A low redshift X-ray survey: understanding the co-evolution of AGN and galaxies across cosmic time.

1. Motivation: The AGN space density drops sharply from $z \approx 1$ to the present day, in a way that is strikingly similar to the well established decline of the global star-formation (SF) density. Independent observational evidence also indicates that the growth of the supermassive black holes (SBH) at the centres of galaxies and the formation of stars in these systems are closely linked. Consequently, in order to understand the evolution of AGN one needs to study their host galaxies and vice versa.

Recent deep multiwaveband surveys (e.g. AEGIS, COSMOS, GOODS) are designed to study the relation between AGN and galaxies at $z \approx 1$, close to the peak of the SF and accretion history of the Universe (e.g. Hopkins 2004; Hasinger et al. 2005). Similar studies at lower redshift are also essential however to elucidate the physial mechanism responsible for the strong evolution of the SBH accretion since $z \approx 1$. Unfortunately, although a huge amount of observational resources has been devoted to deep pencil-beam samples, there is currently no systematic effort to complement them with a low redshift survey.

In order to bridge this gap it is proposed to use XMM to perform a wide-angle shallow X-ray survey with the specific goal of compiling a large sample of X-ray selected AGN at $z < 0.2$ to explore their relation to their host galaxies and to compare with similar samples at $z \approx 1$. A key feature of the proposed program is that it is designed so that the low-z AGN sample has almost identical selection criteria to deep pencil-beam surveys. This is important as the way one selects the sample has a strong impact on the properties of the AGN and their host galaxies. For example, broad-line QSOs are known to represent a minority of the full AGN population biased against dusty systems, narrow emission-line selection methods include a significant fraction of LINERs, most of which are found in early type galaxies, while there is a debate on how many are powered by accretion on a central SBH, while radio selected AGN are biased towards early-type hosts in high density environments and are not at all representative of the overall population of active SBHs.

Therefore if one wants to study the co-evolution of AGN and galaxies at different epochs, one has to make sure that AGN are selected in a similar way at different redshifts. X-ray surveys are the least biased method for compiling representative AGN samples at any redshift, with a selection function that can be easily quantified. At low redshifts, $z \approx 0.1$, the Sloan Digital Sky Survey (SDSS) has provided superb quality optical spectra that offer an alternative very efficient tool for finding AGN, even at low luminosities (e.g. LINERs). However, with current instrumentation, the SDSS optical selection at $z \approx 0.1$ *cannot* be extended to high redshift, $z \approx 1$. At these redshifts, X-ray surveys are the *only* way for compiling unbiased AGN samples. Consequently, although the SDSS has provided detailed information about the relation between narrow emission-line AGN and their host galaxy properties, it is still unclear how the AGN sample relates to the high redshift X-ray selected AGN in deep surveys. As optical emission line selection is impossible for large samples at high redshift, the only way to resolve this issues is to complement high redshift X-ray AGN samples with an X-ray survey of the low redshift Universe.

2. Survey setup: It is proposed that the XMM observations are carried out in the area of the SDSS. This is the largest optical survey of the nearby Universe (≈ 0.1), providing high quality optical photometry and spectroscopy over about $10\,000\mathrm{deg}^2$ as well as advanced data products, such as star-formation rates, stellar masses and local galaxy density measurements.

The main spectroscopic sample of the SDSS includes galaxies brighter than $r = 17.7$ with a redshift distribution that extends out to $z \approx 0.2$. To take advantage of the SDSS optical spectroscopy it is proposed to limit the AGN sample to that redshift. The area of the proposed XMM survey is set by the requirement to to provide a representative view of the Universe at $z < 0.2$ and at the same time have similar selection criteria with the deep surveys of the high-z Universe. It is required in particular that the volume probed by the pro-

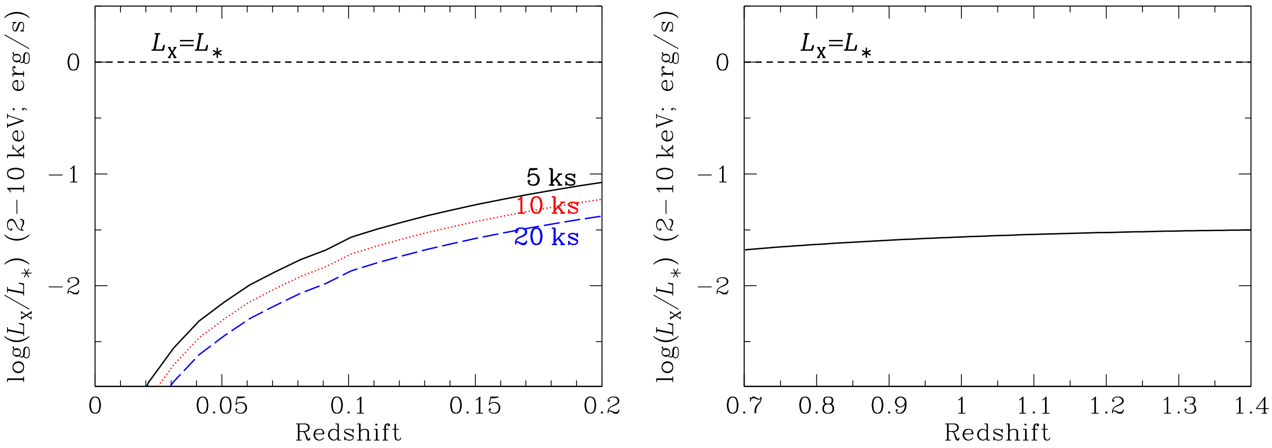

Figure 2: In both panels plotted as a function of redshift is the 2-10 keV X-ray luminosity limit normalised to the characteristic luminosity, L_*, of the AGN X-ray luminosity function (XLF) estimated by Barger et al. (2005). The horizontal short-dashed line corresponds to $L_X = L_*$. **Left panel:** the curves correspond to the L_X/L_* limit at $z < 0.2$ of an XMM survey with exposure times of 5, 10 and 20 ks. **Right panel:** plotted for comparison is the L_X/L_* for a 200 ks Chandra survey in the redshift interval $0.7 - 1.4$. A wide-angle 5 ks XMM survey at $z \approx 0.1$ probes the same part of the AGN XLF (i.e. $\approx L_* - 1.5$) as deep pencil beam samples at $z \approx 1$.

posed survey at $z < 0.2$ matches that of the high-z pencil-beam X-ray surveys. This requirement sets the area of the survey to $\approx 200\,\mathrm{deg}^2$ (see Fig. 1).

For the depth of the proposed XMM survey, it is required that it samples the same part of the AGN X-ray Luminosity Function (XLF) as deep X-ray surveys at $z \approx 1$. This sets the minimum exposure time to 5 ks. This is demonstrated in Fig. 2 , where it is plotted as a function of redshift the limiting X-ray luminosity normalised to the characteristic X-ray luminosity of the XLF at that redshift. For this exercise we adopt the 2-10 keV XLF of Barger et al. (2005). It can be seen that 5 ks with XMM sample luminosities 1.5 dex fainter than L_* at $z \approx 0.1$. This is similar to deep surveys at $z \approx 1$. As an example we show in Fig. 2 the limiting luminosity of a Chandra 200 ks survey.

The expected numbers of AGN at $z < 0.2$ in a 5 ks XMM survey over $200\,\mathrm{deg}^2$ are plotted in Fig 3. We expect to find about 3000 sources with $L_X(2-10\,\mathrm{keV}) > 10^{41}\,\mathrm{erg\,s^{-1}}$ to $z = 0.2$, of which about 200 with $L_X(2-10\,\mathrm{keV}) > 10^{43}\,\mathrm{erg\,s^{-1}}$ which corresponds to the L_* at these redshifts. A large sample of AGN brighter than L_* is important, as some models for the co-evolution of AGN and galaxies suggest a change in the properties of the AGN population at these luminosities.

3. Choice of field:

It has been argued above that a $200\,\mathrm{deg}^2$ XMM survey in the SDSS area is needed, with an exposure time of 5 ks per pointing. An obvious field choice for such a survey is the part of the SDSS that is going to be observed spectroscopically by AAT/AOmega as part of the Galaxy And Mass Assembly (GAMA) survey. This optical survey consists of 3 equatorial SDSS fields covering a total area of $200\,\mathrm{deg}^2$ (see Fig. 4). In addition to the existing SDSS observations, GAMA will provide optical spectroscopy for *all* galaxies to $r = 19.8$ mag about, 2 mag fainter than the SDSS main spectroscopic sample. The multiwavelength data in this field are presented in Table 1. The wealth of observations in this patch of the sky guarantee minimal requirements in terms of follow-up observations.

The XMM Survey Science Centre has constructed a serendipitous catalogue of X-ray sources (2XMM) using archival XMM observations that could potentially be used for the proposed study. The overlap between 2XMM and SDSS is about $100\,\mathrm{deg}^2$. However, about 25 per cent of these fields are targeting extended sources, such as clusters or nearby galaxies, resulting in high background and bright effective point source detection limit. These fields are therefore unsuitable for the

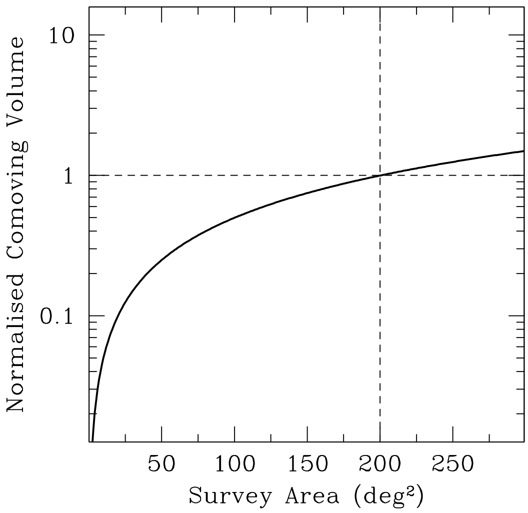

Figure 1: We plot as a function of survey area the comoving volume for $z < 0.2$ normalised by the volume of a 1.8deg^2 survey in the redshift interval $0.7-1.4$. 1.8deg^2 is the total area covered by the current deepest Chandra surveys: AEGIS, COSMOS, Extended CDFS and CDF-North/South. All these fields have at least 200ks exposure over the surveyed area and a wealth of multiwavelength follow-ups. Because of the evolution of the AGN X-ray luminosity function these surveys are dominated by sources in the redshift interval $0.7-1.4$. The plot shows that a local Universe survey of about 200 deg^2 will probe the same volume at $z < 0.2$ as the current deep surveys at $z \approx 1$.

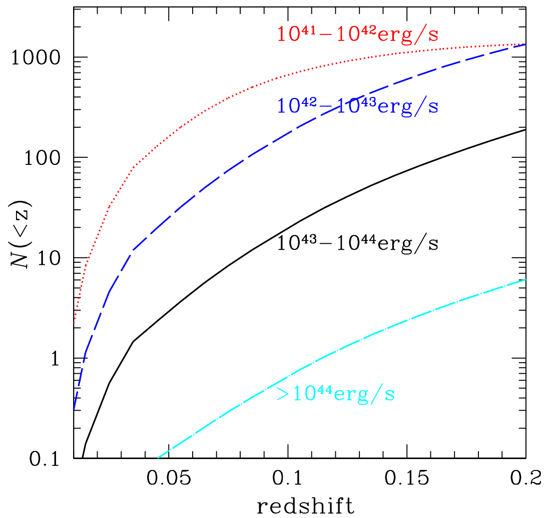

Figure 3: Cumulative number of hard X-ray detected (2-10 keV) AGN as a function of redshift for a 5 ks XMM survey over 200 deg^2. The XLF of Ueda et al. (2003) is used to calculate the expected number of AGN at different redshifts. A total of about 3000 sources with $L_X(2-10\,\mathrm{keV}) > 10^{41}\,\mathrm{erg\,s^{-1}}$ of which about 200 brighter that $L_X(2-10\,\mathrm{keV}) > 10^{43}\,\mathrm{erg\,s^{-1}}$ which corresponds to the L_* at low redshifts. Some models for the co-evolution of AGN and galaxies predict different formation histories and hence different properties for sources brighter/fainter than L_*. The proposed survey will provide a large sample of these sources to explore their properties.

proposed study and limit the usable overlap between SDSS and 2XMM to about 75 deg^2. Such a serendipitous survey is useful for most of goals of the proposed study and can be used in addition to the proposed observations, reducing the requested time by 30%. The penalty in this approach is that one looses the GAMA spectroscopic survey data.

A clear gap in the multiwavelength coverage of Table 1 is the mid- and far-IR. This is unfortunate as the mid-IR is proposed as a promising wavelength regime for selecting AGN, especially heavily obscured ones. However, we still do not understand the mid/far-IR SEDs of AGN well enough to device useful selection criteria. One way to address this issue is to survey with XMM SWIRE fields that overlap with the SDSS. There are 3 such fields, ELAIS-N1/N2 and Lockman Hole, covering a total area of 24 deg^2. The penalty here is again that the GAMA survey does not overlap with any of the SWIRE fields. Fig. 5 demonstrates that the SWIRE flux limits are sufficient to detect a large fraction of the X-ray AGN at $z < 0.2$, at least in the IRAC and MIPS-24μm data, but probably not the MIPS 70 and 160μm.

In summary, it is proposed that an XMM survey is performed over 100deg^2 in the GAMA area and 24 deg^2 in the SWIRE ELAIS-N1/N2 and Lockman Hole fields. This will be complemented with 75 deg^2 of archival data in the SDSS to provide a 200 deg^2 X-ray survey of the low-z Universe, $z < 0.2$. Assuming a setup time for XMM of 4 ks per pointing and 0.2 deg^2 FOV it is estimated that the proposed program requires 5.6Ms.

4. Specific science aims:

(i) Constrain the kpc and Mpc scale environment of AGN at $z < 0.2$ and compare with similar studies at $z \approx 1$. At high-z a number of studies show that X-ray AGN are found in regions of enhanced galaxy density, i.e. groups or clusters (Fig. 6). There are also suggestions for a luminosity dependent clustering for X-ray AGN at high redshift, in the sense that more X-ray luminous sources are found in denser environments (Fig. 7). This is contrary to narrow emission-line AGN at low redshift ($z \approx 0.1$), where more luminous sources (measured by the [OIII] 5007 line) are in less dense regions (Kauffmann et al. 2004; Serber et al. 2006; Li et al. 2007), while lower luminosity LINERs are

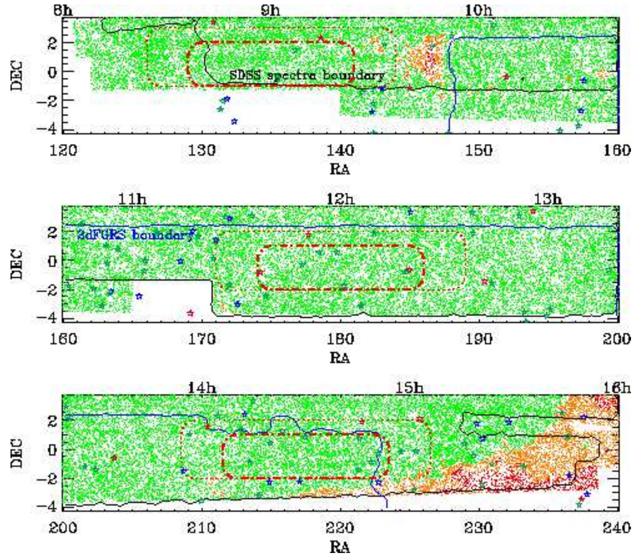

Figure 4: SDSS regions that will be targeted by AOmega as part of the GAMA spectroscopic survey to $r = 19.8$, 2 mag deeper than the SDSS main spectroscopic sample. The points represent SDSS galaxies in a narrow magnitude range. Green points represent areas where Galactic extinction in $r < 0.2$; orange points for $0.2 - 0.4$; and red points for > 0.4. The black and blue lines define the boundaries for spectroscopy from SDSS and 2dFGRS, respectively. The stars represent stars from the bright star catalogue. The thick dash-and-dotted red lines represent our initial 3x12deg^2 target regions.

more clustered that the overall AGN population (Constantin & Vogley 2006). It is not clear if these differences between high and low redshift samples are because of selection effects, i.e. X-ray vs optical, or because of evolution effects, i.e. group and clusters where more active in the past, while today this activity has shifted to lower density regions. The proposed study will address this issue. In the latter case the decline of the AGN activity since $z \approx 1$, may be related to the availability of cold gas supply in moderate density environments where interactions are more frequent leading to inflows of material to the central galaxy regions. The AGN/galaxy cross-correlation function from 0.1-10 Mpc will also allow study of the significance of mergers in the evolution of AGN.

(ii) Models for the co-evolution of AGN and galaxies suggest that at high redshift the AGN population is dominated by sources where the BH ac-

Table 1: Multi-wavelength coverage of the equatorial 200deg^2 SDSS strip where the Galaxy And Mass Assembly (GAMA) spectroscopic survey is going to be carried out. The spectroscopic data from both the SDSS and the GAMA and the high quality optical and near-IR photometry make this strip ideal for a shallow wide area XMM survey of the nearby Universe.

Survey/Mission name	waveband	flux/magnitude limit
SDSS-photometry	$ugriz$	$r \approx 22.5$ mag
SDSS-spectroscopy	3500-9000Å	$r < 17.7$ mag
GAMA-spectroscopy	3500-9000Å	$r < 19.8$ mag
UKIDSS-LAS	$YJHK$	$K \approx 18.5$ mag
FIRST	1.4 GHz	$S_{1.4\mathrm{GHz}} \approx 1$ mJy

cretion is triggered my major merger events. At lower redshift ($z < 0.5$) stochastic accretion on the SBH ("Seyfert mode") in disk galaxies becomes important and a large fraction of the AGN population is expected to be powered by this mechanism, especially for X-ray luminosities $< L_*$. The colour-magnitude diagram (CDM) can be used as a proxy of the stellar population of galaxies. X-ray AGN at $z \approx 1$ are shown to be mostly associated with red-cloud (Nandra et al. 2007; 8) early-type galaxies (Pierce et al. 2007), possibly merger remnants (Georgakakis et al. 2008). Contrary to that, at $z \approx 0.1$, narrow emission-line AGN peak in the valley between the red and the blue cloud, suggesting later-type host galaxies with bluer colours (Martin et al. 2007; Fig. 8). This difference may be because of the optical/X-ray selection of the AGN, or an evolution effect, i.e. at low redshift the AGN population is dominated by Seyfert-mode late-type and bluer galaxies. In this case the decline of the AGN density is associated with the decline in the gaseous major merger rate with redshift.

(iii) Observations show that the typical stellar mass of galaxies that have stopped forming stars in the recent past, decreases with redshift, a trend which is often termed as downsizing (e.g. Bundy et al. 2006). If BH accretion is related to the SF quenching, then AGN hosts should also shift to smaller stellar masses with decreasing redshift. We have recently found tentative evidence in favour of this picture. In Fig. 9 the mean stellar mass of AGN hosts decreases with redshift, at the same rate as quenched galaxies.

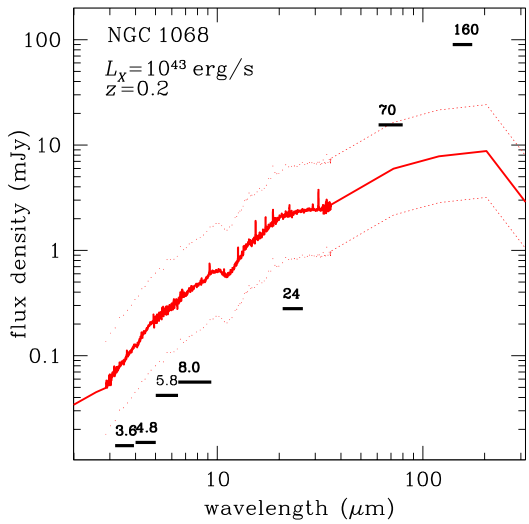

Figure 5: Expected mid-IR fluxes for an AGN with $L_X(2-10\,\mathrm{keV}) = 10^{43}\,\mathrm{erg\,s^{-1}}$. We adopt the template of NGC 1068 and the correlation between X-ray and 12μm luminosities of Horst et al. (2007) to convert X-ray to mid-IR fluxes. The dotted lines correspond to the 1 sigma rms scatter of the Horst et al. $L_X - L_{12.3\mu m}$ relation. The flux limits of the SWIRE survey in the IRAC and MIPS bands are shown with the horizontal bars. We expect to detect a large fraction of the X-ray AGN with $L_X > 10^{42}$ at $z < 0.2$ to the IRAC and MIPS-24μm flux limits. However, at longer wavelengths SWIRE is too shallow to detect the X-ray selected AGN, expect if there is substantial star-formation, i.e. higher than that in NGC 1068. Study of the mid-IR SED of a nearby X-ray AGN sample will help better understand how to select different types of AGN (obscured/unobscured) using mid-IR selection criteria.

The proposed project will allow thorough investigation of the preliminary result of Fig. 9. The expected large AGN sample and the UKIDSS near-IR data, which provide a good proxy to stellar mass and are least affected by AGN emission, will allow the determination of the Mass Function (MF) of AGN hosts at $z \approx 0.1$. This will be complemented by X-ray selected AGN samples at $z \approx 1$, to assess the evolution of the AGN host MF and to explore evidence for downsizing similar to that of galaxies.

Deep surveys alone cannot address this issue. The X-ray population shows a prominent peak at

$z \approx 1$ and therefore pencil-beam samples are affected by poor statistics and cosmic variance at low redshift. More importantly the flux limit of the survey (as in any flux limited sample) induces spurious correlations between redshift and distance-dependent quantities (e.g. stellar mass), further complicating the interpretation. It is only when combining samples at different depths/redshifts with similar selection criteria that one can start exploring downsizing scenarios.

Downsizing of the AGN host stellar mass, if confirmed, implies downsizing of the BH mass, assuming that the local BH-spheroid mass relation (Gebhardt et al. 2000) does not evolve with z. This provides a natural explanation for the luminosity dependent evolution of AGN at X-rays (e.g. Hasinger et al. 2005). Therefore, the proposed project has the potential to link the evolution of galaxies and the accretion history of the Universe to the same underlying physical process: AGN quenching of the SF.

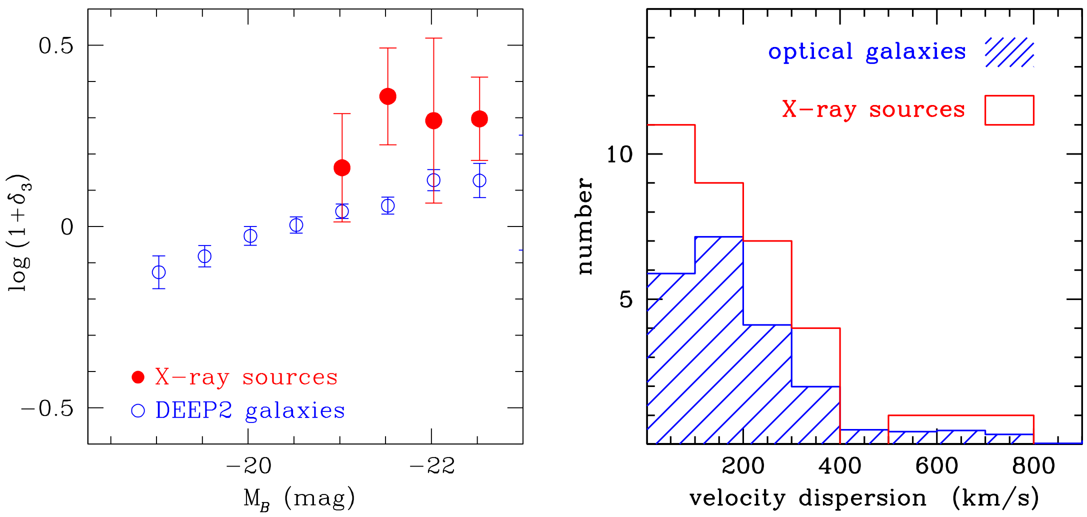

Figure 6: At high redshift, $z \approx 1$, X-ray selected AGN are in relatively dense environments. **Left panel:** Mean overdensity estimator $\log(1+\delta_3)$ (δ_3 is the projected space density to the 3rd nearest neighbour) against M_B for X-ray sources (filled circles) and optical galaxies (open circles) at $z \approx 1$ (Georgakakis et al. 2007). The data are from the AEGIS survey (Davis et al. 2007). X-ray AGN are found, on average, in higher density regions (higher δ_3) compared to the overall optical galaxy population. **Right panel:** The AEGIS data have been used to identify groups of galaxies at $z \approx 1$ (Gerke et al. 2005) and to explore the incidence of X-ray AGN in these systems (Georgakakis et al. 2008). For group members, the plot shows the distribution of X-ray AGN (red histogram) and optical galaxies (hatched blue) in group velocity dispersion. At $z \approx 1$ X-ray sources are more frequently found in groups compared to the overall optical galaxy population at the 99.97 significance level.

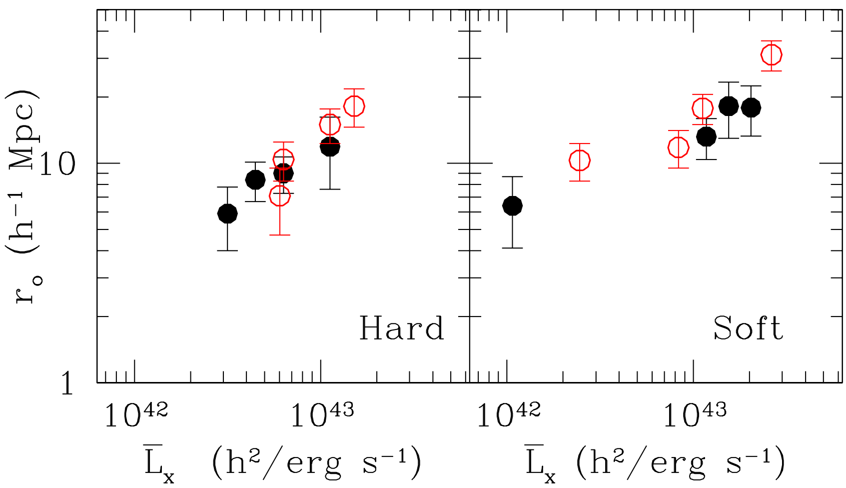

Figure 7: Plionis et al. (2008) find evidence for luminosity dependent clustering of AGN at $z \approx 1$, in the sense that more luminous sources are found on average in denser environments. The plot shows the clustering length r_0 of X-ray AGN in the CDF-N (filled symbols) and CDF-South (open symbols) as a function of the median intrinsic X-ray luminosity of each subsample. The left and right panels correspond to the hard and soft bands respectively.

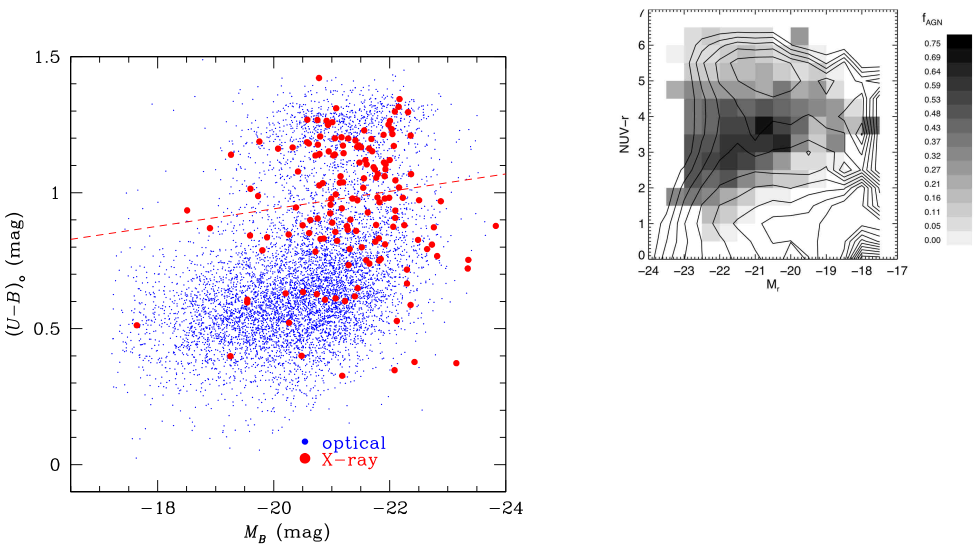

Figure 8: Colour magnitude diagram of X-ray AGN at $z \approx 1$ (Nandra et al. 2007; left panel) and narrow-line AGN at $z \approx 0.1$ form the SDSS (Martin et al. 2007; right panel). At $z \approx 1$ the highest density of X-ray AGN is in the red cloud, while at $z \approx 0.1$ narrow-line AGN peak in the valley between the red and blue clouds. This may be due to selection effects (i.e. optical vs X-ray) or evolution effects, i.e. the host galaxy properties of AGN change from $z \approx 1$ to the present day. Models indeed predict that at low redshift ($z < 0.5$) stochastic accretion in disk galaxies dominate over merger-induced black hole accretion (Hopkins & Hernquist 2006). The proposed survey will solve this discrepancy by constructing the CMD of X-ray AGN with selection criteria similar to those of high redshift X-ray AGN samples.

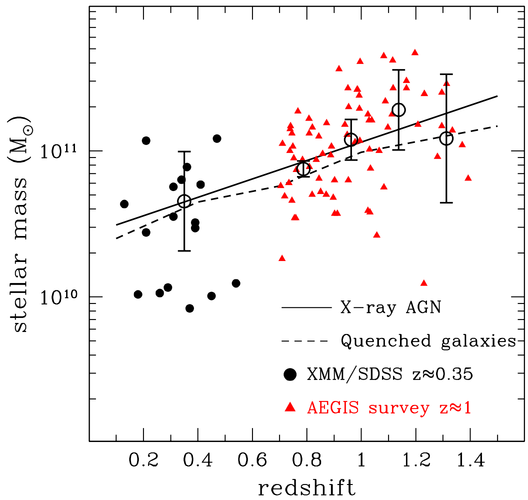

Figure 9: AGN-host stellar-mass ($M_\star$) against redshift. The triangles (red) are X-ray selected AGN in the range $0.7 < z < 1.4$ from the AEGIS survey (Davis et al. 2007). The filled circles (black) are preliminary results for X-ray AGN at $z \approx 0.3$ (Georgakakis et al. in prep). These are selected from XMM/SDSS fields covering 5deg^2. The large open circles correspond to the mean $M_\star$ of AGN-hosts in different redshift bins. The continuous line is the best-fit $\log M_\star - z$ relation to these points. The dashed line shows the mean $M_\star$ of optically selected galaxies that have recently stopped forming stars, and which are in the transition from late to early types (Hopkins et al. 2007). This curve closely traces the mean stellar mass of AGN hosts, suggesting a link between BH accretion and quenched galaxies. The proposed project will provide a large sample of AGN at low redshift, $z < 0.2$. This will complement our VLT program at $z \approx 0.3$ and deep surveys at $z \approx 1$ (AEGIS, GOODS), thereby providing an estimate of the AGN-host Mass Function (not just the mean $M_\star$) and its evolution over a wide redshift range, to explore evidence for AGN host downsizing.