The Expected Shape of the Milky Way's Dark Matter Halos

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Outline

1. Motivation
   - Evidences of Dark Matter (DM)
   - DM density in our Milky Way (MW)
   - Observational constraints on MW's DM halo
   - The utility of Cosmological simulations
   - Simulations and observations
2. Our study
   - Objectives
   - How do we calculate DM shapes in terms of radius? (simulations)
   - Convergence analysis
   - Radial dependence of shape
   - The effect of gas
   - Historical and radial correlations

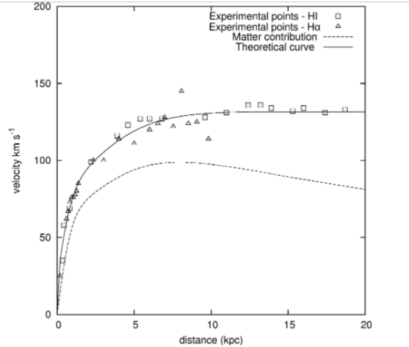

Figure 2: Plot of the rotational velocity v versus distance r from the galactic center, for the galaxy NGC 2403. Squares (⊡) are the velocities determined from HI observations (see Bergman [1987]), while triangles (△) are Hα observations (see Blais-Ouellette et al. [2004]). The solid line is the theoretical curve (see text), while the dashed line is the contribution due to the local matter.

Figure: arxiv:1111.5793

- Rotation curves
- Weak lensing
- CMB
- Large-scale structure of the universe
- Modified gravity

- We have not measured DM directly.
- **DM density field** of an object is needed.
- DM evidence is not that far: MW
- MW is the only object of which we have tridimensional view from the interior.

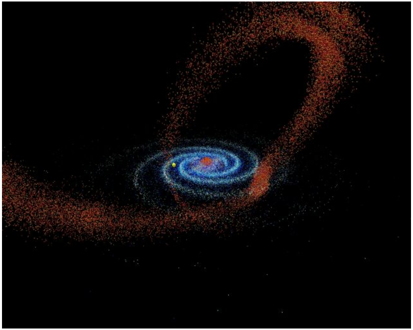

Figure: Sagitarius stream. David Law

The DM density field is often reduced to a radial profile:

$$\rho(\vec{r}) \to \rho(r) = \frac{\delta_c \rho_{crit}}{\frac{r}{r_c}\left(1 + \frac{r}{r_c}\right)}, \tag{1}$$

which is universal in a hierarchical model of formation [1].

Radial profiles omit angular dependence of density (**shape**).

DM halos are not **spherical** but **triaxial** [2] (acretion)

Why do we want to define a shape?

Besides being a more complete characterization of density, it can keep memory of past events of formation.

Some efforts for constraints on the MW's DM halo shape. [3, 4, 5, **?**]

CONSTRAINTS ON THE SHAPE OF THE MILKY WAY DARK MATTER HALO FROM JEANS EQUATIONS APPLIED TO SDSS DATA

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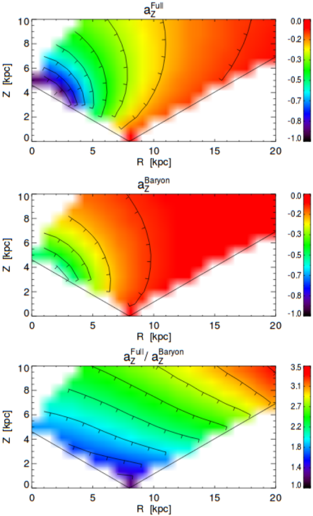
ABSTRACT

We search for evidence of dark matter in the Milky Way by utilizing the stellar number density distribution and kinematics measured by the Sloan Digital Sky Survey (SDSS) to heliocentric distances exceeding ∼10 kpc. We employ the cylindrically symmetric form of Jeans equations and focus on the morphology of the resulting acceleration maps, rather than the normalization of the total mass as done in previous, mostly local, studies. Jeans equations are first applied to a mock catalog based on a cosmologically derived N-body + SPH simulation, and the known acceleration (gradient of gravitational potential) is successfully recovered. The same simulation is also used to quantify the impact of dark matter on the total acceleration. We use Galfast, a code designed to quantitatively reproduce SDSS measurements and selection effects, to generate a synthetic stellar catalog. We apply Jeans equations to this catalog and produce two-dimensional maps of stellar acceleration. These maps reveal that in a Newtonian framework, the implied gravitational potential cannot be explained by visible matter alone. The acceleration experienced by stars at galactocentric distances of ∼20 kpc is three times larger than what can be explained by purely visible matter. The application of an analytic method for estimating the dark matter halo axis ratio to SDSS data implies an oblate halo with $q_{DM} = 0.47 \pm 0.14$ within the same distance range. These techniques can be used to map the dark matter halo to much larger distances from the Galactic center using upcoming deep optical surveys, such as LSST.

Subject headings: stars: kinematics and dynamics — stars: statistics — Galaxy: general — Galaxy: kinematics and dynamics — Galaxy: structure — Galaxy: halo



- Jean's axisymmetric equations relate a_z, a_R with stellar number density ν, mean azimuthal velocity $\overline{v}_\phi$ and velocity dispersions.
- Dark matter contribution can be estimated from observations (SDSS) and Jean's equations [6, van der Marel 1991].
- Their result was an oblate halo with $q_{DM} = 0.47 \pm 0.14$.

A more interesting approach: The Sagitarius stream with a triaxial halo [4, Law & Majewski 2010].

THE SAGITTARIUS DWARF GALAXY: A MODEL FOR EVOLUTION IN A TRIAXIAL MILKY WAY HALO

DAVID R. LAW[1,2] AND STEVEN R. MAJEWSKI[3]

DRAFT: March 4, 2010

ABSTRACT

We present a new N-body model for the tidal disruption of the Sagittarius (Sgr) dwarf that is capable of simultaneously satisfying the majority of angular position, distance, and radial velocity constraints imposed by current wide-field surveys of its dynamically young ($\lesssim$ 3 Gyr) tidal debris streams. In particular, this model resolves the conflicting angular position and radial velocity constraints on the Sgr leading tidal stream that have been highlighted in recent years. While the model does not reproduce the apparent bifurcation observed in the leading debris stream, recent observational data suggest that this bifurcation may represent a constraint on the internal properties of the Sgr dwarf rather than the details of its orbit. The key element in the success of this model is the introduction of a non-axisymmetric component to the Galactic gravitational potential which can be described in terms of a triaxial dark matter halo whose minor/major axis ratio $(c/a)_\Phi = 0.72$ and intermediate/major axis ratio $(b/a)_\Phi = 0.99$ at radii $20 < r < 60$ kpc. The minor/intermediate/major axes of this halo lie along the directions $(l, b) = (7°, 0°)$, $(0°, 90°)$, and $(97°, 0°)$ respectively, corresponding to a nearly-oblate ellipsoid whose minor axis is contained within the Galactic disk plane. This particular disk/halo orientation is difficult to reconcile within the general context of galactic dynamics (and CDM models in particular), suggesting either that the orientation may have evolved significantly with time or that inclusion of other non-axisymmetric components (such as the gravitational influence of the Magellanic Clouds) in the model may obviate the need for triaxiality in the dark matter halo. The apparent proper motion of Sgr in this model is estimated to be $(\mu_l \cos b, \mu_b) = (-2.16, 1.73)$ mas yr^{-1}, corresponding to a Galactocentric space velocity $(U, V, W) = (230, -35, 195)$ km s^{-1}. Based on the velocity dispersion in the stellar tidal streams, we estimate that Sgr has a current bound mass $M_{\rm Sgr} = 2.5^{+1.3}_{-1.0} \times 10^8 M_\odot$. We demonstrate that with simple assumptions about the star formation history of Sgr, tidal stripping models naturally give rise to gradients in the metallicity distribution function (MDF) along the stellar debris streams similar to those observed in recent studies. These models predict a strong evolution in the MDF of the model Sgr dwarf with time, indicating that the chemical abundances of stars in Sgr at the present day may be significantly different than the abundances of those already contributed to the Galactic stellar halo. We conclude by using the new N-body model to reevaluate previous claims of the association of miscellaneous halo substructure with the Sgr dwarf.

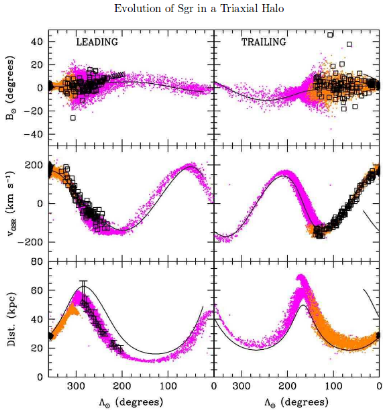


Figure: Simulated Sagitarius stream (color) vs Observed properties of the stream (figures)

- Characterization of the sagitarius stream.
- Variation of parameters: Match simulations with observations.
- Mismatch between an axisymmetric halo and observations.
- The best fit parameters are $c/a = 0.72$, $b/a = 0.99$ at $20 < r < 60 kpc$.
- Axis orientation

Strong assumptions or simplifications:

- **Loebman et al.**: DM halo is perfectly oblate, cylindric Jean's equations.
- **Law & Majewski**: Approximation of stream as CM. Omission of LMC.

Observational difficulties:

- Perpendicular velocities
- Radial mass distribution

Support tool for observation and theory.

Evolution of DM and gas in a ΛCDM cosmology:

Self-gravitating collisionless fluid for DM

$$\frac{d\rho}{dt} = \frac{\partial \rho}{\partial t} + \vec{v} \cdot \frac{\partial \rho}{\partial \vec{x}} + \frac{\partial \Phi}{\partial \vec{x}} \cdot \frac{\partial \rho}{\partial \vec{v}} \tag{2}$$

Non-viscid thermal fluid for the gas

$$\frac{d\rho}{dt} + \rho \vec{\nabla} \cdot \vec{v} = 0 \tag{3}$$

$$\frac{d\vec{v}}{dt} = -\frac{\vec{\nabla} P}{\rho} - \vec{\nabla}\Phi \tag{4}$$

$$\frac{du}{dt} = -\frac{P}{\rho}\vec{\nabla} \cdot \vec{v} - \frac{\Lambda(\vec{u}, \rho)}{\rho} \tag{5}$$

$$P = (\gamma - 1)\rho u \tag{6}$$

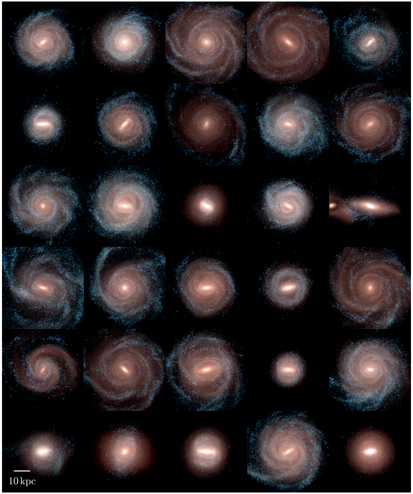


Figure: Auriga simulations. http://auriga.h-its.org

- Evolution: SPH MMH.
- Energetic feedback.
- We focus on AURIGA [7] simulations made with AREPO [8].
- Various degrees of realism.
- Magnetic fields.

A study of the shape in terms of the radius and history.

The Shape of Dark Matter Haloes in the Aquarius Simulations: Evolution and Memory

Carlos A. Vera-Ciro[1★], Laura V. Sales[1,4], Amina Helmi[1], Carlos S. Frenk[2], Julio F. Navarro[3], Volker Springel[5,6], Mark Vogelsberger[7] and Simon D. M. White[4]

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8 April 2011

ABSTRACT

We use the high resolution cosmological N-body simulations from the Aquarius project to investigate in detail the mechanisms that determine the shape of Milky Way-type dark matter haloes. We find that, when measured at the instantaneous virial radius, the shape of individual haloes changes with time, evolving from a typically prolate configuration at early stages to a more triaxial/oblate geometry at the present day. This evolution in halo shape correlates well with the distribution of the infalling material: prolate configurations arise when haloes are fed through narrow filaments, which characterizes the early epochs of halo assembly, whereas triaxial/oblate configurations result as the accretion turns more isotropic at later times. Interestingly, at redshift $z = 0$, clear imprints of the past history of each halo are recorded in their shapes at different radii, which also exhibit a variation from prolate in the inner regions to triaxial/oblate in the outskirts. Provided that the Aquarius haloes are fair representatives of Milky Way-like $10^{12}M_{\odot}$ objects, we conclude that the shape of such dark matter haloes is a complex, time-dependent property, with each radial shell

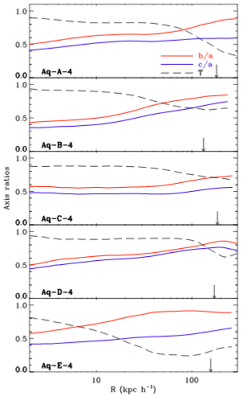


Figure: Dependence of shape on radius

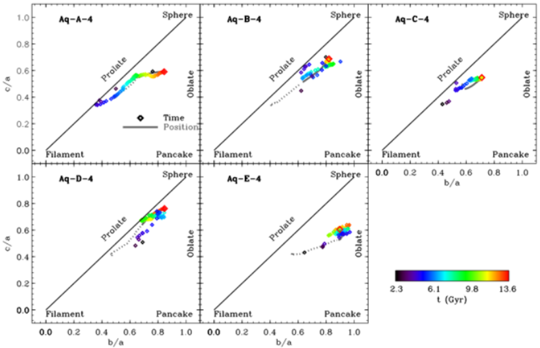


Figure: Dependence of shape on history

Aquarius simulations [9].

Shape in terms of radius? How to measure it?

Their main results are:

- Dependence on the radius.
- Correlation of historical shape and present shape.
- Halos evolve towards prolate shapes.

Improvement on observational constraints:

CONSTRAINTS ON THE SHAPE OF THE MILKY WAY DARK MATTER HALO FROM THE SAGITTARIUS STREAM

CARLOS VERA-CIRO[1,2] & AMINA HELMI[2]
Draft version July 29, 2013

ABSTRACT

We propose a new model for the dark matter halo of the Milky Way that fits the properties of the stellar stream associated with the Sagittarius dwarf galaxy. Our dark halo is oblate with $q_z = 0.9$ for $r \lesssim 10$ kpc, and can be made to follow the Law & Majewski model at larger radii. However, we find that the dynamical perturbations induced by the Large Magellanic Cloud on the orbit of Sgr cannot be neglected when modeling its streams. When taken into account, this leads us to constrain the Galaxy's outer halo shape to have minor-to-major axis ratio $(c/a)_\Phi = 0.8$ and intermediate-to-major axis ratio $(b/a)_\Phi = 0.9$, in good agreement with cosmological expectations.

Subject headings: galaxies: dwarf - galaxies: interactions - Local Group

Iprovement of Law & Majewski 2010 study with relaxed asumptions.

The DM halo assumptions:

- Axisymmetric at inner parts, **coherent with the MW disk**.
- Triaxial on the outer-skirts.
- Smooth transition.

They used variation of parameters yield:

- $qz = 0.9$ at $r \approx 10kpc$
- $b/a = 0.9, c/a = 0.8$ at $r >> 30kpc$

- Study the shape of the DM halo in terms of the radius in the AURIGA simulations.
- Study the correlation of the radial and historical profiles.
- **Analyze the relation or the effect of baryons on the DM halo shape.**

We follow Vera-Ciro et al. 2011 (Allgood et al. 2006) to calculate shapes.

Shapes are determined by the semiaxes a, b, c of the ellipsoid associated to the halo.

First we choose a radius R. We calculate the reduced inertia tensor for all particles within the defined sphere:

$$I_{ij} = \sum_k \frac{x_k^{(i)} x_k^{(j)}}{d_k^2} \tag{7}$$

The eigenvalues of this tensor are said semiaxes along the corresponding eigenvectors.

But this is not sufficient: Calculate ellipse from spherical selection of particles.

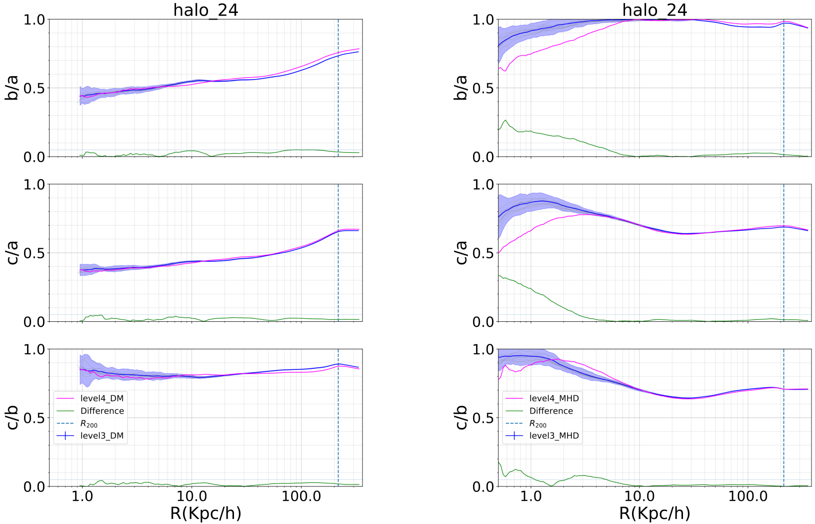
The solution is to rescale positions for the current ellipse to become a sphere and recalculate:

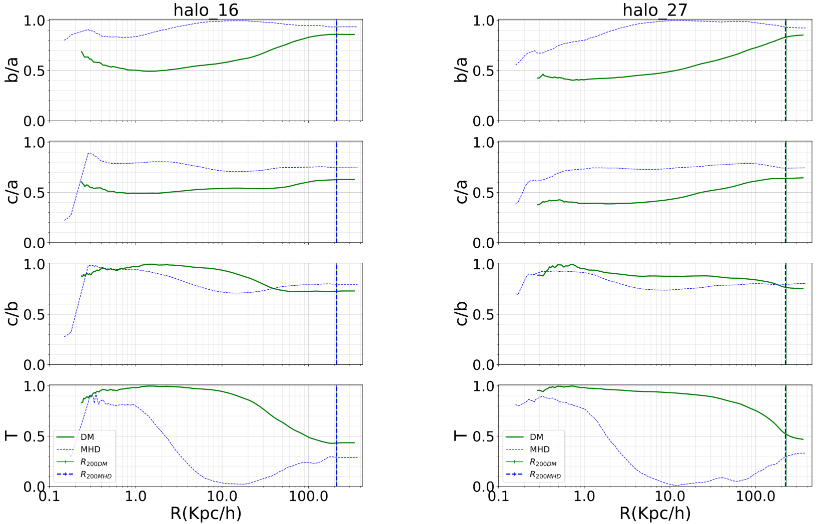
Once obtained the first semiaxes, we rescale:

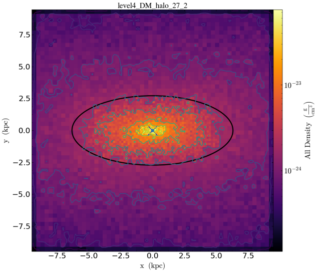
$$(x, y, z) \rightarrow (x, y/q, z/s) \tag{8}$$
$$q = b/a \tag{9}$$
$$s = c/a, \tag{10}$$

This rescaling is used to redefine the contour *sphere* and to calculate the *distance* in the inertia tensor.

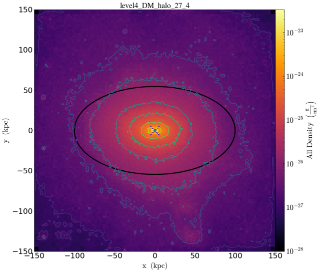
The semiaxes are recalculated the rescaling is performed iteratively until we achieve convergence: changes in semiaxes are less than 10^{-6}


halo_24
b/a
c/a
c/b
level4_DM
Difference
R_{200}
level3_DM
R(Kpc/h)
halo_24
level4_MHD
Difference
R_{200}
level3_MHD
R(Kpc/h)

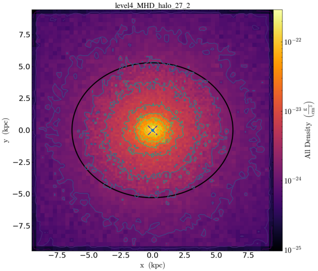

halo_16
halo_27
b/a
c/a
c/b
T
1.0
0.5
0.0
0.1
1.0
10.0
100.0
R(Kpc/h)
DM
MHD
R_{200DM}
R_{200MHD}



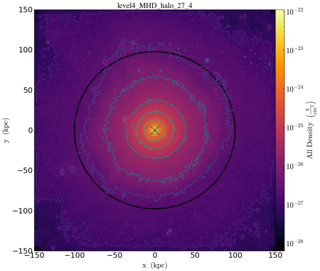
(e) halo 27 DM shape (small radius)



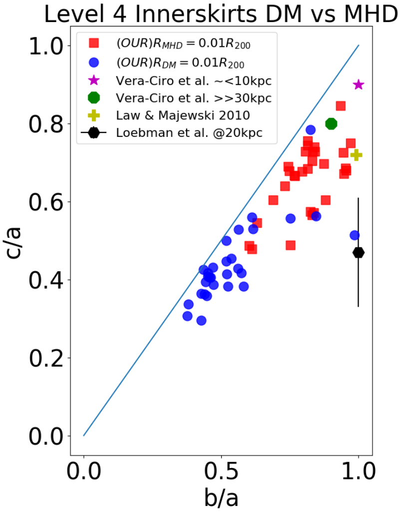
(f) halo 27 DM shape (big radius)



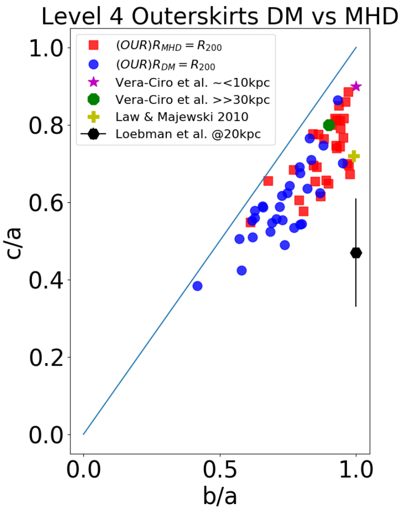
(g) halo 27 MHD shape (small radius)



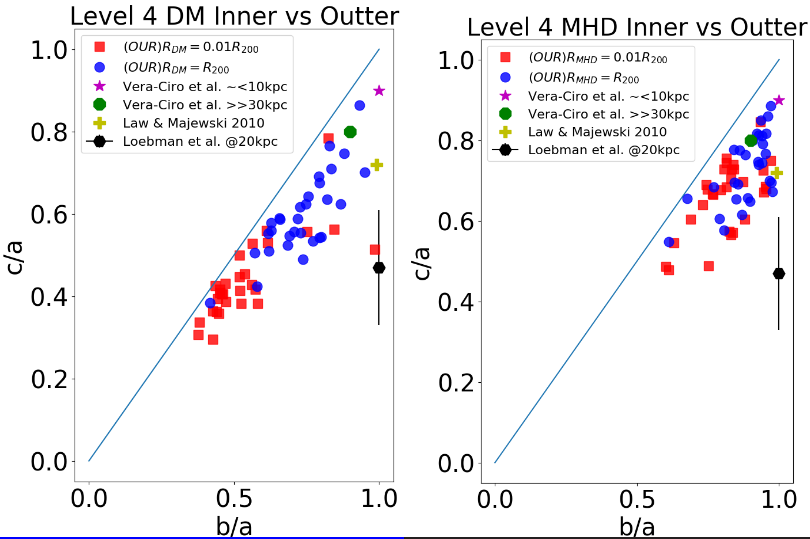
(h) halo 27 MHD shape (big radius)



(i) Level4 MHD Vs DM at inner regions



(j) Level4 MHD Vs DM at outer regions


Level 4 DM Inner vs Outter
$(OUR)R_{DM} = 0.01R_{200}$
$(OUR)R_{DM} = R_{200}$
Vera-Ciro et al. ~<10kpc
Vera-Ciro et al. >>30kpc
Law & Majewski 2010
Loebman et al. @20kpc
c/a
b/a
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.5
1.0
Level 4 MHD Inner vs Outter
$(OUR)R_{MHD} = 0.01R_{200}$
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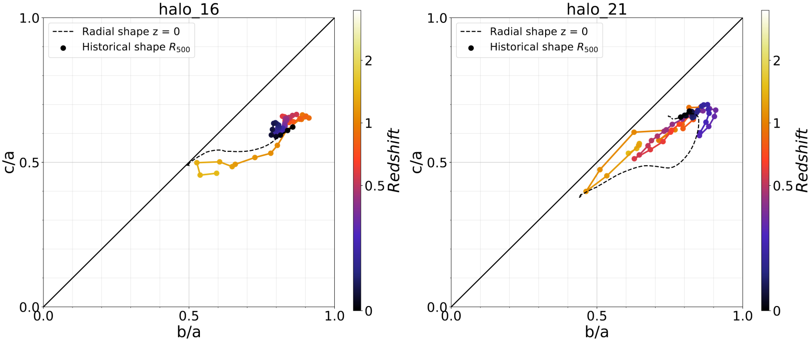
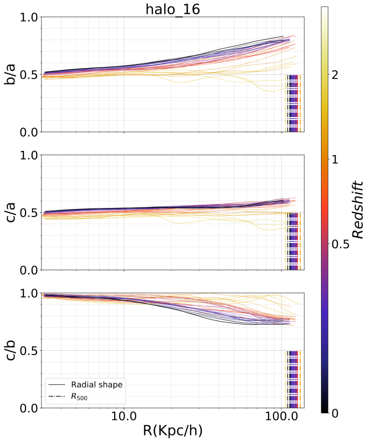
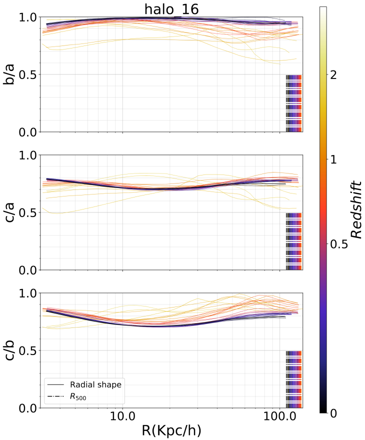


(m) halo 16 DM

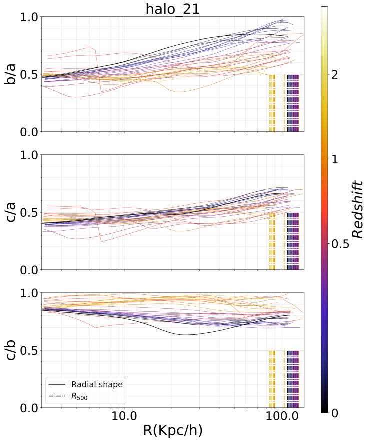
(n) halo 21 DM



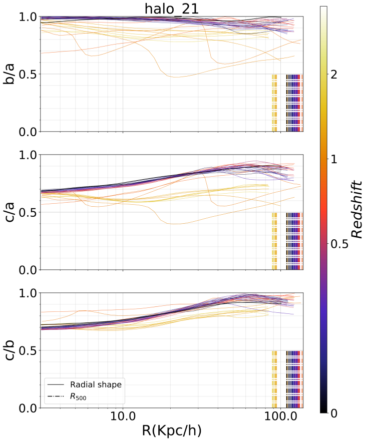
(o) halo 16 DM



(p) halo 16 MHD



(q) halo 21 DM



(r) halo 21 MHD

Figure: Radial profile (comoving) of axial ratios for halo 21 in terms of redshift (color). This halo is disrupted around $z \approx 0.5$ which results in a certain loss of its shape memory.

- Study the effec of environmental structures on halo shape and orientation.
- Study the response of DM halos to the presence of matter (Adiabatic contraction).
- Paper

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