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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"Write a funny quote here."

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Abstract

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by Jesus David Prada Gonzalez

The shape of the Dark Matter (DM) structure (halo) in which a galaxy is embedded is heavily determined by the anisotropic accretion of mass from its specific environment. Therefore, the shape of a galaxy's halo is an important feature to inquire about its formation history and the relation of DM and gas within it. In this work we study the shape of the DM halo of Milky Way-like galaxies from the Auriga simulations. We focus on the radial and time dependence. We found that, on DM-only and Magneto-hydrodynamic (MHD) simulations, the shape of the DM halo is more triaxial in the inner-skirts than in the outter-skirts. We compared simulations with and without gas and verified that the presence of visible matter has an effect of rounding the DM halo which is amplified for smaller radii, where the gravitational potential of the galactic disk becomes more significant. Regarding the effect of time on the DM halo shape, we corroborated that it is well-conserved in comoving units until $z \approx 2$. This means that probing the halo shape at the virial radius in physical units for different redshifts is nearly equivalent to probing the shape at different radii at redshift 0. These results are in accordance with previous work on cosmological and galactic-size simulations, and may serve as guidelines to improve observational constraints on our MW DM halo.

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La forma de la estructura (halo) de Materia Oscura en la cual está embebida una galaxia es altamente determinada por la acreción anisotrópica de materia en el entorno específico en el que ésta se encuentra. Es por esto que la forma del halo de una galaxia es una característica imporatnte para indagar sobre su historia de formación y la relación entre Materia Oscura y gas dentro de ella. En este trabajo estudiamos la forma de los halos de materia oscura en galaxias de tipo Vía Láctea del catálogo de simulaciones Auriga. Nos centramos principalmente en su dependencia radial y temporal. Hemos encontrado, en simulaciones de sólo Materia Oscura y en simulaciones de Magneto-hidrodinámica, que la forma del halo es más triaxial en las partes de adentro que en las afueras. Al comparar simulaciones con y sin gas, verificamos que la presencia de materia visible tiene un efecto de redondeado sobre el halo de Materia oscura, el cual es amplificado en radios pequeños, donde el efecto gravitacional del disco galáctico se torna significante. En cuanto al efecto del tiempo en la forma del halo de Materia Oscura, hemos corroborado que esta se conserva en unidades comóviles hasta $z \approx 2$. Esto se ve reflejado en la aproximada equivalencia entre el muestreo de la forma en el radio virial en unidades físicas a diferentes redshifts y el muestreo a diferentes radios en la actualidad. Estos resultados son respaldados por trabajos previos en simulaciones de escala galáctica y cosmológica, y pueden servir como lineamientos para mejorar las mediciones de la forma del halo de Materia Oscura de nuestra Vía Láctea.

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Given the elusive nature of Dark Matter (DM), indirect measurements are the most common approach to study it observationally. However, to make these studies possible, some assumptions must be made. These assumptions come from complicated theoretical frameworks and the analysis of state-of-the-art cosmolofical simulations. In this work we study the shape of the DM halo of Milky Way-like galaxies from the Auriga simulations. We focus on the radial and time dependence. We found that, on DM-only and Magneto-hydrodynamic (MHD) simulations, the shape of the DM halo is more triaxial in the inner-skirts than in the outter-skirts. We compared simulations with and without gas and verified that the presence of visible matter has an effect of rounding the DM halo which is amplified for smaller radii, where the gravitational potential of the galactic disk becomes more significant. Regarding the effect of time on the DM halo shape, we corroborated that it is well-conserved in comoving units until $z \approx 2$. This means that probing the halo shape in physical units at the virial radius for different redshifts is nearly equivalent to probing the shape at different radii at redshift 0. These results are in accordance with previous work on cosmological and galactic-size simulations, and may serve as guidelines to improve observational constraints on our MW DM halo.

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 [**? ?**] 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 modeling 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 hierarchical 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 labour 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 Sagittarius 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 these parameters, the Sagittarius 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 observational properties of the Sagittarius stream, 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 Sagittarius 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 Cold Dark Matter (CDM) models [**?**]. Specifically, it is expected that the DM and gas distributions are correlated in the sense that matter is accreted similarly 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. In other words, it is expected for minor axes to be rather aligned. Furthermore, due to stability reasons and a historical interaction, the matter distribution should 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 modeling of the non-linear behaviour of matter. This is with the objective of numerically simulating the universe at a wide range of scales and produce consistent systems of which we have full control of their parameters at all stages. In this sense, a computer may become a virtual cosmological-scale laboratory, where we may run an experiment having full control over its initial conditions to compare different outputs and support theoretical frameworks.

In this sense, in the CDM paradigm, we have fully theoretical studies [**? ?**] principally focused in the analysis of Gaussian random fields and the properties of self-similarity that DM must possess. These theoretical frames are then supported by CDM simulations [**?**] and, if possible, by observations. In fact, these theories are usually thoroughly verified and complemented through simulations, given their convenient malleability, before being directly applied to observations.
Redactar mejor (simbiosis entre teor[ia analitica, simulaciones numericas, y observaciones.

One good example of this synergy between analytical models, numerical simulations and observational data is evidenced in the work of Vera-Ciro et al. (2011-2013). In 2011, Vera-Ciro et al. studied the shape of a set of four simulated MW-like DM galaxies with the objective of complementing the predictions of the CDM paradigm. Specifically, the hierarchical model of structure formation predicts that the halo shape is correlated with the environment given that it determines the structures from which it accretes matter [**?**]. However, theoretical studies are restricted to the correlations at reshift 0 and do not say much about history of formation. Intuitively, it is expected that halo shapes vary with the radius taking into account that accretion occurrs at progresively bigger radii in history and that the cosmic structures that determine environments evolve during that time. Due to the collisionless nature of DM, inner shells can interact with outer shells only in a gravitational way. This means that the historical shape is somewhat conserved in the radial shape profile.

Vera-Ciro et al. showed in 2011 that the radial profile of the halo shape is indeed correlated with its accretion history and environment. Furthermore, due to the increase in the cross section of the halos, which contributes to the scattering of particles(?), at later stages and bigger radii, they become more oblate/spherical. This results helped to obtain more insight about the galactic dynamics of formation and also suggested some guidelines to improve Law & Majewski 2010 study.

In 2013, Vera-Ciro et al. proposed an improved study based on the one by Law & Majewski in 2011. Vera-Ciro et al. proposed a halo that is perfectly oblate at inner regions and transitions smoothly to a triaxial halo in the outter-skirts. With this, the angular momentum inconsistency of this constraint with the CDM model is solved. They found that this halo is triaxial in the outter skirts with a medium-to-major axis ratio of 0.9 and minor-to-major axis of 0.8, which is still very oblate regarding the CDM predictions.

However, even when this study solves some inconsistencies with the expected predictions, it demonstrated that small perturbations are important. That is, even when the Sagittarius stream samples the gravitational potential at the outter parts of the halo, where the shape of the inner regions should not be so important, the outter shape is affected to compensate for the change in the regions from inside. This effect takes our attention to a relegated topic: the LMC. In fact, Vera-Ciro et al. demonstrated that the change in shape from the inner regions produces a torque comparable to that of the LMC, which should be taken into account in further researches.

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 describe in detail the specifications of the simulations we are going to work with. Furthermore, we present the chosen method for determining the halo shapes. This chapter is mainly to thoroughly explain how are we going to do everything that we are going to do.

2.1 The Auriga simulations

Cosmological 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 an intricate puzzle and it is still an open and improving field of research. Difficulties in the numerical modeling of these fluids arise from the wide range of values that quantities take in the context of cosmological objects, which can expand in several orders of magnitude, are no much different than actual field discontinuities which are very difficult to treat in a numerical way.

It is clear that this simulations 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, it is by no means sufficient to simulate specific termic processes dominated by quantum or particle physics. Nontheless, 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, these feedback processes were not as well understood nor well modeled as they are today. For this reason, and the advances in technology, it has been possible only until recently the simulation of galactic-sized objects like our MW tracing the evolution of normal matter alongside with DM with exceptional accuracy [?].

In this monograph we use the results of the state-of-the art Auriga simulations [?]. It selected a set of 30 isolated "Friend of Friends" (FOF) [?] halos from the Eagle simulations [?], which follows the evolution of fixed-mass particles of $m_{\rm DM} = 1.15 \cdot 10^7 \rm M_\odot$ from $z = 127$ to $z = 0$. Eagle simulations adopt the cosmological model from Planck Collaboration et al. (2014) by taking the parameters glass-like configuration in a periodic box of 106.5Mpc. The $\Omega_\Lambda = 0.693$, $\Omega_{\rm m} = 0.307$, $\Omega_{\rm b} = 0.048$ & $\rm H_0 = 67.77 kms^{-1}Mpc^{-1}$.

These halos were randomly selected from a sample of the quartile of most isolated halos whose virial mass M_200 varied between $10^{12} M_\odot$ and $2 \cdot 10^{12} M_\odot$. This mass is defined as the mass enclosed within the virial radius R_{200} at which the density becomes 200 times the critical density of the universe. These halos were then re-simulated by increasing the mass resolution of the particles belonging to each halo and diminishing the resolution of the rest of the particles. This would efficiently simulate external gravitational effects over the studied structure and reproduce a high-resoluted version of it.

Various versions of the same halo were simulated for different degrees of realism. All 30 halos were simulated within a level 4 degree of resolution defined for Aquarius simulations which corresponds to $\tilde{4}000000$ high resolution particles of $\tilde{4} \cdot 10^5 M_\odot$. From these halos, 6 of them where re-simulated at level 3 (higher) resolution taking into account a spatial factor of 2 in each dimension. Furthermore, fore each halo in each level of resolution there are two versions of the simulation. One evolves only DM particles and the other has into account all the magneto-hydrodynamical physics. Taking this into account, we can compare the results from different levels of realism to obtain consistency in our analysis.

These simulations were performed using the hydrodynamic code AREPO [?], which combines a moving Voronoi tessellation with the finite volume approach. In this way, AREPO solves the principal sources of nummerical errors from both important paradigms of computational hydrodynamics in the cosmological context. Parallel to the evolution algorithm, there are galaxy formation models which account for the evolution of stars and SMBHs. Specifically, the physics followed by this model includes energetic feedback from supermassive black holes and supernovae, as well as stellar evolution and chemical

Halo	$N_P/10^6$		$M_P/10^5 M_\odot$		R_{vir}/Kpc		$M_{vir}/10^{14} M_\odot$	
	DM	MHD	DM	MHD	DM	MHD	DM	MHD
halo 1	4.068	2.447	2.397	2.022	196.927	187.674	9.062	7.844
halo 2	5.625	5.457	2.481	2.093	235.094	233.934	15.418	15.191
halo 3	3.826	3.852	2.645	2.231	210.693	210.955	11.099	11.141
halo 4	4.585	4.530	2.590	2.185	219.378	215.438	12.529	11.866
halo 5	3.262	3.290	2.533	2.137	196.984	197.246	9.071	9.106
halo 6	3.184	3.110	2.337	1.972	191.840	189.342	8.378	8.054
halo 7	3.878	3.729	2.296	1.937	197.864	196.509	9.193	9.005
halo 8	2.772	2.796	2.451	2.068	190.716	191.764	8.231	8.368
halo 9	3.038	3.010	2.738	2.310	195.826	190.640	8.911	8.222
halo 10	2.700	2.751	2.541	2.144	187.139	188.147	7.777	7.904
halo 11	4.146	4.116	2.541	2.144	221.821	219.568	12.952	12.560
halo 12	2.865	2.908	2.645	2.231	192.280	192.038	8.436	8.404
halo 13	3.520	3.600	2.393	2.019	202.139	203.815	9.801	10.048
halo 14	4.200	4.475	2.499	2.108	215.535	218.927	11.882	12.453
halo 15	2.888	2.845	2.541	2.144	199.848	200.658	9.471	9.588
halo 16	3.821	3.871	2.499	2.108	212.590	212.632	11.401	11.408
halo 17	2.752	2.781	2.552	2.153	188.067	187.404	7.893	7.811
halo 18	3.770	3.624	2.738	2.310	201.124	207.293	9.655	10.571
halo 19	2.989	3.086	2.645	2.231	200.244	200.325	9.527	9.540
halo 20	3.903	3.822	2.481	2.093	210.097	211.423	11.005	11.214
halo 21	4.105	4.075	2.640	2.227	219.527	219.823	12.555	12.604
halo 22	2.794	2.766	2.625	2.215	188.363	184.801	7.931	7.489
halo 23	3.977	4.073	2.795	2.358	217.768	215.959	12.254	11.952
halo 24	4.466	4.426	2.522	2.127	217.440	215.147	12.199	11.817
halo 25	2.902	2.806	2.645	2.231	199.922	198.299	9.482	9.254
halo 26	4.610	4.716	2.506	2.115	219.984	218.939	12.633	12.454
halo 27	5.060	5.018	2.590	2.185	228.036	226.225	14.071	13.740
halo 28	4.184	4.276	2.645	2.231	216.979	217.997	12.121	12.294
halo 29	4.827	4.613	2.499	2.108	225.791	219.935	13.660	12.625
halo 30	3.268	3.112	2.579	2.176	195.043	194.741	8.805	8.763

TABLE 2.1: Specifications of each level 4 galaxy (halo). The DM and MHD versions of each parameters are presented together. The columns of this table indicate: (1) Halo name, (2,3) Number of (millions) of DM particles belonging to the halo, (4,5) Mass per particle in $10^5 M_\odot$, (6,7) Virial radius (R TopHat 200) of the halo in Kpc, (8,9) Virial mass of the halo in $10^{14} M_\odot$.

enrichment. These models are consistent and do not need recalibration of parameters for each level of resolution.

Halo	$N_P/10^6$		$M_P/10^5 M_\odot$		R_{vir}/Kpc		$M_{vir}/10^{14} M_\odot$	
	DM	MHD	DM	MHD	DM	MHD	DM	MHD
halo 6	24.902	24.185	0.292	0.246	191.741	188.367	8.365	7.932
halo 16	29.750	30.334	0.312	0.263	212.622	212.542	11.406	11.395
halo 21	31.993	31.503	0.330	0.278	219.731	220.250	12.588	12.679
halo 23	31.379	31.618	0.349	0.295	217.793	213.358	12.259	11.524
halo 24	34.987	35.153	0.315	0.266	217.313	213.963	12.179	11.624
halo 27	39.617	39.056	0.324	0.273	227.908	223.484	14.048	13.244

TABLE 2.2: Specifications of each level 3 galaxy (halo). The DM and MHD versions of each parameters are presented together. The columns of this table indicate: (1) Halo name, (2,3) Number of (millions) of DM particles belonging to the halo, (4,5) Mass per particle in $10^5 M_\odot$, (6,7) Virial radius (R TopHat 200) of the halo in Kpc, (8,9) Virial mass of the halo in $10^{14} M_\odot$.

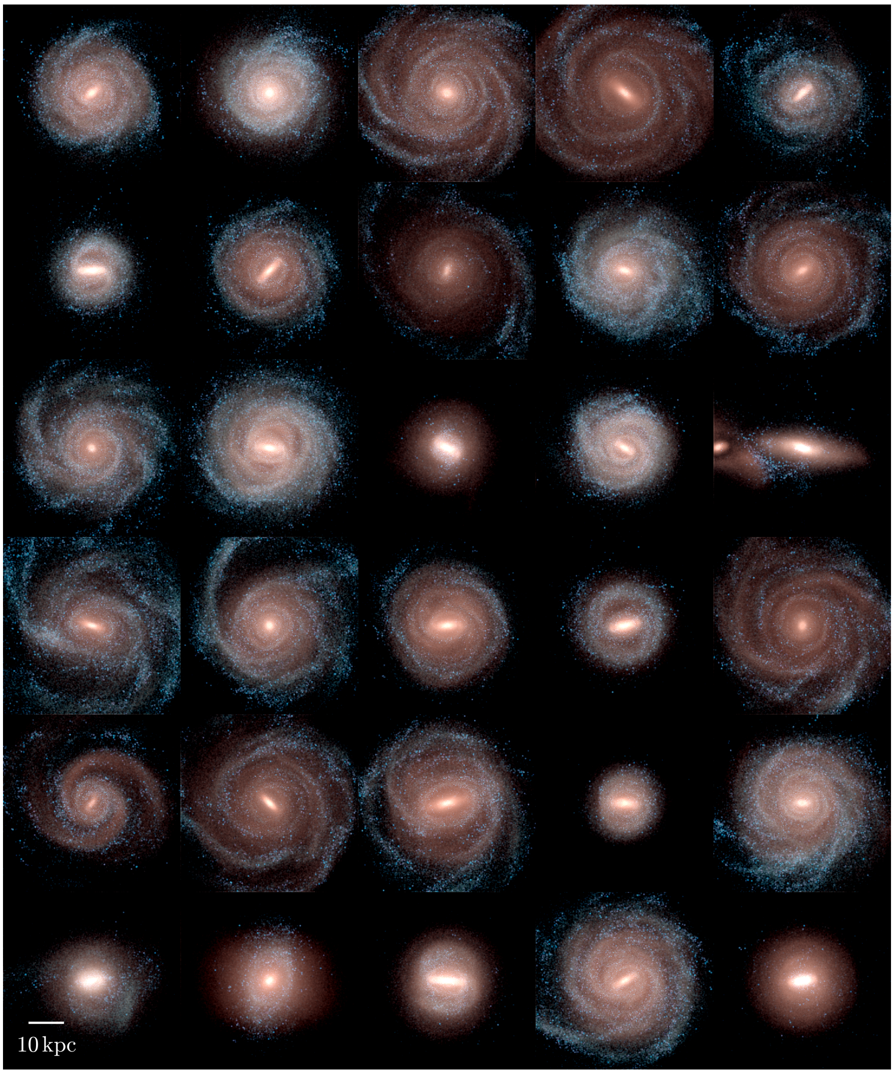


FIGURE 2.1: Set of 30 MW-like simulations, taken from http://auriga.h-its.org/

2.2 Determining the halo shape

The discretization of the DM density field into particles makes it difficult to perform some calculations that would require a more continuous distribution such as those related to the density field. The case of the shape of the halo is no exemption, and therefore there is no trivial way to calculate the DM halo shape at a determined radius. There are different approaches to this problem, such as the use of an inertia tensor or the approximation to the respective contour surface. However, the results do not vary very much from method to method [**?**]. In this work we follow the guidelines by Vera-Ciro et al 2011 which includes the use of the shape method by Allgood 2006[**?**].

Allgood's method starts with particles enclosed within a sphere whose radius r is the initial radius where we want to obtain the shape. We calculate the reduced inertia tensor:

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

which has weighted components by distance $d^2 = x^2 + y^2 + z^2$, so that each particle contribute with same importance to the inertia tensor, neglecting their distance to the center of the halo.

The diagonalization of this tensor yields the principal axes of the structure, as well as the eigen-quantities $a > b > c$ which produce the respective axial ratios. However, if we characterize an ellipsoid taking into account only particles enclosed within a sphere, we are effectively underestimating its triaxiality [**?**]. For this reason, we iteratively recalculate the inertia tensor taking into account the previously characterized ellipsoid.

AllGood et al. propose to use the eigenvalues $a > b > c$ and their respective eigen-axes v_a, v_b, v_c to recalculate the inertia tensor over the particles enclosed by the ellipsoid with principal axes (along the respective eigenvectors) equal to $r, r/q, r/s$, where ere $q = b/a$ and $s = c/a$ are the axial ratios. In other words, we repeat the process of calculating the inertia matrix by taking into account particles within an ellipsoid with axial ratios given by the previous diagonalization, maintaining the principal axis of the enclosing ellipsoid constant (this is a freedom choice).

This method sounds good and it would eventually converge to a more accurate characterization of the halo ellipsoid. However, we are computing the reduced inertia tensor by weighting the contributions with the spherical-metric distance $d^2 = x^2 + y^2 + z^2$, where particles within the same spherical surface are given the same importance. This means we are again underestimating ??? the triaxiality of the structure. For this reason, on each iteration we must calculate the inertia tensor taking into account an elliptic metric: $\tilde{d}^2 = x^2 + y^2/q^2 + z^2/s^2$, assuming x, y, z are the corresponding principal axes.

In case this concept of an elliptic metric is difficult to grasp, let us consider that, instead of converting the initial enclosing sphere to the halo ellipse, we are converting the halo ellipsoid into an sphere by performing scale transforms along the respective eigen-axes. From this point of view, we start our first-guess calculation of the ellipsoid by calculating the reduced inertia tensor (2.1) for particles enclosed within a sphere of radius r. Then with the results of this first guess, we perform the following scale transform:

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

where we assumed the axes x, y, z are oriented at the principal axes. We then repeat the process of calculating the reduced inertia tensor and performing the scale transform until we achieve certain convergence criterion. We stop this iterative process when the sum of the fractional change in axes is less than 10^{-6} to obtain the shape of the halo at the geometric mean radius $(abc)^{1/3}$, which is not much different from the initial radius.

Notice that calculating the inertia tensor with the scaled coordinates x', y', z' is equivalent to calculating it with the un-scaled coordinates x, y, z but using the elliptic-metric distance $\tilde{d}^2 = x^2 + y^2/q^2 + z^2/s^2$, for diagonalization purposes.

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

One of the principal factors that may bias our study is the resolution of the simulations we work with. Fortunately, Auriga simulations have level 3 and level 4 versions of 6 of the gaxies which we can use to serve our purposes. This a tool principally thought to analyze the numerical convergence of the methods used to solve the non-linear equations for matter and give validity over the output results overall. However, resolution may also directly affect our procedure for calculating halo shapes through the reduction of particles taken into account to calculate the inertia tensor.

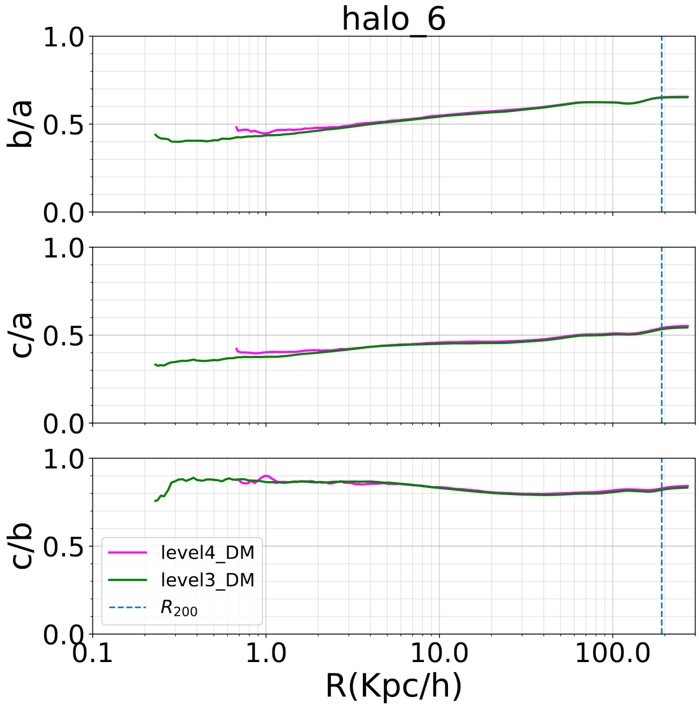
To illustrate this, in figures 3.1 we compare the obtained halo shape at redshift 0 on level 3 and level 4 simulations for a halo in which resolution does not noticeably affect the results. In this case, we can say that there is good convergence of the studied quantities with very small numerical bias. However, this is not the case every simulated halo as they do not evolve similarly and some resolution-sensitive events may influence their history of formation.

By way of example, in figures 3.2 we present one of the halos where resolution played the most appreciable role affecting the shape. In this case, although the difference is not extreme, it requires attention and a more careful analysis.

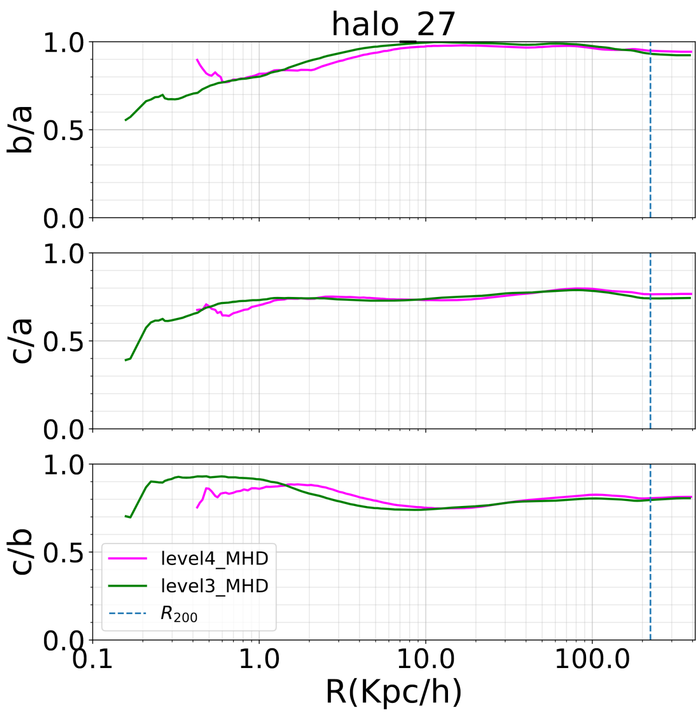
For instance, by simple inspection, we notice that there is no apparent systematic way in which resolution affects the halo shape. That is, sometimes the halo appears rounder and some times it is affected towards a more triaxial shape. This is important for our study as we focus our efforts on the analysis of the triaxial properties of the halo. Incidentally, the DM-only halos remain unchanged with the exemption of the radial regimes where the number of particles naturally affects our shape-calculating method. However, for MHD simulations, the resolution of gas influences the measurement not only in the inner parts, where discretization issues are evident, but it has a more global effect. We suspect this is caused by the scattering of particles due to dense structures formed by gas, whose effect is affected by resolution. Nevertheless, further calculations need to be performed to confirm if these resolution biases are directly caused by AllGood's method for calculating shapes, or are caused because structures are indeed affected by numerical errors from the solution of fluid equations of matter.

Consequently, we decided to isolate the few-particle effect on our shape calculations without recurring to the less-resoluted simulations of level 4. Taking into account that the resolution difference between level 3 and level 4 simulations is a factor of 8 in the number of DM particles, we randomly selected particles from level 3 halos at redshift 0 to produce 10 samples of approximately the same size as level 4 simulations. We then proceeded to analyze the effect of lowering the number of particles on the calculated shape of the halo. In figures 3.3 we ploted the original level 3 shapes as well as the 10 level 3 samples. For each radius, we calculated the standard deviation of the sample shape and illustrated 3-sigma range to compare with the respective level 4 shape values.

From the graphics on 3.3, it is clear that the plotted fractional difference is not actually big and remains under 1% for the majority of the radial profile. It becomes important for radii less than $1Kpc$ due to the lack of particles for approximating an elliptical shape shape. This is corroborated by the 3σ range, which also becomes evident around $1Kpc$. We then deduce from this convergence analysis that for radii bigger than $1Kpc$, the differences of level 3 and level 4 ellipses cannot be explained as an effect of the lack of particles. This is a confirmation that all kinds of matter are directly affected by resolution due to precision-sensitive events on the history of formation or because the



(A) halo 6 DM



(B) halo 27 MHD

FIGURE 3.1: Examples of halos where level 3 (pink) and level 4 (green) calculations are in good agreement.

numerically calculated gravitational potential of matter itself is affected and continuously influences surrounding structures. Either way, even for the most resolution-biased cases, we can say that for the purposes of this study, convergence is achieved to a reasonable extent.

3.2 The shape's radial dependence

One of the first results we obtained in this study is related to the evolution of the DM halo shape in terms of the radius at which it is sampled. We already expect from previous work that the shape does not remain constant along the radius [**?**]. Specifically, we know that halos are gradually constructed from inner shells to outer shells through the accretion of matter from cosmic structures []. Inner shells are shielded from the gravitational potential from outter regions as a consequence of the Gauss law. Therefore, inner shells tend to conserve their shape. Outter shells, on the other side, are affected by the increasing gravitational potential form the inside of the halo, which makes them prone to scattering effects. This scattering of particles has a "rounding" effect on the outerskirts shape. For this reason, we expect on both simulations (MHD and DM) that halos are more triaxial on inner regions and more spherical at bigger radii. This effect has been corroborated on multiple cosmological simulations (Citas)[].

In figures 3.4, we present a halo in which the rounding effect is specially evident for both degrees of realism (Horizontal comparison). However, to eliminate any possible cualitative bias, we present a more detailed and quantitative version of this effect in terms of the radius on figure 3.5. There, we include all axial ratios, which clearly become closer to 1 (more spherical) for bigger radii. Besides the axial ratios, we included a quantification of the triaxiality, namely $T = \frac{1-b/a}{1-c/a}$.

This measurement T tends towards unity when the medium-to-major axis ratio becomes equal to the minor-to-major ratio, i.e. when the halo becomes prolate. In the case where the medium axis is very close to the major axis, having a different minor axis, T tends to a null value, i.e. when the halo tends to a oblate shape. In these terms, halos are expected to be more prolate on the inside and more oblate on the outside. Even though the perfect spherical shape has a divergent/undefined T value, prolate shapes are associated with triaxial characterizations and oblate shapes are identified as approximately spherical shapes. This, however, can be confirmed on the triaxiality plane where we can also demonstrate that this is in fact a global tendency on all halos.

In figure 3.6, we show the axial ratios on the plane $c/aVsb/a$. There, each dot represents a specific halo shape at a specific radius. In this plane, oblate halos are represented by the vertical line $x = 1$, prolate halos are identified on the identity line and spheres are exactly the point $(1, 1)$. This gives us a broader idea of the evolution of the shape than a single number T. In this figure, the tendency is clear for DM and MHD halos to get rounder with increasing radius. In fact, the difference in shape clear enough that it is possible to identify groups in case the radius label is lost.

3.2.1 The effect of gas on the halo shape

We have simultaneously corroborated the rounding effect of radius on the halo shape from DM-only and MHD simulations. However, from the parallel presentation of both of the results, it is easily noticeable that there is also a relation of this rounding effect in terms of the presence of matter, which is to be expected [**?**].

Unlike DM, gas collapses and generate disks which are much denser than the DM structures. This amplifies scattering events and, if we apply the same logic, we would expect that the inner regions of the halo are more spherical when there is presence of gas. We expect the same for outter regions but this effect is predicted to be more significant due to the stronger effect of the gravitational potential of gas on the outter shells.

For instance, recurring again to the figures 3.4, now comparing the graphics vertically, the rounding effect of visible matter is clear. For a more cuantitative illustration of this, we can reffer to figure 3.5.

Although from previous pictures it is evident that the presence of gas affects the halo shape by rounding it, it is not clear that this effect is amplified for bigger radii. To confirm this, we reccurr again to triaxiality plane on 3.7, where this tendency becomes evident.

So far, our results are in accordance with previous work on different kinds of simulations. Nonetheless, on the specific case of MW-like galaxy simulations, we have confirmed the expected tendence in an unprecedented statistically significant sample of 30 galaxies form Auriga, compared to the 4-sample galaxies from the previous state-of-the art DM-only Aquarius simulations. Moreover, we confirmed that these results are sustained for the specific case of novel MHD MW-like galaxy simulations.

3.3 Historical shape

Taking into account the previously explained model of formation of halos as a qualitative theoretical background that supports our results, it is possible to extend its reach not only for refshift 0 predictions but for the analysis of the historical evolution of the halo shape [].

Recalling that inner shells of the halo are isolated from the gravitational effect of outer shells, the only source of disruption in time of this radial regime are external cosmic structures that perform some torque on them. Outter shells must feel this source of deformation too in addition to the effect of scattering from the inner gravitational potential. Consequently, we expect a systematic change on the halo shape with time, which becomes more significant for bigger radii.

Major events, like mergers, may completely disturb a galaxy shape and erase any memory of it. However, from z 1 onwards, these events are very rare [] and we expect that any source of disruption is weak and is reduced to the previously mentioned factors. These sources of anisotropy and scattering randomize DM particle orbits producing a more spherical version of the halo. []

In figures 3.8 we present the evolution of the radial profile of the shape of a halo that managed to conserve its integrity until z 2. In this case, we present our results in terms of the comoving coordinates to make these profiles comparable. The halo becomes sistematically more spherical as it evolves in time, being this effect more relevant for $r > 50Kpc$.

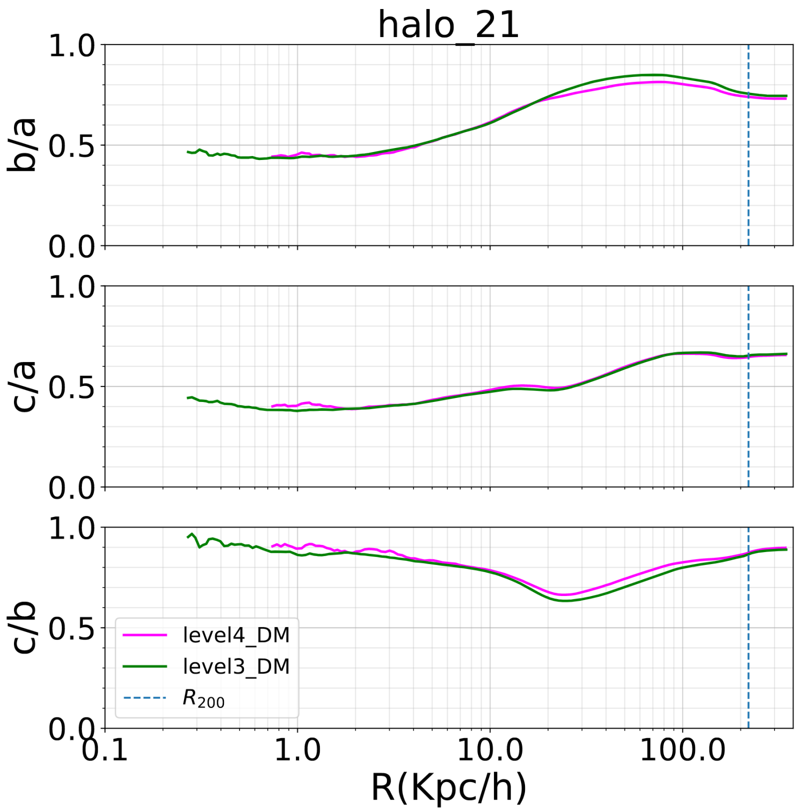
In figures we present a very special case of a halo that was perturbed at some time around $z = 0.5$. It is specially evident because of the discontinuity caused in the radial profile and the large differences in the different virial radii.

Now, these results compare radial profiles in comoving coordinates, but in real life we have physical coordinates. In this order of ideas, we can state this conservation of the shape (obviating the rounding effect) in terms of physical coordinates.

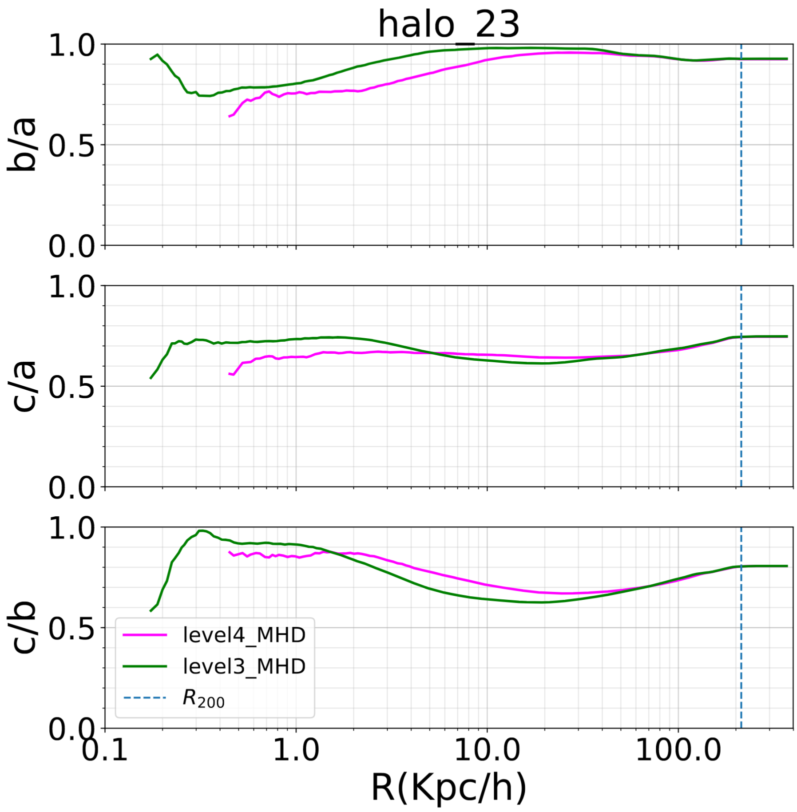
In this case, let us consider a constant physical radius R at which we are going to perform our measurements at different redshifts. For practical purposes let us take, for example, the virial radius at $z = 0$. Then, if we want to obtain the shape at higher redshifts, it is necessary to obtain the corresponding physical radius using the scaling factor a. As the universe is expanding, we are effectively sampling the shape for smaller radii at higher redshifts. Taking into account that the halo shape is well conserved in time, we expect that studying the historical profile of the shape at a certain constant physical radius is nearly equivalent to studying the radial profile of the same halo at the present time.

To illustrate this, in figures **??** we present the historical and radial profiles of the previously analyzed halo shapes. For the halo that maintained a consistent shape during time, there is a clear correlation between the historical and radial profiles, both clearly tending to more spherical shapes at lower redshifts and bigger radii. In the case of the halo that had a major disrupting event, this correlation is not clear, however, a difuse tendence to rounder shapes still remains.

```
\begin{figure}[!ht]
  \centering
  \subfloat[halo 16 MHD]{\includegraphics[width=0.7\columnwidth]{./pics/Redshift/halo
  \hfill
  \subfloat[halo 21 MHD]{\includegraphics[width=0.7\columnwidth]{./pics/Redshift/halo
  \caption{Historic shape Vs radial shape on the Triaxiality plane. The black line re
\end{figure}
```

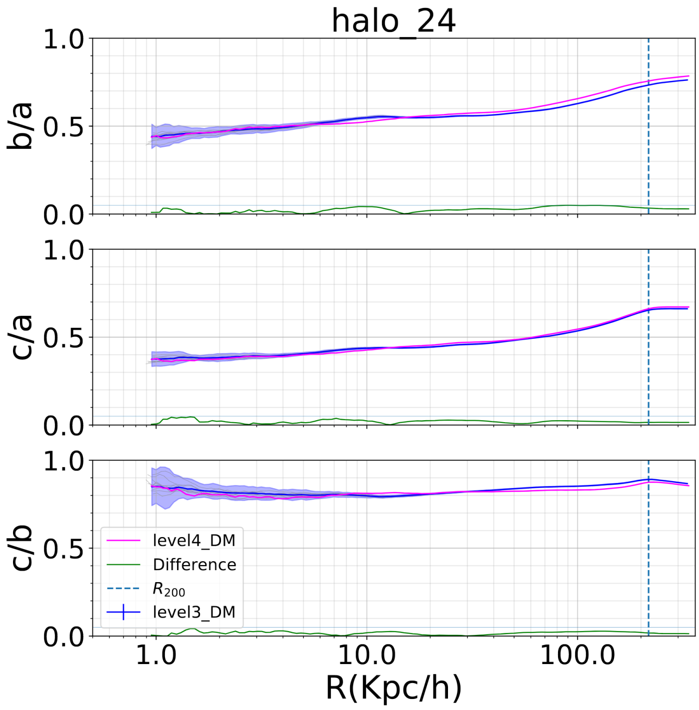


(A) halo 16 DM

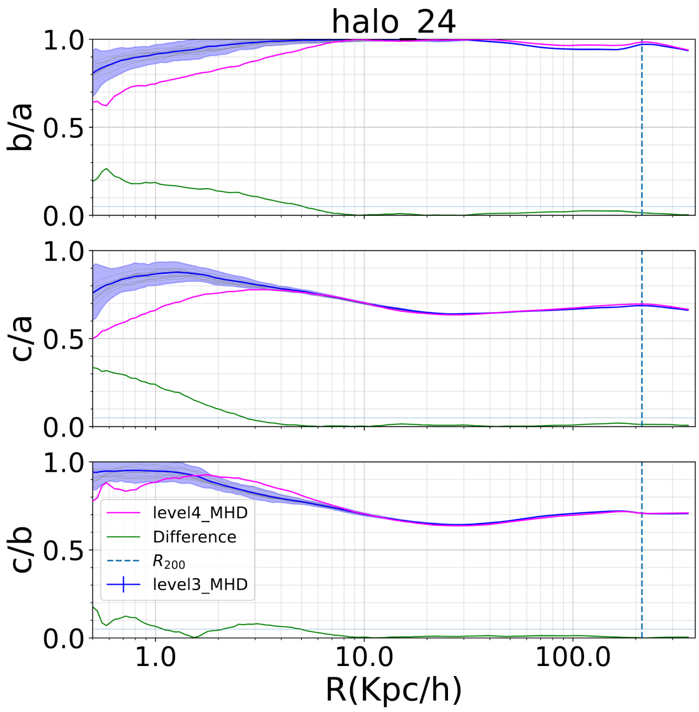


(B) halo 23 MHD

FIGURE 3.2: Examples of halos that have an appreciable difference between level 3 (pink) and level 4 (green) calculations.

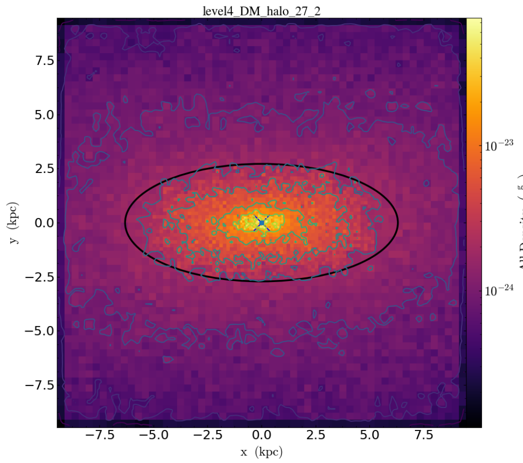


(A) halo 24 MHD

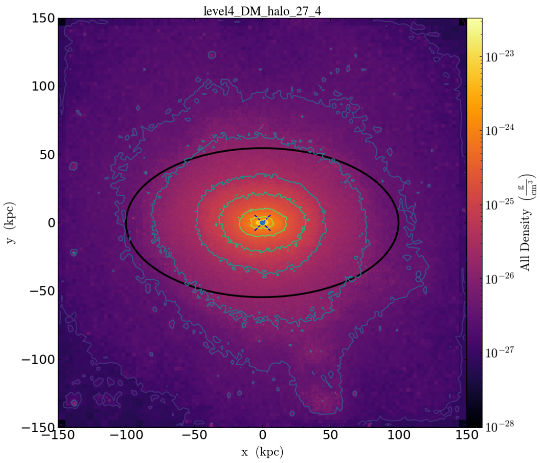


(B) halo 24 DM

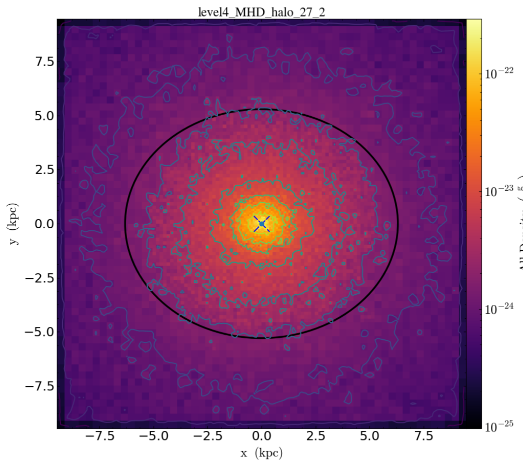
FIGURE 3.3: Comparison of the effect of resolution on DM and MHD simulations. Here level4 curves (magenta) are compared to the mean and 2std (confirm) of the random-sampled curves from level3. For better comparison of the effect of resolution, the difference percent is plotted in green.



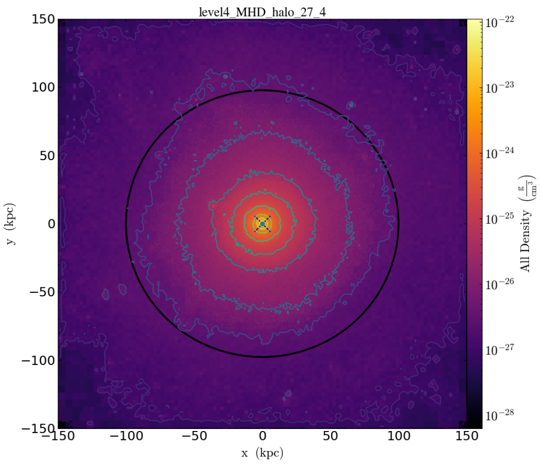
(A) halo 27 DM shape at small radius



(B) halo 27 DM shape at big radius



(C) halo 27 MHD shape at small radius



(D) halo 27 MHD shape at big radius

Figure 3.4: Example of the dependence of shape in terms of the radius. All graphics have matching orientation (which may not be the same) with their respective principal axes at the shown radii. The horizontal and vertical axes are aligned to the major and medium semi-axes respectively.

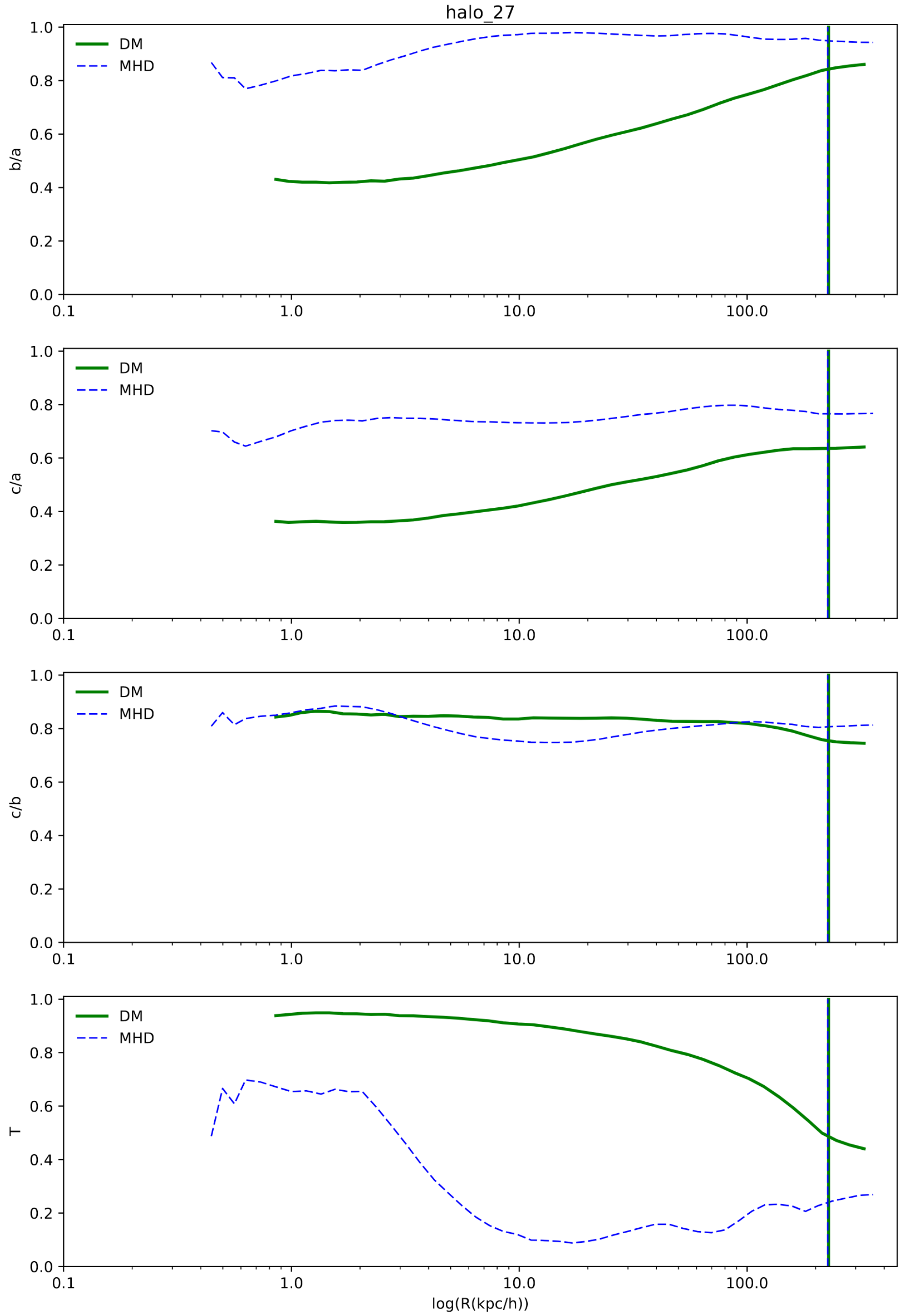
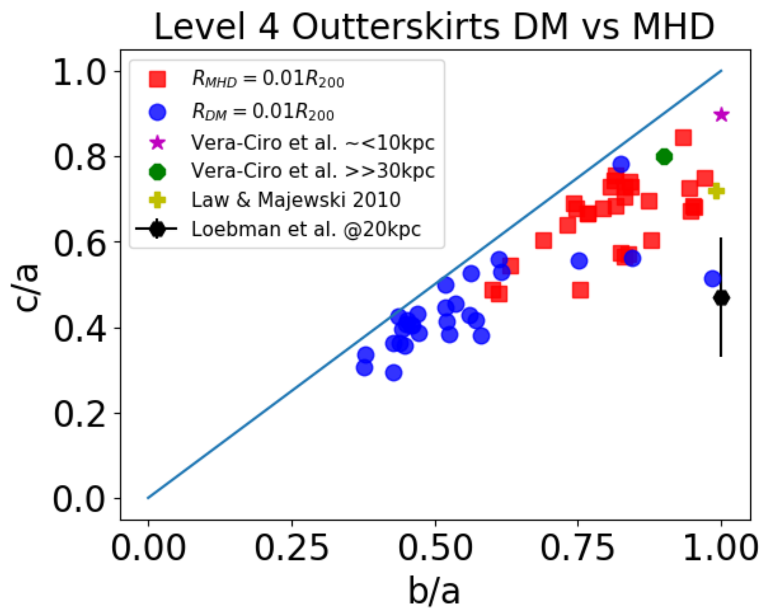
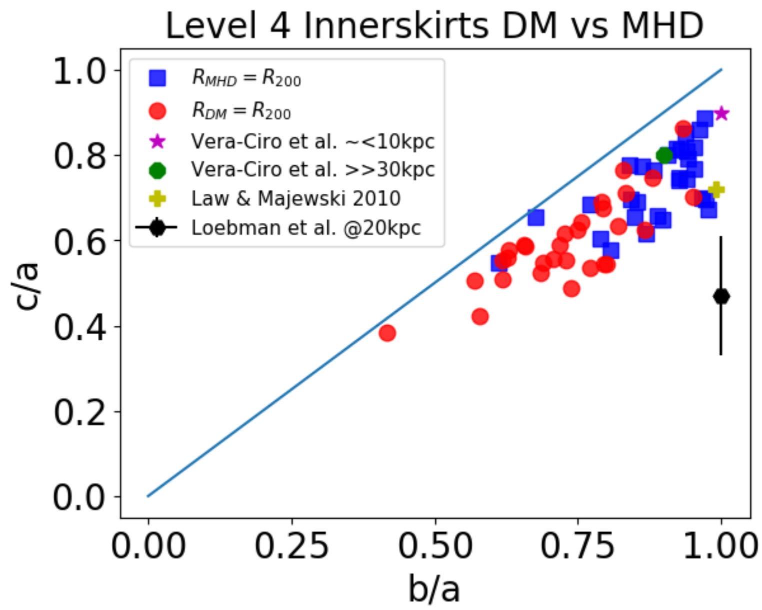


FIGURE 3.5: Semi-axial ratios and triaxiality $\frac{1-b/a}{1-c/a}$ as function of radius for semi-axes $a \geq b \geq c$. The MHD simulation (blue dotted line) shows ratios closer to 1 than those from the DM-only (green solid line) simulation. The rounding effect with radius for each simulation separatedly is also well-appreciable in this graphic. The radial-rounding, as well as the gas-presence amplification can be evidenced on the triaxiality function.

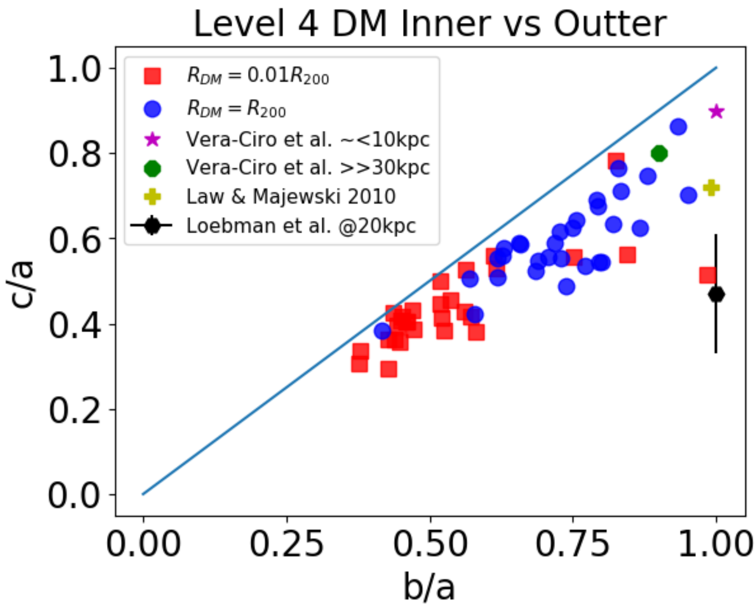


(A) Level4 MHD Vs DM at inner regions

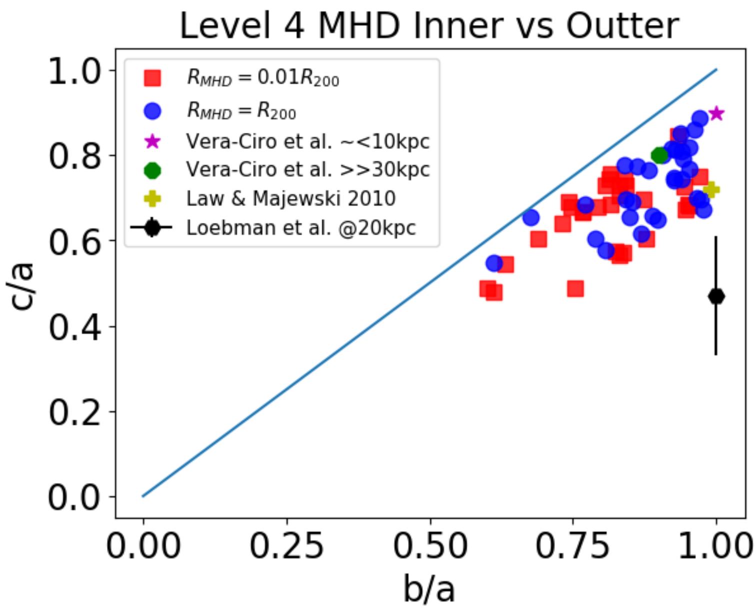


(B) Level4 MHD Vs DM at outter regions

FIGURE 3.6: General tendence on the triaxial plane $c/aVsb/a$. Some observational constraints (stars and error-bar point) are plotted alongside our results

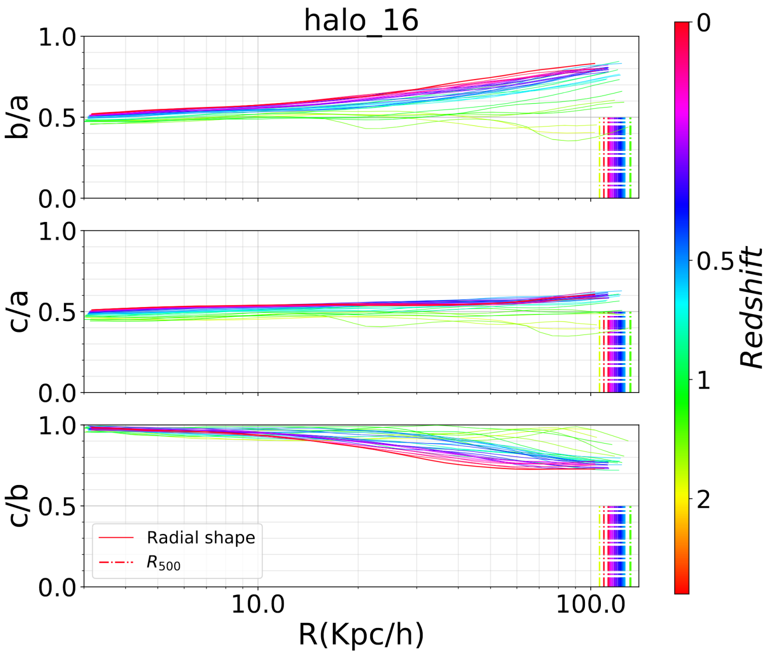


(A) Level4 DM inner Vs outer regions

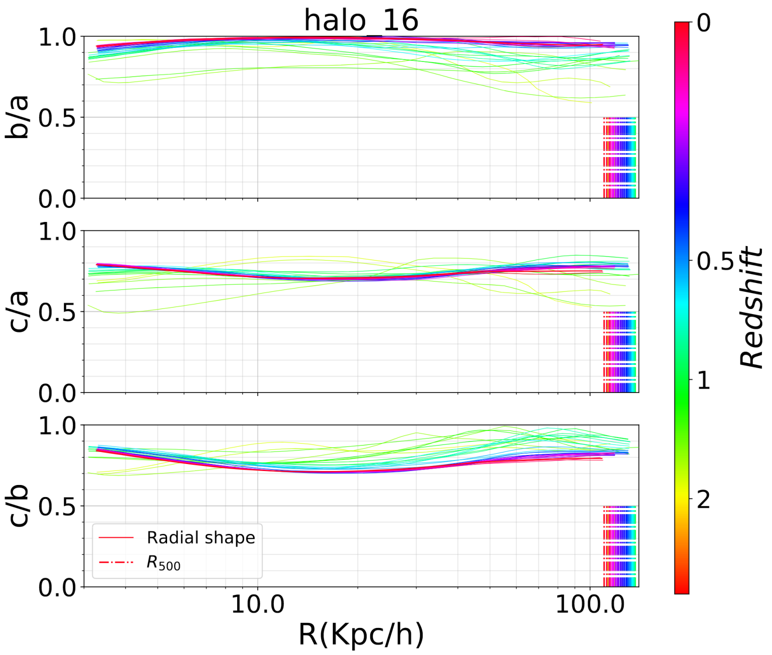


(B) Level4 MHD inner Vs outter regions

FIGURE 3.7: General tendence on the triaxial plane $c/aVsb/a$. Some observational constraints (stars and error-bar point) are plotted alongside our results

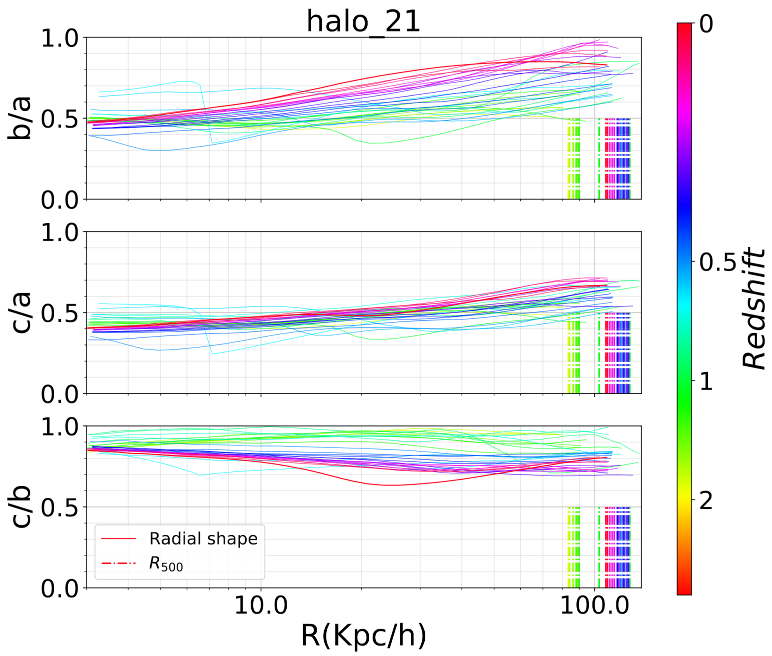


(A) halo 16 DM

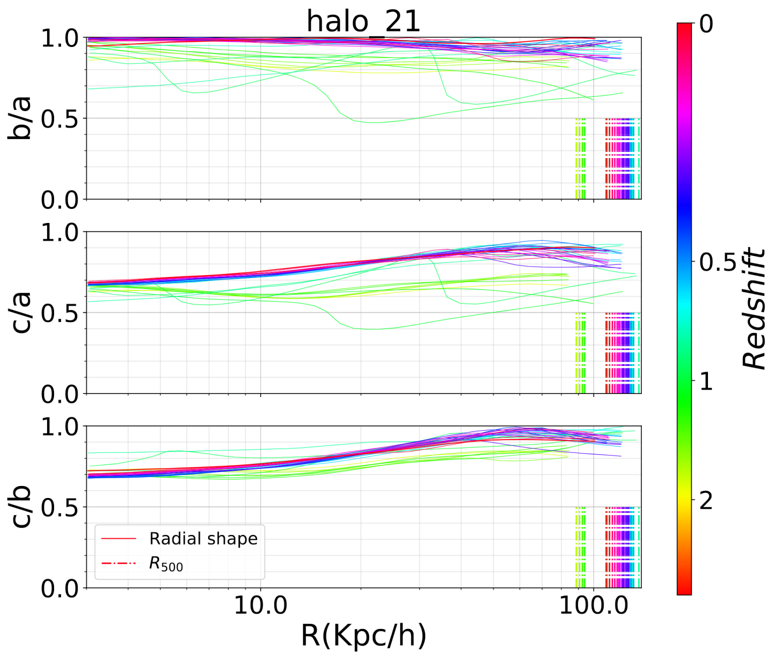


(B) halo 16 MHD

FIGURE 3.8: Example of historic shape conservation in comoving coordinates.



(A) halo 21 DM



(B) halo 21 MHD

FIGURE 3.9: Example of historic shape disruption in comoving coordinates. The consistency between MHD and DM implies some major-event like a close merger or a collision. The non-continuous red line corresponds to a very close moment of this merging event, which is amplified in MHD.

Chapter 4

Conclusions

Conclusions

Appendix A

An Appendix

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