A study of gravitational wakes by satellite galaxies in the MW halo with Auriga simulation

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CONICET

Introduction

The gravitational attraction of dark matter subhalos affects the distribution of stars in the galactic halo (Buschmann et al. 2018), which can be used to discover dark matter subhalos and even test the nature of the particles that compose it. Garavito et al. 2019, through simulations, quantified the impact of the passage of the Large Magellanic Cloud (LMC) by observing changes in the density and kinematics of the MW's stellar halo and the dark matter halo. This phenomenon was later observed in the halo of the Milky Way (MW) using GAIA data by Conroy et al. In Fushimi et al. (2024), we recently used the gravitational wake of the Magellanic Clouds to measure its dark matter halo mass. Any massive subhalo could generate this generic feature, therefore using Auriga's simulation, we explored our galaxy's satellite populations in search of wake signals in a selected population of halo stars. We report the result of the application of our techniques to a lower mass subhalo and discuss the prospects for the upcoming Vera C. Rubin Observatory data.

1. Theoretical model

To determine the mass of the dark matter subhalo, we conducted a statistical analysis using a likelihood function to compare observational/simulation data with the theoretical model proposed by Buschmann et al. 2018. The model assumes a stellar population in equilibrium, described by a Maxwell-Boltzmann distribution in phase space, which is homogeneous and time-independent. The dark matter subhalo is represented by a density profile corresponding to a Plummer sphere with a characteristic radius R_s. The gravitational potential of the subhalo induces a perturbation in the phase space distribution, obtained by solving the collisionless Boltzmann equation, resulting in:

$$f(\bar{r}, \bar{v}, M_s) = f_0(\bar{v}) \left(1 + \frac{2GM_s}{v_0^2} (\bar{v} + \bar{v}_s) \cdot \frac{1}{rv\sqrt{1+\frac{R_s^2}{r^2}}} \frac{\sqrt{1+\frac{R_s^2}{r^2}\frac{\bar{v}}{v}} - \frac{\bar{r}}{r}}{\sqrt{1+\frac{R_s^2}{r^2}} - \frac{\bar{v}\cdot\bar{r}}{rv}} \right)$$

where v_s is the subhalo velocity. The likelihood function used is:

$$p_{6D}(M_s, \theta) = e^{-N_s(M_s)} \prod_{k=1}^{N_d} f(\bar{r}_k, \bar{v}_k, M_s)$$

where N_s represents the number of theoretical stars in the study region and N_d is the number of data points.

For this analysis we performed a roto-translation of the data to write it in the reference frame centered on the perturber. The x-axis of this reference frame aligns with the direction of the dark matter subhalo's velocity, and the z-axis is perpendicular to the orbit.

2. Wake of the Magellanic Clouds

We used Gaia DR3 to create catalogs of K giants and RR Lyrae. We focused on stars 30 to 100 kpc from the galactic center, resulting in catalogs of 6058 K giants and 2446 RR Lyrae. For stars without measured radial velocities, we estimated them using normalizing flows. The distribution of data overdensity revealed two significant overdensities, one linked to the wake and another to the collective response.

Fig. 1 shows that the overdensity in the negative x direction is the wake, and its mean velocity (red arrow) is in the same direction as the CM's movement velocity (pink arrow). This indicates that the halo stars constituting this overdensity were gravitationally affected by the passage of the Magellanic Clouds.

Fig. 2 shows the estimation of the dark matter subhalo mass of the LMC, along with other mass values from the literature calculated using different methods. The error bars on our results are purely statistical and based on a restricted 1-parameter model, calculated using Markov Chain Monte Carlo (MCMC) method for the 3D (case a) and 6D information (case b).

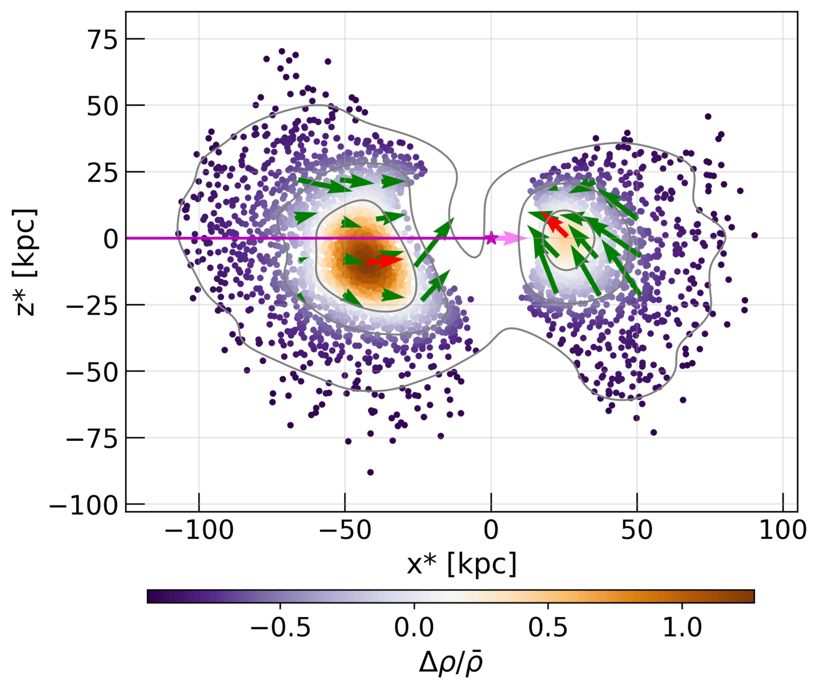

Fig. 1. Overdensity as a function of position in the x*-z* plane perpendicular to the CM's orbit. Magenta line: past orbit of the CM. Magenta star: current position of the CM. Pink arrow: CM velocity. Red arrow: mean velocity of the wake/collective. Green arrow: mean velocity of a 15 kpc bin.

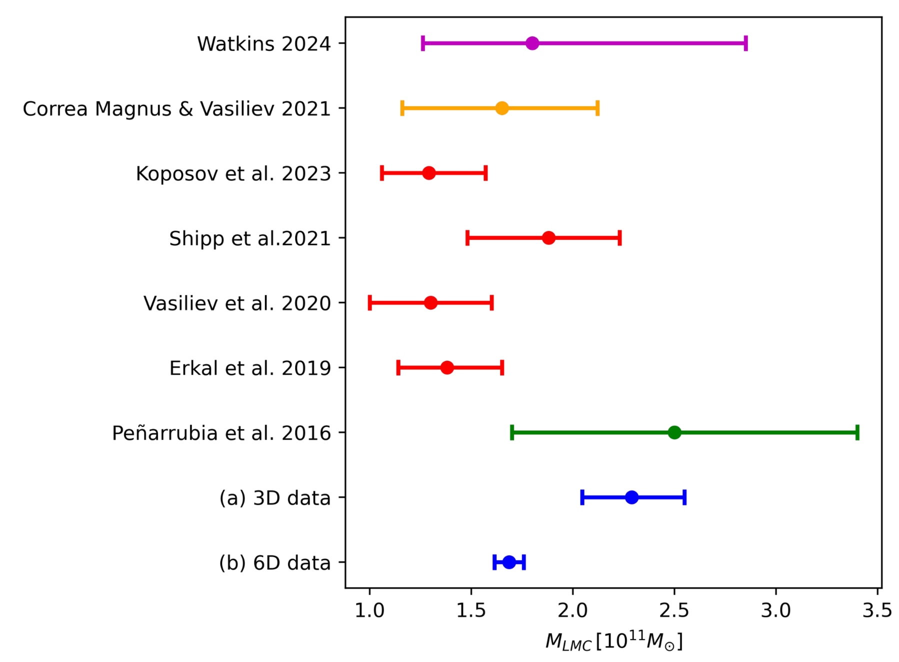

Fig 2. Estimation of the dark matter subhalo mass of the LMC. Blue lines: our results obtained from the likelihood analysis.
Case (a): $M_{LMC}=2.289^{+0.260}_{-0.240}\times10^{11}M_\odot$.
Case (b): $M_{LMC}=1.686^{+0.071}_{-0.072}\times10^{11}M_\odot$.

3. Satellite galaxies

To test the method on smaller satellite galaxies, we used halo 13 from the Auriga simulations (Grand et al. 2024) as a MW satellite. This provides fully 6D data for halo stars and satellites similar to what we expect to obtain with LSST. We selected the most massive subhalo within a radius of 100 kpc, which has the smallest velocity dispersion, that is the Subhalo 26. To obtain this velocity dispersion and the velocity of the subhalo, we selected the closest (bound) stars to this subhalo and applied a 3-sigma clipping.

Next, centered on this subhalo, we performed a roto-translation of the coordinates and velocities of the stars and defined a region of interest of 10.5 kpc around the centered of the wake. Using the data within this region in this new system, we applied the likelihood formalism to determine the subhalo dark matter mass. Our best fit value for the mass is $M_{sh26}=5.98^{+1.39}_{-1.25}\times10^8M_\odot$, meanwhile, the tabulate mass given by Auriga is $M_{sh26}=4.89\times10^8M_\odot$.

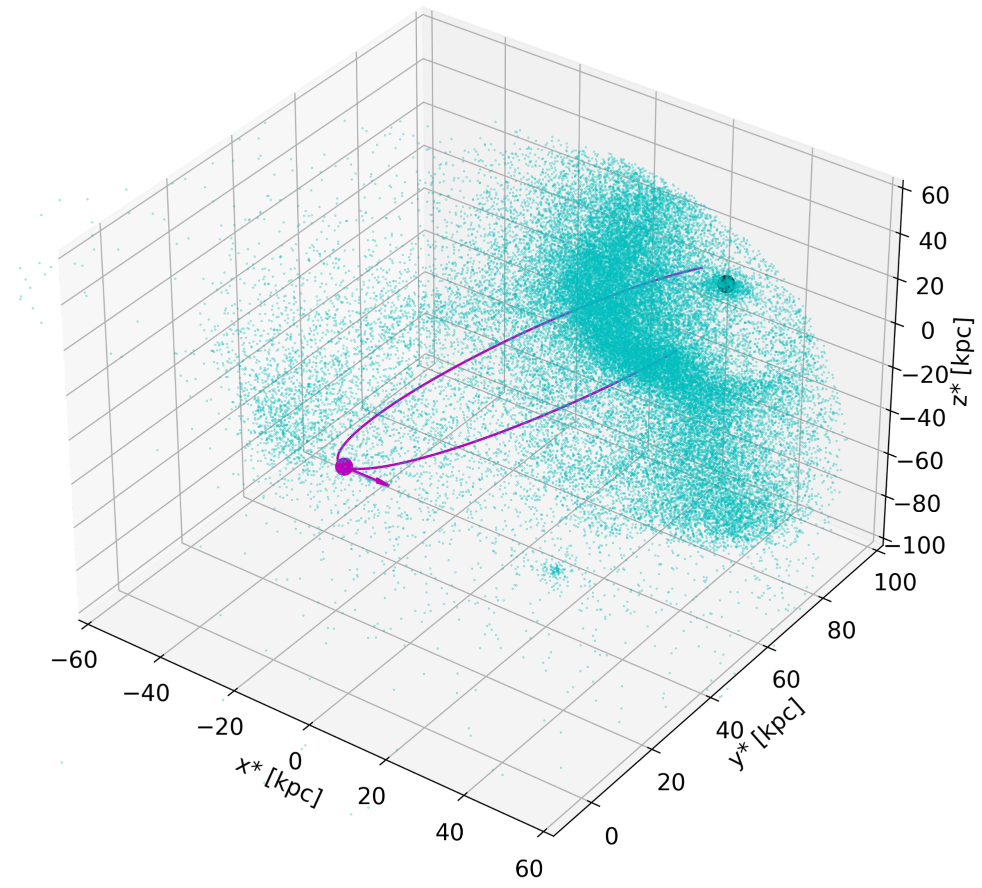

Fig. 3. Spatial distribution of the stars in the reference system centered in the subhalo. Cyan dots: stars. Black dot: MW center. Magenta line: subhalo orbit. Magenta dot: subhalo current position. Magenta arrow: subhalo current velocity.

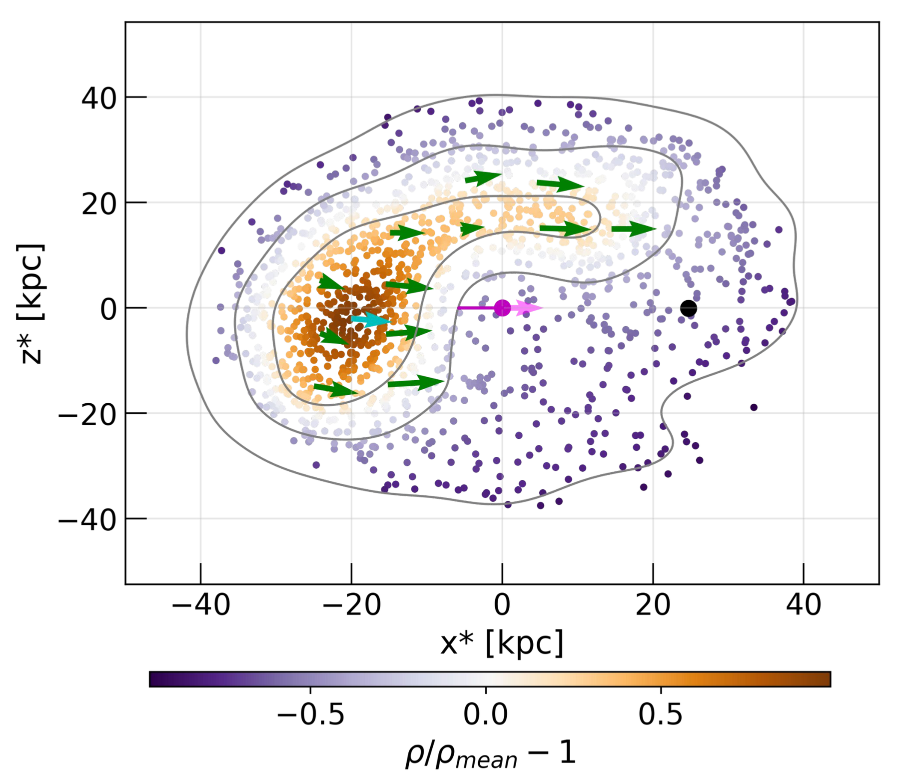

Fig. 4. Overdensity as a function of position in the x*-z* plane perpendicular to the subhalo orbit. Magenta line: past orbit of the subhalo. Magenta dot: current position of the subhalo. Pink arrow: subhalo velocity. Cyan arrow: mean velocity of the wake. Green arrow: mean velocity of a 10 kpc bin.

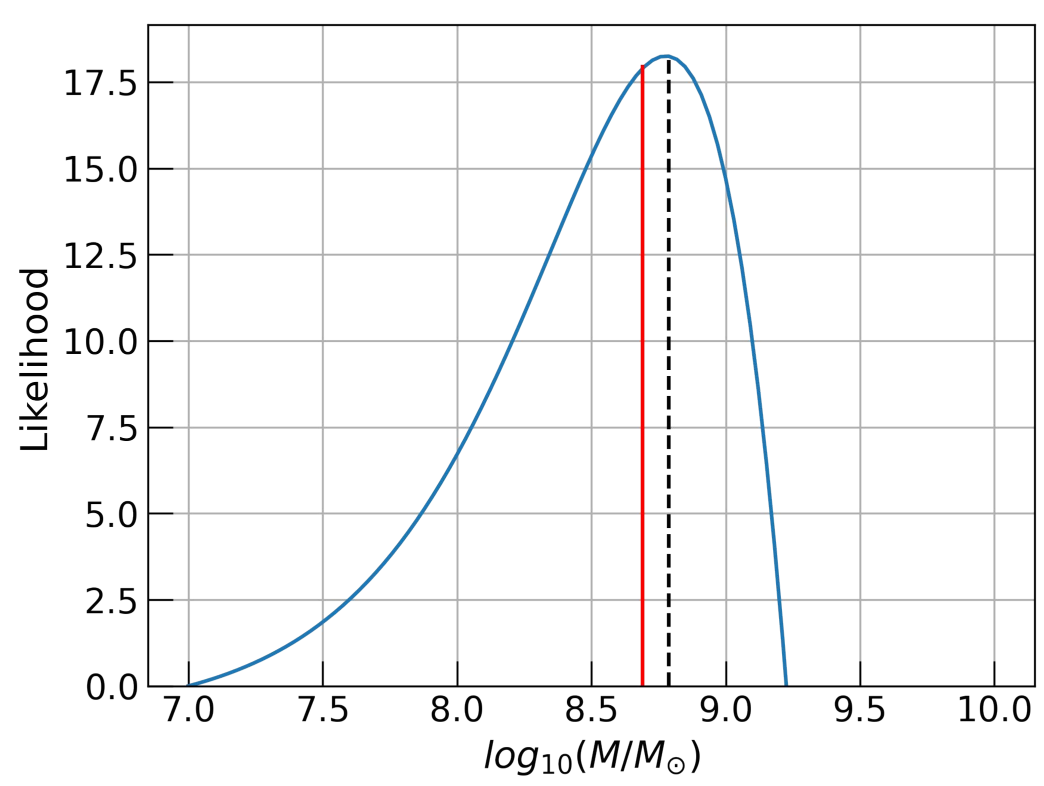

Fig. 5. Likelihood as a function of the logarithm of the subhalo mass (in units of solar mass). Dashed black line: best fit for the subhalo mass $\log_{10}(M/M_\odot)$=8.78. Red line: Auriga tabulated mass $\log_{10}(M/M_\odot)$=8.69.

Conclusions and future work

We were able to identify the overdensities associated with the wake of a subhalo in Gaia-DR3 data and simulations. We applied for the first time the model developed by Buschmann et al. to determine the masses of dark matter subhalos. We managed to estimate the dark matter halo mass of the LMC and obtained values comparable to those reported in the literature. Finally using one example from the Auriga simulations we show that is possible to measure the wake generated by an smaller mass subhalo. This is the first step to estimate the selection function for detecting wakes in the MW stellar halo and possibly detect them using LSST data.

Bibliography

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