Forming supermassive black holes by accreting dark and baryon matter

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ABSTRACT
Given a large-scale mixture of self-interacting dark matter (SIDM) particles and baryon matter distributed in the early Universe, we advance here a two-phase accretion scenario for forming supermassive black holes (SMBHs) with masses around $\sim 10^9 M_\odot$ at high redshifts $z \gtrsim 6$. The first phase is conceived to involve a rapid quasi-spherical and quasi-steady Bondi accretion of mainly SIDM particles embedded with baryon matter onto seed black holes (BHs) created at redshifts $z \lesssim 30$ by the first generation of massive Population III stars; this earlier phase rapidly gives birth to significantly enlarged seed BH masses of $M_{BH,t} \sim 1.4 \times 10^6 M_\odot \sigma_0/(1 \text{ cm}^2 \text{ g}^{-1} \text{ (C}_s/30 \text{ km s}^{-1})^4$ during $z \sim 20 - 15$, where $\sigma_0$ is the cross section per unit mass of SIDM particles and $C_s$ is the velocity dispersion in the SIDM halo referred to as an effective “sound speed”. The second phase of BH mass growth is envisaged to proceed primarily via baryon accretion, eventually leading to SMBH masses of $M_{BH} \sim 10^9 M_\odot$; such SMBHs may form either by $z \sim 6$ for a sustained accretion at the Eddington limit or later at lower $z$ for sub-Eddington mean accretion rates. In between these two phases, there is a transitional yet sustained diffusively limited accretion of SIDM particles which in an eventual steady state would be much lower than the accretion rates of the two main phases. We intend to account for the reported detections of a few SMBHs at early epochs, e.g., SDSS 1148+5251 and so forth, without necessarily resorting to either super-Eddington baryon accretion or very frequent BH merging processes. Only extremely massive dark SIDM halos associated with rare peaks of density fluctuations in the early Universe may harbour such early SMBHs or quasars. Observational consequences are discussed. During the final stage of accumulating a SMBH mass, violent feedback in circumnuclear environs of a galactic nucleus leads to the central bulge formation and gives rise to the familiar empirical $M_{BH} - \sigma_b$ correlation inferred for nearby normal galaxies with $\sigma_b$ being the stellar velocity dispersion in the galactic bulge; in our scenario, the central SMBH formation precedes that of the galactic bulge.

Key words: accretion, accretion discs – black hole physics – cosmology: theory – dark matter – galaxies: formation – quasars: general

1 INTRODUCTION
On the basis of various observational diagnostics and numerous case studies, supermassive black holes (SMBHs) are now widely believed to be ubiquitous, particularly at the nuclei of both normal and active galaxies (e.g., Kormendy & Richstone 1995; Haehnelt 2004). As the central gravitational engines to power most energetic activities of quasi-stellar objects (QSOs) or quasars (e.g., Salpeter 1964; Lynden-Bell 1969; Bardeen 1970), SMBHs dynamically impact the for-
formation and evolution of host galaxies (e.g., Silk & Rees 1998; Page, Stevens, Mittaz & Carrera 2001; King 2003; Murray, Quataert & Thompson 2005). Their most tantalizing manifestations are the observed \( M_{\text{BH}} - \sigma_0 \) correlation (e.g., Magorrian et al. 1998; Laor 2001; H¨ aring & Rix 2004) and its tighter version — the \( M_{\text{BH}} \propto \sigma_0^4 \) correlation for both active and normal galaxies (e.g., Gebhardt et al. 2000; Ferrarese & Merritt 2000; Tremaine et al. 2002), where \( M_{\text{BH}} \) is the black hole mass, \( \sigma_0 \) is the galactic central bulge mass and \( \sigma_0 \) is the stellar velocity dispersion in the galactic bulge.

Given substantial progresses in probing and understanding the basic physics of SMBHs as well as galaxy formation and evolution over past several decades (e.g., Lynden-Bell 1969), much still remain to be learned and explored because of the somewhat speculative nature of the subject to a certain extent. During the extensive Sloan Digital Sky Survey (SDSS), the newly reported SMBH with a mass of \( M_{\text{BH}} \sim 3 \times 10^9 \, M_\odot \) in the quasar SDSS 1148+5251 (Fan et al. 2003; Willott et al. 2003) at a redshift \( z = 6.43 \) particularly highlights the outstanding mystery of the rapid BH mass growth in the early Universe and reveals inconsistency with the local \( M_{\text{BH}} - \sigma_0 \) relation (e.g., Walter et al. 2004).

1 For a sustained Edington accretion of baryon matter, the mass growth rate \( M_{\text{BH}} \) of a BH is presumed to be proportional to the black hole mass \( M_{\text{BH}} \), namely

\[
M_{\text{BH}} = M_{\text{BH}} / t_{\text{sal}} ,
\]

where \( t_{\text{sal}} \) is the so-called Salpeter timescale (Salpeter 1964)

\[
t_{\text{sal}} = \frac{\epsilon M_{\text{BH}} c^2}{(1 - \epsilon) L} = 3.9 \times 10^7 \text{yr} \frac{\epsilon L_{\text{Edd}}}{0.1 (1 - \epsilon) L}
\]

with \( c, L, L_{\text{Edd}} \) and \( \epsilon \) being the speed of light, the luminosity, the Edington luminosity and the radiative efficiency, respectively. For constant \( \epsilon \) and \( L/L_{\text{Edd}} \) parameters, the BH mass grows exponentially in the form of

\[
M_{\text{BH}}(t) = M_0 \exp \left[ (t - t_0)/t_{\text{sal}} \right] ,
\]

where \( M_0 \) is the seed BH mass and \( t_0 \) is the initial time of accretion. Recent observations suggest \( L / L_{\text{Edd}} \lesssim 1 \) (e.g., Vestergaard 2004; McLure & Dunlop 2004) and \( \epsilon \gtrsim 0.1 \) — 0.2 (e.g., Yu & Tremaine 2002; Elvis et al. 2002; Marconi et al. 2004). The latest magnetohydrodynamic (MHD) simulations for disc accretion indicate an \( \epsilon \) higher than the oft-quoted value of \( \sim 0.1 \) (e.g., Gammie, Shapiro & McKinney 2004). A higher value of \( \epsilon \) tends to increase the Salpeter timescale \( t_{\text{sal}} \) and thus makes the mass growth of a SMBH via gas accretion more difficult within a short time (e.g., Shapiro 2005). Given an estimated age of \( \sim 0.9 \) Gyr for the quasar SDSS 1148+5251 at \( z = 6.43 \), it would not be easy to assemble a SMBH of mass \( \sim 3 \times 10^9 \, M_\odot \) from a \( \sim 10 - 100 \, M_\odot \) seed BH (e.g., the remnant of an imploding core of a massive Population III star; Arnett 1996; Heger & Woosley 2002) even for a sustained accretion of baryon matter at the Edington limit all the time.

While speculative to various extents, possible theoretical resolutions to this dilemma of rapid SMBH growth in the early Universe include: (1) more massive seed BHs either from collapses of supermassive stars (e.g., Shapiro 2004) or from accretion of low angular momentum baryon materials in the early Universe (e.g., Kousshiappas, Bullock & Dekel 2004); (2) more frequent BH merging processes (e.g., Yoo & Miralda-Escudé 2004; Shapiro 2005; but see Haiman 2004); (3) rapid mass growths via a sustained super-Edington accretion (e.g., Ruszkowski & Begelman 2003; Volonteri & Rees 2005). All these proposals with various assumptions might produce the required mass \( \gtrsim 10^{9} \, M_\odot \) of a SMBH at \( z = 6.43 \) through a baryon accretion alone.

Alternatively, a sustained accretion of self-interacting dark matter (SIDM) particles (e.g., Spergel & Steinhardt 2000) onto a seed BH have been modelled to reproduce the observed \( M_{\text{BH}} - \sigma_0 \) relation (Ostriker 2000; Hennawi & Ostriker 2002; cf. MacMillan & Henriksen 2002 for an alternative approach). As a different application of these ideas and as a theoretical contest, here we entertain the possibility that a proper combination of SIDM and baryon accretion at distinct stages might lead to desired features of forming SMBHs in the early Universe. It is natural and sensible to imagine that on large scales, SIDM particles and baryons are intermingled and mediated by gravitational interactions through fluctuations in the early Universe. Based on the theoretical knowledge of accreting baryon matter, we therefore advance in this paper a two-phase scenario involving accretion of both quasi-spherical SIDMs and baryon matter. In §2, we describe and elaborate our two-phase accretion model scenario in specifics. Summary and discussion are contained in §3.

2 THE TWO-PHASE ACCRETION SCENARIO

In our two-phase accretion model for SMBH formation, the first phase is featured by a sustained, rapid quasi-spherical and quasi-steady Bondi accretion of mainly SIDM particles (a small fraction of baryon matter mixed therein) onto a seed BH created at \( z \lesssim 30 \) presumably by a core implosion inside a first-generation massive star of Pop III until reaching a BH mass of \( M_{\text{BH}} \sim 30 \, M_\odot \) during the redshift range of \( z \sim 20 - 15 \). The second phase of subsequent BH mass growth is primarily characterized by a baryon accretion to eventually assemble a SMBH of mass \( M_{\text{BH}} \sim 10^6 \, M_\odot \); such SMBHs may form either around \( z \sim 6 \) for a sustained baryon accretion at the Edington limit or later at lower \( z \) for average accretion rates below the Edington limit. For conceptual clarity, we consider these two major phases separately. On the theoretical ground, the first phase should gradually evolve into a diffusively limited accretion of SIDM particles continuing towards the BH. As time goes on, the initial mixture of SIDM particles and baryon matter will eventually become or less separated during the accretion process in the sense that radiative baryon matter gradually flatten to a disc accretion which eventually overwhelms the steady accretion of SIDM particles fading into the diffusively limited process.

1 In this context, we note in passing the recent detection of a gamma-ray burst afterglow with a high redshift \( z \gtrsim 6 \).
2.1 Phase I: a sustained spherical accretion of mainly SIDM particles onto a seed black hole

We presume that the initial seed BHs were created by core implosions of massive Pop III stars with typical remnant BH masses of $M_0 \sim 10 - 100 M_\odot$ in the redshift range $z \sim 30 - 10$ [e.g., Wilkinson Microwave Anisotropy Probe (WMAP) observations for the excess power in cosmic microwave background provide tantalizing evidence for the reionization era; see Kogut et al. 2003]; frequent coalescences of such seed BHs might possibly happen to produce more massive seed BHs around the same epoch or shortly thereafter. When such a seed BH happens to immerse in a dark matter (DM) halo of low angular momentum, it accretes SIDMs together with a small fraction of baryon matter mixed therein. As an optimistic approximation, such a SIDM accretion is envisaged as grossly spherically symmetric by an effective transport of angular momentum outward in the ensemble of SIDM particles (Ostriker 2000). We define the specific cross section $\sigma_0 \equiv \sigma_s/m_s$ for an SIDM particle with a mass $m_s$ and a cross section $\sigma_c$; the mean free path is therefore $\lambda = 1/(\rho_0 \sigma_0)$ with $\rho$ being the mass density of the SIDM including a small mass fraction of baryon matter. For regions within the radial range $r \gtrsim \lambda$, the SIDM is sufficiently dense and may be grossly perceived as a ‘fluid’ [e.g., Peebles 2000; Subramanian 2000; Moore et al. 2000; Hennawi & Ostriker 2002].

As a classical reference of estimates, we begin with the well-known stationary Bondi (1952) accretion. Given a singular isothermal sphere (SIS) mass density profile $\rho = C_\rho^2/(2 \pi G r^2)$ for a SIS halo, the mass growth with time of a BH embedded in a quasi-spherical SIDM halo is $M_{\text{BH}}(t) = 2 C_\rho^2 t/G$, where $G$ is the gravitational constant and $C_\rho$ is the SIS halo “sound speed” (Ostriker 2000). Here the “sound speed” is essentially the local velocity dispersion of SIDM particles and is equal to the virial velocity for the SIS case. A quantitative comparison of the Bondi accretion with the Eddington accretion is given by the ratio

$$\frac{M_{\text{Bondi}}}{M_{\text{Edd}}} = \frac{560}{0.1} \left( \frac{C_\rho}{30 \text{ km s}^{-1}} \right)^3 \left( \frac{M_{\text{BH}}}{10^6 M_\odot} \right)^{-1},$$

(3)

where $M_{\text{Bondi}}$ and $M_{\text{Edd}}$ are the Bondi and Eddington mass accretion rates, respectively. Apparently, given a seed BH mass and a typical halo sound speed (see below), the Bondi mass accretion rate $M_{\text{Bondi}}$ dominates over the Eddington mass accretion rate $M_{\text{Edd}}$. As SIDM particles do not radiate, this super-Eddington accretion will proceed without impedence. For sustained isothermal spherical self-similar collapses or accretion (e.g., Lou & Shen 2004; Shen & Lou 2004), the maximum mass growth rate remains in the same order of magnitude as that of the steady Bondi accretion. We emphasize that in the presence of accretion shocks, the central mass accretion rate should be modified (Shen & Lou 2004; Bian & Lou 2005).

This SIDM accretion phase continues until the mean free path $\lambda$ becomes comparable to the accretion radius $r_A$ with a corresponding timescale $t_1 = \sigma_0 C_\rho/(4 \pi G)$, a BH mass $M_{\text{BH}}(t_1) = \sigma_0 C_\rho^2/(2 \pi G^2)$ and a transitional accretion radius $r_A(t_1) = \sigma_0 C_\rho^2/(2 \pi G^2)$. For typical parameters, we have the following quantitative estimates

$$t_1 \approx 1.1 \times 10^7 \text{ yr} \left( C_\rho/30 \text{ km s}^{-1} \right) \sigma_0/(1 \text{ cm}^2 \text{ g}^{-1}),$$

$$M_{\text{BH},t_1} \approx 1.4 \times 10^6 M_\odot \left( C_\rho/30 \text{ km s}^{-1} \right)^2 \sigma_0/(1 \text{ cm}^2 \text{ g}^{-1}),$$

$$r_A(t_1) \approx 7 \text{ pc} \left( C_\rho/30 \text{ km s}^{-1} \right)^2 \sigma_0/(1 \text{ cm}^2 \text{ g}^{-1}).$$

(4)

For a virialized SIDM halo at high $z$, the typical halo virial velocity or local velocity dispersion of SIDM particles

![Figure 1. The mass growth history of a black hole in the SIDM halo mixed with a fraction of baryon matter. The upper and lower panels are for the histories of mass accretion rate $dM/dt$ and of black hole mass $M_{\text{BH}}$, respectively. The thin solid line before $t_1$ represents the Phase I steady Bondi accretion of SIDM particles, while the other thin lines are the diffusive limited SIDM accretion after $t_1$. The curves of thicker (boldface) line types are the Phase II baryon accretion at the Eddington rate: here, we consider three different cases of the moment that Phase II accretion begins, that is, before (dotted), at (dash-dotted) and after (dashed) $t_1$, respectively. Please note that the dash-dotted line and dotted line almost coincide to the right side of $t_1$. The initial seed black hole mass due to a Pop III star is $30 M_\odot$ at $z = 20$. The input parameters are $C_\rho = 30 \text{ km s}^{-1}$, $\sigma_0 = 1.0 \text{ cm}^2 \text{ g}^{-1}$ and $\epsilon = 0.15$.](image_url)
(mimicked as a ‘sound speed’) may be estimated by
\[ C_s = 8.2(M/10^9 M_\odot)^{1/3}(1 + z)^{1/2} \text{ km s}^{-1} \] (5)

(e.g., Barkana & Loeb 2001). Therefore, an estimate of \( C_s \sim 30 \text{ km s}^{-1} \) for a virialized SIDM halo of mass \( M \sim 10^6 M_\odot \) during \( z \sim 20 - 15 \) appears plausible. The comoving halo number density \( n(M,z) \) with mass \( M \) at a given \( z \) can be calculated from the standard hierarchical structure formation model. We adopt an input power spectrum computed by Eisenstein & Hu (1999). For cosmological parameters, we take \( \Omega_m = 0.3, \Omega_A = 0.7, \Omega_b = 0.045, h_0 = 0.7, \sigma_8 = 0.9 \) and \( n = 1 \) in our model calculations.

Estimated constraints on \( \sigma_0 \) from both observations and theories are briefly summarized at this point. Wandelt et al. (2000) evaluated the constraints on \( \sigma_0 \) and found a \( \sigma_0 \) range of \( \sim 0.5 - 6 \text{ cm}^2 \text{ g}^{-1} \). Yoshida et al. (2000) numerically simulated the evolution of a galaxy cluster for \( \sigma_0 = 10.1, \) and \( 0.1 \text{ cm}^2 \text{ g}^{-1} \), and obtained corresponding radial mass profiles. Using the high-resolution X-ray data of Chandra satellite and the assumption of a hydrostatic equilibrium, Arbadjis et al. (2002) derived a mass profile for the galaxy cluster MS 1358+62 that peaks strongly in the central region. From a comparison with the result of Yoshida et al. (2000), they concluded that \( \sigma_0 \lesssim 0.1 \text{ cm}^2 \text{ g}^{-1} \). However, Markevitch et al. (2004) pointed out that there are certain difficulties with this stringent limit and they provided a less stringent limit of \( \sigma_0 \lesssim 1 \text{ cm}^2 \text{ g}^{-1} \).

In general, \( \sigma_0 \) may well depend on relative velocity \( v \) of SIDM particles (e.g., Firmani et al. 2000). Here, we tentatively adopt a \( \sigma_0 \) in the form of
\[ \sigma_0 = \left( \frac{30 \text{ km s}^{-1}}{v} \right) \text{ cm}^2 \text{ g}^{-1}. \] (6)

where \( v \) may be estimated by the isothermal ‘sound speed’ \( C_s \).

Around and after the time \( t_1 \), a transition to a slower diffusively limited accretion of SIDM particles will gradually occur. The accretion rate is then determined by the accretion rate towards the central black hole becomes more and more important as the diffusively limited accretion of SIDM particles approaches a quasi-steady state. The BH continues to accrete SIDM particles and the BH mass rapidly grows to \( \sim 10^6 M_\odot \).

\[ \frac{M_{\text{DM}}}{M_{\text{edd}}} = 3.4 \times 10^{-5} \frac{\epsilon}{0.1 \text{ cm}^2 \text{ g}^{-1}} \left( \frac{v}{30 \text{ km s}^{-1}} \right)^2 \left( \frac{C_s}{10^6 M_\odot} \right)^{-2}. \] (7)

For order-of-magnitude estimates, we may safely ignore the SIDM accretion more or less after the formation of a significantly enlarged seed BH around the end of Phase I accretion. In this sense and in reference to the very initial seed BH, we regard it as a ‘secondary seed BH’ for the Phase II accretion of baryon matter. In Figure 1, we have explored three different onset times for the Eddington accretion rate of baryon matter for comparison. Within our scenario, it is more sensible to have the baryon accretion all along with the SIDM accretion, roughly corresponding to the heavy dotted curve.

### 2.2 Phase II: a disk accretion of baryon matter

In contrast to baryon matter accretion at the Eddington limit as estimated by equation (2), a rapid quasi-spherical accretion of SIDM particles during Phase I dominated during the first \( \sim 10^5 \) yr more and the BH mass rapidly grows to \( M_{\text{BH},t_1} \sim 10^6 M_\odot \) to become a secondary seed BH for the subsequent baryon matter accretion. After this almost instantaneous Phase-I accretion in reference to the Salpeter timescale \( t_{\text{Sal}} \), the accumulation of SIDMs proceeds at a much slower pace with an inefficient loss cone accretion (Ostriker 2000; Hennawi & Ostriker 2002). With favourable environments or sustained reservoirs of fuels, accretion of baryon matter gradually becomes dominant to increase the BH mass by a factor of \( \sim 10^3 \) within subsequent several Salpeter times (see equation (2)) at the Eddington accretion rate. It is this subsequent accretion of baryon matter that eventually assembles most of the SMBH mass, consistent with observations that the BH mass densities in nearby galactic bulges and in active SMBHs are comparable to the mass density accreted during the optically bright/obscured QSO phase (e.g., Yu & Tremaine 2002; Fabian 2004; Haehnelt 2004).

Based on the explorations in Figure 1, it would not matter that much as for the exact moment when the Phase II Eddington baryon accretion sets in. In fact, it may begin at any moment (either before or after \( t_1 \)). However, the Phase I SIDM accretion can produce a massive enough seed BH for the Phase II baryon accretion. Figure 1 illustrates a black hole growth history including the two phases. The Phase I SMBH accretion increases the black hole mass substantially, and then the Phase II baryon accretion enhances the enlarged seed black hole further. The accretion due to SIDM particles after \( t_1 \) peter out rapidly into the diffusively limited regime.

### 2.3 Model applications to high-z quasars

Figure 2 shows the mass range of forming high-\( z \) SMBHs, where we take on three observed SDSS high-\( z \) quasars with reported SMBH masses (Fan et al. 2001, 2003; Willott et al. 2003; Vestergaard 2004): J144816.64+525150.3 (\( z = 6.43, M_{\text{BH}} \sim 3 \times 10^9 M_\odot \)), J103027.10+052455.0 (\( z = 6.28, M_{\text{BH}} \sim 3.6 \times 10^9 M_\odot \)), and J130608.26+035626.3 (\( z = 5.99, M_{\text{BH}} \sim 2.4 \times 10^9 M_\odot \)) distinguished by dashed, dotted, and dash-dotted curves, respectively. Based on our model scenario, we trace BH masses back to higher \( z \), assuming a sustained baryon Eddington accretion and three different radiative efficiencies \( \epsilon = 0.1, 0.15, 0.2 \) to compute the required minimum BH mass of the phase-I accretion as a function of redshift \( z \). We plot the actual final BH mass \( M_{\text{BH},t_1} \) of the phase-I accretion (light solid curves in Fig. 2) in DM halos with 4-\( \sigma \) and 5-\( \sigma \) fluctuations at a given \( z \), using equation 4 and \( C_s \) given by equation 5. As an exploration, we also calculate \( M_{\text{BH},t_1} \) with \( C_s \sim 100 \text{ km s}^{-1} \) yet with a smaller specific cross section \( \sigma_0 = 0.02 \text{ cm}^2 \text{ g}^{-1} \) shown by the heavy dashed line in Fig. 2.

As shown in Fig. 2, our model (i.e., light solid curves) can readily account for the three high-\( z \) SMBHs for \( \epsilon = 0.1 \) and 0.15, without invoking either super-Eddington baryon accretion or numerous BH merging processes. For a higher \( \epsilon = 0.2 \), it is unnatural to explain the presence of high-\( z \) SMBHs with 4-\( \sigma \) fluctuations. For 5-\( \sigma \) fluctuations, the
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Figure 2. Three sets of dashed, dotted, dash-dotted curves with radiative BH efficiency $\epsilon = 0.2, 0.15, 0.1$ respectively are the required minimum BH masses for $10 < z < 30$ after the phase-I SIDM accretion, with distinct line types referring to three reported high-$z$ quasars (SMBHs). The heavy solid lines show the virialized dark matter halo mass $M_{\text{vir}}(z)$ with $4\sigma$ and $5\sigma$ fluctuations at different $z$ values. The light solid lines show the secondary seed BH mass $M_{\text{BH},1}$, created by the first rapid accretion phase at various $z$ for $C_s$ and $\sigma_b$ according to equations $\ref{eq:MBH}$ and $\ref{eq:sigmab}$. The heavy dashed line shows $M_{\text{BH},1}$ with a constant sound speed $C_s = 100$ km s$^{-1}$ and a smaller cross section $\sigma_0 = 0.02$ cm$^2$ g$^{-1}$.

mass requirement can be just met. It is clear that only under rare circumstances, extremely massive SIDM halos may give birth to seed BHs with required Phase-I masses in our scenario.

There are fundamental differences between the two main accretion phases, among which the most important one is that baryon accretion produces strong detectable feedback (e.g., intense radiations and outflows or jets etc) into surroundings. Reviving some ideas of Silk & Rees (1998), King (2003) found a simple yet remarkable association between quasars (SMBHs). The heavy solid lines show the virialized dark matter halo mass $M_{\text{vir}}(z)$ with $4\sigma$ and $5\sigma$ fluctuations at different $z$ values. The light solid lines show the secondary seed BH mass $M_{\text{BH},1}$, created by the first rapid accretion phase at various $z$ for $C_s$ and $\sigma_b$ according to equations $\ref{eq:MBH}$ and $\ref{eq:sigmab}$. The heavy dashed line shows $M_{\text{BH},1}$ with a constant sound speed $C_s = 100$ km s$^{-1}$ and a smaller cross section $\sigma_0 = 0.02$ cm$^2$ g$^{-1}$.

3 SUMMARY AND DISCUSSION

We summarize the two-phase accretion model of SMBH formation in the early Universe below and discuss a few observational implications.

Phase I involves a rapid quasi-spherical accretion of mainly SIDM particles mixed with a small fraction of baryon matter onto an initial seed BH created by a Pop III star. Such a BH grows rapidly to $\sim 10^6 M_\odot$ within a fairly short timescale of $\sim 10^5$ yr.

Phase II involves an accretion of primarily baryon matter (initially mixed with SIDM particles) at the Eddington limit to accumulate most of the BH mass. Since the BH mass is sufficiently massive at the beginning of this phase II, it takes only several Salpeter $\epsilon-$folding times to grow a BH mass of $\sim 10^9 M_\odot$ according to the estimate of an exponential growth by equation (2).

The transition from Phase I to the much slower diffusion limited accretion of SIDM particles goes on concurrently with the gradual dominance of baryon accretion at the Eddington limit in Phase II.

The Phase-I accretion of SIDMs is crucial to produce a sufficiently massive secondary seed BH for further growth by accreting baryon matter. In this scenario, the reported high-$z$ SMBHs of $\sim 10^5 M_\odot$ can be produced, without invoking the hypotheses of either super-Eddington baryon accretion or extremely frequent BH merging processes. Based on a sample of six quasars with $z > 5.7$ observed by the SDSS, Fan et al. (2003) estimated a comoving density of such luminous quasars at $z \sim 6$ and found these quasars showing a $\sim 5\sigma$ peak in the density field. This inference may be readily accounted for by our cosmological model results shown in Fig. 2. We attempt to combine the models of quasi-spherical and quasi-steady SIDM accretion with a baryon accretion to give more plausible schemes of accretion leading to early formation of SMBHs with masses $\sim 10^5 M_\odot$ at high redshifts of $z \gtrsim 5 - 6$.

We now elaborate on consequences of this two-phase scenario. If most SMBHs form by this two-phase accretion with fairly rare BH mergers, the currently observed upper
mass limit for a SMBH \( < M_{\odot} \) constrains the combination of the specific SIDM cross section \( \sigma_o \) and the effective baryon accretion time \( t_2 \) (cf. equation 4), such that

\[
\frac{\sigma_o}{1 \text{ cm}^2 \text{ g}^{-1}} \left( \frac{C_s}{100 \text{ km s}^{-1}} \right)^4 \exp\left(\frac{t_2}{t_{\text{Edd}}}\right) \lesssim 60 , \tag{9}
\]

where the Eddington luminosity is adopted.\(^3\) For SIDM halos formed at low \( z \), they may become massive enough to make the virialized velocity dispersion or ‘sound speed’ of the order of \( C_s \sim 100 \text{ km s}^{-1} \). So the baryon accretion time \( t_2 \) cannot exceed \( \sim 5 t_{\text{Edd}} \) for low-\( z \) QSOs. For typical parameters of \( \epsilon = 0.1 \) and \( L = L_{\text{Edd}} \), it would require a \( t_2 \) \( \sim 2 \times 10^8 \) yr, consistent with the observational QSO lifetime of \( t_Q \sim 10^7 - 10^9 \) yr estimated for low-\( z \) QSO populations (e.g., Yu & Tremaine 2002; McLure & Dunlop 2004).

If we take on reference values of equation (9) for the particular \( z = 6.43 \) SMBH with \( \sigma_o = 1 \text{ cm}^2 \text{ g}^{-1} \) and \( C_s = 30 \text{ km s}^{-1} \), it would have accreted baryon matter over \( \sim 5 t_{\text{Edd}} \) \( \sim 3 \times 10^8 \) yr for \( \epsilon = 0.1 \) and \( L = L_{\text{Edd}} \), in the absence of accretions at super-Eddington rates and of BH merging processes. Such a Phase II accretion time is much longer than the low-\( z \) QSO lifetime, but accounts for only \( \sim 1/3 \) of ages for these quasars. We speculate that high-\( z \) quasars may have longer effective accretion times than low-\( z \) quasars as the former might have more abundant fuel supplies. The plausible physical reasons include: (1) gas materials in galaxies have been much consumed by star formation activities in the low-\( z \) quasars; (2) interactions among galaxies might have been more frequent in the early Universe, that may trigger high accretion activities. Insufficient or interrupted baryon accretion would very likely lead behind less massive SMBHs with masses well below the \( M_{\text{BH}} - \sigma_o \) relation curve.

We note that the Phase I accretion will not affect observations at low-\( z \) galaxies. First, the Phase I SIDM Bondi accretion is more dominant than the Eddington accretion of baryons only for very early \((z > 10) \) SIDM halos, as such halos tend to have a high ‘sound speed’ \( C_s \) (cf. equations 3–5). Secondly, the phase-I accretion might be severely limited by the inner density profile of the SIDM halo. We have used a SIS mass density profile \( \rho \propto r^{-2} \). For a self-similar accretion at a given time, one would have \( \rho \propto r^{-3/2} \) (e.g., Jing & Suto 2000; Lou & Shen 2004; Bin & Lou 2005; Yu & Lou 2005). Numerical N-body simulations (e.g., Navarro et al. 1997) indicate an inner \( \rho \propto r^{-1} \), i.e. the NFW profile (see discussions of Ostriker 2000). For the more inclusive family of the hypervirial models, we have \( \rho \propto r^{-(2-p)} \) with the index \( p \) falling in the range of \( 0 < p \leq 2 \) (Evans & An 2005). A shallower profile may lead to a less efficient accretion of SIDMs (e.g., Hennawi & Ostriker 2002). Observations find that the inner density profiles (e.g., \( \rho \propto r^{-0.5} \)) of dark matter halo of nearby galaxies are shallower than both the SIS and NFW density profiles, and therefore the resulting secondary seed BH mass \( M_{\text{BH}}, t_{11} \) may be expected to be smaller.

\(^3\) Should we take into account of BH merging processes by a significant mass amplification factor of \( \sim 10^4 \) (e.g., Yoo & Miralda-Escudé 2004), then this upper limit would be reduced by a factor of \( \sim 10^4 \) accordingly.

Specific to our Milky Way galaxy, the central black hole has been inferred to possess a mass of \( \sim 4 \times 10^6 M_\odot \) by stellar dynamic diagnostics. For such a less massive SMBH, there are many possible ways to assemble such a BH and it is not necessary to invoke our two-phase scenario.

Finally, we note possible observational signatures and consequences of the two-phase scenario envisaged in this paper. If some large regions in the early Universe were somehow distributed with considerable less baryon matter (e.g., the gravitational potential well of the halo may not be deep enough to bind the high speed baryons due to supernova or hypernova feedbacks), then we may find some DM halos with BHs at their centres but without forming host galaxies. In other words, these BHs grow entirely by Phase I SIDM quasi-spherical Bondi accretions ended with diffusiively limited phase, and the baryon accretion has never occurred in a significant manner. Such unusual systems of DM halo-BHs might be revealed directly by chance through gravitational lensing effects.

Very recently, Magain et al. (2005) reported the discovery of a bright quasar HE0450-2958 yet without a massive host galaxy. The black hole of HE0450-2958 may well be embedded within a dark matter halo (‘dark galaxy’), constituting a DM halo-BH system. Ambient interactions with such a massive object could more readily explain the ring-like starburst in the neighbouring galaxy as well as the capture of gas materials, leading to the eventual onset of quasar activities we observe. Our model can readily account for such kind of phenomena. The phase I SIDM accretion in the dark matter halo produced a seed black hole with a mass range of \( \sim 10^6 - 10^7 M_\odot \), but the phase II baryon accretion has never occurred due to the absence of a host baryon galaxy. As such a massive seed black hole travelled across a neighbouring disc galaxy, it began to induce baryon accretion activities violently to give rise to a bright quasar. We will further develop models on the basis of such a scenario in a separate paper.

Another interesting piece of observational evidence comes from the galaxy NGC 4395 (Peterson et al. 2005). A very ‘small’ low-luminosity SMBH \( \sim 3 \times 10^5 M_\odot \) resides in the bulgeless galaxy NGC 4395, implying that the stellar bulge is not a necessary prerequisite for a black hole in the nucleus of a galaxy. Our model can provide a plausible explanation in the sense that a relatively small SMBH is the product of the phase I SIDM accretion, while the phase II baryon accretion at the Eddington rate is almost absent in a bulgeless galaxy (of course, a very low rate baryon accretion might take place).

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