Higgs boson as a probe of dark sectors with dark gauge symmetries

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We consider a class of hidden sector dark matter (DM) models with local dark gauge symmetries and singlet portals to dark sector, and discuss generic aspects of these models in the context of Higgs phenomenology and extra dark radiation. We first describe the guiding principles for DM model building: hidden sector DM and dark gauge symmetry, renormalizability and imposing the full SM gauge group instead of its unbroken subgroup. It is shown that DM and Higgs phenomenology based on the effective field theory for singlet fermion or vector DMs with Higgs portal can be significantly different from their simplest UV completions, most importantly in the direct detection cross section of DM on nucleon. In these cases, there are always the SM singlet scalar that mixes with the SM Higgs boson, which make a generic destructive interference in the amplitude for direct detection cross section of the DM. Also one of the two Higgs-like scalar bosons can easily escape the detections at the LHC, and there will be a universal reduction of the signal strength for the observed 125 GeV Higgs-like boson, which could be tested at the LHC with more data in the future. Finally, depending on the nature of dark gauge symmetry, unbroken or broken, and confining or not, there could be some extra dark radiation which would be constrained by Planck and other cosmological observations.

I. INTRODUCTION

The standard model (SM) has been tested from atomic scale up to electroweak scale by many experiments, and has been extremely successful. However, there are some observational facts which call for new physics beyond the SM (BSM):

- Baryon number asymmetry of the universe (BAU)
- Neutrino masses and mixings
- Nonbaryonic dark matter (DM)
- Inflation in the early universe

There are many models and suggestions for each problem listed above. The most economical way to solve the BAU and the neutrino masses and mixings is probably the seesaw mechanism by introducing heavy right-handed (RH) neutrinos. Leptogenesis through the RH neutrino decays can turn to baryogenesis around electroweak phase transition by sphalerons. For nonbaryonic DMs, there are many models: from the lightest supersymmetric particles (LSP) to axion (and axino) to lightest hidden sector particle (LHP) if its decay is protected by some unbroken local dark symmetry.

Any new physics models at the electroweak scale are strongly constrained by electroweak precision test and CKM phenomenology, if new particles feel SM gauge interactions. In this case, the new physics scales should be larger than $\sim O(1)$ TeV and $\sim O(100)$ TeV in order to be safe from the EWPT and CKM phenomenology, respectively, if one makes naive estimates. On the other hand, fine tuning problem of (Higgs mass)$^2 = m_H^2$ requires that new physics scale should be around $\lesssim O(1)$ TeV. Thus there is strong tension between two. In this talk, I will ignore the fine tuning problem for m_H^2, and will pursue how to build DM models with explicit mechanisms stabilizing nonbaryonic weak scale DM particles.

If any new particles are neutral under the SM gauge group and do not feel SM gauge interactions, the constraints from the EWPT and CKM fit can be significantly relaxed and new physics scales could be easily at the EW scale or even lower. Thus we are led to consider a weak scale hidden sector which is made of particles neutral under the SM gauge interaction. The hidden sector matters can be easily thermalized if there are suitable messengers between the SM and the hidden sectors. We assume all the singlet operators play the role of messengers. In this talk, I will discuss generic aspects of hidden sector dark matter models based on the works [1–7].

II. HIDDEN SECTOR DM AND LOCAL DARK GAUGE SYMMETRY

Hidden sector is defined as collections of particles which are singlets under the SM gauge group $G_{\rm SM}$. They may have their own gauge interaction associated with $G_{\rm hidden}$. As mentioned in Sec. I, the hidden sector is weakly constrained by EWPT and CKMology. Therefore the hidden sector particles can be very light, and the lightest hidden particle (LHP) could be good candidates for the CDM of the universe. And its stability could be guaranteed if there is an unbroken hidden sector gauge symmetry.

Hidden sector is very generic in many BSMs. For example, in any SUSY models, SUSY is spontaneously broken in a hidden sector, and its effects are transmitted to visible sector (MSSM sector) by some messengers. Beyond this, hidden sector in most SUSY models does not play any further role. However one can imagine a possibility that some hidden sector particles are relatively light, with mass around EW scale or even lighter. Then they could play an important role both in particle physics and in cosmology as CDM.

Hidden sector gauge groups is also well motivated in superstring theory, in which the rank of gauge group is much larger than the SM value, which is 4). One can imagine that the original $G_{\rm string}(E_8 \times E_8^{'}$ or $SO(32)$, for example) is broken down to $G_{\rm SM} \times G_{\rm hidden}$. Thus we would be naturally led to a hidden sector with its own gauge symmetry group in the low energy world of superstring theory.

Another motivation for local dark gauge symmetry $G_{\rm hidden}$ in the hidden sector is to stabilize the DM particle by dark charge conservation laws, in the same way electron is absolutely stable because it is the lightest charged particle and electric charge is absolutely conserved. Therefore we consider dark gauge theory associated with dark charge conservation, which is the reason behind the absolute stability of dark matter. It could be either unbroken or broken, for the latter of which DM can decay in general and we have to make it sure its lifetime is long enough to be a good DM candidates [19].

In order to highlight the idea of local dark gauge symmetry, let us consider a scalar DM S with Higgs portal with discrete Z_2 symmetry ($S \rightarrow -S$). The model Lagrangian is given by Eq. (5) in the following section [8], and we are asking if discrete Z_2 symmetry can be global or not. If it is global symmetry, it would be broken by quantum gravity effects, which can be described by Z_2-breaking nonrenormalizable dim-5 operators such as

$$\mathcal{L}_{\rm dim-5}(Z_2 \text{ breaking}) \sim \frac{c}{M_{\rm Planck}} S O_{\rm SM}^{\rm dim-4}, \tag{1}$$

for which the scalar DM decay rate would be

$$\Gamma(S) \sim \frac{c^2}{M_{\rm Planck}^2} m_S^3 \sim c^2 \left(\frac{m_S}{100 \text{GeV}}\right)^3 10^{-37} \text{ GeV}. \tag{2}$$

Then the corresponding lifetime for electroweak scale DM with $m_S \sim 100$ GeV would be too short for $c \sim O(1)$, and the scalar boson S with weak scale mass cannot be a good CDM of the universe [20]. Therefore global Z_2 cannot stabilize electroweak scale DM, and we have to implement it to some local symmetry.

Suppose dark matter X (now this is a complex scalar, not a real scalar) carries a new conserved charge associated with local $U(1)_X$ and this symmetry is spontaneously broken by dark Higgs ϕ_X. If X and ϕ_X carry the same $U(1)_X$ charges equal to '1', the previous dangerous dim-5 operator would be replaced by the following dim-6 operator invariant under local $U(1)_X$ symmetry:

$$\mathcal{L}_{\rm dim-6} \sim \frac{1}{M_{\rm Planck}^2} \phi_X^\dagger X O_{\rm SM}^{\rm dim-4} \tag{3}$$

After ϕ_X develops a nonzero VEV $v_X \sim O(100)$ GeV breaking $U(1)_X$ spontaneously, this operator becomes

$$\mathcal{L}_{\rm dim-6} \sim \frac{v_X}{M_{\rm Planck}^2} X O_{\rm SM}^{\rm dim-4}$$

and the lifetime of X becomes long enough to be a good CDM. However this $U(1)_X$ charge assignment causes another serious problem from the $U(1)_X$ invariant dim-4 operator:

$$\phi_X^\dagger X H^\dagger H,$$

which would make scalar DM candidate X decay immediately after $U(1)_X$ symmetry breaking. This is due to the Higgs field which can make dim-2 gauge invariant operator $H^\dagger H$. In a sense, Higgs makes EW scale DM unstable [21].

This problem can be resolved if we break $U(1)_X$ down to local Z_2 by judicious choice of $U(1)_X$ charges. Let us assume that X and ϕ_X carry $U(1)_X$-charges equal to 1 and 2, respectively. Then the renormalizable Lagrangian of this model is given by

$$\begin{aligned}\mathcal{L} \ = \ & \mathcal{L}_{\rm SM} - \frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} - \frac{1}{2}\sin\epsilon \hat{X}_{\mu\nu}\hat{B}^{\mu\nu} + D_\mu \phi_X D^\mu \phi_X + D_\mu X^\dagger D^\mu X - \mu\left(X^2 \phi_X^\dagger + H.c.\right) - m_X^2 X^\dagger X \\ & -\lambda_X \left(X^\dagger X\right)^2 - \lambda_\phi \left(\phi_X^\dagger \phi_X - \frac{v_\phi^2}{2}\right)^2 - \lambda_{\phi X} X^\dagger X \phi_X^\dagger \phi_X - \lambda_{\phi H} \phi_X^\dagger \phi_X H^\dagger H - \lambda_{HX} X^\dagger X H^\dagger H, \end{aligned} \tag{4}$$

which is much more complicated than the original Z_2 scalar DM model, Eq. (5). Even after $U(1)_X$ symmetry breaking by nonzero $\langle \phi_X \rangle = v_X$, there still remains a Z_2 symmetry, $X \to -X$, which guarantees the scalar DM to be absolutely stable even if we consider higher dimensional operators. The $U(1)_X$ breaking also lifts the degeneracy between the real and the imaginary parts of X. This model is very similar to the models in the literature, which were devised in order to explain 511 keV and PAMELA positron excess, except that the mass splitting is generated by dark Higgs field ϕ_X, and not by hand. It would be interesting to see if this model can explain some cosmic ray anomalies or not, without conflict with the CMB constraints [9].

Finally note that all the observed particles in Nature feels gauge interactions in addition to gravity [22]. Therefore it looks very natural to assume that dark matter of the universe (at least some of the DM species) also feels some (new) gauge force, in addition to gravity.

These are reasons why we consider local dark gauge symmetry as one guiding principle for DM model building.

III. HIGGS PORTAL DM: EFT VS. RENORMALIZABLE THEORIES

A. Higgs portal DM in effective field theory framework

The Higgs portal DM models are usually defined by the following Lagrangians [10]:

$$\mathcal{L}_{\rm scalarDM} = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \frac{\lambda_{HS}}{2} H^\dagger H S^2 - \frac{\lambda_S}{4} S^4 \tag{5}$$

$$\mathcal{L}_{\rm fermionDM} = \overline{\psi}\left[i \not{\partial} - m_\psi \right] \psi - \frac{\lambda_{H\psi}}{\Lambda} H^\dagger H \overline{\psi} \psi \tag{6}$$

$$\mathcal{L}_{\rm vectorDM} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \frac{1}{2} m_V^2 V_\mu V^\mu + \frac{1}{4}\lambda_V (V_\mu V^\mu)^2 + \frac{1}{2}\lambda_{HV} H^\dagger H V_\mu V^\mu \tag{7}$$

for a real scalar DM (S), a singlet fermion DM (ψ) and a vector DM (V), respectively. In all cases, *ad hoc* discrete Z_2 symmetries ($S \to -S, \quad \psi \to -\psi, \quad V_\mu \to -V_\mu$) are imposed by hand in order to stabilize DM particles. Let me discuss a few problems with these Higgs portal DM Lagrangians:

- It is not clear at all where these Z_2 symmetries come from, and whether these Z_2 symmetries are global or local. In the previous section, we already argued that global Z_2 may not be enough to guarantee stability or longevity of dark matter.

- In the EFT approach, the fermion or vector DM couplings with the Higgs field ($\lambda_{H\psi}$ in Eq. (6) and λ_{HV} in Eq. (7)) are strongly constrained by direct searches of DM such as XENON100 or CDMS. And the singlet fermion or the vector DM models are strongly constrained by these experiments. However this is not the case if we consider the UV completions of these models.

- The Lagrangian for the singlet fermion DM is not renormalizable and should be UV-completed. The simplest renormalizable extension of Eq. (6) will be described in the next subsection, and we show that DM and Higgs phenomenology will be very different. The effective field theory (EFT) description of the singlet fermion DM gives erroneous results. One can consider a dim-4 operator $\lambda_{h\psi} h \bar{\psi} \psi$ (where h is the SM Higgs boson after EWSB) instead of dim-5 operator in Eq. (6). But this operator does not respect the full SM gauge symmetry, and is good only at low energy, and not at high energy.

- The Lagrangian for the vector DM, Eq. (7), looks renormalizable. However it is not really the case, because the vector DM mass is given by hand. And the model has bad high energy behavior and unitarity would be violated, as is well known from the old intermediate vector boson theory for the massive $W^\pm$ in weak interaction. We have to include some agency which provides the vector DM mass, and the simplest and calculable way is to introduce a dark Higgs as in the SM Higgs. Then we would find that the DM and Higgs phenomenology for vector DM in EFT and the model with dark Higgs are very different, and the Lagrangian (7) produces wrong results.

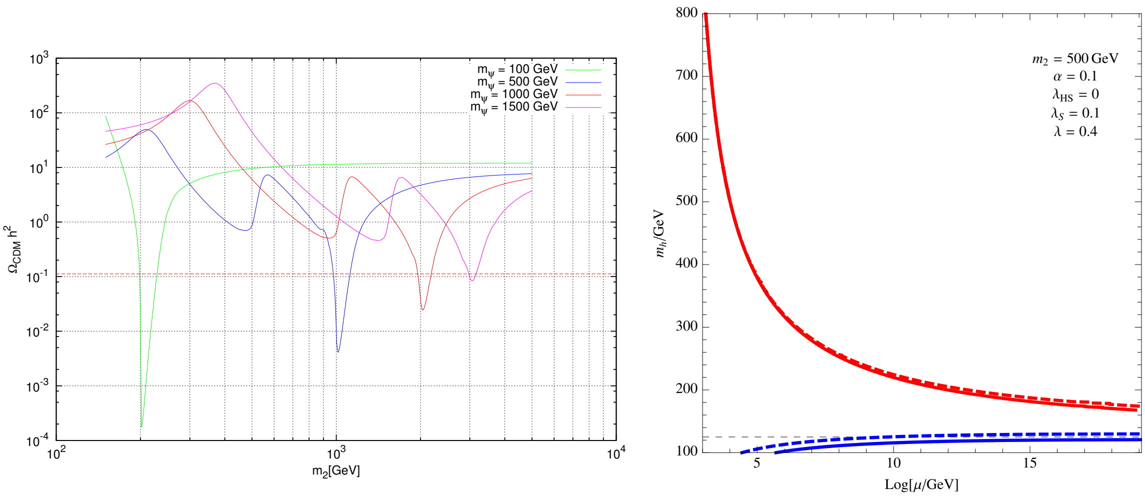

FIG. 1: (a) Dark matter thermal relic density ($\Omega_{\rm CDM}h^2$) as a function of m_2 for $m_1 = 125\,{\rm GeV}$, $\lambda = 0.4$, $\alpha = 0.1$ and $m_\psi = 100, 500, 1000, 1500\,{\rm GeV}$ from top to bottom at right side. The dotted red line corresponds to the observed value, $\Omega_{\rm CDM}h^2 = 0.112$. (b) The mass bound of SM-like Higgs (m_1) as a function of energy scale for $(\alpha, \lambda_{HS}) = (0, 0.2)$(left),$(0.1, 0)$(right) with $\lambda_S = 0.1$ and $\lambda = 0.4$. The red/blue line corresponds to triviality/vacuum-stability bound in SM(dashed) and our model(solid). The dashed black line corresponds to $m_1 = 125\,{\rm GeV}$.

B. Hidden sector singlet fermion DM model

1. *Model*

Let us consider the simplest UV completion of a singlet fermion dark matter model Eq. (6) by introducing a real singlet scalar messenger S [4]:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm hidden} + \mathcal{L}_{\rm portal}, \tag{8}$$

where

$$\mathcal{L}_{\rm hidden} = \frac{1}{2}(\partial_\mu S \partial^\mu S - m_S^2 S^2) - \mu_S^3 S - \frac{\mu_S'}{3} S^3 - \frac{\lambda_S}{4} S^4 + \overline{\psi}(i\not\partial - m_\psi)\psi - \lambda S \overline{\psi}\psi, \tag{9}$$

$$\mathcal{L}_{\rm portal} = -\mu_{HS} S H^\dagger H - \frac{\lambda_{HS}}{2} S^2 H^\dagger H, \tag{10}$$

We assume ψ carries some conserved dark charge, and is distinguished from the right-handed neutrinos. In the UV completion, there are two scalar bosons in our model (h and s), and we will find that the physics results from our model are very different from those based on Eq. (6).

2. *Constraints*

There are a number of constraints on the model parameters: *(i)* the perturbative unitarity condition on the Higgs sector, *(ii)* the LEP bound on the SM Higgs boson mass, *(iii)* the oblique parameters S, T and U obtained from the EWPT, *(iv)* the observed CDM density, $\Omega_{\rm CDM}h^2 = 0.1123 \pm 0.0035$ which we assume is saturated by the thermal relic ψ, and *(v)* the upper bound on the DM-proton scattering cross section obtained by the XENON100 experiment. Note that the first three constraints are independent of the dark matter sector, and they apply to the SM plus a singlet scalar model without dark matter as well. It turns out that the EWPT constraint on our model is generically much less severe than on the SM even for heavy Higgs case.

3. *Dark matter phenomenology*

The observed DM relic density, $\Omega_{\rm CDM}h^2 \simeq 0.1123 \pm 0.0035$ is related with the thermally averaged annihilation cross section times relative velocity at freeze-out temperature. The annihilation cross section of a DM pair is proportional to $\sin^2 2\alpha$. Since the EWPT and LHC observation of the SM-like Higgs boson restricts α to be small, the cross section is generically much smaller than is needed to explained the current relic density. This can be seen in Fig. 1 (a) except for resonance regions.

We used the micrOMEGAs package for numerical calculation of DM relic density and direct detection cross section. In Fig. 1 (a), we show the CDM relic density as a function of m_2 for various choices of $m_\psi = 100, 500, 1000, 1500$ GeV, with $\lambda = 0.4$ and $\alpha = 0.1$. We can always find out the m_2 value which can accommodate thermal relic density of the singlet fermion CDM ψ. Note that there is no strong constraint on the heavier Higgs with a small mixing angle α, because H_2 would be mostly a singlet scalar so that it is very difficult to produce it at colliders, and also it could decay into a pair of CDM's with a substantial branching ratio.

The spin-independent dark matter scattering on proton target is given by

$$\sigma_p \simeq 8.6 \times 10^{-9} \text{ pb} \left(\frac{125\,\text{GeV}}{m_1}\right)^4 \left(1 - \frac{m_1^2}{m_2^2}\right)^2 \left(\frac{\lambda \sin\alpha \cos\alpha}{0.1}\right)^2 . \tag{11}$$

Note that there is a generic cancellation between the H_1 and H_2 contributions [23], which can never seen within the EFT approach with the SM Higgs only based on Eq. (6). Due to this cancellation, the constraint from direct detection of dark matter becomes much weaker on the Higgs couplings to the DM's. This shows that it is very important to consider renormalizable models for singlet fermion DM models.

4. Vacuum stability and the strong 1st order phase transition

Having a singlet scalar S has another virtues. It improves the stability of the EW vacuum upto Planck scale for $m_h = 125$ GeV. We studied this issue and the phase structure of the singlet fermion DM model very carefully in Ref. [5], and found that the SM vacuum can be stable up to Planck scale within this model (see Fig. 1 (b)). Also the stronger 1st order phase transition is possible, which opens a possibility of electroweak baryogenesis as noted in a number of works [11], if there is an additional source of CP violation beyond the KM phase in the CKM matrix.

5. Implications for the Higgs search at the LHC

Now let us investigate if it is possible to discover both Higgs-like scalar bosons at the LHC, taking into account of all the constraints discussed in the previous subsubsection. We calculate the signal strength r_i defined as

$$r_i \equiv \frac{\sigma_{H_i} B_{H_i \to X_{\rm SM}}}{\sigma_{H_i}^{\rm SM} B_{H_i \to X_{\rm SM}}^{\rm SM}} \quad (i = 1, 2), \tag{12}$$

where σ_{H_i} and $B_{H_i \to X_{\rm SM}}$ are the production cross section of H_i, and the branching ratio of $H_i \to X_{\rm SM}$ respectively, while $\sigma_{H_i}^{\rm SM}$ and $B_{H_i \to X_{\rm SM}}^{\rm SM}$ are the corresponding quantities of the SM Higgs with mass m_i. Note that the signal strength r_i becomes less than "1" in a universal manner due to the mixing between h and s, even if the invisible mode ($H_i \to \psi\overline{\psi}$) or the Higgs-splitting mode ($H_2 \to H_1 H_1$) is kinematically forbidden in the Higgs decay. In other words, a universally reduced signal of the Higgs boson at the LHC would be a generic signature of the mixing of the SM Higgs boson with extra singlet scalar boson(s). The constraint on the possible mixing of the SM Higgs boson with a singlet scalar from the LHC data is discussed in detail in Ref. [12].

We study the following three benchmark scenarios classified according to the Higgs mass relations: *(i)* scenario 1 (S1): $m_1 \sim 125$ GeV $\ll m_2$, *(ii)* scenario 2 (S2): $m_1 \sim m_2 \sim 125$ GeV, and *(iii)* scenario 3 (S3): $m_1 \ll m_2 \sim$ 125 GeV. We scanned the remaining parameters in the range

$$0 < \lambda < 1, \quad 10 \;\text{ GeV} < M_\psi < 100 \;\text{ GeV}, \quad 0 < \alpha < \pi/2. \tag{13}$$

The results are shown in Fig. 2 (a)–(c). All the points in the plots satisfy the constraints described earlier.

We can divide the σ_p (in pb) into two regions:

$$\sigma_p^> : 10^{-9} < \sigma_p < 10^{-8}, \quad \sigma_p^< : \sigma_p < 10^{-9}, \tag{14}$$

where the former region can be probed in near future direct search experiments. The relic density is also divided into two regions:

$$(\Omega_{\rm CDM} h^2)^{3\sigma} : 0.1018 < \Omega_{\rm CDM} h^2 < 0.1228, \quad (\Omega_{\rm CDM} h^2)^< : \Omega_{\rm CDM} h^2 < 0.1018. \tag{15}$$

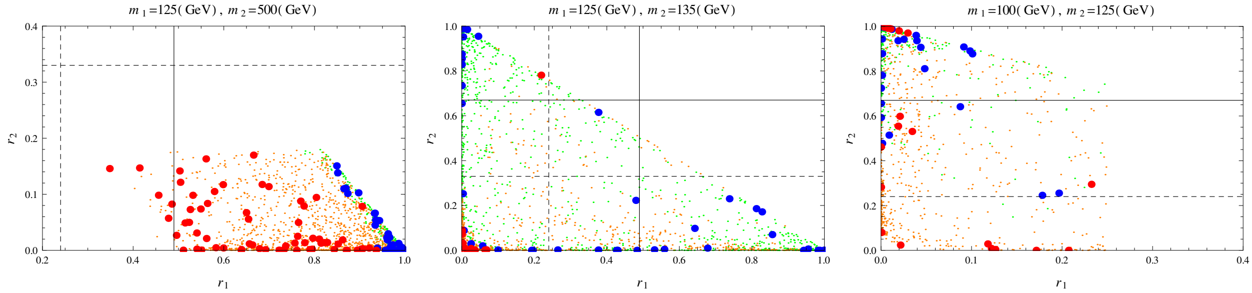

FIG. 2: Scatter plot in (r_1, r_2) plane for the scenario S1, S2 and S3 (from left). The region that the LHC can probe at 3σ level with 5 (10) fb^{-1} luminosity is represented by solid (dashed) line. The points represent 4 different cases: $(\Omega_{\rm CDM}h^2)^{3\sigma}$, $\sigma_p^>$ (big red), $(\Omega_{\rm CDM}h^2)^{3\sigma}$, $\sigma_p^<$ (big blue), $(\Omega_{\rm CDM}h^2)^<$, $\sigma_p^>$ (small orange), and $(\Omega_{\rm CDM}h^2)^<$, $\sigma_p^<$ (small green).

where the former is the WMAP 3σ allowed region.

The region that the LHC at 14 TeV can probe at 3σ level with 5 (10) fb^{-1} luminosity is represented by solid (dashed) line. The S1 scenario can be tested fully at the LHC with 10 fb^{-1} by observing H_1. In the case of S2 the LHC may see both Higgs bosons with the standard search strategy. However, there are still some points which the LHC has difficulty to find two Higgs bosons. These are the points near the origin ($r_1 \approx r_2 \approx 0$) where the invisible decays becomes dominant. In S3 the region with small $r_2(< 0.24)$ can not be probed with the standard decay channels. However, once $H_2 \to H_1 H_1$ is open, this region can also be tested at the LHC.

C. Vector CDM models

Now let us turn to the Higgs portal vector dark matter described by the effective Lagrangian Eq. (7). This model is very simple, compact and seemingly renormalizable since it has only dim-2 and dim-4 operators. However, it is not really renormalizable and violates unitarity. It is in fact a kind of EFT, just like the intermediate vector boson model for charged weak interaction before Higgs mechanism was developed. Therefore the model Lagrangian (7) does not capture dark matter or Higgs boson phenomenology correctly.

Let us consider a vector boson dark matter, V_μ, which is assumed to be a gauge boson associated with Abelian dark gauge symmetry $U(1)_X$. The simplest way to generate the VDM would introduce a $U(1)_X$-charged dark Higgs field Φ, whose VEV generates the VDM mass via Higgs mechanism. X_μ [6]:

$$\mathcal{L}_{VDM} = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + (D_\mu\Phi)^\dagger(D^\mu\Phi) - \lambda_\Phi\left(\Phi^\dagger\Phi - \frac{v_\Phi^2}{2}\right)^2 - \lambda_{H\Phi}\left(H^\dagger H - \frac{v_H^2}{2}\right)\left(\Phi^\dagger\Phi - \frac{v_\Phi^2}{2}\right) , \quad (16)$$

where the covariant derivative is defined as $D_\mu\Phi = (\partial_\mu + ig_X Q_\Phi V_\mu)\Phi$, where $Q_\Phi \equiv Q_X(\Phi)$ is the $U(1)_X$ charge of Φ and we will take $Q_\Phi = 1$ throughout the paper. Assuming that the $U(1)_X$-charged complex scalar Φ develops a nonzero VEV, v_Φ, and thus breaks $U(1)_X$ spontaneously, $\Phi = \frac{1}{\sqrt{2}}(v_\Phi + \varphi(x))$. Therefore the Abelian vector boson V_μ gets mass $M_V = g_X|Q_\Phi|v_\Phi$, and the hidden sector Higgs field (or dark Higgs field) $\varphi(x)$ will mix with the SM Higgs field $h(x)$ through Higgs portal of the $\lambda_{H\Phi}$ term, like the singlet scalar S in the singlet fermion DM case. In particular there is a generic cancellation in the direct detection cross section of VDM on nucleon target, and the constraints from XENON100 and CDMS become relaxed significantly. Also the stability of EW vacuum is improved and the strong 1st order phase transition is possible, as in the singlet fermion DM model.

D. Lessons

In this section, we considered renormalizable models for the singlet fermion DM and for the VDM with Higgs portal, and showed that the results are different from those based on EFT's, Eqs. (6) and (7). The constraints from direct detection cross section (XENON100 and CDMS) still allows a large parameter space in these models. It is crucial to work with a model that is renormalizable, and not with effective Lagrangian. Including the hidden sector Higgs field also improves the vacuum stability of the model for $m_H = 125$ GeV upto the Planck scale as in Ref. [5, 6]. Our model can be tested at colliders by searching for the 2nd Higgs boson and/or the signal strength of the 125 GeV Higgs boson. It would take long in order to observe the 2nd Higgs boson since its signal strength is smaller than 0.3. In our model, r_i is universally suppressed relative to the SM case for all channels. This could be a useful criterion when the signal strengths of 125 GeV Higgs boson are measured with smaller uncertainties. If r_i is not universally suppressed or larger than one, then our model shall be excluded.

IV. ALTERNATIVES TO THE NEW MINIMAL SM : SINGLET PORTAL EXTENSION OF THE STANDARD SEESAW MODELS TO A DARK SECTOR WITH LOCAL $U(1)_X$ DARK SYMMETRY

A. Model

Now let us construct a realistic DM model based on local dark symmetry. We assume that dark matter resides in a hidden sector, and it is stable due to unbroken local dark gauge symmetry, say $U(1)_X$ for simplicity. All the SM fields are taken to be $U(1)_X$ singlets. Assuming that the RH neutrinos are portals to the hidden sector, we need both a scalar (X) and a Dirac fermion (ψ) with the same nonzero dark charge. Then the composite operator $\psi X^\dagger$ becomes a gauge singlet and thus can couple to the RH neutrinos N_{Ri}'s [24].

With these assumptions, we can write the most general renormalizable Lagrangian as follows [7]:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_X + \mathcal{L}_\psi + \mathcal{L}_{\rm portal} + \mathcal{L}_{\rm inflation} \tag{17}$$

where $\mathcal{L}_{\rm SM}$ is the standard model Lagrangian and

$$\begin{aligned}
\mathcal{L}_X &= \left| \left(\partial_\mu + i g_X q_X \hat{B}'_\mu \right) X \right|^2 - \frac{1}{4} \hat{B}'_{\mu\nu} \hat{B}'^{\mu\nu} - m_X^2 X^\dagger X - \frac{1}{4} \lambda_X \left(X^\dagger X \right)^2 & (18) \\
\mathcal{L}_\psi &= i \bar{\psi} \gamma^\mu \left(\partial_\mu + i g_X q_X \hat{B}'_\mu \right) \psi - m_\psi \bar{\psi} \psi & (19) \\
\mathcal{L}_{\rm portal} &= -\frac{1}{2} \sin\epsilon \hat{B}'_{\mu\nu} \hat{B}^{\mu\nu} - \frac{1}{2} \lambda_{HX} X^\dagger X H^\dagger H \\
&- \frac{1}{2} M_i \overline{N_{Ri}^C} N_{Ri} + \left[Y_\nu^{ij} \overline{N_{Ri}} \ell_{Lj} H^\dagger + \lambda^i \overline{N_{Ri}} \psi X^\dagger + {\rm H.c.} \right] & (20)
\end{aligned}$$

g_X, q_X, $\hat{B}'_\mu$ and $\hat{B}'_{\mu\nu}$ are the gauge coupling, $U(1)_X$ charge, the gauge field and the field strength tensor of the dark $U(1)_X$, respectively. The field $\hat{B}_{\mu\nu}$ is the gauge field strength of the SM $U(1)_Y$. We assume $m_X^2 > 0$, $\lambda_X > 0$, $\lambda_{HX} > 0$, so that the local $U(1)_X$ remains unbroken and the scalar potential is bounded from below at tree level. We assume the inflation occurs á la Starobinky [13] and Shaposhnikov and Bezrukov [14], and the dark energy (DE) is described by the cosmological constant, which is the minimal setup for DE.

This model has only 3 more fields compared to the standard seesaw models, and is based on local gauge principle for absolutely stable DM rather than ad hoc Z_2 symmetry [8, 15]. Therefore, our model could be considered as an alternative to the so-called new minimal SM [15].

B. Implications on particle physics and cosmology

Our model is simple enough, but has sufficiently rich structures, and it can accommodate various observations from cosmology and astrophysics with definite predictions for Higgs physics:

- Dark scalar X can improve the stability of the electroweak vacuum up to Planck scale, unlike the SM for $m_h \sim 125\,{\rm GeV}$ and $m_t = 173.2\,{\rm GeV}$ and $\alpha_s = 0.118$, if $\lambda_X > 0$ and $\lambda_{HX} \gtrsim 0.2$.
- Perturbativity of quartic couplings for scalar fields H and X up to Planck scale puts theoretical constraints on λ_X and λ_{HX} such that $\lambda_X \lesssim 0.2$ and $\lambda_{HX} \lesssim 0.6$.
- Massless dark photon mediates long range between dark matter, and can solve the small scale problem of DM subhalo while satisfying constraints from inner structure and kinematics of dark matter halos, if $g_X \lesssim 2.5 \times 10^{-2} \left(m_X / 300\,{\rm GeV} \right)^{3/4}$.
- If dark fermion ψ were lighter than X and became DM, then its thermal relic density would be too large since it can annihilate only into a pair of dark photon ($\sigma_{\rm ann} v \propto g_X^4$). On the contrary the dark scalar X can be diluted efficiently even if g_X is very small, since there is a Higgs portal term which makes $XX^\dagger \leftrightarrow$ (SM particles).

- Direct detection experiments such as XENON100 and CDMS put strong bounds on the combination of the gauge kinetic mixing $10^{-12} \lesssim \epsilon g_X \lesssim 10^{-5}$ for $6\,\text{GeV} \lesssim m_X \lesssim 1\,\text{TeV}$ when the upper bound on g_X is used.
- Massless dark photon in our model would contribute to the number of effective neutrinos which can be measured accurately by Planck satellite and others. We find that dark photon contributes to dark radiation by ~ 0.08, which is in agreement with the recent Planck data, $\Delta N_{\rm eff} = 3.30 \pm 0.27$ at 68% CL.
- The decay of right-handed(RH) neutrinos generate both matter and dark matter thanks to see-saw mechanism. However the asymmetric component of dark matter disappears as the heavy dark fermion ψ decays eventually, that can also generate visible sector lepton number asymmetry large enough to match the observation.
- Higgs inflation can work in our model since the gauge singlet scalar coupled to SM Higgs field cures the instability of potential in Higgs-singlet system. Inflation along the SM Higgs direction does not pose any new constraint on the model parameters.
- In case $U(1)_X$ is unbroken, the Higgs signal strength should be equal to "1", independent of production and decay channels. If we consider other variations of the model with broken $U(1)_X$ or only dark scalar or dark fermion, the number of Higgs-like scalar bosons can be more than one, with universally reduced Higgs signal strength (see Table 1).
- It would be straightforward to construct supersymmetric version of this model, which would have rich structures in DM physics because both the usual LSP and the hidden sector particles would make CDM candidates [9].

In conclusion, we presented a simple extension of the standard seesaw model, where dark matter physics is constructed with unbroken $U(1)_X$ local dark gauge symmetry. One can make variations on this model, which are summarized in Table I. See Ref. [16] and the original paper [7] for more details about this model.

TABLE I: Dark fields in the hidden sector, messengers, dark matter (DM), the amount of dark radiation (DR), and the signal strength(s) of the i scalar boson(s) (μ_i) for unbroken or spontaneously broken (by $\langle\phi\rangle \neq 0$) $U(1)_X$ models considered in this work. The number of Higgs-like neutral scalar bosons could be 1,2 or 3, depending on the scenarios.

Dark sector fields	$U(1)_X$	Messenger	DM	Extra DR	μ_i
$\hat{B}'_\mu, X, \psi$	Unbroken	$H^\dagger H, \hat{B}'_{\mu\nu}\hat{B}^{\mu\nu}, N_R$	X	~ 0.08	1 $(i=1)$
$\hat{B}'_\mu, X$	Unbroken	$H^\dagger H, \hat{B}'_{\mu\nu}\hat{B}^{\mu\nu}$	X	~ 0.08	1 $(i=1)$
$\hat{B}'_\mu, \psi$	Unbroken	$H^\dagger H, \hat{B}'_{\mu\nu}\hat{B}^{\mu\nu}, S$	ψ	~ 0.08	< 1 $(i=1,2)$
$\hat{B}'_\mu, X, \psi, \phi$	Broken	$H^\dagger H, \hat{B}'_{\mu\nu}\hat{B}^{\mu\nu}, N_R$	X or ψ	~ 0	< 1 $(i=1,2)$
$\hat{B}'_\mu, X, \phi$	Broken	$H^\dagger H, \hat{B}'_{\mu\nu}\hat{B}^{\mu\nu}$	X	~ 0	< 1 $(i=1,2)$
$\hat{B}'_\mu, \psi$	Broken	$H^\dagger H, \hat{B}'_{\mu\nu}\hat{B}^{\mu\nu}, S$	ψ	~ 0	< 1 $(i=1,2,3)$

V. EWSB AND CDM FROM STRONGLY INTERACTING HIDDEN SECTOR

Another nicety of models with hidden sector is that one can experiment the idea of technicolor (TC) type EWSB in the hidden sector [1–3]. In this section, I describe a model where both EWSB and CDM come from new strongly interacting hidden sector which has some resemblance with the conventional TC except that the condensing hidden sector quarks are all SM singlets. In this model, all the mass scales including the DM mass are generated by dimensional transmutation in the hidden sector.

A. Nicety of QCD

Quantum Chromodynamics (QCD) is a nonabelian $SU(3)$ gauge theory with a number of quarks in the fundamental representation of $SU(3)$. It describes strong interaction among (anti)quarks and gluons, and has been well tested at quantum level. Let me list a number of its nice properties:

- Aymptotic freedom: QCD is asymptotically free, and the theory is well defined upto Planck scale.
- Color confinement: color is confined presumably because interaction becomes strong at low energy scale.
- Dynamical generation of mass scale: the scale $\Lambda_{\rm QCD}$ is generated dynamically. This is true even for pure gluon dynamics and massless QCD where there are no dimensionful parameters at classical lagrangian. A scale is generated by quantum effects (dimensional transmutation).
- Spontaneous chiral symmetry breaking: massless QCD with N_f flavors possesses $SU(N_f)_L \times SU(N_f)_R$ global chiral symmetry, which is spontaneously broken into $SU(N_f)_V$ by nonzero vacuum expectation value $\langle \bar{q} q \rangle$. There appear $N_f^2 - 1$ Nambu-Goldstone bosons (pions, kaons and η) which are massless. Nonzero current quark masses in the real world break chiral symmetry explicitly, thereby generating nonzero small masses for π's, K's and η.
- Pions (and other NG bosons) are stable under strong interaction, because of flavor conservation of underlying QCD which is an accidental symmetries of QCD. Its longevity is guaranteed by renormalizability and local gauge symmetry, not by some ad hoc symmetry put in by hand. Of course it is broken by nonrenormalizable operators unless the coefficients of those operators are suppressed enough.
- Proton is stable due to baryon number which is an accidental symmetry of the SM QCD, and its composite nature. Current lower bound on the proton lifetime indicates that the scale for baryon number violation is $\sim O(10^{16})$ GeV.

Considering niceties of QCD, it is natural to ask if one can construct models where all the mass scales are generated by quantum effects [17], and stability or longevity of CDM is due to some accidental symmetry and not by ad hoc symmetry such as $R-$parity (Z_2) in SUSY models. And seemingly unrelated one is to consider a hidden sector which is neutral under the SM gauge interaction. In this section, I will demonstrate that it is indeed possible to construct such a model with a hidden sector with a new vectorlike confining gauge theory like QCD.

B. Scale invariant extensions of the SM with strongly interacting hidden sector

In order to generate all the mass scales in quantum mechanical way, we replace the mass parameters in the standard seesaw model by singlet scalar S:

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm kin} + \mathcal{L}_{\rm Yukawa} - \frac{\lambda_H}{4} \, (H^\dagger H)^2 - \frac{\lambda_{SH}}{2} \, S^2 \, H^\dagger H - \frac{\lambda_S}{4} \, S^4. \tag{21}$$

Since there are no mass parameters in this Lagrangain, this is a suitable starting point to investigate if it is possible to have all the masses from quantum mechanical effects. Note that the real singlet scalar S plays the role of messenger connecting the SM Higgs sector and the hidden sector quarks. Radiative electroweak symmetry breaking of this model was considered by Meissner and Nicolai [18] without considering dark matter.

Now let us add to the above Lagrangian a hidden sector with new strong interaction which is vectorlike and confining like ordinary QCD and has classical scale invariance:

$$\mathcal{L}_{\rm hidden} = -\frac{1}{4} \mathcal{G}_{\mu\nu}^a \mathcal{G}^{a\mu\nu} + \sum_{k=1,\ldots,f} \overline{\mathcal{Q}}_k \left[iD \cdot \gamma - \lambda_k S \right] \mathcal{Q}_k. \tag{22}$$

Thus we are led to scale invariant extension of the SM with strongly interacting hidden sector.

In this model, dimensional transmutation in the hidden sector will generate the hidden QCD scale and chiral symmetry breaking with developing nonzero $\langle \bar{\mathcal{Q}}_k \mathcal{Q}_k \rangle$. Then there appear a number of Nambu-Goldstone bosons π_h which are stable at renormalizable level. They will make a good CDM candidate assuming the effects of nonrenormalizable interactions such as $\overline{\mathcal{Q}}_i \mathcal{Q}_j H^\dagger H$ are suppressed by small coefficients associated with them. Also hidden sector baryons $\mathcal{B}_h$ will be formed, the lightest of which would be stable due to the accidental h-baryon conservation and could make a good CDM candidates. Once a nonzero $\langle \bar{\mathcal{Q}}_k \mathcal{Q}_k \rangle$ is developed, the $\lambda_k S$ term generate the linear potential for the real singlet S, leading to nonzero $\langle S \rangle$. This in turn generates the hidden sector current quark masses through λ_k terms as well as the EWSB through λ_{SH} term. The π_h will get nonzero masses, and becomes a good CDM candidate. For the NG boson DM π_h, thermal relic density and direct detection cross section can be estimated using effective chiral Lagrangian approach [2, 3] or linear

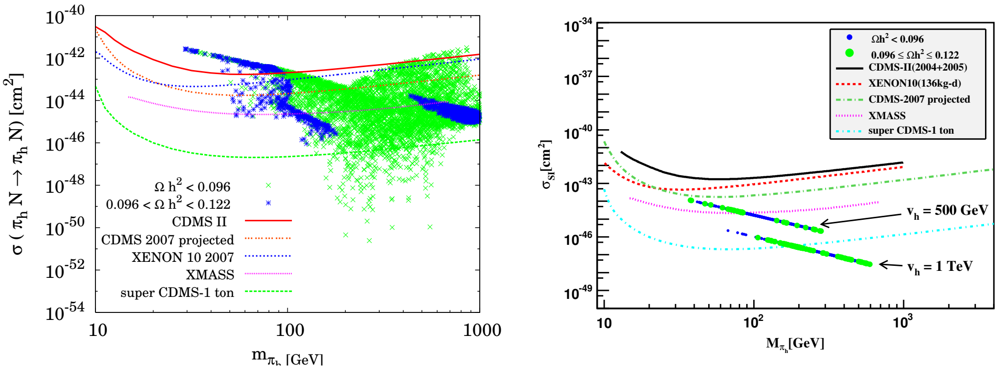

FIG. 3: $\sigma_{SI}(\pi_h p \to \pi_h p)$ as functions of m_{π_h} for (a) $\tan\beta = 1$ in Model I [1], and (b) Model II [3].

sigma model [1, 2], whereas those of the hidden baryons are more difficult to handle quantitatively. Due to the presence of the messenger S, the π_h pair annihilation into the SM particles occurs more efficiently, and it is easy to accommodate the WMAP data on $\Omega_{\rm CDM}h^2$. Direct detection rates of π_h are in the interesting ranges (see Fig. 2). Note that the masses of both hidden sector hadrons π_h and $\mathcal{B}_h$ are generated dynamically by dimensional transmutation, similarly to the masses of proton and pion in ordinary QCD. See Ref. [1–3] for more detail.

VI. CONCLUSIONS

In this talk, I discussed a number of hidden sector dark matter models with singlet portals, and discussed their interplay with phenomenology of the SM Higgs boson. We also demonstrated that it is important to consider renormalizable models with the full SM gauge symmetry. Generic signatures of hidden sector dark matter with local dark gauge symmetry can be summarized as follows:

- Thermal relic density of hidden sector DM can be easily compatible with the WMAP observation, and they can be detected in the direct detection experiments.

- A real singlet scalar boson S should be introduced as a messenger between the hidden sector and the SM sector, if the hidden sector has fermions and/or massive gauge bosons only. Therefore there are two or more physical Higgs-like scalar bosons.

- There is a destructive interference in the contributions from two scalar bosons in direct detection cross section (see Eq. (11)), which can not be seen in the effective lagrangian approach.

- Higgs can decay into a pair of CDM, if kinematically allowed, which is begun to constrained by the LHC data.

- Production cross section for Higgs boson is smaller than the SM Higgs boson because of the mixing with composite scalars from the hidden sector.

- Depending on the parameters, only one or none of the two Higgslike scalar boson(s) could be found at the LHC.

- Recent results on the Higgs-like new boson with mass around with 125 GeV from the LHC constrain this class of models. In particular there is a universal reduction of the signal strength in all the channels. If the future data do not respect this universal suppression, our model would be excluded, independent of discovery of the second Higgs boson.

- If dark gauge symmetry is unbroken and there is massless dark gauge fields, they can contribute to dark radiation, unless hidden gauge symmetry is confining. Therefore the data on dark radiation will constrain the nature of dark gauge symmetry gauge group. For example, weakly interacting unbroken $SU(N_X)$ hidden gauge group with $N_X \geq 4$ is disfavored by extra dark radiation [9], $\Delta N_{\rm eft} = 0.254^{+0.54}_{-0.51}$. See Table II for the summary [9].

TABLE II: The number of neutral Higgs bosons, Higgs signal strengths and dark radiation and dark matter particles for various hidden sector gauge groups [9].

Dark matter	**Unbroken $U(1)_X$**	**Local Z_2**	**Unbroken $SU(N_X)$ (weak)**	**Unbroken $SU(N_X)$ (confining)**
Scalar DM	$\mu_{i=1} = 1$ 0.08 complex scalar	$\mu_{i=1,2} < 1$ ~ 0 real scalar	$\mu_{i=1} = 1$ $\sim 0.08 \times (N_X^2 - 1)$ complex scalar	$\mu_{i=1} = 1$ ~ 0 composite h-mesons and h-baryons
Fermion DM	$\mu_{i=1,2} < 1$ 0.08 Dirac fermion	$\mu_{i=1,2} < 1$ ~ 0 Majorana fermion	$\mu_{i=1,2} < 1$ $\sim 0.08 \times (N_X^2 - 1)$ Dirac fermion	$\mu_{i=1,2} < 1$ ~ 0 composite h-mesons and h-baryons

One can summarize the results in the following Table II. When I started working on hidden sector DM models some years ago [1–3], I thought that it would be difficult to make any useful and testable predictions, since we don't know anything about the hidden sector. However the situation turned out much more promising, since there are some generic predictions as summarized in Table II, which is valid as long as there is only one SM Higgs doublet. At the moment, this assumption of only one SM Higgs doublet is consistent with the LHC data, no charged scalar boson having been observed yet. Also the amount of dark radiation, which can be precisely measured by Planck and others, and the number of neutral Higgs-like scalar bosons and their signal strengths at the LHC will give hints on the nature of the hidden sector gauge interaction, whether it is broken or not, and whether it is weakly interacting or confining like ordinary QCD. These observables should be crucial keys to understanding the hidden sector DM models, and should be measured as precisely as possible, since they would shed light on the nature of DM and its interplay with the SM Higgs boson in a simple but an intriguing way.

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[1] T. Hur, D. -W. Jung, P. Ko and J. Y. Lee, Phys. Lett. B **696**, 262 (2011) [arXiv:0709.1218 [hep-ph]].

[2] P. Ko, Invited talk at the 4th International Conference on Flavor Physics, KITPC, Sep. 24-28, 2007, Beijing. Int. J. Mod. Phys. A **23**, 3348 (2008) [arXiv:0801.4284 [hep-ph]]; P. Ko, Invited talk at the Dark Side of the Universe, Melbourne. AIP Conf. Proc. **1178**, 37 (2009); Talk at ICHEP 2010, Paris. PoS ICHEP **2010**, 436 (2010) [arXiv:1012.0103 [hep-ph]].

[3] T. Hur and P. Ko, Phys. Rev. Lett. **106**, 141802 (2011) [arXiv:1103.2571 [hep-ph]].

[4] S. Baek, P. Ko and W. -I. Park, JHEP **1202**, 047 (2012) [arXiv:1112.1847 [hep-ph]].

[5] S. Baek, P. Ko, W. -I. Park and E. Senaha, JHEP **1211**, 116 (2012) [arXiv:1209.4163 [hep-ph]].

[6] S. Baek, P. Ko, W. -I. Park and E. Senaha, JHEP **1305**, 036 (2013) [arXiv:1212.2131 [hep-ph]].

[7] S. Baek, P. Ko and W. -I. Park, JHEP **1307**, 013 (2013) [arXiv:1303.4280 [hep-ph]].

[8] V. Silveira and A. Zee, Phys. Lett. B **161**, 136 (1985); C. P. Burgess, M. Pospelov and T. ter Veldhuis, Nucl. Phys. B **619**, 709 (2001) [hep-ph/0011335].

[9] S. Baek, P. Ko and W.I. Park, work in progress

[10] A. Djouadi, O. Lebedev, Y. Mambrini and J. Quevillon, Phys. Lett. B **709**, 65 (2012) [arXiv:1112.3299 [hep-ph]].

[11] J. R. Espinosa and M. Quiros, Phys. Lett. B **305**, 98 (1993) [hep-ph/9301285]; J. Choi and R. R. Volkas, Phys. Lett. B **317**, 385 (1993) [hep-ph/9308234]; E. Senaha, Phys. Rev. D **88**, 055014 (2013) [arXiv:1308.3389 [hep-ph]].

[12] S. Choi, S. Jung and P. Ko, arXiv:1307.3948 [hep-ph].

[13] A. A. Starobinsky, Phys. Lett. B **91**, 99 (1980); E. Senaha, Phys. Rev. D **88**, 055014 (2013) [arXiv:1308.3389 [hep-ph]].

[14] F. L. Bezrukov and M. Shaposhnikov, Phys. Lett. B **659**, 703 (2008) [arXiv:0710.3755 [hep-th]].

[15] H. Davoudiasl, R. Kitano, T. Li and H. Murayama, Phys. Lett. B **609**, 117 (2005) [hep-ph/0405097].

[16] S. Baek, P. Ko and W. -I. Park, arXiv:1310.6229 [hep-ph]. Talk delivered by W.I. Park at the Particle Physics and Cosmology Workshop (PPC 2013), July 8-13 (2013), Deadwood, SD, USA.
[17] S. R. Coleman and E. J. Weinberg, Phys. Rev. D **7**, 1888 (1973); C. T. Hill, hep-th/0510177; F. Wilczek, Int. J. Mod. Phys. A **21**, 2011 (2006) [physics/0511067]; F. Wilczek, Int. J. Mod. Phys. A **23**, 1791 (2008) [Eur. Phys. J. C **59**, 185 (2009)] [arXiv:0708.4236 [hep-ph]].
[18] K. A. Meissner and H. Nicolai, Phys. Lett. B **648**, 312 (2007) [hep-th/0612165].
[19] The case for spontaneous breaking of dark gauge symmetry and the resulting longevity of hidden sector DMs will be discussed in a separate publication [9].
[20] If S is very light like an axion, its lifetime can be 10^{26-27} sec or longer, and can make good dark matter.
[21] Similar arguments can be made for fermionic DM stabilized by global Z_2.
[22] The RH neutrino in the standard seesaw mechanism is gauge singlet, and so it does not feel any gauge force, unless lepton number is gauged. It is not clear at the moment whether the RH neutrino is absolutely neutral or not.
[23] This cancellation is due to the $SO(2)$ nature of the rotation matrix from the interaction eigenstates (h, s) to mass eigenstates (H_1, H_2) , and is analogous to the GIM mechanism in quark flavor physics.
[24] If we did not assume that the RH neutrinos are portals to the dark sector, we did not have to introduce both ψ and X in the dark sector. This case is discussed in brief in Table I.