Gravitino Dark Matter in The μνSSM

Very Well Known SUSY Models

The MSSM: Minimal content of fields

The NMSSM: *Solves a problem of naturalness in the MSSM: the μ problem*

Beyond the MSSM and NMSSM

Why?

Beyond the MSSM and NMSSM

Why?

- Neutrino Physics

Super-Kamiokande 1998 $\rightarrow$ Neutrinos are massive

First evidence of particle physics beyond the SM, MSSM, NMSSM ...

Proposal for a new Minimal Supersymmetric Standard Model : The μνSSM

We can use the sneutrino Right-Handed $\tilde{\nu}^c$ field to solve the μ-problem.

This motivate to postulate a New Supersymmetric Standard Model, with the minimal natural matter content and without μ-problem:

$$\lambda \tilde{\nu}^c H_1 H_2 \qquad\qquad \mu = \lambda < \tilde{\nu}^c >$$

The μ from ν Supersymmetric Standard Model ($\mu\nu$SSM)

L-F and Carlos Muñoz, *Phys. Rev. Lett. B* **97** (2006) 041801 [arXiv:hep-ph/0508297]

The Superpotential

$$W = \epsilon_{ab} \left(Y_u^{ij} \, \hat{H}_2^b \, \hat{Q}_i^a \, \hat{u}_j^c + Y_d^{ij} \, \hat{H}_1^a \, \hat{Q}_i^b \, \hat{d}_j^c + Y_e^{ij} \, \hat{H}_1^a \, \hat{L}_i^b \, \hat{e}_j^c + Y_\nu^{ij} \, \hat{H}_2^b \, \hat{L}_i^a \, \hat{\nu}_j^c \right)$$

$$- \epsilon_{ab} \lambda^i \, \hat{\nu}_i^c \, \hat{H}_1^a \hat{H}_2^b + \frac{1}{3} \kappa^{ijk} \hat{\nu}_i^c \hat{\nu}_j^c \hat{\nu}_k^c \, ,$$

R-parity is explicitly broken

Soft Terms

$$
\begin{aligned}
-\mathcal{L}_{\rm soft} &= m_{H_1}^2 \, H_1^{a\,*} \, H_1^a + m_{H_2}^2 \, H_2^{a\,*} H_2^a + (m_{\tilde{\nu}^c}^2)^{ij} \, \tilde{\nu}_i^{c\,*} \tilde{\nu}_j^c + \ldots \\
&+ \left[\epsilon_{ab} (A_\nu Y_\nu)^{ij} \, H_2^b \, \tilde{L}_i^a \, \tilde{\nu}_j^c + \ldots + \frac{1}{3} (A_\kappa \kappa)^{ijk} \tilde{\nu}_i^c \tilde{\nu}_j^c \tilde{\nu}_k^c \; + \mathrm{H.c.} \right] \\
&- \frac{1}{2} \left(M_3 \, \tilde{\lambda}_3 \, \tilde{\lambda}_3 + M_2 \, \tilde{\lambda}_2 \, \tilde{\lambda}_2 + M_1 \, \tilde{\lambda}_1 \, \tilde{\lambda}_1 + \mathrm{H.c.} \right) \, .
\end{aligned}
$$

Once the electroweak symmetry is spontaneously broken, the neutral scalars develop in general the following VEVs:

$$
\langle H_1^0 \rangle = v_1 \, , \quad \langle H_2^0 \rangle = v_2 \, , \qquad \langle \tilde{\nu}_i \rangle = \nu_i \, , \quad \langle \tilde{\nu}_i^c \rangle = \nu_i^c \, .
$$

For one family of neutrinos the minimization condition are

$$\frac{1}{4}(g_1^2+g_2^2)(\nu^2+v_1^2-v_2^2)v_1+\lambda^2 v_1\left(\nu^{c\,2}+v_2^2\right)+m_{H_1}^2 v_1-\lambda\nu^c v_2\left(\kappa\nu^c+A_\lambda\right)$$
$$-\lambda Y_\nu \nu\left(\nu^{c\,2}+v_2^2\right)=0\,,$$
$$-\frac{1}{4}(g_1^2+g_2^2)(\nu^2+v_1^2-v_2^2)v_2+\lambda^2 v_2\left(\nu^{c\,2}+v_1^2\right)+m_{H_2}^2 v_2-\lambda\nu^c v_1\left(\kappa\nu^c+A_\lambda\right)$$
$$+Y_\nu^2 v_2\left(\nu^{c\,2}+\nu^2\right)+Y_\nu \nu\left(-2\lambda v_1 v_2+\kappa\nu^{c\,2}+A_\nu \nu^c\right)=0\,,$$
$$\lambda^2\left(v_1^2+v_2^2\right)\nu^c+2\kappa^2\nu^{c\,3}+m_{\tilde{\nu}^c}^2\nu^c-2\lambda\kappa v_1 v_2\nu^c-\lambda A_\lambda v_1 v_2+\kappa A_\kappa \nu^{c\,2}$$
$$+Y_\nu^2\nu^c\left(v_2^2+\nu^2\right)+Y_\nu\nu\left(-2\lambda\nu^c v_1+2\kappa v_2\nu^c+A_\nu v_2\right)=0\,,$$
$$\frac{1}{4}(\mathbf{g_1^2}+\mathbf{g_2^2})(\nu^2+\mathbf{v_1^2}-\mathbf{v_2^2})\nu+\mathbf{m}_{\tilde{\nu}}^2\nu$$
$$+\mathbf{Y}_\nu^2\nu^{\mathbf{c}\,2}\nu+\mathbf{Y}_\nu\left(-\lambda\nu^{\mathbf{c}\,2}\mathbf{v_1}-\lambda\mathbf{v_2^2}\mathbf{v_1}+\kappa\mathbf{v_2}\nu^{\mathbf{c}\,2}+\mathbf{A}_\nu\nu^{\mathbf{c}}\mathbf{v_2}\right)=\mathbf{0}\,.$$

Observe that: $\nu \lesssim m_D$

The Neutralino-Neutrino mass matrix is:

$$\mathcal{M}_n = \begin{pmatrix} M & m \\ m^T & 0_{3\times 3} \end{pmatrix},$$

$$M = \begin{pmatrix} M_1 & 0 & -Av_d & Av_u & 0 & 0 & 0 \\ 0 & M_2 & Bv_d & -Bv_u & 0 & 0 & 0 \\ -Av_d & Bv_d & 0 & -\lambda_i \nu_i^c & -\lambda_1 v_u & -\lambda_2 v_u & -\lambda_3 v_u \\ Av_u & -Bv_u & -\lambda_i \nu_i^c & 0 & -\lambda_1 v_d + Y_{\nu_{i1}} \nu_i & -\lambda_2 v_d + Y_{\nu_{i2}} \nu_i & -\lambda_3 v_d + Y_{\nu_{i3}} \nu_i \\ 0 & 0 & -\lambda_1 v_u & -\lambda_1 v_d + Y_{\nu_{i1}} \nu_i & 2\kappa_{11j}\nu_j^c & 2\kappa_{12j}\nu_j^c & 2\kappa_{13j}\nu_j^c \\ 0 & 0 & -\lambda_2 v_u & -\lambda_2 v_d + Y_{\nu_{i2}} \nu_i & 2\kappa_{21j}\nu_j^c & 2\kappa_{22j}\nu_j^c & 2\kappa_{23j}\nu_j^c \\ 0 & 0 & -\lambda_3 v_u & -\lambda_3 v_d + Y_{\nu_{i3}} \nu_i & 2\kappa_{31j}\nu_j^c & 2\kappa_{32j}\nu_j^c & 2\kappa_{33j}\nu_j^c \end{pmatrix},$$

where $A = \frac{G}{\sqrt{2}} \sin\theta_W$, $B = \frac{G}{\sqrt{2}} \cos\theta_W$, and

$$m^T = \begin{pmatrix} -\frac{g_1}{\sqrt{2}}\nu_1 & \frac{g_2}{\sqrt{2}}\nu_1 & 0 & Y_{\nu_{1i}}\nu_i^c & Y_{\nu_{11}} v_u & Y_{\nu_{12}} v_u & Y_{\nu_{13}} v_u \\ -\frac{g_1}{\sqrt{2}}\nu_2 & \frac{g_2}{\sqrt{2}}\nu_2 & 0 & Y_{\nu_{2i}}\nu_i^c & Y_{\nu_{21}} v_u & Y_{\nu_{22}} v_u & Y_{\nu_{23}} v_u \\ -\frac{g_1}{\sqrt{2}}\nu_3 & \frac{g_2}{\sqrt{2}}\nu_3 & 0 & Y_{\nu_{3i}}\nu_i^c & Y_{\nu_{31}} v_u & Y_{\nu_{32}} v_u & Y_{\nu_{33}} v_u \end{pmatrix}$$

From the previous matrix, neutrino masses are given effectively by a see saw TeV scale

In first approximation the light neutrinos mass matrix is:

$$M_\nu = m^T M^{-1} m$$

With neutrino masses of order $10^{-2}\ \mathrm{eV} = 10^{-11}$ GeV $\Rightarrow$

$$10^{-11}\mathrm{GeV} = \frac{\mathrm{Y}_\nu^2 (10^2\mathrm{GeV})^2}{10^3\mathrm{GeV}} \rightarrow Y_\nu \sim 10^{-6}$$

$$Y_\nu H_2 L \nu^c$$

- Escudero, L-F, Muñoz, Ruiz de Austri, 08

  - Analysis of the parameter space: Viable regions
  - Spectrum, Higgs, masses for the neutralinos, etc.

- Ghosh, Roy, 09

  - Correct Neutrino physics: Solutions are find even with diagonal neutrinos
  - Decay of the lightest neutralino as LSP. Branching ratios show correlations with neutrino mixing angles, which can be tested at the LHC

- Barlt, Hirsch, Vicente, Liebler, Porod, 09

  - LHC phenomenology: The neutralino-LSP may decay within the detector.

  Fidalgo, L-F, Muñoz, Ruiz de Austri, 09

  - Neutrino Physics: Description of how see-saw works in the model. Descrption of how find easy solutions.
  - SCPV included.

Effective Neutrino mass matrix

(Diagonal Yukawas for Neutrinos)

$$\left(m_{eff|real}\right)_{ij} \simeq \frac{v_u^2}{6\kappa\nu^c} Y_{\nu_i} Y_{\nu_j} \left(1 - 3\,\delta_{ij}\right) - \frac{1}{2M_{eff}} \left[\nu_i \nu_j + \frac{v_d \left(Y_{\nu_i}\nu_j + Y_{\nu_j}\nu_i\right)}{3\lambda} + \frac{Y_{\nu_i} Y_{\nu_j} v_d^2}{9\lambda^2} \right]$$

$$M_{eff} \equiv M \left[1 - \frac{v^2}{2M\left(\kappa\nu^{c^2} + \lambda v_u v_d\right)\, 3\lambda\nu^c} \left(2\kappa\nu^{c^2} \frac{v_u v_d}{v^2} + \frac{\lambda v^2}{2} \right) \right] \qquad \frac{1}{M} = \frac{g_1^2}{M_1} + \frac{g_2^2}{M_2}$$

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$$v_d \longrightarrow 0 \qquad \left(m_{eff|real}\right)_{ij} \simeq \frac{v_u^2}{6\kappa\nu^c} Y_{\nu_i} Y_{\nu_j} \left(1 - 3\delta_{ij}\right) - \frac{1}{2\,M_{\rm eff}} \nu_i \nu_j$$

or $\nu_i >> \frac{Y_{\nu_j} v_d}{3\lambda}$

$$M_{\rm eff} = M\left(1 - \frac{v^4}{12\kappa M \nu^{c^3}}\right)$$

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$$v_d \longrightarrow 0$$

$$M_{\rm eff} \approx M$$

$$\left(m_{eff|real}\right)_{ij} \simeq \frac{v_u^2}{6\kappa\nu^c} Y_{\nu_i} Y_{\nu_j} \left(1 - 3\delta_{ij}\right) - \frac{1}{2M} \nu_i \nu_j$$

Effective Neutrino mass matrix

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$$v_d \to 0$$
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Gaugino see saw

Effective Neutrino mass matrix

(Diagonal Yukawas for Neutrinos)

$$\left(m_{eff|real}\right)_{ij} \simeq \frac{v_u^2}{6\kappa\nu^c} Y_{\nu_i} Y_{\nu_j} \left(1 - 3\,\delta_{ij}\right) - \frac{1}{2M_{eff}} \left[\nu_i \nu_j + \frac{v_d \left(Y_{\nu_i}\nu_j + Y_{\nu_j}\nu_i\right)}{3\lambda} + \frac{Y_{\nu_i} Y_{\nu_j} v_d^2}{9\lambda^2} \right]$$

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ν_R-Higgsino see saw

Then also with diagonal Yukawas for neutrinos the mixtures could be genereted

In particular in the: ν_μ-ν_τ degenerate case.

$$m_{eff} = \begin{pmatrix} d & c & c \\ c & A & B \\ c & B & A \end{pmatrix}$$

$$\sin^2\theta_{13} = 0 \qquad \sin^2\theta_{23} = \tfrac{1}{2};$$

$$c = A + B - d \longrightarrow \sin^2\theta_{12} = 1/3$$

Then close to the ν_μ-ν_τ degenerate case. and $c \approx A + B - d$

$$\sin^2\theta_{23} \approx \tfrac{1}{2}; \qquad \sin^2\theta_{13} \approx 0 \qquad \sin^2\theta_{12} \approx 1/3$$

If we start at GUT scale with diagonal Yukawas for quarks and neutrinos we will obtain small off-diagonal Yukawas at low scale.

In the quark sector this gives small mixing angles but not in the neutrino sector.

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In the quark sector this gives small mixing angles but not in the neutrino sector.

In some sense we have an explanation of : Why the two sectors are so different?

- Charginos mix with charged leptons

$$\Psi^{+T} = (-i\tilde{\lambda}^{+}, \tilde{H}_u^{+}, e_R^{+}, \mu_R^{+}, \tau_R^{+}) \qquad \Psi^{-T} = (-i\tilde{\lambda}^{-}, \tilde{H}_d^{-}, e_L^{-}, \mu_L^{-}, \tau_L^{-})$$

$$-\frac{1}{2}(\psi^{+T}, \psi^{-T}) \begin{pmatrix} 0 & M_C^T \\ M_C & 0 \end{pmatrix} \begin{pmatrix} \psi^{+T} \\ \psi^{-T} \end{pmatrix}$$

$$M_C = \begin{pmatrix} M_2 & g_2 v_u & 0 & 0 & 0 \\ g_2 v_d & \lambda_i \nu_i^c & -Y_{e_{i1}} \nu_i & -Y_{e_{i2}} \nu_i & -Y_{e_{i3}} \nu_i \\ g_2 \nu_1 & -Y_{\nu_{1i}} \nu_i^c & Y_{e_{11}} v_d & Y_{e_{12}} v_d & Y_{e_{13}} v_d \\ g_2 \nu_2 & -Y_{\nu_{2i}} \nu_i^c & Y_{e_{21}} v_d & Y_{e_{22}} v_d & Y_{e_{23}} v_d \\ g_2 \nu_3 & -Y_{\nu_{3i}} \nu_i^c & Y_{e_{31}} v_d & Y_{e_{32}} v_d & Y_{e_{33}} v_d \end{pmatrix}$$

- Neutral Higgs mix with sneutrinos

- Charged Higgs mix with charged sleptons

SUSY renormalizable theory: $\mu\nu$SSM

$M_{SUSY} \sim$ 1 TeV

All known particles (including neutrinos) + SUSY partners

Dark Matter ???

LSP is not stable

Neutralino is not a Dark Matter candidate

Also sneutrino (with right-handed component) it is not

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But .....

Dark Matter ???

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Also sneutrino (with right-handed component) it is not

But .....

Neutralino has an important role in the SUSY see-saw (without imposing R parity)

Also sneutrino Right handed as part of the Higgs ⟶ important role

What about Dark matter???

What about Dark matter???

The only confirmed indications that Dark Matter exist are gravitational

SUSY

$\mu\nu$SSM

$M_{SUSY} \sim$ 1 TeV

(Renormalizable)

Gravity ($G_{\mu\nu}$)

(Non Renormalizable)

M_{Planck} ~ 10^16 TeV

SUSY

$\mu\nu$SSM

M_{SUSY} ~ 1 TeV

(Renormalizable)

SUGRA (local SUSY)

$(G_{\mu\nu}, \Psi_{\mu})$

(graviton, gravitino)

M_{Planck} ~ 10^16 TeV

(Non Renormalizable)

Tree level amplitudes

SUSY

$\mu\nu$SSM

M_{SUSY} ~ 1 TeV

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Tree level amplitudes

SUSY

$\mu\nu$SSM

$M_{SUSY} \sim$ 1 TeV

(Renormalizable)

Similar as in a Fermi theory where

$G_F \sim 1/M_W^2$

Gravitino: Could be Dark matter

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Direct detection: Not possible ☹

Gravitino: Could be Dark matter

Direct detection: Not possible ☹

Indirect detection: In principle possible !!! ☺

K-Y Choi, L-F, C. Muñoz, R. Ruiz de Austri, arXix:0906.3681 [hep-ph]

Tree level interactions

Takayama, Yamaguchi, 2000

gravitino-photon-photino (λ):

$$L_{int} = -\frac{i}{8M_{pl}} \bar{\psi}_\mu [\gamma^\nu, \gamma^\rho] \gamma^\mu \lambda F_{\nu\rho},$$

$$\Gamma(\Psi_{3/2} \to \sum_i \gamma \nu_i) \simeq \frac{1}{32\pi} \mid U_{\tilde{\gamma}\nu} \mid^2 \frac{m_{3/2}^3}{M_P^2} ,$$

Lifetime of the gravitino can be longer than the age of the Universe (~10^{17}s)

$$\tau_{3/2} = \Gamma^{-1}(\tilde{G} \to \gamma\nu) \simeq 8.3 \times 10^{26}\,\mathrm{sec} \times \left(\frac{m_{3/2}}{1\mathrm{GeV}}\right)^{-3} \left(\frac{|U_{\gamma\nu}|^2}{7 \times 10^{-13}}\right)^{-1}.$$

Relic density

$$\Omega_{3/2}h^2 \simeq 0.27 \left(\frac{T_\mathrm{R}}{10^{10}\,\mathrm{GeV}}\right)\left(\frac{100\,\mathrm{GeV}}{m_{3/2}}\right)\left(\frac{m_{\tilde{g}}}{1\,\mathrm{TeV}}\right)^2$$

$\Omega_{3/2}h^2 \simeq 0.1$ for $T_R \sim 10^8 - 10^{11}$ GeV, with $m_{\tilde{g}} \sim 1$ TeV

DETECTION

- Decays of **gravitinos** in the galactic halo, at a sufficiently high rate, would produce gamma rays that could be detectable in future experiments

An experiment such as **FERMI**, launched last year, might in principle detect these gamma rays

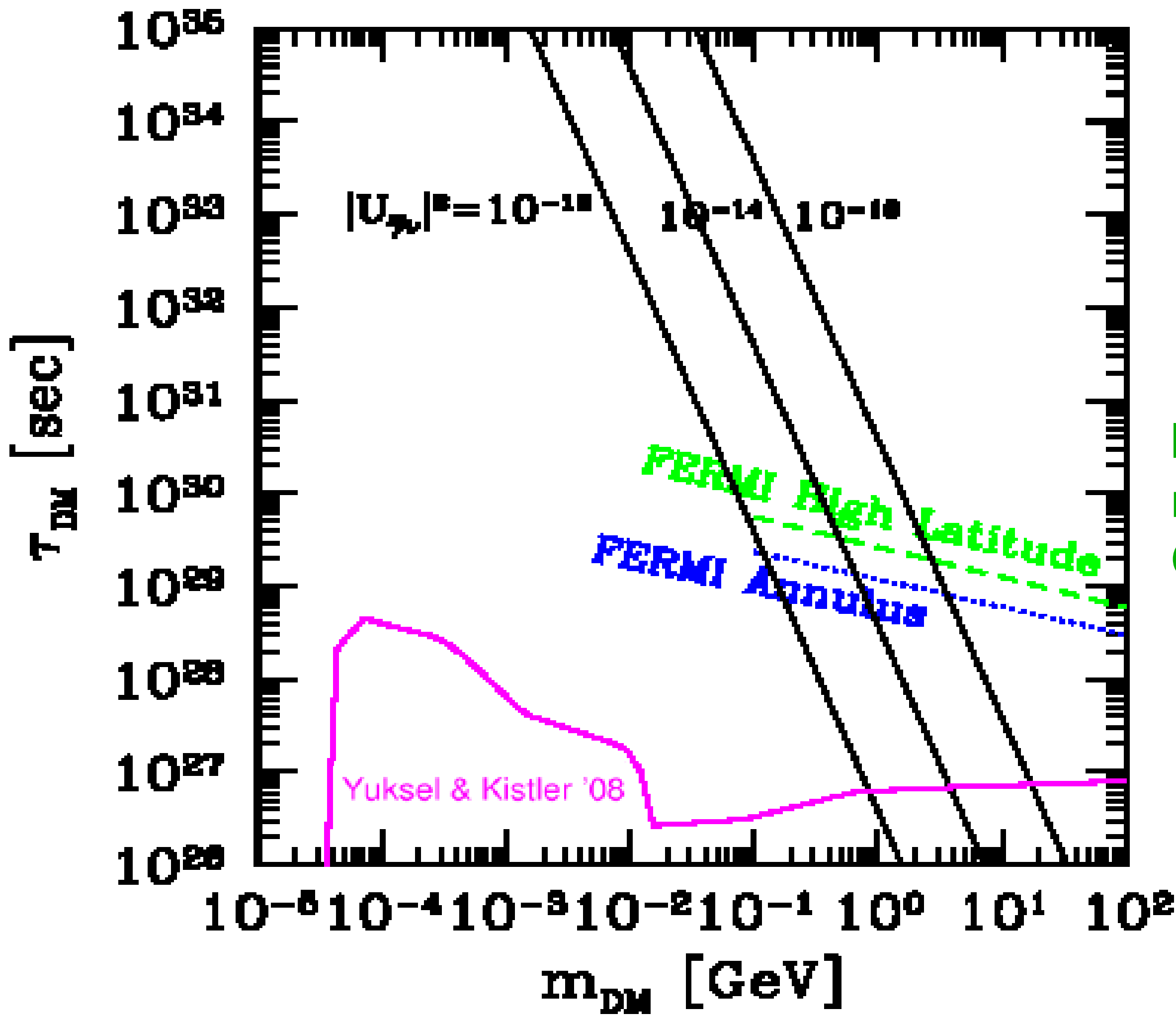
Buchmuller, Covi, Hamaguchi, Ibarra, Yanagida, 2007
Bertone, Buchmuller, Covi, Ibarra, 2007
Ibarra, Tran, 2008

$$\left[E^2 \frac{dJ}{dE}\right]_{\rm halo} = \frac{2E^2}{m_{3/2}} \frac{dN_\gamma}{dE} \frac{1}{8\pi\tau_{3/2}} \int_{\rm los} \rho_{\rm halo}(\vec{l}) d\vec{l} \,,$$

The integration extends over the line of sight implying an angular dependence on the direction of observation. This produces an anisotropic gamma ray flux

Since the gravitino decays into a photon and neutrino, this produces two monochromatic lines at energies equal to $\mathbf{m_{3/2}/2}$

Indirect detection

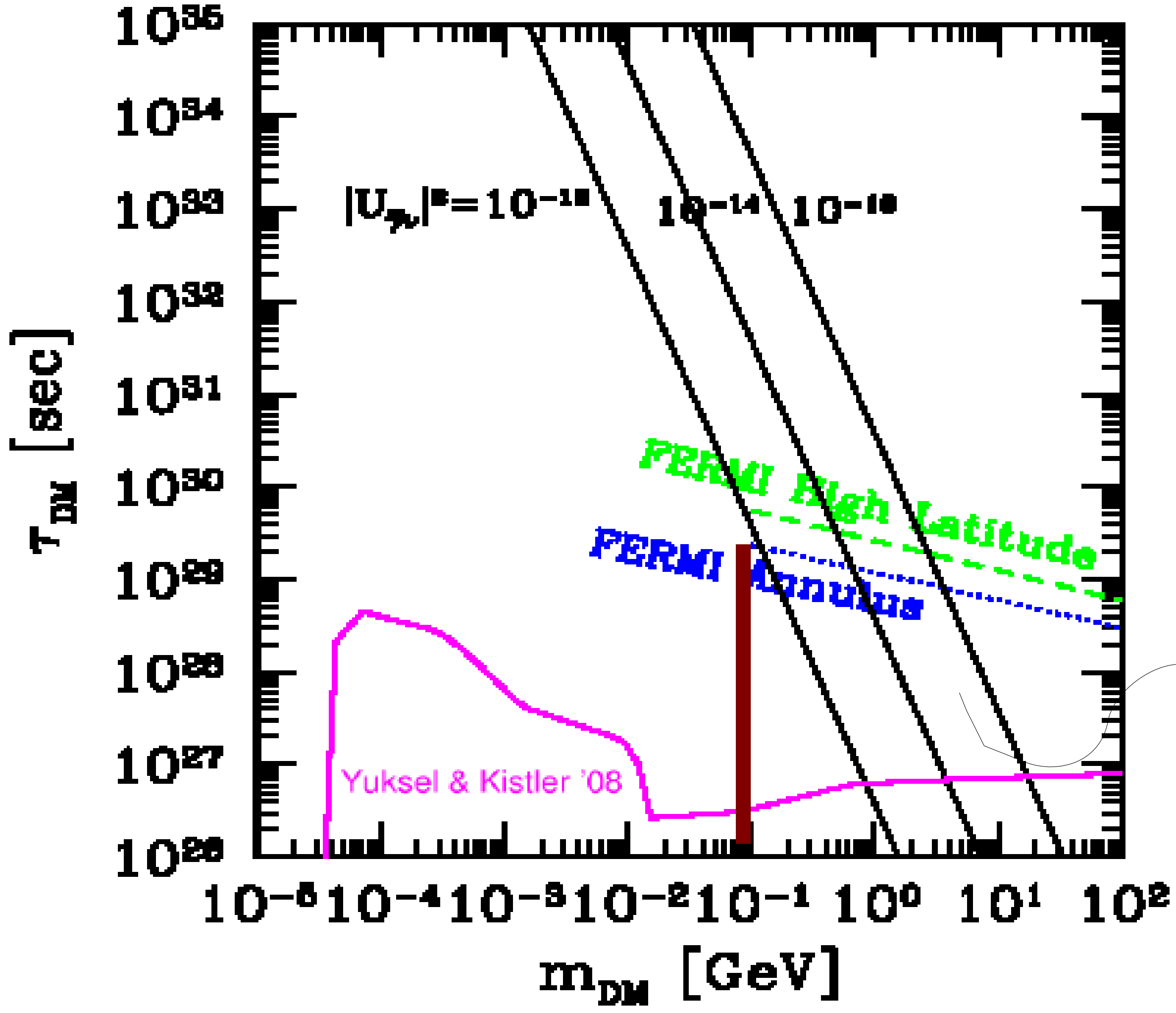


$U \sim g_1\ \nu/M_1 \sim 10^{-6} - 10^{-8}$

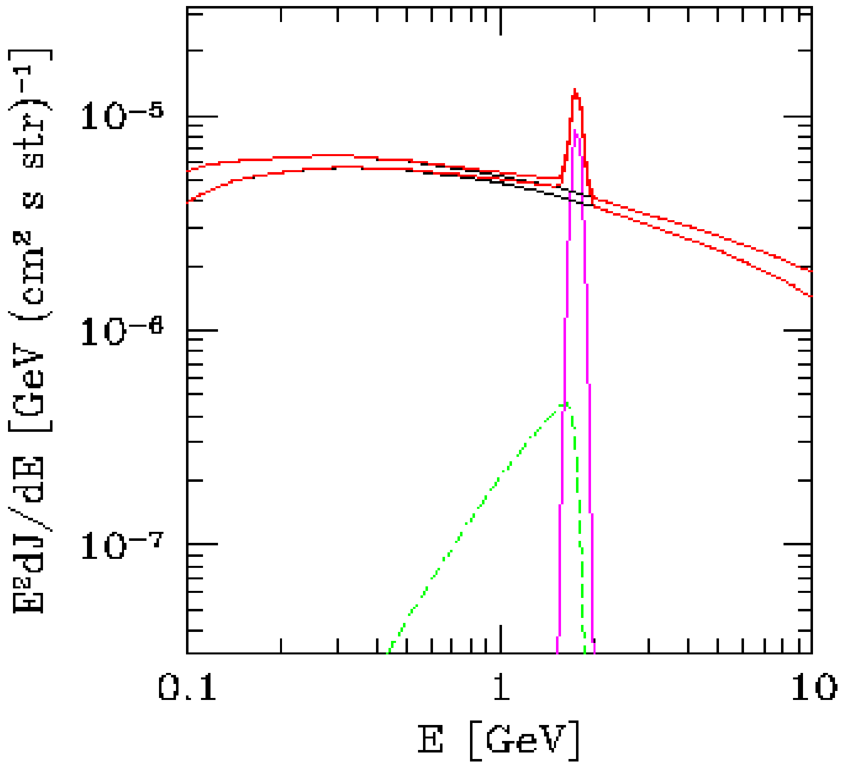
latitude >20° but excluding the region within 35° of the Galactic Center

within 25° to 35° of Galactic Center but excluding ±10° of the Galactic equator

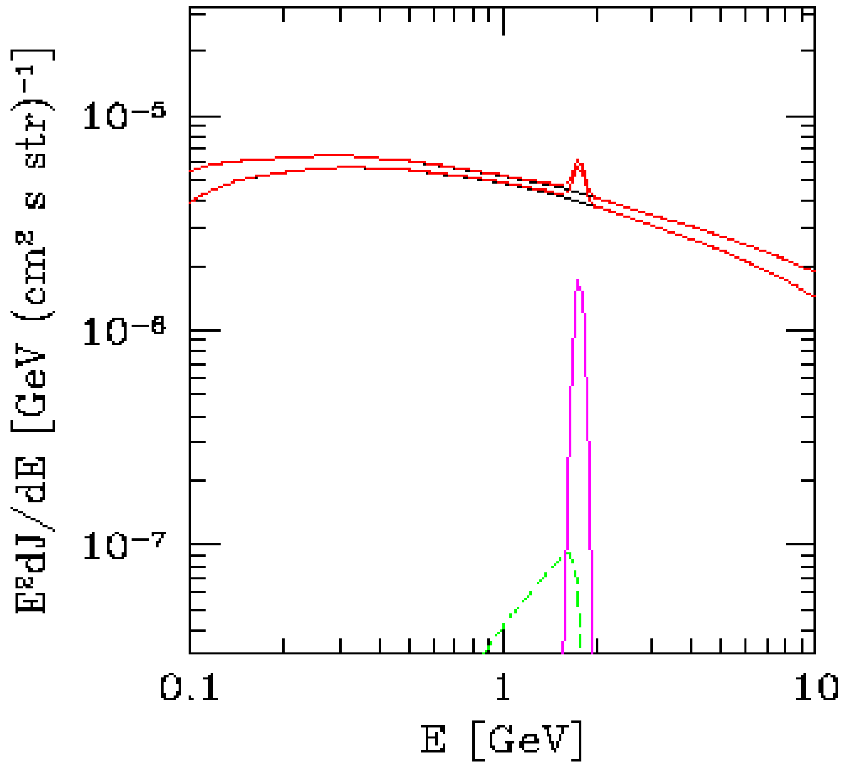
Indirect detection



Observable



(a)



(b)

Figure Expected gamma-ray spectrum for an example of gravitino dark matter decay in the mid-latitude range ($10° \leq |b| \leq 20°$) in the $\mu\nu$SSM with $m_{3/2} = 3.5$ GeV and (a) $|U_{\tilde{\gamma}\nu}|^2 = 8.8 \times 10^{-15}$ corresponding to $\tau_{3/2} = 10^{27}$ s, (b) $|U_{\tilde{\gamma}\nu}|^2 = 1.7 \times 10^{-15}$ corresponding to $\tau_{3/2} = 5 \times 10^{27}$ s. The green dashed, magenta solid, and black solid lines correspond to the diffuse extragalactic gamma ray flux, the gamma-ray flux from the halo, and to the conventional background. respectively. The total gamma-ray flux is shown with red solid lines.

Conclusion

❶ Very Rich and different Phenomenology from MSSM/NMSSM

❷ We used the right-handed sneutrino field to solve the μ-problem of the MSSM without introducing and extra field as in the NMSSM

❸ We include Neutrino Physics in a very natural way.
Renormalizable theory with the minimal content of matter (with tree level masses for the three neutrinos) only one scale M_{SUSY}

❹ After EW symmetry breaking → see saw mechanism at EW scale
R parity is broken → Neutralino important roll in the see saw

❺ Gravitino is the supersymmetric partner of graviton,
(in a local SUSY theory, Non-Renormalizable, is part of the spectrum)
→ could be Dark Matter, and might be tested

RGEs

$$\frac{d}{dt}\kappa_{ijk} = \frac{1}{16\pi^2}(\kappa_{ljk}\gamma^{\nu^c_l}_{\nu^c_i} + \kappa_{lik}\gamma^{\nu^c_l}_{\nu^c_j} + \kappa_{lji}\gamma^{\nu^c_l}_{\nu^c_k}) \ ,$$

$$\frac{d}{dt}\lambda_i = \frac{1}{16\pi^2}(\lambda_j\gamma^{\nu^c_j}_{\nu^c_i} + \lambda_i\gamma^{H_u}_{H_u} + \lambda_i\gamma^{H_d}_{H_d}) + \frac{1}{16\pi^2}Y_{\nu_{ji}}\gamma^{L_j}_{H_d} \ ,$$

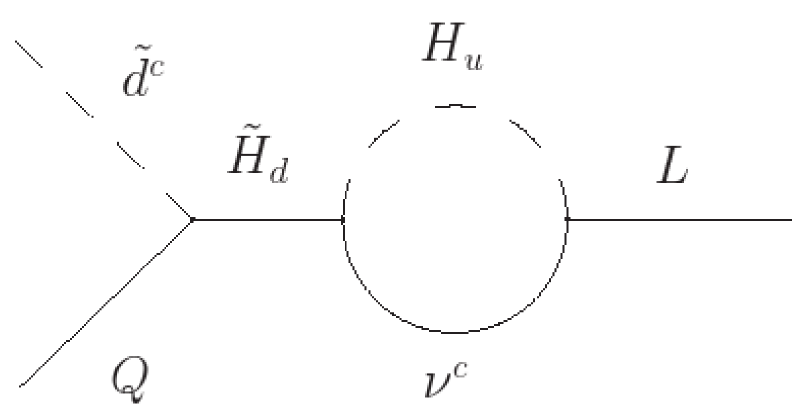
$$\frac{d}{dt}Y_{\nu_{ij}} = \frac{1}{16\pi^2}(Y_{\nu_{ij}}\gamma^{H_u}_{H_u} + Y_{\nu_{ik}}\gamma^{\nu^c_k}_{\nu^c_j} + Y_{\nu_{kj}}\gamma^{L_k}_{L_i}) + \frac{1}{16\pi^2}\lambda_j\gamma^{H_d}_{L_i} \ ,$$

$$\frac{d}{dt}Y_{e_{ij}} = \frac{1}{16\pi^2}(Y_{e_{ij}}\gamma^{H_d}_{H_d} + Y_{e_{ik}}\gamma^{e^c_k}_{e^c_j} + Y_{e_{ik}}\gamma^{L_k}_{L_j}) \ ,$$

$$\frac{d}{dt}Y_{d_{ij}} = \frac{1}{16\pi^2}(Y_{d_{ik}}\gamma^{d^c_k}_{d^c_j} + Y_{d_{kj}}\gamma^{Q_k}_{Q_i} + Y_{d_{ij}}\gamma^{H_d}_{H_d}) \ ,$$

$$\frac{d}{dt}Y_{u_{ij}} = \frac{1}{16\pi^2}(Y_{u_{ik}}\gamma^{u^c_k}_{u^c_j} + Y_{u_{kj}}\gamma^{Q_k}_{Q_i} + Y_{u_{ij}}\gamma^{H_u}_{H_u}) \ ,$$

$$\frac{d}{dt}\lambda'_{ijk} = \frac{1}{16\pi^2}Y_{d_{jk}}\gamma^{H_d}_{L_i} \ .$$



$$\gamma_{\nu_i^c}^{\nu_j^c} = -2(\kappa_{ilk}\kappa_{jlk} + \lambda_i\lambda_j + Y_{\nu_{ki}}Y_{\nu_{kj}}) \ ,$$

$$\gamma_{H_u}^{H_u} = \frac{3}{2}g_2^2 + \frac{3}{10}g_1^2 - 3Y_{u_{ij}}Y_{u_{ij}} - \lambda_i\lambda_i - Y_{\nu_{ij}}Y_{\nu_{ij}} \ ,$$

$$\gamma_{H_d}^{H_d} = \frac{3}{2}g_2^2 + \frac{3}{10}g_1^2 - Y_{e_{ij}}Y_{e_{ij}} - 3Y_{d_{ij}}Y_{d_{ij}} - \lambda_i\lambda_i \ ,$$

$$\gamma_{L_i}^{L_j} = \frac{3}{2}g_2^2 + \frac{3}{10}g_1^2 - Y_{e_{ik}}Y_{e_{jk}} - Y_{\nu_{il}}Y_{\nu_{jl}} \ ,$$

$$\gamma_{L_i}^{H_d} = \gamma_{H_d}^{L_i} = -Y_{\nu_{ij}}\lambda_j \ ,$$

$$\gamma_{e_i^c}^{e_j^c} = \frac{6}{5}g_1^2 - 2Y_{e_{ik}}Y_{e_{jk}} \ ,$$

$$\gamma_{d_i^c}^{d_j^c} = \frac{8}{3}g_s^2 + \frac{2}{15}g_1^2 - 2Y_{d_{ik}}Y_{d_{jk}} \ ,$$

$$\gamma_{u_i^c}^{u_j^c} = \frac{8}{3}g_s^2 + \frac{8}{15}g_1^2 - 2Y_{u_{ik}}Y_{u_{jk}} \ ,$$

$$\gamma_{Q_i}^{Q_j} = \frac{8}{3}g_s^2 + \frac{3}{2}g_2^2 + \frac{1}{30}g_1^2 - Y_{u_{ik}}Y_{u_{jk}} - Y_{d_{ik}}Y_{d_{jk}} \ ,$$