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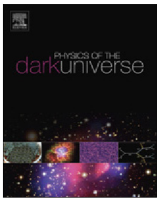

Novel constraints on fermionic dark matter from galactic observables I: The Milky Way

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ABSTRACT

We have recently introduced a new model for the distribution of dark matter (DM) in galaxies based on a self-gravitating system of massive fermions at finite temperatures, the Ruffini–Argüelles–Rueda (RAR) model. We show that this model, for fermion masses in the keV range, explains the DM halo of the Galaxy and predicts the existence of a denser quantum core at the center. We demonstrate here that the introduction of a cutoff in the fermion phase-space distribution, necessary to account for the finite Galaxy size, defines a new solution with a central core which represents an alternative to the black hole (BH) scenario for SgrA*. For a fermion mass in the range $mc^2 = 48$–345 keV, the DM halo distribution is in agreement with the Milky Way rotation curve data, while harbors a dense quantum core of about $4 \times 10^6 M_\odot$ within the S2-star pericenter.

1. Introduction

The problem of the distribution of stars in globular clusters, and more general in galactic systems, has implied one of the results of most profound interest in classical astronomy. In particular, in the pioneering works of Michie [1] and King [2], they considered the effects of collisional relaxation and tidal cutoff by studying solutions of the Fokker–Planck equation. There, it was shown that stationary solutions exist and are well described by isothermal spheres models, based on simple Maxwellian energy distributions with a constant subtracting term interpreted as an energy cutoff. An extension of this statistical analysis with thermodynamic considerations, which includes the effects of violent (collisionless) relaxation, has been studied in [3], with implications to the problem of virialization in galaxies which are still of current interest (see e.g. [4]).

Following the work of Ruffini and Bonazzola [5] the attention has been directed to the possible role of quantum statistics as opposed to the Boltzmannian description. Attention has correspondingly shifted from stars to elementary particles. There the case of bosons as well as fermions was considered. This also shifted the interest from the baryonic matter composing a star to a new field of interest, which has become since of great relevance, the dark matter (DM) components of galactic structures.

A first significant attempt was made by Baldeschi et al. [6] who called attention on the possible role of self-gravitating bosons for explaining galactic halos. Their result suggested as a viable DM candidate low particle masses down to 10^{-24} eV. This idea was further developed by a large number of authors. For a recent review of the initial work as well as the large number of intervening works see e.g. [7], and references therein.

While the works on bosons were addressing the possible smallest particle mass in nature an alternative line of research of self-gravitating fermions of masses larger than few keV, also indicated by Baldeschi et al. [6], addresses the system of semi-degenerate self-gravitating fermions with the aim of describing galactic DM halos (see e.g. [8]). Further, it was considered a quantum fermionic distribution taking into account the possible presence of a cutoff in the energy as well as in the angular momentum [9–11]. A remarkable contribution in the understanding of these issues was given in [12], based on the study of generalized kinetic theories accounting for collisionless relaxation processes, and leading to a class of generalized Fokker–Planck equation for fermions. It was there explicitly shown the possibility to obtain, out of general thermodynamic principles, a generalized Fermi–Dirac distribution function including an energy cutoff, extending the former Boltzmannian results by Michie [1] and King [2] to quantum particles.

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More recently, it was shown that quantum particles fulfilling fermionic quantum statistics and gravitational interactions are able to successfully describe the distribution of galactic DM halos when compared with observations [13–17]. A similar approach to galactic halos has been developed in [18] within the so-called fermionic King model, but lacking information on the fermion mass and of general relativistic effects which become important for the quantum cores approaching the critical mass for gravitational collapse. In particular, Ruffini et al. [17] proposed a new model (hereafter RAR model) addressing the simultaneous fulfillment of the dense quantum core to the classical halo distribution. There the RAR model was proposed as a viable possibility to establish a link between the dark central cores to DM halos within a unified approach.

In this paper we extend the RAR model by introducing a cutoff in the momentum distribution to account for (1) finite galaxy sizes (analogously as previously done in [11]), and (2) to account for more realistic galaxy relaxation mechanisms as indicated above and in [12]; providing a new family of solutions with an overall re-distribution of the bounded fermions.

Consequently, the more stringent outer halo constraints of our novel configurations allow a higher compactness of the central cores. In fact, the possibility of a fermion core at the Galactic center as an alternative to the central BH, first studied in [19] in the framework of Newtonian gravity, did not succeed in reaching the correct compactness of the quantum core since the cutoff energy parameter was not there considered.

Thus, the key questions to be answered here are the following:

- can the gravitational potential of the new quantum core sited at the center of the DM halo be responsible for the observed dynamics of the surrounding gas and stars, without the necessity of introducing a central BH?
- if so, which is the allowed DM fermion mass range to account for such observational constraints?

We answer here the above questions by making a detailed analysis of the theoretical RAR DM profiles. We present in Section 2 the details of the general relativistic equilibrium equations of this model and discuss the general features of the physical variables. Then, by using a recent and extensive observational study of the Milky Way rotation curves [20], and including the central S-star cluster data [21], we show here (see Section 3) for the first time:

1. That a regular and continuous distribution of keV fermions can be an alternative to the BH scenario in SgrA*, being at the same time in agreement with the Milky Way DM halo, and without spoiling the known baryonic (bulge and disk) components which dominate at intermediate scales.
2. By constraining the DM quantum core to have the minimum compactness required by the S2 star dynamics, and by requesting the gravitational stability of the entire DM configuration, the fermion mass can be constrained to the range $mc^2 = 48$–345 keV.

Finally in Section 4 we provide a discussion of the main results of our work, and further comment on where it stands with respect to the current affairs of cosmological DM and structure formation, indicating its potentiality to solve some of the actual discrepancies within the standard ΛCDM and ΛWDM cosmologies.

2. The Ruffini–Argüelles–Rueda (RAR) model

Following [11,22], we consider a system of self-gravitating massive fermions with a cutoff in the phase-space distribution under the assumption of thermodynamic equilibrium in general relativity.

A quantum phase-space function of this kind can be obtained as a (quasi) stationary solution of a generalized Fokker–Planck equation for fermions including the physics of violent relaxation and evaporation, appropriate to treat non-linear galactic DM halo structure formation [12]. These phase-space solutions fulfill a maximization (Fermi–Dirac) entropy principle at fixed DM halo mass (bounded in radius) and temperature, consistent with the solutions given here, and further justifying the above assumed thermodynamic equilibrium approximation.

The fermionic equation of state can be written by

$$\rho = m\frac{2}{h^3}\int_0^{\epsilon_c} f_c(p)\left(1+\frac{\epsilon(p)}{mc^2}\right)d^3p\,, \tag{1}$$

$$P = \frac{1}{3}\frac{2}{h^3}\int_0^{\epsilon_c} f_c(p)\,\epsilon\,\frac{1+\epsilon(p)/2mc^2}{1+\epsilon(p)/mc^2}d^3p\,, \tag{2}$$

where the integration is carried out over the momentum space bounded from above by $\epsilon \le \epsilon_c$, with ϵ_c the cutoff energy (see below); $f_c(p)$ is the phase-space distribution function differing from the standard Fermi–Dirac in the energy cutoff as

$$f_c(\epsilon \le \epsilon_c) = \frac{1-e^{(\epsilon-\epsilon_c)/kT}}{e^{(\epsilon-\mu)/kT}+1}, \qquad f_c(\epsilon > \epsilon_c) = 0\,, \tag{3}$$

where $\epsilon = \sqrt{c^2p^2+m^2c^4} - mc^2$ is the particle kinetic energy, μ is the chemical potential with the particle rest-energy subtracted off, T is the temperature, k is the Boltzmann constant, h is the Planck constant, c is the speed of light, and m is the fermion mass. We do not include the presence of anti-fermions, i.e. we consider temperatures $T \ll mc^2/k$. The full set of (functional) parameters of the model are defined by the temperature, degeneracy and cutoff parameters, $\beta = kT/(mc^2)$, $\theta = \mu/(kT)$ and $W = \epsilon_c/(kT)$, respectively.

We consider the system as spherically symmetric so we adopt the metric

$$ds^2 = e^{\nu}c^2dt^2 - e^{\lambda}dr^2 - r^2d\Theta^2 - r^2\sin^2\Theta d\phi^2, \tag{4}$$

where (r, Θ, ϕ) are the spherical coordinates, and ν and λ depend only on the radial coordinate r.

The thermodynamic equilibrium conditions are [23,24]:

$$e^{\nu/2}T = \text{constant}, \tag{5}$$

$$e^{\nu/2}(\mu + mc^2) = \text{constant}. \tag{6}$$

The cutoff condition comes from the energy conservation along a geodesic,

$$e^{\nu/2}(\epsilon + mc^2) = \text{constant}, \tag{7}$$

that leads to the cutoff (or *escape* energy) condition

$$(1 + W\beta) = e^{(\nu_b-\nu)/2}, \tag{8}$$

where $\nu_b \equiv \nu(r_b)$ the metric function at the boundary of the configuration, i.e. $W(r_b) = \epsilon_c(r_b) = 0$ [10], and r_b is the boundary radius often called *tidal* radius. The above cutoff formula reduces to the known escape velocity condition $v_e^2 = -2\phi$ in the classical limit $c \to \infty$ ($e^{\nu/2} \approx 1 + \phi/c^2$) considered by King [2], where $V = m\phi$ with ϕ the Newtonian gravitational potential, adopting the choice $V(r_b) = 0$.

The above conditions together with the Einstein equations lead to the system of equilibrium equations

$$\frac{d\hat{M}_{DM}}{d\hat{r}} = 4\pi\hat{r}^2\hat{\rho}, \tag{9}$$

$$\frac{d\theta}{d\hat{r}} = -\frac{1-\beta_0(\theta-\theta_0)}{\beta_0}\frac{\hat{M}_{DM}+4\pi\hat{P}\hat{r}^3}{\hat{r}^2(1-2\hat{M}_{DM}/\hat{r})}, \tag{10}$$