PROCEEDINGS OF SCIENCE

Cosmic Matter-Antimatter Separation and Sterile Neutrino Dark Matter

Mikhail Shaposhnikov[a,*]

[a] *Institute of Physics, École Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland*

E-mail: `mikhail.shaposhnikov@epfl.ch`

The lattice studies provided evidence of a smooth crossover between the hadronic and quark-gluon phases at high temperatures and zero chemical potential for baryonic number. We argue that these simulations may not rule out relatively weekly first-order phase transition. This first-order QCD phase transition may lead to cosmic separation of phases, creating temporarily macroscopic domains occupied by matter and antimatter. We demonstrate that this possibility enhances the keV scale sterile neutrino production and may lead to its abundance consistent with the observable energy density of dark matter.

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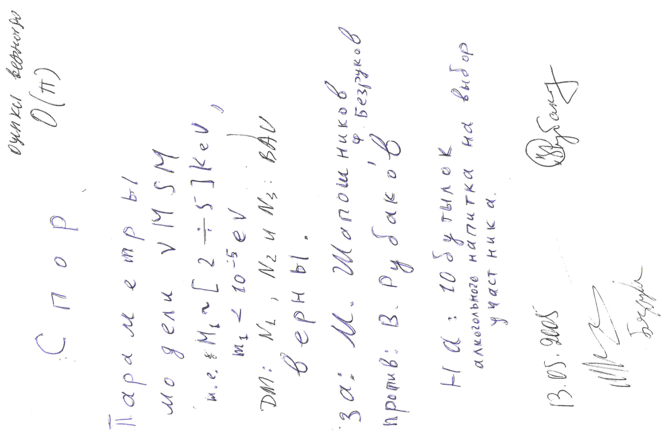
1. Introduction

This talk is dedicated to the memory of Valery, an outstanding physicist, an exceptional person, a friend and a collaborator. Rubakov pioneered groundbreaking ideas and methods in many domains of particle physics and cosmology. The physics part of the talk is based on the work Alexey Smirnov and I just posted to Arxiv right before this conference [1]. It is about a specific type of dark matter - sterile neutrino, and how the QCD phase transition may change its production in the Early Universe. Valery worked on sterile neutrinos himself. In the pioneering work with Akhmedov and Smirnov [2], he proposed that the oscillations of sterile neutrinos can lead to baryon asymmetry of the Universe (BAU), and in the paper with Gorbunov and Khmelnitsky [3] he derived constraints on sterile neutrino dark (DM) matter following from phase space density observations. The sterile neutrinos were also a subject of the bet Valery had with Fedor Bezrukov and me back in 2005, see Fig. 1. Fedor and I were convinced that the νMSM, explaining the DM and BAU is a correct theory extending the Standard Model, whereas Valery had an opposite opinion. The bet has not been resolved yet. In my talk, I will explain what is the νMSM, what is the DM sterile neutrino, and how the QCD phase transition may enter the game. The technical details will be omitted, they can be found in [1]. I will conclude by discussing the prospects for settling the bet.

2. The νMSM

The νMSM [4, 5] is an extension of the Standard Model (SM) in the neutrino sector by three Majorana leptons N_I with masses M_I below the Fermi scale (below we will use for these particles the name suggested by the Particle Data Group, Heavy Neutral Leptons, or HNLs for short). What makes it different from the minimal type I see-saw model [6–10] is the choice of the Majorana masses and Yukawa couplings $F_{I\alpha}$, where α is the SM generation index. In the type I see-saw model it is assumed that the Yukawa couplings of new singlet fermions to leptonic doublets are of the order of one. To get the correct neutrino masses, this requires superheavy N_I, with masses of the order of 10^{15} GeV. In the νMSM it is assumed that the masses of N_I are in the domain of



оценки верны до $O(\pi)$

Спор.

Параметры модели νMSM

т.е. $M_1 \sim [2 \div 5]$ keV,

$m_1 < 10^{-5}$ eV

DM: N_1, N_2 и N_3: BAU

верны.

за: М. Шапошников, Ф. Безруков

против: В. Рубаков

На: 10 бутылок алкогольного напитка на выбор участника.

13.05.2005

Estimates are correct up to $\mathcal{O}(\pi)$

Bet

Parameters of the model νMSM
i.e. $M_1 \sim [2-5]$ keV, $m_1 < 10^{-5}$eV
DM: N_1, N_2 and N_3: BAU are correct.
In favour: M. Shaposhnikov, F. Bezrukov
against: V. Rubakov
prize: 10 bottles of alcoholic drink
according to participant's choice
13.05.2005
Signatures

Figure 1: The bet about sterile neutrinos, original and translation.

masses of usual quarks and leptons, meaning that their Yukawa couplings are required to be small, $F_{I\alpha} \lesssim 10^{-7}$. The νMSM is the simplest theory of new physics which can explain all experimental drawbacks of the Standard Model. These are neutrino masses and oscillations, dark matter, and baryon asymmetry of the Universe. It also may incorporate the cosmological Higgs inflation [11]. Contrary to the type I see-saw model, in which HNLs are superheavy and thus cannot be directly produced in experiments, the νMSM is experimentally testable, as new particles can be created at different accelerators.

3. DM Sterile Neutrino

The lightest of HNLs, N_1, is the sterile neutrino dark matter candidate [12, 13]. Two others (N_2, N_3) are responsible for neutrino masses and baryogenesis [2, 5]. There are several cosmological constraints on DM sterile neutrino (for reviews see, e.g. [14–16]). Their lifetime must be larger than the age of the Universe, their decay width into neutrino and photon, $N_1 \to \nu\gamma$ must be small enough to be in accordance with the X-ray observations [17–19], and their free-streaming length (which depends on their mass and the mechanism of the cosmological production) should be small enough to allow the cosmological structure formation at small scales [16, 18, 20]. Interestingly, evidence for an X-ray line at 3.5 keV which would correspond to decays of 7 keV DM sterile neutrino was reported in [21, 22]. It remains to be seen if this line indeed corresponds to the radiative decay of DM particles (for discussion of the current status and controversies see [16, 23–27]).

In the νMSM, the DM sterile neutrinos are most effectively produced via mixing with active neutrinos in reactions with other particles of the SM, such as $l^+l^- \to \nu N_1$, at temperatures T of a few hundred MeV [1]. In the case of small lepton asymmetries of the Universe (the Dodelson-Widrow - DW mechanism [12]), the required νN_1 mixing angle is in contradiction with the X-ray and structure formation constraints.

The situation changes if the Universe contains sufficiently large lepton asymmetry at $T \sim 100$ MeV. We define it as $\Delta_L = L/s$, where L is the density of the total lepton number and s is the entropy density. If the asymmetry is much larger than the baryon asymmetry [33, 34], and furthermore

$$\Delta_L \gtrsim \Delta_{\rm crit} \equiv 6.6 \times 10^{-5}\,, \tag{1}$$

then the production of the sterile neutrinos is resonantly enhanced according to the Shi-Fuller (SF) mechanism [13] and all the constraints mentioned above can be satisfied (for a review see [16]). The quantities Δ_L and $\Delta_{\rm crit}$ in eq. (1) are taken at a temperature 4 GeV, and it is assumed that the lepton numbers of different generations can only be changed due to the mixing with DM sterile neutrino (or, in other words, that the processes with $N_{2,3}$ of the νMSM are irrelevant). The number $\Delta_{\rm crit}$ depends on the flavour composition of the lepton asymmetry, on the sterile neutrino mixing angle θ, and on the mass of the DM sterile neutrino [33, 34]. The specific value of $\Delta_{\rm crit}$ given above in (1) corresponds to $L_e = L_\mu = L_\tau = L/3$, $M_1 = 7$ keV and $\theta^2 = 5 \times 10^{-11}$ [34].

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[1] The DM sterile neutrino may also be created in the processes including physics beyond the νMSM. The proposals include the decays of extra scalar particles [28, 29], higher-dimensional operators [30], Einstein-Cartan 4-fermion gravitational interaction [31], left-right symmetric theories [32] etc.

The lepton asymmetries of this magnitude can indeed be produced in the νMSM, albeit in a fine-tuned domain of the parameter space leading to strong mass degeneracy between heavier HNLs N_2 and N_3 [35–37].

4. Sterile Neutrino and inhomogeneities

In all approaches to sterile neutrino production proposed so far, the Universe was taken to be homogeneous and isotropic at the relevant temperatures of the order of 200 MeV. However, this is a mere assumption. The success of the Big Bang Nucleosynthesis (BBN) indicates that this was very likely to be the case at smaller temperatures $T \sim 1$ MeV, but the inhomogeneities at $T \sim 200$ MeV with a size as large as few meters are admitted [38], as they dissipate before the BBN starts. Moreover, even the existence of matter-antimatter domains with a baryon-to-entropy ratio of the order of one (or minus one) is allowed, provided their size is smaller than the neutron diffusion length at the BBN epoch.

The presence of these domains may change considerably the sterile neutrino DM abundance and their momentum distribution, important for structure formation. Indeed, even though the average baryon asymmetry of the Universe is small, it can be large locally, leading to the resonant production of sterile neutrinos. Furthermore, the resonance will occur for the left chirality of sterile neutrinos in one type of domain, and with right chirality in another, producing the chiral symmetric DM, contrary to the resonance production in the homogeneous situation.

How the matter-antimatter domains can appear in the Universe? One of the mechanisms suggested in the literature a while ago is associated with a possible existence of stochastic hypermagnetic fields at temperatures above the sphaleron freeze-out [39] (see also [40, 41]). The electroweak anomaly converts the hypermagnetic fields into baryons and thus leads to an inhomogeneous Universe with matter-anti-matter domains. Yet another possibility to have matter-antimatter domains appears in theories with two sources of CP-violation - spontaneous and intrinsic [42]. Also, the matter-antimatter domains may appear in inhomogeneous baryogenesis, described in [43, 44].

Below we will give yet another example, associated with the first-order QCD phase transition. We will show that in the scenario with matter-antimatter separation at the first-order QCD phase transition, the sterile neutrino DM production may be enhanced considerably. The enhancement can be efficient even if the asymmetry is small $\Delta_L < \Delta_{\text{crit}}$, or even absent, $\Delta_L = 0$. Though we concentrate on these specific mechanisms of matter-antimatter separation at the QCD epoch, our findings about sterile neutrino DM generation are universal and applicable also to other possibilities, mentioned above.

5. QCD phase transition

There is a common belief that the evolution of the Universe at the QCD epoch is smooth. Potentially, during the Universe's cooling after the Big Bang, one could encounter the QCD phase transition at $T \sim 200$ MeV from the quark-gluon plasma (QGP) to the gas of hadronic states. The nature of this phase transition cannot be resolved by the use of perturbation theory, and one has to use non-perturbative methods such as lattice simulations. The lattice studies [45–48] reported evidence for the smooth cross-over, cutting off the discussions of cosmological applications of the first-order QCD phase transition, such as black hole formation, gravitational wave generation, non-homogeneous nucleosynthesis, amplification of cosmological density perturbations, to list a few.

The lattice simulations are extremely challenging because of the need to incorporate the nearly massless quarks u, d and eventually s. Large volumes and small lattice spacings are very demanding. In most simulations, the spatial size of the lattice l was limited by $lT_c = 5$, where $T_c \simeq 160$ MeV is the “pseudo-critical” temperature of the phase transition (i.e. the temperature at which the most rapid changes of the quark-gluon plasma bulk parameters occur).

The first-order phase transition may disappear if the volume of the system is too small. The free energy is an analytic function of temperature if the volume $V = l^3$ of the system is finite. In other words, there are no phase transitions when $V < \infty$. Still, the lattice studies do allow us to trace the simultaneous existence of different minima of the effective potential for an order parameter, provided they exist at finite volume. It may happen, however, that the finite volume and lattice spacing effects change the form of the effective potential substantially removing the double-phase structure, see Fig. 2, left. In this case, if made at “small” volumes and “large” lattice spacings, the lattice simulations will report the smooth cross-over rather than the first-order phase transition. Our experience with the much simpler high-temperature electroweak theory [49] tells us that for the gauge-Higgs system, we need to have $lm_W > 5$ in order not to miss the phase transition (here m_W is the vector boson mass at the crossover point). Of course, the physics of the QCD phase transition is different, but it is alarming to see that $lm_\pi < 5$ (m_π is the pion mass) for the majority of simulations.

We tend to conclude from here that the lattice simulations with considerably larger volumes might be needed to elucidate the nature of the QCD phase transition. They should include also the analysis of static correlation length in channels with different quantum numbers, to track the possible finite size effects.

How large the necessary lattice sizes should be? A possible (naive) estimate comes from the

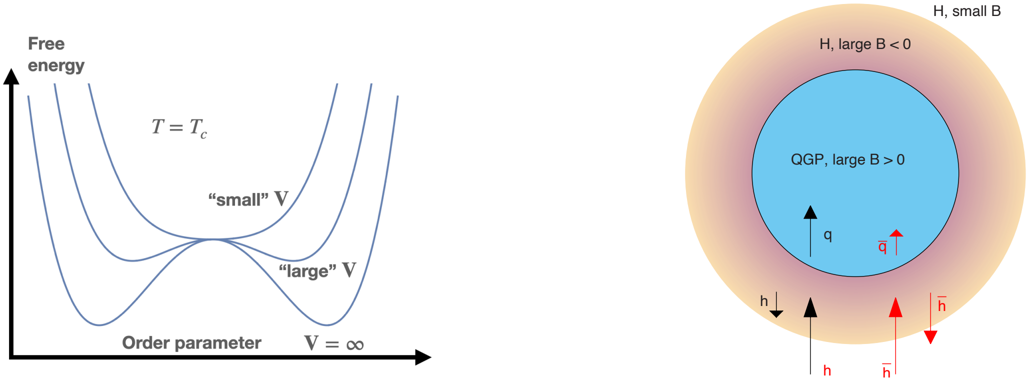

Figure 2: Left: The effective potential at the critical temperature for a first-order phase transition. It has two separated minima at infinite or “large” volumes of the system. The double-phase structure disappears at small volumes. **Right:** Scattering of quarks and hadrons on the bubble wall separating the quark and hadron phases. It leads to the macroscopic separation of baryon and antibaryon numbers.

requirement to track the presence of baryons in the lattice volume. If one uses the zero-temperature proton mass at T_c, one finds that the lattice with the size $lT_c = 4$ and a number $N = 64$ of lattice steps in a spatial direction usually used in the simulations accommodates just 0.16 spin states of the proton. To have a reasonable presence of other hadrons, such as, say, two Λ's inside the lattice volume to account for strangeness, one would need $LT_c \sim 12$, and thus the spacial lattice sizes as large as $N^3 = 128^3$. We also remark here that the number of lattice steps in the temporal temperature direction is usually taken to be $N_t = 8$, which can only accommodate just two non-trivial Matsubara harmonics along the imaginary "time" direction.

From now on we will assume the QCD phase transition is of the first order and study how it may develop in the early Universe.

6. Matter-antimatter separation

Let us assume for the time being that there are just two phases - hadronic and QGP that may coexist in some interval of temperatures $T_- < T < T_+$. A more intricate and very speculative possibility will be discussed at the end of this section.

Suppose that before the QCD phase transition, the Universe was homogeneous. As was argued by Witten [50] the first-order QCD phase transition may lead to cosmic separation of hadronic and QGP phases. When the universe supercools somewhat below the critical temperature T_c (we take it to be $T_c \simeq 160$ MeV for numerical estimates) the bubbles of new, hadronic phase nucleate. The shock waves originating from the bubble expansion reheat quickly the quark phase up to the critical temperature, and the universe stays at a constant temperature T_c during the sizeable fraction of the Hubble time until the end of the transition. The hadron bubbles grow slowly and roughly with the Hubble rate H. They start to percolate at the moment t_0 when their fraction reaches $\sim 50\%$ of the space. After that, the situation is reversed - the hadronic phase is dominating, and the droplets with the quark-gluon plasma inside shrink slowly. The horizon size at this time is ~ 10 km, the distance between the bubbles is estimated to be between 1 cm and 1 m, and the duration of the phase transition is of the order of $\sim 10^{-5}$ seconds.

This process may lead to the separation of the net baryon number [50]: the droplets with the plasma are much richer in baryon number than the baryonic phase, because quarks are lighter than hadrons and the transport of the baryon number over the phase boundary is suppressed [50, 51]. It was conjectured in [50] that the baryon asymmetry inside the droplets can be of the order of one at the end of the phase transition.

This effect can be further enhanced if the Universe contains sizable lepton asymmetry $\Delta_L = L/s \gg B/s = \Delta_B \simeq 9 \times 10^{-11}$. The lepton excess creates asymmetries in quark flavours $\sim \Delta_L$, to make the plasma electrically neutral. This leads to C, CP and CPT breaking in the plasma. It is plausible to think that these breakings are transmitted to the interaction of quarks and hadrons with the interphase boundary between the different phases. In the picture of a dilute gas of quarks and hadrons, this would result in a difference between reflection and transmission coefficients for particles carrying baryon and anti-baryon numbers. For example, for a quark incident in the QGP phase, the probability of reflection back would be different from that of the antiquark. Since the interactions between quarks and hadrons are strong, it is conceivable to assume that the CP(T) asymmetry in reflection coefficients is of the order of lepton asymmetry. The expansion of the bubbles then leads to the creation of matter-antimatter domains with nuclear density, see Fig. 2, right. The mechanism discussed above resembles a lot the scenario of domain wall electroweak baryogenesis (for a review see [52] and references therein).

The matter-antimatter separation scenario strongly deviates from the standard one in which the universe is homogeneous and isotropic since inflation. An obvious question is about the Big Bang Nucleosynthesis. The sufficiently short-scale inhomogeneities disappear by the nucleosynthesis time [53–56] via the combined action of neutrino inflation and neutron diffusion. Baryon number fluctuations affect BBN provided they are sizable enough over the neutron diffusion scale (3×10^5 cm) at the onset of nucleosynthesis at $T \simeq 100$ keV. The neutron diffusion scale, blue-shifted to the QCD phase transition scale $T_c \simeq 160$ MeV, becomes, $L_{\rm diff}(T_c) = 2$ m, somewhat larger than the expectation for the distance between the bubble centres, providing an estimate of the scale of baryon number fluctuations. It would be interesting to see whether this may change the BBN predictions and thus put bounds on the possible parameters of the QCD phase transition and lepton asymmetry of the Universe.

Before coming to a possible cosmological consequence of the matter-antimatter separation scenario we will consider now a much more speculative possibility to have matter-antimatter separation, which would work even without the presence of (large) lepton asymmetry.

Back in 1969 Omnes [57] proposed an idea of matter-antimatter separation on cosmological scales in an attempt to understand why we have only baryons in the local vicinity of our solar system. He argued that if baryons and antibaryons are repulsed from each other at small distances, the phase diagram of the strong matter allows the existence of two phases, one with an excess of baryons and another with an excess of antibaryons. If true, this would mean the spontaneous breaking of charge-conjugation symmetry in hadronic matter. According to [58, 59], these phases can coexist at some interval of temperatures around ~ 350 MeV, and the Universe's evolution may lead to the separation of domains of matter and antimatter at the cosmological scales.

As was noted by many researchers (see, e.g. [60, 61]), the idea fails for many reasons. First, the horizon scale at temperatures ~ 350 MeV is too small to create any structures with masses exceeding the solar mass. Second, theoretical computations of nucleon dynamics at these temperatures cannot be reliable due to the strong coupling. Moreover, the domain of temperatures found by Omnes is already in the QGP region, where quarks and gluons provide a better description of dynamics.

Still, it seems to us that the Omnes-type phase diagram such as the one presented in Fig. 3, though extremely exotic, cannot be completely excluded by the present state-of-the-art lattice simulations. So, we find it interesting to discuss the Universe's evolution if it is indeed realised, but we cannot put any argument for why *it should be realised*.

As we have strong coupling, it would be natural to assume that at the critical temperature, the baryonic density of the Omnes states is of the order of the nuclear density, i.e. much larger than the baryon and lepton asymmetries of the Universe. In this case, the breaking of the degeneracy between the minima with different baryon numbers will be small and not essential for the initial stages of the QCD phase transition. The Omnes phase transition would start somewhat below T_c, as in the discussion in Section 6. However, now two types of bubbles of the hadronic phase will be nucleated. Approximately half of them will carry a positive baryon number, and another half – negative baryon number. The bubbles will grow and at some moment start to percolate, but now with the simultaneous existence of all three possible phases. The QGP phase will be eaten by the hadronic bubbles and cease to exist at temperature T_- at the latest, and we are left with domains of positive and negative baryonic number densities. The presence of lepton and baryon asymmetries, resulting in the breaking of the degeneracy, will lead to somewhat faster growth of the droplets that have lower free energy. At the temperature T_{omnes} (Fig. 3) the spontaneous C-breaking comes to an end, and the Universe will be in the hadronic phase, with large inhomogeneities in the distribution of the baryon number, with a typical distance scale of the order of the initial separation between the bubble centres. At this temperature, roughly half of the space will carry a positive baryon number, and another half will be rich in antibaryons, with baryon asymmetry of the order of ±1 in each of the domains. This is to be compared with the previous scenario, where in the larger part of the space we have an excess of (say) matter, and in a smaller part of the space occupied by the QGP an excess of antimatter.

Most probably, the BBN can constrain the parameters of the Omnes-type phase transition (such as the average distance between the bubbles and the amplitude of the baryon asymmetry in different C-odd phases). This is not attempted here. Instead, in the next Section we will consider possible cosmological consequences of the matter-antimatter separation associated with the production of Dark Matter sterile neutrinos.

7. QCD phase transition and production of sterile neutrino dark matter

Let us assume now that the QCD phase transition goes as described in Section 6 via the formation of QGP droplets with enhanced baryon number. Also, we take that the average value of the leptonic asymmetry is much larger than the baryon asymmetry but smaller than the critical value $\Delta_{\text{crit}} \simeq 6.6 \times 10^{-5}$. In this case, 7 keV sterile neutrinos with the mixing angle $\theta^2 = 5 \times 10^{-11}$ cannot accommodate all DM in the Universe if the QCD phase transition were absent.

The key feature of this scenario is that the droplets of QGP shrink, and consequently, the baryon number density in them increases. That is, soon after the time of formation of droplets t_0 (percolation time of hadron bubbles), the baryon number density inside the droplets, n_B^d, grows like

$$n_B^d(t) \propto \left[\frac{r(t_0)}{r(t)}\right]^3 . \tag{2}$$

For later times, the baryon density would follow

$$n_B^d(t) \propto \left[\frac{r(t_1)}{r(t)}\right]^\kappa , \tag{3}$$

where $\kappa > 3$ depends on the asymmetry in the reflection coefficients for quarks and antiquarks.

The behaviour (3) corresponds to the matter-antimatter separation. The total baryon number of the Universe does not change. Still, it gets unequally distributed in the domains (droplets) occupied by the QGP and hadronic matter, the first type carrying an excess of baryons and the second - an excess of antibaryons (or vice versa, depending on the sign of CP-violation in reflection coefficients). Moreover, the baryon asymmetry in the droplets of the QGP can get much larger than the initial lepton asymmetry once the volume fraction occupied by QGP shrinks.

Of course, the assumption that the baryon number cannot leak out of the QGP droplets is presumably too strong and is likely to be wrong at the end of the phase transition, when the density

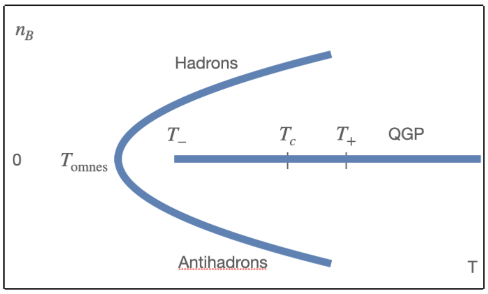

Figure 3: Omnes type QCD phase diagram. In addition to the QGP phase with vanishing baryon number density there are two distinct hadron phases with opposite baryon number densities. The Omnes phase exists at $T_{\rm omnes} < T < T_+$, and the QGP phase at $T > T_-$.

of the baryonic charge approaches that of nuclear density. The unknown strong dynamics prevented us (and the authors before, e.g. [50, 62]) from making any definite conclusions concerning this point. We would like just to mention that the qualitative remark of [50] remains in force: the critical temperature of the QCD phase transition with non-zero baryon number decreases when the baryonic chemical potential increases, meaning that the QGP droplets may survive till the temperatures smaller than T_c, say $T_c/2$ [50].

To estimate the number of sterile neutrinos produced in a resonant way, two cases should be considered. First, the droplet sizes can be larger than the active neutrino mean free path $\lambda_\nu \simeq 0.4$ cm. Here the resonant transitions occur inside the droplets of QGP. If the droplet sizes are smaller than λ_ν, one should consider the scattering of neutrino on droplets, $\nu + \text{droplet} \longrightarrow N_1 + \text{droplet}$. In the case of large droplets, the computation goes along the lines of the resonant creation of N_1 for the case of the homogeneous media, but accounting for the fact that only the part of space occupied by the droplets leads to N creation and that the density inside the droplets is growing according to (3). The scattering on small droplets leads essentially to the same number.

A precise computation is hardly possible because of many uncertainties, associated with barely known droplet dynamics and CP-asymmetry in the interaction of hadrons and quarks with the interphase boundary between QGP and hadron phases. Still, the reasonable assumptions about the dynamics of phase transition allow us to make rough estimates, summarised below (for details see [1]).

For the lepton asymmetry-driven matter-antimatter separation, the efficient production of DM is possible even for lepton asymmetries a factor ~ 100 below the value needed in the homogeneous case (for 7 keV N_1 with the mixing angle $\theta^2 = 5 \times 10^{-11}$, increasing the asymmetry allows to decrease the mixing angle). This may shed light on the mass scale of the heavier HNLs in the νMSM. A detailed study of [63] has shown that the lepton asymmetry of the Universe generated at the freeze in of $N_{2,3}$[2] can only reach the necessary value provided the masses of $N_{2,3}$ are sufficiently small. The Fig. 4 shows that the asymmetry, greater than, say, $\Delta_L \gtrsim 10^{-5}$ can be achieved in the νMSM only for HNL masses between 1 and 2.5 GeV if the neutrino mass ordering is normal. So large asymmetry cannot be generated if the neutrino mass hierarchy is inverted. The asymmetry larger than $\Delta_L \gtrsim 10^{-6}$ can be generated for a somewhat larger interval of HNL masses, between

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[2] The production of large lepton asymmetries at this moment does not require a delicate fine-tuning between the Majorana mass splitting and the Higgs induced mass splitting [64].

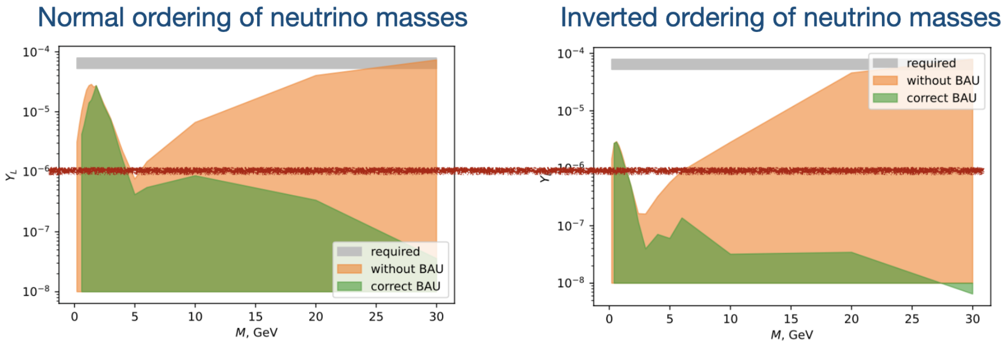

Figure 4: The maximal lepton asymmetry generated at freeze in of $N_{2,3}$. In the green region, the correct BAU is produced, in the orange region the BAU constraint is not imposed. The grey thick line indicates the total lepton asymmetry which is needed for N_1 to compose 100% of DM in the homogeneous situation. The red thick line represents the optimistic estimate of the minimal asymmetry needed to create all DM if matter-antimatter separation takes place at the first-order QCD phase transition. Adopted from [63].

0.2 and 4.5 GeV for normal ordering and between 0.2 and 1.5 GeV for inverted. This may serve as the very first indication of the scale of the mass of HNLs: the explanation of neutrino masses and baryogenesis, together with BBN constraints only provides a lower bound on their mass, $M_N > 140$ MeV (for a review see [14]). For the Omnes-type phase transition, one can have an efficient production of DM even for sterile neutrino with mixing angles well below $\theta^2 \simeq 5 \times 10^{-11}$, indicated by 3.5 keV X-rays line of [21, 22]. In both cases, the spectrum of produced sterile neutrinos may be considerably cooler than that in DW or SF mechanisms, making N_1 essentially a cold DM candidate with momentum well below the thermal one, even if its mass is, say, $2 - 5$ keV.

8. Conclusions

In this talk, we argued that rejecting the possibility of the first-order QCD phase transition might be premature. The conclusion on the absence of the phase transition is based on lattice simulations performed up to now, and the use of much larger lattices may be needed to clarify its nature. We think that it makes sense to assume that it happened and explore its possible consequences.

We advocated that the QCD phase transition may lead to matter-antimatter separation. This is a speculation about the unknown strong dynamics: neither the existence of the Omnes-type phase transition nor the CP-breaking properties of the interphase tension between the hadronic phase and the QGP in the presence of lepton asymmetries were derived from the first principles and are simply assumed. At the same time, we found no arguments which forbid these possibilities. A much better understanding of QCD at temperatures $T \sim 200$ MeV is needed to address these questions.

The most robust part of our work is associated with sterile neutrino DM production in the non-homogeneous situation. If the matter-antimatter separation takes place by these or some other mechanisms, the production of sterile neutrino dark matter may be enhanced in comparison with the homogeneous situation. For the Omnes-type phase transition, we found that one can easily accommodate all DM in sterile neutrinos. In another scenario (with two co-existing phases but a CP-violating boundary due to the presence of lepton asymmetry) the DM sterile neutrinos may be effectively produced if the lepton asymmetry exceeds by $\sim 4 - 5$ orders of magnitude the average

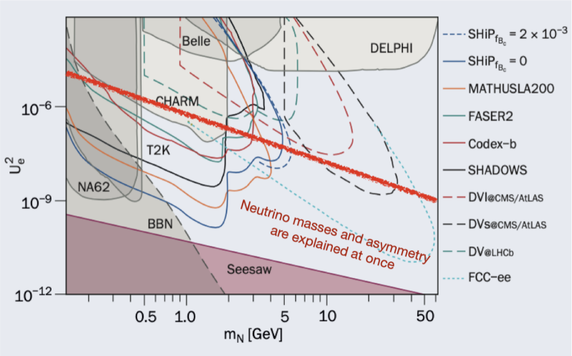

Figure 5: The projection of bounds on HNL coupling to electrons. Below the red line neutrino masses and baryon asymmetry of the Universe can be explained simultaneously. The area below the Seesaw and BBN lines is excluded by neutrino physics and cosmology. The Seesaw line is indicative and corresponds to the total mixing which includes all neutrino flavours.

baryon asymmetry in the Universe $\Delta_L \gtrsim 10^{-6}$. These asymmetries can be produced at the freeze-in of heavier HNLs, without fine-tunings, if their mass is below a few GeV.

How much time would be needed to discover HNLs and also resolve our bet with Valery? The dark matter sterile neutrino can be found by X-ray telescopes in space, such as XRISM launched in September 2023, and precision experiments such as HUNTER [65]. The two others can be searched for in accelerator experiments at the intensity frontier in pp or e^+e^- collisions. The dedicated intensity frontier experiments, such as the most ambitious and mature SPS-based SHiP [66, 67], have the potential to complete the Standard Model of particle physics during the next 10-15 years. On a longer time scale, a failure of searches for relatively light HNLs in pp reactions would call for the use of the FCC-ee, capable of discovering HNLs with considerably larger masses [68]. These two types of experiments probe different parts of the allowed parameter space and are complementary to each other, see Fig. 5. For a recent review see [27].

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