The role of self-interacting right-handed neutrinos in galactic structure

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Abstract

We show that warm dark matter keV fermions ('inos') can be responsible for both core and halo galactic structure, in agreement with current astrophysical/cosmological constraints. We identify the inos with sterile right-handed neutrinos. The possible mass range of up to a few tens of keV, obtained independently from the galactic structure and dark matter astroparticle physics, points towards an important role of the right-handed neutrinos in the cosmic structure.

Keywords: Dark matter, Beyond Standard Model physics: neurtrinos, Galaxies: halos, Galaxies: nuclei

1. Introduction

The Cold Dark Matter model of the Universe, characterized by ordinary matter (about 5%), a vacuum dark energy (more than 68%), and dark matter (DM, 27%), with an equation of state resembling a positive-cosmological-constant (Λ) type fluid (a.k.a. ΛCDM model) seems to be, at least currently, the cosmological scenario that best fits the plethora of the available cosmological and astrophysical data. At present, the nature of dark matter still elude us. Supersymmetry, which provides leading candidates for cold DM, has not been discovered as yet, thus prompting us to consider alternative candidates for DM such as axions, or sterile right-handed neutrinos with masses higher than 100 keV.

On the other hand, right-handed neutrinos of warm dark matter (WDM) type, with masses less than 50 keV may still play a role in particle physics today, as conjectured in the so-called right-handed neutrino minimal (non-supersymmetric) extension of the standard model (νMSM) proposed in [1, 2, 3, 4, 5]. This model involves three right-handed neutrino states, in addition to the three left-handed active neutrinos of the standard model (SM) sector, of which the lightest, of mass at most a few tens of keV, can live longer than the age of the Universe, thus constituting a viable dark matter candidate. Such relatively light right-handed neutrinos appear compatible with cosmological dark matter and Big-Bang-Nucleosynthesis constraints, provided their mixing angles with the active neutrinos of the SM sector are sufficiently small, as shown in fig. 1.

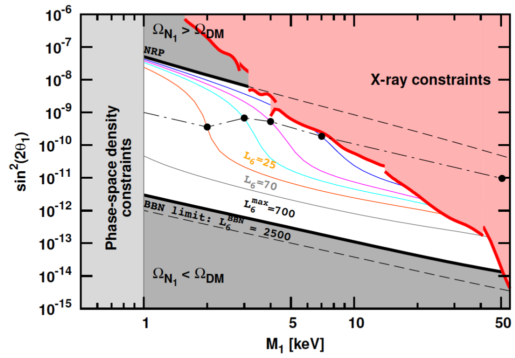

Figure 1: Cosmological constraints on the mass (M_1) and mixing (θ_1) parameters of the lightest sterile neutrino state N_1 of the νMSM model, consistent with all the current astrophysical and cosmological data [1, 2, 3, 4, 5].

From the astrophysical point of view, we have recently argued [6, 7, 8, 9, 10, 11, 12] that a system of self-gravitating fermions, which we have referred to as 'inos', with masses in the WDM regime, plays an important rôle for the galactic structure. In particular, the density of these inos, which we propose here to be identified with right-handed Majorana neutrinos[1], when viewed as a function of the radius, shows a segregation of three physical regimes: 1) an inner core of almost constant density governed by degenerate quantum statistics; 2) an intermediate region with a sharply decreasing density distribution followed by an extended plateau, implying quantum corrections; 3) an asymptotic, $\rho \propto r^{-2}$ classical Boltzmann regime fulfilling, as an eigenvalue problem, a fixed value of the flat rotation curves. It was further shown, that this eigenvalue problem allows to determine the mass of the ino as well as the

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[1]These neutrinos could be of the DM type appearing in νMSM, but such an identification is not binding.

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radius and mass of the inner quantum core. This novel approach was applied for different galaxy types ranging from dwarf to big spirals, presenting, for $m \sim 10$ keV$/c^2$, an excellent agreement with the dark matter halo observables (see [8, 10, 12], for details); and at the same time providing a theoretical correlation between the inner quantum core and the halo mass contrastable with observations [12]. We also evaluated the possibility of an alternative interpretation to the black hole in SgrA*, in terms of the high concentration of dark matter in the inner quantum core. We concluded that, although a compact degenerate core mass $M_c \sim 4 \times 10^6 M_\odot$ is definitely possible with an ino of $m \sim 10$ keV$/c^2$, the core radius is larger by a factor $\sim 10^2$ than the one obtained from the observational limits imposed by the of S-star trajectories such as S1 and S2 orbiting around SgrA* [13, 14]. To solve this problem, we propose here the inclusion of specific interactions among the inos which, as we shall show below, allows for higher central degeneracies and higher compactness of the inner quantum core.

2. Self-interacting right-handed neutrinos

We start the minimal extension of the model of the lightest-right-handed-fermion sector of νMSM [1, 2, 3], which plays the role of dark matter, by introducing on the basis of a phenomenological effective picture, self-neutrino interactions through a massive vector meson V_μ mediator. The necessity of considering self-interactions in dense and very low temperature[2] fermionic systems as the ones considered here, has been proven in laboratory experiments. Indeed, in [15] and references therein, it was shown that the behavior of ultra-cold atomic collisions in (effective) Fermi gases such as ^{6}Li can be explained in terms of a grand-canonical many-body Hamiltonian with a term accounting for the (spin-enhanced) fermion-fermion interaction, analogously as proposed in the sequel. Clearly, while in laboratory physics it is needed an external trapping potential (such as magnetic fields), in the context of dark matter in galaxies the trapping is ensured by gravity.

The Lagrangian of the right-handed neutrino sector, including gravity, reads (we use units $\hbar = c = 1$):

$$\mathcal{L} = \mathcal{L}_{GR} + \mathcal{L}_{N_{R1}} + \mathcal{L}_V + \mathcal{L}_I \tag{1}$$

where

$$\begin{aligned} \mathcal{L}_{GR} &= -\frac{R}{16\pi G}, & (2)\\ \mathcal{L}_{N_{R1}} &= i\,\overline{N}_{R1}\gamma^\mu \nabla_\mu N_{R1} - \frac{1}{2} m\, \overline{N^c}_{R1} N_{R1}, & (3)\\ \mathcal{L}_V &= -\frac{1}{4} V_{\mu\nu}V^{\mu\nu} + \frac{1}{2} m_V^2 V_\mu V^\mu, & (4)\\ \mathcal{L}_I &= -g_V V_\mu J_V^\mu = -g_V V_\mu \overline{N}_{R1}\gamma^\mu N_{R1}\,, & (5) \end{aligned}$$

[2]At temperatures of fraction of the Fermi energy, or equivalently, for thermal de-Broglie wavelengths larger than the inter-particle mean distances, the self-interactive behavior becomes relevant [15].

with R the Ricci scalar for the static spherically symmetric metric background $g_{\mu\nu} = \text{diag}(e^\nu, -e^\lambda, -r^2, -r^2\sin^2\theta)$, where e^ν and e^λ depend only on the radial coordinate, r. The quantity m is the mass of the sterile neutrino, $\nabla_\mu = \partial_\mu - \frac{i}{8}\,\omega_\mu^{ab}[\gamma_a, \gamma_b]$ is the gravitational covariant derivative acting on a Majorana spinor, with ω_μ^{ab} the spin connection and $[\,,\,]$ the commutator. The vector-meson mass is m_V, whose microscopic origin is not discussed here, and $V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$, where the Lorentz gauge has been applied for the vector meson (VM) field V_μ. Latin indexes denote flat tangent space indexes and are raised and lowered with the Minkowski η_{ab} metric, and J_V^μ is the sterile neutrino current[3]. Notice that in Eq. (4) we included a kinetic term for the VM-field. However, in the mean-field approximation we shall employ in this work, such kinetic terms are irrelevant, thus allowing contact four-fermion interactions among the right-handed neutrinos of Nambu-Jona-Lasinio type to be studied in a similar way. In the latter case, the VM-field is auxiliary.

From a detailed analysis of the equations of motion obtained from (1) for the spherically symmetric metric, and using the generalized Tolman and Klein conditions with the inclusion of a VM extra field (see [16] for details), respectively,

$$\begin{aligned} e^{\nu/2} T &= \text{constant}, & (6)\\ e^{\nu/2}\mu + g_V V_0 &= e^{\nu/2}(\mu + C_V\, n) = \text{constant}, & (7) \end{aligned}$$

we obtain

$$\frac{d\hat{M}}{d\hat{r}} = 4\pi \hat{r}^2 \hat{\mathcal{E}}, \tag{8}$$

$$\frac{d\nu}{d\hat{r}} = 2\frac{\hat{M} + 4\pi\hat{\mathcal{P}}\hat{r}^3}{\hat{r}^2(1 - 2\hat{M}/\hat{r})}, \tag{9}$$

$$\frac{d\theta}{d\hat{r}} = -\frac{1}{2\beta}\frac{d\nu}{d\hat{r}}\frac{\left(1 + \frac{C_V m^2}{4\pi^3}\hat{n} - \frac{C_V m^2}{4\pi^3}\beta\frac{d\hat{n}}{d\beta}\right)}{\left(1 + \frac{C_V m^2}{4\pi^3}\frac{1}{\beta}\frac{d\hat{n}}{d\theta}\right)}, \tag{10}$$

$$\beta = \beta_0 e^{\frac{\nu_0 - \nu(r)}{2}}\,, \tag{11}$$

where we have used the relativistic mean-field approximation (RMF) for the VM-field $V_\mu \equiv V_0 = \frac{g_V}{m_V^2} J_0^V$ ($J_\mu^V \equiv J_O^V$)

[3]The current is conserved if decays of sterile neutrinos are ignored. In general one may add to (1) a Yukawa term, coupling the right-handed neutrino to the active neutrino sector (see, e.g., [1, 2, 3]) $\mathcal{L}_{\rm Yuk} = F_{\alpha 1}\,\overline{\ell}_\alpha\, N_{R1}\phi^c + \text{h.c.}$, where ℓ_α are the lepton doublets of the SM, $\alpha = e, \mu, \tau$, $F_{\alpha 1}$ are appropriate Yukawa couplings, and ϕ^c is the SM conjugate Higgs field, *i.e.* $\phi^c = i\tau_2\phi^\star$, with τ_2 the 2×2 Pauli matrix. Upon considering such a coupling, one obtains the stringent X-ray and BBN constraints of the mixing angle and mass of N_{R1} depicted in fig. 1. In such a case J_V^μ is *not* conserved in time. For our purposes we shall ignore such a mixing with the SM sector, setting $F_{\alpha 1} = 0$. The important feature for us are the self-interactions of the right-handed neutrino, which will be used for ensuring phenomenologically correct values for the radius and mass of the galactic core. Since, as we shall see, the mass range we obtain is compatible with the one in figure 1, one may switch on the Yukawa term in a full phenomenological study, including the SM sector, and in particular neutrino oscillations and Early Universe physics (e.g. leptogenesis [1, 2, 3]), without affecting our conclusions.

with the notations $\langle V_0 \rangle \equiv V_0$ and $\langle J_V^0 \rangle \equiv J_0^V = n\, u_0$, where $u_0 = e^{\nu/2}$ is the time-component of the (average) future-directed four velocity vector, and we have used the normalization condition $u^\mu u_\nu = 1$. The number density for singlet right-handed Majorana fermions is

$$n = e^{-\nu/2} \langle \overline{N}_{R\,1}(k) \gamma^0 N_{R\,1}(k) \rangle = \frac{1}{(2\pi)^3} \int d^3k\, f(k)\,, \quad (12)$$

where the integration is extended over all the momentum space, $f(k) = (\exp[(\epsilon(k) - \mu)/(k_B T)] + 1)^{-1}$ is the Fermi-Dirac distribution function, with $\epsilon(k) = \sqrt{k^2 + m^2} - m$ is the particle kinetic energy, μ is the chemical potential with the particle rest-energy subtracted off, T is the temperature of the heat bath, and k_B is the Boltzmann constant. We have also introduced the parameter $C_V \equiv g_V^2/m_V^2$, which encodes information about the strength of the coupling of the effective interactions of the fermions and the mass of the vector meson mediator. We introduced the dimensionless quantities: $\hat{r} = r/\chi$, $\hat{n} = Gm\chi^2$, $\hat{M} = GM/\chi$, $\hat{\mathcal{E}} = G\chi^2\mathcal{E}$, $\hat{\mathcal{P}} = G\chi^2\mathcal{P}$, with $m_p = \sqrt{1/G}$ the Planck mass, and we have introduced the dimensional factor $\chi = 2\pi^{3/2}(1/m)(m_p/m)$ with units of length, scaling as m^{-2}. We have also introduced the temperature and degeneracy parameters $\beta = k_B T/m$, and $\theta = \mu/(k_B T)$, respectively; and we have evaluated the constants of the generalized equilibrium conditions of Tolman and Klein at the center $r = 0$, which we indicate with a subscript '0'. The energy-momentum tensor is $T^{\mu\nu} = (\mathcal{E} + \mathcal{P})u^\mu u^\nu - \mathcal{P} g^{\mu\nu}$, where $\mathcal{E}$ and $\mathcal{P}$ are the total energy-density and pressure

$$\mathcal{E} = \mathcal{E}_\mathcal{C} + \mathcal{E}_V\,, \quad \mathcal{P} = \mathcal{P}_\mathcal{C} + \mathcal{P}_V\,, \quad (13)$$

with

$$\mathcal{E}_\mathcal{C} = m \frac{1}{(2\pi)^3} \int f(k) \left[1 + \frac{\epsilon(k)}{m}\right] d^3k, \quad (14)$$

$$\mathcal{P}_\mathcal{C} = \frac{1}{3} \frac{1}{(2\pi)^3} \int f(k) \left[1 + \frac{\epsilon(k)}{2m}\right] \epsilon\, d^3k, \quad (15)$$

the fermion contribution in the RMF approximation, while

$$\mathcal{E}_V = \mathcal{P}_V = \frac{1}{2} e^{-\nu} m_V^2 V_0^2 = \frac{1}{2} C_V\, n^2\,, \quad (16)$$

is the contribution from the VM-field. We shall next proceed to solve the system of equations (8–11), including a discussion on the boundary conditions appropriate for the description of the Milky Way, as a self-consistency check of the approach.

3. Numerical solution

The boundary conditions are given by the request of the observational agreement of the inner core and halo with the following Milky Way properties: 1) the compactness of its 'dark' center (SgrA*), 2) the dark matter outer halo mass M_h and radius r_h, and 3) the flat galactic rotation curves with the specific value of the circular velocity v_h at r_h. It is important to recall that we define the radius of the inner quantum core r_c as the distance at which the rotation curve reaches its first maximum, and the outer halo radius r_h at the onset of the flattening rotation curve, which occurs at the second maximum (see also Fig. 1 in Ref. [12]). The rotation curve is given by the circular velocity

$$v(r) = \sqrt{\frac{GM(r)}{r - 2GM(r)}}. \quad (17)$$

Following the above procedure, we shall constrain the physical conditions β_0 and θ_0, together with the physical parameters, such as the sterile neutrino mass m, as well as the coupling parameter C_V. As we have shown in [12], the specific value of the circular velocity in the flat region is intimately related to the temperature parameter, β.

We adopt the ansatz that the self-interactions occur only in the quantum regime and thus within the core, where the thermal de-Broglie wavelength,

$$\lambda_B = \frac{h}{\sqrt{2\pi m k_B T}}, \quad (18)$$

is larger than the inter-particle mean distance l, i.e. $\lambda_B/l > 1$. To this end, we set:

$$C_V(r) = \begin{cases} C_0 & \text{at} \quad r < r_m \quad \text{when} \quad \lambda_B/l > 1\,, \\ 0 & \text{at} \quad r \geqslant r_m \quad \text{when} \quad \lambda_B/l < 1\,, \end{cases} \quad (19)$$

where C_0 is a positive constant and $r_m = r_c + \delta r$ is the core-halo matching point, with r_c the core radius and δr the thickness of the core-halo intermediate layer. As we shall show, $\delta r \ll r_c$, and thus the core-halo matching satisfies $r_m \approx r_c$. In the regime $r \geqslant r_m$, where the dark matter distribution is in a much more dilute state (i.e. $\lambda_B/l \ll 1$), there is the transition from the quantum degenerate state to the Boltzmannian one.

As we show below, the density profile obtained for the interacting case has a similar behavior, with the aforementioned three different regions, as the non-interactive case $C_V = 0$ [12]. We normalize hereafter the coupling constant C_0, for the sake of reference, to the Fermi constant $C_F \approx^{-5}$ GeV^{-2} of the SM weak-interaction,[4] i.e. we introduce the dimensionless constant $\overline{C}_0 = C_0/C_F$.

The mass M_c of the degenerate quantum core must agree with the mass enclosed within the region bounded by the pericenter of the S2 star. At the same time, we use

[4] We introduce the SM Fermi constant only for normalization purposes, thus C_0 must not be thought as a fundamental interaction strength (i.e weak) of the SM. Indeed, the fact that the effective interactions considered here are mediated by a chargeless VM field playing the role of neutral-current interactions through the scattering channel, implies that the inos remain unaffected except for momentum transfer. Therefore, we here adopt a complete phenomenological analysis by studying the maximum possible range of effective interactions strengths which are in agreement with the Milky Way observables.

the pericenter of S2 as an upper limit to the core radius $r_{c(S2)}$, i.e. [14]

$$M_c = 4.4 \times 10^6\, M_\odot\,, \quad r_{c(S2)} = 6 \times 10^{-4}\,\mathrm{pc}\,. \tag{20}$$

There is an error of 8% in the above value of M_c due to the uncertainties in the measurement of the distance to the galactic center $R_0 = 8.33 \pm 0.35$ kpc, while the error in the pericenter of the S2 star is of about 4% [14]. The above parameters imply a central density of order $\sim 10^{16} M_\odot/\mathrm{pc}^3$, which is almost five orders of magnitude larger than the one obtained for the model without self-interactions [12] with the same core mass. It is important to make clear that any core radius $r_{\rm Sch} \lesssim r_c \lesssim r_{c(S2)}$ is accepted within our phenomenological treatment, implying central densities in the range $10^{16} M_\odot/\mathrm{pc}^3 \lesssim \rho_0 \lesssim 10^{23} M_\odot/\mathrm{pc}^3$, with $r_{\rm Sch}$ the Schwarschild radius of a black hole of $4.4 \times 10^6 M_\odot$. Indeed, as we show below, already for an ino mass $m \approx 350$ keV/c^2 it is possible to obtain a critical core dark matter core of fully degenerate inos of mass $M_c = 4.4 \times 10^6 M_\odot$ with a radius $r_c \approx 2.5 r_{\rm Sch}$. The critical objects are the last equilibrium configurations, just before undergoing gravitational collapse (see also Ref. [11]).

For the observables in the halo region, we adopt as in [12] the following dark matter halo parameters [17]. According to Ref. [17], the dark matter best-fit distribution for the Milky Way is provided from the two parametric cored Burkert profile with a specific central density parameter $\rho_B^0 = 2 \times 10^{-2} M_\odot/\mathrm{pc}^3$, and a dark halo length scale parameter $h = 10$ kpc. This corresponds to a halo radius r_h, and as we define it at the maximum of the rotation curve marking the onset of its flat behavior, it leads to an associated halo velocity v_h and mass M_h, as given by Eq. (21). Thus, we have:

$$r_h = 32.4\,\mathrm{kpc}\,, v_h = 155\,\mathrm{km/s}\,, M_h = 1.75 \times 10^{11} M_\odot\,, \tag{21}$$

where the subscript h indicates quantities at the halo radius. All the halo parameters are subject to a $\sim 10\%$ of error [17]. The above value of the circular velocity determinates the value of the temperature parameter at the halo, β_0^h. For these parameters, we obtain $\beta_0^h = 1.065 \times 10^{-7}$.

We discuss now to the core-halo transition. In there, the generalized Tolman and Klein equilibrium conditions have to be fulfilled. The Tolman's condition together with the condition imposed by the continuity of the spacetime metric, lead to the continuity of the temperature parameter $\beta(r_m) = \beta_0^h$. Now, from the Klein's condition we can obtain the jump in the degeneracy parameter at the matching point r_m, where the (diluted) halo region begins:

$$\theta(r_m) = \theta_0^h - \frac{C_0 n(r_m)}{m\beta_0^h}\,, \tag{22}$$

$$n(r_m) = \frac{\sqrt{2} m^3 (\beta_0^h)^{3/2}}{\pi^2} (F_{1/2} + \beta_0^h F_{3/2})\,, \tag{23}$$

where θ_0^h is value of θ from the halo side, and the generalized Fermi-Dirac integrals are evaluated at r_m: $F_j = \int_0^\infty dx x^j (1 + \beta_0^h x/2)^{1/2}/[1 + e^{x-\theta(r_m)}]$.

Following the above procedure, in Table 1 we summarize the solution of the boundary-value problem which fulfills the core and halo observables (21) and (20) respectively,for the maximum allowed possible range of the interaction constant $\overline{C_0}$, central degeneracy θ_0 and ino mass m. Even if the upper limit in the sterile neutrino mass ($m \lesssim 50$ keV/c^2) is imposed by cosmological and astrophysical constraints under the assumption of mixing with the SM sector (*cf.* fig. 1), we also explore larger (phenomenologically) values of the ino mass, which is possible for sterile neutrinos that do not interact with the *active* sector.

4. Discussion

Two important conclusions can be drawn from the numerical analysis presented in Table 1:

I) For $m < 47$ keV/c^2 and $m > 350$ keV/c^2 there is no pair of parameters $(\overline{C_0}, \theta_0)$ able to be in agreement with the observables. While $m = 47$ keV/c^2 is the lowest admissible particle mass up to which the core observational constraints are fulfilled (within observational errors), $m = 350$ keV/c^2 is the uppermost bound set by the reaching of the critical core mass for gravitational collapse [9], $M_c^{cr} \propto M_{pl}^3/m^2 \approx 4.4 \times 10^6 M_\odot$, where M_{pl} is the Planck mass[5].

II) As the value of the coupling constant $\overline{C_0}$ increases from the unity, the contribution to the total energy and pressure from the meson-vector field ($\sim C_0 n^2$) becomes more and more relevant. For instance, as can be seen in Table 1, for $\overline{C_0} \sim 10^{14}$ and for $m = 47$ keV/c^2, a slightly lower value for the central degeneracy is needed to have the same core mass as compared with the $\overline{C_0} \sim 1$ regime. In other words, if the same central degeneracy as in the former $\overline{C_0} \sim 1$ case is used, an increase of $\sim$ few % in the core mass M_c would appear. For this lower ino mass bound, the self-interactions cannot exceed $\overline{C_0} \sim 10^{16}$, because otherwise the now lower central degeneracy needed to compensate for the core mass, would be too low to fulfill with the upper core radius constraint $r_{c(S2)}$. More evident is the case when the ino mass reaches $m = 350$ keV/c^2, where the highest interaction regime $\overline{C_0} \sim 10^{18}$ fulfilling the core radius and mass, is reached at a central degeneracy about two orders of magnitude lower with respect to the $\overline{C_0} = 1$ case.

It is interesting to notice that the degenerate keV fermion core can reach core radii as small as few times the Schwarschild radius $r_{\rm Sch}$ of a black hole of $M = 4.4 \times 10^6 M_\odot$. This implies that within the self-interacting approach here presented, the compactness of SgrA* can be also in agreement with the highest lower bound imposed for a dark

[5]Strictly speaking, the relation $M_c^{cr} \propto M_{pl}^3/m^2$ is valid only for fully degenerate and non-interacting inos. However for the majority of the interaction regimes here analyzed, the energy density and pressure contribution of the MV field to the total ones is such that $\mathcal{E}_V \ll \mathcal{E}_C$ and $\mathcal{P}_V \ll \mathcal{P}_C$, and therefore no appreciable effect to the critical mass is present.

m (keV)	$\overline{C_0}$	θ_0	β_0	r_c (pc)	δr (pc)	$\theta(r_m) \approx \theta_0^h$
47	1	3.70×10^3	1.065×10^{-7}	6.2×10^{-4}	2.1×10^{-4}	-29.3
	10^{14}	3.63×10^3	1.065×10^{-7}	6.2×10^{-4}	2.2×10^{-4}	-29.3
	10^{16}	2.8×10^3	1.065×10^{-7}	6.3×10^{-4}	2.4×10^{-4}	-29.3
350	1	2.40×10^6	1.431×10^{-7}	1.3×10^{-6}	6.7×10^{-7}	-37.3
	10^{14}	1.27×10^5	1.104×10^{-7}	5.9×10^{-6}	9.4×10^{-7}	-37.3
	4.5×10^{18}	1.7×10^1	1.065×10^{-7}	5.9×10^{-4}	2.0×10^{-4}	-37.3

Table 1: Set of model parameters leading to a solution of the boundary-value problem imposed by the Milky Way observables.

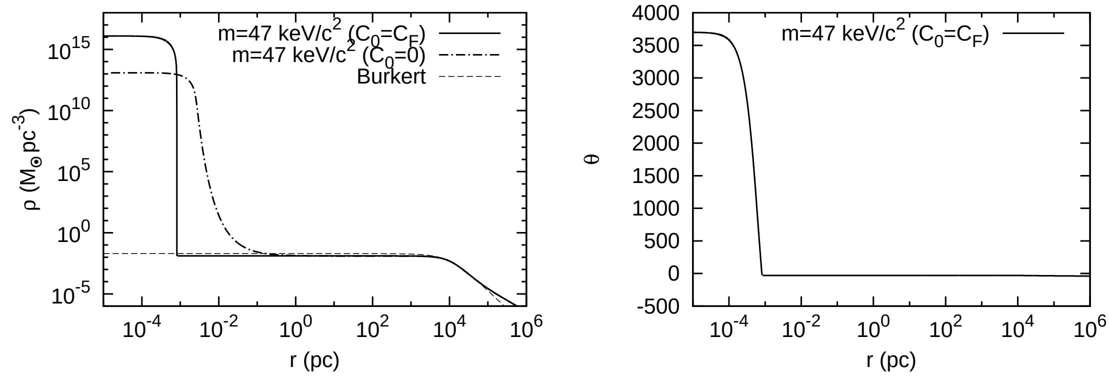

Figure 2: Left: mass density profiles for $m = 47$ keV$/c^2$ in the interaction regime $\overline{C_0} = 1$ where core and halo observational constraints (20–21) are fulfilled, compared with the non-interacting case ($\overline{C_0} = 0$) for the same ino mass in disagreement with the core observables. We also show for comparison the two parametric Burkert profile $\rho_B/[(1 + r/h)(1 + (r/h)^2)]$ with $\rho_B = 2 \times 10^{-2} M_\odot/pc^3$ and h =10 kpc, which is the best dark matter halo fit of the Milky Way according to [17]. Right: degeneracy parameter profile in the interaction regime $\overline{C_0} = 1$ for the same ino mass.

constant-density distribution alternative to the black hole, as obtained from $\sim$ 1 mm VLBI observations (see e.g. [18]). This alternative approach acquires special interest for ongoing and future observational campaigns (e.g. the BlackHole-Cam project[6]), which would allow to verify the general relativistic effects expected in the surroundings of the central compact source in SgrA*; leading to a deeper scrutiny for the not-yet confirmed black hole hypothesis.

In Fig. 2 we present, for comparison, the overall density distribution $\rho(r)$ for a specific self-interacting case as well as the in the $\rho(r)$ profile in the non-interacting case for the same ino mass $m = 47$ keV$/c^2$. This comparison shows that, while in the non-interacting case ($\overline{C_0} = 0$) the core observables (20) *are not* fulfilled, the presence of self-interactions allows to have higher degenerate cores satisfying both the core and halo Milky Way observables (20–21). It is important to notice that the density profile in the observationally well constrained halo region of Fig. 2, coincides with the one obtained in ref. [12] in the absence of self-interactions for the same ino mass, and are in full agreement with the Burkert profile, best dark matter halo fit for the Milky Way, as shown in Ref. [17].

[6]http://horizon-magazine.eu/space

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