# Abstract

In the local Universe, it is well established that the mass of supermassive black holes (SMBHs) tightly correlates with several key properties of their host galaxies, such as the bulge mass, bulge luminosity, and stellar velocity dispersion. However, when and how this relationship was established over 13 billion years remains unclear. Understanding the physical origin of BH–galaxy co-evolution is one of the central goals of modern astrophysics. Active galactic nuclei (AGNs), luminous phenomena powered by mass accretion onto SMBHs, are important tracers of this co-evolution process. Yet, observational biases often cause faint AGNs associated with low-mass SMBHs ($< 10^8\ M_\odot$) to be missed. As a result, their growth histories remain poorly constrained. In this thesis, I present the SMBH–host galaxy connection for low-mass SMBHs across cosmic time ($0 < z < 4$) using three complementary data sets from state-of-the-art observational programs: (1) the Hyper Suprime-Cam Subaru Strategic Program (HSC-SSP), (2) the James Webb Space Telescope (JWST) Advanced Deep Extragalactic Survey (JADES), and (3) new spectroscopic observations of $\sim 800$ X-ray sources obtained with the Subaru Prime Focus Spectrograph (PFS).

(1) Most AGNs show the stochastic variability over timescales from hours to years. Optical variability is considered a powerful method for identifying low-mass SMBHs, as broad emission lines not obscured by the dust torus can be observed, and low-luminosity AGNs tend to show large variability amplitudes. These characteristics make optical variability an effective tool for estimating the low masses of SMBHs. Using the large sample of variability-selected AGNs constructed from the deep optical to near-infrared data ($g$, $r$, $i$, and $z$-band) in the HSC-SSP, we combined multi-wavelength spectroscopy and photometry to derive both SMBH masses and total stellar masses. This work enabled the first statistical evaluation of the BH-stellar mass relation for low-mass SMBHs in the distant universe ($0 < z < 4$), and the first observational indication that most low-mass SMBHs tend to show undermassive BH systems which may follow a "galaxy-first" evolutionary path, in which galaxies build up their stellar mass before substantial BH growth.

(2) Directly comparing BH mass and bulge mass over a wide redshift range provides a key clue to understanding how their co-evolution has progressed over the cosmic time. Using the unprecedented high-sensitivity and spatial resolution infrared data from the JWST, we identified 14 AGNs hosting low-mass SMBHs based on the broad H$\alpha$ line and AGN contribution inferred from the spectral energy distribution model. Among them, 9 objects are rare cases of AGNs with ultra low-mass SMBHs of the $< 10^7\ M_\odot$ at $2 < z < 4$. Furthermore, we successfully constrained their bulge masses using two-dimensional image decomposition, revealing systems with low BH-to-bulge mass ratios compared to those of the early-type galaxies in the local universe. This provides the direct evidence that a "galaxy-first" evolutionary sequence in which bulge formation precedes SMBH growth exists even in the distant universe.

Combining these two low-mass SMBH samples, we also investigate the redshift evolution of the BH-stellar/bulge mass ratio. In the low-mass SMBH regime, the BH-stellar/bulge mass ratios

show systematically low values relative to the BH-bulge mass ratio. Furthermore, the resultant negative slope also supports a “galaxy-first” evolutionary pathway for low-mass systems, in which bulge formation precedes the rapid growth of the central black hole.

(3) We also plan to expand low-mass SMBH sample using Subaru Prime Focus Spectrograph (PFS). We have analyzed the first data from our open-use program (S25A-096, PI Hoshi), which observed over 800 X-ray sources in the Extended Groth Strip (EGS), one of the deepest Chandra imaging fields. PFS's wide wavelength coverage (380–1260 nm) and high multiplexing capability (2400 objects) allow simultaneous access to rest-frame optical and near-infrared spectral features, making it particularly powerful for studying low-luminosity AGNs and their host galaxies. PFS will play a crucial role in constraining the BH–bulge mass relation at intermediate redshift and in establishing the systematic evolutionary pathways of SMBHs and galaxies across the cosmic time.