

Right-handed Sneutrino Cosmology and Hadron Collider Signatures

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with

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Outline

- Motivation
- The Theory
 - Sneutrino mass matrix & mixing
- Right-handed sneutrino (\tilde{N}_R) dark matter
- \tilde{N}_R Tevatron and LHC signatures
- Conclusions

Motivation

Neutrino has mass

Old Standard Model (SM) had only left-handed $\nu_L^{e,\mu,\tau}$

Oscillation experiments : $\nu_L^\alpha \leftrightarrow \nu_L^\beta$: $m_\nu \approx 0.1\text{eV}$

A renormalizable theory for mass requires adding:

Right-handed Neutrino (N_R^i .) OR Higgs triplet

If Supersymmetry and N_R^i . then right-handed sneutrino

Dark Matter

WMAP result (2003) $\Omega_m h^2 = 0.135^{+0.008}_{-0.009}$; $h^2 \approx 0.5$

If \tilde{N}_R LSP ... overclose the universe? ... Dark Matter?

Is it possible to test this? ... Collider implications?

SUSY Sector

Most general (renormalizable) theory, with Lepton-# violation

Superpotential

$$\mathcal{W} = N^c Y_N L \cdot H_u + N^c \frac{M_N}{2} N^c + W_{\text{MSSM}}$$

SUSY Breaking terms

$$\begin{aligned} \mathcal{L}_{\text{SUSYBr}} = & - \tilde{\ell}_L^\dagger m_\ell^2 \tilde{\ell}_L - \tilde{N}_R^\dagger m_N^2 \tilde{N}_R + h.c. \\ & - \tilde{N}_R^\dagger A_N \tilde{\ell}_L \cdot h_u + h.c. \\ & + \tilde{N}_R^T \frac{b_N^2}{2} \tilde{N}_R + h.c. \end{aligned}$$

Neutrino Mass

$$\mathcal{L}_{mass}^{\nu} = -\bar{N}v_u Y_N \nu - \bar{N}^c \frac{M_N}{2} N + h.c.$$

$$m_{\nu} = \frac{v_u^2 Y_N^2}{M_N}$$

For $m_{\nu} \sim 0.1\text{eV}$

- If $M_N \sim 10^{14}\text{GeV}$ then $Y_N \sim O(1)$ (Seesaw)
- **If $M_N \sim 10^2\text{GeV}$ then $Y_N \sim 10^{-6}$**
- If no M_N term then $Y_N \sim 10^{-12}$ (Dirac ν) [Asaka et al. '05]

Sneutrino mass matrix

$$\mathcal{L}_{mass}^{\tilde{\nu}} = - \begin{pmatrix} \tilde{\nu}_L^\dagger & \tilde{N}_R^\dagger & \tilde{\nu}_L^T & \tilde{N}_R^T \end{pmatrix} \mathcal{M}_{\tilde{\nu}} \begin{pmatrix} \tilde{\nu}_L \\ \tilde{N}_R \\ \tilde{\nu}_L^* \\ \tilde{N}_R^* \end{pmatrix}$$

From now assume as real : m_{LL}^2 , m_{RR}^2 , m_{RL}^2 , c_ℓ , b_N^2

Redefine:

$$\begin{aligned} \tilde{\nu}_L &= (\tilde{\nu}_1 + i\tilde{\nu}_2)/\sqrt{2} \\ \tilde{N}_R &= (\tilde{N}_1 + i\tilde{N}_2)/\sqrt{2} \end{aligned}$$

Mass matrix becomes...

$$\mathcal{L}_{mass}^{\tilde{\nu}} = -\frac{1}{2} \begin{pmatrix} \tilde{\nu}_1^T & \tilde{N}_1^T & \tilde{\nu}_2^T & \tilde{N}_2^T \end{pmatrix} \mathcal{M}_{\tilde{\nu}}^r \begin{pmatrix} \tilde{\nu}_1 \\ \tilde{N}_1 \\ \tilde{\nu}_2 \\ \tilde{N}_2 \end{pmatrix}$$

$$\mathcal{M}_{\tilde{\nu}}^r = \begin{pmatrix} m_{LL}^2 - c_\ell & m_{RL}^2 + v_u Y_N^T M_N^* & 0 & 0 \\ m_{RL}^2 + v_u M_N^\dagger Y_N & m_{RR}^2 - b_N^2 & 0 & 0 \\ 0 & 0 & m_{LL}^2 + c_\ell & 0 \\ 0 & 0 & m_{RL}^2 - v_u M_N^\dagger Y_N & m_{RR}^2 + b_N^2 \end{pmatrix} \begin{pmatrix} \tilde{\nu}_1 \\ \tilde{N}_1 \\ \tilde{\nu}_2 \\ \tilde{N}_2 \end{pmatrix}$$

[Hirsch et al., Grossman et al. '97]

Diagonalization

$$\begin{pmatrix} \tilde{\nu}_i \\ \tilde{N}_i \end{pmatrix} = \begin{pmatrix} \cos \theta_i^{\tilde{\nu}} & -\sin \theta_i^{\tilde{\nu}} \\ \sin \theta_i^{\tilde{\nu}} & \cos \theta_i^{\tilde{\nu}} \end{pmatrix} \begin{pmatrix} \tilde{\nu}'_i \\ \tilde{N}'_i \end{pmatrix}; \quad s_i \equiv \sin \theta_i^{\tilde{\nu}}$$

Mixing angle is:

$$\tan 2\theta_i^{\tilde{\nu}} = \frac{2 \left| -\mu^* v_d Y_N + v_u A_N \pm v_u M_N^\dagger Y_N \right|}{(m_{LL}^2 \mp c_\ell) - (m_{RR}^2 \mp b_N^2)}$$

Assume: $A_N \equiv a_N Y_N m_\ell$; $\Rightarrow s_1 \approx Y_N \frac{v_u}{m_\ell} \alpha_m$

$$Y_N \sim 10^{-6}; \quad A_N \sim a_N \cdot 0.1 \text{ MeV}; \quad s_1 \sim 10^{-6} \alpha_m; \quad \tilde{\nu}_0 \approx \tilde{N}_1$$

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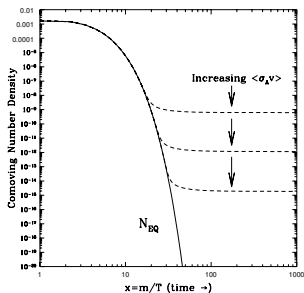
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Boltzmann Equation

Big Bang \rightarrow Inflation $\rightarrow \dots \rightarrow$ BBN \rightarrow Today

Thermal equilibrium if $\langle \sigma v \rangle_{SI} n_{\tilde{\nu}_0} > 3H$

Freeze-out



[Kolb & Turner, Early Universe]

$$\Omega_0 \equiv \frac{n_0 M}{\rho_c} \approx 4 \times 10^{-10} \left(\frac{\text{GeV}^{-2}}{\langle \sigma v \rangle} \right)$$

When is $\tilde{\nu}_0$ Thermal? $\langle \sigma v \rangle n > 3H$

Self-interaction processes

$$(a_s) \quad \tilde{\nu}_0 \tilde{\nu}_0 \rightarrow \nu_L \nu_L \quad \tilde{W}^3 ; \tilde{B} \text{ exchange}$$

$$(d_s) \quad \tilde{\nu}_0 \tilde{\nu}_0 \rightarrow \nu_L \bar{\nu}_L ; e_L \bar{e}_L \quad \tilde{H}_u^+ ; \tilde{H}_u^0 \text{ exchange}$$

Process	Cross-section	Limit
(a_s)	$\frac{s_1^4}{16\pi} \left(\frac{g^2}{M_{\tilde{W}}} + \frac{g'^2}{M_{\tilde{B}}} \right)^2$	$\alpha_m Y_N > 10^{-3}$
(d_s)	$\frac{Y_N^4 c_1^4}{16\pi} \frac{1}{M_H^2} \left(\frac{m_e}{M_{\text{LSP}}} \right)^2$	$Y_N > 10^{-3}$

When is $\tilde{\nu}_0$ Thermal? $\langle \sigma v \rangle n > 3H$

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Thermalization

Thermalization conditions not met \Rightarrow Nonthermal $\tilde{\nu}_0$

\tilde{N}_R interacts only through tiny Yukawa, so Nonthermal for:

- $Y_N \lesssim 10^{-6}$ i.e., $\tilde{\nu}_0$ is almost pure right-handed
- Low Reheat temp $T_{RH} < 100$ GeV ; Reheat into $\tilde{\nu}_0 + \text{SM}$

[S.G., Prood, de Gouvea, hep-ph/0602027 - JCAP]

Tevatron and LHC Signatures

Unique features

- Heavier SUSY decays thro Y_N (tiny?) Disp vtx?
- All SUSY decays must have a lepton (charged or neutrino)
- Expect non-universality in e, μ, τ events
- 3 gens of \tilde{N}_R Cascade decays give leptons (how soft?)

At hadron colliders look for:

$$q q / g g \rightarrow \tilde{t} \tilde{t}^* , \tilde{g} \tilde{g} , \dots$$

Monte Carlo Program: **Pythia** 6.327:

With modification to include angular dep of 3-body stop decays
[Special thanks to Stephen Mrenna & Peter Skands for help with Pythia]

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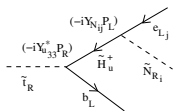
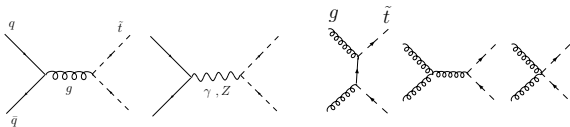
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\tilde{t}_R production and decay

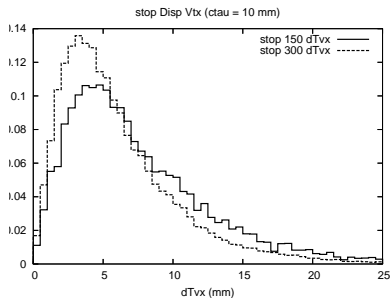
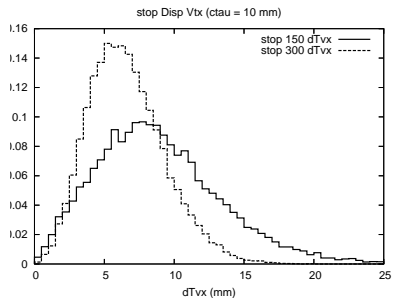


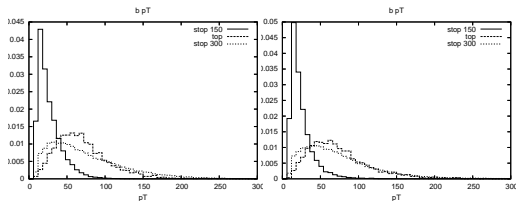
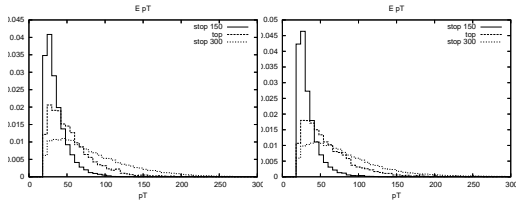
Level 1 cuts:

The rapidity cuts $\eta_\ell < 2.5$, $\eta_b < 2.5$.

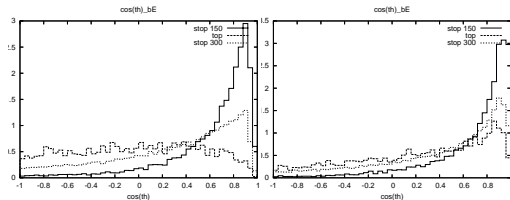
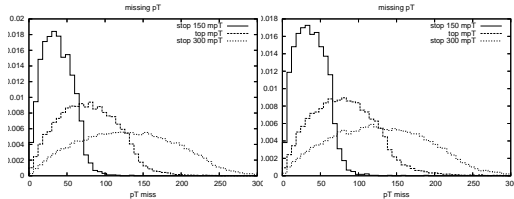
The transverse momentum cuts $p_{T\ell} > 20$ GeV, $p_{Tb} > 10$ GeV.

The isolation cut $R_{b\ell} > 0.4$, where $R_{b\ell}^2 \equiv (\phi_b - \phi_\ell)^2 + (\eta_b - \eta_\ell)^2$

\tilde{t}_R production and decay : Disp Vtx

p_T distributions $b p_T$  $l p_T$ 

distributions

 $\cos(\theta_{bl})$  pT miss

Tevatron and LHC Reach

		σ (pb)	α	# (for 1 fb^{-1})	S/\sqrt{B} (for 1 fb^{-1})	\mathcal{L} (fb^{-1} for 5σ)
Top	Tevatron	5.6	0.79	8	-	-
	LHC	488	0.7	484	-	-
$M_{\tilde{t}_R} = 150$	Tevatron	1.04	0.29	17	6	0.7
	LHC	167	0.24	1947	88	0.003
$M_{\tilde{t}_R} = 175$	Tevatron	0.42	0.47	18	6.6	0.57
	LHC	81.8	0.43	3062	139	0.001
$M_{\tilde{t}_R} = 250$	Tevatron	0.04	0.71	4	1.4	12.7
	LHC	14.65	0.66	1292	58	0.007
$M_{\tilde{t}_R} = 500$	LHC	0.37	0.81	49	2.22	5.1
$M_{\tilde{t}_R} = 750$	LHC	0.03	0.85	4.3	0.19	692

Conclusions

- Pure right-handed $\tilde{\nu}$ investigated here
 - When SUSY breaking, Majorana mass at weak scale;
 $Y_N \sim 10^{-6}$
 - Nonthermal dark matter candidate
- Tevatron and LHC Signatures
 - Displaced Vertex
 - Look for nonuniversal lepton signature

Backup Slides

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Sneutrino mass matrix

$$\mathcal{L}_{mass}^{\tilde{\nu}} = - \begin{pmatrix} \tilde{\nu}_L^\dagger & \tilde{N}_R^\dagger & \tilde{\nu}_L^T & \tilde{N}_R^T \end{pmatrix} \mathcal{M}_{\tilde{\nu}} \begin{pmatrix} \tilde{\nu}_L \\ \tilde{N}_R \\ \tilde{\nu}_L^* \\ \tilde{N}_R^* \end{pmatrix}$$

$$\mathcal{M}_{\tilde{\nu}} = \frac{1}{2} \begin{pmatrix} m_{LL}^2 & m_{RL}^{2\dagger} & -v_u^2 c_\ell^\dagger & v_u Y_N^\dagger M_N \\ m_{RL}^2 & m_{RR}^2 & v_u M_N^T Y_N^* & -b_N^{2\dagger} \\ -v_u^2 c_\ell & v_u Y_N^T M_N^* & m_{LL}^{2*} & m_{RL}^{2\dagger} \\ v_u M_N^\dagger Y_N & -b_N^2 & m_{RL}^{2*} & m_{RR}^{2*} \end{pmatrix}$$

$$m_{LL}^2 = (m_\ell^2 + v_u^2 Y_N^\dagger Y_N + \Delta_\nu^2); \quad \Delta_\nu^2 = (m_Z^2/2) \cos 2\beta$$

$$m_{RR}^2 = (M_N M_N^* + m_N^2 + v_u^2 Y_N Y_N^\dagger)$$

$$m_{RL}^2 = (-\mu^* v_d Y_N + v_u A_N)$$

Real fields

Mixing effects

- $m_{RL}^2 : \tilde{\nu}_L \leftrightarrow \tilde{N}_R$ mixing
- $c_\ell : \tilde{\nu}_L \leftrightarrow \tilde{\nu}_L^*$ mixing
- $M_N : \tilde{\nu}_L \leftrightarrow \tilde{N}_R^*$ mixing
- $b_N^2 : \tilde{N}_R \leftrightarrow \tilde{N}_R^*$ mixing

From now assume as real : $m_{LL}^2, m_{RR}^2, m_{RL}^2, c_\ell, b_N^2$

Redefine:

$$\begin{aligned}\tilde{\nu}_L &= (\tilde{\nu}_1 + i\tilde{\nu}_2)/\sqrt{2} \\ \tilde{N}_R &= (\tilde{N}_1 + i\tilde{N}_2)/\sqrt{2}\end{aligned}$$

Mass matrix becomes...

$$\mathcal{L}_{mass}^{\tilde{\nu}} = -\frac{1}{2} \begin{pmatrix} \tilde{\nu}_1^T & \tilde{N}_1^T & \tilde{\nu}_2^T & \tilde{N}_2^T \end{pmatrix} \mathcal{M}_{\tilde{\nu}}^r \begin{pmatrix} \tilde{\nu}_1 \\ \tilde{N}_1 \\ \tilde{\nu}_2 \\ \tilde{N}_2 \end{pmatrix}$$

$$\mathcal{M}_{\tilde{\nu}}^r = \begin{pmatrix} m_{LL}^2 - c_\ell & m_{RL}^{2T} + v_u Y_N^T M_N^* & 0 & 0 \\ m_{RL}^2 + v_u M_N^\dagger Y_N & m_{RR}^2 - b_N^2 & 0 & 0 \\ 0 & 0 & m_{LL}^2 + c_\ell & m_{RL}^{2T} - v_u Y_N^T M_N^* \\ 0 & 0 & m_{RL}^2 - v_u M_N^\dagger Y_N & m_{RR}^2 + b_N^2 \end{pmatrix}$$

[Hirsch et al., Grossman et al. '97]

c_ℓ , b_N and M_N split $\tilde{\nu}_1 \leftrightarrow \tilde{\nu}_2$ degeneracy, and $\tilde{N}_1 \leftrightarrow \tilde{N}_2$ degeneracy

Denote LSP as $\tilde{\nu}_0$; Heavy states as $\tilde{\nu}_H$

Bose symmetry forbids $Z\tilde{\nu}_0\tilde{\nu}_0$ coupling

\therefore leads to acceptable relic density

[Hall et al. '97]

Thermal History of the Universe

Big Bang \rightarrow Inflation $\rightarrow \dots \rightarrow$ BBN \rightarrow Today

Hubble rate:

$$H \equiv \frac{\dot{a}}{a}; \quad H^2 = \frac{8\pi G}{3} \rho$$

$$H = 1.66 \sqrt{g_*} \frac{T^2}{M_{Pl}} \quad (\text{Rad Dom})$$

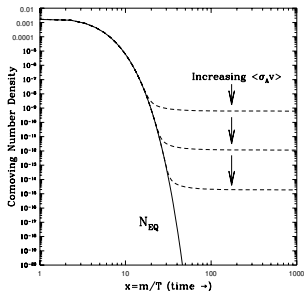
Boltzmann Equation

Big Bang \rightarrow Inflation $\rightarrow \dots \rightarrow$ BBN \rightarrow Today

$$\frac{d}{dt} n_{\tilde{\nu}_0} = -3Hn_{\tilde{\nu}_0} - \langle\sigma v\rangle_{SI} (n_{\tilde{\nu}_0}^2 - n_{\tilde{\nu}_0}^2_{eq}) - \langle\sigma v\rangle_{CI} (n_{\tilde{\nu}_0} n_{\phi} - n_{\tilde{\nu}_0} n_{\phi}^{eq}) + C_{\Gamma}$$

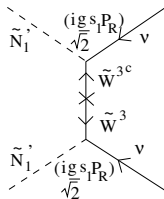
Thermal equilibrium if $\langle\sigma v\rangle_{SI} n_{\tilde{\nu}_0} > 3H$; $\langle\sigma v\rangle_{CI} n_{\phi} > 3H$

Freeze-out



[Kolb & Turner, Early Universe]

$$\Omega_0 \equiv \frac{n_0 M}{\rho_c} \approx 4 \times 10^{-10} \left(\frac{\text{GeV}^{-2}}{\langle\sigma v\rangle} \right)$$

Mixed $\tilde{\nu}_0$ Dark Matter

$$\Omega_0 h^2 = \frac{10^{-4}}{s_1^4} \left\{ \left[g^2 \left(\frac{100 \text{ GeV}}{M_{\tilde{W}}} \right) + g'^2 \left(\frac{100 \text{ GeV}}{M_{\tilde{B}}} \right) \right]^2 \right\}^{-1}$$

$\therefore s_1 \approx 0.2$ results in observed relic density

Relic from Decays

Contribution from $C_\Gamma \sim n_\chi \Gamma(\chi \rightarrow \tilde{\nu}_0 X)$

- $\tilde{H}_u \rightarrow \tilde{\nu}_0 L$

$$\Omega_{0(ab)} h^2 \sim 10^{26} c_1^2 Y_N^2 \frac{M_{\text{LSP}}}{M_{\tilde{H}}} f_{PS}^2$$

- $\tilde{\nu}_H \rightarrow \tilde{\nu}_0 \bar{\psi} \psi$ h_u exchange

$$\Omega_{0(bD)} h^2 = 10^{24} (c_1^2 - s_1^2)^2 Y_c^2 \frac{A_N^2 M_{\tilde{\nu}_H} M_{\text{LSP}}}{M_{h_u}^4} f_{3PS}^2$$

Does not overclose if

$$Y_N \lesssim 10^{-13} ; \quad A_N \lesssim 10 \text{ eV} ; \quad s_1 \lesssim 10^{-12}$$

(Decays just before BBN!)

Dirac case [Asaka et al. '05]

When is $\tilde{\nu}_0$ Thermal?

$$\langle \sigma v \rangle n > 3H$$

Self-interaction processes

$$(a_s) \quad \tilde{\nu}_0 \tilde{\nu}_0 \rightarrow \nu_L \nu_L \quad \tilde{W}^3 ; \tilde{B} \text{ exchange}$$

$$(d_s) \quad \tilde{\nu}_0 \tilde{\nu}_0 \rightarrow \nu_L \bar{\nu}_L ; e_L \bar{e}_L \quad \tilde{H}_u^+ ; \tilde{H}_u^0 \text{ exchange}$$

Process	Cross-section	Limit
(a_s)	$\frac{s_1^4}{16\pi} \left(\frac{g^2}{M_{\tilde{W}}} + \frac{g'^2}{M_{\tilde{B}}} \right)^2$	$\alpha_m Y_N > 10^{-3}$
(d_s)	$\frac{Y_N^4 c_1^4}{16\pi} \frac{1}{M_H^2} \left(\frac{m_e}{M_{\text{LSP}}} \right)^2$	$Y_N > 10^{-3}$

When is $\tilde{\nu}_0$ Thermal? $\langle \sigma v \rangle n > 3H$

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When is $\tilde{\nu}_0$ Thermal?

Co-interaction processes with other SUSY particles

Boltzmann suppressed by

$$\beta_\phi \equiv e^{-(\Delta M_\phi/T)}; \quad \Delta M_\phi \equiv (M_\phi - M_{\text{LSP}})$$

Co-interaction with SUSY

(b_c) $\tilde{\nu}_0 \tilde{s} \rightarrow \tilde{e}_L \tilde{s}'$ W^\pm exchange

(e_c) $\tilde{\nu}_0 \tilde{\nu}_H \rightarrow c \bar{c}; t \bar{t}$ h_u exchange

Process	Cross-section	Limit
(b _c)	$\frac{g^4 s_1^2}{16\pi} \frac{M_{\text{LSP}}^2}{M_Z^4} f_{PS}^2$	$\beta_{\tilde{s}} \alpha_m f_{PS} Y_N > 10^{-6.5}$
(e _c)	$\frac{(c_1^2 - s_1^2)^2 Y_u^2}{16\pi} \frac{1}{M_{h_u}^2} \left(\frac{A_N}{M_{h_u}}\right)^2 f_{PS}^2$	$Y_u \beta_{\tilde{\nu}_H} \alpha_m f_{PS} Y_N > 10^{-7}$

When is $\tilde{\nu}_0$ Thermal?

Co-interaction with SM

 $(a_M) \tilde{\nu}_0 t_{R,L} \rightarrow \tilde{\nu}_L t_{L,R} \quad h_u \text{ exchange}$ $(b_M) \tilde{\nu}_0 t_L \rightarrow \nu_L \tilde{t}_R \quad \tilde{H}_u \text{ exchange}$

Process	Cross-section	Limit
(a_M)	$\frac{A_N^2 Y_t^2}{16\pi} \frac{1}{M_{h_u}^4} f_{PS}^2$	$\beta_t \alpha_m f_{PS} Y_N > 10^{-7}$
(b_M)	$\frac{Y_N^2 Y_t^2}{16\pi} \frac{1}{M_{\tilde{H}}^2} f_{PS}^2$	$\beta_t f_{PS} Y_N > 10^{-7}$

Nonthermal $\tilde{\nu}_0$

Thermalization conditions not met \Rightarrow Nonthermal $\tilde{\nu}_0$

Happens when :

- $Y_N \lesssim 10^{-6}$ i.e., $\tilde{\nu}_0$ is almost pure right-handed
- Low Reheat temp $T_{RH} < 100$ GeV ; Reheat into $\tilde{\nu}_0 + \text{SM}$
 - No Relic-from-decay of heavier SUSY particles
 - No $\tilde{\nu}_0$ thermalization from co-interaction with SUSY or Top

\tilde{N} Relic density depends on Inflaton coupling to SM and \tilde{N}

- Work in progress

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