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Understanding planes of satellites

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Abstract. Reproducing the planes of co-orbiting satellites observed in the MW and M31 so far has represented a challenge for cosmological simulations. We have developed a new method to search for kinematically-coherent groups of satellites and applied it to 2 different cosmological hydro-simulations of disc galaxies. In each simulation we have found such a group, that represents roughly half of the total satellite population and is distributed on a fairly thin plane that persists in time. These results are compatible with the MW and M31 observed planes.

Keywords. galaxies: dwarf, formation, evolution; cosmology: theory, observations

1. Introduction

The satellite galaxies of the Milky-Way (MW) show an anisotropic distribution tracing a common plane in positions which is approximately perpendicular to the Galactic disc and contains a high fraction (≈40%) of co-orbiting satellites ("VPOS", Pawlowski *et al.* 2012; Fritz *et al.* 2018). Planar configurations of satellites have been also observed in Andromeda (M31, Ibata *et al.* 2013) and claimed for in other nearby galactic systems (CenA, Müller *et al.* 2018). Subsequent studies have tried to link these observations to a cosmological context, searching for correlations between planes of satellites and large scale structure in cosmological simulations of dark matter only (e.g. Libeskind *et al.* 2005; Libeskind *et al.* 2009; Buck *et al.* 2015), and more recently also including hydrodynamics (Shao *et al.* 2016; Ahmed *et al.* 2017; Maji *et al.* 2017; Gillet *et al.*2017). Simulations predict accretion of dwarf galaxies along filaments, which introduces certain anisotropy to the phase-space distribution of the resulting satellite population. However, the strength of the anisotropy and the degree of co-orbitation found in reported simulations so far has been insufficient to explain observational data. Therefore the question remains whether the observed planes around the MW and M31 are a unique occurrence in nature, if there are certain physical conditions that may favour their emergence, or if the standard cosmological model is incomplete.

2. The simulations

We have analyzed two zoom-in cosmological hydrodynamical simulations of disc galaxies: PDEVA-5004 (Serna *et al.* 2003) and Aquarius-C (Tissera in prep; Springel *et al.*

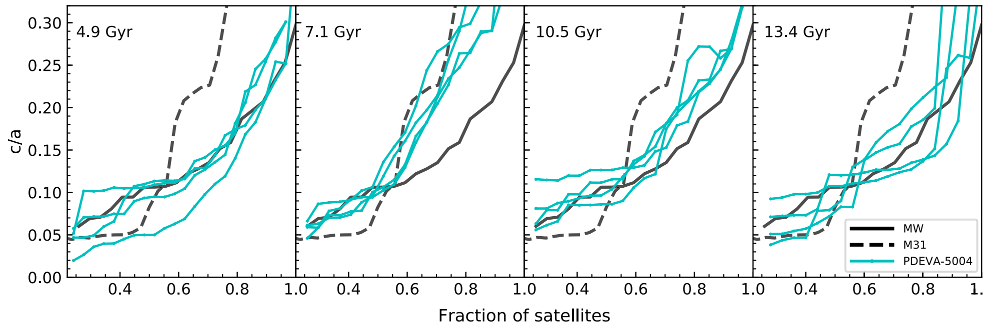

Figure 1. Variation of c/a with the fraction of satellites included in the plane-fitting. The 4 best structures found in PDEVA-5004 at the given timestep are shown.

2008). These simulations have been run with different codes and subgrid physics prescriptions (see Martínez-Serrano *et al.* 2008; Pedrosa & Tissera 2015, respectively). Both of them have produced MW-like galaxies with thin stellar discs, numerous satellites and an overall quiet merger history. Baryonic particle resolution is $3.8\times10^5 M_\odot$ and $1.3\times10^5 M_\odot$, for PDEVA-5004 and Aq-C, respectively.

Satellites have been selected at redshift $z\approx0.5$ to include objects that may end up accreted by the disc later on, and their particles have been followed back in time. We have applied a bias to account for Galactic obscuration, which prevents us from observing satellites orbiting in the plane of the disc, in an amount that is time-dependent. This leaves a maximum number of 32 satellites in PDEVA-5004, and 26 in Aq-C.

The fact that these two simulations have been run with different codes will allow to reach conclusions that are independent of simulation modelling, and instead provide insight into the influence of dynamical and cosmological fundamental processes.

3. Planes of satellites from positional analysis

We have started searching for planes in the simulations following the *4-galaxy-normal density plot* method (Pawlowski *et al.* 2013) which allows to obtain the most-prominent planar arrangements of a given satellite system. We have applied this method to each of the two systems at every timestep of the simulation. Density plots evolve with time and never reflect a totally random distribution.

For each prominent over-density in a density plot, we fit a plane to the positions of the 7 satellites that contribute the most, through the tensor of inertia method. Then, adding 1 satellite at a time by order of contribution, we iteratively fit planes to the resulting groups. To assess the quality of these prominent planar arrangements we study how the short-to-long axis ratio (c/a; thickness of the planar fit) changes as the number of satellites it includes increases. Results for PDEVA-5004 at representative timesteps are shown in Fig. 1 as an example. Note the gray solid and dashed lines, which show the same analysis for the MW and M31 galaxies, respectively†. The two galaxies seem to have very different satellite distributions: while the MW satellite system is a stable structure that remains a fairly thin (c/a<0.3) plane even when including all its satellites, less than half of M31's satellites form a thin plane, the structure breaking down when including more to the plane-fitting. PDEVA-5004 presents at every timestep both thin and populated planes, that are compatible with the observed structures. In fact, the average c/a value for the best planes fitted to 70% (90%) of the total number of satellites at each timestep is 0.15 (0.30), representing higher quality planes than those reported

† We use the same samples as in Pawlowski *et al.* (2013), with 27 and 34 satellites for the MW and M31 respectively (data from McConnachie 2012)

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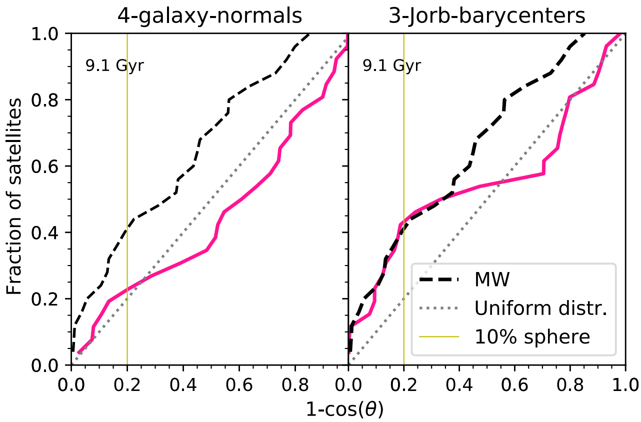

Figure 2. Fraction of co-orbiting satellites in the best structure found at a given timestep in PDEVA-5004 using the *4-galaxy-normals* and *3-Jorb-barycenters* methods.

in previous studies with hydro-simulations. However, as also occurred in those studies, these planes are not kinematically-coherent structures but transient, since they present a low ($< 20\%$, averaging over time) fraction of co-orbiting satellites‡ within the plane (left panel Fig. 2). We quantify this by measuring the angular distance on the sphere between the projection of the satellites' orbital angular momentum vectors and the normal to the plane they define $\theta(\vec{n}_{\rm plane}, \vec{J}_{\rm orb})$, and counting how many satellites fall within 36.78° (which represents 10% of the area of the sphere and has been used to quantify the number of MW satellites co-orbiting the VPOS; Fritz *et al.* 2018).

4. Finding kinematically-coherent satellites

In order to find kinematically-coherent planes like the ones observed around the MW and M31, we have developed a new method. It consists in calculating the barycenter of every combination of 3 $\vec{\rm J}_{orb}$ (Santos-Santos in prep.). These barycenters are projected on a sphere to create a density map where the over-densities or accumulation areas signal the presence of a kinematically-coherent group of satellites. When measuring now the angular distance between the center of the over-densities and the satellites' $\vec{\rm J}_{orb}$ vectors, we find at all timesteps groups where at least 40% (>50%) of satellites in PDEVA-5004 (Aq-C) are co-orbiting (Right panel Fig. 2), matching the MW value at $z = 0$ (40%).

Planes are iteratively fitted to groups of satellites as ordered by smaller angular distance between their $\vec{\rm J}_{orb}$ and the peak of the over-density. To define a persistent group of kinematically-coherent satellites we use a criteria of choosing those that contribute most to the best planes (lowest c/a) with 40% of the satellites at each timestep. In this way, a group of 14 and 11 satellites is found for PDEVA-5004 and Aq-C, respectively. These satellites present clustered $\vec{\rm J}_{orb}$ vectors for a long period of time, which translates in a persistent plane. In particular, PDEVA-5004 (Aq-C) shows an average c/a value of 0.25 (0.14) and the group represents on average the 46% (38%) of the total number of satellites at each timestep (Fig. 3).

Interestingly, both planes are approximately polar to the galactic disc during most part of the analyzed periods in each case, with an average $\theta(\vec{n}_{\rm plane}, \vec{J}_{\rm disc})$ of 74° for PDEVA-5004 and 78° for Aq-C.

‡ Note that we do not differentiate between co-rotation and counter-rotation with the disc.

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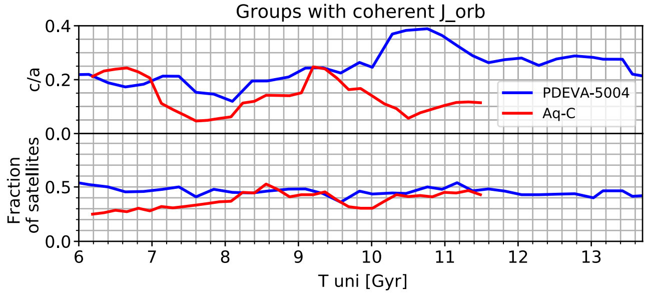

Figure 3. Variation with cosmic time of the properties (c/a and fraction of satellites involved) of the planes formed by the kinematically-coherent satellites. The analysis for Aq-C ends at 11.5 Gyr to avoid the effect of a late-time merger.

5. Possible origin of persistent planes of satellites

A common large scale structure origin, as has been suggested in previous studies, may be driving the appearance of these persistent, coherent planes. To study this we have traced back in time the baryonic particles of the coherent satellites. Although more statistics and a proper numerical quantification of these effects is needed, results suggest that material may originate at different locations of the local Cosmic Web at high redshift, but as the system evolves and mass collapses, a high fraction of satellites follow the main directions of this collapse, gaining a common dynamics (see Libeskind *et al.* 2015). For example, in Aq-C mass collapses to a wall in which the galaxy is embedded. In addition, an overall quiet merger history prevents the destabilization of the system and allows angular momentum conservation, what possibly favors these kinematically-coherent groups to persist in time (Santos-Santos *et al.* in prep.).

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