

THE ORIGINS OF SUPERMASSIVE BLACK HOLES:
A STUDY OF ACTIVE GALACTIC NUCLEI AND DWARF GALAXIES

by

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ABSTRACT

The original seed conditions and growth processes of supermassive black holes (BHs) are currently poorly understood. Since we cannot directly observe BH seeds in the early Universe, astronomers have developed a novel method for studying them. This method studies the “fossil record” of BH seeds through BH-host galaxy scaling relations using observations of low-mass BHs residing in local dwarf galaxies. While this strategy avoids the biases (towards brighter objects) and limitations of high-redshift observations, it remains fraught with other issues; the signatures of BHs in dwarf galaxies can be confused with star-formation processes and true scaling relations are difficult to disentangle from empirically-derived scaling relations which can depend on galaxy type/sample. In this work, we 1. place samples of galaxies on two different scaling relations and 2. warn against multiple pitfalls involved with the “fossil record” strategy. We first use Sloan imaging with galaxy bulge-disk decompositions to place a sample of active galactic nuclei (AGNs) on the BH-bulge mass relation. We show that AGN host galaxies do not follow the same scaling relations defined for early-type galaxies, hinting that AGNs physically interact differently with their host galaxies compared to their inactive counterparts. Next, we investigate four galaxies with AGN-like, mid-infrared colors that do not show AGN signatures at other wavelengths. We use Hubble imaging and stellar population synthesis modeling to demonstrate that these colors could be coming instead from very young, massive nuclear star clusters. We therefore advise caution using mid-infrared color as an AGN selection technique specifically in dwarf galaxies. Lastly, using Magellan spectroscopy, we place a sample of six dwarf AGNs on the BH mass-stellar velocity dispersion and BH mass-stellar mass relations. These galaxies generally seem to follow the relations defined by larger, early-type galaxies, however, further samples are needed to draw conclusions about BH seeding. Overall, we make progress on populating scaling relations with active and low-mass galaxies, which is a crucial step in understanding BH seed formation/evolution. Additionally, we contribute to a body of work attempting to understand issues involved with extrapolating observational techniques derived for high-mass galaxies into the low-mass regime.

INTRODUCTION

Supermassive Black Holes

Of all the extreme objects that exist across the universe, one of the most extraordinary are supermassive black holes (BHs, or just “massive” BHs). Originally a mathematical head-scratcher, BHs have now been observed in almost every corner of the universe. Just in our own milky way, stellar mass ($\sim 10 M_\odot$) BHs are expected to number in the hundreds of millions [151] and massive ($10^6 - 10^9 M_\odot$) BHs occupy the centers of all massive galaxies [130]. Even more enticing, despite their pervasiveness across the universe, we know very little for certain about the origins (or “seeding”) of supermassive BHs. We observe massive BHs out to just hundreds of millions of years after the big bang [e.g., 118, 131], however, exactly how they got there and how they grew so large in such a short time remains uncertain.

Seed Formation Models

One potential seeding mechanism is the collapse of Population III (Pop III) stars [34, 129]. Pop III stars were likely very massive [36], so their BH remnants would have been on the order of $10^2 M_\odot$. However, massive BHs starting at this mass require rapid growth to reach today’s mass distribution. Another possible mechanism is the collapse of a massive gas cloud, known as direct collapse [83, 123]. This kind of collapse would produce seeds of higher mass than the typical star-collapse stellar mass BHs (on the order of $10^4 - 10^6 M_\odot$). The occupation fraction for this mode is expected to be much lower than for Pop III star collapse since very specific conditions are needed for this mode to work [75]. One of these conditions is low-metallicity; higher metallicity gas will cool more efficiently and fragment into multiple individual stars rather than one large BH seed [82]. The last main potential

mechanism is the collision of many stars during a gravitational runaway event in a stellar cluster [8, 19], producing BH seeds on the order of $10^3 - 10^4 M_\odot$. In the “slow scenario” [142], one massive star would produce a stellar mass BH ($\sim 50 M_\odot$) which would merge with multiple other BHs nearby in the dense cluster, eventually producing the BH seed. In the “fast scenario” [162], many massive stars would undergo a collisional runaway, potentially forming a supermassive star, and, eventually, a BH seed. These three seeding mechanisms are shown in Figure 1.

Intermediate-Mass Black Holes

Naturally, if we want to understand the seeding process we should try to observe it happening. Considerable technological advances have been made since the first telescope was invented and the current observable horizon reflects that, with James Webb Space Telescope observing galaxies/BHs now out to $z > 10$ ($\lesssim 500$ Myr after the big bang) [e.g., 118, 132]. Unfortunately, the epoch at which BH seeds are expected to have formed is even further than that and remains out of direct observational reach [190, 217, 223].

Therefore, in the hopes of side-stepping current observational limitations, a new strategy has been gaining steam. Instead of observing seeds while they are forming we attempt to observe their “fossil record”. Galaxies form through the merging of many smaller structures and then grow, similarly, via merger events with other galaxies (i.e., hierarchical assembly). As galaxies merge, gas is funneled down towards the central BHs, enhancing their accretion and growth. This means that smaller dwarf galaxies, which tend to have undergone fewer mergers than more massive galaxies, host relatively pristine BHs that have also undergone fewer mergers events [219]. This results in dwarf galaxies hosting the least-massive BHs known [e.g., 173] that retain a memory of their initial primordial state. Therefore, identifying and characterizing low-mass BHs ($M_{\text{BH}} \sim 10^2 - 10^5 M_\odot$) in local dwarf galaxies ($M_* \lesssim 10^{9.5} M_\odot$) can place observational constraints on seed BHs from the early Universe.

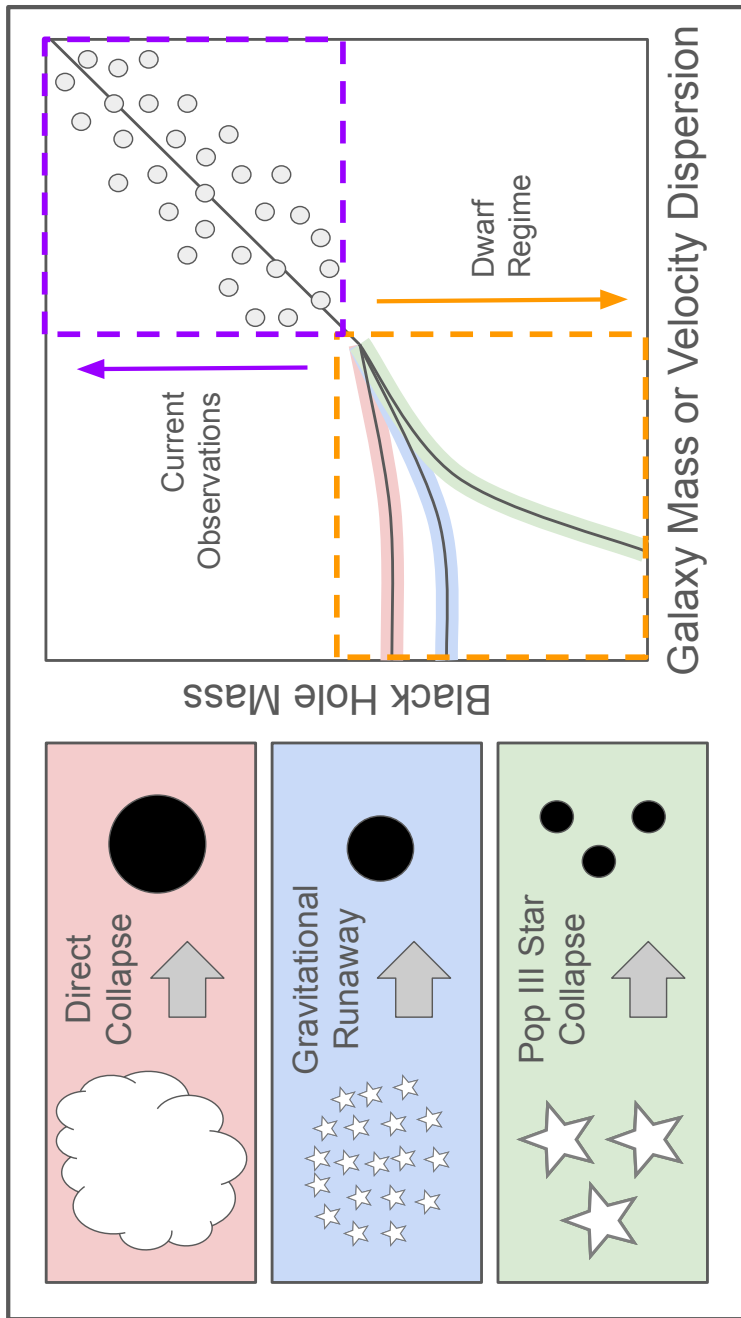


Figure 1 Massive BH seeding mechanisms. On the left, we show a cartoon of three potential seeding mechanisms: the direct collapse of a massive gas cloud, a gravitational runaway event and Pop III star collapse. On the right, the purple box shows broadly where current observations of more massive galaxies fall on scaling relations while the orange box shows where dwarf BHs are expected to be found. In the dwarf regime, scaling relations between BH mass and host galaxy properties are predicted to diverge based on the dominant seeding mechanism, shown with the different trajectories colored the same as the corresponding seeding mechanism from the left.

Scaling Relations

Galaxy properties, including velocity dispersion [64, 140], bulge luminosity [134] and bulge mass [95, 113, 137], have been observed to correlate with the mass of their central massive BH, which we quantify with scaling relations. Canonical scaling relations have traditionally been derived using dynamical BH mass measurements made from observations of high-mass BHs living in nearby, early-type, inactive galaxies with classical stellar bulges. However, observations have revealed that some types of galaxies do not follow the same canonical relations defined by this very biased sample. Galaxies that are morphologically distinct (i.e. they lack a classical bulge), such as late-type galaxies or galaxies with pseudobulges, have been observed to deviate from canonical scaling relations [63, 93, 112]. Additionally, active galaxies, megamaser galaxies and dwarf galaxies [70, 74, 76, 174, 225], where AGN/stellar feedback processes may play a more consequential role, also seem to follow a different relation than the early types. This means that in order to populate the sparse low-mass end, we cannot blindly extend scaling relations directly down from the high-mass regime.

However, remembering our BH seed “fossil record” strategy, in order to study BH formation and evolution we must study the low-mass regime of scaling relations (see Figure 1). It has been shown that the dominant seeding mechanism (or combination of mechanisms) should be reflected in both the slope and scatter of scaling relations at low-mass [221]; if the seed mass is high (from either direct collapse or gravitational runaway), the relations should flatten around that mass. In terms of evolution and growth, the BH accretion mode and efficiency is also predicted to impact where galaxies lie on scaling relations [155, 176]. Therefore, populating the low-mass end of scaling relations should provide a valuable tool for understanding the birth of massive BHs.

AGN Feedback

One potential physical reason behind why galaxies with AGNs might fall off canonical scaling relations is BH feedback. Feedback describes the effects of a central AGN on its host galaxy in the form of radiation, winds and jets [59]. When these BH products interact with the interstellar medium of the host galaxy, they can heat up [47, 188] or even eject the cool star-forming gas [109], effectively terminating star formation and sending the galaxy into quiescence [205]. Quenching star formation and removing the gas from its vicinity also has the side effect of removing the AGN’s fuel source, leading to the suppression of accretion onto the BH. With the capability to reduce the final BH mass after a merger by an order of magnitude, self-regulation of the central BH is critical for setting its final mass [55]. As smaller galaxies merge and grow into larger galaxies, feedback in active galaxies could play an important role in offsetting those galaxies from the typical scaling observed between an AGN and its host for inactive galaxies.

Previously, feedback was generally ignored in low-mass galaxies, however, there has been mounting recent evidence that it is actually quite important. Penny et al. [158] presents observational evidence of the first AGNs preventing star formation in galaxies within the mass range of $5 \times 10^9 M_{\odot}$. Following this work, AGN-driven outflows have been identified in dwarf galaxies using spatially resolved kinematics [122, 133, 143]. This observational evidence is backed by analytical work [51] and simulations showing AGN feedback can produce significant outflows and quench star formation in dwarf galaxies [115, 198]. Additionally, while negative feedback (where the AGN quenches star-formation) is generally seen, positive feedback has also been observed. Shocks produced by AGN outflows have been observed to trigger star formation in the dwarf galaxy Henize 2-10 [193]. With the addition of the AGN energy in the form of outflows/shocks, the increased gas turbulence and pressure within star-forming clouds could enhance star-formation [145].

Observing BHs

As the name implies, BHs themselves are not directly observable; once below the event horizon, light cannot escape the BH’s gravitational pull. However, if a BH is actively accreting, the material around it emits across the full electromagnetic spectrum (see Figure 2). When a massive central BH is in this active state we refer to it as an active galactic nucleus (AGN).

The Structure of AGNs

Surrounding the BH is an accretion disk consisting of rapidly orbiting gas [197]. As the gas orbits, material within the disk interacts via viscous forces/friction, converting gravitational potential energy to both heat and UV/optical photons, causing the material to plummet closer and closer to the central BH. The accretion disk emits as a sum of black bodies, with temperature decreasing as a function of distance from the BH [208].

Further out from the accretion disk is the broad-line region (BLR) and the narrow-line region (NLR) [154]. These regions are named for their emission-line widths. The BLR is closer to the BH and, as a result, the gas is moving very rapidly (with velocity dispersion $\sigma \sim 1000$ km/s). The NLR, sitting at a much larger radius than the BLR/accretion disk, is notably diffuse ($n_e \sim 10^3 \text{cm}^{-3}$) such that “forbidden” emission lines (e.g. [O III], [S II], [N II]) can be observed. Forbidden transitions are highly improbable and, in most normal environments, a collision typically occurs before the transition can be made. However, since the density is so low in the NLR, these forbidden transitions happen often enough to be observable [106].

Generally thought to reside above/below the accretion disk is the X-ray corona [39, 81]. When UV/optical photons from the disk interact with hot electrons in the corona, they get up-scattered via the Compton effect into X-ray photons. Radio jets are sometimes observed

in AGN [91]. These jets are made up of relativistic electrons spiraling around magnetic field lines and emitting synchrotron radiation at radio frequencies. They can be quite large, ejecting material from the vicinity of the BH up to Mpc away. Lastly, obscuring material within the torus surrounding the AGN absorbs UV emission from the accretion disk and re-emits it in the infrared (IR) [5].

Observational Techniques for Identifying AGN

The emission from each of these distinct structures combine to create a unique spectral shape for AGNs compared to other astrophysical objects, which we can use to classify them both photometrically and spectroscopically. Photometry is an imaging technique where the flux from an object is measured through a filter, which blocks all but a certain range of wavelengths. Spectroscopy is a much more precise technique that involves splitting light into small enough wavelength bins that individual absorption/emission lines can be distinguished. Due to the characteristic spectral shape of different emission sources, comparing observations of objects in multiple filters or observing emission/absorption line strengths/widths can be used to infer the identity of the source (see Figure 2).

Optical/UV: Observing in the optical is one of the most widely used techniques for finding AGNs. Since the NLR, BLR and accretion disk all emit at optical wavelengths, there is a plethora of AGN signatures available within this regime. AGNs are highly energetic which allows us to distinguish them from other stellar objects/processes by looking for higher ratios of collisionally-excited, forbidden narrow emission lines, such as $[\text{N II}]\lambda 6583$, $[\text{S II}]\lambda\lambda 6716, 6731$ and $[\text{O III}]\lambda 5007$, to another line, such as $\text{H}\alpha$ or $\text{H}\beta$ [e.g., the BPT diagram 14, 106]. There is a theoretical limit to how high these ratios can get from just extreme star formation [101, 105], so observing narrow emission line ratios above this limit is a good indication for the presence of an accreting massive, central BH.

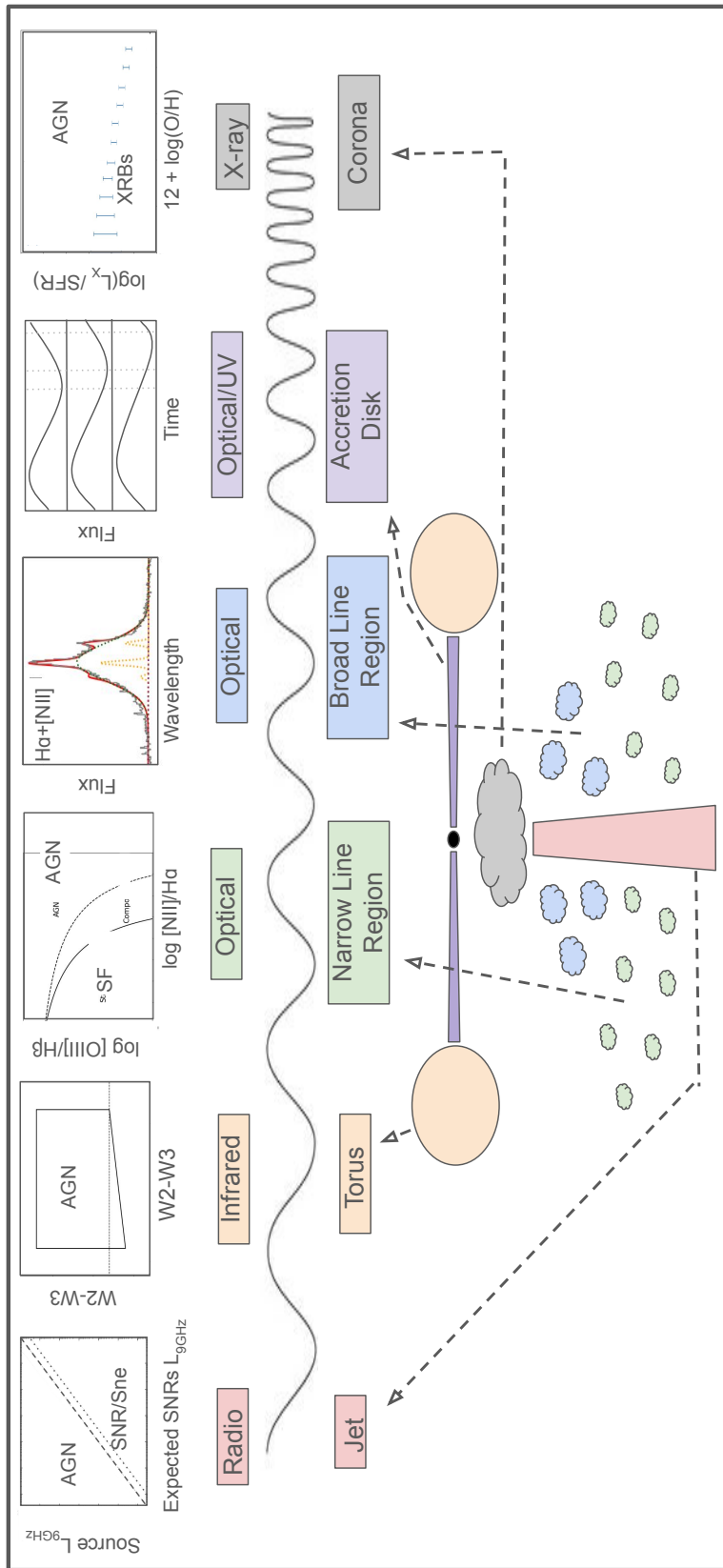


Figure 2 Observing AGN. We show a cartoon of the bottom half of an AGN, comprised of a central BH, an accretion disk, broad and narrow line regions, a radio jet, an X-ray corona and a dusty, obscuring torus. Each of these distinct structural features emit at different wavelengths with characteristic spectral shapes. This allows us to use different diagnostics to distinguish emission originating from AGNs from emission originating from other galactic sources. Examples of these diagnostics are shown at the top, from left to right: a distinction between possible SNR/Sne and AGNs in the radio as calculated in Reines et al. [168], the mid-IR WISE color-color diagram with an AGN selection box from Jarrett et al. [98], the BPT [14] emission line ratio diagram with characterization scheme defined in Kewley et al. [106], a broad component observed in the $\text{H}\alpha$ emission line (green dotted line) from Sturm et al. (in press.), reverberation mapping cartoon depicting the time lag between observations at different wavelengths, AGN candidates lying above the predicted XRB luminosity/SFR ratio from Lehmer et al. [120].

AGNs can also be found based on their broad emission lines (specifically broad $H\alpha$). Since the BLR is in such close vicinity to the central BH, the gas from which the broad emission lines originate can reach velocity dispersions too high to be produced by other astrophysical objects (e.g., stellar winds). In addition to identifying the presence of an AGN, measuring the width of broad emission lines provides a method for estimating the virial BH mass [72, 169].

Furthermore, we can trace AGNs using their distinctive luminosity variability. Reverberation mapping studies the time delay between variations of hotter emission from the accretion disk compared to cooler emission from the BLR. Through these correlated fluctuations we can measure the light travel time between the two emitting regions and, from that time, derive the mass of the central BH [30, 159, 160].

Mid-IR: Dust circling around a BH absorbs emission from the AGN and re-emits in the mid-infrared (mid-IR), creating a characteristic power-law spectrum. Mid-IR observations have the advantage of suffering minimally from nuclear and galaxy scale obscuration. Therefore, multiple diagnostics have been developed to use mid-IR color ratios as AGN indicators. Following similar logic as the optical diagnostics, emission from dust heated by AGNs displays a different spectral shape than mid-IR emission from stellar processes, making AGNs appear redder in the mid-IR [98, 135, 206]. At high mass, these diagnostics have been widely applied to Wide-Field Infrared Survey Explorer [WISE, 230] observations and produced robust samples of AGNs [7, 195].

Radio: The radio wavelength regime is exceptionally well-suited for observing dwarf AGN candidates since, regardless of strength, AGNs almost always produce radio emission at centimeter wavelengths [92] that is impervious to dust extinction. Supernova remnants (SNRs), young supernovae (SNe), and ionized gas from HII regions can all produce considerable radio emission, however, again, these objects all have a theoretical limits to

the luminosity that they can produce. Therefore, observing a radio point source above a certain theoretical threshold provides good evidence for an AGN [e.g., 168]. Additionally, water maser emission can be detected in this wavelength regime, which can be used to estimate the central BH mass via dynamical arguments [e.g., 116].

X-Ray: X-ray observations probe the accretion flows of AGNs [96], since X-rays originate from the inverse Compton scattering of photons emitted from the accretion disk. AGNs can be identified by their characteristic power-law spectral shape in the X-ray regime [e.g., 57]. Additionally, they usually dominate over any stellar contribution in the hard X-rays (>2 keV). Other significant X-ray emitters are essentially limited to high-mass and low-mass X-ray binaries (XRBs). Therefore, similar to the potential contamination sources at other wavelengths, we can identify AGN candidates if they exceed a maximum expected luminosity for XRBs [e.g., 119].

Complications in the Dwarf Regime

Unfortunately, observing massive BHs in the dwarf regime can be a complicated process. The maximum luminosity of an AGN can be related to its mass via the Eddington limit, which comes from equating the opposing radiation pressure and gravitational force. The Eddington limit is directly proportional to the mass of the BH, meaning that, at low mass, AGNs have lower maximum possible luminosities than their higher mass counterparts. Moreover, AGNs are not typically accreting at the Eddington luminosity [192]. Therefore, observations are biased towards finding higher mass BHs that are accreting at lower rates, rather than dwarf AGN.

On top of them being simply harder to see, searching for broad emission lines can miss low-luminosity/mass AGNs, which may lack a traditional BLR or have broad lines that are weak/hard to detect [58, 80, 212, 213]. Furthermore, X-ray emission, specifically, in dwarf AGNs is generally lower than their more massive counterparts [e.g., 203] meaning that they

can be confused with other sources, such as X-ray binaries.

Moreover, to make the problem twofold, certain problems related to the host galaxies emerge at low mass. For one, AGN selection techniques in the dwarf regime can suffer significant contamination from star-formation processes in their host galaxies. For low-metallicity galaxies, photoionization modeling shows that it becomes difficult to distinguish between AGN and star-formation using BPT narrow emission line ratio diagnostics [41, 79]; the lower metallicity AGNs cannot produce the line ratios needed to push them into the AGN region. In the mid-IR, dwarf starburst galaxies have been observed to heat dust enough to shift into the AGN region of the WISE color-color diagram [78, 85, 97].

Additionally, dwarf galaxies generally have low central stellar densities and more irregularly shaped potential wells than their massive counterparts. At larger radii in the galaxy, a BH primarily relies on interactions via dynamical friction to cause it to spiral down into the center. In this kind of interaction, the BH accelerates other lighter objects in the galaxy through gravitational forces, creating an over-density behind it and causing it to slow down. For a small BH interacting with these kinds of systems, the dynamical friction timescales are much longer than the Hubble time [24, 128, 209], meaning that if a BH leaves the center of its host galaxy, it is unlikely to ever return. Consequently, when BH seeds either form outside of a galaxy center [191] or, likely more often, when merger events involving tidal stripping [23, 214] or gravitational slingshotting [141, 222] occur, the result can be a large population of wandering BHs residing in the halos of their host galaxies. Bellovary et al. [22] predicts that $\sim$ half of all BHs in dwarf galaxies are wandering. Therefore, it is possible that large spectroscopic surveys pointed towards the centers of galaxies are simply missing wandering BHs residing in the outskirts of their host galaxies.

This Work

In this work, we use both photometry and spectroscopy to perform multi-wavelength analyses on multiple samples of AGN candidates. In Chapter 2 we utilize galaxy bulge-disk decompositions presented in Simard et al. [201] to decompose a sample of 117 AGN hosts into their constituent galactic components and calculate the mass of the bulge component specifically. With this measurement, we place our sample of AGNs on the BH-bulge mass scaling relation and find that the sample generally falls below canonical scaling relations derived from large, elliptical/classical bulge galaxies. This finding supports the idea that different types of galaxies follow different scaling relations and emphasizes the need to study distinct samples.

In Chapter 3 we investigate a sample of four dwarf galaxies that were initially selected as AGN candidates based on mid-IR selection techniques. However, in a follow-up study performed by Latimer et al. [119], these galaxies were not found to have accompanying AGN signatures in X-ray observations. We test the possibility of a central star cluster being the source of the AGN-like, mid-IR colors by comparing HST imaging of these galaxies to a simple stellar population synthesis model to estimate cluster ages, extinctions and masses. Our results are consistent with these galaxies hosting very massive, extremely young, dusty, nuclear star clusters that are most likely the source of the extremely red mid-IR colors.

In the final chapter (Chapter 4), we return to studying scaling relations using spectroscopic observations of a sample of six AGNs, five of which are dwarfs. We measure both their stellar velocity dispersions and BH masses from their absorption/emission line spectra and place them on the BH mass versus velocity dispersion scaling relation. We find that our sample generally follows canonical scaling relations, but also emphasize the need for further observations in this mass regime. Interestingly, this sample contained a pleasantly surprising discovery of a triple-peaked AGN; each of the narrow emission lines

(except for [O III]) were obviously triple-peaked. We performed custom fitting on this object in attempts to understand the physical reasoning for this spectral shape and, while we cannot make certain conclusions, we find good agreement for this spectral shape being consistent with AGN outflows plus a ring/disk of star-formation.

A BREAKDOWN OF THE BLACK HOLE - BULGE MASS RELATION IN LOCAL
ACTIVE GALAXIES

Contribution of Authors and Co-Authors

Manuscript in Chapter 2

Author: Megan Sturm

Contributions: Performed the data analysis and was the lead author of the manuscript.

Author: Amy Reines

Contributions: Provided comments on the manuscript and advised the analysis.

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Abstract

We investigate the relation between black hole (BH) mass and bulge stellar mass for a sample of 117 local ($z \sim 0$) galaxies hosting low-luminosity, broad-line active galactic nuclei (AGN). Our sample comes from Reines & Volonteri [174], who found that, for a given *total* stellar mass, these AGNs have BH masses more than an order of magnitude smaller than those in early-type galaxies with quiescent BHs. Here we aim to determine whether or not this AGN sample falls on the canonical BH-to-*bulge* mass relation by utilizing bulge-disk decompositions and determining bulge stellar masses using color-dependent mass-to-light ratios. We find that our AGN sample remains offset by more than an order of magnitude from the $M_{\text{BH}} - M_{\text{bulge}}$ relation defined by early-type galaxies with dynamically detected BHs. We caution that using canonical BH-to-bulge mass relations for galaxies other than ellipticals and bulge-dominated systems may lead to highly biased interpretations. This work bears directly to predictions for gravitational wave detections and cosmological simulations that are tied to the local BH-to-bulge mass relations.

Introduction

Supermassive black holes (SMBH) are thought to live in the center of every massive galaxy [130] and have even been found in dwarf galaxies with masses comparable to the Magellanic Clouds [169]. SMBHs with masses exceeding $10^9 M_{\odot}$ have been observed as early as hundreds of millions of years after the Big Bang [226], however, it is currently unclear how exactly they formed and grew to such large sizes so quickly. Various seeding mechanisms have been proposed (e.g., stellar remnants from Population III stars [34] and direct collapse scenarios [20, 123]) and each have their own signatures that should be detectable in the local universe. Semi-analytic models and simulations can predict what the population of SMBHs should look like in the local universe for each seeding mechanism [22, 176, 218, 220], which

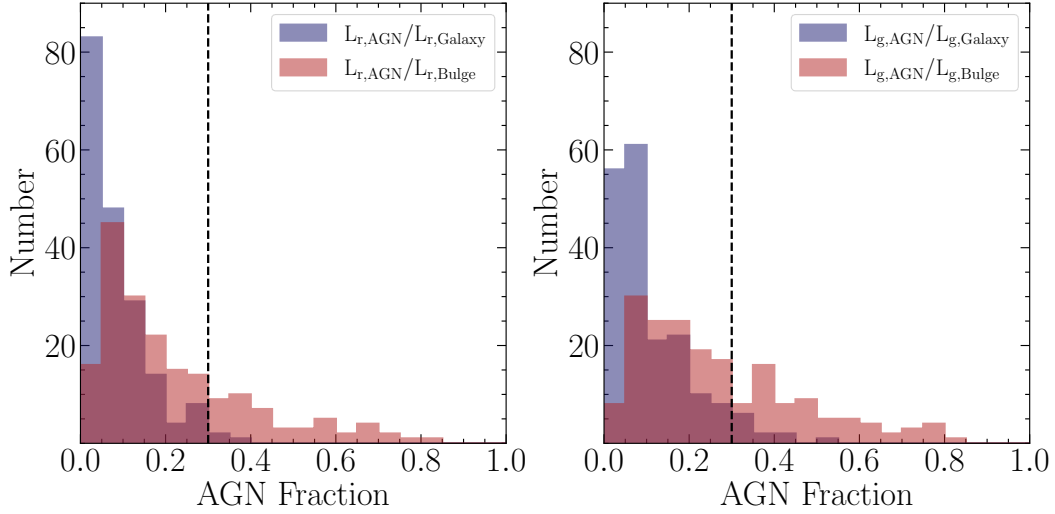


Figure 3 Ratio of AGN to total galaxy luminosity (blue) and bulge luminosity (red) in the r - (left panel) and g - (right panel) bands. We remove galaxies from our sample where the AGN fraction relative to the bulge in either the r - or g -band is greater than 30%, shown by the dashed line in both panels.

we can then compare to observations.

Clues to BH seeding may come from black hole - host galaxy scaling relations in the low-mass regime [176, 221]. Properties including velocity dispersion [64, 140], bulge luminosity [134] and bulge mass [95, 113, 137] have all been found to scale with the mass of the central BH in relatively massive galaxies. Understanding and accurately quantifying these scaling relations across the full range of BH masses, particularly at low masses [9, 194], could reveal information about the origin and evolutionary history of SMBHs.

Canonical scaling relations have traditionally been derived from dynamical BH mass measurements made from observations biased towards high-mass BHs living in nearby, early-type, inactive galaxies with classical stellar bulges [e.g., 113]. However, these relations are often applied to vastly different types of systems where the relations may not hold, including dwarf or late-type galaxies (where classical bulges may be absent), high redshift galaxies (where stellar bulges, if they exist, cannot be resolved) and active galactic nuclei (AGN, which make up the vast majority of detected SMBHs). Observations have indeed revealed

that some types of galaxies do not follow the same canonical relations defined by early-type galaxies with dynamically detected BHs [63, 70, 74, 76, 93, 112, 184, 225].

In particular, Reines & Volonteri [174] investigated the relationship between BH mass and total stellar mass in a large sample of nearby broad-line AGNs to provide a benchmark for studies that cannot avail themselves of bulge masses and/or dynamical BH masses. Reines & Volonteri [174] found a clear correlation between BH mass and total stellar mass for the active galaxies with a near-linear slope, similar to that of early-type galaxies with dynamically detected BHs. However, the normalization of the relation defined by the AGNs is more than an order of magnitude lower than that of the comparison sample of early-type galaxies. These findings suggest that early-type galaxies alone provide an incomplete description of the overall population of galaxies hosting central BHs.

Here, we expand upon the work done by Reines & Volonteri [174], who noted that the AGN host galaxies on the lower BH-to-*total* stellar mass relation could potentially fall on the canonical BH-to-*bulge* mass relation if the bulge masses for the AGN hosts were, on average, only 5% of the total stellar masses. To test this, we use bulge-disk decompositions from Simard et al. [201] for a subset of the Reines & Volonteri [174] sample, derive bulge masses, and compare our results to the BH-bulge mass relation in Kormendy & Ho [113]. In Section 2.2 we describe the galaxy sample, the bulge-disk decomposition method, and stellar mass calculations. Our results are presented in Section 2.3 and we conclude with a discussion in Section 2.4. As in Reines & Volonteri [174], we adopt $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and use SDSS magnitudes.

Galaxy Sample

Our primary sample consists of 117 galaxies hosting broad-line AGNs identified by Reines & Volonteri [174] that also have bulge-disk decompositions in Simard et al. [201]. As described below, we restrict our broad-line AGN sample to those systems where the

AGN luminosity is low compared to the bulge luminosity to help ensure the bulge-disk decompositions are not significantly impacted by the presence of a bright AGN point source.

NSA ID	zdist	Model	n	M_r				$g - r$		$\log(M/M_\odot)$	
				AGN	Bulge	Disk	Galaxy	Bulge	Disk	BH	Galaxy
25955	0.04	n4	4.00	-17.05	-20.84	-20.68	-21.51	0.66	0.65	6.21	10.45
11183	0.03	free	4.53	-16.05	-17.59	-19.77	-19.90	0.69	0.61	5.70	9.20
7741	0.04	free	6.41	-18.57	-20.12	-21.17	-21.51	0.50	0.50	6.50	9.90
82570	0.02	n4	4.00	-16.89	-20.69	-19.84	-21.10	0.67	0.69	6.51	10.42
15665	0.03	free	7.70	-18.93	-20.21	-21.20	-21.57	0.23	0.54	6.74	9.49
109525	0.05	n4	4.00	-18.04	-21.07	-20.50	-21.57	0.80	0.59	7.25	10.79

Table 1 Sample of 117 active galaxies with low-luminosity, broad-line AGNs and bulges. Column 1: NSA identification number. Column 2: **zdist** parameter in the NSA, which is based on the SDSS NSA redshift and the peculiar velocity model of Willick et al. [228]. Column 3: Optimal decomposition model from Simard et al. [201] based on a 1σ cutoff on the likelihood. Column 4: Bulge Sérsic index if a two-component model is preferred or galaxy Sérsic index if a single-component model is preferred. Column 5: AGN absolute r -band magnitude from Reines & Volonteri [174]. Column 6: Bulge absolute r -band magnitude from Simard et al. [201] with the AGN contribution removed. Column 7: Disk absolute r -band magnitude from Simard et al. [201]. Column 8: Galaxy absolute r -band magnitude (from combining AGN-subtracted bulge magnitude and disk magnitude). Column 9: Bulge $(g - r)$ color. Column 10: Disk $(g - r)$ color. Column 11: Log BH mass from Reines & Volonteri [174]. Column 12: Log bulge stellar mass as calculated in this work. Column 13: Log total galaxy stellar mass as calculated in this work. Masses are reported as $\log(M/M_\odot)$. Bulge masses are calculated by subtracting the AGN contribution calculated by Reines & Volonteri [174] from the bulge light reported in Simard et al. [201] and using the mass-to-light ratio from Zibetti et al. [237]. Disk masses are calculated in the same manner, but without subtracting the AGN contribution. Total galaxy stellar mass is calculated by adding the bulge mass and the disk mass. For the 14 galaxies that are pure bulge, the disk magnitude and color are reported with a dash.

(This table is available in its entirety in machine-readable form.)

Broad-line AGNs

Reines & Volonteri [174] started with a large sample of nearby galaxies ($z \leq 0.055$) from the NASA-Sloan Atlas (NSA), which provides a reanalysis of the SDSS Data Release 8 (DR8) spectroscopic catalog [1] using improved optical photometry [31] and spectroscopy [232, 233]. Reines & Volonteri [174] performed spectral analysis on $\sim 67,000$ galaxies and identified 244 galaxies hosting broad-line AGNs based on the detection of broad $H\alpha$ emission. The broad $H\alpha$ full width at half maximum (FWHM) was restricted to be $\geq 500 \text{ km s}^{-1}$. Additionally, the sources were required to have narrow-line ratios falling in both the AGN region of the $[OIII]/H\beta$ vs. $[NII]/H\alpha$ diagram and the Seyfert region of the $[OIII]/H\beta$ vs. $[SII]/H\alpha$ diagram. These requirements help ensure a clean sample of broad-line AGNs and eliminate sources of broad $H\alpha$ due to star-formation-related emission [e.g., 13]. Lastly, a handful of sources in which the AGN contributed more than 50% of the integrated light were removed since the stellar masses for these objects were unreliable. BH masses were estimated using the single-epoch virial mass estimator based on the FWHM and luminosity of broad $H\alpha$ emission and given by equation 5 in Reines et al. [169]. These BH mass estimates carry uncertainties of ~ 0.5 dex.

We cross-match the 244 broad-line AGNs from Reines & Volonteri [174] with BH mass estimates to the Simard et al. [201] catalog of 1.2 million galaxies with bulge-disk decompositions, yielding 192 matches.

Bulge-Disk Decompositions

Simard et al. [201] provide catalogs of three different galaxy fitting models for over a million galaxies in the SDSS using Galaxy Image 2D (GIM2D) to extract bulge and disk components [202]. The first model fits the entire galaxy with a single Sérsic component with Sérsic index n_g . The second model fits the galaxy with two components: an exponential disk (with fixed $n=1$) and a classical bulge (with fixed $n_b = 4$). The last model fits the galaxy

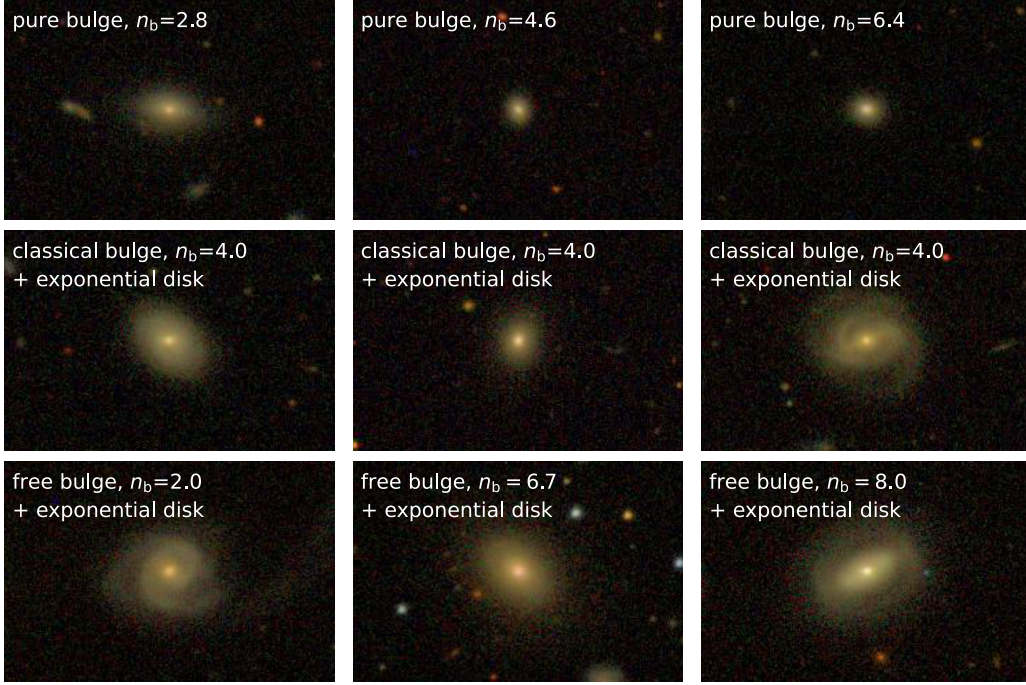


Figure 4 Images of galaxies in our sample from the NSA that were decomposed into a single Sérsic component (top row), a classical bulge + exponential disk (middle row) and a free n_b bulge + exponential disk, determined using a 1σ cutoff on the likelihood as reported by Simard et al. [201].

again with two components, one being an exponential disk (with fixed $n=1$), but in this case, the bulge Sérsic index is a free parameter within the range $0.5 < n_b < 8$.

Simard et al. [201] reports the bulge, disk and total galaxy absolute magnitudes (in the g - and r -bands) for each fit. They also provide probabilities for each model calculated using χ^2 statistics to indicate the most likely model for each galaxy. Probabilities are provided for each model in relation to more complicated models, i.e. how likely it is that a galaxy requires a two-component model compared to a single-component model or that it needs a free bulge Sérsic index compared to a classical bulge with fixed Sérsic index. We tested a range of cutoff values on the probability for choosing the best model. Increasing the cutoff increases the number of galaxies requiring the most complicated two-component, free n_b model and decreasing it permits the single-component and $n_b = 4$ models to begin being utilized. Simard et al. [201] notes that a lower cutoff extracts a more reliable sample of bulges while a higher cutoff more thoroughly describes overall galaxy properties.

We explore the full range of cutoffs, however, we report results using a 1σ cutoff of 0.32 on the probability for choosing the appropriate galaxy model as described in Simard et al. [201]. This resulted in 119 galaxies best described by the classical bulge + exponential disk model, 58 galaxies best described by a free n_b + exponential disk model and 15 single-component galaxies. For the single-component galaxies, we set a limit of $n_g > 2$ [112], above which we consider the galaxy to be a pure bulge and below to be a pure disk. One galaxy in our sample was classified as a pure disk (also categorized as an Scd type galaxy in Huertas-Company et al. 94), leaving us with 191 galaxies with bulges.

The work done by Simard et al. [201] has generally proven to be robust and is widely used. In their paper, Simard et al. [201] compares their galaxy Sérsic index and half-light radius values to the New York University Value-Added Galaxy Catalog [32], which also provides Sérsic measurements for SDSS galaxies. They report that, accounting for differences in the two decomposition methods, their decompositions show good agreement with the NYU

catalog. Additionally, in recent work on a sample of ~ 8 million galaxies from the Hyper Suprime-Cam Wide Survey, Ghosh et al. [67] performs galaxy decompositions using the machine-learning framework Galaxy Morphology Posterior Estimation Network (GaMPEN). They compare their results to the decompositions done by Simard et al. [201] for the galaxies falling in both samples and find strong correlations between the two measurements for multiple parameters, namely bulge-to-total light ratio, half-light radius and flux.

Furthermore, we find good agreement between the Sérsic index for galaxies requiring a single-component decomposition from Simard et al. [201] to the Sérsic index found by a single-component fit as reported in the NSA. For the 57,415 galaxies from Simard et al. [201] that both require a single component decomposition and are also in the NSA, we find a median offset in the two Sérsic indices of 0.12 ± 1.21 and for the 14 pure bulges in our sample we find a median offset of -0.16 ± 1.07 . Therefore, the Sérsic indices derived through single-component fits in the NSA are generally consistent with those found by Simard et al. [201].

As a final check, we use the GIM2D software to reproduce the galaxy models for a subset of our sample using the decomposition parameters chosen based on our 1σ cutoff. We find good agreement between the SDSS image and the model for our galaxies and see minimal features in the residuals.

Restricting to Low-Luminosity AGN

Since the decompositions of Simard et al. [201] do not account for a potential AGN point source at the center of the galaxy, we restrict our sample of broad-line AGNs to those that have a low luminosity relative to the bulge. An unaccounted-for, bright, central point source could skew the Sérsic index towards higher values and the half-light radius towards lower values, (i.e. the galaxy would seem to be more compact than it actually is). This in turn would have the potential to make the decompositions and our subsequent mass

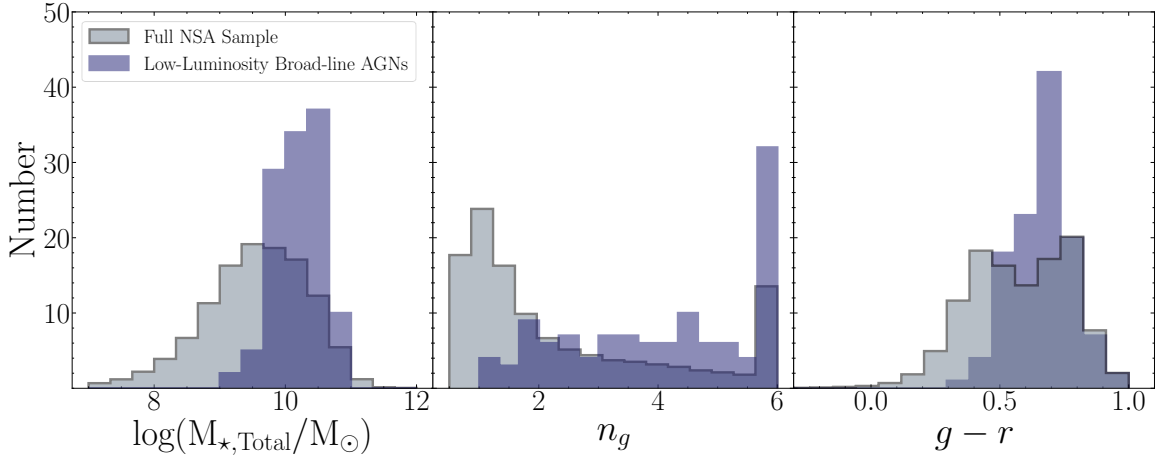


Figure 5 Total stellar mass (left), galaxy Sérsic index (middle) and $g - r$ galaxy color (right) for the 117 active galaxies with low-luminosity, broad-line AGNs in our sample (blue) compared to the full NSA parent sample (gray; normalized to our sample size). All values are as reported in the NSA. Sérsic indices are from single-component fits. We note that the maximum Sérsic index reported by the NSA is 6 causing a false peak. Our sample is biased towards galaxies with higher mass and higher Sérsic index.

measurements unreliable.

Here we dub “low-luminosity” to indicate that the AGN luminosity is sub-dominant relative to the bulge luminosity in both the g - and r -bands such that $L_{\text{AGN}}/L_{\text{bulge}} \leq 0.3$. Our threshold of 0.3 is informed by the analysis of Getachew-Woreta et al. [66] that demonstrates various morphological parameters generally are not significantly impacted until an AGN fraction of at least $\sim 30\%$.

Estimated AGN flux densities come from the work of Reines & Volonteri [174]. They created a mock AGN spectrum consisting of a scaled power law and observed strong emission lines, and then convolved it with the SDSS filter throughput curves. Figure 3 shows the distribution of AGN fractions relative to the bulge and total galaxy light. We remove 71 galaxies from our sample where the AGN contribution is above 30% in either g - or r -band (or both). We further address the validity of using the Simard et al. [201] decompositions for the remaining sample of 120 galaxies in Section 2.2.5 below.

Figure 4 shows galaxies in our final sample with different bulge-disk decompositions

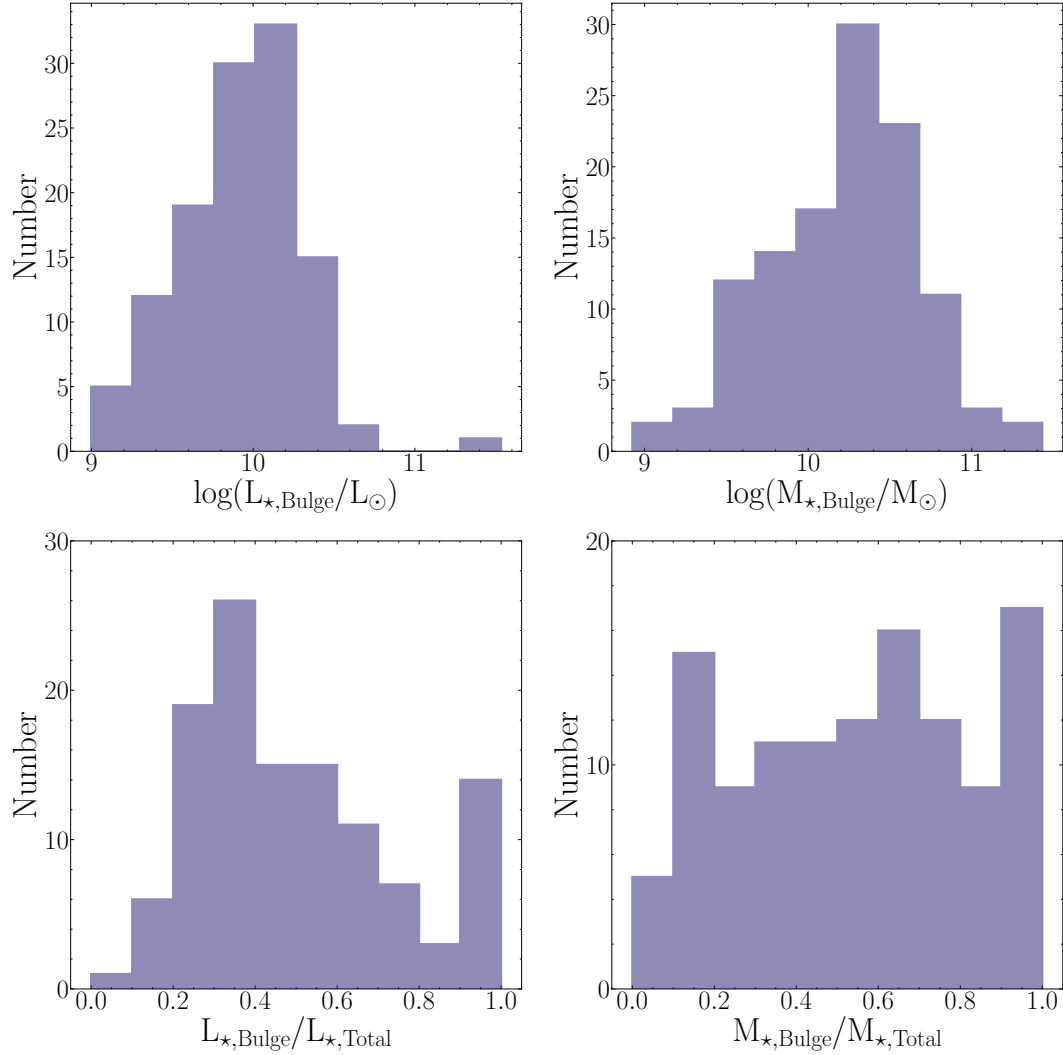


Figure 6 **Top:** Bulge r -band luminosity (left) and mass (right). **Bottom:** Bulge-to-total r -band luminosity (left) and mass (right) fractions for our sample of low-luminosity, broad-line AGNs. Bulge masses and luminosities are calculated using magnitudes as reported in Simard et al. [201] with color-dependent mass-to-light ratios from Zibetti et al. [237] and AGN luminosity estimates are from Reines & Volonteri [174].

performed by Simard et al. [201]. The distribution of total stellar masses, Sérsic indices, and colors for our sample of low-luminosity, broad-line AGNs is shown in comparison with the full NSA parent sample in Figure 5.

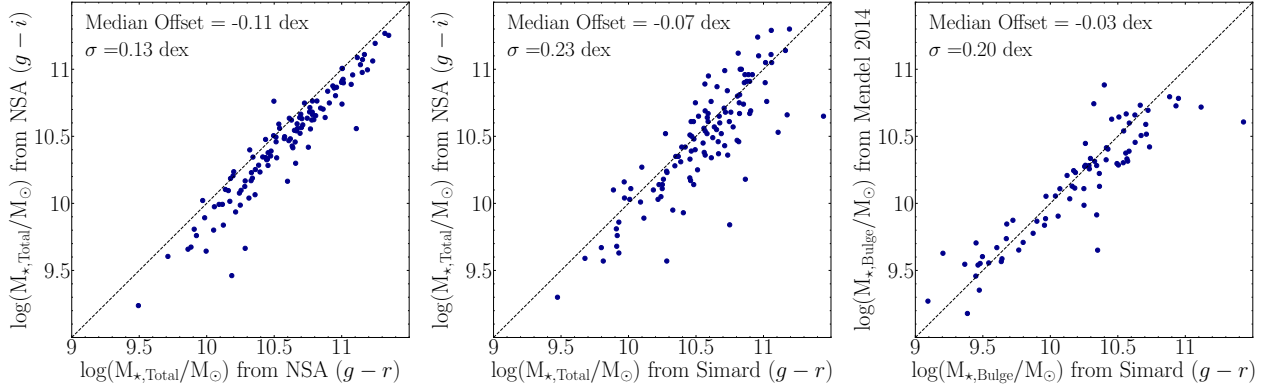


Figure 7 **Left:** Total stellar masses calculated using different combinations of integrated magnitudes reported in the NSA. Using g - and i -band data (as in Reines & Volonteri 174) results in a median offset of -0.11 dex with respect to using g - and r -band data. **Middle:** Total stellar mass calculated with g and i -band data from the NSA again but now versus total stellar masses that we calculate using bulge and disk g - and r -band data from Simard et al. [201] and summing the bulge and disk masses. This results in a median offset of -0.07 dex. **Right:** Bulge mass calculated by Mendel et al. [139] versus our g - and r -band-calculated bulge masses. Despite using a different method for determining which decomposition model to use, the median offset is -0.03 dex.

Bulge and Total Stellar Mass Calculations

We estimate bulge masses and total stellar masses following a similar procedure as Reines & Volonteri [174] for consistency, using color-dependent mass-to-light ratios from [237] for the 120 remaining galaxies in our sample. Simard et al. [201] uses the SDSS spectroscopic redshift, while Reines & Volonteri [174] adopt the `zdist` parameter provided by the NSA, which is based on the SDSS NSA redshift and the peculiar velocity model of Willick et al. [228]. We therefore make a correction to the absolute magnitudes in Simard et al. [201] to ensure all quantities are calculated consistently using the `zdist` redshift.

Next, we subtract out the AGN contribution to the flux of the bulge and convert disk and bulge magnitudes to disk and bulge masses using the following color-dependent mass-to-light ratio from Zibetti et al. [237] and a solar r -band magnitude of 4.67 from Bell et al. [21]:

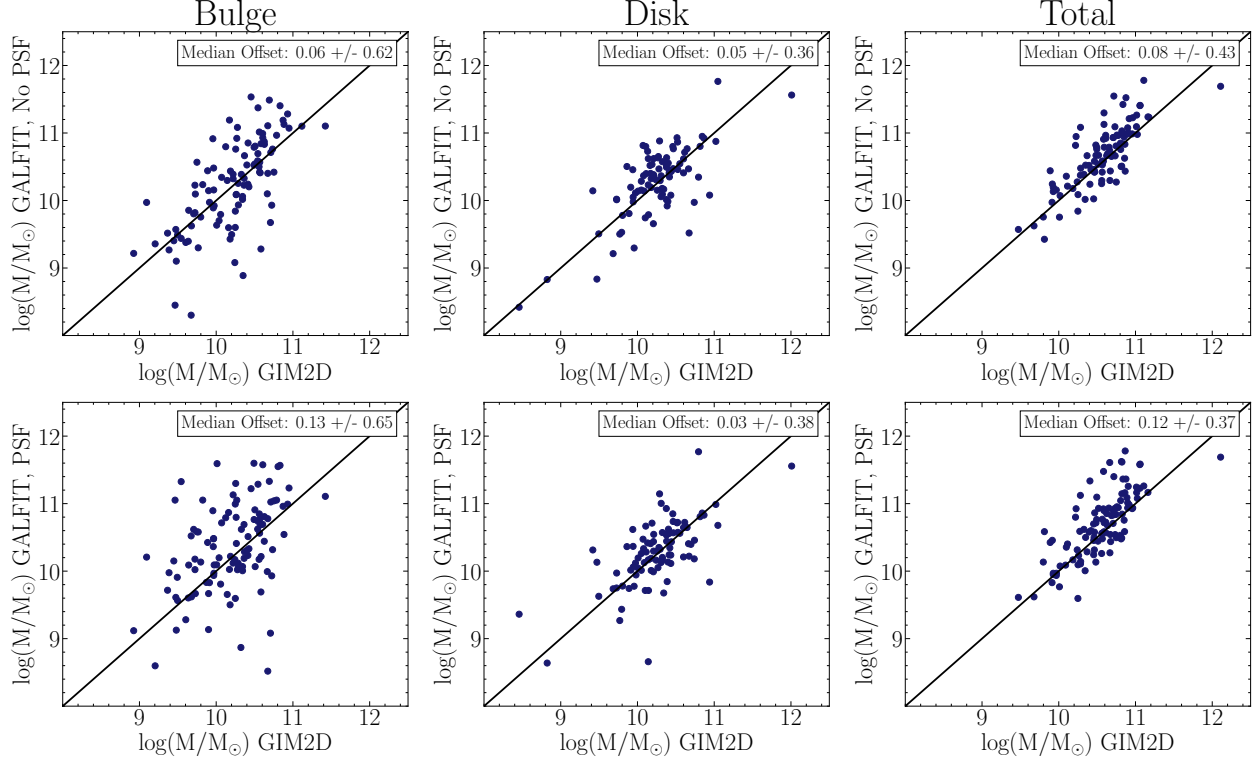


Figure 8 Bulge (left column), disk (middle column) and total (right column) stellar masses calculated using magnitudes determined by two-component (bulge + disk) decompositions from Simard et al. [201] using the GIM2D software with AGN magnitudes subtracted from the bulge component versus masses derived using magnitudes measured using both two (bulge + disk, top row) and three (bulge + disk + central PSF, bottom row) component fits and the GALFIT software. The black line shows the one-to-one line. We confirm that the two-component fits performed by Simard et al. [201] are adequate for our sample of low-luminosity AGNs (see §2.2.5).

$$\log(M/L_r) = 1.654(g - r) - 0.840. \quad (1)$$

We adopt total stellar masses as the sum of the bulge mass plus the disk mass. This produces more physically meaningful results than simply converting total galaxy magnitudes provided by Simard et al. [201] to masses. We found that using the latter method sometimes resulted in a total stellar mass that was less than the calculated bulge mass, which is clearly not physical. Disks and bulges often have very different colors and applying a single color-dependent mass-to-light ratio to the integrated galaxy magnitude would not account for these variations.

One galaxy had an unreliably high disk mass ($\log(M_{\text{Disk}}/M_{\odot}) \sim 18$) so we remove it from our sample. Additionally, we propagate errors on the magnitudes reported by Simard et al. [201] through our calculations and find one galaxy with an anomalously high bulge mass error (~ 3 dex), so we remove it from our subsequent analysis. The results from our mass calculations are given in Table 1. The resulting bulge fractions in both luminosity and mass are shown in Figure 6. Of this sample of 118 galaxies, 65 are best described by the classical bulge + exponential disk model, 38 are best described by a free n_b + exponential disk model and 15 are single-component galaxies, with one of those being a pure disk galaxy. Therefore, in the end, we have a final sample of 117 galaxies with bulges that we can place on the BH mass - bulge mass relation.

The stellar masses we calculate are based on r -band mass-to-light ratios as a function of $g - r$ color (since Simard et al. 201 report magnitudes in the g - and r -bands), whereas Reines & Volonteri [174] use i -band mass-to-light ratios as a function of $g - i$ color based on integrated photometry in the NSA. To determine the consistency of these methods, we first check how using different bands affects total stellar masses calculated using NSA photometry.

Using the corresponding mass-to-light conversions reported in Zibetti et al. [237], we calculate total stellar masses using g - and i -band data (as in Reines & Volonteri 174) as well as g - and r -band data, both from the NSA, finding that the former produces lower masses with a median offset of 0.11 dex. When we instead compare total stellar masses using g - and i -band data from the NSA to our total stellar masses calculated using g - and r -band data from Simard et al. [201, as bulge mass plus disk mass], we find a median offset of 0.07 dex albeit with more scatter. While the offset can be attributed to the different bands, the increased scatter is likely due to using different photometry. Figure 7 shows that, overall, our masses are consistent with previously calculated masses in Reines & Volonteri [174].

We also compare our masses to those calculated by Mendel et al. [139]. They provide a catalog of bulge, disk and total stellar mass estimates using SED modelling and the Simard et al. [201] decompositions. However, we note that they use a slightly different method of distinguishing between galaxies requiring a single or two component fit than we do in this work. 78 of our galaxies have mass estimates in this catalog, and for 10 of these, we used a single component decomposition model while they used a two component model or vice versa. Despite this, we find that our bulge masses are consistent with the ones they calculate, with a median offset of 0.03 ± 0.20 dex (see Figure 7). Since their calculated bulge masses remain comparable to ours even when a different decomposition model is used, we conclude that our bulge mass estimates are robust.

GALFIT Modeling

To further ensure that the presence of low-luminosity AGNs does not impact our results, we re-fit our sample of galaxies using the GALFIT [157] software both with and without a central point source component in the fitting. The first represents the more thorough method of accounting for the dim central AGN and the latter replicates the fitting performed by Simard et al. [201]. As described below, we find that the bulge masses do not change

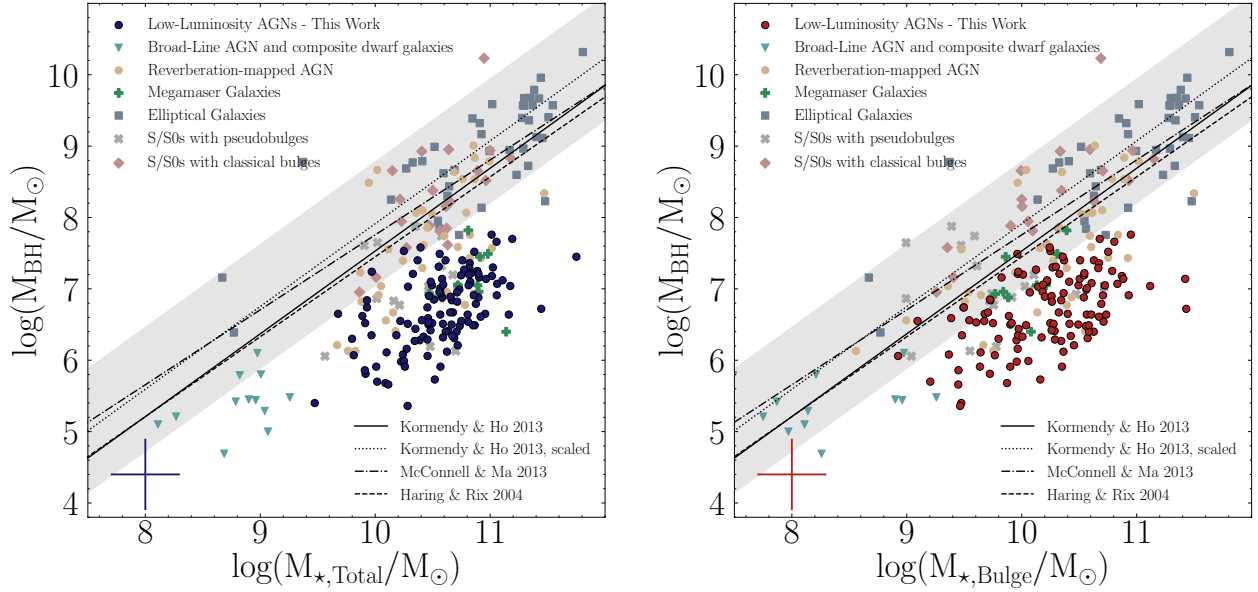


Figure 9 BH mass versus total stellar mass (left) and stellar bulge mass (right). The Kormendy & Ho [113], [95], and McConnell & Ma [137] BH-bulge mass relations are shown, with the shaded region indicating the 3σ intrinsic scatter of the Kormendy & Ho [113] relation as reported in their paper. Error bars in the bottom left of each plot show the median uncertainties associated with our sample. For comparison, we show the sample of elliptical galaxies and S/S0 galaxies with classical bulges and pseudobulges, all with dynamical mass measurements. The ellipticals and classical bulges were originally used to derive the Kormendy & Ho [113] relation. We also plot megamaser galaxies from Läscher et al. [127], reverberation-mapped AGNs with BH masses from Bentz & Manne-Nicholas [29] and broad-line AGN/composites in dwarf galaxies with bulge masses determined by [194, see §2.2.6].

significantly by adding a central point source and that we can safely use the decompositions from Simard et al. [201] despite the fact that they do not include a central point source.

We first create a point-spread function (PSF) for each galaxy image to both convolve with our models and act as the function describing the central AGN point source in the three-component model. We use the parameters provided by SDSS in the corresponding ‘psField’ images and extract a PSF image using the SDSS `read_PSF` software utility. We then fit this PSF image in GALFIT using as many Sérsic components as necessary to create an accurate PSF model, which is used in our subsequent modeling.

We follow Simard et al. [201] in giving apparent and absolute magnitude as:

$$m = -2.5\log_{10}(F/t) - \chi\sec z - m_0 \quad (2)$$

$$\begin{aligned} M_g &= m_g - e_g - DM(z) - k_g \\ M_r &= m_r - e_r - DM(z) - k_r, \end{aligned} \quad (3)$$

where χ is the extinction coefficient, $\sec z$ is the airmass, m_0 is the magnitude zero-point, e_g and e_r are the line-of-sight Galactic extinctions, $DM(z)$ is the distance modulus at redshift z and k_g and k_r are the k -corrections. We obtain values for χ , $\sec z$ and m_0 from the SDSS ‘tsField’ images and values for e_g , e_r , k_g and k_r from the NSA.

We perform galaxy fits using estimated AGN magnitudes from Reines & Volonteri [174] and the best-fit parameter values for the bulge and disk from Simard et al. [201] as the initial parameter guesses for GALFIT. To more closely replicate the simultaneous g- and r-band fits done by Simard et al. [201], we first fit the r-band images and use the resulting parameter values for both bulge and disk position angle (ϕ_b and ϕ_d), half-light radius (r_b and r_d) and the ellipticity (e_b and e_d) as fixed parameters in the g-band fit. Based on the distribution of χ^2 values from our resulting fits and visual inspection of the images, we consider the GALFIT result successful if the reduced χ^2 value associated with the fit is <5 . We obtain successful GALFIT models for 95/117 of our galaxies that have bulges. See the Appendix A for an example.

We compare the resulting bulge, disk and total stellar masses (calculated using the procedure described above in Section 2.2.4) between the two-component GIM2D fit from

Simard et al. [201] and our GALFIT models, both with and without a central point source included as a part of the fit (Figure 8). Not including a central point source generally makes the two measurements agree slightly better as expected. However, the median offset in bulge and total mass increases by only ~ 0.05 dex when we add a PSF component. The median offset between the GALFIT and GIM2d bulge, disk and total stellar masses is small in all cases, ~ 0.04 dex for the disk and ~ 0.1 dex for the bulge and total stellar mass. This demonstrates that while there may be a small systematic mass offset between using the two different softwares, the presence of our low-luminosity AGNs does not significantly impact the bulge masses, on average, calculated using a two-component decomposition without a central point source. While the scatter in the bulge masses is ~ 0.6 dex, our results on the BH – bulge mass relation would not change significantly as described in more detail in Section 2.3.1.

Additional Objects

For comparison to our low-luminosity, broad-line AGN sample, we also include the objects that are compiled in [194] in their study of the BH-bulge mass relation including dwarf galaxies. Schutte et al. [194] includes 88 galaxies with dynamical BH masses, composed of 79 galaxies from Kormendy & Ho [113] and nine megamaser galaxies from Läscher et al. [127]. They also include 37 reverberation-mapped AGN with BH masses taken from Bentz & Manne-Nicholas [29]. Lastly, they add 12 broad-line AGNs/composites in dwarf galaxies, two of which are included in our main low-luminosity, broad-line AGN sample. For all of these objects, we follow the methods described in Schutte et al. [194] to calculate bulge stellar masses in a manner consistent with our low-luminosity, broad-line AGN sample. In other words, all bulge stellar masses are estimated in the most consistent way that is feasible, using color-dependent mass-to-light ratios from Zibetti et al. [237]. We refer the reader to Schutte et al. [194] for details on the samples, bulge stellar mass calculations, and BH mass

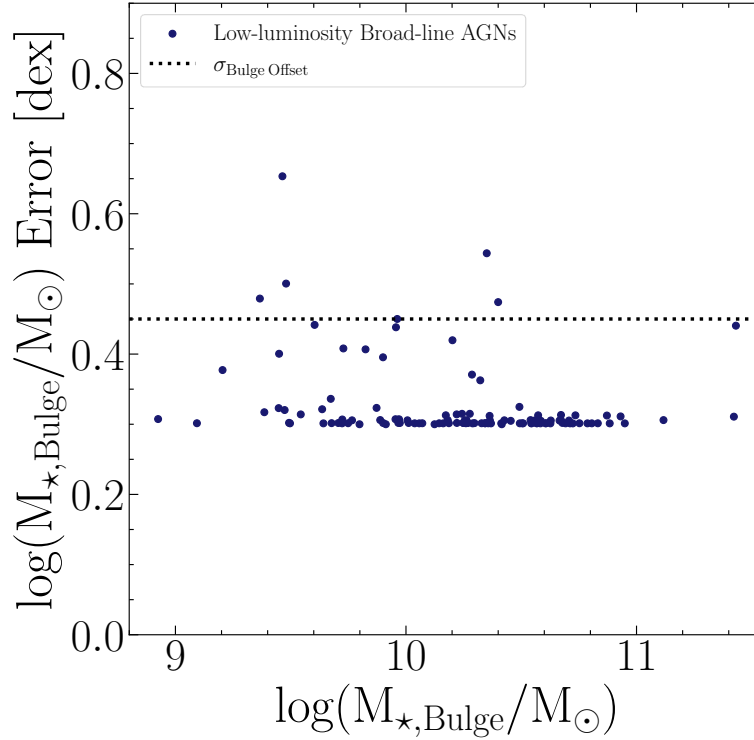


Figure 10 Error in bulge mass versus bulge mass. Errors incorporate uncertainties in the bulge-disk decompositions from Simard et al. [201] and a 0.3 dex uncertainty from stellar evolution models [49]. The dotted line shows the scatter in the distribution of black hole mass versus bulge mass. Only six of our galaxies have individual errors exceeding the scatter in the distribution indicating that the horizontal offset cannot be explained by uncertainties in bulge masses.

estimates.

Results

BH-Bulge Mass Relation

We plot BH mass as a function of both total stellar mass and bulge mass in Figure 9. The BH mass - total stellar mass relation was originally explored in Reines & Volonteri [174], where they found that the AGN host galaxies fell on average an order of magnitude below early-type galaxies with dynamically detected BHs. Here we intend to determine if using bulge mass rather than total stellar mass brings the AGN host galaxies in line with

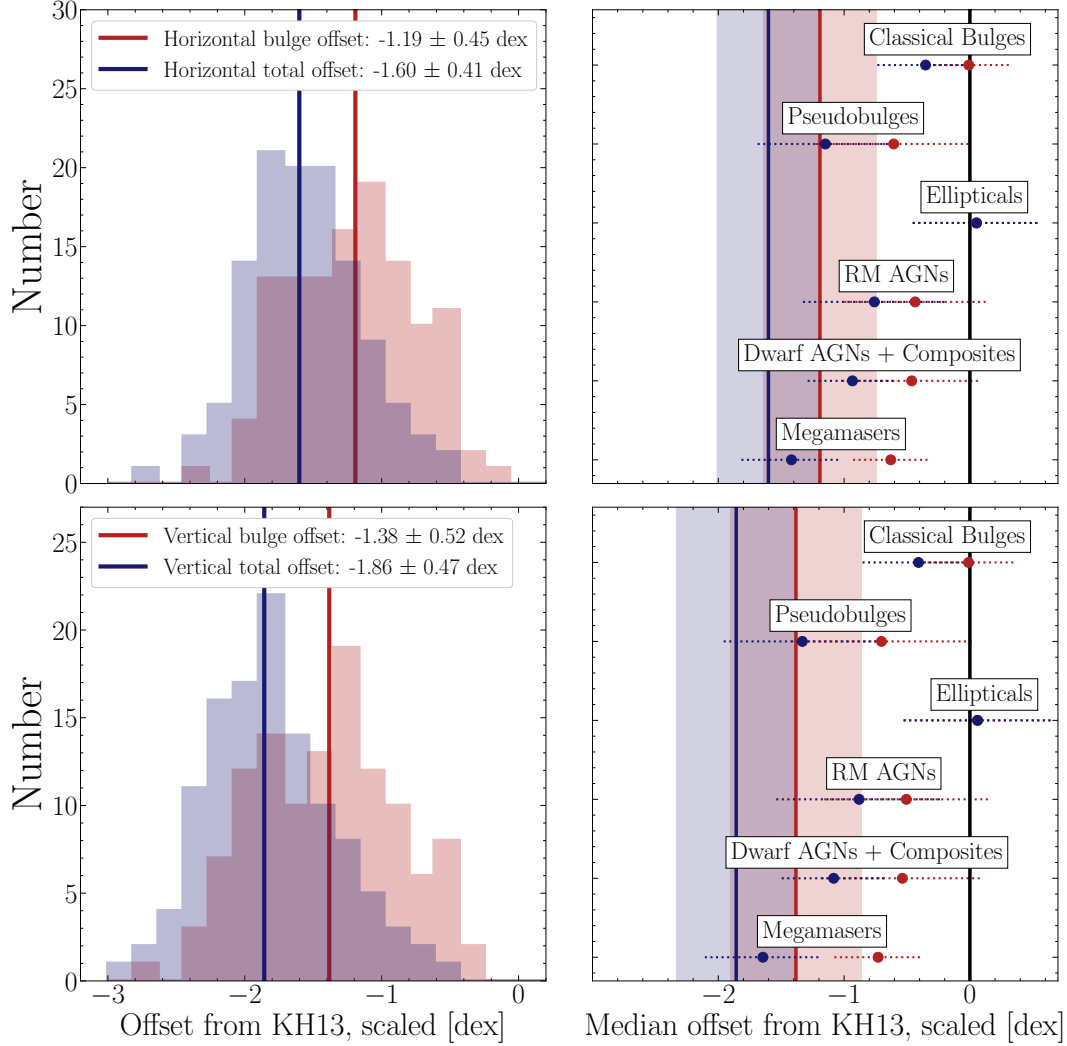


Figure 11 **Left:** The horizontal (top) and vertical (bottom) offsets of our sample from the Kormendy & Ho [113] M_{BH} versus M_{bulge} relation. We report the $3\text{-}\sigma$ -clipped median and standard deviation using the bulge & total stellar mass. Although using just the bulge mass brings our sample closer to the Kormendy & Ho [113] line, it is still significantly offset. **Right:** Median horizontal (top) and vertical (bottom) offset from the Kormendy & Ho [113] relation for each of our comparison samples, with blue points indicating the total offset and red points indicating the bulge offset. The vertical lines show the median and the shaded regions show the dispersion for our active galaxy sample. The black vertical line shows zero offset. Dotted error bars represent the 1σ scatter in the distribution for each sample. Ellipticals and classical bulges that were originally used to create the relation have a median almost directly on the line, while other types of galaxies tend to fall below, even when the bulge component is extracted.

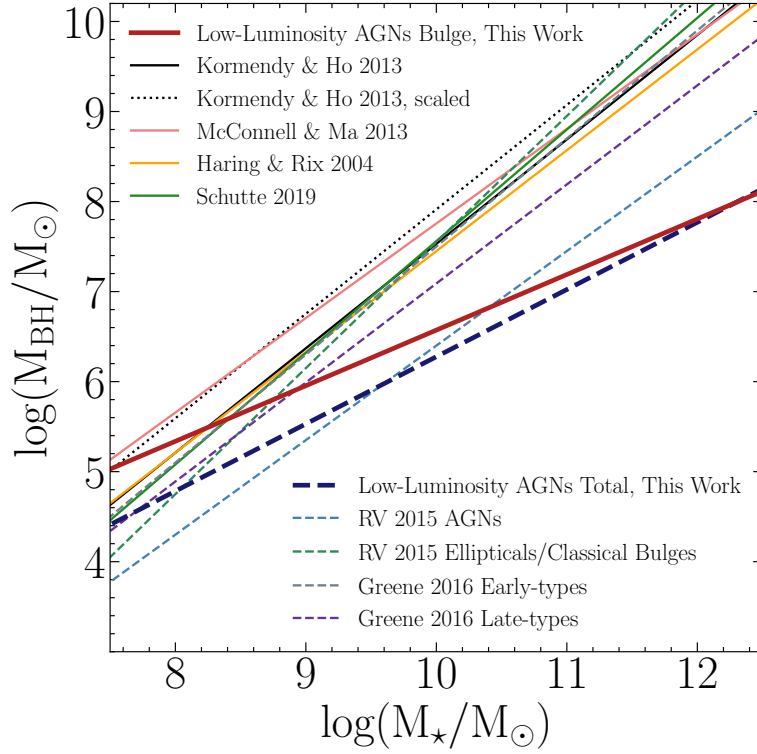


Figure 12 Linear fit of BH mass versus stellar bulge mass (red line) and total stellar mass (blue dashed line) for our sample of low-luminosity, broad-line AGNs in comparison with the canonical Kormendy & Ho [113] BH-bulge mass relation (the scaled relation is shown as a dotted line), the Reines & Volonteri [174] relation (labeled as RV 2015 AGNs) for BH mass versus total stellar mass for AGNs and multiple other relations from the literature. We indicate BH-bulge mass relations with solid lines and BH-total mass relations with dashed lines (see §2.3.2.)

the early-type galaxies that define the canonical BH mass - bulge mass relations.

For consistency with Reines & Volonteri [174], we primarily compare our results to the Kormendy & Ho [113] BH-bulge mass relation (equation 10 in their paper). As noted in [174], there is a difference in the assumed IMFs between Kormendy & Ho [113] and Zibetti et al. [237] that results in systematically higher masses in the former by 0.33 dex, so we scale the Kormendy & Ho [113] relation accordingly since we have adopted masses using the Zibetti et al. [237] relations throughout this work.

For each of the galaxies in our low-luminosity, broad-line AGN sample we calculate the horizontal shift from the canonical relation (i.e., the offset in bulge mass at a given BH mass). The median horizontal offset from the Kormendy & Ho [113] line is -1.60 ± 0.41 dex for total stellar mass and -1.19 ± 0.45 dex for the bulge mass. Extracting the bulge component of the stellar mass shifts the median of the sample ~ 0.41 dex closer to the [113] relation and has a similar scatter, however the sample remains significantly offset from the canonical relation. Similarly, the active galaxies fall below the Kormendy & Ho [113] relation with a median vertical offset of -1.86 ± 0.48 dex for the total stellar mass and -1.38 ± 0.52 for the bulge mass. Moreover, at a given bulge mass, there is a large spread in BH masses.

The errors reported above are the 1σ scatter in the distribution of offsets. These values are larger than the systematic errors associated with individual points, indicating the offsets are significant. For the vertical offset, the scatter in the distribution is larger than the systematic uncertainties in single epoch virial BH masses (~ 0.5 dex). For the horizontal offset, we find individual bulge mass errors by propagating systematic uncertainties through our calculations (see §2.2.4), resulting in a median error of ~ 0.06 dex. In most cases, our stellar and bulge mass errors are therefore dominated by uncertainties in stellar evolution, expected to be ~ 0.3 dex [49]. Adding the individual errors and the uncertainties in stellar evolution in quadrature, the scatter in the distribution of horizontal offsets for our sample is greater than the uncertainties for all but six galaxies, shown in Figure 10. This indicates

that errors in bulge mass estimates cannot account for the discrepancy between our sample of low-luminosity, broad-line AGNs and the canonical BH-bulge mass relation.

We note that changing the cutoff probability for model selection (see §2.2.2) in Simard et al. [201] does not significantly change the bulge offsets from the canonical relation. When the cutoff was set to zero and all galaxies were described with pure Sérsic profiles, the median bulge mass (horizontal) offset was -1.27 ± 0.47 dex. Increasing the cutoff to one, with all galaxies being described by the two-component, free n_b model, returns a median bulge offset of -1.16 ± 0.48 dex. In both cases, the AGN sample is still significantly offset from the canonical relation.

Furthermore, when using the results of our GALFIT modeling (§2.2.5), the AGN sample remains significantly offset from the Kormendy & Ho [113] relation (see the Appendix A). We find that the median horizontal bulge offset when using GALFIT is -1.40 ± 0.70 when including a central point source and -1.22 ± 0.75 dex when not including a central point source in the models. The median horizontal offset does not change substantially between GALFIT and GIM2D, or between including/not including a central point source.

For comparison, we also find the median offsets between the groups of additional objects described in §2.2.6 and the Kormendy & Ho [113] BH-bulge mass relation. Figures 11 shows the results for both total stellar mass and bulge mass; extracting the bulge component always brings the galaxies closer to the canonical relation. As expected, the elliptical galaxies along with classical bulges in spiral galaxies originally used to derive the canonical Kormendy & Ho [113] relation have a median horizontal and vertical offset of approximately zero. However, even with the bulge extracted, all the other types of galaxies tend to fall below the relation to varying degrees. Reverberation-mapped AGNs and dwarf AGNs/composites fall ~ 0.5 dex below the relation on average. Megamaser galaxies and pseudobulges fall even further below the relation, at ~ 0.7 dex. Our sample of low-luminosity, broad-line AGNs falls the furthest (more than 1 dex) below the canonical relation, with zero offset inconsistent within 2σ from

the median. We note that some of these objects have small sample sizes in Figure 11.

Linear Fit

We fit a linear relation between $\log$ BH mass and $\log$ stellar bulge mass, as well as $\log$ total stellar mass for our sample. For consistency, we follow the procedure outlined by Reines & Volonteri [174] using the Bayesian linear regression method of Kelly [104] which takes into account errors in both the BH and bulge or total stellar mass. We parameterize the relation with the following:

$$\log(M_{\text{BH}}/M_{\odot}) = \alpha + \beta \log(M_{\star}/10^{11}M_{\odot}) \quad (4)$$

and find,

$$\begin{aligned} \alpha_{\text{Bulge}} &= 7.18 \pm 0.09, \quad \beta_{\text{Bulge}} = 0.60 \pm 0.11 \\ \alpha_{\text{Total}} &= 7.03 \pm 0.07, \quad \beta_{\text{Total}} = 0.72 \pm 0.13, \end{aligned} \quad (5)$$

where the slope and intercept are the median of 10,000 draws from the posterior probability distribution of the parameters and the reported errors are the 1σ scatter.

We compare the BH-bulge mass relation best-fit parameters that we find for our low-luminosity, broad-line AGNs to values in the literature derived from various samples of galaxies (shown in Figure 12). We include the Kormendy & Ho [113] relation as well as the Häring & Rix [95] and McConnell & Ma [137] relations, all of which are based on samples of early-type galaxies. We also include the relation derived by Schutte et al. [194] based on a variety of galaxy types and included here as a comparison sample of additional objects (see §2.2.6). Schutte et al. [194] include 12 dwarf galaxies [169], 37 reverberation-mapped AGN from Bentz & Manne-Nicholas [29], nine megamaser galaxies from Läsker et al. [127] and

the Kormendy & Ho [113] sample.

We also show four relations in the literature between BH mass and total stellar mass in Figure 12. We first include the AGN relation from Reines & Volonteri [174]. Although our sample is a subset of their sample, we find a different BH mass to total stellar mass relation with a shallower slope. There are likely two reasons for this. First, we retain less than half of their original sample after cross-matching with Simard et al. [201] and removing galaxies with high AGN-to-bulge luminosity ratios that could lead to unreliable bulge-disk decompositions (see §2.2.3). Second, our total stellar masses are calculated somewhat differently as described in §2.2.4. For completeness, we also include in Figure 12 the BH mass to total stellar mass relation in Reines & Volonteri [174] for early-type galaxies with quiescent BHs.

We also include the two relations found by Greene et al. [77]. They combine a sample of seven megamaser galaxies with the Saglia et al. [179] sample of 97 elliptical, classical bulge and pseudobulge galaxies and then split this sample into early-type and late-type galaxies to calculate a regression line relating BH-to-total stellar mass for each separately. Our slope again is shallower and our intercept is lower than both of these comparison relations.

The variety of scaling relations derived here and from the literature shown in Figure 12 demonstrates the criticality of using the most relevant relation for a given galaxy sample. The various relations apply to different properties of galaxies (i.e., M_{BH} vs. $M_{\star, \text{Bulge}} \neq M_{\text{BH}}$ vs. $M_{\star, \text{Total}}$) and/or are derived from samples biased towards certain types of galaxies. As a result, there are significantly different slopes and intercepts among the various relations. As with previous works, we emphasize that all galaxies do not follow a single all-encompassing scaling relation between BH mass and either bulge or total stellar mass. Moreover, it is important to continue to investigate and derive scaling relations for diverse types of galaxies in order to estimate BH masses for similar samples.

No Strong Correlations with Galaxy Properties

To explore possible causes for deviations from the canonical BH-bulge relation for our sample, we examine correlations between offset in BH mass from the Kormendy & Ho [113] relation (i.e., how far off the observed BH mass is from the value predicted by the canonical relation at a given bulge mass) as a function of various potentially relevant galaxy properties. Figure 13 shows the offset in BH mass versus bulge $g - r$ color, D_n4000 strength¹, AGN r -band luminosity, AGN-to-bulge r -band luminosity ratio, bulge and galaxy Sérsic indices, redshift, and bulge-to-total r -band luminosity. We do not find a strong correlation between the offset from the Kormendy & Ho [113] relation with any of these properties (see Figure 13).

We calculate the Pearson and Spearman rank correlation coefficients (r) to quantitatively assess the strength of the correlation between each of these galaxy properties with the offset from the Kormendy & Ho [113] relation. The Spearman rank correlation coefficient describes how well the relationship can be described by a monotonic function and the Pearson correlation describes how well it can be described specifically by a linear function. We find moderate correlations ($0.4 \lesssim r \lesssim 0.6$) for the offset from the Kormendy & Ho [113] relation versus $g - r$ color and AGN fraction but the rest of the galaxy properties show weak correlations ($r \lesssim 0.4$). The coefficients are shown in Figure 13. All of these values are statistically significant based on their p-values calculated using a t-test.

The moderate negative correlation between offset in BH mass with bulge color indicates that bluer bulges tend to lie closer to the Kormendy & Ho [113] relation while the reddest bulges fall the farthest below the relation. This result could be interpreted to support a

¹The D_n4000 parameter [15] describes the average flux ratio of the continuum on the red versus blue side of the 4000 Å break. A higher value indicates a relatively weak UV/blue component in the spectrum due to a lack of young hot stars and increased absorption in the atmospheres of older, more metal rich stars. A D_n4000 value of 1.5 corresponds to an average stellar population of ~ 1 Gyr and therefore is generally used as a criteria for separating star-forming and quiescent galaxies [84, 89, 102, 103, 107]. We use the D_n4000 strength as reported in the NSA, which is based on spectroscopy obtained within a 3'' fiber.

connection between BH growth and star formation, either via concurrent fueling and/or AGN feedback. However, we caution that this result could also be an artifact from the color dependency of the mass-to-light ratios. That is, for a given luminosity, bulges that are redder in color receive a higher stellar mass estimate.

Conclusion and Discussion

In this paper we test whether or not the canonical BH-bulge mass relation holds for a sample of 117 nearby ($z \leq 0.055$), low-luminosity, broad-line AGNs identified by Reines & Volonteri [174] with bulge-disk decompositions from Simard et al. [201]. Investigating active galaxies probes a subset of galaxies that is distinct from samples of early-type galaxies with dynamically detected BHs that have been used to derive canonical BH mass - bulge mass relations [e.g., 113].

Our work was primarily motivated by the findings of Reines & Volonteri [174] regarding BH mass - total stellar mass relations in the local Universe. In particular, they found that their sample of broad-line AGNs fell on average more than an order of magnitude below early-type galaxies with quiescent BHs. Our main goal here was to determine whether or not this same sample of broad-line AGNs follows the canonical BH-to-bulge mass relation.

We find that our sample of active galaxies as a whole tends to fall below canonical scaling relations, hosting central BHs that are smaller than predicted by the BH mass – bulge mass relation by a factor of ~ 10 . We do not find a strong systematic trend between any galaxy property with offset from the canonical relation.

Whether or not dwarf galaxies follow the canonical scaling relations may indicate signatures of BH seeding mechanisms, however, observations in this mass regime are scarce. While Schutte et al. [194] and Baldassare et al. [9] find that their samples of dwarf galaxies align with the canonical $M_{\text{BH}} - M_{\text{bulge}}$ and $M_{\text{BH}} - \sigma$ relations, respectively, both of these works note the selection bias for finding brighter BHs, which are typically of higher mass,

meaning that they could simply be detecting the upper envelope of BH masses in dwarf galaxies and potentially the rest of the population lies below the canonical relations.

Our work adds to the growing body of evidence that the canonical BH-to-bulge scaling relations derived from highly biased samples of early-type galaxies with dynamical BH mass measurements should be used with caution as they are not applicable to all types of galaxies [63, 74, 76, 112, 225]. In their work, Kormendy & Ho [113] note that this relation only holds for classical bulges and ellipticals and should not be applied to objects such as pseudobulges, which tend to fall below the relation. Through this work, we emphasize the importance of using the most appropriate scaling relation according to the properties of a given sample, since we find that our sample of local, low-luminosity, broad-line AGNs are significantly offset from the canonical BH-bulge mass scaling relation defined by early-type galaxies. Consequently, this work has important implications for predicting black hole merger rates for the *Laser Interferometer Space Antenna* and Pulsar Timing Arrays that will detect the gravitational wave emission from these events, as well as cosmological simulations that are tied to the local BH-to-bulge mass relations.

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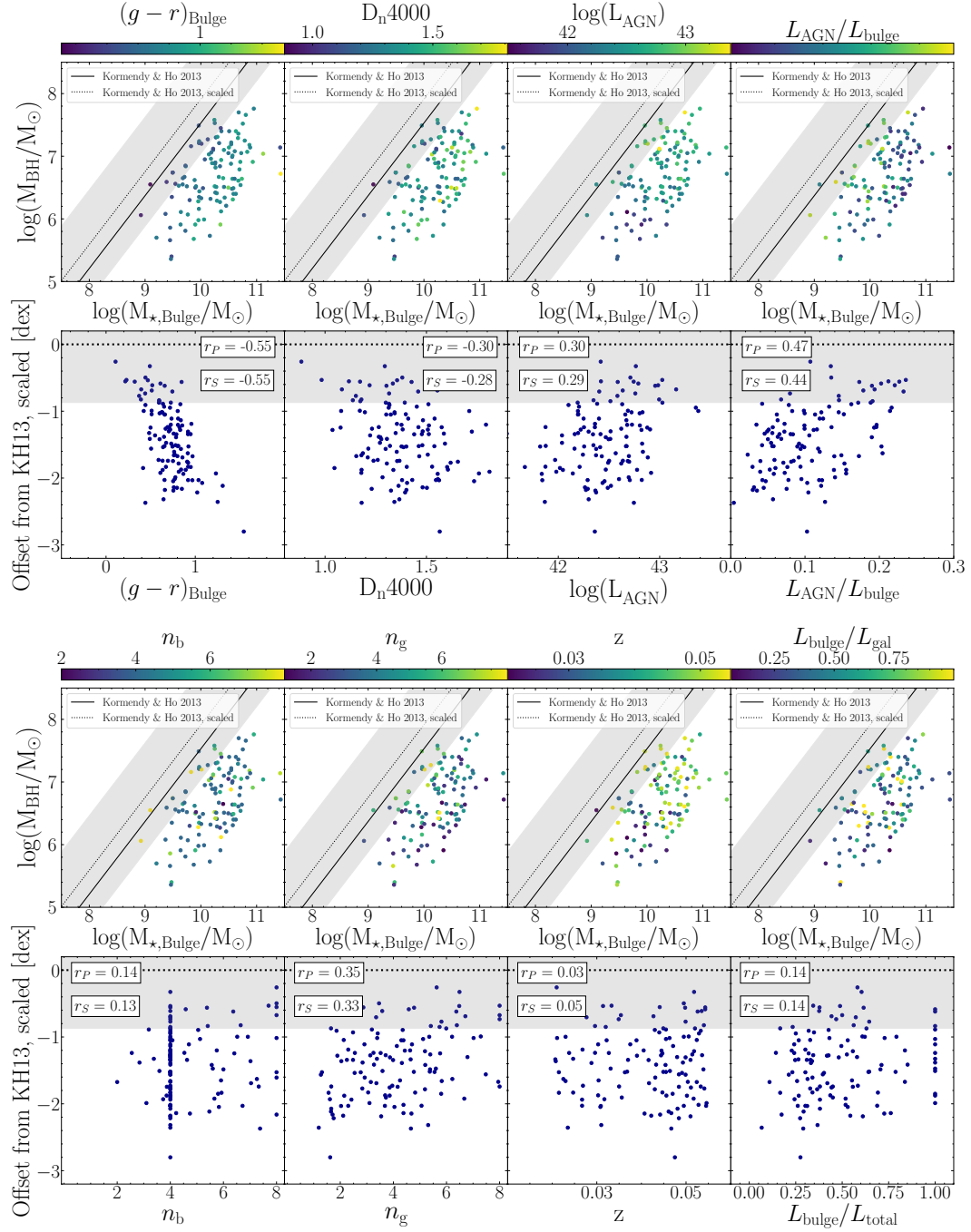


Figure 13 Bulge color, D_{n4000} , AGN r -band luminosity, AGN-to-bulge r -band luminosity ratio, bulge and galaxy Sérsic indices, redshift and bulge-to-total r -band luminosity ratio versus the offset in BH mass from the Kormendy & Ho [113] relation. Negative offset corresponds to BHs with observed masses less than predicted. The dotted line shows zero offset. In all plots, the shaded region indicates the 3σ intrinsic scatter of the Kormendy & Ho [113] scaled relation as reported in their paper. We find no strong correlations with galaxy properties and their offset from the Kormendy & Ho [113] relation.

HST OBSERVATIONS OF YOUNG NUCLEAR STAR CLUSTERS MIMICKING AGN
SIGNATURES IN THE MID-INFRARED

Contribution of Authors and Co-Authors

Manuscript in Chapter 3

Author: Megan Sturm

Contributions: Performed the data analysis, was the lead author of the manuscript, and advised undergraduate student Bayli Hayes.

Author: Bayli Hayes

Contributions: Contributed to the data analysis and writing the initial draft.

Author: Amy Reines

Contributions: Provided comments on the manuscript and advised the analysis.

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Abstract

Effectively finding and identifying active galactic nuclei (AGNs) in dwarf galaxies is an important step in studying black hole formation and evolution. In this work, we examine four mid-IR-selected AGN candidates in dwarf galaxies with stellar masses between $M_\star \sim 10^8 - 10^9 M_\odot$, and find that the galaxies are host to nuclear star clusters (NSCs) that are notably rare in how young and massive they are. We perform photometric measurements on the central star clusters in our target galaxies using *Hubble Space Telescope* optical and near-IR imaging and compare their observed properties to models of stellar population evolution. We find that these galaxies are host to very massive ($\sim 10^7 M_\odot$), extremely young ($\lesssim 8$ Myr), dusty ($0.6 \lesssim A_v \lesssim 1.8$) nuclear star clusters. Our results indicate that these galactic nuclei have ongoing star-formation, are still at least partially obscured by clouds of gas and dust, and are most likely producing the extremely red AGN-like mid-IR colors. Moreover, prior work has shown that these galaxies do not exhibit X-ray or optical AGN signatures. Therefore, we recommend caution when using mid-IR color-color diagnostics for AGN selection in dwarf galaxies, since, as directly exemplified in this sample, they can be contaminated by massive star clusters with ongoing star formation.

Introduction

Massive black holes (BHs) with masses of $M_{\text{BH}} \sim 10^6 - 10^9 M_\odot$ are highly prevalent objects in the Universe, living in the centers of almost all massive ($\gtrsim 10^{10} M_\odot$) galaxies [e.g., 130]. Multiple seed formation scenarios have been proposed [20, 34, 123], however we do not have enough observational evidence yet to identify which gave rise to the population of massive BHs that we observe in the early and present-day Universe. Although the James Webb Space Telescope (JWST) has pushed the boundaries of observable active galactic nuclei (AGN) in the Universe to new limits [110, 132, 152], the origins and earliest stages of

growth for these BH seeds are still out of direct observational reach [190, 217, 223].

Since high-redshift seed BHs remain observationally elusive, as a proxy for directly observing the initial formation and growth of such BHs, we can instead study massive BHs with $M_{\text{BH}} \lesssim 10^5 M_{\odot}$ residing in dwarf galaxies ($M_{\star} \lesssim 10^{9.5} M_{\odot}$) in the local Universe. Following from the idea of hierarchical assembly, dwarf galaxies tend to have undergone fewer mergers in comparison to more massive galaxies keeping their BHs from growing as much [219] and, indeed, they host the least-massive BHs known from an observational standpoint [for a review, see 167]. Therefore, identifying and characterizing BHs in local dwarf galaxies can place observational constraints on seed BHs from the early Universe.

One method for identifying massive BHs is through observations of AGNs, which emit radiation across the full electromagnetic spectrum. Various diagnostic diagrams [e.g., the BPT optical emission line diagram; 14] can distinguish emission originating from AGNs versus star-formation processes. In the mid-infrared (mid-IR), the characteristic power-law spectrum of dusty AGNs can be used as a diagnostic and has the advantage of suffering minimally from nuclear and galaxy scale obscuration. Multiple works have proposed mid-IR color-color diagnostics to distinguish between emission originating from dust heated by an AGN and dust heated by stellar processes, which will typically be at a much lower temperature [98, 135, 206]. Combining these diagnostics with observations from the all-sky mid-IR *Wide-field Infrared Survey Explorer* [WISE, 230] has produced large samples of AGNs and quasars [7, 195] with high reliability in moderate to high-mass galaxies.

However, multiple works have attempted to extrapolate these mid-IR diagnostics to the dwarf galaxy regime and find that the AGN fraction increases at low mass [185, 187], contradictory to findings at other wavelengths. *WISE* has a relatively low resolution ($\sim 6''$), which both complicates the cross-matching process to identify the correct host galaxies [126] and means that, in addition to emission from a potential AGN, emission from the host galaxy will also be present. At low mass, AGNs have lower Eddington limits, meaning they must

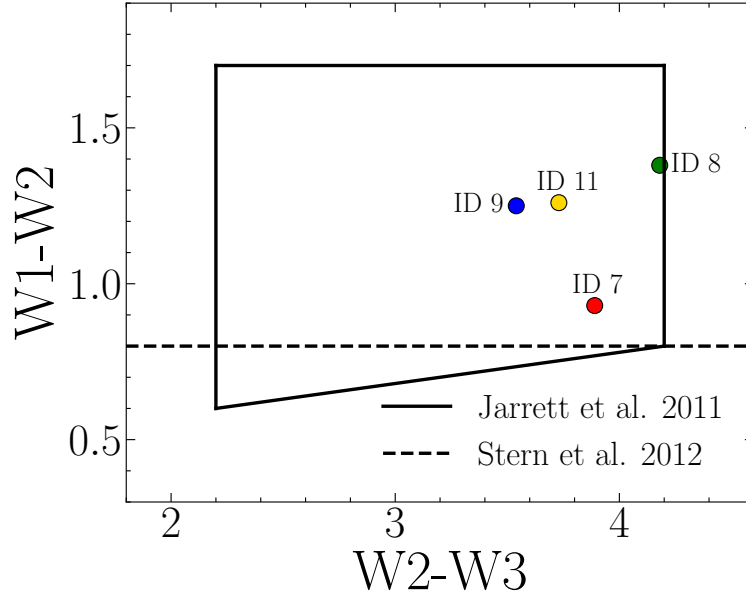


Figure 14 WISE color-color diagram for the four BPT star-forming dwarf galaxies in our sample. We show the AGN selection box from Jarrett et al. [98] as the solid line and the $W1-W2 > 0.8$ cut from Stern et al. [206] as the dashed line. Following both of these diagnostics, our galaxies are categorized as AGNs despite a lack of evidence at optical and X-ray wavelengths [119].

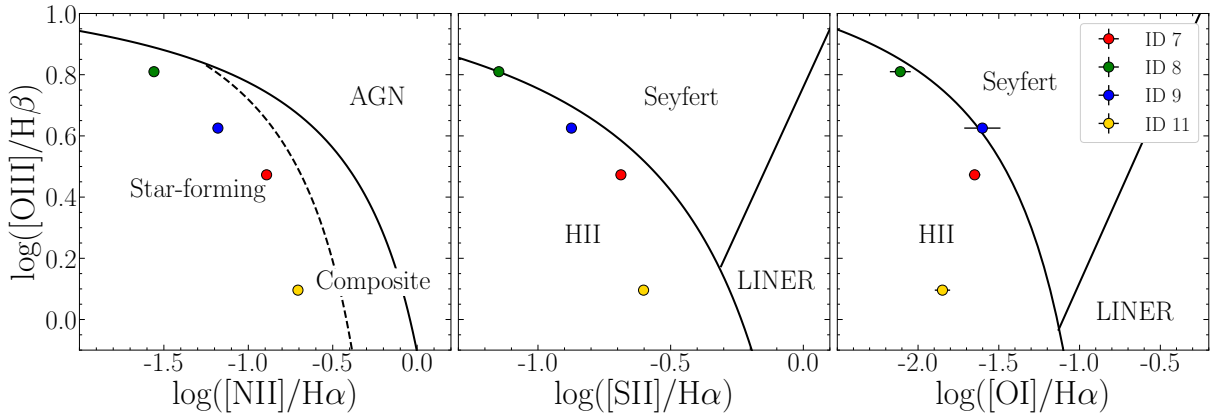


Figure 15 Narrow emission line ratio diagnostic diagrams for the four galaxies in our sample. Values for our sample come from Latimer et al. [119] using the methods described in Reines et al. [169]. The lines separating different regions in each plot are from Kewley et al. [106]. Our galaxies are consistent with being dominated by star-formation based on all of these diagnostic diagrams.

be highly accreting in order to be observed over the stellar/star-formation-related emission from the host galaxy. Even looking at a sample of highly-accreting, optically-selected AGNs [169], Hainline et al. [85] find that the majority are *not* selected as AGNs in WISE since the mid-IR emission is dominated by the host galaxy.

It is generally rare for BHs to be accreting at their Eddington limit [192], however, as seen at higher galaxy mass, selecting galaxies based on AGN-like WISE colors does create a bias towards bolometrically dominant AGNs. Moreover, it is possible for a $\sim 10^4 M_\odot$ BH to have bolometric luminosity equivalent to that of a $\sim 10^9 M_\odot$ dwarf galaxy ($\sim 10^{42} \text{ erg s}^{-1}$). However, if these AGNs are highly accreting, then it is notable that we do not always observe complementary optical or X-ray AGN signatures [119]. On the other hand, many AGNs are Compton-thick and about half of mid-IR selected AGNs are heavily obscured [e.g., Fig. 1 in 161]. Additionally, photoionization modeling has shown that at low metallicity/BH mass, BPT diagnostics likely fail [41, 79], and the literature appears to support X-ray emission in dwarf galaxy AGNs being lower than in their more massive counterparts [e.g., 203], including even in BPT AGNs with broad lines [12] and BPT AGNs with red WISE colors [119]. In any case, it is important to consider other explanations for the very red mid-IR colors of dwarf galaxies, particularly for those without other supporting evidence for AGNs.

Dwarf starburst galaxies have been observed to heat dust enough to produce very red mid-IR colors [78, 97]. In this case, invoking the presence of an AGN is not even necessary to produce the extreme mid-IR colors. Notably, Hainline et al. [85] find that dwarf starburst galaxies can mimic the mid-IR colors of AGNs. They demonstrate that a single $W1 - W2$ AGN color selection is subject to severe contamination from dwarf starburst galaxies, finding that dwarf galaxies with the reddest mid-IR colors also have the youngest stellar populations and highest star formation rates.

In a follow-up study, Latimer et al. [119] present *Chandra X-ray Observatory* and *Hubble Space Telescope (HST)* observations of a subset of dwarf galaxies from the Hainline et al.

[85] sample that fall in the Jarrett et al. [98] mid-IR two-color AGN selection box. Roughly half of the galaxies have optical emission line ratios indicating an AGN, while the remaining galaxies are classified as star-forming based on the optical BPT diagram. While nearly all of the optically-selected AGNs have detectable X-ray point sources with luminosities exceeding that expected from star formation, Latimer et al. [119] do not find compelling evidence for AGNs in the star-forming dwarf galaxies based on their X-ray analysis.

In this work, we seek to determine the stellar properties of the BPT star-forming galaxies that have mid-IR colors mimicking AGNs using observations from *HST*. In Section 3.2 we describe our sample of star-forming dwarf galaxies. In Section 3.3 we describe the observations and our method of performing photometry on the *HST* optical images. Finally, we compare colors and spectral energy distributions of the central star clusters with models of stellar cluster evolution to estimate cluster ages, extinctions, and masses in Section 3.4. A discussion and our conclusions are presented in Section 3.5.

ID	SDSS Name	NSAID	RA	DEC	z	$\log(M_*/M_\odot)$	F140W	F336W	F606W
7	J005904.10+010004.2	6205	00:59:04	01:00:04	0.01743	8.7	21.24	19.17	19.61
8	J154748.99+220303.2	98135	15:47:49	22:03:03	0.03154	8.2	21.77	18.77	19.19
9	J160135.95+311353.7	57649	16:01:36	31:13:54	0.03085	8.6	21.90	20.28	20.32
11	J233244.60-005847.9	151888	23:32:45	-00:58:46	0.02437	9.3	20.95	19.39	19.62

Table 2 Column 1: Galaxy ID from Latimer et al. [119]. Column 2: SDSS name. Column 3: NSAID. Column 4: Right ascension in units of hours:minutes:seconds. Column 5: Declination in units of degrees:arcminutes:arcseconds. Column 6: redshift from NSA parameter zdist. Column 7: log galaxy stellar mass from Latimer et al. [119]. Columns 8-10: ST magnitudes of the central star clusters in the F140W, F606W and F336W filters.

Sample of Star-forming Galaxies

Our sample consists of four dwarf galaxies (listed in Table 2) that are classified as hosting AGNs using *WISE* mid-IR selection techniques [85], but they do not show optical or X-ray AGN signatures [119]. These galaxies were originally part of the Hainline et al. [85] sample of $\sim 18,000$ dwarfs ($M_* \lesssim 3 \times 10^9 M_\odot$) in the NASA-Sloan Atlas (NSA) with significant mid-IR detections in the first three bands of the ALLWISE data release. Hainline et al. [85] find 41 of these galaxies having mid-IR colors consistent with an AGN; having $W1 - W2$ versus $W2 - W3$ colors falling within the Jarrett et al. [98] *WISE* AGN selection box (shown in Figure 14).

In a follow-up X-ray and optical study, Latimer et al. [119] selects 11 of these 41 galaxies that have both optical emission-line measurements (redshifts and fluxes) and signal-to-noise ratios > 5 in all four *WISE* bands. Following Reines et al. [169] methods and using SDSS spectra, they find that, despite the fact that all 11 of the galaxies in their sample are considered mid-IR AGNs, five lie in the star-forming region of the BPT diagram according to the classification scheme of Kewley et al. [106, see Figure 27]. For this work, we select the four galaxies from these five BPT star-forming galaxies that have *HST* imaging to study further.

Three of our galaxies (IDs 7, 8 and 9) were not detected at all in the *Chandra* X-ray imaging presented in Latimer et al. [119], placing an upper limit on their X-ray luminosities of $L_{2-10\text{keV}} \lesssim 10^{39.6} \text{ erg s}^{-1}$. All three of these upper limits are consistent with the expected contributions from high-mass X-ray binaries (XRBs). The last target (ID 11) does have an X-ray point source detected with $L_{2-10\text{keV}} = 39.8 \text{ erg s}^{-1}$. However, this X-ray point source is offset from the center of the galaxy and the brightest near-IR source, and the luminosity is consistent with the expected contribution from XRBs or an ultra-luminous X-ray source (ULX). Interestingly, in addition to its AGN-like mid-IR colors, ID 11 was found to also

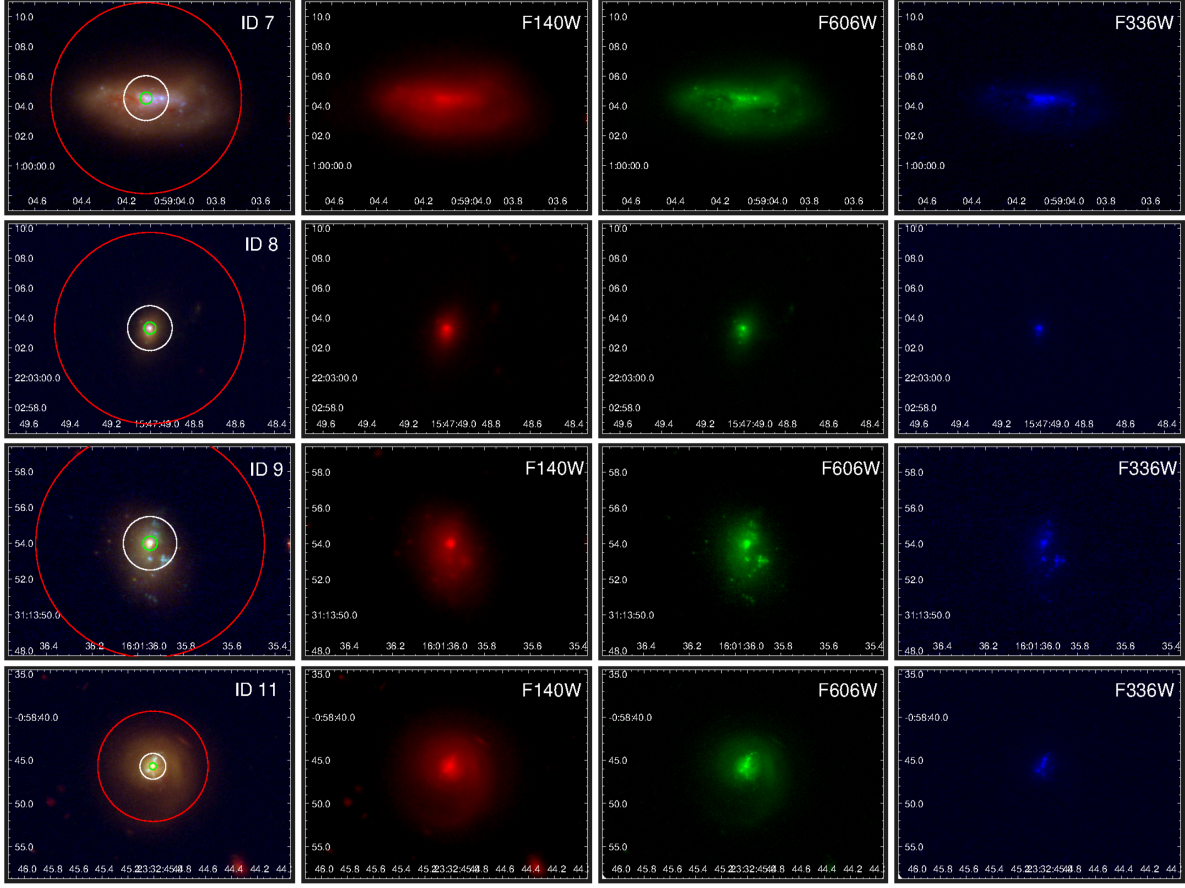


Figure 16 Three-color *HST* images of the four BPT star-forming galaxies in our sample. The red images represent the near-infrared (NIR) band (F140W filter), green images show the optical band (F606W filter) and blue images show U/UV band (F336W filter). In the left column, the green circles show the peak of the NIR emission in the *HST* images with radius of $0''.4$, which we define as our central star clusters, the red circles show the WISE W2-band resolution of $6''.4$ and the white circles show the SDSS $3''.0$ spectroscopic apertures.

show variability in the mid-IR indicative of the presence of an AGN¹ [196]. Despite having mid-IR colors (and, in the case of ID 11, variability in the mid-IR) that look AGN-like, there is not compelling evidence at optical or X-ray wavelengths that these dwarf star-forming galaxies host AGNs.

HST Optical and Near-IR Photometry

Observations

The *HST* observations for these four galaxies were taken in 2019 (Proposal 15607, PI: Reines; found at [10.17909/rdw9-n374]<http://dx.doi.org/10.17909/rdw9-n374>) and were first presented in Latimer et al. [119]. We use HST/WFC3 UVIS and IR imaging in three different filters: F336W ($\sim$ U-band), F606W ($\sim$ wide V-band) and F140W (JH gap). During these observations, each galaxy was observed for one orbit with exposure times of $\sim$ 7-9 minutes in the IR F140W filter, $\sim$ 11-12 minutes in the UVIS F606W filter, and $\sim$ 12-15 minutes in the UVIS F336W filter. The images were processed using the automated AstroDrizzle pipeline [68].

We make relative astrometry corrections by manually aligning stars in the F336W and F140W filters to the corresponding stars in the F606W filter and adjusting the WCS for the first two accordingly. This resulted in astrometric shifts up to $0''.16$. This step ensures that the central star clusters of interest lie directly on top of each other in all filters. Three-color *HST* images of our galaxies are shown in Figure 16.

Aperture Photometry Measurements

We are interested in the photometric properties of the central star cluster in each galaxy. The center point of the cluster is selected as the peak of the NIR emission in the *HST* images

¹We check multiple other works for variability signatures in our other galaxies but did not find any [6, 9, 10, 38, 227].

following Latimer et al. [119]. Our star clusters generally reside within a radius of $\sim 0''.4$, so we use this aperture size in the photometry measurements for all four of our targets for consistency.

We find source counts by performing aperture photometry in each filter using the `photutils` software package [35]. We estimate the background counts within the target aperture by first finding the median background counts per area within an annulus, surrounding the target aperture. The total source counts is then calculated as the counts within the circular aperture ($r_{\text{aperture}} = 0''.4$) minus the median counts per area from the background annulus times the area of the circular aperture. The dominant source of uncertainty in our measurements comes from our choice of the background annulus, so we vary both the inner radius of the annulus (from $0''.5$ to $0''.8$) and the width of the annulus (from $0''.1$ to $0''.3$) and find errors $\lesssim 15\%$ for all targets/filters.

Lastly, we perform aperture corrections based on our target aperture size of $0''.4$ (0.84 for the F140W filter, 0.91 for the F606W filter and 0.89 for the F336W filter). We report our measured ST magnitudes in each filter in Table 2.

Properties of the Star Clusters

We compare our broadband photometric measurements to a GALEV simple stellar population (SSP) synthesis model [114] in order to estimate the ages, extinctions, and masses of the central star clusters in our target galaxies. We opt for using GALEV over other models because it provides the option of including a set of metallicity-dependent emission lines [4], which make up a non-negligible portion of the flux at optical wavelengths in very young stellar clusters [172]. Our GALEV model uses the Padova isochrones, a timestep of 4 Myr, a Kroupa initial mass function (IMF) ($0.1\text{-}100M_{\odot}$), a metallicity of $[\text{Fe}/\text{H}] = -0.7$ (as appropriate for these galaxies; Latimer et al. 119) and an initial mass of $10^5 M_{\odot}$.

Uncertainties in derived quantities using stellar population synthesis models arise

from theoretical/observational unknowns, including those associated with different phases of stellar evolution and the IMF. Additionally, there is an age-metallicity degeneracy, where an older, metal-poor population cannot always be distinguished from a younger, metal-rich population [229]. However, Conroy et al. [49] find that including these model uncertainties does not strongly impact physical properties such as star formation rates, stellar masses, ages, and metallicities. Specifically, they state that stellar masses have errors of ~ 0.3 dex. Furthermore, looking at their GALEV model $V - K$ colors versus time, Kotulla et al. [114] find that the color evolution agrees with true colors/ages for star clusters in the Large Magellanic Cloud within 0.4 dex.

While there are inherent uncertainties associated with using SSP models, our choice of filters helps mitigate the effects of these uncertainties in drawing conclusions about the nature of the observed star clusters. We have photometric observations in three filters, including both red and blue optical filters and a NIR filter. When comparing observed SEDs to SSP models, this variety of filters provides a balanced, representative distribution in age, metallicity and extinction, as demonstrated in de Grijs et al. [52]. Specifically, our choice of filters includes both the U and V bands, which are found to be important in determining cluster ages [3]. Additionally, de Grijs et al. [52] show that assuming a generic, subsolar metallicity, as we do in this work, results in increased scatter in the age distribution of clusters, however, the peak generally remains the same.

Age and Extinction Estimates

We estimate the ages of our stellar clusters using a color-color diagram. We plot the observed F336W-F606W versus F606W-F140W color for each of our targets along with the expected trajectory from the GALEV model in Figure 17. However, we expect these observed colors to be reddened by dust both in the target galaxies themselves as well as within the Milky Way. We account for Galactic extinction within the Milky Way using the Cardelli

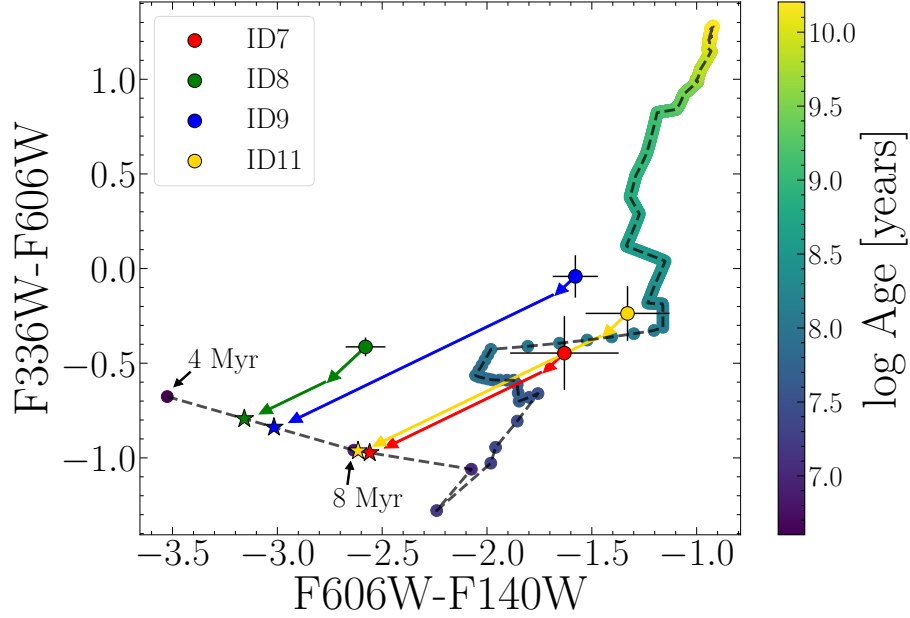


Figure 17 F336W-F606W versus F606W-F140W color-color diagram. We plot the expected color-color evolutionary track from the GALEV models (color-coded by age). We also plot the observed colors for each galaxy as circles. We draw de-reddening vectors from each point, accounting for both extinction within the Milky Way and internal extinction within the target galaxy. The intersection point for each of the de-reddening vectors with the model is shown with a star. All of the clusters intersect with the GALEV model at ages $\lesssim 10$ Myr, confirming that these are indeed young stellar clusters with significant amounts of dust extinction. See §3.4.1. Error bars represent uncertainties resulting from the photometric measurements.

et al. [44] extinction curve with the typical value of $R_v=3.1$ and $A_{v,\text{Gal}}$ values corresponding to the location of each galaxy from Schlegel et al. [189], ranging from $A_{v,\text{Gal}}=0.08-0.2$. Given the mid-IR colors of our galaxies, we expect significant internal extinction within the target galaxies. Following the work of Reines et al. [171], we account for the internal extinction using a 30 Doradus extinction curve [62] and using a R_v value of 4.48 from De Marchi & Panagia [53].² This allows us to get a direction for the internal reddening vectors in F336W-F606W vs. F606W-F140W color space.

We extend de-reddening vectors for each cluster to find where their inferred intrinsic colors intersect with our GALEV models (shown in Figure 17). Since these clusters are presumably responsible for the red mid-IR colors in *WISE*, we expect them to be young with significant dust extinction at the shorter wavelengths explored here. Therefore, while the clusters in ID 7 and ID 11 intersect the models at both young and old ages (once at $\sim 10^7$ years, again at $\sim 10^{7.8}$ years and lastly $\sim 10^8$ years), we think it is much more likely that they are young with $A_v > 1$. Under this assumption, all four clusters intersect with the GALEV model color-color evolutionary track within $\sim$ the first 2 points (ages $\lesssim 10$ Myr). We interpolate between the first three points in the model to find a more precise age for the clusters (~ 5 to 8 Myr) and report these values in Table 4.

As a consistency check, we make an additional age measurement for our star clusters using the equivalent width of the $H\alpha$ emission line, which quantifies the ratio of ionizing radiation from star formation to the continuum flux density as follows:

$$W_{H\alpha} = \frac{F_{H\alpha}}{f_{\text{cont}}} \quad (6)$$

²We use $R_v=4.48$ to more accurately model the dusty environment expected within the target galaxies, however, we note that using the typical Milky Way value of 3.1 only increases our age estimates by 0.1 dex (1-2 Myr) and does not change our cluster mass estimates at all.

where $F_{\text{H}\alpha}$ is the flux of the $\text{H}\alpha$ emission line and f_{cont} is the underlying continuum flux density.

We use $\text{H}\alpha$ equivalent width values for our targets from the NSA and compare the values to those predicted by the Starburst99 model [121]. We use the Starburst99 model with instantaneous star formation, IMF $\alpha=2.35$, $Z=0.004$ (corresponding to the metallicity of our GALEV model) and $M_{\text{up}}=100 M_{\odot}$. These ages are also reported in Table 4. We calculate nearly identical ages using the GALEV color-color model and the Starburst99 $\text{H}\alpha$ equivalent width.

Since we find remarkably similar age measurements using a completely different method from a separate model, we consider our age estimates to be robust. Furthermore, we consider our SSP-derived ages robust since, in their work, Kacharov et al. [100] perform composite stellar population fits with detailed star formation histories and find that the light-weighted age measurements using these fits are in good agreement with those calculated just using SSPs. Additionally, Walcher et al. [224] compare ages calculated by fitting SEDs to composite versus SSP models. They find that for the nuclei with older stellar populations, the χ^2 value for the composite fits are significantly better, however, for their one galaxy with significant populations of young stars and age $\sim 10^7$ years, similar to the ages we find for our sample, the χ^2 value for the composite versus SSP models are comparable.

We calculate the expected internal extinction from our color-color diagram and find A_v values in the range $0.6 \lesssim A_v \lesssim 1.8$. We also find that the nebular extinction in these galaxies, calculated from the Balmer decrement and using $\text{H}\alpha$ and $\text{H}\beta$ fluxes as reported in the NSA, results in $A_{v,\text{nebular}} = 0.36 - 0.63$. These are smaller than the stellar A_v calculated from our color-color diagram, which is likely due to the fact that our photometry probes just the central star clusters (with aperture radius of $0''.4$), while the NSA fluxes come from SDSS spectroscopy (with fiber diameter of $3''.0$). The NSA fluxes come from a much larger region that includes more diffuse areas in the outer regions of the galaxies that are expected

to have lower extinction.

Star Cluster Mass Estimates

We estimate masses of the star clusters as follows. Using the age and extinction estimates derived from the color-color diagram in Figure 17, we compare our observed photometric measurements to the model spectra at the closest age for our clusters (4 Myr for IDs 8 and 9, and 8 Myr for IDs 7 and 11; see Figure 18). In order to compare our observed photometry measurements to the GALEV model spectra, we de-redden the observed fluxes by removing the extinction estimated from Section 3.4.1. We then shift our GALEV model spectra to the corresponding redshift of each galaxy and convolve it with the *HST* filter throughput curves in order to derive simulated photometry in our *HST* bands. Since the GALEV spectra are normalized to a distance of 10 pc, we scale the model flux densities according to the distance of each galaxy.

We compare the model photometry with our de-reddened, observed photometry in each filter to find a scaling between the two. In the models, the flux density is linearly proportional to the mass of the cluster. Therefore, we are able to use this scaling along with the initial model mass of $10^5 M_{\odot}$ (the stellar mass does not change significantly between the first two points in the model) to estimate masses of the observed clusters. We use the scaling that we calculate from the F336W filter, since the F606W filter can be significantly impacted by emission lines [172] and the F140W filter could be boosted by red supergiants and/or very hot dust³ [171]. Our estimated star cluster masses are reported in Table 4. All of our cluster masses are $\sim 10^7 M_{\odot}$.

³We note that using the scaling calculated from the F140W filter results in mass estimates that are larger by ~ 0.1 dex.

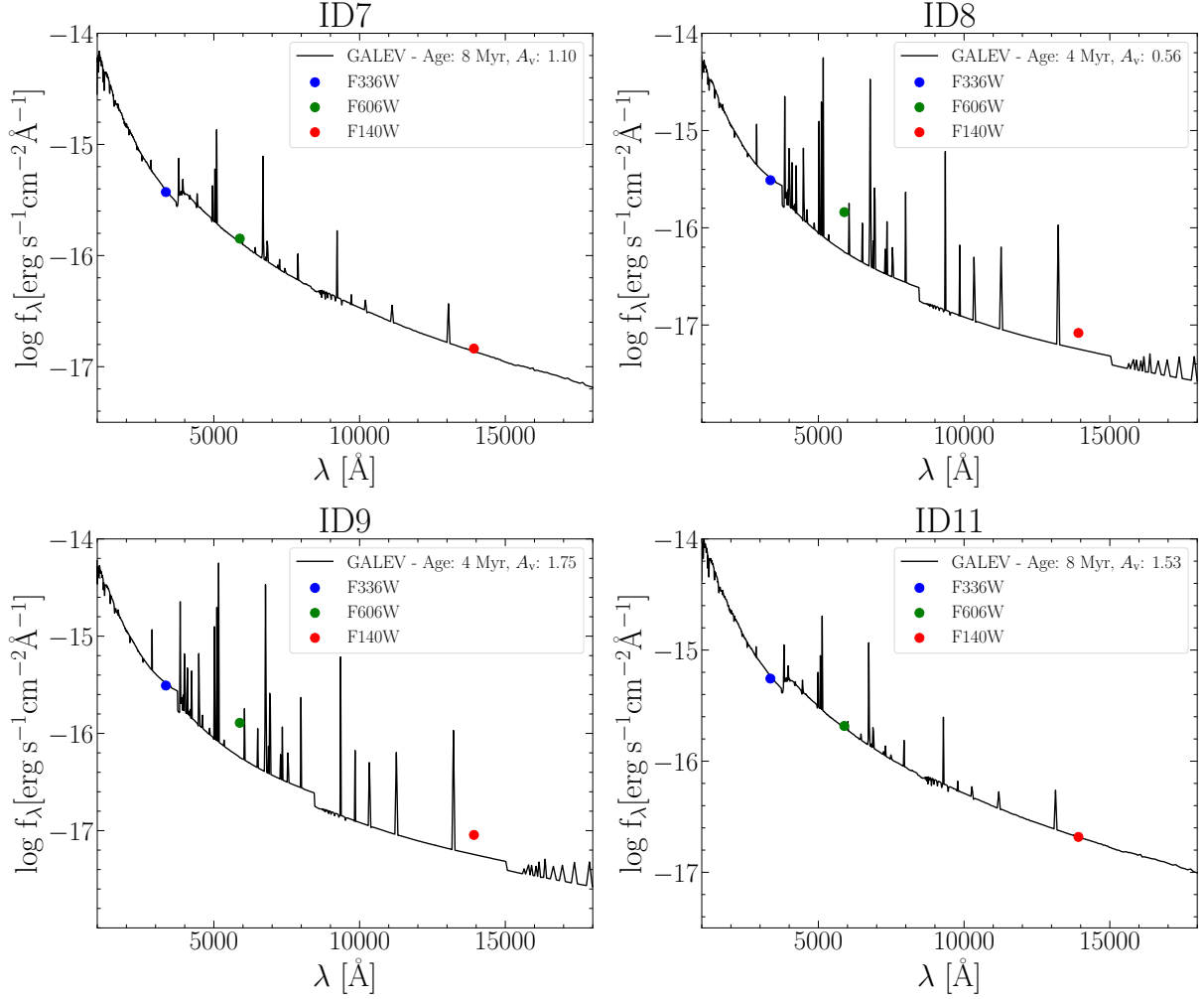


Figure 18 GALEV model spectra corresponding to the color-color-derived age of each galaxy. For each of these spectra we scale them to match the observed photometry of our galaxies and apply the expected reddening. We overlay our photometric observations in each filter as colored points.

ID	log Age (colors) [years]	log Age (H α EW) [years]	log M $_*$ [M $_{\odot}$]	A $_v$ [mag]
7	6.9	6.9	6.9	1.10
8	6.8	6.7	7.0	0.56
9	6.8	6.8	7.0	1.75
11	6.9	6.8	7.3	1.53

Table 3 Column 1: Galaxy ID. Column 2: Log cluster age in years estimated from the color-color diagram in Figure 17. Column 3: Log cluster age in years estimated by comparing the H α equivalent width from the NSA to the Starburst99 models. Column 4: Log cluster mass in solar masses. Column 5: Internal A_V due to dust extinction. Uncertainties from using stellar population synthesis models are ~ 0.3 dex for stellar mass [49] and ~ 0.4 dex for age [114].

Discussion and Conclusions

In this work, we investigate the properties of the central star clusters in a sample of four dwarf galaxies that exhibit very red mid-IR colors, leading to them being categorized as AGNs using typical color-color diagnostics for *WISE* observations. Contrary to the pro-AGN evidence in the mid-IR, they do not have optical narrow emission line ratios or X-ray signatures supporting the case for AGNs [119]. Furthermore, the mid-IR color evidence for AGNs is not all that compelling; our galaxies follow the general trend of optically-selected star-forming dwarf galaxies in the WISE color-color diagram [see Figure 6 in 85] and may have scattered into the Jarrett et al. [98] AGN selection box due to relatively hot dust [see Figure 7 in 85]. We use *HST* optical and near-IR photometry in conjunction with stellar population synthesis models (GALEV and Starburst99) to characterize the properties of the central star clusters in these galaxies. The clusters coincide with the peak of the near-IR emission in each galaxy and we hypothesize that they are responsible for the red mid-IR colors in *WISE*.

We derive stellar masses of $\sim 10^7 M_{\odot}$ for the central star clusters in our sample. These masses are consistent with nuclear star clusters (NSCs; Neumayer et al. 146) and higher

than typical young super star clusters [e.g., 138, 171] and globular clusters [18, 71]. NSCs are most commonly found in galaxies having stellar masses $8 < \log (M_{\text{stellar}}/M_{\odot}) < 10$, with $\sim 80\%$ of both early and late-type galaxies of mass $\sim 10^9 M_{\odot}$ hosting an NSC [33, 45, 56, 65, 153, 182]. For comparison, the host galaxy stellar masses of our targets are in the range $8.2 < \log (M_{\text{stellar}}/M_{\odot}) < 9.3$. The NSC masses are at the high end, but consistent within the scatter, of the linear scaling relation found between host galaxy stellar mass and NSC mass from Neumayer et al. [146, equation 1 in their paper] found by combining multiple samples of NSCs.

Furthermore, we find that the NSCs in our sample of dwarf galaxies are likely quite dusty, with internal A_v values between 0.56 and 1.75. While these A_v values are not particularly high, we note that they are derived using optical emission, which is not able to penetrate the potential denser regions of clumpy dust surrounding the nucleus which would be emitting in the mid-IR [69, 170]. Nonetheless, the A_v values for these clusters indicate they are still at least partially enshrouded in dust, aligning with the fact that our NSCs are quite young; we find that the ages of our clusters are all $\lesssim 8$ Myr.

Our sample of dwarf galaxies are likely host to NSCs that formed (or are in the process of forming) via in situ star formation. In this scenario, a burst of star formation is caused by gas infalling to the central few parsecs of the galaxy, and it is thought to be the dominant growth mechanism for NSCs in late-type galaxies [146]. Concentrations of young stars have also been observed in the NSCs of the Milky Way [124, 156], M31 [26, 46, 65] and nearby early-type galaxies [148, 150], however, light-weighted ages for the full cluster that are as young as those in our sample are uncommon for typical NSCs. The ages of our sample are more typical for young super star clusters but the masses ($\sim 10^7 M_{\odot}$) are larger than typical super star clusters by more than an order of magnitude [e.g., 138, 171].

The prevalence of galaxies falling within the WISE AGN-selection box is quite low: $\sim 0.2\%$ in Hainline et al. [85]. On the other hand, NSCs being found in low-mass galaxies

is quite common, implying that the presence of any generic NSC is unlikely to be the cause of the AGN-like WISE colors. However, we emphasize that our sample is extremely unique in just how young the light-weighted ages we calculate for our NSCs are. While the masses and central positions of the clusters are consistent with NSCs, their ages are more in line with super star clusters/young massive clusters. Looking at samples of NSCs in late-type galaxies, both Kacharov et al. [100] and Sarzi et al. [186] find light-weighted ages only down to $\mathcal{O}(100 \text{ Myr})$ and (except for one galaxy) both Walcher et al. [224] and Rossa et al. [178] calculate light-weighted ages down to $\sim 30 \text{ Myr}$. Out of the ~ 40 galaxies presented in these papers, only one galaxy (NGC 2139) has a light-weighted age comparable to those in our sample ($< 10 \text{ Myr}$).

These works also examine the detailed star formation histories (SFHs) of the NSCs in their samples using composite stellar population fits. These SFHs reveal a series of increased periods of star formation followed by periods of quiescence [100, 178], meaning that most NSCs contain populations of stars at a variety of ages. When present, populations of stars as young as those that we find in our target galaxies ($< 10 \text{ Myr}$) generally make up $\lesssim 1\%$ of the mass of the clusters [100, 224] and, as mentioned above, they find light-weighted ages much older than what we find for our targets.

Only the one galaxy (NGC 2139) in Walcher et al. [224] has $\sim 7\%$ of the mass made up by stars with age 3 Myr and they conclude that it is either a young NSC in the process of forming or its bright young population is outshining the underlying, older population; an old population (10 Gyr) with equal mass as the young population would contribute only 1% of the light. Because of this and since we are calculating ages based on the integrated light of the entire cluster, we cannot distinguish between NSCs that are initially forming or NSCs that have had a recent burst of star-formation. However, either way, finding ages as young as we do for our targets means that a significant burst of star formation would have had to occur within the past 10 Myr , such that this new burst would outshine the rest of the older

stars in the cluster.

The high optical extinctions, young ages and large masses of the clusters support the idea that these NSCs are likely dominating the mid-IR emission of the dwarf galaxies and mimicking the *WISE* colors of AGNs. However, we cannot definitively rule out the presence of AGNs or quiescent BHs in these objects. Indeed, there are multiple examples of NSCs and central BHs coexisting, such as M31, M32, NGC 3115, and the Milky Way [146]. Specifically in our sample, it is possible that ID 11 has both a young, central star cluster and a central AGN, causing the variability in the mid-IR observed in Secrest & Satyapal [196].

Reliably identifying AGNs in local dwarf galaxies is particularly important in the context of understanding the origins of massive BH seeds. Along with other works [85, 119], we advise caution when using mid-IR color-color selection techniques for dwarf galaxies (at least at the resolution of *WISE*). In this work, we present a sample of galaxies hosting remarkably young, dusty and massive star clusters in their nucleus, which negates the need to invoke the presence of an AGN in these galaxies by providing a plausible alternative explanation for the WISE observations; our observational study directly demonstrates that young, massive, dusty NSCs can indeed mimic the mid-IR colors of AGNs.

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MAGELLAN SPECTROSCOPY OF AGNS IN DWARF GALAXIES: SCALING
RELATIONS AND A TRIPLE-PEAKED AGN

Contribution of Authors and Co-Authors

Manuscript in Chapter 4

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Contributions: Provided comments on the manuscript.

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Abstract

In this work, we aim to further populate the low-mass regime of black hole (BH) scaling relations to better understand the formation and growth mechanisms of central supermassive BHs. We target six dwarf galaxies with stellar masses reported to be $M_{\star} < 5 \times 10^9 M_{\odot}$ that have been previously identified as hosting active galactic nuclei (AGN) based on optical spectroscopy from the Galaxy and Mass Assembly (GAMA) survey or the Sloan Digital Sky Survey (SDSS). Using follow-up optical spectroscopy from the Magellan Echellette Spectrograph (MagE), we extract galaxy velocity dispersions ($\sigma_{\star}$) and estimate virial BH masses from broad $H\alpha$ emission. We find that the galaxies in our sample do not deviate significantly from either the $M_{\text{BH}}-\sigma_{\star}$ or $M_{\text{BH}}-M_{\star}$ scaling relations defined by higher mass galaxies. Additionally, we identify one galaxy ($M_{\star} \sim 10^{10.69} M_{\odot}$) with triple-peaked [S II], [N II], $H\alpha$ and $H\beta$ emission lines. This spectral shape is not shared by [O III] and, in fact, the [O III] line appears to have distinct kinematics from the other emission lines. Incorporating the spatial distribution of the various emission lines, we find that the galaxy spectrum is consistent with a prominent central AGN driving an outflow, surrounded by an extended ring/disk of gas predominantly ionized by shocks and/or star formation. This work has implications for the demographics of BHs in dwarf galaxies and the role of AGN feedback.

Introduction

Galaxy properties including velocity dispersion [64, 140], bulge luminosity [134] and bulge mass [95, 113, 137] have been observed to correlate with the mass of their central supermassive black hole (SMBH), which are quantified with scaling relations. Historically, we have looked towards the centers of massive galaxies for dynamical BH mass measurements, or bright, easily observable broad-line AGNs and, as a result, we have amply populated

the upper mass range of these scaling relations. In this upper mass range, we observe relatively tight scaling relations correlating increased BH mass with increased bulge mass, bulge luminosity and velocity dispersion.

While filling in the high-mass range of scaling relations is important, the low-mass regime is of particular interest in the context of BH growth and evolution. Studying the demographics of BHs at low galaxy/BH mass allows us to observe early phases of BH growth and place constraints on the initial seed properties/distinguish between possible seeding mechanisms. Both the slope and scatter in the low-mass regime of the $M_{\text{BH}} - \sigma_*$ relation are expected to depend on the seed formation mechanism [221], with higher mass seeds resulting in a flattening of the relation around $10^5 M_\odot$. Furthermore, the BH fueling and growth efficiency are predicted to impact the distribution of galaxies along this relation [75, 155, 176].

Directly observing BH seeds at the epoch which they are expected to have formed is currently not possible. Moreover, studies looking for low-mass BHs in the early Universe are biased towards only the most luminous sources that can be detected at such high redshift [e.g., 88, 99, 110, 131, 136, 152, 234]. Therefore, we instead opt for filling in scaling relations with dwarf galaxies from the local Universe. Compared to larger galaxies, dwarf galaxies generally have experienced fewer merger events that can erase initial BH seed properties [?]. Furthermore, since the smallest known massive BHs reside in dwarf galaxies ($\sim 10^{4-5} M_\odot$), we can use them to place upper limits on BH seed masses [167].

Two important works investigating the $M_{\text{BH}} - \sigma_*$ relation in the low-mass regime are Xiao et al. [231] and Baldassare et al. [9]. The sample analyzed in Xiao et al. [231] consists of 76 AGNs with $M_{\text{BH}} \lesssim 10^{6.5} M_\odot$ selected from the Greene & Ho [73] catalog of low-mass broad-line AGNs in SDSS DR4. Baldassare et al. [9] presents new observations of eight dwarf galaxies ($M_\star \lesssim 3 \times 10^9 M_\odot$) with broad-line AGNs that were identified in Reines et al. [169] (based on SDSS DR8), plus seven other dwarf galaxies with existing velocity

dispersion and BH mass measurements. In both of these works, they find that their low-mass samples are generally in good agreement with the scaling relations derived from higher mass galaxies. However, as explained in Baldassare et al. [9], the results in the dwarf regime, where differences in seeding models should become apparent in the scaling relations, are still limited by the sample size and possibly selection bias. Since the Eddington limit of a BH is proportional to its mass and continuous accretion at the Eddington limit is unlikely [192], observationally, we are biased towards finding higher mass BHs that are accreting at lower rates. This means that current samples of BHs occupying the low mass regime of scaling relations could just represent an upper bound on the true population demographics.

In this work, we place four new galaxies (three of which are dwarfs) on the $M_{\text{BH}} - \sigma_*$ and $M_{\text{BH}} - M_*$ scaling relations and compare to canonical relations. Additionally, we identify one galaxy with triple-peaked emission lines. Our paper is laid out as follows. We present our sample in Section 4.2 and describe our new MagE observations and data reduction in Section 4.3. Our spectral analysis, including galaxy continuum/absorption line + AGN emission line fitting, is presented in Section 4.4. Specifically in Section 4.4.6, we show a unique galaxy with triple-peaked emission lines and describe the spectral fitting for it. We discuss how our galaxies compare to canonical scaling relations in Section 4.5. Finally, we discuss possible physical interpretations of our triple-peaked emission line galaxy in Section 4.6. Throughout this work we adopt $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

ID	RA	DEC	z	$\log (M_*/M_\odot)$	M_r	$g-r$	$r-i$	BPT	Broad H α
GAMA 2258819	30.87	-9.49	0.252	9.60	-21.22	0.27	0.29	AGN	detected
GAMA 2123678	34.81	-5.72	0.054	9.48	-19.15	0.54	0.32	Comp	detected
GAMA 5227891 ¹	341.86	-32.25	0.215	10.69	-20.69	...	0.55	AGN	hint
GAMA 5240292	343.27	-33.98	0.224	9.59	-21.97	0.12	0.16	AGN	detected
GAMA 5275222	345.36	-34.21	0.210	9.64	-22.26	0.06	0.12	AGN	detected
SDSS J1605+0850	241.44	8.85	0.015	9.45	-17.64	0.67	0.35	Comp	-

Table 4 Column 1: Identification number in GAMA/SDSS. Column 2: RA in degrees. Column 3: DEC in degrees. Column 4: Redshift. Column 5: Log galaxy stellar mass. Column 6: Absolute r -band magnitude. Column 7: $g-r$ color. Column 8: $r-i$ color. Column 9: BPT classification in the [O III]/H β versus [N II]/H α diagram from Reines et al. [169] or Salehirad et al. [180]. Column 10: Whether broad H α was detected ('detected'), not detected ('-') or if there was a hint of broad H α ('hint') in either Salehirad et al. [180] or Reines et al. [169].

¹Due to unreliable magnitudes reported in GAMA for this object, we recalculate magnitudes and total stellar mass, as described in Section 4.2.

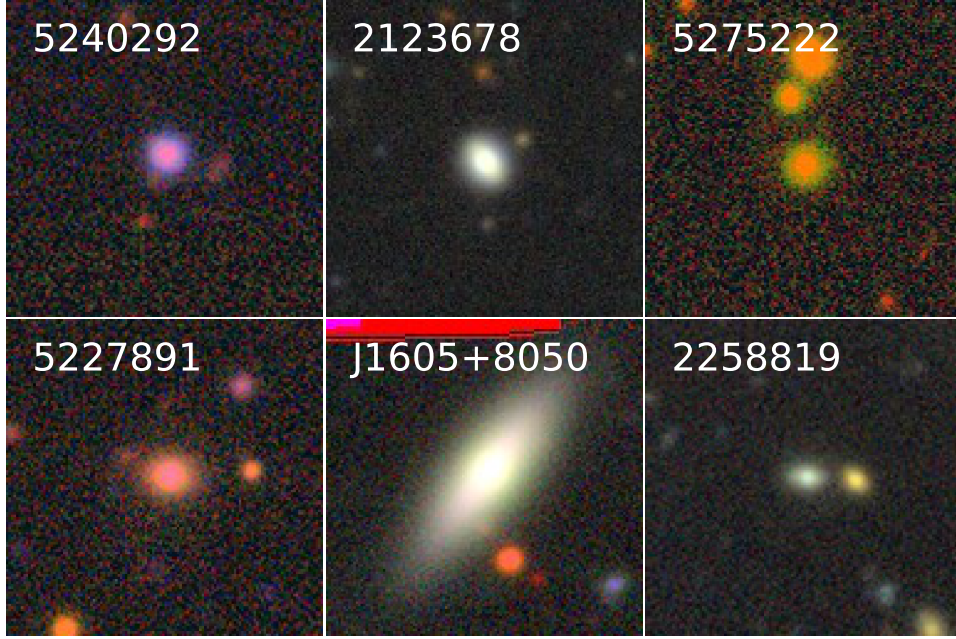


Figure 19 DESI Legacy Imaging Survey SkyViewer Images of our six dwarf galaxies.

Sample of Low-Mass Active Galaxies

Our targets primarily come from the new sample of AGNs in low-mass galaxies discovered in the Galaxy and Mass Assembly (GAMA) survey by Salehirad et al. [180] using optical spectroscopy. They restrict the SED-derived stellar masses (as reported from GAMA) of their galaxies to $M_{\star} \leq 10^{10} M_{\odot}$. Additionally, following Reines et al. [169], they impose restrictions on the signal-to-noise (S/N) ratio and equivalent width (EW) of certain emission lines: $H\alpha$, $[O III]$ and $[N II]$ must have $S/N \geq 3$ and $EW > 1 \text{ \AA}$ and $H\beta$ must have $S/N \geq 2$. Finally, they make a redshift cut ($z \leq 0.3$) to make sure the $[S II]$ doublet is within the observed wavelength range, leaving them with a final parent sample of 23,460 galaxies.

In their work, they use various emission line diagnostics to distinguish AGNs from star-forming galaxies and produce a final sample of 388 new low-mass, spectroscopic AGNs. We select a subset of five galaxies to further investigate in this work. Our galaxies were all

classified as either AGNs or composites using the Baldwin, Philips and Terlevich [BPT; 14] diagram. Moreover, four of the galaxies have broad $H\alpha$ detected in the GAMA spectra and the remaining galaxy (GAMA 5227891) was identified as a narrow-line AGN displaying an asymmetric $H\alpha$ line, hinting at a potential additional, underlying broad component that could be a solid detection with higher resolution spectra, similar to the case of RGG 118 [11]. With the detection of broad $H\alpha$ emission, we are able to derive BH mass estimates. Lastly, all of the galaxies we selected have stellar masses $M_\star < 5 \times 10^9 M_\odot$ as reported in GAMA.

The g-band image for GAMA 5227891 has an issue at the location of the target and the magnitudes reported in GAMA were unreliable. Therefore, we perform aperture photometry and re-measure the magnitudes, colors and resulting total stellar mass for this object. We calculate total stellar mass using the mass-to-light ratio presented in Zibetti et al. [237] along with the r-band magnitude and the $(r-i)$ color as follows, $\log(M/L_r) = 3.482(r-i) - 1.155$. For this object, we find $M_\star = 10^{10.69} M_\odot$, making it no longer considered a dwarf galaxy.

The final galaxy in our sample was selected as a filler object from the work of Reines et al. [169], where they selected AGNs in dwarf galaxies (as described above) based on optical spectra from SDSS. After imposing the S/N, EW and redshift cuts, their parent sample includes 25,974 galaxies. The galaxy we select is ID 128 in their work (ID J1605+0850 in SDSS), which was classified as a BPT composite galaxy and did not show signs of broad $H\alpha$ in the SDSS spectrum. Properties of our sample are provided in Table ?? . Images of our 6 target galaxies from the DESI Legacy Imaging Survey SkyViewer [?] are shown in Figure 19.

Observations and Data Reduction

We obtain new, high-resolution spectra of our galaxies using the Magellan Echellette Spectrograph (MagE) on the 6.5 m Clay Telescope at Las Campanas Observatory. All of

our targets were observed on 22 August 2023 using a 1 arcsecond slit for three 30 minute exposures, totalling 1.5 hours of integration time each. In echellette mode, MagE spans the full rest-frame optical range from 3100–10000Å and has a spectral resolution of $R \sim 4100$ ($\sim 20 \text{ km s}^{-1}$).

We start our data reduction using the reduction pipeline `pypeit` [163, 164]. The pipeline performs bias subtraction, flat-fielding, wavelength calibration (using exposures of a ThAr lamp) and flux calibration. We use the standard star EG274 [86] for the flux calibration. The final product of this pipeline is a 1-D spectrum for each echellette order in units of $10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Å}^{-1}$. For the subsequent fitting, we combine all available orders into a complete 1-D spectra for each target.

Spectral Analysis

Continuum and Absorption-Line Subtraction

Before we can fit an AGN emission line spectrum, we must first remove the host galaxy contribution from the observed spectrum. We fit the continuum and absorption lines in our galaxy spectra using the Penalized Pixel Fitting software [pPXF; 43]. We first trim each galaxy spectrum to remove the edge orders with relatively high noise. We then fit the trimmed spectra using GALAXEV stellar population synthesis model templates of stellar continua and absorption lines [37]. These templates have a FWHM of 3.0Å in the wavelength range of our spectra. Additionally, we include multiplicative and additive polynomials of degree 1 and 2, respectively. This allows us to correct for higher order fluctuations and get a more accurate velocity dispersion measurement [42]. We show these fits in Figures 20 and 21. This best fit model is subtracted from each spectrum to obtain a pure AGN emission line spectrum to be used for emission line fitting.

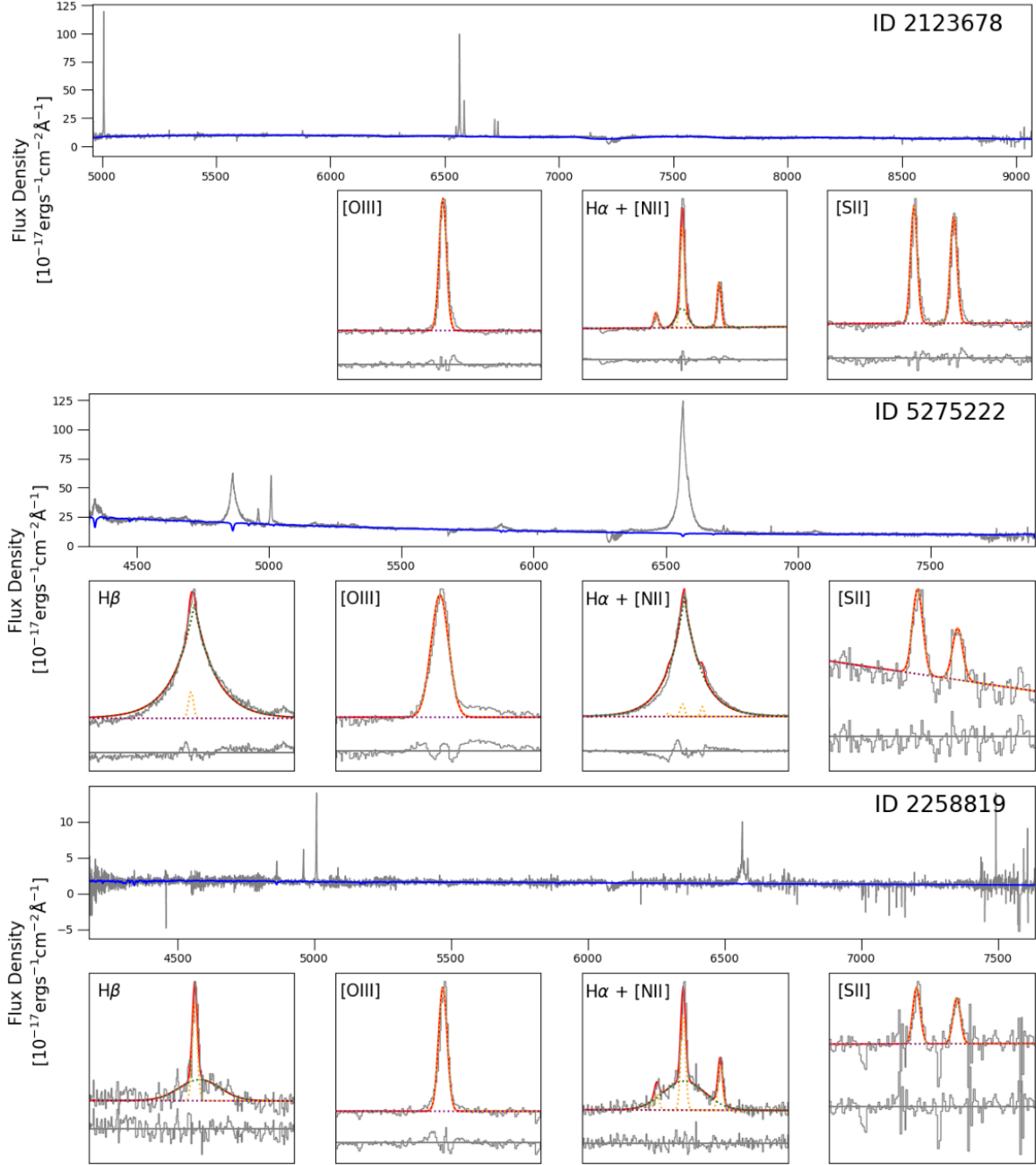


Figure 20 Absorption and emission line fits for three of our galaxies (the remaining three galaxies are shown in Figure 21). For each target, the top panel shows the full MagE galaxy spectrum with the pPXF fit to the stellar continuum overlaid in blue. The bottom panels show close-up views of relevant emission lines. The narrow line fits are shown in orange and the broad line fits (when present) are shown in green. We show the residuals below each emission line fit with a vertical offset for clarity. We perform a custom fitting process to the triple-peaked emission line galaxy GAMA 5227891 as described in Section 4.4.6.

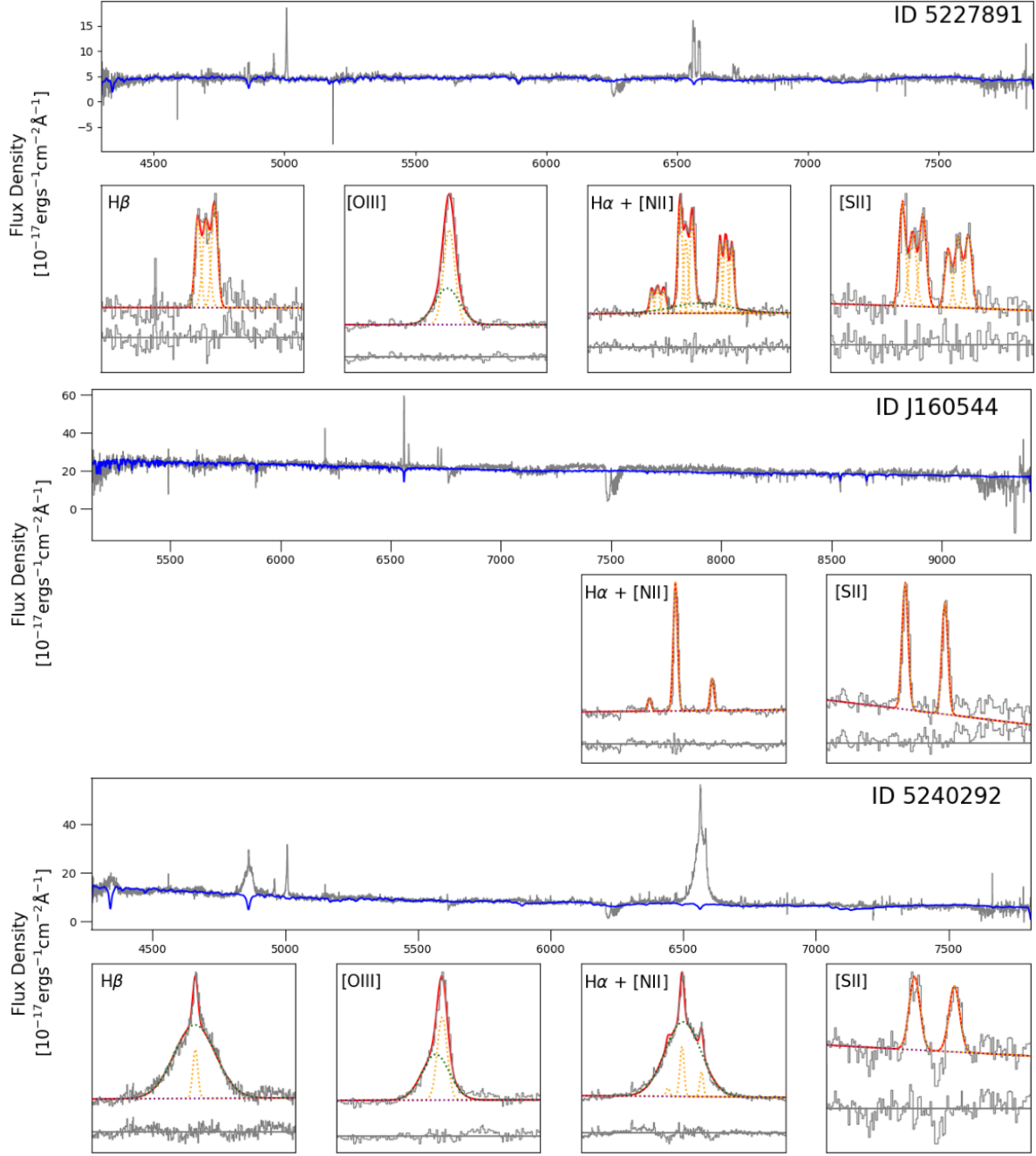


Figure 21 Same as Figure 1 but for the three remaining galaxies. For GAMA 5275222, we model the broad component to the Balmer lines with an exponential profile.

ID	H β_n $\lambda 4861$	H β_b $\lambda 4861$	[O III] _n $\lambda 5007$	[O III] _b $\lambda 5007$	H α_n $\lambda 6563$	H α_b $\lambda 6563$	[N II] $\lambda 6583$	[S II] $\lambda 6716$	[S II] $\lambda 6731$
GAMA 2258819	7 (1)	11 (1)	17 (2)	23 (23)	21 (1)	57 (2)	10 (1)	6 (1)	5 (1)
GAMA 2123678			99 (12)	222 (13)	309 (16)	...	106 (5)	45 (4)	42 (4)
GAMA 5227891 - central ²	10 (5)	...	36 (4)	31 (3)	21 (2)	38 (4)	20 (1)	6 (1)	5 (1)
GAMA 5227891 - red ³	8 (3)	...	...	...	32 (1)	...	17 (1)	7 (1)	4 (1)
GAMA 5227891 - blue ⁴	10 (3)	...	...	...	29 (1)	...	17 (1)	7 (1)	5 (1)
GAMA 5240292	41 (3)	500 (8)	47 (3)	78 (78)	110 (5)	1402 (15)	47 (3)	16 (1)	15 (1)
GAMA 5275222	41 (5)	1265 (2)	255 (4)	...	64 (10)	3997 (6)	41 (4)	24 (1)	14 (1)
SDSS J1605+0850					143 (2)	...	32 (2)	32 (3)	29 (3)

Table 5 Column 1: Identification number in GAMA/SDSS. Column 2-10: Emission line flux (and flux uncertainties in parentheses) in units of 10^{-17} erg s $^{-1}$ cm $^{-2}$ resulting from the LMFIT line fitting described in Section 4.4.2. A blank space indicates that the emission line is not present in the MagE spectrum for that object due to the wavelength range of MagE and the redshift of the galaxy. A three-dot ellipsis indicates that no line is detected.

²The fitting process for this object is described in Section 4.4.6. The [O III] fluxes are reported for Model 2.

³The fitting process for this object is described in Section 4.4.6. The [O III] fluxes are reported for Model 2.

⁴The fitting process for this object is described in Section 4.4.6. The [O III] fluxes are reported for Model 2.

AGN Emission Line Fits

We fit the relevant AGN emission lines in our host-galaxy-subtracted spectra using the least-squares fitting methods of **LMFIT** [147]. All lines are modeled using a sum of various Gaussians + a linear component to account for any errors in the **pPXF** stellar continuum fitting. One of our galaxies displays triple-peaked emission lines and we will discuss it further in Section 4.4.6. For the remaining five galaxies, we follow the procedure of Reines et al. [169], described below.

We first fit the [S II] doublet using both one and two Gaussian components for each line. We fix the separation of the two peaks of the doublet to be the rest-frame wavelength separation and constrain the widths of the two peaks to be equal in velocity space. For the two component model, we constrain the relative heights, widths, and positions of each component to be equal for both lines in the doublet. If adding the second components decreases the χ^2 from the single component model by 20% or more, we assume that a two component model is preferred. Only one of our galaxies (ID 2123678) required a two Gaussian component model. For the remaining four galaxies, a single Gaussian component is preferred for each line in the doublet.

Once we have the best-fit Gaussian parameters for the [S II] lines, we use them as a template for the narrow H α and [N II] emission lines. We fix the separation of the [N II] lines to their rest-frame wavelength separation and require that $\sigma_{[N II]}$ is equal to $\sigma_{[S II]}$ in velocity space. We also constrain $\sigma_{H\alpha, \text{ narrow}}$ to be $< 1.25 \times \sigma_{[S II]}$ in velocity space. Additionally, if necessary, we include a broad H α component with no restrictions except that $\sigma_{H\alpha, \text{ broad}} > \sigma_{H\alpha, \text{ narrow}}$ ⁵. The fit including a broad H α component is preferred if the χ^2 is improved by at least 20%. Three out of the five galaxy spectra that we fit in this section

⁵Galaxy GAMA 5275222 has very broad tails on its Balmer emission lines. Following from Kollatschny & Zetzl [111], we test fitting the broad lines using Gaussian (doppler motion), Lorentzian (turbulent motion), exponential (electron scattering) and logarithmic (inflow/outflow motion) profiles. The best model for the broad lines in this galaxy is an exponential profile [e.g., 117].

are best fit with a model including broad $H\alpha$ emission, consistent with the findings from [180]. One of the galaxies without detectable broad $H\alpha$ emission, SDSS J1605+0850, also did not show broad $H\alpha$ in the previous work done by Reines et al. [169]. However, Salehirad et al. [180] did detect weak broad $H\alpha$ in the spectrum of GAMA 2123678. This is likely because our MagE spectrum has higher spectral resolution than GAMA and so the second component in the [S II] doublet was not detected in the GAMA spectrum.

We fit the $H\beta$ emission line in the same way as the $H\alpha$ line; constraining its width to be $< 1.25 \times \sigma_{[S\ II]}$ in velocity space and allowing for a broad component (with width larger than the narrow component) if it reduces the χ^2 value by $>20\%$. Since two of our galaxies (GAMA 2123678 and SDSS J1605+8050) are at such low redshift, the $H\beta$ emission line is outside of the wavelength range observed with MagE. Of the remaining three galaxies, all of them are consistent with having broad $H\beta$.

We fit the [O III] λ 5007 line independently because the profile of this line does not necessarily resemble the other narrow emission lines [72]. [O III] sometimes displays a broad component which can be due to ionized gas outflows [90]. These outflows have been found to be generally blueshifted in AGNs [181, 235]. Since the [O III] line is not produced in the broad-line region around a BH, additional velocity components in this line can be a tracer of ionized gas dynamics in the narrow-line region. Therefore, we use a Gaussian model with no constraints to fit this emission line. Once again, we opt for a model including a broad component if it improves the χ^2 value by at least 20%. Due to its redshift, for one galaxy (SDSS J1605+8050) the [O III] emission line is outside of the wavelength range observed with MagE. For the remaining galaxies, one (GAMA 5275222) is best fit with a single narrow component and three are best fit with a narrow + broad component. These broad components are generally blue-shifted, ranging from 30-117 km s $^{-1}$ offset. One galaxy (ID 2123678) has a broad component that is red-shifted by 55 km s $^{-1}$. The widths of these broad components range from 55-220 km s $^{-1}$.

The best-fit emission line models for our galaxies are shown in Figures 20 and 21. The fluxes we measure are reported in Table 5. For two of our galaxies (GAMA 2123678 and SDSS J1605+0850) not all of the emission lines needed for the BPT diagram are within the observed MagE wavelength range and so we cannot measure their narrow emission line ratios. The three remaining galaxies are found to be BPT AGNs, which is consistent with the previous findings of Salehirad et al. [180].

BH Mass Estimates

In agreement with previous work, three galaxies with detected broad $H\alpha$ in Salehirad et al. [180] also display broad $H\alpha$ in their MagE spectra⁶. While transient broad $H\alpha$ in star-forming galaxies can be attributed to supernovae, persistent broad $H\alpha$ with BPT AGN narrow emission line ratios provide a robust indicator of the presence of an AGN [13]. For these galaxies, we are able to estimate their BH masses. Assuming the gas in the broad-line region (BLR) is virialized, the BH mass scales proportional to the size of the BLR and the average gas velocity squared. We measure the average gas velocity as the full width at half maximum (FWHM) of the broad $H\alpha$ line and estimate the size of the BLR using the broad $H\alpha$ luminosity as a proxy [72]. Therefore, as presented in Reines et al. [169], the virial BH mass can be estimated as:

$$\log\left(\frac{M_{\text{BH}}}{M_{\odot}}\right) = \log\epsilon + 6.57 + 0.47\log\left(\frac{L_{H\alpha}}{10^{42}\text{ergs}^{-1}}\right) + 2.06\log\left(\frac{\text{FWHM}_{H\alpha}}{10^3\text{kms}^{-1}}\right) \quad (7)$$

We use $\epsilon = 1$ as in Reines et al. [169]. Uncertainties associated with using this method are ~ 0.5 dex.

⁶The one galaxy with a ‘hint’ of broad $H\alpha$ in Salehirad et al. [180] will be discussed in Section 4.4.6.

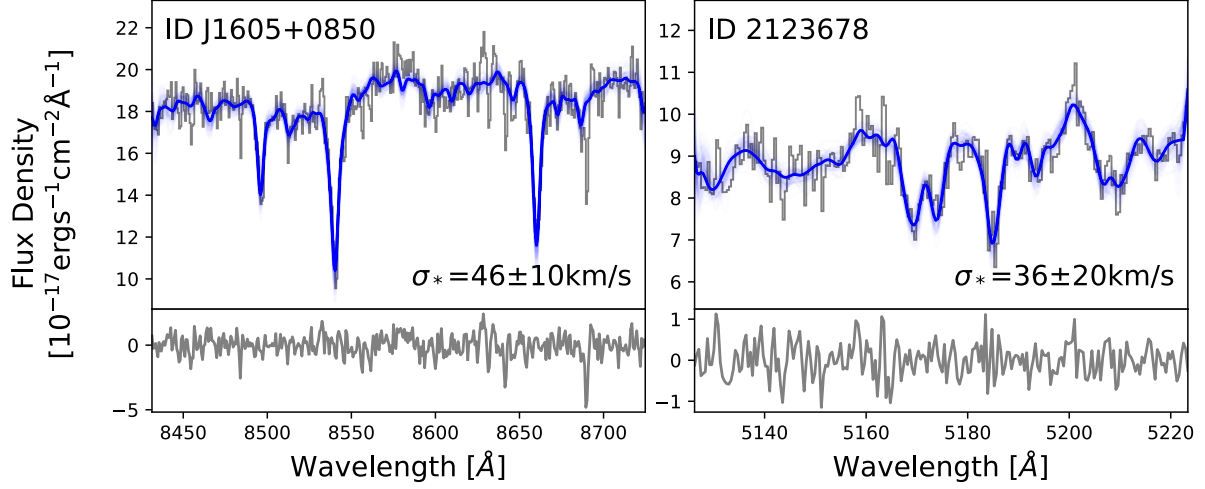


Figure 22 pPXF fits for the two galaxies in our sample exhibiting strong absorption lines (top) and the resulting residuals (bottom). The resulting fits from all 100 noise realizations from the Monte Carlo bootstrapping are shown in blue.

The $(L_{H\alpha})_b$ range from $10^{39.8-42.6}$ erg s^{-1} and the broad $H\alpha$ FWHMs range from 1167-2030 km s^{-1} . The M_{BH} we calculate using these luminosities and FWHMs range from $10^{6.2-7.3} M_{\odot}$. Our mass estimates are presented in Table 6. These values are consistent with those previously calculated using the GAMA spectra in Salehirad et al. [180], with our BH masses differing by 0.15 dex on average (for these four galaxies).

Two of our galaxies (GAMA ID 2123678 and SDSS J1605+8050) do not have detectable broad $H\alpha$ and so we cannot derive a virial BH mass for these objects. However, following the analysis done in Reines et al. [169], we can estimate an upper limit on the BH mass based on the minimum observable broad $H\alpha$ flux. We estimate this by adding a Gaussian to the $H\alpha$ line with FWHM 500 km s^{-1} and incrementally increase the height until the broad component is detected by our code. The minimum detectable broad $H\alpha$ luminosities for GAMA 2123678 and SDSS J1605+8050 are 1×10^{39} erg s^{-1} and 2×10^{38} erg s^{-1} , which translate to upper BH mass limits of $10^{4.58} M_{\odot}$ and $10^{4.22} M_{\odot}$, respectively. Using the Reines & Volonteri [174] AGN $M_{\text{BH}} - M_{\star}$ relation for their stellar masses results in BH mass estimates of $M_{\text{BH}} \sim 10^{5.8} M_{\odot}$ for both galaxies. Using the Kormendy & Ho [113] $M_{\text{BH}} - \sigma_{\star}$ relation for their velocity

dispersions (see 4.4.4) results in BH mass estimates of $M_{\text{BH}} \sim 10^{5.2} M_{\odot}$ for GAMA 2123678 and $M_{\text{BH}} \sim 10^{5.7} M_{\odot}$ for SDSS J1605+8050. Both of these scaling relations give roughly consistent BH mass estimates. These measurements are not consistent with the upper mass limit derived using the minimum detectable broad $\text{H}\alpha$ luminosity, however, we note that limit was calculated assuming the AGN has a broad-line region, which may not be the case for low-luminosity AGNs [e.g., 58, 80, 212, 213]. That calculation would also not hold for the case of Type II AGNs.

Stellar Velocity Dispersion Measurements from Mg *Ib* and Ca II

In order to obtain more precise velocity dispersion measurements, we trim each spectrum around both the Mg *Ib* (5167 Å, 5172 Å and 5183 Å) and Ca II triplets (8498 Å, 8542 Å and 8662 Å) and fit the spectrum again using pPXF. Since we have focused into the specific absorption line regions, we fit each region using stellar spectra rather than the model stellar population templates. For the Mg *Ib* region, we follow the work of Baldassare et al. [13] and fit the trimmed spectra using a set of a wide range of stars from the ELODIE spectral database [165]. These spectra span 3900-6800Å and have spectral resolution $R = 10,000$. For the Ca II region, we follow Caglar et al. [40] and use the G, M and K stars in the X-shooter spectral library from Chen et al. [48]. These spectra span 3000-10200Å and have resolution $R=10,000$. We also include multiplicative and additive polynomial of degrees 3 and 12, respectively ⁷.

We calculate uncertainties associated with this fitting process via a Monte Carlo bootstrapping method; iteratively adding noise to each flux point in the subsequent spectra based on a Gaussian with σ equal to the standard deviation of the residuals from the previous fit. We do this for 100 noise realizations, where $\sigma_* > \sigma_{\text{instrument}}$; if the resulting velocity

⁷Increasing the polynomial degrees aids in obtaining a more accurate fit by correcting for spectral calibration inaccuracies, dust reddening, and sky subtraction errors. Specifically the additive polynomials can help to deepen individual absorption lines [42].

dispersion found by the `ppxf` fit is smaller than our instrumental resolution, we discard the fit. For our final reported velocity dispersion we remove the effects of the instrumental dispersion from the σ_* found by `pPXF`.

Two of our galaxies display absorption lines in both the Ca II and the Mg *Ib* triplets. For galaxy SDSS J1605+0850, the Ca II triplet is significantly more visually prominent than the Mg *Ib* triplet, while for galaxy GAMA 2123678, the Mg *Ib* triplet is the more distinctive absorption line complex. Therefore, we take the stellar velocity dispersion measurement for the more distinctive complex. SDSS J1605+0850 has a velocity dispersion of $46 \pm 10 \text{ km s}^{-1}$ and GAMA 2123678 has a velocity dispersion of $36 \pm 20 \text{ km s}^{-1}$. The results of this fitting are shown in Table 6 and Figure 22.

Four of our galaxies do not have detectable stellar absorption lines. For these galaxies, we estimate stellar velocity dispersion measurements using the ionized gas velocity dispersion as described in the following section (§4.4.5).

Velocity Dispersion Measurements from [N II]

Since the galaxy absorption lines were not detectable for multiple galaxies, we were not able to obtain stellar velocity dispersion measurements in the same way as described in Section 4.4.4. For these galaxies, we instead use the ionized gas velocity dispersion (σ_g), measured through the FWHM of the [N II] lines, as a proxy [11, 16, 231]. The scatter around the $\sigma_* - \sigma_g$ correlation is ~ 0.15 dex so our [N II]-derived velocity dispersion measurements carry extra contribution to the uncertainty than those directly measured through the `pPXF` fitting. The resulting σ_* values for our galaxies range from $37\text{--}80 \text{ km s}^{-1}$ and are shown in Table 6.

We note that for GAMA 2123678 and SDSS J1605+0850 we were able to obtain stellar velocity dispersion measurements using both stellar absorption lines and the [N II] emission lines. The σ_* values we calculate for both of these objects are consistent within their

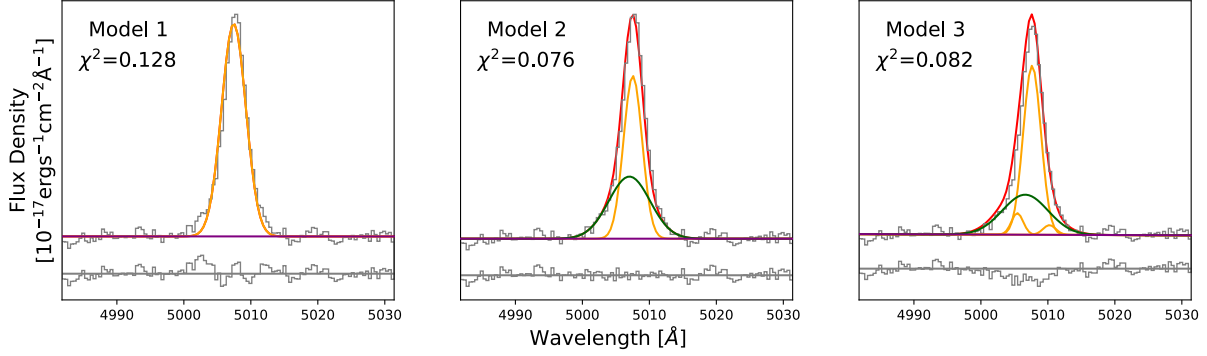


Figure 23 The three models we consider for fitting the [O III] emission line (see §4.4.6). Model 1 includes a single Gaussian component. Model 2 includes one narrow component + one broad component. Model 3 includes three narrow components + one broad component. For the red/blue peaks in Model 3, we constrain the widths/centers based on the corresponding peaks in the other emission lines. In all three models, narrow components are shown in yellow, broad components are shown in green and the full sum of all components is shown in red. We show the residuals below each emission line fit with a vertical offset for clarity.

uncertainties for both methods.

A Triple-Peaked Emission Line Galaxy

One of our galaxies, GAMA 5227891, has triple-peaked emission lines in $H\alpha$, [N II], [S II] and $H\beta$ ⁸. For the following analysis, we refer to the three peaks in each emission line as the “red”, “blue” or “central” peak. We fit each of the three peaks in all emission lines with their own Gaussian. We also assume that all correspondingly shifted components individually abide by the constraints described earlier in Section 4.4.2 (e.g., the separation between the two red peaks, the two blue peaks and the two central peaks of the [N II] doublet are all constrained to be the rest-frame wavelength separation).

We first fit the [S II] doublet, fixing the relative wavelength separation between the two red peaks, the two blue peaks and the two central peaks. This fitting results in red/blue peaks offset from the central component by $+145 \text{ km s}^{-1}$ and -144 km s^{-1} . We use the line profiles for the red, blue and central peaks from this fit as a model for the corresponding

⁸We ensure the triple peaks are real, as described in the Appendix.

peaks in the $H\alpha$ and $[\text{N II}]$ lines and constrain their widths in velocity space, as in the previous fits (see Section 4.4.2). We again allow for a broad $H\alpha$ component if the χ^2 is reduced by at least 20%. We find that the resulting best-fitting model includes three narrow peaks for the $[\text{N II}]$ doublet and the $H\alpha$ line and one broad $H\alpha$ component⁹. The red and blue peaks for both $H\alpha$ and $[\text{N II}]$ lie -138 km s^{-1} and $+146 \text{ km s}^{-1}$ offset from the central peak. We measure the broad $H\alpha$ luminosity and FWHM as $L(H\alpha)_b = 10^{40.6} \text{ erg s}^{-1}$ and $\text{FWHM}(H\alpha)_b = 1609 \text{ km s}^{-1}$, giving a BH mass of $M_{\text{BH}} = 10^{6.3} M_{\odot}$.

We follow a similar process for the $H\beta$ line as for the $H\alpha$, by constraining the Gaussian widths in velocity space based on the respective widths of the various peaks of the $[\text{S II}]$ doublet and allowing a broad component if the χ^2 value is reduced by 20% or more. The best fit model for this emission line includes just three narrow peaks. The red/blue peaks are offset by $+155 \text{ km s}^{-1}$ and -151 km s^{-1} from the central peak.

Lastly, we fit the $[\text{O III}]\lambda 5007$ line. This line does not exhibit three obvious visible peaks. However, since the other lines do show three peaks, we test multiple methods of fitting the $[\text{O III}]$ emission line and compare the resulting χ^2 values. The models we test are:

1. Model 1: a single Gaussian component model
2. Model 2: a two component model (a central narrow peak + a broad component)
3. Model 3: a four component model (three red/central/blue narrow peaks + a broad component)

Models 1 and 2 are the same as the models we consider in Section 4.4.2 for fitting a single-peaked $[\text{O III}]$ emission line coming from a central AGN. Model 2 is clearly a better fit than Model 1, reducing the χ^2 value significantly (from 1.531 to 0.927), with the broad

⁹This galaxy had a “hint” of broad $H\alpha$ in the GAMA spectra, meaning that there was some asymmetry suggesting that the line would be best fit with multiple components.

component offset from the narrow component by -30 km s^{-1} and having a velocity dispersion of 182 km s^{-1} .

Given the triple-peaked nature of the other emission lines, we consider Model 3 to test whether the [O III] line may be also be fit with three peaks. However, the central peak clearly dominates the line profile and is due to emission from a central AGN (as evidenced by line ratios in both the MagE, see section 4.6.2, and GAMA spectra). Nevertheless, we aim to determine whether or not there may be additional, presumably weak, red and blue peaks in the [O III] line and constrain their properties. We first fit Model 3 without constraints, but the fitting process always resulted in one of the peaks having a flux of $\sim$ zero. Next, we force the profiles of the red/blue peaks of [O III] to emulate the other emission lines by constraining the offsets, widths and flux ratios of the red and blue peaks to be approximately within the range seen for the other emission lines that exhibit obvious triple peaks. Modeling the [O III] emission line in this way results in red/blue peaks that are offset by -131 km s^{-1} and $+156 \text{ km s}^{-1}$, respectively, and they are both extremely sub-dominant with respect to both the narrow and broad components of the central peak. Moreover, the width of the [O III] central peak is much larger than the central peak in the other emission lines, with a dispersion of 80 km s^{-1} compared to $\sim 50 \text{ km s}^{-1}$ for the other lines. The broad component is offset from the central peak by -60 km s^{-1} and has a velocity dispersion of 203 km s^{-1} . The χ^2 value for this model is 0.986, comparable to that of Model 2 (see Figure 23).

Emission line fluxes for this object are reported in Table 5 and the fits are shown in Figure 21. We note that the three peaks observed in all of the emission lines (except [O III]) are remarkably symmetric. The red/blue peaks are each offset by $\sim 140 \text{ km s}^{-1}$ and all three peaks have similar velocity dispersions ranging from $44\text{--}61 \text{ km s}^{-1}$ with an average of 49 km s^{-1} . We use the width of the central peak in the [N II] emission line as a proxy for the galaxy stellar velocity dispersion in the same way as for the other galaxies lacking strong absorption lines, as described in Section 4.4.5. We obtain a value of 39 km s^{-1} for this galaxy. We will

ID	$\log L(\text{H}\alpha)_b$ [erg s ⁻¹]	FWHM(H α) _b [km s ⁻¹]	$\log M_{\text{BH}}$ [M _⊙]	$\sigma_{[\text{N II}]}$ [km s ⁻¹]	$\sigma_{*,[\text{N II}]}$ [km s ⁻¹]	σ_* [km s ⁻¹]
2258819	40.9	1252 ± 135	6.2	50 ± 9	50 ⁺¹⁹ ₋₁₆	...
2123678 ¹⁰	...	...	...	25 ± 4	25 ⁺⁷ ₋₆	36 ± 20
5227891	40.6	1609 ± 159	6.3	39 ± 14	39 ⁺²⁹ ₋₂₅	...
5240292	42.2	2030 ± 25	7.3	80 ± 7	80 ⁺¹⁴ ₋₁₂	...
5275222	42.6	1167 ± 12	7.0	76 ± 5	76 ⁺¹¹ ₋₉	...
J1605+0850 ^a	...	...	...	37 ± 5	37 ⁺¹⁰ ₋₈	46 ± 10

Table 6 Column 1: Identification number in GAMA/SDSS. Column 2: Broad H α luminosity. Uncertainties on this are $\sim 3\%$. Column 3: Broad H α FWHM. Column 4: Virial BH mass estimated using fits to the broad H α emission line. Uncertainties on these masses are ~ 0.5 dex. Column 5: Gas velocity dispersion measured from the [N II] emission line width. These values are used as a proxy for the stellar velocity dispersion in Figure 24. Column 6: Stellar velocity dispersion measured from the gas velocity dispersion. Uncertainties from both the line widths and from the relation between $\sigma_{[\text{N II}]}$ and σ_* [16] are added in quadrature. Column 7: Stellar velocity dispersion measured from fits to the stellar absorption line spectra using `ppxf`. For ID 2123678 we report the σ_* calculated from fitting the Mg *Ib* complex while for ID J1605+0850 we report the σ_* calculated from fitting the Ca II triplet. A three-dot ellipsis in this column indicates that the galaxy did not have strong absorption lines present in its spectrum and, therefore, we could not measure the stellar velocity dispersion using `ppxf`.

discuss possible physical interpretations for the triple-peaked lines in Section 4.6.

Scaling Relations

Using our virial BH masses and velocity dispersion measurements, we investigate how our sample compares to two different canonical scaling relations and other samples of galaxies. We consider the $M_{\text{BH}} - \sigma_*$ and the $M_{\text{BH}} - M_*$ relations.

The $M_{\text{BH}} - \sigma_*$ Relation

We place our galaxies on the $M_{\text{BH}} - \sigma_*$ relation in Figure 24. For comparison, we also include the sample of classical bulges and elliptical galaxies with dynamical BH mass

¹⁰Broad H α was not detected for these objects, so we are not able to calculate the broad H α luminosity/FWHM or BH mass.

measurements from Kormendy & Ho [113] and the samples of low-mass AGNs from Xiao et al. [231] and Baldassare et al. [9]. Xiao et al. [231] investigated a sample of 76 Seyfert 1 galaxies with low-mass BHs from SDSS that were originally presented in Greene & Ho [73]. Baldassare et al. [9] looked at a sample of eight dwarf galaxies that were also from SDSS and identified as broad-line AGNs in Reines et al. [169]. Additionally, in their work, Baldassare et al. [9] considers seven other objects with previously measured BH masses/velocity dispersions, including NGC 4395 [60, 61], Pox 52 [17, 211], RGG 118 [11, 12], RGG 119 [13] and three galaxies with dynamical BH mass measurements, M 32 [216], NGC 5206 and NGC 205 [149, 150]. In both of these works, they find that the galaxies are generally consistent with the relation defined by the higher-mass, inactive counterparts. Our work agrees with both of these findings; all of our galaxies lie within the 3σ -scatter for the canonical relation defined by Kormendy & Ho [113].

Volonteri & Natarajan [221] show that the initial BH seed mass should be reflected in the low-mass regime of this relation. Although the seeds do not initially land on the canonical relation, galaxies tend to migrate onto the relation through merger and accretion events, with higher mass galaxies tending to migrate faster. They find that a heavy seeding model results in a population of galaxies with over-massive BHs at low-mass and, therefore, a broadening of the relation. On the other hand, they find that a light seeding model tends to manifest in a downturn of the relation. Pacucci et al. [155] estimate that this downturn should occur at $\sigma_* \approx 65 \text{ km s}^{-1}$. From our work, we cannot distinguish between these seeding models. We do not observe any galaxies with significantly over-massive BHs especially at low σ_* that would be indicative of a heavy seeding model.

The $M_{BH} - M_*$ Relation

Originally, BH mass was found to correlate with bulge mass [e.g., 95, 113, 137]. However, comparing BH mass to total galaxy stellar mass has recently become a useful tool since

extracting bulge masses can be a complicated process and is not feasible in high-redshift galaxies. Moreover, multiple works have shown that galaxies of different types than those originally used to create the canonical bulge mass relation defined by Kormendy & Ho [113, i.e. large, local, elliptical/classical bulge galaxies] tend to deviate from it, including dwarfs, late-type galaxies, high-redshift galaxies and AGNs [63, 70, 74, 76, 93, 112, 174, 184, 207, 225].

We show our sample on the BH mass versus galaxy total stellar mass (M_*) scaling relation using masses and uncertainties reported in the GAMA tables `StellarMassesG02CFHTLS v24` and `StellarMassesGKV v24` [25, 210], except for GAMA 5227891, which we re-calculate magnitudes and total stellar masses as described in Section 4.2. We compare our sample to the BH-stellar mass relations derived in Reines & Volonteri [174] both for local broad-line AGNs (predominantly in galaxies with disks) and for quiescent, early-type galaxies in Figure 25.

Again, our galaxies are generally consistent with the canonical scaling relations. Three galaxies (IDs 2258819, 5275222 and 5240292) are consistent within 3σ of the intrinsic scatter of both relations. Our triple-peaked galaxy (GAMA 5227891) falls below the relation for early-type galaxies, but is consistent with the local AGNs from Reines & Volonteri [174].

Observational Bias

We note that our sample is small and likely a result of observational bias towards higher luminosity objects. The four objects we placed on the $M_{\text{BH}} - \sigma_*$ relation are at redshift $z \sim 0.2$ and, although most are dwarf galaxies (with $M_* < 5 \times 10^9 M_\odot$), they host relatively large central BHs. The three dwarf objects fall above the $M_{\text{BH}} - M_*$ relation defined by Reines & Volonteri [174] for local AGNs. Since smaller BHs have lower Eddington limits and are, therefore, less likely to be accreting at the levels needed to be observed at such large distances [192], it is possible that we are simply missing a population of dwarf

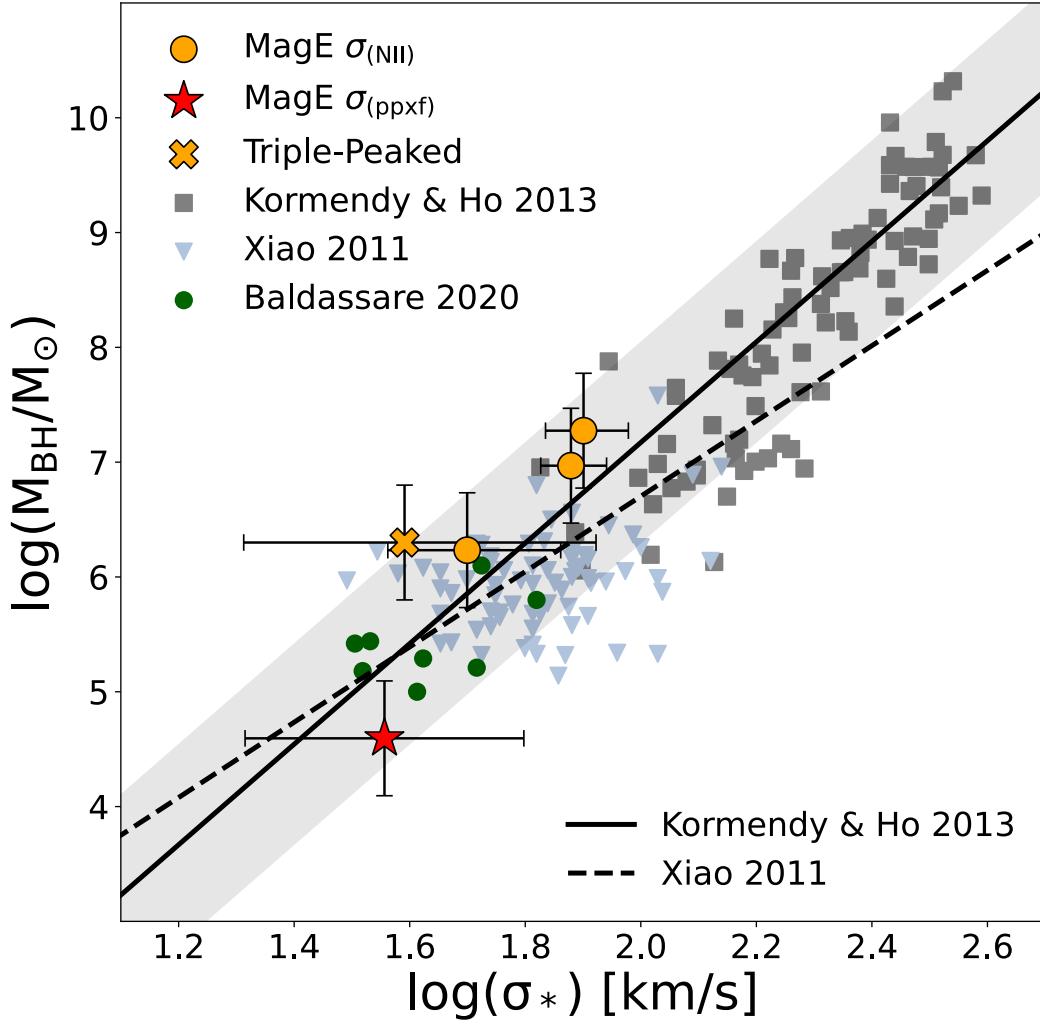


Figure 24 The $M_{\text{BH}} - \sigma_*$ relation. Our galaxies are shown in orange with σ derived using [N II]. Vertical error bars represent the ~ 0.5 dex uncertainty involved in using virial BH mass estimates and horizontal error bars incorporate both the uncertainty in the width of the [N II] lines and the 0.15 dex uncertainty in the $\sigma_* - \sigma_g$. For comparison, we also show the sample of elliptical and classical bulge galaxies from Kormendy & Ho [113] and the sample of low-mass AGNs from Xiao et al. [231]. We also show dwarf AGN and dwarf galaxies with dynamical BH masses, which includes the sample from Baldassare et al. [9] as well as their additional objects from the literature described in Section 4.5.1. The solid line shows the best fit relation derived from the elliptical and classical bulges from Kormendy & Ho [113] and the shaded region indicates the 3σ intrinsic scatter. We also show the relation found by Xiao et al. [231] for their sample of low-mass AGNs (dashed line).

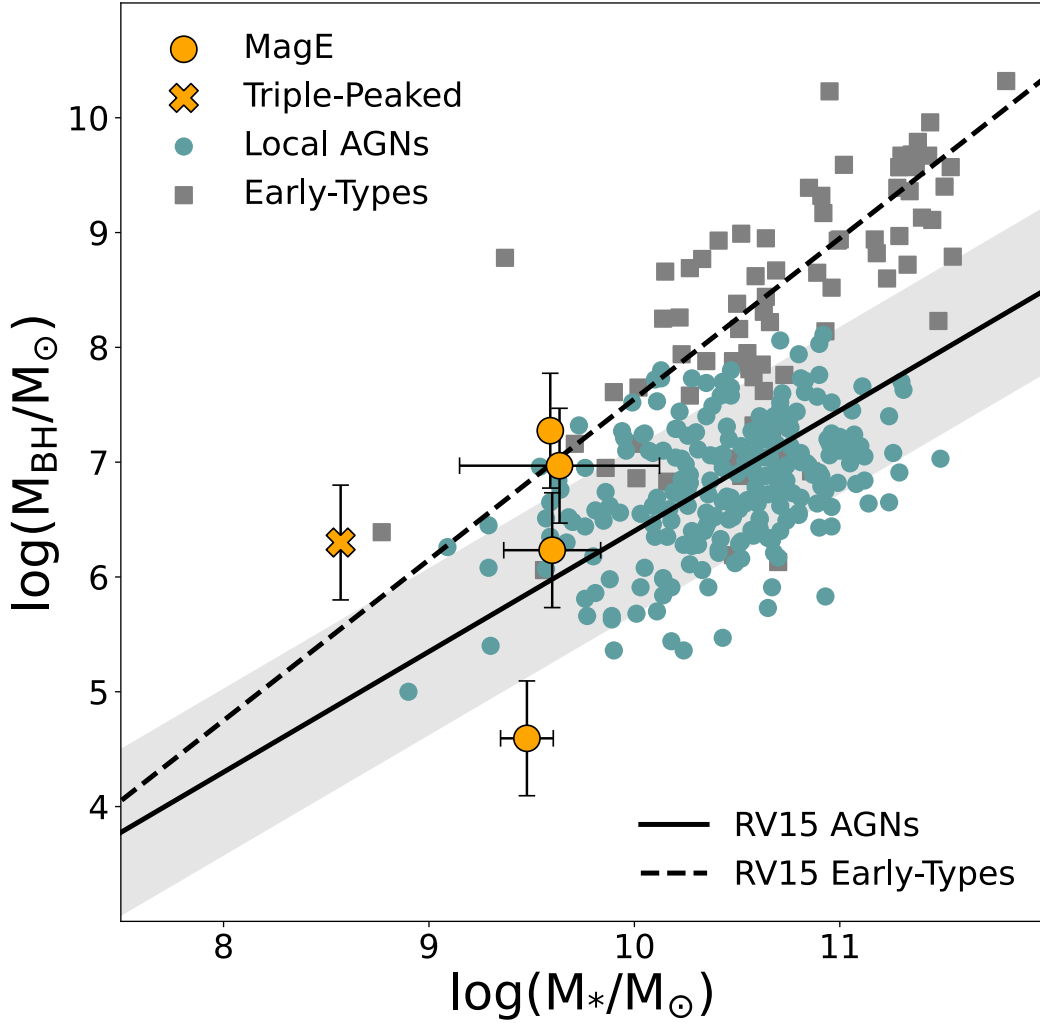


Figure 25 The BH mass versus total galaxy stellar mass ($M_{\text{BH}} - M_*$) relation. Our galaxies are shown in orange. Vertical error bars represent the ~ 0.5 dex uncertainty involved in using virial BH estimates and horizontal error bars are the reported uncertainties in stellar mass from Taylor et al. [210] and Bellstedt et al. [25]. For comparison, we show the sample of local AGNs presented in Reines & Volonteri [174] and the sample of early-type galaxies (elliptical and S/S0 with classical bulges) that have dynamically-detected BHs from Kormendy & Ho [113] with total stellar masses calculated in Reines & Volonteri [174]. We also show the BH-stellar mass relations derived by Reines & Volonteri [174] for the AGNs (solid line) and for the early-types (dashed line).

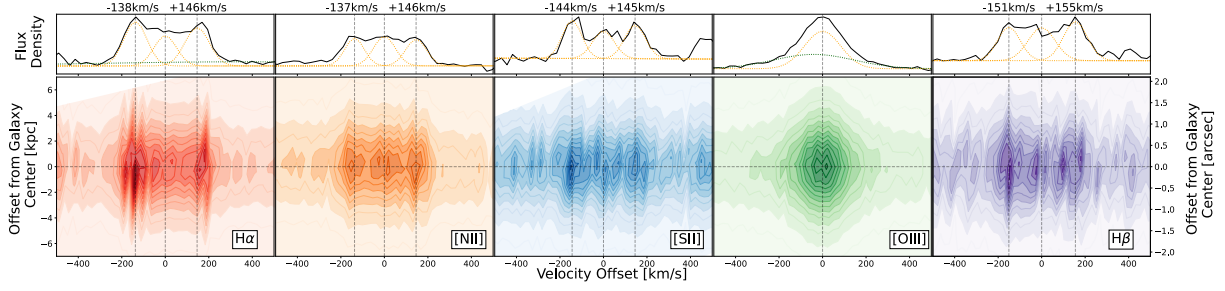


Figure 26 2-D (bottom) and 1-D (top) spectra for galaxy GAMA 5227891, which exhibits triple-peaked emission lines. In the top panel, orange lines show the best fit narrow line components and green lines show the best fit broad components. In the bottom panel, the horizontal grey dotted line shows the center of the galaxy within the slit. The vertical grey dotted lines show the center points of the red and blue shifted line components, and their offset from the center line is given at the top of each line. We give the offset from the galaxy center both in kpc and arcseconds.

galaxies occupying regions of the M_{BH} versus σ_* or M_* relation that are inconsistent with the canonical relations. For example, since we are effectively observationally limited in BH mass, there could be a downturn in the relation (i.e., galaxies with $M_{\text{BH}} < 10^{4.5} M_{\odot}$ and $\sigma_* \sim 10^{1.6}$) that we are not able to observe. We are also limited by the resolution of our spectra ($\sim 20 \text{ km s}^{-1}$), meaning that we are not able to detect galaxies with smaller velocity dispersions.

Investigating the Triple-Peaked Emission Line Galaxy

Here we return to the triple-peaked emission line galaxy to further analyze its spectrum and discuss possible physical interpretations. In Section 4.4.6, we fit the $\text{H}\alpha$, $[\text{N II}]$, $[\text{S II}]$ and $\text{H}\beta$ emission lines each with three narrow gaussian peaks. For all of these emission lines, the red/blue peaks have similar velocity dispersions and offsets from the central peak. Since the $[\text{O III}]$ line did not have clear triple peaks, we tested three different model fits, ultimately finding that a two component model (one broad + one narrow peak) was the best fit. However, using a four component model (a central dominant peak with a narrow + broad component, as well as weak narrow red and blue peaks) also resulted in a similar

χ^2 value. We will consider both of these models in the following discussion of the possible physical origins of the emission in this galaxy.

Spatial Distribution of Emission

In Figure 26, we show the 2-D spectrum around the $H\beta$, $[O\ III]\lambda 5007$, $H\alpha$, $[N\ II]\lambda 6585$ and $[S\ II]\lambda 6716$ emission lines. This shows the spatial position of the gas (offset from the galaxy center) versus velocity offset (relative to the central peak of the emission line fit). It is immediately apparent that both the spatial and velocity distribution of the $[O\ III]$ emission is markedly different from the other emission lines. The $[O\ III]$ emission is clearly dominated by a central source (i.e., the AGN). In contrast, the other lines have significant emission offset in both velocity and position. There is not a consistent decrease in emission at higher velocities/radii (as seen in the $[O\ III]$ line), indicating that the primary emission source for these lines is likely further out in the galaxy than the primary source of the $[O\ III]$ emission.

Ionization Sources and Gas Density

We investigate the ionization source(s) of the gas in the triple-peaked system by studying the emission line ratios of the various peaks. Following broadly from the idea that ionization from AGNs can produce more high energy photons than stellar processes, we can distinguish AGN emission by looking for higher ratios of collisionally-excited, forbidden emission lines (such as $[N\ II]\lambda 6583$, $[S\ II]\lambda\lambda 6716, 1731$ and $[O\ III]\lambda 5007$) to a line such as $H\alpha$ or $H\beta$. For the $[O\ III]/H\beta$ versus $[N\ II]/H\alpha$ diagram [BPT; 14], this separation has been defined in Kewley et al. [106] by combining a distinction between purely star-forming/HII galaxies and composite galaxies from Kauffmann et al. [101] with an extreme starburst limit from Kewley et al. [105], above which (theoretically) only AGNs could produce the observed emission. Kewley et al. [106] also outlines a classification scheme for the $[O\ III]/H\beta$ versus $[S\ II]/H\alpha$ diagram, using the theoretical extreme starburst limit from Kewley et al. [105] again to separate AGNs from star-forming galaxies in addition to a Seyfert-LINER separation line.

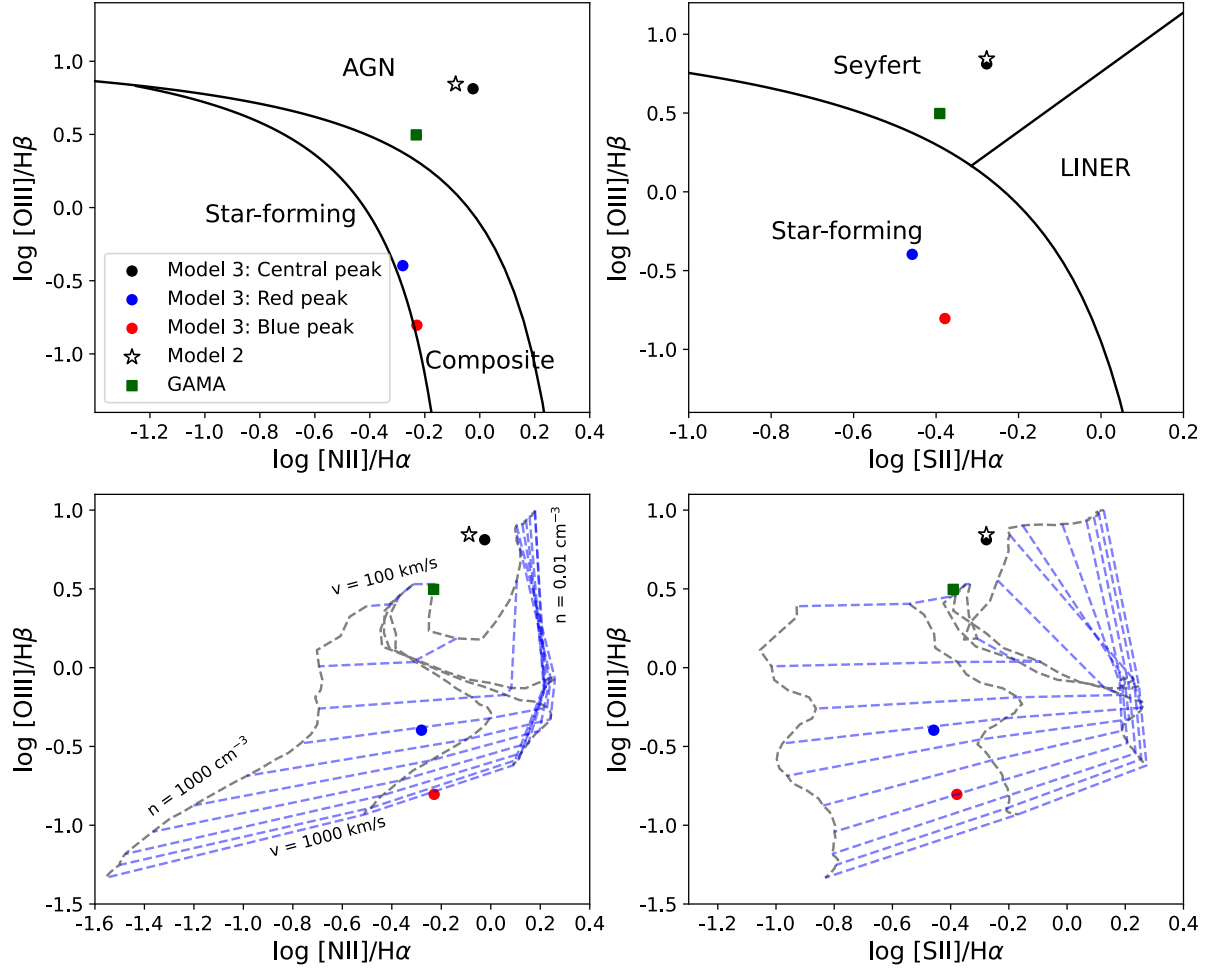


Figure 27 Top: Narrow emission line ratio diagnostic diagrams for various fits to the [O III] emission line. Based on the GAMA spectrum, the galaxy lies in the AGN/Seyfert region (shown as the green square). Using Model 2, the galaxy lies in the AGN/Seyfert region (shown as the black star). For Model 3, the central peak lies in the Seyfert region of both the [O III]/H β versus [N II]/H α and [O III]/H β versus [S II]/H α diagrams (shown as the black dot), and is in almost the same position as for Model 2. On the other hand, both the red and blue peaks lie in the composite/star-forming regions (shown as the red/blue dots). Bottom: Shock excitation models from Allen et al. [2] with fixed transverse magnetic field of $b = 1 \mu\text{G}$, velocities ranging from 100-1000 km s^{-1} and electron densities ranging from 0.01-1000 cm^{-3} . The red and blue peaks for Model 3 are also consistent with ionization due to shocks with gas density $n \sim 100 \text{ cm}^{-3}$ and at velocities of $\sim 400\text{-}1000 \text{ km s}^{-1}$.

For this analysis, we consider both Model 2 and Model 3 for the [O III] emission line. The [O III] flux for Model 2 includes both the narrow and broad component. The central peak for Model 3 includes the central narrow component plus the broad component. These give nearly identical results on the diagnostic diagrams (since any possible red/blue peaks are quite weak) and demonstrate that AGN emission dominates (Figure 27). For comparison, we also show the results of Salehirad et al. [180] using the GAMA spectrum. The GAMA spectrum is at lower resolution than the MagE spectrum we use in this work and the three peaks were not resolved in GAMA. Therefore, the GAMA spectrum shows the dominant emission source in the galaxy (i.e., an AGN).

For Model 3, the red and blue peaks lie in the composite and star-forming regions in the [N II]/H α and [S II]/H α diagrams, respectively. Therefore, if these red/blue peaks in the [O III] line do indeed exist, the line ratios suggest a star-formation origin (or shock ionization, see below). These findings are consistent with the fact that we observe significant emission (e.g., in H α) that is red/blue-shifted and originating from outer regions in the galaxy (see Figure 26).

Motivated by the AGN outflow observed in the [O III] emission line and the BPT location of the red/blue peaks of Model 3, we also compare our emission line ratios to models of shock ionization. We use shock models from Allen et al. [2] with a transverse magnetic field of $b = 1 \mu\text{G}$ and varying velocities ($v = 100\text{-}1000 \text{ km s}^{-1}$) and electron densities ($n = 0.01\text{-}1000 \text{ cm}^{-3}$). We show these models with our emission line ratios overlaid in the bottom panels of Figure 27. The red and blue peaks in Model 3 are consistent with shock models for an electron density of $n \sim 100 \text{ cm}^{-3}$ and shock velocities of $\sim 400\text{-}1000 \text{ km s}^{-1}$. These shock velocities are comparable to the outflow velocity of $\sim 500 \text{ km s}^{-1}$ derived from the broad component of the [O III] emission line (using either Model 2 or 3). We also examined shock

¹¹Following Salehirad et al. [181] and Zakamska & Greene [235], we define the outflow velocity as W_{80} , which is the line width including 80% of the flux. For a gaussian, $W_{80} = 1.09\text{FWHM}$.

+ precursor models and found that the observed line ratios are not consistent with those models.

Finally, we estimate the electron density (n_e) of each peak using the flux ratio of the [S II] doublet. We follow Sanders et al. [183] and compute $n_e = (cR - ab)/(a - R)$, with $R = [\text{S II}]\lambda 6716/[\text{S II}]\lambda 6731$, $a = 0.4315$, $b = 2107$ and $c = 627.1$. We note that n_e saturates at a value of $R \sim 1.45$, however this can still give us a good estimate of the relative electron densities for each peak. The central peak has the lowest value of $R = 1.06$ and, therefore, the highest electron density of $\sim 10^{2.6} \text{ cm}^{-3}$, which is consistent with typical values for the NLR around low-mass BHs [$10^2 - 10^3 \text{ cm}^{-3}$, 125]. The red peak has a slightly higher value of $R = 1.25$ and lower electron density of $10^{2.2}$ (consistent with the shock models described above), while the blue peak has a much lower electron density, saturating the flux ratio with $R = 1.78$. The lower electron densities in the blue/red peaks compared to the central peak is consistent with the scenario presented above in which the central peak is dominated by the AGN, while the blue/red peaks may have star-formation origin. This is qualitatively similar to the results in Zhang [236], who study a sample of Type-1 AGNs, Type-2 AGNs and HII galaxies, and find that the HII galaxies have mean $R \sim 1.4$, while the AGNs tend to have lower ratios ($R \sim 1.13$ for Type-1 and $R \sim 1.21$ for Type-2), and thus higher electron densities.

Physical Interpretation

Here we discuss possible physical interpretations for the triple-peaked emission lines in the dwarf galaxy GAMA 5227891. Multi-peaked emission lines are not unprecedented, however, it can be difficult to distinguish between the various possible physical origins including a rotating gas disk (in the galaxy or NLR), bipolar outflows and multiple AGNs [e.g., 144].

Samples of dual-AGN candidates have been produced by searching for double peaks

(corresponding to distinct kinematics from the two AGNs) in the [O III] $\lambda\lambda$ 4960, 5007 emission lines [54, and references therein]. These lines are typically used since they are expected to be the brightest optical emission lines resulting from AGN photoionization [177]. While we cannot definitively rule out the possibility that our galaxy hosts a system of three AGNs [with each peak in the emission lines corresponding to a separate NLR, e.g., 27, 28], we consider this highly unlikely for a number of reasons. First, even dual AGNs are quite rare, with Shen et al. [199] suggesting that up to 90% of the double-peaked [O III] lines result from jets or disks in the NLR, not two BHs. Moreover, the red/blue peaks of the [O III] line are very dim, if present at all (see §4.4.6).

While three AGNs seem exceedingly unlikely, the emission line ratios clearly indicate the presence of an AGN in the galaxy using the central peaks of the H α , H β , [N II], and [S II] emission lines regardless of the model used for the [O III] line (Figure 27). Given the justified assumption of a single AGN in the galaxy and that the [O III] line profile is dominated by a central peak with a narrow + *broad* component, we also infer the presence of an outflow associated with the central AGN [e.g., 181].

We now turn to possible origins for the red/blue peaks robustly detected in the other emission lines (e.g., H α , H β , [N II], [S II]). The red/blue peaks may be produced by ionized gas that is in some sort of kinematic structure such as a rotating ring or disk. A bipolar outflow is also a possibility, although the red and blue peaks in the aforementioned emission lines have a relatively symmetric appearance and flux ratios consistent with unity (Table 5), favoring a disk scenario [e.g., 204]. The spatial extent of the aforementioned emission lines seen in Figure 26 provide supporting evidence for an extended structure distinct from the nucleus. Given the relatively weak [O III] emission at high velocity and spatial offsets and the associated line ratios, the gas in this structure is likely ionized predominantly by star formation or shocks.

Shocks produced by AGN outflows have been observed to trigger star formation in the

dwarf galaxy Henize 2-10 [193] and we consider such a scenario a possibility here, albeit with some significant differences. There is unambiguous evidence for a central AGN in GAMA 5227891 based on optical line ratios and the robust detection of a broad component in the [O III] emission line is indicative of an outflow from the AGN. While speculative, it is possible that the AGN-driven outflow takes the form of non-collimated ionized winds that are impacting the interstellar medium further out in the galaxy, resulting in a ring/disk structure of shocked gas. While such a scenario is consistent with the observations described above, additional observations are needed to test this hypothesis.

Conclusions

Investigating the behavior of scaling relations in the dwarf regime is crucial in the context of understanding BH/galaxy formation and coevolution. Relating BH mass to galaxy velocity dispersion and stellar mass can provide insight to both the primary seeding mechanism at play in the early universe as well as important growth processes for both the BHs and their host galaxies.

In this work, we present new high-resolution MagE spectra of six galaxies (five dwarfs) previously identified as hosts to AGN [169, 180] in an effort to help populate the low-mass end of BH scaling relations. We fit both the galaxy absorption line spectra and the AGN emission line spectra, allowing us to make velocity dispersion measurements and estimate BH masses based on broad $H\alpha$ emission and standard virial techniques. We place our galaxies on two scaling relations, comparing BH mass to both stellar velocity dispersion and total galaxy stellar mass. We also identify a triple-peaked emission line galaxy hosting an AGN. Our main findings are as follows:

1. We measure velocity dispersions in the range $\sigma \sim 25 - 80 \text{ km s}^{-1}$ for the six galaxies in our sample. Four of the galaxies have detectable broad $H\alpha$ emission with corresponding

BH mass estimates of $M_{\text{BH}} \sim 10^{6.2-7.3} M_{\odot}$.

2. These four objects are consistent with the canonical $M_{\text{BH}} - \sigma_*$ relation at the low-mass end.
3. Our sample exhibits more scatter around the $M_{\text{BH}} - M_*$ relation, but the small sample size prevents us from making any strong conclusions regarding BH seeding models.
4. Our MagE spectrum of one galaxy reveals triple-peaked emission lines in $\text{H}\alpha$, $\text{H}\beta$, $[\text{N II}]$, and $[\text{S II}]$ that were not resolved in GAMA. However, the $[\text{O III}]$ line profile is dominated by a single peak with an additional broad component, likely signifying an AGN outflow. The red/blue peaks detected in the other lines can be attributed to an extended ring/disk primarily ionized by star formation or shocks from the AGN.

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CONCLUSION

Throughout this multi-faceted work, we investigate several aspects of AGNs and dwarf galaxies, motivated by the overarching goal of discovering how massive BHs initially formed. While we cannot draw any seeding-mechanism conclusions, our work 1. adds multiple data points to scaling relations in the low-mass regime and 2. warns against two crucial pitfalls involved with placing dwarf galaxies on scaling relations. The results from this dissertation will guide future observations/work and aid in accurately distinguishing the dominant seeding mechanisms for massive BHs.

In Chapter 2, we test the accuracy of blindly applying canonical scaling relations to all types of galaxies in the Universe. Specifically, we study how local AGNs compare to the canonical $M_{\text{BH}}\text{-}M_{\text{Bulge}}$ scaling relation, which was derived from massive, early-type, elliptical galaxies. When we plot BH masses calculated in Reines & Volonteri [174] against bulge masses extracted using bulge-disk decompositions presented in Simard et al. [201], we find that the sample generally falls below the canonical scaling relation. Similar to many other morphologically-distinct galaxy types (e.g., galaxies with pseudobulges), AGNs seem to evolve uniquely along the BH-bulge mass scaling relation. Through this work, we add to the body of research demonstrating that different types of galaxies seem to follow their own scaling relations and, therefore, emphasize the need to use the relevant scaling relation for the sample being studied. This is important in the context of making accurate simulations and observational predictions, which can depend on scaling relations, as well as when considering BH growth/evolution. Rather than being indicative of a certain seeding mechanism, deviations from canonical scaling relations could have a different underlying cause.

Obvious further work on this project includes performing new bulge-disk decompositions on the full sample of galaxies from Reines & Volonteri [175]. While this likely would not

produce significantly different results, it could provide interesting insight to where higher luminosity AGN host galaxies fall compare to the hosts of lower luminosity AGN, relative to the canonical scaling relations. Another interesting follow-up project for this work would be to check where these galaxies fall on other BH-host galaxy scaling relations, such as the M_{BH} versus σ_* relation. Using high resolution spectra of these galaxies, we could measure σ_* and relate where they lie on the $M_{\text{BH}}-M_{\text{Bulge}}$ relation versus the $M_{\text{BH}}-\sigma_*$ relation. This could provide insight to how AGNs and their host galaxies evolve along scaling relations; AGN-driven suppression of star-formation is expected to manifest in galaxies following the $M_{\text{BH}}-\sigma_*$ relation but lying below the $M_{\text{BH}}-M_*$ [200].

In Chapter 3, we point out one of the hazards related to working with dwarf galaxies. We present a sample of galaxies that were initially selected as AGN hosts using mid-IR color diagnostics. However, these galaxies do not display X-ray signatures of AGNs, as shown in Latimer et al. [119]. Comparing a simple stellar population synthesis model to HST observations of the galaxies reveals that these galaxies are likely host to massive, young NSCs, rather than AGNs. At low galaxy mass, intense star-formation within the galaxy can mimic the signatures of dwarf AGN, at least in the mid-IR. Therefore, AGN samples at low mass may be fraught with, for one example, young, massive NSC interlopers. Identifying clean samples of AGN candidates is crucial for drawing meaningful conclusions about BH seeding; if there are too many non-AGNs contaminating the sample, observed trends will not truly reflect the AGN population.

As always, obtaining higher resolution imaging/spectra for our sample of galaxies could allow us to draw more substantial conclusions. These four galaxies have now been observed with WISE, SDSS, Chandra and HST. However, gathering higher-resolution spectra from the central regions of these galaxies would further constrain the possible emission sources. Data from surveys like the Dark Energy Spectroscopic Instrument (DESI), which has a much smaller spectroscopic fiber than SDSS, would better isolate the emission originating from the

central AGN/NSC and provide more accurate BPT classifications [166]. Observations with the James Webb Space Telescope (JWST) Mid-Infrared Instrument (MIRI) would also reduce galaxy contamination compared to WISE observations, which would allow for more accurate mid-IR emission measurements. MIRI imaging could also better resolve the structure of the central parts of the galaxies in this wavelength regime. Additionally, it could be enlightening to perform the same Chandra/HST follow-up imaging on more objects with similar WISE colors at lower redshift; with a larger sample, statistical trends could be studied. Moreover, if the sample is in the nearby Universe, the inner galaxy structure would be better resolved in HST observations, meaning a central point source (an AGN) could be distinguished from a small, central sérsic component (an NSC) [e.g., 108].

In Chapter 4, we switch gears from catching issues related to scaling relations/dwarf galaxies and, instead, we expand the samples of dwarf galaxies on two different scaling relations. We obtain new MagE spectra of six dwarf AGN candidates, that were only recently discovered in the GAMA survey [180], allowing us to measure their galaxy velocity dispersions and BH masses. We find that our dwarf galaxies generally follow the trends defined by their higher mass counterparts when examining the BH mass versus galaxy stellar mass and galaxy velocity dispersion scaling relations. While we find no compelling evidence leaning towards one seeding mechanism over another, we enlarge the currently small samples of galaxies placed on these relations in the low-mass regime. Furthermore, we point out the potential effects of observational bias at low mass and reiterate that we may be simply observing an upper envelope of relatively high-mass/easily observable BHs residing in dwarf galaxies. Only through further observations/analysis similar to that which we present here will allow us to fully detect the BH-galaxy trends in the dwarf regime.

Additionally, in Chapter 4, we stumbled upon a very unique galaxy spectrum. One of our galaxies displayed obviously triple-peaked emission lines in $H\alpha$, N II, S II and $H\beta$, but not O III. We performed custom analysis on this object by testing different models for fitting

the emission lines, and were ultimately able to extract BH mass and velocity dispersion estimates to be able to place this galaxy on scaling relations. Therefore, through this work, we provide a template fitting process that future observations with similar spectral features could follow. We also present a comprehensive discussion on the physical interpretation of such a spectral shape, concluding that the most likely scenario, based on our emission line fitting, involves both AGN outflows and a ring/disk of star-formation, potentially caused by AGN shocks. If this galaxy truly does have AGN shocks triggering star-formation, it could provide evidence for positive AGN feedback similar to what was observed in the dwarf galaxy Henize 2-10 [193].

The sample studied in this project has ample room for future work. Most obviously, the triple-peaked emission line galaxy could be observed again with higher-resolution spectrograph such as the Gemini High-resolution Optical SpecTrograph (GHOST), with $R \sim 76000$ (compared to MagE with $R \sim 4100$). Additionally, this object would benefit from integral field spectroscopy (IFU) observations [e.g., Sydney-AAO Multi Integral field (SAMI) Galaxy Survey 50]. IFU data would be able to show the spatial distribution of emission within the galaxy, from which we could observe where the emission source is dominated by AGN versus star-formation. Along the same lines, imaging could be taken for this galaxy with telescopes such as HST or JWST to further resolve the galaxy structure and observe if certain areas are particularly bright in certain filters (e.g., the $H\alpha$ filter).

In terms of the rest of the sample, we have demonstrated that our methods of using MagE spectra can both produce galaxy stellar velocity dispersion measurements and virial BH mass estimates for galaxies whose spectra are not completely dominated by the AGN emission; our one object with both absorption-line-measured stellar velocity dispersion and a virial BH mass estimate has the lowest BH mass. Therefore, this method is well-suited for placing low-mass BHs on scaling relations and could be used on a low-mass subset of the remaining 383 AGN candidates found in the GAMA survey in Salehirad et al. [180].

Furthermore, this same methodology could be used on any sample of AGN candidates, such as those identified in Reines et al. [169] from SDSS and in Pucha et al. [166] from DESI. With a larger sample, it is possible that the dominant seeding mechanism(s) would begin to become apparent.

In the broader field of studying BH seeding in the early Universe, JWST has already produced large samples of galaxies/AGNs at extraordinarily high redshifts. Making use of its full repertoire of instruments, in its first year active, JWST identified multiple individual AGNs at redshift $z \geq 5$ [110, 152] including CEERS_1019, which had a record-high redshift ($z=8.679$) and a notably small mass for that redshift ($\sim 10^6 M_\odot$) [118]. This record stood only momentarily until another even further AGN was found; the galaxy GN-z11 sits at a redshift of $z=10.6$ and its central BH is estimated to weigh in at $M_{\text{BH}} \sim 10^6 M_\odot$ [132]. Moreover, larger scale searches have now revealed several samples of AGNs and provided a census of these high-redshift objects across multiple surveys, including JADES, PEARLS, EIGER, FRESCO, ERO and CEERS [88, 99, 136, 234]. Most agree in their results, finding AGN fractions of $\sim 5\text{-}10\%$ and BH masses of $\sim 10^5 - 10^8 M_\odot$. This mass range is in the regime of Direct Collapse Black Holes meaning that, if these truly are AGNs being detected, we are now able to probe down to the predicted masses of some BH seeds [131]. In fact, one work finds that, based on their models, the observable BH population at $z \geq 10$ were likely seeded via direct collapse [215]. JWST is uniquely equipped for finding AGN at high-redshift and has been incredibly successful in this endeavor in its short time observing so far.

Complementary to the multitude of electromagnetic (EM) observation techniques that have been described thus far, BHs have recently been studied using gravitational waves (GW). GWs are ripples in space-time produced when massive, compact objects spiral around each other in the process of merging. In 2015, the Laser Interferometer Gravitational-wave Observatory (LIGO) detected the first gravitational waves originating from a merger event between two BHs. Since then, it has detected many more merger events for BHs between

$\sim 10^1 - 10^2 M_\odot$. In the near future, the Laser Interferometer Space Antenna (LISA) is expected to use these GW methods to observe merging massive BHs in the early Universe. LISA will be sensitive to frequencies between $\sim 10^{-4} - 10^{-1}$ Hz, which is the frequency range expected to be produced by $\sim 10^5 - 10^7 M_\odot$ binaries. Additionally, GWs have the advantage over EM observations that they interact very weakly with matter, meaning that there is not significant distortion of the signal when observing at high redshift. GW observations with LISA will provide a new window into understanding the BH population at high redshift.

Furthermore, recently, a purported massive BH has been found in one of our closest neighboring dwarf galaxies, the Large Magellanic Cloud (LMC). By tracing the trajectories of hypervelocity stars produced when a binary is disrupted by a massive BH, Han et al. [87] find their origin to most likely be a $10^{5.8} M_\odot$ BH in the center of the LMC. If there truly is an inactive BH residing in the center of this galaxy, it could provide a very unique opportunity to study an intermediate-mass BH at unprecedented proximity to us as well as have important implications to the predicted occupation fraction in this mass range.

Overall, the answer to which seeding mechanisms were at play in the early universe remains unclear. Our work chips just a small bit away from this daunting problem, however, significant future research is needed to draw robust conclusions. Populating the low mass regime of scaling relations is extremely important and the development of better telescopes/observational tools will hopefully combat the observational bias currently limiting dwarf samples. However, as these new methods come to fruition, they must remain vigilant in both using appropriate scaling relations and maintaining the integrity of dwarf AGN samples by watching out for contamination sources.

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APPENDICES

APPENDIX A

A BREAKDOWN OF THE BLACK HOLE - BULGE MASS RELATION IN LOCAL
ACTIVE GALAXIES - APPENDIX

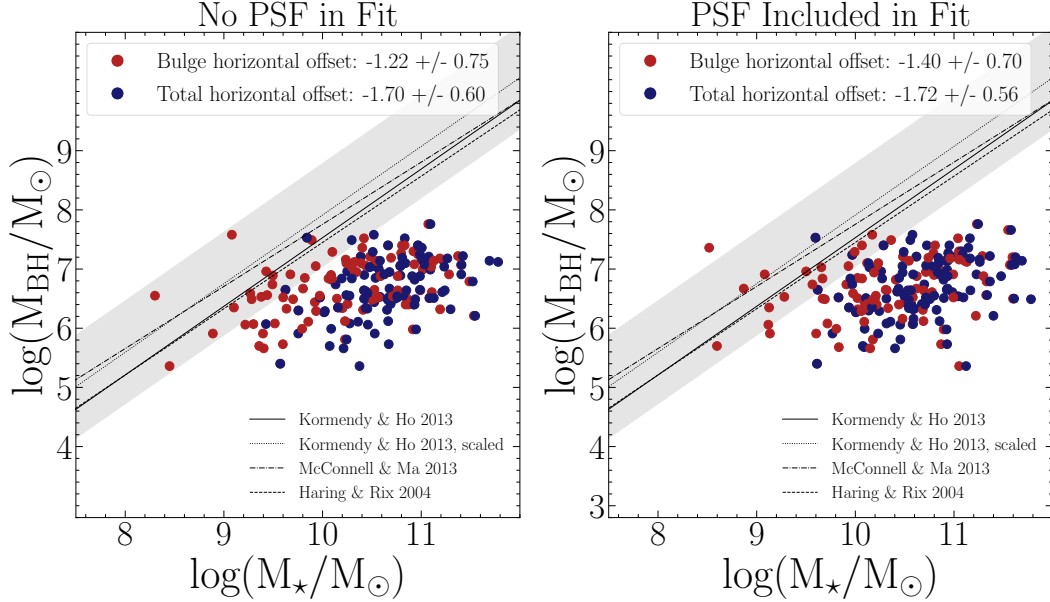


Figure 28 BH mass versus total stellar mass (blue) and stellar bulge mass (red) using decompositions from GALFIT (see §??). The left panel shows results from decompositions done using a two component bulge+disk model, while the right panel shows results from decompositions done using a three component bulge+disk+central point source (PSF) model. Both using a two and three component model results in our sample being offset from the canonical relations. The Kormendy & Ho [113], [95], and McConnell & Ma [137] BH-bulge mass relations are shown, with the shaded region indicating the 3σ intrinsic scatter of the Kormendy & Ho [113] relation as reported in their paper.

We show the BH-bulge mass relation calculated using our GALFIT decompositions in Figure 28. Our sample of low-mass AGNs remains offset from canonical relations even if we use the GALFIT models where we perform three component decompositions using a bulge+disk+central point source, and in fact, the offset is greater than when using the two component decompositions done by Simard et al. [201].

We show an example of the GALFIT decompositions that we performed for one galaxy in Figure 29. We perform these fits using both two and three component models in each band. The resulting galaxy component masses that we find are very similar to those calculated by Simard et al. [201] using two component decompositions.

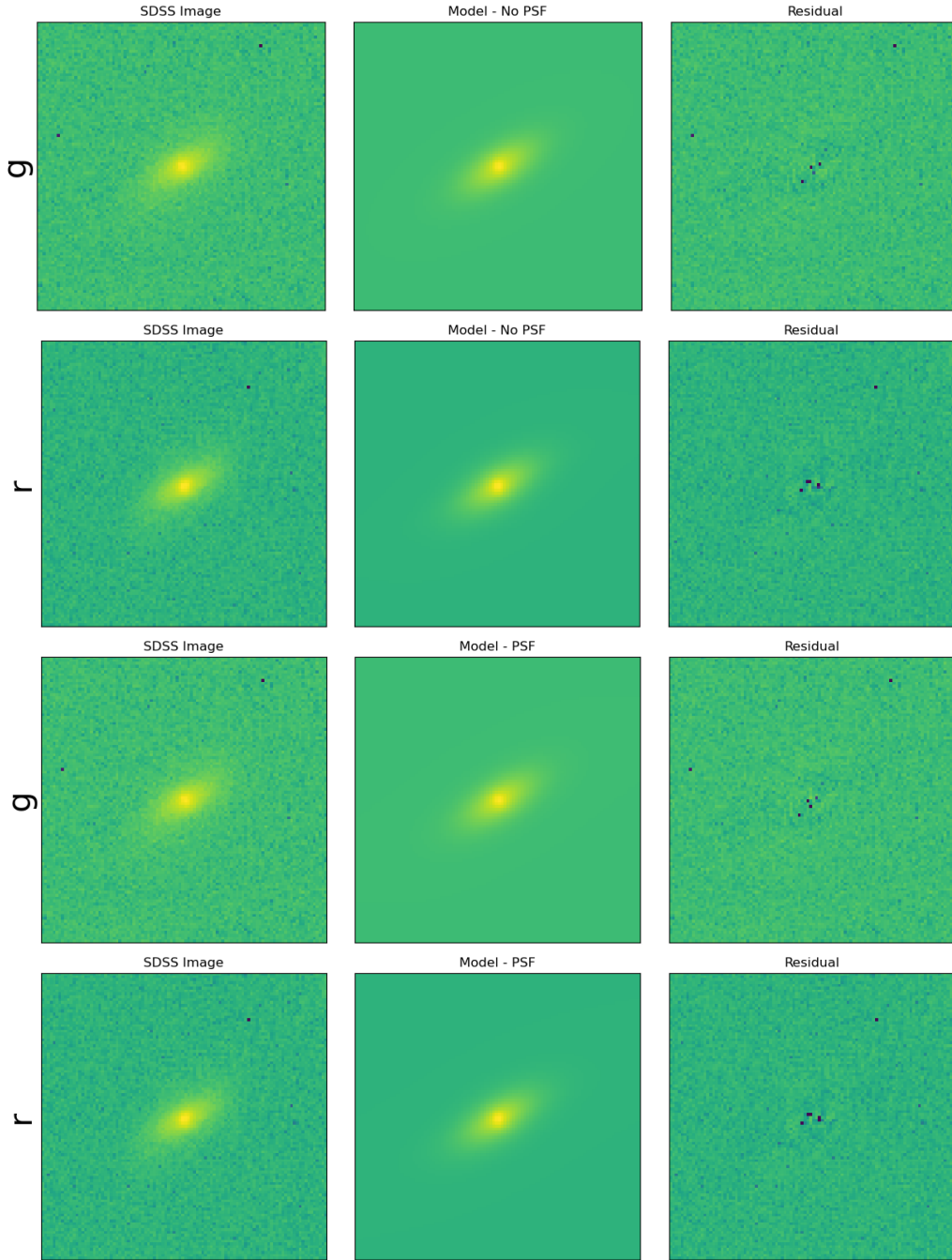


Figure 29 An example of the GALFIT models made for one galaxy (ID 587725469598417019 from Simard et al. [201]). The columns show the SDSS images (left), the GALFIT models (middle) and the resulting residuals (right). The top two rows show fits using a two component (bulge+disk) model in both g- and r-bands and the bottom two rows show fits using a three component (bulge+disk+PSF) model in both g- and r-bands.

APPENDIX B

MAGELLAN SPECTROSCOPY OF AGNS IN DWARF GALAXIES: SCALING
RELATIONS AND A TRIPLE-PEAKED AGN - APPENDIX

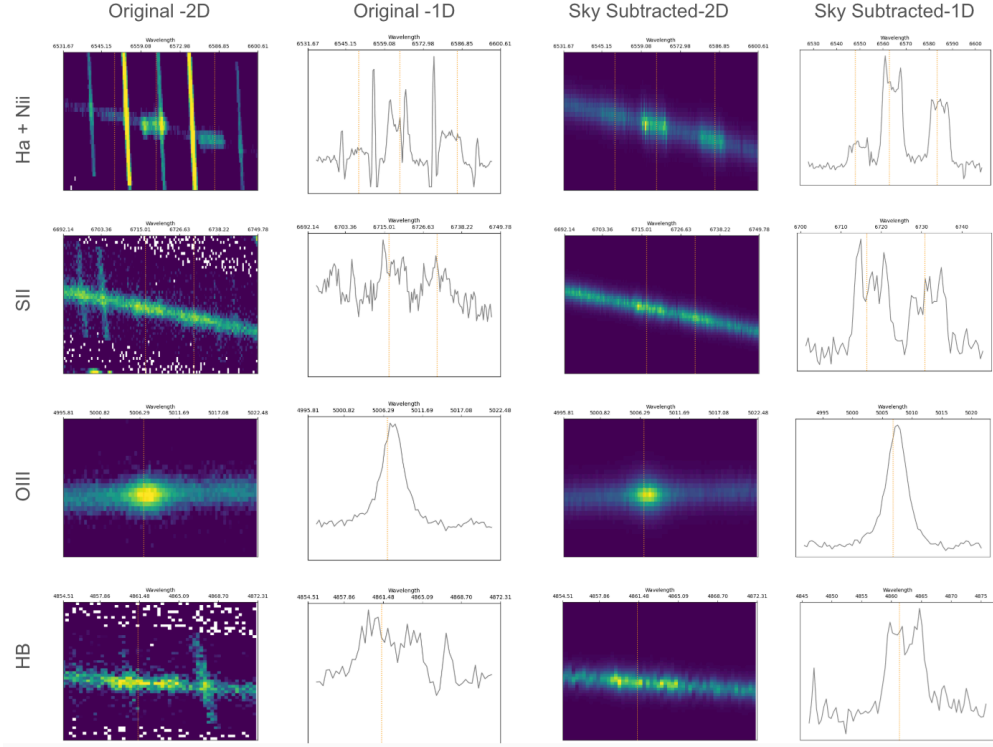


Figure 30 The raw 2-D (first column) and 1-D (second column) spectra and the sky-subtracted 2-D (third column) and 1-D (fourth column) spectra resulting from the reduction pipeline for our triple-peaked galaxy. The triple peaks are visible both in the raw data and in the sky-subtracted images, indicating that the triple peaks are real and not introduced as a result of the reduction process.

We ensure that the emission lines in galaxy ID 5227891 are truly triple-peaked and not just a product of our data reduction by visually examining the 2-D spectra before performing any data reduction. If the sky modeling/subtraction is done incorrectly in the reduction process, it could potentially cause artificial triple peaks in the emission lines. We show both the raw and post-reduction 2-D and 1-D spectra around each emission line in Figure 30. Since the multiple peaks are discernible even before we perform any sky-subtraction, we know that the data reduction pipeline is not the source of the triple-peaks and instead there is a physical origin for this observation.