DETECTING TRIAXIALITY IN THE GALACTIC DARK MATTER HALO THROUGH STELLAR KINEMATICS.

II. DEPENDENCE ON NATURE DARK MATTER AND GRAVITY

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Abstract

Recent studies have presented evidence that the Milky Way global potential may be non-spherical. In this case, the assembling process of the Galaxy may have left long-lasting stellar halo kinematic fossils due to the shape of the dark matter halo, potentially originated by orbital resonances. We further investigate such a possibility, now considering potential models further away from ΛCDM halos, like scalar field dark matter halos and Modified Newtonian Dynamics (MOND), and including several other factors that may mimic the emergence and permanence of kinematic groups, such as a spherical and triaxial halo with an embedded disk potential. We find that regardless of the density profile (DM nature), kinematic groups only appear in the presence of a triaxial halo potential. For the case of a MOND-like gravity theory no kinematic structure is present. We conclude that the detection of these kinematic stellar groups could confirm the predicted triaxiality of dark halos in cosmological galaxy formation scenarios.

Key words: Galaxy: halo – Galaxy: kinematics and dynamics

1. INTRODUCTION

The ΛCDM scenario is considered the standard model in cosmology because it self-consistently incorporates many large scale properties of the universe. An intrinsic feature of this scenario is the hypothesis of the existence of cold dark matter (CDM) particles required to explain the cosmic structure formation. The ΛCDM model is also able to make predictions on galactic scales, i.e., relating the process of galaxy formation with the internal properties of galaxies, triggering a vivid debate in the astronomical community (e.g., White & Rees 1978; Kauffmann et al. 1993; Moore 1994; Ghigna et al. 1998; van den Bosch 1998; Klypin et al. 1999; Moore et al. 1999; Avila-Reese 2006; Gnedin et al. 2006; Pizzagno et al. 2007; Valenzuela et al. 2007; Governato et al. 2012).

Cosmological simulations have shown that the formation of galactic-size dark matter halos occurs through the hierarchical assembly of CDM structures (Kauffmann 1993; Klypin et al. 1999; Moore et al. 1999), where small systems form first and then merge together to form more massive ones. This process leads to halos with a strongly triaxial shape (Allgood et al. 2006; Vera-Ciro et al. 2011).

Therefore, the possible detection of the triaxiality of the dark matter halos would be of great importance for these galactic evolution and formation theories as it would confirm one of their most intrinsic predictions.

In Paper I (Rojas-Niño et al. 2012), we introduced a new strategy in order to detect triaxiality in the Milky Way halo, in addition to those commonly discussed in the literature (Jing & Suto 2002; Gnedin et al. 2005; Zentner et al. 2005; Steffen & Valenzuela 2008; Law et al. 2009; Peñarrubia et al. 2009; Loebman et al. 2012; Lux et al. 2012; Valluri et al. 2012; Debattista et al. 2013; Deg & Widrow 2013; Valenzuela et al. 2014; Vera-Ciro et al. 2014). In a more recent paper, Loebman et al. (2014) solved the Jeans equation to constrain the shape and distribution of the dark matter halo within the Milky Way and found that the solution is consistent with an oblate halo. The former method is very promising, although it has an important dependence on assumptions currently validated mostly by cosmological MW formation simulations, which are still uncertain. Our work is independent and complementary to the abovementioned research. Our strategy is based on the stellar kinematics in the Galaxy halo. The idea was to compare the orbital structure generated by a spherical halo with the orbital structure generated by a triaxial halo. The kinematic differences between both cases and their comparison with observational data could help to determine whether the Galactic halo is really triaxial. An important difference between a triaxial potential and a spherical one is that in the first case there are abundant resonant orbits, while in the second rosette orbits are dominant and have no angular preference. The presence of resonant orbits favors the formation of moving groups of stars: the kinematic groups.

In Paper I we showed that if the dark matter halo of the Milky Way possesses a triaxial shape, the assembling history of the stellar halo is able to populate the quasi-resonant orbits triggering kinematic stellar groups.

Analysis of the resulting kinematic and orbital structure may give evidence for halo triaxiality.

In Paper I we only used the gravitational potential of a Navarro–Frenk–White (NFW) dark matter halo with a density profile resulting from CDM-only simulations (Navarro et al. 1996). Regardless of the great success of the ΛCDM scenario in explaining the large scale structure of the universe, the lack of clear positive results in the attempts of direct dark matter detection have motivated the exploration of alternative models. In this way, with the purpose of testing theories other than CDM and their effects on the dynamical structure of the Galaxy, we introduce two different models for the potential, one based on modified gravity theories (modified Newtonian dynamics (MOND), specifically) and a halo model motivated by scalar field dark matter (SFDM).

The work of Milgrom (1983) is one of the most popular proposals in astrophysics regarding MOND. A common feature in this family of theories is that the only source of
gravity is baryons. In the case of the Milky Way, this implies that, for the most part, the flat disk potential is responsible for the whole amount of galactic dynamics, particularly in the stellar halo.

On the other hand, the SFDM is an alternative scenario that has recently received a lot of attention. The main hypothesis is that the nature of dark matter is determined by a fundamental scalar field that condensates to form Bose–Einstein condensate “drops” (Guzmán and Matos 2000; Magaña and Matos 2012) where these condensates represent galaxy dark matter halos. Robles & Matos (2013) consider that dark matter is a self-interacting real scalar field embedded in a thermal bath at temperature $T$ with an initial $Z_2$ symmetric potential. Due to the expansion of the universe, the temperature drops in such a way that the $Z_2$ symmetry is spontaneously broken and the field rolls down to a new minimum.

To study the galactic scale of the model, one can solve the Newtonian limit of the equation that describes a scalar field perturbation, i.e., where the field is near the minimum of the potential that describes its interaction and where the gravitational potential is locally homogeneous. For galaxies, this Newtonian approximation provides a good description, giving an exact analytic solution within the Newtonian limit. The following density profile represents halos in the condensed state or halos in a combination of excited states, $\rho = \rho_0 \sin^2(kr)/(kr)^2$, where $\rho_0$ and $k$ are fitting parameters. Efforts to include the baryonic influence on SFDM halos are necessary to have accurate comparisons with observations; however, they are still in very early stages of understanding (González-Morales et al. 2013).

An important feature of SFDM density profiles is the presence of wiggles, characteristic oscillations of scalar field configurations in excited states. This could result in some differences in the gravitational potential for a scalar field halo compared with the ΛCDM profile, possibly imprinting a signature in the stellar kinematics of the galactic stellar halo.

The aim of this paper is to generalize the results obtained in Paper I, where we only employed triaxial and spherical NFW halos. Now we carry out numerical simulations with other galactic components as a Miyamoto–Nagai disk, and a different dark matter density profile and other gravity theory as a MOND disk. Finally, for this work we also generalize the initial conditions used in Paper I.

This paper is organized as follows. In Section 2 the 3D galactic potentials used to compute orbits are briefly described. In Section 3 we introduce our numerical simulations and techniques and a strategy aimed to efficiently explore the stellar phase space accessible to a hypothetical observer; we also present the results of our numerical simulations. In Section 4 we generalize our initial condition scheme. Finally, in Section 5 we present a discussion of our results and our conclusions.

2. THE POTENTIAL MODELS

In Paper I we assumed a steady NFW (Navarro et al. 1996) triaxial dark matter halo as a proof of concept that a triaxial halo develops and preserves the abundant structure in the stellar phase space because of the resonant orbital structure. It is worth mentioning that this is also applicable to other non-spherical halo profiles (i.e., oblate, prolate). With that study we were able to produce clear features in the velocity space (i.e., halo moving groups), but we did not include any other galactic components or halo representations other than a galactic triaxial NFW profile halo.

In this paper, with the purpose of testing the generality of the results from Paper I, we have extended our studies to now include the effects of a disk and a very different triaxial halo potential. We have also explored a disk that responds to a modified law of gravity (MOND).

Our results are applicable regardless of the specific values of the gravitational potential parameters as they only depend on the triaxiality; therefore, a kinematic signature is expected either in the Milky Way or other galaxies that may have non-spherical halos. Since the best known case is the Milky Way which will have stellar kinematics observations available nearest in the future, we will consider it as our test bed system. However, we emphasize that the study does not need a detailed model of the Milky Way Galaxy.

2.1. Halo Potentials

We have implemented two intrinsically different potential halos, one as in Paper I, produced by an NFW density profile (Peñarrubia et al. 2009)

$$\Phi(x, y, z) = 2\pi G a b c \rho_0 \tau^2 \times \int_0^\infty \frac{s(\tau)}{r_s + s(\tau)} \frac{d\tau}{\sqrt{(a^2 + \tau)(b^2 + \tau)(c^2 + \tau)}}. \quad (1)$$

where $\rho_0$ is the characteristic halo density, the dimensionless quantities $a$, $b$, and $c$ are the three main axes, and $r_s$ is the radial scale. The triaxiality effect is accounted for by using elliptical coordinates where

$$s(\tau) = \frac{x^2}{a^2 + \tau} + \frac{y^2}{b^2 + \tau} + \frac{z^2}{c^2 + \tau}. \quad (2)$$

For the NFW halo, the density profile depends on the free parameters $r_s$, $\rho_0$, and the axis ratios $a$, $b$, and $c$. As in Paper I, the rotation curve is used as one of the primary observational constraints for the parameters, so we kept $r_s = 8.5$ kpc and $\rho_0 = 0.056 M_\odot$ pc$^{-3}$, both obtained assuming a maximum rotation velocity of 220 km s$^{-1}$.

For the second halo we used the density profile of a scalar field configuration (Robles & Matos 2013) and included the triaxiality using the formulae of Chandrasekhar (1969), which leads to the next gravitational potential

$$\Phi(x, y, z) = \frac{\pi G a b c \rho_0}{k^2} \times \int_0^\infty \frac{\ln(s(\tau)) - Ci(2k s(\tau))}{\sqrt{a^2 + \tau} \sqrt{b^2 + \tau} \sqrt{c^2 + \tau}} d\tau, \quad (3)$$

where $a$, $b$, and $c$ are the three main axes and $Ci$ is the cosine integral function.

For the scalar field halo we chose the parameters $k = 0.123$ kpc$^{-1}$ and $\rho_0 = 0.0196$ $M_\odot$ pc$^{-3}$ to guarantee a maximum rotation velocity of 220 km s$^{-1}$. It is worth mentioning here that with a correct selection of the parameters, the SFDM model has proved to be in good agreement with observational data at galactic scales, particularly with rotation curves; for several cases, an SFDM halo fits data even better.
than an NFW halo (see, e.g., Figures 5–8 of Martinez-Medina & Matos 2014).

2.2. Disk Potential

With the halo potential we have included a potential that simulates the Galactic disk. We considered two cases, a Miyamoto–Nagai and a Kuzmin model for a modified gravity case. With these models we performed numerical simulations in order to explore the influence of the disk on the orbital structure of the Galaxy.

2.2.1. Miyamoto–Nagai Potential

A commonly used model for the Galactic disk is the one proposed by Miyamoto & Nagai (1975),

$$\Phi(R, z) = -\frac{GM}{\sqrt{R^2 + \left(a + \sqrt{z^2 + b^2}\right)^2}}.$$  \hspace{1cm} (4)

This potential has three free parameters, $a$ and $b$ which represent the radial and vertical length scale, respectively, and $M$, the total mass of the disk. For the case of the Milky Way we adopted $a = 5.3178$ kpc, $b = 0.25$ kpc, and $M = 8.56 \times 10^{10} M_\odot$ (Allen and Santillán 1991), values that are in good agreement with observations.

2.2.2. MOND Kuzmin Disk Potential

With the purpose of searching for a difference in the orbital structure (moving groups) induced by using the typical models for the Galactic potential that assume the existence of dark matter massive triaxial halos and modified Newtonian dynamical models for the gravity, we have constructed a MOND galactic disk, as proposed by Milgrom (1983), as an alternative to the dark matter halo.

Unlike Newtonian gravity, the MOND version of the Poisson equation is nonlinear and extremely difficult to solve. However, for some mass distributions, it is possible to find the gravitational potential and a Kuzmin disk is one of these cases. The advantage of employing a Kuzmin disk is that the MOND gravitational field can be obtained from the Newtonian field (Read & Moore 2005),

$$g = g_N \sqrt{1 + \left(1 + 4a_0^2 / g_N^2 \right)^{1/2} - 2},$$  \hspace{1cm} (5)

where $a_0$ is the MOND constant, $g_N$ the Newtonian gravitational field generated by the Kuzmin disk, and $g$ is the corresponding MOND gravitational field.

Consequently, since the Miyamoto–Nagai potential reduces to a Kuzmin potential when $b = 0$, this corresponds to the case of a completely flat disk. The potential produced in this case is

$$\Phi(R, z) = -\frac{GM}{\sqrt{R^2 + (a + |z|)^2}}.$$  \hspace{1cm} (6)

Thus, $g_N$ is calculated from the Kuzmin potential first, and then we obtain $g$ with Equation (5); once we have $g$, we carry out the integration.

In the next section we explore the effect of the halo and disk potential in the resulting orbital structure.

3. NUMERICAL TEST PARTICLE SIMULATIONS

Our physical system consists of test particles moving under the influence of a fixed gravitational potential, which is the superposition of different galactic components as described in the sections above. The temporal evolution of the system is solved using the Bulirsch–Stoer method (Press et al. 1992) which works best when following motion in smooth gravitational fields. Using this tool, we follow the evolution of $x(t)$, $y(t)$, and $z(t)$ for each particle by integrating the equations of motion numerically. As shown in Paper I, the orbital analysis is performed in the velocity space focusing on the kinematic projections $v_x$–$v_z$ by means of an orbital classification. For this purpose we apply the spectral method by Carpintero & Aguilar (1998) that automatically classifies an orbit, distinguishing it between a regular and an irregular one. It can also identify loop, box, and other resonant orbits, as well as high order resonances.

In our previous work we saw that for a triaxial halo, resonances trigger kinematic stellar structure in the case of single accretion events and also when the potential is populated in a stochastic way trying to mimic the stellar halo assembly history.
In order to generalize the results seen in Paper I, we follow two approaches to generate the initial setups. With the first one, used in the previous paper, we choose the observation point in advance. The particles are placed randomly around this point with velocities ranging between zero and the local escape velocity. This setup will mimic the contribution of many accretion events with different orientations and energies, but keeping only bounded orbits.

This method has proven efficient in exploring the available phase space, as will be confirmed in the next sections when using more general initial conditions. This is because a star that falls into a resonance will return to the neighborhood of the observation point; therefore, we are focusing on orbits that the artificial observer will detect. The process produces persisting kinematic groups at the velocities around resonances because irregular and open orbits will almost never return. In contrast, a non-resonant region will present nearly evenly distributed types of orbits as a result of phase mixing, and also non-kinematic groups after some mixing timescales. This method increases our particle statistics without the use of high computational times.

### 3.1. Triaxial Halo With Disk

The observation neighborhood is defined as a sphere 1 kpc in radius and is centered at the given observation point, in this case \((x = 15 \text{ kpc}, y = 0, z = 0)\). We set \(2 \times 10^6\) stars randomly distributed inside this sphere with velocities ranging between zero and the escape velocity. Because we are focusing in the stellar halo, stars generated with \(v_z \approx 0\) \((v_z/v_t < \tan 10^\circ)\) are removed from the initial conditions. These stars will move close to the \(X-Y\) plane, remaining in this plane all along the simulation, and will always have \(v_z\) close to zero. If we populated the entire halo this orbit concentration would be compensated, with neighboring orbits thrown out from different galaxy positions. These orbits would appear in the velocity plane as a horizontal band, but do not form a kinematic group, as we verified with the spectral orbit classifier (Carpintero & Aguilar 1998). These particles are an artifact, as has already been explained in a previous paper (Rojas-Niño et al. 2012), and should not be confused with the ones induced by the presence of the disk (see Figure 1). The system evolves for some 12 Gyr and, at the end of this integration time, we studied the stellar kinematic distribution. This integration time...
is long enough to be comparable to the Milky Way halo evolution (Kalirai 2012). For our purpose we consider the stars that are found after the simulation inside the “artificial observer neighborhood.” In Figure 1 we show the kinematic distribution of stars at the end of the simulation for two different cases as seen by an observer at 15 kpc from the halo center. The upper panel of Figure 1 corresponds to a spherical NFW halo \( (a=1.0, b=1.0, c=1.0) \), the bottom panel corresponds to a triaxial NFW halo where, in order to generalize the results of Paper I, we adopt the same values for the axis ratios \( (a=1.47, b=1.22, c=0.98) \), consistent with cosmological simulations (Jing & Suto 2002; Vera-Ciro et al. 2011).

Both cases contain a Miyamoto–Nagai disk as described in Section 2.2.1. The Miyamoto–Nagai disk is axisymmetric, which is not necessarily true in the presence of a triaxial halo, since the potential of the latter could deform the disk. However, this does not affect the results because an elliptical disk aligned with the major axis of the halo only reinforces the kinematic signature of triaxiality. Note that the only structure that appears in the first case is a band close to \( v_z = 0 \), corresponding to the stars moving in the \( X-Y \) plane. As explained in Paper I, although these orbits would appear in the velocity plane as a horizontal band, they do not form a kinematic group. In the second case we can observe symmetrical bands at \( v_z \approx \pm 80 \text{ km s}^{-1} \). This figure shows a clear difference between both cases. The symmetrical bands, associated with resonant orbits, would be evidence for the presence of a triaxial halo.

### 3.1.1. Changing the Axes

The previous choice of axes for the triaxial dark matter halo allows us to compare our results with those in Paper I. Now we change the axis ratios \( (a=1.47, b=0.97, c=0.48) \) and orientate the disk and the dark matter halo according to the halo model that better fits the Sagittarius stream (Law et al. 2009). In this way, the minor and major axes...
lie in the galactic plane with the intermediate axis perpendicular to the disk; with the new values of the axes we obtain $b_p/a_p = 0.83$ and $c_p/a_p = 0.67$, corresponding to the axis ratios of the potential.

Figure 2 shows the result of this experiment, with an orientation of the axes different from those mentioned above but motivated by observational constraints. The track of the halo triaxiality is even more visible for this particular orientation of the axes different from those mentioned above.

3.2. **Kuzmin Disk With MOND**

In this section we describe the numerical simulations carried out considering a Kuzmin disk within the MOND theory (Milgrom 1983) as an alternative to dark matter.

In this theory, dark matter does not exist at all. Instead, it is proposed that Newtonian dynamics should be modified to explain the observations. In the MOND version, the gravity law has a more general form,

$$\mu \left( \frac{g}{a_0} \right) g = \frac{GM}{r^2},$$

(7)

where $a_0$ is a universal constant that determines the transition between the regime of the strong and weak fields, and its value is approximately $1.2 \times 10^{-10}$ m s$^{-2}$. The function $\mu(x)$ is not determined in this theory, but must satisfy the condition $\mu(x) \approx 1$ when $x \gg 1$ and $\mu(x) \approx x$ when $x \ll 1$.

In the outer part of the galaxies, the weak field regime is valid and $\mu(x) \approx x$. This leads to a rotation velocity of $v = (GMA_0)^{1/2}$, therefore, the rotation velocity in the outer part of galaxies is independent of $r$. Thus, MOND can explain the flattening of the rotation curve at great distances from the center of the galaxies without invoking the existence of dark matter. This is its main achievement and one of the reasons it was born.

However, MOND also has several problems, especially in, e.g., correctly describing the dynamics of galaxy clusters (Sanders 1999; Clowe et al. 2004). Nevertheless, despite the fact that dark matter is the most accepted theory, MOND (or modifications of it) has not been totally ruled out.

For this purpose we construct the initial conditions in the same way as in the cases of the triaxial halo and a disk: $2 \times 10^6$ stars within a sphere 1 kpc in radius, but with the observer neighborhood centered at $(x = 15 \text{ kpc}, y = 0, z = 0)$, with random velocities between zero and the escape velocity.

We analyze the resulting velocity space after an integration time of 12 Gyr. Figure 3 shows the kinematic structure for this case. An area of higher density in velocity space is formed, but without the symmetric bands that characterize the case of a triaxial halo.

As shown also in Figure 3, a classification of orbits gives us more information about the kinematic structure, with no presence of stellar groups and dominated by loop orbits.

Although the geometry of the kinematic structure is preserved regardless of the detailed model of the disk, we decided to repeat the calculations with a Kuzmin disk within a triaxial halo with Newtonian gravity, and found that the structure is very similar to the one shown in Figure 2, where we used a Miyamoto–Nagai disk; we show this result in Figure 4.

4. **GENERALIZED INITIAL CONDITIONS**

As described above, the initial condition setup, used in the previous sections and in Paper I, provides an observer with good kinematic accuracy, though only inside a limited vicinity, and avoids populating the entire halo with particles, ensuring a relatively low computing cost. However, this initial distribution of particles is not isotropic around the halo center and the question remains about whether or not this choice for the initial conditions has a non-negligible effect on the final kinematic structure for the triaxial dark matter halo employed in Paper I. With this in mind, we introduced a more general and complete initial condition setup, different than that described above.

In order to do this, we consider initial conditions with spherical symmetry around the halo center populating the entire simulated domain. This is done by increasing the number of particles distributed inside a sphere 25 kpc in radius centered at $(x = 0, y = 0, z = 0)$. The velocities were selected randomly between zero and the local escape velocity.

Although computationally expensive, sampling the entire halo and increasing the number of particles gave us a more conclusive mapping of the gravitational potential to establish its relationship with the distribution of stars in velocity space. The choice for the initial conditions ensures that the kinematic stellar structure is not due to the sampling, but due to the physical system.

With these new initial conditions, we now repeat the experiment of Paper I with just a triaxial NFW halo. Finally, a different density profile for the dark matter halo motivated within the SFDM model is also employed. The generation of stellar groups within these two, very different in nature, triaxial halo potentials allow us to establish its origin in the triaxiality of the halo rather than in the nature of the dark matter.
4.1. Triaxial NFW Halo

In this experiment we use the potential of Equation \(\text{(1)}\) with parameters \((a = 1.47, b = 1.22, c = 0.98)\) for the axis of the triaxial halo.

We used the generalized initial conditions described above, \(16 \times 10^6\) particles populating a sphere 25 kpc in radius centered at \((x = 0, y = 0, z = 0)\) with velocities selected randomly between zero and the local escape velocity. We selected \((a = 1.47, b = 1.22, c = 0.98)\) for the triaxial halo axes and evolved the system for 12 Gyr. Figure 5 shows the \(V_x-V_z\) projection of the velocity space at the end of the integration time as seen by a hypothetical observer placed 15 kpc from the halo center. Overdensities are distinguishable in the kinematic structure, mostly around \(V_z \approx 45\) km s\(^{-1}\) and \(V_x \approx -45\) km s\(^{-1}\). By doing a classification of orbits, one notes that these overdensities have a resonant origin and are independent of the initial conditions.

4.2. Triaxial SFDM Halo

For the triaxial halo from Equation \(\text{(3)}\) we used the generalized initial conditions described above, \(12 \times 10^6\) particles populating a sphere 25 kpc in radius centered at \((x = 0, y = 0, z = 0)\) with velocities selected randomly between zero and the local escape velocity.

We selected \((a = 1.47, b = 1.22, c = 0.98)\) for the triaxial halo axes and evolved the system for 12 Gyr. Figure 6 shows the \(V_x-V_z\) projection of the velocity space at the end of the integration time as seen by a hypothetical observer placed 8.5 kpc from the halo center.

In Figure 6 we found a horizontal structure resembling that seen in our previous experiments. We performed a simulation with the spherical case \((a = 1, b = 1, c = 1)\) for comparison and found that the velocity space is featureless and homogeneous. This suggests that the kinematic structure seen in the velocity space of the triaxial halo corresponds, again, to stars librating in the vicinity of resonances. We verified this by using the spectral orbital method of Carpintero & Aguilar (1998), finding that the most remarkable regions of the velocity space are dominated by resonant orbits.

In Figure 7 we show the \(V_x-V_y\) projection for another measure of the data but now moving the hypothetical observer to a distance of 20 kpc from the halo center. At this distance...
we found again a horizontal pattern as in the figures before, which means that the effect of triaxiality acts across the entire stellar halo. By again applying the spectral orbital method we can see that dark matter halo resonances are able to densely populate the stellar velocity space with this characteristic horizontal pattern.

5. DISCUSSION AND CONCLUSIONS

In this work we extend the orbital study of a stellar system under the influence of the gravitational potential generated by a steady triaxial dark matter halo from the spherical ones in Paper I (Rojas-Niño et al. 2012). We now have added a Milky Way-like disk to our study in order to investigate a way to separate the effects from a non-spherical halo and a disk. We have also tested a different type of dark matter halo profile based on theories of SFDM. Finally, we have included a Kuzmin disk assuming an MOND gravity theory in order to test the consequences on the orbital behavior and the possible production of moving groups.

We show that, independently of the nature of dark matter, a non-spherical shape of the Milky Way dark matter halo strongly influences the stellar halo kinematic structure, as seen from the long-lasting resonant features formed in simulations. As was pointed out in Paper I, there is an enormous difference with the spherical case, where no kinematic structure is triggered. We have also tested a different halo profile motivated by SFDM. This model presents an important difference, the presence of density wiggles produced by characteristic oscillations of scalar field configurations. We conclude that these scalar field density wiggles are unable to trigger any moving groups in the spherical case. However, in the triaxial case, this profile produces structures with the same resonant origin as in the typical NFW triaxial halos.

We also confirm that the structures seen in the velocity space for triaxial halos do not depend on the initial conditions and the effect was still present, in spite of the two different initial distribution strategies of particles used in this paper. The fact that the kinematic structure is independent of the initial conditions makes the resonant nature stronger versus an
incomplete relaxation of initial conditions. Our strategy for our initial conditions is motivated by the fact that there are not self-consistent phase space distributions for triaxial halos; it can be argued that incomplete relaxation is producing the kinematic structure reported in this paper. However, the fact that such structure is produced only in the non-spherical case, lasts for longer than the universe age, and is not altered by the stellar disk presence makes our conclusions robust.

In this work, a disk potential was introduced in order to understand whether this component is able to erase the orbital structure produced by a triaxial halo, or if the disk itself could produce moving groups in the halo that could be erroneously taken as the ones produced by a triaxial halo. With this study we learned that the disk influence is only important close to it, and that it is unable to erase the orbital structure induced by the halo in all cases we studied. In the same manner, we studied the effect of the disk on the production of kinematic structures in the halo, and we found that for an axisymmetric disk, there are no dominant resonant structures (moving groups). Although it is known that non-axisymmetric structures (such as spiral arms and bars) in the disk may produce important kinematic structures into galactic disks, their influence quickly diminishes outside the disk plane.

Finally, we have also tested the results comparing a modified gravity model (MOND) with a Kuzmin disk. In this case we find no kinematic structure at all.

In the near future we will likely be able to distinguish, for instance, satellite remnant groups originated from a single event from those associated with the dark matter halo shapes with the help of the stellar population data. Great surveys such as *Gaia*, SDSS, etc., will allow us to detect these types of kinematic groups, which could be a clear indication of the triaxiality (non-sphericity) of the Milky Way dark matter halo, and will be of great importance for the galaxy formation theories and the $\Lambda$CDM scenario.

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