Early Black Hole Formation by Accretion of Gas and Dark Matter

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ABSTRACT: Recent discovery of luminous quasars at \( z > 6 \) has posed a severe challenge to the theory of structure formation of the universe. These quasars are thought to be powered by supermassive black holes (SMBHs). However no consensus is yet to be reached as to the origin and early formation mechanism of massive SMBHs. We propose a model in which intermediate-mass black holes (IMBHs) with mass of \( \sim 10^4 M_\odot \) are formed in early dark matter halos. We carry out detailed stellar evolution calculations for the first generation stars including annihilation energy of dark matter (DM) particles. We show that very massive stars, as massive as \( 10^4 M_\odot \), can be formed in an early DM halo. Such stars are extremely bright with \( \log L/L_\odot \gtrsim 8.2 \). They will gravitationally collapse to form IMBHs. These black holes could have seeded the formation of early SMBHs.

KEYWORDS: dark matter theory, galaxy formation, massive black holes, first stars.
1. Introduction

Recently bright quasars at redshifts greater than six were discovered by the Sloan Digital Sky Survey[1]. These quasars are thought to be powered by SMBHs whose mass exceeds $\sim 10^9 M_\odot$[2]. The implication is that such SMBHs must be in place as early as when the age of the universe is about 800 Myr. It is often argued that early generation of stars might have left BH remnants that could be the seeds for SMBHs[3, 4]. According to one such viable scenario[5], seed black holes (BHs) of $\sim 200 M_\odot$ are formed at redshifts of about 24 and these seeds grow to become SMBHs through merging and highly super-Eddington accretion. Some authors [6, 7, 8, 9] argued that early SMBH formation is possible without invoking such a highly efficient accretion process, but then these seed BHs have to be formed very early in the universe. One way to ease these constraints is that the seed BHs are much more massive, such as IMBHs with $\sim 500 - 10^5 M_\odot$, rather than stellar mass BHs. Here we explore such a possibility.

Structure formation in the universe is largely driven by gravitational forces exerting on dark matter (DM) which is a major matter content. DM plays a crucial role particularly in primordial star formation[10]. The standard model of early structure formation suggests that the first stars are formed in small-mass DM halos with mass of $\sim 10^{5-6} M_\odot$[11, 12] when the age of the universe is less than a few hundred million years old. In this model, star-forming gas clouds are embedded at the center of a DM halo, and hence the formation and evolution of first stars are expected to be affected by DM.

Weakly-interacting massive particles (WIMPs) are popular candidates for dark matter. For these particles to be the bulk of dark matter as thermal relics, they must have a large pair-annihilation cross-section of the order $\langle \sigma v \rangle_{\text{annihilation}} \sim 10^{-26}$ cm$^3$ s$^{-1}$. Hence such
WIMPs are expected to self-annihilate in high density regions, e.g., at the centers of DM halos, where they are converted into high-energy photons and particles. Although the DM annihilation signatures have not been confirmed, observations with the FERMI satellite may prove the existence of WIMPs. For reviews of dark matter candidates, see [13].

The effect of DM annihilation on cosmic structure formation has been studied in various contexts [14]. Effective heating by DM annihilation could halt the collapse of a pre-stellar gas cloud [15]. Primordial stars can also capture DM particles [16, 17], which will then produce a significant energy at the center of stars. These stars comprise a new category – stars powered and sustained by the DM annihilation energy, sometimes called “dark stars” [15, 18, 19].

Most previous works studied dark stars with constant masses. However, it is likely that first stars largely grow their mass during the evolution through mass-accretion. Therefore, in this paper we calculate the growth and evolution of primordial stars using several plausible accretion models.

2. Dark matter model and calculation method

We consider the DM capture via off-scattering [17] and include energy generation by DM annihilation in the stellar core. Several authors, instead, have investigated DM supplied by the adiabatic contraction (AC). As the gas collapses into the star, DM particles are gravitationally pulled along with it. According to [20], this adiabatically contracted DM inside an accreting first stars runs out relatively soon (at around $M \sim 780 M_\odot$). Also the adiabatically contracted DM density profile is roughly flat inside a star, while the captured DM is thermalized and highly concentrated at the center. Therefore, if DM capture is effective, or the DM-baryon scattering cross section is sufficiently large, captured DM heating is expected to dominate for the later evolutionary stages of an accreting star. Hence, we only consider the captured DM in this paper. We note that adiabatic contraction may significantly change the early evolution before the Kelvin-Helmholtz contraction stage, but the results for $M >> 100 M_\odot$ are almost independent of these “initial” conditions.

For the DM particle parameters, we adopt commonly used “fiducial” values; the DM particle mass, $m_\chi = 100$ GeV, the DM-baryon elastic scattering cross section $\sigma = 10^{-38} \text{cm}^{-2}$ [21], the DM self-annihilation cross-section $\langle \sigma v \rangle_{\text{annihilation}} = 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$. The DM density at the center of the halo is assumed to be $\rho_\chi = 10^{11}$ GeV cm$^{-3}$[22]. We note that these parameters, most notably the DM density, is still quite uncertain. Since the DM annihilation produces energy at a rate per unit volume, $\epsilon_{\text{DM}} = \langle \sigma v \rangle_{\text{annihilation}} \rho_\chi^2 / m_\chi$, larger cross-section, larger DM density and smaller DM mass generally result in larger energy generation. As long as the product of these quantities is similar to our fiducial value, the DM annihilation causes essentially the same effect to those described in the present paper. We show a few test results with enhanced annihilation rates in Section 4.

We mention that the adopted cross-section is close to the upper limits for spin-dependent interactions off a proton, recently derived from direct detection experiments XENON 10 [21]. The adopted DM density is much larger than the average DM density in an early dark halo, but the ambient DM density around an accreting population III star
can be as large as this or even larger, due to the adiabatic contraction of DM[24]. Recently, Natarajan, Tan & O’Shea [25] performed three-dimensional cosmological simulations and found that the central dark matter density reached \( \rho_{\chi} \sim 10^{10} \text{ GeV cm}^{-3} \) when the gas density is \( n_H \sim 10^{10} \text{ cm}^{-3} \) in one of their simulations. Since the gas further collapses over 10 orders of magnitude in density to the formation of a protostar [26], we expect that the dark matter density also increases by adiabatic contraction (see the extrapolated density profile in [25]). While three-dimensional effects during the cloud collapse, such as tidal torques and turbulent motions of the gas will likely prevent dark matter to contract further, the fact that Natarajan et al. found at least one case with \( \rho_{\chi, \text{center}} \sim 10^{10} \text{ GeV cm}^{-3} \) at an intermediate stage is encouraging.

There are two time scales relevant for dark star evolution[23]. One is \( \tau_{\chi} \), and the equilibrium between the dark matter (DM) capture and annihilation is established after this time scale. The other is the thermal time scale \( \tau_{\text{th}} = 4\pi m_{\chi} R_{\star}^{7/2} / 3\sqrt{2G\sigma_0 M_{\star}^{3/2}} \). Here \( R_{\star} \) and \( M_{\star} \) are stellar radius and mass, respectively. The captured DM gets redistributed in the interior of the star in \( \tau_{\text{th}} \), reaching a thermal distribution \( n_{\chi}(r) = n_c \exp(-r^2/r_{\chi}^2) \), with \( r_{\chi} = \sqrt{3kT_{c}/2\pi G\rho_c m_{\chi}} \), where \( T_c \) and \( \rho_c \) are the core temperature and density, \( n_c = C_{\tau_{\chi}}/\pi^{3/2}r_{\chi}^3 \) is the DM density at the stellar center, and \( C \) is the DM capture rate which is explicitly given in [17]. Since we assume a dark star in equilibrium, these two time scales should be smaller than the time step of the evolutionary calculations. We have confirmed that \( \tau_{\chi} \) is always sufficiently small and also \( r_{\chi} \) is much smaller than the core radius.

\( \tau_{\text{th}} \) is also sufficiently small for most of the time except early periods of the evolution. \( \tau_{\text{th}} \) is typically larger than the stellar evolutionary time-scale before the Kelvin-Helmholtz contraction stage[20]. In this case, the annihilation energy may be exponentially suppressed. We have investigated this early suppression and confirmed that the results perfectly converged after the Kelvin-Helmholtz contraction stage. In our models, the results converged for \( M > 30M_{\odot} \) and hence this effect does not change our conclusions.

The DM annihilation luminosity \( L_{DM} \) and the DM capture rate \( C \) are roughly proportional, such that \( L_{DM} \propto C \propto \sigma \rho_{\chi}/m_{\chi} \) when a DM star is in equilibrium[23]. The adopted DM density is much larger than the average DM density in a dark halo, but the ambient DM density around an accreting population III star is expected to be as large as this or even larger due to the adiabatic contraction of DM[24].

We adopt the method in [27, 28] to calculate stellar evolution from \( M \sim 1 - 1.5M_{\odot} \) up to the onset of carbon burning. We show that after this stage further evolution to core-collapse is very rapid.

Of critical importance in our evolution calculations are the gas mass accretion rates. We first adopt constant accretion rates of \( \dot{M} = 10^{-4} - 10^{-2}M_{\odot}\text{yr}^{-1} \), which will cover a plausible range for primordial star formation [29]. However, the analytic models based on self-similar collapse solutions [30, 31] and cosmological simulations [32, 33] suggest that accretion rates will decrease with time (and hence with increasing mass). Therefore, we also adopt several cases with these time-dependent accretion rates. Also, since the radiative feedback can reduce accretion rates in the late evolution phase, we consider this effect also, following [31] as described below in Sec.3.1.
3. Dependence on the gas mass accretion rates

The stellar evolution for models with constant gas mass accretion already shows several interesting features. Fig. 1 shows the evolution of mass and radius for the accreting stars without (upper panel) and with (lower panel) DM annihilation heating.

![Figure 1: Stellar mass - radius evolution for each model. The upper and lower panels show the models without and with the DM annihilation energy, respectively. The model names for \( \dot{M} = 10^{-2}, 10^{-3}, 10^{-4} \) cases are A, B, C, and Ad, Bd, Cd, for the cases without and with the DM heating, respectively.](image)

The adopted constant gas mass accretion rates are, \( \dot{M} = 10^{-2} \) (Model A, Ad), \( 10^{-3} \) (B, Bd), and \( 10^{-4} \) (C, Cd) \( M_\odot \) yr\(^{-1}\), for without and with DM (for the letters without and with
the additional ‘d’). The overall evolution for the models without DM heating is similar to those found in previous works [28, 29]. With DM heating, all models go through the Kelvin-Helmholz contraction phase when the stellar mass is several to several tens solar masses, and eventually reach the “main-sequence” phase[28]. Gravitational contraction is halted by nuclear and/or DM annihilation energy generation. As Fig.2 shows, the DM energy generation rate at the center exceeds the nuclear energy generation for the models considered here.

**Figure 2:** Nuclear and dark matter annihilation energy generation rate at center ($\epsilon_c$ in erg g$^{-1}$ s$^{-1}$) (upper panel), and central density ($\rho_c$ in g cm$^{-3}$) and temperature ($T_c$ in K) (lower panel) as a function of stellar mass for models (B) and (Bd).

Therefore, this star is a dark star and sustained by DM annihilation energy. However the
nuclear energy generation rate is not negligible; CNO-cycle hydrogen burning is indeed taking place in the central part. The stars evolve on the main-sequence track over a few million years, with their luminosity increasing with mass. Fig.2 also shows the central temperature and density as a function of stellar mass, for B and Bd models.

We find that the fate of the stars depends importantly on the accretion rate. The DM annihilation supplies an extra energy to support a star against gravitational contraction, and thus the star consumes less hydrogen per unit time, with its lifetime prolonged. The luminosity vs. “final” mass relation for various models are shown in Fig. 3. Besides the steady accretion models A(d), B(d), and C(d), various models with time-dependent accretion are also shown. In many cases, the final stellar mass is larger than 1000$M_\odot$.

Figure 3: Final mass and luminosity for various models. Models A(d), B(d), C(d) are the same as in Fig.1. Models D, Y, F, and G are the cases with the accretion rate $\dot{M} = 10^{-5}M_\odot$ yr$^{-1}$, rates in [33], [31], and [34], respectively. Lower case letters ‘d’ in the model names, such as Dd, indicate that the fiducial dark matter annihilation energy is included. Models M and Md use the rates in [31] with a cut off at $M = 300M_\odot$. In the models Cd×3 and Fd×3, the dark matter capture rate is enhanced by a factor of 3 than the models Cd and Fd, respectively. The solid straight line represents the Eddington Luminosity. The mass range bounded by the dotted lines, labeled PISN, shows the mass range in which the stars explode as pair-instability supernovae and do not form massive BHs. The models with arrows are “stalling”, or, their central temperatures are decreasing. Therefore, their mass may increase further.

The most interesting is Model Bd, the case with $\dot{M} = 10^{-3}M_\odot$ yr$^{-1}$ (see Figs. 1,
2 and 3). It lives long and continues to grow, and becomes a very massive star with 
\( M > 10^5 M_\odot \) (see Fig. 3). Hydrogen burning takes place throughout the evolution after 
the zero-age main sequence, but the DM heating becomes more and more important at later 
evolutionary phases (see Fig. 2). When the stellar mass becomes \( M \gtrsim 5000 - 6000 M_\odot \), the 
central convective regions where hydrogen is partly exhausted, reaches the outer hydrogen-
unexhausted region, conveying fresh hydrogen into its interior. Because of this convection, 
the central hydrogen fraction starts to increase for \( M \gtrsim 5000 - 6000 M_\odot \), and then the hydrogen 
consumption timescale (\( \sim \) the star’s lifetime) becomes infinitely long, or the evolution is 
stalling. The arrow for the model Bd in Fig.3 indicates that the model is “stalling”, or, its 
central temperature is decreasing. Therefore, its mass may increase further as long as the 
mass-accretion continues with the same accretion rate. Note that without DM annihilation 
the final mass of this model (B) is only modest, \( \sim \) several thousand \( M_\odot \).

The stalling phase is expected to end, for example, when the ambient DM density 
becomes lower. The evolution after this stage toward the stellar core-collapse is described 
detail in Sec.5.

### 3.1 Time dependent mass accretion rates

For the time-dependent mass accretion rates, we use the ones given in [33, 34]. These 
authors performed cosmological hydrodynamic simulations. They derive realistic gas mass 
accretion rates for a typical population III stars formed at around \( z \sim 20 \) [33], and also for 
a very rare object (“the very first star”) which forms around at \( z \sim 50 \) from a peak of 
large-scale density fluctuations [34]. Since the \( z \sim 6 \) quasar is a rare object, using the rate 
in [33] is more suitable to explain the SMBH in the high redshifted quasars. In Fig.3 we 
name the models using the rate in [33] and the rate of the model R5wt in [34], as models 
Y and G, respectively. We use the following expression for the accretion rate of model 
Y: 
\[
\dot{M}(M_\odot\text{yr}^{-1}) = 0.045(M/M_\odot)^{-2/3}(\text{for } M \leq 300 M_\odot) \quad \text{and} \quad 16.25(M/M_\odot)^{-1.7}(\text{for } M \geq 300 M_\odot).
\]

For model G, we use: 
\[
\dot{M}(M_\odot\text{yr}^{-1}) = \min(0.18(M/M_\odot)^{-0.6}, 6.0 \times 10^4(M/M_\odot)^{-2.24}).
\]

As mentioned above, the models G and Gd correspond to very rare objects which 
form from peaks of large-scale density fluctuations. In the hierarchical structure formation 
model, such high density peaks grow eventually to luminous quasars that host SMBHs at 
redshifts greater than six [6, 35]. These models result in larger BH mass (several thousands 
solar mass) than the models Y and Yd where the rate in [33] is used.

These rates do not include possible radiative feedback effects from the accreting star 
and accretion disk in the case of the disk-like accretion. Such effects for a disk-like accretion 
model was explored in [31]. In model F we assume the same rate as model G for \( M \lesssim 90 M_\odot \) 
but it reduces as \( \dot{M} = 155.6(M/M_\odot)^{-2.096} \) for larger masses. This rate is similar to the 
model \( K' = 2 \) in [31]. In [31] it was suggested that stellar feedback terminates accretion 
at the time when the disk evaporation time scale equals the accretion time scale. If this is 
the case, the final stellar mass would be upper bounded as the model M in Fig.3. However, 
these models themselves are also based on approximations and geometrical simplifications. 
Since the star’s lifetime is prolonged in our model due to DM annihilation, longer timescale 
evolution has to be followed in order to determine whether or not gas accretion is completely 
quenched before the star dies.
The final masses for the models F and Fd are both \( \sim 1000 M_\odot \) and the effects of the DM annihilation is not so large for the fiducial DM parameter set. However as shown in the next section if the DM annihilation energy is larger, the final mass would be much larger as in the model Fd×3 in Fig.3.

4. Dependence on the DM annihilation rates

A sufficiently high accretion rate of \( \dot{M} \gtrsim 10^{-3} M_\odot \text{yr}^{-1} \) is required for Model Bd which results in the most massive case in our studies (see Fig. 3). However, we find that if the DM heating is stronger the evolution of the accreting star can continue even with lower accretion rates. We have tested this case by enhancing the DM capture rate by a factor of 3. The same effect is expected if the DM annihilation cross-section is enhanced by the Sommerfeld enhancement. Then the steady growth and evolution were seen even for \( \dot{M} \gtrsim 10^{-4} M_\odot \text{yr}^{-1} \) (Model Cd). As long as the accretion continues and the DM density is kept high enough, the stellar mass will continuously increase and the star will become brighter. These cases are shown by \((\times 3)\) to respective models (e.g., Cd×3, etc.) in Fig. 3. We note that these models result in very massive stars, as large as \( \sim 10^4 M_\odot \) or larger (e.g., Model Cd×3), and even for models including radiative feedback where accretion rates decrease with time (e.g., Model Fd×3).

5. Evolution toward gravitational collapse

We have shown that evolution of accreting population III stars may be stalled, or their lifetime will become essentially infinite, if both the DM capture rate and the baryon mass accretion rates are kept sufficiently high. For example, for the fiducial DM parameter set, the evolution stalls if \( \dot{M} \gtrsim 10^{-3} M_\odot \text{yr}^{-1} \). We find also that \( \dot{M} \gtrsim 10^{-4} M_\odot \text{yr}^{-1} \) is enough for stalling if DM capture rate \( \propto \sigma \rho \chi / m \chi \) is enhanced by a factor of 3.

Here we describe in detail how such stalling stars can evolve finally to IMBHs. There are three possible scenarios to end the stalling phase. The first case occurs when “nothing is changed”. If mass accretion continues and the ambient DM density stays constant, then the general relativistic instability is triggered when the stellar mass is \( M \sim 10^6 M_\odot \). Then the star collapses to become a blackhole.

It is, however, not certain whether or not, and at which mass the instability actually occurs, because for a more massive star the captured DM energy generation is larger. If the core temperature of dark stars is too low, the general relativistic instability may not take place even for \( M > 10^6 M_\odot \). We will leave the conclusion concerning this issue for our future work.

The second case occurs when baryon mass accretion ceases but the ambient DM density is unchanged. As shown in Fig.2 when the stellar mass is less than about \( 10^4 M_\odot \), the central temperature is about \( T \sim 10^8 \text{K} \). This temperature is high enough to burn hydrogen. Therefore, if mass accretion ceases when mass is below \( \sim 10^4 M_\odot \), central hydrogen is exhausted within \( 10^8 \) years. On the other hand, a star more massive than \( 10^5 M_\odot \) has
a lower core temperature, and thus cannot evolve quickly by merely stopping the mass accretion because of strong DM heating.

Even for $M \lesssim 10^4 M_\odot$ dark stars, it is not trivial to answer a question of whether the central temperature will rise sufficiently high to proceed to helium and subsequent higher order nuclear burning stages. We confirmed that for stars with $M \lesssim 10^3 M_\odot$ the effect of DM annihilation is not very large. These stars evolve up to the Fe-core formation, and the collapse of the Fe-core is triggered as for stars without DM energy. DM heating is stronger for $M \sim 10^4 M_\odot$ dark stars. We have found that small amount of He-burning causes the stellar core to expand, lowering the central temperature and density to stop the He-burning, i.e., the stellar core oscillates. Eventually this oscillating He-burning should be over (because stellar mass is fixed now), but the lifetime will be much longer than the case without DM heating. Therefore, this case may not necessarily provide a prompt IBMH formation scenario.

The third case occurs when the ambient DM density becomes lower. This can happen, for example, when the star moves out of the high-density region of DM. We find that in this case core collapse is induced most efficiently. The evolution after the central hydrogen exhaustion is particularly interesting for $M \gtrsim 1.2 \times 10^4 M_\odot$. To see this, we show in Fig. 4 the evolution after the DM density is lowered by a factor of 0.3 when the stellar mass is $M = 12,000 M_\odot$. As shown in this figure, the central temperature of the star increases when the DM density is reduced. Then core hydrogen is exhausted within a few times $10^7$ years, and helium core burning follows.

As described in the figure caption, after the He-ignition it takes only a few days before it collapses to a BH. This is because pressure in the stellar interior is dominated by radiation and thus the adiabatic index of the equation of state, $\gamma$, is close to $4/3$. The collapse even more accelerates once the core enters the pair-instability region at around $\log \rho_c \simeq 2.6$. Interestingly, the collapse is so fast that the core directly collapse to a BH before He exhaustion.

Since the collapse is so rapid that there is not enough time to burnout helium before the central temperature reaches $T \sim 10^{10}$K where the composition is determined by the nuclear statistical equilibrium. At this stage there is no way to stop the whole star to collapse into a very massive BH.

6. Discussions and summary

The accreting stars with DM heating were also explored in [36, 20]. However, these authors adopted a very simple polytropic model approach without carrying out actual stellar evolution calculations. Their studies were also confined to smaller accretion rates in [33], and only minimal effects of DM capture were included. Consequently, we find that our results are significantly different from theirs, even qualitatively – e.g., their mass does not go beyond $\sim 1000 M_\odot$ even with DM.

Spolyar et al. [20] discussed that a dark star may have lower temperatures than a normal star with the same mass, and so they may be distinguished. However, this is in general quite difficult because the observed temperature is determined by the location of
Figure 4: The evolution of Model Bd after the DM density is reduced by a factor of 0.3 when the stellar mass is $M = 12,000 M_\odot$. The upper panel shows the central He mass fraction as a function of central density. Vertical lines with numbers indicate the time to collapse. At first, hydrogen burning takes place and helium mass fraction increases from 0.5 to 1.0 in 17Myr. After the beginning of He-burning the star collapses only in 3 days. The middle panel shows the energy generation rate at the center by DM annihilation and nuclear burning. The nuclear energy generation rate becomes negative (as shown by the dashed line) after entering the (He) photo-dissociation region. In the bottom panel the dashed line shows the central density - temperature trajectory. The thick solid line indicates that the star is unstable above this line.

the photosphere, that may locate far above the star for an accreting star [29]. The geometry of the photosphere may not even be spherical if the accretion is aspherical. In that case, only the reliable observational data will be the total luminosity of the star, which correlates
with the stellar mass.

Since these very massive (dark) stars shine with the Eddington luminosity (see Fig.3), they could actually be observed by future missions such as James Webb Space Telescope\(^1\), Thirty Meter Telescope\(^2\), Giant Magellan Telescope\(^3\), and European Extremely Large Telescope\(^4\). In general, normal and dark stars cannot be distinguished by the luminosity only. For example, if DM has significantly smaller scattering cross section than the fiducial value, \(\sigma = 10^{-38}\) cm\(^{-2}\), then only adiabatic contraction of dark matter may contribute to the stellar evolution. In this case, according to [20], the DM effects will be small for \(M > \sim 800M_\odot\). Hence, it will be quite difficult to distinguish between normal and dark stars. Nevertheless, if stars with \(\log L/L_\odot \gtrsim 8.2\) or \(M \gtrsim 4000M_\odot\) are discovered, it might be suggestive of the effect of DM annihilation.

A direct collapse model for massive black formation was proposed by Bromm & Loeb [8]. In a proto-galactic size halo, the gas can cool efficiently via hydrogen atomic cooling. In the absence of molecular hydrogen, due to a strong intergalactic UV background, the gas can rapidly collapse to become a massive black hole. While the actual mass of the formed black hole is rather uncertain, the model offers a viable scenario for the formation of massive black holes without invoking dark matter annihilation. Interestingly, the model predicts that the gas mass accretion rate is very large in such a gas cloud [9]. Therefore, the combined effects of efficient gas cooling and the DM capture that we consider here, might make the formation of massive black holes even easier in large proto-galactic halos.

In summary, we carried out detailed stellar evolution calculations of accreting dark stars that include stellar evolution consistently up to gravitational collapse. For the first time we showed, explicitly, that DM annihilation can make the first stars much more massive than suggested so far. These very massive stars easily will gravitationally collapse to IMBHs of mass as high as \(10^4M_\odot\). Thus we offer a new possibility that, formation of IMBHs with mass substantially higher than \(1000M_\odot\) in the early universe opens a new viable path for early formation of very massive SMBHs with hierarchical mergers.

Acknowledgments

We would like to thank M. J. Rees, F. Takahashi and S. Mandal for useful comments and discussions. We thank an anonymous referee who gave many constructive comments, which improved the manuscript. This work has been supported in part by the grant-in-Aid for Scientific Research from the JSPS, MEXT of Japan, and by the World Premier International Research Center Initiative of MEXT.

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