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# In Pursuit of the Elusive Intermediate-mass Black Holes

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There is a largely-missing population of intermediate-mass black holes (IMBHs) with masses greater than that formed by stars today ($M_\bullet \approx 1.4$–$120\,\mathrm{M}_\odot$: Belczynski et al. 2010; Crowther et al. 2010) and less massive than the supermassive black holes (SMBHs, $M_\bullet = 10^5$–$10^{10}\,\mathrm{M}_\odot$: e.g., Graham & Scott 2015) known to reside at the centers of massive galaxies. Not surprisingly, astronomers around the world are hotly pursuing the much-anticipated discovery of IMBHs. This was keenly evident, with global media coverage regarding the LIGO/Virgo consortium's discovery of the collisional creation of an IMBH ($M_\bullet = 142^{+28}_{-16}\,\mathrm{M}_\odot$: Abbott et al. 2020), which built on the earlier report of a collisionally-created $98^{+17}_{-11}\,\mathrm{M}_\odot$ black hole (Zackay et al. 2019). The ground-based gravitational wave interferometers used to make these detections are constrained to detections less than $\sim200\,\mathrm{M}_\odot$, and the planned space-based interferometer LISA—a billion dollar project to determine the abundance of IMBHs and probe the gravitational radiation connected to IMBHs and SMBHs—will not be online for at least another decade (Amaro-Seoane et al. 2022).

Traditional astronomical observations have also hit a wall in their ability to spatially resolve the Keplerian orbits within the gravitational sphere-of-influence around black holes (BHs) less massive than $\approx10^5$–$10^6\,\mathrm{M}_\odot$. While a full spectrum of IMBHs may exist, it is not clear that it must. In addition to providing a fundamental input to the cosmic inventory of our Universe (Fukugita & Peebles 2004), i.e., knowing the abundance, or rarity, and thus the mass/energy density of IMBHs, this much sought after knowledge has implications for the formation of not just IMBHs but also the Universe's most massive BHs. The further discovery of IMBHs would be a great boon to research/theory and provide potential multi-messenger targets for future generations of gravitational wave detectors.

As yet, there is no consensus as to how SMBHs came to be. While the observed extent of quasar activity over the history of our Universe has revealed that the accretion of baryons fattened them up (e.g., Shankar et al. 2004), we do not know what their (potentially range of) birth masses were. Some theories have speculated that their birth or "seed" masses were $\approx10^5\,\mathrm{M}_\odot$, thereby providing a kick-start to explain the early-formation of the high-$z$, active galactic nuclei (AGN) with surprisingly large BH masses ($\approx10^9\,\mathrm{M}_\odot$) in a young Universe (e.g., Mortlock et al. 2011). Such theories have included primordial BHs (e.g., Grobov et al. 2011), massive metal-free Population III stars which subsequently collapse to form massive BHs (e.g., Madau & Rees 2001; Schneider et al. 2002), or the direct collapse of massive gas clouds, effectively by-passing the stellar phase of evolution (e.g., Bromm & Loeb 2003; Mayer et al. 2010).

The suggestion of massive seeds arose from the notion that the "Eddington limit" of gas accretion onto a BH implied that stellar-mass BHs did not have sufficient time to grow into the SMBHs observed in the young, high-redshift AGN (e.g., Mortlock et al. 2011). However, there is growing evidence that the Eddington limit on the accretion rate applies only to (unrealistic) spherical conditions (e.g., Nayakshin et al. 2012; Alexander & Natarajan 2014) and can be significantly exceeded in real systems. For example, super-critical accretion can happen when the accretion flow is mostly confined to the disk plane while most of the radiation emerges perpendicular to it; and when radiative efficiency is reduced by energy advection through the horizon and photon trapping. Most ultra-luminous X-ray sources (ULXs) are now explained as stellar-mass X-ray binaries accreting much faster than their Eddington limit (Feng & Soria 2011; Kaaret et al. 2017), partly negating the need for massive seeds.

An additional motive for starting things off with massive seeds was that BHs with masses intermediate between that of stellar-mass BHs and SMBHs had not been directly observed, and therefore may not exist. However, as alluded to above, this may be a sample selection bias because the sphere-of-gravitational-influence around such IMBHs, where one would directly observe a Keplerian rotation curve (or velocity dispersion spike), is typically too small to resolve spatially. Furthermore, there is now a small but growing number of somewhat randomly detected IMBH candidates based upon indirect estimates of the BH mass (Farrell et al. 2009; Baldassare et al. 2015; Graham et al. 2016; Nguyen et al. 2017, 2019; Jiang et al. 2018; Davis & Graham 2021).

There is no shortage of scenarios for how a bridging population of IMBHs may have arisen, including the runaway collapse of dense "nuclear star clusters" at the centers of galaxies (Portegies Zwart & McMillan 2002), especially if gas-drag is in play, or the gas-fuelled growth of a stellar-mass BH that has not yet devoured enough material to become an SMBH. These ideas, along with smaller seed masses from the previously-mentioned scenarios, would place at least some IMBHs at the centers of galaxies, where established BH mass scaling relations involving SMBHs, such as the famous $M_\bullet$–$\sigma$ relation (Ferrarese & Merritt 2000), can be applied/extrapolated to lower masses[1], yielding predictions of IMBHs at the centers of galaxies with low stellar velocity dispersions. Of course, whether or not they are there requires further information.

Recently, I was involved with an international collaboration to use multiple scaling relations, including X-ray and radio luminosity relations, to search for possible IMBHs (Koliopanos et al. 2017). Subsequent research has included the *Chandra* Virgo Cluster Survey of Spiral Galaxies (Soria et al. 2022), which presents an analysis of the ultraluminous X-ray source population in 75 Virgo Cluster late-type galaxies, including all those with a star formation rate $\gtrsim 1\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$. In Graham et al. (2019, 2021b), we predicted the central BH masses in these galaxies using the latest BH mass scaling relations involving spiral-arm pitch angle ($\phi$), $\sigma$, and total galaxy stellar mass ($M_{\star,\mathrm{tot}}$); focused study of promising candidates is currently underway. So far, this project has demonstrated the potential for half-a-dozen, high-impact papers.

In Graham et al. (2019), we identified three late-type galaxies in the Virgo Cluster with both a predicted BH mass of $\lesssim 10^5\,\mathrm{M}_\odot$ and a centrally located X-ray point source. Later in Graham et al. (2021b), we revealed 11 more such galaxies, more than tripling the number of active IMBH candidates among late-type galaxies of the Virgo Cluster. We intend to pursue observations of this object and the aforementioned $(3 + 11 =)$ 14 additional IMBH candidate targets. Early-stage research is also proceeding in collaboration with Bogdan Ciambur (Observatoire de Paris), involving a focused study of 40–50 IMBH-candidate galaxies from (Graham & Scott 2013) and the bulgeless LEDA 87300 (Graham et al. 2016). In Davis & Graham (2021), we have combined ten different BH mass estimates for a single galaxy (NGC 3319) in order to produce a probability density function of BH mass for the galaxy, and thus a refined mass estimate with a better precision than that of individual estimates. Ongoing research (Davis et al. 2022) will repeat this procedure and measure pitch angles for all (85) of the later type spiral galaxies (i.e., Hubble type Sd) in the Third Reference Catalogue of Bright Galaxies (de Vaucouleurs et al. 1991), in a further search for IMBH candidates.

The build-up of structure in our hierarchical Universe dictates that satellite galaxies should accrete onto their host galaxies. If the dwarf galaxies carry a nuclear IMBH, they could eventually merge with a SMBH. IMBHs hold the key for our understanding of galaxy evolution, feedback, and the growth of the Universe's most massive BHs. Astronomers have collected limited observational evidence of dwarf galaxies in the process of being tidally disrupted as they plunge into their parent galaxies. Even more limited observational evidence has been collected on the existence of X-ray luminous IMBH candidates, which may have originated from previously disrupted dwarf galaxies.

What is still wholly missing is simultaneous observational proof of both aspects of this scenario: a dwarf galaxy with a candidate IMBH, currently in the process of merging and getting disrupted. We may have found such evidence. We made a serendipitous discovery of a potential shredded offset nuclear star cluster with an IMBH, identified by an X-ray source and optical/infrared counterpart (Graham et al. 2021a). Further, we intend to continue searching for such star clusters that may be delivering BH seeds to the center of galaxies via capture and sinking.

Our full sample is interesting because it targets both early- and late-type galaxies, which have different formation processes and which we now know follow different $M_\bullet$–$M_{\mathrm{bulge}}$ scaling relations (Sahu et al. 2019a). Moreover, it may potentially represent a significant increase on the four or five known IMBH ($10^2 < M_\bullet/\mathrm{M}_\odot < 10^5$) candidates at the centers of galaxies (with X-ray point-sources and broad H$\alpha$ lines), includes targets with multiple BH mass predictions of $10^4$–$10^5\,\mathrm{M}_\odot$, and has the potential to open the flood gates on the already active topic of IMBHs, seed-mass BHs, and BH–galaxy coevolution. Moreover, two of the already known IMBH candidates are some ten times (150 and 160 Mpc) further away, making our sample (at $\approx$17 Mpc) easier to follow-up on with both bulge/disc decompositions for extending/refining the $M_\bullet$–$M_{\mathrm{bulge}}$ relation (e.g., Davis et al. 2019) and high spatial resolution radio observations for the "fundamental plane of BH activity" (Merloni et al.

[1] For reference, NGC 205 has a directly-measured BH mass less than $10^5\,\mathrm{M}_\odot$: $M_\bullet = 7.1^{+10.7}_{-5.3} \times 10^3\,\mathrm{M}_\odot$, $\sigma = 33\,\mathrm{km\,s}^{-1}$ (Nguyen et al. 2019). NGC 404's directly-measured BH mass is $5.5^{+4.1}_{-3.8} \times 10^5\,\mathrm{M}_\odot$ (Davis et al. 2020).

2003) providing an additional independent estimate of the BH masses. One could also pursue deeper X-ray exposures with the XMM satellite to obtain and model the X-ray spectral energy distributions to compare with stellar and SMBHs.

The high-energy photons, originating from the (not so) dead centre of these galaxies, are likely coming from the accretion disk around a compact object because the point-source nature rules out spatially-extended star-formation. This activity in the low-mass galaxies will light up the "broad-line region" of the surrounding gas clouds, enabling us to probe the central mass. We are now, exceedingly well-placed to discover (the abundance or rarity of) the long sought after, largely-missing, population of IMBHs at the centers of galaxies. How many of these turn out to be stellar-mass X-ray binaries (XRBs), IMBHs, or SMBHs, can be answered with optical spectra. Few IMBH examples exist: NGC 205 (see footnote 1); possibly GW190521 although the location in its galaxy is unknown (Abbott et al. 2020); LEDA 87300 (Baldassare et al. 2015; Graham et al. 2016, no $\sigma$ yet); and NGC 3319 (Jiang et al. 2018; Davis & Graham 2021, no good emission line spectra yet). However, from a sample of 305 galaxies, Chilingarian et al. (2018) recently used the width and luminosity of the H$\alpha$ emission line to identify six somewhat distant (>100 Mpc) galaxies with probable AGN (including LEDA 87300), which have a central X-ray point-source and an indirect BH mass estimate less than $\approx 10^5$ M$_\odot$, that is, not in the $10^5$–$10^6$ M$_\odot$ range.

We desire optical spectra to check for broad H$\alpha$ (6563 Å) emission associated with the potential AGN in our nearby sample of Virgo Cluster galaxies, plus LEDA 87300 and NGC 3319 mentioned above. The width and luminosity of the H$\alpha$ line, when kinematically-broadened by a BH, is used to estimate the BH's mass (e.g., Filippenko & Sargent 1989; Greene & Ho 2005; Bentz et al. 2009, 2013; Reines et al. 2013; Baldassare et al. 2015; Subramanian et al. 2016). However, transient stellar phenomena such as "tidal-disruption events" (TDEs) or core-collapse supernovae can also produce high-ionization and broad Balmer lines (H$\alpha$ and H$\beta$), and thus we will also measure the narrow emission lines, giving the [O III] (5007 Å) to H$\beta$ (4861 Å), and the [N II] doublet (6583 and 6548 Å) to H$\alpha$ (6563 Å) line ratios required to place the sources in the BPT (Baldwin et al. 1981) diagram, as revised by Kewley et al. (2006). This diagram is the go-to diagnostic for identifying flux as either coming from star formation or AGN. For this task, we require the spectral resolution to resolve the [N II] and [O III] lines[2] in galaxies with $\sigma \approx 25$–$60\,\mathrm{km\,s^{-1}}$.

The size (R) of an AGN's "broad line region" is known to scale with the optical continuum luminosity at 5100 Å (e.g., Kaspi et al. 2000). This size, rather than the H$\alpha$ luminosity mentioned above, can also be combined with the velocity dispersion ($\sigma_{\rm BL}$) of the broad H$\alpha$ and H$\beta$ lines to estimate the BH mass via the virial theorem: $M_\bullet \propto \sigma_{\rm BL}^2 R$ (e.g., Kaspi et al. 2000).

In addition to establishing the frequency of IMBHs, this will complement research into the $M_\bullet$–$M_{\rm bulge}$ and $M_\bullet$–$M_{\rm galaxy}$ diagrams (Davis et al. 2018, 2019; Sahu et al. 2019a), further facilitating the advancement of BH/galaxy coevolution theories (e.g., Croton et al. 2006). Stellar absorption lines such as the Mg$_{\rm b}$ triplet, from 5100 to 5250 Å, will also provide us with the velocity dispersion of the stars, enabling us to better define the low-mass end of the $M_\bullet$–$\sigma$ diagram (Sahu et al. 2019b), which along with the $M_\bullet$–$M_{\rm bulge}$ relation, is a go-to calibrator for many cosmological simulations of galaxy growth.

The discovery of an abundance of BHs in this new mass domain will contribute to breakthrough science. Similarly, if we find an on-going rarity, it will be hugely informative. This work should have a large array of implications, which include:

- better extending the BH scaling relations to predict BH masses in other galaxies;
- informed knowledge for the creation of SMBH seeds;
- knowledge of the BH mass function from stellar to SMBHs and BH mass density of the Universe (e.g., Graham & Driver 2007; Davis et al. 2014; Mutlu-Pakdil et al. 2016);
- connections with, and stability of, nuclear star clusters (e.g., Hurley 2007; Graham & Spitler 2009); and
- predictions for what to expect from (and how best to design) space-based gravitational wave interferometers involving longer-wavelength radiation than ground-based interferometers can detect (e.g., Mapelli et al. 2012).

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[2] We note that the [S II] doublet (6717 and 6731 Å) and the [O I] (6300 Å) lines are also sometimes measured for further diagnostic checks, and the width of the [S II] lines are sometimes assumed to also hold for the other narrow emission lines if their signal-to-noise (S/N) ratio is low.


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