Project Title: Gas in the Cosmic Web: Feeding and Feedback of Galaxies

I. Aims and Background. **The objective of this DECRA application is to understand the complete cycle of gas in galaxies: from the process of feeding galaxies, going through star formation, to the process of outflowing gas from galaxies.** This requires a full description and understanding of (i) the accretion processes: inflow of gas to halos, through halos, until gas settles down in galaxies, (ii) the process of star formation through a modelling of the gas phases in the interstellar medium of galaxies and star formation, and (iii) feedback in galaxies: how is that energetic events in galaxies, such as supernovae, impact the gas content of galaxies and the capability of forming new stars in the short and long term. This work is bounded to complement major planned observational efforts in Australia, such as the Square Kilometer Array (SKA) and its Australian Pathfinder (ASKAP), as it will provide them with large, physically motivated simulations of galaxy formation containing, for the first time, a full physical description of the neutral gas in the Universe. With this DECRA fellowship I will set the grounds on this subject by presenting the most complete treatment of HI to date.

Galaxy formation is a complex process as it requires the interplay between many processes to be modelled coherently. Often the physics which underpins these processes is only understood at a rudimentary level. Phenomena such as star formation and the injection of energy into the interstellar medium (ISM) by stars are nonlinear. The physicists' approach to understand galaxy formation is to work forwards from the Big Bang and model galaxy formation in the context of the growth of structure in the dominant dark matter component. The basic tenants of this methodology were presented in convincing models of galaxy formation by White & Frenk (1991). I am one of the main developers of the widely known semi-analytic model of galaxy formation `GALFORM` (Cole et al., 2000), which solves for the formation of galaxies in an ab-initio fashion. Semi-analytic models consists of coupling large N-body dark matter only simulations with the baryonic physics governing galaxy formation (see schematic of Fig. 1).

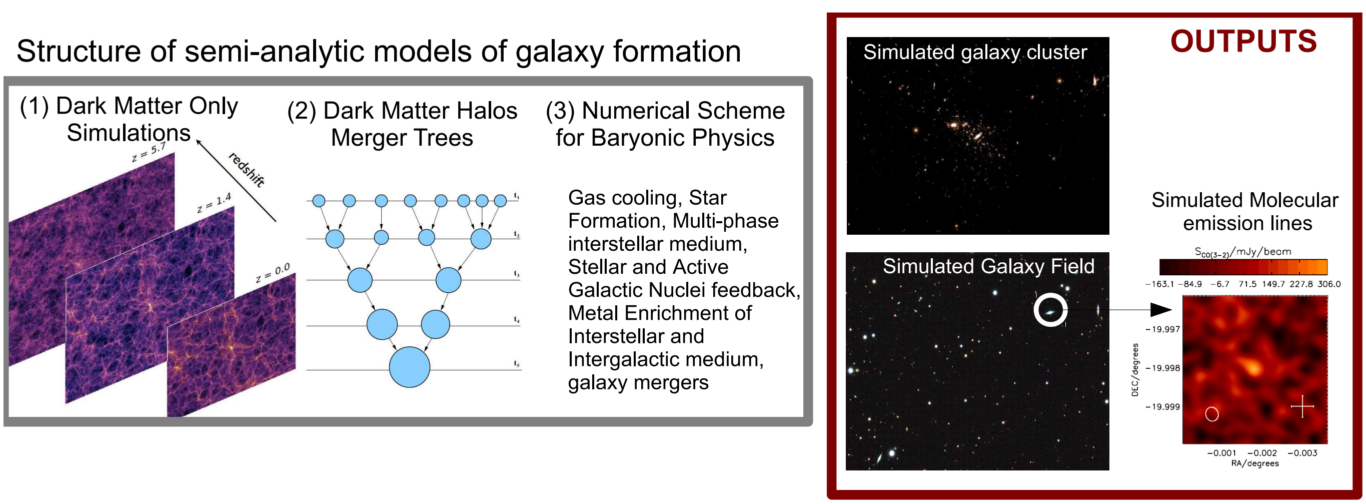

Figure 1. The structure of semi-analytic models of galaxy formation are based on Dark Matter only simulations (1), the extraction of merger trees for each dark matter halo of the simulation (2), and a numerical scheme of the baryonic physics run throughout the history of the dark matter halos (3). *Right Rectangle:* Examples of outputs of the semi-analytic model: multi-wavelength predictions, emission lines (including atomic and molecular) and different galaxy environments.

An understanding of galaxy formation requires an understanding on how the gas flows to and from galaxies. Two of the fundamental processes in galaxy formation, the formation of stars from the cold gas in the ISM, and the impact of injecting energy into the ISM, for example through supernovae, on subsequent star formation, have been treated in a rather simplistic fashion to date, which has drawn criticism from sceptics. The process of suppressing star formation by the effect of injecting energy into the ISM, called "feedback", has long been identified as crucial to reconcile the predictions of hierarchical models with the observed Universe. Nevertheless both processes have been treated in a rather simplistic fashion to date, which has drawn criticism from sceptics. In the case of star formation, it was modelled by assuming that all of the cold gas in a galaxy was available to form form stars. Typically two parameters were used to calculate a star formation timescale for each galaxy, with little or no guidance as to what the acceptable range of values should be for these parameters. Observations showed this assumption to be incorrect; the star formation activity in galaxies clearly matched their molecular hydrogen content rather than the atomic hydrogen (e.g. Leroy et al., 2008). For supernovae feedback, it was assumed that the circular velocity and the star formation rate were the only fundamental properties setting the outflow rate driven by this energetic feedback. My work has been focused on these two processes and investigates the use of improved, more physical models, completely overhauling the treatment of star formation and feedback in semi-analytic models of galaxy formation.

During my PhD thesis and my fellowship at ESO, I made two major breakthroughs, and that represent the first major steps forward in these areas in more than a decade. The implementation of a more general treatment of star formation, which is able to track the molecular hydrogen content of galaxies rather than the total cold gas mass allowed essentially all of the theoretical models of star formation on the market to be implemented into the `GALFORM` model (Lagos et al. 2011a). As a result of this extension to the model, the parameter space available was greatly reduced, and completely new predictions, such as the HI and H_2 contents of galaxies was made possible (see Fig. 2). These new predictions for the gas content of the ISM can be confronted directly to observations from new major telescopes, such as ALMA (Atacama Large Millimeter Array), EVLA (Extended Very Large Array) and ASKAP, rather than having to rely on uncertain extrapolations, opening up a completely novel way to constrain the models. These predictions allowed for the first time a statistical assessment of the relation between HI and H_2, star formation, stellar masses and luminosities, providing a physical explanation of observed local and high-redshift relations (Lagos et al. 2011b; Geach et al. 2011; Lagos et al. 2012; Kim et al. 2013a; Lagos et al. 2014 see Fig. 2). The second major breakthrough is a physical model of the expansion of bubbles inflated in a multi-phase ISM by supernovae (Lagos, Lacey & Baugh 2013). This work shows that the ejection of mass from the disk of galaxies is not at all well described by the circular velocity scalings which are de rigour in galaxy formation models. The normalisation and slope of the ejection rates when plotted as a function of circular velocity change with the type of galaxy (quiescent or starbursting) and redshift. Although important progress has been done posterior 2010, there is still *key aspects of galaxy formation that need revision and improvement and that can significantly change what we understand of galaxies. These aspects are related to how galaxies are fed by gas infalling into halos and the long term effect of feedback on galaxies. I aim to work on these aspects and answer the key questions related to feeding and feedback of galaxies with this DECRA fellowship.*

II. Research Quality and Innovation. The open questions related to the neutral gas content of galaxies and outside galaxies that I aim to answer with this DECRA fellowship are describe below. (I number the projects in parenthesis throughout the text.)

NEUTRAL GAS IN THE INTERGALACTIC MEDIUM (FEEDING GALAXIES)

What is the dominant source of the neutral gas content of the Universe? How much of the atomic hydrogen in the Universe is in the form of cold and warm flows coming into the galaxy halo? These are crucial questions in galaxy formation, since they are related to the channels that fuel star formation and, at early epochs, to how the epoch of reionisation proceeded. High-quality measurements of the 21 cm emission in large surveys of local galaxies (Zwaan et al. 2005) and absorption-line measurements in the spectra of quasi-stellar objects (Noterdaeme et al. 2012), have allowed an accurate measurement of the evolution of the global density of atomic hydrogen from $z = 0$ to $z \approx 4$ (see right-hand panel of Fig. 2). These observations suggest very little evolution of the atomic hydrogen global density with time.

In my semi-analytic model (Lagos12), by accounting for the atomic hydrogen content in the ISM of galaxies, I am able to explain the observed atomic hydrogen global density at $z < 2.5$ (see Regime I in Fig. 2). At higher redshifts, the model predicts an abundance lower by a factor of $\gtrsim 2$ compared to the observations, suggesting that the atomic hydrogen at higher redshifts might primarily be outside galaxies (Regime II in Fig. 2). Observations have shown that this neutral gas would still be close to galaxies, in the halo, within $\approx 20 - 40$ kpc of the galaxy (Krogager et al. 2012).

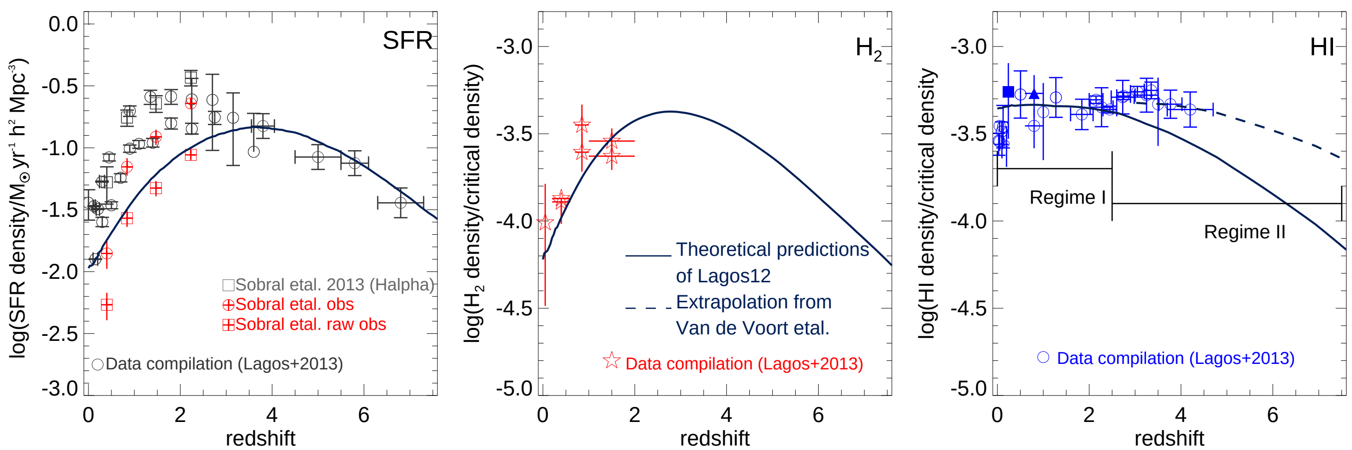

Figure 2: Key prediction of the model presented in Lagos et al. (2012; Lagos12): the redshift evolution of the star formation rate density (SFR; left panel), and the molecular hydrogen (H_2; middle panel) and atomic hydrogen (HI; right panel) densities. Observations are shown by symbols. As can be seen, the SFR and H_2 follow a qualitatively similar evolution: a steep rise from $z = 0$ to $z \approx 3$ followed by a decline at higher redshifts. The HI shows a dramatically different evolution: very little change from $z = 0$ to $z \approx 3$, followed by a slow decline. A expectation for the HI contribution from gas outside galaxies is shown as dashed line.

At $z > 3$, hydro-dynamical simulations show that about half of the atomic hydrogen in the universe is expected to be outside galaxies, mostly inside the galaxy halo (Van der Voort et al. 2012; Dave et al. 2013). However, a key step needed to answer the questions above comes from the challenge of modelling how much atomic hydrogen is accounted for in the intergalactic medium (IGM) and in gas flows in a self-consistent way. My plan is to use hydrodynamic simulations to study different geometries to calculate the neutral gas fraction in halos (using the recent EAGLE simulation of the VIRGO consortium), and complement this knowledge with semi-analytical calculations of the neutral gas at the epoch of reionisation (Kim et al. 2013b) (**Project I**). In Fig. 2, I show a simple expectation to what the HI gas content of halos (but outside galaxies; dashed line) is based on extrapolating the results of Van der Voort et al. (2012) and combing them with the predictions of Lagos et al. (2012). I also plan to investigate the coupling of semi-analytic galaxies with a hydrodynamic description of the IGM. Such a technique has been recently presented by Moster, Maccio & Somerville (2014), but so far with applications only for galaxy mergers. Both techniques will lead to an ultimate answer to what is the predicted density of HI all the way from $z = 0$ to $z = 12$ including all possible sources of neutral gas in an ab-initio galaxy formation simulation. *Such a consistent treatment of the HI content of the Universe has never been done before, and we plan to set the ground on this subject* *by presenting the most complete treatment of HI.*

ABSORPTION-LINE PREDICTIONS. Another key component needed to answer the questions above is the confrontation of theory and observations. This will allow me to test the physical treatment of the gas included in galaxy formation models, further improving the physics involved. This will also help me to make direct predictions for the new generation of radio telescopes, such as ASKAP (with its imaging surveys, such as WALLABY and DINGO, and its absorption experiments, such as FLASH). For direct imaging it is necessary to model the 21 cm emission line profiles and its flux, which is a work that will be presented in Lagos et al. (2014, in prep.). For absorption studies, the model should be able to predict observed column densities towards different line-of-sights. FLASH, a large ASKAP programme, promises to be the largest absorption campaign ever performed. *Predictions based on ab-initio galaxy formation models in large cosmological volume will be needed for the interpretation of the observations of FLASH. I plan to make these predictions available through the combination of* `GALFORM` *with ray-tracing algorithms* (**Project II**). Note that the sky areas and depth that will be probed by ASKAP and SKA are unprecedentedly large. This means that we will need dark matter simulations (step (1) in Fig. 1) much larger than currently available. *These simulations will be performed at University of Western Australia by Professor Chris Power and his computational team.*

NEUTRAL GAS IN THE INTERSTELLAR MEDIUM (FEEDING STAR FORMATION)

Will the SKA detect high-redshift molecular gas? Can it be used to search for dense gas at the epoch of reionisation? A major step needed to answer the questions above is to connect the molecular content of galaxies with the Carbon-Monoxide emission in a physical way. I led the development of a novel hybrid approach which estimated theoretically the Carbon-Monoxide emission of galaxies by combining the galaxy formation model `GALFORM` with the ISM chemistry, radiative transfer simulations performed by the Oxford-UCL group (Lagos et al. 2012; see also Fig. 1). This work represented a major step towards the observations of the new generation of millimeter telescopes, such as ALMA. However, radio telescopes, such as SKA and EVLA, are expected to play a major role in the search of molecular emission lines in the high-redshift Universe (Geach et al. 2012). A novel approach to do so is using the technique of intensity mapping (Carilli 2011). Intensity mapping gives the two-dimensional spatial information at a given redshift of the emission line; imaging is obtained by aggregating the emission of thousands of galaxies on very large scales to get the summed signal of galaxies that are not individually detected. One of the aspects that needs to be included in the model before producing the lightcones necessary to explore the molecular gas at the epoch of reionisation is the thermalisation of the ISM of galaxies due to the cosmic microwave background. I plan to include this effect in the photon dominated region models in collaboration with Estelle Bayet (Oxford) and Serena Viti (University College London). *I plan to explore the capabilities of SKA in the search for high-redshift dense gas by using lightcones created with this improved model of the ISM, which will include the full spectral line energy distribution of the most used molecular emission line: the Carbon Monoxide* (**Project III**).

THE EFFECT OF SUPERNOVAE FEEDBACK (FEEDBACK OF GALAXIES)

Are supernovae responsible for quenching star formation? How is the star formation history of galaxies affected by supernovae feedback? Supernova feedback represents a long standing problem in galaxy formation model. Until recently, toy models are used to treat supernova feedback, which are parametrized to reproduce the faint-end of the luminosity function (Guo et al. 2011). These toy models do not take into account key physical conditions, such as the density of the ISM of galaxies or how much energy is being released by supernovae. This is a fundamental issue in galaxy formation theory, given the importance of supernova feedback in determining the star formation history of galaxies.

In Lagos, Lacey & Baugh (2013), I presented a full numerical treatment of supernovae driven outflows, which were modelled in a physical way by following their evolution from the point of energy injection, passing through the creation of pressurised cavities (bubbles) that sweep up gas from the ISM, until these bubbles break-out from the galaxy and become an outflow. This numerical hydrodynamic treatment of the growth of bubbles in the ISM led to robust conclusions that the gas surface density was a fundamental property in determining the mass entrainment of outflows and that had been ignored in the past. This numerical description gives predictions of mass entrainment and outflow velocities in good agreement with observations. However, the development of a galaxy wide outflow does not necessarily mean that such outflow will produce a long term damage to the gas reservoir of the galaxy, i.e. if the outflow expands slowly, the outflowing gas would rapidly stop and be reincorporated back onto the ISM. *I plan to calculate the evolution of these large scale outflows until they become confined within the galaxy halo or escape from it. This will provide the ultimate answer to where and when outflows can affect the gas content of galaxies as to quench them* (**Project VI**). We will start from the current set up of simulations presented by Lagos, Lacey & Baugh (2013), where radial profiles of the outflow and circular velocity are provided (see Fig. 3). In addition to this, I plan to provide physical parametrisation of the reincorporation timescales of the outflowing gas onto the halo gas reservoir. The latter parametrisation has shown to be one of the key unknowns in galaxy formation, which lead to very different star formation histories of galaxies. Henriques et al. (2013) showed that a different parametric form would help the build-up of the stellar mass predicted by models to get closer that what is inferred from observations. *My model would be able to answer such a question from physical grounds.*

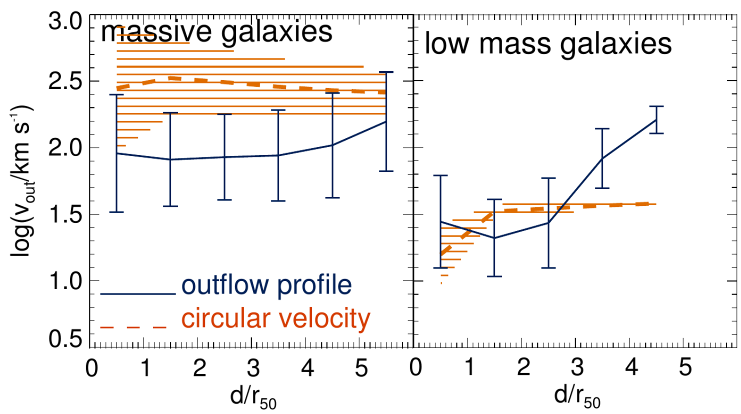

Figure 3: Outflow velocity as a function of the distance from the galactic centre normalised by the half-mass radius, for the model of Lagos, Lacey & Baugh (2013). Predictions are plotted for galaxies at $z = 0$ for massive galaxies ($M_\star \approx 10^{11}\,M_\odot$) and low mass galaxies ($M_\star \approx 2 \times 10^7\,M_\odot$). Solid lines with errorbars represent the expectations for the outflow velocity profiles, while the shaded regions correspond to the circular velocity profiles.

NEBULAR EMISSION LINE PREDICTIONS FOR IFS INSTRUMENTS. One of the main strengths of the model developed by Lagos, Lacey & Baugh (2013) is that we have a full radial description of the outflows and the metal enrichment of the ISM. A key step to make our predictions fully comparable to the observations is to calculate the nebular emission line fluxes in the outflow and ISM components. To do this is necessary to couple our current predictions with radiative transfer calculations of HII regions. I plan to use available radiative transfer codes, such as `MAPPINGS` (Levesque, Kewley & Larson 2010; Orsi et al. 2014), and collaborate with Dr. Alvaro Orsi (CEFCA, Spain) and Brent Graves (MPIA, Germany) to develop the technique of coupling the outputs of my simulation and their radiative transfer code (**Project V**). These predictions can then be used to interpret observations of IFS instruments such as the Sydney-AAO

Multi-object Integral field spectrograph (SAMI) and KMOS in the Chile.

III. Research Environment. The DECRA fellowship will be based at the University of Western Australia at the International Centre for Radio Astronomy Research (ICRAR). ICRAR has recently been established with an allocation of A$30 million to pursue an aggressive programme of research into galaxy formation and evolution in addition to its computational and instrumentation programmes. The University of Western Australia (UWA) node of ICRAR currently has over 30 staff and students based in an modern purpose-designed building. The majority of these astronomers are engaged in aspects of galaxy formation (theoretical and observational) providing a strong intellectual environment to support this project. ICRAR also hosts experts in advanced databases technologies who can provide technical support for the data-intensive aspects of my projects. The current computational facilities at UWA will allow the full completion of this project within the timescale of the DECRA. In addition to the facilities, the local expertise on N-body and hydrodynamical simulations by Professor Chris Power and Dr. Danail Obreschkow will complement my own expertise, which is in the modelling of galaxy formation. Recently, UWA was awarded a maximum 5 rating in the Australian ERA research assessment exercise, reflecting the dynamic work being conducted in Australias youngest astronomy group. In addition, WA is the host State for both ASKAP and the US-India-Australia Murchison Widefield Array (MWA); UWA is a key partner in both of these facilities. Furthermore, as the scientifically outstanding candidate site, WA is co-hosting, along with South Africa, the international SKA collaboration. With this successful bid, the University is confident that its astronomy and astrophysics research will continue to attract investment and grow stronger well into the future.

IV. Feasibility and Benefit. The proposed projects within this DECRA has three main parts that correspond to 'Feeding Galaxies', 'Feeding Star Formation' and 'Feedback of Galaxies' (see Fig. 4). The first will develop state-of-art methods which have started to be explored by myself and collaborators (tasks 1 to 2.4). The second one will make use of lightcones that are already available for my model and other `GALFORM` models, that include my radiative transfer treatment of dense gas in the ISM (tasks 3 to 3.2). A novel method will be develop to calculate intensity mapping of molecular emission lines. The third part will develop the treatment for large scale bubbles in the halos of galaxies (tasks 4 to 5.3). A more detailed plan is presented in a Gantt chart in Fig. 4.

List of tasks for this DECRA shown in the Gantt chart of Fig. 4 (Milestones are marked as $\diamondsuit$):

• Task 1: Implement formalism to calculate neutral gas outside galaxies (**Project I**). Provided this task is well advance, I can proceed to tasks 1.1 and 1.2.

  ◦ Task 1.1: Write paper presenting formalism and first comparisons with observations ($\diamondsuit$).

  ◦ Task 1.2: Present Project I at conferences.

• Task 2: Combine the model with ray-tracing algorithms (**Project II**). Provided this task is well advanced, I can proceed to tasks 2.1, 2.2, 2.3 and 2.4.

  ◦ Task 2.1: Write paper presenting coupling and predictions for the column densities of HI ($\diamondsuit$).

  ◦ Task 2.2: Write a second paper presenting properties of DLAs.

  ◦ Task 2.3: Present Project II at conferences.

  ◦ Task 2.4: Build simulated catalogue with predictions and make it available to the wide community.

• Task 3: Explore SKA capabilities of detecting dense gas at high-redshift (**Project III**). Provided this task is well advanced, I can proceed to task 3.1 and 3.2.

  ◦ Task 3.1: Write paper presenting the study of SKA capabilities ($\diamondsuit$).

  ◦ Task 3.2: Present Project III at specialise SKA conferences.

• Task 4: Implement evolution of large scale bubbles in galaxy halos (Part I **Project IV**). Provided this task is well advanced, I can proceed to task 4.1, 4.2, 4.3 and 4.4.

  ◦ Task 4.1: Compare results of implementations with hydrodynamic simulations (Part II **Project IV**).

◦ Task 4.2: Write paper presenting Project IV (♢).

◦ Task 4.3: Explore physical parametrisations of the reincorporation timescale of gas onto halos. Provided this task is well advanced I can proceed to 4.3.1.

◦ Task 4.3.1: Write paper presenting physical parametrisations.

◦ Task 4.4: Present Project IV at conferences.

• Task 5: Couple simulation for the evolution of ISM bubbles with radiative transfer code (**Project V**). Provided this task is well advanced, I can proceed to 5.1, 5.2 and 5.3.

◦ Task 5.1: Write paper presenting the results of Project IV and comparison with observations (♢).

◦ Task 5.2: Present Project V at conferences.

◦ Task 5.3: Build simulated catalogue with emission line predictions and make it available to the wide community.

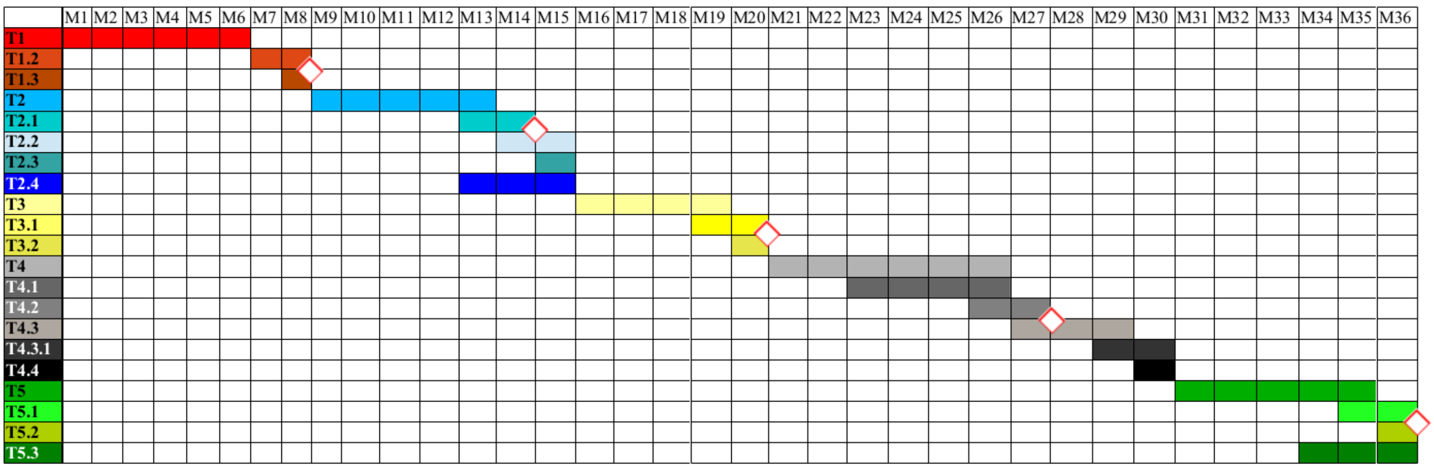

Figure 4: Gantt chart of this DECRA project from month 1 (M1) to month 36 (M36). Milestones are shown as diamonds.

V. DECRA Candidate. My extensive experience with the modelling of relevant physical processes in galaxies has translated into high quality, high impact science although only a year out of my PhD, I already have published more than 20 peer-reviewed articles in leading international journals in astrophysics and space science, a number of which are ground-breaking and have redefined the state-of-the-art in the field of galaxy formation. Of those 20 peer-reviewed articles, 9 correspond to first author papers; 3 of which were published during my Master degree, 4 during my PhD thesis and 2 so far during my fellowship at the European Southern Observatory. My citation record is outstanding, with more than 440 citations and an impact factor of 12 (12 papers with at least 12 citations). Since my bachelor degree I have been awarded university prizes due to outstanding performance (for two consecutive years during my bachelor and the Physics Faculty prize at Durham University during my PhD studies). My PhD thesis was awarded two prestigious international prizes: the Springer Thesis prize, which is given to the best theses in Physics Worldwide and includes the publication of the thesis by Springer, and the MERAC Prize given by the European Astronomical Society to the best PhD thesis in Astronomy in Europe. My world-leading expertise in galaxy formation modelling has brought me invitations as review or highlight speaker at 12 international conferences around Europe, United States and Australia, contributed speaker in 14 international conferences, and several invitations for seminars at Universities and institutes. Part of the MERAC prize is the possibility of a funding of $50,000$ euros per year for two years. I plan to top up that quantity with this DECRA to hire a PhD student to work in the projects I described throughout this proposal. Other than that, I will be fully dedicated to the projects of this DECRA. Given to this full time dedication, my expertise on galaxy formation modelling and the advantage of the local expertise at in hydrodynamic simulations and data intensive management at ICRAR, I expect to reach all my goals on time.

VI. Management of Data. The projects listed for this DECRA will lead to the creation of light-cones of emission and absorption lines of HI, nebular lines and molecular lines. The main datasets that will be generated by this project include the complete growth history of galaxies in large cosmological volumes (with properties such as masses, luminosities, sizes and rates of accretion, outflow and star formation) from the early universe to date. The expectation is to produce and release this information for tenths of millions of galaxies. As part of the project we are also planning to create observed catalogues, which will include the information observers need to test their techniques and also compare against, such as absorption and emission line profiles. During the project I plan to use the data managment service prodived at the University of Western Australia, specifically the UWA institutional research data store. The data management plan is to make the simulated datasets as soon as we have the papers accepted for publication in peer-reviewed journals, through the UWA research data online. Note that the creation of simulated catalogues are contemplated in tasks 2.4 and 5.3. In addition to the expertise of the information services at UWA, the ICT group at ICRAR are developing new techniques for data visualisation and have a great expertise managing large datasets (for example for MWA). This group of experts will assist me in finding the most efficient and user friendly ways of handing out the data to the wider scientific community and to create appealing visualisation we can use to engage the general public in the work produced at UWA and ICRAR.

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