PROCEEDINGS OF SCIENCE

νMSM: the model, its predictions and experimental tests

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Supplemented with three right-handed sterile neutrinos the Standard Model can explain neutrino oscillations (active neutrino masses via seesaw type-I mechanism), baryon asymmetry of the Universe (via leptogenesis by sterile-active neutrino oscillations in the primordial plasma) and dark matter phenomenon (by a population of the lightest sufficiently long-lived sterile neutrino). This seems to be the minimal extension of the SM capable of addressing all the major phenomenological issues we have. The lightest sterile neutrino (the dark matter candidate) mass is in 1-50 keV range and the mass scale of the heavier two sterile neutrinos is 0.1-50 GeV. The model predictions for neutrino physics (e.g. low neutrinoless double beta decay rate), particle physics (direct production and decay of heavy sterile neutrinos at beam-dump experiments like SHiP and colliders like ee-FCC) and astrophysics (cosmic X-rays due to dark matter sterile neutrino radiative decay) can be tested at the ongoing and future experiments.

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1. Introduction to the major phenomenological problems we have

Standard Model of particle physics (SM) accurately describes all the results of experiments dealing with electroweak and strong interactions, except neutrino sector. Indeed, neutrino oscillations yield the only direct evidence for the physics beyond the SM. There are two more puzzles certainly asking for new physics: dark matter phenomena and baryon (or matter-antimatter) asymmetry of the Universe. SM and General Relativity fail to explain them. One can introduce a new ingredient—sterile neutrinos—in order to address the issue of neutrino oscillations. Sterile neutrinos through mixing with active neutrinos provide the latter with masses and mixing required to properly describe all the confirmed results of neutrino oscillation experiments. Quite remarkably, the same sterile neutrinos are capable of unraveling the two other, cosmological, puzzles. Namely, the lightest sterile neutrino can serve as dark matter, while either sterile-active neutrino oscillations in the primordial plasma or sterile neutrino decays can produce the lepton asymmetry (leptogenesis) which transfers to the baryon asymmetry by the electroweak sphalerons. This is one of the most economical way of extending the SM (only 6 new degrees of freedom are introduced) in such a way that all the three major phenomenological problems find viable solutions.

Sterile neutrinos is one of the optional physics beyond the SM. These new fermions are called *sterile* because they are singlet with respect to the SM gauge group. They are also called *neutrino* because they mix with the SM neutrinos (which are called then as *active*). This new physics exhibits several attractive features. First, the modification can be achieved within the renormalizable class of models. Second, only two Majorana fermions, sterile neutrinos, are needed to describe the neutrino oscillations. Third, the two sterile neutrinos are enough to generate the required amount of the matter-antimatter asymmetry via the leptogenesis in the early Universe. Fourth, the explanation of dark matter phenomena implies one more sterile neutrinos at any rate. Thus, simultaneous solution of all the three problems asks for three sterile neutrinos at least. Fifth, the three Majorana fermions provide the active neutrinos with right-handed components making the SM matter content left-right symmetric.

2. νMSM: a specific variant of see-saw type I model

This talk is devoted to a specific variant of the three-fermion modification of the SM, called νMSM for *Neutrino Minimal extension of the SM* [1, 2]. It advertises the philosophy of minimalism and completeness: use as little “new physics” as possible required to describe correctly the neutrino oscillations and then explain the dark matter and baryon asymmetry of the Universe.

The most general renormalizable lagrangian with 3 right-handed neutrinos N_I, $I = 1,2,3$ reads

$$\mathscr{L}_N = \overline{N}_I i\partial\!\!\!/ N_I - f_{\alpha I}\overline{L}_\alpha \tilde{H} N_I - \frac{M_{N_I}}{2}\overline{N}_I^C N_I + \mathtt{h.c.}\,, \tag{2.1}$$

where M_{N_I} are Majorana masses and $f_{\alpha I}$ are Yukawa couplings, $\alpha = e,\, \mu,\, \tau$. To describe 9 physical parameters in the active neutrino sector the lagrangian (2.1) contains 18 parameters: 3 Majorana masses, 15 Yukawa couplings. When Higgs doublet gets nonzero vacuum expectation value $\langle H\rangle \equiv v/\sqrt{2}$ the Yukawas take responsibility for the Dirac mass matrix $M^D = \hat{f}v/\sqrt{2}$, which possesses 3 mass eigenvalues, 6 mixing angles and 6 CP-violating phases. The 9 out of 18 parameters remain free after fitting to the active neutrino data, which opens a possibility to explain the cosmological problems we discussed above.

In case of a hierarchy between diagonal and off-diagonal components of the neutral fermion mass matrix, $M_N \gg M_D \propto v\,\frac{f}{\sqrt{2}}$, we find the eigenvalues in sterile and active subsectors:

$$\simeq \hat{M}_N \qquad \text{and} \qquad \hat{m}^\nu = -\hat{M}_D\frac{1}{\hat{M}_N}\hat{M}_D^T \propto f^2\frac{v^2}{M_N} \propto \frac{M_D^2}{M_N^2}M_N \lll M_N\,,$$

which explicitly demonstrates the see-saw mechanism ensuring that the active neutrino masses are double suppressed by the chosen small active-sterile mixing

$$\hat{\theta} = M_D^T M_N^{-1} = \hat{f}^T M_N^{-1} v/\sqrt{2} \ll 1\,. \tag{2.2}$$

This mixing enters the relation between the active neutrino gauge states ν_α, and mass states ν_i, $i = 1,2,3$ as follows

$$\nu_\alpha = U_{\alpha i}\nu_i + \theta_{\alpha I} N_I^C \tag{2.3}$$

with $\hat{U}$ being the Pontecorvo–Maki–Nakagawa–Sakata matrix describing the very mixing in active neutrino sector.

Note that the see-saw mechanism[1] itself says nothing about the sterile neutrino mass scale M_N. Indeed, one can have one and the same active neutrino masses either with Yukawas of order one, $f \sim 1$, and high neutrino mass scale, $M_N \sim 10^{14}$ GeV or with small Yukawas, $f \lll 1$ and neutrinos below the electroweak scale. In both cases one expects that mixing (2.2) is small but not necessarily: the matrix eigenvalues might be small even with all the entries of order one, though it implies a certain fine tuning between them. The Yukawa interactions (2.1) yield proportional to M_I quantum corrections to the Higgs boson mass, hence relatively light sterile neutrinos may be advertised as more natural choice.

νMSM is a variant of the see-saw model with all the three neutrino masses below electroweak scale. Two of the heaviest neutrinos provide the active neutrinos with masses via see-saw type I mechanism. They are taken to be degenerate in mass, $|M_2 - M_3| \ll M_2$, which amplifies the oscillations in the primordial plasma and helps to efficiently redistribute the lepton asymmetry between the active and sterile neutrinos. Lepton number is violated explicitly by the Majorana mass term in (2.1). Complex phases of Yukawas $f_{\alpha I}$ trigger CP-violation, one of the Sakharov's condition of successful asymmetry generation. The asymmetry in active neutrino sector transfers to the baryon asymmetry by electroweak sphaleron transitions. Thus, they are responsible for both active neutrino masses and baryon asymmetry of the Universe [2]. The allowed region of masses $M = M_2 \approx M_3$ and sterile neutrino lifetimes $\tau \propto 1/\theta_{\alpha I}^2$ is presented in Fig. 1. It is confined by curves "BAU" and "Seesaw", there is also a limit from Big Bang Nucleosynthesis. Letters "N" and "I" refer to the cases of normal and inverted hierarchies of active neutrino masses, respectively.

Another neutrino N_1 is in keV mass-range and forms the dark matter component. This component is unstable because of active-sterile neutrino mixing: decays into three active neutrinos are kinematically allowed. Dark matter lifetime must exceed the age of the Universe, which for the sterile neutrino places an upper limit on the mixing strong enough to make the dark matter neutrino

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[1] Here we are dealing with type I see-saw [3].

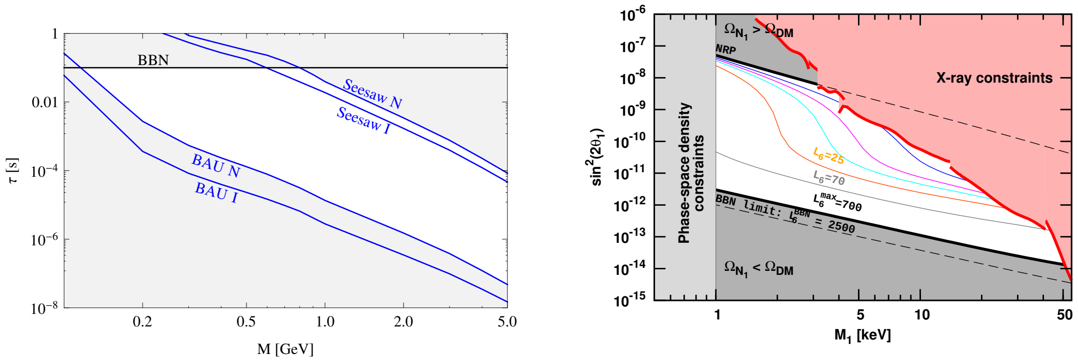

Figure 1: The allowed part of model parameter space is blank, see main text for details. *Right panel*: the heavy degenerate neutrinos [4]. *Left panel*: the dark matter neutrino [5].

contribution to the active neutrino masses negligibly small. Consequently, *the general prediction of νMSM is two massive and one almost massless active neutrino*. There is a very bright signature of dark matter sterile neutrino associated with its radiative decay into photon and active neutrino,

$$N_1 \to \gamma \nu_\alpha \tag{2.4}$$

coming from 1-loop diagram with virtual W-boson and charged lepton l_α. Then one expects an almost monochromatic line in cosmic X-rays due to the two-body radiative decays of dark matter particles in the Milky Way and all other galaxies. The absence of such a signal in X-ray telescope data imposes strong constraints on the model parameters, presented in Fig. 1.

These constraints together with limits from the phase space densities, see Ref. [6] for details, exclude the possibility of dark matter production in the early Universe through the ordinary active-sterile oscillations in the primordial plasma. However, another mechanism exploiting this mixing remains as a viable option: in the presence of lepton anisotropy in the primordial plasma the oscillations get amplified and the same amount of dark matter can be generated with (much) smaller mixing angle. In Fig. 1 we indicate the value of mixing needed at a given sterile neutrino mass M_1 to produce the right abundance of dark matter by utilizing this *resonant production* for a set of lepton asymmetry amount, L_6 is in units of 10^{-6}. To generate the required asymmetry within the νMSM one must resort to a strongly fine-tuned scenario with highly degenerate masses of the heavy neutrinos, much more degenerate that needed for the successful leptogenesis. Otherwise one must involve another mechanism of dark matter production, which implies new fields and interactions to be incorporated into νMSM. A viable option is sterile neutrino dark matter production by decaying inflaton [7].

3. Testing νMSM

An attractive feature of νMSM is that its major predictions can be directly tested, and largest part of parameter space can be dully explored with existing experimental techniques.

The sterile neutrino dark matter can be probed thanks to the expected radiative two-body decay (2.4). Recently an anomalous signal of such type has been observed [8] in stacking spectra of many galaxies, especially Perseus cluster, and later in the spectrum of Andromeda galaxy[9].

The anomalous signal can be explained by sterile neutrino of mass $M_1 \approx 7\,\text{keV}$ with the mixing angle inside the allowed region in Fig. 1. This explanation can be tested to a certain extent by the upcoming space mission Astro-H.

The two heavier sterile neutrinos initiate various lepton number violating processes. Their virtual contributions to the processes like $\mu \to e\gamma$, $\mu \to eee$, etc [10] and double beta decay [11, 10] are too small to be observed, since the rates are proportional to the quartic mixing angle. However, sterile neutrinos can be searched for in weak decays of mesons, where an admixture of the heavy component emerges due to mixing (2.3). The decay rates go proportionally to the squared mixing angles, and the interesting branching ratios start at the level of 10^{-7}-10^{-8} for D- and B-mesons, see Ref. [12] for details. The numbers are not very small, but seem beyond the reach of LHCb and Belle-II.

Much more promising are fixed-target type experiments, where the heavy mesons produced by the incident protons on target decay into sterile neutrinos. Being very weakly (small mixing!!) interacting and sufficiently long-lived, see Fig. 1, they propagate freely through the downstream dump and then decay in the vacuum vessel producing a couple of charged particles, e.g.

$$N_{2,3} \to \pi^{\pm}\mu^{\mp}, \quad e^+e^-\nu, \ \mathtt{etc}$$

These decays suggest a very-well recognizable signature: two charged tracks coming out of a single vertex in vacuum. The number of signal events is proportional to the quartic mixing angle, that is a small number, but it is compensated by the huge amount of protons on target (PoT), typically $\sim 10^{18}$-10^{22}. Sterile neutrinos have been searched in previous beam dump experiments and a part of parameters space can be excluded from the analysis of their negative results, see Fig. 2. The blank region there between the “Seesaw”, “BBN” and “BAU” lines is phenomenologically and cosmologically viable and the red line in that region shows the expected sensitivity [4] of a 5m × 5m × 100m size detector placed at a distance of 100 m downstream the dump for 400 GeV protons assuming the intensity of 10^{20}PoT available with CERN SPS. Recently this idea has been developed into proposal of the SHiP experiment [13].

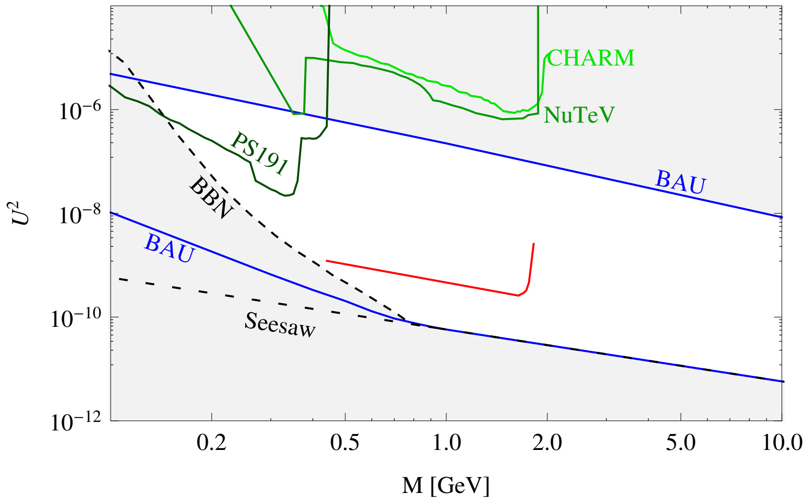

Figure 2: The allowed part (blank) of model parameter space for heavy neutrinos [4].

4. Conclusions

To summaries, the νMSM suggests the most economic explanation of neutrino oscillations within renormalizable approach, where only two Majorana neutrinos are required. The model is capable of explaining baryon asymmetry of the Universe even without CP-violation in the active neutrino sector, i.e. at $\delta_{CP} = 0$. One more neutrino can serve as (naturally Warm) dark matter.

Direct tests of the model predictions are feasible. Searches for dark matter can be performed at future space telescopes observing the sky in X-rays: a narrow line positioned and energy equal to half of the neutrino mass is anticipated due to neutrino two-body radiative decay. Searches for seesaw sterile neutrinos responsible for leptogenesis can be carried out at future beam-dump experiments like SHiP fixed-target experiment at CERN SPS proton beam [13]. At SHiP the two charged particles (tracks) from a singe vertex form a golden signature of νMSM.

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