Compact massive objects in Virgo galaxies: the black hole population

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ABSTRACT

We investigate the distribution of massive black holes (MBHs) in the Virgo cluster. Observations suggest that active galactic nuclei activity is widespread in massive galaxies ($M_* \gtrsim 10^{10}\,\mathrm{M}_\odot$), while at lower galaxy masses star clusters are more abundant, which might imply a limited presence of central black holes in these galaxy-mass regimes. We explore if this possible threshold in MBH hosting is linked to *nature*, *nurture* or a mixture of both. The *nature* scenario arises naturally in hierarchical cosmologies, as MBH formation mechanisms typically are efficient in biased systems, which would later evolve into massive galaxies. *Nurture*, in the guise of MBH ejections following MBH mergers, provides an additional mechanism that is more effective for low mass, satellite galaxies. The combination of inefficient formation, and lower retention of MBHs, leads to the natural explanation of the distribution of compact massive objects in Virgo galaxies. If MBHs arrive to the correlation with the host mass and velocity dispersion during merger-triggered accretion episodes, sustained tidal stripping of the host galaxies creates a population of MBHs which lie above the expected scaling between the holes and their host mass, suggesting a possible environmental dependence.

Key words: black hole physics – galaxies: clusters: general – galaxies: nuclei – cosmology: theory.

1 INTRODUCTION

The nearby Virgo cluster is a perfect laboratory to investigate the evolution of galaxies in a dense environment. Recently, observations of a large sample of galaxies suggested that the properties of nuclei, either quiescent or active, in Virgo galaxies are strongly mass-dependent. This latter finding is in very good agreement with the general trend found also in the Sloan Digital Sky Survey (SDSS), where very few active galactic nuclei (AGN) are found in galaxies with stellar mass $M_* < 10^{10}\,\mathrm{M}_\odot$ (Kauffmann et al. 2003; Kewley et al. 2006).

Decarli et al. (2007) analysed nuclear activity in late-type galaxies in the Virgo cluster. They conclude, quite remarkably, that at galaxy mass[1] $M_{\rm gal} > 10^{10.5}\,\mathrm{M}_\odot$ the AGN fraction is unity. As a central black hole is a necessary condition for AGN activity, we conclude that the black hole occupation fraction (BHOF) must be unity as well. Côté et al. (2006), Wehner & Harris (2006) and Ferrarese et al. (2006) find that, below $M_* \sim 10^{10}\,\mathrm{M}_\odot$, Virgo galaxies exhibit nuclear star clusters, whose mass scales with M_* in the same fashion as those of the massive black holes detected in brighter galaxies (Magorrian et al. 1998; Marconi & Hunt 2003; Häring & Rix 2004). Although the existence of a nuclear star cluster does not rule out a small, hidden massive black holes (MBH), it is suggestive that Ferrarese et al. (2006) conclude that 'bright galaxies often, and perhaps always, contain supermassive black holes but not stellar nuclei. As one moves to fainter galaxies, nuclei become the dominant feature while MBHs might become less common and perhaps disappear entirely at the faint end'.

There are three interlaced sides of the intriguing story which appears to link stellar nuclei and MBHs: (i) understand if (and why) MBHs populate preferentially bright galaxies; (ii) understand why stellar nuclei populate preferentially faint galaxies and (iii) understand why the ratio of nuclear to galaxy mass is identical to the ratio of MBH to galaxy mass. In this paper, we address the first issue. A possible hint to explain the predominance of star clusters in small galaxies may come from comparing the dynamical time-scale and the fragmentation time-scale of the infalling gas. Detailed calculations are necessary to test this hypothesis, but it can be argued that in shallow potentials gas could fragment before reaching the centre of the galaxy. This is even more suggestive in the case of merger-induced gaseous infall. Regarding the third issue, Emsellem & van de Ven (2008) for instance show that if galaxies have Sersic profiles, radial compressive forces trigger the collapse of gas in the central regions, and the mass of the nuclear cluster that forms is about 0.1 per cent of the mass of the host galaxy. So, nuclear cluster formation and MBH feedback might produce the same scaling relation with galaxy mass, but it is unclear whether this is a coincidence or the result of a single, unexplored process.

Volonteri, Lodato & Natarajan (2008) investigate the overall distribution of MBHs in galaxies, as a function of the host velocity

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[1] Decarli et al. (2007) measure the dynamical mass of the galaxy within the optical radius, determined at the 25 mag arcsec^{-2} isophote in the B band. This is an upper limit to the stellar mass of galaxies, but a lower limit to the total baryonic mass.

dispersion, σ_*, as traced by the host halo (cf. Ferrarese 2002), and find that the efficiency of MBH formation decreases with halo mass, and isolated dwarf galaxies are most likely to be devoid of a central MBH. This is a common feature of MBH formation models which invoke gas-dynamical processes in the high-redshift Universe, either via direct collapse (e.g. Haehnelt & Rees 1993; Loeb & Rasio 1994; Eisenstein & Loeb 1995; Bromm & Loeb 2003; Begelman, Volonteri & Rees 2006; Lodato & Natarajan 2006), or via an intermediate stage of metal free Population III star (e.g. Carr, Bond & Arnett 1984; Madau & Rees 2001; Volonteri, Haardt & Madau 2003). The common feature is the need for deep potential wells at cosmic epochs when the protogalaxy population was dominated by minihaloes ($M_{\rm h} < 10^7\,{\rm M}_\odot$).

A second physical phenomenon strengthens the likelihood that dwarf galaxies, even if seeded with a MBH at early times, are now lacking one: the gravitational recoil, that is, the general-relativistic effect which imparts velocity to the centre of mass of a merging MBH binary, when the MBHs plunge into each other's last stable orbit by emission of gravitational radiation. Gravitational waves carry, in general, a non-zero net linear momentum, which establishes a preferential direction for the propagation of the waves. As a consequence, the centre of mass of the binary recoils in the opposite direction (Redmount & Rees 1989), possibly causing the ejection of MBHs from the potential wells of their host galaxies (e.g. Haiman 2004; Madau & Quataert 2004; Madau et al. 2004; Merritt et al. 2004; Volonteri & Rees 2006; Schnittman & Buonanno 2007). The progress of numerical relativity is now leading to a convergence in the estimates of the recoil. Schwarzschild, i.e. non-spinning, black holes (e.g. Baker et al. 2006) are expected to recoil with velocities below $200\,{\rm km\,s^{-1}}$, and a similar range is expected for black holes with low spins, or with spins (anti-)aligned with the orbital axis. However, when the spin vectors have opposite directions and are in the orbital plane, the recoil velocity can be as large as a few thousands $\rm km\,s^{-1}$ (Campanelli et al. 2007a,b; González et al. 2007).

Schnittman (2007) shows that the hierarchical nature of galaxy assembly implies that ejections do not lead to void nuclei, even in the high-recoil limit. This is weaved into the very nature of galaxy assembly, via a series of mergers, in a pattern typically dubbed 'merger tree'. The botanical essence of the tree implies that many branches converge into a central trunk, so that in every generation of the tree, the number of galaxies decreases, while the fraction of MBHs can increase, even if ejections operate. This is especially true for 'central galaxies', which represents the trunk of the merger tree.

The situation is different for satellites in a galaxy cluster: they correspond to loose branches that do not merge into the main trunk. Satellites are indeed galaxies that enter the dark matter halo of the cluster, but do not merge with the central galaxy.

In this paper, we develop simple models that describe the dynamical evolution of satellite galaxies in a cluster, focusing on the fate of their nuclei. We estimate the influence of MBH formation mechanisms and MBH ejections for shaping the BHOF in the Virgo cluster today.

2 MBH FORMATION AND DYNAMICAL EVOLUTION

We follow the evolution of the MBH population in a Λcold dark matter (ΛCDM) Universe along the history of a cluster-size halo. Our technique and cosmological framework are similar to the one described in Volonteri et al. (2003). However, we now focus on the merger history of haloes which have a total mass $M_{\rm h} = 10^{15}\,{\rm M}_\odot$ at $z = 0$ (see also Yoo et al. 2007). We track the dynamical evolution of MBHs ab initio and follow their assembly down to $z = 0$. We adopt very simplified assumptions on MBH formation and mass growth, based on a phenomenological approach. Our goal is to highlight the influence of two main processes, efficiency of MBH formation and dynamics, rather than develop an omni-comprehensive evolutionary model plagued by free parameters.

Several theoretical arguments indicate that MBH formation proceeds at very high redshift, and probably in biased haloes (e.g. Madau & Rees 2001; Haiman 2004; Shapiro 2005; Volonteri & Rees 2005, 2006). Additional parameters, such as the angular momentum of the gas, its ability to cool and its metal enrichment, are likely to set the exact efficiency of MBH formation and the redshift range when the mechanism operates (for a thorough discussion see Volonteri et al. 2008).

We explore here four simplified models: a very high efficiency model (model I, 'higheff'), where all haloes with a formation redshift $z > 5$ host a MBH, an intermediate efficiency model (model II, 'mideff'), where all haloes with a formation redshift $z > 12$ host a MBH and finally two biased, low-efficiency model, where MBHs form only in haloes which represent density peaks with $\nu_{\rm c} = 3^2$ (model III, 'peak3') or $\nu_{\rm c} = 3.5$ (model IV, 'peak3.5') and have a formation redshift $z > 12$. The choice $\nu_{\rm c} = 3.5$ in model IV is based on the results in Volonteri et al. (2003), and is meant as a hard threshold to illustrate the effect of biased formation. Our models link the formation of a MBH seed to the halo mass and formation redshift of a given galaxy only, and we do not assume here that MBHs are *formed* in bulges. Several models of MBH formation (e.g. Eisenstein & Loeb 1995; Koushiappas, Bullock & Dekel 2004; Begelman, Volonteri & Rees 2006; Lodato & Natarajan 2006) additionally require that MBH seed hosts have low angular momentum, thus hindering the existence of MBHs in pure disc galaxies.

Our four 'models' of MBH formation define how often and when haloes are populated with MBHs. They provide the initial occupation fraction, and they set the minimum mass of MBH hosts today. The higher the redshift when MBH formation ceases, the larger the typical MBH host today is. This is a direct consequence of hierarchical CDM models (cf. Madau & Rees 2001).

Additionally, we have to follow the dynamical evolution of haloes and embedded MBHs all the way to $z = 0$ in order to determine the occupation fraction of MBHs and their properties. We focus here on the effect that MBH ejections, namely due to gravitational waves recoils, have on the properties of the MBH population at $z = 0$. The magnitude of the recoil depends on the mass ratio of the merging MBHs, the spins of the MBHs, the orbital parameters of the binary.

First, to evaluate mass ratios, we have to model the mass growth of MBHs. We base our modelling on plausible assumptions, supported by both simulations of AGN triggering and feedback (Springel, Di Matteo & Hernquist 2005), and analysis of the relationship between MBH masses ($M_{\rm BH}$) and the properties of their hosts (McLure & Dunlop 2004; Wyithe & Loeb 2005). Wyithe & Loeb (2005) show that if the relationship between the mass of a MBH and the velocity dispersion of the host found for local galaxies (Ferrarese & Merritt 2000; Gebhardt et al. 2000; Tremaine et al. 2002) does not evolve with redshift, then the correlation between the masses of MBHs and their hosts evolves with redshift in a way compatible

[2] $\nu_{\rm c} = \delta_{\rm c}(z)/\sigma(M, z)$ is the number of standard deviations which the critical collapse overdensity represents on mass scale M. $\sigma(M_{\rm h}, z)$ is the root mean square fluctuation of the linear density field at redshift z, and $\delta_{\rm c}(z)$ is the threshold density for collapse of a homogeneous spherical perturbation at redshift z (see e.g. Peebles 1993).

with observational results by McLure & Dunlop (2004). Additionally, Springel et al. (2005) suggest that the ditto $M_{\rm BH}$–σ_* relation is established during galaxy mergers that also fuel MBH accretion and form bulges. We therefore assume that after every merger between two galaxies with a mass ratio larger than 1 : 10, their MBHs attain the mass predicted by the $M_{\rm BH}$–σ_* for each of the merging galaxies.

Hence, although in our models the presence of a MBH is not uniquely coupled with bulge formation, the mass of a black hole is set during the same event that forms the host bulge. Accordingly, when a binary of MBHs merge, their mass ratio scales with the $M_{\rm BH}$–σ_* relation appropriate for the velocity dispersions of the progenitor haloes of the MBHs. Note that if the $M_{\rm BH}$–σ_* relation scales with redshift as suggested by, for example, Woo et al. (2006) and Treu, Malkan & Blandford (2004) the mass ratio of merging binaries would be unchanged, so the occupation fraction of black holes would not be affected. We further assume that MBHs merge within the merger time-scale of their host haloes, which is a likely assumption for MBH binaries formed after gas-rich galaxy mergers (Escala et al. 2004; Dotti, Colpi & Haardt 2006; Dotti et al. 2007).

To determine the efficiency of MBH ejections due to gravitational recoils, we need also information on the magnitude and orientation of MBH spins at the time of the merger. We will express MBH spins as a function of the dimensionless parameter $\hat{a} \equiv J_{\rm h}/J_{\rm max} = cJ_{\rm h}/GM_{\rm MBH}^2$, where $J_{\rm h}$ is the angular momentum of the black hole.

Non-spinning MBHs, or binaries where MBH spins are aligned with the orbital angular momentum are expected to recoil with velocities below 200 km s^{-1}. The recoil velocity is largest for MBHs with large spins, when the spin vectors have opposite directions and are in the orbital plane (Campanelli et al. 2007a,b; González et al. 2007). Assuming that BHs at the time of the merger always have anti-aligned spins in the orbital plane (as in Volonteri 2007) would provide a strict upper limit to the effect of the recoil. However, the configuration yielding the highest recoil velocities is probably rather uncommon, as pointed out by Bogdanović, Reynolds & Miller (2007). Bogdanović et al. (2007) suggest that when the MBH merger happens in a gas-rich environment, and is accompanied by accretion, the most likely configuration has spins aligned (or anti-aligned) with the orbital angular momentum, thus avoiding the highest recoil velocity. Conversely, in gas poor mergers there is no preferential spin alignment, so all spin/orbital parameters configurations are equally probable. We will assume in the following that orbital parameters and spin configuration are isotropically distributed, likely providing a soft *upper limit* to the strength of the recoil.

The distribution and most probable value of MBH spins are observationally largely unconstrained. There is evidence that MBHs in some local AGN galaxies do spin (Streblyanska et al. 2005; Brenneman & Reynolds 2006; Comastri, Brusa & Gilli 2008) based on iron line profiles (Fabian et al. 1989; Laor 1991; Miller 2007). High spins in bright quasars are also indicated by the high-radiative efficiency of quasars, as deduced from observations, by applying Soltan's argument (Soltan 1982; Wang et al. 2006, and references therein). However, neither observation firmly establishes that most MBHs have large spins, although there are theoretical arguments to expect so (Moderski, Sikora & Lasota 1998; Volonteri et al. 2005) as spin-up is a natural consequence of prolonged disc-mode accretion for any hole that has (for instance) doubled its mass by capturing material with constant angular momentum axis (Bardeen 1970; Thorne 1974). King et al. (2005) argue instead that most MBHs have very low or no spin, due to preferential accretion of counter-rotating material, or to short-lived accretion episodes (King et al. 2005). Waiting for additional observations,[3] we consider here two extreme cases, that likely allow us to bracket the typical configurations: either that all MBHs have exactly null spin or that all MBHs have $\hat{a} = 0.9$. The latter value is slightly lower than the canonical $\hat{a} = 0.998$ (Thorne 1974), but it is consistent with magnetohydrodynamical simulations of disc accretion (Gammie, Shapiro & McKinney 2004). We also run a control simulation where we set the recoil velocity to zero for all MBH mergers.

For every galaxy merger, we track jointly the dynamical evolution of the MBHs and host halo. In addition to the dynamics of MBH binaries, as described above, we trace the mass evolution of their hosts, including the *increase* due to galaxy mergers and the *decrease* due to mass stripping of the halo within the gravitational potential of the halo. Our treatment is very simple: we integrate the equation of motion of the satellite in the gravitational potential of the cluster (assuming a non-singular isothermal sphere), including the dynamical friction term. At every step of the integration, we compare the density of the satellite to the density of the cluster halo at the location of the satellite. Tidal stripping occurs at the radius within which the mean density of the satellite exceeds the density of the galaxy interior to its orbital radius (Taylor & Babul 2001). We trace tidal stripping of all satellites from the time of the merger to $z = 0$.

3 BLACK HOLES OCCUPATION FRACTION AND MASS SCALING

By applying the assumptions described in Section 2 to the assembly history of galaxies in a region that can be identified as a cluster at $z = 0$, we can determine the fraction of the galaxies which host a MBH, and if there are trends with the size and mass of the host galaxy. We note here that when we refer to the mass of the host, we assume for simplicity the total baryonic mass, which we scale with the cosmic baryon fraction (14 per cent). The stellar mass M_* of galaxies, as well as the dynamical mass within the optical radius, $M_{\rm gal}$, is undoubtedly non-constant functions of the halo mass, environmental density and star formation history of the satellite itself. Total baryonic masses are therefore *upper limits* to the measurable stellar and dynamical masses of the hosts. Given our assumptions on MBH formation and growth, the occupation fraction does not sensibly depend on bulge mass, but rather on the total mass of a galaxy, considered a tracer of the cosmological formation time (linked to the halo bias) and of the dynamical evolution (within the cluster potential). We stress, however, that pure disc galaxies are likely unsuitable for MBH formation (see discussion in Section 2).

We determine the BHOF as a function of halo mass (compare with the standard definition for galaxies, e.g. Peacock & Smith 2000), which is shown in Fig. 1 for the four different models I, II, III and IV. We compare our BHOF to the distribution of AGN in Virgo galaxies by Decarli et al. (2007), who find signs of AGN activity in all *late-type* galaxies in Virgo with galaxy mass above $3 \times 10^{11}\,{\rm M}_\odot$. Clearly, the AGN occupation function is a lower limit to the BHOF, that is, at every galaxy mass: BHOF($M_{\rm gal}$, AGN) $\leqslant$ BHOF($M_{\rm gal}$) $\leqslant 1$.

[3] The spin is a measurable parameter, with a very high accuracy, in the gravitational waves *Laser Interferometer Space Antenna* (*LISA*) signal (Barack & Cutler 2004; Vecchio 2004; Berti, Buonanno & Will 2005; Lang & Hughes 2006). Gravitational waves emitted when a stellar mass MBH, or even a white dwarf or neutron star, falls into a massive black hole can be used to map the space time of MBHs, and as a consequence, MBH spins.

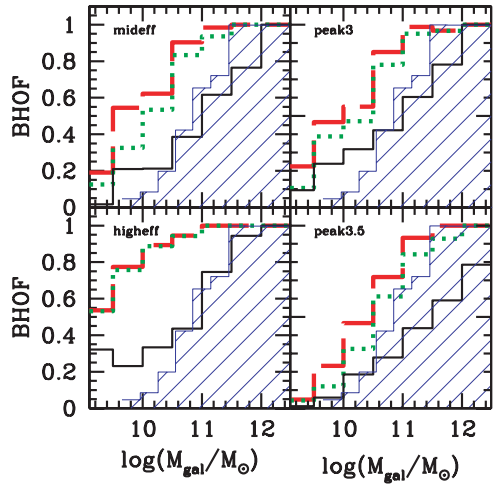

Figure 1. Occupation fraction of MBHs in Virgo galaxies. Hatched histogram: (Decarli et al. 2007). Dashed histogram: no recoil. Dotted histogram: $\hat{a} = 0$. Solid histogram: $\hat{a} = 0.9$. From bottom left-hand panel, clockwise: model I (higheff), model II (mideff), model III (peak3) and model IV (peak3.5). Model histograms are based on total baryonic masses.

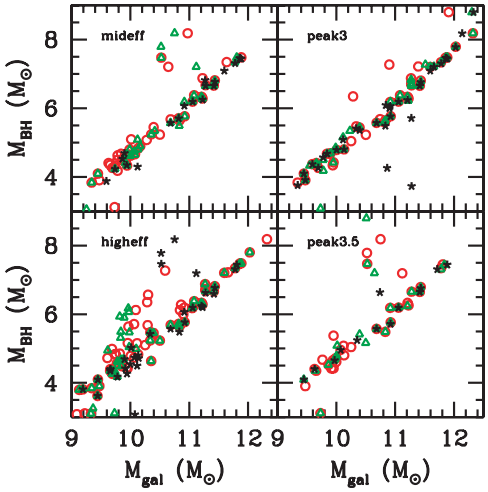

Figure 2. MBH mass against baryonic mass. Circles: no recoil. Triangles: $\hat{a} = 0$. Stars: $\hat{a} = 0.9$. From bottom left-hand panel, clockwise: model I (higheff), model II (mideff), model III (peak3) and model IV (peak3.5).

The BHOF of our models where the recoil velocity is set to zero informs us of the 'nature' scenario, in that only the initial conditions of MBH formation at high redshift enter into the final BHOF that we find at $z = 0$. We see that in all models I, II, III and IV, the BHOF is of the order of unity only above a certain galaxy mass. It is apparent that the existence of a threshold in a galaxy mass (as traced also by the velocity dispersion) is a natural outcome of MBH formation scenarios where the formation redshifts are pushed to high redshift. We note here that it is indeed necessary that MBHs are formed early on, as luminous quasars are detected at redshift 5 and higher (e.g. Fan et al. 2004). Obviously, the lower the typical MBH formation redshift, the higher the fraction of dwarf galaxies that can host a MBH. Even without additional physical processes, our analysis shows that the possible decrease in BHOF at low galaxy mass is an expected feature in models that are based on realistic MBH seed formation mechanisms. A similar behaviour, that is, an increasing BHOF with galaxy mass, is expected also in field galaxies (Volonteri et al. 2008), but it is exacerbated in cluster satellite galaxies, where coalescence rounds (using the terminology of Sesana 2007) are truncated.

The dynamical evolution of the MBH population modifies the BHOF in the direction of decreasing it, as MBHs are prone to ejections, and the ejection probability depends on the galaxy mass, via the escape velocity. Although the changes are not dramatic, that is, MBH kicks do not deplete most $z = 0$ galaxies of their MBHs (Schnittman 2007; Volonteri 2007), the effects are non-negligible, especially for galaxies with mass below $10^{11}\,\mathrm{M}_\odot$. The BHOF becomes a steeper function of the galaxy mass, and the threshold for BHOF close to unity shifts towards higher masses. If we compare our models to the results by Decarli et al. (2007), who find that all galaxies with mass above $3 \times 10^{11}\,\mathrm{M}_\odot$ show signs of AGN activity, hence host a central MBH, we can rule out very high biased models (model IV, peak3.5) with high recoil velocity (solid lines in Fig. 1), so if MBH formation is indeed very biased, either MBH spins align during the pre-merger orbital decay, as suggested by Bogdanović et al. (2007), or MBHs have small spins.

An additional prediction that arises from our models is that galaxies which have experienced sustained tidal stripping in the deep potential of the cluster host MBHs which lie above the expected $M_{\rm BH}$–$M_{\rm gal}$ correlation. After a merger episode that grew MBH and galaxy, if the orbital decay of the host brings it in dense regions, tidal stripping will decrease the galaxy mass, while the MBH mass will not be modified. The effect is more pronounced if MBHs are widespread as shown in Fig. 2. If MBHs form at early times, and evolve jointly with their hosts, with accretion bringing the MBHs exactly on the $M_{\rm BH}$–σ_* relation (Di Matteo, Springel & Hernquist 2005), then this population of 'overmassive' MBHs is unavoidable in galaxy clusters. We strongly stress that our results are robust in a qualitative way, although they should not be assumed quantitatively correct. For instance, the slope of our $M_{\rm BH}$–$M_{\rm gal}$ correlation is of the order of 5/3, because of our assumed rigid scaling between halo properties and MBH properties. Regardless of the exact slope, however, the presence of stripped galaxies with overmassive black holes is a robust prediction of models where MBHs form, and grow, early on. We also draw the attention to the possible environmental dependence of the $M_{\rm BH}$–$M_{\rm gal}$ correlation, but not of the $M_{\rm BH}$–σ_*, as the central velocity dispersion is not likely to be affected by the stripping.

There is observational evidence of overmassive MBHs for a given M_* in Virgo. Kormendy et al. (1997) used ground-based spectroscopic observations of NGC 4486B, the satellite galaxy to NGC 4486 (M87), along with isotropic dynamical models to find a central dark object of mass $M = 6^{+3}_{-2} \times 10^8\,\mathrm{M}_\odot$, though three integral, axisymmetric models cannot rule out absence of a MBH. Magorrian et al. (1998) later modelled NGC 4486B with two integral, axisymmetric dynamical models to find a mass of $M = 9.2^{+0.055}_{-0.033} \times 10^9\,\mathrm{M}_\odot$. The galaxy contains a double nucleus, which may pose problems for isotropic and axisymmetric models, but the presence of a double nucleus, itself, is explained by an eccentric disc of stars, which requires a MBH as in M31 (Tremaine 1995) So while the mass estimate may be uncertain, there is strong evidence for a MBH in NGC 4486B. Even if the mass estimate is high by a factor of a few, with a stellar mass of $\sim 6 \times 10^9\,\mathrm{M}_\odot$ (Kormendy et al. 1997) the MBH is more massive than those in galaxies with comparable bulge mass (see e.g. Magorrian et al. 1998). NGC 4486B is almost certainly tidally stripped, though this could be primarily a result of much stronger interactions with M87 (Evstigneeva et al. 2007) rather than milder stripping from the cluster potential.

Another potential example in Virgo is the S0 galaxy NGC 4342 with a measured black hole mass of $M = 3.0^{+1.7}_{-1.0} \times 10^8\,\mathrm{M}_\odot$ and bulge mass of $M = 1.2 \times 10^{10}\,\mathrm{M}_\odot$ (Cretton & van den Bosch 1999), making it another extreme high outlier by a factor of $\sim$30 (Häring & Rix 2004).

We note that the population of 'undermassive' MBHs, signature of the gravitational recoil, described for example in Volonteri (2007) and Volonteri et al. (2008), is basically absent here, due to the more simplistic modelling we performed. We have in fact assumed that whenever two galaxies with MBHs merge, with a mass ratio larger than 1:10, the MBHs are placed directly on the $M_{\rm BH}$–σ_*. This consequently puts MBHs preferentially on the $M_{\rm BH}$–$M_{\rm gal}$ correlation. The cases where the MBH is below the mass predicted by the $M_{\rm BH} - M_{\rm gal}$ are those in which the galaxy has not had any major merger recently, so the MBH mass has not grown, while the galaxy mass has (via minor mergers, cf. the discussion in Volonteri et al. 2003).

4 CONCLUSIONS

We explored the influence of formation epoch of MBHs, bias of their hosts, and MBHs dynamical evolution on the occupation distribution of MBHs in galaxy clusters. The possible decrease of the occupation fraction at low galaxy mass proposed by Wehner & Harris (2006) and Ferrarese et al. (2006) is not a surprising result and follows naturally from the evolution of the MBH population of galaxies in clusters.

(i) When the formation mechanisms of MBH seeds are taken into consideration, implying formation of MBHs in massive high-redshift haloes, the BHOF in cluster galaxies in an increasing function of galaxy mass, in line with observations of the AGN fraction in Virgo.

(ii) The exact mass threshold above which BHOF = 1 depends on the details of the formation mechanism (host masses and redshift of formation, 'nature') and on the dynamical evolution, including MBH spin magnitude ('nurture').

(iii) The repercussions of 'nurture' are magnified in cluster galaxies. If a satellite galaxy looses its MBH due to a dynamical interaction, it has a negligible chance of capturing a new one following a subsequent galaxy merger, except for the central galaxy in the cluster.

(iv) We also predict that if MBHs co-evolve with galaxies during galaxy mergers, and satellite galaxies experience tidal stripping during their orbital evolution, then a population of galaxies where the MBH mass lies above the standard $M_{\rm BH} - M_{\rm gal}$ is expected. Two such examples could be NGC 4486B and NGC 4342.

We emphasize that our models do not in any way imply that MBHs and nuclear clusters are mutually exclusive. We, however, predict that the occupation fraction decreases with galaxy mass. If, as suggested by Wehner & Harris (2006), lacking a MBH is a necessary condition for nuclear cluster formation, radio or hard X-ray observations will inform us of the complementary or mutually exclusive essence of MBHs and nuclear clusters. Gallo et al. (2007) recently observed 32 galaxies in Virgo with the *Chandra* X-ray Observatory, and found, in agreement with Decarli et al. (2007) that nuclear X-ray activity increases with the mass of the host galaxy. Intriguingly, at least in one case, VCC1178, a nuclear X-ray source is detected jointly with a central star cluster. Seth et al. (2006) also report that a small AGN might be hosted within the core of the nuclear star cluster in NGC 4206.

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