SMBH Seeds: Model Discrimination with High-energy Emission Based on Scaling Relation Evolution

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Abstract

We explore the expected X-ray (0.5–2 keV) signatures from supermassive black holes (SMBHs) at high redshifts (z ~ 5–12) assuming various models for their seeding mechanism and evolution. Seeding models are approximated through deviations from the $M_{\text{BH}}-\sigma$ relation observed in the local universe, while $N$-body simulations of the large-scale structure are used to estimate the density of observable SMBHs. We focus on two seeding model families: (i) light seed BHs from remnants of Pop-III stars and (ii) heavy seeds from the direct collapse of gas clouds. We investigate several models for the accretion history, such as sub-Eddington accretion, slim disk models, and torque-limited growth models. We consider observations with two instruments: (i) the Chandra X-ray Observatory and (ii) the proposed Lynx. We find that all of the simulated models are in agreement with the current results from the Chandra Deep Field South, i.e., consistent with zero SMBHs in the field of view. In deep Lynx exposures, the number of observed objects is expected to become statistically significant. We demonstrate the capability to limit the phase space of plausible scenarios of the birth and evolution of SMBHs by performing deep observations at a flux limit of $1 \times 10^{-19}$ erg cm$^{-2}$ s$^{-1}$. Finally, we show that our models are in agreement with current limits on the cosmic X-ray background (CXRB) and the expected contribution from unresolved quasars. We find that an analysis of CXRB contributions down to the Lynx confusion limit yields valuable information that can help identify the correct scenario for the birth and evolution of SMBHs.

Key words: early universe – quasars: supermassive black holes – stars: Population III – X-rays: general

1. Introduction

Data accumulated over the past three decades suggest that most of the galaxies host a quiescent supermassive black hole (SMBH) at the center (Ferrarese & Ford 2005). The mass of the observed SMBHs is well correlated with properties of the host spheroid, such as its stellar component velocity dispersion and luminosity (Kormendy & Richstone 1995; Gültekin et al. 2009). The observed correlations point to coevolution of SMBHs and their host galaxies, most likely through feedback effects from the SMBHs.

The detection of quasars at high redshifts has posed challenges to the Pop-III scenario. In order to grow a $10^9 M_\odot$ BH to a $10^{10} M_\odot$ SMBH in less than ~1 Gyr (the current record holder, ULAS J1120+0641 at a redshift of $z \sim 7.1$, merely 770 Myr after the Big Bang, has an estimated mass of $2^{+0.5}_{-0.7} \times 10^9 M_\odot$; Mortlock et al. 2011), we need to assume a continuous accretion at the Eddington limit during most of its lifetime (e.g., Haiman & Loeb 2001). This is an unlikely premise due to expected feedback effects from the accreting massive black hole (MBH). A possible solution is to assume the BH undergoes short yet strong growth episodes during which its accretion rate is well in excess of its Eddington accretion rate (e.g., Wyithe & Loeb 2012; Alexander & Natarajan 2014; Madau et al. 2014; Pezzulli et al. 2016). This solution raises further difficulties, as the capability of a BH to sustain super-Eddington accretion without dispersing the cold gas streams that feed it is debatable. Another problem encountered by the Pop-III scenario results from recent simulations of the formation of the first generation of stars (Clark et al. 2008; Turk et al. 2009). These suggest that the IMF is not as top-heavy as initially expected, and it is no longer clear whether enough objects will end their lives in a direct collapse to a BH to account for the density of SMBHs in the local universe (Volonteri 2010).

The difficulties raised by the Pop-III scenario (hereafter “light seed models”) in explaining the presence of quasars at high redshifts have prompted searches for alternative channels for the birth of SMBH seeds. Models such as the direct collapse of a gas cloud to an MBH (e.g., Haehnelt & Rees 1993; Loeb & Rasio 1994; Eisenstein & Loeb 1995; Bromm & Loeb 2003) or the generation of a giant protostar that further collapses to an MBH are accepted today as viable solutions. These scenarios advocate that SMBHs originate from heavy seeds with masses of $10^5$–$10^6 M_\odot$; hereafter, we label this family of models “heavy seed models.” Since the growth time of an SMBH is inversely proportional to its seed mass (e.g., Haiman & Loeb 2001), this family of models alleviates many of the problems encountered by the Pop-III scenario.

Despite the growing interest in the field, there is still no clear evidence for the correct scenario for the birth of SMBH seeds. A key problem encountered when looking for evidence in the local universe is that signatures of the seeding mechanism can...
be washed out during the SMBH—host galaxy coevolution (Natarajan 2011). Moreover, with current capabilities, one observes only massive, high-luminosity objects at high redshift, i.e., those that have already undergone major growth past the seed stage (Merloni 2016). Many searches for the signatures of intermediate MBHs at high redshift have been performed so far, with a significant number of them in the X-ray band (e.g., Vito et al. 2013; Weigel et al. 2015). A fundamental advantage of X-ray observations is that the emitted photons are in general energetic enough to escape dust and gas clouds surrounding the MBH and therefore can give us a full census of the flux distribution related to the MBH accretion rate and mass. While flux limits from current X-ray observatories such as Chandra and XMM-Newton can, in general, detect an MBH with a mass of $\sim10^8 M_\odot$ up to a redshift of $z \sim 7$ (see Section 2), no such objects have been robustly detected, even in the deepest surveys (e.g., Treister et al. 2013).

In this paper, we explore the X-ray flux distribution from MBHs at high redshifts as they emerge from the seed state and coevolve with the host galaxy. We investigate whether current or future experiments can shed light on the mechanism responsible for the birth of SMBH seeds at high redshift. By using physically motivated models, we estimate the X-ray flux distribution from MBHs at high redshift and determine whether different seeding and growth models yield different signatures during the initial stages of MBH—host coevolution when observed in the X-ray band. We focus on two observational programs: the Chandra Deep Field South survey (CDFS; Xue et al. 2011; Luo et al. 2017) and a similar observing program with the proposed Lynx. Due to its excellent spatial resolution (half-power diameter (HPD) of $0.5''$), Chandra is currently the best instrument for detecting low-flux objects at the high redshifts we consider. The CDFS has a point-source detection limit of $9.1 \times 10^{-16}$ erg cm$^{-2}$ s$^{-1}$ at energies of $0.5$–$2$ keV in a $5' \times 5'$ field of view (FoV). Lynx is a future X-ray observatory aiming at a spatial resolution similar to that of Chandra with an effective area orders of magnitude greater. Lynx is designed to reach a flux limit of $\sim10^{-17}$ erg cm$^{-2}$ s$^{-1}$ over 400 arcmin$^2$ in its deepest surveys.

Our paper is organized as follows. In Section 2, we describe the basic assumptions in our models, discuss the reasoning behind them, and present the methodology used to estimate the expected observed X-ray flux distributions for the experiments under study. Section 3 gives an analysis of the results with an emphasis on model discrimination given the derived X-ray flux distributions. In Section 4, we investigate models allowing super-Eddington accretion. A summary and conclusions are given in Section 5. Throughout the paper, we assume a standard $\Lambda$CDM cosmology with $h = 0.7$, $\Omega_m = 0.27$, and $\sigma_8 = 0.82$, in agreement with current Planck measurements (Planck Collaboration et al. 2016) and the parameters used in several of the leading numerical simulations (e.g., Klypin et al. 2011).

## 2. Methodology

Our goal is to investigate whether the detected high-energy emission with current (Chandra) and future (the proposed Lynx) telescopes allows us to discriminate between the various scenarios for the birth and growth of SMBHs. We first determine the minimum mass of an MBH that can be detected with a given experiment as a function of the luminosity scaling parameter $\lambda$ under favorable conditions (e.g., no circumnuclear, interstellar medium (ISM), and intergalatic medium (IGM) absorption). Guided by merger-tree simulations for the growth of SMBHs, we estimate the evolution of the $M_{\text{BH}}$–$\sigma$ relation at high redshifts, which allows us to relate MBHs to their host dark matter (DM) halos. Using cosmological simulations to estimate the number density of DM halos, we derive the expected number of observable MBHs at a given redshift for each seeding model and $\lambda$. The derived numbers provide input parameters to our Monte Carlo (MC) simulation that estimate the expected X-ray flux distributions from MBHs. The number of observed MBHs and their X-ray flux distributions are the observables in the 2D phase space we study, a phase space in which one axis is a parameter related to the birth mechanism and the other axis is a luminosity scaling parameter related to the MBH accretion rate.

In this work, we focus on the post-seeding stage and the initial coevolution of the MBH with its host galaxy. Therefore, we do not attempt to model SMBH seed formation but assume that all models are encoded via deviations from the $M_{\text{BH}}$–$\sigma$ relation observed in the local universe (i.e., a modified model and redshift-dependent $M_{\text{BH}}$–$\sigma$ relation). The coevolution stage is expected to be significantly longer than the seeding stage ($\gtrsim 1$ Gyr versus $\sim 0.1$ Gyr; see Volonteri 2010; Agarwal et al. 2013; Natarajan et al. 2017) and might offer a significant statistic in our effort to study the discriminating power of X-ray flux distribution for a wide range of models. In some cases, X-ray emission at the seed stage is expected to be detected (Pacucci et al. 2015). While this can give additional discrimination power, we do not consider it in this work. A detailed description for each step in our methodology follows.

### 2.1. BH Mass and Flux Limits

The minimum mass of an observable MBH will depend on the object’s emitted X-ray luminosity $L_\gamma$ and its luminosity distance $D_L$ (see Section 2.4 for other factors that might affect an MBH observed flux). Initially, we focus on sub-Eddington luminosities, so that the BH bolometric luminosity is given by $L_{\text{bol}} = L_{\text{edd}}$. Here $L_{\text{edd}}$ is the BH Eddington luminosity, $L_{\text{edd}} = 3.2 \times 10^{44} (M_{\text{BH}}/M_\odot) (L_\star/\text{L}_\odot)$ (Rybicki & Lightman 1979; Trakhtenbrot et al. 2017), and $0 < \lambda \leq 1$ is a scaling parameter. We focus on rest-frame energies of 3–26 keV, as photons of such energies emitted at $z \sim 5$–12 (initial coevolution of host and SMBH seed; Volonteri 2010; Natarajan et al. 2017) will be redshifted to energies of 0.5–2 keV, the energy band with the peak response in the experiments we investigate. We make a conservative assumption regarding the flux fraction emitted at energies above 2 keV $\epsilon_{2\text{keV}} = 0.1$ (e.g., Hopkins et al. 2007), and so the X-ray flux observed between 0.5 and 2 keV is given by

$$F_{\nu} = \epsilon_{2\text{keV}} \frac{\Lambda_{\nu}}{4\pi D_L^2} \times k_{\text{corr}} \approx 3.2 \times 10^{44} \frac{f_{2\text{keV}} \lambda k_{\text{corr}}}{4\pi D_L^2} \left( \frac{M_{\text{BH}}}{M_\odot} \right) L_\star.$$  

The $K$-correction $k_{\text{corr}}$ depends on the spectral energy distribution of the emitted object, which we assume behaves like a power law with an index of 1.8 so that $f(E) \propto E^{-1.8}$ (e.g., Ishibashi & Courvoisier 2010; Mateos et al. 2010). Figure 1 shows the X-ray flux dependency on mass (left panel)
and redshift (right panel). We plot the detection limits of the CDFS survey \( (9.1 \times 10^{-18} \text{ erg cm}^{-2} \text{ s}^{-1}; \text{ Xue et al. 2011}) \) and the expected Lynx deep-field detection limit \( (1 \times 10^{-19} \text{ erg cm}^{-2} \text{ s}^{-1}; \text{ Lynx, footnote 3}) \) for comparison. Only MBHs with masses above \( \sim 10^6 M_\odot \), luminosities approaching \( L_{\text{seed}} \), and closer than redshift \( z \sim 7 \) can be detected with \textit{Chandra}. On the other hand, Lynx allows us to detect BHs with masses as low as \( \sim 10^4 M_\odot \) at the same redshifts, providing access to the seed population.

2.2. A Redshift-dependent \( M_{\text{BH}}-\sigma \) Relation

Empirical correlations between SMBH masses and various properties of their host galaxies have been established over the past two decades. Power-law fits to these correlations provide efficient means to estimate BH masses in a statistically significant sample (Beifiori et al. 2012; McConnell & Ma 2013). Several authors have argued that the empirical scaling relations are rooted in a more fundamental relation between \( M_{\text{BH}} \) and properties of the host galaxy DM halo, such as the halo virial mass \( (M_{\text{DM}}^\text{vir}) \) or \( v_{\text{circ}}^\text{max} = \sqrt{\frac{GM(<r)}{r}} \max \), the maximum circular velocity achieved beyond the bulge (e.g., Ferrarese 2002; Saxton et al. 2014; Larkin & McLaughlin 2016). In this work, we use \( v_{\text{circ}}^\text{max} \) as provided by numerical simulations that trace DM halo evolution from primordial density fluctuations in combination with the correlation found between \( M_{\text{BH}} \) and the stellar velocity dispersion of the bulge \( \sigma \). We relate the mass of the BH to the \( v_{\text{circ}}^\text{max} \) of the host by assuming that the \( M_{\text{BH}}-\sigma \) relation can be cast to an \( M_{\text{BH}}-v_{\text{circ}}^\text{max} \) relation through a simple numerical factor \( \eta = v_{\text{circ}}^\text{max} / \sigma \) that takes values of 2–4 (Dutton et al. 2004; Padmanabhan et al. 2004; Kravtsov 2009). We use the correlation found by McConnell & Ma (2013) for late-type galaxies, \( \log_{10}(M_{\text{BH}}) = 8.07 + 5.06 \log_{10}(\sigma/200 \text{ km s}^{-1}) \), as these are the majority of galaxies we expect to observe at the redshifts.

The \( M_{\text{BH}}-\sigma \) relation has been demonstrated across several orders of magnitude in SMBH masses in the local universe (i.e., \( z \sim 0 \)). Since we investigate MBHs after the seeding stage and during initial coevolution with the host, we assume a modified \( M_{\text{BH}}-\sigma \) relation has already been established. Current observations, as well as theoretical modeling, are inconclusive regarding the evolution of the \( M_{\text{BH}}-\sigma \) relation at high redshifts. While several studies argue for a steepening of the slope in the \( M_{\text{BH}}-\sigma \) relation (e.g., Treu et al. 2007; Targett et al. 2012; Trakhtenbrot et al. 2015), others argue for no evolution with redshift (e.g., Jahnke et al. 2009; Schramm & Silverman 2013) and even flattening of the slope at high redshifts (Shapiro et al. 2009). Any deviation from the local \( M_{\text{BH}}-\sigma \) relation will encode the physics of the seeding mechanism, and we therefore relate the \( M_{\text{BH}}-\sigma \) relation at high redshift to the seeding mechanism and MBH accretion history. Merger-driven BH growth simulations, which track the growth of MBHs and their host galaxies from initial seeds, can be used to estimate the change in the \( M_{\text{BH}}-\sigma \) relation at high redshift. We follow the reasoning presented in Volonteri & Natarajan (2009): (i) SMBHs originating from massive seeds start off above the \( M_{\text{BH}}-\sigma \) relation observed in the local universe and migrate onto it by initially growing \( \sigma \), after which further major mergers trigger accretion episodes that result in growth spurts for the MBHs; and (ii) SMBHs originating from light seeds migrate to the local \( M_{\text{BH}}-\sigma \) from below, with the MBH seeds growing without significantly altering \( \sigma \). The modification of the \( M_{\text{BH}}-v_{\text{circ}}^\text{max} \) relation is introduced by adding a model-dependent mass scaling parameter \( X(z) = M_{\text{BH}} / M_{\text{BH}}^\text{loc} \). Overall, the \( M_{\text{BH}}-\sigma \) relation observed at the local universe is modified to an \( X(z) M_{\text{BH}}^\text{loc} \sim \sigma \) at high redshift. Guided by tree-merger simulation results (Volonteri & Natarajan 2009), we assume a functional form of \( X = e^{b(z-2)} \), and so the redshift-dependent relation settles to the observed \( M_{\text{BH}}-\sigma \) relation in the local universe at \( z = 2 \) (see left panel in Figure 2). We allow different realizations of the parameter \( X \), with \( b \) varying from \(-0.3 \) to \( 0.3 \). For \( b = 0 \), there is no change in the local \( M_{\text{BH}}-\sigma \) relation (the mass scaling parameter, luminosity scaling parameter, and duty cycle are correlated with the SMBH mass at a later stage of its evolution, and we take this into account during our MC simulation; see Section 2.4). A model with a positive (negative) value of the parameter \( b \) implies that the MBH that resides at the center of a DM halo with a specific value of \( v_{\text{circ}}^\text{max} \) is heavier (lighter) than the MBH found at lower redshift in a DM halo of similar \( v_{\text{circ}}^\text{max} \), i.e., a steepening (flattening) of the slope of the \( M_{\text{BH}}-\sigma \) relation at high redshifts; see right panel in Figure 2. We find for each specific model
what is the minimum $v_{\text{circ}}^{\text{max}}$ for which a halo will host an MBH that can be detected with each telescope. The value of min ($v_{\text{circ}}^{\text{max}}$) will be used next to estimate the density of observed objects using halo densities derived from cosmological simulations of the evolution of the large-scale structure in the universe.

### 2.3. Deriving the Density of Observed Sources

Once we determine the $\min(v_{\text{circ}}^{\text{max}})$ of an halo that hosts a detectable MBH for each model, we ask what is the comoving density of halos with $v_{\text{circ}} \leq \min(v_{\text{circ}}^{\text{max}})$. This allows us to estimate the spatial density of detectable MBHs from each model with each telescope.

In this work, we use the Bolshoi N-body simulation\(^4\) to estimate the density of MBHs at high redshifts based on the modified $M_{\text{BH}}-\sigma$ relation and $\min(v_{\text{circ}})$ for a detectable MBH. The Bolshoi simulation (Klypin et al. 2011) covers a volume of 250 $h^{-1}$ Mpc on a side using $\sim 8$ billion particles, allowing us to probe halos with $v_{\text{circ}}$ as low as 50 km s\(^{-1}\). It uses $v_{\text{circ}}$ as the main property of halos, since it is a more stable quantity for characterizing the physical parameters of the central regions of DM halos than the halo virial mass and therefore a better quantity for relating DM halos to the galaxies they host. Klypin et al. (2011) showed that 90% of the halos have circular velocities within 8% of the median value. Using $v_{\text{circ}}$ as the main characteristic of a DM halo, we directly derive the cumulative MBH density function using the modified $M_{\text{BH}}-\sigma$ relation.

Over a broad range in mass and redshift, the halo cumulative number density can be parameterized according to (Klypin et al. 2011)

$$n(v) = A v^{-3} \exp \left( - \frac{v}{v_0} \right),$$

where $v$ is the halo velocity. The parameters in the density function, $A$, $\alpha$, and $v_0$, are evolving according to $\sigma_8(z)$, the variance in the density perturbation amplitude smoothed over an 8 $h^{-1}$ Mpc box, with\(^5\)

$$A = 1.52 \times 10^4 \sigma_8^{-3/4}(z) [h^{-1} \text{Mpc/km s}^{-1}],$$

$$\alpha = 1 + 2.15 \sigma_8^{1/3}(z),$$

and

$$v_0 = \frac{3300}{1 + 2.5 \sigma_8^2(z)} [\text{km s}^{-1}].$$

By integrating the comoving halo density equation with a lower bound set to $\min(v_{\text{circ}}^{\text{max}})$, we get the number of detectable MBHs for each model $N_{\text{Obs}}^{\text{max}}$:

$$N_{\text{Obs}}^{\text{max}}(z) = \int_{z'=z-\Delta z}^{z'=z+\Delta z} \frac{dV}{d\Omega}(d\Omega) \times n(z'; v_{\text{circ}}^{\text{max}} > \min(v_{\text{circ}}^{\text{max}})) dz'. $$

In the equation above, we assume that each halo has an MBH at its center (i.e., the occupancy $\eta_{\text{occ}} = 1$) and that each MBH in a given FoV is continuously accreting and radiating at the specified value of $\lambda$ (i.e., the duty cycle $\eta_{\text{dc}} = 1$). The actual number of observed objects is $N_{\text{Obs}}(z) = \eta_{\text{occ}} \times \eta_{\text{dc}} \times N_{\text{Obs}}^{\text{max}}(z)$. Table 1 summarizes the parameter space we explore in this paper.

### 2.4. MC Realization

In the previous section, we used physically motivated models and relations to estimate the number of observable MBHs and their flux distribution as a function of redshift. Our models are represented by two parameters: the mass scaling parameter $X = \frac{M_{\text{BH}}}{M_{\text{BH}_{\text{crit}}}}$ and the luminosity scaling parameter $\lambda = \frac{L}{L_{\text{edd}}}$. In some of the cases, the parameters we use for each

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\[^4\] hipacc.ucsc.edu/Bolshoi

\[^5\] We assume $\sigma_8$ evolves according to the scale factor $a(t)$ and is normalized to 0.82, in agreement with recent Planck results (Planck Collaboration et al. 2016).
model are drawn from a distribution and will vary for different objects.

The variance and uncertainty in the parameters we use blur the differences in the observables between models. We take this effect into account by performing an MC simulation for each model. The results of the MC run allow us to assess the differences in the observables between models. We take into account by performing an MC simulation for each model. The results of the MC run allow us to assess

For each model, we run a series of MC realizations with the following assumptions:

1. The number of observable MBHs in the FoV follows a Poisson distribution with $N = n_{\text{loc}} \times N_{\text{obs}}(z)$, where $N_{\text{obs}}(z)$ is the average number of observable MBHs when varying $b$ between a value of 2 and 4 and $n_{\text{loc}}$ is the occupancy factor. Volonteri et al. (2008) argued that the host occupancy is of the order of $\sim 10\%$ (4–25% in models presented), with the occupancy increasing as a function of host mass. We therefore assume that $n_{\text{loc}}$ follows a normal distribution with $n_{\text{loc}} = 0.14$ and $\sigma = 0.04$.

2. The BH masses follow a normal distribution with a mean equal to the weighted average BH mass and $\sigma$ being the standard deviation of the distribution weighted by the cumulative halo density function.

3. The luminosity scaling parameter $\lambda = \frac{L}{L_{\text{edd}}}$ follows a log-normal distribution with $\nu = 0.4$ (Kelly et al. 2010). We apply an upper limit of $\lambda = 1$ to avoid cases of super-Eddington accretion (see Section 2.2 for an analysis of models allowing super-Eddington luminosities).

4. To estimate the flux attenuation due to circumnuclear and gas absorption, we assume a normal distribution for column densities with an average of $N_{\text{H}} = 10^{23} \text{ cm}^{-2}$ and $\sigma = 5 \times 10^{22} \text{ cm}^{-2}$ (Vito et al. 2013, 2014). We make the assumption that the amount of attenuation is uncorrelated with the age/evolution of the MBH past seeding and initial host/MBH coevolution for rest-frame energies of 3–26 keV (Treister et al. 2011, 2013; Natarajan et al. 2017). We further assume that the fraction of obscured SMBHs is not evolving at this stage, similar to observational data at intermediate redshifts ($z \sim 3$–5; Vito et al. 2014). This assumption can be revised with future results from JWST (Volonteri et al. 2017). We model the amount of signal attenuation using the xspec model pclouds, which assumes a power-law SED emission transmitted through a spherical distribution of cold and dense matter, taking into account Compton scattering (Yaqoob 1997; Vito et al. 2013).

5. In order to estimate the duty cycle for each MBH realized in the run, we calculate the $t_{\text{acc}}^\text{max}$ of the MBH host and evolve it to a redshift $z = 2$ according to results from the Bolshoi N-body simulation (see Section 2.2). We calculate $M_{\text{BH}}$ for the evolved halo assuming the $M_{\text{BH}}$–$\sigma$ relation has settled to the one observed in the local universe (i.e., $X = 1$). We derive the amount of time $t_{\text{acc}}$ the MBH will need to accrete the mass difference, assuming the MBH specific value of $\lambda$ and accretion efficiency $\epsilon = 0.2$ (i.e., coherent accretion; Berti & Volonteri 2008). We assume that the contribution from MBH mergers is negligible (e.g., Volonteri & Natarajan 2009; Kalisky et al. 2015). The duty cycle is then estimated according to $t_{\text{dc}} = \frac{t_{\text{acc}}}{t_{\text{acc}}}$, with $t_{\text{dc}}$ being the time elapsed between the redshift at which the MBH is observed and redshift $z = 2$.

Table 1: Parameter Space

| Parameter                  | Value          | Distribution | Comments |
|----------------------------|----------------|--------------|----------|
| $\lambda = \frac{L}{L_{\text{edd}}}$ | 0.1–1          | Log-normal   |          |
| $X = \frac{M_{\text{BH}}}{X_{\text{edd}}}$ | $b = -0.3$ $-0.3$ | Log-normal   | $X = e^{b(z-2)}$ |
| $\eta = \frac{M_{\text{BH}}}{X_{\text{edd}}}$ | 2.4–4         | Log-normal   |          |
| $\eta_{\text{loc}}$ | ...            | Normal       | ...      |
| $\eta_{\text{loc}}$ | 14%            | Normal       |          |
| Column density $N_{\text{H}} = 10^{23} \text{ cm}^{-2}$ | Normal | Torque-limited models | |
| $\lambda = \frac{L}{L_{\text{edd}}}$ | 1.7–2.1 | Log-normal   |          |
| $X = -2.49 + 1.93 \log(1 + z)$ | Log-normal   | Torque-limited models | |
| Notes.                          | | | |
| $^a$ Padmanabhan et al. (2004); Dutton et al. (2004); Kravtsov (2009), Volonteri et al. (2008). | | | |
| $^b$ Yaqoob (1997); Vito et al. (2013). | | | |
| $^c$ Anglés-Alcázar et al. (2013, 2015). | | | |

For each model, characterized by $\lambda$ and the mass scaling parameter $X$, we run 500 MC realizations. The output of our MC run is a list of MBHs, each characterized by mass, redshift, observed X-ray flux, and duty cycle. Since we study MBHs past the seeding stage and only after initial host–MBH coevolution, we verify for each BH whether its mass is above the detection limit of the experiment we investigate, after we take circumnuclear absorption into account. Conservatively, we discard a simulated MBH in case it did not pass the aforementioned criteria.

6 https://heasarc.gsfc.nasa.gov/xanadu/xspec/manual/XSmodelPclouds.html
With the MC output in hand, we count the number of observable MBHs for each telescope, taking into account the duty cycle of each source. The results are shown in Figure 3. For Lynx, the high number of observed objects allows us to examine the expected X-ray flux distribution. We therefore bin the data in redshift (seven bins) and flux (50 bins) to derive the redshift- and model-dependent X-ray flux distributions; see Figures 4–5.

3. Analysis and Discussion

The expected number of detected objects and the redshift-dependent X-ray flux distributions vary significantly between the two telescopes and between models. We analyze the MC simulation results in the context of our capability to differentiate between the various models.

For all simulated models, the number of MBHs expected to be detected by the Chandra X-ray Observatory is a few at most. Only models in which the MBH luminosities are comparable to the Eddington limit yield any detectable objects. Due to the small number of observable sources, there is no significant statistical difference between the light and heavy seed models, as shown by the top panels of Figure 3. Indeed, analysis of CDFS data (e.g., Treister et al. 2013; Vito et al. 2013; Weigel et al. 2015; Trakhtenbrot et al. 2016) shows no clear detection of intermediate MBHs in the FoV, in agreement with our simulation results. Our findings further emphasize the limitations of current observations, owing to the small effective area of the telescope and the small FoV.

Considering instead the Lynx detection limit and FoV, the number of detectable sources varies from several dozen (light seed models with \( \lambda = 0.025 \)) to \( \sim 4000 \) (heavy seed models with \( \lambda \sim 0.7 \)), as illustrated in the bottom panels of Figure 3. The high number of detectable MBHs allows us to examine the X-ray flux distribution at various redshifts, as shown in Figures 4–5. The results exhibit three dominant trends. (i) In the light seed models, the peak of the distribution is around the detection limit; this seems to be in agreement with the underlying halo density, as halos of lower \( v_{\text{circ}}^{\max} \) are more abundant than halos of higher \( v_{\text{circ}}^{\max} \), and the peak is determined by the limiting flux of the experiment under study. In the heavy seed models, the peak of the flux distribution moves to higher flux values for higher values of \( \lambda \) in all models, as most of the MBHs have evolved above the mass associated with the flux limit, while the smaller halos, which in general would have hosted a detectable MBH, do not host such an object.

(ii) The maximum number of objects is detected in models with \( \lambda = 0.6-0.7 \). Whereas, in general, one would assume that the maximum number of objects would be detectable in models in which the MBHs shine at their Eddington luminosity, these models have a lower average duty cycle; therefore, at a certain value of \( \lambda \), the low duty cycle overcomes the higher accretion rate. This effect is more significant for higher values of the

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Figure 3. Expected number of observed MBHs for Chandra (top) and Lynx (bottom) as a function of the luminosity scaling parameter, \( \lambda \), and the mass scaling parameter, \( b \). Light (heavy) seed models appear in the left (right) panels. While Chandra is expected to detect a few MBHs at most, Lynx is expected to detect a statistically significant sample of MBHs for both light and heavy seed models.

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\(^7\) The number of bins is chosen to optimize the statistical significance of our results as a function of phase-space resolution. When deriving the expected number of observed objects, as well as the flux distributions, we average over the 500 MC realizations, with the statistical error being the standard deviation of the 500 MC runs.
mass scaling parameter \( X \), since the median duty cycle approaches an asymptotic value of unity for smaller values of \( X \). (iii) For higher values of the mass scaling parameter, the number of objects detectable at very high redshifts (\( 10 < z < 12 \)) increases from zero \( (b = 0, \lambda = 0.025) \) to \( \sim 200 \) objects \( (b = 0.3, \lambda = 0.7) \), while in the case of light seed models, no significant number of objects is expected to be detected above redshift \( z > 10 \); this is in agreement with published models, arguing that detection of Pop-III SMBH seeds at high redshifts is unlikely (Natarajan et al. 2017). We emphasize that there is a clear degeneracy between \( \lambda \) and \( b \) when examining the overall number of detected objects, but the relative number of observed objects at a given redshift is a good indicator of the evolution and seeding mechanism of MBHs.

As can be seen from the redshift-dependent X-ray flux distributions, a clear difference between the simulated light and heavy seed models is observed in most cases. In order to get a quantitative understanding of the discrimination power in some limiting cases, we perform \( \chi^2 \) tests for the light and heavy seed models. For the light seed models, we assume that the null hypothesis is the light seed model \( (b = 0.05; \lambda = 0.2) \), while for the heavy seed models, we assume that the null hypothesis is the light seed model \( (b = -0.05; \lambda = 0.8) \). We choose these two null hypotheses because the flux distributions derived for these models are similar to the expected distributions from the opposite group of models but do not represent extreme cases. The results, shown in the top panels of Figure 6, clearly imply that discrimination at a level of \( 3\sigma \) can be achieved across most of the phase space, excluding some extreme cases for each group of models. In order to quantify our ability to constrain the parameters used to characterize a specific model, we perform \( \chi^2 \) tests within a given family of models. For the light seed models, we assume a null hypothesis of \( (b = -0.15; \lambda = 0.5) \), while for the heavy seed models, the null hypothesis is \( (b = 0.15; \lambda = 0.5) \); see the bottom panels of Figure 6. We find that while the simulation is clearly degenerate for several parameters (mass scale parameter, luminosity scale parameter, seed generation efficiency, and duty cycle), the observational results from \( \text{Lynx} \) can direct us to the phase space in which plausible scenarios reside within a specific family of models.

3.1. Additional Constraints from the Cosmic X-Ray Background

The observed X-ray background (XRB) is thought to be the result of two main contributions: (i) the galactic XRB emitted by hot gas in the solar neighborhood governs the soft end of the XRB (\(< 0.3 \) keV); and (ii) the cosmic X-ray background (CXR B) is associated with the accumulated emission from unresolved sources, mainly obscured and unobscured active galactic nuclei (AGNs), normal galaxies, and the IGM (Cappelluti et al. 2012). Current \textit{Chandra} measurements of the CXRB yield a value of \( 4.6 \pm 0.3 \times 10^{-12} \) erg cm\(^{-2}\) s\(^{-1}\) deg\(^{-2}\), from which \( 23\% \pm 3\% \) is unresolved (1–2 keV band; Hickox & Markovitch 2006, 2007). Several studies indicate that at low flux levels, the AGN contribution to the CXRB drops, whereas the contribution from normal galaxies rises. At the CDFS flux limit, 46% ± 5% of the source counts are normal galaxies (Lehmer et al. 2012). We therefore examine next whether any of the models in our MC simulation violate the CXRB limit and whether current or future observations can shed some light on the origins of the CXRB.
We ran MC simulations for all models, with an upper limit set to the flux limit in the CDFS observations, as MBHs that can generally be detected as point sources by Chandra do not contribute to the unresolved CXRB. We do not apply a lower limit on the point-source flux but keep the mass lower limit associated with each seeding model, as this is associated with the physics of SMBH seed generation and not with any observational limit.

Our results show that in all cases, the CXRB contribution from AGNs at high redshifts lies below the current upper limit. For the light seed models, we find that the MBH contribution varies from $10\% \pm 5\%$ for the $[b = -0.3; \lambda = 0.025]$ model to $24\% \pm 9\%$ for the $[b = 0; \lambda = 1]$ model, while for the heavy seed models, we find contributions at the level of $18\% \pm 6\%$ for the $[b = -0.3; \lambda = 0.025]$ model and $81\% \pm 18\%$ for the $[b = 0.3; \lambda = 0.575]$ model. We emphasize that when considering the diminishing contributions from AGNs at the Chandra low-flux limit, heavy seed models with $0.3 < b < 0.225$ provide a factor of 1.5–2 more flux than expected (for higher values of $\lambda$, the duty cycle drops, so the overall integrated flux drops as well; see previous section). We also investigate what the expected contribution is from unresolved AGNs to the unresolved CXRB, assuming we perform observations down to the Lynx flux limit. We ran the same MC simulation with an upper limit set to $1 \times 10^{-19}$ erg cm$^{-2}$ s$^{-1}$. The results indicate that for the heavy seed models, the contribution from unresolved AGNs will be below 5% of the total unresolved CXRB, so most of the AGN contribution falls between the Lynx and Chandra detection limits. For the light seed models, we find that a significant fraction of the MBHs contributing to the unresolved CXRB will remain below the detection limit, in agreement with Natarajan et al. (2017).

We conclude that estimates of the contribution of MBHs at high redshift to the CXRB, combined with deep observations with a future high-resolution X-ray telescope, can yield additional constraints on the scenarios by which SMBH seeds are generated and evolve.

## 4. Other Models

### 4.1. Super-Eddington Accretion

While the scenario in which an SMBH seed is the outcome of the collapse of a gas cloud to an $\sim 10^5 M_\odot$ BH is a possible solution to the problem raised by the discovery of quasars at $z \sim 6$–7, an alternative is the growth of SMBH seeds through super-Eddington accretion in several short episodes ($\sim 0(10)$ Myr; e.g., Wyithe & Loeb 2012; Tanaka 2014; Castelló-Mor et al. 2016; Pezzulli et al. 2017). We turn now to investigating a family of models that assumes mild super-Eddington accretion by an SMBH seed, namely the slim disk models (Abramowicz et al. 1988; Jiang et al. 2014, 2017).

Madau et al. (2014) analyzed the case of a slim disk solution in which the viscosity-generated heat in the accretion disk is not radiated away immediately but is advected into the central SMBH seed. In this model, mild super-Eddington accretion can take place for several Myr, thus shortening the characteristic e-folding time of the MBH. Madau et al. (2014) analyzed two cases in which a Pop-III seed (Natarajan et al. 2017) will grow into a quasar by $z \sim 7$: (i) three major episodes, each lasting $50$ Myr, in which $3 < l < 4$, followed by a $100$ Myr period of quiescence (duty cycle $0.5\%$), and (ii) one major episode, lasting $100$ Myr, followed by a $1000$ Myr period of quiescence (duty cycle $1\%$). We also investigate what the expected contribution is from unresolved AGNs to the unresolved CXRB, assuming we perform observations down to the Lynx flux limit. We ran the same MC simulation with an upper limit set to $1 \times 10^{-19}$ erg cm$^{-2}$ s$^{-1}$. The results indicate that for the heavy seed models, the contribution from unresolved AGNs will be below 5% of the total unresolved CXRB, so most of the AGN contribution falls between the Lynx and Chandra detection limits. For the light seed models, we find that a significant fraction of the MBHs contributing to the unresolved CXRB will remain below the detection limit, in agreement with Natarajan et al. (2017). We conclude that estimates of the contribution of MBHs at high redshift to the CXRB, combined with deep observations with a future high-resolution X-ray telescope, can yield additional constraints on the scenarios by which SMBH seeds are generated and evolve.

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*Figure 5. Expected X-ray flux distributions for heavy seed models as observed with Lynx.*

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8 While slim disk models were analyzed in the literature in the context of both heavy and light seed models (Natarajan et al. 2017), we follow Madau et al. (2014) and focus on the application of slim disk accretion in the light seed scenarios.
cycle = 0.5); and (ii) five major accretion episodes of 20 Myr in which $\lambda = 4$, followed by a 100 Myr period of quiescence (duty cycle = 0.2). In an attempt to examine the observables for these scenarios, we repeat the MC simulation described earlier. We assume that the $M_{\text{BH}} - \sigma$ relation at high redshift is similar, on average, to the one observed in the local universe (i.e., $b = 0$ in terms of the parameters used for the sub-Eddington models), as MBHs at the end of an accretion phase will be more massive with respect to their host halo, while MBHs at the end of a quiescent phase will be less massive with respect to their host halo. While the two cases discussed above are able to produce quasars by $z \sim 7$, the relative comoving number density of quasars to MBHs at $z > 6$ is expected to be $10^{-6}-10^{-5}$ (e.g., Bromley et al. 2004), and so we choose a combination of $\lambda$ and duty cycle that generates the expected density ratio. In a bootstrap analysis of models in which $\lambda$ has a log-normal distribution, the duty cycle is constrained so that the $M_{\text{BH}} - \sigma$ relation observed in the local universe holds for all redshifts, and the two models analyzed by Madau et al. (2014) yield the expected density of quasars at $z \sim 6$, constraining us to a phase space in which $\lambda = 1.7-2.1$. All other assumptions in our MC simulation are not changed (see Section 2.4). We perform 500 MC runs and average over the results, shown in Figure 7. The overall number of sources expected to be detected is similar to that of the sub-Eddington heavy seed models. The flux-redshift distribution, however, is different, with the peak at a higher value relative to the sub-Eddington cases. The lower skewness of distribution is due to our assumption on the probability distribution of $\lambda$, which is more symmetric for higher values of $\lambda$. Further analysis needs to be performed in order to assess the significance of our result, if one assumes a different probability density function (PDF) for $\lambda$. In addition, we find more sources to be observable at high redshifts ($z > 7$) than in the sub-Eddington case, since in general, the sources are expected to be brighter due to the high value of the luminosity scaling parameter and not due to the higher mass of the SMBH seeds, as in the heavy seed models (with the degeneracy between various parameters in the models...
evident again in this case). We repeat the $\chi^2$ test with the null hypothesis as the average of the slim disk models X-ray flux distributions. Our goal is to get a quantitative understanding of the difference between the heavy seed sub-Eddington and slim disk models. The results suggest that discrimination at the level of $>\sigma$ can be achieved across all of the phase space we examine in Section 3.

Summing the contribution from AGNs below the Chandra flux limit, we find that for the slim disk models, SMBH seeds will contribute $28\% \pm 6\%$ of the unresolved CXRB—well below current upper limits from CDFS (Lehmer et al. 2012) and similar to the results derived for the sub-Eddington light seed models described in Section 3.1.

4.2. Torque-limited Accretion Models

The observed scaling relations between SMBHs and their host galaxies are often explained by self-regulated growth of the MBH seeds and coevolution with the hosts. Some of the models induce self-regulation by strongly coupling winds from the accreting MBHs to the gas supply in the galactic scale (e.g., Wyithe & Loeb 2003; Springel et al. 2005; Deburr et al. 2011; Hambrick et al. 2011; Kim et al. 2011; Choi et al. 2012; Dubois et al. 2012). However, there is no direct evidence for the self-regulation to be caused by feedback from the accretion process. In the SMBH growth model studies by Anglés-Alcázar et al. (2013, 2015), no direct feedback from the MBH accretion process is assumed. Instead, galaxy-scale gravitational torques induced by interactions or self-gravitating disks are the limiting factors in supplying gas from the galactic scale to the MBH sphere of influence, thus limiting the MBH growth. These models yield MBHs that evolve naturally onto the observed galaxy–SMBH scaling relations regardless of the initial conditions. While Anglés-Alcázar et al. (2015) showed a detailed analysis at lower redshifts than the ones we examine in this work, we extend their results to higher redshifts using the methodology described in Section 2, with the following changes:

1. We anchor the MBH to $v_{\text{circ}}^\text{max}$ at $z = 12$, assuming $\eta = 2–4$. The MBHs are 10 times heavier (lighter) than inferred from the $M_{\text{BH}}-\sigma$ relation observed at $z = 0$. This represents heavy (light) seeds.
2. Heavy seeds grow into the $M_{\text{BH}}-\sigma$ relation in $1.5 \times t_{\text{Hubble}}$, where $t_{\text{Hubble}} = 0.96 \text{Gyr}[(1 + z)/z]^{-3/2}$ is the Hubble time at redshift $z$, while light seeds grow into the local $M_{\text{BH}}-\sigma$ relation in $0.5 \times t_{\text{Hubble}}$. Anglés-Alcázar et al. (2015) showed that this assumption is independent of the redshift at which we anchor the SMBH seeds to the $M_{\text{BH}}-\sigma$ relation.
3. We examine only the MBH population during initial coevolution until the local scaling relations have been established. For the heavy seed models, this implies $z \sim 5–12$, whereas for the light seed models, this implies $z \sim 8–12$.
4. Here $\lambda$ is constant within a redshift bin and evolves according to $\lambda = -2.49 + 1.93 \log(1 + z)$ (Anglés-Alcázar et al. 2015), where $\lambda$ follows a log-normal distribution as described in Section 2.
5. We apply a minimum mass for an MBH according to the seeding mechanism: $5 \times 10^4 M_\odot$ for heavy seeds and $100 M_\odot$ for light seeds.

Figure 8 shows the expected X-ray flux distributions for observations taken with Lynx for torque-limited growth of heavy seeds anchored at $z = 12$.

5. Summary and Conclusions

In this paper, we investigated the expected X-ray flux distributions ($0.5–2 \text{keV}$ observed) from MBHs at high redshifts ($z > 5$). We examined several models for SMBH birth and evolution: light seeds (Pop-III stars) and heavy seeds (direct collapse of a gas cloud) with sub-Eddington accretion, slim disk models allowing mild super-Eddington accretion (light seeds only), and torque-limited accretion for both light and heavy seeds. We assumed that observations are taken with two experiments: the CDFS, with a detection limit of $9.1 \times 10^{-18} \text{erg cm}^{-2} \text{s}^{-1}$ at photon energies of $0.5–2 \text{keV}$ over a $5' \times 5'$ FoV, and the proposed Lynx, with a detection limit of $1 \times 10^{-19} \text{erg cm}^{-2} \text{s}^{-1}$ at energies of $0.5–2 \text{keV}$ over a 400 arcmin$^2$ FoV. For Chandra, such observations have been analyzed, so we can test our simulated results with respect to the existing analysis of the CDFS (e.g., Treister et al. 2013; Vito et al. 2013; Weigel et al. 2015), while for deeper observations to be performed by future observatories, our results are of a predictive nature. Our assumption that the redshifts of the observed objects will be known by complementary data at other wavebands guides us to consider only observations performed with instruments allowing high spatial resolution ($\sim 1''$ or better), in order to avoid confusion with other targets in the beam (such as is the case with the XMm-Newton and Athena X-ray observatories, with 6'' and 5'' HPD, respectively; Arnaud et al. 2011; Collon et al. 2014).

We assume that the observed MBHs are past the seeding stage and have commenced coevolution with the host galaxy.
As the MBHs and their hosts evolve toward the scaling relations observed in the local universe, a modified version of the scaling relation is realized at earlier times, which encodes the physics of the seeding mechanism (e.g., Volonteri & Natarajan 2009; Anglés-Alcázar et al. 2013, 2015). After determining for each model the redshift-dependent minimum $r_{\text{min}} \leq r_{\text{circ}}$ of a DM halo that hosts a detectable MBH, we used the Bolshoi $N$-body simulation to estimate the spatial density of detectable sources. We continued with an MC simulation for each model to account for the statistical distributions and uncertainties of the various parameters and constructed the expected X-ray flux distributions to be observed with each X-ray telescope.

We found that the number of high-redshift MBHs with X-ray flux levels above the Chandra confusion limit is of order unity, statistically in agreement with zero observed sources. This is in agreement with the current analysis of CDFS observations, as up to the time of the writing of this paper, there is still no clear and unambiguous detection of a high-redshift MBH. These results clearly demonstrate the limits of current X-ray observatories. When assuming flux limits and FoV identical to the ones anticipated for the proposed Lynx, the number of expected observable MBHs rises considerably. More so, we find that the observed distributions from each family of models varies and allows us to limit the phase space in which the plausible scenario (or scenarios, in case more than one is realized in nature) resides. We studied the expected contribution to the unresolved CXRB in each model and found that in most of the simulated models, the contribution lies below the upper limit set by CDFS measurements, even when considering the observed diminishing contribution from AGNs at low flux levels (Hickox & Markevitch 2006, 2007; Lehmer et al. 2012). Investigating the expected contribution to the CXRB from each model down to the Lynx detection limit suggests that additional constraints are attainable by examining the flux level unaccounted for by resolved point sources.

Our simulated models make various assumptions about physical parameters affecting an MBH birth, evolution, and emission—and while we use theoretically and observationally motivated arguments, the models are by no means exhaustive. As more data is accumulated about SMBHs in both the local and high-redshift universe and a better theoretical understanding is obtained for various seeding and evolution models, one can further refine the underlying assumptions we make when simulating MBH flux and spatial distributions. Nevertheless, the results obtained in this work show the benefits, as well as the limitations, of X-ray observations of MBHs at high redshifts with existing and proposed experiments. The recent discovery of gravitational waves from BH mergers has once again focused interest on the nature and evolution of BHs. While future gravitational-wave observatories—such as LISA, expected to be launched in 2034—will explore rapid events in the evolution of BHs (e.g., mergers), in this work, we have explored what the quasi–steady-state observational signatures expected from MBHs are as they evolve to the SMBHs found at the center of local galaxies. In that way, gravitational-wave experiments and deep high-resolution X-ray observations are complimentary approaches, both being crucial to our understanding of the evolution of the most massive objects known. The two approaches combined will allow us a better understanding of the physical processes responsible for the birth and evolution of SMBHs, which in turn will shed more light (figuratively speaking) on the emergence of structure in the universe less than a billion years after the Big Bang.

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