Light dark matter in a minimal extension with two additional real singlets

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The direct searches for heavy scalar dark matter with a mass of order 100 GeV are much more sensitive than for light dark matter of order 1 GeV. The question arises whether dark matter could be light and has escaped detection so far. We study a simple extension of the Standard Model with two additional real singlets. We show that this simple extension may provide the observed relic dark matter density, does neither disturb big-bang nucleosynthesis nor the cosmic microwave background radiation observations and fulfills the conditions of clumping behavior for different sizes of galaxies. The potential of one Standard Model-like Higgs-boson doublet and the two singlets gives rise to a changed Higgs phenomenology, in particular, an enhanced invisible Higgs-boson decay rate is expected, detectable by missing transversal momentum searches at the ATLAS and CMS experiments at CERN.

1. INTRODUCTION

Recently it has been reported \cite{1} that the NGC1052–DF2 galaxy with a stellar mass of approximately $2 \times 10^8$ solar masses has a rotational movement in accordance with its observed mass. If this negative indirect search for dark matter (DM) is confirmed it challenges any attempt to solve the puzzle of galaxy rotations by modifications of gravity.

On the other hand we are facing very severe negative results from direct searches of DM, for instance from the cryogenic experiments SuperCDMS \cite{2}, CRESST \cite{3}, EDELWEISS \cite{4}, and the noble liquid experiments ArDM \cite{5}, DarkSide \cite{6}, DEAP \cite{7}, LUX \cite{8}, PandaX \cite{9}, WARP \cite{10}, XENON \cite{11}, and ZEPLIN \cite{12}. These experiments provide very low upper limits for the interaction cross sections of DM with nucleons. For instance, the XENON100 \cite{13} direct detection experiment at Gran Sasso excludes spin-independent elastic nucleon cross sections down to values as tiny as $2 \times 10^{-45}$ cm$^2$ for DM particles with a mass of 55 GeV at 90% confidence level.

In case that the Higgs boson couples to DM, also collider experiments may detect DM; for an overview of this subject we refer to \cite{14}. Even that DM is expected not to show traces in the detector components, since it is expected to couple only very weakly to Standard Model (SM) particles, it may be discovered as missing transversal momentum in collisions. In particular, in this way a DM candidate may enhance the invisible decay rate of a SM-like Higgs boson. Note that in the SM the only invisible decay channel of the Higgs boson ($h$) is via two electroweak $Z$ bosons which subsequently decay into pairs of neutrinos ($\nu$), that is, $h \to ZZ \to 4\nu$.

The collider experiments ATLAS \cite{15} and CMS \cite{16} have measured upper limits on the spin-independent DM-nucleon scattering cross section \cite{17,18}. Under the assumption that DM couples to the Higgs boson, these measurements provide the most stringent bounds available on light DM detection, far below the underground DM-nucleon direct-detection limits. However, the upper bounds for light scalar DM are orders of magnitudes less stringent than the bounds for heavy DM particles with masses of $O(100)$ GeV.

Let us in this context recall that interactions of DM with SM particles can also not be arbitrarily small: supposing that DM is produced dynamically in the evolution of the Universe, for decreasing annihilation cross sections of the DM particles to Standard Model particles, the annihilation processes become more and more rare in the evolution of the Universe and freeze out happens earlier – corresponding to a higher DM number density. Eventually this would lead to an overclosure of the Universe.

One example of this is the so called Lee-Weinberg bound \cite{19}: in case of leptonic dark matter it has been shown that its mass has to be greater than of the order of 2 GeV in order not to lead to an overclosure of the Universe. However this bound refers to dark matter lepton candidates. If instead the annihilation is not mediated by electroweak gauge bosons this bound does not apply – opening the window for light dark matter.

Supersymmetric models provide generically new weakly interacting bosons and fermions, and therefore in principle these models can provide light DM particles. However, at least the simplest supersymmetric extension of the Standard Model appears to be disfavored, since there is a tension of the predicted Higgs mass spectrum in contrast to observations – in particular the detected Higgs boson is too heavy in order to be a supersymmetric particle in the minimal supersymmetric extension (see for instance the review \cite{20}).

Here we want to study a simple model with two additional real scalars. One of these scalars serves as a DM candidate ($\chi$) and the other is a scalar mediator ($\eta$). Since we expect that the DM particles $\chi$ annihilates into a pair of scalar mediators $\eta$, we are not confronted with the Lee-Weinberg bound and we may have sufficiently large annihilation cross sections $\chi\chi \to \eta\eta$. On the other hand, through couplings of the mediator $\eta$ to neutrinos, similar to the studies \cite{21,22}, this annihilation cross section does
neither disturb big bang nucleosynthesis nor the observed cosmic microwave background radiation \[23\]. Moreover, through the coupling of DM $\chi$ to the mediator $\eta$ we automatically get DM self-interactions \[24\] \[25\] which do not contradict structure formation simulations for different sizes of galaxies \[26\].

The potential of the Higgs doublet $h$ and the two real scalars $\chi$, $\eta$ provides couplings among these elementary particles. These couplings give a changed Higgs phenomenology compared to the SM. For instance, from the coupling of the Higgs boson $h$ to the DM candidate $\chi$, we get an enhanced invisible Higgs-decay rate at colliders, since $\chi$ is expected to be stable and escapes detection. Therefore it is expected to have an enhanced invisible decay rate at the large hadron collider at CERN at the experiments ATLAS and CMS. The signature comes from missing transversal momentum with respect to the collision direction in observations at these experiments.

Scalar DM has been studied, for instance in \[27\] \[31\] and references therein. In \[21\] \[32\] \[33\] \[34\] models are studied with the DM candidate accompanied by a mediator. We arrange these couplings by imposing the right-handed neutrinos to transform under $Z_2'$ rather restricted.

The parameters should provide stability of the potential and the observed electroweak symmetry breaking, that is, from the quadratic terms with respect to the DM mass squared we find from the potential, the domain wall problem \[36\], appearing inevitably for a spontaneously broken discrete symmetry, is expected to be circumvented in the usual way: we assume that the discrete symmetry $Z_2'$ is broken explicitly by an additional cubic mass-parameter term linear in $\eta$. This additional term however is Planck-mass suppressed and therefore only of relevance at very high energies and therefore negligible in our analysis here and not further taken into account.

We want the mediator $\eta$ to decay sufficiently fast in order to not disturb big-bang nucleosynthesis. This can be achieved by a coupling of $\eta$ to right-handed neutrinos. We arrange these couplings by imposing the right-handed neutrinos to transform under $Z_2'$ as

$$\nu_{R,e} \rightarrow \nu_{R,e} + \nu_{R,\mu}, \quad \nu_{R,\mu} \rightarrow -\nu_{R,\mu}, \quad \nu_{R,\tau} \rightarrow -\nu_{R,\tau}, \quad (3)$$

and add appropriate Majorana kinetic terms and mass terms

$$\mathcal{L}_{\nu_R} = i \nu_{R, i} \overline{\nu}_{R, i} - \left( \frac{\lambda_{ij}}{2} \eta \nu_{R, i} \nu_{R, j} + h.c. \right), \quad (4)$$

with $i, j \in \{e, \mu, \tau\}$ the indices denoting the three flavors of the neutrinos. Different choices for the $Z_2'$ symmetry behavior of the right-handed neutrinos in \[35\] could be chosen, however this assignment keeps the number of parameters for the matrix $\lambda_{ij}$ rather restricted.

The parameters should provide stability of the potential and the observed electroweak symmetry breaking, that is, in this case we have a global minimum of the potential with

$$\langle \varphi \rangle = \left( \frac{0}{\sqrt{2} v_h} \right), \quad \langle \eta \rangle = v_\eta, \quad \langle \chi \rangle = 0. \quad (5)$$

We write the neutral component of the Higgs-boson doublet and the scalar $\eta$ expanded about their respective vacuum-expectation values,

$$\varphi(x) = \left( \frac{\varphi^+ (x)}{\sqrt{2}}, \frac{\varphi^0 (x)}{\sqrt{2}} \right), \quad \eta(x) = v_\eta + \eta_c (x), \quad (6)$$

with $h(x)$ and $\eta_c (x)$ real fields. The necessary tadpole conditions for stability at the vacuum yield

$$\frac{1}{2} v_h^2 = \lambda_{h_2} \mu_2^2 - 2 \lambda_{h_2} \mu_2^2 + \frac{1}{2} v_\eta^2 = \lambda_{h_2} \mu_2^2 - 2 \lambda_{h_2} \mu_2^2 \quad (7)$$

For the DM mass squared we find from the potential, that is, from the quadratic terms with respect to the DM field $\chi$ after electroweak symmetry breaking,

$$m_\chi^2 = 2 \mu_2^2 + \lambda_{\chi_2} v^2 + 2 \lambda_{\chi_3} v^2. \quad (8)$$

We get for the mixing matrix of the excitations $h$ and $\eta_c$ in the basis $(h, \eta_c)$

$$\begin{pmatrix} 2 v_h^2 \lambda_h & v_h v_\eta \lambda_{h_2} \\ v_h v_\eta \lambda_{h_2} & 2 v_\eta^2 \lambda_{h_2} \end{pmatrix}. \quad (9)$$
This mixing matrix is diagonalized by an orthogonal matrix with mixing angle $\theta$,
\begin{equation}
\tan(2\theta) = \frac{v_h v_\eta \lambda_{h\eta}}{v_h^2 \lambda_h - v_\eta^2 \lambda_\eta}
\end{equation}
and we get the mass eigenstates $h'$ and $\eta'$. In order to get a Higgs boson with the observed mass of about 125 GeV and a light mediator, we see that the mixing angle, or equivalently the parameter $\lambda_{h\eta}$, has to be rather tiny.

Eventually, from the spontaneous breaking with respect to $\eta$, the right-handed neutrino-mass matrix is generated,
\begin{equation}
(M_\nu)_{ij} = \lambda_{ij} \langle \eta \rangle, \quad i, j = e, \mu, \tau.
\end{equation}

3. PHENOMENOLOGY OF DARK MATTER AND THE MEDIATOR

Let us start with a study of the relic abundance of DM in the model with two additional real scalars. With view on the potential (2) we see that DM ($\chi$) may annihilate into pairs of mediators $\eta'$ (the mass eigenstate is denoted by $\eta'$). This annihilation arises from the quartic $\chi$-$\chi$-$\eta$-$\eta$ coupling, as well as via the trilinear $\chi$-$\chi$-$h$ and $\chi$-$\chi$-$\eta$ couplings which come from the quartic couplings after spontaneous symmetry breaking. At tree level we get from these interactions besides the direct coupling two s-channel diagrams with a Higgs-boson, respectively mediator propagator and one t-channel diagram with a mediator propagator. The s-channel diagram with a Higgs-boson propagator is kinematically suppressed due to the light DM and mediator masses compared to the Higgs-boson mass. Therefore the relic density of DM depends mainly on the coupling parameter $\lambda_{\chi\eta}$ besides the masses $m_\chi$ and $m_\eta'$. For $\eta'$ lighter than $\chi$, the DM annihilation cross section is too large, freeze out occurs too late and the resulting relic density is too small.

In Fig. 1 we show the values for the mediator mass $m_\eta'$ versus the quartic parameter $\lambda_{\chi\eta}$ which provide the observed relic density of $\Omega_{DM} h^2 = 0.1200(12)$ [37] (the value in parenthesis gives the 1-$\sigma$ uncertainty). This study is done for four different values of the DM mass, that is, $m_\chi$ in the range from 0.5 to 2 GeV as indicated in the figure. From this study we see that it is possible for a light DM candidate accompanied by a slightly heavier mediator to achieve the right, that is, indirectly observed relic density. We see that for increasing values of the mediator mass $m_\eta'$, the right relic density can be obtained by strongly raising the quartic coupling $\lambda_{\chi\eta}$ over orders of magnitude as shown in this semi-logarithmic figures. As mentioned above, the annihilation of dark matter into mediators occurs besides the quartic DM mediator coupling via s- and t-channel diagrams. Varying the mediator mass we get competing contributions of the remaining different diagrams corresponding to the different regions of the mediator mass. This behavior is reflected by the kink structure in Fig. 1.

As discussed later in the context of DM self-interactions, we want to avoid a too strong DM self-interaction, therefore we set the quartic parameter $\lambda_\chi$ to zero and consider rather small values for the parameter $\lambda_{\chi\eta}$. The relic density is numerically calculated from the solutions of the Boltzmann equation using the package MICROMEGAS [38, 39]. All other parameters are fixed to $m_{h'} = 125$ GeV, $v_h = 246$ GeV (the standard electroweak parameters), $v_\eta = 3$ GeV, $\lambda_{h\eta} = 1 \times 10^{-7}$, $\lambda_{\chi\chi} = 0.1$, a vanishing parameter $\lambda_\chi$, and we fix the non-vanishing right-handed neutrino-mixing-matrix parameters (11) to $\lambda_{\mu\nu} = \lambda_{e\tau} = 0.1$. The remaining parameters $\lambda_\eta$, $\lambda_\eta$ and the sine of the Higgs-mediator mixing angle, $\sin \theta$, are then determined by the tadpole conditions (7).

We proceed with a study of DM self-interactions; for an introduction to this subject we refer to [26]. Observations show rather flat distributions in the cores in smaller galaxies of dwarf size up to galaxies of the size of our Milky Way. In contrast, simulations of galaxy formations, assuming that DM is collisionless, predict a cusp in the density profile for these sizes of galaxies. This mismatch between observation and simulation can be resolved if DM has self-interactions $\chi\chi \rightarrow \chi\chi$ with a cross section per DM mass of the order of $\sigma/m_\chi \approx 1 \text{ cm}^2/g$ [24] for smaller galaxy sizes up to our Milky Way and is approximately collisionless for sizes larger than our Milky Way up to galaxy clusters, that is, with self-interaction cross sections per DM mass dropping to values below 0.1 cm$^2$/g. Typical rotational velocities for dwarf galaxies are 10 km/s, for Milky Way type galaxies 200 km/s and for galaxy clusters 1000 km/s [26].

In the model considered here with two additional scalars, the self-interactions arise, as can be seen from the potential, from the quartic DM self coupling with parameter $\lambda_\chi$, from the $\chi$-$\chi$-$\eta$-$\eta$ coupling with parameter $\lambda_{\chi\eta}$, and from the $\chi$-$\chi$-$h$-$h$ coupling with parameter $\lambda_{\chi\chi}$. Since we are considering light DM, the contribution from the SM-like Higgs boson $h'$ is suppressed. The quartic coupling $\lambda_\chi$ on the other hand has to be suppressed also since otherwise we immediately overshoot the self-interaction cross sections. In addition to the quartic $\chi$ interaction, we encounter self-interactions from trilinear couplings of $\chi$ with the Higgs boson $h$ and the mediator $\eta$ in s- and t-channel diagrams.

In Fig. 2 we show a study of DM self-interactions. The contour plots show the mediator mass $m_\eta'$ versus the quartic coupling parameter $\lambda_{\chi\eta}$ with respect to the DM self-interaction cross section per DM mass. Similar to the study of the DM relic density we have varied the value of DM in the range of 0.5 GeV to 2.0 GeV as indicated in the figure. We have chosen a relative velocity of 10 km/s, corresponding to dwarf galaxies with a required value of $\sigma(\chi\chi \rightarrow \chi\chi)/m_\chi = 1 \text{ cm}^2/g$ [26]. We see that it is possible to get the observed value for the self-interaction. In this figure we also replicate the results from the DM relic density study, as shown previously in Fig. 1. The correct relic density curve (green line) raises much steeper than the contours for the self-interaction cross section per
Figure 1: Mass of the mediator $m_{\eta'}$ versus the quartic coupling parameter $\lambda_{\chi\eta}$ providing the observed relic density of $\Omega_{\text{DM}} h^2 = 0.1200(12)$ \cite{37} (with 1-$\sigma$ uncertainty). The study shows the values for four different choices of a light DM particle, that is, $m_\chi$ equals 0.5 GeV (upper left), 1.0 GeV (upper right), 1.5 GeV (lower left), and 2.0 GeV (lower right). The width of the line corresponds to the 1-$\sigma$ variation.

DM mass (black line) with respect to increasing values of the mediator mass $m_{\eta'}$. All other parameters are set as above in the study of the DM relic density. In particular we see that both curves intersect, giving parameter values which on the one hand provide the observed DM relic density and on the other hand provide the correct DM-self-interaction cross section. As we can see in this study, even for a vanishing quartic DM-coupling parameter $\lambda_\chi$ the quartic $\chi-\chi-\eta-\eta$ parameter $\lambda_{\chi\eta}$ has to be rather small. In principle multiple exchanges between the DM particles could lead to Sommerfeld enhancement \cite{40} of the self-interactions, however these long-range interactions are for the here considered similar masses of DM and the mediator negligible. Let us note that the Sommerfeld enhancement is implemented in the MICROMEGAS package.

We study also the dependence of the self-interaction cross section per DM mass on the relative velocity of DM. From the explicit calculation of the cross section we find that the self-interacting cross section per DM mass drops orders of magnitude with increasing relative velocities. In particular, if we arrange the parameters such that we get for a relative velocity of $v_{\text{rel}} = 10$ km/s (corresponding to dwarf galaxies) the wanted cross section per DM mass of $\sigma(\chi\chi \to \chi\chi)/m_\chi = 1$ cm$^2$/g, then we find for larger values of the relative velocity, that is, $v_{\text{rel}} > 200$ km/s (corresponding to galaxy sizes larger than our Milky Way) values below 0.1 cm$^2$/g. Therefore, the study as shown in Fig. 2 gives parameters which not only give the right self-interactions of DM, but also naturally drop to values in agreement with observations of density profiles of different sizes of galaxies.

In the early Universe the mediators thermalize with the right-handed neutrinos, but below a temperature of about the mass of the mediator, that is, of the GeV order, the right-handed neutrinos decouple. Since they are stable they contribute to the relic neutrino density. The energy density of radiation of neutrinos $\rho_{\nu}$ with respect to photons $\rho_{\gamma}$ after the time of electron-positron annihilation is \cite{41}

$$
\frac{\rho_{\nu}}{\rho_{\gamma}} = \frac{7}{8} N_{\text{eff}} \left( \frac{4}{11} \right)^{4/3}.
$$

(12)
where the fraction $7/8$ originates from the fermionic Nature of neutrinos and the factor $(4/11)^{1/3}$ comes from the reheating of the photons from electron-positron annihilation. In the Standard Model, the number of effective neutrinos has been calculated to $N_{\text{eff}}^{\text{SM}} = 3.045$ for three neutrino species. Every additional neutrino contributes to the number of effective neutrinos \cite{43, 44},

$$\Delta N_{\text{eff}} = \left( \frac{g(T_{\text{dec}})}{g(T_{\text{dec}}^0)} \right)^{4/3}$$  \hspace{1cm} (13)$$

with $g(T)$ the effective number of degrees of freedom at temperature $T$, where the respective neutrinos decouple. Since the left-handed neutrinos decouple at the MeV scale, but the right-handed neutrinos in the model considered here decouple at the GeV scale, we find

Figure 2: Contour plots of self-interacting DM cross section per DM mass $\sigma(\chi\chi \rightarrow \chi\chi)/m_\chi$ in the $m_\eta'$-$\lambda_{\chi\eta}$ plane for four different values of the light DM mass, that is, $m_\chi$ equals 0.5 GeV (upper left), 1.0 GeV (upper right), 1.5 GeV (lower left), 2.0 GeV (lower right). The legend gives the regions of different values of the DM self-interaction per DM mass in units of $\text{cm}^2/\text{g}$, the central black curve in the figures corresponds to $\sigma(\chi\chi \rightarrow \chi\chi)/m_\chi = 1 \text{ cm}^2/\text{g}$. In the calculation of the cross section per DM mass, the relative velocity of DM particles is set to 10 km/s corresponding to dwarf galaxies. The steeply raising green line replicates the results from Fig. 1 corresponding to the right DM relic density of $\Omega_{\text{DM}}h^2 = 0.1200(12)$ \cite{37} (with 1-$\sigma$ uncertainty).
from \[ [15] \] with \( g(MeV) = 9.5 \) and \( g(GeV) = 76.5 \) for every right-handed neutrino the rather small contribution, \( \Delta N_{\text{eff}} = 0.062 \). On the other hand we get from the recent cosmic microwave background measurement from the Planck satellite experiment (combined with baryon acoustic oscillation), \( N_{\text{eff}} = 2.99 \pm 0.17 \) [27]. This means that the measurement of \( N_{\text{eff}} \) is in agreement with the light DM model considered here. We conclude that no substantial change of microwave background radiation, nor big-bang nucleosynthesis is to be expected (for the case of new scalars coupled to Standard Model particles we refer to the overview [46]).

Eventually we want to study the Higgs phenomenology in the model considered here. Compared to the SM, the Higgs-boson doublet is accompanied by two additional scalars, \( \chi \) and \( \eta \). The potential [2] involves in addition to the quadratic and quartic self couplings also couplings among the three scalars. As discussed in section 2 we encounter a mixing of the neutral component of the doublet \( h \) with the mediator \( \eta \) forming a Higgs mass eigenstate \( h' \). From (10) we see that the tangent of twice the mixing angle is proportional to the potential parameter \( \lambda_{h\eta} \).

Since the Higgs boson \( h \) couples on the one hand to the DM particle \( \chi \) with coupling strength \( \lambda_{h\chi} \) and on the other hand has the usual Yukawa couplings to the fermions, we see that DM interacts with the hadrons of the nucleon. This DM-nucleon interaction is therefore expected to be detectable at direct detection experiments – in the introduction we have mentioned some direct-detection experiments searching for DM-nucleon interactions.

Moreover, the coupling of the DM candidate to the Higgs boson opens the possibility to detect DM at collider experiments. In particular, since we are considering light DM, that is, we assume to have \( m_{h'} > 2m_{\chi} \), the SM-like Higgs boson \( h' \) can decay into a pair of DM particles \( \chi \). Since the DM particles are assumed to be stable, these decays do not show visible traces in the detector components of collider experiments. However, these events can be discovered from the observation of missing transversal momentum. The invisible decay width of the SM-like Higgs boson \( h' \) into a pair of \( \chi \)'s at tree-level reads

\[
\Gamma_{h' \rightarrow \chi\chi}^{\text{inv}} = \frac{\lambda_{h\chi}^2 v^2 \beta_{\chi}}{8 \pi m_{h'}}, \quad \text{with } \beta_{\chi} = \sqrt{1 - \frac{4 m_{\chi}^2}{m_{h'}^2}}. \tag{14}
\]

This decay width is obviously proportional to the quartic potential parameter \( \lambda_{h\chi} \) squared. In Fig. 3 we study the branching ratios of the SM-like Higgs boson \( h' \) varying this quartic coupling parameter \( \lambda_{h\chi} \). In this study we have chosen all other parameters as mentioned above with a DM mass of \( m_{\chi} = 0.5 \) GeV and the mediator slightly heavier, that is, \( m_{\eta'} = 0.55 \) GeV. This pair of values together with the parameter \( \lambda_{\chi\eta'} = 10^{-4} \) yields the correct values for the relic density of DM and for the DM self-interactions; see Fig. 2. Since the Higgs boson \( h' \) has a tiny mediator \( \eta \) component it could also decay into neutrinos and in addition there are couplings of the Higgs boson to mediator particles. However for the tiny mixing parameter \( \lambda_{h\eta} \) considered here these contributions are negligible, as shown explicitly in Fig. 3.

As we can see in this study we find for larger values of the parameter \( \lambda_{h\chi} \) a dominant Higgs-decay channel into DM particles \( \chi \). Depending on the parameter \( \lambda_{h\chi} \) we find therefore an enhanced invisible branching ratio compared to the SM. Let us remind us that in the SM the Higgs boson can only decay invisibly via \( Z \) bosons which subsequently decay into neutrinos, that is, \( h \to ZZ \to 4\nu \).

Since the invisible decay rate it restricted from the missing transversal momentum searches at the CMS and ATLAS experiments at the LHC this translates into an upper bound on the coupling strength between the Higgs boson and the DM particle. The ATLAS collaboration has recently measured [17] the upper limits of the invisible branching ratio and finds 0.13 at the 95% confidence level in agreement with the Standard Model. The CMS collaboration has published [15] an invisible branching ratio of 0.24 compared to the Standard Model expectation of 0.23. From the calculation of the branching ratios as shown in Fig. 3 we get for an upper bound of 0.13 for the invisible branching ratio the constraint \( \lambda_{h\chi} < 0.01 \) for the potential parameter. Let us also mention the context of the coupling parameter \( \lambda_{h\chi} \) to the spin-independent DM-nucleon cross section, which reads [37]

\[
\sigma_{hN}^{\text{SI}} = \frac{\lambda_{h\chi}^2 m_N^2}{f_N^2 m_h} \left( \frac{m_{\chi} + m_N}{m_{h'}} \right)^2. \tag{15}
\]

Here \( m_N \) is the nucleon mass and \( f_N \) a nucleon form factor. Based on phenomenological and lattice-QCD calculations, a Higgs-nucleon form factor of \( f_N = 0.308(18) \) has been calculated [15]. The coupling parameter \( \lambda_{h\chi} \) which appears in the DM-nucleon cross section (15) can now, using (14), be replaced by the invisible decay rate. Therefore, the measured upper bound on the invisible decay rate in Higgs-boson decays translates into an upper bound for the DM-nucleon cross section [17]. The 90% upper confidence limits on the spin-independent DM-nucleon scattering cross section are compared to the direct detection limits in [15]. It is shown that the CMS and ATLAS results from the measurement of the invisible decay of the Higgs boson are orders of magnitudes more sensitive than direct detection experiments for scalar DM masses up to 7 GeV. These are currently the most stringent limits available – assuming that there is a Higgs-DM coupling.

4. CONCLUSIONS

The rotational movement of stars in galaxies is typically faster than expected from the visible mass. Attempts to modify gravity appear disfavored due to the observation of exceptional galaxies showing no mismatch. New, yet undiscovered, elementary dark matter particles
could solve the puzzle. However, direct detection experiments of dark matter-nucleon interactions have not revealed any dark matter particle. The lowest bounds in these experiments come from searches of dark matter particles with a mass of the order of 100 GeV. Therefore it appears quite natural to look for light DM particles. In case the light DM candidate is leptonic with a mass below 2 GeV – the so-called Lee-Weinberg bound – this would lead to an overcrowding of the Universe. Here we have discussed a simple model with two additional scalars, odd under discrete symmetries, not restricted by the Lee-Weinberg bound. The scalar potential of the model provides interactions among the DM candidate, a mediator and a SM-like Higgs boson. These interactions provide DM annihilation into a pair of mediators. The mediators in turn decay into pairs of right-handed neutrinos. This process is sufficiently fast, that is, before big-bang nucleosynthesis takes place, and in particular neither DM nor the mediator decay into Standard Model particles. Therefore we neither expect displaced vertices in colliders, decays into muons, nor changed meson decays.

The objective of this study is to investigate the agreement of the simple light DM model with different observations in telescopes, underground experiments, and collider experiments with respect to DM. The relic density in this two-real-scalar extension has been computed, and it has been shown that, for a dark matter mass in the range of 0.5 GeV to 2 GeV and a mediator slightly heavier, we can get the observed relic density. Also we have studied dark matter self-interactions which may explain the observation of rather flat DM density profiles in cores of dwarf galaxies up to galaxies of the size of our Milky Way. In the model considered here the interaction of DM with the mediator provides these self-interactions quite naturally. Moreover, due to the Nature of these interactions transmitted by the mediator, these self-interactions automatically drop for larger relative velocities in galaxy clusters – in agreement with simulations of galaxy formations.

Since the mediator decays into right-handed neutrinos which are stable, these neutrinos contribute to the neutrino background radiation. Indirectly this background could change big-bang nucleosynthesis or the cosmic microwave background. This effect is encoded in the number of effective neutrinos which is measured at the Planck satellite experiment yielding \( N_{\text{eff}} = 2.99 \pm 0.17 \) \cite{37}, whereas in the SM the calculation gives \( N_{\text{eff}}^{\text{SM}} = 3.045 \) \cite{42} in agreement with the one sigma deviation of the observation. In the two-singlet model we calculate that every right-handed neutrino contributes \( \Delta N_{\text{eff}} = 0.062 \) to the effective number of neutrinos. This originates from the fact that the right-handed neutrinos decouple earlier as the left-handed neutrinos in the evolution of the Universe. The effective number of neutrinos is therefore in agreement with observation.

Eventually we have studied the Higgs-boson phenomenology compared to the Standard Model. The interactions of the Higgs boson with the DM candidate and the mediator give on the one hand a mixing of the Higgs boson with the mediator and on the other hand provides interactions of the Higgs boson with the DM particle. These latter interactions in turn give rise to interactions of DM with nucleons – observable at underground DM-nucleon detection experiments, but also detectable at collider experiments: the Higgs bosons produced at LHC in the CMS or ATLAS detectors may decay into stable dark matter particles, detectable as events with missing transverse momentum. Upper bounds on such searches have been published by both experiments and are here translated into upper bounds on the corresponding DM-Higgs coupling parameter.

![Figure 3: Branching ratios of the SM-like Higgs boson \( h' \) depending on the quartic potential parameter \( \lambda_{hX} \). The decay rates are for a pair of DM particles \( \chi\chi \), for a \( b\)-quark pair \( b\bar{b} \), gluons \( gg \), leptons \( ll \), \( c\)-quarks \( c\bar{c} \), and branching rates of nearly the same size for photons \( \gamma\gamma \) and a \( s\)-quark pair \( s\bar{s} \).](image-url)
Eventually we would like to mention that it is quite striking that a simple extension of the Standard Model with two real singlets complies with the different types of DM searches discussed and also shows no contradiction with our understanding of the evolution of the Universe.

Acknowledgments

The work is supported, in part, by the Grants UBB Materia obscura y los bosones de Higgs, No. DIUBB 193209 /R and FONDECYT regular with No. 1200641.

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