Evidence for keV fermion dark matter from Galactic halo kinematics

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Abstract

The enclosed mass of the Milky Way (MW) at halo scales ($\gtrsim 10\,\mathrm{kpc}$) has been recently estimated with good precision through the Galactic globular clusters kinematics data of the second Gaia data release (DR2) and the Hubble Space Telescope (HST). Further estimates are inferred from the kinematics of tidal streams. Especially, the anaylsis from the Sagittarius stream in the outer halo indicates a 'skinny Milky Way'. This implies a Keplerian behavior with a nearly constant enclosed mass when compared with results from the globular cluster kinematics, e.g. $v(r) \propto r^{-1/2}$ for $r \gtrsim 40\,\mathrm{kpc}$. We show here that these latest measurements favor clearly the Ruffini-Argüelles-Rueda (RAR) model of fermionic dark matter (DM), for a particle mass of $mc^2 = 48\,\mathrm{keV}$, over the Navarro-Frenk-White (NFW) and Burkert phenomenological DM profiles.

Keywords: Methods: numerical – Cosmology: dark matter – Galaxies: nuclei, disk, halo, structure

1. Introduction

The decomposition of the Milky Way galaxy is a topic of great interest. In its simplest form the Galaxy is composed of a Galactic core (or nucleus), a stellar bulge structure (e.g. inner and main bulge), a stellar disk and a dark matter halo. Following Sofue (2013), then a standard bulge and disk are assumed, e.g. an exponential sphere model for the inner as well as main bulge and an exponential disk model for the disk. Of greater debate is the nature of the Galactic core and halo. The standard assumption is that a BH – though an inactive one — harbors in the center of the Galaxy and the halo is described by a phenomenological DM model (e.g. NFW).

Information about the Galactic center (at sub-parsec scales) is provided through the orbital measurements of the S-cluster stars (Gillessen et al., 2009). Those stars are very well described by Keplerian orbits, indicating a compact object in the galactic center with a core mass $M_{\mathrm{core}} = 4.2 \times 10^6\,\mathrm{M}_\odot$ enclosed within the S2 star pericentre $r_{p(S2)} = 6 \times 10^{-4}\mathrm{pc}$.

The bulk of the baryonic matter dominated region ($r \approx 1\,\mathrm{pc} - 10\,\mathrm{kpc}$) is very well covered by the rotation curve of Sofue (2013). The same data provides also circular velocities far beyond $\sim 10\,\mathrm{kpc}$, though with large uncertainties what leaves a wide window for different DM models.

More recently, kinematics of Galactic globular clusters, measured by Gaia (DR2) and the Hubble Space Telescope, allowed to constraint the enclosed total mass $M(r)$ within a radius r (Watkins et al., 2018). Thus, such an analysis yields that the enclosed mass of the Milky Way is $0.22^{+0.04}_{-0.03} \times 10^{12}\,M_\odot$ at 21.1 kpc and $0.40^{+0.08}_{-0.05} \times 10^{12}\,M_\odot$ at 39.5 kpc.

Those results are very good in agreement with early estimates of the enclosed mass at 50 kpc, e.g. $0.54^{+0.02}_{-0.36} \times 10^{12}\,M_\odot$ (Wilkinson and Evans, 1999) and $0.42 \pm 0.04 \times 10^{12}\,M_\odot$ (Deason et al., 2012).

The analysis of tidal streams such as the Palomar 5 stream (Küpper et al., 2015) and the Sagittarius stream (Gibbons et al., 2014) give further constraints for the Galactic halo. The former is in good agreement with the results from globular cluster kinematics, giving $0.21 \pm 0.04 \times 10^{12}\,M_\odot$ at 19 kpc. The latter, on the other hand, gives a tight constraint of $0.41 \pm 0.04 \times 10^{12}\,M_\odot$ at the outer halo at 100 kpc.

It is important to emphasize here, that the series of measurements gives evidence for a nearly constant total MW mass beyond $\sim 40\,\mathrm{kpc}$. This implies a tight Keplerian behavior in the rotation curve, e.g. $v(r) \propto r^{-1/2}$.

We show in this paper that this Keplerian trend can be explained by fermionic dark matter including cutoff effects (Argüelles et al., 2018) in combination with a reasonable standard disk (Sofue, 2013). In contrast, phenomenological DM models, like NFW and Burkert as considered here, cannot explain the Keplerian trend and require a negligible disk component.

The outline of this paper is as following. In section 2 we explain the chosen set of constraints, recall briefly few theoretical models of galactic components, define three different MW composition scenarios and describe our method

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in fitting the MW. The results of this analysis then are presented in section 3.

2. Method

For the Galactic halo we consider here the more recent observables, inferred from globular cluster kinematics (Watkins et al., 2018) and tidal stream analysis (Küpper et al., 2015; Gibbons et al., 2014). For the baryonic matter dominated regime (e.g. $r \sim 1\,\mathrm{pc} - 10\,\mathrm{kpc}$) we take into account the rotation curve of Sofue (2013). Note, that in light of the more recent data for the Galactic halo we focus in this dataset only on the radial extent within 15 kpc. Thus, beyond 15 kpc the observables in Sofue's dataset are ignored. At sub-parsec scales we adopt the core mass $M_{\mathrm{core}} = 4.2 \times 10^6\,\mathrm{M}_\odot$, describing a Keplerian trend (e.g. $v(r) \propto r^{-1/2}$) towards the Galactic center.

In order to explain the observables along the entire radial extent of the MW ($r \sim 1 \times 10^{-4}\,\mathrm{pc} - 100\,\mathrm{kpc}$) we recall briefly few known MW components on theoretical ground.

The bulge structure is characterized by an inner and main bulge, each described by an exponential sphere model, $\rho(r)/\rho_b = \mathrm{e}^{-r/R_b}$, with a density scale ρ_b and a length scale R_b. The enclosed mass is given by $M(r) = \int_0^r 4\pi r^2 \rho(r)\,\mathrm{d}r$. The circular velocity is then simply given by

$$\frac{v^2(r)}{\sigma_b^2} = \frac{M(r)}{M_b}\frac{R_b}{r} \tag{1}$$

with $M_b = 4\pi\rho_b R_b^3$ and $\sigma_b^2 = GM_b/R_b$.

The disk component is described by an exponential disk model where the surface density follows an exponential law, $\Sigma(r)/\Sigma_d = \mathrm{e}^{-r/R_d}$. The mass is then given by $M(r) = \int_0^r 2\pi r \Sigma(r)\,\mathrm{d}r$. For this axisymmetric system the circular velocity is given by

$$\frac{v^2(y)}{\sigma_d^2} = 2y^2\left[I_0(y)K_0(y) - I_1(y)K_1(y)\right] \tag{2}$$

with the substitution $y = r/(2R_d)$. Here, $I_n(y)$ and $K_n(y)$ are the modified Bessel functions, R_d is the length scale, $M_d = 2\pi\Sigma_d R_d^2$ is the total disk mass, what represents the mass scale, and $\sigma_d^2 = GM_d/R_d$ gives the scale factor for the circular velocity.

The above bulge and disk models describe the baryonic mass distribution on intermediate scales ($r \sim 1\,\mathrm{pc} - 10\,\mathrm{kpc}$). In next, we continue to describe the Galactic core (e.g. sub-parsec) and halo ($\gtrsim 10\,\mathrm{kpc}$).

Following Argüelles et al. (2018), then there is an underlying semi-degenerate DM mass distribution composed of massive fermions, being able to explain the Galactic core and halo at the same time without spoiling the intermediate baryonic matter. This DM model, hereafter RAR model, is described by four parameters: the fermion particle mass m, the central temperature parameter β_0, the central degeneracy parameter θ_0 and the central cutoff parameter W_0. See Ruffini et al. (2015); Argüelles et al. (2018) and references therein for details about the RAR model. Note that solutions of the RAR model develop in the Galactic center a quantum core which acts as an alternative to the BH scenario in SgrA*. Here, we fix the fermion particle mass, $mc^2 = 48\,\mathrm{keV}$, and the core mass, $M_c = M_{\mathrm{core}}$. The RAR core mass $M_c \equiv M(r_c)$ is given at the core radius r_c, what is defined at the first maximum in the DM rotation curve. The given core mass allows to constraint one of the three RAR configuration parameters, e.g. β_0 such that θ_0 and W_0 remain free parameters.

For comparison, we consider alternatively a phenomenological DM model for the Galactic halo while the Galactic core is described by an independent compact object (e.g. BH) of the same core mass M_{core}. The Keplerian trend at sub-parsec scales then is given by

$$\frac{v^2(r)}{\sigma_c^2} = \frac{R}{r} \tag{3}$$

with the gravitational constant G, an arbitrary length scale R and the velocity length scale $\sigma_c^2 = GM_{\mathrm{core}}/R$.

Alternatively and for comparison, in this analysis we are interested in the NFW model given by the density (Navarro et al., 1996)

$$\frac{\rho(r)}{\rho} = \frac{1}{\frac{r}{R}\left[1 + \frac{r}{R}\right]^2} \tag{4}$$

and the Burkert model given by (Burkert, 1995)

$$\frac{\rho(r)}{\rho} = \frac{1}{\left[1 + \frac{r}{R^2}\right]\left[1 + \frac{r^2}{R^2}\right]} \tag{5}$$

Here, ρ and R are the scale factors for density and length.

In sum, we consider three scenarios:

1. RAR + baryons
2. NFW + baryons + core
3. Burkert + baryons + core

We remind that the RAR model contains information about the Galactic core while for the phenomenological DM models it is necessary to introduce additionally a compact object (e.g. BH). In all scenarios the core mass is set to $M_{\mathrm{core}} = 4.2 \times 10^6\,\mathrm{M}_\odot$, the baryonic structure (inner bulge + main bulge + disk) is described by 6 parameters (2 for each component) and the DM component by 2 parameters. In total, the mass distribution of the Milky Way depends on 8 free parameters.

Given the observables with uncertainties and the theoretical descriptions of the MW components we perform a least-square fitting by minimizing the χ^2 value,

$$\chi^2(\boldsymbol{p}) = \sum_{i=1}^{N} \frac{\left[y_i - y(r_i, \boldsymbol{p})\right]^2}{\Delta y_i} \tag{6}$$

Here, $N = 57$ is the number of constraints, y_i is the given observable at radius r_i, Δy_i is the corresponding uncertainty, $y(r_i, p)$ is the theoretical response value and $\boldsymbol{p}$ is the model parameter vector. The given constraints are a mix of velocity and mass observables. For every scenario the enclosed mass is simply a superposition of each component j,

$$M(r) = \sum_j M_j(r) \tag{7}$$

while the total circular velocity is given by

$$v^2(r) = \sum_j v_j^2(r) \tag{8}$$

Note that the set of components j is different in each scenario. Given a scenario of MW components, the aim is to vary the corresponding parameter vector $\boldsymbol{p}$ in order to find a local minimum for χ^2.

3. Results

The best-fit solutions for each scenario are presented through rotation curves and compared with observational data, see fig. 1. In all plots the selected data set of Sofue's measurements (within 15 kpc) are shown as black dots with error bars. The ignored observables, due to more recent and precise data (beyond 15 kpc), are shown as light grey dots for comparison. The more recent observables are shown as coloured diamonds with much better precision.

The observables then are compared with the total rotation curve (baryons + DM) of the best-fit solutions, plotted as a solid line. For a better understanding of the different MW components the baryonic contribution (bulge + disk) is shown as a dash-dotted line. Of more interest is the decomposition of the disk (dotted line) and the DM halo (dashed line).

The main result of this analysis is that the scenario with the fermionic DM provides here the best fit and explanation for the Galactic disk and halo. Thus, the Keplerian trend beyond ~ 40 kpc requires necessary cutoff effects (e.g. evaporation) in the DM halo. Further, the fermionic DM scenario yields a reasonable disk in mass and size.

In contrast, the NFW and Burkert scenarios cannot explain the Galactic halo, especially the Keplerian trend in the outer halo due the $\rho(r) \propto r^{-3}$ trend in the density profile. This is resembled in the worse least-square values, $\chi^2 = 17.3$ for NFW and $\chi^2 = 15.7$ for Burkert (compared with $\chi^2 = 12.6$ for the RAR scenario). Moreover, both scenarios yield a negligible disk due to the relatively wide maxima of the DM halo. See table 1 for a detailed list of the best-fit parameters for each scenario.

We expect that the Keplerian trend in the NFW and Burkert scenarios can be achieved only with a truncation (e.g. when DM density falls below a critical density value) of the phenomenological dark matter distribution. This approach would increase the DM halo in mass and size, allowing more reasonable disk parameters.

However, we want to emphasize that fermionic dark matter including cutoff effects can explain naturally the

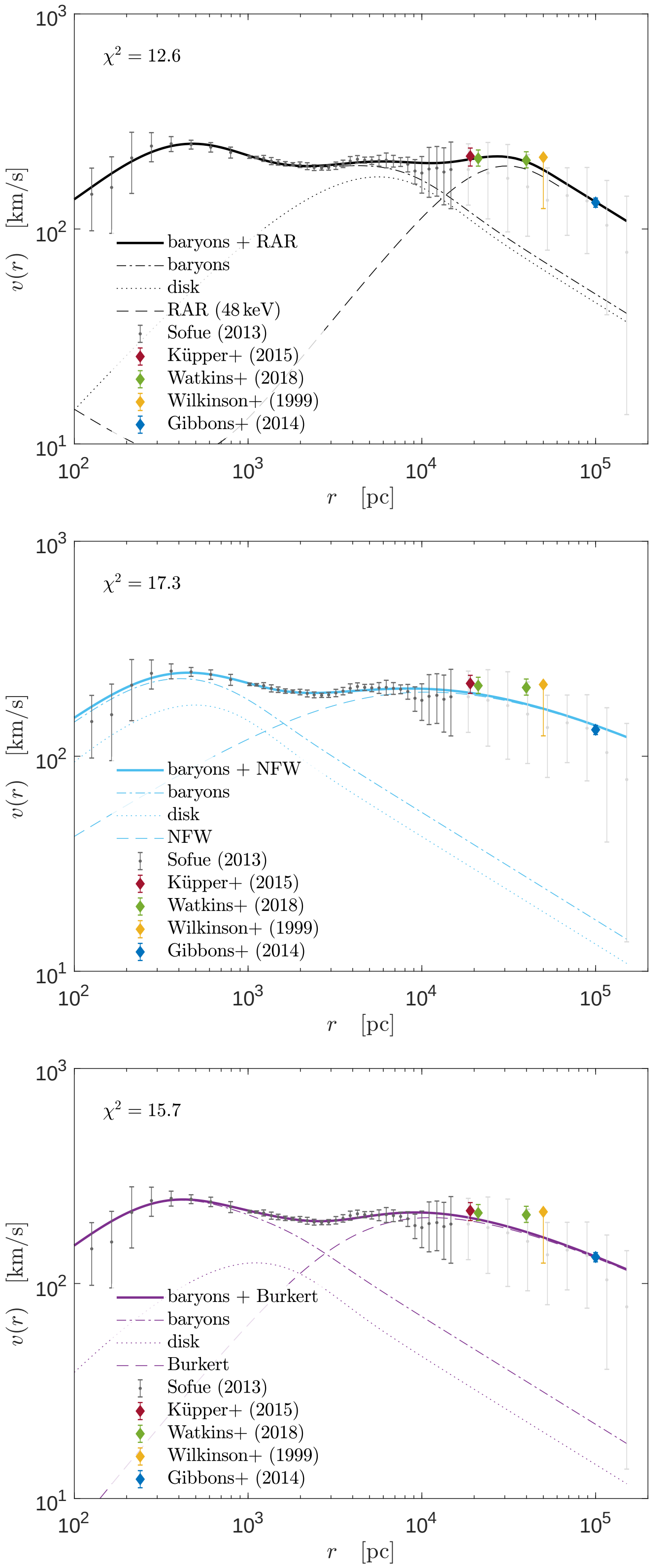

Figure 1: Rotation curve of the best-fit solution in the RAR (top), NFW (middle) and Burkert scenario (bottom).

component	parameter	unit	RAR	NFW	Burkert
core	mass $M_{\rm core}$	$M_\odot$	4.2×10^6	4.2×10^6	4.2×10^6
inner bulge	length scale R_b	pc	5.4	4.5	4.70
	density scale ρ_b	$M_\odot/\mathrm{pc}^3$	1.5×10^4	1.8×10^4	1.81×10^4
main bulge	length scale R_b	pc	1.4×10^2	9.8×10^1	1.09×10^2
	density scale ρ_b	$M_\odot/\mathrm{pc}^3$	1.5×10^2	1.2×10^2	2.05×10^2
disk	length scale R_d	pc	2.6×10^3	2.3×10^2	5.25×10^2
	total mass M_d	$M_\odot$	4.8×10^{10}	4.1×10^9	4.86×10^9
DM	halo radius r_h	pc	3.1×10^4	1.1×10^4	1.1×10^4
	halo mass M_h	$M_\odot$	2.8×10^{11}	9.8×10^{10}	1.1×10^{11}
total	least-square χ^2		12.6	17.3	15.7

Table 1: List of best-fit parameters for the RAR, NFW and Burkert scenario. For a better comparison of the DM models, the length and mass scale of each DM halo are provided where r_h is defined at the maximum in the DM halo rotation curve and $M_h \equiv M_{\rm dm}(r_h)$.

Keplerian trend. Additionally, the cutoff effects are responsible for a narrow DM maximum bump in the rotation curve what gives excellent conditions for an accompanying disk with convenient parameters. Moreover, we want to recall that such RAR solutions (e.g. for $mc^2 = 48\,\mathrm{keV}$) develop a compact quantum core in the Galactic center as an alternative to the BH scenario in SgrA* (Argüelles et al., 2018).

In sum, the RAR scenario explains the Keplerian trend, a reasonable disk and the compact quantum core without spoiling the intermediate baryonic matter. This scenario doesn't require the introduction of a BH nor a truncation of the DM density profile. Instead, the Galactic core and halo are naturally explained by fermionic dark matter including cutoff effects. This result gives further evidence for fermionic dark matter in the keV regime.

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