Overmassive black holes in the $M_{\text{BH}} - \sigma$ diagram do not belong to over (dry) merged galaxies

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ABSTRACT

Semi-analytical models in a ΛCDM cosmology have predicted the presence of outlying, “overmassive” black holes at the high-mass end of the (black hole mass – galaxy velocity dispersion) $M_{\text{BH}} - \sigma$ diagram (which we update here with a sample of 89 galaxies). They are a consequence of having experienced more dry mergers – thought not to increase a galaxy’s velocity dispersion – than the “main-sequence” population. Wet mergers and gas-rich processes, on the other hand, preserve the main correlation. Due to the scouring action of binary supermassive black holes, the extent of these dry mergers (since the last significant wet merger) can be traced by the ratio between the central stellar mass deficit and the black hole mass ($M_{\text{def}}$/M$_{\text{BH}}$). However, in a sample of 23 galaxies with partially depleted cores, including central cluster galaxies, we show that the “overmassive” black holes are actually hosted by galaxies that appear to have undergone the lowest degree of such merging. In addition, the rotational kinematics of 37 galaxies in the $M_{\text{BH}} - \sigma$ diagram reveals that fast and slow rotators are not significantly offset from each other, also contrary to what is expected if these two populations were the product of wet and dry mergers respectively. The observations are thus not in accordance with model predictions and further investigation is required.

Key words: galaxies: evolution – galaxies: formation – galaxies: elliptical and lenticular, cD – black hole physics

1 INTRODUCTION

Our growing awareness of substructures and the actual relations within various black hole mass ($M_{\text{BH}}$) scaling diagrams is important because it provides us with clues into the joint evolution of black hole and host spheroid. For example, Graham (2012), Graham & Scott (2013) and Scott, Graham & Schombert (2013) have shown that the bent $M_{\text{BH}} - M_{\text{sph},\text{dyn}}$ (spheroid dynamical mass), $M_{\text{BH}} - L_{\text{sph}}$ (spheroid luminosity) and $M_{\text{BH}} - M_{\text{sph},*}$ (spheroid stellar mass) relations reveal that black holes grow roughly quadratically with their host spheroid until the onset of dry merging, as signalled by the presence of partially depleted galaxy cores and a linear scaling at the high-mass end of these diagrams. The clever many-merger model of Peng (2007), Hirschmann et al. (2010) and Jahnke & Maccì (2011) was therefore ruled out because it required convergence along a distribution in the $M_{\text{BH}} - M_{\text{sph},*}$ diagram with a slope of unity, rather than the observed buildup (to higher masses) along the quadratic relation.

In addition, the demographics in the $M_{\text{BH}} - \sigma$ (stellar velocity dispersion) diagram (Ferrarese & Merritt 2000; Gebhardt et al. 2000) have disclosed a tendency for barred galaxies to be offset, to higher velocity dispersions, than non-barred galaxies (Graham 2007, 2008a,b; Hu 2008; Graham & Li 2009). This may well be due to the elevated kinematics associated with bars (e.g. Graham et al. 2011; Brown et al. 2013; Hartmann et al. 2014). Speculation as to the role played by secular evolution and the possibility of “anaemic” black holes in pseudo-bulges (e.g. Graham 2008a; Hu 2008) does however still remain an intriguing possibility (Kormendy, Bender & Cornell 2011), although their current lack of an offset about the bent $M_{\text{BH}} - M_{\text{sph},*}$ relation (Graham & Scott 2013) argues against this.

An interesting suggestion for the presence of additional substructure in the $M_{\text{BH}} - \sigma$ diagram has recently been offered by Volonteri & Ciotti (2013), who investigated why central cluster galaxies tend to be outliers, hosting black holes that appear to be “overmassive” compared to expectations from their velocity dispersion. On theoretical grounds it is well known that – as a consequence of the virial theorem and the
conservation of the total energy – the mass, luminosity and size of a spheroidal galaxy increases more readily than its velocity dispersion when a galaxy undergoes (parabolic)\(^1\) dissipationless mergers with other spheroidal galaxies (e.g. Ciotti & van Albada 2003; Nipoti, Londrillo & Ciotti 2003; Ciotti, Lanzoni & Volonteri 2007; Naab, Johansson & Ostriker 2009). In this scenario, the supermassive black hole grows through black hole binary merger events, while the galaxy velocity dispersion remains unaffected, moving the black hole/galaxy pair upward in the \(M_{\text{BH}} - \sigma\) diagram. Using a combination of analytical and semi-analytical models, Volonteri & Ciotti (2013) show that central cluster galaxies can naturally become outliers in the \(M_{\text{BH}} - \sigma\) diagram because they experience more mergers with spheroidal systems than any other galaxy and because these mergers are preferentially gas-poor.

Here we test this interesting idea with the latest observational data. In so doing, we update the \(M_{\text{BH}} - \sigma\) diagram to include 89 galaxies now reported to have directly measured black hole masses.

2 RATIONALE

The high-end mass of the \(M_{\text{BH}} - \sigma\) diagram, where a few "overmassive" outliers have now been reported to exist, is mainly populated by core-Sérsic galaxies (Graham et al. 2003; Trujillo et al. 2004), i.e. galaxies (or bulges) with partially depleted cores relative to their outer Sérsic light profile. While these galaxies are also "core galaxies", as given by the Nuker definition (Lauer et al. 2007), it should be noted that ~20\% of "core galaxies" are not core-Sérsic galaxies (Dullo & Graham 2014, their Appendix A.2), i.e. do not have depleted cores. Such Sérsic galaxies have no central deficit of stars. It has long been hypothesized that the presence of a partially depleted core indicates that the host galaxy has experienced one or more "dry" major mergers (Begelman, Blandford & Rees 1980). During such dissipationless mergers, the progenitor supermassive black holes are expected to sink towards the centre of the remnant, form a bound pair and release their binding energy to the surrounding stars (Milosavljević & Merritt 2004; Merritt 2013b and references therein). Indeed, the latest high-resolution observations (e.g. Sillanpää et al. 1988; Komossa et al. 2003; Maness et al. 2004; Rodriguez et al. 2006; Dotti et al. 2006; Burke-Spolaor 2011; Fabbiano et al. 2011; Ju et al. 2013; Liu et al. 2014) are providing us with compelling evidence of tight black hole binary systems. The evacuation of stars takes place within the so-called "loss-cone" of the black hole binary and has the effect of lowering the galaxy’s central stellar density (e.g. Merritt 2006a, his Figure 5; Dotti, Sesana & Decarli 2012; Colpi 2014). Upon analyzing the central stellar kinematics of a sample of core galaxies, Thomas et al. (2014) concluded that the homology of the distribution of the orbits matches the predictions from black hole binary theoretical models, and argued that the small values of central rotation velocities favor a sequence of several minor mergers rather than a few equal-mass mergers. Subsequent to the dry merging events, AGN feedback likely prevents further star formation in the spheroids of the core-Sérsic galaxies (e.g. Ciotti, Ostriker & Proga 2010, and references therein). High-accuracy \(N\)-body simulations (Merritt 2006b) have shown that, after \(N\) (equivalent) major mergers, the magnitude of the stellar mass deficit \(M_{\text{def},*}\) scales as \(N\) times the final mass of the relic black hole \((M_{\text{BH},*} \approx 0.5N M_{\text{BH}})\). This result has been used to make inferences about the galaxy merger history (e.g. Graham 2004; Ferrarese et al. 2006; Hyde et al. 2008; Dullo & Graham 2014). If one assumes that the "overmassive" black holes belong to galaxies that have undergone a larger number of dry mergers compared to galaxies that obey the observed \(M_{\text{BH}} - \sigma\) correlation (McConnell & Ma 2013; Graham & Scott 2013), it is a natural expectation that these \(M_{\text{BH}} - \sigma\) outliers may also display a higher \(M_{\text{def},*}/M_{\text{BH}}\) ratio when compared to the "main-sequence" population. This argument motivates our first test.

A second test can be built by looking at the kinematics of the objects that populate the \(M_{\text{BH}} - \sigma\) diagram. A galaxy’s velocity dispersion remains unaffected only in the case of a dissipationless merger (with another spheroidal galaxy), whereas it accordingly increases after a dissipational (gas-rich) merger, preserving the \(M_{\text{BH}} - \sigma\) correlation (Volonteri & Ciotti 2013). Wet and dry mergers may produce remnants with different kinematical structures, classified as fast (disc) and slow rotators, respectively (e.g. Emsellem et al. 2008 and references therein). Therefore, an instinctive question is whether the populations of slow and fast rotators are significantly offset from each other in the \(M_{\text{BH}} - \sigma\) diagram. This will be our second test.

3 DATA

Our galaxy sample (see Table 1) consists of 89 objects for which a dynamical detection of the black hole mass and a measure of the stellar velocity dispersion have been reported in the literature. We include in our sample all the 78 objects presented in the catalog of Graham & Scott (2013), plus 10 objects taken from Rusli et al. (2013) and 1 object from Greenhill et al. (2003). Partially depleted cores have been identified according to the same criteria used by Graham & Scott (2013). When no high-resolution image analysis was available from the literature, we inferred the presence of a partially depleted core based on the stellar velocity dispersion, \(\sigma\): a galaxy is classified as core-Sérsic if \(\sigma > 270\) km s\(^{-1}\), or as Sérsic if \(\sigma \leq 166\) km s\(^{-1}\). This resulted in us assigning cores to just 6 galaxies, none of which were used in the following mass deficit analysis. We employ a 5\% uncertainty on \(\sigma\) in our regression analysis.

A kinematical classification (slow/fast rotator) is available for 34 of our 89 galaxies from the ATLAS\(^{3D}\) survey.
All galaxies are categorised as barred/unbarred objects according to the classification reported by Graham & Scott (2013), with the following updates. An isophotal analysis and unsharp masking of Spitzer/IRAC 3.6 µm images (Savorgnan et al. in preparation) has revealed the presence of a bar in the galaxies NGC 0224 (in agreement with Athanassoula & Beaton 2006; Beaton et al. 2007; Morrison et al. 2011), NGC 2974 (confirming the suggestion of Jeong et al. 2007), NGC 3031 (see also Elmegreen, Chromey & Johnson 1995; Gutiérrez et al. 2011; Erwin & Debattista 2013), NGC 3245 (see also Laurikainen et al. 2010; Gutiérrez et al. 2011), NGC 3998 (as already noted by Gutiérrez et al. 2011), NGC 4026, NGC 4388 and NGC 4736 (see also Moellenhoff, Matthias & Gerhard 1995). Although the fast rotator galaxy NGC 1316 has been frequently classified in the literature as an elliptical merger remnant, Graham & Scott (2013) identified this object as a barred lenticular galaxy. D’Onofrio (2001) found that a single-component model cannot provide a good description of the light profile of this galaxy and de Souza, Gadotti & dos Anjos (2004) fit NGC 1316 with a bulge + exponential disc model. Sani et al. (2011) adopted a three-component model, featuring a bulge, an exponential disc and a central Gaussian (attributed to non-stellar nuclear emission). Upon an analysis of the two-dimensional velocity field obtained from the kinematics of planetary nebulae, McNeil-Movlan et al. (2012) claimed that NGC 1316 represents a transition phase from a major-merger event to a bulge-dominated galaxy like the Sombrero galaxy (M104). We find evidence for the presence of a bar in NGC 1316 from an isophotal analysis and unsharp masking of its Spitzer/IRAC 3.6 µm image (Savorgnan et al. in preparation), but we exclude it for now to avoid any controversy. Central stellar mass deficits (with individual uncertainties) have been estimated for 23 core-Sérsic galaxies – with directly measured black hole masses – by Rusli et al. (2013a). Briefly, they fit the surface brightness profiles of these galaxies with a core-Sérsic model and computed the light deficit as the difference between the luminosity of the Sérsic component of the best-fitting core-Sérsic model and the luminosity of the core-Sérsic model itself. Light deficits were then converted into stellar mass deficits through dynamical, individual stellar mass-to-light ratios. Rusli et al. (2013a) used galaxy distances slightly different from those adopted in this work (see Table I), therefore we adjusted their stellar mass deficits (and uncertainties) accordingly. Among the 23 core-Sérsic galaxies whose stellar mass deficits have been computed by Rusli et al. (2013a), 10 were also analyzed by Dullo & Graham (2014) measured light deficits with a method similar to that employed by Rusli et al. (2013a), but they converted light deficits into stellar mass deficits using stellar mass-to-light ratios derived from V − I colours together with the color-age-metallicity diagram (Graham & Spitler 2009). Their stellar mass deficits are accurate to 60% (Dullo, private communication) and were rescaled according to the galaxy distances adopted here. In Figure 1, we compare these 10 common mass deficit estimates. The agreement is remarkably good, although a slight deviation from the 1:1 line can be noticed for the galaxies with the lowest or highest mass deficits, for which M_{def,*} reported by Dullo & Graham (2014) is larger or smaller than Rusli et al. (2013a), respectively. We checked and found that this effect actually depends in a random, i.e. non-systematic, way on the different choices to estimate the stellar mass-to-light ratios and/or their different galaxy data and modelling. We return to this point in the next Section. For these individual 10 galaxies we compute a weighted arithmetic mean of their two available stellar mass deficits.

3.1 Dark matter

The 10 black hole masses from Rusli et al. (2013a) – not to be confused with the different 10 galaxies with central mass deficits from Rusli et al. (2013a) that are in common with Dullo & Graham (2014) – were computed by taking into account the effects of dark matter. For these 10 galaxies, Rusli et al. (2013a) also published black hole masses estimated without the inclusion of dark matter halos. Among the 78 black hole masses reported by Graham & Scott (2013), only 8 had dark matter included in their derivation,
Table 1. Galaxy sample. *Column (1):* Galaxy names; for the 18 galaxies marked with a *, the black hole masses were estimated including in the modelling the effects of dark matter. *Column (2):* Distances. *Column (3):* Black hole masses; for the 10 measurements taken from [Rusli et al. (2013d)], we report in parenthesis also the measurements obtained without including in the modelling the effects of dark matter. *Column (4):* Stellar velocity dispersions. *Column (5):* References of black hole mass and velocity dispersion measurements reported here (G+03 = [Greene & Ho 2003], R+13 = [Rusli et al. 2013d], GS13 = [Graham & Scott 2013]). *Column (6):* Presence of a partially depleted core. The question mark is used when the classification has come from the velocity dispersion criteria mentioned in Section 3. *Column (7):* Presence of a bar. *Column (8):* Central stellar mass deficits as measured by [Dullo & Graham (2014)]. *Column (10):* Kinematical classification (fast/slow rotator).

| Galaxy         | Dist  | M	extsubscript{BH} | σ      | Ref. | Core | Bar | M	extsubscript{R+13, def} | M	extsubscript{DG13, def} | Kinematics |
|----------------|-------|---------------------|--------|------|------|-----|----------------------------|-----------------------------|------------|
|                | Mpc   | 10	extsuperscript{6} M	extsubscript{☉} | [km s	extsuperscript{-1}] |      |      |     | 10	extsuperscript{6} M	extsubscript{☉} | 10	extsuperscript{6} M	extsubscript{☉} |            |
| A1836-BCG      | 158.0 | 39±4               | 309±15 | GS13 | yes  | no  | -                          | -                           | -          |
| A3565-BCG      | 40.7  | 11±2               | 335±17 | GS13 | yes  | no  | -                          | -                           | -          |
| Circinus       | 4.0   | 0.017±0.004        | 158±8  | G+03 | no   | no  | -                          | -                           | -          |
| CygnusA        | 232.0 | 25.7±0.003         | 270±13 | GS13 | yes  | no  | -                          | -                           | -          |
| IC 1459        | 28.4  | 24.1±0.10          | 306±15 | GS13 | yes  | no  | 16±7                      | -                           | -          |
| IC 2560        | 40.7  | 0.044±0.04         | 144±7  | GS13 | yes  | no  | -                          | -                           | -          |
| M32            | 0.8   | 0.024±0.005        | 55±3   | GS13 | no   | no  | -                          | -                           | -          |
| Milky Way      | 0.008 | 0.043±0.004        | 100±5  | GS13 | no   | no  | -                          | -                           | -          |
| NGC 0224       | 0.7   | 1.4±0.9            | 170±8  | GS13 | no   | yes | -                          | -                           | -          |
| NGC 0253       | 3.5   | 0.1±0.1            | 109±5  | GS13 | no   | yes | -                          | -                           | -          |
| NGC 0524       | 23.3  | 8.3±2.7            | 253±13 | GS13 | yes  | no  | FAST                      | -                           | -          |
| NGC 0821       | 23.4  | 0.39±0.26          | 206±10 | GS13 | no   | no  | FAST                      | -                           | -          |
| NGC 1023       | 11.1  | 0.42±0.04          | 204±10 | GS13 | no   | yes | FAST                      | -                           | -          |
| NGC 1068       | 15.2  | 0.084±0.003        | 163±8  | GS13 | no   | yes | -                          | -                           | -          |
| NGC 1194       | 53.9  | 0.66±0.03          | 148±7  | GS13 | no   | no  | -                          | -                           | -          |
| NGC 1300       | 20.7  | 0.73±0.35          | 229±11 | GS13 | no   | yes | -                          | -                           | -          |
| NGC 1316       | 18.6  | 1.5±0.75           | 226±11 | GS13 | no   | yes | FAST                      | -                           | -          |
| NGC 1332       | 22.3  | 1.4±0.2            | 320±16 | GS13 | no   | no  | -                          | -                           | -          |
| NGC 1374       | 19.2  | 5.8±0.5            | 167±8  | R+13 | yes  | no  | FAST                      | -                           | -          |
| NGC 1399       | 19.4  | 4.7±0.6            | 329±16 | GS13 | yes  | no  | 324±42                    | 93±56                       | SLOW       |
| NGC 1407       | 28.1  | 45.9±14            | 276±14 | R+13 | yes  | no  | 43±9                      | (70)                        | -          |
| NGC 1550       | 51.6  | 37.4±14            | 270±13 | R+13 | yes  | no  | 109±19                    | (117)                       | -          |
| NGC 2273       | 28.5  | 0.083±0.004        | 145±7  | GS13 | no   | yes | -                          | -                           | -          |
| NGC 2549       | 12.3  | 0.14±0.02          | 144±7  | GS13 | no   | yes | FAST                      | -                           | -          |
| NGC 2778       | 22.3  | 0.18±0.09          | 162±8  | GS13 | no   | yes | FAST                      | -                           | -          |
| NGC 2960       | 81.0  | 0.117±0.005        | 166±8  | GS13 | no   | yes | -                          | -                           | -          |
| NGC 2974       | 20.9  | 1.7±0.2            | 227±11 | GS13 | no   | yes | FAST                      | -                           | -          |
| NGC 3031       | 3.8   | 0.74±0.21          | 162±8  | GS13 | no   | yes | -                          | -                           | -          |
| NGC 3079       | 20.7  | 0.024±0.024        | 60−150 | GS13 | no   | yes | -                          | -                           | -          |
| NGC 3091       | 51.3  | 36.1±2             | 297±15 | R+13 | yes  | no  | 157±34                    | (224)                       | -          |
| NGC 3115       | 9.4   | 8.8±1.0            | 252±13 | GS13 | no   | yes | -                          | -                           | -          |
| NGC 3227       | 20.3  | 0.15±0.10          | 133±7  | GS13 | no   | yes | -                          | -                           | -          |
| NGC 3245       | 20.3  | 0.10±0.06          | 210±10 | GS13 | no   | yes | FAST                      | -                           | -          |
| NGC 3368       | 10.1  | 0.073±0.015        | 126±6  | GS13 | no   | yes | -                          | -                           | -          |
| NGC 3377       | 10.9  | 0.7±0.06           | 139±7  | GS13 | no   | no  | -                          | -                           | -          |
| NGC 3379       | 10.3  | 4.1±0.1            | 209±10 | GS13 | yes  | no  | 12±1                      | 19±12                       | FAST       |
| NGC 3384       | 11.3  | 0.17±0.02          | 148±7  | GS13 | no   | yes | FAST                      | -                           | -          |
| NGC 3393       | 55.2  | 0.34±0.02          | 197±10 | GS13 | no   | yes | -                          | -                           | -          |
| NGC 3414       | 24.5  | 2.4±0.3            | 237±12 | GS13 | no   | no  | SLOW                      | -                           | -          |
| NGC 3489       | 11.7  | 0.058±0.008        | 103±7  | GS13 | no   | yes | FAST                      | -                           | -          |
| NGC 3585       | 19.5  | 3.1±1.4            | 296±10 | GS13 | no   | no  | -                          | -                           | -          |
| NGC 3607       | 22.2  | 1.3±0.5            | 224±11 | GS13 | no   | yes | FAST                      | -                           | -          |
| NGC 3608       | 22.3  | 2.1±0.1            | 190±10 | GS13 | yes  | no  | 1.0±0.1                   | 3±2                         | SLOW       |
| NGC 3842       | 98.4  | 97.3±30            | 270±13 | GS13 | yes  | no  | 80±15                     | 104±63                      | -          |
and no dark matter halo was included by Greenhill et al. (2003) in their black hole mass estimate. The majority of the 23 stellar mass deficits from Rusli et al. (2013a) were derived from their analysis which incorporated dark matter to obtain the central mass-to-light ratios. However, Rusli et al. (2013a) did not publish the corresponding stellar mass deficits for the no-dark-matter case. Therefore,

4 Stellar mass deficits for IC 1459, NGC 3379, NGC 4374 and NGC 4261 were estimated by Rusli et al. (2013a) with single-component dynamical modelling, i.e. without dark matter.

and the sample of 89 galaxies that we use in our analysis contains 18 black hole masses estimated with the inclusion of a dark matter halo and the 23 stellar mass deficits published by Rusli et al. (2013a). We have already shown in Section 3 that the stellar mass deficits measured by Dullo & Graham (2014), without accounting for dark matter, are in good agreement with the Rusli et al. (2013a) estimates which accounted for dark matter. The slight disagreement observed for the lowest and highest mass deficits (see Figure 1) does not significantly affect the conclusions of our analysis. However, one could wonder whether our results change when using exclusively

| Galaxy       | Dist Mpc | MBH [10^8 M☉] | σ [km s⁻¹] | Ref. | Core | Bar | MR+13 [10^8 M☉] | MGD13 [10^8 M☉] | Kinematics |
|--------------|----------|---------------|------------|------|------|----|----------------|----------------|------------|
| NGC 3998     | 13.7     | 8.1±2        | 365±15     | GS13 | no   | yes| FAST          |                |
| NGC 4026     | 13.2     | 1.8±0.3      | 178±19     | GS13 | no   | yes| FAST          |                |
| NGC 4151     | 20.0     | 0.6±0.07     | 150±14     | GS13 | no   | yes| -             |                |
| NGC 4258     | 7.2      | 0.39±0.01    | 134±7     | GS13 | no   | yes| -             |                |
| NGC 4261     | 30.8     | 2.8±0.004    | 309±15     | GS13 | yes  | no | SLOW | 89±15       |
| NGC 4291     | 25.5     | 3.3±0.9      | 285±14     | GS13 | yes  | no | SLOW | 11±2        |
| NGC 4342     | 23.0     | 4.5±1.5      | 253±13     | GS13 | yes  | no | FAST | 6±4         |
| NGC 4374     | 17.9     | 9.0±0.8      | 290±15     | GS13 | yes  | no | SLOW | 66±11        |
| NGC 4388     | 17.0     | 0.07±0.002   | 107±5      | GS13 | no   | yes| -             |                |
| NGC 4459     | 15.7     | 0.68±0.13    | 178±9      | GS13 | no   | yes| FAST          |                |
| NGC 4472     | 17.1     | 2.5±3 (17)   | 300±15     | R+13 | yes  | no | SLOW | 37±6 (55)   |
| NGC 4473     | 15.3     | 1.2±0.9      | 179±9      | GS13 | no   | yes| FAST          |                |
| NGC 4486     | 15.6     | 58.0±3.5     | 334±17     | GS13 | yes  | no | SLOW | 612±121      |
| NGC 4486a    | 17.0     | 0.1±0.08     | 110±2      | GS13 | no   | yes| -             |                |
| NGC 4552     | 14.9     | 4.7±0.5      | 252±13     | GS13 | yes  | no | SLOW | 3±0         |
| NGC 4554     | 14.6     | 0.60±0.09    | 157±8      | GS13 | no   | yes| FAST          |                |
| NGC 4592     | 9.5      | 6.4±0.1     | 297±15     | GS13 | yes  | no | -             |                |
| NGC 4596     | 17.0     | 0.79±0.33    | 149±12     | GS13 | no   | yes| FAST          |                |
| NGC 4621     | 17.8     | 3.9±0.4      | 225±11     | GS13 | no   | yes| FAST          |                |
| NGC 4649     | 16.4     | 4.7±10       | 335±10     | GS13 | yes  | no | SLOW | 105±16       |
| NGC 4697     | 11.4     | 1.8±0.1      | 171±9      | GS13 | no   | yes| FAST          |                |
| NGC 4736     | 4.4      | 0.06±0.1     | 104±5      | GS13 | no   | yes| -             |                |
| NGC 4751     | 26.3     | 14±1 (14)    | 355±18     | R+13 | yes  | no | -             |                |
| NGC 4826     | 7.3      | 0.016±0.004  | 91±5       | GS13 | no   | yes| -             |                |
| NGC 4889     | 103.2    | 210±160      | 347±17     | GS13 | yes  | no | SLOW | 597±176      |
| NGC 4945     | 3.8      | 0.014±0.007  | 91±5       | GS13 | no   | yes| -             |                |
| NGC 5077     | 41.2     | 7.4±4.7      | 255±13     | GS13 | yes  | no | -             |                |
| NGC 5128     | 3.8      | 0.45±0.15    | 120±18     | GS13 | no   | yes| -             |                |
| NGC 5328     | 64.1     | 42.9          | 333±15     | R+13 | yes  | no | SLOW | 270±41 (557) |
| NGC 5516     | 58.4     | 33±2 (32)    | 328±16     | R+13 | yes  | no | SLOW | 135±31 (145) |
| NGC 5576     | 24.8     | 1.6±0.4      | 171±9      | GS13 | no   | yes| SLOW          |                |
| NGC 5813     | 31.3     | 6.8±0.7      | 239±12     | GS13 | yes  | no | SLOW | 6±1        |
| NGC 5845     | 25.2     | 2.6±1.5      | 238±12     | GS13 | yes  | no | FAST          |                |
| NGC 5846     | 24.2     | 11±1        | 237±12     | GS13 | yes  | no | SLOW | 23±3        |
| NGC 6086     | 138.0    | 37±13        | 318±16     | GS13 | yes  | no | SLOW | 76±18        |
| NGC 6251     | 104.6    | 5.9±2.0      | 311±16     | GS13 | yes  | no | -             |                |
| NGC 6264     | 146.3    | 0.305±0.004  | 159±8      | GS13 | no   | no | -             |                |
| NGC 6323     | 112.4    | 0.100±0.001  | 159±8      | GS13 | no   | yes| -             |                |
| NGC 6801     | 27.3     | 20.7±2.2     | 389±19     | GS13 | yes  | no | -             |                |
| NGC 7052     | 66.4     | 3.7±1.3      | 277±14     | GS13 | yes  | no | -             |                |
| NGC 7582     | 22.0     | 0.55±0.19    | 156±8      | GS13 | no   | yes| -             |                |
| NGC 7619     | 51.5     | 25±3 (4.2)   | 292±15     | R+13 | yes  | no | SLOW | 134±28 (232) |
| NGC 7768     | 112.8    | 13±5         | 257±13     | GS13 | yes  | no | SLOW | 25±5         |
| UGC 3789     | 48.4     | 0.108±0.005  | 107±3      | GS13 | no   | yes| -             |                |
black hole masses and stellar mass deficits derived without the inclusion of dark matter. To address this question, we derived the no-dark-matter stellar mass deficits for 7 of the 10 galaxies whose black hole masses were measured by Rusli et al. (2013b). We repeated the analysis by (i) employing for these 7 galaxies the no-dark-matter black hole masses (published by Rusli et al. 2013b) and the no-dark-matter stellar mass deficits (derived by us), and (ii) excluding the remaining black hole mass estimates with the inclusion of dark matter. We found that none of our conclusions was affected by this change.

4 RESULTS

In Figure 2 we show the updated $M_{BH} - \sigma$ diagram for the 89 galaxies listed in Table 1. Core-Sérsic galaxies are colour coded according to their $M_{def,*/M_{BH}}$ ratio. If no $M_{def,*}$ estimate is available, they appear as open circles. Unbarred Sérsic galaxies are represented with (small) black dots and barred Sérsic galaxies with starred symbols. Errors bars are reported only for unbarred galaxies used to derive Equation 1. The black solid line shows the OLS($\sigma$/$M_{BH}$) linear regression for all non-barred galaxies and the black dashed lines mark the associated total rms scatter ($\Delta = 0.53$) in the log($M_{BH}$) direction.

Figure 2. $M_{BH} - \sigma$ diagram for the 89 galaxies presented in Table 1. Core-Sérsic galaxies are colour coded according to their $M_{def,*/M_{BH}}$ ratio. If no $M_{def,*}$ estimate is available, they appear as open circles. Unbarred Sérsic galaxies are represented with (small) black dots and barred Sérsic galaxies with starred symbols. Errors bars are reported only for unbarred galaxies used to derive Equation 1. The black solid line shows the OLS($\sigma$/$M_{BH}$) linear regression for all non-barred galaxies and the black dashed lines mark the associated total rms scatter ($\Delta = 0.53$) in the log($M_{BH}$) direction.

Figure 3. Vertical offset from the $M_{BH} - \sigma$ relation versus the $M_{def,*/M_{BH}}$ ratio. Symbols are colour coded according to Figure 2. The vertical error bars represent the uncertainty on $M_{BH}$. The horizontal solid line is equivalent to a zero vertical offset from the expected mass ($M_{BH,exp}$) and the horizontal dashed lines show the total rms scatter ($\Delta = 0.53$) of the OLS($\sigma$/$M_{BH}$) linear regression in the log($M_{BH}$) direction.

The no-dark-matter stellar mass deficits were calculated as $M_{def,DM} = M_{def,*} - (M/L)^{DM} - 1 - (M/L)^{obs,DM}$, where $M_{def,DM}$ are the mass deficits from Rusli et al. (2013a) which had dark matter incorporated in their derivation, and $(M/L)^{DM}$ and $(M/L)^{obs,DM}$ are the mass-to-light ratios from Rusli et al. (2013a) estimated with and without accounting for dark matter respectively.

The 10 empty symbols refer to 6 suspected, plus 4 apparent core-Sérsic galaxies.

Although we have used the black hole mass for NGC 1399 from Gebhardt et al. (2003), we note that Houghton et al. (2006) had reported a value twice as large ($\sim 10^9 \ M_\odot$). Nevertheless, this is still too low to yield a positive offset for this galaxy in Figure 2.
core density (Redmount & Rees 1989; Merritt et al. 2004; Boylan-Kolchin, Ma & Quataert 2004). Kick-induced partially depleted cores can be as large as \(M_{\text{det,s}} \sim (4 - 5)M_{\text{BH}}\) (Gualandris & Merritt 2008) and could complicate the use of central mass deficits as a tracer of dry galaxy mergers. However, they don’t explain the low \(M_{\text{det,s}}/M_{\text{BH}}\) ratios observed in the “overmassive” black hole sample.

In Figure 3 we plot the vertical offset from the \(M_{\text{BH}} - \sigma\) relation versus the \(M_{\text{det,s}}/M_{\text{BH}}\) ratio. The vertical offset is defined as \(\log(M_{\text{BH,obs}}/M_{\text{BH,exp}})\), where \(M_{\text{BH,obs}}\) is the observed black hole mass and \(M_{\text{BH,exp}}\) is the black hole mass expected from the galaxy velocity dispersion using an OLS(\(\sigma|M_{\text{BH}}\)) linear regression\(^8\) for all non-barred\(^9\) galaxies:

\[
\log\left(\frac{M_{\text{BH,exp}}}{M_\odot}\right) = (8.24 \pm 0.10) + (6.34 \pm 0.80) \times \log\left(\frac{\sigma}{200 \text{ km s}^{-1}}\right). \tag{1}
\]

Clearly, there is no positive trend in Figure 3. The significance of a correlation is rejected by a Spearman’s test (Spearman’s correlation coefficient \(r_s = -0.33\), likelihood of the correlation occurring by chance \(P > 5\%\)). We conclude that no positive correlation is observed between the vertical offset from the \(M_{\text{BH}} - \sigma\) relation and the \(M_{\text{det,s}}/M_{\text{BH}}\) ratio. Repeating the analysis using only the [Rusli et al. (2013a)](https://doi.org/10.1093/mnras/stt696) mass deficits, i.e. without computing 10 weighted arithmetic means for the galaxies in common with [Dullo & Graham (2014)](https://doi.org/10.1093/mnras/stu1431), gives the same conclusion. Similarly, the same conclusion is reached when using only the [Dullo & Graham (2014)](https://doi.org/10.1093/mnras/stu1431) derived mass deficits.

In Figure 4 we show the distribution of fast and slow rotators in the \(M_{\text{BH}} - \sigma\) diagram. Our aim is to check whether the two populations are vertically offset from each other, in the sense that wet mergers can create fast rotating discs, while dry mergers can increase the black hole mass but not the velocity dispersion. Since the work of [Graham (2008)](https://doi.org/10.1086/532615), we know that barred galaxies tend to be offset rightward from the \(M_{\text{BH}} - \sigma\) correlation defined by non-barred galaxies. It is therefore crucial to exclude the barred galaxies from the following analysis.

To avoid biasing the results, we use the BCES code from [Akritas & Bershady (1996)](https://doi.org/10.1086/150082) to obtain four different linear regressions for both the (unbarred) fast and slow rotators. The results are shown in the first part of Table 2. Regardless of the linear regression method used, the best-fit slopes and intercepts of fast and slow rotators are consistent with each other within the 1\(\sigma\) uncertainty. To test the robustness of our results, we repeated the linear regression analysis excluding the most deviating data points: one fast rotator with a positive vertical offset (NGC 1374) and two slow rotators with a negative vertical offset (NGC 1399 and NGC 4261). The second part of Table 2 reports the new values of the best-fit slopes and intercepts, which remain consistent with each other.

### Table 2. Linear regression analysis for the populations of unbarred fast and slow rotators.

| Regression | \(\text{Slow rot.}\) | \(\text{Fast rot.}\) |
|-----------|-----------------|-----------------|
| \(\log(M_{\text{BH}}/M_\odot) = \alpha + \beta \log(\sigma/(200 \text{ km s}^{-1})\\) | \(\beta\) | \(\alpha\) | \(\beta\) | \(\alpha\) |
| OLS(\(M_{\text{BH}}\)) | 3.7 \pm 1.1 | 8.40 \pm 0.08 | 4.4 \pm 0.6 | 8.33 \pm 0.09 |
| OLS(\(\sigma|M_{\text{BH}}\)) | 6.8 \pm 1.7 | 8.1 \pm 0.3 | 5.9 \pm 1.0 | 8.3 \pm 0.1 |
| Bisector | 4.8 \pm 1.0 | 8.3 \pm 0.1 | 5.1 \pm 0.5 | 8.33 \pm 0.09 |
| Orthogonal | 6.7 \pm 1.6 | 8.1 \pm 0.3 | 5.8 \pm 1.0 | 8.3 \pm 0.1 |

| Excluding NGC 1374, NGC 1399 and NGC 4261. | \(\beta\) | \(\alpha\) | \(\beta\) | \(\alpha\) |
| OLS(\(M_{\text{BH}}\)) | 5.3 \pm 0.8 | 8.36 \pm 0.09 | 4.7 \pm 0.6 | 8.27 \pm 0.08 |
| OLS(\(\sigma|M_{\text{BH}}\)) | 6.2 \pm 0.9 | 8.3 \pm 0.1 | 5.4 \pm 0.8 | 8.28 \pm 0.08 |
| Bisector | 5.7 \pm 0.8 | 8.3 \pm 0.1 | 5.0 \pm 0.6 | 8.27 \pm 0.08 |
| Orthogonal | 6.1 \pm 0.9 | 8.3 \pm 0.1 | 5.4 \pm 0.8 | 8.28 \pm 0.08 |

5 DISCUSSION AND CONCLUSIONS

The presence of a central, supermassive black hole, coupled with the scarcity of binary supermassive black hole systems, suggests that the progenitor black holes have coalesced in most merged galaxies. They can do this by transferring their orbital angular momentum to the stars near the centre of their host galaxy and thereby evacuating the core. If a galaxy’s \(M_{\text{det,s}}/M_{\text{BH}}\) ratio is a proxy...
for its equivalent number of major dry merger events since its last wet merger (e.g., Merritt (2006a)), then our analysis (see Figures 2 and 3) reveals that the apparent “overmassive” outliers at the high-mass end of the $M_{BH} - \sigma$ diagram are galaxies that have undergone the lowest degree of such recent dry merging. Although a final major wet merger may contribute to their low $M_{BH} / \sigma$ ratio, these galaxies are among the most massive early-type galaxies in the local Universe and they reside in the central regions of galaxy clusters, where wet major mergers are unlikely to occur (e.g., Fraser-McKelvie, Brown & Pimbblet 2014) due to prior ram pressure stripping of gas from infalling galaxies (Boselli & Gavazzi 2006; Haines et al. 2013; Boselli et al. 2014a). That is, the “overmassive” black holes in central cluster galaxies cannot be explained by a large number of dissipationless mergers growing the black hole mass at a fixed galaxy velocity dispersion.

In addition to this, no significant offset is observed between the (unbarred) populations of fast and slow rotators in the $M_{BH} - \sigma$ diagram (see Table 2), contrary to what is expected if fast and slow rotators are, in general, the products of wet and dry mergers respectively. This is because dry mergers will increase the black hole mass, but are said not to increase the velocity dispersion. This result is also in broad agreement with the observation that the (unbarred) Sérsic and core-Sérsic galaxies follow the same $M_{BH} - \sigma$ relation (Graham & Scott 2013). Our results appear consistent with studies of luminous elliptical galaxies which have shown that the galaxy luminosity scales with the velocity dispersion (Schechter 1980; Malumuth & Kirshner 1981; von der Linden et al. 2007; Bernardi et al. 2007; Li et al. 2008), i.e., the velocity dispersion appears not to completely saturate but rather still increases with increasing galaxy luminosity, contrary to what one would predict if these galaxies were built only by dry mergers on parabolic orbits.

An alternative possibility for the central cluster galaxies may be that they experience minor dry merger events that do not bring in a massive black hole but rather stars, and nuclear star clusters, which may partly or fully refill a depleted galaxy core. However, simulations are needed to verify whether, in a ΛCDM cosmology, the extent of minor dry merging experienced by a central cluster galaxy in late cosmic times can supply enough stellar mass ($\sim 10^9 - 10^{10} M_\odot$) to replenish the galaxy’s core.

Eventually, one should also consider the possibility that some of the overmassive black holes might have had their masses overestimated. Past studies have demonstrated the importance of resolving the black hole sphere-of-influence when measuring a black hole mass, to avoid systematic errors or even spurious detections (e.g., Ferrarese & Merritt 2000; Merritt & Ferrarese 2001; Valluri, Merritt & Emsellem 2004; Ferrarese & Ford 2005). Merritt (2013a) cautions against the use of black hole mass measurements obtained from stellar-dynamical data sets. His Figure 2.5 points out that no more than three galaxies — all belonging to the Local Group — have been observed with enough spatial resolution to exhibit a prima facie convincing Keplerian rise in their central stellar velocities. At the same time, gas kinematics can have motions not solely due to the gravitational potential of the black hole. For example, Mazzalav et al. (2014) showed that the gas dynamics in the innermost parsecs of spiral galaxies is typically far from simple circular motion. One possible example of such an overestimated black hole may be that reported by van den Bosch et al. (2012) for the galaxy NGC 1277 ($M_{BH} = 1.7 \times 10^{7} M_\odot$). In fact, upon re-analyzing the same data, Emsell et al. (2013) showed that a model with a 2 times smaller black hole mass provides an equally good fit to the observed kinematics, and emphasized the need for higher spatial resolution spectroscopic data.

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10 The sphere-of-influence is the region of space within which the gravitational potential of the black hole dominates over that of the surrounding stars.
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