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SUPER-MASSIVE BLACK HOLE MASS SCALING RELATIONS

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ABSTRACT

Using black hole masses which span 10^5–$10^{10} M_\odot$, the distribution of galaxies in the (host spheroid stellar mass)–(black hole mass) diagram is shown to be strongly bent. While the core-Sérsic galaxies follow a near-linear relation, having a mean $M_{\rm bh}/M_{\rm sph}$ mass ratio of ∼0.5%, the Sérsic galaxies follow a near-quadratic relation. This is not due to offset pseudobulges, but is instead an expected result arising from the long-known bend in the $M_{\rm sph}$–σ relation and a log-linear $M_{\rm bh}$–σ relation.

Key words: black hole physics; galaxies: bulges; galaxies: fundamental parameters; galaxies: nuclei

1. THE $M_{\rm bh}$–σ DIAGRAM

As one of the most popular topics in astronomy over the past 15 years, the $M_{\rm bh}$–σ diagram (Ferrarese & Merritt 2000; Gebhardt et al. 2000) needs little introduction. The relation between a galaxy's central supermassive black hole mass and its velocity dispersion is shown in Figure 1 for 72 galaxies. Taken from Graham & Scott (2013, see also McConnell & Ma, 2013), the non-barred Sérsic galaxies can be seen to follow the same $M_{\rm bh} \propto \sigma^{5.5}$ scaling relation as the non-barred core-Sérsic galaxies**[1]**. The barred galaxies have a tendency to be offset to larger velocity dispersions, a result explained in terms of elevated dynamics due to the bar (Hartmann et al. 2013, see also Brown et al. 2013 and Debattista et al. 2013).

In addition to bar dynamics, the observed velocity dispersion can be overestimated due to strong rotational gradients within the inner region, as was noted in Graham et al. (2011, their section 4.2.2). Removing these biases to obtain the spheroid's, rather than galaxy's, velocity dispersion will reduce the observed velocity dispersion and likely decrease some of the scatter in the $M_{\rm bh}$–σ diagram**[2]**. Most recently, from an expanded sample of 89 galaxies with directly measured black hole masses, Savorgnan & Graham (2014) find a slope of $\sim 6.34 \pm 0.80$ for the 57 non-barred members, and a vertical scatter of 0.53 dex in the $M_{\rm bh}$-direction.

2. THE $L_{\rm sph}$–σ AND $M_{\rm sph}$–σ DIAGRAM

Over half a century ago, Minkowski (1962) noted a correlation between luminosity and velocity dispersion for early-type galaxies (see the review in Section 3.3.3 of Graham 2013). Schechter (1980) and Malumuth & Kirshner (1981) subsequently reported a slope of ∼5 for the luminous galaxies (i.e. $L \propto \sigma^5$), and then Davies et al. (1983) reported a slope of ∼2 for the low- and intermediate-luminosity early-type galaxies. Samples containing mixtures of these two populations have slopes closer to 3 (e.g. Tonry et al. 1981) or 4 (e.g. Faber & Jackson 1976) depending on the relative number of bright to faint galaxies in one's sample.

The $L \propto \sigma^2$ relation extends from the lowest luminosity dwarf elliptical galaxies ($\sigma \approx 20$ km s^{-1}, and stellar masses a few times $10^8 M_\odot$) up to $M_{\rm sph,*} \sim 10^{11} M_\odot$ upon where massive spheroids and elliptical galaxies with partially depleted cores dominate (e.g. Matković & Guzmán 2005; Evstigneeva et al. 2007; Forbes et al. 2011; Kourkchi et al. 2012). The massive galaxies follow the relation $L \propto \sigma^{5-6}$ (von der Linden et al. 2007; Liu et al. 2008), with depleted cores starting to appear in galaxies with $\sigma \gtrsim 170$ km s^{-1} and becoming quite prevalent once $\sigma \gtrsim 230$ km s^{-1} (e.g. Dullo & Graham 2012).

In addition to the dwarf and intermediate luminosity early-type (Sérsic) galaxies ($-14 > M_B > -20.5$ mag) following the same log-linear L–σ relation noted above, their unification as a single population is also evident through the log-linear L–n and L–μ_0 relations that they share (Young & Currie 1994; Jerjen & Binggeli 1998, see also Caon et al. 1993 and Schombert 1986), where n is the Sérsic (1963) index and μ_0 is the central surface brightness. Furthermore, they display a similar

[1] To date, no barred core-Sérsic galaxy is known.
[2] This challenge has been taken up by Woo (2015).

behavior in terms of the occurrence of a rotating stellar disk and various other kinematic substructure (e.g. Emsellem et al. 2011; Scott et al. 2014; Toloba et al. 2014). Due to their systematically changing Sérsic index with luminosity (i.e. the L–n relation), the difference between μ_0 and μ_e (the surface brightness at the effective half light radius R_e) varies non-linearly with luminosity. This produces the dramatically curved L–μ_e relation, and the curved L–R_e relation, whose bright and faint arms have in the past been mis-interpreted as evidence for a dichotomy between dwarf and intermediate luminosity early-type galaxies because the curvature is greatest at $M_B \approx -18$ mag ($\approx$ 2–3 $\times 10^{10} M_\odot$)[3]. For those who are interested to learn more about galaxy structure, Graham (2013) provides an historical and modern review with references to over 500 papers, including many pioneer and often over-looked papers.

Naturally, the bent L_gal–σ relation mentioned above for early-type galaxies maps into a bent M_gal–σ relation. The (dynamical mass)–(effective velocity dispersion) diagram from Cappellari et al. (2013b; their figure 1) has been reproduced here in Figure 2a using the same data[4] from table 1 of Cappellari et al. (2013a). Their dynamical mass is twice their Jeans Anisotropic Multi-Gaussian-Expansion (JAM) mass within the effective half-light radius R_e, and the 'effective velocity dispersion' (σ_e) is the velocity dispersion within R_e.

At $\sigma_\mathrm{e} \sim 50$ km s^{-1}, the dynamical masses are around $4 \times 10^9 M_\odot$ (Figure 2a), while the spheroidal stellar masses are around $10^9 M_\odot$ (Figures 1 & 2b, assuming a common black hole mass around $10^5 M_\odot$)[5]. To be consistent, this would require early-type galaxies with $\sigma_\mathrm{e} \sim 50$ km s^{-1} to have 3 times as much dark matter as luminous matter, based on the JAM models. This agrees with an extrapolation of the data presented in figure 10 from Cappellari et al. (2013b)[6], and thus there is a consistency.

In passing we make two notes. The bulges of spiral galaxies with $\sigma_\mathrm{e} \sim 50$ km s^{-1} may not have such relatively high dynamical-to-stellar masses if these galaxies' purported dark matter dominates at larger radii. Second, as one progresses from early-to-later type disk galaxies, *on average* the radius $R_\mathrm{e,gal}$ will increasingly resemble $R_\mathrm{e,disk}$ rather than $R_\mathrm{e,bulge}$ (i.e. $R_\mathrm{e,spheroid}$). As such, use of virial mass estimators ($\sigma^2.R_\mathrm{e,gal}$) will increasingly over-estimate the dynamical mass of the bulge.

We write "on average" in the preceding paragraph because the spectrum of disk galaxies, represented by the Hubble-Jeans tuning-fork sequence (Jeans 1919, 1928; Hubble 1926, 1936) or the "Hubble comb" for the Revised David Dunlap Observatory system (van den Bergh 1976; Laurikainen et al. 2010, 2011; Cappellari et al. 2011) may be better described by a kind of "Hubble grid" (Morgan & Osterbrock 1969; Graham 2014) in which galaxies of each morphological type (not just the S0 galaxies) span a range of bulge-to-disk mass ratios.

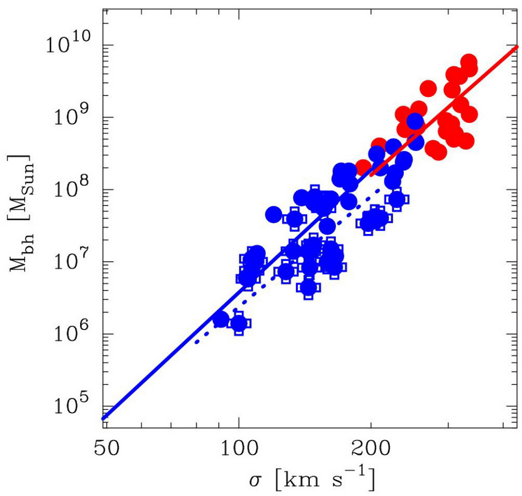

Figure 1. Variation of the (black hole mass)–(velocity dispersion) Figure 2a from Graham & Scott (2013). The red points are core-Sérsic galaxies, while the blue points are Sérsic galaxies. The crosses designate barred galaxies, which tend to be offset to higher velocity dispersions. The three lines are linear regressions, in which the barred Sérsic galaxies and the non-barred Sérsic galaxies are fit separately from the core-Sérsic galaxies (none of which are barred).

3. THE M_bh–M_sph DIAGRAM

Graham & Scott (2013) used K_s-band magnitudes from the Two Micron All-Sky Survey (2MASS) Extended Source Catalogue (Jarrett et al. 2000) to confirm that the M_bh–L_sph relation is bent (Graham 2012). Using improved 2MASS magnitudes from the ARCHANGEL photometry pipeline (Schombert & Smith 2012), these revised spheroid magnitudes were converted into stellar masses by Scott, Graham & Schombert (2013), and the M_bh–M_sph relation was shown to be bent. Shown in Figure 2b is the data from Scott et al. (2013) combined with data for 139 Active Galactic Nuclei (AGN). Virial estimates for the AGN black hole masses are provided in Jiang et al. (2011a, b), and the apparent spheroid magnitudes reported there have been converted into stellar masses by Graham & Scott (2014). The lines shown in Figure 2b are from the fit in Scott et al. (2013) to the core-Sérsic and Sérsic galaxies with directly measured SMBH masses. The core-Sérsic relation has a slope of 0.97±0.14, see also Graham (2012) and Graham & Scott (2013) which reports that the mean $M_\mathrm{bh}/M_\mathrm{sph}$ ratio is 0.49% for the core-Sérsic galaxies (see also Laor 2001). The steeper Sérsic M_bh–M_sph relation

$$\log \frac{M_\mathrm{bh}}{M_\odot} = (2.22\pm0.58) \log \left[\frac{M_\mathrm{sph,*}}{2 \times 10^{10} M_\odot} \right] + (7.89\pm0.18) \quad (1)$$

[3] Due to the presence of disks in the lenticular galaxies, minor perturbations are expected and found (e.g. Janz & Lisker 2008) about these unifying relations.

[4] The velocity dispersions within $R_\mathrm{e}/8$ from table 1 of Cappellari et al. (2013b) produce a somewhat similar distribution.

[5] Note: For low mass spheroids the velocity dispersion profiles are rather flat, and $\sigma_\mathrm{e} \approx \sigma_{\mathrm{e}/8} \approx \sigma_0$.

[6] Some tension is noted with figure 14 from Forbes et al. (2008) which suggests that there may be roughly equal amounts, or little need for dark matter.

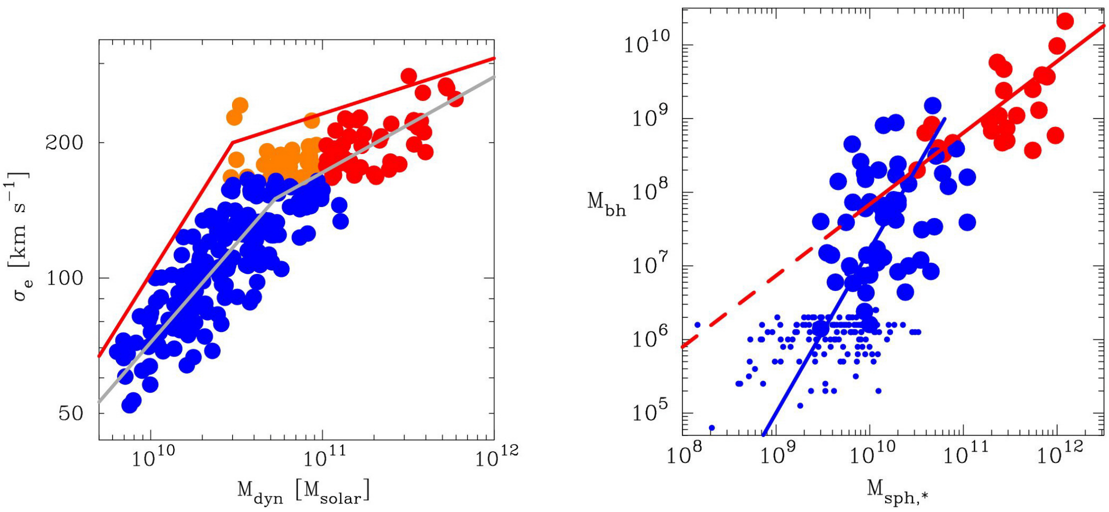

Figure 2. Left: Adaption of Figure 1 from Cappellari et al. (2013b), with the colour scheme roughly matching galaxy type such that orange indicates either a core-Sérsic galaxy or a Sérsic galaxy. The lines are from their figure. Right: Building on Figure 3 from Scott et al. (2013), we have added 139 AGN (smaller symbols) from Jiang et al. (2011a, b) — see Graham & Scott (2014) for details. The red points are core-Sérsic galaxies while the blue points are Sérsic galaxies. The regressional lines to the non-AGN data from Scott et al. (2013) reveal that the near-quadratic relation for the Sérsic galaxies matches the AGN data well. The systematic, rather than random, deviation from the near-linear core-Sérsic relation is increasingly evident at lower masses.

can be seen to match well with the distribution of AGN data, and reveals that the Sérsic $M_{\rm bh}$–$M_{\rm sph}$ relation extends down to $M_{\rm bh} \sim 10^5 M_{\odot}$. This explains the steeper relations seen in the data of Laor (1998, 2001) and Wandel (2001).

4. SUMMARY

If $M_{\rm bh} \propto \sigma^{5.5}$, and $L \propto \sigma^2$ for Sérsic galaxies, then $M_{\rm bh} \propto L^{2.75}$. Given $M_{\rm dyn}/L \propto L^{1/3}$ (Cappellari et al. 2006), one has that $M_{\rm bh} \propto M_{\rm dyn}^{2.06}$ (or $M_{\rm bh} \propto M_{\rm dyn}^{2.44}$ if $M_{\rm bh} \propto \sigma^{6.5}$, Savorgnan & Graham 2014). This bodes well with the relation $M_{\rm bh} \propto M_{\rm sph,*}^{2.22\pm0.58}$ reported in Scott et al. (2013).

If the sample of AGN from Jiang et al. (2011a,b) were associated with pseudobulges having randomly low black hole masses relative to their host bulge mass — an idea originally proposed by Hu (2008) and Graham (2008) — then they would not display the distribution seen in Figure 2b. They would instead appear randomly offset to lower black hole masses rather than following the near-quadratic $M_{\rm bh}$–$M_{\rm sph,*}$ relation.

This near-quadratic, or possibly super-quadratic, scaling relation has many implications. For one, the accretion and growth process, a popular topic at this meeting (e.g. Qiao 2015; Han 2015; Yang 2015, Taam 2015) does not obey a constant $M_{\rm bh}/M_{\rm sph}$ mass ratio. There are also important implications for gravitational radiation, another popular theme at this meeting (e.g. Hobbs 2015; Kang 2015; Kim 2015; Lee 2015). Due to the relatively smaller black hole masses in the lower-mass Sérsic galaxies, which also typically house a dense nuclear star cluster, the detectable number of low-frequency 'extreme mass ratio inspiral' events (Amaro-Seoane et al. 2014, and references therein) may be an order of magnitude lower than compared to expectations if $M_{\rm bh}/M_{\rm sph} \approx 0.1\%$ (Mapelli et al. 2012). These and other consequnces of the new bent scaling relation are described in Graham & Scott (2014).

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