UNIVERSIDAD DE LOS ANDES

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

by

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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.
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- 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

UNIVERSIDAD DE LOS ANDES

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	$=$	$2.997\ 924\ 58 \times 10^{8}$ 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 [**? ?**] and our galaxy's formation history [**? ? ?**].

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 [**?**] to modelling the dynamics of satellite systems such as the Sagittarius stream and the Large Magellanic Cloud [**? ? ?**]. 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 [**? ? ?**]. 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 [**?**] have made possible simulations that were considered impossible a decade ago. This code has been used to perform the *Auriga Project* [**?**], 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 [**?**] 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 [**?**] 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 objecs. 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.

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 was found at a minor/major axis ratio $(c/a)_\Phi = 0.72$ and intermediate/major axis ratio $(b/a)_\Phi = 0.99$. However, this

Talk about Loebman et al., Law-Majewski2010 as examples of different approaches and mention other work's results.

This section must end emphasizing about observational biases.

1.2 State of the art on MW simulations

Introduction of this section is logical continuation of previous section.

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 [**?**] following the steps by Vera-Ciro2010.

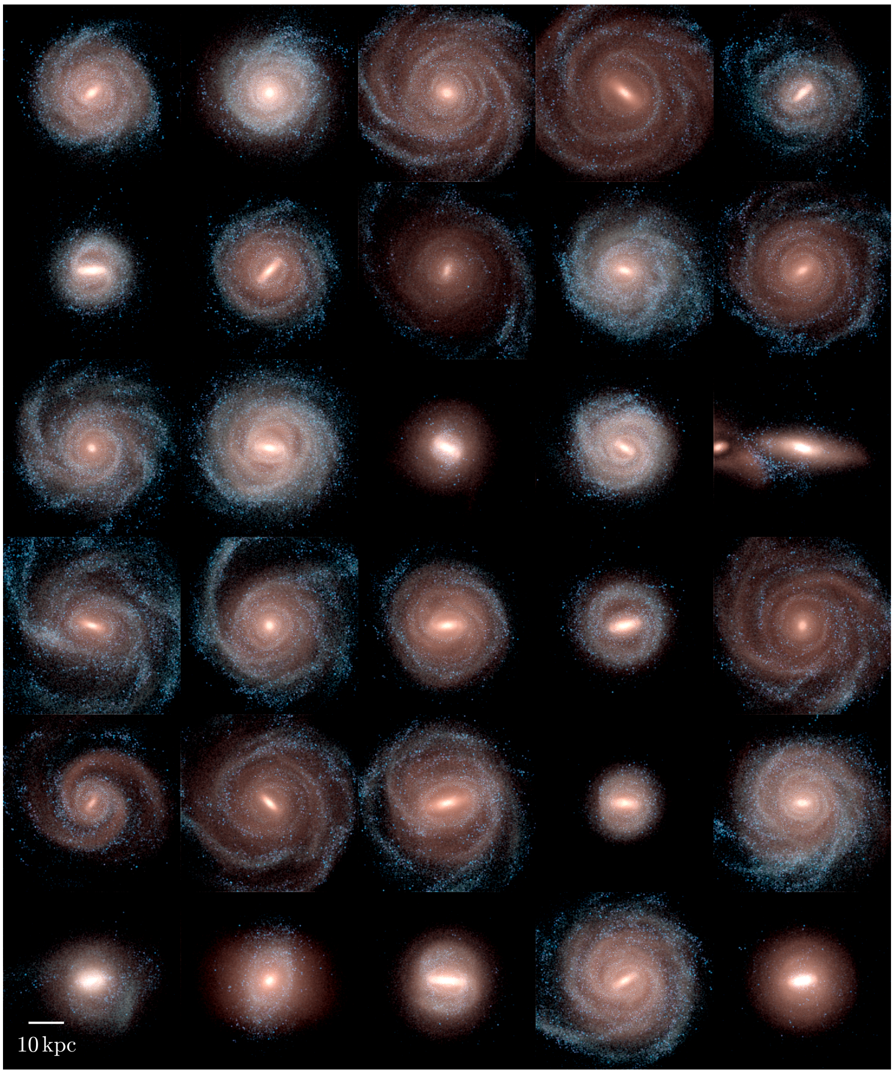


FIGURE 2.1: Set of 30 MW-like simulations, taken from http://auriga.h-its.org/

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).

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

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

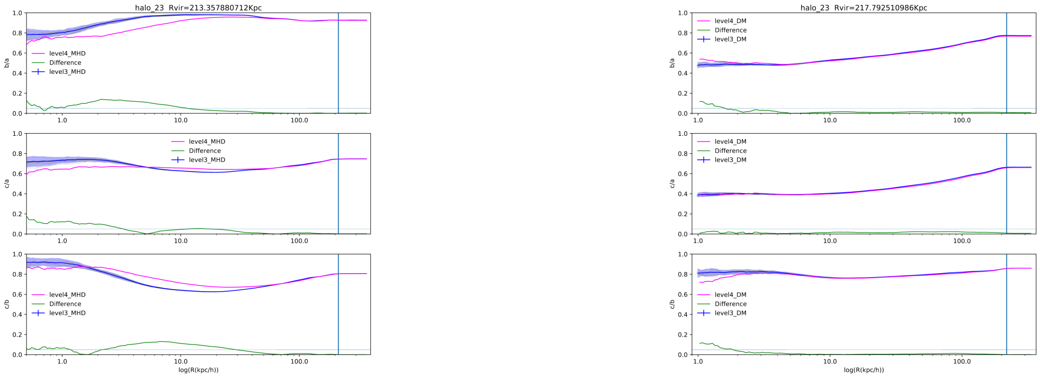
In this chapter we are going to present our results. First some remarks about resolution and convergence of the shape within Auriga simulations for DM and MHD. Then we study the radial and historic profiles of DM and MHD halos, where we obtain the expected tendence found by Vera-Ciro et al. 2011. Then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