Neutrino mass from neutrinophilic Higgs and leptogenesis

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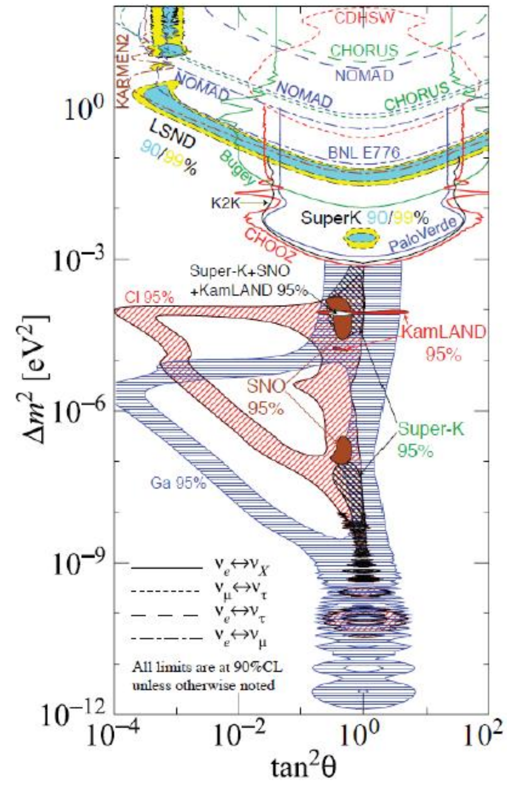
Phys. Rev. D 84, 103524 (2011)

with Naoyuki Haba

Phys. Rev. D 87, 123540 (2013)

with Naoyuki Haba and Yuya Yamaguchi

§ 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, 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

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

§ Neutrinophilic Higgs doublet models

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

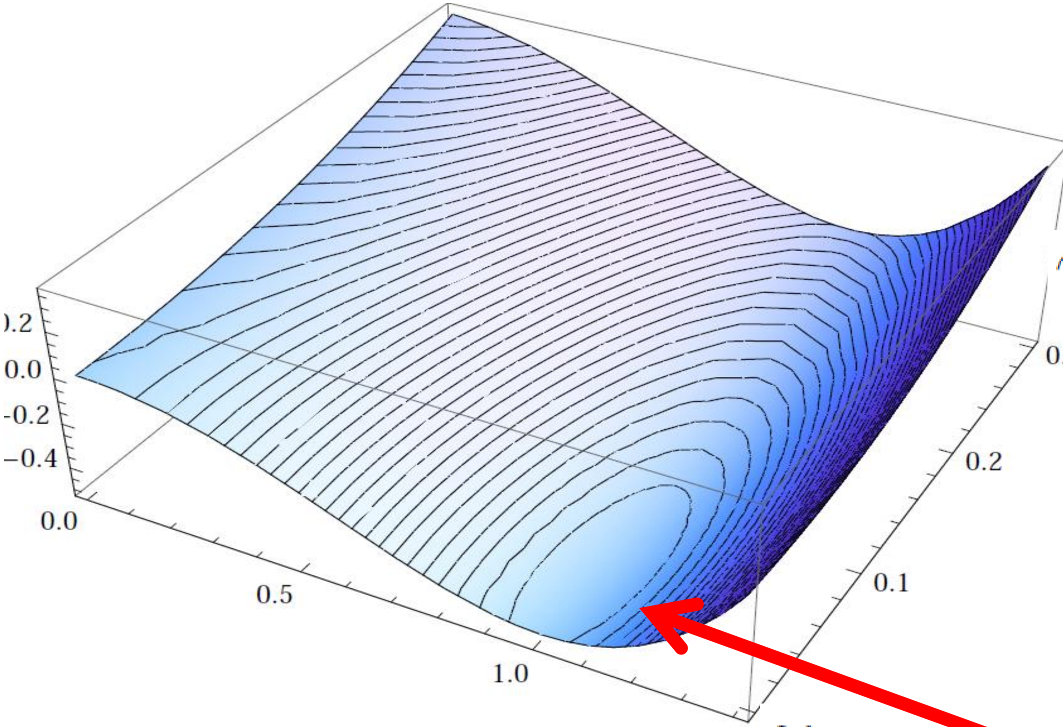
soft breaking

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

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

s doublet models

ndi (2007),…]



Dirac/Majorana

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

soft breaking

small VEV

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

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

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

§ § Concept of neutrinophilic Higgs

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

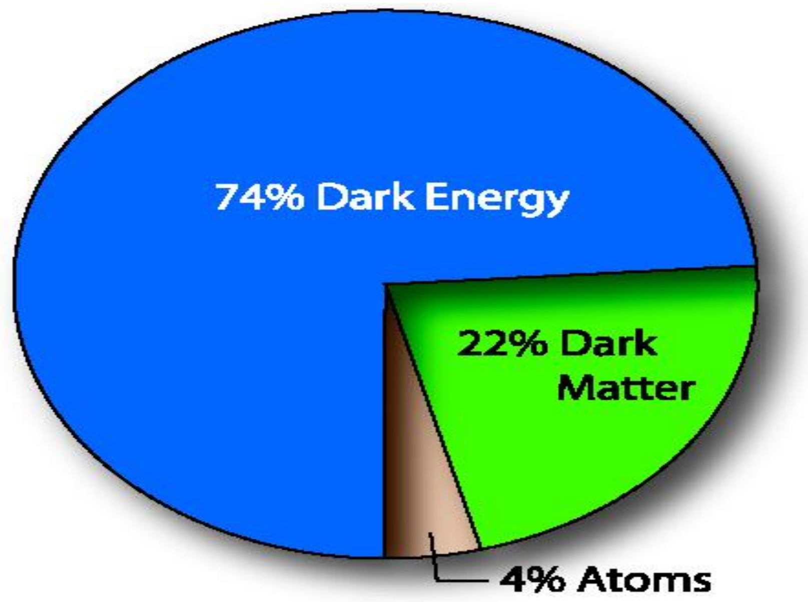
v_ν ↓ y_ν ↑

- 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_ν ↓ y^ν ↑ and/or M_k ↓

§ Introduction 2: 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

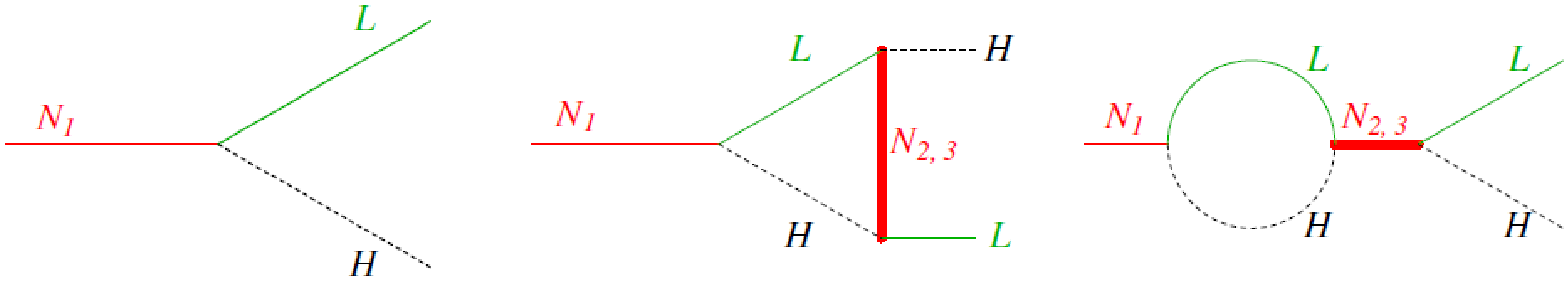
§ Baryon asymmetry from thermal leptogenesis by a heavy N

- 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

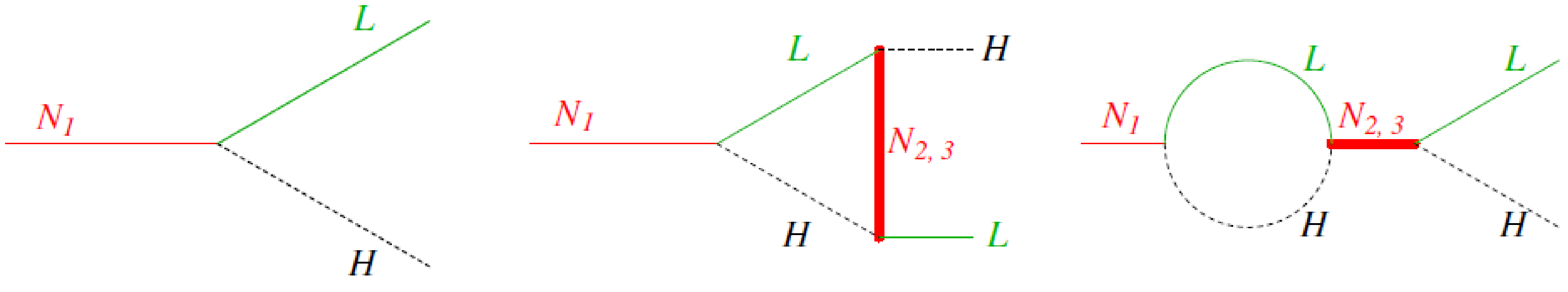
$$\varepsilon_1 \simeq -\frac{3}{8\pi}\frac{1}{\left(h_\nu h_\nu^\dagger\right)_{11}}\sum_{i=2,3}\mathrm{Im}\left[\left(h_\nu h_\nu^\dagger\right)^2_{1i}\right]\frac{M_1}{M_i}$$

$$M_1 \gtrsim 10^9\left(\frac{\eta_B}{5\times10^{-11}}\right)\left(\frac{.06eV}{m_3}\right)\left(\frac{2\times10^{-4}}{n_{\nu_R}/s\ \delta}\right)\ \mathrm{GeV}$$

- The lower bound on RH neutrino mass

[Davidson and Ibarra (2002)]

§ § CP asymmetry (ν-philic)



- In hierarchical right-handed neutrino mass

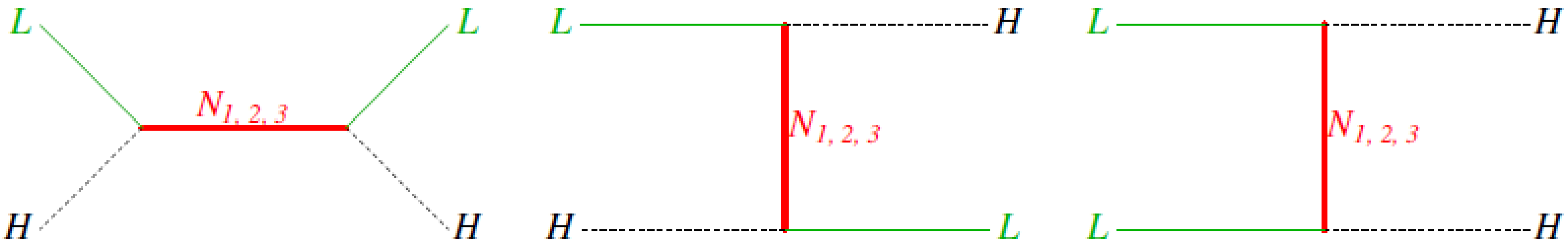
$$\varepsilon \simeq -\frac{3}{8\pi}\frac{1}{(y^{\nu\dagger}y^{\nu})_{11}}\left(\mathrm{Im}(y^{\nu\dagger}y^{\nu})^2_{12}\frac{M_1}{M_2}+\mathrm{Im}(y^{\nu\dagger}y^{\nu})^2_{13}\frac{M_1}{M_3}\right)$$

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

- Relaxed lower bound on RH neutrino mass

§§ Washout (ν-philic)

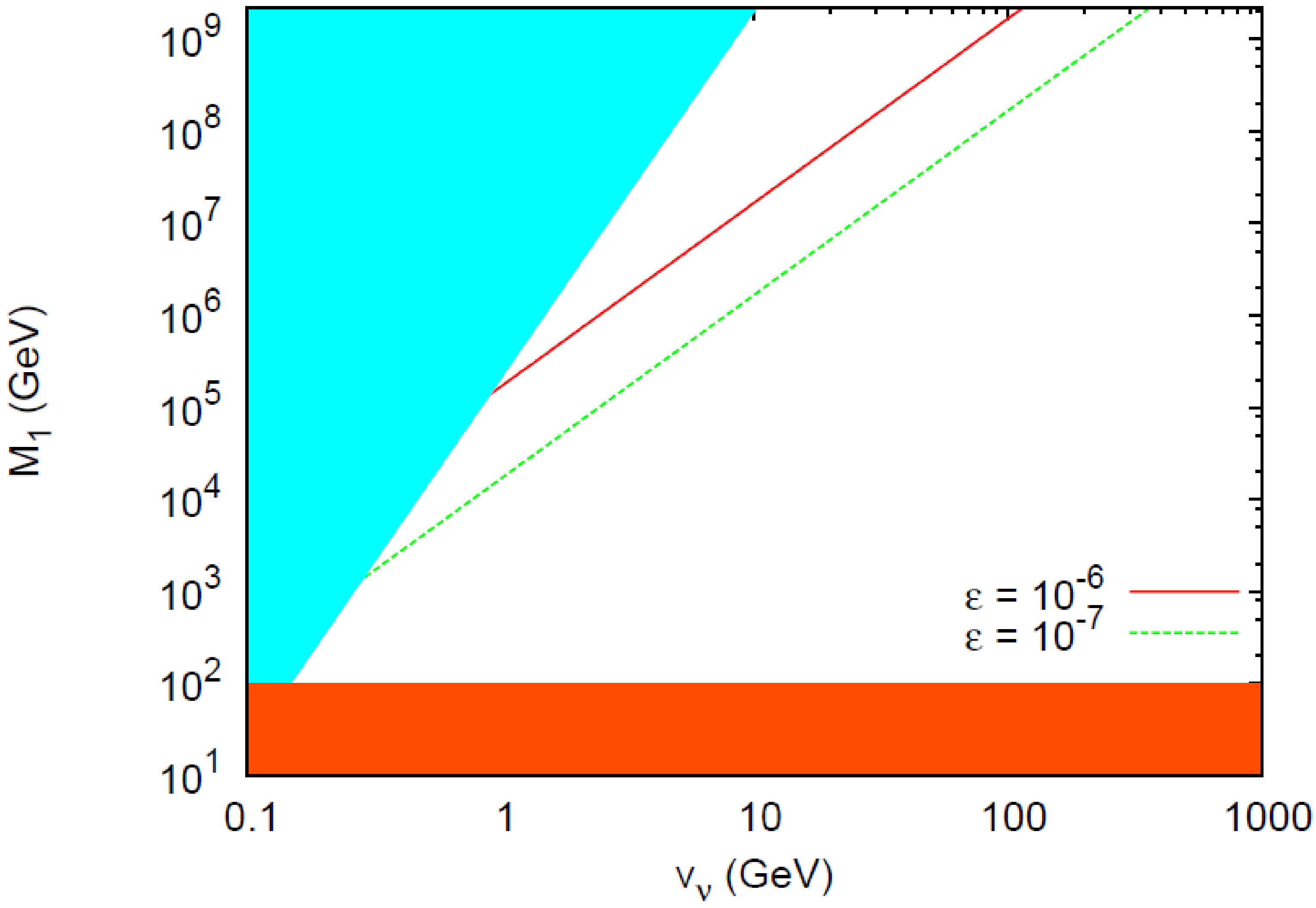
- ΔL=2 scattering could be effective.



- Condition

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

§§ Result [Haba and OS (2011)]



§ For lighter N case : resonant leptogenesis

§ § Resonant leptogenesis

- Large CP violation below the DI bound.
- Very strong degeneracy for a large CPV...
- CP violation enhanced by self-energy with degenerated RH neutrinos [Pilaftsis and Underwood (2004)]

$$\varepsilon_i = \frac{\Gamma(N_i \to L\Phi) - \Gamma(N_i \to \bar{L}\Phi^*)}{\Gamma(N_i \to L\Phi) + \Gamma(N_i \to \bar{L}\Phi^*)}$$

$$\simeq \frac{\mathrm{Im}(y^{\nu\dagger} y^{\nu})^2_{ij}}{(y^{\nu\dagger} y^{\nu})_{ii}(y^{\nu\dagger} y^{\nu})_{jj}} \frac{\tilde{m}_j M_j}{8\pi v^2} \frac{M_i M_j}{M_i^2 - M_j^2}$$

§ § Resonant leptogenesis (ν-philic)

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- Relaxed degeneracy for a large CPV!
- CP violation enhanced by self-energy with degenerated RH neutrinos [Pilaftsis and Underwood (2004)]

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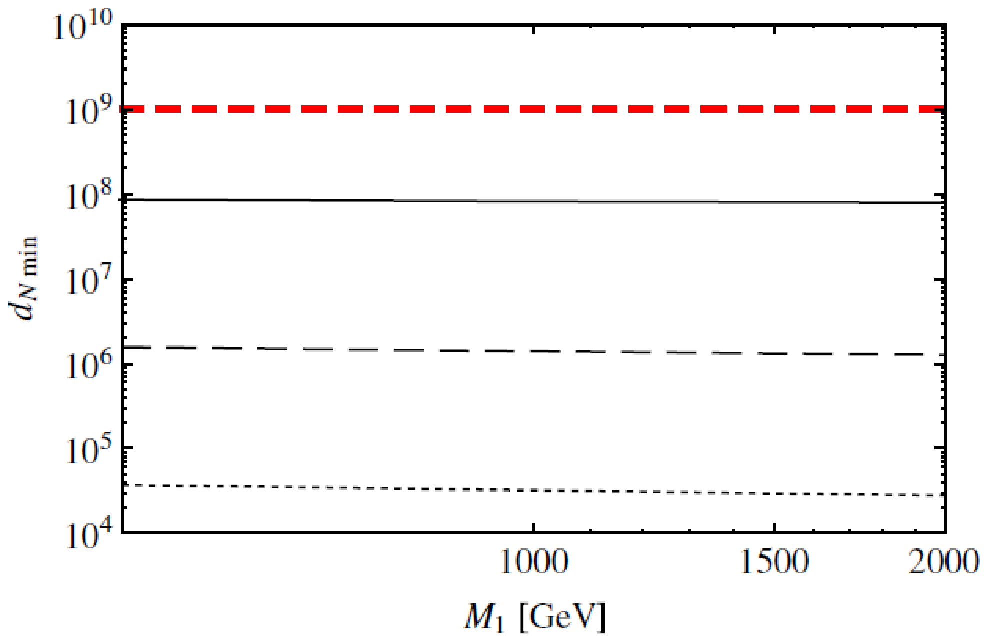
$$\simeq \frac{\mathrm{Im}(y^{\nu\dagger}y^{\nu})^2_{ij}}{(y^{\nu\dagger}y^{\nu})_{ii}(y^{\nu\dagger}y^{\nu})_{jj}} \frac{\tilde{m}_j M_j}{8\pi \boxed{v_\nu^2}} \frac{M_i M_j}{M_i^2 - M_j^2}$$

§ § Resonant leptogenesis (ν-philic)

- 😃 Large CP violation below the DI bound.
- 😃 Relaxed degeneracy for a large CPV!
- Degree of degeneracy [Haba, OS and Yagamuchi (2013)]

$$d_N \equiv \frac{M_1 M_2}{M_2^2 - M_1^2}$$



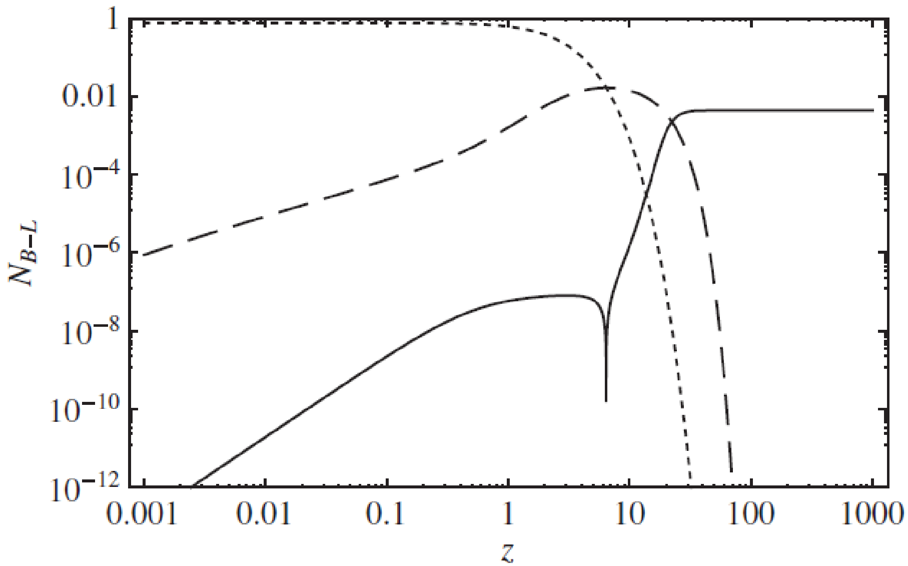
(a) M_1 dependence of $d_{N\,\mathrm{min}}$ for $K_1 = 0.01$

$y_\nu = 10^{-6}, 10^{-5}$, and 10^{-4}.

$$K_1 = \frac{\Gamma_{N_1}}{H(T = M_1)}$$

§ § Resonant leptogenesis (ν-philic)

- Large CP violation below the DI bound.
- Relaxed degeneracy for a large CPV!
- N_2 washout and sphaleron [Haba, OS and Yagamuchi (2013)]



y_ν is large

→N_2 in equilibrium

→washout by N_2

FIG. 1. Time evolution of N_{B-L} with $\varepsilon_1 = -1$, $M_1 = 2$ TeV, $y_\nu = 10^{-4}$, and $K_1 = 10^{-2}$. The dashed, dotted, and solid lines correspond to N_1, N_2, and N_{B-L}, respectively.

§ Supersymmetric case

§ § SUSY neutrinophilic model

- Superpotential

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

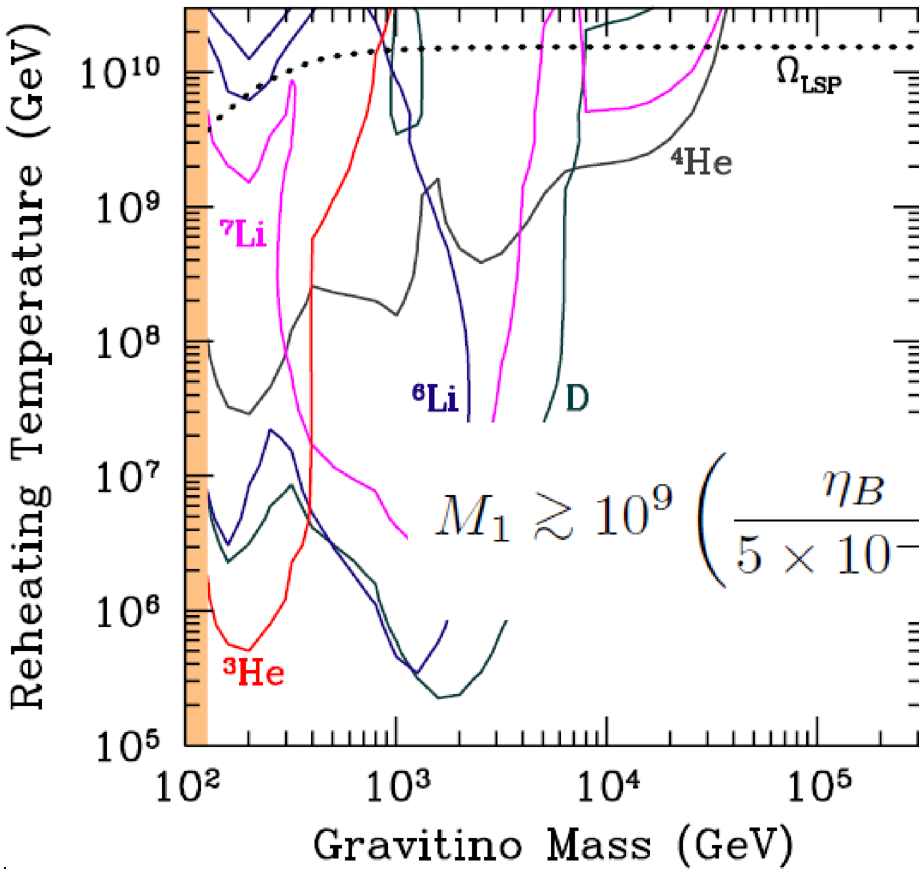
soft breaking

- 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	$+$

§ § Leptogenesis vs gravitino

- Gravitino problem

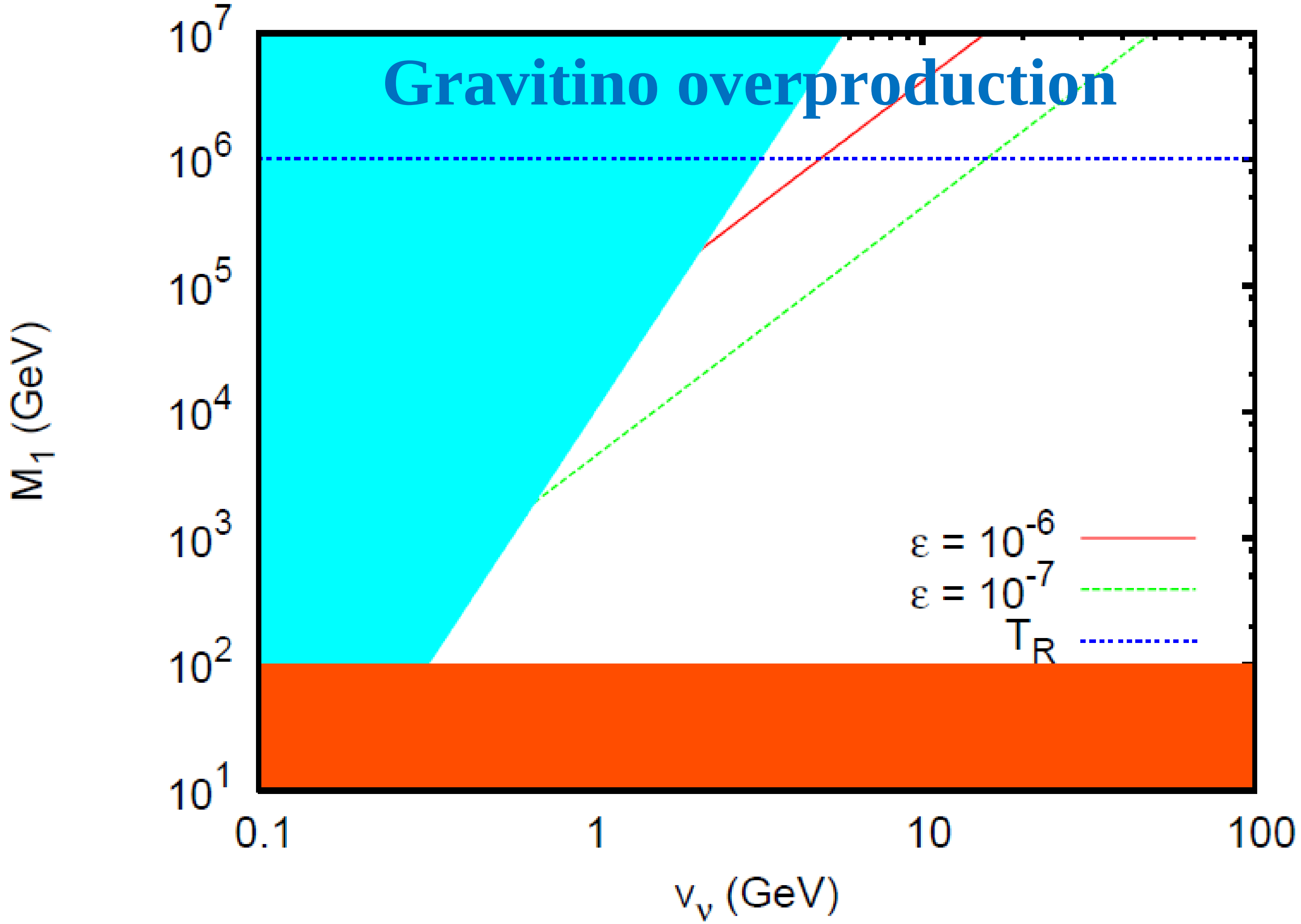


[Kawasaki et al (2008)]

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 Result [Haba and OS (2011)]



§ Summary

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

- Low scale thermal leptogenesis with $v_\nu \cong 1$ GeV and $M_N \approx 10$ TeV
- Strong degeneracy for resonant leptogenesis can be relaxed.
- Gravitino problem free in supergrvity