1. Overview

In the past two decades, a general framework of galaxy evolution has emerged from the progress in both observational and theoretical cosmologies. In this framework, supermassive black holes (SMBHs) are found to be a crucial piece of the picture as the energy released through accretion onto these SMBHs (manifested as ``active galactic nuclei", or AGNs) plays an important role in regulating the growth of galaxies, therefore shaping the well-established tight relation between the central BH and galaxy bulge properties (see Alexander and Hickox 2012 for a review). However, observational constraints remain inconclusive for many aspects of this galaxy evolution framework, and thus urges new observational programs to explore the processes governing the observable Universe. As a member of some of the world's leading extragalactic survey teams, I have led a number of projects that advanced the field of galaxy and SMBH co-evolution as well as identified essential unanswered questions. Here I summarize my research programs that will tackle these questions with large multiwavelength datasets from hard X-ray to far-IR wavelengths with Chandra, Herschel, NuSTAR, Spitzer, XMM-Newton, and a number of ground-based telescopes. The research programs include (1) probing the SMBH-galaxy co-evolution as a function of large-scale environment and galaxy morphology for the dominant galaxy population since z~2; (2) revealing the nature of AGN obscuration by studying the X-ray properties of different types of galaxies; and (3) unveiling large new populations of AGNs hosted by dwarf galaxies and provide observational constraints on the primordial BH seeding scenarios. I also discuss a range of collaborative projects and consider prospects for the next generation of observatories.

2. The co-evolution between SMBHs and galaxies

Studies based on AGNs selected using their ubiquitous X-ray emission (see Brandt & Alexander 2015 for a review) have revealed many facets of the coevolution between SMBHs and their host galaxies, such as the connection between AGN fraction (above a fixed X-ray luminosity, or L_X) and $M_\star$ (e.g., Xue et al. 2010), the correlation between star formation rate (SFR) and black-hole accretion rate (BHAR) in luminous X-ray AGNs (e.g., Rosario et al. 2012), and the elevated merger fraction of luminous quasars (e.g., Kocevski et al. 2015). Intriguingly, the SMBH-galaxy correlation appears to only exist in the most luminous AGNs despite the fact that the tight BH-bulge relation is found in galaxies of a wide range of $M_\star$. Recently, Chen et al., (2013) and Hickox et al., (2014) identified an observational bias that explains the lack of apparent SMBH-galaxy correlation in typical AGNs. Since SMBH accretion varies on a timescale much shorter than that of galactic star formation, SFR is only correlated to the ***long-term average*** BH accretion rate. The missing link between SFR and the observed, ***instantaneous*** BHAR is simply caused by this AGN variability. Recent studies focusing on sample-averaged black-hole accretion rates (BHAR) found these correlations to exist not only in luminous quasars, but also in more general galaxy populations (e.g., Chen et al. 2013; Hickox et al. 2014; Yang et al. 2017a).

To date, a coherent picture has not emerged on how different physical mechanisms dictate the coevolution of galaxies and SMBHs spanning such wide ranges of luminosity and mass. Some studies have asserted that massive galaxies evolve through gas-rich major mergers during which the common cold gas supply fuels both galaxy star formation and SMBH accretion (e.g., Hopkins et al. 2006; Somerville et al. 2008), while other investigations support the idea that SMBHs in more typical galaxies grow largely via secular processes (e.g., Schawinski et al. 2011; Kocevski et al. 2012). However, the relative importance of major mergers vs. secular processes across a wide range of redshift and galaxy properties ***remain largely unconstrained*** observationally, primarily due to the stochastic nature of

SMBH accretion, which could only be overcome with statistical analysis of large samples of AGNs and galaxies.

At USTC, I plan to capitalize the ***latest deep-wide X-ray surveys*** for making exciting breakthroughs on the studies of galaxy and black hole coevolution. I am a co-PI of a recently awarded XMM-Newton ``Multi-year Heritage Program'' of 3.4 Ms *XMM-Newton* observation time. Combined with the 1.3 Ms XMM-Newton ``Very Large Program'' awarded in 2015, which I have recently finished the data analysis (Chen et al., submitted, a link to the submitted article is available in the reference section), the X-SERVS fields have the ideal depth-area combination at many wavelengths. This will allow us to probe the full-range of cosmic environments (e.g., the largest cosmic structure at z~1 is around ~2 deg^2, which is larger than other existing surveys with sufficient depth to probe the dominant galaxy population, see Fig. 1), and greatly ameliorate the cosmic variance effects, thereby enabling the construction of a more complete picture of galaxy and SMBH evolution.

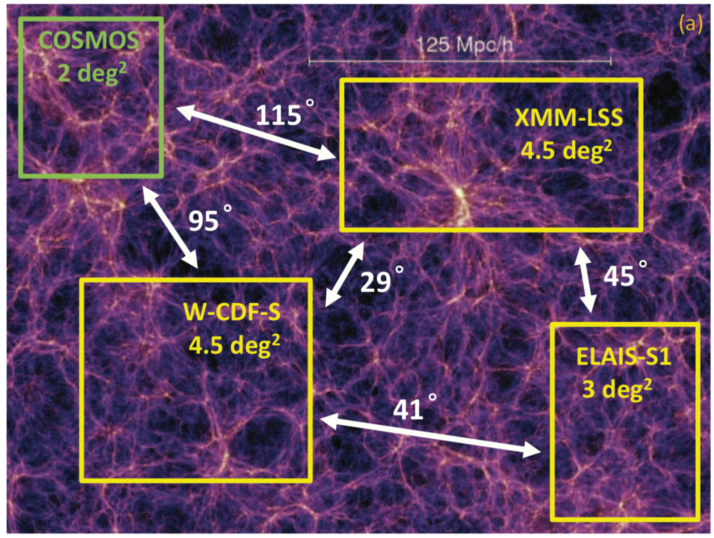

Fig. 1 — Projected density map at z = 1.4 with comoving size 350×450 Mpc2 from the Millennium Simulation (Springel et al. 2005). These regions are widely spaced in the sky as noted by the double-headed arrows with degree separations marked. Multiple distinct fields will overcome cosmic variance and allow reliable studies of environmental effects. The XMM-LSS field is now completed (Chen et al., submitted), and I am leading the 3.4 Ms XMM program that will observe W-CDF-S and ELAIS-S1 in the next 3 years.

Coinciding with DES/LSST deep-drilling fields, these sky regions will also be among the most intensively studied sky regions in the next few decades (e.g., see Table 1 of Chen et al., submitted). I am also a member of the recently awarded Chandra Deep Wide Field Survey (CDWFS, ~6 deg^2 in the Boötes field with similar X-ray survey depth as X-SERVS: XMM-LSS). I plan to combine the data from these survey regions to construct the largest X-ray AGN sample with highly complimentary optical-to-radio data, which will enable studies to accurately constrain the distribution of BHAR in the multidimensional space of galaxy parameters. In addition to measuring the BHAR distributions, I also look forward to engage on building the *conditional X-ray luminosity function* in different environments. Combined with the recent developments in environment-dependent stellar mass function (e.g., Papovich et al. 2018), we will be able to trace the cosmological evolution of the galactic *specific X-ray luminosity function* (e.g., Aird et al. 2018, Yang et al. 2017b) in unprecedented details. I am particularly excited about the prospects of collaborating with the faculty members at USTC on various projects related to extragalactic astrophysics and AGNs using these data.

3. *The nature of obscured AGN and their implications on galaxy evolution*

A popular galaxy evolution framework for massive galaxies is that they evolve through gas-rich major mergers during which large quantities of cold gas efficiently fuels the growth for both the SMBH and galaxy, hence shaping the observed tight relations between the galactic bulges and SMBHs (e.g., Hopkins et al., 2008). An important challenge of studying the dust-enshrouded phase of SMBH and galaxy evolution observationally is the limited X-ray photon counts due to dust absorption. Recently,

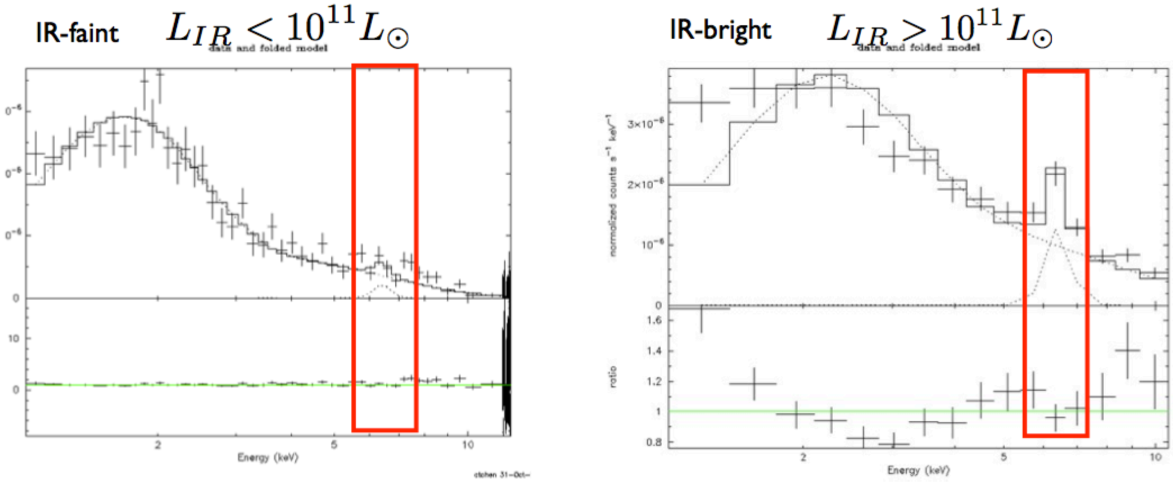

Fig. 2— Stacked rest-frame X-ray spectra for Herschel detected galaxies in Chandra Deep Field South. Far-IR bright galaxies (right) have a stronger 6.4 keV Iron Kα emission line, suggesting a connection between large-scale star-forming dust and the small-scale AGN obscuration (Chen et al., in prep.)

Chen et al. (2015) pointed out that galactic-scale dust that obscures the AGN optical emission is actually closely correlated to star formation, implying that galaxies with active star formation might harbor heavily obscured AGNs. ***The nature of these obscuring material in dust-enshrouded galaxies remains an unresolved puzzle***. For instance, Buchner et al. (2016) use gamma-ray burst to study the distribution of galactic-scale dust and found that the column densities attributed to the host galaxies do not exceed ~10^{23} cm^{-2}. However, cosmic X-ray background suggests that a substantial population of rapidly growing SMBHs should be even more heavily obscured (e.g., Gilli et al. 2007).

Deep X-ray surveys are the most efficient and reliable way of hunting for heavily obscured AGNs in star-forming galaxies due the penetrating power of X-ray photons. Although individual galaxies might not have enough X-ray photons for detailed studies, the average X-ray property for a population of galaxies could still be explored with rest-frame X-ray spectral stacking technique. Intriguingly, the average X-ray spectrum for far-IR luminous AGNs exhibit a strong Iron Kα emission line at 6.4 keV, suggesting a connection between the large-scale far-IR dust and small-scale torus responsible for the reflected Iron Kα emission (Chen et al., in preparation, also see Fig. 2), which is also suggested by NuSTAR observations of NGC 1068 (Bauer et al., 2015). Due to the limited photon counts from the 4Ms CDF-S, the detection of the Iron Kα emission was questionable. I plan to expand the rest-frame X-ray spectral stacking technique using the latest 7 Ms CDF-S dataset and other deep X-ray surveys, which will provide a direct way of studying the relation between large-scale dust and nuclear obscuration. The X-ray spectral stacking tools will also be extremely powerful for studying the average SMBH properties in different types of galaxies, therefore providing crucial insights to the research projects discussed in the previous section.

4. Towards a complete census of low-mass AGNs

Despite the success of the recent development in the general framework of galaxy evolution, the ``chicken-or-egg" origin of black holes and galaxies has remained a mystery, largely because conventional AGN selection criteria are heavily biased against accreting SMBH hosted by low-mass galaxies (Trump et al., 2015, Chen et al., 2017). In addition to searching directly for the first SMBHs, a more trackable approach is to study the properties of the intermediate-mass black holes (IMBHs, 10^4

$M_{sun} \leq M_{BH} \leq 10^6\ M_{sun}$) in the centers of local dwarf galaxies, as this approach provides an important constraint to different BH-seed formation scenarios (e.g., Greene 2012, Reines et al. 2013). Such IMBHs also provide the means to test whether the well-known scaling relation between supermassive black hole mass and hosting bulge velocity dispersion extends to the low-mass regime (see Kormendy & Ho 2013 for a review).

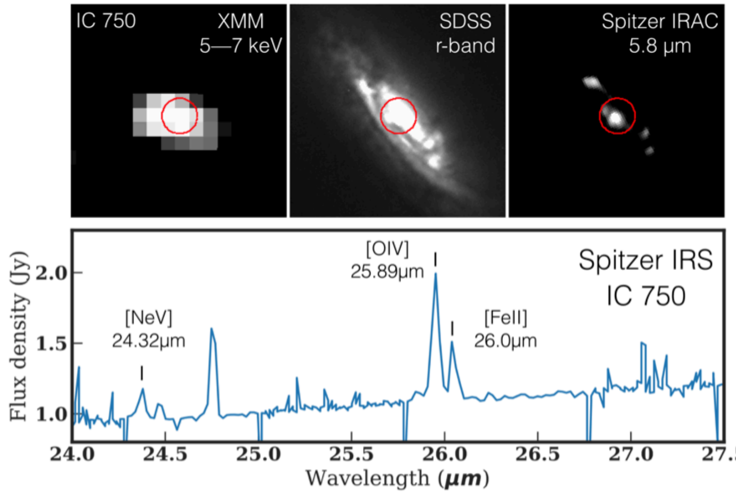

Fig. 3 — Multiwavelength properties of IC750, the Compton-thick AGN candidate identified in Chen et al. (2017). The XMM-Newton 5—7 keV image (top-left panel) demonstrate the presence of a Iron Kα reflection emission, the Spitzer IRAC image (top-right panel) also shows a bright nuclear source powered by hot dust heated by an AGN. The high-ionization lines shown in the Spitzer IRS spectrum in the bottom panel also supports the presence of a heavily obscured AGN.

Much effort has been made to search for IMBH signals using data from large optical sky surveys such as SDSS, leading to discoveries of a few hundreds of low-mass galaxies that show AGN-powered emission lines. However, current searches are often limited by severe star formation (SF) dilution effects as IMBH emission could be easily buried in galaxies with active star formation activities. I have also lead a project using the hard X-ray telescope, NuSTAR, to search for AGN signals in low-mass galaxies. In Chen et al., (2017), I have revealed that there is a substantial (~ 30%) population of AGNs hosted by dwarf galaxies that cannot be detected with current optical spectroscopic surveys. Intriguingly, one of the low-mass AGNs studied in Chen et al. (2017) are found to be a candidate Compton-thick AGN (i.e., the obscuring column densities exceed the limit of the unity optical depth for Compton scattering). These findings naturally lead to an important yet tractable problem — do ***many or even most of the accreting IMBHs remain elusive?***

To answer this key question, I am leading a project utilizing archival Spitzer IRS spectra for low-mass galaxies found in SDSS to systematically search for more obscured low-mass AGNs using the presence of mid-IR high-ionization lines such as [OIV] or [NeV] (Chen et al., in preparation, Fig. 3). I am excited about the scope of this project as a pilot study for future James Webb Telescope surveys, as its revolutionary mid-IR capability will certainly enable detections of obscured AGN signals in many more low-mass galaxies, which will bring us one step closer towards solving the chicken-or-egg problem of BH formation.

5. Current collaborations and future prospects

In addition to the research projects described here, I would also be eager to build new collaborations with researchers in USTC and elsewhere on various topics. Since arriving at PSU in 2015, I have become involved in a number of studies with faculty and students here. The ongoing projects include:

- Spatially Resolving the Fossil Record of Black Hole Seeds with Hobby Eberly Telescope IFU survey of dwarf SF galaxies from SDSS (Joanna Bridge and Jonathan Trump)
- X-ray properties of the most luminous galaxies in the universe (F. Vito et al.)

I am also an active member of several NuSTAR science working groups (obscured AGN, AGN physics, and extragalactic surveys) since 2015, and I have also been actively involved in building new collaborations with scientists outside the NuSTAR working groups. The wide range of projects in which I am currently involved include:

- NuSTAR legacy surveys — deep exposures around sources discovered in Stripe 82X, Boötes, and XMM-LSS (NuSTAR extragalactic WG).
- Connection between AGN X-ray photon index and Eddington ratio (M. Brightman et al.)
- Chandra Deep Wide Field Survey in Boötes (R. Hickox et al.)
- A Joint Study of X-ray and IR Reprocessing in Obscured Swift/BAT AGN (L. Lanz et al.).

Starting the summer of 2016, I have participated in planning the science cases for the proposed LYNX mission, which would launch on a ~20 year time scale and would perform large area X-ray surveys with Chandra-like angular resolution. The detection of tens of millions of X-ray AGNs will revolutionize our understanding of AGN populations. I look forward to using them along with a wide range facilities available at USTC to make further progress in our understanding of black holes and galaxies in the coming decades.

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• Chen et al. (submitted) is available at http://ctjchen.github.io/xservs_lss_submitted.pdf