

# Grand Unification, Dark Matter, Baryon Asymmetry, and the Small Scale Structure of the Universe

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We consider a minimal grand unified model where the dark matter arises from non-thermal decays of a messenger particle in the TeV range. The messenger particle compensates for the baryon asymmetry in the standard model and gives similar number densities to both the baryon and the dark matter. The non-thermal dark matter, if massive in the GeV range, could have a free-streaming scale in the order of 0.1 Mpc and potentially resolve the discrepancies between observations and the  $\Lambda$ CDM model on the small scale structure of the Universe. Moreover, a GeV scale dark matter naturally leads to the observed puzzling proximity of baryonic and dark matter densities. Unification of gauge couplings is achieved by choosing a “Higgsino” messenger.

## INTRODUCTION

The standard model of particle physics is believed to be incomplete. For decades the strongest arguments are based more on aesthetic reasonings than on empirical evidence. One example is the fine-tuning in the mass of the scalar Higgs requires new physics at around 1 TeV to stabilize the electroweak scale, for which the benchmark solution is weak scale supersymmetry (SUSY). Another example is the gauge coupling unification which suggests a grand unified theory (GUT) at high energy scale [1], assuming a desert between the GUT scale and the electroweak scale where all the particles come in complete multiplets of the GUT group. It turned out that in the minimally supersymmetric standard model (MSSM) [2], gauge couplings unify to a much better precision than in the standard model, which adds to the attractiveness of the weak scale SUSY.

On the empirical side the situation has dramatically improved over the last few years due to insights from precision cosmological observations, including the existence of dark matter, the acceleration of the cosmic expansion, the baryon-asymmetric Universe, and a nearly scale-invariant density fluctuations, none of which can be explained within the standard model. (A minimal model addressing all these issues has been proposed in [3].) Emerging from the observations is a description of the Universe based on the  $\Lambda$ CDM model [4]: a tiny cosmological constant plus cold dark matter.

Neither the MSSM nor the  $\Lambda$ CDM model is perfect, however. In the MSSM the most notable problems are the SUSY flavor problem, new flavor violations from various superpartners, and the non-observation of a light Higgs as well as any light sparticles, which implies fine-tuning at a few percents level [5]. These problems prompted the proposal [6] of giving up SUSY as a solution to the hierarchy problem. But if gauge coupling unification (and the neutralino dark matter) is the main motivation for SUSY, there is a much simpler model, the standard model with “Higgsinos”, which is just as good [7]. On the other hand, there has been evidence

suggesting, albeit not yet conclusively, inconsistencies between observations and numerical simulations of the  $\Lambda$ CDM model on the galactic and sub-galactic scales [8]; it seems that  $\Lambda$ CDM model predicts too much power on the small scales. One way out is to introduce warm dark matter (WDM) [9, 10] which has a small free-streaming scale  $\lambda_{\text{FS}} \lesssim 0.1$  Mpc, hence suppressing density fluctuations on scales smaller than  $\lambda_{\text{FS}}$ .

In this letter, using unification instead of naturalness as the main incentive, we show that the three otherwise independent aspects: gauge coupling unification, the puzzling proximity of  $\Omega_{\text{DM}}$  and  $\Omega_b$ , and the small free-streaming scale, can all be intertwined in a non-trivial way. It is based on the model discussed in [11] where the dark matter arises from late-time decays of a heavy messenger particle compensating for the baryon asymmetry in the standard model. First, gauge coupling unification suggests the existence of “Higgsinos,” which is the messenger particle, at the TeV scale and sets the GUT scale to be  $\sim 10^{14}$  GeV [7]. Next cosmology constrains the decay temperature of the “Higgsinos” to be  $\sim 10$  MeV and determines the scale of the higher dimensional operators responsible for the Higgsino decay to be  $10^{14-15}$  GeV [11], a most natural value in the GUT picture. Then the measured ratio of  $\Omega_{\text{DM}}/\Omega_b$  can be used to fix the dark matter mass to be  $\sim 1$  GeV, which turns out to come with the necessary free-streaming scale to suppress small scale structures of the Universe. Alternatively, the need for a sub Mpc free-streaming scale can be used to argue for a GeV scale dark matter, with which the  $\Omega_{\text{DM}}$  is naturally close to the  $\Omega_b$ .

## THE MODEL

The basic idea in [11] is that the dark matter  $S$  is produced non-thermally from the decay of a heavy messenger particle  $X$ , which carries the baryon number and compensates for the baryon asymmetry in the Universe. Both  $S$  and  $X$ , which we call the dark sector, are assumed to be charged under a  $Z_2$  symmetry, the  $T$ -parity, while

the whole standard model is  $T$ -even. The dark matter  $S$  is then a stable particle being the lightest  $T$ -odd particle (LTP). At the time of baryogenesis, we assume that the  $B-L$  number is distributed between the  $T$ -even and  $T$ -odd sectors, resulting in the following relation:

$$n_{B-L}^{\text{SM}} = -n_{B-L}^X = -q_{B-L}(n_X - n_{\bar{X}}), \quad (1)$$

where  $q_{B-L}$  is the  $B-L$  charge of the messenger  $X$ , and  $n_{B-L}^{\text{SM}}$  and  $n_{B-L}^X$  are the  $B-L$  number densities in the standard model and the dark sector, respectively. On the other hand, since both  $X$  and  $\bar{X}$  eventually decay into the LTP, the dark matter candidate  $S$ , its number density is given by the total number of  $X$  and  $\bar{X}$  particles

$$n_{\text{DM}} = n_X^{\text{tot}} \equiv n_X + n_{\bar{X}}, \quad (2)$$

which is independent of the  $n_{B-L}^{\text{SM}}$  in Eq. (1) and would suggest there is *no* connection between the baryonic and dark matter densities, unless  $n_X \gg n_{\bar{X}} \sim 0$  or the other way around. This implies the lifetime of  $X$  should be long enough so that it does not decay until after most of the  $\bar{X}$  particles annihilate with  $X$ , which will be the case if there is no relevant or marginal operator contributing to the decay of  $X$ . Then at temperature  $T < m_X$ , where  $m_X$  is the mass of the messenger, particle  $X$  starts to annihilate with its anti-particle  $\bar{X}$  through gauge interactions and we are left with an abundance of  $X$ . Consequently,

$$n_{B-L}^{\text{SM}} = -n_{B-L}^X \simeq -q_{B-L} n_{\text{DM}}. \quad (3)$$

This is a very general framework. In [11] we worked out the cosmological constraints, as well as an example and the associated collider phenomenology. The model we are interested here, is that with a singlet scalar dark matter  $S$  and a ‘‘Higgsino’’ messenger  $X$ . Recently it is pointed out [7] that standard model plus Higgsinos achieves gauge coupling unification at around  $10^{14}$  GeV with an accuracy similar to that of the MSSM. At two-loop level, for  $m_X = 1$  TeV this minimal model predicts smaller values of  $\alpha_s$  than measured by  $\mathcal{O}(5\%)$ , whereas larger values are predicted in the MSSM. A GUT scale in the order of  $10^{14}$  GeV is too small for a conventional GUT model due to the constraint from proton decay. One possibility, as discussed in [7], is to embed the setup in extra-dimensional or deconstructed models to lower the string scale down to  $10^{14}$  GeV or so. This has the bonus of resolving the triplet-doublet splitting problem in conventional GUT models. A crucial departure from the model in [7] arises in that there the dark matter is a mixture of the neutral component of the Higgsinos and an extra singlet fermion, which is the usual WIMP scenario, whereas in our model the dark matter comes from non-thermal decays of Higgsinos and has a mass which will be determined to be in the GeV range.

The scenario proceeds in three stages. In the first stage, baryogenesis is achieved by the out-of-equilibrium,

CP-violating decay of a  $T$ -odd scalar particle  $P$  into  $\bar{\ell}_i + X$  and  $\ell_i + \bar{X}$ , where  $\ell_i$  is the lepton doublet in the  $i$ th generation in the standard model. CP violation enters through the phases in the Yukawa couplings of the  $P$  with  $\ell_i$  and  $X$  if there are more than one  $P$ 's. So at one loop one obtains an asymmetry proportional to the imaginary parts of the Yukawa couplings of the  $P$ 's. After the  $P$ 's drop out of the thermal equilibrium, we are left with an asymmetry in lepton number in the standard model. Note that this mechanism is reminiscent of the leptogenesis [12], in which  $P$  is a heavy neutrino and  $X$  is the ordinary scalar Higgs. The effective  $B-L$  number of  $X$  in Eq. (1) is determined to be  $q_{B-L} = -1$ .

The second stage is the complete annihilation of the Higgsino with its anti-particles. This constrains the mass of the messenger particle  $m_X$  so that  $n_X \gg n_{\bar{X}} \sim 0$ . The thermally averaged cross section is estimated to be  $g^4/(256\pi m_X^2)$  for  $s$ -wave annihilations into  $SU(2)$  gauge bosons which gives an upper bound on  $m_X$ :

$$m_X \ll 150 \text{ TeV} \left( \frac{1 \text{ GeV}}{m_S} \right). \quad (4)$$

However, in order to establish the connection between the baryon and dark matter number densities,  $n_{B-L}^{\text{SM}} \sim -q_{B-L} n_{\text{DM}}$ ,  $m_X$  is preferred to be much lower than the upper bound [11]. Moreover, a heavy  $X$  spoils the gauge coupling unification. We found that, increasing  $m_X$  from 1 TeV to 100 TeV, the accuracy is worsened by  $\mathcal{O}(1\%)$ . On the other hand, the lower bounds on  $m_X$  simply come from direct searches of new fermions which is about 100 GeV. Therefore it is quite natural for the messenger particle to have a mass in the  $\mathcal{O}(\text{TeV})$  range.

The third stage is the late time decay of the Higgsinos into the dark matter. The decay has to occur before the big bang nucleosynthesis (BBN), and after the completion of the pair annihilation, as previously explained, which requires the Higgsino to survive long after it falls out of thermal equilibrium:

$$10 \text{ MeV} \lesssim T_d \ll \frac{m_X}{20}, \quad (5)$$

where  $T_d$  is the temperature at which  $X$  decays. The long lifetime can be realized by assuming that  $X$  only decays through a dimension five operator

$$\mathcal{O}_{\text{decay}} = \frac{1}{M} (XS)(He_i^c), \quad (6)$$

where  $H$  is the scalar Higgs and  $e_i^c$  is the right-handed charged lepton in the  $i$ th generation. The above bounds on  $T_d$  translate into bounds on  $M$ :

$$10^{10} \text{ GeV} \left( \frac{m_X}{1 \text{ TeV}} \right)^{1/2} \ll M \lesssim 10^{14} \text{ GeV} \left( \frac{m_X}{1 \text{ TeV}} \right)^{3/2}. \quad (7)$$

If we assume that the particle responsible for baryogenesis,  $P$ , is thermally produced, the reheating temperature

of the Universe is restricted to be

$$m_X \leq m_P \lesssim T_R \lesssim 1 \text{ TeV} \left( \frac{M}{10^{14} \text{ GeV}} \right)^2, \quad (8)$$

where the upper bound comes from the requirement that the thermally produced  $S$  through the operator in Eq. (6) is less significant than the non-thermal component. Eq. (8) gives a stronger lower bound on  $M$ :  $10^{14} \text{ GeV} (m_X/1 \text{ TeV})^{1/2}$ . Therefore, to be consistent with Eq. (7), we need  $m_X \gtrsim 1 \text{ TeV}$ . For example, if  $m_X \sim 10 \text{ TeV}$ ,  $M$  can be  $\sim 3 \times 10^{14-15} \text{ GeV}$  and the reheating temperature could be  $10 - 10^3 \text{ TeV}$ . We emphasize that the lower bound in Eq. (8) depends on the assumption that the  $P$  particle is thermally produced. In a scenario where  $P$  dominates the energy density of the Universe and then decays into  $X$  and radiation,  $T_R$  can be much smaller than  $m_X$ . Then  $m_X$  is bounded below only by direct searches.

From the discussions above, we see that it is quite natural to identify  $M$  with  $M_{\text{GUT}} \sim 10^{14} \text{ GeV}$ . In this case, the decay temperature  $T_d$  is just before the BBN,  $T_d \sim 10 \text{ MeV}$ , for  $m_X \sim 1 \text{ TeV}$ . A priori it is not clear at all that the cosmological bounds on  $M$  should be consistent with the GUT scale  $\sim 10^{14} \text{ GeV}$  in our model. For example, if the messenger were to decay through a dimension six operator, then the bounds on  $M$  would lie between  $10^8$  and  $10^9 \text{ GeV}$  [11], which would make the identification with  $M_{\text{GUT}}$  less convincing.

There are in fact two dangerous marginal operators allowed by  $T$ -parity:  $\mathcal{O}_4 = \bar{\ell}_i X S$ , which contributes to the Higgsino decay, and  $\mathcal{O}'_4 = S S H^\dagger H$ , which could thermally produce  $S$ . The first one, being a Yukawa-type coupling, will be absent if we set the initial value at  $M_{\text{GUT}}$  to zero, which we will do. The second one can be fine-tuned away, since we are not motivated by naturalness principle. In fact, if we extend the model a little bit by using a complex scalar for  $S$ , then  $\mathcal{O}_4$  is forbidden by a  $Z_3$  symmetry under which both  $S$  and  $X$  have unit charge. Then the Higgsinos decay through  $\bar{X} \ell S S$ . (Another dangerous operator,  $\bar{X} \ell S^\dagger$ , can be forbidden by a  $Z_2$  symmetry under which  $X$  is even and  $S$  is odd.) In addition,  $\mathcal{O}'_4 = S S^\dagger H H^\dagger$  is generated radiatively with a coefficient suppressed by lepton Yukawa couplings, thus alleviating the fine-tuning. In any case, the scalar masses, the Higgs and the dark matter, are fine-tuned.

Note that even though  $X$  decays into dark matter plus leptons, the excess in lepton number doesn't get converted into the baryon number because the decay always happens after the electroweak phase transition [11] and the sphaleron process is ineffective. We then obtain the number densities  $n_B$  and  $n_{\text{DM}}$  as follows:

$$n_B = \epsilon n_{B-L}^{\text{SM}}, \quad n_{\text{DM}} = |n_{B-L}^{\text{SM}}|, \quad (9)$$

where the efficiency  $\epsilon$  is the relation between the  $B-L$  number and the baryon asymmetry in the presence of the

sphaleron process. It is different from the standard model value [13], now that the presence of  $X$  modifies the charge neutrality conditions, and calculated to be 25/79 with the additional constraint that the total  $(B-L)$  number is zero before the decay of  $X$ . Therefore the ratio of the baryonic and dark matter densities  $\Omega_{\text{DM}}/\Omega_b$  is given by

$$\frac{\Omega_{\text{DM}}}{\Omega_b} = 3.16 \frac{m_{\text{DM}}}{m_p}, \quad (10)$$

from Eq. (9), where  $m_p$  is the proton mass. The measured ratio is  $\Omega_{\text{DM}}/\Omega_b \sim 5.1$  which implies  $m_{\text{DM}} \sim 1.6 m_p = 1.5 \text{ GeV}$ . Eq. (10) is a central prediction of our model: the baryonic mass density in our Universe will be close to the dark matter density if the dark matter has a mass close to the nucleon mass. Indeed, we will see that considerations from reducing the small scale structure of the Universe prefers light dark matter,  $\mathcal{O}(\text{GeV})$ , showing a non-trivial consistency in this framework.

## COSMOLOGY

The cosmology with a dark matter candidate arising from non-thermal decays is very interesting. In the  $\Lambda$ CDM model the dark matter decouples from the thermal bath while being non-relativistic and has a velocity distribution peaked at around zero at the time of structure formation. In other words, the momentum profile is Maxwellian. On the other hand, the non-thermal dark matter (NTDM) is relativistic when produced through decays of the messenger particle and its momentum distribution is peaked at  $m_X/2$ , which subsequently gets red-shifted by the expanding Universe and becomes non-relativistic.

Such a primordial velocity dispersion has important implications in structure formation, as the dark matter can smooth out inhomogeneities by streaming out of overdense regions and into underdense regions, the so-called Landau damping [14], which is characterized by the free-streaming scale  $\lambda_{\text{FS}}$ . By definition cold dark matter has a small  $\lambda_{\text{FS}}$  that is irrelevant for structure formation, whereas hot dark matter,  $\lambda_{\text{FS}} \gtrsim 40 \text{ Mpc}$ , has such a large free-streaming scale that would prevent galaxy formation in the early epoch. So far observations on large scale structures clearly prefers a dark matter candidate that is cold, and hence the  $\Lambda$ CDM model. Nevertheless, as mentioned, on small scales (sub Mpc) simulations of CDM seems to be at odds with observations. First, the substructure of CDM halos is predicted to be richer than observed. Second, the simulated density profiles of dark matter halos are generally cuspier than inferred from rotation curves. At this moment it is not clear if this is indeed a failure of the  $\Lambda$ CDM model, as there are complex issues with large N-body and hydrodynamics simulations.

These discrepancies do not diminish the tremendous successes of the  $\Lambda$ CDM model on larger scales, however, if these problems are real, they present a great opportunity. The simplest known mechanism for smoothing out small scale structures is the Landau damping. In this regard a popular candidate is the WDM, hot dark matter cooled down, which has a free-streaming scale [10]

$$\lambda_{\text{FS}} = 0.2 (\Omega_{\text{WDM}} h^2)^{\frac{1}{3}} \left( \frac{m_{\text{WDM}}}{\text{keV}} \right)^{-\frac{4}{3}} \text{ Mpc}. \quad (11)$$

Observed properties of Lyman  $\alpha$  forest constrain the power spectrum at small scales and therefore put a lower bound on the mass of the WDM [15]:  $m_{\text{WDM}} \geq 750 \text{ eV}$ , which translates into  $\lambda_{\text{FS}} \leq 0.16 \text{ Mpc}$  for  $\Omega_{\text{WDM}} h^2 = 0.15$ . (A more recent analysis puts a weaker bound:  $m_{\text{WDM}} \geq 550 \text{ eV}$  [16].) Furthermore, high-resolution cosmological N-body simulations seem to find better agreements with observations for  $\lambda_{\text{FS}} \sim 0.1 \text{ Mpc}$  [17]. For comparison, we can calculate the free-streaming scale for the NTDM in our case [14],

$$\begin{aligned} \lambda_{\text{FS}} &= \int_{t_{\text{decay}}}^{t_{\text{EQ}}} \frac{v(t)}{a(t)} dt \simeq \int_0^{t_{\text{EQ}}} \frac{v(t)}{a(t)} dt \\ &\simeq 0.16 \left( \frac{m_X}{3 \text{ TeV}} \right) \left( \frac{\text{GeV}}{m_S} \right) \left( \frac{10 \text{ MeV}}{T_d} \right) \text{ Mpc}, \end{aligned} \quad (12)$$

where  $v(t)$  and  $a(t)$  are the physical velocity and the FRW scale factor, respectively, of the NTDM at time  $t$ , and  $t_{\text{EQ}}$  denotes the time for matter-radiation equality. Therefore, for a prototypical  $m_X/m_S/T_d = 3 \text{ TeV}/1 \text{ GeV}/10 \text{ MeV}$  scenario that is well-motivated from previous discussions, the NTDM is able to produce enough power on the small scales to be consistent with the Lyman  $\alpha$  forest data and potentially resolve the discrepancies mentioned above. There are also constraints coming from studies of phase space density [18], which are weaker than those coming from Lyman  $\alpha$  forest [19].

On the other hand, the NTDM is not exactly the same as the WDM, since they still have different momentum distributions. As an example, power spectrum of non-thermal production of neutralinos by the decay of topological defects was considered in [19] and found to be different from that of a  $1 \text{ keV}$  WDM for  $k > 5 h \text{ Mpc}^{-1}$ .

## SUMMARY

Using gauge coupling unification and cosmology as the main hints for physics beyond the standard model, we have considered a minimal GUT model which attributes a common origin to the baryon asymmetry and the dark matter, giving similar number densities to both the dark matter and the baryon. The dark matter, a singlet scalar, is produced by non-thermal decays of a messenger particle, the Higgsinos, whose existence implies the unification at  $\sim 10^{14} \text{ GeV}$ . There are checks

on the the model from several orthogonal directions. Cosmological bounds point to a Higgsino in the TeV range and a mass scale consistent with the GUT. The ratio  $\Omega_{\text{DM}}/\Omega_b$  can be used to determine the mass of the dark matter to be GeV, which in turn gives a sub Mpc free-streaming scale consistent with observations and, at the same time, has the potential of resolving the  $\Lambda$ CDM crisis by reducing the power spectrum on small scales. Cosmology may be the best arena to test this model. The Higgsinos, on the other hand, might be too heavy to be discovered in the coming collider experiments.

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