PhD research proposal

Unveiling the formation of massive galaxies across cosmic time

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Abstract

The current hierarchical model of structure formation and evolution applies to both dark matter and baryons, giving rise to more massive dark matter halos and galaxies with time. However, new JWST observations of massive (stellar masses around $10^{11}\mathrm{M}_\odot$) quiescent galaxies at $z \sim 3-5$ appear to contradict this model as they exist in larger number densities than expected. It is not completely understood yet how this rather common population of galaxies is able to assemble their huge masses and undergone their star-forming phase at such early times, neither which mechanisms are capable of turning off catastrophically the incipient star formation. There are several hypothesis that have been proposed: extreme star formation efficiencies would be necessary to form the stars first, but afterwards galaxy processes such as Active Galactic Nuclei (AGN) feedback would be required to prevent the gas from cooling and subsequently form stars again. In this thesis, we aim to model galaxy formation and evolution via semi-analytic models of galaxy formation to tackle these questions about the massive quiescent galaxy population across cosmic times. The idea is to carry out an analysis of the global properties of these galaxies, as well as tracking them across cosmic time to unveil their progenitor and descendant counterparts and find possible evolutionary links between different galaxy populations (e.g. massive-quenched galaxies and QSOs). We will compare the results of at least two semi-analytic models with differing treatment for the modelling of the baryons. We will then compare both models with upcoming JWST observations from the large program OutThere (PI Glazebrook). This analysis is essential to have a better understanding not only of the onset of massive quiescent galaxies, but of galaxy formation and evolution in general from both the computational and observational points of view.

1 Research project

1.1 ΛCDM: hierarchical model

Galaxies form on cosmological timescales embedded in the cosmic web, hence, we need a cosmological model to describe galaxy formation and evolution. The current cosmological model supported by observations is the so-called Λ cold dark matter (ΛCDM) model, in which dark energy driving the accelerated expansion of the universe contributes around 70% to the energy density content of the universe, while the remainder part is attributed to matter. The matter content is dominated by dark matter (DM), contributing more than 80%, and only the remaining 20% is accounted for by baryons. Therefore, the visible matter that makes up the light we observe from galaxies contributes a small fraction to the matter budget.

The ΛCDM universe is isotropic and homogeneous at large scales. However, to form structures such as galaxies, we need some tiny deviations from this homogeneity, which are thought to be originated by quantum perturbations imprinted in the early universe. These tiny perturbations give rise to small matter overdensities that grow due to gravity. Once the overdensities are large enough, they are able to decouple from the Universe's expansion and collapse gravitationally.

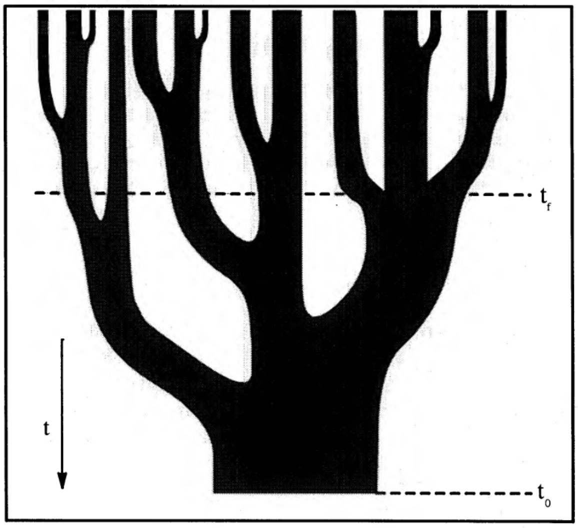

Figure 1: Schematic representation of the hierarchical model for the DM overdensities from C. Lacey et al. (1993) in the form of merger trees. Gravitationally bound overdensities, a.k.a. DM halos, grow with time via accretion and mergers.

The growth of matter overdensities occurs in a hierarchical or "bottom-up" scenario (as pictured in Figure 1), which means that small overdensities merge with each other giving rise to larger ones. DM, only affected by gravity, starts to form structures and collapse before the baryonic content, since at that time baryons are still coupled to radiation. The DM overdensities' collapse generates bound structures or halos with a gravitational potential strong enough for baryons to fall into by the time they are free to form structures. Both DM and baryons continue collapsing into the DM halos in such a way that baryonic structures or galaxies are formed inside them in what is referred to as "biased galaxy formation" (White et al., 1978). After baryons fall into the DM halos, they cool and condensate into a cold gas disk. In the cold disk, the conditions are suitable for star formation, giving rise to new stars and ultimately galaxies.

Following the "bottom-up" scenario, both DM and baryons evolve hierarchically, producing more massive halos and galaxies at later times. The two channels of growth are: halos/galaxies accreting matter smoothly from the surrounding medium and halos/galaxies undergoing mergers. However, baryons do not evolve in the same way as DM owing to their different nature. DM is just affected by gravity, which generally leads to DM halos monotonically increasing in mass with time; while for the baryons the picture is more complex since they are able to dissipate the potential energy by radiative processes, leading to the collapse of the gas and eventually to star formation. Feedback effects can then start to play a role in galaxy evolution. Supernova explosions and stellar winds from stars (stellar feedback), as well as accretion onto the supermassive black hole (SMBH) in the galaxy center or jets coming from this SMBH (AGN feedback) can lead to the ejection of gas from the galaxy and/or prevent gas from cooling and being accreted onto the galaxy. This prevents or at least lowers further star formation, leading to an effective decoupling between the galaxy and DM halo evolution. Galaxies thus, have stellar populations that are inconsistent with a "bottom-up" scenario, displaying even what is called "downsizing" signatures: massive galaxies in the local universe appear to have formed earlier and on shorter timescales than lower mass galaxies (e.g. Thomas et al. 2010).

1.2 JWST: abundance of massive quiescent galaxies at $z \sim 3-5$

The hierarchical ΛCDM model of structure formation has been widely successful describing the large scale structure of the universe and its evolution, providing evidence for the cosmic microwave background (CMB) or the matter power spectra (Planck Collaboration et al., 2020) in which galaxies are distributed in a cosmic web pattern. However, at scales smaller than ~ 1Mpc there are some well-known tensions not explained by the model (Bullock et al., 2017) as e.g. missing satellite galaxies or the cusp/core problem for the DM density profiles. Apart from that, new high-redhsift JWST observations seem to introduce more potential tensions for ΛCDM by suggesting the existence of very massive galaxies at $z > 10$ (Labbé et al. 2023, Boylan-Kolchin 2023) and massive-quiescent galaxies at $z \gtrsim 4$ (Carnall, McLeod, et al., 2023).

JWST has brought a completely new era in the observational field thanks to its deep resolution and high sensitivity. Its new instruments designed for near and mid-infrared (IR) astronomy allow us to image early/distant/high-redshift objects (as early objects have their optical light redshifted to the IR), which were not possible to observe before due to their faintness and red colours. Recent observations from JWST reported numerous massive, quiescent galaxies at relatively high redshift $z \sim 3-5$ (Nanayakkara et al. 2022, Carnall, McLeod, et al. 2023).

Massive quenched galaxies at $z \sim 3-5$ have the following properties: low star formation rates (SFR) (obtained from emission line tracers), large stellar masses around $10^{11}\mathrm{M}_{\odot}$ (from kinematics) and stellar ages between 100Myr and 1Gyr (from absorption lines). They were formed very early at $z > 6$ (even some at $9 < z < 12$) during the epoch of reionization and also show a large variety in quenching timescales. The record right now for the earliest galaxy found of this type is a galaxy imaged at $z = 4.658$ (Carnall, McLure, et al., 2023), just 1.25 Gyr after the Big Bang. The fitted spectral energy distribution (SED) for one of them is shown in Figure 2. Thanks to the derivation of their star formation histories (SFHs), it is possible to infer that their SF peak already happened and now they are gas-starving. Thus, these galaxies primarily formed at very high redshift, underwent a star-forming phase (likely a starburst-phase) and afterwards the SF was turned off.

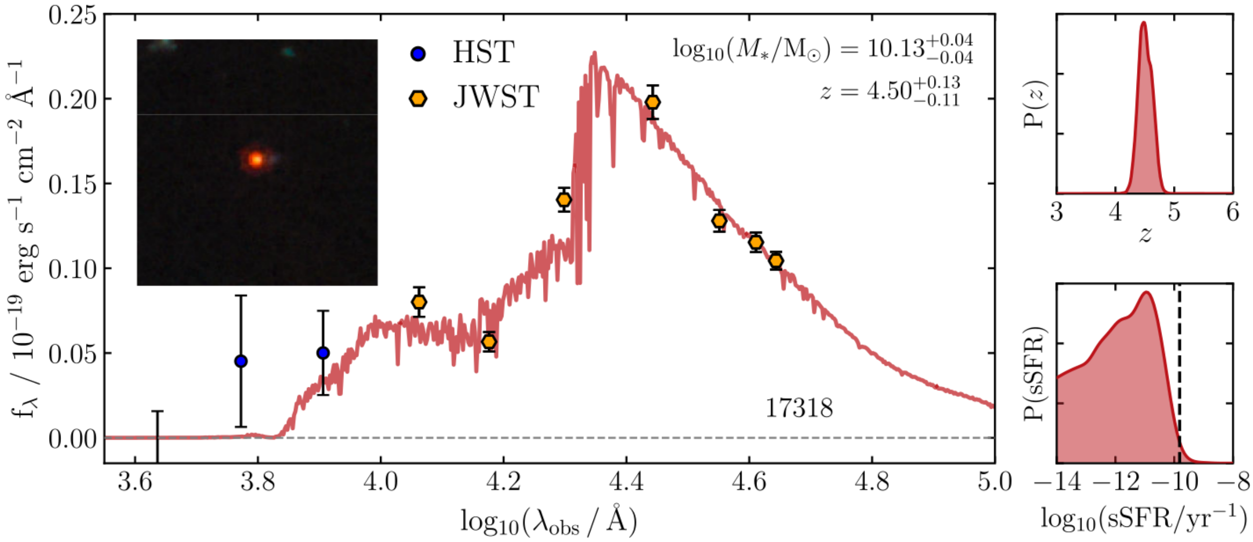

Figure 2: Spectral energy distribution (SED) and cutout images for one of the galaxies found in Carnall, McLeod, et al. (2023). The blue datapoints come from HST observations, the yellow ones are the new JWST results. The red solid line is the corresponding SED model. The right panels show the probability distribution function for the redshift and specific star formation rate (sSFR) of the galaxy (the dashed vertical line in the sSFR panel represent the threshold for quiescence adopted by the authors).

Similar galaxies had been found previously (e.g. Glazebrook et al. 2017, Schreiber et al. 2018, Weaver et al. 2022). Nonetheless, JWST has found that this population is not as scarce as it was thought to be (Nanayakkara et al. 2022, Carnall, McLeod, et al. 2023) with a number density evolution for these massive quenched galaxies that is 3-5 times higher than previous works (as can be seen in Figure 3, compared to previous observational data and other galaxy stellar mass function (GSMF) estimates).

The main problem is that it seems it is not possible to reach the number densities constrained by the JWST observations with the hierarchical ΛCDM model, specially if these galaxies quenched a few hundred million years before they are being observed, as the derived SFHs suggest. On the one hand, it is not well understood how to assemble that number of massive galaxies in those short timescales in the early universe. Some possible formation scenarios put forward include that they should have had higher SFRs at earlier times, which means they either had a higher SF efficiency (more massive halos could be more SF efficient at earlier times if AGN feedback is not yet affecting galaxies) or they had an extreme and short starburst phase (which could be an option given the post-starburst-like spectrum of the best fit in Figure 2).

Moreover, it is not clear how they quenched: there must have been some mechanism that stopped star formation (gas must be suppressed or heated so that no SF can proceed). Currently, the most promising one would be feedback coming from AGNs due to the high SMBH masses reported in these galaxies (Carnall, McLure, et al., 2023). It has also been proposed that this population could be connected to QSOs or high-redshift sub-mm or dusty star-forming galaxies (DSFGs) (Long et al., 2022) (galaxies very bright in the sub-mm wavelengths due to their high SFRs and the huge amounts of dust) before the quenching phase. The other possible explanation for these galaxies is that there could be potential systematic effects. This option would maintain our understanding of the current cosmological model, but more studies critically analysing the derivation of stellar masses or SFHs are necessary.

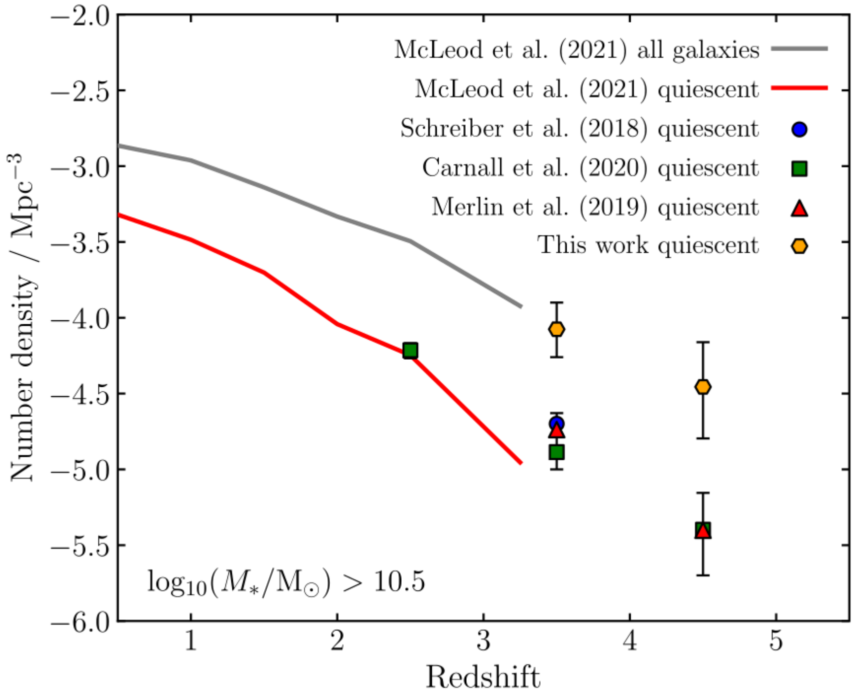

Figure 3: Number density evolution of the massive quenched population with the new JWST results from Carnall, McLeod, et al. (2023) (yellow datapoints). The other datapoints are previous estimates for quiescent galaxies, pre-JWST era, while the solid lines are some GSMF estimates. The new JWST data appears to prefer a much higher number density than previous estimates.

A natural way to interpret the JWST observations above is via cosmological simulations. These simulations are based on the ΛCDM model, thus they allow us to understand how they fit within the current cosmological framework. Moreover, they enable us to test to which extent models for baryon mechanisms like AGN feedback, gas-dust depletion timescales, SF via starburst or the treatment of dust at high-z; implemented in simulations allow for the existence of these galaxies. In fact, as different simulations rely on different prescriptions of galaxy processes, we can use them to explore which one of them reproduces observations. Consequently, cosmological simulations are essential to deal with this massive quiescent population independently of the final scenario: either to have a better knowledge of the formation, quenching and evolution of these galaxies, and/or to show potential shortcomings with the observational inferences of mass, SFHs, among other galaxy properties.

1.3 Using semi-analytical models of galaxy formation to interpret observations

Cosmological simulations trace the evolution of matter (baryons and DM) across time and they have become an essential tool in interpreting observations across different cosmic times and environments. There is a wide variety of options to model the baryonic content of the universe (Wechsler et al., 2018), with the most physical ones being hydrodynamical simulations and semi-analytical models (SAMs). The former solves the equations for both DM (gravity) and baryons (gravity and fluid dynamics), as well as their interactions. Thus, they are quiet computationally expensive and it is more difficult to produce statistically reasonable results concerning massive objects in large volumes with enough resolution. A more efficient way to model baryons are SAMs, which are ideally placed to explore the mechanisms and the prescriptions that take part in galaxy formation and evolution in large cosmological volumes. Considering the number densities for the massive-quiescent galaxies in Figure 3, we will need simulated volumes large enough to have a statistically representative sample of them and that is why we will focus primarily on SAMs to analyse the JWST observations.

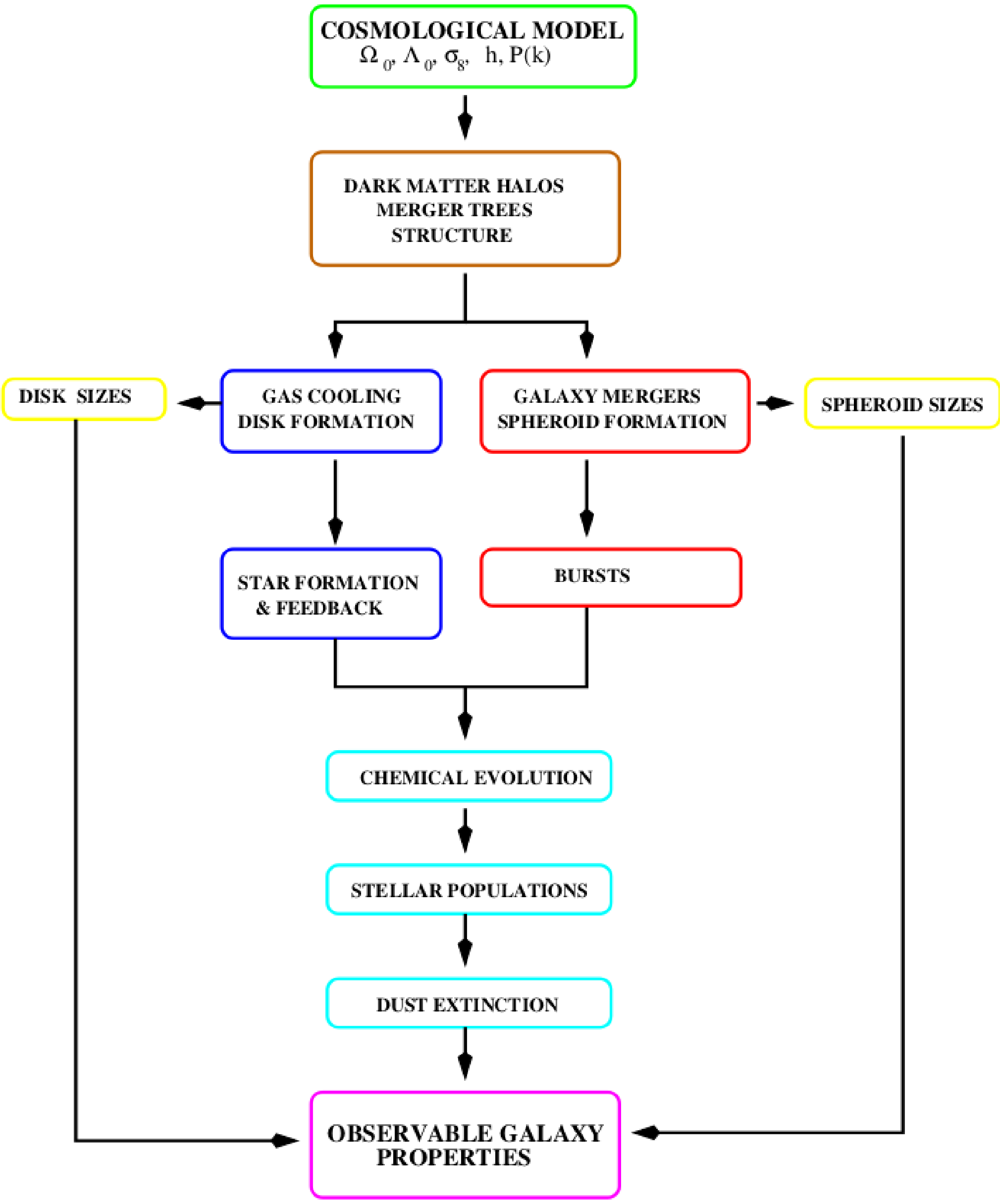

Figure 4: Schematic representation of the processes involved in galaxy formation and evolution modelling from Baugh (2006).

SAMs separate the problem of the evolution of the large scale structure from that of baryon evolution. First, one solves for the large scale structure evolution of the universe, which is dominated by DM (i.e. the universe is evolved due to gravity only). Then the physics governing baryons and leading to the formation and evolution of galaxies is modelled using the cosmic web evolution as the backbone. In the practice, this looks first like running a suite of DM-only simulation, and from there reconstructing the assembly histories of DM halos. Then SAMs solve a series of analytical equations describing the baryonic physics. This leads to the evolution of the different baryonic components (gas, stars, SMBHs), involving multiple processes taking place in galaxies (SF, mergers, gas outflows and cooling and growth of black holes, among others). A representation of the physical processes considered by SAMs is shown in Figure 4. The equations contain of the order of 20 free parameters, that describe our ignorance about those processes, and that are usually tuned to reproduce certain observables such as the galaxy stellar mass function, luminosity functions, stellar-BH mass relation or Tully-Fisher relation. Although many free parameters are present in the model, many have small effects on the galaxy population and only a handful play a significant role and are worth to vary (Bower et al., 2010).

A significant step between producing the N-body simulations and running SAMs is the identification of gravitationally bound DM halos and the reconstruction of their merger histories. In order to do it, we need to: (I) first employ **halo finder** codes to identify DM halos in the multiple cosmic times generated by these simulations with normally a 2-level hierarchy (halo-subhalo); (II) secondly **merger tree** codes are necessary to make the progenitor-descendant connection between halos at consecutive output times. After running these codes, we have the mass assembly history or merger tree for each structure on top of which the SAMs are run. It is well known that both types of codes mentioned above in general work well, but when dealing with massive systems undergoing merger events they tend to struggle assigning the mass to each halo or connecting halos properly between consecutive times. In such a way, the codes do not always produce reliable results, what has been reported in the literature (Srisawat et al. 2013, Avila et al. 2014, Srisawat et al. 2013, Poole et al. 2017), but a quantification of how they affect the output generated is still needed. As explained before, these issues appear to be more prevalent in the more massive halos whose assembly histories are more complex, thus modelling massive galaxies (which are hosted by massive halos) using SAMs requires consideration of these problems. As a minimum one needs to be aware of the issues that can possibly arise and understand how they can affect the resulting galaxy population.

1.4 Aims

In this PhD, we will run several SAMs such as SHARK (Lagos et al., 2018) (in its updated version with a more detailed recipe for AGN feedback; Lagos et al. in preparation) and GALFORM (C. G. Lacey et al., 2016) over cosmological DM-only simulations to analyse massive galaxies. There are studies that have analysed the problem with a similar approach via hydrodynamical simulations (Lustig et al. 2023, Lovell et al. 2022) and SAMs (Weaver et al. 2022, Nanayakkara et al. 2022), but here we focus on the comparison of several SAMs and particularly the evolutionary stage of the galaxies. We would like to understand their mass assembly and quenching mechanisms. My PhD plan is divided into 3 main projects.

1. First, we will generate assembly histories of massive DM halos as correct/smooth as possible to make sure we obtain trustworthy results when running the SAMs. In order to do that, we need to address the main failures in the merger trees of state-of-the-art simulations generated by different combination of halo finder and merger tree codes. Once the issues are identified, we would like to find why they arise and if they are relevant. The ideal scenario would be to get rid of them, but if it is not possible we want to minimise them exploring combinations of DM halo codes. In case the failures are still present, we would know at least the frequency in which they happen and they affect our results.
2. Second, we will run the SAMs and obtain predictions for quenched galaxies across cosmic time and dynamical mass. In this second project, we will focus on the properties of

the galaxies at its actual time: studying several global properties such as their number densities, stellar mass function, fractions, their clustering, stellar-to-halo mass relation, and the stellar mass to BH mass relation. This will give us a good understanding of the effect of AGN feedback and environmental processes in producing the population of massive quenched galaxies.

3. Finally, we will focus on the evolution of these galaxies, tracing them forward and backward. We will analyse their assembly histories, SFHs, the link with lower and higher redshift objects like sub-mm bright galaxies as in Long et al. (2022) and QSOs. It will be critical to understand how long-lived is the quenching status of these galaxies: how many restart their star formation, and if so what is the mechanism for that? We will investigate where these galaxies end up at $z = 0$, and if it is possible to predict the environments they live in and will end up at based on properties observed at high redshift.

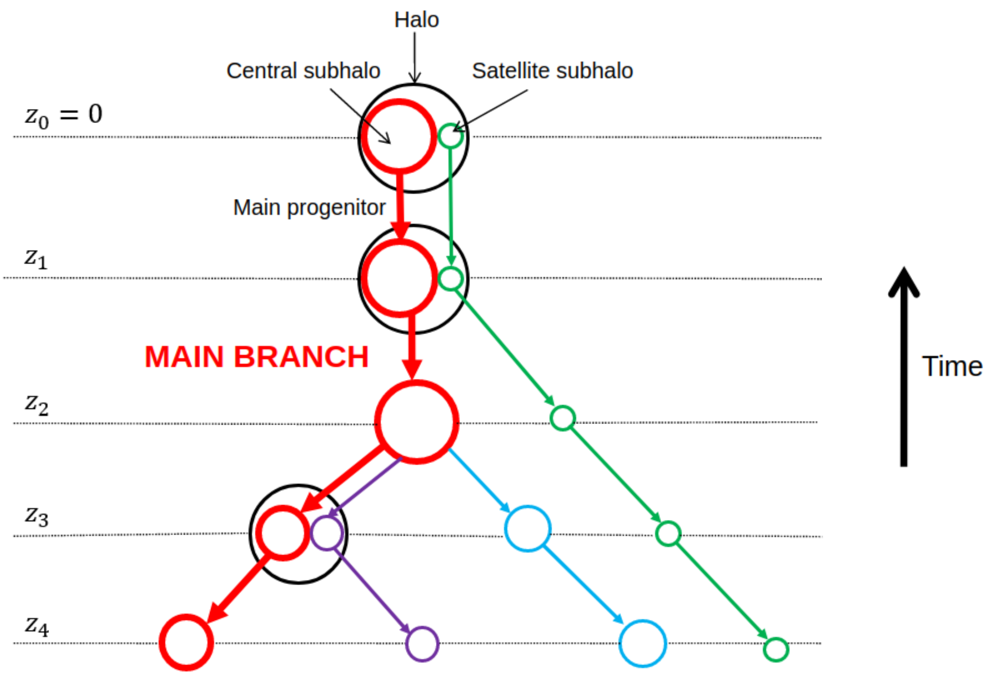

Figure 5: Diagram showing the nomenclature used regarding halo finder and merger tree codes. Each colour is associated with a different halo/subhalo: the red central subhalo follows the main branch backward; while the circle size for each structure represents qualitatively its mass.

If time allows, we would like to introduce results from the upcoming COLIBRE hydrodynamical simulation into the comparison, although we are aware we would need large simulated volumes that may not be available in the near future. Apart from this, we are part of the JWST large program OutThere (PI Glazebrook), and so we have exclusive access to exquisite data that will allow us to be at the forefront of the comparison with observations. My primary supervisor A/Prof Claudia Lagos is also an international associate in the Cosmic DAWN Centre of Excellence in Denmark and via those collaborations we also have access to proprietary results from well-known JWST surveys, such as COSMOS-Webb.

Another interesting research line we would like to explore is the analysis of the multiple definitions of quenching adopted in the observations (cuts in SFR, sSFR, the separation with respect to the star-forming main sequence (SFMS), and colour cuts as well with new proposed ones in Gould et al. (2023) to truly separate quenched galaxies from dusty obscured SF ones), critically analysing their equivalency, contamination, etc.

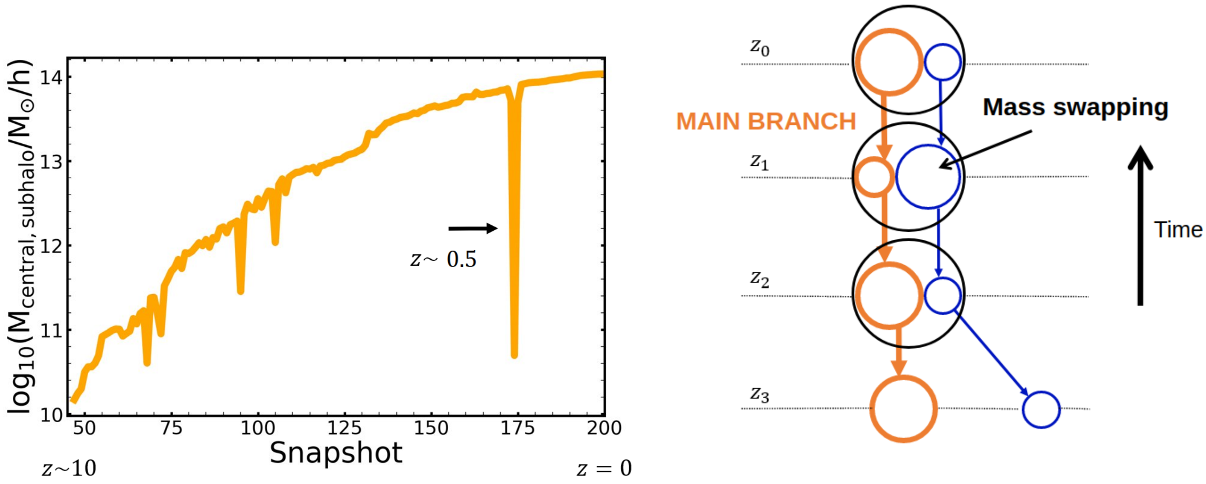

Figure 6: Mass swapping event. Left panel: mass accretion history of a central subhalo undergoing a mass swapping event. The abrupt mass loss around snapshot 175 ($z \sim 0.5$) is clearly visible. Right panel: diagram describing what it is happening in the central subhalo, where each colour refers to a different structure and the circle size represents qualitatively its mass.

1.5 Current status

We have been focused on the first project. We analysed the mass assembly histories of DM halos generated by state-of-the-art-simulations such as FLAMINGO (Schaye et al., 2023) (both DM-only and hydrodynamical run) and PMillennium (Baugh et al., 2019) (studying only 31 of the 1024 subvolumes that form the simulation) that are based on a different halo finder - merger tree code combination. The former uses VELOCIraptor (Elahi et al., 2019) as halo finder and DHALOS (Jiang et al., 2014) as merger tree code, while the latter uses SUBFIND (Springel et al., 2001) as halo finder and DHALOS as merger tree builder. To carry out this analysis we ran a new diagnostic tool called "dendograms" (Poulton et al., 2018) to have a more schematic view of the outputs that allows to critically review possible failures. This diagnostic tool did not have the proper format to process the merger trees produced by DHALOS, hence we had to implement new code to make it useful to us.

Initially, we need to introduce a bit of nomenclature employed in cosmological DM-only simulations (e.g. Srisawat et al. 2013), which we described schematically in Figure 5. The halo finder provides a list of DM overdensities that can be nested in 2 levels of hierarchy: larger overdensities/structures named **halos**, and smaller overdensities/substructures located inside these halos named subhalos at every cosmic time or snapshot. The most massive of these substructures is referred as the **central subhalo**, while the other ones are named **satellite subhalos**. When there are no more substructures inside a halo, that halo is at the same time a central subhalo. In terms of the temporal structure, every halo/subhalo has a direct **main progenitor** at the previous cosmic time of the simulation usually selected by the fraction of total or most bound mass inherited. If there is no main progenitor, it means the halo has just been found in the simulation for the first time (it has been born). Following the central subhalos that reach $z = 0$ in the simulation backwards in time through their main progenitors, we track what it is called the **main branch**.

Thanks to the "dendograms", we were able to look into the mass accretion histories of halos

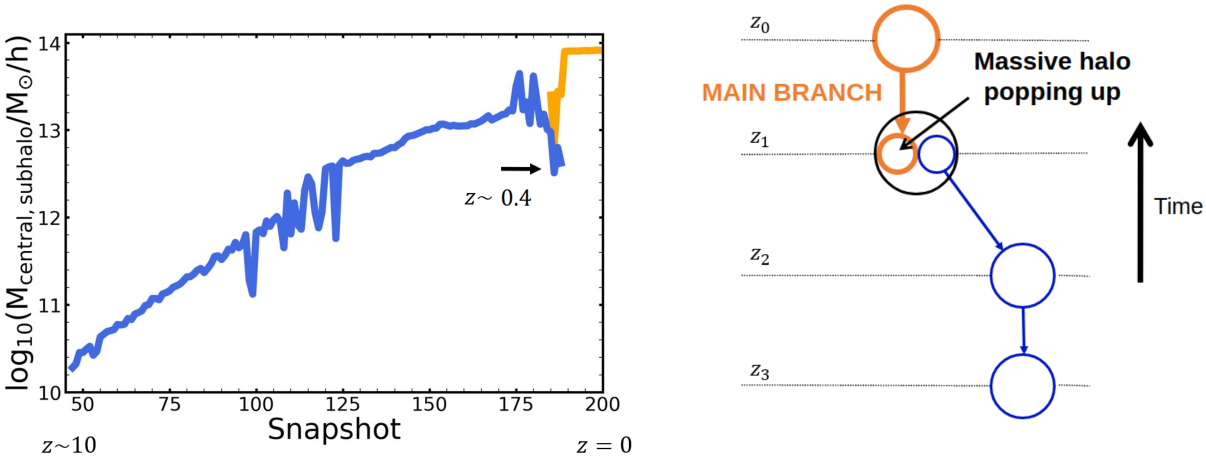

Figure 7: Massive halo popping up at late times. Left panel: mass accretion history of a central subhalo that suddenly pops up at late cosmic times, around snapshot 180 ($z \sim 0.4$). It is clear that the blue and orange halos in this case should have been linked as progenitor/descendant by the merger tree, but this does not happen. Right panel: diagram describing what it is happening in the central subhalo, where each colour refers to a different structure and the circle size represents qualitatively its mass..

along its main branch and we noticed there are 2 major issues that appear to come up in all the simulations+halo finder+merger tree codes we tested. Consequently, we could quantify these failures tracking the main branches and computing how many of these branches inherit them.

1. Mass swapping: some halos experience huge mass losses in their accretion histories, as the one highlighted in Figure 6. Most of the subhalo mass is suddenly transferred to a nearby halo, usually due to swapping in the central-satellite subhalo hierarchy. We found that these swapping events happen most of the times when the main branch halo is not the most massive. We define these events when the main branch subhalo suffers a mass loss greater than 50% of the previous mass. In the top panel of Figure 8, we show the fraction of the main branches that suffer at least one of these events during their lifetimes, as a function of the maximum mass in the main branch. We find that mass swapping affects more than half of the main branches for halos whose maximum mass is greater than $10^{12}\mathrm{M}_\odot/\mathrm{h}$, and there are even mass losses greater than 90% for a third of them. It is clear that massive halos are more severely affected.

2. Halos forming for the first time with large masses: at late cosmic times, halos with hundreds or thousands of particles suddenly pop up unexpectedly. The expectation is that halos should be born with around 20 particles, which is the minimum mass for a halo to be detected in the simulation. The lately-formed halos steal most of the mass from previously well-defined halos. This is shown in Figure 7, where the blue subhalo is being redefined, continuing as a completely different subhalo (orange subhalo) in the simulation. We quantify the frequency of these events by looking at main branch halos being born with more than 100 particles. In the bottom panel of Figure 8, we can see that they are present in around 20% of the more massive halos, even with some of them being born with more than 10000 particles. In this case, the results for the hydrodynamical simulation seem to be more correct, probably due to the fact that baryons are more concentrated and help sample the deeper parts of the gravitational potential better, allowing for a better progenitor/descendant linking. Note that these halos are specially tricky

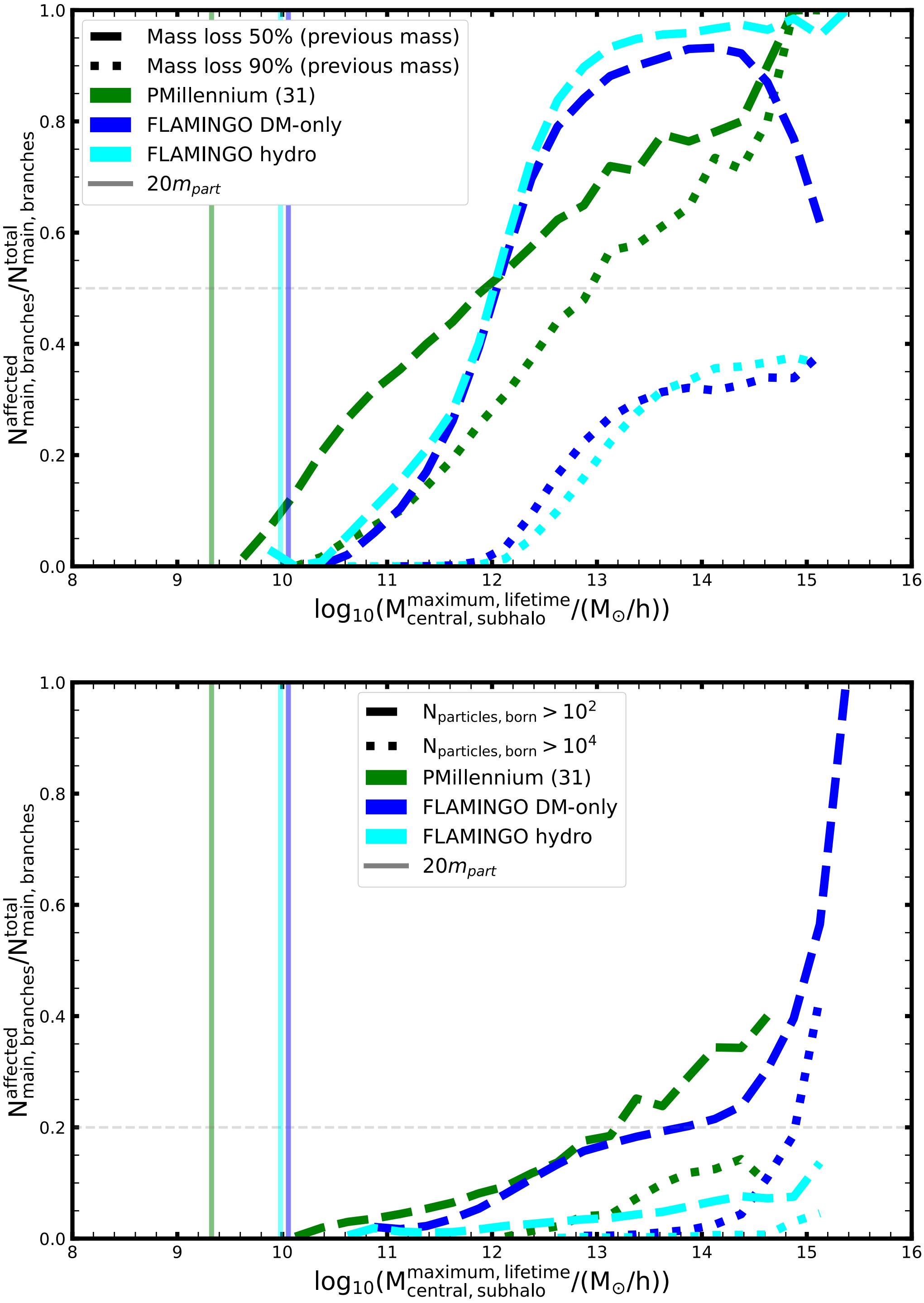

Figure 8: Top panel: fraction of main branches (central subhalos that reach z=0) that have at least 1 mass loss during their lifetime of more than 50% (dashed line), or 90% (dotted line), as a function of the maximum main branch mass for different simulations: PMillennium (green lines), FLAMINGO DM-only (blue lines) and FLAMINGO full hydrodynamics (cyan lines). The vertical lines represent 20 DM particles, associated with the minimum particle number to form a DM halo. Bottom panel: same as the top panel, but here it is shown the fraction of main branches that are born in the simulation with more than 100 particles (dashed line), or more than 10000 (dotted line) as a function of the maximum main branch mass.

for SAMs, as they translate into a massive halo forming, with a large gas reservoir that collapses to form a massive starburst, in a situation where BHs have not been able to grow. The latter implies that AGN feedback will not be effective in these situations, and we end up with overly star-forming massive galaxies. This is however, an artifact of these massive halos being wrongly linked through time rather than a failure of the physics implemented in the SAM.

In summary, both failures appear at a similar frequency in simulations that use different halo finder and merger tree codes. The main conclusion is that the failures seem to be more prevalent for the more massive halos, thus we expect them to directly impact the modelling and interpretation of massive quiescent galaxies observed recently by JWST. Our future goal is to discover the reason why these issues arise, and finally obtain a combination of halo finder and merger tree codes that at least minimises them. This could take the form of investigating different parameters in SUBFIND or VELOCIRAPTOR and DHALOS for example, or deciding to entirely adopt different codes. It will also be important to check what happens when we run the SAMs on top of the main branches with these failures, and quantify how these failures impact what we obtain for massive galaxies.

We highlight this work has been presented recently at the Australian Society for Astronomy Annual Meeting (ASA AM) in Sydney, July 2023 in the form of a poster and a sparkler talk.

We stress we have also generated our own DM-only simulations with the same cosmology and parameters as FLAMINGO, but smaller in size. These smaller simulated boxes allow us to test more easily how the VELOCIRAPTOR and DHALOS parameters affect the merger tree outputs. My role has been to run DHALOS on top of the produced data varying its parameters to see if the failures improved. This is still work in progress and we do not have definite conclusions to draw yet.

2 Research project details & Training

2.1 Confidential/Sensitive information

This project does not involve the collection of confidential or sensitive information.

2.2 Intellectual property

This project will use the codes SHARK and GALFORM. A/Prof Claudia Lagos developed the former code and is an official collaborator of the later one. I will be using other codes that are publicly available, as well as data from different cosmological simulations in which my supervisors are official collaborators such as PMILLENNIUM or FLAMINGO. Access to observations from the large program OUTTHERE will be managed by the PI Prof. Karl Glazebrook, who is an ASTRO3D cross-node collaborator.

2.3 Fieldwork information

This research will be conducted in ICRAR/UWA. If international/domestic travels are required, I will inform the GRS and follow the recommended guidelines.

2.4 Facilities

I have access to the facilities and equipment required for this research: a laptop is provided by UWA, while I have an account on different supercomputers (Setonix, OzSTAR and Hyades) in Australia to do my research.

2.5 Statistical component

I will mostly undertake the statistical analysis for this project using the Python programming language, with which I have broad experience from my Bachelor and Master years. If needed, there is a lot of expertise in astro-statistics in house at ICRAR.

2.6 Skill audit

The skills required for this PhD project are listed in Table 1 with the corresponding current and desired proficiency levels.

Research Skill	**Current rating**	**Evidence**	**Desired Rating**
Understanding and application of relevant data collection and analysis method	Competent	Master's thesis involved using simulation data and statistical analysis	Proficient
Identifying and accessing relevant literature	Competent	Master's thesis required an extensive literature review	Proficient
Use of supercomputers facilities and efficient coding	Competent	Master's thesis required the management of large datasets, and in the first 6 months of my PhD I have been heavily using different supercomputers in Australia.	Proficient
Familiar with the principles and conventions of academic writing	Basic	Master's thesis, and Scientific Writing unit undertaken at UWA	Competent
Ability to constructively defend research outcomes at seminars and conferences	Basic	Bachelor and Master's theses seminars, and recent presentation at ASA AM.	Competent

Table 1: Outline of skills required for this PhD projects with the corresponding current and desired competence.

2.7 Research project communication

In August, I will present an overview of my PhD plan to a scientific panel at ICRAR/UWA. They will provide feedback and comments about the project, and will assess the progress of my research on a yearly basis (at the start of February of 2024 - 2026). In addition, I present my progress once a month during the Computational & theory group meeting at ICRAR. The results from my PhD will be published as journal papers, with each one focusing on each one of the described PhD projects:

- Paper 1: I will study the main failures of state-of-the-art cosmological simulations such as FLAMINGO or PMillennium and quantify them. I will try to understand why these failures arise and if they are relevant. The final aim would be to solve or minimize them.
- Paper 2: I will run the SAMs SHARK and GALFORM on top of cosmological simulations to study massive quiescent galaxies. I will analyse the statistical properties of this galaxy population: number densities, fraction, stellar mass function, stellar to halo mass relation or stellar to SMBH relation, among others.
- Paper 3: I will analyse the evolutionary stage of the massive quiescent galaxies, focusing on connecting them with their progenitor and descendant counterparts. I will need to obtain their assembly histories, SFHs, quenching and formation times or if they are able to form stars again.

2.8 Approvals

There are no required approvals for this PhD project.

2.9 Data management

The data required for this project will be mainly stored in different supercomputers (Setonix, OzSTAR and Hyades) in Australia in which I have an account. Code scripts will have also a backup on GitHub.

2.10 Research project and training plan

Figure 9 displays a Gantt chart indicating the planned research training plan and the research project plan. The latter specifies the estimated time for each chapter and thesis.

2.11 Confirmation of candidature

The tasks required to be completed for the Confirmation of Candidature are as follows:

- GRS Online Induction: completed on 27 Feb 2023.
- GRS Welcome: completed on 20 Mar 2023.
- Academic Conduct and Research Integrity (ACRI9000): completed on 21 May 2023.
- Research proposal: due 9 Aug 2023.
- Research proposal seminar: scheduled 2 Aug 2023.
- Coursework to a total of 6 points: Scientific writing to complete on Aug 2023 (ICRAR/UWA requirement).
- Annual progress report: Due 10 Feb 2024.
- Annual progress seminar: To complete in February 2024.

Working hours: The working hours for this PhD are Monday to Friday 8:00 - 16:00.

3 Budget

The costs of this PhD will be covered by the GRS, the EMS faculty and ICRAR. I am part of the ASA and ASTRO3D, which provide funds for international travel and travel assistance to Schools and conferences. Table 2 shows a detailed description of the projected expenses.

Item description	**Estimated cost**	**Funds available**	**Funding Source**
Laptop computer	$1250	$1250	EMS
Additional IT supplies	$500	$500	ICRAR
Travel (domestic and international)	$8000	$4500	GRS
		$3000 (subject to approval)	ICRAR
		$500 (subject to approval)	ASA ASTRO3D
Total	$9750	$9750	-

Table 2: Outline of the budget for this PhD.

4 Supervision

Principle and Coordinating Supervisor [60%]: A/Prof. Claudia Lagos.

Co-supervisor [40%]: Prof. Chris Power.

A/Prof Lagos, Prof Power and I meet on a weekly basis. A/Prof Lagos provides guidance in the studying of the physics of galaxy formation and evolution. She developed the SHARK SAM and is also part of the team behind GALFORM. Prof. Power is an expert in cosmological simulations and SAMs, and has been running new N-body simulations for my PhD project.

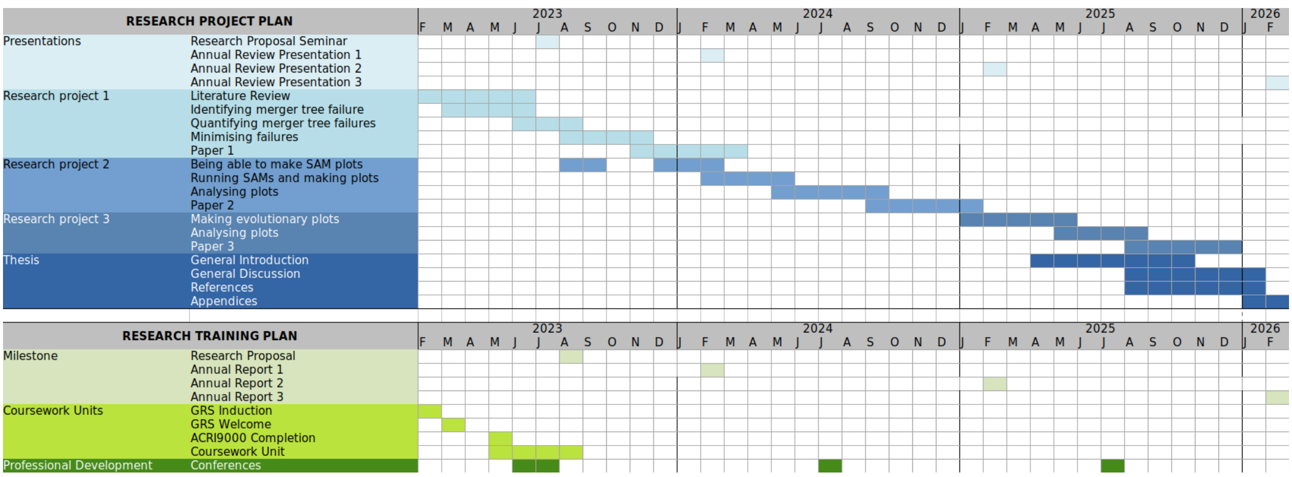

Figure 9: Timeline research plan.

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