

# THE XMM-NEWTON WIDE FIELD SURVEY IN THE COSMOS FIELD: REDSHIFT EVOLUTION OF AGN BIAS AND SUBDOMINANT ROLE OF MERGERS IN TRIGGERING MODERATE LUMINOSITY AGN AT REDSHIFT UP TO 2.2

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## ABSTRACT

We present a study of the redshift evolution of the projected correlation function of 593 X-ray selected AGN with  $I_{AB} < 23$  and spectroscopic redshifts  $z < 4$ , extracted from the 0.5-2 keV X-ray mosaic of the 2.13deg<sup>2</sup> XMM-COSMOS survey. We introduce a method to estimate the average bias of the AGN sample and the mass of AGN hosting halos, solving the sample variance using the halo model and taking into account the growth of the structure over time. We find evidence of a redshift evolution of the bias factor for the total population of XMM-COSMOS AGN from  $\bar{b}(\bar{z} = 0.92) = 2.30 \pm 0.11$  to  $\bar{b}(\bar{z} = 1.94) = 4.37 \pm 0.27$  with an average mass of the hosting DM halos  $\log M_0 [h^{-1} M_\odot] \sim 13.12 \pm 0.12$  that remains constant at all  $z < 2$ .

Splitting our sample into broad optical lines AGN (BL), AGN without broad optical lines (NL) and X-ray unobscured and obscured AGN, we observe an increase of the bias with redshift in the range  $\bar{z} = 0.7 - 2.25$  and  $\bar{z} = 0.6 - 1.5$  which corresponds to a constant halo mass  $\log M_0 [h^{-1} M_\odot] \sim 13.28 \pm 0.07$  and  $\log M_0 [h^{-1} M_\odot] \sim 13.00 \pm 0.06$  for BL /X-ray unobscured AGN and NL/X-ray obscured AGN, respectively.

The theoretical models which assume a quasar phase triggered by major mergers can not reproduce the high bias factors and DM halo masses found for X-ray selected BL AGN with  $L_{BOL} \sim 2 \times 10^{45} \text{ erg s}^{-1}$ . Our work extends up to  $z \sim 2.2$  the  $z \lesssim 1$  statement that, for moderate luminosity X-ray selected BL AGN, the contribution from major mergers is outnumbered by other processes, possibly secular such as tidal disruptions or disk instabilities.

*Subject headings:* Surveys - Galaxies: active - X-rays: general - Cosmology: Large-scale structure of Universe - Dark Matter

## 1. INTRODUCTION

Investigating the clustering properties of active galactic nuclei (AGN) is important to put tight constraints on how the AGN are triggered and fueled, to identify

the properties of the AGN host galaxies, and to understand how galaxies and AGN co-evolve. In addition, in the framework of the cold dark matter (CDM) structure formation scenario, clustering properties or the bias of AGN, may be related to the typical mass of dark matter (DM) halos in which they reside (Mo & White 1996; Sheth & Tormen 1999; Sheth et al. 2001; Tinker et al. 2005) and allow various types of AGN to be placed in a cosmological context.

Recently, several studies have been made, employing spectroscopic redshifts to measure the three dimensional correlation function of X-ray AGN. The majority of the X-ray surveys agree with a picture where X-ray AGN are typically hosted in DM halos with mass of the order of  $12.5 < \log M_{DM} [h^{-1} M_\odot] < 13.5$ , at low ( $z < 0.4$ ) and high ( $z \sim 1$ ) redshift (Gilli et al. 2005; Yang et al. 2006; Gilli et al. 2009; Hickox et al. 2009; Coil et al. 2009; Krumpke et al. 2010; Cappelluti et al. 2010). This implies that X-ray AGN more likely reside in massive DM halos and preferentially inhabit dense environment typical of galaxy groups.

There have been attempts to detect X-ray luminosity dependence of the clustering. At  $z \sim 1$ , neither Gilli et al. (2009) nor Coil et al. (2009) found significant dependence of the clustering amplitudes on the optical luminosity, X-ray luminosity or hardness ratio, partially due to the larger statistical errors. Recent works by Krumpke et al. (2010) and Cappelluti et al. (2010) found,

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however, that high X-ray luminosity AGN cluster more strongly than low X-ray luminosity ones at  $2\sigma$  level for  $z \sim 0.3$  and  $z \sim 0$ , respectively.

Until recently, the clustering of AGN has been studied mainly in optical, particularly in large area surveys such as 2dF (2QZ, Croom et al. 2005; Porciani & Norberg 2006) and Sloan Digital Sky Survey (SDSS, Li et al. 2006; Shen et al. 2009; Ross et al. 2009). Croom et al. (2005) analysed the clustering of 2QZ QSO as a function of redshift finding a strong evolution of QSO bias, with  $b_Q(z = 0.53) = 1.13 \pm 0.18$  at low redshift and  $b_Q(z = 2.48) = 4.24 \pm 0.53$  at high redshift, as also observed in Porciani & Norberg (2006). The evidence of an evolution over time of the bias factor for SDSS quasars has been found in Shen et al. (2009), with bias values ranging from  $b_Q(z = 0.50) = 1.32 \pm 0.17$  to  $b_Q(z = 3.17) = 7.76 \pm 1.44$ . The results from these surveys have also shown that the bias evolution of optically selected quasars is consistent with an approximately constant mass at all redshifts of the hosting DM halo in the range  $\log M_{DM} \sim 12.5 - 13 [h^{-1} M_\odot]$ .

Besides models of major mergers between gas-rich galaxies appear to naturally produce the bias of quasars as a function of  $L$  and  $z$  (Hopkins et al. 2008; Shen 2009; Shankar et al. 2009, 2010; Shankar 2010; Bonoli et al. 2009), supporting the observations that bright quasars host galaxies present a preference for merging systems. It is still to be verified if the results from optical surveys can be extended to the whole AGN population and in particular to the X-ray selected AGN.

In this paper, we concentrate on the study of the bias evolution with redshift using different X-ray AGN samples and we focus on the estimation of the bias factor and the hosting halo mass using a new method which properly account for the sample variance and the strong evolution of the bias with the time.

The paper is organized as follows. In section §2 we describe the XMM-COSMOS AGN sample and the AGN subsets used to estimate the correlation function. In §3 we describe the random catalog generated to reproduce the properties of the data sample and the method to measure two-point statistic is explained in §4. The results of the AGN auto-correlation based on the standard method of the power-law fitting of the signal and using the two-halo term are given in §5. In §6 we present our own method to estimate the AGN bias factor and the DM halos masses in which AGN reside, solving the sample variance and the bias evolution with redshift and in §7 the results. In §8 we present the redshift evolution of the bias factor and the corresponding DM halo masses for the different AGN subsets. We discuss the results in the context of previous studies in §9 and we conclude in §10. 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. We use a  $\Lambda$ CDM cosmology with  $\Omega_M = 0.3$ ,  $\Omega_\Lambda = 0.7$ ,  $\Omega_b = 0.045$ ,  $\sigma_8 = 0.8$ . The symbol  $\log$  signifies a base-10 logarithm.

## 2. AGN CATALOG

The *Cosmic Evolution Survey* (COSMOS) is a multi-wavelength observational project over  $1.4 \times 1.4 \text{ deg}^2$  of equatorial field centred at  $(RA, DEC)_{J2000} = (150.1083, 2.210)$ , aimed to study AGN, galaxies, large scale structure of the Universe and their co-evolution. The sur-

vey uses multi wavelength imaging from X-ray to radio bands, including HST (Scoville et al. 2007), SUBARU (Taniguchi et al. 2007), Spitzer (Sanders et al. 2007) and GALEX (Zamojski et al. 2007). The central  $0.9 \text{ deg}^2$  of the COSMOS field has been observed in X-ray with *Chandra* for a total of 1.8 Ms (Elvis et al. 2009). In addition spectroscopic campaigns have been carried out with VIMOS/VLT and extensive spectroscopic follow-up have been granted with the IMACS/Magellan, MMT and DEIMOS/KeckII projects.

XMM-*Newton* surveyed  $2.13 \text{ deg}^2$  of the sky in the COSMOS field in the 0.5-10 keV energy band for a total of  $\sim 1.55$  Ms (Hasinger et al. 2007; Cappelluti et al. 2007, 2009) providing an unprecedentedly large sample of point-like X-ray sources (1822).

The XMM-COSMOS catalog has been cross-correlated with the optical multiband catalog (Cappelluti et al. 2007), the K-band catalog (McCracken et al. 2010), the IRAC catalog (Sanders et al. 2007; Ilbert et al. 2010) and the MIPS catalog (Le Floc'h et al. 2009). Brusa et al. (2010) presented the XMM-COSMOS multiwavelength catalog of 1797 X-ray sources with optical/near infrared identification, multiwavelength properties and redshift information (from Lilly et al. 2007, 2009; Trump et al. 2007; Adelman-McCarthy et al. 2006; Prescott et al. 2006; Salvato et al. 2009).

In this paper we focus on the clustering analysis of 1465 XMM-COSMOS AGN detected in the energy band 0.5-2 keV, for which we have a spectroscopic completeness of  $\sim 53\%$  (780/1465). From this sample of 780 objects we selected 593 sources with  $I_{AB} < 23$  (this magnitude cut increases the spectroscopic completeness to about 65%) and redshift  $z < 4$ . The redshift distribution of the AGN sample (Fig. 1 *left panel*) shows prominent peaks at various redshifts,  $z \sim 0.12$ ,  $z \sim 0.36$ ,  $z \sim 0.73$ ,  $z \sim 0.95$ ,  $z \sim 1.2$ ,  $z \sim 2.1$ . In particular, the structure at  $z \sim 0.36$  was also observed at other wavelengths in COSMOS (Lilly et al. 2007) and already discussed (Gilli et al. 2009). The median redshift of the sample is  $\langle z \rangle = 1.22$ .

The sources have been classified in Brusa et al. (2010) in broad optical line AGN (BL AGN, 354), non-broad optical line AGN (NL AGN, 239) using a combination of X-ray and optical criteria, motivated by the fact that both obscured and unobscured AGN can be misclassified in spectroscopic studies, given that the host galaxy light may over shine the nuclear emission. Fig. 2 shows the redshift distribution of BL AGN with  $\langle z \rangle = 1.55$  and NL AGN with  $\langle z \rangle = 0.74$ .

We also studied the clustering properties of X-ray unobscured and obscured AGN derived on the basis of the observed X-ray hardness ratio and corrected to take into account the redshifts effects. In particular we used the hard X-ray band (2-10 keV) (which allows us to sample the obscured AGN population) to select a subset of 184 X-ray unobscured sources (X-unobs hereafter) with  $\log N_H < 22 \text{ cm}^{-2}$  and 218 X-ray obscured (X-obs hereafter) sources with  $\log N_H \geq 22 \text{ cm}^{-2}$ . The median redshift of the two sub-samples are  $\langle z \rangle = 1.12$  and  $\langle z \rangle = 1.30$ , respectively (see fig. 2, *right panel*). The 47% (40%) of BL (NL) AGN have been also observed in the hard band and classified as X-unobs (X-obs) AGN.

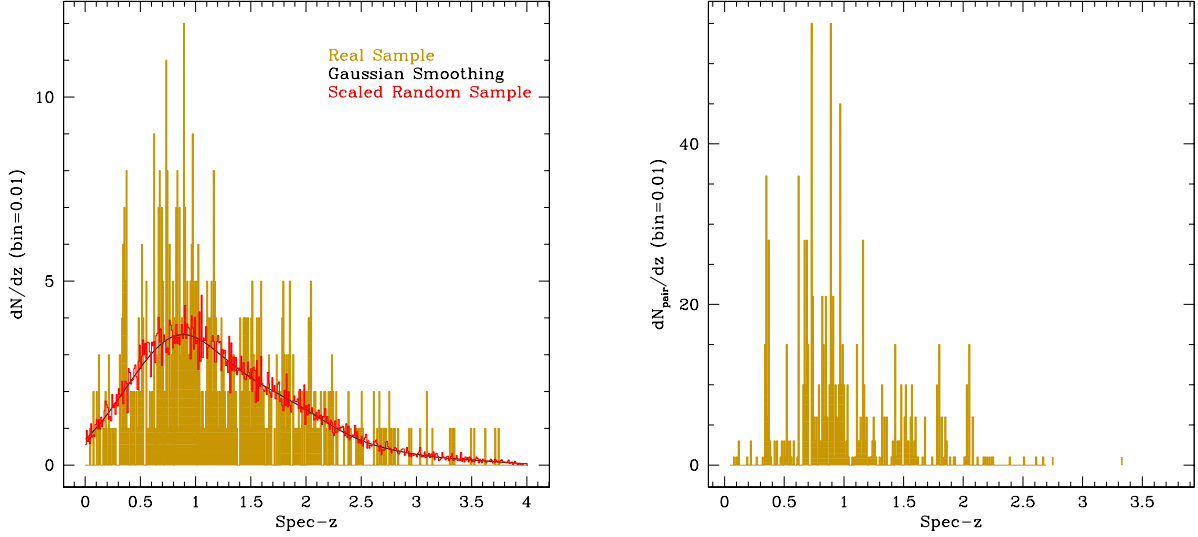


FIG. 1.— *Left panel*: Redshift distribution of 593 AGN (gold filled histogram) in bins of  $\Delta z = 0.01$ , with median  $\bar{z} = 1.22$ . The solid black curve is the Gaussian smoothing of the AGN redshift distribution with  $\sigma_z = 0.3$ , used to generate the random sample (red empty histogram). *Right panel*: distribution of AGN pairs in redshift bins  $\Delta z = 0.01$ .

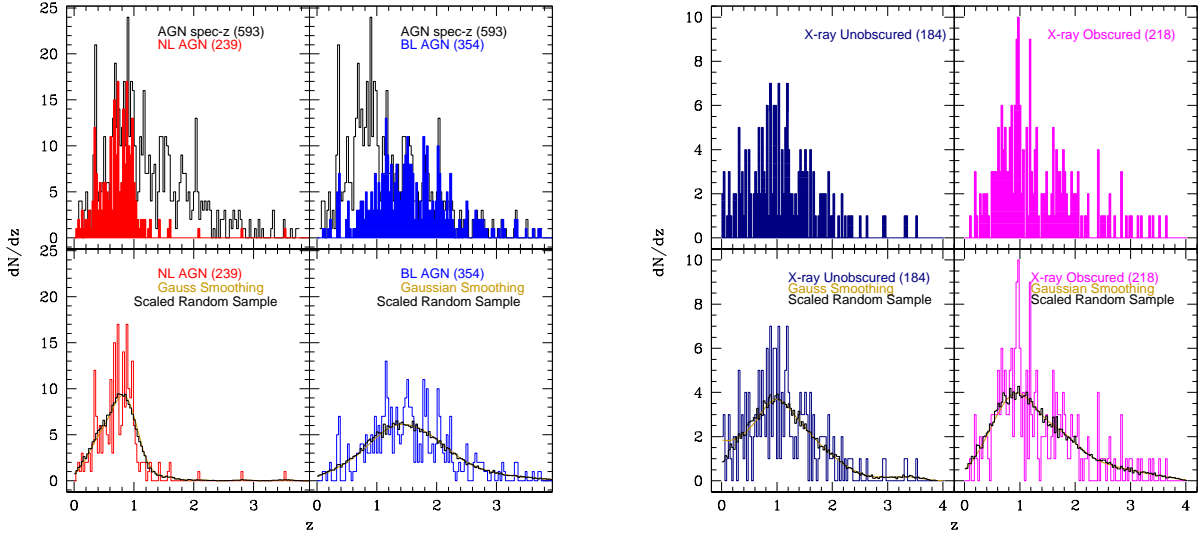


FIG. 2.— *Left Panel*: Redshift distribution of XMM-COSMOS AGN (open histogram) selected in the soft band, compared with the redshift distribution of BL AGN (blue histogram, *upper right quadrant*) and NL AGN, (red, *upper left quadrant*). Lower quadrants show the redshift distribution of the random catalogs (open black histograms) for both the AGN sub-samples, obtained using a Gaussian smoothing (gold lines) of the redshift distribution of the real samples. *Right Panel*: Redshift distribution of unobscured (dark blue histogram) and obscured (magenta histogram) AGN selected in the hard band according with the column density (*upper quadrants*). Lower quadrants show the redshift distribution of the random catalogs (open black histograms) for both the AGN sub-samples, obtained using a Gaussian smoothing (gold lines) of the redshift distribution of the real samples.

### 3. RANDOM CATALOG

The measurements of two-point correlation function requires the construction of a random catalog with the same selection criteria and observational effects as the data, to serve as an unclustered distribution to which to compare. XMM-Newton observations have varying sensitivity over the COSMOS field. In order to create an AGN random sample, which takes the inhomogeneity of the sensitivity over the field into account, each simulated source is placed at random position in the sky, with flux randomly extracted from the catalog of real sources

(we verified that such flux selection produces the same results as if extracting the simulated sources from a reference input  $\log N$ - $\log S$ ). 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). Placing these sources at random position in the XMM-COSMOS field has the advantage of not removing the contribution to the signal due to angular clustering. On the other hand, this procedure does not take into account possible positional biases related to the optical follow-up program. Gilli et al. (2009), who

instead decided to extract the coordinates of the random sources from the coordinate ensemble of the read sample, showed that there is a difference of only 15% in the correlation lengths measured with the two procedures.

The corresponding redshift for a random object is assigned based on the smoothed redshift distribution of the AGN sample. As in Gilli et al. (2009) we assumed a Gaussian smoothing length  $\sigma_z = 0.3$ . This is a good compromise between scales that are either too small, thus affected by local density variations or too large and thus oversmooth the distribution (our results do not change significantly using  $\sigma_z = 0.2 - 0.4$ ). Fig. 1 (*left panel*) shows the redshift distribution of 593 XMM-COSMOS AGN and the scaled random sample ( $\sim 41000$  random sources) which follows the red solid curve obtained by Gaussian smoothing.

#### 4. TWO-POINT STATISTICS

A commonly used technique for measuring the spatial clustering of a class of objects is the two-point correlation function  $\xi(r)$ , which measures the excess probability  $dP$  above a random distribution of finding an object in a volume element  $dV$  at a distance  $r$  from another randomly chosen object (Peebles 1980):

$$dP = n[1 + \xi(r)]dV \quad (1)$$

where  $n$  is the mean number density of objects. In par-

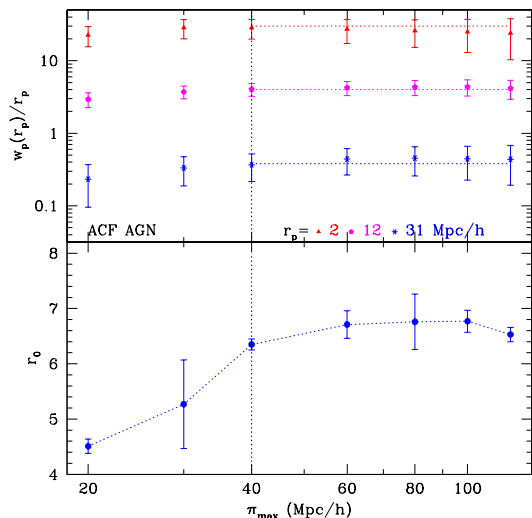


FIG. 3.— Projected AGN correlation function  $w_p(r_p)$  computed at different  $r_p$  scale (see label) as function of the integral radius  $\pi_{max}$ . Horizontal lines show that the ACF saturates for  $\pi_{max} > 40$  Mpc/h, which is also the minimum  $\pi_{max}$  at which  $w_p(r_p)$  converges and returns the smaller error on the best-fit correlation parameter  $r_0$ , with  $\gamma$  fixed to 1.8.

ticular, the auto-correlation function (ACF) measures the excess probability of finding two objects from the same sample in a given volume element. With a redshift survey, we cannot directly measure  $\xi(r)$  in physical space, because peculiar motions of galaxies distort the line-of-sight distances inferred from redshift. To separate the effects of redshift distortions, the spatial correlation function is measured in two dimensions  $r_p$  and  $\pi$ , where  $r_p$  and  $\pi$  are the projected comoving separations be-

tween the considered objects in the directions perpendicular and parallel, respectively, to the mean line-of-sight between the two sources. Following Davis & Peebles (1983),  $r_1$  and  $r_2$  are the redshift positions of a pair of objects,  $s$  is the redshift-space separation ( $r_1 - r_2$ ), and  $l = \frac{1}{2}(r_1 + r_2)$  is the mean distance to the pair. The separations between the two considered objects across  $r_p$  and  $\pi$  are defined as:

$$\pi = \frac{\mathbf{s} \cdot \mathbf{l}}{|\mathbf{l}|} \quad (2)$$

$$r_p = \sqrt{(\mathbf{s} \cdot \mathbf{s} - \pi^2)} \quad (3)$$

Redshift space distortions only affect the correlation function along the line of sight, so we estimate the so-called projected correlation function  $w_p(r_p)$  (Davis & Peebles 1983):

$$w_p(r_p) = 2 \int_0^{\pi_{max}} \xi(r_p, \pi) d\pi \quad (4)$$

where  $\xi(r_p, \pi)$  is the two-point correlation function in term of  $r_p$  and  $\pi$ , measured using the Landy & Szalay (1993, LS) estimator:

$$\xi = \frac{1}{RR'} [DD' - 2DR' + RR'] \quad (5)$$

$DD'$ ,  $DR'$  and  $RR'$  are the normalized data-data, data-random and random-random number of pairs defined by:

$$DD' = \frac{DD(r_p, \pi)}{n_d(n_d - 1)} \quad (6)$$

$$DR' = \frac{DR(r_p, \pi)}{n_d n_r} \quad (7)$$

$$RR' = \frac{RR(r_p, \pi)}{n_r(n_r - 1)} \quad (8)$$

where  $DD$ ,  $DR$  and  $RR$  are the number of data-data, data-random and random-random pairs at separation  $r_p \pm \Delta r_p$  and  $\pi \pm \Delta \pi$  and  $n_d$ ,  $n_r$  are the total number of sources in the data and random sample, respectively. Fig. 1 (*right panel*) shows the number of pairs in redshift bins  $\Delta z = 0.01$  for the AGN sample.

The LS estimator has been used to measure correlations in a number of surveys, for example, SDSS (Zehavi et al. 2005; Li et al. 2006), DEEP2 (Coil et al. 2007, 2008), AGES (Hickox et al. 2009), COSMOS (Gilli et al. 2009). If  $\pi_{max} = \infty$ , then we average over all line-of-sight peculiar velocities, and  $w_p(r_p)$  can be directly related to  $\xi(r)$  for a power-law parameterization, by:

$$w_p(r_p) = r_p \left( \frac{r_0}{r_p} \right)^\gamma \frac{\Gamma(1/2)\Gamma[(\gamma - 1)/2]}{\Gamma(\gamma/2)} \quad (9)$$

In practice, we truncate the integral at a finite  $\pi_{max}$  value, to maximize the correlation signal. One should avoid values of  $\pi_{max}$  too large since they would add noise to the estimate of  $w_p(r_p)$ ; if instead,  $\pi_{max}$  is too small one would not recover all the signal. To determine the appropriate  $\pi_{max}$  values for the XMM-COSMOS AGN correlation function, we estimated  $w_p(r_p)$  for different values of  $\pi_{max}$  in the range 20-120 Mpc  $h^{-1}$ . Besides, we determined the correlation length  $r_0$  for this set of  $\pi_{max}$

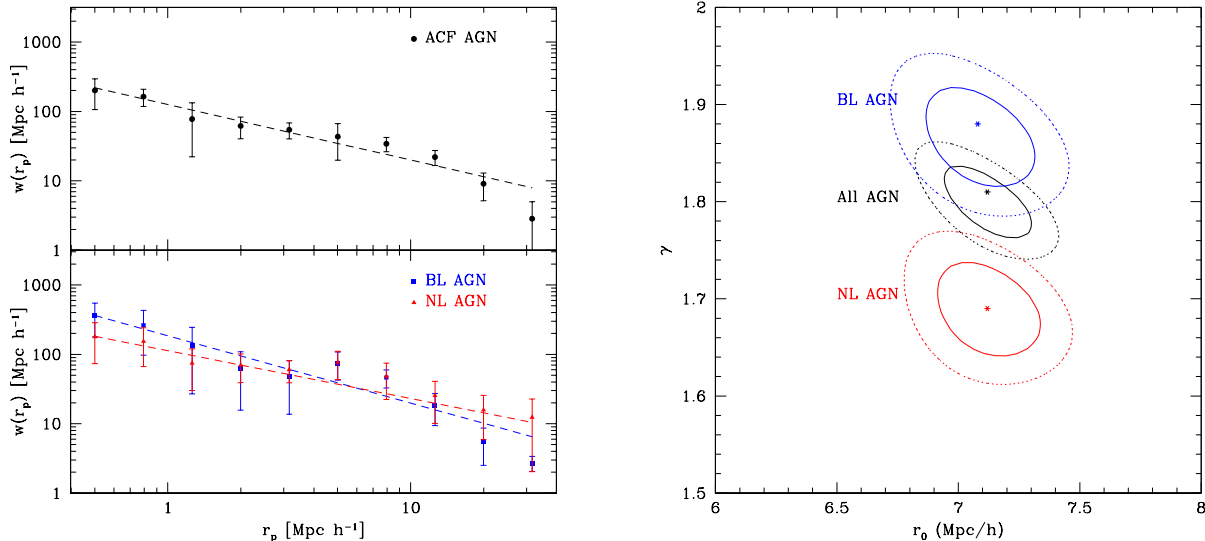


FIG. 4.— *Left panel*: Projected AGN ACF (black circles) compared to the auto-correlation of BL AGN (blue squares) and NL AGN (red triangles). The data points are fitted with a power-law model using the  $\chi^2$  minimization technique; the errors are computed with a bootstrap resampling method. *Right panel*: The confidence contours of the power-law best-fit parameters  $r_0$  and  $\gamma$ , for the whole AGN sample (black), for the BL AGN (blue) and NL AGN (red) sub-samples. The contours mark the 68.3% and 95.4% confidence levels (respectively corresponding to  $\Delta\chi^2 = 2.3$  and 6.17) are plotted as continuous and dotted lines.

values, by fitting  $w_p(r_p)$  with a fixed  $\gamma=1.8$  over  $r_p$  in the range 0.5-40  $\text{Mpc } h^{-1}$ . In Fig. 3 we show the increase of the projected AGN auto-correlation  $w_p(r_p)$  as a function of the integration radius  $\pi_{max}$ . The  $w_p(r_p)$  values appear to converge for  $\pi_{max} > 40 \text{ Mpc } h^{-1}$ . Therefore we adopt  $\pi_{max} = 40 \text{ Mpc } h^{-1}$  in the following analysis, which is the minimum  $\pi_{max}$  at which the correlation function converges. Such  $\pi_{max}$  selection returns the smallest error on the best-fit correlation parameter  $r_0$ .

## 5. PROJECTED AUTO-CORRELATION FUNCTION

### 5.1. Standard Approach

To estimate the AGN auto-correlation function  $\xi(r_p, \pi)$  using the LS formula (Eq. 5), we created a grid with  $r_p$  and  $\pi$  in the range 0.1-100  $\text{Mpc } h^{-1}$ , in logarithmic bins  $\Delta\log(r_p, \pi) = 0.2$  and we projected  $\xi(r_p, \pi)$  on  $r_p$  using Eq. 4.

In literature, several methods are adopted for error estimates in two-point statistics and no one has been proved to be the most precise. It is known that Poisson estimators generally underestimate the variance because they do not account for the fact that the points are not statistically independent, i.e. the same objects appear in more than one pair. In this work we computed the errors on  $w_p(r_p)$  with a bootstrap resampling technique (Coil et al. 2009; Hickox et al. 2009; Krumpe et al. 2010; Cappelluti et al. 2010).

The standard approach used to evaluate the power of the clustering signal is to fit  $w_p(r_p)$  with a power-law model (Coil et al. 2009; Hickox et al. 2009; Gilli et al. 2009; Krumpe et al. 2010; Cappelluti et al. 2010) of the form given in Eq. 9, using a  $\chi^2$  minimization technique, with  $\gamma$  and  $r_0$  as free parameters. Fig. 4 (*left panel, upper quadrant*) shows the projected AGN ACF, evaluated in the projected separation range  $r_p = 0.5-40 \text{ Mpc } h^{-1}$ . The best-fit correlation length and slope and the corre-

sponding  $1\sigma$  errors, are found to be  $r_0 = 7.12^{+0.28}_{-0.18} \text{ Mpc } h^{-1}$  and  $\gamma = 1.81^{+0.04}_{-0.03}$ .

We estimated the projected correlation function of BL and NL AGN in the range  $r_p = 0.5 - 40 \text{ Mpc } h^{-1}$ , as shown in Fig.4 (*left panel, lower quadrant*). For BL AGN we found a correlation length  $r_0 = 7.08^{+0.30}_{-0.28} \text{ Mpc } h^{-1}$  and  $\gamma = 1.88^{+0.04}_{-0.06}$ , while for NL AGN we measured  $r_0 = 7.12^{+0.22}_{-0.20} \text{ Mpc } h^{-1}$  and a flatter slope  $\gamma = 1.69^{+0.05}_{-0.05}$ . Fig. 4 (*right panel*) shows the power-law best-fit parameters for the different AGN samples with the  $1\sigma$  and  $2\sigma$  confidence intervals for a two parameter fit, which correspond to  $\chi^2 = \chi^2_{min} + 2.3$  and  $\chi^2 = \chi^2_{min} + 6.17$ .

We can estimate the AGN bias factor using the power-law best fit parameters:

$$b_{PL} = \sigma_{8,AGN}(z)/\sigma_{DM}(z) \quad (10)$$

where  $\sigma_{8,AGN}(z)$  is rms fluctuations of the density distribution over the sphere with a comoving radius of 8  $\text{Mpc } h^{-1}$ ,  $\sigma_{DM}(z)$  is the DM correlation function evaluated at 8  $\text{Mpc } h^{-1}$ , normalized to a value of  $\sigma_{DM}(z=0) = 0.8$ . For a power-law correlation function this value can be calculated by (Peebles 1980):

$$(\sigma_{8,AGN})^2 = J_2(\gamma) \left( \frac{r_0}{8 \text{ Mpc}/h} \right)^\gamma \quad (11)$$

where  $J_2(\gamma) = 72/[(3-\gamma)(4-\gamma)(6-\gamma)2^\gamma]$ . As the linear regime of the structure formation is verified only at large scales, the best-fit parameters  $r_0$  and  $\gamma$  are estimated fitting the projected correlation function on  $r_p = 1 - 40 \text{ Mpc } h^{-1}$ . The  $1\sigma$  uncertainty of  $\sigma_{8,AGN}$  is computed from the  $r_0$  vs.  $\gamma$  confidence contour of the two-parameter fit corresponding to  $\chi^2 = \chi^2_{min} + 2.3$ .

### 5.2. Two-halo Term

In the halo model approach, the two-point correlation function of AGN is the sum of two contributions: the

TABLE 1  
BIAS FACTORS AND HOSTING DM HALO MASSES

(1) <i>AGN Sample</i>	(2) $\langle z \rangle^a$	(3) $b_{PL}$ Eq. 10	(4) $b_{2-h}$ Eq. 16	(5) $\log \bar{M}_{DM}^b$ $h^{-1} M_\odot$
Total (593)	1.22	$2.80^{+0.22}_{-0.90}$	$2.98 \pm 0.13$	$13.23 \pm 0.06$
BL (354)	1.55	$3.11^{+0.30}_{-1.22}$	$3.43 \pm 0.17$	$13.14 \pm 0.07$
NL (239)	0.74	$2.78^{+0.45}_{-1.07}$	$2.70 \pm 0.22$	$13.54 \pm 0.10$
X-unobs (184)	1.12	$2.98^{+0.34}_{-0.37}$	$3.01 \pm 0.21$	$13.33 \pm 0.08$
X-obs (218)	1.30	$1.66^{+0.31}_{-0.32}$	$1.80 \pm 0.15$	$12.30 \pm 0.15$
Subsample at $z < 1$				
BL (70)	0.57	$2.18^{+0.95}_{-1.02}$	$2.32 \pm 0.26$	$13.50 \pm 0.11$
NL (137)	0.53	$1.68^{+0.45}_{-0.57}$	$1.40 \pm 0.15$	$12.65 \pm 0.18$

<sup>a</sup> Median redshift of the sample.

<sup>b</sup> Typical DM halo masses based on Sheth et al. (2001) and van den Bosch (2002).

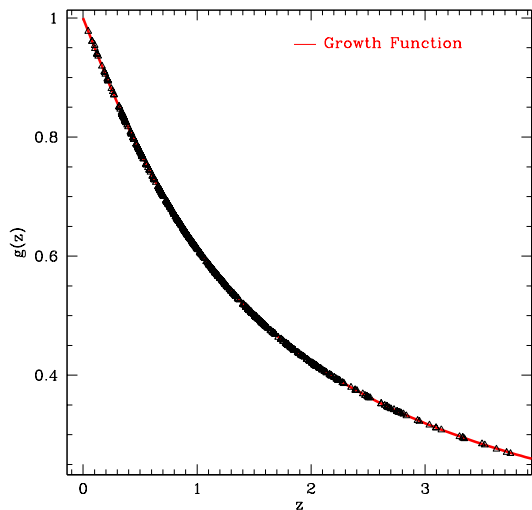


FIG. 5.— Factor  $g$  as defined in Eq. 21, estimated at the redshift of each AGN (black triangles). The data points are fitted by the function  $D_1(z)/D_1(z=0)$ , where  $D_1(z)$  is the growth function (see Eq. (10) in Eisenstein & Hu 1999 and references therein). The bias of each AGN is weighted by this factor according to the redshift  $z$  of the source.

first term (1-halo term) is due to the correlation between objects in the same halo and the second term (2-halo term) arises because of the correlation between two distinct halos:

$$w_{AGN}(r_p) = w_{AGN}^{1-h}(r_p) + w_{AGN}^{2-h}(r_p) \quad (12)$$

As the 2-halo term dominates at large scales, we can consider this term to be in the regime of linear density fluctuations. In the linear regime, AGN are biased tracers of the DM distribution and the AGN bias factor defines the relation between the two-halo term of DM and AGN.

$$w_{AGN}^{2-h}(r_p) = b_{AGN}^2 w_{DM}^{2-h}(r_p) \quad (13)$$

We first estimated the DM 2-halo term at the median redshift of the sample, using:

$$\xi_{DM}^{2-h}(r) = \frac{1}{2\pi^2} \int P^{2-h}(k) k^2 \left[ \frac{\sin(kr)}{kr} \right] dk \quad (14)$$

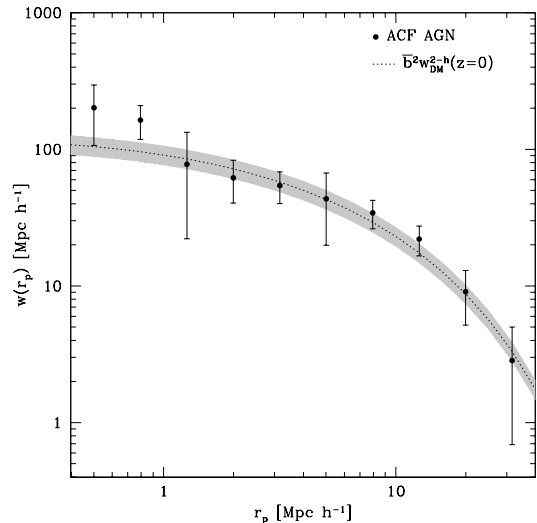


FIG. 6.— Projected AGN ACF (black circles) compared to  $\bar{b}^2 w_{DM}^{2-h}(r_p, z=0)$  (dotted line), where the weighed bias  $\bar{b}$  is defined in Eq. 22. The shaded region shows the projected DM 2-halo term scaled by  $(\bar{b} \pm \delta \bar{b})^2$ .

where  $P^{2-h}(k)$  is the Fourier Transform of the linear power spectrum, assuming a power spectrum shape parameter  $\Gamma = 0.2$  and  $h = 0.7$ . Following Hamana et al. (2002), we estimated  $\xi_{DM}^{2-h}(r)$  and then the DM projected correlation  $w_{DM}^{2-h}(r_p)$  using:

$$w_{DM}^{2-h}(r_p) = 2 \int_{r_p}^{\infty} \frac{\xi_{DM}^{2-h}(r) r dr}{\sqrt{r^2 - r_p^2}} \quad (15)$$

Using this term, we can estimate the AGN bias simply dividing the projected AGN correlation function at large scale ( $r_p > 1 \text{ Mpc } h^{-1}$ ) by the DM 2-halo term:

$$b_{AGN}^2 = (w_{AGN}^{2-h}(r_p) / w_{DM}^{2-h}(r_p))^{1/2} \quad (16)$$

and then averaging over the scales  $r_p = 1 - 40 \text{ Mpc } h^{-1}$ . Table 1, column 4 shows the AGN bias factors using this method, compared with the ones based on the power-law fits of the ACF (column 3) for the different AGN subsets. The two sets of bias values from the different approaches are consistent within  $1\sigma$ , but the errors on  $b_{PL}$  are bigger consistently with the fact that the AGN ACF is not well described by a power-law.

## 6. SOLVING FOR SAMPLE VARIANCE USING HOD

The standard approaches used in previous works on clustering of X-ray AGN (Mullis et al 2004; Yang et al. 2006; Gilli et al. 2005; Coil et al. 2009; Hickox et al. 2009; Krumpel et al. 2010; Cappelluti et al. 2010) to estimate the bias factors from the projected AGN ACF are based on the power-law fit parameters (method 1). This method assumes that the projected correlation function is well fitted by a power-law and the bias factors are derived from the best fit parameters  $r_0$  and  $\gamma$  of the clustering signal at large scale.

Most of the authors (Hickox et al. 2009; Krumpel et al. 2010; Cappelluti et al. 2010) used an analytical expression (as the one described in Sheth & Tormen 1999;

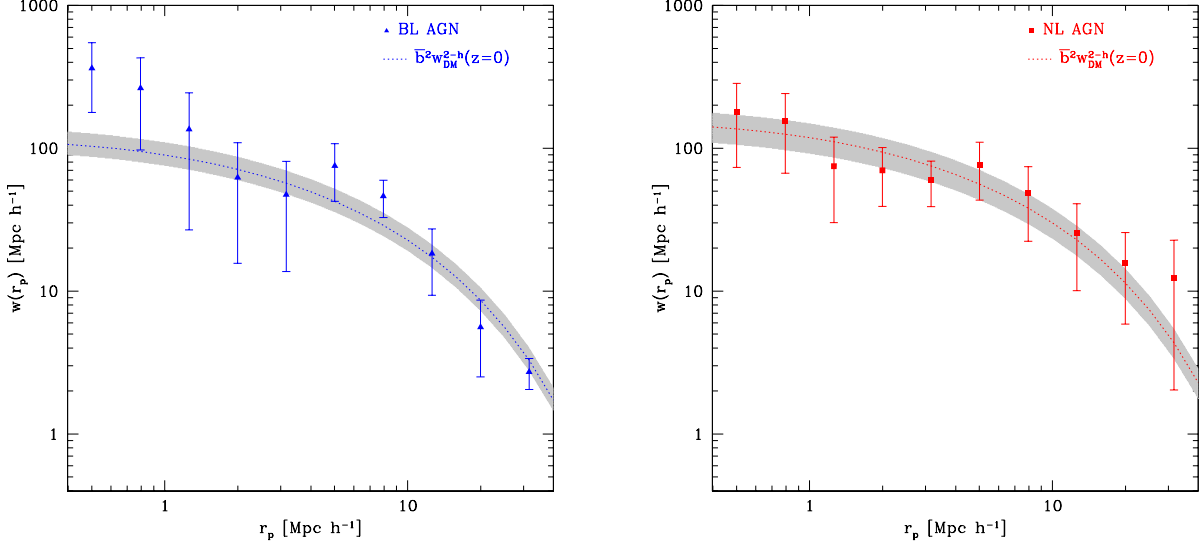


FIG. 7.— Projected ACF of BL AGN (blue triangles, *left panel*) and NL AGN (red squares, *right panel*), compared to  $\bar{b}^2 w_{DM}^{2-h}(r_p, z=0)$  (dotted line), where the weighed bias  $\bar{b}$  is defined in Eq. 22. The shaded region shows the projected DM 2-halo term scaled by  $(\bar{b} \pm \delta\bar{b})^2$ .

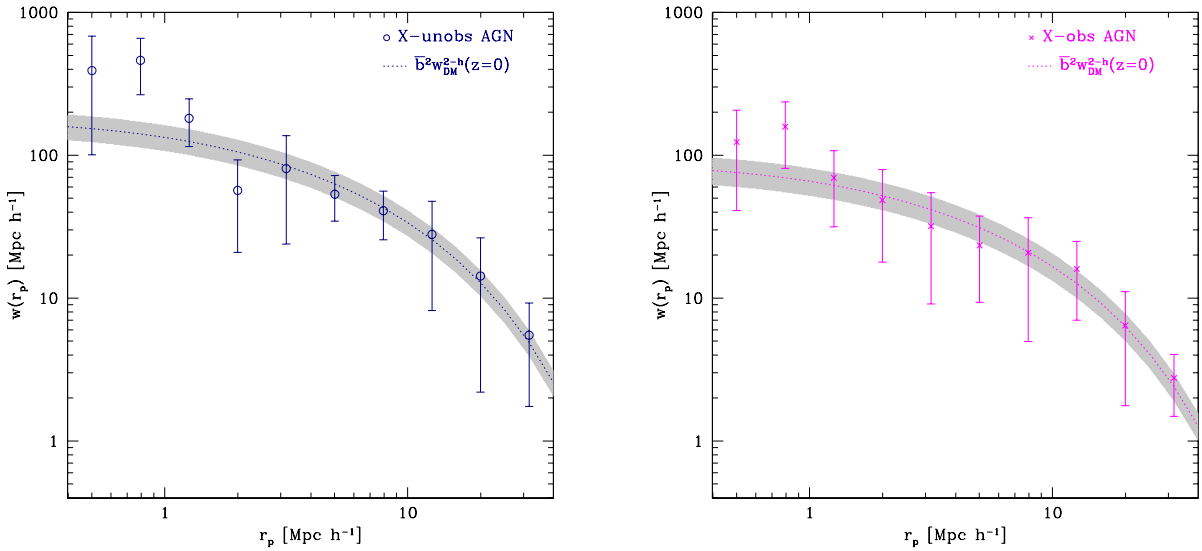


FIG. 8.— Projected ACF of X-unobs AGN (darkblue open circles, *left panel*) and X-obs AGN (magenta diagonal crosses, *right panel*), compared to  $\bar{b}^2 w_{DM}^{2-h}(r_p, z=0)$  (dotted line), where the weighed bias  $\bar{b}$  is defined in Eq. 22. The shaded region shows the projected DM 2-halo term scaled by  $(\bar{b} \pm \delta\bar{b})^2$ .

Sheth et al. 2001; Tinker et al. 2005) to assign a characteristic DM halo mass to the hosting halos. The incongruity of this approach is that the bias used is the average bias of a given sample at a given redshift. However, the average bias is sensitive to the entirety of the mass distribution so that distributions with different average masses, can give rise to the same average bias value. In the halo model approach the large scale amplitude signal is due to the correlation between objects in distinct halos and the bias parameter defines the relation between the large scale clustering amplitude of the AGN ACF and the DM 2-halo term (method 2).

In literature, the common model used for the AGN HOD is a three parameter model including a step func-

tion for the HOD of central AGN and a truncated power-law satellite HOD (introduced by Zehavi et al. 2005, for galaxies). Here we assumed that all the AGN reside in central galaxies. This assumption is supported by Starikova et al. (2010). They found that X-ray AGN are predominantly located in the central galaxies of the host DM halos and tend to avoid satellite galaxies, fixing the limit to the fraction of AGN in non-central galaxies to be less than 10%. The same fraction of satellite galaxies hosting AGN is suggested in Shen (2009). Shankar et al. (2010) modelled the measurements of quasar clustering derived in the SDSS (Shen et al. 2009) and they verified that the predicted bias factors and the correlation functions are not altered including subhalos as quasar hosts.

TABLE 2  
WEIGHTED BIAS FACTORS AND HOSTING DM HALO MASSES

(1) <i>AGN</i> <i>Sample</i>	(2) $\bar{b}$ Eq. 22	(3) $\bar{z}$ Eq. 23	(4) $\log M_0$ $h^{-1} M_\odot$	(5) $b_{S01}$ <sup>a</sup>
Total (593)	1.91 ± 0.13	1.21	13.10 ± 0.06	2.71 ± 0.14
BL (354)	1.74 ± 0.17	1.53	13.24 ± 0.06	3.68 ± 0.27
NL (239)	1.80 ± 0.22	0.82	13.01 ± 0.08	2.00 ± 0.12
X-unobs (184)	1.95 ± 0.21	1.16	13.30 ± 0.10	3.01 ± 0.26
X-obs (218)	1.37 ± 0.15	1.02	12.97 ± 0.08	2.23 ± 0.13
Subsample at $z < 1$				
BL (70)	1.62 ± 0.26	0.63	13.27 ± 0.10	1.95 ± 0.17
NL (137)	1.56 ± 0.15	0.60	12.97 ± 0.07	1.62 ± 0.15

<sup>a</sup> Bias estimated from  $M_0$  using Sheth et al. (2001).

A further consideration is that there is in practice no distinction between central and satellite AGN in the 2-halo term that we used to estimate the AGN bias factor.

We assumed a simple parametric form of the AGN halo occupation  $N_A$ , described by a delta function:

$$N_A(M_{DM}) = f_A \delta(M_{DM} - M_0) \quad (17)$$

where  $f_A$  is the AGN duty cycle. It is clear that we are not considering the full HOD model, but we are assigning to all the AGN the same average mass of the hosting halos. The motivation is that X-ray AGN mainly reside in massive halos with a narrow distribution of the hosting halo masses. It's clear that this assumption is specific to AGN and e.g. is not applicable to galaxies.

The AGN HOD described by  $\delta$ -function is motivated by the results of Miyaji et al. (2011) showing that the AGN HOD rapidly decreases at high halo masses. In addition Martini et al. (2009) and Silverman et al. (2009) found that AGN preferentially reside in galaxy groups rather than in clusters.

The  $\delta$ -function is the simplest possible assumption in the treatment of the sample variance, which is due to the variation in the amplitude of source counts distribution. It has been shown in Faltenbacher et al. (2010), that the variation in the density field, which is responsible for the sample variance, can be replaced by the variation of the halo mass function. In terms of halo model, the bias factor as a function of the fluctuations  $\Delta$  in the density field is expressed by:

$$b_A(\Delta) = \frac{\int_{M_h} N_A(M_h) b_h(M_h) n_h(M_h, \Delta) dM_h}{\int_{M_h} N_A(M_h) n_h(M_h, \Delta) dM_h} \quad (18)$$

where  $N_A$  is the AGN HOD,  $b_h(M_{DM})$  is the halo bias and  $n_h(M_{DM}, \Delta)$  is the halo mass function, which depends on the density field. On the other hand the sample variance does not effect the AGN halo occupation. In Allevato et al. (in prep.) we confirm the assumption of constancy of the AGN HOD with the density field.

When we assume that all AGN reside in DM halos with the same mass, Eq. 18 becomes simpler:

$$\frac{\int_{M_h} \delta(M_h - M_0) b_h(M_h) n_h(M_h, \Delta) dM_h}{\int_{M_h} \delta(M_h - M_0) n_h(M_h, \Delta) dM_h} = b(M_0) \quad (19)$$

The equation shows that when the AGN HOD is close to a  $\delta$ -function, the variations in the density field only

change the AGN number density and put more weight on AGN bias at the redshift of large scale structure (LSS), but do not change the bias of AGN inside the structure. Our claim differs from the results presented in Gilli et al. (2005) and (Gilli et al. 2009). They found that excluding sources located within a large-scale structures, the correlation length and then the bias factor strongly reduces. Such bias behaviour can be used to constrain more complicated shapes of the AGN HOD than a  $\delta$ -function type distribution.

However, even in the case of a  $\delta$ -function HOD, we still need to consider the two effects which are often omitted in the clustering analysis: the LSS growth and the evolution of the bias factor with  $z$ . Ignoring these effects can by itself lead to a difference in the results reported for the different AGN samples.

The bias factor depends on the redshift as the structures grow over time, associated with our use of a large redshift interval. For the  $i^{th}$  source at redshift  $z_i$ , we considered the bias factor corresponding to a halo mass  $M_{DM} = M_0$ :

$$b_i = b(M_0, z_i) \quad (20)$$

where  $b(M_0, z)$  is evaluated using van den Bosch (2002) and Sheth et al. (2001). For each AGN at redshift  $z$  we estimated the factor  $g(z)$  defined as the square root of the projected DM 2-halo term at redshift  $z$  normalized to the projected DM 2-halo term evaluated at  $z = 0$ :

$$g(z) = \sqrt{\frac{w_{DM}(z, r_p)}{w_{DM}(z=0, r_p)}} \quad (21)$$

averaged over the scales  $r_p = 1 - 40$  Mpc  $h^{-1}$ . As the amplitude of the projected DM 2-halo term decreases with increasing redshift,  $g$  is a decreasing function of  $z$  (see fig. 5), well described by the term  $D_1(z)/D_1(z=0)$ , where  $D_1(z)$  is the growth function (see eq. (10) in Eisenstein & Hu (2001) and references therein).

By accounting for the fact that the linear regime of the structure formation is verified only at large scales, we estimated the AGN bias considering only the pairs which contribute to the AGN clustering signal at  $r_p = 1 - 40$  Mpc  $h^{-1}$ . We defined the *weighted* bias factor of the sample as:

$$\bar{b}(M_0) = \sqrt{\frac{\sum_{i,j} b_i b_j g_i g_j}{N_{pair}}} \quad (22)$$

where  $b_i b_j$  is the bias factor of the  $i^{th}$  and  $j^{th}$  source in the pair  $i - j$ ,  $g_i g_j$  is the  $g$  factor of the pair and  $N_{pair}$  is the total number of pairs in the range  $r_p = 1 - 40$  Mpc  $h^{-1}$ .

Similarly, we defined a weighted average redshift of the AGN sample, weighting the redshift of each pair for the  $g$  factor and the bias of the pair ( $b_i b_j$ ):

$$\bar{z} = \frac{\sum_{i,j} b_i b_j g_i g_j z_{pair}}{\sum_{i,j} b_i b_j g_i g_j} \quad (23)$$

where  $z_{pair} = (z_i + z_j)/2$ . Following this approach we can find the value of  $M_0$  that satisfies:

$$b_1 = \bar{b}(M_0)$$



where  $b_1$  is the square root of the projected AGN ACF normalized to the projected DM 2-halo term at  $z = 0$ :

$$b_1 = \sqrt{\frac{w_{AGN}(r_p)}{w_{DM}(z=0, r_p)}} \quad (24)$$

averaged over the scale  $r_p = 1 - 40 \text{ Mpc } h^{-1}$ .

By performing the test in narrow redshift intervals, we can study the dependency of the halo mass  $M_0$  on redshift (see §8). Moreover with just a single measurement of the amplitude of the 2-halo term, one cannot constrain the AGN HOD. Already with several measurements sampling different density fields, the shape of the HOD can be linked to the LSS density-dependence of the bias. In addition, the 1-halo term of the AGN auto-correlation and AGN-groups cross-correlation can be used to discriminate between different HOD models, which will be argument of our following work.

## 7. MEASUREMENTS

The weighted bias factors  $\bar{b}$  and redshifts  $\bar{z}$ , and the corresponding DM halo masses  $M_0$  estimated for the different AGN sub-samples using the method described in the previous section are shown in Table 2.

Fig. 6, 7 and 8 show the ACF of the AGN, BL/NL AGN and X-unobs/obs AGN samples, compared to the term  $\bar{b}^2 w_{DM}^{2-h}(r_p, z=0)$  (dotted line), where the weighed bias  $\bar{b}$  is defined in Eq. 22. The shaded region shows the projected DM 2-halo term scaled by  $(\bar{b} \pm \delta\bar{b})^2$ .

The AGN bias factor indicates that XMM-COSMOS AGN reside in halos with average mass  $\log M_0 = 13.01 \pm 0.09 [h^{-1} \log M_\odot]$ , characteristic of moderate-size poor groups, a result consistent with previous works on X-ray selected AGN that indicate that the typical DM halo mass hosting AGN is in the range  $12.5 \lesssim \log M_{DM} \lesssim 13.5 [h^{-1} M_\odot]$ .

We found that BL and NL AGN which peak at  $\bar{z} = 1.53$  and  $\bar{z} = 0.82$ , present consistent bias factors which correspond to DM halo average masses  $\log M_0 = 13.24 \pm 0.06 [h^{-1} M_\odot]$  and  $13.01 \pm 0.08 [h^{-1} M_\odot]$ , respectively. As described in Brusa et al. (2010), only a small fraction of the objects classified as NL AGN are located at  $z > 1$ , to be compared with 350 in the BL AGN sample. This is mostly due to the fact that high-redshift NL AGN are optically faint (typically  $I \sim 23-24$ ) and have not been targeted yet with dedicated spectroscopic campaigns. Our results might be affected by the limitations in the obscured AGN classification, considering that some models on the evolution of the obscured AGN fraction predict an increase of the fraction with the redshift (Hasinger et al. 2008). In order to avoid the problem of different redshift distribution in comparing BL/NL AGN clustering amplitude, we selected for each sample a subset (BL AGN with 70 sources and NL AGN with 137) at  $\bar{z} \sim 0.6$ . At the same redshift we found that BL and NL AGN have a bias factor  $\bar{b}_{BL} = 1.62 \pm 0.26$  and  $\bar{b}_{NL} = 1.56 \pm 0.15$ , which correspond to average halo masses  $\log M_0 = 13.27 \pm 0.10 [h^{-1} M_\odot]$  and  $12.97 \pm 0.07 [h^{-1} M_\odot]$ , respectively.

Similar results have been obtained using X-unobs and X-obs AGN samples; unobscured AGN at  $\bar{z} = 1.16$  inhabit halos with average mass  $\log M_0 = 13.30 \pm 0.10 [h^{-1} M_\odot]$  which is higher at  $2.5 \sigma$  level than the halo mass hosting

obscured AGN ( $\log M_0 = 12.97 \pm 0.08 [h^{-1} M_\odot]$ ), at similar redshift.

In order to compare our results with previous works on the bias of X-ray selected AGN, we evaluated the bias factors corresponding to the halo mass  $M_0$  at  $\bar{z}$  using Sheth et al. (2001) as shown in Table 2, col (5).

Our results support the picture that at a given redshift, X-ray selected BL/X-unobs AGN reside in more massive halos compared to X-ray selected NL/X-obs AGN. This result would be expected if the two classes of AGN correspond to different phases of the AGN evolution sequence (Hopkins et al. 2006, 2008; Hickox et al. 2009).

## 8. BIAS EVOLUTION AND CONSTANT MASS THRESHOLD

In order to investigate the redshift evolution of the bias factor, we split the XMM-COSMOS AGN sample in three redshift bins. The sizes of the redshift bins have been determined such that there are more or less the same number of objects in each bin. The values of  $\bar{b}$ ,  $\bar{z}$  and  $M_0$  for the total AGN sample are shown in Table 3. The meaning of the table columns are: (1) sample; (2) number of sources; (3) bias parameter from the projected DM 2-halo term, evaluated at the median  $\langle z \rangle$  of the sample; (4) typical halo mass using van den Bosch (2002) and Sheth et al. (2001); (5) weighted bias of the sample; (6) weighted redshift of the sample; (7) Average DM halo mass; (8) Bias factor from  $M_0$  estimated using Sheth et al. (2001).

We observed an increase of the AGN bias factor with redshift, from  $\bar{b}(\bar{z} = 0.92) = 1.80 \pm 0.19$  to  $\bar{b}(\bar{z} = 1.94) = 2.63 \pm 0.21$  with a DM halo mass consistent with being constant at  $\log M_0 [h^{-1} M_\odot] \sim 13.1$  in each bin. These results support the picture that the bias of XMM-COSMOS AGN evolves with time according to a constant halo mass track at all redshifts  $z < 2$ .

This conclusion, based on the analysis of the global XMM-COSMOS AGN sample, can however be affected by the fact that the relative proportions of BL and NL AGN are a strong function of redshift. In fact, since the XMM-COSMOS AGN sample is a flux limited sample, more luminous AGN are selected at high redshift and, also because of our magnitude limit, high- $z$  sources in our sample are mainly BL AGN (see §2). For this reason BL AGN sample could be analysed up to  $z \sim 2.25$ , while the maximum average redshift of the two redshift bins for NL AGN is  $z \sim 0.91$ . We found evidence of a strong increase of the BL AGN bias factor in four redshift bins (see Table 3), with a DM halo mass constant at  $\log M_0 [h^{-1} M_\odot] \sim 13.28$  at all redshifts  $z < 2.25$ . For NL AGN we estimated  $\bar{b}(\bar{z} = 0.62) = 1.59 \pm 0.13$  and  $\bar{b}(\bar{z} = 0.91) = 1.87 \pm 0.19$ , which correspond to a constant halo mass values  $\log M_0 [h^{-1} M_\odot] \sim 13.02$ . We split the X-unobs and X-obs AGN samples in two redshift bins up to  $\bar{z} \simeq 1.5$  and we found that the bias of X-unobs AGN (X-obs AGN) evolves according to a constant halo mass consistent with the mass of BL AGN (NL AGN) hosting halos. Fig. 9 (*left panel*) shows the redshift evolution of the average DM halo mass  $M_0$  for all the AGN subsets. The horizontal lines represent the mean value of  $M_0$  for BL/X-unobs AGN (dashed-blue), NL/X-obs AGN (long dashed-red) and for the whole AGN sample (dotted-black). Fig. 9 (*right panel*) shows the redshift

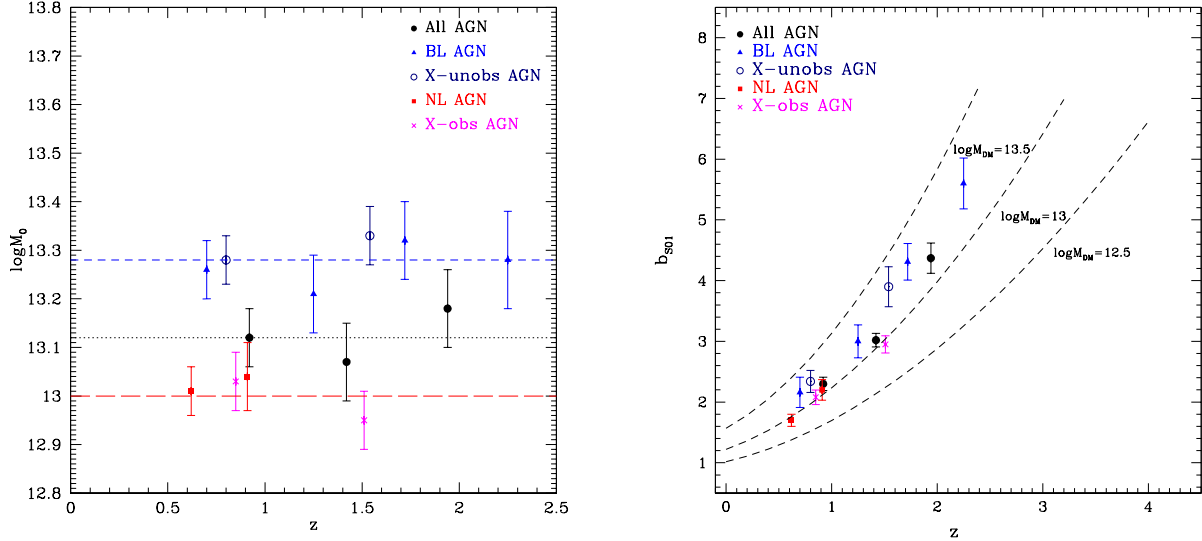


FIG. 9.— *Left Panel:* DM halo mass  $M_0$  as a function of  $z$  for different AGN sub-samples (see legend). The horizontal lines show the mean value of  $M_0$  for BL/X-unobs AGN (dashed-blue), NL/X-obs AGN (long dashed-red) and for the whole AGN sample (dotted-black). *Right Panel:* Redshift evolution of the bias parameter  $b_{S01}$  of different AGN sub-samples. The dashed lines show the expected  $b(z)$  of typical DM halo masses  $M_{DM}$  based on Sheth et al. (2001). The masses are given in  $\log M_{DM}$  in units of  $h^{-1}M_\odot$ . BL/X-unobs AGN present a strong bias evolution with redshift with a constant DM halo mass  $\log M_0 = 13.28 \pm 0.07[h^{-1}M_\odot]$  up to  $\bar{z} \sim 2.4$ . NL/X-obs AGN reside in less massive halos with  $\log M_0 = 13.00 \pm 0.06[h^{-1}M_\odot]$ , constant at  $\bar{z} < 1.5$ .

TABLE 3  
BIAS EVOLUTION

(1) $\langle z \rangle^a$	(2) N	(3) $b_{2-h}$ Eq. 16	(4) $\log \overline{M}_{DM}^b$ $h^{-1}M_\odot$	(5) $\bar{b}$	(6) $\bar{z}$	(7) $\log M_0$ Eq. 16	(8) $b_{S01}^c$ $h^{-1}M_\odot$
<i>All AGN</i>							
0.80	190	$2.70 \pm 0.19$	$13.48 \pm 0.10$	$1.80 \pm 0.19$	0.92	$13.12 \pm 0.06$	$2.30 \pm 0.11$
1.30	220	$3.10 \pm 0.18$	$13.21 \pm 0.10$	$2.14 \pm 0.18$	1.42	$13.07 \pm 0.08$	$3.02 \pm 0.11$
2.07	183	$5.18 \pm 0.21$	$13.30 \pm 0.11$	$2.63 \pm 0.21$	1.94	$13.18 \pm 0.08$	$4.37 \pm 0.27$
<i>BL AGN</i>							
0.67	70	$2.62 \pm 0.20$	$13.57 \pm 0.10$	$1.52 \pm 0.20$	0.70	$13.26 \pm 0.06$	$2.16 \pm 0.25$
1.25	108	$3.06 \pm 0.23$	$13.24 \pm 0.08$	$2.02 \pm 0.23$	1.25	$13.21 \pm 0.08$	$3.00 \pm 0.27$
1.71	92	$5.37 \pm 0.28$	$13.60 \pm 0.08$	$3.57 \pm 0.28$	1.72	$13.32 \pm 0.08$	$4.31 \pm 0.30$
2.46	85	$6.82 \pm 0.27$	$13.41 \pm 0.10$	$4.02 \pm 0.27$	2.25	$13.28 \pm 0.10$	$5.60 \pm 0.42$
<i>X-unobscured AGN</i>							
0.65	98	$2.46 \pm 0.17$	$13.51 \pm 0.11$	$1.62 \pm 0.17$	0.80	$13.28 \pm 0.05$	$2.34 \pm 0.18$
1.66	86	$4.85 \pm 0.18$	$13.51 \pm 0.10$	$2.10 \pm 0.18$	1.54	$13.33 \pm 0.06$	$3.90 \pm 0.33$
<i>NL AGN</i>							
0.53	137	$1.40 \pm 0.13$	$12.65 \pm 0.12$	$1.59 \pm 0.13$	0.62	$13.01 \pm 0.05$	$1.70 \pm 0.10$
1.02	102	$2.11 \pm 0.19$	$12.88 \pm 0.15$	$1.87 \pm 0.19$	0.91	$13.04 \pm 0.07$	$2.20 \pm 0.17$
<i>X-obscured AGN</i>							
0.73	106	$1.80 \pm 0.14$	$13.01 \pm 0.11$	$1.51 \pm 0.14$	0.85	$13.03 \pm 0.06$	$2.08 \pm 0.12$
1.84	112	$3.51 \pm 0.16$	$12.94 \pm 0.13$	$1.96 \pm 0.16$	1.51	$12.95 \pm 0.06$	$2.95 \pm 0.14$

<sup>a</sup> Median redshift of the sample.

<sup>b</sup> Typical DM halo masses based on Sheth et al. (2001) and van den Bosch (2002).

<sup>c</sup> Bias estimated from  $M_0$  using Sheth et al. (2001).

evolution of the bias factors  $b_{S01}$  (Table 3, col (7)) for different AGN sub-samples. The dashed lines show the expected  $b(z)$  associated to the typical DM halo mass based on Sheth et al. (2001).

These results show that X-ray selected BL/X-unobs AGN reside in more massive DM halos compared to X-ray selected NL/X-obs AGN at all redshifts  $z$  at  $\sim 3\sigma$  level. This suggests that the AGN activity is a mass triggered phenomenon and that different AGN phases are associated with the DM halo mass, irrespective of

redshift  $z$ .

## 9. DISCUSSION

### 9.1. Which DM halos host X-ray AGN?

We have introduced a new method that uses the 2-halo term in estimating the AGN bias factor and that properly accounts for the sample variance and the growth of the structures over time associated with our use of large redshift interval of the AGN sample. Using this approach we have estimated an average mass of the XMM-

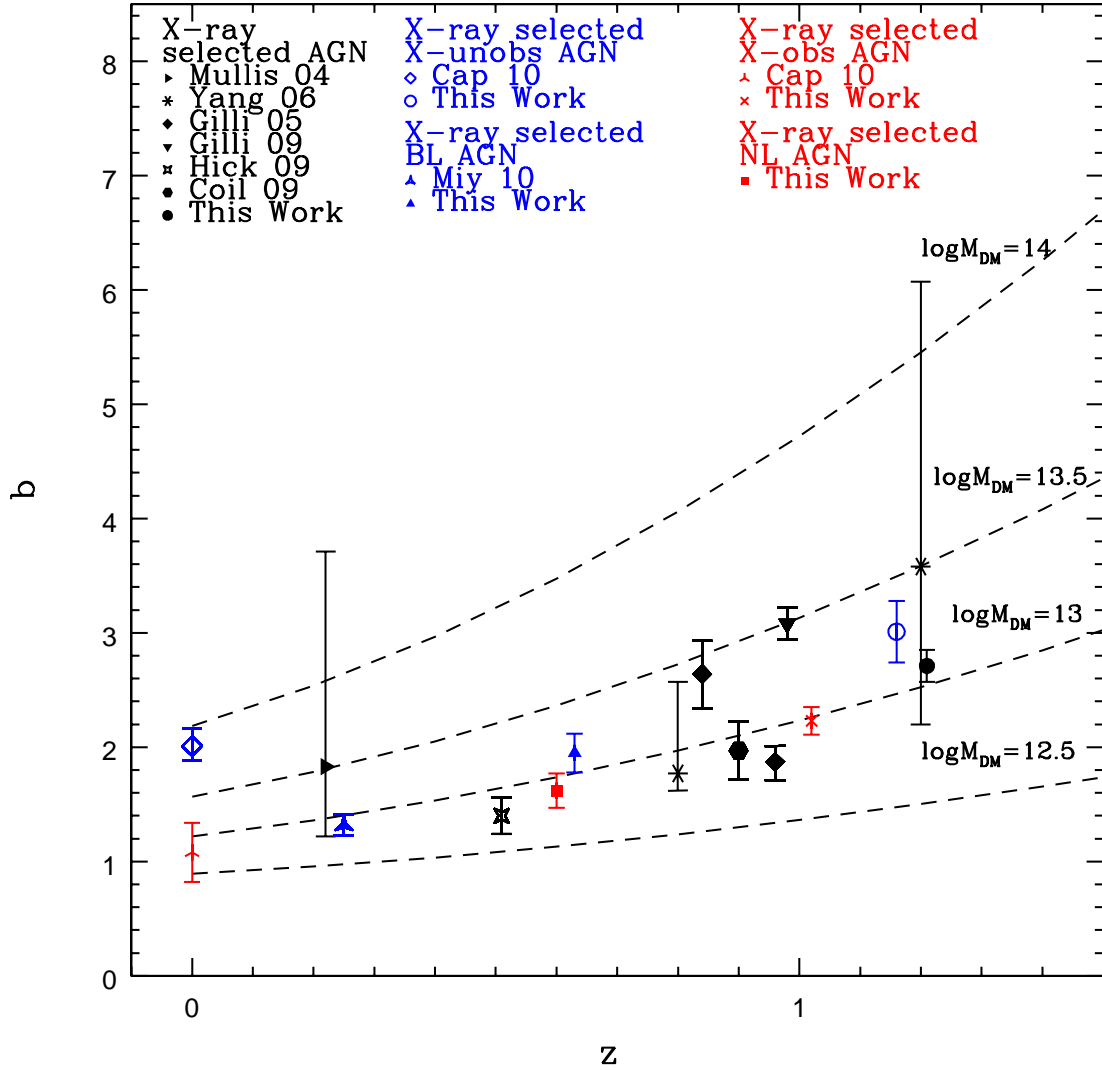


FIG. 10.— Bias parameter as a function of redshift for various X-ray selected AGN (black data points), X-ray selected BL/X-unobs AGN (blue data points) and X-ray selected NL/X-obs AGN (red data points) as estimated in previous studies and in this work according to the legend. Our results refer to the bias factor  $b_{S01}$  showed in Table 2 col (5). The dashed lines show the expected  $b(z)$  of typical DM halo masses  $M_{DM}$  based on Sheth et al. (2001). The masses are given in  $\log M_{DM}$  in units of  $h^{-1} M_{\odot}$ .

COSMOS AGN hosting halos equal to  $\log M_0 [h^{-1} Mpc] = 13.10 \pm 0.06$  which differs at  $\sim 1.6\sigma$  level from the typical halo mass  $M_{DM}$  based on Sheth et al. (2001) using the method 2 (see §5.2). The difference between the standard method and our own method is also clear for the mass of BL and NL AGN hosting halos. We have found that BL AGN inhabit DM halos with average mass  $\log M_0 [h^{-1} Mpc] = 13.24 \pm 0.06$  at  $\bar{z} = 1.53$  while halos hosting NL AGN have average mass  $\log M_0 [h^{-1} Mpc] = 13.01 \pm 0.08$ . BL AGN reside in more massive halos than NL AGN also selecting two subsamples that peak at the same median redshift  $\bar{z} \sim 0.6$ . We obtained similar results using X-ray unobserved AGN at  $\bar{z} = 1.16$  and X-ray obscured AGN at  $\bar{z} = 1.02$  ( $\log M_0 [h^{-1} Mpc] = 13.30 \pm 0.10$  and  $\log M_0 [h^{-1} Mpc] = 12.97 \pm 0.08$ , respectively).

Instead the typical halo mass based on Sheth et al.

(2001) using the AGN bias estimated with the method 2, strongly depends on the median redshift of the sample. According to the method 2, BL AGN at  $\langle z \rangle = 1.55$  reside in less massive halos compared to NL AGN at  $\langle z \rangle = 0.74$ , while the result is different selecting two samples of BL and NL AGN at the same  $\langle z \rangle \sim 0.5$ . Our results agrees with the majority of the recent studies of X-ray surveys which suggest a picture in which X-ray AGN are typically hosted in DM halos with mass in the range  $12.5 < \log M_{DM} [h^{-1} Mpc] < 13.5$ , at low ( $< 0.4$ ) and high ( $\sim 1$ ) redshift. Starikova et al. (2010) found that *Chandra/Bootes* AGN are located at the center of DM halos with  $M > M_{min} = 4 \times 10^{12} h^{-1} M_{\odot}$ . This mass estimate represents a threshold value, since they are assuming a halo occupation described by a step function (zero AGN per halo/subhalo below  $M_{min}$  and one above it). Our approach, in terms of HOD, is completely

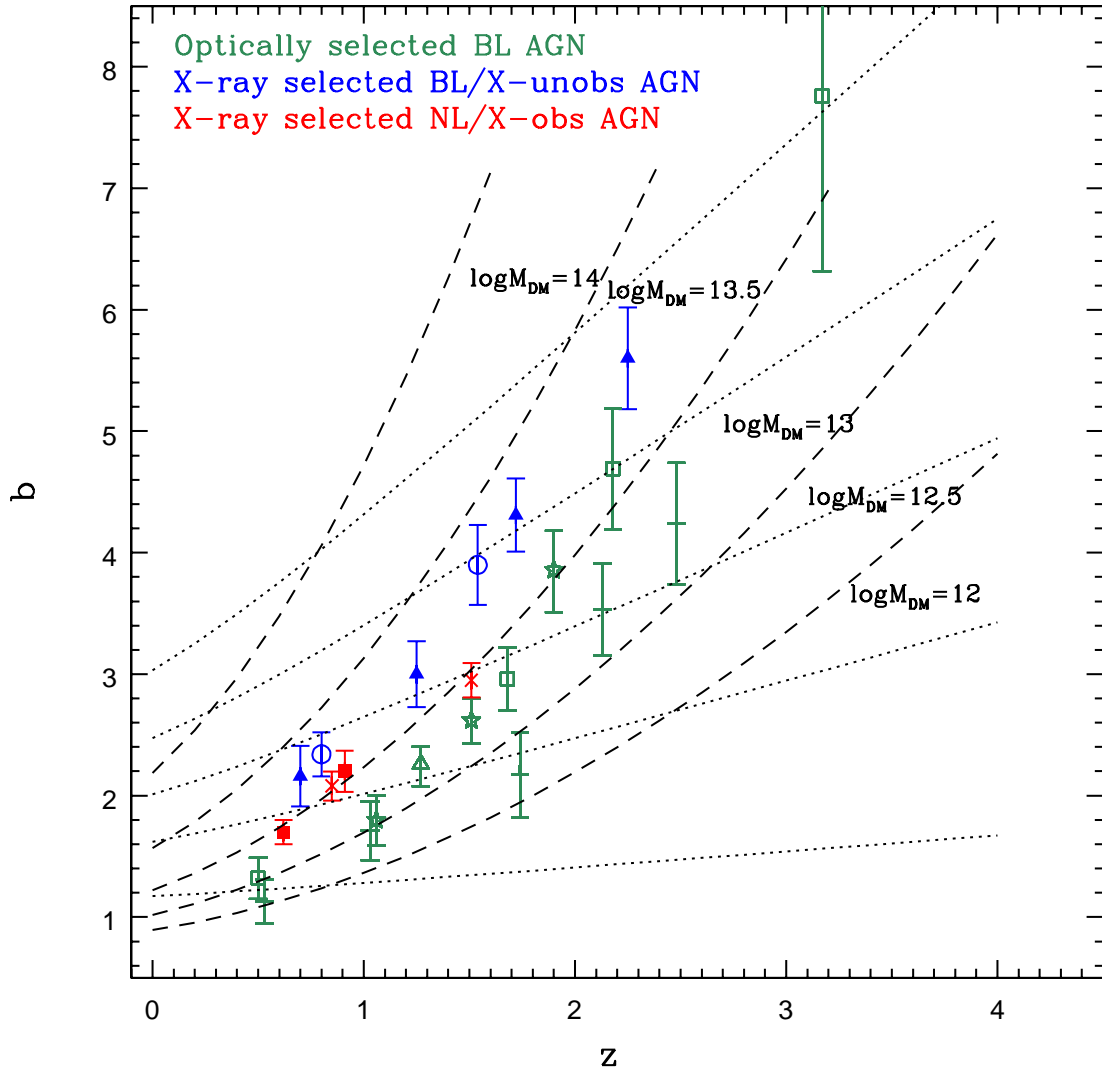


FIG. 11.— Bias parameter as a function of redshift for optically selected BL AGN from previous works (Croom et al. 2005), green-crosses; Porciani & Norberg (2006), green-stars; Shen et al. (2009), green-open squares; Ross et al. (2009), green-open triangle) and X-ray selected BL (blue triangles) and X-unobs (blue open-circles) AGN and NL (red squares) and X-obs (red crosses) AGN as estimated in this work. The dashed lines show the expected  $b(z)$  of typical DM halo masses based on Sheth et al. (2001) and the dotted lines represent the *passive evolution* of the bias, as described in Fry et al. (1996). The bias of optically selected BL AGN evolves with redshift following an evolution at constant halo mass, with a typical mass which remains practically in the range  $\log M_{DM} \sim 12.5 - 13h^{-1}M_{\odot}$  at all redshifts  $z < 2.25$ . X-ray selected BL/X-unobs AGN reside in more massive DM halos at all redshifts  $z < 2.25$ , according to a typical mass of the hosting halos constant over time in the range  $\log M_{DM} \sim 13 - 13.5h^{-1}M_{\odot}$ . The bias evolution of NL/X-obs AGN seems to indicate that they reside in DM halo mass  $\log M_{DM} \sim 13h^{-1}M_{\odot}$  constant at all  $z < 1.5$ . These results suggest the picture that X-ray selected BL AGN are triggered by secular processes as tidal disruption or disk instabilities instead of major mergers between gas-rich galaxies as confirmed by semi-analytic models and observations for optically selected quasars.

different. We assume a halo occupation described by  $\delta$ -function, supported by the fact that AGN only reside in massive halos (then the AGN HOD can be described by a narrow halo mass distribution at high mass values, but not by a step function).

Fig. 10 shows the bias factors of X-ray selected AGN (black), BL/X-unobs AGN (blue) and NL/X-obs AGN (red) as estimated in different surveys (according to the legend). Our results refer to the bias factors  $b_{S01}$  showed in Table 2, column (5). The dashed lines show the expected  $b(z)$  assuming a constant typical DM halo mass  $M_{DM}$ , based on Sheth et al. (2001).

The previous studies of Gilli et al. (2005) for the CDFN, Gilli et al. (2009), Mullis et al. (2004), Yang et al. (2006) for CLASXS AGN suggest the scenario in which the typical DM halo mass hosting X-ray selected AGN is  $\log M_{DM}[h^{-1}M_{\odot}] \sim 13.5$ . The bias values measured in Gilli et al. (2005) on CDFS, in Hickox et al. (2009), Coil et al. (2009) and Yang et al. (2006) and in this work, correspond to a lower halo mass ( $\log M_{DM}[h^{-1}M_{\odot}] \sim 13$ ). A possible explanation could be that at fixed redshift, the bias and then the mass of the hosting halo, depends on the luminosity of the sample. The same explanation might be applied to the results on

BL/X-unobs AGN.

The bias estimates at  $z < 1$  for NL/X-obs AGN in Cappelluti et al. (2010) and in this work, seem to indicate that the mass of NL/X-obs AGN hosting halos is  $\log M_{DM}[h^{-1}M_{\odot}] \sim 13$ .

### 9.2. Optically selected vs X-ray selected AGN

We first found evidence of a redshift evolution of the bias factor of X-ray selected BL/ X-unobs AGN (fig. 11, blue data points) and NL/X-obs AGN (red data points). The bias evolves with redshift at constant average halo mass  $\log M_0[h^{-1}M_{\odot}] \sim 13.3$  for BL/X-unobs AGN and  $\log M_0[h^{-1}M_{\odot}] \sim 13$  for NL/X-obs AGN at  $z < 2.25$  and  $z < 1.5$ , respectively. Fig. 11 shows the expected  $b(z)$  assuming a constant typical DM halo mass based on Sheth et al. (2001) (dashed lines) and the so called *passive bias evolution* (dotted lines Fry et al. 1996). The observed bias evolution suggests an average halo mass of the hosting halos, constant over time in the range  $\log M_{DM}[h^{-1}M_{\odot}] = 13 - 13.5$ , instead of an evolution of the bias in a model in which objects are formed at a fixed time and their distribution evolves under the influence of gravity.

There have been several studies of the bias evolution of optical quasar with the redshift as shown in fig. 11 (green data points), based on large survey samples such as 2QZ and SDSS (Croom et al. 2005; Porciani & Norberg 2006; Shen et al. 2009; Ross et al. 2009). Since the quasar samples used in these clustering analysis are defined as spectroscopically identified quasars with at least one broad (FWHM > 1000 km s<sup>-1</sup>) emission line, we refer to them as optically selected BL AGN.

All the previous studies infer the picture that the quasar bias evolves with redshift following a constant mass evolution, with the average mass that can vary in the range  $\log M_{DM}[h^{-1}M_{\odot}] \sim 12.5 - 13$ , may be depending on the AGN sample luminosity as already suggested for X-ray selected AGN. The simplest interpretation according to the observed redshift evolution of the bias factors is that 1) X-ray selected AGN whether BL/X-unobs or NL/X-obs AGN inhabit DM halos with mass higher than the mass of optically selected quasar hosting halos in the range  $z = 0.5 - 2.25$ ; 2) X-ray selected BL/X-unobs AGN reside in more massive halos compared to NL/X-obs AGN for  $z = 0.6 - 1.6$  and the discrepancy between the bias factors of the two samples increases with  $z$ ; 3) the AGN activity is a mass triggered phenomena and the different AGN evolutionary phases are associated with just the DM halo mass, irrespective of the redshift  $z$ .

### 9.3. External vs Internal Triggering

The major merger of galaxies is one of the promising mechanisms suggested to be responsible for fuelling quasars and in particular to be dominant for bright quasars at high redshift. Models of major mergers appear to naturally produce many observed properties of quasars, as the quasar luminosity density, the shape and the evolution of the quasar luminosity function and the large-scale quasar clustering as a function of  $L$  and  $z$  (Hopkins et al. 2008; Shen 2009; Shankar et al. 2009, 2010; Shankar 2010; Bonoli et al. 2009).

Clear evidence for higher incidence of mergers is seen among quasars (Serber et al. 2006; Hopkins et al. 2006;

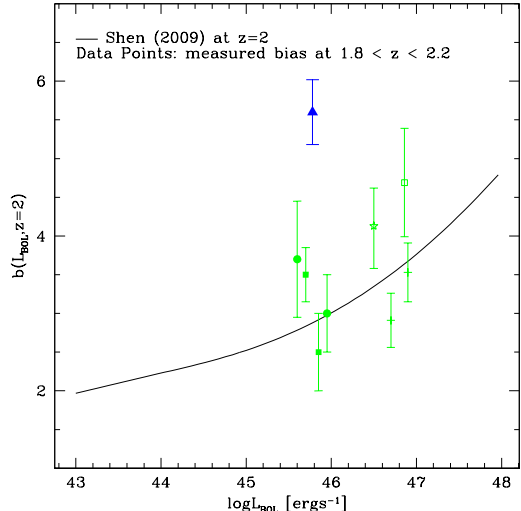


FIG. 12.— Predicted bias as a function of luminosity, computed according to Shen (2009) fixing  $z = 2$ , compared to previous bias estimates at  $1.8 < z < 2.2$ , for optically selected BL AGN and for XMM-COSMOS BL AGN. Points are measurements from Croom et al. (2005, green-crosses), Porciani & Norberg (2006, green-star), Shen et al. (2009, green-open square), da Ângela et al. (2008, green-circles), Myers et al. (2007, green-squares) and our result (blue triangle). For ease of comparison, all luminosities are converted to bolometric luminosities using the corrections from Hopkins et al. (2007). The theoretical model which assumes a quasar phase triggered by major merger reproduces the results obtained for the bias of quasars, but can not reproduce the high bias factors found for X-ray selected BL AGN and then can not explain why optically selected quasars that have higher bolometric luminosity compared to COSMOS X-ray selected BL/X-unobs AGN, reside in more massive halos. These differences suggest a switch to a different dominant mechanism for AGN triggering, from major mergers between gas-rich galaxies to secular processes as tidal disruptions or disk instabilities.

Veilleux et al. 2009). Additionally a large fraction of luminous quasars at low redshift are associated with either morphologically disturbed objects (Canalizo & Stockton 2001; Guyon et al. 2006), or early-type hosts with fine structure in their optical light distribution, indicative of past interactions (Canalizo et al. 2007; Bennert et al. 2008). In the local Universe, for instance, the study of the environment of Swift BAT Seyfert galaxies (Koss et al. 2010) appeared to show an apparent mergers  $\sim 25\%$  which suggests that AGN activity and merging are critically linked. Moreover it is believed that major merger dominates at high redshift and bright luminosities (Hasinger et al. 2008; Hopkins et al. 2006), while minor interaction or bar instabilities or minor tidal disruptions are important at low redshift ( $z \lesssim 1$ ) and low luminosities ( $L_{BOL} \lesssim 10^{44} \text{ erg s}^{-1}$ ) (Hopkins & Henquist 2009).

Our results on the bias evolution of X-ray selected BL/X-unobs AGN infer that these objects with  $L_{BOL} \sim 2 \times 10^{45} \text{ erg s}^{-1}$  reside in massive DM halos  $M_{DM} \sim 2 \times 10^{13} M_{\odot} h^{-1}$ . Besides studies on BL AGN in the COSMOS field (Merloni et al. 2010; Trump et al. 2011) suggest that our sample is characterized by BH masses in the range  $M_{BH} = 10^7 - 10^9 M_{\odot}$  and Eddington ratio  $\lambda > 0.01$ . Optically selected quasars from large survey samples such as 2QZ and SDSS are high-luminosity quasars  $L_{BOL} \gtrsim 10^{46} \text{ erg s}^{-1}$  with BH masses in the range

$M_{BH} = 10^8 - 10^{10} M_{\odot}$  and  $\lambda > 0.01$ . Clustering analysis of optical quasars have shown that they reside in DM halos with  $M_{DM} \sim 10^{12} M_{\odot} h^{-1}$ .

Fig. 12 shows the predicted bias as a function of luminosity computed according to Shen (2009) at  $z = 2$ . The theoretical model which assumes a quasar phase triggered by major mergers predicts an increasing bias with luminosity and reproduces the previous results obtained for optical quasars at  $1.8 < z < 2.2$  (Croom et al. (2005, green-crosses), Porciani & Norberg (2006, green-star), Shen et al. (2009, green-open square), da Ângela et al. (2008, green-circles), Myers et al. (2007, green-squares)). On the other hand the model can not reproduce the high bias factor found for X-ray selected COSMOS BL AGN (blue triangle) and then can not explain why optically selected quasars characterized by higher bolometric luminosity compared to X-ray selected COSMOS BL/X-unobs AGN, are found in less massive halos. These differences suggest a switch to a different dominant mechanism for AGN triggering.

Hopkins & Hernquist (2006) introduced a model for the fueling of low-luminosity AGN (Seyferts, with  $L_{BOL} \lesssim 10^{44} - 10^{45} \text{erg s}^{-1}$  and  $M_{BH} \lesssim 10^7 M_{\odot}$ ), which proposes AGN triggered by random accretion of gas via internal, secular processes. The stochastic accretion model and the merger-driven activity are fundamentally different, the former being determined by stochastic encounters with a cold gas supply in a quiescent system, the latter by the violent torquing of cold gas throughout entire galaxies into the galaxy center in major mergers. Accretion of cold gas in quiescent systems can account for low luminosity Seyferts but can not explain the higher luminosities and the larger BH masses observed for XMM-COSMOS BL AGN. The high Eddington ratios at masses in the range  $M_{BH} \sim 10^8 - 10^9 M_{\odot}$  can not be maintained through this mode of accretion. Furthermore, this fueling mechanism predicts lower bias factors compared to the major merger picture for bright quasars, which is completely in disagreement with our results.

Fueling by stellar winds or hot gas accretion may represent yet a third qualitatively distinct mode of fueling. Ciotti & Ostriker (1997, 2001) investigated the episodic AGN activity model in early-type galaxies, assuming at their center the presence of a massive BH growing with the accretion of matter and affecting the inflow through feedback. The duration of the single accretion event are extremely short but the maximum luminosities reached during the accretion events can be of the order of  $L_{BOL} \sim 10^{46} - 10^{47} \text{erg s}^{-1}$ , depending on the input parameters of the model. The central BH grows by episodic accretion up to a mass in the observed range ( $M \sim 10^{8.5} - 10^{9.5} M_{\odot}$ ) in all giant ellipticals. On the other hand the observational consequence of this model is that the duty cycle is very low, typically of the order of  $10^{-2} - 10^{-3}$ . This result implies a small fraction of giant ellipticals observed in an AGN phase, too low compared to the observed 10% of X-ray AGN residing in massive galaxies.

In the AGN evolutionary model described in Hickox et al. (2009), optically bright quasars are hosted by ongoing disk galaxy mergers and immediately precede an optically faint X-ray AGN phase, which evolves into an

early-type galaxy. Following this evolutionary sequence, NL/X-obs AGN should be triggered in the first initial phase of vigorous star formation and obscured accretion which supports the scheme of NL AGN inhabiting halos with low typical masses  $\log M_{DM} [h^{-1} M_{\odot}] \sim 12.5$ . An X-ray AGN phase immediately follows the quasar phase. Since DM halos grow and accumulate mass over time, X-ray AGN reside in more massive DM halos with typical mass  $\log M_{DM} [h^{-1} M_{\odot}] \sim 13 - 13.5$ . This model predicts that X-ray AGN reside in more massive halos than QSO, but assumes a decline of the BH accretion rate from its peak in the quasar phase to  $\dot{M} \lesssim 10^{-2} M_{Edd}$  or lower, which is in disagreement with *the high Eddington ratios* found for XMM-COSMOS BL AGN (Merloni et al. 2010; Trump et al. 2011).

A plausible scenario requires that high-luminosity quasars ( $L_{BOL} > 10^{46} \text{erg s}^{-1}$ ) are triggered by external processes such as major mergers between gas-rich galaxies with masses of the order of  $M_* \sim 10^{10} M_{\odot}$ . Instead for BL AGN with  $L_{BOL} \sim 2 \times 10^{45} \text{erg s}^{-1}$ , internal mechanisms such as tidal disruptions or disk instabilities in massive galaxies ( $M_* \sim 10^{11} M_{\odot}$ ) might play a dominant role.

The morphology of the AGN hosts galaxies provides an important clue into the mechanism that triggers their current AGN activity. It was observed that many AGN are not fueled by major mergers and only a small fraction of AGN are associated with morphologically disturbed galaxies. Cisternas et al. (2010) analysed a sample of X-ray selected AGN host galaxies and a matched control sample of inactive galaxies in the COSMOS field. They found that mergers and interactions involving AGN hosts are not dominant and occur no more frequently than for inactive galaxies. Over 55% of the studied AGN sample which is characterized by  $L_{BOL} \sim 10^{45} \text{erg s}^{-1}$  and by mass of the host galaxies  $M_* \gtrsim 10^{10} M_{\odot}$  are hosted by disk-dominated galaxies. This high disk fraction means that the lack of disturbed morphologies observed among the AGN hosts can not simply be due to a time lag between merger activity and X-ray visibility and suggests that secular fueling mechanisms can be high efficient.

It was also suggested by Georgakakis et al. (2009) that bar instabilities and minor interactions are more efficient in producing luminous AGN at  $z \lesssim 1$  and not only Seyfert galaxies and low-luminosity AGN as the Hopkins & Hernquist (2006); Hopkins & Henquist (2009) model predicts. Besides several works on the AGN host galaxies (Dunlop et al. 2003; Grogin et al. 2005; Pierce et al. 2007; Gabor et al. 2009; Reichard et al. 2009; Tal et al. 2009) show that the morphologies of the AGN host galaxies do not present a preference for merging systems.

At the redshift of our interest, recent findings of Schawinski et al. (2011) and Rosario et al. (2011), who examined a smaller sample of AGN at  $z \sim 2$  in the ERS-II region of the GOODS-South field, inferred that late-type morphologies are prevalent among the AGN hosts. The role that major galaxy mergers play in triggering AGN activity at  $1.5 < z < 2.5$  was also studied in the CDF-S. Kocevski et al. (in prep.) found that X-ray selected AGN at  $z \sim 2$  do not exhibit a significant excess of distorted morphologies while a large fraction reside in late-type galaxies. They also suggest that these late-type galaxies are fueled by the stochastic accretion of cold gas,

possibly triggered by a disk instability or minor interaction.

We want to stress that our results by no means infer that mergers make no role in the AGN triggering. On the contrary, high luminosity AGN and probably a fraction of moderate luminosity AGN in our sample might be fuelled by mergers. In fact, given the complexity of AGN triggering, a proper selection of an AGN sub-sample, using for instance the luminosity, can help to test a particular model boosting the fraction of AGN host galaxies associated with morphologically disturbed galaxies.

Our work might extend the statement that for moderate luminosity X-ray selected BL AGN secular processes might play a much larger role than major mergers up to  $z \sim 2.2$ , compared to the previous  $z \lesssim 1$ , even during the epoch of peak merger-driven accretion.

## 10. CONCLUSIONS

We have studied the redshift evolution of the bias factor of 593 XMM-COSMOS AGN with spectroscopic redshifts  $z < 4$ , extracted from the 0.5-2 keV X-ray image of the  $2deg^2$  XMM-COSMOS field. We have described a new method to estimate the bias factor and the associated DM halo mass, which accounts for the growth of the structures over time and the sample variance. Key results can be summarized as follows:

1. We estimated the AGN bias factor  $b_{S01} = 2.71 \pm 0.14$  at  $\bar{z} = 1.21$  which corresponds to a mass of DM halos hosting AGN equal to  $\log M_0 [h^{-1} M_\odot] = 13.10 \pm 0.10$ .
2. We split the AGN sample in broad optical emission lines AGN (BL) and AGN without optical broad emission lines (NL) and for each of them we considered a subset with  $\bar{z} = 0.6$  and we found that BL and NL AGN present  $b_{S01} = 1.95 \pm 0.17$  and  $b_{S01} = 1.62 \pm 0.15$ , which correspond to masses equal to  $\log M_0 [h^{-1} M_\odot] = 13.27 \pm 0.10$  and  $12.97 \pm 0.07$ , respectively.
3. We selected in the hard band a sample of X-ray unobscured and X-ray obscured AGN according to the column density and we found that X-ray unobscured (X-ray obscured) AGN inhabit DM halos with the same mass compared to BL (NL) AGN with  $\log M_0 [h^{-1} M_\odot] = 13.30 \pm 0.10$  ( $\log M_0 [h^{-1} M_\odot] = 12.97 \pm 0.08$ ).

4. We found evidence of a redshift evolution of the bias factors for the different AGN subsets, corresponding to a constant DM halo mass threshold which differs for each sample. XMM-COSMOS AGN are hosted by DM halos with mass  $\log M_0 = 13.12 \pm 0.07 [h^{-1} M_\odot]$  constant at all  $z < 2$ , BL/X-ray unobscured AGN reside in halos with mass  $\log M_0 = 13.28 \pm 0.07 [h^{-1} M_\odot]$  for  $\bar{z} < 2.25$  while XMM-COSMOS NL/X-ray obscured AGN inhabit less massive halos  $\log M_0 = 13.00 \pm 0.06 [h^{-1} M_\odot]$ , constant at all  $\bar{z} < 1.5$ .
5. The observed bias evolution for XMM-COSMOS BL and NL AGN at all  $z < 2.25$ , suggests that the AGN activity is a mass triggered phenomenon and that different AGN evolutionary phases are associated with just the DM halo mass, irrespective of the redshift  $z$ .
6. The bias evolution of X-ray selected BL/X-ray unobscured AGN corresponds to halo masses in the range  $\log M_{DM} [h^{-1} M_\odot] \sim 13 - 13.5$  typical of poor galaxy groups at all redshifts. Optically selected BL AGN instead reside in lower density environment with constant halo masses in the range  $\log M_{DM} [h^{-1} M_\odot] \sim 12.5 - 13$  at all redshifts. This indicates that X-ray and optically selected AGN do not inhabit the same DM halos.
7. The theoretical models which assume a quasar phase triggered by major mergers can not reproduce the high bias factors and DM halo masses found for X-ray selected BL AGN up to  $z \sim 2.2$ . Our results might suggest the statement that for moderate luminosity X-ray selected BL AGN secular processes such as tidal disruptions or disk instabilities play a much larger role than major mergers up to  $z \sim 2.2$ , compared to the previous  $z \lesssim 1$ .

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