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Evolution of dark matter haloes in CIELO simulations

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Resumen / Este artículo analiza la evolución de las propiedades de los halos de materia oscura (MO) a través del tiempo. Para este estudio usamos una submuestra de halos tipo 'Vía Láctea' pertenecientes al Proyecto CIELO (ChemodynamIcal propertiEs of gaLaxies and the cOsmic web). Este projecto, que consiste en simulaciones del tipo zoom-ins, apunta a estudiar la formación de galaxias en distintos entornos. Analizamos la estructura de los halos de MO en las zonas internas y externas. En particular, estudiamos el efecto sobre las formas y el proceso de ensamblaje.

Abstract / This article analyze the dark matter (dm) halo evolution through time. For this study we use a Milky Way like haloes subsample from CIELO (ChemodynamIcal propertiEs of gaLaxies and the cOsmic web) project. This project aims at studying the formation of galaxies in different environments using zoom-ins simulations. We analyse the relation of the properties of the dm haloes in the inner and outer regions. In particular, we inspect the effects on the halo shapes and the assembly process.

Keywords / galaxies: evolution — galaxies: kinematics and dynamics — dark matter

1. Introduction

In our current understanding of the cosmological model Λ-CDM, dark matter (dm) and dark energy are the main ingredients that drive the formation and evolution of the cosmic structures. In particular, dm haloes grow hierarchically, from the accretion of lower mass haloes (e.g. Ghigna et al., 1998; Springel et al., 2008). The theoretical predictions for their structures, have been studied extensively using cosmological simulations.

N-body simulations have shown that haloes present triaxial shapes while being more prolate in the inner regions (e.g. Frenk et al., 1988; Jing & Suto, 2002; Allgood, 2005; Stadel et al., 2009). Cosmological hydrodynamical simulations have proven to be of great help to investigate the effects of baryons on different properties of the dm haloes (e.g. Tissera & Dominguez-Tenreiro, 1998; Kazantzidis et al., 2004; Zavala et al., 2016; Zhu et al., 2017; Chua et al., 2019; Cataldi et al., 2020).

The observational determination of the shapes of dm haloes is a challenging task. In the case of the Milky Way (MW), the shape constraints often rely on the kinematics of stars, which include the proper motions of hypervelocity stars (Gnedin et al., 2005) and the dynamics of stellar streams (Koposov et al., 2010). This studies show a nearly spherical halo (Ibata et al., 2001; Law et al., 2005, 2009; Law & Majewski, 2010), in agreement with numerical studies (e.g. Chua et al., 2019; Cataldi et al., 2020).

Here we use CIELO haloes to deepen previous studies (Cataldi et al., 2020; Cataldi et al., 2022) on halo shapes including now the temporal evolution of the analysed properties.

2. CIELO simulation

The Chemo-dynamIcal propertiEs of gaLaxies and the cOsmic web (CIELO) is a project aimed to study the formation of galaxies in different environment. Rodríguez et al. (2022). Simulations are performed at two resolution levels, using dm particles with masses, $m_{dm} = 1.36 \times 10^5 M_\odot\, h^{-1}$ for L12 level and $m_{dm} = 1.28 \times 10^6 M_\odot\, h^{-1}$ for L11 level. A version of GADGET-3 based on GADGET-2 (Springel & Hernquist, 2003; Springel, 2005) was used in order to run the CIELO simulation. CIELO also includes a multiphase model for the gas component metal-dependant cooling, star formation and energy feedback Type II and Type Ia Supernovae (SNII and SNIa , respectively), as described in Scannapieco et al. (2005) and Scannapieco et al. (2006).

The MW like haloes were taken from a dark matter only run of a cosmological periodic box of side length $L = 100 \mathrm{Mpc} h^{-1}$ $\Omega_0 = 0.317$, $\Omega_\Lambda = 0.6825$, $\Omega_B = 0.049$,

Oral contribution

Table 1. An overview of the main characteristics of the analyzed haloes in CIELO simulations at $z = 0$. In each row we show: the halo id, the total virial mass (M_{200}^{tot}), the total stellar and dm virial mass, (M_{200}^{star}, M_{200}^{dm}) and the virial radius (r_{200}). In bold, the halo with a recent merger.

LG1	M_{200}^{tot}	M_{200}^{star}	r_{200}
h4337	$1.37 \times 10^{12} M_{\odot}$	$6.0 \times 10^{10} M_{\odot}$	236.8kpc
h4469	$4.6 \times 10^{11} M_{\odot}$	$9.1 \times 10^{9} M_{\odot}$	166.1kpc
LG2	M_{200}^{tot}	M_{200}^{star}	r_{200}
h87	$5.1 \times 10^{11} M_{\odot}$	$4.2 \times 10^{9} M_{\odot}$	172.0kpc
h115	$3.0 \times 10^{11} M_{\odot}$	$4.8 \times 10^{9} M_{\odot}$	142.5kpc

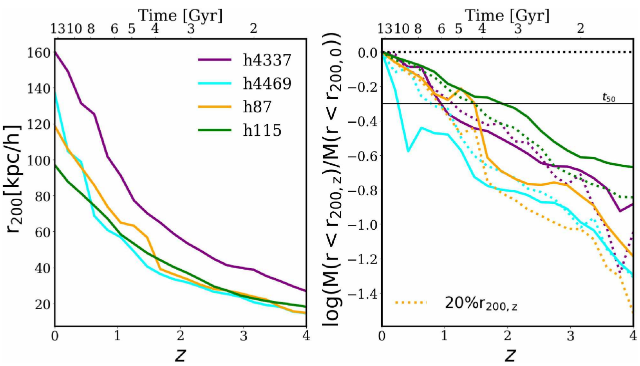

Figure 1. The virial radius r_{200} evolution (*left panel*) and the mass accretion history of dark matter (MAH,*right panel*) of the haloes vs redshift z in CIELO and TNG50 haloes. In dashed lines, the same relation within $r < 20\% r_{200}$. Black horizontal line in MAH panels is used as reference to estimate the formation time of the haloes, as the redshift at which the mass of the halo reach half of their mass (t_{50}) at $z = 0$.

$h = 0.6711$.

A first set of 40 MW-like haloes were selected from which six of them were resimulated with a dm particle resolution of $1.2 \times 10^6 \, M_{\odot} \, h^{-1}$. Table 1 summarizes the dark matter halo properties of the selected sample. Baryons were added with an initial mass of $10^{5.3} \, M_{\odot} \, h^{-1}$. Among them we select for this study two Local Group (LG1 and LG2) analogues. In particular, LG1 was previously used by Rodríguez et al. (2022) to study the evolution of infalling disc satellites and by Tapia et al. (2022) to analyse the metallicity gradients of the central galaxies.

3. Results

In Fig. 1 we show the grow history through the evolution of the virial radius r_{200} (*left panel*) and the mass accretion history (MAH, *right panel*), for redshift in the range of $0 < z < 4$. Inspecting the evolution of r_{200}, we observe two different regimes. First a slow increase of r_{200} in time, up to $z = 2$ and then, an acceleration of the increase in halo size indicating the turnaround, (e.g. Lagos et al., 2017; Zavala et al., 2016). The halo size increases over time ($0 < z < 2$) with a nearly constant velocity. Major merger events (like id halo h4469), produce a visibly change in slope at recent times.

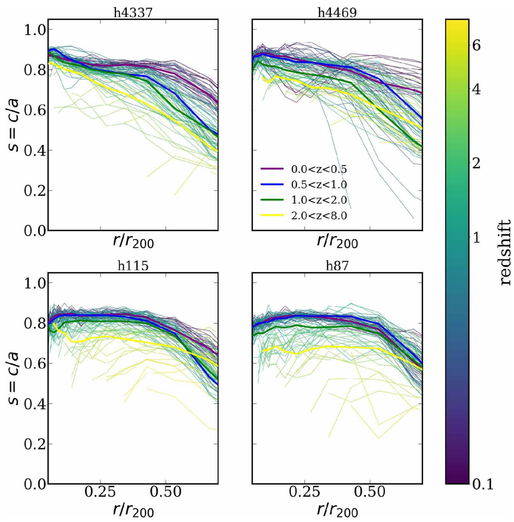

Figure 2. We show the s parameter for the CIELO haloes, versus r/r_{200}, colored by the redshift between $0 < z < 8$. We also show the median values for four subsample in redshift bins. Purple lines for $0 < z < 0.5$, blue for $0.5 < z < 1.0$, green $1.0 < z < 2.0$ and yellow lines $2.0 < z < 8.0$. In all cases for our selected haloes, the s parameter increase for inner radii and for lower redshifts.

In the *right panel* of Fig. 1, the full lines show the accretion of dm in the virial radius, and the dashed ones, inside the $20\% r_{200}$. We also show with the black horizontal line the estimated time when the halo reach half of their mass (t_{50}) at $z = 0$. The effects of merger (see h4469) are shown as a sudden peak in the curve of MAH, product of a abruptly gain or loss in mass.

The perturbations in the MAH curve, product of a merger event, con also be spotted at $20\% r_{200}$ (dashed lines in Fig. 1) but with smoother changes with respect to the outer regions of the haloes.

There is a general trend, of haloes to increase their mass within time, with haloes with minor merger reaching sooner their t_{50} with respect to the haloes with more major mergers events (h4469).

In order to dig into the evolution of halo shape, we estimate the morphology of the selected haloes. We measures the shapes using the semi-axes of the triaxial ellipsoids, a > b > c, where a, b and c are the major, intermediate and minor axis respectively of the *shape tensor* S_{ij} (e.g. Bailin & Steinmetz, 2005; Zemp et al., 2011). An iterative method is used, starting with particles selected in a spherical shell (i.e. q = s = 1 Dubinski & Carlberg, 1991; Curir et al., 1993).

To obtain $q \equiv b/a$ and $s \equiv c/a$, we diagonalized the reduce inertia tensor to compute the eingervectors and eigenvalues, as described in Tissera & Dominguez-Tenreiro (1998). Traditionally the s shape parameter has been used as a measure of halo sphericity (e.g. Allgood, 2005; Vera-Ciro et al., 2014; Chua et al., 2019).

In Fig. 2, we show that for more recent redshifts, the haloes became more spherical, as expected. At ear-

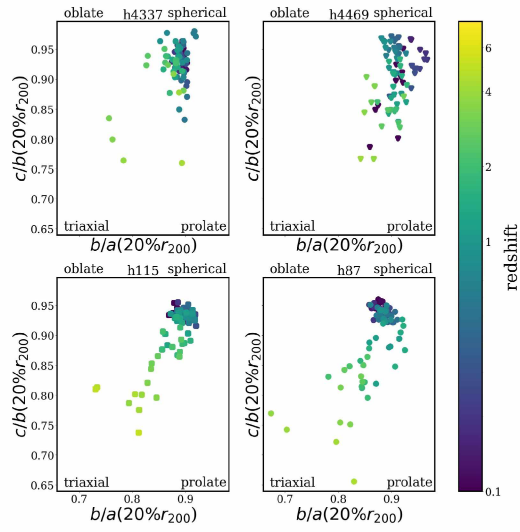

Figure 3. The inner halo axial ratios measured at $20\%r_{200}$ colored for different redshifts, for the CIELO haloes. In the upper right corner, when $b/a \sim 1.0$ and $c/b \sim 1.0$, the haloes are more spherical. We observe more spherical haloes for the four haloes at more recent redshift. The overall evolution across the shape parameter space, was for haloes evolution from triaxial to spherical configuration. The effects of recent merger events can be observed in h4469 at $z = 0$, with a backward tendency of sphericalization.

lier times shapes were more triaxial. The s parameter evolves in time increasing across all radii, with haloes more relaxed and more round. Additionally, it can be seen through redshift, the tendency to more spherical shape in central radii while more triaxial in outer regions of the halo for our halo sample, in agreement with previous works (Allgood, 2005; Chua et al., 2019; Cataldi et al., 2020).

The path to sphericalization of haloes can be seen in Fig. 3 where we show the axial ratios b/a vs c/b within $20\%r_{200}$ for dm particles. The morphology of dm haloes, although with dispersion, present a trend to be more spherical at more recent times. Interestingly, recent merger event in h4469 halo at $z \sim 0.5$ can be spot in this parameter space with a sudden shift in recent times (blue dots) to more prolate shapes.

4. Conclusions

We analyse the DM haloes shape in connection with their assembly evolution using a sub-sample of four MW-like haloes from the CIELO zoom-in simulation. Our main findings can be summarized as follow:

The concentration of the halo density profiles increases for lower redshifts and for more massive haloes. This increment in concentration, a product of the baryonic condensation in the inner regions and the relaxation of haloes, diminish with merger events. The MAH also show the effects of mergers: haloes with major merger in recent times, reach the t_{50} afterward.

We find that at more recent times, haloes become less elliptical. Also, haloes evolves to more spherical shapes in the inner regions. Mergers events across filamentary structures in the cosmic web produce less-spherical morphologies, perturbing the general trend towards spherical relaxed haloes.

As the next step, we are currently studying the relation of the halo morphology with their cosmic web environment, as well as, the dependence with the infalling material modes and directions.

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