THE CENSUS OF HIGHLY OBSCURED SMBH THROUGH THE COSMIC EPOCHS: CHANDRA SNAPSHOTS OF EXTREME SWIRE AGNS

At high redshifts (z$\sim$ 1–3) highly obscured and Compton Thick QSOs are expected to be as numerous as unobscured QSOs. However, even the deepest X-ray surveys have proven to be rather inefficient to search for these elusive AGNs, and, at present, only a handful of objects are known beyond the local Universe. Alternative selection criteria, combining far to near infrared to optical photometry, seems more promising, and were indeed successfull to pin-point many candidate obscured AGNs. We selected a well defined and homogeneous sample of candidate obscured AGNs by making use of the wealth of multiwavelength data available in the SWIRE survey on about 30 deg^2, and requiring extreme values of the 24μm to optical flux ratio and bright 24μm fluxes, which are demonstrated to be reliable proxies of high luminosity and high obscuration. We propose Chandra observations of 16 of these sources. They are expected to host the most luminous and obscured AGN in the high redshift Universe. The combination of X-ray and infrared information will be used to measure the number density of highly obscured AGNs. By joining this sample to the CDFs and other smaller area survey samples, we will be able to determine the evolution of the obscured AGN population, a step forward in completing the census of SMBH through the cosmic epochs.

1 Obscured accretion and SMBH

Active Galactic Nuclei (AGN) are not only witnesses of the phases of galaxy formation and/or assembly, but are most likely among leading actors. Indeed, three seminal discoveries indicate tight links and feedbacks between super-massive black holes (SMBH), nuclear activity and galaxy evolution. The first is the discovery of SMBH in the center of most nearby bulge dominated galaxies, and the steep and tight correlation between their masses and galaxy bulge properties (Gebhardt et al. 2000, ApJ 539, L13, Ferrarese & Merritt 2000, ApJ 539, L9, Marconi & Hunt 2003, ApJ 589, L21 and references therein). The second is that AGN evolution is luminosity dependent, with lower luminosity AGNs peaking at a lower redshift than luminous QSOs (Hasinger 2005, A&A, 441, 417, Fiore et al. 2003, A&A, 409, 79, Ueda et al. 2003, ApJ, 598, 886, La Franca et al. 2005, ApJ, 635, 864), a bimodal behaviour recalling the evolution of starforming galaxies and that of massive spheroids (Franceschini et al. 1999, MNRAS, 310, L5). The third is that the growth of SMBH is mostly due to accretion of matter during their active phases, and therefore that most bulge galaxies went through a phase of strong nuclear activity (Soltan 1982, MNRAS, 200 115, Marconi et al. 2004, MNRAS, 351, 169). **Obtaining a complete census of accreting SMBH through the cosmic epochs and constraining accretion efficiency and feedbacks are therefore crucial steps toward the understanding of Galaxy formation and evolution.**

First attempts to constrain models for the formation and evolution of structure in the Universe using the evolving optical and X–ray AGN luminosity functions (LF) have been presented by Granato et al. (2004, ApJ, 600, 580), Di Matteo et al. (2005, Nature, 43, 604), and Menci et al. (2004, ApJ, 606, 58, 2006, ApJ, 647, 753). These models correctly predict the observed shift of the peak of AGN space density, which moves to high redshift at high luminosities. However, quantitatively, **the models overpredict by a factor of about 2 the space density of low-to-intermediate luminosity AGN at z=1.5-2.5 with respect to present X-ray observations**. Furthermore, Marconi et. al. (2004, 2007 in preparation) derived a **SMBH mass function from the X-ray selected AGN luminosity functions that falls short by a factor ~ 2 to the “relic” SMBH mass function**, evaluated by using the $M_{BH}-\sigma_V$ / $M\odot-M_B$ relationships and the local bulge's luminosity function. **Both discrepancies vanish if *"a factor 2"* population of**

heavily obscured AGNs is folded in the model predictions. However, this population is so far only loosely constrained.

A blind search for highly obscured AGN among serendipitous X–ray sources is inefficient, even by using ultra-deep exposures (see e.g. Tozzi et al. 2006, A&A, 451, 457). All present X-ray surveys **miss most of the highly obscured, but still strongly accreting objects**, the so called Compton Thick (CT) AGNs (those with a column density $N_H \gtrsim 10^{24}$ cm^{-2}, see Comastri 2004, astro-ph/0403693). The handful of objects so far discovered in the X–ray band, may represent just the tip of the iceberg while CT objects may well be common at high redshift (e.g. Fabian, 1999, MNRAS, 308, L39, Silk & Rees, 1998, A&A, 311, L1; Gilli et al. 2007 A&A 463, 79).

A more efficient approach to find CT AGNs is to select sources with AGN luminosities in the mid-infrared and faint optical or near infrared emission (e.g. Martinez-Sansigre et al. 2005, Nature, 436, 666, Houck et al. 2005, ApJ, 622, L105 Weedman et al. 2006, ApJ, 653, 101, 2006, ApJ, 651, 101, Fiore et al. 2007, ApJL submitted[1]). Briefly, Martinez-Sansigre and collaborators obtained optical spectroscopy of a small sample (a dozen) of bright 24μm objects with faint optical and 3.6μm counterparts finding that most of them are narrow line type 2 QSOs. Houck, Weedman and collaborators obtained Spitzer IRS spectra of a larger sample (several tens) of objects with extreme F(24μm)/F(optical) (MIR/O) flux ratio finding that most of them are dominated by strong silicate absorption (detectable with IRS only up to z$\sim$ 2.5–2.7), characteristic of obscured AGN. We found that a sample of GOODS sources with extreme MIR/O flux ratios and red optical to near-infrared colors have faint but detectable X-ray counterparts when stacking together the counts at the position of the extreme MIR/O sources. X-ray fluxes and hardness ratios (HR) strongly suggests a highly obscured AGN population. In summary, all these studies indicate that the majority (70 to 90%) of the sources with extreme MIR/O ratios ($> 1000 - 2000$ are highly obscured AGN. Given that the MIR/O ratio correlates with the MIR luminosity which is considered a proxy of the bolometric one (see fig. 1) a selection based on the 24μm flux is particularly well suited to find highly obscured QSOs, and, at present, it represents the most promising selection method to complement X-ray surveys in obtaining a complete census of accreting SMBH.

2 Immediate Objective and sample selection

To quantify the relative efficiency of the infrared selection criterium, and therefore to assess the real number density of highly obscured AGNs, we need to firmly establish the AGN nature of the MIR selected sources and to assess their X-ray properties. More in detail, we need to evaluate the fraction of the MIR selected highly obscured AGNs which **would have been selected also by X-ray surveys**. This will allow us to a) complement the LF of Compton thin AGN directly detected in X-rays with the fraction of CT AGN faint in X-rays but shining in the mid-IR, making possible the first reliable estimate of AGN "bolometric" LF at high z; b) constrain the AGN N_H distribution at high column densities, through the comparison of the observed MIR to X-ray flux ratios with the expectations of dust reprocessing models (e.g. Silva et al. 2004, ApJ, 509, 103).

This is already quantitatively possible for low luminosity, Seyfert-like objects found in the relatively small fields target of the deepest Spitzer, Hubble and Chandra surveys (< 0.1 deg^2 for the CDFs to 0.3 deg^2 for the EGS field to maximum of 2 deg^2 for the COSMOS field). As an example, fig. 2 left panel shows the X-ray (2-10 keV) to MIR (24μm) flux ratio (X/MIR) as a function of the X-ray flux for the CDFS sources. The figure shows that the fraction of highly obscured sources increases strongly at low X/MIR flux ratios. The Chandra exposure is deep enough to sample a large range of column densities, reaching a X/MIR flux ratio of 0.01 (more

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[1] http://www.oa-roma.inaf.it/~fiore/goods_mipsagn.pdf

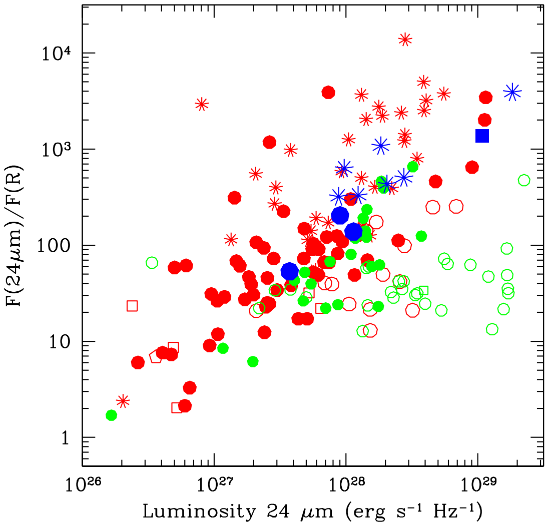

Figure 1: MIR/O as a function of the 24μ Luminosity for three X-ray source samples (CDFS-MUSIC, red points, ELAIS-S1, green points and HELLAS2XMM, large blue points , Pozzi et al. 2007). Open circles = type 1 AGN; filled circles = non type 1 AGN; stars = photometric redshifts. Note as MIR/O of non broad line AGN is strongly correlated with the luminosity.

than ten times lower than that of moderately obscured AGN in the local Universe, the so called Piccinotti AGNs). Most of the highly obscured objects are low to medium luminosity AGNs, in agreement with the expectations of the Seyfert 2 Spectral Energy Distribution (SED) of Silva et al. (2004) at z=0.5-2, see fig. 2.

On the other hand, a quantitative, complete assessment of the demography of highly obscured AGN with intermediate-to-high luminosity (the so called type 2 QSOs), is still lacking. The reason is that building up complete samples of highly obscured, high luminosity QSOs with homogeneous selection criteria is difficult and time-consuming, because of the large area that must be covered with deep multi-band observations. **The SWIRE survey, covering with medium–deep MIPS and IRAC photometry about 50 deg^2 of the sky, provides a unique opportunity to build up such a complete sample of highly obscured QSOs**. At present, the X-ray coverage of the SWIRE fields is highly inhomogenoeus and incomplete. To reach an X/MIR flux ratio of ~ 0.01, thus allowing a sensitive search for high obscuration as explained above, would already require an X-ray flux limit $\lesssim 10^{-14}$ cgs for the brightest SWIRE sources. This implies Chandra and XMM exposure times of the order of 30ks for highly obscured (logN$_H \sim 24$) spectra. Shallower exposures, like those already available on the XMM-LSS field ($\sim$ 10ks) and the Bootes NOAO/Chandra wide field ($\sim$ 5ks) are not able to probe low X/MIR flux ratios and therefore AGNs with such high column densities. **Covering to the desired depth all SWIRE fields is practically unfeasible with today instrumentation**. An alternative and more efficient approach is to perform targeted observations of candidate CT AGNs, pre-selected on the basis of their high the MIR/O ratio, as described in the previous section.

To this purpose, we have collected all available Spitzer data, optical photometry and X-ray data on four SWIRE fields: ELAIS-S1, ELAIS-N1, ELAIS-N2 and Lockman Hole. We have also collected Spitzer, XMM and Subaru data on the XMM SXDS field. Multi-band catalogs from these fields have been cleaned from bright stars and spurious detections. Aperture photometry of the optical

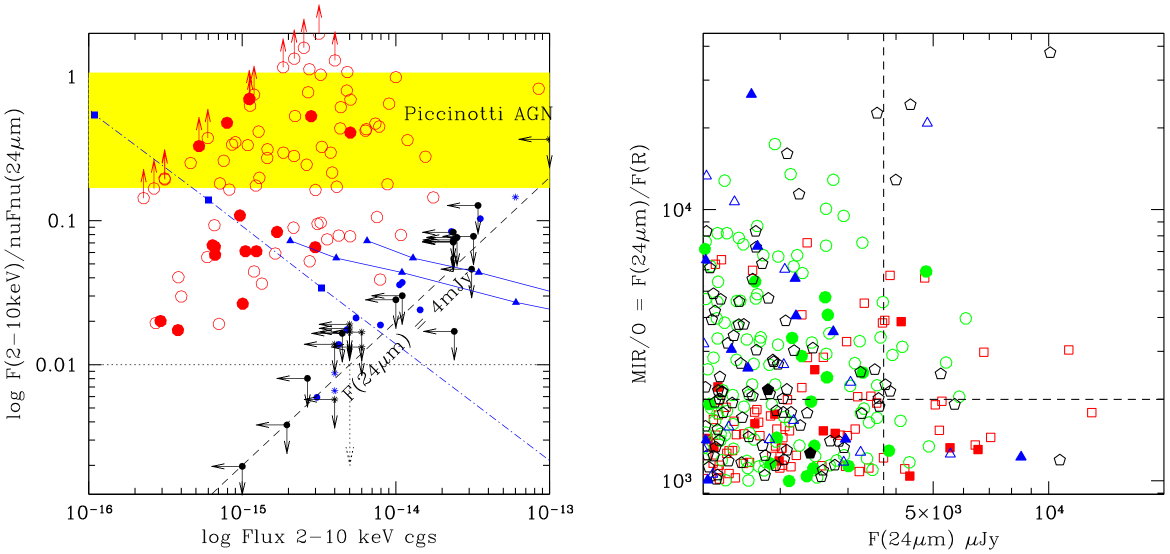

Figure 2: Left panel: The X-ray (2-10 keV) to MIR (24μm) flux ratio as a function of the 2-10 keV flux for the sources in the CDFS. Filled circles = highly obscured AGN (log$N_H > 23.7$). Small filled circles (stars) are SWIRE (COSMOS) sources with F(24μm)/F(R)$>$ 2000 and F(24μm)$>$ 2mJy. The dashed line marks the locus of constant 24μm flux equal to 4mJy, the flux limit of the sample selected for this proposal. The small filled triangles connected by solid lines are the expectations of the X-ray to IR SED of IRAS09104+4109 at z=4,3,2,1 (from left to right) for logL(2-10keV)=44.5 (lower points and curve) and logL(2-10keV)=45 (upper points and curve). The small filled squares connected by a dot-dashed line are the expectations of a Seyfert 2 SED with logL(2-10keV)=42.5 (adapted from Silva et al. 2004) at z=2,1,0.5 (left to right). Right panel: MIR (24μm) to optical (R band) flux ratio as a function of the 24μm flux for the sources in the ELAIS-S1 (blue triangles), ELAIS-N1 (green circles), ELAIS-N2 (black pentagons) and Lockman Hole (red squares) SWIRE fields. Filled symbols mark sources with X-ray data coverage. *The sources selected for this proposal are those in the upper right corner defined by the two dashed lines. They will fill the presently sparsely populated area of the diagram in the left panel below the dashed line and above X/MIR=0.01.*

counterparts fainter than the field detection limits has been obtained at the position of the MIPS sources on the original optical images. A summary of the X-ray and multiwavelength coverage of the SWIRE fields can be found at the following URL: http://www.oa-roma.inaf.it/∼fiore/XSWIRE. Figure 2 right panel shows the MIR (24μm) to optical (R band) flux ratio as a function of the 24μm flux for the sources of this SWIRE sample. There are 18 sources with MIR/O$>$ 2000 and F(24μm)$\gtrsim$4mJy. This flux limit is a convenient compromise between targeting the brightest possible sources and building up a statistically meaningfull sample. The X-ray information available on such bright 24μm sources is disappointingly very limited. Only six SWIRE sources have X-ray coverage, three are detected in the X-ray images at a flux levels of $3 - 15 \times 10^{-15}$ cgs. The faintest source is the LH CT source of Polletta et al. (2006, ApJ, 642, 673) at z=2.54 (Weedman et al. 2006), and also the other 2 sources have hard HR, thus supporting the effectiveness of our strategy. Three sources are not detected with shallow flux limits of $2.5 - 3 \times 10^{-14}$. Very few sources with similar MIR/O and F(24μm) have been discovered in other fields with X-ray coverage. As an example, there are only two such sources in the whole COSMOS field, one detected with a hard HR.

The number of 24μm selected sources increases strongly toward lower fluxes and more information is available on the X-ray properties of high MIR/O AGNs among these fainter sources. As an example, we have collected all available X-ray data for the SWIRE, GOODS and COSMOS sources with MIR/O> 2000 and F(24μm)>2mJy (37 sources, see fig. 2). 14 sources have an X-ray detection and another dozen have X-ray limits deep enough to reach X/MIR$\lesssim$0.02, thus suggesting extreme column densities. Most of these sources have hard HR. Fig. 2 also shows how complementary are the wide field data with respect to the CDFs data. While CT Seyfert like galaxies are certainly present in the CDFS, highly obscured QSOs are rare and can hardly be found in such pencil beam surveys. These sources are likely to be present in the SWIRE sample, as suggested by the expectations of the X-ray to IR SED of IRAS09104+4109 for z=2-4 and logL(2-10keV)=44.5-45.

Our proposal is to obtain **sensitive Chandra data of the 16 brightest F(24μm) SWIRE sources F(24μm)$\gtrsim$4mJy) with faint optical counterparts (MIR/O>2000)** and with no or insufficient X-ray coverage, down to a flux limit deep enough to reach X/MIR=0.01. This will form a statistically sizable and complete sample of AGN with more extreme properties than those sampled by the CDFs and the COSMOS survey, largely increasing the present coverage of the luminosity-redshift plane. Having used well defined and homogeneous selection criteria, we will be able to use the combination of the X-ray and IR information to measure the number density of highly obscured AGN. **By joining this sample to the CDFs and COSMOS samples we will be able to determine the AGN "bolometric" luminosity function in several redshift bins, including both unobscured and highly obscured AGN**. This is an ambitious goals which should allow us to start to quantitatively investigate the inconsistencies between the LF and evolutions obtained by surveys at different wavelengths (e.g. Hopkins et al. 2006, ApJ, 652, 864).

In addition to the Chandra observations we require coordinated Spitzer IRS observations for those sources with optical counterpart fainter than R$\sim$24 (7 sources). The Spitzer spectra have two aims, fully complementary to the Chandra data. First, the IRS data will validate the nature of these sources by showing mid-IR spectral features that are characteristic of obscured AGNs (steeply rising power-law and silicate absorption); this will provide a complementary confirmation of the nature of these sources with a totally independent approach with respect to the X-ray data. Second, the detection of the silicate absorption feature in these soruces will provide their redshift, which cannot be obtained otherwise due to the extreme optical faintness of these sources. The redshift of the sources in our sample is crucial to determine their luminosity, hence to determine their LF and its cosmic evolution.

Optical images with MIPS 24μm contours overlayed of the 18 sources of the SWIRE complete sample can be found at: http://www.oa-roma.inaf.it/~fiore/XSWIRE

3 Technical justification of joint facilities

To evaluate the count rate expected from a highly obscured AGN is not an easy task, because the spectrum is complex, with Compton scattering further reducing the direct AGN emission, in addition to photoelectric absorption. On the other hand, a scattering component is often observed, increasing the low energy count rate. In these cases it is safer to resort to real observations rather than to simulations. As mentioned in the previous section, one of the two sources in the SWIRE sample with an X-ray detection is one of the CT ($N_H \gtrsim 10^{24}$ cm^{-2}), high luminosity QSOs in Polletta et al. (2006). The ACIS full band flux of this source is $\sim 3 \times 10^{-15}$cgs and the observed count rate is 1.6×10^{-4} cts/s. Similar conversion factors applies to the other 4 CT AGN in Polletta et al. (2006) and similar numbers are also found in our Chandra/XMM survey of the ELAIS-S1 field.

Our exposure times have been computed in order to have at least 7 ACIS-I counts, enough to provide a robust detection, and to reach X/MIR=0.01. They go from 10ks for the brightest source of the sample to 30ks for the faintest sources. **The total requested exposure time is 423ks.**

If the sources are unobscured, or moderately obscured AGN they will provide spectra with $50-100$counts in the requested exposure time, allowing us to constrain tightly the absorbing column density. In such a case this would imply that similar sources are already present in the samples used to build the 2-10 keV LF, and therefore MIR selected AGNs do not select a different population nor add a further contribution to the SMBH mass function. Conversely, if they turn out to be mildly CT they could have escaped detection and/or identification in both deep (e.g. CDFs) and shallower (EGS, COSMOS) Chandra and XMM surveys. As an example, assuming for the sources the same SED of IRAS09104+4109, a rest frame logN_H=24 cm^{-2}, logL(2-10keV)=45 and z=2 their 2–10 keV flux should be of the order of 2×10^{-14} cgs, which should provide $\sim$ 30 ACIS-I counts in 30 ksec, enough to provide a rough CT classification (see e.g. Polletta et al. 2006). If the sources are undetected at the faint limits implied by the requested exposures they would most likely be heavily CT (logN_H $>$ 25 cm^{-2}), and therefore almost completely missing in 2–10 keV surveys. If this is the case the present observations will allow us to put an upper limit on the X–ray luminosity and by comparison with the infrared (bolometric) luminosity, and for reasonable bolometric corrections, a lower limit on the column density.

We have checked the pitch angle constraints for the two proposed sources. The sources are never in the critical pitch angle zone.

In addition to the sources target of this proposal many more Spitzer sources will be present in the Chandra pointings. This program will therefore provide valuable datasets for many more additional studies. To facilitate and expedite the exploitation of this unique dataset we are willing to wave our proprietary rights.

The goals of the Spitzer spectroscopic coordinated observations are: 1) confirm that these objects are dominated by AGN emission in the mid-IR band, i.e. are characterized by a steeply rising ($\sim$power law) mid-IR continuum, with no or little PAH contribution; 2) confirm that these objects are *heavily obscured* AGNs (QSO2s) through the detection of a deep silicate absorption at $\sim 9.7\mu$m; 3) use the latter feature to determine the spectroscopic redshift of these sources. These goals, and in particular the confident detection of the silicate feature, require a spectrum with a S/N>10. We also need a spectral coverage ranging from $\sim 8\mu$m to $\sim 35\mu$m, so that a putative Silicate feature can be detected over a wide redshift range. The latter requirement implies the use of the SL1,LL2 and LL1 IRS modes. All of these sources are located in regions of low background. Given a typical flux density of 3.7 mJy at 24μm, we infer the expected fluxes in each of the three IRS modules by using as a template the IRS spectrum of the IRAS09104+4109, redshifted at z=2. According to the Spitzer Performance Estimation Tool, a S/N$\sim$10 can be achieved with 60sec$\times$3cycles in SL1 and 14sec$\times$35cycles in LL2/LL1, yielding a total exposure of 366 sec in SL1 and 1028 sec in each of the two LL modules. Similar exposures have been successfully used for other IRS observations of high-z sources with similar brightness. Once overheads are included Spitzer-SPOT gives a total duration of the AOR of 4002 sec for each source. We need to observe 7 sources and therefore the total requested exposure time is of 7.8 hours.

4 Previous *Chandra* programs

AO2 Chasing quasar 2, Proposal number 04900449, ObsID 4273, 4274. Data published in Mignoli et al. 2004 A&A, 418, 827.

AO7 The dark side of accretion: chasing type 2 QSOs, proposal number 07900290, ObsID 7016, 7017, 7018, 7019, 7020. Data from this pilot program have been received on Oct 2006 and have been analyzed. A paper presenting the results is in preparation (Feruglio et al. 2007). Chandra accurate positions have already been used to improve the localization of the counterparts of the XMM sources (see http://www.oa-roma.inaf.it/ELAIS-S1).