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Dark matter from an effective couplings approach

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In this work we briefly review dark matter evidence, in the Weakly Interacting Massive Particles (WIMP) paradigm we study the cases of scalar and fermion dark matter candidates. Our study introduces effective couplings between dark matter and Standard Model matter, it is intended as an exercise for academic purposes setting up the required tools for a further analysis. Under the last assumption, we calculate the relic density in order to constrain the model parameter space.

Keywords: Dark Matter; relic density; beyond standard model.

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1. Dark matter evidences

Since Fritz Zwicky observations of the anomalous dynamics of the Coma Cluster, the existence of gravitating non-visible matter has been established. Similarly, Vera Rubin tackled the problem of radial velocity in galaxies investigating the dynamics of spiral galaxies and examining over 80 galaxies within the Virgo Cluster (Fig. 1). She concluded that orbit matter velocities in the galaxies are faster than predicted by Newtonian models in presence of luminous matter only. These observations can be explained by the presence of a matter halo beyond the limits of the galactic disk, the Dark Matter (DM) proposed by Zwicky 40 years early.

Dark Matter evidence extends beyond the anomalous dynamics of galaxies. Gravitational lensing reveals the bending of light trajectories in presence of massive compact objects, which in this context, corresponds to non-visible and massive matter. Furthermore, the distribution of gas in objects like the Bullet Cluster provides another compelling piece of evidence, as it can only be explained by the existence of DM [2].

The most important DM evidence has been provided by the Cosmic Microwave Background (CMB). The nearly uniform signal in temperature, measured at $T_0 = 2.7255 \pm 0.0006$ K, carries valuable information about primordial matter fluctuations, exhibiting anisotropies of $\Delta T/T_0 \approx 10^{-5}$ [3]. These anisotropies are one order of magnitude lower than what would be predicted if only Baryonic Matter (BM) was present. Hence, it becomes evident that both gravitating and non-baryonic matter are essential in effectively reducing these anisotropies [3]. The Relic Density values for both DM and BM can be derived as functions of the *gravitating matter* abundance. Current measurements obtained by the Planck Telescope constrain abundance values [4], yielding $\Omega_{\text{c}}h^2 = 0.1200 \pm 0.0012$ and $\Omega_{\text{b}}h^2 = 0.02237 \pm 0.00015$ for DM and BM, respectively. The universe is characterized by the remarkable fact that DM prevailed approximately five times more than BM. The evolution of the Large Scale Structure (LSS) of the universe is also considered as evidence for DM [5]. Since the CMB decoupling event is only possible due to the presence of DM within the current cosmological Standard Model, namely the Lambda Cold Dark Matter (ΛCDM) model [4].

In this work, we study DM phenomena from the particle physics perspective. In Sec. 2, as an academic exercise, we introduce a minimal SM extension and calculate Dark Matter relic density for a set of model parameters. In Secs. 3 and 4 we propose scalar and fermion WIMP candidates, respectively. Finally, the numerical results for the effective couplings, masses and relic density are presented in Sec. 5.

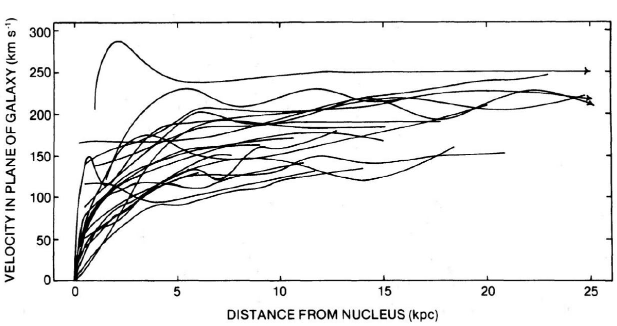

FIGURE 1. Rotation curves of the different spiral galaxies as a function of the distance from the galaxy center. The curves show constant velocities for long distances [1].

2. The Standard Model of particle physics and Dark Matter

The Standard Model (SM) in particle physics is the quantum field theory that successfully describes three of the four fundamental interactions in physics, except gravity. However, this model cannot explain the DM phenomena; hence, a theory Beyond the Standard Model (BSM) is required [6-9].

Figure 2 shows a schematic representation of the processes in which DM interacts with SM particles and could be detected.

In this work, we will focus on an Indirect Detection (ID), at the $\chi\chi \to$ SM SM annihilation process. Specifically the

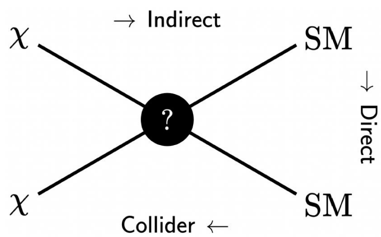

FIGURE 2. Different types of $\chi_{\rm DM}$ detection, where the arrows describe the direction of the field interactions.

relic density $\Omega_{\rm c}h^2$, which is obtained as a function of the model parameters. The obtained value will be required to be in agreement with the reported value by Planck.

Cosmology and BSM theories provide limits and constraints for DM candidates. In general, for a particle to be considered DM particle, it is not only required to be consistent with the reported value of $\Omega_{\rm c}h^2$ but also with the constraints imposed by ID limits. DM candidates should be non baryonic, weakly interacting and electrically neutral. To be consistent with astrophysical bounds, DM should be massive, non-relativistic and comply with LSS [10]. With these boundary conditions in mind, a WIMP (Weakly Interacting Massive Particle) [11] model can be built under simple BSM extensions.

3. DM from a Scalar field

Our analysis is based on the type of interaction introduced between DM and SM particles. In the initial SM extension a scalar field is introduced as a potential DM candidate. The scalar interaction between DM and the Higgs boson is expressed as follows:

$$\mathcal{L}_{S,h} = \partial_\mu S^* \partial^\mu S + m_S^2 S^* S - \lambda_s v S^* S h - \frac{\lambda_s}{2} S^* S h^2\,, \tag{1}$$

where $m_s^2 = \mu_S^2 + (1/2)\lambda_s v^2$ is the mass term associated to the S field and h the real scalar field of the Higgs doublet in unitary gauge, that is, $H^\dagger = (1/\sqrt{2})(0, v+h)$. Therefore, in this model, the effective Lagrangian takes into account not only the interaction presented in Eq. (1), but also the SM model interactions, $\mathcal{L}_{\text{eff SM}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{S,h}$.

We closely follow the notation and study developed by John McDonald [12]. His proposal assumes a scalar field introduced as a real singlet under $SU(2)_L$. The result from [12] depicts a series of curves in the parameter space of DM mass and potential quartic coupling (denoted as λ_s), for several values of relic density and Higgs boson mass. In this study, we incorporate the latest values of the Higgs mass and DM relic density, $m_H = 125$ GeV and $\Omega_{\rm c}h^2 = 0.1200 \pm 0.0012$.

The interacting vertex between DM and SM matter is illustrated in Fig. 3, the diagram in the left panel is commonly referred to as the Higgs portal.

The second model inserts an effective coupling between DM and a neutral vector boson, as shown in the Fig. 4. This

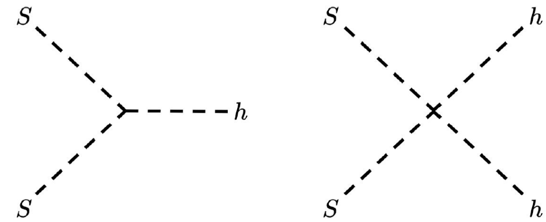

FIGURE 3. Interacting vertex between DM and Higgs in SM extended by the addition of the scalar field S. The left Feynman diagram is known as the Higgs portal.

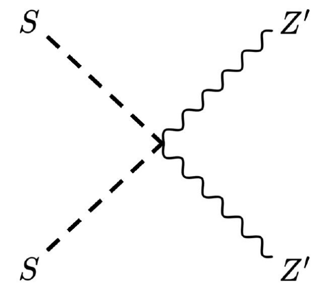

FIGURE 4. Feynman diagram for the interaction between the S and Z'.

neutral vector boson, denoted as Z', can be derived from an extension of the SM that enhances the local gauge group [7]; the Lagrangian for this model is

$$\mathcal{L}_{S,h,Z'} = \partial_\mu S^* \partial^\mu S + m_s^2 S^* S - \lambda_s v S^* S\, h - \frac{\lambda_s}{2} S^* S h^2 - \lambda_v S^* S Z'_\mu Z'^\mu. \tag{2}$$

The total effective Lagrangian can be written as $\mathcal{L}_{\text{eff SM}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{S,h,Z'}$. It is notable that when $\lambda_v = 0$ (2) is reduced to (1), otherwise when $\lambda_s = 0$ the interactions between S and Z' are as follows

$$\mathcal{L}_{S,Z'} = \partial_\mu S^* \partial^\mu S + m_s^2 S^* S - \lambda_v S^* S Z'_\mu Z'^\mu\ , \tag{3}$$

where the last interaction term does not contribute to the mass constraints of m_s under $\Omega_{\rm c}h^2$. The current Z' boundaries and collider searches fixed the mass upper limit $m_{Z'} > 1.3$ TeV [13], based on models that consider Z' candidates in the electroweak scale. In the most general case of this study, the model parameters are $\{m_s, m_{Z'}, \lambda_s, \lambda_v\}$.

4. DM from a Fermion field

We propose an extension within the fermion sector adding a neutral fermion singlet under the electroweak gauge symmetry. If the fermion field is introduced as a Dirac field, the interaction can be described by

$$\mathcal{L}_{f,H} = \bar{f} i \gamma^\mu \partial_\mu f - m_f \bar{f} f + \bar{f}\left(c_s + c_p \gamma^5\right) f\, h\,, \tag{4}$$

where m_f is the f field mass, c_s and c_p correspond to dimensionless scalar and pseudoscalar couplings, respectively.

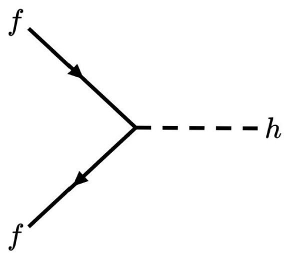

FIGURE 5. Effective dark vertex, extending the fermion sector with the f field, via the Higgs portal.

The mass term arises from the coupling of c_s with a $H^{\dagger}H$ term, resulting in $m_f \propto c_s v^2$. However, the main purpose of this model is to investigate a Higgs portal interaction term, with m_f assumed to be in the range of 100-550 GeV. The Lagrangian for the DM fermion can be expressed as $\mathcal{L}_{\text{eff SM}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{f,H}$. In this case, the free parameters are $\{m_f, c_s, c_p\}$. Figure 5 shows the Higgs portal for fermionic DM.

5. Numerical results

For the numerical analysis, the SM parameters are taken from the reported values [13], while the DM parameters including masses and couplings are explored in an extended numerical range, from 0-1 for dimensionless couplings and 0-2000 GeV for candidate masses. The `LanHep` program is used to generate model files [14] and Feynman rules are obtained in the momentum representation. Subsequently, the `MicrOMEGAs` program [15] is employed to solve numerically the Boltzmann equation and to for relic density calculations. With this information, we proceed to explore the parameter space and identify allowed regions constrained by $\Omega_c h^2$ reported values.

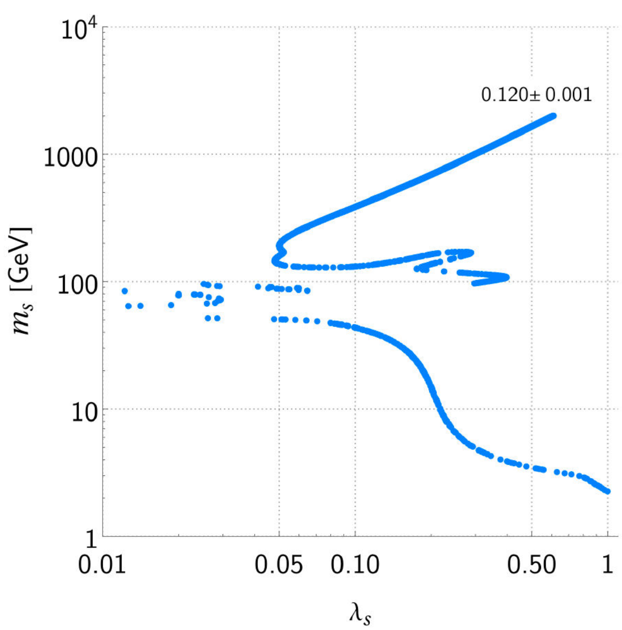

FIGURE 6. Candidates that comply with relic density constraints in the scalar model.

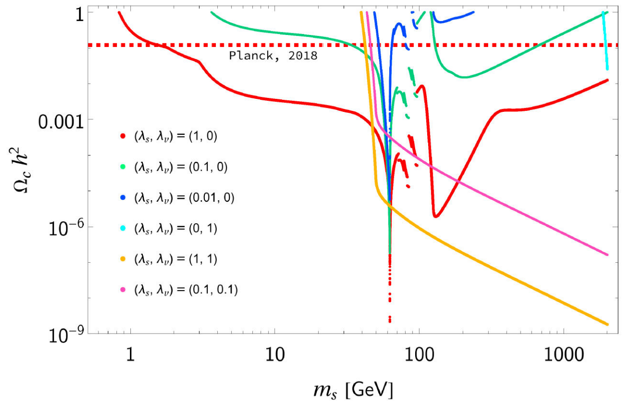

FIGURE 7. Scalar mass regions with fixed λ_s and λ_v, scalar WIMP candidate model. The red dashed line corresponds to the $\Omega_c h^2$ Planck value.

For the first scalar model, in Fig. 6 is shown the DM scalar mass and quartic coupling that satisfy $\Omega_c h^2 = 0.1200 \pm 0.0012$. When John McDonald's model was published, the SM Higgs mass was unknown and relic density $\Omega_c h^2$ value had a less precise limit. Our results indicate a correlation between the DM mass and the quartic coupling λ_s. To maintain consistency with John McDonald's model, we analyzed the correlation among the model parameters using the numerical values depicted in Fig. 6.

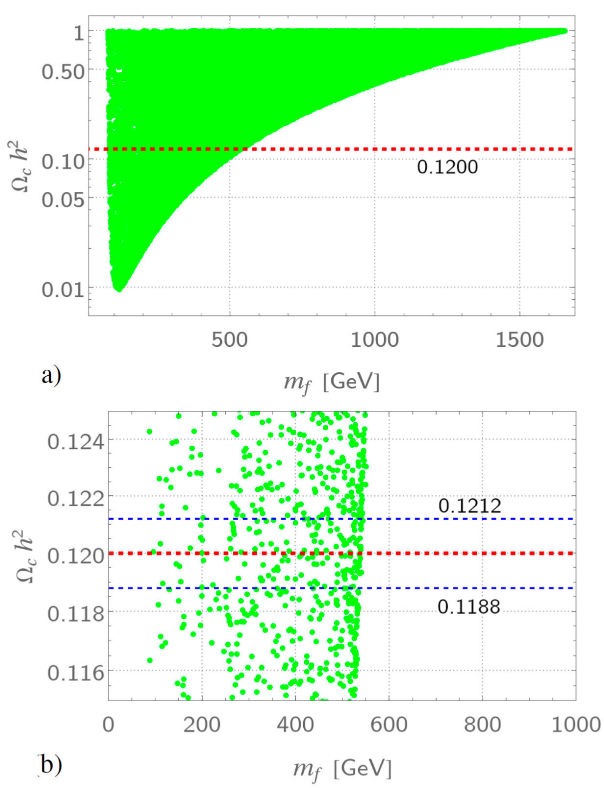

FIGURE 8. Relic density as function of the fermionic DM mass, a) shows a broader mass range in logarithmic scale meanwhile b) provides a zoomed in mass region.

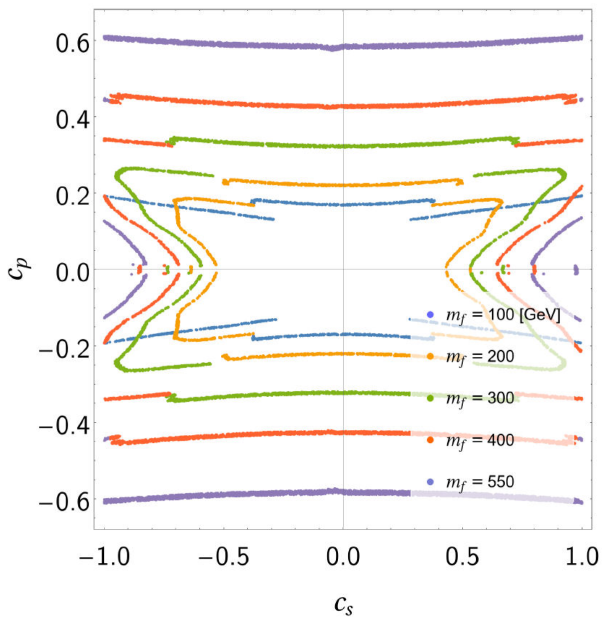

FIGURE 9. Values of scalar and pseudoscalar couplings that yield $\Omega_c h^2$, with the plots for representative fermion DM masses.

The results for the model based on Eq. (2) are presented in Fig. 7, $\Omega_c h^2$ as a function of DM mass for fixed values of $\lambda_{s,v}$.

In the fermion model a larger mass range is explored, see Fig. 8a), and it is found that DM masses below 600 GeV reproduce the correct relic density.

Once the mass range was explored, see Fig. 8b), the model parameters were set to analyse DM candidates with masses below 600 GeV. The allowed values for scalar and pseudoscalar couplings are shown in Fig. 9.

In the case of the model with simultaneous interaction when Higgs portal and Z' boson is assumed, the DM mass is found, for instance, for a coupling of $\lambda_s = 1$ together with an additional coupling of $\lambda_v = 1$ the DM mass value is equal to 41.96 GeV, while for $\lambda_s = \lambda_v = 0.1$, we obtain $m_s = 45.95$ GeV, Fig. 7. We also note that the numerical values for DM mass can present a significant increase over 1 TeV, when $\lambda_v = 1$ and $\lambda_s = 0$ we obtain $m_s = 1939.17$ GeV. In contrast, when $\lambda_v = 0$ and $\lambda_s = 1$ the numerical values for DM mass is equal to 1.75 GeV.

6. Conclusions

Our study analyses DM models with the smallest number of free parameters considering scalar and fermion candidates. The relic density for dark matter is obtained and compared with the most recent value reported in the literature. To perform the numerical analysis, we consider the currently reported values for SM parameters, including a Higgs mass of 125 GeV.

For a singlet scalar field, there are only two free parameters λ_s and m_s. Hence, a correlation is established between these parameters to ensure agreement with the reported relic density value, Fig. 6. This is achieved by solving the Boltzmann equation using a `micrOMEGAs` routine.

Finally, we find allowed values for the mass in the case of a neutral Dirac fermion. The mass interval that satisfies the relic density is 86.21 GeV $< m_f <$ 547.65 GeV, Fig. 8. For the allowed mass interval we obtain the relation between the scalar and pseudoscalar couplings, Eq. (4), shown in Fig. 9.

In this academic exercise, we developed computational routines in the standardized tools to calculate DM relic density in simplified models. The further implementation of these routines will be used to calculate other DM observables and will be applied to SM extensions that contain viable scalar or fermion fields as DM particles.

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