CAN YOU MAKE AN INTERMEDIATE-MASSIVE BLACK HOLE IN DWARF GALAXIES WITH ACCRETION FOR THE PAST 9 GYRS? [WORKING TITLE]

1 Motivation

Until today, the "chicken-or-egg" origin of massive black holes (mBHs) and their host galaxies has remained a mystery. Particularly, observational constraints for different formation paths of the first mBHs are scarce because directly observing the first black holes at high redshift are extremely challenging with most existing instruments. Therefore, most of the observational efforts to address this question have mainly 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 more massive ($> 10^4 M_\odot$) 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 $M_{\rm BH} > 10^5 M_\odot$. The BH occupation fraction is 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 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). 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 black holes 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 (Trump et al. 2015) and mid-IR color (Hainline et al. 2016), and the limited survey area and 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 remain far from clear.

Average $M_{\rm BH}$ accreted for the past 9 Gyrs: Here we propose an alternative approach to measure the mass of black holes in dwarf galaxies: instead of finding AGNs in individual low-mass galaxies 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** $M_\star = 10^{9.5} M_\odot$ (the mass of the Large Magellanic Cloud) across different redshift epochs. With the *Chandra* data from several multiwavelength survey fields including the CANDELS fields and the COSMOS survey region, we will focus on the redshift range starting at the epoch during which the cosmic SMBH accretion rate density peaks, $z \approx 2.0$, to the low-redshift universe, $z \approx 0.2$. This redshift range spans more than 9 Gyrs of cosmic time, and most of BH growth via accretion is expected happen during this epoch. 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 bulk of dwarf galaxies can harbor IMBHs through pure accretion, or the existence of IMBHs in the local universe require 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.

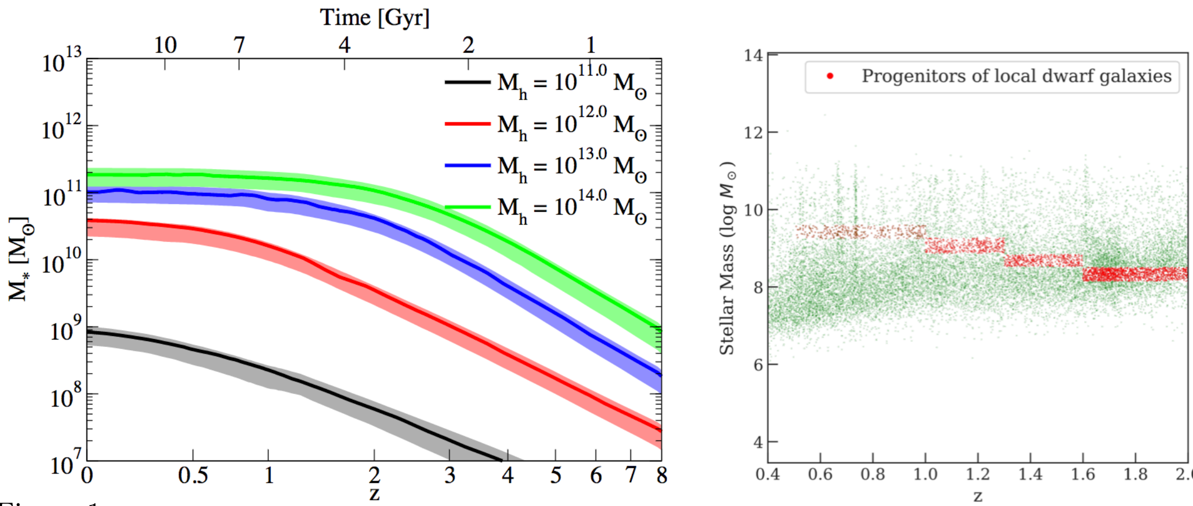

Figure 1: Left: The stellar mass histories for galaxies hosted by dark matter halos of different mass, adopted from Behroozi et al. (2013). For demonstration purposse, we adopt the stellar mass history for galaxies with $M_\star = 10^9.5 M_\odot$ at $z = 0$, and select the progenitors of these local dwarf galaxies from the Santini et al. (2015) CANDELS sample in GOODS-South. 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 at four different redshift epochs are shown as the red dots.

2 Specific Science Goals and Proposed Archival Analyses

We propose archival analyses of *Chandra* observations in order to place a strong constraint on the average mass of the IMBHs hosted by dwarf galaxies at $z \approx 0.2$.

Tracing the dwarf galaxy progenitors at $z \approx 0.2-2$: The key to measuring the cumulative $M_{\rm BH}$ is to select galaxies that are progenitors of local dwarf galaxies at different redshift epochs. There are a number of different approaches that can identify the progenitors and descendants for a galaxy population, such as the assumption of a constant cumulative comoving number density (e.g., van Dokkum et al. 2010, 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. Another approach is based simulations of structure formation models. For instance, Behroozi et al. (2013) studied the dark matter halo 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 easily obtained (see Fig. 1 –left). 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 BH accretion rate for samples of progenitor galaxies 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 have deep *Chandra* observations (GOODS-South: 7 Ms, Luo et al. 2017; GOODS-North: 2 Ms, Xue et al. 2016; EGS: 800 ks, Nandra et al. 2015; UDS: 600 ks, Kocevski et al. in prep.; COSMOS: 200 ks, Civano et al. 2016) and extensive, deep multiwavelength coverage from ground-based telescopes (with 18–42 bands of photometry) that enabled accurate stellar mass 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 ($z \approx 1$) where the pencil-beam CANDELS fields have limited volume, we will supplement the analysis with the full COSMOS sample. For demonstration purpose, we

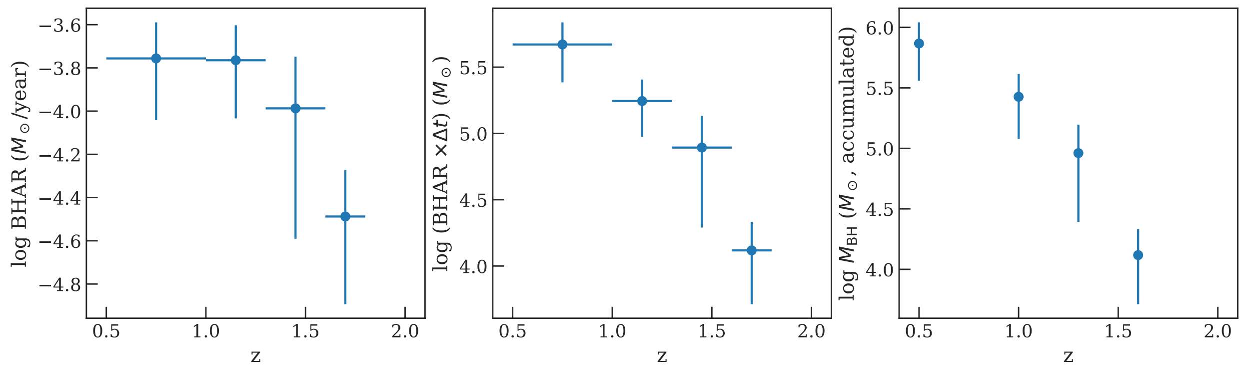

Figure 2: *Left*: The average BHAR for the progenitor galaxies selected from the Santini et al. (2015) GOODS-South sample (the red dots shown in Fig. 1–right), calculated using X-ray stacking analyses. The horizontal error bars shows the redshift bin size. The vertical error bars are obtained via Monte 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 show that present-day dwarf galaxies already harbor an IMBH at $z \approx 0.5$ formed without any significant BH seed at $z \approx 2.0$. However, accuracy of this test sample is limited 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.

utilize the Santini et al. (2015) sample of CANDELS galaxies in GOODS-South and select the progenitor galaxies 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 selected progenitor galaxies at $0.5 < z < 2.0$ are shown in Fig. 1.

Measuring the sample-average BH accretion rate with deep *Chandra* observations: We will divide our progenitor samples into several redshift epochs and adopt an X-ray stacking analysis to obtain the average X-ray flux for each redshift epoch. This is a crucial step because the instantaneous BHAR can vary over several orders of magnitude over the time span of each redshift bin, and the stacking analysis can be used to account for the average X-ray emission originated from galaxies that are not individually X-ray detected (e.g., Chen et al. 2013, Hickox et al. 2014, Yang et al. 2017). We have utilized the deep *Chandra* observations for the GOODS-South progenitor galaxies described in the previous paragraph. We divide the progenitor galaxies into four redshift bins and carried out the stacking analyses for the 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), in which the stacked X-ray photons are assumed to follow a power-law spectrum with an effective photon index of $\Gamma = 1.8$. The X-ray detected sources were excluded from the stacking analyses, and their X-ray luminosities were calculated based on spectral fitting results assuming a standard absorbed power-law model (see §2.3 of Yang et al. 2017 for details). The average BH accretion rate in each bin is then derived based on the AGN bolometric luminosity and a radiation efficiency 0.1. The AGN bolometric luminosity is obtained assuming the luminosity-dependent bolometric correction factors from Lusso et al. (2012). Note that the X-ray luminosity in each bin is dominated by the X-ray detected sources with $L_{\rm X} > 10^{42}$ erg s^{-1}, where the bolometric correction factors are well-constrained. In each redshift epoch, we can then quantify the average black hole mass gained for the stacked galaxies. 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 result of our test sample appears to show that on average, the central black holes in the progenitors of local dwarf galaxies can accumulate most of its mass and grow into an IMBH since $z \approx 2$ (Fig. 2–right). This implies only very light primordial BH seeds are required, which appears to contradict with previous studies of X-ray AGN fractions in dwarf galaxies that favor heavy BH seeds (e.g., Pardo et al. 2016, Mezcua et al. 2017).

However, the accuracy of stacking only the GOODS-South sources is severely limited by the small sample size of X-ray detected AGNs. Large statistical variance and potential Eddington bias could skew the results higher than the true values. Including samples from CDF-N, UDS, and COSMOS will immediately mitigate these problems and expand the redshift range, providing an accurate measurement on the average $M_{\rm BH}$ at $z = 0.2$. As shown in Fig. 2 and previous studies that stacked galaxies with similar $M_\star$ (Yang et al. 2017), the X-ray luminosities for the selected progenitor galaxies are comparable to those originated from the X-ray binary population. 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. For the proposed analyses, we will further assess how the scattering in the Lehmer et al. (2016) relation and the statistical fluctuations of the X-ray emission from the X-ray binaries in individual galaxies (e.g., Gilfanov et al. 2004) affect the cumulative $M_{\rm BH}$ using Markov Chain Monte Carlo (MCMC) simulations. Additionally, we will include the uncertainty in our progenitor selection methods into the MCMC process to obtain the realistic uncertainties of our results (e.g., uncertainties of stellar mass, photometric redshifts, and the stellar mass history models). We will then compare the average BH mass 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 $z \approx 0.2 - 2$ progenitors of local dwarf galaxies with $M_\star$ similar to that of the Large Magellanic Cloud. 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 towards understanding the formation and evolution of massive black holes.

3 Use of Funds Narrative

To be completed

References: (to be completed) • Behroozi et al., 2013ApJ, 770, 57B • Chen et al., 2013ApJ, 773, .3C • Chen et al., 2017ApJ, 837, 48C • Gilfanov et al., 2004MNRAS.351.1365G • Lehmer et al., 2016ApJ, 825, .7L • Mezcua et al., 2018arXiv180201567M • Miller et al., 2015ApJ, 799, 98M • Pardo et al., 2016ApJ, 831..203P • Santini et al., 2015ApJ, 801, 97S • Volonteri & Madau, 2008, ApJ, 687, 57 • Volonteri & Begelman, 2010MNRAS.409.1022V • Yang et al., 2017ApJ, 842, 72Y • Yang et al., 2018MNRAS, 475, 1887Y