Assisted freeze-out

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Abstract

We explore a class of dark matter models with two dark matter candidates, only one interacts with the standard model sector. One of the dark matter is thermalized with the assistance of the other stable particle. While both stable particles contribute to the total relic density only one can elastically scatter with nuclei, thus effectively reducing the direct detection rate.

Keywords: Freeze-out, Multi dark matter
I. INTRODUCTION

The most natural explanation for the astrophysical and cosmological indications of a large component of dark matter in the Universe is a new weakly interacting massive particle that behaves as cold dark matter. Such dark matter candidates are found in different extensions of the standard model (SM) \[1\]. However, dark matter (DM) could be composed of more than one particle, and several multi component DM models have been suggested recently \[2–8\]. Interest for multi component DM arose, in particular, from hints for signals in cosmic rays as well as in direct detection experiments corresponding to two completely different DM mass scales. On the one hand, the PAMELA experiment \[9\] has reported an cosmic ray excess of positrons which would be consistent with a TeV scale DM candidate annihilating mainly into leptons. On the other hand, DAMA \[10\], CoGeNT \[11\] and CRESST \[12\] have all reported excesses in the direct detection rate that would be compatible with DM around 10 GeV. Even though there is no conclusive evidence that these signals are due to DM, it is interesting to investigate multi component DM models to expand the range of DM models at a time when DM searches in indirect, direct and collider experiments are increasing their sensitivities. Furthermore, replacing the usual R-parity symmetry that guarantees the stability of the lightest R-parity odd particle by an enlarged symmetry group allows not only multiple DM candidates but also new freeze-out mechanisms. In particular, the semi-annihilation mechanism where two DM particles annihilate into another DM particle and a SM particle was proposed in Ref. \[13\].

In this paper, we propose a new type of freeze-out mechanism, assisted freeze-out, within the framework of multi component DM models. In this new freeze-out mechanism, one DM candidate can be thermalized only through the assistance of the other stable particle. Thus, the decoupling of one DM particle from the thermal bath is influenced by the other DM particle. Consequently, the relic density of DM is solved by using two coupled Boltzmann equations for two stable fields. In the analysis of the right-handed sneutrino DM \[14\], a similar situation has been already considered even though this model has only one stable particle. After setting the Boltzmann equations, we construct a simple model with two hidden DM sectors corresponding to two new \(U(1)\) gauge symmetries, only one of which interacts with the SM sector. This is achieved through kinetic mixing of the new and standard gauge bosons. The DM particles are assumed to be Dirac fermions. We then show
how both particles can contribute to the relic density of DM while only one can scatter elastically on nucleons. Although the direct detection rate tends to be rather high in this model, we show examples, where all constraints can be satisfied, including a case with a DM candidate around 10 GeV.

This paper is organized as follows. The basic set-up is presented in section 2. An explicit model is constructed in section 3 and the implications for the relic density of DM as well as for the direct detection rates on nucleons are studied. Section 4 contains our conclusions.

II. BASIC SET-UP

We consider the case where $\chi_1$ and $\chi_2$ are stable dark matter candidate particles. This can be achieved, for example, with a $Z_2 \otimes Z'_2$ symmetry. We assume that $m_2 > m_1$ with $m_i = m_{\chi_i}$ and that $\chi_2$ can only annihilate into $\chi_1$ and not into SM particles.

A set of coupled Boltzmann equations describe the evolution of the number density $n_i$ of particle $\chi_i$. In the following, $X$ stands for some SM particles and $m_X < m_1$.

\[
\frac{dn_2}{dt} + 3Hn_2 = -\langle \sigma v \rangle_{22 \to 11} \left[ (n_2)^2 - \frac{(n_2^{eq})^2}{(n_1^{eq})^2} (n_1)^2 \right],
\]

\[
\frac{dn_1}{dt} + 3Hn_1 = -\langle \sigma v \rangle_{11 \to XX} \left[ (n_1)^2 - (n_1^{eq})^2 \right] - \langle \sigma v \rangle_{11 \to 22} \left[ (n_1)^2 - \frac{(n_1^{eq})^2}{(n_2^{eq})^2} (n_2)^2 \right]
\]

\[
= -\langle \sigma v \rangle_{11 \to XX} \left[ (n_1)^2 - (n_1^{eq})^2 \right] + \langle \sigma v \rangle_{22 \to 11} \left[ (n_2)^2 - \frac{(n_2^{eq})^2}{(n_1^{eq})^2} (n_1)^2 \right],
\]

where $H$ is the Hubble parameter and $n_i^{eq}$ is the equilibrium number density of particle $i$. In solving the Boltzmann equations (1) and (2), it is useful to introduce the variable $Y_i \equiv n_i/s$ describing the actual number of particle $i$ per comoving volume, where $s$ is the entropy density of the Universe. Solving these coupled Boltzmann equations, one can find $Y_i$ as a function of $x \equiv m_1/T$.\footnote{Note that as opposed to the familiar case of coannihilation \cite{15}, one cannot assume that $n_1^{eq}/n_2^{eq} \simeq n_1/n_2$ which relies on the fact that scattering with background SM particles, e.g. $\chi_2X \rightarrow \chi_1X'$, occurs at a high rate. In the assisted freeze-out scenario, such reactions do not take place. Thus, we do not use this approximation.}

In the new variables, the Boltzmann equations are recast as

\[
\frac{dY_2}{dx} = -x^{-2} \lambda_{22 \to 11} \left[ (Y_2)^2 - \frac{(Y_2^{eq})^2}{(Y_1^{eq})^2} (Y_1)^2 \right],
\]

\[
\frac{dY_1}{dx} = -x^{-2} \lambda_{11 \to XX} \left[ (Y_1)^2 - (Y_1^{eq})^2 \right] + x^{-2} \lambda_{22 \to 11} \left[ (Y_2)^2 - \frac{(Y_2^{eq})^2}{(Y_1^{eq})^2} (Y_1)^2 \right],
\]
where
\[ \lambda_{ij \rightarrow kl} \equiv \left[ \frac{s}{1/T} \right]_{x=1} \langle \sigma v \rangle_{ij \rightarrow kl}(x). \] (5)

The equilibrium number of particle \( i \) per comoving volume \( Y_i^{\text{eq}} \equiv n_i^{\text{eq}}/s \) has the following forms:
\[ Y_1^{\text{eq}} = \frac{g_1}{g_{ss}} \frac{45}{4\pi^4} x^2 K_2[x], \quad Y_2^{\text{eq}} = \frac{g_2}{g_{ss}} \frac{45}{4\pi^4} (rx)^2 K_2[rx], \] (6)
where \( r \equiv m_2/m_1 \), \( g_i \) is the number of internal degrees of freedom of particle \( i \) and \( K_2[x] \) is the modified Bessel function.

The heavier particle \( \chi_2 \) will not be in thermal equilibrium during freeze-out unless \( \langle \sigma v \rangle_{22 \rightarrow 11} \ll \langle \sigma v \rangle_{11 \rightarrow XX} \). Thus, solving the Boltzmann equation in the case where many different processes contribute to annihilation would be complicated. In this analysis, we assume that \( s \)-wave annihilation processes dominate. This allows to simplify the computation of the thermally averaged cross section for \( \chi_2 \) when solving the Boltzmann equation while illustrating the dependence of the relic density on each parameter.

If we limit our analysis to \( s \)-wave annihilation for simplicity, we can simply express the relevant \( s \)-wave matrix elements as
\[ \alpha \equiv M_{22 \rightarrow 11} = M_{11 \rightarrow 22}, \quad \beta \equiv M_{11 \rightarrow XX}. \] (7)

It is then straightforward to solve the two coupled Boltzmann equations (3) and (4) to obtain the abundance of \( \chi_1 \) and \( \chi_2 \). To illustrate the assisted freeze-out mechanism, we choose the DM masses \( m_1 = 100 \text{ GeV} \) and \( m_2 = 150 \text{ GeV} \), taking different values for the annihilation amplitudes \( \alpha \) and \( \beta \). The evolution of the abundances \( Y_1, Y_2 \) are displayed in fig. for \( \alpha \) and \( \beta \): \( (\alpha, \beta) = (0.1, 1), (0.01, 1) \) and \( (1, 0.1) \). The blue and red solid lines are respectively \( Y_1 \) and \( Y_2 \), and dashed lines show the corresponding equilibrium comoving number densities. When \( \chi_2 \) interacts weakly with \( \chi_1 \) (see the top panels of fig.), the abundance of \( \chi_1 \) is mainly determined by its interaction with SM particles and due to the weak interactions the final DM abundance is dominated with \( \chi_2 \). A comparison of the cases \( \alpha = 0.01 \) and \( \alpha = 0.1 \) shows that the abundances of both particles are reduced by the interactions between \( \chi_1 \) and \( \chi_2 \). When the interactions of \( \chi_1 \) with \( \chi_2 \) are stronger than with SM particles, i.e. \( \alpha \gg \beta \) (the bottom panel of fig.), the freeze-out of \( \chi_2 \) is delayed and its abundance is, consequently, much reduced. Because of the interactions with \( \chi_2 \), the abundance of \( \chi_1 \) increases in comparison with the previous case. The abundance of \( \chi_1 \) now largely dominates over that of \( \chi_2 \).
FIG. 1: The evolution of the abundances of $\chi_1$ (blue) and $\chi_2$ (red) per comoving volume as a function of $x \equiv m_1/T$. Dashed lines are the equilibrium comoving number densities. Dark matter masses are fixed as $m_1 = 100$ GeV and $m_2 = 150$ GeV. The corresponding matrix elements are shown in each figure.

III. DARK MATTER CANDIDATES WITH TWO EXTRA $U(1)'$S

As an explicit example of how the assisted freeze-out mechanism can occur in a specific DM model, we consider a toy model with a hidden sector containing two extra Abelian gauge symmetries, $U(1)'$ and $U(1)''$, and two Dirac fermions $\psi_1$ and $\psi_2$. The particle $\psi_1$ is charged under both $U(1)'$ and $U(1)''$ gauge symmetries, and $\psi_2$ is only charged under the $U(1)''$ symmetry. If $\psi_1$ is the lightest particle charged under the $U(1)'$ symmetry and $\psi_2$ is the lightest one only charged under the $U(1)''$ symmetry, then $\psi_1$ and $\psi_2$ can be naturally stable particles like the electron in the SM. We assume that the hidden sector couples to the SM sector only through a kinetic mixing between $U(1)'$ and $U(1)_Y$. Then, the full Lagrangian
including this kinetic mixing is

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2} \sin \epsilon \hat{B}_{\mu \nu} \hat{X}^{\mu \nu} - \frac{1}{4} \hat{X}'_{\mu \nu} \hat{X}^{\mu \nu} - \frac{1}{4} \hat{X}''_{\mu \nu} \hat{X}^{\mu \nu} + \frac{1}{2} m_{\hat{X}'}^2 \hat{X}'^2 + \frac{1}{2} m_{\hat{X}''}^2 \hat{X}''^2$$

$$- g X' \bar{\psi}_1 \gamma^\mu \psi_1 - g X'' \bar{\psi}_2 \gamma^\mu \psi_2$$

where the hidden $U(1)$'s are assumed to be spontaneously broken leading to the gauge boson masses $m_{\hat{X}'}$ and $m_{\hat{X}''}$. In this toy model, we will neglect the possible effect of a mixing between the SM and hidden sector Higgs fields for the simplicity of analysis. In the SM sector, the mass of the $\hat{Z}$ gauge boson is $m_{\hat{Z}}$ and the gauge couplings are denoted by $\hat{g} = e/s_{\hat{W}}$ and $\hat{g}' = e/c_{\hat{W}}$.

The kinetic and mass mixing terms are diagonalized away by the following transformation:

$$\hat{B} = c_{\hat{W}} A - (t_{\hat{\epsilon}} s_{\hat{W}} + s_{\hat{W}} c_{\hat{\epsilon}}) Z + (s_{\hat{W}} s_{\hat{\epsilon}} - t_{\hat{\epsilon}} c_{\hat{W}}) Z'$$

$$\hat{W}_3 = s_{\hat{W}} A + c_{\hat{W}} c_{\hat{\epsilon}} Z - c_{\hat{W}} s_{\hat{\epsilon}} Z'$$

$$\hat{X}' = \frac{s_{\hat{\epsilon}}}{c_{\hat{\epsilon}}} Z + \frac{c_{\hat{\epsilon}}}{c_{\hat{W}}} Z'$$

$$\hat{X}'' = Z''$$

where the rotation angle $\hat{\epsilon}$ is determined by

$$\tan 2\hat{\epsilon} = -\frac{m_{\hat{Z}}^2 s_{\hat{W}} \sin 2\epsilon}{m_{\hat{X}'}^2 - c_{\hat{\epsilon}}^2 s_{\hat{\epsilon}}^2 s_{\hat{W}}^2}$$

and the weak mixing angle $s_{\hat{W}}$ is very close to the physical value $s_W$ due to the stringent $\rho$ parameter constraint. Then, the $Z$ and $Z'$ gauge bosons obtain the redefined masses:

$$m_{\hat{Z}}^2 = m_{\hat{Z}}^2 (1 + s_{\hat{W}} t_{\hat{\epsilon}} t_{\hat{\epsilon}})$$

$$m_{\hat{Z}'}^2 = m_{\hat{X}'}^2 (1 + s_{\hat{W}} t_{\hat{\epsilon}} t_{\hat{\epsilon}})$$

on the other hand, the $Z''$ gauge boson mass is the same as the $\hat{X}''$ gauge boson: $m_{\hat{Z}''}^2 = m_{\hat{X}''}^2$.

Let us list all the interaction vertices of the $W', Z, Z'$ and $Z''$ gauge bosons relevant for our analysis. The $Z''$ boson has the following non-modified couplings:

$$\mathcal{L} = -g_{X''} Z''_{\mu} [\bar{\psi}_1 \gamma^\mu \psi_1 + \bar{\psi}_2 \gamma^\mu \psi_2]$$

However, the other gauge bosons have modified couplings. In order to describe the interac-
tion vertices of $W, Z$ and $Z'$, let us define the various couplings, $g$'s, as follows:

$$\mathcal{L} = W^{\mu}_{\mu} + g_f^W [\bar{\nu} \gamma^\mu P_L e + \bar{u} \gamma^\mu P_L d] + c.c.$$

$$+ Z_\mu \left[ g_{fL}^Z f \bar{\gamma}^\mu P_L f + g_{fR}^Z f \bar{\gamma}^\mu P_R f + g_{\psi_1}^Z \bar{\psi}_1 \gamma^\mu \psi_1 \right] + g_W^Z \left[ (ZW^+ W^-) \right]$$

$$+ Z'_\mu \left[ g_{fL}^{Z'} f \bar{\gamma}^\mu P_L f + g_{fR}^{Z'} f \bar{\gamma}^\mu P_R f + g_{\psi_1}^{Z'} \bar{\psi}_1 \gamma^\mu \psi_1 \right] + g_W^{Z'} \left[ (Z'W^+ W^-) \right]$$

$$+ h \left[ g_{ZZ} h Z_\mu Z_\mu Z_\mu Z_\mu + g_{Z'Z'} h Z_\mu Z_\mu Z_\mu Z_\mu \right].$$  \hspace{1cm} (14)$$

One can find these redefined couplings expressed by the physical observables (unhatted parameters) in the appendix of [16] which describes a hidden sector with only a $U(1)'$ symmetry. The only difference between the gauge boson sectors of two models is the additional gauge boson associated with $U(1)''$ that we assume to be decoupled from the SM sector.

A. Relic density

The relic abundances of two stable particles $\psi_{1,2}$ are determined by solving two coupled Boltzmann equations (3) and (4). The thermal relic density of DM is the sum of the relic densities of the two candidates $\psi_{1,2}$, $\Omega_{\psi_1} h^2 = \Omega_{\psi_2} h^2$. The free parameters of the model include the mass parameters $m_1, m_2, m_{Z'}$, and $m_{Z''}$ as well as the hidden gauge couplings $g_{X'}$ and $g_{X''}$ and the kinetic mixing parameter $\sin \epsilon$. In order to examine the dependence of the relic abundance of $\psi_{1,2}$ on each parameter, in our numerical analysis we search for the parameter space which satisfies the observed DM relic density limit [17], in the $m_1 - m_{Z''}$ plane fixing the other parameters.2

The annihilation of $\psi_1$ pairs into SM particles proceeds through $s$–channel exchange of $Z$ and $Z'$: possible final states are $f \bar{f}, W^+ W^-$ and $Zh$. The dominant annihilation mode depends on the DM mass $m_1$, into only fermions when $m_1 < M_W$ into additionally gauge bosons otherwise. In addition, all amplitudes are proportional to the kinetic mixing $\sin \epsilon$ and the coupling $g_{X'}$. The $s$–channel exchange can be strongly enhanced by a resonance effect. We therefore expect the relic density to drop rapidly when $m_1 \approx m_Z/2$ or $m_{Z'}/2$. The

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2 In all the numerical analysis, we assume that $m_{Z''} > 2m_1$ to avoid a stable $Z''$. Moreover, for the $Z'$ boson, electroweak precision test bounds and LHC detection prospects were already studied in Ref. [16, 18]. We fix the kinetic mixing to its experimental upper bound given in [16, 18]. Smaller values of $g_{X'} \sin \epsilon$ are, of course, even less constrained.
annihilation of $\chi_2$ proceeds uniquely through the exchange of $Z''$ and is therefore determined solely by the coupling $g_{X''}$ and the masses $m_{Z''}, m_2$.

The relic densities $\Omega_{\psi_1} h^2$ and $\Omega_{\psi_2} h^2$ are displayed in fig. 2 in the $m_1 - m_{Z''}$ plane for the reference case of $g_{X'} = 0.5, g_{X''} = 0.9, m_2 = 150$ GeV and $m_{Z'} = 150$ GeV. The enhanced annihilation near the $Z$ ($Z'$) resonances explains the drop in $\Omega_{\psi_1} h^2$ for $m_1 \approx 45 \ (75)$ GeV. Similarly, the enhanced annihilation near the $Z''$ resonance means that $\Omega_{\psi_2} h^2$ is small for $m_{Z''} \approx 300$ GeV. Note that there is a lower bound, $m_{Z''} > 2m_1$ because we impose the condition that the $Z''$ is not stable. The total DM relic density $\Omega_{\psi_1} h^2 + \Omega_{\psi_2} h^2$ is displayed in the bottom panel of fig. 2. The region between two thick dashed lines represents the points consistent with the recent WMAP relic density result [17], allowing for 3$\sigma$ experimental uncertainties. In two bands at low values of $m_{Z''}$ where $m_1 \approx 35$ GeV and $m_1 \approx 110$ GeV, the DM relic density is dominated by $\psi_1$ while $\Omega_{\psi_2} h^2$ dominates for $m_{Z''} \approx 1$ TeV. In the transition between these regions, both particles give a significant contribution to the total DM relic density.

The annihilations of $\psi_1$ and $\psi_2$ are controlled by the hidden gauge couplings $g_{X'}$ and $g_{X''}$, respectively. To study their effect, we reduce each coupling separately. In fig. 3, the total DM thermal relic density $\Omega_{\psi_1} h^2 + \Omega_{\psi_2} h^2$ is shown for the two representative cases $g_{X'} = 0.3$ or $g_{X''} = 0.3$ in the $m_1 - m_{Z''}$ parameter space. For the other parameters, we take the same values as in the reference case of fig. 2. Comparing the bottom panel of fig. 2 with $(g_{X'}, g_{X''}) = (0.5, 0.9)$ with the left panel of fig. 3 with $(g_{X'}, g_{X''}) = (0.3, 0.9)$, one sees that the allowed bands at low values of $m_{Z''}$ move closer to either $m_Z/2$ or $m_{Z''}/2$. This is because as the hidden gauge coupling $g_{X'}$ decreases, the annihilation of $\psi_1$ is weaker, and stronger resonance effect is therefore required to obtain appropriate annihilation strength. This also means that in the mass region between the two resonances, $m_1 \approx 60$ GeV, the relic density of $\psi_1$ increases. Therefore, the total DM density can be in agreement with the measured value for lighter $Z''$ masses. When the hidden gauge coupling is decreased to $g_{X''} = 0.3$, the requirement of a stronger resonance effect means that the region in agreement with the observed value of the relic density moves to lower values of $m_{Z''}$, see the right panel of fig. 3.

The interactions of the DM particle $\psi_1$ also depend on the $Z'$ mass $m_{Z'}$. In fig. 4, we display the total DM relic abundance $\Omega_{\psi_1} h^2 + \Omega_{\psi_2} h^2$ in the $m_1 - m_{Z''}$ parameter space to illustrate the dependence on the $Z'$ mass $m_{Z'}$. In the figure, the left panel corresponds to $m_{Z'} = 200$ GeV and the right panel to $m_{Z'} = 25$ GeV. In this analysis, we used the
FIG. 2: Contour plots for the relic abundances of the dark matter particles \( \psi_1 \) (top-left), \( \psi_2 \) (top-right) and the total (bottom) in the \( m_1 - m_{Z'} \) plane. We fix the other parameters as follows: \( g_{\chi'} = 0.5, \ g_{\chi''} = 0.9, \ m_2 = 150 \text{ GeV} \) and \( m_{Z'} = 150 \text{ GeV} \). In the bottom panel, the region between two thick dashed lines is allowed by the WMAP result on the DM relic density.

reference values for the other parameters. As can be seen clearly from fig. 4, there are two well separated resonance regions, one around \( m_{Z}/2 \), the other near \( m_{Z'}/2 \). In addition, the right panel shows that the lighter particle \( \psi_1 \) can be a DM candidate around 10 GeV when \( Z' \) is light. Thus, this model could have a light DM candidate as hinted by some direct
FIG. 3: Contour plots for the total relic abundance of the dark matter particles $\psi_1$ and $\psi_2$ in the $m_1 - m_{Z''}$ plane. The left and right panels correspond to $(g_{X'}, g_{X''}) = (0.3, 0.9)$ and $(0.5, 0.3)$ respectively. The other parameters are fixed at the reference parameter values. In each plane, the region between two thick dashed lines is preferred by the WMAP DM relic density result.

detection results, see more details in the next section.

Finally, we investigate the dependence of the DM relic density on the $\psi_2$ mass $m_2$. In fig. 5, the total DM relic density of $\psi_1$ and $\psi_2$ is shown for the representative case $m_2 = 200$ GeV in the $m_1 - m_{Z''}$ plane which is to be compared with fig. 2 for which $m_2 = 150$ GeV. All other parameters are kept to the reference values, $g_{X'} = 0.5$, $g_{X''} = 0.9$ and $m_{Z'} = 150$ GeV. As expected, for larger $\psi_2$ mass, the preferred parameter space moves to larger $m_{Z''}$ region, now $m_{Z''} \approx 1.2$ TeV due to the change of the $m_{Z''}$ resonance region while the preferred value for $m_1$ at low values of $m_{Z''}$ is not much shifted. One can see the tendency from the bottom panel of fig. 2 and fig. 5.

B. Direct detection

We have shown that this simple model realizing the assisted freeze-out mechanism can satisfy the observed DM relic abundance. We now discuss the influence of this mechanism on the prospects of observing DM in direct detection experiments. The most distinguishing
FIG. 4: Contour plots for the total relic abundance of the dark matter particles $\psi_1$ and $\psi_2$ in the $m_1 - m_{Z'}$ plane for the cases $m_{Z'} = 200$ GeV and $m_{Z'} = 25$ GeV. The parameters $g_{X'}, g_{X''}$ and $m_2$ are fixed as the reference values. The regions between two thick dashed lines are allowed by the recent DM relic density observation.

feature of the assisted freeze-out scenario compared with the other multi-DM scenarios is that only lighter DM particle $\psi_1$ can directly interact with the SM sector. Consequently, only $\psi_1$ can be detected in DM direct detection experiments. The lighter DM particle $\psi_1$ can elastically scatter off a target nucleus through $t-$channel $Z$ and $Z'$ gauge boson exchange. One can easily calculate the spin-independent (SI) $\psi_1$-nucleon cross section using the following effective operator:

\[
\mathcal{L}_{\text{eff}} = b_f \bar{\psi}_1 \gamma_\mu \psi_1 \bar{f} \gamma^\mu f,
\]

where

\[
b_f = \frac{g_{Z'}^2 (g_{fL}^2 + g_{fR}^2)}{2 m_{Z}^2} + \frac{g_{Z}^2 (g_{fL}^2 + g_{fR}^2)}{2 m_{Z'}^2}.
\]

The current experimental bounds on $\sigma_n^{\text{SI}}$ are extracted from DM direct detection experiment results assuming that the couplings to protons ($f_p$) and neutrons ($f_n$) are equal. However, the couplings are different in this model. In order to compare directly with the limits on $\sigma_n^{\text{SI}}$ given by experiments, we thus use the normalized cross section on a point-like
FIG. 5: Contour plots for the total relic abundance of the dark matter particles $\psi_1$ and $\psi_2$ in the $m_1 - m_{Z'}$ plane for the case $m_2 = 200$ GeV. The reference values are used for the other parameters. The regions between two thick dashed lines are allowed by the recent DM relic density observation.

nucleus $^{19}$:

$$
\sigma_{\psi_1N}^{\text{SI}} = \frac{\mu_{\psi_1}^2}{\pi} \frac{[Zf_p + (A - Z)f_n]^2}{A^2}.
$$

(17)

Moreover, the experimental limits are also extracted assuming that the local DM density is due to only one DM candidate. However, in our model only the lighter particle $\psi_1$ can be observed by DM direct detection experiments. Therefore, we rescale the SI scattering cross section by $\Omega_{\psi_1}h^2/\Omega_{DM}h^2$ assuming that the contribution of each DM particle to the local density is the same as their contribution to the relic density.

In fig. 6 we present the normalized SI scattering cross sections of $\psi_1$ as a function of $m_1$ for $(g_{X'}, m_{Z'}) = (0.5, 150$ GeV), $(0.5, 200$ GeV) and $(0.3, 200$ GeV) fixing $g_{X''} = 0.9$ and $m_2 = 150$ GeV. The value of $m_{Z'}$ is chosen to follow the contour $\Omega_{\psi_1}h^2 + \Omega_{\psi_2}h^2 = 0.13$. The first feature is that the rescaled cross section decreases around the resonance points $(m_1 \approx m_Z/2, m_{Z'}/2)$, this is simply because $\Omega_{\psi_1}h^2$ decreases sharply near the resonances. Actually, the elastic cross section itself has a much milder and smoother dependence on $m_1$.

Comparing the cases $(g_{X'}, m_{Z'}) = (0.5, 150$ GeV) and $(0.5, 200$ GeV), one can see that the cross sections become smaller for larger $m_{Z'}$ because of the suppressed contribution of the $Z'$.
FIG. 6: SI scattering cross section of $\psi_1$ normalized to Xenon target nucleus and rescaled by $\Omega_{\psi_1} h^2 / \Omega_{\text{DM}} h^2$ (see text). The red solid, green dotted and blue dot-dashed lines correspond to $(g_{X'}, m_{Z'}) = (0.5, 150 \text{ GeV}), (0.5, 200 \text{ GeV})$ and $(0.3, 200 \text{ GeV})$, respectively. $g_{X''}$ and $m_2$ are fixed to 0.9 and 150 GeV. The experimental limit, which is taken from XENON100 [20], is shown by the black dashed line.

exchange diagram. Thus, one can recover a region where the elastic cross section drops below the limit of XENON100 [20]. Both the $Z$ and $Z'$ exchange diagrams are also suppressed for smaller values of $g_{X'}$, we therefore obtain smaller cross sections in this case as can be seen by comparing the curves for $(g_{X'}, m_{Z'}) = (0.5, 200 \text{ GeV})$ and $(0.3, 200 \text{ GeV})$. Note that in fig. 6 there is a discontinuity in the direct detection curves when $m_{Z'} = 200 \text{ GeV}$, which is because the $\Omega h^2 = 0.13$ contour is also disconnected, see fig. 4. In our analysis, we fix $\sin \epsilon$ to the experimental upper limit as mentioned in the previous subsection. If we use smaller $\sin \epsilon$, the effect is very similar to the case of smaller $g_{X'}$ since the interactions between $\psi_1$ and SM particles are approximately proportional to $g_{X'} \sin \epsilon$. In summary, we therefore find that it is easier to satisfy the direct detection constraint for smaller values of $g_{X'} \sin \epsilon$ and larger values of $m_{Z'}$ than those of the reference case.

In this analysis, we apply the normalization of the cross section to Xenon, Eq. (17), since XENON100 provides the most stringent limit in most mass range. Actually, the cross section for Germanium is very similar to the Xenon case due to similar $Z/A$ ratios in both nuclei.
FIG. 7: SI scattering cross section of $\psi_1$ for the Xenon target with $g_{X'} = 0.5$, $g_{X''} = 0.9$, $m_2 = 150$ GeV and $m_{Z'} = 25$ GeV. The experimental limit from XENON100 [20] is shown by the black dashed line.

In order to check the possibility of a light DM hinted by the data from DAMA [10], CoGeNT [11] and CRESST [12], we show the SI scattering cross section corresponding to a light $Z'$. We choose $m_{Z'} = 25$ GeV using $g_{X'} = 0.5$, $g_{X''} = 0.9$ and $m_2 = 150$ GeV in fig. 7. As can be seen from the figure, the scattering cross section is severely constrained by the XENON100 limit since the scattering rate is enhanced due to the small mass of $Z'$. Nevertheless, we can find small allowed region around the $Z'$ resonance point of $m_1 \approx m_{Z'}/2$. One can easily expand this region, where the SI cross section drops below the XENON100 bound, using smaller $g_{X'} \sin \epsilon$. In addition, lighter DM particle $\psi_1$ can satisfy the scattering cross sections required by the DAMA, CoGeNT or CRESST results.

IV. CONCLUSION

We have illustrated with a simple toy model containing two stable dark matter particles, how the assisted freeze-out mechanism worked and could reproduce the measured value for the relic density of dark matter. The main feature of this type of model is that only one of the DM particles is involved in direct detection searches while both contribute to the relic density. In particular, when the DM particle that interacts with SM particles is the
subdominant DM component, it is possible to reconcile models with large elastic scattering rates on nuclei with the exclusion bounds of XENON100. Moreover, the lighter particle can be a light DM candidate around 10 GeV as indicated by the DAMA, CoGeNT and CRESST results.

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