Global vs. Local $Z_2$ Symmetries for Real Scalar Dark Matter

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We present a scalar dark matter (DM) model where DM ($X_I$) is stabilized by local $Z_2$ symmetry originating from a spontaneously broken local dark $U(1)_X$. Compared with the usual scalar DM with global $Z_2$ symmetry, the local $Z_2$ model possesses three new extra fields, dark photon $Z'$, dark Higgs $\phi$ and the excited partner of scalar DM ($X_R$), with kinetic and Higgs portal interactions dictated by local dark gauge invariance. The resulting model can accommodate thermal relic density of scalar DM without conflict with the invisible Higgs branching ratio and the bounds from DM direct detections and addressing GeV scale $\gamma$-ray excess from the Galactic Center (GC). In local $Z_2$ model, there are 3 new extra fields (dark Higgs, dark photon, an unstable excited dark scalar $X_R$) dictated by local dark gauge symmetry. Due to the additional fields and presumed local dark gauge symmetry, the phenomenology of dark matter is expected to be distinctly different from the usual $Z_2$ scalar DM model described by Eq (1).

**INTRODUCTION**

One of the great mysteries of particle physics and cosmology is the so called nonbaryonic dark matter (DM) which occupies about 27% of the energy density of the present universe [1, 2]. DM particle should be very long-lived the weak scale DM and interact with photon or gluon very weakly (no renormalizable interaction), but lived or absolutely stable, and with other otherwise its properties are largely unknown.

The simplest DM model is the real scalar DM model described by the Lagrangian [3–6]:

$$\mathcal{L}_{\text{DM}} = \frac{1}{2} \partial_{\mu} S \partial^{\mu} S - \frac{m_S^2}{2} S^2 - \lambda_H S^2 H^\dagger H - \frac{\lambda_S}{4!} S^4, \quad (1)$$

with $Z_2$ symmetry ($S \to -S$). This model has been studied extensively in literature, and could be considered as a canonical model for non-supersymmetric DM.

However $Z_2$ symmetry in Eq. (1) is not usually specified whether it is global or local. If it were global, it may be broken by gravity effects, described by higher dimensional nonrenormalizable operators such as

$$\mathcal{L}_{Z_2 \text{breaking}} = \frac{c_5}{M_{\text{Planck}}} S O_{\text{SM}}^{(4)}$$

where $O_{\text{SM}}^{(4)}$ is any dim-4 operator in the SM such as $G_{\mu\nu}G^{\mu\nu}$ or Yukawa interactions, etc.. Such a dim-5 operator makes the scalar DM $S$ decay immediately unless its mass is very light $< O(1)$ keV if $c_5 \sim O(1)$ [7]. Therefore global $Z_2$ would not be enough to stabilize or make long-lived the weak scale DM $S$, and it would be better to use local $Z_2$ symmetry to stabilize weak scale DM [7].

This new local gauge symmetry has another nice feature that DM also has its own gauge interaction just as all the SM particles do feel some gauge interaction, with a possibility of strong self interaction for light dark gauge bosons and/or dark Higgs [8]. Dark gauge symmetry can be realized naturally in superstring theory, for example, where the original gauge group with a huge rank is broken into $G_{\text{SM}} \times G_{\text{Dark}}$.

In this letter, we propose a simple scalar dark matter model based on a local $Z_2$ discrete symmetry originated from a spontaneously broken local $U(1)_X$, and investigate its phenomenology including relic density, possibilities of direct/indirect detections and addressing GeV scale $\gamma$-ray excess in Fermi-LAT $\gamma$-ray data in the direction of the Galactic Center (GC). In local $Z_2$ model, there are 3 new extra fields (dark Higgs, dark photon, an unstable excited dark scalar $X_R$) dictated by local dark gauge symmetry. Due to the additional fields and presumed local dark gauge symmetry, the phenomenology of dark matter is expected to be distinctly different from the usual $Z_2$ scalar DM model described by Eq (1).

**MODEL**

Let us assume the dark sector has local $U(1)_X$ gauge symmetry with scalar dark matter $X$ and dark Higgs $\phi$ with $U(1)_X$ charges equal to $q_X(X, \phi) = (1, 2)$ [9]. The local $U(1)_X$ is spontaneously broken into local $Z_2$ subgroup by nonzero VEV of $\phi$, $v_\phi$. Then the model Lagrangian invariant under local dark gauge symmetry is given by

$$\mathcal{L} = \mathcal{L}_{\text{SM}} - \frac{1}{4} \bar{X}_{\mu\nu} \bar{X}^{\mu\nu} - \frac{1}{2} \sin \epsilon \bar{X}_{\mu\nu} \bar{B}^{\mu\nu} + D_\mu \phi D^\mu \phi + D_\mu X^\dagger D^\mu X - m_X^2 X^\dagger X + m_\phi^2 \phi^\dagger \phi$$

$$- \lambda_\phi (\phi^\dagger \phi)^2 - \lambda_X (X^\dagger X)^2 - \lambda_{\phi X} X^\dagger X \phi^\dagger \phi - \lambda_{\phi H} \phi^\dagger \phi H^\dagger H - \lambda_{H X} X^\dagger X H^\dagger H - \mu (X^2 \phi^\dagger + H.c.). \quad (2)$$
We assume all $\lambda$’s and $\mu$ are positive, and the covariant derivative associated with the gauge field $X^\mu$ is defined as $D_\mu \equiv \partial_\mu - i q_X g_X X_\mu$ with $g_X$ being the strength of $U(1)_X$ gauge interaction. We have kept renormalizable operators only, assuming the effects from nonrenormalizable operators are negligibly small.

Once the $U(1)_X$ symmetry is broken by nonzero VEV of $\phi$, we can replace $\phi \rightarrow (v_\phi + \phi)/\sqrt{2}$. Then the $\mu$–term becomes

$$\mu (X^2 \phi^3 + H.c.) = \frac{1}{\sqrt{2}} \mu v_\phi (X_R^2 - X_I^2) (1 + \frac{\phi}{v_\phi}),$$

and generates the mass splitting between $X_R$ and $X_I$, breaking $U(1)_X$ into $Z_2$. Here we used $X = (X_R + i X_I)/\sqrt{2}$. Note that the local $Z_2$ symmetry guarantees the stability of the dark matter even if we consider Planck-scale-suppressed nonrenormalizable operators.

The local $Z_2$ symmetry requires extra new fields (dark Higgs $\phi$ and dark photon $Z_\mu$), as well as an excited partner of DM, $X_R$) compared with a singlet scalar dark matter model with unbroken global $Z_2$ symmetry described by Eq. (1). These three new fields play important roles in DM phenomenology, resulting in results qualitatively different from those in the usual $Z_2$ scalar DM model. In particular, if we replace the dark Higgs field $\phi$ by its VEV and ignores the dark Higgs degree of freedom, our model becomes exactly the same as the excited DM which were discussed in the context of 511 keV gamma ray and PAMELA positron excess [10, 11]. The main difference of our model from the usual excited DM model is the presence of dark Higgs field, which is dynamical and would change DM phenomenology completely. For example, thermal relic density can be dominated by $X_I X_I \rightarrow \phi \phi$ and not by $X_I X_I \rightarrow Z' Z'$, unlike the usual excited DM models. Detailed discussion of this and related issues will be discussed elsewhere.

The $U(1)$ gauge kinetic mixing term can be diagonalized by the following transformation [12]:

$$\begin{pmatrix} \hat{B}_\mu \\ \hat{X}_\mu \end{pmatrix} = \begin{pmatrix} 1 - \tan \epsilon & 0 \\ 0 & 1/ \cos \epsilon \end{pmatrix} \begin{pmatrix} B_\mu \\ X_\mu \end{pmatrix}$$

Diagonalizing the mass matrix subsequently, one then finds

$$\hat{B}_\mu = c_W A_\mu - (t sc_\zeta + s_W c_\zeta) Z_\mu + (s_W s_\zeta - t c_\zeta) Z'_\mu,$$
$$\hat{X}_\mu = \frac{s_\zeta}{c_\zeta} Z_\mu + \frac{c_\zeta}{c_\zeta} Z'_\mu,$$
$$\hat{W}_\mu = s_W A_\mu + c_W c_\zeta Z_\mu - c_W s_\zeta Z'_\mu.$$

Here $s_W(c_W) = \sin \theta_W \cos \theta_W$ with $\theta_W$ being the weak mixing angle and $\zeta$ is defined as

$$\tan 2\zeta = -\frac{m_\chi^2 s_W \sin 2\tau}{m_\chi^2 - m_Z^2 (c_\mu^2 - s_\mu^2 s_W^2)}$$

with $m_\chi^2$ and $m_Z^2$ being the mass-squared of SM Z-boson and $X_\mu$ before diagonalization of kinetic and mass terms. In the limit of small kinetic mixing ($\epsilon \ll 1$) and $m_\chi^2 \ll m_Z^2$ we are interested in, we find $t \zeta \sim s_W t_\tau$. A summary of various constraints can be found in Ref. [13, 14].

From the model Lagrangian Eq. (2), we can work out the particle spectra at the tree level:

$$m_{2R}^2 = 4 g_X^2 v_\phi^2,$$
$$m_{R}^2 = m_X^2 + \sqrt{2} \mu v_\phi + \frac{1}{2} \lambda_{H} v_\phi^2 + \frac{1}{2} \lambda_{X} v_\phi^2,$$
$$m_{I}^2 = m_X^2 - \sqrt{2} \mu v_\phi + \frac{1}{2} \lambda_{H} v_\phi^2 + \frac{1}{2} \lambda_{X} v_\phi^2$$

which show that the dark matter in our scenario is $X_I$. In the true vacuum, the mass matrix elements are

$$m_{hh}^2 = 2 \lambda_{H} v_\phi^2,$$
$$m_{h\phi}^2 = \lambda_{H} v_\phi v_H,$$
$$m_{\phi\phi}^2 = 2 \lambda_{X} v_\phi^2$$

where $v_H = 246$ GeV is the VEV of SM Higgs. The mass eigenvalues are

$$m_{1,2}^2 = \frac{1}{2} \left[ (m_{hh}^2 + m_{h\phi}^2) \pm \sqrt{(m_{hh}^2 - m_{h\phi}^2)^2 + 4 m_{\phi\phi}^2} \right]$$

Requiring $m_{1,2}^2 > 0$, one finds

$$|\lambda_{H}| < 2 \sqrt{\lambda_{X} \lambda_{H}}$$

Interaction eigenstates can be expressed in terms of mass eigenstates as

$$\begin{pmatrix} h \\ \phi \end{pmatrix} = \begin{pmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} H_2 \\ H_1 \end{pmatrix}$$

where the mixing angle $\alpha$ is defined as

$$\tan 2\alpha = \frac{2 m_{h\phi}^2}{m_{hh}^2 - m_{\phi\phi}^2}.$$
either $\epsilon$ extremely small or $m_{Z'}$ large enough. In the latter case, even if we take $m_{Z'} > m_f$ so that DM annihilation to dark photons is kinematically forbidden, most of DM phenomenology discussed in the following would still be valid. In particular, GeV scale excess of $\gamma$-ray from the GC can still be explained from the annihilation of DM to dark Higgs although the working parameter space would become narrower.

**DARK MATTER PHENOMENOLOGY**

From now on, we denote $m_{1,2}$ as $m_{\phi,h}$ and assume

$$30 \text{ GeV} \lesssim m_{1,2} \sim m_{\phi,h} \lesssim 80 \text{ GeV}$$  \hspace{1cm} (12)$$
as the relevant range for GeV scale $\gamma$-ray excess in the direction of GC. We also assume $m_{Z'} \sim 20 \text{ MeV}$ for the anomaly of muon $(g - 2)$ as previously discussed. These mass ranges imply $v_\phi \gtrsim \mathcal{O}(100)$ GeV for $\lambda_\phi \lesssim 1$ from Eq. (7), and $g_X \lesssim 10^{-4}$.

Our model allows tree-level dark matter self-interactions mediated by dark photon and scalar particles $H_{1,2}$ coming from $\phi$ and SM Higgs, for suitable choice of their masses and couplings (see Ref. [8] for DM self-interactions in the scalar DM model with local $Z_2$ symmetry). However, for $m_1, m_\phi$ and $m_{Z'}$ in the ranges of our interest, the effects of DM self-interactions are negligible and can be safely ignored. And DM self-interaction does not impose any meaningful constraint on $\alpha_X$.

**Relic density**

If kinematically allowed, DM can annihilate to dark photon, non-SM Higgs and SM particles. The Feynman diagrams for $X_I X_I \rightarrow Z'Z'$ are shown in Fig 1. The first three diagrams in Fig. 1 give thermal cross section which is too small to saturate canonical thermal cross section for small $g_X$ limit. However, in the presence of the $s$-channel diagram (d), the scattering amplitude is finite even if $g_X = 0$ because of the longitudinal component of $Z'$, and only the diagram (d) becomes relevant. In this case, ignoring the mass of dark photon in the final states, one finds the DM annihilation cross section is approximately given by

$$\langle \sigma v_{\text{rel}} \rangle\, Z'Z' \approx \frac{1}{8\pi v_\phi^2} \lambda_1 c_\alpha \frac{\lambda_1 c_\alpha}{s - m_\phi^2 + i \Gamma_\phi m_\phi} + \frac{\lambda_2 s_\alpha}{s - m_h^2 + i \Gamma_h m_h}$$  \hspace{1cm} (13)$$

where

$$\lambda_1 = (\lambda_{\phi X} v_\phi - \sqrt{2} \mu) c_\alpha - \lambda_{H X} v_H s_\alpha$$  \hspace{1cm} (14)$$

$$\lambda_2 = (\lambda_{\phi X} v_\phi - \sqrt{2} \mu) s_\alpha + \lambda_{H X} v_H c_\alpha$$  \hspace{1cm} (15)$$

and $\Gamma_\phi$ and $\Gamma_h$ are the decay rate of $H_{1,2}$, respectively.

In case of two $H_1(\approx \phi)$ production ($X_I X_I \rightarrow \phi \phi$), we take the small mixing angle limit again. For a reasonable choice of parameters (e.g., $\lambda_{\phi H} \ll \lambda_H \sim \lambda_\phi \sim 0.1$ and $m_\phi < m_I$), as long as $m_I$ is far away from the $s$-channel resonance band, one finds that the contact interaction dominates DM annihilation into $\phi \phi$, and we get

$$\langle \sigma v_{\text{rel}} \rangle_{\phi \phi} \approx \frac{1}{64 \pi m_I^2} (\lambda_{\phi X}^2 + \lambda_{H X}^2) \beta_\phi$$  \hspace{1cm} (16)$$

$$\approx 2.46 \times 10^{-9} \frac{\lambda_{\phi X}^2}{\text{GeV}^2} \left( \frac{100 \text{ GeV}}{m_I} \right)^2 \beta_\phi.$$  \hspace{1cm} (17)$$

Here $\beta_\phi \equiv \sqrt{1 - 4m_{\phi}^2/s}$ and we have used $\lambda_{H X} = 0.1$ and $\alpha = 0.1$ in the second line.

DM can also annihilate directly to SM particles. For $m_I$ in the range of our interest, the thermally-averaged annihilation cross section is

$$\langle \sigma v_{\text{rel}} \rangle_{f \bar{f}} \approx \frac{N_c f}{4 \pi} \left( \frac{s}{4m_I^2} \right)^{1/2} \lambda_{f I}^2 \left( \frac{1 - 4m_f^2}{s} \right)^{3/2}$$  \hspace{1cm} (17)$$

where $N_c$ is the color factor, $\lambda_{f I} = -\sqrt{2}(m_f/v_H)s_\alpha$ and $\lambda_{f I} = \sqrt{2}(m_f/v_H)c_\alpha$ with $m_f$ being the mass of SM fermion $f$.

In Fig. 2, the contour(s) of $\langle \sigma v_{\text{rel}} \rangle$ for each of annihilation channel is shown in the plane of $(\lambda_{\phi X}, \lambda_{H X})$. As shown in the figure, the annihilation cross sections of all three channels $(X_I X_I \rightarrow Z'/Z'Z'/\phi\phi/ff)$ can be comparable to $\langle \sigma v_{\text{rel}} \rangle_{26}$ if either $\lambda_{\phi X}$ or $\lambda_{H X}$ is of $\mathcal{O}(0.1)$. Interestingly, for $\langle \sigma v_{\text{rel}} \rangle_{Z'/Z'} < \langle \sigma v_{\text{rel}} \rangle_{26}$ for a much smaller or larger $\mu$, such a band disappears for $\lambda_{\phi X}, \lambda_{H X} \lesssim 1$.

If $X_R$ and $X_I$ are highly degenerate, the co-annihilation of $X_R$ and $X_I$ is also possible. However, for $\mu = \mathcal{O}(1 - 10)$ GeV and $v_\phi \sim 100$ GeV which we take in this paper, the degeneracy is not high. In this case, even if $X_R$ might not decay until $X_I$ freezes out, the number
The model at hand in this paper can work in the same way for the pair-annihilation to light non-SM Higgses ($\langle \sigma v_{\text{rel}} \rangle_{\phi\phi}$), and keep $\langle \sigma v_{\text{rel}} \rangle_{\phi\phi}$ being in the right range for the GeV excess, by choosing a proper value of $\mu$.

As discussed in Ref. [17], contrary to singlet fermion DM, our scalar dark matter allows a s-wave annihilation mediated by scalar particles. This means that in our scenario DM annihilation directly to SM particles might be another possibility to explain the $\gamma$-ray excess from GC too for $30 \text{ GeV} \lesssim m_X \lesssim 40 \text{ GeV}$. However we found that the relevant parameter space does not satisfy the bound from the direct detection of dark matter that is discussed in the next section.

### Direct detection

In the local $Z_2$ model presented in this letter, the direct detection cross section for the DM does not apply for the dark photon $t-$channel exchange, because it is always inelastic ($X_I N \rightarrow X_I N$) and does not take place for $\delta m \gg E_{\text{kin}}$. Therefore, the kinetic mixing $\epsilon$ is not constrained by direct detection experiments, in sharp contrast with the unbroken $U(1)_X$ case which was studied in Ref. [7] in great detail.

In addition, even if Higgs exchange of DM-nucleon scattering is potentially crucial to constrain our local $Z_2$ scalar DM model, 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 Higgses [35, 36], and the constraint from direct searches can be satisfied rather easily. Note that this feature is not captured at all in the global $Z_2$ scalar DM model where dark Higgs (and also dark photon, although it is irrelevant here) is absent [44].

The Higgs mediated spin-independent elastic DM-nucleon scattering is given by

$$\sigma_p^{\text{SI}} = \frac{m_p}{4\pi} \left( \frac{m_p}{m_X} \right)^2 \frac{c_\alpha^4}{m_1^2} f_p^2 \left( \lambda_{\text{eff}} \frac{v_\phi}{v_H} t_\alpha \left( 1 - \frac{m_1^2}{m_2^2} \right) - \lambda_{HX} \left( t_\phi^2 + \frac{m_1^2}{m_2^2} \right) \right)^2$$

where $m_r = m_X m_p/(m_X + m_p)$, $f_p \simeq 0.326$ [38] (see also Ref. [39] for more recent analysis), and $\lambda_{\text{eff}} \equiv (\lambda_{\phi X} - \sqrt{2} \mu/v_\phi)$. Currently, the most stringent constraint is from LUX [40], and we may take the bound as $\sigma_p^{\text{SI}} < 7.6 \times 10^{-46} \text{ cm}^2$ for $30 \text{ GeV} \lesssim m_1, m_\phi \lesssim 80 \text{ GeV}$.

In Fig. 3, we show parameter space satisfying the direct detection constraint from LUX, and providing a right amount of relic density for $m_l = 80 \text{ GeV}$ and $m_\phi = 75 \text{ GeV}$ as an example with a couple of choices of $\mu$. Also, depicted is the region in which GeV scale excess density of $X_R$ is much smaller than that of $X_I$. Hence, we can ignore the possible effect of co-annihilation. For $\delta m \equiv m_R - m_I \gg m_{Z'}$, the decay rate of $X_R$ is

$$\Gamma_R \approx \frac{\alpha_X}{4} \left( \frac{m_R}{m_{Z'}} \right)^2 m_R \left[ 1 - \frac{m_I^2}{m_R^2} \right]^{3/2} \frac{\sqrt{2} \mu^2 v_\phi}{m_R^2} \quad (18)$$

Hence, unless $\mu$ is smaller than GeV scale by many orders of magnitude, $X_R$ decays well before its would-be freeze-out. Note that, if the mass splitting between $X_R$ and $X_I$ were given by hand, $\Gamma_R$ would diverge in the limit of $m_{Z'} = 0$ (or $v_\phi = 0$), but in our local $Z_2$ model such a divergence is absent.

### Indirect detection: GeV scale $\gamma$-ray excess at Fermi-LAT

In Ref. [17], some of present authors showed that DM pair-annihilation to light non-SM Higgses ($\phi$) which eventually decay dominantly to $b\bar{b}$ or $\tau\bar{\tau}$ can explain the GeV scale $\gamma$-ray excess in the direction of the Galactic Center (GC) if $\langle \sigma v \rangle_{\phi\phi} \sim 10^{-26} \text{ cm}^3/\text{s}$ [18–26] (see also [27–34]). The model at hand in this paper can work in the same way for the $\gamma$-ray excess as long as we take

$$\frac{m_R}{2} < m_I \lesssim 80 \text{ GeV}, \quad \frac{m_I - m_\phi}{m_I} \ll \mathcal{O}(0.1) \quad (19)$$

Alternatively, DM annihilation to $Z'$s ($X_I X_I \rightarrow Z'Z'$) with $m_{Z'}$ replacing $m_\phi$ in Eq. (19) can do the similar job [32, 33]. However here we simply take $m_{Z'} \sim 20 \text{ MeV}$ for muon ($g - 2$) discussed before. In this case, dark photon can decay only to a electron-positron pair, and could affect the expected $\gamma$-ray signals. If it is phenomenologically problem, we can reduce $\langle \sigma v_{\text{rel}} \rangle_{Z'Z'}$ and keep $\langle \sigma v_{\text{rel}} \rangle_{\phi\phi}$ being in the right range for the GeV excess, by choosing a proper value of $\mu$.

![FIG. 2](image) Contours satisfying $\langle \sigma v_{\text{rel}} \rangle_{I} = \langle \sigma v_{\text{rel}} \rangle_{26}$ ($i = Z'Z', f f, \phi \phi$) as functions of $\lambda_X$ and $\lambda_{HX}$ for $a = 0.1, m_I = 80 \text{ GeV}$, $m_\phi = 75 \text{ GeV}$, $v_\phi = 100 \text{ GeV}$, and $\mu = 5 \text{ GeV}$. Dotted green, dashed red, and solid blue lines are for $X_{I} X_{I} \rightarrow Z'Z', f f, \phi \phi$, respectively. $\langle \sigma v_{\text{rel}} \rangle_{I} < \langle \sigma v_{\text{rel}} \rangle_{26}$ in the region between green lines, below red line, and left of the blue line, respectively.
In this letter, we presented a scalar DM model where local $Z_2$ symmetry originating from spontaneously broken local $U(1)_X$ guarantees the DM stability. Contrary to the usual global $Z_2$ scalar DM model, our model contains three new extra fields (dark photon $Z'_\mu$, dark Higgs $\phi$ and the excited DM partner $X_R$) with kinetic and Higgs portal interactions dictated by local gauge invariance and renormalizability. Analyzing this model, we showed that the existence of those three extra fields results in dark matter phenomenology which is qualitatively different from the usual $Z_2$ scalar DM models. The resulting new model can accommodate thermal relic density of scalar DM without conflict with the invisible Higgs branching ratio and the bounds from DM direct detections due to the newly opened channels $X_I X_I \rightarrow Z' Z', \phi\phi$. In particular, the dark Higgs allows for the model to accommodate the GeV scale excess of $\gamma$-rays from the direction of Galactic Center, that might be also the origin of 511keV line at INTEGRAL/SPI as recently claimed [41]. Also, when the mass of dark photon is around 20 MeV, the muon $(g - 2)_\mu$ can be explained without conflict with the recent data from BaBar experiment.

We considered the GC $\gamma$-ray and the muon $(g - 2)$ anomalies for phenomenological analysis of the local $Z_2$ scalar DM model, which depended only on a particular corner of parameter space of the model. Even if some of these anomalies go away, the local $Z_2$ model presented here could be regarded as an alternative to the usual real scalar DM model defined by Eq. (1) with global $Z_2$ symmetry. The local $Z_2$ model has many virtues: (i) dynamical mechanism for stabilizing scalar DM is there with massive dark photon and opens new channels for DM annihilation, (ii) DM self-interaction could be accommodated due to the new fields in the local $Z_2$ model [8], (iii) the dark Higgs improves EW vacuum stability up to Planck scale [35, 36, 42], and opens a new window for Higgs inflation [43], (iv) the excited DM $X_R$ is built in the model due to $U(1)_X \rightarrow Z_2$ dark symmetry breaking. All of these facts make the local $Z_2$ model interesting and DM phenomenology becomes very rich due to the underlying local dark gauge symmetry stabilizing the scalar DM. We plan to present more extensive phenomenological analysis of local $Z_2$ scalar DM model in separate publications, along with phenomenology of the excited DM and also the local $Z_2$ fermion DM model.

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