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Dark matter as the signal of grand unification

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We argue that the existence of dark matter (DM) is a possible consequence of grand unification (GUT) symmetry breaking. In GUTs like $SO(10)$, discrete Z_2 matter parity $(-1)^{3(B-L)}$ survives despite broken $B-L$, and group theory *uniquely* determines that the only possible Z_2-odd matter multiplets belong to representation **16**. We construct the minimal nonsupersymmetric $SO(10)$ model containing one scalar **16** for DM and study its predictions below M_G. We find that electroweak symmetry breaking occurs radiatively due to DM couplings to the standard model Higgs boson. For thermal relic DM the mass range $M_{\rm DM} \sim \mathcal{O}(0.1\text{–}1)$ TeV is predicted by model perturbativity up to M_G. For $M_{\rm DM} \sim \mathcal{O}(1)$ TeV to explain the observed cosmic ray anomalies with DM decays, there exists a lower bound on the spin-independent direct detection cross section within the reach of planned experiments.

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I. INTRODUCTION

The existence of dark matter (DM) of the Universe is now established without doubt [1]. However, the fundamental physics behind it is unknown at present. In the most popular new physics scenario containing DM—supersymmetry (SUSY)—discrete R parity is imposed by hand to prevent phenomenological disasters such as fast proton decay [2]. Similarly, in dedicated DM extensions of the standard model (SM) with new singlet [3], doublet [4], or higher multiplet scalars [5], *ad hoc* Z_2 symmetry must be added to ensure the stability of DM. These phenomenological models cannot answer the two most fundamental questions related to DM: (i) why this particular multiplet or particle constitutes the DM of the Universe and (ii) what is the origin of the imposed Z_2 symmetry? Therefore the underlying physics principles related to the existence of DM remain obscure.

In this work we argue that the existence of DM of the Universe can be a consequence of grand unification (GUT). The GUT framework not only explains the origin of DM but also determines the type of the DM particle and constrains its properties. In this scenario the existence of DM, nonzero neutrino masses via seesaw [6], and baryon asymmetry of the Universe via leptogenesis [7] all point to the same GUT framework.

We show that the Z_2 symmetry needed for DM stability could be a discrete remnant of GUT symmetry group, such as $SO(10)$ [8] that we choose to work with in the following. When breaking $SO(10)$ down to the SM gauge group $SU(2)_L \times U(1)_Y$, the $SO(10)$ embedded $U(1)_X$, where X is orthogonal to the SM hypercharge Y, leaves unbroken Z_2 [9,10],

$$P_X = P_M = (-1)^{3(B-L)}, \tag{1}$$

which is the well-known matter parity P_M. Because of its gauge origin P_M is a symmetry of any SM extension including non-SUSY ones. In the latter case group theory predicts *uniquely*, without any detailed model building, that the only possible Z_2-odd multiplet under Eq. (1) is the **16** of $SO(10)$ [11]. As inclusion of the fourth fermion generation $\mathbf{16}_4$ to the SM is not supported by experimental data, the non-SUSY $SO(10)$ GUT *predicts* that the DM is a mixture of $SU(2)_L \times U(1)_Y$ P_M-odd complex scalar singlet S and neutral component of doublet H_2 belonging to a new scalar **16** of $SO(10)$. Thus the DM of the Universe corresponds to the scalar analogues of the fermionic neutral matter fields, the right-handed neutrino N_R and the left-handed neutrino ν_L, respectively. Preserving P_M requires $SO(10)$ breaking by an order parameter carrying even charge of $B-L$ [9,10]. Therefore $SO(10)$ breaking also generates heavy Majorana masses which induce the seesaw mechanism as well as leptogenesis.

To test the proposed DM scenario we study the scalar potential of a minimal $SO(10)$ GUT model containing one scalar **16** for the DM and one scalar **10** for the SM Higgs doublet. We derive [12] renormalization group equations (RGEs) for scalar mass parameters μ_i^2 and interaction couplings λ_i below the GUT breaking scale and study the vacuum stability and perturbativity conditions for those parameters. We find that the SM Higgs mass parameter μ_1^2 runs negative due to the presence of DM couplings with Higgs boson and triggers *radiative* electroweak symmetry breaking (EWSB) as in SUSY models [13]. Perturbativity up to $M_G = 2 \times 10^{16}$ GeV restricts all scalar self-couplings to be $\lambda_i < 1$ at M_Z predicting a restricted mass window 70 GeV $\lesssim M_{\rm DM} \lesssim$ 2 TeV for thermal relic DM mass. The operator $m/(\Lambda_N M_P) LLH_1H_2$ induces 3-body decays DM $\to l^- \nu W^+$ which may explain the recently observed cosmic ray anomalies. For the DM mass preferred by this solution, $M_{\rm DM} \sim \mathcal{O}(1)$ TeV, our framework predicts *a lower bound* on the spin-independent direct cross section of DM with nuclei, which is within the reach of sensitivity of proposed experiments.

II. DM, LEPTOGENESIS, AND SEESAW MECHANISM

The $SO(10)$ gauge group contains two orthogonal $U(1)$ charges, which can be chosen to be the SM hypercharge Y remaining unbroken after $SO(10)$ breaking at M_G, and broken $X = 3(B-L) + 4T_{3R}$, where T_{3R} is the third component of $SU(2)_R \in SO(10)$ isospin. If $SO(10)$ is broken by fields with even X charge, the discrete subgroup Z_2 of $U(1)_X$ remains unbroken [9]. As $4T_{3R}$ is always even, the surviving P_X parity is nothing but the matter parity, Eq. (1). Because of the $SO(10)$ breaking, $B-L$ is broken at GUT scale generating large Majorana masses for right-handed neutrinos N_{R_i} which suppress the light neutrino masses via the seesaw mechanism. The N_{R_i} decays in early Universe induce the baryon asymmetry via leptogenesis. Thus, in our model, the existence of DM due to the matter parity Eq. (1), the existence of baryon asymmetry, and the existence of seesaw suppressed masses of light neutrinos have the same GUT origin. To our knowledge, $U(1)_X$, $X = 5(B-L) - 2Y$ [14], has been used to forbid proton decay operators in GUTs, explicit examples of gauged $U(1)_{B-L}$ SUSY seesaw models generating R parity have been presented in [15] and low-energy non-SUSY SM extension with extra $U(1)'$ gauge symmetry generating Z_2 is presented in [16], but the connection between nonsupersymmetric DM and P_X was first proposed in [11].

The P_X parity of $SO(10)$ matter multiplets is uniquely determined by group theory. Therefore the proposed $SO(10)$ GUT scenario leaves *no choice* as to what the DM particle multiplets are. Under the group theoretic decomposition $SU(5) \times U(1)_X$, the $\mathbf{16}$ representation of $SO(10)$ reads $\mathbf{16} = \mathbf{1}^{16}(5) + \bar{\mathbf{5}}^{16}(-3) + \mathbf{10}^{16}(1)$, where the X charges of the component multiplets are given in the brackets. While the X charges are different, all the fields in $\mathbf{16}$ of $SO(10)$ are *odd* under the conserved Z_2 parity Eq. (1). Interestingly, fields in $\mathbf{16}$ provide the only P_X odd particles because all other fields coming from small $SO(10)$ representations, $\mathbf{10}$, $\mathbf{45}$, $\mathbf{54}$, $\mathbf{120}$, and $\mathbf{126}$, are even under P_X. Thus the SM fermions belonging to $\mathbf{16}_i$, $i = 1, 2, 3$, are all P_M-odd while the SM Higgs boson doublet is P_M-even because $\mathbf{10} = \mathbf{5}^{10}(-2) + \bar{\mathbf{5}}^{10}(2)$.

Although $B-L$ is broken in nature by the heavy neutrino Majorana masses, discrete $(-1)^{3(B-L)}$ is respected by the interactions of *all* matter fields. Therefore, without any model building, general GUT group theoretic argument implies that the nonsupersymmetric DM must belong to $\mathbf{16}$ of $SO(10)$. Adding a new fermionic $\mathbf{16}$ is equivalent to adding a new generation, which, due to mixing with lighter generations, cannot give DM. The only possibility is the new scalar $\mathbf{16}$ of $SO(10)$, which contains two DM candidates, the complex singlet S and the neutral component of the doublet H_2.

III. MINIMAL $SO(10)$ GUT-INDUCED DM MODEL

The $SO(10)$ symmetric scalar potential of one $\mathbf{16}$ and one $\mathbf{10}$,

$$\begin{aligned} V = {}& \mu_1^2 \mathbf{10}\,\mathbf{10} + \lambda_1(\mathbf{10}\,\mathbf{10})^2 + \mu_2^2 \overline{\mathbf{16}}\,\mathbf{16} + \lambda_2(\overline{\mathbf{16}}\,\mathbf{16})^2 \\ & + \lambda_3(\mathbf{10}\,\mathbf{10})(\overline{\mathbf{16}}\,\mathbf{16}) + \lambda_4(\mathbf{16}\,\mathbf{10})(\overline{\mathbf{16}}\,\mathbf{10}) \\ & + \lambda_S'[\mathbf{16}^4 + \text{H.c.}] + \frac{\mu_{SH}'}{2}[\mathbf{16}\,\mathbf{10}\,\mathbf{16} + \text{H.c.}], \end{aligned} \tag{2}$$

provides the minimal example of GUT DM model. Here we have taken all parameters to be real for simplicity. We assume $SO(10)$ to break at M_G down to $SU(2)_L \times U(1)_Y \times P_M$ in such a way that only one SM Higgs boson doublet $H_1 \in \mathbf{10}$ and the DM candidate complex singlet $S \in \mathbf{16}$ and the inert doublet $H_2 \in \mathbf{16}$ are light, with all other particle masses of order M_G. The $SO(10)$ symmetry breaking may occur in one or in several steps through intermediate symmetries such as $SU(5) \times U(1)_X$. We assume those steps to occur close to the GUT scale. Thus, between M_G and the EWSB scale M_Z, the DM is described by the $H_1 \to H_1$, $S \to -S$, $H_2 \to -H_2$ invariant scalar potential

$$\begin{aligned} V = {}& \mu_1^2 H_1^\dagger H_1 + \lambda_1 (H_1^\dagger H_1)^2 + \mu_2^2 H_2^\dagger H_2 + \lambda_2 (H_2^\dagger H_2)^2 + \mu_S^2 S^\dagger S + \frac{\mu_S'^2}{2}[S^2 + (S^\dagger)^2] + \lambda_S (S^\dagger S)^2 + \frac{\lambda_S'}{2}[S^4 + (S^\dagger)^4] \\ & + \frac{\lambda_S''}{2}(S^\dagger S)[S^2 + (S^\dagger)^2] + \lambda_{S1}(S^\dagger S)(H_1^\dagger H_1) + \lambda_{S2}(S^\dagger S)(H_2^\dagger H_2) + \frac{\lambda_{S1}'}{2}(H_1^\dagger H_1)[S^2 + (S^\dagger)^2] \\ & + \frac{\lambda_{S2}'}{2}(H_2^\dagger H_2)[S^2 + (S^\dagger)^2] + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1) + \frac{\lambda_5}{2}[(H_1^\dagger H_2)^2 + (H_2^\dagger H_1)^2] \\ & + \frac{\mu_{SH}}{2}[S^\dagger H_1^\dagger H_2 + \text{H.c.}] + \frac{\mu_{SH}'}{2}[S H_1^\dagger H_2 + \text{H.c.}], \end{aligned} \tag{3}$$

together with the GUT scale boundary conditions

$$\begin{aligned} & \mu_1^2(M_G) > 0, \qquad \mu_2^2(M_G) = \mu_S^2(M_G) > 0, \\ & \lambda_2(M_G) = \lambda_S(M_G) = \lambda_{S2}(M_G), \qquad \lambda_3(M_G) = \lambda_{S1}(M_G), \end{aligned} \tag{4}$$

and

$$\begin{aligned} & \mu_S'^2, \mu_{SH}^2 \lesssim \mathcal{O}\left(\frac{M_G}{M_P}\right)^n \mu_{1,2}^2, \\ & \lambda_5, \lambda_{S1}', \lambda_{S2}', \lambda_S'' \lesssim \mathcal{O}\left(\frac{M_G}{M_P}\right)^n \lambda_{1,2,3,4}. \end{aligned} \tag{5}$$

We require $\mu_i^2(M_G) > 0$ in order not to break the SM gauge symmetry spontaneously at GUT scale. While the parameters in Eq. (4) are allowed by $SO(10)$, the ones in Eq. (5) can be generated only after $SO(10)$ breaking by operators suppressed by n power of Planck scale M_P. If all parameters in Eq. (5) vanished identically, Peccei-Quinn (PQ) symmetry would imply degenerate real and imaginary components of DM. However, direct search for inelastic DM requires the mass splitting to exceed $\mathcal{O}(100)$ keV. Smallness of λ_5, as given by Eq. (5), allows one to interpret the annual modulation observed by DAMA experiment with inelastic scattering of DM in the inert doublet model [17]. In our model there are more possibilities to obtain small mass splitting between real and imaginary components of DM candidates, cf. Eq. (3). In the following we assume the PQ symmetry to be broken *softly* by $0 < |\mu_S'^2| \ll |\mu_1^2|$.

IV. VACUUM STABILITY CONSTRAINTS

In the SM the requirements of vacuum stability and scalar potential perturbativity up to M_G put the lower and upper bounds on the Higgs boson mass $127 < M_H < 170$ GeV, respectively (see [18] and references therein). In our model the vacuum stability requires

$$\begin{aligned}
&\lambda_1 > 0, & &\lambda_3 > -2\sqrt{\lambda_1\lambda_2},\\
&\lambda_2 > 0, & &\lambda_3 + \lambda_4 - |\lambda_5| > -2\sqrt{\lambda_1\lambda_2},\\
&\lambda_S + \lambda_S' > |\lambda_S''|, & &8(\lambda_S - \lambda_S')\lambda_S' > \lambda_S''^2,\\
&4\lambda_1(\lambda_S + \lambda_S' + \lambda_S'') > (\lambda_{S1} + \lambda_{S1}')^2, & &4\lambda_2(\lambda_S + \lambda_S' + \lambda_S'') > (\lambda_{S2} + \lambda_{S2}')^2,\\
&4\lambda_1(\lambda_S + \lambda_S' - \lambda_S'') > (\lambda_{S1} - \lambda_{S1}')^2, & &4\lambda_2(\lambda_S + \lambda_S' - \lambda_S'') > (\lambda_{S2} - \lambda_{S2}')^2.
\end{aligned} \tag{6}$$

Because there are more scalar couplings than in the SM, they can counteract the top quark Yukawa term in the beta function for λ_1 presented in the next section and lower the vacuum stability bound on M_H below the LEP2 experimental bound of 114.4 GeV consistently with Eq. (6). Therefore, in our model, the precision data indications for light SM Higgs boson does not contradict vacuum stability constraints.

V. RGE ANALYSES

Because our low-energy model is induced by GUT, it must stay perturbative up to the GUT scale. This requirement implies stringent constraints on the model parameters and consequently on the properties of DM. We have derived [12] the full set of RGEs of the model Eq. (3). The one-loop beta functions are given by

$$\beta_{\lambda_1} = 24\lambda_1^2 + 2\lambda_3^2 + 2\lambda_3\lambda_4 + \lambda_4^2 + \lambda_5^2 + \lambda_{S1}^2 + \lambda_{S1}'^2 + \frac{3}{8}(3g^4 + g'^4 + 2g^2g'^2) - 3\lambda_1(3g^2 + g'^2 - 4y_t^2) - 6y_t^4,$$

$$\beta_{\lambda_2} = 24\lambda_2^2 + 2\lambda_3^2 + 2\lambda_3\lambda_4 + \lambda_4^2 + \lambda_5^2 + \lambda_{S2}^2 + \lambda_{S2}'^2 + \frac{3}{8}(3g^4 + g'^4 + 2g^2g'^2) - 3\lambda_2(3g^2 + g'^2),$$

$$\beta_{\lambda_3} = 4(\lambda_1 + \lambda_2)(3\lambda_3 + \lambda_4) + 4\lambda_3^2 + 2\lambda_4^2 + 2\lambda_5^2 + 2\lambda_{S1}\lambda_{S2} + 2\lambda_{S1}'\lambda_{S2}' + \frac{3}{4}(3g^4 + g'^4 - 2g^2g'^2) - 3\lambda_3(3g^2 + g'^2 - 2y_t^2),$$

$$\beta_{\lambda_4} = 4(\lambda_1 + \lambda_2)\lambda_4 + 8\lambda_3\lambda_4 + 4\lambda_4^2 + 8\lambda_5^2 + 3g^2g'^2 - 3\lambda_4(3g^2 + g'^2 - 2y_t^2),$$

$$\beta_{\lambda_5} = 4(\lambda_1 + \lambda_2 + 2\lambda_3 + 3\lambda_4)\lambda_5 - 3\lambda_5(3g^2 + g'^2 - 2y_t^2),$$

$$\beta_{\lambda_S} = 20\lambda_S^2 + 2\lambda_{S1}^2 + \lambda_{S1}'^2 + 2\lambda_{S2}^2 + \lambda_{S2}'^2 + 36\lambda_S'^2 + \frac{27}{2}\lambda_S''^2,$$

$$\beta_{\lambda_S'} = \lambda_{S1}'^2 + \lambda_{S2}'^2 + 24\lambda_S\lambda_S' + \frac{9}{2}\lambda_S''^2,$$

$$\beta_{\lambda_S''} = 4\lambda_{S1}\lambda_{S1}' + 4\lambda_{S2}\lambda_{S2}' + 36(\lambda_S + \lambda_S')\lambda_S'',$$

$$\beta_{\lambda_{S1}} = 4(3\lambda_1 + 2\lambda_S + \lambda_{S1})\lambda_{S1} + 4\lambda_{S1}'^2 + (4\lambda_3 + 2\lambda_4)\lambda_{S2} + 6\lambda_{S1}'\lambda_S'' - \frac{3}{2}(3g^2 + g'^2 - 4y_t^2)\lambda_{S1},$$

$$\beta_{\lambda_{S2}} = 4(3\lambda_2 + 2\lambda_S + \lambda_{S2})\lambda_{S2} + 4\lambda_{S2}'^2 + (4\lambda_3 + 2\lambda_4)\lambda_{S1} + 6\lambda_{S2}'\lambda_S'' - \frac{3}{2}(3g^2 + g'^2)\lambda_{S2},$$

$$\beta_{\lambda'_{S1}} = (4\lambda_3 + 2\lambda_4)\lambda'_{S2} + 4(3\lambda_1 + \lambda_S + 2\lambda_{S1} + 3\lambda'_S)\lambda'_{S1} + 6\lambda_{S1}\lambda''_S - \frac{3}{2}(3g^2 + g'^2 - 4y_t^2)\lambda'_{S1},$$
$$\beta_{\lambda'_{S2}} = (4\lambda_3 + 2\lambda_4)\lambda'_{S1} + 4(3\lambda_2 + \lambda_S + 2\lambda_{S2} + 3\lambda'_S)\lambda'_{S2} + 6\lambda_{S2}\lambda''_S - \frac{3}{2}(3g^2 + g'^2)\lambda'_{S2}.$$
$$\beta_{\mu_1^2} = 12\mu_1^2\lambda_1 + 4\mu_2^2\lambda_3 + 2\mu_2^2\lambda_4 + 2\mu_S^2\lambda_{S1} + 2\mu_S'^2\lambda'_{S1} + \frac{1}{2}(\mu_{SH}^2 + \mu_{SH}'^2) - \frac{3}{2}\mu_1^2(3g^2 + g'^2 - 4y_t^2),$$
$$\beta_{\mu_2^2} = 12\mu_2^2\lambda_2 + 4\mu_1^2\lambda_3 + 2\mu_1^2\lambda_4 + 2\mu_S^2\lambda_{S2} + 2\mu_S'^2\lambda'_{S2} + \frac{1}{2}(\mu_{SH}^2 + \mu_{SH}'^2) - \frac{3}{2}\mu_2^2(3g^2 + g'^2),$$
$$\beta_{\mu_S^2} = 8\mu_S^2\lambda_S + 4\mu_1^2\lambda_{S1} + 4\mu_2^2\lambda_{S2} + 6\mu_S'^2\lambda''_S + \mu_{SH}^2 + \mu_{SH}'^2,$$
$$\beta_{\mu_S'^2} = 4\mu_S'^2\lambda_S + 4\mu_1^2\lambda'_{S1} + 4\mu_2^2\lambda'_{S2} + 12\mu_S'^2\lambda'_S + 6\mu_S^2\lambda''_S + 2\mu_{SH}\mu'_{SH},$$
$$\beta_{\mu_{SH}} = 2\mu_{SH}(\lambda_3 + 2\lambda_4 + \lambda_{S1} + \lambda_{S2}) + 2\mu'_{SH}(3\lambda_5 + \lambda'_{S1} + \lambda'_{S2}) - \frac{3}{2}\mu_{SH}(3g^2 + g'^2 - 2y_t^2),$$
$$\beta_{\mu'_{SH}} = 2\mu'_{SH}(\lambda_3 + 2\lambda_4 + \lambda_{S1} + \lambda_{S2}) + 2\mu_{SH}(3\lambda_5 + \lambda'_{S1} + \lambda'_{S2}) - \frac{3}{2}\mu'_{SH}(3g^2 + g'^2 - 2y_t^2). \tag{7}$$

We also include the one-loop β functions for g, g', g_3, and y_t, given by

$$\beta_{g'} = 7g'^3, \qquad \beta_g = -3g^3, \qquad \beta_{g_3} = -7g^3,$$
$$\beta_{y_t} = y_t\left(\frac{9}{2}y_t^2 - \frac{17}{12}g'^2 - \frac{9}{4}g^2 - 8g_3^2\right). \tag{8}$$

Based solely on the running due to the low-energy RGEs, we identify the unification scale 2×10^{16} GeV by the RGE solution for $g_2 = g_3$. The exact values of gauge couplings at M_G are given by $g_1 = \sqrt{5/3}g' = 0.58$, $g_2 = g_3 = 0.53$. Based solely on the running due to the low-energy RGEs, the precision of unification of all three gauge couplings in our model is better than in the SM because of the existence of an extra scalar doublet. We assume that an exact unification can be achieved due to the GUT threshold corrections in full $SO(10)$ theory which we cannot estimate because the details of GUT symmetry breaking are not known. Those corrections can have only small logarithmic influence on our numerical estimates of g_i just below M_G and affect our numerical results for DM negligibly. In our numerical analysis we follow the strategy used in similar studies of parameter running in SUSY GUT theories. We fix all the measured model parameters and the SM Higgs boson mass at M_Z and calculate the corresponding μ_1^2 and λ_1. We run them up to the GUT scale where we randomly generate new physics parameters assuming the $SO(10)$ boundary conditions. We iterate running until the relative error between fixed and calculated μ_1^2 and λ_1 at M_Z gets smaller than 1%. After that we calculate the DM abundance and direct detection cross section at M_Z.

We find that the new physics parameters are strongly constrained by the vacuum stability and perturbativity arguments. For example, assuming all λ_i allowed by Eq. (2) to be equal at M_Z, perturbativity of them up to M_G requires $\lambda_i(M_Z) < 0.194, 0.187, 0.170$ for $M_H = 120, 140, 160$ GeV, respectively. We also impose the GUT boundary conditions Eq. (4).

We present one consistent example of the evolution of scalar self-couplings λ_i and mass parameters μ_i between M_Z and M_G in Figs. 1 and 2, respectively. We assume $M_H = 140$ GeV and take $\mu'_{SH}(M_G) = 1$ GeV. The couplings $\lambda_i(M_Z)$ must be small as not to reach the Landau pole below M_G. The SM gauge symmetry $SU(2)_L \times U(1)_Y$ is not broken at M_G because all scalar mass parameters are positive $\mu_i^2(M_G) > 0$. However, the SM Higgs mass parameter μ_1^2 exhibits stronger running than the DM mass parameters and triggers the radiative EWSB as in SUSY models [13]. In our case the EWSB is induced by DM couplings to the SM Higgs boson. (Previously, EWSB via a Coleman-Weinberg-like mechanism has been considered in the inert doublet model [19].)

An interesting feature of the model, demonstrated in Fig. 2, is that the singlet DM mass parameter at low energies is always smaller than the doublet one, $\mu_S^2(M_Z) < \mu_2^2(M_Z)$. Thus, for small singlet-doublet mixing as is assumed in this example, the DM particle is predominantly scalar singlet S whose real and imaginary component mass degeneracy is lifted by small $|\mu_S'^2| \ll |\mu_1^2|$.

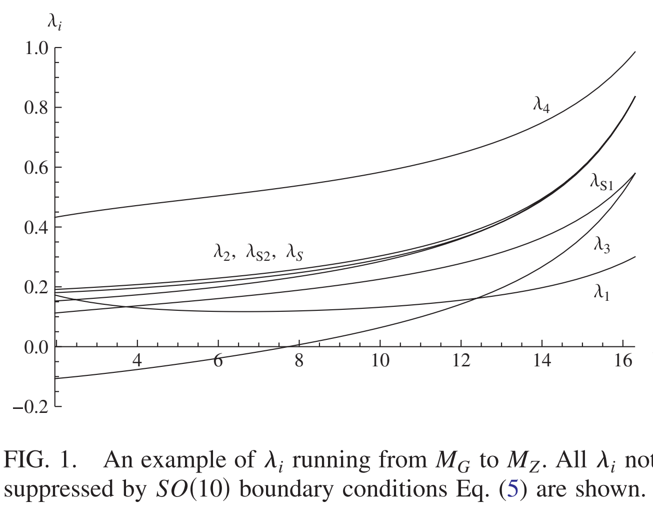

FIG. 1. An example of λ_i running from M_G to M_Z. All λ_i not suppressed by $SO(10)$ boundary conditions Eq. (5) are shown.

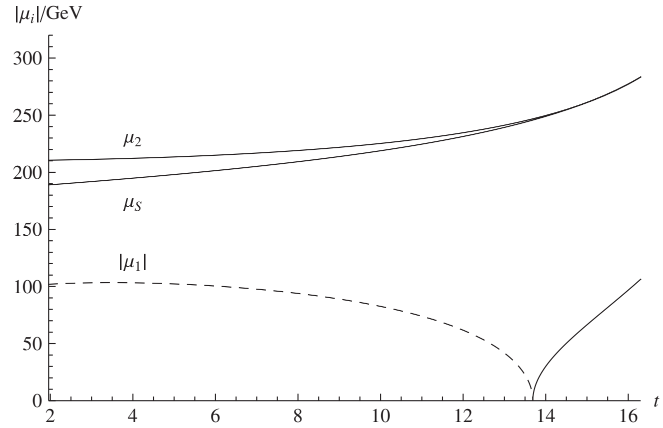

FIG. 2. An example of $\mu_{1,2,S}$ running from M_G to M_Z. Dashed line represents negative values of μ_1^2 inducing EWSB.

VI. PREDICTIONS FOR DM MASS AND DIRECT DETECTION CROSS SECTION

We assume that DM is a thermal relic and calculate its abundance and direct cross section with matter using the MICROMEGAS package [20]. The DM interactions (3) were calculated using the FEYNRULES package [21]. We scan over the entire parameter space satisfying Eq. (4), and calculate the RGE evolution of those parameters down to the EW scale.

Figure 3 presents a scattered plot of the spin-independent DM direct detection cross section per nucleon as a function of DM mass $M_{\rm DM}$ for the SM Higgs boson mass range from 115 (red, light) to 170 GeV (violet, dark). The whole parameter space allowed by theoretical constraints of vacuum stability and positive masses and experimental constraints from LEP2 and the WMAP 3σ result $0.094 < \Omega_{\rm DM}h^2 < 0.129$ [1] is shown. After fixing λ_1 and μ_1^2 from the assumed SM Higgs boson mass, we randomly generate the remaining scalar self-couplings and mass parameters at M_G in the ranges $0 < |\lambda_i| < 4\pi$ and $0 < \mu_i^2 < (10\ \text{TeV})^2$. After RGE running the numerical ranges for nonzero parameters at M_Z are $0.117 < \lambda_1 < 0.239$, $0.024 < \lambda_2 < 0.227$, $-0.424 < \lambda_3 < 0.247$, $-0.584 < \lambda_4 < 0.599$, $0.037 < \lambda_S < 0.177$, $0.000 < \lambda_S' < 0.098$, $-0.212 < \lambda_{S1} < 0.221$, $0.031 < \lambda_{S2} < 0.234$, $-14\,548 < \mu_1^2 < -7056\ \text{GeV}^2$, $3147 < \mu_2^2 < 1.72 \times 10^7\ \text{GeV}^2$, $2894 < \mu_S^2 < 3.84 \times 10^6\ \text{GeV}^2$, $-11\,634 < \mu_{SH}' < 11\,504$ GeV.

The present [22] and future [23] experimental sensitivities for DM direct detection are shown in Fig. 3. As a result, we find that the DM mass is restricted to the window $70\ \text{GeV} \lesssim M_{\rm DM} \lesssim 2$ TeV. The lower bound comes from nonobservation of charged scalars at LEP2. The upper bound $M_{\rm DM} \lesssim 2$ TeV comes from the requirement of perturbativity of the model parameters up to M_G. Therefore, the DM mass scale $M_{\rm DM} \lesssim \mathcal{O}(0.1\text{–}1)$ TeV is a *prediction* of our scalar DM GUT scenario.

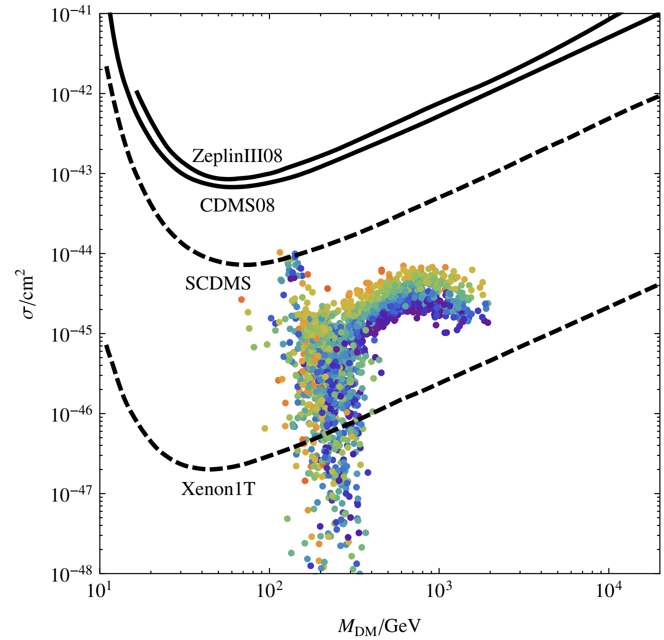

FIG. 3 (color online). DM direct detection cross section per nucleon versus $M_{\rm DM}$. Color shows SM Higgs masses from 115 (red, light) to 170 GeV (violet, dark). The points shown encompass the whole parameter space allowed by theoretical and experimental constraints.

The direct DM interaction with nuclei occurs via the SM Higgs boson exchange. The dominant DM-Higgs effective coupling involved in this process is

$$\lambda_{\rm eff}v = \frac{1}{2}(\sqrt{2}sc\mu_{SH}' + 2s^2(\lambda_3 + \lambda_4)v + 2c^2\lambda_{S1}v), \quad (9)$$

where s, c are the sine, cosine of the singlet-doublet mixing angle. If $M_{\rm DM} \lesssim 300$ GeV, cancellation between different terms in Eq. (9) is possible and the spin-independent direct detection cross section can be accidentally small, cf. Fig. 3. However, for larger DM masses both Eq. (9) and thermal freeze-out cross section are dominated by a large μ_{SH}' term, and one obtains a relation between the DM abundance and the direct detection cross sections with only mild dependence on M_H via RGEs. For $M_{\rm DM} = 1$ TeV the WMAP result predicts *a lower bound* $\sigma/n > 7 \times 10^{-45}(115\ \text{GeV}/M_H)^4\ \text{cm}^2$, which is well within the reach of the planned experiments, cf. Fig. 3.

VII. DM INDIRECT DETECTION

The PAMELA [24], ATIC [25], H.E.S.S. [26], and Fermi [27] anomalies of cosmic ray positron/electron fluxes can be explained with $\mathcal{O}(1)$ TeV mass DM decays [28] via $d = 6$ operators [29], preferably to multiparticle final state [30,31]. Nonobservation of photons associated with DM annihilation in the Galactic center [32] and in DM halos in the Universe [33] as well as the suppression of hadronic annihilation modes [34] strongly favor DM decays over annihilations as a solution to the anomalies.

In our scenario the decays of DM are most naturally explained via the seesawlike operator LLH_1H_2 which, in addition to the suppression by heavy Majorana neutrino scale M_N, must be suppressed by the Z_2 breaking effects by additional M_P. We obtain that below EWSB scale the dominant decay mode is given by

$$\frac{\lambda_N}{M_N}\frac{m}{M_P}LLH_1H_2 \to 10^{-30}\ \mathrm{GeV}^{-1}\nu l^- W^+ H_2^0, \qquad (10)$$

where we have taken $\lambda_N \sim 1$, $M_N \sim 10^{14}$ GeV, and $m \sim v \sim 100$ GeV. In the decays of W^+ antiprotons are produced in about 10% of decays. Such a small fraction of antiprotons is still allowed by PAMELA data taking into account uncertainties in the cosmic ray propagation models [35]. Such a small effective Yukawa coupling of Eq. (10) can explain the long DM lifetime 10^{26} s without conflicting with the present observational constraints.

VIII. CONCLUSIONS

We have argued that the existence of DM, the baryon asymmetry of the Universe, and small neutrino masses may all signal the same underlying GUT physics. Although $B - L$ is broken in nature by heavy neutrino Majorana masses, Z_2 parity $(-1)^{3(B-L)}$ is respected by interactions of all matter fields. Hence, group theory predicts that in $SO(10)$ GUTs the nonsupersymmetric DM must be contained in the scalar representation **16**.

Based on $SO(10)$ GUT, we have presented a minimal DM model, calculated the full set of its RGEs, and studied its predictions. We find that the EWSB occurs radiatively due to SM Higgs boson couplings to the DM, analogously to SUSY models. The thermal relic DM mass is predicted to be $M_{\mathrm{DM}} \lesssim \mathcal{O}(0.1–1)$ TeV by the requirement of perturbativity of model parameters up to the GUT scale. If $M_{\mathrm{DM}} \gtrsim 300$ GeV as suggested by DM decay solution to the recently observed cosmic ray anomalies, the WMAP measurement of DM abundance predicts a lower bound on DM spin-independent direct cross section with nuclei, which is within the reach of planned experiments for all values of the SM Higgs boson mass.

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