Self-Interacting Scalar Dark Matter and Higgs Decay

M.C. Bento, O. Bertolami
Instituto Superior Técnico, Departamento de Física, Av. Rovisco Pais 1, 1049-001 Lisboa, Portugal

R. Rosenfeld
Instituto de Física Teórica, R. Pamplona 145, 01405-900 São Paulo - SP, Brazil

L. Teodoro
Centro Multidisciplinar de Astrofísica, Instituto Superior Técnico, Av. Rovisco Pais 1, 1049-001 Lisboa, Portugal

Abstract. 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, leading to an invisibly decaying Higgs, is an interesting candidate for this self-interacting dark matter particle.

1. Introduction

Finding clues for the nature of dark matter in the Universe is one of the most pressing issues in the interface between particle physics and cosmology. In this talk we briefly review some work we have done in the direction of finding a suitable, particle physics motivated, candidate that could solve some of the recent problems with the usual cold dark matter scenario.

The cold dark matter model (CDM) supplemented by a cosmological constant successfully explains, in the context of inflationary models, the observed structure of the Universe on large scales, the cosmic microwave background anisotropies and type Ia supernovae observations for a given set of density parameters, e.g., $\Omega_{DM} \sim 0.30$, $\Omega_{Baryons} \sim 0.05$ and $\Omega_{\Lambda} \sim 0.65$. According to this scenario, initial Gaussian density fluctuations, mostly in non-relativistic 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 recent observational data that raise problems in the CDM scenarios. N-body simulations predict a number of halos which is a factor $\sim 10$ larger than the observed number at the level of Local Group. Furthermore, CDM models yield dispersion velocities in the Hubble flow within a sphere of 5 $h^{-1}$ Mpc between 300–700 kms$^{-1}$ for $\Omega_{DM} \sim 0.95$ and between 150 – 300 kms$^{-1}$ for $\Omega_{DM} \sim 0.30$. 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 simulation box of comoving volume \(10^6 h^{-3} \text{Mpc}^3\) [3]. A related issue is that astrophysical systems which are DM dominated like dwarf galaxies [3, 4, 5], low surface brightness galaxies [3] and galaxy clusters without a central cD galaxy [6] 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 resolution N-body simulations [11, 12, 13, 14] which have singular cores, with \(\rho \sim r^{-\gamma}\) and \(\gamma\) 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 [3].

A 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. Self-interaction induces a characteristic length scale via 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 [16, 17] and has been recently revived in order to address the issues discussed above [18]. 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 allows for the transfer of conductive heat to the halo cores, a quite desirable feature [18]. Recently performed numerical simulations indicate that strongly self-interacting dark matter does indeed lead to better predictions concerning satellite galaxies [19, 20, 21, 22]. However, only in presence of weak self-interaction [23] the core problem might be solved.

The two-body cross section is estimated to be in the range of \(\sigma/m \sim 10^{-24} - 10^{-21} \text{cm}^2/\text{GeV}\), from a variety of arguments, such as the requirement of a mean free path between 1 and 1000 kpc [18], the core expansion time scale to be smaller than the halo age [8, 24] and analysis of cluster ellipticity [25]. Larger value of \(\sigma/m \sim 10^{-19} \text{cm}^2/\text{GeV}\) corresponds to the best fit to the rotation curve of a low surface brightness in simulations [19]. In our work, we assume for definiteness that the 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.

2. A model for self-interacting, non-dissipative 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 [26]. In this section, we provide a simple example for the realization of the idea proposed in [18] of a self-interacting, non-dissipative cold dark matter candidate that is based on an extra gauge singlet, \(\phi\), coupled to the standard model Higgs boson, \(h\), with a Lagrangian density given by:

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

where \(g\) is the field \(\phi\) self-coupling constant, \(m_{\phi}\) is its mass, \(v = 246 \text{ GeV}\) is the Higgs vacuum expectation value and \(g'\) is the coupling between the singlet \(\phi\) and \(h\). We assume that the \(\phi\) mass does not arise from spontaneous symmetry break-
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ing since tight constraints from non-Newtonian forces eliminates this possibility due to the fact that, in this case, there is a relation among coupling constant, mass and vacuum expectation value that leads to 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 [27, 28]. We mention that a model with features similar to ours has been discussed long ago in [29].

We shall assume that \( \phi \) interacts only with \( h \) and with itself. It is completely decoupled for \( g' \to 0 \). 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 [30]. 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.

These particles are non-relativistic, with typical velocities of \( v \simeq 200 \text{ km} \text{s}^{-1} \). Therefore, there is no dissipation of energy by, for instance, creating more particles in reactions like \( \phi \phi \to \phi \phi \phi \phi \). Only the elastic channel is kinetically accessible and the scattering matrix element near threshold \( (s \simeq 4 m_\phi^2) \) is given by:

\[
\mathcal{M}(\phi \phi \to \phi \phi) = ig .
\]

Near threshold the cross section is given roughly by:

\[
\sigma(\phi \phi \to \phi \phi) \equiv \sigma_{\phi \phi} = \frac{g^2}{16\pi s} \simeq \frac{g^2}{64\pi m_\phi^2} .
\]

We shall derive limits on \( m_\phi \) and \( g \) by demanding that the mean free path of the particle \( \phi \), \( \lambda_\phi \), 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:

\[
\lambda_\phi = \frac{1}{\sigma_{\phi \phi} n_\phi} = \frac{m_\phi}{\sigma_{\phi \phi} \rho_\phi} ,
\]

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

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

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

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

\[1\text{We are thankful to A. Zee for pointing that out for us.}\]
Demanding the mean free path of the $\phi$ 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 non-dissipative CDM implies that halos are spherical [25]. 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 (7). Indeed, gravitational lensing arguments are acknowledged to be crucial in validating SIDM; however, estimates made in [25] were criticized as they rely on a single system and because their intrinsic uncertainties actually allow for consistency with SIDM [20].

In order to estimate the amount of $\phi$ particles that were produced in the early Universe and survived until present, we assume that $\phi$ 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 inflaton sector couples with the gauge sector only through the gravitational interaction. Hence, the number of $\phi$ particles expressed in terms of the ratio $Y_\phi \equiv \frac{n_\phi}{s_\gamma}$, where $s_\gamma$ is the photonic entropy density, is related with the inflaton ($\chi$) 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 $Y_\phi$ is a conserved quantity since $\phi$ does not couple to fermions. In the context of $\mathcal{N} = 1$ Supergravity inflationary models, the upper bound on the reheating temperature in order to avoid the gravitino problem (see [31] and references therein), $Y_\chi$ is given by the ratio of the reheating temperature and the inflaton mass and, for typical models

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

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

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

where $\eta_B \simeq 5 \times 10^{-10}$ is the baryon asymmetry of the Universe.

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

$$\Omega_\phi \simeq 18.5 \epsilon \ 2^{2/3} \left( \frac{\lambda_\phi}{\text{Mpc}} \right)^{1/3} \Omega_B , \quad (12)$$
which allows identifying $\phi$ as the cosmological dark matter candidate, i.e. $\Omega_\phi \simeq \Omega_{DM} \lesssim 0.3$ \cite{2}, for $\epsilon \sim 0.5$, $g$ of order one and $\lambda_\phi$ of about 1 Mpc.

We have also found that the $\phi$ particle do not generate dangerous non-Newtonian forces \cite{3}.

3. Conclusions

In this work \cite{1}, we suggest that a scalar gauge singlet coupled with the Higgs field in such a way as to give origin to an invisible Higgs is a suitable candidate for self-interacting dark matter. This proposal has some quite distinct features. Firstly, since gauge invariance prevents the scalar singlet to couple to fermions, hence 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 main aspects of our proposal are quite unambiguously expressed by Eqs. (5), (6) and (12). Confronting the result of simulations with our candidate for different values of the relevant parameters with observations may turn out to be crucial for validating our proposal. We would like to add that a recent detailed study of our simple model \cite{32} has shown that our abundance computation is valid only if the Higgs field is very weakly coupled to the scalar gauge singlet ($g' < 10^{-8}$), since otherwise the scalar field will reach thermal equilibrium \cite{32}. The study of phion annihilation processes via exchange of virtual Higgs particles indicates that in order to achieve $\Omega_\phi h^2 \lesssim 0.3$ requires $g' \gtrsim 2$ \cite{32} which leads to a Higgs decay width that is distinctly different than the Standard Model one.

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