Minimal Supergravity Scalar Neutrino Dark Matter and Inverse Seesaw Neutrino Masses

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(Received 27 June 2008; published 15 October 2008)

We show that within the inverse seesaw mechanism for generating neutrino masses, minimal supergravity naturally provides the scalar neutrino as the lightest superparticle. We also demonstrate that such schemes naturally reconcile the small neutrino masses with the correct relic scalar neutrino dark matter abundance and accessible direct detection rates in nuclear recoil experiments. This way, inverse seesaw minimal supergravity offers a common solution to the generation of the neutrino mass and to the origin of dark matter.

DOI: 10.1103/PhysRevLett.101.161802 PACS numbers: 12.60.Jv, 11.30.Pb, 14.60.Pq, 95.35.+d

Introduction.—Over the last 15 years, we have had solid experimental evidence for neutrino masses and oscillations [1], providing the first evidence for physics beyond the Standard Model. On the other hand, cosmological studies clearly show that a large fraction of the mass of the Universe is dark and must be nonbaryonic.

The generation of neutrino masses may provide new insight on the nature of the dark matter [2]. In this Letter, we show that in a minimal supergravity (mSUGRA) scheme where the smallness of neutrino masses is accounted for within the inverse seesaw mechanism, the lightest supersymmetric particle is likely to be represented by the corresponding neutrino superpartner (sneutrino), instead of the lightest neutralino.

This opens a new window for the mSUGRA scenario. Here, we consider the implications of the model for the dark matter issue. We demonstrate that such a model naturally reconciles the small neutrino masses with the correct relic abundance of sneutrino dark matter and experimentally accessible direct detection rates.

Minimal sugra inverse seesaw model.—Let us add to the Minimal Supersymmetric Standard Model (MSSM) three sequential pairs of SU(2) ⊗ U(1) singlet neutrino superfields $\hat{\nu}^c_i$ and $\hat{S}_i$ (i is the generation index), with the following superpotential terms [3,4]:

$$\mathcal{W} = \mathcal{W}_{\rm MSSM} + \varepsilon_{ab} h^{ij}_{\nu} \hat{L}^a_i \hat{\nu}^c_j \hat{H}^b_u + M^{ij}_R \hat{\nu}^c_i \hat{S}_j + \frac{1}{2}\mu^{ij}_S \hat{S}_i \hat{S}_j \tag{1}$$

where $\mathcal{W}_{\rm MSSM}$ is the usual MSSM superpotential. In the limit $\mu^{ij}_S \to 0$, there are exactly conserved lepton numbers assigned as $(1, -1, 1)$ [3,4] for ν, ν^c, and S, respectively.

The extra singlet superfields induce new terms in the soft-breaking Lagrangian,

$$\begin{aligned} -\mathcal{L}_{\rm soft} = {} & -\mathcal{L}^{\rm MSSM}_{\rm soft} + \tilde{\nu}^c_i \mathbf{M}^2_{\nu^c ij} \tilde{\nu}^c_j + \tilde{S}_i \mathbf{M}^2_{\mathbf{S} ij} \tilde{S}_j \\ & + \varepsilon_{ab} A^{ij}_{h_\nu} \tilde{L}^a_i \tilde{\nu}^c_j H^b_u + B^{ij}_{M_R} \tilde{\nu}^c_i \tilde{S}_j + \frac{1}{2} B^{ij}_{\mu_S} \tilde{S}_i \tilde{S}_j \end{aligned} \tag{2}$$

where $\mathcal{L}^{\rm MSSM}_{\rm soft}$ is the MSSM SUSY-breaking Lagrangian.

Small neutrino masses are generated through the inverse seesaw mechanism [3–5]: the effective neutrino mass matrix $m^{\rm eff}_\nu$ is obtained by the following relation:

$$m^{\rm eff}_\nu = -v^2_u h_\nu (M^T_R)^{-1} \mu_S M^{-1}_R h^T_\nu = (U^T)^{-1} m^{\rm diag}_\mu U^{-1} \tag{3}$$

where h_ν defines the Yukawa matrix and v_u is the H_u vacuum expectation value. The smallness of the neutrino mass is ascribed to the smallness of the μ_S parameter, rather than the largeness of the Majorana-type mass matrix M_R, as required in the standard seesaw mechanism [5]. In this way, light (eV scale or smaller) neutrino masses allow for a sizeable magnitude for the Dirac-type mass $m_D = v_u h_\nu$ and a TeV-scale mass M_R for the right-handed neutrinos, features which have been shown to produce an interesting sneutrino dark matter phenomenology [6]. For references to other approaches to sneutrino dark matter, see Ref. [6] and references therein.

The main feature of our model is that the nature of the dark matter candidate, its mass, and couplings all arise from the same sector responsible for the generation of neutrino masses. In order to illustrate the mechanism, we consider the simplest one-generation case. In this case, the sneutrino mass matrix reads

$$\mathcal{M}^2 = \begin{pmatrix} \mathcal{M}^2_+ & \mathbf{0} \\ \mathbf{0} & \mathcal{M}^2_- \end{pmatrix}, \quad \text{where: } \mathcal{M}^2_\pm = \begin{pmatrix} m^2_L + \frac{1}{2} m^2_Z \cos 2\beta + m^2_D & \pm(A_{h_\nu} v_u - \mu m_D \mathrm{cotg}\beta) & m_D M_R \\ \pm(A_{h_\nu} v_u - \mu m_D \mathrm{cotg}\beta) & m^2_{\nu^c} + M^2_R + m^2_D & \mu_S M_R \pm B_{M_R} \\ m_D M_R & \mu_S M_R \pm B_{M_R} & m^2_S + \mu^2_S + M^2_R \pm B_{\mu_S} \end{pmatrix} \tag{4}$$

in the CP eigenstates basis: $\Phi^\dagger = (\tilde{\nu}_+ \tilde{\nu}_+^c \tilde{S}_+ \tilde{\nu}_- \tilde{\nu}_-^c \tilde{S}_-)$. Once diagonalized, the lightest of the six mass eigenstates is our dark matter candidate, and it is stable by R-parity conservation.

A novel supersymmetric spectrum.—Let us now consider the model within a minimal SUGRA scenario. In the absence of the singlet neutrino superfields, the mSUGRA framework predicts the lightest supersymmetric particle (LSP) to be either a stau or a neutralino, and only the latter case represents a viable dark matter candidate. In most of the mSUGRA parameter space, however, the neutralino relic abundance turns out to exceed the WMAP bound [7], and hence the cosmologically acceptable regions of parameter space are quite restricted.

In contrast, when the singlet neutrino superfields are added, a combination of sneutrinos emerges quite naturally as the LSP. Indeed, we have computed the resulting supersymmetric particle spectrum and couplings by adapting the SPHENO code [8] so as to include the additional singlet superfields. An illustrative example of how the minimal SUGRA particle spectrum is modified by the presence of such states is given in Fig. 1. This figure shows explicitly how a sneutrino LSP is in fact realized.

A more general analysis in the mSUGRA parameter space is shown in Fig. 2: the dark (blue) shaded area is excluded either by experimental bounds on supersymmetry and Higgs boson searches, or because it does not lead to electroweak symmetry breaking, while the (light) yellow region refers to stau LSP in the conventional (unextended) mSUGRA case. As expected, in all of the remaining region of the plane, the neutralino is the LSP in the standard mSUGRA case. The new phenomenological possibility which opens up thanks to the presence of the singlet neutrino superfields where the sneutrino is the LSP corresponds to the full dashed (red) and light (yellow) areas. In what follows, we demonstrate that in this region of parameter space such a sneutrino reproduces the right amount of dark matter and is not excluded by direct detection experiments.

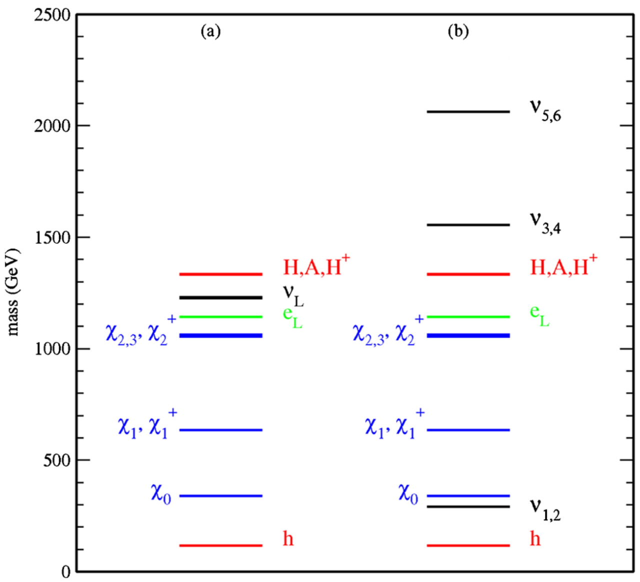

FIG. 1 (color online). Supersymmetric particle spectrum in the standard mSUGRA scheme [panel (a)] and in the inverse seesaw mSUGRA model [panel (b)] with parameters chosen as: $m_0 = 358$ GeV, $m_{1/2} = 692$ GeV, $A_0 = 0$, $\tan\beta = 35$, and sign $\mu > 0$. The sneutrino sector has the additional parameter B_{μ_S}, fixed at 10 GeV^2. The squark sector is not shown.

Sneutrino LSP as dark matter.—The novelty of the spectrum implied by mSUGRA implemented with the inverse seesaw mechanism is that it may lead to a bosonic dark matter candidate, the lightest sneutrino $\tilde{\nu}_1$, instead of the fermionic neutralino. To understand the physics, it suffices for us to consider the simple one sneutrino generation case. For a detailed discussion on the relic density calculation for sneutrino dark matter, see Ref. [6].

The lightest mass eigenstate is also a CP eigenstate and coannihilates with the NLSP, a corresponding heavier opposite-CP sneutrino eigenstate. We notice that this situation provides a nice realization of inelastic dark matter, a case where the dark matter possesses a suppressed scattering with the nucleon, relevant for the direct detection scattering cross section. From Fig. 3, we see that a large

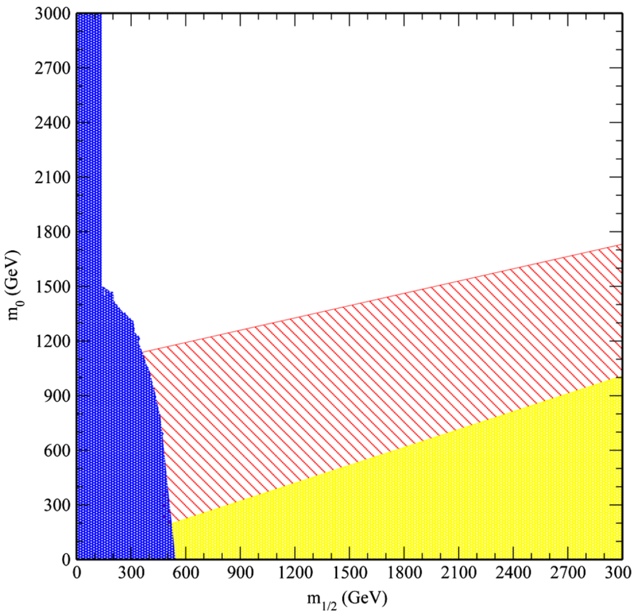

FIG. 2 (color online). The $m_0 - m_{1/2}$ plane for $\tan\beta = 35$, $A_0 = 0$, and $\mu > 0$. The shaded (red) and light (yellow) areas denote the set of supersymmetric parameters where the sneutrino is the LSP in inverse seesaw models (it includes all the light (yellow) region where the $\tilde{\tau}$ is the LSP in the standard mSUGRA case). The white region has the neutralino as LSP in both standard and modified mSUGRA. For the sneutrino LSP region, the additional parameters are: $B_{\mu_S} = 10$ GeV^2, $M_R = 500$ GeV, $m_D = 5$ GeV, and $\mu_S = 100$ eV. The dark (blue) region is excluded by experimental and theoretical constraints.

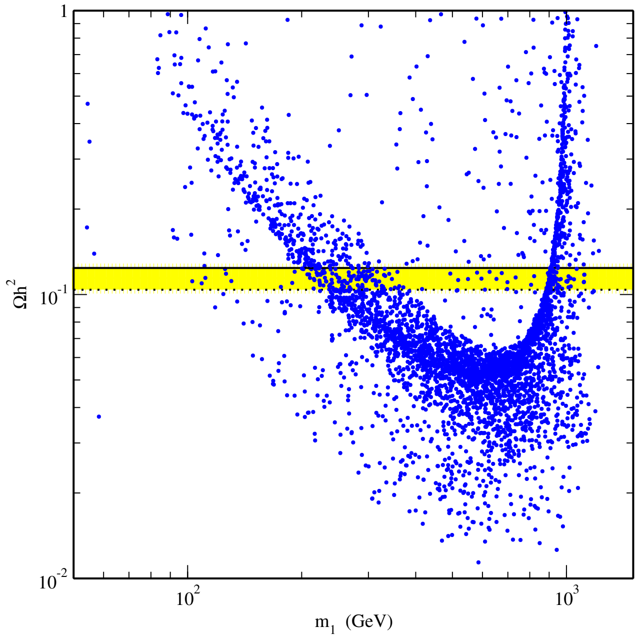

FIG. 3 (color online). Sneutrino relic abundance Ωh^2 as a function of the LSP sneutrino mass m_1, for a scan of the supersymmetric parameter space: $100\ \mathrm{GeV} < m_0 < 3\ \mathrm{TeV}$, $100\ \mathrm{GeV} < m_{1/2} < 3\ \mathrm{TeV}$, $A_0 = 0$, $3 < \tan\beta < 50$, $1\ \mathrm{GeV}^2 < B_{\mu_S} < 80\ \mathrm{GeV}^2$, $500\ \mathrm{GeV} < M_R < 1\ \mathrm{TeV}$, $10^{-9}\ \mathrm{GeV} < \mu_S < 10^{-6}\ \mathrm{GeV}$. The yellow band delimits the WMAP [7] cold dark matter interval at 3σ of C.L.: $0.104 \le \Omega_{\mathrm{CDM}} h^2 \le 0.124$.

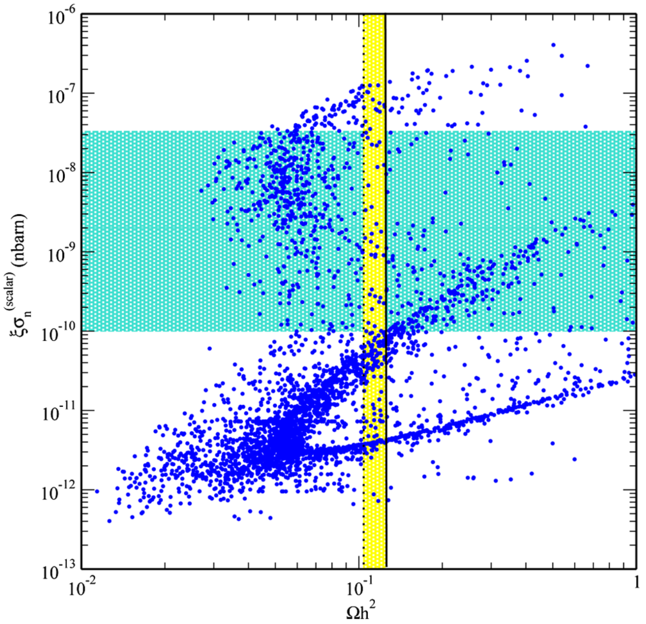

FIG. 4 (color online). Sneutrino-nucleon scattering cross section $\xi\sigma^{(\mathrm{scalar})}_{\mathrm{nucleon}}$ vs the sneutrino relic abundance Ωh^2, for the same scan of Fig. 3. The horizontal band denotes the current sensitivity of direct detection experiments; the vertical band delimits the 3σ C.L. WMAP cold dark matter range [7].

fraction of sneutrino configurations is compatible with the WMAP cold dark matter range, and therefore represents viable sneutrino dark matter models. Figure 4 in addition shows that direct detection experiments do not exclude this possibility: instead, a large fraction of configurations are actually compatible and under exploration by current direct dark matter detection experiments. This fact is partly possible because the mass splitting between the lightest and second lightest sneutrino induces a suppressed coupling to the Z boson, and this allows to reduce the direct detection cross section to acceptable levels (for details, see [6]). A key parameter determining the sneutrino mass splitting is B_{μ_S}, which should exceed about $1\ \mathrm{GeV}^2$ in order to successfully suppress the direct detection scattering to acceptable levels. The points with the largest cross section in Fig. 4 are in fact those for which B_{μ_S} is close to $1\ \mathrm{GeV}^2$.

We stress that all models reported in Figs. 3 and 4 have the inverse seesaw-induced neutrino masses consistent with current experimental observations for natural values of its relevant parameters. We also note that the lepton-number violating parameter B_{μ_S} also has an impact on the neutrino sector, since it can induce one-loop corrections to the neutrino mass itself (for details, see Ref. [6] and references therein). These corrections must be small, in order not to violate the bounds on neutrino masses, and this in turn implies that the mass splitting between the sneutrino LSP and NLSP is small (less than MeV or so) [6], implying the inelasticity of the sneutrino scattering with nuclei [6]. We find that the neutrino mass bound constrains B_{μ_S} to be smaller than about $80\ \mathrm{GeV}^2$. The presence of the new scalar superfield $\hat{S}$ therefore plays a crucial role in controlling both the neutrino mass generation (through the parameter μ_s) and the sneutrino relic abundance and direct detection cross section (through the parameter B_{μ_S}).

In conclusion, in this Letter, we have presented an mSUGRA scenario in which neutrino masses and dark matter arise from the same sector of the theory. Over large portions of the parameter space, the model successfully accommodates light neutrino masses and sneutrinos dark matter with the correct relic abundance indicated by WMAP as well as direct detection rates consistent with current dark matter searches. The neutrino mass is generated by means of an inverse seesaw mechanism, while in a large region of parameters, the dark matter is represented by sneutrinos. The small superpotential mass parameter μ_S and the parameter B_{μ_S} control most of the successful phenomenology of both the neutrino and sneutrino sector. In the absence of μ_S, neutrinos become massless, Eq. (3). The bilinear superpotential term $\mu_S^{ij}\hat{S}_i\hat{S}_j$ could arise in a spontaneous way in a scheme with an additional lepton-number-carrying singlet superfield σ, implying the existence of a majoron [9]. In this case, the dominant decays of the Higgs bosons are likely to be into a pair of majorons [10]. Such invisible mode would be "seen" experimentally as missing momentum, but the corresponding signal did not show up in the LEP data [11]. Although hard to catch at the LHC, such decays would provide a clean signal in a future ILC facility. Similarly, the standard bilinear superpotential term $\mu H_u H_d$ present in the minimal supergravity model could also be substituted by a trilinear, in a NMSSM-like scheme [12].

Note that our proposed scheme may also have important implications for supersymmetric particle searches at the LHC, due to modified particle spectra and decay chains. Additional experimental signatures could be associated with the (quasi-Dirac) neutral heavy leptons formed by ν^c and S, whose couplings and masses are already restricted by LEP searches [13,14].

We warmly thank M. Hirsch for stimulating discussions. Work supported by: MEC Grant No. FPA2005-01269; EC Contracts RTN network No. MRTN-CT-2004-503369 and ILIAS/N6 No. RII3-CT-2004-506222; FCT Grant No. POCI/FP/81919/2007; MIUR and INFN grants within the *Astroparticle Physics Project*.

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