INTER-UNIVERSTITY CENTRE OF
ASTRONOMY AND ASTROPHYSICS

# Interplay of galaxy formation and the evolution of dark matter haloes in the cosmic web

Synopsis of the thesis submitted for the degree of
**Doctor of Philosophy** (in Physics)

by

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supervised by

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to

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# Synopsis

## Background

Dark matter is inferred exclusively through its gravitational effects to make up over 80% of all the matter in the Lambda-cold dark matter ($\Lambda$CDM) model of the Universe. Tiny fluctuations in the initial density field cause them to clump into gravitationally collapsed structures called haloes [1, 2]. These haloes are fundamental to understanding cosmology as they form the building blocks of the large-scale structure and also reveal insights into the particle physics of dark matter. Dark matter haloes have been extensively studied in gravity-only scenarios both in isolated systems and over cosmological volumes. For example, the haloes identified in cosmological $N$-body simulations on $\Lambda$CDM cosmology are known to be triaxial [3], and their sphericalised mass profiles are found to have a universal form [4–6].

Dark matter haloes also provide the primary environment for the formation and evolution of galaxies [7], making them crucial for understanding astrophysical processes. Gas, through various non-gravitational baryonic interactions, can cool and condense towards the halo center [8, 9], eventually producing stars and other astrophysical bodies. However, the complexity and incomplete knowledge of these baryonic processes, along with their large dynamic range, make it impossible to study galaxy formation directly from first principles using cosmological simulations.

One approach to studying galaxy formation is to use semi-analytic techniques, modeling its formation within the halo based on properties known from gravity-only simulations. These semi-analytic models have various free parameters that need to be constrained typically by observations [10]. The formation of galaxies driven by the baryonic interactions within these haloes also affect the spatial distribution of dark matter through gravitational coupling. This response of a halo's dark matter content to the baryons it hosts must be accounted for to understand the coupled evolution of haloes and galaxies.

The state-of-the-art approach to galaxy formation involves numerical hydrodynamical simulations in cosmological volumes, using subgrid recipes to model baryonic physics at unresolved scales. Although some baryonic processes are included only as effective models with parameters constrained by observations, this approach is more realistic than semi-analytical models for making predictions. This method also incorporates the backreaction of galaxies on dark matter haloes, though it is computationally challenging. Modern cosmological simulations like EAGLE [11] and IllustrisTNG [12] were performed on high-performance clusters over several months.

Understanding the mutual effects of dark matter halo formation and galaxy formation on each other is relevant for various problems. For example, halo shapes respond to galaxy formation [13, 14], which is important for weak-lensing studies [15]. Similarly, galaxy formation changes the dark matter density profile of the halo, affecting the galaxy's rotation curve. However, previous works have not reached a consensus on the backreaction of galaxy formation on halo properties in simulations, making it a pressing open problem.

From a cosmological viewpoint, these 'baryonic' effects are often a nuisance in parameter inference; e.g., the effects of feedback from active galactic nuclei (AGN) can be degenerate with the effects of a massive neutrino species or a thermally produced 'warm' dark matter candidate at Fourier scales $k \sim 1\,h\,\mathrm{Mpc}^{-1}$ (see, e.g., [16, 17]). The response of dark matter (DM) to baryons must be quantified and distinguished from observational effects of (non-standard) primordial physics.



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While the former problem has a long history [18–28], the latter has only recently begun to be studied in detail [17, 29–33].

## Thesis Statement

In this thesis, we study the interplay between galaxy formation and its host halo evolution, focusing on changes in the radial distribution of dark matter in response to galaxy formation and evolution. We build a comprehensive understanding using both hydrodynamical simulations of realistic galaxies in cosmological volumes and more tractable self-similarly evolving systems of individual galaxies with their host haloes. This unified picture of the role of various galactic astrophysical processes in mediating the response of dark matter haloes also provides useful timescales for predicting dynamical changes in radial mass profiles due to astrophysical processes.

## Overview

### Chapter 1

This chapter introduces the background material and the primary objectives of the thesis, along with a review of existing knowledge and the relevance of this work in the broader context of ongoing research in physics.

### Chapter 2

We describe the simulation data and techniques primarily employed in this thesis. Currently, the most robust technique to understand the consequences of gas assembly and galaxy formation on dark matter structure is the use of high-resolution cosmological hydrodynamical (zoom) simulations, using 'sub-grid' recipes for modeling small-scale astrophysics such as feedback from stellar/supernovae activity or the effects of active galactic nuclei (AGN). In this thesis, we mainly use publicly available data from such cosmological simulations of galaxies performed as part of large collaborative projects, namely IllustrisTNG [34], EAGLE [35], and CAMELS [36, 37]. This chapter provides a brief description of these simulations and the identification of halo objects in their respective cosmological volumes, focusing on details relevant to this thesis.

We also develop a matching algorithm to assign each halo in the full hydrodynamic simulations a matched 'partner' halo in a collisionless, gravity-only simulation performed using the same initial random fluctuations. We demonstrate its robustness, as comparing these hydrodynamically simulated haloes against their partner haloes is key to investigating the simulated backreaction of galaxies on dark matter haloes.

Early work modeled halo response using adiabatic invariants within individual haloes [38–41]. Using simplifying assumptions such as spherical symmetry, no shell crossing, angular momentum conservation with circular orbits for dark matter particles, a simple formula was derived to quantify the *adiabatic relaxation* of the radial distribution of dark matter in terms of the radial distribution of baryons. This idealized model of adiabatic relaxation [40] was found to be inaccurate in various simulations [see, e.g., 13, 42–50]. This led to developing models that are direct extensions of the idealized model with additional parameters constrained by the simulated response [13, 42, 43, 46].

We characterize halo response within this quasi-adiabatic relaxation framework, primarily through the relation between relaxation ratios and enclosed mass ratios, quantifying changes in the sphericalised mass profiles of dark matter and baryons, respectively. The chapter concludes with a description and demonstration of the techniques used in computing these quantities in simulated pairs of haloes.

# Chapter 3

In this chapter we perform a systematic, statistical study of the dark matter response to galaxies in high-resolution hydrodynamical simulations of realistic galaxies in cosmological volumes from IllustrisTNG and EAGLE projects at the present epoch. We explore this response across a wide range of halo masses, spanning four orders of magnitude, and over various halo-centric distances at redshift ($zsimeq0$).

We establish that the dark matter's response to baryons cannot be accurately described by the commonly used quasi-adiabatic relaxation models, which typically relate the relative change in radius ($r_f/r_i - 1$) of a dark matter shell solely to the relative change in their enclosed masses ($M_i/M_f - 1$). Instead, our findings reveal that the relaxation response ($r_f/r_i$) also explicitly depends on the halo-centric distance ($r_f/R_{\rm vir}$), a dependency that is consistent across different halo masses and between the IllustrisTNG and EAGLE simulations.

Our study also identifies an unmodeled effect likely driven by feedback-related outflows. This effect shows that even shells with no overall change in the enclosed mass ($M_i/M_f \simeq 1$) can exhibit relaxation of its radius ($r_f/r_i < 1$). This suggests that existing models need to incorporate this additional parameter to more accurately capture the complex interplay between dark matter and baryonic processes.

We present a new, physically motivated model that incorporates these findings, offering a better fit for the dark matter response over the examined range of halo masses and distances. This model introduces an additional parameter to account for feedback-induced offsets, providing a more comprehensive description of the dark matter relaxation process.

Moreover, we investigate the dependence of this response on various halo and galaxy properties beyond total mass. We find that halo concentration and star formation rate play significant roles in influencing the dark matter response. These insights are crucial for improving semi-analytical models and for applications such as baryonification schemes in emulating the small-scale power spectrum and modeling the rotation curves of galaxies.

# Chapter 4

In this chapter, we investigate the influence of astrophysical modeling on the relaxation response of dark matter haloes at different epochs, specifically focusing on $z = 0$ and $z = 1$. The analysis is divided into three main parts, each shedding light on the role of various astrophysical processes in shaping the dark matter content of haloes.

## 1. Early Epoch in IllustrisTNG Simulations

We begin by examining the relaxation response at an earlier redshift ($z = 1$) using the IllustrisTNG simulations. Our study reveals that dark matter relaxation tends to be stronger at $z = 1$ compared to $z = 0$. We assess this using four distinct halo samples, which highlight the variations in relaxation across different halo masses. Notably, we observe that cluster-scale haloes at $z = 1$ show significant relaxation that becomes a function of the change in enclosed mass, in contrast to similar haloes at the present epoch.

Our findings suggest that the relaxation relation at this earlier epoch can also be modeled effectively using the locally linear model developed in Chapter 3, demonstrating the robustness of this approach in capturing the dark matter response across redshifts. Moreover, the parameters of the radially dependent relaxation are found to be more universal across a much wider range of masses at $z = 1$. For example, the progenitors of even the most massive clusters are well characterized by the simple three-parameter model of relaxation that was developed with a focus on galactic-scale haloes at $z = 0$.

## 2. Variation in Astrophysical Feedback Using CAMELS Simulations

Next, we explore variations in astrophysical feedback strengths within the IllustrisTNG model using simulations from the CAMELS project, which varies four different feedback parameters: two for stellar feedback and two for AGN feedback. Our analysis shows that the parameters controlling the energy flux of the feedback have a significant impact on the relaxation of dark matter at different epochs. In contrast, the parameters governing the speed and burstiness of feedback have negligible effects on the halo relaxation response.

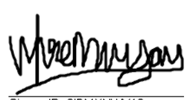
We find that variations in stellar feedback strengths have a larger impact among dwarf galaxy-scale haloes, while variations in AGN feedback parameters exert a stronger influence on Milky Way-scale haloes. Notably, the relaxation offset in the outer well-resolved regions is stronger at the present epoch than at $z = 1$, contrasting with results from the inner regions explored in the IllustrisTNG simulations in the first part of this chapter.

The stronger implementation of AGN feedback tends to result in greater relaxation at both $z = 0$ and $z = 1$ in the outer regions of the haloes. However, in the slightly inner regions, stronger AGN feedback implementation leads to a weaker relaxation offset at $z = 0$ and a stronger offset at $z = 1$. We interpret this as a consequence of the overall reduction in total feedback at $z = 0$ due to the suppression of star formation caused by higher AGN feedbacks in the past. These results highlight the significance of feedback mechanisms in building a physical understanding of dark matter halo relaxation.

## 3. Role of Astrophysical Models in the EAGLE Simulations

Finally, we assess the impact of different astrophysical models in the EAGLE simulations. Supernova feedback strengths show a similar trend to that observed in the CAMELS simulations. Additionally, we find that the gas equation of state has the strongest effect on the relaxation response of dark matter, particularly among haloes hosting dwarf galaxies.





Overall, this chapter underscores the intricate relationship between baryonic processes and dark matter halo relaxation, illustrating the variations that arise due to different astrophysical models and redshifts.

## Chapter 5

In this chapter, we examine the dynamical evolution of dark matter's relaxation response to galaxy evolution as simulated in the IllustrisTNG suite of cosmological hydrodynamical simulations. Our analysis reveals several key findings about the connection between halo relaxation and astrophysical properties.

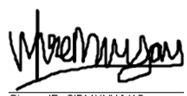
We confirm that the radially-dependent linear relaxation relation model, established in Chapter 3, accurately describes the relaxation response even at higher redshifts of $z = 5$. We then primarily focus on the relaxation offset parameter $q_0$, which quantifies the excess relaxation of dark matter shells. In populations of haloes selected by their mass, this offset is found to be stronger in the epochs following the peak star formation epoch for those haloes.

Our results demonstrate that star formation activity is strongly connected with the halo relaxation response of individual haloes throughout their evolutionary history. Typically, the processes related to star formation have immediate impacts on the relaxation response in the inner haloes, whereas the impacts in the outer regions manifest with a delay of approximately 2 to 3 billion years. This temporal relationship underscores the complex dynamics between star formation and halo relaxation.

While the metal content shows a weaker correlation with halo relaxation compared to star formation rates, the cumulative wind from feedback processes exhibits a stronger connection. This finding emphasizes the importance of feedback mechanisms in driving halo relaxation dynamics.

The insights gained from this study enhance our understanding of halo relaxation mechanisms and have important implications for baryonification schemes





and semi-analytical galaxy formation models. Specifically, knowledge of the relevant time-scales for dark matter relaxation can lead to improved descriptions of the halo profiles, allowing for modeling with fewer parameters. This is particularly relevant for large-scale surveys such as Euclid.

Additionally, incorporating time-dependent transformation procedures in semi-analytical models may enable a more accurate representation of the dynamical evolution of dark halos alongside galaxy evolution, which is often neglected. These results also suggest that the relaxation response of dark matter haloes may serve as a valuable probe into the evolutionary history of the galaxies they host.

## Chapter 6

In this chapter, we present a self-similar model for galaxy formation through gas collapsing within an isolated dark matter halo. This model addresses the evolution of both gas and dark matter simultaneously, incorporating the backreaction of the galaxy on the dark matter halo.

Firstly, we build upon existing models of self-similar gas accretion by incorporating radiative cooling and artificial viscosity. This approach allows for self-similarly accreting gas onto a galaxy disk-like structure in a parametrized manner, producing shell trajectories that qualitatively match results from full hydrodynamical simulations.

Secondly, we develop a novel iterative method to solve for the gravitationally coupled self-similar evolution of gas cooling and accreting onto a galaxy-like structure, alongside dark matter accreting onto the halo. We then characterize the relaxation response in these haloes using the framework of quasi-adiabatic relaxation.

We find that the relaxation relations are qualitatively similar to those observed in realistic simulations of galaxies within cosmological volumes. Through systematic variation of parameters in this more tractable model, we investigate the role of halo and galaxy properties on the relaxation response of the dark matter halo.

Notably, the accretion rate and gas equation of state significantly influence the relaxation relation, while other parameters, such as the cooling rate, have only a minor effect. In particular, the relaxation is found to be weaker when the gas is modeled with a steeper equation of state, aligning with the results found in the EAGLE simulation presented in Chapter 4.

Overall, this chapter underscores the potential of self-similar models in advancing our understanding of galaxy formation and dark halo dynamics, while also identifying avenues for further research. This framework provides an efficient way to explore the nonlinear impacts of multiple astrophysical processes on dark matter profiles.

## Chapter 7

We conclude this thesis with a brief summary of the key findings and their applications. We also discuss future directions for this work in this chapter.

# Organization of the Thesis

- In the first chapter of this thesis, we review the background material and define the primary objectives, along with their relevance to the broader context.

- In the second chapter, we demonstrate the specific techniques we employed in studying the simulated response of dark matter haloes to galaxy formation and evolution within simulations of cosmological volumes.

- In the third chapter, we present our findings from state-of-the-art galaxy formation simulations, IllustrisTNG and EAGLE, characterizing the dark matter response in a wide variety of haloes at present epoch. We introduce novel fitting functions that accurately describe this relaxation response, revealing an additional dependence on halo-centric distance and highlighting the significant role of star formation-related feedback processes.

- In the fourth chapter, we explore the role of astrophysical modeling in producing the halo response at different epochs in simulations. We find the gas equation of state to have significant influence in EAGLE haloes, and we also quantify the strong influence of AGN and stellar feedback in CAMELS simulations. Our results show a more universal relaxation response at an earlier epoch ($z = 1$) compared to $z = 0$. These findings are applicable to semi-analytical tools for modeling galactic and large-scale structures.

- In the fifth chapter, we uncover the causal connections between star formation activities, feedback processes, and halo relaxation. Through time-series analyses, we provide new insights into the immediate and delayed effects across different halo regions. Our estimates of the timescales can potentially improve the description of halo profiles in existing baryonification schemes and semi-analytical galaxy formation models.

- In the sixth chapter, we develop a spherical self-similar model for galaxy formation that simultaneously and self-consistently solves for the evolution of gas and dark matter, producing pseudo galaxy disks within the halo. This complementary approach offers a framework to rapidly explore the sensitivity of halo response to various astrophysical processes. We find quasi-adiabatic halo relaxation similar to full non-linear simulations, with similarly strong trends related to the gas equation of state.

- In the seventh chapter, we summarize the key findings of this thesis and discuss the future outlook.

## Publications included

1. Velmani P., Paranjape A., 2023, "The quasi-adiabatic relaxation of haloes in the IllustrisTNG and EAGLE cosmological simulations", *Monthly Notices of the Royal Astronomical Society*, **520**(2):2867-2886. doi:10.1093/mnras/stad297 https://ui.adsabs.harvard.edu/abs/2023MNRAS.520.2867V

2. Velmani P., Paranjape A., 2024, "Dynamics of the response of dark matter halo to galaxy evolution in IllustrisTNG", *arXiv e-prints*, arXiv:2407.08030. doi:10.48550/arXiv.2407.08030

3. Velmani P., Paranjape A., 2024, "A self-similar model of galaxy formation and dark halo relaxation", *Journal of Cosmology and Astroparticle Physics*, **2024**(5):080. doi:10.1088/1475-7516/2024/05/080 https://ui.adsabs.harvard.edu/abs/2024JCAP...05..080V

4. Velmani P., Paranjape A., 2024, "Role of astrophysical modeling on dark matter halo relaxation response at redshifts z = 0 and z = 1", *in prep.*



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