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Detecting the Birth of Supermassive Black Holes Formed from Heavy Seeds

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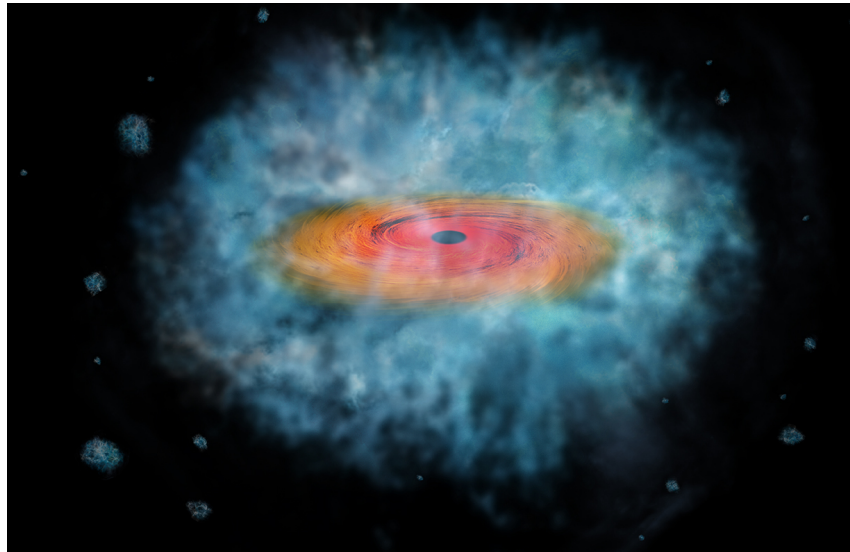
Artistic representation of a heavy black hole seed, formed in the early Universe. Despite numerous theoretical and observational efforts to observe the birth of the first population of black holes, thus far we are still lacking a confirmed detection. The formation of these objects would be among the most spectacular events in the history of the Universe. (Credit: NASA/CXC/M. Weiss)

Introduction

The dawn of the first black holes (and stars) occurred $\sim 100\,\mathrm{Myr}$ after the Big Bang (Barkana and Loeb 2001). It is very remarkable that numerous observations in the past two decades have shown the presence of Super-Massive Black Holes (SMBHs, with masses $10^{9-10}\,\mathrm{M_\odot}$) less than $700\,\mathrm{Myr}$ later (e.g., Fan et al. 2006; Mortlock et al. 2011; Wu et al. 2015; Bañados et al. 2018). A "seed" is the original black hole that, growing via gas accretion and mergers, generates a SMBH. Seeds are categorized in light ($\lesssim 10^2\,\mathrm{M_\odot}$, formed as stellar remnants) and heavy ($\sim 10^4 - 10^6\,\mathrm{M_\odot}$). Heavy objects formed by the direct collapse of primordial gas clouds are named Direct Collapse Black Holes (DCBHs, Haehnelt and Rees 1993; Bromm and Loeb 2003; Lodato and Natarajan 2006).

It is challenging to grow a black hole from a light seed in time to match the observations of SMBHs in the early Universe (Haiman and Loeb 2001; Haiman 2004, see also reviews by Volonteri and Bellovary 2012; Haiman 2013; Woods et al. 2018). Possible solutions to decrease the growth time are: (i) start the growth from heavy seeds (Bromm and Loeb, 2003), and (ii) allow extremely large accretion rates in the high-z Universe (Begelman, 1979; Volonteri and Rees, 2005; Pacucci and Ferrara, 2015; Inayoshi et al., 2016; Pezzulli et al., 2016). Notwithstanding several efforts in theoretical predictions and observations (e.g., Sobral et al. 2015; Pallottini et al. 2015; Pacucci et al. 2015a; Valiante et al. 2018a,b), thus far there is no confirmed detection of any black hole seed. DCBHs may be relatively common in the early universe, with recent work suggesting a comoving number density of $\sim 10^{-6}\,\mathrm{Mpc^{-3}}$ and as high as $\sim 10^{-3}\,\mathrm{Mpc^{-3}}$ in dense regions (Wise et al., 2019). Previous studies which also explored the issue of DCBH formation include Yoshida et al. (2003); Visbal et al. (2014); Chon et al. (2016); Maio et al. (2018); Inayoshi et al. (2018). These theoretical findings highlight the great potential relevance of this formation channel.

DETECTING THE DAWN OF BLACK HOLES

FUTURE OBSERVATORY	IMPORTANCE FOR SEEDS
JWST (LAUNCH: 2021)	• DETECT PEAK EMISSION OF TYPICAL SEEDS • DETECT HEAVILY OBSCURED SEEDS
ATHENA (PLANNED: 2031)	• LARGER FIELD OF VIEW FOR SURVEYS • DETECT COMPTON-THIN SOURCES
LYNX (CONCEPT STUDY)	• HIGHER ANGULAR RESOLUTION • DETECT HEAVILY COMPTON-THICK SOURCES
LISA (PLANNED: 2034)	• UNEQUIVOCALLY DETERMINE MAIN FORMATION CHANNEL OF SEEDS

Figure 1: Overview of future observatories that will detect the dawn of black holes.

Shedding light on the dawn of black holes will be one of the key tasks that the astronomical community will focus on in the next decade. The unknowns in this field are several

and largely unconstrained. *What is the main formation channel? Assuming that both heavy and light seeds were formed, what is their typical formation ratio? What is the peak redshift of their formation?* Investigating the dawn of black holes will have crucial consequences on the theory of galaxy formation/evolution and on gravitational wave astronomy. A better understanding of the initial conditions of this high-z population will provide fundamental clues on its evolution at lower redshifts, down to the local Universe around us. In fact: (i) there is a tight connection between some properties of the host galaxy and the mass of the SMBH at its center (e.g., Kormendy and Ho 2013), and (ii) the progenitors of the merging black holes that we observe via gravitational waves could have formed as high-z light seeds (e.g., Kinugawa et al. 2014).

The formation of SMBHs by the DCBH scenario at $z \gtrsim 10$ is very appealing on many grounds (e.g., Oh and Haiman 2002; Bromm and Loeb 2003; Lodato and Natarajan 2006; Pacucci et al. 2015a). Direct collapse of a gas cloud onto a 10^{4-6} black hole would be among the most spectacular events in the history of the Universe. **In this white paper we address the question of what capabilities are required to identify and study SMBHs formed by heavy seeds in the early Universe.** On similar topics, see the white papers by Natarajan et al. (2019); Haiman et al. (2019).

In the electromagnetic spectrum, infrared and X-ray observations offer the best chances to investigate the dawn of black holes. In fact, while infrared wavelengths probe the spectral region of highest emission, X-ray photons are able to escape from the extremely large column densities that their hosts are predicted to have (e.g., Pacucci and Ferrara 2015). Future observatories in both spectral ranges, like the James Webb Space Telescope (*JWST*), *Athena* and the proposed *Lynx*, will certainly play a major role in unraveling the dawn of black holes (see Fig. 1). The *JWST*, with its impressive angular resolution and a light-collecting area seven times larger than the Hubble Space Telescope (*HST*), will observe the infrared sky farther than ever before. *Athena*, with its large field of view, will be fundamental for X-ray surveys. *Lynx*, with excellent angular resolution, high throughput and spectral resolution for point-like and extended sources, will collect X-ray photons from the most obscured accreting sources in the high-z Universe.

How can we identify $z \gtrsim 10$ heavy seeds?

Currently we probe only the most luminous high-z black holes: $\sim 10^{9-10}\,\mathrm{M_\odot}$ objects at $z \sim 6-7$ (Fan et al. 2006; Mortlock et al. 2011; Bañados et al. 2018). This is clearly the tip of the iceberg of their mass distribution (see e.g. the SHELLQs survey, Matsuoka et al. 2018). Upcoming facilities will revolutionize our view of the early Universe, by probing mass scales $\lesssim 10^6\,\mathrm{M_\odot}$ (Pacucci et al. 2015a; Woods et al. 2018). To exemplify the extent of the observational revolution that we are about to witness, NIRCam onboard the *JWST* will reach $m = 30.5$ at 5σ with an exposure of $\sim 88\,\mathrm{hr}$ (Finkelstein et al., 2015). Depending on the models and on the brightness of the host galaxy, this will enable the detection of objects of $\sim 10^{5-6}\,\mathrm{M_\odot}$ at $z \gtrsim 10$. These capabilities will open up, for the first time in history, the window to the dawn of black holes.

In order to observationally identify heavy seeds it is thus crucially important to understand the observational signatures that we are seeking. **To obtain an unequivocal detection of heavy seeds we need to probe mass scales of** $\sim 10^{5-6}\,\mathrm{M_\odot}$ **at redshift** $z \gtrsim 10$. Observing them early in their evolution (i.e., at birth or soon after) is crucial: once a black hole has evolved from its original seed, the initial conditions are rapidly deleted and become undetectable (Valiante et al., 2018a).

The observational methodologies proposed can be divided in *direct* and *indirect*. A direct method affirms, within some error margin, whether a source is a heavy black hole seed or not. An indirect method, instead, looks at a group of objects and infer whether it is likely that at least a

fraction of them originated from heavy seeds. In this white paper we focus on direct methods. See Haiman et al. (2019) for a review of indirect methods.

The next generation of telescopes will provide an unprecedented number of high-quality spectra. Thus, it is important to understand the spectral signatures of heavy seeds. Pacucci et al. (2015a) presented the first, accurate study of spectral templates (continuum + lines) for heavy seeds, spanning from the sub-mm to the X-ray (see Fig. 2). For a typical heavy seed, buried under very large absorbing column densities, the emission occurs in the observed infrared-submm ($1 - 1000 \, \mu m$) and X-ray ($0.1 - 100 \, \mathrm{keV}$) bands. These sources feature a very steep spectrum in the infrared, because much of the radiation emitted by the central source is reprocessed at lower energies by the intervening matter (Pacucci et al., 2016). At the fiducial redshift $z = 10$, the signal generated by a heavy seeds will be easily detectable by the *JWST* at a mass scale $\sim 10^5 - 10^6 \, \mathrm{M_\odot}$, while *Lynx* will go down to $\sim 10^4 \, \mathrm{M_\odot}$; *Athena* will be able to detect these sources down to a mass scale $\sim 10^6 \, \mathrm{M_\odot}$. Thanks to its higher angular resolution, images from *Lynx* will also be affected by a lower source confusion due to foreground objects. All the aforementioned estimates assume a Compton-thin irradiation scenario. In fact, as shown in several studies (e.g., Pacucci et al. 2017; Valiante et al. 2018b) the spectrum depends on multiple parameters: (i) black hole mass, (ii) column density and gas metallicity of the host, (iii) presence of stars. Pacucci et al. (2015a); Natarajan et al. (2017) indicate that heavy seeds will be primary targets for all these upcoming facilities.

Additional observational signatures of $z \gtrsim 10$ heavy seeds may come from the very large absorbing column density of their host galaxies (e.g., Pacucci and Ferrara 2015; Latif et al. 2013; Begelman and Volonteri 2017). In fact, column densities comparable to or well in excess of the Compton-thick limit ($N_H \sim 1.5 \times 10^{24} \, \mathrm{cm^{-2}}$) may be reached during the formation of the seed, or shortly after for periods of $\sim 100 \, \mathrm{Myr}$ (Pacucci et al., 2015b). The effects of large absorbing column densities are: (i) X-ray fluxes in the soft and in the hard bands ($0.5 - 10 \, \mathrm{keV}$) are significantly reduced by factors up to ~ 100 for extreme values of the column density ($N_H \gtrsim 10^{25} \, \mathrm{cm^{-2}}$), and (ii) X-ray photons are re-emitted in the infrared bands, due to Auger-like cascade effects (Pacucci et al., 2015a). In summary, the increase in column density to values $N_H \gtrsim 1.5 \times 10^{24} \, \mathrm{cm^{-2}}$ causes a decrease in the X-ray emission and an increase in the infrared emission. Supported by radiation-hydrodynamical simulations, Pacucci et al. (2015a); Natarajan et al. (2017) suggest that extremely absorbed heavy seeds will have a ratio of X-ray flux to optical flux $F_X/F_{444 \, \text{Å}} \gg 1$, and a ratio of X-ray flux to infrared flux $F_X/F_{1 \, \mu m} \ll 1$.

Additional probes are available if future instruments will detect not only the central black hole, but also its host galaxy. For instance, Agarwal et al. (2013); Visbal and Haiman (2018), utilizing a cosmological N-body simulation, show that before the $\sim 10^5 \, \mathrm{M_\odot}$ DCBH at $z \gtrsim 10$ grows to $\sim 10^6 \, \mathrm{M_\odot}$, it will have a black hole mass to halo mass ratio larger than expected for remnants of Pop III stars, grown to the same mass. Thus, a combination of infrared and X-ray observations will be able to distinguish high-z DCBHs from lighter seeds due to this peculiarly large ratio.

What observational capabilities do we need to detect $z \gtrsim 10$ heavy seeds?

Any effort to detect $z \gtrsim 10$ heavy seeds will likely need a pre-selection of sources with observational properties meeting some criteria. In this regard, a blind X-ray survey will play a fundamental role. The final confirmation of the heavy seed nature of a $z \gtrsim 10$ source will eventually need a high-resolution spectrum showing high-ionization lines and no metal lines. Pacucci et al. (2016) introduced a photometric selection criteria for heavy seeds, leading to the first identification of
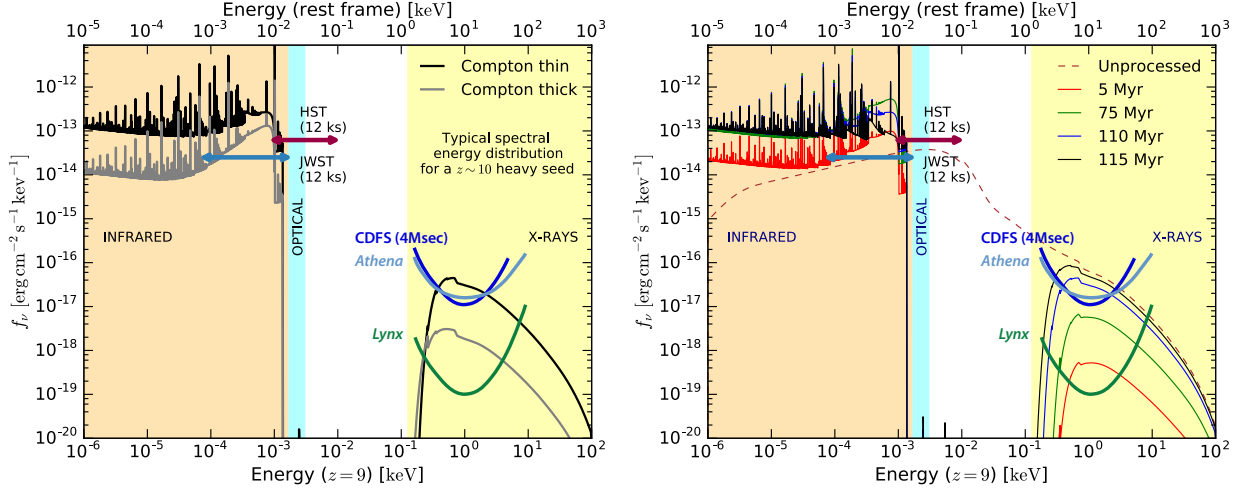
Figure 2: Spectral predictions for a typical heavy seed. The flux limits for future/proposed (*JWST*, *Athena*, *Lynx*) and current (*HST*, *Chandra*) observatories are shown. **Left:** Spectral predictions are shown at peak infrared emission and in the Compton thin and Compton thick cases. **Right:** Spectral predictions are shown at different times during the seed evolution. The unprocessed spectrum refers to the radiation emitted by the central source and not processed by the host galaxy. Adapted from Pacucci et al. 2015a.

$z > 6$ candidates. The criteria arise from the observation that the infrared spectral energy distribution of seeds is predicted to be significantly steeper when compared to other high-z sources. Other works extended this study (Natarajan et al., 2017; Volonteri et al., 2017). For instance, Valiante et al. (2018b) introduced a careful modeling of the metallicity and dust evolution of the hosts. Their improved selection method employs a combined analysis of near-infrared colours, infrared excess, and ultraviolet continuum slopes to distinguish host galaxies with growing heavy seeds from starburst-dominated systems in *JWST* surveys. The search for heavy seeds thus far is limited to the GOODS-S field, spanning $\sim 800 \, \mathrm{arcmin}^2$, leading to 2 candidates and the prediction of finding $\lesssim 10$ (Natarajan et al., 2017). Applying the same criteria to larger surveys ($\gtrsim 1 \deg^{-2}$) will allow the detection of significantly more candidates, building the first census and opening the way to follow-up spectroscopic observations with the *JWST*. A major role in the search for candidates will be played by *WFIRST*. Below we review the observational requirements and how they compare with planned instruments (see Fig. 1).

Near Infrared: Employing radiation-hydrodynamic simulations, several studies have shown that the peak emission for a typical heavy seed at $z \gtrsim 10$ falls in the near-infrared, at $\approx 1 \, \mu\mathrm{m}$ (Pacucci et al., 2015a; Inayoshi et al., 2016; Natarajan et al., 2017; Valiante et al., 2018b). This fact is true under very general conditions, i.e. independently of the time elapsed from the formation of the seed, of the environmental metallicity and of the specifics of the accretion. The same studies show that the luminosity of a typical heavy seed varies wildly depending on the aforementioned parameters. It is very challenging to define the "expected luminosity" of a high-z seed, as we are dealing with massively active, and thus rapidly varying, sources. Overall, to observe a $10^5 \, \mathrm{M_\odot}$ heavy seed at $z \gtrsim 10$ in the middle of its lifespan ($\sim 100 \, \mathrm{Myr}$) and assuming a Compton-thin scenario, we need to reach a flux density of at least $10^{-16} \, \mathrm{erg \, s^{-1} \, cm^{-2}}$. This depth is very well achieved by the planned specifications of *JWST*, expected to reach a flux density limit

$\approx 3 \times 10^{-17}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$ for a $10\,\mathrm{ks}$ exposure at $\sim 1\,\mu\mathrm{m}$. Assuming we can observe any DCBHs accreting at $z \gtrsim 10$ producing a flux density $\gtrsim 3 \times 10^{-17}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$, we calculate how many sources of this kind we expect to observe with *JWST*. The predicted number density of DCBHs widely varies in the range $\sim 10^{-10} - 10^{-1}\,\mathrm{Mpc^{-3}}$ at $z \sim 10$ (Habouzit et al., 2016). The extreme span in the predictions is mainly due to the uncertainties on the critical external Lyman-Werner radiation field strength that can fully suppress the H_2 formation. Employing intermediate values for the number density (Agarwal et al., 2012; Habouzit et al., 2016), we obtain a number of DCBHs detectable with *JWST* at $z \gtrsim 10$ of $1 - 10\,\mathrm{deg^{-2}}$. Assuming more optimistic values for the number density of DCBHs, this prediction would increase by several orders of magnitude.

X-rays: High-energy spectral predictions for typical heavy seeds (Pacucci et al., 2015a; Valiante et al., 2018b) need to take into account the fundamental variable of the column density of the host. In general, the X-ray emission is predicted to be bell-shaped, with a peak at $\sim 1\,\mathrm{keV}$ in the observed frame at $z \sim 10$ and rapidly fading at $\lesssim 0.1\,\mathrm{keV}$. For Compton-thin sources the minimum requirement to observe a $z \gtrsim 10$ DCBH is a flux density $10^{-16}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$, (Valiante et al., 2018b) which is well contemplated by the flux limit of *Athena* (Aird et al., 2013). For Compton-thick sources ($N_H \gtrsim 1.5 \times 10^{24}\,\mathrm{cm^{-2}}$) instead, more sensitive instruments will be needed, able to reach sources at least $1 - 2$ orders of magnitude fainter (Pacucci et al., 2015a). Flux limits of $\sim 10^{-19}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$ are expected to be provided by *Lynx* (Lynx Team, 2018). In fact, future X-ray missions will play a key role in unraveling the dawn of black holes, especially its most obscured components. Employing again intermediate values for the number density of DCBHs, with *Lynx* we expect to observe $5 - 50\,\mathrm{deg^{-2}}$ sources of this kind at $z \gtrsim 10$. As already mentioned in the infrared case, larger values for the number density of DCBHs would lead to a significantly higher prediction for the number of detectable sources. X-ray and infrared observations are fully synergetic in the study of the dawn of black holes. While infrared bands are invaluable to study the spectral energy distribution and emission lines of high-z sources, X-ray observations will provide crucial insights into their emission mechanisms. Consequently, a high-sensitivity observatory as *JWST* needs to be complemented with equally sensitive high-energy observatories (e.g., *Athena* and *Lynx*) to efficiently study the dawn of black holes. Moreover, a high-sensitivity instrument such as *Lynx* could be able to detect heavy seeds at slightly lower mass scales ($\sim 10^5\,\mathrm{M_\odot}$) when compared to *JWST* (Pacucci et al., 2015a), and for a longer period of time in the evolution of the seed (see Fig. 2, right panel).

Gravitational Waves: Gravitational waves observations will be fundamental to gain a clear view of the population of black hole seeds at $z \gtrsim 10$. According to its technical specifications (e.g. Klein et al. 2016), *LISA* will be able to detect the merger of $\sim 10^5\,\mathrm{M_\odot}$ black hole seeds at $z \gtrsim 8$ with a signal-to-noise ratio of ~ 200. Latest predictions (Ricarte and Natarajan, 2018) suggest that *LISA* should be able to detect the merger of $\sim 10^5\,\mathrm{M_\odot}$ heavy seeds in the number of $2 - 20$ in about 4 years of operations (see also e.g. Sesana et al. 2004, 2007; Tanaka and Haiman 2009). Although gravitational waves observations are invaluable to discriminate between seeding models, only synergetic observations in the electromagnetic realm (e.g., with *JWST*, *Lynx*, *Athena*) will provide crucial insights on their formation and growth processes.

To conclude, detecting heavy black hole seeds at $z \gtrsim 10$ in the next decade will be challenging but, according to current theoretical models, feasible with upcoming and/or proposed facilities. Their detection will be fundamental to understand the early history of the Universe, as well as its evolution until now.

References

B. Agarwal, S. Khochfar, J. L. Johnson, E. Neistein, C. Dalla Vecchia, and M. Livio. Ubiquitous seeding of supermassive black holes by direct collapse. *MNRAS*, 425:2854–2871, Oct. 2012. doi: 10.1111/j.1365-2966.2012.21651.x. URL http://adsabs.harvard.edu/abs/2012MNRAS.425.2854A.

B. Agarwal, A. J. Davis, S. Khochfar, P. Natarajan, and J. S. Dunlop. Unravelling obese black holes in the first galaxies. *MNRAS*, 432:3438–3444, July 2013. doi: 10.1093/mnras/stt696. URL https://ui.adsabs.harvard.edu/#abs/2013MNRAS.432.3438A.

J. Aird, A. Comastri, M. Brusa, N. Cappelluti, A. Moretti, E. Vanzella, M. Volonteri, D. Alexander, J. M. Afonso, F. Fiore, I. Georgantopoulos, K. Iwasawa, A. Merloni, K. Nandra, R. Salvaterra, M. Salvato, P. Severgnini, K. Schawinski, F. Shankar, C. Vignali, and F. Vito. The Hot and Energetic Universe: The formation and growth of the earliest supermassive black holes. *arXiv e-prints*, art. arXiv:1306.2325, June 2013. URL https://ui.adsabs.harvard.edu/#abs/2013arXiv1306.2325A.

E. Bañados, B. P. Venemans, C. Mazzucchelli, E. P. Farina, F. Walter, F. Wang, R. Decarli, D. Stern, X. Fan, F. B. Davies, J. F. Hennawi, R. A. Simcoe, M. L. Turner, H.-W. Rix, J. Yang, D. D. Kelson, G. C. Rudie, and J. M. Winters. An 800-million-solar-mass black hole in a significantly neutral Universe at a redshift of 7.5. *Nature*, 553:473–476, Jan. 2018. doi: 10.1038/nature25180. URL https://ui.adsabs.harvard.edu/#abs/2018Natur.553..473B.

R. Barkana and A. Loeb. In the beginning: the first sources of light and the reionization of the universe. *Physical Reports*, 349:125–238, July 2001. doi: 10.1016/S0370-1573(01)00019-9. URL http://adsabs.harvard.edu/abs/2001PhR...349..125B.

M. C. Begelman. Can a spherically accreting black hole radiate very near the Eddington limit? *MNRAS*, 187:237–251, Apr 1979. doi: 10.1093/mnras/187.2.237.

M. C. Begelman and M. Volonteri. Hyperaccreting black holes in galactic nuclei. *MNRAS*, 464:1102–1107, Jan. 2017. doi: 10.1093/mnras/stw2446. URL https://ui.adsabs.harvard.edu/#abs/2017MNRAS.464.1102B.

V. Bromm and A. Loeb. Formation of the First Supermassive Black Holes. *ApJ*, 596:34–46, Oct. 2003. doi: 10.1086/377529. URL http://adsabs.harvard.edu/abs/2003ApJ...596...34B.

S. Chon, S. Hirano, T. Hosokawa, and N. Yoshida. Cosmological Simulations of Early Black Hole Formation: Halo Mergers, Tidal Disruption, and the Conditions for Direct Collapse. *ApJ*, 832: 134, Dec. 2016. doi: 10.3847/0004-637X/832/2/134. URL http://adsabs.harvard.edu/abs/2016ApJ...832..134C.

X. Fan et al. A Survey of z≳5.7 Quasars in the Sloan Digital Sky Survey. IV. Discovery of Seven Additional Quasars. *AJ*, 131:1203–1209, Mar. 2006. doi: 10.1086/500296. URL http://adsabs.harvard.edu/abs/2006AJ....131.1203F.

S. L. Finkelstein, J. Dunlop, O. Le Fevre, and S. Wilkins. The Case for a James Webb Space Telescope Extragalactic Key Project. *arXiv e-prints*, art. arXiv:1512.04530, Dec. 2015. URL https://ui.adsabs.harvard.edu/#abs/2015arXiv151204530F.

M. Habouzit, M. Volonteri, M. Latif, Y. Dubois, and S. Peirani. On the number density of 'direct collapse' black hole seeds. *MNRAS*, 463:529–540, Nov. 2016. doi: 10.1093/mnras/stw1924. URL https://ui.adsabs.harvard.edu/#abs/2016MNRAS.463..529H.

M. G. Haehnelt and M. J. Rees. The formation of nuclei in newly formed galaxies and the evolution of the quasar population. *MNRAS*, 263:168–178, July 1993. doi: 10.1093/mnras/263.1.168. URL http://adsabs.harvard.edu/abs/1993MNRAS.263..168H.

Z. Haiman. Constraints from Gravitational Recoil on the Growth of Supermassive Black Holes at High Redshift. *ApJ*, 613:36–40, Sept. 2004. doi: 10.1086/422910. URL http://adsabs.harvard.edu/abs/2004ApJ...613...36H.

Z. Haiman. The Formation of the First Massive Black Holes. In T. Wiklind, B. Mobasher, and V. Bromm, editors, *Astrophysics and Space Science Library*, volume 396 of *Astrophysics and Space Science Library*, page 293, 2013. doi: 10.1007/978-3-642-32362-1-6. URL http://adsabs.harvard.edu/abs/2013ASSL..396..293H.

Z. Haiman and A. Loeb. What Is the Highest Plausible Redshift of Luminous Quasars? *ApJ*, 552: 459–463, May 2001. doi: 10.1086/320586. URL http://adsabs.harvard.edu/abs/2001ApJ...552..459H.

Z. Haiman et al. Electromagnetic Window into the Dawn of Black Holes, 2019.

K. Inayoshi, Z. Haiman, and J. P. Ostriker. Hyper-Eddington accretion flows on to massive black holes. *MNRAS*, 459:3738–3755, July 2016. doi: 10.1093/mnras/stw836. URL https://ui.adsabs.harvard.edu/#abs/2016MNRAS.459.3738I.

K. Inayoshi, M. Li, and Z. Haiman. Massive black hole and Population III galaxy formation in overmassive dark-matter haloes with violent merger histories. *MNRAS*, 479:4017–4027, Sept. 2018. doi: 10.1093/mnras/sty1720. URL http://adsabs.harvard.edu/abs/2018MNRAS.479.4017I.

T. Kinugawa, K. Inayoshi, K. Hotokezaka, D. Nakauchi, and T. Nakamura. Possible indirect confirmation of the existence of Pop III massive stars by gravitational wave. *MNRAS*, 442: 2963–2992, Aug. 2014. doi: 10.1093/mnras/stu1022. URL http://adsabs.harvard.edu/abs/2014MNRAS.442.2963K.

A. Klein, E. Barausse, A. Sesana, A. Petiteau, E. Berti, S. Babak, J. Gair, S. Aoudia, I. Hinder, F. Ohme, and B. Wardell. Science with the space-based interferometer eLISA: Supermassive black hole binaries. *Physical Review D*, 93(2):024003, Jan. 2016. doi: 10.1103/PhysRevD.93. 024003. URL http://adsabs.harvard.edu/abs/2016PhRvD..93b4003K.

J. Kormendy and L. C. Ho. Coevolution (Or Not) of Supermassive Black Holes and Host Galaxies. *Annual Review of Astronomy and Astrophysics*, 51:511–653, Aug. 2013. doi:

10.1146/annurev-astro-082708-101811. URL https://ui.adsabs.harvard.edu/#abs/2013ARA&A..51..511K.

M. A. Latif, D. R. G. Schleicher, W. Schmidt, and J. Niemeyer. Black hole formation in the early Universe. *MNRAS*, 433:1607–1618, Aug. 2013. doi: 10.1093/mnras/stt834. URL http://adsabs.harvard.edu/abs/2013MNRAS.433.1607L.

G. Lodato and P. Natarajan. Supermassive black hole formation during the assembly of pre-galactic discs. *MNRAS*, 371:1813–1823, Oct. 2006. doi: 10.1111/j.1365-2966.2006.10801.x. URL http://adsabs.harvard.edu/abs/2006MNRAS.371.1813L.

Lynx Team. The Lynx Mission Concept Study Interim Report. *arXiv e-prints*, art. arXiv:1809.09642, Sept. 2018. URL https://ui.adsabs.harvard.edu/#abs/2018arXiv180909642T.

U. Maio, S. Borgani, B. Ciardi, and M. Petkova. The seeds of supermassive black holes and the role of local radiation and metal spreading. *arXiv e-prints*, Nov. 2018. URL http://adsabs.harvard.edu/abs/2018arXiv181101964M.

Y. Matsuoka et al. Subaru High-z Exploration of Low-luminosity Quasars (SHELLQs). IV. Discovery of 41 Quasars and Luminous Galaxies at $5.7 \leq z \leq 6.9$. *The Astrophysical Journal Supplement Series*, 237:5, Jul 2018. doi: 10.3847/1538-4365/aac724.

D. J. Mortlock, S. J. Warren, B. P. Venemans, M. Patel, P. C. Hewett, R. G. McMahon, C. Simpson, T. Theuns, E. A. Gonzáles-Solares, A. Adamson, S. Dye, N. C. Hambly, P. Hirst, M. J. Irwin, E. Kuiper, A. Lawrence, and H. J. A. Röttgering. A luminous quasar at a redshift of z = 7.085. *Nature*, 474:616–619, June 2011. doi: 10.1038/nature10159. URL http://adsabs.harvard.edu/abs/2011Natur.474..616M.

P. Natarajan, F. Pacucci, A. Ferrara, B. Agarwal, A. Ricarte, E. Zackrisson, and N. Cappelluti. Unveiling the First Black Holes With JWST:Multi-wavelength Spectral Predictions. *ApJ*, 838: 117, Apr. 2017. doi: 10.3847/1538-4357/aa6330. URL http://adsabs.harvard.edu/abs/2017ApJ...838..117N.

P. Natarajan et al. Disentangling nature from nurture: tracing the origin of seed black holes, 2019.

S. P. Oh and Z. Haiman. Second-Generation Objects in the Universe: Radiative Cooling and Collapse of Halos with Virial Temperatures above 10^4 K. *ApJ*, 569:558–572, Apr 2002. doi: 10.1086/339393.

F. Pacucci and A. Ferrara. Simulating the growth of Intermediate Mass Black Holes. *MNRAS*, 448: 104–118, Mar. 2015. doi: 10.1093/mnras/stv018. URL http://adsabs.harvard.edu/abs/2015MNRAS.448..104P.

F. Pacucci, A. Ferrara, M. Volonteri, and G. Dubus. Shining in the dark: the spectral evolution of the first black holes. *MNRAS*, 454:3771–3777, Dec. 2015a. doi: 10.1093/mnras/stv2196. URL http://adsabs.harvard.edu/abs/2015MNRAS.454.3771P.

F. Pacucci, M. Volonteri, and A. Ferrara. The growth efficiency of high-redshift black holes. *MNRAS*, 452:1922–1933, Sept. 2015b. doi: 10.1093/mnras/stv1465. URL http://adsabs.harvard.edu/abs/2015MNRAS.452.1922P.

F. Pacucci, A. Ferrara, A. Grazian, F. Fiore, E. Giallongo, and S. Puccetti. First identification of direct collapse black hole candidates in the early Universe in CANDELS/GOODS-S. *MNRAS*, 459:1432–1439, June 2016. doi: 10.1093/mnras/stw725. URL https://ui.adsabs.harvard.edu/#abs/2016MNRAS.459.1432P.

F. Pacucci, A. Pallottini, A. Ferrara, and S. Gallerani. The nature of the Lyman α emitter CR7: a persisting puzzle. *MNRAS*, 468:L77–L81, June 2017. doi: 10.1093/mnrasl/slx029. URL http://adsabs.harvard.edu/abs/2017MNRAS.468L..77P.

A. Pallottini, A. Ferrara, F. Pacucci, S. Gallerani, S. Salvadori, R. Schneider, D. Schaerer, D. Sobral, and J. Matthee. The brightest Ly α emitter: Pop III or black hole? *MNRAS*, 453:2465–2470, Nov. 2015. doi: 10.1093/mnras/stv1795. URL http://adsabs.harvard.edu/abs/2015MNRAS.453.2465P.

E. Pezzulli, R. Valiante, and R. Schneider. Super-Eddington growth of the first black holes. *MNRAS*, 458:3047–3059, May 2016. doi: 10.1093/mnras/stw505.

A. Ricarte and P. Natarajan. The observational signatures of supermassive black hole seeds. *MNRAS*, 481:3278–3292, Dec. 2018. doi: 10.1093/mnras/sty2448. URL https://ui.adsabs.harvard.edu/#abs/2018MNRAS.481.3278R.

A. Sesana, F. Haardt, P. Madau, and M. Volonteri. Low-Frequency Gravitational Radiation from Coalescing Massive Black Hole Binaries in Hierarchical Cosmologies. *ApJ*, 611:623–632, Aug 2004. doi: 10.1086/422185.

A. Sesana, M. Volonteri, and F. Haardt. The imprint of massive black hole formation models on the LISA data stream. *MNRAS*, 377:1711–1716, June 2007. doi: 10.1111/j.1365-2966.2007.11734.x. URL http://adsabs.harvard.edu/abs/2007MNRAS.377.1711S.

D. Sobral, J. Matthee, B. Darvish, D. Schaerer, B. Mobasher, H. J. A. Röttgering, S. Santos, and S. Hemmati. Evidence for PopIII-like Stellar Populations in the Most Luminous Lyman-α Emitters at the Epoch of Reionization: Spectroscopic Confirmation. *ApJ*, 808:139, Aug. 2015. doi: 10.1088/0004-637X/808/2/139. URL http://adsabs.harvard.edu/abs/2015ApJ...808..139S.

T. Tanaka and Z. Haiman. The Assembly of Supermassive Black Holes at High Redshifts. *ApJ*, 696:1798–1822, May 2009. doi: 10.1088/0004-637X/696/2/1798. URL http://adsabs.harvard.edu/abs/2009ApJ...696.1798T.

R. Valiante, R. Schneider, L. Graziani, and L. Zappacosta. Chasing the observational signatures of seed black holes at z ¿ 7: candidate statistics. *MNRAS*, 474:3825–3834, Mar. 2018a. doi: 10.1093/mnras/stx3028.

R. Valiante, R. Schneider, L. Zappacosta, L. Graziani, E. Pezzulli, and M. Volonteri. Chasing the observational signatures of seed black holes at z > 7: candidate observability. *MNRAS*, 476: 407–420, May 2018b. doi: 10.1093/mnras/sty213. URL https://ui.adsabs.harvard.edu/#abs/2018MNRAS.476..407V.

E. Visbal and Z. Haiman. Identifying Direct Collapse Black Hole Seeds through Their Small Host Galaxies. *ApJ*, 865:L9, Sept. 2018. doi: 10.3847/2041-8213/aadf3a. URL https://ui.adsabs.harvard.edu/#abs/2018ApJ...865L...9V.

E. Visbal, Z. Haiman, and G. L. Bryan. Direct collapse black hole formation from synchronized pairs of atomic cooling haloes. *MNRAS*, 445:1056–1063, Nov. 2014. doi: 10.1093/mnras/stu1794. URL http://adsabs.harvard.edu/abs/2014MNRAS.445.1056V.

M. Volonteri and J. Bellovary. Black holes in the early Universe. *Reports on Progress in Physics*, 75(12):124901, Dec. 2012. doi: 10.1088/0034-4885/75/12/124901. URL http://adsabs.harvard.edu/abs/2012RPPh...75l4901V.

M. Volonteri and M. J. Rees. Rapid Growth of High-Redshift Black Holes. *ApJ*, 633:624–629, Nov. 2005. doi: 10.1086/466521. URL http://adsabs.harvard.edu/abs/2005ApJ...633..624V.

M. Volonteri, A. E. Reines, H. Atek, D. P. Stark, and M. Trebitsch. High-redshift Galaxies and Black Holes Detectable with the JWST: A Population Synthesis Model from Infrared to X-Rays. *ApJ*, 849:155, Nov. 2017. doi: 10.3847/1538-4357/aa93f1. URL https://ui.adsabs.harvard.edu/#abs/2017ApJ...849..155V.

J. H. Wise, J. A. Regan, B. W. O'Shea, M. L. Norman, T. P. Downes, and H. Xu. Formation of massive black holes in rapidly growing pre-galactic gas clouds. *arXiv e-prints*, art. arXiv:1901.07563, Jan. 2019. URL https://ui.adsabs.harvard.edu/#abs/2019arXiv190107563W.

T. E. Woods et al. Titans of the Early Universe: The Prato Statement on the Origin of the First Supermassive Black Holes. *arXiv e-prints*, art. arXiv:1810.12310, Oct. 2018. URL https://ui.adsabs.harvard.edu/#abs/2018arXiv181012310W.

X.-B. Wu, F. Wang, X. Fan, W. Yi, W. Zuo, F. Bian, L. Jiang, I. D. McGreer, R. Wang, J. Yang, Q. Yang, D. Thompson, and Y. Beletsky. An ultraluminous quasar with a twelve-billion-solar-mass black hole at redshift 6.30. *Nature*, 518:512–515, Feb. 2015. doi: 10.1038/nature14241. URL http://adsabs.harvard.edu/abs/2015Natur.518..512W.

N. Yoshida, T. Abel, L. Hernquist, and N. Sugiyama. Simulations of Early Structure Formation: Primordial Gas Clouds. *ApJ*, 592:645–663, Aug. 2003. doi: 10.1086/375810. URL http://adsabs.harvard.edu/abs/2003ApJ...592..645Y.