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Supermassive black hole demographics: evading $M-\sigma$

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ABSTRACT

We consider black hole–galaxy coevolution using simple analytic arguments. We focus on the fact that several supermassive black holes are known with masses significantly larger than suggested by the $M-\sigma$ relation, sometimes also with rather small stellar masses. We show that these are likely to have descended from extremely compact 'blue nugget' galaxies born at high redshift, whose very high velocity dispersions allowed the black holes to reach unusually large masses. Subsequent interactions reduce the velocity dispersion, so the black holes lie above the usual $M-\sigma$ relation and expel a large fraction of the bulge gas (as in WISE J104222.11+164115.3) that would otherwise make stars, before ending at low redshift as very massive holes in galaxies with relatively low stellar masses, such as NGC 4889 and NGC 1600. We further suggest the possible existence of two new types of galaxy: low-mass dwarfs whose central black holes lie below the $M-\sigma$ relation at low redshift, and galaxies consisting of very massive ($\gtrsim 10^{11}$ M$_\odot$) black holes with extremely small stellar masses.

Key words: black hole physics – galaxies: active – galaxies: Seyfert – quasars: general – X-rays: galaxies.

1 INTRODUCTION

The realization that observations imply scaling relations between supermassive black holes (SMBH) and their host galaxies (cf Magorrian et al. 1998; Ferrarese & Merritt 2000; Gebhardt et al. 2000; Häring & Rix 2004) has stimulated significant efforts to identify the underlying physics (see Kormendy & Ho 2013 and King & Pounds 2015 for reviews of observations and theory, respectively). These have thrown up a range of ideas, some involving the potential effects of merger averaging, or stellar feedback. But the fact that the binding energy of the SMBH always far exceeds that of the host galaxy bulge strongly suggests black hole feedback as the basic cause.

In recent years a fairly coherent picture of SMBH growth and feedback in the local Universe has begun to emerge. It appears that low-redshift SMBH with a sufficient supply of surrounding gas grow their masses M to the $M-\sigma$ value

$$M = M_\sigma \simeq \frac{f_{\rm g}(1-f_{\rm g})\kappa}{\pi G^2}\sigma^4 \simeq 3\times 10^8 f_{\rm g}(1-f_{\rm g})\sigma_{200}^4\,{\rm M_\odot} \qquad (1)$$

fixed by momentum-driven feedback from wide angle winds driving off the SMBH accretion disc in Eddington–limited phases SMBH (cf King 2003, 2005). Here $\sigma = 200\sigma_{200}\,{\rm km\,s^{-1}}$ is the velocity dispersion of the galaxy bulge, $f_{\rm g}$ the gas fraction of baryonic matter in the bulge, κ the electron scattering opacity, and G the gravitational constant. At this mass, SMBH feedback becomes energy-driven, and drives away the remaining bulge gas, with typical velocity (King 2005; Zubovas & King 2012)

$$v_{\rm out} \simeq 1230\sigma_{200}^{2/3} l^{1/3}\,{\rm km\,s^{-1}} \qquad (2)$$

where l is the ratio of the driving SMBH accretion luminosity to the Eddington value. This generally halts significant further SMBH growth, which can only resume if events such as mergers or dissipation rebuild the bulge gas and restart evolution towards equation (1) with larger M and σ. Some growth beyond equation (1) can occur if the SMBH has a low spin and so is relatively inefficient in driving gas away (Zubovas & King 2019, submitted), but this is relatively small.

In the simple picture described above, SMBHs can only grow significantly above M_σ through mergers with other holes, or by sub-Eddington accretion exerting little feedback. Both these routes suggest that SMBH masses M should be at most only slightly larger than M_σ, which is presumably why the $M-\sigma$ relation is observable at all. It is hard to find masses for SMBH below equation (1), because of the need to resolve their sphere-of-influence radii $R = 2GM/\sigma^2$ (cf. Batcheldor 2010), so it is possible that the $M-\sigma$ relation is really an upper limit to M for given σ. Recent observational evidence (e.g. Yang et al. 2019) out to redshifts $z = 3.0$ does suggest that the SMBH accretion rate and the star formation rate are effectively linearly related, which would maintain the scaling relations specifically rather than as upper limits.

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Despite the above discussion, there is clear evidence that M is significantly larger than expected from the $M-\sigma$ relation in a few galaxies, particularly at large M. The most compelling examples are NGC 4889 (McConnell et al. 2011) and NGC 1600 (McConnell et al. 2011; Thomas et al. 2016) in the centres of the Coma and Leo clusters, respectively. These have SMBH masses $M = 2\times10^{10}\,\mathrm{M_\odot}$ and $1.7\times10^{10}\,\mathrm{M_\odot}$. But using equation (1) even with the most favourable value $f_{\rm g} = 1/2$, their observed velocity dispersions $\sigma = 350\,\mathrm{km\,s^{-1}}$ and $293\,\mathrm{km\,s^{-1}}$ give $M_\sigma = 7\times10^9\,\mathrm{M_\odot}$, $3\times10^9\,\mathrm{M_\odot}$, respectively. For more likely values $f_{\rm g}\sim0.16$ the predicted masses are $3.5\times10^9\,\mathrm{M_\odot}$ and $1.5\times10^9\,\mathrm{M_\odot}$, an order of magnitude below the measured masses. Kormendy & Ho (2013) refer to such objects as 'monsters', and note that their discrepancies from the SMBH mass–bulge mass relation $M\simeq10^{-3}M_{\rm bulge}$ (Häring & Rix 2004) are even larger than the offset from $M-\sigma$, in the sense that the bulge mass is considerably reduced compared with this relation. There are also several very large measured SMBH masses in the sample shown in Matsuoka et al. (2018), fig. 4 and references cited there. These have no measured σ, but the claimed masses would require extremely large values $\sigma\sim500-1000\,\mathrm{km\,s^{-1}}$ to be compatible with equation (1). Evidently the coevolution of black holes and galaxies is more complex than the simple picture sketched above, and our aim here is to clarify this.

2 SMBH MASS EVOLUTION

SMBH mass growth is controlled by three critical masses. These are M_σ as defined above, the gas mass $M_{\rm g}$ in the host galaxy bulge, and the maximum SMBH mass $M_{\rm max}$ allowed if the SMBH is to have a luminous accretion disc and so exert feedback. Equation (1) gives M_σ, and we take the simple isothermal approximation

$$M_{\rm g} = \frac{2f_{\rm g}\sigma^2}{G}R \tag{3}$$

for $M_{\rm g}$. The mass $M_{\rm max}$ is given by requiring the black hole ISCO to be just equal to the disc self-gravity radius. At this mass the disc breaks up into stars, severely inhibiting gas accretion on to the hole and the resultant feedback on the host galaxy. This gives (King 2016)

$$M_{\rm max} = 5\times10^{10}\,\mathrm{M_\odot}\alpha_{0.1}^{7/13}\eta_{0.1}^{4/13}(L/L_{\rm Edd})^{-4/13}f_5^{-27/26}. \tag{4}$$

Here $\alpha_{0.1}$ is the standard viscosity parameter in units of 0.1, $\eta_{0.1}$ is the black hole accretion efficiency in units of 0.1, L and $L_{\rm Edd}$ are, respectively, the accretion luminosity and Eddington luminosity of the black hole, and $f_5(a)$ is the spin dependence of the innermost stable circular orbit (ISCO) radius in units of a typical value $5GM/c^2$, corresponding to a prograde spin $a\sim0.6$. The full range $-1<a<1$ allows $M_{\rm max}$ values from $2\times10^{10}\,\mathrm{M_\odot}$ up to $3\times10^{11}\,\mathrm{M_\odot}$ (King 2016, fig. 1). SMBH mass growth beyond $M_{\rm max}$ is still possible, indeed quite likely (see Section 2.3), but SMBH with masses $M > M_{\rm max}$ cannot exert feedback on their host galaxies.

The limit in equation (4) appears to be compatible with all extant observations. The SMBH in NGC 1600 is significantly below it for any spin rate, and this is probably true of NGC 4889 (cf. King 2016). A contender for the most extreme system is currently the very dust-obscured WISE J104222.11+164115.3, at redshift $z = 2.52$ (Matsuoka et al. 2018). This galaxy has strongly blueshifted oxygen lines corresponding to an outflow velocity $\sim1100\,\mathrm{km\,s^{-1}}$, close to the prediction in equation (2). A luminous accretion disc is required to launch this, and from equation (4) the claimed SMBH mass $M = 10^{11}\,\mathrm{M_\odot}$ requires it to have a spin $a\gtrsim0.7$ and accrete prograde at the time of launch. We note that some caution is in order with this estimate, as the nature of the blowout phase may affect the reliability of the usual virial mass estimators.

For simplicity in treating these effects in the analysis that follows we consider a fixed value

$$M_{\rm max} = 3\times10^{10}\,\mathrm{M_\odot}, \tag{5}$$

corresponding to a spin parameter a close to zero. This choice does not qualitatively affect our results, as we shall see.

For a given gas fraction $f_{\rm g}$ we can write the ratios of these three critical masses in the simple forms

$$\frac{M_\sigma}{M_{\rm g}} = \left(\frac{\sigma}{\sigma_0}\right)^2\frac{R_0}{R} \tag{6}$$

$$\frac{M_{\rm g}}{M_{\rm max}} = \left(\frac{\sigma}{\sigma_0}\right)^2\frac{R}{R_0} \tag{7}$$

$$\frac{M_\sigma}{M_{\rm max}} = \left(\frac{\sigma}{\sigma_0}\right)^4 \tag{8}$$

where σ_0 and R_0 depend on $f_{\rm g}$. We take $f_{\rm g} = 0.5$ for 'gas-rich' cases, and $f_{\rm g} = f_{\rm c}\simeq0.16$ for typical 'cosmological' conditions. These choices give $(\sigma_0, R_0) = (564\,\mathrm{km\,s^{-1}}, 0.42\,\mathrm{kpc})(\sigma_0, R_0) = (658\,\mathrm{km\,s^{-1}}, 0.98\,\mathrm{kpc})$ for the gas-rich and cosmological cases, respectively.

These values show that we can expect deviations from the usual low-redshift condition $M\lesssim M_\sigma$ only in galaxies born with very high velocity dispersions $\sigma\gtrsim550\,\mathrm{km\,s^{-1}}$. But values of σ like this are required for galaxy bulges to have acquired large gas masses $\sim10^{12}\,\mathrm{M_\odot}$ (close to the upper limit for rapid infall; Rees & Ostriker 1977; White & Frenk 1991) by the redshifts $z\gtrsim6$ where large SMBH masses are observed, as the gas cannot assemble faster than the dynamical rate

$$\dot{M}_{\rm dyn}\sim\frac{f_g\sigma^3}{G}. \tag{9}$$

This infall only operates after cosmological outflow has slowed sufficiently (the turnround time) so typically for a fraction ~0.2 of the lookback time $t_{\rm look}\simeq10^9\,\mathrm{yr}$ at this redshift. Then the requirement

$$\frac{f_g\sigma^3}{G}\times0.2t_{\rm look}\gtrsim10^{12}M_{12}\,\mathrm{M_\odot} \tag{10}$$

for galaxies of mass $10^{12}M_{12}\,\mathrm{M_\odot}$ gives an absolute lower limit, assuming continuous accretion, of

$$\sigma\gtrsim350-460\times M_{12}^{1/3}\,\mathrm{km\,s^{-1}} \tag{11}$$

for $f_{\rm g} = 0.5-0.16$. Simulations (e.g. van der Vlugt & Costa 2019) do indeed find large dispersions for massive galaxies at this epoch.

The three relations in equations (6), (7) and (8) divide the $\sigma-R$ plane into the six regions $1-6$ shown in Fig. 1. We can now use it to see how SMBH grow in various cases.

2.1 SMBH growth for given σ, R

Initially, we consider how black holes grow in galaxy bulges in each region of Fig. 1, and consider the effects of evolution across the (σ, R) plane later.

In region 1 we have the familiar hierarchy $M_{\rm g} > M_{\rm max} > M_\sigma$, so SMBH growth in this region terminates at $M = M_\sigma$, as expected in the simple picture sketched in Section 1. SMBH feedback removes the excess gas ($M_{\rm g} > M_\sigma$) once M reaches M_σ, and further growth

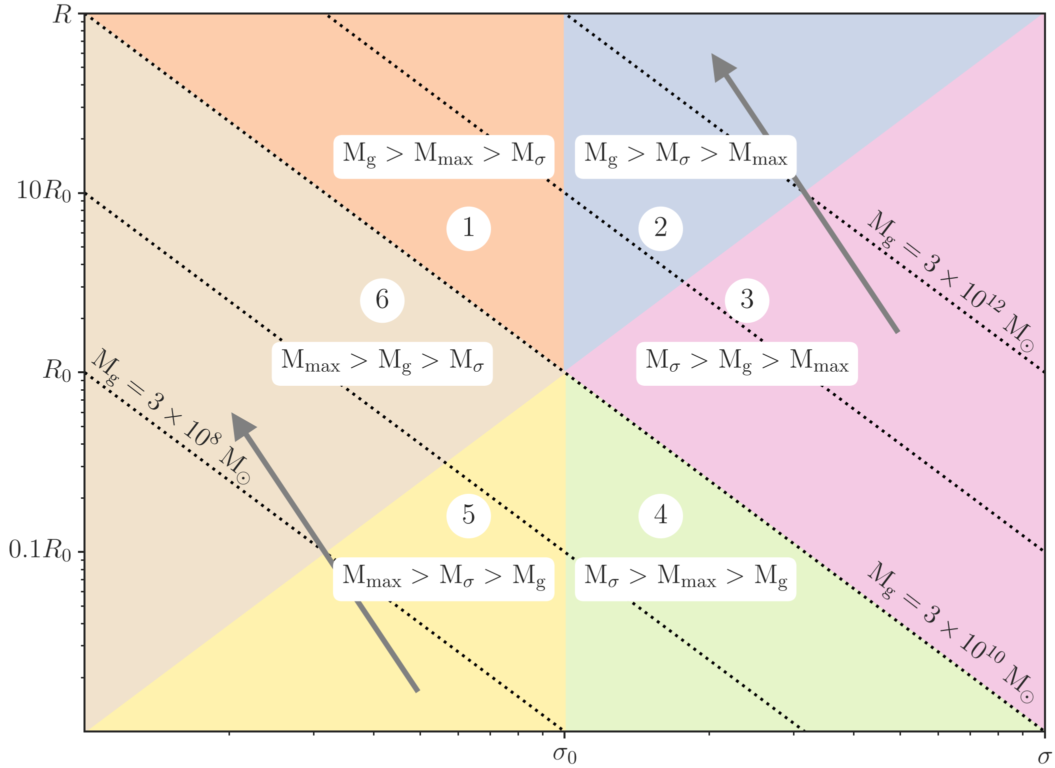

Figure 1. The (σ, R) plane for galaxy bulges and their central black holes. The orderings between the three critical masses M_σ, M_g and M_{max} (cf. equations 6–8) divide this into regions 1−6 as shown. The effect of minor mergers or tidal stripping is to move a galaxy in the direction of the thick arrows. At low redshift most galaxies are observed with SMBH masses $M \lesssim M_\sigma$ and modest velocity dispersions σ in the 'normal' regions 1 and 6, depending on their total bulge gas masses M_g. Small but very dense galaxies ('blue nuggets') are found at high redshift and necessarily with high σ (cf equation 11) in regions 2 or 3. These can grow large SMBH masses M which are below M_σ in those regions, but exceed the lower values of M_σ prevailing in regions 1 if minor mergers or other processes such as dissipation move them there. This offers possible evolutionary routes to forming low-redshift galaxies whose SMBH have $M > M_\sigma$, such as NGC 1600 and NGC 4889, probably via systems like WISE J104222.11+164115.3, whose vigorous feedback despite its very high SMBH mass suggests that $M_{max} > M > M_\sigma$ here also. The figure is drawn for a single value of $M_{max} = 3 \times 10^{10}\,M_\odot$. Relaxing this to include the full range $2 \times 10^{10}\,M_\odot - 3 \times 10^{11}\,M_\odot$ leaves the global behaviour of galaxies qualitatively unchanged, but blurs the boundaries between the regions 1 and 6.

requires an increase in the bulge velocity dispersion. In region 6, M_σ is again the smallest of the three masses, so here too SMBH growth stops at $M = M_\sigma$. Regions 1 and 6 differ only in the overall mass of the galaxy, which is evidently larger in region 1 than 6. They contain the majority of galaxies observed at low redshift, almost all having $M \le M_\sigma$.

In regions 4 and 5, the gas mass M_g is smaller than the other two critical masses, so SMBH growth stops before either M_σ or M_{max} is reached. At low redshift these galaxies would appear as low-mass dwarfs with black hole masses $M < M_\sigma$. These masses must lie below the flattened $M - \sigma$ and $M - M_b$ (where M_b is the bulge mass) relations found by Martín-Navarro & Mezcua (2018) and Reines & Volonteri (2015), but their possible presence agrees with the suggestion (from semi-analytic modelling) by Pacucci et al. (2018) of small central BH masses in dwarf galaxies.

The most interesting regions in Fig. 1 are 2 and 3, where M_{max} is the smallest of the three critical masses, and so always smaller than M_σ. This means that feedback by itself cannot prevent SMBH

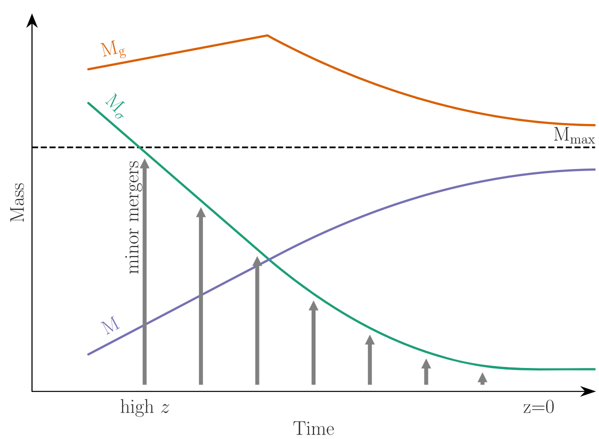

Figure 2. Schematic view of the evolution producing galaxies such as NGC 4889 and NGC 1600. Minor mergers gradually reduce the central velocity dispersion, reducing the critical mass M_σ and leaving the SMBH mass M above the $M - \sigma$ relation, while feedback from SMBH accretion removes much of the gas mass M_g and prevents the growth of a large stellar population.

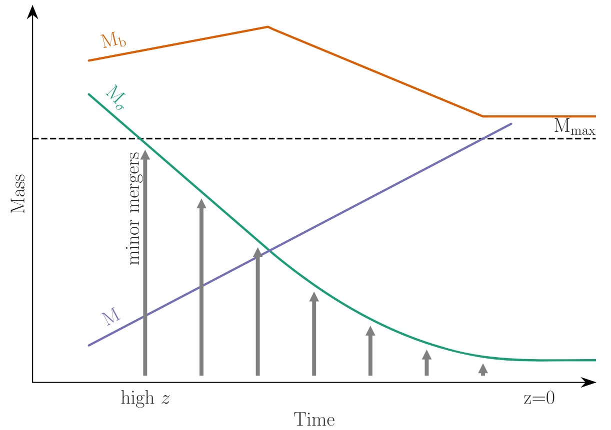

Figure 3. Schematic view of the evolution producing galaxies with very massive SMBH and a minimal stellar component. This is similar to that of Fig. 2, but here the SMBH evolves beyond $M_{\rm max}$. These objects would be almost undetectable by electromagnetic observations, but potentially observable by LISA.

growth, in principle all the way up to $M_{\rm max}$ and beyond (see below). What actually happens depends ultimately on what physical processes drive gas accretion on to SMBH, and how this relates to other galaxy properties, which is currently not fully understood.

If the black hole reaches mass $M_{\rm max}$, there is even less of a barrier to further SMBH growth since accretion now produces neither radiation nor feedback, and there is no viscous accretion disc to slow accretion either. We consider this in Section 2.3.

2.2 SMBH growth in evolving galaxies

So far, we have considered SMBH growth in galaxy bulges which evolve too little to move between the regions of Fig. 1. But in reality there are several ways that galaxy evolution can affect SMBH growth, such as the processes of transformation and dissipation (Bezanson, van Dokkum & Franx 2012), mergers with other galaxies, and tidal stripping. In bulges undergoing transformation, star formation is quenched and σ is likely to remain fixed. Since the long-term average SMBH accretion rate correlates with star formation rate, at least for bulge-dominated galaxies (e.g. Yang et al. 2019) this presumably means that SMBH also stop growing. This is reasonable, since the SMBH mass M and the bulge stellar mass $M_{\rm b}$ are both proportional to σ^4 (cf. Power et al. 2011; King & Pounds 2015, section 6). So these quiescent galaxies are likely to remain on both the Faber–Jackson (Faber & Jackson 1976) and $M-\sigma$ relations, and therefore also on the SMBH – bulge mass relation $M = \lambda M_{\rm b}$, where λ is constant at a value between 10^{-2} and 10^{-3} if average SMBH accretion and star formation track each other (Yang et al. 2019: note that the treatment in Power et al. 2011 left the relation between these two quantities unspecified).

In contrast, dissipation causes gas to sink to the centre of the bulge, increasing the central gravitating mass and so σ, and decreasing the effective radius R. Similarly if a galaxy gains mass in minor mergers with other galaxies this reduces the velocity dispersion as $\sigma \sim M_{\rm g}^{-1/2}$ (Bezanson et al. 2009; the dispersion is likely to remain unchanged in major mergers – cf. Marian et al. 2019). Tidal stripping can also reduce the velocity dispersion in an essentially similar way.

Using equation (3) we see this means that minor mergers or tidal stripping move galaxies along tracks $\sigma \propto R^{-1/4}$, as shown in Fig. 1 with the grey arrows. So either dissipation or mergers can reduce an initially large σ below σ_0, particularly in the central regions near the SMBH, moving galaxies from regions 2 and 3 into region 1. Here the large SMBH mass grown in regions 2 and/or 3 may exceed the new, lower value of M_σ specified by the central velocity dispersion. This will allow powerful SMBH feedback to restart, provided that M has not yet reached $M_{\rm max}$. Full expulsion of the gas from the galaxy probably has to wait until σ in the outer regions drops below the critical value, leaving M above the $M-\sigma$ value defined by the smaller central velocity dispersion.

This evolution fits that of the system WISE J104222.11+164115.3 (Matsuoka et al. 2018) discussed above. This appears to be in the blowout phase, which would normally require its SMBH mass $M \simeq 10^{11}\,{\rm M}_\odot$ to be close to M_σ. But even for a gas-rich galaxy the required value $\sigma \sim 1208\,{\rm km\,s^{-1}}$ is extremely high, so it is likely instead that M is significantly greater than M_σ, as expected if it has evolved from regions 2 or 3 into region 1. An evolution like this ultimately produces galaxies like NGC 4889 and NGC 1600. Because the bulge is largely gas, the strong SMBH feedback significantly depletes it before it can form stars, leaving the black hole marooned at a mass M such that $M_{\rm max} > M > M_\sigma$, together with a rather low stellar mass for the whole galaxy. This suggests a plausible evolutionary track from formation in regions 2 or 3, through galaxies with very high SMBH masses and currently in the blowout phase like WISE J104222.11+164115.3, ending as systems like NGC 4889 and NGC 1600. This is shown schematically in Fig. 2.

2.3 SMBH growth beyond $M_{\rm max}$?

We emphasized above that $M_{\rm max}$ is only a limit for the mass of an SMBH undergoing luminous accretion from a disc. Given a continuing mass supply, a SMBH with $M \geq M_{\rm max}$ can quietly swallow whole some of the stars forming near the ISCO, as it is well above the limit for tidally disrupting them. It can grow its mass even more easily than before, as it is now freed of constraints such as the Eddington limit or the $M-\sigma$ mass, which are only relevant if accretion produces feedback. Fig. 1 of King (2016) shows that several SMBH are very close to this regime. In a gas-rich case this process could leave the galaxies with very low stellar masses, and an extremely massive black hole (cf. Fig. 3).

3 CONCLUSIONS

We have shown that galaxies formed by rapid gas infall at redshifts $z \gtrsim 6$ may grow central black holes with very large masses. As their velocity dispersions decrease over cosmic time, feedback from the SMBH can remove a significant fraction of the gas otherwise available for star formation. At low redshift these galaxies have SMBH well above the usual $M-\sigma$ and the SMBH–bulge mass relations. These properties agree with those of NGC 4889 and NGC 1600, and probably other galaxies too. We point out the possible existence of low-mass dwarf galaxies whose central black holes lie significantly below the M–σ relation, and galaxies with very massive black holes but extremely small stellar masses.

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