

SUPERMASSIVE SEEDS FOR SUPERMASSIVE BLACK HOLES

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ABSTRACT

Recent observations of quasars powered by supermassive black holes (SMBHs) out to $z \gtrsim 7$ constrain both the initial seed masses and the growth of the most massive black holes (BHs) in the early universe. Here we elucidate the implications of the radiative feedback from early generations of stars and from BH accretion for popular models for the formation and growth of seed BHs. We show that by properly accounting for (1) the limited role of mergers in growing seed BHs as inferred from cosmological simulations of early star formation and radiative feedback, (2) the sub-Eddington accretion rates of BHs expected at the earliest times, and (3) the large radiative efficiencies ϵ of the most massive BHs inferred from observations of active galactic nuclei at high redshift ($\epsilon \gtrsim 0.1$), we are led to the conclusion that the initial BH seeds may have been as massive as $\gtrsim 10^5 M_\odot$. This presents a strong challenge to the Population III seed model, which calls for seed masses of $\sim 100 M_\odot$ and, even with constant Eddington-limited accretion, requires $\epsilon \lesssim 0.09$ to explain the highest- z SMBHs in today's standard Λ CDM cosmological model. It is, however, consistent with the prediction of the direct collapse scenario of SMBH seed formation, in which a supermassive primordial star forms in a region of the universe with a high molecule-dissociating background radiation field, and collapses directly into a 10^4 – $10^6 M_\odot$ seed BH. These results corroborate recent cosmological simulations and observational campaigns which suggest that these massive BHs were the seeds of a large fraction of the SMBHs residing in the centers of galaxies today.

Key words: accretion, accretion disks – black hole physics – cosmology: theory – early universe – quasars: general – radiation mechanisms: general

Online-only material: color figures

1. INTRODUCTION

What is the origin of the supermassive black holes (SMBHs) that power the most distant quasars? There are currently three main scenarios for the formation of the initial “seed” black holes (BHs) from which these SMBHs grew (e.g., Haiman 2009, 2012; Natarajan 2011; Volonteri 2010, 2012): (1) massive Population (Pop) III seeds, which form from the collapse of ~ 30 – $300 M_\odot$ primordial stars in dark matter (DM) minihalos with total masses of $\sim 10^5$ – $10^6 M_\odot$ at redshifts $z \gtrsim 20$ (e.g., Madau & Rees 2001); (2) supermassive stellar remnant seeds, which form with initial masses of 10^4 – $10^6 M_\odot$ from the direct collapse of $\sim 10^4$ K primordial gas in atomic cooling DM halos with total masses of $\sim 10^7$ – $10^8 M_\odot$ at $z \gtrsim 10$ (e.g., Bromm & Loeb 2003); (3) and seeds formed from the collapse of $\sim 10^3 M_\odot$ stars created in runaway collisions in dense stellar clusters at $z \sim 10$ – 20 (e.g., Devecchi & Volonteri 2009; Davies et al. 2011).

Distinguishing between these three scenarios poses significant challenges, in large part because the high- z regime in which these seed BHs are born is too distant to be probed directly by existing facilities. However, significant progress has been made in detecting $\gtrsim 10^9 M_\odot$ SMBHs powering quasars at $z \gtrsim 6$, the existence of which provides significant constraints on the nature and growth of their BH seeds (e.g., Willott et al. 2003; Fan 2006). The strongest constraints to date come from the $\sim 2 \times 10^9 M_\odot$ SMBH inferred to be powering a quasar at $z = 7.085$ (Mortlock et al. 2011). Given the $\lesssim 800$ Myr available for the growth of such a massive BH, only the most optimistic models can explain their origin from $\sim 100 M_\odot$ Pop III seeds,

suggesting that more massive seeds may have a role to play (e.g., Baumgarte & Shapiro 1999; Tyler et al. 2003; Shapiro 2005; Volonteri & Rees 2006; Tanaka et al. 2012).

Also consistent with supermassive seeds are observations of high- z quasars powered by SMBHs that are very massive compared to the stellar component of their host galaxies (e.g., Wang et al. 2010, 2013; Willott et al. 2013), much more so than would be predicted following the observed relation in the local universe (e.g., Ferrarese & Merritt 2000; Gebhart et al. 2000; but see van den Bosch et al. 2012 for a notable exception).⁴ As discussed by Agarwal et al. (2013), such relatively massive BHs in early galaxies are easily accommodated in the supermassive star (SMS) seed model.

At the same time, a growing body of theoretical work is providing renewed support for the long-standing supermassive stellar remnant model (e.g., Fowler & Hoyle 1964; Appenzeller & Fricke 1972; Shapiro & Teukolsky 1979; Bond et al. 1984). In particular, there are now strong suggestions that the conditions required for the formation of SMSs may be satisfied more often in the early universe than previously assumed (Wise et al. 2008; Regan & Haehnelt 2009; Sethi et al. 2010; Shang et al. 2010; Bellovary et al. 2011; Wolcott-Green et al. 2011; Agarwal et al. 2012; Inayoshi & Omukai 2012; Johnson et al. 2013; Latif et al. 2013a, 2013b; Petri et al. 2012; Choi et al. 2013; Prieto et al. 2013; van Borm & Spaans 2013). In addition, modeling the evolution of rapidly accreting SMSs (e.g., Begelman 2010; Hosokawa et al. 2012; Inayoshi et al. 2013) and the radiative feedback they exert during their growth (Johnson et al. 2012; but see also Dotan & Shaviv 2012) shows that they can attain masses

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⁴ Interestingly, there is also some observational evidence that local BHs may have been seeded by direct collapse (Greene 2012).

$\gtrsim 10^5 M_\odot$ before collapsing to BHs. These massive BH seeds could in principle grow to SMBHs much more quickly than $10\text{--}10^3 M_\odot$ seeds. This is especially true in light of numerous other recent theoretical (e.g., Volonteri et al. 2005; Pelupessy et al. 2007; Alvarez et al. 2009; Milosavljević et al. 2009a; Noble et al. 2009; Park & Ricotti 2011, 2012, 2013; Jeon et al. 2012) and observational (e.g., Elvis et al. 2002; Wang et al. 2006, 2009; Davis & Laor 2011; Bambi 2012; Li et al. 2012) results which suggest that accretion onto BHs in the early universe was suppressed due to radiative feedback.

Here we examine the limits that can be placed on the initial seed masses and growth of the most massive high- z BHs, by accounting for the radiative feedback from early stellar generations and from the accretion of gas onto these BHs. In the next section we show that adopting appropriate initial Pop III seed DM halo masses and accounting for the limited production of Pop III seeds due to the Lyman–Werner (LW) background radiation field allows us to conclude that mergers play only a small role in the growth of the most massive BHs at high- z . In Section 3 we survey the possible range of time-averaged growth rates and radiative efficiencies of high- z SMBHs in the context of growth solely via gas accretion. In Section 4 we discuss how local radiative feedback from both accreting BHs and their progenitor stars acts to limit the rate of growth of Pop III seed BHs and, in particular, hinders the growth of the least massive BHs. Finally, we discuss the implications for the main models of seed formation in Section 5, and we summarize our results in Section 6.

2. LIMITED GROWTH VIA MERGERS DUE TO GLOBAL LYMAN–WERNER FEEDBACK

Here we make a simple, but novel, argument for why the role of mergers in growing the most massive high- z BHs must be limited, in part, due to global molecule-dissociating, LW radiative feedback. This will allow us to dramatically simplify our discussion of SMBH growth in the early universe in later sections, by focusing solely on growth via gas accretion.

Many previous works have examined the possibility of SMBHs growing from Pop III seeds via mergers and gas accretion (Menou et al. 2001; Haehnelt 2003; Islam et al. 2003; Yoo & Miralda-Escudé 2004; Volonteri et al. 2003, 2005; Tanaka & Haiman 2009). If sufficient mass can be locked up in the seeds, merging the BHs is an effective means of growing a single SMBH that avoids the radiative feedback limitations associated with accreting gas. Most recently, Tanaka et al. (2012) have reported that mergers of Pop III remnant seeds born in DM halos with virial temperatures $T_{\text{vir}} = 400$ K enhance the final masses of SMBHs by a factor of $10\text{--}100$.⁵ However, accounting for the substantially more massive halos, with $T_{\text{vir}} \sim 1000\text{--}2000$ K,⁶ in which Pop III star formation is found to occur in cosmological simulations (e.g., Yoshida et al. 2003; O’Shea & Norman 2007), even at the earliest epochs (e.g., Gao et al. 2007), implies a decrease in the host halo abundance by a factor of $1\text{--}2$ orders of magnitude (as found from large-scale cosmological simulations of hierarchical structure formation; e.g., Reed et al. 2007). Assuming the same star formation efficiency and Pop III initial

mass function from Tanaka et al. (2012), this, in turn, suggests that the number of mergers that occur in the assembly of a high- z SMBH is $1\text{--}2$ orders of magnitude lower than Tanaka et al. find, which implies that mergers are likely to contribute only minimally to the growth of SMBHs at high- z (see also Madau et al. 2004).⁷ This dramatically limits the masses to which BHs can grow from Pop III seeds, in particular.

The rate of mergers that grow SMBHs from Pop III seeds is further reduced due to the build-up of the molecule-dissociating LW radiation field which acts to slow the collapse of primordial gas in DM halos, and thus lowers the Pop III star formation rate (SFR; e.g., Haiman et al. 1997; Glover & Brand 2001; Machacek et al. 2001; Ricotti et al. 2001; Ciardi & Ferrara 2005; Mesinger et al. 2006; Wise & Abel 2007; O’Shea & Norman 2008). The most recent cosmological simulations tracking the build-up of the LW radiation field suggest that the Pop III SFR is reduced by a factor of a few compared to the SFR in the absence of LW feedback (Ahn et al. 2012; Hummel et al. 2012; Johnson et al. 2013; Wise et al. 2012).⁸ Accounting for this further reduction in the number density of Pop III seed BHs, beyond the reduction due to the more massive host halos, we can conclude that mergers are likely to be responsible for only a small portion of the growth of SMBHs. The vast majority of the growth must be due instead to accretion of gas (see also, e.g., Hopkins & Quataert 2010) and perhaps to a much lesser extent DM (e.g., Hu et al. 2006; Guzmán & Lora-Clavijo 2011). This justifies our simplified approach in later sections of focusing on the growth of BHs solely from accretion and neglecting mergers. In turn, as we will show in the next sections the limited role of mergers in early SMBH growth implies a strong challenge to the Pop III seed model, which relies on frequent mergers to grow the most massive BHs.

A lower rate of (gas-poor) mergers of seed BHs also suggests higher values for the spins of the seeds (e.g., Gammie et al. 2004; Volonteri et al. 2005, 2012; Berti & Volonteri 2008), since mergers of BHs with randomly oriented spins will tend to spin down fast rotating BHs (e.g., Hughes & Blandford 2003). This translates into a higher radiative efficiency of accretion, since more energy can be extracted from the spin of the BH (Blandford & Znajek 1977) and from the hotter accretion disk that extends further inward towards the horizon of a faster-spinning BH (e.g., Novikov & Thorne 1973).⁹ That we find mergers to be relatively unimportant is then broadly consistent with the inferred high radiative efficiencies of high- z SMBHs, which we shall discuss in Section 4.

3. OBSERVATIONAL CONSTRAINTS ON SUPERMASSIVE BLACK HOLE SEEDS

We now turn to highlight the observational constraints on the accretion history of high- z SMBHs that can be derived from the evolution of the comoving number density of SMBHs

⁵ These authors also account for the reduced rate of gas accretion onto BHs when they are kicked out into the low density regions of their host halos due to the emission of gravitational waves during mergers (e.g., Favata et al. 2004; Merritt et al. 2004; see also Madau et al. 2004). They also emphasize that the bulk of the growth in mass comes from gas accretion, not mergers.

⁶ The virial temperature of a halo increases with halo mass as $T_{\text{vir}} \propto M_{\text{halo}}^{2/3}$ (e.g., Barkana & Loeb 2001).

⁷ Consistent with this are the results of recent large-scale cosmological simulations tracking the build-up of SMBHs at high redshift which suggest that only a negligible fraction of their mass is acquired in mergers (DeGraf et al. 2012).

⁸ Tanaka et al. (2012) also considered the impact of LW feedback and found it to be insignificant; however, this is likely due, at least in part, to their use of the fitting formula from Machacek et al. (2001) which has been shown to significantly underestimate the minimum halo mass for star formation in the presence of LW radiation (see, e.g., O’Shea & Norman 2008).

⁹ It is worth noting that the spins of local SMBHs are found to be $\gtrsim 60\%$ of the maximum allowed value (Brenneman et al. 2011), which suggests that their radiative efficiencies are higher than the value expected for a non-rotating BH, $\epsilon \gtrsim 0.06$ (e.g., Noble et al. 2011).

over cosmic time. In particular, we place constraints on the time-averaged accretion rates and on the efficiency with which radiation is produced during accretion, as described below.

In general, the radiative luminosity, L , of a black hole accreting at a rate \dot{M}_{BH} is given by $L = \epsilon \dot{M}_{\text{BH}} c^2 / (1 - \epsilon)$, where c is the speed of light and ϵ is the radiative efficiency, defined as the fraction of the rest mass energy of infalling matter that is converted into radiation during accretion.¹⁰ We express the radiative luminosity as a fraction f_{Edd} of the Eddington luminosity of the BH, $L = f_{\text{Edd}} L_{\text{Edd}}$, where $L_{\text{Edd}} = 1.2 \times 10^{38} \text{ erg s}^{-1} (M_{\text{BH}}/M_{\odot})$. The accretion rate at which a BH will radiate at a given fraction f_{Edd} of its Eddington luminosity L_{Edd} is then given by

$$\dot{M}_{\text{BH}} = \frac{(1 - \epsilon) f_{\text{Edd}} L_{\text{Edd}}}{\epsilon c^2}. \quad (1)$$

We integrate Equation (1) over time to find the final SMBH mass $M_{\text{BH,final}}$, as a function of its initial seed mass, $M_{\text{BH,init}}$, the duty cycle f_{duty} at which it accretes (defined as the fraction of time spent accreting), and the radiative efficiency ϵ . This yields

$$M_{\text{BH,final}} = M_{\text{BH,init}} \times \exp \left[\frac{f_{\text{Edd}} f_{\text{duty}} (1 - \epsilon)}{\epsilon} \left(\frac{t_{\text{final}} - t_{\text{init}}}{t_{\text{Edd}}} \right) \right]. \quad (2)$$

Here $t_{\text{Edd}} = 450 \text{ Myr}$,¹¹ while t_{final} and t_{init} are the ages of the universe when the BH attains its final mass and at the time of seed formation, respectively.

With $f_{\text{Edd}} = 1$ and $f_{\text{duty}} = 1$, Equation (2) reduces to the standard equation describing BH growth at the Eddington rate (defined as that which produces the Eddington luminosity; e.g., Volonteri & Rees 2006). The contours in Figure 1 denote the redshifts z by which a number density n_{SMBH} of black holes with masses $\geq 10^9 M_{\odot}$ can be grown, assuming constant accretion at the Eddington rate with radiative efficiency ϵ . For a given ϵ , this allows us to constrain the growth histories and initial seed masses of high- z SMBHs from their observationally-derived number density.

For our comparison with the observational data in Figure 1, we have expressed t_{final} as a function of redshift, using the *WMAP7* results (Komatsu et al. 2011) for the relevant cosmological parameters ($\Omega_{\text{M}} = 0.27$, $\Omega_{\Lambda} = 0.73$ and $H_0 = 70.3 \text{ km s}^{-1} \text{ Mpc}^{-1}$), and following the approach in Barkana & Loeb (2001).¹² In order to determine t_{init} in Equation (2), as a function of n_{SMBH} , we have used the Warren et al. (2006) DM halo mass function to find the highest redshift at which the comoving number density of the DM halos with masses $\geq M_{\text{halo,init}}$ which can host BH seed formation is $\geq n_{\text{SMBH}}$. In principle, some of these halos could have merged with one another before t_{final} . In this case, the initial abundance of some of the seeds of SMBHs would have been higher, suggesting that

¹⁰ We note that only a fraction $(1 - \epsilon)$ of the rest mass of the accreting material is finally accreted by the BH, as seen by an observer at infinity (e.g., Salpeter 1964; Thorne 1974). The radiation generated during accretion which escapes to infinity accounts for the rest mass that such an observer concludes is lost due to gravitational redshifting and time dilation as material falls into the potential well of the BH.

¹¹ This timescale follows directly from the definition of the Eddington luminosity: $t_{\text{Edd}} = \sigma_{\text{T}} c / 4\pi G m_{\text{p}}$, where σ_{T} is the Thomson cross section for electron scattering, G is Newton's constant, c is the speed of light and m_{p} is the mass of the proton.

¹² While we adopt the standard Λ CDM cosmological model, the constraints on early BH growth are, of course, different in different cosmological models (e.g., Melia 2013).

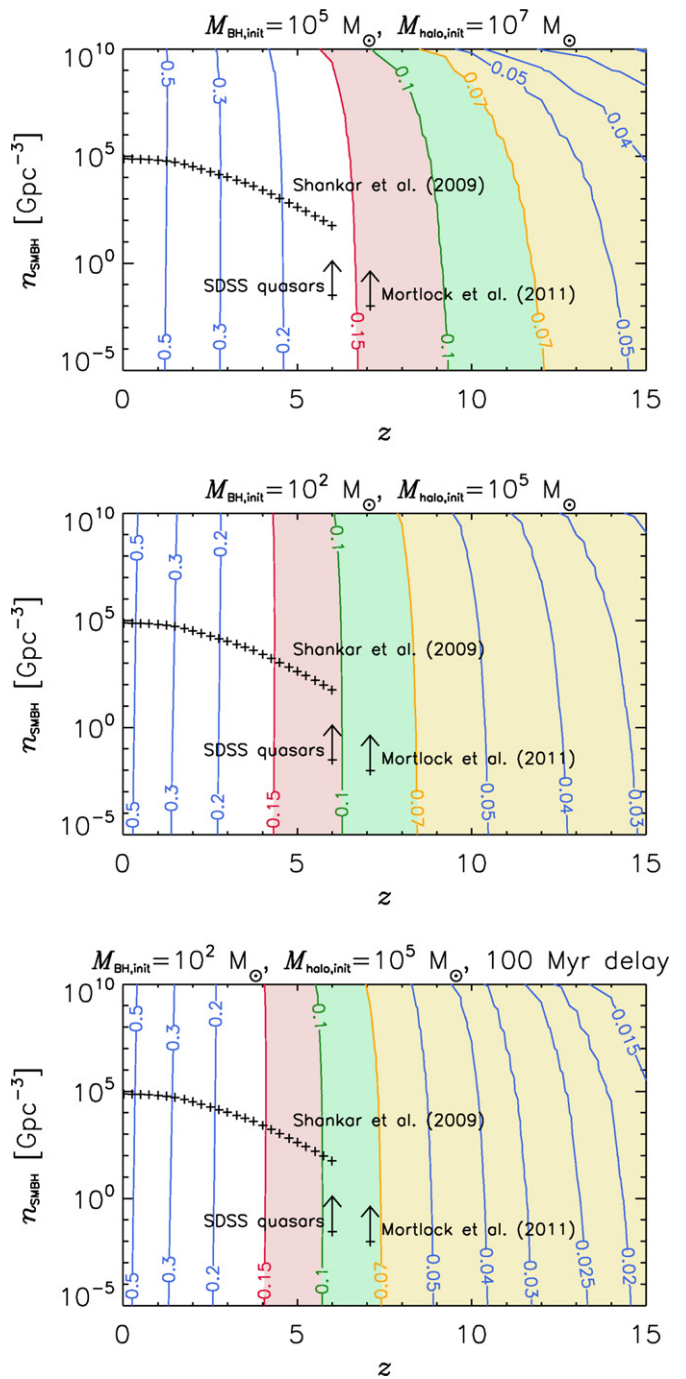


Figure 1. Upper limits for the radiative efficiency (ϵ) required for various BH seeds to produce a space density n_{SMBH} (y-axes) of SMBHs with masses $M_{\text{BH,final}} \geq 10^9 M_{\odot}$ by redshift z (x-axes), assuming accretion is limited to the Eddington rate ($f_{\text{Edd}} f_{\text{duty}} \leq 1$). Contours show the maximum values of ϵ required, for three initial BH seeds: $M_{\text{BH,init}} = 10^5 M_{\odot}$ SMS progenitors in $M_{\text{halo,init}} = 10^7 M_{\odot}$ DM halos (top), $10^2 M_{\odot}$ Pop III progenitors in $10^5 M_{\odot}$ halos (middle), and the same case but with accretion delayed by 100 Myr due to radiative feedback (bottom). Time-averaged super-Eddington accretion rates are required in the colored regions to the right of the red, green, and yellow lines for radiative efficiencies of $\epsilon = 0.07$, 0.1 , and 0.15 , respectively. The black crosses denote values of n_{SMBH} for SMBHs with masses $\geq 10^9 M_{\odot}$ inferred from observations. A seed BH with $M_{\text{BH,init}} = 10^5 M_{\odot}$ (top) has to accrete continuously ($f_{\text{duty}} = 1$) at the Eddington rate ($f_{\text{Edd}} = 1$) with a radiative efficiency $\epsilon \lesssim 0.14$ to explain the existence of the $z \simeq 7$ quasar, while a $M_{\text{BH,init}} = 100 M_{\odot}$ seed (middle) can only do so if accreting with a radiative efficiency $\epsilon \lesssim 0.09$.

(A color version of this figure is available in the online journal.)

they formed at later times when the abundance of their host halos was likewise higher. Because, following our arguments in Section 2, we neglect mergers in our modeling, this implies that the values for t_{init} we adopt are lower limits.

Finally, we note that the Warren et al. (2006) mass function we have adopted provides a reasonable fit at the high redshifts (e.g., $z \simeq 30$) of seed formation to the halo mass functions found from cosmological simulations by Reed et al. (2007). That said, Figure 1 also shows that our results are relatively insensitive to the exact value of n_{SMBH} , except at the highest redshifts where there is the least time for SMBHs to form in large numbers (as shown by the downturn of the contours at the highest number densities).

In Figure 1 we compare these theoretical curves with the observational constraints on the evolution of the comoving number density n_{SMBH} of SMBHs over cosmic time. We show lower limits on n_{SMBH} for BHs with masses $\geq 10^9 M_\odot$ at the highest redshifts, as found from detections of $z \simeq 6$ quasars in the Sloan Digital Sky Survey (SDSS; e.g., Fan et al. 2006; Tanaka & Haiman 2009; see also Willott et al. 2010) and from the single quasar at $z \simeq 7$ detected in the United Kingdom Infrared Deep Sky Survey (UKIDSS; Mortlock et al. 2011).¹³ At lower redshifts, Figure 1 also shows the number densities of $\geq 10^9 M_\odot$ BHs obtained by integrating the BH mass function inferred from the observed luminosity function of active galactic nuclei by Shankar et al. (2009).

In each of the three panels of Figure 1, the observed number densities of SMBHs are plotted together with the theoretical contours of ϵ , for three different models of the initial BH seeds and their early evolution.¹⁴ In the top panel, we take values of the initial seed mass $M_{\text{BH,init}} = 10^5 M_\odot$ and initial DM host halo mass $M_{\text{halo,init}} = 10^7 M_\odot$, corresponding to the SMS remnant model. In the middle panel, we take $M_{\text{BH,init}} = 10^2 M_\odot$ and $M_{\text{halo,init}} = 10^5 M_\odot$, corresponding to the Pop III remnant model. Finally, in the bottom panel we take the same values as in the middle panel, but we assume accretion onto the seed BH is delayed for the first 100 Myr; as discussed in Section 4.2, numerous cosmological simulations suggest that this may be the case for BHs born in minihalos at high- z due to radiative feedback from the progenitor star and from the accretion process (e.g., Kitayama et al. 2004; Whalen et al. 2004; Yoshida 2006; Alvarez et al. 2009).

For a given value of ϵ , the contours show the range of redshifts over which there is sufficient time to grow a BH from its initial seed mass to $M_{\text{BH,final}} \geq 10^9 M_\odot$ assuming accretion at the Eddington rate ($f_{\text{Edd}} f_{\text{duty}} = 1$). In particular, the yellow, green, and red contours in Figure 1 correspond to efficiencies $\epsilon = 0.07$, 0.1, and 0.15, respectively. The colored regions show the range of redshifts at which $\geq 10^9 M_\odot$ BHs must have grown at time-averaged rates exceeding the Eddington limit for each of these efficiencies. As these colored regions extend to lower redshifts in the Pop III remnant cases (bottom two panels), it is clear that relatively low-mass Pop III BHs could only be the seeds of the SMBHs inferred at $z \gtrsim 6$ in the SDSS and UKIDSS if they grew at super-Eddington rates for a significant fraction of time and/or if their radiative efficiency of accretion is relatively low, $\epsilon \lesssim 0.09$

¹³ We have estimated a conservative lower limit for n_{SMBH} at $z \sim 7$ by noting that just one $\geq 10^9 M_\odot$ BH was found in the UKIDSS Large Area Survey which covered \simeq one-tenth of the sky, and by assuming that such a SMBH could have been detected out to $z = 10$. While this is a rough estimate, Figure 1 shows that our results are relatively insensitive to values of n_{SMBH} in this range.

¹⁴ For simplicity, we consider the two models described in Section 1 which bracket the range of expected initial seed masses: the Pop III remnant model and the SMS remnant model.

(see, e.g., Volonteri & Rees 2006 for less stringent constraints on ϵ gleaned from models based on a higher, *WMAP1* σ_8 parameter which implied much earlier seed BH formation). However, the much more massive SMS remnant seeds could accrete at sub-Eddington rates and still grow to $M_{\text{BH,final}} \geq 10^9 M_\odot$ sufficiently rapidly, even allowing for a radiative efficiency of up to $\epsilon \simeq 0.14$.

In the next two sections we consider the values expected for the parameters ϵ , f_{Edd} and f_{duty} , and what they imply for models of SMBH seed formation.

4. SUPPRESSION OF BLACK HOLE GROWTH VIA LOCAL RADIATIVE FEEDBACK

Here we discuss various ways in which radiation limits the rate of growth of BHs in the early universe, and what values are expected for the radiative efficiency ϵ and the time-averaged accretion rates $f_{\text{Edd}} f_{\text{duty}}$ of early BHs. We then consider what these limits, taken together, imply for the initial seed masses of SMBHs.

4.1. Low Eddington Accretion Rate due to High Radiative Efficiency

Following Equation (1), for higher ϵ the Eddington luminosity is generated at lower accretion rates, which implies that Eddington-limited accretion proceeds at a lower rate for higher radiative efficiencies. For higher ϵ , a BH must accrete at a higher time-averaged accretion rate $f_{\text{Edd}} f_{\text{duty}}$ to grow to a given mass within a given time.

Given that the Eddington accretion rate is sensitively dependent on ϵ and that the radiative efficiencies of BHs can range from $\epsilon \simeq 0.025$ to $\simeq 0.4$ (see, e.g., Milosavljević et al. 2009b and references therein),¹⁵ it is vital to constrain this quantity in order to understand the growth of the earliest SMBHs (e.g., Shapiro 2005; King & Pringle 2006; Volonteri & Rees 2006; Tanaka et al. 2012). Fortunately, there is a growing body of observational evidence which provides some guidance, and in particular suggests that SMBHs at high- z tend to have relatively high radiative efficiencies, which suggests in turn that they are rapidly rotating. Numerous authors have argued that in order to account for the observations, SMBHs must have typical values of $\epsilon \gtrsim 0.1$ – 0.15 (e.g., Elvis et al. 2002; Yu & Tremaine 2002; Volonteri et al. 2005; Shankar et al. 2010; but see, e.g., Raimundo et al. 2012), and that ϵ tends to increase with redshift (Wang et al. 2006, 2009; Barausse 2012; Volonteri et al. 2012; see also Maio et al. 2013) and with BH mass (e.g., Davis & Laor 2011; Shankar et al. 2013), with inferred values as high as $\epsilon \sim 0.3$ – 0.4 for $\gtrsim 10^9 M_\odot$ BHs at high- z (Li et al. 2012). If the seeds of the highest-redshift SMBHs do indeed have such high radiative efficiencies, then this would imply very strong constraints on the initial masses of these seeds. In particular, it would imply much more massive seeds than can be explained in the Pop III model, but which can be much more easily accommodated in the SMS model.

As shown in Figure 1, for such high efficiencies (e.g., $\epsilon \gtrsim 0.15$) $\sim 100 M_\odot$ Pop III seed remnants would have to grow at super-Eddington time-averaged accretion rates (i.e., with $f_{\text{Edd}} f_{\text{duty}} > 1$) in order to explain the Mortlock et al. (2011) SMBH, the SMBHs powering the SDSS quasars, and other $\gtrsim 10^9 M_\odot$ BHs at $z \gtrsim 4$. However, more massive ($\gtrsim 10^5 M_\odot$)

¹⁵ These values are expected for accretion through geometrically thin disks. For spherically symmetric or advection dominated accretion (as expected at low accretion rates; e.g., Narayan & Yi 1995), the radiative efficiency can be much lower.

SMS remnants could grow sufficiently fast to explain these high- z SMBHs, even at sub-Eddington rates.

Figure 1 also shows that for the highest radiative efficiencies $\epsilon \sim 0.3$ – 0.4 , even the supermassive seeds from SMS would have to accrete at super-Eddington time-averaged rates (i.e., $f_{\text{Edd}} f_{\text{duty}} > 1$) just to grow to $M_{\text{BH,final}} \geq 10^9 M_{\odot}$ by $z \simeq 2$ – 3 . This suggests that SMBHs with such high radiative efficiencies at higher redshifts may have undergone a period of rapid accretion with a lower radiative efficiency in the past. While we cannot know the entire accretion history of a given SMBH at high- z , we can place some constraints on the amount of high energy radiation emitted during its growth from the observationally-inferred size of the H II region surrounding it. For the case of the $z \simeq 7$ quasar, Mortlock et al. (2011) report that it resides in an H II region that is $\simeq 1.9$ physical Mpc in extent, which is smaller than those typically found surrounding quasars at $z \gtrsim 6$. This suggests that accretion may indeed have been radiatively inefficient during much of the growth of the BH. Alternatively, however, the accreting BH could have instead been obscured for much of its lifetime, resulting in a small fraction of ionizing photons escaping into the intergalactic medium (see Bolton et al. 2011). This would be consistent with the galaxy merger-driven model for SMBH growth (e.g., Sanders et al. 1988; Hopkins et al. 2006) as well as with recent observational evidence suggesting that a large fraction of accreting SMBHs at high- z are in fact buried within significant amounts of gas and dust that prevent the escape of ionizing radiation (e.g., Fiore et al. 2012; see also Kelly & Shen 2013).¹⁶

We emphasize that there are uncertainties in the estimated radiative efficiencies that we have quoted here, in some cases of up to a factor of a few (e.g., Li et al. 2012). Nonetheless, the general trends, as found from multiple measurements, that radiative efficiencies increase with BH mass and with redshift are strongly suggestive of high (e.g., $\epsilon \gtrsim 0.1$) values for the most massive BHs in the early universe, which are our focus in this work.

4.2. Sub-Eddington Accretion due to Progenitor- and Accretion-generated Radiation

By definition, accretion is in principle limited to the Eddington rate due to electron scattering of the photons generated in the accretion process, but other radiative processes can further limit the accretion rate. Milosavljević et al. (2009a, 2009b) find that photoheating and pressure from ionizing and Ly α photons render the accretion of gas onto a BH intermittent ($f_{\text{duty}} < 1$), with a time-averaged accretion rate of just ~ 0.3 times the Eddington rate (i.e., $f_{\text{Edd}} f_{\text{duty}} \sim 0.3$). Park & Ricotti (2011, 2012, 2013) report similar results, although they find that accretion at the Eddington rate can be achieved for sufficiently dense accreting gas (see also Li 2011). The results of larger-scale cosmological simulations also support the conclusion that accretion onto early BHs occurs at sub-Eddington rates due to accretion-generated radiative feedback (e.g., Pelupessy et al. 2007; Alvarez et al. 2009; DeGraf et al. 2012; Jeon et al. 2012).

An additional bottleneck to efficient accretion onto Pop III seeds born in minihalos is that the intense ionizing radiation emitted by their progenitor stars drives dense gas out of the halo (Kitayama et al. 2004; Whalen et al. 2004; Alvarez et al. 2006),

leaving the BH in a low-density medium from which it cannot accrete rapidly (Yoshida 2006; Abel et al. 2007; Johnson & Bromm 2007).¹⁷ This results in accretion rates orders of magnitude below the Eddington rate for up to $\sim 10^8$ years before dense gas recollapses into the halo. The bottom panel of Figure 1 shows the effect of such a delay in accretion onto a $100 M_{\odot}$ Pop III seed BH initially formed in a $10^5 M_{\odot}$ DM halo.¹⁸ Comparing this to the case without a delay (middle panel) shows that the effect is comparable to a decrease of ~ 10 – 20% in the average accretion rate onto the seeds of SMBHs formed by $z \sim 6$ – 8 . Thus, the radiative feedback from Pop III progenitor stars can significantly slow down the growth of Pop III seeds to SMBHs.

While radiative feedback from both accretion and the progenitor star are likely to limit M_{BH} to sub-Eddington values at early times, we note that SMBH-powered quasars at $z \sim 6$ are inferred to have Eddington ratios (f_{Edd}) near unity. Their duty cycles (f_{duty}), however, are not well-constrained (Willott et al. 2010; see also Shankar et al. 2010), although they are likely to be larger than those inferred for SMBHs at lower redshifts (e.g., Trakhtenbrot et al. 2011). Overall, however, we conclude that radiative feedback, at least at the earliest times, appears likely to keep the time-averaged accretion rate of Pop III remnant seeds at $f_{\text{Edd}} f_{\text{duty}} < 1$.

Accretion-generated radiative feedback may also limit the growth of SMS remnant BH seeds to sub-Eddington rates (e.g., Johnson et al. 2011). However, as the intense ionizing radiation emitted by rapidly growing SMSs cannot escape their heavy accretion flows, their host halos are less likely to be photoevaporated (Johnson et al. 2012; see also Hosokawa et al. 2012); in turn, the BH remnants they leave behind are likely to accrete more rapidly than Pop III remnant seeds. We note that this is in basic agreement with the suggestion by Salvaterra et al. (2012) that more massive seed BHs accrete with higher Eddington fractions than do lower mass seeds.

5. IMPLICATIONS AND DISCUSSION

In the previous sections we have highlighted the constraints that observations of high- z quasars place on the nature of the BH seeds and subsequent growth of SMBHs in the early universe, and we have reviewed the ways in which radiative feedback from stars and accreting BHs is expected to limit the growth of these objects. We now discuss the implications of these findings for the main models of SMBH seed formation.

In Sections 2 and 3 we showed that mergers of BH seeds are likely to play only a minor role in growing SMBHs, and that the rate of accretion required to grow the observed SMBHs depends only weakly on their number density (see Figure 1). Thus, we are justified in taking the simplified approach of solving Equation (2) for the initial seed mass $M_{\text{BH,init}}$ as a function of ϵ , f_{Edd} , and f_{duty} , without regard for the role of mergers or for the precise redshift of formation of the seeds. Figure 2 shows the minimum BH seed mass, $M_{\text{BH,init}}$, required to grow a SMBH to a mass of $10^9 M_{\odot}$ by redshift z , with the three panels corresponding to the scenarios shown in the panels in Figure 1. In each panel, the minimum BH

¹⁶ While Treister et al. (2011) argued for a large population of dust-obscured BHs at high- z , this result has been shown to be erroneous by Willott (2011).

¹⁷ Less massive (20 – $40 M_{\odot}$) Pop III progenitor stars may not evacuate the gas as completely, but the BHs they create are also likely to be ejected from their host halos due to kicks they receive during core collapse (Whalen & Fryer 2012).

¹⁸ We note that a similar delay in the formation of Pop III seed BHs in low-mass DM halos could also result from the super-sonic streaming of DM halos relative to the gas, as discussed by e.g., Greif et al. (2011), Maio et al. (2011), and Stacy et al. (2011).

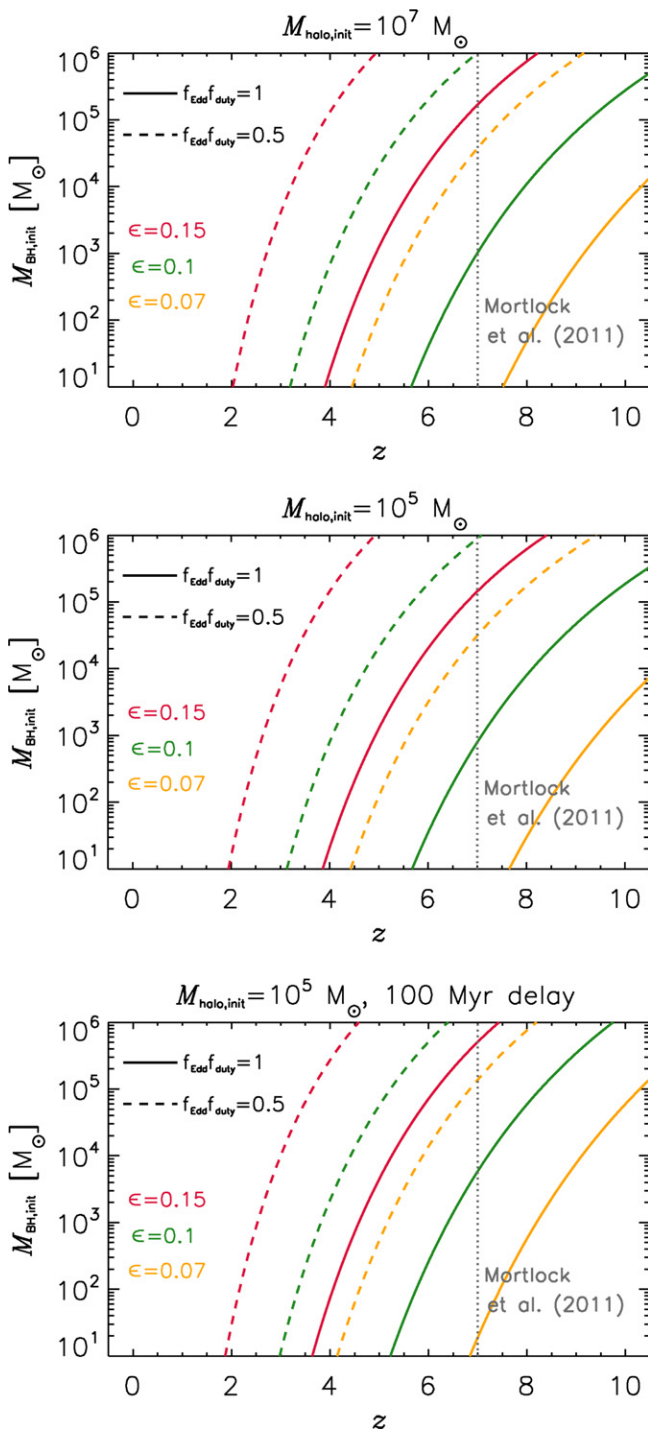


Figure 2. Minimum initial BH seed mass $M_{\text{BH,init}}$ required to form a $M_{\text{BH,final}} \geq 10^9 M_\odot$ SMBH by redshift z , at time-averaged Eddington fractions of $f_{\text{Edd}} f_{\text{duty}} = 1$ (solid lines) and 0.5 (dashed lines), for three different radiative efficiencies: $\epsilon = 0.15$ (red), 0.1 (green), and 0.07 (yellow). The three panels correspond to the cases shown in the panels of Figure 1. The largest seed masses are implied for the case of seed formation in a $M_{\text{halo,init}} = 10^5 M_\odot$ halo and accretion delayed by 100 Myr due to radiative feedback (bottom panel), while less stringent constraints are given for the cases with no delay (middle panel) and with larger initial halo mass ($M_{\text{halo,init}} = 10^7 M_\odot$ instead of $M_{\text{halo,init}} = 10^5 M_\odot$) (top panel). Given the high radiative efficiencies ($\epsilon \gtrsim 0.1$ –0.15) inferred for high- z SMBHs, these objects likely grew via constant (or time-averaged) super-Eddington accretion and/or started as massive $M_{\text{BH,init}} \gtrsim 10^3$ – $10^5 M_\odot$ BH seeds. The dotted gray vertical line denotes the redshift of the Mortlock et al. (2011) quasar. Compared to the earlier $10^9 M_\odot$ SMBHs uncovered in the SDSS at $z \simeq 6$, this single quasar implies a seed mass that is an order of magnitude higher.

(A color version of this figure is available in the online journal.)

seed mass is shown for two choices of the time-averaged Eddington fraction ($f_{\text{Edd}} f_{\text{duty}} = 0.5$ and 1) and for the same three radiative efficiencies highlighted in Figure 1 ($\epsilon = 0.07, 0.1$, and 0.15). For each of these cases we have assumed a value of t_{init} corresponding to a space density of SMBHs of $n_{\text{SMBH}} = 1 \text{ Gpc}^{-3}$ (comoving), but as Figure 1 shows the results are not strongly sensitive to this choice.

The top two panels differ very little, which is a reflection of the fact that the time between the formation of the first $10^5 M_\odot$ halo and that of the first $10^7 M_\odot$ halo in a 1 Gpc^3 comoving cosmological volume is small compared to the time from their formation to redshift z (on the horizontal axis). The values of $M_{\text{BH,init}}$ shown in the bottom panel, however, are somewhat higher, reflecting the fact that the 100 Myr delay assumed in this case is longer than the time between the formation of the first 10^5 and $10^7 M_\odot$ halos. In every case, it is clear that high radiative efficiencies ($\epsilon \gtrsim 0.1$ –0.15), such as those inferred from observations of high- z SMBHs (see Section 4.1), imply seed masses for observed SMBHs at $z \gtrsim 7$ of $M_{\text{BH,init}} \gtrsim 10^3$ – $10^5 M_\odot$, assuming constant Eddington-limited accretion ($f_{\text{Edd}} f_{\text{duty}} = 1$). For lower time-averaged accretion rates, as suggested by simulations of BH accretion (see Section 4.2), the implied minimum seed masses are much higher, up to $M_{\text{BH,init}} \gtrsim 10^6 M_\odot$ for $f_{\text{Edd}} f_{\text{duty}} \sim 0.5$ over the same range of radiative efficiencies.

If accretion is radiatively efficient and the time-averaged accretion rate is sub-Eddington, as discussed in Section 4, then the initial seed masses of the highest redshift SMBHs must have been very high, perhaps exceeding even the range predicted by the SMS remnant model (10^4 – $10^6 M_\odot$) in order to explain the $2 \times 10^9 M_\odot$ BH reported at $z \simeq 7$ (Mortlock et al. 2011). Interestingly, this is also consistent with the results of recent large-scale cosmological simulations tracking SMBH growth which suggest that such high- z quasars can be explained by starting with initial seed BH masses of $10^5 M_\odot$ (Li et al. 2007; Di Matteo et al. 2012). Taken together, we conclude that the available theoretical and observational evidence strongly suggests that the seeds of SMBHs at high- z were likely very massive. In turn, as the SMS remnant model produces the most massive seeds of the three main models discussed in the Introduction, the evidence suggests that this model may be the most viable (see also, e.g., Natarajan & Volonteri 2012).¹⁹

One of the arguments against the SMS remnant model has been that SMSs are exotic objects, and they may never form in our universe. A growing body of work is elucidating the conditions required for these objects to form (e.g., Bromm & Loeb 2003; Koushiappas et al. 2004; Lodato & Natarajan 2006; Begelman et al. 2006; Spaans & Silk 2006; Regan & Haehnelt 2009; Shang et al. 2010; Schleicher et al. 2010; Ball et al. 2011; Wolcott-Green et al. 2011; see also Mayer et al. 2010 on massive seed formation from metal-enriched gas),²⁰ and there are suggestions that the conditions for SMS formation may occur much more often in the early universe than previously assumed (Dijkstra et al. 2008; Agarwal et al. 2012; Johnson et al. 2013;

¹⁹ Our generic conclusion is that higher initial seed masses are more consistent with the available observational data and theoretical modeling. In this, we conclude that the ($\sim 100 M_\odot$) Pop III seed model is the weakest, the ($\sim 10^3 M_\odot$) stellar cluster seed model is somewhat more favorable, and the (10^4 – $10^6 M_\odot$) SMS seed model is the strongest.

²⁰ We note that while Mayer et al. (2010) argue for this alternative route to SMS formation, they require that these objects form in $\sim 10^{11} M_\odot$ halos, which would form much later than the $10^7 M_\odot$ halos we have focused on here. As this leaves far less time for their growth to $10^9 M_\odot$, it is unlikely that these can be the seeds of the highest- z SMBHs.

Petri et al. 2012). Indeed, Agarwal et al. (2012) find that, due to locally high LW fluxes generated by Pop II stars in the early universe, a sufficient number of SMSs may form to provide the seeds for a large fraction of the SMBHs in the centers of galaxies today (see also Greene 2012). This development offers a completely independent reason to seriously consider SMS remnants.

While the SMS remnant model offers an explanation for the origins of the earliest SMBHs that is consistent with the available data, we note that other models starting with lower initial seed masses can, in principle, also explain the data. For instance, as shown in Figure 2, if $M_{\text{BH,init}} \sim 10^2 M_\odot$ seeds accrete gas with very low radiative efficiency ($\epsilon \lesssim 0.09$) continuously at the Eddington rate or, perhaps intermittently, above it (e.g., Jaroszynski et al. 1980; Collin et al. 2002; Kawaguchi et al. 2004; Ohsuga et al. 2005; Volonteri & Rees 2005; Kurosawa & Proga 2009; Wyithe & Loeb 2011; Begelman 2012a; Li 2012), then, even allowing for a ~ 100 Myr delay due to radiative feedback (bottom panel), they could grow to $\gtrsim 10^9 M_\odot$ by $z \gtrsim 7$.²¹ However, it is possible that a large fraction of the mass in such super-Eddington flows is lost to a wind instead of being accreted onto the BH (see, e.g., Begelman 2012b; Dotan & Shaviv 2011). It also remains to be demonstrated that these conditions are likely to be realized at $z \gtrsim 7$. On the contrary, the available observational evidence suggests high radiative efficiencies (e.g., $\epsilon \sim 0.1$ – 0.15 or higher; see Section 4.1) and the available theoretical modeling suggests sub-Eddington accretion (see Section 4.2); as we have discussed here, the SMS seed model can explain the presence of the highest- z SMBHs, even given such high radiative efficiencies and limited accretion rates, while the Pop III seed model cannot.

It is difficult to verify the SMS remnant model without direct observational evidence of the existence of SMSs. We note, however, that there are observational signatures of SMSs that may be detected by future missions such as the *James Webb Space Telescope* (e.g., Johnson et al. 2012). They may also leave unique chemical signatures that could be detected in Lyman-limit systems (Woosley 1977; Fuller & Shi 1997). In addition, upon their collapse, SMSs are predicted to emit a large neutrino flux that could be detectable (by e.g., *IceCube*; Shi & Fuller 1998; Linke et al. 2001; Fryer & Heger 2011; Montero et al. 2012), as well as to produce gravitational wave signatures that could be uncovered by the Laser Interferometer Gravitational Wave Observatory (e.g., Fryer & New 2011),²² and extremely bright supernovae (e.g., Fuller et al. 1986) that could be found by the Wide-Field Infrared Survey Telescope (e.g., Whalen et al. 2012). In lieu of such observations, the best evidence for the existence of SMSs remains the SMBHs to which their remnants may have grown at the highest redshifts.

6. SUMMARY

In closing, we provide a summary of our new results and conclusions:

1. With proper accounting for the masses of the halos in which Pop III stars form at high redshift, as well as for the suppression of the Pop III star formation rate due to the

build-up of the LW background radiation field, we conclude that mergers played a limited role in the growth of Pop III seed BHs (see Section 2).

2. Because the time available for the growth of seed BHs to the $\gtrsim 10^9 M_\odot$ SMBHs observed at high redshift is only weakly dependent on the number density n_{SMBH} of these objects, we can safely assume that all such SMBHs have roughly the same amount of time to grow by a given redshift (see Section 3). This allows us to estimate the minimum initial seed mass required to grow them, as a function of just the radiative efficiency ϵ and the time-averaged fraction of the Eddington rate at which they accrete, $f_{\text{Edd}} f_{\text{duty}}$.
3. Using the most recent cosmological parameters (from *WMAP7*), we have shown that the highest-redshift SMBHs known can only be explained by the Eddington-limited growth of seed BHs with masses of $M_{\text{BH,init}} \sim 100 M_\odot$ (Pop III seeds) and $\sim 10^5 M_\odot$ (SMS seeds), if the radiative efficiency of accretion is $\epsilon \lesssim 0.09$ and $\lesssim 0.14$, respectively (see Section 3). Accounting for the likely suppression of accretion at early times, due to radiative feedback from the BH seed progenitor stars and from accretion onto the seeds themselves, leads to even tighter constraints on the Pop III seed model (see Section 4.2).
4. In turn, the high radiative efficiencies that are estimated for the highest-redshift and most massive SMBHs ($\epsilon \gtrsim 0.1$ – 0.15 ; see Section 4.1) are much more easily accommodated in the SMS seed model than in the Pop III seed model, given the much larger initial seed masses expected in the former (see Section 5). This is especially true if the time-averaged accretion rates of seed BHs are sub-Eddington, as suggested by much recent theoretical work (see Section 4.2).

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²¹ We also note that Umemura et al. (2012) have argued that Pop III seeds could form in much smaller $\sim 10^4 M_\odot$ halos, which would have formed at earlier cosmological times. If this result is confirmed, it would suggest somewhat reduced constraints on the Pop III seed model for SMBH formation.

²² See also, e.g., Barausse (2012) on distinguishing between the SMS and Pop III remnant models using the gravitational wave signal of BH mergers.

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