TRACKING THE GROWTH OF MASSIVE BLACK HOLES IN THE PROGENITORS OF DWARF GALAXIES

1 Motivation

The origin of the intermediate-mass black holes (IMBH, i.e., black holes with $M_{\rm BH} \approx 10^4 - 10^6 M_\odot$) found in local dwarf galaxies ($M_\star \lesssim 10^{10} M_\odot$) has remained a longstanding mystery in astrophysics. Particularly, observational constraints for different formation paths of primordial IMBH seeds are scarce because directly observing these sources at high redshift is extremely challenging, if not impossible, with existing instruments. Therefore, many of the observational efforts to address this question have focused on determining the black-hole occupation fraction in local dwarf galaxies. The mass of IMBH seeds formed via direct collapse of a gas cloud is heavy ($10^4 - 10^5 M_\odot$), but only a fraction of the primordial galaxies would have such massive BH seeds. In this scenario, $\approx 60\%$ of the $M_\star \approx 10^9 M_\odot$ galaxies at $z = 0$ are expected to harbor an IMBH with $M_{\rm BH} > 10^5 M_\odot$, because many local dwarf galaxies may be the fossil records of the high-redshift galaxies that have undergone little or no galaxy mergers (e.g., Volonteri & Madau 2008). The BH occupation fraction for the same $z \approx 0$ dwarf galaxies would be close to unity if IMBH seeds grew via mergers of stellar-mass BHs formed from massive Population III stars (see Greene 2012 for a review). Therefore, the BH occupation fraction in local dwarf galaxies can be used to discern different primordial BH seeding scenarios. The lack of a central IMBH found in several nearby dwarf galaxies (e.g., M33, Gebhardt et al. 2001) has provided an upper limit on the BH occupation fraction. However, directly determining the presence of a central IMBH via gas or stellar dynamics is currently limited to a small number the nearby galaxies due to the angular resolution and sensitivity constraints of current instruments. Many works (e.g., Reines et al. 2013, Schramm et al. 2013, Moran et al. 2014, Miller et al. 2015, Pardo et al. 2016, Chen et al. 2017, Mezcua et al. 2018) have therefore searched for the IMBHs with accretion signatures. There are also various observational limits such as severe host galaxy contamination in optical emission lines (e.g., Reines et al. 2013, Trump et al. 2015) and mid-IR color (e.g., Hainline et al. 2016, Chen et al. 2017), and the challenges in detecting signals from weakly accreting IMBHs (e.g., Miller et al. 2015) Therefore, these measurements can only provide a lower-limit on the BH occupation fraction, and the origin of the IMBHs hosted by local dwarf galaxies remains far from clear.

Average $M_{\rm BH}$ accreted by dwarf galaxies in the past 9 Gyr: Here we propose an alternative approach to study the IMBHs in local dwarf galaxies: Instead of finding AGNs or measuring $M_{\rm BH}$ in individual dwarf galaxies, we will measure the **average BH accretion rates for the progenitors of present-day dwarf galaxies** with $M_\star = 10^{9.5} M_\odot$ (about the mass of the Large Magellanic Cloud) for the past 9 Gyr. With the *Chandra* data from several multiwavelength survey fields such as the CANDELS fields, we can study galaxies at redshift up to $z \approx 2.0$ and still have a *volume-limited* sample of progenitors of local dwarf galaxies down to $M_\star \approx 10^8 M_\odot$, thanks to the ultra-deep *Hubble Space Telescope* coverage ($F160W < 27.5$, e.g., Galametz et al. 2013). The redshift range between $z \approx 2.0$ and the present-day universe accounts for ≈ 9 Gyr of cosmic time. For dwarf galaxies, most of their IMBH growth via accretion is expected to happen during this epoch because of the "AGN-Downsizing" phenomenon (e.g., Fanidakis et al. 2012, Brandt & Alexander et al. 2015), where lower-luminosity AGNs shine later in cosmic history than their more luminous counterparts. *Chandra* observations can detect photons with rest-frame energy > 10 keV for $\approx 80\%$ of the cosmic time since $z \approx 2.0$, therefore most of the obscured accretion activities can still be detected. Therefore, by measuring the average black hole accretion rate (BHAR) for the dwarf-galaxy progenitors throughout this redshift range, we can measure robustly the **average cumulative $M_{\rm BH}$ produced by accretion**. This approach has recently been tested to work well

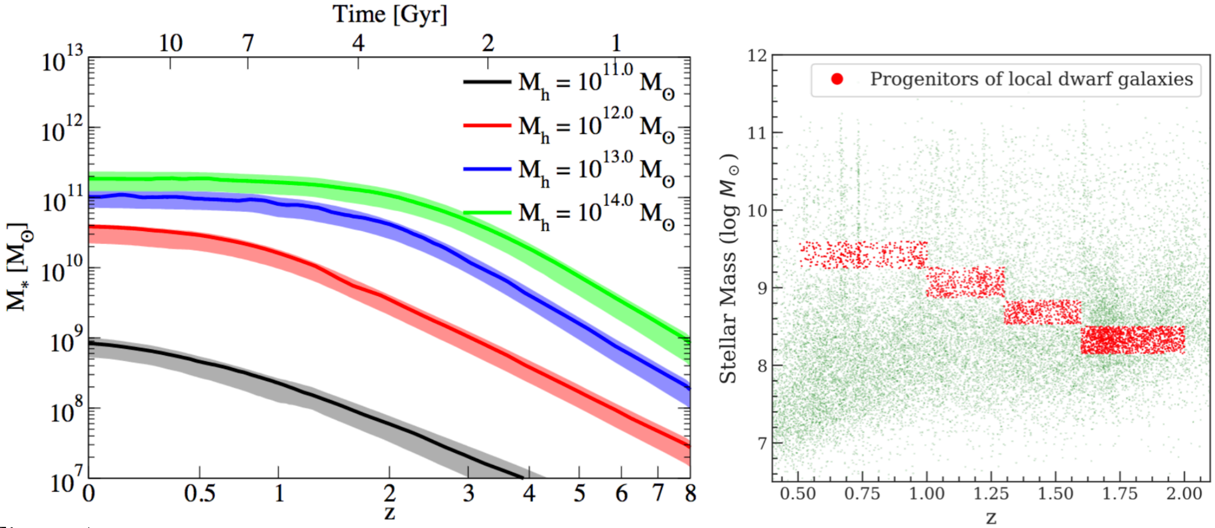

Figure 1: *Left*: The stellar mass histories for galaxies hosted by dark matter halos of different mass, adopted from Fig. 9 of Behroozi et al. (2013). For this proposal, we make use of the stellar mass history for the dark matter halos hosting galaxies with $M_\star = 10^{9.5} M_\odot$ at $z = 0$ (interpolated based on the Behroozi et al. 2013 results, comparable to the black curve shown here). *Right*: The redshift-$M_\star$ distribution of the GOODS-South sample. The full GOODS-South sample from Santini et al. (2015) is displayed as the green dots. The progenitor galaxies selected based on the Behroozi et al. (2013) stellar mass history method are shown as the red dots in four different redshift epochs. We note that the sample size in GOODS-South is limited by its small volume, and we will make use of samples from all CANDELS fields and COSMOS for the proposed work.

for reproducing the $M_{\rm BH} - M_\star$ relation for local massive ($M_\star \approx 10^{11} M_\odot$) galaxies (see Sec. 4.3 of Yang et al. 2018). Through studying the average BH mass accumulated via accretion for the bulk of cosmic history, we will determine whether the majority of dwarf galaxies can harbor IMBHs grown through pure accretion, or if the existence of IMBHs in the local universe requires heavy BH seeds formed via direct collapse of primordial gas clouds. This will shed new light on one of the most fundamental questions in extragalactic astronomy.

2 Specific Science Goals and Proposed Archival Analyses

We propose archival analyses of *Chandra* observations in order to place a useful constraint on the total accreted masses of the IMBHs hosted by dwarf galaxies at lower redshift.

Tracing the dwarf-galaxy progenitors since $z \approx 2$: The key to measuring the cumulative accreted $M_{\rm BH}$ is to select galaxies that are progenitors of local dwarf galaxies at different redshifts. There are a number of different approaches that can identify the progenitors and descendants for a galaxy population. For example, Behroozi et al. (2013) studied galaxy evolution based on structure-formation models for dark-matter halos under the ΛCDM framework. The observed galaxies are then matched to dark matter halos using the halo-abundance-matching method. This approach can quantify stellar-mass growth histories of galaxies of different masses throughout the simulated cosmic history. Therefore the mass of the progenitors and descendants for galaxies of an arbitrary mass can be obtained (see Fig. 1–left). In this approach, the growth of galactic stellar mass is driven by both mergers and in-situ star formation. Another commonly used approach is assuming a constant cumulative comoving number density (e.g., van Dokkum et al. 2010), which can be used to trace the galaxy progenitors when galaxy mergers are properly treated (e.g., Ownsworth et al. 2014). In this method, the progenitors and descendants of a galaxy population can be obtained by simply matching the cumulative comoving number density, which is assumed to be a constant for each unique galaxy population. We plan to adopt these two different schools of progenitor-descendant selection methods and construct samples of progenitors of local dwarf galaxies.

Multiwavelength surveys: In order to study the average BHAR for samples of progenitors of local dwarf galaxies across different redshift ranges, it is critical to have *mass-complete* samples of galaxies. Given the faint nature of dwarf galaxies at high redshifts, very deep optical-to-IR and X-ray observations are essential. For this proposal, we plan to utilize data from the CANDELS

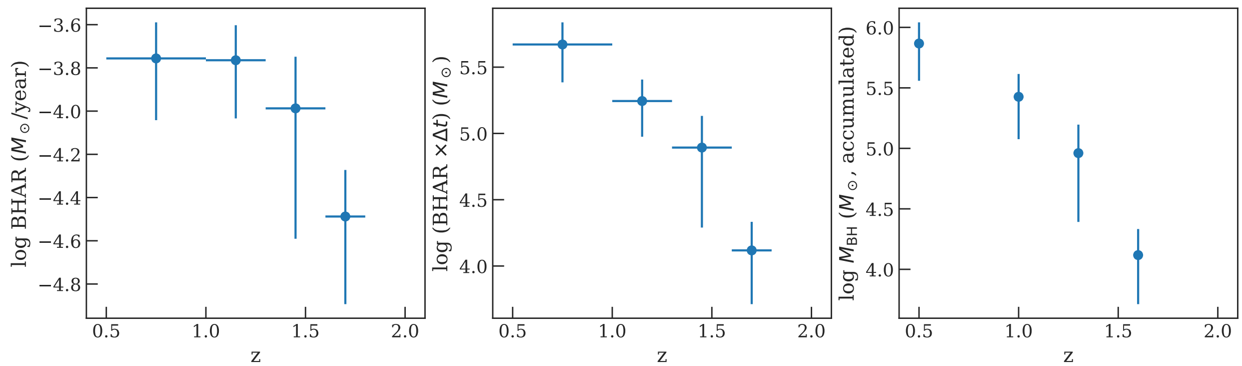

Figure 2: *Left*: The average BHAR for the progenitor galaxies selected from the Santini et al. (2015) GOODS-South sample (the red dots shown in Fig. 1–right), calculated using the X-ray detected sources and X-ray stacking analyses. The horizontal error bars show the redshift bin size. The vertical error bars are obtained via bootstrap Monte Carlo simulations (see Yang et al. 2017 for details). *Middle*: The average black hole mass accreted at each redshift epoch. *Right*: The cumulative $M_{\rm BH}$ in each redshift bin. The results from GOODS-South suggest that the IMBH mass in dwarf galaxies at $z \approx 0.5$ may be dominated by accretion and is not sensitive to the BH seed mass at $z \approx 2$. However, the accuracy of this test sample is limited due to the small sample size, and many systematic errors are not yet taken into account. We propose to expand this analysis to include the other CANDELS fields and COSMOS, and include rigorous error analyses (see Sec. 2).

surveys with ultra-deep *Chandra* coverage, including GOODS-South & North, EGS, and UDS (600 ks–7 Ms, see Nandra et al. 2015, Xue et al. 2016, Luo et al. 2017, and Kocevski et al. in prep.). The multiwavelength data in the selected CANDELS fields will enable us to trace a volume-limited sample of dwarf-galaxy progenitors with $10^{9.25} M_\odot < M_\star < 10^{9.75} M_\odot$ since $z \approx 2$. At lower redshifts (e.g., $z \lesssim 1$) where the selected CANDELS fields (total area = 743 arcmin^2) have limited volume, we will supplement the analysis with the full COSMOS sample, which also has excellent *Chandra* (200 ks, Civano et al. 2016) and optical-to-IR coverage ($H < 24.5$, see Laigle et al. 2016) over a wide (2 deg^2) area. All of the survey regions have deep coverage from ground- and space-based telescopes (with 18–42 bands of photometry) that enable robust $M_\star$ and photometric-redshift measurements. For demonstration purposes, we utilize the Santini et al. (2015) sample of CANDELS galaxies in GOODS-South and select the progenitors of the local dwarf galaxies based on the Behroozi et al. (2013) model. The redshift-$M_\star$ distributions for the full GOODS-South sample and the ≈ 2500 selected progenitors at $0.5 < z < 2.0$ are shown in Fig. 1–right.

Measuring the sample-averaged BH accretion rate with deep *Chandra* observations: We will divide our progenitor samples into several redshift bins and measure the average X-ray flux for each bin. Here we make use of the 7 Ms *Chandra* observations for the GOODS-South progenitor galaxies (Fig. 1–right). For each X-ray detected source in this sample, the X-ray luminosity is calculated based on spectral fitting results (see §2.3 of Yang et al. 2017 for details). In addition to the X-ray detected sources, a critical step in measuring the sample-averaged BHAR is to gauge the average X-ray emission for individual galaxies that are not detected in the X-rays with stacking analyses, because the accretion rate for individual AGNs can vary over several orders of magnitude on time scales of $10^3 - 10^6$ years due to the self-regulating nature of AGN accretion (e.g., Hickox et al. 2014). Therefore, it is important to include the accretion rates for all of the X-ray non-detected galaxies when calculating the sample average (e.g., Chen et al. 2013). We divided the GOODS-South progenitor galaxies into four redshift bins and carried out the stacking analyses for the X-ray non-detected progenitor galaxies in each redshift bin. We convert the stacked X-ray count rates to fluxes following the approach described in Vito et al. (2016) and Yang et al. (2017). We then calculate the average X-ray luminosity for all galaxies in each redshift bin, and derive the BHAR assuming the luminosity-dependent bolometric correction factors from Lusso et al. (2012) and an accretion radiative efficiency of 0.1. In each redshift epoch, we can then quantify the average black hole mass gained. Due to the limited volume of GOODS-South, we only focus on galaxies at $z = 0.5 - 2$ in this test sample of ≈ 2500 galaxies. The average BHAR, $M_{\rm BH}$ gained in each redshift epoch, and the cumulative $M_{\rm BH}$, are shown in Fig. 2.

Interpretation and uncertainty assessments: The preliminary results of our test sample appear to show that, on average, the central black holes in the progenitors of local dwarf galaxies can accumulate most of their mass and grow into an IMBH through accretion only since $z \approx 2$ (Fig. 2–right). This implies heavy BH seeds are not a necessary condition for making IMBHs found in local dwarf galaxies, which appears to contradict previous studies of X-ray AGN fractions in dwarf galaxies that favor heavy BH seeds (Pardo et al. 2016, Mezcua et al. 2018). However, the accuracy of the results shown in Fig. 2 is limited because the average X-ray emission is dominated by a small number of X-ray AGNs. Including data from CDF-N, EGS, UDS will increase sample size by a factor of 4. Including the COSMOS survey will further improve the survey area by a factor of 10. These will immediately mitigate the statistical variance due to the limited sample size, especially for the lower-redshift progenitors. Additionally, the uncertainties for each X-ray detected AGN cannot be properly accounted for with the bootstrap approach we adopted for the test sample. Thus, we will carefully examine the redshift, X-ray spectrum, SED, and bolometric correction for each X-ray detected source to ensure that the result is not skewed due to any systematic errors. The measurements of the cumulative $M_{\rm BH}$ can also be affected by other sources of uncertainty, particularly, the uncertainty due to the progenitor selection methods (e.g., the stellar mass history uncertainties of the Behroozi et al. 2013 method) and the errors in $M_\star$ and photometric redshifts. Moreover, emission from X-ray binaries (XRBs) can be significant for the stacked X-ray signals for galaxies in this mass range (e.g., Yang et al. 2017). For the test sample shown here, we have subtracted the XRB contribution based on the Lehmer et al. (2016) scaling relation between XRB luminosities, $M_\star$, and SFR, but the parameters from the Lehmer et al. (2016) scaling relation can also have systematic errors due to age and metallicity effects in XRB population synthesis models (e.g., Lehmer et al. 2014 , 2016, Lehmer et al., in preparation), and possible residual AGN contamination in the XRB samples (Lehmer et al., 2016). Therefore, the results shown in Fig. 2 are far from conclusive. For the proposed analyses, we will carry out comprehensive Monte Carlo re-samplings for all of the aforementioned uncertainties to obtain realistic errors for our results. We will then make practical comparisons between the average $M_{\rm BH}$ derived based on the *Chandra* observations with those based on theoretical models and semi-analytical simulations (e.g., Somerville et al. 2008, Volonteri & Begelman 2010, Sijacki et al. 2015, Dubois et al. 2016) and shed new light on how IMBHs observed in local dwarf galaxies were formed.

3 Use of Funds Narrative

We request $98,900 of funding to execute this archival project. The main request is for the support of Dr. Chien-Ting Chen, a postdoctoral research associate who will work on this project for 12 months ($48,000 in salary). Under the supervision of Prof W.N. Brandt, Chen will perform the needed work on sample construction, archival X-ray data analysis, uncertainty assessments, physical interpretation, and preparation of a journal article describing the results. We also request funding for one domestic trip of Chen to attend a conference where the results from this work will be formally presented ($1,850). The remaining funds will cover the standard University indirect costs and fringe benefits.

References: • Behroozi et al., 2013, ApJ, 770, 57 • Brandt & Alexander, 2015A&ARv, 23, 1 • Chen et al., 2013, ApJ, 773, 3 • Chen et al., 2017, ApJ, 837, 48 • Civano et al., 2016, ApJ, 819, 62 • Dubois et al., 2016, MNRAS, 463, 3948 • Schramm et al., 2013, ApJ, 773, 150 • Sijacki et al., 2015, MNRAS, 452, 575 • Fanidakis et al., 2012, MNRAS, 419, 2797 • Galametz et al., 2013, ApJS, 206, 10 • Gebhardt et al., 2001, AJ, 122, 2469 • Gilfanov et al., 2004, MNRAS, 351, 1365 • Greene 2012, NatCo., 3E1304 • Hainline et al., 2016, ApJ, 832, 119 • Hickox et al., 2014, ApJ, 782, 9 • Laigle et al., 2016, ApJS, 224, 24 • Lehmer et al., 2014, ApJ, 789, 52 • Lehmer et al., 2016ApJ, 825, 7 • Luo et al., 2017, ApJS, 228, 2 • Lusso et al., 2012, MNRAS, 425, 623 • Mezcua et al., 2018, arXiv:1802.01567 • Miller et al., 2015, ApJ, 799, 98 • Moran et al., 2014, AJ, 148, 136 • Ownsworth et al., 2014, MNRAS, 445, 2198 • Pardo et al., 2016, ApJ, 831, 203 • Reines et al., 2013, ApJ, 775, 116 • Santini et al., 2015, ApJ, 801, 97 • Somerville et al., 2008, MNRAS, 391, 481 • • Trump et al., 2015, ApJ, 811, 26 • van Dokkum et al., 2010, ApJ, 709, 1018 • Vito et al., 2016, MNRAS, 463, 348 • Volonteri & Madau, 2008, ApJ, 687, 57 • Volonteri & Begelman, 2010, MNRAS, 409, 1022 • Xue et al., 2016, ApJS, 224, 15 • Yang et al., 2017ApJ, 842, 72 • Yang et al., 2018MNRAS, 475, 1887