Empirical Constraints on the Coevolution of Supermassive Black Holes and their Host Spheroids

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ABSTRACT

We investigate the evolution of the $M_{\text{BH}} - \sigma$ relation by examining the relationship between the intrinsic scatter in the $M_{\text{BH}} - \sigma$ relation and galaxy bolometric nuclear luminosity, the latter being a proxy for the accretion rate of the black hole (BH). Our sample is composed of galaxies with classical bulges when possible, of which 38 have dynamically measured BHs masses, and 17 have BHs masses measured by reverberation mapping. In order to obtain the bolometric nuclear luminosity for galaxies with low nuclear luminosity, we convert the X-ray nuclear luminosity measured by Chandra to bolometric luminosity. We find that the scatter in the $M_{\text{BH}} - \sigma$ relation is uncorrelated with nuclear luminosity over seven orders of magnitude in luminosity, with the high luminosity end approaching the Eddington luminosity, $\sim L_{\text{Edd}}$. This suggests that at the present epoch galaxies evolve along the $M_{\text{BH}} - \sigma$ relation. This conclusion is consistent with the standard paradigm that BHs grow contemporaneously with their host stellar spheroids.

Key words: black hole physics – accretion – galaxies: nuclei – galaxies: kinematics and dynamics

1 INTRODUCTION

The existence of a supermassive BH in the centers of galaxies is well-established (Kormendy & Richstone 1995; Richstone et al. 1998; Kormendy & Gebhardt 2001). Strong links exist between the supermassive BH and host galaxy properties, as evidenced by the BH mass-stellar velocity dispersion ($M_{\text{BH}} - \sigma$) relation (Ferrarese & Merritt 2000; Gebhardt et al. 2000), amongst others. The $M_{\text{BH}} - \sigma$ relation has been demonstrated not to be a selection effect by Gültekin et al. (2011), to be the strongest correlation between $M_{\text{BH}}$ and galaxy properties by Beifiori et al. (2011), and has been estimated most recently by Gültekin et al. (2009) based on 49 $M_{\text{BH}}$ measurements and 19 $M_{\text{BH}}$ upper limits, by Graham et al. (2011) based on 64 $M_{\text{BH}}$ measurements, and by Beifiori et al. (2011) based on 49 $M_{\text{BH}}$ measurements and 94 $M_{\text{BH}}$ upper limits.

Despite the wealth of observational data, the origin of this relation is not firmly established. There are several theoretical models that explain the origin of the observed correlations between BH mass and galaxy properties. Feedback from BH accretion on the hosting galaxy is one proposal (Silk & Rees 1998; Fabian 1999; Burkert & Silk 2001). Simulations often involve galaxy mergers with strong inflow of gas that feeds the BH, powers the quasar and expels enough gas to quench both star formation and further fueling of the BH (Kauffmann & Haehnelt 2000; Weith & Loeb 2003; Di Matteo et al. 2005; Murray et al. 2006; Robertson et al. 2006; Johansson et al. 2007; Hopkins et al. 2009; Silk & Nusser 2010). This feedback from active galactic nuclei (AGN) regulates the BH-galaxy systems, and leads to tight BH mass-galaxy property relations. This scenario predicts that $M_{\text{BH}}$ and $\sigma$ coevolve.

Further mechanisms have been proposed to explain the tight correlation between BH mass and galaxy properties. Peng (2007) and Hirschmann et al. (2010) construct a model for the origin of the $M_{\text{BH}} - M_{\text{bulge}}$ relation in which mergers do not lead to accretion-based growth on the BH. In this model a tight $M_{\text{BH}} - M_{\text{bulge}}$ relation is established through the central limit theorem. Recently, Jahnke & Macciò (2011) build on this model by including BH accretion and star formation (these processes are uncorrelated in the model). They conclude that a causal link between galaxy growth and BH growth is not necessary for obtaining the observed BH mass-galaxy property relations.

In this article we investigate how galaxies evolve in the $M_{\text{BH}} - \sigma$ plane, and thereby place constraints on these and other models for the origin and evolution of the $M_{\text{BH}} - \sigma$ relation. We focus on local galaxies with classical bulges, and investigate the scatter in the $M_{\text{BH}} - \sigma$ relation as a function of galaxy nuclear luminosity. Our results indicate...
a scenario where BH mass and $\sigma$ evolve along the $M_{BH} - \sigma$ relation, thereby favoring models where BH mass and host stellar spheroids coevolve.

2 METHOD

First, we describe the criteria adopted to select our sample and the methods used to analyze the data. We consider the samples compiled by Gültekin et al. (2009) and Graham et al. (2011), which include galaxies with dynamically measured BHs and stellar velocity dispersions. In addition, we include galaxies studied by Greene et al. (2010), who measured the central BH mass via masers. We refer to the sum of these samples as our dynamically-based sample. We consider a second set of galaxies with BHs estimated via reverberation mapping (Woo et al. 2010).

We select galaxies with classical bulges when possible. This is done because Kormendy et al. (2011) observe that $M_{BH}$ does not correlate with the properties of galaxy disks or pseudobulges, and Sani et al. (2011) find smaller intrinsic scatter of BH mass-host galaxy property relations when excluding galaxies with pseudobulges. According to bulge classification of the galaxies included in Greene et al. (2011), whose classification relies on the galaxy morphology and stellar population property, we select the only galaxy (N1194) that has a classical bulge with nuclear luminosity at $10^{-17} L_{Edd}$, and we also select the galaxy (UGC 3789), which has an unclassified bulge with nuclear luminosity at $10^{-15} L_{Edd}$. For the other dynamically-based galaxies, we select classical bulge galaxies according to Sani et al. (2011), who classify galaxies with classical bulges by selecting galaxies which have Sérsic indices higher than two. We include all the reverberation-based galaxies as it is difficult to classify the morphology of galaxies with AGN.

Next, we estimate the bolometric nuclear luminosity. First, we consider the sample of Greene et al. (2010), who estimate the nuclear bolometric luminosity for their sample using O(III) emission from bright X-ray binaries. For the reverberation-based galaxies, we select those with known X-ray luminosity in the NASA/IPAC Extragalactic Database (NED) because these galaxies have nuclear luminosity ($\sim 2 \times 10^{45}$ erg s$^{-1}$) much higher than the X-ray binaries, the X-ray luminosity of the galaxy is dominated by the AGN. Thus, we associate the X-ray luminosity of the galaxy with that of the AGN. Most of the X-ray data are obtained from XMM-Newton (Bianchi et al. 2009; Markowitz et al. 2007; Nandra et al. 2007), except for Mrk202 and IC 120, which are obtained from ASCA (Ueda et al. 2005) and BeppoSAX (Verrecchia et al. 2007) separately (detailed properties and references see Table 2). In order to obtain the X-ray luminosity from X-ray fluxes, we estimate distances assuming $H_0 = 73$ km s$^{-1}$Mpc$^{-1}$, $\Omega_m = 0.27$, $\Omega_{\Lambda} = 0.73$ for $z > 0.01$ galaxies, with redshift measurements obtained from NED, which compiled multiple consistent redshift measurements for each galaxy. For $z < 0.01$ galaxies, we obtain distances from the Extragalactic Distance Database, which gives updated best distances for galaxies within 3000 km s$^{-1}$ (Tully et al. 2009).

To convert the X-ray luminosity to bolometric luminosity, we first convert the X-ray luminosity of different bands in the literature to luminosity in the band 2−10 keV assuming an energy index of $-1$ ($\nu f_\nu = constant$) with an uncertainty factor of $\sim 2$ (Martin Elvis, private communication). Then, we convert the X-ray luminosity to bolometric luminosity by the bolometric correction for AGNs: $L_{bol}/L_X = 15.8$, with an uncertainty factor of $\sim 0.3$ dex (Ho 2009). Therefore, the nuclear bolometric luminosity is calculated as:

$$L_{bol} = 15.8L_X \frac{\ln(10/2)}{\ln(E_2/E_1)}$$

where $E_2$ and $E_1$ represent the upper and lower bound of the observed X-ray band.

We include the properties of the BH and host spheroids for our dynamically-based and reverberation-based sample in Table 1 and Table 2 separately.

In reality the correction factor, $L_{bol}/L_X$, depends on the nuclear luminosity: low luminosity AGNs tend to be “X-ray-loud” (Ho 1994, 2009). In other words, the lower X-ray nuclear luminosity corresponds to an even lower bolometric nuclear luminosity and vice versa. Note that this additional complexity does not mix the order of galaxies with respect to their nuclear luminosity. As we compare galactic properties of lower nuclear luminosity galaxy to those of higher nuclear luminosity galaxies, without computing the exact bolometric luminosity, our conclusion is not affected by assuming a constant bolometric correction factor. Because the bolometric correction factor only introduces an uncertainty of $\sim 0.3$ dex (Ho 2009), the total uncertainty of the bolometric luminosity is less than the smallest bin width, one dex. Therefore, we expect our results to be largely unaffected by the uncertainties in nuclear bolometric luminosity.

In total, we have 38 galaxies with dynamically measured BH mass and 17 galaxies with reverberation-mapping BH mass measurements in our sample. For the dynamically-based sample, the range of the nuclear luminosity is limited because the nuclear luminosity is difficult to measure for low nuclear luminosity galaxies and the BH mass is difficult to

\begin{table}
\centering
\begin{tabular}{|c|c|c|c|}
\hline
\textbf{Galaxy} & \textbf{BH Mass} & \textbf{X-ray Luminosity} & \textbf{Reverberation} \\
\hline
\textbf{Sample 1} & \textbf{Sample 2} & \textbf{Sample 1} & \textbf{Sample 2} \\
\hline
\end{tabular}
\end{table}
Table 1. Properties of Dynamically-based sample

| Name     | \(\sigma\) | \(\epsilon_\sigma\) | \(\log M_{BH}\) | \(\epsilon_{\log M_{BH}}\) | \(\log [L_{bol}/L_{Edd}]\) | ref   |
|----------|-------------|----------------------|-----------------|---------------------------|-----------------------------|------|
|          | km s\(^{-1}\) | km s\(^{-1}\)       | \(M_\odot\)     |              |                |      |
| (1)      | (2)         | (3)                  | (4)             | (5)           | (6)            | (7)  |
| IC1459   | 340         | 17                   | 9.45            | 0.34          | -5.52          | (1)  |
| M31(a)   | 160         | 8                    | 8.18            | 0.09          | -8.67          | (5)  |
| M32(a)   | 75          | 3                    | 6.49            | 0.08          | -7.48          | (1)  |
| M60(a)   | 385         | 19                   | 9.32            | 0.37          | -8.17          | (1)  |
| M81(a)   | 143         | 7                    | 7.90            | 0.06          | -4.15          | (4)  |
| M84(a)   | 296         | 14                   | 9.18            | 0.35          | -6.62          | (1)  |
| M87(a)   | 375         | 18                   | 9.56            | 0.37          | -5.70          | (1)  |
| N524(b)  | 253         | 25                   | 8.92            | 0.10          | -7.27          | (1)  |
| N1194(c) | 148         | 24                   | 7.82            | 0.05          | -2.17          | (6)  |
| N2787(a) | 189         | 9                    | 7.63            | 0.04          | -6.35          | (3)  |
| N2974(b) | 227         | 23                   | 8.23            | 0.08          | -4.85          | (1)  |
| N3115(a) | 230         | 11                   | 7.98            | 0.13          | -7.19          | (1)  |
| N3227(a) | 133         | 12                   | 7.18            | 0.32          | -5.12          | (1)  |
| N3245(a) | 205         | 10                   | 8.34            | 0.10          | -4.52          | (1)  |
| N3377(a) | 145         | 7                    | 8.04            | 0.04          | -6.74          | (1)  |
| N3379(a) | 206         | 10                   | 8.08            | 0.33          | -6.90          | (1)  |
| N3384(a) | 143         | 7                    | 7.26            | 0.02          | -6.09          | (1)  |
| N3414(b) | 237         | 24                   | 8.40            | 0.07          | -7.19          | (1)  |
| N3585(a) | 213         | 10                   | 8.53            | 0.08          | -6.54          | (1)  |
| N3607(a) | 229         | 11                   | 8.08            | 0.14          | -6.22          | (1)  |
| N3608(a) | 182         | 9                    | 8.32            | 0.14          | -7.05          | (1)  |
| N4026(a) | 180         | 9                    | 8.32            | 0.08          | -6.85          | (1)  |
| N4261(a) | 315         | 15                   | 8.74            | 0.09          | -4.58          | (1)  |
| N4459(a) | 167         | 8                    | 7.87            | 0.39          | -6.41          | (1)  |
| N4552(b) | 252         | 25                   | 8.68            | 0.07          | -6.37          | (1)  |
| N4596(a) | 136         | 6                    | 7.92            | 0.13          | -6.40          | (2)  |
| N4621(b) | 225         | 23                   | 8.60            | 0.07          | -6.62          | (1)  |
| N5128(a) | 150         | 7                    | 7.65            | 0.13          | -3.54          | (1)  |
| N5813(b) | 239         | 24                   | 8.85            | 0.07          | -5.24          | (1)  |
| N5846(b) | 237         | 9                    | 9.04            | 0.04          | -6.70          | (1)  |
| N6251(a) | 290         | 14                   | 8.78            | 0.18          | -2.36          | (2)  |
| N7457(a) | 67          | 3                    | 6.61            | 0.25          | -5.64          | (1)  |
| UGC3789(c)| 107         | 12                   | 7.05            | 0.05          | -0.82          | (6)  |

Notes. Column 1: galaxy name and references on \(M_{BH}\), \(\sigma\). Column 2: stellar velocity dispersion (\(\sigma\)). Column 3: measurement error on \(\sigma\). Column 4: black hole mass (\(M_{BH}\)). Column 5: measurement error on \(\log M_{BH}\) (\(M_\odot\)). Column 6: X-ray luminosity references. References. \(M_{BH}\) and \(\sigma\) measurements (Column 1.)(a) Gültekin et al. (2009) (b) Graham et al. (2011) (c) Greene et al. (2010) Nuclei X-ray luminosity measurements (Column 7.) (1) Pellegrini (2010); (2) González-Martín et al. (2009); (3) Pellegrini (2005); (4) Zhang et al. (2009); (5) Li et al. (2011); (6) Greene et al. (2010)

To estimate dynamically for high nuclear luminosity galaxies, the reverberation mapping measurements are normalized by setting a constant virial coefficient so that the reverberation mapping-based and dynamically-based \(M_{BH} - \sigma\) relations agree. The assumption of a constant virial coefficient could potentially introduce a larger scatter for the reverberation-based sample. In addition, the virial coefficient may depend on the nuclear luminosity. If so, choosing a constant virial coefficient may introduce a BH mass uncertainty that depends on the nuclear luminosity. This could affect our result. In order to mitigate this potential bias, we do not rely heavily on comparing galaxies across our two samples.

With \(M_{BH}\), \(\sigma\) and nuclear luminosity in hand, we are now in a position to consider the scatter in the \(M_{BH} - \sigma\) relation with respect to nuclear luminosity. In order to obtain the scatter, we perform a linear fit to the \(M_{BH} - \sigma\) relation by minimizing \(\chi^2\) for the dynamically-based sample, as done by Tremaine et al. (2002). Our best-fit parameters are consistent with those in the literature: \(\log (M_{BH}/M_\odot) = 8.27 + 4.05 \log (\sigma/200\text{ km s}^{-1})\), with an intrinsic scatter of 0.27. The scatter between the measured \(M_{BH}\) for an individual galaxy and the \(M_{BH} - \sigma\) relation, in units of the uncertainty, is calculated as:

\[
\text{scatter} = \frac{\Delta M_{BH}}{\sqrt{\epsilon_M^2 + b^2 \epsilon_\sigma^2}},
\]

where \(\Delta M_{BH}\) is the difference between the measured BH mass and the BH mass corresponds to the fitted \(M_{BH} - \sigma\) relation, \(\epsilon_M\) is the measurement uncertainty of BH mass, and \(\epsilon_\sigma\) is the measurement uncertainty of stellar velocity dispersion.
### Table 2. Properties of Reverberation-based sample

| Name   | σ (km s⁻¹) | εσ (km s⁻¹) | log MBH (M⊙) | εlog MBH (M⊙) | log [Lbol/L_Edd] | ref |
|--------|------------|-------------|--------------|--------------|-----------------|-----|
| 3C 120 | 162        | 20          | 7.72         | 0.23         | -0.18           | (5) |
| Ark 120| 221        | 17          | 8.15         | 0.11         | -0.60           | (4) |
| Mrk 79 | 130        | 12          | 7.70         | 0.16         | -0.99           | (6) |
| Mrk 110| 91         | 7           | 7.38         | 0.14         | 0.14            | (3) |
| Mrk 202| 78         | 3           | 6.13         | 0.22         | -0.58           | (2) |
| Mrk 279| 197        | 12          | 7.52         | 0.15         | -0.52           | (3) |
| Mrk 590| 189        | 6           | 7.66         | 0.12         | -0.46           | (7) |
| Mrk 1310| 84       | 5           | 6.33         | 0.17         | -0.30           | (1) |
| Mrk 1383| 217       | 15          | 9.09         | 0.16         | -1.21           | (3) |
| N3227  | 136        | 4           | 7.60         | 0.24         | -2.06           | (5) |
| N3516  | 181        | 5           | 7.61         | 0.18         | -1.13           | (5) |
| N3783  | 95         | 10          | 7.45         | 0.13         | -0.10           | (3) |
| N4051  | 89         | 3           | 6.18         | 0.19         | -1.05           | (8) |
| N4151  | 97         | 3           | 7.64         | 0.11         | -1.46           | (4) |
| N4253  | 93         | 32          | 6.23         | 0.30         | 0.11            | (3) |
| N4593  | 135        | 6           | 6.97         | 0.14         | -1.07           | (4) |
| N5548  | 195        | 13          | 7.80         | 0.10         | -0.99           | (4) |
| N6814  | 95         | 3           | 7.25         | 0.12         | -1.52           | (4) |
| N7469  | 131        | 5           | 7.06         | 0.11         | -0.32           | (9) |

Notes. Column 1: galaxy name. Column 2: stellar velocity dispersion (σ). Column 3: measurement error on σ. Column 4: black hole mass (MBH). Column 5: measurement error on log MBH(M⊙). Column 6: X-ray luminosity references.

References.
Nuclei X-ray luminosity measurements and instruments (Column 7.)
(1) Verrecchia et al. (2007), BeppoSAX; (2a) Bianchi et al. (2009), XMM; (2b) Markowitz et al. (2009), XMM; (2c) Nandra et al. (2007), XMM; (3) Ueda et al. (2005), ASCA
Local galaxy (z<0.01) distance measurements: N3227, N3516, N3783, N4051, N4151, N4593: Tully et al. (2009);

εσ is the measurement uncertainty of the velocity dispersion and b is the slope of the MBH − σ relation. For a fixed slope of the MBH − σ relation, the scatter in BH mass determines the scatter in σ (scatter_BH = b × scatter_σ). Measuring the scatter in BH mass makes it more convenient to compare with the literature, where intrinsic scatter in BH mass is discussed (eg. Tremaine et al. 2002).

### 3 RESULTS

In Figure 1 we plot the MBH − σ relation for our sample. In order to compare the scatter in the MBH − σ relation with the nuclear luminosity, we color code the symbols by the nuclear luminosity level, log Lbol/L_Edd. Because the reverberation mapping method has a higher uncertainty in BH mass (because a constant virial coefficient is adopted), the scatter in the reverberation-based sample is slightly larger than that for the dynamically-based sample. It is apparent already from this figure that there is no strong correlation between MBH − σ scatter and nuclear luminosity within each sample.

In order to investigate the dependence of the scatter on nuclear luminosity quantitatively, we show in Figure 2 the scatter versus the nuclear luminosity (top panel) and the average scatter in bins of the nuclear luminosity level (bottom panel). To keep track of the standard deviation of the scatter at each nuclei luminosity bin, we plot the standard deviation in each bin as vertical dash error bars. We choose

![Figure 1](image-url)  
**Figure 1.** MBH − σ relation for galaxies with classical bulges and dynamically-based BH masses (stars), and reverberation-based masses (circles). The color bar indicates the nuclear luminosity levels, log Lbol/L_Edd. This figure demonstrates visually that there is no strong correlation between the scatter and the nuclear luminosity.

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This result can be seen another way by considering the timescales that govern the growth of the BH mass and the dynamical time. We define the BH growth timescale as:

$$t_{\text{acc}} = \frac{M_{\text{BH}}}{M_{\text{BH}}}$$

$$= 4 \times 10^7 \left( \frac{\epsilon}{0.1} \right) \left( \frac{L_{\text{bol}}}{L_{\text{Edd}}} \right)^{-1} \text{yr},$$

where $\epsilon$ is the radiative efficiency, which we take to be 0.1, $L_{\text{Edd}} = 3.5 \times 10^3 \left( \frac{M_{\odot}}{M_{\odot}} \right)$ is the Eddington luminosity.

The dynamical time is defined via:

$$t_{\text{dyn}} = \frac{R_e}{\sigma},$$

where $R_e$ is the effective radius of the galaxy. Because we are interested in the two timescales when the BH is accreting rapidly, we set an arbitrary threshold $(4 \times 10^{-3} L_{\text{Edd}})$ and select galaxies with nuclear bolometric luminosity higher than this value. Our result is independent of this threshold. This leaves us with 3 dynamically-based measurements, and all the reverberation-based measurements. Then, to calculate $t_{\text{dyn}}$, we obtain the effective radii of these galaxies from the literature [Sani et al. 2011; Bentz et al. 2009; Lauer et al. 2007; Marconi & Hunt 2003]. For the galaxies with no measured effective radii in the literature (N194, UGC3789, Mrk 202 and N4253), we use the galaxy radius calculated as the following. We estimate the radii of the galaxy by multiplying the angular radii by the angular-size distances. We obtain the angular radii from the 2MASS isophotal measurements with reference level of the radii set at 20 K – band magnitude arcsec$^{-2}$. The angular-size distance is calculated assuming $H_0 = 73 \text{ km s}^{-1}\text{Mpc}^{-1}$, $\Omega_m = 0.27$, $\Omega_\Lambda = 0.73$ as the four galaxies are all $z > 0.01$ galaxies. The redshift of the galaxies are obtained from NED, which compiled multiple consistent redshift measurements for each galaxy.

In Figure 3 we plot the ratio of $t_{\text{acc}}$ to $t_{\text{dyn}}$ as a function of the nuclear luminosity in units of the Eddington luminosity. We fit a straight line and find the slope of the line is $-0.94$ and the ratio approaches unity when the nuclear luminosity approaches the Eddington limit. As discussed in section 2, the bolometric correction factor depends on the nuclei luminosity. By fixing a constant correction factor, the nuclear bolometric luminosity is probably underestimated at high luminosity by roughly factor of 2. This causes $t_{\text{acc}}$ to be overestimated at high luminosity by the same factor. Thus, plotting the “true” $t_{\text{acc}}$ versus the “true” luminosity, which are overestimated and underestimated separately by the same factor, the points in Figure 3 should shift to the left along our observed trend. Therefore, the trend in Figure 3 is robust against the uncertainties in nuclear luminosity.

4 DISCUSSION

The relationship between scatter in the $M_{\text{BH}} - \sigma$ relation and the accretion rate of the BH puts interesting constraints on how galaxies evolve in the $M_{\text{BH}} - \sigma$ plane. For example, if BH growth and host stellar spheroid growth are uncorrelated then we would expect that galaxies with rapidly accreting BHs to lie systematically off of the $M_{\text{BH}} - \sigma$ relation. In contrast, if BHs and spheroid coevolve, then we would expect
no correlation between scatter in $M_{\text{BH}} - \sigma$ and BH activity, which is precisely what we observe. Our results therefore favor the scenario wherein spheroid and BHs coevolve along the $M_{\text{BH}} - \sigma$ relation.

In support of our conclusion, we also find that the dynamical time of the galaxy becomes comparable to the BH accretion timescale when the nuclear luminosity approaches the Eddington luminosity (Figure 3). We can understand how galaxies populate the space in Figure 3 in light of our results. Galaxies cannot be in the upper right region of Figure 3 because otherwise the BH would grow much slower than $\sigma$, resulting in a correlation between scatter and nuclear luminosity, which is not observed. We can also understand why there are no galaxies in the lower left region of Figure 3: there is no limit to how long $t_{\text{acc}}$ can be (because the accretion rate can be arbitrarily close to zero), while there is a limit to how small $t_{\text{dyn}}$ can be. So $t_{\text{acc}}/t_{\text{dyn}}$ can increase at lower $L/L_{\text{Edd}}$. For systems experiencing rapid growth in the BHs, the growth timescale of the BH is comparable to the dynamical time, supporting the idea that galaxies evolve along the $M_{\text{BH}} - \sigma$ relation.

As a further extension, we also consider the intrinsic scatter of galaxies with $M_{\text{BH}}$ measured by the virial method (Xiao et al. 2011; Shen et al. 2011) for high redshift AGN. We find that the intrinsic scatter of those is similar to the intrinsic scatter of the galaxies with BH masses measured by the reverberation-mapping method. The virial method uses the radius-luminosity relation to estimate the radius of the broad-line region, and then uses the reverberation mapping method formalism to measure BH masses. Thus, the mass of the BH has an even bigger uncertainty. Barring these additional uncertainties, this suggests that high-$z$ galaxies may also evolve along $M - \sigma$ relation.

Our result is inconsistent with models that predict a non-causal origin of BH mass-galaxy property relations. As discussed in Jahnke & Macciò (2011), in a non-causal origin model, the BH mass growth rate is uncorrelated with the growth of $\sigma$, and the BH mass-galaxy property relation converge only through the central limit theorem. Thus, when a given BH is growing its mass at high nuclear luminosity, $\sigma$ does not “catch up” until after several merger events. Such a model would therefore predict the scatter in $M_{\text{BH}} - \sigma$ to be lower for higher nuclear luminosity, in contradiction to our results.

On the other hand, our conclusion is consistent with the scenario emerging from simulations that episodes of major spheroid growth and BH growth occur on similar timescales via mergers. Simulations find that the epoch of rapid BH accretion is limited by AGN feedback to be $\sim 100$ Myr, which is similar to the dynamical time (e.g., Kauffmann & Haehnelt 2000; Di Matteo et al. 2005; Sijacki et al. 2007; Hopkins et al. 2009; Hopkins 2011; Blecha et al. 2011). This suggests that the BH mass and $\sigma$ change concurrently. Models that appeal to fueling of the BH by recycled gas (e.g., Ciotti & Ostriker 2007) must satisfy our constraint that galaxies evolve along $M_{\text{BH}} - \sigma$ even during high accretion rate phases.

In addition, our result reinforces the assumptions in various studies. For instance, it shows that BH grows simultaneously with the potential well formation in mergers, which is assumed by Shankar et al. (2009) to investigate the cosmological evolution of the $M_{\text{BH}} - \sigma$ relation. The self-regulated growth of supermassive BH is assumed when investigating the link between quasars and the red galaxy population by Hopkins et al. (2004), and when constraining the accretion history of massive BHs by Volonteri et al. (2006). Moreover, it constrains the total timescale of the episodic random accretion model proposed by Wang et al. (2004) to be similar to $t_{\text{dyn}}$.

In our dynamically-based sample we only have one galaxy with nuclear bolometric luminosity higher than 0.1$L_{\text{Edd}}$, and three galaxies with nuclear bolometric luminosity higher than 0.001$L_{\text{Edd}}$. We can expect more stringent constraints on the coevolution of galaxies and BHs as additional maser-based BH masses are obtained for higher nuclear luminosity galaxies.

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