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Next decade of sterile neutrino studies

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ABSTRACT

We review the status of sterile neutrino dark matter and discuss astrophysical and cosmological bounds on its properties as well as future prospects for its experimental searches. We argue that if sterile neutrinos are the dominant fraction of dark matter, detecting an astrophysical signal from their decay (the so-called 'indirect detection') may be the only way to identify these particles experimentally. However, it may be possible to check the dark matter origin of the observed signal unambiguously using its characteristic properties and/or using synergy with accelerator experiments, searching for other sterile neutrinos, responsible for neutrino flavor oscillations. We argue that to fully explore this possibility a dedicated cosmic mission – an X-ray spectrometer – is needed.

1. Dark matter problem and particle physics

The nature of dark matter is among the most intriguing questions of modern physics. There is a body of strong and convincing evidence of its existence. Indeed, numerous independent tracers of gravitational potential (observations of the motion of stars in galaxies and galaxies in clusters; emissions from hot ionized gas in galaxy groups and clusters; 21 cm line in galaxies; both weak and strong gravitational lensing measurements) demonstrate that the dynamics of galaxies and galaxy clusters cannot be explained by the Newtonian potential created by visible matter only. Moreover, cosmological data (analysis of the cosmic microwave background anisotropies and of the statistics of galaxy number counts) show that the cosmic large scale structure started to develop much before decoupling

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of photons at recombination of hydrogen in the early Universe and, therefore, much before ordinary matter could start clustering. This body of evidence points at the existence of a new substance, universally distributed in objects of all scales and providing a contribution to the total energy density of the Universe at the level of about 25%. Various attempts to explain this phenomenon by the presence of macroscopic compact objects (such as, for example, old stars) or by modifications of the laws of gravity (or of dynamics) failed to provide a consistent description of all the above phenomena. Therefore, a microscopic origin of dark matter phenomenon (i.e. a new particle or particles) remains the most plausible hypothesis.

The only electrically neutral and long-lived particle in the Standard Model are neutrinos. As the experiments show that neutrinos have mass, they could play the role of dark matter particles. Neutrinos are involved in weak interactions that keep these particles in the early Universe in thermal equilibrium down to the temperatures of few MeV. At smaller temperatures, the interaction rate of weak reactions drops below the expansion rate of the Universe and neutrinos "freeze out" from the equilibrium. Therefore, a background of relic neutrinos was created just before primordial nucleosynthesis. As interaction strength and, therefore, decoupling temperature and concentration of these particles are known, their present day density is fully defined by the sum of the masses for all neutrino flavors. To constitute the whole DM this mass should be about 11.5 eV (see e.g. [1]). Clearly, this mass is in conflict with the existing experimental bounds: measurements of the electron spectrum of β-decay put the combination of neutrino masses below 2 eV [2] while from the cosmological data one can infer an upper bound of the sum of neutrino masses is 0.58 eV at 95% CL [3]. The fact that neutrinos could not constitute 100% of DM follows also from the study of phase space density of DM dominated objects that should not exceed the density of degenerate Fermi gas: fermionic particles could play the role of DM in dwarf galaxies only if their mass is above few hundreds of eV (the so-called 'Tremaine–Gunn bound' Tremaine, 1979, for review see [4] and references therein) and in galaxies if their mass is tens of eV. Moreover, as the mass of neutrinos is much smaller than their decoupling temperature, they decouple relativistic and become non-relativistic only deeply in matter-dominated epoch ("*hot dark matter*"). For such a dark matter the history of structure formation would be very different and the Universe would look rather differently nowadays [5]. All these strong arguments prove convincingly that *dominant fraction of dark matter* cannot be made of the Standard Model neutrinos and therefore *the Standard Model of elementary particles does not contain a viable DM candidate.* Therefore, the DM particle hypothesis necessarily implies an extension of the SM.

Phenomenologically little is known about the properties of DM particles. The mass of fermionic DM is limited from below by the 'Tremaine–Gunn bound'.[1] They are not necessarily stable, but their lifetime should significantly exceed the age of the Universe (see e.g. [6]); DM particles should have become non-relativistic sufficiently early in the radiation-dominated epoch (although a sub-dominant fraction might have remained relativistic much later).

A lot of attention has been devoted to the class of dark matter candidates called *weakly interacting massive particles* (WIMPs) (see e.g. [7,8] for review). These *hypothetical* particles generalize the neutrino DM [9]: they also interact with the SM sector with roughly electroweak strength, however their mass is large enough so that these particles become non-relativistic already at decoupling. In this case the present day density of such particles depends very weakly (logarithmically) on the mass of the particle as long as it is heavy enough. This "universal" density happens to be within the order of magnitude consistent with DM density (the so-called "*WIMP miracle*"). Due to their large mass and interaction strength, the lifetime of these particles would be extremely short and therefore some special symmetry has to be imposed in the model to ensure their stability.

The interest for this class of candidates is due to their potential relation to the electroweak symmetry breaking, which is being tested at the LHC in CERN. In many models trying to make the Standard Model "natural" like, for example, supersymmetric extensions of the Standard Model, there are particles that could play the role of WIMP dark matter candidates. The WIMP searches are important scientific goals of many experiments. Dozens of dedicated laboratory experiments are conducted to detect WIMPs in the Galaxy halo by testing their interaction with nucleons (*direct detection experi-*

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[1] A much weaker bound, based on the Liouville theorem, can be applied for bosonic DM, see e.g. [178,179].

ments) (see e.g. [10] and references therein). Searches for the annihilation products of these particles (*indirect detection*) are performed by PAMELA, Fermi and other high-energy cosmic missions (see e.g. reviews [11,12]). No convincing signals has been observed so far in either "direct" or "indirect" searches.

Additionally, no hints of new physics at electroweak had turned up at the LHC or in any other experiments. This makes alternative approaches to the DM problem ever more viable.

2. Sterile neutrino dark matter

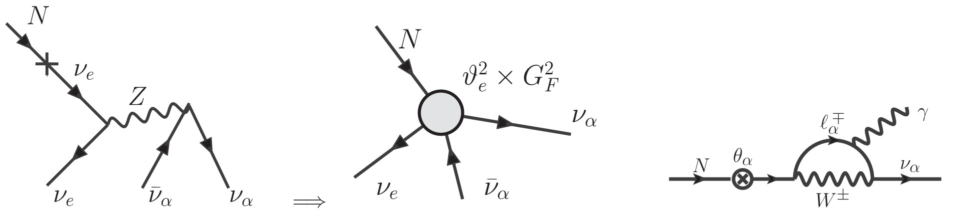
Another viable generalization of the neutrino DM idea is given by *sterile neutrino dark matter* scenario [13–20], see [14,15] for review. Sterile neutrino is a right-chiral counterpart of the left-chiral neutrinos of the SM (called '*active* ' neutrinos in this context). Adding these particles to the SM Lagrangian makes neutrinos massive and is therefore their existence provides a simple and natural explanation of the observed neutrino flavor oscillations. These particles are *singlet leptons* because they carry no charges with respect to the Standard Model gauge groups (hence the name), and therefore along with their Yukawa interaction with the active neutrinos (='Dirac mass') they can have a Majorana mass term (see e.g. [16] for details). They interact with the matter via creation of virtual active neutrino (quadratic *mixing*) and in this way they effectively participate in weak reactions (see e.g. Fig. 1(a)). At energies much below the masses of the W and Z-bosons, their interaction can be described by the analog of the Fermi theory with the Fermi coupling constant G_F suppressed by the *active-sterile neutrino mixing angle*θ – the ratio of their Dirac to Majorana masses (Fig. 1(b)) :

$$\theta_\alpha^2 = \sum_{\text{sterile } N} \left| \frac{m_{\text{Dirac},\,\alpha}}{M_{\text{Majorana}}} \right|^2 \tag{1}$$

(this mixing can be different for different flavors α).

It was observed long ago that such particles can be produced in the Early Universe through mixing with active neutrinos [13] and have a correct relic density for any mass [13,17-27].

The existence of sterile neutrinos is motivated by the *observational phenomena beyond the Standard Model* (unlike WIMPs that are motivated first of all by the theoretical considerations of stability of the Higgs mass against quantum corrections that could require a fine-tuning of parameters of the model). Namely, sterile neutrinos would provide a simple and natural explanations of the *neutrino flavor oscillations* [20-23]. However, a *single* sterile neutrino would be unable to explain the two observed mass splittings between Standard Model neutrinos – at least two sterile neutrinos are needed for that. Moreover, should sterile neutrino play the role of DM, its mixing with active neutrinos would be too small to contribute significantly to the flavor oscillations – its life time should be very large and, therefore, interaction strength should be too feeble [24,25]. Therefore, in order to explain dark matter and neutrino mass (one for each SM flavor), the minimal model should contain 3 right-handed



(a) Decay of sterile neutrino $N \to \nu_e \nu_\alpha \bar{\nu}_\alpha$ through neutral current interactions. A virtual ν_e is created and the quadratic mixing (marked by symbol "×") is proportional to θ^2.

(b) At energies $E_N \ll M_Z$, the process in the left panel can be described by the Fermi-like interaction with the "effective" Fermi constant $\theta_e \times G_F$.

(c) Two-body decay of sterile neutrino. The energy of the photon is $E_\gamma = \frac{1}{2} M_N$.

Fig. 1. Example of interactions of sterile neutrino: decay $N \to \nu_e \nu_\alpha \bar{\nu}_\alpha$ (panel (a)) and its effective Fermi-like description (panel (b)) and loop-mediated decay $N \to \gamma + \nu_\alpha$ (panel (c)).

neutrinos [24]. In such a model, the lowest mass eigen-state of the active neutrinos will be (almost) zero and the sum of neutrino masses $\sum m_\nu \approx \kappa\sqrt{|\Delta m^2_{\rm atm}|}$, where $\kappa = 1$ or 2 for normal (inverted) hierarchy [25]. This is one of the predictions of such a model.

In spite of the fact that dark matter sterile neutrino plays essentially no role in the neutrino oscillations, the fact that 3 particles are needed to explain *both* dark matter and neutrino oscillations is crucial. As we will see below, primordial properties of sterile neutrino dark matter are determined by two other sterile neutrinos.

If the masses of the two sterile neutrinos, responsible for neutrino oscillations, are below ∼2 GeV (mass of *c*-quark), such particles can be searched with existing experimental techniques [26,27], see Section 3.1. This is a unique situation when one can directly test the nature of neutrino oscillations in 'intensity frontier' [28] experiments. For masses above 2 GeV the searches become more difficult (see Section 3.2 for details).

It turns out that in the region of masses between 100 MeV and electroweak scale out-of equilibrium reactions with these two sterile neutrinos are capable of generating the observed matter–antimatter asymmetry of the Universe (baryogenesis) [29]. These observations motivated a lot of recent efforts for developing this model, called the ν MSM – *Neutrino Minimal Standard Model* (see [14] for review). Therefore, finding these particles in intensity frontier experiments would provide an unparalleled possibility to test baryogenesis in laboratory. Moreover, if some particles are found in such experiments it will be possible not only to check whether they are responsible for baryogenesis or not, but also unambiguously predict the properties of sterile neutrino DM.

Because its interaction with the Standard Model particles is very feeble, sterile neutrino does not need to be stable. The decay channel for sterile neutrinos of all masses is to 3 (anti)neutrinos (Fig. 1(a)) .[2] However, the most characteristic feature of sterile neutrino DM is its ability to decay to photon and neutrino (with cosmologically long lifetime) [30-32], see Fig. 1(c). The emitted photon is almost mono-energetic (the width of the DM decay line is determined entirely by the motion of DM particles). Although the lifetime of the DM particles turns out to be *much longer than the age of the Universe*, humongous amount of these particles around us implies that the combined emission may be sizable.

If dark matter is made of sterile neutrinos, detecting astrophysical signal from their decay (the "indirect detection") may be the only way to identify this particle experimentally. However, it may be possible to prove the dark matter origin of observed signal unambiguously using its characteristic properties.

In summary, one sees that three sterile with the masses below electroweak scale form a minimal testable model that provides a unified description of three major *observational* problems "beyond-the-Standard-Model" [14,24,29,33] [3]

(1) neutrino flavor oscillations;
(2) the absence of primordial anti-matter in the Universe;
(3) existence of dark matter.

2.1. Production of sterile neutrinos in the early Universe

The active-sterile neutrino mixing is strongly suppressed at temperatures above a few hundred MeV and peaks roughly at [13]

$$T_{\rm peak} \sim 130\left(\frac{M_{N_{\rm DM}}}{1\ {\rm keV}}\right)^{1/3}\ {\rm MeV}, \tag{2}$$

Sterile neutrinos DM are *never in thermal equilibrium* and their number density is significantly smaller than that of the active neutrinos (that is why they can account for the observed DM abundance with-

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[2] For masses above 1 MeV additional decay channels become kinematically possible.

[3] It should be noted, that the model with this choice of the parameters cannot explain existing "anomalies" in short-baseline neutrino experiments (that can be interpreted as a presence of one or two additional mass eigenstates with $\Delta m^2 \sim 1$ eV^2), see [16] for review. It is however trivial to extend the right-handed sector to incorporate extra species (the number of right-handed neutrinos does not have to be equal to 3) if these results are confirmed.

out violating ‘Tremaine–Gunn bound’). In particular, the shape of the primordial momentum distribution of thus produced sterile neutrinos is roughly proportional to that of the active neutrinos [30]:

$$f_{N_{\rm DM}}(t,p) = \frac{\chi}{e^{p/T_\nu(t)}+1}\ , \tag{3}$$

where the normalization $\chi \sim \theta_{\rm DM}^2 \ll 1$ and where $T_\nu\,(t)$ is the temperature of the active neutrinos.[4] Comparing the production temperatures Eq. (2) of DM sterile neutrinos with their masses shows that they are produced relativistically in the radiation-dominated epoch. Indeed, for the primordial DM distribution of the form (3) one has $\langle p\rangle \sim T_{\rm peak} \gtrsim M_{N_{\rm DM}}$ for $M_{N_{\rm DM}} \lesssim 40$ GeV. Relativistic particles stream out of the overdense regions and erase primordial density fluctuations at scales below the *free-streaming horizon* (FSH) – particles’ horizon when they becomes nonrelativistic (for a detailed discussion of characteristic scales see e.g. [34] and references therein). This effect influences the formation of structures. If DM particles decouple nonrelativistically (*cold* DM models, CDM) the structure formation occurs in a “bottom-up” manner: specifically, smaller scale objects form first and then merge into the larger ones [35]. CDM models fit modern cosmological data well. In the case of particles, produced relativistically and *remaining relativistic* into the matter-dominated epoch (i.e. *hot* DM, HDM), the structure formation goes in a “top-down” fashion [36], where the first structures to collapse have sizes comparable to the Hubble size [37-39]. The HDM scenarios contradict large-scale structure (LSS) observations [5]. Sterile neutrino DM that is produced relativistic and is then redshifted to nonrelativistic velocities in the radiation-dominated epoch is an intermediate, *warm dark matter* (WDM) candidate [18,30,40]. Structure formation in WDM models is similar to that in CDM models at distances above the free streaming scale. Below this scale density fluctuations are suppressed, compared with the CDM case. The free-streaming scale can be estimated as [38]

$$\lambda_{\rm FS}^{\rm co} \sim 1\ {\rm Mpc}\left(\frac{\rm keV}{M_{N_{\rm DM}}}\right)\frac{\langle p_N\rangle}{\langle p_\nu\rangle}\ . \tag{4}$$

where 1 Mpc is the (comoving) horizon at the time when momentum of active neutrinos $\langle p_\nu\,\rangle \sim 1$ keV. If the spectrum of sterile neutrinos is nonthermal, then the moment of non-relativistic transition and $\lambda_{\rm FS}^{\rm co}$ is shifted by $\langle p_N\rangle/\langle p_\nu\rangle$.

This mechanism specifies a *minimal* amount of sterile neutrinos that will be produced for given M_1 and θ_1. The requirement that 100% of DM be produced via such mixing places an *upper bound* on the mixing angle θ_1 for a given mass. This conclusion can only be affected by entropy dilution arising from the decay of some heavy particles below the temperatures given in Eq. (2) [41,42].

The production of sterile neutrino DM may substantially change in the presence of lepton asymmetry when the resonant production (*RP*) of sterile neutrinos [17] occurs, analogous to the Mikheyev–Smirnov–Wolfenstein effect [43,44]. When the dispersion relations for active and sterile neutrinos cross each other at some momentum p, the effective transfer of an excess of active neutrinos (or antineutrinos) to the population of DM sterile neutrinos occurs. The maximal amount of sterile neutrino DM that can be produced in such a way is limited by the value of lepton asymmetry, $\eta_L \equiv |n_\nu - n_{\bar\nu}|/s$, where s is the entropy of relativistic species in plasma. The present DM abundance $\Omega_{\rm DM} \sim 0.25$ translates into the requirement of $\eta_L \sim 10^{-6}\left(\frac{\rm keV}{M_{N_{\rm DM}}}\right)$ in order for RP sterile neutrinos to constitute the dominant fraction of DM. One notices that the resonant production occurs only for values of lepton asymmetry, η_L much larger than the *measured* value of *baryon asymmetry of the Universe*: $\eta_B \equiv \frac{n_B}{s} \sim 10^{-10}$ [3]. Such a value of η_L does not contradict to any observations though. Indeed, the upper bounds on η_L are based on either primordial nucleosynthesis (BBN) or CMB measurements (as chemical potential of neutrinos would carry extra radiation density) [45,46]. These bounds read $|\eta_L| \lesssim \text{few} \times 10^{-3}$ (see e.g. [47-49]). We see, therefore, that the lepton asymmetry, required for resonant sterile neutrino production is still considerably smaller than the upper limit. Notice, that at epochs prior to BBN even $\eta_L \sim 1$ is possible (if this lepton asymmetry disappears later). Such a scenario is realized e.g. in the *Neutrino Minimal Standard Model*, νMSM (see [14] for review), where the lepton

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[4] The true distribution of sterile neutrinos is in fact colder than that shown in Eq. (3). Specifically, the maximum of $p^2 f_{N_1}(p)$ occurs at $p/T_\nu \approx 1.5$–1.8 (depending on $M_{N_{\rm DM}}$), as compared with $p \approx 2.2T_\nu$ for the case shown in Eq. (3) [19,180].

asymmetry keeps being generated below the sphaleron freeze-out temperature and may reach $\eta_L \sim 10^{-2} \div 10^{-1}$ before it disappears at $T \sim$ few GeV [50].

2.2. Structure formation with sterile neutrino dark matter

Non-negligible velocities of 'warm' sterile neutrinos alter the power spectrum of density fluctuations at scales below the *free-streaming horizon* scale. Additionally, the suppression of the halo mass function below a certain scale [51] and different history of formation of first structures affects the way the first stars were formed and therefore the reionization history of the Universe, abundance of the oldest (*Population III*) stars, etc [52-57].

The effects of suppression of the matter power spectrum are probed with the *Lyman-α forest method* [58-61] (see [34] for critical overview of the method and up-to-date bounds). Using neutral hydrogen as a tracer of overall matter overdensity, one can reconstruct the power spectrum of density fluctuations at redshifts $2 < z < 5$ and scales 0.3–5 h/Mpc (in comoving coordinates) by analyzing Lyman-α absorption features in the spectra of distant quasars.

If all DM is made of sterile neutrinos with a simple Fermi–Dirac-like spectrum of primordial velocities (3), the matter power spectrum has a sharp (cut-off like) suppression (as compared to ΛCDM) at scales below the free-streaming horizon (4) (similar to the case of 'thermal relics' [40]). In this case the Lyman-α forest data [34,58-62] puts such strong constraints at their free-streaming length, which can be expressed as the *lower bound* on their mass $M_{N_{\rm DM}} \geq 8$ *keV* (at 3σ CL) [34]. Such WDM models produce essentially no observable changes in the Galactic structures (see e.g. [34,63-66]) and therefore, from the observational point of view such a sterile neutrino DM (although formally 'warm') would be indistinguishable from pure CDM.

On the other hand, resonantly produced sterile neutrinos have spectra that significantly differ from those in the non-resonant case [17,67]. The primordial velocity distribution of RP sterile neutrinos contains narrow resonant (*cold*) *plus* a nonresonant (*warm*) components – CWDM model (see [34,68] for details).[5] In the CWDM case, however, Lyman-α constraints allow a significant fraction of DM particles to be very warm [34]. This result implies for example, that sterile neutrino with the mass as low as 1–2 keV is consistent with all cosmological data [68].

The first results [69] demonstrate that RP sterile neutrino DM, compatible with the Lyman-α bounds [68], do change the number of substructure of a Galaxy-size halo and their properties. Qualitatively, structures form in these models in a bottom-up fashion (similar to CDM). The way the scales are suppressed in CWDM models is more complicated (and in general less severe for the same masses of WDM particles), as comparable with pure warm DM models. The first results of [69] demonstrate that the resonantly produced sterile neutrino DM models, compatible with the Lyman-α bounds of [68], do change the number of substructure of a Galaxy-size halo and their properties. The discrepancy between the number of observed substructures with small masses and those predicted by ΛCDM models (first pointed out in [70,71]) can simply mean that these substructures did not confine gas and are therefore completely dark (see e.g. [72-75]). This is not true for larger objects. In particular, CDM numerical simulations invariably predict several satellites "too big" to be masked by galaxy formation processes, in contradiction with observations [70,71,76,77]. Resonantly produced sterile neutrino DM with its non-trivial velocity dispersion, turns out to be "warm enough" to amend these issues [69] (and "cold enough" to be in agreement with Lyman-α bounds [68]).

Ultimate investigation of the influence of *dark matter decays* and of *modifications in the evolution of large scale structure* in the 'sterile neutrino Universe' as compared with the ΛCDM model requires a *holistic approach*, where all aspects of the systems are examined within the same set-up rather than studying the influence of different features one-by-one. Potentially observable effects of particles' free streaming and decays are expected in terms of

- formation and nature of the first stars [53,54,78,79];
- reionization of the Universe [55,57,80-82];

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[5] Axino and gravitino models may have similar spectra of primordial velocities, c.f. [181].

– the structure of the intergalactic medium as probed by the Lyman-α forest [34,60-62,68,83-85];
– the structure of dark matter haloes as probed by gravitational lensing [85-89];
– the structure and concentration of haloes of satellite galaxies [69,90-93].

The results of this analysis will be confronted with measured cosmological observables, using various methods: Lyman-α analysis (with BOSS/SDSS-III or X-Shooter/VLT [94]), statistics and structure of DM halos, gravitational lensing, cosmological surveys).

The weak lensing surveys can be used to probe further clustering properties of dark matter particles as sub-galactic scales, as the next generation of these surveys will be able to measure the matter power spectrum at scales down to 1–10 h/Mpc with a few percent accuracy. The next generation of lensing surveys (such as e.g. KiDS, LSST, WFIRST, Euclid) can provide sensitivity, compatible with the existing Lyman-α bounds [86,87]. As in the case of the Lyman-α forest method the main challenge for the weak lensing is to properly take into account baryonic effects on matter power spectrum. The suppression of power spectrum due to primordial dark matter velocities can be extremely challenging to disentangle from the modification of the matter power spectrum due to baryonic feedback [84,95,96]. Finally, the modified concentration mass relation, predicted in the CWDM models, including those of resonantly produced sterile neutrinos [68,97] can be probed with the weak lensing surveys (see e.g. [98,99]) if their sensitivity can be pushed to halo masses below roughly 10^{12} $M_\odot$.

2.3. Sterile neutrinos as decaying dark matter

Sterile neutrino is an example of decaying dark matter candidate. The astrophysical search for decaying DM is very promising. First of all, a positive result would be conclusive, as the DM origin of any candidate signal can be unambiguously checked. Indeed, the decay signal is proportional to the *column density* $S = \int \rho_{\mathrm{DM}}(r)dr$ along the line of sight and not to the $\int \rho^2_{\mathrm{DM}}(r)dr$ (as it is the case for annihilating DM). As a result, a vast variety of astrophysical objects of different nature would produce a comparable decay signal (c.f. [100-102]). Therefore (i) one has a freedom of choosing the observational targets, avoiding complicated astrophysical backgrounds; (ii) if e.g. a candidate spectral line is found, its surface brightness profile may be measured (as it does not decay quickly away from the centers of the objects), distinguished from astrophysical emissions (that usually decay in outskirts) and compared among several objects with the same expected signal. This allows to distinguish the decaying DM signal from any possible astrophysical background and therefore makes astrophysical search for the decaying DM *another type of direct (rather than indirect) detection experiment*. The case of the astrophysical search for decaying DM has been presented in the recent White Papers [103,104]. This approach has been illustrated on the recent claim of [105] that a spectral feature at $E \sim 2.5$ keV in the *Chandra* observation of Willman 1 can be interpreted a DM decay line. Ref. [106] demonstrated that such an interpretation is ruled out by archival observations of M31 and Fornax/Sculptor dSphs with high significance (see also [107,108]).[6]

The 'Tremaine–Gunn bound' restricts the lowest energies in which one can search for the fermionic decaying DM to the *X-ray range*. An extensive search of the DM decay signal in the keV range using archive data was conducted recently, using *XMM-Newton*, *Chandra* and *Suzaku* observations of extragalactic diffuse X-ray background, galaxies and galaxy clusters [100,109-120]. This search allowed to probe large part of the parameter space of decaying DM (between 0.5 keV and ~14 MeV) and establish a *lower bound* on the lifetime of dark matter decay for both DM $\to \nu + \gamma$ and also DM $\to \gamma + \gamma$ (the latter would be the case e.g. for axion or majoron [121]). The combined restrictions on the lifetime (see [6]) turns out to exceed 10^{26} s, almost independent on the mass.

Let us consider the implications of the negative results of searches for decaying dark matter line in the νMSM , taking it as a minimal (baseline) model. Its parameter space is presented in Fig. 2. For any

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[6] We do not discuss here the claim [182] that the intensity of the Fe XXVI Lyman-γ line at 8.7 keV, observed in [183] cannot be explained by standard ionization and recombination processes, and that the DM decay may be a possible explanation of this apparent excess. Spectral resolution of current missions does not allow to reach any conclusion. However, barring an *exact* coincidence between energy of decay photon and Fe XXVI Lyman-γ, this claim may be tested with the new missions, discussed in Section 2.5.

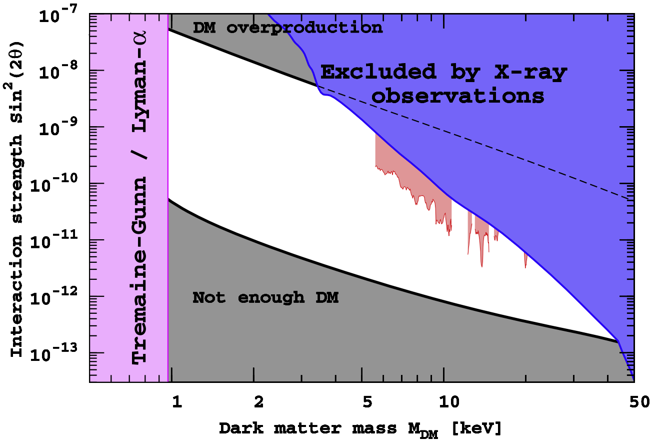

Fig. 2. The allowed region of parameters of sterile neutrino dark matter in the νMSM (white unshaded region) confronted with existing and projected experimental bounds. For any combination of mass and mixing angle between two black curves the necessary amount of dark matter can be produced (given the presence of certain amount of lepton asymmetry in the plasma, generated by two other sterile neutrinos). The blue shaded region in the upper right corner is excluded by the non-observation of decaying DM line in X-rays [100,109-110,112,116-120]. Red regions between ~5 keV and ~20 keV show *expected sensitivity* from a *combination of a large number of archival observations* (as described in Section 2.4). The gaps are due to the presence of strong instrumental lines at certain energies (where the combination method does not provide any improvement over earlier bounds). The lower limit of ~5 keV is due to the presence of instrumental lines and absorption edge at energies 1–2.5keV and emission of the Milky Way, dominating at lower energies. In the region below 1 keV sterile neutrino DM is 'too light' and is ruled out based on 'Tremaine–Gunn' like arguments [4] and on the Lyman-α analysis [34,68]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

combination of mass and mixing angle between two black curves the necessary amount of dark matter can be produced (given the presence of certain amount of lepton asymmetry in the plasma). If interaction strength is too high, too much dark matter is produced in contradiction with observations. If the interaction strength is too low – one cannot account for 100% of dark matter with sterile neutrinos and additional "dark" particles would be needed). The shaded region in the upper right corner is excluded due to non-observation of decaying dark matter line with X-ray observatories [100,109-120]. Confronting the requirement to produce the correct DM abundance with the X-ray bounds, one is able to deduce the upper limit on the mass of sterile neutrino DM to be about 50 keV [119]. Finally, a lower limit on the mass of DM sterile neutrino $M_N \sim 1$–2 keV comes from the analysis of the Lyman-α forest data [34,68].[7] As a result, the combination of X-ray bounds and computations of primordial abundance shows that in the νMSM the parameter space of sterile neutrino DM is *bounded on all sides*.

To further advance into the allowed region of the νMSM (the simplest model, predicting sterile neutrino DM) one has either drastically improve the statistics of observations of DM-dominated objects (Section 2.4), or employ new technologies of detecting X-rays in space that deliver better spectral resolution than existing X-ray missions (Section 2.5).

2.4. Advance with existing missions: stacking of observations

Significant improvement of sensitivity for decaying DM line with the current X-ray missions (*XMM-Newton*, *Chandra*, *Suzaku*) is quite challenging. Indeed, an improvement by an order of magnitude would require an increase of observational time by *two* orders of magnitude. The best existing constraints in X-rays are based on observations with exposure of several hundreds of ks. Therefore, one

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[7] Notice, that the lower bound on the mass of sterile neutrino DM, produced via non-resonant mixing (having a simple Fermi–Dirac-like spectrum) is at tension with the upper bound on the mass, coming from X-ray observations (see e.g. [34,118] and references therein).

would need $\gtrsim 10$ Ms of dedicated X-ray observations. Such a huge cleaned exposure is extremely difficult to obtain for a *single* DM-dominated object (for example, the whole year of observational programme of the *XMM-Newton* satellite is only 14.5 Ms).

Using archive of the *XMM-Newton* observations[8] it is possible to collect about 20 Ms of observations of nearby spiral and irregular galaxies [122] (galaxy clusters have much stronger emission in the keV range and their combined analysis would require a completely different strategy). Therefore a possible way to advance with the existing X-ray instruments is *to combine a large number* of X-ray observations of different DM-dominated objects. The idea is that the spectral position of the DM decay line is the same for all these observations, while the astrophysical backgrounds in the combined spectrum would "average out", producing a smooth continuum against which a small line would become visible. Naively, this should allow to improve the existing bounds by at least an order of magnitude.

However, this turns out to be a highly non-trivial task. Indeed, such a large exposure means that the statistical errors in each energy bin can be as small as 0.1%. To extract meaningful bounds one would need therefore *comparably small* systematic errors. However, the level of systematics of the *XMM-Newton* is much higher (at the level 5–10%, see e.g. [123]) due to the instrument's degradation with time and variability of the instrumental (=cosmic-ray induced) background that constitutes a significant part of a signal in each energy bin (and becomes a dominant component above few keV (c.f. [124-127]). The exposure of '*closed filter*' dataset[9] is ~1 Ms. As a result, the usual practice of *subtraction* of rescaled instrumental background data (see e.g. [126-128]) would mean at least ~3 times larger errorbars due to the smaller exposure of the instrumental dataset. Moreover, the instrumental component of the *XMM-Newton* background is self-similar only on average which would introduce additional errors (at the level of few %, see [116]). Another standard procedure of working with diffuse sources – subtraction of the 'blank sky' data[10] will not be applicable in this case as well. First of all, such a dataset would also contain decaying dark matter line originating from the decays in the Milky Way halo (this fact has been exploited before to put bounds on decaying DM in [112,116]). Secondly, subtracting the 'blank sky' data would again reduce all the advantages of a large dataset by lowering statistics (as the exposure of the latest blank-sky co-added observations is again of the order of ~1 Ms).

This means that *to take all the advantages of this long-exposure dataset, one cannot use the standard data-processing methods*. Therefore, an alternative method of data analysis has to be developed, that has the sensitivity towards the searching for narrow lines at the level, dictated by the statistics of the combined dataset. The results will be reported in [122]. The estimated level of sensitivity of this method is shown as the red line in Fig. 2.

2.5. X-ray micro-calorimeters

Really significant progress (that allows, for example, to cover the whole region of parameter space in Fig. 2) in searching for decaying DM cannot be achieved with the existing instruments by simply increasing the exposure of observations. Indeed, the width of the DM decay line, $\Delta E/E_\gamma$ is determined by the virial velocities of DM particles in halos and ranges from $\mathcal{O}(10^{-4})$ for dwarf spheroidal galaxies to $\mathcal{O}(10^{-3})$ for the Milky Way-size galaxies to 10^{-2} for galaxy clusters. If the spectral resolution is much bigger than the width of the line, one averages the photons from the line with the background photons over a large energy bin. This is the case for all existing X-ray missions, whose detectors are based on CCD technology (c.f. [129]) and where the spectral resolution is at the level $\Delta E/E \gtrsim 10^{-2}$, see Fig. 4. Therefore, *an X-ray spectrometer with the energy resolution at least $\Delta E/E \sim 10^{-3}$is crucial for detection of a decaying DM line*.

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[8] *XMM-Newton* has the largest 'grasp' (=product of the field-of-view and effective area) as compared to *Chandra* and *Suzaku*, which would allow to collect the largest amount of photons from 'diffuse sources', such as the signal from DM decays in the DM halos of the nearby galaxies.

[9] A special dataset (obtained with the filter of the X-ray telescope closed, so that no X-ray photons can reach the detector) created specifically to determine the (time-averaged) shape of the instrumental background and used to remove the most prominent instrumental features from observations of diffuse sources, see e.g. [127,184].

[10] Combination of many observations of X-ray quiet parts of the sky [124,126]. Unlike the 'closed filter' dataset collects the physical emission from the Milky Way.

The technology behind such spectrometers (known as *X-ray micro-calorimeters*, see e.g. [131,132]) has been actively developed by the high-energy astrophysical community in the last decades. There is a strong interest for building such a spectrometer, and different versions of high resolution X-ray missions had been proposed in response to the ESA and NASA calls (including the ESA's call for Fundamental Physics Roadmap), see e.g. [103,133-136]. Astrophysical interest to X-ray spectrometer is motivated by a number of important applications to observational cosmology, providing crucial insight into the nature of dark matter by studying the structure of the "cosmic web". In particular, (i) search for *missing baryons* in the cosmic filaments; through their emission and absorption ; (ii) trace the evolution and physics of clusters out to their formation epoch; (iii) use gamma-ray bursts as backlight to observe the warm-hot intergalactic media in absorption; (iv) study the evolution of massive star formation using Gamma Ray Bursts to trace their explosions back to the early epochs of the Universe ($z \sim 6$) (see e.g. [133,135,136]).

The first spectrometer based on this technology was flown (albeit unsuccessfully) on *Suzaku* mission [137] and another one is being planned for the Astro-H [134,138] (to be launched in 2014). However, currently planned and proposed X-ray micro-calorimeter missions (Astro-H [134], Athena [136], ORIGIN [135], etc.) are not optimal for the purpose of decaying dark matter search. These missions are optimized for the astrophysical goals and have limited field-of-view (usually, much below 1 deg^2), good angular resolution and narrow energy range.

On the contrary, the *key parameters* that determine the sensitivity of the proposed instrument for decaying dark matter search are (see Fig. 4):

- a spectral resolution $\Delta E/E \lesssim 10^{-3}$ over the range of energies 0.5–25 keV (this is the minimal energy range, that would allow to probe the parameter space of our baseline model, the νMSM);
- large '*grasp*' $\sim 10^3$–10^4 $\text{cm}^2 \times \text{deg}^2$. There are essentially two possibilities to achieve such a grasp. One can either launch a non-imaging spectrometer (with a 'collimator' having a field-of-view as large as $\sim 10^2$ deg^2)[11]; or install mirrors (thus increasing the effective area beyond the geometric size of the detectors, probably to as much as 10^3 cm^2). The latter option allows to have also imaging capabilities, however, it is usually extremely costly to cover the required energy range and to have sufficiently large (at least $1^\circ \times 1^\circ$) field of view.

Fig. 4 summarizes sensitivity of existing and proposed missions and demonstrates that none of them would provide a sufficient improvement with respect to the existing constraints (see [103,130] for discussion).

Currently, there exists a project (the *X-ray quantum calorimeter*, XQC [139]) that can be considered a prototype of the proposed mission. It has the field of view of about 1 sr (3.5×10^3 deg^2), an effective area of ~ 1 cm^2 and the energy resolution of 10 eV over the energy range 0.1–4 keV [139].[12] This calorimeter has been flown several times on sounding rockets [139]. Although each flight had been very short (about 100 s), it allowed to demonstrate that the Milky Way emission in the energy range 0.1–1 keV (which looks as a continuum in the spectra obtained with X-ray imaging instruments, see e.g. [126,140] is actually a "forest" of thin lines (see Fig. 3). Because of its superior spectral resolution, decaying DM bounds based on the ~ 100 s exposure of the flight of this spectrometer [139] are comparable with 10^4 s of the *XMM-Newton* exposure [130].

To detect a dark matter decay line, that is much weaker than the lines resolved with the XQC spectrometer, a significantly longer exposure (~ 1 year) would be required. The requirement to keep the cryostat of such a spectrometer in the stable regime, means that one cannot use the sounding rockets,

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[11] Making field-of-view significantly larger than about $10^\circ \times 10^\circ$ would of course further increase the sensitivity towards the line detection. However, in this case it would become challenging to identify the nature of the candidate line (if found), as in this case none of the nearby DM dominated objects with large angular size (Andromeda galaxy, Large and Small Magellanic clouds, Virgo cluster) will look like 'hot spots' of DM decays. Moreover, in this case it will not be possible to build a DM surface brightness profile as one varies the directions off the Galactic Center and investigate whether it is consistent with DM distribution in the Milky Way.

[12] A similar calorimeter used in Suzaku was capable of delivering a similar resolution up to the maximal energy range of 12 keV [137].

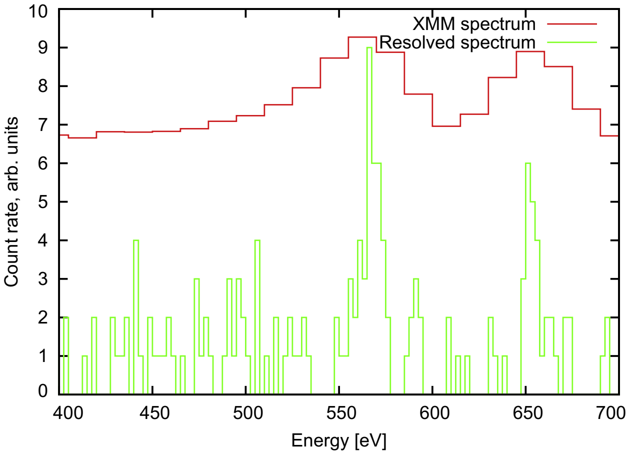

Fig. 3. Galactic diffuse background (observed with *XMM-Newton* (red) and the same data, observed with the X-ray spectrometer (XQC project [139]). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

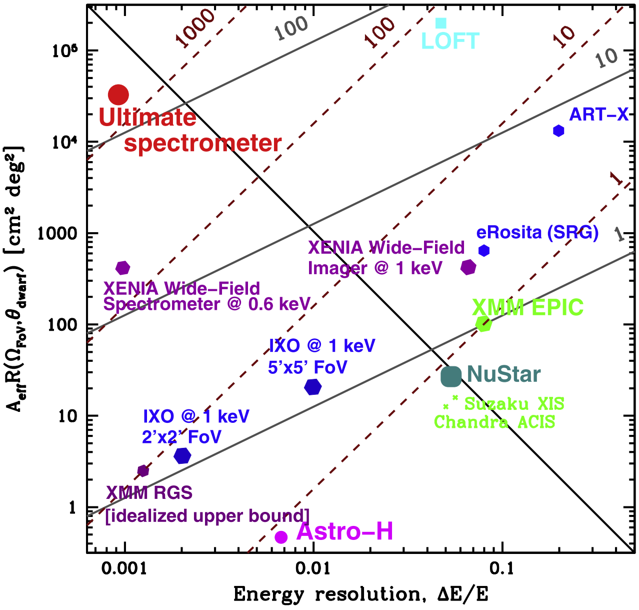

Fig. 4. Comparison of sensitivities of existing and proposed/planned X-ray missions for the detection of the DM decay line in a nearby dwarf spheroidal galaxy of the angular size of 1°.

but rather needs to use a satellite (probably, staying in Low Earth Orbit, unlike *XMM-Newton* or *Chandra*). The project therefore becomes a small-to-medium scale cosmic mission.

2.6. Laboratory searches for sterile neutrino DM

Finally, several words should be said about laboratory searches of DM sterile neutrinos. As Fig. 2 demonstrates, their mixing angle is always smaller than $\sim 10^{-7}$ (even for the lightest admissible masses of ∼1 keV). This makes their laboratory searches extremely challenging. One possibility would be to measure the event-by-event kinematics of β-decay products [141]. This experiment, however, is plagued by the bremsstrahlung emission of the finite state electrons that changes their energy. Other possibilities of searches for the keV-scale sterile neutrinos are discussed e.g. in [142-144]. All these experiments require essentially background-free regime and it is not clear whether any of them can realistically touch cosmologically interesting region of parameters of sterile neutrino.

3. Accelerator searches for sterile neutrinos: present and future

Although only one sterile neutrino plays the role of dark matter, the fact that three of them are needed to explain *both* dark matter and neutrino oscillations is crucial as these two particles set up *the initial conditions* for sterile neutrino DM production and affect their primordial properties [17,33,50,67]. If the masses of sterile neutrinos responsible for neutrino oscillations are below electroweak scale (as it is the case in the νMSM), such particles can be found in 'intensity frontier' experiments, opening the road for the experimental resolution of three major observational problems 'beyond-the-Standard-Model': neutrino flavor oscillations, matter-antimatter asymmetry of the Universe and dark matter.

3.1. Direct searches for sterile neutrinos with MeV–GeV masses

The idea that the SM can be extended in the neutrino sector by adding several relatively light neutral fermions was discussed intensively since the 1980s. Two distinct strategies has been used for these searches. The first one is related to their production. The neutral leptons participate in all reactions the ordinary neutrinos do with a probability suppressed by their mixing angles with active neutrinos. Since they are massive, the kinematics of 2-body decays $K^\pm \to \mu^\pm N$, $K^\pm \to e^\pm N$ or 3-body decays $K_{L,S} \to \pi^\pm + e^\mp + N$ changes when N is replaced by an ordinary neutrino [145]. Therefore, the study of *kinematics* of rare meson decays can constrain the strength of the coupling of heavy leptons. This strategy has been used for the search of neutral leptons in the past, where the spectrum of electrons or muons originating in decays π and K mesons has been studied ([146-152] see discussion in [153-155]). The second strategy is to look for the decays of sterile neutrinos[13] inside a detector ('*nothing* ' → leptons and hadrons). Typical patterns and branching ratios of sterile neutrino decays can be found in [26].

Such searches have beeen undertaken at CERN, FNAL, PSI and other laboratories (e.g. PS191 [156-158], BEBC, CHARM [159], NOMAD [160] and NuTeV [161], see [26,154,162,163] for review). However only recently understanding that the *light singlet fermions in the region of accessibility of existing accelerators can explain neutrino oscillations allowed to fix an ultimate goal for searches of neutral leptons*.

Moreover, sterile neutrinos with such parameters can also provide an explanation of *the observed matter–antimatter asymmetry* of the Universe [24,33,164], and therefore if these particles are found, one receives *a unique possibility of direct experimental verification of the mechanism of baryogenesis*, checking if the parameters of the found sterile neutrinos satisfy the requirements of successful baryogenesis. Out of experiments already made, only CERN PS191 [158] entered deeply into the cosmologically interesting part of parameters for the masses of singlet fermions below that of kaon.

The lower limit on the mass of these particles is determined by combination of particle physics and cosmological considerations and should be above $\sim$100 MeV [154,165] while no known solid upper bound, better than the electroweak scale, can be applied. At the same time, various considerations indicate that their mass may be in $\mathcal{O}(1)$ GeV region [50,166].

3.2. Future searches for sterile neutrinos with intensity frontier experiments

A future "intensity frontier" experiments (such as NA62 [167], measuring very rare kaon decay $K \to \pi\nu\bar{\nu}$; Long-Baseline Neutrino Experiment (LBNE) [168,169]; etc.) or even modifications of some

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[13] These sterile neutrinos are also produced in the weak decays of heavy mesons and baryons. From the experimental point of view, the distinct mass ranges are associated with the masses of parent mesons: below 500 MeV (K meson), between 500 MeV and 2 GeV (D-mesons), between 2 and 5 GeV (B-mesons), and above 5 GeV. (see [26,27] for details).

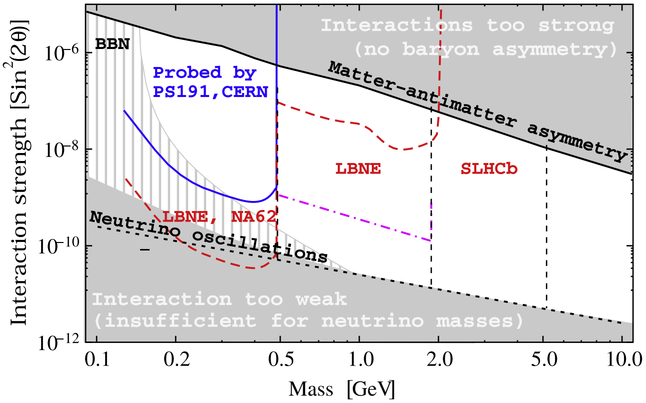

Fig. 5. Parameter space of sterile neutrinos responsible for neutrino oscillations (region above dotted line "neutrino oscillations") and providing successful baryogenesis (the unshaded region below black solid line "matter–antimatter asymmetry"). "Interaction strength" axis demonstrates by how much the interaction of sterile neutrinos with matter is weaker than the Fermi constant (G_F). Different points within the allowed region correspond to different choices of the parameters of the active-sterile Yukawa matrix. Accelerator searches for sterile neutrinos had explored the region above the blue solid lines (PS191 experiment [156-158]; other fixed-target experiments (CHARM [159], NuTeV [161], NOMAD [160]) did not enter into the cosmologically interesting region, see [33,154] for details). Sterile neutrinos with the parameters within the hatched region "BBN" would result in overproduction of primordial Helium-4 in the early Universe [170,171]. Combination of these bounds with the accelerator searches limit mass of sterile neutrinos to be $M \gtrsim 100$ MeV. Prospects for sterile neutrino searches with the future experiment (NA62, LBNE [168], upgrade of LHCb [172]) are showed by the red dashed line [168]. Vertical dashed lines show the masses of kaon, D-meson and B-quark (in each region a different experiment shall be used). The region above the magenta dashed-dotted line can be probed with a single section of a detector similar to the one used in PS191 experiment but of larger size (length $l_{||} \sim 100$ m, height 5 m and width $l_{\perp} \sim 5$ m), placed about hundred meters from a beam target; see the proposal [27] for details. The parameter space is shown, assuming inverted hierarchy of neutrino masses, see [33] for full details.

of the existing experiments (such as e.g. T2K, see [26]) would be able to enter cosmologically interesting region of the sterile neutrino parameter space shown in Fig. 5. An experimental setup can be the following. Heavy mesons (and baryons) are produced in "fixed target experiments" (beam of energetic protons hitting a target). Sterile neutrinos are created in the decays of these mesons and one can then search for their decays into pairs of charged particles (the probability of production and subsequent decay is proportional to $\theta_\alpha^2 \times \theta_\beta^2$, where α and β are flavor indexes).

Before the decay (taking into account their Lorentz factor) sterile neutrinos would travel large distances ($c\tau_N \sim \mathcal{O}(10)$ km). Hence, sterile neutrino decays into SM particles due to mixing with active neutrino can be searched for in the near detector, see Fig. 6.

It is feasible fully explore the νMSM parameter space for sterile neutrino masses in the interesting range $M_N \sim$ 0.5–2 GeV, where sterile neutrinos are dominantly produced in charmed hadron decays, one needs the following configuration (see [27] for details): (i) high intensity proton beam with about 10^{20} protons incident on the target per year; (ii) near detector, having the size 5 m × 5 m × 100 m and placed at a distance of about 1 km.[14] Each detector may be relatively cheap, empty-space with simple tracker system inside and calorimeter at the far end. Its design may repeat the design of the CHARM experiment on searches for sterile neutrino decays at CERN SPS beam [159].

At the mass range above 2 GeV the searches become more difficult, as the intensity of proposed flavor factories does not seem to be enough to collect sufficient amount of hadrons [26,27] (see e.g. [173] for an overview of intensities of planned flavor factories). Some part of the parameter space of sterile neutrinos below b-quark mass (5 GeV) can be probed with the upgrade of LHCb experiment, see [172], especially Section 2.2.1 there.

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[14] To register all the expected sterile neutrino decays one may consider installing many detectors of a reasonable size rather than one large detector [27].

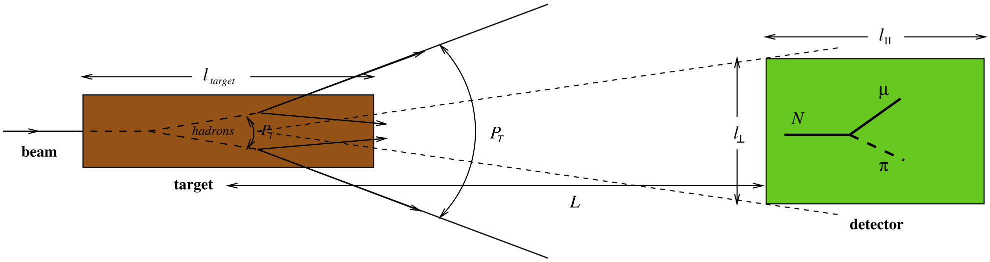

Fig. 6. Sketch of a typical experiment, searching for sterile neutrino decays. Heavy mesons (and baryons) are produced by the beam of energetic protons hitting the target material. Sterile-active neutrino mixing gives rise to sterile neutrino production and subsequent decay into the SM particles. From [27].

Additionally, experiments, searching for $\mu \to e\gamma$ and $\mu \to eee$ decays may touch the cosmologically interesting region of the parameter space of sterile neutrinos at masses above 10 GeV [174].

Finally, we notice, that the neutrinoless double-beta decay ($0\nu\beta\beta$) does not provide significant restrictions on the parameters of these sterile neutrinos (contrary to the case discussed in e.g. [163]), see discussion in [153,154,175]. In particular, this is the case in the νMSM [176], where the mass limits are 1.3 meV < $m_{\beta\beta}$ < 3.4 meV (13 meV < $m_{\beta\beta}$ < 50 meV) for normal (inverted) hierarchy. Detection of $m_{\beta\beta}$ outside these ranges would rule out the simplest model with only two sterile neutrinos with the masses in MeV–GeV range, responsible for neutrino oscillations.

4. Conclusion

After almost 20 years of research sterile neutrino remains a viable dark matter candidate. Observations of neutrino flavor oscillations further increased the interest to this candidate. Recent discovery of a Higgs like particle with the mass 125–126 GeV and absence of signs of new physics at the LHC or in DM direct detection experiments call for alternative (not related to electroweak symmetry breaking) testable BSM models (including dark matter). Attempts to solve all BSM problems with particles with masses below electroweak scale [14,177] provide an novel approach to the problem of naturalness of the SM.

Dedicated cosmic experiment, an X-ray spectrometer, searching for signatures of decaying dark matter, has a capability to identify the dark matter particle. Combination of this experiment with the searches for neutral leptons at beam-target experiments gives a unique possibility to resolve experimentally three major BSM problems: the nature of neutrino flavor oscillations; the mechanism of generation of matter–antimatter asymmetry in the Universe; and the existence of dark matter. It could provide not only a possibility to detect new particles, but also do independent cross checks of the mechanisms of DM production and baryogenesis. Even negative results would allow to shed a light on the DM properties and therefore restrict the class of extensions of the SM.

Although current data, describing formation of structures, is fully consistent with the ΛCDM ‘concordance’ model, sterile neutrino DM (that can be ‘warm’, ‘cold’ or ‘mixed’ (cold+warm)) is also fully compatible with the observations. Future cosmic surveys will be able to measure the matter power spectrum with the sufficiently high precision to detect the imprints that such DM leaves in the matter power spectrum at sub-Mpc scales.

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