An evolving Milky Way dark matter halo, the influence of the Large Magellanic Cloud.

1 Introduction

In the current cosmological paradigm about 23% of the energy and matter content of the Universe is dark matter and 1% is baryonic matter. Dark matter particles collapse gravitationally to form large structures knows as halos. In the context of the ΛCDM, where structure grows hierarchically, baryonic matter accumulates within dark matter halos, allowing galaxies to form and evolve. Therefore, galaxy formation processes are strongly related with the evolution of dark matter halos. In particular, the morphology, kinematics, dynamics of galaxies disks and satellite remnants of hierarchical processes such as streams are useful observables that help to constrain halos' properties like their total mass, density and shape.

Crucial theoretical efforts have been made to model the properties of dark matter halos. [Hernquist, 1990], Plummer, Dehnen, derived analytical expressions for the density profiles of spherical dark matter halos. Using cosmological simulations [Navarro et al., 1996, 1997] found an analytical expression for spherical dark matter profiles in a cold dark matter universe.

Nevertheless accretion of subhalos to the halos is an asymmetric process that depends on the large scale structure [Tormen et al., 1997, Colberg et al., 1999], therefore, the structure of halos should not be spherical. These have been found in cosmological N-body simulations [Barnes and Efstathiou, 1987, Frenk et al., 1988, Dubinski and Carlberg, 1991, Warren et al., 1992, Tormen et al., 1997, Thomas et al., 1998] and in more recent simulations with higher resolution, all these works agree in the fact.

In observations the shape of dark matter halos might be derived from X-rays clusters, gravitational lensing, shapes of galactic disks observations and in the spatial distribution of galaxies in groups.

In the Milky Way close satellite galaxies and globular clusters that orbit around can trace the mass and shape of the halo if the position, line of sight velocities and tangential velocities are known. Such observations have been made for several objects, allowing different research groups to constrain the mass of the Milky Way, nevertheless, there is not a consistent agreement yet.

Due to the dynamical friction satellite galaxies and globular clusters will decay over time. During this process the satellite will be destroyed leaving tidal streams as tracers of this process [Toomre and Toomre, 1972, Lynden-Bell and Lynden-Bell, 1995, Johnston et al., 1996]. These streams are observed in the Milky Way , The first disrupting satellite

Halo Shape	Author	Parameters
Spherical	Ibata et al 01	
Spherical	Law05	
Spherical	Fellhauer06	
Prolate	Helmi 04	
Oblate	Johnston05	
Oblate	MartinezDelgado07	
Triaxial	LMJ09	
Triaxial	LM	
Oblate-Triaxial	Vera-Ciro13	

Table 1: Halo Shape models derived from streams.

galaxy observed inside the Milky Way halo was the Sagittarius dwarf galaxy [Ibata et al., 1994]. Sections of streams associated with Sagittarius were observed in (ivezic00, yanny00, ibata01b). These streams segments were revealed to be connected, forming a stream spanning for more than 360 (majewsky03, piladiaz13, belokurov14), the stream have a width (> 20) (belokurov06) and it warps for more than 360. The velocity space is ($> 20km/s$) (koposov13) which suggests that the Sgr stream is dynamically hot.

With these observations several groups have attempted to reproduce the stream with N-body models 1, founding different halo shapes. From these models, the [Law and Majewski, 2010] model has been the more successful by reproducing the observed positions and velocities of the stream. Nevertheless, it's halo configuration is unusual because the major axis is perpendicular to the plane of the disk; this configuration is not favorable for the formation of the Milky Way Disk [Debattista et al., 2013].

These disagreements motivate the use of other streams to map the halo, recently [Pearson et al., 2015] used the Palomar 5 (Pal5) stream to constrain the dark matter halo of the Milky Way. The stream is 22 long and with a width of 0.7. The globular cluster is currently at the apocenter of the orbit at 23.6kpc from the Sun (Dotter et al 2011). Interestingly the potential that reproduce the morphology of Pal5 is spherical. Recent observations of Pal5 [Fritz and Kallivayalil, 2015] also suggest a spherical halo with $V_0 = 220km/s$ and $V_{20kpc} = 218km/s$. These results are in disagreement with the [Law and Majewski, 2010] model that reproduce the Sagittarius stream and also such a halo shape is uncommon in the ΛCDM paradigm.

However, all of the studies that constrain the dark matter halo using streams assume a static dark matter halo. [Buist and Helmi, 2015] claim that if the dark matter halo is changing in time misalignments on the orbit of long streams could appear.

The Milky Way is not isolated, in fact it is interacting with a massive satellite $1 \times 10^{11} M_{\odot}$ (**where this came from**), the Large Magellanic Cloud (LMC), which is in the first passage about the MW and is currently at the pericenter of the orbit at 50Kpc from the Galactic center. Such a massive satellite inside the virial radius ($R_{vir} \sim 261kpc$) of the Milky Way should be distorting the it's dark matter halo.

Due to the LMC, the dark matter halo of the Milky Way might be distorted and evolving in time. Consequently, a detailed study of the influence of the LMC on the MW dark matter halo shape is needed. Two main questions are addressed in this work: What are the evolving shape of the inner (<20kpc) and outer halo (>20kpc) and what are the torques applied to streams in the inner halo.

We use N-body simulations, which reproduce the orbital history of the Large Magellanic Cloud around the Milky Way. In these simulations the Milky Way is modeled using an spherical halo that is distorted by the Large Magellanic Cloud. In §2 we described the models used for the Large Magellanic Cloud and the Milky Way. In §**??** we explained how we derived our initial conditions that reproduce the orbital history of the Large Magellanic Cloud. In §**??** we explained the methods used to study the shape of the halos. In §**??** we present our results.

2 Numerical Methods

We set up a suite of 15 controlled N-body simulations using the public available code `Gadget2`. We have three models for the Milky Way and five models for the Large Magellanic Cloud, the detailed parameters of the models are resumed in table **??** and 3. In section 2.1 and 2.2 we discuss the motivation and observational evidence for these models. The initial conditions of the Milky Way and the Large Magellanic Cloud model were set up using the public available code `GalIC`.

In order to reproduce the actual position and velocity of the Large Magellanic Cloud with respect to the Milky Way in a first infall scenario, we integrate the orbits backwards analytically from the present position and velocity.

2.1 Milky Way models:

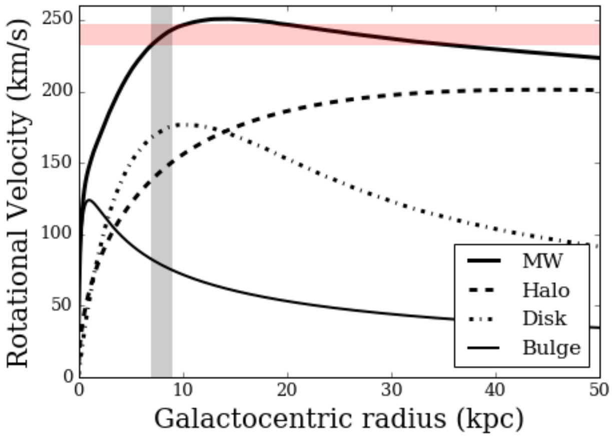
Many groups have attempted to measure the mass of the Milky Way with different approaches. `Sohn et al 13` measures the galactocentric velocity of the Leo I satellite which is moving at $196.0 \pm 19.4 km/s$. This suggest a minimum mass of $M_{vir} = 0.75 \times 10^{12} M_{\odot}$. [van der Marel et al., 2012] using the timing argument estimate that the mass of the Local Group is $3.17 \pm 0.5 \times 10^{12} M_{\odot}$ this implies that at most the mass of the Milky Way is $M_{vir} = 2 \times 10^{12} M_{\odot}$. Due to this uncertainty we model the Milky Way mass within a range of $1 - 2 \times^{10} M_{\odot}$.

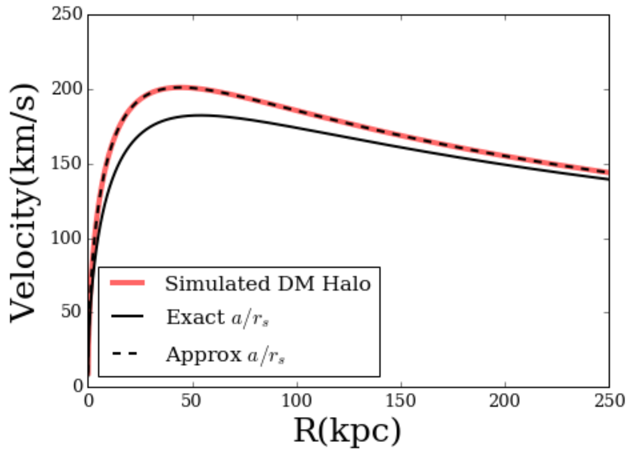
Following [**?**] each of the models of the Milky Way have a halo, a disk, and a bulge component. The halo is modeled using a Hernquist profile with the condition that the enclosed mass within r_{vir} is the same as with an NFW profile see **??**, for a detailed calculation see **??** and the appendix in [**?**]. The concentration of the halo is computed following [**?**] which derives a concentration mass relation for halos in a ΛCDM Universe. Nevertheless, with such a concentration, the disk have to be more massive in order to reproduce the observed rotation curve of the Milky Way, or the concentration parameter should be $\sim 30\%$ larger. Finally, the Disk of the Milky Way is modeled using an exponential profile disk and the Bulge with a Hernquist profile, the detailed parameters are summarized in table 2.

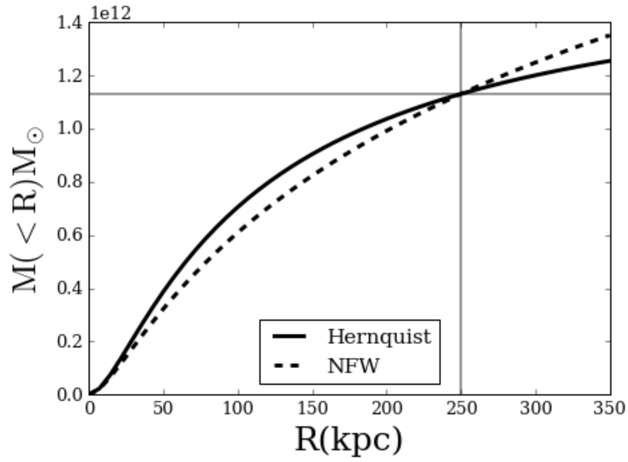
M_{vir}	R_{vir}	r_s	M_{disk}	10	M_{bulge}	c_{bulge}	M_{Halo}	c_{halo}	$R_{vir,halo}$	$M_{H,halo}$	r_h
100	261	26.47	6.5	3.5	1.0	0.7	92.5	9.918	255.82	135	53.73
150	299	31.27	5.5	3.5	1.0	0.7	143.5	9.59	294.6	211	61.3
200	329	35.15	5.0	3.5	1.0	0.7	194	9.38	325.8	289	69.2

Table 2: Summary of the Milky Way models & parameters.

$M_{200,MW} = 1.77E12 M_{\odot}$ $M_{200,halo} = 1.67E12 M_{\odot}$ $r_{200} = 250 kpc$ $a_{200} = 54.02$ $M_{200,NFW} = 1.13E12 M_{\odot}$ $r_{s,200} = 26.04 kpc$ $c_{200} = 9.6$ $c_{vir} = 12.86$







The disk and bulge rotation curves are shown bellow:

2.2 Large Magellanic Cloud models:

The mass of the LMC is also uncertain, the rotation curve peaks at $v_c = 91.7 \pm 18.8 km/s$ [?] and remains flat up to $8.7kpc$, this set a mass of $M(8.7kpc) = 1.7 \pm 1 \times 10^{10} M_{\odot}$. There is also evidence that the LMC extends up to $15kpc$ which in this case set the minimum value of the LMC at $3 \times 10^{10} M_{\odot}$. However due to the interaction with the Milky Way dark matter halo the Large Magellanic cloud have loss material. \citep{Fox14+ have estimated that the mass outside the Large Magellanic Cloud at $55kpc$ is $2 \times 10^{9} M_{\odot}$, nevertheless, the Magellanic stream has been observed up to $100kpc$ which could increase the baryonic mass up to $4 \times 10^{9} M_{\odot}$. Using baryon fraction arguments the maximum mass of the Large Magellanic Cloud at infall is $1.7 \times 10^{11} M_{\odot}$.

We use a Hernquist profile to model the dark matter halo of the Large Magellanic Cloud. The model mass and parameters are resumed in table 3. The scale length was derived in such a way that the enclosed mass $M(9kpc) = 1.3 \times 10^{10} M_{\odot}$ see Figure XX. The corresponding rotation curves of these models are shown in Fig XX.

$M_{LMC}(10^10 M\odot)$	3	5	8	10	18	25
$r_p(kpc)$	8	11	14	15	20	22.5
$r_h(kpc)$	4.91	8.97	13.75	16.43	25.13	30
$r_h(kpc)$	3.13	6.64	10.81	13.13	20.7	26.02

Table 3: Large Magellanic Clouds parameters

2.3 The Large Magellanic Cloud orbit:

2.4 Dark Matter halo shape:

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