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MODELING OF SUPERMASSIVE BLACK HOLE GROWTH AT REDSHIFT $Z = 7$

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Abstract. It is widely accepted that SMBHs reside in centers of massive galaxies and quasars. SMBHs are formed by a combination of gas accretion and merges with other massive BHs. Some SMBHs are detected in very early Universe ($\sim$ 800 Myr). We use Millennium II simulation in order to find out if SMBHs can be formed that early with known growth mechanisms. We find that BH seeds with masses $100\mathrm{M}_\odot$ that accrete at the Eddington ratio 2.9 can form SMBH with mass $10^9\mathrm{M}_\odot$ at $z = 6.2$ or at $z = 7.3$ for accretion at the Eddington ratio 3.2. Accretion at the Eddington ratio ~ 3 is still difficult to explain, but it might be possible especially after new observational evidence of quasars that accrete at super-Eddington ratio of the similar values.

1. INTRODUCTION

Massive elliptical and spiral galaxies host super-massive black holes (SMBHs) with masses $10^6\mathrm{M}_\odot$ to $10^{10}\mathrm{M}_\odot$ at their centers (Kormendy & Richstone 1995). Quasars, powered by SMBH with mass $\sim 10^9\mathrm{M}_\odot$ are discovered at redshift $z > 6$. The most distant SMBH known so far is the one with mass $2 \times 10^9\mathrm{M}_\odot$ detected at $z = 7.1$ (Mortlock et al. 2011). In order to grow to such massive SMBH, a single light BH seed (100 $\mathrm{M}_\odot$) need to continuously accrete at the Eddington luminosity for 840 Myr. This means that it would be impossible to grow SMBH from light BH seeds at the Eddington limit by $z = 7$. It raises a question how massive were the initial BH seeds and what values BH growth parameters can take?

1. 1. BH SEEDS FORMATION AND GROWTH PARAMETERS

Two main BH seed formation mechanisms are Pop III stars and direct collapse of gas into BH.

Pop III stars, the first metal-free stars, might be progenitors of BH seeds that grew to SMBHs at high redshift quasars (Madau & Rees 2001; Heger et al. 2003; Wise & Abel 2005). Masses of those BH seeds depend on the masses of Pop III stars, which could be in range $60 - 300\,\mathrm{M}_\odot$ (Bromm et al. 2009), or even $1000\,\mathrm{M}_\odot$ (Hirano et al. 2013). It is typically assumed in the literature that Pop III stars form BH seeds with masses close to $100\,\mathrm{M}_\odot$. Previous attempts to form $\sim 10^9\,\mathrm{M}_\odot$ SMBHs at $z \sim 6$

from Pop III seeds required continuous accretion close to or exceeding the Eddington limit (Haiman & Loeb 2001, Tyler et al. 2003, Volonteri & Begelman 2010, Whalen & Fryer 2012, Johnson et al. 2012). There are theoretical uncertainties whether BH seeds can sustain such high accretion rates for a long time (e.g., Milosavljević et al. 2009, Jeon et al. 2011).

Another possible mechanism for BH seed formation is direct collapse of gas into BH. Those BH seeds have masses in range $\sim 10^4 - 10^6 \mathrm{M}_\odot$ and can easier reach $10^9 \mathrm{M}_\odot$ at $z > 6$ (Loeb & Rasio 1994, Eisenstein & Loeb 1995, Oh & Haiman 2002, Bromm & Loeb 2003, Koushiappas et al. 2004, Begelman et al. 2006, Lodato & Natarajan 2006, Begelman et al. 2008). Direct collapse is possible if fragmentation and star formation are avoided. Fragmentation will not occur if gas has no metals and if formation of H_2 molecules is prevented via strong UV background. Alternatively, major mergers may lead to a rapid gas inflow. In such case, turbulence may be the inhibitor of fragmentation, and the requirement of metal-free gas may be relaxed (Mayer et al. 2010).

BH growth due to gas accretion depends on three gas accretion parameters. Those parameters are radiative efficiency, Eddington ratio and the time that a BH spends accreting.

Radiative efficiency, ϵ, is the efficiency of conversion of rest-mass into energy during accretion and it depends on BH spin. Mean value of radiative efficiency for quasars is $\epsilon \geq 0.1$ (Elvis et al. 2002, Yu 2002, Davis & Laor 2011) and can be estimated using Soltan's argument (Soltan 1982).

Eddington ratio is $f_{\mathrm{Edd}} = \frac{L}{L_{\mathrm{Edd}}}$, where L is a radiative luminosity of a BH and $L_{\mathrm{Edd}}[\mathrm{erg\ s^{-1}}] = 1.26 \times 10^{38} M_{\mathrm{BH}}\ [\mathrm{M}_\odot]$ is Eddington luminosity. It is usually assumed that BH luminosity during accretion cannot exceed the Eddington luminosity. However, recent observational (Kelly & Shen 2013, Du et al. 2014, Page et al. 2013) and theoretical (Volonteri & Rees 2005, 2006, Volonteri & Silk 2014, Dehnen & King 2013) works showed that quasars, at least at some point in their evolution, can accrete at the super-Eddington luminosities.

Quasars lifetimes can also be estimated using Soltan's argument (Soltan 1982). Observations usually show that quasars lifetimes are comparable with Salpeter's time (Salpeter 1964), which is e-folding time scale for SMBH growth:

$$t_{\mathrm{s}} = M/\dot{M} = 4.5 \times 10^7 (\frac{\epsilon}{0.1})(\frac{L}{L_{\mathrm{Edd}}})^{-1}. \tag{1}$$

Yu & Tremaine (2002) showed that quasar lifetime is a function of BH mass. They found that the mean lifetime is $t_Q = 3 - 13 \times 10^7$ yr for $\epsilon = 0.1 - 0.3$ and $10^8 < M_{\mathrm{BH}} < 10^9 \mathrm{M}_\odot$.

After the accretion episode, final BH mass is given by (Johnson et al. 2013):

$$M_{\mathrm{BH}} = M_{\mathrm{BH,0}} \times \exp\,[\,\frac{f_{\mathrm{Edd}}\,(1-\epsilon)}{\epsilon}\ \frac{t_{\mathrm{f}} - t_{\mathrm{i}}}{t_{\mathrm{Edd}}}] \tag{2}$$

where $t_{\mathrm{Edd}} = 450$ Myr, t_{f} i t_{i} are the ages of the universe when the BH attains its final mass and at the time of seed formation, respectively.

We use data from Millennium II simulation (Boylan-Kolchin et al. 2009) to examine if BH mergers in merger trees of this simulation contribute to the growth of $10^9\ \mathrm{M}_\odot$ SMBH at $z > 6$.

2. METHOD

Our goal is to find out under what conditions BH seeds from various models can produce SMBH with mass $> 10^9 \mathrm{M}_\odot$ at $z > 6$. We use publicly available data from Millennium II simulation (Boylan-Kolchin et al. 2009) to make merger tree which tracks halo merger history from redshift $z = 19.9$ to $z = 6.2$. Millennium II simulation (Boylan-Kolchin et al. 2009) is large N-body simulation which follows 2163^3 particles within a periodic simulation cube of side length $L = 100h^{-1}$ Mpc. Each simulation particle has mass 6.885×10^6 $\mathrm{M}_\odot$.

We use Millennium II database to select halos with mass $> 10^{11} \mathrm{M}_\odot$ at redshift $z = 6.2$. For all selected halos we find their progenitor halos, i.e. halos that have merged at previous snapshot to form the selected halos. We repeat this procedure up to redshift $z = 19.9$ where first mergers are recorded. We assume that each newly formed halo hosts one BH and that two BHs merge right after their host halos merge. BHs can grow by merging with other BHs and by gas accretion. We treated separately minor and major mergers. Merger is major if $\frac{M_{\mathrm{halo1}}}{M_{\mathrm{halo2}}} \geq 0.3$ for $M_{\mathrm{halo1}} < M_{\mathrm{halo2}}$. In the case of minor merger mass of the newly formed BH is a simple sum of the previous BH masses and in the case of major merger gas accretion is triggered (equation 2).

2. 1. INITIAL BH MASSES AND PARAMETERS CHOICE

Final BH mass depends on the initial BH mass, Eddington ratio, radiative efficiency and quasars lifetime (equation 2.). For radiative efficiency we choose commonly accepted value $\epsilon = 0.1$ (Elvis et al. 2002, Yu & Tremaine 2002, Davis & Laor 2011). In each accretion episode BHs are able to accrete for a period of time given by Yu & Tremaine (2002).

Free parameters in our model are the initial BH mass and the Eddington ratio. In each of our semi-analytical simulation runs we vary the values of these two parameters with a condition that BH mass at $z = 7.3$, i.e $z = 6.2$, has to be $> 10^9$ $\mathrm{M}_\odot$.

3. RESULTS

Figure 1. shows the minimum value of the Eddington ratio (f_{Edd}) necessary to be assigned to BHs in every accretion episode along the merger tree, in order for merger tree to produce SMBH with mass $> 10^9 \mathrm{M}_\odot$ at redshifts $z = 7.3$ and $z = 6.2$. In every accretion episode radiative efficiency is fixed at $\epsilon = 0.1$, and quasar lifetime is taken from Yu & Tremaine (2002). Each point in Figure 1. is a result of one semi-analytic simulation which produces SMBH with mass $> 10^9 \mathrm{M}_\odot$ for the given combination of Eddington ratio and initial BH mass.

Figure 1. shows that light BH seeds with masses $100 \mathrm{M}_\odot$ need to accrete on the Eddington ratio $f_{\mathrm{Edd}} = 2.9$ in order to form SMBH with mass $> 10^9 \mathrm{M}_\odot$ at $z = 6.2$ (black line). At redshift $z = 7.3$ (red line) Eddington ratio $f_{\mathrm{Edd}} = 3.2$ is needed.

In further analysis we concentrate on one halo with the most massive BH at redshift $z = 7.3$ and its progenitors. We examine light BH seeds with masses $100 \mathrm{M}_\odot$ and assume that in every accretion episode radiative efficiency is $\epsilon = 0.1$ and Eddington ratios are $f_{\mathrm{Edd}} = 3.2$.

Figure 2. represents every major merger in the merger tree of the halo which hosts $> 10^9$ $\mathrm{M}_\odot$ SMBH at $z = 7.3$. It shows the mass of more massive halo in each major

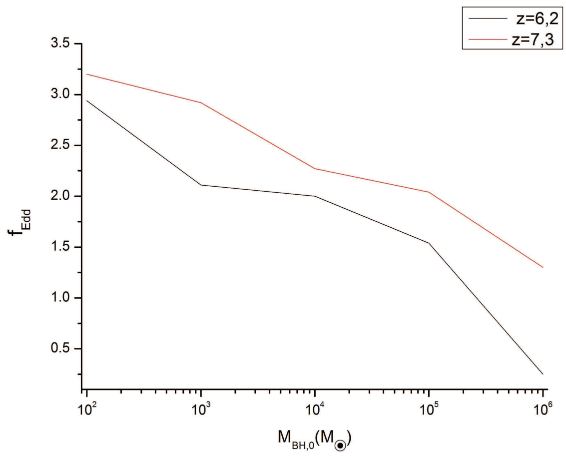

Figure 1: Eddington ratio as function of initial BH masses. Figure shows different combinations of Eddington ratio and initial BH masses that produce SMBH with mass $> 10^9 M_\odot$ at redshift $z = 6.2$ (black line), and $z = 7.3$ (red line), respectively, with $\epsilon = 0.1$.

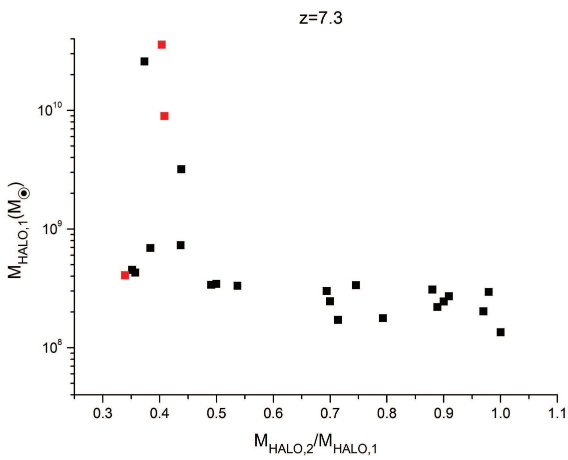

Figure 2: Mass of more massive halo in major merger as a function of mass ratio of these two halos. Red squares represent major mergers of the main halo, and black squares are major mergers of halos in the side branches of the merger tree. This figure shows parallel accretion.

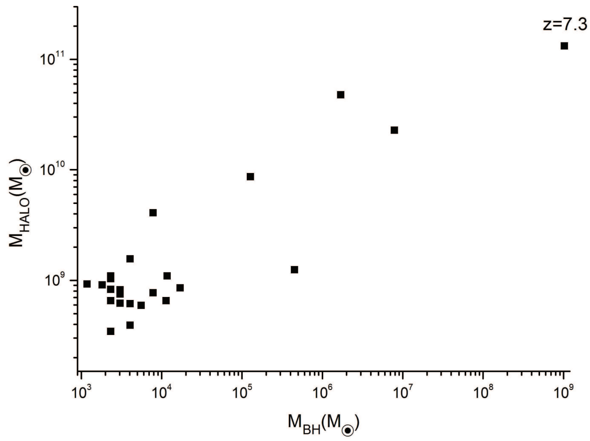

Figure 3: Halo mass as a function of BH mass in its center. BH have sufficient reservoir of gas for accretion and BH mass never exceeds 1% of the halo mass.

merger as a function of mass ratio of these two halos. Red squares represent major mergers of the main halo, and black squares represent major mergers of halos that will merge with the main halo later. This figure shows that beside the main halo accretion, there is a large number of halos that accrete at the same time and when they merge with the main halo they already host massive BH in their center, not only the BH with initial mass of $100M_{\odot}$. Hence, instead of one BH constantly accreting we have many BHs in shorter, parallel accretion episodes. This approach increases impact of mergers, and reduces impact of accretion.

Figure 3. shows halo mass as a function of BH mass in its center. If we assume the cosmological ratio of dark and luminous matter, baryonic matter makes approximately 10% of dark matter. In other words, 10% of the halo mass makes gas that BH can accrete. This figure shows that BHs have sufficient reservoir of gas for accretion and that BH mass never exceeds 1% of the halo mass.

4. DISCUSSION AND CONCLUSION

Using Millennium II cosmological simulation (Boylan-Kolchin et al. 2009) we make merger tree which track dark matter halo merger history to $z = 6.2$. BH in their centers can grow in BH mergers and by gas accretion. In each accretion episode radiative efficiency is fixed at $\epsilon = 0.1$ (Elvis et al. 2002, Yu & Tremaine 2002, Davis & Laor 2011) and accretion timescale is given by Yu & Tremaine (2002).

We find that remnants of Pop III stars can produce $> 10^9$ $M_{\odot}$ SMBH at redshift $z = 7.3$ if at each accretion episode they are able to accrete at the Eddington ratio of $f_{\rm Edd} = 3.2$, or at redshift $z = 6.2$ and the Eddington ratio $f_{\rm Edd} = 2.9$. Recent observations have suggested that moderate super-Eddington accretion ($1 < f_{\rm Edd} < 10$) might be possible (Kelly & Shen 2013, Du et al. 2014, Page et al. 2013) .

For typical values of the accretion parameters required to explain formation of $> 10^9$ $M_{\odot}$ SMBH (100 $M_{\odot}$, $\epsilon = 0.1$ and continuous accretion at $f_{\rm Edd} = 1$) the accretion lasts for 840 Myr or 280 Myr in case where $f_{\rm Edd} = 3$. In our model, the longest accretion episode is defined by Yu & Tremaine (2002) and it does not exceed 75 Myr. Thus, we have managed to significantly reduce the time that BH needs to spend accreting thanks to the parallel accretion onto BHs in side branches of the merger tree. Instead of one BH constantly accreting for a long time we have many BHs in shorter parallel accretion episodes. This approach increases the importance of mergers on SMBH growth. We also show that BH masses in our model never exceeds 1% of the host halo mass, and that BHs have enough gas for accretion.

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