Cosmological implications of neutrinophilic Higgs

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Refs: Prog. Theor. Phys. 125, 1155 (2011)

Phys. Rev. D 84, 103524 (2011) Leptogenesis, **Majorana**

with Naoyuki Haba

Phys. Rev. D 86, 043515 (2012) Dark matter, **Dirac**

with Ki-Young Choi

§ Introduction 1

- “Higgs” discovery is not the end of story.

- Many BSM have non-minimal Higgs sector.

1. Multi Higgs Doublet
   1-1 2HDM (MSSM, ...)
2. “B-L” would be a broken gauge symmetry.
3. Triplet Higgs (Type-II seesaw)
4. Singlet Higgs (NMSSM, ...)
5. ....

§ Introduction 1

- “Higgs” discovery is not the end of story.

- Many BSM have non-minimal Higgs sector.

1. Multi Higgs Doublet
   1-* Neutrinophilic Higgs (neutrino mass)
2. “B-L” would be a broken gauge symmetry.
3. Triplet Higgs (Type-II seesaw)
4. Singlet Higgs (NMSSM, ...)
5. ....

§ Neutrinophilic Higgs doublet models [Ma 2001 2006, Gabriel and Nandi 2007,…]

- Yukawa couplings

Dirac/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

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

§ Neutrinophilic Higgs doublet models [Ma 2001 2006, Gabriel and Nandi 2007,…]

- Yukawa couplings

Dirac/Majorana

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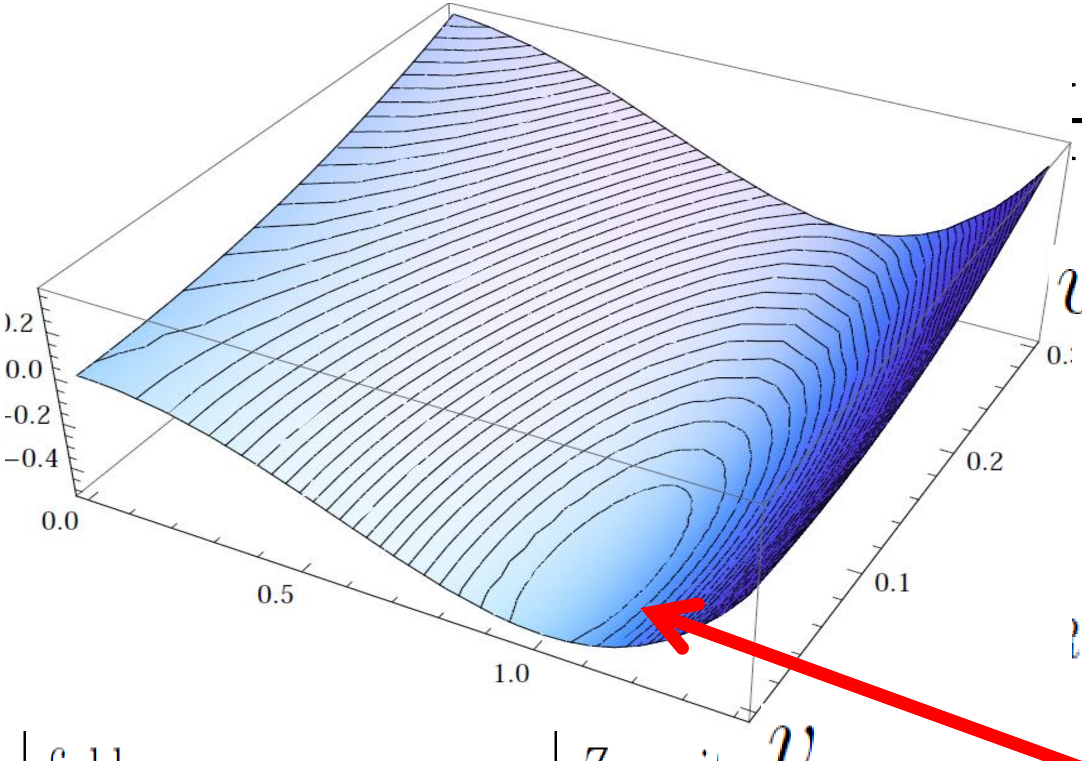
fields	Z_2-parity
SM Higgs doublet, Φ	$+$
new Higgs doublet, Φ_ν	$-$
right-handed neutrinos, N	$-$
others	$+$

soft breaking

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

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



Higgs doublet

el and Nandi 2007,…]

Dirac/Majorana

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

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

- If neutrino mass is given by $m_\nu = y_\nu v_\nu$

$v_\nu \downarrow$ $y_\nu \uparrow$

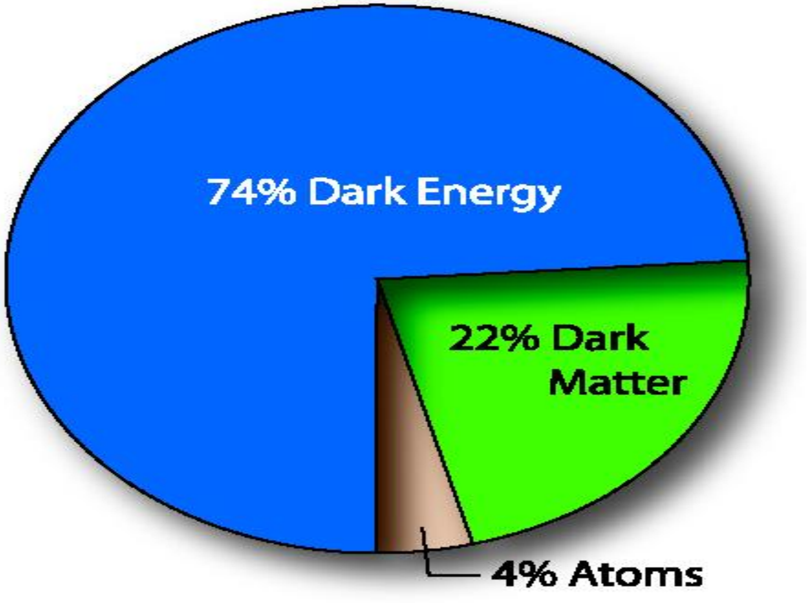
- If neutrino mass is given by $\frac{y^{\nu}_{ik} v_\nu y^{\nu T}_{kj} v_\nu}{M_k}$, the smallness is at least partially due to smallness of Higgs VEV

$v_\nu \downarrow$ $y^\nu \uparrow$ and/or $M_k \downarrow$

§ Introduction 2:
Matter content in Universe

- Open questions in cosmology

1. the origin of baryon asymmetry
2. the identity of dark matter



[NASA]

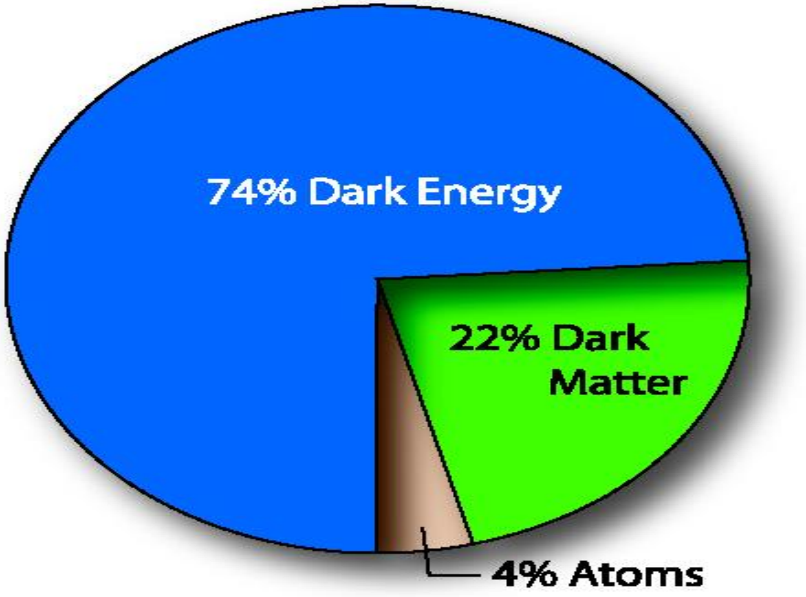
§ contents

- Baryon asymmetry from thermal leptogenesis with Majorana neutrino

- Right-handed sneutrino dark matter with Dirac neutrino

§ Baryon asymmetry

- Why baryon number in our Universe is not same as anti-baryon number?



[NASA]

- Baryogenesis via leptogenesis [Fukugita and Yanagida 1986]

Thermal leptogenesis

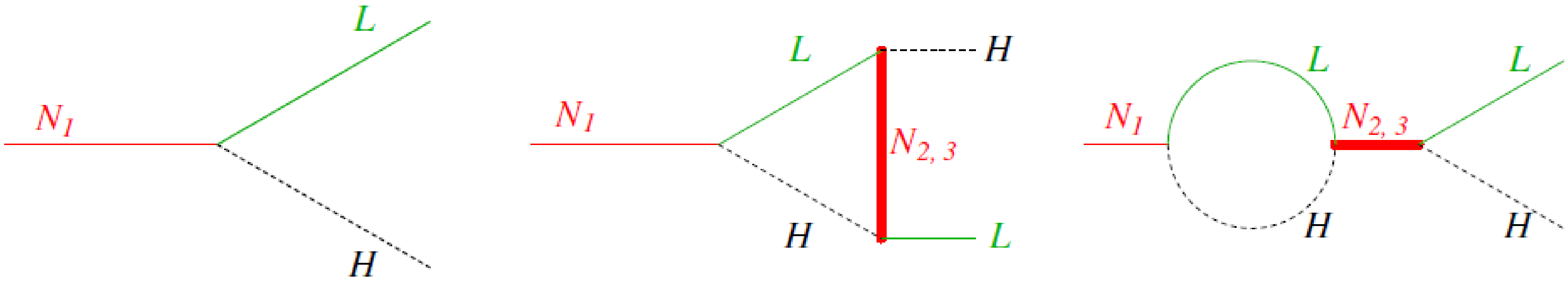
Baryon asymmetry from thermal leptogenesis by a heavy *N*

- Resultant baryon asymmetry

$$\frac{n_b}{s} \simeq C\kappa\frac{\varepsilon}{g_*}$$

- CP asymmetry $\varepsilon \equiv \frac{\Gamma(N_1 \to \Phi + \bar{l}_j) - \Gamma(N_1 \to \Phi^* + l_j)}{\Gamma(N_1 \to \Phi + \bar{l}_j) + \Gamma(N_1 \to \Phi^* + l_j)}$
- Efficiency (dilution, washout) factor $\kappa < \mathcal{O}(0.1 \sim 1)$
- Sphaleron transfer C
- Degrees of freedom in thermal bath

CP asymmetry



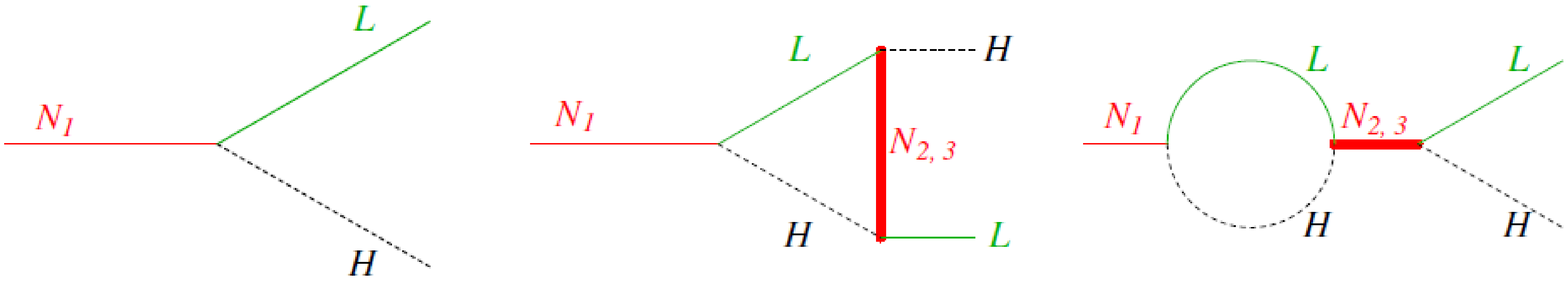
- In hierarchical right-handed neutrino mass

$$\varepsilon_1 \simeq -\frac{3}{8\pi}\frac{1}{\left(h_\nu h_\nu^\dagger\right)_{11}}\sum_{i=2,3}\mathrm{Im}\left[\left(h_\nu h_\nu^\dagger\right)^2_{1i}\right]\frac{M_1}{M_i}$$

$$M_1 \gtrsim 10^9\left(\frac{\eta_B}{5\times 10^{-11}}\right)\left(\frac{.06eV}{m_3}\right)\left(\frac{2\times 10^{-4}}{n_{\nu_R}/s\ \delta}\right)\ \mathrm{GeV}$$

- The lower bound on RH neutrino mass

§ § CP asymmetry (ν-philic)



- In hierarchical right-handed neutrino mass

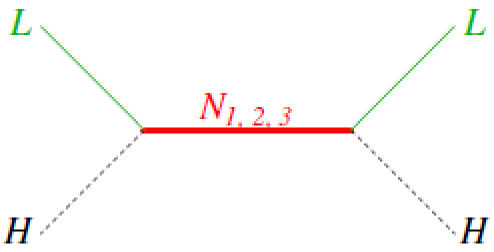
$$\varepsilon \simeq -\frac{3}{8\pi}\frac{1}{(y^{\nu\dagger}y^{\nu})_{11}}\left(\mathrm{Im}(y^{\nu\dagger}y^{\nu})^2_{12}\frac{M_1}{M_2}+\mathrm{Im}(y^{\nu\dagger}y^{\nu})^2_{13}\frac{M_1}{M_3}\right)$$

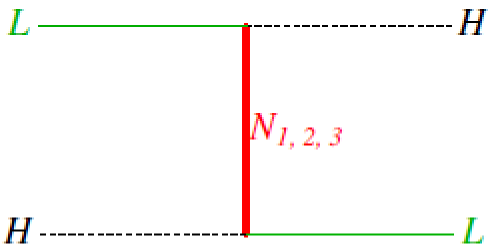
$$\simeq -\frac{3}{16\pi}10^{-6}\left(\frac{0.1\mathrm{GeV}}{v_\nu}\right)^2\underline{\left(\frac{M_1}{100\mathrm{GeV}}\right)}\left(\frac{m_\nu}{0.05\mathrm{eV}}\right)\sin\theta$$

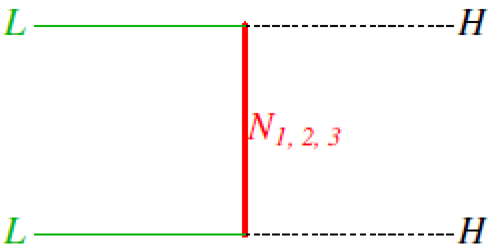
- Relaxed lower bound on RH neutrino mass

§ § Washout (ν-philic)

- $\Delta L=2$ scattering could be effective.



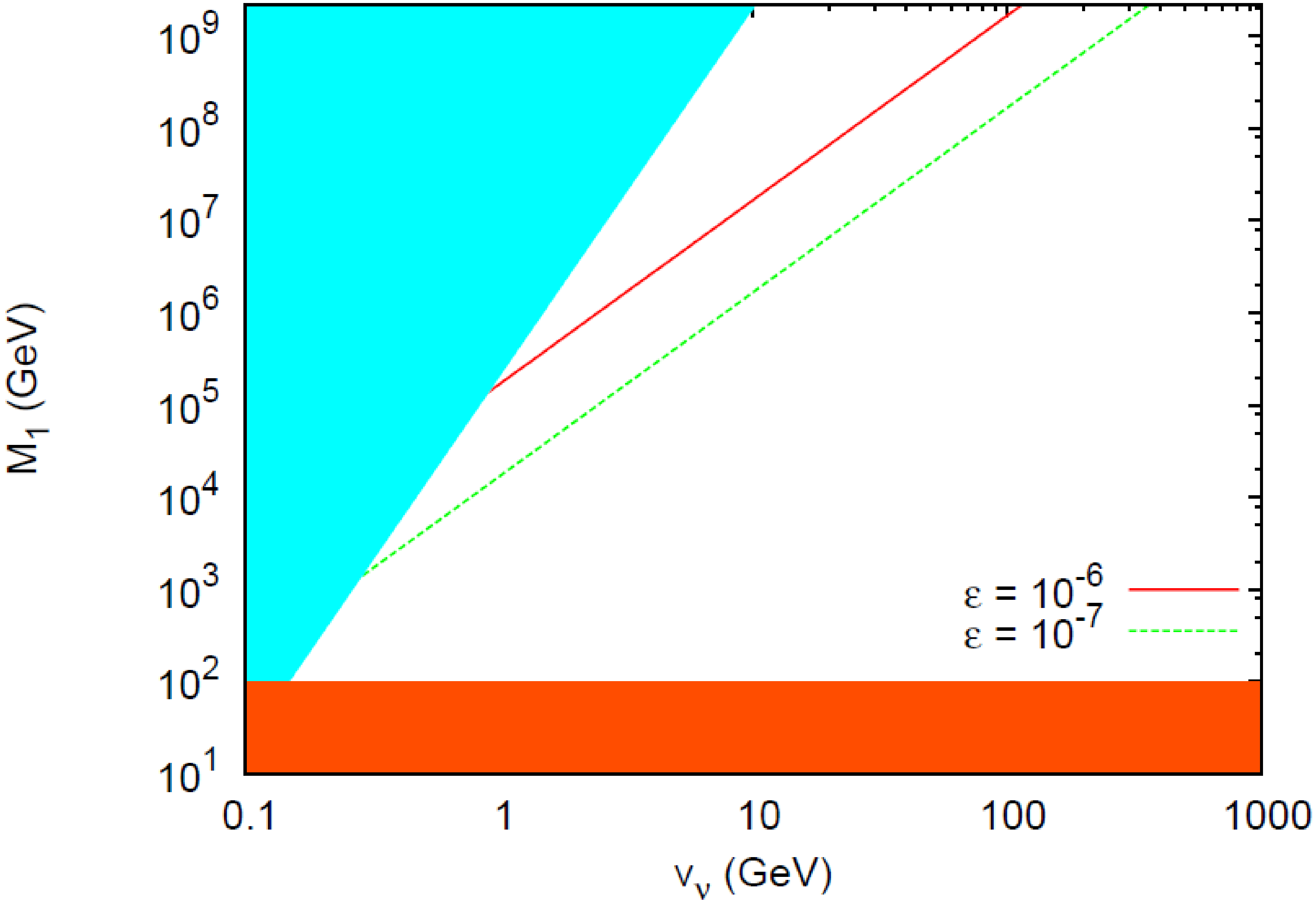




- Condition

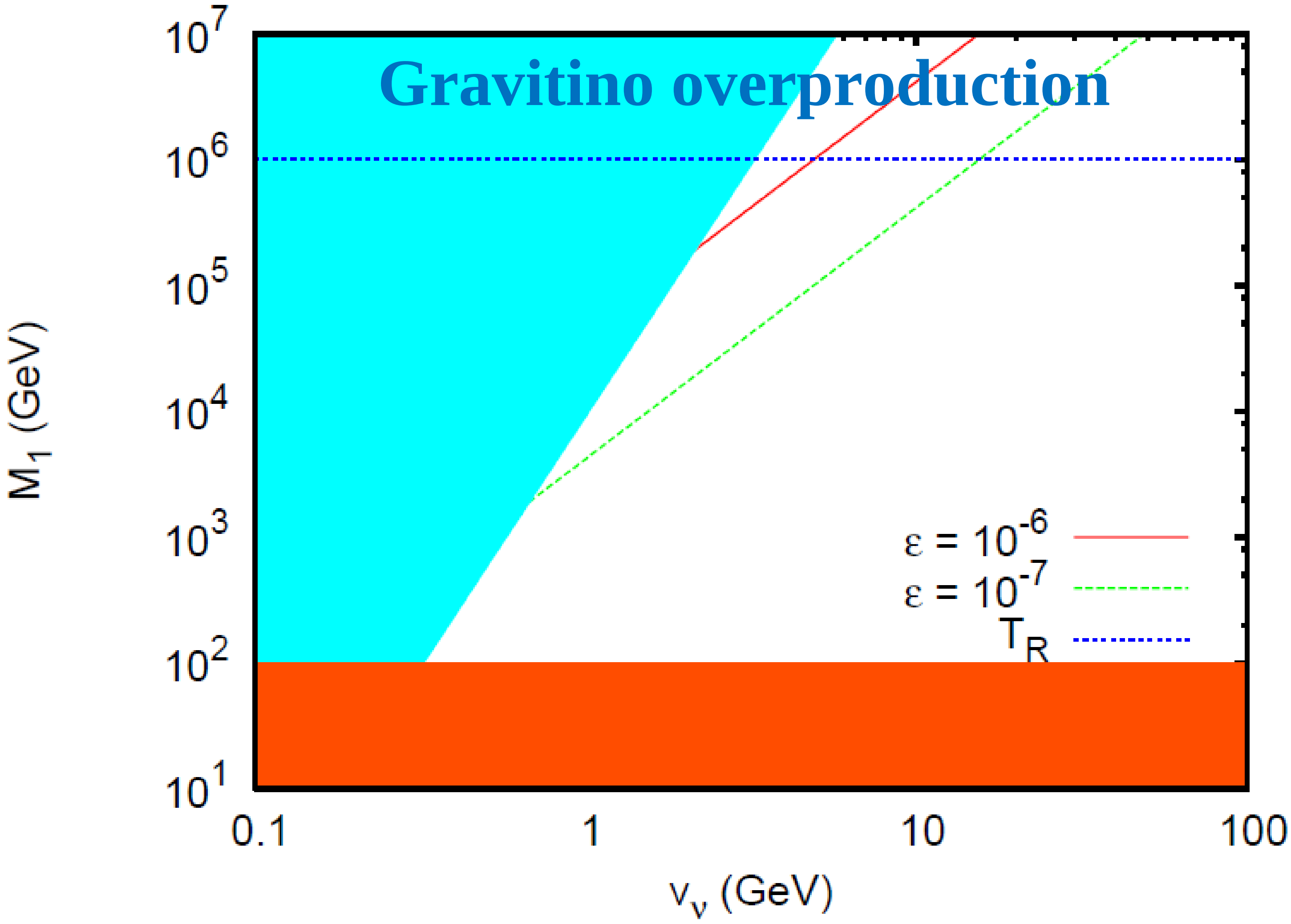
$$\sum_i \left(\sum_j \frac{y^{\nu}_{ij} y^{\nu}_{ji}{}^{\dagger} v_{\nu}^2}{M_j} \right)^2 < 32\pi^3 \zeta(3) \sqrt{\frac{\pi^2 g_*}{90}} \frac{v_{\nu}^4}{T M_P}$$

§ § Result



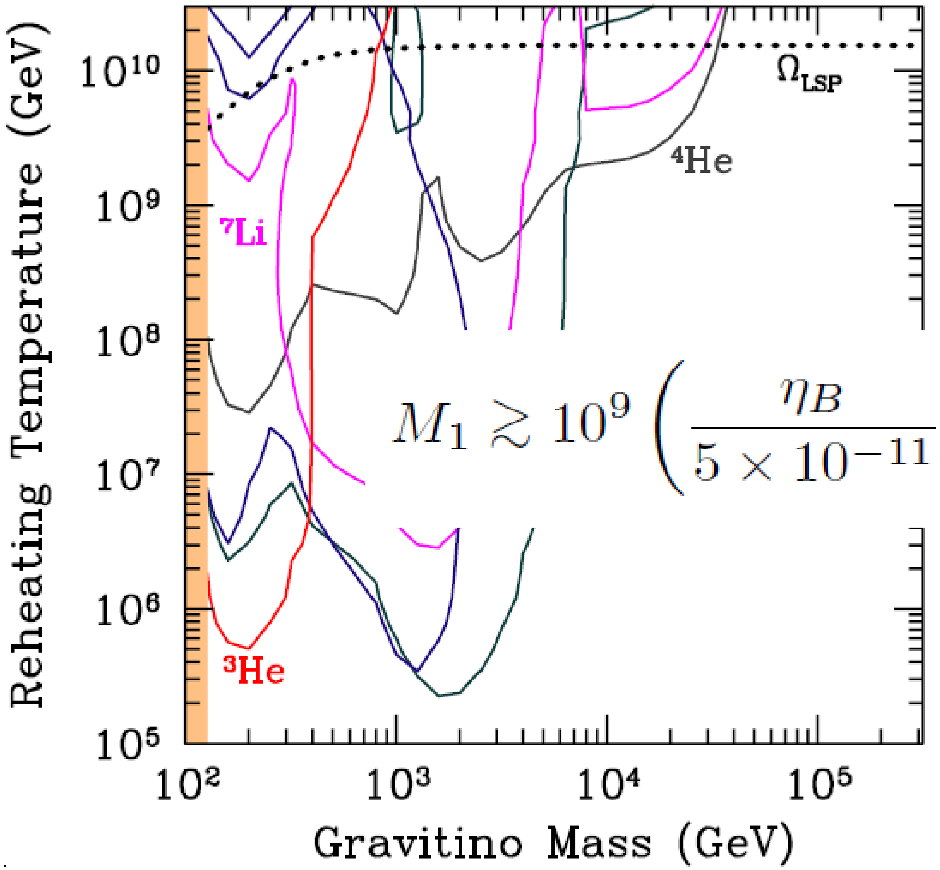
M_1 (GeV)
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
0.1
1
10
100
1000
v_ν (GeV)
$\varepsilon = 10^{-6}$
$\varepsilon = 10^{-7}$

§ § SUSY Result


Gravitino overproduction
$\varepsilon = 10^{-6}$
$\varepsilon = 10^{-7}$
T_R
M_1 (GeV)
v_ν (GeV)
10^7
10^6
10^5
10^4
10^3
10^2
10^1
0.1
1
10
100

§ § Leptogenesis vs gravitino

- Gravitino problem



[Kawasaki et al (2008)]

Bound on N mass for leptogenesis

$$M_1 \gtrsim 10^9 \left(\frac{\eta_B}{5\times 10^{-11}}\right)\left(\frac{.06eV}{m_3}\right)\left(\frac{2\times 10^{-4}}{n_{\nu_R}/s\ \delta}\right)\ \mathrm{GeV}$$

§ § SUSY neutrinophilic model

- Superpotential

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

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	$+$

§ Dirac sneutrino dark matter

- SUSY DM candidate

  Dirac RH sneutrino

  the minimal model [Asaka et al 2006]

- Neutrinophilic Higgs sector

§ § Dirac RH sneutrino

- Yukawa couplings

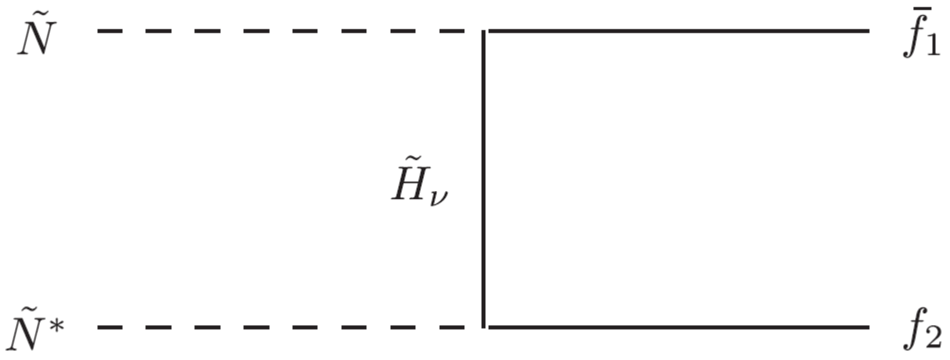
$$W = y_\nu \hat{H}_u \hat{L} \hat{\nu}_R^c + \mu_H \hat{H}_u \hat{H}_d$$

- Neutrino mass

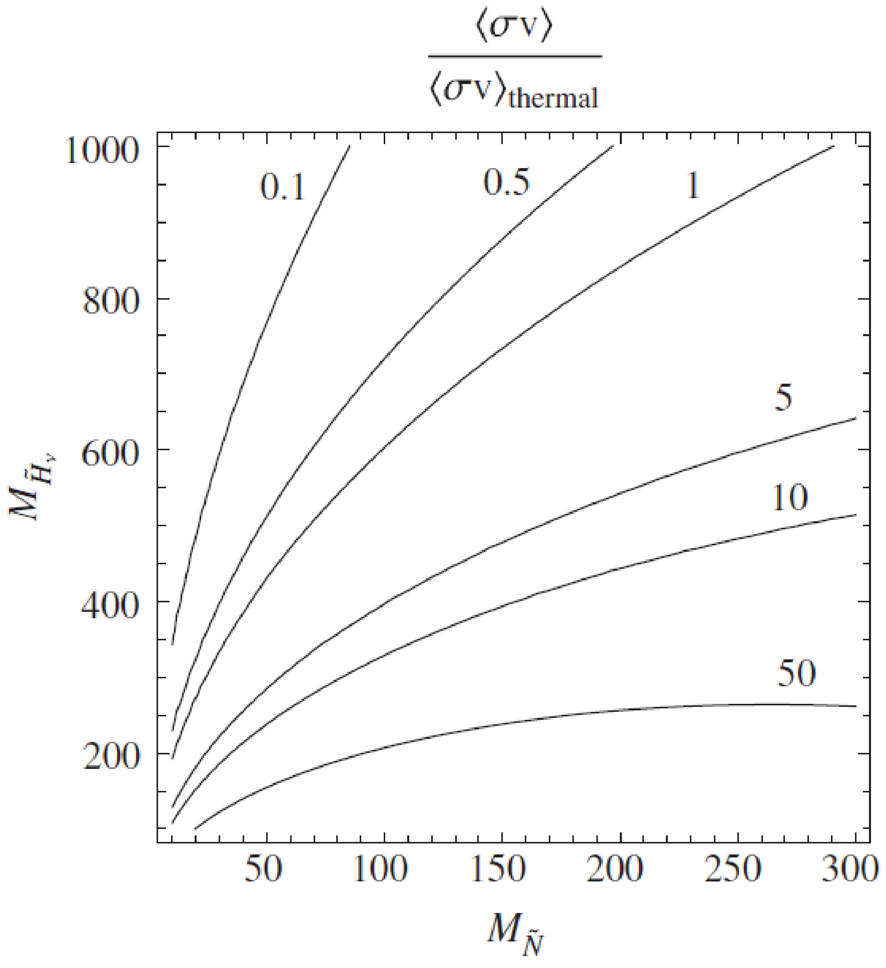
$$m_\nu = y_\nu \langle H_u^0 \rangle = y_\nu v \sin\beta$$

§ § Thermal relic density

- Annihilation

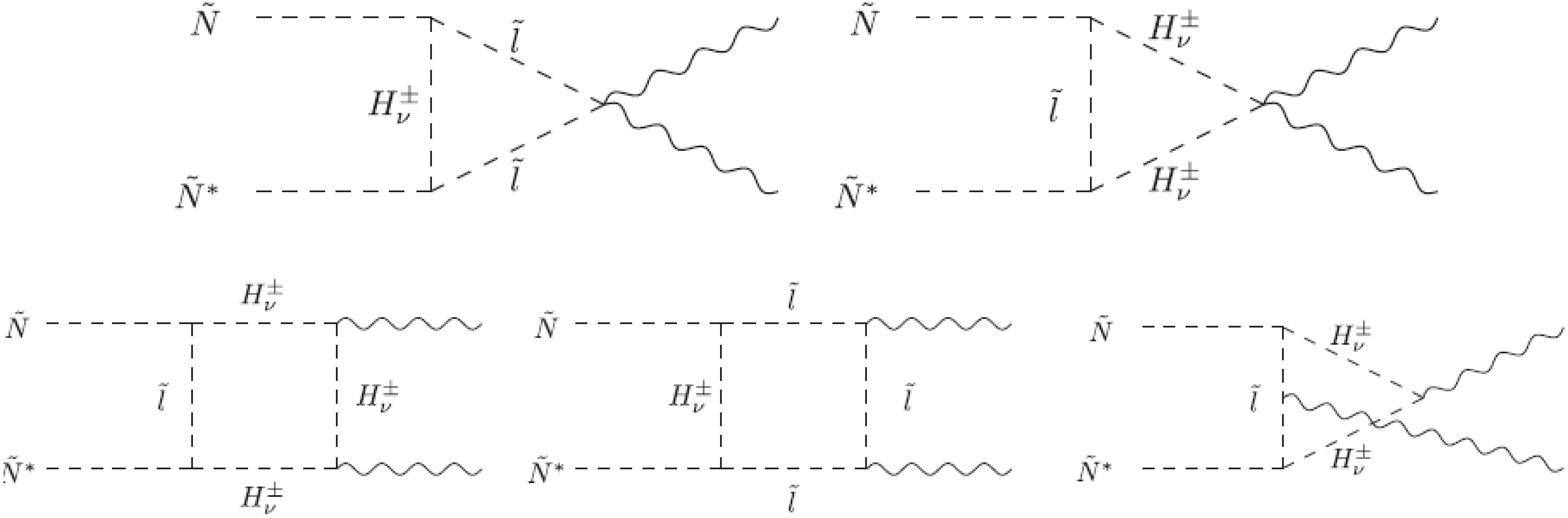


$$\langle\sigma v\rangle = \sum_f \left(\frac{y_\nu^4}{16\pi}\,\frac{m_f^2}{(M_{\tilde{N}}^2 + M_{\tilde{H}_\nu}^2)^2} + \frac{y_\nu^4}{8\pi}\,\frac{M_{\tilde{N}}^2}{(M_{\tilde{N}}^2 + M_{\tilde{H}_\nu}^2)^2}\,\frac{T}{M_{\tilde{N}}} + \dots \right),$$



§ § Annihilation into γ

- Annihilation into 2 γ



§ § Annihilation into γ

- Annihilation into 2 γ

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

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

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

- Fermi 130 GeV γ line anomaly [Weniger 2012]

§ Summary

- We investigated cosmological consequence of (supersymmetric) neutrinophilic Higgs in baryogenesis and dark matter

- Low scale thermal leptogenesis $v_\nu \cong 1$ GeV
- Gravitino problem free in SUSY

- Supersymmetric dark matter candidate (Dirac RH sneutrino) annihilating into line gammas