THE UNIVERSITY OF WESTERN AUSTRALIA
&
INTERNATIONAL CENTRE FOR RADIO ASTRONOMY RESEARCH

PhD Research Proposal

The Relationship between Dark Matter Halos and Galaxies

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Contents

1 Project Title and Summary

The dynamical state of dark matter halos and their galaxy populations

Dark matter is the predominant constituent of matter in the Universe. As such, the gravitational potential and therefore the motion of baryons is governed by the dark matter distribution. The intricacies of the relationship between the dynamics of dark matter and galaxies have not been fully established and more studies are required in this area. For example, the motion of galaxies in clusters is governed by a plethora of phenomenon like tidal stripping, harassment, ram pressure and dynamical friction to name a few. As a result, the velocity dispersion of galaxies in clusters deviates from what would be expected if they were ideal point-mass tracers in dynamical equilibrium with the cluster potential; this biases cluster mass estimates based on galaxy dynamics. Since the astrophysical processes involved in such interactions are complex, it is best addressed using advanced numerical simulations. We aim to address two open questions using data from the EAGLE suite of hydrodynamical simulations (Schaye et al. 2015): what impact does the dynamical state of a dark matter halo have on the observable properties of its central galaxy; and what impact does the dynamical state of galaxy populations within rich clusters have on their observable mass estimates. This is of special importance considering upcoming galaxy surveys. Results from Australian-led surveys will improve simulations, and our simulations would also benefit from those surveys. Through these two projects we wish to work on problems which are of interest to both observers and simulators.

2 Research Project

2.1 Background

Dark Matter

The earliest hint for the presence of non-baryonic "dark" matter in the Universe came with the observational result by Zwicky (1937) who showed that the amount of matter demanded by the virial theorem and inferred from motion of galaxies in clusters, far exceeds that determined from emitted radiation. A few decades later it was theoretically shown that self-gravitating disks are unstable (Hohl 1971; Miller 1974) but can be stablised by a massive spherical potential (Ostriker & Peebles 1973). The rotation curves of spiral galaxies observed in later years made this explicit by implying that galaxies should be surrounded by invisible halos consisting of a novel form of matter which only interacts gravitationally, which was hence called "dark matter" (Rubin 1983; van Albada et al. 1985; Persic & Salucci 1988; Begeman et al. 1991). This was also confirmed for clusters by comparing baryonic matter with potentials inferred by gravitational lensing (Lynds & Petrosian 1986; Tyson et al. 1990; Kaiser & Squires 1993) and by stellar velocity dispersion studies (e.g. Merritt 1987). The observation of the Bullet cluster served as a "smoking gun" by depicting distinct distributions for the baryons and the dark matter due to a collision between the two subclusters which reinforced the idea of dark matter's collisionless nature that is distinct from the observed baryons (Clowe et al. 2006). The contribution of dark matter to the energy budget of the Universe has been quantified through the analysis of anisotropies in the Cosmic Microwave Background (CMB) and found to be $\approx 80\%$ of the total matter density (Netterfield et al. 2002).

Dark matter particles can theoretically exist in three regimes based on their mass and therefore the mean free path. These are "cold", "warm" and "hot" in the decreasing order of mass and increasing order of mean free path. The primordial fluctuations in the Universe lead to structure formation later on but the fine details of this structure will depend on the type of dark matter. As the Universe evolves, all the fluctuations at scales smaller than the mean free path of dark matter will be damped such that the abundance of smaller halos decreases from cold to hot. Therefore, galaxies form later and have lower abundance in "hotter" dark matter models (Schaeffer & Silk 1988). Cosmological models with cosmological constant and cold dark matter (ΛCDM) have been able to reproduce most observations of the large-scale structure of the Universe and therefore most state-of-the-art simulations are based on it. The most persistent problems with this model are the so called "core-cusp" (De Blok 2010), the "missing satellite" (Klypin et al. 1999), and the "too big to fail" (Boylan-Kolchin et al. 2011) problems. The first one refers to the discrepancy between the observed flat density profile of dark matter in the central regions of some galaxies and the steeply increasing dark matter density profile seen in simulations that is accurately described by the NFW profile (Navarro et al. 1997). The second one refers to the lower number of satellite galaxy halos observed for the Milky Way (Moore et al. 1999), and other massive galaxies compared to simulations . The third one refers to subhalos of Milky Way like galaxies in dark matter only simulations being too dense compared to the observed satellites of the Milky Way. The first problem has essentially been solved by considering inefficient galaxy formation after reionisation and tidal disruption (Simon & Geha 2007). The second problem remains and its solution may imply that dark matter is not cold, or that simulations do not properly model the complex non-linear coupling between baryons and dark matter on small scales. The third problem was recently claimed to be solved by Ostriker et al. (2019) who showed that the mass gap between brightest and second brightest galaxy exists in simulations due to gravitational interactions within groups.

The EAGLE Simulations

The formation and evolution of galaxies is an intricate process because it involves complex baryonic physics and dark matter structure growth. Modelling using simulations that involve hydrodynamics and gravitation laws can provide deeper understanding. Early hydrodynamical simulations had serious drawbacks (see Scannapieco et al. 2012):

1. The galaxy stellar mass functions had wrong shape and normalisation.
2. There were too many massive and compact galaxies.
3. The stars were formed earlier than they should.
4. Star formation in high mass galaxies was not quenched.
5. They couldn't reproduce stellar masses and thermodynamical properties of gas in groups and clusters.

Hydrodynamical simulations try to overcome these issues by automatically including the baryon-dark matter back reaction, allowing simulataneous modelling of galaxies and the intergalactic medium, and more detailed comparison with observations owing to their higher resolution. More realism can be achieved by including the critically important feedback from starbursts and AGNs. EAGLE, which stands for "Evolution and Assembly of GaLaxies and their Environments", is a suite of hydrodynamical simulations using large cosmological volumes in a ΛCDM Universe (Schaye et al. 2015). This is a project by the Virgo Consortium run with the GADGET-3 code [1] (based on GADGET-2 described by Springel (2005)), with a modern implementation of smooth particle hydrodynamics (SPH), time stepping, and the subgrid models. They have a force resolution of 0.7 physical kpc which was chosen to marginally resolve the Jeans collapse scales in the warm interstellar medium (ISM). The subgrid physics includes star formation, radiative cooling, stellar mass loss, metal enrichment, feedback from starburst, mergers, gas accretion related to supermassive black holes and AGN feedback.

The subgrid physics models are calibrated to some known observed relations due to limited resolution, typically the galaxy stellar mass function (GSMF), the galaxy mass-size relations, the stellar-BH mass relation and the star formation law. These calibrations are done to match the observed galaxy stellar mass function at $z \sim 0$ because it is well measured and many applications of the simulations (e.g CGM properties) depend on the stellar-halo mass relationship.

The major advantage of these simulations are:

1. improvement in the feedback implementation from stars and AGN such that there are no other restrictions (e.g mass loading) required to produce the winds.
2. good agreement with non-calibrated observables imply that the simulations have predictive power.

The next forthcoming upgrade on this is the EAGLE-XL project which will have a larger sample of galaxies and larger volume (300 cubic Mpc as opposed to the 100 cubic Mpc of the original EAGLE volume). The data from this simulation will be available from next year.

[1] https://github.com/sbird/MP-Gadget3

2.2 How and what do we aim to address?

We will work on two projects which will essentially focus on two open questions in the dark matter research community. These are as follows:

- Is there any correlation between dark matter dynamics and galaxy properties?
  It is known that the dynamical state of halos is correlated with halo properties (Ishiyama et al. 2013; Lemze et al. 2012; Ludlow et al. 2012). Halo mass has been found to be correlated to galaxy properties (Weinmann et al. 2006; He 2019). We think this might be hinting that the dynamical state of host halos could be correlated to galaxy properties. The formation time of a halo is defined as the time at which 1/2 of the final halo mass was first assembled in the main progenitor. A halo could be "relaxed" if the formation time is longer than the system's crossing time (Ludlow et al. 2012). The dynamical state of a dark matter halo can be quantified using some parameters which are collectively called "relaxation parameters". Three of the most widely used parameters are:

  1. Virial Ratio: this is defined as $\eta = 2\mathrm{T}/|\mathrm{U}|$, where T is the total kinetic energy of the dark matter particles in the halo within the virial radius (r_{vir}) and U is the total gravitational potential energy. For an ideal virialised system, this ratio should be 1.
  2. Substructure mass fraction: this is the fraction of total mass in the halo that resides in the subhalos that reside within the virial radii of the halo, excluding the central or the most massive subhalo. It is represented as f_{sub}.
  3. Centre of mass displacement: the normalised offset between the potential centre and the center of mass of the dark matter particles within the virial radius. This is determined as $s_{dm} = |r_c - r_{com}|/r_{vir}$, where r_c is the position vector of the potential center, r_{com} is the position vector of the center of mass of dark matter, and r_{vir} is the the virial radius of the halo. This is thought to be a more robust parameter than η for mutiple reasons. The U of a halo depends on r_{vir} and therefore putting a single threshold on η for defining relaxation can remove massive halos which might otherwise be considered relaxed (Power et al. 2011).

  We are investigating these parameters, but we will consider others that may provide a more meaningful assessment of the dynamical state in the central regions of DM halos where galaxies form. For instance, we could use the fraction of the virial mass in the first and second biggest subhalos after the central, or the fraction of substructure in halo's central regions. By placing certain restrictions on these parameters, we can classify a halo as "relaxed" or not. Once the halos are classified, one can look for possible trends of galaxy properties with the dynamical state of halos in which they reside. We are going to use the Virgo Consortium's EAGLE hydrodynamical simulations of large cosmological volumes using the ΛCDM cosmology. Halos will be classified on the basis of their dynamical state to test whether there is any correlation with the observable properties of their central galaxies. This includes quantities like difference in specific star formation rate, effective radius, emission line profile asymmetry etc. If we do observe significant trends, we will try to find physical explanations for them. Moreover, we will compare the observable properties of our simulated galaxies with observed systems to reveal the dynamical state of their (invisible) dark matter halos.

- How does velocity bias arise in clusters?
  Cluster formation takes place over time through accretion and galaxy mergers. This transfers the gravitational energy into the motion of the intracluster medium (ICM) and galaxies. If we consider the random motion of galaxies as the only or predominant component of their kinetic energy within the group, this should be responsible for preventing its gravitational collapse and the system would be in dynamical equilibrium with the potential well of the cluster. Under this assumption, there are two methods of estimating total cluster mass from optical observations of galaxies:

  1. Mass from the Jeans equation: the projected number density of galaxies ($\Sigma(R)$) and the projected velocity dispersion ($\sigma_p(R)$), as functions of the projected radius R, can be used to determine the mass profile or mass within a radius r from the cluster center $M(< r)$ using the following equation:

$$\frac{d[\rho\sigma_r^2]}{dr} + \frac{2\rho(r)\beta\sigma_r^2}{r} = -\frac{G\rho(r)M(< r)}{r^2} \tag{1}$$

2. Mass from the Virial theorem: if σ is the global velocity dispersion of galaxies, the virial theorem can be used to estimate the virial mass of the cluster as:

$$M_{vir} = \frac{\sigma^2 r_{vir}}{G} \tag{2}$$

where r_{vir} is the virial radius of the cluster. But as observers we can only measure the projected or line of sight velocity dispersion σ_p. For spherically symmetric virialized systems, the projected and true velocity dispersion are always related by $\sigma^2 = 3\sigma_p^2$. The equation thus becomes,

$$M_{vir} = \frac{3\pi}{2}\frac{\sigma_p^2 r_{vir}}{G} \tag{3}$$

It turns out, neither of these mass estimators are reliable and differ from the true mass by $\sim 10-15\%$ (Biviano et al. 2006). There are other factors which affect the dynamics of galaxies in cluster: tidal interactions, ram pressure and dynamical friction are a few examples. These processes give rise to a "velocity bias" that consequently introduces a bias in the mass estimates based on Jeans modelling or the virial theorem. To be valid, the assumption of equilibrium requires that the galaxies have a velociy dispersion similar to that of halo particles in a relaxed cluster. The bias is therefore quantified in terms of the velocity dispersion of galaxies relative to that of the dark matter as:

$$b_v = \frac{\sigma_{gal}}{\sigma_{dm}} \tag{4}$$

where σ_{gal} is the velocity dispersion of galaxies and σ_{dm} is that of the dark matter particles. The above formulation is called the "single point" bias is the most used one in literature. Another way to define the bias is using the "two-point" bias which is given as:

$$b_{v,1\ 2} = \frac{\sigma_{gal,gal}(r)}{\sigma_{dm,dm}(r)} \tag{5}$$

This is the ratio of dispersion of galaxy pairs and dark matter pairs having the members separated by a distance r.

The dynamical state of dark matter particles in the halos might have some role in introducing the mass bias through gravitational interaction with the member galaxies. If the dark matter halo is not in a dynamical equilibrium, it might prevent the galaxies from achieving the equilibrium state by causing perturbations in their orbits due to the asymmetric potential. But the bias is even present in relaxed halos which implies other factors might also be contributing to it. Dynamical friction due to interaction with dark matter has also been shown to affect galaxy properties (Debattista & Sellwood 1998). Hence, the dynamical friction on galaxies due to the dark matter could also contribute to the velocity bias. In the projects, we aim to look into this more closely and comprehend the origin of the velocity bias in clusters. We aim to do this in two ways. First, we will be conducting controlled cluster simulations by taking a cluster with a relaxed halo and populate it with galaxies as test particles. The galaxies will be given initial tangential velocities such that they are in equillibrium with the cluster potential and the simulation will be allowed to evolve. The masses of these test galaxies will be slowly increased to see what is the effect of dynamical friction on the emergent velocity bias. This will be more of an academic study of the velocity bias. Second, we will be using the EAGLE simulations to examine the properties and origin of velocity bias in realistic clusters. This is also in preparation for the EAGLE-XL suite of hydrodynamical simulations which will be conducted next year. We will also be comparing our results to the GAMA group catalogue.

2.3 Originality and Importance

As mentioned earlier, the PhD will consist of two projects. The first is based on the relationship between dynamical state of the dark matter halos and galaxy properties. This has been a long standing question for some decades, yet the understanding of this relation is still incomplete. Earlier related studies in the literature have covered topics like galaxy formation in merged halos (Kauffmann et al. 1993), the core assymetry-halo mass relation (White et al. 2006), the dark matter-bar rotation relation (Debattista & Sellwood 1998), the dynamical state versus concentration relationship (Ludlow et al. 2012), the stellar mass versus halo properties (Matthee et al. 2016) and the relationship of galaxy properties with peak circular velocity of the dark matter halo (Chaves-Montero et al. 2016; He 2019). Our project is based on an approach of examining the dark matter-baryon relationship which has not been used before. This study will extend our understanding of the influence of dark matter physics on the formation and evolution of galaxies. Using different dark matter models for this and comparing the results could shed some light on the nature of dark matter particle as well.

For the second project, we will be addressing the origin of velocity bias which affects the measurements of cluster mass using member galaxy velocities. Accurate determination of cluster masses plays a vital role in studies where they are used to constrain the cosmological parameters (e.g. Vikhlinin et al. 2009). It is also important in view of present (e.g. BOSS, White et al. 2011) and future spectroscopic surveys (e.g. Euclid, Laureijs et al. 2011) which use calibrations between σ_{gal} and halo mass. The parameters of the scaling relationship vary between studies and it is not clear what is the reason for this variation. As such, understanding the origin of this bias addresses a matter of importance by providing insights not only into processes contributing to it but also its consequence on cosmological interpretations. There have been related works in the past concerned with understanding velocity bias using dark matter halo simulations (Colin et al. 2000), the role of baryonic dynamical processes in introducing velocity bias (Munari et al. 2013), comparison of different mass estimators (Wu & Fang 1997), scatter in the stellar-halo mass relation (Matthee et al. 2016) and cosmology with velocity dispersion counts (Caldwell et al. 2016). But no study has been conducted which has used controlled cluster simulations or EAGLE to understand the physical origin of the velocity bias in clusters. Having access to the EAGLE suite of simulations is a great opportunity for the projects because they have improved subgrid physics and one of the most accurate models to date. We will be using EAGLE-XL, the next generation of this suite which will be upgraded on the aspects of subgrid physics and cosmological volume thereby offering better accuracy and statistics.

2.4 Progress so far

We have been looking at dependence of size (R_{eff}) and specific star formation rate ($sSFR = SFR/M_*$) of central galaxies on the relaxation of host group halos where the relaxation state has been defined based on the three paremeters defined previously in Sec. 2.2. The results for the 100 Mpc simulation box for $z = 0$ are shown in Figure 1. It can be seen that the R_{eff} seems independent of halo's relaxation while the $sSFR$ for centrals in unrelaxed halos is higher by about a factor of two than that in relaxed halos over a broad range of stellar masses. This suggests that stars are formed faster in galaxies residing in unrelaxed halos. We will now explore other galaxy properties.

We have also started making mock H I observations of EAGLE galaxies using the MARTINI code [2] developed by Kyle Oman. Since the EAGLE data does not include mass and abundace for the atomic hydrogen and rather provides them for the total hydrogen in a gas particle, we have applied radiative transfer approximation using the approach given by Rahmati et al. (2013) in order to get the H I masses. The profiles are made assuming specifications of the Australian Square Kilometre Array Pathfinder (ASKAP) Telescope and thermal broadening. Figure 2 shows synthetic H I line profiles for two central galaxies residing in the most relaxed and the most unrelaxed Milky Way like halos with $M_{vir} \sim 10^{12}$ $M_\odot$, where $M_\odot$ is the solar mass. From visual inspection it is clear that the profile of the galaxy in the relaxed halo is more symmetric than the one in the unrelaxed halo. The H I profile for the galaxy in the unrelaxed halo also shows higher velocity width which implies that, as expected, it is a more energetic system. The next step is to compute H I line symmetry measurements for well resolved galaxies in the 100 Mpc box.

[2] https://github.com/kyleaoman/martini

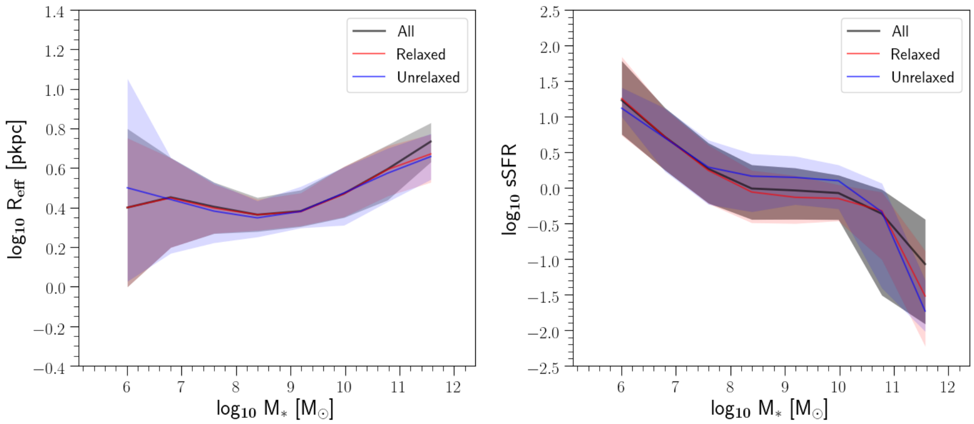

Figure 1: Dependence of size (R_{eff}) and specific star formation rate ($sSFR$) of central galaxy on halo relaxation. *Left*: The R_{eff} vs M_* relationship. *Right*: $sSFR$ vs M_* relationship. A halo is considered to be relaxed if it satisfies $\eta < 1.15$, $s_{dm} < 0.05$ and $f_{sub} < 0.05$ simultaneously. The unrelaxed halos satisfy $\eta > 1.15$, $s_{dm} > 0.08$ and $f_{sub} > 0.08$. The *solid-blue* curve shows the median values for galaxies in unrelaxed halos. The *solid-red* curve shows the median values for galaxies in relaxed halos. The *solid-black* curve shows the median values for galaxies in all halos. The shaded colored regions represent 1σ scatter in the corresponding curves.

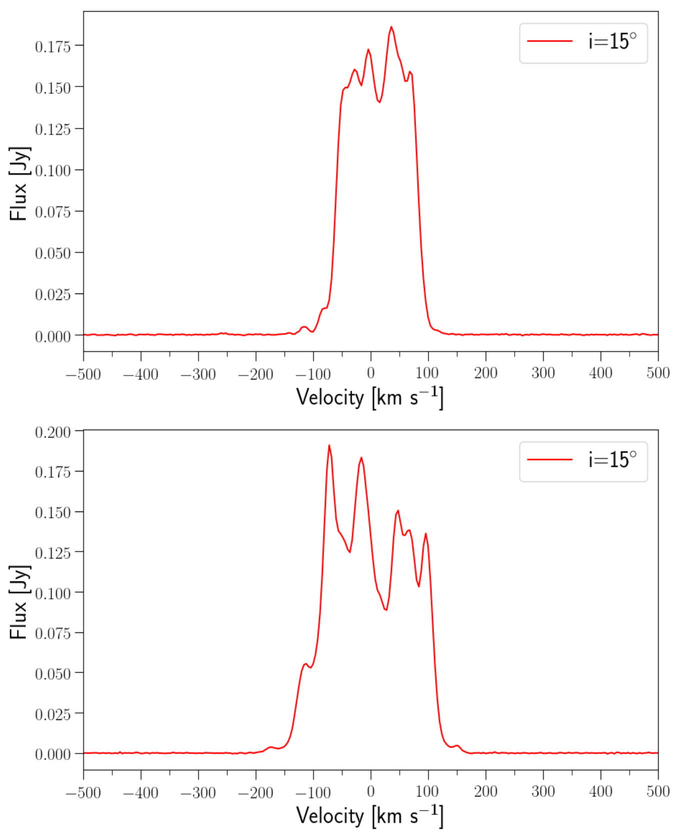

Figure 2: The integrated H I line profiles of central galaxies residing in most relaxed and unrelaxed milky way like halos of $M_{vir} \sim 10^{12}$ M$_\odot$. Both the galaxies are inclined at 15° with respect to the plane of the sky. *Top*: The profile for the galaxy in the relaxed halo which has two major broad peaks, each with minor subpeaks, of similar heights on either side of $v = 0$ km s^{-1}. *Bottom*: The profile for the galaxy in the unrelaxed halo which has two major peaks with different heights. The profile for galaxy in the unrelaxed halo clearly has lesser symmetry than the one in relaxed halo. The velocity width of H I corresponding to the unrelaxed halo is also larger than that corresponding to the relaxed halo.

3 Research Project Details

3.1 Confidentiality

No confidential data/information will be collected in the projects. The Graduate Research School (GRS) and ICRAR's advisors will be contacted if this changes.

3.2 Intellectual Property

The project will primarily use data from the EAGLE and the EAGLE-XL simulations. My primary supervisor, Dr. Aaron Ludlow, is an official member of the teams behind these simulations and therefore has full access to the data. My access to the data is provided by him.

3.3 Fieldwork

I hereby declare that I have read and understood the University field work and insurance policies.

3.4 Facilities

In addition to a laptop for smaller jobs, I have access to the Pleiades supercomputer at ICRAR as well as Pawsey supercomputers like MAGNUS and ZEUS for more memory intensive computations. All the relevant literature can be obtained online.

3.5 Statistics

The statistical methods that are required for the projects have been covered by the coursework on Astrostatistics of which Dr. Aaron Robotham was one of the lecturers.

3.6 Skills

The simulation data is dealt with using Python routines. I already have the required programming skills in Python from my Masters project and coursework. Moreover, I have also completed a course on Astrostatistics and Computational Astronomy in the University which helped me learn programming in R and various statistical analysis techniques that will be useful for this study. Any additional skills will be obtained from my supervisors, on-line tutorials, textbooks and fellow students.

3.7 Communication

The project results are expected to be communicated to the *Monthly Notices of the Royal Astronomical Society* (MNRAS) in the form of three manuscripts. They will also likely be presented, as either talks or posters, at national and international conferences like the Astronomical Society of Australia (ASA) Annual Scientific Meeting.

3.8 Approvals

No approval is required for the project.

3.9 Data management

All Data generated during the projects will be stored on the appropriate servers located at ICRAR.

3.10 Research project plan

The plan is divided considering 2 projects, thesis writing and submission. The stage wise plan for the project is shown in the Gantt chart (Figure 3).:-

Relationship between halo dynamics and galaxy properties (March 2019 - December 2019)

- Test codes on smaller simulation boxes.
- Optimize the codes to reduce processing time.
- Determine relaxation parameters for halos in the 100 Mpc simulation box.
- Determine properties of galaxies in those halos.
- Compare results with observed galaxy properties in surveys.
- Prepare the manuscript of paper 1.

The origin of velocity bias in clusters (January 2020 - March 2021)

- Run the controlled simulations of clusters with galaxies as test particles.
- Prepare the manuscript of paper 2.
- Study the velocity bias in realistic clusters using the 300 Mpc box of EAGLE-XL.
- Determine statistical properties of the bias.
- Compare results to the GAMA group catalogue.
- Prepare the manuscript of paper 3.

Thesis (May 2021 - Dec 2021)

- Thesis writing
- Revisions
- Submission

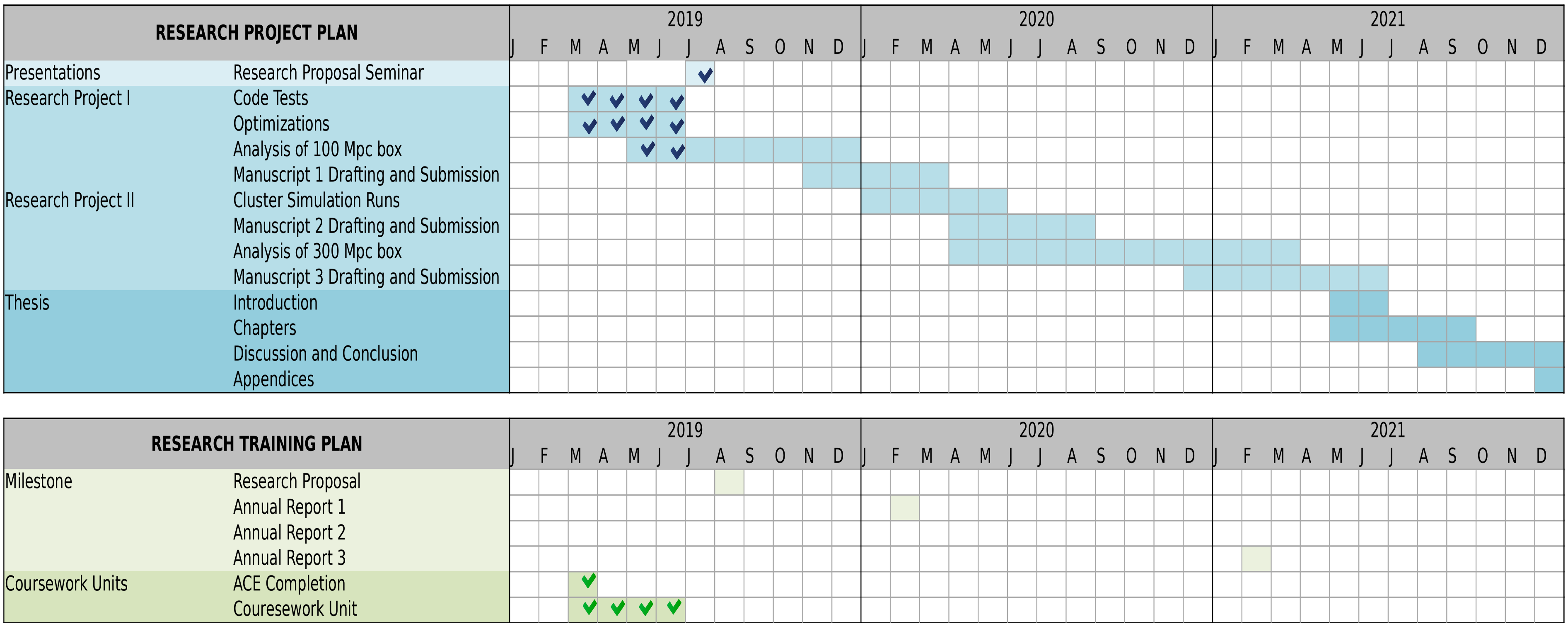

Figure 3: Project Gantt chart representing the time-line of the PhD plan.

4 Research Training

4.1 Research Training Plan

The research training has been planned as follows:

Annual Report	[Feb 2020]
Confirmation of Candidature	[Feb 2020]
Academic Conduct Essentials	[**Completed**]
Coursework	[**Completed (PHYS4418)**]
ICRAR Induction	[**Completed**]
GRS Induction	[**Completed**]

4.2 Confirmation of Candidature

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

Task	**Completion Status**
Annual Report	[Feb 5 2020]
Confirmation of Candidature	[Feb 5 2020]
Academic Conduct Essentials	[**Completed**]
Coursework (6 credits)	[**Completed (PHYS4418)**]
Substantial piece of writing	[Paper Draft]

4.3 Working Hours

The project is expected to involve 37.5 hours of work per week.

5 Budget

The costs will be covered by ICRAR, the School of Physics, the Graduate Research Office, The Astronomical Society of Australia and the University Postgraduate Award. A detailed breakdown on these costs is presented in Table 1.

		Year				*Source*		
	2019	*2020*	*2021*	*School*	*GRS*	*ICRAR*	*ASA*	*UPA*
Equipment								
Computer	$2300					$2300		
Data storage	$ 150	$150	$150			$ 450		
Travel expenses								
HWWS, ASA and observing		$2200	$700			$2400	$500	
Admin expenses								
Thesis binding			$840					$840
Subtotals	$4650	$850	$990			$5150	$500	$840
Total								$6490

Table 1: Budget for the projects. In addition to the above mentioned costs there are other hidden costs including stationary, local travel, utilities etc. which will be covered by ICRAR, School of Physics, Mathematics and Computing, and GRS.

6 Supervision

- **Principle Supervisor: Dr. Aaron Ludlow** (50%)
  Dr. Ludlow is part of the Virgo Consortium which is behind the EAGLE cosmological simulations. He has an expertise in dark matter research, hydrodynamical simulations and handling big data involved therein. He is also part of the team behind EAGLE-XL. Dr. Ludlow will be supervising me throughout the duration of my research.

- **Co-supervisor 1: A/Prof. Chris Power** (20%)
  A/Prof. Power is the leader of the Computational Astrophysics group. He has an expertise in numerical simulations and considerable experience in dark matter halo studies. Prof. Power will be providing scientific oversight and help with the technical aspects of the simulations that will be used for the projects.

- **Co-supervisor 2: Dr. Aaron Robotham** (20%).
  Dr. Robotham is experienced in analyzing the optical data and statistical analysis using R. He will be helping me with statistical methods as well as programing in R. He has also produced the GAMA group catalogue that we will compare our results to.

- **Co-ordinating and Co-supervisor 3: Prof. Simon Driver** (10%)
  Prof. Driver is the principle investigator of the WAVES and GAMA survey. He has a lot of experience in photometric and spectroscopic galaxy surveys. As the Co-ordinating supervisor, Prof. Driver will provide science oversight and administer the Graduate Research School requirements.

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