Dark Matter In Minimal Supersymmetric Inverse-Seesaw Models

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Motivation

- Dark matter (DM) need to be explained

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- Supersymmetry provides candidates
- lightest ν_R (keV range), $\tilde{\nu}_R$ (superpartner of ν_R)

Minimal Inverse-Seesaw Model: Structure

Superpotential

$$\mathcal{W} = \mathcal{W}_{MSSM} + \frac{1}{2}(M_R)_{ij}\hat{\nu}_{R,i}\hat{\nu}_{R,j} + (Y_\nu)_{ij}\hat{L}_i \cdot \hat{H}_u\hat{\nu}_{R,j} \quad (1)$$

Soft-breaking terms

The corresponding soft breaking terms are

$$\mathcal{V}^{soft} = \mathcal{V}^{soft}_{MSSM} + (m^2_{\tilde{\nu}_R})_{ij}\tilde{\nu}^*_{R,i}\tilde{\nu}_{R,j} + \frac{1}{2}(B_{\tilde{\nu}})_{ij}\tilde{\nu}_{R,i}\tilde{\nu}_{R,j} + (T)_{ij}\tilde{L}_i \cdot H_u\tilde{\nu}_{R,j}. \quad (2)$$

Parameterization(Casas-Ibarra-like):arXiv:1505.05880

With this parametrization, the neutrino Yukawa coupling is:

$$Y_\nu = -i\frac{\sqrt{2}}{v_u}U^*_{PMNS}H^* m_l^{\frac{1}{2}}(m_l R^\dagger + R^T M_h)M_h^{-\frac{1}{2}}\bar{H}.$$

The neutrino mixing matrix U is a function of $m_l = \text{diag}(m_1, m_2, m_3)$, $M_h = \text{diag}(M_4, M_5, M_6)$, U_{PMNS} matrix and matrix H and R. Where Hs are:

$$H = (I + m_l^{1/2}R^\dagger M_h^{-1} R m_l^{-1/2})^{-1/2} \quad \bar{H} = (I + M_h^{1/2} R m_l^{-1} R^\dagger M_h^{-1/2})^{-1/2},$$

and the matrix R is parametrized as:

$$R = \begin{pmatrix} 1 & & \\ & c_{56} & s_{56} \\ & -s_{56} & c_{56} \end{pmatrix} \begin{pmatrix} c_{46} & & s_{46} \\ & 1 & \\ -s_{46} & & c_{46} \end{pmatrix} \begin{pmatrix} c_{45} & s_{45} & \\ -s_{45} & c_{45} & \\ & & 1 \end{pmatrix}$$

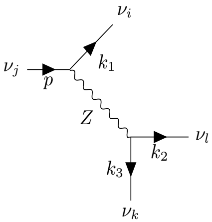
where $c_{ij} = \cos\theta'_{ij}$ and θ'_{ij} are the mixing angles in this 3×3 mixing matrix, $\theta'_{ij} = \rho_{ij} + i\gamma_{ij}$.

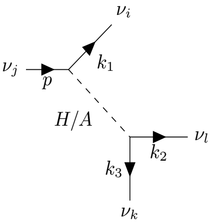
Upshot

γ change the magnitude of Y_ν exponentially: minimal inverse-seesaw

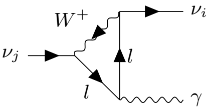
Minimal Inverse-Seesaw Model: Decay Processes

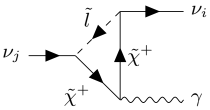
- Three-Body Decay

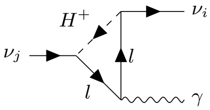




- Radiative Decay







Numerical Results: ν_4 (keV)

Our Results:

$\Gamma \approx 10^{-47}$GeV,

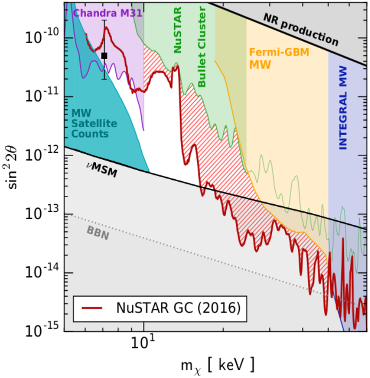
$\text{BR}(\nu_4 \to \nu\gamma) \simeq 10\%$

$\sin^2 2\theta = \sum_i^3 |U_{i,4}|^2$,

$\Gamma \propto \sin^2(2\theta) \left(\frac{m_{\nu_4}}{\text{keV}}\right)^5 s^{-1}$

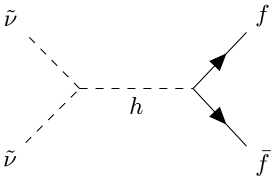
M_{ν_4}(keV)	min. $\sin^2 2\theta$
7	3.38462×10^{-9}
20	1.18462×10^{-9}
30	7.89744×10^{-10}
40	5.92308×10^{-10}
50	4.73847×10^{-10}

NuSTAR Results (arXiv:1609.00667):



- Condition: neutrinos are produced by Shi-Fuller mechanism.

Numerical Results: $\tilde{\nu}$



- Calculated with `SPheno` and `micrOMEGAS`

	Variation	
Variable	Values	Magn. of Ωh^2
Y_ν	10^{-12}	10^{7}
$M^2_{\tilde{\nu}}$	$8000(\text{ GeV})^2$	10^{2}
$M^2_{\tilde{\nu}}$, T_ν	$M^2_{\tilde{\nu}} = 8000(\text{ GeV})^2$, $T_\nu = 100$	10^{-1}
$M^2_{\tilde{\nu}}$, T_ν, $Y_{\nu,1}$	$M^2_{\tilde{\nu}} = 6000(\text{ GeV})^2$, $T_\nu = 100$, $Y_{\nu,1} = 10^{-5}$	10^{-2}

- $T_\nu = A_\nu Y_\nu = 100,\ A_\nu = 10^7 \rightarrow$ charge breaking minimum

BLSSM (B-L Supersymmetric Standard Model) : Structure

Gauge Group

$$U(1)_Y \times SU(3)_c \times SU(2)_L \times U(1)_{B-L}$$

Structure

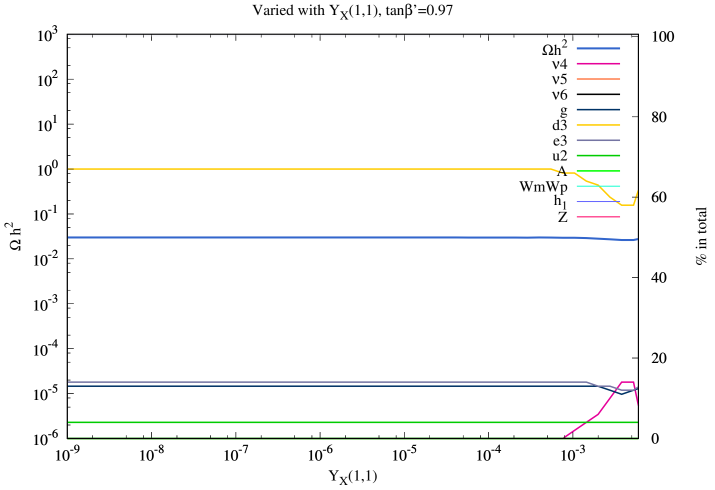
MSSM particles + η, $\bar{\eta}$

$$\begin{aligned} W =& W_{MSSM} + Y_\nu^{ij} \hat{L}_i \hat{H}_u \hat{\nu}_j - \mu' \hat{\eta} \hat{\bar{\eta}} + Y_x^{ij} \hat{\nu}_i \hat{\eta} \hat{\nu}_j , \\ \mathcal{L}_{SB} =& \mathcal{L}_{MSSM} - m_\eta^2 |\eta|^2 - m_{\bar{\eta}}^2 |\bar{\eta}|^2 + \ldots \end{aligned} \tag{3}$$

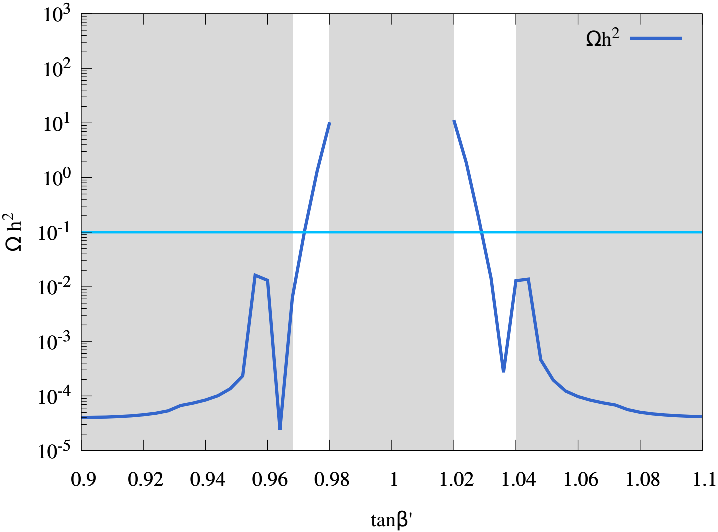
Idea:

- Typical 2 light H: 1 MSSM, 1 singlet
- Build up Higgs funnel with one of the light Higgs which is mainly η-like: $M_h \simeq 2M_{\tilde{\nu}}$, controlled by $\tan\beta' = \frac{v_\eta}{v_{\bar{\eta}}}$
- This will exhaust $\tilde{\nu}$ DM and produce ν_4

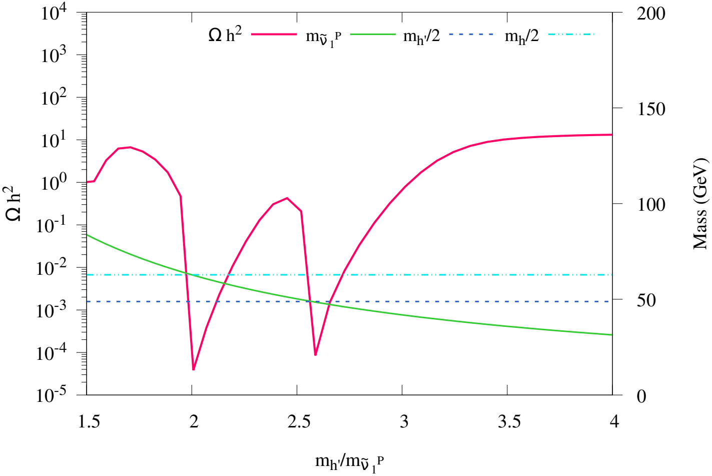
Varied $Y_x(1,1)$


Varied with YX(1,1), tanβ'=0.97
Ωh2
ν4
ν5
ν6
g
d3
e3
u2
A
WmWp
h1
Z
Ω h2
% in total
YX(1,1)
10-9
10-8
10-7
10-6
10-5
10-4
10-3
103
102
101
100
10-1
10-2
10-3
10-4
10-5
10-6
100
80
60
40
20
0

Varied $\tan\beta'$, $Y_x(1,1) = 10^{-5}$



Varied Mass Ratio



Conclusion

Minimal Inverse-Seesaw model:

- keV range neutrino DM, excluded if ν_R are produced through Shi-Fuller mechanism
- excluded for $\tilde{\nu}$ DM if ν_4 in keV range.

BLSSM

- Exists regions where $\tilde{\nu}$ DM allowed : observed relic density, collider experiments.

THANK YOU!

For your attention.

BACK UP

MSSM (minimal supersymmetric standard model)

Superpotential

$$W_{MSSM} = \mu \hat{H}_u \cdot \hat{H}_d - \hat{\bar{U}} Y_u \hat{Q} \cdot \hat{H}_u - \hat{\bar{D}} Y_d \hat{Q} \cdot \hat{H}_d - \hat{\bar{E}} Y_e \hat{L} \cdot \hat{H}_d. \tag{4}$$

Soft-breaking Terms

$$\begin{aligned}
\mathcal{L}_{SOFT} = & -\frac{1}{2}(M_3 \tilde{g}^\alpha \cdot \tilde{g}^\alpha + M_2 \tilde{W}^\alpha \cdot \tilde{W}^\alpha + M_1 \tilde{B} \cdot \tilde{B} + h.c.) \\
& - m^2_{\tilde{Q}ij} \tilde{Q}_i^\dagger \cdot \tilde{Q}_j - m^2_{\tilde{\bar{U}}ij} \tilde{\bar{U}}_i^\dagger \tilde{\bar{U}}_j - m^2_{\tilde{\bar{D}}ij} \tilde{\bar{D}}_i^\dagger \tilde{\bar{D}}_j \\
& - m^2_{\tilde{\bar{L}}ij} \tilde{\bar{L}}_i^\dagger \cdot \tilde{\bar{L}}_j - m^2_{\tilde{\bar{E}}ij} \tilde{\bar{E}}_i^\dagger \tilde{\bar{E}}_j \\
& - m^2_{H_u} H_u^\dagger \cdot H_u - m^2_{H_d} H_d^\dagger \cdot H_d - (b H_u \cdot H_d + h.c.) \\
& - a_u^{ij} \tilde{\bar{U}}_i \tilde{Q}_j \cdot H_u + a_d^{ij} \tilde{\bar{D}}_i \tilde{Q}_j \cdot H_d + a_e^{ij} \tilde{\bar{E}}_i \tilde{L}_j \cdot H_d + h.c.
\end{aligned} \tag{5}$$

Approximations for the Integrals[1]

Loop integrals I, J, K, I^2 appear in the decay width, and the original forms can have numerical problems when setting the light neutrino mass to 0.

$$I = \frac{1}{m_j^2 - m_i^2} \int_0^1 \frac{dx}{1-x} \log\left(\frac{m^2 x + M^2(1-x) - m_j^2 x(1-x)}{m^2 x + M^2(1-x) - m_i^2 x(1-x)}\right) \quad (6)$$

$$J = \frac{1}{m_j^2 - m_i^2} \int_0^1 \frac{dx}{x} \log\left(\frac{m^2 x + M^2(1-x) - m_j^2 x(1-x)}{m^2 x + M^2(1-x) - m_i^2 x(1-x)}\right) \quad (7)$$

$$I^2 = \frac{1}{m_j^2 - m_i^2} \int_0^1 dx \log\left(\frac{m^2 x + M^2(1-x) - m_j^2 x(1-x)}{m^2 x + M^2(1-x) - m_i^2 x(1-x)}\right) \quad (8)$$

$$K = \frac{-1}{m_j^2 - m_i^2} \int_0^1 dx \left[1 + \frac{m^2 x + M^2(1-x) - m_j^2 x(1-x)}{x(1-x)(m_j^2 - m_i^2)} \times \log\left(\frac{m^2 x + M^2(1-x) - m_j^2 x(1-x)}{m^2 x + M^2(1-x) - m_i^2 x(1-x)}\right)\right]. \quad (9)$$

Approximations

Basic idea

$M_j, m << M$, expand the integrals with $x = \frac{M_j^2}{M^2}$, $y = \frac{m^2}{M^2}$ to the second order around 0.

For example:

$$
\begin{aligned}
I =& \frac{1}{36M^2}[2x^2(93y^2 + 42y + 11) \\
&+ 6(2x^2(18y^2 + 6y + 1) + 3x(8y^2 + 4y + 1) \\
&+ 6(2y^2 + 2y + 1)) \log(y) + 9x(8y^2 + 6y + 1) + 36]
\end{aligned} \tag{10}
$$

BLSSM: Method

Paramters

- $\tan\beta' = \frac{v_\eta}{v_{\bar\eta}}$: controls the Higgs mass and sneutrino masses;
- Y_x: Yukawa coupling of the singlet Higgs;
- Induced variables: $M^2_{\tilde\nu}$, $B_{\mu'} = m^2_{A^0}\frac{\sin 2\beta'}{2}$, $T_x(1,1) = A_x(1,1)Y_x(1,1)$

Idea

- set the mass difference: $m_{\tilde\nu_1^S} - m_{\tilde\nu_1^P} = 0.5$ GeV
- vary one variable at a time, solve out the induced varibles
- calculate with `SPheno-4.0.3` and `micrOMEGAS-4.3.5`