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COSMOLOGY VERSUS STANDARD MODEL

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I will discuss a proposal for a unified solution of the problems of neutrino masses, dark matter, baryon asymmetry of the Universe and inflation, which *does not require* introduction of any new energy scale besides already known, namely the electroweak and the Planck scales. This point of view, supplemented by a requirement of simplicity, has a number of experimental predictions which can be tested, at least partially, with the use of existing accelerators and the LHC, with current and future X-ray telescopes, and with the Planck mission.

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INTRODUCTION

The Standard Model (SM) of elementary particles has successfully predicted a number of particles and their properties. However, there is no doubt that the SM is not a final theory. Indeed, over the last several decades it became increasingly clear that it fails to explain a number of *observed* phenomena in particle physics, astrophysics and cosmology. These phenomena *beyond the SM* (BSM) are:

(i) *Neutrino oscillations* (transition between neutrinos of different flavors).

(ii) *Baryon asymmetry* (excess of matter over anti-matter in the Universe).

(iii) *Dark matter* (some 80% of all matter in the Universe consists of unknown particles).

(iv) *Inflation* (a period of the rapid accelerated expansion in the early Universe).

(v) *Dark energy* (late time accelerated expansion of the Universe).

This list of *well-established observational* drawbacks of the SM is complete at the present time[*]. All the other BSM problems are those of theoretical fine-tuning: the «gauge hierarchy problem», strong CP-problem, etc.

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[*] There are few other problems in astrophysics and cosmology, such as the origin of high-energy cosmic rays, the existence of 0.511 MeV annihilation line in the direction of the Galaxy center, pulsar-kick velocities, etc. However, these phenomena do not provide a «smoking gun» signature for BSM physics as several standard physics explanations were proposed to deal with them. There are also several anomalies in particle physics experiments, such as discrepancy between experiment and theory prediction of anomalous magnetic moment of muon, LSND anomaly, evidence of the neutrinoless double decay presented by a part of the Heidelberg group, etc. However, none of these anomalies has been confirmed by other experiments.

Once the SM is not a fundamental theory, one has to ask oneself: «At what energies should the SM be superseded by some other, more fundamental theory?»

The existence of gravity with the coupling related to the Planck scale $M_{\rm Pl} = G_N^{-1/2} = 1.2 \cdot 10^{19}$ GeV (G_N is the Newtonian gravitational constant) implies that the cutoff is *at least* below the Planck scale. If the cutoff is identified with $M_{\rm Pl}$, the low-energy Lagrangian can contain all sorts of higher-dimensional $SU(3) \times SU(2) \times U(1)$ invariant operators, suppressed by the Planck scale:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_{n=5}^{\infty} \frac{\mathcal{O}_n}{M_{\rm Pl}^{n-4}} \ . \qquad (1)$$

Here $\mathcal{L}_{\rm SM}$ is the Lagrangian of the SM. These operators lead to a number of physical effects that cannot be described by the SM, such as neutrino masses and mixings, proton decay, etc.

Alternatively, one can put a cutoff $\Lambda \ll M_{\rm Pl}$ in (1). This would imply that new physics (and new particles) appear much below the Planck scale at energies $E \sim \Lambda$. If $\Lambda \gg M_W$, where M_W is the mass of the weak W boson, the resulting theory suffers from the so-called *gauge hierarchy problem*, i.e., the problem of quantum stability of the mass of the Higgs boson against quantum corrections from heavy particles.

This talk is devoted to the short description of the scenario for BSM physics and its consequences for astrophysics and cosmology, in which no any new energy scale (besides the *electroweak* and the *Planck* scales) is introduced. In such an approach the hierarchy problem gets shifted to the Planck scale and one has no firm reasons to believe that the field-theoretical logic is still applicable to it. Due to the lack of space, no references will be given to the original works. Also, the problem of Dark Energy will not be discussed. More details can be found in reviews [1, 2], containing the references to original papers.

1. CONSTRUCTION OF THE MINIMAL MODEL

The assumption of the absence of a new energy scale between the Fermi and Planck scales is very powerful, as it allows one to conclude that new light particles must be added to the Standard Model. Indeed, the observed pattern of neutrino oscillations cannot be explained by the action (1) with the Planck scale cutoff. The lowest order five-dimensional operator

$$\mathcal{O}_5 = A_{\alpha\beta}(\bar{L}_\alpha \tilde{\phi}) \left(\phi^\dagger L_\beta^c\right) \qquad (2)$$

leads to the Majorana neutrino masses of the order $m_\nu \sim v^2/M_{\rm Pl} \simeq 10^{-6}$ eV (here L_α are left-handed leptonic doublets, the index $\alpha = e, \mu, \tau$ labels generations, ϕ is a Higgs doublet with $\tilde{\phi}_j = i(\tau_2)_j^k \phi_k^*$, c is the sign of charge conjugation, and $v = 174$ GeV is the vacuum expectation value of the Higgs field). At the same time, the atmospheric neutrino mass difference sets the scale $m_{\rm atm} \simeq 0.05$ eV, where $m_{\rm atm} = \sqrt{|\Delta m^2_{\rm atm}|}$, $|\Delta m^2_{\rm atm}| = 2.40^{+0.12}_{-0.11} \cdot 10^{-3}$ eV^2.

A way to extend the SM suggests itself after a look at the fermionic content of the SM, see Fig. 1, *a*. All left fermions of the SM, except neutrinos, have their right counter-parts. Let us complete this table by adding three right-handed neutrinos N_I, see Fig. 1, *b*. We will call the resulting theory the νMSM — the Neutrino Minimal Standard Model. It is defined by a renormalizable Lagrangian,

$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\bar{N}_I \partial_\mu \gamma^\mu N_I - \left(F_{\alpha I}\, \bar{L}_\alpha N_I \tilde{\phi} - \frac{M_I}{2}\, \bar{N}^c_I N_I + \text{h.c.} \right), \qquad (3)$$

where $F_{\alpha I}$ are new Yukawa couplings. The Majorana masses M_I are consistent with the gauge symmetries of the SM. Without loss of generality, the Majorana mass matrix can be chosen in diagonal form; we keep the number of N_I $\mathcal{N}$ arbitrary for the moment.

SM fermions quarks

Left	u	d	c	s	t	b
Right	u	d	c	s	t	b
Left	ν_e	e	ν_μ	μ	ν_τ	τ
Right		e		μ		τ

Leptons *a*

νMSM fermions quarks

Left	u	d	c	s	t	b
Right	u	d	c	s	t	b
Left	ν_e	e	ν_μ	μ	ν_τ	τ
Right	N_e	e	N_μ	μ	N_τ	τ

Leptons *b*

Fig. 1. Femions of the SM (*a*) and of the νMSM (*b*)

This model can be valid up to the Planck scale, and is able to explain neutrino masses and oscillations, dark matter and baryon asymmetry of the Universe, and provide the inflation, making the universe flat, homogeneous and isotropic, and producing the necessary spectrum of perturbations. This is described below.

2. NEUTRINO MASSES

If the Dirac masses $M_D = F_{\alpha I}\langle\phi\rangle$ are much smaller than Majorana masses M_I, *the type I see-saw formula* holds:

$$(m_\nu)_{\alpha\beta} = -\sum_{I=1}^{\mathcal{N}} (M_D)_{\alpha I} \frac{1}{M_I} (M_D^T)_{I\beta}, \qquad (4)$$

where m_ν is a 3×3 matrix of active neutrino masses, mixings and (possible) CP-violating phases. An elementary analysis of (4) shows that the number of right-handed singlet fermions $\mathcal{N}$ must be at least two to fit the data of neutrino oscillations. If there were only one sterile neutrino, then two active neutrinos would be massless. With two singlet fermions only one of the active neutrinos is massless, which does not contradict experiment. Moreover, in this case the number of new parameters in the Lagrangian (3) is 11 (they can be counted as follows: 2 Majorana masses, 2 Dirac masses, 4 mixing angles and 3 CP-violating phases) and is larger than the number of parameters (7) describing the mass matrix of active neutrinos with one zero eigenvalue. In other words, already for $\mathcal{N} = 2$ the Lagrangian (3) can describe the pattern of neutrino masses and mixings observed experimentally. Of course, the situation gets even more relaxed for $\mathcal{N} = 3$. In this case one of the singlet fermions may be decoupled from active fermions without spoiling the explanation of neutrino mixing.

The see-saw formula (4) leaves the mass of singlet neutrinos to be a free parameter: multiplying M_D by any number x and M_I by x^2 does not change the right-hand side of formula (4). Therefore, the choice of M_I is a matter of theoretical prejudice, which cannot be fixed by active neutrinos experiments only. To estimate what neutrino data implies for the Yukawa couplings, we take the larger of two mass splittings $|\Delta m^2_{\text{atm}}|$ and find from the see-saw relations (4) that

$$|F|^2 \approx \frac{\sqrt{|\Delta m^2_{\text{atm}}|}M_I}{v^2} \sim 2 \cdot 10^{-15} \frac{M_I}{\text{GeV}}, \tag{5}$$

where $|F|^2$ is a typical value of Yukawa couplings $F_{\alpha I}$. The condition $M_I \lesssim 10^2$ GeV would imply that $|F|^2 \lesssim 10^{-13}$.

3. DARK MATTER

It was noticed long ago that a sterile neutrino may be an interesting Dark Matter candidate. In the νMSM, it is simply one of the singlet fermions (for definiteness we consider it to be N_e). The interaction strength of the sterile neutrino with the matter is *super-weak* with the characteristic strength $\theta\, G_F$, where G_F is the Fermi constant, and *mixing angle* $\theta \ll 1$ is defined as

$$\theta_1^2 = \sum_{\alpha=e,\mu,\tau} \frac{v^2 |F_{\alpha 1}|^2}{M_1^2} \,. \tag{6}$$

For the lightest singlet fermion N_e to be a legitimate DM candidate, the following conditions should be satisfied.

(i) *Cosmological production.* N_e are created in the early Universe in reactions $l\bar{l} \to \nu N_e$, $q\bar{q} \to \nu N_e$, etc. We should get the correct DM abundance.

(ii) *Stability.* Through its mixing with the usual neutrinos, N_e can decay (via Z-boson exchange) into three (anti)neutrinos. The lifetime of N_e must exceed the age of the Universe.

(iii) *X rays.* N_e decays radiatively, $N_e \to \gamma\nu$, producing a narrow line which can be detected. This line can be searched for with the use of X-ray satellites such as Chandra or XMM-Newton. It has not been seen yet.

(iv) *Structure formation.* If N_e 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. The analysis of the smallest DM-dominated objects (dwarf spheroidal galaxies of the Milky Way, dSphs) gives the most conservative constraint $M_{\rm DM} \geqslant 400$ eV.

The combined constrains are shown in Fig. 2, *a*. The allowed region of parameters for DM sterile neutrinos produced via mixing with the active ones corresponds to the unshaded region. Two thick black lines bounding this region are production curves for nonresonant production (upper line, $L_6 = 0$, where L_6 is the lepton asymmetry defined by $L_6 \equiv 10^6(n_{\nu_e} - n_{\bar{\nu}_e})/s$, s is the entropy density) and for resonant production (RP) with the maximal lepton asymmetry, attainable in the νMSM (lower line, $L_6^{\max} = 700$). The thin curves between these lines represent (from top to bottom) production curves for $L_6 = 8, 12, 16, 25, 70$. The dark grey shaded region in the upper right corner represents X-ray constraints (rescaled by a factor of 2 to account for possible systematic uncertainties in the determination of DM content). The black dash-dotted line shows approximately the RP models with minimal $\langle q \rangle$ for each mass, i.e., the family of models with the largest cold component. The black filled circles along this line are compatible with the Lyman-α bounds, while those with $M_1 \leqslant 4$ keV are also compatible with X-ray bounds. Region below 1 keV is ruled out from the phase-space density arguments.

The fact that the constraints exist from all sides makes the model testable with the use of X-ray observations. Unfortunately, the new data from *Chandra* and *XMM-Newton* can hardly improve the constraints by more than a factor of 10 because these instruments have the energy resolution exceeding greatly the expected width of the DM line. To go much further, one would need an improvement of spectral resolution up to the natural line width ($\Delta E/E \sim 10^{-3}$), have a reasonably wide field of view $\sim 1^\circ$ (size of a dSph) and perform a wide energy scan, from $\mathcal{O}(100)$ eV to $\mathcal{O}(100)$ keV.

4. BARYON ASYMMETRY

The baryon (B) and lepton (L) numbers are not conserved in the νMSM. The lepton number is violated by the Majorana neutrino masses, while $B+L$ is broken by the electroweak anomaly. As a result, the sphaleron processes with baryon-number nonconservation are in thermal equilibrium for $100 < T < 10^{12}$ GeV. As for CP breaking, the νMSM contains 6 CP-violating phases in the lepton sector and a Kobayashi–Maskawa phase in the quark sector. This makes two

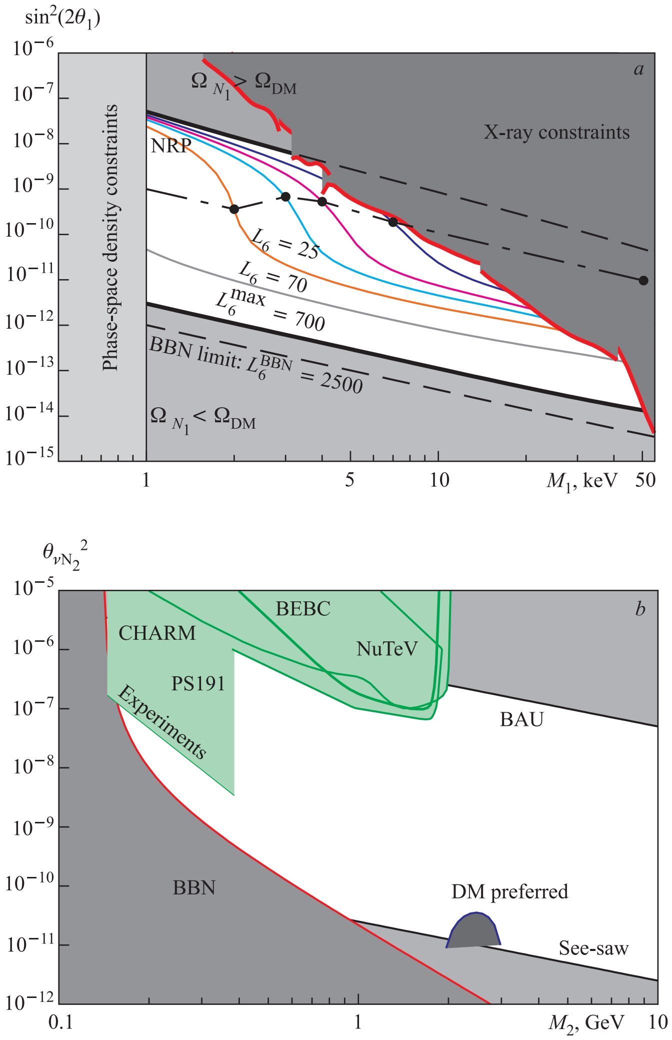

Fig. 2. *a*) Constraints on the mixing angle of DM sterile neutrinos. *b*) Constraints on the mixing angle of BAU generating singlet fermions

of the Sakharov conditions for baryogenesis satisfied. Similarly to the SM, this theory does not have an electroweak phase transition with allowed values for the Higgs mass, making impossible the electroweak baryogenesis, associated with the nonequilibrium bubble expansion. However, the νMSM contains extra degrees of freedom — sterile neutrinos — which may be out of thermal equilibrium exactly because their Yukawa couplings to ordinary fermions are very small. The latter fact is a key point for the baryogenesis in the νMSM, ensuring the validity of the third Sakharov condition.

Remarkably, a pair of nearly degenerate light singlet fermions $N_{2,3}$ leads to efficient baryogenesis due to the mechanism related to coherent oscillations of right-handed neutrinos. 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 $T_{\rm EW} \sim 100$ GeV. 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 nonperturbative EW effects.

In Fig. 2, *b* we present different constraints on singlet fermion mixing angle versus their mass. Above the line 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 $T_{\rm EW}$ 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.

5. INFLATION

Within the variety of inflationary models there is one which plays a special role. It does not require introduction of any new physics and identifies the inflaton with the Higgs field of the Standard Model. The key observation which allows such a relation is associated with a possible nonminimal coupling of the Higgs field H to the gravitational Ricci scalar R,

$$L_{\rm nonminimal} = \xi H^\dagger H R. \tag{7}$$

For large Higgs backgrounds $\xi h^2 \gtrsim M_P^2$ (here $M_P = 2.4 \cdot 10^{18}$ GeV is the Planck scale and $h^2 = 2H^\dagger H$) the masses of all the SM particles *and* the induced Planck mass $[M_P^{\rm eff}]^2 = M_P^2 + \xi h^2$ are proportional to one and the same parameter, leading to independence of physical effects on the magnitude of h. In other words, the Higgs potential in the large-field region is effectively flat and can result in successful inflation.

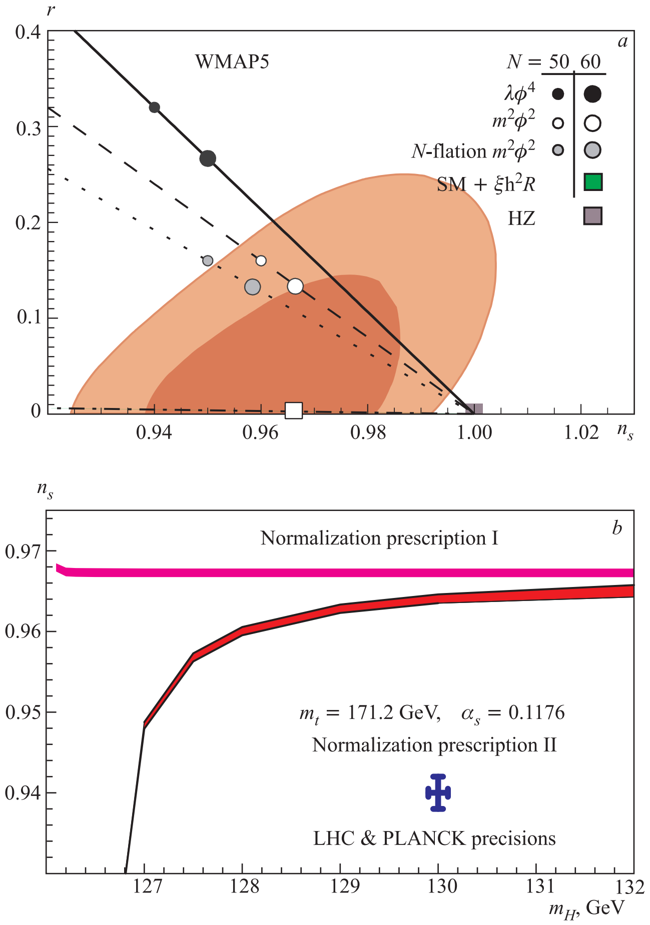

Fig. 3. *a*) The allowed WMAP region for inflationary parameters (r, n_s). The white box is our prediction for Higgs inflation. Black and white dots are predictions of usual chaotic inflation with $\lambda\phi^4$ and $m^2\phi^2$ potentials, HZ is the Harrison–Zeldovich spectrum. *b*) Dependence of the spectral index of scalar perturbations on the Higgs mass in two different renormalization prescriptions, related to the computations in the Jordan and Einstein frames. The cross indicates the accuracy to be achieved in the measurements of the Higgs mass at the LHC and of the spectral index n_s with the Planck satellite

The constant ξ is fixed by the Higgs mass and by the amplitude of scalar fluctuations known from COBE observations of the CMB. After inflation the Universe is heated up to the temperature $T = T_{\mathrm{reh}} > 1.5 \cdot 10^{13}$ GeV, creating all particles of the SM.

Higgs inflation predicts the specific values for spectral indices describing scalar (n_s) and tensor (r) perturbations, which are in accordance with the WMAP-5 observations, see Fig. 3, *a*. It reveals the nontrivial relation between the Higgs mass and properties of cosmological perturbations, shown in Fig. 3, *b*.

6. SUMMARY OF 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. For normal (inverted) hierarchy the constraints read: $1.3 < m_{\beta\beta} < 3.4$ meV ($13 < m_{\beta\beta} < 50$ 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 (it is weaker than the one coming from Lyman-α discussed above). Direct experimental searches and BBN require $M_{2,3} > 140$ MeV, whereas baryogenesis due to sterile neutrino oscillations is possible if $\Delta M = |M_2 - M_3| < 800\ m_{\rm atm}\,(M/{\rm GeV})^2$.

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) the predictions and constraints can be strengthened further. Namely, the DM sterile neutrino mass should be in the interval $4 < M_1 < 50$ keV (the lowest bound is related to Lyman-α observations), the DM sterile neutrino mixing angle is predicted to be in the region $2 \cdot 10^{-15} < \theta_1^2 < 2 \cdot 10^{-10}$. 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 $\Delta M \lesssim 10^{-4} m_{\rm atm}$, 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%.

Higgs inflation is only possible in a specific interval of the Higgs boson masses, $m_{\rm min} < m_H < m_{\rm max}$, where

$$m_{\rm min} = \left[126.1 + \frac{m_t - 171.2}{2.1} \cdot 4.1 - \frac{\alpha_s - 0.1176}{0.002} \cdot 1.5\right]\ {\rm GeV}, \tag{8}$$

and

$$m_{\rm max} = \left[193.9 + \frac{m_t - 171.2}{2.1} \cdot 0.6 - \frac{\alpha_s - 0.1176}{0.002} \cdot 0.1\right]\ {\rm GeV}, \tag{9}$$

with theoretical uncertainty of ±2 GeV. Moreover, the inflationary spectral indices have definite values in the Higgs inflation, what can be tested by the Planck satellite.

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 the 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 us, 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. The laboratory search for this particle would require an extremely challenging detailed analysis of kinematics of β decays of different isotopes.

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