ABSTRACT

Recent studies show that a universal relation between black-hole (BH) growth and stellar mass \( M_\star \) or star formation rate (SFR) is an oversimplification of BH-galaxy co-evolution, and that morphological and structural properties of host galaxies must also be considered. Particularly, a possible connection between BH growth and host-galaxy compactness was identified among star-forming (SF) galaxies. Utilizing \( \approx 6300 \) massive galaxies with \( I_{814W} < 24 \) at \( z < 1.2 \) in the COSMOS field, we perform systematic partial-correlation analyses to investigate how sample-averaged BH accretion rate (BHAR) depends on host-galaxy compactness among SF galaxies, when controlling for morphology and \( M_\star \) (or SFR). The projected central surface-mass density within 1 kpc, \( \Sigma_1 \), is utilized to represent host-galaxy compactness in our study. We find that the BHAR-\( \Sigma_1 \) relation is stronger than either the BHAR-\( M_\star \) or BHAR-SFR relation among SF galaxies, and this BHAR-\( \Sigma_1 \) relation applies to both bulge-dominated galaxies and galaxies that are not dominated by bulges. This BHAR-\( \Sigma_1 \) relation among SF galaxies suggests a link between BH growth and the central gas density of host galaxies on the kpc scale, which may further imply a common origin of the gas in the vicinity of the BH and in the central ~ kpc of the galaxy. This BHAR-\( \Sigma_1 \) relation can also be interpreted as the relation between BH growth and the central velocity dispersion of host galaxies at a given gas content, indicating the role of the host-galaxy potential well in feeding BHs.

Key words: galaxies: active – galaxies: evolution – galaxies: nuclei – X-rays: galaxies

1 INTRODUCTION

Correlations between black-hole (BH) mass and host-galaxy properties observed in the local universe (e.g. Magorrian et al. 1998; Marconi & Hunt 2003; Kormendy & Ho 2013; McConnell & Ma 2013) have inspired investigations of
so-called “BH-galaxy co-evolution” over the past couple decades. As the BH accretion rate of individual objects has large long-term variability that hinders us from revealing any intrinsic link between the BH growth and its host galaxy (e.g. Hickox et al. 2014; Sartori et al. 2018; Yuan et al. 2018), one effective way to investigate BH-galaxy co-evolution “in action” is performing large-sample studies. With X-ray emission serving as a reliable tracer of BH accretion (e.g. Brandt & Alexander 2015), these sample studies utilize the average BH accretion rate (BHAR) of a sample of galaxies sharing similar properties to approximate the long-term average BH growth of galaxies with these properties; i.e., they take BH growth to be ergodic. Relations between BHAR and $M_*$ or SFR have been revealed (e.g. Chen et al. 2013; Aird et al. 2017, 2018; Yang et al. 2017, 2018a), which are considered as observational evidence of a link between BH growth and the potential well or the gas mass of host galaxies.

However, a “universal” relation between BH growth and $M_*$ or SFR is likely a substantial oversimplification of BH-galaxy co-evolution. Yang et al. (2019) found that morphology must be considered when studying BH-galaxy co-evolution: for bulge-dominated (BD) galaxies, BH growth mainly depends on SFR rather than $M_*$; for galaxies not dominated by bulges (Non-BD), BH growth mainly depends on $M_*$ rather than SFR. This finding is consistent with the observational result in the local universe that BH mass ($M_{BH}$) only correlates tightly with bulge mass ($M_{bulge}$), rather than $M_*$ of the whole host galaxy (e.g. Kormendy & Ho 2013). The role of compactness (which measures the mass-to-size ratio of galaxies) has also triggered attention in recent years: Kocevski et al. (2017) found an elevated active galactic nucleus (AGN) fraction among compact star-forming (SF) galaxies when compared with mass-matched extended SF galaxies. This finding is consistent with the predicted scenario that BH growth can be triggered by the high central gas density during a wet compaction event (e.g. Wellons et al. 2015; Dekel et al. 2019; Habouzit et al. 2019).

Given all these findings, Ni et al. (2019) examined the effectiveness of compactness in predicting the amount of BH growth when controlling for various other host-galaxy properties (including morphology) using galaxies in the $\approx 0.25 \ deg^2$ CANDELS survey fields (Grogin et al. 2011; Koekemoer et al. 2011). Ni et al. (2019) found that compactness can only effectively predict BHAR among SF galaxies, and the central surface-mass density within 1 kpc ($\Sigma_1$) is more effective in predicting the amount of BH growth than the surface mass density in the central 50% of galaxies. These results led Ni et al. (2019) to speculate that the BHAR-$\Sigma_1$ relation, if confirmed, could reflect a link between BH growth and the central ~ kpc gas density of host galaxies (that could be related to $\Sigma_1$ among SF galaxies). Ni et al. (2019) found evidence that the relation between BHAR and $\Sigma_1$ is not simply a secondary manifestation of the BHAR-$M_*$ relation among SF Non-BD galaxies; while the number of SF BD galaxies in Ni et al. (2019) was too small to confirm a significant ($>3\sigma$) BHAR-$\Sigma_1$ relation (when controlling for SFR), BD galaxies with relatively high SFR values suggest the link between BH growth and $\Sigma_1$. If a significant BHAR-$\Sigma_1$ relation can be confirmed among SF BD galaxies (when controlling for SFR), it will provide a natural explanation for over-massive BH “monsters” in the local universe that live in compact galaxies (e.g. Kormendy & Ho 2013; Walsh et al. 2015, 2017). It is plausible that a BHAR-$\Sigma_1$ relation that is more “fundamental” than either the BHAR-M$_*$ or BHAR-SFR relation may apply for all SF galaxies regardless of morphology. If so, this would provide strong evidence for a link between BH growth and the central gas density of host galaxies, which may reveal how BHs feed from gas in the central parts of galaxies: this is especially important given that it is difficult to measure the central gas density directly for a large sample of AGNs due to current observational constraints.

In this paper, we use a large sample of galaxies and AGNs at $z<1.2$ in the $\approx 1.4\ deg^2$ COSMOS survey field (that has UltraVISTA and ACS coverage; Koekemoer et al. 2007; Leauthaud et al. 2007; Laigle et al. 2016) to probe further the relation between BH growth and host-galaxy compactness among SF galaxies. Specifically, we will address the following questions: Is the BHAR-$\Sigma_1$ relation more fundamental than the BHAR-M$_*$ relation among SF Non-BD galaxies? Is there a significant BHAR-$\Sigma_1$ relation when controlling for SFR among SF BD galaxies? Is the BHAR-$\Sigma_1$ relation “universal” among all SF galaxies? If so, what are the properties of this BHAR-$\Sigma_1$ relation?

This paper is structured as follows. In Section 2, we describe the sample construction process. In Section 3, we perform data analyses and present the results. In Section 4, we interpret the analyses results and present relevant discussions. Section 5 summarizes this work and discusses future prospects. Throughout this paper, $M_*$ is in units of $M_\odot$; SFR and BHAR are in units of $M_\odot\ yr^{-1}$; $\Sigma_1$ is in units of $M_\odot/kpc^2$. $L_X$ indicates X-ray luminosity at rest-frame 2–10 keV in units of erg s$^{-1}$. Quoted uncertainties are at the 1$\sigma$ (68%) confidence level, unless otherwise stated. A cosmology with $H_0 = 70 \ km \ s^{-1} Mpc^{-1}$, $\Omega_M = 0.3$, and $\Omega_{\Lambda} = 0.7$ is assumed. We consider a partial correlation to be significant if it has a $p$-value $<0.0027$, which corresponds to a significance level $>3\sigma$. Significant results throughout the paper are marked in bold in the tables.

2 DATA AND SAMPLE

Our objects are selected from the COSMOS2015 catalog (Laigle et al. 2016). Only sources within both the COSMOS and UltraVISTA regions are kept, and we remove saturated objects in bad areas (FLAG_COSMOS = 0, FLAG_HJMCC = 0, and FLAG_PETER = 0). We further limit our selection to $I_{814W} < 24$ galaxies: $I_{814W} < 24$ is a common threshold adopted in the $HST$ COSMOS field for morphological classifications (e.g. Scarlata et al. 2007). We obtain spectroscopic redshifts (spec-$z$) for sources from Marchesi et al. (2016a); Delvecchio et al. (2017); Hasinger et al. (2018); and

1 BH “monsters” are BHs that have $M_{BH}$ significantly larger than expected from the $M_{BH}$ relation with bulge mass ($M_{bulge}$).

2 Throughout this paper, when A relates with both B and C, if the relation between A and B is significant when controlling for C while the relation between A and C is not significant when controlling for B in partial-correlation analyses, we say the relation between A and B is more fundamental than the relation between A and C.
Salvato et al. in prep. We note that ≈ 60% of sources utilized in Section 3 have spectroscopic redshifts. For sources without spectroscopic redshifts, we adopt the high-quality photometric redshift (photo-z) measurements from Laigle et al. (2016).

For the selected COSMOS sources, in Section 2.1, we measure their $M_\star$ and SFR values; in Section 2.2, we measure their structural parameters including Sérsic index ($n$) and effective radius ($r_e$) that will be utilized to calculate $\Sigma_1$; in Section 2.3, we classify objects as BD/Non-BD. In Section 2.4, we construct samples that will be used for the analyses in Section 3. In Section 2.5, we explain how BHAR utilized in Section 3 is estimated.

2.1 Stellar mass and star formation rate measurements

We measure $M_\star$ and SFR with X-CIGALE (Yang et al. 2020), which is a new version of CIGALE (e.g., Boquien et al. 2019) with updated AGN modules. Photometric data in 38 bands (including 24 broad bands) from NUV to FIR (Laigle et al. 2016) are utilized. For the NUV to NIR photometry, we correct the aperture flux to total flux following Appendix A2 of Laigle et al. (2016). For the 3 Herschel/SPIRE bands, we use photometric data reported in a super-deblended catalog described in Jin et al. (2018) which utilizes the deblending technique in Liu et al. (2018). For X-ray undetected galaxies, we fit them with a two-run approach: we first fit them with pure galaxy templates. We adopt a delayed exponentially declining star formation history (SFH), a Chabrier initial mass function (Chabrier 2003), the extinction law from Calzetti et al. (2000), and the dust emission template from Dale et al. (2014), following Ciesla et al. (2015) and Yang et al. (2020). We also add nebular emission to the SED libraries. Details of the fitting parameters can be seen in Table A. Then, we add an additional AGN component presented in X-CIGALE, SKIRTOR (that is established based on Stalevski et al. 2012, 2016), during the fitting (detailed parameters can also be found in Table A). One free parameter in SKIRTOR is the fractional contribution of AGN emission to the total IR luminosity ($\text{frac}_{\text{AGN}}$), which can range from 0 to 1, and we use a step of 0.1 during the fitting. We find that while the measurements of $M_\star$ are not significantly influenced by adding an AGN component, the SFR measurements are smaller by ≈ 0.2–0.5 dex on average when $\text{frac}_{\text{AGN}} \geq 0.3$ (when $\text{frac}_{\text{AGN}} < 0.3$, adding an AGN component affects the SFR measurements by less than ≈ 0.2 dex, which is negligible considering the uncertainty of the SFR measurements; see Appendix A for details). Thus, when the estimated Bayesian 1σ lower limit of $\text{frac}_{\text{AGN}}$ is $\geq 0.25$ (≈ 1% of total objects), we adopt the Bayesian $M_\star$ and SFR values from the solution with an AGN component. Otherwise, we adopt the Bayesian $M_\star$ and SFR values from the solution without an AGN component.

For X-ray detected galaxies, we directly fit them with both galaxy and AGN components. We have also incorporated the Chandra X-ray flux (Civano et al. 2016) into the fitting following Yang et al. (2020) (through the X-ray module in X-CIGALE) to constrain the AGN SED contribution, as the X-ray SED of AGN is empirically connected to the UV-to-IR SED (e.g. Just et al. 2007). Chandra X-ray fluxes are adopted following the preference order of hard band (2–10 keV), full band (0.5–10 keV), and soft band (0.5–2 keV), thus minimizing the effects of X-ray obscuration. We require that the deviation from this empirical SED relation ($\Delta O_X$) should not be larger than 0.2 (which corresponds to the 2σ scatter of the empirical relation; e.g. Just et al. 2007). We note that for our X-ray detected galaxies, adding the X-ray module or not will not significantly affect the Bayesian $M_\star$ and SFR measurements; the scatter between the two sets of $M_\star$ (SFR) measurements is ≈ 0.1 (0.2) dex.

A comparison between our SED-based $M_\star$ and SFR measurements and SED-based $M_\star$ and SFR measurements with Prospector (Leja et al. 2019a) for a subset of COSMOS galaxies is presented in Appendix A, showing the general consistency between the two approaches. As our $M_\star$ measurements are systematically smaller than those reported in Leja et al. (2019a) by ≈ 0.15 dex, we correct our measurements for this systematic offset in the final adopted $M_\star$ values (see Appendix A for details).

As the SED fitting process is “dominated” by the large number of UV-to-NIR bands that may underestimate SFR in the high-SFR regime (e.g. Wuyts et al. 2011; Yang et al. 2017), FIR-based SFR values are adopted when available (for ≈4%/26% of objects in the SF BD/SF Non-BD samples defined in Section 2.4). When an object is detected with S/N > 5 in a Herschel band (Lutz et al. 2011; Oliver et al. 2012; Laigle et al. 2016; Jin et al. 2018), we derive its total IR luminosity from the FIR flux in this band utilizing the SF galaxy template in Kirkpatrick et al. (2012). Then, a weighted total IR luminosity is calculated from all available Herschel bands with the FIR flux error serving as the weight. The total IR luminosity is then converted to SFR following Equation 1 in Ni et al. (2019), assuming that most UV photons are absorbed by the dust. We have also compared our SED-based SFR values with these FIR-based SFR values, showing the consistency of these two methods (see Appendix A for details). We note that FIR-based SFR measurement also has its short comings (e.g. Kennicutt 1998a; Hodge & da Cunha 2020); we verified that our results in Section 3 do not change qualitatively if we solely adopt SED-based SFR values.

2.2 Structural measurements with GALFIT

2.2.1 Image and noise cutouts

We prepare image cutouts for the selected objects from ACS F814W COSMOS science images v2.0 (Koekemoer et al. 2007) that have bad pixels and cosmic rays removed. Following Matharu et al. (2019), our cutouts have 15 × FLUX_RADIUS pixels in the x/y-axis (FLUX_RADIUS is the half-light radius measured by SExtractor in Leauthaud et al. 2007), with the target galaxy at the center. The noise cutouts with same sizes are made following van der Wel et al. (2012) and Matharu et al. (2019), where the noise is a quadrature combination of the Poisson noise of the image and other noises where the sky-background noise dominates. We estimate the sky-background noise as well as the background sky level with segmentation maps generated for each image cutout by SExtractor v2.19.5 (Bertin & Arnouts 1996), following section 3 and table 1 of Leauthaud et al. (2007). With the information provided by these segmentation maps, we select all pixels that do not belong to sources in the image cutout, and use these pixels to estimate the
background sky level/noise, which is the mean/root-mean-square value of these background pixels.

2.2.2 PSF generation

The PSF model used in this work is generated by the IDL wrapper of TinyTim (Krist 1995) introduced in Rhodes et al. (2006, 2007), assuming a G8V star and a focus at $-3.0\mu$m. This IDL wrapper can generate the PSF model with a pixel scale of 0.03” to match the oversampled version of ACS COSMOS science images that have geometric distortion removed. We neglect the change of PSF both temporally and across the CCD at the level of a few percent (Rhodes et al. 2007; Gabor et al. 2009). We have also compared the PSF model with real stars in the COSMOS field, and we find that the differences between the encircled flux fractions at a given radius are generally small (within a few percent).

2.2.3 GALFIT setup

We fit our objects with a single-component Sérsic profile in GALFIT (Peng et al. 2002):

$$I(r) = I_o \exp \left( -\frac{r}{r_e} \right)^{1/n}$$

where $n$ is the Sérsic index, $r_e$ is the half-light radius, $I(r)$ represents light intensity at a radius of $r$, $I_o$ is the light intensity at $r_o$, and $b_n$ is coupled to $n$ to make half of the total flux lie within $r_e$.

Following van der Wel et al. (2012), we set constraints in GALFIT to keep $0.2 < n < 8$, $0.5 < r_e < 800$ (in units of pixels), $0.0001 < q < 1$ ($q$ is the axis ratio). Rather than fitting a single object, we fit all the sources in the cutout simultaneously, which can substantially improve the accuracy of fitting (e.g. Peng et al. 2002; Matharu et al. 2019). We do not fit for the sky during the fit (e.g. Häsler et al. 2007; Barden et al. 2012); we set the sky level as the background sky level estimated in Section 2.2.1. For $\approx 87\%$ of objects, GALFIT reached a solution without hitting any constraints (we mark them with GALFIT_flag = 0); for $\approx 4\%$ of objects, GALFIT hit the constraints (we mark them with GALFIT_flag = 2); for $\approx 9\%$ of objects, GALFIT did not manage to converge. Since fitting a lot of additional objects simultaneously may cause GALFIT to fail due to these objects, we fit the $\approx 9\%$ of objects where GALFIT did not manage to converge again without fitting neighboring objects: in this second run, we use the SExtractor segmentation map to mask all neighboring objects (masked pixels within an ellipse of $3 \times$ Kron ellipse $+ 20$ pixels of the central object are regarded to contain the source flux, so we unmask them in the segmentation map), and we only fit the target object at the center. If GALFIT reached a solution without hitting any constraints in this second run, we mark the object with GALFIT_flag = 1; if GALFIT hit the constraints, we mark the object with GALFIT_flag = 2; if GALFIT failed again, we mark the object with GALFIT_flag = 3. We will only use the $\approx 87\%$ GALFIT_flag = 0 and $\approx 8\%$ GALFIT_flag = 1 objects for our analyses, and our results do not change qualitatively if we limit our analyses to GALFIT_flag = 0 objects only. In Appendix B, we show the reliability of our results by comparing with the GIM2D measurements of $I_{F814W} < 22.5$ galaxies in COSMOS (Sargent et al. 2007). We also assess the level of potential AGN contamination to host-galaxy light profiles in Appendix B. We find that for X-ray AGNs included in our sample (see Section 2.4 for the sample selection), the AGN contamination is largely negligible.

2.3 Deep-learning-based morphology

We use a deep-learning-based method to classify $I_{F814W} < 24$ galaxies in COSMOS (Leauthaud et al. 2007) as BD galaxies or Non-BD galaxies. Details of this deep-learning-based BD/Non-BD classification process are presented in Appendix C. Our selection of BD galaxies is broadly consistent with the selection of “pure bulges” in Huertas-Company et al. (2015, see Appendix C for details).

2.4 Sample construction

We first confine our sample to galaxies at $z < 1.2$, where the HST F814W band can characterize the rest-frame optical emission of galaxies ($\approx 370 – 800$ nm), so that our morphological measurements are not strongly affected by the “morphological k-correction”. The relatively low redshift range probed here compared with the $z = 0.5–3$ sample in Ni et al. (2019) also generally enables more accurate morphology-first AGN characterization. Following Yang et al. (2018a) and Ni et al. (2019), we remove broad-line (BL) AGNs (Marchesi et al. 2016a) from the sample (which make up $\approx 6\%$ of total X-ray detected galaxies), as the strong emission from BL AGNs prohibits us from obtaining reliable measurements of host-galaxy properties. The exclusion of BL AGNs should not affect the analysis results assuming the unified model (e.g. Netzer 2015). According to the unified model, BL AGNs and type 2 AGNs are purely orientation-based AGN classes: when our line-of-sight does not intercept the torus, a BL AGN is observed; otherwise, a type 2 AGN is observed. Thus, as detailed in Section 2.4.1 of Ni et al. (2019), excluding the contribution from BL AGNs when estimating sample-averaged BH growth only decreases BHAR by a similar fraction for utilized subsamples of galaxies in Section 3, so it will not influence our investigations of the dependence of BH growth on various host-galaxy properties. We also confine our sample to GALFIT_flag = 0 or 1 objects, where reliable structural measurements are available (see Section 2.2). Through doing this, we also reject AGNs which cause strong contamination to the host-galaxy light profiles as we do not take objects with extremely large $n$. In this step, an additional $\approx 10\%$ of X-ray detected galaxies are removed. We calculate $\Sigma_1$ values for the selected galaxies assuming a constant $M_*$-to-light ratio throughout the galaxy, with $M_*$ measured in Section 2.1, and $I(r)$ measured in Section 2.2:

$$\Sigma_1 = \frac{\int_0^{1kpc} I(r)2\pi r dr}{\int_0^{1kpc} I(r)2\pi r dr} \cdot \pi(1kpc)^2$$

We use the star formation main sequence derived in Whitaker et al. (2012) at the appropriate redshift to select SF galaxies: if the SFR value of a galaxy is above the star formation main sequence or no more than 1.4 dex below the
star formation main sequence, we classify this galaxy as a SF galaxy. This division roughly corresponds to galaxies lying above the local minimum in the distribution of SFRs at a given $M_\star$ (see Figure 1).

We construct a SF Non-BD sample and a SF BD sample to study the role of $\Sigma_1$ in predicting BH growth when controlling for morphology and $M_\star$ (or SFR). The SF Non-BD sample will be used in Section 3.1 to assess if the BHAR-$\Sigma_1$ relation is more fundamental than the BHAR-$M_\star$ relation. As the relation between BHAR and $M_\star$ or $\Sigma_1$ has cosmic evolution (e.g. Yang et al. 2018a; Ni et al. 2019), we require that the SF Non-BD sample is mass-complete and has a uniform mass cut across the entire probed redshift range, so that the probed relation will not be significantly affected by the cosmic evolution. The $M_\star$ completeness curve as a function of redshift for $I_{814W} < 24$ COSMOS galaxies is shown in Figure 2. The limiting $M_\star$ is derived following Section 3.2 of Ilbert et al. (2013) and Section 2.4.1 of Ni et al. (2019). By selecting log $M_\star > 10.2$ SF Non-BD galaxies at $z < 0.8$ (log $M_\star = 10.2$ is the limiting $M_\star$ at $z = 0.8$), we constitute the SF Non-BD sample with a sample size of ≈ 6000, six times that in Ni et al. (2019) in similar $M_\star$ and $z$ ranges. We note that ≈78% of total Non-BD galaxies in the same $M_\star$ and $z$ ranges are SF Non-BD galaxies. Thus, studying the relations between BH growth and various host-galaxy properties in the SF Non-BD sample can help us investigate BH-galaxy co-evolution in the majority of the Non-BD population.

The SF BD sample will be used in Section 3.2 to test if the BHAR-$\Sigma_1$ relation exists when controlling for SFR. According to Yang et al. (2019), BHAR among BD galaxies follows a linear relation with SFR in the log-log space with no obvious additional dependence on $M_\star$, and no evident cosmic evolution is found for this relation. Thus, a mass-complete sample of SF BD galaxies or a sample in a narrow redshift bin is not necessary to test if the conclusion of Yang et al. (2019) holds true, or if $\Sigma_1$ is indeed playing an important role in predicting the amount of BH growth in this sub-population. Therefore, we select all massive (log $M_\star > 10$) SF BD galaxies at $z < 1.2$ to constitute the SF BD sample, which gives us a large sample of ≈1000 galaxies, three times that in Ni et al. (2019) in the similar redshift range. We note that while galaxies in the SF BD sample only make up ≈ 20% of total BD galaxies in the same $M_\star$ and $z$ ranges, ≈76% of the BH growth takes place within these ≈20% of objects (we estimate the amount of BH growth as described in Section 2.5), which makes characterizing the relation between BH growth and host-galaxy properties particularly important for this subsample.

The properties of the SF Non-BD sample and the SF BD sample are shown in Table 1. In Figure 3, we show the $\Sigma_1$ vs. $M_\star$ and $\Sigma_1$ vs. SFR distributions for the SF Non-BD sample and the SF BD sample, demonstrating the parameter space probed in this work.

We also construct a sample of SF galaxies to study the properties of the BHAR-$\Sigma_1$ relation regardless of morphology in Section 3.3. This sample (we call it the ALL SF sample in short hereafter) is a mass-complete sample with a sample size of ≈ 6300, constituted by all SF galaxies with log $M_\star > 10.2$ at $z < 0.8$. The properties of the ALL SF sample are also listed in Table 1.

2.5 Sample-averaged black-hole accretion rate

Following Yang et al. (2018b) and Ni et al. (2019), we calculate BHAR for a given sample of galaxies sharing similar properties with contributions from both X-ray detected sources and X-ray undetected sources to cover all BH accretion, thereby estimating the long-term average BH growth (see Section 1).

The X-ray fluxes of detected sources are adopted from the COSMOS-Legacy X-ray survey catalog (Civano et al. 2016), which is obtained from deep Chandra observations in the field. We convert the X-ray fluxes (following the preference order of hard band, full band, and soft band, thus minimizing the effects of X-ray obscuration) to $L_X$ assuming a power-law model with Galactic absorption and $\Gamma = 1.7$ (e.g. Marchesi et al. 2016b; Yang et al. 2016). As discussed in
Table 1. Summary of sample properties. (1) Name of the sample. (2) Redshift range of the sample. (3) $M_*$ range of the sample. (4) Number of galaxies in the sample. (5) Number of spec-$z$/photo-$z$ sources. (6) Number of X-ray detected galaxies.

| Sample       | Redshift Range | Mass Range | Number of Galaxies | Number of Spec-$z$/Photo-$z$ Sources | Number of X-ray Detections |
|--------------|----------------|------------|--------------------|---------------------------------------|---------------------------|
| SF Non-BD    | 0–0.8          | log$M_*$ > 10.2 | 5979               | 3823/2156                            | 179                       |
| SF BD        | 0–1.2          | log$M_*$ > 10   | 1020               | 421/599                              | 81                        |
| ALL SF       | 0–0.8          | log$M_*$ > 10.2 | 6334               | 4041/2293                            | 206                       |

Figure 3. Left panel: $\Sigma_1$ vs. $M_*$ and $\Sigma_1$ vs. SFR for galaxies in the SF Non-BD sample. The contours encircle 68%, 80%, 90%, and 95% of galaxies. The silver stars represent X-ray detected galaxies. Right panel: Similar to the left panel, but for galaxies in the SF BD sample.

Yang et al. (2018b), the underestimation of X-ray flux due to obscuration in this scheme is small on average ($\approx 20\%$). We account for this systematic effect of obscuration by increasing the X-ray fluxes of detected sources by 20%, following Yang et al. (2019) and Ni et al. (2019). The X-ray emission of a group of X-ray undetected sources is taken into account via X-ray stacking techniques using the full-band Chandra X-ray image. Details of this stacking process can be seen in section 2.4.2 of Yang et al. (2018b).

Following section 2.3 of Ni et al. (2019), the average AGN bolometric luminosity ($L_{\text{bol}}$) for a given sample can be calculated from $L_X$ of each X-ray detected source and the average X-ray luminosity of all the X-ray undetected sources ($L_{X,\text{stack}}$) obtained via stacking, assuming the $L_X$-dependent bolometric correction from Hopkins et al. (2007). We also subtract the contributions from X-ray binaries (XRBs) from $L_X$ and $L_{X,\text{stack}}$ before applying the bolometric correction. The XRB luminosity ($L_{X,\text{XRB}}$) can be estimated through a redshift-dependent function of $M_*$ and SFR (model 269, Fragos et al. 2013), which is derived utilizing observations in Lehmer et al. (2016). The equation for calculating $L_{\text{bol}}$ is

$$L_{\text{bol}} = \frac{\sum_{i=0}^{N_{\text{det}}} (L_X - L_{X,\text{XRB}}) k_{\text{bol}} + (L_{X,\text{stack}} - L_{X,\text{XRB}}) N_{\text{non}} k_{\text{bol}}}{N_{\text{det}} + N_{\text{non}}},$$

where $N_{\text{det}}$ ($N_{\text{non}}$) represents the number of X-ray detected (undetected) galaxies; $L_{X,\text{XRB}}$ ($L_{X,\text{XRB}}$) is the expected XRB luminosity in each individual X-ray detected galaxy (the average XRB luminosity expected for all X-ray undetected galaxies); $k_{\text{bol}}$ ($k_{\text{bol}}$) is the bolometric correction applied to each individual X-ray detected galaxy (all X-ray undetected galaxies). In this equation, X-ray detected sources contribute most of the numerator (i.e., the total $L_{\text{bol}}$ of the sample); X-ray undetected sources mainly contribute to the denominator by $N_{\text{non}}$ (assuming ergodic BH growth, averaging the total $L_{\text{bol}}$ over the whole sample is equivalent to averaging the total $L_{\text{bol}}$ over the whole duty cycle). Then, $L_{\text{bol}}$ can be

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3 For the subsamples utilized in this work, the contribution from XRBs makes up $\approx 1$–10% of the total X-ray emission, so that our analyses should not be affected materially by uncertainties related to the XRB modeling.
converted to BHAR adopting a constant radiative efficiency of 0.1:\(^4\)

\[
BHAR = \frac{(1 - \epsilon)L_{bol}}{\epsilon c^2} = \frac{1.58L_{bol}}{10^{46} \text{ erg s}^{-1}} M_\odot \text{ yr}^{-1}
\]

(4)

The uncertainty of BHAR can be obtained via bootstrapping the sample 1000 times.

### 3 ANALYSES AND RESULTS

In Section 3.1, we will study if the BHAR-\(\Sigma_1\) relation is a more fundamental relation than the BHAR-\(M_\star\) relation among SF Non-BD galaxies. In Section 3.2, we will study if the BHAR-\(\Sigma_1\) relation also exists among SF BD galaxies. In Section 3.3, we will first study if the BHAR-\(\Sigma_1\) relation among SF Non-BD galaxies is the same BHAR-\(\Sigma_1\) relation among SF BD galaxies, and if the BHAR-\(\Sigma_1\) relation that could apply to all SF galaxies seamlessly is a more fundamental relation than either of the BHAR-\(M_\star\) or BHAR-SFR relations. We will then study the properties of the BHAR-\(\Sigma_1\) relation and its cosmic evolution.

#### 3.1 A BHAR-\(\Sigma_1\) relation that is more fundamental than the BHAR-\(M_\star\) relation among SF Non-BD galaxies

Ni et al. (2019) found that the BHAR-\(\Sigma_1\) relation among SF Non-BD galaxies is not likely to be a secondary manifestation of the BHAR-\(M_\star\) relation, and it is plausible that the BHAR-\(\Sigma_1\) relation is indeed more fundamental than the BHAR-\(M_\star\) relation. In this section, we test the significance of the BHAR-\(\Sigma_1\) (BHAR-\(M_\star\)) relation when controlling for \(M_\star\) among galaxies in the SF Non-BD sample with partial-correlation (PCOR) analyses. If we find a significant BHAR-\(\Sigma_1\) relation when controlling for \(M_\star\) but do not find a significant BHAR-\(M_\star\) relation when controlling for \(\Sigma_1\), we can conclude that the BHAR-\(\Sigma_1\) relation is more fundamental than the BHAR-\(M_\star\) relation among SF Non-BD galaxies.

We bin galaxies in the SF Non-BD sample based on both \(M_\star\) and \(\Sigma_1\) and calculate BHAR for each bin. The bins are chosen to include approximately the same numbers of sources (\(\approx 370\); see Figure 4 for the 2D bins). Bins where BHAR does not have a lower limit > 0 or the number of X-ray detected galaxies is less than 2 (which will introduce large uncertainty into the estimated BHAR) will be excluded from the PCOR analyses. We input the median log \(M_\star\), median log \(\Sigma_1\), and log BHAR of valid bins to PCOR.R in R statistical package (Kim 2015), and the significance levels of the BHAR-\(\Sigma_1\) (BHAR-\(M_\star\)) relation when controlling for \(M_\star\) (\(\Sigma_1\)) with both the Pearson and Spearman statistics are calculated. The PCOR test results are summarized in Table 2. The parametric Pearson statistic is used to select significant results (we note that both the BHAR-\(M_\star\) and BHAR-\(\Sigma_1\) relations are roughly linear in log-log space; see Yang et al. (2019) and Ni et al. (2019) for details), and the nonparametric Spearman statistic is also listed for reference. We can see from Table 2 that the BHAR-\(\Sigma_1\) relation turns out to be more fundamental than the BHAR-\(M_\star\) relation among SF Non-BD galaxies. Our results do not qualitatively change with different binning approaches (see Appendix D for details).

#### 3.2 The existence of a BHAR-\(\Sigma_1\) relation among SF BD galaxies

We test the significance of the BHAR-\(\Sigma_1\) relation when controlling for SFR among galaxies in the SF BD sample with PCOR analyses, as Yang et al. (2019) concluded that BHAR among BD galaxies mainly correlates with SFR. We bin galaxies in the SF BD sample based on both SFR and \(\Sigma_1\) and calculate BHAR for each bin. The bins are chosen to include approximately the same numbers of sources (\(\approx 110\);
see Figure 5 for the 2D bins). We input the median log SFR, median log Σ, and log BHAR of valid bins to PCOR. A and the significance levels of the BHAR-Σ (BHAR-SFR) relation when controlling for SFR (Σ) with both the Pearson and Spearman statistics are calculated. The PCOR test results are summarized in Table 3.

From the PCOR test results, we can see that the BHAR-Σ relation is significant when controlling for SFR, suggesting the important role of Σ in predicting the amount of BH growth. The BHAR-SFR relation, at the same time, is not significant when controlling for Σ. We note again that our results do not qualitatively change with different binning approaches (see Appendix D for details). We also use the PCOR analyses to assess the significance levels of the BHAR-Σ relation when controlling for M* in a similar manner, and the results are listed in Table 3. The BHAR-Σ relation remains significant, demonstrating that the observed BHAR-Σ relation in the SF BD sample is not simply a manifestation of the BHAR-M* relation. Thus, we can conclude that the BHAR-Σ relation exists among SF BD galaxies. We note that our findings do not challenge the existence of the BHAR-SFR relation among BD galaxies in general (see Appendix E).

### 3.3 A BHAR-Σ relation among all SF galaxies

We have confirmed the BHAR-Σ relation in both the SF Non-BD sample (see Section 3.1) and the SF BD sample (see Section 3.2). We will now study if the BHAR-Σ relation among SF BD galaxies and the BHAR-Σ relation among SF Non-BD galaxies make consistent predictions at a given Σ, so that no ad hoc morphological division among SF galaxies is needed to study this relation. As the SF BD sample and the SF Non-BD sample are selected with different M* and z criteria (and only the SF Non-BD sample is a mass-complete sample), we use the 355 SF BD galaxies with log M* > 10.2 at z < 0.8 to perform the comparison. For each of these 355 galaxies, we select two galaxies from the larger SF Non-BD sample that have the closest Σ values to it (not allowing duplications) to constitute a comparison sample. We find that the log BHAR of these 355 SF BD galaxies is $-2.62^{+0.12}_{-0.15}$ and the log BHAR of SF Non-BD galaxies in the comparison sample is $-2.41^{+0.11}_{-0.15}$, showing the consistent predictions of the BHAR-Σ relation among SF BD galaxies and SF Non-BD galaxies.

We will now study this BHAR-Σ relation that does not depend on morphological classes utilizing the ALL SF sample, which is constituted of all SF galaxies with log M* > 10.2 at z < 0.8. This sample of SF galaxies is mass-complete, so the derived BHAR-Σ relation will not be significantly affected by the cosmic evolution of this relation. We use PCOR analyses to assess if the BHAR-Σ relation in the ALL SF sample is still more fundamental than the BHAR-M* relation. The 2D bins in the Σ vs. M* plane that are utilized for PCOR analyses are presented in Figure 6. As expected, the BHAR-Σ relation is significant when controlling for M*, and the BHAR-M* relation is not significant when controlling for Σ (see Table 4). This result does not qualitatively change with different binning approaches (see Appendix D for details). We also perform the PCOR analyses in a similar manner for Σ and SFR, and it turns out that the BHAR-Σ relation is more fundamental than the BHAR-SFR relation (see Table 4).

To study the properties of the BHAR-Σ relation, we di-

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**Table 3. p-values (significances) of partial correlation analyses for the SF BD sample**

| Relation   | Pearson | Spearman |
|------------|---------|----------|
| BHAR-Σ     | $5 \times 10^{-6}$ (4.1σ) | $3 \times 10^{-4}$ (3.7σ) |
| BHAR-SFR   | $4 \times 10^{-3}$ (2.8σ)  | $2 \times 10^{-3}$ (3.1σ) |
| BHAR-Σ     | $9 \times 10^{-4}$ (3.3σ)  | $1 \times 10^{-3}$ (3.2σ) |
| BHAR-M*    | 0.33 (1.0σ)                   | 0.39 (0.9σ)       |

**Table 4. p-values (significances) of partial correlation analyses for the ALL SF sample**

| Relation   | Pearson | Spearman |
|------------|---------|----------|
| BHAR-Σ     | $2 \times 10^{-5}$ (4.2σ)  | $2 \times 10^{-4}$ (3.7σ) |
| BHAR-M*    | 0.28 (1.1σ)                     | 0.14 (1.5σ)       |
| BHAR-Σ     | $6 \times 10^{-5}$ (4.0σ)  | $9 \times 10^{-6}$ (4.4σ) |
| BHAR-SFR   | 0.46 (0.7σ)                     | 0.18 (1.3σ)       |

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5 We do not directly derive the BHAR-Σ relation among SF BD galaxies and SF Non-BD galaxies separately and compare, as quantifying the BHAR-Σ relation solely among SF BD galaxies will suffer from uncertainty that is too large to conduct any meaningful comparison.
vide galaxies in the ALL SF sample into $\Sigma_1$ bins with approximately the same number of X-ray detected galaxies ($> 10$) per bin, and calculate BHAR and its 1$\sigma$ confidence interval for each bin. In Figure 7, we plot BHAR of these bins as a function of the median $\Sigma_1$ value of each bin. We use the python package emcee (Foreman-Mackey et al. 2013) to fit a log-linear model to the BHAR-$\Sigma_1$ relation, where the maximum-likelihood method is implemented by the Markov chain Monte Carlo Ensemble sampler. By fitting all the data points in Figure 7, we obtain:

$$\log \text{BHAR} = (1.6 \pm 0.2) \times \log \Sigma_1 + (-18.3 \pm 2.6).$$

(5)

The best-fit model and its 1$\sigma$/3$\sigma$ pointwise confidence intervals are also shown in Figure 7.

Two subsamples of $H_{160W} < 24.5$ SF galaxies with log $M_*>10.2$ in the CANDELS fields drawn from the Ni et al. (2019) sample will also be utilized to probe how the BHAR-$\Sigma_1$ relation evolves over the history of the Universe: one subsample is constituted of $\approx 1500$ SF galaxies at $z=0.8$–1.5 (where $\Sigma_1$ values are inferred from $J_{125W}$-band light profiles), and the other subsample is constituted of $\approx 1800$ SF galaxies at $z=1.5$–3 (where $\Sigma_1$ values are inferred from $H_{160W}$-band light profiles). Though the utilized HST bands are different, we note that the light profiles are always measured in the rest-frame optical. $H_{160W} < 24.5$ galaxies in the CANDELS fields are mass-complete at log $M_*>10.2$ up to $z=3$, so these subsamples are also mass-complete samples. For each subsample, we divide objects into $\Sigma_1$ bins, and calculate BHAR and its 1$\sigma$ confidence interval for each bin. The BHAR values of these bins as a function of $\Sigma_1$ are shown in Figure 8 along with the data points in Figure 7 (which show BHAR as a function of $\Sigma_1$ in the ALL SF sample that is constituted by $z=0$–0.8 SF galaxies in the COSMOS field). We then use the emcee package to fit a log-linear model to the BHAR-$\Sigma_1$ relation among each subsample, as we did for the ALL SF sample. The best-fit BHAR-$\Sigma_1$ relations of SF galaxies in different redshift ranges are presented together in Figure 8. We can see that while the slope of the best-fit log-linear model does not change significantly with redshift, for a given $\Sigma_1$ value, the expected BHAR is higher at higher redshift: BHAR at $z=1.5$–3 is higher than that at $z=0$–0.8 by $\sim 1$ dex when controlling for $\Sigma_1$.

4 DISCUSSION

4.1 What is implied by the apparent link between BH growth and host-galaxy compactness?

4.1.1 The link between BH growth and the central gas density of host galaxies: a common origin of the gas in the vicinity of the BH and the central $\sim$ kpc?

In Section 3, we confirmed a BHAR-$\Sigma_1$ relation that is more fundamental than either the BHAR-$M_*$ or BHAR-SFR relation among SF galaxies, which reveals the link between long-term average BH growth and host-galaxy compactness. This BHAR-$\Sigma_1$ relation is only significant among SF galaxies (Ni et al. 2019). If we plot BHAR as a function of $\Sigma_1$ for quiescent galaxies (see Figure 9), we can see that BHAR does not have a lower limit of $> 0$ from bootstrapping or the number of X-ray detected galaxies is less than 2, ‘N/A’ is shown instead.

As $M_*$ values utilized in Ni et al. (2019) to calculate $\Sigma_1$ are also measured with parametric SFHs that tend to underestimate the true $M_*$ (Leja et al. 2019b), we apply a $=0.15$ dex correction to $\Sigma_1$ values of galaxies in the two CANDELS subsamples to maintain consistency with the $M_*$ scheme utilized in this paper.

Figure 6. Color-coded BHAR in different bins of $M_*$ and $\Sigma_1$ for galaxies in the ALL SF sample. Each 2D bin contains $\approx 390$ sources. The black plus sign indicates the median $M_*$ and $\Sigma_1$ of the sources in each bin. For each bin, the number of X-ray detected galaxies is listed. For bins where BHAR does not have a lower limit of $> 0$ from bootstrapping or the number of X-ray detected galaxies is less than 2, ‘N/A’ is shown instead.

Figure 7. The BHAR-$\Sigma_1$ relation among SF galaxies. Galaxies in the ALL SF sample are divided into bins according to their $\Sigma_1$ values, with $= 10$ X-ray detected galaxies in each bin. The horizontal position of each data point indicates the median $\Sigma_1$ of the sources in the bin; the error bars represent the 1$\sigma$ confidence interval of BHAR from bootstrapping. The black solid line and the dark/light blue shaded region represent the best-fit BHAR-$\Sigma_1$ relation and the 1$\sigma$/3$\sigma$ pointwise confidence intervals on the regression line.
not vary significantly with $\Sigma_1$ among quiescent galaxies, and the fitted slope (0.9 ± 0.5) of the log BHAR-log $\Sigma_1$ relation among quiescent galaxies is flatter compared with the slope among SF galaxies, being consistent with zero at a $\sim 2\sigma$ level. This led us to speculate that the BHAR-$\Sigma_1$ relation reflects a link between BH growth and the central gas density (on the $\sim$ kpc scale) of host galaxies (among quiescent galaxies, $\Sigma_1$ cannot effectively trace the central gas density).\footnote{We note that there is still limited SF activity among the quiescent galaxies we selected (see Section 2.4), so that there may still be a shallow trend between $\Sigma_1$ and the central gas density (though with large scatter), which could explain the observed shallow slope of the log BHAR-log $\Sigma_1$ relation in Figure 9.}

The observed cosmic evolution of the BHAR-$\Sigma_1$ relation in Section 3.3 supports our speculation: observations show that the average (molecular) gas fraction among galaxies increases by a factor of $\sim 10$ from $z = 0$ to $z = 2$ (e.g. Schinnerer et al. 2016; Tacconi et al. 2018), and this could well-explain our observed result that for a given $\Sigma_1$, BHAR increases by a factor of $\sim 10$ from $z = 0$ to $z = 1.5$—3.

If we can approximate $\Sigma_1$ as a function of gas surface density ($\Sigma_{\text{gas}}$) in the central $\sim$ kpc of galaxies, we will be able to convert the BHAR-$\Sigma_1$ relation to a BHAR-$\Sigma_{\text{gas}}$ relation. According to the Kennicutt-Schmidt law (e.g. Kennicutt 1998b), the SFR surface density ($\Sigma_{\text{SFR}}$) is tightly linked with $\Sigma_{\text{gas}}$ with a power-law index $\sim 1.4 \pm 0.15$. Also, observations and simulations suggest that $\Sigma_{\text{SFR}}$ on the $\sim$ kpc scale correlates with $M_*$ ($\Sigma_{\text{SFR}}$) on the same scale in SF regions (e.g. Cano-Díaz et al. 2016; Hsieh et al. 2017; Trayford & Schaye 2019; Hani et al. 2020), though the reported slope values ($\beta$) of the log $\Sigma_{\text{SFR}}$-log $\Sigma_{\text{SFR}}$ relation vary from $\sim 0.7$ to $\approx 1$. Given all these findings, we can approximate $\Sigma_1$ as a power-law function of $\Sigma_{\text{gas}}$ in the central $\sim 1$ kpc of galaxy with an index of $\approx 1.4/\beta$, suggesting that the BHAR-$\Sigma_{\text{gas}}$ relation has a power-law index of $\sim 2.4$. Further studies that utilize high-resolution ALMA observations to resolve the gas density will help to quantify directly the relation between $\Sigma_1$ and $\Sigma_{\text{gas}}$, thus making the conversion from the BHAR-$\Sigma_1$ relation to a BHAR-$\Sigma_{\text{gas}}$ relation more reliable; alternatively, future accumulation of ALMA observations in combination with deep X-ray observations will enable us to probe the BHAR-$\Sigma_{\text{gas}}$ relation directly.

Assuming $\Sigma_1$ serves as an indicator of $\Sigma_{\text{gas}}$, the BHAR-$\Sigma_1$ relation may indicate that gas in the vicinity of the BH that will be accreted has the same origin as gas in the central $\sim$ kpc part of galaxies. It is plausible that gas could be transported from the inner $\approx 1$ kpc of galaxies all the way to the torus and accretion disk via gravitational instabilities (see Storchi-Bergmann & Schnorr-Müller 2019 and references therein). If $\Sigma_{\text{gas}}$ (on kpc scales) correlates with the ambient gas density ($\rho$) of BHs (on pc to sub-kpc scales) well, the relation between BH growth and $\rho$ may be quantitatively examined. However, while we can convert the BHAR-$\Sigma_1$ rela-

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**Figure 8.** The cosmic evolution of the BHAR-$\Sigma_1$ relation among SF galaxies. $z = 0$—0.8 galaxies from COSMOS; $z = 0.8$—1.5 galaxies from CANDELS is examined. However, while we can convert the BHAR-$\Sigma_1$ rela-

**Figure 9.** The BHAR-$\Sigma_1$ relation among quiescent galaxies. 3400 quiescent galaxies with log $M_*$ > 10.2 at $z < 0.8$ are divided into bins according to their $\Sigma_1$ values, with $\approx 20$ X-ray detected galaxies in each bin. The horizontal position of each data point indicates the median $\Sigma_1$ of the sources in the bin; the error bars represent the $1\sigma$ confidence interval of BHAR from bootstrapping. The black dashed line and the dark/light blue shaded region represent the best-fit BHAR-$\Sigma_1$ relation among quiescent galaxies and the $1\sigma$/$3\sigma$ pointwise confidence intervals on the regression line. The black solid line and the dark/light blue shaded region are adopted from Figure 7, representing the best-fit BHAR-$\Sigma_1$ relation among SF galaxies in the same $M_*$ and $z$ ranges and the $1\sigma$/$3\sigma$ pointwise confidence intervals on the regression line. At a given $\Sigma_1$, the BHAR values of quiescent galaxies are below the $3\sigma$ lower limit of the best-fit BHAR-$\Sigma_1$ relation among SF galaxies, and the best-fit slope of the log BHAR-log $\Sigma_1$ relation among quiescent galaxies is much flatter compared with the best-fit slope among SF galaxies.
tion to a BHAR-$\Sigma_{\text{gas}}$ relation, this does not necessarily mean the dependence of BH growth on $\rho$ can be directly inferred.

BH growth may depend on other factors that also correlate with $\Sigma_1$. Bondi-type accretion models (e.g. Bondi 1952; Springel et al. 2005) predict that the amount of BH growth should be approximately proportional to $M_{\text{BH}}c_s^3$ (assuming that the gas has negligible velocity relative to the BH as an initial condition; $c_s$ is the sound speed in the gas), and both $M_{\text{BH}}$ and $c_s$ correlate with $\Sigma_1$ (though with considerable scatters). We can roughly infer the correlation between $\Sigma_1$ and $M_{\text{BH}}$ from the $M_{\text{BH}}-M_*$ relation (though with considerable scatters). We can roughly infer the correlation between $\Sigma_1$ and $M_{\text{BH}}$ from the $M_{\text{BH}}-M_*$ relation (though with considerable scatters).

Alternatively, the BHAR-$\Sigma_1$ relation may reflect a link between BH growth and the host-galaxy potential well depth at a certain gas content among SF galaxies. We note that $\Sigma_1$ is tightly correlated with the inferred central velocity dispersion ($\sigma_{\text{inf}}$; Bezanson et al. 2011) of galaxies:

$$\sigma_{\text{inf}} = \sqrt{\frac{GM_*}{K_\nu(n)c_v}} ,$$

where $K_\nu(n) = 0.557 \times K_\nu(n)$.

At $z \sim 0$, $\sigma_{\text{inf}}$ has proven to be a good approximation of the true central velocity dispersion ($\sigma$; Bezanson et al. 2011), which measures the potential well depth of galaxies.\footnote{In Bezanson et al. (2011), the comparison between $\sigma_{\text{inf}}$ and $\sigma$ is mainly performed using a large sample of SDSS galaxies at sample in the $\Sigma_1$ versus $\sigma_{\text{inf}}$ plane.}

As the $1\sigma$ uncertainty of the slope is large, the exact form of the BHAR-$\sigma_{\text{inf}}$ relation remains unclear. It has been suggested that AGNs can feed efficiently from surrounding dense gas clumps, at rates close to the dynamical rate $M_{\text{dyn}}$ (assuming that the gas is initially in rough virial equilibrium; Zubovas & King 2019):

$$\frac{M_{\text{dyn}}}{G} = \frac{f_{g}\sigma^3}{\sigma_{\text{inf}}} ,$$

where $f_g$ is the gas fraction in the galaxy that could explain the cosmic evolution of the BHAR-$\Sigma_1$ (or the BHAR-$\sigma_{\text{inf}}$) relation. Among quiescent galaxies that lack gas, $M_{\text{dyn}}$ cannot be achieved, so that BHAR does not have strong dependence $z \sim 0$ where a good agreement is confirmed. At high redshift, only tens of objects have measurements of $\sigma$ (with large error bars). Their $\sigma_{\text{inf}}$ values are in general consistent with $\sigma$ measurements. Bezanson et al. (2011) thus assume that $\sigma_{\text{inf}}$ can also be a good approximation of $\sigma$ at high redshift. This is also the underlying assumption when we use $\sigma_{\text{inf}}$ to approximate $\sigma$ for objects in our sample.

\footnote{We note that the BHAR-$\sigma_{\text{inf}}$ relation is not necessarily "responsible" for producing the $M_{\text{BH}}-\sigma$ relation among local bulges. The $M_{\text{BH}}-\sigma$ relation may simply mark the turning point where both the BH and galaxy cannot be fueled efficiently (e.g. King 2005, 2010).}
on $\sigma_{\text{gal}}$ (or $\Sigma_1$). The predicted slope (of 3) is within the $\sim 2\sigma$ confidence interval of the fitting result. A larger sample of galaxies/AGNs will be needed to provide further constraints on the relation that could validate or rule out this scenario, and provide more insights into the BH feeding mechanism among SF galaxies.

We also note that, from the side of galaxy evolution, $\Sigma_1$ (or $\sigma$) is linked with the color (or specific SFR) of galaxies (e.g. Fang et al. 2013; Whitaker et al. 2017), and serves as a good predictor of quiescence. AGN activity reaches the high-point among high-$\Sigma_1$ SF galaxies that become quiescent later on, which indicates that there is a potential link between AGNs and the quenching of galaxies: whatever process (i.e., AGN feedback, morphological quenching, halo gas shock heating) that quenches galaxies may also slow down the BH growth (see Figure 9 for the BH growth among high-$\Sigma_1$ quiescent galaxies).

4.2 Potential connections between the $\text{BHAR-} \Sigma_1$ relation and the $M_{\text{BH}}-M_{\text{bulge}}$ relation, and implications for BH “monsters” among local bulges

In Section 3.2, we confirmed the $\text{BHAR-} \Sigma_1$ relation among SF BD galaxies, and we also verified that the $\text{BHAR-} \Sigma_1$ relation among all SF galaxies applies to BD galaxies and Non-BD galaxies seamlessly in Section 3.3. The $\text{BHAR-} \Sigma_1$ relation and the $M_{\text{BH}}-M_{\text{bulge}}$ relation may indeed reflect the same underlying link. As discussed in Section 4.1, this link may be the direct dependence of BH growth on the central $\sim$ kpc gas density of host galaxies, or the dependence of BH growth on the host-galaxy potential well depth at a given gas content (which will also manifest a link between BH growth and $\Sigma_\text{gas}$ on the $\sim$ kpc scale). We will show below how the $\text{BHAR-} \Sigma_1$ and the $M_{\text{BH}}-M_{\text{bulge}}$ relation quantitatively agree. Among ellipticals and classical bulges in the local universe, the $M_{\text{BH}}-M_{\text{bulge}}$ relation takes the form of:

$$M_{\text{BH}} \propto M_{\text{bulge}}^\alpha$$

(11)

and the reported values of $\alpha$ range from $\approx 1.2$ (e.g. Kormendy & Ho 2013) to $\approx 1.4$ (e.g. Reines & Volonteri 2015). If we assume that this relation also approximately holds true at higher redshift (see Figure 38c of Kormendy & Ho 2015) and take the (time) derivative of this formula, we obtain:

$$dM_{\text{BH}} \propto M_{\text{bulge}}^{-\alpha-1} \times dM_{\text{bulge}}.$$  

(12)

which suggests that:

$$\text{BHAR} \propto M_{\text{bulge}}^{-\alpha-1} \times \text{SFR}_{\text{bulge}}.$$  

(13)

where SFR_{bulge} is the SFR of the bulge component. As bulges are compact with sizes of kpc, it is fair to assume that SFR_{bulge} is proportional to $\Sigma_{\text{SFR,1 kpc}}$. We can thus further express SFR_{bulge} as a function of $\Sigma_1$: $\text{SFR}_{\text{bulge}} \propto \Sigma_1^\beta$, where $\beta$ is the slope of the log $\Sigma_{\text{SFR}}$-log $\Sigma_1$ relation ($\beta \approx 0.7$; e.g. Cano-Diaz et al. 2016; Hsieh et al. 2017; Trayford & Schaye 2019; Hani et al. 2020). We can also approximate $M_{\text{bulge}}$ as a power-law function of $\Sigma_1$: through fitting all log $M_{\star} > 10.2$ BD galaxies at $z < 0.8$ in our sample, we find

If we fit the SFR-$\Sigma_1$ relation directly among the SF BD sample, we obtain a power-law index of $\approx 0.7 \pm 0.1$, consistent with the adopted $\beta$ values.
that the power-law index is \( \sim 1.6 \). We can then write the right side of equation 13 as a pure function of \( \Sigma_1 \):

\[
\text{BHAR} \propto \Sigma_1^{1.6} (\alpha - 1) \times \Sigma_1^{0.6}.
\] (14)

Different combinations of \( \alpha \) and \( \beta \) values predict the power-law index of the BHAR-\( \Sigma_1 \) relation to be \( \sim 1.6 \pm 0.2 \), which is consistent with our derived index of \( 1.6 \pm 0.2 \) in Section 3.3. Thus, it is plausible that the observed \( M_{\text{BH}} - M_{\text{bulge}} \) relation reflects the same underlying link as the BHAR-\( \Sigma_1 \) relation. This picture of the same underlying link for both the BHAR-\( \Sigma_1 \) and \( M_{\text{BH}} - M_{\text{bulge}} \) relations is also supported by the observed scatter of the \( M_{\text{BH}} - M_{\text{bulge}} \) relation. The \( \Sigma_1 \) values of SF BD galaxies in our sample at a given \( M_\star \) have a scatter of \( \sim 0.2 \) dex. Considering the BHAR-\( \Sigma_1 \) relation, we would expect a \( \sim 0.3 \) dex scatter for the \( M_{\text{BH}} - M_{\text{bulge}} \) relation, which is the scatter observed in Section 6.6.1 of Kormendy & Ho (2013).

It is plausible that the \( M_{\text{BH}} - M_{\text{bulge}} \) relation cannot characterize the BH “monsters” (i.e. BHs found in local compact galaxies that have \( M_{\text{BH}} \) values much larger than expected from the \( M_{\text{BH}} - M_{\text{bulge}} \) relation) well simply because in cases where the bulge is so compact and the gas is so highly concentrated, the central \( \sim \) kpc gas density (or the central velocity dispersion that is tightly linked with compactness) cannot be well approximated by the SFR of the whole bulge. Our derived BHAR-\( \Sigma_1 \) relation in Section 3.3, at the same time, may manifest the underlying link better in ultra-compact SF bulges, and it has the potential to explain the local BH “monsters”. We will take NGC 4486B as an example, where the \( \sim 6 \times 10^4 \) M\(_\odot\) BH is “overmassive” by \( \sim 1.7 \) dex (Kormendy & Ho 2013). NGC 4486B has \( r_c \approx 0.2 \) kpc and \( n = 2.2 \) (Kormendy et al. 2009). If we compare NGC 4486B with a typical local bulge that has \( r_c \approx 3 \) kpc and \( n = 3 \), we find that the percentage of mass concentrated in the central \( 1 \) kpc of NGC 4486B is greater than that of a typical bulge by a factor of \( \sim 5 \). This means that the \( \Sigma_1 \) value of NGC 4486B is larger than the typical \( \Sigma_1 \) value at the same \( M_{\text{bulge}} \) by \( \sim 0.7 \) dex. If we assume this deviation approximately holds true during all BH-growth episodes of NGC 4486B, a \( \sim 1.1 \) dex deviation in its \( M_{\text{BH}} \) compared with typical local bulges that have similar \( M_{\text{bulge}} \) values will be generated according to the derived BHAR-\( \Sigma_1 \) relation (see Equation 9). We also note that for a given \( \Sigma_1 \), the expected amount of BH growth could increase by \( \sim 1 \) dex when the redshift rises (see Figure 8). If NGC 4486B is a “relic” galaxy that had finished growing most of its \( M_{\text{BH}} \) by \( z \approx 2 \), an additional deviation of its \( M_{\text{BH}} \) by up to \( \sim 1 \) dex compared with typical local bulges that have similar \( M_{\text{bulge}} \) values can be expected. Taking all these into account, the \( \sim 1.7 \) dex deviation in \( M_{\text{BH}} \) of NGC 4486B from the \( M_{\text{BH}} - M_{\text{bulge}} \) relation is understandable as BHs among SF galaxies follow the BHAR-\( \Sigma_1 \) relation.

5 CONCLUSIONS AND FUTURE WORK

Utilizing extensive multiband observations in the COSMOS survey field, we have revealed and studied the dependence of BH growth on host-galaxy compactness represented by \( \Sigma_1 \) among SF galaxies. The main points from this paper are the following:

- (i) We built a catalog of \( f_{\text{F814W}} < 24 \) galaxies at \( z < 1.2 \) from the COSMOS survey field (Section 2). We measured their \( M_\star \) and SFR values utilizing UV-to-FIR photometry (Section 2.1 and Appendix A). We measured their structural parameters (Section 2.2 and Appendix B), and classify them as BD or Non-BD galaxies (Section 2.3 and Appendix C) utilizing the high-resolution HST F814W mosaics. Drawing upon all these measurements, we compiled a sample of SF Non-BD galaxies and a sample of SF BD galaxies, as well as an ALL SF sample regardless of morphology (Section 2.4). \( \Sigma_1 \) values of galaxies are calculated from \( M_\star \) and structural parameters. Deep Chandra X-ray observations in the field are utilized to estimate BHAR for samples of galaxies (see Section 2.5).

- (ii) Utilizing partial-correlation analyses, we found that the BHAR-\( \Sigma_1 \) relation is more fundamental than the BHAR-\( M_\star \) relation among SF Non-BD galaxies (Section 3.1), as we observe a significant BHAR-\( \Sigma_1 \) relation when controlling for \( M_\star \), while we do not observe a significant BHAR-\( M_\star \) relation when controlling for \( \Sigma_1 \). We also found that the BHAR-\( \Sigma_1 \) relation is significant when controlling for SFR in the SF BD sample (Section 3.2), which suggests that the BHAR-\( \Sigma_1 \) relation also exists among SF BD galaxies.

- (iii) We confirmed that the same BHAR-\( \Sigma_1 \) relation applies to both SF Non-BD and SF BD galaxies, and this BHAR-\( \Sigma_1 \) relation is more fundamental than either the BHAR-\( M_\star \) or BHAR-SFR relation among SF galaxies (Section 3.3). Our best-fit log BHAR-log \( \Sigma_1 \) relation has a slope of \( 1.6 \pm 0.2 \). While the slope of the log BHAR-log \( \Sigma_1 \) relation does not exhibit noticeable changes with redshift, BHAR at a given \( \Sigma_1 \) evolves with redshift in a manner that could be well explained by the cosmic evolution of the gas content (Section 3.3 and Section 4.1). The BHAR-\( \Sigma_1 \) relation among SF galaxies could suggest a link between BH growth and the central \( \sim \) kpc gas density of host galaxies. A common origin for gas in the vicinity of the BH and in the central \( \sim \) kpc part of the galaxy may be further implied by this relation. The BHAR-\( \Sigma_1 \) relation could also be interpreted as a relation between BH growth and the central velocity dispersion of host galaxies at a given gas content, indicating the role of the host-galaxy potential well in feeding BHs (Section 4.1).

- (iv) The quantitatively derived BHAR-\( \Sigma_1 \) relation in Section 3.3 has the potential to explain local BH “monsters” among compact galaxies (Section 4.2). It is plausible that both the BHAR-\( \Sigma_1 \) and \( M_{\text{BH}} - M_{\text{bulge}} \) relations manifest the same underlying link between BH growth and host galaxies discussed in Section 4.1, and local BH “monsters” deviate from the \( M_{\text{BH}} - M_{\text{bulge}} \) relation simply because the total SFR of ultra-compact bulges cannot approximate the central \( \sim \) kpc gas density (or the velocity dispersion) well.

In the future, deep JWST imaging combined with deep X-ray coverage could help to quantify the BHAR-\( \Sigma_1 \) relation among SF galaxies better with a larger sample of galaxies/AGNs that has lower limiting \( M_\star \). JWST IFU observations (as well as grism observations) could measure the gas/stellar velocity dispersion of galaxies/AGNs, enabling the first characterization of the BHAR-\( \sigma \) relation. Future accumulation of ALMA pointings that have HST-like resolution in deep X-ray survey fields could help to probe the relation between BH growth and host-galaxy central gas density.
directly. Quantifying these relations could provide insights into the feeding mechanism of BHs, and how it links with the host galaxies.

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APPENDIX A: ASSESSING $M_*$ AND SFR MEASUREMENTS FROM X-CIGALE

In Table A, we list the parameters used to construct the SED templates when fitting $M_*$ and SFR with X-CIGALE in Section 2.1. In Figure A1, we show the comparison between our SED-based $M_*$ (SFR) measurements with X-CIGALE and SFR-based $M_*$ (SFR) measurements with Prospector in Leja et al. (2019a) for log $M_*$ > 9.5 COSMOS SF galaxies at $z = 0.2-0.8$, as well as the comparison of the obtained specific SFR (sSFR; which is calculated as SFR/$M_*$). In Leja et al. (2019a), a more flexible nonparametric SFH, a more flexible dust attenuation law, and a more flexible dust-emission model are utilized, which is beyond the scope of this work due to the large amount of computational time needed. We can see that our $M_*$ measurements are systematically smaller than those reported in Leja et al. (2019a) by $\approx 0.15$ dex. As reported in Leja et al. (2019b), this offset is expected mainly due to the usage of a nonparametric SFH in Prospector. We correct for this systematic offset in the final adopted $M_*$ values (by adding 0.15 dex to the obtained log $M_*$ values), though we note that as we only quantitatively study the slope of the log BHAR-log $\Sigma_1$ relation in this paper, the systematic offset in $M_*$ measurements should not affect our results. Our SFR measurements do not show any systematic offset when compared with SFR measurements in Leja et al. (2019a). The relatively small scatter of $\approx 0.1$ dex in $M_*$ and $\approx 0.2$ dex in SFR between the two sets of measurements demonstrates that though our adopted SED libraries may not be the ideal approach, they are an acceptable approach. For X-ray detected galaxies especially, the systematic offset and the scatter of $M_*$ are close to those for the general galaxy population; there is a $\approx 0.1$ dex offset between the two sets of SFR measurements and the scatter is relatively larger ($\approx 0.35$ dex) due to the default usage of AGN templates in our study (SED-based SFR measurements mainly depend on the UV and IR SED where the AGN component has non-negligible contributions). We note that even with the offset and the relatively larger scatter, $\approx 81\%$ of X-ray detected objects have SFR values in the two sets of measurements agreeing within 0.5 dex.

We also compare our SED-based SFR measurements with FIR-based SFR measurements, as can be seen in Figure A2. We can see that the median offset between the two measurements is small ($\approx 0.19$ dex). For $\approx 87\%$ of the objects ($\approx 73\%$ of X-ray detected objects), SFR values measured by these two methods agree within 0.5 dex, which demonstrates that our SED-based SFR measurements are in general agreement with the FIR-based SFR estimation.

APPENDIX B: ASSESSING STRUCTURAL MEASUREMENTS FROM GALFIT

Sargent et al. (2007) provide GIM2D structural measurements for $I_{F814W} < 22.5$ objects in COSMOS. We compare our measured $r_e$ values and $n$ values with those reported in Sargent et al. (2007) in Figure B1. As can be seen from the figure, our $r_e$ and $n$ measurements have negligible systematic offsets when compared with Sargent et al. (2007) (our $r_e$ and $n$ values are slightly larger in general), and the scatter between the two sets of measurements is $\approx 0.05$ dex for $r_e$ and...
Table A1. Utilized X-CIGALE modules with fitting parameters. Default values are adopted for parameters not listed.

| Module                                      | Parameters          | Values                          |
|---------------------------------------------|---------------------|---------------------------------|
| Star formation history: sfhdelayed          | τ (Myr)             | 100, 150, 200, 250, 300, 350, 400, 500, 600, 800, 1200, 2000, 3000, 5000, 8000 |
|                                             | t (Myr)             | 50, 100, 200, 300, 400, 500, 600, 800, 1000, 1500, 2000, 2500, 3000, 3500, 4000, 5000, 6000, 8000, 10000 |
| Stellar population synthesis model: bc03    | Initial mass function | Metallicity                      | Chabrier (2003)                     |
|                                             |                     | 0.02                             |
| Nebular emission: nebular                   |                     | E(B − V) for the young population | 0.0–1.5 in a step of 0.1 |
| Dust attenuation: dustatt CALZETTI          |                     | E(B − V) reduction factor of the old population | 0.44 |
| Dust emission: dale2014                     |                     | α in dM_dust = U^{−α}dU          | 1.5, 2.0, 2.5 |
| AGN emission: skirtor2016                  | Torus optical depth at 9.7μm | 7 |
|                                             | Viewing angle (°)   | 30, 70                          |
|                                             | AGN fraction in total IR luminosity (frac_{AGN}) | 0–0.9 in a step of 0.1, 0.99 |
|                                             | E(B − V) of AGN polar dust | 0.1, 0.2, 0.3, 0.4, 0.5 |

**Figure A2.** Similar to Figure A1, but for SED-based SFR values (measured with X-CIGALE) versus FIR-based SFR values for all log M* > 9.5 COSMOS galaxies.

≈ 0.1 dex for n,\(^{11}\) which demonstrates that our structural measurements are consistent with Sargent et al. (2007).

We note that while point-like emission from AGNs has the potential to contaminate host-galaxy light profiles which may affect the reliability of structural measurements, this contamination is small in our sample (where AGNs that dominate over host galaxies are removed; see Section 2.4). We stack the F814W-band surface brightness profiles of ≈ 650 X-ray AGNs (log L_X > 42 sources) at z < 1.2 in our compilation. For each of these X-ray AGNs, we select one galaxy not detected in the X-ray that has the closest n and r_e values to it (without duplications). We then stack the F814W-band surface brightness profiles of these matched X-ray undetected galaxies. The comparison between the stacked surface brightness profiles of X-ray AGNs and X-ray undetected galaxies with similar structural parameters can be seen in Figure B2. We can see that the stacked surface brightness profile of X-ray AGNs is very similar to that of X-ray undetected galaxies without any obvious “excess” in the center which suggests nuclear contamination from AGNs (see section 3.1 of Kocevski et al. 2017). The median reduced χ^2 of the single-component Sérsic fits of X-ray AGNs (≈ 1.1) is also similar to that of X-ray undetected galaxies. We also model how the point-like emission from AGN may affect the host-galaxy surface brightness profile: for the stacked surface brightness profile of X-ray undetected galaxies, we add point-like emission which accounts for ≈ 5% of its total integrated light (the point-like emission is modeled utilizing the PSF generated in Section 2.2.2). The obtained composite surface brightness profile clearly shows higher surface brightness than X-ray AGNs in the centers of galaxies (see Figure B2). Thus, the contamination to the host-galaxy light profile in the HST F814W band is small for X-ray AGNs in our sample. For comparison, we also show the stacked surface brightness profile of X-ray AGNs removed from our sample in Figure B2, which demonstrates high levels of AGN contamination.

**APPENDIX C: IDENTIFYING BD GALAXIES IN THE COSMOS FIELD**

We classify galaxies as BD/Non-BD utilizing a convolutional neural network (CNN). To train the CNN, we select ≈ 8000 galaxies among all f_{814W} < 24 galaxies (MU_CLASS = 1; MU_CLASS is a star/galaxy classifier in the COSMOS ACS catalog; Leauthaud et al. 2007) in the COSMOS HST field (Capak et al. 2007; Leauthaud et al. 2007), and manually assign each of them a binary label of BD (1) or Non-BD (0). In order to make the selection of BD galaxies consistent with Kartaltepe et al. (2015) and Huertas-Company et al. (2015) (here we are pointing to objects with f_spb > 2/3, f_disk < 2/3, and f_ire < 1/10), 4015 galaxies in the training set are selected from the CANDELS-COSMOS field, where...
morphological classifications from Huertas-Company et al. (2015) are available. When labeling these sources, we try to be consistent with Huertas-Company et al. (2015), and the overall agreement is ≈ 95%. Approximately 71%/99% of BD/Non-BD galaxies identified in Huertas-Company et al. (2015) are still labeled as BD/Non-BD galaxies. The reason for the relatively low level of agreement among BD galaxies can be attributed to both the morphological k-correction and the different angular resolution of CANDELS F160W images (0.06”/pixel) and COSMOS F814W images (0.03”/pixel) (see Figure C1). The other 4271 galaxies are randomly selected across the whole COSMOS field, and we visually classify them as consistently as possible. Among the 8286 galaxies in total, 891 galaxies are classified as BD galaxies (see Figure C2).

We split these labeled galaxies into a training set (5286 galaxies), a validation set (1500 galaxies), and a test set (1500 galaxies). We then create cutouts for them of size 64×64 pixels from ACS COSMOS science images v2.0 (Koekemoer et al. 2007), and store the normalized FITS file as NumPy arrays.

Before the training, we copy the the training set nine times and add random Gaussian noise (that is small enough to be not noticeable) to the training set, but not in the validation and test set.

The relatively large number of objects placed in the validation/test set compared to common practice is due to the limited fraction (≈ 10%) of BD galaxies: the number of BD galaxies in the validation/test set should be large enough for reasonable statistics.

---

**Figure B1.** Upper panel: 2D KDE plot of our \( r_e \) values measured with GALFIT versus \( r_e \) measured with GIM2D (Sargent et al. 2007) in log-log space. Black error bars represent the median GALFIT-based \( r_e \) in different bins of GIM2D-based \( r_e \) and the scatter between the two sets of measurements in each bin. The black solid line represents a 1:1 relation. Lower panel: Similar to the upper panel, but for \( n \) measured with GALFIT versus \( n \) measured with GIM2D in Sargent et al. (2007).

**Figure B2.** Stacked \( I_{814W} \)-band surface brightness profiles of X-ray AGNs (black squares) and X-ray undetected galaxies with similar \( n \) and \( r_e \) values (red circles). The blue triangles show the modeled surface brightness profile when X-ray undetected galaxies have a ≈ 5% contamination to their total integrated light from AGNs on average. The green dots show the stacked surface brightness profile of removed X-ray AGNs in Section 2.4.

**Figure C1.** Examples of BD galaxies classified in Huertas-Company et al. (2015) with \( H_{160W} \)-band images, but not classified as BD galaxies in our training sample. In each subfigure, the left panel is the \( I_{814W} \)-band cutout of size 64 × 64 pixels, and the right panel is the \( H_{160W} \)-band cutout of size 64 × 64 pixels.
At the beginning of each learning epoch, we use the Adam optimizer (Kingma & Ba 2014) to minimize the loss, and we also apply the inverse class ratio as the weight to the loss. The network depth, filter size, and number of channels are set based on our observations, and we find that the number of FP is larger than the number of FN (due to the sample imbalance). For the purpose of this work, we require the “contamination” in the BD sample to be as small as possible. Thus, we use the validation set to select a higher probability threshold that can make the number of FP approximately equal to the number of FN. The final training results can be seen in Table C2.

We test the obtained model with the test set. When converting the predicted probability into a binary label, we first use the default threshold of 0.5 to classify BD/Non-BD galaxies, and we find that the number of FP is larger than the number of FN (due to the sample imbalance). For the purpose of this work, we require the “contamination” in the BD sample to be as small as possible. Thus, we use the validation set to select a higher probability threshold that can make the number of FP approximately equal to the number of FN. The final training results can be seen in Table C2.

We can correctly predict ≈ 87.3% of BD galaxies and 98.4% of Non-BD galaxies in the test set, and the number of predicted BD galaxies is roughly equal to the number of true BD galaxies.

With the trained CNN and the tuned probability threshold, we classify ≈ 115,000 4FW-< 24 galaxies in the COSMOS ACS field as BD or Non-BD. Figure C3 shows example cutouts of the predicted BD galaxies and Non-BD galaxies (the presented galaxies are randomly drawn from the sample). In Figure C4 we show the distributions of n among classified BD galaxies and Non-BD galaxies. The clear separation in the distribution of n between the two populations demonstrates further the validity of our classification. We also note that our classification is consistent with that of Huertas-Company et al. (2015) when comparing the relative numbers of BD galaxies. At z < 0.8 and log $M_*$ > 10.2, 2117 galaxies in our sample are classified as BD galaxies. This number is 453 for the CANDELS field, with BD galaxies identified in Huertas-Company et al. (2015). The ratio between these two numbers is roughly consistent with the ratio between our utilized area of COSMOS (≈ 1.4 deg$^2$) and the area of CANDELS (≈ 0.25 deg$^2$).

### APPENDIX D: PCOR ANALYSES WITH DIFFERENT BINNING APPROACHES

We verified that the PCOR analysis results in Section 3 do not change qualitatively when the binning approach changes.

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**Figure C2.** Example I$_{4714}$-band cuts (64 × 64 pixels) of BD galaxies visually identified in the training set.

**Table C1.** Convolutional Neural Network Configuration.

| Layer       | Filter Size | Feature Number | Output Shape                |
|-------------|-------------|----------------|-----------------------------|
| Conv2D      | 3x3         | 32             | (64, 64, 32)                |
| Conv2D      | 3x3         | 32             | (64, 64, 32)                |
| MaxPooling2D| 2x2         | -              | (32, 32, 64)                |
| Conv2D      | 3x3         | 64             | (32, 32, 64)                |
| Conv2D      | 3x3         | 64             | (32, 32, 64)                |
| MaxPooling2D| 2x2         | -              | (16, 16, 64)                |
| Conv2D      | 3x3         | 128            | (16, 16, 128)               |
| Conv2D      | 3x3         | 128            | (16, 16, 128)               |
| MaxPooling2D| 2x2         | -              | (8, 8, 128)                 |
| Dense       | -           | 1024           | 1024                        |
| Dropout(0.2)| -           | -              | -                           |
| Dense       | -           | 1              | 1                           |

**Table C2.** Training results assessed with the test set of 1500 galaxies.

|          | TP  | FP  | TN  | FN  | Accuracy | F1  |
|-----------|-----|-----|-----|-----|----------|-----|
| BD        | 144 | 21  | 1314| 21  | 87.3%    | 0.87|
| Non-BD    |     |     |     |     | 98.4%    |     |
| Overall   | 144 | 21  | 1314| 21  | 97.2%    |     |

where

\[
\text{precision} = \frac{\text{True Positive (TP)}}{\text{True Positive (TP) + False Positive (FP)}}
\]

\[
\text{recall} = \frac{\text{True Positive (TP)}}{\text{True Positive (TP) + False Negative (FN)}}
\]

The F1 score is widely used to assess the quality of binary classification. For imbalanced data sets, it is more sensitive to the true quality of classification than accuracy. We drop the learning rate by a factor of 2 if the F1 score of the validation set stops increasing for 10 epochs. When the F1 score of the validation set stops increasing for 50 epochs, we stop the training process and save the model.
Our finding in Section 3.1/Section 3.3 that the BHAR-Σ_{1} relation is more fundamental than the BHAR-M_{*} relation for the SF Non-BD/ALL SF sample holds true when we use 5 × 5 bins or 6 × 6 bins. Also, if we bin objects so that each 2D bin has the same number of X-ray detected galaxies (see Figure D1), our results do not change qualitatively (see Table D1). Similarly, our finding in Section 3.2 that the BHAR-Σ_{1} relation exists when controlling for SFR for the SF BD sample holds true when we use 4 × 4 bins; this result does not change qualitatively when we bin objects based on the number of X-ray detected galaxies (see the middle panel of Figure D1 and Table D1).

### APPENDIX E: THE BHAR-SFR RELATION AMONG BD GALAXIES IN GENERAL

Though in Section 3.2 we found that among SF BD galaxies, the BHAR-Σ_{1} relation is significant when controlling for SFR while the BHAR-SFR relation is not significant when controlling for Σ_{1}, we note that the BHAR-SFR relation is still the dominant relation among BD galaxies in general (i.e., including quiescent BD galaxies; see Figure E1), consistent with the findings in Yang et al. (2019). In Figure E1, we show that the BHAR-SFR trend for all BD galaxies with log M_{*} > 10 at z < 1.2 in the COSMOS field is close to the BHAR-SFR relation obtained in Yang et al. (2019) utilizing z = 0.5–3 galaxies in the CANDELS field.\footnote{The Yang et al. (2019) relation is well-constrained from log SFR = 1.5 to log SFR = −2, probing log BHAR from z = −1 to z = −4.5, so that it could be applied to the parameter space probed in this work.}

We also show that the difference in Σ_{1} at a given SFR value does not associate with a significant difference in BHAR except for the highest SFR bin (where a ≈ 3.7σ difference in BHAR is associated with Σ_{1}).

As discussed in Ni et al. (2019) and Section 4.2, the BHAR-SFR relation among BD galaxies and the BHAR-Σ_{1} relation only among SF BD galaxies may reflect the same link between BH growth and the central ~ kpc gas density of host galaxies. In general, as BD galaxies are typically compact with r_e on ~ kpc scales, the SFR among BD galaxies could serve as an indicator of the central ~ kpc gas density. However, if the distribution of the cold gas among a BD galaxy is far from being uniform, then the SFR of the whole bulge component may not be an ideal indicator of the central ~ kpc gas density. Among SF BD galaxies, Σ_{1} could serve as a better indicator (though this indicator only works for SF galaxies).

#### Table D1. p-values (significances) of partial correlation analyses for the samples binned by the number of X-ray detected galaxies

| Relation   | Pearson | Spearman |
|------------|---------|----------|
| BHAR-Σ_{1} | 9 × 10^{-5} (3.9σ) | 2 × 10^{-4} (3.7σ) |
| BHAR-M_{*} | 0.08 (1.8σ) | 0.23 (1.2σ) |

| Relation   | Pearson | Spearman |
|------------|---------|----------|
| BHAR-Σ_{1} | 2 × 10^{-3} (3.1σ) | 7 × 10^{-3} (2.7σ) |
| BHAR-SFR  | 0.04 (2.1σ) | 0.73 (0.4σ) |

| Relation   | Pearson | Spearman |
|------------|---------|----------|
| BHAR-Σ_{1} | 2 × 10^{-4} (3.8σ) | 5 × 10^{-3} (2.8σ) |
| BHAR-M_{*} | 0.10 (1.6σ) | 0.22 (1.2σ) |
Figure D1. Left panel: Color-coded BHAR in different bins of $M_*$ and $\Sigma_1$ for galaxies in the SF Non-BD sample. Each 2D bin contains $\approx 11$ X-ray detected galaxies. The black plus sign indicates the median $M_*$ and $\Sigma_1$ of the sources in each bin. Middle panel: Color-coded BHAR in different bins of SFR and $\Sigma_1$ for galaxies in the SF BD sample. Each 2D bin contains $\approx 9$ X-ray detected galaxies. The black plus sign indicates the median SFR and $\Sigma_1$ of the sources in each bin. Right panel: Color-coded BHAR in different bins of $M_*$ and $\Sigma_1$ for galaxies in the ALL SF sample. Each 2D bin contains $\approx 13$ X-ray detected galaxies. The black plus sign indicates the median $M_*$ and $\Sigma_1$ of the sources in each bin.

Figure E1. BHAR vs. SFR for BD galaxies with log $M_*$ > 10 at $z < 1.2$ in the COSMOS field divided into SFR bins with $\approx 1000$ sources per bin. Each SFR bin (black circles) is further divided into two subsamples with $\Sigma_1$ above (blue upward-pointing triangles) and below (red downward-pointing triangles) the median $\Sigma_1$ of the bin, respectively. The black solid line represents the best-fit BHAR-SFR relation in Yang et al. (2019). We can see that the general BHAR-SFR trend is close to that obtained in Yang et al. (2019).
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