Inferences on Relations between Distant Supermassive Black Holes and Their Hosts Complemented by the Galaxy Fundamental Plane

John D. Silverman\textsuperscript{1,2} , Junyao Li\textsuperscript{1,3} , and Xuheng Ding\textsuperscript{1} \textsuperscript{1} Kavli Institute for the Physics and Mathematics of the Universe, The University of Tokyo, Kashiwa, 277-8583 (Kavli IPMU, WPI), Japan
\textsuperscript{2} Department of Astronomy, School of Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan
\textsuperscript{3} CAS Key Laboratory for Research in Galaxies and Cosmology, Department of Astronomy, University of Science and Technology of China, Hefei 230026, People’s Republic of China

Received 2022 February 25; revised 2022 June 1; accepted 2022 June 5; published 2022 July 12

Abstract

The realization of fundamental relations between supermassive black holes and their host galaxies would have profound implications in astrophysics. To add further context to studies of their coevolution, an investigation is carried out to gain insight as to whether quasars and their hosts at earlier epochs follow the local relation between black hole mass ($M_{\text{BH}}$) and stellar velocity dispersion ($\sigma$). We use 584 Sloan Digital Sky Survey quasars at $0.2 < z < 0.8$ with black hole measurements and properties of their hosts from the Hyper Suprime-Cam Subaru Strategic Program. An inference of $\sigma$ is achieved for each based on the total stellar mass ($M_*$) and size of the host galaxy by using the galaxy mass fundamental plane for inactive galaxies at similar redshifts. In agreement with past studies, quasars occupy elevated positions from the local $M_{\text{BH}} - \sigma$ relation which can be considered as a flattening of the relation. Based on a simulated sample, we demonstrate that an evolving intrinsic $M_{\text{BH}} - \sigma$ relation can match the observations. However, we hypothesize that these changes are simply a consequence of a non-evolving intrinsic relationship between $M_{\text{BH}}$ and $M_*$. Reassuringly, there is evidence of migration onto the local $M_{\text{BH}} - \sigma$ for galaxies that are either massive, quiescent or compact. Thus, the bulges of quasar hosts at high redshift are growing and likely to align onto the mass scaling relation with their black holes at later times.

Unified Astronomy Thesaurus concepts: Quasars (1319); AGN host galaxies (2017); Active galactic nuclei (16)

1. Introduction

Supermassive black holes (SMBHs) are an enigma which surprisingly play an important role in the evolution of galaxies (e.g., Somerville & Davé 2015). Because of our inability to resolve the sphere of influence of practically all SMBHs, we look for clues from their surrounding host galaxies on the physics at work which instil the known relations between the mass of the black hole and the properties of its host galaxy (Kormendy & Ho 2013). In particular, the closest relation is between the mass of the SMBH and the stellar velocity dispersion ($\sigma$), even down to low masses (Greene & Ho 2006; Baldassare et al. 2020), for which the latter is indicative of the mass and concentration of the central potential well (e.g., Ferrarese & Merritt 2000; Gehardt et al. 2000). The functional form of this relation may reveal the coupling between an active galactic nucleus (AGN)-driven outflow and the ISM of their host galaxy (e.g., King 2003).

It is important to recognize that these relations are primarily based on inactive SMBHs. Their host galaxies are no different than any other typical massive galaxies, as shown by their location along the well-established fundamental plane (e.g., Hopkins et al. 2007). As a result, the stellar mass and effective radius can be used together to produce a local mass relation with similar dispersion to that based on the velocity dispersion (van den Bosch 2016). This opens the question as to whether the hosts of all SMBHs, including those in an active phase and in the distant universe, follow the fundamental plane relations (and exhibit similar scaling with black hole mass).

There are many studies trying to understand how galaxies and their SMBHs migrate onto the local mass relation (see Haehnelt et al. 1998; Peng et al. 2006; Volonteri & Natarajan 2009; Agarwal et al. 2013 for early efforts) using AGNs and luminous quasars across cosmic time. Apart from issues pertaining to the measurement of black hole mass, the challenge is to disentangle the host galaxy light from the bright glare of an AGN. This can been achieved with high signal-to-noise spectroscopy or imaging observations coupled with state-of-the-art analysis tools and consideration of observational systematic effects. Ideally, a measure of the velocity dispersion of AGN host galaxies up to high redshift is preferred given its strong correlation with black hole mass in the local universe. However, it is costly to observe $\sigma$ for a large sample of galaxies hosting AGNs (e.g., Woo et al. 2010), particularly those at higher redshift, which are faint. Even so, there have been some successful efforts (Woo et al. 2006; Shen et al. 2015).

To alleviate the need for large spectroscopic observing programs, the detection of the total stellar mass through image detection using wide-area and deep surveys has been successful from space and the ground. To date, there seems to be consensus that the ratio of the black hole mass to total galaxy stellar mass is nearly constant with redshift after considering inherent selection biases (Jahnke et al. 2009; Cisternas et al. 2011; Mullaney et al. 2012; Sun et al. 2015; Ding et al. 2020). Recently, the Hyper Suprime-Cam Subaru Strategic Program (HSC-SSP) reported on the tightest constraints on the (lack of) evolution and its coupling to the intrinsic scatter, which also shows no difference with the local dispersion (Li et al. 2021b). However, there remains the question as to whether the mass of SMBHs is more tightly coupled to the total stellar mass, bulge mass, or velocity dispersion for AGNs beyond the local universe.
High-resolution imaging of quasar hosts not only provides a stellar mass measurement of the host galaxy but also an effective radius, which typically is defined as the value which encompasses half the light. As implemented in this study for the first time, the stellar mass and effective radius are used in conjunction to predict the value of the velocity dispersion under the premise that quasar hosts follow the stellar mass fundamental plane of galaxies at their respective epochs; there is supporting observational evidence for the latter in the local universe based on quasars (Wolf & Shethin 2008) and radio AGNs (Bettoni et al. 2001; Woo et al. 2004; Herbert et al. 2011).

Coupled with the $M_{\text{BH}}-\sigma_*$ relation, one can then construct a relation between the mass of a SMBH and the properties of its host galaxy in terms of stellar mass and effective radius, as done in van den Bosch (2016) for the local universe. This means that imaging alone may be sufficient to assess the black hole mass of a particular galaxy, if this relation holds for a broad range of redshift, type of galaxy, and environment. The question is whether the relation between black hole mass, stellar mass, and host size from van den Bosch (2016) applies to higher redshift galaxies. One would think so, since galaxies irrespective of type still follow the local fundamental plane (e.g., Bezanson et al. 2015). However, the local $M_{\text{BH}}-\sigma_*$ relation must hold as well.

Here, we further examine whether quasars and their host galaxies follow the local mass relations in terms of the stellar mass and effective radius. This study is possible due to the 2D decomposition of uniformly selected quasars and their host galaxies at $0.2<z<0.8$ using the unique combination of depth, area, and high spatial resolution of the HSC-SSP (Li et al. 2021a). Equally important, we construct a large simulated sample of galaxies with quasars to ensure that our results are not due to selection. Published studies of the stellar mass fundamental plane at higher redshifts are employed to gain insight into the form of the $M_{\text{BH}}-\sigma_*$ relation over the redshift range of our sample. These results then aid in the interpretation of direct observations of $\sigma_*$ from the literature. Throughout this paper we use a Hubble constant $H_0=70$ km s$^{-1}$ Mpc$^{-1}$ and cosmological density parameters $\Omega_m=0.3$ and $\Omega_{\Lambda}=0.7$. We assume a Chabrier initial mass function for estimates of stellar mass.

2. Data

2.1. Sloan Digital Sky Survey/Hyper Suprime-Cam Quasars

We use 584 Sloan Digital Sky Survey (SDSS) quasars ($0.2<z<0.8$) selected uniformly from $\sim5000$ ($z<1$; Pâris et al. 2018) with optical imaging from the Second Data Release (PDR2) of the HSC-SSP (Aihara et al. 2019). The black hole masses are available from Rakshit et al. (2020) and based on single-epoch spectroscopy using the virial method (Peterson et al. 2004; Vestergaard & Peterson 2006). Typical uncertainties are $\sim0.4$ dex.

Li et al. (2021a) provides the stellar mass and size of their host galaxies. This is achieved by decomposing the optical images into the quasar and host galaxy contributions with accurate knowledge of the point-spread function. Using lenstronomy (Birrer & Amara 2018; Birrer et al. 2021), the host galaxy is forward modeled with a single Sérsic profile that returns a measure of the half-light radius, axis ratio, Sérsic index, flux, and position. The robustness of the size measurements has been extensively tested using 2D simulations for both model and real galaxies (see Li et al. 2021a, for details). The stellar mass of the host galaxy is then derived using the five-band photometry (griyz) of the host galaxy (free of quasar emission) and CIGALE (Boquien et al. 2019), a tool to fit the spectral energy distribution (SED) of astrophysical objects. Each quasar host is then classified as either star-forming or quiescent based on a rest-frame color–stellar mass diagram. We refer the reader to Li et al. (2021a, 2021b) for full details on the construction of this sample and higher-level data products.

2.2. Simulated Quasar Sample

Following Li et al. (2021b), our analysis requires a simulated sample of quasars and their host galaxies to understand the effect of selection on the observed mass relation. Here, we provide a general overview of the procedure and refer the reader to (Li et al. 2021b, particularly their Figure 3) for further details.

Our Monte Carlo simulation of $5 \times 10^5$ galaxies starts with a sampling in redshift that matches the observed distribution of the SDSS/HSC quasars. The stellar masses cover the same range as the observed sample and are distributed to match the known functional form of the stellar mass function of galaxies (Muzzin et al. 2013), separately for star-forming and quiescent cases. A large simulated sample is needed to ensure sufficient numbers of massive cases. We then randomly assign a size (i.e., half-light radius) using the best-fit relations and their intrinsic dispersion given in Li et al. (2021a) for quasar hosts. As a check, we repeat the analysis using a size distribution based on Sérsic fits to 1.5 million galaxies covering $\sim100$ deg$^2$ of the HSC-SSP (Kawinwanichakij et al. 2021), which have been measured using the same analysis tool as applied to the quasars.

We then consider two separate cases to assign a black hole mass to each galaxy. In the first case, the black hole mass scales linearly with the stellar mass as parameterized by Ding et al. (2020). Our motivation is based on the nearly constant mass ratio seen up to $z \sim 1.8$ (Ding et al. 2020; Li et al. 2021b). We include 0.3 dex scatter based on the intrinsic dispersion in the mass relation as given in Li et al. (2021b). The second case is based on the well-established local $M_{\text{BH}}-\sigma_*$ relation. As further described below, we use the galaxy mass fundamental plane to predict $\sigma_*$ and then insert it into the function form of the $M_{\text{BH}}-\sigma_*$ relation given in Onken et al. (2004). We incorporate observational uncertainties on black hole mass (0.34 dex), galaxy size (0.1 dex), and stellar mass (0.2 dex). A quasar bolometric luminosity is then assigned by assuming that the sample follows the Eddington ratio distribution of broad-line AGNs given in Schulze et al. (2015) as a Schechter function. The sample is restricted to match the magnitude limits of the observations by determining an i-band magnitude for the simulated quasars using a bolometric correction of 12 (Richards et al. 2006) and a k-correction based on a power-law quasar SED with spectral index $\alpha_i=-0.44$ (Vanden Berk et al. 2001). In the end, we have a large sample of simulated galaxies covering the same range of the observational parameter space as the SDSS/HSC quasar sample.

In Figure 1, we demonstrate the impact of selection on the location of quasars in the $M_{\text{BH}}-M_*$ plane by showing the simulated sample before (dashed contours) and after (solid contours) observational selection has been applied. The latter is primarily the result of an imposed limit on the magnitude of the
quasars which depends on the catalog (ugri, BOSS core, eBOSS core). As reported in Li et al. (2021b), the SDSS/HSC quasars (magenta data points) closely follow the local mass relation shown by the slanted black line. The slight offsets to higher black hole masses of the SDSS/HSC quasars are attributed to selection as detailed in the aforementioned work; this is seen by the close agreement of the parameter space spanned by the observed quasar sample and the simulated sample after selection is applied (solid contours).

3. Initial Motivation: The Local Relation

We start with the formulation from van den Bosch (2016) that integrates two well-established relations in the local universe, namely the mass fundamental plane of galaxies and the $M_{\text{BH}} - \sigma_*$ relation, to provide a single equation between SMBH mass, stellar mass and effective radius of their host galaxy. This relation, given in Equation (5) of their study, is based on a linear fit to the local sample of galaxies. If quasars and their hosts at higher redshifts follow the local relations (stellar mass fundamental plane and $M_{\text{BH}} - \sigma_*$), the van den Bosch (2016) relation would be universal and thus enable an independent assessment of the black hole mass for galaxies at any redshift with knowledge of their stellar mass and size. We note that van den Bosch (2016) use the major axis of the isophote for the size that contains half of the light, thus equivalent to the sizes from our Sérsic fits.

We test whether the van den Bosch (2016) relation is applicable for SMBHs at higher redshifts by using our SDSS/HSC quasars that have measurements of black hole mass (from single-epoch spectra), stellar masses and effective radii with the latter two based on the 2D decomposition of HSC imaging (Li et al. 2021a). In Figure 2, we plot the virial (observed) black hole mass as a function of the expected black hole mass from the van den Bosch (2016) relation. The SDSS/HSC quasars are indicated by magenta circles. For reference, the slanted black line is the one-to-one relation and the other data points are galaxies used to establish the local relations which are further colored by their classification in Kormendy & Ho (2013) as ellipticals or classical bulges in red and spirals in blue.

As easily seen, the SDSS/HSC quasars are significantly offset with black hole masses higher than the expected values based on the local fundamental relations. The offset is progressively larger with decreasing expected black hole mass (abscissa). The discrepancies between the high-redshift quasars and the local inactive samples likely indicate that the host galaxies of quasars are either not close to being virialized systems, the local $M_{\text{BH}} - \sigma_*$ relation is not universal (i.e., fixed at redshifts), or some combination of the two. Before we proceed in exploring the consequences of this possible breakdown in our understanding of the relation between black holes and their host galaxies, we need to evaluate such connections at the equivalent epochs and check for systematic effects due to sample selection, which are well known to exist in quasar samples.

4. Predicting $\sigma_*$ for Quasar Hosts Using the Fundamental Plane of Galaxies

We implement a proxy for $\sigma_*$ to gain an insight into the relations between SMBHs and their host galaxies at higher redshifts. The stellar mass fundamental plane (hereafter FP; Equation (1)) of galaxies is used to infer the likely value for $\sigma_*$ based on measurements of the stellar mass and effective radius of the host galaxy where $\Sigma_e \equiv M_*/2\pi R_e^2$:

$$\log R_e = \alpha \times \log \sigma_* + \beta \times \log \Sigma_e + \gamma. \quad (1)$$

At comparable redshifts to our quasar sample, recent studies find little change in the tilt ($\alpha$, $\beta$) and evolution of the zero-point ($\gamma$) of the stellar mass FP (Bezanson et al. 2015; Zahid et al. 2016). We employ the fixed shape and zero-point of the FP from Hyde & Bernardi (2009; $\alpha = 1.629$, $\beta = -0.84$, $\gamma = 4.424$) with an additional offset in the zero-point of 0.042
as given in Zahid et al. (2016) based on a sample of quiescent galaxies at $z < 0.6$ from the hCOSMOS survey (Damjanov et al. 2018). This characterization of the mass FP is consistent with galaxies at $z \sim 0.8$ from LEGA-C (Bezanson et al. 2015; de Graaff et al. 2021), irrespective of being quiescent or star-forming. This is a key point since the majority of the host galaxies of SDSS/HSC quasars are forming stars. We refrain from including addition scatter since the dispersion is low (0.1 dex) in log $\sigma_p$ at $z \sim 0.7$ (Bezanson et al. 2015). Equation (2) gives the parameterization of the expected value of $\sigma_p$ for quasar hosts that follow the FP:

$$\log \sigma_p^p = 0.516 \times \log M_* - 0.417 \times \log R_e^p - 3.153. \tag{2}$$

The superscript “$p$” is meant to indicate that this quantity is a “predicted” value rather than being directly measured. We employ this notation throughout. The half-light radius is given with a superscript “$e$” to indicate that the size here is a circularized quantity. For our SDSS/HSC quasar sample, we convert the sizes appropriately ($R_e^c = R_e \times \sqrt{1 - e}$), where epsilon is the ellipticity. The sizes have been scaled to the rest-frame at 6030 Å using the relation given in van der Wel et al. (2014), which accounts for color gradients dependent on redshift and mass.

This formulation of $\sigma_p$ is also used to derive an expected black hole mass for the simulated sample (Section 5.1) while assuming the local relation $M_{BH} - \sigma_p$ as parametrized in Onken et al. (2004) and provided here in units of $M_\odot$:

$$\log M_{BH} = 4.58 \times (\log \sigma_p^p - 2.30) + 8.22. \tag{3}$$

5. Results: a High-$z$ Assessment of the $M - \sigma$ Relation

In Figure 3, we plot black hole mass ($M_{BH}$) as a function of the predicted stellar velocity dispersion ($\log \sigma_p^p$) for our quasar sample. For reference, the best-fit local $M_{BH} - \sigma_*$ relation (Equation (3)) is indicated by the solid black line. Equivalent to results shown in Section 3, the majority of the quasars have elevated black hole masses from the local relation at their respective velocity dispersion. These offsets are larger at lower values of $\sigma_*^p$. The increase in the scatter, as compared to that of the local $M - \sigma_*$ relation, is due to measurement uncertainties on black hole mass, stellar mass, and size plus the intrinsic dispersion in the galaxy mass fundamental plane.

To lend support to these results, we compare the location of the SDSS/HSC quasars, in the same figure, to a sample of 88 quasars at $0.1 < z < 1$ having direct measurements of $\sigma_*$ from high signal-to-noise spectra, which are acquired through the SDSS Reverberation Mapping Project (Shen et al. 2015). In addition, Woo et al. (2006, 2008) provide measurements at $z \sim 0.36$ and 0.56 for 20 Seyfert 1 galaxies using Keck. Reassuringly, the SDSS/HSC quasars and the samples with direct $\sigma_*$ measurements share the same parameter space, and thus the offsets in the $\log M_{BH} - \log \sigma_p^p$ plane are likely accurate.

A correlation between $M_{BH}$ and $\sigma_p^p$ is seen for the SDSS/HSC quasar sample (Figure 3; magenta dashed line) which is considerably flatter than the local relation (Onken et al. 2004). This is in general agreement with the best-fit observed relation from Shen et al. (2015). The difference in slope is likely due to measurement uncertainties and sample selection. To further interpret these results, we use simulated quasar samples under different assumptions on the relation of black hole mass to galaxy properties (i.e., $M_*$ and $R_e$) in the next section.

5.1. Comparison to Simulated Samples

We demonstrate the impact of selection on the location of quasars in the $M_{BH} - \sigma_*$ plane by showing simulated samples (as described in Section 2.2) before and after observational selection has been applied. In Figures 3 and 4(a), we display the simulated sample with black hole mass assumed to be a function of only the stellar mass and follow the local $M_{BH} - M_*$ relation, which has been shown to agree with our SDSS/HSC quasar sample (Li et al. 2021b). The simulated sample is shown by contours with (solid) and without (dashed) observational selection being applied. First, we find very good agreement between the location of the observed SDSS/HSC quasars, as indicated by the magenta circles, within the solid contours, which depict the simulation with selection applied. Both the offsets toward lower values of $\sigma_p^p$ relative to the local relation and the dispersion of the data are similar.

For comparison, we show in Figure 4(b) the parameter space for a different simulation where black hole mass is assumed to be a function of $\sigma_p^p$ that follows the local relation (Equation (3)). The two sets of contours reflect the application of observational selection as done in panel (a). In this case, there is a clear mismatch between the observed and simulated sample since the locus of the data points is off-centered with the solid contours. Therefore, the SDSS/HSC quasars and their hosts do not follow the local relation with the observed offsets primarily due to selection effects.

5.2. An Evolving $M_{BH} - \sigma_*$ Relation

The offsets from the local relation can be interpreted as a flattening of the $M_{BH} - \sigma_*$ relation at higher redshift. As shown in Figure 3, the simulated sample with selection applied matches the observed data when assuming a fixed black hole--
mass relation for inactive galaxies from Kawinwanichakij et al. (2021)

Even so, as an exercise, we explore whether there exists a redshift-dependent model between black hole mass and $\sigma_p^*$ which can reproduce the observed parameter space of our SDSS/HSC quasar sample. We use the following relation to make a prediction on the black hole mass at a given velocity dispersion for our simulated sample:

$$\log M_{\text{BH}} = 4.58 \times (1 + z)^\alpha$$

$$\times \log \sigma_p^* - 2.31 + \beta \times \log(1 + z).$$

We find that $\alpha = -1.4$ and $\beta = 25$ bring the simulations into broad agreement with the data (Figure 5). This model has a slope of the $M_{\text{BH}}-\sigma_p^*$ relation that flattens with increasing redshift and rises in normalization. Thus SMBHs are further offset above the local relation with decreasing $\sigma_p^*$ and increasing redshift.

To conclude, we highlight that the offsets in the $M_{\text{BH}}-\sigma_p^*$ relation at high-$z$ may simply be a manifestation of having a constant ratio $M_{\text{BH}}/M_*$ with redshift. As shown in Figures 3 and 4(a), the simulated sample, prior to selection effects being applied, is in-itself offset and significantly flatter than the local $M_{\text{BH}}-\sigma_p^*$ relation. Indeed, Li et al. (2021b) find that a nonevolving $M_{\text{BH}}-M_*$ relation best describes the SDSS/HSC sample. This brings into question whether the black hole mass is more closely connected with the velocity dispersion or total stellar mass.

5.3. Migration Onto the Local Relation

As seen in the previous figures, there is a subset of the SDSS/HSC quasars that do overlap with the local $M_{\text{BH}}-\sigma_p^*$ relation. We further investigate whether there may be a trend that aligns quasars with the local relation for host galaxies of a specific property. For this exercise, we measure the difference, in log, between the observed black hole measurements and the values expected based on the predicted values of $\sigma_p^*$ (Equation (2)) and the local $M_{\text{BH}}-\sigma_p^*$ relation (Equation (3)). We further split the observed sample into those with hosts classified as either star-forming or quiescent as reported in Li et al. (2021a). We note that, for our purposes, the offset in the mass FP of $\sim 0.02$ dex between star-forming and quiescent galaxies (Bezanson et al. 2015; de Graaff et al. 2021) is inconsequential and thus not applied.

In Figure 6, we plot this difference in black hole mass ($\Delta \log M_{\text{BH}}$) as a function of $\sigma_p^*$. Considering the full sample, the galaxies with higher predicted velocity dispersions have black hole masses closer to those expected based on the local scaling relations. There is a progressive departure in black hole mass with decreasing $\sigma_p^*$. Furthermore, the quasars with quiescent hosts have black hole masses in closer agreement than the star-forming galaxies, as indicated by their mean mass offset, given in the caption and labeled by the colored horizontal lines. A similar conclusion is reached for those that have the highest mass surface density (i.e., compactness; not shown).

6. Concluding Remarks

There is now mounting observational evidence (after considering selection effects and measurement errors) for a nonevolving relation between the mass of SMBHs and the total stellar mass of their host galaxies up to $z \sim 2$ (Jahnke et al. 2009; Cisternas et al. 2011; Sun et al. 2015; Ding et al. 2020;
Li et al. 2021a). It naturally follows that SMBHs at higher redshifts have, on average, higher masses relative to the bulges of their host galaxies (Ding et al. 2020). This is due to the fact that the fraction of stellar mass in a bulge component increases with cosmic time for the overall galaxy population (Bruce et al. 2014). In accordance with this scenario, the most massive SMBHs in the local universe reside in bulge-dominated galaxies (i.e., the ellipticals) while those in the distant universe are primarily hosted by galaxies with prominent stellar disks (e.g., Schawinski et al. 2012).

Here, our aim is to further illustrate the evolution between SMBHs and their hosts by using the stellar mass and size information to infer the stellar velocity dispersion for quasars at redshifts well beyond those that establish the local mass relations. The stellar velocity dispersion is recognized in the local universe as having the tightest relation to black hole mass (Kormendy & Ho 2013). Therefore, it is imperative to make comparisons between black hole mass and velocity dispersion in quasars and AGNs at higher redshifts. While there are studies that directly measure the stellar velocity dispersion (Woo et al. 2006, 2008; Shen et al. 2015), the sample sizes do not yet reach those comparable with wide and deep imaging surveys which cover larger samples of AGNs and quasars.

We extend our studies of a well-constructed sample of 584 SDSS quasars at $0.2 < z < 0.8$ (Li et al. 2021a, 2021b) with optical imaging from the HSC-SSP. A decomposition of the optical emission yields a measure of the host stellar mass and size (i.e., half-light radius). The stellar velocity dispersion is then inferred based on these two quantities and a premise that quasar hosts follow the galaxy mass fundamental plane. To interpret our results, we use a simulated sample of SMBHs and their hosts as constructed by Li et al. (2021b). Based on our analysis, we report the following:

1. The distribution of $M_{BH}$ and $\sigma_p$ is inconsistent with the local relation since there are significant positive offsets that increase with decreasing $\sigma_p$.
2. The parameter space of $M_{BH}$ and $\sigma_p$ covered by our sample agrees with an independent assessment based on direct measurements of $\sigma_p$ (Woo et al. 2006, 2008; Shen et al. 2015) using smaller samples.
3. Relying on the validity of our simulated sample, we find that the $M_{BH}-\sigma_p$ relation is intrinsically flatter than the
local relation. This is counter to the interpretation given in Shen et al. (2015).

4. While an evolutionary model of the \( M_{BH} - \sigma_* \) relation can match the observations with a significant flattening and increase in the normalization with redshift, we put forward an hypothesis that these changes in the \( M_{BH} - \sigma_* \) relation can be naturally produced by a situation where the ratio \( M_{BH}/M_* \) is constant up to \( z \sim 1 \), and possibly out to \( z \sim 2 \) (Cisternas et al. 2011; Ding et al. 2020). Therefore, a relation between black hole mass and total stellar mass may be the more fundamental link between galaxies and their black holes.

5. We find evidence for the migration of quasar hosts onto the local relation. The most massive galaxies and those which had their star formation quenched are more closely aligned with the local \( M_{BH}-\sigma_* \) relation.

Taken together, these results support a scenario in which quasar hosts are in the process of building their central mass concentration (while continuing to grow their black hole; Silverman et al. 2019; Li et al. 2021a). With substantial stellar mass in the disk component of their hosts, a process is required to redistribute the stars that already exist in the disk to the bulge. Also, a nonnegligible fraction of the bulge mass is likely built up in situ, as evident by recent Atacama Large Millimeter/submillimeter Array detections of centrally concentrated star formation in high-z galaxies and AGNs (e.g., Puglisi et al. 2019; Gómez-Guijarro et al. 2022). A picture is emerging in which the bulge needs to be further assembled for galaxies and their SMBHs to align with the local relation. It now appears that AGN feedback is required to maintain a constant scatter in the mass relations (Li et al. 2021b) which agrees with simulations (Ding et al. 2022).

We provide final words of caution that the intrinsic dispersion in the relations discussed herein, measurement uncertainties, and scatter in the galaxy mass fundamental plane likely restrict predictions of black hole mass based on the properties of individual host galaxies. The degree to which predictions of black hole mass for an ensemble can be improved by utilizing the structural properties of their hosts is reserved for a future study.

We thank the anonymous referee for the constructive comments and Ivana Damjanov, Rachel Beznanos, Tommaso Treu and Hassen Yesuf for helpful discussions. J.S. is supported by JSPS KAKENHI (grant Nos. JP18H01251 and JP22H01262) and the World Premier International Research Center Initiative (WPI), MEXT, Japan. X.D. is supported by JSPS KAKENHI grant No. JP22K14071.

ORCID iDs

John D. Silverman @ https://orcid.org/0000-0002-0000-6977
Junyao Li @ https://orcid.org/0000-0002-1605-915X
Xuheng Ding @ https://orcid.org/0000-0001-8917-2148

References

Aihara, H., AlSayyad, Y., Ando, M., et al. 2019, PASJ, 71, 114
Agarwal, B., Davis, Andrew J., Khochar, S., Natarajan, P., & Dunlop, J. S. 2013, MNRAS, 432, 3438
Baldassare, V. F., Dickey, C., Geha, M., & Reines, A. E. 2020, ApJL, 898, L3
Bettoni, D., Falomo, R., Fasano, G., et al. 2001, A&A, 380, 471
Bezanson, R., Franx, M., & van Dokkum, P. G. 2015, ApJ, 799, 148
Birrer, S., & Amara, A. 2018, PDU, 22, 189
Birrer, S., Shajib, A., Gilman, D., et al. 2021, JOS, 6, 3283
Boquien, M., Burgarella, D., Rosolowsky, E., et al. 2019, A&A, 622, A103
Bruce, V. A., Dunlop, J. S., McMullin, R. J., et al. 2014, MNRAS, 444, 1660
Cisternas, M., Jahnke, K., Bongiorno, A., et al. 2011, ApJL, 741, L11
Damjanov, I., Zahid, H. J., Geller, M. J., Fabricant, D. G., & Hwang, H. S. 2018, ApJS, 234, 21
de Graaff, A., Bezanson, R., Franx, M., et al. 2021, ApJ, 913, 103
Ding, X., Silverman, J., Treu, T., et al. 2020, ApJ, 888, 37
Ding, X., Silverman, J. D., Treu, T., et al. 2022, arXiv:2205.04481
Ferrarese, L., & Merritt, D. 2000, ApJL, 539, L9
Gebhardt, K., Bender, R., Bower, G., et al. 2000, ApJL, 539, L13
Gómez-Guijarro, C., Elbaz, D., Xiao, M., et al. 2022, A&A, 659, A196
Greene, J. E., & Ho, L. C. 2006, ApJL, 641, L21
Huang, C.-F., Cisternas, M., Jahnke, K., et al. 2021, ApJ, 921, 38
Huchra, M. G., Natarajan, P., & Rees, M. J. 1998, MNRAS, 300, 817
Herbert, P. D., Jarvis, M. J., Willott, C. J., et al. 2011, MNRAS, 410, 1360
Hopkins, P. F., Hernquist, L., Cox, T. J., Robertson, B., & Krause, E. 2007, ApJ, 669, 67
Hyde, J. B., & Bernardi, M. 2009, MNRAS, 396, 1171
Jahnke, K., Bongiorno, A., Brusa, M., et al. 2009, ApJL, 706, L215
King, A. 2003, ApJL, 596, L27
Kormendy, J., & Ho, L. C. 2013, ARAA, 51, 511
Li, J., Silverman, J. D., Ding, X., et al. 2021a, ApJL, 918, 22
Li, J., Silverman, J. D., Ding, X., et al. 2021b, ApJL, 922, 142
Mullaney, J. R., Daddi, E., Béthermin, M., et al. 2012, ApJL, 753, L30
Muzzan, A., Marchisini, D., Stefanon, M., et al. 2013, ApJ, 777, 18
Onken, C. A., Ferrarese, L., Merritt, D., et al. 2004, ApJ, 615, 645
Páris, I., Petitjean, P., Aubourg, É., et al. 2018, A&A, 613, A51
Peng, C. Y., Impey, C. D., Ho, L. C., Burton, E. J., & Rix, H.-W. 2006, ApJ, 640, 114
Peterson, B. M., Ferrarese, L., Gilbert, K. M., et al. 2004, ApJ, 613, 682
Puglisi, A., Daddi, E., Liu, D., et al. 2019, ApJL, 877, L23
Rakshit, S., Stalín, C. S., & Kotilainen, J. 2020, ApJS, 249, 17
Richards, G. T., Lacy, M., Storrie-Lombardi, L. J., et al. 2006, ApJS, 166, 470
Schawinski, K., Simmons, B. D., Urry, C. M., Treister, E., & Glikman, E. 2012, MNRAS, 425, L61
Schulze, A., Bongiorno, A., Cappelluti, N., et al. 2015, MNRAS, 447, 2085
Shen, Y., Greene, J. E., Ho, L. C., et al. 2015, ApJ, 805, 96
Silverman, J. D., Treu, T., Ding, X., et al. 2019, ApJL, 887, L5
Somerville, R. S., & Davé, R. 2015, ARA&A, 53, 51
Sun, M., Trump, J. R., Brandt, W. N., et al. 2015, ApJ, 802, 14
van den Bosch, R. C. E. 2016, ApJ, 831, 134
van der Wel, A., Franx, M., van Dokkum, P. G., et al. 2014, ApJL, 788, 28
Vanden Berk, D. E., Richards, G. T., Bauer, A., et al. 2001, AJ, 122, 549
Vestergaard, M., & Peterson, B. M. 2006, ApJ, 641, 689
Volonteri, M., & Natarajan, P. 2009, MNRAS, 400, 1911
Wolf, M. J., & Sheinis, A. I. 2008, AJ, 136, 1587
Woo, J.-H., Treu, T., Barth, A. J., et al. 2010, ApJ, 716, 269
Woo, J.-H., Treu, T., Malkan, M. A., & Blandford, R. D. 2006, ApJ, 645, 900
Woo, J.-H., Treu, T., Malkan, M. A., & Blandford, R. D. 2008, ApJL, 681, 925
Woo, J.-H., Urry, C. M., Lira, P., van der Mare, R. P., & Maza, J. 2004, ApJ, 617, 903
Zahid, H. J., Damjanov, I., Geller, M. J., Hwang, H. S., & Fabricant, D. G. 2016, ApJ, 821, 101