PHD PROJECT PROPOSAL: JANUARY 2019

A COMPREHENSIVE TREATMENT OF GAS IN SEMI-ANALYTIC MODELS OF GALAXY FORMATION

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Abstract

Simulations of cosmological structure and galaxy formation have recently proven to be exceptionally powerful predictive tools in extragalactic astrophysics. In order to understand the physics behind galaxy observations to come from new generation arrays and telescopes (e.g. the Australian Square Kilometre Array Pathfinder - ASKAP, Atacama Large Millimetre Array - ALMA, James Webb Space Telescope - JWST), large-scale, physically motivated simulation-based predictions must be capable of connecting sub-galactic scales to cosmological scales. In this thesis I will be using a combination of dark matter (DM)-only and hydrodynamical simulations, together with a state-of-the-art semi-analytic model (SAM) SHARK, to study how different physical models can modify the baryonic matter build-up and regulation of DM halos throughout cosmic time. I will be revising some of the most fundamental assumptions made by SAMs regarding how gas accretion, in terms of both mass and angular momentum, is traced by DM accretion, with the aim of understanding the effect this has on the predicted galaxy populations and their gas content.

1 Research Project

1.1 Background

1.1.1 Galaxy formation: overview

At present, knowledge of the rich physics behind galaxy formation is being bolstered at pace by the complimentary results concurrently being derived from observation and theory/simulations. As such, it is becoming increasingly possible to study in-depth which mechanisms are responsible for the key features of galaxies we see in the Universe. The widely accepted "standard cosmological model" - the Λ-CDM paradigm (Planck Collaboration, 2014) - depicts a Universe composed of 70% vacuum energy, 25% dark matter (DM) and 5% baryons ("ordinary" or atomic matter) at redshift (z) = 0.

In this paradigm, the qualitative picture of galaxy formation is as follows: over-densities in the DM field collapse and become gravitationally bound to form "halos", which further attract both dark and baryonic matter. The baryonic matter (predominantly gas) that falls towards these halos can either be shock heated when crossing the virial radius of the halo (and then cool radiatively - referred to as "hot-mode" accretion), or fall-in directly to the centre of the halo (referred to as "cold-mode" accretion) depending on initial conditions. Once gas settles into a dense central region, it will naturally form a disk, and locally overdense regions of cold gas are able to collapse and form stars. In these now formed galaxies, gas can be expelled via energetic feedback from massive stars and supernovae, and also from super-massive black holes often found at the galaxy's center (known as active galactic nuclei, AGN). Both of these feedback mechanisms (supernovae feedback and AGN feedback), combined with cosmic gas accretion, act to regulate the baryon content of galaxies (see Benson (2010) for a review of galaxy formation theory). Modelling the process of baryon build-up and regulation requires knowledge of the numerous non-linear physical phenomena involved, and how they can interact, see Somerville and Davé (2015). Fig. 1(a) shows a detailed illustration of the baryon flow in galaxies.

1.1.2 Galaxy formation: observation and theory

Current observational constraints on baryon build-up in galaxies is somewhat limited, the main calibrator being the stellar mass function (the distribution of stellar masses found in galaxies). This said, coming observational facilities will offer further constraints to the physics regulating baryon build-up, beyond simply stellar mass growth. The density of gas is currently being probed with the Atacama Large Millimetre Array (ALMA) in the sub-mm to mm wavelength regime, as well as the Australian Square Kilometre Array Pathfinder (ASKAP) and soon the Square Kilometre Array (SKA), both in the radio regime. The warm and hot ionised phase of the interstellar medium (ISM) and intergalactic medium (IGM) will be probed with the James Webb Space Telescope (JWST) in the optical/near infrared (NIR) regime, and e-ROSITA in the X-ray regime. These facilities will reveal the masses, metallicity and dynamics of baryonic matter in galaxies in unprecedented detail. In order to determine which physical processes cause the observations to come from leading edge studies, modelling galaxy formation in a theoretical framework is imperative to produce robust predictions and interpretations using different galaxy formation physics. This is especially true for the case of baryon (ordinary matter) build up and regulation within galaxies.

Broadly speaking, there are two main flavours of physically motivated cosmological galaxy formation simulations: hydrodynamical simulations, and semi-analytic models (SAMs). Hydrodynamical simulations are an all-inclusive computational approach to simulating galaxy formation, where the equations of gravity and fluid dynamics are solved simultaneously within a standard cosmological framework (including baryons and DM). Sub-grid physics modules are implemented where physical processes cannot be resolved by the simulation as a whole (including star formation and all forms of feedback). These simulations have been able to roughly reproduce the low density gas structures of galaxies with a single-phase interstellar medium (ISM), and also provide a spatially resolved picture of the properties of galaxies (see Schaye et al. (2015) for a recent example). This method, however, is quite computationally expensive when compared to SAMs, which take a more simplistic approach. This is explored in depth below in 1.1.3.

1.1.3 Semi-analytic models (SAMs) of galaxy formation

Based on the simplifying assumptions made, SAMs are computationally inexpensive compared to hydrodynamical simulations, meaning large volumes of galaxies can be produced and statistically analysed. Importantly, this means that SAMs are the best-suited theoretical tool to replicate the volumes to be explored by the aforementioned large scale surveys to come, and to give a cosmologically representative sample with halos in diverse environments. They also provide a very expedient test-bed for implementing different physical models in the same cosmological framework to contrast the outputs. Based on these strengths, continuing to improve the physical accuracy of models used in SAMs has the potential to yield great reward.

SAMs typically start by taking the results a cosmological DM-only N-body simulation, where DM overdensities correspond to the site of halo formation from a structure-finding algorithm. These halos are followed and linked through the time spanned by the simulation with a halo tree generator to form a halo catalogue (see Fig. 3 for a visual representation). Based on the static output of the N-body simulation and generated merger trees, a SAM will initialise a singular galaxy where a subhalo first appears in the catalogue (i.e. the first snap a halo appears, having no progenitors). At this stage, unlike hydrodynamical simulations which track baryonic and matter particles within halos directly, SAMs

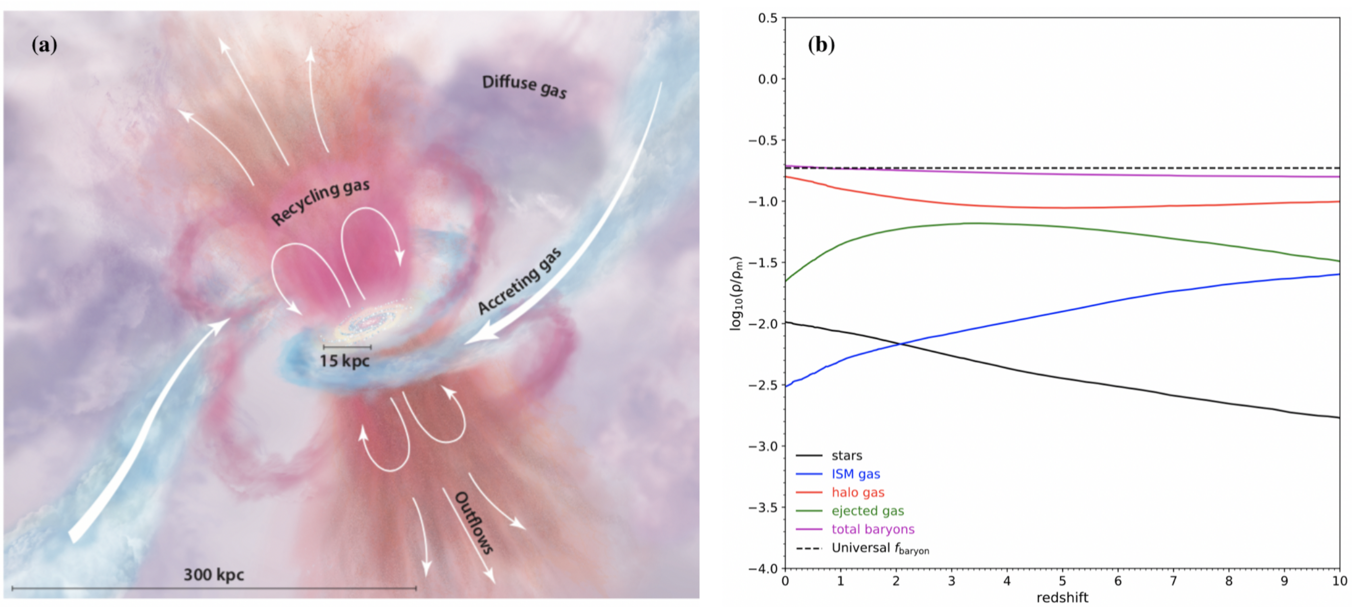

Figure 1: *Panel (a)*: Figure from Tumlinson et al. (2017). Illustration of baryon flow towards a halo or galaxy. The labels are also often the reservoirs modelled discretely in SAMs surrounding identified halos, including diffuse halo gas, accreting gas, gas outflows and recycling and ISM gas. *Panel (b)*: The baryon budget with different components across redshift in the SHARK SAM from a large scale SURFS DM-only N-body run.

Hydrodynamical Simulations	**Semi-Analytic Models**
• Parallel approach: N-body physics, structure finding and galaxy evolution sub-grid modules implemented in an 'inline' manner • Detailed galaxy structure: the distribution of matter is tracked directly • No assumptions on surface density profiles (modelled directly)	• Series approach: N-body physics run, followed by structure finding and merger trees, then galaxy evolution physics • Limited spatial data about galaxies: mostly integrated output properties • Surface density profiles are sometimes assumed to have analytical forms (but not necessarily)

Figure 2: A comparison of the characteristics of hydrodynamical simulations and semi-analytic models.

use some simplifying assumptions in that they assign baryonic matter to one of a collection of finite, discrete reservoirs associated with halos and galaxies. This typically includes a hot diffuse gas halo component, galaxy ISM gas (sometimes further decomposed into a disk and bulge), a reservoir of ejected galaxy gas (from supernovae and AGN feedback), and a reservoir of matter locked up in stars (galaxy stellar mass). Discretising these reservoirs makes SAMs more computationally efficient than hydrodynamical simulations, the drawback being we lose information about the detailed internal structure of galaxies, particularly their non-axisymmetric features.

Where a galaxy is first found in a merger tree, SAMs will typically then initialise baryons to the diffuse gas component of the halo, based on a fraction of its dark matter mass: $M_{\mathrm{baryon,halo}} = \Omega_{\mathrm{B}}/\Omega_{\mathrm{M}} \times M_{\mathrm{halo}}$. One should take particular note that this approach inherently assumes that the baryons follow the dark matter distribution perfectly, on both cosmological and galactic scales. Subsequently, through consecutive simulations snapshots, this gas is allowed to move between the aforementioned discrete gas reservoirs based on a set of differential equations. A linearised and simplified version of the equations used in the SAM GALFORM is shown below in Fig. 4, illustrating the complex interplay between the different reservoirs. The new SAM SHARK (Lagos et al., 2018) includes even more baryon components and, as such, a larger matrix. Including the exchange of metals and angular momentum between these baryonic components increases the size of the matrix three-fold. Across time, it is the physics within and interplay between these gas reservoirs in SAMs which determines how a galaxy will evolve. Small scale processes such as star formation and stellar feedback, black hole growth, AGN feedback, and cooling are modelled to process the baryonic content of a galaxy and give output integrated quantities. These smaller scale processes cannot be modelled directly in an ab-initio manner in SAMs (nor hydrodynamical simulations) due to resolution issues.

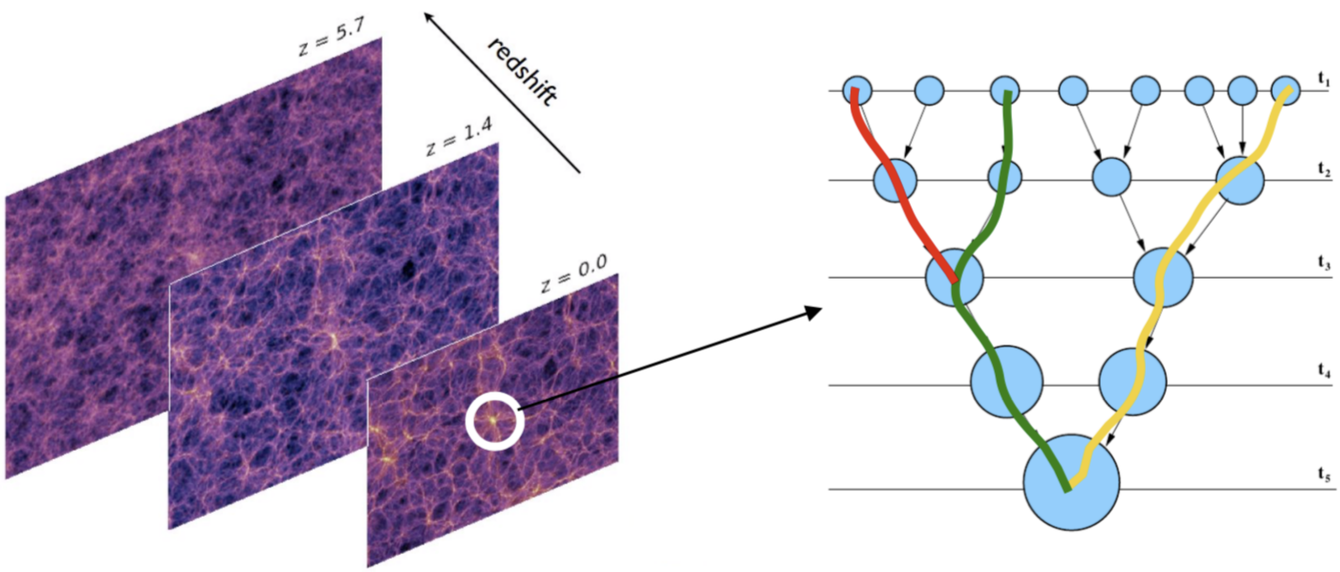

Figure 3: A visual representation of the serial nature of SAMs: the static N-body simulation outputs being connected via merger trees.

$$\begin{bmatrix} \dot{M}_{\mathrm{diffuse}} \\ \dot{M}_{\mathrm{ISM}} \\ \dot{M}_{\mathrm{ejected}} \\ \dot{M}_{\star} \end{bmatrix} = \begin{bmatrix} f_{\mathrm{B}} \dot{M}_{\mathrm{H}} \\ 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} -1/\tau_{\mathrm{infall}} & 0 & 1/\tau_{\mathrm{ret}} & 0 \\ 1/\tau_{\mathrm{infall}} & -(1-R+\beta_{\mathrm{ml}})/\tau_{\star} & 0 & 0 \\ 0 & \beta_{\mathrm{ml}}/\tau_{\star} & -1/\tau_{\mathrm{ret}} & 0 \\ 0 & 0 & (1-R)/\tau_{\star} & 0 \end{bmatrix} \begin{bmatrix} M_{\mathrm{diffuse}} \\ M_{\mathrm{ISM}} \\ M_{\mathrm{ejected}} \\ M_{\star} \end{bmatrix}$$

Figure 4: A linearised matrix form of the equations governing matter flow in GALFORM. Adapted from Mitchell et al. (2018).

On the SAM side, great progress has been made exploring different methodologies for implementing small scale physical phenomena, for instance understanding star formation laws (Lagos et al., 2011), gas reincorporation (Mitchell et al., 2014), stellar population synthesis (Gonzalez-Perez et al., 2014) and stellar feedback (Hirschmann et al., 2016). Some efforts have allowed for spatial modelling, with galaxies treated in concentric shells (Stringer and Benson, 2007; Fu et al., 2010; Stevens et al., 2016). Of course, the course-grained semi-analytic approach does not come without inherent drawbacks. One of the main downfalls of SAMs are the aforementioned assumptions regarding larger scale matter flow. The results of all SAMs are heavily predicated on the assumption that gas follows large scale dark matter structure perfectly, and moves into halos in tandem. In principle, this is not necessarily the case: while DM is only subject to gravitational forces, baryonic matter is self-interacting and is dynamically affected by hydrodynamic forces and radiative cooling (Benson et al., 2001). Hirschmann et al. (2012) shows that SAMs typically overestimate gas accretion rates to galaxies, and also overpredict the proportion of "hot mode" accretion compared to "cold mode" accretion. In general, from a baryon modelling perspective, SAMs should strive to reproduce the results of hydrodynamical simulations where a more full treatment is in place. This is not the case for many SAMs, as discussed below.

To summarise the differences between SAMs and hydrodynamical simulations, Mitchell et al. (2018) compared a well-known SAM, GALFORM (Cole et al., 2000; Lacey et al., 2016), with the also well-known cosmological hydrodynamical simulation EAGLE (Schaye et al., 2015; Crain et al., 2015). The authors found notably that while the median stellar mass assembly over cosmic time between GALFORM and EAGLE was in agreement, there was significant tension between the mass in other baryonic reservoirs (e.g. ISM, stellar mass, ejected gas, halo gas, see Fig. 5(a)). With this inaccuracy, it is possible that the numerous free parameters and calibration at different steps implemented by SAMs (especially AGN feedback) could effectively mask the unphysical baryon accretion rates, while still giving favourable large scale statistics (Mitchell et al., 2018). Tension also exists between hydrodynamical simulations and SAMs regarding total baryon density within halos. In Fig. 5 from Mitchell et al. (2018), we can see that in both observations and theory, the fraction of matter in halos in the form of baryons is low for low mass halos and rises for increasing halo mass. The location of this transition, however, depends strongly on the model. In EAGLE, the universal baryon fraction is reached only at very high mass halos (corresponding to clusters), with $M_{\rm H} > 10^{14} M_{\odot}$. The transition appears even slower in the observations of McGaugh (2010), many concluding that much of the baryons in the universe exist in the form of hot or warm gas coronae surrounding halos (Nicastro et al., 2008; Tumlinson et al., 2017). Observations on this topic are however inconclusive, with recent Sunyaev-Zeldovich effect measurements indicating that the amount

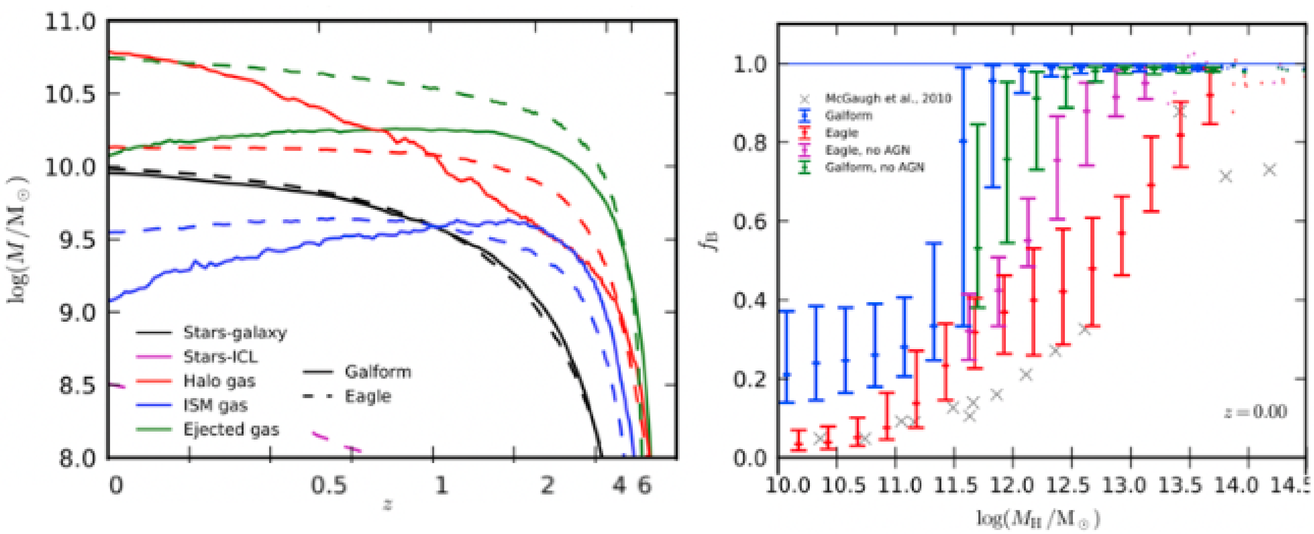

Figure 5: *Panel (a)*: The components of baryon mass evolving over redshift in GALFORM (solid lines) and EAGLE (dashed lines) illustrating tension between the two. Figure adapted from Mitchell et al. (2018). *Panel (b)*: The baryon fraction ($f_{\rm b}$) of galaxies in GALFORM and EAGLE as a function of halo mass, compared to the universal baryon fraction. Figure adapted from Mitchell et al. (2018).

of baryons in halos down to masses of $10^{12.5}M_{\odot}$ is fully consistent with the universal baryon fraction (Lim et al., 2018). Regardless, compared to hydrodynamical simulations, SAMs consistently demonstrate this transition at much lower halo masses - indicating that lower mass halos may be too baryon rich in these models. As demonstrated in Fig. 5(b), halos in GALFORM reach the universal baryon fraction at much lower halo masses, $M_{\mathrm{H}} > 10^{12}M_{\odot}$ comparted to the EAGLE simulation. Similarly, the SHARK SAM exhibits similar behaviour (see Fig. 8), with the universal baryon fraction reached for halos with $M_{\mathrm{H}} > 10^{11.5}M_{\odot}$. It is possible that this divergent behaviour between SAMs and hydrodynamical simulations is, to some extent, due to the inaccurate modelling of baryon accretion to these halos.

Another item of interest is comparing the internal kinematics of the baryons within halos in SAMs compared to hydrodynamical simulations. In hydrodynamical simulations, since gas is simulated directly, angular momentum of both the baryonic constituents of halos as well as the gas surrounding halos is self-consistently followed. In semi-analytics, this is not so trivial, and important assumptions have to be made: notably, that the angular momentum of baryonic matter traces that of dark matter exactly. In hydrodynamical simulations, the circum-galactic medium (CGM) has much higher specific angular momentum than galaxies themselves, indicating that losses must take place (Stevens et al., 2017; Stewart et al., 2017). In SAMs, it is not clear how these losses should be modelled with the existing number of assumptions already in place. Mitchell et al. (2018) found that in EAGLE, the star-forming ISM has a lower specific angular momentum than the total ISM (indicating the star-forming ISM has more centrally concentrated angular momentum), while in GALFORM, the total ISM and star-forming ISM are implicitly assumed to have the same angular momentum. In addition, EAGLE and GALFORM predict significantly different stellar angular momentum distributions as function of stellar mass - GALFORM predicts that the specific angular momentum of galaxy disks mimics that of their DM halos, while EAGLE indicates that the stellar angular momentum is lower than that of the host dark matter halo by a facter of 0.6 dex below $z = 6$ (Mitchell et al., 2018) (while the angular momentum of the ISM remains consistent with the host DM halo). Angular momentum is known to be critical in determining galaxy properties (especially sizes), and can have profound impact on internal galaxy kinematics and morphology. As such, the manner in which angular momentum is modelled in SAMs is incredibly important for physical accuracy in the context of galaxy formation, and we should use the results of hydrodynamical simulations (Mitchell et al., 2014; Hirschmann et al., 2016) to better inform them. At present, such results have not converged.

Until recently, another drawback of many of these SAMs was the lack of on-the-fly model editing and availability of the source code, meaning that many physical models would be effectively hard-coded into the simulation with little flexibility. This limited the scope for testing of alternative approaches and independent development. A new SAM called SHARK, presented in Lagos et al. (2018), offers a solution to this issue. The code is structured as a framework within which different models and treatments of both small- and large- scale processes can be interchanged with ease. Such a framework is critical to solve ongoing problems in theoretical galaxy formation, such as those discussed above. The phenomena which influence the baryonic component of galaxies (such as star formation, stellar feedback, and cooling) occur on scales too fine for SAMs and hydrodynamical simulations to directly resolve, and there are many (not necessarily physically motivated) free parameters implemented (particularly in SAMs) to match selected observations (Somerville et al., 2008; Bower et al., 2010; Benson and Bower, 2011; Hirschmann et al., 2012). Moving forward with SAMs, the obvious first step to improve their performance and accuracy is to reduce the need for free-parameter tuning and to using more physically motivated models. This simply highlights the importance of being able to seamlessly make changes to a model, and compare results in the same cosmological and computational framework to converge on the best approach.

1.2 Aims

Based on the discussion in Section 1.1.3, the main aim of this project is to provide a novel and more physically accurate implementation of baryon build-up in galaxies within semi-analytic models of galaxy formation. Since SAMs are ideally placed to compare with coming observations with ASKAP, SKA and JWST, we view improving their performance as an endeavour of potentially profound reward. Instead of using DM-only simulations as a base to SAMs, we plan to use N-body DM *and* gas simulations to better inform SAMs, both in terms of input halo accretion, as well as their internal physical modelling. Such an idea is unprecedented, and begins to blur the distinction between SAMs and hydrodynamical simulations. Mentioned earlier, the SHARK SAM (Lagos et al., 2018) provides an exemplary test-bed for this project due to its flexibility and modularity.

The main research questions to be explored can be summarised as follows:

- How does a more realistic implementation of cosmological baryon accretion and intra-halo baryon modelling affect galaxy populations in SAMs?
- How does a more realistic implementation of cosmological baryon accretion and angular momentum modelling affect galaxy populations in SAMs?
- How does a more realistic implementation of baryon build-up in halos together with physically motivated cooling models affect the baryon budget and gas properties of halos in SAMs?

Improving the performance of SAMs provides an excellent (and necessary) base for comparisons with coming observations, as we move towards an era of precision understanding of galaxy formation.

1.3 Methodology

The main action item of the project is to provide more physically relevant information in connecting the N-body stage (now with DM *and* gas) to the SAM (SHARK) stage, in particular with regard to the build-up of baryons in halos. This will involve, in order (aligned with aims and proposed papers, see Section 2.5):

1. Creating an algorithm (in the C++ programming language) which first calculates baryon accretion rates to halos at the N-body stage, and subsequently can feed this information to the SAM SHARK to more accurately model baryon accretion rates to halos.
   (a) Based on these results, investigating whether changes should be made to the models governing baryon regulation within SHARK to re-calibrate with observations and hydrodynamical simulations.
2. Creating an algorithm which first calculates baryon angular momentum transfer to halos at the N-body stage, and subsequently can feed this information to the SAM SHARK to more accurately model the transfer of angular momentum from the circum-galactic medium (CGM) to halos.
   (a) Based on these results, investigating whether changes should be made to the models governing angular momentum transfer within SHARK to re-calibrate with observations and hydrodynamical simulations.
3. After completing items (1) and (2), we plan to review the models used in SAMs (specifically SHARK) governing thermodynamics and cooling of halos. This will likely involve investigating the AGN feedback model for its physical accuracy with intent to recalibrate and reproduce observed gas profiles, temperature mass relations and baryon fractions of halos, within the new baryon build-up framework.

In order to satisfy the aims of the project outlined in 1.2, one must understand in depth each step of how semi-analytic models work. A simplified flow diagram of the different stages involved in SAMs is given in Fig. 6 together with the specific implementations to be used for this project. Since this project involves each of these different stages, its scope is decidedly large and quite multi-faceted. Over the first 3 months of candidature, I have successfully worked to understand, run, and use the results from each of the 3 steps outlined in red in Fig. 6.

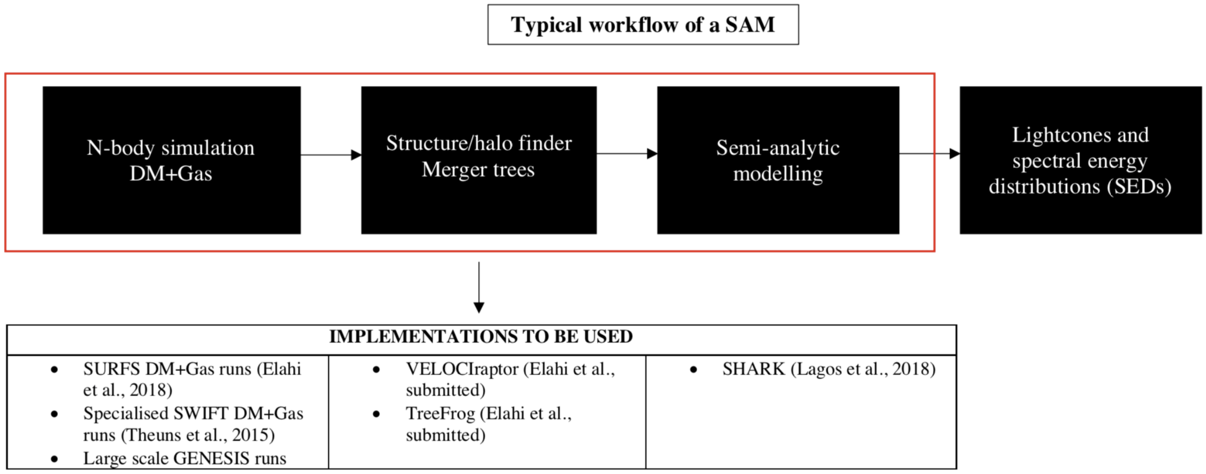

Figure 6: The components which together form a SAM, shown with the implementations of each step to be used for this project. The red box emphasises the components which will be most used for this project. Note that at the N-body stage I will be implementing DM & gas particles, where before SAMs would only simulate DM particles.

1.4 Preliminary Results

1.4.1 N-body Simulations

With assistance from my coordinating supervisor Chris Power, I have successfully run both GADGET-2 (Springel, 2005) and SWIFT (Schaller et al., 2018) N-body simulation codes on my local machine and the cluster at ICRAR, Hyades. These were relatively small runs (6.25Mpc and 25Mpc boxes respectively), however gas has been implemented into both (instead of DM-only, like the current base of most SAMs). The next steps will be to make some higher resolution runs, and also begin to treat gas cooling.

1.4.2 VELOCIRAPTOR & TreeFrog

After running the aforementioned N-body simulations, I ran VELOCIRAPTOR structure finder (Elahi et al., submitted) with appropriate conditions to locate and characterise all halos and subhalos that the simulations had formed. The halos are linked through time with a program called TreeFrog (Elahi et al., submitted), which allows individual halos to be tracked as they evolve. As a proof-of-concept exercise, using the outputs of VELOCIRAPTOR and TreeFrog on the N-body SWIFT run described above, I created a plot of gas accretion rate to halos vs. DM accretion rate to halos, using the changes in VELOCIRAPTOR halo mass output as the accretion rate. These mass outputs can be subject to numerical noise, and will likely not be used for the remainder of the project, however do serve as a good first pass. The result is shown in Fig. 7. Already, one can observe the spread of accretion rates about the universal baryon fraction, indicating that the assumption of gas following DM on cosmological scales is indeed flawed to some extent. The discrete nature of the points at lower accretion rates is likely due to resolution issues, where the effect of individual particles in the N-body simulations becomes obvious.

1.4.3 SHARK

I have become familiar with and also run the semi-analytic model SHARK (Lagos et al., 2018) successfully on my local machine, as well as ICRAR's Hyades computer cluster with outputs from large SURFS (Elahi et al., 2018) runs, and am comfortable with changing the various physical models currently available (see Fig. 8). In addition, I have implemented small changes in the code relating to halo recycling and gas reincorporation. This has involved some familiarisation with the C++ programming language, however I need to continue this process before I am fully confident in understanding and editing the code. The next major item to address with the project is synthesising an efficient C++ script to take the raw particle data from an N-body simulation (together with the structure properties

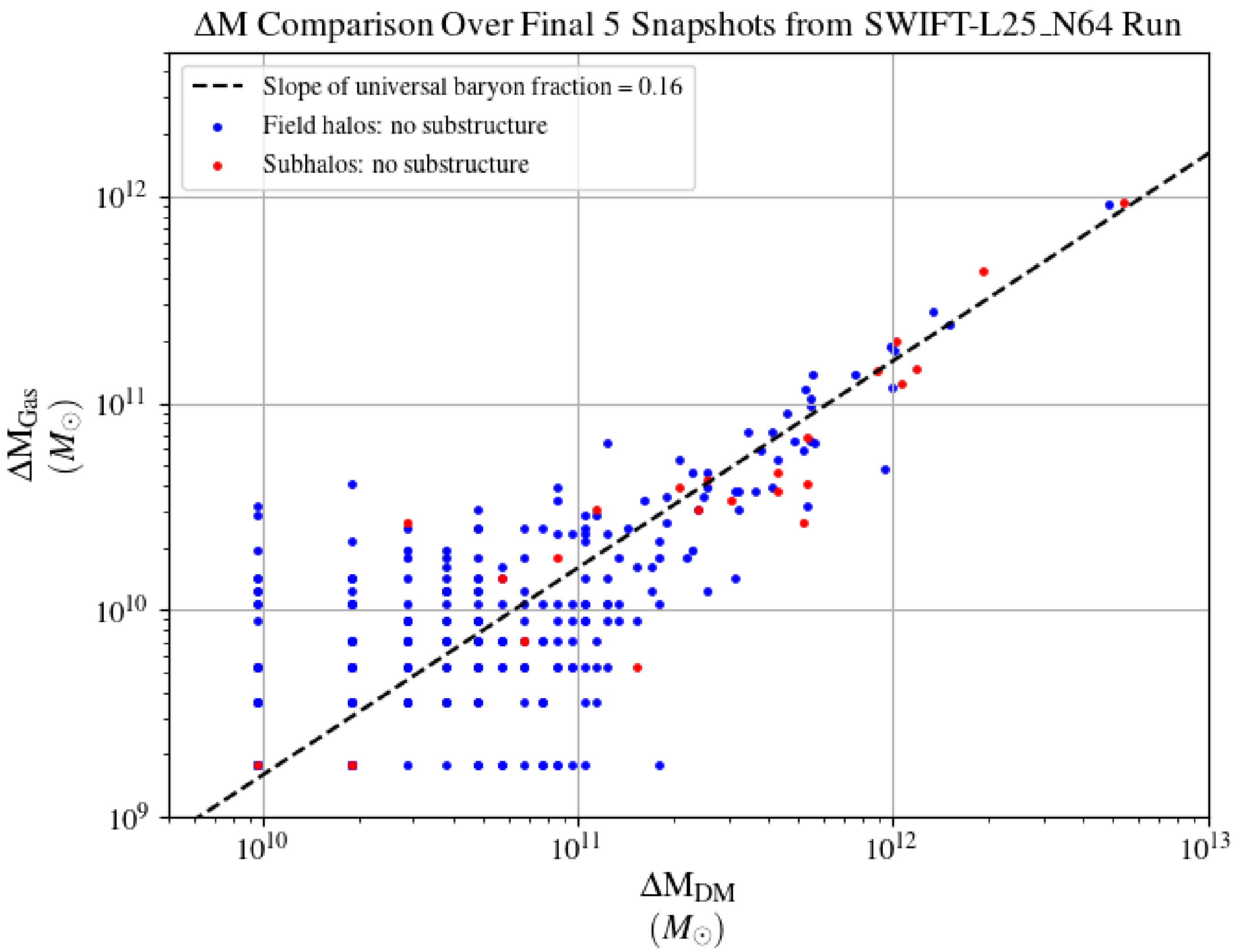

Figure 7: The gas and DM accretion rates to halos in a 25Mpc SWIFT N-body DM & gas run.

derived from this run in VELOCIRAPTOR and TreeFrog) and measure directly the accretion rates to halos as the flux of particles across a pre-determined boundary. The SHARK code will be edited to accept this as input for halo accretion rates. Subsequently, a similar procedure will allow SHARK to use the angular momentum of assembling baryonic matter as input for each halo directly from the N-body outputs.

2 Research Project Details & Training

2.1 Confidential & Intellectual Property Information

The N-body codes which will potentially be utilised (GADGET-2, SWIFT) are publicly available via Git-based repositories. To generate initial conditions for each of these codes, we plan on using the package 2LPTIC, which is also publicly available. The structure finder and merger tree generator I will implement for outputs of these N-body codes are called VELOCIRAPTOR and TreeFrog respectively, both of which are publicly available as GitHub repositories and have been developed at ICRAR. The semi-analytic model I will utilise, SHARK, is publicly available and has also been developed by my primary supervisor, Claudia Lagos. As such, I have no issue with availability of the resources I require, and in most cases have direct contact with respective developers for assistance.

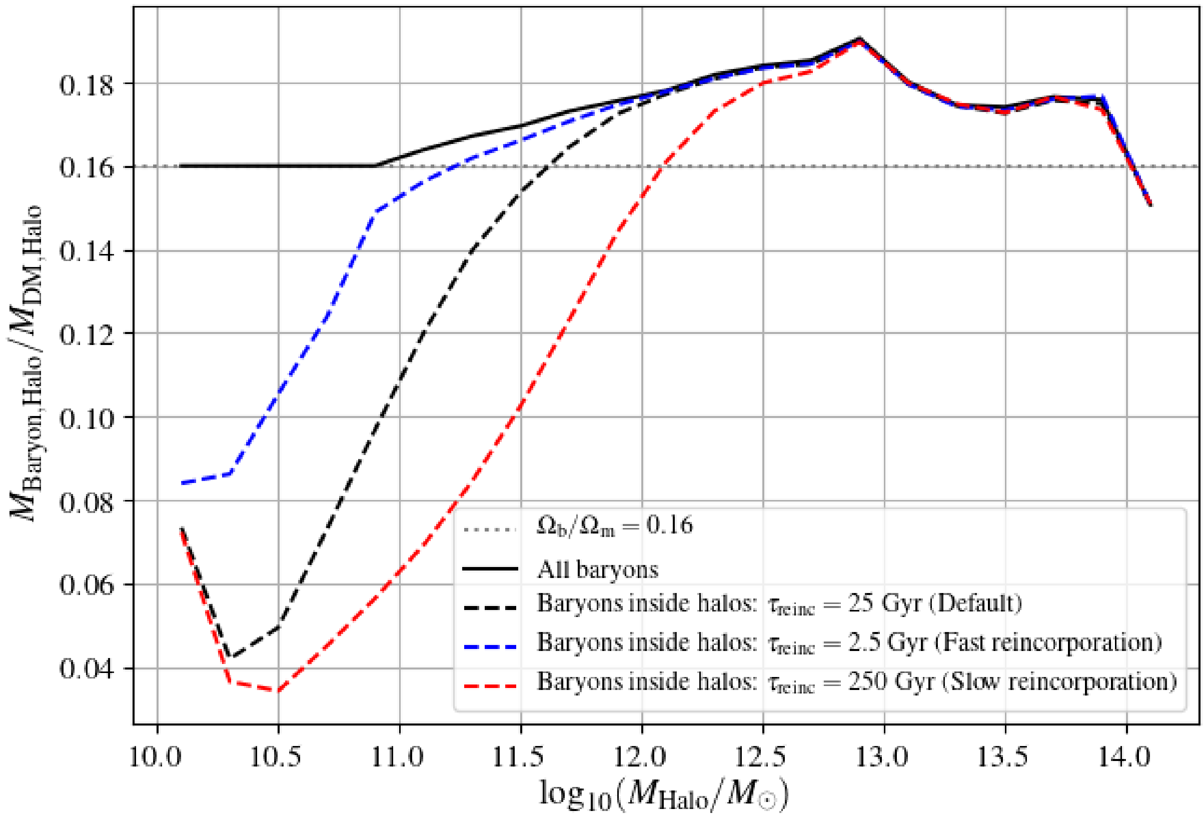

Figure 8: Comparison at z=0 of baryon fractions in SHARK halos with altered reincorporation timescales for ejected gas, compare to Fig. 5(b). The black line corresponds to the recommended/tuned default value, while the short and fast timescales are non-physical and illustrate how the physics can be seamlessly changed in SHARK.

2.2 Fieldwork Information

Most research work will be conducted directly at the UWA node of the International Center for Radio Astronomy Research (ICRAR/UWA). Should the opportunity to travel to domestic or international conferences arise, I will follow the protocols set out by the GRS.

2.3 Facilities

The facilities at ICRAR/UWA are largely sufficient for the purposes of my research. Time on an external powerful cluster or supercomputer may be required for high resolution cosmological simulations, such as the Pawsey Centre's MAGNUS supercomputer. 1.1 million CPU hours have been secured at MAGNUS in 2019 for this project and other SHARK related projects.

2.4 Skills Audit

For the purposes of the PhD project, I have listed the skills which will be required and my corresponding proficiency at each in Table 1.

Research Skill (description)	**Current Rating**	**Evidence**	**Desired Rating**
Understanding and application of relevant data collection and analysis methods.	Competent	Undergraduate and Honours level study in physics including data analysis. Honours project was heavily involved with data processing.	Proficient
Identifying and accessing appropriate bibliographic resources.	Competent	Completed honours thesis and have submitted paper to high impact research journal.	Proficient
Use of information technology relevant for research.	Competent	Honours level high performance computing unit; experience with python, fortran, R, MATLAB, and Mathematica.	Proficient
Familiar with the principles and conventions of academic writing.	Basic	Honours thesis, submitted paper.	Competent
Ability to constructively defend research outcomes at seminars and conferences.	Basic	Honours thesis seminar.	Competent

Table 1: Outline of skills required for PhD project and my current perception of competence in each.

2.5 Research Project Communication

I will defend my research proposal to a 3-member ICRAR-based panel on the 6$^{\text{th}}$ February, 2019. My progress will be presented to the same panel on an annual basis in the form of a seminar (mid-August in each year between 2019-2021), at which point I will receive constructive feedback on my work and items to improve. I plan to present my thesis as a series of papers. For each, I have provided a brief overview of their content below.

Paper 1: Baryon Accretion to Halos in Semi-analytic Models: The Baryon Budget
This paper will investigate how using simulation-based baryon accretion rates to halos as input to SAMs affects the resultant baryon budget and properties of galaxies. There is the potential for this paper to be split into two separate pieces of work: firstly presenting a pure analysis of DM vs. gas accretion rates for isolated halos (a seldom explored area); and secondly the how using this information as input to SHARK impacts baryon budget and output galaxy properties.

Paper 2: Baryon Accretion to Halos in Semi-analytic Models: Angular Momentum Balance
This paper will investigate how using simulation-based baryon angular momentum modelling as input to SAMs affects the resultant properties of galaxy populations. In addition, there is scope to re-calibrate models of angular momentum transfer in SHARK using the more informed N-body data regarding baryon angular momentum.

Paper 3: Baryon Accretion to Halos in Semi-analytic Models: Thermodynamics and Cooling
This paper will investigate how physical models in SAMs (such as AGN feedback) which affect thermodynamics and cooling, within the new SAM framework with simulation-based baryon accretion and angular momentum modelling, can be altered and/or re-calibrated to increase physical accuracy. This will be done with intent to reproduce observed gas profiles, temperature mass relations and baryon fractions of halos.

2.6 Approvals

No research approvals regarding ethics or otherwise are required for my project at this time. If approvals are required in due course, the GRS will be contacted.

2.7 Data Management

The data I require for my project will primarily be stored on the laptop provided by the institute, in conjunction with an external hard drive. In addition, the Hyades computing cluster at ICRAR will be used to store high volumes of non-essential, temporary data.

2.8 Research Project & Training Plan

With the aforementioned goals and project requirements in mind, Fig. 9 illustrates the planned timeline (including key outcomes and events) of my PhD candidature.

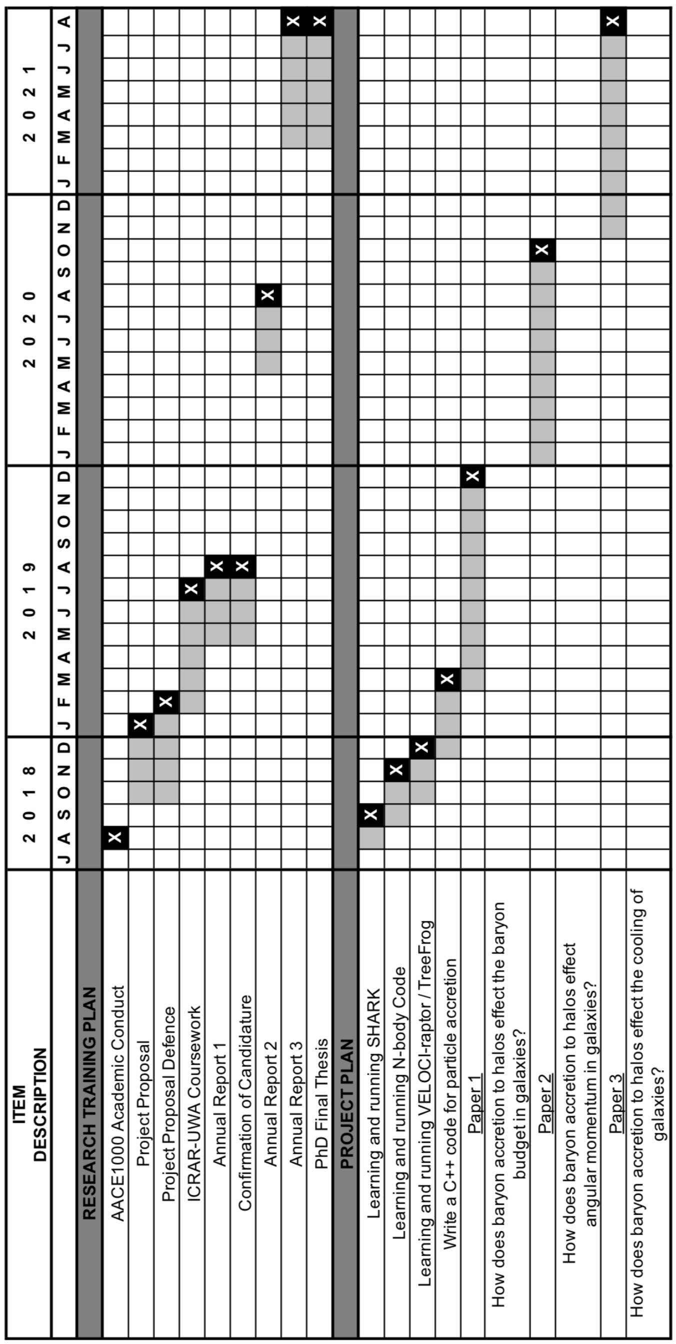

Figure 9: Research training and project plan in Gantt chart form.

ITEM DESCRIPTION	Amount Spent / Estimated Cost	Amount Dedicated / Amount Available or Remaining	Funding Source
Laptop Computer (13" MacBook Pro)	$2491.78	$1250.00 $1241.78	ECM ICRAR
Additional IT Supplies (mouse, keyboard, external hard drive)	$367.08	$367.08	ICRAR
Domestic Travel (flights, accommodation, food, conference)	$2000.00	$1640.22 Undisclosed (subject to approval)	ICRAR ASTRO-3D
International Travel (flights, accommodation, food, conference)	$3500.00	$1640.22 $1850.00 Undisclosed (subject to approval)	ICRAR GRS ASTRO-3D
TOTALS	**$8358.86 AUD**	**$8358.86 AUD**	-

Table 2: Budget for resources and travel required for PhD together with funding sources.

2.9 Confirmation of Candidature

To complete my confirmation of candidature I have agreed to fulfill the following tasks.

- AACE1000 Academic Conduct Essentials: Completed March 2014 (undergraduate degree)
- Project proposal report: To submit 18$^{\text{th}}$ January 2019 (due 16$^{\text{th}}$ February 2019)
- Project proposal presentation: Scheduled 6$^{\text{th}}$ February 2019
- Coursework to a total of 6 points: To complete July 2019 (UWA/ICRAR requirement)
  - Will take the unit PHYS4002 (Astro-statistics and Computational Astronomy)
- Annual progress report: To complete by 16$^{\text{th}}$ August each year in 2019, 2020, 2021
- Annual progress seminar: To complete August each year in 2019, 2020, 2021

2.10 Working Hours

My regular working hours will nominally be 8am - 5pm from Monday to Friday (with variation as required), with time allocated for lunch and a maximum of ≈ 4 teaching hours per week during the UWA semester.

3 Budget

I have provided an overview of the various costs associated with my PhD project in Table 2. I have been allocated up to $1250 from the ECM faculty for a work laptop, $1850 from the GRS for international conference travel, $3250 from ICRAR for miscellaneous costs, and an undisclosed amount (funding requests subject to approval) from ASTRO-3D (ARC Centre of Excellence for All-Sky Astrophysics in 3-Dimensions).

4 Supervision

Principle Supervisor [50%]: Dr. Claudia Lagos
Dr. Lagos and I will meet on a weekly basis (often in conjunction with A/Prof. Chris Power). Dr. Lagos provides extensive expertise in semi-analytic models of galaxy formation (SAMs) and has developed the code for SHARK.

Coordinating Supervisor [40%]: A/Prof. Chris Power
A/Prof. Power and I will meet as and when required (often with Dr. Lagos) regarding N-body simulation runs required for the project and computational matters. Prof. Power has expertise in N-body simulations and hydrodynamical simulations.

Co-supervisor [10%]: Prof. Lister Staveley-Smith
Prof. Staveley-Smith and I will meet as and when required regarding the observational parallels and outcomes related to my theoretical research. Prof. Staveley-Smith provides expertise on the observational counterpart of gas in and around galaxies.

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