Mergers trigger active galactic nuclei out to $z \sim 0.6$

F. Gao$^{1,2}$, L. Wang$^{1,2}$, W. J. Pearson$^{1,2}$, Y. A. Gordon$^3$, B. W. Holwerda$^4$, A. M. Hopkins$^5$, M. J. I. Brown$^6$, J. Bland-Hawthorn$^7$, and M. S. Owers$^8,9$

1 Kapteyn Astronomical Institute, University of Groningen, Postbus 800, 9700 AV Groningen, The Netherlands  
e-mail: gzmargaret@gmail.com  
2 SRON Netherlands Institute for Space Research, Landleven 12, 9747 AD Groningen, The Netherlands  
3 Department of Physics and Astronomy, University of Manitoba, Winnipeg, MB R3T 2N2, Canada  
4 Department of Physics and Astronomy, 102 Natural Science Building, University of Louisville, Louisville, KY 40292, USA  
5 Australian Astronomical Optics, Macquarie University, 105 Delhi Rd, North Ryde, NSW 2113, Australia  
6 School of Physics and Astronomy, Monash University, Clayton, VIC 3800, Australia  
7 Sydney Institute for Astronomy, School of Physics A28, University of Sydney, Sydney, NSW 2006, Australia  
8 Department of Physics and Astronomy, Macquarie University, Sydney, NSW 2109, Australia  
9 Astronomy, Astrophysics and Astrophotonics Research Centre, Macquarie University, Sydney, NSW 2109, Australia

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ABSTRACT

Aims. The fueling and feedback of active galactic nuclei (AGNs) are important for understanding the co-evolution between black holes and host galaxies. Mergers are thought to have the capability to bring gas inward and ignite nuclear activity, especially for more powerful AGNs. However, there is still significant ongoing debate on whether mergers can trigger AGNs and, if they do, whether mergers are a significant triggering mechanism.

Methods. We selected a low-redshift ($0.005 < z < 0.1$) sample from the Sloan Digital Sky Survey and a high-redshift ($0 < z < 0.6$) sample from the Galaxy And Mass Assembly survey. We took advantage of the convolutional neural network technique to identify mergers. We used mid-infrared (MIR) color cut and optical emission line diagnostics to classify AGNs. We also included low excitation radio galaxies (LERGs) to investigate the connection between mergers and low accretion rate AGNs.

Results. We find that AGNs are more likely to be found in mergers than non-mergers, with an AGN excess up to 1.81 ± 0.16, suggesting that mergers can trigger AGNs. We also find that the fraction of mergers in AGNs is higher than that in non-AGN controls, for both MIR and optimally selected AGNs, as well as LERGs, with values between 16.40 ± 0.5% and 39.23 ± 2.10%, implying a non-negligible to potentially significant role of mergers in triggering AGNs. This merger fraction in AGNs increases as stellar mass increases, which supports the idea that mergers are more important for triggering AGNs in more massive galaxies. In terms of merger fraction as a function of AGN power we find a positive trend for MIR selected AGNs and a complex trend for optically selected AGNs, which we interpret under an evolutionary scenario proposed by previous studies. In addition, obscured MIR selected AGNs are more likely to be hosted in mergers than unobscured MIR selected AGNs.

Key words. galaxies: active – galaxies: interactions

1. Introduction

Almost every massive galaxy in the Universe hosts a super massive black hole (SMBH; Richstone 1998), although most of them are dormant like the one in our Galaxy with an accretion rate $\lesssim 10^{-8} M_\odot$ yr$^{-1}$ (Baganoff et al. 2003). Despite its small scale compared to the host galaxy, it has long been confirmed that tight correlations exist between the mass of the SMBH and host galaxy properties. For example, black hole (BH) mass correlates with the velocity dispersion of the galaxy bulge ($M_{\text{BH}}-\sigma_{\text{bulge}}$ relation, e.g., Ferrarese & Merritt 2000; Gebhardt et al. 2000). Black hole mass also correlates with the luminosity (and stellar mass) of the galaxy bulge (e.g., McLure & Dunlop 2001, 2002). These tight relations support a popular scenario in which SMBHs co-evolve with their host galaxies (see Kormendy & Ho 2013, for a review). Active galactic nuclei (AGNs) are rapidly accreting black holes and are proposed to be the link connecting the central engine and the host galaxy. Both AGN activity and cosmic star formation activity reach their peaks at $z \sim 2$ (Richards et al. 2006; Madau & Dickinson 2014), which further supports the co-evolution picture. These vigorous monsters can shape their hosts either through radiation pressure (radiative or quasar mode: Silk & Rees 1998; Haehnelt et al. 1998; Vogelsberger et al. 2013) or via radio jets (maintenance or radio mode: Blandford & Königl 1979; Croton et al. 2006; Bower et al. 2006; Lister et al. 2009).

An important question in AGN research is, which processes bring gas inward making it lose most of its angular momentum and accrete in the disk, thus fueling nuclear activity. This takes place from host galaxy scale (~10 kpc) down to SMBH scale (~10 pc). Early studies of luminous infrared galaxies (LIRGs) and ultra luminous infrared galaxies (ULIRGs) reveal a high fraction of interactions (e.g., Murphy et al. 1996; Veilleux et al. 2002). Most of these luminous IR galaxies are thought to be AGNs (e.g., Sanders & Mirabel 1996), thus leading to a popular explanation in AGN triggering: mergers. In this scenario, the strong gravitational torque funnels gas inward and triggers the accretion activity around the central black hole as well as accelerating star formation in the bulge, thus connecting the growth of SMBHs and their host galaxies (e.g., Hopkins et al. 2006). Simulations
mergers or AGN, are able to transport gas reservoirs to the inner region of galaxies and trigger nuclear activity, reproducing the observed AGN luminosity function (Hopkins et al. 2008).

Many efforts have been made to find an observational connection between galaxy mergers and AGNs. However, the results are still mixed. On the one hand, studies focusing on AGN fraction in mergers compared to non-mergers show that mergers are more likely to host AGNs than non-mergers (Ellison et al. 2011; Lackner et al. 2014; Satyapal et al. 2014; Weston et al. 2017; Donley et al. 2018; Goulding et al. 2018). AGN fraction also increases as the separation between galaxy pairs decreases (e.g., Ellison et al. 2011, 2013; Silverman et al. 2011; Koss et al. 2012; Satyapal et al. 2014; Khabiboulline et al. 2014). On the other hand, studies focusing on merger fraction in AGNs compared to non-AGN controls show conflicting results. Some found that AGNs reside more frequently in galaxy mergers compared to non-active counterparts, especially for those with higher luminosity, or dust reddened AGNs or even Compton-thick AGNs (Treister et al. 2012; Santini et al. 2012; Kocevski et al. 2015; Comerford et al. 2015; Fan et al. 2016; Ellison et al. 2019).

While others did not find a difference of merger fraction in active and non-active galaxies (Grogin et al. 2005; Gabor et al. 2009; Cisternas et al. 2011; Kocevski et al. 2012; Mechtley et al. 2016; Villforth et al. 2017), or a dependence on AGN luminosity (e.g., Hewlett et al. 2017), suggesting that major mergers are not the dominant mechanism in triggering AGN activity, even for higher luminosity ones.

Various reasons are thought to be responsible for these conflicting results. Selection bias is perhaps one of the most important factors. In terms of AGN selection, different studies use different selection criteria for AGNs, such as mid-infrared (MIR) color selection (e.g., Satyapal et al. 2014; Donley et al. 2018; Goulding et al. 2018; Ellison et al. 2019), X-ray selection (e.g., Hasinger 2008; Kocevski et al. 2012; Lackner et al. 2014; Hewlett et al. 2017; Secrest et al. 2020), optical emission line ratios (the so-called BPT diagram, Baldwin et al. 1981) and radio (Ellison et al. 2015; Chiaberge et al. 2015; Gordon et al. 2019). AGNs selected in different ways may represent different stages in the merger evolutionary scenario (e.g., Sanders et al. 1988).

In terms of merger selection, some studies take advantage of spectroscopic redshift surveys to pick up galaxy pairs within a certain distance (e.g., Ellison et al. 2011; Satyapal et al. 2014), which are more likely to be early stage mergers, while others focus on images to select morphologically disturbed galaxies (e.g., Kocevski et al. 2012; Donley et al. 2018; Ellison et al. 2019). Morphologically selected mergers can select galaxies with signs of disturbance caused by merging but without a visible merging companion. In addition, some studies use small samples that may not cover a wide range of redshifts, stellar masses, and luminosities and do not establish a matched control sample for comparison. When identifying mergers, many studies use visual inspection (e.g., Cisternas et al. 2011; Kocevski et al. 2015; Ellison et al. 2019), which is based on subjective ranking, or the fitting of Sérsic profiles (e.g., Fan et al. 2016; Mechtley et al. 2016), which relies on careful point source subtraction. Also, simulations show that non-parametric measurements such as Gini and M20 coefficients (e.g., Villforth et al. 2017) work well at the first pass and final coalescence stages but fail at other stages (Lotz et al. 2008), and are sensitive to mass ratios and gas fractions (Lotz et al. 2010a,b). Moreover, the timescale of AGN activity may also play an important role. Typically AGN lifetimes are ∼107–109 years (e.g., Marconi et al. 2004). This is quite short compared to that of mergers, which can last up to a few giga years (Lotz et al. 2008; Moreno et al. 2019). This difference in timescale can lead to fewer AGNs being detected in some stages of the merger process. In addition, the time delay between merger events and the triggering of AGN activity as inflowing gas eventually falling into the vicinity of BH would bias towards fewer AGNs being observed (e.g., Villforth et al. 2014; Shabala et al. 2017).

In this work, we select our samples from two spectroscopic surveys, the Sloan Digital Sky Survey (SDSS; York et al. 2000) at lower redshifts and the Galaxy And Mass Assembly (GAMA; Driver et al. 2009) survey at higher redshifts. We take advantage of the deep learning convolutional neural networks (CNN) to identify mergers, using SDSS images for the SDSS sample and Kilo Degree Survey (KiDS; de Jong et al. 2013a,b) images for the GAMA sample. Convolutional neural networks allow us to rapidly classify very large numbers of objects in a consistent and reproducible manner. With upcoming large area surveys, such as Euclid (Laureijs et al. 2011) and the Large Synoptic Survey Telescope (LSST Science Collaboration 2009), which are expected to produce images of billions of images of galaxies, CNNs offer an efficient way to analyze this data. We use a MIR color cut criterion and optical emission lines diagnostics to identify AGNs. We also use a low excitation radio galaxies (LERGs) catalog from Best & Heckman (2012) to study the connection between low accretion rate AGNs and mergers. Our goal is to combine sophisticated merger selection, large samples, and multiple AGN selection methods to explore the merger-AGN connection in the low-redshift Universe.

This paper is structured as follows. In Sect. 2, we describe our sample construction, merger identification method, and AGN selection methods. In Sect. 3, we show our results on the AGN fraction in mergers and non-merger controls, and merger fraction in AGNs and non-AGN controls. We also investigate the dependence of merger fraction on stellar mass and AGN power. Discussions of our results and comparisons with previous work are presented in Sect. 4. In Sect. 5 we summarize our work. Throughout this paper, we assume a flat $\Lambda$CDM universe with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

2. Data and methods

We select our samples from two major galaxy surveys. For the first sample we use the SDSS DR7 spectroscopic catalog (Abazajian et al. 2009) covering $\sim$14 000 deg$^2$ at $0.005 < z < 0.1$ with a magnitude limit of $r < 17.77$. The redshift range is limited by the redshift range of the training sample. The second sample comes from the GAMA spectroscopic survey (Driver et al. 2011; Liske et al. 2015) in the three GAMA equatorial fields (G09, G12, G15, totaling 180 deg$^2$) at $0 < z < 0.6$. The GAMA spectroscopic survey contains $\sim$300 000 galaxies with a magnitude limit of $r < 19.8$, covering a sky area of $\sim$286 deg$^2$. The KiDS survey is an optical imaging survey that covers $\sim$1500 deg$^2$, reaching a magnitude limit of $r < 25.2$ and a point spread function (PSF) full width at half maximum (FWHM) of $<0.7''$, compared to $\sim$1.4'' median seeing of SDSS images. The SDSS provides us with a large sample of galaxies in the local universe. The GAMA survey combined with KiDS (which offers much better imaging quality in terms of depth and angular resolution) allows us to push our study out to higher redshift.

2.1. Merger identification using CNN

The classification of mergers is performed through the deep learning CNN developed in Pearson et al. (2019a,b), based on
the SDSS gri images for the SDSS sample and the KiDS r-band images for the GAMA sample. We summarize the merger identification method briefly as follows. We use the CNN from Pearson et al. (2019a) for SDSS images and from Pearson et al. (2019b) for KiDS images. The SDSS network was trained using 3003 merging galaxies visually identified within Galaxy Zoo 1 (Lintott et al. 2008), and then visually confirmed by Darg et al. (2010a,b). A further 3003 non-merging galaxies that have the same redshift range (0.005 ≤ z < 0.1) and r-band magnitude limit (<17.77) were also selected. Unlike the SDSS images, the training sample of the KiDS images is based on a combination of visual classification and morphological disturbance measurement. The KiDS network was divided into four redshift bins: 0.0 ≤ z < 0.15, 0.15 ≤ z < 0.3, 0.3 ≤ z < 0.45, and 0.45 ≤ z < 0.6. The KiDS-z00 network (in the lowest redshift bin 0.0 ≤ z < 0.15) was trained using galaxies from the latest KiDS data release 4 (Kuijken et al. 2019). The merging galaxies were selected to have the weighted fraction of votes identifying the galaxy as a merger above 0.5 from GAMA-KiDS-Galaxy Zoo (Holwerda et al. 2019) and were also identified as a merging galaxy using the smoothness and asymmetry non-parametric statistics (Conselice 2003), totaling 1917 galaxies. A further 1917 non-merging galaxies were selected that did not meet either of these criteria.

For the higher redshift KiDS networks there are no pre-classified galaxies available for training. Thus, we used the galaxies used to train the KiDS-z00 network and made them fainter and smaller to appear like higher redshift galaxies, randomly selecting one redshift between 0.15 ≤ z < 0.30, one redshift between 0.30 ≤ z < 0.45, and one redshift between 0.45 ≤ z < 0.60 for each galaxy. The apparent magnitude of the galaxy was corrected for the luminosity distances at the assigned redshifts, removing any galaxies that fell below the limiting magnitude of the KiDS survey. For the remaining galaxies, a rotation by a random angle between 0° and 360°, or a skew by a random angle between ±10° and ±30° was applied. For each galaxy we randomly selected one of the two transformations or no transformation. The images were then re-binned to match the physical resolution of the KiDS survey for the assigned redshifts and Gaussian noise was added, with a standard deviation of the noise in the original image. The images were not corrected for the change in wavelength of the rest-frame emission. The number of merging and non-merging galaxies were then balanced within each redshift bin by randomly removing galaxies of the classification with more objects. This results in 1902, 1870, and 1789 objects in the 0.15 ≤ z < 0.30, 0.30 ≤ z < 0.45 and 0.45 ≤ z < 0.60 redshift bins, respectively.

The CNNs used in this work are trained with visually selected galaxy mergers and non-mergers, with the addition of non-parametric statistics for the KiDS networks. The galaxies identified by these networks are likely to be galaxy mergers that are physically close, either when passing each other or at final coalescence, as visually identified mergers are typically biased towards these merger periods (e.g., Pearson et al. 2019b). However, that does not exclude the possibility that the network cannot identify galaxy mergers where the merging objects have a greater separation. It is possible to train a CNN to identify merging galaxies that have greater physical separation if such galaxies are present in the training set. However, we do not have a pre-selected sample of such galaxies available as a training set for this study and other studies using simulations have shown that larger separation of the merging galaxies can reduce the accuracy of a CNN (Pearson et al. 2019b).

Details of the architectures of the networks can be found in Pearson et al. (2019a,b). There are 54,928 mergers (16.1%) and 30,033 mergers (29.6%) identified using CNN in the SDSS sample and the GAMA sample, respectively. In order to demonstrate the difference between the SDSS and KiDS imaging surveys, Fig. A.1 shows cutouts of some example galaxies that are covered by both surveys.

2.2. AGN classification using MIR color cut and optical emission lines

We select AGNs in two different ways, one by using a MIR color cut and the other through the BPT diagram. These two methods are combined together to provide a more complete AGN sample. The MIR color cut selection can pick up more dust obscured AGNs that may be missed by optical selection (e.g., Lacy et al. 2004).

We crossmatched our SDSS and GAMA samples with ALLWISE catalog from the Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010) by selecting the closest pair within a matching radius of 6″, which is close to the angular resolution of 6.1″ in the 3.6 μm band (denoted as W1). The angular separation is <1″ for the vast majority of matched sources (86% of SDSS sample and 85% of GAMA sample). We adopted a single color cut m3.6 μm−m4.5 μm > 0.8 (W1−W2 > 0.8, in Vega magnitudes; Stern et al. 2012) for W2 ≤ 15 and required a signal-to-noise ratio S/N ≥ 5 in both bands to select MIR AGNs. We also used the unWISE (Lang 2014) data, which provide a new set of coadds of the WISE images that are not blurred, and tried a W1−W2 > 0.5 (Assaf et al. 2013) criterion for both sets of WISE data, since Blecha et al. (2018) argue that the W1−W2 > 0.5 cut can greatly improve completeness without significantly decreasing reliability. However, since the results are very similar using these two catalogs, and the two color cuts, for the analysis presented here we only show the W1−W2 > 0.8 AGN selection from ALLWISE.

Besides the MIR AGNs, we also used optical emission line diagnostics to classify optical AGNs. For the SDSS sample, we used the MPA-JHU spectroscopic analysis to obtain BPT AGN classification based on emission line ratios. This classification follows procedures described in Brinchmann et al. (2004) that used demarcation lines from Kewley et al. (2001) to ensure a minimum contamination to the fluxes from star formation. We also adopted the Schawinski et al. (2007) criteria to exclude low ionization nuclear emission line regions (LINERs), since whether LINERs can be recognized as AGNs is still debated (Maoz et al. 2005; Yan & Blanton 2012; Singh et al. 2013).

Optically selected AGNs in the GAMA sample at z < 0.3 (for a reliable detection of Hα line) are obtained using emission line information from the SpecLineSFRv05 catalog (Gordon et al. 2017). Specifically, narrow-line AGNs are selected by requiring BPT diagnostics satisfying both the Kewley et al. (2001) and Schawinski et al. (2007) criteria for the Seyfert classification, excluding LINERs. Where either Hβ or [OIII]5007 Å lines are not detected, AGN classification is done via WHAN diagnostics (WΦα vs N II/Hα, Cid Fernandes et al. 2011) using the criteria of Gordon et al. (2018).

We refer to AGNs selected by the WISE color cut and optical emission line information as MIR AGN and OPT AGN respectively. There are 421 and 96 AGNs that are both OPT and MIR AGNs in the SDSS and GAMA sample respectively. We do not split MIR or OPT AGNs further into subgroups according to whether they are also classified in the other method, in order to
where following equation (Bassani et al. 1999; Lamastra et al. 2009) decrement (assuming an intrinsic value of 3.0) according to the \([O \text{ III}]\) luminosity is corrected for extinction using the Balmer dust obscuration (Kaukis located outside of the torus, and thus experiences moderate \([O \text{ III}]\) is radiated by gas in the narrow line region (NLR), which cation model of AGN (Urry & Padovani 1995; Antonucci 1993), an indicator of the AGN accretion power. According to the unifi-

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Wiseman et al. 2003; Heckman et al. 2005). These results propose that highly accreting AGNs are triggered by large gas reservoirs brought into the central SMBHs by merg-

These two types are believed to have different black hole accre-

respectively, we only used \(L_{2-10\text{keV}}\) as a rough indicator of AGN bolometric power.

Figures 1–3 show the distributions of the SDSS and GAMA AGNs in the \(M_*-z\), \(L_{6\mu m}-z\) and \(L_{[O \text{ III}]}-z\) parameter space respectively. Figure 4 shows the histograms of each parameter. In Fig. 1 we can see that the host galaxies of SDSS OPT AGNs are more massive than the host galaxies of SDSS MIR AGNs. This is also clear from the histogram of stellar mass distribution in panel a of Fig. 4. In addition, the host galaxies of the MIR and OPT AGNs in the SDSS sample are less massive than the host galaxies of the MIR and OPT AGNs in the GAMA sample.

2.3. Low accretion rate AGNs

Studies of radio AGNs divide them into two distinct types according to the mode of feedback, one with strong radiation (high-excitation radio galaxies, HERGs) and the other with jets (low-excitation radio galaxies, LERGs; Best & Heckman 2012). These two types are believed to have different black hole accretion rates, with HERGs accreting at a higher rate than LERGs (e.g., Smolčić 2009; Janssen et al. 2012; Mingo et al. 2014). Previous studies propose that highly accreting AGNs are triggered by large gas reservoirs brought into the central SMBHs by mergers, while low accreting rate AGNs are fueled by a smaller amount of gas transported by secular processes (Heckman et al. 1986; Best & Heckman 2012; Tadhunter 2016). These results
are supported by a normal LERG fraction in galaxy mergers (Ellison et al. 2015), with the exception of the low mass merger population (Gordon et al. 2019). We selected LERGs from Best & Heckman (2012) that matched with our SDSS merger identification and built a control sample, totaling 1225 LERGs and 11 250 mass- and redshift-matched non-LERG controls, in order to investigate the connection between mergers and these low accretion rate AGNs. There are only 5 (20) LERGs that are also MIR (OPT) AGNs, suggesting that they may represent a different evolutionary stage of AGNs. Figure 5 shows mass and redshift distributions of the MIR AGNs, OPT AGNs, and LERGs in the SDSS sample. It is clear that the LERGs are in general more massive.

3. Results

In this work, we investigate the AGN-merger connection from two angles. We first study the AGN fractions in mergers and non-mergers to assess whether mergers are a viable triggering mechanism. In this first experiment, the indication that mergers are able to trigger AGN is the existence of a higher fraction of AGN in the mergers sample, compared to the non-mergers. To address the first aspect, we start from a merger sample and a non-merger control sample, and investigate the difference in the AGN fraction in these two samples.

In the second experiment we study the merger fractions in AGN and non-AGNs in order to find out whether mergers dominate the triggering of AGNs (also see Ellison et al. 2019). To address the second aspect, we start from an AGN sample and a non-AGN control sample, for the MIR as well as the optical AGN selection methods, and investigate the merger fraction in these two samples.

Following Ellison et al. (2011), for each merger in the SDSS and GAMA samples, we identify a non-merger counterpart that satisfies the following requirements:

1. $|z_{\text{control}} - z_{\text{sample}}| \leq 0.01$
2. $|\log M_*^{\text{control}} - \log M_*^{\text{sample}}| \leq 0.1$ dex.

Fig. 2. Rest-frame 6\(\mu\)m luminosity \(L_{6\mu m}\) vs. redshift \(z\) distributions for the SDSS and GAMA MIR AGNs. The solid lines indicate the running median for each group. The dashed lines mark the edges of the redshift bins for the GAMA MIR AGNs. In the same redshift range, the GAMA MIR AGNs are less powerful than the SDSS MIR AGNs.

Fig. 3. [O III] luminosity \(L_{\text{OIII}}\) vs. redshift \(z\) distributions for the SDSS and GAMA OPT AGNs. The solid lines indicate the running median for each group. The dashed lines mark the edges of the redshift bins for the GAMA OPT AGNs. In the same redshift range, the GAMA OPT AGNs are less powerful than the SDSS OPT AGNs.
For the first experiment we only included mergers that have no fewer than ten non-merger counterparts and randomly chose ten of them to establish a non-merger control sample. For the second experiment we first adopted a conservative method for building the non-AGN control samples. For the MIR AGNs we set $W_1 - W_2 < 0.5$ when selecting controls and for OPT AGNs we excluded composites when selecting controls, in order to ensure a minimum AGN contamination in the control samples. Similar to the first experiment, we then randomly selected ten non-AGN counterparts for each AGN satisfying the above requirements and excluded AGNs that had fewer than ten counterparts. The non-AGN control samples for MIR AGNs do not contain OPT AGNs and vice versa. We note here that the sources in the control group are not necessarily unique, and some of them may appear more than once. Table 1 shows the number of galaxies in each subgroup. The number of the galaxies in the control sample for each subgroup is ten times larger.

Besides the main merger sample described above, we also built a stricter merger sample and non-merger control sample. The output of the CNN can be seen as the probability of a galaxy being a merger. We increased the threshold for identifying mergers and decreased the threshold for selecting non-mergers in both SDSS and GAMA samples. For example, the SDSS CNN uses $p_{\text{merger}} > 0.57$ as merger threshold. We raised this threshold to $p_{\text{merger}} > 0.8$ for a stricter and less contaminated merger sample, and lowered this threshold to $p_{\text{merger}} < 0.4$ for selecting more conservative non-merger controls.
Table 1. Number of sources in each group.

<table>
<thead>
<tr>
<th>Survey</th>
<th>All</th>
<th>Merger_main</th>
<th>Merger_stricter</th>
<th>MIR AGN</th>
<th>OPT AGN</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDSS 0.005 &lt; $z$ &lt; 0.1</td>
<td>341 908</td>
<td>54 642</td>
<td>33 151</td>
<td>799</td>
<td>5420</td>
</tr>
<tr>
<td>GAMA 0 &lt; $z$ &lt; 0.6</td>
<td>101 470</td>
<td>29 560</td>
<td>19 231</td>
<td>543</td>
<td>2750</td>
</tr>
</tbody>
</table>

Notes. The size of sources in the control sample for each subgroup is ten times larger. The main merger sample is the default merger sample in our study. We apply a stricter merger selection to build a stricter merger sample.

3.1. AGN fractions in mergers and non-mergers

First, we focused on the AGN fraction in mergers and matched non-merger galaxies to explore whether mergers can trigger AGN. Figure 6 shows the comparisons of AGN fractions in mergers and non-mergers based on the MIR and optical selections. According to the merger classification networks (see Sect. 2.1), we also separated the GAMA sample into three redshift bins: 0 ≤ $z$ < 0.15 (denoted as G1), 0.15 ≤ $z$ < 0.3 (denoted as G2), and combined 0.3 ≤ $z$ < 0.45 and 0.45 ≤ $z$ < 0.6 into one redshift bin (denoted as G3) in the right half of each panel. Redshift bin G3 is not included in the GAMA OPT AGNs because the optical emission line diagnosis in the GAMA sample is limited to $z$ < 0.3 since the Hα line at higher redshift will move outside of the spectral range of the spectrograph used in the GAMA survey (see Gordon et al. 2017).

We find that in general the AGN fraction in mergers is larger than that in non-mergers for both the SDSS and GAMA samples and both AGN selection methods. In the SDSS sample, 1.63 ± 0.05% and 0.34 ± 0.02% of mergers host OPT AGNs and MIR AGNs respectively, while the percentages of non-mergers in the SDSS sample are 1.45±0.02% and 0.20 ± 0.01% respectively. In the GAMA sample, 3.63 ± 0.11% and 0.73 ± 0.05% of mergers host OPT AGNs and MIR AGNs respectively, while the percentages of non-mergers in the GAMA sample adopted by Gordon et al. (2017) is slightly lower: 2.53 ± 0.03% and 0.53 ± 0.01%. Although the overall AGN fraction is low, we can still see a slight enhancement of AGN fraction in mergers as opposed to non-mergers (up to ~1.5 AGN excess), suggesting that mergers do trigger AGN activity. When applying a stricter merger sample, generally we observe a greater AGN excess, which also supports our argument. In addition, the MIR AGN excess is larger than OPT AGN excess when a less contaminated merger sample is applied, which may imply that mergers are more important in triggering MIR AGNs. The numbers of galaxies and fractions for each group are listed in Table 2.

Although it seems that the lowest redshift (0 ≤ $z$ < 0.15) and the highest redshift (0.3 ≤ $z$ < 0.45) bin of GAMA MIR AGNs shows an inverse trend with more MIR AGNs found in non-mergers, we argue that they are not significant (within 1σ uncertainty). Comparing horizontally between the SDSS sample and the GAMA sample in the lowest redshift bin in the two panels in Fig. 6, it seems that for the MIR AGNs, the SDSS sample agrees well with the GAMA sample in the lowest redshift bin, while for the OPT AGNs, the SDSS sample shows a lower AGN fraction in mergers and non-mergers. We note here that unlike the MIR AGN classification, the OPT AGN classification in the GAMA sample adopted by Gordon et al. (2017) is slightly...
Table 2. MIR and OPT AGN fractions in mergers and non-mergers for the SDSS sample and the GAMA (sub)samples.

<table>
<thead>
<tr>
<th></th>
<th>MIR AGN in merger</th>
<th>MIR AGN in non-merger</th>
<th>OPT AGN in merger</th>
<th>OPT AGN in non-merger</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDSS</td>
<td>0.34 ± 0.02%</td>
<td>0.20 ± 0.01%</td>
<td>1.63 ± 0.05%</td>
<td>1.45 ± 0.02%</td>
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<tr>
<td></td>
<td>(184/54642)</td>
<td>(1100/546420)</td>
<td>(889/54642)</td>
<td>(7905/546420)</td>
</tr>
<tr>
<td>GAMA</td>
<td>0.73 ± 0.05%</td>
<td>0.53 ± 0.01%</td>
<td>3.63 ± 0.11%</td>
<td>2.53 ± 0.03%</td>
</tr>
<tr>
<td></td>
<td>(216/29560)</td>
<td>(1572/295600)</td>
<td>(1074/29560)</td>
<td>(7473/295600)</td>
</tr>
<tr>
<td>G1</td>
<td>0.28 ± 0.07%</td>
<td>0.30 ± 0.02%</td>
<td>3.17 ± 0.24%</td>
<td>2.15 ± 0.06%</td>
</tr>
<tr>
<td>0 &lt; z &lt; 0.15</td>
<td>(15/5266)</td>
<td>(164/54019)</td>
<td>(167/5266)</td>
<td>(1160/54019)</td>
</tr>
<tr>
<td>G2</td>
<td>0.85 ± 0.07%</td>
<td>0.47 ± 0.02%</td>
<td>5.33 ± 0.17%</td>
<td>3.75 ± 0.03%</td>
</tr>
<tr>
<td>0.15 &lt; z &lt; 0.3</td>
<td>(145/17018)</td>
<td>(792/168124)</td>
<td>(907/17018)</td>
<td>(6313/168124)</td>
</tr>
<tr>
<td>G3</td>
<td>0.77 ± 0.10%</td>
<td>0.84 ± 0.03%</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>0.3 &lt; z &lt; 0.6</td>
<td>(56/7276)</td>
<td>(619/73457)</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Notes. Errors are calculated through binomial statistics.

different from that in the SDSS sample, including OPT AGNs that may be missed when Hβ or [O III]5007 Å lines are not detected (see Sect. 2.2).

Compared to previous studies, we find a smaller contrast of AGN fractions in mergers and non-mergers, with an AGN excess of up to ~1.5 in mergers relative to non-merger controls. Ellison et al. (2011) found an increase of AGN fraction by a factor of 2.5 in galaxy pairs relative to the control sample, using a sample of 11 060 SDSS pairs. Silverman et al. (2011) found that galaxy pairs are 1.9 times more likely to host X-ray AGNs than mass-matched isolated galaxies, for a sample of 562 galaxies in pairs at 0.25 < z < 1.05. Satyapal et al. (2014) found that as the separation between galaxies decreases, the excess of MIR AGN fraction in pairs relative to controls increases, reaching a factor of 10–20 of AGN excess in post-mergers. Weston et al. (2017) found it 5–17 (3–5) times more likely for mergers to host MIR selected AGNs compared to non-mergers, for a sample of 130 mergers (1069 interactions) with stellar mass above 2 × 10^{10} M_⊙.

Goulding et al. (2018) found that mergers are 2–7 times more likely to host obscured MIR AGNs than non-interacting galaxies with a sample of 2552 obscured AGNs.

Even though our work adopts a different method (CNN) to identify mergers than visual inspection, a different definition of mergers (e.g., galaxy pairs in Ellison et al. 2011; Satyapal et al. 2014), a slightly different threshold in classifying AGNs, as well as different sample distributions in terms of redshift and stellar mass, our results are qualitatively consistent with previous studies. In addition, when applying a stricter merger selection that is less affected by contamination, the AGN excess can be more than two, which is more consistent with previous studies.

3.2. Merger fractions in AGNs and non-AGNs

In Sect. 3.1 we assess whether mergers exhibit an enhanced AGN fraction. In this section, we perform the reverse experiment, by assessing whether AGNs are preferentially hosted by merging galaxies compared to non-AGN controls. The left and right panels of Fig. 7 show the comparisons of merger fractions in AGN and non-AGNs based on MIR and optical selections respectively. We also separate the GAMA sample into different redshift bins in the right half of each panel.

From Fig. 7 we can see that the fraction of AGNs that are mergers is higher than the fraction of non-AGN controls that are mergers, for both samples and both AGN selections. More than 16% of MIR and OPT AGNs in the SDSS sample are merging and ~40% of MIR and OPT AGNs in the GAMA sample are merging, while the fraction of merging control galaxies is ~15–29%. Our findings are qualitatively in agreement with previous studies in which AGNs show a higher merger fraction than the non-AGN control sample (e.g., Hong et al. 2015; Ellison et al. 2019). If we limit our mergers to the less contaminated ones (with stricter threshold), we can observe an increase of the merger excess in the AGNs relative to non-AGNs. Similar to Fig. 6, the merger excess in MIR AGNs is larger than that in OPT AGNs when a stricter merger threshold is applied, suggesting that mergers may be more important in MIR AGN triggering (e.g., see Ellison et al. 2019). Although it seems that the lowest redshift (0 < z < 0.15) and the highest redshift (0.3 < z < 0.45) bin of GAMA MIR AGNs show an inverse trend, with more mergers found in non-AGNs, we argue that they are not significant (within 1σ uncertainty). Also, adopting a stricter merger selection, we observe a >1 merger excess, indicating a higher merger fraction in AGNs than non-AGNs. The numbers of galaxies and fractions for each group are listed in Table 3. The overall merger fraction is higher in the GAMA sample than the SDSS sample, which could be due to the deeper imaging of KiDS revealing subtle features, the higher redshift range in the GAMA sample, and/or differences in the training sample used in the CNN.

3.3. Merger fraction dependence on stellar mass, bolometric luminosity, and obscuration

In order to investigate the dependence of merger fraction on stellar mass, we separated AGNs into different mass bins for the SDSS sample, for which stellar masses are derived using the methods described in Kauffmann et al. (2003) and Salim et al. (2007). For the GAMA sample, in addition to stellar mass bins we also divided the sample into three redshift bins for MIR AGNs and two redshift bins for OPT AGNs (as in Sect. 3.1). The stellar masses of the GAMA sample were derived from spectral energy distribution (SED) fitting (Taylor et al. 2011). By selecting galaxies that appear in both the GAMA and SDSS samples, we confirm that stellar masses derived through two different methods do not have a significant difference, with a median M_{stellar} = 10^{10} M_⊙.

Figure 8 shows the comparisons of main merger fractions and stricter merger fractions in MIR and OPT AGNs as a function of the stellar mass for the SDSS sample in the mass complete regime (above the lowest mass at the highest redshift),
compared to the merger fractions in the non-AGN control samples. We can clearly observe an increase in the merger fraction in AGNs as stellar mass increases, suggesting that AGNs in more massive hosts are more likely to undergo a merger event (e.g., Hopkins et al. 2008; Ellison et al. 2019). The positive trend with increasing stellar mass is weaker or non-existent in the non-AGN controls. Figure 9 shows the comparisons of main merger fractions and stricter merger fractions in the OPT AGNs as a function of stellar mass, as well as the redshift for the GAMA sample in the mass complete regime, in comparison with the non-AGN control samples. We do not show plots for the MIR AGNs because the sample is insufficiently large. For the GAMA sample, we can observe a similar trend for the merger fraction in the OPT AGNs, while for control samples we find a more flat trend as stellar mass increases. However, the GAMA sample and SDSS sample are not identical in terms of merger identification. Nonetheless, our analysis supports the idea that mergers are more important in triggering AGNs hosted by more massive galaxies.

We also split the AGNs into bins of bolometric power to investigate if any dependence exists. Some studies found a higher occurrence of mergers in more luminous AGNs (e.g., Hasinger 2008; Rosario et al. 2012; Santini et al. 2012; Ellison et al. 2019), while others did not (e.g., Hewlett et al. 2017; Villforth et al. 2017). We used the rest-frame $6\mu m$ luminosity and [O III] luminosity to represent bolometric AGN luminosity for MIR AGNs and OPT AGNs respectively. Similar to Sect. 3.1, for the GAMA sample we also divided the sample into three redshift bins for MIR AGNs and two redshift bins for OPT AGNs. Figures 10 and 11 show merger fractions as AGN luminosity and [O III] luminosity to represent bolometric AGN luminosity for MIR AGNs and OPT AGNs as a function of stellar mass, as well as the redshift for the GAMA sample in the mass complete regime, in comparison with the non-AGN control samples. We do not show plots for the MIR AGNs because the sample is insufficiently large. For the GAMA sample, we can observe a similar trend for the merger fraction in the OPT AGNs, while for control samples we find a more flat trend as stellar mass increases. However, the GAMA sample and SDSS sample are not identical in terms of merger identification. Nonetheless, our analysis supports the idea that mergers are more important in triggering AGNs hosted by more massive galaxies.

Table 3. Merger fractions in AGNs and non-AGNs for the SDSS and GAMA sample.

<table>
<thead>
<tr>
<th></th>
<th>Merger in MIR AGN</th>
<th>Merger in MIR control</th>
<th>Merger in OPT AGN</th>
<th>Merger in OPT control</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDSS</td>
<td>23.03 ± 1.49%</td>
<td>15.02 ± 0.40%</td>
<td>16.40 ± 0.50%</td>
<td>14.30 ± 0.15%</td>
</tr>
<tr>
<td>GAMA</td>
<td>39.23 ± 2.10%</td>
<td>28.73 ± 0.61%</td>
<td>39.09 ± 0.93%</td>
<td>28.39 ± 0.27%</td>
</tr>
<tr>
<td>G1 0 &lt; z &lt; 0.15</td>
<td>25.00 ± 5.79%</td>
<td>27.29 ± 1.91%</td>
<td>34.43 ± 2.15%</td>
<td>25.48 ± 0.63%</td>
</tr>
<tr>
<td>G2 0.15 &lt; z &lt; 0.3</td>
<td>49.31 ± 2.94%</td>
<td>28.76 ± 0.83%</td>
<td>40.10 ± 1.03%</td>
<td>29.15 ± 0.30%</td>
</tr>
<tr>
<td>G3 0.3 &lt; z &lt; 0.6</td>
<td>28.43 ± 3.21%</td>
<td>29.09 ± 1.03%</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Notes. Errors are calculated through binomial statistics.
Fig. 8. **Top:** merger fractions in AGNs and non-AGNs as stellar mass increases for the SDSS sample. For the SDSS MIR AGNs (left) and OPT AGNs (right), the merger fraction increases as stellar mass increases in the mass complete regime. **Bottom:** same as the top panel, but with stricter merger identification. Errors are calculated through binomial statistics.

Fig. 9. **Top:** merger fractions in AGNs and non-AGNs as stellar mass increases for the GAMA sample. For the GAMA OPT AGNs, the merger fraction increases as stellar mass increases in the mass complete regime in different redshift bins (indicated in the bottom right corner in each panel). **Bottom:** same as the top panel, but with stricter merger identification. Errors are calculated through binomial statistics. We find an increase of the merger fractions in AGNs as stellar mass increases.
For MIR AGNs, we also took advantage of their optical-IR color to split them into unobscured and obscured AGNs. We adopted the Hickox et al. (2007) criterion $m_r - m_{\lambda,5\mu m} = 6.1$ (in Vega magnitude) using the SDSS $r$-band photometry and WISE 4.6$\mu$m photometry. Figure 12 shows the merger fractions in obscured and unobscured MIR AGNs for the SDSS sample and the GAMA sample. Obscured AGNs in the SDSS sample are more likely to be hosted in mergers than unobscured AGNs, despite the large uncertainty due to the small number of obscured AGNs (22 SDSS MIR AGNs are obscured). Of obscured AGNs in the SDSS sample 59.09$\pm$10.48% are mergers, while 22.01$\pm$1.49% of unobscured AGNs in the SDSS sample are mergers. This higher fraction of mergers in obscured AGNs is consistent with previous studies in the IR and X-ray bands, for example, early studies on LIRGs and ULIRGs (e.g., Sanders & Mirabel 1996; Veilleux et al. 2002), hot dust-obscured galaxies (e.g., Fan et al. 2016), and heavily obscured X-ray AGNs (e.g., Kocevski et al. 2015). The GAMA sample lacks significant contrast, possibly due to the fact that the majority ($\sim$85%) of the GAMA obscured AGNs are at $z > 0.2$, which might cause difficulty in identifying mergers. When we limit our observations to the lowest redshift bin, 50.00$\pm$25.00%
We find a merger fraction of 30.26 ± 1.31% in LERGs (comparable to Gordon et al. 2019) and 22.94 ± 0.38% in non-LERGs. These are higher than the merger fractions in the SDSS MIR and OPT AGNs and controls, suggesting that mergers still contribute to triggering these low accretion rate AGNs. In Fig. 13 we split LERGs and non-LERG controls into different stellar mass bins and find a positive trend as stellar mass increases, demonstrating an increasing importance of mergers in more massive AGNs. If we limit our observations to stricter merger identification, we observe a similar trend to that in Gordon et al. (2019), who found no difference of merger fraction in LERGs relative to non-LERGs in the most massive bin.

The following points summarize our findings:

- We find a higher AGN fraction in mergers than in non-merger controls, suggesting that mergers do trigger AGNs.
- We find a higher merger fraction in AGNs than in non-AGN controls, implying that mergers play a significant role in AGN triggering.
- We find a dependence of merger fraction on stellar mass as mergers become more important for massive AGN hosts.
- As AGN bolometric luminosity increases, merger fractions in MIR AGNs and OPT AGNs show different trends. Both methods show a high merger fraction in more powerful AGNs.
- We find a higher merger fraction in obscured AGNs than in unobscured AGNs, consistent with previous studies.
- We find that mergers also play a significant role in triggering LERGs.

4. Discussion

In Sect 3.1 we found that our sample shows a smaller contrast of AGN excess in mergers relative to non-mergers compared with previous studies. In Sect. 3.2 we also found that our work shows a smaller contrast of merger fractions in AGNs and non-AGNs, with a merger excess of up to ∼1.5 in AGNs relative to non-AGN controls. Ellison et al. (2019) found that AGNs are approximately two times more likely to be hosted in mergers compared to non-AGN controls, for a sample of 1124 optically selected AGNs and 254 MIR selected AGNs. In addition to the differences of our sample discussed in Sect. 3.1, Goulding et al. (2018) proposed that AGN activity can occur sporadically at any stage of the merger event. During the first and second passage, the non-AGN phase can last longer than AGN activity. When the galaxies approach each other and begin to coalesce, AGN activity becomes more long-lived. Visual inspection biases merger selection toward more obvious mergers, which are more likely to be found in association with AGN activity than non-AGN activity. This leads to a significant merger excess in AGNs relative to non-AGNs. If we limit our observations to stricter mergers, the merger excess can be ∼2, which is more consistent with previous studies.

Many studies reported no excess of morphological disturbances in AGN hosts compared to a control sample, mostly using X-ray detected AGNs at high redshifts (e.g., Gabor et al. 2009; Cisternas et al. 2011; Kocevski et al. 2012). High redshift samples can be biased toward luminous quasars (Mechtley et al. 2016; Villforth et al. 2017) that outshine their host galaxies, making it harder to identify mergers, especially post-mergers. In addition, highly obscured AGNs in which soft X-ray photons are obscured can be missed, showing an excess of merger fraction that is hidden in other studies (Kocevski et al. 2015).

Simulations predict that galaxy mergers are able to transport gas inward, leading to accretion around the central black hole (Springel et al. 2005a), and to produce more luminous AGNs that cannot be explained by stochastic fueling (Hopkins et al. 2014). However, Draper & Ballantyne (2012) found that mergers are not the only triggering mechanism for AGNs and non-merger processes are the dominant triggering mechanism by AGN population synthesis modeling. Also, Steinborn et al. (2018) found that less than 20% of AGN hosts at z = 0–2 have experienced a recent merger. Our work finds an increase of merger fraction in AGNs that reside in more massive galaxies and are most powerful. The percentage of AGNs that are mergers relative to all AGNs is 16–40%, suggesting a significant though perhaps not dominant role for mergers in AGN triggering.

4.1. Comparison with previous works

In Sect. 3.1 we found that our sample shows a smaller contrast of AGN excess in mergers relative to non-mergers compared with previous studies. In Sect. 3.2 we also found that our work shows a smaller contrast of merger fractions in AGNs and non-AGNs, with a merger excess of up to ∼1.5 in AGNs relative to non-AGN controls. Ellison et al. (2019) found that AGNs are approximately two times more likely to be hosted in mergers compared to non-AGN controls, for a sample of 1124 optically selected AGNs and 254 MIR selected AGNs. In addition to the differences of our sample discussed in Sect. 3.1, Goulding et al. (2018) proposed that AGN activity can occur sporadically at any stage of the merger event. During the first and second passage, the non-AGN phase can last longer than AGN activity. When the galaxies approach each other and begin to coalesce, AGN activity becomes more long-lived. Visual inspection biases merger selection toward more obvious mergers, which are more likely to be found in association with AGN activity than non-AGN activity. This leads to a significant merger excess in AGNs relative to non-AGNs. If we limit our observations to stricter mergers, the merger excess can be ∼2, which is more consistent with previous studies.

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4.2. Merger sequence

Previous studies proposed an evolutionary track in the merger process: when two galaxies have a close encounter, gas is funneled toward the central region, increasing the local surface density and triggering starbursts. This large gas reservoir also fuels the nuclear accretion activity when gas lose most of their angular momentum and fall into the vicinity of central black holes due to gravitational torques (e.g., Di Matteo et al. 2005; Springel et al. 2005b, a). As merging proceeds and galaxies coalesce, most AGNs are obscured by circum-nuclear dust, making them look extraordinarily red. These dust-enshrouded AGNs explain why most ULIRGs show merging features in early studies (e.g., Sanders & Mirabel 1996; Murphy et al. 1996; Veilleux et al. 2002). After final coalescence, when AGNs...
eventually expel the surrounding dust (e.g., through AGN feedback, Springel et al. 2005a), they outshine the host galaxies and become optically visible, resulting in unobscured AGNs (Sanders et al. 1988; Hopkins et al. 2006; Kocevski et al. 2015).

In terms of the dependence of merger fraction on AGN bolometric luminosity, we observe an increasing trend in MIR selected AGNs, while for OPT AGNs we find a more flat trend at lower luminosities and an enhancement in the higher luminosity regime in the lower redshift range. In the higher redshift range the enhancement regime may not be covered by the dynamical range of our sample. We speculate that MIR selected AGNs exist more in late stage mergers with a thick dust envelope (see illustration in Kocevski et al. 2015). The more powerful AGN luminosity caused by more violent accretion that brings more gas supply could be easily recognized by a more disturbed morphology, leading to more merger identifications as luminosity increases. Or this increasing trend between merger fraction and AGN power could simply be a by-product of the increasing trend between merger fraction and stellar mass. We do not have enough samples to decide which factor is intrinsic. In contrast with MIR AGNs, OPT selected AGNs occur more in early stages or post-merger stages in which the dust is not compact enough to ensnare the nuclei or already expelled. The level of disturbance is not as clear as that in late stage mergers, leaving a relatively flat trend. Those OPT AGNs with higher luminosity could be in a transitioning merger phase, from early stage to late stage, showing more disturbed morphology and having more matter supply that would support rapid accretion. Furthermore, the merger evolutionary scenario predicts that obscured AGNs are more likely to be hosted in mergers than their unobscured counterparts (Satyapal et al. 2014; Kocevski et al. 2015; Weston et al. 2017), which can be seen from the comparison of merger fractions in obscured and unobscured MIR AGNs.

4.3. Caveats

Despite the high accuracy when identifying mergers using CNNs, the overall merger fraction in all galaxies is low, leading to the misidentification of non-mergers as mergers. Assuming 1000 galaxies in which 10% are real mergers, even a 90% accuracy will cause 100 galaxies to be incorrectly identified. In an extreme situation where these 100 galaxies are all non-mergers misidentified as mergers, then the final CNN-identified merger sample will include 200 galaxies (100 real mergers plus 100 misidentified galaxies), causing half of the sample to be contaminated by non-mergers. This contamination exists in both the AGN sample and the non-AGN control sample.

To assess the influence of this contamination and given the fact that it would be extremely time-consuming to visually inspect all the mergers, we only visually inspected the 184 and 213 mergers in the MIR AGNs of the SDSS sample and the GAMA sample respectively. For the controls we also visually inspected the 1200 mergers in the non-MIR AGNs of the SDSS sample and randomly selected 600 mergers from the entire 1560 mergers in the non-MIR AGNs of the GAMA sample. The visual inspection was done independently by three of the co-authors. By selecting all mergers that have more than one, two, and all three positive votes, in Fig. 14 we find an increase of the merger excess in MIR AGNs relative to non-AGN controls for the SDSS sample and the GAMA sample.

There are advantages and disadvantages in terms of merger identification methods using CNN and visual inspection. Our CNN merger identification method is affected by non-merger contamination, but it can work efficiently on a large sample. Visual inspection, even though it is not always reliable, is less likely to be affected by contamination, but it would have a bias toward more obvious mergers, and is very time consuming. Despite the non-merger contamination, our results are in qualitative agreement compared to previous studies using visual inspecting to identify mergers. In addition, when applying a stricter merger threshold and visually inspecting a smaller sample of mergers, our results are more consistent.

5. Conclusion

We selected the SDSS DR7 spectroscopic data at redshifts $0.005 < z < 0.1$ and the GAMA spectroscopic data at redshifts $0 < z < 0.6$. We took advantage of deep leaning convolutional neural networks to identify mergers based on SDSS and KiDS images. We adopted two methods to classify AGNs, a WISE MIR color cut and optical emission line diagnostics, totaling 799 MIR AGNs and 5420 OPT AGNs for the SDSS sample, and 543 MIR AGNs and 2750 OPT AGNs for the GAMA sample. We also selected LERGs to analyze the connection between mergers and low accretion rate AGNs. We built a strictly matched control sample for each subgroup to investigate the connection between mergers and AGNs. Our findings are as follows:
In terms of AGN fraction in mergers compared to non-mergers, AGNs are more likely to be found in mergers than in non-mergers, with a comparison of 1.63 ± 0.05% versus 1.45 ± 0.02% (0.34 ± 0.02% versus 20 ± 0.01%) for the SDSS OPT (MIR) AGNs and controls, and 3.63 ± 0.11% versus 2.53 ± 0.03% (0.73 ± 0.05% versus 0.53 ± 0.01%) for the GAMA OPT (MIR) AGNs and controls, suggesting that mergers are able to trigger nuclear activity.

(2) Of the SDSS OPT (MIR) AGNs, 16.40 ± 0.5% (23.03 ± 1.49%) show merging features, and 39.09 ± 0.93% (39.23 ± 2.1%) of the GAMA OPT (MIR) AGNs show merging features. The difference in the two samples may be attributed to the fainter detection limit of the KiDS imaging survey, the high redshift range, and/or the difference in the training samples of the CNN. Mergers play a significant role in triggering AGNs. Whether mergers dominate AGN triggering is still not confirmed considering the quality of the merger sample, the different timescales of merger events and AGN activity, and so on.

(3) At the same redshift, the merger fraction in AGNs increases as stellar mass increases, indicating that mergers are more important in triggering AGNs in more massive host galaxies.

(4) For LERGs that accrete at low rates we also observe a higher fraction of mergers than controls (30.26 ± 1.31% versus 22.94 ± 0.38%).

(5) Merger fraction in MIR selected AGNs shows an increase as AGN power increases, while we do not see a clear trend with AGN power for optically selected AGNs. In both selection methods, mergers are more important in triggering AGNs in more powerful AGNs. We interpret this phenomenon under a merger evolution scenario, which is also supported by a higher merger fraction in obscured AGNs than non-obscured AGNs, selected according to their optical-WISE color.

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References
Appendix A: Cutouts of mergers and non-mergers

In this appendix we show cutouts of the same galaxies in the SDSS and KiDS imaging surveys. Examples of merging galaxies are shown in the top four rows and non-mergers in the bottom four rows. As the KiDS survey is deeper by ~2.5 mag than the SDSS imaging survey, subtle features are clearer in the KiDS images, which can help merger identification.

Fig. A.1. Cutouts of the same mergers (top four rows) and non-mergers (bottom four rows). First two rows: SDSS mergers, second two rows: GAMA/KiDS mergers, third two rows: SDSS non-mergers, and last two rows: GAMA/KiDS non-mergers. SDSS images are in gri composite bands (first and third rows) with a size of 50.7” × 50.7”. KiDS images are in r-band (second and fourth rows) with a size of 54.8” × 54.8”. The depth of the KiDS imaging survey is ~2.5 mag fainter than that of the SDSS imaging survey, revealing more subtle features.