

The growth and evolution of super massive black holes

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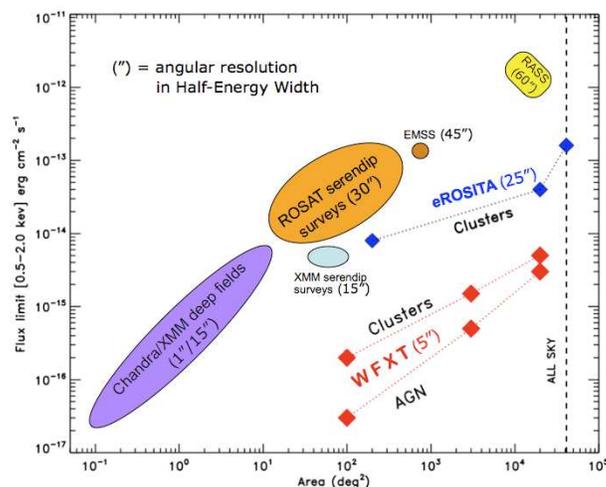
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Science Frontier Panels

Primary Panel: Galaxies across Cosmic Time (GCT)

Secondary panel: Cosmology and Fundamental Physics (GFP)

Project emphasized: The Wide-Field X-Ray Telescope (WFXT); <http://wfxt.pha.jhu.edu/>



Executive summary. We discuss the central role played by X-ray studies to reconstruct the past history of formation and evolution of supermassive Black Holes (BHs), and the role they played in shaping the properties of their host galaxies. We shortly review the progress in this field contributed by the current X-ray and multiwavelength surveys. Then, we focus on the outstanding scientific questions that have been opened by observations carried out in the last years and that represent the legacy of Chandra and XMM, as for X-ray observations, and the legacy of the SDSS, as for wide area surveys: **1) When and how did the first supermassive black holes form? 2) How does cosmic environment regulate nuclear activity (and star formation) across cosmic time? 3) What is the history of nuclear activity in a galaxy lifetime?** We show that the most efficient observational strategy to address these questions is to carry out a large-area X-ray survey, reaching a sensitivity comparable to that of deep Chandra and XMM pointings, but extending over several thousands of square degrees. Such a survey can only be carried out with a Wide-Field X-ray Telescope (WFXT) with a high survey speed, due to the combination of large field of view and large effective area, i.e., grasp, and sharp PSF. We emphasize the important synergies that WFXT will have with a number of future ground-based and space telescopes, covering from the radio to the X-ray bands and discuss the immense legacy value that such a mission will have for extragalactic astronomy at large.

1 Introduction

Several pieces of evidence point towards an intimate relation between the evolution of galaxies and the accretion of supermassive black holes (SMBHs) at their centers, indicating that most galaxies in the Universe spent a fraction of their lifetimes as active galactic nuclei (AGN). In the local Universe, most galaxy bulges host a SMBH [16], whose mass scales with the bulge mass and stellar velocity dispersion [17, 18]. Furthermore, the growth of SMBHs during active accretion phases, traced by the cosmological evolution of the AGN luminosity function [19, 20, 21, 22], eventually matches the mass function of SMBHs in the local Universe [23, 24, 25]. Finally, both BH growth and star formation appear to follow the same "anti-hierarchical" behaviour over cosmic time. The peak activity of luminous QSOs occurs at $z \sim 2$, where large galaxies were also forming most of their stars, while moderately luminous AGN are more common at the current epoch, where stars are forming in smaller galaxies. The role played by nuclear activity in modulating star formation processes in the host galaxies ("feedback") is the subject of huge research efforts.

While the SMBH vs galaxy co-evolution is now an accepted scenario, the details of this joint evolution are not yet fully understood. In particular, the processes that control BH growth are uncertain. Nuclear activity in bright QSOs is thought to be induced by major mergers or close encounters of gas-rich galaxies in the context of hierarchical structure formation [26, 8], but the case for the importance of such mergers in low-to-moderate luminosity AGNs is much less clear [52]. Furthermore, the early phases of nuclear activity triggered by merger events are thought to be buried by large columns of gas and dust, possibly with concurrent vigorous star formation [8]. Evidence for coeval star formation and nuclear activity produced by galaxy interactions has been indeed found in populations of bright IR/submillimeter galaxies at $z \sim 2$ and beyond [44]. In contrast, the majority of $z \sim 2$ AGN selected at faint X-ray fluxes are hosted by galaxies with a spectral energy distribution typical of passively evolving objects [27]. It has been suggested that the concu-

rent growth of black holes and stellar mass observed in IR galaxies at $z \sim 2$ is a long-lived (> 0.2 Gyr) phenomenon, unlikely to be triggered by rapid major-merger events [28], which is instead the common interpretation to explain the highly efficient star formation and BH accretion observed in the highest redshift ($z > 6$) QSOs to date [6]. The current picture has several unsolved issues:

- 1) the early stages of BH and galaxy formation, where strong star formation events are expected to be associated with vigorous nuclear accretion, are still unknown.
- 2) the dependence of the cosmic accretion history on galaxy merging and interactions, hence on galaxy environment, is currently debated.
- 3) the history and duty cycle of nuclear activity in a galaxy lifetime, especially the relative phases of obscured and unobscured accretion, have still to be understood.

Since most of the accretion onto SMBHs is expected to be obscured, deep X-ray surveys complemented by multiwavelength followup are needed to sample the whole AGN population. At the moment such surveys (e.g. CDFs, COSMOS, AEGIS) do not have enough sensitivity nor sky coverage to provide the statistics necessary to address the above issues.

2 Super Massive Black Holes in the Early Universe

When and how did the first supermassive black holes form?

While most stars in the Universe appear to have formed at $0.5 < z < 3$, when SMBHs were also growing most of their mass [51], the first objects formed at even earlier epochs, as soon as baryons were able to cool within dark matter halos. To date, about 30 galaxies and about 20 QSOs have been observed at redshifts above 6 [49, 50]. The BH masses measured for these very high redshift QSOs are of the order of $10^9 M_\odot$ [1], which must have been built in less than 1 Gyr (the age of the Universe at $z = 6$). These giant black holes are thought to have formed through mass accretion onto smaller seed black holes with mass in the range $10^2 - 10^4 M_\odot$. A number of possibilities for the origin of these seed black holes have been proposed, which range from being the $10^2 M_\odot$ remnants of massive, PopIII, stars [2], to being the $10^4 M_\odot$ products of direct collapse of large molecular clouds [3]. Whatever the seed origin is, the huge mass gain over a cosmologically short timescale implies that the BH growth in these objects was close to (or even higher than) the Eddington limit and continuous over that time. Recent hydrodynamical simulations, have shown that, within large dark matter halos, merging between proto-galaxies at $z \sim 14$ with seed BH masses of $10^4 M_\odot$ may trigger Eddington limited nuclear activity to produce a 10^9 solar mass BH by $z \sim 6$ [6]. The frequency and efficiency with which this merging and fueling mechanism can work is however unknown.

Currently, given the scarcity of observational constraints, BH and galaxy formation at early epochs is speculative work. For example, the relation between the BH mass and the galaxy gas mass has been measured for a few bright QSOs at $z \sim 5 - 6$, in which the ratio between the BH mass and that of the dynamical mass within a few kpc radius, as measured from CO line observations, is of the order of 0.02-0.1 [4, 5]. This is more than one order of magnitude larger than the ratio between the BH mass and stellar bulge mass measured in local galaxies (see also [53] for similar conclusions for a sample of $z > 1$ AGN). Despite the uncertainties on these measurements (see e.g. [7]), the possibility that SMBHs are leading the formation of the bulge in proto-galaxies, poses severe constraints to galaxy formation models. In general, it is not clear whether the M_{BH}/M_{bulge} ratio measured in these objects

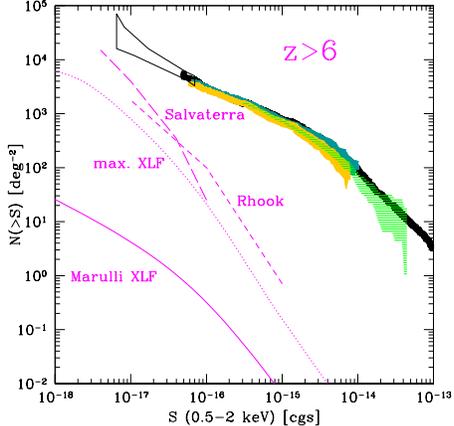


Figure 1: The 0.5-2 keV $\log N$ - $\log S$ expected for AGN at $z > 6$ according to different models as labeled. Note the vertical scale and the very large scatter in the model predictions. The detection with WFXT of a few thousand objects at $z > 6$ (and \sim a hundred at $z > 8$) at fluxes of 10^{-17} - 10^{-16} erg/cm²/s would constrain early BH formation. We note that such a practical goal is beyond the capabilities of eROSITA, which is confusion limited around fluxes of a few $\times 10^{-15}$ erg/cm²/s, where the surface density of high- z AGN is extremely low.

is a feature of peculiar sources or it can be extrapolated to the full galaxy population (see e.g. [45]). Large statistical samples of $z > 6$ AGN are needed to understand the relation between the BH growth and formation of stars in galaxies at their birth.

Another observational constraint regarding accreting SMBHs in the early Universe is the space density measured for luminous, optically-bright QSOs selected by the SDSS, which suggests that the the space density of quasars with $L_{bol} > 10^{46}$ erg/s declines from $z \sim 3$ to $z > 6$ [50]. This measurement only applies to the most luminous optical QSOs, i.e. to a presumably tiny fraction of the active BH population at $z > 6$, which is instead expected to be made primarily by less massive, $10^6 M_{\odot}$, and less luminous, $L_{bol} \sim 10^{44}$ erg/s, objects. Many semi-analytical models of early BH formation within the growth of cosmic structures have been proposed in recent years [9, 10, 11], in which the BH formation rate depends on several factors such as: i) where (i.e. in which dark matter halos) they form; ii) what is their average accretion rate; iii) what is the triggering mechanism: galaxy merging and fly-by? Accretion of cold gas independent of galaxy interactions? Measuring the space density of low luminosity AGN at $z > 6$ would constrain most the model parameters, and will therefore be the key to understanding how the population of early BHs has formed.

While optically-bright QSOs at high redshift can be efficiently selected by optical color techniques (e.g. by wide-area optical surveys with LSST and Pan-STARRS) and then identified spectroscopically, this is not the case for obscured high- z QSOs, since they would escape standard color selection. Furthermore, high-excitation narrow emission lines – the sign of nuclear activity in the optical/near-IR spectra of obscured AGN – are often weak or absent. Therefore, major future facilities like JWST or ALMA will measure the redshift of galaxies up to $z > 8$, but will not reliably establish if an obscured AGN hides at their centers.

To date, **no** obscured AGN at $z > 6$ have been discovered, as opposed to 20 unobscured QSO at $z > 6$. Nonetheless, there are several arguments which suggest that a large population of obscured QSOs, probably even larger than that of unobscured QSOs, has to be present at high redshift. First, observations and modeling up to $z < 4$ have shown that obscured AGN outnumber unobscured ones by large factors (2-8) [12] which have been also proposed to increase with redshift [13]. Second, current models of galaxy formation, postulate that the early phase of accretion onto the central black hole is obscured, which would naturally predict many high- z obscured sources. Third, dust and metals have been found to be abundant in the inner regions of $z > 6$ objects [14, 15], which could therefore absorb nuclear radiation in the optical/UV band. The lack of known obscured AGN at very high-

redshift is presumably related to the limitations of current sky surveys. Indeed, the large volumes needed to detect rare, high- z objects have been achieved only by optical surveys like the SDSS and UKIDSS, which are bound to optical color selection criteria, while deep X-ray surveys, which efficiently select obscured objects, are currently covering too small a volume. The discovery space for early obscured AGN is therefore huge, and can have an extreme impact on our understanding of BH and galaxy formation. All Sky Surveys like the RASS are too shallow to detect faint, obscured AGN at $z > 6$, and the X-ray surveys to be performed by the near future mission eROSITA will be confusion limited at X-ray fluxes too bright to detect $z > 6$ objects (see Fig. 1 and 3).

This discovery space can be filled through deep X-ray surveys over large sky areas. To this end an X-ray facility with sharp ($\sim 5''$ HPD) resolution constant over a large (~ 1 deg²) FOV, and large ($\sim 0.5 - 1.0$ m² at 1 keV) effective area would be ideal.¹ The above mentioned requirements are planned for the WFXT mission [54]. In 5 years WFXT can easily observe the equivalent of a thousand Chandra Deep Fields², plus a few thousand Chandra-COSMOS fields, plus several thousand XBoötes fields. Based on extrapolations of current X-ray luminosity functions at $z < 4$, in which the AGN space density declines exponentially at high redshifts (see e.g. [29]) one would expect to detect 1000 obscured AGN, plus 1300 unobscured AGN at $z > 6$. Also, approximately a hundred AGN are expected at $z > 8$. While optical surveys with LSST and Pan-STARRS may be used to isolate candidates high- z unobscured AGN among WFXT sources, the identification process for obscured objects is more problematic and will need a joint effort with the major future optical to IR facilities. Deep and wide photometric IR surveys such as those planned with VISTA and spectroscopic IR surveys like those under study for the ESA/NASA JDEM/Euclid project, are expected to provide redshifts for faint, high- z galaxies over a large portion of the sky. A match between an apparently quiescent galaxy at $z > 6$ revealed by optical/near IR surveys and an X-ray source detected by WFXT would reveal the presence of a hidden AGN in the early Universe.

It is worth noting that the above numbers of high- z AGN to be observed with WFXT are reference numbers. Indeed, the predictions based on semi-analytic models scatter by several orders of magnitude depending on the model assumptions, and it is immediately clear that a statistically large sample such as that provided by WFXT is needed to constrain models of QSO and galaxy formation. Even simple comparisons between the observed source counts at $z > 6$ (and at $z > 8$) with model predictions will do the job (see Fig. 1). WFXT will then constitute a unique tool to probe the population of high- z obscured AGN, a scientific issue which is not achievable with any of the planned facilities in the next 20 years. Even the proposed International X-ray Observatory (IXO), which will have the power to get good quality X-ray spectra for faint high- z sources, will be limited by its small FOV. In this regard, there will be full complementarity, with WFXT detecting high- z obscured candidates to be followed up by IXO.

3 Black hole fueling and the Large Scale Structure

How does cosmic environment regulate nuclear activity and star formation?

¹It is recalled that, for objects at $z > 6$, photons observed at 1 keV correspond to rest frame energies of > 7 keV, i.e. they will be largely unaffected by nuclear obscuration.

²We note here that, when averaged over the field of view, the resolution of Chandra and WFXT will be comparable, Chandra being significantly better than WFXT on axis but significantly worse off axis.

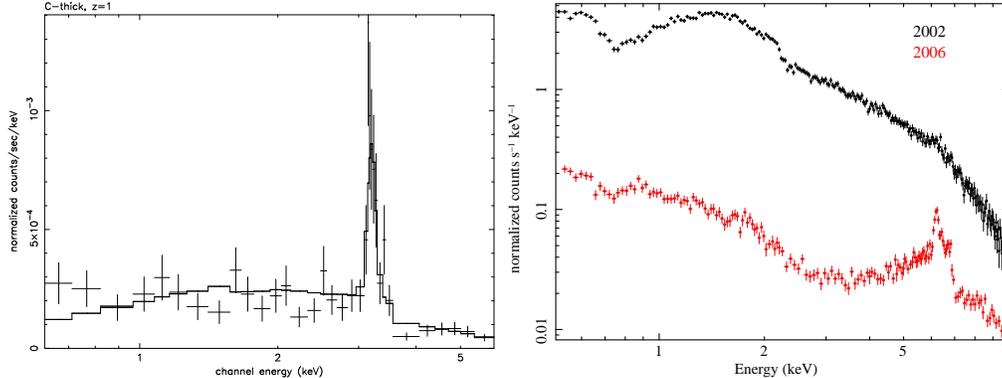


Figure 2: *Left Panel:* simulated X-ray spectrum of a moderately bright Compton-thick AGN at $z = 1$ observed with WFXT. About 500 such objects are expected to be observed with WFXT in 5 years. Note the prominent iron $K\alpha$ line which is both the hallmark of a Compton-thick nucleus and provides the source redshift independently of optical follow-up. *Right panel:* the XMM spectrum of the AGN H0557-385 observed at two different epochs, which is indicative of extremely variable X-ray absorption [46]. Only ~ 10 such objects have been observed to date. The discovery space that will be opened by WFXT on this subject is huge.

The role played by the environment - voids, filaments, groups, clusters - in triggering both nuclear activity and star formation is still a matter of debate. The major deep-and-wide multiwavelength surveys to date, like COSMOS and AEGIS, are producing the first attempts to build matter density maps over a relatively large redshift range, and study the fraction of active galaxies as a function of matter density [22]. Given the limited volumes ($10^6 - 10^7$ Mpc³) covered, these surveys cannot span the full environment range (e.g. rare, massive galaxy clusters are not sampled) and are dealing with limited AGN statistics. Current results are therefore still weak. Increasing the object statistics and having the ability to identify low level AGN activity associated with galaxies in several environments is needed. Clustering techniques can be also used to study the relation between nuclear activity and the environment. The comparison between the clustering properties of AGN and those of dark matter halos predicted by cold dark matter models are commonly used to evaluate the typical mass of the dark matter halos in which AGN form and reside as a function of cosmic time (e.g. $M > 10^{12} M_{\odot}$ for bright optical QSOs at $z < 4$ [31, 32]). The ratio between the AGN space density and that of host dark matter halos provides an estimate of the AGN lifetime [33], which, based on the results from optical surveys, is loosely constrained in the range $10^6 - 10^8$ yr [30, 31]. Very recent works based on X-ray selection suggest instead lifetimes as long as 1 Gyr for moderately luminous AGN. The comparison between the clustering properties of different galaxy types and AGN can be used to estimate AGN hosts and to estimate the descendant and progenitors of AGN at a given redshifts.

The SDSS and the 2QZ surveys have measured the clustering of bright QSOs up to $z = 4$. However, they are not sampling the bulk of the nuclear accretion in the Universe, since they are limited to very luminous QSOs ($L_{bol} > 10^{46} L_{\odot}$). Only sparse clustering measurements have been performed using the major multiwavelength surveys to date [47, 48, 55].

A very large - a few millions - AGN sample selected in the X-rays, which can be divided into several luminosity, redshift, obscuration, and environment bins, will be an ideal tool to study the relation between nuclear activity and galaxy interactions, since it will allow to

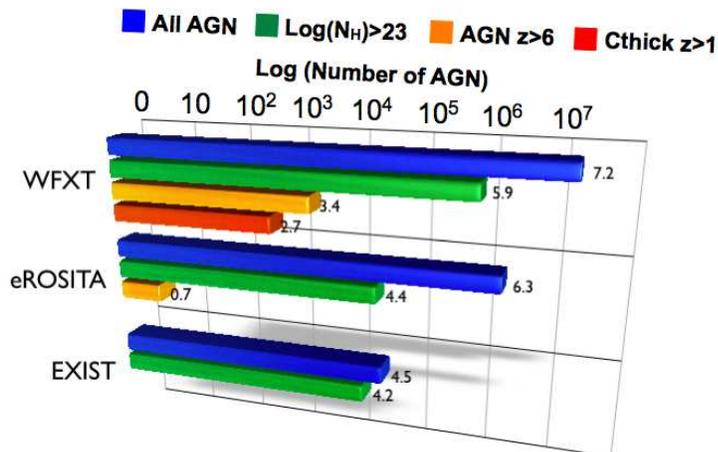


Figure 3: Comparison between the capabilities of future/proposed X-ray missions in providing statistically large samples of objects: blue=total number of AGN detected; green=number of obscured AGN with $N_H > 10^{23}$; yellow=number of AGN detected at $z > 6$; orange=number of *bona fide* Compton thick AGN at $z \geq 1$, i.e. those for which a spectrum of the quality shown in Fig. 2 *left* will be obtained.

measure the AGN luminosity function and evolution as a function of cosmic environment. Such a large sample will measure AGN clustering as a function of redshift, luminosity and obscuration.

The WFXT mission is expected to provide a 10^7 AGN sample distributed over the entire AGN luminosity vs redshift plane. This sample will also include $\sim 10^6$ heavily obscured AGN ($N_H > 10^{23} \text{cm}^{-2}$), allowing studies of the evolution of AGN obscuration as a function of redshift and environment. In addition, it will return a sizable sample of the most obscured ($N_H > 10^{24} \text{cm}^{-2}$), Compton-thick AGN at $z \geq 1$, i.e. the missing source population expected to produce $\sim 1/4$ of the energy density of the cosmic X-ray background [12, 13]. The typical optical counterparts of moderately bright X-ray AGN are expected to have $R \sim 22 - 23$ mag and will be accessible by most current and planned large area surveys (VISTA, LSST, Pan-STARRS). Notably, for about 500 Compton-thick AGN at $z \geq 1$ (i.e. the brightest tail), a good quality X-ray spectrum will be obtained (see Fig. 2 left). For these objects, the prominent iron line at 6.4 keV, shifted to ~ 3 keV in the observed frame, can be used as a powerful tool for both identifying the source as Compton-thick and measuring its redshift independently of any optical identification process. Such a large sample of *bona-fide* Compton-thick AGN at $z \geq 1$ is beyond reach of currently proposed hard X-ray missions (see e.g. Fig. 3). As an example, projects like EXIST and NuSTAR, which are less sensitive than WFXT, will basically detect moderate redshifts objects ($z < 0.5$ or so), i.e. they will not sample the Compton-thick population responsible for the missing CXB. NeXT and Simbol-X instead, will be able to detect $z \geq 1$ Compton-thick AGN, but because of the small grasp, their object statistics will be very limited.

4 AGN variability

What is the history of nuclear activity in a galaxy lifetime?

AGN activity manifests itself through intense variability across the entire electromagnetic spectrum on time-scales from minutes to years, which is an excellent probe of the physical conditions within the most energetic, inner regions. It is now believed that the time dependence of the SMBH emission is closely linked to the underlying physical processes and that these are similar to those characterizing BH accretion in galactic binaries [35].

The variability properties of SMBH have been studied in detail only for a handful of nearby sources, for which long monitoring campaigns and high fluxes make it possible to put constraints on the physics of accretion. The best measurements to date suggest that

variability time-scales scale with BH mass and accretion rate [34, 36, 37]. A few sources have been observed to change between a weakly or a heavily obscured state (see Fig. 2 right), for which the structure and location of the absorber have been studied in detail [38, 39]. For a few other objects, flux and spectral variability over the years trace the on/off switching of the nuclear activity [40].

Little is known about the variability properties of AGNs at intermediate to high-redshifts, due to the lack of large grasp monitoring surveys. However, the few studies based on the monitoring byproduct of deep X-ray surveys (CDFs and Lockman-Hole) verified that, when observed with sufficient photon statistics, most AGNs vary over timescales from hours to years [41, 40, 42]. These studies also suggested that variability may have been more extreme in the past ($z \geq 1$), possibly due to an increase in accretion rates with lookback time. If the link between X-ray variability with mass and accretion rate, recently discovered for local AGNs, is confirmed, monitoring distant AGNs through high-energy observations will provide an unique tool to infer the mass and accretion properties of the SMBH population.

Transient X-ray outbursts from galactic nuclei are also expected when a star, planet, or gas cloud is tidally disrupted and partially accreted by the black hole. A few candidates were discovered in the X-rays by comparing multi-epoch ROSAT observations which detected large amplitude flares (factors of $\sim 20 - 400$ or more) from non-active galaxies, with large peak X-ray luminosities (10^{42-44} erg s $^{-1}$), a decay timescale of months, and a measured detection rate of 10^{-5} yr $^{-1}$ [43]. The detection of significant samples of transient nuclei will be a new constraints to models of stellar dynamics at the galaxy centers.

The above variability studies primarily call for an X-ray survey mission with large grasp. By performing repeated passes over the surveyed area, the WFXM mission will provide the largest AGN sample specifically designed for variability studies. The number of both temporally varying AGNs and transient outbursts in galactic nuclei should increase by orders of magnitude providing sufficient fundamental statistics to understand the AGN inner structure. WFXM will be able to observe variability in 10^5 AGNs in a 100 deg 2 survey down to $\Delta f/f \sim 20\%$, and reconstruct mass and accretion rates for several thousand sources.

Future wide area optical surveys (LSST, Pan-STARRS) will effectively open the time domain to cosmological studies. The synergy with a wide area X-ray mission with monitoring capabilities is expected to open up a new horizon to variability studies.

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