Sterile Neutrinos as the Origin of Dark and Baryonic Matter

Laurent Canetti,[1] Marco Drewes,[2,3] and Mikhail Shaposhnikov[1]
[1]Institute de Théorie des Phénoménes Physiques EPFL, CH-1015 Lausanne, Switzerland
[2]Physik Department T70, Technische Universität München, James Franck Straße 1, D-85748 Garching, Germany
[3]Institut für theoretische Teilchenphysik und Kosmologie, RWTH Aachen, D-52056 Aachen, Germany
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We demonstrate for the first time that three sterile neutrinos alone can simultaneously explain neutrino oscillations, the observed dark matter, and the baryon asymmetry of the Universe without new physics above the Fermi scale. The key new point of our analysis is leptogenesis after sphaleron freeze-out, which leads to resonant dark matter production, evading thus the constraints on sterile neutrino dark matter from structure formation and x-ray searches. We identify the range of sterile neutrino properties that is consistent with all known constraints. We find a domain of parameters where the new particles can be found with present day experimental techniques, using upgrades to existing experimental facilities.

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Introduction.—The standard model (SM) of particle physics and the theory of general relativity describe correctly almost all phenomena observed in nature. Only a handful of experimental facts definitely involve particle physics beyond the SM: neutrino oscillations (NOs), dark matter (DM), and the baryon asymmetry of the Universe (BAU), which is responsible for today's remnant baryon density Ω_B. In Refs. [1,2], it has been suggested that all of them may be explained when the matter content of the SM is complemented by three right-handed neutrinos with masses below the electroweak scale. Different authors have investigated aspects of this idea [1–30]. However, to date, it has not been verified that all requirements can be fulfilled *simultaneously*. Claims made in Ref. [2] were based on estimates and turn out to be premature from today's point of view due to constraints on the properties of DM sterile neutrinos from Ly_α and x-ray observations that were not known at that time. These constraints can be resolved if DM production is enhanced by a lepton asymmetry generated after sphaleron freeze-out. We performed the first quantitative study of this process to identify the range of sterile neutrino parameters that allow us to explain at once NO, DM, and the BAU. In this Letter, we mainly present results; details are given in a more detailed publication [31]. The centerpiece of our analysis is the study of neutrino abundances in the early Universe from hot big bang initial conditions to temperatures $\sim$50 MeV. We combine the results with bounds from direct searches for sterile neutrinos and constraints from big bang nucleosynthesis (BBN), which we reexamined in the face of recent data from neutrino experiments. We verify for the first time that right-handed neutrinos with *experimentally accessible masses and mixings* can solve all these outstanding problems without any new physics above the Fermi scale. We identify the experimentally interesting parameter region for future searches.

The neutrino minimal standard model (νMSM).—The scenario outlined above is realized within the νMSM, described by the Lagrangian

$$\mathcal{L}_{\nu\mathrm{MSM}} = \mathcal{L}_{\mathrm{SM}} + i\bar{\nu}_R \partial\!\!\!/ \nu_R - \bar{L}_L F \nu_R \tilde{\Phi} - \bar{\nu}_R F^\dagger L_L \tilde{\Phi}^\dagger - \frac{1}{2}(\bar{\nu}_R^c M_M \nu_R + \bar{\nu}_R M_M^\dagger \nu_R^c). \quad (1)$$

We have suppressed flavor and isospin indices. $\mathcal{L}_{\mathrm{SM}}$ is the Lagrangian of the SM. F is a matrix of Yukawa couplings, and M_M is a Majorana mass term for the right-handed neutrinos ν_R. $L_L = (\nu_L, e_L)^T$ are the left-handed lepton doublets in the SM, and Φ is the Higgs doublet. We chose a basis where the charged lepton Yukawa couplings and M_M are diagonal. The Lagrangian (1) is well known in the context of the seesaw mechanism [32–35]. In the νMSM, the eigenvalues of M_M are below the electroweak scale [36]. This mass pattern is required to simultaneously explain the BAU and DM; at the same time, it avoids the "hierarchy problem" of the SM in the scale-invariant version of the νMSM [51,52]. The νMSM is motivated by the principle of minimality; in comparison with the SM, there is no modification of the gauge group, the number of fermion families remains unchanged, and no new energy scale *above* the Fermi scale is introduced [6,53].

In the νMSM, neutrino masses are generated from Dirac masses $m_D = Fv$ and Majorana masses M_M by the seesaw mechanism (v is the Higgs vacuum expectation value). In the limit $M_M \gg m_D$, there are two distinct sets of neutrino mass eigenstates. The block diagonalization of the full mass matrix yields mass matrices for active and sterile neutrinos $m_\nu = -\theta M_M \theta^T$ and $M_N = M_M + \frac{1}{2}(\theta^\dagger \theta M_M + M_M^T \theta^T \theta^*)$, respectively. The active mass eigenstates ν_i with masses m_i are mainly mixings of the SM neutrinos $\nu_{L,\alpha}$; the remaining three sterile neutrinos N_I with masses M_I are mainly mixings of $\nu_{R,I}$. Transitions between both are suppressed by the active-sterile mixing matrix $\theta = m_D M_M^{-1}$.

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In the following, we distinguish between three different scenarios. In scenario I, no physics beyond the νMSM is required to explain simultaneously NO, $\Omega_{\rm DM}$, and Ω_B, as outlined in the Introduction. One sterile neutrino (N_1) constitutes all DM. This implies that (a) its mass and mixing are consistent with astrophysical constraints and (b) thermal production can account for the observed $\Omega_{\rm DM}$. The other two ($N_{2,3}$) produce the BAU and generate active neutrino masses via the seesaw mechanism. In scenario II, the roles of the N_I are the same, but we drop requirement (b); i.e., we assume that DM is made of N_1 that was produced by some unspecified mechanism. In scenario III, we consider the νMSM as a theory of baryogenesis only and drop any constraints related to DM.

To explain the observed DM density $\Omega_{\rm DM}$ in scenarios I and II, the lifetime of N_1 must be larger than the age of the Universe. Its decay leaves a distinct x-ray line of energy $M_1/2$ that can be searched for [54,55] with x-ray satellites. Combining x-ray observations with simulations of structure formation and phase space arguments, it was found that N_1 mass and mixing are constrained to 1 keV $< M_1 \lesssim$ 50 keV and $10^{-13} \lesssim \sin^2(2\theta_{\alpha 1}) \lesssim 10^{-7}$ [6]. The seesaw relation $m_i \sim -\theta M_M \theta^T$ implies that the coupling of N_1 is too small to contribute significantly to the active neutrino mass matrix, and one active neutrino is effectively massless in the νMSM [1,15].

In scenario I, N_1 must be produced thermally in the early Universe due to active-sterile mixing [56]. In the absence of lepton asymmetries, $\mu_\alpha = 0$, the resulting spectrum was found in Ref. [23]. For $\mu_\alpha \neq 0$, the N_1 dispersion relation in the primordial plasma is modified, which results in a resonantly amplified N_1 production [3,4,57,58]. This adds a nonthermal, colder component to the N_1 momentum distribution. x-ray observations, structure formation simulations, and Ly$_\alpha$ forest data [6,59–61] suggest that, if $\mu_\alpha = 0$, N_1 cannot account for the observed DM (see Fig. 1). Then, the presence of considerable lepton asymmetries $|\mu_\alpha| \gtrsim 8 \times 10^{-6}$ [4] becomes a necessary condition for sterile neutrino DM production.

The thermal history of the Universe in the νMSM differs from that of the SM, as new interactions generate lepton asymmetries $\mu_\alpha \neq 0$ during production, oscillations, freeze-out, and decay of N_I, when all Sakharov conditions [62] are fulfilled. No significant lepton asymmetries or N_I abundances are created during reheating after inflation due to the smallness of F [5]. Baryogenesis occurs via sterile neutrino oscillations during their thermal production [2,63] in processes as $t\bar{t} \to \nu N$ at $T \gtrsim T_{\rm sph}$, where the temperature of sphaleron freeze-out is $T_{\rm sph} \sim 140$ GeV for a Higgs mass $m_H = 126$ GeV. Although the total lepton number violation is suppressed by $M_I/T \ll 1$, opposite sign asymmetries are created in the sterile and active flavors. The latter are partly converted into a BAU by sphaleron processes [64]. To explain the observed BAU [65], a lepton asymmetry $\mu_\alpha \sim 10^{-10}$ is required at the sphaleron freeze-out ($T \sim T_{\rm sph}$). In scenarios I and II, only $N_{2,3}$ are produced in significant amounts at $T \gtrsim T_{\rm sph}$, as the N_1 coupling is constrained to be tiny. Soon after, they reach equilibrium and μ_α are washed out. They exit equilibrium when $l\bar{l} \to \nu N$ scatterings freeze out ($T \sim$ few GeV) and decay subsequently ($T \lesssim 1$ GeV). These nonequilibrium processes create new lepton asymmetries at a late time. The DM production in scenario I is amplified resonantly at temperatures around $T \sim 100$ MeV due to the presence of these asymmetries.

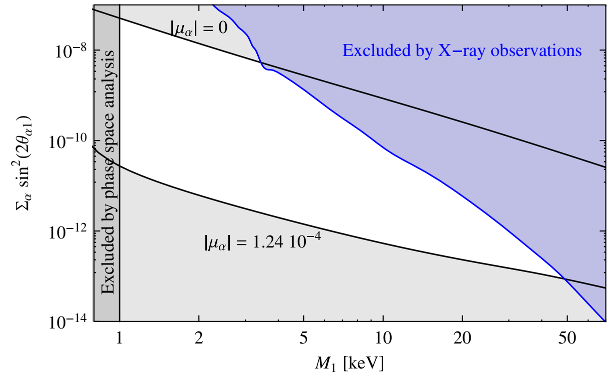

FIG. 1 (color online). Different constraints on N_1 mass and mixing in scenario I. The blue region is excluded by x-ray observations, the dark gray region $M_1 < 1$ keV by the Tremaine-Gunn bound [110–112]. For points on the upper solid black line, the observed $\Omega_{\rm DM}$ is produced for $\mu_\alpha = 0$ [4]; points on the lower solid black line give the correct $\Omega_{\rm DM}$ for $|\mu_\alpha| = 1.24 \times 10^{-4}$, the maximal asymmetry we found at $T = 100$ MeV. The region between these lines is accessible for $0 \leq |\mu_\alpha| \leq 1.24 \times 10^{-4}$. Observations of the matter distribution in the Universe constrain the DM free streaming length. Without resonant production ($\mu_\alpha = 0$), this implies that $M_1 > 8$ keV [59], which excludes the upper black curve and makes resonant production necessary. Combining both production mechanisms ($|\mu_\alpha| \gtrsim 10^{-5}$), this bound relaxes to $M_1 > 2$ keV [59]. However, we do not display it here because it depends on μ_α in a complicated way and the calculation currently includes considerable uncertainties [59]; cf. also Refs. [113,114].

We first focus on scenario I. The two requirements (i) $\mu_\alpha \sim 10^{-10}$ at $T \sim T_{\rm sph}$ (for BAU) and (ii) $|\mu_\alpha| \gtrsim 8 \times 10^{-6}$ at $T \sim 100$ MeV (for DM) can be used to constrain the properties of sterile neutrinos. Since N_1 does not contribute to high and low-temperature leptogenesis, this can be done in an effective theory with two sterile neutrinos, $N_{2,3}$. This theory contains 11 new parameters in addition to the SM. They can be chosen as two active neutrino masses m_i and three mixing angles, a Dirac and a Majorana phase, two Majorana masses in M_M, and one extra complex parameter, associated with CP violation in the sterile sector.

Condition (ii) implies much stronger constraints than (i), so we only consider it in what follows. For the allowed Yukawa couplings, the asymmetry (ii) can only be generated if the CP-violating terms are resonantly amplified by a mass degeneracy between $M_{2,3} \simeq M$ [3]. The asymmetry generation is most efficient for $\Gamma_N \sim \mathrm{H} \sim \omega$, where Γ_N is the thermal N_I width, H is the Hubble rate, and ω is the frequency of $N_{2,3}$ oscillations. It is related to the *physical* mass splitting δM at the time of low-temperature lepton asymmetry generation via $\omega \sim M\delta M/T$ if $M \lesssim T$ or simply $\omega = \delta M$ if $T \lesssim M$. Due to the interplay of thermal, Dirac, and Majorana masses, δM is a complicated function of $M_M = \mathrm{diag}(M - \Delta M/2, M + \Delta M/2)$, F, and T [31]. The required δM should be smaller than 10^{-6} eV for $M = 2$ GeV. Since this is much smaller than active neutrino masses, *two* unknown parameters of the νMSM are almost fixed by this constraint. For $M \sim 2$ GeV, the splitting of the Majorana masses ΔM must be equal with one part in 10^4–10^6 to the mass difference of the active neutrinos [7]. In addition, the combination $|\mathrm{Re}(m_D^\dagger m_D)_{23}|/M$ must be smaller than active neutrino masses by $\sim$4–6 orders of magnitude [31]. These tunings ensure that the Higgs induced contribution to δM cancels the Majorana term ΔM. Scenario I can only be realized within the *constrained* νMSM defined by these tunings. In the constrained νMSM, 7 out of 11 parameters are almost fixed either by experimental data or by requirement (ii). The remaining four parameters are the common mass M of $N_{2,3}$, two CP-violating phases in the active neutrino mass matrix, and yet one extra CP-violating parameter in the sterile neutrino sector.

The high degree of tuning $\delta M/M \lesssim 10^{-13}$ in scenario I is not understood theoretically. Some speculations can be found in Refs. [3,7,11,66]. However, the origin of this fine tuning plays no role for the present work. Scenario II only requires the weaker condition (i) that can be achieved by a much weaker tuning in $\Delta M/M \sim 10^{-3}$ [21]. In scenario III, all three sterile neutrinos can participate in baryogenesis. Due to the additional sources of CP violation, there is no need for a mass degeneracy [29]. Note that this also implies that no degeneracy is needed in scenario II if more than three fields $\nu_{R,I}$ are added to the SM.

Method and results.—The rates of interaction of the SM fields greatly exceed those of sterile neutrinos N_I and the rate of the Universe expansion. Therefore, the SM sector can be described by four numbers: the temperature T and the asymmetries μ_α. The effect of the N_I on the time evolution of temperature and on the effective number of degrees of freedom is negligible. The state of N_I can be described by *matrices of density* ρ_N and $\rho_{\bar{N}}$, commonly used in neutrino physics [67], which allow us to incorporate coherences and oscillations between the two flavors and are probably sufficient for our purpose; cf. Refs. [29,67–86]. The diagonal elements of the 2×2 matrices ρ_N and $\rho_{\bar{N}}$ are the abundances of particles and antiparticles, respectively, defined as the helicity states of the Majorana fields N_I. The time evolution of neutrino abundances is governed by the kinetic equations

$$i\frac{d\rho_N}{dT} = [H, \rho_N] - \frac{i}{2}\{\Gamma_N, \rho_N - \rho^{\mathrm{eq}}\} + \frac{i}{2}\mu_\alpha \tilde{\Gamma}_N^\alpha, \quad (2)$$

$$i\frac{d\rho_{\bar{N}}}{dT} = [H^*, \rho_{\bar{N}}] - \frac{i}{2}\{\Gamma_N^*, \rho_{\bar{N}} - \rho^{\mathrm{eq}}\} - \frac{i}{2}\mu_\alpha \tilde{\Gamma}_N^{\alpha *}, \quad (3)$$

$$i\frac{d\mu_\alpha}{dT} = -i\Gamma_L^\alpha \mu_\alpha + i\mathrm{tr}[\tilde{\Gamma}_L^\alpha(\rho_N - \rho^{\mathrm{eq}})] - i\mathrm{tr}[\tilde{\Gamma}_L^{\alpha *}(\rho_{\bar{N}} - \rho^{\mathrm{eq}})]. \quad (4)$$

Here, ρ^{eq} is the equilibrium density matrix, H is the dispersive part of the finite temperature effective N_I Hamiltonian, and Γ_N, Γ_L^α, and $\tilde{\Gamma}_L^\alpha$ are rates that are responsible for dissipative effects, which are calculated from thermal field theory [31]. They describe sterile neutrino production, oscillations, freeze-out, and decay. Due to the various involved time scales, the dependence of the asymmetries on model parameters can only be estimated under certain assumptions [3,29,70,72] that are too simplifying for a quantitative study.

We focused on scenarios I and II. The most important properties of $N_{2,3}$ from an experimental viewpoint are their masses $M_{2,3} \simeq M$ and mixings with active neutrinos. The latter can be parametrized by the quantity $U^2 \equiv \mathrm{tr}(\theta^\dagger \theta)$. In order to identify the range of M and U^2 consistent with conditions (i) and (ii), we calculated the lepton asymmetries from $T \gg T_{\mathrm{sph}}$ down to $T = 100$ MeV as a function of unknown parameters identified above and varied the others within admitted 1σ uncertainties.

Fixing all known neutrino parameters to the values given in Refs. [87,88], we first identified the Dirac and Majorana phases that maximize the produced asymmetries at $T = T_{\mathrm{sph}}$ and $T = 100$ MeV in different regions in the parameter space. We then scanned for all possible values of the remaining parameters. We performed the analysis several times with different grids. This allows us to identify the parameter regions where conditions (i) or (ii) or both can be fulfilled. They correspond to sterile neutrino properties for which the νMSM can, along with NOs, explain the observed Ω_B, Ω_{DM}, or both. We studied the mass range $1\ \mathrm{MeV} \leq M \leq 10$ GeV; for bigger masses, it is very unlikely that $N_{2,3}$ can be found experimentally in the near future.

The νMSM parameter space is also constrained by direct searches for sterile neutrinos [17,26,91–103]. Here, we focus on the most relevant bounds, coming from the NuTeV [97], CHARM [104], and CERN PS191 [95,96] experiments. The experimental constraints on active-sterile mixing have recently been interpreted in the context of the seesaw Lagrangian (1) [25,26]; cf. also Refs. [91,92]. We used bounds on θ imposed by the negative results of Refs. [95,97,104–109], provided by the authors of Ref. [26], as input and numerically scanned the space of unknown model parameters to identify all combinations of M and U^2 that are compatible with experiment.

Finally, it is a necessary requirement that $N_{2,3}$ have decayed sufficiently long before BBN that their decay products do not affect the abundances of light elements. We estimate the inverse $N_{2,3}$ lifetime τ by $\tau^{-1} \simeq \frac{1}{2}\,\mathrm{tr}\Gamma_N$ at

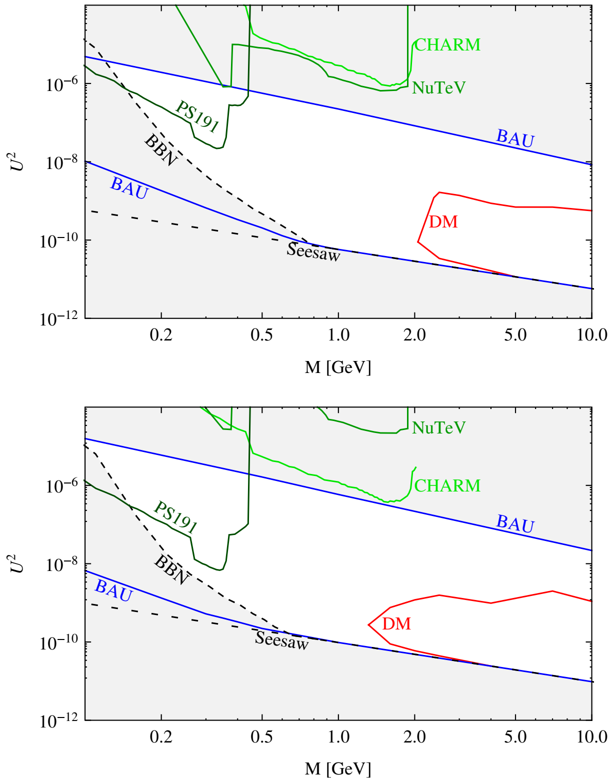

FIG. 2 (color online). Constraints on $N_{2,3}$ masses $M_{2,3} \simeq M$ and mixing $U^2 \equiv \mathrm{tr}(\theta^\dagger \theta)$ in scenarios I (red line) and II (blue line) for normal (upper panel) and inverted (lower panel) hierarchies of neutrino masses. In the regions within the blue and red lines, no physics beyond the νMSM is needed to explain the observed Ω_B and $\Omega_{\rm DM}$, respectively.

$T = 1$ MeV. This is justified as $N_{2,3}$ oscillate rapidly around the time of BBN. We varied all free parameters to identify the region in the M-U^2 plane consistent with the condition $\tau < 0.1$ s.

Our results are summarized in Figs. 1 and 2. Figure 2 shows constraints on $N_{2,3}$ mass and mixing coming from experiments (green lines), BBN (dashed black line), neutrino oscillations experiments (black dashed line that is labeled seesaw), and cosmology. Scenario II can be realized in the region between the blue lines that are labeled BAU. The difference to the result found in Ref. [21] is mainly due to $\theta_{13} \neq 0$. The region within the red line allows us to produce the observed $\Omega_{\rm DM}$. It has been determined for the first time in this work. Although the values for the CP-violating phases and ΔM that maximize the efficiency of baryogenesis and DM production are very different, the region in which Ω_B and $\Omega_{\rm DM}$ can be explained simultaneously (scenario I) almost coincides with the area inside the red line. In most of the parameter space, the relevant CP violation comes mainly from the sterile sector and not from the phases in the Pontecorvo-Maki-Nakagawa-Sakata matrix. The masses of $N_{2,3}$ are correspondingly bounded from below by 1.3 and 2.0 GeV for the inverted and normal hierarchies. For the lower mass range, sterile neutrinos can be created in decays of beauty and charmed mesons, which is crucial for experimental searches [17]. The two larger eigenvalues of $F^\dagger F$ can vary between $\sim 10^{-12}$ and $\sim 10^{-17}$ to simultaneously explain Ω_B and $\Omega_{\rm DM}$. Typical values correspond to Yukawa couplings of $N_{2,3}$ of the order 10^{-6}–10^{-7}, smaller than the electron Yukawa by 1–2 orders of magnitude. The N_1 Yukawa couplings are required to be of the order 10^{-11}–10^{-12}, smaller than those of $N_{2,3}$ by 5 orders of magnitude, which is comparable to the ratio between down and top quark Yukawa couplings.

Solving Eqs. (2)–(4) allows us to determine the maximal lepton asymmetry generated in the νMSM. Its value imposes a lower bound on the mixing of the DM candidate N_1 in scenario I. Our result for $M < 10$ GeV, shown in Fig. 1 along with astrophysical bounds, is about 1 order of magnitude larger than previous estimates [3]. This considerably eases the ultimate goal of x-ray searches for N_1.

Conclusion.—We performed the first complete systematic study of the νMSM parameter space, bringing together cosmological, astrophysical, and experimental constraints. Our results can be summarized as follows: (1) Right-handed neutrinos alone can be the common origin of neutrino oscillations, DM, and the BAU; (2) for a range of model parameters, these particles can be found using present day experimental and observational techniques.

The DM candidate N_1 can be searched for astrophysically, using high resolution x-ray spectrometers to look for the emission line from its decay in DM dense regions. The seesaw partners $N_{2,3}$ can either be discovered as missing energy in the decay of mesons or by creating them in a beam-dump experiment and looking for their decay in a nearby detector [17]. Depending on the mass M, different facilities could be used or upgraded for this search, including the CERN SPS beam and NA62 experiment, LHCb, MINOS, J-PARC, or LBNE at FNAL. The necessary experiments are challenging due to strong constraints on the mixing angle U^2 coming from cosmology.

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