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Right-handed sneutrino as thermal dark matter

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We study an extension of the MSSM with a singlet S with coupling SH_1H_2 in order to solve the μ problem as in the NMSSM, and right-handed neutrinos N with couplings SNN in order to generate dynamically electroweak-scale Majorana masses. We show how in this model a purely right-handed sneutrino can be a viable candidate for cold dark matter in the Universe. Through the direct coupling to the singlet, the sneutrino can not only be thermal relic dark matter but also have a large enough scattering cross section with nuclei to detect it directly in near future, in contrast with most of other right-handed sneutrino dark matter models.

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Introduction. Weakly interacting massive particles (WIMPs) are among the best motivated candidates for explaining the cold dark matter (CDM) in the Universe. WIMPs appear in many interesting extensions of the standard model providing new physics at the TeV scale. Such is the case of supersymmetric models, in which imposing a discrete symmetry (R-parity) to avoid rapid proton decay renders the lightest supersymmetric particle (LSP) absolutely stable and thus a good dark matter (DM) candidate.

The minimal supersymmetric extension of the standard model (MSSM) provides two natural candidates for WIMPs, the neutralino [1] and the (left-handed) sneutrino [2], both of them being neutral and with weak-scale interactions. The neutralino is a popular and extensively studied candidate [3]. On the contrary, the left-handed sneutrino in the MSSM is not a viable dark matter candidate. Given its sizable coupling to the Z boson, sneutrinos either annihilate too rapidly, resulting in a very small relic abundance, or give rise to a large detection cross section and are excluded by direct DM searches [4] (notice however that the inclusion of a lepton number violating operator can reduce the detection cross section [5]).

However, there is a strong motivation to consider an extension of the MSSM, the fact that neutrino oscillations imply tiny but non-vanishing neutrino masses. The latter can be obtained introducing right-handed neutrino superfields. Several models have been proposed to revive sneutrino DM by reducing its coupling with Z-boson. This can be achieved by introducing a mixture of left- and right-handed sneutrino [6–8], or by considering a purely right-handed sneutrino [9–12]. In the former, a significant left-right mixture is realized by adopting some particular supersymmetry breaking with a large trilinear term [6]. Such a mechanism is not available in the standard supergravity mediated supersymmetry breaking, where trilinear terms are proportional to the small neutrino Yukawa couplings. Recently, another realization of large mixing was pointed out [8] by abandoning the canonical see-saw formula [13] for neutrino masses. On the other hand, pure right-handed sneutrinos cannot be thermal relics, since their coupling to ordinary matter is extremely reduced by the neutrino Yukawa coupling [9–11], unless a new gauge interaction is introduced [12]. Furthermore, such gauge-singlet right-handed sneutrinos would be unobservable in direct detection experiments.

There is one more motivation to consider another extension of the MSSM. This is the so-called "μ problem" [14]. The superpotential in the MSSM contains a bilinear term, $\mu H_1 H_2$. Successful radiative electroweak symmetry breaking (REWSB) requires μ of the order of the electroweak scale. The next-to-minimal supersymmetric standard model (NMSSM) offers a simple solution to the μ problem by introducing a singlet superfield S and promoting the bilinear term to a trilinear coupling $\lambda S H_1 H_2$. After REWSB takes place, S develops a vacuum expectation value (VEV) and provides an effective μ term, $\mu = \lambda \langle S \rangle$. Furthermore, the NMSSM also alleviates the "little hierarchy problem" of the Higgs sector in the MSSM [15] and has an attractive phenomenology, featuring light Higgses and interesting consequences for neutralino DM [16].

Motivated by the above two issues, we study an extension of the MSSM where singlet scalar superfields are included, as in Ref. [17]. A singlet S in order to solve the μ problem as in the NMSSM (and which accounts for extra Higgs and neutralino states) and right-handed neutrinos N to obtain non-vanishing neutrino Majorana masses with the canonical, but low scale, see-saw mechanism. Terms of the type SNN in the superpotential can generate dynamically Majorana masses through the VEV of the singlet S. In addition, the presence of right-handed sneutrinos, $\tilde{N}$, with a weak scale mass provides a new possible DM candidate within the WIMP category.

In this letter, we analyse the properties of right-handed sneutrinos, showing that not only they can be thermally produced in sufficient amount to account for the CDM in the Universe because of the direct coupling between S and N, but also that their elastic scattering cross section with nuclei is large enough to allow their detection in future experiments.

The Model. The superpotential in our construction is an extension of that of the NMSSM, including new trilinear coupling among the singlets S and N and Yukawa terms to provide neutrino masses. It reads

$$W = W_{\rm NMSSM} + \lambda_N S N N + y_N H_2 \cdot L N, \quad (1)$$

$$W_{\rm NMSSM} = Y_u H_2 \cdot Q u + Y_d H_1 \cdot Q d + Y_e H_1 \cdot L e - \lambda S H_1 \cdot H_2 + \frac{1}{3}\kappa S^3, \quad (2)$$

where flavour indices are omitted and the dot denotes the $SU(2)_L$ antisymmetric product. As in the NMSSM, a global Z_3 symmetry is imposed for each superfield, so that there are no supersymmetric mass terms in the superpotential. Note that the term NNN and SSN are gauge invariant but not consistent with R-parity and thus are not included.

Once REWSB takes place and the Higgs fields take non-vanishing VEVs, $(v_{1,2}, v_s) = (\langle H_{1,2}\rangle, \langle S\rangle)$, a Majorana mass term is generated, $M_N = 2\lambda_N v_s$. Light masses for left-handed neutrinos are then obtained via a see-saw mechanism,

$$m_{\nu_L} = \frac{y_N^2 v_2^2}{M_N}, \quad (3)$$

which implies small Yukawa couplings, $y_N \lesssim \mathcal{O}(10^{-6})$.

The sneutrino mass matrix can be read from the quadratic terms in the scalar potential as

$$\frac{1}{2}(\tilde\nu_{L1}, \tilde N_1) \begin{pmatrix} m^2_{L\bar L} & m^2_{L\bar R} + m^2_{LR} \\ m^2_{L\bar R} + m^2_{LR} & m^2_{R\bar R} + 2m^2_{RR} \end{pmatrix} \begin{pmatrix} \tilde\nu_{L1} \\ \tilde N_1 \end{pmatrix} + \frac{1}{2}(\tilde\nu_{L2}, \tilde N_2) \begin{pmatrix} m^2_{L\bar L} & m^2_{L\bar R} - m^2_{LR} \\ m^2_{L\bar R} - m^2_{LR} & m^2_{R\bar R} - 2m^2_{RR} \end{pmatrix} \begin{pmatrix} \tilde\nu_{L2} \\ \tilde N_2 \end{pmatrix} \quad (4)$$

Here, sneutrinos are decomposed in real and imaginary components as $\tilde\nu_L \equiv \frac{1}{\sqrt2}(\tilde\nu_{L1} + i\tilde\nu_{L2})$ and $\tilde N \equiv \frac{1}{\sqrt2}(\tilde N_1 + i\tilde N_2)$, and all parameters are defined by

$$\begin{aligned} m^2_{L\bar L} &\equiv m^2_{\tilde L} + |y_N v_2|^2 + {\rm D-term}, \\ m^2_{LR} &\equiv y_N\,(-\lambda_N v_s v_1)^\dagger + y_N A_N v_2, \\ m^2_{L\bar R} &\equiv y_N v_2\,(-\lambda_N v_s)^\dagger, \\ m^2_{R\bar R} &\equiv m^2_{\tilde N} + |2\lambda_N v_s|^2 + |y_N v_2|^2, \\ m^2_{RR} &\equiv \lambda_N\left(A_{\lambda_N} v_s + (\kappa v_s^2 - \lambda v_1 v_2)^\dagger\right), \end{aligned} \quad (5)$$

where $m^2_{\tilde L}$, $m^2_{\tilde N}$, A_{λ_N}, and A_N, are the new soft parameters. These are assumed to be real for simplicity, so that the real and imaginary parts of sneutrinos do not mix. The mixing between left- and right-handed sneutrinos, induced by m^2_{LR} and $m^2_{L\bar R}$, is proportional to the small neutrino Yukawa coupling y_N of Eq. (3), and therefore negligible. Note that m^2_{RR} splits the masses of $\tilde N_1$ and $\tilde N_2$. $\tilde N_2$ is lighter than $\tilde N_1$ for $m^2_{RR} > 0$ and vice versa.

Although the right-handed sneutrino may have a non vanishing VEV breaking R-parity spontaneously [17], by solving the stationary condition we find that the origin $\tilde N = 0$ is the true minimum if $m^2_{R\bar R} - 2|m^2_{RR}| > 0$, which is precisely the condition for the lighest right-handed sneutrino mass squared (4) to be positive. Hereafter we only consider cases where this condition is satisfied. In such a case, the Higgs potential coincides with that in the NMSSM.

The coupling between a Higgs boson, H_i^0, and two right-handed sneutrinos determines most of the sneutrino phenomenological properties. It can be calculated from the superpotential and Lagrangian and reads

$$C_{H_i^0 \tilde N_1 \tilde N_1} = \frac{2\lambda\lambda_N M_W}{\sqrt2 g}\left(\sin\beta S^1_{H_i^0} + \cos\beta S^2_{H_i^0}\right) + \left[\left(4{\lambda_N}^2 + 2\kappa\lambda_N\right) v_s + \frac{\lambda_N A_{\lambda_N}}{\sqrt2}\right] S^3_{H_i^0}\,, \quad (6)$$

where $S^j_{H_i^0}$ $(j = 1,2,3)$ are the elements of the Higgs diagonalisation matrix.

Thermal relic density. The right-handed sneutrino, having a mass of order the EW scale, can be the LSP in our construction for adequate choices of the input parameters (in particular, for small $m_{\tilde N}$). In such a case, it constitutes a good candidate for DM. In order to determine its viability, its thermal relic abundance, $\Omega_{\tilde N_1} h^2$, needs to be calculated and compared to the WMAP result, $0.1037 \le \Omega h^2 \le 0.1161$ [18]. The possible products for $\tilde N_1 \tilde N_1$ annihilation include

- W^+W^-, ZZ, and $f\bar f$ via s-channel Higgs exchange;
- $H_i^0 H_j^0$, via s-channel Higgs exchange, t- and u-channel sneutrino exchange, and a scalar quartic coupling;
- $A_a^0 A_b^0$, and $H_i^+ H_j^-$, via s-channel Higgs exchange, and a scalar quartic coupling;
- NN, via s-channel Higgs exchange and via t- and u-channel neutralinos exchange.

The processes suppressed by the neutrino Yukawa y_N are negligible and have not been taken into account. It is obvious that the annihilation cross section is very dependent on the structure of the Higgs sector. In particular, all the processes involve s-channel Higgs exchange, which implies the presence of rapid annihilation in the resonances, when $2m_{\tilde N_1} \approx m_{H_i^0}$. In addition, annihilations into a neutral Higgs pair turn out to be one of the dominant channels, implying a significant decrease in $\Omega_{\tilde N_1} h^2$ when $m_{\tilde N_1} > m_{H_i^0}$. This is interesting, since very light Higgses are possible (as long as they have a significant singlet component) in the NMSSM. Another important contribution comes from the annihilation into a pair of right-handed neutrinos when $m_{\tilde N_1} > m_N$.

In our calculation we do not include coannihilation effects. These are only important in the regions in which the LSP changes from sneutrino to neutralino and do not affect our conclusions.

Our input parameters are, on the one hand, the usual NMSSM degrees of freedom, λ, κ, $\tan\beta$, μ, A_λ, A_κ,

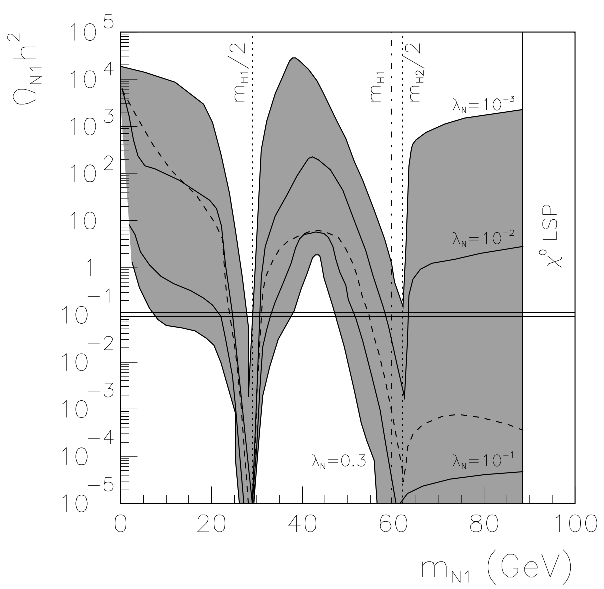

FIG. 1: $\Omega_{\tilde{N}_1} h^2$ as a function of $m_{\tilde{N}_1}$ for $\lambda_N \subset [10^{-3}, 0.3]$ (grey area). The vertical dotted lines indicate the location of the various Higgs resonances for $2m_{\tilde{N}_1} \approx m_{H^0_{1,2}}$, whereas the dot-dashed line indicates the opening of the annihilation channel into $H^0_1 H^0_1$. Points below the dashed line have $m_{\tilde{N}_1} > m_N$. The vertical solid line represents the value of the lightest neutralino mass.

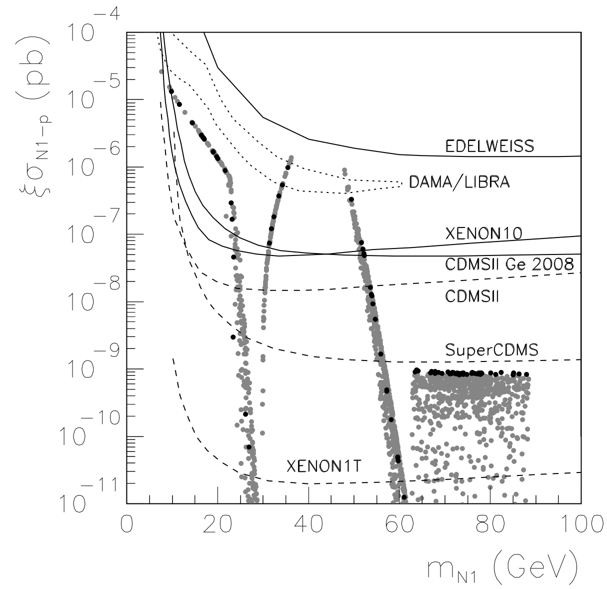

FIG. 2: Theoretical predictions for $\xi\sigma^{\rm SI}_{\tilde{N}_1-p}$, as a function of $m_{\tilde{N}_1}$. The sensitivities of present and projected experiments are represented by means of solid and dashed lines, respectively, in the case of an isothermal spherical halo. The area bounded by dotted lines is consistent with the interpretation of the DAMA/LIBRA [22] experiment in terms of a WIMP.

which we define at low-energy. Regarding the soft parameters, we assume that gaugino masses mimic, at low-energy, the values obtained from a hypothetical GUT unification. Low-energy observables, such as the muon anomalous magnetic moment and BR($b \to s\gamma$), pose stringent constraints on the NMSSM parameter space. In order to avoid these, we consider an example with $m_{L,E} = 150$ GeV, $m_{Q,U,D} = 1000$ GeV, $M_1 = 160$ GeV, $A_E = -2500$ GeV $A_{U,D} = 2500$ GeV, $A_\lambda = 400$ GeV, $A_\kappa = -200$, $\mu = 130$ GeV and $\tan\beta = 5$, that was studied in [16] (see Fig.7 there). The choice $\lambda = 0.2$ and $\kappa = 0.1$ corresponds to a very characteristic point of the NMSSM, featuring a very light Higgs mass, $m_{H^0_1} \approx 60$ GeV, and a lightest neutralino with $m_{\tilde{\chi}_1} \approx 88$ GeV (which sets the upper limit for $\tilde{N}_1$ as the LSP). The viability of this set of NMSSM parameters is checked with the `NMHDECAY` 2.0 code [19], based on which we have built a package which calculates the sneutrino relic density using the numerical procedure described in [20].

Our model contains three new parameters to be fixed, λ_N, $m_{\tilde{N}}$, A_{λ_N}. In order to illustrate the theoretical predictions for $\Omega_{\tilde{N}_1} h^2$ we set $A_{\lambda_N} = 250$ GeV and vary λ_N and $m_{\tilde{N}}$ in the ranges $[10^{-3}, 0.3]$ and $[0, 200]$ GeV, respectively, excluding those points in which $\tilde{N}_1$ is not the LSP or is tachyonic. The resulting $\Omega_{\tilde{N}_1} h^2$ is shown in Fig. 1, where the large suppression on the Higgs resonances is clearly evidenced. The relic abundance increases as λ_N decreases due to the reduction in $C_{H^0_i \tilde{N}_1 \tilde{N}_1}$. Remarkably, the correct relic density can be obtained with natural values of λ_N. In particular, when annihilation into Higgses is possible ($m_{\tilde{N}_1} > m_{H^0_1}$), one needs $10^{-2} \lesssim \lambda_N \lesssim 10^{-1}$. Notice also that very light $\tilde{N}_1$ are viable with $\lambda_N \gtrsim 10^{-1}$ if annihilation into right-handed neutrinos is possible. For our choice of parameters a lower bound $m_{\tilde{N}_1} \approx 10$ GeV is obtained.

Direct detection. The direct detection of sneutrinos would take place through their elastic scattering with nuclei inside a DM detector. At the microscopic level, the low-energy interaction of sneutrinos and quarks can be described in terms of an effective Lagrangian. In our case, there is only one diagram contributing (at tree level) to this process, namely, the t-channel exchange of neutral Higgses. In terms of the Higgs-sneutrino-sneutrino coupling, one can write

$$\mathcal{L}_{eff} \supset \sum_{j=1}^{3} \frac{C_{H^0_j \tilde{N}_1 \tilde{N}_1} Y_{q_i}}{m^2_{H^o_j}} \tilde{N}\tilde{N}\bar{q}_i q_i \equiv \alpha_{q_i} \tilde{N}\tilde{N}\bar{q}_i q_i \,, \qquad (7)$$

where Y_{q_i} is the corresponding quark Yukawa coupling and i labels up-type quarks ($i = 1$) and down-type quarks ($i = 2$). Obviously, the effective Lagrangian contains no axial-vector coupling since the sneutrino is a scalar field, therefore implying a vanishing contribution to the spin-dependent detection cross section.

The total spin-independent sneutrino-proton scattering cross section yields

$$\sigma^{\rm SI}_{\tilde{N}_1-p} = \frac{1}{\pi}\frac{m_p^4}{(m_p+m_{\tilde{N}_1})^2}\, f_p^2\,, \qquad (8)$$

where m_p is the proton mass and

$$\frac{f_p}{m_p} = \sum_{q_i=u,d,s} f^p_{Tq_i}\frac{\alpha_{q_i}}{m_{q_i}} + \frac{2}{27}\, f^p_{TG}\sum_{q_i=c,b,t}\frac{\alpha_{q_i}}{m_{q_i}}\ . \qquad (9)$$

The quantities $f^p_{Tq_i}$ and f^p_{TG} are the hadronic matrix elements which parameterize the quark content of the proton. In our analysis we have considered the most recent values for these quantities, as explained in [21].

It is obvious from the previous formulae that the sneutrino detection cross section is also very dependent on the features of the Higgs sector. In particular, $\sigma^{\rm SI}_{\tilde{N}_1-p}$ becomes larger when $C_{H_i^0\tilde{N}_1\tilde{N}_1}$ (6) increases (e.g., when λ, λ_N or A_{λ_N} are enhanced). Moreover, a larger $\sigma^{\rm SI}_{\tilde{N}_1-p}$ can also be obtained in those regions of the parameter space where the mass of the lightest Higgs becomes small.

The theoretical predictions for $\xi\sigma^{\rm SI}_{\tilde{N}_1-p}$ are represented as a function of the sneutrino mass in Fig. 2. The sneutrino fractional density ξ, is defined to be $\xi = \min[1, \Omega_{\tilde{N}_1}h^2/0.1037]$ in order to have a rescaling of the signal for subdominant DM in the halo [23]. Black dots correspond to points with a relic density consistent with the WMAP results, whereas grey dots stand for those with $\Omega_{\tilde{N}_1}h^2 \le 0.1$ in which $\tilde{N}_1$ is subdominant.

As we can observe, the right-handed sneutrino in our model is not yet excluded by direct searches for dark matter. Interestingly, the predicted $\sigma^{\rm SI}_{\tilde{N}_1-p}$ lies within the reach of projected DM experiments, such as SuperCDMS and XENON1T (unlike a pure right-handed sneutrino with only Yukawa interactions). A complete analysis of the parameter space is beyond the scope of this work and will be presented elsewhere [24].

Conclusions. We propose the right-handed sneutrino as a viable thermal DM candidate in an extension of the MSSM where the singlet superfields, S and N, are included to solve the μ problem and account for neutrino masses. A direct coupling between S and N provides a sufficiently large annihilation cross section for the right-handed sneutrino, as well as a detection cross section in the range of future direct DM searches.

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