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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 higher than that formed by single stars today ($M_\bullet = 1.4$ to $120\,\mathrm{M_\odot}$) and less massive than the supermassive black holes (SMBHs: 10^5 to $10^{10}\,\mathrm{M_\odot}$) known to reside at the centers of massive galaxies. Not surprisingly, astronomers around the world are hotly pursuing the much-anticipated discovery of IMBHs. In addition to providing a fundamental input to the cosmic inventory of our Universe, the abundance, or rarity, of IMBHs has essential implications for the formation of the Universe's most massive black holes.

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 $\approx 10^5\,\mathrm{M_\odot}$, thereby providing a kick-start to explain the early-formation of the high-z, active galactic nuclei (AGN) with big BH masses around $\approx 10^9\,\mathrm{M_\odot}$. 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. 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.

From our recent Chandra X-ray Observatory (CXO) *Large Project* (Soria 2016), we have discovered an IMBH candidate at the centers of several low-mass galaxies just 15–20 Mpc away.example). Our project represented the third-longest allocation of CXO satellite time in Cycle 18, enabling long exposures which discovered the faint X-ray point-sources (consistent with low-mass BHs accreting with a low Eddington ratio) in galaxies for which we have predicted a central IMBH based upon the galaxy's velocity dispersion σ_*, luminosity, and spiral arm pitch angle (Graham & Soria 2019; Graham et al. 2019). These high-energy X-ray photons, originating from the (not so) dead centers of these galaxies, are likely coming from the accretion disk around a BH because the point-source nature of the emission favors an active BH rather than spatially extended star-formation. Also, our stacking and re-analysis of archival Chandra images of early-type galaxies in the Virgo cluster has uncovered three additional IMBH candidates. In total, we have identified 14 galaxies predicted to house a central IMBH for which we have detected an isolated, central, X-ray point-source. These findings are fascinating, and we are now exceedingly well-placed to discover the long sought after, still mostly missing, population of IMBHs at the centers of galaxies.

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 its SMBH. IMBHs hold the key for our understanding of galaxy evolution, feedback, and the growth of the Universe's most massive black holes. Astronomers have collected limited observational evidence of dwarf galaxies in the process of being tidally disrupted as they plunge into their parent galaxy. 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.

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 $M_\bullet$–$M_{\rm bulge}$ scaling relations (Sahu et al. 2019a). Moreover, it may potentially represent a significant increase on the four or five known IMBH ($10^2 < M_\bullet/{\rm M}_\odot < 10^5$) candidates at the centers of galaxies (with X-ray point-sources and broad Hα lines), includes targets with multiple BH mass predictions of 10^4–$10^5\,{\rm M}_\odot$, 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 $M_\bullet$–$M_{\rm bulge}$ relation (e.g., Davis et al. 2019) and high spatial resolution radio observations for the "fundamental plane of black hole activity" (Merloni et al. 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.

Amongst the numerous diagnostics that can be performed, merely acquiring stellar velocity dispersions will enable us to place our targets in the latest $M_\bullet$–σ_* diagram (Sahu et al. 2019b), extending the $M_\bullet$–σ_* relation to lower masses. Improvement in this black hole mass scaling relation will additionally complement research into the $M_\bullet$–$M_{\rm bulge}$ and $M_\bullet$–$M_{\rm galaxy}$ diagrams (e.g., Davis et al. 2018, 2019; Sahu et al. 2019a), further facilitating the advancement of BH/galaxy coevolution theories (e.g., Croton et al. 2006).

The discovery, or absence, of BHs in this new mass domain, has a broad array of additional implications which cannot be adequately covered here. These include: extending the BH scaling relations to predict BH masses in galaxies with quiescent low-mass BHs; establishing the BH mass function from stellar to SMBHs, and then revising the BH mass density of the Universe (e.g., Davis et al. 2014; Mutlu-Pakdil et al. 2016); connections with nuclear star clusters (e.g., Graham & Spitler 2009); and predictions for space-based gravitational wave detections involving longer wavelength radiation than ground-based interferometers can detect (e.g., Mapelli et al. 2012).

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