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Cosmic evolution of supermassive black holes: A view into the next two decades

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☒ Formation and Evolution of Compact Objects ☒ Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☒ Galaxy Evolution ☐ Multi-Messenger Astronomy and Astrophysics

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Abstract:
The discoveries made over the past 20 years by *Chandra* and XMM-*Newton* surveys in conjunction with multiwavelength imaging and spectroscopic data available in the same fields have significantly changed the view of the supermassive black hole (SMBH) and galaxy connection. These discoveries have opened up several exciting questions that are beyond the capabilities of current X-ray telescopes and will need to be addressed by observatories in the next two decades. As new observatories peer into the early Universe, we will begin to understand the physics and demographics of SMBH infancy (at $z > 6$) and investigate the influence of their accretion on the formation of the first galaxies (§ 2.1). We will also be able to understand the accretion and evolution over the cosmic history (at $z \sim$1–6) of the full population of black holes in galaxies, including low accretion rate, heavily obscured AGNs at luminosities beyond the reach of current X-ray surveys (§2.2 and §2.3), enabling us to resolve the connection between SMBH growth and their environment.

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1 Introduction

The past two decades have revealed strong links between the cosmic evolution of supermassive black holes (SMBHs), their host galaxies, and dark matter halos. In the local Universe, SMBH masses are tightly correlated with their host-galaxy bulge luminosity and stellar velocity dispersion (e.g., Kormendy & Ho 2013), while at higher redshifts, the global density of star formation and SMBH growth follow a common trend, rising from the epoch of reionization to $z \sim$ 2–3, then steeply declining to the current epoch. Feedback from growing SMBHs as active galactic nuclei (AGNs; see Laha et al. 2019, Tombesi et al. 2019) is critical for reproducing the observed populations of galaxies and their hot halos in models (e.g., McAlpine et al. 2018, Weinberger et al. 2018). Despite this progress, the nature of SMBH fueling and the interplay between SMBHs and their hosts remain unclear, particularly before the peak epoch of structure formation.

To uncover the co-evolution of SMBHs and galaxies, we must probe the full scope of cosmic time to detect and characterize large samples of AGNs and their hosts, including sources that are heavily obscured by gas and dust (e.g., Hickox & Alexander 2018). While AGNs can be identified and studied across a range of wavelengths (e.g., Padovani et al. 2017), a particularly powerful waveband for AGN selection is in the X-rays. At X-ray energies, the contamination from non-nuclear emission, mainly due to star formation processes, can be far less significant than in broad-band optical and IR observations. This white paper will focus on X-ray observations.

Over the past 20 years, *Chandra* and XMM-*Newton* X-ray surveys have successfully collected a clean and largely unbiased sample of AGNs ($\sim$60,000) up to $z = 5$ (e.g., Brusa et al. 2010, Nandra et al. 2015, LaMassa et al. 2016, Civano et al. 2016, Luo et al. 2017, Chen et al. 2018, Masini et al. in prep.). These samples cover a broad range of luminosities (down to $L_X \sim 10^{44}$ erg s^{-1} at $z = 5$ and $L_X = 10^{39}$ erg s^{-1} at $z = 0.5$; see Fig. 1), corresponding to BH masses of $10^6 - 10^9\ M_\odot$, and include large numbers of both unobscured and obscured AGNs. In concert with multiwavelength data, X-ray observations have made a number of key discoveries: (1) massive ($>10^9$ M$\odot$) accreting SMBHs already existed at $z \sim$ 7.5, challenging seed formation models; (2) AGN number densities peak at $z \sim$ 2–3, with luminous sources peaking earlier in cosmic time and with most of the accretion being obscured; (3) correlations exist between SMBH accretion and galaxy properties, particularly with stellar/dark matter halo mass and (perhaps indirectly) star formation, although due to AGN stochasticity these can only be revealed in statistical samples.

These discoveries have opened up several exciting questions that are beyond the capabilities of current facilities and will need to be addressed by new observatories into the next two decades:

- **How did the first SMBHs form and grow so rapidly in the early Universe**?
- **What is the complete census of growing SMBHs from cosmic dawn ($z \sim$6) to the peak formation epoch ($z \sim$2) and beyond?**
- **How does SMBH accretion influence the growth of galaxies and large-scale structures?**

In this white paper, we will discuss these questions and also highlight how some future missions, such as ESA's *Athena* (Nandra et al. 2013), and proposed concept missions, such as *Lynx* (The Lynx team 2018) and *AXIS* (Mushotzky et al. 2018), will help us address them.

2 Understanding the build up of SMBHs and galaxies

2.1 Black holes and galaxies at cosmic dawn

The ultimate origin of SMBHs is still unknown and remains one of the most pressing open questions in astrophysics. Optical and NIR surveys have revealed the existence of SMBHs with masses

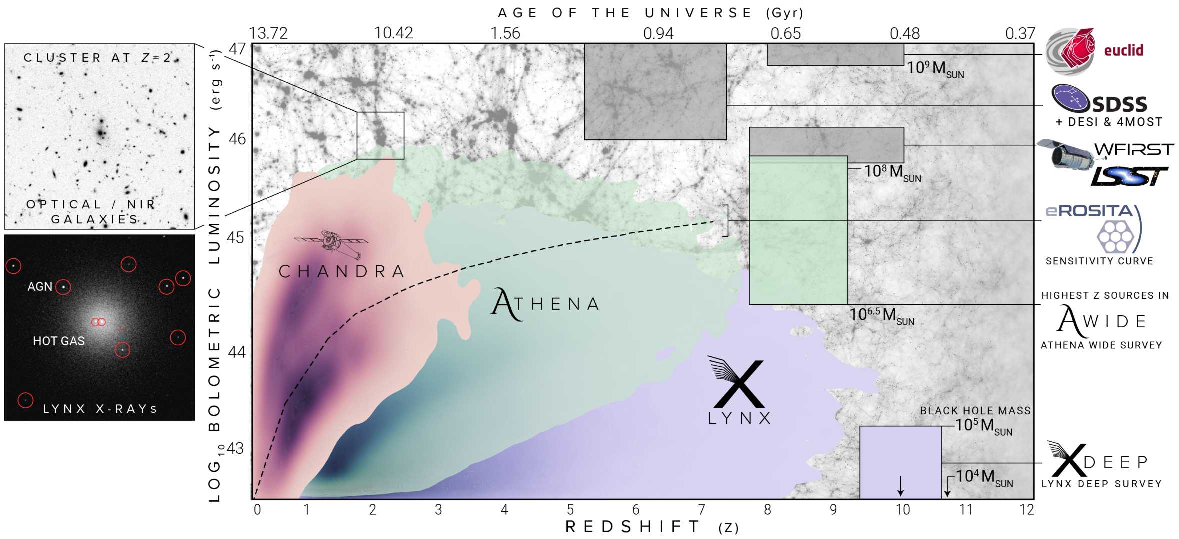

Figure 1: Redshift and bolometric luminosity (with corresponding SMBH masses for Eddington-limited accretion) distributions to be probed by future X-ray facilities (*Athena* and *Lynx*), compared with current *Chandra* surveys and the *eROSITA* limit at the ecliptic poles. In this figure, the total time allocated to surveys for future mission is ~ 25 Ms. The ranges covered by high-redshift optical and NIR wide surveys are reported (gray boxes). The left inset shows how high-resolution observatories will resolve AGNs in groups and cluster of galaxies at $z \sim 2$ (see Mantz et al. 2019).

of 10^9 $M_\odot$ up to $z \sim 7.5$ when the Universe was only 600 Myr old (e.g., Mortlock et al. 2011, Bañados et al. 2018). This discovery lead to the proposal of several BH seed formation models, including: (1) direct collapse of early pristine massive clouds (Begelman et al. 2006); (2) Pop III star remnants (Bromm & Loeb 2006); (3) coalescence of stellar mass BHs in star clusters (e.g., Devecchi & Volonteri 2009); and (4) primordial BHs formed during inflation (Hawking 1971).

A complete understanding of SMBH origins and their contributions to reionization demands both the census of massive, luminous AGNs at $z > 6$ as well as direct measurements of the lower-mass seeds, forming and growing at $z = 10$–15. The first can be observed by surveying wide areas (tens of deg^2) at the equivalent of the faintest *Chandra* flux ($\sim 10^{-17}$ erg s^{-1} cm^{-2}), e.g. with the proposed *Athena-WFI* survey strategy (as in Fig. 1; Aird et al. 2013). The second requires extreme X-ray detection limits (10^{-19} erg s^{-1} cm^{-2}), implying an observatory with both large effective area and sub-arcsecond angular resolution, to avoid source confusion, such as e.g. *Lynx* and *AXIS*.

A major challenge will be obtaining rest-frame optical counterparts for these X-ray sources, since these will be extremely faint at all wavelengths (e.g., Volonteri et al. 2017). In Fig. 2, we compare the limiting BH masses detectable in X-ray surveys with a flux limit range from 10^{-17} erg s^{-1} cm^{-2}, the *Athena* flux limit, to 10^{-19} erg s^{-1} cm^{-2}, the ultimate depth reachable with *Lynx*. *AXIS*, with comparable angular resolution to *Lynx* but a smaller effective area, will reach a depth between these two limits. Fig. 2 shows that the combination of *Athena* and *WFIRST* will provide X-ray and NIR information for growing seeds at $z \sim 5$–8 and *Lynx* (or *AXIS*) will peer into the early Universe to $z \geq 10$ and at lower mass, in concert with *JWST*.

While predictions for the number density of early BH seeds are still uncertain (Haiman et al. 2019), it is clear that combining a deep X-ray survey with sub-arcsecond positional accuracy with *JWST* and *WFIRST* data will return a sample of tens to thousands of X-ray selected SMBH seeds with confirmed counterparts (Fig. 1). With these samples, it will be possible to probe, for the first time, the luminosity function down to $L_X = 10^{43}$ erg s^{-1} at $z \sim 15$, corresponding to 10^{4-5} $M_\odot$ BHs. Progress will also be made by studying the fluctuations of the X-ray background and its

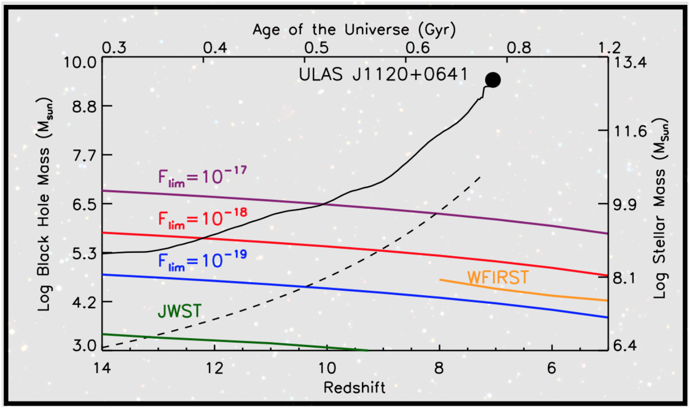

Figure 2: Simulated growth of a massive BH seed (10^5 $M_\odot$ at z=20, solid) up to the the size of $ULAS1120+0641$ and of a low-mass seed (10^2 $M_\odot$ at z=20, dashed) using the prescriptions in Pacucci et al. (2017) and continuous Eddington limited growth, respectively. These are compared with 0.5-2 keV limiting sensitivities for *Athena* (magenta), AXIS (red) and *Lynx* (blue). The BH mass limits (derived from $M_\star$; Song et al. 2016) detectable by *JWST* (green) and *WFIRST* (orange) observations are reported. X-ray observatories will detect the low mass BHs in the first galaxies detected by *JWST* and *WFIRST*.

counterparts (see e.g., Kashlinsky et al. 2018, Cappelluti et al. 2013, 2017), but the strongest constraints will come from direct detections of lower-mass seed BHs in the "first stars" epoch.

2.2 The full population of black holes from cosmic dawn to cosmic noon and the connection with the host galaxy

Beyond the origin of SMBHs, studying their growth from "cosmic dawn" at z >6 to "cosmic noon" at z ∼1–2 is essential for understanding their co-evolution with galaxies, in the epochs when the bulk of the Universe's stars were formed. A recent breakthrough in our understanding of AGNs shows that they are not like light bulbs but instead "flicker" across a wide range of Eddington ratios on relatively short time scales ($< 10^{5-6}$ years; Hickox et al. 2014). Thus, to understand the full AGN population, the full dynamic range in accretion rates (and thus the full luminosity function) needs to be probed across all of cosmic time. This approach has been critical for understanding the connection between BH and galaxy growth, the nature of AGN obscuration and the evolution of AGNs in large-scale structures (e.g., Chen et al. 2013, Yang et al. 2017, Powell et al. 2018).

Observations across a wide range of wavelengths are essential for this work. Optical and IR imaging and spectroscopy can detect luminous AGNs outshining their host galaxies and can characterize the hosts of weak or obscured AGNs, while far-IR–mm observations are critical for constraining star formation and dust masses. However, due to high penetrating power and contrast with host galaxy light, X-ray observations are required for probing the full range of SMBH masses and Eddington ratios. The most recent measurements of the luminosity function probe the X-ray luminosity range 10^{42}–10^{43} erg s^{-1} to $z = 2$ and 10^{45}–10^{46} erg s^{-1} to $z = 5$ (e.g., Ueda et al. 2014, Miyaji et al. 2015, Aird et al. 2015, Tasnim Ananna et al. 2019). In the next few years, *eROSITA* (Merloni et al. 2012) will constrain the bright end of the luminosity function ($> 10^{45}$ erg s^{-1}) with $\sim 10^6$ AGNs over a broad redshift range (Fig. 1).

Furthermore, it is critical to probe deeper, below the "knee" of the luminosity function at the earliest epochs ($z > 3$), requiring large numbers of very faint sources (many thousands compared to the few hundreds available now; see Marchesi et al. 2016, Vito et al. 2018). The first step will be to cover large areas down to the flux limits of the current deepest X-ray survey (the *Chandra* Deep Field-South). This will be feasible with a large effective area telescope (e.g., *Athena*), identifying tens of thousands of distant AGNs over tens of deg^2, to a flux limit currently available only in pencil-beam (0.1 deg^2) fields (Fig. 1). The next step will be to probe to significantly fainter fluxes ($\sim 10^{-19}$ erg s^{-1} cm^{-2}), constraining the X-ray luminosity and Eddington ratio distributions at least an order of magnitude fainter. Such deep flux limits require *both* high effective area *and* angular resolution (e.g., as proposed for *Lynx*; Fig. 1). As a complementary approach, it will be possible to use X-ray stacking techniques with high-resolution X-ray data (e.g., Vito et al. 2016, Fornasini et al. 2018) to push to even fainter average fluxes ($\sim 10^{-20}$ erg s^{-1} cm^{-2}).

Counterpart identifications will be readily available by combining data from next generation space facilities (*JWST*, *WFIRST*, *Euclid*) as well as ground based 30m telescopes (ELT, GMT, TMT), allowing us to explore the distribution of AGN accretion rates as a function of key host properties (i.e., star formation rate, stellar mass, morphology), and perform statistical analyses of clustering to probe the connection between AGN and their host environment (e.g., Mendez et al. 2016, Allevato et al. 2016, Plionis et al. 2018, Yang et al. 2018).

Finally, reaching the very faintest luminosity limits, we will probe down into the galaxy population with emission dominated by X-ray binaries and hot gas ($L_X < 10^{41}$ erg s^{-1}) as well as group and cluster-sized halos at $z \sim 2$. High spatial resolution observatories can distinguish point sources above this diffuse background, enabling simultaneous measurements of AGN properties and a *direct* measure of how AGNs populate large-scale structures (see inset in Fig. 1 and Mantz et al. 2019). Following up halos detected with CMBs-4 and *Athena*, *Lynx* will build on the legacy of *Chandra* and will map the triggering of SMBHs in the build-up of large scale structure out to $z \sim 4$. In lower-redshift systems, high-resolution X-ray imaging and spectrocopy will directly probe the effects of AGN feedback on the hot gas atmospheres in their host galaxies.

2.3 Uncovering the "hidden" black hole population

A significant number of AGNs are "hidden" by dust that only X-ray light can penetrate. The majority of this population are obscured by a dusty "torus" in close proximity to the SMBH, but dust at larger radii in the host galaxy can also shield the AGN from view.

At low-redshifts, around a third of the AGN population are known to be obscured even to hard X-rays (e.g., Risaliti et al. 1999). Dedicated observing campaigns have been focusing on some of the extreme cases (e.g., NGC 1068 with $N_H \sim 10^{25}$ cm^{-2}; e.g. Bauer et al. 2015; see Fig.3). However, little is known about these sources at higher redshifts: only a few 100 candidates have been detected thus far (e.g., Brightman et al. 2014, Lanzuisi et al. 2018) and the evolution of the obscured fraction is poorly constrained (e.g., Liu et al. 2017, Zappacosta et al. 2018). Pioneering work by *NuSTAR*, operating above 20 keV, is now uncovering some of these concealed sources (Civano et al. 2015, Lansbury et al. 2017, Masini et al. 2018) but still with low numbers of photons. Theoretical models predict phases of high obscuration during gas-rich galaxy mergers when feedback from AGN may play an important role in regulating galaxy growth (e.g., Hopkins et al. 2005, Blecha et al. 2018). It is thus critical to uncover and properly model these hidden AGNs, even at the highest redshifts, to understand the connection between the obscured growth of SMBHs, their host galaxies, and the connection with mergers (which can in turn be probed directly with future space-based gravitational wave observatories, e.g. *LISA*).

Reprocessed IR emission offers one way of detecting such AGNs (e.g., Stern et al. 2005, Alexander et al. 2008, Gandhi et al. 2009, Goulding et al. 2011). Unfortunately, this suffers from both contamination and dilution by the host galaxy. High sensitivity and spatial resolution NIR observations with *JWST* and *WFIRST* will begin to uncover these low-to-medium redshift AGNs buried within their host emission. We can directly observe reprocessed AGN emission in the high-energy X-rays, via the 'Compton hump' at 20 – 40 keV and a ubiquitous iron emission line at 6.4 keV. At $z>2$, the Compton hump is redshifted to low-energy X-rays, making the complex spectrum

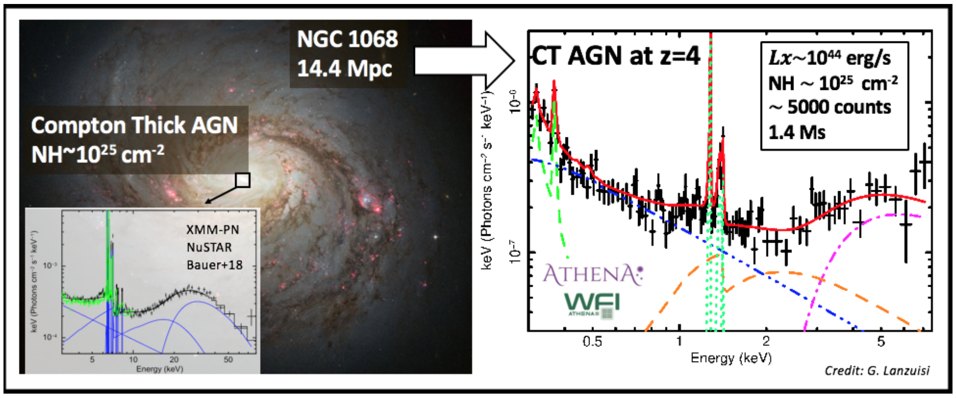

Figure 3: *Athena* will enable detailed spectral analysis of even the most obscured sources. The simulated X-ray spectrum of a z =4 AGN with $N_H \sim 10^{25}$ cm^{-2} as seen by *Athena* (right) is compared with the spectrum of the well known NGC 1068 (left), showing the same obscuring properties in the local Universe.

of these sources accessible by soft X-ray telescopes (Fig. 3).

Probe missions in the soft and hard X-rays (e.g., *STROBE-X* and *HEX-P*, see Hickox et al. 2019) will inform us about the most luminous obscured AGNs out to $\sim$2. Only the leap in sensitivity over *Chandra* and *XMM-Newton* combined with a wide field of view, e.g. such as with *Athena*, will push the census of heavily obscured AGNs beyond the peak epoch of activity out to z =4. We will be able to perform unprecedented spectral modeling, even at high redshifts, uncovering the physics of extremely obscured AGN, at levels currently available only for local sources (Fig. 3; e.g., Georgakakis et al. 2013). At even higher redshifts, the combination of effective area and spatial resolution will enable a mission such as *Lynx* to both uncover the least luminous of these hidden SMBHs and move toward a complete census of SMBH growth across cosmic time.

3 Our vision for an extragalactic survey program into the 2030s

This white paper outlines a very exciting range of science that can be completed with an extragalactic survey program in the next two decades, demanding a substantial leap forward in observing capabilities across a wide range of wavelengths. A full picture of SMBH growth and galaxy evolution requires a tiered, coordinated survey of all components: *starlight* in the rest-frame visible and NIR (planned or proposed facilities include *WFIRST*, *JWST*, LSST, *HabEx*, *LUVOIR*), *gas and dust* in the mid- and far-IR, microwaves, radio as well as sensitive optical/NIR spectroscopy and X-ray imaging (*JWST*, *OST*, ALMA, ngVLA, SKA, CMB-S4, 30m class telescopes, *XRISM* and *Athena*), and the signatures of *SMBH growth*, most powerfully probed in X-rays, IR, radio, and GW (*Athena*, *Lynx*, *AXIS*, *JWST*, *OST*, SKA, *LISA*). X-ray observations will produce the biggest breakthroughs in uncovering the complete AGN population. In the next 5 years, *Chandra Source Catalog 2* and *eROSITA* AGNs will be spectroscopically characterized by SDSS-V, 4MOST and DESI. Afterwards, *Athena* will provide a huge increase in effective area and field of view, allowing us to reach the current faintest X-ray flux levels in the deepest *Chandra* observations but over a vastly larger area (tens of deg^2). *Lynx* would then provide another enormous leap forward with exquisite angular resolution, allowing us to push more than an order of magnitude fainter and directly resolve and study the first BHs in the early Universe. (*AXIS* would make a comparable leap in resolution but with a more modest yield in high-redshift AGNs.) We urge the Astro2020 Decadal Survey Committee to consider the compelling astrophysical questions about the cosmic evolution of SMBH growth outlined here and endorse a plan to address them in the next two decades.

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