

# Modelling the formation of the GD-1 stellar stream inside a host with a fermionic dark matter core-halo distribution.

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## ABSTRACT

**Context.** Stellar streams are a consequence of the tidal forces produced by a host galaxy on its satellites (i.e. globular clusters and dwarf spheroidals). As the self-gravity of stellar streams is almost negligible, they constitute excellent probes of the gravitational potential of the host galaxy. For this reason, some Milky Way stellar streams have been used to put constraints on the dark matter (DM) total mass and shape, under empirical DM distributions (i.e. NFW, logarithmic, etc). Within the set of non-empirical DM distributions, there exists a DM model deduced from first principles by means of the maximization of the coarse-grained entropy for self-gravitating fermions, the MEPP, after Maximum Entropy Production Principle. MEPP profiles have a rich variety of behaviours, being a large subfamily characterized by a dense core of mass  $\approx 4.1 \times 10^6 M_\odot$  (that can mimick a black hole regarding the orbits of the S-stars at Sagittario A\*) and an extended halo with the plasticity of a Burkert profile.

**Aims.** In this work we attempt to model the GD-1 stellar stream using a spherical MEPP distribution which, at the same time, is in sintony with previous fits to the S-stars.

**Methods.** For that purpose we used a genetic algorithm in order to fit both the stream orbit's initial conditions and the fermionic halo. We modelled the barionic potential with a bulge and two disks (thin and thick) with fixed parameters according to the recent literature. The stream observable is 6D phase-space data from the Gaia DR2 survey.

**Results.** We were able to find good fits for a 1D continuous subfamily of models parametrized by the fermion mass going from 56 keV/c<sup>2</sup> to 360 keV/c<sup>2</sup>, respectively corresponding to core radii going from 10<sup>3</sup> to 10 Schwarzschild radii. For smaller and larger values of the fermion mass, there is no solution that simultaneously fits the GD-1 stream and the S-stars. The solutions have a virial radius of 28 kpc and a virial mass of  $1.4 \times 10^{11} M_\odot$ , the latter being at  $2\sigma$  from previous Milky Way DM halo mass estimates using the Sagittarius stream. We do not assume the velocity of the local standard of rest ( $v_{\text{lsr}}$ ) and the result gives  $v_{\text{lsr}} \approx 244$  km/s, in agreement with recent independent estimates.

**Key words.** Galaxy: kinematics and dynamics – Galaxy: stellar streams – dark matter

## 1. Introduction

Stellar streams probe the acceleration field produced by the Milky Way (MW). This information together with barionic measurements help in making claims about the dark matter (DM) halo.

## 2. Methodology

In this section we explain the observables and methods used in this research. The exact pipeline applied in order to obtain the results and plots of this paper can be found at the following GitHub repository: [https://github.com/martinmestre/stream-fit/blob/main/pipeline\\_paper/](https://github.com/martinmestre/stream-fit/blob/main/pipeline_paper/).

### 2.1. Observables and assumed measurements

The main observables used in this project are materialized by the polynomial fits performed by Ibata et al. (2020) on the GD-1 stream using astrometry (Gaia DR2), photometry and high-

precision spectroscopy datasets together with the analysis of the STREAMFINDER algorithm. Those polinomials are the following:

$$\phi_2 = 0.008367\phi_1^3 - 0.05332\phi_1^2 - 0.07739\phi_1 - 0.02007, \quad (1)$$

$$D = -4.302\phi_1^5 - 11.54\phi_1^4 - 7.161\phi_1^3 + 5.985\phi_1^2 + 8.595\phi_1 + 10.36, \quad (2)$$

$$\tilde{\mu}_\alpha = 3.794\phi_1^3 + 9.467\phi_1^2 + 1.615\phi_1 - 7.844, \quad (3)$$

$$\mu_\delta = -1.225\phi_1^3 + 8.313\phi_1^2 + 18.68\phi_1 - 3.95, \quad (4)$$

$$v_h = 90.68\phi_1^3 + 204.5\phi_1^2 - 254.2\phi_1 - 261.5, \quad (5)$$

$$v_h = 90.68\phi_1^3 + 204.5\phi_1^2 - 254.2\phi_1 - 261.5, \quad (6)$$

with  $\phi_1$  and  $\phi_2$  in radians,  $D$  in kpc,  $\tilde{\mu}_\alpha = \mu_\alpha \cos \delta$  and  $\mu_\delta$  in mas/yr and  $v_h$  in km/s. These quantities correspond respectively to longitude and latitude in GD-1 celestial frame of reference (Koposov et al. 2010), heliocentric distance, proper motion in right ascension and declination, and heliocentric radial velocity. The domain of this polinomials is limited to  $-90 < \phi_1 [^\circ] < 10$ . To have our observable data points we sample the domain with 100 points ( $\phi_1^{(i)}$  for  $i = 1, \dots, 100$ ) and evaluate the polinomials there in order to have a complete set of observables ( $\phi_1^{(i)}$ ,

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$\phi_2^{(i)}, D^{(i)}, \tilde{\mu}_\alpha^{(i)}, \mu_\delta^{(i)}, v_h^{(i)}$ ). In one of the experiments we will consider an observable of a different nature and related to the density concentration at the origin, of size  $\lesssim 1$  milliparsec, characteristic of the fermionic halo distribution. By convention, the core radius is defined as the radius when the circular velocity reaches its first maximum. The constraint for the mass of the core of the distribution is assumed to be  $m_{\text{core}} = 3.5 \times 10^6 M_\odot$  in agreement with [Becerra-Vergara et al. \(2020, 2021\)](#); [Argüelles et al. \(2022\)](#).

The assumed measurements used in this paper are the galactocentric distance of the sun  $R_\odot = 8.122$  kpc ([GRAVITY Collaboration et al. 2018](#)) and the sun's peculiar velocity  $v_{\odot p} = (11.1, 12.24, 7.25)$  km/s ([Schönrich et al. 2010](#)).

## 2.2. The fermionic DM model

Our DM model consists of a spherical and isotropic distribution of fermions at finite temperature in hydrostatic equilibrium subject to the law of General Relativity (GR), i.e. T.O.V equations, as defined in [Argüelles et al. \(2018\)](#) with the particularity that we have made a few change of variables in order to make the numerical computation more robust. The system of equations thus obtained is as follows:

$$\frac{dv}{d\zeta} = \frac{1}{2} \left[ e^z + e^{2\zeta} \frac{P(r)}{\rho_{\text{rel}} c^2} \right] [1 - e^z]^{-1}, \quad (7)$$

$$\frac{dz}{d\zeta} = -1 + e^{(2\zeta-z)} \frac{\rho(r)}{\rho_{\text{rel}}}, \quad (8)$$

where

$$\zeta = \ln(r/R), \quad (9)$$

$$z = \ln \psi, \quad \psi = \frac{M_{\text{DM}}(r)}{M} \frac{R}{r}, \quad (10)$$

$$\rho(r) = \frac{4\rho_{\text{rel}}}{\sqrt{\pi}} \int_1^\infty \epsilon^2 [\epsilon^2 - 1]^{1/2} f(r, \epsilon) d\epsilon, \quad (11)$$

$$P(r) = \frac{4\rho_{\text{rel}} c^2}{3\sqrt{\pi}} \int_1^\infty [\epsilon^2 - 1]^{3/2} f(r, \epsilon) d\epsilon, \quad (12)$$

$$R^2 = \frac{c^2}{8\pi G \rho_{\text{rel}}}, \quad (13)$$

$$M = 4\pi R^3 \rho_{\text{rel}}, \quad (14)$$

$$\rho_{\text{rel}} = \frac{G\pi^{3/2} m^4 c^3}{h^3}, \quad (15)$$

where  $G$  is the Gravitational constant,  $c$  is the speed of light,  $h$  is the Planck constant,  $m$  is the fermion mass,  $M_{\text{DM}}(r)$  is DM mass enclosed up to radius  $r$ ,  $\rho(r)$  is the density,  $P(r)$  is the pressure and  $v(r)$  is the metric exponent, i.e. we use the convention  $g_{00} = e^{v(r)}$ . The phase-space function ( $f$ ) is given by a Fermi-Dirac distribution with energy cutoff:

$$f(r, \epsilon) = \begin{cases} \frac{1 - e^{[\epsilon - \epsilon_c(r)]/\beta(r)}}{1 + e^{[\epsilon - \alpha(r)]/\beta(r)}} & \epsilon \leq \epsilon_c(r) \\ 0 & \epsilon > \epsilon_c(r), \end{cases} \quad (16)$$

where  $\alpha(r)$  is the chemical potential (including rest mass),  $\epsilon_c(r)$  is the cutoff energy (including rest mass) and  $\beta(r)$  is the temperature variable.

The above equations should be complemented with two thermodynamic equilibrium conditions given in [Tolman \(1930\)](#) and [Klein \(1949\)](#) together with the condition of energy conservation along the geodesic given in [Merafina & Ruffini \(1989\)](#):

$$\frac{1}{\alpha} \frac{d\alpha}{dr} = \frac{1}{\beta} \frac{d\beta}{dr} = \frac{1}{\epsilon_c} \frac{d\epsilon_c}{dr} = -\frac{1}{2} \frac{dv}{dr}. \quad (17)$$

It is not possible to integrate this equations from  $r = 0$  because the right hand the change of variables  $\zeta(r)$  is divergent at the origin. Nevertheless, it is possible to reach the following approximations for the initial conditions at a value  $r_{\text{min}} \gtrsim 0$ :

$$v(r_{\text{min}}) \approx \frac{1}{6} \frac{\rho_0}{\rho_{\text{rel}}} \left[ \frac{r_{\text{min}}}{R} \right]^2 \equiv \tau, \quad (18)$$

$$\psi(r_{\text{min}}) \approx \frac{1}{3} \frac{\rho_0}{\rho_{\text{rel}}} \left[ \frac{r_{\text{min}}}{R} \right]^2 = 2\tau, \quad (19)$$

which implies

$$\frac{r_{\text{min}}}{R} = \sqrt{6\tau} \frac{\rho_{\text{rel}}}{\rho_0}, \quad (20)$$

where  $\rho_0 \equiv \rho(0)$ . It can be seen that the right hand side of Eq. 7 does not depend on the metric so we can add a constant  $v_0$  to the solution in order to satisfy a condition of continuity with the Schwarzschild metric at the border of the fermion distribution, obtaining:

$$v_0 = 2 \ln \left( \frac{\beta_b}{\beta_0} \sqrt{1 - \psi_b} \right),$$

where  $\psi_b$  and  $\beta_b$  are quantities evaluated at the border.

The system of equations thus obtained has four free parameters:  $m$ ,  $\alpha_0 = \alpha(0)$ ,  $\beta_0 = \beta(0)$ , and  $\epsilon_{c0} = \epsilon_c(0)$  but in practice we will use the following related quantities as parameters:  $m$ ,  $\beta_0$ ,  $\theta_0 = (\alpha_0 - 1)/\beta_0$ , and  $W_0 = (\epsilon_{c0} - 1)/\beta_0$ .

Equations 7-17 are solved using a PYTHON ([Van Rossum & Drake Jr 1995](#)) script<sup>1</sup> that makes use of the NumPy ([Virtanen et al. 2020](#)) and SciPy ([Harris et al. 2020](#)) libraries. We tried all the solvers available in the latter package but the only one that could properly integrate these equations was the LSODA algorithm. We used relative and absolute tolerance parameters respectively given by  $\text{rtol} = 5 \times 10^{-14}$  and  $\text{atol} = 0$ .

## 2.3. Milky Way and stream models

We model our Galaxy with a combination of the fermionic dark halo recently described, whose parameters will be determined in this work, plus a barionic component fixed and identical to the one in Model I of [Pouliasis et al. \(2017\)](#). Here we name this full Galaxy model as Fermionic-MW.

Appart from our model, for some intermediary tasks, we will make use of the Galactic model fitted by [Malhan & Ibata \(2019\)](#) which consists in the MWPotential2014 model with an axisymmetric NFW profile. This fitted model corresponds to a circular velocity at the position of the sun of  $v_c(R_\odot) = 244 \pm 4 \text{ km s}^{-1}$  and a  $z$ -flattening of the DM density distribution of  $q_p = 0.82^{+0.25}_{-0.13}$ . Here we name this Galaxy model as NFW-MW.

As GD-1 is a dynamically cold stream, with its stars keeping a large degree of correlation, its almost one-dimensional distribution in phase-space can be well approximated with the orbit of its progenitor. Another facts in this direction, are that there has not been any observation of the tidal arms feature nor of the progenitor's position ([Malhan & Ibata 2019](#); [de Boer et al. 2018](#); [Malhan et al. 2018](#); [Price-Whelan & Bonaca 2018](#)).

In the code, the orbit model is computed starting from initial conditions in spherical equatorial coordinates, ICRS frame:

<sup>1</sup> model\_def.py

$\alpha$  (RA),  $\delta$  (declination),  $D$ ,  $\tilde{\mu}_\alpha$ ,  $\mu_\delta$ ,  $v_h$ . The code uses the *Astropy* ecosystem (Astropy Collaboration et al. 2022, 2018, 2013) in order to transform the initial condition to galactocentric coordinates assuming a Galactocentric reference frame with the sun at the position  $\mathbf{x}_\odot = (-R_\odot, 0, 0)$  and a sun's velocity given by the sum of the circular velocity at the position of the sun and the sun's peculiar velocity:  $\mathbf{v}_\odot = (11.1, v_c(R_\odot) + 12.24, 7.25)$ . The circular velocity is dependent on the model and the position and given by

$$\begin{aligned} v_c^2(R_\odot) &= R_\odot \|\nabla \Phi(\mathbf{x})\|_{\mathbf{x}=\mathbf{x}_\odot} \\ &= R_\odot \|\nabla \Phi_B(\mathbf{x})\|_{\mathbf{x}=\mathbf{x}_\odot} + G \frac{M_{\text{DM}}(R_\odot)}{R_\odot}, \end{aligned} \quad (21)$$

where  $\Phi$  is the total potential,  $\Phi_B$  is the potential generated by the three barionic components and  $M_{\text{DM}}(r)$  was defined in Eq. (10). We have used the spherical symmetry property of the DM distribution in order to relate the acceleration with the enclosed mass.

A second step is to integrate the orbit forwards and backwards in time during a time interval of  $\Delta t = 0.2$  Gyr, starting in both cases from a given initial condition for the progenitor. In the next sections we will explain how this initial condition was chosen for some simulations and fitted for others. The integrator used is a Runge-Kutta of order eight (DOP853 called from *SciPy*'s `solve_ivp` function) with relative and absolute tolerance parameters respectively given by `rtol` =  $5 \times 10^{-14}$  and `atol` =  $0.5 \times 10^{-14}$ .

After having the stream's orbit integrated, we transform the orbit to both the ICRS and the GD-1 frame of coordinates. For the latter we used the `GD1Koposov10` class defined in the *Gala* package (Price-Whelan 2017; Price-Whelan et al. 2020) which uses the transformation matrix defined by Koposov et al. (2010). After these two transformation we obtain the orbit expressed in the observable variables ( $\phi_1$ ,  $\phi_2$ ,  $D$ ,  $\tilde{\mu}_\alpha$ ,  $\mu_\delta$ ,  $v_h$ ) used in Eqs. (1)-(6). Finally, we build interpolators of these variables as a function of  $\phi_1$  that will be used, together with the observed data defined in Sec. 2.1, to evaluate the following  $\chi^2$  stream function:

$$\chi_{\text{stream}}^2 = \chi_{\phi_2}^2 + \chi_D^2 + \chi_{\tilde{\mu}_\alpha}^2 + \chi_{\mu_\delta}^2 + \chi_{v_h}^2, \quad (22)$$

$$\chi_\eta^2 = \frac{1}{\sigma_\eta^2} \sum_{i=1}^{100} (\eta^{(i)} - \eta(\phi_1^{(i)}))^2, \quad (23)$$

where  $\eta$  represents each of the four corresponding independent variables ( $\phi_2$ ,  $D$ ,  $v_h$ ,  $\tilde{\mu}_\alpha$ ,  $\mu_\delta$ ) and  $\sigma_\eta$  is the average dispersion of the stream data points taken by ocular inspection from Figs. 1,3,4 of Ibata et al. (2020):  $\sigma_{\phi_2} = 0.5^\circ$ ,  $\sigma_D = 1.5$  kpc,  $\sigma_{v_h} = 10$  km/s and  $\sigma_{\tilde{\mu}_\alpha} = \sigma_\delta = 2$  mas/yr. Thus  $\chi_{\text{stream}}^2$  measures the departure of the model from the stream observations. For some fits we will also consider the departure of the model from a dark mass constraint in the core of the distribution:

$$\chi_{\text{core}}^2 = \frac{(m_c - m_{\text{core}})^2}{\sigma_m^2}, \quad (24)$$

where  $m_{\text{core}}$  was defined in Sec. 2.1,  $m_c$  is the core mass of the model, and  $\sigma_m$  was fixed in 1% of  $m_{\text{core}}$ , so sometimes we will use the following compound function:

$$\chi_{\text{full}}^2 = \chi_{\text{stream}}^2 + \chi_{\text{core}}^2. \quad (25)$$

Note that in order to compute the estimated core mass of each model,  $m$  in Eq.(24), we must find the first local maximum of the expression for the circular velocity in GR:

$$v_{\text{DM}}(r) = c \sqrt{\frac{r}{2} \frac{dv(r)}{dr}}. \quad (26)$$

## 2.4. Optimization algorithms

Our objective consists in fitting our MW model by minimizing the  $\chi^2$  function given by Eqs. (22,25). In order to do so we use two optimization algorithms for different purposes that will be explained in Sec. 3. One of them is *SciPy*'s `optimize.differential_evolution` algorithm. This genetic architecture was used with metaparameters given by `strategy="best2bin"`, `maxiter=200`, `popsiz=200`, `tol=5 \times 10^{-8}` and `atol=0`, unless otherwise stated. This method can be run in parallel with shared memory, so a convergence test was made in a cluster's node with 64 logical processors, varying the values of the metaparameters (e.g. halving and doubling the values of `maxiter` and `popsiz`, setting `strategy="best1bin"` and combinations).

The other algorithm is an implementation of the Mesh Adaptive Direct Search algorithm called NOMAD (Audet et al. 2021). The *JULIA* (Bezanson et al. 2017) wrapper of this algorithm, *NOMAD.jl*, is used through the package *Optimization.jl*. We used default values of all the metaparameters except for `maxiters=700`.

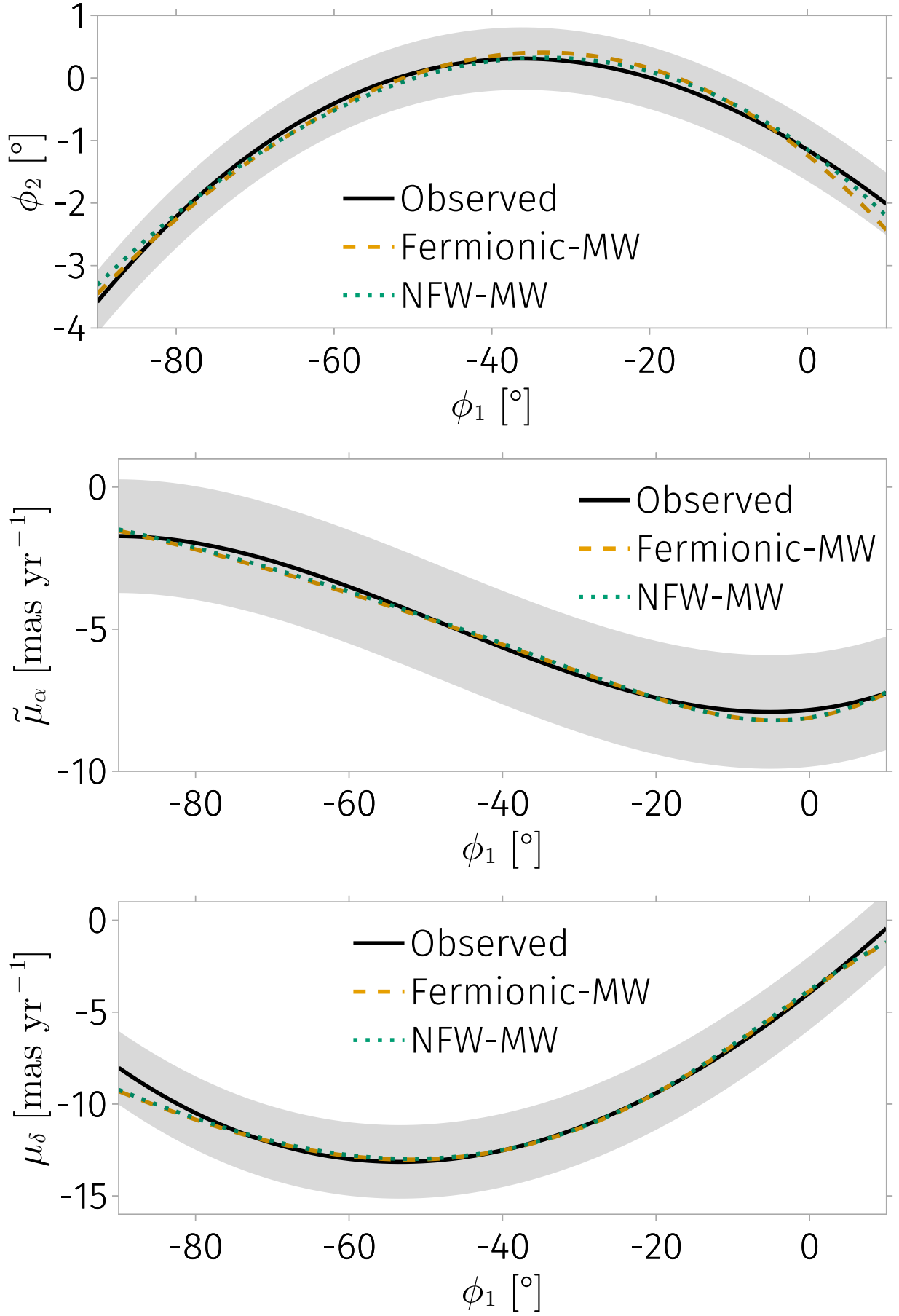
## 3. Results and discussion

### 3.1. Fitting the Fermionic-MW model

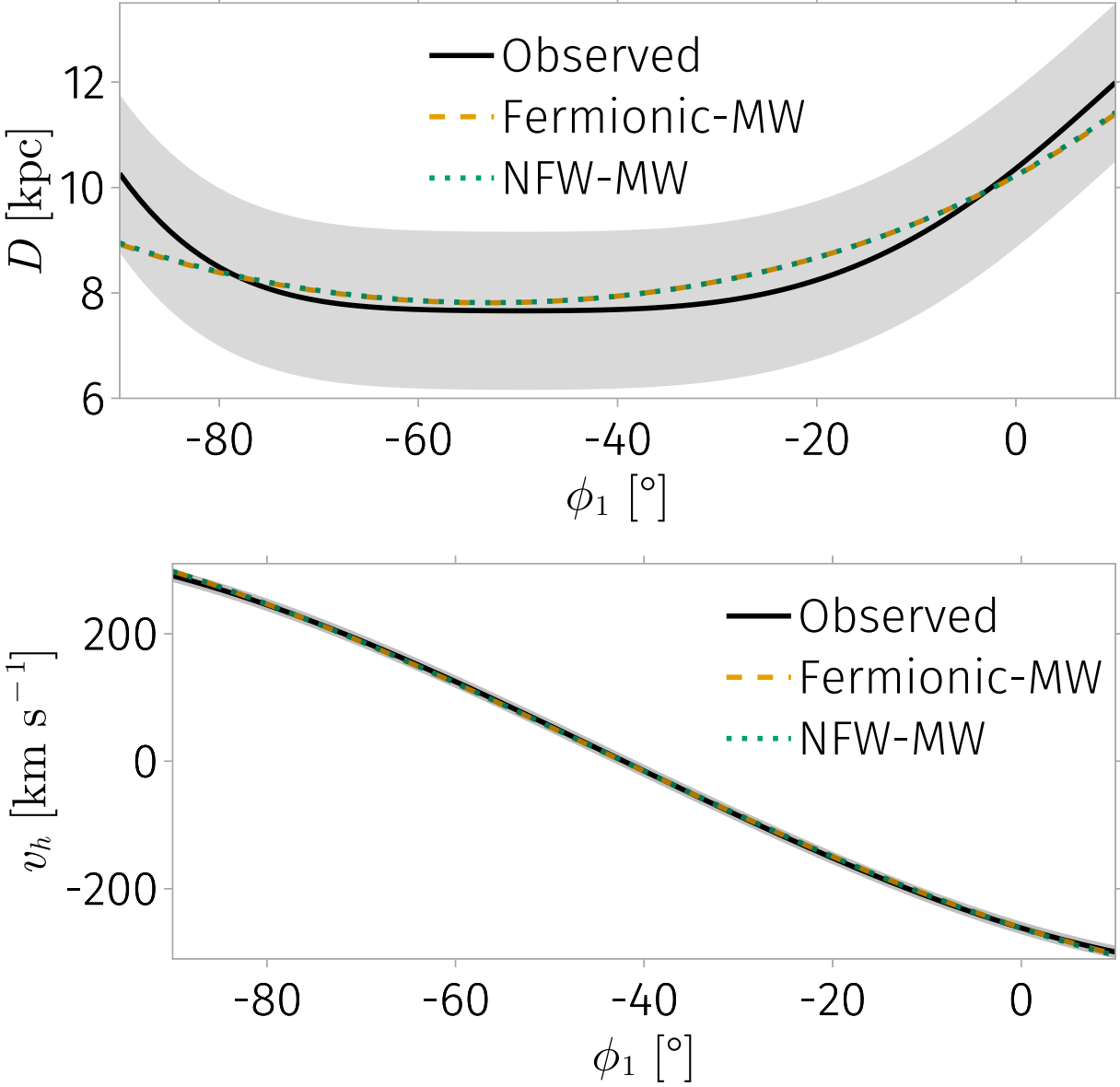
In this section we will fit both the Fermionic-MW model parameters and the initial condition (IC) of the progenitor orbit through a series of steps. Initially, we searched for a (transitory) good enough IC of the progenitor orbit for our Fermionic-MW. For that, we fitted the initial conditions in the (fixed) NFW-MW model defined in Sec. 2.3 by using the  $\chi_{\text{stream}}^2$  function defined in Eq. (22) and the genetic algorithm specified in Sec. 2.4. The genetic algorithm needs to be provided with bounds for the variables so we used boxes with a centre close to the middle point of the observable data, i.e.  $\eta^{(51)}$  that corresponds to  $\alpha = 149.24^\circ$ ,  $\delta = 36.61^\circ$ ,  $D = 7.69$  kpc,  $\tilde{\mu}_\alpha = -5.70$  mas/yr,  $\mu_\delta = -12.48$  mas/yr and  $v_h = -18.81$  km/s, and with generous sides of length equal to their absolute values (except for  $\alpha$  where we used a side of length  $\alpha/5$ ).

It should be said that the NFW-MW model was fitted by Malhan & Ibata (2019) with a set of Gaia DR2 data different from the polynomials used here. Any point along the stream is equally good as an IC. The genetic algorithm converged to a solution given approximately by  $\alpha = 149.17^\circ$ ,  $\delta = 36.51^\circ$ ,  $D = 7.95$  kpc,  $\tilde{\mu}_\alpha = -6.94$  mas/yr,  $\mu_\delta = -12.49$  mas/yr and  $v_h = -18.33$  km/s with a value of  $\chi_{\text{stream}}^2 \approx 17.52$ . The orbit that corresponds to this IC is displayed in the observable space in Fig. 1 (top:  $\phi_2$ , middle:  $\tilde{\mu}_\alpha$ , bottom:  $\mu_\delta$ ) and Fig. 2 (top:  $D$ , bottom:  $v_h$ ) with a dotted (green) line. The solid (black) line shows the corresponding observable  $\eta$  data while the shaded (grey) area demarkates the corresponding  $1\sigma_\eta$  regions.

From previous works (Argüelles et al. 2018; Argüelles et al. 2019; Krut et al. 2023) we know that the fermionic DM model parameters can be approximately grouped in two sets with different functionality. One group is formed by  $\epsilon$  and  $\beta_0$  that control the core of the distribution in the sense that for given values of  $m_{\text{core}}$  (Sec. 2.1) and  $\epsilon$ , it is possible to find a value of  $\beta_0$  in agreement; with a very small influence of the other two parameters:  $\theta_0$  and  $W_0$ . This implies a partial degeneracy between  $\epsilon$  and  $\beta_0$ . The other group is formed by  $\theta_0$  and  $W_0$ , which have small effect on the core region but determine the distribution behaviour in the halo region. Additionally, there is also an approximate degeneracy between these two variables in the sense that it is the



**Fig. 1.** Stream fits in astrometric observable space: sky position (top:  $\phi_2$ ) and proper motions (middle:  $\tilde{\mu}_\alpha$ , bottom:  $\mu_\delta$ ).



**Fig. 2.** Stream fits in observable space: photometric distance (top:  $D$ ) and spectroscopic heliocentric velocity (bottom:  $v_h$ ).

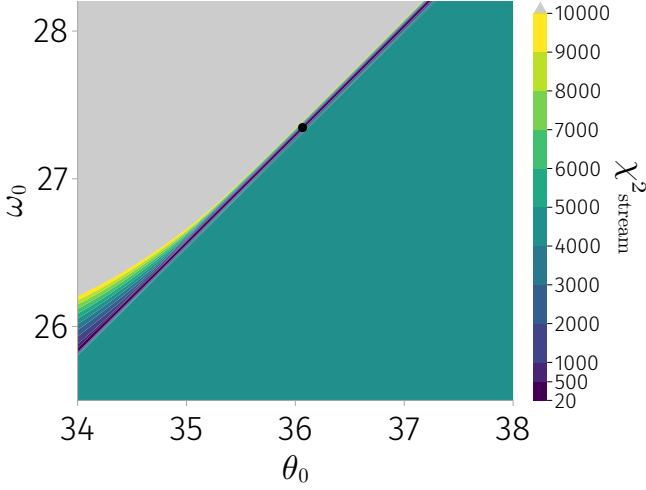
parameter  $\omega_0 = W_0 - \theta_0$  which mainly controls the halo profile, as will be further shown in this paper.

As a starting point for the parameter fit, we took the result from [Becerra-Vergara et al. \(2020\)](#) who found that for  $(\epsilon, \beta_0, \theta_0, W_0) = (56, 1.1977 \times 10^{-5}, 37.765, 66.3407)$  their MW model (DM+barions) satisfies both the geodesic motion of S2 and G2 at Sagittarius A\*, i.e.  $m_{\text{core}} = 3.5 \times 10^5 M_\odot$ , and the rotation curve from [Sofue \(2013\)](#). As a first step, we fixed values for  $\epsilon = 56$  and fixed the IC that was recently fitted for the NFW-MW model, in order to perform a genetic minimization of the  $\chi^2_{\text{full}}$  function in the window:  $(\theta_0, \omega_0, \beta_0) \in [35, 40] \times [25, 30] \times [10^{-5}, 1.5 \times 10^{-5}]$ . Using metaparameter values `maxiter=popsiz=400`, the algorithm converged to  $(\theta_0, \omega_0, \beta_0) \approx (36.0665, 27.3471, 1.25713 \times 10^{-5})$  with a value of  $\chi^2_{\text{stream}} \approx 21.9585$  and  $\chi^2_{\text{core}} \approx 1.117$ . Although the stream fit is good (as will later be shown), the associated value of the core mass was  $m_c \approx 3.537 \times 10^6 M_\odot$  which implies that there is room for improvement. We took this result to shrink the window to  $(\theta_0, \omega_0, \beta_0) \in [35, 37] \times [26, 28] \times [1.2 \times 10^{-5}, 1.3 \times 10^{-5}]$

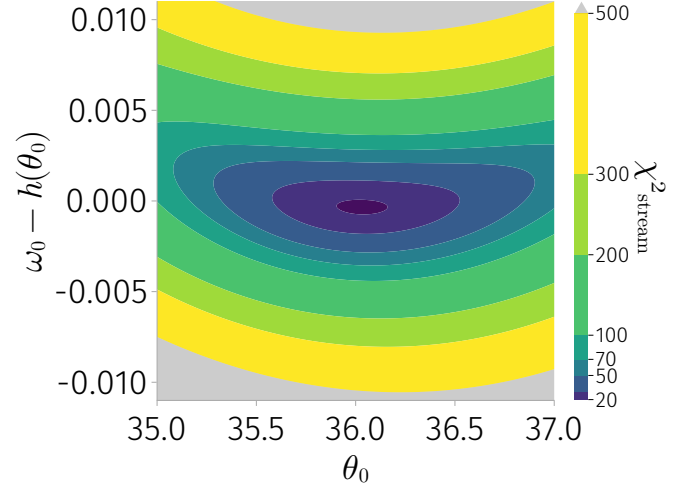
and re-run the genetic algorithm, converging to  $(\theta_0, \omega_0, \beta_0) \approx (36.0661, 27.3468, 1.25769 \times 10^{-5})$  with a value of  $\chi^2_{\text{stream}} \approx 21.9585$  and  $\chi^2_{\text{core}} \approx 1.344 \times 10^{-5}$  which corresponds to a much precise value of the core mass,  $m_c \approx 3.5001 \times 10^6 M_\odot$ . It can be noticed the great sensitivity of the core mass dependence on the model parameters because a change in the fifth significant digit of the parameters propagates to a change of in the third significant digit of  $m_c$ . Nevertheless, both solutions above are astrophysically equivalent because [Becerra-Vergara et al. \(2021\)](#) has proved that core masses in the range  $[3.5, 3.55] \times 10^6 M_\odot$  give good fits of the S-stars.

The last step consisted in fixing the Fermionic-MW parameters while floating the ICs of the orbit with the genetic scheme, with metaparameter values `maxiter=popsiz=400`, which gave us very similar to the FMW-MW case:  $\alpha = 149.21^\circ$ ,  $\delta = 36.69^\circ$ ,  $D = 7.95$  kpc,  $\tilde{\mu}_\alpha = -6.94$  mas/yr,  $\mu_\delta = -12.45$  mas/yr and  $v_h = -19.15$  km/s, with an improved value of  $\chi^2_{\text{stream}} \approx 19.32$ . The corresponding orbit is displayed in the observable space in Figs. 1-2 with a dashed (amber) line where





**Fig. 3.**  $\chi^2_{\text{stream}}$  function for  $(\epsilon, \beta_0) = (56, 1.258 \times 10^{-5})$  in the window  $(\theta_0, \omega_0) \in [34, 38] \times [25.5, 28.2]$ . The black point corresponds to our fitted solution. It can be noticed that the minimum values of the function are located along a thin and finite valley.



**Fig. 4.**  $\chi^2_{\text{stream}}$  function for  $(\epsilon, \beta_0) = (56, 1.258 \times 10^{-5})$  in the window  $(\theta_0, \omega_0 - h(\theta_0)) \in [35, 37] \times [-0.011, 0.011]$ .

it can be noticed that both the Fermionic-MW and NFW-MW models fit the GD-1 stream very well. We have not performed any statistically rigorous comparison between both models to determine which one is more consistent with the data. In fact, here we used a fixed NFW-MW model that was fitted by [Malhan & Ibata \(2019\)](#) with another set of Gaia DR2 observations, as has previously been stated.

We would like to give a glimpse of the behaviour of the  $\chi^2_{\text{stream}}$  function so we have evaluated it for fixed values of  $(\epsilon, \beta_0) = (56, 1.258 \times 10^{-5})$  in a bidimensional grid spanning the box  $(\theta_0, \omega_0) \in [34, 38] \times [25, 30]$ . Fig. 3 shows a contourplot of this grid coloured by the value of their corresponding  $\chi^2_{\text{stream}}$  and the black point corresponds to our fitted solution. It can be noticed that the minimum values of the function are located along a thin and finite valley, implying that the solution of the fitting problem is locally degenerate along a straight line in the  $(\theta_0, \omega_0)$ -plane. In spite of this, it was possible to fit the Fermionic-MW model with a quality as good as in the NFW-MW model. As an additional check, we have fitted a line to those points that satisfy  $\chi^2_{\text{stream}} < 50$  obtaining  $h(x) \approx 0.7989 + 0.7361x$ , subtracted this line to  $\omega_0$  and made a plot of  $\chi^2_{\text{stream}}$  function for  $(\epsilon, \beta_0) = (56, 1.258 \times 10^{-5})$  in the window  $(\theta_0, \omega_0 - h(\theta_0)) \in [35, 37] \times [-0.011, 0.011]$ . The result can be seen in the contour plot of Fig. 4. It is noticeable that the variance along  $\omega_0 - h(\theta_0)$  is two orders of magnitude smaller than the variance along  $\theta_0$ .

### 3.2. Virial quantities

Our dark matter solution has a finite (virial) radius of  $r_{\text{DM, vir}} = 27.4$  kpc and a virial mass of  $m_{\text{DM, vir}} = 1.4 \times 10^{11} M_{\odot}$ . The total baryon mass of our model is approximately  $m_b = 0.9 \times 10^{11} M_{\odot}$ , implying that the total virial mass amounts to  $m_{\text{vir}} = 2.3 \times 10^{11} M_{\odot}$ . This value is between the  $1\sigma$  and  $2\sigma$  errors in the estimation of the total mass of the MW at a radius of 50 kpc presented in Table 3 of [Gibbons...2014](#), which is a total mass of  $2.9 \times 10^{11} M_{\odot}$  with  $(\sigma, 2\sigma) = (0.4, 0.9) \times 10^{11} M_{\odot}$ .

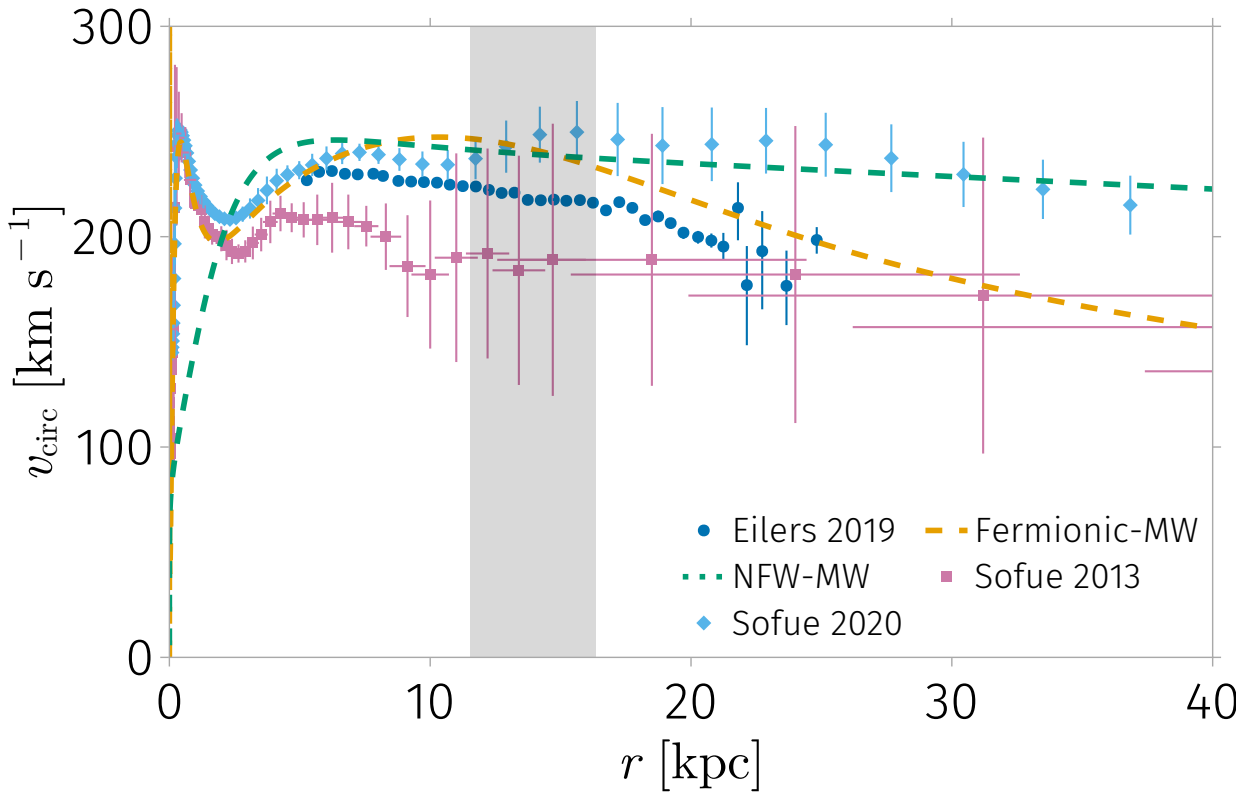
### 3.3. Rotation curves

As a way to compare our stream results with a more classical MW observable, we have computed the rotation curves for both models and plot them together with three independent rotation curve observations in Fig. 5. For the MW models we have used the same line styles and colours that were used in previous figures: dotted (green) for the NFW-MW and dashed (amber) for the Fermionic-MW. The rotation curve data is given according to the following marker styles: squares (magenta) for [Sofue \(2013\)](#), circles (blue) for [Eilers et al. \(2019\)](#) and rhombus (light-blue) for [Sofue \(2020\)](#). Note that for building this rotation observables [Sofue \(2013\)](#) assumes a value of  $(R_{\odot}, v_c(R_{\odot})) = (8 \text{ kpc}, 200 \text{ km/s})$  and [Sofue \(2020\)](#) assumes a value of  $(R_{\odot}, v_c(R_{\odot})) = (8 \text{ kpc}, 238 \text{ km/s})$ , while [Eilers et al. \(2019\)](#) assumes  $R_{\odot} = 8, 122$  kpc and a Galactocentric sun velocity  $v_{\odot} = (11.1, 245.8, 7.8) \text{ km/s}$ , in order to estimate a value of  $v_c(R_{\odot}) = 229 \pm 0.2 \text{ km/s}$ .

According to GD-1 observables, the present Galactocentric distance projected onto the plane  $z = 0$ , belongs to the interval  $11.5 \lesssim D_g \lesssim 16.4$  (kpc), displayed as a vertical shaded (grey) band in Fig. 5. Although the GD-1 stream orbit location corresponds to  $z \in [2.6, 9.7]$  kpc and thus explores the non-sphericity of the full MW models (due to baryons/NFW axisymmetry), the fact that both models approximately agree in their circular velocity values in the GD-1 region gives support to the idea of using stellar streams as Galactic accelerometers ([Ibata et al. 2016](#)). It is interesting to note a coincidence between both models in their values of circular velocity at the position of the sun as they both give a value of  $v_c(R_{\odot}) \approx 244 \text{ km/s}$ . Besides, this values are in perfect agreement with the independent estimate found by [Bovy \(2020\)](#), which are  $v_c(R_{\odot}) = 244 \pm 8 \text{ km/s}$  for  $R_{\odot} \approx 8.275$  kpc, or  $v_c(R_{\odot}) = 242 \pm 8 \text{ km/s}$  for the adopted value of  $R_{\odot}$  in the present paper.

### 3.4. Varying the fermion mass to reach more compact cores

As already mentioned, we have found a solution that is in agreement with both GD-1 data and the geodesic motion of S2 and G2 at Sagittarius A\*. But it is also true that any fermionic solution with a core mass  $m_c \approx m_{\text{core}}$  and more compact than our solution for  $m = 56 \text{ keV}$ , will also satisfy the S-stars constraint. It is interesting to find out how much compactness can be reached



**Fig. 5.** Rotation curve of MW models and observations: NFW-MW model in dotted (green), Fermionic-MW in dashed (amber), Sofue (2013) with squares (magenta), Eilers et al. (2019) with circles (blue) for Eilers et al. (2019) and Sofue (2020) with rhombus (light-blue). The region where the GD-1 stream is located at zero redshift is displayed with a vertical grey band.

while keeping simultaneously the S-stars and GD-1 constraints in the light of the new observations of the Event Horizon Telescope which suggest a compactness of the order of magnitude of 5 Schwarzschild radii. A precise ray tracing study about simulated images of the central cores of fermionic distributions is on progress, trying to put strict constraints on the minimum compactness needed so as to be in agreement with the EHT observations. In order to extend our solutions to other values of the fermion mass ( $m$ ), we used the second optimization algorithm described in Sec. 2.4 for  $\epsilon = 100, 200, 300, 360$  keV. For each fermion mass we divided a given macroscopic orthohedron in parameter space in  $20^3 = 8000$  smaller orthohedrons. Each sub-region was optimized in a parallel distributed scheme, searching for those parameters that minimize  $\chi^2_{\text{full}}$  with the NOMAD algorithm. Afterwards, we selected the global minimum by comparing the results of each distributed process. The result is that for all the fermion masses it is possible to find values of the other parameters in such a way that the GD-1 stream is fitted with the same quality as the initial ( $m = 56$ ) case. In fact, as will be shown in Fig. 6, all the solutions have the same density profile in the halo region, while their difference is limited to the compactness of the core.

## 4. Conclusions

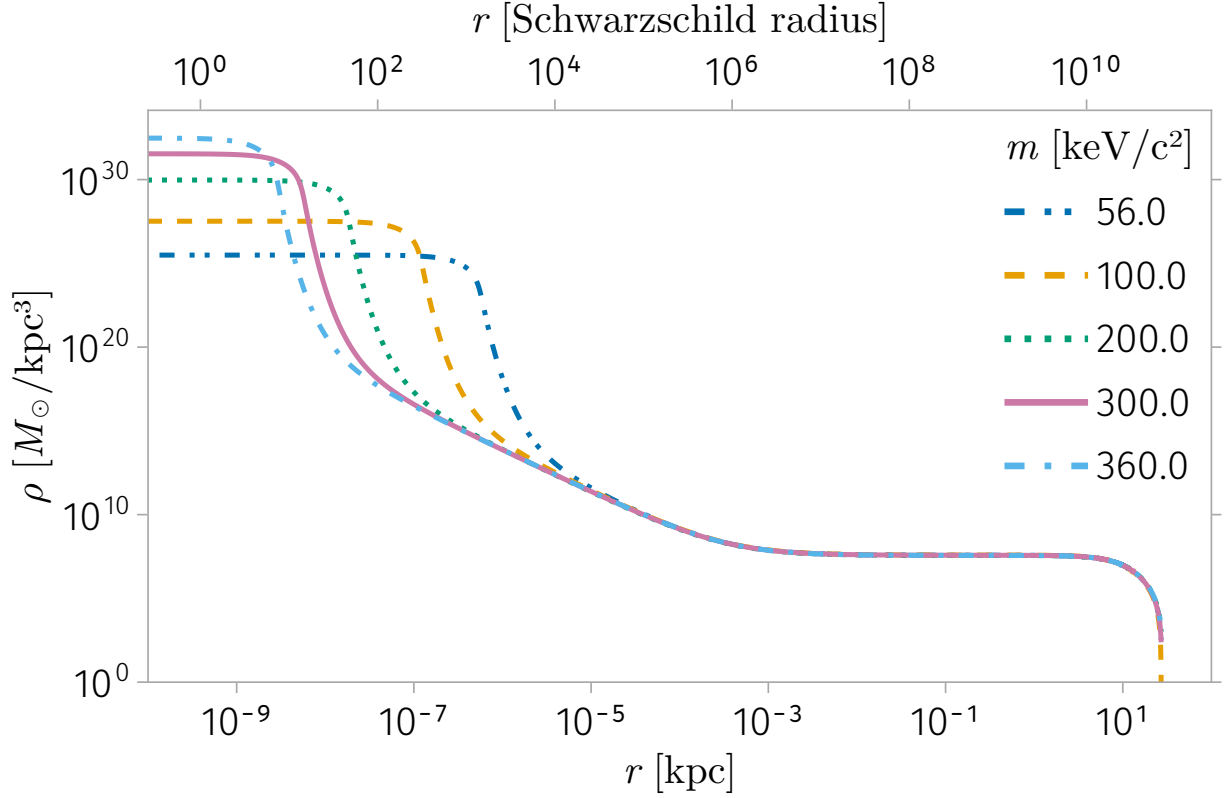
Here the conclusions.

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(<https://ccad.unc.edu.ar/>), which are part of SNCAD – MinCyT, República Argentina. This work also used computational resources from the HPC center DIRAC, funded by Instituto de Física de Buenos Aires (UBA-CONICET) and part of SNCAD-MinCyT initiative, Argentina. The figures presented in this work were made with the *AlgebraOfGraphics.jl* (<https://aog.makie.org/dev/>) and *Makie.jl* (Danisch & Krumbiegel 2021) packages. Some of our optimization results were initially guided by the use of the LN\_NELDERMEAD (Nelder & Mead 1965; Box 1965; Shere 1974) algorithm, from the *NLopt.jl* (Johnson 2007) package. In order to run JULIA in a parallel SLURM environment we made use of the *Distributed.jl* and *SlurmClusterManager.jl* packages.

## References

- Argüelles, C. R., Krut, A., Rueda, J. A., & Ruffini, R. 2019, *Physics of the Dark Universe*, 24, 100278
- Argüelles, C. R., Mestre, M. F., Becerra-Vergara, E. A., et al. 2022, *MNRAS*, 511, L35
- Argüelles, C. R., Krut, A., Rueda, J. A., & Ruffini, R. 2018, *Physics of the Dark Universe*, 21
- Astropy Collaboration, Price-Whelan, A. M., Lim, P. L., et al. 2022, *apj*, 935, 167
- Astropy Collaboration, Price-Whelan, A. M., Sipőcz, B. M., et al. 2018, *AJ*, 156, 123
- Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, *A&A*, 558, A33
- Audet, C., Digabel, S. L., Montplaisir, V. R., & Tribes, C. 2021, *NOMAD version 4: Nonlinear optimization with the MADS algorithm*
- Becerra-Vergara, E. A., Argüelles, C. R., Krut, A., Rueda, J. A., & Ruffini, R. 2020, *A&A*, 641, A34
- Becerra-Vergara, E. A., Argüelles, C. R., Krut, A., Rueda, J. A., & Ruffini, R. 2021, *MNRAS*, 505, L64
- Bezanson, J., Edelman, A., Karpinski, S., & Shah, V. B. 2017, *SIAM review*, 59, 65
- Bovy, J. 2020, *arXiv e-prints*, arXiv:2012.02169
- Box, M. J. 1965, *The Computer Journal*, 8, 42
- Danisch, S. & Krumbiegel, J. 2021, *Journal of Open Source Software*, 6, 3349



**Fig. 6.** Fermionic dark matter density profiles. The Schwarzschild radius was computed assuming a black hole mass of  $m_{\text{bh}} = 4.075 \times 10^6 M_{\odot}$ .

- de Boer, T. J. L., Belokurov, V., Koposov, S. E., et al. 2018, *Monthly Notices of the Royal Astronomical Society*, 477, 1893
- Eilers, A.-C., Hogg, D. W., Rix, H.-W., & Ness, M. K. 2019, *The Astrophysical Journal*, 871, 120
- GRAVITY Collaboration, Abuter, R., Amorim, A., et al. 2018, *A&A*, 615, L15
- Harris, C. R., Millman, K. J., van der Walt, S. J., et al. 2020, *Nature*, 585, 357
- Ibata, R., Thomas, G., Famaey, B., et al. 2020, *The Astrophysical Journal*, 891, 161
- Ibata, R. A., Lewis, G. F., & Martin, N. F. 2016, *The Astrophysical Journal*, 819, 1
- Johnson, S. G. 2007, The NLOpt nonlinear-optimization package, <https://github.com/stevengj/nlopt>
- Klein, O. 1949, *Rev. Mod. Phys.*, 21, 531
- Koposov, S. E., Rix, H.-W., & Hogg, D. W. 2010, *The Astrophysical Journal*, 712, 260
- Krut, A., Argüelles, C. R., Chavanis, P. H., Rueda, J. A., & Ruffini, R. 2023, *ApJ*, 945, 1
- Malhan, K. & Ibata, R. A. 2019, *MNRAS*, 486, 2995
- Malhan, K., Ibata, R. A., Goldman, B., et al. 2018, *Monthly Notices of the Royal Astronomical Society*, 478, 3862
- Merafina, M. & Ruffini, R. 1989, *A&A*, 221, 4
- Nelder, J. A. & Mead, R. 1965, *The Computer Journal*, 7, 308
- Pouliasis, E., Di Matteo, P., & Haywood, M. 2017, *A&A*, 598, A66
- Price-Whelan, A., Sipőcz, B., Lenz, D., et al. 2020, *adrm/gala: v1.3*
- Price-Whelan, A. M. 2017, *The Journal of Open Source Software*, 2
- Price-Whelan, A. M. & Bonaca, A. 2018, *The Astrophysical Journal Letters*, 863, L20
- Schönrich, R., Binney, J., & Dehnen, W. 2010, *Monthly Notices of the Royal Astronomical Society*, 403, 1829
- Shere, K. 1974, *Commun. ACM*, 17, 471
- Sofue, Y. 2013, *Publications of the Astronomical Society of Japan*, 65, 118
- Sofue, Y. 2020, *Galaxies*, 8
- Tolman, R. C. 1930, *Phys. Rev.*, 35, 904
- Van Rossum, G. & Drake Jr, F. L. 1995, *Python tutorial* (Centrum voor Wiskunde en Informatica Amsterdam, The Netherlands)
- Virtanen, P., Gommers, R., Oliphant, T. E., et al. 2020, *Nature Methods*, 17, 261