The Formation and Growth of the First Black Holes

A Whitepaper for the 2010 Decadal Survey

Science Frontier Panel: Galaxies across Cosmic Time (GCT)

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1 Introduction

The path of observational cosmology over the next decade will be focused on the exploration of the early Universe. To determine how the phenomena (i.e., galaxies, stars, planets, etc.) of our local Universe evolved to their present state, we must determine how and when the first stars, galaxies, and black holes formed. In the next decade, observatories such as JWST, ALMA, LSST, TMT, GMT, and E-ELT will provide a phenomenal new perspective on this theme, allowing for the first time in history a direct view of the starlight that originates from the first galaxies; a regime that is only now understood by theoretical inferences. However, it is now clear that galaxy and black hole growth are intimately tied, and therefore knowledge of black hole formation and growth is required to piece together a complete picture of galaxy formation. Specifically, we will need observational facilities designed to address the following questions: *How and when did the first black holes in the Universe form and grow? What influence did the energetic process of accretion onto the first black holes have on the formation and evolution of their host galaxies and in reionizing the Universe?* Addressing these questions requires sensitive X-ray observations, which effectively probe the nearby vicinity of the accreting black holes even through heavily obscured environments. The next great X-ray observatory, the *International X-ray Observatory* (*IXO*), will provide the first key discoveries of luminous accreting supermassive black holes (SMBHs) out to $z \approx 7$–8 and constrain the physical processes responsible for powering these sources. To extend the findings from *IXO* and study for the first time the evolution of representative populations of seed black holes from their birth around $z \approx 8$–15 requires an X-ray observatory capable of detecting extremely faint sources with 0.1–10 keV fluxes of $\approx 10^{-20}$ ergs cm^{-2} s^{-1}, while remaining free from source confusion. To achieve these aims requires an observatory with an effective light collecting area of ≈ 50–100 m^2 and a resolution of $\approx 0\farcs1$; these specifications can provide imaging that is ≈ 1000 times deeper and ≈ 5 times higher resolution than *Chandra*. The *Generation-X* mission specifications have been designed with these requirements in mind. Here we illustrate how *Generation-X* will optimally address these questions.

2 The First Black Holes

How and when did the first black holes in the Universe form?

Theoretical studies of star formation in the early Universe require that the first populations of black holes were formed at $z \approx 15$–20 as a result of the first massive stars ($\gtrsim 260\ M_\odot$) ending their short lives (e.g., Bromm et al. 1999; Gao et al. 2007). The initial masses of such black holes will be more than half that of the progenitor star (e.g., Heger & Woosley 2002) and it is expected that these stars will produce a population of black holes with masses of order 100 $M_\odot$. Though the details are not yet clear, these black holes are expected to lie in nebulous overdense halos, and so shortly after their formation, they will merge with neighboring halos to form increasingly more massive overdensities. Through this process, the black holes can grow both via mass accretion and black hole–black hole mergers (Volonteri et al. 2003). As the gas in these overdense regions cools, new generations of stars will form and these first galaxies and black holes will continue to grow through accretion.

X-ray observations provide a very effective means for probing the conditions in the immediate vicinity of accreting black holes and are capable of penetrating through thick columns of obscuring material. We now know from deep *Chandra* and *XMM-Newton* data that the X-ray band is, at present, the most effective way of identifying and studying large populations of accreting supermassive black holes (SMBHs), seen as active galactic nuclei (AGNs), over a wide range of luminosities and over the entire history of the Universe (e.g., Brandt & Hasinger 2005). The deepest X-ray surveys conducted with *Chandra* (Alexander et al. 2003; Luo et al. 2008) find about ten times more AGNs per square degree than the deepest optical surveys (e.g., Bauer et al. 2004), and many of which cannot be identified via optical spectroscopy (e.g., Barger et al. 2005). Beyond the local universe, the best way to find SMBHs will be to search for nuclear activity probed by X-ray emission. The X-ray signatures of an accreting black hole are very clear even out to $z \approx 6$: a luminous X-ray source with a hard powerlaw spectrum extending to high energies (e.g., Shemmer et al. 2006). At even higher redshifts, the 0.1–10 keV bandpass probes hard rest-frame X-ray energies, which are capable of penetrating extremely thick obscuring environments reaching optical extinctions of 100s to 1000s of magnitudes.

It is known from observational studies of local galaxies and their nuclear environments that by the present day nearly all nucleated galaxies host SMBHs in their centers (e.g., Kormendy & Richstone 1995; Magorrian et al. 1998). It has also been recently discovered that the masses of these SMBHs are strongly correlated with the masses of the giant stellar bulges residing in the host galaxies (e.g., Gebhardt et al. 2000). A key inference from these observations is that SMBHs and their host galaxies grew in tandem, with the growth of each component influencing that of the other despite the host galaxy being $\approx 10^9$ times larger in physical size and ≈ 1000 times more massive than the SMBH. Therefore, a more complete understanding of how galaxies and their SMBHs formed and evolved together requires observations constraining the formation of both the first black holes and galaxies.

While there are several paths to the formation of SMBHs (e.g., Rees 1984), the fact that the SMBH–galaxy bulge mass relationship holds in the local Universe constrains models. Some of the black holes may have grown via Eddington accretion from a seed black hole, while others may have formed through the direct collapse of "quasi-stars" that are embedded within massive hydrostatic gaseous envelopes, which allow accretion above the Eddington limit (e.g., Ohsuga & Mineshige 2007; Begelman et al. 2008). Additionally, it is thought that black-hole–black-hole mergers may also be important in the build-up of black holes mass as the galaxies themselves interact and merge (e.g., Volonter et al. 2003; Li et al. 2007). A population of seed black holes growing at the Eddington rate would take a billion years to produce billion solar mass black holes, as required by the discovery of powerful quasars at $z \approx 6$ (e.g., Fan et al. 2003); however, in theory this timescale will be significantly reduced for black holes formed via the direct collapse scenario. The next great X-ray observatory *IXO* will effectively detect and constrain the physics of moderately massive ($\gtrsim 3 \times 10^6\ M_\odot$) SMBHs out to $z \approx 8$. To identify the seeds of these SMBHs at

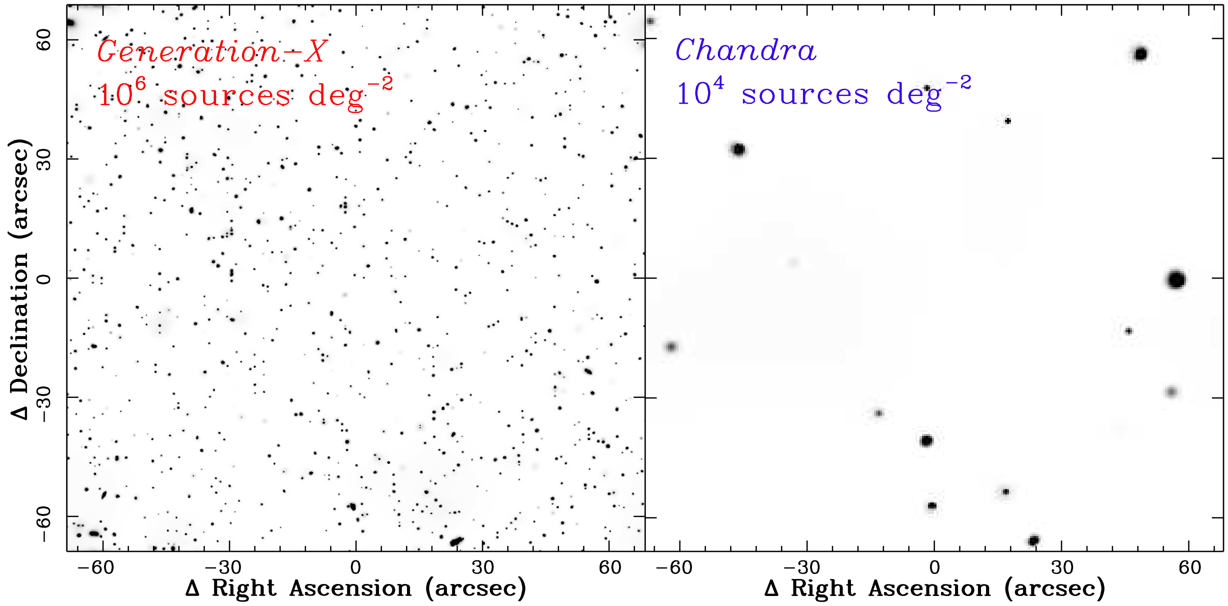

Figure 1: Simulated image of a ≈ 2 Ms exposure of a $\approx 2' \times 2'$ extragalactic field with *Generation-X* (*left*) compared with the same region in a ≈ 2 Ms *Chandra* image (*right*), which is characteristic of the deepest *Chandra* exposures yet taken (Alexander et al. 2003; Luo et al. 2008). The *Generation-X* image reaches source densities of $\approx 10^6$ deg^{-2}, while the deepest *Chandra* surveys reach source densities of $\approx 10^4$ deg^{-2}. Many of the X-ray sources in the *Generation-X* image are normal galaxies and AGNs seen across the majority of cosmic time ($z \approx 0$–6); however, the important $z = 8$–15 black hole population can be detected and studied at the extreme depths reached by *Generation-X*.

$z = 8$–15 and the mechnisms by which they formed and evolved requires X-ray imaging reaching a depth of $\approx 10^{-20}$ to 10^{-19} ergs cm^{-2} s^{-1}. This flux regime is roughly 2–3 orders of magnitude fainter than that being probed in the deepest *Chandra* observations.

In a 2×10^6 s exposure with *Generation-X*, these sources could be easily found, with luminosities and photon spectra derived out to a rest-frame energy of ≈ 100 keV. Figure 1 shows a simulated $\approx 2' \times 2'$ region of such a *Generation-X* exposure (*left panel*) as compared to a 2×10^6 s exposure with *Chandra* (*right panel*). Over the entire planned $\approx 5' \times 5'$ area of *Generation-X* cold dark matter merger-driven models predict that 10s to 100s of accreting black holes will be discovered at $z \approx 8$–15 (Rhook & Haehnelt 2008). Furthermore, because the linear-to-angular size ratio decreases at high redshift, *Generation-X* will also be able to constrain the role of merger activity by resolving pairs of accreting black holes separated by only 300–400 pc (i.e., $0.''1$) at $z = 10$. If we assume that the SMBH–galaxy bulge mass ratio at $z \approx 10$ covers a similar range of values as observed over $z \approx 0$–3 (e.g., McLure et al. 2006; Peng et al. 2006) then the $10^5\ M_\odot$ growing black holes identified with *Generation-X* would reside in host galaxies with masses of 10^7–$10^8\ M_\odot$, which can be studied using the next generation of space and ground-based telescopes (e.g., JWST, ALMA, LSST, TMT, GMT, and E-ELT).

How did accretion onto the first black holes influence the formation of their host galaxies and reionize the Universe?

Modern theoretical simulations of galaxy formation and evolution have found that reproducing key features of observed galaxies, such as the galaxy luminosity function and the distribution of optical colors, requires black hole driven feedback (e.g., Bower et al. 2006; Croton et al. 2006). Such feedback is thought to effectively truncate star-formation activity and further black hole accretion in massive galaxies and may be responsible for shaping and maintaining the SMBH–galaxy bulge mass relationship (e.g., Churazov et al. 2005). It is expected that as the first black holes grew via accretion, radiatively-driven winds originating from the black hole accretion disks deposited energy into the interstellar and local intergalactic mediums. Signatures of AGN outflows can be identified in X-ray spectra as absorption features from metal edges and lines. These features will constrain the masses and velocities of the highest enrgy outflowing material, which originates near the launching site and is responsible for transporting most of the outflowing mass and energy. *Generation-X* will be capable of observing outflow signatures in AGNs well into the "dark ages" (i.e., out to $z \approx 10$), an epoch where black holes and their galaxies are undergoing significant fractional growth.

In addition to modifying the formation of their host galaxies, the first accreting black holes are theoretically predicted to play a significant role in the reionization of the intergalactic medium (IGM; Madau et al. 2004; Wyithe & Loeb 2004). As the first galaxies and black holes formed, energetic processes associated with their growth began to ionize a neutral IGM through the formation of bubbles of ionized Hydrogen surrounding these young systems (see Fig. 2). The bubbles then expanded quickly and completely overlapped by $z \approx 6$, where the Universe is observed to be almost completely reionized. Recent radiative transfer models show that the first accreting black holes with masses $\gtrsim 10^5\ M_\odot$ are capable of producing ionizing bubbles on their own (e.g., Madau et al. 2004; Thomas & Zaroubi 2008). In the next decade, new radio observatories (e.g., LOFAR, MWA, 21CMA, and SKA) will detect rest-frame 21 cm emission originating at $z \approx 6$–15 and will resolve and map the locations of these ionization bubbles. However, to constrain the role of such AGNs in the formation of ionization bubbles requires measurements of their energetics. *Generation-X* will isolate with high precision the locations of AGNs and simultaneously provide measures of their ionizing emission.

3 Conclusions

As outlined above, studying the birth and growth of the first black holes is an essential next step to the planned multiwavelength observatories of the next decade (*IXO*, JWST, ALMA, LSST, TMT, GMT, and E-ELT). To identify and measure the energetics of the first black holes requires an X-ray telescope with both high-resolution and large effective aperture operating efficiently over the 0.1–10 keV waveband. In the next decade, *IXO* will begin to provide our first insight, through high-resolution spectroscopy, into the physics governing accretion onto black holes and wind-driven feedback over the majority of cosmic history ($z \lesssim 8$). With this new insight, *Generation-X* will then extend the observational parameter space covered by *IXO* to the dark ages, when the first black holes formed and underwent a period of rapid fractional growth.

To reach the *Generation-X* mission parameters, $\approx 50\ \mathrm{m}^2$ collecting area at $\approx 0\farcs1$ imaging resolution, will require substantial technological developments in the next decade. The technology needed for making $0\farcs1$ X-ray mirrors is currently progressing and is dependent on the success of the *IXO* mirrors. The *IXO* mission is planned to have *XMM-Newton* style mirrors but at a factor of ≈ 10 times lower mass-to-effective area ratio than *XMM-Newton*. For *Generation-X*, improvements over those required for *IXO* will be needed to enable $0\farcs1$ resolution in addition to the large collecting area. Therefore, investment in a technology development program will be needed to make new improvements to the small-scale mirror surface and the use of adjustable active X-ray optics. Successful implementation of such a program will create the basis of the *Generation-X* mission, sometime after 2020.

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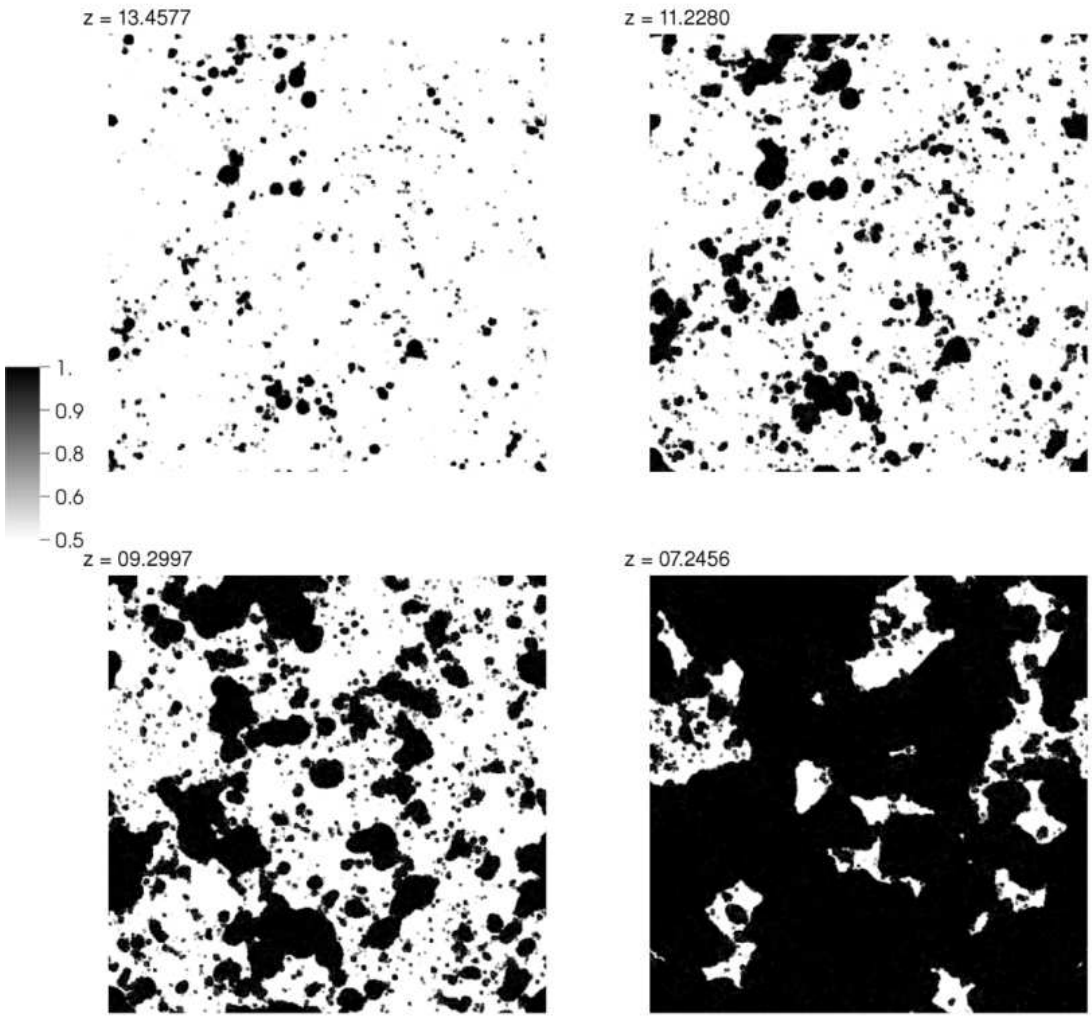

Figure 2: Shin et al. (2008) simulated maps of the ionization regions in a $\approx 140 \times 140$ Mpc^2 region of the Universe at redshifts $z \sim$ 13.5, 11.2, 9.3, and 7.2. Black represents highly-ionized ($\gtrsim 50\%$) regions, white represents regions with $\lesssim 50\%$ ionization. The global ionization fractions are $\sim 10\%$, 30%, 50%, and 90% for $z \sim$ 13.5, 11.2, 9.3, and 7.2, respectively.