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Realization of self-interacting freeze-in dark matter

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Abstract We explore the freeze-in production of dark matter in the singlet–doublet model where the dark matter is the lightest admixture of the neutral components of $SU(2)_L$ vector doublet and singlet fermion. Here, the scalar sector is extended by a MeV scalar mediating the self-interaction of the fermion dark matter, which solves the small-scale anomaly of the Universe. The scalar particle is stable and contributes to the relic density of the dark matter. Self-interacting dark matter scenario demands large interaction between the dark particles, which makes this sector strongly coupled. In this case, thermal equilibrium occurs in the dark sector after the freeze-in, and the relic abundance of the fermion dark matter gets suppressed in the radiation-dominated early Universe. However, the non-standard cosmological evolution in the early Universe helped the fermion dark matter to achieve almost whole contribution towards the observed relic.

1 Introduction

Different astrophysical observations indirectly show that dark matter (DM) exists and give clues about its characteristics. Dark matter must be stable, or at least its life-time has to be longer than the current age of the Universe. It also needs to be electrically neutral and non-relativistic (or cold) during the matter-radiation equality phase. Eventually, dark matter has to keep a certain relic density ($\Omega h^2 \simeq 0.12$) to account for 27 percent of the total energy in the present Universe.

Among different dark matter candidates, the most popular and well-studied one is weakly interacting massive particles (WIMPs). These WIMPs achieve thermal equilibrium with the thermal plasma, and the observed amount of dark matter is determined by a process called freeze-out. The concept of WIMP is interesting because it allows for investigation through different types of experiments, such as direct, indirect, and collider searches. However, despite these efforts, no supporting evidence has been found. As a result, the feebly interacting massive particle paradigm (FIMP) [1] suggested as an alternative to WIMPs, is gaining attention. FIMP provides a natural explanation for the absence of signals in dark matter search experiments due to its weak interaction strength. In this framework, dark matter is produced out of equilibrium because of its feeble interaction, and freeze-in determines its abundance.

However, collision-less cold dark matter fails to address small-scale issues in the Universe, such as core-cusp problems [2], missing satellites, and too-big-to-fail problems. The self-interaction of dark matter [3] has the potential to resolve these small-scale challenges. While self-interacting WIMP dark matter has been extensively studied, research on self-interaction in the case of freeze-in dark matter is limited in the literature [4]. A strong dark matter self-interaction requires a light mediator with a mass of MeV, regardless of the production mechanism. In addition, there is the possibility of achieving thermal equilibrium in the dark sector due to strong self-interaction between dark matter and the light mediator, leading to a reduction in dark matter abundance.

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This study focuses on a scenario where a GeV fermion dark matter is the dominant component. A significant interaction strength between the dark fermion and scalar is necessary to achieve substantial self-interaction. Furthermore, this strongly coupled dark sector induces thermal equilibrium separately, with these particles evolving at a temperature different from the standard model (SM).

The investigation concentrates on self-interacting dark matter produced via freeze-in. In this context, a simple extension of the standard model (SM) is considered, involving an $SU(2)_L$ vector doublet and a singlet fermion. The lightest combination of the neutral components of the doublet and singlet serves as the dark matter candidate (χ). The scalar sector is minimally extended with a light scalar (ϕ) mediating the self-interaction for the fermion dark matter. This scalar particle remains stable in the framework as it lacks a decay channel. The dark matter starts annihilating to ϕ once fermion dark matters number density develops through freeze-in. Both dark matters maintain dark thermal equilibrium until the decoupling of χ. In case of radiation-dominated Universe, χ becomes a subdominant dark matter component due to significant annihilation into pairs of ϕ before the dark freeze-out of χ.

A non-standard cosmology [5] is adopted, which assists in making the fermion dark matter a major component by suppressing the annihilation to a pair of ϕ due to rapid expansion. The dark matter not only exhibits astrophysical signatures due to self-interaction but can also be probed at colliders by examining the displaced vertex signature.

2 Model

We augment the particle spectrum of the Standard Model (SM) by introducing a $SU(2)_L$ vector doublet fermion (Ψ) and singlet fermion (χ) with hypercharges $Y = -\frac{1}{2}$ and $Y = 0$, respectively [4]. In addition, we extend the scalar sector minimally by including a real singlet scalar field (ϕ) to facilitate the self-interaction of the dark matter (DM).

In this framework, the SM particles and the scalar ϕ retain their sign under the discrete symmetry $\mathcal{Z}_2$, while the beyond Standard Model (BSM) fermions transform non-trivially under this symmetry. The $\mathcal{Z}_2$ charges of the BSM fields are outlined in Table 1, and it is noteworthy that all interaction terms preserve $\mathcal{Z}_2$ symmetry.

The Lagrangian for the scalar sector is given by

$$\mathcal{L}_{\text{scalar}} = |D^\mu H|^2 + \frac{1}{2}(\partial^\mu \phi)(\partial_\mu \phi) - V(\phi, H), \tag{1}$$

with

$$D^\mu = \partial^\mu - ig\frac{\sigma^a}{2}W^{a\mu} - ig'\frac{Y}{2}B^\mu, \tag{2}$$

where g and g' are the gauge couplings of $SU(2)_L$ and $U(1)_Y$, respectively. The scalar potential is expressed as

$$\begin{aligned} V(\phi, H) = -\mu_H^2(H^\dagger H) + \lambda_H(H^\dagger H)^2 + \tfrac{m_\phi^2}{2}\phi^2 + \tfrac{\lambda_\phi}{4!}\phi^4 \\ + \tfrac{b_3}{3!}\phi^3 + \tfrac{\lambda_{\phi H}}{2}\phi^2(H^\dagger H) + a_3\phi(H^\dagger H). \end{aligned} \tag{3}$$

Assuming all mass scales and coupling coefficients are real and positive, the vacuum expectation values (vev) of the scalars H and ϕ are obtained by minimizing the potential V as $\langle H \rangle = \frac{v}{\sqrt{2}}$ and $\langle \phi \rangle = 0$. The Lagrangian for the fermion sector takes the form

$$\begin{aligned} \mathcal{L}_f = i\overline{\Psi}\gamma_\mu D^\mu \Psi + i\overline{\chi}\gamma_\mu \partial^\mu \chi - m_\Psi \overline{\Psi}\Psi - m_\chi \overline{\chi}\chi \\ - Y\overline{\Psi}\tilde{H}\chi + h.c. - \lambda\phi\overline{\chi}\chi - \delta\phi\overline{\Psi}\Psi, \end{aligned} \tag{4}$$

Table 1 $\mathcal{Z}_2$ charge assignments

Fields	$\mathcal{Z}_2$
Ψ	$-$
χ	$-$
ϕ	$+$

where $\Psi^T = (\psi^+ \;\; \psi^0)$. After electroweak symmetry breaking, mixing develops between the neutral fermions. Diagonalizing the Dirac mass matrix yields the mass eigenstates, with mass eigenvalues of the new states ξ_1 and ξ_2 given by

$$m_{\xi_1} \approx m_\chi - \frac{M_D^2}{m_\Psi - m_\chi}, \;\; m_{\xi_2} \approx m_\Psi + \frac{M_D^2}{m_\Psi - m_\chi}, \tag{5}$$

where $M_D = \frac{Yv}{\sqrt{2}}$. The lightest state ξ_1 serves as the dark matter candidate. The singlet–doublet mixing is parameterized as $\sin 2\theta \simeq \frac{2Yv}{\Delta M}$, where $\Delta M = m_{\xi_2} - m_{\xi_1} \approx m_\Psi - m_\chi$ in the small Y limit. Here, ξ_1 is identified as the singlet χ, making it the dark matter candidate for the remainder of our discussion.

3 Dark matter relic

In our framework, the stable particles χ and ϕ can contribute to the total abundance of DM. We consider relatively large interaction strength ($\lambda \sim \mathcal{O}(10^{-1})$) and $m_\phi \ll m_\chi$ to address the small-scale issue of the Universe. The Yukawa coupling $Y(\ll 1)$ is an important parameter since it links the DM with the SM. Therefore, the Yukawa coupling (Y) and the coupling (λ) associated with the self-interaction play an important role in determining the dynamics of our framework.

3.1 Radiation-dominated scenario

In the context of standard Big Bang cosmology, the Universe is considered radiation-dominated preceding Big Bang nucleosynthesis (BBN). Both components initially possess zero number density. Primarily, χ is populated through the decays of dark fermions. Notably, scattering processes, such as $\Psi\Psi \to \chi\chi$ mediated via ϕ, remain subdominant in the limit $Y \gg \delta$ despite $\lambda \sim \mathcal{O}(0.1)$. Once a number density of χ develops, the production of ϕ initiates through the $\chi\chi \to \phi\phi$ process. In addition, ϕ can annihilate to χ when its population is sufficient, leading to local thermal equilibrium in the dark sector. The dark sector evolves with a uniform temperature T_D, where the condition $r \equiv \frac{n_\chi \langle\sigma v\rangle_{\chi\chi\to\phi\phi}}{\mathcal{H}} \gg 1$ must be satisfied. Eventually, the freeze-out of χ occurs, contributing to the relic abundance. The dynamics of both particles are described by the following set of Boltzmann equations:

$$\frac{dY_\phi}{\mathrm{d}z} = \frac{s}{\mathcal{H}z}\langle\sigma v\rangle^{T_D}_{\chi\chi\to\phi\phi}\left[Y_\chi^2 - \left(\frac{Y_\chi^{\mathrm{eq}}(T_D)}{Y_\phi^{\mathrm{eq}}(T_D)}\right)^2 Y_\phi^2\right] \tag{6}$$

$$\frac{\mathrm{d}Y_\chi}{dz} = -\frac{s}{\mathcal{H}z}\langle\sigma v\rangle^{T_D}_{\chi\chi\to\phi\phi}\left[Y_\chi^2 - \left(\frac{Y_\chi^{\mathrm{eq}}(T_D)}{Y_\phi^{\mathrm{eq}}(T_D)}\right)^2 Y_\phi^2\right] + \frac{\langle\Gamma_\Psi\rangle^T}{\mathcal{H}z}(Y_\Psi^{\mathrm{eq}}(T) - Y_\chi), \tag{7}$$

where $\langle\Gamma_\Psi\rangle^T$ represents the thermally averaged decay width, and $Y_i (i = \chi, \phi)$ refers to the abundance of the i^{th} component. The relic abundance of the i^{th} component is calculated by $\Omega_i h^2 = 2.755 \times 10^8 \times m_i \times Y_i(z = \infty)$. Two prescriptions for estimating the dark temperature exist in the literature. We follow the approach presuming that dark sector particles reach thermal equilibrium and share a common temperature. After obtaining the solutions of the Boltzmann equations, we numerically verify the equilibrium condition and calculate the dark temperature by solving the Boltzmann equation for the total energy density of the dark sector.

Figure 1 shows the evolution of the comoving number density of dark matters χ and ϕ. Focusing on the blue dotted line, originating from zero number density, it is produced through decay via freeze-in, achieving dark thermal equilibrium. Subsequently, χ decouples from the dark thermal bath due to the Universe's expansion, leading to dilution of χ number density until the $\chi\chi \to \phi\phi$ process freezes out. The magenta line depicts the evolution of ϕ, also populated via freeze-in through the scattering process $\chi\chi \to \phi\phi$. Initially, ϕ abundance is determined by freeze-in, and its production resumes due to χ annihilation after decoupling, finally stabilizing after dark freeze-out. In this scenario, $\Omega_\chi h^2 \ll \Omega_\phi h^2$ due to substantial dilution of χ abundance from significant annihilation before freeze-out, making it impossible for fermion dark matter to be the primary component in the radiation-dominated early Universe.

In Fig. 2, the evolution of dark particles is shown in the presence of modified cosmology with $n = 2$ and $T_r = 110$ MeV. Here, the dilution of χ abundance from decoupling to freeze-out is less. In this case, fast expansion reduces the annihilation of χ to ϕ, but dark thermal equilibrium is maintained. Consequently, the fermion dark

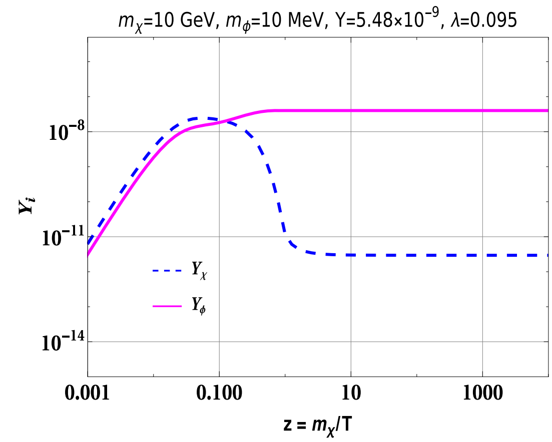

Fig. 1 The plot illustrates the evolution of the comoving number density of both dark matters with the dimensionless quantity $z(= m_\chi/T)$

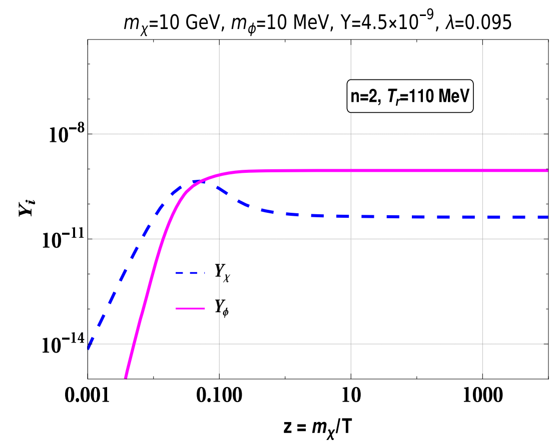

Fig. 2 The plot illustrates the evolution of the comoving number density of both dark matters with the dimensionless quantity $z(= m_\chi/T)$

matter dominantly contributes to the relic density, making ϕ subdominant. Thus, fast expansion drives a scenario where χ becomes the main dark matter component.

3.2 Non-standard cosmology

The conventional cosmological view posits radiation domination before Big Bang nucleosynthesis. However, without direct evidence of early radiation domination, the possibility arises for a non-standard fluid to dominate the early Universe's energy budgets. This fluid may redshift faster or slower than radiation.

Here, we consider the presence of an additional species (η) alongside the radiation component. The redshift behavior of η follows $\rho_\eta \propto a^{-(4+n)}$ for $n > 0$. In this scenario, the modified expansion rate is expressed as [5]

$$\mathcal{H}(T) = H_R(T)\left(\frac{T}{T_r}\right)^{n/2}, \quad (T \gg T_r) \tag{8}$$

where T_r is a reference temperature at which the energy density of radiation and the η field are equal. The effects of modified cosmology can be described by two parameters, n and T_r. Scenarios with $n = 2$ and $n > 2$ represent kination domination and faster-than-quintessence with negative potential, respectively (see Ref. [5] for details).

The impact of fast expansion on the dynamics of fermion and scalar dark matter will be discussed next.

4 Self-interaction of dark matter

Our framework adopts a two-component dark matter model. As demonstrated earlier, χ can emerge as a primary dark matter (DM) component, contributing nearly the entire relic density in the context of non-standard cosmology. Thus, χ emerges as a promising candidate for self-interacting dark matter. Specifically, the self-interaction processes

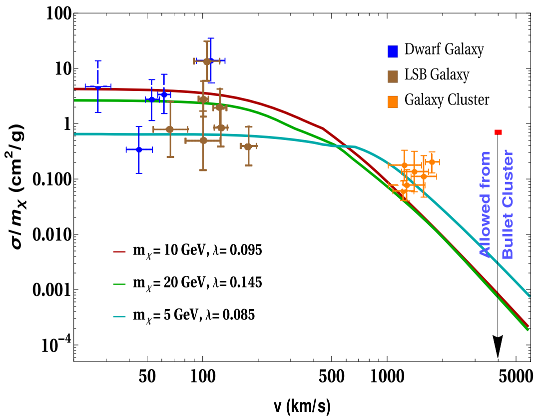

Fig. 3 Plot shows the variation of self-interaction cross-section as function of velocity for the two different sets of (m_χ, λ) used to demonstrate the dark matter phenomenology. The black arrow dictates the constraint from the Bullet Cluster which is $\frac{\sigma}{m_\chi} < 0.7$ cm^2/g for $v = 4000$ km/s [6]. We set m_ϕ at 10 MeV. We also depicts the observational data from dwarfs (blue), low surface brightness (LSB) galaxies (brown), and galaxy clusters (orange) as taken from [8]

include $\chi\chi \to \chi\chi$, $\overline{\chi\chi} \to \overline{\chi\chi}$, and $\overline{\chi}\chi \to \overline{\chi}\chi$. Analytical expressions from Refs. [6, 7] are employed for computing these self-interactions, and the variation of the self-interaction cross-section is depicted in Fig. 3. Additional details are available in our original article [4].

5 Conclusion

The singlet–doublet model is a simple extension of a doublet and a singlet fermion where the mixing of the singlet and doublet provides a viable DM candidate after the electroweak symmetry breaking. In this work, we have studied the potential of a non-thermally produced GeV scale fermion DM to address the small-scale issue of the Universe.

We extended the scalar sector minimally with a MeV scalar mediating the self-interaction of the fermion DM. This scalar mediator is stable as no decay mode is available for it in our model. Here, the fermion dark matter is populated non-thermally via freeze-in in the early stage of the Universe. Generally, a sizable coupling is needed between the fermion DM and the scalar mediator to drive strong self-interaction. With such a concept, our calculations have shown that the conversion process from the fermion DM to the scalar mediator is very efficient, and it enormously reduces the fermion DM's relic abundance when these particles maintain an internal dark thermal equilibrium. We end up with a situation where the mediator becomes way more abundant than the DM in the present time of the Universe. It is evident that the conversion process is very significant in the radiation-dominated early Universe, and as a result, our singlet–doublet DM candidate remains unsuccessful in contributing to the relic abundance as a major component.

We considered alternative cosmology to resolve this problem. Tuning of the parameters of the non-standard cosmology provides two exciting scenarios. In one case, we have found that the fast expansion significantly slowed down the conversion process, and the suppression due to this process is reduced considerably. In another scenario, the dark thermal equilibrium is never reached due to the pronounced fast expansion, and we achieve a pure freeze-in scenario.

We wind up with the comment that the fast expansion helps to realize self-interacting freeze-in DM by making it the main DM component. Due to its feeble interaction, the detection prospect is generally very weak for freeze-in DM. Interestingly, because of its strong self-interaction, our model offers to probe freeze-in DM directly in the astrophysical experiments at galaxy scale. In addition, the DM can also be tracked at collider on account of alternative cosmology.

Data Availability Datasets generated during the current study are available from the corresponding author on reasonable request.

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