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STATISTICS OF RECOILING SUPERMASSIVE BLACK HOLES FROM COSMOLOGICAL SIMULATION

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Abstract. Black hole (BH) mergers are one of the most powerful sources of gravitational wave emission. During BH mergers asymmetry in the binary system will lead to the asymmetric emission of gravitational radiation and BH recoil. In this process newly formed BH receives a kick, whose magnitude depends on the characteristics of the BH binary system. Those recoiling BHs could be observed as spatially offset active galactic nuclei (AGN).

We compare trajectories of recoiling BHs in analytical and numerical models of galaxy merger remnants. Our results suggest that BH escape velocities in numerical major merger remnant galaxies can be up to 25 per cent lower compared to those in analytical models. Further, we use results from the Illustris cosmological simulation to explore statistics of spatially offset AGN in numerical and analytical models.

1. INTRODUCTION

Hierarchical model of structure formation predicts that massive galaxies experience a large number of mergers throughout their history. Following a galaxy merger, central black holes (BHs) will form a binary system whose further evolution depends on galaxy morphology, gas content, and mass ratio of progenitor galaxies. In gas rich mergers, gas that is fueled to the central regions will lead to efficient binary hardening and final merger, while galaxy mergers with low mass ratio do not necessary lead to BH merger (e.g. Khan et al. 2016 and references therein).

When the separation between BHs becomes $\leq 10^{-3}$ pc, gravitational wave radiation becomes an efficient mechanism for extraction of angular momentum and energy from the binary system, which leads to rapid BH merger (Begelman et al. 1980). Any asymmetry in the binary system, caused by BHs with unequal masses and/or spins, will lead to the asymmetric emission of gravitational radiation and BH recoil. Newly formed BH receives a kick velocity, whose magnitude 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. Distribution of possible kick velocities is wide, ranging from few to several thousands km/s, meaning that BHs can be ejected even from the most massive elliptical galaxies (Gonz´ales et al. 2007; Campanelli et al. 2007; Lousto & Zlochower 2011).

Recoiling BHs could be observed as spatially or kinematically offset active galactic nuclei (AGN). Numerous candidate offset AGN have been observed, although alternative explanations cannot be ruled out (we refer to Ward et al. 2020 for more detailed summary of offset AGN observations). Smole et al. (2019) investigated trajectories of recoiling BHs in various analytical and numerical models of merger remnant galaxies in order to test how central BH mass distribution and the mass ratio of progenitor galaxies influence escape velocities of recoiling BHs. Our results show that static analytical models of major merger remnant galaxies overestimate the BHs escape velocities. During major mergers violent relaxation leads to the decrease of galaxy mass and lower potential at large remnant radii. This process is not depicted in static analytical potential, making the evolving numerical model a more realistic description of dynamical processes in galaxies with merging BHs. We find that BH escape velocities in numerical major merger remnant galaxies can be up to 25 per cent lower compared to those in analytical models.

Here, we extend the above work and use the results to calculate analytical and numerical escape velocities for major merger remnant galaxies extracted from the Illustris-1 simulation. Then, for a given kick velocity distribution, we are able to estimate number of offset AGN at cosmological scales, and make a statistical comparison between analytical and numerical models. In Section 2 we describe the method. In Section 3 we present our results. We summarize and discuss our results in Section 4.

2. METHOD

In order to compare analytical and numerical models of major merger remnant galaxies, we use publicly available data from the Illustris-1 cosmological simulation (Nelson et al. 2015). The Illustris-1 is a large cosmological simulation which was conducted with the moving-mesh hydrodynamics code AREPO (Springel 2010). The simulation has a periodic simulation cube of side length $L = 106.5h^{-1}$ Mpc, with a dark matter particle mass of 6.26×10^6 $\mathrm{M}_\odot$ and a typical gas cell mass of 1.26×10^6 $\mathrm{M}_\odot$. ΛCDM cosmology used for the Illustris-1 simulation is the following: $\Omega_\mathrm{m} = 0.2726$, $\Omega_\Lambda = 0.7274$, $\Omega_\mathrm{b} = 0.0456$ and $h = 0.704$, where h is the Hubble constant at $z = 0$ in units of 100 km/s/Mpc.

From the Illustris-1 simulation we extracted merger histories of a sample containing all galaxies with masses in range $10^{11} - 10^{13}\,\mathrm{M}_\odot$ at $z = 0$. Next, we search through the merger trees of the sample galaxies selecting major merger events, defined as a mergers of galaxies with the total mass ratio $\geq 1 : 3$. Additionally, we require that merger remnant galaxies have a minimum total mass of 10^{10} $\mathrm{M}_\odot$. We do not include low mass galaxy mergers in our analysis since the resulting merger remnants have low potential wells and even low kick velocities can lead to the complete BH ejection. This sample of merging galaxies, containing ~ 6000 major merger remnants, is further populated with BHs, using two different approaches. In the first model BH masses are taken directly from the simulation. In the Illustris-1 simulation a BH particle with a seed mass of 10^5 $\mathrm{M}_\odot$ is placed in each galaxy more massive than 7.1×10^{10} $\mathrm{M}_\odot$, and then allowed to grow via gas accretion and by mergers. However only ~ 7 per cent of all merging pairs have both pre-merger galaxies more massive then a threshold for a BH seed in the Illustris-1 simulation. This excludes a significant number of mergers from our analysis. In the second model we explore an alternative approach where we populate merging galaxies with BHs whose masses are estimated using $M_{\mathrm{BH}} - M_{\mathrm{HALO}}$ local scaling relation (Ferrarese 2002). Since this model does not hold a minimum threshold for BH seeds, in this case all major mergers from the original sample are included in the analysis. BH mass distribution for both models is shown on Fig. 1 and further discussed in the next section.

When major mergers events are extracted from the cosmological simulation and each pre-merger galaxy is seeded with a central BH, the next step is to assign escape velocity to each remnant galaxy. Numerical and analytical escape velocities are estimated for each post-merger galaxy using the results from our previous work (Smole et al. 2019). For the given merger remnant mass, its central BH mass and the mass ratio of the merging galaxies, escape velocities calculated in Smole et al. (2019) are extrapolated and assigned to each galaxy from our the Illustris-1 sample. The next step is to calculate kick velocities for each newly formed BH, adopting the method described by Micic et al. (2011). Kick velocity depends on BH mass ratio and BH spins, both orientation and magnitude. Following Micic et al. (2011), we employ two models for BH spins: in the first model BH spin parameters are taken from a uniform distribution ("random spins" model), while in the second model BH spins are always aligned with the orbital angular moment of the binary ("aligned spins" model), resulting with lower kick velocities. For each merger remnant galaxy BH kick velocities are sampled from one of those distributions 10000 times, in order to employ Monte Carlo method and create a statistical analysis of offset AGN distribution.

The final step is to compare escape and kick velocities for each merger remnant galaxy in order to estimate number of offset AGN. Here we adopt a crude definition for an offset AGN described as a post merger galaxy with escape velocity lower then the kick velocity. We note that kick velocities close to escape velocities may place central BH on a bound orbit outside of the galactic nuclei for a prolonged period of time, however investigation of BH orbits is beyond scope of this work.

3. RESULTS

Fig. 1. shows the distribution of BH masses taken from the scaling relation (filled histogram with dashed borderline) and directly from the Illustris-1 simulation (open histogram with solid borderline). The total number of major merger events where both pre-merger galaxies host a central BH is significantly lower for BHs taken from the Illustris-1. This results from a minimum mass threshold imposed for BH seeds in the Illustris-1 simulation. Further this implies that a majority of major merger events are in fact mergers of galaxies with masses $< 7.1 \times 10^{10}$ (threshold for a BH seed), and can partially explain generally less massive BHs calculated from the scaling relation. Additional difference between BH masses taken from two different models comes from using local scaling relation between host galaxy and the central BH, which might not hold high redshift galaxies. Recent work (Kazuhiro & Takuma 2019) have shown that quasars at $z \sim 6$ have at least one order of magnitude more massive central BHs than their local counterparts with the same mass. However, choosing one relation over the other does not ultimately affect our result regarding offset AGN statistics, since the resulting kick velocity depends only on the mass ratio of the merging BH and not on their total mass.

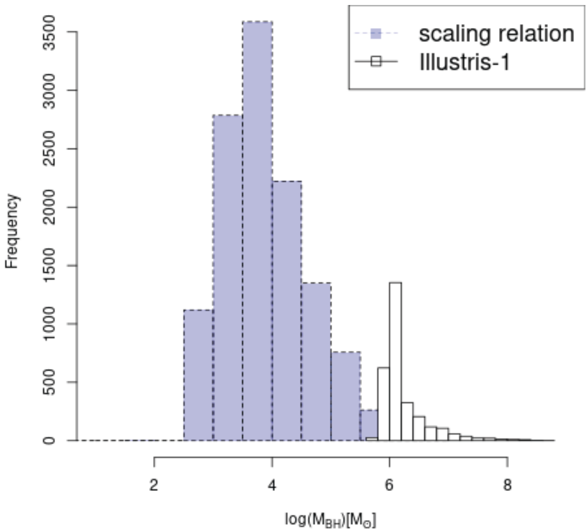

Figure 1: Histogram of BH masses populating pre-merger galaxies taken from the Illustris-1 (open histogram with solid borderline) and from $M_{\rm BH} - M_{\rm halo}$ relation (filled histogram with dashed borderline).

Fig. 2 shows statistics of offset AGN with 2-sigma confidence level as a function of redshift, for different models of kick velocity distribution, i.e. for "random spins" and "aligned spins" models. Left panels show BH masses estimated from the Illustris-1 simulation, while right panels show BH masses from scaling relation. Percentage of offset AGN in analytical and numerical models are represented with circles and triangles, respectively. Fig. 2 shows that each model reveals statistically significant difference between numerical and analytical potential. Evolving numerical potential predicts greater number of offset AGN at both high and low redshifts, and this trend is insensitive to the particular choice of BH mass and/or BH spins distribution. We note that for the Illustris-1 BH mass distribution at $z > 3$ our model predicts no offset AGN in both analytical and numerical models. However, our results in this region are biased since the number of major mergers with progenitor galaxies more massive than the threshold for a BH seed in the Illustris-1 is too low for statistical predictions, resulting with zero to several merger events per redshift bin.

Statistics of offset AGN changes drastically with a particular choice of BH mass distribution. BH masses taken from the simulation predict significantly lower fraction of offset AGN compared to the case where BH masses are taken from the scaling relation. This is a consequence of two combined effects induced by adopting a particular BH mass distribution. When BH masses are estimated using scaling relation, major mergers in lower mass galaxies are included in analysis. Such galaxies tend to have shallow potential wells, making them prone to BH ejections. Second, when BH massed are taken from $M_{\rm BH} - M_{\rm HALO}$ relation, BH mass ratio will always be $\geq 1:3$, which is our major merger definition. Mergers of two BHs with similar masses will always results with higher amplitude of kick velocities (Micic et al. 2011, figure 2), adding to the difference between percentage of offset AGN for different BH mass distributions. On the other hand, BH masses taken from the Illustris-1 show greater diversity in mass ratios, which also reflects at their kick velocities, however number of merger events for galaxies at $z > 3$ is simply to low to make statistical predictions.

Kick velocity distribution models bring only a lesser influence on offset AGN statistics. "Aligned spins" model yields lower kick velocities, reducing the percentage of offset AGN in both numerical and analytical models.

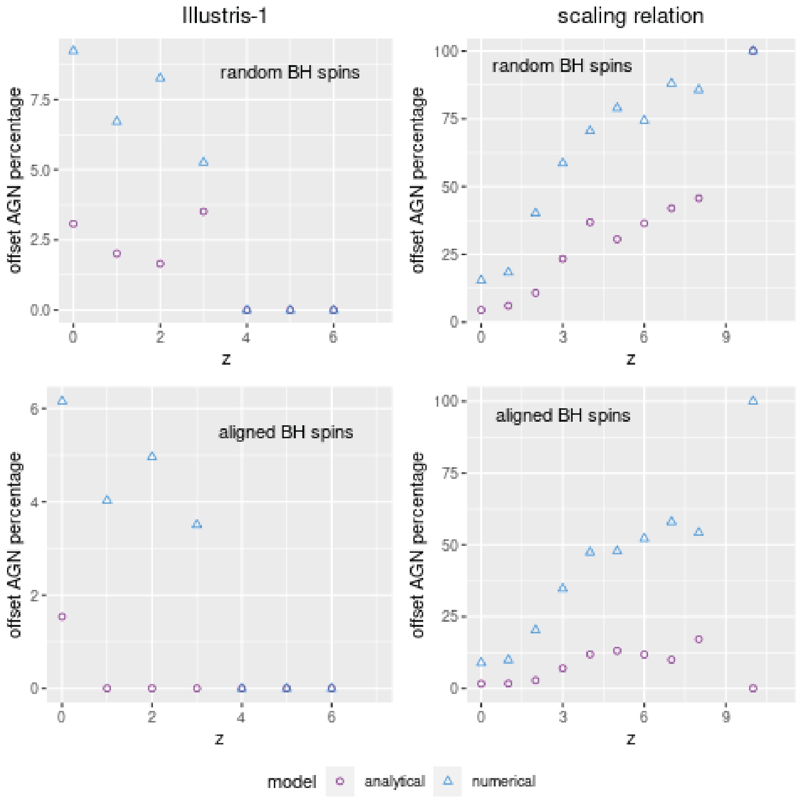

Figure 2: Percentage of offset AGN with 2-sigma confidence level as a function of redshift, for different models of kick velocity distribution, and for analytical (circles) and numerical (triangles) models. Left panels show offset AGN for BH masses taken from the Illustris-1, while right panels show BH masses from $M_{\rm BH} - M_{\rm HALO}$ relation.

4. SUMMARY

We have investigated statistics of offset AGN on cosmological scales with the main goal to compare percentage of offset AGN in analytical and numerical models. Major merger remnants and properties of pre-merger galaxies are extracted from the Illustris-1 simulation and then seeded with central BHs, whose mass is taken either directly from the simulation, or estimated using local $M_{\rm BH} - M_{\rm HALO}$ relation. Here we use a simple definition for offset AGN referring to a recoiling BH whose kick velocity is greater the the escape velocity of the host galaxy. Escape velocities of recoiling

BHs were estimated using the results from Smole et al. (2019), where we calculated analytical and numerical escape velocities for various merger remnants. BH kick velocities are sampled from one of two different distributions (assuming random or aligned BH spins), using Monte Carlo method.

We have shown that numerical models predict a greater number of offset AGN on cosmological scales. Numerical models represent a better description of dynamical processes occurring in galaxies with merging BHs, which are not taken into account in analytical models, leading to overestimation of escape velocities in the later case.

However, the statistics of offset AGN changes severely with a particular choice of BH seed mass model. For BH masses taken directly from the Illustris-1 simulation, the imposed threshold for a BH seed limits the number of BH merger events especially at high redshifts, leaving only massive galaxies with deep potential wells capable to retain recoiling BHs, except for rare high kick velocities. On the other hand, if BH masses are estimated from scaling relation, number of BH merger events is significantly higher, however this approach induce bias toward mergers of BH with equal masses that always result with high kick velocities. Observing recoiling BHs has proven to be a challenging task, however the results from the recent study favor models which predict a low percentage of offset AGN, i.e. BH masses taken from the Illustris-1 and aligned BH spins (Ward et al. 2020).

We note that this work serves as a proof of concept to demonstrate differences between analytical and numerical potential. More appropriate approach, which we are going to employ in the future work, would be to use BH merger catalogs that are written at much higher time resolution than simulation snapshots. Using BH merger catalogs makes it possible to track process of BH mergers between simulation snapshots, providing a more precise model for successive merger events.

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