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

This is a simple template for authors to write new MNRAS papers. See `mnras_sample.tex` for a more complex example, and `mnras_guide.tex` for a full user guide.

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).

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) **?**, that recursively links particles if they are closer than some distance threshold referred as linking length. EAGLE follows the evolution of fixed-mass particles of $m_{\rm DM} = 1.15 \cdot 10^7 \rm M_\odot$ from $z = 127$ to $z = 0$, adopting the ΛCDM model from the (**?**, Planck Collaboration et al. (2014)), which is characterized by the parameters: $\Omega_\Lambda = 0.693$, $\Omega_{\rm m} = 0.307$, $\Omega_{\rm b} = 0.048$ & $\rm H_0 = 67.77 kms^{-1}Mpc^{-1}$.

These halos were randomly selected from a sample of the 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. This would efficiently simulate external gravitational effects over the studied structure while focusing on a high-resolution 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 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

The discretization of the DM density field into particles makes it difficult to perform some calculations that would require a more continuous distribution. Therefore, there is no trivial way to calculate the DM halo shape at a determined radius. There are different approaches **ISODENSITY, ISOPOTENTIAL, potential gets rounder, cite binney Talk about difference between volume method and isodensity contour at least for DM halos** **?**. In this work we follow the guidelines by (**?**, Vera-Ciro et al. 2011) which includes the use of the shape method proposed by (**?**, Allgood et al. 2006).

To calculate the DM halo shape, we initially consider

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particles enclosed within a sphere of radius r. We calculate the reduced inertia tensor:

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

whose components are weighted by the distance $d^2 = x^2 + y^2 + z^2$, so that each particle contribute with same importance to the sum regardless of their radius from the center.

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 $a > b > c$. **SUMARIZE** However, if we characterize an ellipsoid taking into account only particles enclosed within a sphere, we are effectively miscalculating its triaxiality **?**. For this reason, we iteratively recalculate the inertia tensor taking into account the previously characterized ellipsoid.

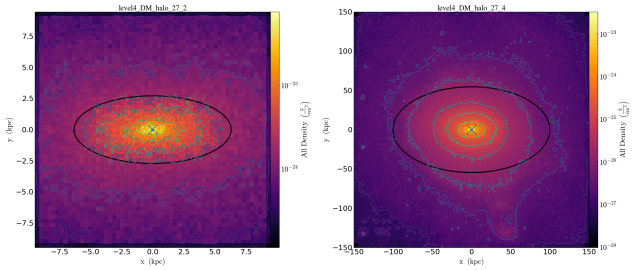
AllGood et al. propose to use the eigenvalues $a > b > c$ and their respective eigen-axes v_a, v_b, v_c to recalculate the inertia tensor over the particles enclosed by the ellipsoid with principal axes (along the respective eigenvectors) equal to $r, r/q, r/s$, where ere $q = b/a$ and $s = c/a$ are 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. In this case, as the constant of proportionality is a free parameter, we choose to hold the size (not the direction) of the principal axis constant.

This method looks reliable 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 introducing some error in 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.

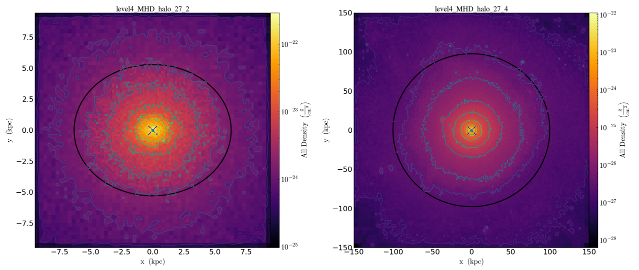
In case this concept of an elliptic metric is difficult to grasp, let us consider that, instead of converting the initial enclosing sphere to the halo ellipse, we are converting the halo ellipsoid into a sphere by performing scale transforms along the respective eigen-axes. From this point of view, we start our first-guess calculation of the ellipsoid by computing the reduced inertia tensor (1) for particles enclosed within a sphere of radius r. Then with the results of this first guess, we perform the following scale transform:

$$\begin{aligned} (x, y, z) &\to (x', y', z') = (x, y/q, z/s) \\ q &= b/a \\ s &= c/a, \end{aligned} \tag{2}$$

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



(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)

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

4 RESULTS

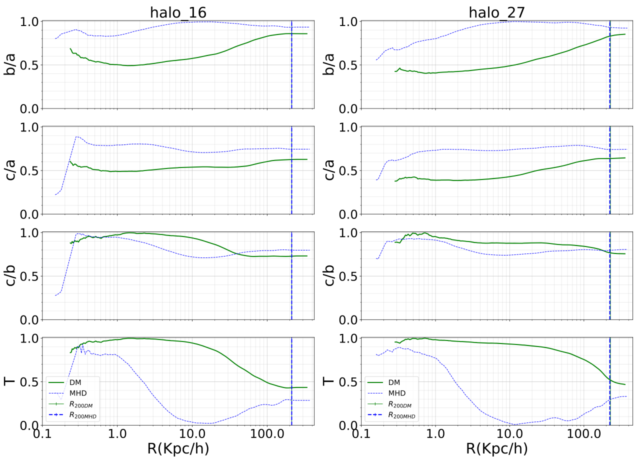
Here we present our principal results blah blah blah.

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.

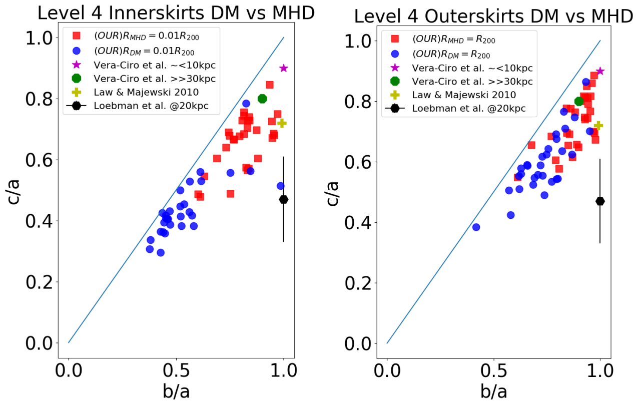
4.2 The rounding effect of baryons

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



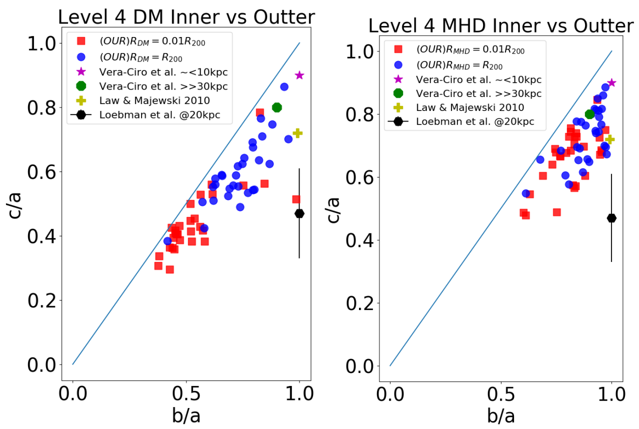
(a) halo 16 (b) halo 27

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 ≈ 3Kpc), which can be confirmed with the triaxiality parameter. (Merged Column)



(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)



(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)

asphericity Vs Star Density.png

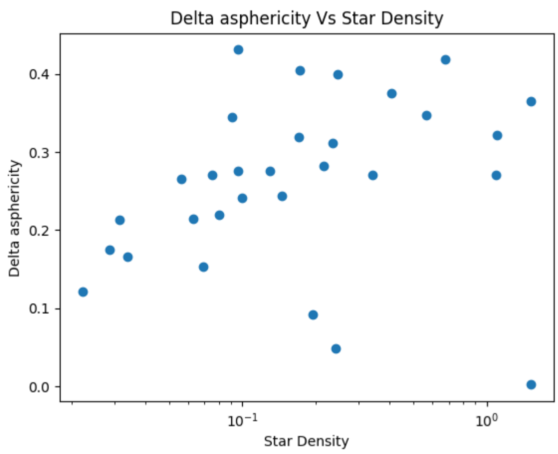


Figure 5. Difference in asphericities between MHD and DM shapes Vs Star Density of the simulation.

4.3 The historical shape

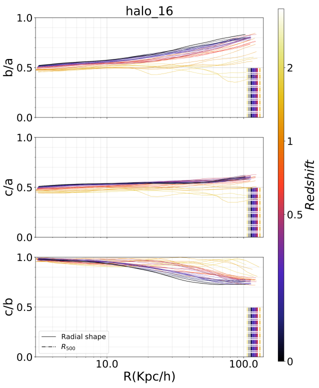
Here we study the memory shape and how it can be deduced from the historic radial shapes. Also why it is lost for MHD even when radial profiles have the same historic tendencies.

4.4 The orientation of the principa axes

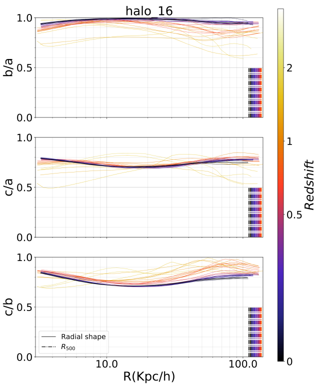
This is an important result of our study. We study the radial evolution of the principal axes, compared also to the angular momentum vector from the disk. We found that while the angular momentum tend to be aligned with the minor axis of the ellipsoid, this may not be the case all times. When there is 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.



(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.

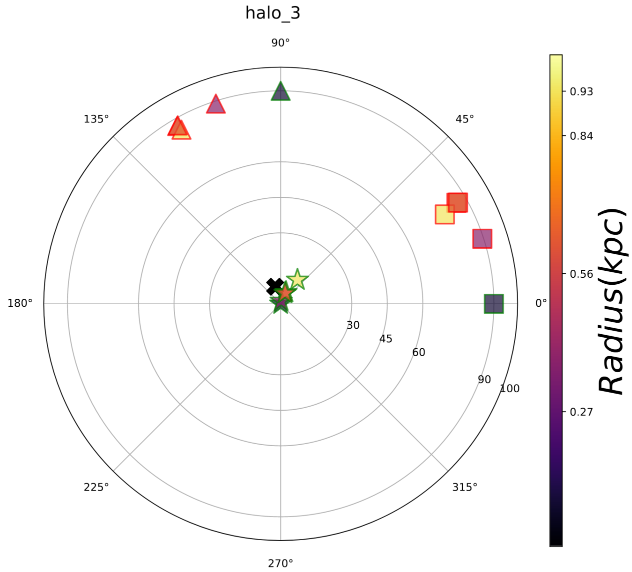
REFERENCES

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

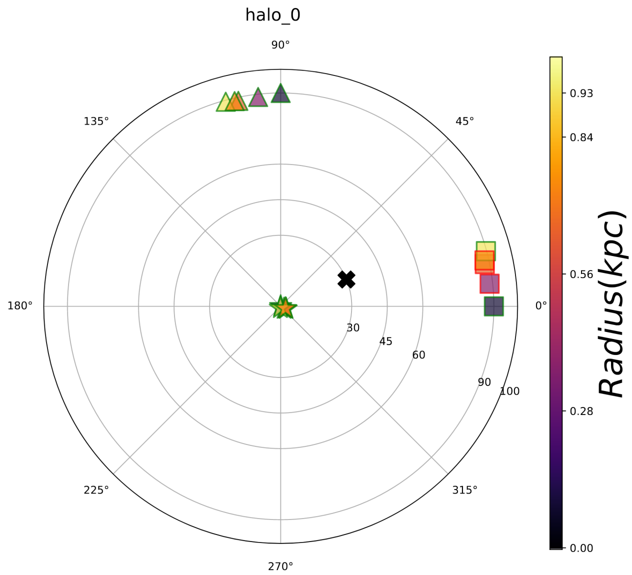
APPENDIX A: SOME EXTRA MATERIAL

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.

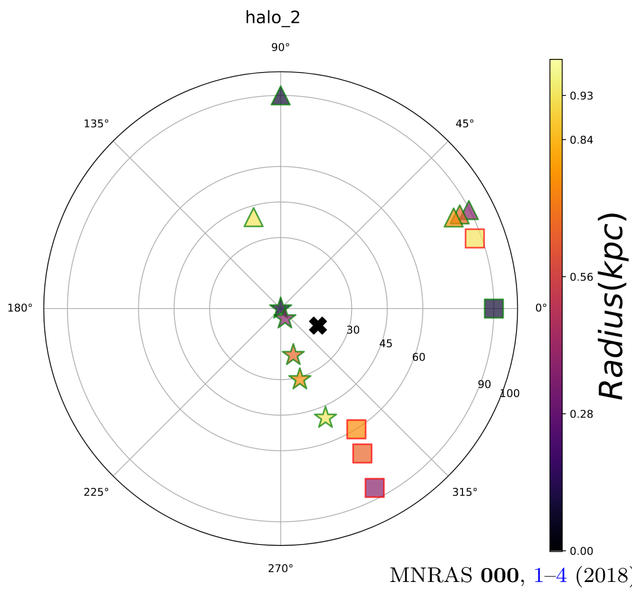
This paper has been typeset from a TEX/LATEX file prepared by the author.



(a) Aligned Axes



(b) Rotating Axes



(c) Chaotic Axes

Figure 7. Description of axes alignments