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Charge Asymmetry of New Stable Families in Baryon Asymmetrical Universe

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Abstract: The new stable fermion family, with Standard Model electroweak (EW) charges, should take part in sphaleron transitions in the early Universe before breaking of the EW symmetry. The conditions of balance between the excess of new fermions (additional generation of new superheavy U, D quarks and new E, N leptons) and baryon asymmetry, were considered at temperatures above, and below, the phase transition, using a system of equations for chemical potentials.

Keywords: baryon asymmetry; new stable quarks; sphaleron transition; dark matter; dark atoms

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Citation: Beylin, V.A.; Khlopov, M.Y.; Sopin, D.O. Charge Asymmetry of New Stable Families in Baryon Asymmetrical Universe. *Symmetry* **2023**, *15*, 657. https://doi.org/10.3390/sym15030657

Academic Editors: Stefano Profumo and Sergei D. Odintsov

Received: 27 December 2022
Revised: 25 January 2023
Accepted: 13 February 2023
Published: 6 March 2023

1. Introduction

The modern cosmological paradigm inevitably involves a new form of stable matter (hidden mass or dark matter) as a requirement, with an origin, structure and dynamics that are predicted by physics beyond the non-closed Standard Model (BSM) of elementary particles (see References [1–18] and references therein). It should be noted that, the analysis of the cosmological model within the framework of thermodynamics of open macroscopic systems was proposed in pioneering works [19,20] and extended in the analysis of entropy production and temperature evolution in the Universe [21]. Multiple particle production in the Universe can, indeed, be considered both as a set of elementary acts of interaction, generation and decay of new particles in the framework of quantum field theory, and on the basis of the thermodynamics of irreversible matter creation in open systems, considering, in particular, the interaction and mutual influence of the Universe subsystems, such as dark matter, dark energy, radiation and ordinary matter [22,23]

The joint use of the approaches of quantum field theory and thermodynamics of macroscopic systems (so-called sphaleron transitions between different vacua states) makes it possible to analyze another important issue of modern cosmology, namely baryosynthesis, which is considered a necessary stage of evolution that ensures the observed baryon asymmetry of the Universe. The connection between the densities of baryons and dark matter may be a consequence of the common origin of these forms of matter, psrticularly if dark matter is being described by an excess of new generation stable quarks balanced by an excess of baryons. (see e.g., Reference [24]).

In this work, a scenario where the SM was extended by an additional fermion family, having the SM electroweak charge, was considered [25]. Such a fourth generation, containing new heavy U, D quarks and E, N leptons, could naturally emerge in heterotic string models. For instance, the heterotic string with the E_6 symmetry allows for such a scenario. Besides, because of the rank of the E_6 group being higher than the rank of the SM group ($r_{E_6} = 6$ and $r_{SM} = 4$ correspondingly), the extended gauge symmetry generates the new conserved charge. As a consequence, some new particles could be stable and could be considered dark matter candidates.

The SM extended scenario under consideration and the method of the sphaleron transitions describing a solution of the system of equations for chemical potentials, with a subsequent analysis of the density rates, are given in subsections of Section 2. Some discussion of the results is presented in Conclusions.

2. Balance between Baryon and Dark Matter Densities Due to Sphaleron Transitions

2.1. Model

The fermion sector of the extended model consists of three standard SM generations and the additional, fourth, one. It is assumed that new quarks (U and D) are superheavy with masses $m_U,\ m_D \sim 1$ TeV and $m_U < m_D$. A value close to this mass is assumed for the new lepton: $m_E \sim 1$ TeV. However, the mass of the heavy neutrino should be appreciably different to avoid contradiction with precision measurements of the SM parameters. The radiation corrections related to heavy fermions (they are an order of $\log(M_Z/M_F)$, where M_F are the masses of new fermions) should be compensated in Peskin–Tackeuchi parameters by heavy neutrino contributions. This is possible in the case of $M_Z/2 < m_N < M_Z$, and, thus, we assume that $m_N \sim 50$ GeV [26].

In this scenario, up-like quark, U, and heavy neutrino, N, are stable, due to conservation of the new gauge charge y (see Table 1). This is the result of additional $U(1)$ symmetry. All SM particles belong to the trivial representation of this group, and for all SM fields the following holds: $y_{SM} = 0$. This also prevents mixing between standard and new generations, and. thus, new baryon and lepton numbers of the fourth generation appear which are separated from the standard ones.

The neutral and stable bound state looks like the following: $(\bar{U}\bar{U}\bar{U}\bar{N})^{--}He^{++}$. This is the so-called Anti-Neutrino-O-helium (ANO-helium) state, and is a suitable dark matter candidate. The ANO-helium evolution in the early Universe was considered in [25]. The down-like D quark and heavy electron E are metastable and are, therefore, not substantial for cosmology. They decay rapidly through a weak channel, producing an additional excess of stable U quarks and neutrinos N, respectively.

It is important to note that, in order to realize this scenario, the anti-U excess should be generated in (fourth) baryon number violating processes. In this case, the sphaleron transitions are considered a source of such baryon excess. This process is freezed out at low temperature, $T_* = 150$–250 TeV [27], and, after this, the observed ratio $\dfrac{\Omega_{DM}}{\Omega_b}$ is finally formed.

Table 1. Properties of Fourth generation.

Particle	Mass	Charge q	Charge y	New Lepton Number	New Baryon Number
U	∼1 TeV	$\frac{2}{3}$	$-\frac{1}{3}$	0	$\frac{1}{3}$
D	∼1 TeV	$-\frac{1}{3}$	$-\frac{1}{3}$	0	$\frac{1}{3}$
E	∼1 TeV	−1	1	1	0
N	∼50 GeV	0	1	1	0

2.2. Chemical Potentials

In order to consider possible sphaleron transitions, the approach, as developed in [28,29], was used. The following chemical potentials were introduced for SM particles:

- $\mu_{uL/R}, \mu_{dL/R}$ for all left-/right-handed and up-/down-like quarks, correspondingly;
- $\mu_{eL/R}$ for all charged leptons;
- $\mu = \sum_i \mu_{\nu_i L}$, $\mu_{\nu_i R}$, i=e, μ, τ for left-/right-handed neutrino;
- μ_W for W^-, note that the chemical potential of neutral vector boson is vanishing;
- μ_0 and μ_- for the Higgs doublet.

Chemical potentials for the fourth generation particles are denoted as follows:

- $\mu_{UL/R}, \mu_{DL/R}$ for left-/right-handed U and D correspondingly;
- $\mu_{EL/R}, \mu_{NL/R}$ for left-/right-handed E and N correspondingly.

Assuming thermal equilibrium, it is possible to use several conditions which are dictated by weak interaction:

- for any up-/down-like right fermion "i"

$$\mu_{iR} = \mu_{iL} \pm \mu_0; \tag{1}$$

- for particle "i" with isospin projection $-1/2$ and corresponding particle "j" with isospin projection $1/2$

$$\mu_i = \mu_j + \mu_W; \tag{2}$$

It is now possible to formulate the equations for corresponding number densities and sphaleron transitions.

2.3. Equations

Chemical potentials of subsystems can be found from equations which set physical conditions for the system: equilibrium, neutrality and others. After the number densities are defined, the baryon number excess density looks like the following:

$$B = \frac{6}{gT^2} \sum_i \frac{1}{3} (n_i - n_{\bar{i}}) = \sum_i \frac{1}{3} \sigma_i \left(\frac{m_i}{T} \right) \mu_i, \tag{3}$$

where Taylor expansion by the small ratio $\frac{\mu_i}{T}$ was used for the number density of the (anti)particles. This number density is of the following form:

$$n = g \int \frac{d^3k}{(2\pi)^3} \frac{1}{e^{\frac{E-\mu}{T}} + 1}. \tag{4}$$

The weighting factor $\sigma(z)$ can be found by means of the following formula:

$$\sigma(z) = \frac{6}{4\pi^2} \int_0^\infty dx\, x^2 \cosh^{-2} \left(\frac{1}{2} \sqrt{x^2 + z^2} \right). \tag{5}$$

Factor 1/3 in Equation (3) is the baryon number for the each quark.

Lepton number density L, lepton and baryon number densities of the fourth generation, FL and FB, are defined in an analogous manner. In that case:

$$\begin{aligned} B &= \frac{1}{3} \cdot 3 \cdot (2 + \sigma_t)(\mu_{uL} + \mu_{uR}) + \frac{1}{3} \cdot 3 \cdot 3 \cdot (\mu_{dL} + \mu_{dR}) = \\ &= (10 + 2\sigma_t)\mu_{uL} + 6\mu_W, \end{aligned} \tag{6}$$

$$\begin{aligned} L &= \Sigma(\mu_{\nu_i L} + \mu_{\nu_i R} + \mu_{iL} + \mu_{iR}) = \\ &= 4\mu + 6\mu_W, \end{aligned} \tag{7}$$

$$\begin{aligned} FB &= \frac{1}{3} \cdot 3 \cdot \sigma_U(\mu_{UL} + \mu_{UR}) + \frac{1}{3} \cdot 3 \cdot \sigma_D(\mu_{DL} + \mu_{DR}) = \\ &= 2(\sigma_U + \sigma_D)\mu_{UL} + 2\sigma_D\mu_W + (\sigma_U - \sigma_D)\mu_0, \end{aligned} \tag{8}$$

$$\begin{aligned} FL &= \sigma_E(\mu_{EL} + \mu_{ER}) + \sigma_N(\mu_{NL} + \mu_{NR}) = \\ &= 2(\sigma_N + \sigma_E)\mu_{NL} + 2\sigma_E\mu_W + (\sigma_N - \sigma_E)\mu_0. \end{aligned} \tag{9}$$

Conditions of electro- and y-neutrality can also be formulated in terms of densities (similarly to Equation (3)). In that case the following equations arise:

$$Q = 0 = \frac{2}{3} \cdot 3 \cdot (2 + \sigma_t)(\mu_{uL} + \mu_{uR}) - \frac{1}{3} \cdot 3 \cdot 3 \cdot (\mu_{dL} + \mu_{dR}) + \\ + \frac{2}{3} \cdot 3 \cdot \sigma_U(\mu_{UL} + \mu_{UR}) - \frac{1}{3} \cdot \sigma_D(\mu_{DL} + \mu_{DR}) - \\ - 3(\mu_{eL} + \mu_{eR}) - \sigma_E(\mu_{EL} + \mu_{ER}) - 4\mu_W - 2\mu_-, \tag{10}$$

$$Y = 0 = -\frac{1}{3} \cdot 3 \cdot \sigma_U(\mu_{UL} + \mu_{UR}) - \frac{1}{3} \cdot 3 \cdot \sigma_D(\mu_{DL} + \mu_{DR}) + \\ + \sigma_E(\mu_{EL} + \mu_{ER}) + \sigma_N(\mu_{NL} + \mu_{NR}), \tag{11}$$

It should be noted that characteristic temperature for the sphaleron transitions is unknown. That means that the freezing out temperature for these transitions, T_*, can be both higher and lower than the temperature of the electroweak phase transition. (EWPT) T_c.

Before the EWPT SM particles are massless. However, this is not true for the fourth generation. There should be a new mass-acquiring mechanism in the case of superheavy fermions. The details of such a mechanism are not discussed in this work. (Possibly, the presence of several scales in the modified scalar sector is required, but the appearance of additional heavy scalars significantly complicates the dynamics of the system.) The density of weak isospin projection I_3 should be zero in the symmetric phase:

$$I_3 = 0 = \frac{1}{2} \cdot 3 \cdot 3 \cdot (\mu_{uL} - \mu_{DL}) + \frac{1}{2} \cdot 3 \cdot (\mu_{\nu_i L} - \mu_{eL}) - 4\mu_W - (\mu_0 + \mu_-) + \\ + \frac{1}{2} \cdot 3 \cdot (\sigma_U \mu_{UL} - \sigma_D \mu_{DL}) + \frac{1}{2}(\sigma_N \mu_{NL} - \sigma_E \mu_{EL}). \tag{12}$$

After EWPT SM particles do have masses, which, however, are negligibly small in comparison with the temperature T_* (except the t-quark mass). It is impossible to require $I_3 = 0$ now and, therefore, necessary to complete the system of equations with the condition for the chemical Higgs potential:

$$\mu_0 = 0. \tag{13}$$

The equation describing sphaleron transitions is similar to Equations (1) and (2):

$$3(\mu_{uL} + 2\mu_{dL}) + \mu + (\mu_{UL} + 2\mu_{DL}) + \mu_{NL} = 0. \tag{14}$$

It is different from a similar equation in [30]. In this work, the condition of electroneutrality was taken into account correctly.

The solution of the resulting system has an expression of the following form: $\mu_{UL} = \mu_{UL}(m_i, T_*, B, FB)$. Masses and freezing out temperature of sphaleron transitions are the model parameters, which should be varied, while densities and the last chemical potential should be found within the framework of some other approach.

2.4. Density Rate

It is possible to rewrite the definition (3) in terms of matter densities using a number of approximations. In particular, let the baryon density of the Universe be provided by protons only. Then:

$$B \approx \frac{6}{gT^2}\frac{\rho_c \Omega_b}{m_p}, \tag{15}$$

In the other case, let the dark matter mostly consist of ANO-helium. The large mass of this particle is provided by anti-U core $\bar{U}\bar{U}\bar{U}$, and the contribution of neutrino and helium is negligible. Thus, the following holds:

$$\Omega_{DM} \approx \Omega_{\text{ANO-He}} \approx \Omega_{\bar{U}\bar{U}\bar{U}}, \tag{16}$$

and, consequently:

$$-\frac{FB}{B} \approx \frac{1}{3}\frac{m_p}{m_U}\frac{\Omega_{UUU}}{\Omega_b}, \tag{17}$$

where the minus sign occurs due to excess of anti-particles of the fourth generation. To prove this, it is enough to consider the solution of the system of equations for chemical potentials under the assumption $FB = kB$.

Equations (15) and (17) allow finding the ratio $\frac{\Omega_{DM}}{\Omega_b} = A(m_U, T_*)$ in the equal masses approximation, $m_U = m_D = m_E$. This ratio is plotted in Figure 1 for $T_* > T_c$ and in Figure 2 for $T_* < T_c$. It is also possible to find the values of model parameters to explain the observable ratio in both cases.

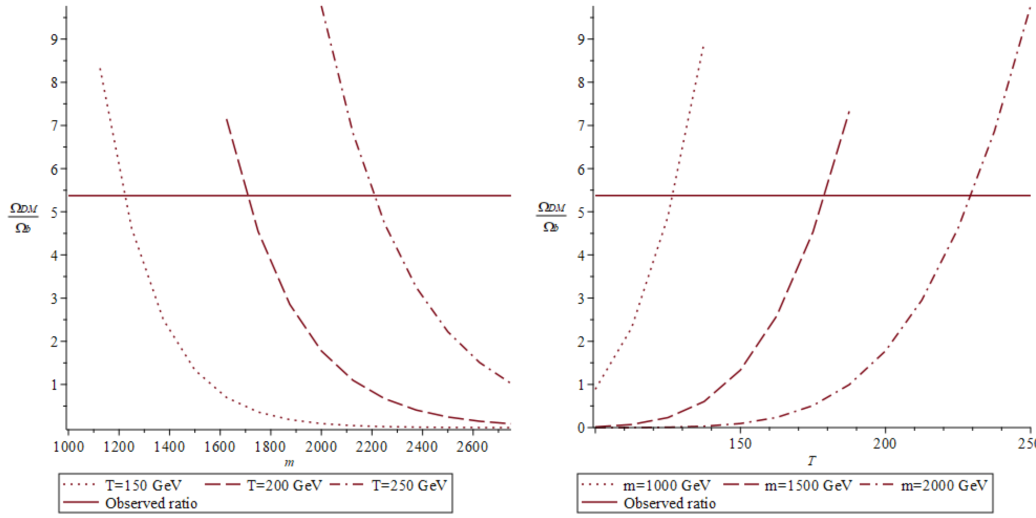

Figure 1. The ratio of dark and baryonic matter densities for the case of sphaleron transition when freezing out temperature is above the temperature of the EWPT: $T_* > T_c$. The observed ratio plotted according to PLANCK collaboration data [31]. In this work the equal masses approximation was used.

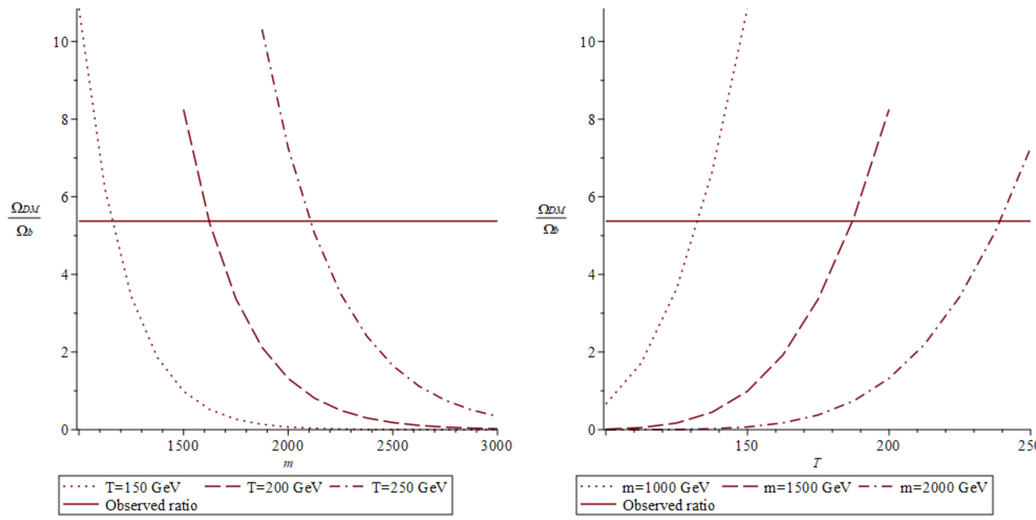

Figure 2. The ratio of dark and baryonic matter densities for the case of sphaleron transition when freezing out temperature is below the temperature of the EWPT: $T_* < T_c$. The observed ratio plotted according to PLANCK collaboration data [31]. In this paper the equal masses approximation was used.

The considered system of equations can be solved with respect to any pair of number densities. It is, therefore, possible to find $B \pm L$, $FB \pm FL$, $\frac{FB}{L}$ etc. as functions of masses, temperature and coefficient k. The last parameter is well known [31]. Unfortunately, these functions are too bulky to be written here.

Among all the possible combinations, the most notable one is the lepton to baryon number density ratio $\frac{L}{B} = \frac{L}{B}(m_i, T_*, k)$. It grows like $\frac{1}{\sigma_U}$, with an increase of the fourth generation's mass or a decrease of the freezing out temperature of the sphaleron transition (see Figure 3). To be more precise, this means that the masses of new fermions should not be too heavy due to standard anti-lepton danger of overproduction.

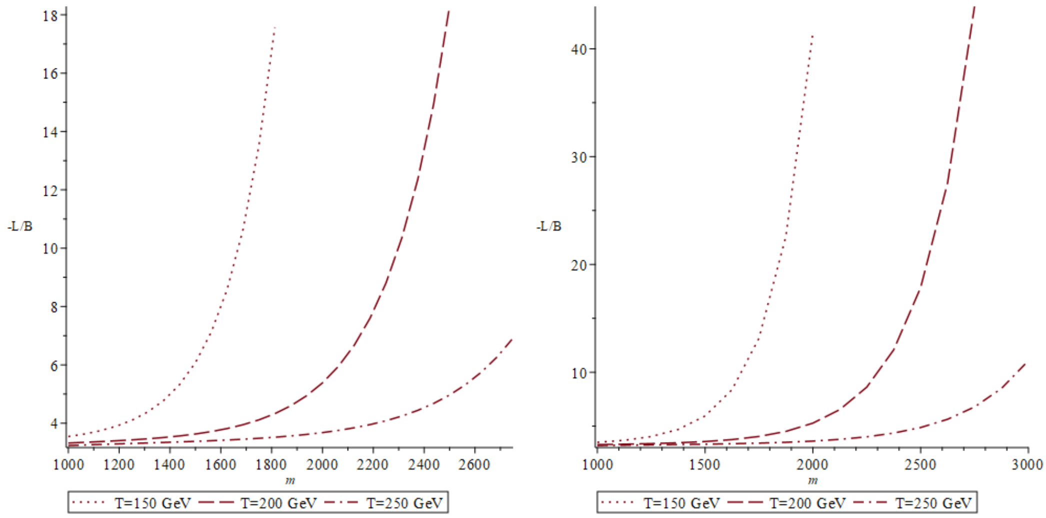

Figure 3. The absolute value of lepton number density to baryon number density ratio for $T_* > T_c$ (**right**) and for $T_* < T_c$ (**left**). The approximation of equal masses was used. Dark matter density provided only by anti-clusters $\bar{U}\bar{U}\bar{U}$.

A noticeable effect occurs at the nucleosynthesis stage only if $-\frac{L}{B} \sim 10^7$–10^8 [32]. Such values correspond to heavy quark masses of about $m_U \sim 5$–8 TeV (for different sphaleron freezing out temperatures), when dark matter can not be provided only by ANO-helium (see Figures 1 and 2).

Thus, as follows from calculations, an agreement with the observed ratio of densities is in order if the masses of new heavy fermions vary approximately in the interval 1.5–2.0 TeV. At the same time, the calculated value of this ratio arises already at very low freezing out temperatures if masses are sufficiently low. This result means that an additional assumption is required to restrict a reasonable region of the model parameter values.

2.5. Non-Equal Masses

It is possible to estimate how the ratios change in the case of unequal masses of new particles. The mass changing of the D quark and heavy electron E only affects the values of the weighting functions σ_D and σ_E. Let us define these differences in the following manner:

$$d, e = \sigma\left(\frac{m_{D,E}}{T_*}\right) - \sigma\left(\frac{m_U}{T}\right), \tag{18}$$

where parameters m_U and T should be fixed. For the first approximation, it is natural to choose their values as follows: $m_U = 1.5$ TeV and $T = 200$ GeV (these are the average values for the intervals used above). These functions can have values in the interval $[-\sigma_U, 0]$ if $m_U < m_D$, m_E.

Figure 4 displays how the ratios of densities $\left(\frac{\Omega_{DM}}{\Omega_b} \text{ and } \frac{L}{B}\right)$ depend on such differences if the sphaleron transitions freeze out, before and after EWPT. The red dot marks the results obtained in the approximation of equal masses. The main features are the following:

- both ratios strongly depend on the mass difference of U and D quarks, but hardly depend on the mass of the heavy electron E;
- the ratio $\frac{\Omega_{DM}}{\Omega_b}$ is suppressed if D quark is too heavy. This fact can be used to correct the result obtained in the approximation of equal masses;
- standard lepton to baryon asymmetry increases.

The overproduction of dark matter that could be found at low masses ($m \sim 1$ TeV) in Figure 1 and 2 can be eliminated by introducing a noticeable difference of the masses of heavy quarks.

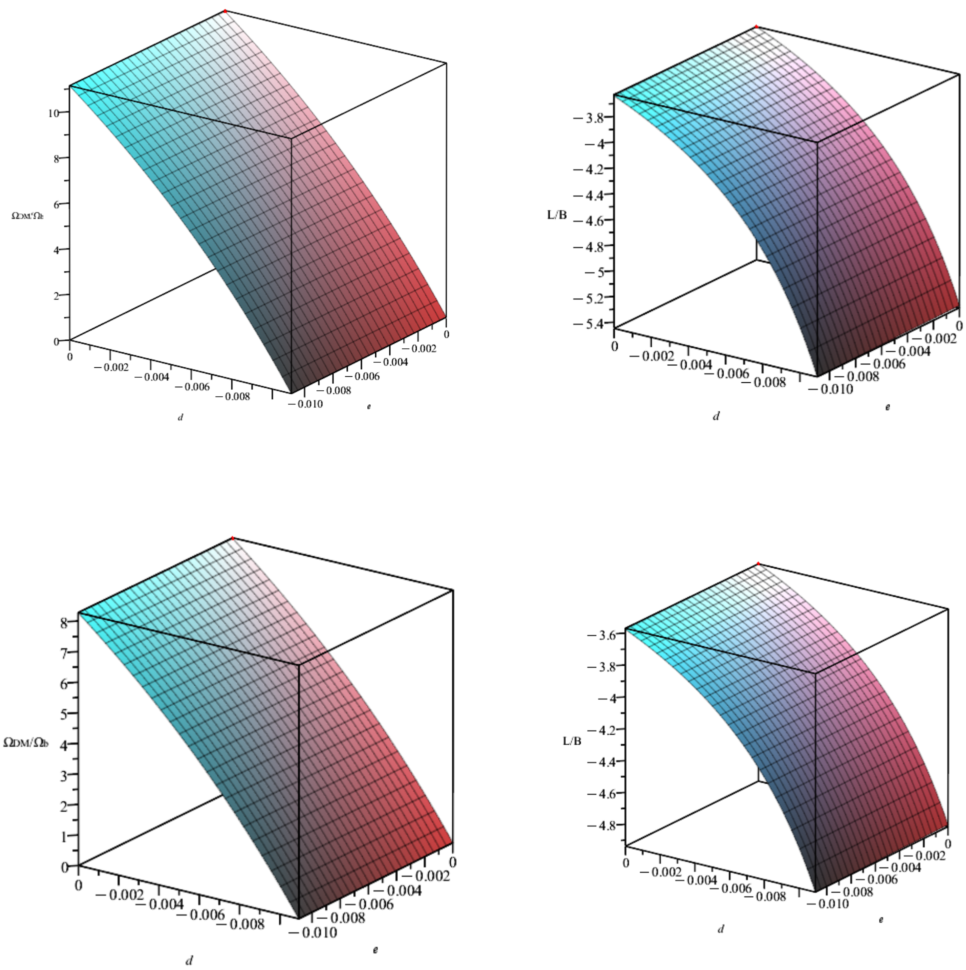

Figure 4. The ratio of the dark and baryonic matter densities (**left column**) and the ratio of the lepton and baryon number densities (**right column**) for different masses of heavy fermions. **Top row:** sphaleron transitions freeze out before EWPT. **Bottom row:** sphaleron transitions freeze out after EWPT. The red dot corresponds to the value obtained in the approximation of equal masses.

3. Conclusions

Sphaleron transitions are the key mechanism to explain the densities ratio of dark and baryon matters. In the model with complementary generation of superheavy states it is possible to explain the value of the observed ratio by assuming that the dark matter consists only of ANO-helium $\bar{U}\bar{U}\bar{U}\bar{N}He$. From the improved estimation of the fourth generation masses, it follows that $m_{ANO-He} \approx 5.0$ TeV. Such an estimate of the dark matter candidate mass makes it possible to search for these particles at the LHC by analogy with the search for long-lived particles (R-hadrons, bound color-singlet objects generated by hadronization of gluino) from various SUSY scenarios, namely in events with displaced vertices (and the resulting hadronic jets) [33–35]. Possibly, such events can be highlighted as the ones with large missed transversal momentum and displaced vertices where the neutral bound state (excited ANO-helium) decays, producing jets.

The suggested scenario can be studied in collider experiments when heavy electrons E can be produced. These reactions can be detected due to the fast decay $E^* \to W + N$. As the $W-$boson decays into hadronic jets or standard $l\tilde{\nu}_l$ give well-known signatures and the new heavy neutrino, N, is stable, such events can be observed as the ones with large missed energy and transversal momentum. It should also be noted that the cross section for the production of two unstable heavy electrons, E, for example, in the process of the gauge bosons fusion $W^*W^* \to Z^* \to E\bar{E} \to WW + N\bar{N}$, should be suppressed in comparison with the cross section of one heavy electron production with its subsequent decay $W^*Z^* \to W^* \to E^*N \to WN$.

Hadronic dark matter can also be presented by new heavy hadrons, which are bound states of standard light quarks and additional singlet up-like quarks U. Masses of such stable new hadrons were estimated to be ∼10 TeV [36]. Analysis of stability and dynamics of the states with new heavy U quarks and their ability to participate in sphaleron transitions contributing to the hadron excess, is in progress.

If new particles have estimated masses, the decrease of helium abundance, due to its binding with $(\bar{U}\bar{U}\bar{U}\bar{N})^{--}$, is inevitable. An increase of the U quark mass leads to a decrease of this deficit. However, if the fourth generation is too heavy, the overproduction of standard anti-leptons is possible. This overproduction could influence the balance of beta processes, which determine the frozen out neutrons to protons ratio. Thus, such overproduction should be taken into account in estimations of helium abundance.

Furthermore, we add that the analysis of an equilibrium system of particles, in which sphaleron transitions occur, should be apparently supplemented with more detailed dynamical information on the interactions in the system considered (cross sections etc.). This is important for refining the collision integral in the kinetic equation, where the contribution of sphaleron transitions should also be considered. Besides, this would narrow the temperature and mass ranges in which sphaleron transitions could occur, providing the correct ratio of the densities of the dark matter and baryons.

Author Contributions: Conceptualization, M.Y.K.; formal analysis, D.O.S. and V.A.B.; writing—original draft preparation, D.O.S. and V.A.B.; writing—review and editing, M.Y.K. All authors have read and agreed to the published version of the manuscript.

Funding: The research by V.B. and M.K. was financially supported by Southern Federal University, 2020 Project VnGr/2020-03-IF.

Data Availability Statement: Not applicable.

Acknowledgments: We thank Ramin K. Barak for reading the manuscript and providing valuable recommendations to improve its English. The research by V.B. and M.K. was financially supported by Southern Federal University, 2020 Project VnGr/2020-03-IF.

Conflicts of Interest: The authors declares no conflict of interest.

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