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Dwarf Galaxies and the Black–Hole Scaling Relations

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ABSTRACT

The sample of dwarf galaxies with measured central black hole masses M and velocity dispersions σ has recently doubled, and gives a close fit to the extrapolation of the $M \propto \sigma$ relation for more massive galaxies. We argue that this is difficult to reconcile with suggestions that the scaling relations between galaxies and their central black holes are simply a statistical consequence of assembly through repeated mergers. This predicts black hole masses significantly larger than those observed in dwarf galaxies unless the initial distribution of uncorrelated seed black hole and stellar masses is confined to much smaller masses than earlier assumed. It also predicts a noticeable flattening of the $M \propto \sigma$ relation for dwarfs, to $M \propto \sigma^2$ compared with the observed $M \propto \sigma^4$. In contrast black hole feedback predicts that black hole masses tend towards a universal $M \propto \sigma^4$ relation in all galaxies, and correctly gives the properties of powerful outflows recently observed in dwarf galaxies. These considerations emphasize once again that the fundamental physical black-hole — galaxy scaling relation is between M and σ. The relation of M to the bulge mass M_b is acausal, and depends on the quite independent connection between M_b and σ set by stellar feedback.

Key words: galaxies: active – galaxies: Seyfert – quasars: general – quasars: supermassive black holes – black hole physics – X–rays: galaxies

1 INTRODUCTION

It is now widely accepted that the centre of every medium– or high–mass ($\gtrsim 10^{10}\mathrm{M}_\odot$) galaxy contains a supermassive black hole (SMBH). The hole mass M is observed to scale with both the velocity dispersion σ of the host galaxy spheroid (or bulge) and the bulge stellar mass M_b as

$$M \propto \sigma^\alpha,\ M \sim 10^{-3} M_b \quad (1)$$

with $\alpha \sim 4$ (see e.g. Kormendy & Ho 2013 for a review). These scalings give important constraints on how the SMBH and their host galaxies evolve. In this paper we argue that recent observations of the central black holes in dwarf galaxies distinguish sharply between two approaches to understanding the scaling relations.

One picture of these relations uses the fact that the SMBH binding energy $E_{\rm BH} = \eta M c^2$ (where $\eta \sim 0.1$ is the accretion efficiency) is typically $> 1000\times$ the binding energy $\sim f_g M_b \sigma^2$ of the bulge gas (where $f_g \sim 0.16$ is the gas fraction) of the host galaxy. (We use the term 'bulge' to include pseudobulges also, where the velocities are dominated by ordered rotation. The distinction has no significance for either picture of the scaling relations, assuming that the observed velocities dynamically specify the mass distributions.)

So it is plausible that the scaling relations (1) may result from feedback via the powerful 'UFO' (UltraFast Outflow) winds observed from the accreting SMBH. These carry the Eddington momentum (i.e. $\dot M_w v_w \simeq L_{\rm Edd}/c$ (see King & Pounds 2015 for a review). The shocks of the wind against the bulge gas cool rapidly (giving 'momentum–driven' feedback) for SMBH masses M less than

$$M_\sigma \simeq 3 \times 10^8 \sigma_{200}^4 \mathrm{M}_\odot \quad (2)$$

(King, 2003; here $\sigma_{200} = \sigma/(200\,{\rm km\,s^{-1}})$) and push the surrounding gas into a thin shell which expands but cannot escape the galaxy. But at the mass (2), shock cooling becomes ineffective and the wind now does expel the gas that would have fuelled any significant further SMBH growth, in an 'energy–driven' outflow (King, 2005). An expulsive Eddington wind is even more likely in dwarf galaxies than in the larger ones for which the theory is well verified, since the ratio of the dynamical mass inflow rate $\dot M_{\rm dyn} \simeq f_g \sigma^3/G$ potentially driving accretion to the required Eddington ac-

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cretion rate $\dot{M}_{\rm Edd} \propto L_{\rm Edd} \propto M \propto \sigma^4$ goes as $\sigma^{-1} \propto M^{-1/4}$. The predicted limiting mass (2) is in good agreement with observations (see Section 2 below) of the SMBH mass as a function of σ. Observational selection effects (see Batcheldor 2010) make it difficult to measure black hole masses significantly below this value for a given σ, in particular because of the need to resolve the SMBH sphere of influence (radius $\propto M\sigma^{-2}$), so observationally–determined SMBH masses tend to lie close to the relation (2). The $M - M_b$ relation now follows 'acausally' (cf Power et al. 2011) since the observed Faber–Jackson (FJ) relation

$$L_b \propto \sigma^4, \tag{3}$$

where L_b is the luminosity of the bulge stars (Faber & Jackson 1976) and the assumption of a standard mass–to–light ratio $M_b \propto L_b$ for these stars gives a parallel relation $M_b \propto \sigma^4$ (cf Murray et al, 2005). This parallelism arises because the SMBH and the bulge stars each separately drive momentum–driven feedback, respectively via UFOs, and stellar winds and supernovae. These separately limit M and M_b to values which are each proportional to σ^4, but differ by a factor $\sim 10^3$. Importantly, unlike the $M - \sigma$ relation, there is no physics in the connection between M and M_b – that is, black holes do not set M_b.

Both forms of feedback are present in dwarf galaxies, and in particular vigorous AGN–driven winds are directly observed in them, as we discuss in Section 4 below. The feedback these produce depends only on the current black hole mass, irrespective of the previous history of SMBH growth, provided only that most of this mass was acquired by gas accretion. This is expected at least at low redshift from the Soltan (1982) relation.

A very different idea (Peng, 2007; Jahnke & Macciò, 2011) asserts that the scaling relations (1) are not a result of black hole feedback, and are instead largely statistical. If the SMBH and galaxy spheroids satisfying these relations are built from mergers of large numbers of much smaller galaxies with uncorrelated stellar and black hole masses, the central limit theorem implies a linear relation $M \propto M_b$, with a dispersion tightening for larger M, M_b because on average more mergers have taken place. In practice, to improve the fit to the observed $M - M_b$ relation, Jahnke & Macciò (2011) go beyond the pure merger picture by adding in the effects of star formation, black hole accretion, and the conversion to bulge mass of a fraction of the stars formed in the disc component of each halo. They do not explicitly derive an $M - \sigma$ relation, but for high–mass galaxies this follows, since the FJ relation gives $M_b \propto \sigma^4$, which then implies $M \propto \sigma^4$. In this assembly picture the normalizations of both the scaling relations (1) are presumably fixed by the original uncorrelated mass distributions of black holes in small galaxies before any mergers take place.

These two pictures – feedback or assembly – predict very different outcomes for low–mass galaxies. In the feedback picture all galaxies limit the growth of their central black holes through the physics producing the $M - \sigma$ relation, so we expect this relation to hold for dwarf galaxies, and we expect to see energy–driven winds driving away the gas that would otherwise increase the black hole mass above M_σ. But in the assembly picture galaxies of sufficiently low mass do not experience enough mergers to produce a tight relation between M and M_b (cf Jahnke & Macciò, 2011, Fig. 4). Further, we will see that this picture predicts a significant flattening ($M_\sigma \propto \sigma^2$) in the $M - \sigma$ relation at low galaxy masses, contrary to observation. As this implies SMBH which are *more* massive than expected from a simple extrapolation of the $M - \sigma$ relation for higher–mass galaxies, the fact that observations do not seem to find them is significant.

These distinctions between feedback and assembly mean that observations of dwarf galaxies potentially give clean tests of whether either theory offers viable explanations of the scaling relations. Recent papers report observations of two types bearing directly on this question, and we discuss these in the rest of this paper.

2 THE $M - \sigma$ RELATION FOR DWARF GALAXIES

Baldassare et al. (2020) used the Keck Echellete Spectrograph and Imager to measure stellar velocity dispersions for eight active dwarf galaxies ($M_b < 3 \times 10^9 {\rm M}_\odot$) with virial black hole masses. This increases from 7 to 15 the number of dwarf galaxies which have measurements of both the black–hole mass M and the velocity dispersion σ. This combined sample fits tightly on to the extrapolation of the $M - \sigma$ relation to low black–hole masses $M \lesssim 10^6 {\rm M}_\odot$ (Baldassare et al. 2020, Fig. 3). In addition Davis et al (2020) used sub–parsec resolution ALMA observations to find a further dwarf galaxy (NGC 404) lying on the $M - \sigma$ relation, with $M \simeq 5 \times 10^5 {\rm M}_\odot$ and $M_b \sim 10^9 {\rm M}_\odot$. Here both the observed molecular gas and the stellar kinematics independently require this same black hole mass.

These results discriminate sharply between feedback and assembly. In the feedback picture the physics producing the $M - \sigma$ relation holds for all galaxy masses, so the extrapolation to lower masses is unproblematic. But this same extrapolation runs strongly against the assembly theory. First, this produces a large scatter in black hole masses at low galaxy masses. Fig. 4 of Jahnke & Macciò (2011) predicts a significant population of SMBH with masses $M \gtrsim 10^7 {\rm M}_\odot$ at stellar masses $M_* \lesssim 10^9 {\rm M}_\odot$. These black hole masses are considerably higher than those observed. Since they would have larger spheres of influence, in which stars move with higher velocities, it is unlikely that they have been missed because of selection effects. Evidently this problem arises because the maximum masses of the initial seed black holes allow many of them to exceed observed black hole masses after only a few mergers. So one might try to alleviate the problem by reducing the initial black– hole mass scatter below the 10^4 range adopted by Jahnke & Macciò (2011). Since the predicted low–redshift scatter scales roughly as $\sqrt{N}$, and is about an order of magnitude above observations, this reduces the required initial scatter in black hole mass to a factor $\lesssim 100$.

This already makes the assembly picture considerably less attractive, but a second problem for it appears in deriving the $M - \sigma$ relation at low galaxy masses. Instead of the $M_b \propto \sigma^4$ relation which follows from the FJ relation for massive galaxies, galaxies with velocity dispersions $\sigma \lesssim 100$ km s^{-1} instead obey

$$M_b \propto L_b \propto \sigma^2 \tag{4}$$

(Kourkchi et al., 2012: see also Davies et al. 1983; Held et al. 1992; and Matković & Guzmán, 2005, de Rijcke et al, 2005). Assuming continuity between the two relations (3, 4) at $\sigma \simeq 100$ km s^{-1} inevitably means that the flatter σ^2 relation gives an M_b value 4× larger than given by the σ^4 relation at $\sigma = 50$ km s^{-1}. Taking $M \simeq 10^{-3} M_b$ (Häring & Rix, 2004) gives

$$M_b \simeq 2 \times 10^9 \sigma_{50}^2 \mathrm{M}_\odot \tag{5}$$

Here σ_{50} is the galaxy velocity dispersion σ in units of 50 km s^{-1}. This is flatter than the $M_b \propto \sigma^4$ Faber–Jackson relation found for large galaxies, and implies that the stellar components of dwarf galaxies all have roughly similar radii R_b. Approximating dwarfs as isothermal spheres, i.e.

$$R_b \simeq \frac{GM_b}{2\sigma^2} \tag{6}$$

gives R_b of order 1 kpc largely independently of M_b or σ – we will find a best–fit value

$$R_b \simeq 2.3 \pm 1.1\,\mathrm{kpc} \tag{7}$$

(cf Fig. 2). Inspection of Fig. 2 of Manzano–King et al. (2019) confirms that this is a reasonable approximation for the sizes of the hosts in their dwarf AGN sample (see the discussion in Section 3 below). Adopting (7) avoids the need to assign mass–to–light ratios for these small galaxies. The origin of the near–constant radius (7) is unclear, but cosmological simulations do find this effect at low masses (Furlong et al., 2017; but see also Ludlow et al., 2019). A possible physical cause may relate to the fact that at gas temperatures $\sim 10^4$ K typical of the warm ISM, the Jeans length is of order 1 kpc.

Since assembly can only ever give a linear $M - M_b$ relation, it predicts an $M - \sigma$ relation flattening to

$$M_\sigma \simeq 2 \times 10^6 \sigma_{50}^2 \mathrm{M}_\odot \tag{8}$$

for $\sigma \lesssim 100$ km s^{-1}.

Kormendy & Ho (2012) find a larger normalization $M \simeq 5 \times 10^{-3} M_b$ for the $M - M_b$ relation than Häring & Rix (2001), so this relation would become

$$M_\sigma \simeq 1 \times 10^7 \sigma_{50}^2 \mathrm{M}_\odot \tag{9}$$

in this case. We note that from (6) that this normalization implies rather large radii for dwarfs compared with the sizes seen in Fig. 2 of Manzano–King et al., (2019).

We plot the two relations (8, 9) in Fig. 1, where the discrepancies are clear. We also plot the original $M \propto \sigma^4$ relation (2) for comparison.

3 THE BLACK–HOLE VS BULGE–MASS RELATION FOR DWARF GALAXIES

The Faber–Jackson–like relation (4) for dwarfs implies that their total stellar masses vary as σ^2 rather than σ^4. Then accepting that $M_\sigma \propto \sigma^4$ as in the sample studied by Baldassare et al. (2019), means that we no longer get a linear relation like (1) between M and M_b. Eliminating σ between eqns (2, 5) instead gives

$$M \simeq 4 \times 10^4 M_9^2 \mathrm{M}_\odot \mathrm{R}_{\mathrm{kpc}} \tag{10}$$

if the SMBH masses are close to M_σ. We include a factor $R_{\mathrm{kpc}} = R_b/(1\,\mathrm{kpc})$ (the near–constant radius of low–mass

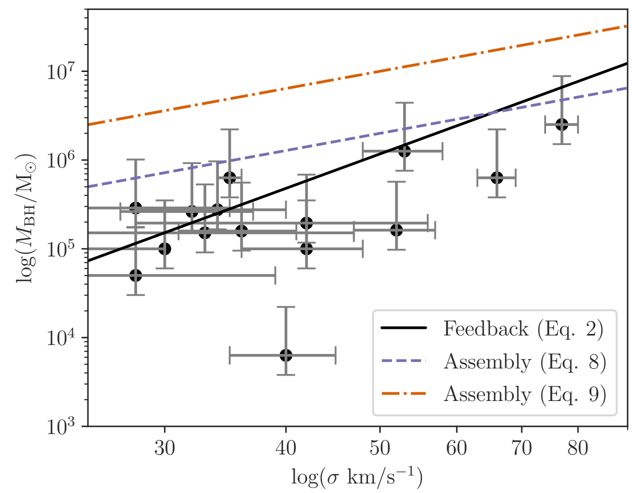

Figure 1. M-σ relation using the data from Baldassare et al. 2020 and the references quoted therein. The $M \propto \sigma^2$ relations (8, 9) predicted by the assembly picture are the orange (dashed) and blue (dash–dot) lines, while the black (solid) curve is the original $M \propto \sigma^4$ relation (2) predicted by feedback.

galaxies predicted by (4, 6)) to allow for enforcing continuity between the high–mass and low–mass FJ relations (3, 4) at slightly different σ.

Fig. 2 compares the best–fit value of (10) with the AGN sample of Baldassare et al. (2020) Table 1 and Davis et al., 2020), with the $M - M_b$ relation found by Schutte, Reines & Greene (2019) plotted for comparison. This figure suggests that SMBH are less massive relative to their hosts at low galaxy masses, perhaps because the stellar feedback fixing M_b is less effective in removing gas before it makes stars. Garratt–Smithson et al., (2019) suggest that this does happen, because gradual stellar feedback delays the unbinding of most of the gas. Instead it makes ‘chimneys’ in the dense shell surrounding the hot feedback region, venting the hot gas from the galaxy before it can remove much of the star–forming gas.

It appears that the central black holes in dwarf galaxies play a similar active role in their evolution as in more massive galaxies, even though they may be relatively less massive compared with their hosts. Läsker et al., (2016) and Nguyen et al. (2019b) also find black hole masses lying below a linear extrapolation of the $M - M_b$ scaling relation in dwarf galaxies. This presumably makes them harder to discover, supporting the arguments of Kaviraj et al. (2019) for a large black hole occupation fraction in dwarfs. This would probably require even smaller initial seed SMBH masses M in the assembly picture than the decrease of a factor 100 we estimated in Section 2, while the fundamental difficulty in fitting the observed $M - \sigma$ relation would remain unchanged.

Of course dwarf galaxies are not a homogenous group, and in particular there is likely to be a sub–population where the central black hole has not grown to an energetically significant mass $\sim M_\sigma$ (cf Pacucci et al., 2018, King & Nealon, 2019).

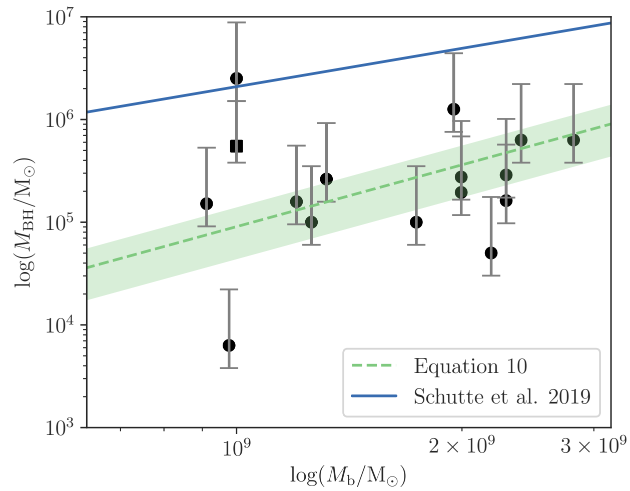

Figure 2. The quadratic $M - M_b$ relation (10, with best–fit value $R_b = 2.3{\pm}1.1$ kpc) for low–mass galaxies plotted against the data from Table 1 of Baldassare et al (2020) and references therein, together with the point from Davis et al., (2020) (as a square). The best–fit linear $M - M_b$ relation found by Schutte, Reines & Greene (2019) for the full SMBH sample for all galaxies is plotted for comparison. This used photometric modeling and colour–dependent mass–to–light ratios to determine M_b.

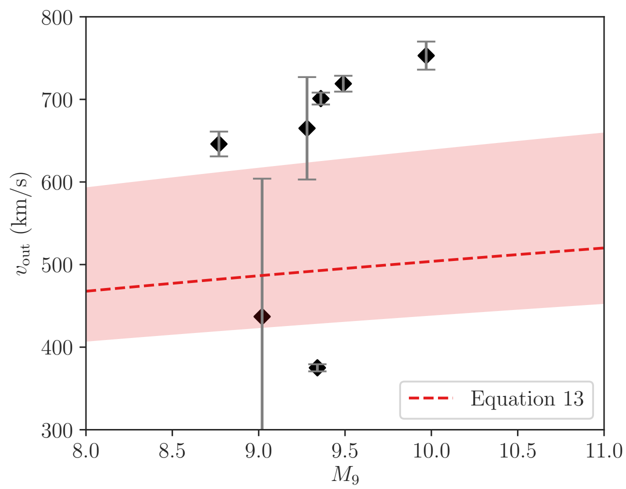

Figure 3. The outflow velocity $v_{\rm out}$ (column 7 of Table 1 of MK19) versus galaxy mass M_9 in the dwarf AGN sample of MK19. In almost all cases these are significantly higher than would be predicted (equation 13, shown) for outflows which had not yet escaped the visible galaxy. Here we use $R_{\rm kpc}$ fit in Figure 2, with the uncertainties shown in the shaded region. The exception is J084234.51+031930.7, the only one whose narrow lines give a composite BPT classification.

4 OUTFLOWS FROM DWARF GALAXIES

A second recent set of observations offers another test of the origin of the scaling relations. Manzano–King et al. (2019: hereafter MK19) give spatially–resolved kinematic measurements of AGN–driven outflows in dwarf galaxies in the stellar mass range $M_b \sim 6\times10^8 - 9\times10^9{\rm M}_\odot$ These are selected from SDSS DR7 and DR8 and followed up with Keck/LRIS spectroscopy. In a total sample of 50 dwarf galaxies, they find ionized gas outflows out to distances up to 1.5 kpc in 13, all having velocities above the escape value for their dark matter halos. There are line–ratio indications of AGN activity in 9 of the 13 galaxies with outflows, and in 6 of these the outflow appears to be driven by the AGN rather than a starburst, with one further less clear example.

Although mild outflows are allowable in the assembly picture, they have no particular significance there. But powerful outflows are an inevitable and tightly constrained consequence of the feedback picture (cf King, 2003; King 2005; Zubovas & King 2012, summarized in King & Pounds, 2015). Once M reaches the value (2), all of the mechanical energy of the UFO wind is communicated to the host's bulge ISM in a forward shock, driving this gas away in an energy–driven outflow. In an isothermal potential this has speed

$$v_{\rm out} \simeq 1230\sigma_{200}^{2/3}\left(\frac{lf_c}{f_g}\right)^{1/3}\ {\rm km\,s^{-1}} \tag{11}$$

(King 2005, Zubovas & King, 2012). Here $l \sim 1$ is the ratio of the driving SMBH accretion luminosity to the Eddington value, and $f_c \simeq 0.16$ is the cosmological mean value of f_g. (The dark matter halo at larger radii is irrelevant for the baryonic physics determining $v_{\rm out}$ and M_σ.) The corresponding mass outflow rate is

$$\dot M_{\rm out} = 3700\sigma_{200}^{8/3}l^{1/3}\,{\rm M_\odot\,yr^{-1}} \tag{12}$$

where f_g has been taken equal to $f_c = 0.16$ (in King & Pounds (2015) the corresponding equation [(57)] gives the exponent of σ incorrectly as 10/3 rather than 8/3). Once the energy–driven outflow described by (11, 12) begins to escape the baryonic part of the galaxy it accelerates above the speed (11) (cf Zubovas & King 2012b).

There is a large body of observational data (cf references in the review of King & Pounds, 2015, Section 5.3) showing that many massive galaxies drive out gas roughly as described by (11, 12). In applying this formalism to dwarf galaxies we in principle need velocity dispersions σ. These are not measured for the MK19 sample, but inspection of Fig. 2 of MK19 confirms that (7) is a reasonable approximation for the visible size of these galaxies. Then we use (5) to eliminate σ from eqn (11) in favour of M_b. (This procedure also avoids the need to estimate the stellar mass–to–light ratio.) We find

$$v_{\rm out} \simeq 307M_9^{1/3}x^{1/3}\ {\rm km\,s^{-1}} \tag{13}$$

where $M_9 = M_b/10^9{\rm M}_\odot$, and

$$x = \frac{lf_c}{R_{\rm kpc}f_g} \tag{14}$$

with $R_{\rm kpc} = R_b/{\rm kpc} \simeq 1$ the radius of the visible galaxy. We expect x to have similar values ~ 0.5 for all 8 dwarfs with AGN–driven outflows in the sample of MK19. MK19 do not measure black hole masses M, but these do not appear in the expressions (11, 12) as we have assumed that M has reached the limiting value (2) and triggered an energy–driven outflow.

Fig. 3 compares the data of MK19 with (13), using the fitted value of $R_{\rm kpc}$ from Fig. 2 (corresponding to $x = 0.44 \pm 0.30$). It is immediately obvious from Fig. 3 that all but one of the observed outflow velocities are significantly larger than given by (13), as we expect if the outflows have already largely escaped the visible galaxies. This is strongly suggested by their large spatial scales, of order the half–light radii. (The exception is J084234.51+031930.7, the only one whose narrow lines give a composite BPT classification.)

Similarly we expect that the mass outflow rate in these galaxies should currently be somewhat higher than the values $\dot{M}_{\rm out} \simeq 100{\rm M}_\odot\,{\rm yr}^{-1}$ predicted by (12) with $\sigma \sim 50\,{\rm km\,s^{-1}}$. Then if feedback is continuous, a galaxy would lose most of its gas in a total time

$$t_{\rm deplete} \sim \frac{f_g M_b}{\dot{M}_{\rm out}} \sim 10^6\,\frac{M_9}{\sigma_{50}^{8/3}}\,{\rm yr} \tag{15}$$

where $M_9 = M_b/10^9{\rm M}_\odot$, and we have used (6, 7). Again replacing σ_{50} with M_9 from (5) we find

$$t_{\rm deplete} \sim 2.5\times 10^6 M_9^{-1/3}\,{\rm yr}. \tag{16}$$

So we estimate depletion times of a few million years for all dwarf galaxies in the energy–driven stage of AGN feedback expected as the SMBH mass approaches M_σ, only weakly dependent on galaxy mass.

5 CONCLUSION

Recent observations extend the tight $M-\sigma$ relation found for massive galaxies to dwarf galaxies with low–mass ($M \sim 10^5 - 10^6{\rm M}_\odot$) black holes. This is natural if feedback causes the scaling relations, but hard to reconcile with the assembly picture. The initial (M, M_b) seed pairs must be much smaller, and have a far tighter dispersion than thought. Independently of these significant adjustments, assembly always gives a linear M, M_b relation. Then the empirical Faber–Jackson–like relation (5) for dwarf galaxies means that the assembly picture predicts a significant flattening in the slope of the $M-\sigma$ relation for black holes in dwarf galaxies, from $M \sim \sigma^4$ to $M \sim \sigma^2$. These predicted higher–mass SMBH are not found, even though all selection effects would favour this. There is no degree of freedom in the assembly picture to overcome this problem, as the assumption of a linear $M - M_b$ relation arising from the central limit theorem is fundamental to it.

The apparent inadequacy of the assembly picture in explaining the SMBH–galaxy relations at all masses arises because it implicitly assumes that the relation between M and M_b drives the $M-\sigma$ relation. It appears instead that the fundamental physical scaling relation is between M and σ, and is caused by SMBH feedback, as already strongly suggested by the wide discrepancy between SMBH and bulge binding energies. The $M - M_b$ relation between black hole and bulge mass is acausal, arising from the quite independent connection between M_b and σ set by stellar rather than black–hole feedback.

The discovery of powerful AGN–driven winds rapidly removing gas from dwarf galaxies gives additional support to the feedback picture. This is in line with recent work (cf de Nicola, Marconi & Longo, 2019; Chen et al., 2020) on massive galaxies. Further observations of dwarf galaxies and their central black holes are likely to give critical insights into the origins of the black hole – galaxy scaling relations.

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DATA AVAILABILITY STATEMENT

No new data were generated or analysed in support of this research.

REFERENCES

Baldassare V. F., Dickey C., Geha M., Reines A. E., 2020, ApJL, 898, L3
Batcheldor D., 2010, ApJ, 711, L108
Chen Z., Faber S. M., Koo D. C., Somerville R. S., Primack J. R., Dekel A., Rodríguez-Puebla A., et al., 2020, ApJ, 897, 102
Davies R. L., Efstathiou G., Fall S. M., Illingworth G., Schechter P. L., 1983, ApJ, 266, 41
Davis T. A., Nguyen D. D., Seth A. C., Greene J. E., Nyland K., Barth A. J., Bureau M., et al., 2020, MNRAS, 496, 4061
de Nicola S., Marconi A., Longo G., 2019, MNRAS, 490, 600
de Rijcke S., Michielsen D., Dejonghe H., Zeilinger W. W., Hau G. K. T., 2005, A & A, 438, 491
Faber S. M., Jackson R. E., 1976, ApJ, 204, 668
Furlong, M., Bower, R. G., Crain, R. A., Schaye, J., Theuns, T., Trayford, J. W., Qu, Y., Schaller, M., Berthet, M., Helly, J. C., 2017, MNRAS, 465, 722
Garratt-Smithson L., Wynn G. A., Power C., Nixon C. J., 2019, MNRAS, 489, 4278
Held E. V., de Zeeuw T., Mould J., Picard A., 1992, AJ, 103, 851
Jahnke, K., Macciò, A. V., 2011, ApJ 734, 92
Kaviraj, S., Martin, G., Silk, J., 2019, MNRAS, 489
King A. R., 2003, ApJ, 596, L27
King A., 2005, ApJ, 635, L121
King A. R., Pounds K. A., 2015, ARA&A, 53, 115
Kormendy J., Ho L. C., 2013, ARA&A, 51, 511
Kourkchi, E., Khosroshahi, H. G., Carter, D., et al., 2012, MNRAS, 420, 2819
Kourkchi, E., Khosroshahi, H. G., Carter, D., Mobasher, B.,2012, MNRAS, 420 2835
Läsker, R., Greene, J. E., Seth, A., van de Ven, G., Braatz, J. A., Henkel, C., Lo, K. Y., 2016, ApJ, 825,3
Ludlow, Aaron D., Schaye, J., Schaller, M., Richings J., 2019, MNRAS, 488, 123L
Manzano–King, C., Canalizo, G., Sales, L., 2019, ApJ, 884, 54
Murray, N., Quataert, E., Thompson, T.A., 2005, ApJ 660, 211
Nguyen, D. D., Seth, A. C., Neumayer, N., Iguchi, S., Cappellari, M., Strader, J., Chomiuk, L., Tremou, E., Pacucci, F., Nakanishi, K., Bahramian, A., Nguyen, P. M., den Brok, M., Ahn, C. C., Voggel, K., T., Kacharov, N., Tsukui, T., Ly, C. K., Dumont, A., Pechetti, R., 2019 ApJ, 872, 104
Pacucci F., Loeb A., Mezcua M., Martín–Navarro I., 2018, ApJ, 864, L6
Power C., Zubovas K., Nayakshin S., King A. R., 2011, MNRAS, 413, L110
Peng, C.J., 2007, ApJ, 671, 1098
Schutte, Z., Reines, A. E., Greene, J. E., 2019, ApJ, 887, 245
Soltan A., 1982, MNRAS, 200, 115
Zubovas, K., King A., 2012, ApJ, 745, L34

Zubovas, K., King A., 2012, MNRAS, 426, 2751