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Hidden Sector DM Models with Local Dark Gauge Symmetries: Higgs Portal DM Models and Beyond

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In this article, I review a class of electroweak (EW)-scale dark-matter (DM) models where DM stability or longevity is the result of underlying dark gauge symmetries: (i) DM is stable because of unbroken local dark gauge symmetry or topology, or (ii) it is long-lived due to the accidental global symmetry of underlying dark gauge theories. Compared with the usual phenomenological dark matter models (including DM effective field theory (EFT) or simplified DM models), there are new particles in addition to DM, namely, dark gauge boson(s), dark Higgs bosons and sometimes excited dark matter, and their interactions are completely fixed by the local gauge principle. The idea of singlet portals, including the Higgs portal, can thermalize DM very efficiently so that this DM could easily be thermal DM. I also discuss the limitation of the usual DM effective field theory or simplified DM models with only unbroken $SU(3)_{\rm color} \times U(1)_{\rm em}$ gauge symmetry in the context of Higgs portal DM models and emphasize the importance of the full SM gauge symmetry and renormalizability, especially for DM searches at high-energy colliders.

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I. INTRODUCTION

The standard model (SM) has been extremely successful in explaining various experimental data from low energy atomic scale up to $\sim O(1)$ TeV scale. However, there are some observational facts which call for new physics beyond the SM (BSM): (i) baryon number asymmetry of the universe (BAU), (ii) nonzero neutrino masses and mixings, (iii) nonbaryonic dark matter (DM), (iv) inflation in the early universe, and (v) large scale structure formation in the universe. In this article, I will concentrate on the issue of DM, assuming that BAU and neutrino masses and mixings are accommodated by the standard seesaw mechanism by introducing heavy right-handed (RH) neutrinos.

First of all, I discuss the basic assumption for DM models, emphasizing the role of dark gauge symmetry, renormalizability, unitarity and limitation of DM effective field theory (EFT). I start with the simple Higgs portal DM models, both in EFT and in renormalizable and unitary models, emphasizing the limitations of EFT. Then I give specific examples where (i) DM is absolutely stable because of some unbroken dark gauge symmetry or (ii) topological reason, and (iii) DM is long-lived because of some accidental global symmetry of underlying dark gauge symmetry. One of the common features of these models is the existence of a new neutral scalar boson from dark sector, which I will call dark Higgs boson. I show that dark Higgs boson can play a new key role in Higgs inflation, EW vacuum stability, light mediator generating self-interaction of DM, and explaining the galactic center γ-ray execss. This article is based on a series of my works [1–21] with various collaborators.

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II. BASIC ASSUMPTIONS FOR DM MODELS

1. Relevant Questions for DM

So far the existence of DM was confirmed only through the astrophysical and cosmological observations where only gravity play an important role. Let us first list the relevant questions we have to answer for better understanding of DM:

- How many species of DM are there in the universe?
- What are their masses and spins?
- Are they absolutely stable or very long-lived?
- How do they interact among themselves and with the SM particles?
- Where do their masses come from?

In order to answer (some of) these questions, we have to observe its signals from colliders and/or various (in)direct detection experiments.

So far, SUSY models have been the (arguably) leading candidate for BSM, because it addresses the fine tuning problem of the Higgs mass, is consistent with the idea of grand unification, and provides good CDM candidates (neutralino or graviton LSP). Since there are no hints for SUSY at the LHC so far, it would be better to be open-minded about the BSM, especially regarding the new physics models regarding the DM.

The most unique and important property of DM (at least, to my mind) is that DM particle should be absolutely stable or long-lived enough, similarly to the case of electron and proton in the SM. Let us recall that electron stability is accounted for by electric charge conservation (which is exact), and this implies that there should be massless photon, the gauge boson of unbroken $U(1)_{\rm em}$ gauge symmetry. On the other hand, the longevity of proton is ascribed to the baryon number that is an accidental global symmetry of the SM, and is broken only by dim-6 operators. We would like to have DM models where DM is absolutely stable or long-lived enough by similar reasons to electron and proton. And this special property of DM has to be realized in the fundamental Lagrangian for DM in a proper way in QFT, similarly to QED and the SM. Local dark gauge symmetry will play important roles, by guaranteeing the stability/longevity of DM, as well as determine dynamics in a complete and mathematically consistent manner.

2. Hidden Sector DM and Local Dark Gauge Symmetry

If one introduces new particles with nonzero SM charges and weak scale masses, there are very strong constraints from electroweak precision test and CKM phenomenology. The simplest way to evade these two strong constraints is to assume a weak scale hidden sector which consists of particles which do not carry the SM gauge charges. Stable or long-lived hidden sector particles could be a good cold DM (CDM) candidates of the universe, if it is absolutely stable or long lived. Note that hidden sectors are very generic in many BSMs, including SUSY models and superstring theories. The hidden sector matters may have their own gauge interactions, which we call dark gauge interaction associated with local dark gauge symmetry $G_{\rm hidden}$. They can be easily thermalized through some messengers connecting the SM and the hidden sectors. We shall assume all the singlet operators such as Higgs portal, right-handed neutrinos (if it is a gauge singlet) or $U(1)$ gauge kinetic mixing play the role of messengers.

Another motivation for local dark gauge symmetry $G_{\rm hidden}$ in the hidden sector is to stabilize the weak scale DM particle by dark charge conservation laws, if it is unbroken or it has unbroken subgroup, in the same way electron is absolutely stable because it is the lightest charged particle and electric charge is absolutely conserved. Dark gauge symmetry could be helpful for longevity of DM too.

Finally note that all the observed particles in Nature feel some gauge interactions in addition to gravity. 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.

III. EFT *vs.* RENORMALIZABLE THEORIES: HIGGS PORTAL DM MODELS AS EXAMPLES

1. Higgs Portal DM Models

Let us start with the Higgs portal DM models, which is the simplest DM models in terms of the number of new degrees of freedom in addition to the SM fields. In the literature, three types of Higgs portal DM models have been considered [23–26]:

$$\mathcal{L}_{\rm scalar} = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \frac{1}{2}\lambda_{HS} S^2 H^\dagger H, \quad (1)$$

$$\mathcal{L}_{\rm fermion} = \overline{\chi}\left[i \not{\partial} - m_\chi \right] \chi - \frac{\lambda_{H\chi}}{\Lambda} H^\dagger H \overline{\chi}\chi, \quad (2)$$

$$\begin{aligned}\mathcal{L}_{\rm VMD} &= -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \frac{1}{2} m_V^2 V_\mu V^\mu \\ &\quad - \frac{\lambda_{HV}}{2} V_\mu V^\mu |H|^2 - \frac{\lambda_V}{4!} V^4, \quad (3)\end{aligned}$$

where we have imposed dark Z_2 symmetries in order to stabilize the DM particles: under Z_2, the DM fields transform as

$$S \to -S, \quad \chi \to -\chi, \quad V_\mu \to -V_\mu.$$

Note that the scalar DM Lagrangian is renormalizable, and has no problem. On the other hand, the Lagrangians for fermion and vector DM are not renormalizable or unitary. Effective field theory (EFT) approaches such as Eqs. (2) and (3) are often adopted for DM physics, which however could lead to unphysical results, especially at high energy colliders. Therefore it is safer to consider and their UV completions, where unitarity and renormalizability is restored. Let us discuss these two cases one by one.

2. Fermionic DM with Higgs Portal

In order to illustrate this point clearly, let us start with a singlet fermion DM model with Higg portal in EFT, Eq. (2). This simple model is nice for phenomenology, since one can study DM physics with just two new parameters, $\lambda_{H\chi}/\Lambda$ and m_χ. Thus it has been widely discussed in literature. However this model has to be improved for a number of reasons.

Let us consider one of its UV completions [4,5]:

$$\begin{aligned}\mathcal{L}_{\rm DM} &= \frac{1}{2}(\partial_\mu S \partial^\mu S - m_S^2 S^2) - \mu_S^3 S - \frac{\mu_S'}{3} S^3 - \frac{\lambda_S}{4} S^4 \\ &+ \overline{\chi}(i \not{\partial} - m_\chi)\chi - \lambda S \overline{\chi}\chi \\ &- \mu_{HS} S H^\dagger H - \frac{\lambda_{HS}}{2} S^2 H^\dagger H. \quad (4)\end{aligned}$$

We have introduced a singlet scalar S in order to make the model (1) renormalizable. Then there will be two neutral scalar bosons H_1 and H_2 (linear combinations of H and S) in our model, and the additional scalar S makes the DM phenomenology completely different from those from Eq. (1). This is also true for vector DM models [6,12].

For example, the direct detection experiments such as XENON100 and LUX exclude thermal DM within the EFT model (1), but this is not true within the UV completion (2), because of generic cancellation mechanism in the direct detection due to a generic destructive interference between H_1 and H_2 contributions for fermion or vector DM [4,6]. Also the direct detection cross section in the UV completion is related with that in the EFT by [14]

$$\sigma_{\rm SI}^{\rm ren} = \sigma_{\rm SI}^{\rm EFT} \left(1 - \frac{m_{125}^2}{m_1^2}\right)^2 \cos^4\alpha \ , \quad (5)$$

which includes the cancellation mechanism and corrects the results reported by ATLAS and CMS (see Fig. 1). And it turns out that the same cancellation mechanism works for unitary and gauge invariant model for vector DM with Higgs portal [12] Here m_1 is the mass of the singlet-like scalar boson and $m_{125} \equiv m_2$ is the Higgs mass found at the LHC. Note that the EFT result is recovered when $\alpha \to 0$ and $m_1 \to \infty$.

3. Dark Higgs Mechanism for the Vector DM and Galactic Center (GC) γ-ray Excess

One can also consider Higgs portal DM both in EFT and in a unitary and renormalizable model [6], where dark Higgs is naturally introduced. The Higgs portal VDM model is usually described by Eq. (3). Although all the operators are either dim-2 or dim-4, this Lagrangian breaks gauge invariance, and is neither unitary nor renormalizable.

One can consider the renormalizable Higgs portal vector DM model by introducing a dark Higgs Φ that generate nonzero mass for VDM by the usual Higgs mechanism:

$$\begin{aligned}\mathcal{L}_{VDM} &= -\frac{1}{4} X_{\mu\nu} X^{\mu\nu} + (D_\mu \Phi)^\dagger (D^\mu \Phi) \\ &- \lambda_\Phi \left(|\Phi|^2 - \frac{v_\Phi^2}{2} \right)^2 \\ &- \lambda_{\Phi H} \left(|\Phi|^2 - \frac{v_\Phi^2}{2} \right) \left(|H|^2 - \frac{v_H^2}{2} \right) \ , \quad (6)\end{aligned}$$

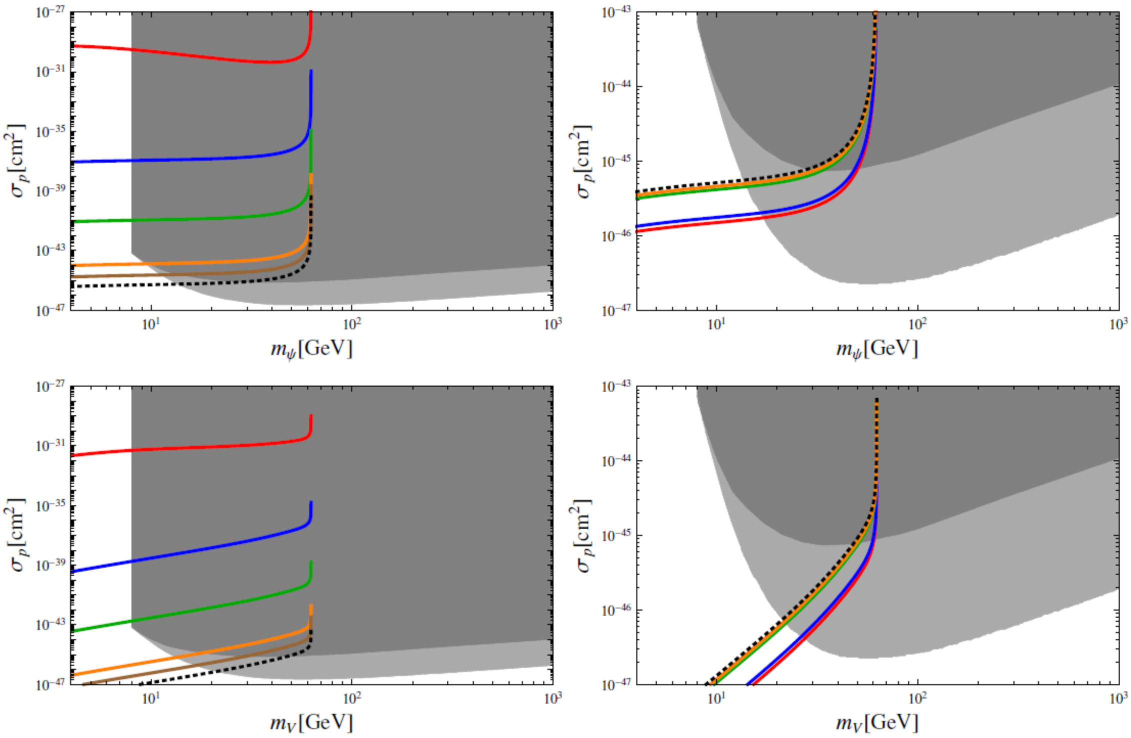

Fig. 1. (Color online) $\sigma_p^{\rm SI}$ as a function of the mass of dark matter for SFDM (top) and VDM (bottom) for a mixing angle $\alpha = 0.2$. Left panel: $m_1 = 10^{-2}$, 1, 10, 50, 70 GeV for solid lines from top to bottom. Right panel: $m_1 =$ 100, 200, 500, 1000 GeV for dashed lines from bottom to top. The black dotted line is EFT predictions presented by ATLAS and CMS [27,28]. Dark-gray and gray region are the exclusion regions of LUX and projected XENON1T (gray).

Then the dark Higgs from Φ mixes with the SM Higgs boson in a similar manner as in SFDM. And there should be a generic cancellation again in the direct detection cross section. Therefore one can have a wider range of VDM mass compatible with both thermal relic density and direct detection cross section (see Ref. 6 for more details). In particular the dark Higgs can play an important and crucial role in DM phenomenology (see below the discussion about the GeV scale γ-ray excess from the GC).

Another important observable is the Higgs invisible decay width. The invisible Higgs decay width in the EFT VDM model is given by

$$(\Gamma_h^{\rm inv})_{\rm EFT} = \frac{\lambda_{VH}^2}{128\pi}\frac{v_H^2 m_h^3}{m_V^4} \times \left(1-\frac{4m_V^2}{m_h^2}+12\frac{m_V^4}{m_h^4}\right)\left(1-\frac{4m_V^2}{m_h^2}\right)^{1/2}. \quad (7)$$

Note that the invisible decay rate in the EFT becomes arbitrarily large as $m_V \to 0$, which is not physical. Let us compare this with the invisible Higgs decay in the renormalizable and unitary Higgs portal VDM model, which is given by

$$\Gamma_i^{\rm inv} = \frac{g_X^2}{32\pi}\frac{\kappa_i m_i^3}{m_V^2}\left(1-\frac{4m_V^2}{m_i^2}+12\frac{m_V^4}{m_i^4}\right)\left(1-\frac{4m_V^2}{m_i^2}\right)^{1/2}. \quad (8)$$

where m_V is the mass of VDM and $\kappa_1 = \cos^2\alpha$ and $\kappa_2 = \sin^2\alpha$ (we assume H_2 is the observed 125 GeV scalar boson). In this case $m_V = g_X v_\Phi$ so that the invisible decay width does not blow up when $m_V \to 0$, unlike the EFT VDM case. This is another example demonstrating the limitation of the EFT calculation.

Having the dark Higgs can be very important in DM phenomenology. Let me demonstrate it in the context of the GeV scale γ-ray excess from the GC. In the Higgs portal VDM with dark Higgs, one can have a new channel for γ-rays: namely, $VV \to H_2H_2$ followed by $H_2 \to b\bar{b}, \tau\bar{\tau}$ through a small mixing between the SM Higgs and the dark Higgs. As long as V is slightly heavier than H_2 with $m_V \sim 80$ GeV, one can reproduce the γ-ray spectrum similar to the one obtained from $VV \to b\bar{b}$

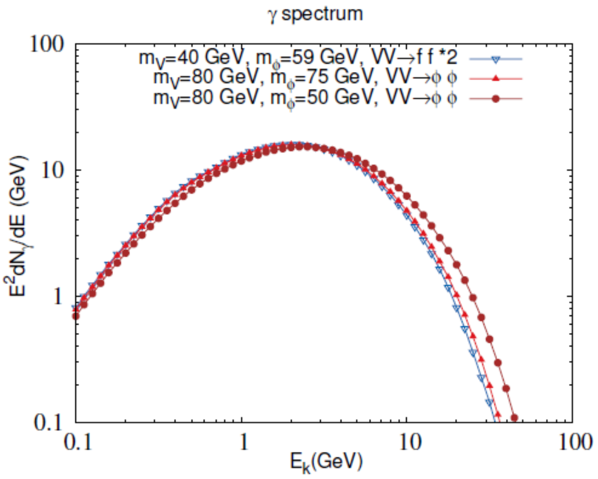

Fig. 2. (Color online) Illustration of γ spectra from different channels. The first two cases give almost the same spectra while in the third case γ is boosted so the spectrum is shifted to higher energy.

with $m_V \sim 40$ GeV (see Fig. 2 and Ref. 12 for more detail). Note that this mass range for VDM was not allowed within the EFT approach based on Eq. (4), where there is no room for the dark Higgs at all. It would have been simply impossible to accommodate the GC γ-ray excess within the Higgs portal VDM within EFT, simply because there is no dark Higgs boson in the EFT. Also this mechanism is generically possible in hidden sector DM models [15].

4. Collider Search for DM : Beyond the DM EFT and Simplified Models

Finally let us discuss the collider search for the dark Higgs boson and DM particles. A classic signature for DM search would be mono X + missing E_T. In early 2015, both ATLAS and CMS reported such studies in the monojet + missing E_T and $t\bar{t}$ + missing E_T, respectively. Their analyses are based on the simplified model which is neither renormalizable nor unitary.

Let us consider the following example:

$$\mathcal{L}_{SS} \equiv \frac{1}{\Lambda_{dd}^2}\bar{q}q\bar{\chi}\chi \quad \text{or} \quad \frac{m_q}{\Lambda_{dd}^3}\bar{q}q\bar{\chi}\chi. \qquad (9)$$

Here χ is a Dirac fermion DM that is stabilized by some conserved quantum number. And a lot of results have been obtained on the scale Λ_{dd} of this operator in literature, assuming the complementarity among direct detection, collider search and indirect detection (or thermal relic density) [20].

However, the above operator is not suitable for DM search study at high energy colliders since it is not invariant under the full SM gauge symmetry. Therefore this operator has to be mended in order that the full SM gauge symmetry could be implemented. Note that the operator $\bar{q}q$ can be written into $\overline{Q}_L H d_R$ and $\overline{Q}_L \widetilde{H} u_R$ for down-type and up-type quarks (nothing but the Yukawa couplings) resepctively, which respect the full SM gauge symmetry. Here $Q_L \equiv (u_L, d_L)^T$. Likewise, the singlet fermion χ cannot have renormalizable couplings to the SM Higgs boson ($h\bar{\chi}\chi$ where h is the Higgs field after electroweak symmetry breaking), since χ is a singlet whereas the Higgs field comes from a doublet. Similarly, the quark bilinear $\bar{q}q$ does not have renormalizable couplings to a singlet scalar field S.

All these problems can be resolved if we introduce a real singlet scalar field S and write down a renormalizable operator that is invariant under the full SM gauge group [4,6]. The SM Higgs will mix with the S Higgs fields after EWSB. Then one can generate Eq. (9) by $s\bar{\chi}\chi \times h\bar{q}q \to \frac{1}{m_s^2}\bar{\chi}\chi\bar{q}q$ through the $h-s$ mixing, which results in two physical neutral scalars H_1 and H_2 with the mixing angle α. Exchange of these two H_1 and H_2 for DM direct detection scattering result in a generic cancellation between two contributions from two neutral scalars, which cannot be seen within EFT approach [4, 6].

Such a model for a singlet fermion DM χ and a singlet scalar S was already discussed in Sec. III.B, Eq. (4). and one can calculate the $\psi q \to \psi q$ scattering amplitude therein: The interaction Lagrangian of H_1 and H_2 with the SM fields and DM χ is given by

$$\begin{aligned}\mathcal{L}_{\rm int} &= -(H_1\cos\alpha + H_2\sin\alpha) \\ &\times \left[\sum_f \frac{m_f}{v_H}\bar{f}f - \frac{2m_W^2}{v_H}W_\mu^+ W^{-\mu} - \frac{m_Z^2}{v_H}Z_\mu Z^\mu\right] \quad (10) \\ &+ \lambda(H_1\sin\alpha - H_2\cos\alpha)\bar{\chi}\chi\ , \quad (11)\end{aligned}$$

The observed 125 GeV scalar boson is denoted by H_1. The mixing between h and s leads to the universal suppression of the Higgs signal strengths at the LHC, independent of production and decay channels [4].

The DM-quark scattering amplitude can be calculated in the renormalizable model, Eq. (4): $\chi(p) + q(k) \to$

$\chi(p')+q(k')$, the parton level amplitude of which is given by

$$\mathcal{M} = -\overline{u(p')}u(p)\overline{u(k')}u(k)\ \frac{m_q}{v_H}\lambda \sin\alpha\cos\alpha$$
$$\times \left[\frac{1}{t-m_{H_1}^2+im_{H_1}\Gamma_{H_1}} - \frac{1}{t-m_{H_2}^2+im_{H_2}\Gamma_{H_2}}\right] \quad (12)$$
$$\to \overline{u(p')}u(p)\overline{u(k')}u(k)\ \frac{m_q}{2v_H}\lambda\sin 2\alpha \left[\frac{1}{m_{H_1}^2} - \frac{1}{m_{H_2}^2}\right] \quad (13)$$
$$\equiv \frac{m_q}{\Lambda_{dd}^3}\overline{u(p')}u(p)\overline{u(k')}u(k), \quad (14)$$

where $t \equiv (p'-p)^2$ is the (4-momentum transfer)^2 to the nucleon. In the second line, we assumed $t \to 0$, keeping the DM-nucleon scattering in mind. Then two scalar bosons H_1 and H_2 make destructive interference in the amplitude for the DM direct detection cross section [4] The scale of the dim-7 effective operator, $m_q\,\bar{q}q\,\overline{\chi}\chi$ in Eq. (8), is defined in terms of Λ_{dd}:

$$\Lambda_{dd}^3 \equiv \frac{2m_{H_1}^2 v_H}{\lambda\sin 2\alpha}\left(1-\frac{m_{H_1}^2}{m_{H_2}^2}\right)^{-1}, \quad (15)$$
$$\bar{\Lambda}_{dd}^3 \equiv \frac{2m_{H_1}^2 v_H}{\lambda\sin 2\alpha}, \quad (16)$$

where $\bar{\Lambda}_{dd}$ is derived from Λ_{dd} assuming $m_{H_2} \gg m_{H_1}$. Since the amplitude (12) was derived from renormalizable and unitary Lagrangian with the full SM gauge symmetry, it can be used for studying DM searches at high energy colliders.

The amplitude for the monojet with missing transverse energy($\not{E}_T$) signature at hadron colliders is connected to the amplitude (12) by crossing symmetry $s \leftrightarrow t$, and the effective scale $\Lambda_{\rm dd}^3$ should be replaced by

$$\frac{1}{\Lambda_{dd}^3} \to$$
$$\frac{1}{\bar{\Lambda}_{dd}^3}\left[\frac{m_{H_1}^2}{\hat{s}-m_{H_1}^2+im_{H_1}\Gamma_{H_1}} - \frac{m_{H_1}^2}{\hat{s}-m_{H_2}^2+im_{H_2}\Gamma_{H_2}}\right] \quad (17)$$

where $\sqrt{\hat{s}} \equiv m_{\chi\chi}$ is the DM pair invariant mass. Note that we have to include two scalar operators, one for the 125 GeV Higgs boson and the other for the dark Higgs boson which can not be seen in the usual DM EFT or simplified DM models. This is the result of our requesting the model to be renormalizable and unitary [1]. Note

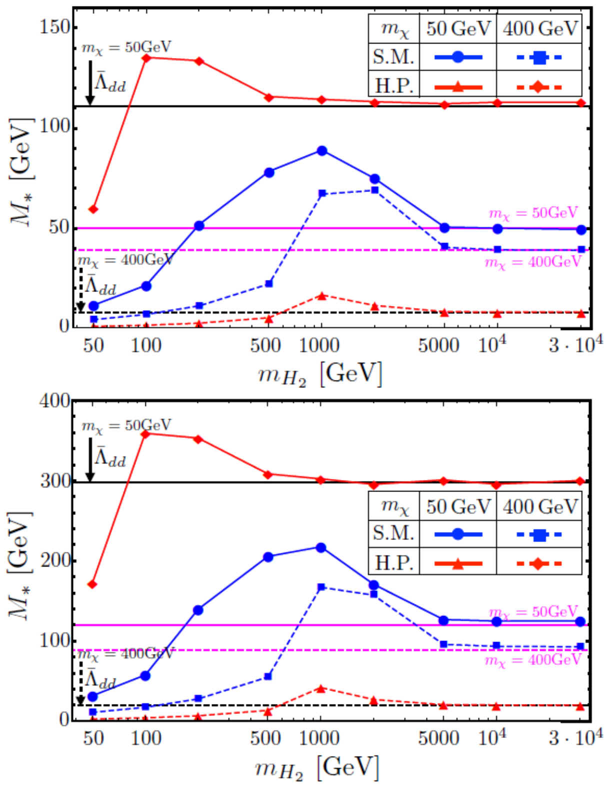

Fig. 3. (Color online) Observed exclusion limits in terms of m_χ and M_* with 90% CL. from mono-jet+$\not{E}_T$ search (left) and $t\bar{t}$+$\not{E}_T$ search (right).

that there is only a single propagator introduced to replace $1/\Lambda^2$ in the usual simplified DM models, and such presciption would break gauge invariance and unitarity in general. The two propagators would interfere destructively for very high $\hat{s}$ or small t (direct detection), but constructively for $m_{H_1}^2 < \hat{s} < m_{H_2}^2$.

If one can fix $\hat{s}$ and $m_{H_2}^2 \gg \hat{s}$, we can ignore the 2nd propagator. But at hadron colliders, $\hat{s}$ is not fixed, except for the kinematic condition $4m_\chi^2 \le \hat{s} \le s$ (with $s = 14$ TeV for example at the LHC@14TeV). Therefore we cannot say clearly when we can ignore $\hat{s}$ compared with $m_{H_2}^2$ at hadron colliders, unless $m_{H_2}^2 > s$ (not $\hat{s}$).

One can derive the bound on the effective mass scale M_* within the full renormalizable and unitary models and compared with the bounds derived with the EFT approaches, with the same $\bar{\Lambda}_{dd}$. The results are shown in Fig. 3: the left panel on the monojet + $\not{E}_T$ from ATLAS data and the right panel on the $t\bar{t}$ + $\not{E}_T$ from the CMS data. The blue lines are the results from the simplified model with a singlet scalar propagator, and the red lines are those from the renormalizable and unitary

[1] In fact, having two independent propagators for the mediators are very generic because the SM fermions have two different chiralities, and the SM gauge interactions are chiral. See Ref. 22 for more discussions on this point.

(and gauge invariant for the VDM) models. Note that the bounds depend very much on the underlynig model assumption, and are sensitive to the 2nd scalar boson, which does not appear in the EFTW or the usual simplified model. These plots show that it is very important to analyze the monojet + $\not{E}_T$ and $t\bar{t}+\not{E}_T$ data from the LHC within well-defined renormalizable, unitary and gauge invariant DM models. The usual EFT and the simplified models without the full SM gauge symmetry do not describe DM physics at high energy colliders properly.

Finally, the Higgs portal DM search at ILC has been studied within the renormalizable and unitary models in Ref. 31. Readers are invited to the original paper on this issue.

IV. STABLE DM WITH UNBROKEN DARK GAUGE SYMMETRIES

1. Local Z_2 Scalar Case

In order to highlight the idea of local dark gauge symmetry, let us consider a scalar DM S with Higgs portal described by Eq. (1). This model is the simplest DM model in terms of the number of new degrees of freedom beyond the SM, and its phenomenology has been studied comprehensively. However the origin and the nature of Z_2 symmetry has not been specified at all in the literature.

If this Z_2 symmetry is global, it could be broken by gravitation effect with Z_2-breaking dim-5 operator:

$$\frac{\lambda}{M_{\rm Planck}} S F_{\mu\nu} F^{\mu\nu} \ , \quad \frac{\lambda}{M_{\rm Planck}} S \overline{Q}_L H d_R \ , \quad etc. \quad (18)$$

Then the decay rate of S due to these Z_2-breaking dim-5 operators is given by

$$\Gamma(S) \sim \frac{\lambda^2 m_S^3}{M_{Planck}^2} \sim \lambda^2 \left(\frac{m_S}{100 \text{ GeV}}\right)^3 10^{-37} \text{ GeV} \quad (19)$$

Therefore EW scale CDM S will decay very fast and cannot be a good CDM candidate, unless the coefficient of this dim-5 operator is less than 10^{-8}. This is one possibility, but another possibility is to implement the global Z_2 symmetry as an unbroken subgroup of some local dark gauge symmetry.

In fact, one can construct local Z_2 model, by assuming that a DM X and a dark Higgs ϕ_X carry $U(1)_X$-charges equal to 1 and 2, respectively. The renormalizable Lagrangian of this model is given by [16]

$$\begin{aligned} \mathcal{L} \ =& \ \mathcal{L}_{\rm SM} - \frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} - \frac{1}{2}\sin\epsilon \hat{X}_{\mu\nu}\hat{B}^{\mu\nu} \\ &+ \ D_\mu \phi_X D^\mu \phi_X + D_\mu X^\dagger D^\mu X - \mu \left(X^2 \phi_X^\dagger + H.c.\right) \\ &- \ m_X^2 |X|^2 - \lambda_X |X|^4 - \lambda_\phi \left(|\phi_X|^2 - \frac{v_\phi^2}{2}\right)^2 \\ &- \ \lambda_{\phi X}|X|^2|\phi_X|^2 - \lambda_{\phi H}|\phi_X|^2|H|^2 - \lambda_{HX}|X|^2|H|^2, \end{aligned} \quad (20)$$

which is much more complicated than the original Z_2 scalar DM model, Eq. (1). After $U(1)_X$ symmetry is broken by the 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, X_R and X_I respectively. Compared with the global Z_2 scalar DM model described by Eq. (4), the local Z_2 model has three more fields: dark photon Z', dark Higgs ϕ_X and the excited scalar DM X_R, assuming X_I is lighter than X_R. Then the DM phenomenology would be much richer than the global Z_2 scalar DM model. For example, one can consider $X_I X_I \to \phi_X \phi_X$ and the subsequent decay of ϕ_X into the SM particles through the small mixing between dark Higgs ϕ_X and the SM Higgs boson h, as a possible explanation of the galactic center γ-ray excess (see Ref. 16 for more detail).

2. Local Z_3 Scalar DM Model

In this subsection, we discuss another model with spontaneous $U(1)_X \to Z_3$ breaking á la Krauss and Wilczek. This can be achieved with two complex dark scalars ϕ_X and X with $U(1)_X$ charges being equal to 1 and 1/3, respectively [10,15]. Here ϕ_X is the dark Higgs that breaks $U(1)_X$ into its Z_3 subgroup by nonzero VEV. Then the most general renormalizable Lagrangian for the SM fields and the dark sector fields, $\tilde{X}_\mu, \phi_X$ and

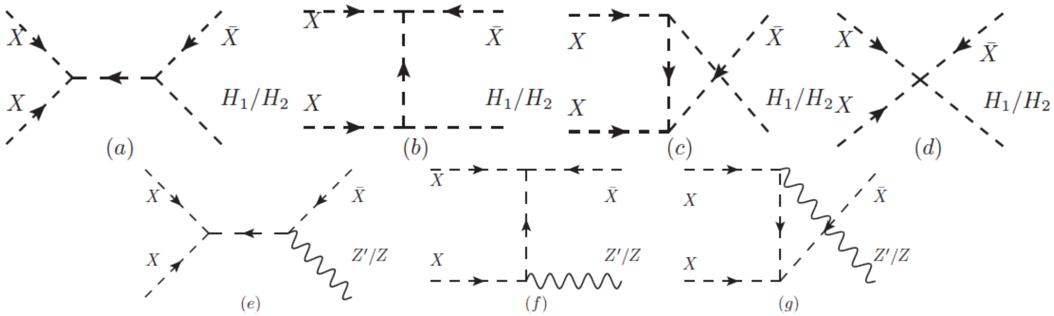

Fig. 4. Feynman diagrams for dark matter semi-annihilation which are not present in the Z_2 model discussed in IV.A. There are only (a), (b), and (c) with H_1 as final state appear in the global Z_3 model [29], whereas all diagrams could contribute in local Z_3 model [10,15].

Table 1. Comparison between the global and the local Z_3 scalar dark matter models. Here X is a complex scalar DM, H is the observed SM-HIggs like boson, and ϕ is the dark Higgs from $U(1)_X$ breaking into Z_3 subgroup.

	Global Z_3	Local Z_3
Extra fields	X	X, Z', ϕ
Mediators	H	H, Z', ϕ
Constraints	Direct detection	Can be relaxed
	Vacuum stability	Can be relaxed
DM mass	$m_X \gtrsim 120$ GeV	$m_X < m_H$ allowed

X is given by

$$\begin{aligned} \mathcal{L} &= \mathcal{L}_{\rm SM} - \frac{1}{4}\tilde{X}_{\mu\nu}\tilde{X}^{\mu\nu} - \frac{1}{2}\sin\epsilon \tilde{X}_{\mu\nu}\tilde{B}^{\mu\nu} \\ &+ D_\mu\phi_X^\dagger D^\mu\phi_X + D_\mu X^\dagger D^\mu X - V(H,X,\phi_X) \quad (21) \\ V &= -\mu_H^2|H|^2 + \lambda_H|H^\dagger H|^4 - \mu_\phi^2|\phi_X|^2 + \lambda_\phi|\phi_X|^4 \\ &+ \mu_X^2|X|^2 + \lambda_X|X|^4 + \lambda_{\phi H}|\phi_X|^2|H|^2 \\ &+ \lambda_{\phi X}|X|^2|\phi_X|^2 + \lambda_{HX}|X|^2|H|^2 \\ &+ \left(\lambda_3 X^3\phi_X^\dagger + H.c.\right) \quad (22) \end{aligned}$$

with $D_\mu \equiv \partial_\mu - i\tilde{g}_X Q_X \tilde{X}_\mu$.

Let us consider the phase with the following VEVs for the scalar fields in the model:

$$\langle H\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_h \end{pmatrix}, \ \langle\phi_X\rangle = \frac{v_\phi}{\sqrt{2}}, \ \langle X\rangle = 0. \quad (23)$$

This vacuum will break electroweak symmetry into $U(1)_{\rm em}$, and $U(1)_X \to Z_3$, thereby guaranteeing the stability of the scalar DM X even if we consider higher dimensional nonrenormalizable operators which are invariant under $U(1)_X$. This can be compared with the global Z_3 model in Ref. 29. Also the particle contents and the resulting DM phenomenology in two models will be very different as summarized in Table 1.

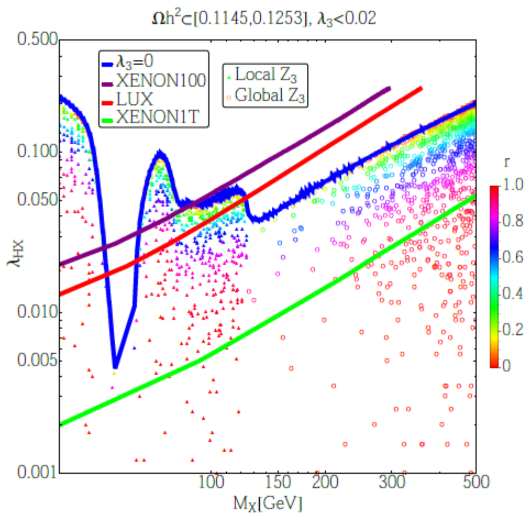

Fig. 5. (Color online) Illustration of difference between global and local Z_3 symmetry. We have chosen $M_{H_2} = 20$ GeV, $M_{Z'} = 1$ TeV and $\lambda_3 < 0.02$ as an example. Colors in the scatterred triangles and circles indicate the relative contribution of semi-annihilation, r defined in Eq. (24). The curved blue band, together with the circles, gives correct relic density of X in the global Z_3 model. And the colored triangles appears only in the local Z_3 model.

In Fig. 4, I show the Feynman diagrams relevant for thermal relic density of local Z_3 DM X. If we worked in global Z_3 DM model instead, we would have diagrams only with H_1 in (1),(b) and (c). For local Z_3 model, there are two more new fields, dark Higgs H_2 and dark photon Z', which can make the phenomenology of local Z_3 case completely difference from that of global Z_3 case. In fact, this can be observed immediately in Fig. 5, where the open circles are allowed points in global Z_3 model, whereas the triangles are allowed in local Z_3 case.

The main difference is that in global Z_3 case, the same Higgs portal coupling λ_{HX} enters both thermal relic density and direct detections. And the stringent constraint from direct detection forbids the region for DM below 120 GeV. On the other hand this no longer true in local Z_3 case, and there are more options to satisfy all the constraints [10,15].

The fraction of the contribution from the semi-annihilation can be described in terms of the following parameter:

$$r \equiv \frac{1}{2} \frac{v\sigma^{XX \to X^* Y}}{v\sigma^{XX^* \to YY} + \frac{1}{2} v\sigma^{XX \to X^* Y}}. \tag{24}$$

Also one can drive the low energy EFT and discuss its limitation, the details of which can be found in Ref. 10. The main message is that the EFT cannot enjoy the advantages of having the full particles spectra in the gauge theories, namely not-so-heavy dark Higgs and dark gauge bosons, which could be otherwise helpful for explaining the GC γ-ray excess or the self-interacting DM if either H_2 or Z' is light enough [10,15]. Therefore it is important to know what symmetry stabilizes the DM particles.

3. Other Possibilities

Sterile neutrinos including the RH neutrinos are natural candidates for hidden sector fermions with dark gauge charges. In fact there have been some attempt to construct models for CDM interacting with sterile neutrinos in order to solve the some puzzles in the standard CDM paradigm as well as to reconcile the amount of dark radiation reported by Planck observation and the sterile neutrino masses and mixings that fit the neutrino oscillation data [11]. One can also consider unbroken $U(1)_X$ dark gauge symmetry with scalar DM and the RH neutrinos decay both to the SM and the dark sector particles [7].

V. STABLE DM DUE TO TOPOLOGY: HIDDEN SECTOR MONOPOLE AND VECTOR DM, DARK RADIATION

In field theory there could be a topologically stable classical configuration. The most renowned example is the 't Hooft-Polyakov monopole. This object in fact puts a serious problem in cosmology, and was one of the motivations for inflationary paradigm. In Ref. 9, we revived this noble idea by putting the monopole in the hidden sector and introducing the Higgs portal interaction to connect the hidden and the visible sectors.

We shall consider $SO(3)_X$-triplet real scalar field $\vec{\Phi}$ and add the following Lagrangian to the SM Lagrangian:

$$\begin{aligned} \mathcal{L}_{\rm new} &= -\frac{1}{4} V^a_{\mu\nu} V^{a\mu\nu} + \frac{1}{2} D_\mu \vec{\Phi} \cdot D^\mu \vec{\Phi} - \frac{\lambda_\Phi}{4} \left(\vec{\Phi} \cdot \vec{\Phi} - v_\phi^2 \right)^2 \\ &- \frac{\lambda_{\Phi H}}{2} \left(\vec{\Phi} \cdot \vec{\Phi} - v_\phi^2 \right) \left(H^\dagger H - \frac{v_H^2}{2} \right). \end{aligned} \tag{25}$$

We added $\lambda_{\Phi H}$ term describing the Higgs portal interaction, which is a new addition to the renowned 't Hooft-Polyakov monopole model.

For nonzero $\langle \vec{\Phi}(x) \rangle = (0, 0, v_\Phi)$, the original dark gauge symmetry $SO(3)_X$ is broken into its subgroup $SO(2)_X (\approx U(1)_X)$. Then, the hidden sector particles are composed of massive dark vector bosons $V^\pm_\mu$ [2] with masses $m_V = g_X v_\Phi$, massless dark photon $\gamma_{h,\mu} \equiv V^3_\mu$, heavy (anti-)monopole with mass $m_M \sim m_V/\alpha_X$, and massive real scalar ϕ (dark Higgs boson). The massive hidden vector $V^\pm$ are stable due to the unbroken $SO(2)_X$ whereas the hidden monopole is stable due to topological reason. And the dark Higgs boson will mix with the SM Higgs boson through the Higgs portal term as usual.

Note that the kinetic mixing between γ_h and the SM $U(1)_Y$-gauge boson is forbidden at renormalizable level unlike the $U(1)_X$-only case. This is because of the non Abelian nature of the hidden gauge symmetry. Also the VDM is stable even if we consider higher dimensional operators because of the unbroken $SO(2)_X$. This would not have been the case, if the $SU(2)_X$ were completely broken by a complex $SU(2)_X$ doublet, where the VDM would decay in general in the presence of nonrenormalizable interactions [30]. Of course, it would be fine as long as the lifetime of the decaying VDM is long enough so that it can still be a good CDM candidate. In the VDM model with a hidden sector monopole, the unbroken $SO(2)_X$ subgroup not only guarantees the stability of VDM $V^\pm_\mu$, but also contributes to the dark radiation at the level of ~ 0.1. We refer the readers to the original paper on more details of phenomenology of this model [9].

[2] Here ± 1 in $V^\pm_\mu$ indicate the dark $U(1)_X$ charge, and not the usual electric charges.

VI. EWSB AND CDM FROM STRONGLY INTERACTING HIDDEN SECTOR: LONG-LIVED DM DUE TO ACCIDENTAL SYMMETRIES

Another nicety of models with hidden sector is that one can construct a model where all the masses of the SM particles and DM are generated by dimensional transmutation in the hidden sector [1–3]. Basically the light hadron masses such as proton or ρ meson come from confinement, which is derived from massless QCD through dimensional transmutation. One can ask if all the masses of observed particles can be generated by quantum mechanics, in a similar manner with the proton mass in the massless QCD. The most common way to address this question is to employ the Coleman-Weinberg mechanism for radiative symmetry breaking. Here I present a new model based on nonpertubative dynamics like technicolor or chiral symmetry breaking in ordinary QCD.

Let us consider a scale-invariant extension of the SM with a strongly interacting hidden sector:

$$\begin{aligned}\mathcal{L} &= \mathcal{L}_{\rm SM,kin} + \mathcal{L}_{\rm SM,Yukawa} - \frac{\lambda_H}{4}(H^\dagger H)^2 \\ &- \frac{\lambda_{SH}}{2}\, S^2 H^\dagger H - \frac{\lambda_S}{4} S^4 \\ &- \frac{1}{4}\mathcal{G}^a_{\mu\nu}\mathcal{G}^{a\mu\nu} + \sum_{k=1,\dots,f} \overline{\mathcal{Q}}_k \left[iD\cdot\gamma - \lambda_k S\right] \mathcal{Q}_k . \end{aligned} \quad (26)$$

Here $\mathcal{Q}_k$ and $\mathcal{G}^a_{\mu\nu}$ are the hidden sector quarks and gluons, and and the index k is the flavor index in the hidden sector QCD. We introduced a real singlet scalar S and replaces all the mass parameters by S field in order to respect classical scale symmetry. In this model, we have assumed that the hidden sector strong interaction is vectorlike and confining like the ordinary QCD. Then we can use the known aspects of QCD dynamics to the hidden sector QCD.

In this model, dimensional transmutation will take place in the hidden sector and generate the hidden QCD scale and chiral symmetry breaking with nonzero $\langle \bar{\mathcal{Q}}_k \mathcal{Q}_k \rangle$. 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, which in turn results in the nonzero $\langle S \rangle$. Then the hidden sector current quark masses are induced through λ_k terms, and the EWSB can be triggered through λ_{SH} term if it has a correct sign. Then the Nambu-Goldstone boson in the hidden sector (π_h) will get nonzero masses, and becomes a good CDM candidate. Their dynamics at low energy can be described by chiral Lagrangian method. Also hidden sector baryons $\mathcal{B}_h$ will be formed, the lightest of which would be long lived due to the accidental h-baryon conservation. See Ref. 3 for more details.

VII. LIGHT MEDIATORS AND SELF-INTERACTING DM

Another nice feature of the dark matter models with local dark gauge symmetry is that the model includes new degrees of freedom beyond DM particle: namely, dark gauge bosons and dark Higgs boson(s), that can play the role of force mediators from the beginning because of the rigid structure of the underlying gauge theories. In fact one can utilize the light mediators in order to explain the GeV scale γ-ray excess, or the self-interacting DM which would solve three puzzles in the CDM paradigm: (i) core-cusp problem, (ii) missing satellite problem and (iii) too-big-to-fail problem. These would have been simply impossible if we adopted the EFT approach for DM physics (see Ref. 10 for more detail on this issue).

In the EFT approach for the DM, these new degrees of freedom are very heavy compared with the DM mass as well as the energy scale we are probing the dark sector (*e.g.*, the collider energy scale). However, we don't know anything about the mass scales of these mediators, and it would be too strong an assumption. Without these light mediators, we could not explain the GeV scale γ-ray excess as described in Sec. III C, or have strong self-interacting DM. This illustrates one of the limitations of DM EFT approaches.

VIII. HIGGS INFLATION ASSISTED BY THE HIGGS PORTAL

The final issue related with DM models with local dark gauge symmetris is the Higgs inflation in the presence of the Higgs portal interaction to the dark sector:

$$\frac{\mathcal{L}}{\sqrt{-g}} = -\frac{1}{2\kappa}\left(1 + \xi \frac{h^2}{M_{\rm Pl}^2}\right) R + \mathcal{L}_h + \lambda_{\phi H}\phi^2 h^2 \quad (27)$$

in the unitary gauge, where $\kappa = 8\pi G = 1/M_{\rm Pl}^2$ with $M_{\rm Pl}$ being the reduced Planck mass, and $\mathcal{L}_h$ is the Lagrangian of the SM Higgs field only. Here ϕ denotes a generic dark Higgs field which mixes with the SM Higgs field after dark and EW gauge symmetry breaking.

In the presence of the Higgs portal interaction, we have recalculated the slow-roll parameters. Relegating the details to Ref. 13, I simply show the results: at a bench mark point for Fig. 2 of Ref. 13, we get the following results:

$$n_s = 0.9647 \ , \ r = 0.0840 \ , \tag{28}$$

for $N_e = 56$, $h_*/M_{\rm Pl} = 0.72$, $\alpha = 0.07422199$ and $\xi = 12.8294$ for a pivot scale $k_* = 0.05{\rm Mpc}^{-1}$. There is a parameter space where the spectral running of n_s is small enough at the level of $|n_s'| \lesssim 0.01$. It is amusing to notice that the r could be as large as $\sim O(0.1)$ in the presence of the Higgs portal interactions to a dark sector, independent of the top quark and the Higgs boson mass in the standard Higgs inflation scenario.

IX. HIGGS PHENOMENOLOGY, EW VACUUM STABILITY, AND DARK RADIATION

Now let us discuss Higgs phenomenology within this class of DM models. Due to the mixing effect between the dark Higgs and the SM Higgs bosons, the signal strengths of the observed 125 GeV Higgs boson will be universally reduced from "1" in a universal manner [4,6]. Also the 125 GeV Higgs boson could decay into a pair of dark Higgs and/or a pair of dark gauge boson, which is still allowed by the current LHC data [8]. These predictions will be further constrained by the next round experiments.

Finally the dark Higgs can make the EW vacuum stable upto the Planck scale without any other new physics [5,6], and this was very important in the Higgs-portal assisted Higgs inflation discussed in the previous section.

In most cases, there is generically a singlet scalar which is nothing but a dark Higgs, which would give a new motivation to consider singlet extensions of the SM. Traditionally a singlet scalar was motivated mainly by why-not or $\Delta\rho$ constraint, or the strong first order EW phase transition which could be working for electroweak baryogenesis if there are new sources of CP violation. Being a singlet scalar, the dark Higgs will satisfy all these motivations, as well as stability of DM by local dark gauge symmetry. It would be important to seek for this singlet-like scalar at the LHC or the ILC, but the colliders cannot cover the entire mixing angle down to $\alpha \sim 10^{-8}$ (for MeV dark Higgs) relevant to DM phenomenology.

Massless dark gauge boson or light dark fermions in hidden sectors could contribute to dark radiation of the universe In a class of models we constructed, the amount of extra dark radiation is rather small by an amount consistent with the Planck data due to Higgs portal interactions [7,9,11].

X. CONCLUSION AND OUTLOOK

In this article, I discussed a class of dark matter models where dark gauge symmetry plays an important role in stabilizing electroweak scalar DM or making them long lived enough compared with the age of the universe. I first discussed the limitation of the DM EFT or simplified DM models in the context of fermion and vector DM models with Higgs portal. DM EFT and naive simplified models are either nonrenormalizable or violate the full SM gauge invariance and unitarity in general, which could lead to unphysical results especially for DM phenomenology at high energy colliders. Then I discussed three explicit examples: (i) DM is stable due to unbroken dark gauge symmetry Z_2 and Z_3 originating from $U(1)_X$ gauge symmetry, (ii) DM is stable due to topological reason, the famous 't Hooft-Polyakov monopole in the hidden sector, and the unbroken $U(1)$ subgroup gaurantees the stability of the vector DM in the monopole sector, and (iii) DM is long lived due to global flavor symmetry which is an accidental symmetry of underlying new strong interaction in the dark sector. In the models where DM is stable or long-lived due to some underlying dark gauge symemtries, there appear generically new fields, namely dark Higgs or dark gauge bosons which can play important role in DM self-interaction or galactic center γ-way execss, which are not possible in the Higgs portal EFT for vector DM.

One of the generic predictions of the Higgs portal DM models and hidden sector DM models with local dark gauge symmetry is the existence of a new neutral scalar boson which is mostly the SM singlet if the DM particles are either fermion or vector. It affects the DM signatures at high energy colliders because of the form factors with two scalar propagators with negative sign, Eq. (14). This feature is a consequence of the full SM gauge invariance and renormalizability, and can not be seen in the usual EFT approach or simplified DM models. The detailed study of the Higgs portal DM phenomenology at future colliders will be presented elsewhere.

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