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Theoretical Re-evaluations of Scaling Relations between SMBHs and Their Host Galaxies—1. Effect of Seed BH Mass

Hikari Shirakata[1*], *Toshihiro Kawaguchi*[2], *Takashi Okamoto*[1], *Ryu Makiya*[3,4], *Tomoaki Ishiyama*[5], *Yoshiki Matsuoka*[6], *Masahiro Nagashima*[7], *Motohiro Enoki*[8], *Taira Oogi*[3] and *Masakazu A. R. Kobayashi*[9]

[1] Department of Cosmosciences, Graduate School of Science, Hokkaido University, Sapporo, Japan, [2] Department of Economics, Management and Information Science, Onomichi City University, Onomichi, Japan, [3] Kavli Institute for the Physics and Mathematics of the Universe, Todai Institutes for Advanced Study, University of Tokyo, Kashiwa, Japan, [4] Max-Planck-Institut fur Astrophysik, Garching, Germany, [5] Institute of Management and Information Technologies, Chiba University, Chiba, Japan, [6] Research Center for Space and Cosmic Evolution, Ehime University, Matsuyama, Japan, [7] Faculty of Education, Bunkyo University, Koshigaya, Japan, [8] Faculty of Business Administration, Tokyo Keizai University, Kokubunji, Japan, [9] Faculty of Natural Sciences, National Institute of Technology, Kure College, Kure, Japan

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****Correspondence:***
Hikari Shirakata
shirakata@astro1.sci.hokudai.ac.jp

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We use a semi-analytic model of galaxy formation and investigate how the mass of a seed black hole affect the scaling relation between black hole mass and bulge mass at $z \sim 0$. When the mass of the seed is set at $10^5 M_\odot$, we find that the model results become inconsistent with recent observational results of the scaling relation for dwarf galaxies. On the other hand, when we set seed black hole mass as $10^3 M_\odot$ or as randomly chosen value within a $10^{3-5} M_\odot$ range, we find the results are consistent with observational results including the dispersion. We also find that black hole mass—bulge mass relations for less massive bulges at $z \sim 0$ put stronger constraints on the seed BH mass than the relations at higher redshifts.

Keywords: galaxies, active galactic nuclei, bulge, galaxy formation, statistics

1. INTRODUCTION

Many observations (e.g., Kormendy and Richstone, 1995; Magorrian et al., 1998; Häring and Rix, 2004; McConnell and Ma, 2013) have suggested that the mass of supermassive black holes ($M_{\rm BH}$) correlates with the properties of their host galaxies such as stellar mass of bulges ($M_{\rm bulge}$) at $z \sim 0$. This $M_{\rm BH} - M_{\rm bulge}$ relation might suggest that supermassive black holes (SMBHs) would have co-evolved with their host galaxies.

SMBHs grow to the current mass ($\gtrsim 10^6 M_\odot$) from their initial mass. The initial mass and its distribution have been debating. Although, there are many theoretical suggestions of formation mechanism and mass of seed BHs (e.g., Begelman et al., 2006), we cannot obtain what is the dominant mechanism by comparing theoretical models with observations since seed BHs are not observable directly.

Here, we focus on the $M_{\rm BH} - M_{\rm bulge}$ relation for galaxies with bulge mass is less than $10^{10} M_\odot$ to get the constraints on mass of seed BHs. This paper is a summary of Shirakata et al. (2016) in which we investigate the effect of the seed BHs' mass on model predictions of $M_{\rm BH} - M_{\rm bulge}$ relation at $M_{\rm bulge} \lesssim 10^{10} M_\odot$ by using an semi-analytic model of galaxy formation (hereafter SA model). In section 2 we briefly review the SA model we used. Section 3 includes the main results. Finally, in section 4, we summarize this review and briefly mention future prospects.

2. MODELS

We use a revised version of an SA model, "*New Numerical Galaxy Catalogue*" (ν^2GC ; Makiya et al., 2016, hereafter M16), where the models related to the SMBH and AGNs are described in Enoki et al. (2003), Enoki et al. (2014), and Shirakata et al. (2015). We consider star formation in galactic disk and bulge, mergers of galaxies, atomic gas cooling, gas heating by UV feedback and feedbacks via supernovae and AGNs, and the growth of SMBHs by coalescence and gas accretion from their host galaxies.

Merging histories of dark matter halos are calculated from state-of-the-art cosmological N-body simulations (Ishiyama et al., 2015). The cosmological simulations have a high mass resolution and large volume compared to previous simulations (e.g., mass resolution is roughly four times better than those of Millennium simulations, Springel et al., 2005). Here we employ a simulation with $L = 70.0$ [h^{-1} Mpc] of box size and 512^3 particles, which corresponds to $M_{\rm min} = 2.20 \times 10^8 [h^{-1} M_\odot]$ of minimum halo mass.

We assume a ΛCDM universe which have the following parameters: $\Omega_0 = 0.31$, $\lambda_0 = 0.69$, $\Omega_{\rm b} = 0.048$, $\sigma_8 = 0.83$, $n_{\rm s} = 0.96$, and a Hubble constant of $H_0 = 100\,h$ km s^{-1} Mpc^{-1}, where $h = 0.68$ (Planck Collaboration et al., 2014).

2.1. Setting of Seed Black Holes

We place a seed BH soon after the time of a galaxy formation. We present results with $M_{\rm BH,seed} = 10^3 M_\odot$ (hereafter "light seed model") where $M_{\rm BH,seed}$ is the seed BH mass, and $10^5 M_\odot$ ("massive seed model"). In addition, we employ the model in which $M_{\rm BH,seed}$ takes uniformly random values in the logarithmic scale in the range of $3 \leq \log(M_{\rm BH,seed}/M_\odot) \leq 5$ (hereafter "random seed model").

2.2. Summary of Bulge and SMBH Growth Model

We assume that the bulge grows via starbursts and the migration of disk stars. Starbursts are triggered by mergers of galaxies (major and minor) or disk instability. The model of merger driven bulge formation in ν^2GC is based on Hopkins et al. (2009). We consider that mergers of galaxies occur both by dynamical friction (central-satellite merger) and random collision (satellite-sattelite merger). We also introduce the spheroid formation by disk instability following Mo et al. (1998) and Cole et al. (2000). In both cases, the gas supplied from galactic disk to the bulge is completely exhausted by a starburst and fueling onto their central SMBHs.

SMBHs in ν^2GC are mainly grown by gas accretion from their host galaxy. When a starburst occurs in a bulge, a part of cold gas gets accreted by the SMBH :

$$M_{\rm acc} = f_{\rm BH}\ \ \Delta M_{*,{\rm burst}}, \tag{1}$$

where $M_{\rm acc}$ is the cold gas mass accreted onto the SMBH, which is assumed to be proportional to the stellar mass formed by a current starburst, $\Delta M_{*,{\rm burst}}$. Here we set $f_{\rm BH} = 0.01$. SMBHs also grow via coalescence of BHs which occurs with mergers of host galaxies. For simplicity, we assume BHs merge instantaneously when their host galaxies merge.

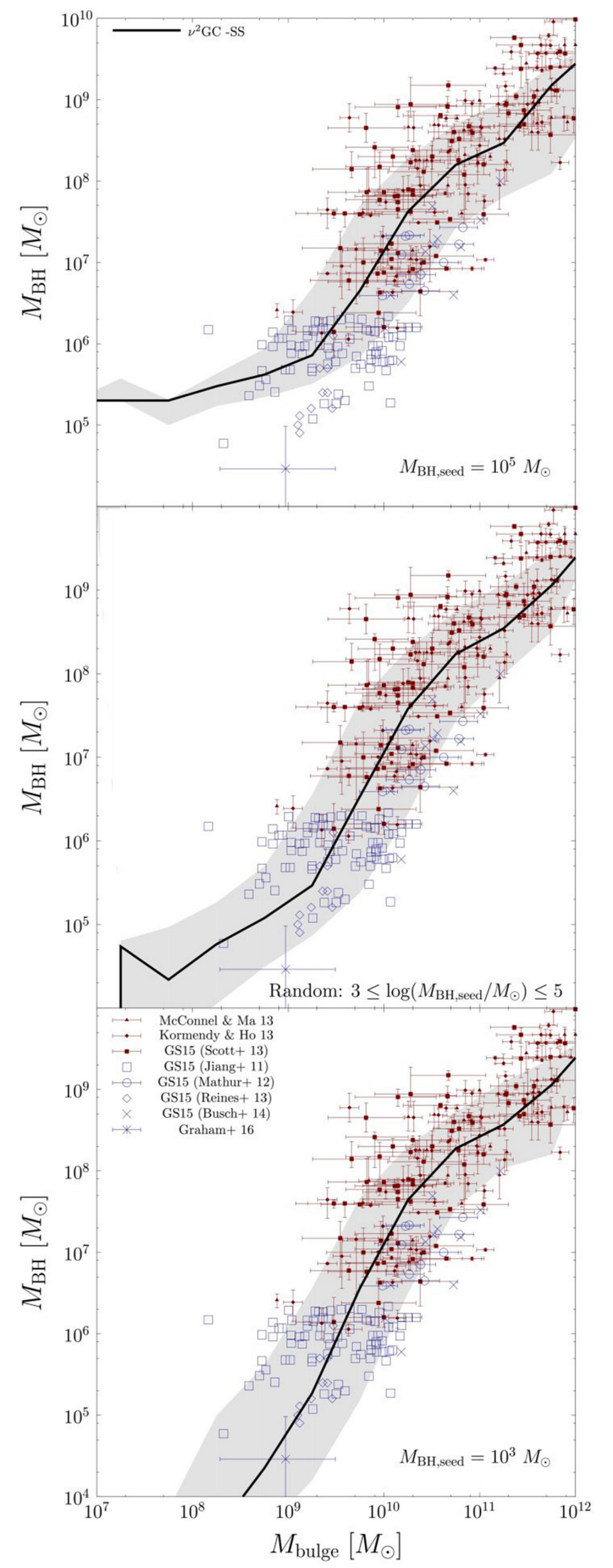

FIGURE 1 | $M_{\rm BH} - M_{\rm bulge}$ relations at $z \sim 0$ for different $M_{\rm BH,seed}$; the massive **(top)**, random **(middle)**, and light **(bottom)** seed models. Black solid *(Continued)*

FIGURE 1 | Continued
lines track the median, and shaded regions indicate 10–90 percentile of the models of the model result. Red filled symbols indicate observational results obtained from McConnell and Ma (2013), Kormendy and Ho (2013), and GS15[3](triangles, diamonds, and squares, respectively). Blue open symbols are AGN sample obtained from GS15, (see the text for more details). Blue asterisks correspond LEDA 87300 (Baldassare et al., 2015; Graham et al., 2016).

3. RESULTS

Figure 1 shows the main result which depicts the $M_{\rm BH}$ – $M_{\rm bulge}$ relation at $z \sim 0$ obtained from the model and observations. Each panels correspond to the results of massive seed model (top), random seed model (middle), and light seed model (bottom), respectively. Red solid lines represents the model result, blue and green points represents the observational data.

We find all of the models reproduce the relation at $M_{\rm bulge} \gtrsim 10^{10} M_{\odot}$, while the massive seed model has an inconsistency in the observational results for less massive galaxies ($M_{\rm bulge} \lesssim 10^{10} M_{\odot}$). Random and light seed models, on the other hand, provide the consistent results in the range of $M_{\rm BH} \gtrsim 10^{5.5} M_{\odot}$, with observational estimates. We thus conclude that to explain recent observational data of the $M_{\rm BH}$ – $M_{\rm bulge}$ relation at $z \sim 0$, seed BH mass should dominate with $\sim 10^3 M_{\odot}$.

We note that since the number of samples of galaxies with $M_{\rm BH} \lesssim 10^{5.5} M_{\odot}$ (corresponds to $M_{\rm bulge} \lesssim 10^{10} M_{\odot}$) are not sufficient. Observational data with the mass range are thus necessary to investigate the detailed mass distribution of the seed BHs. It is however difficult to estimate BH and bulge mass of less massive galaxies. We thus investigate whether the $M_{\rm BH}$ – $M_{\rm bulge}$ relation at higher redshifts could be useful for getting further constraints on the mass of seed BHs. **Figure 2** displays the ratio of the average BH masses in the light seed model ($\equiv \langle M_{\rm BH} \rangle_3$) and those in the massive seed model ($\equiv \langle M_{\rm BH} \rangle_5$), as a function of bulge masses. The difference in the seed mass significantly appears in galaxies with bulge mass below $3 \times 10^9 M_{\odot}$ at $z \sim 0, 1$, and 2. We also find that the difference becomes smaller at higher redshift for a given $M_{\rm bulge}$. Observations of less massive bulges at $z \sim 0$ would thus be more important than at higher redshifts for investigating the mass distribution of seed BHs.

4. SUMMARY AND FUTURE PROSPECTS

We investigate how the mass of the seed BHs affects model predictions of the local $M_{\rm BH}$ – $M_{\rm bulge}$ relation by using an SA model. The results suggest that seed BHs with as massive as $10^5 M_{\odot}$ should not be dominant for reproducing the observed $M_{\rm BH}$ – $M_{\rm bulge}$ relation at $z \sim 0$ over a wide range of bulge masses down to $M_{\rm bulge} \lesssim 10^{10} M_{\odot}$. Obtaining stronger constraints of the detailed mass distribution of seed BHs observations of $M_{\rm BH} \lesssim 10^{5.5} M_{\odot}$ would be required.

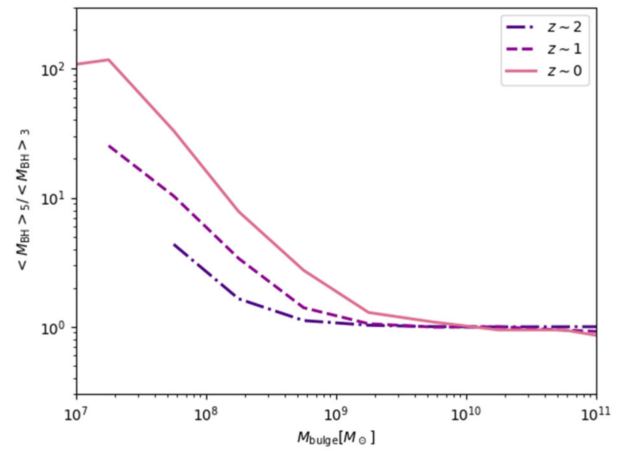

FIGURE 2 | The difference of averaged SMBH mass due to the seed BH mass at $z \sim 2$ (dash-doted line in blue), $z \sim 1$ (dashed line in purple), and $z \sim 0$ (solid line in pink) as a function of their bulge stellar mass with the ν^2GC -H2 simulation. The difference becomes smaller at higher redshift.

We have shown results of the local $M_{\rm BH}$ – $M_{\rm bulge}$ relations varying the mass of seed BHs. According to Shankar et al. (2016), $M_{\rm bulge}$ obtained from observations could be biased in favor of larger stellar masses. If so, we might have to use $M_{\rm BH}$ – velocity dispersion relation instead of the local $M_{\rm BH}$ – $M_{\rm bulge}$. We leave it for future studies.

The spheroids formed through disk instability might be classified as so-called "pseudo bulges". There are some debates whether pseudo bulges and classical bulges follow the same $M_{\rm BH}$ – $M_{\rm bulge}$ relation (e.g., Kormendy and Ho, 2013). We might need the model of the properties of pseudo bulges in the near future.

AUTHOR CONTRIBUTIONS

HS, RM, MN, ME, and MK have developed ν^2GC . In addition, HS analyze the output data obtained from ν^2GC . TK, TakO, and TaiO gave comments for the analysis. TI provides merger trees obtained from cosmological N-body simulations for ν^2GC . YM gave fruitful comments from a standpoint of AGN observations.

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[3]Originally obtained from Scott et al. (2013).

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