Co-Evolution of Central Black Holes and Galaxies
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Determination of the Intrinsic Scatter in the $M_{\rm BH}$–σ and $M_{\rm BH}$–$L_{\rm bulge}$ Relations

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Abstract. We derive improved versions of the relations between supermassive black hole mass $M_{\rm BH}$ and host-galaxy bulge velocity dispersion σ and luminosity L (the $M_{\rm BH}$–σ and $M_{\rm BH}$–$L_{\rm bulge}$ relations), based on ∼50 $M_{\rm BH}$ measurements and ∼20 upper limits. Particular attention is paid to recovery of the intrinsic scatter (ϵ_0) in both relations. We find the scatter to be significantly larger than estimated in most previous studies. The large scatter requires revision of the local black hole mass function, and it implies that there may be substantial selection bias in studies of the evolution of the $M_{\rm BH}$–σ and $M_{\rm BH}$–$L_{\rm bulge}$ relations. When only considering ellipticals, the scatter decreases. These results appear to be insensitive to a wide range of assumptions about the measurement errors and the distribution of intrinsic scatter. We also investigate the effects on the fits of culling the sample according to the resolution of the black hole's sphere of influence.

Keywords. galaxies: elliptical and lenticular, galaxies: bulges, black hole physics, methods: statistical.

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1. Overview

The $M_{\rm BH}$–$L_{\rm bulge}$ and $M_{\rm BH}$–σ relations – the relations between a black hole's mass and the host galaxy's (bulge) luminosity, L, or velocity dispersion, σ – strongly suggest a fundamental link between galaxy and black hole (BH) evolution (Dressler 1989; Kormendy 1993; Magorrian *et al.* 1998; Gebhardt *et al.* 2000; Ferrarese & Merritt 2000). In this contribution to the proceedings, we discuss recent developments in the study of these relations and how they relate to coevolution of black holes and galaxies. Fundamental to the understanding of the $M_{\rm BH}$–σ and $M_{\rm BH}$–$L_{\rm bulge}$ relations is the measurement of the relation's *intrinsic* or *cosmic scatter*, as distinct from scatter due to measurement errors. The fact that there is a relation between BH mass and stellar velocity dispersion is not surprising, but the scatter is remarkably small, estimated by Tremaine *et al.* (2002) to be no larger than 0.25–0.3 dex. The *total* scatter of the relations (intrinsic combined with statistical and systematic measurement errors) is what makes the relation useful as a secondary tool for BH mass estimation. The intrinsic scatter, however, is the measure of the fundamental link between the physical quantities in question.

The magnitude of the intrinsic scatter is extremely important for several reasons. First, the range of BH masses in galaxies of a given velocity dispersion or bulge luminosity constrains BH formation and evolution theories. Many theories of BH formation and galaxy evolution have used the $M_{\rm BH}$–σ relation either as a starting point for further work or as a prediction of the theory (e.g., Silk & Rees 1998; Fabian 1999; King 2003); for a review, see Richstone (2004). A further test of such theories is whether they can reproduce the observed cosmic scatter in the relation. For example, there may be an increased intrinsic scatter in low-mass galaxies because BHs are ejected by asymmetric gravitational wave

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emission and low-mass spheroids have lower escape velocities (Volonteri 2007; Volonteri *et al.* 2008).

Understanding the scatter in the $M_{\rm BH}$–σ relation is also essential for estimating the space density of the most massive BHs in the local universe. One of the most useful aspects of the $M_{\rm BH}$–σ relation is that it allows one to estimate a galaxy's central BH mass from the more easily measured velocity dispersion. Because of the steep decline in number density of galaxies having high velocity dispersion (Sheth *et al.* 2003; Bernardi *et al.* 2006; Lauer *et al.* 2007), the majority of the extremely large BHs will reside in galaxies with moderate velocity dispersions that happen to contain BHs that are overmassive for the given velocity dispersion (Yu & Tremaine 2002; Marconi *et al.* 2004; Lauer *et al.* 2007). Knowing the magnitude of the intrinsic scatter is thus required to find the density of the most massive BHs. For example, the number density of BHs with $M > 10^{10}\ M_\odot$ is ~ 3 Gpc^{-3} if the intrinsic scatter is 0.15 dex and ~ 30 Gpc^{-3} if the intrinsic scatter is 0.30 dex (Lauer *et al.* 2007).

Both the magnitude of the intrinsic scatter and its distribution (e.g., normal or log-normal in mass) are also important to know for studies of the evolution of the $M_{\rm BH}$–σ relation (e.g., Treu *et al.* 2004, 2007; Hopkins *et al.* 2006; Peng *et al.* 2006; Shen *et al.* 2007, 2008; Vestergaard *et al.* 2008). Lauer *et al.* (2007) showed that there is a bias when comparing BH masses derived from observations of inactive galaxies at low redshifts to BH masses from active galaxies at higher redshift. The bias arises because the sample of nearby galaxies measures the distribution of BH masses for a given host velocity dispersion or luminosity, whereas the sample from high-redshift galaxies tends to measure the distribution of the host luminosity or host velocity dispersion for a given BH mass. Lauer *et al.* (2007) found that the bias in the inferred logarithmic mass scales as the square of the intrinsic scatter in logarithmic mass. In order to account for this bias correctly, not only the magnitude but also the distribution of the deviations from the $M_{\rm BH}$–σ relation is needed.

2. Most Recent Scaling Relations and Their Scatter

Using a sample of ~ 50 BH mass measurements and ~ 20 upper limits, Gültekin *et al.* (2009b) used a generalized maximum likelihood method to fit the $M_{\rm BH}$–σ and $M_{\rm BH}$–$L_{\rm bulge}$ relations with an intrinsic scatter component. Figure 1 and Figure 2 show $M_{\rm BH}$–σ and $M_{\rm BH}$–$L_{\rm bulge}$ relations. Their best fit for $M_{\rm BH}$–σ was

$$\log\left(\frac{M_{\rm BH}}{M_\odot}\right) = 8.12 \pm 0.08 + (4.24 \pm 0.41)\log\left(\frac{\sigma}{200\ {\rm km\ s^{-1}}}\right) \tag{2.1}$$

with an intrinsic scatter distributed normally in logarithmic mass with standard deviation $\epsilon_0 = 0.44 \pm 0.06$. When considering only ellipticals, they found that the intrinsic scatter drops to $\epsilon_0 = 0.31 \pm 0.06$. Their best fit for $M_{\rm BH}$–$L_{\rm bulge}$ was

$$\log\left(\frac{M_{\rm BH}}{M_\odot}\right) = 8.95 \pm 0.11 + (1.11 \pm 0.18)\log\left(\frac{L_V}{L_{\odot,V}}\right) \tag{2.2}$$

with an intrinsic scatter distributed normally in logarithmic mass with standard deviation $\epsilon_0 = 0.38 \pm 0.09$. Different assumptions about the error distribution in black hole mass measurements and intrinsic scatter did not significantly alter these conclusions.

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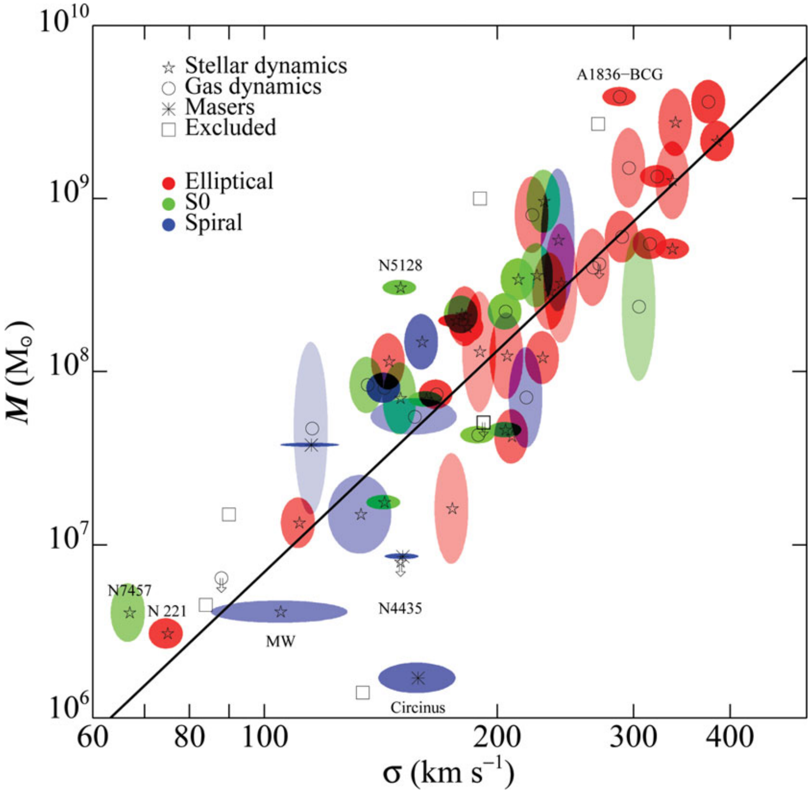

Figure 1. The $M_{\rm BH}$–σ relation for galaxies with dynamical measurements. The symbol indicates the method of BH mass measurement: stellar dynamical (*pentagrams*), gas dynamical (*circles*), masers (*asterisks*). Arrows indicate 3σ upper limits to BH mass. The shade of the error ellipse indicates the Hubble type of the host. The saturation of the shades in the error ellipses is inversely proportional to the area of the ellipse. The line is the best fit relation to the full sample: $M_{\rm BH} = 10^{8.12}\ M_\odot(\sigma/200\ \text{km s}^{-1})^{4.24}$. The mass uncertainty for NGC 4258 has been plotted much larger than its actual value so that it will show on this plot. (Adapted from Gültekin *et al.* 2009b.)

3. Implications for Scatter: Potential for Bias in Co-Evolution Studies

The intrinsic scatter is essential for determining the cosmic density of the most massive black holes. Because of the exponential drop in number density at the high end, very large galaxies are extremely rare. This means that in a fixed volume, the greatest number of big black holes do not come from the intrinsically rare, large galaxies but from the more common modest-sized galaxies that happen to have an over-massive black hole. Thus, deriving the number density of the largest black holes from the number density of galaxies depends on this effect.

The tendency for the largest black holes to come from more modest-sized galaxies also leads to a potential bias in studies of the evolution of scaling relations (Lauer *et al.* 2007). The samples of high-redshift black holes, which are measured from AGNs, tend to probe the distribution of σ or $L_{\rm bulge}$ for a given black hole mass whereas the local, quiescent sample tends to probe the distribution of $M_{\rm BH}$ for a given host-galaxy property. Direct comparison of the two samples leads to a bias that would lead one to incorrectly infer that at high redshift black holes were more massive than they are at low redshift, for a

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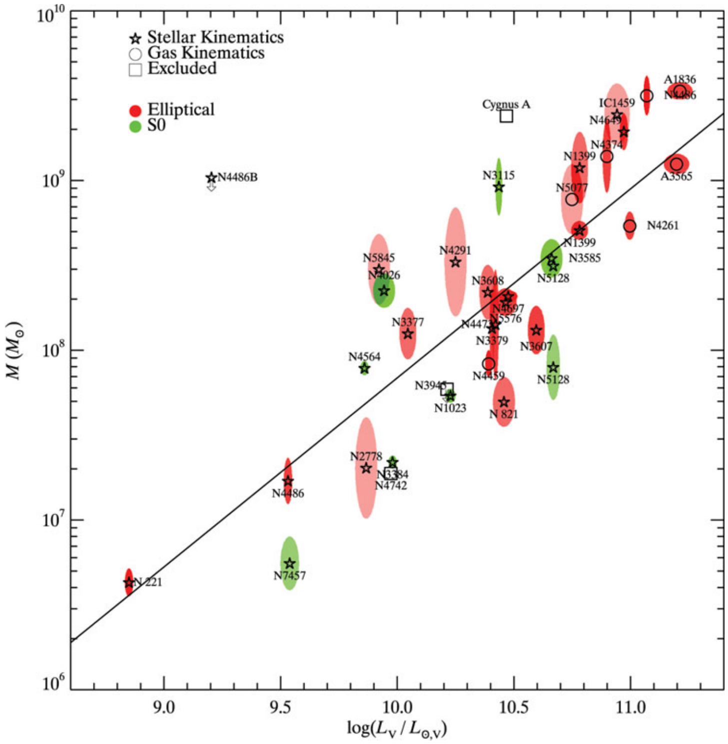

Figure 2. The $M_{\rm BH}$–$L_{\rm bulge}$ relation for galaxies with dynamical measurements. The symbol indicates the method of BH mass measurement: stellar dynamical (*pentagrams*) and gas dynamical (*circles*). Arrows indicate upper limits for BH mass. The shade of the error ellipse indicates the Hubble type of the host galaxy, and the saturation of the shade is inversely proportional to the area of the ellipse. The line is the best-fit relation for the sample without upper limits: $M_{\rm BH} = 10^{8.95}\ M_\odot (L_V/10^{11}\ L_{\odot,V})^{1.11}$. (Adapted from Gültekin *et al.* 2009b.)

given velocity dispersion or bulge luminosity. This bias depends critically on the poorly constrained wings of the distribution of the intrinsic scatter.

Another previously neglected caveat is that it may be impossible to disentangle evolution of just the intrinsic scatter of the relations from the evolution of the slope and/or intercept of the relations. That is, to correct for this effect when looking for evolution of $M_{\rm BH}$–σ or $M_{\rm BH}$–$L_{\rm bulge}$, one needs to assume that at high redshift the intrinsic scatter is the same as at low redshift in the quiescent population. This assumption, that one aspect of the relation (the scatter), is constant while measuring changes in other aspects (the intercept and slope) is difficult to justify and may lead to erroneous conclusions. Finally, a very recent study (Shen & Kelly 2009) has shown that an independent bias arising from uncertainties in BH mass estimators and the shape of the BH mass function may lead to an overestimate of the true BH masses.

4. Scaling Relations Are Biased When Black Hole Masses Are Censored by Sphere-of-Influence Resolution

Some have advocated the removal of BHs from scaling relation estimation if the BH's radius of influence on the sky is below a given threshold (e.g., Ferrarese & Ford 2005). This is based on a misconception that under-resolved BHs will yield biased BH mass estimates. In fact, under-resolved BHs yield lower precision masses, but with no bias in

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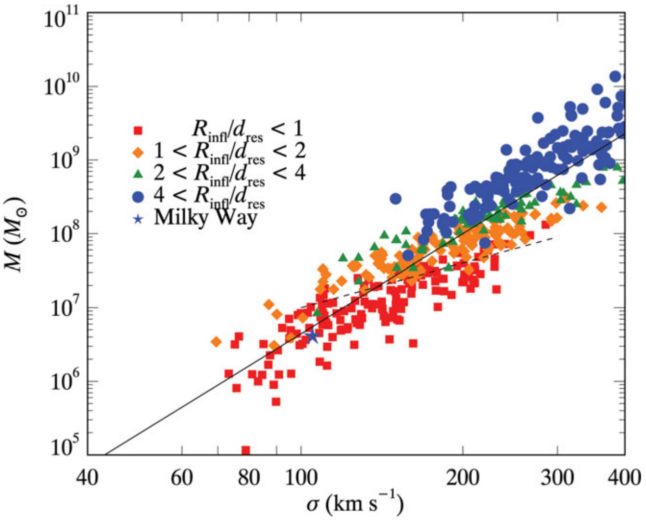

Figure 3. This figure shows results of a synthetically generated sample of 500 galaxies with BH mass generated from an $M_{\rm BH}$–σ relation with $\alpha = 8$ and $\beta = 4.0$ and a log-normal scatter of 0.3 dex with measurement errors of 0.2 dex. The $M_{\rm BH}$–σ ridge line is drawn as a black line. The Galaxy is plotted as a pentagram. Different symbols indicate different levels of resolution: $R_{\rm infl}/r_{\rm res} < 1.0$ (*squares*), $1.0 < R_{\rm infl}/r_{\rm res} < 2.0$ (*diamonds*), $2.0 < R_{\rm infl}/r_{\rm res} < 4.0$ (*triangles*), and $R_{\rm infl}/r_{\rm res} > 4.0$ (*circles*). Fitting the combined subsamples with $R_{\rm infl}/r_{\rm res}$ exceeding a given value yields biased estimators compared to the underlying $M_{\rm BH}$–σ relation. The reason for the bias in slope is that cuts in $R_{\rm infl}$ tend to fall along lines of $M_{\rm BH} \propto \sigma^{\beta-2}$ (since $R_{\rm infl} \propto M_{\rm BH}\sigma^{-2}$ and $M_{\rm BH} \propto \sigma^{\beta}$). This is illustrated by the dashed line of slope 2.0. (Adapted from Gültekin *et al.* 2009b.)

accuracy (Gültekin *et al.* 2009a,b). On the other hand, we may demonstrate the effects of censoring data based on $R_{\rm infl}$ with a synthetic $M_{\rm BH}$–σ data set. The synthetic data set consists of a sample of 500 galaxies, uniformly distributed in volume out to a distance of 30 Mpc. Each galaxy is given a velocity dispersion from a normal distribution in $\log(\sigma/200\ {\rm km\ s}^{-1})$ centered at 0 with standard deviation 0.2. Each galaxy is given a BH mass from an $M_{\rm BH}$–σ relation with intercept $\alpha = 8$, slope $\beta = 4.0$, and log-normal intrinsic scatter with $\epsilon_0 = 0.3$ dex. The BH's logarithmic mass is measured with a normally distributed measurement error of 0.2 dex and the velocity dispersion has a 5% error. Since each galaxy has a distance, a BH mass, and a velocity dispersion, we calculate $R_{\rm infl} = GM_{\rm BH}\sigma^{-2}$ and assume the galaxy to be observed with an instrument with resolution of $d_{\rm res} = 0\farcs1$. The results (Fig. 4) show that cutting out BH masses based on their level of resolution would clearly skew fits to the data set since $R_{\rm infl} \sim M_{\rm BH}\sigma^{-2}$ and $M_{\rm BH} \sim \sigma^{\beta}$ so that $R_{\rm infl} \sim M_{\rm BH}\sigma^{\beta-2}$, resulting in biasing cuts across the data set (Gültekin *et al.* 2009b).

5. Future Work on Intrinsic Scatter

The current data set of BH masses is insufficient to test some important questions about scaling relations, especially in regards to their intrinsic scatter. One of the most important is whether the magnitude of the intrinsic scatter changes across galaxy size. This would change the extent of the Lauer *et al.* (2007) bias. In order to accurately measure the intrinsic scatter across galaxy size, the existing data must be augmented.

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