TRACKING THE GROWTH OF MASSIVE BLACK HOLES IN THE PROGENITORS OF DWARF GALAXIES OVER THE PAST 9 GYR

1 Motivation

The chicken-or-egg origin of massive black holes (mBHs) and their host galaxies has remained a longstanding mystery in astrophysics. Particularly, observational constraints for different formation paths of primordial mBHs are scarce because directly observing the first mBHs 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. For mBH formation via direct collapse of a gas cloud at high redshift, the BH seed mass 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 $10^9 M_\odot$ galaxies at $z = 0$ are expected to harbor a mBH with $M_{\rm BH} > 10^5 M_\odot$, because local dwarf galaxies are 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 $z = 0$ dwarf galaxies would be close to unity if mBHs 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 . However, direct measurements of BH occupation fraction are limited to the most nearby galaxies (e.g., the AMUSE survey, see Miller et al. 2015), which can only provide a lower-limit on the BH occupation fraction due to the challenges in detecting weak X-ray emission from individual galaxies with mBHs that are not accreting actively. Many works (e.g., Reines et al. 2010, 2013, Schramm et al. 2013, Moran et al. 2014, Pardo et al. 2016, Chen et al. 2017, Mezcua et al. 2017) have therefore searched for actively accreting intermediate-mass black holes (IMBHs, black holes with $M_{\rm BH} = 10^4 - 10^6 M_\odot$), as the fraction of dwarf galaxies hosting active galactic nuclei (AGN) powered by IMBHs can be regarded as a proxy of the BH occupation fraction. Due to various observational constraints 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), and the limited area of existing surveys, and the bias against obscured sources of < 10 keV X-ray observations (Chen et al. 2017), our understanding of the AGN fraction and BH occupation fraction in local dwarf galaxies remains far from clear.

Average $M_{\rm BH}$ accreted for dwarf galaxies in the past 9 Gyr: Here we propose an alternative approach to study the mBHs 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 progenitor galaxies of present-day dwarf galaxies** with $M_\star = 10^{9.5} M_\odot$ (about the mass of the Large Magellanic Cloud) in different redshift epochs. With the *Chandra* data from several multiwavelength survey fields including the CANDELS fields and the COSMOS survey region, 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, thanks to the ultra-deep *Hubble Space Telescope* coverage as well as the rich optical-to-infrared data from ground-based telescopes. The redshift range between $z \approx 2.0$ to the present day universe accounts for $\approx$ 9 Gyr of cosmic time. For mBHs hosted by dwarf galaxies, most of the BH growth via accretion is expected to happen during this epoch because of the "AGN-Downsizing" phenomena (e.g., Fanidakis et al. 2012), where lower-mass, lower-luminosity mBHs grow later in cosmic history than the their more massive counterparts. Therefore, by measuring the average black hole accretion rate (BHAR) for the dwarf-galaxy progenitors throughout this redshift range, we can measure the **average cumulative $M_{\rm BH}$**. Through studying the average BH mass accumulated via accretion for the bulk of the cosmic history, we will determine whether the majority of dwarf galaxies can harbor IMBHs grown through pure accretion, or if the existence of

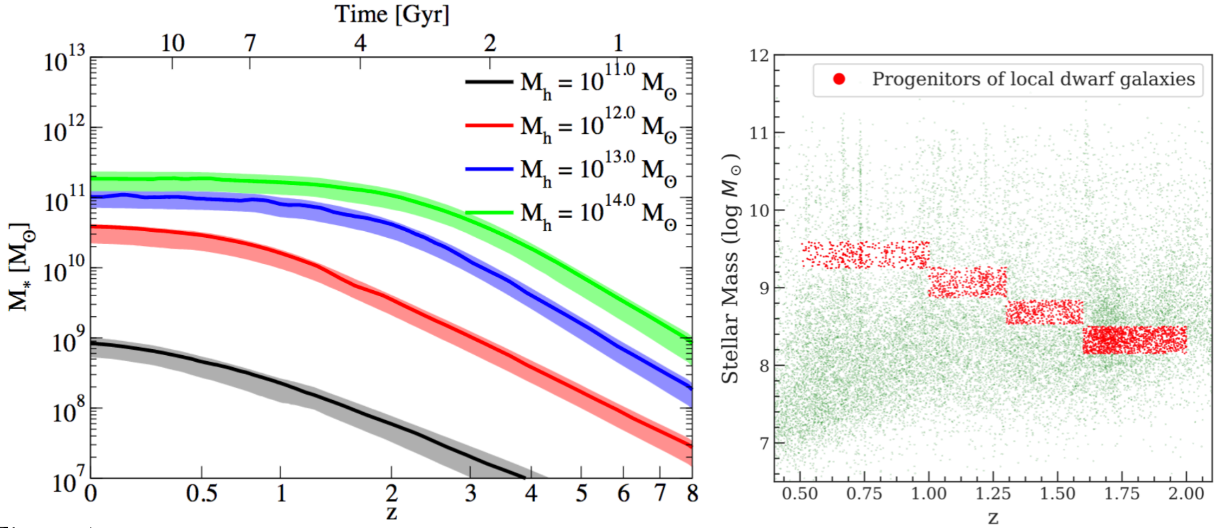

Figure 1: *Left*: The stellar mass histories for galaxies hosted by dark matter halos of different mass, adopted from Fig. 9 of Behroozi et al. (2013). For this proposal, we make use of the stellar mass history for the dark matter halos hosting galaxies with $M_\star = 10^{9.5} M_\odot$ at $z = 0$ (interpolated 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.

IMBHs in the local universe requires massive BH seeds formed via direct collapse of primordial gas clouds. This will shed 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 strong 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 $M_{\rm BH}$ 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 instance, Behroozi et al. (2013) studied the galaxy evolution based on the 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 could be used to reliably tracing the galaxy progenitors when galaxy mergers are take into account (e.g., Ownsworth et al. 2014, Wellons & Torrey 2016) 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. We will also make use of state-of-the-art cosmological simulations such as Illustris simulation project or the Horizon-AGN simulation to identify the dwarf galaxy progenitors using more practical assumptions.

Multiwavelength surveys: In order to study the average BHAR for samples of progenitors of local dwarf galaxies across different redshift ranges, it is important to have *mass-complete* samples of galaxies. Given the faint nature of dwarf galaxies at high redshifts, deep optical-to-IR and X-ray observations are essential. For this proposal, we plan to utilize data from the CANDELS surveys, including GOODS-South & North, EGS, UDS, and the COSMOS survey. All of the survey regions

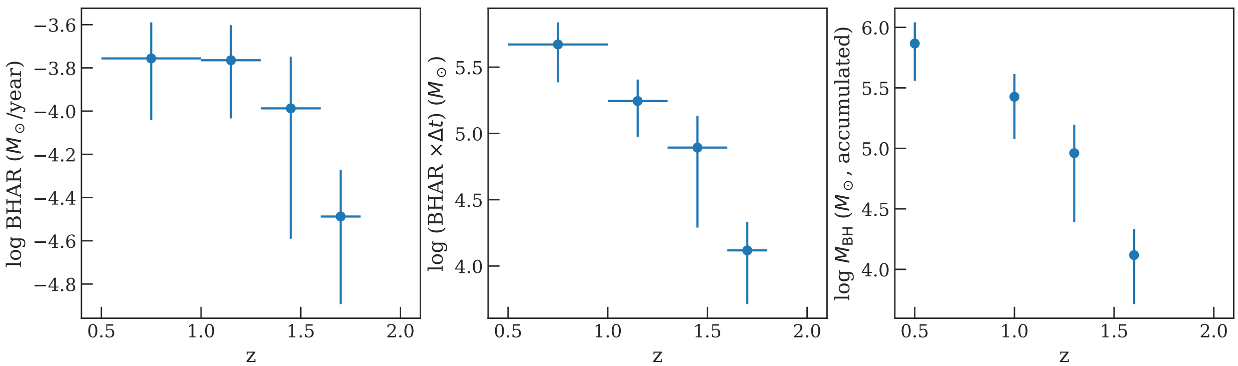

Figure 2: *Left*: The average BHAR for the progenitor galaxies selected from the Santini et al. (2015) GOODS-South sample (the red dots shown in Fig. 1–right), calculated using X-ray stacking analyses. The horizontal error bars show the redshift bin size. The vertical error bars are obtained via bootstrap 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 mBH 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. We propose to expand this analysis to include all of the galaxies from the five CANDELS fields as well as those from COSMOS.

have deep *Chandra* observations (> 200 ks, see Nandra et al. 2015, Civano et al. 2016, Xue et al. 2016, Luo et al. 2017, and Kocevski et al. in prep.) and extensive, deep multiwavelength coverage from ground- and space-based telescopes (with 18–42 bands of photometry) that enable accurate stellar-mass and photometric redshift measurements. For these survey regions, we will focus on mass-complete subsamples with $M_\star > 10^8 M_\odot$ at $z \approx 2$ from the ≈ 900 arcmin^2 CANDELS fields. This will enable us to trace a volume-limited sample of progenitors for local dwarf galaxies 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 pencil-beam CANDELS fields have limited volume, we will supplement the analysis with the full COSMOS sample. For demonstration purpose, 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 epochs and measure the average X-ray flux for each redshift 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 assuming a standard absorbed power-law model (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 BH accretion rate 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 mBHs can vary over several orders of magnitudes in time scales of $10^3 - 10^6$ years due to the self-regulating nature of mBH accretion (e.g., Novak et al. 2011, Hickox et al. 2014, Thacker 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 divide 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 recipe 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 a radiation efficiency 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 $z = 0.5 - 2$. 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 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 with previous studies of X-ray AGN fractions in dwarf galaxies that favor heavy BH seeds (Pardo et al. 2016, Mezcua et al. 2017). 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, and COSMOS can increase the sample size by a factor of 40, which will immediately mitigate the statistical variance due to the limited sample size and can also expand the tractable redshift range. 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, bolometric correction, and potential Eddington bias for each X-ray detected source "" to ensure that the result is not skewed due to systematic errors. The results can also be affected by other sources of uncertainties, 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 the X-ray binary contribution 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 X-ray binary contribution based on the Lehmer et al. (2016) scaling relation between X-ray binary luminosities, $M_\star$, and SFR, but the parameters from the Lehmer et al. (2016) scaling relation also have uncertainties. 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 the realistic errors of 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).

Conclusion: In our proposal, we plan to select a sample of $z \lesssim 2$ progenitors of local dwarf galaxies with $M_\star \approx 10^{9.5} M_\odot$. By measuring the average BH accretion rates for the dwarf-galaxy progenitors separated into different redshift bins using deep *Chandra* observations, we can calculate the total $M_{\rm BH}$ accumulated during the bulk of cosmic history. Since the vast majority of the BH mass growth via accretion happens during this epoch, our result will shed light on whether massive primordial BH seeds formed via direct collapse of gas clouds are necessary to form the IMBHs observed in local dwarf galaxies, therefore making a critical step toward understanding the formation and evolution of massive black holes.

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: (to be completed) • Behroozi et al., 2013, ApJ, 770, 57 • Chen et al., 2013, ApJ, 773, 3 • Chen et al., 2017, ApJ, 837, 48 • Fanidakis et al., 2012, MNRAS, 419, 2797 • Gilfanov et al., 2004, MNRAS, 351, 1365 • Lehmer et al., 2016ApJ, 825, 7 • Mezcua et al., 2018, arXiv:1802.01567 • Miller et al., 2015, ApJ, 799, 98 • Pardo et al., 2016, ApJ, 831, 203 • Santini et al., 2015, ApJ, 801, 97 • Volonteri & Madau, 2008, ApJ, 687, 57 • Volonteri & Begelman, 2010, MNRAS, 409, 1022 • Yang et al., 2017ApJ, 842, 72 • Yang et al., 2018MNRAS, 475, 1887