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Supermassive black holes in merger-free galaxies have higher spins which are preferentially aligned with their host galaxy

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ABSTRACT

Here, we use the Horizon–active galactic nucleus (AGN) simulation to test whether the spins of supermassive black hole (SMBH) in merger-free galaxies are higher. We select samples using an observationally motivated bulge-to-total mass ratio of <0.1 , along with two simulation-motivated thresholds selecting galaxies which have not undergone a galaxy merger since $z = 2$, and those SMBHs with < 10 per cent of their mass due to SMBH mergers. We find higher spins ($>5\sigma$) in all three sample compared to the rest of the population. In addition, we find that SMBHs with their growth dominated by BH mergers following galaxy mergers are less likely to be aligned with their galaxy spin than those that have grown through accretion in the absence of galaxy mergers (3.4σ). We discuss the implications this has for the impact of active galactic nucleus (AGN) feedback, finding that merger-free SMBHs spend on average 91 per cent of their lifetimes since $z = 2$ in a radio mode of feedback (88 per cent for merger-dominated galaxies). Given that previous observational and theoretical works have concluded that merger-free processes dominate SMBH-galaxy co-evolution, our results suggest that this co-evolution could be regulated by radio mode AGN feedback.

Key words: methods: data analysis – methods: statistical – galaxies: bulges – galaxies: evolution – quasars: supermassive black holes.

1 INTRODUCTION

The tight correlations observed between the mass of a galaxy's supermassive black hole (SMBH) with velocity dispersion (Magorrian et al. 1998; Merritt & Ferrarese 2001; Hu 2008; Kormendy, Bender & Cornell 2011; McConnell et al. 2011; van den Bosch 2016) and stellar bulge mass (Marconi & Hunt 2003; Häring & Rix 2004) have long been interpreted as evidence for the merger-driven co-evolution of SMBHs and galaxies. However, recent simulations have shown that less than 35 per cent of SMBH growth since $z = 3$ is due to accretion triggered by galaxy mergers (possibly less than 15 per cent; Martin et al. 2018; McAlpine et al. 2020), which challenges the observational paradigm of merger-driven galaxy-SMBH co-evolution regulated by active galactic nucleus (AGN) feedback. To study this observationally, a sample of host galaxies with merger-free evolutionary histories, selected to lack the bulges

that develop following major or minor galaxy mergers (Walker, Mihos & Hernquist 1996; Hopkins, Quataert & Murray 2012; Tonini et al. 2016, including those rare gas-rich mergers after which a stellar disc reforms, e.g. Sparre & Springel 2017) can be constructed. Galaxies with bulge-to-total ratios <0.1 are thought not to have had a merger since at least $z \sim 2$ (Martig et al. 2012; Martin et al. 2018) and can be selected observationally to isolate merger-free systems. Simmons, Smethurst & Lintott (2017) showed that 101 unobscured AGN hosted by such disc-dominated galaxies with assumed merger-free evolutionary histories had substantial SMBH masses, with the majority lying well above (up to 2 dex) the stellar bulge mass–SMBH mass correlation that is observed for galaxies with significant merger histories, and lying on the typical total stellar mass–SMBH mass correlation.

Follow-up studies of a subset of this disc-dominated sample by Smethurst et al. (2019, 2021) revealed outflows ionized by the AGN from these merger-free systems. AGN feedback is thought to be a key regulator of co-evolution and considered necessary in cosmological volume simulations employing Lambda cold dark matter (Λ CDM), yet the role of AGN feedback in the absence of mergers is currently unknown. Merger-free AGN growth and feedback are severely

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understudied, in part because the bulk of previous observational studies either explicitly examine systems with merger-dominated growth histories (e.g. ULIRGs; Tadhunter et al. 2018; Perna et al. 2021) or focus on samples where the merger-driven and merger-free accretion histories cannot be disentangled (i.e. a mixed morphology sample across the entirety of SDSS such as Rakshit & Woo 2018). For this reason, the processes powering the SMBHs accretion that leads to the AGN outflows revealed by Smethurst et al. (2019, 2021) is still poorly understood. Given that a flurry of new results are suggesting that SMBHs grow predominantly through galaxy merger-free processes (Simmons et al. 2017; Martin et al. 2018; Smethurst et al. 2019, 2021; McAlpine et al. 2020; and see also a companion paper to this work Smethurst et al. 2023), it is imperative that we understand the galaxy-merger-free mechanisms responsible for the majority of SMBH growth and the subsequent AGN feedback.

One important property of SMBHs influenced by their co-evolution with their host galaxy is the magnitude of the BH spin, along with its orientation with respect to its host galaxy. The spin magnitude determines the efficiency with which the SMBH converts accreted mass to feedback energy, while the spin direction determines where feedback energy is deposited if the SMBH is driving a jet. We do have clear theoretical predictions for the expected distribution of the spins and geometries of SMBHs in systems evolving in the absence of mergers which could power such outflows. Nayakshin, Power & King (2012) discussed the implications of merger versus non-merger-driven accretion on to a black hole (BH). Merger-driven accretion occurs chaotically, with material infalling towards the SMBH at random angular momentum vectors, on average spinning down the BH (Berti & Volonteri 2008; Dotti et al. 2013). Conversely, material infalling to the SMBH in the centre of a non-merger grown system will come from within the galactic disc at a constant angular momentum vector, spinning up the SMBH to maximum (Nayakshin et al. 2012; Dubois, Volonteri & Silk 2014a; Bustamante & Springel 2019).¹ The Bardeen-Petterson effect is then thought to realign the spin of the BH according to that of the accretion disc formed from infalling gas (and therefore the galactic disc in a system fed by planar accretion; Bardeen & Petterson 1975). The time-scales of this process have been the subject of much discussion (see e.g. Rees 1978; Papaloizou & Pringle 1983; Scheuer & Feiler 1996; Fragile et al. 2007; Sorathia, Krolik & Hawley 2013) but are thought to be much shorter than the lifetimes of outflows or jets (Natarajan & Pringle 1998). Theoretical understanding therefore suggests that outflows will be produced perpendicular to galactic discs specifically in isolated, merger-free systems, and produced at random orientations in systems that have undergone a merger.

There is very little agreement in the literature over the accuracy of methods that claim to be able to probe the spin of SMBHs observationally (e.g. using X-ray reflection spectroscopy to probe the spin; see review by Reynolds 2014). In addition, although the orientation of outflows has been studied extensively in the literature with many studies finding no correlation with disc orientation (e.g. see Kinney et al. 2000; Schmitt et al. 2003; Ruschel-Dutra et al. 2021), there has not yet been an observational study on the orientation

¹Interestingly, Nayakshin et al. (2012) concluded from this theoretical consideration that secularly grown SMBHs should be overmassive in comparison to merger grown BHs, which they pointed out was in contradiction to measurements of SMBH masses in galaxies with pseudo-bulges available at the time (e.g. Kormendy et al. 2011). However, the work of Simmons et al. (2017) and Martin et al. (2018) has significantly eased this contradiction.

of outflows in purely secularly fed systems, only those with mixed accretion histories.

We note that this would be possible with the high resolution provided by the *Hubble Space Telescope (HST)* ramp filters used to isolate outflowing [O III] emission ionized by the AGN. However, since such data does not yet exist, and given the debate over whether it is observationally possible to determine the SMBH spin with X-ray reflection spectroscopy, we turn to simulations to test our hypothesis of non-merger-driven SMBH growth. Following the ideas of Nayakshin et al. (2012) and the results of Smethurst et al. (2019), we test whether SMBHs in merger-free systems have higher spin magnitudes and are subsequently aligned with their galactic discs using the Horizon-AGN simulation.² Horizon-AGN is a modern, large-scale galaxy evolution simulation that evolves the evolution of a large sample of galaxies from cosmic dawn to redshift $z = 0$. It has been shown to reproduce a wide range of observable properties of the galaxy and BH population, such as the galaxy mass functions and cosmic star formation history, the BH mass and luminosity functions, and correlations between BHs and their host galaxies such as the BH-stellar mass relation. While Horizon-AGN did not track BH spin evolution on the fly, BH spins were post-processed for all BHs in Horizon-AGN and presented in Dubois et al. (2014a).

We describe the Horizon-AGN simulation in Section 2.1, the calculation of BH spins in Section 2.2 and our galaxy sample selection in Section 2.3. Our results are shown and discussed in Section 3, and we summarize our conclusions in Section 5.

2 SIMULATION DATA

2.1 Horizon-AGN simulation

Horizon-AGN is a cosmological-volume hydrodynamical simulation, which has been described in detail in Dubois et al. (2014b). Here, we only reiterate its most important features.

Horizon-AGN was run using the adaptive mesh refinement code RAMSES (Teyssier 2002), using a standard Λ CDM cosmology with total matter density $\Omega_m = 0.272$, dark energy density $\Omega_\Lambda = 0.728$, amplitude of the matter power spectrum $\sigma_8 = 0.81$, baryon density $\Omega_b = 0.045$, Hubble constant $H_0 = 70.4 \text{ kms}^{-1} \text{ Mpc}^{-1}$, and spectral index $n_s = 0.967$ using WMAP-7 cosmology (Komatsu et al. 2011). The simulation box has a size of $L_{\text{box}} 100 h^{-1} \text{ Mpc}$ (comoving) and is refined on a root grid of 1024^3 . From here, cells are further adaptively refined up to a maximum resolution of $\Delta x = 1$ proper kpc (level 17). Cells are (de)refined when the mass in a cell is more (less) than 8 times the initial mass resolution. The simulation has a DM mass resolution of $M_{\text{DM}} \sim 8.27 \times 10^7 M_\odot$, and includes prescription for gas cooling including the contribution from metal released by SN feedback, background UV heating, star formation, and stellar feedback. Star formation is modelled according to a Schmidt law with a 1 per cent efficiency, using a Salpeter initial mass function. Stellar feedback is modelled to include stellar winds, type Ia and type II supernovae (Dubois & Teyssier 2008; Kimm et al. 2015). The minimum stellar resolution is $\sim 2 \times 10^6 M_\odot$.

BHs are created at $z > 1.5$ in cells that exceed the density threshold for star formation ($n_0 = 0.1 \text{ Hcm}^{-1}$) with an initial seed mass of $10^5 M_\odot$. To avoid multiple BHs forming in the same galaxies, a 50 comoving kpc exclusion zone for new BH formation is enforced around each existing BH. BH accretion and feedback is modelled

²<https://www.horizon-simulation.org/>

as in Dubois et al. (2012). BHs accrete gas via the Bondi–Hoyle–Lyttleton formalism $\dot{M}_{\text{BH}} = 4\pi\alpha G^2 M_{\text{BH}}^2 \bar{\rho} / (\bar{c}_s^2 + \bar{u}^2)^{3/2}$, where M_{BH} is the BH mass, G is the gravitational constant, $\bar{\rho}$, \bar{c}_s and \bar{u} are the average gas density, sound speed and gas velocity, and α is a dimensionless boost factor. We set $\alpha = n/n_0$ if the gas number density $n > n_0$, and $\alpha = 1$ otherwise (Booth & Schaye 2010). Accretion on to the BH is limited at the Eddington accretion rate \dot{M}_{Edd} . The Eddington ratio is defined to $f_{\text{edd}} = \dot{M}_{\text{BH}}/\dot{M}_{\text{Edd}} \leq 1$, and measures the efficiency of BH accretion. BH spin is not followed throughout the simulation and is instead computed in post-processing (see Section 2.2).

AGN feedback energy is released at a rate of $\dot{E}_{\text{AGN}} = \epsilon_f \epsilon_r \dot{M}_{\text{BH}} c^2$ where $\epsilon_r = 0.1$ is the assumed radiative efficiency and c is the speed of light. When $f_{\text{edd}} > 0.01$, the AGN is *quasar* mode, and energy is injected isotropically as thermal energy with coupling efficiency $\epsilon_f = 0.15$. If $f_{\text{edd}} \leq 0.01$, the AGN is in *radio* mode, where energy is released in bi-conical outflows, $\epsilon_f = 1$, and drive powerful jets when $10^{-4} < f_{\text{edd}} < 10^{-2}$. BHs in Horizon-AGN are able to move freely within their host galaxy, rather than being pinned to their centre. To account for un-resolved dynamical friction forces, a subgrid force of magnitude $\mathcal{F}_{\text{DM}} = f_{\text{gas}} 4\pi\alpha\rho(GM_{\text{BH}}/\bar{c}_s)^2$ is added following Ostriker (1999). $f_{\text{gas}} = 0-2$ (Chapon, Mayer & Teyssier 2013) is a factor that depends on the Mach number. BHs merge when located within 4 kpc of each other, and when their relative velocity is smaller than the escape velocity of the binary.

2.2 Computing SMBH spin evolution

BH spin was not included in the Horizon-AGN run. Instead, it is post-processed from quantities recorded at each coarse time-step throughout the simulation. For our analysis, we use the spins calculated in Dubois et al. (2014a), using an analytic model that estimates the SMBH spin evolution using gas quantities at the resolution scale of the simulation, as well as information on BH–BH mergers. We briefly reiterate the key features of the model here but refer readers to Dubois et al. (2014a) for details.

All BHs are assumed to form with zero spin (BH spin parameter $|a| = 0$). The evolution of BH spin direction and magnitude is integrated throughout its evolution using the BH accretion rate, instantaneous BH mass and BH angular momentum \mathbf{J}_{BH} , and the angular momentum vector of the accreted gas at each time-step recorded throughout the simulation. In brief, the model works as follows. At each time-step, the angular momentum of the gas \mathbf{J}_{gas} to be accreted is measured from the simulation within the accretion region of the BH. This measured angular momentum is only used to determine the direction of angular momentum accreted by the BH, not the magnitude. If the angular momentum of the gas and BH are misaligned, the gas exerts a torque on the BH spin through the Bardeen–Petterson effect (Bardeen & Petterson 1975). In this case, the inner accretion disc will warp and both BH spin and disc momentum will reorient until \mathbf{J}_{BH} and \mathbf{J}_{gas} are aligned (or anti-aligned) with $\mathbf{J}_{\text{tot}} = \mathbf{J}_{\text{BH}} + \mathbf{J}_{\text{gas}}$, which determines the new direction of the spin vector of the BH. At this point, BH and accretion disc can be either aligned or anti-aligned, which we determine using (King et al. 2005).

The change in BH spin magnitude due to angular momentum accreted from the disc on to the BH is computed following Bardeen (1970). Each accretion event is treated as the formation of a new accretion disc. We do not model the spin-down of BHs through the Blandford–Znajek mechanism (Blandford & Znajek 1977), during which BHs can be spun down as spin energy is extracted by BH-driven jets. During BH–BH mergers, the BH spin of the

merger remnant is computed from the properties of the primary and secondary BH following Rezzolla et al. (2008).

The galaxy spin axis is measured by computing the angular momentum vector \vec{a}_{gal} of all star particles associated with the galaxy. The angle, $\phi_{\text{gal,BH}}$, between the vectors defining the galaxy spin, \vec{a}_{gal} , and SMBH spin, \vec{a}_{BH} , in $\{x, y, z\}$ Cartesian coordinates within the simulation, was calculated as in the inverse cosine of the dot product of the two vectors divided by the product of their magnitudes:

$$\cos \phi_{\text{gal,BH}} = \left(\frac{\vec{a}_{\text{gal}} \cdot \vec{a}_{\text{BH}}}{|\vec{a}_{\text{gal}}| |\vec{a}_{\text{BH}}|} \right). \quad (1)$$

2.3 Galaxy sample selection

Galaxies and dark matter halos in Horizon-AGN were identified using ADAPTAHOP (Aubert, Pichon & Colombi 2004; Tweed et al. 2009), using a local density threshold of $\rho_t = 178$ times the average dark matter density, the 20 closest neighbours and a force softening of 2 kpc. A minimum stellar mass cut of $M_* = \sim 10^9 M_{\odot}$ was applied, where M_* is the total mass of all star particles associated with a given galaxy as identified by ADAPTAHOP. Bulge masses are computed as in Volonteri et al. (2016), using a first Sersic profile with $n = 1$ for the disc component, and a second Sersic profile with the best fit of $n = 1, 2, 3$, or 4 for the bulge component.

To identify BHs with galaxies for analysis, we combine two spatial criteria: to be assigned to a galaxy, a BH must be located within 10 per cent of the galaxy’s DM host halo virial radius, and simultaneously within two effective radii of the galaxy. Galaxy effective radii are computed by taking the geometric mean of the half-mass radius of the projected stellar densities along each of the simulation’s Cartesian axes. If several BHs meet both criteria for a given galaxy, the most massive BH is retained (see Volonteri et al. 2016, for details) and all other (i.e. secondary or wandering) BHs are discarded from the data set analysed here. Galaxy mergers were identified using the DM halo merger trees constructed from the halo catalogues for $z < 6$, which are built from snapshots that are spaced on average every 130 Myr. Galaxy mergers are classified into major (stellar mass ratios $> 1:4$) and minor (stellar mass ratios $1:4$ to $1:10$) galaxy mergers (see Martin et al. 2018, for details). During a BH merger, the less massive BH is considered to merge into the more massive one, whose identifier is retained.

We identified a sample of 6851 galaxies at $z = 0.0556$, (the average redshift of the observed merger-free ‘bulgeless’ galaxy sample of Simmons et al. 2017 for ease of comparison) from the Horizon-AGN simulation, which had central SMBH and for which bulge masses were computed. From this sample of galaxies, we selected sub-samples using three different criteria:

(i) A galaxy merger-based criterion, which selects galaxies according to the total number of galaxy mergers (both major, mass ratios $> 1:4$, and minor, mass ratio $1:10 - 1:4$) since redshift $z = 2$. The threshold of $z = 2$ is motivated by the need for hierarchical structure formation at earlier epochs, as per Λ CDM, and is observationally motivated by the studies of Martig et al. (2012); Martin et al. (2018) who showed that galaxies with low bulge-to-total ratios have had no major mergers since at least $z \sim 2$. Galaxy mergers were identified using the DM halo merger tree in Horizon-AGN. We combined the number of major and minor mergers into a single parameter, N_{merger} , to quantify the total number of mergers a galaxy has undergone since $z = 2$. We use this to select a sample of galaxies which have been evolving in isolation with $N_{\text{merger}} = 0$, which resulted in 1781 (26 per cent) galaxies. We compare these to galaxies that have had

their history dominated by galaxy mergers, with $N_{\text{merger}} \geq 3$ (2117 galaxies, ~ 31 per cent).

(ii) A BH merger-based criterion, which applies cuts to $f_{\text{BH,merge}}$, the cumulative mass fraction of a BH gained through BH mergers. For an equal mass BH-BH merger, $f_{\text{BH,merge}} = 0.5$ while for a 1:4 mass ratio merger, $f_{\text{BH,merge}} = 0.2$. $f_{\text{BH,merge}}$ can exceed 0.5 if a BH undergoes repeated mergers. No lower mass ratio cut is applied to mergers tracked in this way. We use this to select a sample of SMBHs that have evolved with minimal BH mergers with $f_{\text{BH,merge}} < 0.1$, which resulted in 2137 (~ 31 per cent) galaxies. Note that 1609 galaxies in the simulation had $f_{\text{BH,merge}} = 0$, with no mass contribution from mergers, and 3508 galaxies (~ 51 per cent of the Horizon-AGN population at $z = 0.0556$) have $f_{\text{BH,merge}} < 0.25$ and so have had their SMBH growth dominated by non-merger evolution. We note that while there is a link between galaxy mergers and SMBH mergers, one of the reasons that the galaxy-merger based sample and the SMBH-merger based sample are not identical is that numerical SMBH mergers can be significantly delayed in comparison to the merger of their host galaxies, even without considering further delays due to processes on scales that are unresolved in HORIZON-AGN (Volonteri et al. 2020).

(iii) An observationally motivated bulge to total (B/T) cut to produce a disc-dominated sample, based on the ratio between the galaxy bulge mass M_{bulge} and the total galaxy stellar mass M_* . We use this to select a sample of galaxies with assumed galaxy merger-free histories with $B/T < 0.1$ (as is done observationally, e.g. Simmons et al. 2013; Simmons et al. 2017) which resulted in 179 (~ 3 per cent) galaxies. This small sample size is a combination of the low numbers of truly disc-dominated galaxies produced in simulations (due to disc instability triggered bulge formation), and the poor resolution of the simulation outputs on which the mass decomposition is performed (leading to an overestimate of the bulge mass in the simulation).

81 galaxies are found in each of the three samples (i.e. with $N_{\text{merger}} = 0$, $f_{\text{BH,merge}} < 0.1$ and $B/T < 0.1$). 1346 galaxies are found in both the galaxy merger-free and BH merger-free samples (i.e. $N_{\text{merger}} = 0$ and $f_{\text{BH,merge}} < 0.1$). Of the 179 galaxies selected to be disc dominated, 112 (63 per cent) are classed as both disc dominated and have not undergone a major or minor galaxy merger since $z = 2$ (i.e. $N_{\text{merger}} = 0$ and $B/T < 0.1$). This suggests that the disc-dominated galaxies observed by Simmons et al. (2013); Simmons et al. (2017); Smethurst et al. (2019, 2021) are not a unique subset of galaxies, but are instead representative of the merger-free galaxy population.

3 RESULTS

Figs 1–3 show the properties of galaxies with merger-free and merger-dominated evolutionary histories identified using our three different criteria: bulge-to-total ratio (B/T ; Fig. 1), number of minor and major galaxy mergers since $z = 2$ (N_{merger} ; Fig. 2), and the fraction of the SMBH mass gained through BH mergers ($f_{\text{BH,merge}}$; Fig. 3). We investigate the differences in the distributions of SMBH mass (M_{BH}), total stellar mass (M_*), bulge stellar mass (M_{bulge}), bulge-to-total ratio (B/T), fraction of the SMBH mass gained through BH mergers ($f_{\text{BH,merge}}$), SMBH spin magnitude ($|a_{\text{BH}}|$), and the angle between the SMBH spin and galaxy spin ($\phi_{\text{gal,BH}}$; see equation 1).

The masses of non-merger grown SMBHs are lower than for the rest of the population. This is apparent when non-merger grown SMBHs are selected using an observational cut with galaxy B/T ratio and with the cuts that simulations make possible of number of mergers and fraction of SMBH mass grown by mergers ($>5\sigma$

statistical significance in a Kolmogorov–Smirnov test in all cases). This is also apparent for total and bulge stellar masses, with non-merger grown galaxies having lower stellar masses across Figs 1–3.

Non-merger grown SMBHs selected on galaxy B/T and number of galaxy mergers are confirmed to have low $f_{\text{BH,merge}}$ (see Figs 1 and 2). However, those galaxies selected with $f_{\text{BH,merge}} < 0.1$ do not uniformly have low bulge-to-total mass ratios. The distribution in Fig. 3 is bimodal, with a peak at low and high B/T ratio, either side of the peak for the rest of the population. This suggests that galaxies that have grown their SMBHs without BH mergers ($\lesssim 10$ per cent by mass) can have significant bulges, perhaps grown by disc instabilities, although we caution that at ~ 1 kpc resolution, disc instabilities are likely to be suppressed in HORIZON-AGN.³ Using a semi-analytic model, Parry, Eke & Frenk (2009) show in the Millennium simulation that bulge growth is dominated by disc instabilities⁴ for galaxies with total stellar masses $< 10^{11} M_{\odot}$, with mergers only dominating for the most massive galaxies. This leads to secular growth of both bulges and SMBHs, resulting in the distribution of B/T for non-merger grown systems seen in Fig. 3.

The distribution of the SMBH spin magnitudes are $>5\sigma$ different for each of the three selections of non-merger grown systems. It is most apparent for those galaxies selected using $f_{\text{BH,merge}} < 0.1$; this is unsurprising since this traces the true amount of mass in a SMBH grown by BH mergers (since B/T and N_{merger} are both proxies for merger SMBH growth). The spins of non-merger grown SMBHs are maximal (confirming the hypothesis of Smethurst et al. 2019, which built on the work of Nayakshin et al. 2012), in agreement with the results of Dubois et al. (2014a) and Bustamante & Springel (2019). We note that these results hold when incomplete, total stellar mass-matched samples of merger-free and merger-dominated systems are also compared.

However, the distributions of alignment between the SMBH spin and galaxy spin, $\phi_{\text{gal,BH}}$, are not statistically significantly different between the non-merger-selected galaxies and the rest of the population in either of Figs 1–3. This appears to contradict the secular feeding hypothesis of Smethurst et al. (2019) and the results from Bustamante & Springel (2019). We investigated this further in Fig. 4. Under the secular feeding hypothesis, SMBHs grown by non-merger processes should be spun up due to alignment between galaxy and SMBH spin, so should have maximal spin ($1 - |a| \sim 0$) and be aligned ($\cos \phi_{\text{gal,BH}} = 1$). While the majority of such systems display this behaviour there is still a large tail to misaligned and anti-aligned systems (the bottom left corner of Fig. 4) due to the fact that individual accretion episodes can realign BH spin when alignment time-scales are short, which increases the scatter in $\phi_{\text{gal,BH}}$ (see appendix C of Dubois et al. 2014a). For a model with longer accretion time-scales, we would expect a larger discrepancy between BHs in non-merger systems, who would have time to align with their host galaxy, and those in merger-dominated system, where BH spin alignment would lag after any changes in galactic spin due to galaxy merger. In such a scenario, merger-grown systems would be

³The lack of resolution within the vertical structure of the disc acts like an extra source of temperature in the disc that most likely prevents it from secularly barring.

⁴Bulge growth due to instabilities is computed in the Millennium simulation using an inequality quantifying the dynamics of the disc, which when satisfied leads to either partial or full (depending on the model used) collapse of the mass in the disc into a spheroid. Horizon-AGN, being a hydrodynamical simulation, natively follows the formation of bulges through distributed star formation within the galaxy, but is limited by its spatial resolution of $\Delta x = 1$ kpc.

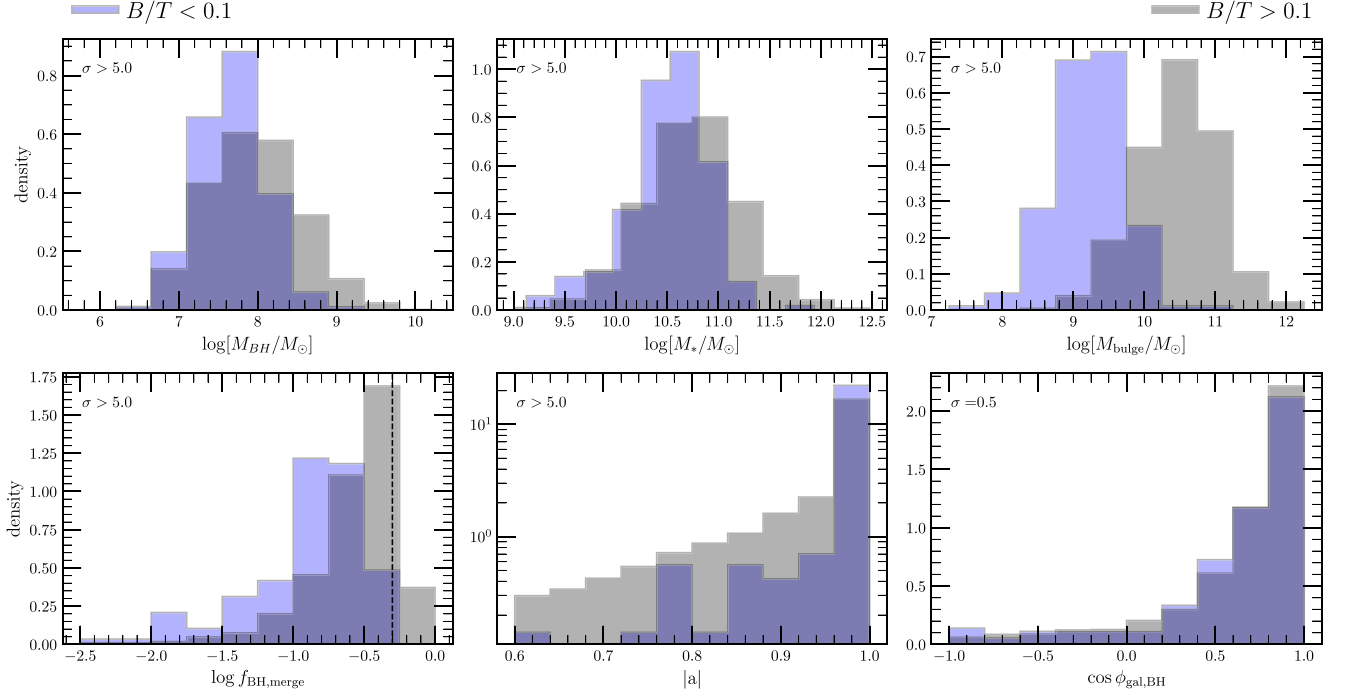


Figure 1. The distribution of properties across the Horizon-AGN sample for galaxies selected to have low bulge-to-total ratios, $B/T < 0.1$ (blue; assumed to have accretion grown SMBHs), compared to the rest of the sample with $B/T > 0.1$ (black; i.e. merger and accretion grown SMBHs). Shown are the SMBH masses, M_{BH} ; total stellar masses, M_* ; bulge stellar mass, M_{bulge} ; the fraction of the SMBH mass resulting from mergers, $f_{\text{BH,merger}}$ (the dashed line shows $f_{\text{BH,merger}} = 0.5$ and denotes the threshold between non-merger on the left and merger dominated growth on the right); the spin magnitude of the SMBH, $|a|$; and the angle between the spin of the SMBH and the galaxy, $\cos \phi_{\text{gal,BH}}$. A value of $\cos \phi_{\text{gal,BH}} = 1$ means the SMBH and galaxy spins are aligned; $\cos \phi_{\text{gal,BH}} = 0$ means they are misaligned by 90° ; and $\cos \phi_{\text{gal,BH}} = -1$ means they are misaligned by 180° . A value of $|a| = 1$ represents a maximally spinning BH. ‘Bulgeless’ systems with $B/T < 0.1$ have statistically significantly lower SMBH masses, lower stellar masses, lower bulge masses, and lower SMBH merger mass fractions. However, they have statistically significantly higher spin magnitudes, yet no statistically significant difference in spin alignment. We note that these results hold when incomplete, total stellar mass-matched samples of merger-free and merger-dominated systems are compared.

expected to be spun down and misaligned with their galaxies due to the variation in angular momentum of accreted gas introduced by galaxy mergers. In our sample, merger-dominated systems show a similar scatter in $\phi_{\text{gal,BH}}$ values as non-merger grown systems, suggesting that secular processes dominate the evolution of SMBHs in the epochs between galaxy mergers. While it is evident that BH merger-grown BHs are spun down by the mergers in Fig. 4, there is no correlation between $\phi_{\text{gal,BH}}$ and BH spin magnitude $|a|$ (solid line). The caveat is that the spatial resolution of $\Delta x = 1$ kpc under-resolves the angular momentum structure in the centre of the galaxy, let alone on scales closer to the event horizon of the BH. While (Dubois et al. 2014b) have shown that the spin evolution of a BH is reasonably well converged on resolutions of 10–80 pc, the significantly lower resolution of Horizon-AGN means that we probably overpredict the alignment between galactic and BH spin. We also note that the BH spin evolution model used here treats each accretion event as independent. If the time-scales for a newly formed accretion disc to be consumed are significantly longer than the time-step of the simulation this would artificially increase the scatter in Fig. 4.

The right-hand panel of Fig. 4 shows that there are differences in spin and spin alignment with $f_{\text{BH,merger}}$, but they are gradual enough across the parameter space that the single-threshold distributions of Figs 1–3 are not able to capture them. However, it is clear in Fig. 4 the SMBHs with the highest average mass fraction grown by BH mergers, $f_{\text{BH,merger}}$, are found in the lowest spin, most misaligned bins. This is only apparent when controlling for $f_{\text{BH,merger}}$ and so in Fig. 5

we once again look at the distribution of $\cos \phi_{\text{gal,BH}}$ but for the true extremes of the population; those non-merger-driven systems with $f_{\text{BH,merger}} < 0.1$ (2137 systems) and $f_{\text{BH,merger}} > 0.6$ (318 systems). Their distributions of $\cos \phi_{\text{gal,BH}}$ are statistically significantly different ($\sigma = 3.4$ in a KS test), with BH merger grown systems more likely to be misaligned ($\cos \phi_{\text{gal,BH}} \sim 0$) or anti-aligned ($\cos \phi_{\text{gal,BH}} \sim -1$), due to the spin flips caused by the misaligned orbital angular momentum of SMBH during mergers. It is only when probing the extremes of the population that this is apparent. The rest of the SMBH population evolves with a mix of merger and non-merger histories, with non-merger processes dominating (51 per cent of SMBH have $f_{\text{BH,merger}} < 0.25$, i.e. have not undergone a major merger with a mass ratio of at least 1:3 since $z \sim 2$), where high spins and alignment are expected. We note that while BH–BH mergers could not happen without the galaxy mergers that deliver multiple BHs to the same galaxy, the effect discussed here is entirely driven by the re-alignment of BH spins during a BH–BH merger, not by the rearranging of the galactic spin during galaxy mergers. As can be seen in the bottom right-hand panel of Fig. 2, there is no noticeable difference in the distribution of alignment angles between BH and galaxy for merger-rich and merger-poor galaxies. In addition, BH spins for BHs in both samples of galaxies are highly aligned with their host galaxy spin. This result will be at least partially influenced by the limited resolution of Horizon-AGN, and should be treated as an upper limit: at 1 kpc of resolution, the angular momentum distribution in the centres of galaxies is insufficiently well

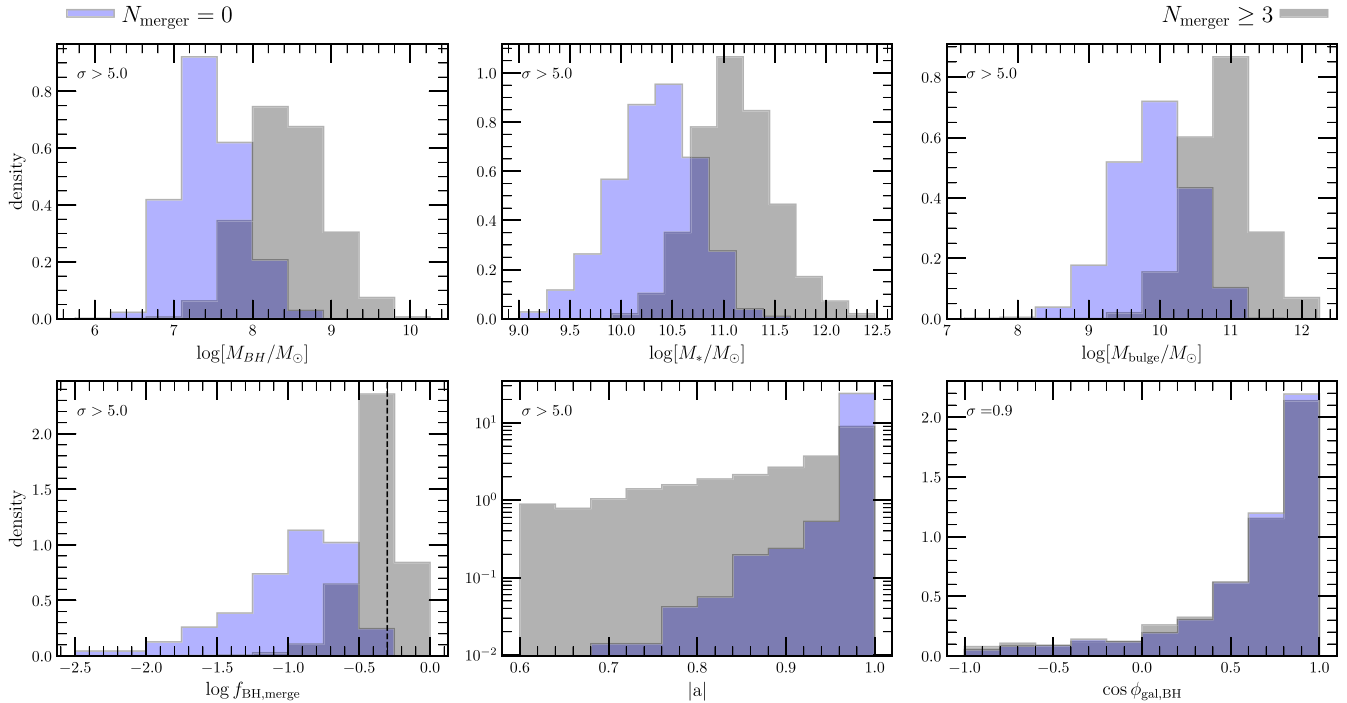


Figure 2. The distribution of properties across the Horizon-AGN sample for galaxies selected to have had no major or minor mergers since $z = 2$, $N_{\text{merger}} = 0$ (blue; assumed to have accretion grown SMBHs), compared to those which have had more than three major or minor mergers since $z = 2$, $N_{\text{merger}} > 3$ (black; i.e. merger dominated SMBH growth). Shown are the SMBH masses, M_{BH} ; total stellar masses, M_* ; bulge stellar mass, M_{bulge} ; the fraction of the SMBH mass resulting from mergers, $f_{\text{BH,merge}}$ (the dashed line shows $f_{\text{BH,merge}} = 0.5$ and denotes the threshold between non-merger on the left and merger dominated growth on the right); the spin magnitude of the SMBH, $|a|$; and the angle between the spin of the SMBH and the galaxy, $\cos \phi_{\text{gal,BH}}$. A value of $\cos \phi_{\text{gal,BH}} = 1$ means the SMBH and galaxy spins are aligned; $\cos \phi_{\text{gal,BH}} = 0$ means they are misaligned by 90° ; and $\cos \phi_{\text{gal,BH}} = -1$ means they are misaligned by 180° . A value of $|a| = 1$ represents a maximally spinning BH. Accretion dominated systems with $N_{\text{merger}} = 0$ have statistically significantly lower SMBH masses, lower stellar masses, lower bulge masses, and lower SMBH merger mass fractions. However, they do have statistically significantly higher SMBH spin magnitudes, yet once again no statistically significant difference in spin alignment. We note that these results hold when incomplete; total stellar mass matched samples of merger-free and merger-dominated systems are compared.

resolved to significantly decouple from the larger galactic angular momentum.

4 DISCUSSION

4.1 Time-scales of spin alignment

Our results have shown that SMBHs in merger-free galaxies have higher spins ($>5\sigma$) than the rest of the galaxy population and are more likely to be aligned with their galaxy spin (3.4σ). These results support the secular feeding hypothesis of Nayakshin et al. (2012) and Smethurst et al. (2019), where material inflowing to the SMBH in the centre of a non-merger grown system will come from within the galactic disc at a constant angular momentum vector, spinning up the SMBH to maximum, and subsequently align the spin of the SMBH according to that of the accretion disc formed from infalling gas through the Bardeen–Peterson effect (Bardeen & Peterson 1975).

However, two populations of BHs remain difficult to explain in this hypothesis: (i) merger-grown SMBHs that are aligned with their galaxy but have low-spin magnitudes, and (ii) merger-grown SMBHs with high-spin magnitudes. Some of these effects will be statistical: for some BH–BH mergers, the spins of the two BHs and orbital angular momentum will roughly align, which means the spin of the post-merger BH will remain high. For others, the post-merger spin will happen to align closely with that of the galaxy. For aligned, low-spin BHs it is most likely a question of time-scales: the time-scale for

a BH to re-align its spin vector with that of the host galaxy is much shorter than the characteristic time-scale for it to increase its spin magnitude, as can be seen by that fact that on average all BHs in our sample, no matter their merger history, preferentially align with their host galaxy. A BH that has undergone a not-too-recent major merger, or series of more minor mergers, would only need a comparatively small amount of coherent accretion, possibly following a period of chaotic accretion during a galaxy merger that reduces its spin, to then realign itself with its host galaxy while retaining a low spin. The rate of this accretion would be too low to cause significant mass gain or spin-up the BH spin magnitude. Finally, systems might end up spinning highly if they are dominated by their orbital angular momentum: Gammie, Shapiro & McKinney (2004) argue that following a merger between two BHs, it is reasonable to assume that the final BH has an angular momentum that is equal to that of the binary. Specifically, ‘the merger of two BHs of comparable mass will immediately drive the spin parameter of the merged hole to 0.8,’ where the spin parameter is J/M_{BH} .

4.2 Spin alignment and the impact of AGN feedback

Understanding the relation between the SMBH spin magnitude and alignment of the galaxy and SMBH spin vectors in merger versus non-merger grown systems is crucial for our understanding of the impact of AGN feedback and therefore of galaxy evolution in its entirety. AGNs in Horizon-AGN are thought to be in one of

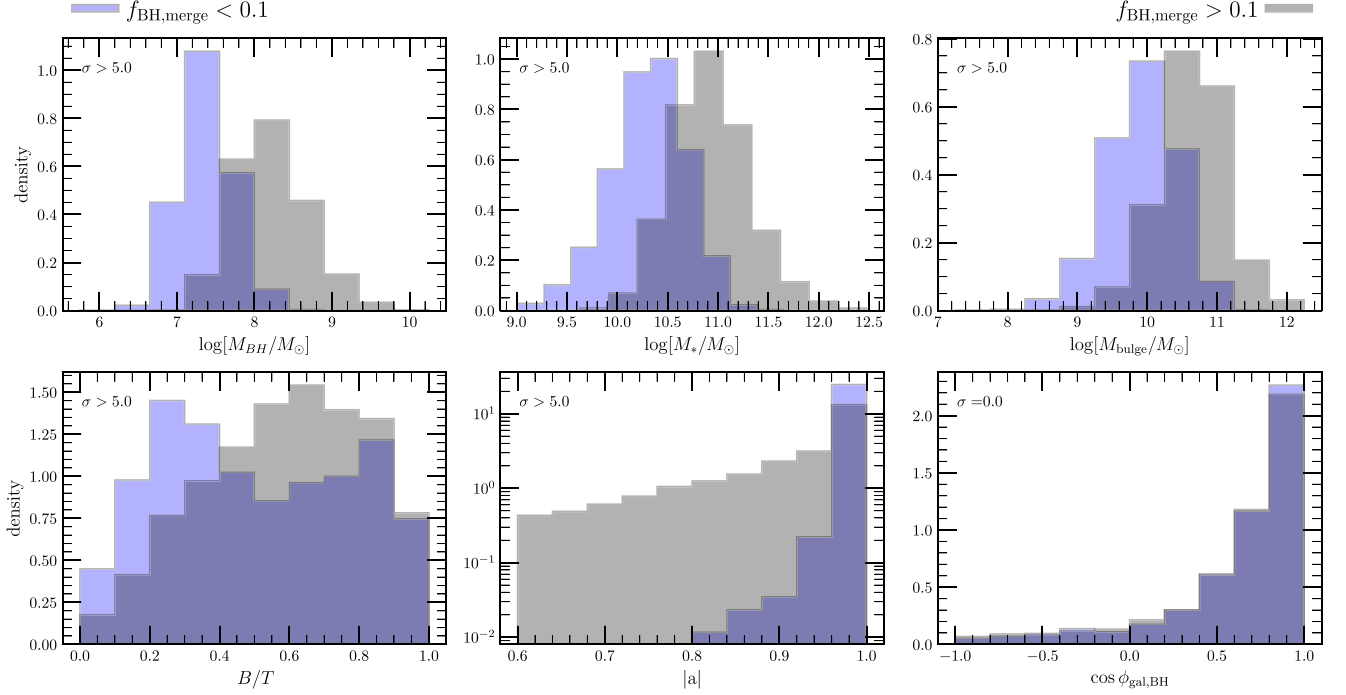


Figure 3. The distribution of properties across the Horizon-AGN sample for galaxies selected to have low SMBH mass fractions grown by mergers, $f_{\text{BH,merge}} < 0.1$ (blue; and therefore accretion dominated SMBH growth), compared to the rest of the sample with $f_{\text{BH,merge}} > 0.1$ (black; i.e. merger and accretion grown SMBHs). Shown are the SMBH masses, M_{BH} ; total stellar masses, M_* ; bulge stellar mass, M_{bulge} ; the bulge-to-total stellar mass ratio B/T ; the spin magnitude of the SMBH, $|a|$; and the angle between the spin of the SMBH and the galaxy, $\cos \phi_{\text{gal,BH}}$. A value of $\cos \phi_{\text{gal,BH}} = 1$ means the SMBH and galaxy spins are aligned, $\cos \phi_{\text{gal,BH}} = 0$ means they are misaligned by 90° , and $\cos \phi_{\text{gal,BH}} = -1$ means they are misaligned by 180° . A value of $|a| = 1$ represents a maximally spinning BH. Systems with SMBH mass fractions grown by mergers, $f_{\text{BH,merge}} < 0.1$, have statistically significantly lower SMBH masses, lower stellar masses, and lower bulge masses. They have a bimodal distribution in bulge-to-total ratio, B/T , which is statistically significantly different to the rest of the population. They also have statistically significantly higher spin magnitudes, yet once again no statistically significant difference in spin alignment. We note that these results hold when incomplete, total stellar mass-matched samples of merger-free and merger-dominated systems are compared.

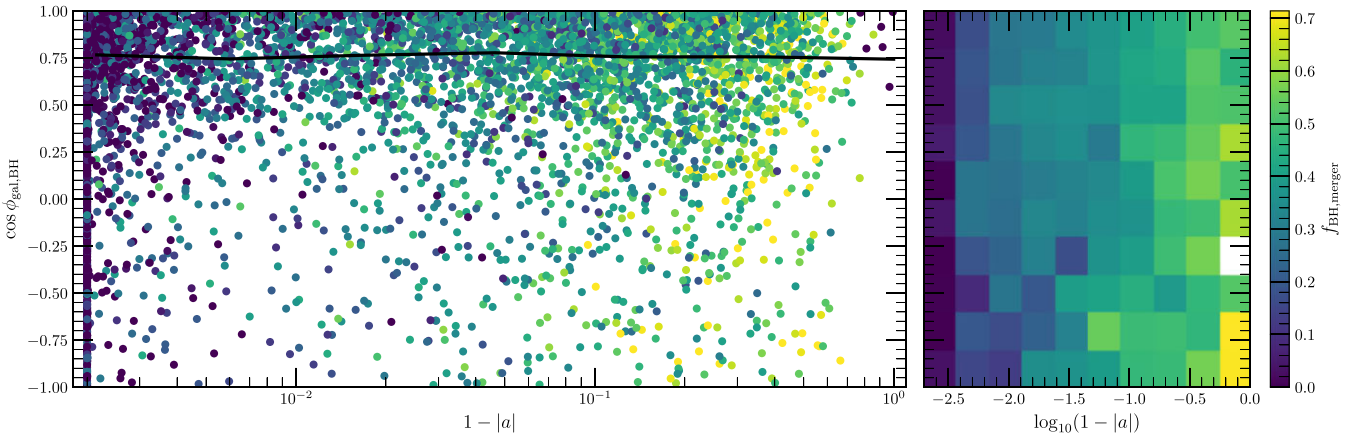


Figure 4. The SMBH spin magnitude, $1 - |a|$, plotted against the angle between the SMBH spin vector and galaxy spin vector, $\cos \phi_{\text{gal,BH}}$, for our entire Horizon-AGN sample. In the left-hand panel, the data are plotted as a scatter plot with the points coloured by the fraction of the SMBH built by mergers, $f_{\text{BH,merge}}$, with the black line showing the change in the average alignment with SMBH spin magnitude. In the right-hand panel, the data are binned and the median $f_{\text{BH,merge}}$ value is shown for each bin. While there appears to be no obvious correlation between SMBH spin and alignment in the left-hand panel, the right-hand panel reveals that the highest $f_{\text{BH,merge}}$ values are found at the lowest spin in the most misaligned systems (either perpendicular to the galaxy spin, or anti-aligned). Note that a low value of $1 - |a|$ corresponds to a maximally spinning SMBH. We show $1 - |a|$ here, as opposed to $|a|$, on a logarithmic scale to better appreciate the range of spins in maximally spinning systems. A value of $\cos \phi_{\text{gal,BH}} = 1$ means the SMBH and galaxy spins are aligned, $\cos \phi_{\text{gal,BH}} = 0$ means they are misaligned by 90° , and $\cos \phi_{\text{gal,BH}} = -1$ means they are anti-aligned by 180° . We note that these results hold when incomplete, total stellar mass matched samples of merger-free and merger-dominated systems are compared.

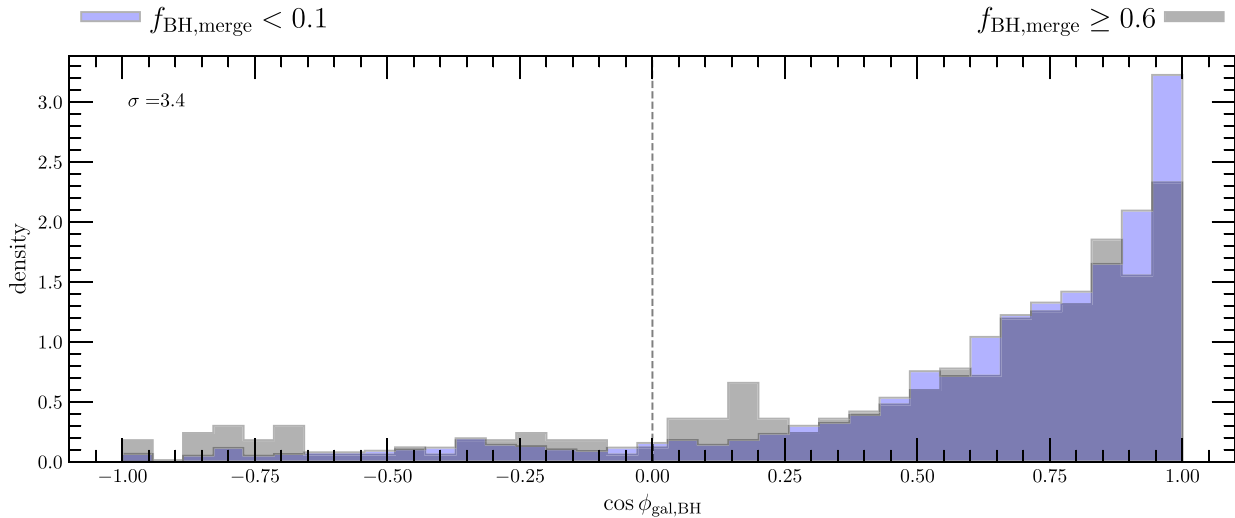


Figure 5. The distribution of the angle between the galaxy and BH spin vector, $\cos \phi_{\text{gal,BH}}$, for galaxies with SMBHs with less than 10 per cent of their mass due to mergers ($f_{\text{BH,merge}} < 0.1$) and with more than 60 per cent of their mass due to mergers ($f_{\text{BH,merge}} \geq 0.6$). These are the two extremes of the population, with distributions that are statistically significantly different (3.4σ). SMBHs dominated by non-merger growth are more likely to be aligned to their galaxy spins than SMBHs dominated by merger growth. A value of $\cos \phi_{\text{gal,BH}} = 1$ means the SMBH and galaxy spins are aligned, $\cos \phi_{\text{gal,BH}} = 0$ means they are misaligned by 90° (marked by the dashed line), and $\cos \phi_{\text{gal,BH}} = -1$ means they are misaligned by 180° .

two feedback modes. Those SMBHs with Eddington ratios, $f_{\text{Edd}} < 1$ per cent are thought to cause a ‘radio/kinetic/jet/maintenance mode’ of AGN feedback, mostly affecting the galaxy halo. Whereas, those SMBHs with Eddington ratios, $f_{\text{Edd}} > 1$ per cent are thought to cause a ‘quasar/thermal/radiative mode’ of AGN feedback, heating the central regions of the galaxy during the peak luminosity of the AGN. In both modes, the radiative efficiency changes as a function of BH spin magnitude, with higher spinning BHs typically converting a larger fraction of their accreted mass into feedback energy. Given that we have shown that galaxy-merger-free grown SMBHs are more likely to have a higher spin, and therefore higher rotational energy, this could have important implications for the AGN feedback efficiency in such systems.

Our results also suggest that such outflows from merger-free systems will be preferentially aligned with the galaxy spin and will therefore be ejected out of the plane of the galaxy if the AGN is in the directional ‘radio/kinetic/jet/maintenance’ mode, rather than the isotropic ‘quasar/thermal/radiative’ mode; such increased feedback efficiency may then only impact both the very centre of the galaxy and the galaxy halo, rather than progressing through the galactic disc. Davé et al. (2019) using the SIMBA simulation found that the ‘radio/kinetic/jet/maintenance mode’ of AGN feedback can drive population-wide galactic quenching from the ‘outside-in’ as it heats the halo and cuts off the gas supply from the galactic halo to the disc. This quenches galaxies even in the absence of the more energetic ‘quasar/thermal/radiative mode’ of AGN feedback which heats the surrounding galactic regions around the SMBH. Similar results on the importance of quenching in the absence of galaxy mergers were reported for IllustrisTNG (Weinberger et al. 2018; Xu et al. 2022) and Horizon-AGN (Dubois et al. 2016; Beckmann et al. 2017; Martin et al. 2018).

This difference in spin direction will only impact where the AGN feedback energy is delivered if the AGN spend a significant fraction of their time in ‘radio/kinetic/jet’ mode. To understand whether this is the case, we investigated the SMBH Eddington ratios in those galaxies with merger-free ($N_{\text{merger}} = 0$) and merger-dominated

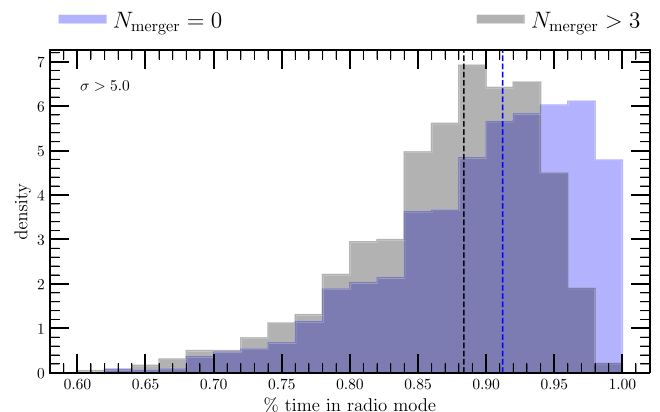


Figure 6. The distribution of the time spent in a radio mode of AGN feedback (i.e. with $f_{\text{Edd}} < 1$ per cent) since $z = 2$ for galaxies with merger-free evolutionary histories ($N_{\text{merger}} = 0$; blue) and those with merger-dominated evolutionary histories ($N_{\text{merger}} > 3$; black). The median value for each distribution is shown by the dashed lines in the corresponding colours. The distributions are statistically significantly different ($>5\sigma$) with merger-free systems more likely to spend a larger proportion of their lifetimes in a radio mode of AGN feedback.

($N_{\text{merger}} > 3$) evolutionary histories. We calculated the fraction of time since $z = 2$ that SMBHs spend in a radio mode of AGN feedback (i.e. with $f_{\text{Edd}} < 10^{-2}$). The distributions for each sample are shown in Fig. 6 along with the median values shown by the dashed lines. The two distributions are statistically significantly different [with $\sigma > 5$ in a Kolmogorov–Smirnov (KS) test], with merger-free galaxies more likely to spend a higher proportion of their evolutionary histories in a radio mode of AGN feedback. Despite this, the averages for both samples remain high: SMBHs in merger-free galaxies spend, on average, 91 per cent of their lifetime in radio mode AGN feedback, while the sample in merger-dominated galaxies spends on average, 88 per cent of their lifetime in radio mode AGN feedback. While in radio mode, AGN drive powerful jets (here defined as $10^{-4} <$

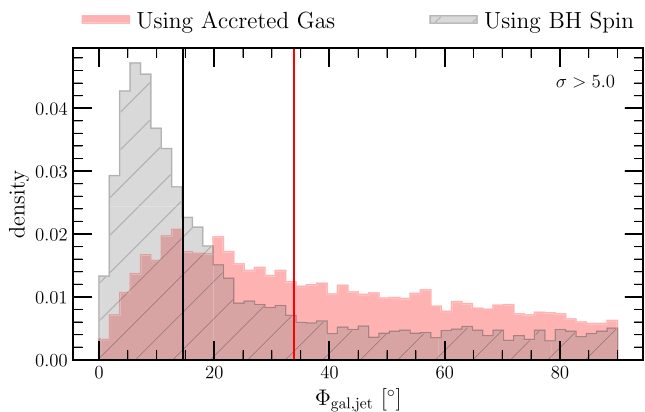


Figure 7. Distribution of $\Phi_{\text{gal, jet}}$, the angle between the jet and the galactic angular momentum, for two jet models: a gas-based model where jets are injected along the angular momentum axis of gas accreted during the last accretion event (red solid) and a spin-based model where jets are injected along the spin axis of the SMBH (grey hatched). Median values for each distribution are shown by the solid lines of corresponding colours. As it disregards the inherent angular momentum of a spinning SMBH, the gas-based model (red solid) shows a higher degree of scatter and less long-term alignment between SMBH jets and galactic angular momentum than the spin-based model (grey hatched).

$f_{\text{edd}} < 10^{-2}$) for a significant fraction of their time: 64 per cent for SMBHs in merger-free galaxies and 59 per cent for SMBHs in merger-dominated galaxies. This similarity does not strongly depend on the exact threshold value of f_{edd} chosen when transitioning from jet to quasar mode, with merger-free galaxies continuing to spend ~ 5 per cent more time in jet mode than merger-dominated galaxies for over an order of magnitude in difference in transition threshold. This means that for a non-negligible fraction of their evolution, AGN feedback energy for merger-free galaxies is injected with a higher efficiency at a given accretion rate than for merger-grown SMBH due to the higher spin of SMBH in merger-free galaxies. This could potentially enhance the importance of radio-mode quenching (as advocated by Weinberger et al. 2018; Davé et al. 2019) in merger-free galaxies, and compensate for the short-lived luminosity bursts of AGN post-galaxy merger (McAlpine et al. 2011; Volonteri et al. 2016), which can lead to the effective quenching of the merger remnant (Dubois et al. 2016). In addition, the similarity between the average time spent in a radio-mode feedback for the merger-free and merger-dominated samples again suggests that in the long epochs between galaxy mergers, merger-free accretion dominates the growth of SMBHs even in galaxy merger-rich systems and possibly makes an important contribution to their long-term co-evolution.

4.3 Post-processed versus on-the-fly SMBH spin evolution

One limitation of the work shown here is that the spin-evolution is post-processed from the BH mass evolution history, rather than self-consistently run on the fly. If the BH spin model had been run on the fly, AGN feedback in the simulation would have differed in the following two ways:

(i) First, AGN jets would realign more slowly and coherently, as the BH spin vector is computed as an integrated quantity while the local gas angular momentum is an instantaneous quantity. This can be seen in Fig. 7, which shows the angle between the galactic angular momentum and the jet for two cases: when using the instantaneous SMBH spin (spin-based model, post-processed), and

using the angular momentum of the accreted gas for any given accretion and subsequent feedback event (gas-based model, which was used as the simulation was run). The gas-based model leads to less alignment between jets and the galactic angular momentum than the spin-based model. For disc galaxies, this would mean more jet energy is deposited directly into the circumgalactic medium in a spin-based than in a gas-based jet model. The difference in alignment between gas-based and spin-based models arises because in a spin-based model, the inherent angular momentum of the SMBH stabilizes the jets against sudden realignment, while the direction of the central accreted angular momentum can be quite stochastic even for a well-ordered disc galaxy. Based on this insight, we would expect an on-the-fly spin-based model to drive jets into the circumgalactic more often than the current gas-based model, which would lead to a more indirect impact on galactic star formation, by cutting off large-scale gas flows, rather than direct quenching of star formation in galaxies.

(ii) Secondly, if SMBH spin were taken into account in BH's radiative luminosity ϵ_r , a given SMBH might produce anywhere from 0.3 to ~ 4 times the feedback energy at the same accretion rate in comparison to a fixed ϵ_r . This would both change how much feedback energy the galaxy is receiving, and how fast the SMBH is growing (as the SMBH gains mass at a rate of $1 - \epsilon_r$). For the model used here, feedback efficiency peaks for maximally spinning SMBH at a value of about 4 times the fixed $\epsilon_r = 0.1$ used to run the simulation, so we would expect secularly grown SMBHs to grow more slowly than those in merger-driven galaxies. This could reduce some of the effects of SMBHs in merger-free galaxies being overmassive in comparison to their host galaxy reported in the companion paper (Smethurst et al. 2023), or delay (but not prevent) the efficient spin-up of SMBHs in merger-free galaxies shown here in Fig. 3. The exact impact is hard to predict as SMBHs undergo self-regulation: strong feedback episodes reduce accretion on to the SMBHs in the short term, but in long term the balance between gas inflows and SMBH feedback might simply settle at a new equilibrium that produces a population of SMBHs with ultimately similar properties. How exactly a full on-the-fly model will differ from post-processing will have to be tested using a follow-up simulation.

4.4 Follow-up observational work

Given the predictions of our simulations presented here which suggest that the spin magnitude and orientation of galaxy-merger-free SMBHs are indeed different from the wider galaxy population and that this may lead to increased AGN feedback efficiency, high-resolution observational studies are therefore essential to test these predictions. First, a study to test the alignment of AGN outflows with respect to their galactic discs in merger-free galaxies. For example, using narrow-band filters centred on [O III] ionization with the high-spatial resolution provided by the *Hubble Space Telescope* to probe the alignment of AGN outflows. While previous studies have found no alignment between outflows and the galaxy minor axis (i.e. an alignment of SMBH spin and galaxy spin; see Kinney et al. 2000; Schmitt et al. 2003; Ruschel-Dutra et al. 2021), such studies were of samples with mixed morphologies and therefore mixed evolutionary histories. By isolating merger-free systems, e.g. by observationally selecting bulgeless galaxies, and studying the orientation of their outflows we can observationally test the hypotheses discussed here.

Secondly, an observational study on the subsequent impact of the outflow on the galaxy star formation rate is required. A high spatial and spectral resolution integral field unit, such as MUSE or VIRUS, will be able to spatially resolve the areas of disc-dominated merger-free galaxies impacted by AGN outflows and spectrally separate

the emission ionized by star formation and the outflow. Such a study would allow us to observationally test the assertions of Davé et al. (2019) and the hypothesis discussed here: whether merger-free powered radio mode AGN feedback could indeed be the cause of galaxy population wide quenching.

Smethurst et al. (2021) found that their observational sample of four ‘bulgeless’ (assumed merger-free) AGN with outflows, had outflow rates, energy injection rates and momentum fluxes that were comparable to a sample of low- z Type 1 AGN from Rakshit & Woo (2018, within the scatter). Smethurst et al. (2021) suggested that this result implied that it is possible that the majority of low-redshift AGNs (both SMBH growth and outflows) are powered by non-merger processes. Given our results above, this suggests that the majority of this low- z AGN feedback will occur via a radio mode. If future observational studies reveal that this feedback is capable of causing galaxy quenching, this could explain why a correlation is still observed between e.g. total stellar mass and SMBH mass for merger-free systems (see Simmons et al. 2013; Simmons et al. 2017 and companion paper Smethurst et al. 2023); co-evolution regulated by radio mode AGN feedback is occurring due to secular processes.

5 CONCLUSIONS

We have investigated the SMBH spin magnitude and spin alignment in the context of the spin of their host galaxy for merger-free and merger-dominated galaxies using the Horizon-AGN simulation. Our conclusions are summarized as follows:

(i) Galaxies that have evolved in the absence of mergers host SMBHs with preferentially higher spin magnitudes than those with merger-dominated evolutionary histories. This is true for both SMBH mergers and galaxy mergers and supports the hypothesis of Smethurst et al. (2019), building on the work of Nayakshin et al. (2012).

(ii) SMBHs with low-mass fractions built by BH mergers ($f_{\text{BH,merge}} < 0.1$), as well as galaxies with few galaxy mergers, have a bi-modal distribution of bulge-to-total ratios (see Figs 3 and 2) suggesting that galaxies which have grown their SMBHs in the absence of mergers can still have significant stellar bulges, in agreement with Parry et al. (2009). This leads to secular co-evolution of both bulges and SMBHs.

(iii) At first glance, SMBHs in galaxies with and without mergers have a very similar distribution of the angle between the spin vectors of the SMBH and their galaxy, $\phi_{\text{BH,gal}}$ and show similar scatter in $\phi_{\text{BH,gal}}$ (see Fig. 4). It is only when probing the extremes of the population that it becomes apparent that the distribution of $\phi_{\text{BH,gal}}$ are statistically significantly different (3.4σ) for SMBH dominated ($f_{\text{BH,merge}} > 0.6$) or not ($f_{\text{BH,merge}} < 0.1$) by BH mergers. This once again suggests that secular processes drive the evolution of SMBHs in the epochs between galaxy mergers, which for most objects dominates their overall evolution.

(iv) Given that previous observational and theoretical works have also concluded that galaxy merger-free processes dominate SMBH-galaxy co-evolution, this suggests secular processes power the majority of the subsequent AGN feedback. We investigated the Eddington ratios of galaxies with merger-free and merger-dominated evolutionary histories, determining the time spent in a radio mode of AGN feedback (i.e. $f_{\text{Edd}} < 1$ per cent; see Fig. 6). We found that merger-free systems spend 91 per cent of their evolutionary history in a radio mode, similar to merger-dominated systems which spend 88 per cent of their time in radio mode, suggesting that the majority

of AGN feedback occurs in this mode, in agreement with the findings from the SIMBA simulation (Davé et al. 2019). Given that we find that galaxy merger-dominated systems spend a similar average time in a radio mode, this once again suggests that in the epochs between galaxy mergers, merger-free accretion dominates the growth of their SMBHs. If future observational studies reveal that this feedback is capable of causing galaxy quenching, this then suggests that the correlations between, e.g. total stellar mass and SMBH mass, seen for samples of merger-free galaxies (Simmons et al. 2013; Simmons et al. 2017; Smethurst et al. 2023) is caused in part by secularly driven co-evolution regulated by radio mode AGN feedback.

High-resolution observational studies on the impact of AGN outflows and alignment with respect to their galactic discs in a pure sample of merger-free galaxies (e.g. disc-dominated galaxies) is therefore essential to both test these hypotheses of secularly powered AGN feedback which seems to dominate galaxy-SMBH co-evolution.

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First authorship is shared between RSB and RJS. RSB assembled simulation data catalogues, interpreted results and wrote the manuscript. RJS conceived of the project, analysed data, interpreted results and wrote the manuscript.

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DATA AVAILABILITY

All data used in this paper is available upon request to the first authors.

⁵<http://www.astropy.org>

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