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The growth of supermassive black holes in pseudo-bulges, classical bulges and elliptical galaxies

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ABSTRACT
Using results from structural analysis of a sample of nearly 1000 local galaxies from the Sloan Digital Sky Survey, we estimate how the mass in central black holes is distributed amongst elliptical galaxies, classical bulges and pseudo-bulges, and investigate the relation between their stellar masses and central stellar velocity dispersion σ. Assuming a single relation between elliptical galaxy/bulge mass, $M_{\rm Bulge}$, and central black hole mass, $M_{\rm BH}$, we find that 55 per cent of the mass in black holes in the local universe is in the centres of elliptical galaxies, 41 per cent in classical bulges and 4 per cent in pseudo-bulges. We find that ellipticals, classical bulges and pseudo-bulges follow different relations between their stellar masses and σ, and the most significant offset occurs for pseudo-bulges in barred galaxies. This structural dissimilarity leads to discrepant black hole masses if single $M_{\rm BH} - M_{\rm Bulge}$ and $M_{\rm BH} - \sigma$ relations are used. Adopting relations from the literature, we find that the $M_{\rm BH} - \sigma$ relation yields an estimate of the total mass density in black holes that is 70 per cent larger than if the $M_{\rm BH} - M_{\rm Bulge}$ relation is used.

Key words: galaxies: bulges – galaxies: evolution – galaxies: formation – galaxies: fundamental parameters – galaxies: kinematics and dynamics – galaxies: photometry

1 INTRODUCTION

In the past 10 years or so, there has been mounting evidence that massive galaxies host supermassive black holes in their centres, and that the mass of the black hole correlates with other galaxy properties, particularly stellar mass (or bulge stellar mass in the case of disc galaxies) and central velocity dispersion (see e.g. Magorrian et al. 1998; Gebhardt et al. 2000, and references therein). Such relations are being discussed and revised, with several important details being disclosed (Tremaine et al. 2002; Häring & Rix 2004; Ferrarese & Ford 2005; Lauer et al. 2007b; Graham & Driver 2007; Tundo et al. 2007), and a consensus emerges that they reveal a connected growth of black holes and their host galaxies or bulges, e.g. via mechanisms of feedback (e.g. Wyithe & Loeb 2003; Di Matteo et al. 2005; Younger et al. 2008). With growing evidence that galaxy bulges are not a single, homogeneous class, but in fact comprise classical bulges and pseudo-bulges, with different formation histories (see e.g. Gadotti 2008, and references therein – hereafter Paper I), a new ingredient is added to this investigation. Do black holes in elliptical galaxies, classical bulges and pseudo-bulges follow similar relations between their masses and host galaxy/bulge mass or velocity dispersion? Hu (2008) suggests that the relation between black hole mass $M_{\rm BH}$ and velocity dispersion σ is different for classical bulges (including there elliptical galaxies) and pseudo-bulges.

To address this issue, one would ideally have secure, direct measurements of $M_{\rm BH}$ for a statistically significant sample of galaxies, which is currently not available. In this Letter, we approach the question by using measurements of the stellar mass in elliptical galaxies and bulges, obtained in Paper I, for a sample of nearly 1000 systems from the Sloan Digital Sky Survey (SDSS). We combine these results with σ measurements from SDSS, and investigate how the stellar mass of the bulge relates to σ in ellipticals, classical bulges and pseudo-bulges. By assuming that we can infer $M_{\rm BH}$ from bulge stellar masses using a single relation, we indirectly assess the $M_{\rm BH} - \sigma$ relation for these systems.

In the next section, we briefly recall how the bulge stellar mass measurements were done, as well as how ellipticals, classical bulges and pseudo-bulges were defined, and address our use of SDSS σ measurements. In Sect. 3, we show the results, which are discussed in Sect. 4.

2 DATA

In Paper I, we have performed careful and detailed image fitting of the galaxies in the sample in the g, r and i bands, in-

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cluding up to three components in the models, namely bulge, disc and bar. This allowed a reliable determination of the bulge luminosity. The presence of these components was assessed by individual inspection of images, surface brightness profiles and isophotal maps. A galaxy is defined as elliptical if it does not show any signature of a disc, in which case it was fitted with a single "bulge" component. Classical bulges and pseudo-bulges are separated using the Kormendy (1977) relation, where pseudo-bulges can be identified as outliers in an objective fashion.

Since we have done multi-band decompositions, we were able to estimate the $g-i$ integrated colour of each component separately. Using the relation between $g-i$ and the stellar mass-to-light ratio in the i-band from Kauffmann et al. (2007), we have all parameters necessary to accurately calculate the stellar masses of the ellipticals and bulges in the sample.

It should also be noted that the sample analysed was drawn from a volume-limited sample of galaxies at redshifts $0.02 \leqslant z \leqslant 0.07$, and stellar masses larger than 10^{10} M$_\odot$, and it was found to be representative of the local population of massive galaxies. In order to produce reliable decompositions, and avoid dust and projection effects, the final sample contains only galaxies close to face-on, i.e. with an axial ratio $b/a \geqslant 0.9$, where a and b are, respectively, the semi-major and semi-minor axes of the galaxy at the 25 g-band mag arcsec^{-2} isophote. We have found that this introduces a selection effect, in the sense that the probability of selecting an elliptical galaxy is a factor of 1.3 larger than that of selecting a disc galaxy. The reader is referred to Paper I for a detailed account of the sample selection and image decomposition.

We have used σ measurements from SDSS Data Release 6 (DR6), since estimates from previous releases can be overestimated in the case of low mass galaxies (see discussion in Paper I, Sect. 4.4). Since the spectral resolution of SDSS spectra is limited, one should avoid spectra with signal-to-noise ratio below 10, or with warning flags. In the sample, only one galaxy does not comply with the former criterion, and only 8 do not comply with the latter. The pseudo-bulges in our sample have relatively low σ values, close to the SDSS instrumental resolution (70 km/s). In fact, 24 of the 61 pseudo-bulges for which σ is measured have σ below 70 km/s. We decided to keep these measurements for reasons which will be clear below. However, they should be considered as upper limits. We applied aperture corrections to the SDSS measurements, using the prescription by Jorgensen et al. (1995), obtaining σ at 1/8 of the bulge effective radius σ_8. This prescription is based on measurements for bulge-dominated galaxies, and it is unclear if it is also valid for disc-dominated galaxies. As we will discuss below, the corrections applied are small, and do not affect our results significantly.

3 RESULTS

If the ellipticals and bulges in our sample host supermassive black holes in their centres, then we can estimate the black hole masses, using the relation between elliptical galaxy/bulge mass and black hole mass from Häring & Rix (2004, a significant update of the results in Magorrian et al. 1998) and our elliptical galaxy/bulge mass measurements. Furthermore, we can also see how the mass in black holes is distributed amongst the different galaxies. We have done these calculations and find that 55 per cent of the mass in supermassive black holes in the local universe is in the centres of elliptical galaxies, 41 per cent in classical bulges and 4 per cent in pseudo-bulges, after accounting for the selection effect introduced by the axial ratio cut, discussed in detail in Paper I (see also Sect. 2). The uncertainty in these fractions from Poisson statistics only is between 1 and 2 percentage points.

We note that there is no particular reason why black hole masses obtained using a relation between bulge mass, $M_{\rm Bulge}$, and black hole mass are more correct than those obtained through an $M_{\rm BH}-\sigma$ relation. We could have used as well an $M_{\rm BH}-\sigma$ relation from the literature to obtain black hole masses. We have used the Häring & Rix (2004) $M_{\rm BH}-M_{\rm Bulge}$ relation to obtain black hole masses for all galaxies simply because we do not have measurements of σ for all our galaxies, and thus this does not imply that the $M_{\rm BH}-M_{\rm Bulge}$ relation is to be preferred over the $M_{\rm BH}-\sigma$ relation. The consequences of this choice are discussed below when necessary.

Using the σ_8 values, we can also check how bulge mass and black hole mass relate to velocity dispersion in ellipticals, classical bulges and pseudo-bulges. This is done in Fig. 1. One sees that elliptical galaxies follow a well-defined relation between their stellar masses and σ_8, as expected from the Faber & Jackson (1976) relation. Classical bulges deviate slightly from this relation and follow a somewhat offset line, with lower masses for the same velocity dispersion. The fits to the data shown in the left panels of Fig. 1 were obtained by minimising χ^2 as in Eq. (3) of Tremaine et al. (2002), i.e. weighting every point by the inverse of its measurement uncertainties, except that only uncertainties in σ_8 were considered, since those in bulge mass are not available. Nevertheless, we have verified that there is no substantial change in the fits obtained if no weighting is included. Pseudo-bulges tend to fall far off the ellipticals' relation, being on average much less massive than one would expect from this relation. Note also that one cannot see a *clear* relation between bulge mass and σ_8 for pseudo-bulges alone. These results might be not too surprising, considering that structural differences between pseudo-bulges, classical bulges and ellipticals are found in Paper I. These differences can have consequences on the $M_{\rm BH}-\sigma$ relation, since black hole mass is correlated with bulge mass. This is explicitly shown in the right panels of Fig. 1. The $M_{\rm BH}-\sigma$ relation we find for ellipticals is generally well described by relations found with real black hole mass measurements (Gebhardt et al. 2000; Tremaine et al. 2002; Ferrarese & Ford 2005; Hu 2008), although our ellipticals seem to follow a somewhat shallower relation. Evidently, black holes in classical bulges follow a slightly offset line, while those in pseudo-bulges are, on average, significantly detached from the ellipticals' $M_{\rm BH}-\sigma$ relation.

Despite the small σ aperture corrections, it is legitimate to be concerned about the fact that the extrapolation from σ to σ_8 is relatively more significant to pseudo-bulges than to classical bulges and ellipticals. In fact, the mean relative difference $(\sigma_8-\sigma)/\sigma$ is 12 per cent for pseudo-bulges, 9 per cent for classical bulges and 5 per cent for ellipticals. However, since these corrections follow a power law, the results

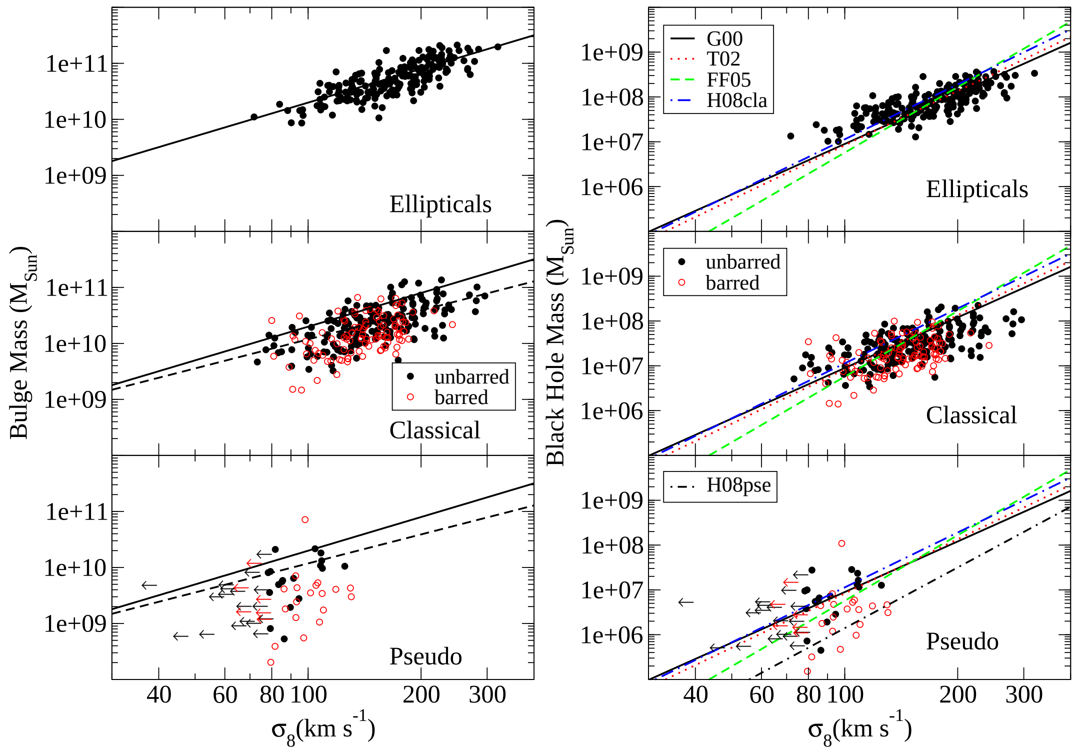

Figure 1. Left: bulge mass plotted against velocity dispersion for elliptical galaxies, classical bulges and pseudo-bulges, as indicated. The solid line is a fit to the ellipticals, while the dashed line is a fit to the classical bulges. Right: black hole mass [obtained from the $M_{\rm BH} - M_{\rm Bulge}$ relation in Häring & Rix (2004)] against velocity dispersion. The lines are relations obtained from the literature. Arrows indicate those galaxies with velocity dispersion measurements below 70 km/s. Their σ_8 values should be considered as upper limits. [G00: Gebhardt et al. (2000); T02: Tremaine et al. (2002); FF05: Ferrarese & Ford (2005); H08cla: Hu (2008, classical bulges); H08pse: Hu (2008, pseudo-bulges).]

in Fig. 1 do not depend on whether the corrections applied correspond to σ at 1/8 of the bulge effective radius or at any other fraction of it, as the difference in such corrections produces only a constant shift. For instance, we have verified that exactly the same offsets are seen if we use σ at the effective radius, which involves even smaller corrections, instead of σ_8. Furthermore, these results are essentially unchanged even if no aperture correction is applied.

These findings thus indicate that ellipticals, classical bulges and pseudo-bulges can not follow a single $M_{\rm BH} - M_{\rm Bulge}$ relation *and* a single $M_{\rm BH} - \sigma$ relation. This conclusion follows directly from the fact that these systems have different $M_{\rm Bulge} - \sigma$ relations. Therefore, it does not depend on whether the Häring & Rix (2004) relation we use here correctly predicts black hole masses. In order to precisely determine such relations, with direct black hole mass measurements, one should thus look carefully at the different stellar systems for which such measurements are available. These differences could partially account for the discordant relations found in the literature (see in particular discussion in Tremaine et al. 2002).

Figure 1 shows that barred galaxies, particularly with pseudo-bulges, have bulges with lower masses, at fixed velocity dispersion, on average, than their unbarred counterparts. This is in agreement with the results from the fundamental plane in Paper I (see Fig. 16). Indeed, the offset from the $M_{\rm Bulge} - \sigma$ relation for pseudo-bulges is caused mostly by barred galaxies. Furthermore, the $M_{\rm BH} - \sigma$ relation found by Hu (2008) for pseudo-bulges originates *almost exclusively* from barred galaxies. In fact, one sees in the bottom right panel of Fig. 1 that his relation describes reasonably well the pseudo-bulges in barred galaxies in our sample. This also agrees with the results in Graham (2008). It is thus interesting to confirm with higher resolution data whether the deviation of pseudo-bulges from the $M_{\rm Bulge} - \sigma$ and $M_{\rm BH} - \sigma$ relations occurs regardless of its host galaxy being barred or unbarred, or if the presence of a bar is a necessary condition, as our results suggest.

It thus seems that studies on black hole demographics (e.g. Yu & Tremaine 2002; Wyithe & Loeb 2003; Marconi et al. 2004; Shankar et al. 2004; Benson et al. 2007) might have different results depending on whether black hole masses are obtained using an $M_{\rm BH} - \sigma$ relation or an $M_{\rm BH} - M_{\rm Bulge}$ relation. This comes not only from the possibility of different relations for ellipticals and bulges, but also from the fact that we find a flatter relation between M_{BH} and σ, using the Häring & Rix (2004) $M_{\rm BH} - M_{\rm Bulge}$ relation, than published $M_{\rm BH} - \sigma$ relations. This could affect both the total black hole mass density and the black hole mass distribution. To quantitatively assess how strong such effects can be, we have recalculated the black hole masses of the galaxies in our sample using the $M_{\rm BH} - \sigma$ relation in Tremaine et al. (2002). The total black hole mass density using this $M_{\rm BH} - \sigma$ relation is 70 per cent[1] higher than that

[1] To make this assessment, we use the velocity dispersion mea-

using the Häring & Rix (2004) $M_{\rm BH} - M_{\rm Bulge}$ relation. Interestingly, this is mostly a result from the different $M_{\rm BH}$ estimates in classical bulges. Although black hole masses in pseudo-bulges are by far more severely discrepant, their contribution to the overall difference in the total black hole mass is small, due to their small masses, and the fact that the scatter around the $M_{\rm BH} - \sigma$ relation in our sample (see Fig. 1) roughly cancels this effect out. Such scatter also contributes to reduce the total black hole mass discrepancy in the case of classical bulges and ellipticals.

In Fig. 2, we explore how the black hole mass distribution varies according to the relation used to obtain $M_{\rm BH}$. The top panel shows explicitly that the difference between the two estimates is on average negligible at higher masses, increases towards lower masses, and is typically a factor of a few. The bottom panel shows the corresponding black hole mass distributions. Also shown are fits to the data, using the same fitting function as in Shankar et al. (2004). Uncertainties were calculated as $\sqrt{N}$ (where N is the number of measurements in each bin) and used to weight each data point when determining the fits. As expected, the distribution obtained using the Tremaine et al. (2002) $M_{\rm BH} - \sigma$ relation is different from that obtained via the Häring & Rix (2004) $M_{\rm BH} - M_{\rm Bulge}$ relation. The former peaks at a higher mass, by $\approx 0.1 - 0.2$ dex, and indicates a larger number of black holes at the high mass end (see also Lauer et al. 2007a).

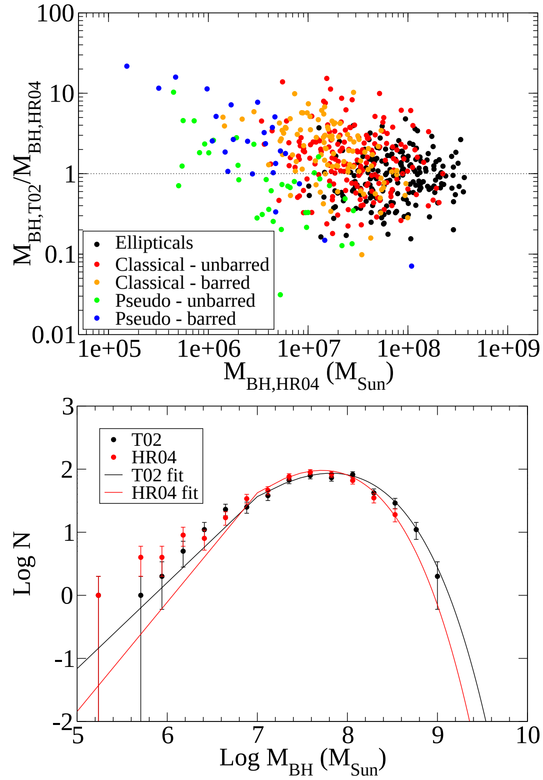

Figure 2. Top: ratio between $M_{\rm BH}$ from the $M_{\rm BH} - \sigma$ relation in Tremaine et al. (2002) and $M_{\rm BH}$ from the $M_{\rm BH} - M_{\rm Bulge}$ relation in Häring & Rix (2004) plotted against the latter. Bottom: distributions of $M_{\rm BH}$ from the two relations, as indicated. Error bars are $\sqrt{N}$.

4 DISCUSSION

4.1 Comparison with previous work

Using published distribution functions of the velocity dispersion in early and late-type galaxies (from Sheth et al. 2003), and the Tremaine et al. (2002) $M_{\rm BH} - \sigma$ relation, Shankar et al. (2004, see also Marconi et al. 2004) found that 29 per cent of the mass in black holes is in late-type galaxies. The separation between early and late-type galaxies was done as in Bernardi et al. (2003), i.e. mainly with a cut in the concentration index $R90/R50$ at 2.5. Graham et al. (2007) used the $M_{\rm BH} - n$ relation (where n is the bulge Sérsic index), and luminosity distribution functions for red and blue spheroids (from Driver et al. 2007), and found a corresponding fraction of 22 per cent. To directly compare these results with ours is difficult due to the fact that early-type (or red) galaxies in such studies should include not only ellipticals but also a substantial fraction of galaxies with classical bulges, and some pseudo-bulges as well. While 99 per cent of our ellipticals have $R90/R50 > 2.5$, this is also the case for 76 per cent of our galaxies with classical bulges, and 8 per cent of our galaxies with pseudo-bulges. Bernardi et al. (2003) also used other criteria to separate early-type galaxies, but it is unlikely that these criteria excluded most disc galaxies. Thus, the fact that we find that 45 per cent of the mass in black holes is in bulges, a higher fraction than the previous estimates for late-type galaxies, is naturally expected. However, we can assume that the "early-type galaxy" bin in these previous studies includes the same fractions of elliptical galaxies and galaxies with classical and pseudo-bulges as those we find in our sample using the same threshold in concentration. Since this is the main morphological criterion applied to define the samples used by Sheth et al. (2003), it should allow a rough comparison at least with the results from Shankar et al. (2004). We thus combine 99 per cent of our estimate of the black hole mass in ellipticals, 76 per cent of that in classical bulges, and 8 per cent of that in pseudo-bulges, to obtain a total black hole mass that can be compared to that in the early-type galaxies of Shankar et al. (2004). Applying these zeroth-order corrections, we get that 14 per cent of the mass in black holes is in what could be called late-type galaxies, already accounting for our selection effect due to the axial ratio cut. This is below the estimate in Shankar et al. (2004), but consistent with that in Graham et al. (2007), with the uncertainties they quote. The difference with respect to the former study might be at least partially a result from the different relations used to estimate $M_{\rm BH}$.

4.2 Bulge formation and black hole growth

The results described above indicate that pseudo-bulges have higher σ for their masses, as compared to classical bulges, which also have, on average, higher σ for their masses when compared to elliptical galaxies. We have kept the low

surements from releases prior to DR6, since most of the studies mentioned used these estimates. If we use the DR6 estimates then the corresponding difference falls to 40 per cent.

σ estimates from SDSS for pseudo-bulges to avoid artificially strengthening these results. For these systems, it is unclear, however, if such results arise from the inability of SDSS measurements to correctly measure σ in cases where the true velocity dispersion is lower than the instrumental resolution. In other words, one could argue that the pseudo-bulges for which σ is available are only those at the high end of the velocity dispersion distribution. In fact, we have σ estimates for only 30 per cent of the pseudo-bulges in our sample. The corresponding fractions for classical bulges and ellipticals are, respectively, 60 and 76 per cent. In such a case, our results would only indicate that pseudo-bulges display a very large scatter around the $M_{\rm Bulge} - \sigma$ relation. While we can not presently rule out such possibility, we note that there seems to be a gradual transition from elliptical galaxies to classical bulges and pseudo-bulges in Fig. 1 and in the edge-on view of the fundamental plane (Paper I). This suggests that our results are the outcome of a real effect, since classical bulges have σ estimates typically substantially larger than the SDSS instrumental resolution.

The result that pseudo-bulges have higher velocity dispersion than classical bulges, at a fixed stellar mass, goes in the opposite direction as one would naively infer from the virial theorem, particularly because pseudo-bulges are more rotationally supported than classical bulges. However, pseudo-bulges are not expected to be fully relaxed systems, which is one of the main assumptions in the virial theorem. Although recent numerical experiments yield similar results (Younger et al. 2008), it remains to be verified if this is not only a consequence of the presence of bars (see also Graham 2008). A bar is expected to enhance the central velocity dispersion in its host galaxy *even in face-on galaxies*, if it has evolved for a sufficient time (see Gadotti & de Souza 2005, and references therein), and such effect should be more dramatic in galaxies with less conspicuous bulges. It should also be noted that it is likely that a fraction of our unbarred galaxies contain small bars (smaller than $2-3$ kpc in semi-major axis) which have been missed due to the relatively poor spatial resolution of SDSS images. Such fraction should be larger in galaxies with pseudo-bulges, since these bars are more often hosted by galaxies with small bulge-to-total ratios. This could explain the few pseudo-bulges in "unbarred" galaxies that are also outliers in the $M_{\rm Bulge} - \sigma$ relation, should the exception caused by pseudo-bulges be only due to the presence of a bar.

Thus, our results indicate that either the $M_{\rm BH} - M_{\rm Bulge}$ relation or the $M_{\rm BH} - \sigma$ relation (or even both), has to have different forms for ellipticals and classical bulges, and also possibly for pseudo-bulges. This most likely results from different formation and evolutionary histories, which translate into the observed different $M_{\rm Bulge} - \sigma$ relations. If so, then one may not need to invoke distinct black hole fuelling mechanisms to explain different $M_{\rm BH} - M_{\rm Bulge}$ or $M_{\rm BH} - \sigma$ relations for different stellar systems. The existence of such different relations is yet another important detail that has to be taken into account by studies on black hole demographics and the connection between the properties of black holes and their host galaxies.

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