Snowmass2021 - Letter of Interest

Neutrino Minimal Standard Model — a unified theory of microscopic and cosmic scales

NF Topical Groups:

■ (NF1) Neutrino oscillations
■ (NF3) Beyond the Standard Model

Other frontiers/Topical Groups:

■ (CF1) Cosmic Frontier/Dark Matter: Particle-like
■ (CF3) Cosmic Frontier/Dark Matter: Cosmic Probes
■ (EF09) Energy Frontier/BSM: More general explorations
■ (TF09) Theory Frontier/Astro-particle physics & cosmology
■ (TF11) Theory Frontier/Theory of neutrino physics
■ (RF4) Rare processes and precision measurements/Baryon and Lepton Number Violating Processes
■ (RF6) Rare processes and precision measurements/Dark Sector Studies at High Intensities
■ (AF5) Accelerator frontier/Accelerators for PBC and Rare Processes

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Abstract: The previous century has witnessed the development of the most comprehensive theory of nature ever created — the Standard Model of particle physics (SM). However, several laboratory experiments and astrophysical observations clearly point at the incompleteness of the SM. These phenomena include: neutrino flavor oscillations, the baryon asymmetry of the Universe, and the nature of dark matter. The *Neutrino Minimal Standard Model* (νMSM) provides an economical explanation of all these phenomena by adding to the SM only three new particles — right-handed neutrinos (or *heavy neutral leptons* – HNLs). The νMSM is testable with existing experimental means since the masses of all its new particles can be below the electroweak scale. A coordinated action of scientists on several Frontiers is required in order to:
– fully work out the predictions of the νMSM in the early Universe;
– explore the parameter space of the model at the LHC, future colliders, and Intensity Frontier experiments;
– study the properties of dark matter particles, including the distribution of matter at sub-galactic scales.
The νMSM is not only a candidate for a complete effective model of particle physics and Big Bang cosmology, but also an example of a self-consisten theory that could be valid up to the Planck scale. This warrants its comprehensive exploration.

Theory of the νMSM

The existence of neutrino masses, the origin of the baryon asymmetry of the universe (BAU), and Dark Matter (DM) are the only well established empirical signs of particle physics beyond the Standard Model (SM). It is intriguing that all above-mentioned problems can be solved by the Neutrino Minimal Standard Model (νMSM). The νMSM extends the particle content of the SM by three right-handed neutrinos $N_{1,2,3}$ [1–3]. Two heavier particles $N_{2,3}$ generate the masses of active neutrinos via the seesaw mechanism [4–9]. The same two right-handed neutrinos are also responsible for generating the BAU provided that their masses are close to each other. The lightest sterile neutrino N_1 is the DM candidate [10–14]. The requirement to be a viable DM candidate forces the Yukawa couplings of N_1 to be tiny, leaving the lightest active neutrino almost massless [1, 15].[1] Interestingly, the mass degeneracy of $N_{2,3}$ along with the tiny couplings of N_1 can be a consequence of a slightly broken global symmetry [18–23]. The measured values of the Higgs and top quark masses are such that the νMSM is a consistent effective theory to very high scales, possibly all the way up to the Planck scale [24–27].

Leptogenesis in the νMSM. As the heavy neutrinos $N_{2,3}$ are produced in the early Universe, they oscillate in a CP-violating manner and through these oscillations produce a lepton asymmetry [2, 28], in a process dubbed *leptogenesis via neutrino oscillations*. This mechanism is operational for GeV-scale heavy neutrinos, and is therefore testable at existing and near-future experiments. In the past years, several groups have studied the parameter space of leptogenesis via neutrino oscillations in the νMSM [29–43]. However, a complete systematic study accounting for all the necessary details is still missing.

Sterile neutrino dark matter. Assuming vanishing initial abundance after inflation [44], DM production in the νMSM can only occur through mixing with active neutrinos [10–14, 45].[2] The production is efficient in the presence of large lepton asymmetry at temperatures $\mathcal{O}(200)$ MeV [11, 12, 14, 49–53]. Such an asymmetry is generated in the νMSM provided that the mass splitting between $N_{2,3}$ is tiny [54]. The requirement of successful DM production in the νMSM is the most limiting one [29, 30, 51, 55] and a comprehensive study of the parameter space accounting for the recent theoretical progress is necessary.

Theoretical aspects of HNLs in the early Universe. The parameter space of GeV-scale leptogenesis is quite restricted, particularly if the further goal is set that lepton asymmetries much larger than the baryon asymmetry are generated at low temperatures, in order to facilitate sterile neutrino dark matter production. In this situation it is important to compute precisely the rate coefficients and the thermal mass corrections that affect the production of baryon and lepton asymmetries in the early Universe. Given that the temperature ($T \sim O(100)$ GeV) can be much larger than the sterile neutrino mass, such computations require the tools of relativistic thermal field theory. This is a notoriously challenging field, as the standard tool of particle physics, the loop expansion in terms of Feynman diagrams, typically breaks down, and suitable "resummations" need to be implemented to include large effects from infinitely high loop orders. Among the major future challenges is the systematic implementation of such resummations and thereby a quantitatively accurate analysis of the role that sterile neutrinos may play in cosmology.

Experimental and observational signatures of the νMSM

The mixing of heavy and light neutrinos not only gives light neutrinos their masses, but also allows the heavy neutrinos to take part in weak interactions, albeit with a rate suppressed by the *mixing angles* $\Theta_{\alpha I}$, whose magnitude has to be $\ll 1$ in order to explain the smallness of the light neutrino masses.[3] Because their interactions are suppressed even compared to the neutrinos, HNLs act as *feebly interacting particles* (FIPs). The idea of experimental searches for such particles goes back to the 1980s [see e.g. 62–66] and FIPs

[1] This prediction can potentially be tested by the Euclid space mission [16] or by directly measuring the mass of the lightest neutrino in an experiment like KATRIN [17].

[2] In the νMSM augmented with Higgs inflation [46] HNLs can be produced from higher-dimensional operators [47]. N_1 can also be produced by a universal four-fermion interaction which is inevitably present in the Einstein-Cartan formulation of gravity [48].

[3] The magnitude of the mixings can vary a lot while still being in agreement with neutrino masses in a technically natural manner [22, 23, 56–61].

searches are part of many experiments operating both at the intensity and energy frontiers [67–101]. Results of forthcoming neutrino and $0\nu 2\beta$ decay experiments, combined with searches at energy and intensity frontiers allow in principle for the determination of all parameters of $N_{2,3}$ [35, 36, 61, 93, 102].

Heavy neutrino searches at intensity frontier. From the point of view of HNLs searches, the most interesting are the intensity frontier experiments where HNLs are copiously produced in decays of heavy mesons [95, 103–107] or indirectly probed [108]. The most prominent experiments of this type are SHiP [87, 109–112], MATHUSLA [89], NA62 [91, 101, 113], FASER [114, 115], CODEX-b [82], AL3X [116], and ANUBIS [100]. HNLs can be also searched for at next generation neutrino experiments, such as DUNE [98, 117–119]. keV-scale sterile neutrinos can be searched in tritium β-decay experiments [120], such as Troitsk Nu-Mass [121] and KATRIN/TRISTAN [122].

Heavy neutrino searches at colliders. If the HNL masses exceed a few GeV, existing and future colliders are the best experimental facilities for their searches. There is a large number of potential signatures, such as displaced vertices and same-sign dilepton process [61, 90, 96, 123–139]. In the near future, we can expect improved bounds on heavy neutrinos from the high-luminosity upgrade of the LHC [93, 140] while the future lepton colliders, such as the ILC, FCC-ee, or CEPC [39, 130, 141–143], are especially promising.

Neutrinoless double beta decay and heavy neutrinos. The neutrino spectrum in the νMSM is hierarchical with the lightest neutrino being virtually massless [1]. This affects the prediction for the effective Majorana mass for neutrinoless double beta decay [144]. This point has been further studied in refs. [36, 145–148].

Cosmological constraints on HNLs. Particles $N_{2,3}$ may affect the primordial abundances of light elements. The consistency of measured ^{4}He and D abundances with the predictions of the SM Big Bang nucleosynthesis provides an upper limit on the lifetime on HNLs [149–161].

Sterile neutrino DM with mass around a few keV is created relativistic in the νMSM [14] and is *warm dark matter* (WDM) [162]. WDM affects the formation of dwarf galaxies and structures at smaller scales. There are several unsettled issues here, from both theoretical and observational sides. The matter distribution at these scales can be probed with observations of the Lyman-α forest. These data built from high-resolution quasar spectra exhibit a clear cut-off at comoving scales $\sim \mathcal{O}(0.1\,\mathrm{Mpc})$ [163–169]. The origin of this cut-off is under active investigation: it can be explained by WDM, including sterile neutrinos [164, 168], or may be entirely due to thermal effects [163, 166–168]. There are other WDM probes, such as those based on gravitational lensing [170], gaps in the stellar streams [171], or satellite counts [172]. All these methods are currently under active development, as they aim to probe sub-galactic scales where the influence of baryonic physics may be significant and the respective systematic uncertainties have to be clearly assessed.

The sterile neutrino is a *decaying DM* candidate. In particular, it exhibits a two-body decay $N_1 \to \nu\gamma$ [173], hence one expects a monochromatic emission line from any region with a large DM density. Such a line at $E \sim 3.5$ keV was reported in [174, 175] followed by a number of detections and non-detections (as reviewed in [176, 177]). The status of the line remains controversial, see recent works [178–182] and will likely be settled with new data of the SRG mission [183]. If the DM origin of the line is confirmed, a new era of *dark matter astronomy* will open [177, 184, 185], though the nature of DM (sterile neutrino?) will be specially investigated [186]. The absence of monochromatic lines at a particular frequency puts strong upper bounds on the lifetime of sterile neutrino DM of mass equal to double frequency, see [120, 177, 187] for summary plots. Further searches will be performed at future X-ray telescopes: XRISM [188], Athena+ [189], and Lynx [190].

Conclusions and call to action

The νMSM is a minimal model that can explain three well established hints of physics beyond the SM: neutrino masses, dark matter, and the origin of the BAU by adding three heavy neutrinos to the SM. Furthermore, it can explain all of these phenomena without new physics above the electroweak scale - it is in principle possible that we find the answers to the remaining burning questions of particle physics within the next few decades. To test this exciting possibility, a concerted effort is required on several frontiers, and hence we present this *call to action* from the theoretical, observational and experimental communities.

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