UNIVERSIDAD DE LOS ANDES

The expected shape of the Milky Way's dark matter halo

by

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A thesis submitted in partial fulfillment for the degree of Master of Sciences in Physics

in the
Faculty of Sciences
Physics Department

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Declaration of Authorship

I, AUTHOR NAME, declare that this thesis titled, 'THESIS TITLE' and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed: ____

Date: ____

"Write a funny quote here."

If the quote is taken from someone, their name goes here

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Abstract

Faculty of Sciences
Physics Department

Master of Sciences

by Jesus David Prada Gonzalez

The Thesis Abstract is written here (and usually kept to just this page). The page is kept centered vertically so can expand into the blank space above the title too...

Acknowledgements

The acknowledgements and the people to thank go here, don't forget to include your project advisor...

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Abbreviations

LAH **L**ist **A**bbreviations **H**ere

Physical Constants

Speed of Light $c = 2.997\ 924\ 58 \times 10^{8}\ \mathrm{ms}^{-\mathrm{S}}$ (exact)

Symbols

a	distance	m
P	power	W (Js^{-1})
ω	angular frequency	$rads^{-1}$

For/Dedicated to/To my...

Chapter 1

Introduction

A complete physical picture of Dark Matter (DM) is still missing. This is one of the biggest puzzles to fully understand the composition of our Universe. So far, its presence can only be measured through its gravitational effect on the surrounding visible matter. One of best the astronomical systems that can be used to probe DM on astronomical scales is our own galaxy: the Milky Way (MW). Probing the DM density field around our galaxy (it's so-called DM halo) can shed light on the nature of DM [1, 2] and our galaxy's formation history [3–5].

One of the most basic features that can be measured in the MW DM halo is its shape. Different observational methods have been developed to constrain it. They range from the use of Jean's equations applied to stellar kinematics [6] to modelling the dynamics of satellite systems such as the Sagittarius stream and the Large Magellanic Cloud [7–9]. However, different assumptions are made in these studies producing widely different results. Thus, constraining the density field of the DM halo of the Milky Way remains an open research topic in present-day astronomy.

Today, computational astrophysics can support all these observationally projects by helping to prove (or disprove) the range of validity of different assumptions [5, 10, 11]. Simulations can also serve to find priors on the expected MW DM halo shape. However, using simulations comes at a cost. First, different degrees of realism in the implemented physical models can yield different results. Second, artifacts can appear due to the always limited numerical resolution. For these reasons, the study of simulations of astronomical or cosmological systems, as well as the research for reducing the aforementioned biases of computation, is an important field of study in modern astrophysics.

Recently, the growth of computational power and the improvement of numerical models have made possible to perform realistic simulations. These simulations can trace the non-linear interactions of DM and baryonic (i.e. usual gas and stars) components. For instance, the recent development of an state-of-the-art simulation AREPO [12] have made possible simulations that were considered impossible a decade ago. This code has been used to perform the *Auriga Project* [13], which simulates 30 galaxies that reproduce the main Milky Way features such as their stellar masses, rotation curves, star formation rates and metallicities.

For this thesis we will use the results from Auriga project [13] to study the halo density field of the 30 simulated galaxies. Specifically, we will measure the shape of the DM halo as a function of its radius and its time evolution. We will follow the methods presented in a study of the simulation project that preceeded the Auriga Project over 5 years ago [5] that simulated 5 times less galaxies, without any hydrodynamics and at a lower numerical resolution. This is the first time that studies of the DM density field are performed with this level of realism. The simulations in the *Auriga Project* were performed with different hydrodynamical characteristics which will also allow us to measure the impact of such differences on the DM halo shape.

The results from our study will help to constrain the expected DM density distribution around our galaxy, providing a benchmark for all researchers interested in a better understanding of our Galaxy and its dark matter distribution.

1.1 Constraining the Milky Way's DM Halo

According to the hierachichal model of structure formation, DM halos are a commmon and important feature to understand galactic and extra-galactic sized objects. However, performing direct measurements of DM is very difficult given its elusive nature. Therefore, constraining the main characteristics of DM halos is an important field of study not only in the context of astrophysics but for any other area interested in obtaining some insight in the fundamental enigma of DM.

DM haloes have two important features that can be constrained. On one hand there is the density profile, which has been demonstrated to follow an approximately universal model [**?**]. On the other hand, there is the halo shape, which is directly related to its spin. According to the hierarchichal model of structure formation, due to the anisotropic history of accretion DM haloes are triaxial and therefore, their shape and spin are important characteristics to **diagnose** their formation history [**?**].

In this sense, it is of special interest to constrain the DM halo shape of the only cosmological object of which we have a tridimensional view from inside: our Milky Way. However, this is a very difficult endeavour given the observational restrictions of observation. Many approaches have been made to constrain the MW's DM shape. One of them is to make use of theoretical models that relate the content of matter of our galaxy with the gravitational potential.

For example, Loebman et al. [**?**] used the axisymmetric Jean's equations [**?**] that relate the stellar content of our galaxy, with the radial and axial accelerations. The observed accelerations cannot be completely explained by visible matter only and DM presence is needed. Loebman et al. estimated that, around 20Kpc, the DM halo must be perfectly oblate with axis ratio of $q_{DM} = 0.47 \pm 0.14$ to account for this discrepancy. Nevertheless, the axial symmetry that characterizes this halo is inherited from the use of axisymmetric Jean's equations. Although this is a strong asumption, a more general theoretical background is much more difficult to implement given the difficulty to obtain the needed data from observations. Even authors aknowledge that "while it is premature to declare $q_{DM} = 0.47 \pm 0.14$ as a robust measurement of the dark matter halo shape, it is encouraging that the simulation is at least qualitatively consistent with SDSS data in so many aspects". This demonstrates that this field of study is still very young and any calculated constraint may lead us to a better understanding of our MW's DM halo shape.

A more common and strong approach is to use the streams of close dwarf galaxies that have been deformed by the gravitational potential of the MW. This effect is very important because the torca generated by the anisotropy in our halo is sensible to its parameters and thus, these streams are strong evidence to constrain the shape of our MW's DM halo [**?**]. In fact, it is known that a static axisymmetric halo cannot simultaneously explain all the features of the Sagitarius leading arm **citaa**.

In this context Law and Majewski 2010 proposed an analytical model of the MW consisting of a fixed analytical gravitational potential formed by a Miyamoto-Nagai [**?**] disk, a Hernquist spheroid and a logarithmic halo. This halo is triaxial and is characterized by its axial ratios and orientation. Given all this parameters, the Sagitarius stream was simulated and evolved forward and backwards in time for various choices of the halo parameters. The best fit, compared to a detailed study of the parameters of the Sagitarius stream properties, was found at a minor/major axis ratio $(c/a)_\Phi = 0.72$ and intermediate/major axis ratio $(b/a)_\Phi = 0.99$. The minor axis of this triaxial halo was found to be pointing in some direction contained in the galactic-disk plane.

This sophisticated model succeeded at simultaneously reproducing the radial velocity and angular position trends of the Sagitarius leading arm, which were troublesome to model with simpler approaches. Nevertheless, the coexistence of a triaxial DM halo and an axisymmetric galactic disk is not supported by CDM models [**?**]. Specifically, it is expected that the DM and gas distributions are correlated, which means that matter is accreted simmilarly as is DM, being the interaction properties the principal difference in the behaviour. Having this into account, gas and DM must have aligned angular momenta to certain extent because all kinds of matter are expected to be accreted from the same cosmic structures which append matter with simmilar angular momenta. In other words, it is expected for minor axes to be rather aligned. Furthermore, one expects the matter distribution to be non-axisymmetric in the presence of a non-axisymmetric halo potential.

Law Majewski comment in their paper: "... by no means do they (results) represent best-fit models in a statistical sense. Therefore, the predictions made cannot be considered exclusive or definitive but serve to guide where future observations could focus to distinguish between various models.". Particularly, this discrepancy with the current CDM paradigm may be a feature of the specific model. Other important observational constraints were dismissed in this study, such as the non-symmetric influence of the Large Magellanic Cloud (LMC). This feature may obviate the triaxial halo and produce a more CDM-consistent model. However, observationally obtaining the detailed information of the LMC needed for this kind of research is extremely difficult.

Studies of this kind are by nature non-conclusive(deterministic?, not so conclusive?) due to the dificulty in obtaining precise information from observations. In observations, we take 2-dimensional snapshots of the sky and therefore, we loose resolution of the radial density field due to screening. This makes the process of obtaining a tridimensional view of a cosmological-scale object an extremely difficult endeavour. Furthermore, we can determine radial velocities with dopler effect, but there is no obvious way of obtaining tangencial velocities. Bearing this in mind, any study which is sensible to very detailed observational parameters for obtaining non-direct measurements of the DM density field will be either non-conclusive for reasonable-difficulty models (as is the process of constraining), or must be extremely sophisticated to achieve a significantly conclusive result.

1.2 State of the art on MW simulations

To address this specific difficulty of obtaining information from observations, there is a vast and important field consisting in the modelling of the non-linear behaviour of matter. This is with the objective of numerically simmulating the universe at a wide range of scales and produce in this way self-consistent systems of which we have full control of their parameters at all stages.

These simulations, are restricted to modeling DM as a non collisional fluid and gas as an Eulerian(?) collisional fluid. Efficiently solving these systems of non-linear equations is still an open and improving field of research. This difficulty in the fluid modeling arise from the wide range of values that quantities take in the context of cosmological objects, which can expand in several orders of magnitude, and can be seen as field discontinuities which are very difficult to treat in a numerical way.

It is clear that this simmulations are limited to some resolution depending on the current power of computing super-clusters. This resolution is variable between simulations and is adjustable to the specific objective of the research. However, this resolution is by no means sufficient to simulate specific termic processes dominated by quantum or particle physics. However, specific details which are consequence of this non-modelable physics, are needed to accurately model cosmological structures. This is why energy and mass feedback processes such as supernovae (SN) explosions, black hole (BH) accretion and radiation, are usually reduced to some simplification dependent on some free parameters. A decade ago, thee feedback processes were not as well understood nor well modelled as they are today. For this reason, and the advances on technology, it has been possible only until recently the simulation of galactic objects

Briefly talk about the work of Vera-Ciro2011 and how it is correlated with Vera-Ciro2013.

This section must end emphasizing that we will perform our study based on this previous work on Auriga simulations.

1.3 Outline

Set the outline of the thesis.

Chapter 2

Remarks about our study

In this chapter we are going to describe in detail the specifications of the simulations we are going to work with, as well as the method for determining the halo shapes. This shapter is mainly to thoroughly explain how are we going to do everything that we are going to do.

2.1 The Auriga simulations

State all the important specs of the Auriga simulations. On the first paragraph.

Talk about the different degrees of realism in this simulation¿ DM, MHD, resolution levels. State the importance of these aspects for the soundness (look better word) of the studies.

2.2 Determining the halo shape

Start saying that there is no unique method for determining the shape at a specific radius. In general this process is not trivial and there are many different(in theory) approaches which produce esentially the same results [**?**]. Mention that we are going to use method by Allgood et al 2006 [14] following the steps by Vera-Ciro2010.

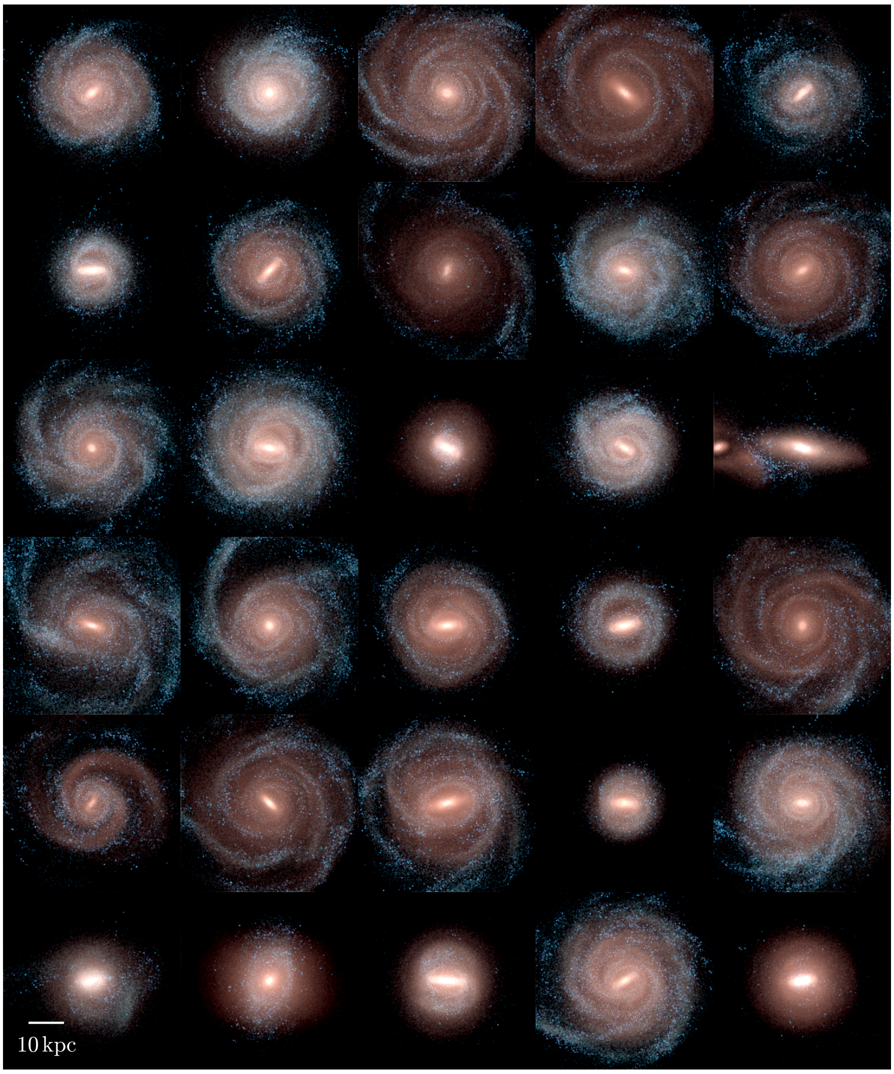


Figure 2.1: Set of 30 MW-like simulations, taken from http://auriga.h-its.org/

The method starts with particles enclosed within a sphere, we calculate the reduced inertia tensor:

$$I_{ij} = \sum_k \frac{x_k^{(i)} x_k^{(j)}}{d_k^2}, \tag{2.1}$$

that is not sufficient, which is why we recalculate until we achieve convergence. Present this recalculation explicitly with a scale transformation which intuitively means that our ellipse is becoming a sphere under that transformation which at the end is fully consistent (find better words).

$$\begin{aligned}(x, y, z) &\to (x, y/q, z/s) \\ q &= b/a \\ s &= c/a,\end{aligned} \tag{2.2}$$

Specify that with this process we obtain both the radial profile and the historical shape by simply applying this method at different radii and redshifts.

Chapter 3

Our results

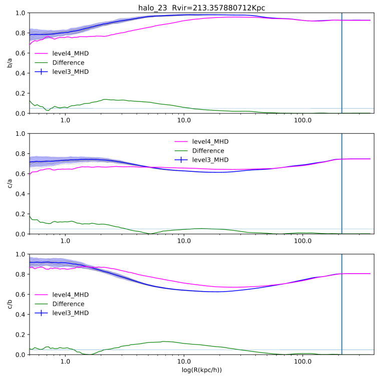
In this chapter we are going to present our results. First some remarks about resolution and convergence of the shape within Auriga simulations for DM and MHD. Then we study the radial and historic profiles of DM and MHD halos, where we obtain the expected tendence found by Vera-Ciro et al. 2011. Then present our principal results, which are the ones referring the comparison DM-MHD.

3.1 Analysis of convergence

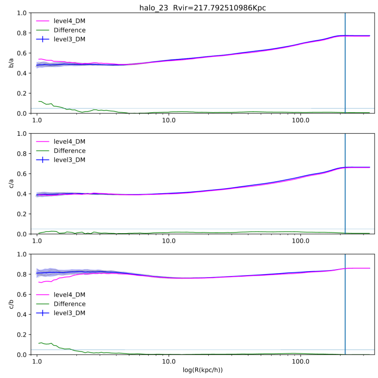
We decided to analyze de radial profiles at redshift 0 and compare level5 to level3 simulations. In general, the DM halo shapes remain unchanged with the exeption of the radial regimes where resolution becomes important. However, for MHD simulations, the resolution of gas affects the measurement not only in the inner parts, where resolution issues are evident, but it has a more global effect, presumably because of the scattering of particles which is also supporting the claim that matter affects the halo shape through scattering.

We address this problem by performing random sampling of the level3 simulations to reproduce level4 measurements and estimate the associated error.

State the main conclusions about this analysis of convergence. The effect of particle resolution does not sistematically affect the measurements. However, the error produced is specially apreciable at inner parts where for MHD it has a more global effect through scattering.



(A) MHD



(B) DM

FIGURE 3.1: Comparison of the effect of resolution on DM and MHD simulations. Here level4 curves (magenta) are compared to the mean and 2std (confirm) of the random-sampled curves from level3. For better comparison of the effect of resolution, the difference percent is plotted in green.

3.2 Radial profiles

Set the outline of the thesis

3.3 The effect of gas on the halo shape

3.4 Historical shape

Chapter 4

Conclusions

Conclusions

Appendix A

An Appendix

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