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## STRUCTURE AND MORPHOLOGY OF X-RAY-SELECTED ACTIVE GALACTIC NUCLEUS HOSTS AT $1 < z < 3$ IN THE CANDELS-COSMOS FIELD

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### ABSTRACT

We analyze morphologies of the host galaxies of 35 X-ray-selected active galactic nuclei (AGNs) at  $z \sim 2$  in the Cosmic Evolution Survey field using *Hubble Space Telescope*/WFC3 imaging taken from the Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey. We build a control sample of 350 galaxies in total by selecting 10 non-active galaxies drawn from the same field with a similar stellar mass and redshift for each AGN host. By performing two-dimensional fitting with GALFIT on the surface brightness profile, we find that the distribution of the Sérsic index ( $n$ ) of AGN hosts does not show a statistical difference from that of the control sample. We measure the nonparametric morphological parameters (the asymmetry index  $A$ , the Gini coefficient  $G$ , the concentration index  $C$ , and the  $M_{20}$  index) based on point-source-subtracted images. All the distributions of these morphological parameters of AGN hosts are consistent with those of the control sample. We finally investigate the fraction of distorted morphologies in both samples by visual classification. Only  $\sim 15\%$  of the AGN hosts have highly distorted morphologies, possibly due to a major merger or interaction. We find there is no significant difference in the distortion fractions between the AGN host sample and control sample. We conclude that the morphologies of X-ray-selected AGN hosts are similar to those of non-active galaxies and most AGN activity is not triggered by a major merger.

*Key words:* galaxies: active – galaxies: high-redshift – galaxies: structure – X-rays: galaxies

*Online-only material:* color figure

### 1. INTRODUCTION

There is a long-standing question about what triggers active galactic nucleus (AGN) activity. Even now, 50 yr after quasars (QSOs; i.e., luminous AGNs) were discovered (Schmidt 1963), there is no convincing answer to this question. Major mergers are preferred candidates under the framework of hierarchical structure formation (e.g., Hopkins et al. 2006). Other secular mechanisms, such as minor mergers, disk/bar instabilities, colliding clouds, and supernova explosions, have also been proposed to fuel black hole (BH) accretion and trigger AGN activity (see Kormendy & Kennicutt 2004; Martini 2004; Jooe 2006 for reviews).

One possible approach is to analyze morphologies of AGN host galaxies and compare them with those of non-active galaxies. However, most morphological analyses of AGN hosts can be seriously biased if AGNs contribute significantly to the total flux (e.g., Gabor et al. 2009; Pierce et al. 2010; Böhm et al. 2013). High-resolution images and careful decomposition of a point-like source and AGN host are necessary to confirm the contribution of AGNs to the total flux. With the advent of the *Hubble Space Telescope* (HST), such morphological analyses for large AGN samples at  $z < 1.3$  and  $z \sim 2$  in the rest-frame optical were taken with the Advanced Camera for Surveys and Wide Field Camera 3 (WFC3), respectively.

Previous studies have yielded different results. At low redshift ( $z < 1.3$ ), some researchers found that a significant fraction of AGNs have bulge-dominated morphologies from a nonparametric classification (e.g., Grogan et al. 2005; Pierce et al. 2007), which could be biased by the point-source component which is not removed in these studies. By contrast, other researchers

using a careful point-source removal have found that AGN hosts either show a wide range of morphologies between bulge- and disk-dominated (Gabor et al. 2009) or over half of them have a significant disk component (Cisternas et al. 2011). In these studies, no enhancement of merger or interaction signatures have been found in AGN hosts by comparing them with control samples. However, Urrutia et al. (2008) found a high merger fraction (11 out of 13 in their luminous red QSOs sample). This may lead to an explanation that merger fraction is dependent on AGN luminosity (Treister et al. 2012; but see also Villforth et al. 2013). At  $z \sim 2$ , AGN hosts seem to be disk-dominated with a merger fraction similar to those of non-active galaxies (Schawinski et al. 2011, 2012; Simmons et al. 2012) or have a significant fraction of disk galaxies with a bulge component (Kocevski et al. 2012).

In this Letter, we take the comprehensive structural and morphological analyses of X-ray-selected AGN host galaxies in the Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey-Cosmic Evolution Survey (CANDELS-COSMOS) field using *HST*/WFC3 *H*-band imaging at  $1 < z < 3$ . We try to find whether there is a special morphological type to which AGN hosts typically belong, and we examine whether there is a significant difference in morphological properties between AGN hosts and control samples. In Section 2, we describe our selections of the X-ray-selected AGN and control samples. In Section 3, we describe the methods used to measure the morphological parameters. First, we perform two-dimensional light profile fitting with GALFIT using a Sérsic model representing host galaxy contribution and a point spread function (PSF) model representing the point-source contribution. Then, based on the point-source-subtracted images, we

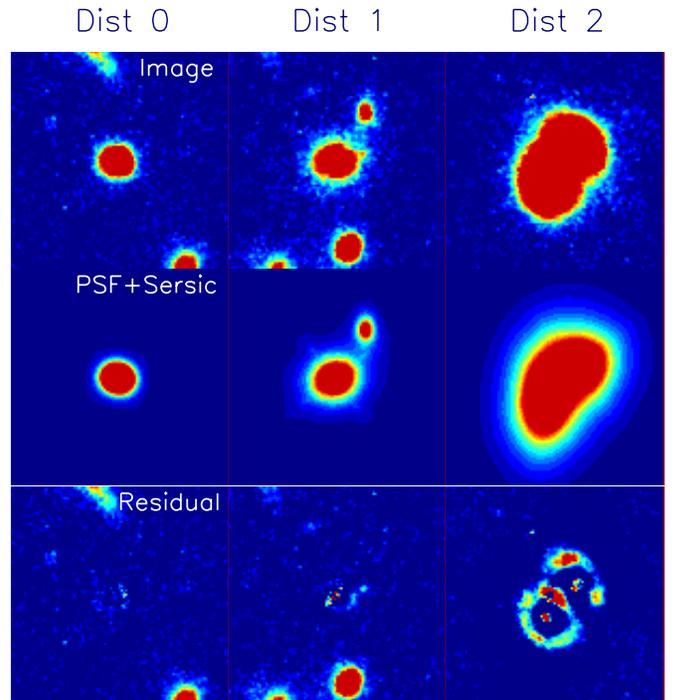
compute the nonparametric morphological parameters. Finally, we perform the visual classification based on the  $H$ -band image and the residual image. In Section 4, we give the main results of our morphological analyses. In Section 5, we summarize and discuss our results. Throughout this Letter, we assume a concordance  $\Lambda$ CDM cosmology with  $\Omega_m = 0.3$ ,  $\Omega_\Lambda = 0.7$ ,  $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ .

## 2. SAMPLE SELECTION

We use the X-ray-selected AGN catalog presented in Bongiorno et al. (2012). They selected AGNs from the XMM-COSMOS catalog (Cappelluti et al. 2009) with the optical identifications and multiwavelength properties as discussed by Brusa et al. (2010) and new photometric redshifts from Salvato et al. (2011). More than half of them have available spectroscopic redshifts. Bongiorno et al. (2012) also derived the host galaxy properties, such as colors and stellar masses, based on a two-component model fit of spectral energy distributions (SEDs) of an AGN and its host galaxy.

The central region of the COSMOS survey (Scoville et al. 2007) has been imaged with  $HST/WFC3$  as part of the CANDELS multi-cycle treasury program (Grogin et al. 2011; Koekemoer et al. 2011). The  $HST$  WFC3/IR images have been prepared by drizzling the individual exposures onto a grid with rescaled pixel sizes of 60 mas (Koekemoer et al. 2011). We use the  $H$ -band ( $HST/WFC3$  F160W filter) source catalog presented in van der Wel et al. (2012) to match the X-ray-selected AGN sample. With available spectroscopic or photometric redshifts, we select 37 AGNs with  $H$ -band detections within the redshift range of  $1 < z < 3$ . Among them, two sources lie on the edge of the CANDELS-COSMOS field and therefore have been discarded for further morphological analysis. In total, we have 35 X-ray-selected AGNs with  $H$ -band images. Out of 35 sources 13 have been classified as Type 1 (unobscured) AGNs and the other 22 have been classified as Type 2 (obscured) according to optical spectra, X-ray luminosities, and multiwavelength SEDs (Salvato et al. 2011). The high obscured fraction indicates that the light from the AGNs may not be significant at the rest frame optical band where we perform the morphological analyses. Out of 35 sources 28 have been detected in the 2–10 keV band and the rest have 0.5–2 keV band detection. Their rest-frame 2–10 keV luminosities  $L_{2-10\text{keV}}$  (without absorption correction) have been derived using  $L_{2-10\text{keV}} = 4\pi D_L^2 f_{2-10\text{keV}}(1+z)^{\Gamma-2}$ , where  $f_{2-10\text{keV}}$  is the observed 2–10 keV flux,  $D_L$  is the luminosity distance, and  $\Gamma = 1.8$  is the intrinsic AGN spectral index (e.g., Xue et al. 2011). For seven objects with only 0.5–2 keV band detection, we derive their observed 2–10 keV flux from  $f_{0.5-2\text{keV}}$  by adopting an observed AGN spectral index  $\Gamma_{\text{obs}} = 1.4$  (e.g., Xue et al. 2011). The  $L_{2-10\text{keV}}$  of our sample have a range from  $\sim 3 \times 10^{43} \text{ erg s}^{-1}$  to  $10^{45} \text{ erg s}^{-1}$  with a median value of  $1.5 \times 10^{44} \text{ erg s}^{-1}$ , about one order of magnitude higher than the previous moderate-luminosity sample in a similar redshift range (e.g., Simmons et al. 2012; Kocevski et al. 2012). Stellar masses of host galaxies derived by SED fitting in Bongiorno et al. (2012) show most of them are massive, with an average value of  $5 \times 10^{10} M_\odot$ .

To construct the control sample, we randomly select 10 non-active galaxies from the CANDELS-COSMOS  $H$ -band catalog (van der Wel et al. 2012) for each AGN host. Here we use the photometric redshifts of non-active galaxies derived by Muzzin et al. (2013). We require that the selected non-active galaxies have stellar masses and redshifts similar to the matched AGN host. We select those non-active galaxies with stellar masses



**Figure 1.** Examples of our GALFIT analysis (see Section 3.1) and visual classification (see Section 3.3).  $HST$  WFC3 F160W ( $H$ -band) images are shown in the first row. The corresponding model (Sérsic + PSF) and residual images can be found in the second and third rows, respectively. We also show examples of AGN host galaxy images arranged into three different distortion classes, which are defined based on the  $H$ -band cutouts and residual images (see Section 3.3), in three columns, respectively.

(A color version of this figure is available in the online journal.)

within a factor of two and with redshift difference less than 0.5 compared to the AGN host (i.e.,  $|\Delta \log M_*| \leq 0.3$  and  $|\Delta z| \leq 0.5$ ). Finally, a total of 350 non-active galaxies that meet the criteria have been selected.

## 3. STRUCTURAL AND MORPHOLOGICAL PARAMETERS

### 3.1. GALFIT Analysis

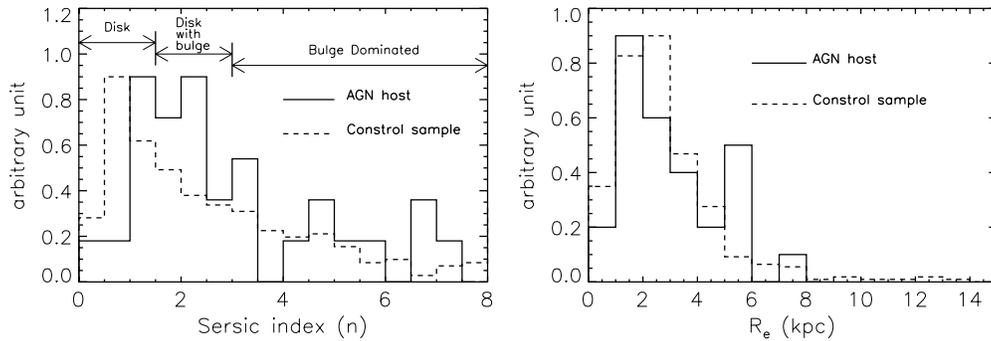
We use the *GALFIT* package (Peng et al. 2002) to fit the surface brightness profiles of our AGN host and control samples. The fits are performed in the  $H$ -band cutout images.<sup>7</sup> As we did in our previous work (Fan et al. 2013), we use the empirical PSF instead of the model PSF. We extract it from 43 stars with  $S/N > 50$  in the CANDELS-COSMOS field using PSFEX (Bertin 2011).

For the AGN host sample, we use a PSF to model the nuclear point source, plus a Sérsic function to model the host galaxy (see Figure 1). We constrain the Sérsic index within a proper range (i.e.,  $0.1 \leq n \leq 10$ ). For those objects with a dominant nuclear point source (6/35, defined by  $\text{mag}_{\text{host}} > \text{mag}_{(\text{point source})}$ ), the two-dimensional fitting with a Sérsic + PSF model will become very unreliable. We use a single PSF model for these objects instead. For the control sample, we use the structural parameters from van der Wel et al. (2012) which have been measured with a single Sérsic function.

### 3.2. Nonparametric Morphological Parameters

For the AGN host and control samples, we also measure nonparametric morphological parameters, such as the Gini

<sup>7</sup> <http://www.mpia-hd.mpg.de/homes/vdwell/candels.html>



**Figure 2.** Structural parameters of AGN host galaxies and non-active galaxies. Left: the distribution of Sérsic indices  $n$ . Right: the physical effective radii  $R_e$ . The solid line represents the X-ray-selected AGN host galaxies at  $z \sim 2$ , while the dashed line represents the control sample. The Kolmogorov–Smirnov (K-S) test probabilities ( $P_{KS}$ ) are 0.47 and 0.56 for the distributions of Sérsic indices and effective radii of the AGN host and control samples, respectively.

coefficient (the relative distribution of the galaxy pixel flux values),  $M_{20}$  (the second-order moment of the brightest 20% of the galaxy’s flux), the concentration index ( $C$ ), and rotational asymmetry index ( $A$ ). Compared to the Sérsic index, these parameters are model-independent and therefore can be applied to irregulars as well as standard Hubble-type galaxies (e.g., Abraham et al. 1996; Conselice 2003; Lotz et al. 2004; Kong et al. 2009, Fang et al. 2009, 2012; Wang et al. 2012).

For non-active galaxies in the control sample, we measure these parameters using the original  $H$ -band images while for AGN hosts, the case becomes a bit complicated. The presence of the highly symmetric nuclear point source will strongly bias all the measurements of host morphological parameters (Pierce et al. 2010; Böhm et al. 2013). Therefore we measure these parameters of AGN host galaxies using the same method as Gabor et al. (2009) did. We subtract the best-fit model nuclear point source derived in Section 3.1 from each AGN  $H$ -band image. For objects with a dominant nuclear point source, we use residual images from our PSF-only-fit subtraction.

### 3.3. Visual Classification

Besides the structural and morphological parameter measurements of the AGN host and control samples, we also investigate the merger or interaction fraction of the AGN host and control samples via visual classification. Using the same method presented in Cisternas et al. (2011), all AGN host and non-active galaxies have been visually classified by five human classifiers independently, based on the  $H$ -band cutouts and residual images by subtracting the best-fit Sérsic +PSF model presented in Section 3.1. We use the same definition of “distortion class” as Cisternas et al. (2011) to describe the degree of distortion of the galaxy. We use three classes: Dist 0, Dist 1, and Dist 2. Class “Dist 0” represents undisturbed and smooth galaxies, showing no interaction signatures. Class “Dist 1” represents galaxies with mild distortions, possibly due to a minor merger or accretion. Class “Dist 2” represents galaxies with strong distortions, which are potential signs for ongoing or recent mergers. Illustrative examples of distortion classes can be found in Figure 1.

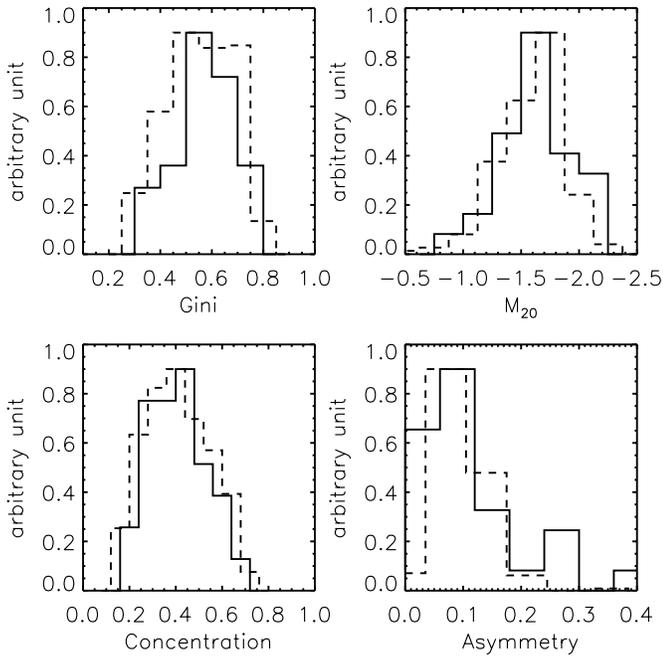
## 4. RESULTS

In Figure 2, we plot the distributions of Sérsic index  $n$  (left panel) and the physical effective radii  $R_e$  (right panel) of AGN host galaxies and non-active galaxies. The objects with a dominant nuclear point source are not included in this plot. We compute the Kolmogorov–Smirnov (K-S) test probabilities ( $P_{KS}$ ) which are 0.47 and 0.56 for the distributions of Sérsic

indices and effective radii of the AGN host and control samples, respectively. The results are consistent with both Sérsic indices and effective radii of AGN hosts being drawn from the same distributions as the control sample.

The distribution of Sérsic indices of X-ray-selected AGN host galaxies indicates a broad range of morphologies, from disk-dominated ( $n < 1.5$ ) and disk with a prominent bulge component ( $1.5 \leq n \leq 3.0$ ), to bulge-dominated ( $n > 3.0$ ). The fractions of disk-dominated, intermediate, and bulge-dominated morphologies are 27.6%, 34.5%, and 37.9%, respectively, in our AGN host galaxy sample. Disks (with and without a prominent bulge component) are the most common morphology in X-ray-selected AGN host galaxies (close to two-thirds of the entire sample), while there is also a significant fraction (more than one-third of the entire sample) dominated by bulges. These fractions are quantitatively consistent with those of X-ray-selected AGN host galaxies at redshifts  $0.3 < z < 1.0$  (Gabor et al. 2009). However, some previous findings (e.g., Schawinski et al. 2011, Simmons et al. 2012) showed a higher fraction of X-ray-selected AGN host galaxies in disk galaxies at similar redshift  $z \sim 2$ . They found that  $\sim 80\%–90\%$  of X-ray-selected AGN host galaxies with luminosities of  $10^{42} \text{ erg s}^{-1} < L_X < 10^{44} \text{ erg s}^{-1}$  had low Sérsic indices ( $n < 3$ ) indicative of disk-dominated light profiles. Compared to their results, AGN hosts in our sample have a lower fraction of disks and a higher fraction of bulge-dominated morphology. One possible explanation for the difference between our results is that AGN host morphology could vary with X-ray luminosity. The X-ray luminosities of our sample have an average value of  $\sim 10^{44} \text{ erg s}^{-1}$ , about one order of magnitude higher than those in their previous works. Host galaxies of AGNs with higher X-ray luminosities may have a higher fraction of bulge-dominated morphology. This possibility has been tested and confirmed by an independent work of Kocevski et al. (2012) via visual inspection of a moderate-luminosity AGN sample at  $z \sim 2$ . They observed a dramatic rising in the bulge-dominated fraction: from 18.4% in the subsample with  $L_X < 10^{43} \text{ erg s}^{-1}$  to 40.6% in the subsample with  $L_X > 10^{43} \text{ erg s}^{-1}$ . We note that the bulge-dominated fraction ( $\sim 40\%$ ) in their subsample with  $L_X > 10^{43} \text{ erg s}^{-1}$  agrees well with that value in our result.

In Figure 3, we plot the distributions of four nonparametric morphological parameters (Gini,  $M_{20}$ , concentration and asymmetry) of AGN host and non-active galaxies. We perform a K-S test to determine whether the AGN host and control sample populations are consistent with being drawn from the same underlying distribution. We find that all distributions of these parameters for AGN hosts have no difference from those of



**Figure 3.** Distributions of nonparametric morphological parameters (top-left: Gini; top-right:  $M_{20}$ ; bottom-left: concentration; bottom-right: asymmetry) of AGN host and non-active galaxies. The solid line represents the X-ray-selected AGN host galaxies at  $z \sim 2$ , while the dashed line represents the control sample. K-S test probabilities that nonparametric morphological parameters of AGN host galaxies are drawn from the same distributions as their control sample are 0.91, 0.85, 0.94, and 0.38 for Gini,  $M_{20}$ , concentration and asymmetry, respectively.

**Table 1**

Mean Distortion Classification of AGN Host and Control Samples

Distortion Class	$\mu_{\text{AGN}}^a$	$\mu_{\text{CS}}^a$
Dist-0	$54.3\% \pm 10.1\%$	$57.1\% \pm 6.9\%$
Dist-1	$30.9\% \pm 8.7\%$	$29.0\% \pm 5.3\%$
Dist-2	$14.8\% \pm 2.4\%$	$13.9\% \pm 4.3\%$

**Note.** <sup>a</sup> Mean of the five classifications.

non-active galaxies, with K-S test probabilities of 0.91, 0.85, 0.94, and 0.38 for Gini,  $M_{20}$ , concentration, and asymmetry, respectively. We note that the nonparametric morphological parameter measurements of six objects with a dominant nuclear point source are very uncertain. However, we find that the inclusion of these six objects or not will not change our main conclusion.

In Table 1, we summarize the mean fractions of three distortion classes in the AGN host and control samples via visual classification. Several main results can be addressed.

1. Over 50% of AGN host galaxies have an undisturbed and smooth light profile, showing no evidence for an ongoing merger.
2. Visual morphologies of near 50% of AGN host galaxies are distorted to different degrees, showing possible signatures for ongoing minor/major mergers. However, among these distorted AGN host galaxies, most of them have mild morphological distortion. Only  $<15\%$  of the entire AGN host galaxies show strong distortions, which are potential signs for ongoing or recent major mergers.
3. The fractions of distortion classes of AGN host galaxies are consistent with those of the control galaxies. We find no evidence that AGNs host a higher fraction of distorted

morphologies (Dist 1 and Dist 2 classes) than non-active galaxies.

These results are generally consistent with the previous findings of Cisternas et al. (2011) at lower redshift ( $0.3 < z < 1.0$ ) and of Kocevski et al. (2012) at similar redshift ( $z \sim 2$ ).

## 5. SUMMARY AND DISCUSSION

In this Letter, we analyze the structure and morphology of X-ray-selected AGN host galaxies in the CANDELS-COSMOS field using *HST*/WFC3 imaging in the *H* band at  $z \sim 2$  and compare them with those of a mass-matched non-active galaxy sample. Our primary findings are as follows. (1) Nearly two-thirds of X-ray-selected AGN host galaxies in our sample at  $z \sim 2$  have disk-like morphologies (including disk-dominated and disk with a bulge component morphologies), while a significant fraction (over one-third) of them are bulge-dominated. (2) All structural (Sérsic index  $n$  and effective radius  $R_e$ ) and morphological (Gini,  $M_{20}$ , concentration and asymmetry) parameters of AGN host galaxies in our sample have distributions similar to those of non-active galaxies. We conclude that, from the point of view of structure and morphology, AGN host galaxies and non-active galaxies are indistinguishable. From other points of view, such as color-color gradients and stellar population properties, Rosario et al. (2013) also found that X-ray-selected AGN host galaxies and non-active galaxies are indistinguishable. (3) Only a small fraction ( $\sim 15\%$ ) of X-ray-selected AGN host galaxies have major merger signatures according to our visual classification. Compared to the mass-matched non-active galaxy sample, AGN hosts do not show a significant excess of distorted morphologies.

As shown by previous host galaxy simulations (e.g., Simmons & Urry 2008; Gabor et al. 2009; Pierce et al. 2010), the result that AGN host galaxies are disk-dominated characterized by a low fitted Sérsic index  $n$  is reliable. While disk contribution cannot be ruled out in a bulge-dominated galaxy with a high fitted Sérsic index  $n$ , Simmons & Urry (2008) found that bulge-dominated AGN host galaxies with  $n > 4$  may have a significant disk contribution (up to 45% of their total host galaxy light). The disk fraction ( $\sim 63\%$ ) of AGN host galaxies in our sample should be taken as a lower limit. This value is a bit lower than the disk fraction of 75% in Simmons et al. (2012), and is much lower than the disk fraction  $\sim 90\%$  in Schawinski et al. (2011). The relatively lower disk fraction in our sample could be the result of different sample selections. The X-ray luminosities of AGNs in our sample are on average one order of magnitude higher than those in Schawinski et al. (2011).

Complemented by several previous findings at  $0 < z < 3$  (e.g., Gabor et al. 2009; Cisternas et al. 2011; Schawinski et al. 2011; Simmons et al. 2012; Kocevski et al. 2012), some consistent results can be summarized for X-ray-selected AGNs with  $10^{42} \text{ erg s}^{-1} < L_X < 10^{45} \text{ erg s}^{-1}$  up to  $z \sim 3$ : they have no enhanced distorted morphologies and have structure and morphologies similar to non-active galaxies. These points indicate that major mergers are not necessary for triggering AGN activities in the galaxies of the X-ray-selected sample. Secular internal processes, such as gravitational instabilities and dynamical friction should play a crucial role in triggering X-ray-selected AGN activities and black hole-host galaxy co-evolution. Our findings do not conflict with supermassive black hole (SMBHs)-host galaxy co-evolution scenarios in which major mergers are responsible for triggering both star formation and luminous QSO activities (e.g., Hopkins et al. 2006). Unlike

X-ray-selected AGNs, a very high fraction (up to  $\sim 100\%$ ) of luminous QSOs are commonly formed in major mergers and are specifically found in dust-shrouded, merger-induced starbursts (e.g., Urrutia et al. 2008; Treister et al. 2012). Thus two different modes of BH triggering and growth have been indicated: BH growth by secular evolution of disk galaxies is important for low-luminosity AGNs, while major mergers may feed luminous quasars (e.g., Kormendy & Ho 2013).

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*Facilities:* *HST* (WFC3), *XMM*

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