

Self-interacting dark matter and the Higgs boson

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Self-interacting dark matter has been suggested in order to overcome the difficulties of the cold dark matter model on galactic scales. We argue that a scalar gauge singlet coupled to the Higgs boson, which could lead to an invisibly decaying Higgs boson, is an interesting candidate for this self-interacting dark matter particle. We also present estimates on the abundance of these particles today as well as the consequences to non-Newtonian forces.

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I. INTRODUCTION

Finding clues for the nature of dark matter (DM) in the Universe is one of the most pressing issues in the interface between particle physics and cosmology. The cold dark matter model supplemented by a cosmological constant (Λ CDM), in the context of inflationary models, explains successfully the observed structure of the Universe on large scales, the cosmic microwave background anisotropies, and type Ia supernova observations [1] for a given set of density parameters, e.g., $\Omega_{\text{DM}} \sim 0.30$, $\Omega_{\text{Baryons}} \sim 0.05$, and $\Omega_{\Lambda} \sim 0.65$. According to this scenario, initial Gaussian density fluctuations, mostly in nonrelativistic collisionless particles, the so-called cold dark matter, are generated in an inflationary period of the Universe. These fluctuations grow gravitationally, forming dark halos into which luminous matter is eventually condensed and cooled.

However, despite its successes, there is a growing wealth of observational data that raise problems in the CDM scenarios. N -body simulations predict a number of halos which is a factor ~ 10 larger than the observed number at the level of the local group [2,3]. Furthermore, CDM models yield dispersion velocities in the Hubble flow within a sphere of $5h^{-1} \text{ Mpc}$ between 300 and 700 km s^{-1} for $\Omega_{\text{DM}} \sim 0.95$ and between 150 and 300 km s^{-1} for $\Omega_{\text{DM}} \sim 0.30$. The observed value is about 60 km s^{-1} . Neither model can produce a single local group candidate with the observed velocity dispersion in a volume of $10^6 h^{-3} \text{ Mpc}^3$ [4]. A related issue is that astrophysical systems which are DM dominated like the core, dwarf galaxies [5–7], low surface brightness galaxies [8], and galaxy clusters without a central cD galaxy [9] show shallow matter-density profiles which can be modeled by isothermal spheres with finite central densities. This is in contrast with galactic and galaxy cluster halos in high reso-

lution N -body simulations [10–13] which have singular cores, with $\rho \sim r^{-\gamma}$ and γ in the range between 1 and 2. Indeed, cold collisionless DM particles do not have any associated length scale leading, due to hierarchical gravitational collapse, to dense dark matter halos with negligible core radius [14].

It has been argued that astrophysical processes such as feedback from star formation or an ionizing background to inhibit star formation and expelling gas in low mass halos [15–17] may solve some of the above-mentioned problems. However, such processes have been difficult to accommodate in our understanding of galaxy formation since galaxies outside clusters are predominantly rotationally supported disks and their final structure does not result from the struggle between gravity and winds but rather are set by their initial angular momentum.

Another possible solution, coming from particle physics, would be to allow DM particles to self-interact so that they have a large scattering cross section and negligible annihilation or dissipation. The self-interaction results in a characteristic length scale given by the mean free path of the particle in the halo. This idea has been originally proposed to suppress small scale power in the standard CDM model [18,19] and has been recently revived in order to address the issues discussed above [20]. The main feature of self-interacting dark matter (SIDM) is that large self-interacting cross sections lead to a short mean-free path, so that dark matter particles with mean-free path of the order of the scale length of halos allow for the transfer of conductive heat to the halo cores, a quite desirable feature [20]. Recently performed numerical simulations indicate that strongly self-interacting dark matter does indeed lead to better predictions concerning satellite galaxies [21–23]. However, only in the presence of weak self-interaction [24] might the core problem be solved.

The two-body cross section is estimated to be in the range of $\sigma/m \sim 10^{-24}$ to $10^{-21} \text{ cm}^2/\text{GeV}$, from a variety of arguments, including a mean-free path between 1 and 1000 kpc [20], requiring the core expansion time scale to be smaller than the halo age [7,25] and analysis of cluster ellipticity

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[26]. A larger value of $\sigma/m \sim 10^{-19} \text{ cm}^2/\text{GeV}$ was obtained from a best fit to the rotation curve of a low surface brightness in a simulation where some extra simplifying assumptions were made [21]. In this work, we shall assume for definiteness that the cross section is fixed via the requirement that the mean-free path of the particle in the halo is in the range 1–1000 kpc.

II. A MODEL FOR SELF-INTERACTING, NONDISSIPATIVE CDM

Many models of physics beyond the standard model suggest the existence of new scalar gauge singlets, e.g., in the so-called next-to-minimal supersymmetric standard model [27]. In this section, we provide a simple example for the realization of the idea proposed in [20] of a self-interacting, nondissipative cold dark matter candidate that is based on an extra gauge singlet ϕ , coupled to the standard model Higgs boson h with a Lagrangian density given by

$$\mathcal{L} = \frac{1}{2} (\partial_\mu \phi)^2 - \frac{1}{2} m_\phi^2 \phi^2 - \frac{g}{4!} \phi^4 + g' v \phi^2 h, \quad (1)$$

where g is the field ϕ self-coupling constant, m_ϕ is its mass, $v = 246 \text{ GeV}$ is the Higgs vacuum expectation value and g' is the coupling between the singlet ϕ and h . We assume that the ϕ mass does not arise from spontaneous symmetry breaking since, as we shall see in the next section, tight constraints from non-Newtonian forces eliminate this possibility due to the fact that, in this case, there is a relation among coupling constant, mass, and vacuum expectation value that results in a tiny scalar self-coupling constant. In its essential features our self-interacting dark matter model can be regarded as a concrete realization of the generic massive scalar field with quartic potential discussed in [28,29]. A model similar to the one presented here was used in order to explain energy transport in fireball models of gamma ray bursts [30].

We shall assume that ϕ interacts only with h and with itself. It is completely decoupled for $g' \rightarrow 0$. For reasonable values of g' , this new scalar would introduce a new, invisible decay mode for the Higgs boson. This could be an important loophole in the current attempts to find the Higgs boson at accelerators [31]. This coupling could, in principle, be relevant for $\phi\phi$ scattering but we shall be conservative and assume that it is small and neglect its contribution. However, we point out that even for nonzero values of g' , the new scalar is stable in this model.

These particles are nonrelativistic, with typical velocities of $v \approx 200 \text{ km s}^{-1}$. Therefore, it is not possible to dissipate energy by, for instance, creating more particles in reactions such as $\phi\phi \rightarrow \phi\phi\phi\phi$. Only the elastic channel is kinetically accessible and the scattering matrix element near threshold ($s \approx 4m_\phi^2$) is given by

$$\mathcal{M}(\phi\phi \rightarrow \phi\phi) = ig. \quad (2)$$

Near threshold the cross section is given roughly by

$$\sigma(\phi\phi \rightarrow \phi\phi) \equiv \sigma_{\phi\phi} = \frac{g^2}{16\pi s} \simeq \frac{g^2}{64\pi m_\phi^2}. \quad (3)$$

We shall derive limits on m_ϕ and g by demanding that the mean-free path of the particle ϕ , λ_ϕ should be in the interval $1 \text{ kpc} < \lambda_\phi < 1 \text{ Mpc}$. This comes about because, if the mean-free path were much greater than about 1 Mpc, dark matter particles would not experience any interaction as they fly through a halo. On the other hand, if the dark matter mean-free path were much smaller than 1 kpc, dark matter particles would behave as a collisional gas altering substantially the halo structure and evolution. Hence, we have

$$\lambda_\phi = \frac{1}{\sigma_{\phi\phi} n_\phi} = \frac{m_\phi}{\sigma_{\phi\phi} \rho_\phi^h}, \quad (4)$$

where n_ϕ and ρ_ϕ^h are the number and mass density in the halo of the ϕ particle, respectively. Using $\rho_\phi^h = 0.4 \text{ GeV/cm}^3$, corresponding to the halo density, one finds

$$\sigma_{\phi\phi} = 2.1 \times 10^3 \left(\frac{m_\phi}{\text{GeV}} \right) \left(\frac{\lambda_\phi}{\text{Mpc}} \right)^{-1} \text{ GeV}^{-2}. \quad (5)$$

Equating Eqs. (3) and (5) we obtain

$$m_\phi = 13 g^{2/3} \left(\frac{\lambda_\phi}{\text{Mpc}} \right)^{1/3} \text{ MeV}. \quad (6)$$

Demanding the mean-free path of the ϕ particle to be of order of 1 Mpc implies in the *model-independent* result

$$\frac{\sigma_{\phi\phi}}{m_\phi} = 8.1 \times 10^{-25} \left(\frac{\lambda_\phi}{\text{Mpc}} \right)^{-1} \text{ cm}^2/\text{GeV}. \quad (7)$$

Recently, it has been argued, on the basis of gravitational lensing analysis, that the shape of the MS2137-23 system is elliptical while self-interacting nondissipative CDM implies that halos are spherical [26]. Furthermore, the limit

$$\frac{\sigma_{\phi\phi}}{m_\phi} < 10^{-25.5} \text{ cm}^2/\text{GeV}, \quad (8)$$

arises from that analysis, which is about an order of magnitude smaller than Eq. (7). Indeed, gravitational lensing arguments are acknowledged to be crucial in validating SIDM; however, estimates made in [26] were criticized as they rely on a single system and because their intrinsic uncertainties actually allow for consistency with SIDM [22].

Let us now estimate the amount of ϕ particles that were produced in the early Universe and survived until present. We shall assume that ϕ particles were mainly produced during reheating after the end of inflation. A natural setting to consider this issue is within the framework of $\mathcal{N}=1$ supergravity inspired inflationary models where the inflation sector couples with the gauge sector through the gravitational interaction. Hence, the number of ϕ particles expressed in terms of the ratio $Y_\phi \equiv n_\phi/s_\gamma$, where s_γ is the photonic entropy density, is related with the inflation (χ) abundance after its decay by

$$Y_\phi = \frac{1}{N} Y_\chi, \quad (9)$$

where N is the number of degrees of freedom. Notice that Y_ϕ is a conserved quantity since ϕ does not couple to fermions. In the context of $\mathcal{N}=1$ supergravity inflationary models, given the upper bound on the reheating temperature in order to avoid the gravitino problem (see [32] and references therein), Y_χ is given by the ratio of the reheating temperature and the inflation mass and, for typical models

$$Y_\chi = \frac{T_{\text{RH}}}{m_\chi} = \epsilon \times 10^{-4}, \quad (10)$$

where ϵ is an order one constant. This estimate allows us to compute the energy density contribution of ϕ particles in terms of the baryonic density parameter:

$$\Omega_\phi = \frac{1}{N} \frac{T_{\text{RH}}}{m_\chi} \frac{1}{\eta_B} \frac{m_\phi}{m_B} \Omega_B, \quad (11)$$

where $\eta_B \approx 5 \times 10^{-10}$ is the baryon asymmetry of the Universe [33].

Using Eq. (6) and taking $N \approx 150$, we obtain

$$\Omega_\phi \approx 18.5 \epsilon g^{2/3} \left(\frac{\lambda_\phi}{\text{Mpc}} \right)^{1/3} \Omega_B, \quad (12)$$

which allows identifying ϕ as the cosmological dark matter candidate, i.e., $\Omega_\phi \approx \Omega_{\text{DM}} \lesssim 0.3$ [34], for $\epsilon \sim 0.5$, g of order one, and λ_ϕ of about 1 Mpc.

We should note that even though the ϕ - h interaction is not relevant today for the dynamics of the dark matter halo, it is possible that for sufficiently strong coupling the scalars can come into thermal equilibrium in the early Universe by interactions with the Higgs boson at temperatures above the Higgs mass. This would be another mechanism for producing the dark matter particles, in addition to the one proposed here. However, there are so far no experimental bounds on the coupling g' and therefore no firm results on the ϕ cosmological abundance that could be obtained from this mechanism.

III. THE CASE OF A NON-NEWTONIAN INTERACTION

In the previous section we have considered self-interacting DM particles interacting with ordinary matter via gravity. In this section, we shall consider the possibility of allowing the self-interacting DM particle to couple to ordinary matter via a non-Newtonian type force as well. This possibility has been intensively discussed in the past and repeatedly sought in the laboratory (see [35] and references therein). Moreover, it has recently been revived in the context of the accelerated expansion of the Universe [36]. This is a fairly interesting possibility as the carrier of a putative new interaction can quite naturally be regarded as a DM candidate [35,37,38]. In what follows, we will show that the carrier of the non-Newtonian force necessarily has an extremely small self-coupling.

Assuming that the Lagrangian density of the new force carrier φ is given by

$$\mathcal{L} = \frac{1}{2} (\partial_\mu \varphi)^2 - \frac{1}{2} m_\varphi^2 \varphi^2 - \frac{g_\varphi}{4} \varphi^4, \quad (13)$$

while its coupling with nucleons of mass m_N and photons is given by

$$\mathcal{L}_{\text{int}} = c_N \frac{\varphi}{\langle \varphi \rangle} m_N \bar{\psi} \psi + c_G \frac{\varphi}{\langle \varphi \rangle} F_{\mu\nu} F^{\mu\nu}, \quad (14)$$

where $\langle \varphi \rangle$ is a large scale associated with the new interaction and c_N , c_G are coupling constants. This last interaction implies that φ exchange leads to a non-Newtonian contribution for the interaction energy $V(r)$ between two point masses m_1 and m_2 , which can be expressed in terms of the gravitational interaction as

$$V(r) = - \frac{G_\infty m_1 m_2}{r} (1 + \alpha_5 e^{-r/\lambda_5}), \quad (15)$$

where $r = |\mathbf{r}_2 - \mathbf{r}_1|$ is the distance between the masses, G_∞ is the gravitational coupling for $r \rightarrow \infty$, α_5 and λ_5 are the strength and the range of the new interaction so that $\lambda_5 = m_\varphi^{-1}$, and

$$\alpha_5 = \frac{c_N^2}{4\pi} \left(\frac{M_P}{\langle \varphi \rangle} \right)^2, \quad (16)$$

where $M_P \equiv G_\infty^{-1/2}$ is the Planck mass. Existing bounds on α_5 (see [35]) imply for c_N of order one that $\langle \varphi \rangle \sim M_P$. If however, $c_N \lesssim 10^{-5}$, then one could have instead $\langle \varphi \rangle \sim 10^{-5} M_P$ [39].

The issue is, however, that in order to generate a vacuum expectation value to φ from Eq. (13) so as to satisfy Eq. (6), one must have $m_\varphi^2 < 0$, from which would imply that $g_\varphi = (|m_\varphi|/\langle \varphi \rangle) \ll 1$, meaning that for either choice of $\langle \varphi \rangle$ quoted above, φ DM particles have a negligible self-interaction. This argument can be generalized for any potential that gives origin to a vacuum expectation value for φ as specified above. We can therefore conclude that the carrier of a non-Newtonian force is not an acceptable candidate for SIDM.

IV. OUTLOOK

In this Rapid Communication we suggest that a scalar gauge singlet coupled with the Higgs field in a way to give origin to an invisible Higgs boson is a suitable candidate for self-interacting dark matter. This proposal has some distinct features. First, since gauge invariance prevents the scalar singlet from coupling to fermions, strategies for directly searching this dark matter candidate must necessarily concentrate on the hunt of the Higgs field itself in accelerators. Furthermore, in what concerns its astrophysical and cosmological implications the relevant features of our proposal are quite unambiguously expressed by Eqs. (5), (6), and (12). Confronting the result of the simulations of our candidate for

different values of the relevant parameters with observations may turn out to be crucial in validating our proposal.

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