

Baryon-Dark Matter Coincidence in Mirrored Unification

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(Dated: July 9, 2019)

About 80% of the mass of the present Universe is made up of the unknown (dark matter), while the rest is made up of ordinary matter. It is a very intriguing question why the *mass* densities of dark matter and ordinary matter (mainly baryons) are close to each other. It may be hinting the identity of dark matter and furthermore structure of a dark sector. A mirrored world provides a natural explanation to this puzzle. On the other hand, if mirror-symmetry breaking scale is low, it tends to cause cosmological problems. In this letter, we propose a mirrored unification framework, which breaks mirror-symmetry at the grand unified scale, but still addresses the puzzle. The dark matter mass is strongly related with the dynamical scale of QCD, which explains the closeness of the dark matter and baryon masses. Intermediate-energy portal interactions share the generated asymmetry between the visible and dark sectors. Furthermore, our framework is safe from cosmological issues by providing low-energy portal interactions to release the superfluous entropy of the dark sector into the visible sector.

INTRODUCTION

Cosmological observations have established that the mass of the present Universe is made up by so-called dark matter (DM) in addition to ordinary matter. The mass density of DM is about five times larger than that of ordinary matter, i.e., standard model (SM) baryons [1]. The observed closeness of the mass densities may be a hint on DM and dark sector physics. If DM (dark sector) has nothing to do with SM baryon (visible sector), it is puzzling why their mass densities are close to each other.

The concept of a mirror world is a natural option to explain this puzzle (see Refs. [2–8] for earlier works). In recent years, the mirror world scenarios combined with twin Higgs models also attract attention since they ameliorate the naturalness problem [9–12]. In those scenarios, the dark sector contains mirror partners of the SM particles, and therefore the coincidence is naturally realized. However, if mirror \mathbb{Z}_2 symmetry is kept at a low-energy scale, mirror-world models tend to be inconsistent with cosmology because the dark sector inevitably includes light particles such as the mirror partners of neutrinos and photon.

Instead, in this letter, we pursue a mirrored Grand Unified Theory (GUT) framework, in which \mathbb{Z}_2 symmetry is broken at a GUT scale. We consider a GUT model with gauge dynamics of $G_{\text{VGUT}} \times G_{\text{DGUT}}$ (with a gauge group $G = G_{\text{VGUT}} = G_{\text{DGUT}}$) and an exchanging symmetry between G_{VGUT} and G_{DGUT} [13]. It is remarkable that \mathbb{Z}_2 -symmetry breaking at a high-energy scale does not lose good features as long as the lightest “dark” baryons are DM [14–53] (see Ref. [54] for a review). The baryon-DM coincidence puzzle is divided into two subproblems: the coincidence of masses and that of number densities

between baryons and DM. As for the mass coincidence, the key ingredient is the correspondence between dynamical scales of each sector: the baryon and DM masses are determined by them. Such a correspondence can be achieved once the gauge couplings are related with each other at the GUT scale. As we will see, \mathbb{Z}_2 -symmetry breaking below the GUT scale does not spoil this correspondence.

As for the number density, we consider the asymmetric dark matter (ADM) framework [55–65] (see also Refs. [66–68] for reviews). Since the “dark” baryons have an annihilation cross section as large as the SM baryons have [69, 70], the number density of DM is dominated by an asymmetry between particle and antiparticle. The asymmetries in the two sectors are equilibrated when a portal interaction is efficient at an intermediate scale.

After decoupling of the portal interaction, the entropy densities in the two sectors are conserved separately: the excessive entropy in the dark sector gives a significant contribution to the dark radiation [71]. Therefore, two types of portal interactions are needed for viable (composite) ADM scenarios: intermediate-energy portal interactions to share the asymmetry, and low-energy portal interactions to release the superfluous entropy of the dark sector into the visible sector. Our framework indeed provides such portal interactions, and thus explains the baryon-DM coincidence puzzle in a self-contained manner.

Our framework is based on a supersymmetric Grand Unified Theory (SUSY GUT), in which the \mathbb{Z}_2 symmetry is manifest above the GUT scale. The gauge structure of each sector at low energy depends on a choice of vacuum at GUT scale. In our framework, the visible sector is reduced to the SM, while the dark sector follows two-step symmetry breaking and then has a dynamics similar to quantum chromodynamics (QCD) and quantum electro-

TABLE I. Matter and Higgs contents in the $SU(5)_{\text{VGUT}} \times SU(5)_{\text{DGUT}}$ model. The subscript $S = V, D$ represents the sectors: the fields are charged under $SU(5)_{\text{VGUT}}$ for $S = V$ and charged under $SU(5)_{\text{DGUT}}$ for $S = D$. $i = 1, 2, 3$ denotes the generations of matter chiral multiplets in each sector.

	$SU(5)_{\text{VGUT,DGUT}}$	$U(1)_X$
Ψ_{Si}	10	1
Φ_{Si}	$\bar{5}$	-3
\bar{N}_i, \bar{N}'_i	1	5
H_S	5	-2
\bar{H}_S	$\bar{5}$	2
X_S	5	-2
\bar{X}_S	$\bar{5}$	2
Σ_S	24	0

dynamics (QED). The second symmetry breaking in the dark sector provides the intermediate-energy portal interactions and tiny kinetic mixing of visible photon and “dark” photon. SUSY plays a key role to achieve gauge coupling unification in the visible sector. Electroweak symmetry breaking in the visible sector and “dark” QED breaking are triggered by SUSY breaking effects.

MIRRORED UNIFICATION MODEL

We consider a concrete model with $G = SU(5)$ to demonstrate our framework. \mathbb{Z}_2 is the symmetry interchanging $SU(5)_{\text{VGUT}}$ and $SU(5)_{\text{DGUT}}$. Under the \mathbb{Z}_2 symmetry, dimensionless couplings in the two sectors are identified, while the mass parameters softly break the \mathbb{Z}_2 symmetry.

We show the particle contents of the model in Table I, which are similar to those of the minimal SUSY $SU(5)$ GUT in each sector. The chiral multiplets, Ψ_V and Φ_V , contain all the SM fermions. Ψ_D and Φ_D include the dark-quarks which provide the ingredients of the composite DM. \bar{N}_i and \bar{N}'_i are the right-handed neutrinos, which are doublets under the \mathbb{Z}_2 symmetry. $U(1)_X$ denotes a global $B - L$ symmetry compatible with the unified gauge group. It should be noted that the model have extra Higgs quintuplets, (X_S, \bar{X}_S) , in addition to the usual Higgs quintuplets, (H_S, \bar{H}_S) .

The minimal $SU(5)$ GUT model with $\mathcal{O}(1)$ TeV sfermions contradicts with the nucleon decay experiments [72–75]. To avoid rapid nucleon decay, we simply assume a split spectrum for sparticles [76–79], where sfermions have masses of $\mathcal{O}(10^2)$ TeV while the masses of gauginos and higgsinos are $\mathcal{O}(1)$ TeV [80].

Both sectors are mostly sequestered with each other up to higher-dimensional interactions suppressed by the reduced Planck mass M_{Pl} . The superpotential W_S gives the Yukawa couplings, the Higgs masses, and the Higgs

couplings to fields with subscripts $S = V, D$,

$$\begin{aligned}
 W_S = & \Psi_S Y_u \Psi_S H_S + \Psi_S Y_d \Phi_S \bar{H}_S \\
 & + H_S (M_S + \lambda \Sigma_S) \bar{H}_S \\
 & + \mu_S \text{tr}(\Sigma_S^2) + \lambda_\Sigma \text{tr}(\Sigma_S^3) \\
 & + M'_S X_S \bar{X}_S - \xi \frac{(X_S \bar{X}_S)^2}{M_{\text{Pl}}}.
 \end{aligned} \tag{1}$$

Here, λ , λ_Σ , ξ , and 3×3 matrices $Y_{u,d}$ are dimensionless coupling constants, while M_S , M'_S and μ_S are dimensionful parameters. We assume λ , λ_Σ , and ξ are of $\mathcal{O}(1)$ in the following. The \mathbb{Z}_2 symmetry equates all the dimensionless couplings except the mass parameters in the two sectors: we assume mass hierarchy $M_D, M'_D, \mu_D \ll M_V, M'_V, \mu_V$.

Symmetry Breaking Patterns

$SU(5)_{\text{VGUT}}$ is broken down to the gauge group of the SM, G_{SM} , by a vacuum expectation value (VEV) of Σ_V at the scale of $M_{\text{VGUT}} \simeq \mu_V$, while X 's and H 's do not obtain large VEVs. That is, $SU(5)_{\text{VGUT}} \rightarrow G_{\text{SM}}$ is achieved by

$$\langle \Sigma_V \rangle = \mathcal{O}(\mu_V), \quad \langle X_V \bar{X}_V \rangle = 0. \tag{2}$$

We set $M_{\text{VGUT}} = \mathcal{O}(10^{16})$ GeV, which is expected from the unification of extrapolated gauge coupling constants in the supersymmetric SM (SSM).

The vacuum of dark sector is chosen to be,

$$\langle \Sigma_D \rangle = \mathcal{O}(\mu_D), \quad \langle X_D \bar{X}_D \rangle = \mathcal{O}(M'_D M_{\text{Pl}}). \tag{3}$$

The non-vanishing VEV of $X_D \bar{X}_D$ is due to the forth term of Eq. (1). For $\mu_D \sim M'_D \ll M_{\text{Pl}}$, $SU(5)_{\text{DGUT}}$ is first broken down to $SU(4)_{\text{DGUT}}$ by $\langle X_D \rangle$. $SU(4)_{\text{DGUT}}$ is subsequently broken down to $SU(3)_D \times U(1)_D$ by $\langle \Sigma_D \rangle$ at $M_{\text{DGUT}} = \mathcal{O}(\mu_D)$. The dark sector results in the model of a composite ADM model in [48, 81].

It should be emphasized that the difference between M_{VGUT} and M_{DGUT} is advantageous to explain the tiny kinetic mixing between the dark photon and the visible photon [81]. In fact, a higher-dimensional operator,

$$W_{\text{Pl}} = \frac{1}{M_{\text{Pl}}^2} \text{tr}(\Sigma_V \mathcal{W}_V) \text{tr}(\Sigma_D \mathcal{W}_D), \tag{4}$$

leads to the kinetic mixing parameter of the visible and the dark photons,

$$\epsilon \simeq \frac{M_{\text{VGUT}} M_{\text{DGUT}}}{M_{\text{Pl}}^2} \simeq 10^{-10} \left(\frac{M_{\text{DGUT}}}{10^{10} \text{ GeV}} \right). \tag{5}$$

We obtain a tiny kinetic mixing parameter $\epsilon = 10^{-7} - 10^{-10}$ for $M_{\text{DGUT}} = 10^{10-13}$ GeV, which satisfies all the constraints including the beam dump experiments [82] and supernova 1987A [83, 84] when the dark photon mass is $\mathcal{O}(10^{1-2})$ MeV.

Intermediate-Scale Effective Theory

Below M_{VGUT} , we assume the SSM for the visible sector, where a pair of Higgs doublets from (H_V, \bar{H}_V) remains almost massless by tuning M_V in Eq. (1). All the other components of the extra Higgs have masses of $\mathcal{O}(M_{\text{VGUT}})$ in the visible sector.

In the dark sector, $SU(5)_{\text{DGUT}}$ is broken down to $SU(4)_{\text{DGUT}}$ at $\sqrt{M_{\text{DGUT}}M_{\text{Pl}}} \sim 10^{14-16}$ GeV for $M_{\text{DGUT}} = 10^{10-13}$ GeV. The gauge multiplets and the pseudo-Goldstone components of (X_D, \bar{X}_D) corresponding to $SU(5)_{\text{DGUT}}/SU(4)_{\text{DGUT}}$ obtain masses of $\mathcal{O}(\sqrt{M_{\text{DGUT}}M_{\text{Pl}}})$ [85]. Below the $SU(5)_{\text{DGUT}}$ breaking scale, the matter and the Higgs multiplets are decomposed into the $SU(4)_{\text{DGUT}}$ multiplets by

$$\Psi_D \rightarrow A_D(\mathbf{6}) \oplus Q_D(\mathbf{4}), \quad \Phi_D \rightarrow \bar{Q}_D(\bar{\mathbf{4}}) \oplus N_D(\mathbf{1}), \quad (6)$$

$$H_D \rightarrow H_D(\mathbf{4}) \oplus S_D(\mathbf{1}), \quad \bar{H}_D \rightarrow \bar{H}_D(\bar{\mathbf{4}}) \oplus \bar{S}_D(\mathbf{1}), \quad (7)$$

$$\Sigma_D \rightarrow \Xi(\mathbf{15}) \oplus h'_D(\bar{\mathbf{4}}) \oplus \bar{h}'_D(\bar{\mathbf{4}}) \oplus S'_D(\mathbf{1}). \quad (8)$$

Below M_{DGUT} , $SU(4)_{\text{DGUT}}$ is broken down to $SU(3)_D \times U(1)_D$. We assume a pair of $U(1)_D$ charged Higgs multiplet remains almost massless while all the other components in Eqs. (7) and (8) obtain masses of $\mathcal{O}(M_{\text{DGUT}})$. The $U(1)_D$ charged Higgs multiplet will break the $U(1)_D$ symmetry at the low energy scale.

Since (S_D, \bar{S}_D) do not obtain the VEVs, the matter fields in the dark sector do not obtain masses from the Yukawa interactions in Eq. (1). To generate the mass term, we assume interactions to X_D 's such as,

$$W = y_u \Psi_D \Psi_D X_D + y_d \Psi_D \Phi_D \bar{X}_D + \frac{y'_e}{M_{\text{Pl}}} \Psi_D \Sigma_D \Phi_D \bar{X}_D, \quad (9)$$

with tiny coupling constants [86]. In the following, we take the masses of the dark quarks to be free parameters. For a successful model of ADM, the dynamical scale of $SU(3)_D$, $\Lambda_{\text{QCD}'}$, should be of $\mathcal{O}(1)$ GeV. At least, one generation of the quarks should be lighter than $\Lambda_{\text{QCD}'}$ so that the lightest dark baryon can be the DM [87]. The last term in Eq. (9) split the masses of the dark quarks and leptons in A_D , Q_D , and \bar{Q}_D . We assume that the lightest dark lepton is heavier than $\Lambda_{\text{QCD}'}$ so that the rapid dark matter decay is avoided [81].

The visible and dark sectors are connected through superpotential W_N of the right-handed neutrinos.

$$W_N = \Phi_V y_N \bar{N} H_V + \Phi_D y_N \bar{N}' H_D + \Phi_V Y_N \bar{N}' H_V + \Phi_D Y_N \bar{N} H_D + (\text{mass terms}), \quad (10)$$

where y_N and Y_N are Yukawa coupling constants. The mass terms of the right-handed neutrinos (denoted by M_R collectively) softly break $U(1)_X$. Couplings of \bar{N} to

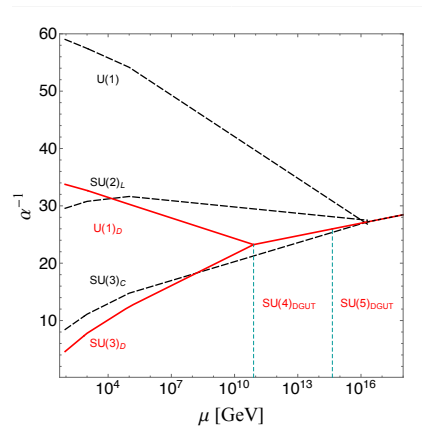


FIG. 1. Renormalization scale μ dependence of the gauge couplings in two sectors. The broken lines show the (S)SM gauge couplings, while the red lines show the running of dark gauge couplings. We assume split spectrum for sparticles: the gaugino scale 1 TeV and the sfermion scale 100 TeV. We also assume that $M_{\text{DGUT}} = 8 \times 10^{10}$ GeV where $SU(3)_D \times U(1)_D$ unifies into $SU(4)_{\text{DGUT}}$.

Φ_V realize thermal leptogenesis and tiny neutrino masses via the type-I seesaw mechanism [88–93], while the couplings of \bar{N}' are irrelevant because we assume that \bar{N}' is much heavier than \bar{N} .

The dark neutrinos (included in Φ_D 's) can easily have either Majorana or Dirac mass terms of $\mathcal{O}(M_{\text{DGUT}})$, and thus our framework is consistent with cosmological constraints on light particles. For example, the Majorana mass would be generated from $U(1)_X$ breaking higher-dimensional operators such as $(X_D \Phi_D)^2$, while the Dirac mass would be generated from the usual Yukawa coupling, $X_D \Phi_D \bar{N}'$.

As shown in Ref. [81], the $B - L$ portal operators between the two sectors are generated by integrating out the right-handed neutrino and the dark-colored Higgs;

$$W_{\text{eff.}} = \frac{(Y_d)_{ij}(Y_N)_{kl}}{\sqrt{2}M_C} \epsilon_{abc} (\bar{U}'^a \bar{D}'^b) (\bar{D}'^c \bar{N}_l). \quad (11)$$

Here, \bar{U}' and \bar{D}' denote the dark quark superfields, and ϵ_{abc} is the totally antisymmetric tensor of $SU(3)_D$. These portal interactions successfully mediate the $B - L$ asymmetry generated by thermal leptogenesis for $M_R < M_C \lesssim 10^2 Y_N Y_d M_R$ [81] [94].

It should be noted that the above portal interactions require at least two generations of dark quarks to be non-vanishing. In the following, we leave only the two generations of U' and D' below the M_{DGUT} scale, for simplicity.

In Fig. 1, we show the one-loop running of the gauge couplings in the two sectors. We take $M_{\text{DGUT}} = 8 \times 10^{10}$ GeV and the corresponding $SU(5)_{\text{DGUT}}$ breaking scale at 10^{14} GeV as an example. M_{DGUT} of $\mathcal{O}(10^{10})$ GeV or larger is compatible with the composite ADM scenario with $M_R \gtrsim 10^9$ GeV for thermal leptogenesis [81]. In this

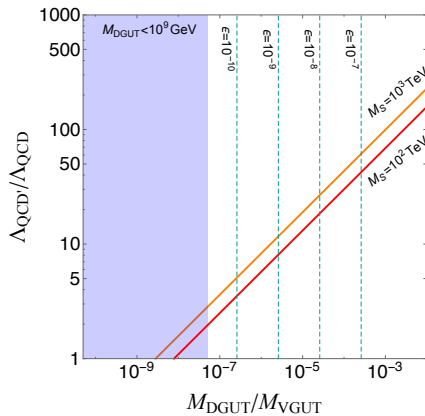


FIG. 2. Confinement scale as a function of $M_{\text{DGUT}}/M_{\text{VGUT}}$. Green-dashed lines represent the magnitude of the kinetic mixing parameter ϵ given in Eq. (4). In the blue-shaded region, the ADM scenario which requires $M_R < M_C \sim M_{\text{DGUT}}$ is not compatible with the successful thermal leptogenesis which requires $M_R \gtrsim 10^9 \text{ GeV}$.

plot, the dark confinement scale $\Lambda_{\text{QCD}'}$, where $SU(3)_D$ coupling $\alpha_s'^{-1}(\Lambda_{\text{QCD}'})$ vanishes, is about 2.8 GeV which is consistent with the dark baryon mass $m_{\text{DM}} = \mathcal{O}(1) \text{ GeV}$ determined by the asymmetries in two sectors [48, 95, 96]. Therefore, the dark baryons with the mass of $\mathcal{O}(1) \text{ GeV}$ can be naturally realized as a consequence of the \mathbb{Z}_2 symmetry at the high-energy scale.

Baryon-DM Coincidence

The dark confinement scale is restricted in our model since the unified couplings in the two sectors are identified at the GUT scale. The analytic solution of renormalization group equations for gauge couplings gives the dark confinement scale

$$\Lambda_{\text{QCD}'} \simeq 2.8 \text{ GeV} \left(\frac{M_{\text{SUSY}}}{10^2 \text{ TeV}} \right)^{\frac{4}{25}} \left(\frac{M_{\text{DGUT}}}{8 \times 10^{10} \text{ GeV}} \right)^{\frac{9}{25}}, \quad (12)$$

where M_{SUSY} is a typical mass scale of (dark) sfermions for two-generation matter in the dark sector below M_{DGUT} .

Fig. 2 shows the ratio of the confinement scales in the two sectors. Here we take $SU(5)_{\text{DGUT}}$ breaking scale smaller than M_{VGUT} . We assume the gauginos and higgsino to be 1 TeV and the sfermion masses to be $M_{\text{SUSY}} = 10^2 \text{ TeV}$ (10^3 TeV) on the red (orange) line. As a prominent feature of the model, the dark confinement scale is no longer a free parameter in our scenario and is predicted to be in the range of $\mathcal{O}(1-10^2)\Lambda_{\text{QCD}}$ for a wide range of $M_{\text{DGUT}}/M_{\text{VGUT}}$. Here we take $\Lambda_{\text{QCD}} \simeq 0.3 \text{ GeV}$. This shows that the \mathbb{Z}_2 symmetry successfully predicts the dynamical scales are close with

each other, despite the vacuum structures are completely different between two sectors below the M_{VGUT} scale.

It should be also noted that the kinetic mixing parameter is predicted to be $\epsilon \simeq 10^{-10}-10^{-8}$ for $\Lambda_{\text{QCD}'}/\Lambda_{\text{QCD}} \simeq 5-50$. This feature is another advantage of the present model.

CONCLUDING REMARKS

In this letter, we have proposed the mirrored GUT framework in which the baryon-DM coincidence is naturally explained. The framework relates the masses of baryon and DM (dynamical scales) and also the number (asymmetry) densities.

In contrast to the models keeping mirror symmetry at a low-energy scale, it is interesting that our framework leads to rich phenomenology and testable signatures [48]. DM decays into SM neutrinos through the intermediate-energy portal interactions [96, 97]. DM annihilates through a dark neutron-antineutron oscillation [98]. When DM is composed of dark “charged” baryons, DM interacts with the SM fermions through tiny kinetic mixing between photon and dark photon. The monopoles from the $SU(4)_{\text{DGUT}} \rightarrow SU(3)_D \times U(1)_D$ breaking, which are finally confined by the cosmic string after the $U(1)_D$ breaking and annihilate efficiently, are also worthy of investigation.

We regard the specific model in this paper as a proof of concept and have not addressed the origins of several fine-tuned parameters. Fine-tunings of parameters are just technically natural thanks to SUSY and furthermore most of tuned parameters are irrelevant to explain the baryon-DM coincidence puzzle. However, it is to be addressed in future why chiral symmetry breaking in the dark sector is so tiny, although the dark sector is a vector-like theory below the $SU(5)_{\text{DGUT}} \rightarrow SU(4)_{\text{DGUT}}$ breaking. We may consider a variant of the present model to ameliorate the parameter tunings in the superpotentials (for example, introducing chiral symmetry to suppress the Higgs μ -term). Although our present model is not fully satisfactory, it demonstrates a new vast field of the DM-model building to be explored.

ACKNOWLEDGEMENTS

A. K. would like to acknowledge the Mainz Institute for Theoretical Physics (MITP) of the Cluster of Excellence PRISMA+ (Project ID 39083149) for enabling A. K. to complete a significant portion of this work. The work of A. K. and T. K. is supported by IBS under the project code, IBS-R018-D1. This work is also supported by JSPS KAKENHI Grant Numbers, JP17H02878, No. 15H05889 and No. 16H03991 (M. I.) and by World Premier International Research Center Initiative (WPI Initiative),

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