Sneutrino dark matter in a SUSY inverse seesaw model

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Motivation

Why do we need to extend the SM?

- Neutrino masses
- Gauge hierarchy problem
- DM candidate
- Gauge coupling unification

Seesaw mechanism by adding RHνs

Supersymmetry

MSSM+type-I seesaw mechanism

Problems above can be solved, but type-I seesaw requires Majorana mass scale as $10^{12-16}\text{GeV}$

How small Majorana mass is possible?
Motivation

Linear scaling of neutrino Yukawa coupling (type-I):

- Coupling is $O(1)$
- Could be accessible
- Impossible to be produced
- Production rate is small

\[
\frac{F^2 \nu^2_{\text{EW}}}{M_N} \simeq 0.1 \text{ eV}
\]
Motivation

There are lots of alternative ideas

- Inverse seesaw (ISS) mechanism
  \[^{[Mohapatra (1986); Mohapatra and Valle (1986)]}\]

Amplify the model by using another gauge singlet

\[
-L \supset y_\nu \tilde{L} H \nu_R + M_N \nu^c_R \nu_R + M_S \overline{S^c} S + \mu \overline{\nu}_R S + h.c
\]

Neutrino mass matrix

\[
M_\nu = \begin{pmatrix}
0 & y_\nu v_{EW} & 0 \\
y_\nu^T v_{EW} & M_N & \mu \\
0 & \mu^T & M_S
\end{pmatrix}
\]

\[
m_\nu = -\frac{y_\nu v_{EW} M_S y_\nu^T v_{EW}}{\mu^2}
\]

Small $M_S$ (Lepton # violation) leads tiny $m_\nu$.
Motivation

Assumption in most of works technically naturalness

\[
M_\nu = \begin{pmatrix}
0 & y_\nu v_{\text{EW}} & 0 \\
y_\nu^T v_{\text{EW}} & 0 & \mu^T \\
0 & \mu^T & M_S
\end{pmatrix}
\]

when \( M_S \rightarrow 0 \) lepton # sym. is recovered

smallness of \( M_S \) is technically natural
Motivation

Assumption in most of works benefit of ISS

Dynamical origin of lepton number violating scale?

Extension at TeV scale with $O(1)$ Yukawa is possible

Rich phenomenology at collider!

Dynamical origin of lepton number violating scale?
Contents

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Model (NCTS model)

Symmetry: $G_{SM} \times \mathbb{Z}_6$

forbid R-parity violating terms without imposing R-parity

<table>
<thead>
<tr>
<th>Superfield</th>
<th>$\hat{Q}_i$</th>
<th>$\hat{U}_i^c$</th>
<th>$\hat{E}_i^c$</th>
<th>$\hat{L}_i$</th>
<th>$\hat{D}_i^c$</th>
<th>$\hat{H}_u$</th>
<th>$\hat{H}_d$</th>
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New super potential in addition to MSSM

\[
\mathcal{W}_\nu = Y_\nu \hat{L}\hat{H}_u \hat{N}_\alpha^c + \mu_{NS} \hat{N}_\alpha^c \hat{S} + \frac{\lambda}{2} \hat{X} \hat{S}^2 + \frac{\kappa}{3} \hat{X}^3
\]

Lagrangian related to neutrino

\[
-\mathcal{L}_\nu = (Y_\nu)_{i\alpha} \hat{L}_i \hat{N}_\alpha^c \hat{H}_u + (\mu_{NS})_{\alpha\beta} \hat{N}_\alpha^c \hat{S}_\beta + \frac{1}{2} \lambda_{\alpha\beta} \hat{S}_\alpha \hat{S}_\beta \hat{X} + \text{H.c.}
\]
Model

Symmetry breaking:

Requirement to scalar fields

- No field takes VEV except for Hu, Hd, X

From potential analysis,

\[ v_X = -\frac{A_\kappa}{4\kappa^2} \pm \frac{\sqrt{A_\kappa^2 - 8\kappa^2 M_X^2}}{4\kappa^2} \]

Origin of "lepton #" violation

\[ \frac{1}{2} \lambda_{\alpha\beta} S_\alpha S_\beta X \quad \rightarrow \quad \frac{1}{2} \lambda_{\alpha\beta} v_X S_\alpha S_\beta \]
Neutrino mass matrix:

\[
M_\nu = \begin{pmatrix}
0 & M_D & 0 \\
M^T_D & 0 & \mu_{NS} \\
0 & \mu^T_{NS} & M_S
\end{pmatrix}
\]

Smallness of \( M_S \equiv \lambda \nu_X \) is explained by coupling As possibilities,

(i) ISS type I: \( \lambda \ll Y_\nu \ll 1 \) \( \mu_{NS} \),

(ii) ISS type II: \( \lambda \sim Y_\nu \ll 1 \) \( \mu_{NS} \),

(iii) ISS type III: \( Y_\nu \ll \lambda \ll 1 \) \( \mu_{NS} \).
Model

Feature of model $G_{SM} \times Z_6$

$Z_3 \times Z_2$

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Matter parity is defined

LSP can be DM candidate!

Neutralino, Sneutrino, Gravitino

Non-MSSM candidate!
Model

Phenomenological constraints?

-LFV

1. Non-SUSY contribution: $\text{Br}(\mu \to e + \gamma) \simeq \mathcal{O}(10^{-20})$

2. SUSY contribution: depends on sparticle mixing

-0νββ decay

1. Non-SUSY contribution: $m_{\text{eff}} \simeq 8 \times 10^{-9}\text{meV} \left(\frac{\mu_{NS}}{\text{TeV}}\right)$

2. SUSY contribution: no contribution due to "R-parity" conservation
DM estimation

arXiv:1806.04468
WIMP in the model

Definition of WIMP before

"Weakly" interacting massive particle
same magnitude as weak interaction

\[ \Omega h^2 \approx 0.1 \times \left( \frac{3 \cdot 10^{-26}\text{cm}^2}{\langle \sigma v (\chi \chi \rightarrow SM) \rangle} \right) \approx \left( \frac{\alpha^2/(200\text{GeV})^2}{\langle \sigma v (\chi \chi \rightarrow SM) \rangle} \right) \]

Definition of WIMP now

"Weakly" interacting massive particle
as weak as you want
as long as you can explain abundance
DM estimation

Boundary conditions

\[ m_0^2 = \frac{1}{9} m_Q^2 = \frac{1}{9} m_D^2 = \frac{1}{9} m_U^2 = m_L^2 = m_E^2 = m_N^2 = m_S^2 = m_{H_u}^2 = m_{H_d}^2 = b_{NS}, \]
\[ M_{1/2} = \frac{1}{3} M_3 = M_2 = M_1, \]
\[ A_i = A_0 Y_i, \quad A_\lambda = A_0 \lambda, \quad A_\kappa = \kappa A_0, \]

- Put arbitrary factor to make colored particles heavy enough

- \( m_0 \) and \( M_{1/2} \) are fixed at high scale

- \( v_X, \mu_{NS}, \lambda \) and \( \kappa \) are fixed at low scale

not to worry about running effect
DM estimation

Dominant (co-)annihilation channels

H-funnel

A-funnel
DM estimation

Sneutrino mass matrix

\[
m_{\tilde{\nu}_R}^2 \approx m_{\tilde{\nu}_I}^2 \approx \begin{pmatrix}
\Re(M_{L}^2) + \frac{1}{2}M_Z^2 \cos(2\beta) & 0 & 0 \\
0 & \Re(M_{\tilde{N}_C}^2 + \mu_{NS}\mu_{NS}^\dagger) & \Re(b_{NS}) \\
0 & \Re(b_{NS}^T) & \Re(M_{\tilde{S}}^2 + \mu_{NS}^\dagger\mu_{NS})
\end{pmatrix}
\]

boundary conditions

\[
m_{\tilde{\nu}_R}^2 \approx m_{\tilde{\nu}_I}^2 \approx \begin{pmatrix}
m_0^2 + \frac{1}{2}M_Z^2 \cos(2\beta) & 0 & 0 \\
0 & m_0^2 + \mu_{NS}^2 & m_0^2 \\
0 & m_0^2 & m_0^2 + \mu_{NS}^2
\end{pmatrix}
\]

Eigenvalues at tree level

\[
m_0^2 + \frac{1}{2}M_Z^2 \cos(2\beta), \mu_{NS}^2, 2m_0^2 + \mu_{NS}^2
\]
DM estimation

Sneutrino mass matrix

\[
\begin{pmatrix}
    m^2_0 + \frac{1}{2} M_Z^2 \cos(2\beta) & 0 & 0 \\
    0 & m^2_0 + \mu^2_{NS} & m^2_0 \\
    0 & m^2_0 & m^2_0 + \mu^2_{NS}
\end{pmatrix}
\]

- RG corrections to them are small enough

- Physical states

\[\tilde{\nu}_{1,2} \approx \frac{1}{\sqrt{2}} \left( \tilde{N}_1^c \mp \tilde{S}_1 \right) \text{ and } \tilde{\nu}_3 \approx \tilde{L}_1\]

- Mass difference between CP-even & odd states

\[m^2_{\tilde{\nu}_R} - m^2_{\tilde{\nu}_I} \approx \frac{1}{2} \lambda v_X \left( \sqrt{2} A_0 - 2\sqrt{2}\mu_{NS} + \kappa v_X \right)\]

\[\mu_{NS} \ll m_0\]

\[m^2_{\tilde{\nu}_1} \approx \mu^2_{NS}\]
DM estimation

Higgs masses ($H_X$ and $A_X$)

- We have two more Higgs compared to MSSM which are composed X-scalar

- Mixing with MSSM scalars is extremely suppressed

\[ \mathcal{O} \text{ (loop factor } \times m^2_{\nu}) \]

- Approximate masses

\[
m^2_{H_X} \approx 2 \kappa^2_0 v^2_X + \frac{v_X}{\sqrt{2}} \kappa_0 A_0 \left(1 - 2.3 \kappa^2_0 \right), \quad m^2_{A_X} \approx -\frac{3 v_X}{\sqrt{2}} \kappa_0 A_0 \left(1 - 2.3 \kappa^2_0 \right)
\]

\[
-\frac{2 \sqrt{2} \kappa_0}{1 - 2.3 \kappa^2_0} v_X \lesssim A_0 < 0
\]
DM estimation

Higgs masses ($H_X$ and $A_X$)

-Comparison
Features of our analysis

-Three exceptions of thermal relic calculation

1. Co-annihilation
2. Annihilation into forbidden channel (near threshold)
3. Annihilation near pole (resonance)

We have to take into account 1 and 3!
DM estimation

Results in $A_X$-funnel scenario

\[ m_{\tilde{\nu}_1^R} + m_{\tilde{\nu}_1^I} = c \, m_{A_X} \]

\[
\begin{align*}
\tau_{A_X} & \quad \text{[sec]} \\
10^{-19} & \\
10^{-20} & \\
\end{align*}
\]

\[ \delta \chi^2 (\Omega h^2) < 5.99 \]

\[ m_{A_X} [\text{GeV}] \]

\[ 150 \quad 180 \quad 210 \quad 240 \quad 270 \quad 300 \]

\[ c = 0.99 \quad \text{red} \quad \text{line} \]

\[ c = 0.97 \quad \text{green} \quad \text{line} \]
DM estimation

Results in $A_X$-funnel scenario

\[ m_{\tilde{\nu}_1^R} + m_{\tilde{\nu}_1^I} = c m_{A_X} \]

\[ \delta \chi^2 (\Omega h^2) < 5.99 \]

\[ \lambda_{11} \times 10^3 \]

\[ m_\chi \text{[GeV]} \]

- $c = 0.99$
- $c = 0.97$
DM estimation

How about $H_X$-funnel?

$H_X$-funnel does NOT work because...

1. $H_X$-funnel has p-wave suppression

2. To compensate, larger $\lambda$ is required

$$\mathcal{W}_\nu = Y_\nu \hat{L} \hat{H}_u \hat{N}^c + \mu_{NS} \hat{N}^c \hat{S} + \frac{\lambda}{2} \hat{X} \hat{S}^2 + \frac{\kappa}{3} \hat{X}^3$$

3. When $\lambda$ gets large, it closes the decay channel into heavy neutrinos due to mass splitting.
DM properties

arXiv:1806.04468
DM properties

Direct detection
- Using $y_1 \sim 10^{-6}$ and $M_{\text{SUSY}} = 1 \text{ TeV}$, Higgs exchange cross section is given as $O(10^{-29}) \text{ pb}$ which is even below neutrino floor.

$Z$ exchange is more suppressed.
DM properties

Indirect detection

-If DM annihilate into two active neutrinos or one active and one heavy neutrino, we could see line signal of active $\nu$ at IceCube

-Since heavy neutrino can decay into SM leptons, we could see some signal from this cascade decay
DM properties

Indirect detection

- Since annihilation cross section into two active neutrinos is \( O(10^{-41}) \text{cm}^3 \text{s}^{-1} \), this signal seems not to be so promising.

Current limit by IceCube: \( 2 \times 10^{-23} \text{cm}^3 \text{s}^{-1} \) (\( m_{\text{DM}} \sim 100 \text{GeV} \))
DM properties

Indirect detection

-The most plausible cross section would be channel into two heavy neutrinos: $O(10^{-29})\text{cm}^3\text{s}^{-1}$

-This cross section is a few order of magnitude smaller than current limit, we could see signal in future!
Conclusions
Conclusions

- SUSY inverse seesaw model
  - Lepton number is dynamically induced
  - Low scale seesaw mechanism can be realized
  - Thermal relic sneutrino DM is possible thanks to existing the origin of lepton # violation
- Our extensions to the MSSM are really hidden, in other words, our model can be easily excluded by observations draw a line to "signalism"
Future prospects

- At the moment, our model is playing hide & seek but we are trying to think...
  - Collider phenomenology
  - Aspects for early universe
  - Astrophysical observations
Open questions

- So far so good as one of the models, but...

- How to find our DM as a signal?

- How to discriminate our model from others?
Thank you for your attention
DM estimation

How to hit the funnel

- First, we define a parameter $c$
  
  $c$ is chosen either 0.97 or 0.99

- Second, we fix $\mu_{NS}$ by using mass formulae

- Third, we run SPheno to calculate mass spectrum, estimate $\mu_{NS}$ again and take the ratio

$$\xi_A = \frac{m_{\tilde{\nu}_1} + m_{\tilde{\nu}_1}}{m_{A_X}}$$

requiring not to deviate more than $2.5 \times 10^{-3}$
DM estimation

How to hit the funnel

\[ \xi_A = \frac{m_{\tilde{\chi}_1^R} + m_{\tilde{\chi}_1^I}}{m_{A_X}} \]