The Formation of Supermassive Black Holes at Early Universe

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Abstract. The high-redshift universe is now the frontier of modern astronomy, and is the key object for current and near-future telescopes. The high-redshift quasars put a tight constraint on existing BH growth model, as it is challenging to form a 10^{10} M_☉ BH at z~6. In this work, we relax the widely-adopted Salpeter BH growth model, to consider a more realistic path. We consider the variation in the mass and angular momentum orientation of gas supply (i.e. through $\epsilon_L$ and $n$), as well as the change in accretion mode (hot versus cold). Moreover, the conventionally considered BH spin impact on the radiative efficiency $\epsilon_M$ is also taken into account. Our key results can be summarized as follows. Firstly, sufficient gas supply (larger in $\epsilon_L$) is obviously a key factor to make the BH grow efficiently. Also, the BH spin ($a_*$), through the radiative efficiency $\epsilon_M$, has a dominant impact on the BH growth, i.e., those high-redshift quasars with $M_{BH} > 10^{10} M_☉$ should be formed in a chaotic gas supply situation, where the angular momentum orientation of the gas is random. Finally, through analyzing the most realistic accretion model, we find that the only existing model of seed BH is through the direct collapse, driven by either dynamical processes or thermodynamics.

1. Introduction

1.1 Early Universe
Our universe began with an explosion of space itself - the Big Bang. In the early days of the Big Bang, matter was in a hot, dense plasma that cooled as the universe expanded. The universe began its structural formation after Planck's satellite observed the corresponding cosmic microwave background radiation in about 380000 years at 2.72548±0.00057K ($z\approx 1067$, $\Delta z \approx 80$). Protons and electrons combine to form hydrogen atoms, and the almost completely neutral universe enters a relatively quiet "dark age". Starting from small density fluctuations in a quasi-homogeneous universe, dark matter perturbations grew under the effect of gravity to the point that they disconnected from the global expansion of the universe, became self-gravitating, and formed halos within which gas eventually condensed to form stars and the luminous portion of galaxies.

1.2 High-redshift Quasars
Quasars or quasi-stellar objects (QSOs) are extremely luminous active galactic nuclei (AGN) containing supermassive central BHs with accretion disks. Their redshifts are measured from the strong spectral lines that dominate their visible and ultraviolet spectra. When astronomers refer to BHs, two different flavors exist. We know of stellar BHs, with masses up to a few ten times the mass of our Sun ($M_☉$) (Fender & Belloni 2012), and supermassive black holes (SMBHs), with masses up to billions of times that of the Sun, which are the focus of this topic. Most of the best-studied quasars have BHs with masses in the range of tens of millions to a few billion M_☉ (Gültekin et al. 2009). For
high-redshift quasars, we can only see relatively bright quasars containing BH with very large mass, which is a strong selection effect. However, for quasars with large-mass BH, the formation time of such quasars is very short, so the accretion physics is put forward very strict requirements.

Astronomers are especially interested in finding new high-redshift quasars (at redshift higher than 6.5) as they are the most luminous and most distant compact objects in the observable universe. Luminous reionization-era quasars (z>6.5) provide unique probes of supermassive black hole (SMBH) growth, massive galaxy formation, and intergalactic medium (IGM) evolution in the first billion years of the universe’s history. Therefore, high-redshift quasars could serve as a powerful tool to probe the early universe.

Searching for high-z quasars presents some technical challenges. Because bright quasars detectable at large redshifts are rare, large fractions of the sky need to be surveyed. The primary means of identifying quasars is based on their multicolor broad-band photometry, which allows efficient separation from the stellar locus in color space, particularly via the prominent Lyman-α break (e.g., Warren et al. 1987). At high redshifts, this requires photometry at the reddest optical bands. For example, the Lyman break falls at the center of the common optical u, g, r, i and z band filters at z = 1.9, 2.9, 4.1, 5.3, and 6.5, respectively. Finally, the large amount of data requires efficient automated data processing. These criteria were first met by the SDSS, resulting in the first handful of quasars at z ≥ 6, beginning with Fan et al. (2000). In the case of high-redshift galaxies, the commonly used spectral lines (Lyman α break, Hα, Hβ, M_g II and so on) to determine redshift tend to be in the red end of optics or even in the infrared band. Therefore, large optical and IR surveys have continued to dominate high-z quasar searches in the past two decades.

### Table 1. List of Surveys Used in the Discoveries of High-Z Quasars at Redshift z ≥ 6

| Survey Name               | Band | Area (deg²) | Number of quasi-stellar objects | References                          |
|---------------------------|------|-------------|---------------------------------|-------------------------------------|
| Subaru (including SHELLQs + Subaru SC) | Optical | 1,400       | 78                              | SHELLQS: Matsuoka et al. 2016, 2018a, b, 2019a; |
| WISE (including unWISE + AllWISE) | mid-IR | All sky     | 71                              | Wright et al. 2010                  |
| UKIDSS (including ULAS, UKIDSS-DXS, and UHS) | IR     | 7,000b      | 64                              | Lawrence et al. 2007                |
| VISTA (including VHS and VIKING) | IR     | 20,000      | 62                              | VHS: McMahon et al. 2013            |
| Pan-STARRS1               | Optical | 31,000      | 44                              | Chambers et al. 2016               |

### 1.3 Techniques in the measurement of the BH mass

There are numerous ways to measure the mass of a BH. Below we provide a brief overview.

The first is through the gravitational wave (GW) evolutionary pattern, as done by LIGO and VIRGO (Abbott et al. 2016). In this method, the evolving pattern of GW of two merging BHs depends on both their masses and spin (including orientation), and a detailed elaborated comparison of
observations to theoretical templates. We emphasize that because of the limitation in waveband, the GW events detected so far are still stellar systems; we are still waiting for the proposed/scheduled LISA and other instruments to investigate the merger of supermassive BH systems.

The rest several methods are based on astronomy and/or astrophysics (see e.g., Kormendy & Ho 2013, for a summary of these techniques). There are several techniques developed based on the dynamics, of either the stars, the hot ionized gas, or the cold molecular gas. All these applications are based on dynamical motions (Newtonian, or sometimes also general relativity) of selected “tracers”, thus are considered to be direct BH mass measurements. For examples, the stellar dynamics is developed in our Galaxy center, where high-resolution infrared observations can resolve the motions of numerous individual stars. The modelling of these motions reveals the existence of a supermassive BH with M_{bh}=4 \times 10^6 M_\odot. The maser observations of cold molecular gas also find a Keplerian velocity (with opposite directions at opposite locations of the “invisible” BH), which can also be used to constrain the mass of BH quite accurately.

Besides these “direct” methods, we also have several indirect techniques, all of which are calibrated by these direct measurements. The first is the so-called Reverberation mapping method. It is a technology based on the assumption that the broad emission lines observed in the UV and optical spectra of quasars and Seyfert galaxies come from regions close to the BH. The second is based on single-epoch spectroscopy, also called Dibai method (Bochkarev & Gaskell 2009; Gaskell 2009). It is a combination of reverberation mapping method and the empirical relationship of location (or radius) of reverberation mapped gas to the continuum luminosity of the AGN (Kaspi et al. 2000, 2005; Bentz et al. 2006), i.e. r \propto L^{0.519 (0.066)(+0.063)}, where L is the optical AGN luminosity. Luminosity and emission-line width together provide M_{BH}, after calibration to the reverberation-mapped AGNs.

Of course, there are other empirical relationships, such as the fundamental plane among BH mass, the radio and X-ray luminosities, that can also be applied to estimate the BH mass, but all these methods are highly uncertain, thus we omit their discussions here.

1.4 Limited evolutionary time at high redshift

One of the key limitations at high redshift is time. As shown in Figure 1, we plot the time (since Big Bang) versus the redshift. Here we adopt the standard \Lambda\,CDM (flat universe with cold dark matter) model, and we take Planck 2013 Cosmology (Planck Collaboration XIII, 2016, A&A, ) with H_0 = 67.8 km s^{-1} Mpc^{-1} (Planck Collaboration XIII 2016). From this plot, the total time available for a BH born at z\approx30 to grow is only about 4\times108 years up to z\approx10, or about 9\times108 years up to z\approx6. Obviously, this duration is fairly limited, i.e. it is only about 8 (at z\approx10) and 18 (at z\approx6) Salpeter time, respectively.

![Figure 1. The diagram of time (since Big Bang) versus redshift. It is clear from this plot that the total evolutionary duration from z\approx30 to z\approx10 is 3*108 yrs](image-url)
1.5 Seed BHs at high redshift

Figure 2. Three pathways that lead to MBH formation that can occur in a distant galaxy. The starting point is a primeval galaxy, composed of a dark matter halo and a central condensation of gas. Most of this gas will eventually form stars and contribute to making galaxies as we know them. However, some of this gas has gone into making an MBH.

Figure 2 shows three pathways to MBH formation that can occur in a distant galaxy. The starting point is a primeval galaxy, composed of a dark matter halo and a central condensation of gas. Most of this gas will eventually form stars and contribute to making galaxies as we know them. However, some of this gas has gone into making an MBH. Figure 3 shows a more detailed classification of seed BH formation models.

One of the most common theoretical hypotheses is to link the first generation of MBHs to the remnants of the first generation of stars. This hypothesis corresponds to the portion of “Pop III remnants” in figure 3. These stars formed out of pristine gas without heavy elements. Simulations of the formation of stars in proto-galaxies (Bromm & Larson 2004) suggested that the first generation of stars might have contained many stars with masses more than a few hundred $\text{M}_\odot$. This is due to the slow subsonic contraction of the gas cloud—a regime set up by the main gas coolant, molecular hydrogen, which is much more inefficient than the atomic line and dust cooling that takes over when heavy elements are present. If stars more massive than roughly 250 $\text{M}_\odot$ form, no process can produce enough energy to reverse the collapse. Thus, an MBH of $\sim 100 \text{M}_\odot$ is born. Whether most of the first stars were born with such large masses is still an open question, and recent simulations revise the initial estimates of the stellar masses to possibly much lower values, just a few tens of solar masses (Hosokawa et al. 2016). If this is the case, it is unlikely that the first stars have generated the first MBHs. A 10 $\text{M}_\odot$ BH would have a very hard time growing by several billion $\text{M}_\odot$ to explain the observed population of MBHs.

Another possible mechanism is MBHs with substantial initial masses, thousands to millions of $\text{M}_\odot$, can form as a consequence of dynamical instabilities that involve either the gaseous or stellar content of proto-galaxies. This mechanism corresponds to portions “stellar mergers in nuclear clusters” and “BH mergers in nuclear clusters” in figure 3. In proto-galaxies, the gaseous component can cool and contract until rotational support takes over: Centrifugal support typically halts collapse before densities required for MBH formation are reached. Gravitational instabilities, however, can reverse the situation and transport mass in at the expense of rotational support. When this occurs, there are two possible outcomes, depending on the strength of instabilities. In globally unstable galactic disks, an MBH seed may form when gas instabilities drive a very rapid accumulation of gas to create a supermassive star, of up to 1 million $\text{M}_\odot$. To avoid the star exploding as a supernova, gas accumulation must occur in less than 2 million years (the thermonuclear time scale). After exhausting its hydrogen, the core of a supermassive star will contract. As a result of core collapse, a BH of a few tens of $\text{M}_\odot$ forms at the heart of the dying star, which is still being bombarded by infalling gas. The resulting system (a “quasi-star”) is composed of a BH that grows by eating its surrounding cocoon from the inside, increases. In today’s universe, a very massive star would lose most of its mass in
powerful winds before collapsing into a stellar mass BH. This channel of MBH formation naturally predicts that MBHs formed only in the early universe.

In globally unstable galactic disks, an MBH seed may form when gas instabilities drive a very rapid accumulation of gas to create a supermassive star, of up to 1 million $M_\odot$ (Begelman et al. 2006; Johnson et al. 2012). This case corresponds to portions “dynamics-driven gas collapse” and “thermodynamics-driven gas collapse” in figure 3. To avoid the star exploding as a supernova, gas accumulation must occur in less than ~2 million years (the thermonuclear time scale). After exhausting its hydrogen, the core of a supermassive star will contract. As a result of core collapse, a BH of a few tens of $M_\odot$ forms at the heart of the dying star, which is still being bombarded by infalling gas. The resulting system (a “quasi-star”) is composed of a BH that grows by eating its surrounding cocoon from the inside, increases. In today’s universe, a very massive star would lose most of its mass in powerful winds before collapsing into a stellar mass BH. This channel of MBH formation naturally predicts that MBHs formed only in the early universe.

Figure 3. Three main seed BH formation channels in literature, and their outcome BH mass range (in solar unit). The vertical coordinate represents the gas metallicity, which has important impact on the existing models (Volonteri M. 2012).

1.6 BH Mass and Salpeter time scale

Assuming that BHs grow mainly through accretion processes, which cause BHs to emit light. Let $L$ be the bolometric luminosity and $\dot{M}_0$ be the rest-mass accretion rate. Define $\epsilon_M$, the efficiency of conversion of rest-mass energy to luminous energy by accretion onto a BH of mass $M$, according to

$$\epsilon_M \equiv \frac{L}{\dot{M}_0 c^2} \quad (1)$$

Define $\epsilon_L$, the dimensionless luminosity, according to

$$\epsilon_L \equiv \frac{L}{L_E} \quad (2)$$

where the Eddington luminosity $L_E$ is defined as (Shakura & Sunyaev 1973)

$$L_E = \frac{4\pi M \mu m_p c}{\sigma_T} \approx 1.3 \times 10^{38} M \text{ erg s}^{-1} \quad (3)$$

According to the Conservation Law of Mass and Energy, part of the rest-mass ($\epsilon_M M_0$) will be radiated out, while the rest of the rest-mass ((1-$\epsilon_M$)M0) will eventually fall into the BH, making it grow up. In other words, the growth rate of BH mass through accretion processes follows the equation (see, e.g., Shapiro 2005)

$$\frac{dM}{dt} = (1 - \epsilon_M) \dot{M}_0 \quad (4)$$

We emphasize that the rest-mass accretion rate ($\dot{M}_0$) cannot be observed directly. Current estimations on $\dot{M}_0$ usually have large uncertainties, sometimes even differ from each other on orders of magnitude. On one hand, the bolometric luminosity ($L$) of the system can be observed/measured.
quite accurately, and the BH mass can also be evaluated at the accuracy of 0.3 dex (e.g., Kormendy and Ho 2013). Then $\epsilon_L$ can be easily derived. On the other hand, thanks to the advance in accretion theories, the radiative efficiency ($\epsilon_M$) can be estimated (e.g., Shakura & Sunyaev 1973, Yuan & Narayan 2014). We thus re-express the BH mass growth rate $\frac{dM}{dt}$ as

$$\frac{dM}{dt} = \frac{\epsilon_L (1-\epsilon_M) M}{\epsilon_M \tau}$$

(5)

where $\tau = \frac{M c^2}{L_E} = \frac{c \sigma_T}{4 \pi \mu \rho_p} \approx 0.45 \mu M^{-1} Gyr$ is the characteristic accretion time scale. We can further define the BH mass growth time scale as $\tau_0 = \frac{c \sigma_T}{4 \pi \mu g m_p} \times \frac{\epsilon_M}{\epsilon_L (1-\epsilon_M)}$. With this expression, we have $\frac{dM}{dt} = \frac{M}{\tau_0}$. Obviously, if $\epsilon_L$ and $\epsilon_M$ are constant, the integration of above equation has an analytical expression, i.e.

$$M(t) = M_{\text{seed}} \exp\left[\frac{t}{\tau_0}\right]$$

(6)

where $M_{\text{seed}}$ is the mass of the seed BH. According to this equation, the BH grows exponentially, i.e. it takes a duration of $\tau_0$ for a BH to grow by a factor of $e$ in mass. If we further assume that, during the whole BH growth, the BH always accretes at the Eddington limit (i.e. $L = L_E$), and the radiative efficiency is also being a constant, with a value of 0.1. Then we have $\epsilon_L = 1, \epsilon_M = 0.1$. Such case is the so-called Salpeter BH growth, with $\tau_{\text{Salpeter}} \approx 0.05$ Gyrs is the Salpeter time scale. The Salpeter BH growth follows

$$M = M_{\text{seed}} \exp\left[\frac{t}{\tau_{\text{Salpeter}}}\right]$$

(7)

We emphasize that the accretion rate is indeed high ($\epsilon_L = 1$).

For a BH whose seed BH is of mass $M_0$, the time for it to grow into a BH of mass $M$ is

$$t = \tau_{\text{Salpeter}} \times \ln \frac{M}{M_0}$$

(8)

To be specific, it takes a seed BH of mass $10^4 M_\odot$ about 5 Gyrs to grow into a BH of mass $10^8 M_\odot$. And it takes a seed BH of mass $10^5 M_\odot$ about 50 Gyrs to grow into a BH of mass $10^8 M_\odot$. In this term, the smaller the mass of the seed BH, the harder it is to form a supermassive BH.

The exponential growth of a BH is based on assumptions. In reality the growth pattern of a BH $e$ is correlated with the value of $\epsilon_L$ and $\epsilon_M$, which have something to do with the spin and accretion model (hot accretion flow and cold accretion flow) of a BH. Both of them complex the growth history of BH. We will address them later. Hot accretion flow is when gases have a very high temperature and very little radiation while the cold accretion flow is totally opposite. The sha timescale, which is widely used because of its simplicity, is based on the cold accretion flow.

2 Theoretical model

2.1 Introduction of accretion physics

BH accretion is a fundamental physical process in the universe and is the primary power source behind active galactic nuclei (AGNs), BH binaries (BHBs), and, possibly, gamma-ray bursts. If the material accreted does not have enough angular momentum relative to the central celestial body, the material will flow to the central celestial body along the radial direction, forming spherically symmetric accretion. However, if the accreted material has a large angular momentum, they do not fall directly to the central celestial body along the radial, but rotate around the central celestial body, forming a disk of poor rotation, known as the accretion disk. In the early universe, there might have been a lot of gas at the center of the galaxy. But how much of that gas would have fallen into the BH, contributing to
the mass growth of the central BH? And how much of the gas will be fed back by the accretion of the central BH and will push away from it? This is now a frontier subject in astrophysics and no clear conclusion has been reached.

2.2 Hot accretion and cold accretion

The first genuine model of an accretion disk—by which we mean a rotating flow with viscous transport of angular momentum—is the celebrated thin disk model developed in the early 1970s. Depending on the mass of the central BH, the gas temperature in this model lies in the range 104–107 K, which is quite cold relative to the virial temperature. The disk is geometrically thin, whereas the gas is optically thick and radiates thermal blackbody-like radiation. Many accreting BH sources have been successfully modeled as thin disks, e.g., luminous AGNs. The thin disk model applies whenever the disk luminosity $L$ is somewhat below the Eddington luminosity $L_{\text{Edd}}$ or, equivalently, when the mass accretion rate $M$ is below the Eddington rate: $M_{\text{Edd}} = L_{\text{Edd}}/(\epsilon_M c^2)$. When $M$ approaches or exceeds $M_{\text{Edd}}$, the accreting gas becomes optically too thick to radiate all the dissipated energy locally (a key requirement of the thin disk model). Radiation is then trapped and advected inward with the accretion flow. Consequently, the radiative efficiency becomes lower, and $L$ becomes progressively smaller. The disk solution that describes such a system is called the slim disk. (Katz 1977, Begelman 1979, Begelman & Meier 1982, Abramowicz et al. 1988, Chen & Taam 1993, Ohsuga et al. 2005)

The thin disk and slim disk both belong to the class of cold accretion flows. Both consist of optically thick gas. In contrast to these disks is the hot accretion flow model, which was first described by Shapiro et al. (1976; hereafter SLE). The temperature of the gas in the SLE solution is much higher, approaching virial, and the gas is optically thin. A key innovation of the SLE model is the introduction of a two-temperature accreting plasma, where the ions are much hotter than the electrons. The main success of the SLE solution, indeed its motivation, is that, for the first time, it was able to explain the hard X-ray emission seen in some BH sources.

2.3 Hot accretion and cold accretion

Actually, radiation is mainly provided by electrons which means that the value of $\epsilon_M$ is dependent on the energy received by electrons. The energy equations for ions and electrons are,

$$\rho T_i \frac{dS_i}{dR} = (1 - \delta) q_{\text{heat}} - q_{\text{ie}}$$

$$\rho T_e \frac{dS_e}{dR} = \delta q_{\text{heat}} + q_{\text{ie}} - q_{\text{rad}}$$

respectively. Here, $S_i$ and $S_e$ are the entropy (per unit mass) of ions and electrons, respectively, $q_{\text{ie}}$ is the ion-electron energy transfer rate due to Coulomb interactions (Stepney & Guilbert 1983), $q_{\text{rad}}$ is the radiative cooling rate and $q_{\text{heat}}$ is the turbulent heating rate, and $\delta$ defines the fraction of the dissipated
energy received by the electrons. There are several possible dissipation mechanisms to heat electrons and ions in accretion disks (see Xie & Yuan 2012, 2016 for brief summaries). Among them, the two leading models proposed in the literature are magnetic reconnection (e.g., Sironi & Spitkovsky 2014; Numata & Loureiro 2015; Sironi & Narayan 2015; Rowan et al. 2017; Ball et al. 2018) and the Landau-damped MHD turbulent cascades (e.g., Quataert & Gruzinov 1999; Howes 2010. In accretion systems, both could happen, irrelevant to what drives the turbulence. Observations of BH accretion systems typically require $\delta \sim 0.1-0.5$ (see Xie & Yuan 2012 and references therein), while theoretical investigations of both the magnetic reconnection and the damped turbulent cascades agree that $\delta$ can be fairly large, and its value increases with decreasing $\beta$ (e.g., Howes 2010; Sironi & Spitkovsky 2014; Sironi & Narayan 2015; Ball et al. 2018).

For cold accretion flow, the value of $q_{ie}$ is so large that electrons can get almost the same temperature as ions and also the value of $\delta$ has almost no effect on the heat received by electrons. Therefore, the radiative efficiency for cold accretion disk ($\epsilon_{(M,SSD)}$) is approximately 10 percent, though it depends on BH spin (see equation 16).

However, for hot accretion flow, $\delta$ plays an important role in determining the radiated power (Xie & Yuan 2012). It can be obviously seen from figure 4 that different accretion modes will lead to totally different relationships of $\epsilon_{M}$ with accretion rate and other microphysics of accretion disk (and also BH spin, not shown here). The efficiency depends strongly on the assumed value of $\delta$. In addition, for a given $\delta$, the efficiency increases steeply with increasing mass accretion rate. Indeed, near the upper end, the efficiency of a hot accretion flow approaches the efficiency $\epsilon_{(M,SSD)}$ (10%) of a cold accretion disk. This means that for studies of the early universe (including the study of current universe), determining the value of $\epsilon_{M}$ and its evolution is a challenging problem. In practice, we may need to rely on the theory and make some theoretical predictions on the model, so as to solve similar problems. Apparently, there is a big uncertainty (sometimes one order of magnitude) in doing this.

2.4 Formula and expressions

We’ve already derived the differential equation for the rate of mass growth of a BH (equation 5) and the exponential equation of BH growth (equation 6). In sha timescale, we assume that the BH always accretes at the Eddington limit ($L= L_{E}$), and the radiative efficiency is also being a constant, with a value of 0.1 ($\epsilon_{L}=1$, $\epsilon_{M}=0.1$). However, in reality, the efficiency of conversion of rest-mass energy to luminous energy $\epsilon_{M}$ is typically a function of the BH spin parameter $a_{*}$, a dimensionless quality ($a_{*}=J/M^{2}$, $J$ is the angular momentum of the BH). It changes with time as the spin evolves. In this term, we need a more complex system to re-express the rate of mass growth of a BH.

Knowing that the rate of mass growth of a BH is correlated with $a_{*}$, it is of top priority for us to find the evolution of $a_{*}$. We express the spin evolution in terms of the nondimensional quality $s=s(a_{*})$, defined by

$$s \equiv \frac{d(a_{*})}{dt} \frac{M}{M_{*}}.$$  

(11)

Inserting equations (4) and (5) into equation (9) yields the evolution equation for $a_{*}$,

$$\frac{d(a_{*})}{dt} = \frac{\epsilon_{L} \delta}{\epsilon_{M}^{2}}.$$  

(12)

Determining $\epsilon_{M}$ ($a_{*}$) and $s(a_{*})$, which are needed to integrate equations (5) and (8), requires a gasdynamical model for BH accretion. We assume that the gas has sufficient angular momentum to form a disk about the hole, and we consider several different accretion disk models: 1) a standard, relativistic, Keplerian “thin disk” with “no-torque boundary conditions” at the innermost stable circular orbit (cold accretion flow) (Pringle & Rees 1973; Novikov & Thorne 1973; see Shapiro & Teukolsky 1983 for review and references), 2) a relativistic, MHD accretion disk that accounts for the presence of a frozen-in magnetic field in a perfectly conducting plasma (hot accretion flow) (De Villiers & Hawley 2003, De Villiers et al. 2003, Gammie et al. 2004, McKinney & Gammie 2004, and references therein), and 3) a hot non-radiative accretion flow.
In a standard thin disk corotating with the BH, the energy and angular momentum per unit rest mass accreted by a BH are the energy and angular momentum of a unit mass at the ISCO, immediately prior to its rapid plunge and capture by the hole:

\begin{align}
E_{\text{ISCO}} &= \frac{\gamma_{\text{ISCO}}^{3/2} - 2\gamma_{\text{ISCO}} + a_+ \sqrt{\gamma_{\text{ISCO}}}}{\gamma_{\text{ISCO}}^{3/2} - 3\gamma_{\text{ISCO}} + 2a_+ \sqrt{\gamma_{\text{ISCO}}}} (13) \\
I_{\text{ISCO}} &= \gamma_{\text{ISCO}}^{3/2} - 3\gamma_{\text{ISCO}} + 2a_+ \sqrt{\gamma_{\text{ISCO}}}(14)
\end{align}

where the ISCO radius \( r_{\text{ISCO}} \) is given by

\begin{equation}
\rho_{\text{ISCO}} = \{3 + Z_2 - [(3 - Z_1)(3 + Z_1 + 2Z_2)]^{\frac{3}{2}}\} (15)
\end{equation}

where

\begin{equation}
Z_1 = 1 + (1 - a_+^2)^{\frac{3}{2}}(1 + a_+^2)^{\frac{1}{2}}(1 - a_+^2) \quad \text{(16)}
\end{equation}

(see, e.g., Shapiro & Teukolsky, 1983, eqs. [12.7.17] – [12.7.18] and [12.7.24]). The mass accretion efficiency and spin evolution parameters corresponding to the thin disk model are then given by

\begin{align}
\epsilon_M &= 1 - \frac{\dot{E}_{\text{ISCO}}}{\dot{\gamma}_{\text{ISCO}}} (18) \\
s &= \frac{I_{\text{ISCO}} - 2a_+ \dot{E}_{\text{ISCO}}}{\dot{\gamma}_{\text{ISCO}}} (19)
\end{align}

In the MHD cold accretion model, the magneto-rotational instability (MRI, Balbus and Hawley, 1991) drives magnetic turbulence and provides the necessary torque to remove angular momentum from the gas and drive the inflow. Magnetic fields are expected to play an essential role in the dynamics of most relativistic objects such as AGNs, X-ray binaries, gamma-ray bursts, and quasars. In accretion disks, the most important role of the magnetic field is angular momentum transport, which twists the field and results in torsional Alfvén waves and associated jet formation (Balbus and Hawley, 1991; Koide et al. 1999).

The MHD model is arguably the most realistic model for disk accretion of magnetized plasma onto a BH while the standard thin disk model provides a simple, analytic, limiting case that is useful as a point of comparison. Indeed, there have been a number of subsequent MHD simulations of cold accretion disks, which have shown that under the three-dimensional framework of general relativity, accretion disks do not always maintain axisymmetric. In other words, the basic assumption of the original standard thin disk (axisymmetric) is no longer satisfied, which obviously will bring great changes to accretion physics. The results of the numerical simulations suggest that in steady state the radiation efficiency parameter \( \epsilon_M \) as a function of \( a_+ \) is remarkably close to the function characterizing the standard thin disk (equation 16), even though there is no sharp transition in the surface density at or near the ISCO. However, the spin evolution parameter \( s (a_+) \) is different and can be represented reasonably well by the least-squares linear fit

\begin{equation}
s = 3.14 - 3.30 a_+ (20)
\end{equation}

(see McKinney & Gammie 2004, Table 2). In the early universe, the galaxy and its environment are fairly complex. For examples, on galaxy scale, the galaxy may suffer minor and/or major mergers with its neighboring galaxies; on nuclear regions, the gases can either from pre-existing cold gases or from wind or ejections of stellar processes. Consequently, these gases may have extremely different dynamical properties from each other (that feed the BH). Considering these complexities, it is natural for us to expect that the accretion onto BHs may have different accretion rates and/or accretion modes. Obviously, with the knowledge above, neither the radiation efficiency of BH accretion nor the spin evolution can be described by a simple expression. Therefore, in our work, in order to consider the impact of random accretion, we assume that \( \epsilon_M \) follows some simple but physically motivated expressions. Technically we also use a random number to determine the value of \( \epsilon_L \). For the evolution of \( a_+ \), we may also include a random number \( n \) (varies between -1 and 1), to account for the random angular momentum direction of the supplied gas, i.e.
3. Results

The key motivation of this project is to investigate the BH growth at early Universe (or equivalently, at high redshift). For this purpose, we relax ourselves from the oversimplified Salpeter assumption, but instead consider more realistic accretion physics, as discussed in Sec. 2. They include the impact of BH spin evolution, as well as the change in accretion mode (hot versus cold, as the accretion rate may change). These complex factors may also couple with each other, thus make the accretion physics (and consequently the BH growth) obscure to audience.

In all our calculations, we take the initial mass and spin of the BH to be $1\times 10^4 M_\odot$ and $1\times 10^{-2}$, respectively.

3.1 Steady gas supply, cold accretion, with same angular momentum direction

We first consider the simplest case, i.e., steady gas supply, which also has the same rotational orientation (i.e., $n=1$ in Equation 19). The abundance of gas near central BH may vary from one source to another, we thus consider different mass supply rate, through parameter $\epsilon_L$ (luminosity in Eddington unit). In this part, we take $\epsilon_L$ as a constant for simplicity. We further assume that the accretion is through cold accretion process, and we take the typical value of $\epsilon_M=0.1$ as an “averaged” radiative efficiency.

The results are shown in Figure 5, where we consider four choices of $\epsilon_L$, i.e., $\epsilon_L=0.03, 0.1, 0.3, 1$. Note that the case of ($\epsilon_M=0.1, \epsilon_L=1$, the black line) represents the standard Salpeter BH growth case. We take $\epsilon_L$ (luminosity in Eddington unit) as a representative variable. The left figure represents the evolution of BH mass while the right figure represents the evolution of $a^*$.

![Figure 5](image)

Figure 5. The BH mass and spin growth over time. In this plot, we consider the difference in mass accretion rate, where we take $\epsilon_L$ (luminosity in Eddington unit) as a representative variable. In all the curves, we take the luminosity ratio $\epsilon_L$ as a constant (independent of time).

It is clear that, if the accretion rate is systematically higher (i.e. larger in $\epsilon_L$), the BH mass will also grow much faster, i.e., the supermassive BHs observed at $z=6-8$, with $M_{BH}>10^9 M_\odot$, requires an efficient BH growth with $\epsilon_L>0.3$, given the initial BH mass $M_{BH}=10^4 M_\odot$. Also, over the course of $10^9$ years, the BH with higher accretion rate ($\epsilon_L=0.3$) grew to approximately $2\times 10^4 M_\odot$ while BH with lower accretion rate ($\epsilon_L=0.03$) grew to approximately $2\times 10^4 M_\odot$, about 100 times the difference (note that the difference in $\epsilon_L$ is only a factor of 10), such larger difference in BH mass is mostly due to the difference in $\tau_0$, i.e. for a given total time available, systems with smaller $\tau_0$ will have more e-folding growth compared to that with larger $\tau_0$.

3.2 Steady gas supply, cold accretion, with same angular momentum direction: impact of $a^*$ on radiative efficiency

We then consider a more complex case, i.e., steady gas supply with same angular momentum direction (i.e., $n=1$ in Equation 19), but involves the impact of $a^*$. Due to the differences between the abundance of gas near the central BH, we vary values of $\epsilon_L$ to represent the difference in mass supply rate. Here, we take $\epsilon_L$ as a constant for simplicity. However, this time we express $\epsilon_M$ in terms of $a^*$ (see section 2, equation 16), i.e. $\epsilon_M$ here is no longer a constant.
In figure 6, we still consider four choices of $\epsilon_L$, i.e., $\epsilon_L = 0.03, 0.1, 0.3, 1$ and $\epsilon_L$ was taken as a representative variable. Still, the left panel represents the evolution of BH mass and the right panel represents the evolution of $a^*$.

Figure 6. Same as Fig. 5, but now the impact of $a_\ast$ onto the radiative efficiency $\epsilon_M$ is taken into account. We emphasize that in all the calculations here, we only consider a cold accretion system.

From figure 6, we still find that if the accretion rate is systematically higher (i.e., larger in $\epsilon_L$), the BH mass will also grow much faster. Similarly, the supermassive BHs observed at $z \sim 6-8$, with $M_{BH} > 10^5 M_\odot$, requires an efficient BH growth with $\epsilon_L > 0.3$, given the initial BH mass $M_0 = 10^4 M_\odot$. Over the course of $10^9$ years, the BH with higher accretion rate ($\epsilon_L = 0.3$) grew to approximately $3 \times 10^5 M_\odot$ while BH with lower accretion rate ($\epsilon_L = 0.03$) grew to approximately $2 \times 10^4 M_\odot$, about 15 times the difference. This is much small than the difference in case 3.1, but still reflects that the higher the accretion rate, the faster the growth of BH.

3.3 Steady gas supply, cold accretion: impact of both $a_\ast$ on radiative efficiency and random gas angular momentum direction

All the above calculations assume a fixed orientation of gases supplied, i.e. they have the same direction in angular momentum. In reality, the gas onto the seed BHs may have various origins (see e.g., Section 2), thus it is naturally for us to expect that they can be of random direction in angular momentum. This will have significant impact on the evolution of $a_\ast$, where we (due to our oversimplification) observed an increase in $a_\ast$ in both Sec. 3.1 and Sec. 3.2.

We thus in this subsection to investigate a steady gas supply but with random gas angular momentum direction. The impact of $a_\ast$ is also taken into account (through radiative efficiency $\epsilon_M$, see equation 16 in section 2). For simplicity as well as clearance in physical impact, we take fixed values of $\epsilon_L$. Considering the un-constrained gas supply near central BH, several choices of $\epsilon_L$ are adopted. Technically, the direction of the angular momentum of accreted gas is modelled by a random number (between -1 and 1) at each time step.

Figure 7. Same as Fig. 6, but now the impact of random gas angular momentum direction is taken into account. We emphasize that in all the calculations here, we only consider a cold accretion system.

The results are shown in figure 7, where consider four choices of $\epsilon_L$, i.e., $\epsilon_L = 0.03, 0.1, 0.3, 1$. The left and the right panels show the evolution of BH mass and $a\ast$. Clearly, $a\ast$ is now much lower compared to previous calculations, and it can be either positive or negative. For most of its early evolution (i.e. before $t<2 \times 10^8$ year), the BH remains non-rotating (i.e. $a\sim 0$). Consequently, we systematically have fairly smaller radiative efficiency ($\epsilon_M$), thus the BH growth is larger, i.e. the BH
grows much faster compared with previous calculations. In this calculation, the BH mass can be greater than 10^{10} M_☉, which is required by recent observations of high-redshift quasars (e.g., Wu et al. 2016).

3.4 Random gas supply, realistic accretion mode change (without the impact of a_* on radiative efficiency)

From accretion theory, it is known that the accretion mode may change at different accretion rate. This effect is not touched by calculated above (mostly because in all these calculations, we always consider a large value of ε_L, thus they will always be in the cold accretion mode), thus will be addressed here. For clarity, we ignore the impact of a_* on the radiative efficiency ε_M.

For this purpose, we consider a random gas supply with sufficient dynamical range in luminosity, i.e. we take ε_L as a random number between 10^{-4} and 1. With the decrease of ε_L, the BH accretion changes from cold accretion to hot accretion. Therefore, we need to consider the consequences (effects) of the difference between hot and cold accretion, i.e. the effect onto ε_M. To derive the expression of ε_M, we first ignore the evolution of a_* and consider ε_M as follow (see e.g., Xie & Yuan 2012; Yuan & Narayan 2014a; below we take it as ε_M=f(ε_L)),

1. ε_M =ε_(M,SSD)=0.1, if ε_L >0.01 (cold accretion case)
2. ε_M =0.08, if 0.01 ≥ ε_L ≥ 0.003 (two-phase accretion case. numerous cold clumps embedded in hot accretion flow)
3. ε_M =0.08×(ε_L /0.003)^2, if ε_L<0.003 (hot accretion case)

Figure 8. The evolution of BH mass, spin and luminosity. We take into account the change in accretion mode, but ignore the impact of BH spin on ε_M (the red line). We take ε_L as a random number uniformly varies between 10^{-4} and 1. For comparison, we also plot the BH accretion model when ε_L and ε_M are all constant (green and yellow lines). In this plot, we consider both cold accretion system and hot accretion system.

The results are shown in Figure 8. The left panel represents the evolution of BH mass, the middle panel represents the evolution of a_*, and the right panel represents the evolution of the luminosity of BH. In the three panels, the red curves show our updated model, i.e. including the effect of different accretion modes but not involving the effect of a_. For comparison, the cases of (ε_M=0.1, ε_L=0.1) and (ε_M=0.1, ε_L=0.3) are also shown here in green and yellow, respectively.

Clearly, in the right panel, the luminosity of BH in this case varies over a wide range (10^{38}~10^{42} ergs s^{-1}). Despite such difference, the evolutions of BH mass and a_* of this new model, as shown in the left and middle panels, are almost equivalent to the case of (ε_M=0.1, ε_L=0.1). This may suggest that the random accretion model adopted here can be approximated by the fueling at the constant 10 percent Eddington value (ε_L=0.1). We admit that this is because random number of ε_L has a uniform distribution, with the luminosity-weighted ε_L is close to 0.1.

We further plot the luminosity distribution of the system, and the result is shown in Figure 9. Interestingly, it shows a gaussian profile, with a peak around 10^{42.3} erg/s, and the FWHM (full width at half maximum) around 1 dex.
3.5 “Real” situation

Finally, we consider the most realistic case, i.e. compared with the Sec. 3.4 we additionally consider the impact of $a_s$ on $\epsilon_M$. We simplify the expression of $\epsilon_M$ as follows:

1) $\epsilon_M = \epsilon_M(a_s) \text{ if } \epsilon_L > 0.01$ (cold accretion case);

2) For hot accretion flow (including the clumpy two-phase accretion), the dependence on BH spin is much weaker than that of the standard cold accretion disk (Yuan & Narayan 2014). In this case, we simply take

$$\epsilon_M = f(\epsilon_L) \times \left( \frac{\epsilon_M(a_s)}{\epsilon_M(a_s = 0.3)} \right)^{0.5} \text{ if } 0.01 \geq \epsilon_L \geq 0.003,$$

$$\epsilon_M = f(\epsilon_L) \times \left( \frac{\epsilon_M(a_s)}{\epsilon_M(a_s = 0.3)} \right)^{0.25} \text{ if } \epsilon_L < 0.003.$$

The results of this realistic model are shown in Figure 10. Again, for comparison the result without the BH spin effect on $\epsilon_M$ (i.e., $\epsilon_M = \epsilon_M(\epsilon_L)$) are shown by the green curves.

Figure 10. Same as Fig. 7, but now the effect of BH spin on $\epsilon_M$ is taken into account. We take $\epsilon_L$ as a random number between $10^{-4}$ and 1. For comparison, we also plot the previous BH accretion model (green line, the case that ignore the impact of BH spin on $\epsilon_M$). In this plot, we consider both cold accretion system and hot accretion system.

The results are shown in figure 10. The red lines are for the $\epsilon_M = \epsilon_M(\epsilon_L, a_s)$ case, while the green lines are for the $\epsilon_M = \epsilon_M(\epsilon_L)$ case. In both cases, we consider a random gas supply. We find that, both cases are not efficient in BH growth, i.e. the BH mass is less than $10^5 M_\odot$, in both cases.

We realize that such result may be due to the high BH spin, which is caused by fixed angular momentum direction of the accreted gas. To resolve this issue, we additionally consider the change in the orbital direction of accreting gas. As done in Sec. 3.3, we assume the orbital direction $n$ (see
Equation 19) is uniformly distribution. Moreover, it is clear that if the average value of $\varepsilon_L$ is too low, the BH cannot grow fast enough. We thus for our most realistic case consider a much narrower dynamical range in $\varepsilon_L$, i.e. uniformly varies between 0.1 and 1. The corresponding results are shown in Figure 9 in blue. We find that, with this update, the BH can grow up to $\sim 1.5 \times 10^6 M_\odot$ within $\sim 8 \times 10^6$ yrs. Such result is welcomed by recent observations of high-redshift quasars. In this case, we also expect the BH to have a low spin, i.e. $a_* < 0.3$, as shown in the right panel of Figure 9.

4. APPLICATION TO OBSERVATIONS: CONSTRAINS ON THE FORMATION OF SEED BHS

We not apply our theoretical model to the observations. For this purpose, we only take two representative high-redshift BHs, one is SDSS J0100+2802 at $z=6.33$ (the Universe has an age of 1.65 $Gyrs$), which harbors the most massive BH ($M_{BH} = 1.24 \times 10^{10} M_\odot$; Wu et al. 2015), the other is J1007+2115 with $M_{BH} = 1.5 \times 10^9 M_\odot$ (Yang et al. 2020), which has the second highest redshift to date, i.e. $z=7.515$ (the Universe has an age of 1.32 Gyrs). In our applications, we assume the seed BHs are created at $z=35$, when the Universe is 0.15 Gyrs old. Obviously, the seed BHs in these two systems have respectively, 1.5 Gyrs and 1.17 Gyrs, to grow up to their observed values. We compare two theoretical models, one is the “ideal” Salpeter BH growth, and the other is the most realistic one.

![Figure 11](image.png)

Figure 11. We take two representative high-redshift BHs, one is SDSS J0100+2802 at $z=6.33$, which harbors the most massive BH ($M_{BH} = 1.24 \times 10^{10} M_\odot$; Wu et al. 2015) (the red line), the other is J1007+2115 with $M_{BH} = 1.5 \times 10^9 M_\odot$ (Yang et al. 2020), which has the second highest redshift to date, i.e. $z=7.515$ (the green line).

Figure 11 shows the ideal Salpeter BH growth. It is clear from this plot that the Salpeter growth is optimistic, i.e. with an initial seed BH of approximately $(1 - 2) \times 10^4 M_\odot$, the BH can easily grow up to $10^9 - 10^{10} M_\odot$. We note that, even with a small difference (a factor of $<2$) in the mass of seed BH, the difference is amplified to a much larger difference, i.e. a factor of $\sim 8 - 10$.

We then check the most realistic case (see Section 3.5), and the results are shown in Figure 11. We find that, in order to have the BH mass at observed redshift (i.e. $z=6-8$), the initial mass at $z=35$ is much larger than the ideal Salpeter growth. The typical value is now changed to $(1 - 2) \times 10^6 M_\odot$. 
The typical value is now changed to $(1 - 2) \times 10^6 M_\odot$.

**Figure 12** We plot the most realistic case (see Section 3.5). We take two representative high-redshift BHs, one is SDSS J0100+2802 at $z=6.33$, which harbors the most massive BH ($M_{BH} = 1.24 \times 10^{10} M_\odot$; Wu et al. 2015) (the red line), the other is J1007+2115 with $M_{BH} = 1.5 \times 10^9 M_\odot$ (Yang et al. 2020), which has the second highest redshift to date, i.e. $z=7.515$ (the green line).

5. SUMMARY

The high-redshift universe is now the frontier of modern astronomy, and is the key object for current and near-future telescopes, e.g., SDSS/BOSS, JWST and LSST in infrared or optical, SKA in radio and Athena in X-rays. Thanks to the advantage of these facilities, we have already observed about 100 galaxies and quasars with redshift greater than 6 (e.g., Yang et al. 2020, and references therein). The high-redshift quasars put a tight constraint on existing BH growth model (e.g., Wu et al. 2016; Yang et al. 2020), as it is challenging to form a $10^{10} M_\odot$ BH at $z \sim 6$.

In this work, we relax the widely-adopted Salpeter BH growth model, to consider a more realistic path. We consider the variation in the mass and angular momentum orientation of gas supply (i.e. through $\epsilon_L$ and $n$), as well as the change in accretion mode (hot versus cold). Moreover, the conventionally considered BH spin impact on the radiative efficiency $\epsilon_M$ is also taken into account. When we compare with observational data, we always consider the seed BHs being born at redshift $z=35$. Our key results can be summarized as follows.

1. Sufficient gas supply (larger in $\epsilon_L$) is obviously a key factor to make the BH grow efficiently. In order to have a sufficient BH growth, we should expect that on average $\epsilon_L > 0.1$ or even $\epsilon_L > 0.3$.

2. The BH spin ($a_*$), through the radiative efficiency $\epsilon_M$, has a dominant impact on the BH growth, i.e., those high-redshift quasars with $M_{BH} > 10^{10} M_\odot$ should be formed in a chaotic gas supply situation, where the angular momentum orientation of the gas is random. In this case, we predict that the final BH as observed should systematically has lower $a_*$. We note that, current observations still have weak/no constraints on these high-redshift BHs, and we await further facilities/observations to test this theoretical prediction.

3. The observed high-redshift quasars put a tight constraint on the formation channel of seed BHs (at $z \sim 35$, when the universe is 0.15 $Gyr$ old). For the ideal Salpeter BH growth model, the seed BH is fairly less massive, i.e. $M_{BH, seed} \sim (1 - 2) \times 10^6 M_\odot$, and there are various models to create such BHs. On the other hand, under the most realistic model where the change in both the orbital direction of accreting gas and the gas mass supply rate (through $\epsilon_L$), the requirement of seed BHs will be approximately $M_{BH, seed} \sim (1 - 2) \times 10^6 M_\odot$. Obviously, these seed BHs are over massive, and their formation channels are indeed limited. We find that, the only existing model is through the direct collapse, driven by either dynamical processes or thermodynamics (see Sec. 1).

4. With our statistical modelling, we should expect that, besides these supermassive BHs (i.e., quickly growing ones), there are also normal BHs that grow gently. These systems should be much dimmer than those observed, but may be observable by upgraded facilities like LSST and/or SKA. It
will be of both theoretical and observational interests to find a less massive (i.e. $M_{BH} \sim 10^6 - 10^7 M_{\odot}$) at these redshifts, since all these objects are the progenitors of the BHs in current ($z \sim 0$) Universe.

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