The abundances and properties of Dual AGN and their host galaxies in the EAGLE simulations

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ABSTRACT
We look into the abundance of Dual AGN (active galaxy nuclei) in the largest volume hydrodynamical simulation from the EAGLE project. We define a Dual AGN as two active black holes with a separation below 30 kpc. We find that only 1 percent of AGN with $L_{\text{HX}} \geq 10^{42}$ erg s$^{-1}$ are part of an observable Dual AGN system at $z = 0$. During the evolution of a typical binary black hole system, the rapid variability of the hard X-ray luminosity on Myr time-scales severely limits the detectability of Dual AGN. To quantify this effect, we calculate a probability of detection, $t_{\text{on}}/t_{30}$, where $t_{30}$ is the time in which the two black holes were separated at distances below 30 pkpc and $t_{\text{on}}$, the time that both AGN are visible (e.g. when both AGN have $L_{\text{HX}} \geq 10^{42}$ erg s$^{-1}$) in this period. We find that the average fraction of visible Dual systems is 3 percent. The visible Dual AGN distribution as a function of black hole separation increases with small separations and it presents a pronounced peak at 20–25 kpc. This shape can be understood as a result of the rapid orbital decay of the host galaxies after their first encounter. Looking at the merger history of the galaxies hosting a Dual AGN, we find that 75 percent of the host galaxies have recently undergone or are undergoing a merger with stellar mass ratio $\geq 0.1$. Finally, we find that the fraction of visible Dual AGN with respect to the total AGN increases with redshift as found in observations.

Key words: galaxies:active – methods: numerical – quasars: supermassive black holes

1 INTRODUCTION
Supermassive Black Holes (BHs) appear to reside in the centre of all massive galaxies (e.g. Kormendi & Ho. 2013). If galaxy mergers are expected to be common in a hierarchical Universe (White & Rees 1978), then BH mergers should be common too. From numerical studies and models, we know now that during galaxies mergers, supermassive BHs follow the trajectory of the nucleus of the host galaxies (see the review of Colpi et al. 2014 and all therein references). Subsequently, a supermassive BH binary (at scales of a few parsecs) is thought to form. The time that will take the BHs to eventually merge will strongly depend on their environment that will be set by the properties of the host galaxy (e.g. Mayer et al. 2007; Mayer 2013; Capelo et al. 2015). While it is observationally difficult to study BH binaries, hints on their evolution can be found in the observational properties of BH pairs, defined to be BHs in interactive galaxies that have not reached the binary stage. Observationally only active BHs can be easily observed, thus many studies have explored the properties of Dual AGN, defined as two active BHs at kpc-scales.

Observational studies suggest that the fraction of Dual AGN is small (Fu et al. 2011a; Rosario et al. 2011). Liu et al. (2011) found that the fraction of Dual AGN within a 30 kpc scale using a large study of optical AGN pairs at $z < 0.16$ is 1.3 percent. Liu et al. (2011) found that the fraction of Dual AGN is 1.3 percent within a 30 kpc scale using a large study of optical AGN pairs at $z < 0.16$ with SDSS spectroscopy. However, detecting Dual AGN at kpc scales in the local Universe is not an easy task since observations at high resolution are needed (Komossa et al. 2003; Hudson et al. 2006; Bianchi 2008; Koss et al. 2011a, 2012; mazzarella 2012; Shields 2012). For example, using SDSS spectroscopy could affect the detection of Dual AGN at kpc scales because of the fibre collision limits. Optical surveys also tend to be incomplete (Hickox et al. 2009; Koss et al. 2011a). To overcome this difficulty, Koss et al. (2012) select moderate luminous AGN in ultra hard-X-rays along with optical observations. They find a much larger Dual AGN fraction: 7.5 percent of their sample are

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in Dual AGN at a separation of 30 kpcs. The Dual AGN fraction goes down to 1.9 percent when both AGN in the Dual system were only detected using X-ray spectroscopy. Another way to find candidates of Dual AGN is by searching for a double-peaked in the narrow emission lines (e.g. Comerford et al. 2009b, 2011; Barrows et al. 2013). Using this technique along with follow-up observations, Comerford et al. (2015) and Müller-Sánchez et al. (2015) found seven Dual AGN where it was possible to resolve two distinct active nuclei at separations of less than 10 kpcs. Some of the observational studies mentioned above found that Dual AGN tend to be in galaxies suffering mergers, suggesting that galaxy mergers enhance AGN activity. For instance, Koss et al. (2012) found that the X-ray luminosity of the AGN in their Dual systems increases with decreasing galaxy separation, being a galaxy merger the key to activate the AGN. Comerford et al. (2015) found similarly that Dual AGN in major mergers are more luminous than those that are not. However, because observations just capture an instant in time, it is not clear if that is the case or if the AGN are active because of internal processes.

The new generation of cosmological hydrodynamics simulations are currently the best tools available to study the incidence of Dual AGN and what drives their activity. Previous numerical studies have found Dual AGN to be rare as well. For instance, Steinborn et al. (2016) use a large simulation with a volume of (182 Mpc$^3$) from the suite of Magnetinum Pathfinder Simulations, to compare very close Dual AGN systems to non active BH pairs and to offset AGN. They define as a BH pair with only one BH active as offset AGN. Steinborn et al. (2016) found a Dual AGN fraction to be less than 1 percent of the total number of AGN at $z = 2$. The non active BH pairs in their simulation accrete less gas from the intergalactic medium than Dual AGN. Volonteri et al. (2016), using the horizon-AGN simulation found that the fraction of Dual AGN living in the same host galaxy with a $< 30$ kpc separation, is 0.1 percent at $z = 0$ for relative massive galaxies. This fraction increases to 2 percent at $z = 1$. They explore the occupation fraction of BHs as a function of stellar mass, finding that the fraction of Dual systems rises as distances become small. In the context of Dual AGN evolution, Tremmel et al. (2017) follow the evolution of a single Dual AGN (with distances below 1 kpc) in the most massive halo in the Romulus simulation with a volume of only (8 Mpc$^3$). They find that this Dual AGN is activated by a major merger.

An interesting question that arises is the cause of the small fraction of Dual AGN. It is because Dual AGN is an ephemeral phase due to the AGN intrinsic properties such as variability or because the host galaxies of Dual AGN have special properties or history. To shed further light on this, we explore the abundances and properties of Dual AGN in the large cosmological hydrodynamical simulation of the EAGLE project (Schaye et al. 2015; Crain et al. 2015) at $z = 0.8 - 1$. We also explore the properties of the host galaxies and their recent merger history.

A series of papers have analysed the galaxy population in EAGLE finding reasonable agreement with the evolution of the galaxy mass functions (Furlong et al. 2015), the evolution of galaxy sizes (Furlong et al. 2017), the colour-magnitude diagram (Trayford et al. 2016), the properties of molecular and atomic gas (Lagos et al. 2015; Bahé et al. 2016) and the oxygen abundance gradients of the star-forming disc galaxies (Tissera et al. in preparation). The simulation also reasonably reproduces the evolution of the AGN luminosity functions in X-ray bands up to $z = 1$ (Rosas-Guevara et al. 2016) and the different observational trends seen on the plane of star formation and black hole accretion rates (McAlpine et al. 2017).

The outline is as follows. In section 2, we describe the simulations and the post-processing analysis to identify Dual AGN. In section 3.1, we show the evolution of a Dual AGN as a study case. In section 3.2, we explore the effects of AGN variability in the detection of a Dual AGN. The Dual AGN fraction as a function of separation is shown in section 3.3. We also investigate the properties of their host galaxies and their recent merger histories in section 3.4, and in section 3.5 we look into the abundances of Dual AGN as a function of redshift. Finally, in section 4, we summarise our findings.

2 METHODOLOGY

2.1 Simulations

The Evolution and Assembly of GaLaxies and their Environment (EAGLE, Schaye et al. 2015; Crain et al. 2015) is a suite of cosmological hydrodynamical simulations, comprising various galaxy formation sub-grid models, numerical resolutions and volumes. The simulations were performed with a heavily modified version of SPH code P-Gadget3 (Springel 2005b) that includes: gas cooling, metal enrichment and energy input from star formation and black hole growth. A full description of the simulation suite can be found in Schaye et al. (2015), with the calibration process described in Crain et al. (2015). Here, we concentrate on the largest simulation with a comoving volume of (100 cMpc)$^3$, denoted as Ref-L100N1504. The mass resolution is $9.7 \times 10^8 M_\odot$ for dark matter particles and $1.81 \times 10^6 M_\odot$ for baryonic particles and a softening length of 2.66 ckpc limited to a maximum physical size of 0.70 pkpc. The simulation adopts the cosmological parameters taken from Planck collaboration et al. (2013).

The simulation outputs were analysed using the SUBFIND algorithm to identify bound sub-structures (Springel et al. 2001; Dolag et al. 2009) within each dark matter halo. We identify these substructures as galaxies and measure their stellar and gas masses within a radius of 30 pkpc (as per Schaye et al. 2015).

1 http://www.eaglesim.org & http://eagle.strw.leidenuniv.nl
2 We will refer to comoving distances with a preceding ‘c’, such as ckpc, to refer to comoving kiloparsec and physical lengths will be preceded by a ‘p’ such as pkpc.
3 The values of the cosmological parameters are: $\Omega_m = 0.693$, $\Omega_k = 0.307$, $\Omega_b = 0.0485$, $\sigma_8 = 0.828$, $h = 0.677$, $n_s = 0.9611$ and $Y = 0.248$.
4 The outputs of the simulation are public available by querying the EAGLE SQL web interface http://icc.dur.ac.uk/Eagle/database.php (McAlpine et al. 2016).
2.2 Black hole sub-grid physics
Black holes (BHs) are seeded into the minimum potential of dark matter halos with masses larger than $1.48 \times 10^{10} M_\odot$. BHs grow via two processes: gas accretion and mergers. The accretion onto BHs is implemented as a modified Bondi prescription, limited to the Eddington rate (Schaye et al. 2015). This modification modulates the high circulation flows with a viscous parameter, $C_{\text{visc}}$, introduced by Rosas-Guevara et al. (2015). A fraction of the accreted mass is converted into thermal energy and released stochastically into the neighbouring gas (Booth & Schaye 2009). The stochastically selected gas particles around a BH are heated by $\Delta T (= 10^9 K$ for the Ref-L100N1504 simulation). We highlight that only a single mode of AGN feedback is adopted, independent of the BH mass or halo mass, using a constant efficiency of 0.1, from which, a fraction of 0.15 is coupled to the interstellar medium.

2.3 Black hole merger criterion
A BH merger will occur in EAGLE when the BHs: (1) are separated by a distance below the smoothing kernel and also below three times the gravitational softening length and (2) their velocity relative to the BH is smaller than the circular velocity at a separation of $h_{\text{BH}}$, $v_{\text{rel}} < (GM_{\text{BH}}/h_{\text{BH}})^{1/2}$, where $h_{\text{BH}}$ and $M_{\text{BH}}$ correspond to the smoothing kernel and the subgrid mass of the most massive BH of the system. This criterion avoids a premature BH merger when their host galaxies are starting to merge.

Because the simulation does not model the dynamical friction for BHs with masses below the initial mass of the gas, it is imposed that BHs with $M_{\text{BH}} < 100 m_{\text{gas}}$ are relocated to the minimum of the gravitational potential of the halo. It is also imposed in each step that the BHs change to the position of the neighbouring particle with the lowest gravitational potential of all the neighbouring particles with two conditions: (1) their velocity relative to the BH is smaller than $0.25c_s$, where $c_s$ is the sound speed and (2) their distance is smaller than three gravitational softening lengths.

2.4 Dual AGN sample
Following Rosas-Guevara et al. (2016), we make use of the ‘snipshots’. These are more frequent outputs of the simulation that have a typical spacing of tens of Myrs. We also use the log files that contain properties of the BHs and of their surrounding gas with a much better temporal resolution to capture meticulously the evolution of AGN.

We use the Eddington ratio as a measure of the activity level of BHs. We define the Eddington ratio as $\lambda_{\text{Edd}} = M_{\text{BH}}/M_{\text{Edd}}$, where $M_{\text{BH}}$ and $M_{\text{Edd}}$ are the instantaneous BH mass accretion rate and Eddington limit respectively. We consider as prominent sources of luminous X-rays to be the BHs with $\lambda_{\text{Edd}} \geq 10^{-2}$, assuming they are surrounded by a thin and efficient nuclear disc and define them as ‘active’. BHs with $\lambda_{\text{Edd}}$ below this ratio are assumed to be enclosed by a thick and inefficient accretion disc and they would not provide a significant contribution of X-ray luminosity. We note that the threshold value taken to define an ‘active’ BH does not significantly affect the evolution of the AGN luminosity functions (see Rosas-Guevara et al. 2015, appendix B).

To remain consistent with the results of Rosas-Guevara et al. (2016) and McAlpine et al. (2017), we define the bolometric luminosity as 10% of the instantaneous mass accretion rate. The bolometric luminosity is converted into hard X-ray luminosity (2-10 keV) using the redshift independent bolometric corrections from Marconi et al. (2004).

We refer to Dual AGN as ‘active’ BH pairs with a separation of 30 pkpc or lower. We exclude AGN with lower distances than 1 pkpc since the simulation does not accurately resolve their evolution at such small scales. We create a sample of ‘visible Dual AGN’ where both members of the close pair are accreting at $L_{\text{BH}} \geq 10^{42} \text{erg s}^{-1}$ in a given snapshot. A ‘One AGN’ sample is also defined where only one member is above this threshold. With this criterion, at $z = 0.8 - 1$, there are 109 Dual AGN, 29 of them belong to the visible Dual AGN sample and 73 to the One AGN sample. The rest of Dual AGN are too faint with a hard X-ray luminosity, $L_{\text{HX}}$, between $10^{40} \text{erg s}^{-1}$ and $10^{42} \text{erg s}^{-1}$, and therefore are not visible in this band even though they could be irradiating near the Eddington limit. To give a sense of the BH masses powering visible Dual AGN, the median BH mass is $4.4 \times 10^6 M_\odot$ and 70 percent of the BHs have a mass larger than $10^6 M_\odot$. The median $M_{\text{BH,1}}/M_{\text{BH,2}}$, where $M_{\text{BH,1}}$ and $M_{\text{BH,2}}$ are the masses of less and more massive BH respectively, is 0.1 and 22 percent of the Dual systems have a $M_{\text{BH,1}}/M_{\text{BH,2}}$ ratio higher than 0.3. We do not make any distinction of Dual AGN with respect to any property of their host galaxy, except in section 3.4.

3 RESULTS
3.1 A study case: The evolution of a Dual AGN system in EAGLE
To understand the evolution of Dual AGN in the simulation, we begin by illustrating the evolution of a typical Dual AGN observed at $z = 1$ within the last 1.4-Gyrs before the BH pair eventually merge. In the left panel of Fig. 1, we show, from top to bottom, the BH mass, hard X-ray luminosity, and AGN separation as a function of cosmic time relative to the merger, where $t = 0$ corresponds to $z = 1$.3. The green and light-blue curves represent, respectively, the evolution of the brighter and the fainter AGN, were the brighter AGN is defined to be the one was brighter when the Dual AGN was observed ($z = 1$). In the right panel, we show a visualisation of the system at three different times (as labelled). These frames are part of a movie now available of the host galaxies of the Dual AGN.

At large separations, the BHs have masses within an order of magnitude of the seed mass ($1.48 \times 10^7 M_\odot$). Both BHs then gradually acquire mass via gas accretion and they sporadically vary between the states that we defined as ‘Dual AGN’, ‘One AGN’ and an ‘inactive pair’. Note that the average $L_{\text{BH}}$ for both BHs is above $10^{42} \text{erg s}^{-1}$ (see the horizontal dashed line) just after 400 Myrs. At this stage, they have comparable masses of $6.3 \times 10^6 M_\odot$ and $10^6 M_\odot$ at $z = 1$ (see the vertical dashed line) in their Dual AGN
Figure 1. The evolution of a Dual AGN in the EAGLE simulation. Left figure: The evolution of the BH mass (top plot), of hard-X-ray luminosity (middle-plot) and the BH separation (bottom plot) in the last 1.4 Gyr before the BHs merged. The markers (triangles for the Bright AGN and diamonds for the faint AGN) represent the average luminosity over a 250 Myr-period and the filled region its error. The vertical dashed line represents the time at \( z = 1 \) and the solid line the time they merged. The grey markers represent the \( L_{\text{HX}} \) at the moment the Dual AGN was observed (\( z = 1 \)). The horizontal dashed line is the distance at which the merger criterion is applied. Right figure: Images of the host galaxies and eventually merging to form a final BH with a mass of \( 2.7 \times 10^9 \text{M}_\odot \). Interestingly, the luminosities in the hard X-ray band vary by two orders of magnitude over a temporal scale of megayears as seen in the middle plot. However, overall, the luminosity increases as the BHs get bigger and as their host galaxies get closer to each other (see markers in the middle plot). In the images, the circles represent the location of each AGN, coloured blue if the AGN is too faint to be visible in the hard X-ray band and red when it is visible. The figure shows that luminosity increases on average as the distance between the host galaxies reduces, but also that the presence of rapid AGN variability significantly reduces the detectability of Dual AGN.

3.2 The Effects of AGN variability

As Fig. 1 has shown, the variability in AGN luminosity can affect the detection of Dual AGN. To quantify the significance of this effect, we measure \( t_{30}/t_{30} \) where \( t_{30} \) is the time in which the BHs spend with a separation \( \leq 30 \text{ pkpc} \) and \( t_{30} \) is the time that both AGN are ‘turned on’ during this period (i.e., when both AGN have \( L_{\text{HX}} \geq 10^{42} \text{erg s}^{-1} \)). This ratio, \( t_{30}/t_{30} \), is the proxy for a probability of detecting a Dual AGN: If this ratio is 1, both AGN are always ‘turned on’ when they are closer than 30 pkpc. When this ratio is 0 implies that it is impossible to detect an AGN pair to these distances.

Fig. 2 shows the cumulative Dual AGN fraction as a function of \( t_{30}/t_{30} \) at \( z = 0.8 - 1 \). The figure illustrates that 60 percent of Dual AGN have a probability of being detected smaller than 0.01 and only 10 percent of Dual AGN are ‘turned on’ for more than 10 percent of the time. With this result, we can estimate the average number of visible Dual AGN respect to the total number of Dual AGN. We found that this average fraction is similar to 3 percent, meaning that from 100 Dual AGN in a given volume, only 3 of them are going to have a hard X-ray luminosity above \( 10^{42} \text{erg s}^{-1} \).

3.3 Incidence of Dual AGN as a function of separation

One of the observational features of Dual AGN that is frequently invoked is their increasing incidence as a function of separation. Since it is widely believed that AGN activity is triggered by mergers, we investigate the separation of visible Dual AGN as a function of radius.

The top panel of Fig. 3 shows the predicted average fraction of visible Dual AGN as a function of AGN separation at \( z = 0.8 - 1.0 \) (blue solid line). We find an enhancement of Dual AGN (blue solid line) at separations of 5 pkpc. This peak is even more pronounced when we go to even smaller scales, but since this behaviour could be affected by the BH merger criterion (see 2.3), we are not showing this on the plot. At larger separations (20 – 25 pkpc), the Dual AGN...
fraction presents a large peak. This peak also appears when we look at other redshift bins (not shown here) and is independent of the bin size. To understand its origin, we follow the separation of the BHs and of their host galaxies through time. The bottom panel of Fig. 3 shows that the BHs (green curve) and their host galaxies (blue circles) follow similar trajectories before the galaxy merger takes place. The last close encounter of the host galaxies before the merger, occurs at 20 – 25 pkpc and then the host galaxies rapidly spiral inwards, merging at 5 – 10 pkpc. This last encounter between galaxies could produce gas that feeds the infall BH creating a Dual AGN. It takes much longer for the BHs to merge, spending more time at closer separations.

The shape of the Dual AGN fraction distribution is also contrasted with the distribution of non active BH pairs (grey line), defining them as any two BHs whose Eddington ratio is $\leq 10^{-4}$. The fraction of non active BH pairs gradually rises with larger distances opposite to the behaviour of the Dual AGN fraction.

Table 1 shows that the Dual AGN fraction distribution could be affected by the reposition of the BHs to the minimum potential of the host halo (see 2.3) that is applied to the BHs with masses smaller than 100 the initial mass of the gas particle. To investigate the possible effect of the BH reposition, we follow the trajectories of the 10 most bound star particles of each host halo at separation $z = 1$ and compare to the trajectories of the BHs. Since the star particles do not suffer any relocation, if the effect of BH reposition were small, the trajectories of the BHs and of the 10 most bound star particles would be similar. Indeed, we find that in most cases the trajectory of the BHs and of the 10 most bound star particles are almost identical for distances above 5 pkpc. A typical example of this is shown in the bottom panel of Fig. 3 where the evolution of 10 most bound star particles are shown as orange circles. Therefore, the BH relocation does not significantly affect the Dual AGN fraction distribution. Moreover, the BH relocation technique seems to satisfactorily reproduce the BH orbits at kpc-scales.

3.4 Properties of the host galaxies of Dual AGN

In this section, we explore the main properties and the recent merger history of the galaxies that host visible Dual AGN at $z = 0.8 – 1$. Firstly, we look at whether the host galaxy/galaxies underwent in the last 2 Gyrs or are undergoing a merger with stellar mass ratio $f_{\text{M}}$, larger than 0.1. Table 1 summarises the recent merger history of the host galaxies: 30 percent of the visible Dual AGN resides in the same galaxy whereas the rest of them lives in distinct host galaxies that are in the process of interaction. From the percentage of visible Dual AGN living in the same host galaxy (30 percent of the total sample), 60 percent of their host galaxies experienced a merger with $f_{\text{M}} \geq 0.1$ in the last 2 Gyrs. The percentage of Dual AGN in distinct galaxies (70 percent of the total sample) with similar stellar mass and in the process of interaction is 0.81. In total, 75 percent of the Dual AGN host galaxies present a major merger in their recent history.

We have also investigated the distribution of stellar mass of the host galaxies of visible Dual AGN and compare to the stellar mass distribution of the galaxies hosting at least one AGN with $L_{\text{HX}} > 10^{42} \text{erg s}^{-1}$. Visible Dual AGN (blue solid line of Fig. 4, top panel) tend to live in more massive galaxies in comparison with the host galaxies.
of the full AGN population (grey solid line). The median stellar mass is \( \sim 10^{10.5} M_\odot \) (blue dotted line) 0.2 dex higher than that of the total AGN population (grey dotted line). Finally, we investigate the gas to stellar mass ratio in the bottom panel of Fig. 4. We compare the median gas to stellar mass fraction (purple solid line with circles) to the one of the host galaxies of visible Dual AGN (green triangles). We find that the galaxies hosting a visible Dual AGN present higher gas to stellar mass fraction than the median of the distribution, apart from a few cases. These few cases (light green open triangles) are satellites that could have run out of gas because of the interaction with the central galaxy.

3.5 The evolution of the DUAL AGN fraction with redshift

Fig. 5 shows that the average fraction of visible Dual AGN (purple solid line) respect to the total AGN. This fraction increases with redshift, from a fraction of 0.1 percent at \( z = 0.0 - 0.5 \) to 3 percent at \( z = 4 - 5 \). If one of the AGN of the Dual system is only visible in the hard X-ray band, the average fraction of Dual AGN increases for a given redshift as the green line shows. For instance at \( z = 0.8 - 1.0 \), it increases from 1 to 2 percent. Note, however, that the average remains small at all redshifts.

We compare qualitatively our results with the current observations in the local Universe. Koss et al. (2012) (empty stars) combine X-ray and optical observations to detect close Dual AGN (distance \( \leq 30 \) pkpc), finding a Dual AGN fraction of 7.5 percent, that decreases to 2 percent when both AGN are only detected in the hard X-ray band (filled stars). Liu et al. 2011 (diamonds) use a sample from the Seventh Data Release of the SDSS survey at \( z = 0.1 \) based on diagnostic emission line ratios. They estimate the Dual AGN fraction with a separation \( \leq 30 \) pkpc, to be 1.3 percent. These fractions are marginally above the simulation prediction. This could be due to the different selections and methods to find a Dual AGN in these studies whose estimates are also discrepant to each other by similar margins. Nonetheless, in both observations and the simulation, Dual AGN are rare events.

We additionally include estimates from other cosmological hydrodynamical simulations. Steinborn et al. (2016) estimate the fraction of very close Dual AGN (separation of \( \leq 10 \) pkpc) at \( z = 2 \) from a simulation that is part of the Magneticum Pathfinder set. This simulation has a similar resolution than that from EAGLE with a larger volume but run to \( z = 2 \). They consider an AGN to be a BH powering at \( L_{\text{bol}} \geq 10^{43} \text{erg s}^{-1} \) \( (L_{\text{HX}} \gtrsim 10^{43} \text{erg s}^{-1}) \). They found a
Dual AGN fraction of 0.5% (pentagon, approximately a half of the simulation prediction). Note, however, that they consider only very close Dual AGN. Volonteri et al. (2016) also estimate Dual AGN fraction (hexagons) \( z = 0 \) and \( z = 2 \), in the cosmological hydrodynamic simulation Horizon-AGN. The volume and resolution of the simulation are similar to EAGLE. For Dual AGN with \( L_{\text{bol}} \geq 10^{42} \text{ erg s}^{-1} \) and hosted by a single galaxy with \( \geq 10^{10} M_\odot \) in stellar mass (this is about the median of the host galaxies of our visible Dual AGN sample), they find an increasing trend in redshift from 0.1 at \( z = 0 \) to 2 percent at \( z = 2 \). Their estimate of the Dual AGN fraction is in broad agreement with our results. They also find much lower fraction in comparison to the observational estimates as in our prediction.

3.6 The effects of the BH merger criterion

We have already discussed that the distribution of Dual AGN as a function of the BH separation could be affected at small distances when the BH merger criterion is applied (see 3.3). We investigate the effects of this in the results of the paper. We obtain similar findings when we take Dual AGN at separations above 2.1 pkpc. The population of Dual AGN living in the same host galaxy reduces at excluding these Dual systems with a separation below 2.1 pkpc, but our main result that relatively major mergers enhance AGN activity is preserved. In the case of the average fraction of Dual AGN detected, it is not highly sensitive to the merger criterion because the median fraction of the time that Dual AGN are turned on is almost independent of the separation of the BH. The increasing trend found in the evolution of the Dual AGN fraction is preserved, however, the Dual AGN fractions tend to be marginally smaller.

4 SUMMARY AND DISCUSSIONS

In this paper, we study the abundance and evolution of Dual AGN in the largest EAGLE simulation. We select Dual AGN as black holes (BH) with Eddington ratio \( \geq 0.01 \), visible in the hard-X-ray band and with a separation of 30 ckpc and lower. We also explore the main properties of their host galaxies and their recent merger histories. Our main results are present as follows:

- We show a study case of the evolution of a typical Dual AGN in the simulation at \( z = 1 \) in the last 1.4 Gyr before the BHs merge. We find that AGN activity is, overall, triggered by gas funnelled by mergers of their host galaxies. We also find that rapid variability in hard X-ray luminosities at scales of Myrs is present (Fig. 1).
- We explore the effects of AGN variability on the detection of a Dual AGN at \( z = 0.8 \) – 1.0. We define a probability of detection, \( t_{\text{var}}/t_{\text{BH}} \), where \( t_{\text{BH}} \) is the time that BHs spend within a separation \( \leq 30 \text{pkpc} \) and \( t_{\text{var}} \) the time that both AGN are ‘turned on’ during this period (i.e., when both AGN have \( L_{\text{bol}} \geq 10^{42} \text{ erg s}^{-1} \)). We find that 60 percent of our Dual AGN sample have a probability of detection below 1 percent (Fig. 2).
- We obtain the Dual AGN fraction as a function of their BH separation at \( z = 0.8 \) – 1.0 (Fig. 3). There is an enhancement in the abundance of Dual AGN at close separations of 5 pkpc. Then it decreases and increases again at 20 pkpc. This is due to the fast evolution of the host galaxies after their last encounter happening around this distance. We find similar results for different redshifts. The peak at 20 pkpc could be ascribed to the gas of the central galaxy being accreted by the infall BH in agreement with observations (Lambas et al. 2003; Alonso et al. 2007). The enhancement in the Dual AGN fraction is also in agreement with observed galaxy pairs with merging features hosting Dual AGN (Koss et al. 2012; Comerford & Greene. 2014).
- We explore the main properties of the host galaxies and their recent merger histories. We find that 75 percent of the host galaxies recently undergone or are undergoing a merger with a mass ratio larger than 0.1. We compare the properties of the host galaxies to the total galaxy population hosting an AGN. We find that Dual AGN tend to live in galaxies with higher stellar mass and higher gas to stellar mass fractions. We also find that some of the host galaxies of Dual AGN have a lower gas to stellar mass fraction, but those are satellite galaxies whose BH could be feeding by gas from the central galaxy (Fig. 4).
- The average visible Dual AGN fraction in hard X-ray (\( L_{\text{bol}} \geq 10^{42} \text{ erg s}^{-1} \)) increases with redshift (Fig. 5). This rising trend is also found in other numerical and observational works (Comerford & Greene. 2014; Volonteri et al. 2016). When only one of the AGN has \( L_{\text{bol}} \geq 10^{42} \text{ erg s}^{-1} \), the average Dual AGN fraction increases.

This paper uses a state-of-the-art cosmological simulation to study the evolution of galaxies. The EAGLE simulation reproduces the observables of galaxies in the local Universe such as stellar masses, colours, sizes. It also reproduces with good agreement the evolution of AGN luminosity functions up to \( z = 1 \) and the contrasting observed trends of the plane of star formation rate–black hole accretion rate. In this paper, the EAGLE simulation allows us to study in a more statistical mean the frequency of Dual AGN and the effects of AGN variability in the detection of Dual AGN at \( z = 0.8 \) – 1. Dual AGN tend to be rare and their detection are affected by AGN variability. The enhancement in the fraction of Dual AGN at small scales is a natural result of the evolution of their host galaxies merging. It also confirms earlier suggestions that Dual AGN might be triggered by significant galaxy mergers. Although the evolution of the Dual AGN is not captured at scales below the BH merger criterion is applied in EAGLE, we show that our findings are preserved. Something that is not completely clear from our work is the conditions of the major mergers to activate a Dual AGN or if major mergers always activate a Dual AGN. In further work, we plan to extend this study in more detail.

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