CLUSTERING OF MODERATE LUMINOSITY X-RAY-SELECTED TYPE 1 AND TYPE 2 AGNS AT Z ∼ 3

V. Allevato1, A. Finoguenov1,2, F. Civano3,4, N. Cappelluti5,6, F. Shankar6,7, T. Miyaji8,9,14, G. Hasinger10, R. Gilli5, G. Zamorani5, G. Lanzuisi11, M. Salvato12, M. Elvis4, A. Comastri5, and J. Silverman13

1 Department of Physics, University of Helsinki, Gustaf Hallström inu katu 2a, FI-00014 Helsinki, Finland
2 University of Maryland, Baltimore County, 1000 Hilltop Circle, Baltimore, MD 21250, USA
3 Department of Physics and Astronomy, Dartmouth College, 6127 Wilder Laboratory, Hanover, NH 03755, USA
4 Harvard Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
5 INAF-Osservatorio Astronomico di Bologna, Via Ranzani 1, I-40127 Bologna, Italy
6 Department of Physics and Astronomy, University of Southampton, Highfield SO17 1BJ, UK
7 GEPI, Observatoire de Paris, CNRS, Univ. Paris Diderot, 5 Place Jules Janssen, F-92195 Meudon, France
8 Instituto de Astronomia, Universidad Nacional Autonoma de Mexico, Ensenada, Mexico
9 Center for Astrophysics and Space Sciences, University of California at San Diego, Code 0424, 9500 Gilman Drive, La Jolla, CA 92093, USA
10 Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822, USA
11 National Observatory of Athens LMetaX & V. Paviolou St. GR-15266 Penteli, GREECE
12 Max-Planck-Institute für Extraterrestrische Physik, Giessenbachstrasse 1, D-85748 Garching, Germany
13 Institute for the Physics and Mathematics of the Universe, The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa-shi, Chiba 277-8583, Japan

Received 2013 December 12; accepted 2014 September 16; published 2014 October 29

ABSTRACT

We investigate, for the first time at z ∼ 3, the clustering properties of 189 Type 1 and 157 Type 2 X-ray active galactic nuclei (AGNs) of moderate luminosity (\(L_{\text{bol}}\sim10^{45.5}\) erg s\(^{-1}\)), with photometric or spectroscopic redshifts in the range 2.2 < z < 6.8. These samples are based on Chandra and XMM-Newton data in COSMOS. We find that Type 1 and Type 2 COSMOS AGNs at z ∼ 3 inhabit DMHs with typical mass of \(M_{\delta} = 12.84^{+0.10}_{-0.11} \times 10^{12} M_{\odot}\) and \(11.73^{+0.45}_{-0.39} h^{-1}M_{\odot}\), respectively. This result requires a drop in the halo masses of Type 1 and 2 COSMOS AGNs at z ∼ 3 compared to z ∼ 2 XMM-COSMOS AGNs with similar luminosities. Additionally, we infer that unobscured COSMOS AGNs at z ∼ 3 reside in 10 times more massive halos compared to obscured COSMOS AGNs, at the 2.6σ level. This result extends to z ∼ 3 the results found in COSMOS at z ∼ 2, and rules out the picture in which obscuration is purely an orientation effect. A model which assumes that the AGNs activity is triggered by major mergers is quite successful in predicting both the low halo mass of COSMOS AGNs and the typical mass of luminous SDSS quasars at z ∼ 3, with the latter inhabiting more massive halos respect to moderate luminosity AGNs. Alternatively we can argue, at least for Type 1 COSMOS AGNs, that they are possibly representative of an early phase of fast (i.e., Eddington limited) BH growth induced by cosmic cold flows or disk instabilities. Given the moderate luminosity, these new fast growing BHs have masses of \(\sim10^{7-8} M_{\odot}\) at z ∼ 3 which might evolve into \(\sim10^{8.5-9} M_{\odot}\) mass BHs at z = 0. Following our clustering measurements, we argue that this fast BH growth at z ∼ 3 in AGNs with moderate luminosity occurs in DMHs with typical mass of \(\sim6 \times 10^{12} h^{-1} M_{\odot}\).

Key words: dark matter – galaxies: active – large-scale structure of universe – surveys – X-rays: general

Online-only material: color figures

1. INTRODUCTION

The connection between black holes (BHs) and their host dark matter halos (DMHs) has been mainly studied via clustering measurements of active galactic nuclei (AGNs). Under an assumed cosmology, the AGN bias (i.e., the square root of the relative amplitude of AGN clustering to that of dark matter; e.g., Kaiser 1984) can be inferred and linked to the typical relative amplitude of AGN clustering to that of dark matter; assuming cosmology, the AGN bias (i.e., the square root of the mass of AGN hosting DMHs (e.g., Jing 1998; Sheth & Tormen 2001) out to z ∼ 3–4. This lack of variation in halo mass implies that the bias factor is an increasing function of redshift, since the DM is more weakly clustered earlier in cosmic time.

In addition, quasar clustering measurements have also facilitated several theoretical investigations on the cosmic evolution of BHs within the hierarchical structure formation paradigm (e.g., Hopkins et al. 2007; Shankar et al. 2009, 2010; White et al. 2008). Interestingly, models of major mergers between gas-rich galaxies appear to naturally produce the evolution of the quasar large-scale bias as a function of luminosity and redshift (Hopkins et al. 2007, 2008; Shen 2009; Shankar et al. 2009, 2010; Bonoli et al. 2009). This supports the scenario in which major mergers dominate the luminous quasar population (Scannapieco et al. 2004; Shankar et al. 2010; Neistein & Netzer 2013; Treister et al. 2012).

X-ray detection is generally recognized as a more robust way to obtain a uniformly selected AGN sample with lower luminosities (\(L_{\text{bol}} \sim 10^{44-46}\) erg s\(^{-1}\)) and with a significant fraction of obscured sources with respect to optical surveys. This means that while deep X-ray AGN samples are from square-degree area surveys, sampling moderate luminosity AGNs, optical

14 Current address: P.O. Box 439027, San Ysidro, CA 92143-9024, USA.
quasars are from thousands of square degree surveys, sampling rare and high luminosity AGN events. Thanks to Chandra and XMM-Newton surveys, large samples of X-ray AGNs are available and clustering measurements of moderate luminosity AGNs are now possible with a precision comparable to that achievable with quasar redshift surveys.

Measurements of the spatial clustering of X-ray AGNs show that they are located in galaxy group-sized DMHs with log $M_h = 13–13.5 \ h^{-1} M_{\odot}$ at low ($\sim 0.1$) and high ($\sim 1–2$) redshift (e.g., Hickox et al. 2009; Cappelluti et al. 2010; Allevato et al. 2011; Krumpe et al. 2010, 2012; Mountrichas et al. 2013; Koutoulidis et al. 2013). The fact that DMH masses of this class of moderate luminosity AGNs are estimated to be, on average, 5–10 times larger than those of luminous quasars has been interpreted as evidence against cold gas accretion via major mergers in those systems (e.g., Allevato et al. 2011; Mountrichas & Georgakakis 2012). Additionally, it has been explained as support for multiple modes of BH accretion (cold versus hot accretion mode; e.g., Fanidakis et al. 2013a). However, this difference, which may not be present at $z < 0.7$ (Krumpe et al. 2012), does not yet have a good explanation.

On the other hand, several works on the morphology of the AGN host galaxies suggest that, even at moderate luminosities, a large fraction of AGNs is not associated with morphologically disturbed galaxies. This trend has been observed both at low ($z \sim 1$, e.g., Georgakakis et al. 2009; Cisternas et al. 2011) and high ($z \sim 2$, e.g., Schawinski et al. 2011; Kocevski et al. 2012) redshift.

Despite the power of clustering measurements in understanding AGN population, little is known about the clustering of obscured AGNs. These sources, based on the results from deep X-ray surveys (e.g., Brandt & Hasinger 2005; Tozzi et al. 2006) and X-ray background synthesis models (e.g., Civano et al. 2005; Gilli et al. 2007), are the most abundant AGN population in the universe. Additionally, they are expected to dominate the history of accretion onto SMBHs (e.g., Fabian & Iwasawa 1999). A basic prediction of orientation-driven AGN unification models is that the clustering strength should be similar for obscured (narrow-line or Type 2) and unobscured (broad-line or Type 1) AGNs. By contrast, in the AGN evolutionary scenario, obscured quasars may represent an early evolutionary phase after a major merger event, when the growing BHs cannot produce a high enough accretion luminosity to expel the surrounding material (e.g., Hopkins et al. 2008; King 2010). Following this argument, the luminous quasar phase might probably correspond to the end of an obscured phase. On the other hand, if the AGN activity is triggered by sporadic gas inflow, not by major mergers, then obscured and unobscured AGNs might be two stages that may occur several times along the galaxy lifetime. The different durations of these two stages and their relation to the environment may produce different clustering properties between obscured and unobscured AGNs (Hickox et al. 2011).

Some studies of optically selected quasars confirm that low-redshift narrow-line AGNs are not strongly clustered and are hosted in galaxies that do not differ significantly from typical non-AGN galaxies (e.g., Wake et al. 2004; Mandelbaum et al. 2009; Li et al. 2006). Hickox et al. (2011), analyzing a sample of 806 Spitzer mid-IR-selected quasars at $0.7 < z < 1.8$ in the Boötes field, find marginal ($\lesssim 2\sigma$) evidence that obscured quasars have a larger bias and populate more massive DMHs than unobscured quasars. Recently, DiPompeo et al. (2014), using mid-IR-WISE-selected AGN candidates at $z \sim 1.1$, infer that red AGNs (i.e., obscured sources) are hosted by massive DMHs of log $M_h \sim 13.3 \ h^{-1} M_{\odot}$. This value is well above the halo mass of log $M_h \sim 12.8 \ h^{-1} M_{\odot}$ that harbor blue (unobscured) AGNs (see also Donoso et al. 2014). On the contrary, Krumpe et al. (2012) find no significant difference in the clustering of X-ray narrow-line and broad-line RASS AGNs at $0.07 < z < 0.5$. A larger clustering amplitude for Type 1 with respect to Type 2 AGNs, has been observed in the Swift-BAT all sky survey at $z \sim 0$ (Cappelluti et al. 2010). The redshift evolution of the bias of moderate luminosity X-ray AGNs have been investigated in Allevato et al. (2011) by using XMM-COSMOS data. They find that the bias increases with redshift tracing a constant halo mass typical of galaxy groups ($\sim 10^{13} \ h^{-1} M_{\odot}$) up to $z \sim 2$. Additionally, their results indicate that obscured XMM-COSMOS AGNs inhabit slightly ($2.3\sigma$) less massive halos than unobscured sources.

The clustering of AGNs at $z \geq 2$ is still poorly investigated. At high redshifts galaxies and AGNs are thought to form in rare peaks of the density field and then to be strongly biased relative to the DM (Kaiser 1984; Bardeen et al. 1986). The clustering of $z > 2.9$ SDSS quasars (Shen et al. 2007, 2009) indicates (with large uncertainties on the bias) that luminous quasars reside in massive halos with mass few times $10^{13} \ h^{-1} M_{\odot}$. Following Shankar et al. (2010), these clustering measurements require a high duty cycle (i.e., the probability for an AGN to be active at a given time) for massive BHs ($\gtrsim 10^8 M_{\odot}$) in luminous quasars ($L_{bol} > 10^{46}$ erg s$^{-1}$). The clustering signal measured by Shen et al. (2009) at $z = 3.2$ has also been interpreted with the halo occupation distribution (HOD) by Richardson et al. (2012). Given the large uncertainty of the signal at $z = 3.2$, especially at small scales, they only infer the mass of central halos hosting quasars ($M_{cen} = 14.1^{+5.8}_{-6.5} \times 10^{12} \ h^{-1} M_{\odot}$).

The clustering of moderate luminosity X-ray AGNs at $z \geq 2$ is indeed largely unexplored. The only attempt of measuring the clustering properties of X-ray AGNs at $z = 3$ is presented in Francke et al. (2008). They estimate the correlation function of a small sample of X-ray AGNs with $L_{bol} \sim 10^{45.8}$ erg s$^{-1}$, in the Extended Chandra Deep Field South (ECDFS). They find indications that X-ray ECDFS AGNs reside in DMHs with minimum mass of log $M_{min} = 12.6^{+0.3}_{-0.5} \ h^{-1} M_{\odot}$. Unfortunately, because of the small number of sources, the bias factor has a very large uncertainty.

In this paper we use a larger sample of X-ray-selected AGNs with $L_{bol} \sim 10^{45.3}$ erg s$^{-1}$, based on Chandra and XMM-Newton data in the COSMOS field, at $2.2 < z < 6.8$. The purpose is to measure the clustering amplitude and the typical hosting halo mass of moderate luminosity AGNs at $z \sim 3$. Additionally, we focus on the measurements of the large-scale bias of Type 1 and Type 2 COSMOS AGNs at $z \geq 2.2$. This redshift range has never been explored before for the clustering of moderate luminosity obscured and unobscured sources. Throughout the paper, all distances are measured in comoving coordinates and are given in units of $Mpc \ h^{-1}$, where $h = H_0/100$ km s$^{-1}$. We use a CDM cosmology with $\Omega_M = 0.3$, $\Omega_L = 0.7$, $\Omega_k = 0.045$, $\sigma_8 = 0.8$. The symbol log signifies a base-10 logarithm.

2. AGNS CATALOG

The Cosmic Evolution Survey (COSMOS; Scoville et al. 2007) is a panchromatic photometric and spectroscopic survey of 2 deg$^2$ of the equatorial sky, observed by the most advanced astronomical facilities, with imaging data from X-ray to radio. The inner part of the COSMOS field ($\sim 0.92$ deg$^2$) has been
imaged for a total of 1.8 Ms by Chandra, while XMM-Newton surveyed 2.13 deg$^2$, for a total of $\sim$1.55 Ms. Large samples of point-like X-ray sources detected in the 0.5–10 keV energy band are presented in the Chandra-COSMOS (C-COSMOS) point-like source catalog (1761 objects; Elvis et al. 2009; Civano et al. 2012) and in the XMM-COSMOS multiband catalog (1822 objects; Cappelluti et al. 2009; Brusa et al. 2010). Of the 1822 XMM-COSMOS sources, 945 have been detected by Chandra. Extensive spectroscopic campaigns have been carried out in the field, providing a total of 890 and 1069 unique, good quality spectroscopic redshifts (spec-$z$) for XMM-COSMOS and C-COSMOS sources, respectively. In addition, photometric redshifts (phot-$z$) for all the XMM-COSMOS sources and for $\sim$96% of the C-COSMOS sources have been obtained by exploiting the COSMOS multiband catalog and are presented in Salvato et al. (2009, 2011).

The prime interest of this paper is to investigate the clustering properties of X-ray AGNs at $z \sim 3$. To this end, we use the catalog of C-COSMOS sources and we limit to a sample of 252 AGNs detected in the soft band, with phot or spec-$z \geq 2.2$, when available. In addition, we include in the analysis 94 AGNs with spec or phot-$z \geq 2.2$, which are outside the inner region observed by Chandra and then detected only by XMM. Then the final sample includes a total of 346 COSMOS AGNs.

The spectroscopic or photometric classification is available for each AGN on the basis of a combined X-ray and optical classification if spectra are available, or by the type of template for each AGN on the basis of a combined X-ray and optical classification. The type of template is classified if spectra are available, or by the type of template for each AGN on the basis of a combined X-ray and optical classification. As shown in Figure 1, the intrinsic bolometric luminosity of the entire sample of 346 COSMOS AGNs spans $\sim$3 orders of magnitude, from $10^{44}$ to $10^{47}$ erg s$^{-1}$. The mean and the dispersion of the distribution are (45.3, 0.6) in log and in unit of erg s$^{-1}$. Therefore, this sample is dominated by moderate luminosity X-ray AGNs with a mean bolometric luminosity $\sim$2 orders of magnitude lower than that of luminous optical quasars at similar redshift (Shen et al. 2009). Due to the lower limiting flux of Chandra with respect to XMM detections, the distribution of bolometric luminosities of C-COSMOS AGNs peaks at lower values. The intrinsic $L_{\text{bol}}$ distributions of 189 Type 1 and 157 Type 2 COSMOS AGNs are shown in Figure 2, with mean and dispersion equal to (45.47, 0.58) and (45.15, 0.58) for Type 1 and 2, respectively (in log and units of erg s$^{-1}$).

In order to evaluate the effect of using photometric redshifts in the clustering measurements, we also construct a sample of 138 COSMOS AGNs detected in the soft band, with available spec-$z \geq 2.2$. The redshift and intrinsic bolometric luminosity distributions for this sample are shown in Figure 1 and the corresponding mean values are quoted in Table 1. Following the spectroscopic classification, the sample has been divided onto 107 Type 1 and 31 Type 2 COSMOS AGNs (see Figure 2).

| Table 1 Properties of the AGN Samples |
|---------------------------------------|
| Sample | $\langle z \rangle$ | $\langle \log(L_{\text{bol}}) \rangle$ (erg s$^{-1}$) | $\langle b \rangle$ | $\langle \log(M_\odot) \rangle$ ($h^{-1}$M$_\odot$) |
|-------|------------------|------------------|-----------------|-----------------|
| All AGNs | 138 | 2.86 | 45.50 | 3.94$^{+0.45}_{-0.46}$ | 12.36$^{+0.17}_{-0.21}$ |
| Type 1 | 107 | 2.82 | 45.58 | 4.93$^{+0.55}_{-0.52}$ | 12.75$^{+0.15}_{-0.16}$ |
| Type 2 | 31 | 2.96 | 45.22 | ... | ... |

3. 2PCF AND AGN BIAS FACTOR

Measurement of the two-point correlation function (2PCF) requires the construction of a random catalog with the same selection criteria and observational effects as the real data. To this end, we construct a random catalog where each simulated source is placed at a random position in the sky, with flux randomly extracted from the catalog of real source fluxes (e.g., Gilli et al. 2009; Allevato et al. 2011). Following this method, the simulated source is kept in the random sample if its flux is above the sensitivity map value at that position (Miyaji et al. 2007; Cappelluti et al. 2009). We prefer this method over the one that keeps the angular coordinates unchanged as that approach has the disadvantage of removing the contribution to the signal due to angular clustering. Nevertheless, Gilli et al. (2005, 2009) and Koutoulidis et al. (2013) have shown that there is only a small difference ($\sim$15%) in the clustering signal derived with the two different procedures.

The corresponding redshifts of the random objects are assigned based on the smoothed redshift distribution of the real AGN sample. Specifically, we assume a Gaussian smoothing length $\sigma_z = 0.2$. This is a good compromise between scales that are too small, which would suffer from local density variations, and those that are too large, which would oversmooth the distribution. The redshift distribution of COSMOS AGNs and of the random samples are shown in Figure 1.
Figure 1. Redshift and intrinsic bolometric luminosity distributions of Chandra-COSMOS AGNs (dashed gray histogram), XMM-only selected AGNs (filled red histogram), and of the combined catalog (solid black histogram) of 138 COSMOS AGNs with known spec \( z \geq 2.2 \) (upper quadrants) and of 346 COSMOS AGNs with known spec or phot-\( z \geq 2.2 \) (lower quadrants). The empty gold histograms in the left panels show the redshift distributions of the random catalogs obtained using a Gaussian smoothing with \( \sigma = 0.2 \). (A color version of this figure is available in the online journal.)

We estimate the projected 2PCF function \( w_p(r_p) \) by using (Davis & Peebles 1983):

\[
w_{\text{AGNs}}(r_p) = 2 \int_0^\pi \xi(r_p, \pi) d\pi \tag{1}
\]

where \( \xi(r_p, \pi) \) is defined in Landy & Szalay (1993, hereafter LS) as:

\[
\xi = \frac{1}{\text{RR}} [\text{DD} - 2\text{DR} + \text{RR}]. \tag{2}
\]

The LS estimator is described as the ratio between AGN pairs in the data sample and those in the random catalog, as a function of the projected comoving separations between the objects (in the directions perpendicular, \( r_p \), and parallel, \( \pi \), to the line-of-sight). The choice of \( \pi_{\text{max}} \) is a compromise between having an optimal signal-to-noise ratio and reducing the excess noise from high separations. Usually, the optimum \( \pi_{\text{max}} \) value can be determined by estimating \( w_{\pi}(r_p) \) for different values of \( \pi_{\text{max}} \) and finding the value at which the 2PCF levels off. Following this approach, we fixed \( \pi_{\text{max}} = 100 \ h^{-1} \) Mpc in estimating the 2PCF of 346 COSMOS AGNs with known spec or phot-z. For the smaller sample of 138 COSMOS AGNs with available spec-z, we set \( \pi_{\text{max}} = 40 \ h^{-1} \) Mpc. The larger \( \pi_{\text{max}} \) adopted in the former case is due to the use of phot-z.

In the halo model approach (e.g., Miyaji et al. 2011, Krumpe et al. 2012), the 2PCF is modeled as the sum of contributions from AGN pairs within individual DMHs (one-halo term, \( r_p < 1 \) Mpc \( h^{-1} \)) and in different DMHs (two-halo term, \( r_p \gtrsim 1 \) Mpc \( h^{-1} \)). The superposition of the two terms describes the shape of the observed 2PCF. In this context, the bias parameter \( b \) reflects the amplitude of the AGNs two-halo term relative to the underlying DM distribution, i.e.,

\[
w_{\text{mod}}(r_p, z) = b^2 w_{\text{DM}}^{2-h}(r_p, z) \tag{3}
\]

We first estimate the DM two-halo term at the mean redshift of the sample, using:

\[
w_{\text{DM}}^{2-h}(r_p) = r_p \int_{r_p}^{\infty} \xi_{\text{DM}}^{2-h}(r) \frac{r dr}{\sqrt{r^2 - r_p^2}} \tag{4}
\]

where

\[
\xi_{\text{DM}}^{2-h}(r) = \frac{1}{2\pi^2} \int P^{2-h}(k) \left[ \frac{\sin(k r)}{k r} \right] dk \tag{5}
\]

\( P^{2-h}(k) \) is the Fourier Transform of the linear power spectrum, assuming a power spectrum shape parameter \( \Gamma = 0.2 \) which corresponds to \( h = 0.7 \).
4. RESULTS

4.1. Bias Factors and DMH Masses

The projected 2PCF function $w_p(r_p)$ of 346 COSMOS AGNs is shown in the left panel of Figure 3, in the range of $r_p = 1–30\, h^{-1}\, \text{Mpc}$. The 1σ errors on $w_p(r_p)$ are the square root of the diagonal components of the covariance matrix (Miyaji et al. 2007, Kruppe et al. 2010), which quantifies the level of correlation among different bins. Following Equation (3), we derive the best-fit bias by using a $\chi^2$ minimization technique with one free parameter, where $\chi^2 = \Delta^T M^{-1}_\text{cov} \Delta$. In detail, $\Delta$ is a vector composed of $w_{\text{AGNs}}(r_p) - w_{\text{mod}}(r_p)$ (see Equations (1) and (3)), $\Delta^T$ is its transpose, and $M^{-1}_\text{cov}$ is the inverse of covariance matrix. The latter is used in the fit to take into account the correlation between errors. We find that, at $\langle z \rangle = 2.8$, COSMOS AGNs have a bias of $b = 3.85_{-0.22}^{+0.10}$, where the 1σ errors correspond to $\Delta \chi^2 = 1$.

We then relate the large-scale bias to a typical mass of the hosting halos, following the bias–mass relation $b(M_h, z)$ defined by the ellipsoidal collapse model of Sheth et al. (2001) and the analytical approximation of van den Bosch (2002). We find that COSMOS AGNs at $\langle z \rangle = 2.8$ inhabit DMHs with log $M_h = 12.37_{-0.09}^{+0.10}$.

Usually, phot-z are characterized by large uncertainty. Hickox et al. (2012) showed that even uncertainties of $\sigma_z = 0.25(1 + z)$ cause the clustering amplitude of AGNs cross-correlated with galaxies in the Boötes field to decrease by only $\sim 10\%$. COSMOS AGNs have the advantage that, at $z > 2$, $\sigma_z/(1 + z) < 0.05$ (Salvato et al. 2011). Hence we do not expect a significant difference from the 2PCF derived using only spec-z.

In order to verify this, we measure the clustering signal for a smaller sample of 138 COSMOS AGNs with available spec-z $\geq 2.2$. The left panel of Figure 3 compares the projected 2PCFs estimated with the two different AGN samples. As expected, by using a larger AGN sample with both phot-z and spec-z, we improve the statistics and thus the quality of the signal. However, we find consistent bias factors, irrespective of including photometric redshifts (see Table 1). This result suggests that the use of a significant fraction of AGNs with known phot-z is not affecting the result systematically. Instead, we are improving the statistics, almost tripling the number of AGNs.

We investigate whether Type 1 COSMOS AGNs are more strongly clustered than Type 2 objects, as already observed at low redshift (e.g., Cappelluti et al. 2010; Allevato et al. 2011). The right panel of Figure 3 shows the projected 2PCF of Type 1 and Type 2 AGNs with known phot and spec-z $\geq 2.2$. We find

![Figure 2. Redshift and intrinsic bolometric luminosity distributions of Type 1 AGNs (dashed blue histogram), Type 2 AGNs (filled red histogram), and of the combined catalog (solid black histogram) of 138 COSMOS AGNs with known spec-z $\geq 2.2$ (upper quadrants) and of 346 COSMOS AGNs with known spec or phot-z $\geq 2.2$ (lower quadrants). The mean values of the distributions are quoted in Table 1. (A color version of this figure is available in the online journal.)](image-url)
that unobscured COSMOS AGNs reside in more massive halos compared to obscured AGNs. In fact, we measure a best-fit bias equal to \(b_{\text{unob}} = 5.26^{+0.35}_{-0.39}\) for Type 1 and \(b_{\text{ob}} = 2.69^{+0.62}_{-0.69}\) for Type 2 AGNs, respectively. These bias factors correspond to typical DMH masses of \(\log M_h = 12.84^{+0.10}_{-0.11}\) and \(\log M_h = 11.73^{+0.39}_{-0.45} h^{-1} M_\odot\), respectively.

We check that the bias factor of Type 1 COSMOS AGNs does not change when limiting the analysis to a sample of 107 unobscured sources with available spec-z \(\geq 2.2\). Unfortunately, we cannot test the effect of phot-z in measuring the 2PCF of obscured sources, given the small number of Type 2 objects (31) with spec-z \(\geq 2.2\). The best-fit bias factors and the corresponding typical DMH masses for each subsample of COSMOS AGNs used in this work are shown in Table 1.

### 4.2. Redshift Evolution of the AGN Bias

The left panel of Figure 4 shows the bias factors derived for our sample of COSMOS AGNs at \(z \sim 3\), along with a collection of values estimated in previous studies at lower redshifts. The different lines mark the redshift evolution of the bias corresponding to different constant DMH masses, as predicted by the ellipsoidal collapse model of Sheth et al. (2001). The filled circles show the redshift evolution of the bias for a comparable sample of moderate luminosity XMM-COSMOS AGNs at \(z \leq 2\), as presented in Allevato et al. (2011).

The right panel of Figure 4 shows the redshift evolution of the corresponding typical DMH masses derived following the bias–mass relation defined by the ellipsoidal collapse model of Sheth et al. (2001). The general picture at \(z \lesssim 2\) is that the bias of moderate luminosity X-ray AGNs increases with redshift, tracing a constant group-sized halo mass. Allevato et al. (2011) have shown that XMM-COSMOS AGNs (with \(L_{\text{bol}} \sim 10^{45.2} \text{erg s}^{-1}\)) reside in DMHs with constant mass equal to \(\log M_h = 13.12 \pm 0.07 h^{-1} M_\odot\) up to \(z \sim 2\) (Figure 4, filled black points).

By contrast, at \(z \sim 3\), we found that our COSMOS AGNs with similar luminosities inhabit less massive DMHs (Figure 4, open black points) with \(\log M_h = 12.37^{+0.10}_{-0.09} h^{-1} M_\odot\). This result is significant at the 6.2\(\sigma\) level.

A similar trend has been observed for both Type 1 and Type 2 COSMOS AGNs. Allevato et al. (2011) found that unobscured AGNs reside in slightly more massive halos than obscured AGNs up to \(z \sim 2.2\) (\(\log M_h = 13.28 \pm 0.07\) and \(13.00 \pm 0.06 h^{-1} M_\odot\), respectively). Instead, our results at \(z \sim 3\) require, compared to \(z \leq 2\) results, a drop in the halo mass to \(\log M_h = 12.84^{+0.10}_{-0.11}\) (3.6\(\sigma\) result) and \(11.73^{+0.39}_{-0.45} h^{-1} M_\odot\) (3\(\sigma\) result) for Type 1 and Type 2 COSMOS AGNs.

### 5. DISCUSSION

In the following sections we will discuss our results and we will attempt to answer the question why the redshift evolution of the bias changes at \(z \geq 2.2\).

First, we note that the number density of \(10^{13} h^{-1} M_\odot\) mass halos tends to evolve faster beyond \(z \sim 3\), with a progressive drop in the abundance of massive (and rarer) host halos at high redshifts. This fact alone suggests a possible increase with redshift in the ratio between the BH mass and host halo mass, with a mapping of moderate luminosity AGNs in progressively less massive halos at higher redshift. Independent studies support such a type of evolution (e.g., White et al. 2008; Shankar et al. 2010).

#### 5.1. Major Merger Models at \(z \sim 3\)

In this section we try to explain our clustering measurements at \(z \sim 3\) within a hierarchical mergers scenario.

Figure 5 shows a collection of bias estimates for broad-line optically selected SDSS quasars at \(z = 3.2\) (Shen et al. 2009), X-ray-selected AGNs in the ECDFS at \(z = 3\) (Francke et al. 2008), and the results presented in this work, as a function of \(L_{\text{bol}}\). For our data points, the errors on the \(L_{\text{bol}}\) axis correspond to the dispersion of the bolometric luminosity distributions for the different subsets. Our sample of COSMOS AGNs and X-ray ECDFS AGNs with slightly lower luminosities have consistent...
bias factors within 1σ. However, our estimate has significantly smaller uncertainty, given the larger number of sources used in the analysis. On the contrary, Shen et al. (2009) measured a slightly higher bias (<2σ) for luminous Type 1 quasars with bolometric luminosity ∼2 orders of magnitude higher with respect to our sample of unobscured AGNs.

The continuous line marks the predicted bias as a function of bolometric luminosity, computed according to the framework of the growth and evolution of SMBHs presented in Shen (2009; see also Shankar et al. 2010) at z = 3. Their model assumes that quasar activity is triggered by major mergers of host halos (e.g., Kauffmann & Haehnelt 2000). In addition, they assume that the resulting AGN light curve follows a universal form with its peak luminosity correlated with the (post-)merger halo mass. The major merger model was adapted to fully reproduce the optical/X-ray data at z < 2–3 (Shankar et al. 2010; Allevato et al. 2011). With no additional fine-tuning the major merger model is quite successful in predicting the bias of COSMOS AGNs at z ∼ 3 as a function of bolometric luminosity and it is in broad agreement with the data points. The drop in the typical DMH mass to a few times 10^{12} M_☉ can then be explained assuming that, unlike z ≲ 2 XMM-COSMOS AGNs, COSMOS AGNs at z ∼ 3 are triggered by galaxy major mergers.

In addition, the major merger model predicts a luminosity-dependent bias, with more luminous AGNs inhabiting more massive DMHs. The evolution of the bias with the bolometric luminosity traced by the data marginally confirms this trend. It is important to note that at lower redshifts the bolometric luminosity dependence is significantly milder (e.g., Myers et al. 2007; Shen et al. 2009) or even reversed (e.g., Allevato et al. 2011).
2011), with moderate luminosity AGNs residing in more massive DMHs with respect to luminous quasars. Such an evolutionary trend is difficult to reconcile with AGN triggering models, at different redshifts, based only on major mergers (Bournaud et al. 2011; Fanidakis et al. 2013a).

In the framework of the BH growth presented in Fanidakis et al. (2013a), our results at $z \sim 3$ can be interpreted in terms of the absence of interplay between cold and hot-halo mode. In fact, they suggest the picture that, in the $z \sim 3$ universe, the cold accretion mode (accretion during disk instabilities and galaxy mergers) is solely responsible for determining the environment of moderate luminosity AGNs, while the AGN feedback is switched off. Our results confirm that $z \sim 3$ is the epoch when the hot-halo mode is still a negligible fuelling channel. At lower redshifts both accretion modes have to be taken into account. The hot-halo mode becomes prominent only in DM halos with masses greater than $\sim 10^{12.5} \, h^{-1} M_\odot$, where AGN feedback typically operates.

### 5.2. Fast Growing BHs at $z \sim 3$

A major merger model can broadly reproduce the clustering of moderate luminosity AGNs at $z \sim 3$. This is because mergers are most efficient in halos of masses around $\sim 3 \times 10^{12} M_\odot$, which is the typical mass scale inferred from our direct clustering measurements. However, this is not a proof of uniqueness of merger models as an explanation of our results. Major galaxy mergers are not a requirement for efficient fuel supply and growth, particularly for the earliest BHs. Alternatively, an early phase of fast BH growth could be induced by cosmic cold flows (e.g., Dekel et al. 2009; Di Matteo et al. 2012; Dubois et al. 2012) or disk instabilities (e.g., Bournaud et al. 2012). Cold flows and disk instabilities in high redshift disk galaxies operate on short timescales (unlike secular processes in low-$z$ disks). In addition, they are efficient, producing a mass inflow similar to a major merger but spread over a longer period (then the duty cycle is higher).

Different BH accretion models (e.g., Marconi et al. 2004; Merloni & Heinz 2008; Shankar et al. 2004, 2009, 2013; Bournaud et al. 2011; Fanidakis et al. 2013a) broadly agree that $z \gtrsim 2$ is the epoch of rapid growth for both low and high-mass BHs. This conclusion holds irrespective of uncertainties in duty cycle, AGN luminosity functions, or even input Eddington ratio distributions. Figure 6 shows the average accretion history of different BH masses as described in Marconi et al. (2004) and Shankar et al. (2013).

Due to the flux and volume limits of our survey, our sample of Type 1 COSMOS AGNs at $z \sim 3$ mainly includes moderate luminosity sources with $L_{\text{bol}} \sim 10^{45} \, \text{erg s}^{-1}$. Thus, it excludes low-luminosity AGNs with typical BH mass $\lesssim 10^8 M_\odot$, or even bright quasars associated with very massive BHs ($>10^9 M_\odot$) and $L_{\text{bol}} > 10^{46} \, \text{erg s}^{-1}$. This means that our sample of Type 1 COSMOS AGNs is possibly representative of AGNs corresponding to a rising population of fast growing (i.e., Eddington limited) BHs with masses of $\sim 10^{7–8} M_\odot$ at $z \sim 3$.

According to the BH accretion histories shown in Figure 6, these fast growing $\sim 10^{7–8} M_\odot$ mass BHs evolve in BHs with mass of the order of $\sim 10^{8–9} M_\odot$ at $z = 0$. This picture is consistent with the fact that moderate luminosity Type 1 AGNs in zCOSMOS at $z = 1–2.2$ (black circle in Figure 6) have BH masses in the range $M_{\text{BH}} = 10^{8–9} M_\odot$ with Eddington ratios $\lambda \sim 0.01–1$, as shown in Merloni et al. (2010).

Following our results, we can argue that these fast growing BHs at $z \sim 3$ reside in DMHs with typical mass of $\sim 10^{12.8} h^{-1} M_\odot$, which is the mass inferred for Type 1 COSMOS AGN hosting halos. Between $z \sim 3$ and $z \sim 2$ the typical halo mass of Type 1 COSMOS AGNs increases. The BH accretion models suggest that these AGNs are also rapidly growing their BH mass. The duty cycle and Eddington ratio, which are close to unity at $z \sim 3$, then decline with decreasing redshift. This leads to a strong evolution of the number density of X-ray AGNs at $z \gtrsim 3$ as observed in COSMOS (Brusa et al. 2010; Civano et al. 2011), albeit for an AGN sample including both Type 1 and 2 objects.

The picture is completely different at $z < 2$, where the bias of Type 1 AGNs starts to follow the constant DMH mass track. The growth of BHs becomes more sub-Eddingtonian (e.g., Vittorini et al. 2005, Shankar et al. 2013, and references therein) and their mass saturates to a constant value down to $z = 0$ (Figure 6). This flat host halo mass at $z \lesssim 2$ for X-ray AGNs with moderate luminosity might be due to high mass halos switching to radio-loud, X-ray weak ($<10^{44} \, \text{erg s}^{-1}$) AGNs. This limits the X-ray AGN population with moderate luminosity to halos with masses $\lesssim 10^{13} M_\odot$. A plausible mechanism is that AGN feedback prevents gas from cooling in very massive halos. These radiatively inefficient, jet-dominated outbursts may be fueled by accretion directly from the hot gas halo and so are only possible in massive galaxies with large hosting halos (e.g., Fanidakis et al. 2012, 2013a, 2013b).

The picture described above for Type 1 COSMOS AGNs, representative of new fast-growing BHs at $z \sim 3$, may or may not be valid for Type 2 COSMOS AGNs. In fact, for the latter, we do not know the typical mass of the central BHs at any redshift. However, it is not unreasonable to assume that for Type 2 AGNs,
the observed redshift evolution of the bias reflects lower mass BHs and DMH masses with respect to Type 1 AGNs. Lower mass halos are more abundant at $z \sim 3$ and are characterized by a slower redshift evolution of the number density. The increase of the fraction of obscured AGNs with redshift (e.g., Hasinger 2008; Merloni et al. 2014) supports this scenario in which Type 1 and Type 2 objects follow different DMH mass tracks as a function of redshift.

5.3. Type 1 versus Type 2 AGNs

In this section we discuss the clustering properties of 189 Type 1 and 157 Type 2 COSMOS AGNs with phot or spec-$z \gtrsim 2.2$, when available.

We find a strong indication that unobscured AGNs reside in 10 times more massive halos (see Table 1) with respect to obscured sources (3σ result). A difference in clustering between obscured and unobscured quasars rules out the simplest unified models (e.g., Urry & Padovani 1995) in which obscuration is purely an orientation effect.

Type 1 and Type 2 COSMOS AGNs have slightly different luminosities. However, the difference in the bias factors between Type 1 and Type 2 AGNs cannot be explained in terms of the luminosity-dependent bias predicted by major merger models. The curve in Figure 5 predicts a milder change of bias with luminosity in the range $\log L_{bol} = 45.1 - 45.5$ erg s$^{-1}$. This result would extend to $z \sim 3$ that found for $z \lesssim 2$ Type 1 and Type 2 XMM-COSMOS AGNs with similar luminosities (Allevato et al. 2011).

6. CONCLUSIONS

We use a sample of 346 moderate luminosity ($\langle L_{bol} \rangle = 10^{45.3}$ erg s$^{-1}$) COSMOS AGNs based on Chandra and XMM-Newton data, with known spec or phot-$z$ in the range $2.2 < z < 6.8$. Our main goal is to measure clustering amplitudes and to estimate characteristic DM halo masses at $z \sim 3$. We also obtain, for the first time at $z \sim 3$, a highly significant clustering signal for Type 1 and Type 2 COSMOS AGNs. This redshift range has never been used before to investigate the clustering of obscured and unobscured AGNs, at these luminosities. We model the 2PCF of COSMOS AGNs with the halo model, which relates the large-scale bias to the amplitude of the AGNs two-halo term relative to the underlying DM distribution. We translate the bias factor into a typical mass of the hosting halos, following the bias–mass relation defined by the ellipsoidal collapse model of Sheth et al. (2001). Key results can be summarized as follows.

1. At $z \sim 3$ Type 1 and Type 2 COSMOS AGNs inhabit DMHs with typical mass of $\log M_h = 12.84^{+0.10}_{-0.06}$ and $11.73^{+0.43}_{-0.39} h^{-1} M_\odot$. This result requires a drop in the halo masses at $z \sim 3$ compared to $z \lesssim 2$ XMM-COSMOS AGNs with similar luminosities.

2. At $z \sim 3$ Type 1 COSMOS AGNs reside in $\sim 10$ times more massive halos compared to Type 2 COSMOS AGNs, at the 2.6σ level. This result extends to $z \sim 3$ the results found in COSMOS at $z \lesssim 2$, and rules out the picture in which obscuration is purely an orientation effect.

3. A plausible explanation of the drop in the halo mass of COSMOS AGNs might be that these moderate luminosity sources at $z \sim 3$ are triggered by galaxy major mergers. In fact, major merger models are quite successful in predicting the halo mass of COSMOS AGNs and luminous SDSS quasars at $z \sim 3$, with the latter inhabiting more massive halos with respect to moderate luminosity AGNs.

4. Alternatively, we can argue that, at least for Type 1 COSMOS AGNs, they are possibly representative of moderate luminosity AGNs associated with an early phase of fast (i.e., Eddington limited) BH growth induced by, for instance, cosmic cold flows or disk instabilities. According to BH accretion models, these new fast growing BHs have masses of $\sim 10^{-8} M_\odot$ at $z \sim 3$ which might evolve into $\sim 10^{8.5-9} M_\odot$ mass BHs at $z = 0$.

5. Following our clustering measurements, we argue that this fast BH growth at $z \sim 3$, in Type 1 AGNs with moderate luminosity, occurs in DMHs with typical mass of $\sim 6 \times 10^{12} h^{-1} M_\odot$.

Improving our understanding of the AGN triggering mechanisms at $z \sim 3$ and beyond using AGN clustering measurements requires a larger data set. The COSMOS Legacy survey (Civano et al. 2014) with 1.45 deg$^2$ at $2 \times 10^{-16}$ erg cm$^2$ s$^{-1}$ will provide the largest survey at this depth ever performed. This will let us constrain the faint end of the AGN luminosity function and of the BH mass functions at $z > 3$. This regime, which is not otherwise sampled, will allow us to understand the BH growth in the early universe and to study the clustering properties of $\sim 350$ expected luminous quasars and $L^*$ AGNs at $3 < z < 6$.

We thank the referee for a very helpful report. We gratefully acknowledge the contributions of the entire COSMOS collaboration consisting of more than 100 scientists. More information on the COSMOS survey is available at http://wwwastro.caltech.edu/cosmos. V.A. and A.F. wish to acknowledge Finnish Academy award, decision 266918. F.C. acknowledges the support of NASA contract 11-ADAP11- 0218. F.S. acknowledges partial support from a Marie Curie grant. V.A. acknowledges support from UNAM-PAPIIT 104113 and CONACyT Grant 179662. We thank Alessandro Marconi for providing the tracks shown in Figure 5 and John Regan for helpful discussions. N.C. acknowledges European Commission funding through the FP7 SPACE project ASTRODEEP (Ref. No.: 312725).

REFERENCES

Allevato, V., Finoguenov, A., Cappelluti, N., et al. 2011, ApJ, 736, 99
Bardeau, J. M., Bond, J. R., Kaiser, N., & Szalay, A. S. 1986, ApJ, 304, 15
Bonoli, S., Marulli, F., Springel, V., et al. 2009, MNRAS, 396, 423
Bournaud, F., Dekel, A., Teyssier, R., et al. 2011, ApJ, 741, 33
Bournaud, F., Juneau, S., Le Floch, E., et al. 2012, ApJ, 757, 81
Brandt, W. N., & Hasinger, G. 2005, ARAA, 43, 827
Civano, F., Brusa, M., Comastri, A., et al. 2010, ApJ, 716, 348
Cappelluti, N., Aiello, M., Burlon, D., et al. 2010, ApJ, 716, 209
Cappelluti, N., Brusa, M., Hasinger, G., et al. 2009, A&A, 497, 635
Cisternas, M., Jaehne, K., Inskip, K. J., et al. 2011, ApJ, 726, 57
Civano, F., Brusa, M., Comastri, A., et al. 2011, ApJ, 741, 91
Civano, F., Comastri, A., & Brusa, M. 2005, MNRAS, 358, 693
Civano, F., Elvis, M., Comastri, A., et al. 2012, ApJS, 201, 30
Civano, F., & the Chandra COSMOS Legacy Team 2014, AAS, 254, 46
Coil, A. L., Georgakakis, A., Newman, J. A., et al. 2009, ApJ, 701, 1484
Croom, S. M., Boyle, B. J., Shanks, T., et al. 2005, MNRAS, 356, 415
Croom, S. M., Richards, G. T., Shanks, T., et al. 2009, MNRAS, 392, 19
da Angela, J., Outram, P. J., Shanks, T., et al. 2005, MNRAS, 360, 1040
da Angela, J., Shanks, T., Croom, S. M., et al. 2008, MNRAS, 383, 565
Davis, M., & Peebles, P. J. E. 1983, ApJ, 267, 465
Dekel, A., Sari, R., & Ceverino, D. 2009, ApJ, 703, 785
Di Matteo, T., Khandai, N., DeGraf, C., et al. 2012, ApJ, 745, 29
DiPompeo, M. A., Myers, A. D., Hickox, R. C., Geach, J. E., & Hainline, K. N. 2014, MNRAS, 442, 3443
Donoso, E., Yan, L., Stern, D., & Assef, R. J. 2014, ApJ, 789, 44
Dubois, Y., Pichon, C., Haehnelt, M., et al. 2012, MNRAS, 423, 3616
Elvis, M., Civano, F., Vignani, C., et al. 2009, ApJS, 184, 158

The Astrophysical Journal, 796:4 (10pp), 2014 November 20

Allevato et al.
