Driving the growth of the earliest supermassive black holes with major mergers of host galaxies

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Abstract

The formation mechanism of supermassive black holes (SMBHs) in general, and of \( \sim 10^9 \) M\(_{\odot}\) SMBHs observed as luminous quasars at redshifts \( z > 6 \) in particular, remains an open fundamental question. The presence of such massive BHs at such early times, when the Universe was less than a billion years old, implies that they grew via either super-Eddington accretion, or nearly uninterrupted gas accretion near the Eddington limit; the latter, at first glance, is at odds with empirical trends at lower redshifts, where quasar episodes associated with rapid BH growth are rare and brief. In this work, I examine whether and to what extent the growth of the \( z > 6 \) quasar SMBHs can be explained within the standard quasar paradigm, in which major mergers of host galaxies trigger episodes of rapid gas accretion below or near the Eddington limit. Using a suite of Monte Carlo merger tree simulations of the assembly histories of 40 likely \( z > 6 \) quasar host halos, I investigate (i) their growth and major merger rates out to \( z \sim 40 \), and (ii) how long the feeding episodes induced by host mergers must last in order to explain the observed \( z \gtrsim 6 \) quasar population without super-Eddington accretion. The halo major merger rate scales roughly as \( \propto (1 + z)^{3/2} \), consistent with cosmological simulations at lower redshifts, with quasar hosts typically experiencing \( \gtrsim 10 \) major mergers between \( 15 > z > 6 \) (\( \approx 650 \) Myr), compared to \( \sim 1 \) for typical massive galaxies at \( 3 > z > 0 \) (\( \approx 11 \) Gyr). The high rate of major mergers allows for nearly continuous SMBH growth if (for example) a merger triggers feeding for a duration comparable to the halo dynamical time. These findings...
suggest that the growth mechanisms of the earliest quasar SMBHs need not have been drastically different from their counterparts at lower redshifts.

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(Some figures may appear in colour only in the online journal)

1. Introduction

Observations have established the presence of a supermassive black hole (SMBH) in the center of virtually every massive galaxy in the local Universe [1]. There is a large body of circumstantial evidence suggesting that feedback from SMBHs during luminous accretion episodes—active galactic nuclei or quasars—plays prominent roles in galaxy evolution [2, and references within]. Quasar activity also helped to reionize and heat the intergalactic medium [3, 4], which may have influenced the formation and evolution of low-mass galaxies and their central BHs [5–9].

The origins of these cosmic behemoths remain a fundamental unsolved problem [see reviews by 10–12]. Particularly puzzling are the SMBHs with masses in excess of $10^{9} \, M_\odot$ powering luminous quasars at redshifts $z \gtrsim 6$ [13–19], less than 1 Gyr after the big bang. To reach such masses in so short a time, these SMBHs must have either accreted nearly continuously near the Eddington limit [e.g. 20–22] or undergone episodes of super-Eddington accretion [23–28]—regardless of whether they formed as the remnants of the first generation of stars [29, 30] or through the ‘direct collapse’ of atomic-cooling gas [31–45]. The notion that SMBHs accreted nearly uninterrupted runs counter to expectations from observations at lower redshifts ($z \lesssim 2$), where only a small fraction of SMBHs are undergoing quasar episodes, which are estimated to last for 1 to 100 Myr [e.g. 46–49].

In this paper, I show that steady and prolific growth of nuclear BHs at $z > 6$ can be reconciled with their relative inactivity at lower redshifts if gas accretion episodes near the Eddington limit are triggered by major mergers of the BH’s host galaxy or dark matter halo. Major mergers of galaxies have long been associated with quasar activity [50–61]. (Note, however, that luminous accretion can also be triggered by secular processes [e.g. 62–65].) Previously, Li et al [55, see section 3] argued, by examining the hierarchical growth of an exceptionally massive dark matter halo a large cosmological simulation, that host major mergers provide a plausible explanation for the growth of $z \gtrsim 6$ quasar SMBHs. Here, I use a semi-analytic Monte Carlo technique [66] to argue that this is the case generally—i.e. that the most massive dark matter halos experience a rapid succession of major mergers prior to $z \approx 6$.

The rate of major galaxy mergers per unit time per dark matter halo evolves extremely rapidly with redshift, roughly as $dz/dt \propto (1 + z)^{5/2}$, where the proportionality holds at the large redshifts of interest here. This is a much steeper dependence than most physical timescales that plausibly govern the duration of a BH feeding event—for example, the dynamical time at the virial radius of dark matter halos scales as $(1 + z)^{-3/2}$. Put another way, we can write the duty cycle of BH growth at any epoch as

$$f_{\text{duty}} = N_{\text{trg}} t_{\text{feed}},$$

(1)

where $N_{\text{trg}}$ is the frequency of trigger events per BH and $t_{\text{feed}}$ is the typical duration of each feeding episode. Both of the quantities on the right hand side can depend on factors such as
redshift, BH mass, the masses of the merging galaxies, and so on—I will return to this point later. For feeding episodes triggered by major mergers of galaxies, the trigger rate \( \dot{N}_{\text{trig}}(z) \) increases so rapidly with redshift that there is a large range of functions \( f_{\text{duty}}(z) \sim 1 \) at high \( z \). I motivate a simple parametrization for \( t_{\text{feed}} \) for the narrow subpopulation of SMBHs of interest \((z \gtrsim 6, \text{masses } M \gtrsim 10^9 \, M_\odot)\), and delineate the region of parameter space that can explain their formation at the observed number densities. An example of a successful growth model is one where major galaxy mergers trigger fast-feeding episodes lasting for a timescale comparable to the dynamical time of the host halo.

This paper is organized as follows. In section 2, I present additional background by summarizing the general properties of luminous quasars and by detailing the argument that \( z \gtrsim 6 \) quasar must have experienced nearly continuous growth if their accretion was Eddington-limited. I present in section 3 results from merger-tree simulations of hierarchical structure formation, showing the prolific growth histories of the massive dark matter halos that are likely to host the \( z > 6 \) quasars. In section 4, I motivate a specific parametrization of SMBH feeding episodes triggered by galaxy mergers, and model the durations of such episodes required to explain the \( z \sim 6 \) quasar SMBHs without super-Eddington accretion. I conclude in section 5.

Throughout this work, I adopt the cosmological parameters \( h = 0.7, \Omega_0 = 0.3, \Omega_\Lambda = 0.7, n_s = 0.96 \) and \( \sigma_8 = 0.8 \); these values are chosen based on the latest published empirical values [67, 68]. While quantities such as the age of the Universe and the mass function of dark matter halos are sensitive to these parameters, the methods and results presented here are qualitatively robust.

2. Luminous quasars and SMBH growth

The majority of the mass in SMBHs in the local Universe appears to have been accumulated during luminous quasar episodes [69, 70]. The brightest quasars have luminosities on the order of \( 0.1-1 \) times the Eddington luminosity of the SMBH engine [e.g. 71, 72], \( L_{\text{Edd}}(M) = 1.3 \times 10^{38} (M/M_\odot) \text{ erg s}^{-1} \). The luminosity can be expressed in terms of the mass energy of the accreted fuel and a radiative efficiency factor \( \eta \) as

\[
L = \eta \dot{M} c^2.
\]

By comparing the cumulative quasar luminosity density at \( z \lesssim 4 \) with the mass density in nuclear SMBHs, the cosmic mean value of \( \eta \) is found to be \( \approx 0.07 \) [48, 73], in rough agreement with theoretical expectations of luminous accretion flows [20, and references therein]. The quasar duty cycle, or the fraction of time SMBHs spend as quasars, is \( \sim 1\% \) at \( z \sim 2 \) (where the number density of quasars peaks) [e.g. 74], and decreases with redshift [e.g. 46, 75–77].

Estimates of quasar lifetimes vary, but tend to fall in the range \( \sim 10^6-10^9 \) yr [e.g. 78–82]. The radiative and kinetic output from the luminous quasar is thought to act as a negative feedback, making growth intermittent [e.g. 83–87]. Although luminous accretion activity is associated with major and minor mergers, as well as possibly secular processes, the detailed mechanism that channels the gas to the nuclear SMBH remains an open topic of study [e.g. 88]. Most hydrodynamical simulations modeling SMBH feeding do not actually resolve the scales of the SMBH accretion flow (\( \sim 10^{-3} \) pc) or even the radius of influence (\( \sim 10 \) pc), but rather rely on assumptions such as the Bondi prescription, with the accretion evaluated at radii of \( \gtrsim 10^2 \) pc [e.g. 84, 89–93]. There is also uncertainty as to how much of the SMBH
growth occurs when it is observable as a quasar, as opposed to other stages—such as in the midst of a galaxy merger—during which the central SMBH is heavily obscured.

For a fixed value of \( \eta \), Eddington-limited accretion implies exponential growth (\( M \propto M' \)), with an e-folding timescale

\[
\tau_{\text{Edd}} = 450 \eta \text{ Myr},
\]

with \( \tau_{\text{Edd}} = 31 \text{ Myr} \) for \( \eta = 0.07 \). For the adopted cosmological parameters, the age of the Universe at \( z = 6 (z = 7) \) is 910 Myr (750 Myr). If the \( z \geq 6 \) SMBHs grew from the remnants of the first generation of stars (Population III or ‘PopIII’ stars) at \( z \geq 30 \), then they would have had approximately \( \tau_{\text{avail}} \approx 700 \text{ Myr} \) to grow to \( \sim 10^9 M_\odot \). (Note that the available growth time \( \tau_{\text{avail}} \) is only marginally longer if the ‘seed’ BH began to grow at, say, \( z = 50 \).)

Nuclear BHs can also grow through hierarchical BH mergers, but the efficiency of this avenue is limited [94] by the gravitational recoil effect [the momentum imparted by asymmetric gravitational-wave emission on the product of a BH merger, e.g. 95–98]—that is, nature cannot simply throw together a thousand seed BHs to form a BH a thousand times more massive. Optimistic estimates suggest that mergers between PopIII remnants could contribute a factor \( \sim 100 \) toward assembling a \( M \sim 10^9 M_\odot \) SMBH by \( z \approx 6–7 \) [7, 8, 22], regardless of whether the seeds formed and began to grow in halos with virial temperatures \( \sim 400 \text{ K} \) or \( \sim 2000 \text{ K} \).

The mean Eddington ratio required to form a SMBH with mass \( M_{\text{SMBH}} \) from a seed BH with mass \( M_{\text{seed}} \) can be written as [equation reproduced from 43]

\[
f_{\text{Edd}} \approx \ln \left( \frac{M_{\text{SMBH}}}{M_{\text{merge}} M_{\text{seed}}} \right) \left( \frac{\tau_{\text{avail}}}{(\eta/0.07)\tau_{\text{Edd}}} \right) \\
\approx 0.676 + 0.045 \ln \left( \frac{M_{\text{SMBH}}}{3 \times 10^9 M_\odot} \frac{30 M_\odot}{M_{\text{seed}} M_{\text{merge}}} \right) \\
\times \left( \frac{\eta}{0.07} \right) \left( \frac{\tau_{\text{avail}}}{700 \text{ Myr}} \right)^{-1}.
\]

The masses of the \( z \geq 6 \) quasars could be explained if they began as PopIII remnants and grew at the Eddington limit for \( \approx 70\% \) of the available time, or at \( \approx 70\% \) of the Eddington limit for the entire available time.

We can repeat the above exercise for the ‘direct collapse’ seed scenario, in which nuclear BHs form in the gravitational collapse of massive, atomic-cooling (temperature \( T \sim 10^4 \text{ K} \)) gas clouds. Such an event could occur if the gas has low metallicity and is inundated by a strong ultraviolet (UV) flux that photo-dissociates molecular hydrogen and thus prevents fragmentation of the cloud into stars of ordinary mass [31, 99, additional references in section 1]. Direct collapse could form BHs with masses \( 10^4–10^5 M_\odot \), but only after redshifts \( z \approx 15 \) [36, 38, 42] (when the Universe is \( \sim 300 \text{ Myr} \) old) if the mechanism is requires the prior emergence of powerful UV sources [see 44, for a discussion]. In other words, direct collapse seeds are expected to begin with a head start in mass, but a delayed start in time. Moreover, because these seeds can only form in rare massive halos under specific circumstances, their opportunities to grow via major mergers is limited (i.e. smaller \( X_{\text{merge}} \) than a scenario where PopIII seeds form and merge). We have [43]
Equations (4) and (5) imply that both the PopIII and direct collapse seed scenarios require the $z \gtrsim 6$ quasar SMBHs to have grown nearly continuously (i.e. accreting more than half of the time), if the growth occurred at rates near the Eddington limit. (Note that the rates required are super-Eddington if the radiative efficiency parameter $\eta$ is larger.) This statement is still true even if $M_{\text{seed}} \sim 10^4 M_\odot$ BHs were to have formed as early as $z \sim 30$ [see 43, for an example of such a scenario]. I present that the key question that needs to be addressed is not whether the required mean accretion rate is below or above Eddington, but rather why (barring intermittent, highly super-Eddington growth spurts [e.g.28, 100]) the duty cycle should be close to unity. The requirement of such large duty cycles poses a stark contrast with the rarity of luminous quasar activity observed at $z \lesssim 2$. It is this contrast that I address in this paper.

3. The prolific merger histories of $z \gtrsim 6$ quasar hosts

I begin by discussing the frequency of major merger events for massive galaxies at redshifts $z \gtrsim 6$. The goal here is to answer a simple question: supposing that a galaxy major merger triggers a feeding episode of the central BH, how often do the hosts of the $z \gtrsim 6$ quasar SMBHs undergo such triggers? In other words, I seek to quantify one of the two factors, $N_{\text{tri}}$ on the right hand side of interest in equation (1); I will turn to the other factor, $t_{\text{feed}}$, in the next section.

Strictly speaking, throughout this paper I am referring to mergers of host dark matter halos, not host galaxies. However, at redshifts of interest, the masses of the most massive halos ($\sim 10^{13} M_\odot$) are comparable to the largest galaxy masses [e.g.101, 102], but not to galaxy clusters. Therefore, in this paper I assume that galaxy counts and halo counts are equivalent, and use the two terms interchangeably.

3.1. Major merger histories of the most massive $z \approx 6$ halos

The number density of $\sim 10^9 M_\odot$ SMBHs at $z \approx 6$ is $n \sim 1$ comoving Gpc$^{-3}$ [103], or of order one or a few in the Millennium Simulation [104] volume. The masses of dark matter halos with comparable abundances are $\approx 10^{13} M_\odot$, and the naive expectation is that these SMBHs are hosted by the most massive class of halos [see, however 105]. Earlier, Li et al. (2007) [55] examined a particularly massive dark matter halo in a cosmological N-body simulation and noted that it experienced seven major mergers (which they defined as mergers with progenitor mass ratio $\xi \gtrsim 1/5$) in rapid succession between $z \approx 14$ and $z = 6$. They showed that this prolific merger history provides a plausible explanation for the growth of a $z \gtrsim 6$, $M \gtrsim 10^9 M_\odot$ SMBH without super-Eddington accretion. Angulo et al. (2012) [106] noted that the most massive $z \approx 6$ halos ($\approx 10^{13} M_\odot$) doubled their masses in the preceding 100 Myr.

I present that the explanation provided by Li et al., if qualitatively correct, is likely to hold quite generally for any comparable volume in the Universe. Figure 1 shows a graphical representation of the merger history of a dark matter halo that reaches a mass of

$$f_{\text{Edd}} \approx 0.580 + 0.063 \ln \left( \frac{M_{\text{SMBH}}}{3 \times 10^9 M_\odot} \frac{10^5 M_\odot}{M_{\text{seed}}} \frac{3}{X_{\text{merge}}} \right) \times \left( \frac{\eta}{0.07} \right) \left( \frac{t_{\text{avail}}}{500 \text{ Myr}} \right)^{-1}.$$
\( M \approx 10^{13} \, M_\odot \) at \( z = 6 \). The merger history is generated using a Monte Carlo merger tree algorithm [108, 109; e.g. 66, 110, 111], whose underlying mathematical formalism provides excellent matches to cosmological \( N \)-body simulations, especially for large halo masses [e.g. 111] and whose numerical implementation has been shown to be highly accurate [66].

The horizontal axis of figure 1 shows the age of the Universe, in linear scale to emphasize the rapid hierarchical growth of the halo. The width of the shaded region represents the mass of the most massive progenitor of the halo (the ‘trunk’ of the merger tree). The diamonds denote significant merger events (progenitor masses more equal than 1:9), with the center of the diamond marking the time of the merger and the width-to-height ratio equal to the progenitor mass ratio.

Between \( z = 16 \) and \( z = 6.3 \), this particular halo experiences 10 mergers with mass ratios \( \xi > 1/3 \), 16 mergers with \( \xi > 1/5 \), and 10 additional mergers with \( 1/5 > \xi > 1/9 \). The physical time between mergers is much shorter at higher redshifts, showing a steep evolution in the merger rate with redshift (more on this point shortly).

Figure 2 presents the same information, but for 40 simulated dark matter halos, all with \( M(z = 6) > 10^{12.9} \, M_\odot \). The merger tree sample is the same as the one used in Tanaka and Li (2014) [43], and has a redshift-dependent mass resolution corresponding to a virial temperature of 1000 K, or \( \approx 10^5 \, M_\odot \) at \( z \approx 40 \). I refer the reader to that paper and references therein for details regarding the algorithm and statistical fidelity of the tree. It is readily apparent from the figure that the points made in the previous paragraph hold generally for this mass class of halos. All of these halos undergo \( N_{\text{mer}} \geq 10 \) major merger events (regardless of whether one defines a major merger with a minimum mass ratio of 1/3 or 1/5) between \( z \approx 15 \) and \( z \approx 6 \), a span of \( \approx 0.65 \, \text{Gyr} \). By contrast, the typical massive galaxy experiences \( \approx 1 \) major merger between \( z \approx 3 \) and \( z = 0 \) [e.g. 112], a span of over 11 Gyr.
3.2. The redshift evolution of the major merger rate

To further emphasize the fact that the prolific merger history found by Li et al is generic for all halos of similar mass at similar redshift, and in an effort to quantify this trend, I show in figure 3 the mean merger rates \( \dot{N} \) per unit time per halo of massive halos. The halo sample includes 40 halos with \( M(z = 6) \approx 10^{10} \, M_\odot \), 100 halos with \( M(z = 6) \approx 10^{10.5} \, M_\odot \), and 100 halos in each mass bin with \( M(z = 6) \approx 10^{11} \, M_\odot \), etc., down to \( M(z = 6) \approx 10^{8.5} \, M_\odot \). The counting statistics for each mass bin are scaled up to match the abundances expected in a 50 comoving Gpc\(^3\) volume ['halo cloning'; see,

\[ \text{Figure 2. The same as figure 1, except that this figure shows the growth histories of 40 simulated DM halos with } M(z = 6) \approx 10^{10} \, M_\odot. \text{ The thickness of each gray region is proportional to } \log(M_{\text{trunk}} / (10^{10} \, M_\odot)). \text{ The diamonds mark merger events with progenitor masses more equal than 1:9, with the width-to-height ratio equal to the progenitor mass ratio. The 'trunk' of each merger tree has a mass of } \sim 10^8 \, M_\odot \text{ at } z = 40. \]

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This method is effective for examining the assembly histories of the most massive DM halos, which are sparsely sampled by even the largest cosmological N-body simulations; on the other hand, it offers much weaker statistical power for all but the most massive objects (i.e. the lower-mass bins are represented by a hundred halos here, but represented in the thousands in large N-body simulations).

In figure 3, the thick blue, medium green, and thin red curves show merger rates of dark matter halos whose (post-merger) masses are \( \log_{10}[M(z)/M_\odot] > 11.5, \)
\( 11.5 > \log_{10}[M(z)/M_\odot] > 9.5 \) and \( 9.5 > \log_{10}[M(z)/M_\odot] > 7.5 \), respectively. The solid and dashed lines show mergers with progenitor mass ratios \( \xi > 1/3 \) and \( \xi > 1/9 \), respectively. The gray curves show the mean merger rates for the main (‘trunk’) progenitor for halos that have \( M > 10^{12.9} M_\odot \) at \( z = 6 \) (the same 40 halos as shown in the previous figure), with the line thickness and color accents indicating when the mean mass of the trunk lies within the three bins described above. For reference, I have also plotted the quantities \( t_\text{dyn}^{-1} \propto (1 + z)^{3/2} \) (solid black line) and \( d\ln z/dt \propto (1 + z)^{5/2} \) (dotted black line).

**Figure 3.** The mean merger rates \( dN/dt \) (per unit time per halo), of DM halos in the merger tree simulation. The thick blue lines denote mergers for halos with \( M > 10^{11.5} M_\odot \), the green lines for halos with \( 10^{11.5} M_\odot > M > 10^{9.5} M_\odot \), and the thin red lines for halos with \( 10^{9.5} M_\odot > M > 10^{7.5} M_\odot \). The solid and dashed lines show mergers with progenitor mass ratios \( \xi > 1/3 \) and \( \xi > 1/9 \), respectively.
on). Note that whereas the blue, green and red curves show the mean merger rates for halos in the entire simulation sample, the gray curves show the merger rates only for the main progenitors of halos that end up with $M\approx\approx\approx \circ M_{12.9}$.

Figure 3 shows some noteworthy trends, most of which have been noted in previous studies utilizing semi-analytic methods [e.g. 113, 114] and $N$-body simulations [e.g.-115, 116]. First, more massive halos have somewhat higher merger rates. Second, mergers of ratios $\xi > 1/3$ are almost as common as mergers of $\xi > 1/9$. This piece of information is useful because the definition of what mass ratios constitute a ‘major’ merger is arbitrary; previous works have used $\xi > 1/4$, $\xi > 1/5$, and so on. This figure suggests that the choice of a minimum $\xi$ value for defining a major merger (i) does not qualitatively affect the (steep) redshift evolution of the inferred major merger rate, and (ii) affects it quantitatively only up to a factor of order unity. (Note that there are other uncertainties in defining and interpreting merger rates of halos and galaxies [117]). Third, and most importantly for the topic of this paper and as suggested by the previous figures, the major merger rate per galaxy evolves very rapidly with redshift. Across the range of halo masses considered here, the rate at $15 \lesssim z \lesssim 20$ is higher by an order of magnitude than the rate at $6 \lesssim z \lesssim 8$, which is in turn $\sim$10 times greater than the predicted major merger rates of quasar hosts at $z \approx 2$ [116, see below]. Finally, the cosmic mean merger rate for halos in a fixed mass range at all redshifts (colored curves) and the mean merger rate for the main progenitors of the $M\approx\approx\approx \circ M_{13}$ halos across five orders of magnitude of mass growth (gray curves) exhibit similar redshift evolution.

For comparison, I have plotted the quantity $\dot{z}/\ddot{z}$, or the rate at which the Universe ages per unit redshift, as a dotted black curve. At the redshift values of interest, $\dot{z}/\ddot{z}$ scales approximately as $\propto (1+z)^{3/2}$. The evolution of the halo merger rate roughly follows this power law, consistent with theoretical expectations and confirming the fidelity of the merger trees. This simply reflects the fact that the theoretical merger rate per redshift $dN_\text{m}/dz$ depends weakly on $z$.

These semi-analytic results can be compared to those of Fakhouri et al (2010) [116], who investigated the halo merger rates in the two Millennium Simulations [104, 118]. Although the cosmological parameters adopted here differ slightly from those in those simulations, the two sets of results are broadly consistent with each other; those authors also found major merger rates of $dN_\text{m}/dt \approx 1$ Gyr$^{-1}$ for massive halos at $z \gtrsim 6$, and that $dN_\text{m}/dz$ scaled roughly as $\propto \dot{z}/\ddot{z} \propto (1+z)^{0.1} \propto (1+z)^{2/6}$. The reader may wish to juxtapose figure 3 in this work to the right-hand panel of figure 3 in Fakhouri et al. Note that whereas that study focused mostly on halo mergers at $z \lesssim 7$, here I’m interested in the range $6 \lesssim z \lesssim 40$.

4. SMBH feeding times

Having quantified the host merger rates, the rate of trigger events in equation (1), I now turn to the effective duration of the SMBH ‘feeding time.’

It is worth re-emphasizing that the exact manner in which galaxy mergers deliver gas to the central BH(s) is not fully understood. Assuming constant growth at fixed Eddington rate is (predictably) problematic, resulting in too many massive SMBHs [22]. While numerous studies—semi-analytic models, as well as simulations that employ sub-grid prescriptions for SMBH growth—have used Bondi–Hoyle accretion, this prescription is known to break down in the presence of radiative feedback from the BH [87], angular momentum [119], inhomogeneous gas cooling and dynamics [120, 121], advection [122, 123], thermal conduction [124, 125], etc. Indeed, many examples of luminous BH activity do not appear to be
represented by Bondi accretion [e.g. 126]. Prescriptions where SMBH growth is coupled to the baryonic properties of the host can be successful with specific model prescriptions [e.g. 127, 128], as are some models with local [e.g. 73, 84], and global regulatory feedback [7].

In discussing the host merger-triggered feeding times, it is important to clarify two points. First, the feeding episode is not a step-function event [e.g. 81], but rather a continuous process during which the SMBH accretion rate varies with time. Here, I refer to the ‘feeding time’, the effective period over which the average accretion rate is equal to Eddington. Second, I distinguish the terms ‘feeding time’ and ‘quasar lifetime’ to emphasize that the two need not be the same. Although quasar episodes are associated with the final stages of SMBH growth via rapid gas accretion, at high redshifts the growth could be preferentially more obscured due to greater gas column densities—particularly so, if obscuration by host mergers are commonplace. Depending on the host morphology, as well as the line of sight, timing and wavelength of the observation, a given feeding episode may or may not be classified as a quasar. Therefore, the feeding times should only be taken as an upper limit to the intrinsic quasar lifetime, just as the SMBH number density (and mass function) generally give upper limits to the quasar number density (luminosity function) for a particular distribution of Eddington ratios.

In general, the feeding time should depend on a number of variables: the total mass and mass ratio of the merging host, the redshift, the mass and spin of each nuclear BH, the gas metallicity, the geometry of a given host merger and the angular momentum of the gas, and perhaps the dynamics of the nuclear BHS as they form a binary and evolve. However, in this particular instance, we’re concerned with a very specific subpopulation of massive dark matter halos that share similar growth histories. All of these halos were selected to have similar masses at $z = 6$, and their mass growth histories $M(z)$ are highly uniform, with the masses of their main progenitors typically only varying by a factor of a few out to $z \sim 40$; see figure 2. (Note that this trend does not extend to lower redshifts; the most massive halos at $z \sim 6$ do not necessarily grow into the most massive halos at $z \lesssim 2$ [e.g. 106].) I will also restrict the following analysis to major mergers with mass ratios $\xi \geq 1/5$.

In addition, these halos always have masses well above the cosmological Jeans (filtering) scales, even in hypothetical scenarios where the intergalactic medium is heated prolifically by early mini-quasar activity [7]. Thus, at any given redshift, these halos are the least sensitive (compared to lower-mass halos) to spatial fluctuations in local radiative backgrounds.

I consider a feeding time of the form

$$t_{\text{feed}}(M_{\text{halo}}, M_{\text{BH}}, z, \xi, \ldots) \sim \langle t_{\text{feed}}(z = 6) \rangle \left(\frac{1 + z}{7}\right)^A.$$  (6)

That is, because in this particular instance the variations in $M_{\text{halo}}(z)$, the merger rates, and the mass ratio $\xi$ are small, I suppose that the duration of the SMBH feeding episode can be characterized by a characteristic mean value $\langle t_{\text{feed}}(z) \rangle$ that follows a redshift evolution $(1 + z)^A$. I assume that at any given redshift, the feeding episode duration can be characterized by a log-normal distribution with scatter $B$.

Many studies have sought to empirically estimate quasar lifetimes, with large uncertainties. The best constraints come from data at $z \lesssim 2$; the limited redshift range, and the fact that the overall quasar sample contains a wide variety of host galaxies and SMBH masses, makes it difficult to evaluate how SMBH growth depends on the redshift and the host properties. For example, Wyithe and Loeb (2009) [82] suggest that the quasar lifetime scales with the dynamical time of the host dark matter halo, $t_{\text{dyn}} \approx 230 \left[(1 + z)/7\right]^{3/2}$ Myr.
For reference, I have plotted $t_{\text{dyn}}^{-1} \propto (1 + z)^{3/2}$ alongside the halo merger rates in figure 3 (solid gray line).

I perform a parameter space survey to quantify what combinations of feeding time parameters—normalization ($t_{\text{feed}}(z = 6)$), redshift evolution slope $A$, and scatter $B$—can explain the observed population of $z \sim 6$, $M \gtrsim 10^9 M_\odot$ quasars via host merger-triggered, Eddington-limited growth. I assume that a nuclear BH is in place in each massive halo with a virial temperature above $10^4$ K, and that following a major merger $\xi \gtrsim 1/5$ the BH accretes for $t_{\text{feed}}$, drawn randomly out of the $z$-dependent log-normal distribution (equation (6)), over which time the BH accretes at the Eddington limit. I take a conservative model, in which a subsequent major merger during $t_{\text{feed}}$ does not extend the feeding episode (i.e. rapid mergers cannot counteract negative feedback by ‘blowout’); an alternative model would be one where the BH accretes for $t_{\text{feed}}$ since the last major merger. This exercise is repeated 100 times (to statistically average different possible Monte Carlo realizations of $t_{\text{feed}}$) for each of the main progenitors of the sample of halos with $M(z = 6) \gtrsim 10^{12} M_\odot$.

This model treatment makes, by design, extreme simplifications. Whereas galaxy (halo) mergers are prolonged events in nature, taking place over dynamical timescales, in the merger tree simulations a merger is associated with a single instantaneous redshift value. If we take this to be the moment when two halos are inside their common virial radius, this would correspond to a fairly advanced stage of galaxy merger (as opposed to an interacting pair). Because the AGN fraction in interacting galaxy pairs may be higher than average [e.g.130–132], assigning the feeding episode to begin after the two halos have merged (according to the merger tree) may be conservative—that is, by triggering the growth after merger, this prescription may be introducing a systematic, artificial delay to SMBH growth. An alternative, even more conservative possibility would be to allow the SMBH to feed with a delay after the tree-defined merger episode. A conflating complication is the issue of the AGN light curve and the corresponding SMBH ‘growth curve’ [e.g. 58, 81]; as mentioned above, the SMBH growth rate should vary as the galaxy merger progresses, but here I have assigned simple exponential growth during the feeding episode.

However, because I am only measuring the $z = 6$ SMBH number density, it does not make a difference if an earlier feeding episode lasting 50 Myr began when the age of the Universe was 600 or 670 Myr (i.e. before, during or after a merger event), or whether the SMBH growth occurred uniformly during that 50 Myr interval or in a spurt at either end of it. The specific choices for the growth curve, and for the temporal offset between halo merger and SMBH growth, impact the model only (i) if a feeding episode overlaps with a subsequent merger (since in this model mergers trigger new growth episodes but do not prolong ongoing ones), and (ii) if a growth episode is ongoing at $z = 6$, when the snapshot for these results are produced. Further, all of these theoretical uncertainties have timescales comparable to the halo dynamical time $t_{\text{dyn}}(z)$ or the feeding time $t_{\text{feed}}$. The duration of each growth episode is selected from a log-normal distribution with spreads of 0.1–0.5 dex, and (as we will see below), the successful models have $t_{\text{feed}}(z) \sim t_{\text{dyn}}(z)$. Thus, the uncertainty in $t_{\text{feed}}$ associated with the above details for the feeding prescription is comparable to $t_{\text{feed}}$ itself—the general findings of this paper should not be sensitive to these details.

Molecular-cooling halos that have just formed PopIII stars will have shallow potentials, and may be more susceptible to negative feedback from BH activity [133, 134]. Therefore, I only allow BHs to grow if their halos are atomic-cooling (virial temperatures $\sim 10^4$ K), which may be a crucial threshold that allows for dense cooling flows to carry gas to the central BH [135–137]. Note that this sample of particularly massive halos becomes atomic-cooling at $z \gtrsim 30$, and exist at the same abundances as the $z \gtrsim 6$ quasars ($\sim \text{Gpc}^{-3}$) as early as $z \sim 40$
[see 43, figure 2]. This is much earlier than the typical redshift for PopIII formation ($z \approx 20$) or proto-galaxy formation ($z \gtrsim 10$). This implies that if the first ‘monster’ SMBHs grew from PopIII seeds, then the numerical simulations focusing on typical halos at $z \sim 10$–20 may not be representative of their cradles.

The collected output is the number density of host halos whose central BHs would have grown to $\sim 10^9 \, M_\odot$ by $z = 6$. In figure 4, I plot this quantity for population synthesis realizations resulting from different combinations of the three model parameter values. I evaluate the number density of halos whose BHs have grown by a factor $f_{\text{grow}} \gtrsim 10^6$ from when the main progenitor of the host halo is atomic-cooling to $z = 6$. That is, the seed BH in the main progenitor must grow by a factor of $\gtrsim 10^6$ via host merger-triggered gas accretion episodes, and acquire $1000 \, M_\odot$ from a combination of the initial mass and BH mergers (e.g. by having $100 \, M_\odot$ at formation and growing by a factor 10 via BH mergers). The white grids in the figure represent model parameter combinations that do not produce any such quasar SMBHs. The dark gray and black grids show models that overproduce massive BHs at $z = 6$. A model may be said to be viable if the predicted number density of $z \sim 6$, $M \gtrsim 10^9 \, M_\odot$ SMBHs matches the observed estimate of $n \sim 10^{-9} \, \text{Mpc}^{-3}$ [103].

The blue solid lines in figure 4 show, for reference, the combination of parameters where $(t_{\text{feed}}(z = 2)) = 10$ Myr and $100$ Myr, representing the approximate quasar lifetimes derived from observations at $z \lesssim 2$. In other words, parameter combinations that lie near or between the blue lines, when extrapolated to lower redshifts, are roughly consistent with observational estimates for quasar lifetimes. (I again emphasize that the time of a feeding cycle should be viewed only as an upper limit for the quasar duty cycle.) These blue lines are meant only as rough guides. Again, (i) quasar lifetimes are not (necessarily) BH feeding times, and (ii) the halos studied here belong to a very narrow subset of the most massive $z > 6$ halos and have quantitatively similar mass growth histories, and may be quite different from hosts of low-redshift quasars.

I repeat the above parameter survey for direct-collapse seed models, which may form by $z \approx 15$ and have initial masses as large as $M \sim 10^5 \, M_\odot$ [see section 2]. Whereas for Population III seed models I considered BHs that have grown by $f_{\text{grow}} \gtrsim 10^6$ between when the host becomes atomic-cooling and $z = 6$, here I consider BHs that have grown by $f_{\text{grow}} \gtrsim 10^4$ between $15 \gtrsim z \gtrsim 6$. The results are plotted in figure 5. The parameter requirements do not differ very much from the PopIII case, which is not surprising given that similar mean Eddington ratios are required for both the PopIII and direct collapse families of models (see equations (4) and (5)). Roughly speaking, both models require BHs of masses $\sim 10^5 \, M_\odot$ to be in place by $z \sim 12$–15, and grow by a factor $\sim 10^4$ by $z \approx 6$.

Figures 4 and 5 show that the $z \gtrsim 6$ quasar population could be explained, for both Population III and direct-collapse seed models, by host merger-triggered accretion near the Eddington limit if feeding episodes last for $(t_{\text{feed}}(z = 6)) \sim 30$–100 Myr and if the slope of the redshift evolution is $A \gtrsim -2$. Large values of the scatter $B \gtrsim 0.3$ in the distribution of feeding times can enhance the number of particularly massive BHs (i.e. if it is more common for major mergers to trigger long feeding episodes).

It is important to note that the parameterization $t_{\text{feed}}(z)$ that can account for the $z \sim 6$, $M \gtrsim 10^9 \, M_\odot$ SMBHs is not necessarily applicable to SMBHs of different masses or at different epochs, or residing in halos of very different mass. Again: it’s probable that $t_{\text{feed}}$ depends in general on $z$, $M_{\text{halo}}$, $M_{\text{SMBH}}$, and other quantities. This analysis takes advantage of

1 Note that the analysis does not require the seed BH to form in the main progenitor; it can form in a UV-inundated satellite halo in the vicinity of the ‘trunk’ halo, which serves as the UV source to aid direct collapse [36], then subsequently fall into the more massive halo.
the fact that halos with similar $M_{\text{halo}} \sim 6$ have similar growth histories $M_{\text{halo}} > 6$ and have experienced similar numbers of major mergers. (This is the same reason that analyses of $N$-body simulations can yield simple fitting formulae of halo growth and merger rates as functions of $M$ and $z$.) Therefore, SMBHs residing in $z \sim 6$ halos with different masses will have grown in different environments, and thus may have had different feeding times $t_{\text{feed}}(z)$ from the most massive $z \sim 6$ halos considered here.

Nevertheless, we can briefly explore the consequences of applying the same feeding time function $t_{\text{feed}}(z)$ to SMBHs in halos with lower masses. Halos with $M_{\text{halo}} \sim 10^{12} M_\odot$ at $z \sim 6$ will have experienced $\sim 20\%$ fewer mergers between $z \sim 15 - 20$ and $z \sim 6$, compared to halos with $M_{\text{halo}} \sim 10^{12} M_\odot$ at the same redshift. Let us suppose that $t_{\text{feed}}$ is the same for SMBHs residing in halos of either mass class. Then, let us also assume that the duty cycle is not saturated (i.e. as long as $t_{\text{feed}} \times N_{\text{merge}} \lesssim 1$) and the e-folding timescale for the SMBH mass is $\sim 50$ Myr. Then the $z \sim 6$ SMBHs residing in $M_{\text{halo}} \sim 10^{12} M_\odot$ halos would be $\sim 20$
times less massive than those residing in $M_{\text{halo}} \sim 10^{13} \, M_\odot$ halos. This is roughly consistent with estimates of the halo-SMBH mass relation at lower redshifts. If we further assume that a plurality of halos in this mass range at $\sim z = 6$ hosts a SMBH, then the corresponding abundance of $M \sim 10^8 \, M_\odot$ SMBHs is $\sim 10^{-6} \, \text{Mpc}^{-3}$, also roughly consistent with observational estimates.

5. Conclusions

I have investigated the merger histories of dark matter halos at $z \gtrsim 6$, focusing on halos that are massive enough ($M(z = 6) \gtrsim 10^{12} \, M_\odot$) to plausibly host the $z \gtrsim 6$ quasars. Below is a summary of the findings.

(i) The mean major merger rate of the main progenitors of the $M(z = 6) \approx 10^{13} \, M_\odot$ halos is approximately equal to $|dz/dt| \propto (1 + z)^{5/2}$, all the way up to redshifts $z \sim 40$. This approximation is valid within a factor of two, whether one defines a major merger by a mass ratio threshold $\xi > 1/9$ or by $\xi > 1/3$. This result is consistent with expectations from semianalytic theory and results from large cosmological $N$-body simulations.

(ii) The steep evolution of the merger rate $dN_{\text{merg}}/dt$ directly implies that for a wide range of physical BH feeding mechanisms with duration $t_{\text{feed}}$, the duty cycle...
\[ f_{\text{dyn}} = \frac{dN_{\text{in}}}{d\tau} \times t_{\text{feed}} \] increases with redshift. While \( t_{\text{feed}} \) can in general depend on a myriad factors, I took advantage of the fact that the halos of interest here share closely similar assembly histories to conjecture that the feeding times for these halos can be characterized as a function of redshift with a reasonably small scatter. The formation of the \( z \gtrsim 6 \) quasar SMBHs can be explained without super-Eddington accretion, for both PopIII and direct collapse seed models, if \( t_{\text{feed}} \) is greater than several 10 Myr at \( z \approx 6 \) and scales with redshift as \((1 + z)^A\) with \( A \gtrsim -1.5 \), for scatter in \( t_{\text{feed}} \) of \( \sim 0.3 \) dex. This parameter space includes \( t_{\text{feed}} \lesssim t_{\text{dyne}}(z) = 230 \left[ (1 + z)/7 \right]^{-3/2} \) Myr. This finding suggests that the SMBH growth scenario suggested by Li et al [55] may be viable for a plurality of all dark matter halos at this mass scale that host a nuclear BH. (iii) The main progenitors of the \( z \gtrsim 6 \) quasar hosts become molecular-cooling (atomic-cooling) very early, at \( z \gtrsim 40 \) (\( z \gtrsim 30 \)), significantly earlier than halos in detailed cosmological simulations that focus on the formation of typical first stars and galaxies, at \( z \gtrsim 20 \) (\( z \gtrsim 10 \)). Such simulations may not be well-suited for studying the evolution of the \( z \gtrsim 6 \) quasar SMBHs, as they would underestimate the effects of halo growth and mergers, especially for PopIII seed models.

When considering the origins of the \( z \gtrsim 6 \) quasar SMBHs, it is important to keep in mind that the observed properties of \( z \gtrsim 6 \) galaxies are remarkably similar to what is found at later cosmological epochs: their masses are comparable to (but somewhat lower than) those of the most massive SMBHs and galaxies in the local Universe; the quasar spectra and metallicities appear identical to what is found at lower redshifts [17, 138]; they exhibit strong star formation [139] and winds [140] associated with post-merger quasar activity. In a similar vein, massive galaxies at \( z \sim 7–9 \) appear to already have metal-enriched stellar populations with ages of \( \sim 100 \) Myr [e.g. 141, 142].

The masses of both the \( z \gtrsim 6 \) quasar SMBHs and their hosts are comparable to the largest masses of SMBHs and galaxies found at lower redshifts. Indeed, the simple expectation from the theory of hierarchical structure formation is that the abundance of galaxies approaching the mass ceiling of galaxies [101] reaches \( \sim \text{Gpc}^{-3} \) by \( z \gtrsim 6 \). That is, the observation of SMBHs at the highest mass scales at \( z \gtrsim 6 \) is coincident with the emergence of the most massive class of galaxies—expected from theory, and observed to be fully evolved. It also follows from theory that after their relatively early arrival on the cosmic stage, the population of massive galaxies should evolve increasingly slowly as the Universe ages—at the largest masses due to the inhibition of gas cooling, and in general due to the precipitous drop in the frequency of major mergers (the triggers of starbursts and SMBH growth) toward low redshifts. This is qualitatively consistent with observed trends in the emergence and growth of the most massive SMBHs and galaxies throughout cosmic time [69, 143].

One then wonders: aside from their early formation, what is extraordinary about the \( z \gtrsim 6 \) quasars and their hosts? That their hosts are more compact, gas-rich and rapidly merging despite having similar masses to their low-redshift counterparts may result in their BHs having somewhat larger Eddington ratios [103] and being heavily obscured for large periods of time (in addition to their being possibly obscured at birth [33]). The latter possibility could negatively affect the detectability of \( z > 7 \) quasars by the James Webb Space Telescope and Athena+ at rest-frame UV and x-ray frequencies, respectively, while making large contributions to the cosmic infrared background [see, e.g. 144, 145]. The correlations between SMBHs and galaxy properties could differ from what is found in the local Universe [e.g. 139], depending on the details of the seeding and growth mechanisms [146, 147].

The formation and evolution of low-mass galaxies and their nuclear BHs may have proceeded quite differently at high redshifts, as gas cooling in small (proto-) galaxies is
known to be more sensitive to the temperature and ionization state of the inter- and circumgalactic media. The transition of the IGM from neutral <100 K gas at \( z \sim 20 \), to ionized gas with temperatures comparable to protogalactic virial temperatures and the atomic-cooling threshold at \( z \sim 7 \), would have affected star formation and BH growth in low-mass galaxies. It is interesting to note that the hosts of the \( z \geq 6 \) SMBHs were likely to be the least affected by this upheaval of the intergalactic environment [e.g. 7].

A minimalistic, zeroth-order ansatz would be that once their immediate environments are ionized and provided that they are above the cosmological Jeans (filtering) mass scale, the formation and evolution of galaxies—SMBHs, metallicities, winds and all—are driven primarily by the gravitational environment of their dark matter halos, at high and low redshift; that while the earliest galaxies and SMBHs at the largest mass scales arise and evolve rapidly, they do so without processes that are either rare or absent (e.g. highly super-Eddington accretion) in galaxies of similar mass at lower redshift. Or, we can turn this ansatz into a question: is there a redshift above which the evolution of massive galaxies and their SMBHs is qualitatively different from what is observed at \( z \lesssim 2 \)? Just as Turner (1991) [148] noted for \( z \sim 4 \) quasars, the formation of the \( z \geq 6 \) quasars could be explained within the confines of ‘conventional cosmic structure formation’.

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References

[1] Kormendy J and Richstone D 1995 Inward bound—the search for supermassive black holes in galactic nuclei Annu. Rev. Astron. Astrophys. 33 581
[2] Kormendy J and Ho L C 2013 Coevolution (or not) of supermassive black holes and host galaxies Annu. Rev. Astron. Astrophys. 51 511–653
[3] Madau P, Rees M J, Volonteri M, Haardt F and Oh S P 2004 Early reionization by miniquasars Astrophys. J. 604 484–94
[4] Fan X, Carilli C L and Keating B 2006 Observational constraints on cosmic reionization Annu. Rev. Astron. Astrophys. 44 415–62
[5] Gnedin N Y 2000 Effect of reionization on structure formation in the Universe Astrophys. J. 542 535–41
[6] Ripamonti E, Mapelli M and Zaroubi S 2008 Radiation from early black holes—I. Effects on the neutral intergalactic medium Mon. Not. R. Astron. Soc. 387 158–72
[7] Tanaka T, Perna R and Haiman Z 2012 X-ray emission from high-redshift miniquasars: self-regulating the population of massive black holes through global warming Mon. Not. R. Astron. Soc. 425 2974–87
[8] Tanaka T L, Li M and Haiman Z 2013 The effect of baryonic streaming motions on the formation of the first supermassive black holes Mon. Not. R. Astron. Soc. 435 5559–67
[9] Jeon M, Pawlik A H, Bromm V and Milosavljević M 2014 Radiative feedback from high-mass x-ray binaries on the formation of the first galaxies and early reionization Mon. Not. R. Astron. Soc. 440 3778–96
[10] Volonteri M 2010 Formation of supermassive black holes Astron. Astrophys. 18 279–315
[11] Haiman Z 2013 The formation of the first massive black holes (Astrophys. Space Sci. Libr. vol 396) ed T Wiklind, B Mobasher and V Bromm p 293
[12] Natarajan P 2014 Seeds to monsters Gen. Relativ. Gravit. 46 1702
[13] Fan X et al 2001 A survey of z > 5.8 quasars in the sloan digital sky survey: I Discovery of three new quasars and the spatial density of luminous quasars at z 6 Astron. J. 122 2833–49
[14] Fan X et al 2003 A survey of z > 5.7 quasars in the sloan digital sky survey II. Discovery of three additional quasars at z > 6 Astron. J. 125 1649–59
[15] Willott C J, McLure R J and Jarvis M J 2003 A 3 × 10³M⊙ black hole in the quasar SDSS J1148 + 5251 at z = 6.41 Astrophys. J. 587 15–18
[16] Willott C J et al 2010 The Canada–France high-z quasar survey: nine new quasars and the luminosity function at redshift 6 Astron. J. 139 906–18
[17] Mortlock D J et al 2011 A luminous quasar at a redshift of z = 7.085 Nature 474 616–9
[18] Venemans B P, Findlay J R, Sutherland W J, De Rosa G, McMahon R G, Simcoe R, González-Solares E A, Kuijken K and Lewis J R 2013 Discovery of three z > 6.5 quasars in the VISTA kilo-degree infrared galaxy (VIKING) survey Astrophys. J. 779 24
[19] de Rosa G et al 2013 Black hole mass estimates and emission-line properties of a sample of redshift z > 6.5 quasars Astrophys. J. 790 145
[20] Shapiro S L 2005 Spin, accretion, and the cosmological growth of supermassive black holes Astrophys. J. 620 59–68
[21] Pelupessy F I, di Matteo T and Ciardi B 2007 How rapidly do supermassive black hole ‘seeds’ grow at early times? Astrophys. J. 665 107–19
[22] Tanaka T and Haiman Z 2009 The assembly of supermassive black holes at high redshifts Astrophys. J. 696 1798–822
[23] King A 2003 Black holes, galaxy formation, and the M∗−σ relation Astrophys. J. 596 27–29
[24] Volonteri M and Rees M J 2005 Rapid growth of high-redshift black holes Astrophys. J. 633 624–9
[25] Begelman M C 2012 Force-feeding black holes Astrophys. J. 749 L3
[26] Wyithe S and Loeb A 2012 Photon trapping enables super-Eddington growth of black-hole seeds in galaxies at high redshift Mon. Not. R. Astron. Soc. 425 2892–2902
[27] Volonteri M and Silk J 2014 The case for super-critical accretion on massive black holes at high redshift arXiv:1401.3513
[28] Madau P, Haardt F and Dotti M 2014 Super-critical growth of massive black holes from stellar-mass seeds Astrophys. J. 784 L38
[29] Haiman Z and Loeb A 2001 What is the highest plausible redshift of luminous quasars? Astrophys. J. 552 459–63
[30] Madau P and Rees M J 2001 Massive black holes as population III remnants Astrophys. J. 551 27–30
[31] Bromm V and Loeb A 2003 Formation of the first supermassive black holes Astrophys. J. 596 34–46
[32] Koushiappas S M, Bullock J S and Dekel A 2004 Massive black hole seeds from low angular momentum material Mon. Not. R. Astron. Soc. 354 292–304
[33] Begelman M C, Volonteri M and Rees M J 2006 Formation of supermassive black holes by direct collapse in pre-galactic haloes Mon. Not. R. Astron. Soc. 370 289–98
[34] Lodato G and Natarajan P 2006 Supermassive black hole formation during the assembly of pre-galactic discs Mon. Not. R. Astron. Soc. 371 1813–23
[35] Spaans M and Silk J 2006 Pregalactic black hole formation with an atomic hydrogen equation of state Astrophys. J. 652 902–6
[36] Dijkstra M, Haiman Z, Mesinger A and Wyithe J S B 2008 Fluctuations in the high-redshift Lyman–Werner background: close halo pairs as the origin of supermassive black holes Mon. Not. R. Astron. Soc. 391 1961–72
[37] Shang C, Bryan G L and Haiman Z 2010 Supermassive black hole formation by direct collapse: keeping protogalactic gas H₂ free in dark matter haloes with virial temperatures Tvir ≥ 10⁴ K Mon. Not. R. Astron. Soc. 402 1249–62
[38] Agarwal B, Khochfar S, Johnson J L, Neistein E, Dalla Vecchia C and Livio M 2012 Ubiquitous seeding of supermassive black holes by direct collapse Mon. Not. R. Astron. Soc. 425 2854
[39] Inayoshi K and Omukai K 2012 Supermassive black hole formation by cold accretion shocks in the first galaxies Mon. Not. R. Astron. Soc. 422 2839–46
[40] Latif M A, Schleicher D R G, Schmidt W and Niemeyer J 2013 Black hole formation in the early Universe Mon. Not. R. Astron. Soc. 433 1607–18
[41] Prieto J, Jimenez R and Haiman Z 2013 Gas infall into atomic cooling haloes: on the formation of protogalactic discs and supermassive black holes at $z > 10$ Mon. Not. R. Astron. Soc. 436 2301–25
[42] Fernandez R, Bryan G L, Haiman Z and Li M 2014 H$_2$ suppression with shocking inflows: testing a pathway for supermassive black hole formation Mon. Not. R. Astron. Soc. 439 3798–807
[43] Tanaka T L and Li M 2014 The formation of massive black holes in $z \sim 30$ dark matter haloes with large baryonic streaming velocities Mon. Not. R. Astron. Soc. 439 1092–100
[44] Visbal E, Haiman Z and Bryan G L 2014 A no-go theorem for direct collapse black holes without a strong ultraviolet background Mon. Not. R. Astron. Soc. 442 L 100
[45] Inayoshi I and Tanaka T L 2014
[46] Haiman Z, Ciotti L and Ostriker J P 2004 Reasoning from fossils: learning from the local black hole population about the evolution of quasars Astrophys. J. 606 763–73
[47] Wang F-M, Chen Y-M and Zhang F 2006 Cosmological evolution of the duty cycle of quasars Mon. Not. R. Astron. Soc. 370 65–68
[48] Bahcall J N, Kirhakos S, Saxe D H and Schneider D P 1997 Hubble space telescope images of a sample of 20 nearby luminous quasars Astrophys. J. 479 642
[49] Kauffmann G and Haehnelt M 2000 A unified model for the evolution of galaxies and quasars Mon. Not. R. Astron. Soc. 311 576–88
[50] Taniguchi Y 2004 Starburst-AGN connection: a lesson from high-$z$ powerful radio galaxies Prog. Theor. Phys. Suppl. 155 202–8
[51] Li Y et al 2007 Formation of $z \sim 6$ quasars from hierarchical galaxy mergers Astrophys. J. 665 187–208
[52] Hopkins P F, Hernquist L, Cox T J and Kereš D 2008 A cosmological framework for the co-evolution of quasars, supermassive black holes, and elliptical galaxies: I. Galaxy mergers and quasar activity Mon. Not. R. Astron. Soc. 375 356–89
[53] Urrutia T, Lacy M and Becker R H 2008 Evidence for quasar activity triggered by galaxy mergers in HST observations of dust-reddened quasars Astrophys. J. 674 80–96
[54] Shen Y 2009 Supermassive black holes in the hierarchical Universe: a general framework and observational tests Astrophys. J. 704 89–108
[55] Treister E, Natarajan P, Sanders D B, Urry C M, Schawinski K and Kartaltepe J 2010 Major galaxy mergers and the growth of supermassive black holes in quasars Science 328 600
[56] Treister E, Schawinski K, Urry C M and Simmons B D 2012 Major galaxy mergers only trigger the most luminous active galactic nuclei Astrophys. J. 758 L 39
[57] McGreer I D, Fan X, Strauss M A, Haiman Z, Richards G T, Jiang L, Bian F and Schneider D P 2014 Close companions to two high-redshift quasars Astron. J. 148 73
[58] Grogin N A et al 2005 AGN host galaxies at $z \sim 0.4$–1.3: bulge-dominated and lacking merger-AGN connection Astrophys. J. 627 97–100
[59] Georgakakis A, Coil A L, Laird E S, Griffith R L, Nandra K, Lotz J M, Pierce C M, Cooper M C, Newman J A and Koekemoer A M 2009 Host galaxy morphologies of x-ray selected AGN: assessing the significance of different black hole fuelling mechanisms to the accretion density of the Universe at $z \sim 1$ Mon. Not. R. Astron. Soc. 397 623–33
[60] Cisternas M et al 2011 The bulk of the black hole growth since $z \sim 1$ occurs in a secular Universe: no major merger-AGN connection Astrophys. J. 726 57
[61] Draper A R and Ballantyne D R 2012 A tale of two populations: the contribution of merger and secular processes to the evolution of active galactic nuclei Astrophys. J. 751 72
[62] Zhang J, Fakhouri O and Ma C-P 2008 How to grow a healthy merger tree Mon. Not. R. Astron. Soc. 389 1521–38
[67] Hinshaw G et al 2013 Nine-year wilkinson microwave anisotropy probe (WMAP) observations: cosmological parameter results Astrophys. J. Suppl. 208 19
[68] Ade P A R et al 2014 Planck 2013 results: XVI. Cosmological parameters Astron. Astrophys. 571 A16
[69] Merloni A 2004 The anti-hierarchical growth of supermassive black holes Mon. Not. R. Astron. Soc. 353 1035–47
[70] Hopkins P F, Narayan R and Hernquist L 2006 How much mass do supermassive black holes eat in their old age? Astrophys. J. 643 641–51
[71] Kollmeier J A et al 2006 Black hole masses and Eddington ratios at 0.3 < z < 4 Astrophys. J. 648 128–39
[72] Netzer H, Lira P, Trakhtenbrot B, Shemmer O and Cury I 2007 Black hole mass and growth rate at high redshift Astrophys. J. 671 1256–63
[73] Ciotti L and Ostriker J P 2008 A synthesis model for AGN evolution: supermassive black holes growth and feedback modes Mon. Not. R. Astron. Soc. 388 1011–30
[74] Shankar F, Crocce M, Miralda-Escudé J, Fosalba P and Weinberg D H 2010 On the radiative efficiencies, Eddington ratios, and duty cycles of luminous high-redshift quasars Astrophys. J. 718 231–50
[75] Shankar F, Weinberg D H and Shen Y 2010 Constraints on black hole duty cycles and the black hole-halo relation from SDSS quasar clustering Mon. Not. R. Astron. Soc. 406 1959–66
[76] Richstone D et al 1998 Supermassive black holes and the evolution of galaxies Nature 395 A14
[77] Martini P and Weinberg D H 2001 Constraining the lifetime of quasars from their spatial clustering Mon. Not. R. Astron. Soc. 326 718–23
[78] White M, Martini P and Cohn J D 2008 Constraints on the correlation between QSO luminosity and host halo mass from high-redshift quasar clustering Mon. Not. R. Astron. Soc. 390 1179–84
[79] Ciotti L and Ostriker J P 2001 Cooling and activity of black holes and their host galaxies Mon. Not. R. Astron. Soc. 328 862–74
[80]di Matteo T, Springel V and Hernquist L 2005 Modelling feedback from stars and black holes in galaxy mergers Mon. Not. R. Astron. Soc. 361 776–94
[81]Bellovary J, Brooks A, Volonteri M, Governato F, Quinn T and Wadsley J 2013 The relative role of galaxy mergers and cosmic flows in feeding black holes Astrophys. J. 779 136
[82]Feng Y, di Matteo T, Croft R and Khandai N 2014 High-redshift supermassive black holes: accretion through cold flows Mon. Not. R. Astron. Soc. 440 1865–79
[83]Sijacki D, Vogelsberger M, Genel S, Springel V, Torrey P, Snyder G, Nelson D and Hernquist L 2014 The illustris simulation: evolving population of black holes across cosmic time arXiv:1408.6842
[84]Volonteri M and Rees M J 2006 Quasars at z = 6: the survival of the fittest Astrophys. J. 650 669–78
[95] Bekenstein J D 1973 Gravitational-radiation recoil and runaway black holes Astrophys. J. 183 657–64
[96] Baker J G, Centrella J, Choi D-I, Koppitz M, van Meter J R and Miller M C 2006 Getting a kick out of numerical relativity Astrophys. J. 653 93–96
[97] Campanelli M, Lousto C, Zlochower Y and Merritt D 2007 Large merger recoils and spin flips from generic black hole binaries Astrophys. J. 659 5–8
[98] Lapi A, Salucci P and Danese L 2013 Statistics of dark matter halos from the excursion set Class. Quantum Grav. 27 114006
[99] Olive-Altamirano P et al 2014 Galaxy and mass assembly (GAMA): testing galaxy formation models through the most massive galaxies in the Universe Mon. Not. R. Astron. Soc. 440 762–75
[100] Willott C J, Albert L, Arzoumanian D, Bergeron J, Crampton D, Delorme P, Hutchings J B, Oliva-Altamirano P et al 2012 Simulations of the formation, evolution and clustering of galaxies and quasars from the merger of generic black hole binaries Class. Quantum Grav. 31 (2014) 244005

Class. Quantum Grav. 31 (2014) 244005  T L Tanaka
[122] Narayan R and Yi I 1994 Advection-dominated accretion: a self-similar solution Astrophys. J. 428 13–16
[123] Blandford R D and Begelman M C 1999 On the fate of gas accreting at a low rate on to a black hole Mon. Not. R. Astron. Soc. 303 1–5
[124] Tanaka T and Menou K 2006 Hot accretion with conduction: spontaneous thermal outflows Astrophys. J. 649 348–60
[125] Johnson B M and Quataert E 2007 The effects of thermal conduction on radiatively inefficient accretion flows Astrophys. J. 660 1273–81
[126] Kuo C Y et al 2014 Measuring mass accretion rate onto the supermassive black hole in M87 using faraday rotation measure with the submillimeter array Astrophys. J. 783 L33
[127] Volonteri M, Haardt F and Madau P 2003 The assembly and merging history of supermassive black holes in hierarchical models of galaxy formation Astrophys. J. 582 559–73
[128] Bromley J M, Somerville R S and Fabian A C 2004 High-redshift quasars and the supermassive black hole mass budget: constraints on quasar formation models Mon. Not. R. Astron. Soc. 350 456–72
[129] Barkana R and Loeb A 2001 In the beginning: the first sources of light and the reionization of the Universe Phys. Rep. 349 125–238
[129] Koss M, Mushotzky R, Treister E, Veilleux S, Vasudevan R and Tripp M 2012 Understanding dual active galactic nucleus activation in the nearby Universe Astrophys. J. 746 L22
[130] Cotini S, Ripamonti E, Caccianiga A, Colpi M, della Ceca R, Mapelli M, Severgnini P and Segreto A 2013 The merger fraction of active and inactive galaxies in the local Universe through an improved non-parametric classification Mon. Not. R. Astron. Soc. 431 2661–72
[133] Ellison S L, Mendel J T, Scudder J M, Patton D R and Palmer M J D 2013 Galaxy pairs in the Sloan digital sky survey—VII. The merger-luminous infrared galaxy connection Mon. Not. R. Astron. Soc. 430 3128–41
[133] Alvarez M A, Wise J H and Abel T 2009 Accretion onto the first stellar-mass black holes Astrophys. J. 701 133–7
[134] Milosavljević M, Bromm V, Couch S M and Oh S P 2009 Accretion onto ‘seed’ black holes in the first galaxies Astrophys. J. 698 766–80
[135] Wise J H and Abel T 2007 Resolving the formation of protogalaxies: I. Virialization Astrophys. J. 665 899–910
[136] Greif T H, Johnson J L, Klessen R S and Bromm V 2008 The first galaxies: assembly, cooling and the onset of turbulence Mon. Not. R. Astron. Soc. 387 1021–36
[137] di Matteo T, Khandai N, DeGraf C, Feng Y, Croft R A C, Lopez J and Springel V 2012 Cold flows and the first quasars Astrophys. J. 745 L29
[138] Juarez Y, Maiolino R, Mujica R, Pedani M, Marinoni S, Nagao T, Marconi A and Oliva E 2009 The metallicity of the most distant quasars Astron. Astrophys. 494 25–28
[139] Wang R et al 2013 Star formation and gas kinematics of quasar host galaxies at z ∼ 6: new insights from ALMA Astrophys. J. 773 44
[140] Maiolino R et al 2012 Evidence of strong quasar feedback in the early Universe Mon. Not. R. Astron. Soc. 425 66–70
[141] Dunlop J S et al 2013 The UV continua and inferred stellar populations of galaxies at z ∼ 7–9 revealed by the hubble ultra-deep field 2012 campaign Mon. Not. R. Astron. Soc. 432 3520–33
[142] Labbé I et al 2013 The spectral energy distributions of z ∼ 8 galaxies from the IRAC ultra deep fields: emission lines, stellar masses, and specific star formation rates at 650 Myr Astrophys. J. 777 L19
[143] Collins C A et al 2009 Early assembly of the most massive galaxies Nature 458 603–6
[144] Yue B, Ferrara A, Salvaterra R, Xu Y and Chen X 2013 Infrared background signatures of the first black holes Mon. Not. R. Astron. Soc. 433 1556–66
[145] Helgason K, Cappelluti N, Hasinger G, Kashlinsky A and Ricotti M 2014 The contribution of z < ∼ 6 sources to the spatial coherence in the unresolved cosmic near-infrared and x-ray backgrounds Astrophys. J. 785 38
[146] Volonteri M and Natarajan P 2009 Journey to the MBH–seed relation: the fate of low-mass black holes in the Universe Mon. Not. R. Astron. Soc. 400 1911–8
[147] Agarwal B, Davis A J, Khochfar S, Natarajan P and Dunlop J S 2013 Unravelling obese black holes in the first galaxies Mon. Not. R. Astron. Soc. 432 3438–44
[148] Turner E L 1991 Quasars and galaxy formation. I—The Z greater than 4 objects Astron. J. 101 5–17