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EARLY GROWTH OF SUPERMASSIVE BLACK HOLES AND GRAVITATIONAL WAVE RECOIL

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Abstract. Formation mechanism of supermassive black holes (SMBHs) observed in the early Universe is still not fully understood. At hight redshifts black holes (BHs) primarily grow through mergers with other BHs and through episodes of gas accretion triggered by major mergers of dark matter (DM) haloes . Combining Millennium-II and Millennium N-body cosmological simulations we find that BH remnants of Pop III stars could explain BH mass function observed at redshift $z = 6$ if Eddington ratio is fixed at $f_{\rm Edd} = 3.7$.

During BH mergers asymmetric emission of gravitational radiation can lead to BH kicks. Gravitational wave recoil can completely eject BH from it's host if the kick velocity is larger than the escape velocity from the galaxy. This process could affect formation of SMBHs if BH mergers are dominant growth mode. Recoiling BHs are investigated in analytical and numerical models of various host galaxies.

This work is a review of several publications that have been included in the PhD thesis.

1. INTRODUCTION

Observations of quasars powered by SMBHs with masses $\sim 10^9\,{\rm M}_\odot$ at redshifts $z > 6$ put strong constrains on their formation and growth mechanisms. One of the most extreme examples of such SMBHs is one with mass $2 \times 10^9\,{\rm M}_\odot$ detected at $z = 7.085$ (Mortlock et al. 2011). In order to explain the existence of such SMBHs, formation of BH seeds had to occur at very high redshifts ($z \gtrsim 15$). Further episodes of intense gas accretion and mergers with other BHs are believed to be the main path for their growth to SMBHs.

1. 1. BH SEEDS AND ACCRETION PARAMETERS

In this thesis remnants of Pop III stars are investigated as seeds of SMBHs. Pop III stars are the first stars that started to form at redshift $z \sim 20$. At that time gas had primordial composition which enabled first stars to have masses in range 10–1000$\,{\rm M}_\odot$, with typical mass of $\sim 100\,{\rm M}_\odot$ (Hirano et al. 2014). Previous works have shown that remnants of Pop III stars require continuous accretion close to or exceeding the Eddington limit in order to explain the mass function of SMBHs in distant quasars (e.g. Johnson et al. 2012, 2013). BH mergers could have significant contribution to

BH growth, but even with the combination of BHs mergers and accretion, low-mass BH seeds would require prolonged accretion episodes at the Eddington limit or early stages of super-Eddington accretion (e.g. Madau et al. 2014).

BH growth due to gas accretion depends on three gas accretion parameters: radiative efficiency ϵ, Eddington ratio $f_{\rm Edd}$ and accretion time. After one accretion episode the final BH mass $M_{\rm BH}$, as a function of its initial mass $M_{\rm BH,0}$ is:

$$M_{\rm BH} = M_{\rm BH,0} \times \exp\left[\frac{f_{\rm Edd}(1-\epsilon)}{\epsilon}\frac{t_{\rm f}-t_{\rm i}}{t_{\rm Edd}}\right] \quad (1)$$

where $f_{\rm Edd} = 450$ Myr, $t_{\rm i}$ and $t_{\rm f}$ are the ages of the Universe at the beginning and the end of accretion episode, respectively (Johnson et al. 2013). Mean values of the radiative efficiency and quasars lifetime can be estimated using the Soltan's argument (Soltan 1982). The mean value of radiative efficiency during accretion is $\epsilon \gtrsim 0.1$ (e.g. Davis & Laor 2011). Quasars lifetime is comparable to Salpeter's time (Salpeter 1964): $t_{\rm s} = 4.5 \times 10^7(\epsilon/0.1)(L/L_{\rm Edd})^{-1}$, which gives 45 Myr for radiative efficiency $\epsilon = 0.1$ and accretion at the Eddington limit.

BH growth models based on the standard thin accretion disc usually assume that BH cannot accrete gas above the Eddington limit. However, recent observations suggest that super-Eddington accretion with values $f_{\rm Edd} \sim 1-5$ might be possible in the early Universe (e.g. Kelly & Shen 2013; Du et al. 2014; Page et al. 2014).

1. 2. ROLE OF GALAXY MERGERS AND BH KICKS

During the merger of two galaxies that host SMBHs, due to the dynamical friction force, BHs sink to the merger remnant centre where they form a binary system. Further interactions with stars and gas carry away energy of the system which leads to the binary hardening (Begelman et al. 1980).

Once the separation between BHs becomes $\lesssim 10^{-3}$ pc, the energy losses due to gravitational radiation cause them to merge. If the merging BHs have unequal masses or spins the asymmetric emission of gravitational radiation can lead to BH kick. Gravitational waves propagate in a preferential direction due to non-zero net linear momentum and the centre of mass of the binary recoils in the opposite direction (Redmount & Rees 1989).

Gravitational wave recoil can displace a newly formed BH from the galaxy core or completely eject it if the BH speed is larger than the escape velocity from the halo centre. The magnitude of the gravitational wave recoil depends on the mass ratio of BHs, the spin magnitude and orientation with respect to the binary orbital plane, and the eccentricity of the orbit. Gravitational wave recoil can significantly affect the SMBH growth through mergers, since ejected BHs are less likely to merge with other BHs.

The aim of this work is to review the results of several publications in order to investigate the influence of gravitational wave recoil on the formation of SMBHs at high redshifts.

In section 2 growth of SMBHs at hight redshift is investigated. In sections 3 and 4 we calculate trajectories of recoiling BHs in static and evolving DM halo potential, and in analytical and numerical models of merger remnant galaxies, respectively. We summarize and discuss the results in Section 5.

2. FORMATION OF SMBHs AT HIGH REDSHIFTS

2. 1. METHOD

We investigate if low-mass BH seeds (100 $M_\odot$) planted into haloes of Millennium simulation (Springel et al. 2005) and Millennium-II simulation (Boylan-Kolchin et al. 2009) can grow into SMBHs that have been observed at $z \sim 7$.

We develop a novel method how to combine these two simulations together in order to have both: early halo formation history with low-mass haloes (to track BH growth history); and a large enough box with high abundancy of largest mass halos (in which $10^9 M_\odot$ SMBH at $z \sim 7$ can be produced). First we place $100 M_\odot$ BH seeds in haloes of Millennium-II simulation which has 125 times better mass resolution then Millennium simulation in order to make BH growth history. Then we take most common BHs from Millennium-II simulation as seeds for Millennium simulation to produce 10^9 $M_\odot$ SMBH at $z \sim 7$. For further details on how simulations were combined we refer to Smole et al. 2015.

We make merger trees which track merger history of DM haloes and associated BHs. Accretion episodes are triggered after every major merger, which is defined as $\frac{M_{\rm halo,1}}{M_{\rm halo,2}} \geq 0.3$, for $M_{\rm halo,1} < M_{\rm halo,2}$. After each accretion episode BH mass depends on the initial BH mass, Eddington ratio, radiative efficiency and accretion time-scale (Eq. 1.) For radiative efficiency we choose commonly accepted value $\epsilon = 0.1$. Every accretion episode is limited to 50 Myr, which is $\sim$ Salpeters time for accretion at the Eddington limit. The only free parameter in our model is the Eddington ratio. We assign a fixed value of this parameter to each accretion episode in one simulation run.

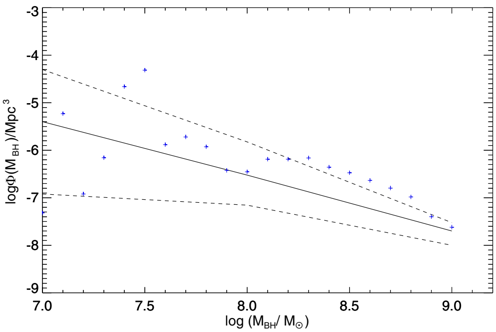

Figure 1: Mass function of BHs in our model (blue pluses), compared to the BH mass function given by Willott et al. (2010) at $z \sim 6$, dashed lines show their upper and lower limit, while the solid line shows their best-fitting (image reproduced from Smole et al. 2015).

We use the observed BH mass function at $z \sim 6$ as a constraint for our model. We run a set of semi-analytical simulations for different values of the Eddington ratio. In each run we assign the same values for the Eddington ratio to each accretion episode. We make sure not to overproduce SMBH at $z = 6$ and once this condition is satisfied, we check if we have 10^9 $M_\odot$ SMBH at $z = 7$ for the specific choice of the Eddington ratio.

2. 2. RESULTS

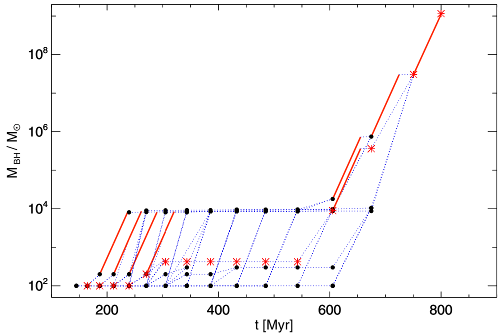

Figure 2: Merger tree of a 10^9 $M_{\odot}$ SMBH at redshift $z = 7$ for $f_{\rm Edd} = 3.7$. It follows the entire growth of a SMBH through all mergers and accretion episodes, as a function of the age of the Universe, see text for details (image reproduced from Smole et al. 2015).

We find that if the Eddington ratio is $f_{\rm Edd} = 3.7$ both conditions of our model are satisfied: BH mass function is consistent with the observed BH mass function at $z \sim 6$ (Willott et al. 2010) and our merger tree produces 10^9 $M_{\odot}$ SMBH at $z = 7$. Fig. 1 shows mass function of BHs that populate haloes of Millennium Simulation at $z \sim 6$. We compare our BH mass function to the BH mass function at $z = 6$ given by Willott et al. (2010). Dashed lines in Fig. 1 represent their upper and lower limits, while the solid line is their best fitting to the data.

Fig. 2 shows the merger tree of a 10^9 $M_{\odot}$ SMBH at redshift $z = 7$. It follows the entire growth of a SMBH through all mergers and accretion episodes, as a function of the age of the Universe. Black circles represent BH masses in side haloes, while red asterisks represent BH masses in the main halo, i.e the halo that host SMBH at $z = 7$. Dotted blue lines follow BH growth by minor mergers and solid red lines show growth through the gas accretion which occurs after every major merger. From Fig 2. it is clear that the BH gains most of its mass in major mergers when accretion is triggered.

In the following sections we investigate if gravitational wave recoil could prevent the formation of SMBH through BH mergers.

3. RECOILING BHs IN STATIC AND EVOLVING DM HALO POTENTIAL

3. 1. METHOD

We follow trajectories of recoiling BHs in a DM halo which is distributed according to a Navarro-Frenk-White (NFW) profile (Navarro et al. 1997). A BH is placed at the halos centre and kicked with recoil velocity $v_{\rm kick}$ at redshift $z_{\rm kick}$. Two different cases are explored: The BH orbits in a static, and in evolving potential. The evolving NFW density profile is modeled using a code given by van den Bosch et al. (2014), which calculates the growth of DM halo for a given DM halo mass and cosmology.

At multiple runs, various kick velocities are assigned to BHs at different redshifts. The consider DM halo has mass of $10^{12}\,\mathrm{M}_\odot$ at redshift $z = 0$ and it represents a Milky Way-type host.

3. 2. RESULTS

Fig. 3 shows displacement r for the static (left) and evolving (right) NFW potential of a kicked BH from a host halo's centre at $z = 0$, as a function of $v_{\rm kick}$ and $z_{\rm kick}$. In the case of static potential, the gravitational well is deep even at high redshifts and moderate kick velocities cannot eject BH from the host halo. BHs kicked from the halo's centre will return to the bottom of the potential well if $v_{\rm kick} \leq 500$ km/s, independent of $z_{\rm kick}$. On the other side, if halo evolution is taken into account, the BH displacement is sensitive to $z_{\rm kick}$. Amplitude of a kick necessary to remove BH from it's host halo varies from 300 km/s at $z = 7$ to 500 km/s at $z = 1$. Black region in Fig. 3 represents the parameter space where a recoiling BH will stay on bound orbits.

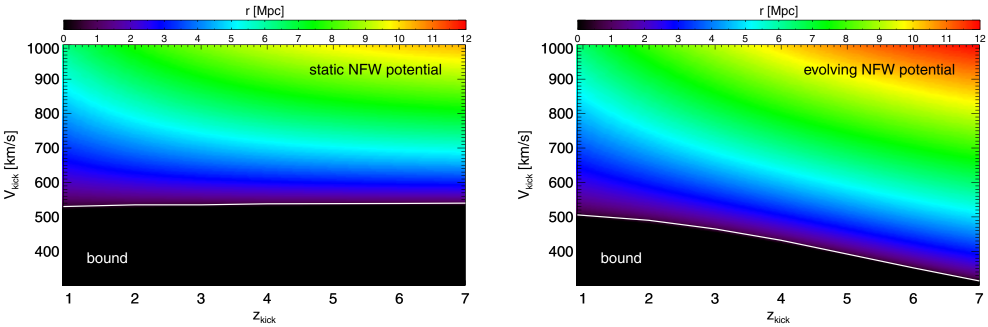

Figure 3: Displacement r of a kicked BH from a host halos centre at $z = 0$ as a function of $v_{\rm kick}$ and $z_{\rm kick}$, for the static (left) and evolving (right) NFW potential. White lines represent critical velocity for complete BH ejection (reproduced from Smole 2015).

Evolution and mass growth of the parent halos clearly impact their capability to retain recoiling BHs. In order to remove BH from it's host at redshift $z = 0$ kick velocity need to have $\sim 40\%$ larger amplitude at $z_{\rm kick} = 1$ compared to $z_{\rm kick} = 7$. Furthermore, at higher redshifts mergers were more common which makes the difference between the static and evolving potential even more pronounced. Growth of the SMBH by mergers might be suppressed in an evolving NFW halo potential, while ejections from a static NFW potential would be rare.

4. RECOILING BHs IN ANALYTICAL AND NUMERICAL GALAXY POTENTIAL

4. 1. METHOD

We follow trajectories of recoiling BHs in analytical and numerical merger remnant galaxy whose components are dark matter halo, bulge and disc. The considered galaxy is similar to Milky Way and has a mass of $10^{12}\,\mathrm{M}_\odot$. In order to investigate if BH trajectories are sensitive to the mass ratio of the progenitor galaxies we separately model major (1:1) and minor (1:10) mergers. Since dynamical friction force increases with the recoiling BH mass, we consider two different galaxy models whose central BH has mass of 10^7 $\mathrm{M}_\odot$ and 10^9 $\mathrm{M}_\odot$.

First we construct analytical merger remnants for each of the galaxy models described above and assign various kick velocities to their central BHs, whose trajectories are then integrated in the given potential. DM halo is described by the NFW density profile. The stellar component is modeled as a spherical bulge with density profile $\rho_* = \sigma_*^2/(2\pi G(r^2 + r_{\mathrm{soft}}^2))$, with velocity dispersion $\sigma_*^2 = GM_*/R_{\mathrm{bulge}}$ (M_* and R_{bulge} are mass and radius of the spherical bulge) and $r_{\mathrm{soft}} = r_{\mathrm{infl}}$, where $r_{\mathrm{infl}} = GM_{\mathrm{BH}}/\sigma_*^2$ is influence radius of the BH. Circumnuclear gas disc composed of cold, star-forming gas is modeled as a Mestel surface density profile $\Sigma = \Sigma_0 R_0/R$. Surface density at radius $R_0 = 0.1$ pc is $\log\Sigma_0 = 2\log(f_{\mathrm{gas,sf}}/0.1) + 12$, where $f_{\mathrm{gas,sf}}$ is star-forming gas fraction. Stellar dynamical friction is also included via the Chandrasekhar formula (Chandrasekhar 1943).

Further, we construct numerical models of galaxies and repeat the same procedure in order to test how redistribution of mass within post-merger galaxy affects its capability to retain a recoiling BH. Our procedure for constructing numerical merger remnants is following: 1) generate initial conditions for each pre-merger galaxy model, 2) evolve galaxy in isolation in order to test stability of each galaxy component, 3) simulate galaxy merger, 4) place a BH in the merger remnant centre and follow the recoiling BH trajectory in numerical potential. Initial conditions are generated using GalactICS code (e.g. Widrow et al. 2008), while galaxy evolution, mergers and trajectories of kicked BHs are simulated using N-body GADGET-2 code (Springel 2015). Each progenitor galaxy is represented with $N = 10^6$ particles.

We assign various kick velocities to BHs in our models and integrate their trajectories until the recoiling BH returns to the galaxy centre or until the integration reaches a Hubble time. Galaxy escape velocity v_{esc} is defined as a BH kick velocity necessary for a BH to return to its host centre after $\gtrsim 10$ Gyr.

For more detailed description of our analytical and numerical models we refer to Smole (2017).

4. 2. RESULTS

Fig. 4 shows galaxy escape velocity in analytical models as a function of escape velocity in numerical models for galaxy with mass of $M_{\mathrm{gal}} = 10^{12}$ $\mathrm{M}_\odot$. Triangles and squares represent major and minor merger remnants, respectively. Filled symbols show galaxy models with massive central BH ($M_{\mathrm{BH}} = 10^9$ $\mathrm{M}_\odot$) and open symbols galaxies with a BH with mass ($M_{\mathrm{BH}} = 10^7$ $\mathrm{M}_\odot$).

If different analytical models are compared with each other, Fig. 4 shows that galaxies with massive BHs have greater escape velocities than galaxies whose BH mass is $M_{\mathrm{BH}} = 10^7\,\mathrm{M}_\odot$. This is the consequence of two effects: 1) galaxy models with massive BHs also have massive bulges and thus greater central density, and 2) more massive BHs experience greater drag force due to dynamical friction. For a given galaxy mass, major and minor merger remnants with massive BHs have equal escape velocities. This directly follows from the accepted analytical model since mass ratio of the merging galaxies influence only the disc density profile, while disc component is neglected in galaxies with massive central BH (for further explanation of analytical

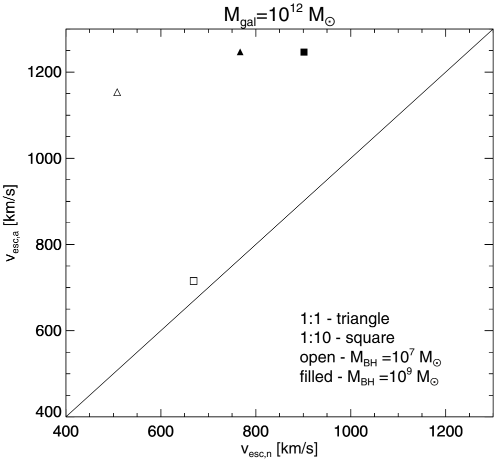

Figure 4: Escape velocities in analytical models as a function of escape velocities in numerical models, for galaxy with different central BH masses.

models see Smole 2017). On the other hand, less massive BHs can be displaced from their host centre more easily, but escape velocities from major and minor remnants differ (open symbols on Fig. 4). This difference is due to the presence of dense circumnuclear disc which is expected to form after major mergers of gas rich galaxies.

In numerical models, during galaxy mergers, a part of gravitational potential energy is converted into the kinetic energy of individual particles. Once a merger process is completed, particles gradually return to the bottom of the potential well, their kinetic energy is converted back into gravitational potential energy and the system becomes virialized. Since BH ejection occurs before the virialization finishes, the recoiling BH trajectory in numerical models is expected to differ from a trajectory of a BH moving through post-merger galaxy with stable, analytical potential.

When different numerical models are compared, Fig. 4 shows that major merger remnants have lower escape velocities than galaxies formed in minor mergers. Even though merger remnant masses are equal, major mergers lead to more significant redistribution of mass within centre of the newly formed galaxy, which results in lower escape velocity. Massive BHs in numerical models also need larger kick velocities in order to leave their host centre, due to the presence of massive bulge and greater influence of dynamical friction force.

Finally, if analytical models are compared with numerical models, Fig. 4 shows that analytical galaxies have greater escape velocities. This occurs because in the numerical models, BHs are ejected before post-merger galaxy establishes virialized potential which should correspond to the potential of the isolated analytical galaxy.

5. SUMMARY

In this work we explore the growth of the first SMBH using Millennium and Millennium-II cosmological simulations. Also, we calculated trajectories of recoiling BHs in different galaxy models in order to investigate if gravitational wave recoil could prevent the formation of SMBHs.

We find that BH seeds with masses $100M_\odot$ could grow to SMBHs in distant quasars if Eddington ratio is fixed at $f_{\rm Edd} = 3.7$ and each accretion episode is limited to 50 Myr. We show that BHs gain most of their mass in major mergers when accretion is triggered. On the other side, we show that major merger remnants in numerical models have the lowest escape velocities which could slow down the BH growth.

However, BH kick amplitudes strongly depend on the binary characteristics and BH spin parameters. Our model is not considerably sensitive to the gravitational wave recoil except for mergers of equal mass BHs in the least massive haloes at high redshifts where kick velocities $\lesssim 100$ km/s could permanently eject BHs from their hosts.

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