AGN Selection Methods Have Profound Impacts on the Distributions of Host-galaxy Properties

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Abstract

We present a comparative study of X-ray and IR active galactic nuclei (AGNs) at z ≈ 2 to highlight the important AGN selection effects on the distributions of host-galaxy properties. Compared with non-AGN star-forming galaxies (SFGs) on the main sequence, X-ray AGNs have similar median star formation (SF) properties, but their incidence (qAGN) is higher among galaxies with either enhanced or suppressed SF, and among galaxies with a larger stellar-mass surface density, regardless if it is measured within the half-light radius (Σe) or central 1 kpc (Σ1kpc). Unlike X-ray AGNs, IR AGNs are less massive and have enhanced SF and similar distributions of colors, Σe and Σ1kpc, relative to non-AGN SFGs. Given that Σe and Σ1kpc strongly correlate with M* s, we introduce the fractional mass within the central 1 kpc (M1kpc/M*), which only weakly depends on M*, to quantify galaxy compactness. Both AGN populations have similar M1kpc/M* distributions compared to non-AGN SFGs. While qAGN increases with Σe and Σ1kpc it remains constant with M1kpc/M*, indicating that the trend of increasing qAGN with Σ is driven by M* more than morphology. While our findings are not in conflict with the scenario of AGN quenching, they do not imply it either, because the incidence of AGNs hosted in transitional galaxies depends crucially on AGN selections. Additionally, despite the relatively large uncertainty of AGN bolometric luminosities, their very weak correlation, if any, with SF activities, regardless of AGN selections, also argues against a direct causal link between the presence of AGNs and the quenching of massive galaxies at z ∼ 2.

Unified Astronomy Thesaurus concepts: AGN host galaxies (2017); High-redshift galaxies (734); Galaxy evolution (594)

1. Introduction

Modern observational cosmology, primarily the observations of cosmic large-scale structures such as baryon acoustic oscillations (e.g., Eisenstein et al. 2005) and the polarization of the cosmic microwave background (e.g., Planck Collaboration et al. 2016), are, for the most part, in good quantitative agreement with the predictions of the Lambda Cold Dark Matter (ΛCDM) paradigm. However, a key prediction of the theory—the mass function of dark matter halos—significantly differs from the observed galaxy stellar-mass function at both the low-mass and high-mass ends (see Wechsler & Tinker 2018 and references therein), which reflects the complex, and still poorly understood, dependence of the physics of star formation on the halo mass and the environment.

In order to reproduce the observations at the high-mass end, a crucial ingredient required by most theoretical models (see Somerville & Davé 2015 and references therein) is the so-called active galactic nucleus (AGN) feedback, which refers to the effects produced by the active nucleus activities (winds, jets, radiation) of a massive galaxy on the surrounding interstellar medium (ISM) and circumgalactic medium (CGM). The concept of AGN feedback was initially introduced by Silk & Rees (1998) and Haehnelt et al. (1998) to explain the observed tight correlations among black hole mass (MBH), bulge mass/luminosity, and velocity dispersion. Recently, depending on the nature of energy output, two major modes of AGN feedback are being considered: radiative and kinetic feedback (see the review of Fabian 2012 and references therein). Kinetic mode, sometimes also known as radio mode, refers to the feedback effects generated by the mechanical energy of radio jets, which are often observed when AGN radiative activities are operating at low levels. In contrast, the radiative mode refers to the feedback effects occurring when AGNs are very luminous. In this work, we will specifically focus on the radiative AGNs.

In the absence of AGN feedback, cosmological simulations under the ΛCDM paradigm produce too many massive galaxies compared to the observations (e.g., Oppenheimer et al. 2010; Kaviraj et al. 2017), and the simulated massive galaxies also are too blue (e.g., Hatton et al. 2003) and too compact (e.g., Peirani et al. 2017). For the simulations, one resolution to those discrepancies is to add the subgrid AGN feedback models to suppress star formation in massive galaxies, a process generically referred to as AGN quenching. While including such models has become increasingly popular in modern cosmological simulations, a big concern is the large uncertainty on how to properly implement AGN physics and couple the feedback effects to the ISM (e.g., Di Matteo et al. 2005; Booth & Schaye 2009; Weinberger et al. 2017). It is therefore of great importance to observationally investigate the effects of AGNs on the host galaxies.
Taking advantage of deep and high-angular resolution X-ray observations, significant progress has been recently made in understanding the relationship between X-ray AGNs (e.g., Xue et al. 2016; Luo et al. 2017; Fornasini et al. 2018; Brown et al. 2019) and the properties of their host galaxies (e.g., Xue et al. 2010; Yang et al. 2017, 2018; Kocevski et al. 2017). Yet, observational evidence of the feedback effects from X-ray AGNs is far from conclusive. For example, at \( z \approx 2 \), where both the quasar activities (Hasinger et al. 2005) and cosmic star formation rate (SFR) density (Madau & Dickinson 2014) peak, AGN feedback (if any) is expected to be strong. A number of studies have been carried out to investigate the star formation properties for the host galaxies of X-ray AGNs out to \( z \approx 3 \) (e.g., Lutz et al. 2010; Santini et al. 2012; Rosario et al. 2012; Rovilos et al. 2012; Page et al. 2012; Harrison et al. 2012; Barger et al. 2015; Hatziminaoglou et al. 2010; Harrison et al. 2012; Stanley et al. 2015; Barger et al. 2019). While many of these studies have consistently shown that the median star formation intensity in galaxies hosting moderately luminous X-ray AGNs (\( 42 < \log L_X < 44 \)) is similar to that in normal star-forming galaxies (SFGs), diverging conclusions emerge in luminous (\( \log L_X > 44 \)) X-ray AGN hosts. For example, using far-infrared (FIR) luminosity as the SFR estimator, some groups (e.g., Page et al. 2012; Barger et al. 2015) reported suppressed star formation in luminous X-ray AGN-hosting galaxies, while others (e.g., Lutz et al. 2010; Santini et al. 2012; Rovilos et al. 2012) reached the opposite conclusion that their samples of luminous X-ray AGNs show enhanced star formation. Yet, other investigators (Harrison et al. 2012; Stanley et al. 2015) reported no dependence of star formation activity on the X-ray AGN luminosity.

One general issue with the observational studies of the effects of the presence of an AGN on the host-galaxy properties is the interpretation of the data. Empirically speaking, compared with non-AGNs, any distinct distribution of physical properties of AGN hosts can be attributed to the presence of AGNs. However, such attribution does not necessarily imply a causal relationship in the sense that the real cause(s) behind might be some other mechanisms that are also likely to trigger AGN activities, even if the latter is only weakly related, if at all, to the properties of the host. One example is galaxy major merger, where strong gravitational torques induced by the merging galaxy/galaxies can drive gas to the center, which as a result can simultaneously (1) make the gas distribution more nucleated, (2) trigger a central starburst and increase the galactic-wide SFR, and (3) trigger a bright AGN (e.g., Mihos & Hernquist 1996; Sanders et al. 1988; Hopkins et al. 2006).

The other issue comes from the AGN selection, which is the focus of this work. While selecting AGNs in X-ray has been shown to be one of the most efficient ways to study them, it is by no mean complete. Because X-ray photons (soft ones in particular) suffer heavily from line-of-sight obscuration, X-ray selection itself can miss a significant fraction of obscured AGNs (e.g., Gilli et al. 2007), which become increasingly important at higher redshifts where the fraction of obscured AGNs becomes larger (e.g., Liu et al. 2017). To get a comprehensive observational picture of AGN feedback, the missing population of AGNs must be taken into account.

Observations at mid-IR (MIR) are efficient to identify those highly obscured AGNs missed by the X-ray selection (e.g., Daddi et al. 2007; Donley et al. 2008), because the MIR directly probes the reprocessed radiation from the absorbed X-ray, UV, and optical photons. The primary issue of studying AGNs in the MIR is the confusion with light from the host galaxies. Unless the AGNs are powerful enough, their spectral energy distribution (SED) in MIR is always a comparable mixture of the reprocessed emission from AGNs and the emission from star formations. Despite the shape of AGN MIR spectra remaining to be characterized in detail by future studies, e.g., with the James Webb Space Telescope (JWST; e.g., Kirkpatrick et al. 2017), substantial progress has been recently made in identifying IR AGNs using the broadband photometry in MIR, including the selection methods based on Spitzer IRAC colors (e.g., Lacy et al. 2004; Stern et al. 2005; Donley et al. 2008, 2012; Kirkpatrick et al. 2013), WISE colors (e.g., Eisenhardt et al. 2012; Stern et al. 2012), and SED decomposition techniques (e.g., Armus et al. 2007; Pope et al. 2008; Kirkpatrick et al. 2012; Berta et al. 2013). Finally, some progress has also been made in understanding the MIR spectroscopic properties of AGNs at high redshifts using the observations from Spitzer/IRS (Kirkpatrick et al. 2013), although such studies are only limited to luminous AGNs given the MIR sensitivities of current instruments.

In this work, we present a comparative study of the properties of the host galaxies of X-ray- and IR-selected AGNs. Specifically, we will compare the star formation and morphological properties of AGN- and the non-AGN-hosting galaxies, focusing on the effects, if any, of the presence of AGNs on their host galaxies. Throughout this paper, we adopt a ΛCDM cosmology with \( \Omega_m = 0.3, \Omega_\Lambda = 0.7, \text{ and } h = H_0/(100 \text{ km s}^{-1} \text{ Mpc}^{-1}) = 0.7. \)

### 2. Sample Selection

In this section, we describe in detail the sample selections in this work. Table 1 lists the number of galaxies in each sample.

#### 2.1. Parent Sample

Our parent sample is the same as that of Lee et al. (2018), which is drawn from 4809 Hubble Space Telescope (HST) \( H_{160} \)-band selected galaxies in the GOODS-S (2500 galaxies) and GOODS-N (2309 galaxies) fields. Both fields have deep HST/ACS data acquired during the GOODS survey (Giavalisco et al. 2004) and the deep HST/WFC3 data acquired during the CANDELS survey (Grogin et al. 2011; Koekemoer et al. 2011). The sample galaxies are selected to be in the redshift range of \( 1.2 < z < 4 \) with \( M_\star > 10^{9.5} M_\odot \) and their isophotal \( H_{160} \) signal-to-noise ratios (S/Ns) are required to be \( S/N > 10 \) in order to get good photometry and hence high-quality photometric redshifts (photo-z) and spectral energy distribution (SED) fitting measures. The full sample is divided into two subsamples according to the star formation properties of the galaxies (Figure 1). SFGs and quiescent galaxies (QGs) are distinguished using the rest-frame \( U/VJ \)-color diagram (see Section 3.1 for the measurements of rest-frame colors) that was initially proposed by Williams et al. (2009). In this work, we adopt the SFG–QG separation boundary from Schreiber et al. (2015), which is built upon

| Field      | Parent Sample | X-Ray AGNs | IR AGNs |
|------------|---------------|------------|---------|
| GOODS-S    | 2500          | 164        | 69      |
| GOODS-N    | 2309          | 74         | 69      |
| All        | 4809          | 238        | 138     |

- Table 1: The Number of Galaxies in Each Sample
and to 10^9 M☉ (spectral shape criteria built upon the intrinsic X-ray luminosity threshold and cross-matching the CANDELS catalog of the parent sample with request the redshifts of sample galaxies = CANDELS galaxies and has been demonstrated to be valid up to 4. Ji et al. (2018) used the simulation done by Guo et al. (2013) to show that the parent sample is ≈80% complete down to 10^9 M☉. In this work, we decide to ignore galaxies with stellar mass less than 10^9.5 M☉ because (1) a lower-mass galaxy statistically tends to have a lower metallicity (e.g., Tremonti et al. 2004) such that the AGN selection based on IR colors can mimic an AGN when really there is none (Satyapal et al. 2014; Hainline et al. 2016; Marleau et al. 2017; Kaviraj et al. 2019), and (2) it is hard for a <10^9.5 M☉ galaxy’s black hole to accrete actively enough to become an AGN from a theoretical point of view (e.g., Fontanot et al. 2011).

2.2. X-Ray AGNs

The identifications of X-ray AGNs are done by spatially cross-matching the CANDELS catalog of the parent sample with the AGN catalogs of the 7Ms Chandra Deep Field South (CDF-S; Luo et al. 2017) and the 2Ms Chandra Deep Field North (CDF-N; Xue et al. 2016). Details of AGN classifications in both fields can be found in Xue et al. (2016) and Luo et al. (2017). In short, an X-ray source is classified as an AGN if it meets the criteria built upon the intrinsic X-ray luminosity threshold and spectral shape (hardness ratio), as well as the flux ratio between the X-ray and other bands (optical, IR, and radio). We cross-match the coordinates of the parent sample (H160 coordinates from the CANDELS catalog) with X-ray AGNs using a 0″5 radius—the same matching radius has also been used in other works (e.g., Yang et al. 2017, 2018). We have checked that our results do not change if we use a smaller (0″3, 0″4) or larger (0″6, 0″7) radius. To further secure the cross-matching, we request the redshifts of sample galaxies (zCANDELS) and those assigned to the matched X-ray counterparts (zXray) are either the same if spectroscopic redshifts are available or within 10% difference (i.e., |zXray − zCANDELS|/zCANDELS ≤ 10%) if photo-z are used. The 10% tolerance of the photo-z difference is because of the different photo-z catalogs used in Luo et al. (2017) and Lee et al. (2018). We have checked that our results do not change if we set the tolerance to be 5% or 15%. With a 0″5 matching radius and 10% tolerance of the photo-z difference, we find that 238 galaxies in the parent sample have X-ray AGNs (no duplicated match).

It is worth pointing out that the approach of searching for a counterpart within a small radius is not ideal for faint galaxies, given both the centroid errors of X-ray sources and the sometimes high background optical/NIR source density. An alternative approach is to use the likelihood-ratio method, which has been carried out in both fields (see Section 2.3.3 in Xue et al. 2016 and Section 4.2 in Luo et al. 2017 for details). We have checked, by comparing the 238 cross-matched X-ray AGNs with the counterparts identified using the likelihood-ratio technique, the two matching results are the same, which is not surprising given that the parent sample are relatively bright (recall that we require all galaxies have S/N > 10 in H160) and the additional redshift difference tolerance can further secure our cross-matching.

2.3. IR AGNs

Because of the availability of deep Spitzer/IRAC photometry in the GOODS fields, IR AGNs are selected using the IRAC color–color diagram from Donley et al. (2012), which was built on a large sample of galaxies in the COSMOS field. This selection is able to effectively identify IR AGNs at high redshifts, which has been demonstrated by many other surveys where IRAC photometry is available (e.g., Mendez et al. 2016; Delvecchio et al. 2017; Leung et al. 2017; Donley et al. 2018).

Two IRAC colors are used to select IR AGNs, namely x = Log(S5.8/S3.6) and y = Log(S8.0/S4.5). A galaxy is classified as an IR AGN host if it meets the following criteria:

\[
\begin{align*}
1.21x - 0.27 & \leq y \leq 1.21x + 0.27 \\
x & \geq 0.08 \\
y & \geq 0.15 \\
S8 & > S_{\text{SS}58} > S_{\text{S15}} > S_{\text{S36}}
\end{align*}
\]

\[
\begin{align*}
z & \geq 2.7 \\
x/y & \leq 0.95 \\
\log S8/S_{\text{S36}} & \geq \begin{cases} 0.39z - 0.69 & \text{if } z = 2.7 - 3.1 \\ 0.18z - 0.04 & \text{if } z = 3.1 - 4.0 \end{cases}
\end{align*}
\]

The black solid lines in Figure 2 form the boxy region defined by the three equations of criterion (1). Galaxies within it have AGN-like SEDs (see Figure 2 of Donley et al. 2012), which have further been confirmed by Kirkpatrick et al. (2013) for a sample of 24 μm-selected 0.5 < z < 4 galaxies with deep Spitzer/IRS spectroscopy. The stellar bump (∼1.6 μm) of normal galaxies at z > 2 is redshifted into the IRAC 4.5, 5.8, and 8 μm bands, which can effectively contaminate the IR AGN selection. To overcome this, the fourth equation of criterion (1) therefore is required to exclude galaxies in the boxy region with nonmonotonically rising SEDs. For galaxies at z > 2.7, the additional criterion is required given that the contamination becomes even worse because the stellar light might dominate all IRAC bands. With the additional criterion (2), Donley et al. (2012) showed that it can effectively exclude (1) galaxies whose spectral shapes in the four IRAC bands are consistent with the rest-frame 1.6 μm stellar bump (the second equation) and (2) galaxies that can be possibly fit by the reddest LIRG/ULIRG templates of Rieke et al. (2009) (the third equation).
bands are of gray points in this region, those are galaxies whose criterion the Figure 2.

The Astrophysical Journal, Lee et al. (2018) and Charlot et al. (2000) selected as IR AGNs using the selection criteria of Kirkpatrick photometry. We have checked, among the 46 galaxies that are Spitzer color selection can miss a fraction of MIR spectroscopically viewing the MIR and FIR observations, unfortunately, only ≈14% of galaxies in the parent sample simultaneously have 24 μm and 100/250 μm photometry. We have checked, among the 46 galaxies that are selected as IR AGNs using the selection criteria of Kirkpatrick et al. (2013), that 39 of them have already been picked up by our IRAC color selection.

With the selection described above, we find 138 IR AGNs, among which 45 (≈33%; a similar percentage (27%) to that found by Delvecchio et al. 2017) are also identified as X-ray AGNs. As demonstrated by Kirkpatrick et al. (2013), the IRAC color selection can miss a fraction of MIR spectroscopically confirmed AGNs, which can be better recovered by adding Spitzer/MIPS 24 μm and far-infrared (FIR) Herschel/PACS 100 μm and SPIRE 250 μm photometry to the selection. Due to the sensitivity and angular resolution of the MIR and FIR observations, unfortunately, only ≈14% of galaxies in the parent sample simultaneously have 24 μm and 100/250 μm photometry. We have checked, among the 46 galaxies that are selected as IR AGNs using the selection criteria of Kirkpatrick et al. (2013), that 39 of them have already been picked up by our IRAC color selection.

3. Measurements and Data Analysis

3.1. SED Fitting

Physical parameters, including $M_*$, SFR, and rest-frame colors, are derived via SED fitting. In the following, we detail the fitting procedure and outline the systematics of the measured parameters.

Throughout this work, we adopt the SED-fitting results of Lee et al. (2018) (hereafter Lee2018), which uses the Bruzual & Charlot (2003) stellar population synthesis code, assumes a Chabrier (2003) initial mass function (IMF), fixed solar metallicity, and the Calzetti et al. (2000) dust attenuation law. Lee2018 takes advantage of the deep CANDELS multi-wavelength photometry that covers from the rest-frame UV to FIR and the official CANDELS photometric redshift catalog (see Dahlen et al. 2013; Hsu et al. 2014) where full probability density functions are used in the determination of photometric redshift. A key feature of the Lee2018 SED-modeling approach is that the fitting procedure applies an advanced Monte Carlo Markov Chain algorithm to treat star formation history (SFH) as a free parameter during the fits. In Lee2018, using mock observations derived from semianalytical models of galaxy evolution, it has been demonstrated that their measurements of $M_*$, SFR, and luminosity-weighted stellar age are much more robust than those derived by setting the functional form of the SFH to a preassigned type.

A concern of using the Lee2018 measurements, in particular for the AGN hosts, is the ignorance of the AGN contribution during the SED fitting. To check these systematics, we have run another set of SED fitting using SED3FIT (Berta et al. 2013) where the AGN component is included in the modeling. We refer the readers to Appendix for a detailed analysis of the uncertainty of individual parameters derived in this way. In short, the comparisons between the Lee2018 and SED3FIT results suggest that, when averaged on the galaxy mix of our sample, ignoring the AGN component in SED modeling:

1. statistically does not affect the $M_*$ measurement in a significant way, although we do find that properly including the AGN contribution is crucial for the $M_*$ measurement of broad-line AGNs (BL AGNs). BL AGNs, however, are a very small fraction (≈5%) of the entire AGN sample, and we have checked that our results are insensitive to including/excluding them;
2. can lead to a ≈0.1 dex overestimation of SFRs for the AGN hosts. This systematics will be taken into account in the following discussions with regard to the star formation properties of the AGN hosts;
3. statistically does not significantly affect the measurement of the rest-frame apparent (dust-attenuated) colors $U - V$ and $V - J$, and dust-corrected colors $(U - V)_{corr}$ and $(V - J)_{corr}$. We also notice that the scatter of the $(V - J)_{corr}$ measurement is slightly larger in IR AGNs than X-ray AGNs and non-AGNs, which is likely due to the generally larger AGN contribution to the $J$ band in IR AGN hosts.

While the SED3FIT tests reveal some tensions in using the Lee2018 measurements for AGN hosts (BL AGNs in particular), fortunately, the rather tight correlations between the parameters derived from the two SED fittings (see figures in Appendix) suggest that the overall determination of the parameters that we have considered is insensitive to the inclusion of the AGN component. Quantifying systematic differences among different SED-fitting procedures to a finer degree of accuracy is beyond the scope of this work. We decide to use the Lee2018 measurements because parts of the following discussions rely on the measurement of the properties of galaxies on the star-forming main sequence, which has been carefully done for the parent sample of Lee2018. Using different SED-fitting algorithms and assumptions for AGNs and non-AGNs might introduce a systematic bias owing to the systematic shifts in the measurements of $M_*$ and SFR (see Appendix and also other works like Leja et al. 2019) that, as small or rare as they are, we prefer to avoid.

In addition to comparing with Lee2018 measurements, running SED3FIT also helps us validate our IRAC color selection method, as well as quantify the AGN luminosity for the IR AGNs (see Section 4.1.2 for details). Figure 3 shows the best-fit SEDs of X-ray and IR AGNs derived by SED3FIT. A significant AGN contribution to the MIR flux is seen in IR AGNs, illustrating the good agreement between the results from the SED decomposition and the adopted IRAC color selection (Section 2.3). The figure also shows that identifying
AGNs at MIR wavelengths can sometimes be hard when galaxy stellar SED dominates the total light in the optical/IR part of the spectrum despite the clear presence of an AGN at X-ray wavelengths, which again highlights the importance of selecting AGNs in more than one wavelength range, as we have already discussed in Section 1. Figure 4 further shows the distribution of the ratio of the AGN IR luminosity divided by the median AGN 5–10 μm IR luminosity ($f^{5-10\mu m}_{AGN}/f^{5-10\mu m}$). Like those seen in the best-fit SEDs, the IR AGNs have a much higher contribution to the MIR flux than the X-ray AGNs.

3.2. Morphological Measurements

The morphological properties of the AGN hosts and normal galaxies are derived by fitting the CANDELS $H_{160}$ images with two-dimensional (2D) light profiles using GALFIT (Peng et al. 2010). The key morphological parameters that we are interested in are effective radius ($R_e$, a.k.a half-light radius), Sérsic index ($n$), stellar-mass surface density within the effective radius ($\Sigma_e$), stellar-mass surface density within the central 1 kpc ($\Sigma_{1kpc}$), and fractional mass within the central 1 kpc ($M_{1kpc}/M_*$). In the following, we will first introduce the basic setup of GALFIT and then describe in detail how we measure the aforementioned morphological parameters and their uncertainties. We will also test the validity of the assumed 2D light profile model and discuss the relevant systematics. We will finally describe in detail our purposes and advantages of using $\frac{M_{1kpc}}{M_*}$ to quantify galaxy compactness.

3.2.1. GALFIT Fittings and Parameter Uncertainties

Before running GALFIT, we center on each sample galaxy to make a $6'' \times 6''$ cutout. We adopt the $H_{160}$ point-spread function (PSF) from the CANDELS team (van der Wel et al. 2012). To get rid of the isophote contamination from the neighboring galaxies, we first find all galaxies in the cutout image with the aid of the CANDELS $H_{160}$ segmentation map. Then, rather than fitting the neighboring galaxies, we fix and model their light profiles using the best-fit 2D Sérsic profiles obtained by van der Wel et al. (2012). For the background sky level of each cutout, we have modeled it in two different ways, namely (1) setting the sky as a free parameter and letting GALFIT find the best-fit value and (2) fixing the sky level to be the median pixel value derived from a 3σ clipping of the pixel values in the cutout image after masking out all $H_{160}$-detected sources. It turns out that our results are insensitive to the method chosen so we decide to fix the sky level as the median pixel value of each cutout. We fit each target galaxy with a single 2D Sérsic profile, from which we can directly obtain $n$ and $R_e$ ($=R_{maj} \times \sqrt{b/a}$), as well as $\Sigma_e = M_*/(2\pi R_e^2)$. With the best-fit Sérsic profile in hand, following the derivation of Graham & Driver (2005), we can get the fractional stellar mass within central 1 kpc through

$$M_{1kpc} = \frac{\gamma(2n, x)}{\Gamma(2n)} \cdot x = b_n \left(\frac{1kpc}{R_e}\right)^{1/n},$$

where $\gamma/\Gamma$ is the ratio of the incomplete gamma function divided by the complete gamma function. When $n > 0.36$, $b_n$ is calculated using the approximate expression proposed by Ciotti & Bertin (1999, their Equation 18), accurate to better than $10^{-4}$, otherwise $b_n$ is calculated by numerically solving $\Gamma(2n) = 2\gamma(2n, b_n)$. Finally, we can obtain the stellar-mass surface density within the central 1 kpc through

$$\Sigma_{1kpc} = \frac{M_{1kpc}}{\pi \cdot 1kpc^2} = \frac{M_*}{\pi \cdot 1kpc^2} \frac{\gamma(2n, x)}{\Gamma(2n)}.$$

Quantifying the uncertainty of these morphological parameters is nontrivial due to the covariance between parameters (e.g., Ji et al. 2020). In this work, we have conducted the covariance analysis by measuring the covariance between $R_e$ and $n$ for the entire AGN sample, aiming to estimate the error bars of each aforementioned morphological parameter. To do so, we first run GALFIT to get the best-fit values of all free parameters and then use GALFIT to generate a number of models by changing $n$ and $R_e$ while fixing any other parameters to the best-fit values. We then calculate the $\chi^2$ distribution of these new models to get the $n-R_e$ covariance. Figure 5 shows the covariances of the nine randomly selected AGNs with different $H_{160}$ S/Ns. Diverse shapes of the covariances are clearly seen even when sources have similar S/Ns.
respectively. Red, green, and blue lines show the corresponding 1σ, 2σ, and 3σ confidence contours.

Figure 5. The $R_e$-n covariances of the nine randomly selected examples. The first, second, and third rows show the cases with $H_{160}$ S/N $\sim$ 20, 70, and 200, respectively. Red, green, and blue lines show the corresponding 1σ, 2σ, and 3σ confidence contours.

demonstrating that the individual determination of $n$ and $R_e$ is nontrivial. For each AGN, we derive the 1σ uncertainty ranges of $R_e$ and $n$ using the covariance. We then plug all possible $R_e$-n combinations along the 1σ-χ^2 contour into Equation (3) to get the corresponding 1σ uncertainty of $\frac{M_{\text{Sérsic}}}{M_*}$. Figure 6 shows the derived uncertainty as a function of $H_{160}$ S/N. While the uncertainty overall decreases as S/N increases, the uncertainty of different morphological parameters is different. For a detection with a decent S/N ($\geq$20), while $R_e$ is reasonably well constrained with a typical $\lesssim$10% 1σ uncertainty, the uncertainty of $n$ can be as large as $\approx$50%. Even for an S/N $\sim$100 detection, the uncertainty of $n$ can still be $\approx$10%.

Importantly, although $n$ itself is usually not well constrained, the measurement of $\frac{M_{\text{Sérsic}}}{M_*}$ (the combination of $R_e$ and $n$) is about as good as that of $R_e$.

3.2.2. Validity of the Single-Sérsic Profile Assumption

We now test the validity of the single-Sérsic profile assumption that we made so far for the morphological measurements. The nonstellar AGN radiation can “pollute” the stellar light distribution and hence introduce a systematic bias in the morphological measurements of host galaxies. To test for this systematic, we have redone the morphological measurements assuming a different model, i.e., a 2D Sérsic profile plus a nuclear point source (Sérsic+PSF). Similarly to what we did for the single 2D Sérsic profile fittings, we have also measured the covariances between $R_e$ and $n$ for the AGN hosts and derived the corresponding 1σ errors. In addition, Sérsic+PSF fittings have also been done among the non-AGNs in the GOODS-S, which we did in order to compare with the AGNs. Figure 7 shows the comparisons of $R_e$, $n$, and $\frac{M_{\text{Sérsic}}}{M_*}$ between the two different light profiles assumed (Sérsic only and Sérsic+PSF). We see clear correlations of $R_e$ and $\frac{M_{\text{Sérsic}}}{M_*}$ and a big scatter of $n$ between the two measurements, suggesting a qualitatively insensitive dependence of $R_e$ and $\frac{M_{\text{Sérsic}}}{M_*}$ but a much more sensitive dependence of $n$ on the assumed light distribution. This further supports what we have already found in Figure 6 that $n$ is not as well constrained as $R_e$ and $\frac{M_{\text{Sérsic}}}{M_*}$.

Compared with the Sérsic-only results, PSF+Sérsic leads to an increase of $R_e$ and a decrease of $\frac{M_{\text{Sérsic}}}{M_*}$, which is expected because adding a nuclear point source is equivalent to fitting a single Sérsic profile to an image with some fraction of the central light removed. In other words, if the nucleated component really has a nonstellar origin like an AGN, the stellar morphology of the host galaxy should be more extended (larger $R_e$ and smaller $\frac{M_{\text{Sérsic}}}{M_*}$) than it is seen from the image. Owing to the limited image depth and spatial resolution at high redshift, however, it is hard to conclusively say if adding the central component to the fitting is physically necessary. For example, we notice that the fitting $\chi^2$ generally improves after adding the nuclear point-like component. In particular, the reduced $\chi^2$ improves by 10% for the PSF+Sérsic model. But, we do not know if the improvement of $\chi^2$ indicates the physical requirement of a central component or simply because the PSF+Sérsic model has more free parameters than the Sérsic-only model and (of course) can fit the data “better.” We can in principle compare the $\chi^2$ change with the expected change that can be theoretically calculated if all the parameters are independent (which unfortunately is not the case; see Figure 5). Even if one can prove that the nucleated point-like source is a physically necessary component, it remains difficult to definitely disentangle its origin, which could be the nonstellar light from an AGN, or the stellar light from galaxy central structures like bulge, or both. It is worth mentioning here that, based on the PSF+Sérsic fitting results, we find a significant positive correlation, with a Pearson correlation test $p$-value of $7 \times 10^{-5}$, between AGN luminosity and $F_{\text{PSF}}/F_{\text{Sérsic}}$, i.e., the flux ratio of the PSF component divided by the Sérsic component. While such a correlation can be simply explained in terms of the AGN contamination being more severe in the rest optical stellar morphology as the AGN
becomes more luminous, we do find evidence that the real cause(s) behind it cannot merely be AGN contamination. We defer detailed analysis and discussions of this issue to an upcoming paper.

Distributions of the relative changes of $R_e$, $n$, and $\frac{M_{\text{PSF}}}{M_e}$ are shown in the bottom panels of Figure 7, where the relative changes are larger for the AGN hosts than normal galaxies. Interestingly, compared with IR AGNs, the relative changes also seem to be larger for X-ray AGNs, which is consistent with the scenario that X-ray AGNs are less (relative to IR AGNs) obscured such that the central AGN light “contaminates” the optical stellar morphology more for X-ray AGNs. The findings above seem to suggest that AGNs either require an extra nuclear nonstellar component for the morphological fitting, or to be preferentially embedded in galaxies that have developed a central compact structure, or both. Regardless of the actual physical reasons, which we will investigate in a future work, our findings suggest that the two-component fitting for AGN hosts very likely is required, and removing the nuclear light can reduce the correlation between AGN presence and galaxy compactness that has been found in previous works. Given the magnitudes of relative changes of $R_e$ and $\frac{M_{\text{PSF}}}{M_e}$, however, we have checked that this will not change our conclusions that AGN prevalence is fundamentally tied to mass more so than compactness (see Sections 4.2.1 and 4.2.2). In the subsequent analysis, we will use the morphological parameters measured from the Sérsic-only fittings.

3.2.3. Quantify Galaxy Compactness with $M_{1\text{kpc}}/M_e$

We now detail our motivations and the advantages of using $\frac{M_{1\text{kpc}}}{M_e}$. This parameter measures the fractional stellar mass within the central 1 kpc and is a metric that quantifies the compactness of a galaxy. To check the effectiveness of this metric, in Figure 8, we compare $\frac{M_{1\text{kpc}}}{M_e}$ with other commonly used morphological metrics, namely the Petrosian radius $R_p$ (Petrosian 1976), Gini, $M_{20}$ (Lotz et al. 2004), and $\Sigma_{1\text{kpc}}$. We see that $\frac{M_{1\text{kpc}}}{M_e}$ does contain information on galaxy compactness in the sense that galaxies with large $\frac{M_{1\text{kpc}}}{M_e}$ statistically are also compact according to other metrics, i.e., large Gini, small $M_{20}$, small $R_p$, and larger $\Sigma_{1\text{kpc}}$.

As we already discussed in Section 3.2.1, $\frac{M_{1\text{kpc}}}{M_e}$ can be measured with a reasonably small uncertainty. Much more importantly, unlike the commonly used compactness metrics like $\Sigma_{1\text{kpc}}$ and $\Sigma_e$, which are biased toward more massive galaxies (see details in the next paragraph), the dependence of $\frac{M_{1\text{kpc}}}{M_e}$ on $M_e$ is much weaker, which can be explicitly seen from Equation (5). This can also be shown using the existing measurement of the $\log M_{1\text{kpc}} - \log M_*$ correlation. For example, in CANDELS/GOODS-S, for this correlation Barro et al. (2017) reported a strong but sublinear relationship with a slope of $\beta \approx 0.9$ and 0.7 for SFGs and QGs, respectively. The slopes do not change across the redshift range $0.5 < z < 3$. If we assume these slopes, we can then get the slope for the $\log \frac{M_{1\text{kpc}}}{M_*} - \log M_*$ correlation, which should be $-0.1$ for SFGs and $-0.3$ for QGs. In both cases, $\frac{M_{1\text{kpc}}}{M_*}$ have a much weaker dependence on $M_*$. Using our sample, Figure 9 further demonstrates that the strong $M_*$ dependence of $\Sigma_{1\text{kpc}}$ is largely eliminated when using $\frac{M_{1\text{kpc}}}{M_*}$ and only a slightly decreasing trend with $\frac{M_{1\text{kpc}}}{M_*}$ still persists for non-AGNs. This is from the low-mass ($\log M_* < 10$) galaxies in our sample, because the
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1 kpc scale (compared with galaxy sizes\(^6\)) probes a relatively larger area for a low-mass galaxy than for a high-mass galaxy, which naturally results in a generally larger \( \frac{M_{\text{NFW}}}{M_*} \) for low-mass galaxies. The trend is much less obvious (it even disappears) for AGN hosts because AGNs are preferentially embedded in more massive galaxies (also see Section 4.2.2).

The criterion commonly used to select compact galaxies in the literature is essentially a threshold cut on stellar-mass surface density \( \Sigma \), which can be formulated as

\[
\log \Sigma > \alpha \log M_* + \beta.
\]

If we select compact galaxies using a fixed threshold of \( \Sigma \), i.e., \( \alpha = 0 \), then Equation (5) becomes \( \log \Sigma > \beta \). Given that galaxies follow the well-defined size–mass relation with the form \( \log R \propto \eta \log M_* \) (e.g., van der Wel et al. 2014), the selection criterion then becomes \( (1 - 2\eta) \log M_* > \text{constant} \). We can now explicitly see that more massive galaxies are more likely to be selected as compact unless \( \eta = 0.5 \), which however is not the case (e.g., see the \( R_{e} - \Sigma_{e} \) relation of Barro et al. 2017). \( \eta \) is \( \approx 0.2 \) for SFGs and \( \approx 0.8 \) for QGs. To reduce this \( M_* \) bias, one can then use an \( M_* \)-dependent threshold cut on \( \Sigma \), i.e., \( \alpha \neq 0 \) (e.g., Barro et al. 2013; Kocevski et al. 2017; Wang et al. 2018). Now, Equation (5) becomes \( (1 - 2\eta) \log M_* > \alpha \log M_* + \text{constant} \). The bias in principle can be fully removed by choosing \( \alpha = 1 - 2\eta \). However, the size–mass relation depends on galaxy properties. For example, observations have shown that SFGs and QGs follow different relations (e.g., Newman et al. 2012; Law et al. 2012; Barro et al. 2017). This means that, even with the \( M_* \)-dependent threshold cut on \( \Sigma \), the bias still cannot be fully removed. The bias remains in at least one galaxy population (SFGs or QGs).

This selection bias becomes particularly important for data interpretation when trying to identify the driven factor (e.g., mass versus morphology) of some observed correlations. For example, as will be discussed later in Section 4.2.2, we find that the prevalence of AGNs positively correlates with \( \Sigma_{1\text{kpc}} \). However, because \( \Sigma_{1\text{kpc}} \) positively correlates with \( M_* \) and the prevalence of AGNs also increases with \( M_* \), we do not know if the observed AGN prevalence–\( \Sigma_{1\text{kpc}} \) correlation is due to \( M_* \), or actually infers the causation between the prevalence of AGNs and galaxy compactness.

To this end, we highlight the advantage of using \( \frac{M_{\text{NFW}}}{M_*} \). Because of its weak dependence on \( M_* \), any relation observed with \( \frac{M_{\text{NFW}}}{M_*} \) should be primarily caused by galaxy morphology.

4. Results

In this section, we aim to investigate the observational evidence of the effects of AGN presences on host galaxies. In the following, we will first compare the star formation properties of AGNs with non-AGNs (Sections 4.1.1 and 4.1.2), and then investigate if the AGN prevalence changes with the star formation properties of their hosts (Section 4.1.3). We will then compare the morphological properties of AGNs and non-AGNs (Section 4.2.1), and then investigate if the AGN prevalence changes with the morphological properties of their hosts (Section 4.2.2).

4.1. Star Formation Properties

4.1.1. Distributions of AGNs on the Star-forming Main Sequence

In Figure 10, we compare the distributions of AGNs with normal SFGs on the star-forming main sequence (SFMS), i.e.,

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\(^{6}\) If we assume the van der Wel et al. (2014) mass–size relation for SFGs, the median \( R_e \) of a \( 10^{11}M_\odot \) galaxy is \( \approx 4 \) kpc at \( z \sim 2 \), while it is \( 2.6 \times (1.6 \times) \) smaller for a \( 10^9 (10^{10}) \) \( M_\odot \) galaxy.
specific star formation rate (sSFR) versus $M_\ast$. The medians and $1\sigma$ (16th–84th) ranges for individual populations are derived in two ways. A common way is to compute median and interquartile sSFR in arbitrarily defined $M_\ast$ bins, which are shown as squares with error bars in the main panel of the figure. The other way of calculating the percentiles is to use the nonparametric quantile regression, in which case no arbitrarily defined bins are required. Here, we adopt the COnstrained B-splines (COBS; see Ng & Maechler 2007, 2020 for details) package in R to carry out the quantile regressions, where the total number of knots required for the regression B-spline method is determined using the Akaike-type information criterion. The results from COBS are inserted to the bottom left of the main panel. Regardless of the way the median relation is calculated, we find that, while the median sSFRs of X-ray AGNs are indistinguishable from those of normal SFGs, enhanced sSFR is observed in IR AGN-hosting galaxies.

Two tests have been done in order to check the robustness of the conclusions above. First, the SFR comparisons in Section 3.1 have shown that our SED fittings can on average overestimate SFRs for AGN-hosting galaxies by $\approx 0.1$ dex due to the AGN components being ignored. However, the magnitude of this systematics is small compared with the scatter of sSFR distribution of X-ray AGNs, and it is also smaller than the strength of sSFR enhancement ($\approx 0.4$ dex) as seen for the whole sample of IR AGNs. We therefore do not expect such overestimation to significantly affect our sSFR comparisons. Second, different $M_\ast$ and redshift distributions of AGNs and non-AGNs can potentially affect our sSFR comparisons because of the evolution of the SFMS (e.g., Whitaker et al. 2014; Lee et al. 2018). We test this by building the $M_\ast-z$ matched subsample of non-AGN SFGs, whose sSFR distribution is then used to compare with that of AGNs. We do this in three $M_\ast$ bins, and for X-ray and IR AGNs separately, because their $M_\ast$ and redshift distributions are also different from each other. For each AGN, we select the two non-AGN SFGs that are the closest to the AGN in the $M_\ast-z$ space to build the $M_\ast-z$ matched subsample. We have checked that our conclusions below do not depend on how the $M_\ast-z$ matched subsample is built. For instance, we have tried building the subsample by randomly selecting two/three non-AGN SFGs whose redshifts are within $\delta z < 0.2$ and $M_\ast$ are within $\delta \log M < 0.3$, and the results remain unchanged.

Figure 11 shows the detailed comparisons of the sSFR distributions for AGNs and non-AGN SFGs. The median sSFR for X-ray AGNs is similar to that of the $M_\ast-z$ matched, non-AGN SFGs, except in the smallest $M_\ast$ bin (i.e., $9.5 < \log M_\ast < 10$), where the X-ray AGN sample suffers from small number statistics. In spite of the similar medians, the two-sample Kolmogorov–Smirnov tests indicate that we can reject the null hypothesis that the two (matched non-AGN SFGs and X-ray AGNs) sSFR distributions are identical with a 91.6% to $\approx 99.7\%$ (i.e., $1.7\sigma$–$3\sigma$, depending on the $M_\ast$ bins; see the figure for details) confidence level. Compared with the $M_\ast-z$ matched non-AGN SFGs, an enhanced sSFR in IR AGNs is still observed, although the magnitude shrinks from $\approx 0.4$ to

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**Figure 10.** AGNs and normal SFGs on the sSFR-$M_\ast$ diagram. X-ray and IR AGNs, and non-AGNs are shown as blue, red, and black dots, respectively. The corresponding color-coded circles with error bars show the median and 16th–84th percentiles of sSFR in each $M_\ast$ bin. AGNs that are identified as both X-ray and IR AGNs are labeled with green squares. The inset on the bottom left of the main panel shows the medians and 16th–84th ranges for individual populations derived by COBS in R using the Constrained B-splines interpolations. The bottom panel shows differences of the mean sSFR between AGNs and non-AGNs in each $M_\ast$ bin.
0.3 dex. A similar enhancement strength is seen in all three $M_*$ bins. The two-sample Kolmogorov–Smirnov tests indicate that we can reject the null hypothesis that the two (matched non-AGN SFGs and IR AGNs) sSFR distributions are identical with a 93.5%–99.6% (i.e., 1.8σ–3σ) confidence level, which, as can be seen in the figure, is likely driven by the shift toward high sSFR for IR AGNs. To this end, we conclude that, rather than measurement uncertainty or different $M_*$ and $z$ distributions between AGNs and non-AGNs, our results do suggest that the median sSFR of (1) IR AGNs is enhanced and (2) that of X-ray AGNs is indistinguishable relative to normal SFGs. In addition, our Kolmogorov–Smirnov tests indicate the entire sSFR distribution for AGNs, either X-ray or IR selected, are different from normal SFGs with a ≈2σ–3σ confidence level.

Figure 11. Comparisons of distributions of sSFR in the three $M_*$ bins, namely $9.5 < \log M_* < 10$ (first row), $10 < \log M_* < 10.5$ (second row), and $10.5 < \log M_* < 12$ (third row). The comparisons are between AGNs, where X-ray AGNs are shown in blue in the left panels and IR AGNs are shown in red in the right panels, and non-AGN SFGs, where the entire non-AGN SFGs are shown in gray and $M_*–z$ matched non-AGN SFGs are shown in black. Downward arrows in each panel show the medians of individual distributions. Also labeled in each panel is the $p$-value of the two-sample Kolmogorov–Smirnov test for the null hypothesis that the sSFR distribution of AGN-hosting (either X-ray- or IR-selected) galaxies is identical to that of $M_*–z$ matched non-AGN SFGs.

For IR AGNs, the enhancement of star formation has also been reported by other works (e.g., Cowley et al. 2016; Ellison et al. 2016; Azadi et al. 2017). The widely accepted interpretation of it is galaxy merger, a violent process that naturally can both ignite starbursts and fuel luminous AGNs (Sanders et al. 1988; also see Figure 6 in Alexander & Hickox 2012 for a schematic view). The observational supports for this scenario primarily come from the morphological studies of host galaxies of IR AGNs. Satyapal et al. (2014) studied a sample of WISE-selected AGNs in SDSS, from which they showed the probability of finding IR AGNs in postmerger systems is ≈10–20 times higher than the control sample. Similar conclusions have also been made by using different MIR selections and at higher redshifts. For instance, Donley et al. (2018) adopted IRAC color selection criteria (the same as used in this work) to study IR AGN populations at $z \lesssim 3$ in the CANDELS/COSMOS, from which they concluded that IR AGNs are significantly more likely to be found in interacting/merging systems compared with Seyfert-like AGNs. These, in turn, can also explain why this IR-selected AGN population is missed in X-ray because obscuration correlates with merger stage and supermassive black holes (SMBHs) can grow during highly obscured stages of galaxy mergers. If the IR selection is more efficient in picking up the AGNs triggered by galaxy mergers/interactions, then we would expect to see the host galaxies of IR AGNs to have enhanced star formation activities, as a consequence of galaxy mergers/interactions. Based on the sSFR comparison itself, nothing can be said on whether ongoing AGN activities have any casual connection with galaxywide star formation or not, as the effects (if any) can be easily “buried” beneath the effects produced by mergers/interactions.

For X-ray AGNs, while their median sSFR is indistinguishable from that of normal SFGs, the sSFR distribution of the X-ray AGNs hosted by massive galaxies ($\log M_* \gtrsim 10.3$) is skewed toward low sSFRs. Moreover, among the massive X-ray AGN hosts, those with high sSFRs often are also identified in IR. If we look at the AGNs that are merely identified by X-ray, skewness toward low sSFRs becomes even clearer. These are consistent with the conclusions of
Mullaney et al. (2015), where they found that the mass- and redshift-normalized SFR distributions of their X-ray AGNs are broader and peaked at lower values than normal main-sequence SFGs, despite the mean SFRs for the two populations being similar. The interpretation of the results above is nontrivial owing to the different timescales involved. While AGN is instantaneous, SFR is not. One would be able to measure instantaneous SFR if a correct SFH were known. As a result, no causal link can be indicated merely based on the SFR comparisons between AGNs and normal SFGs unless AGNs have been “on” for the same timescale as SFRs are being traced. Even so, the interpretation of the similar median sSFRs between AGNs and normal SFGs is not unique. If a time lag (longer than the timescale of the current star formation episode) is required to enable AGN feedback effects observable, not too much can be said by looking at ongoing AGNs. Alternatively, although the fine-tuning of AGN feedback is required, the observed similar median sSFRs can also be produced by the equally positive and negative feedback of X-ray AGNs. The latter one, however, seems to be disfavored by the observed independence (although error bars are large) between AGN luminosities and star formation activities (Section 4.1.2).

4.1.2. AGN Luminosity versus Starburstiness

Phenomenologically speaking, if AGN activities do instantaneously affect galaxywide star formation, a correlation between AGN luminosities and their hosts’ star formation properties is expected. We therefore study the relation between AGN bolometric luminosities ($L_{\text{bol}}$) and starburstiness ($R_{\text{SB}}$), which is defined as the SFMS-normalized sSFR,

$$R_{\text{SB}} = \frac{s\text{SFR}}{s\text{SFR}(z, M_*)},$$

(6)

where $s\text{SFR}(z, M_*)$ is the sSFR for a galaxy on the SFMS with $M_*$ at $z$. We adopt the SFMS measured by Lee et al. (2018), as the relation was measured upon the same galaxy sample using the same SED-fitting algorithm.

The details of $L_{\text{bol}}$ measurements can be found in Z. Ji et al. (2021, in preparation), and we only briefly outline the key steps here. For X-ray AGNs, we first take intrinsic X-ray $0.5–7$ keV luminosities from Xue et al. (2016) and Luo et al. (2017), which were measured by correcting the observed X-ray flux with the obscuration empirically calibrated by X-ray band ratios. We assume an AGN spectral photon index $\Gamma = 1.8$ and convert the intrinsic $0.5–7$ keV luminosities to intrinsic $2–10$ keV luminosities, which are finally converted to $L_{\text{bol}}$ using the $2–10$ keV bolometric correction from Hopkins et al. (2007). For IR AGNs, we first obtain the AGN monochromatic luminosities at $15 \mu m$ using the best-fit SED decomposition by SED3FIT and convert them to $L_{\text{bol}}$ using the $15 \mu m$ bolometric correction of Hopkins et al. (2007). The $15 \mu m$-derived $L_{\text{bol}}$ is consistent with the direct $L_{\text{bol}}$ output from SED3FIT (the difference between the two is $-0.15 \pm 0.2$ dex). We have checked that our conclusions are not sensitive to the choice of MIR-derived $L_{\text{bol}}$, i.e., $15 \mu m$-derived one and the direct output from SED3FIT.

To check the robustness of the measurements, we first checked that our measurements of the ratio of the AGN $2–10$ keV luminosity divided by the AGN IR luminosity are in good agreement with Kirkpatrick et al. (2017). We have also further compared the MIR-derived with the X-ray-derived $L_{\text{bol}}$ for X-ray AGNs and found that the two $L_{\text{bol}}$ are consistent with each other when $L_{\text{bol}} \gtrsim 10^{43.5}$ erg s$^{-1}$ (see Figure 12 and a detailed discussion in Z. Ji et al. 2021, in preparation), although the scatter between the two measurements is large, with a typical $\pm 0.5$ dex, which will hopefully be much improved with the coming MIR capability of JWST and future more sensitive X-ray telescopes. Because only a small fraction of the AGNs are fainter, we have checked that including/excluding those faint AGNs cannot affect our conclusions.

In Figure 13, $R_{\text{SB}}$ is plotted against $L_{\text{bol}}$. IR AGNs in our sample are in general brighter than X-ray AGNs by $\approx 0.5$ dex, indicating that the IRAC color selection adopted by us is less sensitive, and hence detects only most powerful AGNs. The $L_{\text{bol}}$–$R_{\text{SB}}$ correlation is neither seen for X-ray AGNs nor for IR AGNs, which seemingly suggests that instantaneous AGN activities do not affect galaxywide star formation. We point out, however, that the measurement uncertainty of the relation, particularly along the $L_{\text{bol}}$ axis, is large, which may potentially wash out an existing trend. Moreover, stochastic AGN variability can easily weaken the correlations between the observed AGN activities and the star formation properties of AGN hosts (Hickox et al. 2014).

While the overall trend between $L_{\text{bol}}$ and $R_{\text{SB}}$ is unclear, we do notice that the galaxies with the most intense star formation activities (i.e., the highest $R_{\text{SB}}$) seem to also have the most powerful AGNs. In addition, we also see very tentative evidence that, for X-ray AGNs, the median $L_{\text{bol}}$ is smaller at the low end of $R_{\text{SB}}$ although the scatter is very large. Like we did in Section 4.1.1, we also use the constrained B-splines regressions (i.e., COBS) to get the $L_{\text{bol}}$–$R_{\text{SB}}$ quantile curves (top-left inset of Figure 13), according to which we reach the similar conclusions. These findings are consistent with the X-ray-stacking results obtained by Rodighiero et al. (2015), where they found an enhancement (deficit) of X-ray luminosity in their stacked starburst (green valley) galaxies. Possible interpretations of the enhanced X-ray flux in starburst systems are (1) starbursts are more X-ray active just as they are more star-forming (Rodighiero et al. 2015 reported a factor of 2 larger black hole (BH) accretion rate per star formation rate...
B-splines interpolations. Inset on the top left shows the medians and 16th X-ray AGNs and IR AGNs derived by COBS in R using the Constrained

\[ L_{\text{SMBH}} \]

which measures the total radiative energy released from an \( \text{AGN} \) with mass \( M_\ast \).

7 Note that \( L_{\text{bol}}/M_\ast \) can be easily converted to the Eddington ratio by assuming an \( M_{\text{BH}}-M_\ast \) relation.

Finally, we look into the relation of \( R_{SB} \) with AGN bolometric luminosity per stellar mass \( (L_{\text{bol}}/M_\ast) \). Similar to what have been found for \( L_{\text{bol}} \), Figure 14 shows that (1) \( L_{\text{bol}}/M_\ast \) is larger for our IR-selected AGNs, and (2) no clear correlation is seen between \( L_{\text{bol}}/M_\ast \) and \( R_{SB} \). Unlike \( L_{\text{bol}} \) which measures the total radiative energy released from an SMBH, \( L_{\text{bol}}/M_\ast \) measures its accretion efficiency. The larger \( L_{\text{bol}}/M_\ast \) suggests a higher accretion efficiency for IR AGNs than X-ray AGNs, which possibly indicates different fueling mechanisms of SMBHs. While X-ray AGNs are more likely powered by the stochastic fueling processes like the secular evolution of galaxies themselves or galactic disk instabilities, IR AGNs are likely triggered by violent events like galaxy mergers, which are consistent with the findings of morphological studies of AGN hosts (e.g., Kartaltepe et al. 2010; Cisternas et al. 2011; Kocevski et al. 2012; Villforth et al. 2014; Ellison et al. 2016; Donley et al. 2018). Consistent results have also been found recently by Delvecchio et al. (2020), where they empirically modeled AGN luminosity functions for galaxies on and above the SFMS. They found that higher Eddington ratios are required to reproduce the luminosity function for starburst galaxies.

**Figure 13.** The \( R_{SB}-L_{\text{bol}} \) scatter plot of X-ray AGNs (blue), IR AGNs (red), and AGNs that are identified as both X-ray and IR AGNs (green). AGNs hosted by QGs are shown as \( \times \), AGNs hosted by SFGs are shown as dots, with the mean and 16th–84th percentiles overlaid as circles with error bars. The inset on the top left shows the medians and 16th X-ray AGNs and IR AGNs derived by COBS in R using the Constrained B-splines interpolations.

**Figure 14.** Similar to Figure 13, but the y-axis is changed to \( L_{\text{bol}}/M_\ast \).

that both sSFR and \( R_{SB} \) are essentially normalized SFR, with the former being normalized by \( M_\ast \) and the latter being normalized by both \( M_\ast \) and \( z \).

We start with the prevalence of X-ray AGNs. First, regardless of the adopted metric of star formation intensity (SFR, sSFR, or \( R_{SB} \)), \( q_{\text{AGN}} \) is high in galaxies with intense star formation activities. Second, for galaxies with normal/suppressed star formation rates log SFR \( \leq 1.5 \), \( q_{\text{AGN}} \) stays approximately flat with SFR. Because both SFR and \( q_{\text{AGN}} \) increase with \( M_\ast \) (the \( q_{\text{AGN}}-M_\ast \) relation will be studied in Section 4.2.2), normalizing SFR with \( M_\ast \) (i.e., sSFR) can effectively mitigate the \( M_\ast \) dependence to allow a more direct view on the link between \( q_{\text{AGN}} \) and star formation activities. Compared with galaxies with moderate sSFR \( (\sim 1 \text{ Gyr}^{-1}) \), a higher incidence of X-ray AGNs is observed in galaxies with suppressed sSFR (also have green colors, which will be shown in Section 4.2.1). A similar trend is also seen when using \( R_{SB} \), which mitigates not only the \( M_\ast \) but also redshift dependence by normalizing each galaxy with the SFMS. The findings above are consistent with what have been reported by Aird et al. (2019) (their Figure 10 and 11) and Juneau et al. (2013) (their Figure 9), where they showed that the X-ray AGN prevalence is larger both for galaxies with suppressed star formation and for starburst galaxies, although it should be pointed out that, apart from galaxies with X-ray detections, they adopted a Bayesian methodology to also include the X-ray information for galaxies lacking direct flux detection into their analysis while we do not follow such an approach here.

Unlike the X-ray AGN prevalence, the \( q_{\text{AGN}} \) of IR AGNs generally increases with SFR, sSFR, and \( R_{SB} \). The increasing \( q_{\text{AGN}} \) toward galaxies with intense star formation is consistent with the picture of a merger-driven scenario. Compared with X-ray AGNs, the unseen overabundant IR AGNs hosted by galaxies with suppressed star formation show the differences between the two AGN populations and highlight the importance of the AGN selection effect (e.g., X-ray versus IR) in altering the distribution of host-galaxy properties and as a result in building up a comprehensive picture of AGN effects on host galaxies.

Finally, as we already discussed in Section 4.1.2, because the sensitivities of the two AGN selection methods are different, namely that the IR selection is less sensitive at fixed bolometric luminosity (Figure 13), the \( L_{\text{bol}} \) difference, in principle, can
lead to the distinct $q_{\text{AGN}}$ trends seen between X-ray and IR AGNs, if there is a strong dependence of star formation properties with AGN luminosity, which however is not seen (Section 4.1.2) despite the still large uncertainty in the $L_{\text{bol}}$ measurements. Nevertheless, we do test this possibility by setting a cut in $L_{\text{bol}}$, i.e., $10^{44} \text{ erg s}^{-1} \leq L_{\text{bol}} \leq 10^{45.5} \text{ erg s}^{-1}$, on both AGN populations. The cut at the low end of the $L_{\text{bol}}$ distribution aims to exclude the faint AGNs that currently are not picked up by our IR selection. The high-end cut, on the other hand, aims to exclude the brightest and highly obscured AGNs missed by the X-ray selection. As Figure 13 shows, both selection methods are similarly sensitive to the adopted $L_{\text{bol}}$ range. As the bottom panels of Figure 15 show, our conclusions do not change after doing the $L_{\text{bol}}$ cut.

4.2. Morphological Properties

4.2.1. Distributions of AGNs on Color–Morphology Diagrams

In this section, we study how AGNs and non-AGNs distribute in the color–morphology parameter space. In particular, we study their distributions in the diagrams of dust-corrected rest-frame color $(U - V)_{\text{corr}}$ versus $\Sigma_e$, $\Sigma_{1\text{kpc}}$, and $M_{*}$. The reasons for using $(U - V)_{\text{corr}}$, rather than $(V - J)_{\text{corr}}$, are that $(U - V)_{\text{corr}}$ better probes star formation properties and $(2)$ is less sensitive to the assumption of dust attenuation (see Figure 28). We notice that, after doing the dust correction, $(U - V)_{\text{corr}}$ itself can effectively separate SFGs and QGs (see Figure 16). The separation boundary is $(U - V)_{\text{corr}} \approx 1.1$ mag, fully consistent with Kocevski et al. (2017).

As Figure 16 shows, compared with non-AGNs, X-ray AGN hosts are overabundantly seen to be hosted by galaxies with green $(U - V)_{\text{corr}}$ colors, which is consistent with Section 4.1.3 where the relations between $q_{\text{AGN}}$ and star formation properties were investigated. Consistent conclusions also have been obtained by many other studies on X-ray AGNs, both in the local universe (e.g., Martin et al. 2007; Salim et al. 2007; Schawinski et al. 2010) and at high redshifts (e.g., Nandra et al. 2007; Coil et al. 2009). With regard to morphological properties, compared with non-AGNs, X-ray AGNs share a similar locus of parameter space with QGs, which also have a larger stellar-mass surface density ($\Sigma_e$ and $\Sigma_{1\text{kpc}}$) than SFGs. This fully aligns with the finding of Kocevski et al. (2017), where they reported a large fraction of compact SFGs hosting X-ray AGNs at $z \sim 2$.

Figure 16 also clearly shows that IR AGNs are distributed differently in the color–morphology space when compared with X-ray AGNs. Specifically, unlike X-ray AGN hosts peaked in the region with green colors, IR AGNs are bluer and have similar (but slightly redder) colors to normal SFGs. Meanwhile, while IR AGNs seem to have a larger surface stellar-mass density than SFGs, they are not as compact as X-ray AGNs, immediately showing the importance of AGN selection on the distributions of physical properties of AGN-hosting galaxies.
Because both $\Sigma_e$ and $\Sigma_{1\text{kpc}}$ strongly and positively correlate with $M_*$ (see Section 3.2.3), the observed larger $\Sigma_e$ and $\Sigma_{1\text{kpc}}$ of AGN hosts (both X-ray and IR) than those of SFGs can possibly be explained by the fact that AGN hosts are systematically more massive than non-AGNs (Section 4.2.2), rather than the intrinsic relation between galaxy compactness and AGN activities. To check this, in the rightmost panel of Figure 16, $(U-V)_{\text{corr}}$ is plotted against $\frac{M_{\text{1kpc}}}{M_*}$, our compactness metric that only weakly depends on $M_*$ (Section 3.2.3). Unlike using $\Sigma_e$ and $\Sigma_{1\text{kpc}}$, the $\frac{M_{\text{1kpc}}}{M_*}$ distribution of AGNs is very similar to that of SFGs, suggesting no clear link between galaxy compactness and AGN activities. In addition, served as an alternative test, we have compared the $\Sigma_e$, $\Sigma_{1\text{kpc}}$, and $\frac{M_{\text{1kpc}}}{M_*}$ distributions of AGNs with a subsample of $M_*$-matched non-AGNs (the upper panels of Figure 17). Similarly to what we did in Section 3.1, for each AGN, we selected the closest two non-AGNs in the $M_*-z$ space. We have checked, by choosing the closest three/four non-AGNs, that our results do not change. After doing the $M_*-z$ matching, the distributions of both $\Sigma_e$ and $\Sigma_{1\text{kpc}}$ of non-AGNs move toward larger values, making the tendency of AGNs to be more compact less obvious. Also noticed in the figure is that the $\frac{M_{\text{1kpc}}}{M_*}$ distribution does not significantly change after matching $M_*$, again showing the only weak $M_*$-dependence nature of $\frac{M_{\text{1kpc}}}{M_*}$ that has already been discussed in detail in Section 3.2.3.

Because of the different sensitivities of the two AGN selection methods, it is not only $M_*$ but also the $L_{\text{bol}}$ difference that could result in the distinct color–morphology distributions seen between X-ray and IR AGNs, if $L_{\text{bol}}$ somehow plays a crucial role in determining the host galaxies’ colors and morphology. To test this, as we did in Section 4.1.3, we post an $L_{\text{bol}}$ range cut on both AGN samples. Our conclusions do not change after doing the $L_{\text{bol}}$ cut (the bottom panels of Figure 17). We have also checked that our conclusions will not change, if we do the faint-end cut only, i.e., $L_{\text{bol}} \lesssim 10^{44}$ erg s$^{-1}$. Nevertheless, we do notice that the distribution of X-ray AGNs seem to shift slightly toward bluer $(U-V)_{\text{corr}}$ after excluding the faint X-ray AGNs, because the X-ray AGNs hosted by QGs are seemingly fainter than those hosted by SFGs (as already discussed in Section 4.1.2; also see Figure 22 below).

Finally, we compare the normalized $R_e$ of AGNs with non-AGNs. In order to remove the $M_*$ and $z$ dependence, each $R_e$ is divided by the median $R_e$ of a galaxy with the same $M_*$ and at $z$. To do so, we adopt the galaxy mass–size relation measured by van der Wel et al. (2014), which was done for all 3D-HST +CANDELS galaxies at $z < 3$. In particular, we normalize the
of individual galaxies in our sample with the best-fit $M_* - R_e$ relation for late-type galaxies at the closest redshift bin of van der Wel et al. (2014) (see their Table 1). Because the $R_e$ in van der Wel et al. (2014) is the size of the rest-frame 5000 Å, we convert it to the size of $H_{160}$ using Equations (1) and (2) in van der Wel et al. (2014). Figure 18 shows distributions of normalized $R_e$ for X-ray and IR AGNs, where X-ray AGNs are further divided into two subsamples according to star formation properties of host galaxies (Note that almost all IR AGNs are hosted by SFGs so we decide not to divide them into subsamples). The distribution of the normalized $R_e$ of IR AGNs shows that the sizes are in general consistent with sizes of normal SFGs, with a $-0.07$ dex median. Normalized $R_e$ of X-ray AGNs hosted by SFGs are also consistent with normal SFGs, with a median and 16th–84th percentile range of $-0.13^{+0.22}_{-0.37}$ dex. This is expected as QGs are in general more compact than SFGs at fixed $M_*$. If, instead, the $R_e$ of X-ray AGNs hosted by QGs is normalized with the best-fit $M_* - R_e$ relation of van der Wel et al. (2014) for early-type galaxies (blue dashed curve in the Figure), the normalized $R_e$ of X-ray AGNs hosted by QGs (light blue), X-ray AGNs hosted by SFGs (blue), and IR AGNs (red). Each $R_e$ is normalized with the best-fit $M_* - R_e$ relation for normal late-type galaxies (taken from van der Wel et al. 2014). Solid lines are best-fit Gaussian distributions. The bottom panel shows medians and 16th–84th ranges of individual distributions. The blue dashed line shows the distribution of X-ray AGNs hosted by QGs if we instead normalize $R_e$ with the best-fit $M_* - R_e$ relation for early-type galaxies.
changes to $+0.09^{+0.30}_{-0.27}$ dex, indicating that the sizes of X-ray AGNs hosted by QGs are consistent with those of normal QGs.

4.2.2. AGN Prevalence versus Morphological Properties

We now investigate the dependence of $q_{\text{AGN}}$ on $M_*$, $\Sigma_e$, $\Sigma_{1\text{kpc}}$, and $\frac{M_{\text{BH}}}{M_*}$.

To begin, $q_{\text{AGN}}$ increases with $M_*$ (the leftmost panel of Figure 19)—a similar conclusion has also been made by many other authors (e.g., SDSS emission-line-selected AGNs: Kauffmann et al. 2003; X-ray AGNs: Xue et al. 2010; Aird et al. 2012). Given the well-known correlations among $M_{\text{BH}}$, bulge mass, and $M_*$, the positive dependence of $q_{\text{AGN}}$ on $M_*$ is not surprising. Specifically speaking, an AGN is fueled by accretion onto a central SMBH, the rate and radiative efficiency of which together determine its luminosity. $M_{\text{BH}}$ is positively and tightly correlated with bulge mass (see Kormendy & Ho 2013 and references therein), and it is also positively (and likely super-linearly; Delvecchio et al. 2019) correlated with $M_*$ although the correlation is not as tight as seen with bulge mass, (Reines & Volonteri 2015; Volonteri & Reines 2016; Savorgnan et al. 2016; Bentz & Manne-Nicholas 2018). Therefore, galaxies with larger $M_*$ also statistically have larger $M_{\text{BH}}$, and hence tend to have higher absolute accretion rates (e.g., Mullaney et al. 2012; Yang et al. 2018). Given that AGNs are essentially selected according to some luminosity threshold, they are naturally expected to be more likely found in more massive galaxies. The positive trend between $q_{\text{AGN}}$ and $M_*$ is seen both for X-ray and IR AGNs, but with evidence that host galaxies of IR AGNs are less massive than those of X-ray AGNs. Combined with IR AGNs being also more star-forming than X-ray AGNs (Figure 1 and Section 4.2.1), our findings for IR AGNs are consistent with Hickox & Boötes Survey Collaboration (2009), where they reported that IR AGN hosts are bluer and less massive than X-ray AGN hosts.

We also learned from Figure 19 (middle two panels) that $q_{\text{AGN}}$ increases with stellar surface density, which is observed both for X-ray and IR AGNs. The $q_{\text{AGN}}$-$\Sigma_{1\text{kpc}}$ trend could indicate that AGNs prevalently embed in galaxies with high $\Sigma_{1\text{kpc}}$, i.e., central compactness. Alternatively, the trend could be the “by-product” of the positive relations between $q_{\text{AGN}}$ and $M_*$ and between $M_*$ and $\Sigma_{1\text{kpc}}$. Because $q_{\text{AGN}}$ increases with $M_*$, even without any intrinsic relation between $q_{\text{AGN}}$ and galaxy central compactness, we still expect to see the increasing trend of $q_{\text{AGN}}$ with $\Sigma_{1\text{kpc}}$ (a similar argument above can be used for $\Sigma_e$). In order to check if there is a causation between $q_{\text{AGN}}$ and the compactness of galaxies, instead of using the morphological metrics that are correlated with $M_*$ like $\Sigma_{1\text{kpc}}$ and $\Sigma_e$, we therefore look at the relation between $q_{\text{AGN}}$ with $\frac{M_{\text{BH}}}{M_*}$, which has a much weaker dependence on $M_*$.

As shown in the rightmost panel of Figure 19, instead of increasing with $M_*$ and $\Sigma_{1\text{kpc}}$, $q_{\text{AGN}}$ stays more or less as a constant with $\frac{M_{\text{BH}}}{M_*}$, which again is observed for both X-ray and IR AGNs. The flat trend suggests that the probability of the presence of AGNs does not depend on galaxy compactness, i.e., there is no clear evidence for the prevalence of AGNs in compact galaxies. This, in return, indicates that the observed increasing trend between $q_{\text{AGN}}$ and $\Sigma_{1\text{kpc}}$ is primarily caused by the dependence of $q_{\text{AGN}}$ on $M_*$, while the intrinsic connection (if any) between AGN and $\Sigma_{1\text{kpc}}$ can only be the secondary. A similar conclusion has also been reached by Ni et al. (2019), where they found the sample-averaged BH accretion rate does not significantly depend on $\Sigma_{1\text{kpc}}$ and $\Sigma_e$ once SFR and $M_*$ among galaxies are controlled.

Like what we did before (Sections 4.1.3 and 4.2.1), we have checked, by posting an $L_{\text{bol}}$ range cut on both AGN populations
Figure 20. Similar to Figure 19, X-ray AGNs are divided into two subgroups based on star formation properties of their hosts, namely SFGs and QGs. The seemingly decreasing trend of $q_{\text{AGN}}$ with $M_{\text{HMC}}/M_*$ (the rightmost panel) for X-ray AGNs hosted by QGs suffers from the small number statistics at the low-end of $M_{\text{HMC}}/M_*$.

Figure 21. Similar to Figure 20, but X-ray AGN hosts are now divided based on their distances from the SFMS (Section 4.1.2). In particular, X-ray AGNs are divided into four subgroups, namely starburst (SB), main sequence (MS), green valley (GV), and QG.

the bottom panels of Figure 19) to ensure the X-ray and IR selections probe similarly powerful AGNs, our conclusions above do not change.

Finally, we investigate if the relations seen above depend on the star formation properties of host galaxies. This investigation is only conducted for X-ray AGNs because almost all IR AGN hosts are SFGs (see Figure 1). We first use the $UVJ$ diagram to separate X-ray AGNs into two subgroups, namely SFGs and QGs. Figure 20 shows the dependence of $q_{\text{AGN}}$ on each morphological parameter for X-ray AGNs hosted by $UVJ$-selected SFGs and QGs. While increasing trends between $q_{\text{AGN}}$ and $M_*$ are observed among both SFGs and QGs hosting X-ray AGNs, relations between $q_{\text{AGN}}$ and $\Sigma_{1\text{kpc}}$, $\Sigma_e$ depend on types of host galaxies. In particular, while SFGs hosting X-ray AGNs have similar increasing trends between $q_{\text{AGN}}$ and $\Sigma_{1\text{kpc}}$, $\Sigma_e$ as observed for the entire sample of X-ray AGNs, flatter trends are observed for the ones hosted by QGs, which are consistent with the findings of Kocevski et al. (2017). For the $q_{\text{AGN}}$ $M_{\text{HMC}}/M_*$ relation, SFGs hosting X-ray AGNs show a flat trend, while QGs hosting X-ray AGNs seem to have a decreasing trend, which, however, is far from conclusive at this point, owing to the small sample size. We further test the findings by subgrouping X-ray AGN hosts using $R_{SB}$. In Figure 21, we divide the entire sample into four subgroups, namely starburst (SB, $R_{SB} > 3$), main sequence (MS, $1/3 < R_{SB} < 3$), green valley (GV, $1/30 < R_{SB} < 1/3$), and QG ($R_{SB} < 1/30$). Like what we have seen when separating the sample with the $UVJ$ diagram, except for QG-hosting X-ray AGNs that show an almost flat trend of $q_{\text{AGN}}$ with $\Sigma_e$ and $\Sigma_{1\text{kpc}}$, all other X-ray AGN hosts show similar trends to those seen for the entire X-ray AGN sample.

5. Discussions

The main findings of this work can effectively be summarized by the scatter plot of Figure 22, where the $M_*$ dependence has been more or less removed for all parameters shown, including $R_{SB}$ (y-axis), $M_{\text{HMC}}/M_*$ (x-axis), and $L_{\text{bol}}/M_*$ (point size). Despite the still relatively large uncertainty in the $L_{\text{bol}}$ measurement (Section 4.1.2), some general conclusions can be drawn. While there is no clear trend of $L_{\text{bol}}/M_*$ with $R_{SB}$ in the sample of SFGs hosting AGNs, the QGs hosting AGNs, which almost all come from the X-ray selection, appear to have overall lower $L_{\text{bol}}/M_*$ than the SFGs hosting AGNs. Both X-ray and IR AGNs share similar $M_{\text{HMC}}/M_*$ with normal SFGs, suggesting no clear link between galaxy compactness and the presence of AGNs. At the same time, although the median $R_{SB}$ of X-ray AGNs is consistent with normal SFGs, its distribution is skewed toward low $R_{SB}$. A different distribution of $R_{SB}$ is observed for IR AGNs, which generally have larger $R_{SB}$ than normal SFGs. These show that the high incidence of AGNs being hosted by galaxies in the SFG-to-QG transitional region is only observed for X-ray AGNs, rather than for IR AGNs. In the following, we detail our discussions on how our findings can help constrain the effects of the AGN presence on galaxy quenching.
5.1. Toward the General Picture of AGN Quenching

While current cosmological simulations (e.g., Illustris, Vogelsberger et al. 2014; EAGLE, Schaller et al. 2015; IllustrisTNG, Pillepich et al. 2018; SIMBA, Davé et al. 2019) can reproduce the observed statistics of massive galaxies by implementing AGN quenching of star formation, no consensus has yet emerged from the observations that such mechanism is effective in real galaxies.

Comparing star formation properties between AGNs and non-AGNs seems to be among the most straightforward tests. Our finding, that the median sSFR/$R_{SB}$ of AGNs is either similar to (X-ray AGNs) or larger than (IR AGNs) non-AGNs (Section 4.1.1), shows little evidence that the presence of an AGN suppresses the galaxywide star formation. Merely comparing the median/mean star formation properties of AGNs with non-AGNs may bias our view (Mullaney et al. 2015). A more detailed look shows that the distributions for X-ray AGN hosts are skewed toward low sSFR/$R_{SB}$, which seemingly suggests a negative effect of AGNs on their host’s star formation. However, because similar distributions are not seen for IR AGNs, this calls into question whether the skewed distributions of star formation properties of X-ray AGNs are a manifestation of AGNs and quenching or simply an AGN selection effect. Similar results have also been obtained by Ellison et al. (2016), where they found that, compared with the $M_\ast-$z–environment matched non-AGNs, the SFR distributions of AGNs are different among different AGN selections. In particular, they found that their optical-selected AGNs have wide and skewed to low SFR distribution, while the distribution for their MIR-selected AGNs is skewed to high SFR (their Figure 3).

Similarly to what we found by comparing the distributions of star formation properties, we further study the relations of $q_{AGN}$ with SFR, sSFR, and $R_{SB}$ (Section 4.1.3). While both X-ray AGNs and IR AGNs show higher incidence in galaxies with
enhanced star formation relative to the main sequence, a higher incidence of X-ray AGNs is also seen in galaxies with suppressed star formation, which, however, is not seen in IR AGNs. Empirically speaking, any physical process that is observed to have preferentially taken place in the SFG-to-QG transitional phase may contain critical information of galaxy quenching (e.g., Strateva et al. 2001; Bell et al. 2004; Faber et al. 2007). While the overabundance of X-ray AGNs is observed in galaxies with suppressed star formation, such a conclusion certainly cannot be extrapolated to all AGNs, because we know that it is invalid for IR AGNs. We therefore conclude that the direct comparisons of the star formation properties between AGNs and non-AGNs show no clear evidence of a causal link between the presence of AGNs and galaxy quenching.

Next, if ongoing AGN activities really were to play an observable role in affecting galaxy star formation properties, a correlation between AGN luminosities and star formation properties would be expected. In fact, a number of theoretical works predict the existence of a strong link between star formation and BH growth because both processes require cold gas supply (e.g., Di Matteo et al. 2005; Hopkins & Quataert 2010; Anglés-Alcázar et al. 2013). Regardless of the still relatively large measurement uncertainty, the analysis in Section 4.1.2 shows a null correlation between $L_{\text{bol}}$ and $R_{\text{SB}}$ in the SFG-hosting AGNs (both X-ray and IR), except that we see evidence that the brightest AGNs have the most intense star formation activities. These findings are fully aligned with other works (e.g., Lutz et al. 2008; Mullaney et al. 2012; Harrison et al. 2012), suggesting a rather weak/no link between star formation and BH growth. However, because stochastic AGN variabilities can diminish the underlying strong star formation–BH correlation (Hickox et al. 2014) and, unfortunately, little is known about the AGN duty cycle, it is impossible to conclusively say the real cause(s) of the $L_{\text{bol}}$–$R_{\text{SB}}$ null correlation.

While our understanding of the detailed physics driving galaxy quenching is still incomplete, theories suggest one possible evolutionary path, which has been shown by high-resolution zoom-in simulations to be particularly effective in the early universe when dissipative gas inflowing rate is high, namely that a galaxy undergoes a process of compaction as it transforms from an SFG to a QG (e.g., Zolotov et al. 2015; Tacchella et al. 2016). Some evidence supporting such mechanism has been reported based on recent observations, including the similar number densities, masses, and sizes between compact SFGs and compact QGs (Barro et al. 2013), as well as the ALMA-observed compact distribution of molecular gas and highly intense nucleated star formation activities in galaxies at $z \approx 2$ (e.g., Barro et al. 2016; Tadaki et al. 2017; Kaasinen et al. 2020). Similar to what has been reported by Kocevski et al. (2017), our analysis in Section 4.2.1 also finds a comparatively higher incidence of X-ray AGN hosts occupying a similar morphological parameter space as compact SFGs. This evidence seemingly suggests a causal link among the presence of an AGN, galaxy compaction, and quenching. After adding IR AGNs to the same diagrams (Figure 16), however, we immediately realize that IR AGNs occupy different parts of the color–morphology space, namely to distribute more like normal SFGs, with similar $(U-V)_{\text{corr}}$, $\Sigma_{e}$, and $\Sigma_{1\text{kpc}}$. These findings again question the claimed physical association between AGNs and galaxy quenching in the sense that the high incidence of AGNs being hosted by the SFG-to-QG transitional galaxies is only observed for X-ray AGNs and not for IR AGNs. This significantly weakens the argument that (X-ray) AGNs preferentially being hosted in compact SFGs is evidence of AGN quenching, because it depends on how the AGNs are selected and similar morphological characteristics of the host galaxies, i.e., frequent high compactness, are not observed for IR AGN hosts.

A further issue with the causal link between the presences of AGNs and galaxy compactness is noticed when we look at $M_{\text{MH2}}$ the morphological parameter that we introduced as an alternative compactness metric (see Section 3.2.3 for details), which has the distinct advantage of a weak dependence on $M_{\ast}$. If $M_{\text{MH2}}$ is used to define galaxy compactness, we see that not only IR AGNs but also X-ray AGNs have similar $M_{\text{MH2}}$ distributions to normal SFGs’ (Section 4.2.1 and the rightmost panels of Figures 16 and 17). This is different from the conclusions made upon the $\Sigma_{e}$ and $\Sigma_{1\text{kpc}}$ comparisons where X-ray AGNs seem to be more compact (larger $\Sigma_{e}$ and $\Sigma_{1\text{kpc}}$) than normal SFGs. We remind that, however, our purpose here is not to argue which parameter is better in quantifying galaxy compactness. In fact, there is no universal definition of galaxy compactness, and the physical meanings of $\Sigma_{e}$, $\Sigma_{1\text{kpc}}$, and $M_{\text{MH2}}$ obviously are all closely related. Depending on the specific analysis, we view the strong $M_{\ast}$ dependence of $\Sigma_{e}$ and $\Sigma_{1\text{kpc}}$ as a significant drawback when investigating the link between AGN activities and galaxy compactness, because the combination of $M_{\ast}$–$M_{\text{MH2}}$ and $M_{\ast}$–$\Sigma_{e}(1\text{kpc})$ correlations can present a null correlation between the AGN and galaxy compactness as a real one. This can be clearly seen in Section 4.2.2 where the relations of $q_{\text{AGN}}$ with $M_{\ast}$, $\Sigma_{e}$, $\Sigma_{1\text{kpc}}$, and $M_{\text{MH2}}$ are studied. While $q_{\text{AGN}}$ increases with $M_{\ast}$, $\Sigma_{e}$, and $\Sigma_{1\text{kpc}}$, a flat trend is observed with $M_{\text{MH2}}$ for both X-ray and IR AGNs, indicating that the higher incidence of AGNs with larger $\Sigma_{1\text{kpc}}$ is primarily due to $M_{\ast}$ rather than a morphological reason. It is also possible that the $q_{\text{AGN}}$–$\Sigma_{e}$ trends are driven by some other $M_{\ast}$ surrogates, such as bulge fraction (B/T). As already mentioned in Section 3.2.2, we leave the relevant discussions of this possibility to a separate work.

Our combined study of X-ray and IR AGNs highlights the essential importance of AGN selection effects on the distributions of host-galaxy properties. It is likely that different AGN selection methods are sensitive to different galaxy evolutionary states. In a simple BH–galaxy coevolutionary model, one would expect a dusty BH growth, which tends to be picked up by IR observations, to occur in the early state of normal SFGs when both bulge and BH mass are built up and to precede the less/unobscured phase of BH growth that X-ray observations tend to pick up. Observational studies based on the host morphology of IR- and X-ray-selected AGNs find consistent results with this scenario. For example, Kocevski et al. (2015) argued that their IR selection preferentially selects obscured sources in SFGs before quenching has started, while X-ray selection preferentially finds unobscured sources after the central bulge has built up and quenching has begun (see their Figure 10). The fact that we see IR AGNs live in galaxies like normal SFGs and X-ray AGNs live in transitional galaxies is in agreement with this simple evolutionary picture. A direct way to test this scenario would be to obtain high-quality measurements of ages and BH accretion histories in the AGN hosts and then compare the differences between different AGN...
populations, which is the subject of our current investigation. Because SFGs evolve by growing their stellar mass along the SFMS, however, a simplified version of this test would be to fix the sSFR and use the average $M_*$ as a crude proxy for the age of the stellar populations. Figure 23 shows that, at fixed sSFR, IR AGN hosts are systematically less massive than X-ray AGN ones, supporting the idea that IR AGNs are observed at a younger stage, which is consistent with the BH–galaxy coevolutionary model above. Therefore, the findings of this work certainly are not in direct conflict with AGN quenching, i.e., the scenario that AGNs drive the quenching of star formation in massive galaxies. On the other hand, however, the incidence of AGNs hosted by transitional galaxies, namely those with suppressed star formation and larger central surface mass density, depends on how the AGNs are selected. Thus, the fact that X-ray AGNs are preferentially hosted in transitional galaxies cannot be used as evidence of AGN quenching either, because this could also be simply a reflection of unobscured AGNs being more likely to show up during the later, less obscured evolutionary stages of the host without having anything to do with the quenching of the host.

5.2. Outlook for Future Studies—Combining All Radiative AGNs Selected by Different Methods

Our discussions so far have treated X-ray and IR AGNs as two separate populations. Ideally, they should be combined as a single AGN population to compare with their non-AGN counterparts to investigate if the presence of AGNs in general, no matter how they are selected, correlates with host properties. However, the task of combining different AGN populations is nontrivial.

Regarding AGN luminosities, different selection methods are not homogeneous, which, for example, can be seen in Figure 13 in our IR selection not being as sensitive as the X-ray selection for faint AGNs. While it remains difficult to use the existing IR data to push the IR selection to the similar faint limit of X-ray selection, this issue of luminosity inhomogeneity among different AGN selections, hopefully, can be resolved, or at least greatly mitigated, once the MIR capabilities of JWST are online (Rieke et al. 2019).

Because the timescale for a galaxy shining like an AGN is, in practice, an almost instantaneous event, and thus the total number of AGNs expected in a given field and at a given epoch of the universe (e.g., redshift intervals) should be statistically proportional to the timescale of the presence of AGNs. As a result, if the timescales change with the phases (e.g., obscured and unobscured) of BH growth, simply adding different AGNs together means giving more weight to the phase with a longer timescale. Because different AGN selection methods are sensitive to different BH growth phases, e.g., IR/X-ray selection for the obscured/unobscured AGNs, the distributions of the host properties for a simple combined AGN population are biased toward the AGN selection that corresponds to the AGN phase with the longer timescale. Instead of simply adding up all AGNs, if we could add different types of AGNs with weights of the inverse of the corresponding timescales, the bias, in principle, would be eliminated. This would rely on a comprehensive knowledge of the AGN duty cycle, information on which unfortunately remains dramatically missing both theoretically and observationally.

Moreover, it is well known that radiative AGNs can effectively, but are not limited to, be identified by MIR colors and X-rays. AGNs selected through other methods, e.g., optical emission lines (e.g., Agostino & Salim 2019) or MIR SED decompositions, also occupy a significant fraction of AGN population (e.g., Deller et al. 2017). Our work immediately shows that potentially biased conclusions can be made based on a specific AGN selection method. To draw a comprehensive picture of AGN effects on host galaxies, it is therefore crucial for future studies to include all AGNs selected by different methods.

6. Caveats

Finally, we mention the caveats of this work. First, we emphasize that the conclusions above should only apply to luminous AGNs. The current MIR data only allow for very bright IR AGNs to be identified. While the deep X-ray data push the detection limit to $\approx$1 dex fainter for X-ray AGNs (Figure 13), the identified AGNs are still relatively bright ones. It is unclear how the fainter and unidentified AGNs can affect our conclusions. Second, the effects of dust obscuration on our conclusions remain to be tested. Dust gradient can affect the $H_{160} (\approx$ rest-frame V band at $z \sim 2$) light profiles. If, statistically, X-ray and IR AGN-hosting galaxies share similar dust gradients, then the results of this work should not be greatly affected. However, if there exists an intrinsic difference in the dust obscuration between the two AGN populations, our conclusions might be affected. Because the IR selection is more sensitive to highly obscured AGNs, we would expect IR AGNs to more likely be hosted by galaxies with more nucleated dust obscuration, which might be able to even completely bury the central light from starbursts/AGNs. This actually is consistent with what we see in Figure 7 (see Section 3.2.2 for details). However, it is unclear to what extent the potentially different dust distributions can affect our conclusions, particularly for the distinct color–morphology distributions seen between X-ray and IR AGNs. In particular, if a high column density of dust only exists along lines of sight with a very small opening angle such that little stellar light is “blocked,” our results should stand. On the other hand, if the opening angle of the high-column-density dust is large a significant amount of central stellar light is “blocked,” then the IR AGNs could be more (although we do not know how much more) compact than
they are seen in the $H_{160}$ images. It will soon be possible to use JWST high-angular-resolution imaging in MIR, which is much less affected by dust obscuration, to finally investigate this issue.

7. Summary

In this work, we carry out a combined study of X-ray and IR AGNs at $z \approx 2$ and compare the star formation and morphological properties of AGN and non-AGN host galaxies. We show that the criteria used to select AGNs have profound impacts on the distributions of host-galaxy properties.

With regard to star formation properties,

1. while the distributions of star formation properties ($sSFR$ and $R_{SB}$) for X-ray AGN hosts are skewed toward low values, the medians are similar to normal (i.e., non-AGN) SFGs on the SFMS. A similar distribution is not seen for IR AGNs, which show enhanced star formation relative to galaxies on the SFMS (Section 4.1.1).
2. the large measurement uncertainty of $L_{bol}$ notwithstanding, no clear trends, either for X-ray AGNs or for IR AGNs, are seen between $L_{bol}$ and $R_{SB}$ (Section 4.1.2)
3. the trends of $q_{AGN}$ with SFR, $sSFR$, and $R_{SB}$ show that, despite the high incidence seen for both X-ray and IR AGNs in galaxies with intense star formation, the incidence of X-ray AGNs is also high in galaxies with suppressed star formation ($sSFR$ and $R_{SB}$), which however is not seen for IR AGNs (Section 4.1.3).

With regard to morphological properties,

1. the distributions of the morphological properties of X-ray and IR AGN hosts are very different in the color–morphology space (Section 4.2.1). In particular, while X-ray AGN hosts tend to have green colors and large stellar surface mass densities (both $\Sigma_e$ and $\Sigma_{1kpc}$), IR AGN hosts show distributions that are much more similar to those of normal SFGs. Because both $\Sigma_e$ and $\Sigma_{1kpc}$ are strongly correlated with $M_*$, we introduce a new diagnostic of compactness $M_*/M_{1kpc}$, which significantly eliminates the dependence on $M_*$. We show that the distributions of $M_*/M_{1kpc}$ for both X-ray and IR AGNs are similar to normal SFGs'. Consistent results are also obtained by comparing the distribution of normalized $R_e$ between AGNs and non-AGNs.
2. increasing trends of $q_{AGN}$ with $\Sigma_e$ and $\Sigma_{1kpc}$ are seen for both X-ray and IR AGN hosts. The trends with $M_*/M_{1kpc}$, however, remain more or less flat, indicating that the correlation with $\Sigma_e$ and $\Sigma_{1kpc}$ is primarily driven by $M_*$ (Section 4.2.2).

While the findings presented above are not in direct conflict with the scenario of AGNs driving the quenching of massive galaxies, they do not support it either. Our findings show that the frequency of AGNs hosted by transitional (from SFGs to QGs) galaxies, namely galaxies with suppressed star formation and large surface stellar-mass density, depends crucially on how the AGNs are selected. Thus, this calls into question the notion that there is a causal relationship between the presence of AGNs and the quenching of star formation. In fact, interpreting the different physical properties between the two AGN population hosts as evidence of different evolutionary phases of their ISM obscuration, for example, could imply another, yet unidentified, mechanism responsible for both quenching and the apparent evolution of the AGN properties.

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Appendix

Tests of Systematic Uncertainty when Using the Lee2018 SED-fitting Measurements

We use SED3FIT to test whether neglecting the AGN component when carrying out SED fitting with the methodology of Lee2018 can introduce a significant systematic bias into the physical parameters of the AGN sample. SED3FIT is built upon MAGPHYS (da Cunha et al. 2008) and includes an AGN component in the modeling. During the SED3FIT fitting, a galaxy’s SED is modeled as the combination of stellar emission, dust emission (polycyclic aromatic hydrocarbons, hot dust, and cold dust), and a user-defined AGN spectral library. The basic setup of SED3FIT is the same as MAGPHYS, namely using the BC03 stellar population synthesis code, assuming a Chabrier (2003) IMF and the Charlot & Fall (2000) dust attenuation model. SED3FIT uses a parametric SFH, which is assumed to be the summation of two components—an underlying exponential decline SFR ($t \propto \exp(-\gamma t)$) with random bursts superimposed. Given that the data coverage of each sample galaxy is limited (typical number of photometric bands is $\approx 15$, $\approx 60\%$ of AGN samples also have MIPS/24 μm data), we followed the same procedure as Delvecchio et al. (2014) to only adopt a subset of the AGN spectral library of Fritz et al. (2006) and Feltre et al. (2012). By testing with the mock galaxies hosting different types of AGNs (Type I, Type II, or intermediate), Ciesla et al. (2015) showed that the derived parameters such as $M_*$ and SFR are insensitive to the adopted AGN library.

A.1. Stellar Mass $M_*$

Figure 24(a) shows comparisons of the $M_*$ measurements between Lee2018 and SED3FIT. A clear correlation between the two $M_*$ is seen for the AGN sample. A $\approx 0.2$ dex offset between the two measurements is also seen, with $M_*$ derived by SED3FIT being larger than that derived by Lee2018. This offset can be attributed to the different setups between the two SED-fitting procedures, either due to including the AGN component in the modeling, or due to other different assumptions on things like SFH and dust attenuation law which are not related to the presence of AGNs. To check this, we ran MAGPHYS over a subsample of normal galaxies whose $M_*$ and redshift distributions are matched to the AGN sample. For each AGN, we select two normal galaxies that are closest to the AGN in the $M_*-z$ space. Like what is seen for the AGNs, an offset of the $M_*$ measurements between Lee2018 and SED3FIT is also observed for the $M_*-z$ matched normal galaxies. Moreover, as the right panel of Figure 24(a) shows, the magnitude of the offset seen for the non-AGNs ($\approx 0.15$ dex) is also similar as that seen for the AGNs ($\approx 0.17$ dex). These suggest that the offset between the two $M_*$ measurements of our AGNs is primarily from the different assumptions unrelated to the presence of AGNs, very likely due to different assumptions on SFHs and dust reddening laws. This conclusion actually is not surprising given that the
rest-frame UV to NIR SEDs are usually dominated by stellar light even when AGNs exist (see Section 4 in Brandt & Alexander 2015 and references therein). We have further tested the $M_*$ measurements by looking at the relation between the $M_*$ difference $\delta \log M_*$ and AGN X-ray intrinsic luminosity taken from Xue et al. (2016) and Luo et al. (2017). If the AGN component plays a vital role in the determination of $M_*$, then we would expect to see a dependence of $\delta \log M_*$ on AGN luminosity, which however is not seen in Figure 25. We therefore conclude that our $M_*$ measurement using Lee2018 is robust.

Finally, we do notice that some (though a small fraction) AGNs have rather large deviations of $M_*$ measurements between the two SED-fittings (both in Figures 24 and 25). Santini et al. (2012) checked the robustness of their $M_*$ measurements of Type 1 and Type 2 AGNs using two sets of SED fittings, one with the AGN component included while the other without. They found the $M_*$ of Type 2 AGNs can be very well-constrained even without including the AGN component during their SED-fittings, with the mean difference in $M_*$ measurements between the two SED-fittings being zero and only in 1.3% of objects the difference is larger than a factor of 2. For Type 1 AGNs, although the mean difference in $M_*$ is still consistent with $\approx 0$, the difference in 29% of objects is larger than a factor of 2. Similar results have also been found by other authors (e.g., Yang et al. 2018). Motivated by the potential different systematics between Type 1 and Type 2 AGNs, we have cross-matched our AGN sample with the broad-line (BL) X-ray AGNs in the GOODS-S (Silverman et al. 2010) and GOODS-N (Barger et al. 2003). 19 BL AGNs are found and marked as magenta open circles in Figure 24. We find that a considerable number of AGNs with large differences in $M_*$ measurements are BL AGNs. After comparing the difference of $M_*$ measurements between BL AGNs and other AGNs, we reach a similar conclusion to Santini et al. (2012), namely that the mean $M_*$ differences are similar between BL and non-BL AGNs. The distribution of $M_*$ difference of BL AGNs, however, is broader than that of non-BL AGNs, with the standard deviation of the former being larger than that of the latter by a factor of

$$\frac{\sigma(\delta M_*, \text{BL AGNs})}{\sigma(\delta M_*, \text{non-BL AGNs})} \approx 0.53 \text{ dex} \approx 1.9. \quad (A1)$$
It is therefore important to properly model the AGN component to get good measures of $M_*$ for BL AGNs, the detailed methodologies of which are beyond the scope of this work. We decide not to remove BL AGNs from our sample because they are a small fraction of the entire AGN sample and we have checked that our results are insensitive to including/excluding them.

### A.2. Star Formation Rate

Figure 24(b) shows the comparison of SFRs between the two SED-fitting measurements. We refer readers to Lee2018 for a detailed discussion about the uncertainty of their SFR measurements using mock galaxies from semianalytical simulations. A clear correlation between the two SFRs is observed both for the AGNs and the $M_*$–$z$ matched non-AGNs, despite the scatter being larger than in the case of the $M_*$ comparison. The right panel of Figure 24(b) compares the distributions of SFR difference between the AGNs and non-AGNs. Generally speaking, the two SED procedures yield consistent estimates of SFRs for the non-AGNs, with a median $\delta \log SFR = 0.08$ dex. For the AGNs, SFRs from Lee2018 are on average larger than those from SED3FIT by 0.22 dex.

A closer look at the left panel of Figure 24(b) shows that, unlike for galaxies with moderate/high SFRs, SED3FIT predicts larger SFRs than Lee2018 for galaxies with low SFRs, indicating different systematics of SFR measurements between SFGs and QGs. Such systematics are very likely due to the assumptions of SFHs. In Lee2018, they tested the SED-derived SFRs using mock galaxies (see their Figure 6), where they showed that an incorrect SFH can lead to significantly biased SFR measurements for QGs. Also in Leja et al. (2019), they showed that treating SFH as a free parameter is essential for the unbiased measurements of SFRs. While assumptions on the SFH can result in strong deviations of the SFR measurements from the intrinsic values for QGs, the situation for SFGs seems to be much better (see Figure 6 in Lee2018 for an example). Therefore, as Figure 26 shows, we only compare the SFRs between AGNs hosted by SFGs and $M_*$–$z$ matched normal SFGs (note that before we did not put any constraints on the star formation properties when building the $M_*$–$z$ matched normal galaxies). Compared with Figure 24(b), we find that the difference of $\delta \log SFR$ between AGNs and non-AGNs decreases from $\approx 0.2$ dex to $\approx 0.1$ dex, which is much smaller than the 1-$\sigma$ range of entire distributions ($\sim 0.7$ dex). Nevertheless, the remaining 0.1 dex difference between the two SED fittings is very likely due to the AGN component in Lee2018 fits being ignored.

In Figure 27, we also investigate the relation between $\delta \log SFR$ and intrinsic X-ray luminosity. We do not see any clear trend except for the brightest bin ($L_X \sim 10^{44.5}$ erg s$^{-1}$), where the overestimation of SFR can be as large as $\approx 0.5$ dex.

### A.3. Rest-frame Colors

The last parameters that we have checked are the rest-frame colors. We first compare the apparent (i.e., dust-attenuated) rest
colors $U - V$ and $V - J$ derived from the two SED fittings. To do so, we convolve the best-fit spectra with the Bessel $U$, $V$, and 2MASS J filters, respectively. As the left two panels of Figure 28 show, the apparent rest-frame colors derived from the two SED procedures are in very good agreement with each other. The distributions of AGNs on the $UVJ$ diagram (Figure 1) therefore are not sensitive to the choice of the SED-fitting procedure.

A more involved measurement is that of the dust-corrected rest-frame colors, i.e., colors that are corrected for dust attenuation (recall that Lee2018 assumes the Calzetti et al. 2000 dust attenuation law and SED3FIT assumes the Charlot & Fall 2000 model). The comparisons of the dust-corrected colors $(U - V)_{\text{corr}}$ and $(V - J)_{\text{corr}}$ are shown in the right panels of Figure 28. Unlike the dust-uncorrected colors, both systematic offsets and larger scatters between the two measurements are seen for the dust-corrected colors, which illustrate the essential role played by the assumed dust attenuation models when measuring the properties of stellar populations. For $(U - V)_{\text{corr}}$, similar offsets ($\approx 0.3m_{AB}$) and scatters are seen for both AGNs and non-AGNs, which indicates that the differences between the two SED measurements are primarily driven by assumptions unrelated to the presence of AGNs. A similar conclusion can also be made for $(V - J)_{\text{corr}}$, although the scatters of IR AGNs seem to be larger than X-ray AGNs and non-AGNs, very likely because the AGN contribution to the J band is generally larger for IR AGNs than for X-ray AGNs (see Figure 3). We caution that, however, our conclusions, which are drawn based on the comparisons of rest-frame colors above, depend on the correctness of the assumed AGN models. While the SEDs of Type 1 AGNs have been empirically well characterized at the UV through NIR wavelengths, the situation for the fainter Type 2 AGNs in general, such as the majority considered here, is more uncertain. While significant progress has been made to observationally constrain the SEDs of faint AGNs at MIR wavelengths, comparatively little is known about their SEDs at rest-frame UV/optical. If the adopted AGN templates considerably deviate from the true AGN spectral shapes in the UV/optical window, our tests on the optical colors will be biased.

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