Astro2020 Science White Paper

Local Constraints on Supermassive Black Hole Seeds

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☑ Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☐ Galaxy Evolution ☐ Multi-Messenger Astronomy and Astrophysics

Principal Author:
Name: Richard M. Plotkin
Institution: University of Nevada, Reno
Email: rplotkin@unr.edu
Phone: 775-784-6508

Co-authors: Amy E. Reines (Montana State University), Kristina Nyland (U.S. Naval Research Lab), Jeremy Darling (University of Colorado), Elena Gallo (University of Michigan), Jenny E. Greene (Princeton University)

Abstract: Amongst the most outstanding topics in extragalactic astrophysics is determining the mechanisms that formed and grew the first supermassive black holes. Understanding the nature of black hole 'seeds' is crucial for understanding the conditions in the early Universe, and also for the co-evolution of galaxies and their black holes. Observational clues into the first black holes can be inferred from the demographics of massive black holes (in the ten thousand through million Solar mass range) in nearby low-mass galaxies. This white paper discusses how proposed multiwavelength facilities going into the 2020s/2030s will allow us to assemble large samples of weakly accreting active galactic nuclei in low-mass galaxies, in order to constrain the mass-distribution of objects that originally seeded the growth of supermassive black holes.

Introduction

It is now well-established that supermassive black holes with masses ranging from $10^6 - 10^{10}\,M_\odot$ reside in the nuclei of large galaxies. A number of lines of evidence, including the observed scaling relations between supermassive black holes and their hosts, further suggest that the formation and growth of supermassive black holes and their hosts are linked (e.g., Kormendy & Ho, 2013). Despite their prevalence and importance to our understanding of galaxy evolution, the origin of supermassive supermassive black holes at high redshift (e.g., hierarchical merging vs. direct gas collapse) and their formation efficiency remain open areas of research. Thus, a key observational parameter for constraining the formation of supermassive black holes is the mass distribution of so-called 'seed' black holes (Greene, 2012; Reines & Volonteri, 2015; Mezcua et al., 2016). One step in that direction is to perform population studies on black holes in the $10^4 - 10^6 M_\odot$ range, objects that we will refer to as massive black holes (mBHs). *In this white paper we discuss proposed facilities, particularly a next generation Very Large Array (**ngVLA**) combined with high spatial-resolution X-ray missions like **Lynx** and the Advanced X-ray Imaging Satellite (**AXIS**), that would allow population studies of mBHs during the 2030s and beyond.*

The 'Seeding' of Supermassive Black Holes

The existence of high-redshift quasars powered by $\sim 10^9\,M_\odot$ black holes at $z \gtrsim 7$ suggests that the first black hole seeds were 'heavy', with masses $M_{\rm BH} \sim 10^5\,M_\odot$ (which could have formed from the direct collapse of large clouds of gas, e.g., Loeb & Rasio 1994; Begelman et al. 2006). Otherwise, $10^9\,M_\odot$ black holes could not have grown so massive only 700 Myr after the Big Bang (assuming growth through Eddington limited accretion, e.g., Mortlock et al. 2011; Bañados et al. 2018). Whether or not $10^5\,M_\odot$ seeds are the exception or the rule remains uncertain, however, and it is possible that some fraction of black holes could have been seeded with lighter objects in the $\sim 10^2\,M_\odot$ range (i.e., remnants from Population III stars, e.g,. Haiman & Loeb 2001; Madau & Rees 2001; Madau et al. 2014).

While observations of high-redshift quasars provide important constraints and boundary conditions, it is not feasible with current facilities to directly observe black holes as small as $10^5\,M_\odot$ in the very high-redshift Universe (Volonteri & Reines, 2016). To study low-mass black holes, we instead rely on clues that are embedded within black hole populations found in nearby galaxies. In particular, local constraints on the seed black hole population can be placed by the fraction of galaxies hosting a nuclear black hole (as a function of galaxy stellar mass), and by black hole/host galaxy scaling relations at low masses (see, e.g., Volonteri 2010; Greene 2012; Reines & Comastri 2016; Mezcua 2017 for reviews).

Low-mass Black Holes in Nearby Dwarf Galaxies

Because of their relatively quiet evolutionary histories, and the ability for supernova feedback to stunt black hole growth, we do not expect black holes in nearby dwarf galaxies[1] to have grown much within a Hubble time (e.g., Dubois et al., 2015; Habouzit et al., 2017). In turn, characterizing mBHs in dwarf galaxies provides a powerful lever arm for constraining a black hole population that is comparable (albeit not identical) to the initial 'seed' popluation (e.g.,

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[1] Following Reines et al. (2013), we define dwarf galaxies as having stellar masses $M_\star < 3 \times 10^9\,M_\odot$, which is comparable to the Large Magellanic Cloud.

Volonteri & Natarajan, 2009; van Wassenhove et al., 2010; Bellovary et al., 2011). In the past decade we have witnessed an explosion in sample sizes of mBHs in dwarf galaxies, growing from a handful of isolated cases 10-15 years ago (e.g., Filippenko & Ho, 2003; Barth et al., 2004), to now homogeneously selected samples reaching $\sim 10^2$ objects in dwarfs (e.g., Reines et al., 2013; Mezcua et al., 2018) and other low-mass galaxies (e.g., Greene & Ho, 2004, 2007; Dong et al., 2012).

Dynamical searches for mBHs in dwarf galaxies based on the motion of stars within the black hole's sphere of influence are limited to very nearby galaxies (e.g., Nguyen et al., 2019). Thus, discovering mBHs in dwarf galaxies in large numbers relies on finding those that are shining as active galactic nuclei (AGN; see Reines & Comastri 2016 for a review). The most efficient method so far has been selection based on optical emission line diagnostics (e.g., Reines et al., 2013).[2] Optical selection, however, is biased toward AGN with low extinction that are accreting relatively rapidly ($L_{\rm bol}/L_{\rm Edd} > 0.1$).

Low-mass AGN can also be found through X-ray surveys (e.g., Kamizasa et al., 2012; Schramm et al., 2013; Lemons et al., 2015; Mezcua et al., 2016, 2018), although X-ray selection is biased against highly obscured systems. As described below, *radio searches, especially when combined with proposed X-ray missions with high effective area and high spatial resolution (e.g., Lynx, AXIS, Athena) would allow economic selection of large samples of mBH-powered AGN in low-mass galaxies.*

Revealing Low-mass AGN in the Radio Domain

A new radio telescope with order of magnitude improved sensitivity over current facilities, such as an ngVLA, would overcome some of the current limitations to pursuing large population studies, especially when combined with other multiwavelength efforts. At low Eddington ratios ($<10^{-2}\,L_{\rm Edd}$), AGN commonly launch compact, partially self-absorbed synchrotron jets that release large amounts of radiative power in the radio waveband. Most of these compact jets should appear point-like even at ngVLA resolutions, with flat/inverted radio spectra (Blandford & Königl, 1979; Ho, 2008). In this weak accretion regime, the ratio of radio:X-ray luminosity scales in a predictable way with the mass of the accreting black hole according to the fundamental plane of black hole activity (e.g., Merloni et al., 2003; Falcke et al., 2004; Plotkin et al., 2012), which Gültekin et al. (2019) recently refined for use as a black hole mass estimator of the form:

$$\log\left(M/10^{8}M_{\odot}\right) = \mu_0 + \xi_{\mu R}\log\left(L_R/10^{38}{\rm erg\ s^{-1}}\right) + \xi_{\mu X}\log\left(L_X/10^{40}{\rm erg\ s^{-1}}\right)$$

where $\mu_0 = 0.55 \pm 0.22$, $\xi_{\mu R} = 1.09 \pm 0.10$ and $\xi_{\mu X} = -0.59 \pm 0.15$, and $L_{\rm R}$ is at 5 GHz and $L_{\rm X}$ is from 2-10 keV.

Advantages of a radio survey include:

- targeting mBHs in a weak accretion regime will recover objects missed by optical surveys (where the latter rely on diagnostics that are expected to be present mostly at higher accretion rates). Note that for any sensible luminosity function, the majority of AGN accrete at low Eddington ratios;

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[2] Infrared searches have also yielded large sample sizes, although see Hainline et al. (2016) for a discussion on the purity of infrared selected samples.

- jetted radio emission will be detectable from highly absorbed AGN, thereby allowing radio selection to uncover some objects that would be missed by complementary (but often shallower) X-ray and/or optical approaches;
- at Mpc distances, contamination in the radio waveband from stellar-mass X-ray binary systems should be negligible.[3] We stress, however, that statistical techniques applied to X-ray selected samples can also overcome X-ray binary contamination (see, e.g., Miller et al., 2015, and white paper by Gallo);

In Figure 1 we show the radio flux densities expected at 8 GHz for $10^{-5} < L_{\rm X}/L_{\rm Edd} < 10^{-3}$ AGNs powered by 10^4 (red swath), 10^5 (blue swath) and $10^6\ M_\odot$ (grey swath) mBHs as a function of distance.[4] We also show the current VLA $5\sigma_{\rm rms}$ detection limit (dotted horizontal line) and an ngVLA $5\sigma_{\rm rms}$ detection limit (dashed horizontal line) assuming 1 hour integrations. The shaded regions require 2-10 keV X-ray fluxes $F_{\rm X} > 10^{-15}\,{\rm erg\,s^{-1}\,cm^{-2}}$ to illustrate the types of AGN that can easily be accessed with an ngVLA combined with a sensitive, high spatial resolution facility (e.g., *Chandra, Athena, Lynx, AXIS*). An ngVLA would be able to detect relatively massive mBHs ($10^6\ M_\odot$) out to nearly 1 Gpc (almost a factor of four farther than accessible by the current VLA within reasonable exposure times). Excitingly, an ngVLA could detect jetted radio emission from $10^4\ M_\odot$ mBHs accreting at $L_{\rm X} \gtrsim 10^{-4}\ L_{\rm Edd}$, or $10^5\ M_\odot$ mBHs at $\gtrsim 10^{-6}\ L_{\rm Edd}$, at the distance of the Virgo cluster (16.4 Mpc; corresponding to 2-10 keV X-ray fluxes $F_{\rm X} \gtrsim 4 \times 10^{-15}$ and $\gtrsim 4 \times 10^{-16}$ erg s^{-1} cm^{-2}, respectively).

We note that the fundamental plane has an order of magnitude scatter, and as such is of course not a precise mass estimator. However, if one has access to radio and X-ray telescopes that are sensitive enough to obtain routine detections (i.e., $\sim\mu$Jy bm^{-1} sensitivity in the radio and $\sim 10^{-15}$ erg s^{-1} cm^{-2} in the X-ray, as in Figure 1), then the fundamental plane is extremely effective at differentiating between stellar-mass black hole X-ray binaries vs. AGN, and also at differentiating between AGN with black holes with masses in the $\sim 10^4 - 10^6 M_\odot$ range (i.e., what we consider mBHs here) vs. AGN with black holes $\gtrsim 10^6 M_\odot$ (what we consider to be supermassive black holes).

The wide fractional bandwidth of an ngVLA would also allow radio spectral information for brighter sources, which would provide an additional diagnostic to secure an AGN identification, and to further study the physics of the jet. The shape of a jet's radio spectrum reflects the AGN accretion state: a flat/inverted radio spectrum indicates low accretion rates $\lesssim$1% of the Eddington limit (it is only at these low accretion rates where the fundamental plane is applicable), whereas a steep spectrum would indicate higher accretion rates and/or jet interactions with the interstellar medium (e.g., Ho, 2008; Fender et al., 2009)

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[3] At ngVLA sensitivities ($5\sigma_{\rm rms} \approx 1\,\mu$Jy), it is plausible to (rarely) detect emission from transient radio flares produced by accreting stellar mass black holes out to ≈30 Mpc, which could be identified via radio spectral information given the wide fractional bandwidth of an ngVLA. We estimate this limit by scaling an extreme 20 Jy radio flare from the Galactic black hole X-ray binary Cyg X-3 (Corbel et al., 2012).

[4] We note that we expect all AGN accreting at $\lesssim 10^{-2}\ L_{\rm Edd}$ to emit compact radio emission. We adopt the range $10^{-5} - 10^{-3}\ L_{\rm Edd}$ in Figure 1 simply for illustrative purposes, to keep the figure from appearing too cluttered.

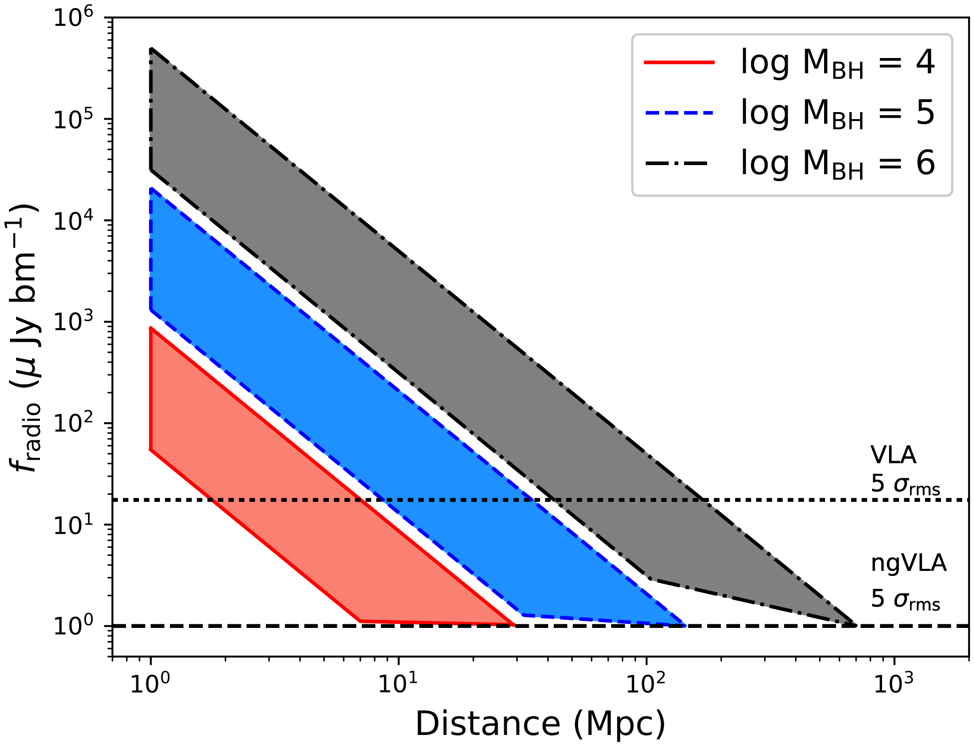

Figure 1: Distances to which an ngVLA could detect compact radio emission from an accreting mBH with 1 hour integrations, if the mBH falls on the fundamental plane of black hole activity (Merloni et al., 2003), and if the mBH has a 2-10 keV X-ray flux $F_{\rm X} > 10^{-15}$ erg s^{-1} cm^{-2}. The red shaded region bounded by red solid lines illustrates the expected radio flux density (at 8 GHz) for a $10^4\,M_\odot$ mBH accreting between $10^{-5} < L_X < 10^{-3}\,L_{\rm Edd}$; the blue shaded region (bounded by dashed lines) and the grey shaded region (bounded by dashed-dotted lines) illustrate the same for a 10^5 and $10^6\,M_\odot$ mBH, respectively. $5\sigma_{\rm rms}$ radio detection limits for an ngVLA and for the VLA are shown as dashed and dotted lines, respectively (both assuming 1 hour on source). An ngVLA could detect relatively massive mBHs out to nearly 1 Gpc, and it could detect mBHs as small as $10^4\,M_\odot$ at the distance of the Virgo cluster of galaxies ($\sim$16.4 Mpc). Note that the fundamental plane has nearly an order of magnitude scatter in radio luminosity, which is not included in this figure.

Finally, we note that in this low-luminosity regime, radio surveys will have to contend with radio emission from star formation (i.e., free-free emission in H II regions) and from supernova remnants. There will naturally be a minimum luminosity at which an AGN jet will be diluted by radio emission from star formation processes. However, we expect most low-accretion rate mBH-powered AGN to have core radio emission that remains point-like at ngVLA spatial-resolutions (sub milli-arcsec). If the jet is more compact than the physical extent of the star formation processes, then we expect in many cases to resolve out radio emission from star formation (depending on observing frequency). In other words, with long baselines, unresolved radio emission should be dominated by core jet emission from a weakly accreting mBH (e.g., Reines & Deller, 2012).

Multiwavelength Efforts into the 2030s

Constraining black hole seeds through AGN in dwarf galaxies is a multiwavelength endeavor, and it is not a problem that can be tackled looking within only a single band of the electromagnetic spectrum. However, in a multiwavelength context, we expect a radio facility like an ngVLA to play a prominent role, with radio-selected AGN candidates awaiting confirmation by other telescopes. In particular, sensitive, high spatial-spatial resolution X-ray facilities are essential. *The technologies of proposed X-ray missions like Lynx and AXIS would allow joint radio/X-ray selection of AGN in dwarf galaxies.*

Noting that combined radio/X-ray searches are optimal for selecting AGN at low accretion rates, recovering a representative sample of mBH AGN will require complementary efforts. In particular, Extremely Large Telescopes will improve selection at higher Eddington ratios ($\gtrsim 0.1 L_{\rm Edd}$), where optical line diagnostics can reveal the presence of mBH-powered AGN. Infrared spectroscopy (e.g., with the *James Webb Space Telescope; JWST*) will also provide crucial line diagnostics that would be capable of discovering optically obscured AGN (e.g., Satyapal et al., 2009; Inami et al., 2013; Cann et al., 2018), although we note that *JWST* will not be efficient at wide-field surveys. Additionally, the new 30m-class of optical telescopes will provide dynamical measurements of nearby mBH masses (see white paper by Greene). A representative mBH census will allow significantly improved constraints on the local black hole occupation fraction (see white paper by Gallo) and the ‘seed’ mBH mass distribution, thereby helping to place observational constraints on the population of objects that seeded the growth of supermassive black holes in the early Universe.

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