Sterile neutrinos in cosmology and how to find them in the lab [1]

Mikhail Shaposhnikov

Institut de Théorie des Phénomènes Physiques, EPFL, CH-1015 Lausanne, Switzerland

E-mail: `Mikhail.Shaposhnikov@epfl.ch`

Abstract. A number of observed phenomena in high energy physics and cosmology lack their resolution within the Standard Model of particle physics. These puzzles include neutrino oscillations, baryon asymmetry of the universe and existence of dark matter. We discuss the suggestion that all these problems can be solved by new physics which exists only below the electroweak scale. The dedicated experiments that can confirm or rule out this possibility are discussed.

Introduction. The aim of this talk is to argue that the existing high intensity protons beams, such as NuMi beam at FNAL, CNGS beam at CERN and future accelerator facilities like J-PARC in Japan, Project X at FNAL can be used to search for physics beyond the SM in new dedicated experiments. A *possible* outcome of these new experiments could be a discovery of new neutrino states – massive neutral leptons, new insight to the origin of neutrino masses, fixing the pattern of neutrino mass hierarchy, and, eventually, discovery of CP-violation in neutrino sector and revealing the origin of baryon asymmetry of the universe and fixing its sign. The *guaranteed* outcome of these new experiments is the improving of the constraints on the couplings of new particles by several orders of magnitude.

The outline of the paper is as follows: first, we will discuss theoretical motivation for existence of relatively light singlet leptons (they can be called singlet fermions, right-handed or sterile neutrinos). It comes from the discovery of neutrino masses, from existence of dark matter (DM) and from baryon asymmetry of the universe (BAU). Then we summarize the predictions of the properties of singlet fermions and describe the strategy for the search for these particles at existing and future accelerators.

Neutrino masses. Neutrinos have mass. A possible origin of this mass is the existence of right-handed neutrinos N_I with masses M_I, $I = 1, ..., \mathcal{N}$. The most general renormalizable Lagrangian incorporating the fields of the Standard Model (SM) and singlet fermions has the form

$$L = L_{\rm SM} + \bar{N}_I i\partial_\mu\gamma^\mu N_I - F_{\alpha I}\,\bar{L}_\alpha N_I\tilde{\Phi} - \frac{M_I}{2}\,\bar{N}_I^c N_I + h.c., \tag{1}$$

where $L_{\rm SM}$ is the Lagrangian of the SM, $F_{\alpha I}$ are the new Yukawa couplings, and Φ is the Higgs boson, $\tilde{\Phi}_i = \epsilon_{ij}\Phi_j^*$. If the Dirac masses $M_D = F_{\alpha I} v$ ($v = 174$ GeV is the vacuum expectation value of the Higgs field) are much smaller than Majorana masses M_I, the type I see-saw formula holds $M_\nu = -M_D\frac{1}{M_I}[M_D]^T$ (for a review see [1]). The number of right-handed singlet fermions

[1] Invited talk at XXIII Int. Conf. on Neutrino Physics and Astrophysics, May 25-31, Christchurch, New Zealand.

must be at least two. If there is only one of them, then two active neutrinos are massless, which is at odds with the data on neutrino masses and mixing. Already for $\mathcal{N} = 2$ the Lagrangian (1) can describe the pattern of neutrino masses and mixings observed experimentally. One of the most important parameters of (1) is the scale of the Majorana neutrino masses. However, this parameter cannot be fixed by knowing M_ν: multiply M_D by any number x and M_I by x^2 – M_ν does not change. Therefore, the choice of M_I cannot be fixed by doing experiments with active neutrinos only.

The GUT see-saw. A popular choice for this scale is based on the following logic. *Assume* that Yukawa couplings of N_I to the Higgs and left-handed lepton doublets are similar to those in quark or charged lepton sector (say, $F_{\alpha I} \sim F \sim 1$, as for the top quark) and find M_I from requirement that one gets correct active neutrino masses: $M_I \simeq \frac{F^2 v^2}{m_{atm}} \simeq 6 \times 10^{14}$ GeV, where $m_{atm} \simeq 0.05$ eV is the atmospheric neutrino mass difference. This scale happens to be close to the scale of Grand Unification. There are theoretical challenges in the GUT see-saw scenario. One of them is related to the hierarchy problem: the mass M_I is much larger than electroweak (EW) scale. Therefore, one should understand not only why $M_W \ll M_{Pl}$ ($M_{Pl} = 1.2 \times 10^{19}$ GeV is the Planck scale, M_W is the mass of the electroweak vector boson), but also why $M_W \ll M_I$ and why $M_I \ll M_{Pl}$. The smallness of the Higgs mass in comparison with M_I would require an extra fine-tuning [2].

The EW see-saw (for a review see [3]). *Assume* that the Majorana masses of N_I are smaller or of the same order as the mass of the Higgs boson and find Yukawa couplings from requirement that one gets the correct active neutrino masses: $F \sim \frac{\sqrt{m_{atm} M_I}}{v} \sim 10^{-6} - 10^{-13}$. The EW see-saw does not introduce any new energy scale besides the one already present in the SM, and, therefore, contains no new hierarchy or fine tuning problem in comparison with the SM. This allows a different approach to hierarchy problem, discussed in [4]. Though the stability of the Higgs mass against radiative corrections gives a theoretical preference to the EW see-saw, the low-energy neutrino experiments are indifferent to the scale of M_I. Therefore, we add below two extra pieces of evidence in favour of EW see-saw, coming from cosmology.

Dark matter. About 23% of the energy in the universe is associated with non-baryonic DM. Amazingly, the theory (1) gives a candidate for dark matter particle, provided one of the singlet fermions is light enough (for a review see [4] and references therein). Indeed, if the Yukawa couplings are small as in the EW see-saw, the lightest sterile neutrino N_1 can be practically stable and have a lifetime which may exceed greatly the age of the universe.

There are several constraints on sterile neutrino as a DM candidate. They are shown in Fig. 1 (left panel). First, due to reactions $l\bar{l} \to \nu N_1$, $q\bar{q} \to \nu N_1$ etc, sterile neutrinos are created in the early universe. Their abundance must correctly reproduce the measured density of DM. Depending on other parameters of the Lagrangian (1), the admitted region lies between two black thick lines in Fig. 1 [5]. Second, the DM sterile neutrino has a sub-dominant radiative decay channel $N_1 \to \nu\gamma$, producing a narrow photon line which can be detected by different X-ray satellites (for a review see [6] and references therein). This line has not been seen. The right upper corner in Fig. 1 corresponds to the forbidden region, coming from the analysis of a number of astronomical objects by different X-ray instruments. Finally, a lower limit on the mass of DM sterile neutrino comes from structure formation. If N_1 is too light it may have considerable free streaming length and erase fluctuations on small scales. This can be checked by the study of Lyman-α forest spectra of distant quasars [7]. The region to the left of the vertical line corresponds to the excluded region [5], which accounts for a non-trivial velocity dispersion of DM particles.

An interesting feature of Fig. 1 is that the admitted region is surrounded by different constraints in all directions, telling that the hypothesis of sterile neutrino as a DM candidate is experimentally testable. Moreover, the $\mathcal{O}(10)$ keV scale for the mass of DM is singled out by these considerations.

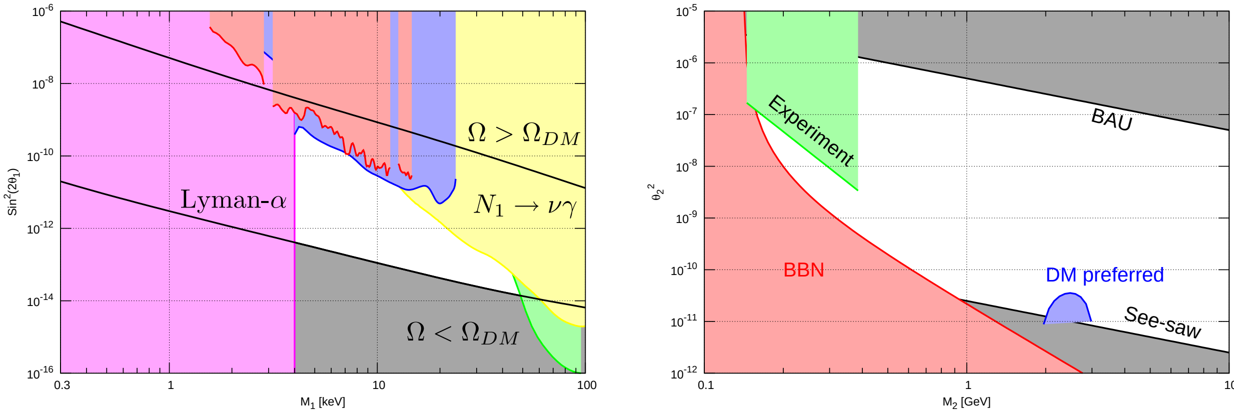

Figure 1. Left: constraints on the mixing angle $\theta_1 = \frac{m_D}{M_I}$ of DM sterile neutrino. Right: constraints on the mixing angle of BAU generating singlet fermions.

An important consequence of the cosmological and astrophysical constraints on DM sterile neutrino is that N_1 does not contribute significantly to the see-saw formula. Therefore, the number of singlet fermions must be at least 3, to explain the DM and observed pattern of neutrino masses and mixing angles. Since the number of fermion families in the SM is 3, we take $\mathcal{N} = 3$ in what follows, making the particle content of the theory (we will call it the νMSM for Neutrino Minimal Standard Model) similar in the left-handed and right-handed sectors.

Besides being a candidate for DM particle, sterile neutrinos may have other interesting applications in astrophysics (for a review see [8]).

Baryon asymmetry. Our universe is baryon asymmetric - it does not contain antimatter in amounts comparable with matter. Quite interestingly, the theory (1) allows for generation of BAU for a large choice of parameters of the model, and in particular for wide range of masses of singlet fermions.

The case of GUT see-saw was discussed in talk by Y. Nir at this Conference. So, we elaborate on the case of EW see-saw only. Remarkably, a pair of nearly degenerate light singlet fermions $N_{2,3}$ also leads to baryogenesis, but due to another mechanism, related to coherent oscillations of right-handed neutrinos (for a review see [4] and references therein). The light N_I enter into thermal equilibrium very late due to the small Yukawa couplings $F_{\alpha I}$. In particular, they may be out of thermal equilibrium at all temperatures above $T_{EW} \sim 100$ GeV, ensuring in this way one of the Sakharov conditions. The coherent character of oscillations leads to amplification of CP-violating effects, to generation of lepton asymmetry and eventually to its transfer to baryons because of non-perturbative EW effects.

In Fig. 1 (right panel) we present different constraints on singlet fermion mixing angle versus their mass. Above the lined marked "BAU" baryogenesis is not possible: here the coupling of $N_{2,3}$ to active neutrinos is so large that they come to thermal equilibrium above the EW temperature. Below the line marked "See-saw" the data on neutrino masses and mixings cannot be explained. The region noted as "BBN" is disfavoured by the considerations of Big Bang Nucleosynthesis - the decays of $N_{2,3}$ must not spoil the standard picture. A small region with the capture "DM preferred" in the domain of masses $2-3$ GeV is quite peculiar: here the generation of BAU above the EW scale and production of DM well below T_{EW} is due to essentially the same mechanism, giving a hint why the DM abundance is similar to that of baryonic matter. Finally, the region marked "Experiment" shows the part of the parameter space excluded by direct searches for singlet fermions. The analysis of the published works of different collaborations reveals that for the mass of the neutral lepton $M > 450$ MeV none of the past or existing experiments enter into interesting for νMSM region below the line "BAU". The NuTeV upper limit on the mixing is at most 10^{-7} in the region $M \simeq 2$ GeV [9], whereas the NOMAD [10] and L3 LEP experiment [11] give much weaker constraints. The best constraints in the small mass region, $M < 450$ MeV are coming from the CERN PS191 experiment [12], shown in Fig. 1.

Summary of constraints on the parameters of the νMSM and its predictions. The first prediction is the absolute values of masses of active neutrinos. One of the active neutrinos must be very light, $m_1 \lesssim \mathcal{O}(10^{-6})$ eV. This fixes the masses of two other active neutrinos: $m_2 \simeq 9 \cdot 10^{-3}$ eV, $m_3 \simeq 5 \cdot 10^{-2}$ eV for normal hierarchy or $m_{2,3} \simeq 5 \cdot 10^{-2}$ eV for the inverted hierarchy. As a result, an effective Majorana mass for neutrinoless double beta decay can be determined [13]. For normal (inverted) hierarchy the constraints read: 1.3 meV $< m_{\beta\beta} <$ 3.4 meV (13 meV $< m_{\beta\beta} <$ 50 meV). A very conservative bound on the mass of DM sterile neutrino comes from analysis of rotational curves of dwarf galaxies and reads $M_1 > 0.4$ keV [14] (it is weaker than the one coming from Lyman-α discussed above). Direct experimental searches and BBN require $M_{2,3} > 140$ MeV [15], whereas baryogenesis due to sterile neutrino oscillations is possible if $\Delta M = |M_2 - M_3| < 800\ m_{atm}\,(M/\mathrm{GeV})^2$ [5].

With quite a weak assumption about the initial conditions for the Big Bang (no sterile neutrinos at the beginning (this assumption is realized in the νMSM where the Higgs field plays the role of the inflaton [16]) the predictions and constraints can be strengthened further. Namely the DM sterile neutrino mass should be in the interval 4 keV $<$ M$_1$ $<$ 50 keV (the lowest bound is related to Lyman-α observations), the DM sterile neutrino mixing angle is predicted to be in the region $2 \times 10^{-15} < \theta_1^2 < 2 \times 10^{-10}$. To produce the DM and BAU in correct amounts, the mass of heavier neutral leptons should be in the region $M_2 \sim 2$ GeV, their level of degeneracy is constrained as $\Delta M \lesssim 10^{-4} m_{atm}$, and their mixing angle should be $\theta_2^2 \simeq 10^{-11}$. The CP asymmetry in $N_{2,3}$ decays should be on the level of 1% [5].

A direct experimental confirmation of the νMSM would be a discovery of DM sterile neutrino and a pair of highly degenerated neutral leptons. We will discuss below how these particles could be searched for.

The search for new leptons responsible for BAU [15]. Let us consider a pair of heavier singlet fermions, N_2 and N_3. Naturally, several distinct strategies can be used for the experimental search of these particles.

The first one is related to their production (θ^2 effect). The singlet fermions participate in all reactions the ordinary neutrinos do with a probability suppressed roughly by a factor θ_2^2. Since they are massive, the kinematics of, say, two body decays $K^\pm \to \mu^\pm N$, $K^\pm \to e^\pm N$ or three-body decays $K_{L,S} \to \pi^\pm + e^\mp + N_{2,3}$ changes when $N_{2,3}$ is replaced by an ordinary neutrino. Therefore, the study of *kinematics* of rare K, D and B meson decays can constrain the strength of the coupling of heavy leptons. This strategy has been used in a number of experiments for the search of neutral leptons in the past [17, 18], where the spectrum of electrons or muons originating in decays π and K mesons has been studied. The precise study of kinematics of rare meson decays is possible in Φ (like KLOE), charm and B factories, or in experiments with kaons where their initial 4-momentum is well known (like NA48 or E787 experiments).

The second strategy is to use the proton beam dump (θ^4 effect). As a first step the proton beam hitting the fixed target creates K, D or B mesons which decay and produce $N_{2,3}$. The second step is a search for decays of N in a near detector, looking for the processes "nothing" $\to$ leptons and hadrons [12, 9, 10]. To this end quite a number of already existing or planned neutrino facilities (related, e.g. to CNGS, MiniBooNE, MINOS or J-PARC), complemented by a near *dedicated* detector can be used. Finally, these two strategies can be unified, so that the production and the decay occurs inside the same detector [11].

For the mass interval $M_I < M_K$ both strategies can be used. Moreover, further constraints on the couplings of singlet fermions can potentially be derived from the reanalysis of the *already existing but never considered from this point of view* experimental data of KLOE collaboration

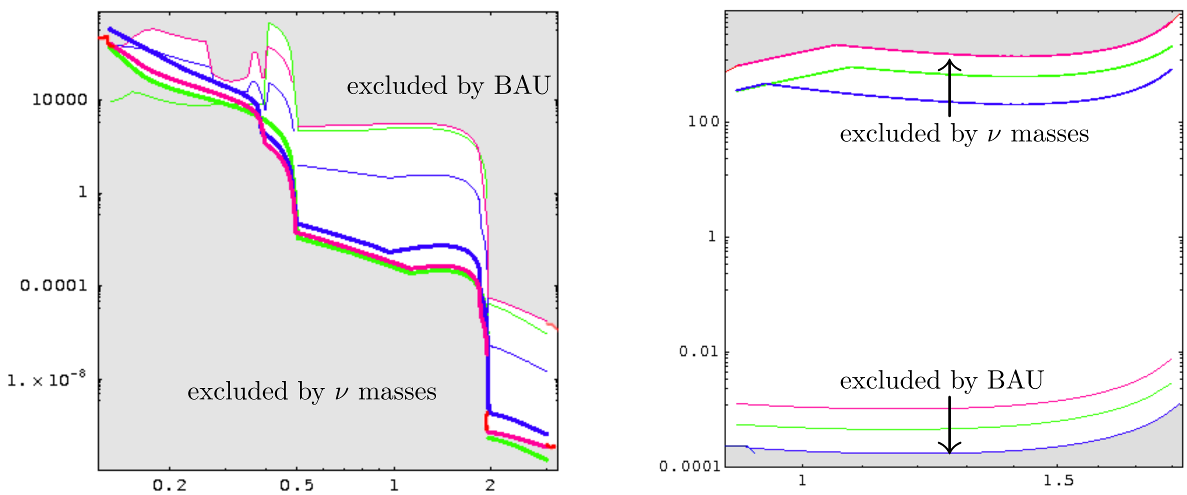

Figure 2. Left panel: The number of singlet fermions decays expected in 5 m long detector during one year with the use of J-PARC beam. Right panel: The length of detector in meters necessary to observe 10 decays of singlet fermions per year if the proton beam of the Project X is used, as a function of a mass. In the upper (lower - right panel) shaded area baryogenesis is not possible. In the lower (upper - right panel) shaded area neutrino masses cannot be explained. Different curves correspond to the different parameter choices in the νMSM.

and of the E787 experiment. In addition, the NA48/3 (P326) experiment at CERN and dedicated experiment at MINERνA site, discussed by F. Vannucci at this Conference, would allow to find or to exclude completely singlet fermions with the mass below that of the kaon.

If $m_K < M_{2,3} < m_D$ the search for the missing energy signal, potentially possible at beauty, charm and τ factories, is unlikely to gain the necessary statistics and is very difficult if not impossible at hadronic machines like LHC. So, the search for decays of neutral fermions is the most effective opportunity. The dedicated experiments on the basis of the proton beam NuMI or NuTeV at FNAL, CNGS at CERN, or J-PARC can touch a very interesting parameter range for $M_I \lesssim 1.8$ GeV. Experiments like NuSOnG (see talk by M. Shaevitz an this Conference) and HiResMν [19] should be able to explore a considerable part of the cosmologically interesting region for masses and mixing angles of singlet fermions.

Going above D-meson but still below B-meson thresholds is very hard if not impossible with present or planned proton machines or B-factories. To enter into cosmologically interesting parameter space would require the increase of the present intensity of, say, CNGS beam by two orders of magnitude or to producing and studying the kinematics of more than 10^{10} B-mesons. In Fig. 2 (left part) we present the number of singlet fermion decays expected in 5 m long detector during one year with the use of J-PARC beam (the similar figures for CNGS, NuMI and NuTeV can be found in [15]). The right part of this figure presents a length of detector necessary to observe 10 singlet fermion decays per year in X-Project beam-damp. In the upper (left panel) and lower (right panel) shaded areas these particles cannot explain BAU, and in the lower (left panel) and upper (right panel) shaded area they cannot explain the observed neutrino masses and mixings. The Fig. 2 shows that it is relatively easy to enter in the region of the parameters interesting for cosmology, whereas it is very challenging to explore all possible mixing angles of singlet fermions below the charm threshold.

The couplings of $N_{2,3}$ are too small to see them at the LHC. Inspite of this, the νMSM offers a specific prediction for the search of new physics at the LHC experiments: nothing but the Higgs in the mass interval $M_H \in [129, 189]$ GeV. This comes about since in order to solve the SM problems (in particular, the one related to inflation and to stability of the Higgs mass against radiative corrections), the νMSM must be a valid field theory all the way up to the Planck scale [4]. Above the upper limit the theory is not consistent due to Landau pole in the scalar self-coupling (for a review see [20]), whereas below the lower limit the EW symmetry breaking vacuum is not stable (for a review see [21]).

Conclusions. New physics, responsible for neutrino masses and mixings, for dark matter, and for baryon asymmetry of the universe may hide itself *below* the EW scale. This possibility can be offered by the the νMSM - a minimal model, explaining simultaneously *all well-established observational* drawbacks of the SM.

This new physics (a pair of new neutral leptons, creating the baryon asymmetry of the universe) can be searched for in dedicated experiments with the use of existing intensive proton beams at CERN, FNAL and planned neutrino facilities in Japan (J-PARC). An indirect evidence in favour of this proposal will be given by LHC, if it discovers the Higgs boson within the mass interval discussed above and nothing else. Moreover, the νMSM gives a hint on how and where to search for new physics in this case. It tells, in particular, that in order to uncover new phenomena in particle physics one should go towards high intensity proton beams or very high intensity charm or B-factories, rather than towards high energy electron-positron accelerators.

To search for DM sterile neutrino in the universe one needs an X-ray spectrometer in Space with good energy resolution $\delta E/E \sim 10^{-3} - 10^{-4}$ getting signals from our Galaxy and its dwarf satellites [22]. The laboratory search for this particle would require an extremely challenging detailed analysis of kinematics of β-decays of different isotopes [23].

Acknowledgments. This work was supported in part by Swiss National Science Foundation. It is a pleasure to thank T. Asaka, F. Bezrukov, S. Blanchet, A. Boyarsky, D. Gorbunov, A. Kusenko, M. Laine, A. Neronov, O. Ruchayskiy, and I. Tkachev for collaboration on the topics described in this talk.

References

[1] A. Strumia and F. Vissani, arXiv:hep-ph/0606054.
[2] F. Vissani, Phys. Rev. D **57** (1998) 7027.
[3] M. Shaposhnikov, arXiv:astro-ph/0703673.
[4] M. Shaposhnikov, arXiv:0708.3550 [hep-th].
[5] T. Asaka, M. Laine and M. Shaposhnikov, JHEP **0606** (2006) 053; JHEP **0701** (2007) 091; M. Shaposhnikov, JHEP **0808** (2008) 008; M. Laine and M. Shaposhnikov, JCAP **0806** (2008) 031.
[6] O. Ruchayskiy, arXiv:0704.3215 [astro-ph], A. Boyarsky et al., MNRAS **387** (2008) 1345, 1361.
[7] U. Seljak et al., Phys. Rev. Lett. **97** (2006) 191303; M. Viel et al., Phys. Rev. Lett. **97** (2006) 071301.
[8] A. Kusenko, arXiv:hep-ph/0609158.
[9] A. Vaitaitis *et al.* [NuTeV Collaboration], Phys. Rev. Lett. **83** (1999) 4943.
[10] P. Astier *et al.* [NOMAD Collaboration], Phys. Lett. B **506** (2001) 27.
[11] P. Achard *et al.* [L3 Collaboration], Phys. Lett. B **517** (2001) 75.
[12] G. Bernardi *et al.*, Phys. Lett. B **166** (1986) 479. G. Bernardi *et al.*, Phys. Lett. B **203** (1988) 332.
[13] F. Bezrukov, Phys. Rev. D **72** (2005) 071303.
[14] A. Boyarsky, O. Ruchayskiy and D. Iakubovskyi, arXiv:0808.3902 [hep-ph].
[15] D. Gorbunov and M. Shaposhnikov, JHEP **0710** (2007) 015.
[16] F. L. Bezrukov and M. Shaposhnikov, Phys. Lett. B **659** (2008) 703.
[17] T. Yamazaki *et al.*, *In *Leipzig 1984, Proceedings, High Energy Physics, vol. 1*, 262.*
[18] M. Daum *et al.*, Phys. Rev. Lett. **85** (2000) 1815.
[19] S. R. Mishra, R. Petti, and C. Rosenfeld, HiResMν03bd-Doc 18.Feb.08-V2.
[20] T. Hambye and K. Riesselmann, Phys. Rev. D **55** (1997) 7255.
[21] J. A. Casas, J. R. Espinosa and M. Quiros, Phys. Lett. B **382** (1996) 374.
[22] A. Boyarsky et al., Phys. Rev. Lett. **97** (2006) 261302.
[23] F. L. Bezrukov and M. Shaposhnikov, Phys. Rev. D **75** (2007) 053005.