SPATIAL CORRELATION FUNCTION OF X-RAY SELECTED AGNS

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ABSTRACT

We summarize our results of an extended study of the two point spatial correlation function of the *Chandra* detected AGNs. The study uses spectroscopic redshift data from the CLASXS, SWIRE Lockman Hole (SWIRE-LH), *Chandra* Deep field North and South (CDFN/S). We confirm that the bias factor of AGNs increase at high redshifts. The typical mass of the halos of the AGN hosts does not show significant evolution up to $z \sim 3$. The typical mass of the host galaxies is $\langle \log M/\mathrm{M}_\odot \rangle \approx 12.4$. We discuss some of the open questions in AGN clustering studies and the opportunities with the XXL survey in consideration. We argue that with the available multi-wavelength data, the Blanco Cosmology Survey field can be an excellent choice for conducting the large area survey.

Subject headings:

1. INTRODUCTION

Clustering of active galactic nuclei (AGNs[5]) provides unique perspective of the evolution and environment of supermassive blackholes in the centers of galaxies. Two point statistics can be used to measure the bias factor of the sources compared to the underlying dark matter distribution. In the cold dark matter (CDM) structure formation scenario, the average mass of the dark matter halos of the AGN hosts directly links to their average bias. Within the assumed CDM model, the clustering strength is also linked to the number density of dark matter halos. The number density of AGNs compared to the expected number density of dark matter halos gives a measure of the duty cycle of AGN activity (Martini & Weinberg 2001).

Until recently, the clustering of AGNs has been studied mainly in optical, particularly in large area surveys such as 2dF (2QZ, Croom et al. 2005) and Sloan Digital Sky Survey (SDSS, Myers et al 2006, 2007a, 2007b, Li et al. 2006), The results from these surveys have shown that on scales $> 20h^{-1}$ Mpc, quasars have similar clustering properties as those of bright galaxies. On the other hand, controversies still exist on the evolution of quasar clustering. Croom et al. (2005) have found that the bias factor increases monotonically from $b \sim 1$ at $z = 0$ to $b \sim 4$ at $z = 3$. At higher redshifts, very large bias is also suggested based on spectroscopic redshift data from SDSS (Shen et al. 2007). Using photometric redshifts from SDSS, Myers et al. (2006, 2007a,b) found no clear evidence of evolution in the clustering of quasars below redshift of 2. Clustering of narrow line AGNs at $z < 0.3$ is found to agree with that of normal galaxies on scale $> 20\,h^{-1}$ Mpc, but show "anti-bias" on smaller scales (Li et al 2006). Radio loud AGNs form a small subset of the known AGN population, but are known to be more strongly clustered than normal galaxies (e.g. Magliocchetti et al. 2004), this is consistent with the observation that radio loud AGNs are preferentially found in dense regions such as the center of galaxies clusters (Best 2004; Croft et al. 2007; Lin & Mohr 2007).

It is unclear if the results from optical surveys can be extended to the whole AGN population. It has been shown in recent deep X-ray surveys that a large fraction of hard X-ray selected AGNs do not show strong optical activity. Most of the hard X-ray selected AGNs have lower observed X-ray luminosities than the optical bright quasars and a significant fraction are likely to be obscured (Barger et al. 2005, Tozzi et al. 2006). Since all known AGNs are X-ray emitters, it is suggested that the hard X-ray selected AGNs probably form a superset of the optical selected AGN population (Mushotzky 2004). The question is, whether the majority of X-ray selected AGNs live in the same type of galaxies as quasars do, or do they follow different evolution path as suggested by recent observations that broad line quasars dominate the high redshift AGN population, while X-ray selected AGNs dominate the AGNs found below redshift of 1 (Steffen et al. 2003).

There are some obvious advantages in using X-ray surveys to study high redshift AGNs: 1) The spatial density of AGNs accessible to the current generation of large X-ray telescopes (such as *Chandra, XMM-Newton*) is much higher than that can be obtained in optical surveys. The higher spatial density, or smaller mean separations between X-ray selected AGNs make it possible to achieve the same signal-to-noise ratio for correlation functions with much smaller survey volume. It is also possible to probe small separations in the nonlinear clustering regime and probe the possible scale dependence of bias; 2) X-ray surveys probe broader luminosity ranges which allows better understanding of how the AGN luminosity function relates to the mass function of AGN hosts; 3) X-ray sky is dominated by AGNs, making X-ray selection possibility the "cleanest" method in finding a uniform AGN sample.

Recent X-ray surveys from *Chandra* and *XMM-Newton* have reached the sensitivity levels to detect significant number of optical normal AGNs and have open a new window for clustering study of AGNs as a population (Gilli et al. 2005, Yang et al. 2006, Miyaji et al. 2007,

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[5] To avoid confusions, we adopt the definition of AGN as supermassive blackholes at the center of galaxies that radiates strongly to produce observable effects.

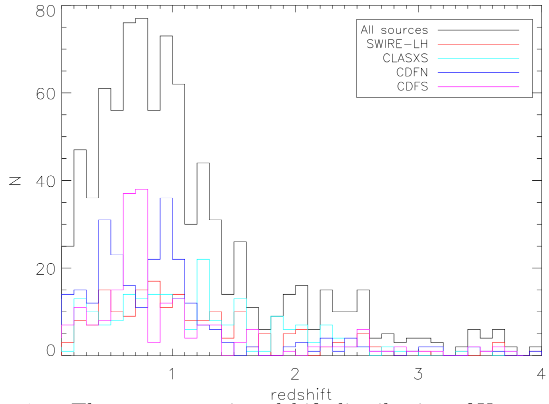

FIG. 1.— The spectroscopic redshift distribution of X-ray sources with optical identifications.

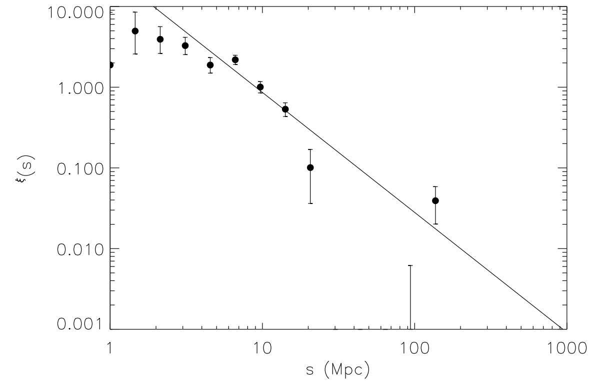

FIG. 2.— The correlation functions and best-fits shown as solid lines using all the 4 *Chandra* fields.

Hickox et al. 2006, Gandhi et al 2006). Most of these surveys, however, cover small solid angles and could be affected by cosmic variance. This is particularly an issue if the angular correlation function is used on small fields (Yang et al. 2003, Miyaji et al. 2007). The size of the survey is still too small to make definitive constraints on the evolution of AGN clustering. To improve the measurement, larger solid angle surveys as discussed in this workshop is needed.

In this paper, I will first discuss the recent results on AGN clustering from our *Chandra* studies. Based on these results I outline the opportunities with a large *XMM-Newton* surveys considered at this workshop. We argue that the existing multiwavelength data from Blanco Cosmology Survey (BCS) make it a excellent choice for conducting such a survey. Through out this paper we assume cosmological model with $h_0 = 71$, $\Omega_M = 0.27$, and $\Omega_\Lambda = 0.73$.

2. THE CHANDRA DEEP AND WIDE SURVEYS

2.1. *Data*

Contiguous wide field is essential to the study of the large scale structure. The data used in this study consists of two contiguous wide moderate deep field in the Lockman Hole NW (LHNW) area: the 0.4 deg^2 CLASXS and 0.6 deg^2 SWIRE Lockman Hole (SWIRE-LH, PI: Wilkes). The CLASXS consists of 9 ACIS-I pointings with exposures from 40-70 ks, and the SWIRE-LH is also composed of 9 contiguous ACIS-I pointings but with $\sim$ 70 ks exposure for each pointing. The two fields are only 2 degrees away from each other. The data from the LHNW fields provide good coverage of spatial correlation functions on comoving scales of $20 - 200h^{-1}$ Mpc. On smaller scales, we use data from the 2 Ms Chandra Deep Field North (CDFN) and the 1 Ms Chandra Deep Field South. The results using only CLASXS and CDFN are reported in Yang et al (2006). We have followed-up the X-ray sources in the CLASXS and SWIRE-LH in optical using Keck telescope. The fraction of X-ray sources that can be spectroscopically identified drop monotonically with the optical flux (roughly correlated with the ensemble averaged X-ray fluxes). A total of 272 spectroscopic redshifts were obtained for the X-ray sources in the CLASXS field (Steffen et al. 2004). We have so far obtained 196 spectroscopic redshifts for sources in the central 0.4 deg^2 region of the SWIRE-LH field. The 2 Ms CDFN and the 1 Ms CDFS each covers a solid angle of ~ 0.1 deg^2. The 306 spectroscopic redshifts from Barger et al. (2003) for the CDFN and 133 spectroscopic redshifts from Szokoly et al. (2005) for the CDFS are used in this analysis.

TABLE 1
THE BEST-FIT PARAMETERS

	CLASXS	SWIRE-LH	LHNW	All fields
s_0[a] (Mpc)	$7.95^{9.05}_{6.05}$	$8.25^{9.65}_{6.65}$	$7.75^{8.85}_{6.65}$	$9.05^{9.65}_{8.45}$
γ[a]	$1.58^{1.96}_{1.26}$	$2.08^{2.68}_{1.61}$	$1.81^{2.13}_{1.54}$	$1.48^{1.59}_{1.41}$

[a] The best-fit value of the redshift-space correlation function and the 1σ upper and lower limits.

2.2. *Results*

The redshift distribution of the optically identified sources is shown in Fig. 1. With the spectroscopic redshifts, both redshift-space and projected correlation functions can be calculated (see Yang et al. 2006 for detail). If the correlation functions assume the form of a power-law, the real-space correlation function can be obtained analytically from the projected correlation function. The redshift-space correlation functions of the X-ray sources between redshift 0.3 and 3 in the comoving coordinates are shown in Fig. 2 and the best-fit parameters are listed in Table 1. The correlation functions of the two LHNW fields agrees within the statistical errors. Because the two LHNW fields are close by, including pairs between the two fields in a joint analysis can improve the signal-to-noise at large separations. The correlation strength of the sources in the CDFS is higher than that in the CDFN, mainly due to a redshift spike in the CDFS field (Gilli et al 2005). Our previous analysis (Yang et al. 2006) have shown that the clustering amplitude in CLASXS and CDFN agree. By including the two CDFs in our sample, the resulting clustering amplitude is higher than that of the LHNW fields alone, but within the margin of errors. There is a clear trend of flattening of the power-law index on separations < 10 Mpc in the combined samples of all the four fields. The trend is mainly due to the flatter power-law seen in the two CDFs. It is unclear if this is an indication of scale dependent bias for AGNs.

Redshift distortion can increase the correlation amplitude in the redshift-space on large scales. Kaiser (1987) showed that to the first order, the ratio of the correlation function in redshift space $\xi(s)$ and the real-space correlation function $\xi(r)$ is a simple function of the redshift distortion factor β,

$$\xi(s) = \xi(r)(1 + \frac{2}{3}\beta + \frac{1}{5}\beta^2). \quad (1)$$

The redshift distortion factor can be approximated as $\beta \approx \Omega_M(z)^{0.6}/b(z)$, where $b(z)$ is bias. Within assumed cosmology, we can estimate the bias factor by comparing the real-space and the redshift-space correlation functions. We estimate (Yang et al 2006) the bias factor of X-ray selected AGNs $b \approx 2.04 \pm 1.02$ at $z \sim 1$.

The large number of spectroscopic redshift data allow us for the first time to study clustering evolution of X-ray selected AGNs. The correlation amplitude of the X-ray selected AGNs in four redshift bins between z=0.1 and 3.0 is shown in Fig. 3. The correlation function of the X-ray sources in the two LHNW fields agrees. Instead of using the correlation length, which can be sensitive to the shape of the correlation function, we measure the clustering amplitude using $\bar{\xi}_{20}$, the averaged correlation function within $20h^{-1}$ Mpc. The clustering amplitudes of the *Chandra* samples agree very well with those from the 2dF quasars, confirming our previous result (Yang et al. 2006). Only mild evolution of clustering amplitude is seen in AGNs between z=0.1 and 2. The correlation function is still poorly constrained between z=2-3 with our sample, and most of the signal in this redshift range come from the two ultra deep fields. Using the clustering amplitudes, we can estimate the bias of AGNs and make inference on the typical halo mass of the AGN hosts. This is done by using the formalism of Sheth, Mo & Tormen (2001). The results are shown in Fig.3. We confirm the increase of bias at high redshifts. We also confirm that there is very little change in the mass of the halos of AGN hosts with redshift. The average halo mass $\langle \log M/\,\mathrm{M}_\odot \rangle \approx 12.4$.

2.3. *Compare with other X-ray surveys*

Our results show very good agreement with the ROSAT NEP survey (Mullis et al 2005), which have a high level of spectroscopic completeness and hence the spatially correlation function can be estimated directly. Our result also agree with the preliminary results from the 9 deg^2 *Chandra* Bootes field survey ($r_0 \sim 6.2h^{-1}$ Mpc, Hickox et al. 2006). For surveys such as XMM-COSMOS and XMM-LSS, only results from angular correlation function are available. The spatial correlation function is estimated by using the Limber equation. The advantage of using angular correlation function is that it is free from optical selection effects. It is, however, sensitive to the errors of the assumed redshift distribution, and also can be affected by rare structures and coincidental projections in the field. The inferred clustering in the XMM-COSMOS field seem to be higher than that from our study as well as those of optical quasars (Miyaji et al. 2007). However, as pointed out by the authors, the integral constraint is a major uncertainty of the study. Basilakos et al. (2004, 2005) found rather high angular clustering signal in a 2 deg^2 survey, an indication of cosmic variance. It is expected that with large field, the effect of cosmic variance would be smaller. The angular clustering of AGNs in the XMM-LSS (4.2 deg^2, Gandhi et al. 2006) field is found to be consistent with our results.

3. OPEN QUESTIONS IN AGN CLUSTERING

3.1. *Luminosity dependence of AGN clustering*

Strong evolution of AGN luminosity function has been seen in both X-ray and optical surveys. On the other hand, only weak, if any, evolution has been observed in AGN clustering properties. No siginificant correlation between AGN luminosity and bias has been found either. This seem to indicate that the very broad luminosity function of X-ray selected AGNs is mainly due to the variation of blackhole accretion rates and the radiative efficiency, and is weakly related to the mass of the galaxies. This is consistent with the recent simulation inspired interpretations of AGN luminosity function, which suggest that the luminosity of AGNs is mainly determined by the evolutionary stages, i.e., quasars are radiating at their peak (Eddington or super Eddington) luminosities, while supermassive black holes spend most of their lives in lower luminosity phases (Lidz et al. 2006) such as the X-ray selected AGNs. It is still surprising that no luminosity dependence is found even in the bright samples of AGNs. It has been shown that the blackhole mass and X-ray luminosity are at least correlated in broadline AGNs (Barger et al 2005; Yang et al. 2005). There is also evidence that the blackhole mass and the halo mass are also correlated (Ferrarese 2002). Therefore, some correlation should exist between the luminosity and AGN bias. However, even if there is a correlation between AGN luminosity and the host galaxy mass, it can be very hard to observe.

To illustrate this point, in Fig. 5 we show a very simple model and the data from AGN surveys and from Chandra and 2dF. The model assumes 1) The hard X-ray luminosity of AGNs is correlated with the blackhole mass; 2) The blackhole mass is related to the host dark halo mass via the correlation found in Ferrarese (2002). These allow us to translate luminosity to bias and the correlation amplitude. It is noticeable that the correlation function only become sensitive to luminosity at the high luminosity end, and the sample at these luminosity maybe too small for establish a correlation. At low luminosities, the correlation strength of AGNs are much higher than that predicted by our simple model. This is because at $10^{40} - 10^{42}$ erg s^{-1}, a significant fraction of the sources are LINERs, which are likely to host massive blackholes that radiate at low efficiency. This effect is clearly seen in the low luminosity sample of SDSS (Constantin & Vogeley 2006).

Therefore, to determine if there is a L_x-$\bar{\xi}$ correlation, a large sample of sources in the medium to high luminosity range is desired.

3.2. *Clustering of AGNs at $z > 3$*

Most of the current AGN surveys, including X-ray surveys, do not provide good probe of high redshift AGNs. The spatial density of AGNs drop quickly and require large survey area. Within errors, the clustering of the X-ray selected AGN agree with that of quasars. The extrapolation of the evolution trend seem to point to a bias of 4-5 for AGN at z = 3. The typical mass of AGN hosts is almost constant. If this is true, the host galaxies

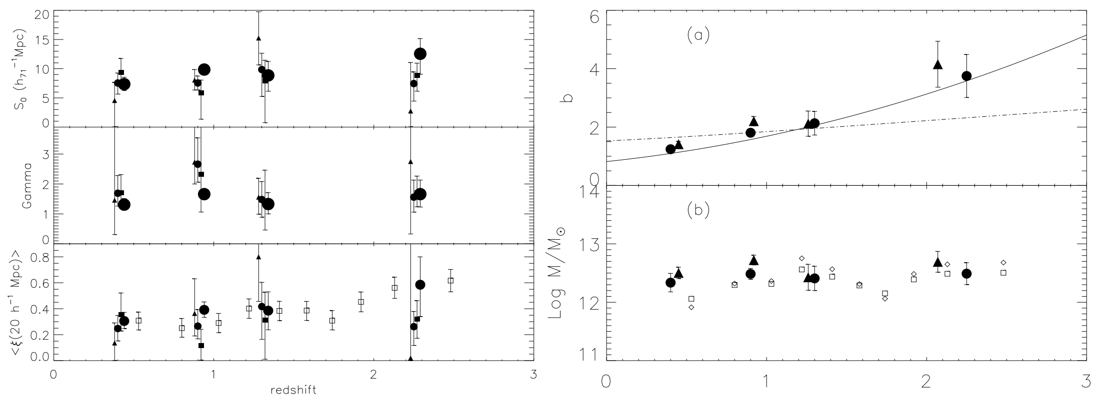

FIG. 3.— *Left*: The correlation functions in 4 redshift bins between z=0.1–3.0. The 3 panels show the evolution of the best-fit parameters and the mean clustering amplitude. Small square: CLASXS; small triangle: SWIRE-LH; small dots: the joint LHNW fields; large dots: all the 4 *Chandra* fields; small boxes: the 2dF quasars from Croom et al. (2005). Right: Bias and typical mass of dark halos of the AGN hosts. Dots: All 4 *Chandra* fields; Triangles: results in Yang et al. (2006). The dash-dotted line shows the linear bias evolution model, and the solid line shows the best-fit of the bias evolution using 2dF quasars.

of AGNs would be similar to the Lyman break galaxies at the same redshift. On the other hand, recent analysis using SDSS data seem to suggest the bias beyond z=3 can be much higher (Shen et al 2007). If confirmed, the AGNs at high redshifts would live in more massive systems such as galaxy clusters.

3.3. *Scale dependence of bias in AGNs and host galaxies*

Feedback from galaxy formation can cause scale dependent bias. This effect is seen in narrow-line AGNs in low redshift samples, where "anti-bias" is seen on small scales (Li. et al. 2007). The effect could be more profound at high redshifts where the bias factor is likely to be higher. The flattening of the correlation function at small separations in the *Chandra* surveys seem to indicate a strong scale dependence of bias, and larger survey is needed to investigate this issue. By comparing directly with numerical simulations, the scale dependent bias can be used to test models of formation and growth of supermassive blackholes. Recent study of 2dF galaxies seem to suggest that passive ("red") and active ("blue") galaxies show different scale dependence of bias (Madgwick et al. 2003). Better constraints on the scale dependent AGN bias may help to understand the global relation between star-formation and AGN activities.

3.4. *Probing large scale structure*

One of the obstacles for using AGNs as a serious cosmology probe is their strong evolution. Nevertheless, there are some potentially interesting cosmological applications of AGNs. For example, if one could determine the bias of AGNs independently (e.g. by means of cross-correlating with populations of galaxies whose bias is better known), then one could use the redshift distortion effect to solve for Ω_M. If the typical mass of AGN host halo indeed changes very little as suggested by 2dF and our X-ray surveys, it would certainly be useful in the cosmological context, even though it seem more promising to use this observation to constrain the host galaxies of AGNs at present time. Indirect methods such as strong gravitational lensing magnification bias can potentially be useful to constrain dark matter. Because of the high bias of AGNs, good signal-to-noise level of the correlation function (or power spectrum) on comoving scales of $100h^{-1}$ Mpc may allow the first detection of the baryon acoustic oscillation peak at redshift ~ 1, an important test for cosmological models.

4. IMPLICATIONS FOR XXL SURVEY

The planned large scale structure XMM-Newton survey that covers area $\sim$ 100 deg^2 will acquire a large sample of galaxy clusters with redshifts up to ~ 1, to allow high precision determination of cosmological parameters. The survey that reaches a 2-8 keV flux limit of $5 \times 10^{-15} - 10^{-14}$ erg cm^{-2} s^{-1} will also generate large sample of $\sim 10,000 - 30,000$ X-ray selected AGNs that could allow us to address some of the very important questions in AGN science. Because of the higher spacial densities of the survey, the correlation functions will be much better determined than previous optical quasar surveys. It will also detect a significant number of high redshift AGNs, including highly obscured AGNs, to allow a better picture of the AGN population at $z > 3$, which has so far been poorly constrained.

Optical identification is crucial for the AGN survey. This requirement limits the depth of the XMM observations. Because of the large PSF, the optical identification of XMM detected AGNs becomes difficult for sources with $R > 24$, where the rate of random identification is $\sim$ 15%. Based on *Chandra* observations the scatter in the X-ray to optical flux rato become large at low fluxes, and a significant fraction of AGNs detect in X-ray with flux $f_{2-8keV} < 10^{-14}$ may have optical counterparts with $R > 24$ and have a good chance to be mis-identified. For this reason a wide field is preferred. Deep multi-color optical data is a must to obtain the photometric redshift of the sources. The depth of the optical data should be able to detect most of the AGN hosts up to redshift of 2, and bright AGNs to redshift > 5.

The Blanco Cosmology Surveys (BCS) is a 100 deg^2 cluster survey that reaches an order of magnitude deeper than the SDSS in the Sloan g, r, i, z bands. The field has also been jointly observed by SPT and APEX-SZ. Spitzer and XMM-Newton observation have been approved for part of the field. The optical observations are completed. The existence of multi-wavelength data make the field a good choice for the planned large XMM survey, because it will provide additional calibration of the major cluster finding methods. For AGN science, with the photometric redshifts, the angular auto- and cross- correlation

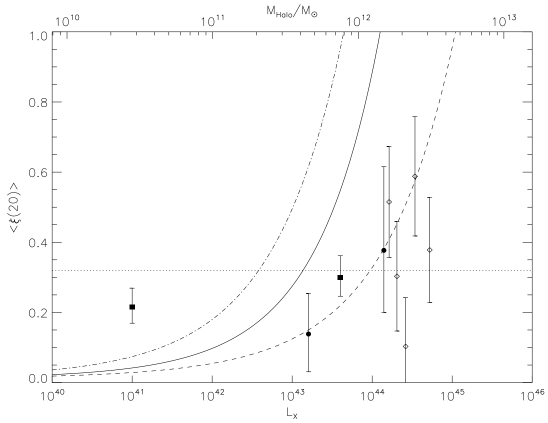

Fig. 4.— Luminosity dependence of clustering of AGNs. Black dots: CLASXS samples; Filled boxes: CDFN samples; Diamonds: 2dF sample (Croom et al. 2004). Lines are the models for different halo profile from Farrarese (2002). Solid line: NWF profile ($\kappa = 0.1$, $\lambda = 1.65$); Dashed line: weak lensing determined halo profile (Seljak, 2002; $\kappa = 0.67$, $\lambda = 1.82$); Dash-dotted line: isothermal model ($\kappa = 0.027$, $\lambda = 1.82$)

functions of AGNs and galaxies can be readily measured. The filter set of BCS is optimized to select high redshift AGNs, which will provide high-z targets for spectroscopic observations. One of the added benefit by surveying the BCS field is that the large number of cluster samples from optical and SZ surveys provide a unique opportunity to study AGN activity in cluster environment. AGNs are suggested to be the major player in the feedback process that heats the intracluster gas (McNamara & Nulsen 2007). It is important to study how AGN affect cluster evolution at redshift up to z=1.

5. CONCLUSIONS

One of the fundamental questions in AGN study is how AGNs trace the large scale structure. The X-ray observations provide the most uniform and least contaminated way of finding AGNs. This will provide the most uniform sample to address the question of AGNs and structure formation. The high spatial density of AGNs that can be detected with *Chandra* and *XMM-Newton* allows better determination of AGN clustering with much smaller survey area compare to SDSS and 2dF. Our studies of the combined *Chandra* deep and wide fields demonstrate the scientific questions that can be answered with the X-ray surveys with rigorous optical follow-up. Our results show no difference in clustering properties between X-ray selected AGNs and optical selected quasars. We found no significant correlation between the X-ray luminosity and bias. On the other hand, we have found marginal evidence that could point to scale dependent bias. The bias of AGNs increases rapidly with redshift, and the typical mass of the AGN host does not seem to change significantly with redshift below redshift of 3. With the planned large area *XMM-Newton*, we will be in much better position in answering questions about the evolution of the bias of AGN hosts to redshifts beyond 3. It would allow for the test for scale dependent bias at high redshifts. Potentially, AGNs can be useful tracers of large scale structure. Optical data is crucial to the success of a AGN large scale structure survey. We suggest the BCS field can be a good choice to perform the XMM survey, given the very rich multi-wavelength data in this field. The added benefit of surveying this field is that one can directly address the issues of AGN and cluster of galaxies at the same time. This provides an good opportunity to study the role of AGN activity in cluster evolution.

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