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DUAL ACTIVE GALACTIC NUCLEI WITHIN ROMULUS25

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A Thesis submitted in fulfilment of requirements for
the degree of Master of Science in Physics

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Contents

Declaration	ii
Acknowledgments	iii
List of Figures	iv
Abstract	1
1 Introduction	2
2 Background Theory	5
3 Romulus25 Simulation & Post-Processing Models	11
4 Results	20
4.1 Merging vs Non Merging DAGN	20
4.2 Galaxy Merger Created DAGNs	34
4.3 Duty Cycles	39
4.4 Merger Timing	45
5 Discussion	49
6 Conclusions	58
7 Appendix	69

Declaration

This is to certify that the work I am submitting is my own and has not been submitted for another degree, either at University College Cork or elsewhere. All external references and sources are clearly acknowledged and identified within the contents. I have read and understood the regulations of University College Cork concerning plagiarism and intellectual property.

Signed: Ben Sheehan

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List of Figures

1	Seed mass constraints from quasars	6
2	Universal BHAR/SFR	10
3	Fraction of DAGNs that merge	21
4	Merger & DAGN rate comparison	22
5	Implications for LISA	23
6	Masses of DAGN hosts	25
7	Masses of DAGNs	28
8	Mass distribution of brighter vs dimmer SMBH in DAGNs	29
9	Eddington fraction comparison for populations	31
10	BHAR/SFR comparison between DAGN and AGN population	35
11	Luminosity comparison between DAGN and AGN population	37
12	sSFR & SFR comparison between DAGN and whole population	38
13	Duty cycle of DAGNs by stellar mass	39
14	Duty cycle of DAGNs by separation	41
15	Relative separation of DAGNs	42
16	DAGN galaxy merger timescales	45
17	DAGN coalescence timescales	47
18	Redshift prevalence of different DAGN formation channels	49
19	Initial separation for in-situ DAGN population	50
20	Case study of in-situ DAGN	53
21	Coalescence timescales for galaxy merger created DAGNs	55
22	Merger & DAGN rate comparison of merger created DAGNs	56
23	DAGN galaxy merger timescales for projected separations	69
24	DAGN coalescence timescales for projected separations	70

Abstract

Dual active galactic nuclei (DAGN) trace the growth of supermassive black holes (SMBHs) during galaxy interactions, while also being an important electromagnetic precursor of SMBH merger which are important for missions such as LISA. In this thesis, we aim to study the properties of DAGN within the Romulus25 simulation, which combines sub-kpc resolution with physically motivated prescriptions for SMBH seed, dynamics, and accretion. We find that many observed DAGNs may merge prior to a Hubble time, making them incredibly important to the LISA mission. DAGNs preferentially occupy the most massive galaxies at all redshifts and are comprised of mostly low mass ratio SMBH pairs. We also investigate if DAGN activity is a good tracer of galaxy merger enhanced star formation or black hole accretion, and find that they only serve as a tracer at redshift greater than 3. We further find DAGNs in massive galaxies display a universal distribution of duty cycles regardless of the epoch which the DAGN underwent its active phase, and that the subpopulation of DAGNs that merge prior to a Hubble time tend to inhabit the larger end of this duty cycle distribution. Important for informing current DAGN observations, we provide estimates on the time since galaxy merger and time until SMBH merger for DAGNs, and find that on average most observed systems are rarely in post-merger galaxies and are > 1 Gyr away from their SMBHs merging. We also identify a novel in-situ formation channel for DAGNs that does not require any galaxy merger, which is afforded to the Romulus25 simulation due to its unique SMBH seeding prescription, and quantify how much this channel effects the results. These results provide insights into many fronts of research into DAGNs, including providing insights into the temporal connection between DAGN activity and the galaxy mergers that formed them and the SMBH mergers they may undergo, whilst also guiding future multi-messenger astrophysics missions which focus on DAGNs, and providing a general overview on the demographics and origins of DAGNs.

1 Introduction

Given the hierarchical structure of the Universe, and that SMBHs have been detected in nearly all massive galaxies and many smaller galaxies in the local Universe ([Kormendy & Richstone, 1995](#); [Gallo et al., 2008](#); [Kormendy & Ho, 2013](#); [Miller et al., 2015](#); [Reines & Volonteri, 2015](#); [Baldassare et al., 2018](#)), it is only natural to expect a population of galaxies hosting multiple SMBHs that are on their way to coalescence. During this path from galaxy merger to SMBH merger, a SMBH pair must undergo multiple complex processes which dictate their dynamics ([Begelman et al., 1980](#); [Colpi, 2014](#)). On scales greater than a parsec, dynamical friction robs the angular momentum of the SMBH pair removing some of its orbital energy, creating a gravitationally bound binary. Below about 10 parsecs, dynamical friction becomes inefficient at removing energy from the SMBH binary and instead stars on radial plunging orbits govern the hardening of the binary by passing close enough to the binary to extract orbital energy and be slingshotted away ([Hills & Fullerton, 1980](#)). Finally, on milliparsec scales, gravitational wave emission continues to reduce the orbital energy of the binary down to the point of their coalescence ([Peters & Mathews, 1963](#); [Zwick et al., 2020, 2021](#)). These processes add a large time delay between galaxy mergers and the inevitable subsequent merger of their individual SMBHs, where two or more SMBHs share a galaxy. During this time a SMBH pair may undergo simultaneous bouts of high accretion creating a close luminous pair of active galactic nuclei (AGNs) known as a DAGN. These DAGNs are clearly phenomena of high interest, due to their connection with both galaxy mergers and SMBH binary formation ([Comerford et al., 2009](#); [Volonteri et al., 2022](#)).

There have been many observations of DAGN systems. They have been detected in many electromagnetic bands using the Sloan Digital Sky Survey (SDSS; [Barrows et al., 2013](#)), the Hubble Space Telescope (HST; [Huang et al., 2014](#); [Stemo et al., 2020](#); [Chen et al., 2022](#)), and the James Webb Space Telescope (JWST; [Li et al., 2025](#); [Perna et al., 2025](#)). Additionally there has been detections made in the radio wavelengths ([Owen et al., 1985](#); [Rubinur et al., 2019](#); [Veres et al., 2021](#)), and in the X-ray ([Comerford et al., 2011](#)). Many of these observations are biased to high-separations systems (typically

$> 10\text{kpc}$), but recently the GAIA space observatory has been able to reduce this bias by allowing for new detection methods and utilizing its tight point spread function, thereby finding DAGNs with sub-arcsecond separation. One such detection method is known as Varstrometry ([Hwang et al., 2020](#)), where Gaia detects the shifting of a photocentre of an unresolved DAGN induced by stochastic variability in the luminosities of the pair. This method can detect DAGNs that have large variations in their luminosity at separations of tens of milliarcseconds. Another technique is known as the Multi-Peak method ([Mannucci et al., 2022](#)). This method searches for secondary fainter peaks in the $0.71'' \times 2.1''$ Gaia photometric window situated around known AGNs, and is optimised for finding DAGNs with separations in the range of $\sim 0.1'' - 0.7''$. Both novel techniques only provide DAGN candidates and require follow up spectroscopic validation or other methods to confirm their nature. The future launch of AXIS will also greatly reduce biases in the population as it is expected to vastly expand the number of known DAGN systems over the course of its mission ([Foord et al., 2024](#)). Overall, problems exist in there not being a statistically significant population of known DAGN systems but much is being done to address this.

Due to the expanding population of known DAGN systems, there is a growing need for studies on their theoretical counterparts to complement these observations. Much of the previous theoretical work has focused on the occurrence rate of DAGNs in large-volume cosmological simulations ([Rosas-Guevara et al., 2019](#); [Puerto-Sánchez et al., 2025](#)) or individual DAGNs in simulations of a single galaxy merger ([Van Wassenhove et al., 2012](#); [Capelo et al., 2017](#)). Only few works have provided statistically significant analysis on a simulated DAGN population and how they link to their galaxy and potential SMBH merger ([Volonteri et al., 2022](#); [Chen et al., 2023](#); [Saeedzadeh et al., 2024b](#)). We aim to add to these works in this thesis by investigating the connection between DAGNs, the galaxy merger that made them, and the SMBH merger they (sometimes) undergo within the Romulus25 simulation. This thesis is laid out as follows: §2 covers theoretical background on SMBHs, while §3 goes over the Romulus25 simulation, some of the post-processing models used in this work, and how we identify DAGNs in the simulation. §4.1 looks at the subpopulation of DAGN systems which

merge prior to a Hubble time. §4.2 investigates the galaxy mergers that form DAGNs and searches for signs of galaxy merger enhanced accretion and star formation as traced by DAGNs. §4.3 looks at the duty cycles of DAGN systems, and §4.4 provides an overview on the timescale of DAGNs at different evolutionary stages. Finally §5 and §6 discusses and concludes the results respectively.

2 Background Theory

Supermassive Black Holes

A black hole is an object that has collapsed into a singularity of infinite density (Schwarzschild, 1916; Kerr, 1963). One flavour in which these black holes come are known as SMBHs, which have masses greater than $10^6 M_{\odot}$, and typically residing in the centres of galaxies. Their gravitational influence dominates their vicinity influencing the motion of nearby gas and stars. Their growth via accretion releases vast amounts of energy, giving rise to some of the most luminous objects in the Universe. The first evidence of SMBHs came in the form of quasars, incredible bright and distant objects whose spectra could only be explained by a massive compact object accreting the interstellar medium (Salpeter, 1964). Further research would show that SMBHs exist in nearly all massive galaxies and many smaller galaxies (Kormendy & Richstone, 1995; Gallo et al., 2008; Kormendy & Ho, 2013; Miller et al., 2015; Reines & Volonteri, 2015; Baldassare et al., 2018). Although being simple and well understood when in isolation, their position as central engines of galaxies makes these objects play a pivotal role in the physics of star formation, galactic scale outflows, and lifetime evolution of galaxies. Therefore understanding their birth, growth, and interplay with their host galaxy is a fundamental challenge of extragalactic astrophysics.

Seeding

The formation of stellar mass black holes is a well understood phenomena, either a massive star near instantaneously collapses into a black hole or a supernova explosion occurs which fails to fully unbind the stellar envelope around a proto-neutron star and is then reaccreted onto it to form a black hole after a short time delay (Mirabel, 2017). One might think that SMBHs are just overgrown stellar mass black holes that have managed to grow by many orders of magnitude in a short period of time. However, even the earliest theorised stellar mass black holes growing constantly at their Eddington limits, or their theoretical maximum accretion limit, would fail to explain the masses of the earliest quasars and JWST discovered AGNs (see Figure 1). Therefore three

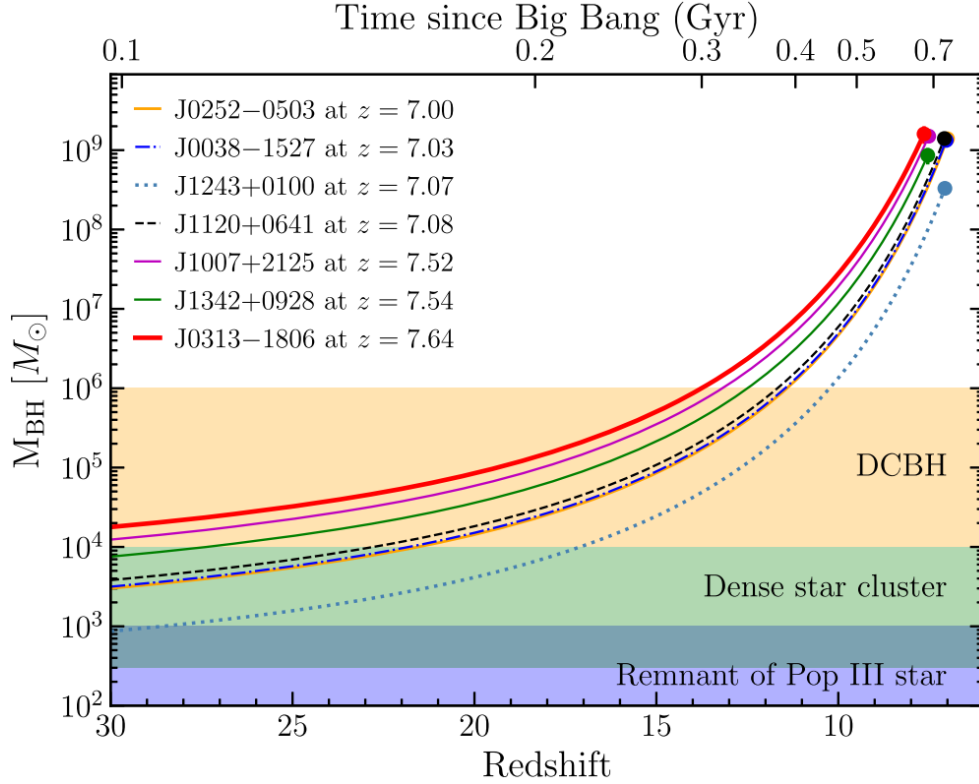


Figure 1: Seed mass constraints from quasars. Points show the inferred mass of quasars at high z , and curved lines show the evolution of the mass if the quasars accreted at their Eddington limit (i.e. show the lower limit of mass as a function of redshift). Stellar mass black holes fail to explain the masses of high- z SMBHs. Figure reprinted from [Wang et al. \(2021\)](#).

seeding formation channels have been proposed in the past which give SMBH seed a head start in their masses.

The first of these formation channels produce "light seeds" which are remnants of population III stars which act as progenitors of SMBHs. These are expected to be black hole seeds in the mass range of $10^1 - 10^3 M_\odot$ that form at $z = 20-30$. These seeds form in pristine gas minihaloes of mass $10^6 M_\odot$ that cool mainly via molecular cooling, with the lack of metals preventing fragmentation and the collapsing of small gas clouds and allowing population III stars to form with large masses ([Bromm, 2013](#)). These population III stars are not completely exotic. Work in recent years has discovered HeII clumps around the GN-z11 galaxy whose ionization can be explained by the present of population III stars in the galaxy, and not by any AGN ionization ([Maiolino](#)

et al., 2024a). In addition there has been a lensed detection of a population III star candidate at $z = 6.6$ (Vanzella et al., 2023). One major problem with the light seed scenario is that to grow to SMBH sizes they are expected to grow in short, intermittent phases of super-Eddington accretion (Pezzulli et al., 2016, 2017), but their environment in low-density, ionized gas may be unfit for such growth (Mayer & Bonoli, 2019), requiring highly idealised, weak feedback models (Gordon et al., 2025).

Another seed formation channel is the runaway collapse of nuclear stellar clusters. These are extremely dense stellar systems that reside in the centre of most low-mass galaxies in the local Universe (Sánchez-Janssen et al., 2019). In these stellar clusters, mass segregation can rapidly sink the massive stars towards the centre where they merge. If dense enough, these can merge on a timescale shorter than the lifetime of a supermassive star (Portegies Zwart et al., 1999; Portegies Zwart & McMillan, 2002; Gürkan et al., 2004), and thus create one that eventually collapses into a intermediate mass black hole ($10^2 - 10^4 M_\odot$). This process is highly dependant on the formation history of the cluster and its binary fraction (Rantala & Naab, 2025; Rantala et al., 2025). This scenario is particularly attractive as it relies on a well understood physical process, and JWST observations are suggesting large amounts of high- z stellar formation in stellar cluster that are much denser than their local Universe counterparts (Adamo et al., 2024). This scenario has in the past been invoked to explain the strange nitrogen to oxygen abundance in high- z galaxies (Cameron et al., 2023).

The final seed formation channel produces "heavy seeds" and is known as the direct collapse black hole scenario (Bromm & Loeb, 2003; Begelman et al., 2006). This process involves dense, pristine regions of gas avoiding efficient cooling and fragmentation which would lead to star formation and instead collapse via atomic cooling in near monolithic fashion into a supermassive star that then directly collapses into a SMBH of mass $10^4 - 10^6 M_\odot$. There are a number of different processes that can prevent star formation until the conditions for direct collapse are achieved. These processes being:

- High baryonic streaming velocities where local differences in the relative velocity of dark matter and baryons suppresses star formation in

lower mass halos (Naoz et al., 2012; Latif et al., 2014a; Schauer et al., 2017).

- Rapid assembly heating the gas and preventing cooling (Fernandez et al., 2014; Wise et al., 2019). A special category of this being the merger of massive gaseous disks causing instabilities in said disk. This instability generates supermassive disks which rapidly undergoes a general relativistic collapse instability and forms a SMBH seed skipping the supermassive star phase (Zwick et al., 2023; Mayer et al., 2024).
- Local sources of intense Lyman-Werner radiation disassociating H_2 and cutting off a critical and efficient cooling path for star formation (Latif et al., 2014b; Regan et al., 2017).

Evidence of SMBH

Whilst quasars hinted towards the existence of SMBHs, the first direct evidence of SMBHs came from the dynamical measurement of stars in the Milky Way's galactic nucleus. Tracing the orbits of stars in the centre of the Galaxy over decades revealed they moved at 1000s of kilometres per second about a hidden object of mass $\sim 4.3 \times 10^6 M_\odot$ whose radius was on the order of a solar system. This hidden object also coincides with a small point like radio source and also a region with observed X-ray flares. All this evidence pointed to the hidden object being a SMBH (Ghez et al., 1998; Gillessen et al., 2009; Genzel et al., 2010). Direct imaging of this very same region and the central region of M87 using 1.3 mm very-long-baseline interferometry would further solidify the existence of SMBHs (Event Horizon Telescope Collaboration et al., 2019, 2022). For more distant SMBHs, they can be identified using the broadening of maser emission at parsec scales away from the SMBH, or of gas emission in the broad line region on $\sim$ milliparsec scale away from the SMBH. These are caused by the high velocities of matter around the SMBH Doppler shifting their emissions. These methods also have the added benefit of being able to measure the velocity of matter around a SMBH. This velocity can be used in conjunction with reverberation mapping, which estimates the size of the broad line region by measuring the time delay between light

emitted very close to the SMBH and the absorption and re-emission of the light by the broad line region, to estimate the mass of the SMBH using the virial theorem. When the accretion onto a SMBH is great, it can turn into a AGN, whose luminosity can outshine its host's entire stellar component. The advent of JWST has allowed observations of AGN to higher redshifts than ever before (Harikane et al., 2023; Übler et al., 2023; Larson et al., 2023; Kokorev et al., 2023; Bogdán et al., 2024; Wang et al., 2024). Most of these high- z AGN are inferred to be already extremely massive in the first billion years of the Universe, and reside in galaxies which are far different from local dwarfs, making them overmassive (Pacucci et al., 2023; Maiolino et al., 2024b). Not only does evidence come via the electromagnetic observations, but gravitational waves provide a complementary window to detect SMBHs just prior to their coalescence with another. Pulsar timing arrays (PTA) have hinted at a detected the gravitational-wave background that is consistent with a population of inspiralling SMBH pairs with masses $> 10^8 M_\odot$ (Agazie et al., 2023; EPTA Collaboration et al., 2023). And the future LISA mission will be able to detect inspiralling SMBH in the mass range of $\sim 10^4 - 10^7 M_\odot$ (eLISA Consortium et al., 2013; Amaro-Seoane et al., 2023).

Co-evolution with Galaxies

The observed correlations between SMBH masses and host galaxy properties provides strong evidence that SMBHs and galaxies are tied together in their evolution. One of the most prominent relationships is the $M_{BH} - \sigma$ (Kormendy & Ho, 2013), which link the mass of a central SMBH to the stellar velocity dispersion of the galactic bulge. Similar trends exist between the SMBH mass and the bulge mass and bulge luminosity (Häring & Rix, 2004; Gültekin et al., 2009; Schramm & Silverman, 2013). Other relations exist as well such as the SMBH-mass stellar-mass relation (Reines & Volonteri, 2015) and even some tentative evidence of a universal SMBH-mass virial-mass relation which is capable of explaining some of the break downs of the previously mentioned relationships being observed at high redshifts (McClymont et al., 2025). In addition to SMBH-galaxy relations, the cosmic SMBH accretion rate density closely follows the cosmic star formation rate density, see Figure 2, with star formation density being ~ 1250 times greater than SMBH accretion density

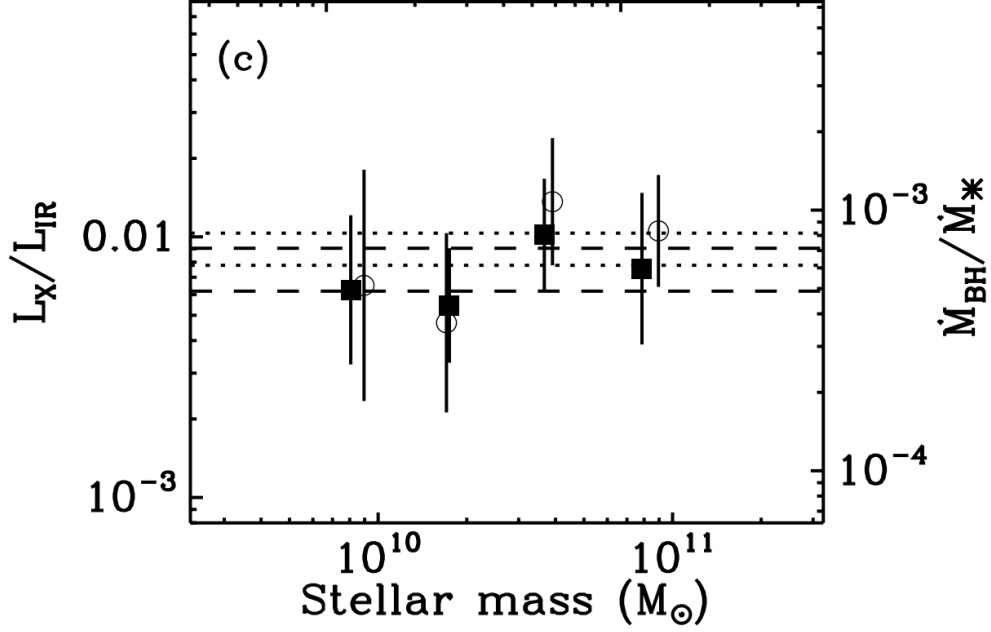


Figure 2: Ratio of SMBH accretion to star formation as probed by the ratio of X-ray to infrared light, for galaxies of different stellar masses. Circles (squares) represent SMBH and galaxies at $z = 1$ ($z = 2$). Dotted (dashed) lines represent the 1σ uncertainty in the ratio at $z = 1$ ($z = 2$). SMBH accretion is coupled to star formation at both redshift and in fact is coupled at higher redshifts too. Figure reprinted from [Mullaney et al. \(2012\)](#).

at all redshifts ([Shankar et al., 2009](#)). One key factor thought to drive this co-evolution is the common gas supply which fuels both star formation and SMBH growth. As gas collapses onto the central SMBH and gets accreted, a commensurate numbers of stars form in the host galaxy due to cold, dense gas being the driver of both processes, sustaining the above mentioned relations. Therefore any process that affects the gas, such as disk instabilities, mergers, feedback from AGN and supernovae, impacts both accretion and star formation in a proportionate amount.

3 Romulus25 Simulation & Post-Processing Models

Romulus25, described in detail in [Tremmel et al. \(2017\)](#), is a $(25 \text{ Mpc})^3$, high-resolution cosmological simulation, run using the N-body and smoothed particle hydrodynamics code ChaNGa ([Menon et al., 2015](#)). It is a uniform volume simulation that contains a uniform sample of 1000s of galaxies with stellar masses between 10^7 and $10^{11} M_{\odot}$. Romulus25 assumes Λ CDM cosmology with the cosmological parameters of $\Omega_0 = 0.3086$, $\Lambda = 0.6914$, $h = 0.6777$, $\sigma_8 = 0.8288$ ([Planck Collaboration et al., 2016](#)). Romulus25 includes various physics modules including cosmic UV background ([Haardt & Madau, 2012](#)), "Blastwave" supernova feedback ([Stinson et al., 2006](#)), and low temperature metal cooling ([Bromm et al., 2001](#)), and others which we go over in detail next.

Gravity

Gravity in the simulation is based on the Barnes-Hut algorithm ([Barnes & Hut, 1986](#)). At every timestep, the entire box containing all particles is split into 8 equally spaced cells, and then each of those cells is divided again into 8 further child cells with half the size of their parents cells if the parent cell contains more than one particle. This process of further refining each cell is continued until all lowest level child cells, also known as leaf cells, contain 0 or 1 particle. This process generates a octree structure, where every node contains 8 internal cells, with the top node representing the whole space and the end nodes containing 8 internal cells which each contain 0 or 1 particles, hence the name leaf cells as they resemble leafs on the end of a tree branch. Instead of calculating the effect of gravity on particle "i" by all other particles, also known as direct summation which is highly inefficient, the octree is used to identify which particles are close to particle "i", and should be treated as single particles, or far from particle "i", and should therefore be grouped with other particles in its vicinity and be treated as one large far-field particle. This is done by traversing up the octree from the leaf cell containing particle "i" and checking the opening angle criteria on every internal cell of every node that contains particle "i". The opening angle criteria being defined as s/d where s is the width of the internal cell being queried and d is the distance between

the particle "i" and the centre of the internal cell. If this opening angle criteria for an internal cell is greater than some user defined input (i.e. internal cell is large and close to particle "i"), then all child cells of this internal cell have their opening angle criteria evaluated and traversed down if its greater than the user defined input. All cells which have opening angle criteria smaller than some user defined input are marked for the gravitational calculation of particle "i". The force of gravity on particle "i" is then calculated from all marked cells, using multipole expansion to hexadecapole order to capture the mass distribution within the internal cell. The monopole moment in this multipole expansion has its mass term softened using a cubic spline kernel (ϵ_g ; Monaghan & Lattanzio (1985)) of length 350 pc such that:

$$M_{\text{mono}} = \sum_j m_j \cdot W(|\mathbf{r}_i - \mathbf{r}_j|, \epsilon_g) \quad (1)$$

where M_{mono} is the mass used in the monopole moment for the marked internal cell, m_j is the mass of a particle "j" in the marked internal cell, $\mathbf{r}_i$ and $\mathbf{r}_j$ are the positions of particle "i" and "j", and $W(x, \epsilon_g)$ is the cubic spline kernel which is 0 for $x = 0$ and slowly transitions to 1 at $x = 2\epsilon_g$. This limits the magnitude of low separation inter-particle forces which reduces artificial two-body relaxation and avoids tiny time stepping. This Barnes-Hut algorithm is used in conjunction with the leapfrog integration technique (Quinn et al., 1997) to calculate the new velocities and positions of particles at every timestep. This processes ultimately results in a $O(N \log(N))$ gravitational force calculation, where the force caused by particles with separations closer than $2\epsilon_g$ are softened, while forces from particles further a field converge to the Newtonian solution.

Star Formation

Star formation can be undertaken by any gas particle in the simulation once it is cold and dense enough. Once a gas particle has a temperature of $< 10^4$ K, temperature which allows molecular hydrogen to form and therefore efficient cooling to occur via rotational transitions, and density of $> 0.2 \text{ m}_p \text{ cm}^{-3}$, star formation proceeds stochastically. Extrapolating the Kennicutt-Schmidt

law (Schmidt, 1959; Kennicutt, 1998), which connects the stellar formation surface density to the gas surface density via a power law, to three dimensions and using the facts that stars form from gas alone (i.e. $dM_* = -dM_{gas}$) yields:

$$\frac{dM_{gas}}{dt} = -c_* \frac{M_{gas}}{t_{dyn}}$$

where M_* and M_{gas} is the stellar and gas mass respectively, c_* is stellar formation efficiency, and t_{dyn} is the local dynamical time of the gas. Solving this ordinary differential equation gives:

$$M_* = M_{gas}(0) - M_{gas}(\Delta t) = M_{gas}(0)(1 - e^{-c_* \frac{\Delta t}{t_{dyn}}})$$

where Δt is the formation time of M_* . Therefore the expected stellar mass (ESM) that can form from a gas mass of m_{gas} can be written as

$$ESM = m_{gas}(1 - e^{-c_* \frac{\Delta t}{t_{dyn}}})$$

but also

$$ESM = p \cdot m_*$$

where p is the probability of stars of stellar mass m_* forming from a gas mass of m_{gas} . Therefore the probability of forming a stellar particle in Romulus25 from a gas particle is given by:

$$p = \frac{m_{gas}}{m_*}(1 - e^{-c_* \frac{\Delta t}{t_{dyn}}}) \quad (2)$$

where m_* is the mass of a stellar particle ($6 \cdot 10^4 M_\odot$), m_{gas} is the masses of a gas particles ($< 2.12 \cdot 10^5 M_\odot$; less than due to possible past stellar particle formation and accretion), and c_* is set to be 0.15 and Δt is assumed to be 10^6 yrs.

SMBH Seeding

Guided by the observed SMBH occupation fraction as a function of stellar mass transitioning from 0 to 1 over a small stellar mass range (Miller et al., 2015), other simulations such as Magneticum (Hirschmann et al., 2014),

EAGLE (Schaye et al., 2015), and Illustris (Vogelsberger et al., 2014) seed their SMBHs in the centre of halos once it surpasses some mass threshold. Romulus25 takes a very different approach to seeding that is based solely on local gas properties. This avoids the need to make any a priori assumptions about what halos should host a SMBH, where in the halo it should be seeded, or how many SMBHs should be seeded in a halo. Only once a gas particle reaches the following criteria does it transition into a SMBH sink particle:

- It is metal poor, with $Z < 3 \times 10^{-4} Z_{\odot}$
- It has a density of $3 \text{ m}_p \text{ cm}^{-3}$ (15 times the star formation threshold)
- It has a temperature between 9500K-10000K

Only once this criteria is met by a gas particle does it convert into a SMBH particle and rapidly accrete nearby gas until it reaches its seed mass of $10^6 M_{\odot}$, conserving mass within the simulation. This simplistic criteria for seeding leads to the vast majority (87%) of SMBH being seeded at $z > 5$. This process is meant to emulate the direct collapse black hole scenario (Bromm & Loeb, 2003; Begelman et al., 2006), where dense, pristine regions of gas avoid efficient cooling and fragmentation which would lead to star formation and instead collapse in near monolithic fashion into a SMBH. Although recent research suggest that the light seed mechanism, where metal-free population III stars generate seeds of mass $10^2 M_{\odot}$ after supernova, can generate seeds that rapidly grow to be $10^5 M_{\odot}$ in $\sim 10^5$ years (Mehta et al., 2024), albeit in highly idealised conditions. Thus light seeds may generate heavy seed-like populations but with a small time delay added and further justifies the use of heavy seeds in Romulus25.

SMBH Accretion & Feedback

Once a SMBH particle has fully formed, it begins to accrete according to a modified Bondi-Hoyle-Lyttleton (Bondi, 1952) prescription given by:

$$\dot{M}_{BH} = \alpha(n) \times \begin{cases} \frac{\pi(GM_{BH})^2 \rho}{(v_{bulk}^2 + c_s^2)^{\frac{3}{2}}} & \text{if } v_{bulk} > v_{\theta} \\ \frac{\pi(GM_{BH})^2 \rho c_s}{(v_{\theta}^2 + c_s^2)^2} & \text{if } v_{bulk} < v_{\theta} \end{cases} \quad (3)$$

where G is the gravitational constant, M_{BH} is the mass of the SMBH particle, ρ and c_s are the smoothed quantities of pressure and speed of sound from the 32 closest gas particles to the SMBH particle. v_{bulk} is the bulk velocity of the gas relative to the SMBH particle estimated as the smallest relative velocity of the 32 nearest gas particles to the SMBH particle. v_θ is the rotational velocity of the ambient gas as estimated at ϵ_g away from the SMBH by calculating the specific angular momentum (j) for all particles within $3\epsilon_g$ (1.05 kpc) and $4\epsilon_g$ (1.4 kpc), and assuming angular momentum is conserved on different scales, $v_\theta(\epsilon_g) = j/\epsilon_g$. v_θ is calculated this way as only past $2\epsilon_g$ does the gravitational forces in the simulation converge to the Newtonian solution. $\alpha(n)$ is a density dependent boost factor which avoids underestimating the accretion rate due to resolution effects (Booth & Schaye, 2009) and is given by

$$\alpha(n) = \begin{cases} \left(\frac{n}{0.2 \text{ m}_p \text{ cm}^{-3}} \right)^2 & \text{if } n > 0.2 \text{ m}_p \text{ cm}^{-3} \\ 1 & \text{if } n < 0.2 \text{ m}_p \text{ cm}^{-3} \end{cases} \quad (4)$$

$0.2 \text{ m}_p \text{ cm}^{-3}$ being the density threshold of star formation in the simulation, and represents the limit beyond which the multiphase ISM cannot be resolved. Accretion is also capped at the Eddington limit and also limited to the mass of all particles within $4\epsilon_g$ as accretion of gas particles beyond this limit is disallowed.

SMBH feedback from accreted matter is modelled assuming a 10% radiative efficiency ($\epsilon_r = 0.1$) and a 2% coupling efficiency of this radiation with the surrounding gas ($\epsilon_f = 0.02$), such that the total energy being imparted to the surrounding gas during a time dt is:

$$E = \epsilon_f \epsilon_r \dot{M} c^2 dt \quad (5)$$

This energy is thermally injected to the nearest 32 gas particles during each SMBH timestep, which is constantly set to be the lowest global timestep of the simulation. This simplistic approach to SMBH feedback leads to accurate large-scale, collimated outflows within the SMBH's host (see fig. 10 & 11 of Tremmel et al. (2019)).

SMBH Dynamics

Romulus25 oversamples its dark matter distribution such that there is 3.375 more dark matter particles compared to gas particles at its initiation, with a dark matter and gas mass resolution of $3.39 \times 10^5 M_\odot$ and $2.12 \times 10^5 M_\odot$ respectively. This oversampled distribution is important for accurately modelling dynamics, as it allows dark matter to be less massive than the SMBHs (Tremmel et al., 2015). However, similarly to nearly all other simulations, Romulus25's integrator does still fail to resolve all dynamical friction exerted on a SMBH which acts to decay their orbit slowly towards the centre of their host. This is due to the gravitational softening not accounting for all the force exerted onto the SMBH by particles closer than two softening lengths ($2\epsilon_g$), leading to an underestimation of the dynamical friction force. Therefore, Romulus25 includes a sub-grid model for dynamical friction capable of accounting for this unresolved force by assuming, within a gravitational softening length of the SMBH particle, the velocity distribution is isotropic and so follows a simplified version of the Chandrasekhar dynamical friction formula (Chandrasekhar, 1943):

$$\mathbf{a}_{DF} = -4\pi G^2 M_{BH} \rho(< v_{BH}) \ln \Lambda \frac{\mathbf{v}_{BH}}{v_{BH}^3} \quad (6)$$

where $\mathbf{v}_{BH}$ is the velocity vector of the SMBH relative to the velocity vector of the centre of mass of the 64 closest dark matter and star particles, $\rho(< v_{BH})$ is the density of particles moving slower than v_{BH} calculated from the same 64 dark matter and star particles, and $\ln \Lambda$ is the Coulomb logarithm found from $\ln\left(\frac{b_{max}}{b_{min}}\right)$, where b_{min} is the 90° deflection impact parameter (b_{90}) or the Schwarzschild radius of the SMBH particle if it is greater than b_{90} . As the dynamical friction from particles further from the SMBH are well resolved by the integrator, b_{min} is set to ϵ_g as to only account for the unresolved gravitational effects of nearby particles and avoid double counting the resolved component of the dynamical friction.

SMBH Mergers

SMBHs within Romulus25 undergo numerical mergers when the relative separation of a pair is less than $2\epsilon_g$ and they have low enough relative velocities to be bound:

$$\frac{1}{2}\Delta\mathbf{v}^2 < \Delta\mathbf{a} \cdot \Delta\mathbf{r} \quad (7)$$

where $\Delta\mathbf{v}$, $\Delta\mathbf{a}$, and $\Delta\mathbf{r}$ are the relative velocity, acceleration and distance vectors of the two SMBH particles (Bellovary et al., 2010). Due to Romulus25's seeding prescription, which relies solely on local gas properties to determine seeding sites, there is a large population of SMBHs that form in very close proximity to one another and merge nearly instantaneously which we deem to be unrealistic and so disregard as a merger. This is done in post-processing by disregarding all mergers where:

$$t_{\text{merge}} - \max(t_{\text{seed } 1}, t_{\text{seed } 2}) < 10 \text{ Myr} \quad (8)$$

where t_{merge} is the time of merger between two SMBHs, and $t_{\text{seed } 1}$ and $t_{\text{seed } 2}$ are the seeding times of the two SMBHs. We choose 10 Myrs as this is close to the time resolution of the simulation. This removal process exclude $\sim 30.1\%$ of all mergers from the simulation. We refer to the remaining mergers as "good mergers".

Post-Processing Models

As similarly implemented in the feedback model for Romulus25, SMBH luminosities are calculated using a 10% radiative efficiency ($\epsilon_r = 0.1$) such that

$$L_{\text{bol}} = \epsilon_r \dot{M} c^2 \quad (9)$$

Additionally, when reporting SMBH masses we use masses recalculated in post processing assuming seeds of $10^5 M_\odot$ such that:

$$M_{\text{BH}}(t) = M_{\text{BH}}^{\text{acc}}(t) + (n + 1) \cdot 10^5 M_\odot \quad (10)$$

where $M_{\text{BH}}(t)$ is the total mass of the SMBH at time t , $M_{\text{BH}}^{\text{acc}}(t)$ is the accreted mass of the SMBH and all of its progenitors up to time t that are good mergers,

and n is the number of good mergers the SMBH has undergone prior to time t . This is done due to the original seed mass of Romulus25, $10^6 M_\odot$, being on the larger side of possible direct collapse seed masses (Volonteri et al., 2008; Latif et al., 2013). This is justified despite the M_{BH}^2 dependence on the accretion model Romulus25 uses, as Ricarte et al. (2019) has shown that Romulus25's SMBH growth is primarily governed by its host's properties rather than the mass of the SMBH itself.

Identifying DAGNs & Subpopulations

We define a DAGN to be any SMBH pair with low relative separation where both SMBHs have high luminosity such that:

- $d < 10 \text{ pkpc}$
- $L_{bol} > 10^{43} \text{ erg s}^{-1}$

where d is the physical relative separation between two SMBHs and L_{bol} is the bolometric luminosity of the SMBHs individually. As Romulus25's SMBH data is saved every million years, we label a DAGN instance to be every million year timestep for a SMBH pair where they meet this criteria. All instances of DAGN activity are marked and all needed properties of the SMBHs and hosts are saved and used to generate the results. There are only two caveats to this processes of identifying DAGNs.

The first one being, we extend our distance criteria to 100 pkpc in section 4.4. The goal of this section is to inform current observation on the timescales of DAGN activity relative to the galaxy mergers that form them and the possible SMBH mergers which they might undergo. As the vast majority of DAGN observations have separations between 10 and 100 pkpc, we require d to be redefined to $< 100 \text{ pkpc}$ to fully inform observations.

Secondly, when reporting duty cycles, or the fraction of time which two nearby SMBHs spend as both active, we report this figure for every system only once, and not at every instance of this system. This is due to the duty cycle being a static property recorded over the entire lifetime of the system. As opposed to a dynamic property such as SMBH mass which is different at every instance of a DAGN system and must therefore be recorded at every instance.

In this work, we study different subpopulations of the DAGN population. Here is a overview on the subpopulations.

1. **All DAGNs.** This is the total DAGN population or all DAGNs instance where the above DAGN criteria for separation and luminosity are met.
2. **Merger Created DAGNs.** This is a subpopulation of the all DAGNs population where both SMBHs can be traced back to have been in different halos at the same time. This ensures that a resolved galaxy merger is the formation mechanism responsible for creating the DAGN system. Another novel creation mechanism is present in Romulus25 and explored further in the discussion. But when reporting results on the timescale of DAGN activity relative to the galaxy merger that created them and when searching for any galaxy merger enhancement in accretion rates of DAGNs relative to single AGNs, we ensure that the formation of the DAGN can be traced to a galaxy merger.
3. **Merging Subpopulation.** This is the subpopulation of the all DAGNs population, where both SMBHs that make up the DAGN system merge prior to a Hubble time. Not only are DAGNs that directly merge with each other considered here, but also SMBHs that merge indirectly are also considered (i.e. two SMBH that are in the same merger tree by $z = 0$ but are on different branches of the tree).

4 Results

4.1 Merging vs Non Merging DAGN

This initial section focuses on the final evolutionary stage for many, but not all, DAGNs, the subpopulation of DAGNs that coalesce within a Hubble time. Many DAGN systems may fail to coalesce prior to a Hubble times due to the lifetime of the system being shorter than the dynamical friction timescale, or possible due to core stalling (Banik & van den Bosch, 2021, 2022), or even one SMBH of the DAGN being ejected from the system. This makes the merging subpopulation important as they may offer unique insights into the conditions and environment needed for efficient dynamical friction or to overcome stalling. Additionally, this subpopulation offers an electromagnetic precursor to gravitational wave sources that are of concern to LISA and PTAs (eLISA Consortium et al., 2013; Amaro-Seoane et al., 2023; Agazie et al., 2023; EPTA Collaboration et al., 2023).

The merging population of SMBHs in Romulus25 has been previously well studied in the context of host morphology, nanohertz sources, and DAGNs. By performing stellar population synthesis and dust radiative transfer on Romulus25 galaxies that host recent SMBH mergers, Bardati et al. (2024a,b) created mock UV, optical, and IR observations, in addition to stellar kinematic maps, and through these identified distinct morphological and kinematic signatures to identify possible hosts of recent SMBH mergers. Saeedzadeh et al. (2024a) studied the hosts of SMBH mergers that are sources of nano-Hertz gravitational wave signals, showing that massive low- z early-type galaxies with old stellar population and low SFR are the host to sources that dominate the nano-Hertz background. Highly appropriate for this section, Saeedzadeh et al. (2024b) studied the DAGNs of Romulus25, mainly comparing properties and statistics of DAGNs to single AGNs, but also performing a minor analysis on the merging subpopulation. Their main conclusion regarding merging DAGN systems was that they possess a diverse set of evolutionary pathways, with 70% merging prior to a Hubble time, 25% stalling in close pairs, and 5% being ejected before they could merge. Their analysis however was confined to DAGNs at $z < 2$ and to coarse timestep analysis (166 Myr average time resolution compared to 1 Myr for this work).

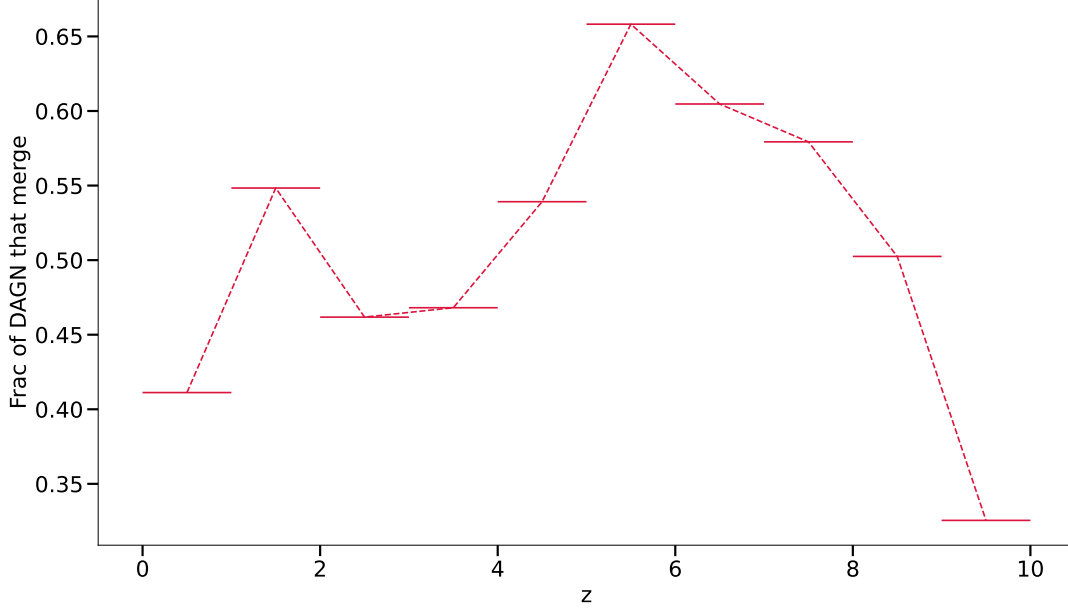


Figure 3: Fraction of DAGN instance from binaries that merge prior to a Hubble time as a function of redshift.

It is important to note, that in the context of this work and nearly all other work that study SMBH mergers in cosmological simulations, the term "merger" refers to the numerical merger of SMBH or the point at which the separation becomes too small for the dynamics to be resolved and so the SMBHs are forced to merge into one. For Romulus25, numerical mergers occur when the SMBHs have low enough relative velocities to one another and have separations lower than two gravitational softening lengths (0.7 kpc). This means that Romulus25 is not able to fully track binary dynamics down to the point of coalescence, missing some of the dynamical friction regime and all of the loss-cone (Hills & Fullerton, 1980) and gravitational-wave emission (Peters & Mathews, 1963) regimes. Therefore, all SMBH merger times should be taken as lower limits.

Figure 3 introduces the prevalence of this merging subpopulation by plotting the fraction of DAGN instances that merge within a Hubble time as a function of redshift. This figure suggests that around $z = 6$ is when this population is most active, and at higher redshift the population has a sharp decrease in the fraction of DAGN instances that merge. These results are indicative of most moderately high- z DAGNs instances occurring in system

that merge prior to a Hubble time but highlight that not all systems are destined to merge prior to a Hubble time.

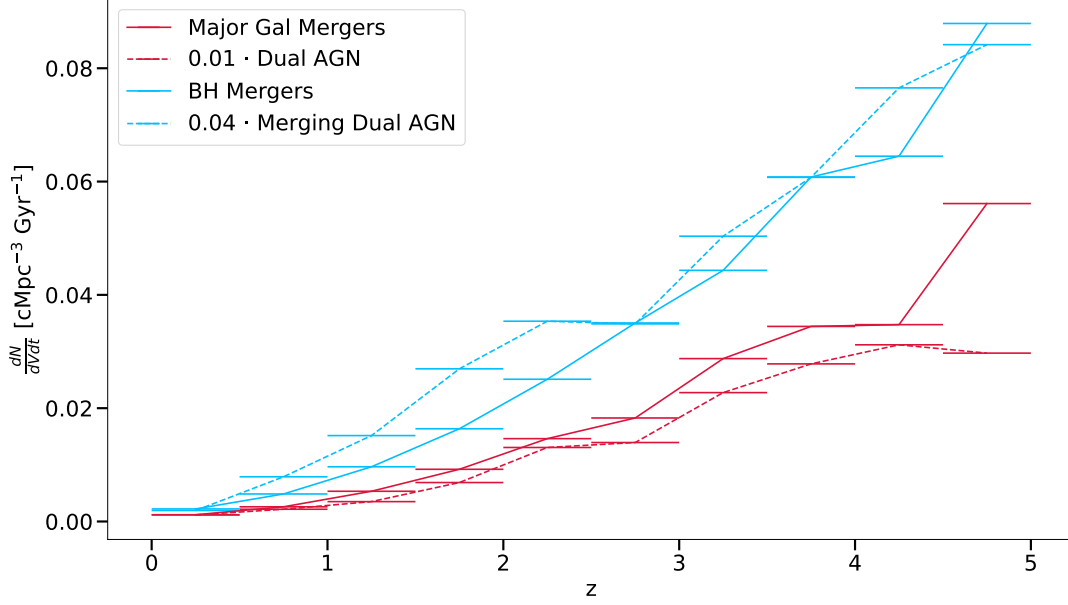


Figure 4: Comparison of rates per unit volume for various events. Solid red being major galaxy mergers, dashed red being all DAGN instances, solid blue being all SMBH numerical mergers, and dashed blue being all DAGN instances from binaries that merge prior to a Hubble time. As a galaxy mergers do produce and SMBH mergers may induce many DAGN instances, we renormalise both the all DAGN instances and merging DAGN instances by 0.01 and 0.04 for visualization purposes.

In search of any merger induced DAGN triggering, Figure 4 compares the rates of different event. With the red lines showing the major galaxy merger rate (mass ratio < 10) and the rate of DAGN instances. We defined the rate of DAGN instances as the number of SMBH pairs that meet the DAGN criteria at any given million year data timestep within a given time T divided by T . If both the red lines were to have the same shape, this would be indicative of DAGNs instances being triggered by major galaxy mergers. However, the definition of DAGN rate does make the comparison between both red lines challenging as a single major galaxy merger may spawn multiple DAGN instances. For that reason the rate of DAGN instances are renormalised by 0.01. In agreement with the findings of [Yu et al. \(2011\)](#), both the red lines closely match each other at low redshifts, indicative that

many low redshift DAGNs instances are created by major galaxy mergers. Having to renormalise by 0.01 to get the lines to match also shows that every major galaxy merger, on average, creates 100 Myr of DAGN activity. But this agreement begins to fade at higher redshifts. The blue lines in this plot show the rate of SMBH mergers and the rate of DAGN instance from pairs that merge prior to a Hubble time. Both lines show similar but slightly different shapes, This is a tentative sign that the merger of the pair does induce or trigger some DAGN activity, although not to the same extent that galaxy mergers do.

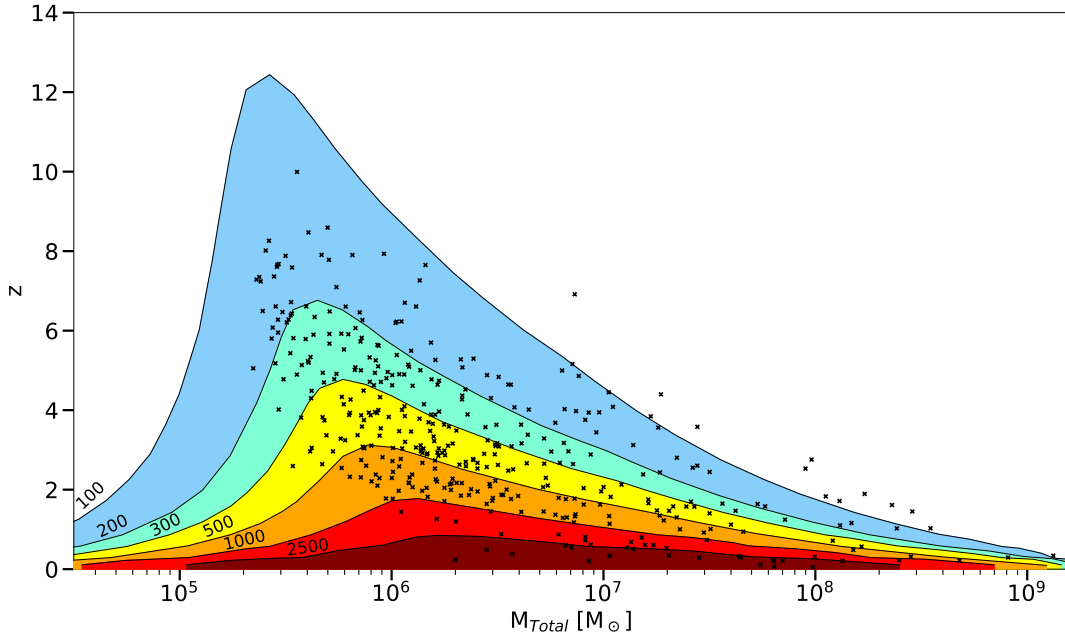


Figure 5: LISA signal-to-noise ratio contours (Amaro-Seoane et al., 2013) as a function of redshift of the merger and rest frame total mass of the merger assuming mass ratio of 1. Crosses show all similar mass mergers ($\log(\frac{M_1}{M_2}) < 0.25$, $M_1 > M_2$) in Romulus25 that underwent DAGN activity within 1 Gyr of the merger. See text for a more complete analysis that accounts for high mass ratio mergers.

Although we find only minimal linking between SMBH mergers and the DAGN phases they undergo prior to merging, DAGNs still are an important possible electromagnetic precursor to gravitational wave sources. As DAGNs can be an important progenitor to future SMBH merger which LISA is sensitive to, understanding their demographics and evolution can

help constrain LISA event rates. However, a substantial amount of DAGN instances come from binaries that do not merge as seen in Figure 3, we therefore give an analysis on the DAGN population that is visible by LISA. Figure 5 plots the signal-to-noise ratio (SNR) contours of Amaro-Seoane et al. (2013) as a function of redshift and total rest frame mass of the SMBH pair assuming equal-mass mergers. Overplotted in crosses are all the SMBH mergers that were DAGNs within 1 Gyr prior to their merger, which all have low mass ratios at the time of their merging ($\log(\frac{M_1}{M_2}) < 0.25$, $M_1 > M_2$) in order to give a fair comparison with the equal-mass ratio SNR contour. While nearly all mergers that were DAGNs recently prior to their merger have $\text{SNR} > 100$ and are LISA sensitive, this plot clearly doesn't show the full picture as it neglects merger of non equal mass SMBHs. Therefore, using the prescription given in Robson et al. (2019), we calculate the SNR for every merger in Romulus25 and characterise each merger as being LISA visible if they have a $\text{SNR} > 10$. In total, 98.9% of all Romulus25 mergers are LISA visible and therefore unsurprisingly 98.4% of all mergers that were DAGNs 1 Gyr prior to their merging are LISA visible. However, only 32.2% of all LISA visible mergers were DAGNs within 1 Gyr prior to their mergers. This shows that inferring whole LISA visible population statistics from DAGNs alone would at most only account for $\sim 1/3$ of total events. This analysis does fail to account for the spin of the SMBHs in the pair and always assumes spinless SMBH, however spin is expected to at most only effect the SNR by a factor of 2 (Robson et al., 2019), and as most mergers have $\text{SNR} \gg 10$, this would not greatly effect results. The analysis also fails to account for the location of the gravitational wave source in the sky and the polarisation of the waves relative to the arms of LISA. We chooses to use the all sky and polarisation averaged signal when calculating the SNR of mergers, a technique which we emphasis may not be the best as most of the SNR, for massive systems like the ones studied here, are accumulated over timescales on the order of days, a timescale in which LISA is effectively stationary and therefore wouldn't record sky and polarisation averaged signals. Accurately sampling the sky location and polarisation could potentially vary the SNR of massive systems like these DAGNs by factor of 10s, and greatly affect the results presented here.

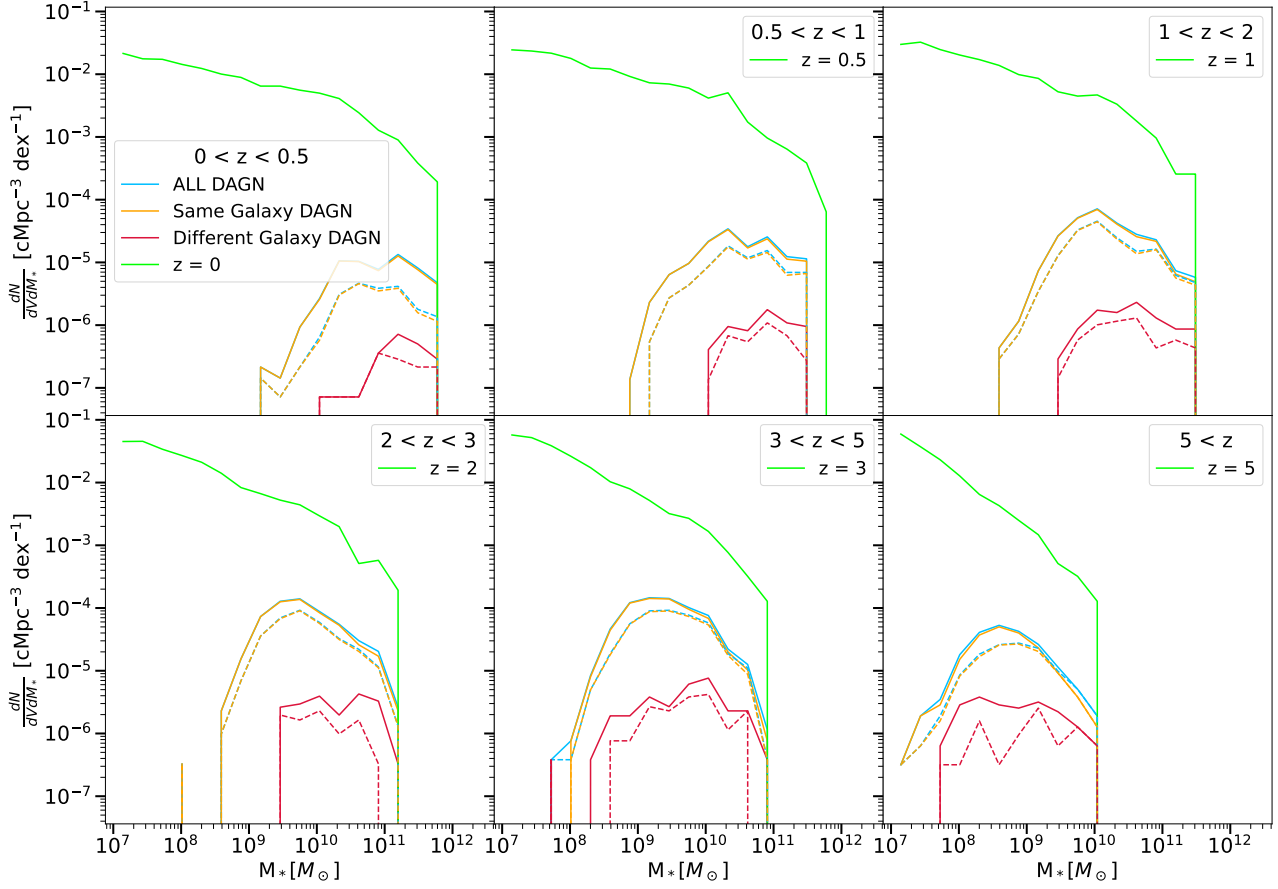


Figure 6: Stellar mass function of DAGN hosts for DAGNs with their SMBHs in the same galaxy (orange), in different galaxies (red), regardless of host galaxy (blue), for redshift ranges shown in the legends. Solid line shows the host mass function for all DAGNs while dashed lines show the host mass function for DAGNs that merge prior to a Hubble time. Lime lines show the stellar mass function of all galaxies at the lowest redshift in the redshift range (i.e. the largest mass function in the redshift range which the DAGN host galaxies can be sampled from.).

Figure 6 shows the stellar mass function for DAGN hosts where both SMBHs are hosted in the same galaxy, different galaxies, and the combined population. This is shown for both the full DAGN population and the merging subpopulation in solid and dashed lines respectively. These stellar mass functions of DAGN hosts are found across the entire redshift range shown in the legend. To construct these mass functions within the specified range, we first identify all simulation timesteps that fall within these ranges, and

for every timestep we created a histogram of the stellar masses of all DAGN hosts weighted by the fraction of total time that the timestep represents within the given redshift range. During this process, the multiplicity caused by a galaxy/galaxy-pair hosting multiple DAGNs at the same time is removed such that the stellar mass of such galaxy/galaxy-pair only contributes to the histogram once. The many histograms are then summed up to yield a galaxy stellar mass function, averaged within the redshift range, weighted by the fraction of time within the redshift range where the galaxy contains at least one DAGN. In addition, when finding the stellar mass functions for DAGNs in different galaxies, the DAGN's host galaxy stellar mass is taken to be the sum of the two galaxies stellar masses. Shown in the lime line is the entire simulations stellar mass function at the lowest redshift in the range, or the largest mass function which the DAGNs can occupy in the range. Of course this is not a fair comparison to the different galaxy DAGN stellar mass function as the hosts stellar mass for these types of DAGN is taken to be the sum of two different galaxy's stellar masses. The galaxies that host DAGNs, whether their SMBHs be in the same galaxy or different galaxies, tend to be among the largest galaxies at that redshift, with peaks in all DAGN hosts mass functions about 1 dex lower than the largest galaxy at that redshift. This suggests DAGNs are biased towards massive, evolved galaxies which generally are more favourable for AGN activity. At all redshift ranges, the all DAGN mass function and the same galaxy DAGN mass function almost perfectly overlap with one another, indicating that the vast majority of DAGNs are hosted in the same galaxy. This is to be expected given the tight distance criteria for our definition of a DAGN of < 10 pkpc, which would naturally favour the system after coalescence of the galaxies. The different galaxy DAGN population seems to only have an effect on the full DAGN population at very large stellar masses, slightly decoupling the same galaxy DAGN and all DAGN mass functions at these masses, suggesting that different galaxy DAGNs typically occur in massive galaxies in the final stages of a merger. The merging subpopulation also seems to follow the full DAGN population closely for all redshifts and all DAGN types, indicating that the stellar mass is not an overall environmental factor that determines whether a system will merge or not.

The top of Figure 7 shows the evolution of the masses of SMBHs that are in DAGNs by plotting all DAGN instances in bins of mass of the more massive SMBH, or the "main" SMBH, in the DAGN and the redshift of the DAGN instance, with each bin being coloured by the average mass ratio of the DAGNs in that bin. In the early Universe, all DAGNs contain two low mass SMBH resulting in all DAGN instance having mass ratios close to 1 on average, as is to be expected as SMBHs have had very little time to grow significantly past their seed mass of $10^5 M_\odot$. By $z = 6-7$ there are a few DAGN instances which occur with more extreme mass ratios ($< 1/10$). These tend to be the DAGN systems that contains the largest main SMBH at that redshift. We do note that some of the DAGN whose main SMBH has a low mass might also have a extreme mass ratio, just that on average these DAGN whose main SMBH has a low mass are involved in DAGNs whose mass ratio is close to 1. The number of extreme mass ratio DAGN instances grow with time, with a maximum of 46% of the DAGNs at $z < 1$ being in bins that have average mass ratios of $< 1/10$. But at all redshifts, the majority of DAGN instances contain two low mass SMBH with low mass ratio. Additionally, at redshifts less than 2, very few DAGN instances occur where the more massive SMBH has a low mass, with only $< 3\%$ of the the DAGN instances in this redshift range having a main SMBH that has failed to grow by a factor of 10 compared to its seed mass, suggesting that low redshift DAGNs rarely occur between two SMBHs that have not experience efficient growth in the past.

A similar trend can be seen on the bottom plot of this figure which shows the same data as the top plot but for the DAGN instances from pairs that merge prior to a Hubble time. Still at all redshifts, the majority of DAGN instances come from low mass-ratio binaries where the main SMBH is low mass, but one large difference between the two populations can be seen for the DAGNs with larger main masses. At these larger masses, the subpopulation is characterised by less extreme mass ratios than the full DAGN population. This shows one of the largest differences between the total population and the merging subpopulation, and shows less extreme mass ratios being a key condition for efficient dynamical friction to occur and allow a DAGN, which have larger main masses, to overcome any angular momentum support that prevents them from merging prior to a Hubble time.

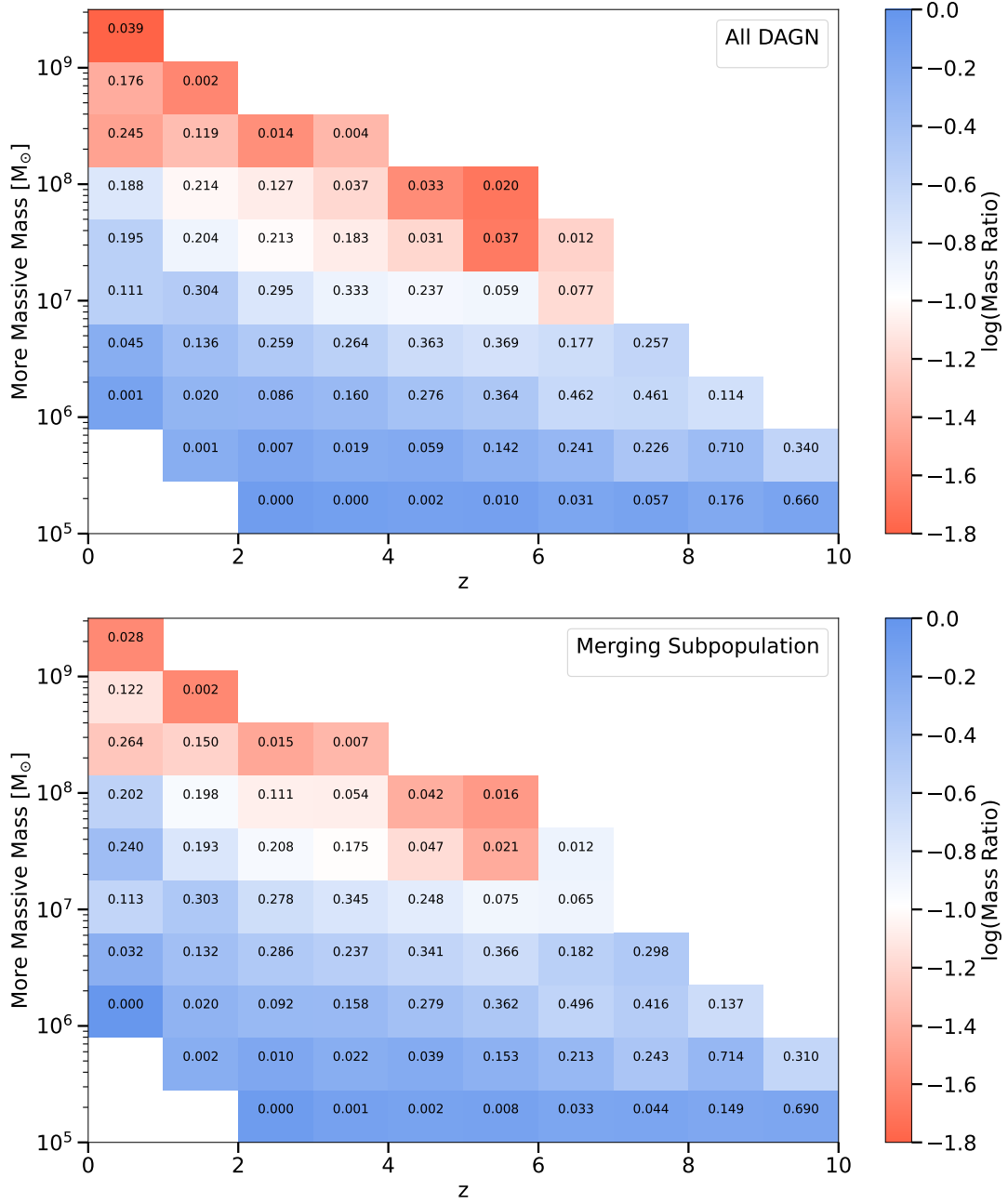


Figure 7: (Top) All DAGN instances binned by mass of the more massive SMBH in the DAGN and redshift of the DAGN instance. Coloured by the average log of the mass ratio of the DAGN. Numbers represent the fraction of DAGN instance in a redshift bin with a more massive SMBH that fits in the more massive mass bin. (Bottom) Similar to the top plot but only DAGN instances from SMBH pairs that merge prior to a Hubble time are included.

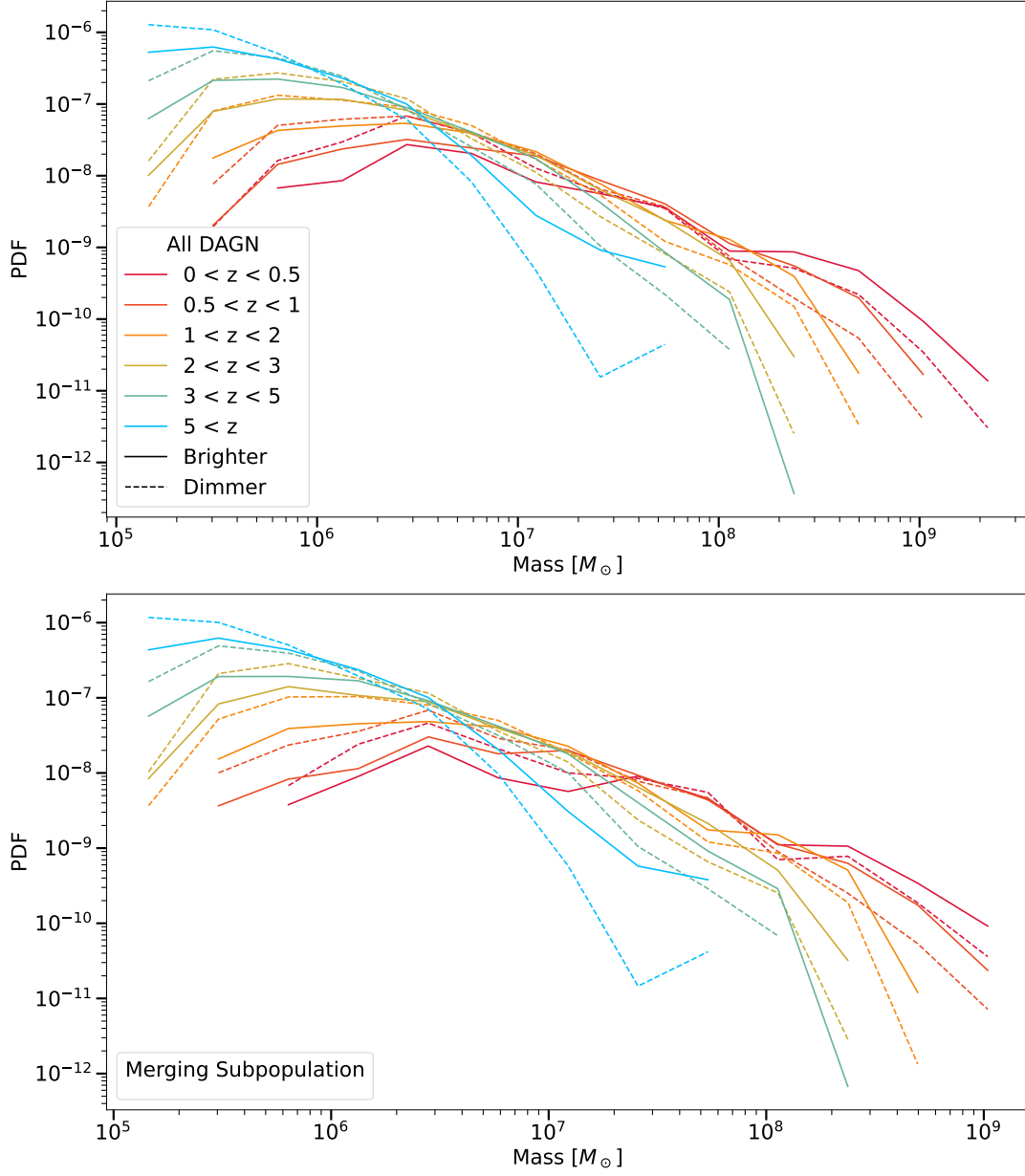


Figure 8: PDF of masses for the brighter SMBH in a DAGN instance (solid lines) versus the dimmer SMBH in the instance (dashed line). Colours represent the redshift of the DAGN instance. This data is shown for all DAGN instances (top) and only the DAGN instance from SMBH pairs that merge prior to a Hubble time (bottom).

While this figure shows the distribution of main SMBH masses and average mass ratios, it does not explore the luminosity of the SMBHs individually. Therefore, in Figure 8 we plot the probability density function

(PDF) of the masses of DAGN instances at different redshifts for the brighter and dimmer SMBH in solid and dashed lines respectively. The top panel shows all DAGN instances while the bottom shows only the instances from DAGN that merge within a Hubble time. In the top panel, across all redshifts, a consistent pattern emerges with the brighter SMBHs dominating at higher masses and the dimmer SMBH at lower masses. A deeper quantitative analysis confirms this with between 50-68% of all DAGN instances at any redshift having a brighter SMBH that is more massive than the dimmer. This result is intuitive given the Bondi-Hoyle-Lyttleton like prescription which sets the accretion rate of Romulus25's SMBHs, which for a given local environment, only depends on the square of the SMBH mass, making the more massive SMBH intrinsically brighter given that two SMBHs that reside within 10 pkpc of each other typically share similar environments. Additionally, the sinking of the more massive SMBH to the gas rich centre of the galaxy is naturally more efficient, as both the dynamical friction naturally captured by the integrator and the additional boost applied via the sub-grid model for unresolved dynamical friction (equation 6) both depend on the mass of the SMBH. On the opposite side, the lower mass SMBH would naturally be more susceptible to dynamical perturbations, casting their orbit to radii far away from the centre of the galaxy which contains the majority of the gas supply and therefore limit their luminosity compared to the more massive SMBH that may stay anchored to the centre. These results are in line with other large-scale simulation which adopt similarly prescriptions for SMBH accretion, seeding, and dynamics. Both Magneticum and Astrid report similar results in their $z = 2$ DAGN population, with the brighter SMBH in a DAGN typically being the more massive one (Steinborn et al., 2016; Chen et al., 2023). Likewise, the Horizon-AGN simulation shows that the the more luminous SMBH in a DAGN tends to have masses larger than the general AGN population while the dimmer remains qualitatively consistent with the broader AGN mass distribution (Volonteri et al., 2022).

The bottom panel which only shows mass distributions from DAGN instances that merge prior to a Hubble time finds a similar trend in this subpopulation, with the brighter SMBH dominating at higher masses and the dimmer SMBH dominating at lower masses at all redshifts. But there

is slightly less separation between the bright and dim distributions, indicative of the less extreme mass ratios of the merging subpopulation. This panel also supports a finding from Figure 7 where in the local Universe, only SMBHs that have grown significantly in the past partake in DAGNs, hence the distribution for the $0 < z < 0.5$ dimmer SMBH mass distribution starting at lower masses for the full DAGN population compared to the merging subpopulation.

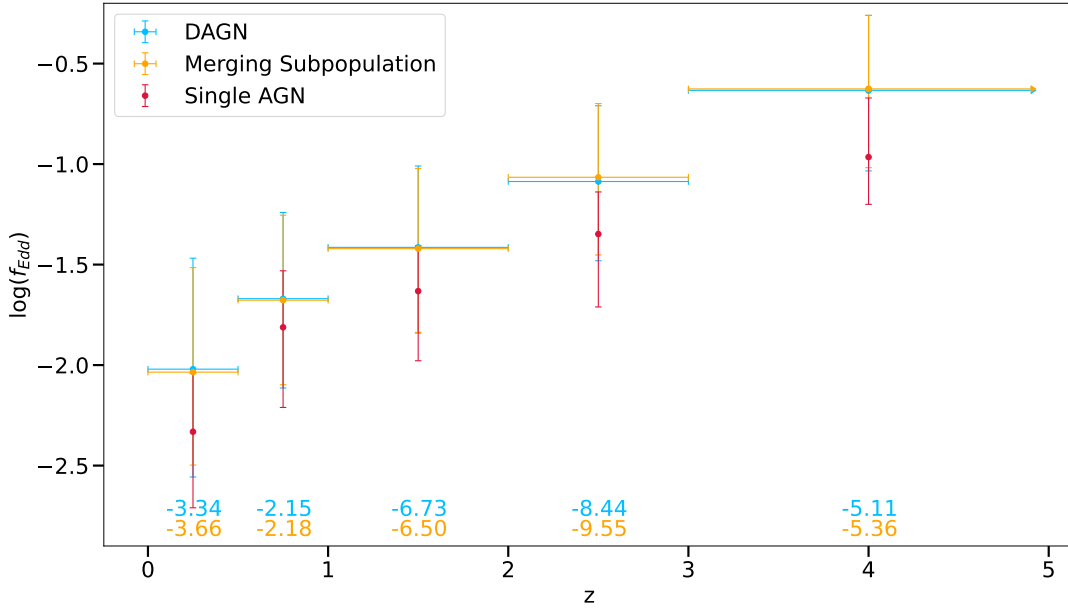


Figure 9: Distribution of Eddington fractions (f_{Edd}) for the entire DAGN population (blue), the DAGN population that merge prior to a Hubble time (orange), and all single AGNs (red). Points show the median of $\log(f_{Edd})$, while the vertical error bars represent the 75th and 25th percentile and horizontal error bars represent the ranges used to bin DAGN instances. Blue numbers show the $\log(p_{value})$ from the Mann–Whitney U test with the null hypothesis that both the single and all dual AGN populations have the same underlying f_{Edd} distribution. Orange numbers show the same but between the single AGN and merging dual AGN population (Wilcoxon, 1945; Mann & Whitney, 1947).

We next turn to the accretion efficiency of both populations, the full DAGN population and the subpopulation that merge. Figure 9 plots the distribution of Eddington fraction (f_{Edd}) for all DAGNs, the subpopulation of DAGN that merge, and the single AGN populations which have the same

minimum luminosity threshold as the DAGNs of 10^{43} erg s $^{-1}$ but no nearby neighbours that surpasses this threshold. The DAGN populations are binned in redshift to get a sample which is numerically significant enough to create a distribution. f_{Edd} is calculated assuming the SMBH is accreting pure ionized hydrogen such that:

$$f_{Edd} = \frac{L_{bol}\sigma_T}{4\pi GM_{BH}m_p c}$$

where L_{bol} and M_{BH} are the bolometric luminosity and mass of the SMBH respectively, G is the gravitational constant, c is the speed of light in a vacuum, m_p is the mass of a proton, and σ_T is the Thomson scattering cross-section for an electron. For fair comparison with the single AGNs, when calculating f_{Edd} for the DAGN populations we only consider the luminosity and mass of the brighter SMBH in the DAGN, which we have shown more often is the more massive SMBH. To test if there is a statistical difference in the f_{Edd} of the DAGN populations and the single AGN population, we use the Mann–Whitney U test (Wilcoxon, 1945; Mann & Whitney, 1947) which is a non-parametric statistical test to assess whether two samples are likely to have come from the same underlying population. It performs an analysis on the rank-sum of the two distributions to check the statistical significance of one containing larger values than the other. We note that while f_{Edd} would be normally distributed if all the SMBHs in Romulus25 were measured, adding a luminosity threshold like $L_{bol} > 10^{43}$ would clearly produce a skewed distribution, making the non-parametric Mann-Whitney U test more suitably for this analysis than more commonly used tests like the t-test. Blue numbers below the the distributions show the $\log(p_{value})$ from the Mann–Whitney U test with the null hypothesis that both the single and all dual AGN populations have the same underlying f_{Edd} distribution. Orange numbers show the same values but with the null hypothesis that both the single AGN and merging DAGN population have the same underlying f_{Edd} distribution. We decide to reject the null hypothesis in favour of the alternative, that both populations have different underlying distributions, at $\log(p_{value}) < -2$ (i.e. 99% confidence interval). This plot shows the f_{Edd} distribution for all DAGNs is higher than the distribution for the single AGN population, with this difference in the distributions being statistically significant at all redshifts. A similar trend can

be seen between the distribution of the merging subpopulation and the single AGN population, as the merging subpopulation shows minimal difference with the total DAGN population. This is likely due to the higher luminosity of DAGNs compared to single AGNs, as we will show in the next section, pushing the f_{Edd} distribution up to be higher than the single AGN population.

4.2 Galaxy Merger Created DAGNs

Understanding the formation channels of DAGN is crucial for tracing the co-evolution of SMBHs and their host galaxies. Galaxy mergers are understood to play a vital role in this co-evolution. Not only do mergers provide ex-situ stellar, gas, dark matter, and SMBH mass to a galaxy but the merger itself can destabilise gas, disrupt any rotationally supported disk, and drive the cold gas reservoir of a galaxy towards its centre to fuel and grow the central SMBH (Capelo et al., 2015; Davies et al., 2024). This same gas inflow can trigger starbursts (Barnes & Hernquist, 1991; Mihos & Hernquist, 1994; Hernquist & Mihos, 1995; Cox et al., 2008). Both these processes generate feedback which acts to quench star formation and cease AGN activity (Springel & Hernquist, 2003; Di Matteo et al., 2005), with the efficiency of each process depending on the mass of the galaxy and whether the entropy of the shocked circumgalactic medium exceeds that of the supernova driven outflows. The dynamics of the possible SMBH binary formed from galaxy mergers can also have a great influence on the galactic centre, scouring the core prior to their coalescence (Rantala et al., 2019). All these processes help maintain correlations like the $M_{BH} - \sigma$ and $M_{BH} - M_{Bulge}$ relations. As DAGNs are traditionally thought to come from galaxy mergers (Comerford et al., 2009), they serve as a tracer of recent galaxy mergers and provide insights into the SMBH-galaxy co-evolution. Therefore, in this section we investigate in detail the galaxy mergers that form DAGNs in the Romulus25 simulation.

The effect that galaxy mergers, as traced by DAGNs, have on the black hole accretion rate (BHAR) and the host star formation rate (SFR), and how DAGNs might trace galaxies with abnormal stellar formation efficiency has not been well studied due to the transient nature of DAGNs. However, the effect that a general galaxy merger has on the BHAR and SFR is well studied with controversy existing as to the degree to which the merger effects both. Looking at the BHAR first, studies show unanimously that the AGN fraction is higher in mergers than in non-mergers (Ellison et al., 2011; Satyapal et al., 2014; Goulding et al., 2018; Gao et al., 2020; La Marca et al., 2024). But conflict exists in the merger fraction of AGNs compared to non-AGNs, with some in favour of AGNs residing in mergers more frequently than non-AGNs

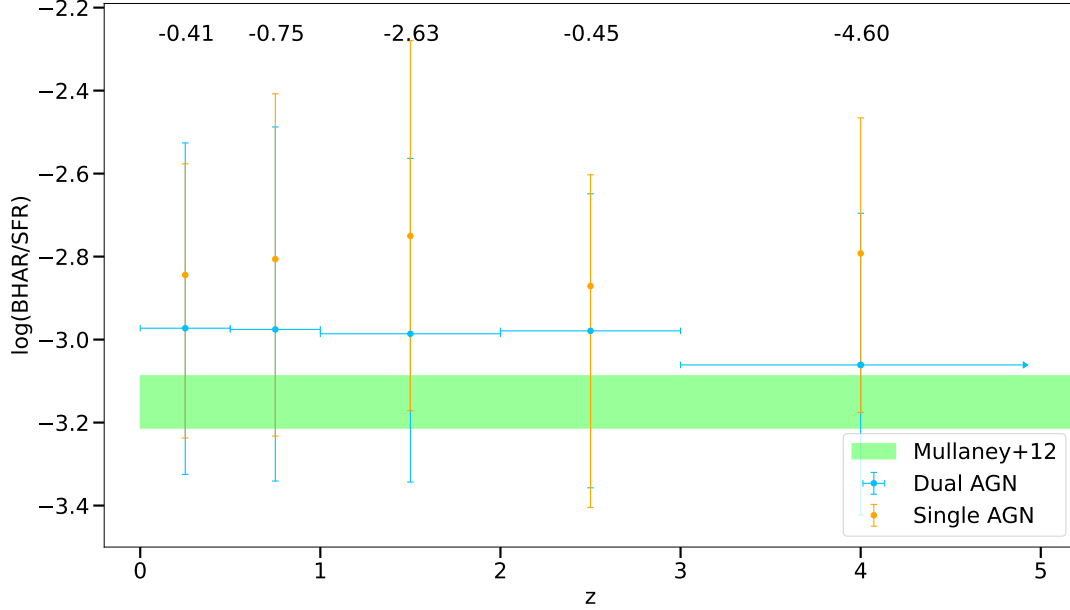


Figure 10: Ratio of black hole accretion rate density (BHAR) to star formation rate (SFR) for the merger-created DAGN population (blue), the single AGN population (orange). Points show the median of $\log(\text{BHAR}/\text{SFR})$, the vertical error bars represent the 75th and 25th percentile, and horizontal error bars represent the ranges used to bin DAGN instances. Numbers above each redshift bin show the $\log(p_{\text{value}})$ from the Mann–Whitney U test with the null hypothesis that both the single and dual AGN populations have the same underlying BHAR/SFR distribution (Wilcoxon, 1945; Mann & Whitney, 1947). Lime region shows the reported BHAR/SFR of Mullaney et al. (2012).

(Ellison et al., 2019; Gao et al., 2020; La Marca et al., 2024), and others finding no difference (Kocevski et al., 2012; Villforth et al., 2017). A similarly obscure picture is seen in the SFR of merging galaxies, with some studies reporting large enhancements to the SFR of mergers (Ellison et al., 2013), and others reporting only small enhancements (Pearson et al., 2019; Shah et al., 2022; Li et al., 2023; Omori et al., 2025), and even a reduction in SFR of some merging galaxies (Knapen et al., 2015). In search of any galaxy-merger enhanced star formation and black hole accretion, Figure 10 shows the ratio of the BHAR to SFR for merger-created DAGNs. The DAGN population is binned in redshift to get a statistically significant population. Only the brightest SMBH in a merger-created DAGNs system at any timestep in a halo

is considered here. This avoids double counting the SFRs of large galaxies that may contain multiple DAGNs, while also allowing for a fair comparison to the single AGN population. Also, all systems reside in a main sequence galaxy ($sSFR = \frac{SFR}{M_*} > 10^{-11} \text{ yr}^{-1}$) in order to make a fair comparison with the BHAR/SFR of [Mullaney et al. \(2012\)](#) which only measures it for star forming galaxies. Also plotted is the BHAR/SFR for all single AGNs, which we define as all SMBHs that have $L_{bol} > 10^{43} \text{ erg s}^{-1}$ and do not reside in a halo that contains a DAGN. Again only the brightest AGN in a halo that is also in a main sequence galaxy is considered. As similarly done in the previous section when comparing the f_{Edd} distribution of the DAGN populations to the single AGN population, we statistically compare the BHAR/SFR distribution of the merger-created DAGN population to the single AGN's using a Mann-Whitney U test. Numbers on the plot show the $\log(p_{value})$ from the Mann-Whitney U test with the null hypothesis that both the single and dual AGN populations have the same underlying BHAR/SFR distribution. We decide to reject the null hypothesis in favour of the alternate, that both populations have different underlying distributions, at $\log(p_{value}) < -2$ (i.e. 99% confidence interval). While the BHAR/SFR of both populations are consistent with observations, we only find the two populations to be statistically different from one another in the redshift ranges of $z = 1-2$ and $z > 3$, with the distributions of DAGNs being lower at these redshift ranges than the single AGN population.

Figures 11 and 12 give clues as to whether this difference is due to DAGNs having lower BHARs or higher SFRs than single AGNs. These figures show the luminosity, SFR, and sSFR of the merger-created dual and single AGN population with luminosity acting as a probe for BHAR as they are directly proportional. The same populations cuts done in Figure 10 are also applied for these figures. Unexpectedly, and in tension with the BHAR/SFR plot, Figure 11 shows that luminosity distributions of the primary SMBH in a merger-created DAGN is higher than the distributions of single AGN, with this difference being statistically significant at nearly all redshifts. Therefore, to explain the distributions of the BHAR/SFR, the SFR of the hosts of merger-created DAGNs needs to be much greater than that of the hosts of single AGN. This can be seen in the right hand plot of Figure 12 where the statistical significance of the SFR difference between the DAGN and single

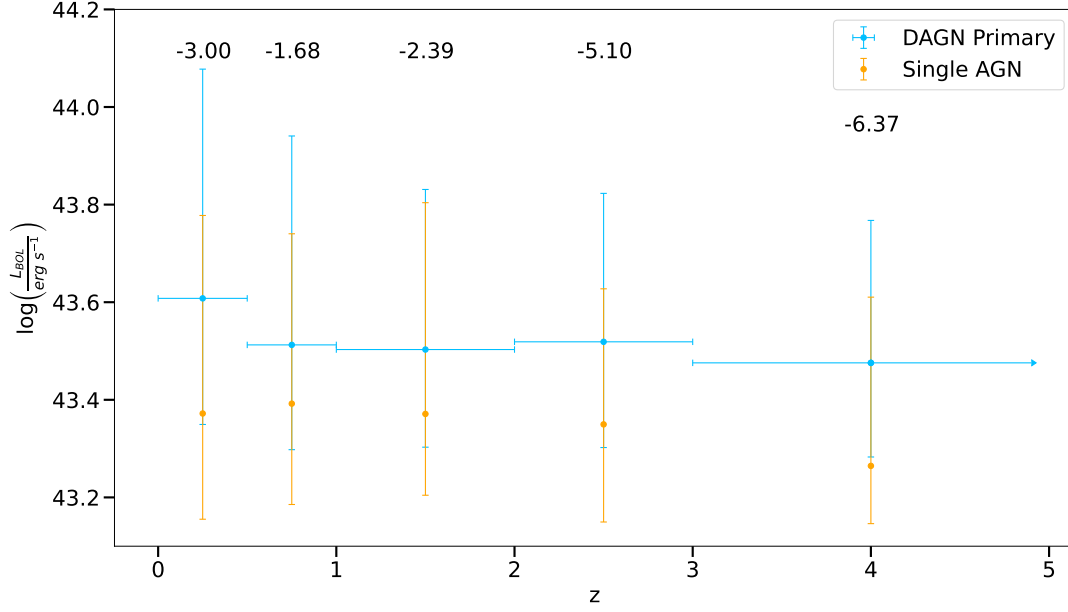


Figure 11: Luminosity comparison between the primary or brightest AGN of a merger-created DAGN (blue) and the single AGN population (orange). Luminosity being directly proportional to the accretion rate of the AGN. Points show the median of $\log(L_{\text{BOL}}/\text{erg s}^{-1})$, the vertical error bars represent the 75th and 25th percentile, and horizontal error bars represent the ranges used to bin DAGN instances. Numbers above each redshift bin show the $\log(p_{\text{value}})$ from the Mann–Whitney U test with the null hypothesis that both the single and dual AGN populations have the same underlying luminosity distribution (Wilcoxon, 1945; Mann & Whitney, 1947).

AGN hosts is large at all redshifts with DAGN host having larger SFRs than single AGN host. We summarise these points in two different redshift ranges. At $z < 3$, the merger-created DAGN population do not show much difference in the BHAR/SFR between dual and single AGNs, with only one of the four redshift bins probed having a statistically different BHAR/SFR distribution between the populations. However, when we look at the numerator and denominator of this ratio carefully, we see similarly statistically significant higher values in both the BHAR and host SFR of DAGNs compared to single AGNs. If galaxy merger enhancement were the cause of the increased SFR, we would also expect an increase in the sSFR. However, we don't see any increase in the host sSFR between the merger-created dual and single AGN population at $z < 3$. We therefore conclude that at these lower redshifts we see

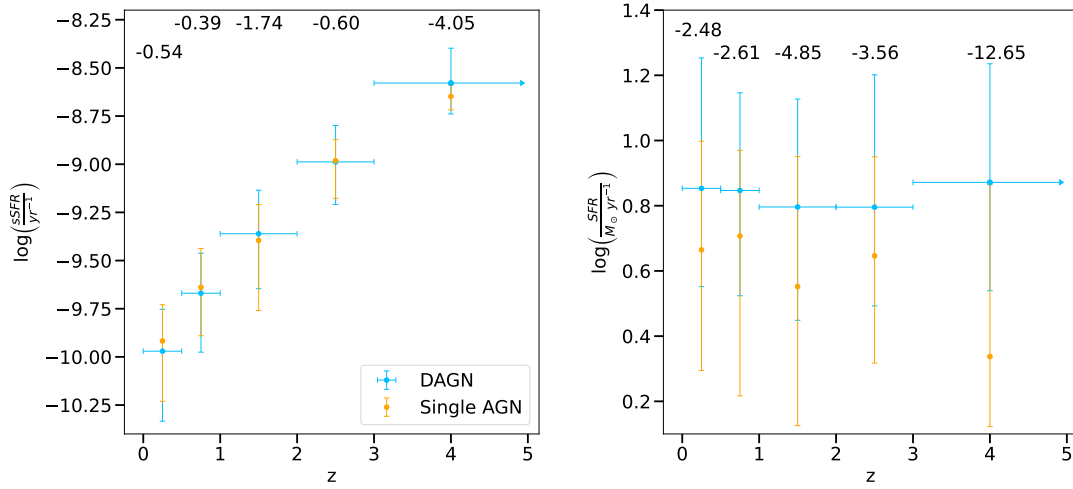


Figure 12: sSFR (left) and SFR (right) comparison between hosts of merger-created DAGN (blue) and single AGN (orange). Points show the median of the quantity plotted on the vertical axis, the vertical error bars represent the 75th and 25th percentile, and horizontal error bars represent the ranges used to bin DAGN instances. Numbers above each redshift bin show the $\log(p_{\text{value}})$ from the Mann–Whitney U test with the null hypothesis that both the single and dual AGN populations have the same underlying BHAR/SFR distribution (Wilcoxon, 1945; Mann & Whitney, 1947).

no enhancement of the SFR of merger-created DAGNs caused by the merger and instead attribute the higher SFR of DAGN hosts to them residing in larger halos that naturally have large SFRs but average sSFRs. At $z > 3$, we see a very different picture with the BHAR/SFR of the DAGNs being much lower than that of the single AGNs, caused by higher SFRs and BHARs compared to the single AGN population, but the difference between the two populations being much larger for the SFR. Due to the sSFR being much larger at this high- z , we do attribute the increase in host SFR of merger-created DAGNs compared to single AGNs to galaxy merger enhancement. These figures ultimately show that, even though DAGNs act as tracers of galaxy mergers and galaxy mergers act to enhance the SFR of galaxies, only in the early Universe does DAGN activity happen in unison with the enhancement of the SFR. In the late Universe, it is possible that too much time has passed between galaxy merger and DAGN activity for the DAGN to act as a tracer of the merger.

4.3 Duty Cycles

The duty cycle, defined by the fraction of time both SMBHs in a DAGN are actively accreting, is a key quantity of DAGNs. Constraining these duty cycles is essential for interpreting the true number of DAGN systems and aids in interpreting the growth of SMBHs. Therefore, this section is concerned with understanding the duty cycles of DAGN systems and the merging subpopulation.

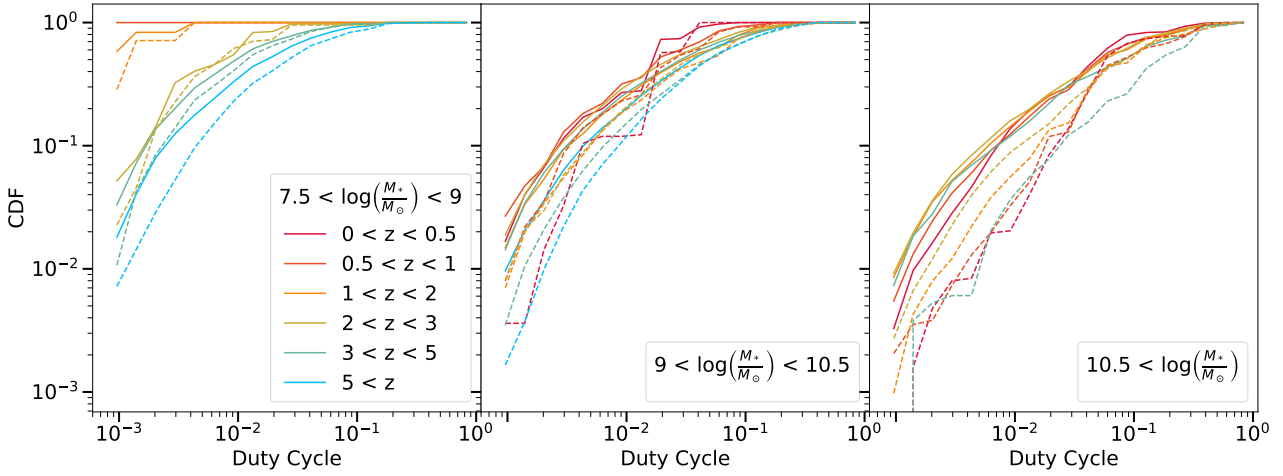


Figure 13: CDF of the duty cycles of DAGN systems (not instances). Colours represent the redshift range when the DAGN system underwent a DAGN phase. Data is binned by the host stellar mass during that DAGN phase ($7.5 < \log\left(\frac{M_*}{M_\odot}\right) < 9$ (left), $9 < \log\left(\frac{M_*}{M_\odot}\right) < 10.5$ (centre), $10.5 < \log\left(\frac{M_*}{M_\odot}\right)$ (right)). Solid lines represent all DAGN systems while the dashed lines represent the subpopulation of systems that merge prior to a Hubble time. Duty cycles are calculated as $t_{\text{DAGN}}(d < 10)/t(d < 10)$, where $t(d < 10)$ is the time the system spends with a separation < 10 pkpc, and $t_{\text{DAGN}}(d < 10)$ is the time the system spends with separation < 10 pkpc and also meets the luminosity criteria for a DAGN.

Figure 13 shows the cumulative distribution function (CDF) of duty cycles of these DAGNs. As the duty cycle is an entire lifetime property of a DAGN, we only show the duty cycles of DAGN systems, and not instances like done for all other properties shown in this research. The duty cycle is shown for DAGN systems that underwent DAGN phases at different redshifts as shown by the line colours and in galaxies of different stellar masses as shown in the legends. A close SMBH pair can undergo multiple DAGN phase at different

redshift and in that time its host galaxy may have grown a substantial amount in stellar mass, and so a single DAGN system's duty cycle may contribute to multiple different lines in this plot. As similarly done in prior plots, in the rare case where a DAGN's SMBHs are hosted in different galaxies, the host's stellar mass is taken to be the sum of the two galaxies stellar masses. The duty cycles are shown for all DAGN systems and only for the DAGN systems which coalesce prior to a Hubble time in solid and dashed lines respectively. We calculate the duty cycle as the fraction of time which a system spends as a DAGN while its SMBHs are within 10 pkpc of each other. A number of trends are observed in these plots. Firstly, in the lowest stellar mass plot, the higher the redshift of the DAGN phase the higher the duty cycle the system has. This trend can also be observed, albeit to a lesser extent, for DAGNs in medium stellar mass galaxies (middle plot), but completely breaks down for DAGNs in larger galaxies (right plot). This complete break down, however, does show another interesting trend in the duty cycles of DAGNs- the seemingly universal distributions of duty cycles of DAGN systems in larger galaxies. A possible explanation for this trend is that a universal duty cycle does exist for a DAGN system, possible regulated by feedback from the two SMBHs of the DAGN themselves. However in lower mass galaxies, which are far more susceptible to gas outflows and heating by supernova creating a chaotic gas supply for the DAGN, the gas supply is disrupting the universal distribution. This explains why the universal distribution is seen in DAGNs hosted by galaxies with $\log(M_*/M_\odot) > 10.5$, the galaxy mass where AGNs begin to dominate the feedback budget of a galaxy ([Martín-Navarro & Mezcua, 2018](#)), and diminishes for DAGNs in lower mass galaxies where supernovae greatly contribute to the total feedback budget. Secondly we see that the merging subpopulation tend to have larger duty cycles, regardless of the epoch they underwent a DAGN phase in or the stellar mass of the DAGN host. The reasoning for this is unclear from this plot alone but will be revealed in the next two plots.

Figure 14 breaks down the contribution of SMBH pairs at different separations to the total duty cycle of the systems by plotting the duty cycle but with a different distance criteria on it. Instead of calculating the duty cycle over the entire lifetime which a SMBH pair spends within 10 pkpc of

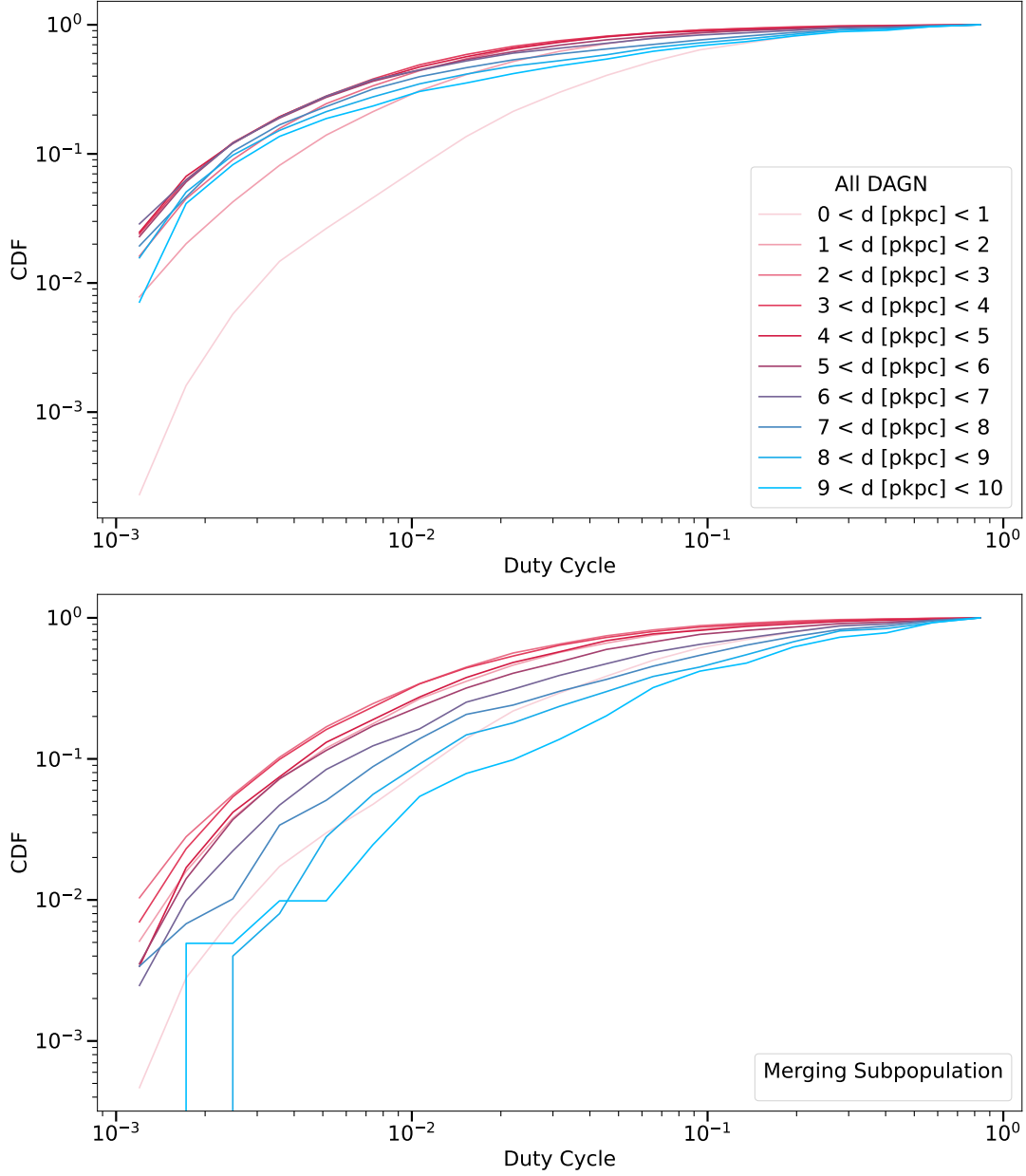


Figure 14: CDF of the distance defined duty cycles of all DAGN systems (top) and the subpopulation of systems that merge prior to a Hubble time (bottom). Duty cycles are calculated as $t_{DAGN}(x < d < y)/t(x < d < y)$, where $t(x < d < y)$ is the time the system spends with separation $> x$ pkpc and $< y$ pkpc, and $t_{DAGN}(x < d < y)$ is the time the pair spend with separation $> x$ pkpc and $< y$ pkpc and also meets the luminosity criteria for a DAGN. Colours represent the different x and y used in the duty cycle calculation.

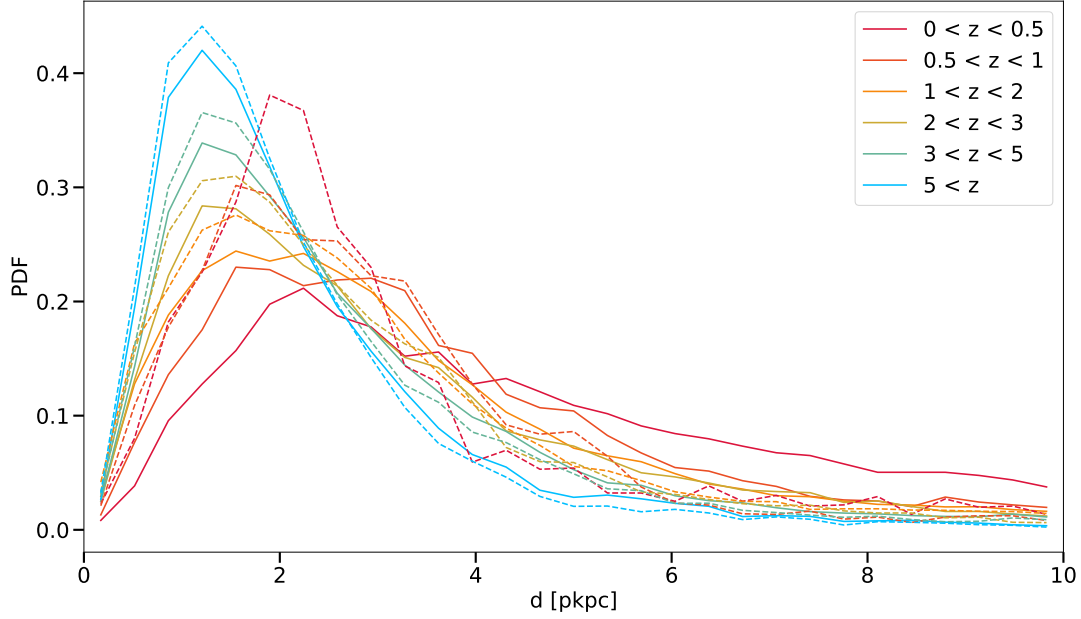


Figure 15: Relative separation for SMBH during DAGNs instance. Solid lines represent the full DAGN population while the dashed lines represent the subpopulation that merge prior to a Hubble time.

each other. It is calculated as the fraction of time which a system spends as a DAGN while its SMBHs have a separation between x and y , where x and y are represent by the different coloured lines shown in the legend. This is shown for the all DAGN system population and the merging subpopulation. Looking at the full DAGN population first, we see contributions to the duty cycle past a separation of 2 pkpc remain low and consistent. But contributions from DAGNs with separations < 2 pkpc tend to be higher. A similar trend can be seen in the merging subpopulations duty cycles, with the duty cycles calculated at lower separations being higher than at high separations. Therefore, if the merging population were to spend more time at lower separations, this would cause the subpopulations duty cycles to be higher than the all DAGN systems populations. There is one caveat in this, being the biased high duty cycles for the merging subpopulation at separations > 6 pkpc. Although, the rareness of the merging DAGN subpopulation at such distances, which we will show next, makes these high duty cycles inconsequential to the total subpopulation's duty cycles.

Figure 15 shows the main cause of the merging subpopulation having

larger duty cycles by plotting the relative distance distribution for all DAGN instances with colours representing the redshift of the DAGN instance. Again solid lines represent the entire DAGN population while the dashed represent the merging subpopulation. We see a clear peak in the distribution at all redshifts at very low separations of < 3 pkpc, and the peak in the distance distribution going to lower separations as higher redshift DAGNs are probed. Most importantly, we see a more pronounced peak in the separation distributions for the merging subpopulation at these lower separations. This is to be expected given the more evolved status of this subpopulation, representing the end life stages of a DAGN. As Figure 14 showed DAGNs at these lower separations are more likely to be active for longer. This would lead to the merging subpopulation naturally having larger duty cycles as seen in Figure 13.

It is crucial to highlight that we extended our distance criteria for a DAGN all the way to 100 pkpc and found no peak apart from the one at < 3 pkpc, and that DAGN activity past these low separations is rare. This single peak in the distance distribution of Romulus25's DAGNs is quite interesting in light of the results of other simulations and observations. Both the ASTRID and Horizon-AGN simulations report similar results in their DAGN population, with ASTRID having a distance distribution peak at < 5 kpc in their $z = 3$ and $z = 2$ DAGN population (Chen et al., 2023), and Horizon-AGN having a peak at $d \sim 6$ kpc in their $z = 3, 2$, and 1 DAGN population (Volonteri et al., 2022). EAGLE on the other hand does not have any clear peak at low separations and instead has a tentative peaks at $d \sim 20$ kpc (Rosas-Guevara et al., 2019). Although the advection based SMBH dynamics scheme used in EAGLE, which pins a SMBH to the centre of the galaxy it is associated to, is known to causes SMBH pairs to merge prematurely and therefore skip the entire low separation phase of DAGNs (Buttigieg et al., 2025). Tension exists in the observations of DAGN distances too. Li et al. (2025) report a uniform distance distribution in their sample of $0.4 < z < 3.4$ & $d < 15$ kpc DAGNs, but Stemo et al. (2021) found peaks at 2-4 kpc and also at 14 kpc in their $0.2 < z < 2.5$ & $d < 20$ kpc DAGN sample. This second peak at 14 kpc coincides with separations corresponding to the galaxy merger that created the DAGN's first pericenter passage and is therefore caused by

merger induced DAGN activity. It is therefore interesting that we don't see a similar peak in the distance distribution of Romulus25's DAGN, even at high redshift where merger induced DAGN activity can be seen in the merger created DAGN population as shown in the previous section.

4.4 Merger Timing

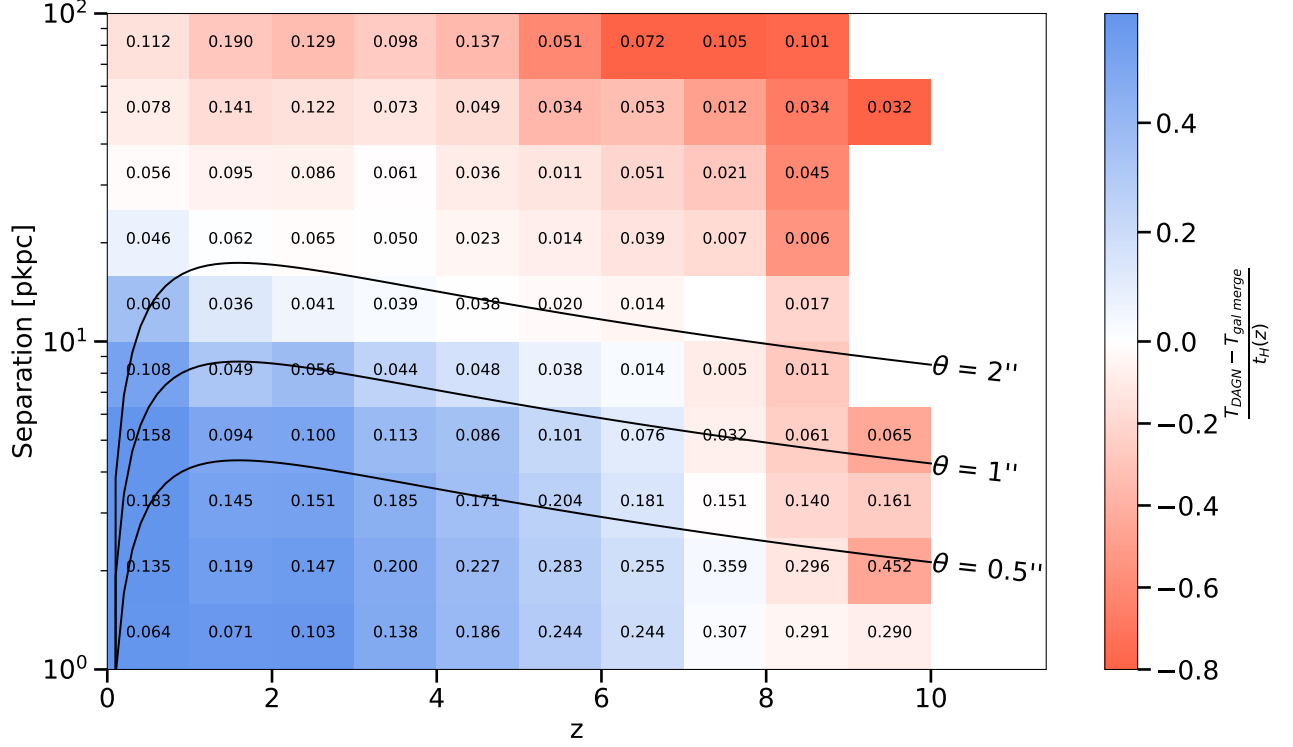


Figure 16: All instances of DAGNs that can be traced to form from a galaxy merger, binned by separation of the pair and redshift of the DAGN instance. Coloured by the average time between DAGN instance and the galaxy merger that formed the DAGN, normalised by the Hubble time at DAGN instance. Numbers represent the fraction of DAGN instance in a redshift bin that occur at that separation. Black lines represent the physical separation as a function of redshift for angular separations of $2''$, $1''$, and $0.5''$.

The temporal relationship between DAGN activity and the time of the galaxy merger that formed the DAGN and the merger of the SMBHs that make up the DAGN is crucial for informing current observations of DAGN, and putting into context which phase of DAGN evolution they might be in. To that end, Figure 16 puts into context the timescales of DAGN phases relative to the galaxy merger that formed them, by histogramming all merger-created DAGN instances into bins of physical separation and redshift. Each bin is weighted by the average time between a DAGN instance and the merger event and is normalising by the Hubble time of the DAGN instance. Fractions in each bin represent the fraction of DAGN instances in a redshift bin occurring

at that separation and black lines show the physical separation at a redshift for angular separation of 2", 1", and 0.5". We define the time of a merger event to occur when both SMBHs that comprise the merger-created DAGN have a separation equal to 10% the virial radius of the halo the SMBH particles are associated to. As many observed DAGNs have projected separations > 10 pkpc, we extend our distance criteria in our definition of a DAGN to 100 pkpc for this plot. To put these timescales into context with observations, we summarise some separations and redshifts of observed DAGNs.

Source	N	z	d (kpc)
Liu et al. (2011)	1286	<0.33	5-100
Eftekharzadeh et al. (2017)	47	<2.5	8-70
Lemon et al. (2018, 2019, 2020)	56	<2.5	8-70
Chen et al. (2022)	40	<3.1	<6.2
Li et al. (2025)	28	0.4-3.4	<15
Hennawi et al. (2010)	8	3-4.3	30-80
Yue et al. (2021, 2023)	2	>4.85	10

Table 1: Total number, redshift range, and separation range of observed DAGNs.

Previous observations, shown in Table 1, are biased towards larger separations and lower redshift. We refer the reader to Figure 1 of [Chen et al. \(2022\)](#) for a visual representation of some of these DAGN along with many other works. All of these DAGNs mentioned generally lie above the angular separation of 1" line except for some of the extremely low- z DAGNs of [Liu et al. \(2011\)](#), all of $z < 3.1$ DAGNs of [Chen et al. \(2022\)](#), and some of the $z < 3.4$ DAGNs of [Li et al. \(2025\)](#). Therefore Figure 16 suggests that most of the DAGNs which have been observed are, on average, either in the pre-merger phase or occurring concurrently with the galaxy merger. This implies that much of the post-merger phase of DAGN activity is not being effectively probed in observations, at least at $z > 0.33$, as [Liu et al. \(2011\)](#) has observed many extremely low separation systems at this extremely low redshift range. Even when AXIS launches, which is expected to usher in a renaissance in DAGN observations by detecting 100s of new DAGNs at $z < 5$, they will all have separation > 1.5" ([Foord et al., 2024](#)) and thus in the high- z Universe will again only probe the pre- and peri-merger phase. This result with the

separation parameter switched out for a projected separation, a more observer motivated quantity, is shown in appendix A. All conclusions inferred from Figure 16 remain the same when the projected separation is taken into account instead.

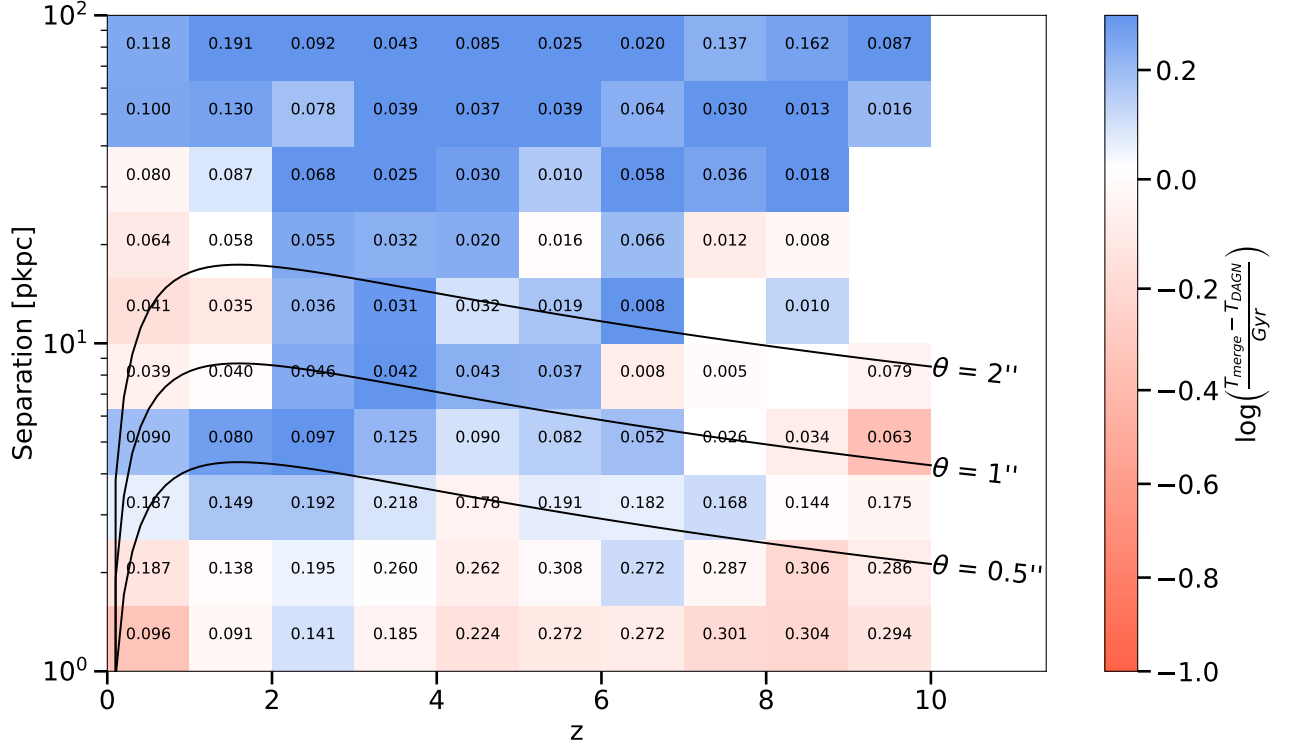


Figure 17: All instances of DAGNs from binaries that coalesce prior to a Hubble time, binned by separation of the pair and redshift of the DAGN instance. Coloured by the average time between the numerical merger of the binary and DAGN instance. Numbers represent the fraction of DAGN instance in a redshift bin that occur at that separation. Black lines represent the physical separation as a function of redshift for angular separations of 2'', 1'', and 0.5''.

Figure 17 puts into context the timescales of these DAGN instances relative to their SMBH merger time, by histogramming all DAGN instances occurring from binaries that merge prior to a Hubble time into bins of physical separation and redshift and colouring the bin based on the average time between SMBH merger and DAGN instance. Fractions in each bin represent the fraction of DAGN instances in a redshift bin that occur at that separation and black lines show the physical separation at a redshift for

angular separation of 2'', 1'', and 0.5''. Again, unlike the rest of our analysis which requires DAGNs to have a separation of < 10 pkpc, we extend our definition to < 100 pkpc for this plot to inform the many DAGN observations at separations larger than 10 pkpc, and remind the reader that almost all observed DAGN systems lie above the $\theta = 1''$ angular separation line at $z < 4.5$, with the exception of some of the extremely low- z DAGNs of [Liu et al. \(2011\)](#), and a handful of $z < 3.4$ DAGNs of [Chen et al. \(2022\)](#) and [Li et al. \(2025\)](#). Similar to Figure 16, Figure 17 shows some relationship between separation, DAGN redshift, and Δt , which we define to be $\Delta t = \text{time of the merger} - \text{time of DAGN activity}$. As most observed DAGNs lie above the $\theta = 1''$ angular separation line, most observed systems are more than a Gyr away from possible merging. Unsurprisingly, it is only systems with very low separation that merge consistently within a Gyr of DAGN activity, with this relationship strengthening for DAGNs at higher redshifts. A version of this plot with projected separation rather than separation is shown in appendix B, but we find no difference between the conclusions drawn from either plot.

5 Discussion

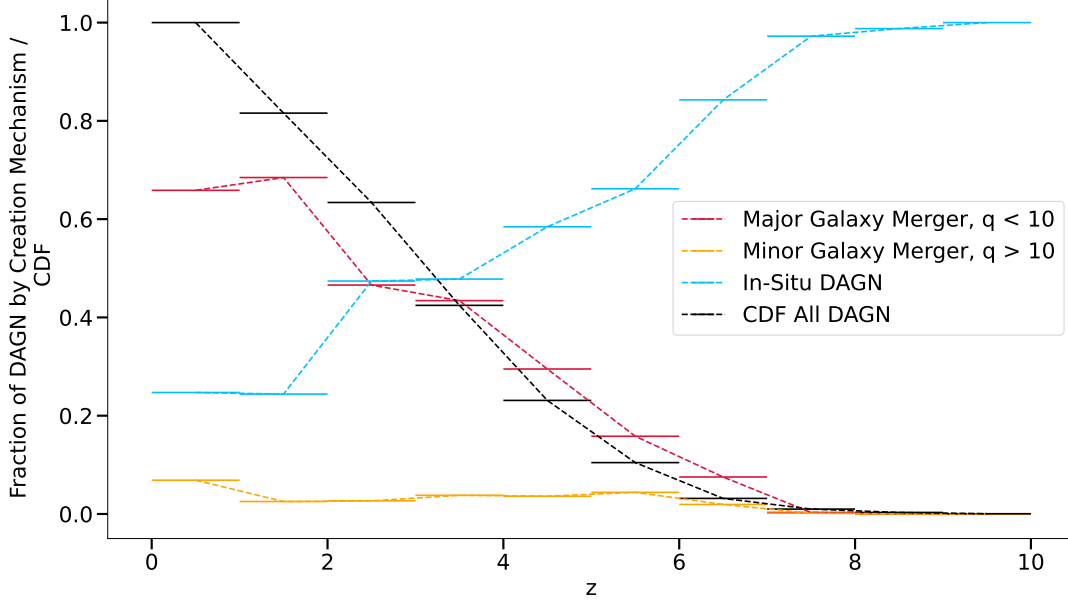


Figure 18: Fraction of DAGN instances within a given redshift range that were created via major galaxy mergers with mass ratio < 10 (red), minor galaxy mergers with mass ratio > 10 (orange), or the in-situ DAGN mechanism (blue). Also plotted is the cumulative distribution function of all DAGN (black) instances to put the creation mechanism fractions into context numerically.

Due to Romulus25's prescription for seeding SMBHs, which is based entirely on local gas properties and not on any halo properties, multiple SMBHs may be seeded in the same halo. This provides a novel creation mechanism for DAGNs that does not require any galaxy merger and which is often overlooked in literature which we dub as the "in-situ DAGN" creation mechanism. In Figure 18 we demonstrate the relative importance of this creation mechanism at different redshifts by plotting the fraction of DAGN instances within a redshift bin that formed from different creation mechanisms, alongside the CDF of all DAGN instances to put the fraction into context. The DAGNs that form from a galaxy merger are split into two separate categories based on the stellar mass ratio (q) of the galaxy merger with a critical value of 10. Romulus25 predicts that in the local Universe, and up to around $z = 2$, most DAGN instances are birthed due to major

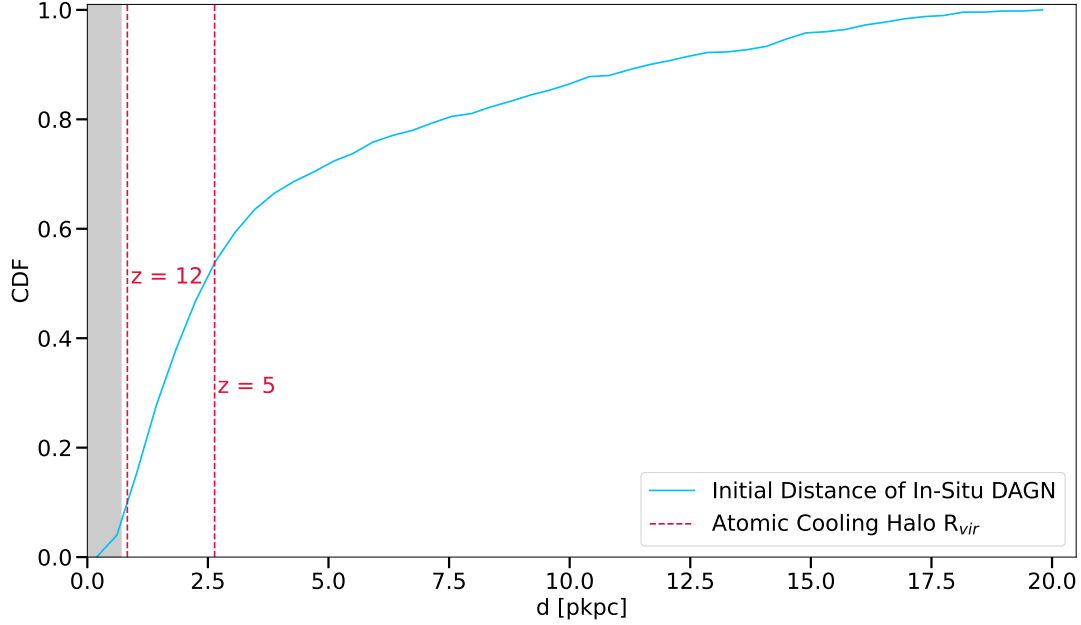


Figure 19: CDF of initial physical separation of in-situ DAGNs (blue). Dashed red lines show the virial radius of atomic cooling halos at $z = 12$ and $z = 5$, typical seeding redshift range of SMBHs for Romulus25. Grey region shows the resolution limit of the simulation or $2\epsilon_g$. Many in-situ DAGNs have initial separations on the order of an atomic cooling halo radius.

galaxy mergers, and that minor galaxy merger are at most responsible for the creation of 7% of DAGNs at any redshift. However, past $z = 2$, the in-situ DAGN mechanism begins to take dominance, and by $z = 7$ it is the creation mechanism for nearly all DAGN. This shows the possible importance of this novel creation mechanism to the DAGN population, particular at early time when major galaxy mergers between large galaxies are rare. Although the rarity of DAGN events at these early times brings into question the statistical significance of the importance of this novel creation mechanism at high redshifts. We caution that this figure shows the creation mechanism for every DAGN instance, not just every DAGN system. Therefore, if a creation mechanism produces a DAGN with a larger duty cycle, this creation mechanism will be represented more in Figure 18, although this aligns with observations as the probability of viewing a pair as a DAGN is clearly proportional to its duty cycle.

The extent to which this novel creation mechanism can be trusted is

precarious. The galaxy mergers creating DAGNs are identified in the simulation using the AMIGA HALO FINDER (AHF; [Knollmann & Knebe \(2009\)](#)). To do this, AHF first estimates the density field using a hierarchical mesh grid with each cell being refined if some particle density is surpassed in the cell. This procedure leads to an octree that follows halos from the inside-out, with each level stepping in density contours from halo centre to background densities. AHF then uses this octree to identify all particles, including SMBH particles, that are associated with a halo by finding regions that are 200 times the critical density of the Universe, whilst being careful to account for substructure and particles that are too energetic to be bound. If two SMBHs meet the criteria for a DAGN instance and each can be traced back in time to where they are associated to different halos by AHF, they are labelled as having a merger creation mechanism. Whereas DAGN instances that can not be traced back to different halos at the same time are labelled in-situ DAGNs. This labelling procedure does introduce a possible problem with identifying in-situ DAGN. As in the early Universe when most SMBHs are being seeded, due to low particle numbers of small halos, and time resolution effects, AHF may struggle to identify two separate halos where each contains a SMBH particle and eventually merge and create a DAGN. This could falsely label a merger-created DAGN as an in-situ DAGN. The exact extent to which this problem may be effecting results is shown in Figure 19 which plots the CDF of initial physical separation of all in-situ DAGN or the physical separation between the SMBHs that make up an in-situ DAGN at the seeding time of the youngest SMBH particle. The grey region represents the resolution limit of the simulation or $2\epsilon_g$, below which dynamics cannot be trusted and is also the distance criteria for SMBH mergers. Dashed vertical lines represent the virial radius of atomic cooling halos (typical seeding environments for direct collapse SMBHs) at $z = 12$ and 5 (a range where Romulus25 seeds 75.5% of SMBHs). Virial radii are found using the viral mass relation from [Fernandez et al. \(2014\)](#):

$$\left(\frac{M_{vir}}{10^6 M_{\odot}} \right)^{2/3} = \frac{T_{vir}}{0.75 \times 1800} \cdot \frac{21}{1+z} \quad (11)$$

and

$$R_{vir} = \sqrt[3]{\frac{3M_{vir}}{4\pi \cdot 200\rho_c(z)}} \quad (12)$$

where z is redshift, T_{vir} is the virial temperature which we set to 10^4K for atomic cooling halos (Bromm & Loeb, 2003; Begelman et al., 2006), and $\rho_c(z)$ is the critical density of the Universe at z , assuming the cosmology of Planck Collaboration et al. (2016) (same cosmology as Romulus25). Many DAGN which are labelled as in-situ DAGNs form with initial separations on the order of an atomic cooling halo radius, and therefore likely were correctly identified as in-situ DAGNs. But nearly half of identified in-situ DAGNs form with initial separations which are greater than the typical size of direct collapse black hole sites and therefore are likely mislabelled as in-situ DAGNs when in fact they are merger created DAGNs which were seeded in galaxies in close proximity to each other and could not be uniquely identified by the AHF. This figure shows that while many identified in-situ DAGNs may be artefacts of the halo finder, there is still a large population of correctly identified in-situ DAGNs in Romulus25.

It is important to note that the in-situ DAGNs are a product of the specific realisation of SMBH seeding used in Romulus25 and highly depend on the prescription being used. We next look at a case study of an in-situ DAGN that did form with an initial separation less than the virial radius of its host in detail. The top of Figure 20 shows the gas column density and stars of a halo that contains an in-situ DAGN, which are marked as orange and blue crosses. The panels are taken at a time of 0.64 Gyr which is the seeding time of the orange SMBH, while the blue SMBH was seeded 0.42 Gyr prior to this. This halo shows no signs of any major merger around the time of the orange SMBH being seeded, even on the extended scale that is not shown in these figures. The bottom three panels of this figure show the bolometric luminosity of the in-situ DAGN, along with its physical separation and host halo growth history. At $t = 0.64$ Gyr we see the orange SMBH being seeded 2 pkpc from the blue SMBH, and through out its lifetime, it remains between 4.5 and 0.2 pkpc of its in-situ DAGN companion before merging at $t = 1.54$ Gyr with one of the other SMBHs in the halo which are shown as red crosses in the top panel. The blue SMBH along with two other SMBHs shown as red crosses will eventually

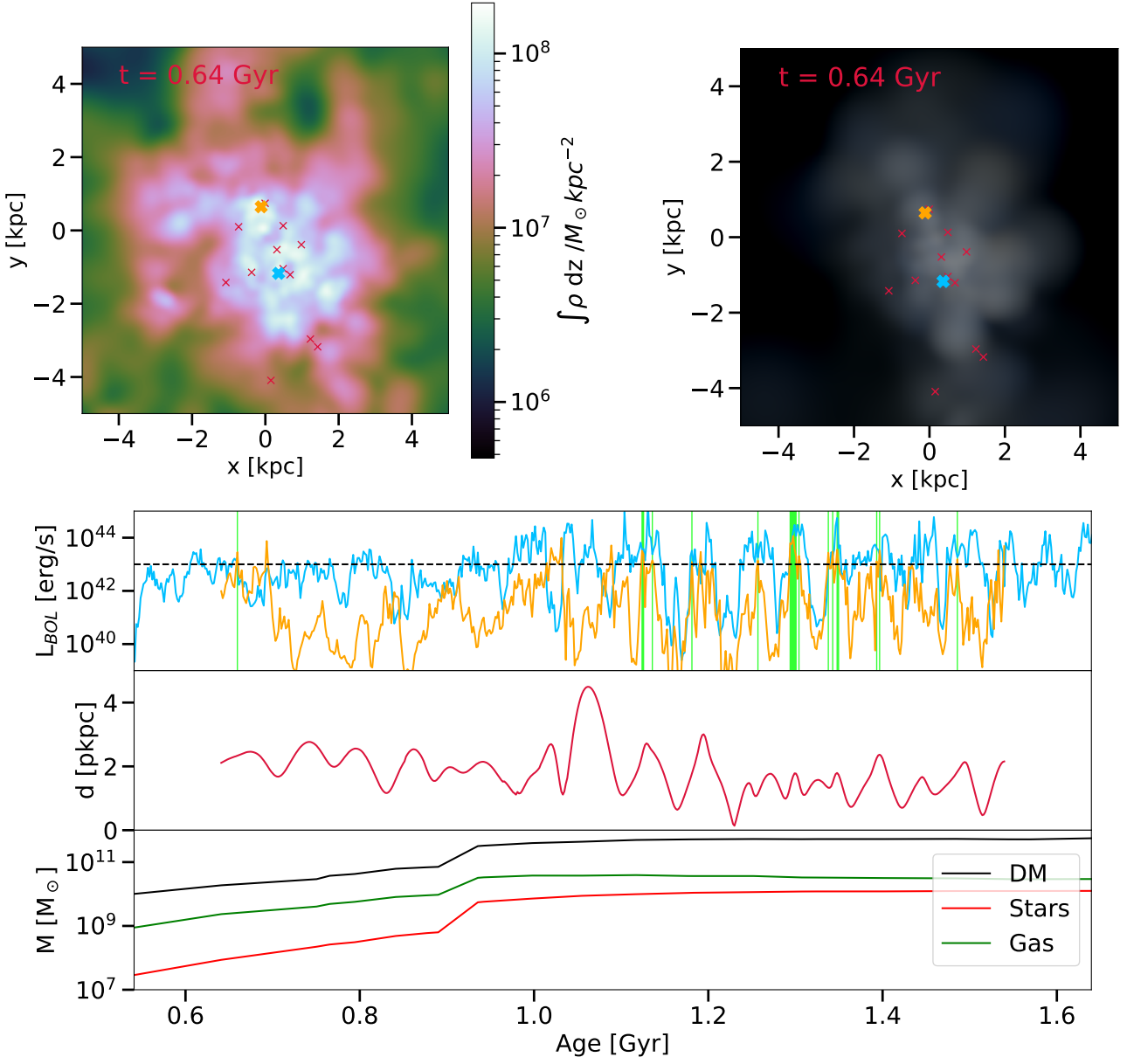


Figure 20: Case study of an in-situ DAGN. Top two panels show the gas column density and stars (UVJ colors assuming a Kroupa IMF) of a halo that contains a in-situ DAGN, with orange and blue crosses marking the SMBHs that make up the in-situ DAGN. Both panels are at a time of 0.64 Gyr, the seeding time of the orange SMBH. Red crosses show all other SMBH in the halo. Bottom three panels, in order, show the bolometric luminosity of the orange and blue SMBHs, with the dashed line being the luminosity criteria for AGN and lime regions showing DAGN phase times, the physical separation of the SMBHs, and the growth history of the halos dark matter, stars, and gas.

merge with this branch prior to 2.33 Gyr. At the time of the orange SMBH's seeding, the halo is undergoing minimal growth with only a small amount of baryonic and dark matter accreting onto the halo. With the only clear signs of a merger occurring at $t = 0.89$ Gyr, long after the seeding of the in-situ DAGN. On the luminosity plot, the dashed line shows the luminosity criteria for a DAGN while lime regions show times where both SMBH surpass this luminosity threshold and are in an DAGN phase. It should be noted that when a SMBH particle is seeded, it rapidly accretes nearby surrounding gas until the particle reaches its seed mass, to conserve mass in the simulation. This rapid accretion artefact at the seeding time is removed when calculating the luminosity. The pair undergoes a small phase of DAGN activity roughly 20 Myrs after the orange SMBH seeds. But later in its lifetime, past $t = 1.1$ Gyr, multiple episodes of longer duration DAGN phase occur. This ultimately gives the in-situ DAGN a duty cycle of 3.55%, meaning for 3.55% of the orange SMBH particle's lifetime it undergoes a DAGN phase with the blue SMBH. These orange and blue in-situ DAGN are not the only DAGN in this halo. In total 4 pairs from the top two panels undergo a DAGN phase all created via the in-situ mechanism. In 3 of these pairs, the blue SMBH is the brightest. The last DAGN does not involve the blue or orange SMBH at all.

How In-Situs Effect Results

Due to the tenuous possible existence of these in-situ DAGNs and their high dependence on the seeding model being used, it is important to quantify how much this population of DAGN effect the results of this work. We do this by recreating the plots shown in the results section but only including DAGNs that can be traced back to a galaxy merger. Figure 21 shows an example of such a result with the in-situs taken out. This figure plots the same data as in Figure 17 but with all in-situ DAGNs removed from the analysis, plotting the average time between the merger of the SMBHs that make up a DAGN, relative to their DAGN phase. What can be seen on this graph is similar to what can be seen on many other plots when the in-situ DAGNs are removed, that there is little to no qualitative difference in the graph. All conclusions drawn from the this graph and nearly all others remain the same.

One plot, however, that does drastically change is the merger and DAGN

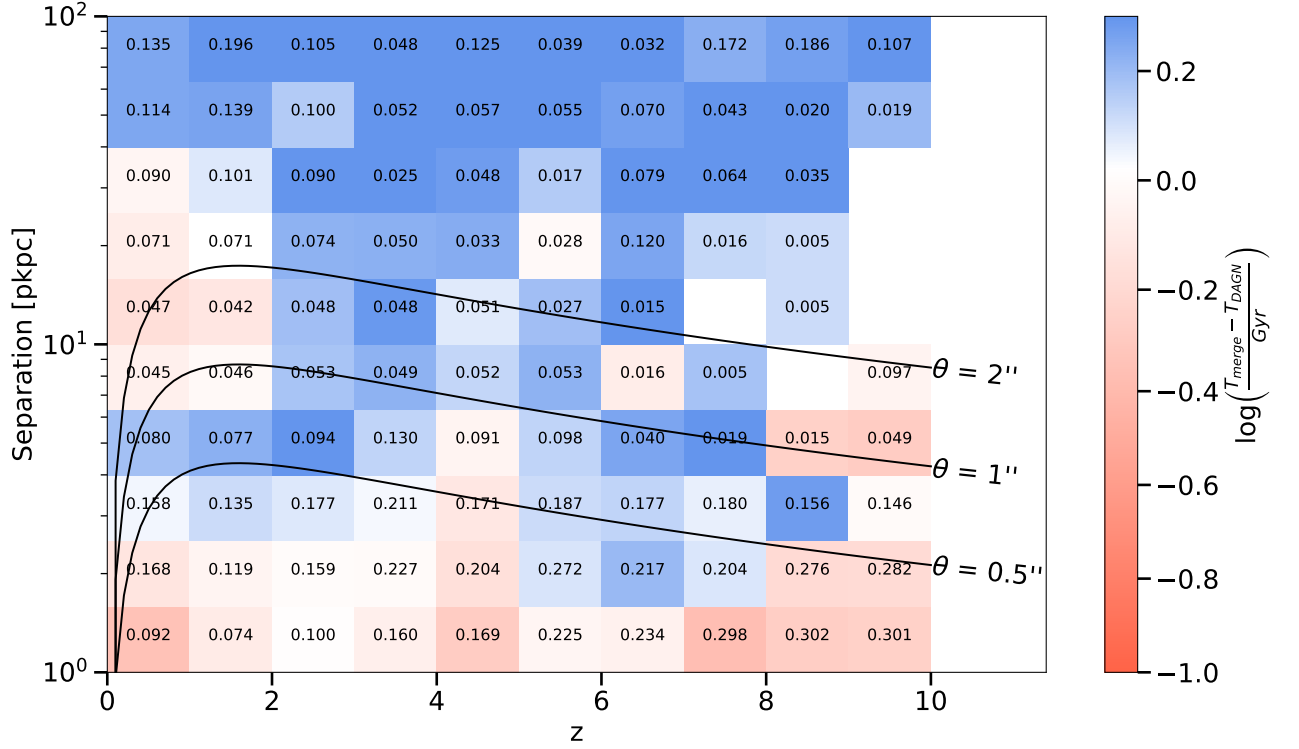


Figure 21: Same as Figure 17 but in-situ DAGNs are removed from the analysis. There is little qualitative difference seen when removing in-situ DAGNs. All instances of DAGNs from binaries that coalesce prior to a Hubble time with in-situ DAGNs removed, binned by separation of the pair and redshift of the Dagn instance. Coloured by the average time between the numerical merger of the binary and Dagn instance. Numbers represent the fraction of Dagn instance in a redshift bin that occur at that separation. Black lines represent the physical separation as a function of redshift for angular separations of $2''$, $1''$, and $0.5''$.

rate comparison plot of Figure 4. The bottom of Figure 22 plots this data again but with the in-situ Dagn removed from the analysis, it is compared to Figure 4 reprinted at the top of this figure. Two drastic changes can be seen from this plot when the in-situ DAGNs are removed. Firstly, the blue dashed lines no longer closely follows the solid blue line with both lines showing distinctly different shapes, regardless of the renormalisation of the merger subpopulations Dagn instance rate. This means the removal of the in-situ population completely decouples the rate of SMBH mergers and the rate of Dagn activity from SMBHs pairs that merge. This changes the conclusions

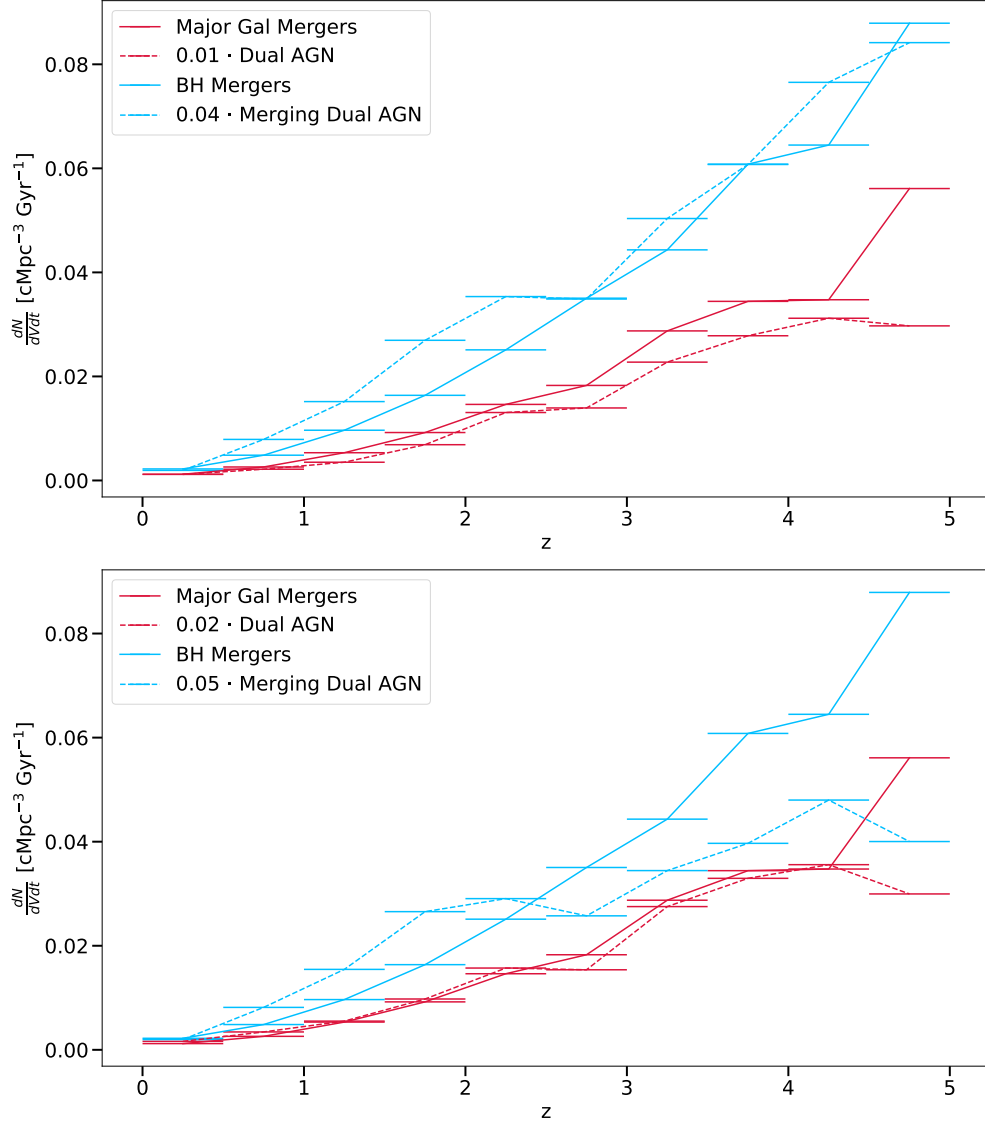


Figure 22: (Top) Same as figure 4. (Bottom) Same as Figure 4 but in-situ DAGNs are removed from the analysis. Comparison of rates per unit volume for various events. Solid red being major galaxy mergers, dashed red being all DAGN instances, solid blue being all SMBH numerical mergers, and dashed blue being all DAGN instances from binaries that merge prior to a Hubble time. As a galaxy mergers do produce and SMBH mergers may induce many DAGN instances, we renormalise both the all DAGN instances and merging DAGN instances by 0.02 and 0.05 for visualization purposes. Removing in-situs from this analysis causes the blue lines to no longer track each other and requires the renormalisation constant for the dashed red line to change from 0.01 to 0.02 in order for both red lines to closely match.

made from Figure 4 that DAGN activity rate is coupled to the SMBH merger rate, to them being completely decoupled from one another. This is a clear sign that the merger of the pair does not induce or trigger any DAGN activity, instead the pair undergoes DAGN phases independently, with the eventual merger occurring coincidentally at a later time. Secondly, while the red lines still closely match each other in shape and still show signs of coupling between the rate of DAGN activity and the rate of major galaxy mergers, the renormalisation factor in front of the DAGN rate has been changed from 0.01 to 0.02. As a DAGN instance can occur every million year timestep (time resolution of SMBHs in Romulus25), this means that every major galaxy merger, on average, creates only 50 Myr of DAGN activity when in-situ DAGNs are removed, instead of the 100 Myrs of DAGN activity reported in Figure 4 when in-situs were included in the analysis.

Can In-Situs be Identified

Given that the host of a galaxy merger created DAGN may lose all morphological and kinematic signs of having recently undergone a galaxy merger, it may be difficult to decipher between a galaxy-merger created DAGN whos host has lost all signs of undergoing a merger and an in-situ DAGN. This makes identifying an in-situ DAGN challenging. However, Figure 16 suggests a possible path for disentangling these formation channels in the early Universe. This plot, that shows the average time between galaxy merger and DAGN activity for galaxy merger created DAGN, suggests all high-z galaxy merger created DAGNs are, on average, in a pre galaxy merger phase. However, Figure 18 shows that nearly all DAGNs at $z > 7$ are in-situ DAGNs. This implies that many of the observed high-z DAGNs that are in the same galaxy, like that of [Übler et al. \(2024\)](#), may actually be created by the in-situ creation mechanism and not galaxy mergers. Even under stricter seeding prescriptions than the one used in Romulus25, the rarity of major galaxy mergers in the early Universe would cause the in-situ formation channel to still be a prominent channel for many of the high-z DAGN systems that reside in the same galaxy- making these types of system important for further studies on the possibility of an in-situ formation channel.

6 Conclusions

In this thesis we investigated the DAGN population of the Romulus25 cosmological simulation. Romulus25's unique set of sub-grid models for SMBH dynamical friction, accretion, and seeding, mixed with its high resolution, allows for early SMBH growth and dynamical history to be tracked down to sub-kpc scales. All this makes Romulus25 particularly well suited for such a study. We find that:

- The merging subpopulation of DAGNs are present and quite prominent at all redshifts, but peak in activity at around $z = 6$. In addition, nearly all of these merging systems are LISA detectable, and about 1/3 of all LISA detectable mergers of SMBHs undergo a DAGN phase within 1 Gyr prior to their merger.
- DAGNs typically reside in the most massive galaxies at every epoch, and the brighter SMBHs in DAGNs tend to accrete much more efficiently than the single AGN population.
- While galaxy mergers tend to enhance BHAR and host SFR, and DAGNs act as a tracer of recent galaxy mergers, we find that DAGN activity does not always indicate any BHAR or SFR enhancement from galaxy mergers. At $z > 3$ the large BHAR and host SFR of DAGNs does coincide with DAGN activity, thus DAGN activity traces merger driven enhancement in the early Universe. However at $z < 3$, we see no enhancement to the BHAR or host SFR of DAGNs that can be attributed to galaxy mergers. This is due to the timing offset between low- z DAGNs and the galaxy merger that made them breaking the link.
- DAGNs in massive galaxies exhibit a universal duty cycle distribution, while in lower mass galaxies the duty cycles are more variable likely due to the more chaotic nature of the gas in such systems disrupting the accretion of DAGNs. The merging DAGN subpopulation also shows some of the highest duty cycles, which we show is driven by prolonged DAGN activity at small SMBH separations which the merging population is more likely to reside at.

- We find average timescales between DAGN activity and the galaxy merger that formed the DAGN, and also DAGN activity and the eventual merger of the SMBH that comprise the DAGN. We find these timescales as a function of DAGN separation and redshift. We find that most observed DAGN systems reside in pre- or peri-merger galaxies, and the majority are likely more than 1 Gyr away from SMBH coalescence.
- We find a novel formation channel for DAGN that require no galaxy merger. Romulus25 predict this in-situ population dominates in the early Universe and is responsible for many DAGNs in the local Universe. However, the significant uncertainties about SMBH seeding make their existence tenuous, while resolution effects make their study in cosmological simulation challenging. However, removing them from the previous analysis has little to no effect on our results, with only a slight change in the conclusions drawn from the rate comparison plot of Figure 4.

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7 Appendix

A

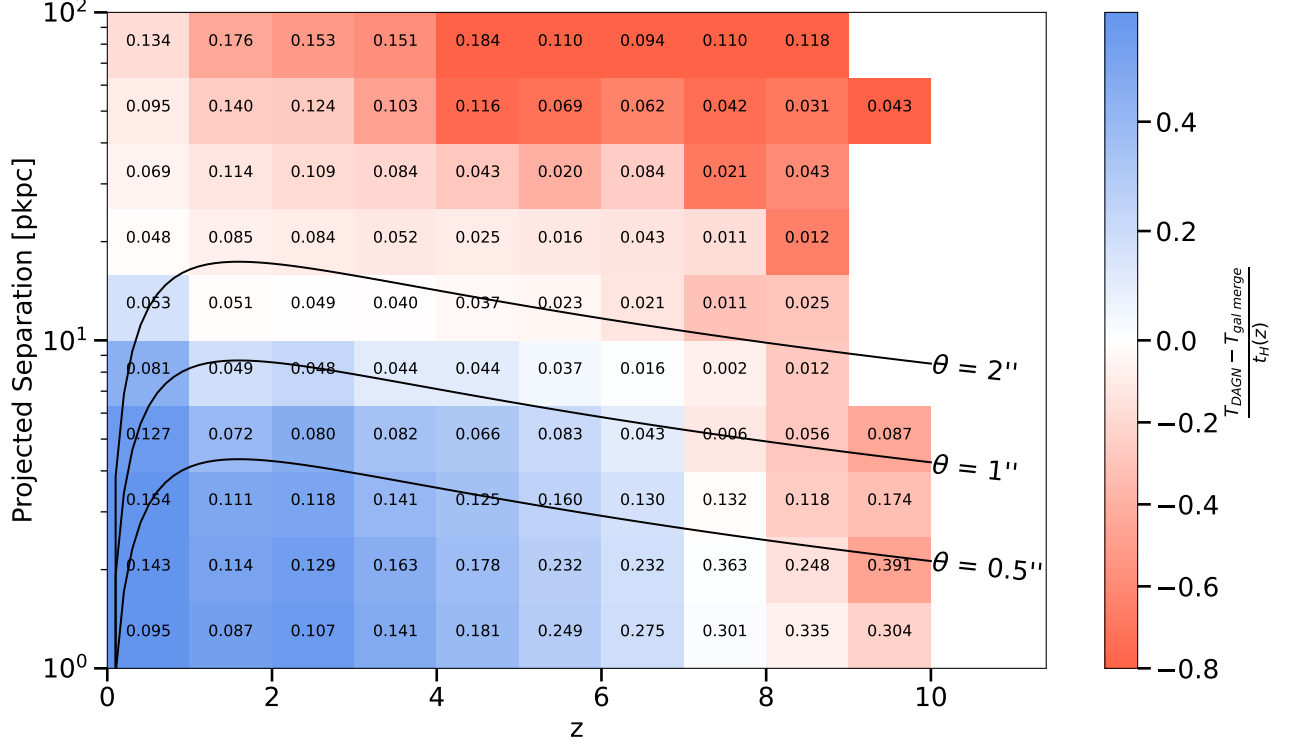


Figure 23: Same as Figure 16 but y-axis is projected separation instead of separation, a distance metric used more often by observers when reporting DAGN separations.

Figure 23 plot the same data as Figure 16 but with projected separation instead of separation. We find no qualitative difference in the plot depending on the type of separation used for the plot. To calculate projected distance instead of distance, we set the the z positional value of the SMBHs to 0 such that the projected separation is:

$$d = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$$

This process assume the observer of the system is always observing along the z -axis, and therefore may bias the distribution of projected separation if there are anisotropies in the simulation. To overcome this, we also check the plots

assuming the systems were being observed along the x-axis and the y-axis and found no qualitative difference in the results.

B

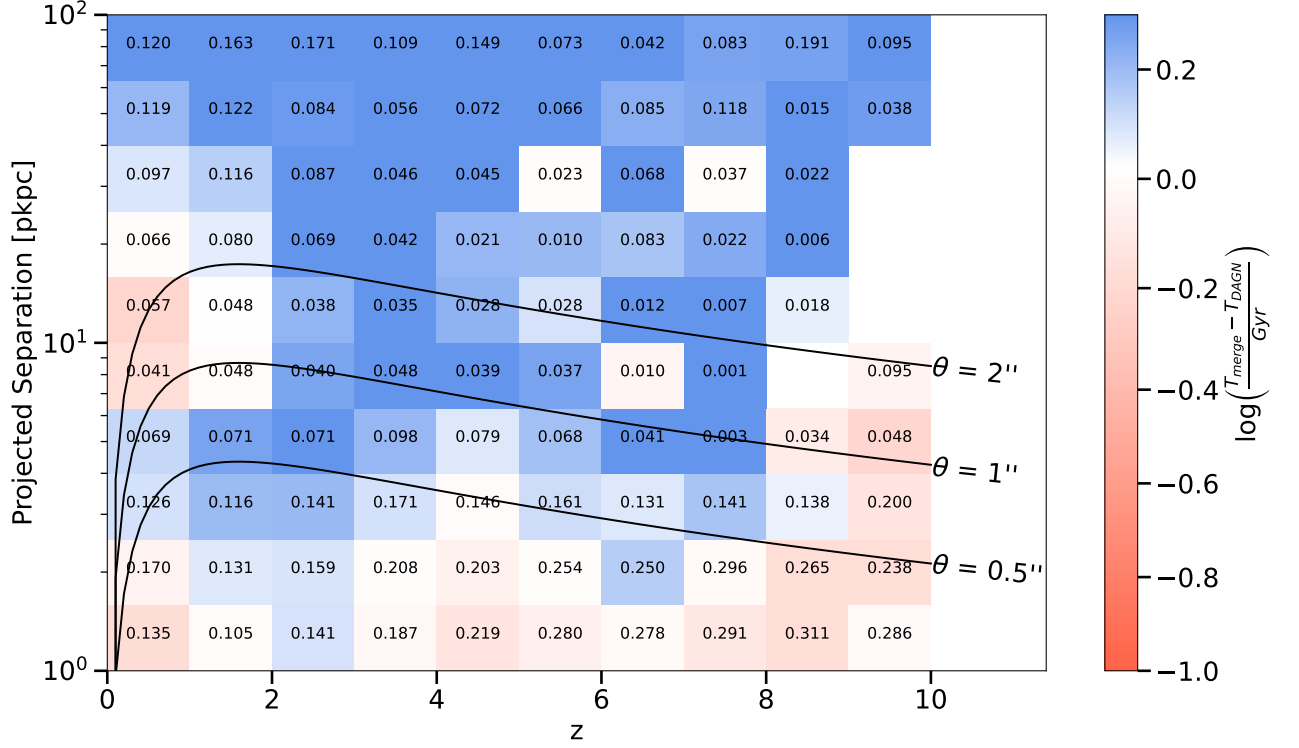


Figure 24: Same as Figure 17 but y-axis is projected separation instead of separation, a distance metric used more often by observers when reporting DAGN separations.

Figure 24 plot the same data as Figure 17 but with projected separation instead of separation. Again, we find no qualitative difference in the plot depending on the type of separation used for the plot. Projected distance is calculated as done in appendix A, assuming the pairs are being observed along the z-axis. This was also done assume the pair was observed along the other axes. For all observing axes assumed, we found no qualitative difference in the plot.