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The expected shape of the Milky Way's Dark Matter halo

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ABSTRACT

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Key words: keyword1 – keyword2 – keyword3

1 INTRODUCTION

All papers should start with an Introduction section, which sets the work in context, cites relevant earlier studies in the field by Others (2013), and describes the problem the authors aim to solve (e.g. Author 2012).

Introduce/ Motivation simulations, sphereical top hat collapse.

One of the principal predictions of the CDM model is that DM halos are ellipsoidal and very well characterized by the principal axes $a > b > c$. This is due, among other causes, to the anisotropical and clumpy accretion of matter influenced by environmental structures (see? **?**). The general concensus in numerical simulations (e.g. **???**) is that halos tend to be prolate with axial ratios b/a *number*, c/a *number* and small differences may arise by the use different methods in numerical recipies for the simulations and the shape-calculation methods (see **?**). Some studies have gone a step further as for analyzing the dependence of shape of the DM halo on the radius and redshift (e.g. **??**), generally finding that halos are rounder at the outerskirts and at lower redshift.

Due to the evasive nature of DM, properly constraining the shape of DM halos is a very difficult endeavour.

Better connector with observations of distant galaxies. Gravitational lensing and star tracers. (Talk about discrepancy with simulations, perhaps later) and state that the preference for axisymmetrical shapes may arise from the observational restrictions (projection) look for citations about this .

In the case of the Milky Way, where we have a three-dimensional view from the inside, there seems to be a general agreement for oblate (i.e. a=b>c) configurations at small distances around $\tilde{<}$20kpc (see **???????**), and more triaxial and prolate configurations on the outter distances $\tilde{>}$20kpc (see **????**). However, some studies are inclined towards prolate configurations even at the inner parts of the halo (see **??**), and although it previously seemed that a triaxial DM halo on the outerskirts would be necessary to fully explain the characterization of the Sagittarius stream (see **?**), more recent studies put into doubt (question) this claim by reporting inconsistencies with narrow stellar streams **??** or finding that the relaxation of other constraints may make this claim unnecessary (wording) **?**.

Although observations predict more symmetric halos than DM-only simulations, this may be an effect of not taking into account the gravitational effects of baryonic matter. The collapse of baryonic matter generate denser structures than those of DM only, whose potential may affect the kinematics that give shape to DM halos by making them more axisymmetrical. Regarding the specifics of this rounding effect and stability, there is much to be known as the simulation of baryonic dynamics in the whole cosmological context to galactic-scale resolution is not a

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trivial task and is usually subject to simplifications to analyze extreme cases as boundary constrains. Simple study the adiabatical growth of a disk potential in DM halos of different triaxiality and in different orientations **??**. While these studies are elucidating about dynamical aspects that may play important roles in the shape rounding, they neglect some important galactic properties that may also contribute to this rounding that can be only analyzed with more sophisticated hydrodynamical simulations with restricted models of feedback **??**. In this way, it can be demonstrated that the galaxy formation efficiency **?** and the history of formation may also determine the extent of this rounding.

In this work, we analyze the novel Auriga simulations wich etc, where we can analyze the effect of dynamical properties together with galactic features, that play a role in the determination of the DM halo shape of realistic MW-like galaxies.

2 NUMERICAL SIMULATIONS

In this work we use the results of the state-of-the art Auriga simulations **?**. It selected a set of 30 isolated halos from the Evolution and Assembly of GaLaxies and their Environments (EAGLE) project **?**. Each halo was identified with the algorithm "Friend of Friends" (FOF) **?**, which recursively links particles if they are closer than some threshold distance referred as linking length. EAGLE follows the evolution of fixed-mass particles of $m_{\rm DM} = 1.15 \cdot 10^7 \mathrm{M}_\odot$ from $z = 127$ to $z = 0$, adopting the ΛCDM model from the (**?**, Planck Collaboration et al. (2014)), which is characterized by $\Omega_\Lambda = 0.693$, $\Omega_{\rm m} = 0.307$, $\Omega_{\rm b} = 0.048$ & $\mathrm{H}_0 = 67.77 \mathrm{kms}^{-1}\mathrm{Mpc}^{-1}$.

These halos were randomly selected from a sample of the most isolated quartile of 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. FOOTNOTE** . These halos were re-simulated with the (AREPOOO HERE) by increasing the mass resolution of the particles belonging to them and diminishing the resolution of the rest of the particles.

Various versions of each halo were modelled with different degrees of realism. All 30 halos were simulated within a level-4-degree of resolution defined for Aquarius simulations corresponding to $\tilde{3} \cdot 10^6$ high resolution particles of $\tilde{2}.5 \cdot 10^5 M_\odot$. The principal details of each of these halos are consigned on the table **??**. 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. For more information about level 3 halos, their details are printed on table **??**. Furthermore, fore each halo in each level of resolution there are two versions of the simulation. One of tracks the evolution of DM-only particles while the remaining one evolves DM and baryions with magneto-hydrodynamical (MHD) physics, including DM.

3 DETERMINING THE HALO SHAPE

There is no trivial way to calculate the DM halo shape at a determined radius due to the discretization of particles. For practical effects, observational models focus on the shape of the DM isopotential **?** or isodensity **?** contours. In cosmological simulations, it is preferred to work with the isodensity contours which is directly calculated from particle positions. However, these density contours are not smooth and are very sensitive to the presence of small satelites **?**. For this reason we determine the shape taking into account volume-enclosed particles, rather than shell-enclosed. While this approach allows the cumulative influence of outter shells on the outter shapes, it has been demonstrated for DM-only simulations that this effect becomes important only for big radii **?**. We therefore follow the method of (**?**, Allgood et al. 2006) that consits in the use of the reduced inertia tensor,

$$I_{ij} = \sum_k \frac{x_k^{(i)} x_k^{(j)}}{d_k^2}, \tag{1}$$

with components weighted by the k-th particle distance $d^2 = x^2 + y^2 + z^2$.

The diagonalization of this tensor yields the principal axes of the structure as well as the eigen-quantities which are proportional to the squared principal axes $a > b > c$. We start our calculations taking into account particles within a sphere of radius R and then recharacterize the triaxial parameters by taking into account particles within an ellipsoid of semi-axes $r, r/q, r/s$ and weighted distance $d^2 = x^2 + (y/q)^2 + (z/s)^2$, where ere $q = b/a$ and $s = c/a$ are the previously calculated axial ratios. We repeat this process until the average deviation of semi-axes is less than 10^{-6}.

4 RESULTS

Here we present our principal results blah blah blah.

4.1 The radial tendency of axial ratios

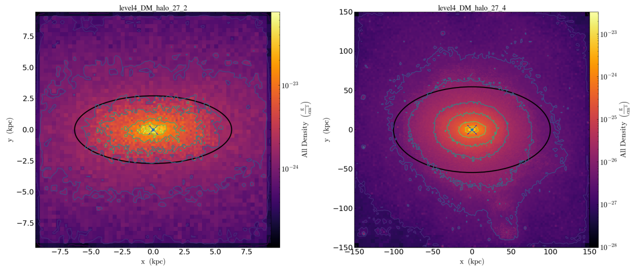
First, it is important to verify that halos are rounder at larger radii, for both MHD and DM simulations.

4.2 The rounding effect of baryons

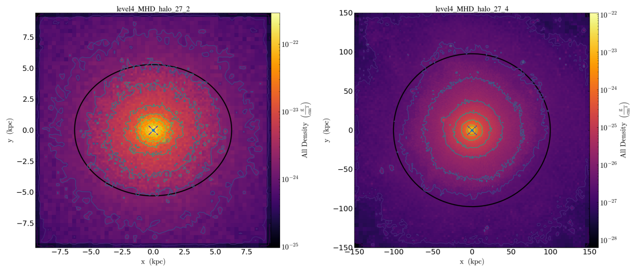
Here we discuss the rounding effect of baryons. We quantify this rounding effect and look for correlations with important baryonic properties of the galaxy.

4.3 The historical shape

Here we study the memory shape and how it can be deduced from the historic radial shapes. Also why it is lost for MHD even when radial profiles have the same historic tendencies.

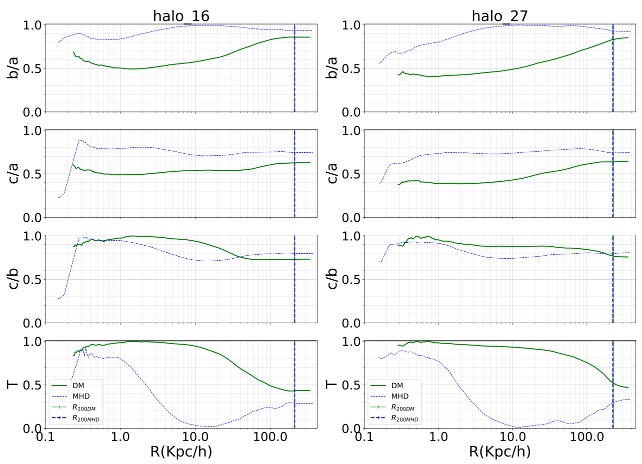


(a) halo 27 DM shape at small radius (b) halo 27 DM shape at big radius



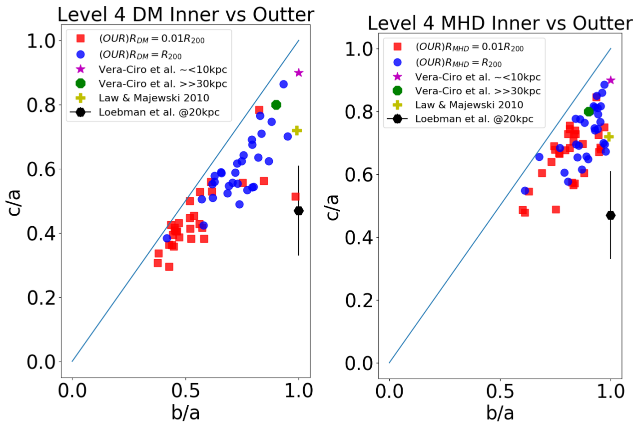
(c) halo 27 MHD shape at small radius (d) halo 27 MHD shape at big radius

Figure 1. DM density for inner (left) and outer (right) parts of the halo 27. We present both versions of the halo: DM (up) & MHD (down). The horizontal (vertical) axes are aligned to the major (medium) axes. (optimaze space and description)



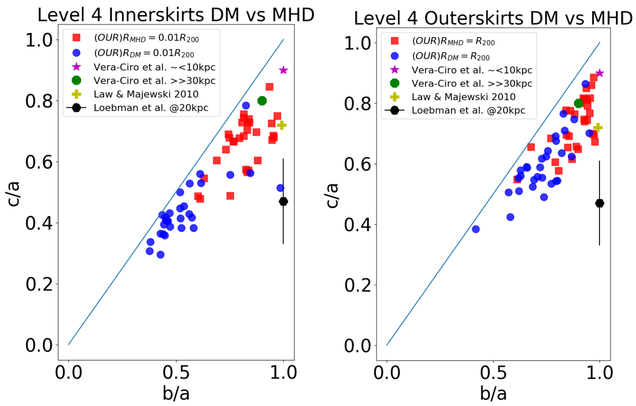
(a) halo 16 (b) halo 27

Figure 2. Radial profile for axial ratios and the triaxiality parameter $T = \frac{1-b/a}{1-c/a}$ from halo 27 and halo 16. These halos have a clear radial tendence towards sphericity (for smaller radii until $\approx$ 3Kpc), which can be confirmed with the triaxiality parameter. (Merged Column)



(a) Level4 DM inner Vs outer regions (b) Level4 MHD inner Vs outer regions

Figure 3. General tendency on the triaxial plane c/a Vs b/a. Some observational constraints are plotted alongside our results (Optimize space. caption replaces title. Present constraints representation of density)



(a) Level4 MHD Vs DM at inner regions (b) Level4 MHD Vs DM at outer regions

Figure 4. Axial ratios as shown on c/a Vs b/a. Each dot represents a halo shape at some radius. Some observational constraints are plotted alongside our results. Here, dots are clustered, proving the general tendence of halos to get rounder on the outer parts.(Optimize space. caption replaces title. Present constraints representation of density)

4.4 The orientation of the principa axes

This is an important result of our study. We study the radial evolution of the principal axes, compared also to the angular momentum vector from the disk. We found that while the angular momentum tend to be aligned with the minor axis of the ellipsoid, this may not be the case all times. When there is an alignment it is usually within 20 degrees. When there is not an alignment, then there is no simple way to determine toward which axis it is oriented. Furthermore, the principal axes alignment usually change with radius (rotation, swap). This really questions the strong constrains on the MW DM halo models.

5 CONCLUSIONS

The last numbered section should briefly summarise what has been done, and describe the final conclusions which the authors draw from their work.

asphericity Vs Star Density.png

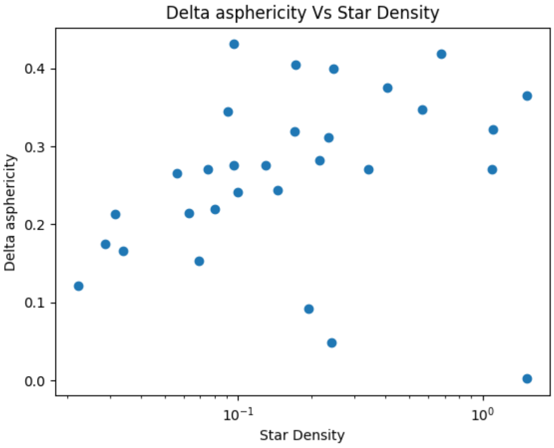
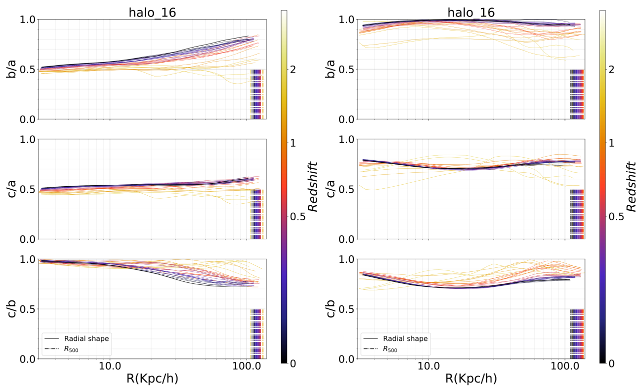


Figure 5. Difference in asphericities between MHD and DM shapes Vs Star Density of the simulation.



(a) halo 16 DM (b) halo 16 MHD

Figure 6. Radial profile (comoving) of axial ratios for halo 16 in terms of redshift (color). This halo maintains its shape until $z \approx 1$ obviating the systematic rounding effect in time from asymmetric potentials.

6 DISCUSSION

ACKNOWLEDGEMENTS

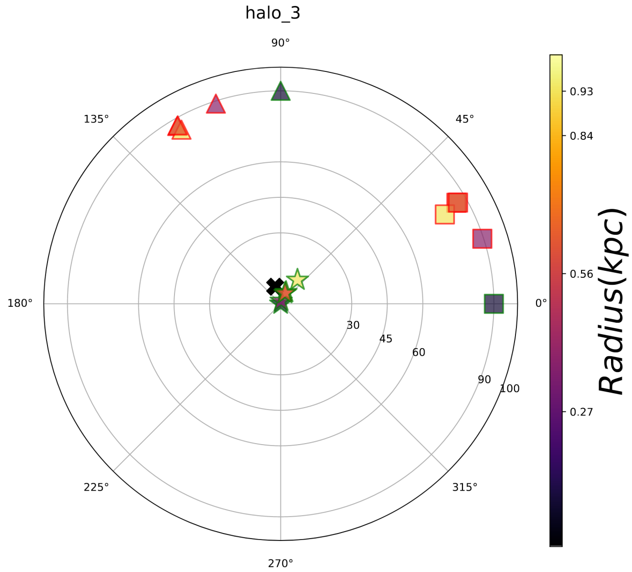
The Acknowledgements section is not numbered. Here you can thank helpful colleagues, acknowledge funding agencies, telescopes and facilities used etc. Try to keep it short.

REFERENCES

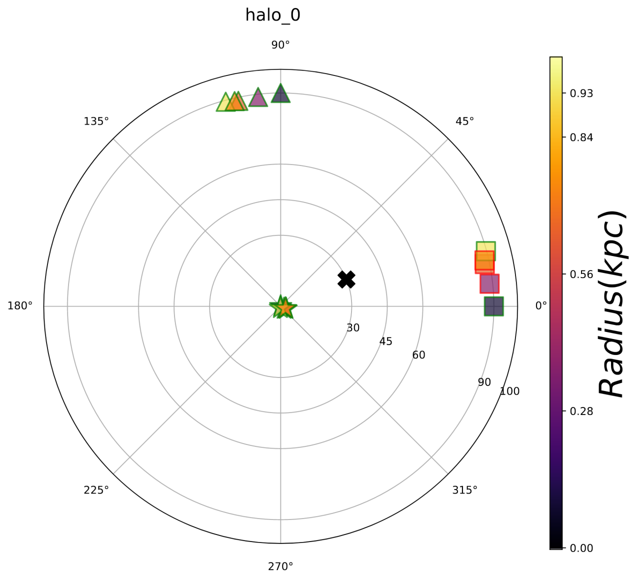
Author A. N., 2013, Journal of Improbable Astronomy, 1, 1
Others S., 2012, Journal of Interesting Stuff, 17, 198

APPENDIX A: SOME EXTRA MATERIAL

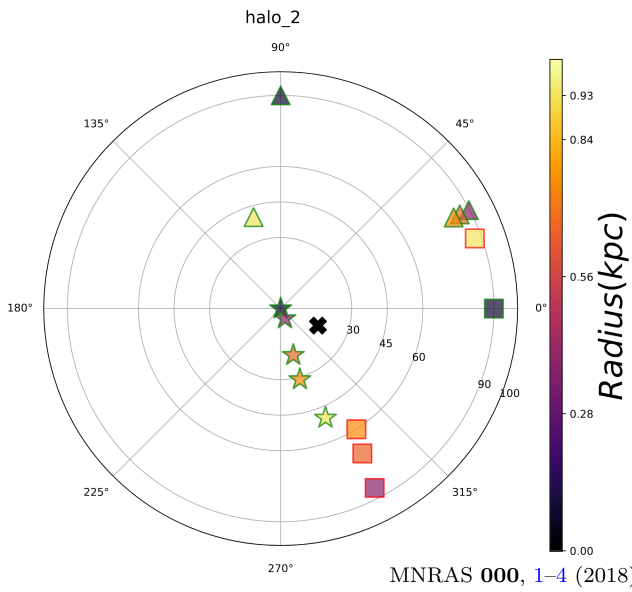
If you want to present additional material which would interrupt the flow of the main paper, it can be placed in an Appendix which appears after the list of references.



(a) Aligned Axes



(b) Rotating Axes



(c) Chaotic Axes

Figure 7. Description of axes alignments

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