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Laura Ferrarese
National Research Council of Canada

Patrick Côté
National Research Council of Canada

Elena Dalla Bontà
National Research Council of Canada

David Merritt
Rochester Institute of Technology

et al.

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A FUNDAMENTAL RELATION BETWEEN COMPACT STELLAR NUCLEI, SUPERMASSIVE BLACK HOLES, AND THEIR HOST GALAXIES[1]

Laura Ferrarese[2], Patrick Côté[2,3], Elena Dalla Bontà[2,4], Eric W. Peng[2,3], David Merritt[5], Andrés Jordán[6,7], John P. Blakeslee[8], Monica Haşegan[3,9], Simona Mei[10], Slawomir Piatek[11], John L. Tonry[12], Michael J. West[13]

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ABSTRACT

Imaging surveys with the *Hubble Space Telescope* (*HST*) have shown that ≈ 50–80% of low- and intermediate-luminosity galaxies contain a compact stellar nucleus at their center, regardless of host galaxy morphological type. We combine *HST* imaging for early-type galaxies from the *ACS Virgo Cluster Survey* with ground-based long-slit spectra from KPNO to show that the masses of compact stellar nuclei in Virgo Cluster galaxies obey a tight correlation with the masses of the host galaxies. The same correlation is obeyed by the supermassive black holes (SBHs) found in predominantly massive galaxies. The compact stellar nuclei in the Local Group galaxies M33 and NGC 205 are also found to fall along this same scaling relation. These results indicate that a generic by-product of galaxy formation is the creation of a *central massive object* (CMO) — either a SBH or a compact stellar nucleus — that contains a mean fraction, ≈ 0.2%, of the total galactic mass. In galaxies with masses greater than $\mathcal{M}_{\rm gal} \sim$ a few $10^{10}\mathcal{M}_\odot$, SBHs appear to be the dominant mode of CMO formation.

Subject headings: black hole physics–galaxies: elliptical and lenticular–galaxies: nuclei–galaxies: structure –galaxies: kinematics and dynamics

1. INTRODUCTION

Stellar and gas dynamical studies in an ever-increasing number of galaxies have established that many — and perhaps all — luminous galaxies contain central supermassive black holes (SBHs). Following the discovery that the SBH masses, $\mathcal{M}_{\rm SBH}$, correlate with various properties of the host galaxy — such as bulge luminosity (Kormendy & Richstone 1995), mass (Häring & Rix 2004), velocity dispersion (Ferrarese & Merritt 2000; Gebhardt et al. 2000a), light concentration (Graham et al. 2001), and halo circular velocity (Ferrarese 2002) — it has become widely accepted that SBH and galaxy formation are closely entwined.

Unfortunately, the physical mechanisms underlying this connection remain obscure (e.g. Silk & Rees 1998; Portegies Zwart et al. 2004; Shapiro 2005). Despite intense observational effort, only about 30 galaxies have secure SBH detections (see the recent review of Ferrarese & Ford 2005), the great majority of which are luminous galaxies with magnitudes in the range $-22 \lesssim M_B \lesssim -18$. It is unclear if fainter and less massive galaxies *also* contain SBHs and, if so, whether such objects would obey extrapolations of the SBH scaling relations defined by the bright galaxies. Searches for SBHs in low-luminosity members of the Local Group have so far produced ambiguous results. There is no evidence for a SBH in either M33 (Merritt et al. 2001; Gebhardt et al. 2001) or NGC 205 (Valluri et al. 2003), yet M32 does appear to contain a SBH with $\mathcal{M}_{\rm SBH} \approx 2.5\times10^6\mathcal{M}_\odot$ (Verolme et al. 2002).

Although they have very different morphologies, M33 (Sc II-III) and NGC 205 (S0/E5pec) share one noteworthy similarity: their centers are both marked by the presence of a compact stellar nucleus (with half-light radius $r_h \lesssim$ 2-4 pc) that is ~ 20 times brighter than a typical globular cluster (e.g., Kormendy & McClure 1993; Butler & Martinez-Delgado 2005). While ground-based surveys of the Virgo and Fornax Clusters had shown $\sim 25\%$ of dE galaxies to contain such nuclei (e.g. Binggeli, Tammann & Sandage 1985; Ferguson 1989; Binggeli & Cameron 1991), recent observations with the *Hubble Space Telescope* (*HST*) have revealed them to be far more common. About 50-70% of late-type galaxies observed by *HST* contain a distinct nuclear star cluster (Carollo, Stiavelli & Mack 1998; Matthews et al 1999; Böker et al. 2002, 2004; Balcells et al. 2003), while a recent *HST* survey of 100 galaxies in the Virgo Cluster has detected nuclei in a comparable fraction (66–82%) of early-type galaxies (Côté et al. 2006; see also Lotz et al. 2004; Graham & Guzman 2003; Grant et al. 2005).

In this *Letter*, we explore the connection between compact stellar nuclei, SBHs and their host galaxies by com-

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[2] Herzberg Institute of Astrophysics, National Research Council of Canada, 5071 West Saanich Road, Victoria, BC, V8X 4M6, Canada; laura.ferrarese@nrc-cnrc.gc.ca
[3] Visiting Astronomer, KPNO/NOAO, which is operated by AURA under cooperative agreement with the NSF.
[4] Dipartimento di Astronomia, Universitá di Padova, Vicolo dell'Osservatorio 2, 35122 Padova, Italy
[5] Dept. of Physics, Rochester Institute of Technology, 84 Lomb Memorial Drive, Rochester, NY 14623
[6] European Southern Observatory, Karl-Schwarzschild-Str. 2, 85748 Garching, Germany
[7] Astrophysics, Denys Wilkinson Building, University of Oxford, 1 Keble Road, Oxford, OX1 3RH, UK
[8] Dept. of Physics, Washington State University, Webster Hall 1245, Pullman, WA 99164-2814
[9] Dept. of Physics and Astronomy, Rutgers University, New Brunswick, NJ 08854
[10] Dept. of Physics and Astronomy, The Johns Hopkins University, 3400 North Charles Street, Baltimore, MD 21218-2686
[11] Dept. of Physics, New Jersey Institute of Technology, Newark, NJ 07102
[12] Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822
[13] Dept. of Physics and Astronomy, University of Hawaii, Hilo, HI 96720

bining *HST* imaging for 100 early-type galaxies from the *ACS Virgo Cluster Survey* (ACSVCS; Côté et al. 2004) with new ground-based long-slit spectra for the brightest 69 of these galaxies. We show that the mass of the Central Massive Object (CMO) — either a compact stellar nucleus or a SBH — scales in direct proportion to the galaxy mass. This finding points to a direct link between SBHs, which are preferentially detected in the brightest galaxies, and the compact stellar nuclei commonly observed in galaxies of low and intermediate luminosity.

2. OBSERVATIONS AND DATA REDUCTIONS

HST images for 100 members of the Virgo Cluster were acquired with the *Advanced Camera for Surveys* (*ACS*; Ford et al. 1998) as part of the ACSVCS (GO-9401). The program galaxies span a range of ≈ 460 in blue luminosity and have early-type morphologies: E, S0, dE, dE,N or dS0. Images were taken in WFC mode with a filter combination roughly equivalent to the g and z bands in the SDSS photometric system. The images cover a $\approx 200'' \times 200''$ field with $\approx 0\farcs1$ resolution and $0\farcs05$ pixel^{-1} sampling. For each galaxy, azimuthally averaged surface brightness profiles were determined as described by Ferrarese et al. (2006) and Côté et al. (2006). We refer the reader to these papers for full details of the analysis.

The 11 ACSVCS galaxies brighter than $M_B \approx -20$ mag are found to have surface brightness profiles that are accurately represented by a "core-Sérsic" model (Graham et al. 2003; Trujillo et al. 2004), described by a Sérsic (1968) model outside a "break radius", r_b, of a few arcseconds, and a shallower power-law interior to r_b. None of these bright galaxies shows clear evidence for a central stellar luminosity excess over the fitted profile. In contrast, nearly all of the fainter galaxies are well fitted with pure Sérsic models; in addition, 60–80% of these 89 galaxies show evidence for a nucleus, identified as a luminosity excess over the best fitted profile within $\sim 1''$. In 51 galaxies, the nucleus is conspicuous enough to allow us to measure photometric and structural parameters; we do so by adding a King model (King 1966) to the Sérsic component when fitting the surface brightness profile. Fig. 1 shows images and surface brightness profiles for two representative galaxies from the ACSVCS: a "core-Sérsic" galaxy with $M_B \approx -21.4$ mag (M60), which also happens to have a dynamically measured SBH mass $\mathcal{M}_{\rm SBH} = 2.0(^{+0.5}_{-0.6})\times 10^8 \mathcal{M}_\odot$ (Gebhardt et al. 2003); and a typical nucleated Sérsic galaxy (IC 3773) with $M_B \approx -17.3$ mag.

Although compact, the central nuclei are resolved in all but a half dozen or so cases: half-light radii range from $r_h \leq 2$ pc (i.e., unresolved) to 62 pc, with a median of ≈ 4 pc. We estimate total masses for the nuclei by multiplying their g, z luminosities (determined by integrating the best-fit King models) with appropriate mass-to-light ratios, Υ_g and Υ_z. Single-burst stellar population models from Bruzual & Charlot (2003) were used to estimate Υ_g and Υ_z for each nucleus, at the metallicity appropriate for the observed color, for a fixed assumed age of $\tau = 5$ Gyr and adopting a Chabrier (2003) IMF. The uncertain ages of the nuclei is the dominant source of uncertainty on the derived masses; the difference (of order $\approx \pm 45\%$) between the 5 Gyr masses and those obtained assuming ages of 2 and 10 Gyr, is taken as representative of the error on the quoted values.

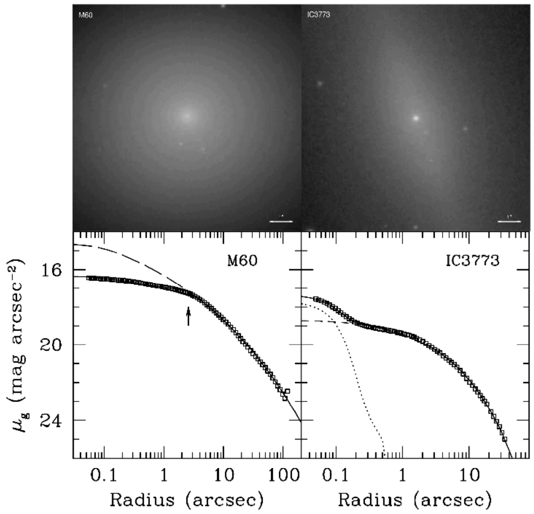

FIG. 1.— *(Upper Panels)* g-band images showing the central regions of M60 (left) and IC 3773 (right), the 3rd and 51st brightest galaxies respectively in the ACSVCS. *(Lower Panels)* Azimuthally-averaged g-band surface brightness profiles for the same two galaxies. M60 is a typical non-nucleated "core-Sérsic" galaxy: the best core-Sérsic model is shown as a solid curve. The vertical arrow shows the radius, r_b, at which the outer Sérsic profile "breaks" to an inner power-law; the long-dashed curve shows the inward extrapolation of the Sérsic model fitted to the data beyond r_b. For IC 3773, we show the best-fit model which consists of a central King model for the nucleus (dotted curve) and a Sérsic model for the underlying galaxy (dashed curve). The solid curve shows the composite model.

Long-slit spectra for the 69 ACSVCS galaxies brighter than $M_B = -16.5$ mag, of which 29 are classified as certainly nucleated, were obtained between 2003 March 10–12 and 2003 March 21–28 using facilities at the Kitt Peak National Observatory (KPNO). All spectra were obtained with the slit oriented along the galaxy photometric major axis, and were centered on the Mg b triplet near 5200 Å. Three separate instrumental setups were used for th‘¡e bright, middle and faint thirds of the sample. Spectral resolutions ranged between 94 km s^{-1} and 220 km s^{-1} at 5200 Å. Exposure times ranged between 2400 s and 5400 s. Between one and three giant or subgiant stars of spectral type G8–K2, to be used as velocity dispersion templates, were observed each night with the same instrumental setup adopted for the galaxies.

Systemic velocities, v, and velocity dispersions, σ, were extracted using the Penalized Pixel-Fitting code of Cappellari & Emsellem (2004) from spectra binned, in the spatial direction, within an aperture of radius equal to the galaxy effective radius, R_e. The final v and σ, and their errors, are the averages and standard deviation of the values obtained using three different template stars.

3. RESULTS

In the left panel of Fig. 2 masses for the nuclei are shown in red, plotted as a function of the extinction-corrected, absolute blue magnitude of the galaxy M_B (Binggeli et al. 1985). In the middle panel, masses are plotted against the stellar velocity dispersion σ, measured within R_e. Solid black dots show SBH masses (from Table II of Ferrarese & Ford 2005; M_B values are mostly from the RC3, de Vaucouleurs et al. 1991) de-

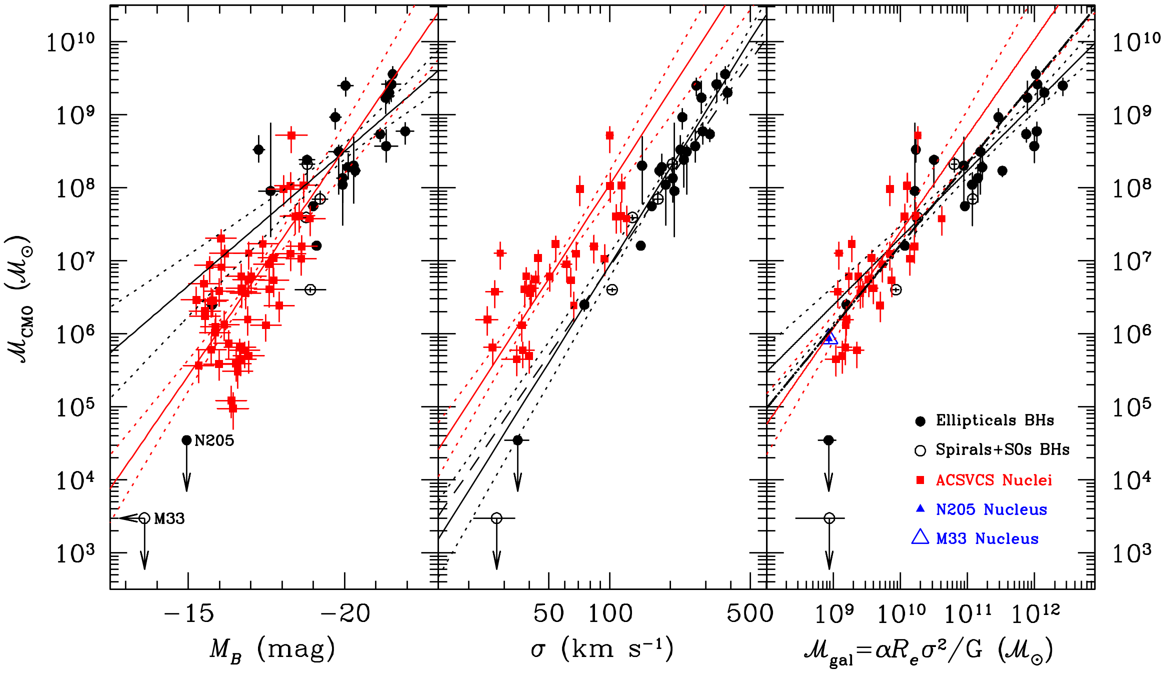

Fig. 2.— *(Left Panel)* Mass of the Central Massive Object (CMO) plotted against absolute blue magnitude of the host galaxy (or bulge for spiral galaxies). Nuclei from the ACSVCS are shown as red squares. The supermassive black holes (SBHs) in early-type and spiral galaxies are shown as filled and open circles respectively. *(Middle Panel)* CMO mass as a function of velocity dispersion of the host galaxy, measured within R_e. *(Right Panel)* CMO mass plotted against galaxy mass, defined as $\mathcal{M}_{\rm gal} \equiv \alpha R_e \sigma^2/G$ with $\alpha = 5$. In all panels, the solid red and black lines show the best fits to the nuclei and early-type SBH samples respectively, with 1σ confidence levels shown by the dotted lines. In the middle panel, the dashed line is the best fit $\mathcal{M}_{\rm SBH}$-σ relation of Tremaine et al. (2002). In the right panel, the dashed line is the fit obtained for the combined nuclei+SBH sample. Coefficients for all fits are listed in Table 1.

tected based on stellar/gas dynamical studies which resolve the sphere of influence. Velocity dispersions for the galaxies with SBHs are from Tremaine et al. (2002) or (for the three galaxies for which no values were published in Tremaine et al.) Ferrarese & Ford (2005).

A first noteworthy point is that there is almost no overlap in the range of M_B and σ occupied by galaxies with nuclei and SBHs, with the former found preferentially in fainter galaxies with lower velocity dispersion. This is partly, but not entirely, due to observational biases. Galaxies brighter than $M_B \sim -20$ mag do not contain nuclei (see §2) but host SBHs[14]. Evidence supporting the latter statement comes from the fact that SBHs have been successfully detected in all galaxies targeted in this magnitude range by dynamical studies, and masses have been found to be consistent with the $\mathcal{M}_{\rm SBH}$-σ relation. Furthermore, the existence of SBHs in all bright galaxies is required to reconcile the local and AGN SBH mass functions (e.g. Marconi et al. 2004; Shankar et al. 2004).

As one moves to fainter galaxies, nuclei become increasingly common, and are almost always present in galaxies fainter than $M_B \sim -18$ mag (Côté et al. 2006). Located at the faint end of the magnitude range spanned by the ACSVCS galaxies, NGC 205 and M33, both of which are strongly nucleated, are not believed to contain SBHs (Merritt et al. 2001; Gebhardt et al. 2001; Valluri et al. 2003). Galaxies with nuclei, SBHs or, possibly, both, are found in the $-18 \lesssim M_B \lesssim -20$ mag range. In the same magnitude range, galaxies exist for which the existence of a SBH is uncertain (e.g. NGC 3379, NGC 4342, Gebhardt et al. 2000b; Cretton and van den Bosch 1999). Overall, therefore, the existing data supports a view in which *bright galaxies often, and perhaps always, contain SBHs but not stellar nuclei. As one moves to fainter galaxies, nuclei become the dominant feature while SBHs might become less common, and perhaps disappear entirely at the faint end.*

Further insight can be gained by relating the masses of nuclei and SBHs to the properties of the host galaxy. Regression fits (Akritas & Bershady 1996) for the early-type galaxies (spirals have been excluded to ensure consistency with the ACSVCS sample) confirm the visual impression from the left and middle panels of Fig 2 that nuclei and SBHs obey statistically different scaling relations with respect to both galaxy magnitude and bulge velocity dispersion (Table 1). However, a different picture emerges (see the right panel of Fig 2) when the virial mass of the host galaxy, $\mathcal{M}_{\rm gal} = \alpha R_e \sigma^2/G$, is considered. Here G is the gravitational constant and $\alpha = 5$ (Cappellari et al. 2006); the geometric effective radius, $R_e = a\sqrt{1-\epsilon}$, a being the radius measured along the isophotal semi-major axis, is taken from Ferrarese et al. (2006) for the ACSVCS galaxies, and from Marconi & Hunt (2003) for the galaxies hosting SBHs. A regression analysis (Table 1) demonstrates that *the nuclei and SBHs obey a common scaling relation linking their mass to the virial mass of the host galaxy*[15]. Furthermore, the same relation is obeyed by the nuclei of NGC 205 (Geha et al. 2006) and M33 (for which we adopt $R_e = 1$ kpc, intermediate to the values of Minniti

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[14] The central light excess in the bright core-Sérsic galaxies M87 (e.g. Ferrarese et al. 2006) and NGC 6166 (Capetti et al. 2000), both of which are strong radio sources, are unresolved and have a non-stellar origin.

Table 1. Scaling Relations for Central Massive Objects (CMOs)

(X, Y)	a	b	χ_r^2	N
$M_B + 19.9$ mag,$\mathcal{M}_{\rm SBH}$	-0.37 ± 0.08	8.46 ± 0.11	19.1	21
$M_B + 16.9$ mag,$\mathcal{M}_{\rm nuc}$	-0.62 ± 0.10	6.59 ± 0.09	3.1	51
$\sigma/(224$ km s$^{-1})$, $\mathcal{M}_{\rm SBH}$	4.41 ± 0.43	8.48 ± 0.07	3.0	21
$\sigma/(54$ km s$^{-1})$, $\mathcal{M}_{\rm nuc}$	4.27 ± 0.61	6.91 ± 0.11	7.0	29
$\mathcal{M}_{\rm gal}/(10^{11.3}\ \mathcal{M}_\odot)$,$\mathcal{M}_{\rm SBH}$	0.92 ± 0.11	8.47 ± 0.08	8.9	21
$\mathcal{M}_{\rm gal}/(10^{9.6}\ \mathcal{M}_\odot)$,$\mathcal{M}_{\rm nuc}$	1.32 ± 0.25	6.91 ± 0.09	6.0	29
$\mathcal{M}_{\rm gal}/(10^{10.3}\ \mathcal{M}_\odot)$,$\mathcal{M}_{\rm CMO}$	1.12 ± 0.07	7.57 ± 0.07	8.9	50
$\mathcal{M}_{\rm gal}/(10^{10.3}\ \mathcal{M}_\odot)$,$\mathcal{M}_{\rm CMO}$	$\equiv 1$	7.56 ± 0.47	7.4	50

Note. — Columns (2) and (3) give best-fit coefficients for linear relations of the form $\log Y = a \log X + b$ (or $\log Y = aX + b$ when fitting to the galaxies' magnitudes). χ_r^2 is the reduced χ^2 of the fit, while N is the number of datapoints used in the fit.

et al. 1994 and Regan & Vogel 1994), while the upper limits on the mass of the central SBH in both galaxies fall well below the best fit line.

On these grounds, we suggest that SBHs and nuclei should be grouped together under the terminology, "Central Massive Object" (CMO), which we adopt for the remainder of this *Letter*. Constraining the slope of the $\mathcal{M}_{\rm CMO}$-$\mathcal{M}_{\rm gal}$ relation to be unity leads to a constant ratio between CMO and galaxy mass $\mathcal{M}_{\rm CMO}/\mathcal{M}_{\rm gal} \approx 0.18\%$ (with a $\pm 1\sigma$ range of 0.06–0.52%), a conclusion also reached, based on photometric data only, by Côté et al. (2006) and Wehner & Harris (2006). We note that our conclusions are insensitive to the exact methodology used in measuring σ. In particular, integrating σ within $1''$ (a region dominated by the nucleus), between $3''$ and R_e (a region dominated by the host galaxy), or within $1/8R_e$ (as in Ferrarese & Merritt 2000), changes the individual measurements (by, on average $\sim$5%, although differences of up to 30% can be seen for some of the fainter galaxies) but does not alter the overall trend.

4. DISCUSSION

The main finding in this paper is that a common $\mathcal{M}_{\rm CMO}$-$\mathcal{M}_{\rm gal}$ relation leads smoothly from SBHs to nuclei as one moves down the mass function for early-type galaxies. This suggests that a single mechanism is responsible for the growth — and perhaps the formation — of both nuclei and SBHs. It also points to galaxy mass as the primary (though not necessarily only) parameter regulating such growth.

Stellar cusps and SBHs have often been linked in the literature, and it is therefore natural to ask whether nuclei could be the by-product of SBH evolution. Since most nuclei in the ACSVCS galaxies are spatially resolved, we can exclude that they formed either via adiabatic growth (Young 1980) or, in the fainter galaxies, via the Bahcall-Wolf (1976) process, since either mechanism generates a power-law cusp only within a fraction of the SBH's influence radius (Merritt & Szell 2005). However, nuclei and SBHs might coexist in *some* galaxies; the most promising cases being M32 (Verolme et al. 2002) and the Milky Way (Ghez et al. 2003; Schödel et al. 2003). Although neither galaxy possesses the kind of nucleus seen in the faintest ACSVCS galaxies, it is quite possible, if not likely, for nuclei to undergo structural changes as a consequence of the presence of the central SBH.

Beyond this, the exact interplay between nuclei and SBHs remains elusive. It is possible that nuclei form in all galaxies, but in the most massive systems either they subsequently collapse to SBHs, or are destroyed or modified by the evolution of pre-existing SBHs. As mentioned in §2, the surface brightness profiles of galaxies brighter than $M_B \sim -20$ mag, which host SBHs but not nuclei, display an inner "deficit" relative to the inward extrapolation of the Sérsic law that best fits the outer parts (Fig. 1; Ferrarese et al. 2006; Trujillo et al. 2004). Such deficits are generally believed to result from the disruptive effects of binary SBH evolution (Ebisuzaki, Makino & Okumura 1991; Milosavljević et al. 2002; Ravinandrath et al. 2002; Graham 2004), so the same process might have led to the destruction of a central nucleus. Nuclei in slightly fainter galaxies which also contain a SBH might have avoided destruction or might have been regenerated at a later time, perhaps, e.g., by subsequent star formation. Determining stellar population ages for the nuclei would provide some observational constraints for this scenario. Age and abundance measurements for our nuclei will be presented in a future ACSVCS paper.

Alternatively, the formation of SBHs and nuclei could be mutually exclusive, with only material collected at the centers of massive systems able to collapse to a black hole, while in less massive galaxies the collapse is halted and a star cluster is formed. SBHs and nuclei are almost certainly mutually exclusive in the faintest galaxies considered here, as suggested by the fact that, although the nuclear masses of NGC 205 and M33 are fully consistent with the $\mathcal{M}_{\rm CMO}$-$\mathcal{M}_{\rm gal}$ relation, the upper limits on their SBH masses are *not*, implying that neither galaxy contains a SBH of the sort expected from extrapolations of the scaling relations defined by SBHs in massive galaxies. If the formation of a SBH prevents the formation of a "NGC 205-type" nucleus (or vice versa), then nuclei of galaxies which are known to host SBHs (e.g., M32, the MW, and potentially all galaxies with a few $\times 10^9\ \mathcal{M}_\odot \lesssim \mathcal{M}_{\rm gal} \lesssim$ a few$\times 10^{10}\ \mathcal{M}_\odot$) would necessarily have to belong to a separate class. A high resolution study of the nuclear morphology in nearby ($d \lesssim 15$ Mpc) galaxies might unveil whether nuclei in galaxies of different mass are structurally distinct. These issues will be explored in more detail in forthcoming papers.

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[15] We note that all nucleated galaxies are early-type (ellipticals and S0s), and so are the galaxies with central SBHs used in performing the fits. For all, $\mathcal{M}_{\rm gal}$ is a measure of the total mass of the galaxy, rather than the mass of the bulge, since even in lenticular galaxies, both bulge and disk components contribute to the measured σ.

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