The Nuclei of Low-Mass Galaxies and the Search for the Smallest Massive Black Holes

A White Paper Submitted to the Astronomy and Astrophysics 2010 Decadal Survey

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1 Introduction

This white paper, addressed to the Galactic Neighborhood panel of the Astro2010 Decadal Survey committee, focuses on new scientific opportunities in the search for black holes (BHs) in the centers of nearby galaxies and star clusters. We begin by highlighting a few of the key questions that will motivate much of the research in this field over the coming decade.

- How massive were the initial "seeds" that grew into the supermassive black holes (SMBHs)[1] found in massive galaxies today? By what mechanism, and at what redshifts, did they form?
- Can intermediate-mass black holes (IMBHs) form in dense star clusters? If so, are they retained by their host clusters or ejected by dynamical processes?
- How do BHs affect the evolution and structure of their host galaxies? How is BH growth influenced by the host galaxy environment, both on large scales (dark matter halo and large-scale host galaxy properties) and small scales (nuclear star clusters)?

Obtaining answers to these questions will require a variety of observational approaches, including dynamical searches for BHs with large optical/IR telescopes, multiwavelength surveys to determine the growth rate of BHs out to the highest observable redshifts, and gravitational-wave observations that will directly detect the signatures of BH mergers and the inspiral of stellar-mass compact objects into massive BHs. In this white paper, we focus on stellar-dynamical searches for BHs in nearby galactic nuclei and star clusters. Specifically, we highlight new opportunities for surveying the population of BHs with $M_{\rm BH} < 10^7\ M_\odot$, and discuss how a better understanding of the population of these objects can contribute to answering the above questions.

2 Massive black hole detections: status and open questions

A key development in extragalactic astronomy during the past 15 years has been the detection of SMBHs having $M_{\rm BH} = 10^{6.5} - 10^{9.5}\ M_\odot$ in the centers of a few dozen nearby galaxies, and the recognition that most (and perhaps all) massive galaxies with bulges host a central SMBH. Most dynamical detections of SMBHs have come from the STIS instrument on the *Hubble Space Telescope* (*HST*), and during the past few years, observations with adaptive optics (AO) systems on 8-10m ground-based telescopes have begun to make important contributions to the search for SMBHs. Observations show that the BH mass is correlated with both the luminosity and the stellar velocity dispersion (σ) of the host galaxy's bulge component [27, 15, 18]. These correlations are remarkable in that they imply that the growth of the SMBH (which itself has a mass of only $\sim 0.1\%$ of the host's bulge mass) must be very closely coupled to the growth and evolution of the host galaxy's properties on kiloparsec scales. The discovery of the surprisingly tight $M_{\rm BH} - \sigma$ correlation in 2000 motivated much of the subsequent observational and theoretical research on SMBHs [14].

In contrast with the situation for $M_{\rm BH} > 10^7\ M_\odot$, our knowledge of BH demographics is very incomplete for $M_{\rm BH} \lesssim 10^7\ M_\odot$ or for galaxies with stellar velocity dispersions below about 100

[1] In this document, we refer to black holes with with $M_{\rm BH} > 10^5\ M_\odot$ as supermassive black holes (SMBHs), and black holes with $10^2 < M_{\rm BH} < 10^5\ M_\odot$ as intermediate-mass black holes (IMBHs).

km s^{-1} (Figure 1). For lower masses and velocity dispersions, the fraction of galaxies that contain a BH is extremely uncertain. Indeed, there are significant non-detections of BHs in a few nearby galaxies from stellar-dynamical observations, most notably the Local Group Scd-type spiral galaxy M33, in which the upper limit to $M_{\rm BH}$ is just a few thousand solar masses [19, 31]. Similarly, in the Local Group dwarf elliptical galaxy NGC 205, $M_{\rm BH} < 3.8 \times 10^4\ M_\odot$ [40]. These results suggest that the SMBH "occupation fraction" in low-mass galaxies might be significantly below unity, but at present it is not possible to carry out measurements of similar sensitivity for galaxies much beyond the limits of the Local Group.

Low-mass BHs can in some cases be detected if they are accreting gas in active galactic nuclei (AGNs). The Sloan Digital Sky Survey has recently enabled the first systematic searches for AGNs with $M_{\rm BH} \lesssim 10^6\ M_\odot$ and an initial exploration of their demographics [22, 3], and X-ray and mid-infrared surveys have begun to explore the regime of low-mass AGNs with $M_{\rm BH} \lesssim 10^6\ M_\odot$ as well [17, 36]. However, the fraction of galaxies containing detectable AGNs drops very steeply below host galaxy stellar masses of $\sim 10^{10}\ M_\odot$, and AGN surveys are only able to set very crude lower limits to the BH occupation fraction in galaxies of lower mass [26, 10].

An important recent development in the study of the relationship between BHs and their host galaxies has been the discovery that most galaxies of low and intermediate luminosity (i.e., the same systems that are expected to contain BHs with $M_{\rm BH} \lesssim 10^7\ M_\odot$) contain distinct stellar nuclear components, usually referred to as nuclear clusters (NCs). Much effort has recently been devoted to studying possible connections between NCs and BHs, as it appears both objects may contribute a comparable fraction of the total galaxy mass across a range of Hubble types [8, 41, 13, 35, 37]. The fraction of low-mass galaxies with NCs that *also* contain BHs remains an open question, however, and stellar dynamical studies for a handful of nearby low-mass galaxies with NCs have yielded only upper limits to the mass of any BHs that may be present [19, 31, 40, 4].

At still lower masses, the possible presence of IMBHs in globular clusters has intrigued astronomers for decades. Some globular clusters have structural properties that are strikingly similar to those of NCs in galactic centers, and a few globulars (such as ω Cen) may actually be the remnants of accreted and stripped dwarf galaxies. Furthermore, the proximity of Milky Way globulars makes them probes of BH demographics in a mass regime ($M_{\rm BH} < 10^5\ M_\odot$) that is not accessible in external galaxies. Radial velocity studies have led to reports of IMBHs in a few clusters [21, 20, 32], with $M_{\rm BH}$ ranging from $\sim 3,000$–$40,000\ M_\odot$. However, the statistical significance of these results is low due to the limited angular resolution of current observations, and the possible existence of IMBHs in globular clusters remains very much an open question.

3 Connecting BH demographics with formation scenarios

The formation of SMBHs is poorly understood, as is evident in the widely varying theories for the formation of the initial "seed" BHs that grew by accretion and merging to become the SMBHs in the centers of galaxies. According to one scenario, the origin of SMBHs can be traced back to the first generation, "Population III" stars that formed out of metal-free gas in the first gravitationally bound baryonic objects. Pop III stars with masses between 40 and 140 $M_\odot$, and above 260 $M_\odot$, are expected to collapse directly into BHs [24]. The deaths of these first-generation stars would have left behind BH seeds with typical masses of order $\sim 100\ M_\odot$ lodged in the potential well of the parent dark matter halo [16, 29]. In an alternative scenario that could have taken place in

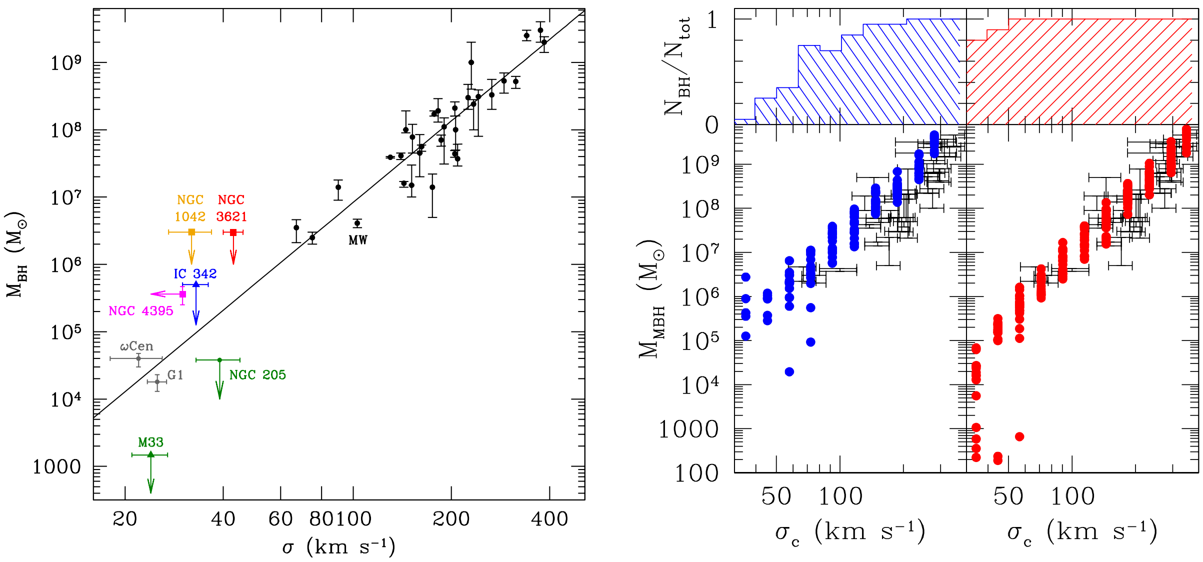

Figure 1. *Left panel:* The $M_{\rm BH}-\sigma$ relation for nearby galaxies, including dynamical measurements for late-type disk galaxies, dwarfs, and globular clusters below $\sigma \sim 100$ km s^{-1} [4]. Black points are the sample compiled from [38]. Colored squares represent late-type galaxies with AGNs, and colored triangles represent inactive late-type galaxies. Below $\sigma = 100$ km s^{-1}, there are very few BH detections or significant upper limits to $M_{\rm BH}$ in nearby galaxies. *Right panel:* Example model predictions for the $M_{\rm BH}-\sigma$ relation and BH occupation fraction ($N_{\rm BH}/N_{\rm tot}$) for two different BH seed formation scenarios (adapted from [39]): (left, blue points) models with high-mass BH seeds with $M_{\rm BH} \sim 10^5\ M_\odot$, and (right, red points) low-mass BH seeds from Pop III stars with $M_{\rm BH} \sim 100\ M_\odot$. For $M_{\rm BH} \lesssim 10^7\ M_\odot$, the two seed formation scenarios make strongly different predictions for BH occupation fraction and the $M_{\rm BH}-\sigma$ relation in present-day galaxies. Black points represent locally measured SMBH masses as compiled from [14].

primordial galaxies, direct formation of a more massive seed BH with $M_{\rm BH} \sim 10^4-10^6 M_\odot$ from a collapsing metal-free gas cloud is possible [7, 5, 28]. A distinct third possibility is that the seed forms via runaway stellar coalescence resulting from mass segregation-accelerated core collapse in a young, metal-poor stellar cluster [33, 11]. More speculatively, rapid stellar coalescence could lead to the creation of seed BHs in nascent massive star clusters in starbursts [23], which would imply that a large number of IMBHs could simultaneously find themselves in the central stellar spheroid formed in the starburst [12]. It is uncertain, however, whether the agglomerate star in the nucleus of a young cluster can avoid catastrophic stellar wind mass loss prior to the collapse into a BH. Whichever the origin of the seed BHs, their path toward growing into SMBHs is strewn with difficulties: accretion onto such small objects is impeded by radiative effects, and interactions and merging with other seed BHs can lead to ejection of BHs into intergalactic space via gravitational radiation recoil or three-body encounters.

The primary motivation for extending the observational census of BHs in local galactic nuclei to lower masses stems from the fossil record of BH formation and early growth that is encoded in the demographics of low-mass BHs. In massive, bulge-dominated galaxies, the SMBH mass is dominated by the material accreted over the history of the galaxy, primarily during quasar accretion episodes. The end product of this growth is an SMBH whose mass is linked to the large-scale properties of the host galaxy's bulge, and any dependence of $M_{\rm BH}$ on the initial seed mass is largely erased. However, low-mass galaxies undergo a quieter merger history, and as a result, *at low masses the BH occupation fraction and the distribution of BH masses still retain some "memory" of the original seed mass distribution* [30, 39]. Figure 1 (*right panel*) illustrates how the local demographics of low-mass BHs can elucidate their early formation history. The figure shows the results of simulations for two extreme cases: one for the scenario of low-mass seeds from Pop III stars, and one for $\sim 10^5$ $M_\odot$ seeds from the direct collapse mechanism [39]. The two cases show markedly different behavior for the predicted BH occupation fraction and $M_{\rm BH}-\sigma$ relation at low masses. In particular, the $M_{\rm BH}-\sigma$ relation in the smallest galaxies ($\sigma \lesssim 50$ km s^{-1}) can distinguish between high-mass and low-mass seeds, and the BH occupation fraction at low masses is strongly dependent on the efficiency of BH seed formation in high-redshift dark matter halos. Furthermore, small galaxies, with shallow potential wells, are more susceptible to becoming deprived of their central BHs as a result of ejections, providing information on the BH dynamics and merger rate.

The crucial goal for future observations is to push dynamical searches for BH as close as possible to the mass scale of BH seeds, where local BH demographics are sensitive to these differences among possible formation histories. As described above, at present the shape of the $M_{\rm BH}-\sigma$ relation is virtually unconstrained for $M_{\rm BH} < 10^7$ $M_\odot$, and only weak lower limits to the BH occupation fraction in this mass range currently exist from dynamical searches or AGN surveys.

4 The decade ahead: the low-mass end of the BH mass function

The primary obstacle in characterizing the low-mass end of the BH mass function is our current inability to resolve angular scales comparable to the gravitational sphere of influence of BHs with mass $<10^7$ $M_\odot$ at distances beyond a few Mpc. The radius of the sphere of influence, within which the BH dominates the gravitational potential, is $r_G = GM_{BH}/\sigma^2$. As an example, a SMBH of mass 10^6 $M_\odot$ residing in a galaxy with $\sigma = 50$ km s^{-1} will have $r_G \approx 1$ pc. At the distance (16.5 Mpc) of the Virgo Cluster – the largest collection of galaxies in the nearby Universe – this corresponds to an angular size of $\theta_{r_G} \approx 12$ milliarcsec (mas), below the diffraction limit, θ_{DL}, of existing 8-10m class telescopes. A key goal for future work will be to carry out a measurement of the low-mass end of the BH mass function for a large (i.e., $N \gtrsim 100$) and representative sample of nearby galaxies.

The instrument required to accomplish this goal would be either (1) a 25-30m optical/IR telescope operating at its diffraction limit (i.e., $\theta_{DL} \approx 9-7$ mas at the Ca II triplet at 0.86 μm, or 23-19 mas for the CO bandhead at 2.29 μm in the K band), or (2) an 8-16m space-based telescope operating at optical wavelengths (i.e., the Mg*b* region at 5200 Å, for $\theta_{DL} \approx 16-8$ mas). In either case, the ideal instrumentation would consist of an integral-field spectrograph with spatial pixel size sufficient to fully sample the telescope's diffraction-limited performance and with spectral resolving power of $R \sim 8000$, in order to map out the kinematic structure of galaxy nuclei and NCs with velocity dispersions as low as $\sigma \sim 15-20$ km s^{-1}.

The higher angular resolution of these new facilities will vastly increase our ability to detect SMBHs with masses $<10^7$ $M_\odot$. This is illustrated in Figure 2. The left panel shows the total number of galaxies within 40 Mpc predicted by the $M_{BH}-\sigma$ relationship to host SMBHs with spheres-of-influence resolvable using a 30m diffraction-limited telescope. Studies of nearby galaxies will be able to find (or place significant upper limits on) hundreds of SMBHs in the 10^{4-7} $M_\odot$

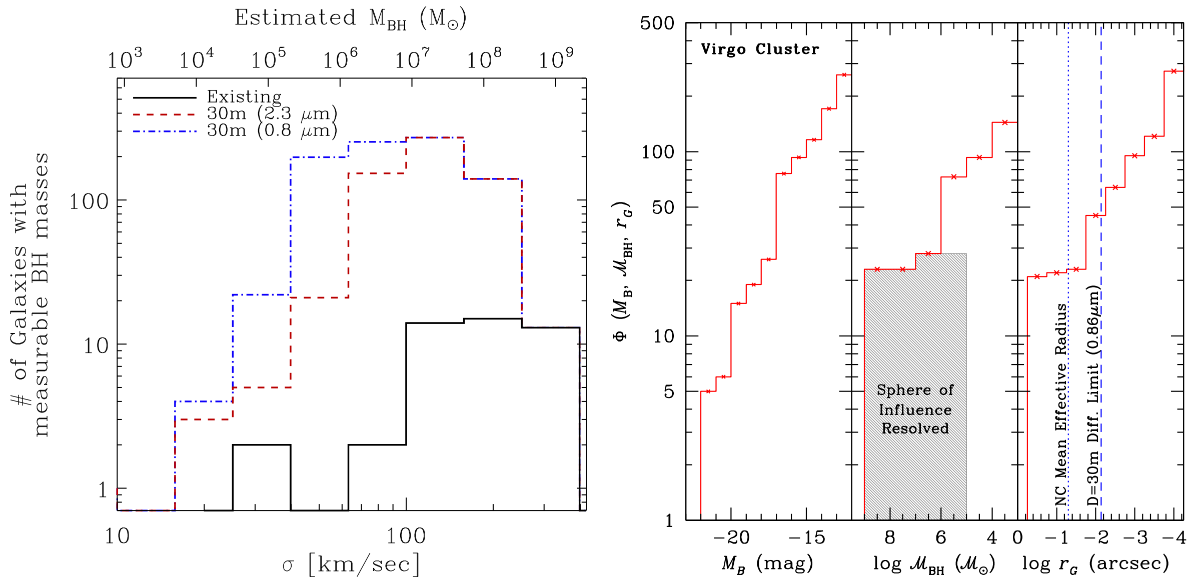

Figure 2. Predictions for the number of galaxies for which dynamical detections of BHs will be possible with a future 30-m ground-based telescope. *Left:* A comparison of the galaxy sample with existing BH mass measurements [38, 14] to galaxies with BH measurements made possible by a 30-m telescope. The upper two histograms show galaxies within 40 Mpc that could have central BHs detectable using diffraction limited observations at the CO bandhead at 2.3 μm (dashed red line) and the Ca II triplet at 0.85 μm (dot-dashed blue line). *Right, first panel:* Luminosity distribution of 956 early-type galaxies belonging to the Virgo Cluster. *Right, second panel:* One prediction for the mass distribution of BHs in this sample of galaxies, obtained by combining the $M_{\rm BH}-\sigma$ and $L_{\rm bulge}$-σ relations [14, 9]. The grey area shows the galaxies for which r_G can be resolved with a 30m telescope operating at its diffraction limit at the Ca II triplet (0.86 μm). *Right, third panel:* Distribution of r_G for the Virgo Cluster BH population. For comparison, the mean effective radius of NCs in the Virgo Cluster [8], and the diffraction limit of a 30m telescope operating at 0.86 μm, are shown by the dotted and dashed lines, respectively.

range, increasing the sample size by roughly two orders of magnitude. The right panels of Figure 2 show a similar prediction for early-type galaxies in the Virgo Cluster, an obvious first target for a systematic survey of SMBHs in a complete mass/luminosity-limited sample of galaxies spanning a significant range in mass. Such a survey would enable a determination of the BH mass function down to $\sim 10^6\ M_\odot$, and increase the number of measured BH masses in the Virgo cluster from six to $\sim$100, allowing a direct measurement of the BH occupation fraction for $M \gtrsim 10^6\ M_\odot$. A next-generation large telescope would also benefit dynamical searches for more massive SMBHs, dramatically increasing both the accuracy of BH mass measurements for nearby galaxies and the number of SMBHs within reach of dynamical detection.

Surveys of nearby galaxy nuclei will also enable comparison of the BH demographics in early-type vs. late-type galaxies; current measurements are very heavily dominated by early-type (elliptical and S0) galaxies, while nearly half of the nearby galaxies with measurable $M_{\rm BH}$ using a future high resolution telescope are late-type (i.e., disk-dominated). Comparing SMBH demographics between galaxy types will help clarify the physical mechanisms responsible for the $M_{\rm BH}-\sigma$ relation. In particular, it remains largely unknown whether galaxies without massive bulges (Sc-Sd spirals) host SMBHs at all. The extremely tight upper limit of $M_{\rm BH} < 1500\ M_\odot$ for the late-type galaxy M33 [19] remains a unique and intriguing measurement, but it is also evident that some late-type, bulgeless galaxies do contain BHs, as demonstrated by the example of the active nucleus in the nearby Sd galaxy NGC 4395 ($M_{\rm BH} \approx 3 \times 10^5\ M_\odot$; [34]). Late-type spirals with NCs such as M33 are very common, and a future large optical/IR telescope will enable us to obtain BH mass constraints similar to that in M33 for dozens of nearby late-type galaxies. Equally important, the stellar content of an individual NC provides a visible record of its formation, so high-angular resolution spectroscopic observations of these NCs will yield direct constraints on the history of star formation and chemical enrichment on spatial scales comparable to r_G for the central SMBHs.

Astrometric searches for IMBHs in globular clusters via proper motion measurements will benefit dramatically from the higher angular resolution afforded by the next generation of large telescopes. A future 8-16m UV/optical space telescope would provide a true breakthrough by achieving a precision of ~ 10 microarcsec year^{-1} over a wide field of view including tens of thousands of stars in the crowded field of a cluster core. Compared with *HST* observations, many more stars in the crowded center could be resolved, and much fainter stars would have sufficient S/N for proper motion determination. This will allow a determination of the velocity dispersion profile to well inside an arcsecond, thus probing the presence of IMBHs down to only hundreds of solar masses, an order of magnitude below what can be probed today. Moreover, much larger samples of globular clusters would become accessible for study. Given the ambiguous results of IMBH searches in globular clusters to date, the definitive dynamical detection of an IMBH would be an important milestone.

A survey of BH demographics at low masses will also have an important impact on the anticipated event rates for future space-based gravitational-wave (GW) observatories. For proposed GW missions with sensitivity in the low-frequency band ($\sim 10^{-4} - 1$ Hz), event rates for massive BH coalescences are expected to be dominated by BHs with $M_{\rm BH} \sim 10^5 - 10^7\ M_\odot$ [25], but this is the same low-mass range where our current knowledge of BH demographics is very incomplete. Extreme mass ratio inspirals (EMRIs), in which a stellar-mass compact object spirals into an IMBH or SMBH, can reveal a wealth of detail about the compact object populations in galaxy nuclei as well as yielding the angular momenta of BHs in the nuclei of low-mass galaxies; predictions for EMRI event rates are also highly sensitive to the BH occupation fraction for $M_{\rm BH} < 10^7\ M_\odot$ [2].

5 Summary

With the development of the next generation of large optical/IR telescopes, we have an opportunity to examine the demographics of massive BHs in a mass regime ($M_{\rm BH} < 10^7\ M_\odot$) that has just barely been explored to date. Extending our knowledge of BH demographics into this low-mass regime with stellar-dynamical studies of well-defined samples of nearby galaxies, and with proper-motion searches for IMBHs in globular clusters, will provide unique new insights into the formation mechanisms and environments of massive BHs and their early growth history.

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