Aspects of RH sneutrino dark matter with neutrinophilic Higgs field

Osamu Seto (Hokkai-Gakuen Univ.)

Refs: Phys. Rev. D 86, 043515 (2012); Phys. Rev. D 88, 035005 (2013)

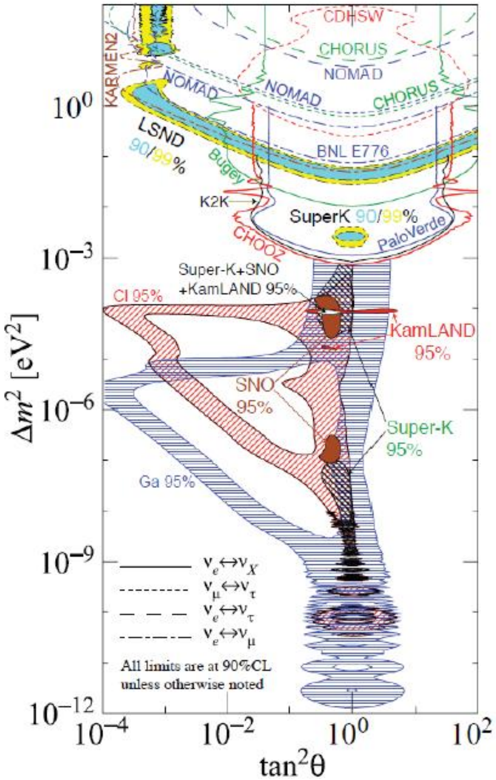
with Ki-Young Choi

JHEP 09 (2014) 068

with Ki-Young Choi and Chang Sub Shin

§ Introduction 1

- Neutrinos are massive.



- Why are neutrino masses so small??

1. by high scale physics (seesaw mechanism)
2. by quantum effects (loop induced)
3. by small Higgs VEV (neutrinophilic Higgs)
4. ...

§ Neutrinophilic Higgs doublet models

[Ma (2001), Gabriel and Nandi (2007),…]

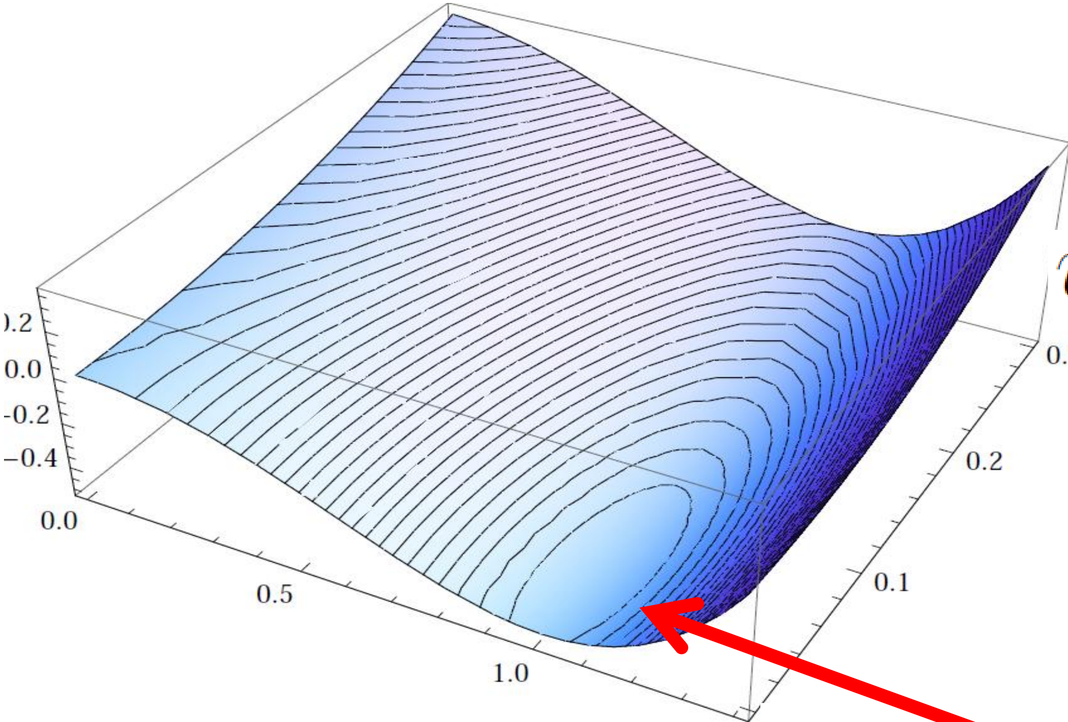
- Yukawa couplings

Dirac or Majorana

$$\mathcal{L}_{yukawa} = y^u \bar{Q}_L \Phi U_R + y^d \bar{Q}_L \tilde{\Phi} D_R + y^l \bar{L} \Phi E_R + y^\nu \bar{L} \Phi_\nu N + \frac{1}{2} M \bar{N}^c N + \text{h.c.}$$

- Higgs potential

$$\begin{aligned} V^{\text{THDM}} &= m_\Phi^2 \Phi^\dagger \Phi + m_{\Phi_\nu}^2 \Phi_\nu^\dagger \Phi_\nu - m_3^2 \left(\Phi^\dagger \Phi_\nu + \Phi_\nu^\dagger \Phi \right) + \frac{\lambda_1}{2} (\Phi^\dagger \Phi)^2 + \frac{\lambda_2}{2} (\Phi_\nu^\dagger \Phi_\nu)^2 \\ &+ \lambda_3 (\Phi^\dagger \Phi)(\Phi_\nu^\dagger \Phi_\nu) + \lambda_4 (\Phi^\dagger \Phi_\nu)(\Phi_\nu^\dagger \Phi) + \frac{\lambda_5}{2} \left[(\Phi^\dagger \Phi_\nu)^2 + (\Phi_\nu^\dagger \Phi)^2 \right]. \end{aligned}$$



s doublet models

v_ν i (2007),…]

Dirac or Majorana

$$\ldots + y^\nu \bar{L} \Phi_\nu N + \frac{1}{2} M \bar{N}^c N + \text{h.c.}$$

fields	Z_2-parity
SM Higgs doublet, Φ	+
new Higgs doublet, Φ_ν	−
right-handed neutrinos, N	−
others	+

small soft breaking

small VEV

$$m_3^2 \left(\Phi^\dagger \Phi_\nu + \Phi_\nu^\dagger \Phi \right) + \frac{\lambda_1}{2} (\Phi^\dagger \Phi)^2 + \frac{\lambda_2}{2} (\Phi_\nu^\dagger \Phi_\nu)^2$$

$$\lambda_4 (\Phi^\dagger \Phi_\nu)(\Phi_\nu^\dagger \Phi) + \frac{\lambda_5}{2} \left[(\Phi^\dagger \Phi_\nu)^2 + (\Phi_\nu^\dagger \Phi)^2 \right].$$

§ § Concept of neutrinophilic Higgs

- For **Dirac** neutrino $m_\nu = y_\nu v_\nu$

  v_ν ↓ y_ν ↑

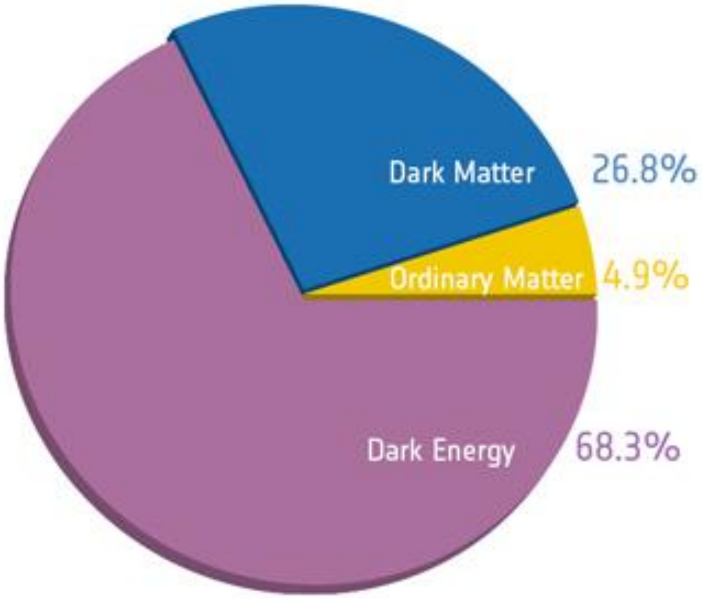
- For **Majorana** neutrino $\frac{y^\nu_{ik} v_\nu y^{\nu T}_{kj} v_\nu}{M_k}$

  the smallness is at least partially due to smallness of Higgs VEV

  v_ν ↓ y^ν ↑ and/or M_k ↓

§ Introduction 2: Cosmological

- What is dark matter?



[ESA]

- SUSY dark matter

RH Sneutrino

$$\Omega_{\rm DM} h^2 \simeq 0.1$$

§ Dirac RH sneutrino dark matter

- RH sneutrino as a new DM candidate

  ∵ neutral, maybe LSP

§ § SUSY neutrinophilic model

- Superpotential for <u>Dirac</u> neutrino

$$W = y^u \bar{Q} H_u U_R + y^d \bar{Q} H_d D_R + y^l \bar{L} H_d E_R$$
$$+ y^\nu \bar{L} H_\nu N + \frac{1}{2} M N^2$$
$$+ \mu H_u H_d + \mu' H_\nu H'_\nu + \rho H_u H'_\nu + \rho' H_\nu H_d$$

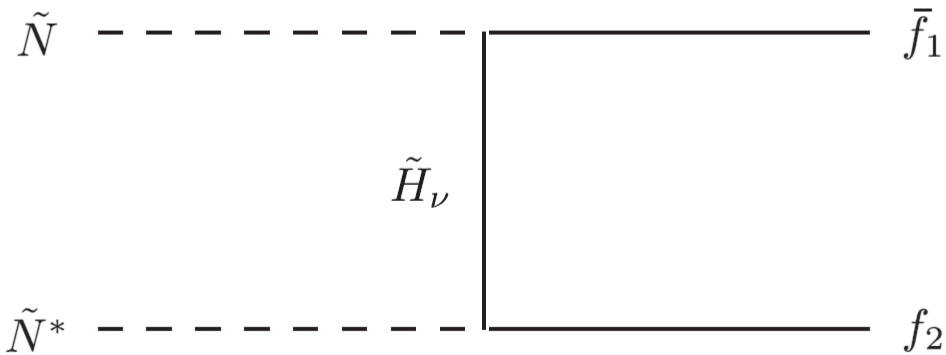
soft breaking

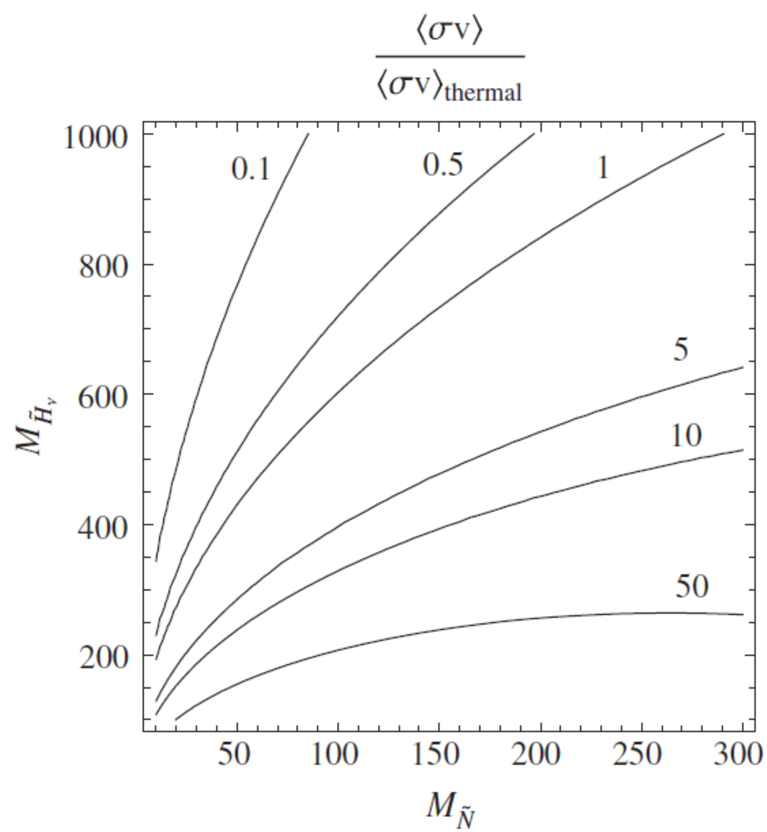
- Parity assignment

fields	Z_2-parity
MSSM Higgs doublets, H_u, H_d	$+$
new Higgs doublets, $H_\nu, H_{\nu'}$	$-$
right-handed neutrinos, N	$-$
others	$+$

§ § WIMP Thermal relic density

- Annihilation [Choi and OS (2012)]

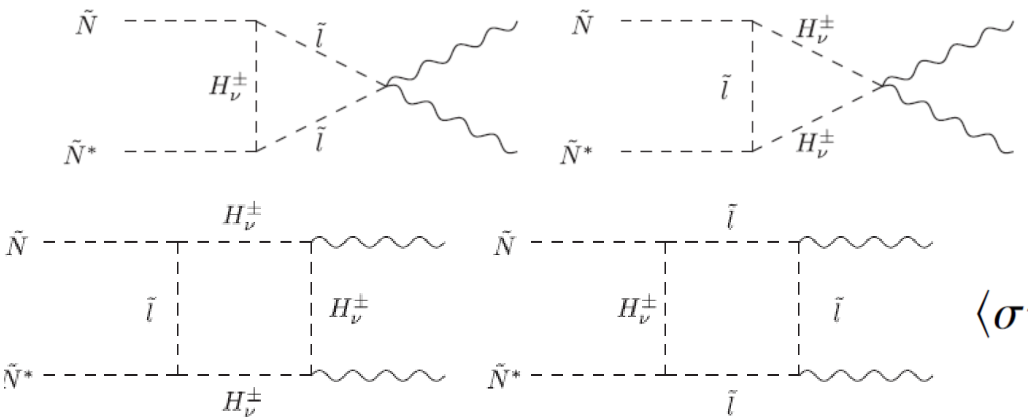




$$\langle \sigma v \rangle = \sum_f \Bigg(\frac{y_\nu^4}{16\pi} \frac{m_f^2}{(M_{\tilde{N}}^2 + M_{\tilde{H}_\nu}^2)^2} + \frac{y_\nu^4}{8\pi} \frac{M_{\tilde{N}}^2}{(M_{\tilde{N}}^2 + M_{\tilde{H}_\nu}^2)^2} \frac{T}{M_{\tilde{N}}} + \ldots \Bigg),$$

§ § Annihilation into γ

- Annihilation into 2 γ [Choi and OS (2012)]



…

$$\langle \sigma v \rangle_{2\gamma} = \frac{|M|^2_{2\gamma}}{32\pi M^2_{\tilde{N}}} \simeq \frac{\alpha^2_{\rm em}}{8\pi^3} \frac{y_\nu^4 (A_\nu^2 + \mu'^2)^2}{M^4_{\tilde{l}}} \frac{4}{M^2_{\tilde{N}}}$$

- Fermi 130 GeV γ line anomaly [Weniger (2012)]

§ § Annihilation into γ

- Annihilation into 2 γ

$$\langle \sigma v \rangle_{2\gamma} = \frac{|M|^2_{2\gamma}}{32\pi M^2_{\tilde{N}}} \simeq \frac{\alpha^2_{\rm em}}{8\pi^3} \frac{y_\nu^4 (A_\nu^2 + \mu'^2)^2}{M^4_{\tilde{l}}} \frac{4}{M^2_{\tilde{N}}}$$

- $\langle \sigma v \rangle_{\chi\chi\to\gamma\gamma} = (1.27 \pm 0.32^{+0.18}_{-0.28}) \times 10^{-27}\ {\rm cm^3\,s^{-1}}$ @130 GeV

$$\to \quad y_\nu^4 (A_\nu^2 + \mu'^2)^2 \simeq 1.8 M^4_{\tilde{l}}$$

- Fermi 130 GeV γ line anomaly [Weniger (2012)]

§ § As an asymmetric DM

- Asymmetric DM: Abundance is given by its asymmetry between DM and anti-DM
  [Barr et al (1990), Hooper at al, Kitano and Low (2005), Kaplan et al (2009)]
- Annihilation $\langle \sigma v \rangle = \langle \sigma v \rangle_{f\bar{f}} + \langle \sigma v \rangle_{2\gamma}$

$$\langle \sigma v \rangle_{2\gamma} \simeq \frac{\alpha_{\rm em}^2}{8\pi^3} \frac{y_\nu^4 (A_\nu^2 + \mu'^2)^2}{M_{\rm ch}^4} \frac{4}{M_{\tilde{N}}^2}$$
$$= 2.8 \times 10^{-8}\ {\rm GeV}^{-2} \left(\frac{6\,{\rm GeV}}{M_{\tilde{N}}} \right)^2 \frac{y_\nu^4 (A_\nu^2 + \mu'^2)^2}{M_{\rm ch}^4}$$

Sneutrino is lepton!

Maybe, lepton asymmetry as $Y_{\tilde{N}} \equiv \frac{n_{\tilde{N}} - n_{\tilde{N}^*}}{s} = \mathcal{O}(10^{-10})$

⇨ **Asymmetric RH sneutrino DM** [Choi and OS (2013)]

§ More comprehensive study

[Choi, OS and Shin (2014)]

§ § Other constraints

- Neutrino oscillation data are imposed.

Benchmarks

normal hierarchy, quasi-degenerated normal,
quasi-degenerated inverted, inverted

Point	*1: normal*	*2: normal*	*3: inverted*	*4: inverted*
$m_{1,3}$ [eV]	$m_1 = 0.0$	$m_1 = 0.07$	$m_3 = 0.05$	$m_3 = 0.0$
$(y_\nu)_{i\alpha}$	$\begin{pmatrix} 0.0 & 0.0 & 0.0 \\ 0.14 & 0.13 & -0.16 \\ 0.22 & 1.0 & 1.0 \end{pmatrix}$	$\begin{pmatrix} 0.96 & -0.57 & 0.36 \\ 0.65 & 0.62 & -0.77 \\ 0.22 & 1.0 & 1.0 \end{pmatrix}$	$\begin{pmatrix} 1.0 & -0.59 & 0.37 \\ 0.68 & 0.65 & -0.80 \\ 0.14 & 0.62 & 0.62 \end{pmatrix}$	$\begin{pmatrix} 1.0 & -0.59 & 0.37 \\ 0.68 & 0.65 & -0.80 \\ 0.0 & 0.0 & 0.0 \end{pmatrix}$
$\sum m_\nu$ [eV]	0.06	0.23	0.19	0.10
v_ν [eV]	0.05	0.08	0.08	0.05

Table 1. Neutrino Yukawa coupling matrix of the four benchmark 1, 2, 3 and 4 used in this work are shown. The resultant $\sum m_\nu$ for a given input parameter m_1 or m_3 is also listed. v_ν is a free parameter. The noted values of v_ν are examples in the case that we normalize the largest element of Yukawa matrix to be 1.0.

§§ Other constraints

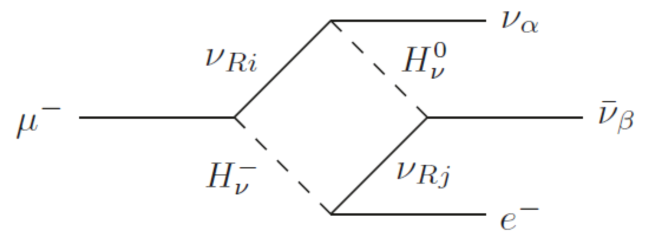
- Neutrino oscillation data are imposed.

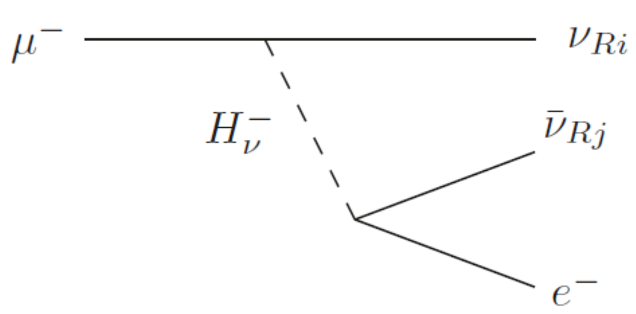
<u>Benchmarks</u>

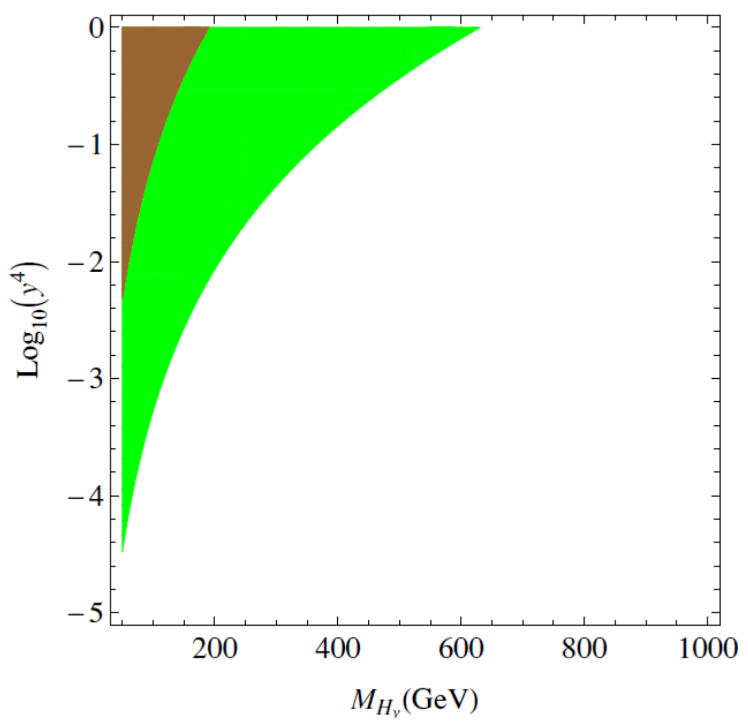
normal hierarchy, quasi-degenerated normal,
quasi-degenerated inverted, inverted

- Muon decay width

Total width, V-A nature



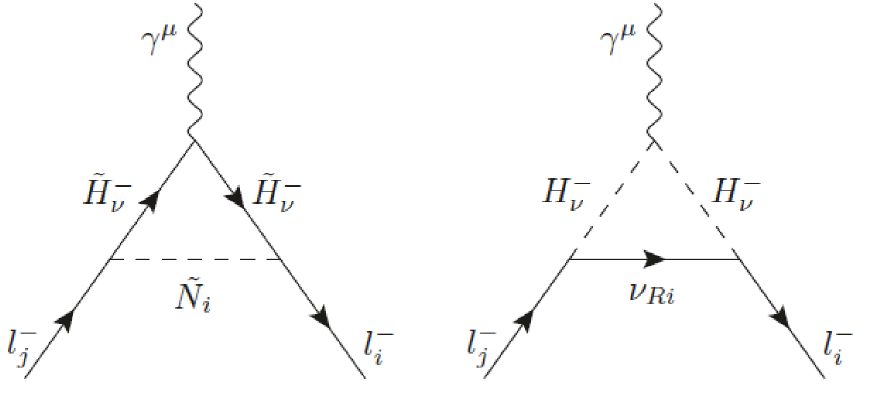




Severer constraint on $M_{H\nu}$ from DR

§ § Other constraints

- Collider (LEP and LHC) constraints
- Lepton flavor violation



constrained as

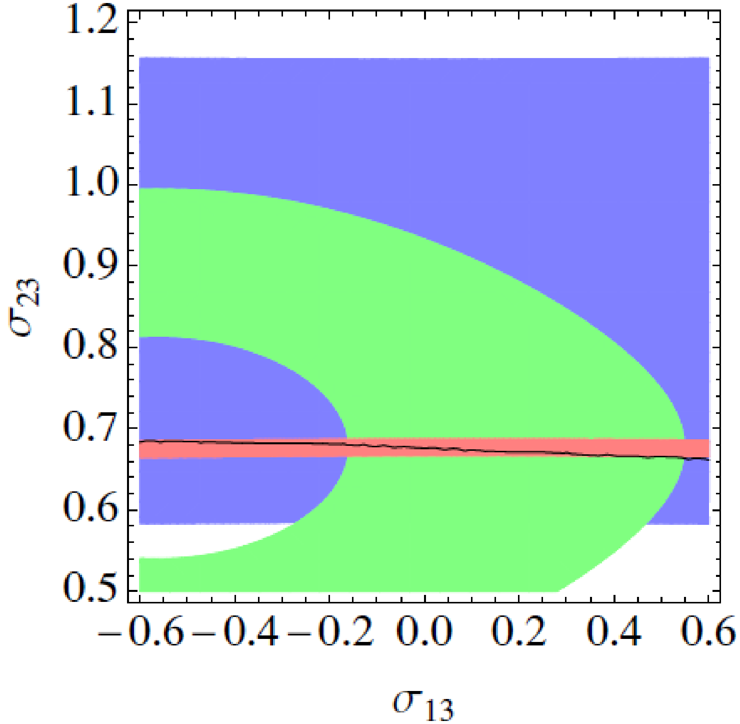
$$\mathrm{Br}(\mu \to e\gamma) < 5.7 \times 10^{-13} \quad (90\%\ \mathrm{C.L.})\,,$$
$$\mathrm{Br}(\tau \to e\gamma) < 3.3 \times 10^{-8} \quad (90\%\ \mathrm{C.L.})\,,$$
$$\mathrm{Br}(\tau \to \mu\gamma) < 4.4 \times 10^{-8} \quad (90\%\ \mathrm{C.L.})\,.$$

- Muon g-2

$$\Delta a_\mu \equiv a_\mu(\mathrm{exp}) - a_\mu(\mathrm{SM}) = (28.6 \pm 8.0) \times 10^{-10}$$

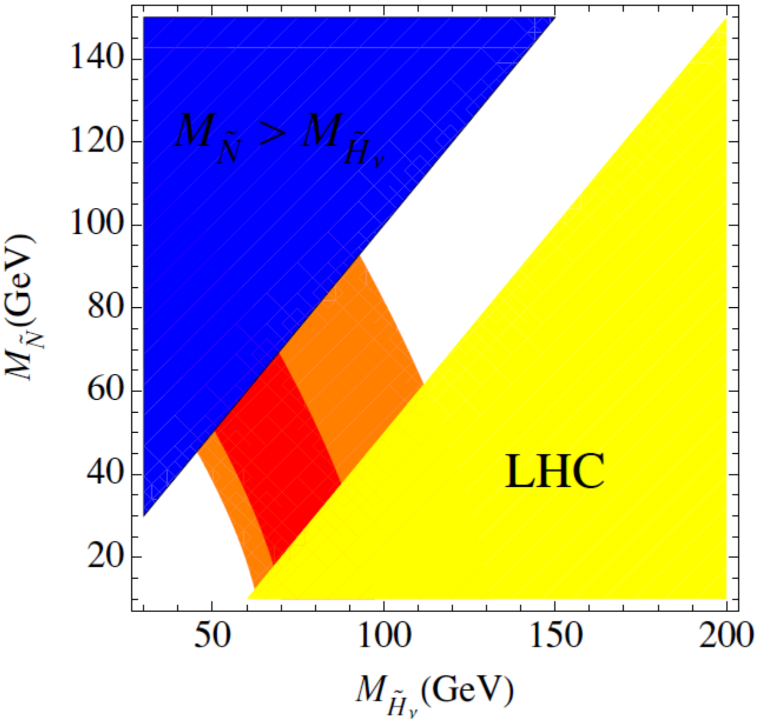
§ § Implications

- LVF constraints



are very stringent.
Appropriate sneutrino mixings are needed.

- Muon g-2



can be explained only for <u>$m_1 = \mathcal{O}(0.01)$ eV</u>

[Choi, OS and Shin (2014)]

§ § DM relic density revisited

- Annihilation

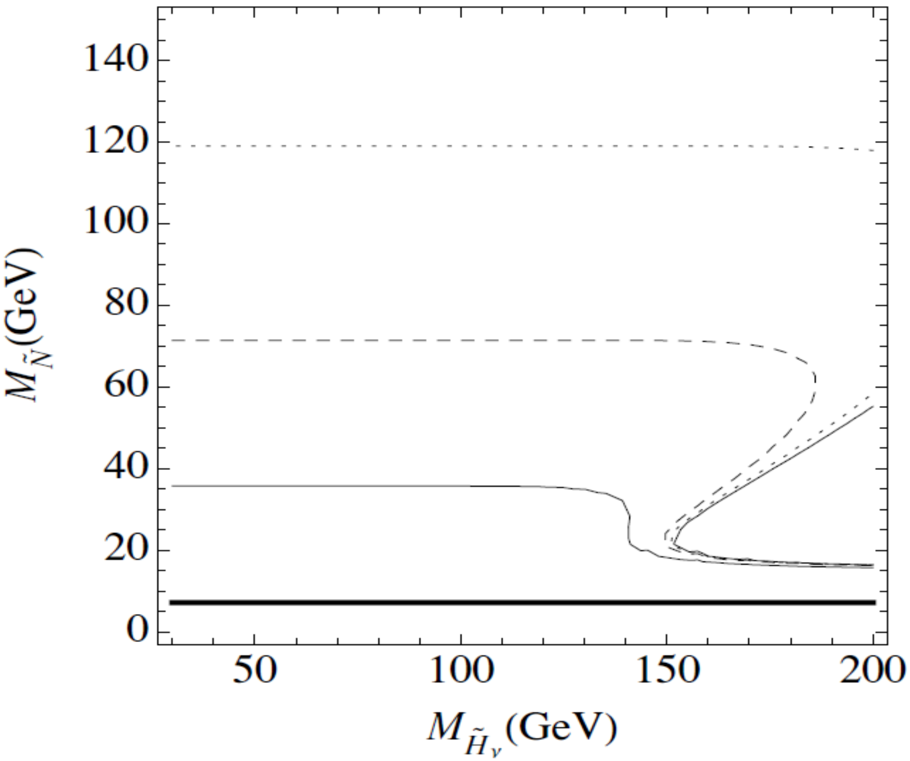
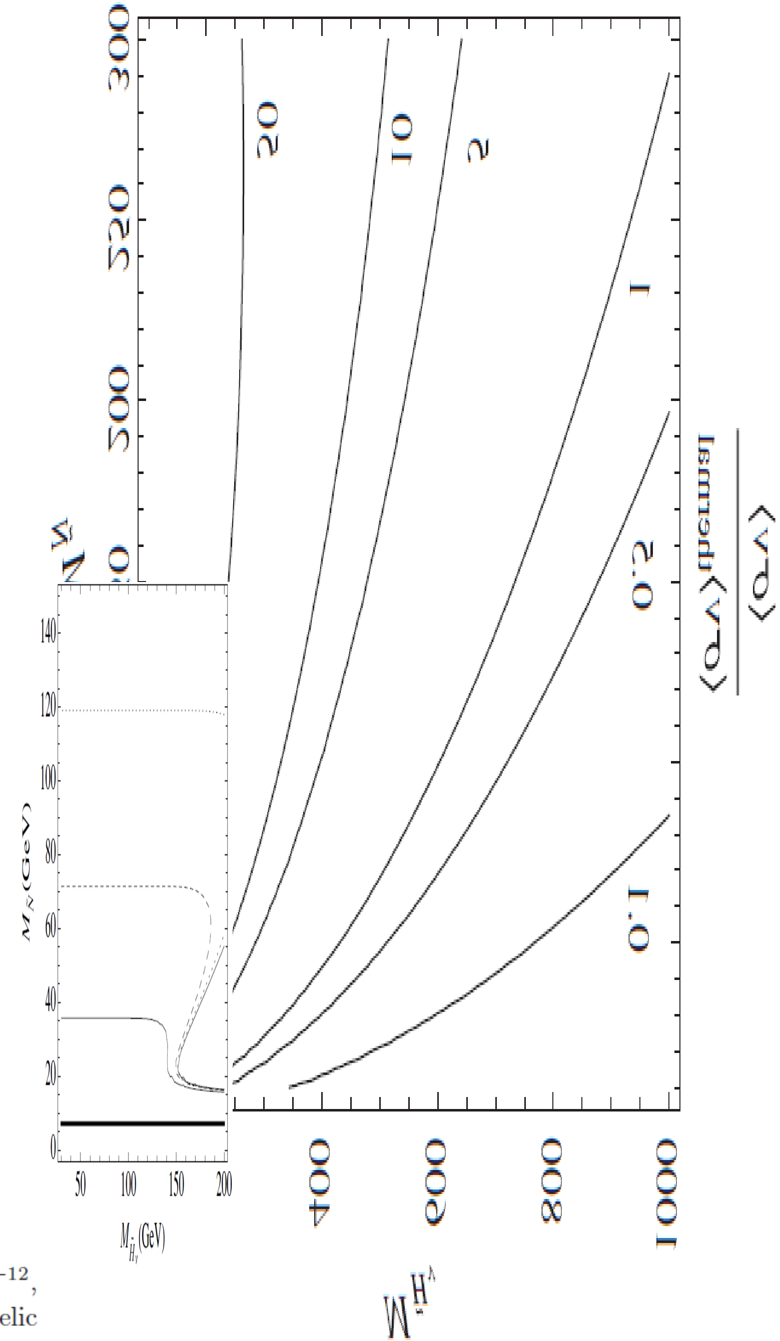
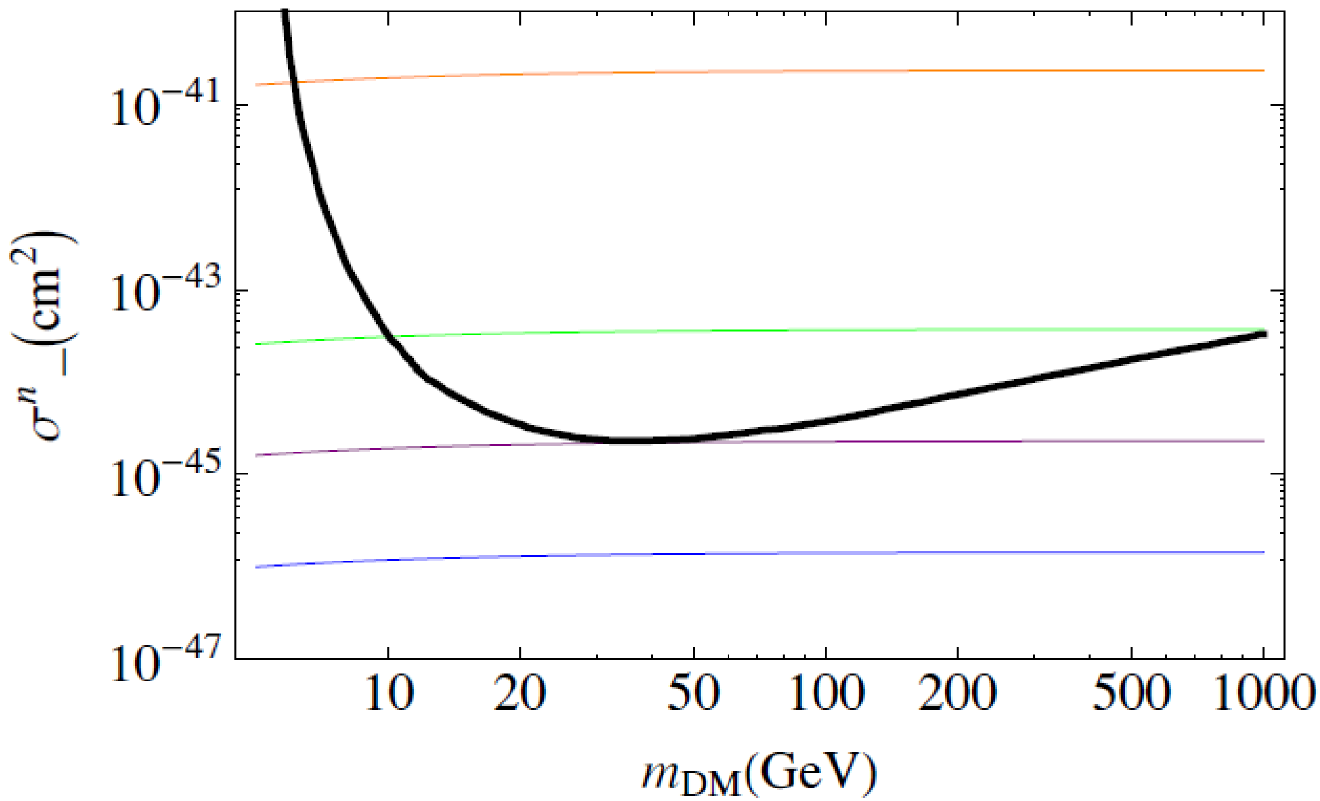


Figure 12. The contour plot of the DM asymmetry $C = (5 \times 10^{-11}, 10^{-11}, 5 \times 10^{-12}, 3 \times 10^{-12}, 10^{-12})$ with (thick solid, solid, dashed, dotted, solid lines) given in eq. (4.8), to give correct relic density for DM in the plane of its mass and Higgsino mass.



§ § DM direct detection

- Depends on $A_\nu/M_{H\nu}$



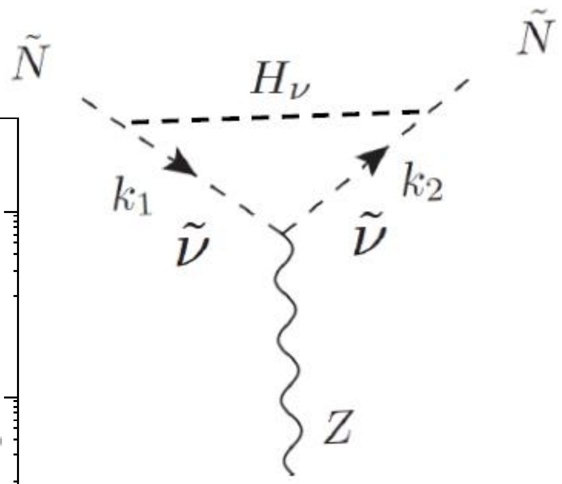


Figure 13. The scattering cross section between the lightest RH sneutrino and a neutron for $(S^T y_\nu)A_\nu/M_{H_\nu} = 0.5, 1, 2, 10$ from the bottom to the top. The current LUX bound on it is also shown with the black thick line.

§ Summary

- We have studied the property of supersymmetric neutrinophilic Higgs models with RH sneutrino DM.

- RH Dirac sneutrino as WIMP/(asymmetic) DM
- Various phenomenological constraints taken into account
- A Prediction :``if the muon g-2 is true, then neutrinos are Dirac and m_1 is not so small.''