FREEZE-IN REGION FOR SELF-INTERACTING VECTOR DARK MATTER*

Mateusz Duch, Bohdan Grzadkowski, Da Huang†

Faculty of Physics, University of Warsaw, Pasteura 5, 02-093 Warszawa, Poland

(Received November 13, 2017)

Inspired by the cosmological small-scale structure problems, we thoroughly study a self-interacting vector dark matter (VDM) model in which the VDM is generated by the freeze-in mechanism via the Higgs portal interaction. The strong VDM self-interactions naturally arise when the dark Higgs boson which induces the VDM mass is much lighter than the VDM. We also carefully consider the constraints from the VDM indirect searches, which restrict the dark Higgs mass to be at most of $\mathcal{O}\,(\mathrm{keV})$.

DOI:10.5506/APhysPolB.48.2397

The emergence of small-scale structure problems of the standard ΛCDM model of the Universe has led to the great interest in models with sizeable dark matter (DM) self-interactions, as they may provide a possible solution [1]. Strong DM self-interactions can be induced, in an intriguing way, by a light mediator, which enhances them non-perturbatively [2–4]. However, it has been recently pointed out in [5] that, because of constraints from DM indirect searches, the standard dark freeze-out mechanism with s-wave annihilation is ruled out, as a possibility to generate DM self-interactions. Thus, it is worthwhile to consider scenarios beyond this conventional framework.

In this article, we study a vector DM (VDM) model [6–8] in which the VDM is produced through the freeze-in mechanism [9] by coupling VDM to the Standard Model (SM) sector via the Higgs portal [10]. The dark Higgs boson which gives the VDM mass can be tuned to be much lighter than the VDM so that the VDM self-interactions can be boosted to the appropriate level to solve the small-scale problems. The main goal of this paper is to

---

* Presented by D. Huang at the XLI International Conference of Theoretical Physics "Matter to the Deepest", Podlesice, Poland, September 3–8, 2017.

† Corresponding author: `da.huang@fuw.edu.pl`

check if this self-interacting VDM model is consistent with constraints from indirect DM searches. A similar scenario has already been investigated in [8] with the non-Abelian version of this model. Here, we discus thoroughly the recent bounds from BBN, CMB, FERMI-LAT, AMS-02, diffuse γ/X-ray and direct detection LUX data.

Following [7], we introduce a dark $\mathrm{U}(1)_X$ gauge symmetry with its gauge boson X_μ, and a complex scalar S which is charged under $\mathrm{U}(1)_X$ but neutral under the SM gauge group. We further impose the following charge conjugate Z_2 symmetry to the dark sector

$$X_\mu \to -X_\mu\,, \qquad S \to S^*\,, \tag{1}$$

under which the mixing term $X_{\mu\nu}B^{\mu\nu}$ between the SM $\mathrm{U}(1)_Y$ gauge boson B_μ and X_μ is forbidden. Thus, we can write down the following dark sector Lagrangian:

$$\mathcal{L}_{\mathrm{d}} = -\tfrac{1}{4}X_{\mu\nu}X^{\mu\nu} + (D_\mu S)^\dagger D^\mu S + \mu_S^2|S|^2 - \lambda_S|S|^4 - \kappa|S|^2|H|^2\,, \tag{2}$$

where H is the SM Higgs doublet, and we define the covariant derivative of S as $D_\mu S \equiv (\partial_\mu + ig_X X_\mu)S$ with g_X the dark gauge coupling constant. Note that only the Higgs portal coupling, $\kappa|S|^2|H|^2$, connects the dark and SM sectors. Moreover, the mass term of S in the potential is negative, which induces the spontaneous symmetry breaking (SSB) of the dark $\mathrm{U}(1)_X$ symmetry. By minimizing the scalar potential, the vacuum expectation values of the SM Higgs doublet $\langle H\rangle \equiv (0, v_H/\sqrt{2}\,)^T$ and the dark Higgs $\langle S\rangle \equiv v_S/\sqrt{2}$ are given as follows:

$$v_H^2 = \frac{4\lambda_S\mu_h^2 - 2\kappa\mu_S^2}{4\lambda_H\lambda_S - \kappa^2}\,, \qquad v_S^2 = \frac{4\lambda_H\mu_S^2 - 2\kappa\mu_H^2}{4\lambda_H\lambda_S - \kappa^2}\,. \tag{3}$$

Note that $\langle S\rangle$ can always be chosen to be real without any loss of generality, and the discrete Z_2 symmetry (1) remains unbroken as required for the stability of X_μ.

After SSB, the dark gauge boson X_μ gets its mass $m_X = g_X v_S$ and we are left with two physical scalars $(\phi_H, \phi_S)^T$, which are defined in the unitary gauge as $H = (0,\ (v_H + \phi_H)/\sqrt{2})^T$ and $S = (v_S + \phi_S)/\sqrt{2}$. The second order expansion of the scalar potential implies the following mass squared matrix for $(\phi_H, \phi_S)^T$:

$$\mathcal{M}^2 = \begin{pmatrix} 2\lambda_H v_H^2 & \kappa v_H v_S \\ \kappa v_H v_S & 2\lambda_S v_S^2 \end{pmatrix}. \tag{4}$$

Hence, the mass eigenstates of scalars $(h_1, h_2)^T$ can be defined with the following orthogonal transformation:

$$\begin{pmatrix} \phi_H \\ \phi_S \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix} \tag{5}$$

with the mixing angle θ. The scalar quartic couplings could be expressed through the mixing angle, Higgs boson masses and vevs as follows:

$$\begin{aligned}\kappa &= \frac{\left(m_{h_1}^2 - m_{h_2}^2\right) s_{2\theta}}{2 v_H v_S}\,, \qquad \lambda_H = \frac{2\left(m_{h_1}^2 c_\theta^2 + m_{h_2}^2 s_\theta^2\right)}{v_H^2}\,,\\ \lambda_S &= \frac{2\left(m_{h_2}^2 c_\theta^2 + m_{h_1}^2 s_\theta^2\right)}{v_S^2}\,.\end{aligned} \tag{6}$$

In the freeze-in mechanism, X_μ and h_2 never thermalize with SM particles, so that the portal coupling κ or s_θ should be very small. Thus, it is evident from Eq. (5) that h_2 is mostly the dark Higgs ϕ_S, while the h_1 boson is SM-Higgs-like. Note that this simple model only contains four free parameters, which are chosen to be $(m_X,\, m_{h_2},\, \kappa,\, g_X)$ for later convenience.

Now, we study the VDM production with the freeze-in mechanism in this model. As a standard assumption in the freeze-in mechanism [9], the initial abundance of the dark sector comprising X_μ and h_2 is negligibly small after reheating. Also, the dark sector cannot thermalize itself or reach an equilibrium with the SM sector, so that the VDM abundance is only produced by the SM particle annihilations and/or decays. When the VDM mass is smaller than the electroweak (EW) phase transition temperature $T_{\rm EW} \simeq 160$ GeV [11], we expect that the VDM is mostly produced in the SM gauge symmetry broken phase. In this case, the freeze-in Boltzmann equation can be written as follows:

$$xHs\frac{{\rm d}Y_X}{{\rm d}x} = \sum_f \gamma_f + \gamma_W + \gamma_{h_1} + \gamma_Z + \gamma_{h_1}^D\,, \tag{7}$$

where the DM yield $Y_X = n_X/s$ is defined as a ratio between the VDM number density n_X and the visible sector entropy density s, $x \equiv m_X/T$, H is the Hubble parameter, and SM particle i annihilations(decays) into VDMs are represented by various reaction densities [12] $\gamma_i^{(D)}$, the precise definitions of which are given in Ref. [10]. Note that we have implemented the model into LanHEP [13] and calculated the cross sections with CalcHEP [14].

On the other hand, in the case of $m_X \gg T_{\rm EW}$, the VDM production only occurs when the EW gauge symmetry is not broken. At tree level, the only channel to produce VDM is $XX \to HH^\dagger$, where H is the SM Higgs doublet. The Boltzmann equation should be expressed as follows:

$$xHs\frac{{\rm d}Y_X}{{\rm d}x} = \gamma_{HH^\dagger}\,. \tag{8}$$

It is interesting to note that all of reaction densities defined above in both the EW symmetric and broken phases have no dependence on g_X and very weak dependence on m_{h_2}, so that they can be expressed as functions of only two model parameters m_X and κ.

By solving the Boltzmann equations in Eqs. (7) and (8), and matching the results to the observed value of DM relic density $\Omega_X h^2 = 0.11$, the value of κ can be obtained as a function of the VDM mass m_X (Fig. 1). There are several features that can be observed. Firstly, there is a small but abrupt increase of κ at $m_X = 160$ GeV, which represents the sudden change of the dominant VDM production channels due to the EW phase transition. The curve of Fig. 1 presents distinctive scaling behaviors of κ as functions of m_X, which reflect different VDM production scenarios. When $m_X \geq m_{h_1}/2$, the only contribution comes from SM particle annihilations, while if $m_X < m_{h_1}/2$, the SM-like Higgs decay $h_1 \to XX$ opens and dominates the VDM creations. We discuss this issue in more detail in Ref. [10].

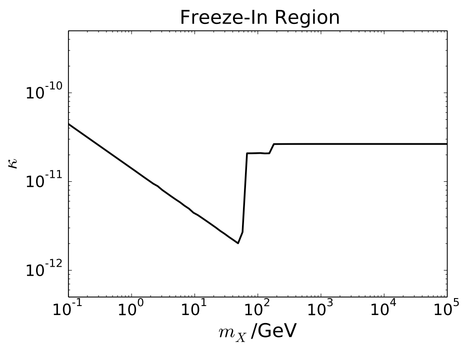

Fig. 1. Along the curve shown in the figure the freeze-in mechanism generates the observed VDM relic density $\Omega_X h^2 = 0.11$.

If DM is generated within pure freeze-in scenario, the dark sector should not thermalize neither with itself nor with the SM sector. It is easy to check that the portal coupling κ shown in Fig. 1 is too small for the dark sector to reach the equilibrium with the SM thermal bath. On the other hand, the condition for non-thermalization within the dark sector is encoded by the following inequality:

$$\langle \sigma(XX \to h_2 h_2) v \rangle n_X \leq H \,, \tag{9}$$

where $\langle \sigma(XX \to h_2 h_2) v \rangle$, n_X, and H denote the thermally averaged cross section for $XX \to h_2 h_2$, the VDM number density, and Hubble parameter, respectively. All of these quantities should be calculated around a temperature when the freeze-in processes end. As will be shown below, this non-thermalization condition will place a strong constraint on the freeze-in parameter space.

It is well-known that one possible solution to the 'cusp *versus* core' and the 'too-big-to-fail' problems is sufficiently strong DM self-interaction at the dwarf galaxy scale [1, 3, 4] with the cross section in the range of $0.1\,\mathrm{cm}^2/\mathrm{g} < \sigma_\mathrm{T}/m_X < 10\,\mathrm{cm}^2/\mathrm{g}$, where the so-called momentum transfer cross section between DM particles is defined as $\sigma_\mathrm{T} \equiv \int \mathrm{d}\Omega(1-\cos\theta)\mathrm{d}\sigma/\mathrm{d}\Omega$. However, observations at the cluster scale severely constrain the DM self-interactions with $\sigma_\mathrm{T}/m_X < 1\ \mathrm{cm}^2/\mathrm{g}$ [15].

A possible scenario that may give rise to so large DM self-interaction is an introduction of a mediator which is much lighter than a DM particle. In the present model, the mass of h_2 is a free parameter and can be tuned to be hierarchically smaller than that of the VDM in order to enhance the VDM self-interactions. Note that VDM self-interactions are characterized by three length scales: the Compton wavelength $1/(\alpha_X m_X)$ with $\alpha_X \equiv g_X^2/(4\pi)$ the dark fine-structure constant, the potential range $1/m_{h_2}$, and de Broglie wavelength $1/(m_X v)$. In the Born region when $1/m_{h_2} \ll 1/(\alpha_X m_X)$, the perturbative result for σ_T in Ref. [3] is applicable. On the other hand, when the above condition is not valid any more, the non-perturbative effect becomes prominent and gives us the attractive Yukawa potential as follows:

$$V(r) = -\frac{\alpha_X e^{-m_{h_2} r}}{r}\,. \tag{10}$$

Note that in the non-perturbative region there are two regimes which depend on the VDM velocity. The classical regime ($m_X v/m_{h_2} \gg 1$) where we can use the approximate analytic formulas for σ_T from Refs. [3, 4] and the resonant regime ($m_X v/m_{h_2} \lesssim 1$), where the quasi-bound states can form. In order to obtain σ_T, we need to solve the non-relativistic Schrödinger equation with the potential in Eq. (10) following Ref. [3]. It is remarkable that σ_T is amplified more significantly as the DM velocity decreases, which can help the VDM self-interactions at the dwarf galaxy scale with the typical DM velocity $v \sim 10$ km/s to evade the constraints from clusters with $v \sim 1000$ km/s.

We now consider the constraints from DM direct and indirect searches. For DM direct detections, the signal comes from the nuclear recoils caused by the VDM scatterings, which are mediated by two neutral scalars $h_{1,2}$. The total VDM-nucleon (XN) cross section is given by

$$\sigma_{XN} = \frac{\kappa^2 f_N^2 m_X^2 m_N^2 \mu_{XN}^2}{\pi m_{h_1}^4 m_{h_2}^2 \left(m_{h_2}^2 + 4\mu_{XN} v^2\right)}\,, \tag{11}$$

where the VDM velocity v is defined in the lab frame, $\mu_{XN} \equiv m_X m_N/(m_N + m_X)$ is the reduced mass of the XN system, and $f_N \approx 0.3$ is the effective nucleon coupling. Due to the fact that $\sigma_{XN} \propto \kappa^2$, it is expected that the direct detection signal is too small to give any sensible constraints to the model, as it has been shown in Ref. [10].

Constraints from indirect searches strongly depend on the properties of the dark Higgs: its mass, dominant decay channels and lifetime τ_{h_2}. Since we focus on the light mediator with $m_{h_2} \lesssim 100$ MeV, we divide our discussion into two cases: *(i)* $m_{h_2} \geq 2m_e$ and *(ii)* $m_{h_2} \leq m_e$, where m_e denotes the electron mass. In the former case, h_2 dominantly decays to e^+e^- pairs, which predicts the h_2 lifetime in the range of 10^4 s $\lesssim \tau_{h_2} \lesssim 10^{12}$ s, while in the latter region, only diphoton channel is kinematically allowed what leads to $\tau_{h_2} \gtrsim 10^{12}$ s. Since the h_2 lifetime is always longer than 10^4 s, h_2 behaves as a decaying DM from the perspective of Big Bang Nucleosynthesis (BBN). The electromagnetic energy injection from the late-time decay of h_2 would spoil the successful predictions of various element abundances, thus the model would be constrained by BBN. Since the dark Higgs h_2 abundance at the BBN epoch is also produced by the freeze-in mechanism, we adopt the recent BBN constraints from Ref. [16]. When 1 MeV $\lesssim m_{h_2} \lesssim 100$ MeV, BBN bounds imply $\sin\theta < 5 \times 10^{-12}$, while for even lighter h_2 constraints are absent. For other indirect detection experiments, we need to consider the two regimes of m_{h_2} separately.

— Region *(i)*: As mentioned before, the lifetime of h_2 is shorter than 10^{12} s, which indicates that the dark Higgs is produced via the freeze-in and later decays before the epoch of Cosmic Microwave Background (CMB) decoupling. Thus, the possibility of indirect detection within this regime comes from the annihilation process $XX \to h_2h_2$ followed by h_2 decays, which suffers from a large Sommerfeld enhancement. Possible signals include modification of the cosmological ionization history, the positron flux excess in the local region, and γ-ray signals from the dwarf galaxies, which could be probed and constrained by CMB observations, AMS-02 measurements, and Fermi-LAT detections, respectively. Note that this VDM annihilation process corresponds to the one-step cascade annihilation, which has already been investigated in Ref. [17]. Therefore, we apply those results directly.

— Region *(ii)*: Due to its long lifetime, $\tau_{h_2} > 10^{12}$ s, h_2 can be considered as a decaying DM component at the CMB epoch. Thus, the photons from h_2 decays can be constrained by precise measurements of CMB power spectrum. Furthermore, when $\tau_{h_2} > \tau_{\rm U}$ with $\tau_{\rm U}$ being the age of the Universe, h_2 is a true DM component, and its decays lead to the excesses of diffuse γ/X-rays. For these two constraints, we use the results from Refs. [18] and [8], respectively.

The final results are shown in Fig. 2, where the left and right panels represent typical situations for the region *(i)* and *(ii)*, respectively. Note that the freeze-in region corresponds to the parameter space below the curve labeled by "Thermalization" in both plots. It is clear that the freeze-in parameter space in region *(i)* is already excluded by the constraints from AMS-02, CMB and BBN. In contrast, there is a parameter window which can satisfy all of the experiments when the h_2 becomes as light as $\mathcal{O}\,(\mathrm{keV})$. This result agrees with that given in Ref. [8].

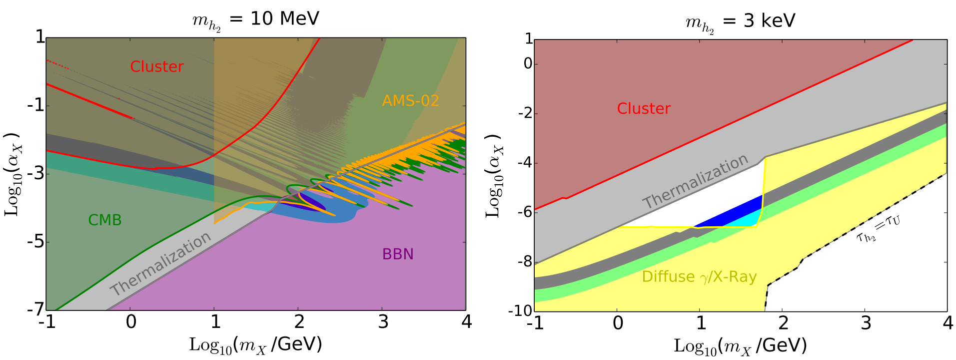

Fig. 2. (Color online) Parameter spaces for region *(i)* with $m_{h_2} = 10$ MeV (left panel) and region *(ii)* with $m_{h_2} = 3$ keV (right panel). The dark gray (blue) and gray (cyan) strips represent the space in which the VDM self-interaction cross section is $1\ \mathrm{cm}^2/\mathrm{g} < \sigma_\mathrm{T}/m_X < 10\ \mathrm{cm}^2/\mathrm{g}$ and $0.1\ \mathrm{cm}^2/\mathrm{g} < \sigma_\mathrm{T}/m_X < 1\ \mathrm{cm}^2/\mathrm{g}$, respectively, which can solve small-scale structure problems at the dwarf scale. The top left gray (red) region is ruled out by the cluster-scale constraints on VDM self-scatterings. The parameters that are excluded by the DM indirect searches from BBN, CMB, AMS-02, and diffuse γ/X-rays are shown as other gray shades (purple, green, orange, and yellow, respectively). The thermalization condition of Eq. (9) is shown to be above the curve labeled by "Thermalization". Note that κ in each plot is taken to be a function of m_X as in Fig. 1.

To summarize, we have studied a self-interacting VDM model in which the VDM is generated via the freeze-in mechanism. The dark Higgs can be tuned to be light what leads to the enhancement of the VDM self-interaction to the level that can solve the cosmological small-scale structure problems. In particular, we properly handle the EW phase transition in predicting the VDM relic density, and carefully consider the indirect detection constraints, which restrict m_{h_2} to be at most of $\mathcal{O}\,(\mathrm{keV})$.

This work is supported by the National Science Centre, Poland (NCN) research project, decision DEC-2014/15/B/ST2/00108.

REFERENCES

[1] A.A. de Laix, R.J. Scherrer, R.K. Schaefer, *Astrophys. J.* **452**, 495 (1995); D.N. Spergel, P.J. Steinhardt, *Phys. Rev. Lett.* **84**, 3760 (2000); S. Tulin, H.B. Yu, `arXiv:1705.02358 [hep-ph]`.

[2] L. Ackerman *et al.*, *Phys. Rev. D* **79**, 023519 (2009); M.R. Buckley, P.J. Fox, *Phys. Rev. D* **81**, 083522 (2010); A. Loeb, N. Weiner, *Phys. Rev. Lett.* **106**, 171302 (2011); J.L. Feng, M. Kaplinghat, H.B. Yu, *Phys. Rev. Lett.* **104**, 151301 (2010); L.G. van den Aarssen, T. Bringmann, C. Pfrommer, *Phys. Rev. Lett.* **109**, 231301 (2012).

[3] S. Tulin, H.B. Yu, K.M. Zurek, *Phys. Rev. Lett.* **110**, 111301 (2013); *Phys. Rev. D* **87**, 115007 (2013).

[4] F.Y. Cyr-Racine *et al.*, *Phys. Rev. D* **93**, 123527 (2016).

[5] T. Bringmann *et al.*, *Phys. Rev. Lett.* **118**, 141802 (2017).

[6] T. Hambye, *J. High Energy Phys.* **0901**, 028 (2009); O. Lebedev *et al.*, *Phys. Lett. B* **707**, 570 (2012); Y. Farzan, A.R. Akbarieh, *J. Cosmol. Astropart. Phys.* **1210**, 026 (2012); S. Baek *et al.*, *J. High Energy Phys.* **1305**, 036 (2013); S. Baek, P. Ko, W.I. Park, *Phys. Rev. D* **90**, 055014 (2014); A. Karam, K. Tamvakis, *Phys. Rev. D* **92**, 075010 (2015); **94**, 055004 (2016); G. Arcadi *et al.*, *J. High Energy Phys.* **1612**, 081 (2016); M. Heikinheimo *et al.*, *Phys. Rev. D* **96**, 023001 (2017).

[7] M. Duch, B. Grzadkowski, M. McGarrie, *J. High Energy Phys.* **1509**, 162 (2015); *Acta Phys. Pol. B* **46**, 2199 (2015).

[8] N. Bernal *et al.*, *J. Cosmol. Astropart. Phys.* **1603**, 018 (2016).

[9] J. McDonald, *Phys. Rev. Lett.* **88**, 091304 (2002); L.J. Hall *et al.*, *J. High Energy Phys.* **1003**, 080 (2010).

[10] M. Duch, B. Grzadkowski, D. Huang, `arXiv:1710.00320 [hep-ph]`.

[11] M. Quiros, `arXiv:hep-ph/9901312`; A. Katz, M. Perelstein, *J. High Energy Phys.* **1407**, 108 (2014).

[12] X. Chu *et al.*, *J. Cosmol. Astropart. Phys.* **1205**, 034 (2012).

[13] A.V. Semenov, `arXiv:hep-ph/9608488`; `arXiv:hep-ph/0208011`; *Comput. Phys. Commun.* **180**, 431 (2009).

[14] A. Belyaev *et al.*, *Comput. Phys. Commun.* **184**, 1729 (2013).

[15] D. Clowe *et al.*, *Astrophys. J.* **604**, 596 (2004); M. Markevitch *et al.*, *Astrophys. J.* **606**, 819 (2004); S.W. Randall *et al.*, *Astrophys. J.* **679**, 1173 (2008). F. Kahlhoefer *et al.*, *Mon. Not. R. Astron. Soc.* **437**, 2865 (2014); D. Harvey *et al.*, *Science* **347**, 1462 (2015); D. Wittman *et al.*, `arXiv:1701.05877 [astro-ph.CO]`.

[16] J. Berger *et al.*, *J. Cosmol. Astropart. Phys.* **1611**, 032 (2016).

[17] G. Elor *et al.*, *J. Cosmol. Astropart. Phys.* **1606**, 024 (2016).

[18] T.R. Slatyer, C.L. Wu, *Phys. Rev. D* **95**, 023010 (2017).