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Higgs portal vector dark matter for GeV scale γ-ray excess from galactic center

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Abstract. We show that the GeV scale γ-ray excess from the direction of the Galactic Center can be naturally explained by the pair annihilation of Abelian vector dark matter (VDM) into a pair of dark Higgs bosons ($VV \to \phi\phi$), followed by the subsequent decay of ϕ into $b\bar{b}$ or $\tau\bar{\tau}$. All the processes are described by a renormalizable VDM model with the Higgs portal, which is naturally flavor-dependent. Some parameter space of this scenario can be tested at the near future direct dark matter search experiments such as LUX and XENON1T.

Keywords: dark matter theory, ultra high energy cosmic rays, gamma ray theory

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Contents

1 Introduction

It has been known for sometime that there is an anomalous GeV scale γ-ray excess from the direction of the Galactic Center [1–10]. Interestingly, the excess seems to be remarkably well described by an expected signal from 31-40 GeV dark matter (DM) annihilating dominantly to $b\bar{b}$ with a cross section $\sigma v \simeq (1.7 - 2.3) \times 10^{-26}\mathrm{cm}^3/\mathrm{s}$ [10, 11]. (See also refs. [12, 13] for discussions on millisecond pulsars as a possible astrophysical alternative.) Because of the importance of DM pair annihilation into $b\bar{b}$ for the GC γ-ray excess, some ideas on flavored DM have been put forth [14, 15].

We should note that it is the shape of γ spectrum from dark matter annihilation that mainly matters rather than the precise value for σv since there is a large uncertainty in the density profile of dark matter near the Milky Way center. As long as $\langle\sigma v\rangle\,(\rho_{\rm DM}/M_{\rm DM})^2$ is at the right amount, a good fit can be achieved for $b\bar{b}$ final state. Actually, $b\bar{b}$ does not need to be the only annihilation channel, since it was shown in ref. [10] that flavor-dependent annihilations can also fit the data well. Such kind of flavor-dependent annihilations may indicate a Higgs-like scalar mediator, since Higgs-like scalar will couple with the heaviest particle it can couple to.

The required cross section is very close to the canonical value for neutral thermal relic dark matter. It can be achieved either by s-wave annihilation or by p-wave annihilation with s-channel resonance at present.[1] However, in the latter case, the resonance band is likely to be very narrow with a severe fine-tuning, which is not that attractive. With this consideration, perhaps the simplest scenario for dark matter model that can explain the γ-ray excess would be those involving scalar mediator with Higgs portal interaction(s), since in this case the scalar mediator will couple strongly to the $b\bar{b}$, the heaviest particles kinematically producible.[2] Then, one can imagine the following simple scenarios of DM having s-wave annihilation channel:

1. Singlet scalar dark matter (SSDM): a real scalar mediator [16].

[1] In case of p-wave annihilation, velocity-dependent DM annihilation cross section would require some change of the DM density profile to match the angular distribution of the observed γ-ray excess. Detailed study of this issue is beyond the scope of the present paper and has not been investigated here. The authors thank the anonymous referee for pointing out this subtlety.

[2] Another possibility would be to consider flavored DM [14, 15].

2. Singlet fermion dark matter (SFDM): a pseudo-scalar mediator [17–19].[3]

3. Singlet Abelian vector dark matter (VDM): a real scalar mediator [20–22].

Note that the structure of above scenarios can be realized easily when DM is charged under a dark gauge symmetry which is broken to, for example, a discrete Z_2 or Z_3 symmetry. Hence those scenarios would also work equally well. For other recent proposals of DM models to address the GeV γ-ray spectrum, see refs. [14, 15, 23, 24].

Potentially the most important constraint on those singlet dark matter models may come from direct search experiments, for example, LUX [25]. However the existence of extra scalar boson mediating dark and visible sectors via Higgs portal interaction(s) has a significant effect on direct searches if the mass of the extra non-SM Higgs is not very different from that of SM Higgs [26], and the constraint from direct searches can be satisfied rather easily. Note that this feature is not captured at all in effective field theory approach, and it is important to work on the minimal renormalizable and unitary Lagrangian for physically sensible results.[4]

In this paper, we revisit VDM scenario with Higgs portal in the context of the the γ-ray excess from the Galactic Center, and show that the VDM model can naturally explain it, while satisfying all of known constraints coming from CMB, Fermi-LAT γ-ray search and LHC experiments. We also show that the parameter space relevant for the γ-ray excess can be probed by the near future direct dark matter search experiment, for example LUX and XENON1T.

This paper is organized as follows. In section 2, we recapitulate the renormalizable VDM model with Higgs portal. In section 3, various relevant constraints on the model are discussed, including relic density estimation, vacuum stability, collider bounds, CMB and direct detection cross section, etc., and we show that our model can explain the γ-ray excess from the galactic center without any conflict with other cosmological and astrophysical observations. In section 4, our conclusion is drawn.

2 The renormalizable VDM with Higgs portal

Let us consider a Abelian vector boson dark matter,[5] X_μ, which is assumed to be a gauge boson associated with Abelian dark gauge symmetry $\mathrm{U}(1)_X$. The simplest model will be defined with a complex scalar dark Higgs field Φ only, and no other extra fields. The VEV of Φ breaks $\mathrm{U}(1)_X$ spontaneously and generates the mass for X_μ through the standard Higgs mechanism (see also ref. [29]):

$$\begin{aligned}\mathcal{L}_{VDM} &= -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} + (D_\mu\Phi)^\dagger(D^\mu\Phi) - \lambda_\Phi\left(\Phi^\dagger\Phi - \frac{v_\Phi^2}{2}\right)^2 \\ & \quad -\lambda_{\Phi H}\left(\Phi^\dagger\Phi - \frac{v_\Phi^2}{2}\right)\left(H^\dagger H - \frac{v_H^2}{2}\right) ,\end{aligned} \tag{2.1}$$

[3]While we were working on these possibilities, this paper was put on the archive, and we don't consider this possibility any more in this work.

[4]See refs. [21, 26] for the original discussions on this point, and ref. [27] for more discussion on the correlation between the invisible Higgs branching ratio and the direct detection cross section in the Higgs portal SFDM and VDM models.

[5]The Abelian VDM was first considered in ref. [28] where the VDM mass assumed to be generated either by the Stückelberg or by dark Higgs mechanism, but the role of dark Higgs boson was ignored within effective field theory (EFT). However, in the presence of the dark Higgs boson, the resulting VDM phenomenology can be vastly different from the one in the VDM model of EFT. See ref. [21] for more detailed discussion.

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in addition to the SM Lagrangian which includes the Higgs potential term

$$\Delta\mathcal{L}_{\rm SM} = -\lambda_H \left(H^\dagger H - \frac{v_H^2}{2} \right)^2 . \tag{2.2}$$

The covariant derivative is defined as

$$D_\mu \Phi = (\partial_\mu + i g_X Q_\Phi X_\mu)\Phi,$$

where $Q_\Phi \equiv Q_X(\Phi)$ is the $\mathrm{U}(1)_X$ charge of Φ and we will take $Q_\Phi = 1$ throughout the paper.

Assuming that the $\mathrm{U}(1)_X$-charged complex scalar Φ develops a nonzero VEV, v_Φ, and thus breaks $\mathrm{U}(1)_X$ spontaneously, we would have

$$\Phi = \frac{1}{\sqrt{2}} \left(v_\Phi + \phi(x) \right) .$$

Therefore the Abelian vector boson X_μ gets mass $M_X = g_X |Q_\Phi| v_\Phi$. And the hidden sector Higgs field (or dark Higgs field) $\phi(x)$ will mix with the SM Higgs field $h(x)$ through the Higgs portal $\lambda_{\Phi H}$ term, resulting in two neutral Higgs-like scalar bosons. The mixing matrix O between the two scalar fields is defined as

$$\begin{pmatrix} h \\ \phi \end{pmatrix} = O \begin{pmatrix} H_2 \\ H_1 \end{pmatrix} \equiv \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} H_2 \\ H_1 \end{pmatrix}, \tag{2.3}$$

where $s_\alpha (c_\alpha) \equiv \sin\alpha (\cos\alpha)$, h, ϕ are the interaction eigenstates and $H_i (i = 1, 2)$ are the mass eigenstates with masses m_i, respectively. The mass matrix in the basis (h, ϕ) can be written in terms either of Lagrangian parameters or of the physical parameters as follows:

$$\begin{pmatrix} 2\lambda_H v_H^2 & \lambda_{\Phi H} v_\Phi v_H \\ \lambda_{\Phi H} v_\Phi v_H & 2\lambda_\Phi v_\Phi^2 \end{pmatrix} = \begin{pmatrix} m_1^2 s_\alpha^2 + m_2^2 c_\alpha^2 & \left(m_2^2 - m_1^2\right) s_\alpha c_\alpha \\ \left(m_2^2 - m_1^2\right) s_\alpha c_\alpha & m_1^2 c_\alpha^2 + m_2^2 s_\alpha^2 \end{pmatrix} . \tag{2.4}$$

Note that one can take m_1, m_2 and α as independent parameters.

In the small mixing limit which is of our interest, the mass eigenstates are approximated to the interaction eigenstates as $(H_2, H_1) \approx (h, \phi)$, and we use (h, ϕ) to represent quantities associated with (H_2, H_1) from now on.

3 Constraints

Our VDM interacts with SM sector via Higgs portal interaction. This means that it is subject to constraints from CMB observations, direct/indirect DM searches, and collider experiments. However, for $30\,\mathrm{GeV} \lesssim m_V \lesssim 80\,\mathrm{GeV}$, constraints from CMB [30] and indirect searches [6, 31–33] can be easily satisfied in our scenario as far as there is no enhancement of annihilation rate relative to the one at freeze-out. So, in this section we consider only low energy phenomenology, direct detection and relic density.

3.1 Vacuum stability

The mixing between Higgs fields (H and Φ) causes a tree-level shift of λ_H relative to that of SM in such a way that the relation

$$\lambda_H = \left[1 - \left(1 - \frac{m_\phi^2}{m_h^2} \right) \sin^2\alpha \right] \frac{m_h^2}{2 v_H^2} \tag{3.1}$$

holds. Hence, for $m_\phi < m_h$ one obtains λ_H even smaller than that of SM, and vacuum instability of SM Higgs potential becomes worse. So, it is better to take α as small as possible.

Although tree-level mixing does not work, vacuum instability can be improved by the additional contribution of $\lambda_{\Phi H}$ to the β-function of λ_H,

$$\Delta\beta_{\lambda_H} = \frac{1}{16\pi^2}\lambda_{\Phi H}^2. \tag{3.2}$$

For $\alpha \lesssim m_\phi/m_h$, one finds $\lambda_\Phi \approx g_X^2/2$ which should be $\mathcal{O}(10^{-2})$ as shown in section 3.4. Then, the tachyon-free condition, $|\lambda_{\Phi H}| < 2\sqrt{\lambda_\Phi \lambda_H}$, results in $|\lambda_{\Phi H}| \lesssim 0.07$ for α and m_ϕ in the range of our interest. It might be large enough to improve the vacuum stability. The exact lower bound on $\lambda_{\Phi H}$ that stabilizes the EW vacuum up to Planck scale depends on the precise values of top quark mass and the strong coupling constant, the detailed discussion of which is beyond this paper.

3.2 Collider bound

For $m_V < m_h/2$, the SM Higgs boson can decay into two VDM particles, which is invisible. Recent analysis from collider experiments showed that the branching fraction of the Higgs boson into invisible particles is constrained as [34]

$$\mathrm{Br}_h^{\mathrm{inv}} < 0.51. \tag{3.3}$$

This bound was derived within the effective-field-theoretic (EFT) VDM model, which should be taken with great care.[6]

The EFT for VDM has two problems: both dim-2 VDM mass operator (which is given by hand in EFT) and dim-4 Higgs portal interaction term break U(1) dark gauge symmetry associated with the VDM field, and thus violate unitarity. In ref. [21], the authors constructed renormalizable and unitary model for Abelian VDM with Higgs portal interaction, eq. (2.1), and showed that DM phenomenology changes dramatically from that within EFT. The main difference is the following: in a renormalizable and unitary theory described by eq. (2.1), new particle (dark Higgs field) and more parameters (dark Higgs mass and the mixing angle between the SM Higgs and dark Higgs bosons) are to be introduced because of dark gauge invariance, and new decay channels of the SM Higgs boson can be open, which is parametrized by non-SM branching ratio $\mathrm{Br}_h^{\mathrm{non-SM}}$. Hence, instead of eq. (3.3), we use

$$c_\alpha > 0.904 + \mathrm{Br}_h^{\mathrm{non-SM}}/2, \tag{3.4}$$

which is an approximation obtained from the result of ref. [35], and $\mathrm{Br}_h^{\mathrm{non-SM}}$ is the branching fractions of the Higgs decay to DMs and non-SM Higgs. In our VDM scenario, $\mathrm{Br}_h^{\mathrm{non-SM}}$ is given by

$$\mathrm{Br}_h^{\mathrm{non-SM}} = \frac{s_\alpha^2 \Gamma_h^{\mathrm{inv}} + \Gamma_h^{\phi\phi}}{c_\alpha^2 \Gamma_h^{\mathrm{SM}} + s_\alpha^2 \Gamma_h^{\mathrm{inv}} + \Gamma_h^{\phi\phi}}, \tag{3.5}$$

[6] See ref. [27] for the recent detailed discussions on the correlation between Higgs invisible branching ratio and DM direct detection cross section in renormalizable and unitary models for SFDM and VDM. This paper shows that the correlation depends on extra two parameters, dark Higgs mass and the scalar mixing angle. The EFT result can be obtained only in a particular limit of these two parameters, and thus cannot represent the whole parameter spaces for SFDM and VDM.

where

$$\Gamma_h^{\rm SM} \simeq 4.07\,{\rm MeV}\,, \tag{3.6}$$

$$\Gamma_h^{\rm inv} = \frac{g_X^2}{8\pi}\frac{m_V^2}{m_h}\left[1+\frac{1}{2}\left(1-\frac{m_h^2}{2m_V^2}\right)^2\right]\left(1-\frac{4m_V^2}{m_h^2}\right)^{1/2}, \tag{3.7}$$

$$\Gamma_h^{\phi\phi} = \frac{1}{32\pi m_h}\lambda_{h\phi\phi}^2\left(1-\frac{4m_\phi^2}{m_h^2}\right)^{1/2}, \tag{3.8}$$

with

$$\begin{aligned}\lambda_{h\phi\phi} &= \lambda_{\Phi H} v_H c_\alpha^3 + 2\left(3\lambda_H-\lambda_{\Phi H}\right)v_H c_\alpha s_\alpha^2 - 2\left[3\left(\lambda_\Phi-\lambda_{\Phi H}\right)v_\Phi\right]c_\alpha^2 s_\alpha - \lambda_{\Phi H} v_\Phi s_\alpha^3 \\ &\sim \lambda_{\Phi H} v_H c_\alpha^3 \simeq \frac{s_\alpha c_\alpha^4\left(m_h^2-m_\phi^2\right)}{v_\Phi}.\end{aligned} \tag{3.9}$$

In the second line of the above equation, we assumed the first term dominates over the others in the small mixing limit.

Using eqs. (3.4) and (3.5), we can constrain the allowed ranges of g_X and α as shown in the white region of the left-panel of figure 1. Note that in figure 1, the mixing angle is constrained to be $\alpha \lesssim 7\times10^{-2}$ for $m_\phi = 60\,{\rm GeV}$. The the upper-bound of α is lowered down for a lighter m_ϕ. Note that the current LHC, LUX or the future XENON1T experiments cover only a part of the allowed parameter region in (α, g_X). There is ample region of parameter space which cannot be explored directly in any experiments.

3.3 Direct detection

For $30\,{\rm GeV} \lesssim m_V \lesssim 80\,{\rm GeV}$, LUX experiment for direct detection of WIMP imposes a strong upper bound on the spin-independent (SI) dark matter-proton scattering cross section [25] as:

$$\sigma_p^{\rm SI} \lesssim (7-9)\times10^{-46}{\rm cm}^2. \tag{3.10}$$

The SI-elastic scattering cross section for VDM to scatter off a proton target is given by

$$\begin{aligned}\sigma_p^{\rm SI} &= \frac{4\mu_V^2}{\pi}\left(\frac{g_X s_\alpha c_\alpha m_p}{2v_H}\right)^2\left(\frac{1}{m_1^2}-\frac{1}{m_2^2}\right)^2 f_p^2, \\ &\simeq 2.2\times10^{-45}{\rm cm}^2\left(\frac{g_X s_\alpha c_\alpha}{10^{-2}}\right)^2\left(\frac{75\,{\rm GeV}}{m_\phi}\right)^4\left(1-\frac{m_\phi^2}{m_h^2}\right)^2,\end{aligned} \tag{3.11}$$

where $\mu_V = m_V m_p/(m_V+m_p)$ and $f_p = 0.326$ [36] (see ref. [37] for more recent analysis) was used. Note that $m_\phi \sim m_h$ results in some amount of cancellation between contributions of ϕ and h to $\sigma_p^{\rm SI}$. As a result, the LUX bound can be satisfied rather easily for $g_X s_\alpha c_\alpha \lesssim 10^{-2}$. As shown in figure 1, direct detection experiments leave a wide range of parameter space uncovered. This is unfortunate since it implies that the model cannot be entirely cross checked by other physical observables.

3.4 Dark matter relic density

The observed GeV scale γ-ray spectrum may be explained if DM annihilates mainly into $b\bar{b}$ with a velocity-averaged annihilation cross section close to the canonical value of thermal relic

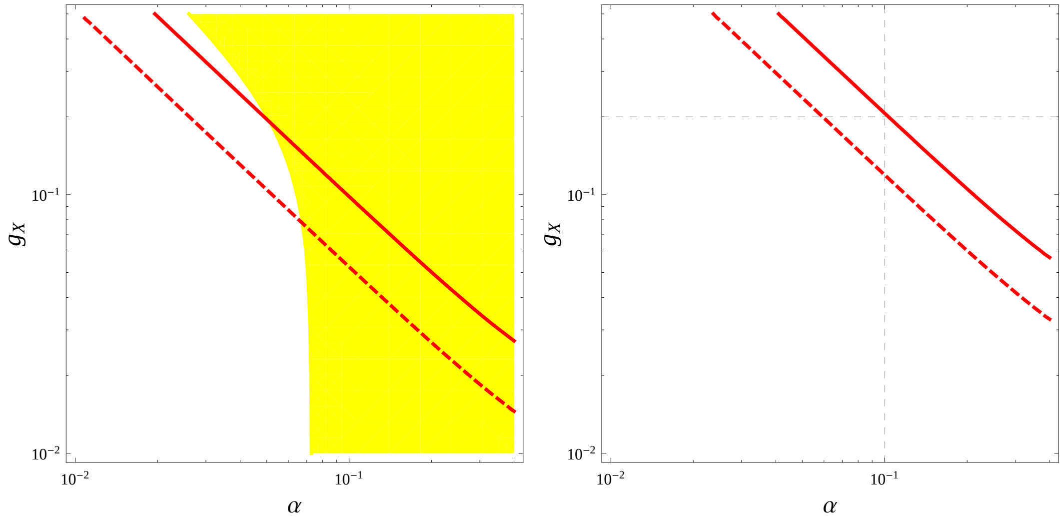

Figure 1. A bound of α and g_X from collider experiments, LUX and projected XENON1T direct DM searches [25] for $m_h = 125$. Left: $m_V = 35\,\text{GeV}$, $m_\phi = 60\,\text{GeV}$, and $\lambda_\Phi = 0.1$. Right: $m_V = 80\,\text{GeV}$, $m_\phi = 75\,\text{GeV}$. Yellow region is excluded by collider constraint on $\text{Br}_h^{\text{non-SM}}$. Solid and dashed red lines are upper-bounds due to the upper-bound of DM-nucleon scattering cross section from LUX and XENON1T projection, respectively.

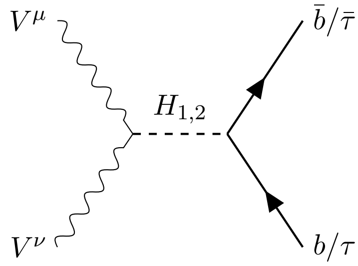

Figure 2. Dominant s channel $b + \bar{b}$ (and $\tau + \bar{\tau}$) production.

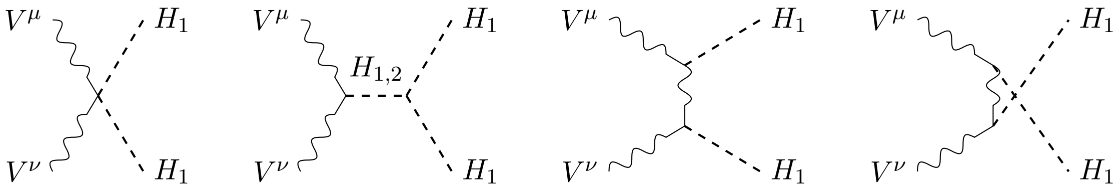

Figure 3. Dominant s/t-channel production of H_1s that decay dominantly to $b + \bar{b}$.

dark matter. This implies that $30\,\text{GeV} \lesssim m_V \lesssim 40\,\text{GeV}$ in case of the s-channel annihilation (figure 2) scenario. It is also possible to produce $b\bar{b}$ with the nearly same energy from the decay of highly non-relativistic ϕ which is produced from the annihilation of DM having mass of $60\,\text{GeV} \lesssim m_V \lesssim 80\,\text{GeV}$ (figure 3). In both cases, it is expected to have $\tau\bar{\tau}$ and $c\bar{c}$ productions too in the final states, because H_1 will decay into them with branching ratios about 7% and 3%.

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In the process of figure 2, the thermally-averaged annihilation cross section of VDM is given by

$$\langle\sigma v_{\rm rel}\rangle_{f\bar{f}} = \sum_f \frac{(g_X s_\alpha c_\alpha)^2}{3\pi} m_X^2 \left|\sum_i \frac{1}{s - m_i^2 + i m_i \Gamma_i}\right|^2 \left(\frac{m_f}{v_H}\right)^2 \left(1 - \frac{4m_f^2}{s}\right)^{3/2}, \tag{3.12}$$

where m_f is the mass of a SM fermion f. Note that eq. (3.12) is suppressed by a factor $s_\alpha^2 m_f^2$. Hence a large enough annihilation cross section for the right amount of relic density can be achieved only around the resonance region. However in the resonance region the annihilation cross section varies a lot, as the Mandalstam s-variable varies from the value at freeze-out to the value in a dark matter halo at present. Therefore, this process can not be used for the GeV scale γ-ray spectrum from the galactic center.

On the other hand, in the process of figure 3 for $m_\phi < m_V \lesssim 80\,\text{GeV}$, the thermally-averaged annihilation cross section of VDM is given by

$$\langle\sigma v_{\rm rel}\rangle_{\rm tot} = \langle\sigma v_{\rm rel}\rangle_{f\bar{f}} + \langle\sigma v_{\rm rel}\rangle_{\phi\phi}\,, \tag{3.13}$$

where

$$\langle\sigma v_{\rm rel}\rangle_{\phi\phi} \simeq \frac{1}{16\pi s}\overline{|\mathcal{M}|^2}\left(1 - \frac{4m_\phi^2}{s}\right)^{1/2}, \tag{3.14}$$

with

$$\overline{|\mathcal{M}|^2} \approx \frac{2}{9}\left[1 + 4\left(\frac{s}{4m_V^2}\right)^2\left(1 - \frac{2m_V^2}{s}\right)^2\right]\left[\left(2c_\alpha^2 g_X^2 + \mathcal{M}_s^0\right) - 8c_\alpha^2 g_X^2\right]^2, \tag{3.15}$$

$$\begin{aligned}\mathcal{M}_s^0 &= 2c_\alpha^4 m_V^2\left(\frac{6\lambda_\Phi}{s - m_\phi^2} - \frac{t_\alpha \lambda_{\Phi H} v_H / v_\Phi}{s - m_h^2}\right) \simeq 4c_\alpha^4\lambda_\Phi\left[1 - \frac{s_\alpha^2 m_V^2\left(m_h^2 - m_\phi^2\right)}{m_\phi^2\left(s - m_h^2\right)}\right] \\ &\sim 2c_\alpha^4 g_X^2\left[1 - \frac{s_\alpha^2\left(m_h^2 - m_V^2\right)}{\left(4m_V^2 - m_h^2\right)}\right].\end{aligned} \tag{3.16}$$

Note that, if we consider the off-resonance region with $2m_V \not\approx m_h$, the contribution of the s-channel H_2 mediation can be ignored and $\langle\sigma v_{\rm rel}\rangle_{\phi\phi}$ does not depend neither on s_α nor on m_f. Hence a right size of annihilation cross section can be obtained by adjusting mostly g_X and $(m_V - m_\phi)/m_V$, with the negligible mixing angle dependence. Figure 4 shows the relic density at present[7] as a function of m_V for $m_\phi = 75\,\text{GeV}$ and $g_X = 0.2$ and the mixing angle $\alpha = 0.1$. From figure 4, we note that the mass of our VDM is constrained to be $m_h/2 < m_V$, since SM-Higgs resonance should be also avoided. And the velocity-averaged annihilation cross section at present epoch can be close to that of freeze-out only for $m_\phi \lesssim m_V$. Note also that, as shown in figure 5, in order to match to the observed γ-ray spectrum, we need $m_\phi \sim m_V$ to avoid a boosted ϕ.

In the region of $60\,\text{GeV} \lesssim m_\phi \sim m_V \lesssim 80\,\text{GeV}$, the SM Higgs boson's decay into VDM is suppressed by the phase space factor or kinematically forbidden. Hence the collider bound on the invisible decay of SM Higgs is irrelevant, but the mixing angle is still constrained by the signal strength of SM channels such that $\alpha \lesssim 0.4$ [35].

[7] We adapted the micrOMEGAs package [38, 39] to our model for numerical calculation.

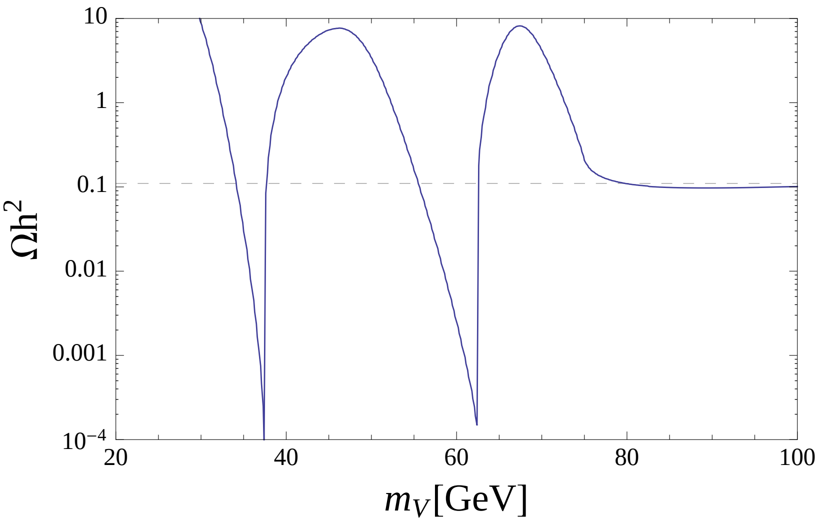

Figure 4. Relic density of dark matter as a function of m_ψ for $m_h = 125$, $m_\phi = 75\,\mathrm{GeV}$, $g_X = 0.2$, and $\alpha = 0.1$.

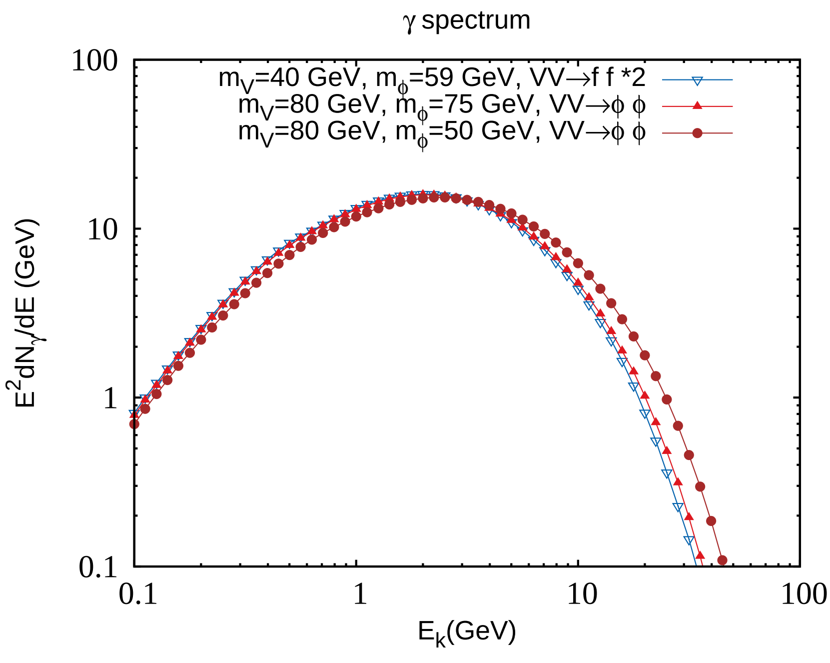

Figure 5. Illustration of γ spectra from different channels. The first two cases give almost the same spectra while in the third case γ is boosted so the spectrum is shifted to higher energy.

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A remark is in order for the present annihilation cross section to obtain observed GeV scale γ-ray. Compared to the case of $30\,\text{GeV} \lesssim m_V \lesssim 40\,\text{GeV}$, the present number density of dark matter for $60\,\text{GeV} \lesssim m_V \lesssim 80\,\text{GeV}$ is smaller by a factor of about a half, but each annihilation produces two pairs of $b\bar{b}$. Hence, the expected flux which is proportional to the square of DM number density is smaller by about a half. However, there are various astrophysical uncertainties in the estimation of required annihilation cross section. In particular, a small change of the inner slope of DM density profile is enough to compensate the difference of about factor two. In addition, as discussed in ref. [10], the GeV scale γ-ray data fits well to cross sections proportional to the square of the mass of the final state SM particles. This kind of flavor-dependence is an intrinsic nature of our VDM scenario, thanks to the Higgs portal interaction. Therefore, with these points in mind, VDM with mass of $60\,\text{GeV} \lesssim m_V \lesssim 80\,\text{GeV}$ can be a natural source of the GeV scale γ-ray excess from the direction of the galactic center.

3.5 Comparison with other Higgs portal DM models

In regard of the GeV scale γ-ray excess from the galactic center, SSDM can work equally well as our VDM scenario. One difference from VDM is the additional Higgs portal interaction of SSDM with SM Higgs, which can improve the vacuum instability problem of SM Higgs potential better than VDM scenario.

Contrary to SSDM or VDM, SFDM with a real scalar mediator results in p-wave s-channel annihilation. In addition, the t-channel annihilation cross section is approximately proportional to $\left(1 - m_\phi^2/m_{\text{DM}}^2\right)^{3/2}$ in the low momentum limit. Since $\left(m_{\text{DM}} - m_\phi\right)/m_{\text{DM}} \ll 1$ is needed in order to avoid a boosted ϕ, such a t-channel annihilation in SFDM scenario is suppressed by an additional factor $\left(1 - m_\phi^2/m_{\text{DM}}^2\right)$ relative to the case of SSDM and VDM. Hence SFDM needs a pseudo-scalar mediator and it makes model a bit complicated (see for example ref. [19]).

Contrary to the case of SFDM where a wide range of pseudo-scalar mass is allowed, the requirement of the t-channel annihilation of DM near threshold in SSDM and VDM constrains the mass of non-SM Higgs ϕ to be within a narrow range of

$$m_h/2 \lesssim m_\phi \lesssim 80\,\text{GeV} \tag{3.17}$$

Therefore, dedicated searches of the second Higgs boson at future collider experiments can focus on this range of invariant mass although too small mixing angle or too small trilinear coupling for $H - \phi - \phi$ would end up a null result.

4 Conclusion

In this paper, we revisited the singlet vector dark matter (VDM) model with Higgs portal in order to see if it can explain the observed GeV scale γ-ray spectrum from the galactic center by the annihilation of dark matter mainly to $b\bar{b}$ or to two non-SM light Higgses which decay subsequently and dominantly to $b\bar{b}$. We found that the Higgs portal VDM scenario can naturally explain the γ-ray spectrum while providing a right amount of relic density for $m_h/2 < m_V \lesssim 80\,\text{GeV}$ and $(m_V - m_\phi)/m_V \ll 1$ with m_V and m_ϕ being the masses of VDM and non-SM Higgs boson. This implies that the mass of the non-SM extra Higgs is constrained to be within a narrow range of

$$m_h/2 \lesssim m_\phi \lesssim 80\,\text{GeV}\,, \tag{4.1}$$

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which can be focused on in dedicated searches of the second Higgs at future collider experiments although a null result due to very small mixing angle α is also possible. The dark gauge coupling is contained to be $g_X \sim 0.2$ for the right amount of relic density while taking α to be small enough to satisfy direct DM search bound. Unfortuantely the LUX or XENON1T cannot explore the entire parameter space of the VDM explaining the GeV-scale γ-ray from the galactic center. Finally, the instability of SM vacuum could be improved due to the additional loop contribution of an extra scalar field.

Acknowledgments

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