies. We set the limit to 4.5 for $z < 0.6$, and 2.0 for $z \geq 0.6$.

In Figure 5, we show the distribution of $D_{\text{opt-IR}}$ derived from all the AGN samples. The bimodality of galaxy color distribution is clearly seen. In the same figure, the color distributions for blue and red galaxies are deconvolved by assuming normal distribution. The peak values of the color distribution for blue and red galaxies are 3.1 and 4.2, respectively. We derive the red galaxy fraction for each AGN group by fitting the color distribution to the model function given with the sum of the two normal distributions.

The luminosity distribution can be derived with the same method as that used for the color distribution described above. The absolute magnitude was calculated by $m_{\text{IR}} - DM(z)$, where $DM(z)$ is the distance modulus at redshift $z$. In Figure 6 we show the color-magnitude diagram obtained for all the AGN samples by the subtraction method. The red sequence and blue cloud are clearly seen. Red sequence galaxies are concentrated in a upper right region ($M < -20$ and $D_{\text{opt-IR}} > 3.5$), while blue cloud galaxies are widely spread in the dimmer part.

4. Results

4.1. Cross-correlation

All the AGN samples are divided into nine redshift-mass groups as shown in Figure 2. Redshift is divided into three ranges 0.1–0.3, 0.3–0.6 and 0.6–1.0. We designate them as $z1$, $z2$, and $z3$, respectively. BH mass is divided into four ranges $\log (M_{\text{BH}}/M_\odot) = 6.5–7.5$, 7.5–8.2, 8.2–9.0, 9.0–
10.0, and they are designated as M65, M75, M82, and M90, respectively. Hereafter we call, for an example, a group of redshift range of 0.1–0.3 and mass range of 6.5–7.5 as M65-z1.

The results obtained by fitting the model function of Equation (7) to the observed average number densities are summarized in the first part of Table 1. In Figure 7, the cross-correlation length $r_0$ obtained for each redshift-mass group is plotted as a function of $M_{\text{BH}}$. The result shows that there is a tendency that $r_0$ increases with $M_{\text{BH}}$, while there is no clear redshift dependence.

The AGN samples are combined for the same mass groups and all the redshift groups, then $r_0$ is calculated for the combined mass groups. The projected number densities for these samples are shown in Figure 8, and the derived cross-correlation lengths are plotted in Figure 9. The difference of $r_0$ between M75 and M90 groups is about three sigma including the systematic errors. For comparison the results obtained in the previous work (Komiyama et al. 2013) are also plotted. They are consistent with the results of this work.

The dark matter halo mass $M_h$ is estimated from the cross-correlation length assuming that the autocorrelation function of the galaxies is expressed by the power-law form with correlation length $r_{\text{GG}} = 5h^{-1}\text{Mpc}$ and index $\gamma = 1.8$. These parameters are obtained for local galaxies at redshift 0.02 and 0.162 (Zehavi et al. 2005). The detailed method is described in section 3.2. We obtained $\log (M_h/[h^{-1} M_\odot]) = 13.59^{+0.31}_{-0.34}, 13.22^{+0.42}_{-0.44}, 14.10^{+0.32}_{-0.29}, 14.64^{+0.30}_{-0.28}$ for mass group M65, M75, M82 and M90, respectively. We also derive $M_h$ assuming the autocorrelation length of galaxies is the same as that of AGNs. Since the cross-correlation is performed at a small distance range (<5 Mpc), it is expected that AGNs and the most of the galaxies cross-correlated with them are located in the same dark matter halo. It is, therefore, natural to assume the same autocorrelation length. We obtained $\log (M_h/[h^{-1} M_\odot]) = 13.23^{+0.20}_{-0.20}, 13.05^{+0.23}_{-0.22}, 13.60^{+0.20}_{-0.18}, 13.95^{+0.21}_{-0.18}$ for mass group M65, M75, M82 and M90, respectively. These results are summarized in Table 2 and plotted in Figure 10.

As is inferred from the mass-redshift distribution shown in Figure 2, even for the same redshift group the higher mass groups tends to be biased to higher redshift. To reduce the redshift bias, we constructed redshift matched samples for each redshift group, and calculated $r_0$ for the samples. The tolerance of the redshift is taken to be 0.02. The result is shown in Figure 11 and summarized in the middle part of Table 1. Although the statistical errors are larger and there is a data point which deviates by $\sim$ two sigma from the others data points around $\log (M_{\text{BH}}/ M_\odot) \sim 8.5$, the tendency of increase of $r_0$ as a function $M_{\text{BH}}$ is again seen in this figure.

The data point of M82-z2 which shows slightly lower than the data points of M82-z1 and M82-z3 is suffered by relatively larger intrinsic fluctuation of clustering strength among the samples. To see such an effect, we divided the samples of M82-z2 into five groups, each of which has 275 samples and the same redshift distribution, and performed the cross-correlation analysis separately. We obtained cross-correlation lengths of 4.82, 5.74, 6.75, 8.23, and 8.30 $h^{-1}\text{Mpc}$ for each group. The standard deviation is 1.53 $h^{-1}\text{Mpc}$. In the same way, we also divided the M82-z3 (M82-z1) samples into five (three) groups, and calculated the cross-correlation lengths. The standard deviations for the M82-z3 and M82-z1 groups are 0.84 $h^{-1}\text{Mpc}$ and 0.47 $h^{-1}\text{Mpc}$, respectively. Thus the intrinsic
fluctuation of clustering strength among M82-z2 samples are relative larger than those of M82-z3 and M82-z1. Taking into account the intrinsic fluctuation the deviation of the data point of M82-z2 in Figure 11 from the other points at the same mass group is only $\sim$ one sigma.

To see the redshift dependence of $r_0$ for the same $M_{BH}$, we constructed mass matched samples with tolerance of 0.2 dex for each mass group and calculated $r_0$ for the samples. The results are shown in Figure 12 and summarized in the last part of Table 1. No clear redshift dependence is seen for any mass group.

These results are consistent with our previous result in Komiya et al. (2013), although we have used the most recent UKIDSS catalog and slightly different data selection criteria and mass correction.

4.2. Properties of Galaxies

To investigate the properties of galaxies at environment of AGNs with the most massive SMBHs, where increase of clustering is found, we calculated the color parameter $D_{\text{opt-IR}}$ for all the detected galaxies and derived its distributions for galaxies associated with the AGNs by using the subtraction method described in section 3.3. $D_{\text{opt-IR}}$ parameter corresponds to the color defined as difference in brightness between the wavelength ranges of 3,000–3,500 Å and 10,000–12,000 Å in the rest frame. In Figure 13 we show $D_{\text{opt-IR}}$ parameter distributions for each redshift and mass sample. The observed distributions are fitted with a two component model (red and blue galaxy components) assuming the normal distribution for both components. The mean and standard deviation of the distribution of each component are fixed to the predetermined values, and only the mixing ratio and the normalization constant are taken as free parameters. The predetermined values of the mean and standard deviation are obtained for each redshift range by fitting the model function to observations corresponding to the samples combined for the whole mass range with taking all the parameters free. The parameter values obtained from this fitting are summarized in Table 3.

The fractions of red galaxies are plotted in the left panel of Figure 14 as a function of $M_{BH}$. The normalized excess densities $\omega'$, which are defined as $\omega' = (n_{\text{on}} - n_{\text{off}})/\rho_0$, are plotted in the right panel of the figure. $n_{\text{on}}$ and $n_{\text{off}}$ are the surface number density of galaxies at projected distance of 0–1Mpc (on region) and 3–5Mpc (off region) from AGN, respectively. The $\omega'$ can be considered as an approximate estimate of the projected cross-correlation function. Since red galaxies are typically brighter than blue galaxies as seen in Figure 6, the observed red galaxy fraction tends to be higher for the higher redshift samples. Thus, the comparison of the red galaxy fraction is meaningful only for the same redshift samples.

At redshift $z1$, both of the red galaxy fraction and the normalized excess density are almost unchanged among the the mass groups of M65, M75 and M82. At redshift $z2$, significant increase of the normalized excess density is seen for the red galaxies of the mass group M90. At redshift $z3$,
blue galaxies are hardly detected and red fraction is \( \sim 100\% \) for mass groups M82 and M90.

The data samples used in Figures 13 and 14 have a slight difference in the redshift distribution among the respective mass groups even for the same redshift groups; the lower mass group has relatively smaller redshift than the higher mass group. The red fraction of the higher mass group, therefore, can be biased to higher value. To reduce the effect of redshift bias, the same analysis was performed also for the redshift matched samples.

The distributions of \( D_{\text{opt-IR}} \) for the redshift matched samples are shown in Figure 15. Since the statistics of lower mass groups are poor, the two lower mass groups are combined. The obtained red galaxy fractions and normalized excess density are plotted as a function of \( M_{\text{BH}} \) in Figure 16. These results also show that red galaxy becomes the dominant component in the higher mass group.

To see the relative difference of luminosity function of galaxies around SMBHs with lower and higher mass, absolute magnitude distributions are compared in Figure 17. They are obtained by using the subtraction method described in section 3.3. In this comparison, redshift matched samples are used so that both of the samples have the same sensitivity on the detection of galaxies. To check the equivalence among the samples in term of the sensitivity of observations, the distributions of \( \rho_0 \) are compared in Figure 18. We found that they are consistent with each other.

The left panel of Figure 17 shows the comparison between the AGN groups of M65+M75 and M82 for redshift range of \( z_1 \), and the ratio (high mass/low mass) of the magnitude distributions is shown in the bottom of the panel. Since the lower mass samples has smaller excess density than the higher mass sample, we combined two lower mass samples to increase the statistics. The red histogram is the distribution of absolute magnitude for higher mass sample, and the blue histogram is for lower mass sample. The absolute magnitude is estimated at wavelength range of 1–1.2 Å in the rest frame by fitting model SED to the observed one using the EAZY code as described in section 3.3. The ratio is peaked around \(-20.25\) mag, and it shows a steep decline at dimmer side. The significance of the depletion of galaxies in the M82-z1 group against (M65+M75)-z1 is \( \sim 2 \) sigma at magnitude range from \(-19.5\) to \(-17.5\) mag. The dashed line on the ratio plot is a power law function fitted to the observations at brighter side below \(-19.5\) mag. The best fit value of the power law index is \(-0.13\pm0.09\) for the ratio between M82-z1 and (M65+M75)-z1 samples.

The same comparison between the mass groups M75+M82 and M90 at redshift \( z_2 \) and \( z_3 \) is shown in the right panel of Figure 17. The observed ratio is fitted with the power law function and the power law index is estimated to be \(+0.034 \pm 0.06\), which is consistent with a constant over the luminosity range. The ratio of M82 and M65+M75 at redshift \( z_1 \) and that of M90 and M75+M82 at redshift \( z_2 \) and \( z_3 \) are compared in Figure 19.
5. Discussion

We have successfully reconfirmed the increase of cross-correlation length above $M_{BH} = 10^{8.2} M_\odot$ (Figure 9), that was already reported in the previous paper by Komiya et al. (2013), by adapting the improved data selection and using the most recent UKIDSS DR9 dataset. We also confirmed that the trend is also seen in the redshift matched samples (Figure 11), and the cross-correlation length does not depend on the redshift (Figure 12). Although the AGN luminosity dependence was not investigated in this paper, the previous work reported no significant dependence on the luminosity (Komiya et al. 2013).

The derived dark matter halo masses $M_h$ (Figure 10) increase with $M_{BH}$ above $10^{8.2} M_\odot$. The halo mass for M75 mass group, which is estimated assuming the galaxy autocorrelation length $r_{GG}$ is the same as that of AGNs, is $M_h \sim 10^{13.0} h^{-1} M_\odot$ with an uncertainty of $\pm 0.2$ dex, which is equivalent to the halo mass of X-ray selected AGNs ($\sim 10^{13} h^{-1} M_\odot$) analyzed by Hickox et al. (2009) and also those of optically bright QSOs in Figure 5 of Alexander et al. (2012).

The halo mass of our mass group M90 is estimated to be $M_h \sim 10^{14.0} h^{-1} M_\odot$ with an uncertainty of $\pm 0.2$ dex, which is slightly larger than that of radio AGNs of Hickox et al. (2009) ($\sim 10^{13.5} h^{-1} M_\odot$). Mandelbaum et al. (2009) also found that the radio AGNs are hosted by dark matter halo with $\sim 1.6 \times 10^{13} h^{-1} M_\odot$. There are observational evidences that radio-loud AGNs are associated with the massive galaxies (Best et al. 2005) and have SMBHs with masses typically larger than $10^9 M_\odot$ (Laor 2000). Ishibashi et al. (2014) also claimed that radio galaxies are preferentially associated with the more massive black holes. It is, therefore, naturally expected from the existing results that the most massive SMBHs are hosted by massive dark matter haloes, and the current result is consistent with them.

As introduced in section 1, the following three modes have been proposed for transferring gas onto the center of galaxy (e.g., Croton et al. 2006; Lagos et al. 2008; Keres et al. 2009; Fanidiakis et al. 2013); (1) a secular mode which arise through internal dynamical processes in the disk such as a bar instability or external processes of galaxy interactions driving the cold gas toward the center of galaxies, (2) a merger mode in which gravitational torques induced by galaxy-galaxy major/minor mergers drive inflows of cold gas toward the center of galaxies (Hopkins et al. 2008), (3) a hot halo mode which is characterized by quiescent accretion of gas from the hot halo (Keres et al. 2009; Fanidiakis et al. 2013).

According to the model of Fanidiakis et al. (2013) the dark matter halo mass expected for AGNs fueled by cold gas via secular or merger mode is less than $10^{12.5} M_\odot$. This is because in a dark matter halo with mass much larger than $10^{12.5} M_\odot$ the AGN feedback starts to prevent gas from cooling, and as a result the cold gas accretion becomes an inefficient mode in fueling the AGNs. Thus the increasing trend of $M_h$ with $M_{BH}$ obtained in this work indicates that the hot halo mode become more prominent as a fueling channels of AGNs.

The main purpose of this paper is to investigate what type of galaxy contributes to the increase...
of galaxy density around the most massive SMBH. In this work we considered two kind of galaxy types which are classified based on the distribution in the color-magnitude diagram. One is a blue cloud galaxy (blue galaxy) which occupies a bluer and dimmer side of the distribution, and the other is a red sequence galaxy (red galaxy) which has a redder and narrower distribution in the color-magnitude diagram (Figure 6).

It should be noticed that detection efficiency for blue galaxy decreases more rapidly than for red galaxy due to the difference in their brightness. As is shown in the bottom panels of Figure 13 at redshift range of $z_3$ ($z = 0.6–1.0$) most of the blue galaxies are below the detection limit. At redshift range of $z_2$ ($z = 0.3–0.6$) the fraction of the detected blue galaxy constitutes about 20% of all the detected galaxies, while at redshift range of $z_1$ ($z = 0.1–0.3$) the fraction increase to around 40%. As shown here, the observed red/blue fraction has strong redshift dependence and should not be compared between different redshift groups.

The results of the two component analysis on the $D_{\text{opt}-\text{IR}}$ distribution (Figures 13, 14) indicate that the increase of clustering strength found in the cross-correlation analysis for the most massive mass group M90 relative to the lower mass groups are mainly due to the contribution of red galaxies. This can be justified from the observational evidence that increase of the normalized excess density at the transition from M82 to M90 for redshift $z_2$ is significant for red galaxies, while it is almost unchanged or rather decreasing for blue galaxies. It is known that early type galaxies tend to be found at high density region such as a cluster/group core (Dressler 1980, Postman & Geller 1984, Balogh et al. 2004). It is, therefore, naturally expected that the high density around the high mass SMBH is coupled with early type galaxies.

The other indication from this analysis is that the increase of the clustering strength found in the cross-correlation analysis for M82 relative to the M75 is due to the contribution from both of the red and blue galaxies. The red fraction is almost unchanged between M82 and M75, and slight increase in the normalized excess density from M75 to M82 is seen in both of the red and blue components for redshift groups $z_1$ and $z_2$.

The same analysis is performed also for the redshift matched samples (Figure 15 and 16). The trend of the increase in the red fraction and normalized excess density for red galaxies of the most massive group (M90) is also seen in this result. The comparison between M82 and M65+M75 at redshift $z_1$ shows that increase in the normalized excess density are seen in both the red and blue galaxies.

Two physical mechanisms can be relevant to this evolution. One is the increase of brightness of blue dim galaxies induced by starburst triggered in a secular and merger mode, which can result in the increase of the detectable galaxy density. There is an indication for the brightening in the comparison of the luminosity functions. Another one is the transition from blue to red galaxies, which can be the result of AGN feedback. The latter process may follows the former process. In case where there is an enough time delay between the both processes, we can observe the increase of density both for red and blue galaxies as is the case of M82 group. If the time delay is short,
only the increase of red galaxy density will be observed, and this can be the case of M90 group. The evolution of properties of galaxies around AGNs observed in this work can be explained in this manner.

According to theoretical works (e.g., Fanidiakis et al. 2013), the hot halo mode can be the most effective accretion mechanism in massive haloes with \( M_h > 10^{12.5} M_\odot \). In such a massive halo most of the galaxies are in red sequence since AGN feedback shut off the gas cooling and star formation. The dominance of red galaxies around AGNs with higher BH mass obtained in this work is indicative of predominance of hot halo mode for the growth of the most massive SMBHs.

We also investigated relative difference of luminosity function between the low and high mass groups. The redshift matched samples are used for making them directly comparable with each other. The equivalence among the samples in term of the sensitivity of observations was checked by comparing the distributions of \( \rho_0 \) (Figure 18), and we found that they are consistent with each other. Thus the distributions of completeness fraction are the same for the redshift matched samples, and the completeness fraction can be canceled by calculating the ratio.

For the redshift range \( z_1 \), comparison between the M82 mass sample and the lower mass sample, which is a combined sample of M65+M75, is made in the left panel of Figure 17. The figure indicates that an increase of galaxy density for the higher mass sample would be caused by galaxies brighter than \( M_{IR} = -19.5 \) mag. At a dimmer side of \( M_{IR} > -19.5 \) mag, on the other hand, the luminosity function of the higher mass sample is smaller than that of the smaller mass group.

The discontinuity seen at \( M_{IR} = -20.5 \) mag for the (M65+M75)-z1 group corresponds to the dimmer boundary of red sequence, and the broad component at the dimmer side below \( M_{IR} = -20.5 \) mag corresponds to the blue cloud. The blue cloud at dimmer side seen in the (M65+M75)-z1 group almost disappear in M82-z1 group, and the dimmer boundary of the red sequence extends by \( \sim 1 \) mag to the dimmer side. The significance of the deficit of galaxies for the higher mass sample relative to the smaller mass sample is two sigma at absolute brightness range from \(-19.5\) to \(-17.5\) mag.

The plot of the ratio between absolute magnitude distributions of M82 and M65+M75 shows that the increase fraction is larger at the dimmer side and peaked around \( M_{IR} = -20.5 \) mag, and it is approximately fitted with the power law function with the power index of \(-0.13\pm0.09\). This may indicate that the dimmer galaxies have higher probability to increase their brightness by interaction and/or major/minor merger.

These results support the above speculation that, at the environment of SMBH belonging to the M82 mass group, galaxies are transiting from dimmer blue galaxies to brighter blue galaxies, and some of the brightened blue galaxies are transformed to red galaxies.

For the redshift ranges \( z_2 \) and \( z_3 \), a comparison between the M90 and M75+M82 groups is made in the right panel of Figure 17 which shows the ratio of the luminosity functions is almost
constant at $M_{\text{IR}} < -20$ mag. If the difference between the two groups is only the rate of blue to red transformation, and the transformation occurs without affecting the brightness in the 1-1.2 Å band, the constant ratio of the luminosity functions is a natural consequence.

6. Conclusions

In this paper, using the updated UKIDSS catalog we have successfully reconfirmed the previous findings of Komiya et al. (2013) that the clustering of galaxies around AGNs with the most massive SMBH is larger than those with less massive SMBH. The dark matter halo mass was derived for each BH mass group under the assumption that galaxy autocorrelation length is the same as that of AGNs. The obtained halo mass are $\log(M_h/[h^{-1} M_\odot]) = 13.2 \pm 0.2$, $13.1 \pm 0.2$, $13.6 \pm 0.2$, $14.0 \pm 0.2$ for mass group M65, M75, M82 and M90, respectively. We further investigated what type of galaxies are associated in the environment of the most massive SMBH to reveal the nature of evolution mechanism of SMBHs and galaxies. Summarizing the results obtained in this work, we can deduce the following scenario on the evolution of SMBH and its environment galaxies as a function of $M_{\text{BH}}$.

Below the critical mass around $10^{8.2} M_\odot$, the environment of SMBH does not depend on $M_{\text{BH}}$ and is almost equivalent to that of a quiescent galaxy. At that environment, the fraction of blue galaxy is more than 40%. Secular evolution can be the main driver for the evolution of these SMBHs.

Above the critical mass, dark matter halo mass increases by more than one order of magnitude. Dim and blue galaxies increase its brightness via starburst induced by most probably interactions with other galaxies or minor/major merger events. Considering that there is a correlation between the transition in properties of environmental galaxies and mass evolution of SMBHs above $M_{\text{BH}} = 10^{8.2} M_\odot$, they are governed by a sort of environmental effect rather than internal secular evolution. This transition makes galaxies observable by pushing up the brightness above the detection limit, and results in the increase of observed galaxy number density and the clustering length.

Some of the brightened blue galaxies are transformed to red galaxies after the AGN feedback operates, then they start their evolution along the red sequence. In the environment of AGNs in M82 mass group, increases in densities for both blue and red galaxies are observed, which can be due to the time lag between the starburst and AGN feedback. In the environment of AGNs in M90 mass group, the increase is seen only for the red galaxies, which can be the result of the shorter time lag relative to the environment of M82 group. The hot halo mode can be the most suitable mechanism of the growth of the most massive SMBHs, as the dark matter halo mass significantly exceeds the maximum quenching of $10^{12.5} M_\odot$ predicted by Fanidiakis et al. (2013) and the dominance of red galaxies in the environment can be naturally explained.

Results are based on data obtained from the Japanese Virtual Observatory, which is operated
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This work is based in part on data obtained as part of the UKIRT Infrared Deep Sky Survey.
Table 1: Parameters derived in the cross-correlation analysis for each BH mass and redshift range

| BH mass | redshift | \(n_{\text{AGN}}\) | \(\langle \log M \rangle\) | \(\langle z \rangle\) | \(r_0^d\) | \(\sigma_{\text{stat}}^e\) | \(\langle \log \rho_0 \rangle^f\) | \(\langle \rho_0 \rangle^g\) |
|---------|----------|-----------------|----------------|----------------|---------|----------------|----------------|----------------|
| \(0.6-1.0\) | 7.5–8.2 | 366 | 7.9 | 0.45 | 5.3±0.9 | 0.49 | 9.45±0.03 | 2.44±0.5 |
| \(0.3–0.6\) | 8.2–9.0 | 362 | 8.5 | 0.47 | 6.7±1.1 | 0.43 | 8.68±0.03 | 2.27±0.5 |
| \(0.6–1.0\) | 9.0–10.0 | 290 | 9.3 | 0.48 | 9.3±1.4 | 0.40 | 8.28±0.04 | 2.18±0.5 |

\(a\) number of sample AGNs

\(b\) average of logarithm of BH mass

\(c\) average redshift

\(d\) correlation length, the error contains systematic error due to uncertainty of \(\rho_0\) and 1\(\sigma\) statistical error.

\(e\) statistical error of \(r_0\)

\(f\) average of projected number density of background galaxies

\(g\) average of the averaged number density of galaxies at the AGN redshift

\(h\) redshift matched sample
Table 2: Parameters derived in the dark matter halo estimate

| mass          | redshift | $r_{AA}^a$ | $b^b$ | $M_n^c$ | $r_{GG} = 5h^{-1}\text{Mpc}^d$ | $r_{GG} = r_{AA}^e$ |
|--------------|----------|------------|------|--------|-------------------------------|----------------------------|
| $\log M_\odot$ | $h^{-1}\text{Mpc}$ |            |      |        |                               |                            |
| 6.5–7.5      | 0.1–0.3  | 7.7$^{+1.9}_{-1.4}$ | 1.83$^{+0.40}_{-0.31}$ | 13.59$^{+0.31}_{-0.34}$ | 6.2$^{+0.7}_{-0.6}$ | 1.51$^{+0.16}_{-0.13}$ | 13.23$^{+0.20}_{-0.20}$ |
| 7.5–8.2      | 0.1–1.0  | 6.0$^{+1.7}_{-1.2}$ | 1.68$^{+0.42}_{-0.30}$ | 13.22$^{+0.42}_{-0.44}$ | 5.5$^{+0.7}_{-0.6}$ | 1.55$^{+0.18}_{-0.15}$ | 13.05$^{+0.23}_{-0.22}$ |
| 8.2–9.0      | 0.1–1.0  | 10.9$^{+3.7}_{-2.3}$ | 3.13$^{+0.94}_{-0.60}$ | 14.10$^{+0.32}_{-0.29}$ | 7.4$^{+1.2}_{-0.8}$ | 2.21$^{+0.31}_{-0.22}$ | 13.60$^{+0.20}_{-0.18}$ |
| 9.0–10.0     | 0.3–1.0  | 18.1$^{+7.8}_{-4.4}$ | 5.16$^{+1.97}_{-1.15}$ | 14.64$^{+0.30}_{-0.28}$ | 9.5$^{+1.9}_{-1.2}$ | 2.89$^{+0.51}_{-0.34}$ | 13.95$^{+0.21}_{-0.18}$ |

$^a$autocorrelation length of AGNs

$^b$AGN bias derived from $r_{AA}$ using Equation (16)

$^c$dark matter halo mass derived from $b$ using Equation (17)

$^d$autocorrelation length of AGNs $r_{AA}$ is derived by assuming $r_{GG} = 5h^{-1}$, $\gamma = 1.8$ for galaxy autocorrelation function

$^e$autocorrelation length of AGNs $r_{AA}$ is derived by assuming $r_{GG} = r_{AA}$, $\gamma = 1.8$ for galaxy autocorrelation function
Table 3: Parameters derived in the two component analysis on $D_{\text{opt}}-\text{IR}$ distributions

| redshift mass | $\mu_{\text{red}}$ | $\sigma_{\text{red}}$ | $\mu_{\text{blue}}$ | $\sigma_{\text{blue}}$ | $F_{\text{red}}$ | $\omega_{\text{red}}^f$ | $\omega_{\text{blue}}^g$ |
|---------------|--------------------|----------------------|----------------------|----------------------|------------------|---------------------|---------------------|
| 0.1–0.3       | 6.5–9.0            | 4.25±0.11            | 0.42±0.08            | 3.17±0.28            | 0.56±0.14        | 0.59±0.18          |                     |
| 6.5–7.5       |                    |                      |                      |                      |                  | 0.61±0.06          | 0.61±0.09          | 0.40±0.07          |
| 7.5–8.2       |                    |                      |                      |                      |                  | 0.55±0.06          | 0.52±0.08          | 0.43±0.07          |
| 8.2–9.0       |                    |                      |                      |                      |                  | 0.58±0.06          | 0.67±0.09          | 0.48±0.08          |
| 0.3–0.6       | 7.5–10.0           | 4.18±0.07            | 0.42±0.05            | 3.05±0.28            | 0.44±0.17        | 0.79±0.11          |                     |
| 7.5–8.2       |                    |                      |                      |                      |                  | 0.84±0.08          | 0.51±0.07          | 0.10±0.05          |
| 8.2–9.0       |                    |                      |                      |                      |                  | 0.74±0.04          | 0.70±0.06          | 0.25±0.04          |
| 9.0–10.0      |                    |                      |                      |                      |                  | 0.92±0.06          | 1.50±0.15          | 0.13±0.10          |
| 0.6–1.0       | 7.5–10.0           | 4.17±0.01            | 0.35±0.02            | 3.05$^h$             | 0.44$h$          | 1.00±0.07          |                     |
| 7.5–8.2       |                    |                      |                      |                      |                  | 0.75±0.24          | 0.40±0.17          | 0.14±0.16          |
| 8.2–9.0       |                    |                      |                      |                      |                  | 1.00±0.08          | 1.28±0.09          | 0.00±0.09          |
| 9.0–10.0      |                    |                      |                      |                      |                  | 1.00±0.13          | 1.37±0.17          | 0.00±0.18          |
| Redshift matched samples | | | | | | | |
| 0.1–0.3$^i$  | 6.5–8.2            | 4.25                 | 0.42                 | 3.17                 | 0.56             | 0.53±0.07          | 0.39±0.07          | 0.35±0.06          |
| 8.2–10.0      |                    |                      |                      |                      |                  | 0.54±0.06          | 0.65±0.10          | 0.55±0.09          |
| 0.3–0.6$^i$  | 7.5–9.0            | 4.18                 | 0.42                 | 3.05                 | 0.44             | 0.84±0.10          | 0.52±0.10          | 0.10±0.07          |
| 9.0–10.0      |                    |                      |                      |                      |                  | 0.92±0.06          | 1.50±0.15          | 0.13±0.10          |
| 0.6–1.0$^i$  | 7.5–9.0            | 4.17                 | 0.35                 | 3.05                 | 0.44             | 0.80±0.11          | 0.78±0.13          | 0.20±0.13          |
| 9.0–10.0      |                    |                      |                      |                      |                  | 0.93±0.11          | 1.41±0.20          | 0.11±0.18          |

*a mean of the $D_{\text{opt}}-\text{IR}$ distribution for red component

$^b$standard deviation of the $D_{\text{opt}}-\text{IR}$ distribution for red component

$^c$mean of the $D_{\text{opt}}-\text{IR}$ distribution for blue component

$^d$standard deviation of the $D_{\text{opt}}-\text{IR}$ distribution for blue component

$^e$fraction of red component

$^f$normalized excess density for red component

$^g$normalized excess density for blue component

$^h$fixed to the values obtained for redshift 0.3–0.6

$^i$redshift matched samples
Fig. 1.— Comparison of black hole masses derived by Shen et al. (2011) (horizontal axis) and Greene et al. (2007a) (vertical axis). The solid red line represents a linear function fitted to the data points.

Fig. 2.— Distribution of redshift and BH mass of AGNs. AGNs from Greene et al. (2007a) and Shen et al. (2011) are plotted in red and blue colors, respectively. The mass correction is applied to AGNs of Greene et al. (2007a) to compensate the systematic difference between the two catalogs.
Fig. 3.— Distribution of BH mass for the same sample as shown in Figure 2. The red histogram with smaller masses is for Greene et al. (2007a), the blue one is for Shen et al. (2011). The sum of them is shown with the black histogram.

Fig. 4.— Distribution of redshift for the same sample as shown in Figure 2. The red histogram with smaller redshift is for Greene et al. (2007a), the blue one is for Shen et al. (2011). The sum of them is shown with the black histogram.
Fig. 5.— $D_{\text{opt-IR}}$ parameter distribution for all the AGN samples is shown with filled black circles with statistical error bars. The distribution is fitted with a two Gaussian model (black solid line). Each component represented with a single Gaussian corresponds to blue cloud (peak with smaller $D_{\text{opt-IR}}$) and red sequence galaxies (peak with larger $D_{\text{opt-IR}}$).

Fig. 6.— Color magnitude distribution for all the AGN samples. Densities are represented with gray scales and contours of equi-density. Red sequence galaxies are concentrated in a upper right region ($M < -20$ mag and $D_{\text{opt-IR}} > 3.5$), while blue cloud galaxies are widely spread in the dimmer part.
Fig. 7.— Cross-correlation lengths derived for each redshift and mass group are plotted as a function of BH mass. The data point of the same redshift groups are connected with a line. Solid circles are for \( z_1 \) redshift group, solid triangles and boxes are for \( z_2 \) and \( z_3 \) redshift groups, respectively.
Fig. 8.— Surface densities of galaxies plotted as a function of projected distance from AGN for mass group M65, M75, M82 and M90.
Fig. 9.— Cross-correlation lengths derived for each mass groups are plotted as a function of BH mass. The redshift range of each mass groups are 0.1~0.3 for M65 mass group, 0.1~1.0 for M75 and M82 mass groups, and 0.3~1.0 for M90 mass group. Results of this work are shown with filled circles and previous work by Komiya et al. (2013) are shown with open circles.

Fig. 10.— Dark matter halo mass derived for each mass group. Solid and open circles represent the result obtained by assuming $r_{GG} = r_{AA}$ and $r_{GG} = 5 \, h^{-1}\text{Mpc}$, respectively.
Fig. 11.— Cross-correlation lengths derived for each redshift matched samples are plotted as a function BH mass. The data point of the same redshift groups are connected with a line. Filled circles are for \( z_1 \) redshift group, filled triangles and boxes are for \( z_2 \) and \( z_3 \) redshift groups, respectively.

Fig. 12.— Cross-correlation lengths derived for each BH mass matched samples are plotted as a function of redshift. The data point of the same mass groups are connected with a line. Filled boxes are for M75 mass group, filled circles and triangles are for M82 and M90 mass groups, respectively.
Fig. 13.— Distributions of $D_{\text{opt}}$–IR parameter for each redshift and mass groups. Filled circles represent observed data points, solid lines are fitting result of the two component model, red solid and blue dashed lines are for red and blue galaxy component, respectively.
Fig. 14.— Left panel: Red galaxy fractions derived from the two component fitting shown in Figure 13 are plotted as a function of BH mass. The results of the same redshift groups are connected with a line. Circles are results for redshift z1 group, and triangles and boxes are for redshift z2 and z3 groups, respectively. Right panel: Normalized excess density derived from the two component fitting. Filled and open circles are results for blue and red galaxies respectively for z1 redshift group. Filled and open triangles are results for z2 redshift groups with the same blue/red galaxy assignment. Filled and open boxes are results for z3 redshift groups with the same assignment, and the arrows represents the upper limit for blue galaxies at redshift z3.
Fig. 15.— Distributions of $D_\text{opt-IR}$ parameter for redshift matched samples. Filled circles represent observed data points, solid lines are fitting result of the two component model, red solid and blue dashed lines are for red and blue galaxy component, respectively.
Fig. 16.— Left panel: Red galaxy fractions derived from the two component fitting shown in Figure 15 are plotted as a function of BH mass. The results of the same redshift groups are connected with a line. Circles are results for redshift z1 group, and triangles and boxes are for redshift z2 and z3 groups, respectively. Right panel: Normalized excess density derived from the two component fitting. Filled and open circles are results for blue and red galaxies respectively for z1 redshift group. Filled and open triangles are results for z2 redshift groups with the same blue/red galaxy assignment. Filled and open boxes are results for z3 redshift groups with the same assignment.
Fig. 17.— Comparison of absolute magnitude distributions between higher (red histogram) and lower (blue histogram) mass groups. The ratios of high/low are plotted in the panel below the histograms. Dashed lines shown in the ratio plot is a result of a linear fit in linear-log scale.

Fig. 18.— Comparisons of the distributions of average number densities of galaxies at AGN redshift between higher (red histogram) and lower (blue histogram) mass groups. The left (right) panel is the comparison at redshift z1 (z2+z3).
Fig. 19.— Comparison of the ratio of absolute magnitude distributions. Filled blue circles represents the ratio of M82 and M65+M75 at redshift z1. Open red circles represents the ratio of M90 and M75+M82 at redshift z2 and z3. Fitting results with a power law function are also shown with the solid lines.
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