Galaxy Evolution and Feedback across Different Environments
Proceedings IAU Symposium No. 359, 2020
T. Storchi-Bergmann, W. Forman, R. Overzier & R. Riffel, eds.
doi:10.1017/S1743921320001726

Substructure in black hole scaling diagrams and implications for the coevolution of black holes and galaxies

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Abstract. Our multi-component photometric decomposition of the largest galaxy sample to date with dynamically-measured black hole masses nearly doubles the number of such galaxies. We have discovered substantially modified scaling relations between the black hole mass and the host galaxy properties, including the spheroid (bulge) stellar mass, the total galaxy stellar mass, and the central stellar velocity dispersion. These refinements partly arose because we were able to explore the scaling relations for various sub-populations of galaxies built by different physical processes, as traced by the presence of a disk, early-type versus late-type galaxies, or a Sérsic versus core-Sérsic spheroid light profile. The new relations appear fundamentally linked with the evolutionary paths followed by galaxies, and they have ramifications for simulations and formation theories involving both quenching and accretion.

Keywords. black hole physics — galaxies: bulges — galaxies: elliptical and lenticular, cD — galaxies: evolution — galaxies: kinematics and dynamics — galaxies: spiral — galaxies: structure

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We have identified 145 galaxies with directly-measured supermassive black hole (SMBH) masses obtained from stellar dynamics, gas dynamics, kinematics of megamasers, proper motions (Sgr A*), or recent direct-imaging techniques (M87*). This sample comprises 96 early-type galaxies (ETGs) and 49 late-type galaxies (LTGs). 2D photometric models were generated for the galaxies using ISOFIT (Ciambur 2015) and their associated surface brightness profiles were modelled using PROFILER (Ciambur 2016). Their multi-component decompositions and stellar masses are presented in Davis *et al.* (2018, 2019) and Sahu *et al.* (2019a).

Sahu *et al.* (2019a) reported $M_{\rm BH} \propto M_{*,\rm sph}^{1.27\pm0.07}$ with a total scatter of $\Delta_{\rm rms|BH} = 0.52$ dex. Importantly, however, they discovered that the ES/S0-type galaxies with disks are offset from the E-type galaxies by more than a factor of ten (1.12 dex) in their $M_{\rm BH}/M_{*,\rm sph}$ ratios. Separately, each population follows a steeper relation with slopes of 1.86 ± 0.20 and 1.90 ± 0.20, respectively. The offset mass ratio is mainly due to the exclusion of each galaxy's disk mass, with the two populations offset by only a factor of two in their mean $M_{\rm BH}/M_{*,\rm gal}$ ratios and in the $M_{\rm BH}$–$M_{*,\rm gal}$ diagram (Figure 1).

By combining their data with LTGs from Davis *et al.* (2018, 2019); Sahu *et al.* (2019a) further showed a striking morphological distinction in the black hole scaling relations that separately govern LTGs and ETGs (Figure 2). Concerning the $M_{\rm BH}$–$M_{*,\rm gal}$ relation, LTGs follow scaling correlations with slopes approximately twice that of ETGs. In all cases, black holes and their host galaxies *do not* grow in lockstep; their coevolution is non-linear with scaling relation slopes greater than one. These varied growth mechanisms among different morphological types have consequences for galaxy/black hole formation

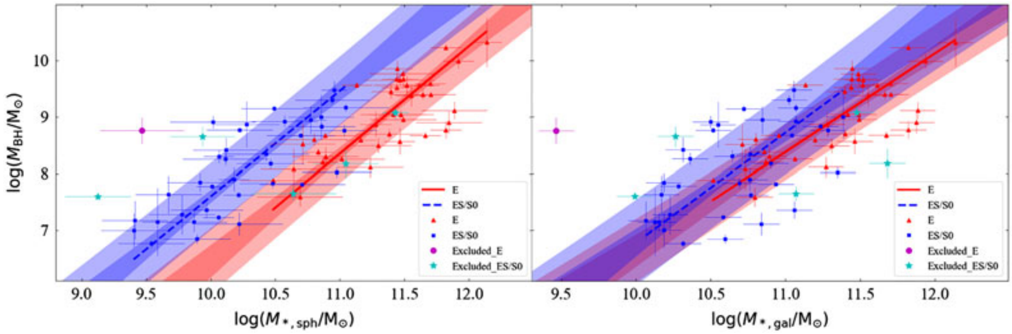

Figure 1. ETGs with (ES/S0) and without (E) disks. $M_{\rm BH}$–$M_{*,\rm sph}$ (left) – the relation for galaxies with disks is offset from the relation for galaxies without disks, revealing two different scaling relations for the two sub-morphological types (ES/S0 and E), with $\Delta_{\rm rms|BH}$ of 0.57 dex and 0.50 dex, respectively. $M_{\rm BH}$–$M_{*,\rm gal}$ (right) – both relations are consistent with each other, suggesting a single relation for galaxies with and without disks.

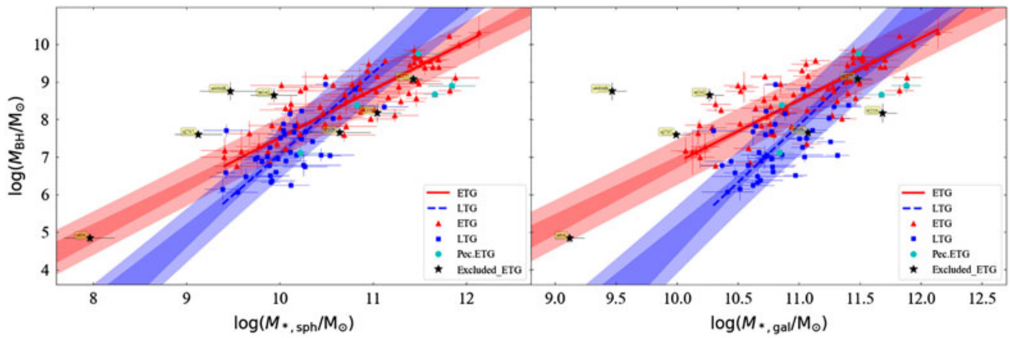

Figure 2. The $M_{\rm BH}$–$M_{*,\rm sph}$ and $M_{\rm BH}$–$M_{*,\rm gal}$ relations for ETGs and LTGs. $M_{\rm BH}$–$M_{*,\rm sph}$(left) – $M_{\rm BH} \propto M_{*,\rm sph}^{1.27\pm0.07}$ for all ETGs combined and $M_{\rm BH} \propto M_{*,\rm sph}^{2.17\pm0.32}$ for LTGs. $M_{\rm BH}$–$M_{*,\rm gal}$(right) – $M_{\rm BH} \propto M_{*,\rm gal}^{1.65\pm0.11}$ for ETGs and $M_{\rm BH} \propto M_{*,\rm gal}^{3.05\pm0.70}$ for LTGs.

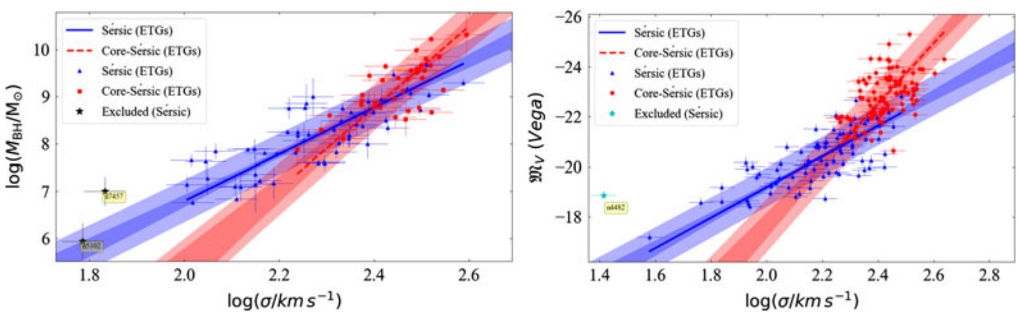

Figure 3. Left – $M_{\rm BH}$–σ diagram for Sérsic and core-Sérsic ETGs, with $M_{\rm BH} \propto \sigma^{5.75\pm0.34}$ and $M_{\rm BH} \propto \sigma^{8.64\pm1.10}$, respectively. Right – diagram of V-band absolute magnitude ($\mathfrak{M}_V$, Vega) vs. central velocity dispersion (σ) for Sérsic and core-Sérsic ETGs, with $L_V \propto \sigma^{2.44\pm0.18}$ and $L_V \propto \sigma^{4.86\pm0.54}$ for Sérsic and core-Sérsic ETGs, respectively.

https://doi.org/10.1017/S1743921320001726 Published online by Cambridge University Press

theories, simulations, and predicting black hole masses. Sahu *et al.* (2019b) further found that Sérsic and core-Sérsic galaxies define two distinct relations in the $M_{\rm BH}$–σ diagram. They also reported how this yielded a consistency with the slopes and bends in the galaxy luminosity (L)–σ relation, due to Sérsic and core-Sérsic ETGs (Figure 3).

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