Supersymmetric model for neutrino masses with two dark matter candidates

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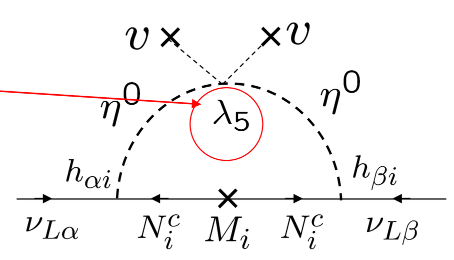
Motivation

- Standard model should be extended to include neutrino masses and dark matter (DM) whose existence has been suggested by experiments.
- Radiative models for neutrino masses present an interesting possibility for such an extension. In these models, neutrino masses are closely related to the existence of DM.
- One of these is an extension of the SM with a doublet scalar η, right-handed neutrinos N_i^c and a Z2 symmetry.

Faults in this model
- hierarchy problem
- smallness of λ_5
- origin of Z2

One-loop neutrino mass



To solve these problems

Supersymmetric extension

Chiral superfield contents
- MSSM contents $f_i,\ H_{u,d}$
- two additional doublet chiral superfields $\eta_{u,d}$
- three singlet chiral superfields N_i^c
- three singlet chiral superfields $\phi,\ \Sigma_\pm$

New symmetry
- anomalous U(1) gauge symmetry
- R-parity

Ψ	f_i	$H_{u,d}$	N_i^c	η_u	η_d	ϕ	Σ_+	Σ_-
R	$-$	$+$	$+$	$-$	$-$	$-$	$+$	$+$
U(1)$_X$	$2n_{f_i}$	$2n_{H_{u,d}}$	$2n_{N_i}+1$	$2n_{\eta_u}+1$	$2n_{\eta_d}+1$	$2n_\phi+1$	$2n_+$	-2
Z_2	$+$	$+$	$-$	$-$	$-$	$-$	$+$	$+$

n_Ψ : interger

Low energy effective model

The low energy effective model is determined through the spontaneous U(1)x breaking to its Z2 subgroup.

$$\begin{cases} V_F=\sum_\varphi\left|\frac{\partial W_h}{\partial\varphi}\right|^2 \quad \Leftarrow \quad W_h=\frac{c_+}{M_{\rm pl}^{n_+-2}}\Sigma_+\Sigma_-^{n_+}+\frac{c_\phi}{M_{\rm pl}^{2n_\phi}}\phi^2\Sigma_-^{2n_\phi+1} \\ V_D=\frac{g_X^2}{2}\left[(2n_\phi+1)|\phi|^2+2n_+|\Sigma_+|^2-2|\Sigma_-|^2+\xi_X\right]^2 \end{cases}$$

Minimization of scalar potential

$$\langle\Sigma_-\rangle\gg\langle\Sigma_+\rangle\neq 0,\ \langle\phi\rangle=0 \qquad \xi_X=\frac{g_X^2{\rm Tr}X}{192\pi^2}M_{\rm pl}^2$$

$$V=V_F+V_D \quad \Rightarrow \quad {\rm U}(1)_X \quad \Rightarrow \quad Z_2$$

After this symmetry breaking

(1) Effective parameters can be derived from the U(1)x invariant nonrenormalizable operators via Froggatto-Nielsen mechanism.

$$h_{ijk}\Psi_i\Psi_j\Psi_k \ \Rightarrow\ h_{ijk}=y_{ijk}\left(\frac{\langle\Sigma_\pm\rangle}{M_{\rm pl}}\right)^{n_{ijk}}, \qquad n_{ijk}=\frac{X_i+X_j+X_k}{-X_{\Sigma_\pm}}$$

$$\mu_{ij}\Psi_i\Psi_j \ \Rightarrow\ \mu_{ij}=y_{ij}\langle\Sigma_\pm\rangle\left(\frac{\langle\Sigma_\pm\rangle}{M_{\rm pl}}\right)^{n_{ij}}, \qquad n_{ij}=\frac{X_i+X_j}{-X_{\Sigma_\pm}}-1$$

Hierarchical structure

Low energy superpotential

$$\begin{aligned}W_0=&h_{ij}^UQ_iU_j^cH_u+h_{ij}^DQ_iD_j^cH_d+H_{ij}^EL_iE_j^cH_d+\mu_HH_uH_d\\&+h_{ij}^NL_iN_j^c\eta_u+\lambda_u\eta_uH_d\phi+\lambda_d\eta_dH_u\phi\\&+\mu_\eta\eta_u\eta_d+\frac{1}{2}M_iN_i^{c2}+\frac{1}{2}\mu_\phi\phi^2\end{aligned}$$

If U(1)x charge Xi is appropriately assigned to the fields, qualitative features of the hierarchical mass eigenvalues of quarks and charged leptons and the CKM matrix can be reproduced.

(2) An anomaly induced Z2 violating interaction is generated nonperturbatively.

Anomaly of U(1)x is cancelled by the shift of the dilaton field *S* associated with the gauge transformation via the Green-Schwarz mechanism:

$$\begin{cases} A_\mu\to A_\mu+\partial_\mu\alpha \\ S\to S+i\frac{\delta_{\rm GS}}{2}\alpha, \qquad \delta_{\rm GS}=\frac{g_X^2}{192\pi^2}{\rm Tr}X\end{cases}$$

This generates a U(1)x invariant nonperturbative superpotential.

$$W_{\rm NP}=c_iM_{\rm pl}e^{-b_i}L_i\eta_u, \qquad b_i=\frac{2(X_{L_i}+X_{\eta_u})}{\delta_{\rm GS}}S$$

Since $\langle S\rangle=g_X^2$ is fixed at the low energy regions, this term can introduce an extremely weak violation of the Z2 symmetry in the case of $b_i\gg 1$.

(3) R-parity remains as the exact symmetry.

Effective model is defined by

Superpotential

$$W=W_0+W_{\rm NP}$$

Soft supersymmetry breaking terms (Universality is assumed.)

$$\begin{aligned}-\mathcal{L}_{\rm SB}=&\tilde m_{\eta_u}^2\tilde\eta_u^\dagger\tilde\eta_u+\tilde m_{\eta_d}^2\tilde\eta_d^\dagger\tilde\eta_d+\tilde m_\phi^2\tilde\phi^\dagger\tilde\phi\\&+A(\lambda_u\tilde\eta_uH_d\tilde\phi+\lambda_d\tilde\eta_dH_u\tilde\phi+{\rm h.c.})\\&+B\left(\mu_\eta\tilde\eta_u\tilde\eta_d+\frac{1}{2}\mu_\phi\tilde\phi^2+\frac{1}{2}M_i\tilde N_i^{c2}+c_iM_{\rm pl}e^{-b_i}\tilde L_i\tilde\eta_u+{\rm h.c.}\right)\end{aligned}$$

Free parameters relevant to DM

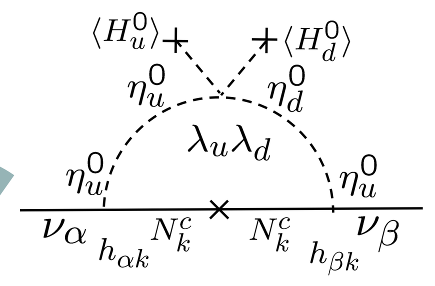
$$m_0^2(=\tilde m_{\eta_{u,d}},\ \tilde m_\phi^2),\ A,\ B, \qquad \left(A=B=\frac{\tilde m_0}{3}\right)$$

$$\mu_\eta,\ \mu_\phi\ M_i,\ c_i,\ b_i$$

Constraints on the model

Neutrino mass generation

Neutrino masses are generated through one-loop diagrams.



assume the special flavor structure

$$h_{ei}=0,\ h_{\mu i}=h_{\tau i}\ (i=1,2);\ h_{e3}=h_{\mu 3}=-h_{\tau 3}$$

Mass matrix

$$\mathcal{M}_\nu=\begin{pmatrix}0&0&0\\0&1&1\\0&1&1\end{pmatrix}(h_{\tau1}^2\Lambda_1+h_{\tau2}^2\Lambda_2)+\begin{pmatrix}1&1&-1\\1&1&-1\\-1&-1&1\end{pmatrix}h_{\tau3}^2\Lambda_3$$

$$\Lambda_i=\frac{\lambda_u\lambda_dv_uv_dM_i}{16\pi^2}\left(g(M_i,m_+)-g(M_i,m_-)\right), \qquad m_\pm=m_0^2+\mu_\eta^2\pm B\mu_\eta$$

$$g(m_a,m_b)=\frac{1}{(m_a^2-m_b^2)^2}\left[m_a^2-m_b^2+m_a^2\ln\frac{m_b^2}{m_a^2}\right]$$

Tri-bimaximal neutrino mixing is realized.

$$U_{\rm MNS}=\begin{pmatrix}\frac{2}{\sqrt6}&\frac{1}{\sqrt3}&0\\-\frac{1}{\sqrt6}&\frac{1}{\sqrt3}&\frac{1}{\sqrt2}\\\frac{1}{\sqrt6}&-\frac{1}{\sqrt3}&\frac{1}{\sqrt2}\end{pmatrix}$$

Only two mass eivenvalues are non-zero.

Neutrino oscillation data

$$h_{\tau1}^2\Lambda_1+h_{\tau2}^2\Lambda_2\simeq\frac{\sqrt{\Delta m_{\rm atm}^2}}{2}, \qquad h_{\tau3}^2\Lambda_3\simeq\frac{\sqrt{\Delta m_{\rm sol}^2}}{3}$$

To generate masses of O(0.1) eV, $\lambda_u\lambda_d$ should be suppressed as $\lambda_u\lambda_d=O(10^{-8})$. This can be guaranteed via the Froggatto-Nielsen Mechanism.

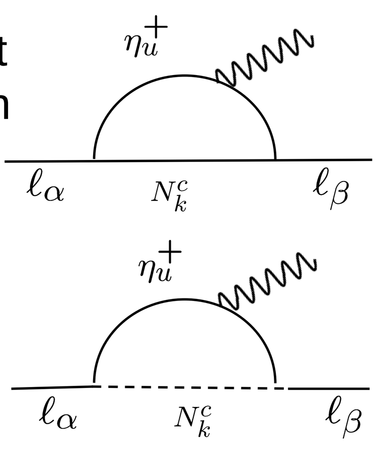
Lepton flavor violating processes (LFV)

Even if supersymmetry breaking does not induce the LFV, new additional fields can cause the LFV.

These contributions can impose strong constraints on the model.

Exp. bounds

$$Br(\mu\to e\gamma)\leq 1.2\times10^{-11}$$
$$Br(\tau\to\mu\gamma)\leq 6.8\times10^{-8}$$



Dark matter abundance $M_1\lesssim M_2<M_3,\ m_\pm,\ \mu_\eta,\ \mu_\phi$

The model has two dark matter candidates:

R-parity ⇒ the lightest neutralino χ

Z2 symmetry ⇒ the lightest right-handed neutrino $\psi_{N_1^c}$

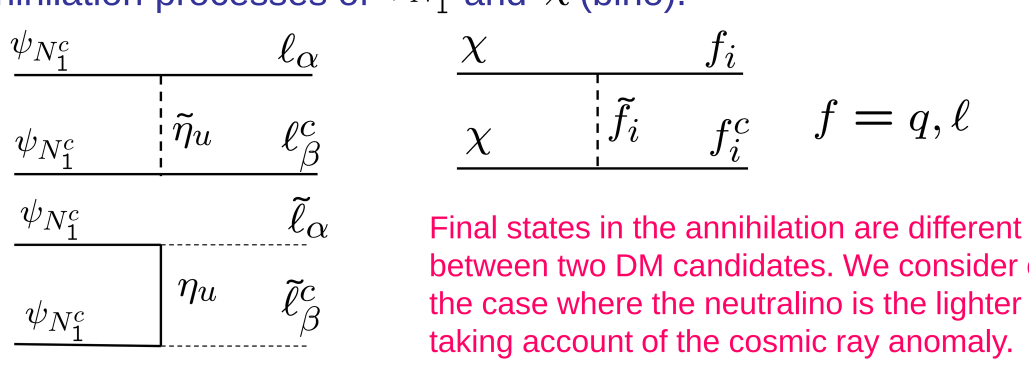
weak violation by the anomaly effect.

$\psi_{N_1^c}$ has the sufficiently long lifetime.

The present DM abundance should be explained by these.

$$\Omega_{\psi_{N_1^c}}h^2+\Omega_\chi h^2=0.11$$

Annihilation processes of $\psi_{N_1^c}$ and χ (bino).



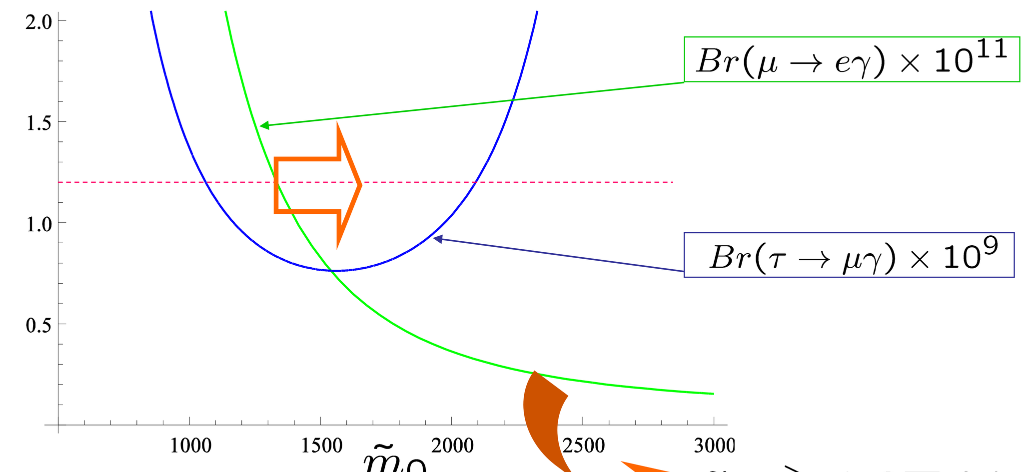
Final states in the annihilation are different between two DM candidates. We consider only the case where the neutralino is the lighter one by taking account of the cosmic ray anomaly.

Consistent parameter regions

$$\lambda_u\lambda_d=6.5\cdot10^{-8},\ M_3=6{\rm TeV}$$

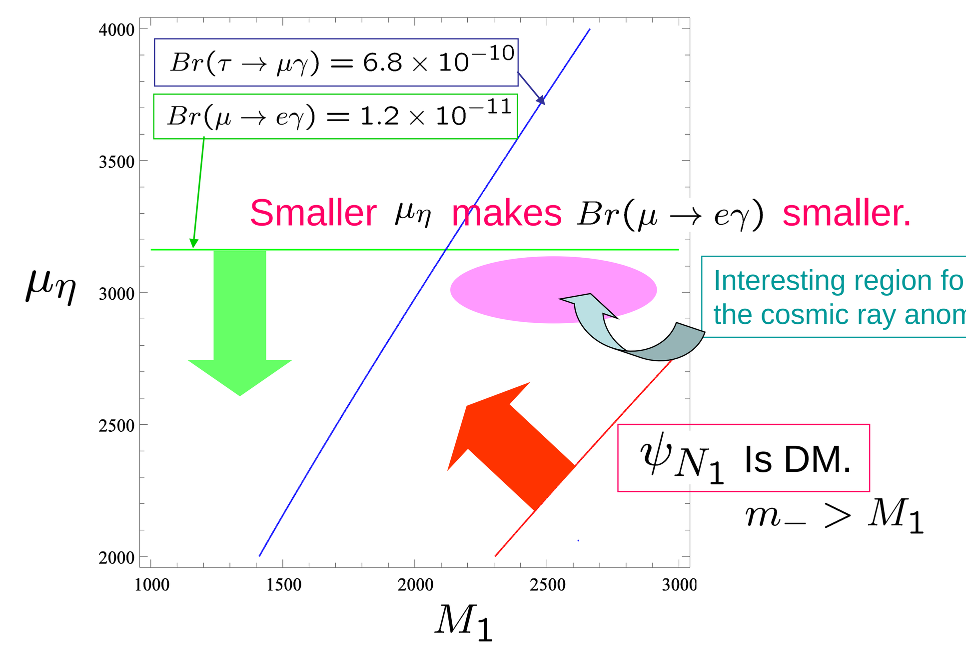
➢ Constraints from the LFV

(1) $M_1=2{\rm TeV},\ \mu_\eta=3{\rm TeV}$



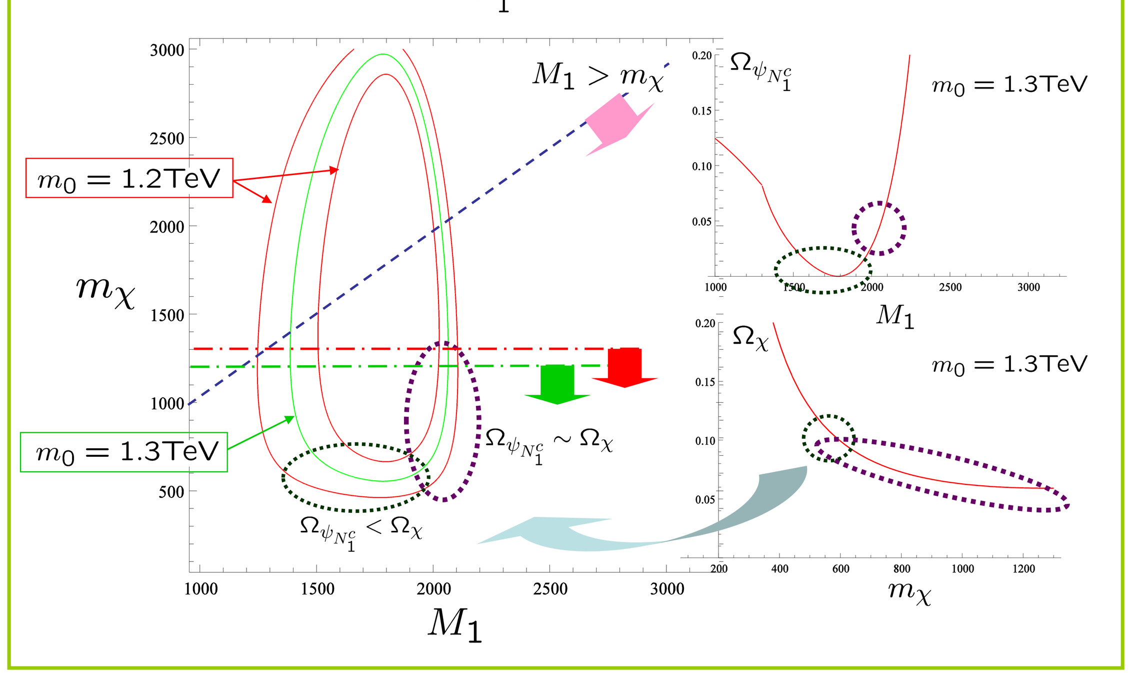
$\tilde m_0\gtrsim 1.3{\rm TeV}$

(2) $m_0=1.4{\rm TeV}$



➢ Constraints from the DM abundance $\mu_\eta=3.2{\rm TeV}$

Region for $\Omega_{\psi_{N_1^c}}h^2+\Omega_\chi h^2=0.11$



Nature of DM

PAMELA and Fermi-LAT

Anomaly has been observed in the flux of charged cosmic rays. If the lifetime of DM is $O(10^{26})$sec , this anomaly can be explained by the DM decay.

Model independent annalises of the anomaly based on the DM decay show :

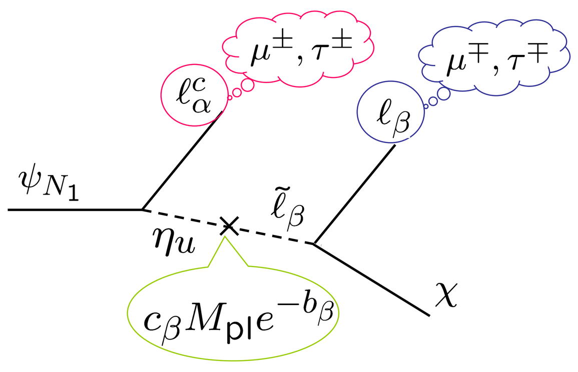
$$\begin{cases}({\rm DM}\ \to\ \mu^+\mu^-)\ \Rightarrow\ M_{\rm DM}=2-4\ {\rm TeV}\\({\rm DM}\ \to\ \tau^+\tau^-)\ \Rightarrow\ M_{\rm DM}=4-7\ {\rm TeV}\end{cases}$$

In the present model, the heavier DM can decay to the lighter one.

If $M_1>m_\chi$ and $c_e=0$

⇒ final states are $\mu^\pm,\tau^\pm$ only.

The lifetime becomes very long for $b_\beta\gg 1$.



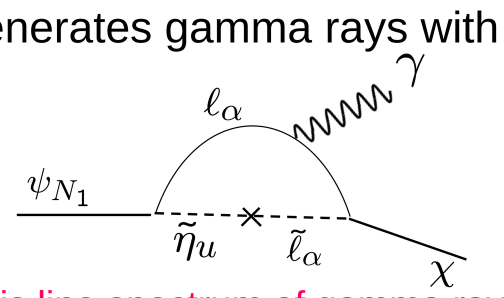
This DM decay may explain the anomaly found in PAMELA and Fermi-LAT as long as b_β takes a suitable value and M_1-m_χ is large enough.

$$\tau_{\psi_{N_1}}\sim10^{26}\times\left(\frac{2\ {\rm TeV}}{M_1}\right)^5\left(\frac{m_\eta}{3\ {\rm TeV}}\right)^4\left(\frac{\tilde m_0^2}{1\ {\rm TeV}}\right)^4\left(\frac{1\ {\rm TeV}}{B}\right)^2\left(\frac{e^{2b_\beta}}{10^{80}}\right){\rm sec}$$

$$b_\beta\simeq 92\ \Rightarrow\ 0(1)$$

Characteristic gamma ray

The heavier DM has a radiative decay mode, which generates gamma rays with a characteristic line spectrum.

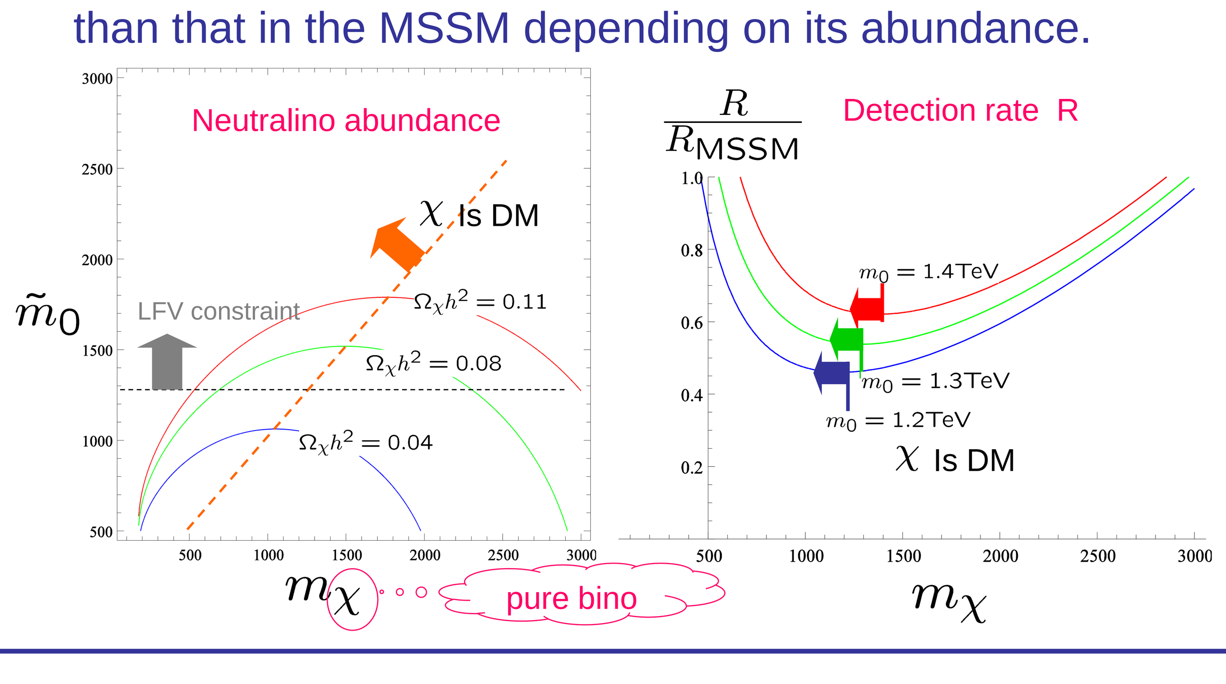


$$E_\gamma\sim\frac{M_1^2-m_\chi^2}{2M_1}$$

This line spectrum of gamma rays can be an important signature of the model.

Direct search of the DM

- Since the heavier DM has no interaction with nuclei at tree level, its direct detection is difficult in near future.
- Detection rate of the neutralino DM χ can be smaller than that in the MSSM depending on its abundance.



Summary and remarks

➢ The supersymmetric radiative seesaw model for neutrino masses is an interesting candidate for the extension of the SM.

➢ The anomalous U(1)x symmetry can play the important roles in this model, i.e. give the origin of hierarchical parameters , the origin of Z2 symmetry and the existence of decaying DM.

➢ The model show the discriminative features, for example, in the line spectrum of gamma rays associated with the DM decay and in the DM direct detection.

➢ It is worth to study features of the model expected to appear in the accelerator experiments; LHC and ILC.