The sustainable growth of the first black holes

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ABSTRACT
Super-Eddington accretion has been suggested as a possible formation pathway of $10^9 M_\odot$ supermassive black holes (SMBHs) 800 Myr after the Big Bang. However, stellar feedback from BH seed progenitors and winds from BH accretion disks may decrease BH accretion rates. In this work, we study the impact of these physical processes on the formation of $z \sim 6$ quasar, including new physical prescriptions in the cosmological, data-constrained semi-analytic model GÂMETE/QSOdust. We find that the feedback produced by the first stellar progenitors on the surrounding does not play a relevant role in preventing SMBHs formation. In order to grow the $z \geq 6$ SMBHs, the accreted gas must efficiently lose angular momentum. Moreover disk winds, easily originated in super-Eddington accretion regime, can strongly reduce duty cycles. This produces a decrease in the active fraction among the progenitors of $z \sim 6$ bright quasars, reducing the probability to observe them.

Key words: accretion, accretion discs - black hole physics - quasars: supermassive black holes - galaxies: active - galaxies: high-redshift

1 INTRODUCTION
Observations of luminous ($L \gtrsim 10^{47}$erg/s) quasars at $z \sim 6$ reveal that these objects host in their centres supermassive black hole (SMBH) with $M_{\text{BH}} \gtrsim 10^9 M_\odot$. This poses strong constraints on theoretical models for the evolution of their last-massive progenitors (seeds). In fact, high-$z$ SMBHs must have formed in $z \lesssim 1$ Gyr, which is the corresponding age of the Universe at those redshifts. How did the first black holes (BHs) seeds grow so fast is still an open question.

First BH seeds should have been born at $z \gtrsim 15$ and different physical mechanisms for their formation have been proposed. The first main scenario predicts light seeds, consisting in Population III (Pop III) stellar remnants with mass $M_{\text{seed}} \sim [10\sim 1000] M_\odot$, formed at $z \gtrsim 20$ mostly in halos with $T_{\text{vir}} < 10^4$ K, called minihalos (Abel et al. 2002; Bromm et al. 2002; Turk et al. 2009; Tanaka & Haiman 2009). The second major channel predicts heavy seeds of $10^3 \sim 10^6 M_\odot$ formed by the direct collapse of a protogalactic gas cloud in Lyman-$\alpha$ (Ly$\alpha$) cooling halos (i.e. halos with $T_{\text{vir}} \gtrsim 10^4$ K) at $z \gtrsim 10$ (Bromm & Loeb 2003; Begelman et al. 2006; Volonteri & Rees 2006; Lodato & Natarajan 2006). The birth-place of direct-collapse black holes (DCBHs) should be metal-free, to prevent metal-line cooling and fragmentation, and has to be illuminated by a strong Lyman Werner flux to efficiently photo-dissociate $H_2$ molecules and prevent the gas from cooling and forming stars (Omukai et al. 2008). In order to build up $z \sim 6$ SMBHs, DCBH scenario may represent a head start, which helps in explaining the existence of such massive, early objects, by starting from high-mass seeds. However, the physical conditions required to their formation seem to be rare (Dijkstra et al. 2014; Habouzit et al. 2016; Chon et al. 2016; Valiante et al. 2016, but see Regan et al. 2017).

On the other hand, forming high-$z$ quasars starting from light seeds and assuming an Eddington limited growth would require uninterrupted gas accretion, which is quite unrealistic. In fact, feedback effects, produced by the accretion process itself, can strongly affect gas inflow in minihalos or, more generally, low-mass dark matter halos, reducing the probability to observe them.

In Pezzulli et al. (2016, hereafter P16) it is shown that $\sim 80\%$ of the mass of $z \sim 6$ SMBH with $M_{\text{BH}} \sim 10^6 M_\odot$ is grown via super-critical accretion events, which represent the dominant contribution at $z \gtrsim 10$. In fact, such accretion regime is favoured in dense, gas-rich environments characterized by high column densities, which are common at high redshift. On the contrary, the assumption of Eddington-limited accretion makes it impossible to reproduce the final SMBH mass.
This early super-Eddington accretion regime might provide an explanation for the current lack of faint AGN observations in the X-ray bands (Treister et al. 2013; Weigel et al. 2015; Georgakakis et al. 2015; Cappelluti et al. 2016; Vito et al. 2016). In fact, short episodes of mildly super-Eddington growth, followed by longer periods of quiescence may decrease the probability of observing BHs in active phases (Pezzulli et al. 2017, see also Prieto et al. 2017).

There are some physical processes that can suppress super-Eddington accretion in a cosmological context. First of all, the rate at which seed BHs can grow, immediately following their formation, strongly depends on the feedback effects of their stellar progenitors. This may create gas poor environment surrounding the BH, giving rise to a delay on the early growth of the first seeds (Johnson & Bromm 2007; Alvarez et al. 2009; Johnson & Haardt 2016). Moreover, an important factor which limits the duration of super-Eddington accretion is the feedback produced by the accretion process on the disk itself. In fact, a large fraction of the super-critical accretion power can drive disk winds, with a consequent loss of matter and, thus, a drop of the accretion rate (Bisnovatyi-Kogan & Blinnikov 1977; Icke 1980; Poutanen et al. 2007).

In this work, we investigate the impact that the above mechanisms have on the early growth of the first BHs, assessing the feasibility of super-Eddington accretion as a channel for the formation of the first SMBHs. To this aim, we study the relative impact of these hampering mechanisms for super-Eddington growth using the cosmological semi-analytic model presented in P16.

\section{Super-Critical Accretion Flows}

The model developed in P16 allows to reconstruct $N_r$ independent merger histories of a dark matter (DM) halo with $M_h = 10^{13} M_{\odot}$, assumed to host a typical $z \sim 6$ SMBH, like SDSS J1148 (e.g. Fan et al. 2004).

The time evolution of the mass of gas, stars, metals and dust in a two-phase interstellar medium (ISM) is self-consistently followed inside each progenitor galaxy and the model free parameters are fixed so as to reproduce some of the observed properties of the selected quasar (BH mass, gas mass, star formation rate, mass outflow rate radial profile).

The hot diffuse gas, that we assume to fill each newly virialized DM halo, can gradually cool. For minihalos, we consider the contribution of H$_2$, OI and CII cooling (Valiante et al. 2016), while for Ly$_\alpha$-cooling halos the main cooling path is represented by atomic transitions. In quiescent evolution, the gas settles on a rotationally-supported disk. It can be disrupted when a major merger ($M_{hi}/M_{hal} = \mu \geq 1/4$) occurs, forming a bulge structure, for which we adopt an Hernquist profile (Hernquist 1990).

In the model introduced in P16, we assume BH seeds to form with a constant mass of 100 $M_{\odot}$ as remnants of Pop III stars in halos with $Z \leq Z_{ci} = 10^{-4} Z_{\odot}$ (Valiante et al. 2016), without considering any stellar radiative feedback effect produced by the first luminous BH progenitors on their environment.

The BH can grow through gas accretion from the surrounding medium and via mergers with other BHs. Our prescription allows to consider quiescent and enhanced accretion, following merger-driven infall of cold gas, which loses angular momentum due to torque interactions between galaxies. We model the accretion rate to be proportional to the cold gas mass in the bulge $M_b$, and inversely proportional to the bulge dynamical time-scale $\tau_b$:

$$M_{acc} = \frac{f_{acc} M_b}{\tau_b}, \quad (1)$$

where $f_{acc} = \beta f(\mu)$, with $\beta = 0.03$ in the reference model and $f(\mu) = \max[1,1 + 2.5(\mu - 0.1)]$, so that mergers with $\mu \leq 0.1$ do not trigger bursts of gas accretion.

At high accretion rates, the standard thin disk model is no longer valid. Therefore, the bolometric luminosity $L_{bol}$ produced by the accretion process has been computed starting from the nu-
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Figure 3. Probability distribution function of the time duration of single super-Eddington accretion events for NL (top panels), L001 (middle panels) and L01 (bottom panels) models. Columns refer to different redshift intervals, $z = 20-25$ (left), $z = 15-20$ (center) and $z = 7-15$ (right), while colours indicate different mass of the BHs’ DM host halos, as labelled in the top-left panel. Vertical dotted lines represent the maximum and minimum values of time resolution $\Delta t$ of the simulation, in the related redshift interval.

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merical solution of the relativistic slim accretion disk obtained by Sadowski (2009), adopting the fit presented in Madau et al. (2014). This model predicts mildly super-Eddington luminosities even when the accretion rate is highly super-critical, limiting the impact of the feedback onto the host galaxy. The energy released by the AGN can then couple with the ISM. We consider energy-driven feedback, which produces powerful galactic-scale outflows, and SN-driven winds, computing the SN rate explosion for each galaxy according to the formation rate, age and initial mass function of its stellar population (de Bennassuti et al. 2014; Valiante et al. 2014).

Finally, in BH merging events, the newly formed BH can receive a large center-of-mass recoil due to the net linear momentum carried by the asymmetric gravitational wave (Campanelli et al. 2007; Baker et al. 2008). We take into account this effect, computing the kick velocities following Tanaka & Haiman (2009), under the assumption of a random distribution of BH spins and angles between the BH spin and the binary orbital angular momentum vectors.

We refer the reader to P16 for a more detailed description of the model. In the following paragraphs, we discuss the new features introduced in the model, i.e. the inclusion of the first stellar BH progenitors feedback on the surrounding gas, and a time-scale for the duration of a super-Eddington accretion event.
2.1 Seeding prescription

For each newly formed galaxy, we compute the star formation rate in the disk and in the bulge as $\dot{M}_{\text{disk}} = \dot{M}_{\text{bulge}} = \dot{M}_{\text{ BH}}$, where $\dot{M}_{\text{ BH}}$ and $\tau_{\text{ BH}}$ are the gas mass and the dynamical time of the disk (labelled ‘d’) and bulge (‘b’), respectively (see section 2.2.1 in P16 for further details).

Following Valiante et al. (2016), we assume Pop III stars to form when $Z < Z_{\text{crit}} = 10^{-4} Z_\odot$ in the mass range $[10 - 300] M_\odot$ according to a Larson IMF (Larson 1998):

$$\Phi(m_*) \propto m_*^{\alpha} e^{-m_*/m_{\text{crit}}},$$

with $\alpha = -1.35$, $m_{\text{crit}} = 20 M_\odot$ (de Bennassuti et al. 2014; Valiante et al. 2016).

For non-rotating stars with $Z = 0$, a $M_{\text{seed}} \sim 100$ $M_\odot$ BH is expected to form from $M_* \gtrsim 260 M_\odot$ (Valiante et al. 2016). We do not consider as light seeds BHs forming from $[40 - 140] M_\odot$ progenitors because lighter BHs are not expected to settle steadily in the minimum of the potential well, due to stellar interactions (Volonteri 2010). Moreover, we do not take into account stars with masses of $M_* = [140 - 260] M_\odot$, that are expected to explode as pair instability supernovae, leaving no remnants (Heger et al. 2003; Takahashi et al. 2016).

The probability to find a BH seed with, at least, $\sim 100$ $M_\odot$, after a single star formation episode is,

$$f_{\text{seed}} = \frac{\int_{100}^{\infty} m_\odot \Phi(m_*) dm_*}{\int_{0}^{\infty} m_* \Phi(m_*) dm_*}.$$  

Based on results obtained by Valiante et al. (2016) through random sampling of the IMF, the condition $f_{\text{seed}} \sim 1$ requires a minimum stellar mass formed in a single burst of $1000 M_\odot$. Thus, conservatively, we assume that one $100 M_\odot$ BH seed forms after a star-formation episode only if the total stellar mass formed $\Delta M_*$ is $\gtrsim 10^7 M_\odot$.

2.2 Stellar progenitors feedback

The stellar progenitors of the first BHs are massive primordial stars, expected to form in minihalos. Their large luminosities, with a huge production of ionizing radiation for few Myr before their collapse (e.g. Schaerer 2002), can couple with the surrounding gas and heat it above the virial temperature of the host dark matter halo. As a result, BH seeds likely form in low-density HII region (e.g. Whalen et al. 2004; Alvarez et al. 2006), with consequent low gas accretion rates (Alvarez et al. 2009; Johnson et al. 2013; Johnson & Haardt 2016). Due to this radiative feedback in minihalos, the newborn BH may wait up to 100 Myr before starting to accrete efficiently.

Another important impact on the early BH growth is produced by SN explosions of massive primordial stars, which can provide a strong limit to the gas reservoir from which Pop III relic BHs can accrete.

To take into account these negative feedback effects, we assume that, following each Pop III star formation burst, all the gas is blown out of the galaxy, in the intergalactic medium (IGM). In addition, to mimic the impact of photo-ionization and heating, which affect the large-scale inflow, we assume that gas accretion from the IGM is inhibited as long as the virial temperature of the host halo remains $T_{\text{vir}} < 10^4 K$. Furthermore, feedback produced by the first stars is strong enough to prevent further cooling and star formation within its host minihalo for the subsequent 200 Myr (Alvarez et al. 2009). For this reason, we suppress gas cooling in minihalos after the first star formation event, and relax this constraint only for halos with virial temperature $T_{\text{vir}} \gtrsim 10^5 K$.

2.3 The duration of super-Eddington accretion events

Idealistic slim accretion disk model predicts that a large fraction of the radiation produced by the accretion process can be advected into the BH instead of escaping. In fact, it is possible to define a radius $R_{\text{ad}}$ within which the trapping of radiation becomes relevant. Trapping of radiation occurs in regions of the accretion disk for
which the diffuse time scales $t_{\text{diff}}(r)$ is larger than the accretion time $t_{\text{acc}}(r)$. Imposing $t_{\text{diff}} = t_{\text{acc}}$, it is possible define the photon trapping radius $R_{\text{pt}}$ (Ohsuga et al. 2002):

$$R_{\text{pt}} = \frac{3}{2} \tilde{m} h R_s,$$

where $R_s = 2GM_{\odot}/c^2$ is the Schwarzschild radius, $\tilde{m} = M_{\text{acc}}/M_{\odot}$ is the Eddington accretion ratio and $h = H/r$ is the ratio between the half disk-thickness $H$ and the disk radius $r$. Since $h \approx 1$ in radiation pressure dominated regions, we assume $h = 2/3$ so that $R_{\text{pt}} = R_s \tilde{m}$.

In realistic cases, however, the accretion process can be suppressed. The outward angular momentum transport, necessary for accretion, also involves a transport of energy. This produces unbounding of gas far from the BH, thus less gas has the possibility to reach it. Moreover, a significant fraction of the accretion power in super-critical flows may drive disk winds. In fact, at large luminosities, flows are supported by radiation pressure, which is likely to induce outflows (Shakura & Sunyaev 1973; Bisnovatyi-Kogan & Blinnikov 1977; Icke 1980; Ohsuga et al. 2005; Poutanen et al. 2007). Results of recent simulations suggest that the mass lost due to disk winds becomes relevant only as photon trapping becomes less important, i.e. in the outer region of the disk (Ohsuga & Mineshige 2007; Takeuchi et al. 2009; Begelman 2012; Sadowski et al. 2014). As already discussed in Volonteri et al. (2015), it is thus possible to assume that a significant disk wind is produced only after the disk radius has reached some fraction of the trapping radius. When this occurs, the mass lost to the outflow reduces the gas accretion rate, which can drop to 10 – 20% of the inflow rate (e.g. Ohsuga & Mineshige 2007), decelerating the BH growth. In addition, the mass outflow increases with the disk radius (Volonteri et al. 2015), so that both effects can eventually quench black hole growth once the trapping radius is reached (see also Volonteri & Rees 2005; Volonteri et al. 2015).

Following Volonteri et al. (2015), we assume that once the disk radius $R_D$ reaches $R_{\text{pt}}$, the disk is blown away, and the accretion process is no longer sustained. This reflects into a condition on the maximum time for which super-Eddington accretion can be sustained\(^1\) (Volonteri et al. 2015):

$$t_{\text{acc}} = 2\lambda^2 \left(\frac{\sigma}{c}\right)^2 t_{\text{diff}},$$

where $t_{\text{diff}} = 0.45$ Gyr is the Eddington time, $\lambda \leq 1$ is the fraction of angular momentum retained by the gas and $\sigma$ is the gas velocity dispersion. The parameter $\lambda$ is defined as the specific angular momentum $L_{\phi}$ of matter crossing the BH sphere of influence, normalized to the Keplerian value, i.e. $\lambda = L_{\phi}/\sqrt{GM_{\odot}R_s^2}$, where $R_s = GM_{\odot}/c^2$.

Since $R_D \ll L_{\phi}$, smaller values of $\lambda$ lead to smaller disk sizes and hence to a prolonged phase of super-Eddington accretion, $t_{\text{acc}}$. For the present study we investigate two different values, $\lambda = 0.01$ and $\lambda = 0.1$. The latter is suggested by studies of angular momentum losses for gas feeding SMBHs during galaxy mergers. Capelo et al. (2015) find $\lambda < 0.5$ (with mean and median values of 0.28 and 0.27, respectively), in simulations with gas softening length of 20 pc. The former represent a more optimistic, but not extreme, case (see Begelman & Volonteri 2017, for a discussion).

### 3 RESULTS

In this section, we explore the impact of stellar feedback and of the disk outflow comparing the results of the new models with those found in P16 where the above effects were not considered. Models with stellar feedback and $\lambda = 0.1$ and 0.01 have been labelled as L01 and L001, respectively. The model P16 described in Sec. 2, including stellar feedback and no disk outflow has been labelled NL. This implies that the only difference between L01 (or L001) and NL resides in accounting or not for disk winds effects. For each model, the results must be intended as averaged over $N_s = 5$ simulations.

#### 3.1 The impact of Stellar feedback

Figure 1 shows the redshift distribution of newly formed BH seeds with (green histograms, NL model) and without (black histograms, P16 model) the effect of stellar feedback. In the no-feedback case, due to efficient metal enrichment, Pop III star formation becomes negligible below $z \sim 20$. The inclusion of stellar feedback causes a shift of BH seed formation to lower redshift. Moreover, while in the no-feedback model we find $\sim 90\%$ of BH-seeds hosts are minihalos, once feedback is considered native galaxies are mostly Ly\textalpha-cooling halos. This stems from the condition that a 100 $M_\odot$ BH remnant requires a minimum Pop III stellar mass of $\sim 10^3 M_\odot$ formed in a single burst, which can be hardly accomplished in minihalos, due to the low-efficiency feedback-limited star formation. The effect is that Pop III stars sterilize minihalos, without giving birth to a BH seed (Ferrara et al. 2014). Once minihalos have grown enough mass to exceed $T_{\text{cool}} = 10^4$ K, gas cooling is more efficient and 100 $M_\odot$ BH seeds have a larger probability to form. As a result, BH seeds continue to form down to $z \sim 15$ in the NL model, in good agreement with what found in Valiante et al. (2016).

#### 3.2 Super-Eddington duration

To understand the impact of the duration of super-Eddington accretion episodes on high-$z$ SMBHs growth, we have compared the L01 and L001 cases with the NL model. In the NL model, disk winds effects are not considered. Thus, the accreting event - and its lifetime - depends only on the presence, in a galaxy, of a BH surrounded by a gas reservoir. Since there is no apriori constraint on the accretion time-scale, it is possible to invert Equation 5 and obtain the distribution of $\lambda$ values shown in Figure 2.

Model NL results in values of $\lambda$ smaller than assumed in models L01 and L001, with $10^{-4} \leq \lambda \leq 10^{-1}$. We find slightly increasing values of $\lambda$ for decreasing redshift, with wider distributions at lower $z$. This effect is dominated by an increasing dispersion in the values of $c$ for decreasing redshift. In fact, the duration of super-Eddington accretion, $t_{\text{acc}}$, follows a narrow distribution around the time resolution $\Delta t$, of the simulation at the corresponding redshift, with BHs accreting at most $\sim$ few times $\Delta t$ (see the top row of Fig. 3). These short durations are consequence of the rapid depletion of gas produced by efficient super-Eddington accretion, which represents the dominant contribution at all but the latest redshift of the SMBH evolution (see P16 for details). Conversely, in models L001 and L01 we have limited super-Eddington accretion to $t_{\text{acc}}$ as obtained from Equation 5, with resulting distributions shown in the
middle (L001) and bottom (L01) panels of Figure 3. It is interesting to note that, under the assumption of $\lambda = 0.01$ or $\lambda = 0.1$, the accretion time-scales at $z > 15$ are shorter than adopted in P16 (hence in the NL model). In fact, larger values of $\lambda$ implies less compact objects and, thus, larger values of $K_z$. This gives rise to shorter super-Eddington accretion episodes. For $z = 20 - 25$, where the entire population of active BHs is accreting at super-critical regimes, the L01 model predicts an accretion-time distribution peaking around $t_{\text{accr}} \sim 100$ yr, to be compared with $t_{\text{accr}} \sim 0.01 (\sim 1)$ Myr in L001 (NL) model, respectively. For lower $z$, the contribution of active galaxies with large gas velocity dispersion $\sigma$ becomes relevant, and the accretion times $t_{\text{accr}}$ become larger. For instance, in the L001 model it is possible to find BHs accreting for longer times (up to $\sim 30$ Myr) with respect to the NL model, where $t_{\text{accr}} \sim 1$ Myr.

The distribution of $t_{\text{accr}}$ shows an increasing trend with increasing dark matter halo mass. This effect is negligible in the narrow distribution predicted by model NL. In models L01 and L001, instead, one order of magnitude increase in dark matter halo masses corresponds to increasing $\frac{z}{6}$ half order of magnitude accretion time-scales $t_{\text{accr}}$.

It is interesting to compare how different assumptions on $\lambda$ affect the BH mass growth. In the left panel of Figure 4 we show the evolution of the total (solid) BH mass, summing over all the progenitors present in the simulation at a given redshift. Dashed lines represent the time evolution of the most massive BH that powers the $z \sim 6$ quasar. At high-$z$, the difference in the total BH mass between NL and L001 models is about one order of magnitude, as a consequence of different total black hole accretion rates (Hanning smoothed), shown in the right panel of Figure 4. This quantity is computed as $M_{\text{BH}} = \Delta M_{\text{BH}} / \Delta t$, i.e. as the average BH mass increase in the simulation time-step $\Delta t$, even if $t_{\text{accr}} < \Delta t$. Hence, lower BH accretion rates are a consequence of the lower $t_{\text{accr}}$. More gas is retained by dark matter halos due to reduced AGN feedback effects, leading to larger BH accretion rates at later times. As a result, in model L01 the total BH mass follows a steeper evolution at $z < 10$ compared to model NL, reaching a factor 2 larger value at $z = 6.4$.

Conversely, the accretion time-scales, $t_{\text{accr}}$, in the L01 model are too small to allow an efficient BH mass growth. Almost all the BHs present in model L01 accrete at super-Eddington rates for $t_{\text{accr}} \sim 100 - 1000$ yr. This leads to a BH mass growth from $\sim 10^5 M_\odot$ to $10^6 M_\odot$ between $z = 15 - 22$ and to a final BH mass $\sim 2$ orders of magnitude lower than predicted by L001 and NL models.

4 CONCLUSIONS

Many models invoke super-Eddington accretion onto the first black holes as a possible route to form high-$z$ SMBHs (Volonteri & Rees 2005; Wyithe & Loeb 2012; Madonna et al. 2014; Alexander & Natarajan 2014; Volonteri et al. 2015; Inayoshi et al. 2015; Sakurai et al. 2016; Ryu et al. 2016; Begelman & Volonteri 2017). In P16, we have shown that super-Eddington accretion is required to form a $\sim 10^6 M_\odot$ SMBH at $z \sim 6$ starting from $\sim 100 M_\odot$ BH remnants of very massive Pop III stars. However, there are different mechanisms which can suppress early super-critical accretion. Feedback effects from the stellar progenitors can strongly affect the gas density around the newborn black holes, reducing the efficiency of gas accretion. In addition, the onset of disk winds can suppress BH growth, setting a maximum time-scale for sustainable super-Eddington accretion.

In this work, we used the cosmological, data-constrained semi-analytic model GAMEETE/QSOdust, described in P16, to estimate the impact of these two physical processes on SMBHs formation at $z > 6$.

We find that the influence of stellar feedback on the surroundings produces a delay on BH seeds formation, shifting their redshift distribution from $z \sim 20$ to $z \sim 15$. However, despite the very conservative assumptions made to maximize stellar feedback effects, we find that this delay does not prevent neither the growth of high-$z$ SMBHs, nor the possibility of their BH progenitors to accrete at super-Eddington rates.

The impact of disk outflows, and the associated reduction of the duration of super-eeddington accretion episodes, strongly depends on the angular momentum of gas joining the accretion disk. Assuming that disk winds suppress BH accretion when the disk radius becomes comparable to the photon trapping radius, the result relies on the value of $\lambda$, which represents the fraction of angular momentum retained by the gas. For $\lambda = 0.1$, $t_{\text{accr}} \sim 100 - 10^4$ yr at $z > 15$, too short to allow the SMBH to grow efficiently, and at $z \sim 6$ the final SMBH mass is $\sim 2$ orders of magnitude lower than what obtained in the model where disk winds are neglected. For $\lambda = 0.01$, instead, super-critical accretion events are sustained for time-scales $\sim 10^4 - 10^6$ yr. This suppresses the early growth phase, but the larger gas mass retained allows a steeper growth of the SMBH mass at later times.

The implication of this study is that the accreted gas must efficiently loose angular momentum to enable super-Eddington growth of the first SMBHs from light BH seeds. If $\lambda < 0.01$, super-Eddington accretion has a very short duty cycle, with $t_{\text{accr}} \ll$ Myr at $z > 15$ and for $\sim 0.1$ Myr for $z = 7 - 15$. This decreases the active fraction of high-$z$ BHs and further strengthens the conclusions of Pezzulli et al. (2017), that the higher-redshift progenitors of $z \sim 6$ quasars are difficult to observe “in the act”, as the short and intermittent super-critical accretion events imply a low fraction of active black holes.

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