Assessing inflow rates in atomic cooling halos: implications for direct collapse black holes

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ABSTRACT

Supermassive black holes are not only common in the present-day galaxies, but billion solar masses black holes also powered \(z \geq 6\) quasars. One efficient way to form such black holes is the collapse of a massive primordial gas cloud into a so-called direct collapse black hole. The main requirement for this scenario is the presence of large accretion rates of \(\geq 0.1 \, M_\odot/yr\) to form a supermassive star. The prime aim of the present work is to determine how and under what conditions such accretion rates can be obtained. We perform high resolution cosmological simulations for three primordial halos of a few times \(10^7 \, M_\odot\) illuminated by an external UV flux, \(J_{21} = 100 – 1000\). We find that a rotationally supported structure of about parsec size is assembled, with an aspect ratio between \(0.25 – 1\) depending upon the thermodynamical properties. Rotational support, however, does not halt collapse, and mass inflow rates of \(\sim 0.1 \, M_\odot/yr\) can be obtained in the presence of even a moderate UV background flux of strength \(J_{21} \geq 100\). To assess whether such large accretion rates can be maintained over longer time scales, we employed sink particles, confirming the persistence of accretion rates of \(\sim 0.1 \, M_\odot/yr\). We propose that complete isothermal collapse and molecular hydrogen suppression may not always be necessary to form supermassive stars, precursors of black hole seeds. Sufficiently high inflow rates can be obtained for UV flux \(J_{21} = 500 – 1000\), at least for some cases. This value brings the estimate of the abundance of direct collapse black hole seeds closer to that high redshift quasars.

Key words: methods: numerical – cosmology: theory – early Universe – high redshift quasars – black holes physics – galaxies: formation

1 INTRODUCTION

The observations of high redshift quasars at \(z \geq 6\) reveal the presence of supermassive black holes of about a few billion solar masses in the early universe (Fan et al. 2003, 2006; Willott et al. 2010; Mortlock et al. 2011; Venemans et al. 2013; Wu et al. 2015). From a theoretical perspective, the assembly of such massive objects within the first billion years after the Big Bang is challenging. How and under what conditions they were formed is a question of prime astrophysical interest. Various models for the formation of supermassive black hole seeds have been proposed (Rees 1984; Volonteri 2011; Volonteri & Bellovary 2012; Haiman 2012). One potential pathway is the collapse of a primordial, i.e., metal-free, “normal” star into a stellar-mass black hole. Earlier numerical simulations performed to study the formation of the first generation of stars (Abel et al. 2002; Bromm et al. 2002; Yoshida et al. 2006) suggested that the masses of the first stars are of the order of a few hundred solar. However, recent simulations found that the protostellar disk forming in the minihalo fragments into multiple clumps (Clark et al. 2011; Greif et al. 2012; Stacy et al. 2012; Latif et al. 2013; Latif & Schleicher 2015) and leads to the formation of multiple stars. In the case of a single star per halo, they may still reach up to a thousand solar masses at \(z = 25\) (Hirano et al. 2014), but feedback from the black hole itself shuts its own accretion and limits its growth (Johnson & Bromm 2007; Alvarez et al. 2009). Perhaps, as suggested by Madau et al. (2014) they may still grow under prolonged episodes of super-Eddington accretion.

The second possibility could be the collapse of a dense stellar cluster into a massive black hole due to the relativistic instability (Shapiro & Kang 1987) or the formation of a black due to the stellar dynamical processes in the first stellar cluster (Devecchi & Volonteri 2009; Goswami et al. 2014; Katz et al. 2015) or even the core collapse of a dense cluster of stellar mass black holes leading to the formation of a massive black hole seed (Davies et al. 2013; Lupi et al. 2014). The expected mass of a seed black hole from these scenarios is a few thousand solar.
A third mechanism could be the collapse of a protogalactic gas cloud into a massive central object so-called direct collapse black hole (Loeb & Rasio 1994; Bromm & Loeb 2003; Begelman et al. 2006; Hosokawa et al. 2014; Schleicher et al. 2013). A detailed discussion of these mechanisms is given in reviews (Volonteri 2010; Volonteri & Bellovary 2012; Haiman 2012), and we summarize there the main features of relevance for this investigation. The particular direct collapse scenario we address here requires the presence of large accretion rates of about \( \geq 0.01 - 0.1 \, M_\odot/\text{yr} \) (Begelman 2014; Hosokawa et al. 2013; Schleicher et al. 2013; Ferrara et al. 2014). This is because such accretion rates are the main pre-requisite to rapidly build a supermassive star of about \( 10^5 \, M_\odot \) which would eventually collapse into a black hole retaining most of the star’s mass (Baumgarte & Shapiro 1999; Shibata & Shapiro 2002). These large accretion rates can either be obtained through dynamical processes or thermodynamically, by keeping the gas warm (i.e., with a higher Jeans mass) to avoid fragmentation and star formation. Begelman et al. (2006) proposed that self-gravitating gas in dark matter halos may lose angular momentum via ‘bars-in-bars’ instabilities and efficiently assemble a central massive star. On the other hand, thermodynamical direct collapse requires the suppression of a molecular hydrogen to avoid fragmentation which leads to a monolithic isothermal collapse. In both cases, the halo has to transfer angular momentum efficiently to avoid collapse to be halted by the angular momentum barrier. For instance, Choi et al. (2014) have found that angular momentum in isothermal conditions can be transported by non-axisymmetric perturbations.

The conditions in primordial halos are ideal for the formation of massive stars due to the lack of efficient coolants in the absence of dust and metals. However, the presence of molecular hydrogen may lead to efficient fragmentation and star formation. UV stellar radiation can quench H\(_2\) formation and consequently fragmentation can be avoided. In fact, numerical simulations show that, in principle, in the absence of molecular hydrogen gas, a metal-free halo collapses isothermally via atomic line cooling. Consequently, a supermassive star of about \( 10^5 \, M_\odot \) could be assembled via large accretion rates of about \( 1 \, M_\odot/\text{yr} \) (Latif et al. 2013a,b, Johnson et al. 2014; Regan et al. 2014).

The above scenario requires a high value of the UV flux to dissociate molecular hydrogen which depends on the radiation spectra of stellar populations. We define \( J_{\text{crit}} \) as the value of the UV background flux above which full isothermal collapse occurs because molecular hydrogen formation is suppressed. \( J_{\text{crit}} \) depends on the spectrum of the stars contributing to the background. For hot stars with \( T_{\text{eff}} = 10^5 \, \text{K} \), such as Population III stars (Pop III), \( J_{\text{crit}} \) is \( \geq 10^4 \) (in units of \( J_1 = 10^{-22} \, \text{erg/cm}^2/\text{s/Hz} \) Omukai 2000; Shang et al. 2010; Latif et al. 2014, 2015). The second generation of stars is, however, favoured as source of UV radiation for this scenario due to their longer lives and higher abundance. If such stars have a softer spectrum with \( T_{\text{eff}} = 10^4 \, \text{K} \), \( J_{\text{crit}} \) is 400-700, much reduced compared to the Pop III case. Recently, however, the spectra of Pop II stars were computed employing the stellar synthesis code STARBURST, finding that realistic stellar spectra of Pop II stars can be mimicked by adopting radiation spectra with temperature between \( 10^4 - 10^5 \, \text{K} \) (Sugimura et al. 2014; Agarwal & Khochfar 2013). Latif et al. (2013) found that the value of UV flux necessary to obtain full isothermal collapse for realistic spectra of Pop II stars is a few times \( 10^4 \) in units of \( J_1 \) and becomes constant for \( T_{\text{eff}} \) between \( 2 \times 10^4 - 10^5 \, \text{K} \). Regan et al. (2014b) considered an anisotropic monochromatic radiation source and found that small amount of \( H_2 \) forms due to the self-shielding even under very strong flux. They further propose that \( J_1 = 1000 \) may be sufficient to form a supermassive star. Similarly, high values of \( J_{\text{crit}} \) are required for complete isothermal collapse where X-ray ionization heating is included (Latif et al. 2013; Inayoshi & Tanaka 2014).

Within a scenario that requires full isothermal collapse, the number density of direct collapse black holes strongly depends on the value of \( J_{\text{crit}} \). The estimates of Dijkstra et al. (2014) suggest that \( J_{\text{crit}} = 1000 \) seems sufficient to produce the observed number of quasars at \( z \geq 6 \). However, the black holes density drops by about a few orders of magnitude below their observed abundance for \( J_{\text{crit}} \geq 10^4 \). This puts this direct collapse model in hot waters by making their sites extremely rare. Hence, it becomes necessary to explore whether high accretion rates can be maintained under non-isothermal conditions. In fact, the work of Latif et al. (2014) for soft idealised radiation spectra of \( 10^5 \, \text{K} \) suggests that it might be possible to form massive stars even in the presence of moderate amount of \( H_2 \). However, it is still unclear whether for a realistic Pop II spectra high accretion rates of \( 0.1 \, M_\odot/\text{yr} \) can be maintained for flux lower than \( J_{\text{crit}} \) and what value of the UV flux will be sufficient for this purpose. If so, are these sites abundant enough to reproduce the number density of quasars at \( z \geq 6 \)? We address these questions in the present work.

In this study, we explore the conditions for the formation of supermassive stars under non-isothermal collapse conditions and determine whether the large inflow rates of \( 0.1 \, M_\odot/\text{yr} \) necessary for their assembly can be obtained. We perform three-dimensional cosmological simulations to study the collapse of massive primordial halos of a few times \( 10^5 \, M_\odot \) forming at \( z \geq 10 \) and vary the strength of background UV flux emitted by Pop II stars. In addition to this, we employ a detailed chemical model which includes all the necessary thermodynamical processes and solve them self-consistently with the cosmological simulations. We derive the dynamical and thermodynamical properties of these halos. The temporal evolution of the mass inflow rates is computed beyond the initial collapse by employing sink particles. Our results show that one may not necessarily need complete isothermal collapse to form a supermassive star. This work has important implications for the observed abundance of quasars at \( z \geq 6 \) and provides the potential pathway for the formation of supermassive black holes at high redshift.

This article is structured as follows. In section 2, we describe the simulations setup and numerical methods. We present our main results in section 3. In subsections 3.1, 3.2 and 3.3, we show the structural properties of halos and their time evolution, expected mass inflow rates and mass estimates of protostars. In section 4, we summarise our main findings and conclusions.
2 NUMERICAL METHODS

The simulations presented in this study adopt the open source three dimensional code enzo [Bryan et al. 2014]. Enzo is an adaptive mesh, parallel, grid based, cosmological hydrodynamical simulations code. It utilises the message passing interface (MPI) library for parallelisation and is well suited for the current simulations. The hydrodynamical equations are solved using the finite difference scheme by employing the piece-wise parabolic method (PPM). The dark matter (DM) evolution is handled by the particle-mesh technique commonly used in the Eulerian codes.

Our simulations start with cosmological initial conditions at $z=100$ and are generated from the "init" package available with enzo. The parameters from the WMAP seven years data are used to generate the initial conditions [Jarosik et al. 2011]. The computational volume has a comoving size of 1 Mpc/h and periodic boundaries both for hydrodynamics and gravity. We first run simulations with a uniform grid resolution of $128^3$ cells (also $128^3$ DM particles) and select the most massive halos forming in the box at $z=15$. The simulations are restarted with nested grid initial conditions, one top and two nested refinement levels each with a grid resolution of $128^3$ cells. We employ in total $5767168$ DM particles to solve the dark matter dynamics which results in DM resolution of about $600 M_\odot$ In addition to this, we add 18 dynamical refinement levels during the course of simulations which provide an effective resolution of about 1000 AU in the central 62 kpc comoving region. Our refinement criteria is based on the gas density, the particle mass resolution and a fixed resolution of 32 cells per Jeans length. The cells are flagged for the refinement if their particle mass resolution and a fixed resolution of 32 cells per Jeans length. The cells are flagged for the refinement if their particle mass resolution and a fixed resolution of 32 cells per Jeans length.

The simulations are evolved beyond the initial collapse by employing sink particles which represent protostars. To solve the thermal evolution of the gas along with the cosmological simulations, we employ the KROME package [Grassi et al. 2014]. Our chemical model is described in detail in [Latif et al. 2013] and here we briefly summarise its main features. The rate equations of $H$, $H^+$, $He$, $He^0$, $He^+$, $e^-$, $H_2$, $H_3^+$ are self-consistently solved with hydrodynamics. We employ a uniform isotropic background ultraviolet (BUV) flux with $T_{\text{rad}} = 2 \times 10^4$ K emitted by Pop II stars in units of $J_{21} = 10^{-21}$ erg/cm$^2$/s/Hz/sr and turn it on at $z=30$. Sugimura et al. [2014] have shown that the realistic spectra of Pop II stars can be mimicked with $T_{\text{rad}} = 10^4 - 10^5$ K and later Latif et al. [2013] found that $T_{\text{rad}} = 2 \times 10^4$ K effectively represents this range as $J_{\text{tot}}$ remains constant between $T_{\text{rad}} = 2 \times 10^4 - 10^5$ K. Our model includes $H_2$ formation, $H_2$ photo-dissociation, $H^+$ photo-detachment, $H_2$ collisional dissociation and the $H_2$ self-shielding fitting formula of [Wolcott-Green et al. 2011]. We include various cooling/heating mechanisms such as molecular hydrogen line cooling, cooling due to the collisional-induced emission, cooling/heating due to the three-body reactions, chemical cooling/heating and atomic line cooling (i.e. cooling due to collisional excitation, collisional ionisation, radiative recombination).

3 RESULTS

We perform three dimensional cosmological simulations for three distinct massive primordial halos of a few $10^7 M_\odot$ for various strengths of BUV flux. The properties of the halos such as their masses, collapse redshifts, spins and the critical strength of UV flux are listed in table 1. In the following, we discuss the structural properties of the halos and their temporal evolution. We also study the thermodynamical and physical properties of the halos under different conditions. We distinguish here between the mass inflow rate, provided by the halo, and the accretion rate that occurs on a putative protostar. The mass inflow rates are computed for the each intensity of the BUV flux and the mass accretion onto the protostar is followed by employing sink particles for a subset of halos.

| Model No | Mass $M_\odot$ | Redshift | $T_{\text{rad}} = 2 \times 10^4$ K | $J_{21}$ | spin parameter $\lambda$ |
|-----------|--------------|----------|-------------------------------|--------|--------------------|
| A         | $5.6 \times 10^7$ | 10.59    | 20000                         | 0.034  |                    |
| B         | $4.06 \times 10^7$ | 13.23    | 40000                         | 0.02   |                    |
| C         | $3.25 \times 10^7$ | 11.13    | 50000                         | 0.03   |                    |

1 http://enzo-project.org/, changeset:48de94f882d8
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Figure 1. Average total (gas + DM) density along the line of sight for halo A illuminated by the BUV flux of strength $J_{21} = 100$. The columns show the structure of the halo at various cosmic times and the rows depict the averaged total density along x, y & z axis. The width of density projections is given in the physical units and the time in mega years after the Bing Bang.

at the intersection of filaments and is mainly fed by three main streams. The mass of the halo ~ 300 Myrs after the Big Bang is $1.4 \times 10^7 M_\odot$ and undergoes a major merger with a halo of $5 \times 10^6 M_\odot$ (i.e., mass ratio ~1:2) about 100 Myrs later. The halo virializes at $\sim z = 11$, when its mass is well above the atomic cooling limit. In the meantime, it is continuously fed by gas flowing from the filaments and by minor mergers.

Halo B goes through many minor mergers with mass ratios of about 1:10 and is also accreting gas via cosmic streams. Eventually, about 300 Myrs after the Big Bang the halo becomes virialized, and has a mass of about $2.7 \times 10^7 M_\odot$. This halo has a very different merger history from halo A as it has not experienced any major merger recently and is assembled ~130 Myrs earlier than halo A. Similar behaviour is observed for all BUV flux strengths as the incident flux does not impact the large scales properties of the halos. Halo C experienced a major merger about 350 Myrs after the Big Bang similar to the history of halo A. The mass ratios of the merging halos is about 1:2 and the halo gets virialized about 50 million years later.

Due to the presence of angular momentum in gas and halos, a central rotationally supported structure is expected to form, as a consequence of gravitational collapse (Oh & Haiman 2002; Volonteri & Rees 2003). However, as discussed by Choi et al. (2014), the triaxiality of dark matter halos (Allgood et al. 2006) exerts gravitational torques and helps in transferring angular momentum via bars in bars instabilities, thus reducing rotational support compared to an axisymmetric case. In order to study the properties of the central regions, specifically their level of rotational support, we have computed the ratio between the rotational velocity, $V_{\text{rot}}$, and the velocity dispersion, $\sigma$. This ratio, $V_{\text{rot}}/\sigma$, provides us the estimate of the disk scale height as $H/R \sim \sigma / V_{\text{rot}}$ where $H$ is the disk height, and $R$ is the disk radius. Our estimates of $V_{\text{rot}}/\sigma$ for halo A are shown in the bottom-left panels of figures 2, 3, 4 and 5 for $J_{21} = 100, 500, 1000$ and $4 \times 10^4$. $V_{\text{rot}}/\sigma$ is $\sim 6$ in the central 10 pc of the halo for $J_{21} = 100$. Rotational support is higher at lower $J_{21}$ values, as cooling in the core of the halo is efficient, because the fraction of molecular hydrogen (shown in the top-left panels) is higher. $V_{\text{rot}}/\sigma$ in fact becomes smaller for higher fluxes...
and approaches unity for the isothermal case. We estimate that the aspect ratio is $\sim 0.25$ for $J_{21} = 100$ and increases up to 0.5 for $J_{21} = 1000$. The aspect ratio is almost unity for the isothermal case, i.e., for $J_{21} = 4 \times 10^4$. This suggests that a fat disk is formed in the halo with aspect ratio higher than 0.1 for all radiation field strengths. Similar behaviour is observed for halo C (not shown). The value of $V_{\text{infl}}/H$ is higher in the case of halo B (see figures 6, 7 and 8) in general, but it decreases as collapse approaches the isothermal state (cf. Oh & Haiman 2002). It indicates that the scale height of the disk varies from halo to halo. The higher rotational support in some halos can delay collapse and may even halt it if the angular momentum is not transferred efficiently. In such a case, it may limit accretion onto the central object and may have important implications for the final masses of stars.

### 3.2 Thermodynamical properties

The thermal properties of halo A for various strengths of BUV flux are shown in the figures 2, 4, and 6 (second panel from top, left). The temperature of the halo is about a few $10^3$ K when the halo mass is lower than the atomic cooling threshold. It increases through virialization and merger shocks until it reaches the atomic cooling limit. We note that in the presence of a BUV flux, irrespective of its strength, the temperature of the gas in the halo is about 8000 K after its virialization at scales larger than 10 pc. This is due to the lack of molecular hydrogen cooling as its abundance remains low, i.e., $< 10^{-6}$. At smaller scales, $H_2$ molecules self-shield from the radiation depending on the strength of the ambient UV flux. For radiation field strengths $< J_{21} = 10^4$, $H_2$ self-shielding becomes effective, $H_2$ abundance gets boosted and consequently the gas temperature decreases to a few hundred K within the central 10 parsecs. The transition from atomic to molecular hydrogen cooling occurs between 1-10 pc and is delayed by a few Myrs for the $J_{21} = 1000$ case in comparison with $J_{21} = 100$. The thermal evolution of the halo B for $J_{21} = 100$, 500 and 1000 is also very similar as shown in figures 6, 7 and 8 halo C (not shown) has also a very consistent behaviour. Their cores are cooled by molecular hydrogen with central temperatures of a few hundred K. The typical core temperatures within the central 10 pc of the three halos are a few hundred K and is the thermal support in some halos can delay collapse and may even halt it. The thermal evolution of the halo...
halos are shown in figures [3] [10] [11]. Either extended (halo A and halo B) or narrow funnels of dense gas connect to the halo centre, providing the high inflow rates we measured.

3.4 Estimates of the masses of supermassive stars

As mentioned in the previous subsection, in halos A and C mass inflow rates of 0.1 M$_\odot$/yr can be obtained for $J_{21} \geq 500$ and even for $J_{21} = 100$. To assess if these accretion rates can be maintained for long time scales, we employed sink particles in our simulations and followed the accretion onto them for about 30000 years after the formation of the first sink particle. The sinks are formed at densities above $10^7$ cm$^{-3}$ and at the maximum refinement level. In general, no vigorous fragmentation is observed in either halo for all strengths of BUV flux. Only a single massive sink is formed per halo.

Figures [12] and [13] show the time evolution of the gas density in the central 10 pc of halos A and C for $J_{21} = 1000$ after the time the sink particle is inserted is less dense and more extended, and it takes about 10000 yrs to move the smaller clumps into the centre and, after that, the inflow rate increases. Additionally, the small clumps that form, eventually merge in the centre. Therefore, in the last 5000 yrs of the simulated time, the mass accretion rate becomes even higher for $J_{21} = 1000$ while the mass accretion rate for $J_{21} = 100$ and 500 cases declines.

The resultant masses of the sinks, which can be taken to represent protostars in our simulations, after 30000 years, are 4700, 6000 and 6770 M$_\odot$ for $J_{21} = 100$, 500 and 1000, respectively. The mass of the sink is 2000 solar masses higher for $J_{21} = 1000$ compared to the weakest flux case. In fact, the mass for the $J_{21} = 100$ shows a plateau around 4700 solar masses and becomes almost constant for the last 10000 years. This is because of the higher rotational support as well as the presence of colder gas compared to the higher flux cases. The small plateau in the sink mass is also observed for $J_{21} = 500$ in the last 5000 yrs and similarly a small decline in the mass accretion rate. However, the mass of the sink seems to keep increasing for the $J_{21} = 1000$ case. Therefore, we expect that the masses of the resultant star may be higher compared to the lower flux cases.

We have also employed sink particles for halo C and followed the evolution for about 30000 yrs. The masses of the sinks and the mass accretion rates onto them are shown in figure [13]. The mass accretion rate starts to increase in the first 10000 yrs due to the sufficient mass supply in the central clump, but starts to decline later. This behaviour is similar to halo A, but the decline is even more significant. The sink mass starts to show a plateau even earlier, at about 18000 yrs after the formation of the sink. The mass accretion rates and the masses of the resultant sink particles instead continue to increase for the rest of the two cases. The masses of the sinks are 4600, 6400 and 7000 M$_\odot$ from the weaker to stronger fluxes, respectively (i.e. $J_{21} = 100$, 500 and 1000). Similar to halo A, mass accretion rates remain above 0.1 M$_\odot$/yr for the simulated time, irrespective of the BUV field strength. The mass accretion rates show some decline for $J_{21}=100$ case, but not for the $J_{21}=500$ and 1000 cases. Mass accretion rates may decline at later stages of evolution if rotational support is enhanced significantly, or efficient fragmentation takes place inside the halo. However, for the duration of our simulation, we confirm $\geq 0.1$ M$_\odot$/yr for the whole time.

Overall, our simulations suggest that the mass accretion rates required to build a supermassive star can be obtained for fluxes below the critical value of UV flux necessary for the isothermal collapse. Particularly, the formation of supermassive stars seems plausible for $J_{21} = 1000$ and 500, at least in one case. If accretion persists at the same rates, the masses of the protostars can reach $10^4 - 10^5$ solar masses.

4 DISCUSSION & CONCLUSIONS

We have performed high resolution cosmological simulations for three distinct halos to study under which conditions the accretion rates necessary for the formation of supermassive stars in massive primordial halos of a few times $10^7$ M$_\odot$ can be achieved. These supermassive stars are the potential cradles of direct collapse black holes which are one of the plausible candidates to explain the existence of high redshift quasars.

The prime objective of this work is to explore the formation of supermassive stars in non-isothermal collapse. Indeed, the key parameter for supermassive star formation appears to be an inflow rate above 0.1 M$_\odot$/yr (Begelman 2010; Hosokawa et al. 2013; Schleicher et al. 2013; Ferrara et al. 2014). Specifically, we are interested in estimating whether the concept of a critical value, $J_{\text{crit}}$, of the BUV flux above which full isothermal collapse can be achieved through complete suppression of molecular hydrogen formation is necessary for black hole formation in the direct collapse scenario.

We also study the structure of the inner regions of the halos to evaluate the role of rotational support. We presume that halos are metal free and illuminated by moderate strengths of BUV flux. A pc-size fat disk is assembled in these halos as a consequence of gravitational collapse and the angular momentum of the infalling gas. The formation of such disk is irrespective of the merger history of the halo. The scale height of the disk varies from 0.25 to 1 depending on the thermodynamical properties of the halo. As predicted by Oh & Haiman (2002), the halos cooled by the molecular hydrogen cooling have higher rotational support and the aspect ratio is typically about 0.25 for the halos collapsing isothermally in the absence of H$_2$ cooling the aspect ratio is close to unity. These results agree with expectations of the theoretical models by Oh & Haiman (2002), Lodato & Natarajan (2006), and Begelman (2010).

Rotational support, however, does not at least initially, hinder the gas collapse in many of the simulated halos. In fact, ur estimates for the mass inflow rates show that the halos irradiated by moderate strengths of UV flux $J_{21} = 500$ and 1000 have typical mass inflow rates of about 0.1 M$_\odot$/yr. Indeed, Regan et al. (2014b) already noticed that sufficiently
high accretion rates can be obtained for halos experiencing (anisotropic) fluxes of $J_{21} \sim 1000$. An inflow rate of $\sim 0.1 \, M_\odot/\text{yr}$ can be achieved even for $J_{21} = 100$ for halos A and C, while halo B has somewhat lower inflow rates. This may perhaps suggest that halos experiencing major mergers in their recent past may form supermassive stars more easily, for lower strengths of UV field, while perhaps this is not happening in haloes formed via minor mergers and accretion. In fact, Mayer et al. (2014) suggested that the merging of very massive galactic cores, $> 10^6 \, M_\odot$, may form a stable nuclear disk with very large gas inflow rates. They argue that merging of such systems leads to the enhanced inflow rates and helps in the formation of a massive black hole. Although the present work explores very different systems, the merging of a few times $10^6 \, M_\odot$ proto-galaxies, it hints that perhaps larger accretion rates can be obtained in the aftermath of a major merger, as mergers induce torques that remove angular momentum from gas, fostering inflows. However, our small sample does not allow us to draw strong conclusions.

To further assess whether such accretion rates can be maintained for long time scales, we have employed sink particles and followed the accretion onto the protostar for $30000$ years after the formation of the first sink particle for halos A and C. No strong fragmentation is found for these halos, irrespective of the employed UV field, and a single star is formed per halo. A mass inflow $\sim 0.1 \, M_\odot/\text{yr}$ can be maintained for long times, at least for the whole simulated time. Our results suggest that $J_{21} \geq 500 - 1000$ may be sufficient to form supermassive stars, at least for some cases. The observed abundance of $z \geq 6$ quasars can be reproduced by the above flux, extrapolating the findings of Dijkstra et al. (2014).

In our simulations, we employed sink particles to follow the mass accretion onto the protostars, which introduce a characteristic length scale below which fragmentation is ignored. To assess fragmentation below this scale would require simulations resolving the collapse down to sub AU scales and it becomes computationally infeasible to evolve them for longer times. This is due to the shorter time-steps involved in these calculations which cover a large range of spatial scales, from cosmological scales down to the scales of AU. However, the analysis of the density structure in these halos indicates that no vigorous fragmentation is expected as $H_2$ cooling is only effective in the core of the halo and most of the gas outside is warm and no signs of substructure are present. Even if fragmentation occurs on very small scales, Latif & Schleicher (2014, 2015) show that clumps may migrate inward on short time scales. Moreover, viscous heating further dissociates molecular hydrogen, stabilises the disk and favours the formation of a massive central object. Based on the results from both these simulations and the complementary analytical studies (Latif & Schleicher 2014, 2015), we argue that formation of supermassive stars in these conditions is possible.

We also found that accretion onto the central star becomes highly anisotropic particularly for the case with $J_{21} = 1000$ where the gas is fed to the central star by a single stream. Such behaviour seems to persist for $30000$ yrs. This may have important implications for the feedback by central star or even by the black hole at later stages. The ionising radiations around a star/BH would escape in the low density region while the gas supply to the central object may continue from a single dense stream even in the presence of feedback. The simulations presented in this work are based on a number of idealized assumptions such as halos are metal free and irradiated by an isotropic flux. In the future, simulations self-consistently taking into account metal enrichment and radiation emitted by the nearby sources should be performed. Such simulations are mainly constrained by the exorbitant computational costs.

Figure 2. The thermodynamical and physical properties of halo A are shown for $J_{21} = 100$. The top panels show the time evolution of gas density, temperature, $H_2$ fraction and the total enclosed mass. The time evolution of the mass accretion rates, $\dot{M}_{\text{acc}}/\sigma$, radial infall and turbulent velocities is shown in the bottom panels. The different line styles represent various cosmic times. The profiles are spherically averaged and radially binned. The vertical dashed black line shows the Jeans length and the horizontal dashed line represents $V_{\text{rot}}/\sigma = 1$. 
Figure 3. The thermodynamical and physical properties of halo A are shown for $J_{21} = 500$. The top panels show the time evolution of gas density, temperature, $H_2$ fraction and the total enclosed mass. The time evolution of the mass accretion rates, $V_{\text{rot}}/\sigma$, radial infall and turbulent velocities is shown in the bottom panels. The different line styles represent various cosmic times. The profiles are spherically averaged and radially binned. The vertical dashed black line shows the Jeans length and the horizontal dashed line represents $V_{\text{rot}}/\sigma = 1$.

Figure 4. The thermodynamical and physical properties of the halo A are shown for $J_{21} = 1000$. The top panels show the time evolution of gas density, temperature, $H_2$ fraction and the total enclosed mass. The time evolution of the mass accretion rates, $V_{\text{rot}}/\sigma$, radial infall and turbulent velocities is shown in the bottom panels. The different line styles represent various cosmic times. The profiles are spherically averaged and radially binned. The vertical dashed black line shows the Jeans length and the horizontal dashed line represents $V_{\text{rot}}/\sigma = 1$. 
Figure 5. The thermodynamical and physical properties of the halo A are shown for $J_{21} = 4 \times 10^4$. The top panels show the time evolution of gas density, temperature, $H_2$ fraction and the total enclosed mass. The time evolution of the mass accretion rates, $V_{\text{rot}}/\sigma$, radial infall and turbulent velocities is shown in the bottom panels. The different line styles represent various cosmic times. The profiles are spherically averaged and radially binned. The vertical dashed black line shows the Jeans length and the horizontal dashed line represents $V_{\text{rot}}/\sigma = 1$.

Figure 6. The thermodynamical and physical properties of the halo B are shown for $J_{21} = 100$. The top panels show the time evolution of gas density, temperature, $H_2$ fraction and the total enclosed mass. The time evolution of the mass accretion rates, $V_{\text{rot}}/\sigma$, radial infall and turbulent velocities is shown in the bottom panels. The different line styles represent various cosmic times. The profiles are spherically averaged and radially binned. The vertical dashed black line shows the Jeans length and the horizontal dashed line represents $V_{\text{rot}}/\sigma = 1$. 
Figure 7. The thermodynamical and physical properties of the halo B are shown for $J_{21} = 500$. The top panels show the time evolution of gas density, temperature, $H_2$ fraction and the total enclosed mass. The time evolution of the mass accretion rate $s$, $V_{\text{rot}}/\sigma$, radial infall and turbulent velocities is shown in the bottom panels. The different line styles represent various cosmic times. The profiles are spherically averaged and radially binned. The vertical dashed black line shows the Jeans length and the horizontal dashed line represents $V_{\text{rot}}/\sigma = 1$.

Figure 8. The thermodynamical and physical properties of the halo B are shown for $J_{21} = 1000$. The top panels show the time evolution of gas density, temperature, $H_2$ fraction and the total enclosed mass. The time evolution of the mass accretion rate $s$, $V_{\text{rot}}/\sigma$, radial infall and turbulent velocities is shown in the bottom panels. The different line styles represent various cosmic times. The profiles are spherically averaged and radially binned. The vertical dashed black line shows the Jeans length and the horizontal dashed line represents $V_{\text{rot}}/\sigma = 1$. 
Figure 9. The averaged density (top panels) and the averaged temperature (bottom panels) weighted by the gas density along y-axis for Halo A are shown here. They are plotted for the BUV of strengths $J_{21} = 100$, 500 & 1000 and show the central 10 pc region of the halo. The plots represent the simulations state when they reach the maximum refinement level prior to the formation of a sink particle.

Figure 10. The averaged density (top panels) and the averaged temperature (bottom panels) weighted by the gas density along y-axis for Halo B are shown here. They are plotted for the BUV of strengths $J_{21} = 100$, 500 & 1000 and show the central 10 pc region of the halo. The plots represent the simulations state when they reach the maximum refinement level prior to the formation of a sink particle.
Figure 11. The averaged density (top panels) and the averaged temperature (bottom panels) weighted by the gas density along y-axis for Halo C are shown here. They are plotted for the BUV of strengths J_{21} = 100, 500 & 1000 and show the central 10 pc region of the halo. The plots represent the simulations state when they reach the maximum refinement level prior to the formation of a sink particle.
Figure 12. The time evolution of the averaged density along y-axis in the central 10 pc of the halo A for $J_{21}=1000$ after the formation of the sink particle is shown here. The time after the formation of the sink particle in each panel is shown in years and the white dot depicts the position of the sink particle.

Figure 13. The time evolution of the averaged density along the y-axis in the central 10 pc of the halo C for $J_{21}=1000$ after the formation of the sink particle is shown here. The time after the formation of the sink particle in each panel is shown in years and the white dot depicts the position of the sink particle.
Figure 14. The masses of the sink particles and their mass accretion rate are shown against time for halo A. The strength of incident field is shown by different colors and line styles as described in the legend.

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