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Asymmetric dark matter, baryon asymmetry and lepton number violation

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ABSTRACT

We study the effect of lepton number violation (LNV) on baryon asymmetry, generated in the early Universe, in the presence of a dark sector with a global symmetry $U(1)_X$, featuring asymmetric dark matter (ADM). We show that in general LNV, observable at the LHC or in neutrinoless double beta decay experiments, cannot wash out a baryon asymmetry generated at higher scales, unlike in scenarios without such dark sector. An observation of LNV at the TeV scale may thus support ADM scenarios. Considering several models with different types of dark matter (DM), we find that the DM mass is of the order of a few GeV or below in our scenario.

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1. Introduction

Both, the cogent astrophysical evidence for DM and the baryon asymmetry of the Universe, call for the existence of new physics beyond the Standard Model (SM). Interestingly, the fractions of the critical density ρ_c of the Universe in baryons and DM are rather close [1,2]:

$$\Omega_B h^2 = 0.02226 \pm 0.00023 \text{ and } \Omega_{\text{DM}} h^2 = 0.1186 \pm 0.0020, \quad (1)$$

corresponding to

$$\Omega_{\text{DM}} \simeq 5.3 \Omega_B, \quad (2)$$

where $h = 0.68$ is the scale factor for the Hubble expansion rate [2]. This coincidence might hint at a relation between the production mechanisms of the baryon asymmetry and the observed DM relic abundance. Such a relation can be realized in the context of ADM scenarios [3], see Refs. [4,5] for recent reviews. Within this framework, either DM particles or antiparticles remain in the Universe due to an asymmetry, similar to the one among baryons and antibaryons. To distinguish between DM particles and antiparticles

requires the existence of a conserved global quantum number X in the dark sector. Then, an X asymmetry results in an asymmetry among the number of DM particles and antiparticles. This can be realized, if e.g. the dark sector possesses a global symmetry $U(1)_X$.

The explanation of neutrino masses also requires physics beyond the SM. Most of the mechanisms, giving mass to neutrinos, assume that they are Majorana particles and thus lepton number (L) to be violated by two units [6–15]. Leptogenesis is a prominent mechanism for generating the baryon asymmetry [16], see Refs. [17–23] for recent reviews, which is based on LNV processes efficient at high energy scales. A positive signal in neutrinoless double beta ($0\nu\beta\beta$) decay experiments would be a sign of LNV and prove the Majorana nature of neutrinos, see Refs. [24–26] for recent reviews. As shown in Refs. [27,28], if $0\nu\beta\beta$ decay is due to light neutrino masses, such LNV corresponds to washout effects of the L asymmetry that are efficient only for temperatures $T \gtrsim 10^{11}$ GeV.

As emphasized recently in Refs. [27–29], any future observation of LNV, such as same-sign dilepton signals at the LHC [29] and contributions to $0\nu\beta\beta$ decay due to new particles with masses around the TeV scale [27,28], will imply LNV processes efficient at temperatures $T \sim 1$ TeV. These in combination with SM sphaleron processes [30,31], that violate $(B + L)$ and are efficient above the sphaleron decoupling temperature T_{sph} , can lead to the washout of both baryon number (B) and L asymmetries [32]. Consequently, a future discovery of LNV processes can falsify mechanisms of

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high-scale baryogenesis and leptogenesis. Typical models which lead to such LNV processes are radiative neutrino mass models [33, 34].

We therefore investigate the impact of LNV processes, efficient at $T \sim 1$ TeV, on particle–antiparticle asymmetries in the dark and the visible sectors in ADM scenarios, where B and X asymmetries are correlated. We focus on LNV processes that violate L by two units. We discuss several models with a symmetry $U(1)_X$ in the dark sector. DM can be a scalar or a fermion, it can be an elementary particle or a composite state and there might exist more than one species of DM. We find that in all models it is possible to preserve B and X asymmetries, even in the presence of LNV processes at temperatures $T \sim 1$ TeV. We can identify two classes of models: those in which the dark sector changes the condition for hypercharge ($U(1)_Y$) neutrality of the Universe [32,35] and those in which the dark sector also modifies SM sphaleron processes [36]. The latter implies a transfer of the particle–antiparticle asymmetries between the dark and the visible sectors. Taking into account LNV processes, efficient at $T \sim 1$ TeV, further constrains the allowed range for the DM mass and requires it to be lower than a few GeV in the models considered, if the ratio of Ω_{DM} and Ω_B in Eq. (2) should be correctly reproduced.

This paper is organized as follows: In section 2, we list the equations relevant for the different chemical potentials, discuss the features which are necessary for preventing the washout of the different asymmetries through LNV processes, and then analyze the correlation between the different asymmetries in a model-independent way. In particular, we show that LNV processes further constrain the DM mass. In sections 3 and 4 we discuss concrete examples, where either the condition for hypercharge neutrality or also SM sphaleron processes are modified through the dark sector, and calculate the correlation between the different asymmetries as well as the upper limit on the DM mass, arising if LNV processes are also considered. We summarize our findings and conclude in section 5.

2. General framework

The following analysis is carried out for temperatures above the electroweak phase transition (EWPT). All statements are valid for situations in which B , L and X asymmetries are exclusively generated above the electroweak (EW) scale. The origin of the asymmetries is not specified. They might, for example, be dynamically generated in the early Universe via some unknown new physics [37]. We focus on ADM scenarios, where Ω_{DM} is only due to the asymmetric component. This can be justified, if there exists a mechanism, such as the exchange of a light gauge boson or the Sommerfeld enhancement [38], efficient enough to annihilate the symmetric component.

We first mention the equations relevant for the different chemical potentials and discuss the features, necessary for preventing the washout of the different asymmetries through LNV processes, efficient at temperatures $T \sim 1$ TeV. In a second step, we analyze the correlation between the different asymmetries in a model-independent way and show the additional constraints on the DM mass arising from the presence of LNV processes.

2.1. Conditions on chemical potentials

Above the EWPT, the SM Yukawa interactions and SM sphaleron processes are in thermal equilibrium and the total hypercharge vanishes. Thus, the following relations for the chemical potentials μ_i hold [32]:

$$\begin{aligned} -\mu_q + \mu_H + \mu_{d_R} &= 0, & -\mu_q - \mu_H + \mu_{u_R} &= 0, \\ -\mu_\ell + \mu_H + \mu_{e_R} &= 0, & 3(3\mu_q + \mu_\ell) &= 0, \\ 3\mu_q + 6\mu_{u_R} - 3\mu_{d_R} - 3\mu_\ell - 3\mu_{e_R} + 2\mu_H &= 0. \end{aligned} \quad (3)$$

Here, the index i denotes the SM particles: q (left-handed quark doublet), u_R (right-handed u -quark), d_R (right-handed d -quark), ℓ (left-handed lepton doublet), e_R (right-handed charged lepton) and H (Higgs doublet). The first three conditions originate from the SM Yukawa interactions, while the fourth and fifth conditions correspond to the SM sphaleron processes and hypercharge neutrality of the Universe, respectively. Since we focus on temperatures above the EWPT, hypercharge neutrality is required instead of electric charge neutrality, and both components of a left-handed doublet have the same chemical potential. For simplicity, we assume that the chemical potentials of the three generations of quarks and leptons are the same, respectively. In particular, non-vanishing off-diagonal elements of the quark mixing matrix and efficient EW interactions are responsible for the B asymmetry being equally shared by the three quark generations. In total, there are six chemical potentials and five constraints, leading to one free parameter, which can be chosen as μ_ℓ . As a result, both B and L asymmetries can be expressed in terms of μ_ℓ [30], see Eq. (11).

Once an LNV process, efficient at temperatures $T \sim 1$ TeV, is introduced, this leads to an additional condition for the chemical potentials, i.e., a sixth constraint (linearly independent of the ones in Eq. (3)), which implies $\mu_\ell = 0$ and hence a washout resulting in vanishing B and L asymmetries [32]. It is worthwhile to mention that all operators which violate L by two units, that are responsible for e.g. Majorana neutrino masses and $0\nu\beta\beta$ decay, listed in Refs. [14,15], yield exactly the same constraint:

$$\mu_\ell + \mu_H = 0. \quad (4)$$

This constraint also follows from the Weinberg operator $(\ell H)^2$. However, in order to correctly produce the light neutrino mass scale the coupling of the Weinberg operator needs to be very small so that it is not effective and thus no further condition for the chemical potentials has to be added. As sphaleron processes are not efficient at converting B and L asymmetries in the SM during or below the EWPT, this washout of the L asymmetry does not imply the washout of the B asymmetry.

As $0\nu\beta\beta$ decay only involves electrons in the final state, an operator giving rise to this process is flavor-sensitive, i.e. it can only lead to the washout of the L asymmetry stored in the electron, but not in the muon or tau flavor. However, if lepton flavor is violated at the same time as L , the total L asymmetry, stored in all flavors, will be entirely erased. Throughout this analysis, we assume that also lepton flavor is violated so that the L asymmetry is equally distributed among the three lepton generations.

In ADM scenarios, the dark sector possesses a global symmetry $U(1)_X$ and an X asymmetry results in an asymmetry among the number of DM particles and antiparticles. If at least some particles of the dark sector transform in a non-trivial way under the SM gauge group $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$, a correlation between the asymmetries in the dark and the visible sectors is induced. The simplest option to consider is one in which particles of the dark sector only carry hypercharge and a charge under the global symmetry $U(1)_X$. Then, only the condition for hypercharge neutrality is modified. The dark and the visible sectors are in contact through Yukawa interactions, see Eq. (19). In this way, a transfer between the asymmetries of the dark and visible sectors is possible. As shown in section 3, in the most minimal scenario the dark sector contains two types of particles, the DM particle and the one also charged under $U(1)_Y$. In this case eight chemical potentials have to fulfill six conditions, the first four conditions displayed

in Eq. (3), the modified condition for hypercharge neutrality, see Eq. (21), and the condition due to the interaction connecting the dark and the visible sectors, see Eq. (20). Thus, two chemical potentials remain as free parameters. If, in addition, L is violated by two units through processes, efficient at temperatures $T \sim 1\text{TeV}$, in this scenario, the condition in Eq. (4) has to be fulfilled, and thus one of the two free parameters becomes fixed. B , L and X asymmetries are in turn proportional to the remaining free parameter and, in particular, are in general non-vanishing.

Another example is the model in Ref. [36] where fermions F of the dark sector transform as doublets under $SU(2)_L$ and are charged under $U(1)_X$. In this case the SM sphaleron processes are modified and the corresponding condition for the chemical potentials reads:

$$3(3\mu_q + \mu_\ell) + n_F\mu_F = 0, \quad (5)$$

where n_F is the number of generations of F and μ_F the chemical potential of F . As a consequence, an X asymmetry in the dark sector, proportional to μ_F , becomes related to B and L asymmetries in the visible sector and the transfer of asymmetries between the dark and the visible sectors is enabled. For simplicity, the decoupling temperature of the modified sphaleron processes is assumed to be similar to the one of the SM sphaleron processes. In general, not only the sphaleron processes are modified in such scenarios, but also the condition, derived from hypercharge neutrality, as particles of the dark sector also carry hypercharge. As discussed in section 4, the conditions due to Yukawa interactions, sphaleron processes, hypercharge neutrality and interactions involving only the dark sector leave two of the chemical potentials as free parameters. Thus, including interactions which violate L by two units reduces the number of free parameters to one and thus correlates B , L and X asymmetries, but still allows them to be non-zero. Instead of LNV interactions one can also consider other constraints leading to one additional condition on the chemical potentials. One example is the preservation of $(B-L)$, as pointed out in Ref. [39]. In this scenario a B asymmetry can thus be produced even without the violation of $(B-L)$. As is clear, the simultaneous presence of both, LNV interactions, efficient at temperatures $T \sim 1\text{TeV}$, and the preservation of $(B-L)$, would lead to the vanishing of all asymmetries, since then all chemical potentials would become fixed.

In cases where the dark sector only contains the DM particle χ and an interaction between the dark and the visible sectors, including the neutrino [40,41] and neutron [40,42] portal

$$\chi^2(\ell H)^2, \quad \chi d_R d_R u_R \text{ (or } \chi^2 d_R d_R u_R), \quad (6)$$

transfers asymmetries between the two sectors, a B asymmetry will be washed out by LNV processes, efficient at temperatures $T \sim 1\text{TeV}$. Both, the latter and the interaction between the dark and the visible sectors, imply an extra condition for the chemical potentials, while the conditions in Eq. (3) are still valid. So, in total seven conditions have to be fulfilled by the seven chemical potentials of SM particles and χ , meaning that these in general have to vanish. As a consequence, not only the asymmetries in the visible sector are erased by LNV processes, but also any X asymmetry such that the ADM scenario becomes invalidated as well.

We would like to point out that the previous arguments are based on the assumption that all interactions, including the Yukawa interactions, sphaleron processes, interactions between the dark and the visible sectors and LNV processes, are simultaneously in thermal equilibrium. If, for example, a certain Yukawa coupling is too small to be effective at the time, when sphaleron processes are efficient, or the interactions between the dark and the visible sectors decouple before the sphaleron processes become operative, the asymmetries of the two sectors can still be correlated even

in the presence of LNV processes. Examples for these cases can be found in Refs. [43] and [35]. In Ref. [43] a model is considered with an additional $SU(2)$ gauge symmetry leading to new sphaleron processes. It is essential that some of the Yukawa couplings are small in order not to destroy the X asymmetry. In the model in Ref. [35] a new charged particle, being part of the dark sector, is added to the SM. Then, an asymmetry in the dark sector entails a B asymmetry, if the asymmetry in the dark sector is generated after the interaction of the new charged particle with the visible sector (needed for it to decay into three charged leptons) becomes ineffective, but above the sphaleron decoupling temperature T_{sph} . Before studying the correlation between B , L and X asymmetries in concrete ADM scenarios without and with LNV processes, that violate L by two units, in sections 3 and 4, we discuss the correlation between the different asymmetries in a model-independent way in the following subsection.

2.2. Correlation of asymmetries

In the following, we consider a theory with the SM and a dark sector, charged under a global symmetry $U(1)_X$. X is a new quantum number, assumed to be different from B , L and $B-L$. In order to be as model-independent as possible, we only require that some of the particles of the dark sector have EW interactions, such that the conditions corresponding to SM sphaleron processes and/or hypercharge neutrality of the Universe, see Eq. (3), are modified. We further assume that the lightest particle χ in the dark sector, the DM particle, is neutral and stable. Its stability is guaranteed by the global symmetry $U(1)_X$.¹ For simplicity, we consider only one species of DM particles in the following. Based on the assumptions made in the preceding subsection, the particles remaining in thermal equilibrium above the sphaleron decoupling temperature, which in the SM is $T_{\text{sph}} \approx 135\text{GeV}$ [44], are all SM particles and (elementary) scalars and fermions of the dark sector. Their chemical potentials can be expressed in terms of two of them. This is equivalent to expressing the different asymmetries as a linear combination of two of them. We choose these in the following as $(B-L)$ and X asymmetry which are denoted by $\Delta(B-L)$ and ΔX . We define B and L asymmetries as well as $\Delta(B-L)$ taking into account only SM particles.

The observed baryon asymmetry, $Y_{\Delta B} = (8.65 \pm 0.09) \times 10^{-11}$ [1,2], can be written as

$$Y_{\Delta B} = a_1 Y_{\Delta(B-L)} + a_2 Y_{\Delta X}, \quad (7)$$

with $a_2 \neq 0$ and $a_1 \neq 1$. The second inequality, $a_1 \neq 1$, implies that there is no direct proportionality *ab initio* between the L asymmetry ΔL and ΔX . Alternatively, one can express $\Delta(B-L)$ as a function of the B asymmetry ΔB and ΔL

$$Y_{\Delta(B-L)} = \frac{a_2}{1-a_1} Y_{\Delta X} - \frac{1}{1-a_1} Y_{\Delta L}. \quad (8)$$

As ΔB and ΔL refer only to the SM particles, they are defined, in terms of the quark and lepton chemical potentials, as

$$Y_{\Delta B} = \frac{45}{4\pi^2 g_\star} (2\mu_q + \mu_{u_R} + \mu_{d_R}), \quad (9)$$

$$Y_{\Delta L} = \frac{45}{4\pi^2 g_\star} (2\mu_\ell + \mu_{e_R}), \quad (10)$$

where g_\star as a function of T counts the total number of relativistic degrees of freedom in the thermal plasma. If only SM particles are

¹ It could be also a discrete subgroup of $U(1)_X$ or another symmetry responsible for the stability of χ .

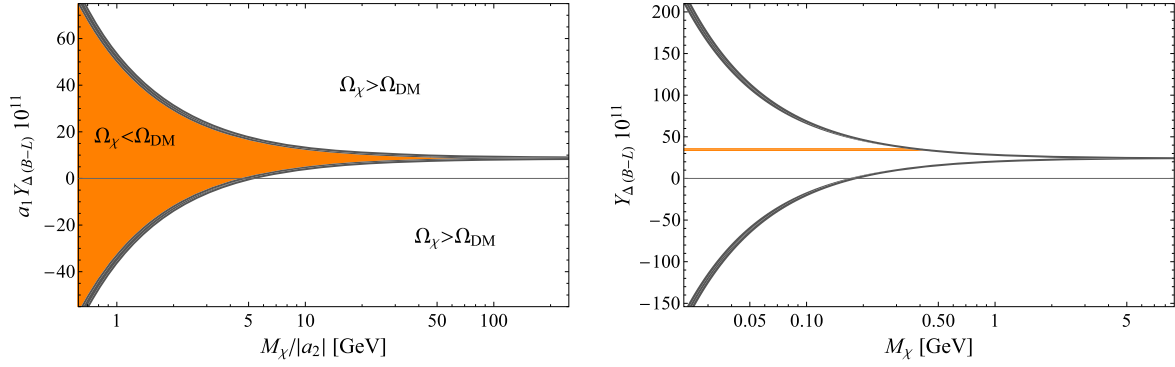


Fig. 1. Left panel. The upper limit on the DM mass M_χ , Eq. (15), for arbitrary choices of a_1 and $|a_2|$. The black thick curves correspond to $\Omega_{\text{DM}} h^2 = 0.1186 \pm 0.0040$ (95% CL). In the entire plane $Y_{\Delta B}$ matches the observed value at the 95% CL. The two regions with $\Omega_\chi > \Omega_{\text{DM}}$ are excluded. **Right panel.** The allowed region $\Omega_\chi \leq \Omega_{\text{DM}}$ (thick orange line) in the plane $Y_{\Delta(B-L)}$ vs M_χ , evaluated for one particular model with $a_1 = 5/14$, $a_2 = -1/28$ and $a_3 = 7$, see Table 1 and section 3, if LNV processes, that violate L by two units, are efficient at temperatures $T \sim 1$ TeV. (For interpretation of the colors in the figure, the reader is referred to the web version of this article.)

in thermal equilibrium at $T \gtrsim T_{\text{sph}}$, we have $a_{2,\text{SM}} = 0$ and $g_\star = 106.75$. We can derive

$$Y_{\Delta B} = -\frac{15}{\pi^2 g_\star} \mu_\ell \quad \text{and} \quad Y_{\Delta L} = \frac{17}{7} \frac{45}{4\pi^2 g_\star} \mu_\ell, \quad (11)$$

from Eq. (3) which implies $a_{1,\text{SM}} = 28/79$, as is well-known.

Similar to Eq. (9), the yield $Y_{\Delta X}$ of the dark sector is given by the sum of the yields $Y_{\Delta i}$ of all particle species i , including the DM particle χ , carrying a non-zero $U(1)_X$ charge,

$$Y_{\Delta i}(z_i) = \frac{15 g_i}{4\pi^2 g_\star} \mu_i \zeta(z_i), \quad (12)$$

where g_i denotes the internal degrees of freedom of the particle i (e.g., spin and gauge multiplicities), μ_i is the chemical potential and $z_i = M_i/T$ with M_i being the mass of particle i and T the temperature of the plasma. The function $\zeta(z)$ depends on the particle statistics and is given by

$$\zeta(z_i) = \frac{6}{\pi^2} \int_{z_i}^{\infty} dx x \sqrt{x^2 - z_i^2} \frac{e^x}{(e^x - \eta_i)^2}, \quad (13)$$

with $\eta_i = 1$ (-1) for a boson (fermion). For a relativistic boson (fermion) with $z_i \ll 1$, we have $\zeta(z_i) \approx 2$ (1). Notice that the relation in Eq. (12) is valid under the assumption that the number density asymmetry of the particle in the early Universe is much smaller than its equilibrium number density, that is $\mu_i/T \ll 1$. For simplicity, we assume that g_\star is always very close to the value of the SM.

The precise values of the coefficients a_1 and a_2 in Eq. (7) are model-dependent, see Table 1 and sections 3 and 4. They are found by solving the system of conditions for the chemical potentials of all particles in the dark and the visible sectors. If an asymmetry ΔB , ΔL or ΔX is created, it will be re-shuffled due to Yukawa interactions and sphaleron processes. How it is exactly re-distributed among ΔB , ΔL and ΔX is encoded in a_1 and a_2 in Eq. (7).

Using Eq. (7) one can derive a correlation between the fraction Ω_B of ρ_c in baryons and the fraction Ω_χ in the DM particle χ

$$\Omega_B = a_1 M_p \frac{s Y_{\Delta(B-L)}}{\rho_c} + a_2 \frac{M_p}{M_\chi} \Omega_\chi, \quad (14)$$

where M_p and M_χ denote the proton and DM mass, respectively. Here, s is the entropy density and as numerical values of M_p and ρ_c we use $M_p = 938.27$ MeV and $\rho_c = 1.88 \times 10^{-26} h^2 \text{ kg/m}^3$. The fraction Ω_χ is defined as $\Omega_\chi \equiv M_\chi (n_\chi - n_{\bar{\chi}})/\rho_c$ with n_χ and $n_{\bar{\chi}}$

being the number densities of DM particles and antiparticles, respectively. From the phenomenological constraint $\Omega_\chi \leq \Omega_{\text{DM}}$, one can derive an upper limit on M_χ :

$$M_\chi \leq M_p \frac{|a_2|}{\left|1 - a_1 \frac{Y_{\Delta(B-L)}}{Y_{\Delta B}}\right|} \frac{\Omega_{\text{DM}}}{\Omega_B}. \quad (15)$$

If we assume that χ makes up all DM, equality holds. The asymmetry $Y_{\Delta(B-L)}$ and the coefficients $a_{1,2}$ in Eq. (15) are evaluated at the sphaleron decoupling temperature T_{sph} . As one can see, the requirement of correctly reproducing the observed value of Ω_B constrains both, the DM mass M_χ and the requisite amount of asymmetry $Y_{\Delta(B-L)}$ (or $Y_{\Delta L}$), to be generated by some mechanism. In Ref. [45] a relation similar to the one in Eq. (15) has been obtained in a specific model where a generalized baryon number is gauged, see section 4 for further details, in particular Eq. (29).

In Fig. 1 (left panel) we display, for arbitrary values of a_1 and $|a_2|$, the allowed region, $\Omega_\chi \leq \Omega_{\text{DM}}$ in orange, while the black thick curves indicate the values of M_χ and $Y_{\Delta(B-L)}$ which saturate the upper limit in Eq. (15). For $M_\chi \gtrsim 50 |a_2| \text{ GeV}$ this requires a fine-tuned value of $Y_{\Delta(B-L)} \approx 9 \times 10^{-11}/a_1$. The thickness of the black curves corresponds to the 95% CL allowed regions for Ω_B and Ω_{DM} , see Eq. (1). The two regions corresponding to $\Omega_\chi > \Omega_{\text{DM}}$ are excluded, unless Ω_χ is diluted at $T < T_{\text{sph}}$ via new entropy injection as demonstrated in, e.g., Ref. [46]. Notice that the observed value of $Y_{\Delta B}$ can be reproduced, even if $(B-L)$ is conserved in the early Universe, i.e. $Y_{\Delta(B-L)} = 0$. In this particular case, the asymmetries of DM particles and baryons are directly proportional, as has been realized in Ref. [39].

Now we assume that LNV processes that violate L by two units are efficient at temperatures $T \sim 1$ TeV. As argued in section 2.1, these lead to one additional condition to be fulfilled by the chemical potentials, see Eq. (4), which reduces the number of free parameters among the chemical potentials to one. Consequently, the asymmetries ΔL and ΔX become proportional to each other

$$Y_{\Delta L} = a_2 a_3 Y_{\Delta X}, \quad (16)$$

with $a_3 \neq 0$. Hence, from Eqs. (7) and (8), we have

$$Y_{\Delta B} = \frac{a_2 (1 - a_1 a_3)}{1 - a_1} Y_{\Delta X}, \quad (17)$$

which in turn implies

$$M_\chi \leq M_p \left| \frac{a_2 (1 - a_1 a_3)}{1 - a_1} \right| \frac{\Omega_{\text{DM}}}{\Omega_B}. \quad (18)$$

Table 1

Prediction of a_1 , a_2 and a_3 in the discussed models. The mass M_χ denotes the upper limit on the mass of the DM particle required to correctly reproduce Ω_{DM} , if LNV processes, that violate L by two units, are present. The minus (plus) sign in a_2 for the SM extended by one additional generation of a complex scalar S and a Dirac fermion F refers to S (F) being the DM particle, given $Q_X = +1$. The parameter \mathcal{B}_2 is the charge of certain dark sector particles under a generalized baryon number and is a free parameter. Both composite models have been endowed with an elementary Higgs H . For details, see sections 3 and 4.

Model	a_1	a_2	a_3	M_χ [GeV]
SM + 1 generation $\{S, F\}$ with charge $Q_X = +1$	$\frac{5}{14}$	$\mp \frac{1}{28}$	7	0.44
Ref. [39]	$\frac{32}{83}$	$-\frac{72}{415}$	$\frac{83}{270}$	1.3
Ref. [45]	$\frac{32}{99}$	$\frac{15-14\mathcal{B}_2}{198}$	$\frac{297(17+2\mathcal{B}_2)}{119(-15+14\mathcal{B}_2)}$	$0.49 2.3 - \mathcal{B}_2 $
Ref. [36] with elementary Higgs H	$\frac{12}{35}$	$-\frac{32}{35}$	$\frac{35}{104}$	6.5
Ref. [47] with elementary Higgs H	$\frac{8}{23}$	$-\frac{21}{46}$	$\frac{23}{63}$	3.2

Again the coefficients a_i are computed at $T = T_{\text{sph}}$, with $1 - a_1 a_3 \neq 0$. Applying Eqs. (16) and (17) to the case of the SM, we have $a_{2,\text{SM}} = 0$ such that the vanishing of B and L asymmetries follows, excluding high-scale baryogenesis and leptogenesis, in accordance with the observations made in Refs. [27–29].

In Fig. 1 (right panel) the allowed region of $\Omega_\chi \leq \Omega_{\text{DM}}$ is shown for a specific choice of a_1 and a_2 , $a_1 = 5/14$ and $a_2 = -1/28$, see Table 1. These values arise in an example, discussed in section 3, where the dark sector consists of one complex scalar S , being the DM particle, and one charged Dirac fermion. If LNV processes, that violate L by two units and that are efficient at temperatures $T \sim 1\text{TeV}$, are present, $a_3 = 7$ and the horizontal orange line in the figure indicates the allowed interval of M_χ and the value of $Y_{\Delta(B-L)}$. In particular, the DM mass is confined to the sub-GeV range, $M_\chi \leq 0.44\text{GeV}$. Low values of M_χ not larger than a few GeV are found in all the discussed ADM scenarios, see Table 1. The latter are discussed, beginning with examples where only the condition for hypercharge neutrality is modified in section 3 and followed by models with elementary and composite particles in section 4 in which also the sphaleron processes are modified.

3. Modification of hypercharge neutrality condition

In this section, we present and discuss a simple example of the case where only the condition for hypercharge neutrality is modified, while sphaleron processes are unchanged with respect to the SM. For this purpose, we consider an extension of the SM with n_F vector-like fermions F_j , and n_S complex scalars S_k . The fermions and scalars mix among each other via mass terms. This mixing leads to common chemical potentials for fermions and scalars, μ_F and μ_S , respectively.² For simplicity, all new particle masses are assumed to be much smaller than the sphaleron decoupling temperature, i.e. $M_{F_j}, m_{S_k} \ll T_{\text{sph}}$. In addition, all particles of the dark sector transform under a global symmetry $U(1)_X$, which guarantees the stability of the lightest one. The lightest particle is neutral and plays the role of the DM candidate. It can be either a fermion or a scalar. All new particles are neutral under $SU(3)_C \otimes SU(2)_L$ and carry the same $U(1)_X$ charge, up to a sign, which we normalize to $Q_X = +1$ so that $X(F_j) = -X(S_k) = 1$. Either F_j or S_k (but not both) is charged under $U(1)_Y$ such that a coupling to right-handed charged leptons $e_{R\alpha}$ is allowed at tree-level

$$\lambda_{jk}^\alpha \bar{F}_{Lj} S_k^* e_{R\alpha}. \quad (19)$$

Here, for each lepton flavor $\alpha = e, \mu, \tau$, λ^α is a complex $n_F \times n_S$ matrix. If λ_{jk}^α is large enough for the Yukawa interactions to be in

thermal equilibrium, this yields a new constraint on the chemical potentials, namely

$$-\mu_F - \mu_S + \mu_{e_R} = 0. \quad (20)$$

The condition for hypercharge neutrality is modified, since one species of particles of the dark sector is charged under $U(1)_Y$. We thus have

$$3\mu_q + 6\mu_{u_R} - 3\mu_{d_R} - 3\mu_\ell - 3\mu_{e_R} + 2\mu_H - 2n_{F(S)}\mu_{F(S)} = 0, \quad (21)$$

in case the fermions (scalars) carry the $U(1)_Y$ charge. The asymmetry $Y_{\Delta X}$ is a function of μ_F and μ_S , see Eq. (12),

$$Y_{\Delta X} = \frac{15}{2\pi^2 g_\star} (n_F \mu_F - n_S \mu_S). \quad (22)$$

Since none of the new particles transforms non-trivially under $SU(2)_L$, SM sphaleron processes, see Eq. (3), are not altered. Taking into account all conditions fulfilled in thermal equilibrium, two chemical potentials remain as free parameters, and we find for the coefficients a_1 and a_2

$$a_1 = 4 \frac{7(n_S + n_F) + n_S n_F}{79(n_S + n_F) + 10n_S n_F} \quad \text{and} \quad (23)$$

$$a_2 = \mp \frac{6n_{F(S)}}{79(n_S + n_F) + 10n_S n_F}.$$

Here, the positive sign and the index S in a_2 correspond to the case with neutral fermions, while the negative sign and the index F refer to the case of neutral scalars. For the special case of $n_F = n_S = 1$, we obtain $a_1 = \frac{5}{14}$ and $a_2 = \mp \frac{1}{28}$, as reported in Table 1 and used in Fig. 1 (right panel).

When introducing LNV processes which violate L by two units, the additional constraint in Eq. (4) has to be included. Consequently, we obtain a correlation between $Y_{\Delta L}$ and $Y_{\Delta X}$, as in Eq. (16), with the coefficient a_3 being

$$a_3 = \frac{79(n_S + n_F) + 10n_S n_F}{11(n_S + n_F) + 2n_S n_F}. \quad (24)$$

For instance, if $n_F = n_S = 1$, one has $a_3 = 7$ which is used in Table 1 and Fig. 1 (right panel). According to Eq. (18), we can set an upper limit on the DM mass M_χ :

$$M_\chi \leq \left(10 \frac{n_{F(S)}}{11(n_S + n_F) + 2n_S n_F} \right) \text{GeV}, \quad (25)$$

for neutral scalars (fermions). For $n_F = n_S = 1$, we find $M_\chi \leq 0.44\text{GeV}$, as reported in Table 1, and the requisite amount of asymmetry $Y_{\Delta(B-L)}$ is displayed in Fig. 1 (right panel).

² Since F_j are vector-like fermions, left-handed and right-handed components have the same chemical potential.

One can straightforwardly generalize these computations to the case of massive fermions F_j and scalars S_k and to cases where $Q_X \neq +1$. The asymmetry $Y_{\Delta X}$, see Eq. (12), is then given by

$$Y_{\Delta X} = \frac{15}{4\pi^2 g_\star} Q_X \left[2\mu_F \sum_{j=1}^{n_F} \zeta \left(\frac{M_{F_j}}{T_{\text{sph}}} \right) - \mu_S \sum_{k=1}^{n_S} \zeta \left(\frac{m_{S_k}}{T_{\text{sph}}} \right) \right] \quad (26)$$

and also the coefficients a_i encode this information, e.g.

$$a_1 = 4 \times \frac{7 \left(\sum_{k=1}^{n_S} \zeta \left(\frac{m_{S_k}}{T_{\text{sph}}} \right) + 2 \sum_{j=1}^{n_F} \zeta \left(\frac{M_{F_j}}{T_{\text{sph}}} \right) \right) + \left(\sum_{k=1}^{n_S} \zeta \left(\frac{m_{S_k}}{T_{\text{sph}}} \right) \right) \left(\sum_{j=1}^{n_F} \zeta \left(\frac{M_{F_j}}{T_{\text{sph}}} \right) \right)}{79 \left(\sum_{k=1}^{n_S} \zeta \left(\frac{m_{S_k}}{T_{\text{sph}}} \right) + 2 \sum_{j=1}^{n_F} \zeta \left(\frac{M_{F_j}}{T_{\text{sph}}} \right) \right) + 10 \left(\sum_{k=1}^{n_S} \zeta \left(\frac{m_{S_k}}{T_{\text{sph}}} \right) \right) \left(\sum_{j=1}^{n_F} \zeta \left(\frac{M_{F_j}}{T_{\text{sph}}} \right) \right)} \quad (27)$$

for the scalars being neutral. Furthermore, one can imagine a more complicated setup, where each pair of a fermion and scalar carries a different $U(1)_X$ charge, and either the fermion or scalar of each pair can be neutral. In this setup, one may thus realize multi-component DM [48–54].

4. Modification of SM sphaleron processes

In this section, we first discuss two models with elementary and then two with composite particles in the dark sector. In all these models, the SM sphaleron processes are modified by the dark sector.

Models with elementary particles in the dark sector are discussed in Refs. [39,45,55,56]. The relevant symmetry group of these models is

$$SU(2)_L \otimes U(1)_Y \otimes U(1)_B \otimes U(1)_L \otimes U(1)_X, \quad (28)$$

with the last three $U(1)$ symmetries referring to generalized baryon number (B), generalized lepton number (L) and X . The generalizations B and L are introduced, since in the discussed models the particles of the dark sector either also carry baryon number, as in Ref. [45], or also lepton number, see Refs. [39,55,56], and we wish to distinguish these from B and L , only taking into account SM particles. The dark sector contains the following fermions

$$\begin{aligned} \Psi_L &\sim (\mathbf{2}, -\frac{1}{2}, B_1, L_1, X_1), & \Psi_R &\sim (\mathbf{2}, -\frac{1}{2}, B_2, L_2, -X_2), \\ \eta_R &\sim (\mathbf{1}, -1, B_1, L_1, X_1), & \eta_L &\sim (\mathbf{1}, -1, B_2, L_2, -X_2), \\ \chi_R &\sim (\mathbf{1}, 0, B_1, L_1, X_1), & \chi_L &\sim (\mathbf{1}, 0, B_2, L_2, -X_2), \end{aligned} \quad (29)$$

following (a generalization of) the conventions of Refs. [45,57].

In Ref. [39] the particles of the dark sector carry generalized lepton number and $U(1)_X$ charge. The charge assignments are $B_1 = B_2 = 0$, $L_1 = L_2 = 1$, $X_1 = X_2 = 1$. In addition, three left-handed fermions, being gauge singlets under the SM, with $U(1)_X$ charge

$$\begin{aligned} \gamma_{1L} &\sim (\mathbf{1}, 0, 0, 0, -1), \\ \gamma_{2L} &\sim (\mathbf{1}, 0, 0, 0, 1), \\ \gamma_{3L} &\sim (\mathbf{1}, 0, 0, 0, 0) \end{aligned} \quad (30)$$

are introduced which have Yukawa interactions with $\Psi_{L,R}$ and the lepton doublets ℓ (and the scalar H'). The global symmetry $U(1)_X$

is violated by sphaleron processes, see Eq. (32). The dark sector also contains two scalars, H' and h , which transform as

$$H' \sim (\mathbf{2}, \frac{1}{2}, 0, -L_1, 0), \quad h \sim (\mathbf{1}, 0, 0, 0, 0). \quad (31)$$

The DM particle is the fermion γ_{1L} , the lightest particle carrying non-zero $U(1)_X$ charge.

In the model in Ref. [45] the particles of the dark sector carry generalized baryon number. The symmetry $U(1)_B$ is gauged in this model. The corresponding charge assignments are $B_1 - B_2 = -3$, required by gauge anomaly freedom of $U(1)_B$, with B_2 being a free parameter, $L_1 = L_2 = 0$ and $X_1 = -X_2 = 1$ under $U(1)_X$. The latter is an accidental global symmetry of the dark sector and its quantum number is denoted with η in Ref. [45]. Note that this symmetry is not violated by sphaleron processes, see Eq. (32). In addition to the fermions, shown in Eq. (29), the dark sector possesses a scalar S_B which also carries generalized baryon number, $S_B \sim (\mathbf{1}, 0, -3, 0, 0)$. When S_B acquires a vacuum expectation value, the gauge symmetry $U(1)_B$ breaks spontaneously and contributions to the masses of the particles of the dark sector are generated. In the special case, discussed in Ref. [45], the DM particle is the Dirac fermion $\chi = \chi_L + \chi_R$ which is a singlet under the SM gauge group.

In both models, the sphaleron processes are modified and the corresponding condition reads

$$3(3\mu_q + \mu_\ell) + \mu_{\Psi_L} - \mu_{\Psi_R} = 0. \quad (32)$$

In addition, the Yukawa interactions involving particles of the dark sector also lead to conditions on the chemical potentials. These are, in particular, necessary in order to convert the X asymmetry to a particle–antiparticle asymmetry of the DM particle.

We report in Table 1 the results from these two models for the coefficients a_i as well as the upper limit on the DM mass in the case in which LNV processes, that violate L by two units and that are efficient at temperatures $T \sim 1$ TeV, are present.

The first ADM model in which sphaleron processes are modified by the dark sector and transfer asymmetries between the dark and the visible sectors has been proposed in Ref. [36]. This model belongs to a class of models where the dark sector contains composite particles and possesses a new strongly interacting Technicolor (TC) gauge group G_{TC} . The relevant symmetry group of the model is

$$G_{\text{TC}} \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_X. \quad (33)$$

A minimal set of new fermions, which does not lead to gauge anomalies, is

$$\begin{aligned} Q_L &= \begin{pmatrix} U \\ D \end{pmatrix}_L \sim (\mathbf{R}_{\text{TC}}, \mathbf{2}, 0, x), \\ U_R &\sim (\mathbf{R}_{\text{TC}}, \mathbf{1}, \frac{1}{2}, x), \quad D_R \sim (\mathbf{R}_{\text{TC}}, \mathbf{1}, -\frac{1}{2}, x), \end{aligned} \quad (34)$$

where \mathbf{R}_{TC} is the particle's representation under G_{TC} and x is the charge under the global symmetry $U(1)_X$, analogous to baryon number in the SM. As opposed to the models with elementary particles discussed above, the dark sector does not contain right-handed $SU(2)_L$ doublets, because these models have been devised to break EW symmetry dynamically via condensation.

The global symmetry $U(1)_X$ is violated by sphaleron processes, see Eq. (35), and, for certain choices of the gauge group G_{TC} and the representation \mathbf{R}_{TC} , the lightest composite particle in the spectrum is neutral and stable below the sphaleron decoupling temperature [36,47,58–61]. For example, if $G_{\text{TC}} = SU(4)$ and \mathbf{R}_{TC} is

the four-dimensional fundamental representation, the state $\chi \sim UDUD$, a singlet under the SM gauge group, is neutral and is the lightest state carrying $U(1)_X$ charge, as discussed in Ref. [36]. If $G_{TC} = SU(2)$ and \mathbf{R}_{TC} is the two-dimensional fundamental representation, then $\chi \sim UD$ is neutral, a singlet under the SM gauge group and the lightest state carrying $U(1)_X$ charge. In this case it is also a Goldstone boson of the strong dynamics, see Ref. [47]. In both models, sphaleron processes are modified and the corresponding condition for the chemical potentials reads

$$3(3\mu_q + \mu_\ell) + \dim(\mathbf{R}_{TC})\mu_{Q_L} = 0. \quad (35)$$

This class of models is nowadays constrained by the observation of the Higgs particle. While the condensate $\langle U_L \bar{U}_R + D_L \bar{D}_R + \text{h.c.} \rangle \sim f^3$, with f being the Goldstone boson decay constant, can yield correct EW symmetry breaking, it may not yield a light Higgs-like excitation. A viable variation may arise from coupling an elementary Higgs H to the dark sector and to the SM fermions via Yukawa interactions [62–68]. Hence, in the simplest case the EW scale is set by

$$v_{EW}^2 = v^2 + N_D f^2, \quad (36)$$

where v is the vacuum expectation value of H and N_D is the total number of $SU(2)_L$ doublets in the dark sector divided by $\dim(\mathbf{R}_{TC})$, meaning $N_D = 1$ in the two examples. The Yukawa interactions of the new fermions and H are of the form

$$\lambda_D \bar{Q}_L H D_R + \lambda_U \bar{Q}_L \tilde{H} U_R. \quad (37)$$

Being in thermal equilibrium above the sphaleron decoupling temperature, they provide conditions for the chemical potentials equivalent to those, arising from the SM Yukawa interactions. We refer to Refs. [65] and [66–68] for explicit constructions of models with the gauge group $G_{TC} = SU(4)$ and $G_{TC} = SU(2)$ and an elementary Higgs H , and to Ref. [69] for how to raise the scale f in such models.

When computing the coefficients a_i for the models, defined in Refs. [36,47], extended with an elementary Higgs H , we do not consider right-handed neutrinos and adapt as normalization of the global quantum number X the one used in Ref. [36].³ The coefficients a_i can also be found in Table 1.

5. Conclusions

We have considered ADM scenarios with a dark sector which possesses a global symmetry $U(1)_X$ and the impact of LNV processes on the particle–antiparticle asymmetries in the dark and the visible sectors. We have shown in a model-independent way and with several examples that B , L and X asymmetries can be preserved in an ADM scenario, even in the presence of LNV processes that violate L by two units and that are efficient at temperatures $T \sim 1\text{TeV}$. This is in contrast to models without ADM, where e.g. the observation of LNV in form of same-sign dilepton signals at the LHC can falsify high-scale baryogenesis and leptogenesis, as has been shown recently in the literature.

The crucial feature of all scenarios are particles in the dark sector that carry hypercharge and/or transform in a non-trivial way under $SU(2)_L$. In the former case, the condition for hypercharge

neutrality is modified, while in the second one SM sphaleron processes are also altered by the dark sector. In both cases it turns out that fulfilling all conditions, derived from Yukawa interactions, hypercharge neutrality and sphaleron processes, leaves two chemical potentials as free parameters. Thus, adding one further condition, imposed by LNV processes on the chemical potentials, reduces the number of free parameters to one. Consequently, all asymmetries become correlated, but are still non-zero in general. The conversion of the asymmetries of the dark and the visible sectors is in the presented examples either achieved through Yukawa interactions between the two sectors and/or modified sphaleron processes. Including LNV processes, considerably reduces the allowed parameter space of the ADM scenarios. In particular, it puts an upper limit on the DM mass of a few GeV. This makes it challenging to test these ADM scenarios with direct DM detection experiments. The observation of LNV and the discovery of new particles, carrying hypercharge and/or transforming in a non-trivial way under $SU(2)_L$, together with an indication for high-scale baryogenesis will be an intriguing hint for the ADM scenarios considered in this analysis. In contrast, an evidence for symmetric DM, such as the confirmation of the origin of a γ - or cosmic-ray excess from DM annihilation, or for the DM mass being larger than $\sim 100\text{GeV}$, could rule out the presented scenarios.

We would like to emphasize that our analysis assumes all interactions, including Yukawa ones, sphaleron processes and other asymmetry transfer interactions, to be in thermal equilibrium. Our conclusions thus do not apply to situations where the B asymmetry is generated below (or during) the EWPT or the dark sector decouples from the visible one before LNV becomes efficient.

As the discussed LNV processes naturally arise in radiative neutrino mass models and several of these also possess a global symmetry and feature a viable DM candidate, a detailed study of these models along the lines of the present analysis would be very interesting.

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³ The $U(1)_X$ charge of Q_L , U_R and D_R is given by one divided by the number of constituents of the DM candidate χ , i.e. $x = 1/4$ and $x = 1/2$ for the model in Ref. [36] and [47], respectively. This definition deviates from the one chosen in Ref. [47] by a factor $1/\sqrt{2}$, see definition of the generator of $U(1)_{TB}$, corresponding to $U(1)_X$, in Ref. [47].

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