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FORMULATION OF EVOLUTION OF SUPERMASSIVE BLACK HOLE MASS

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Abstract. Supermassive black holes (SMBH) with mass greater than 1 million solar masses are found in the core of most massive galaxies in the local Universe. The relationship between the mass of the spheroidal component of the host galaxy and that of their central BH known as the BH-bulge mass relationship has been widely studied. We present a new phenomenological BH-bulge mass relationship with redshift evolution and compare it to the population of BHs produced by six large-scale cosmological simulations. We compare the growth of BHs with redshift in Illustris, Horizon-AGN, SIMBA, TNG100, TNG300, and EAGLE.

Keywords: black hole physics - galaxies: formation - galaxies: evolution - methods: numerical

1 Introduction

Supermassive Black Holes (SMBH) in the centre of galaxies show fast-moving gas revolving around them that are being pulled in by the gravitational field of the black hole. Most of the massive galaxies in the local Universe host a SMBH, including our own Milky Way. The mass of the SMBH is strongly correlated with the mass of the bulge of the host galaxy. This relation has been studied widely due to its significance for the study of galaxy and central black hole co-evolution. Observations allow us to measure this correlation.

One of the important applications of this relation is its key role in calculating the gravitational wave background (GWB) from a population of merging Supermassive Black Hole Binaries (SMBHBs). SMBHBs are formed when two SMBHs start to coalesce, often after the merger of their host galaxies. As the binary components get close at sub parsec scale, more distortion happens in spacetime and produces gravitational waves until they merge. All the existing SMBHBs together form a stochastic GWB emission. The spectral energy distribution of the GWB in the frequency range ($10^{-9} - 10^{-6}$Hz) can be expressed using a formalism that depends on the BH-bulge mass relation (Chen et al. 2019). Pulsar Timing Arrays (PTAs) use radio telescopes to search for this GWB as a common signal by timing an array of millisecond pulsars each acting as an independent arm of a galactic-scale detector*.

Observations have investigated whether the BH-bulge mass relation evolves with redshift, but such studies are complicated by the inability to measure bulge masses, rather than total stellar masses. Furthermore, although many studies find that high redshifts quasars are powered by SMBHs more massive than those at $z = 0$ at fixed stellar mass, this can be caused by a selection bias (Lauer et al. 2007).

A complementary way to study galaxies at high redshift is by using large-scale cosmological simulations. These simulations give a detailed representation of the formation and evolution of the large-scale structures in large volumes of $(100 - 300)^3$ Mpc^3. The initial conditions of these galaxies are based on the power spectrum of density fluctuations in the Early Universe. Then simulations follow the collapse of dark matter into halos, the flow of gas into these halos, gas cooling and the ensuing star formation, as well as the growth of SMBHs in the galaxies. The observed Universe is closely matched by the representations from the cosmological simulations.

For this work we look at the evolution of the masses of galaxies and their central black holes at redshift range $0 \leq z \leq 5$ from the Illustris, Horizon-AGN, SIMBA, TNG100, TNG300, and EAGLE simulations

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*`http://www.ipta4gw.org/`

(Habouzit et al. 2021, and references therein). We formulate the evolution of BH-bulge mass relation by tracking the evolution in these simulations.

A brief review of observational parameters of BH-bulge mass relation is given in Section 2. The simulated GWB spectrum as measured PTA using these different observational parameters is also discussed there. Section 3 gives a formulation of evolution of the BH-bulge mass relation with redshift. In Section 4 we investigate the parameters of the BH-bulge mass relation with redshift for the different simulations. And Section 5 provide our conclusions.

2 BH-Bulge Mass Relation

Optical and near infrared imagining photometry allows us to separate the bulge and disc stellar components of a galaxy at very low redshifts. The connection between the mass of galaxies and their central SMBHs is correlated with galactic bulge. The relation between the SMBH mass and the bulge mass of the host galaxy is

$$M_{BH} = \mathcal{N}\left\{\left(\frac{M_{bulge}}{10^{11}M_\odot}\right)^\alpha 10^\beta, \epsilon\right\}. \tag{2.1}$$

where M_{BH} is the SMBH mass, M_{bulge} is the corresponding galactic bulge mass, α, β and ϵ are the BH-bulge mass parameters. The intrinsic scatter ϵ is associated with the distribution of BH mass around the mean value at fixed bulge mass. $\mathcal{N}$ is the logarithmic normal distribution with standard deviation ϵ and mean defined as

$$\log_{10} M_{BH} = \alpha \log_{10}\left(\frac{M_{bulge}}{10^{11}M_\odot}\right) + \beta. \tag{2.2}$$

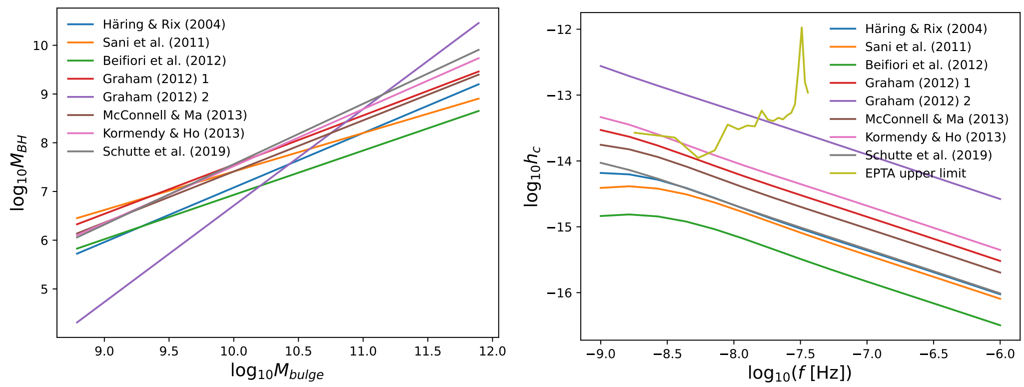

Fig. 1. Left: Plot of equation (2.2) for different BH-bulge mass parameters in the literature. **Right:** The corresponding characteristic strain spectrum of GWB as a function of frequency in the PTA range. The EPTA DR1 upper limit is shown as a reference (Lentati et al. 2015).

Different values of the BH-bulge mass parameters have been observationally determined in the literature (eg. Sesana 2013; Schutte et al. 2019), shown on the left side of Figure 1. The right side of Figure 1 shows the simulated characteristic strain spectrum of the GWB using the corresponding BH-bulge mass parameters computed using equation 1 in Chen et al. (2019). It also shows the importance of the BH-bulge mass relation in predicting the GWB which could be detected with PTAs.

3 Adding Redshift Dependence

We have seen the strong correlation between the mass of a SMBH and the galactic bulge observed in the local Universe. This correlation is anticipated to be seen at higher redshift. It is an indication to link the evolution of SMBH and galactic bulge by a common mechanism. And there is evidence suggesting that galaxy mergers are the possible reason and the correlation is independent of the evolution of the cold gas fraction in the population of galaxies. The strong evolution of the global galaxy merger rate of the Universe with time suggests the evolution of BH-bulge mass relation. The population of SMBHs does not evolve similarly to the bulge and hence the BH-bulge mass relation is compelled to evolve by the evolution in mass of galactic bulge rather than the SMBH. The anticipated correlation does not have a clear picture as some studies claim there is only little evolution in mass of SMBH within the epoch of $z \sim 3$ whereas other studies measured consistent correlation at epoch of $z \sim 2$ for Quasars.

A model for the growth of SMBH which matches with many observations from ($z \lesssim 6$) and local AGN predicted evolution in BH-bulge mass relation as $M_{BH} \propto \zeta(z)^{1/2}(1+z)^{3/2}M_{bulge}$ where $\zeta(z)$ has a weak redshift dependency corresponding with the cosmological parameters. And this is approximated for $z < 2$ as $M_{BH} \sim (1+z)^{1.15}M_{bulge}$ (Wyithe & Loeb 2003). Similar phenomenological model constrained by the evolution of Quasars assuming the growth of SMBHs exclusively through accretion gave $M_{BH} \sim (1+z)^{0.5}M_{bulge}$. The evolution with redshift in this model is weaker comparing with the previous model (Croton 2006, and references therein). Another model for Quasars at $z \gtrsim 6$ gave the BH-bulge mass relation with redshift dependence as (Venemans et al. 2016)

$$\frac{M_{BH}}{M_{bulge}} = \left(\frac{M_{BH}}{M_{bulge}}\right)_{z=0}(1+z)^{\beta} \tag{3.1}$$

where $\beta \approx 0.6$. Using this equation as parametric relation for generic galaxies of six different cosmological simulations (Illustris, Horizon-AGN, SIMBA, TNG100, TNG300, and EAGLE) give inconsistent β parameter for $z \leq 5$, hence we are in need to new formalism. Using the mass of galaxies and their central SMBHs from those six simulations and converting the stellar mass into galactic bulge mass, we formulate a phenomenological BH-bulge mass relation with redshift as the logarithmic normal distribution as equation (2.1) with logarithmic mean of the SMBH mass

$$\log_{10} M_{BH} = \alpha_* \log\left(\frac{M_{bulge}}{10^{11}}\right) + \beta_* + \gamma_* z. \tag{3.2}$$

where γ_* determines the evolution of SMBH mass with redshift, while α_*, β_* and standard deviation ϵ are independent of redshift.

4 BH Mass Parameters for Simulations

We study the masses of galaxies and those of their BHs for $z \leq 5$ in the Illustris, Horizon-AGN, SIMBA, TNG100, TNG300, and EAGLE simulations. These different cosmological simulations use different cosmological parameters and subgrid physics which are described in Habouzit et al. (2021). Many predictions have been made using these simulations on the formation and evolution of galaxies. It is an effective way to understand phenomena at high redshifts which are difficult to observe with current telescopes.

Simulation	α_*	β_*	γ_*	ϵ
Illustris	1.28 ± 0.040	8.38 ± 0.088	$0.18^{+0.046}_{-0.063}$	$0.08^{+0.144}_{-0.058}$
Horizon-AGN	1.03 ± 0.026	8.50 ± 0.036	$0.07^{+0.008}_{-0.020}$	$0.08^{+0.032}_{-0.048}$
SIMBA	1.24 ± 0.046	8.78 ± 0.063	$-0.15^{+0.080}_{-0.064}$	$0.28^{+0.055}_{-0.050}$
TNG100	1.23 ± 0.022	8.91 ± 0.074	$-0.02^{+0.025}_{-0.014}$	$0.16^{+0.078}_{-0.047}$
TNG300	1.29 ± 0.019	8.91 ± 0.050	$-0.02^{+0.007}_{-0.007}$	$0.26^{+0.256}_{-0.115}$
EAGLE	1.39 ± 0.027	8.23 ± 0.039	$0.01^{+0.022}_{-0.035}$	$0.21^{+0.079}_{-0.076}$
Tiamat	1.43 ± 0.185	8.14 ± 0.066	$0.05^{+0.010}_{-0.010}$	$0.18^{+0.140}_{-0.050}$

Table 1. Black hole - bulge mass parameters of the six different simulations from the the fitting process.

The mass of the SMBH and galactic bulge can be fitted using equation (3.2) for the 6 different cosmological simulations individually. The slope of the linear least square fit in the logarithmic scale of the masses from a simulation for all $z \leq 5$ is α_* for that simulation. This slope is taken as the slope for the least square fit of each redshift. The intercept at $z = 0$ is β_* and γ_* can be calculated from the intercept of other redshifts. ϵ is the deviation of mass of SMBH from the phenomenological fit by equation (3.2). The parameters of the BH-bulge mass relation for these different cosmological simulations are given in Table 1.

Figure 2 shows the evolution of SMBH mass with redshift for different simulations using equation (3.2). α, β and ϵ parameters for the Tiamat simulation using equation(2.1) for $z \leq 6$ from Marshall et al. (2020) is

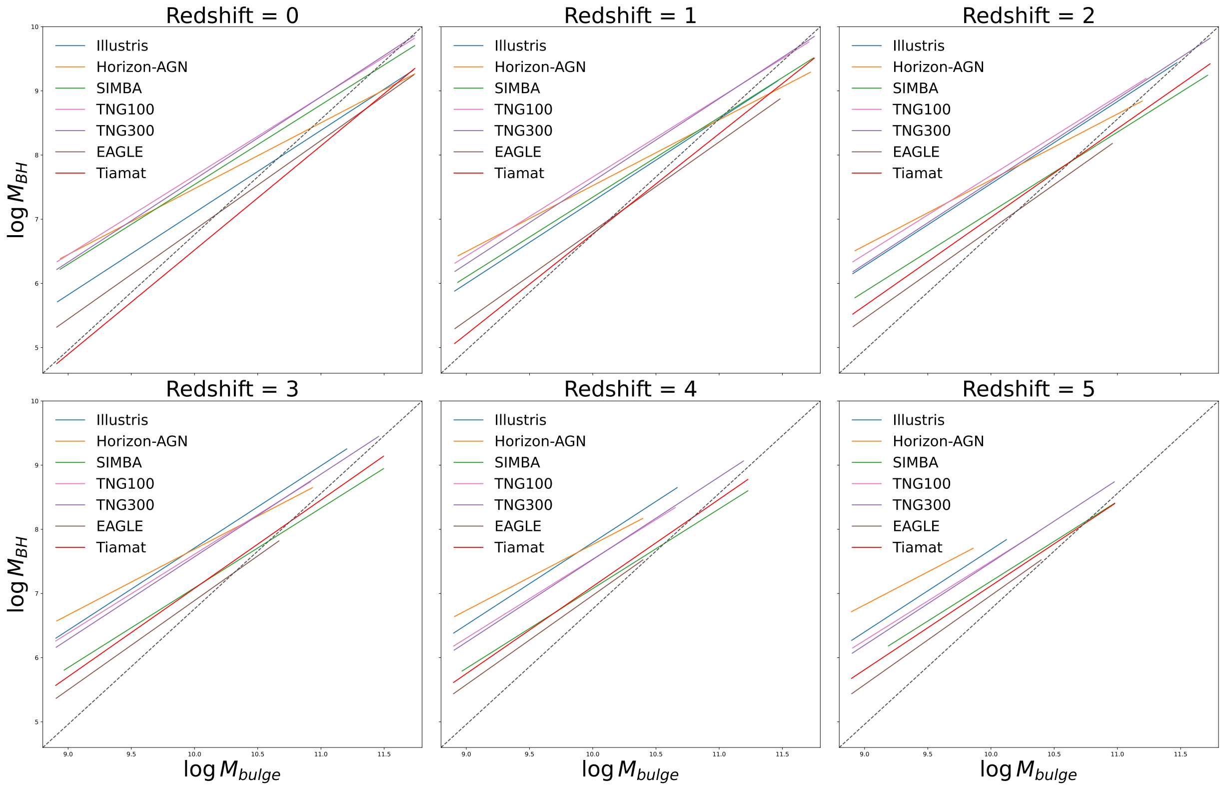

Fig. 2. Fits of SMBH masses using equation (3.2) for redshifts $z = 0, 1, 2, 3, 4$ and 5 for Illustris, Horizon-AGN, SIMBA, TNG100, TNG300, EAGLE and Tiamat simulations. The black dotted reference line is fixed across all panels.

also shown in Figure 2. Converting this BH mass parameters from the Tiamat simulation into parameters of equation (3.2), also gives consistent γ_* value which is given in Table 1.

5 Conclusions

The new formalism for the BH-bulge mass relation is supported by simulations. In the Illustris simulation, SMBH mass increases as we go to higher redshifts in Figure 2 due to the positive value of γ_*. Whereas SMBH mass decreases as we go to higher redshifts in SIMBA because of the negative value of γ_*. The differences found in the redshift evolution of the BH-bulge mass relations likely come from the combination of the different BH and galaxy subgrid physics employed in each simulation (e.g., BH formation, BH accretion rates, AGN feedback, etc.). Current observations, that however may not be unbiased, suggest positive or no evolution with redshift, therefore models with negative evolution are disfavored. The GWB strain in the PTA range we get using the BH-bulge mass parameters with redshift will be different for each simulations similar to Figure 1.

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