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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 $10^9\,\mathrm{M}_\odot$ supermassive black holes (SMBHs) 800 Myr after the big bang. However, stellar feedback from BH seed progenitors and winds from BH accretion discs 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 GAMETE/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 $z \gtrsim 6$ SMBHs, the accreted gas must efficiently lose angular momentum. Moreover, disc 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 – galaxies: active – galaxies: high-redshift.

1 INTRODUCTION

Observations of luminous ($L \gtrsim 10^{47}\,\mathrm{erg\,s^{-1}}$) quasars at $z \sim 6$ reveal that these objects host in their centres supermassive black hole (SMBH) with $M_{\mathrm{BH}} \gtrsim 10^9\,\mathrm{M}_\odot$. This poses strong constraints on theoretical models for the evolution of their less-massive progenitors (seeds). In fact, high-z SMBHs must have formed in $\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 $M_{\mathrm{seed}} \sim [10\text{–}1000]\,\mathrm{M}_\odot$, formed at $z \gtrsim 20$ mostly in haloes with $T_{\mathrm{vir}} < 10^4$ K, called minihaloes (Abel, Bryan & Norman 2002; Bromm, Coppi & Larson 2002; Turk, Abel & O'Shea 2009; Tanaka & Haiman 2009). The second major channel predicts *heavy* seeds of 10^5–$10^6\,\mathrm{M}_\odot$ formed by the direct collapse of a protogalactic gas cloud in Lyman-α (Ly α) cooling haloes (i.e. haloes with $T_{\mathrm{vir}} \geq 10^4$ K) at $z \gtrsim 10$ (Bromm & Loeb 2003; Begelman, Volonteri & Rees 2006; Lodato & Natarajan 2006; Volonteri & Rees 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 photodissociate H_2 molecules and prevent the gas from cooling and forming stars (Omukai, Schneider & Haiman 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, Ferrara & Mesinger 2014; Chon et al. 2016; Habouzit 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 minihaloes or, more generally, low-mass dark matter haloes, resulting in negligible mass growth (Johnson & Bromm 2007; Alvarez, Wise & Abel 2009; Milosavljević et al. 2009; Madau, Haardt & Dotti 2014). A possible solution is the occurrence of short, episodic super-Eddington accretion events (Haiman 2004; Shapiro 2005; Volonteri & Rees 2005; Pelupessy, Di Matteo & Ciardi 2007; Tanaka & Haiman 2009; Madau, Haardt & Dotti 2014; Volonteri, Silk & Dubus 2015; Pezzulli, Valiante & Schneider 2016). Moreover, thanks to an early, efficient super-critical growth, it is possible to achieve in $\sim$ few Myr a BH mass comparable to what predicted by the direct collapse scenario (Madau et al. 2014; Lupi et al. 2016).

In Pezzulli et al. (2016, hereafter P16), it is shown that $\sim$80 per cent of the mass of $z \sim 6$ SMBH with $M_{\mathrm{BH}} \sim 10^9\,\mathrm{M}_\odot$ is grown via super-critical accretion events, which represent the dominant contribution at $z \gtrsim 10$. In fact, such accretion regime

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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 active galactic nucleus (AGN) observations in the X-ray bands (Treister et al. 2013; Georgakakis et al. 2015; Weigel 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 that limits the duration of super-Eddington accretion is the feedback produced by the accretion process on the disc itself. In fact, a large fraction of the super-critical accretion power can drive disc 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.

2 SUPER-CRITICAL ACCRETION FLOWS

The model developed in P16 allows us to reconstruct N_r independent merger histories of a dark matter (DM) halo with $M_{\rm h} = 10^{13}\,{\rm M}_{\odot}$, 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 minihaloes, we consider the contribution of H_2, O I and C II cooling (Valiante et al. 2016), while for Ly α-cooling haloes, the main cooling path is represented by atomic transitions. In quiescent evolution, the gas settles on a rotationally supported disc. It can be disrupted when a major merger ($M_{\rm h,\,1}/M_{\rm h,\,2} = \mu \geq 1/4$) occurs, forming a bulge structure, for which we adopt a Hernquist profile (Hernquist 1990).

In the model introduced in P16, we assume BH seeds to form with a constant mass of $100\,{\rm M}_{\odot}$ as remnants of Pop III stars in haloes with $Z \leq Z_{\rm cr} = 10^{-4}\,{\rm Z}_{\odot}$ (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 us 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 $M_{\rm b}$, and inversely proportional to the bulge dynamical time-scale $\tau_{\rm b}$:

$$\dot{M}_{\rm accr} = \frac{f_{\rm accr} M_{\rm b}}{\tau_{\rm b}}, \tag{1}$$

where $f_{\rm accr} = \beta f(\mu)$, 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* disc model is no longer valid. Therefore, the bolometric luminosity $L_{\rm bol}$ produced by the accretion process has been computed starting from the numerical solution of the relativistic slim accretion disc obtained by Sądowski (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 on to 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 centre-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 disc and in the bulge as $\dot{M}^{\star}_{\rm d,b} \propto M_{\rm d,b}/\tau_{\rm d,b}$, where $M_{\rm d,\,b}$ and $\tau_{\rm d,\,b}$ are the gas mass and the dynamical time of the disc (labelled 'd') and bulge (labelled '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 $Z < Z_{\rm cr} = 10^{-4}\,{\rm Z}_{\odot}$ in the mass range according to a Larson initial mass function (IMF; Larson 1998):

$$\Phi(m_\star) = \frac{{\rm d}N(m_\star)}{{\rm d}m_\star} \propto m_\star^{\alpha-1} {\rm e}^{-m_\star/m_{\rm ch}}, \tag{2}$$

with $\alpha = -1.35$, $m_{\rm ch} = 20\,{\rm M}_{\odot}$ (de Bennassuti et al. 2014; Valiante et al. 2016).

For non-rotating stars with $Z = 0$, an $M_{\rm seed} \sim 100\,{\rm M}_{\odot}$ BH is expected to form from $M_\star \gtrsim 260\,{\rm M}_{\odot}$ (Valiante et al. 2016). We do not consider as light seeds BHs forming from [40–140] ${\rm M}_{\odot}$ 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 $M_\star = [140–260]\,{\rm M}_{\odot}$, which 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

$$f_{\rm seed} = \frac{\int_{260}^{300} m_\star \Phi(m_\star)\, {\rm d}m_\star}{\int_{10}^{300} m_\star \Phi(m_\star)\, {\rm d}m_\star}. \quad (3)$$

Based on results obtained by Valiante et al. (2016) through random sampling of the IMF, the condition $f_{\rm seed} \sim 1$ 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 $\Delta M_\star$ is $\geq 10^3$ $M_\odot$.

2.2 Stellar progenitors feedback

The stellar progenitors of the first BHs are massive primordial stars, expected to form in minihaloes. 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 H II region (e.g. Whalen, Abel & Norman 2004; Alvarez, Bromm & Shapiro 2006), with consequent low gas accretion rates (Alvarez et al. 2009; Johnson et al. 2013; Johnson & Haardt 2016). Due to this radiative feedback in minihaloes, 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 photoionization 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 $T_{\rm vir} < 10^4$ 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 minihaloes after the first star formation event, and relax this constraint only for haloes with virial temperature $T_{\rm vir} \geq 10^4$ K.

2.3 The duration of super-Eddington accretion events

Idealistic slim accretion disc 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 $R_{\rm pt}$ within which the trapping of radiation becomes relevant. Trapping of radiation occurs in regions of the accretion disc for which the diffuse time-scales $t_{\rm diff}(r)$ is larger than the accretion time $t_{\rm accr}(r)$. Imposing $t_{\rm diff} = t_{\rm accr}$, it is possible to define the photon trapping radius $R_{\rm pt}$ (Ohsuga et al. 2002) :

$$R_{\rm pt} = \frac{3}{2} \dot{m}\, h\, R_{\rm s}, \quad (4)$$

where $R_{\rm s} = 2GM_{\rm BH}/c^2$ is the Schwarzschild radius, $\dot{m} = \dot{M}_{\rm accr}/\dot{M}_{\rm Edd}$ is the Eddington accretion ratio and $h = H/r$ is the ratio between the half disc-thickness H and the disc radius r. Since $h \approx 1$ in radiation pressure dominated regions, we assume $h = 2/3$ so that $R_{\rm pt} = R_{\rm s}\dot{m}$.

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 disc 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 disc winds becomes relevant only as photon trapping becomes less important, i.e. in the outer region of the disc (Ohsuga & Mineshige 2007; Takeuchi, Mineshige & Ohsuga 2009; Begelman 2012; Sądowski et al. 2014). As already discussed in Volonteri et al. (2015), it is thus possible to assume that a significant disc wind is produced only after the disc radius has reached some significant 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 per cent of the inflow rate (e.g. Ohsuga & Mineshige 2007), decelerating the BH growth. In addition, the mass outflow increases with the disc radius (Volonteri et al. 2015) so that both effects can eventually quench BH 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 disc radius $R_{\rm d}$ reaches $R_{\rm pt}$, the disc 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):

$$t_{\rm accr} = 2\lambda^{-2} \left(\frac{\sigma}{c}\right)^2 t_{\rm Edd}, \quad (5)$$

where $t_{\rm Edd} = 0.45$ Gyr is the Eddington time, $\lambda \leq 1$ is the fraction of angular momentum retained by the gas and σ is the gas velocity dispersion. The parameter λ is defined as the specific angular momentum ℓ_g of matter crossing the BH sphere of influence, normalized to the Keplerian value, i.e. $\lambda = \ell_g/\sqrt{GM_{\rm BH}R_{\rm g}}$, where $R_{\rm g} = GM_{\rm BH}/\sigma^2$.

Since $R_{\rm d} \propto \lambda^2$, smaller values of λ lead to smaller disc sizes and hence to a prolonged phase of super-Eddington accretion, $t_{\rm accr}$.

For this 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 represents 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 disc 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 Section 2, including stellar feedback and no disc outflow, has been labelled NL. This implies that the only difference between L01 (or L001) and NL resides in accounting or not for disc winds effects. For each model, the results must be intended as averaged over $N_r = 5$ simulations.

[1] Being the disc radius $R_{\rm d} = \lambda^2 R_{\rm g} = \lambda^2\, GM_{\rm BH}/\sigma^2$, and the Eddington luminosity $L_{\rm Edd} = t_{\rm Edd}/(M_{\rm BH}c^2)$, approximating $M_{\rm BH} = \dot{M}_{\rm BH}t$, the condition $R_{\rm d} \leq R_{\rm pt}$ turns into the inequality $(\lambda c/\sigma)^2 (M_{\rm BH}/2t_{\rm Edd}\dot{M}_{\rm BH}) \leq 1$.

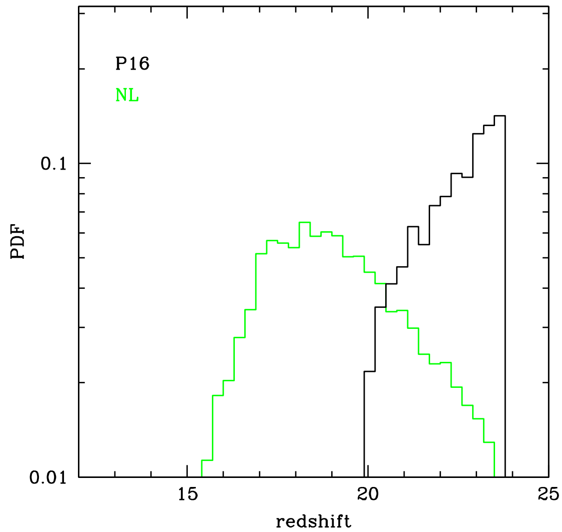

Figure 1. Probability distribution function (PDF) of 100 $M_\odot$ BH seeds formation redshifts. PDFs are averaged over five realizations. Green (black) histograms represent models with (NL) and without (P16) stellar feedback on to BH formation sites.

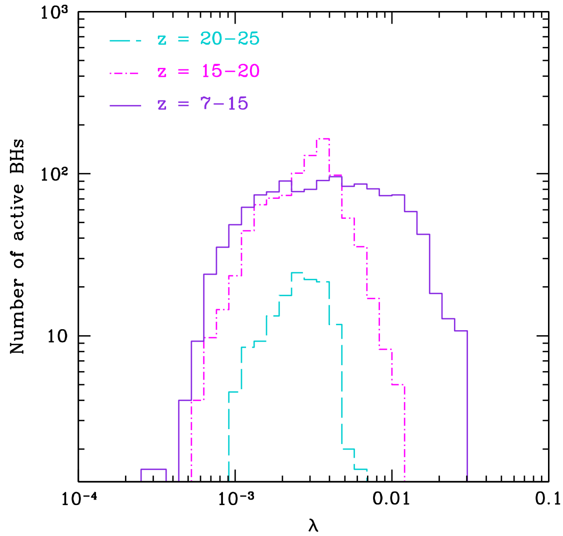

Figure 2. Distribution of the parameter λ in the redshift intervals $z = 20$–25 (turquoise, dashed), $z = 15$–20 (magenta, dash-dotted) and $z = 7$–15 (violet, solid) for NL model.

3.1 The impact of stellar feedback

Fig. 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 ∼90 per cent of BH-seed hosts are minihaloes, once feedback is considered, native galaxies are mostly Lyα-cooling haloes. This stems from the condition that a 100 $M_\odot$ BH remnant requires a minimum Pop III stellar mass of $\Delta M_\star \sim 10^3\, M_\odot$ formed in a single burst, which can be hardly accomplished in minihaloes, due to the low-efficiency feedback-limited star formation. The effect is that Pop III stars sterilize minihaloes, without giving birth to a BH seed (Ferrara et al. 2014). Once minihaloes have grown enough mass to exceed $T_{\rm vir} = 10^4$ 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, disc 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 a priori constraint on the accretion time-scale, it is possible to invert equation (5) and obtain the distribution of λ values shown in Fig. 2.

Model NL results in values of λ smaller than assumed in models L01 and L001, with $10^{-4} \lesssim \lambda \lesssim 10^{-1}$. We find slightly increasing values of λ for decreasing redshift, with wider distributions at lower z. This effect is dominated by an increasing dispersion in the values of σ for decreasing redshift. In fact, the duration of super-Eddington accretion, $t_{\rm accr}$, follows a narrow distribution around the time resolution $\Delta t_{\rm r}$ of the simulation at the corresponding redshift, with BHs accreting at most ∼ few times $\Delta t_{\rm r}$ (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 $t_{\rm accr}$ as obtained from equation (5), with resulting distributions shown in the middle (L001) and bottom (L01) panels of Fig. 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 λ imply less compact objects and, thus, larger values of $R_{\rm d}$. 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 $t_{\rm accr} \sim 100$ yr, to be compared with $t_{\rm accr} \sim 0.01$ (∼1) Myr in L001 (NL) model, respectively. For lower z, the contribution of active galaxies with large gas velocity dispersion σ becomes relevant, and the accretion times $t_{\rm accr}$ become larger. For instance, in the L001 model, it is possible to find BHs accreting for longer times (up to ∼30 Myr) with respect to the NL model, where $t_{\rm accr} \sim 1$ Myr.

The distribution of $t_{\rm accr}$ 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 $\gtrsim$ half order of magnitude accretion time-scales $t_{\rm accr}$.

It is interesting to compare how different assumptions on λ affect the BH mass growth. In the left-hand panel of Fig. 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 BH accretion rates

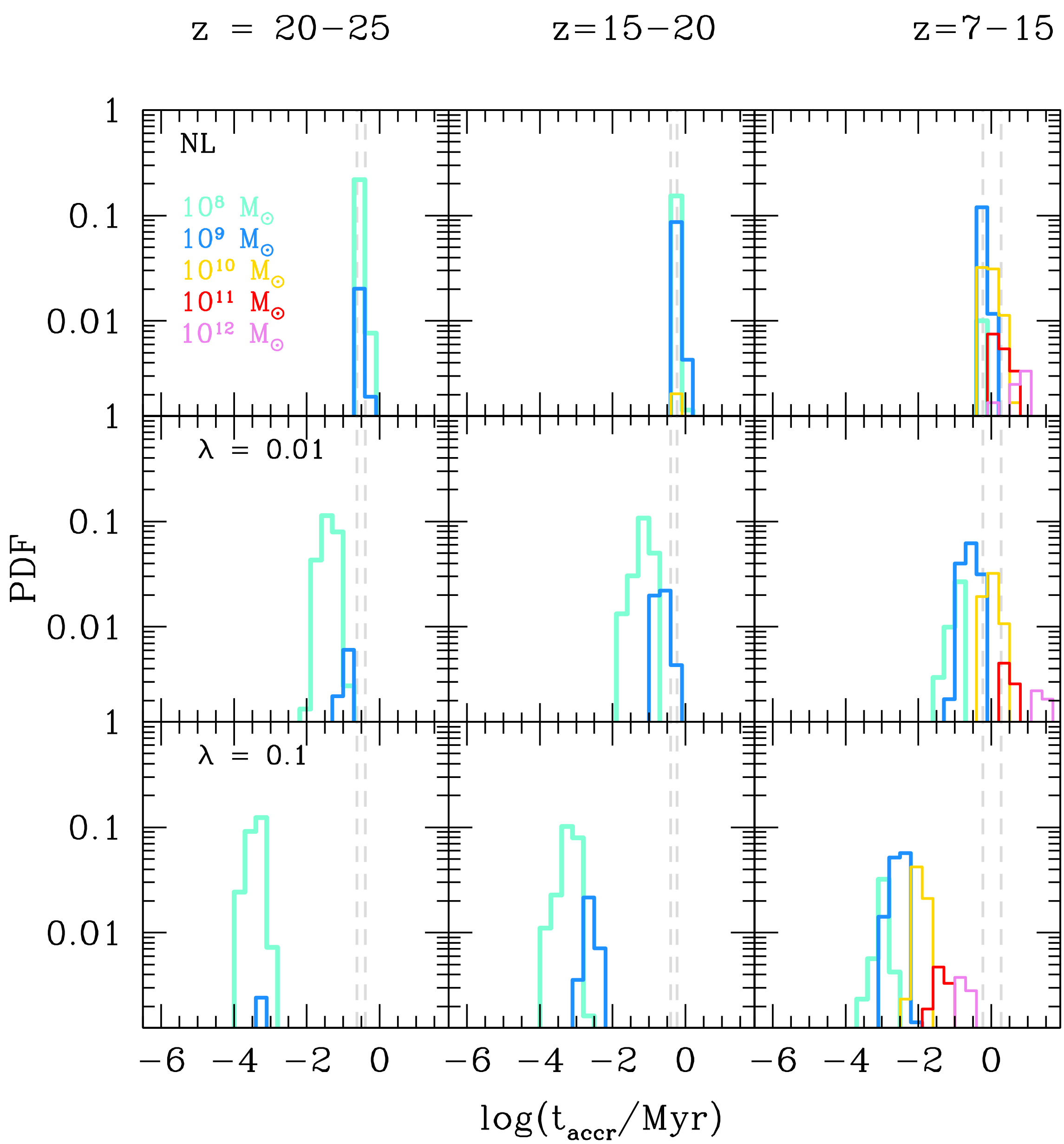

Figure 3. Probability distribution function of the time duration of single super-Eddington accretion events for NL (top panels), L001 (middle panels) and L01 (bottom panels) models. Columns refer to different redshift intervals, $z = 20–25$ (left hand), $z = 15–20$ (centre) and $z = 7–15$ (right hand), while colours indicate different mass of the BHs' DM host haloes, as labelled in the top left-hand panel. Vertical dotted lines represent the maximum and minimum values of time resolution Δt_r of the simulation, in the related redshift interval.

(Hanning smoothed), shown in the right-hand panel of Fig. 4. This quantity is computed as $\dot{M}_{BH} = \Delta M_{BH}/\Delta t_r$, i.e. as the average BH mass increase in the simulation time-step Δt_r, even if $t_{accr} < \Delta t_r$. Hence, lower BH accretion rates are a consequence of the lower t_{accr}. More gas is retained by dark matter haloes due to reduced AGN feedback effects, leading to larger BH accretion rates at later times. As a result, in model L001, 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_{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 $t_{accr} \sim 100-1000$ yr. This leads to a BH mass growth from $\sim 10^5$ to $10^6\,M_\odot$ between $z = 15$ and 22 and to a final BH mass ∼2 orders of magnitude lower than predicted by L001 and NL models.

4 CONCLUSIONS

Many models invoke super-Eddington accretion on to the first BHs as a possible route to form high-z SMBHs (Volonteri & Rees 2005; Wyithe & Loeb 2012; Alexander & Natarajan 2014; Madau, Haardt & Dotti 2014; Inayoshi, Haiman & Ostriker 2016; Volonteri, Silk & Dubus 2015; Ryu et al. 2016; Sakurai, Inayoshi & Haiman 2016; Begelman & Volonteri 2017). In P16, we have shown that super-Eddington accretion is required to form a $\sim 10^9\,M_\odot$ SMBH at $z \sim 6$ starting from $\sim 100\,M_\odot$ BH remnants of very

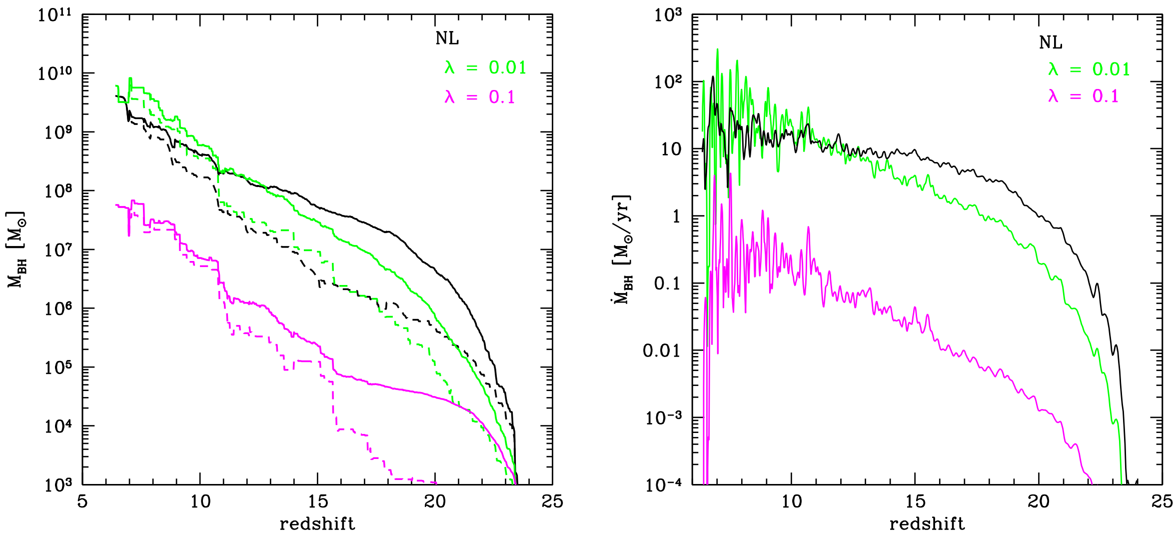

Figure 4. Time evolution of the more massive (dashed lines) and total (solid lines) BH mass (left-hand panel) and BH accretion rate (right-hand panel) evolution for NL (black line), L001 (green line) and L01 (magenta line) models.

massive Pop III stars. However, there are different mechanisms that can suppress early super-critical accretion. Feedback effects from the stellar progenitors can strongly affect the gas density around the newborn BHs, reducing the efficiency of gas accretion. In addition, the onset of disc 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 GAMETE/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 $z \gtrsim 20$ to $z \gtrsim 15$. However, despite the very conservative assumptions made to maximize stellar feedback effects, we find that this delay does not prevent either the growth of high-z SMBHs or the possibility of their BH progenitors to accrete at super-Eddington rates.

The impact of disc outflows, and the associated reduction of the duration of super-Eddington accretion episodes, strongly depends on the angular momentum of gas joining the accretion disc. Assuming that disc winds suppress BH accretion when the disc radius becomes comparable to the photon trapping radius, the result relies on the value of λ, which represents the fraction of angular momentum retained by the gas. For $\lambda = 0.1$, $t_{accr} \sim 100$–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 disc 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 $t_{accr} \ll$ 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 BHs.

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