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DYNAMICS OF DUAL MASSIVE BLACK HOLE SYSTEMS FORMATION IN COSMOLOGICAL SIMULATIONS

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Abstract. Due to hierarchical evolution of galaxies and the fact that almost all massive galaxies have supermassive black hole (SMBH) in their center, galaxy mergers lead to formation of dual SMBH systems or supermassive binary black holes (SMBBH). In order to better understand how properties of SMBBH depend on properties of merging galaxies, we investigate these systems, circumstances of their formation and activity using the results from cosmological simulation IllustrisTNG300. We find that major mergers of gas rich galaxies are the main reason for formation of dual AGNs, with tendency to form more luminous AGNs.

1. INTRODUCTION

Standard cosmological model indicates hierarchy in galaxy formation. Given that almost all massive galaxies host a supermassive black hole (SMBH) in their center, same thing applies for SMBHs: their growth is hierarchical aswell. Therefore, it is expected that galaxy mergers lead to formation of supermassive binary black holes (SMBBH). Namely, dynamical friction during the galaxy merger leads SMBHs to move towards the center of the new galaxy, but interaction with stars at final parsec distance may not be enough for SMBH to merge if there is no gas (Milosavljević & Merritt, 2003).

The first observations of SMBBH discovered dual active galactic nuclei (AGN) at kpc separation length (Komossa et al. 2003; Ballo et al. 2004). In those cases, active SMBHs are distant enough to be observed as the dual core of a galaxy. Observations of a hard-binary, a SMBBH with a distance smaller than pc, are ambiguous. Since a host galaxy is far away SMBHs cannot be distinguished and the resolution limit makes it hard to differentiate dual from offset and single AGN. Although candidates for dual AGN exist their confirmation is not yet reliable and needs more evidence (Bon et al. 2012; Komossa et al. 2020).

The dynamic of SMBBH formation depends on the properties of galaxies that go through a merger. Also, the SMBH feedback processes affect its host galaxy. To understand both SMBH and galaxy evolution it is important to understand the connection between them. Our main goal is to investigate the formation mechanisms of SMBBH and their distribution on cosmological scales.

The description of the data and our method is in Section 2. The results are presented in Section 3. In Section 4, we discuss implications of our results.

2. METHODS

TNG300 is one of the IllustrisTNG cosmological magnetohydrodynamical simulations of galaxy formation (Marinacci et al. 2018; Naiman et al. 2018; Nelson et al. 2018; Pillepich et al. 2018; Springel et al. 2018). Simulation box volume of $(302.6\text{Mpc})^3$ corresponds to 2500^3 gas and 2500^3 dark matter particles. It describes the evolution of galaxies from redshift 20.05 to redshift 0 in 100 snapshots. Besides snapshots, it has supplementary data catalogs. One that we use here is *Blackhole mergers and details* (Kelley et al. 2016; Blecha et al. 2016). The evolution of a black hole starts when a galaxy reaches a mass of $7.38 \times 10^{10}\text{M}_\odot$. At that moment a SMBH of mass $1.18 \times 10^{6}\text{M}_\odot$ is placed in the galaxy center. Further growth of black holes is determined by the Bondi accretion rate limited by Eddington accretion.

The data is taken from *Blackhole mergers and details* and parameters of a SMBH host galaxy are added from snapshot data. Our criteria exclude multiple black hole mergers, mergers of galaxies with stellar mass less than $10^{9}\text{M}_\odot$ and mergers of galaxies with dark matter halo mass less than $10^{10}\text{M}_\odot$ and greater than $8 \times 10^{13}\text{M}_\odot$. Finally, our sample contains binary SMBH mergers in field galaxies described with enough baryon and dark matter particles. SMBH merger in TNG300 means that SMBHs have come to a distance smaller than softening length which is of the order of a kiloparsec. Therefore, the merger of two SMBHs in TNG300 is taken as the formation of SMBBH at separation $\sim$1kpc here.

We distinguish between major (galaxy mass ratio $>$ 1:3) and minor galaxy mergers. Mass ratio of the merging galaxies is calculated at the moment when the secondary galaxy has the maximum mass, thus before the interaction has started. Based on SMBH accretion rate and mass, luminosity is calculated by the equation given for IllustrisTNG in Weinberger et al. (2018). SMBH with luminosity larger than 10^{43}erg/s were considered AGN, while the rest are taken as regular SMBH. Depending on SMBH activity we have three types of SMBBH: dual AGN (both SMBH active), offset AGN (one SMBH active) and inactive SMBBH.

3. RESULTS

Our final sample contains 44157 SMBBH out of which 21.6% are dual AGNs, 33.6% are offset AGNs and 44.8% are inactive SMBBH. Plots in Figure 1 (left and right) show redshift and total galaxy mass distributions for dual AGN (red), offset AGN (blue) and inactive SMBBH (green). The redshift distribution shows that systems with active SMBHs are more common at higher redshifts, while inactive SMBBH are more dominant at lower redshifts. The same trend can be seen in the total galaxy mass distribution. Binaries with active SMBHs are similarly distributed in less massive galaxies mostly formed at higher redshifts, while inactive binaries are dominant in more massive galaxies. This is even more evident in Figure 2, which shows the probability density of total galaxy mass as a function of redshift. At lower redshift, galaxy mass becomes greater and at the same time the span of galaxy mass becomes larger as expected from hierarchical growth. While inactive SMBBH are formed in very massive galaxies, that is not the case for binaries with one or both SMBHs active. The most massive field galaxies currently go through minor mergers which explains why inactive SMBBH are more dominant at lower redshifts.

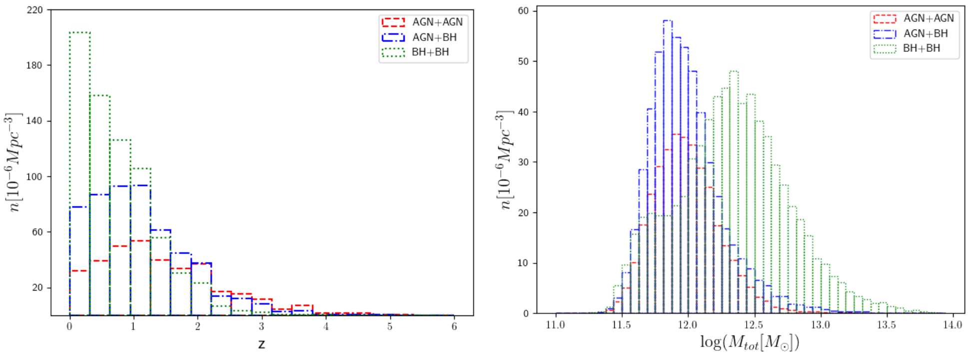

Figure 1: *Left*: Redshift distribution *Right*: Total galaxy mass distribution

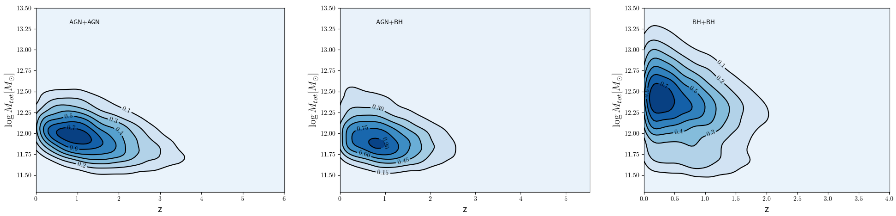

Figure 2: Total galaxy mass as a function of redshift

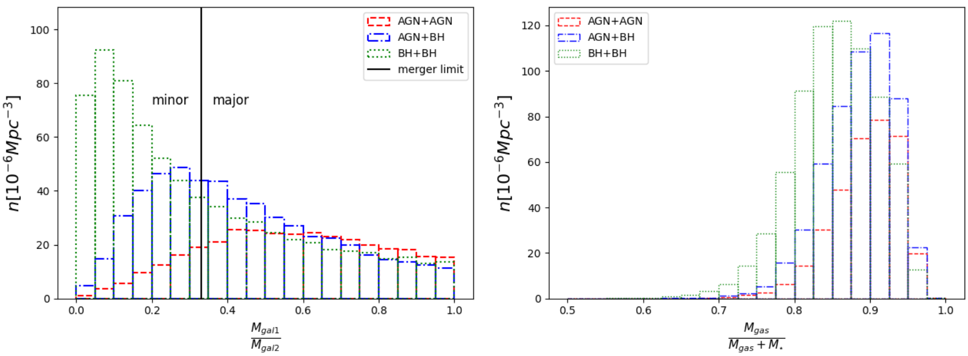

Figure 3: *Left*: Galaxy ratio distribution *Right*: Gas abundance distribution

The importance of major mergers and gas aboundance in SMBBH activity can be seen in Figure 3. Dual AGNs tend to be formed in major mergers, while inactive SMBBH are very dominant in minor mergers. Imporant necessity for a SMBH to be active is fuel that comes from gas in the galaxy. Histogram of gas abundance shows that even though all galaxies are gas abundant, active galaxies are richer with gas. Relation between merger ratio and gas abundance shows that mass ratio is crucial for pair activity since inactive SMBBH can be found in very gas abudant galaxies but almost always in minor mergers.

4. DISCUSSION & CONCLUSIONS

In this work we use TNG300 simulation to investigate the formation of SMBBH and their distribution on cosmological scales. Our results show the importance of galaxy mass ratio in forming different SMBBH types. Although gas abundance is necessary, the main difference between inactive SMBBH and dual AGN is whether the binary formed in a minor or a major merger. Major mergers provide gas to the galaxy center for SMBHs to accrete. The luminosity of a SMBH directly depends on the accretion rate.

It seems that the rest of the parameters essentially show this process. Due to hierarchical growth the most massive isolated galaxies today host inactive SMBBH since they go mainly through minor mergers. At redshift $z > 2$, galaxies were mainly going through major mergers. That explains why we see many active SMBH at higher redshift but find them in less massive galaxies. Less massive galaxies in the early Universe grew through major mergers and hosted a greater number of dual or offset AGN. Inactive SMBBH are currently dominantly formed because field galaxies go more often through minor mergers.

Results shown here refer to mergers of field galaxies that form binary systems. They could be expanded with multiple SMBH systems and mergers of galaxies in clusters. We used general galaxy properties to see their influence on SMBBH forming. Detailed investigation of galaxy morphology and its influence on SMBBH formation will be the subject of future work.

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