R-parity violation assisted thermal leptogenesis

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IPM

This talk is based on

Y. F. and J.W.F. Valle, “R-parity violation assisted thermal leptogenesis in the seesaw mechanism,” hep-ph/0509280, PRL 96 (2006) 11601.

Outline of the seminar

Neutrino masses and the seesaw mechanism

- Baryon asymmetry of the Universe
- Leptogenesis
- Gravitino overproduction problem
- R-parity violation as a solution

A BRIEF REVIEW OF SEESAW

Recent neutrino observations indicate that neutrinos are massive.

Troitsk and Mainz experiments $\Rightarrow m_{\nu_e} < 2.2$ eV

$$m_\nu \ll m_e, m_u, m_d \text{ !!!}$$

Seesaw mechanism

- N=right-handed neutrinos

Singlets of $\mathrm{SU}(2) \times \mathrm{U}(1)$

$$Y_\nu N^T C L \cdot H + M N^T C N$$

$$m_D = Y_\nu \langle H \rangle$$

Seesaw mechanism

$$\begin{bmatrix}(\nu^c)^T & (N^c)^T\end{bmatrix}\begin{bmatrix}0 & m_D \\ m_D & M\end{bmatrix}\begin{bmatrix}\nu \\ N\end{bmatrix}$$

- One of the mass eigenstates can be pushed

Down:

$$m_D \ll M \quad \Rightarrow \quad m_D^2/M,\ M$$

Supersymmetric seesaw mechanism

- To explain neutrino masses heavy right-handed neutrinos are added to the superpotential:

$$W\text{seesaw} = \epsilon_{\alpha\beta}(Y_\nu)_{ij}\widehat{N}_i\widehat{L}_j^\alpha\widehat{H}_u^\beta + \frac{1}{2}M_{ij}\widehat{N}_i\widehat{N}_j$$

Without loss of generality: $M_{ij} = Diag[M_1, M_2, M_3]$

$$m_{weak} \ll M_1 < M_2 < M_3 \Rightarrow m_\nu \ll m_{weak} Y_\nu$$

Seesaw mechanism is not the only mechanism to explain tiny neutrino masses but is specially popular because it can also explain the baryon asymmetry of the universe as bonus.

Baryon asymmetry of the Universe

If, at T~1 GeV, the numbers of baryon and antibaryon were

the same, they would annihilate:

$$B + \bar{B} \rightarrow 2\gamma$$

ending up with $$\frac{n_B}{n_\gamma} = \frac{n_{\bar{B}}}{n_\gamma} \simeq 10^{-18}$$

The observation shows a 8 order of magnitude larger value.

- Averaging WMAP results with result from D abundance

$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} = 6.1 \pm 0.3 \times 10^{-10}$$

Sakharov's three condition

- Baryon number violation
- C and CP violation
- Out of equilibrium

Within the seesaw mechanism, all three
Conditions can be fulfilled.

Baryon number violation

- Lepton number violation

$$W_{\text{seesaw}} = \epsilon_{\alpha\beta}(Y_\nu)_{ij}\hat{N}_i\hat{L}_j^\alpha\hat{H}_u^\beta + \frac{1}{2}M_{ij}\hat{N}_i\hat{N}_j$$

- In the standard model L+B is anomalous.

So B is also violated in this model.

SM+SEASAW-> B-L is violated

CP-violation

- In the basis that mass matrix of right-handed neutrinos is real diagonal, Y_ν can be complex and a source of CP-violation.

Out of equilibrium

$$\Gamma_{\rm tot}(N_i) = \Gamma_{\rm tot}(\tilde{N}_i) = \frac{(Y_\nu Y_\nu^\dagger)_{ii}}{4\pi} M_i$$

- Condition for out of equilibrium:

$$\Gamma_{\rm tot}(N_1) = \Gamma_{\rm tot}(\tilde{N}_1) < H|_{T=M_1}$$

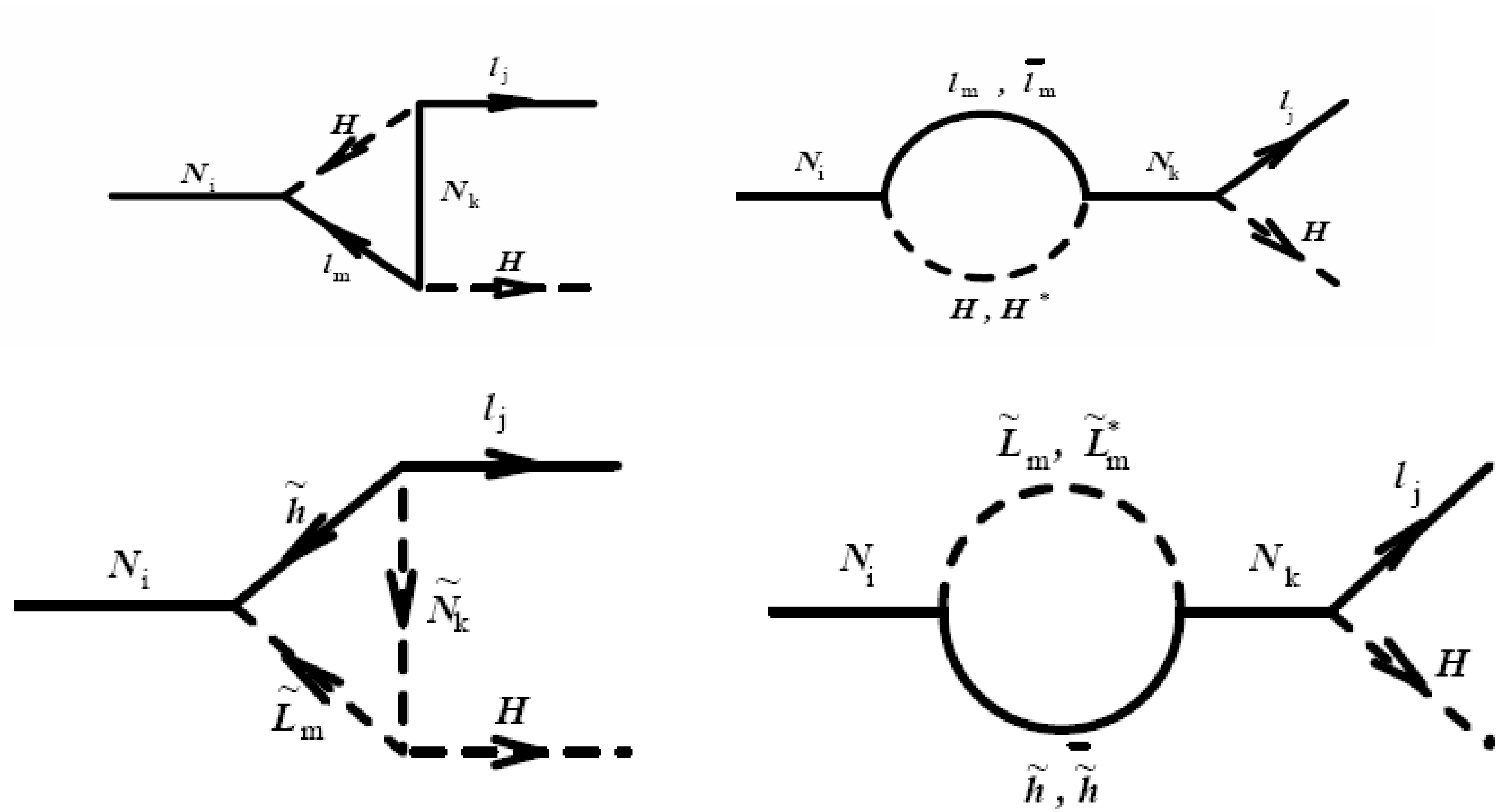
- This put upper bound on

$$\tilde{m}_1 = \frac{(Y_\nu Y_\nu^\dagger)_{11} v^2}{M_1}.$$

Leptogenesis

- M. Fukugita and T. Yanagida, Phys. Lett B174 (1986) 45
- Decay of N_1 and $\tilde{N}_1$ create an asymmetry between lepton and antilepton number. Some of this asymmetry is converted to Baryon asymmetry through sphaleron mechanism.

Relevant diagrams



Definition of asymmetry

$$\epsilon_{N_1} = -\sum_i \left[\frac{\Gamma(N_1 \to \bar{l}_i \bar{H}_u) - \Gamma(N_1 \to l_i H_u)}{\Gamma(N_1 \to \bar{l}_i \bar{H}_u) + \Gamma(N_1 \to l_i H_u)} \right.$$

$$\left. \frac{\Gamma(N_1 \to \bar{\tilde{l}}_i \bar{\tilde{H}}_u) - \Gamma(N_1 \to \tilde{l}_i \tilde{H}_u)}{\Gamma(N_1 \to \bar{\tilde{l}}_i \bar{\tilde{H}}_u) + \Gamma(N_1 \to \tilde{l}_i \tilde{H}_u)} \right]$$

Definition of asymmetry

$$\epsilon_{\tilde{N}_1} = -\sum_i \left[\frac{\Gamma(\tilde{N}_1 \to \bar{l}_i \bar{\tilde{H}}_u) - \Gamma(\tilde{N}_1^* \to l_i \tilde{H}_u)}{\Gamma(\tilde{N}_1 \to \bar{l}_i \bar{\tilde{H}}_u) + \Gamma(\tilde{N}_1^* \to l_i \tilde{H}_u)} \right.$$

$$\left. \frac{\Gamma(\tilde{N}_1^* \to \bar{\tilde{l}}_i \bar{H}_u) - \Gamma(\tilde{N}_1 \to \tilde{l}_i H_u)}{\Gamma(\tilde{N}_1^* \to \bar{\tilde{l}}_i \bar{H}_u) + \Gamma(\tilde{N}_1 \to \tilde{l}_i \tilde{H}_u)} \right]$$

Asymmetries (Covi et al, PLB384 (1996) 169)

$$\epsilon_{N_1} = \epsilon_{\tilde{N}_1} = \frac{1}{2\pi} \sum_{k \neq 1} [g(\frac{M_k^2}{M_1^2}) + \frac{2\frac{M_k}{M_1}}{\frac{M_k^2}{M_1^2} - 1}] \mathcal{I}_{k1}$$

$$g(x) = \sqrt{x} \ln[(1+x)/x]$$

$$\mathcal{I}_{k1} = \frac{\sum_{jm} \mathrm{Im}[(Y_\nu^*)_{1j}(Y_\nu^*)_{1m}(Y_\nu)_{km}(Y_\nu)_{kj}]}{(Y_\nu Y_\nu^\dagger)_{11}}$$

Simplest form of Boltzman equations

$$\frac{dN_{N_1}}{dz} = -(D+S)(N_{N_1} - N_{N_1}^{eq}),$$

$$\frac{dN_{B-L}}{dz} = -\epsilon_{N_1} D(N_{N_1} - N_{N_1}^{eq}) - W N_{B-L}$$

$$z = M_1/T$$

- N_{N_1} =number of $\tilde{N}_1$ + N_1
- D = decay rate S=scattering rate
- Quantum oscillations in the Flavor space
- A. Abada et al., hep-ph/0601083

Wash-out processes

- S, D and inverse decay rate are given by

$$\tilde{m}_1 = \frac{(Y_\nu Y_\nu^\dagger)_{11} v^2}{M_1}.$$

Wash-out $\Delta L = -2$ processes are given by

$$W \propto M_1 \left| Y_\nu^T \frac{1}{M} Y_\nu \right|^2$$

Lower bound on M_1

- W. Buchmuller, P. Di Bari and M. Plumacher, ``Leptogenesis for pedestrians,'' Annals Phys. **315** (2005) 305 [arXiv:hep-ph/0401240].

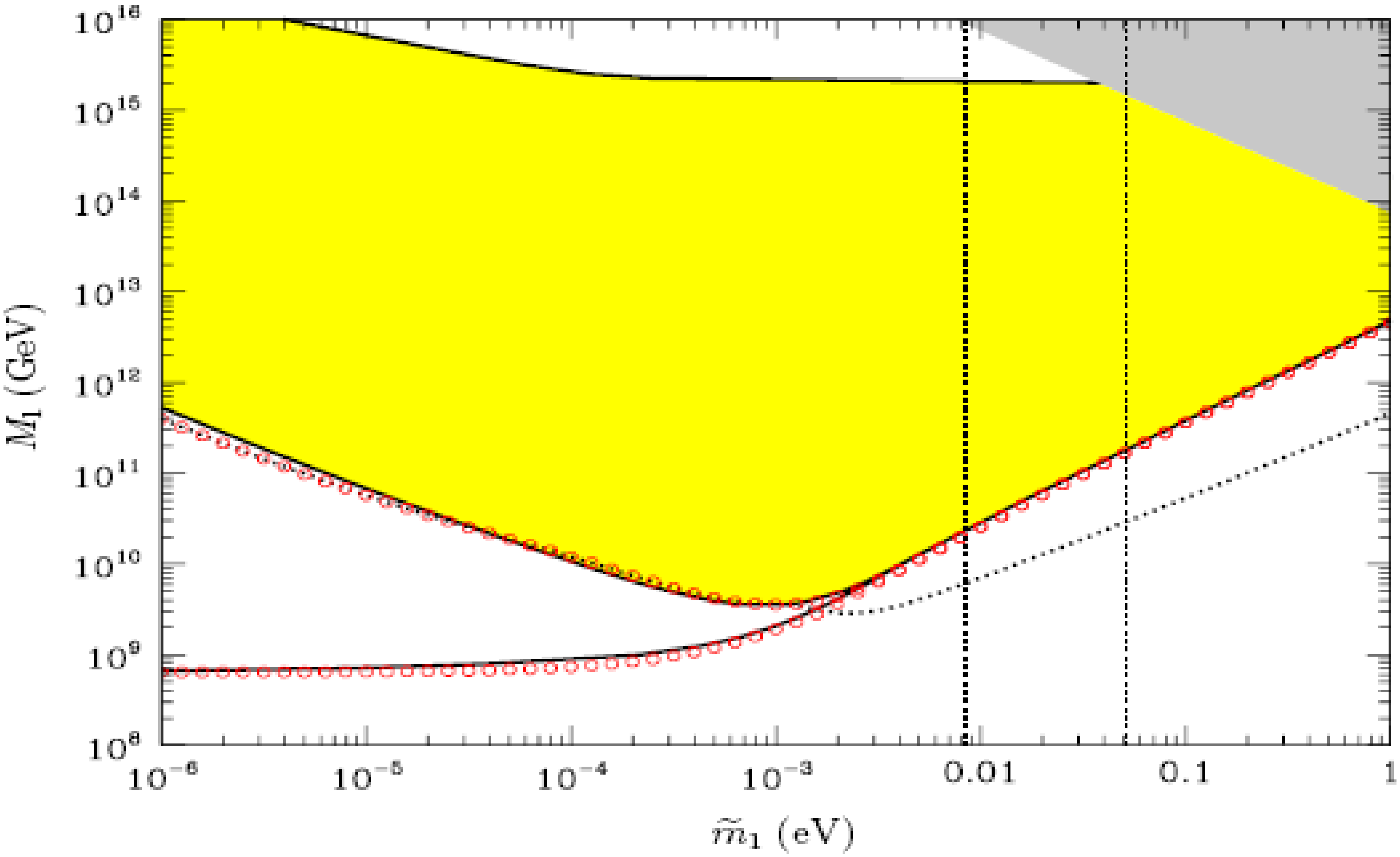
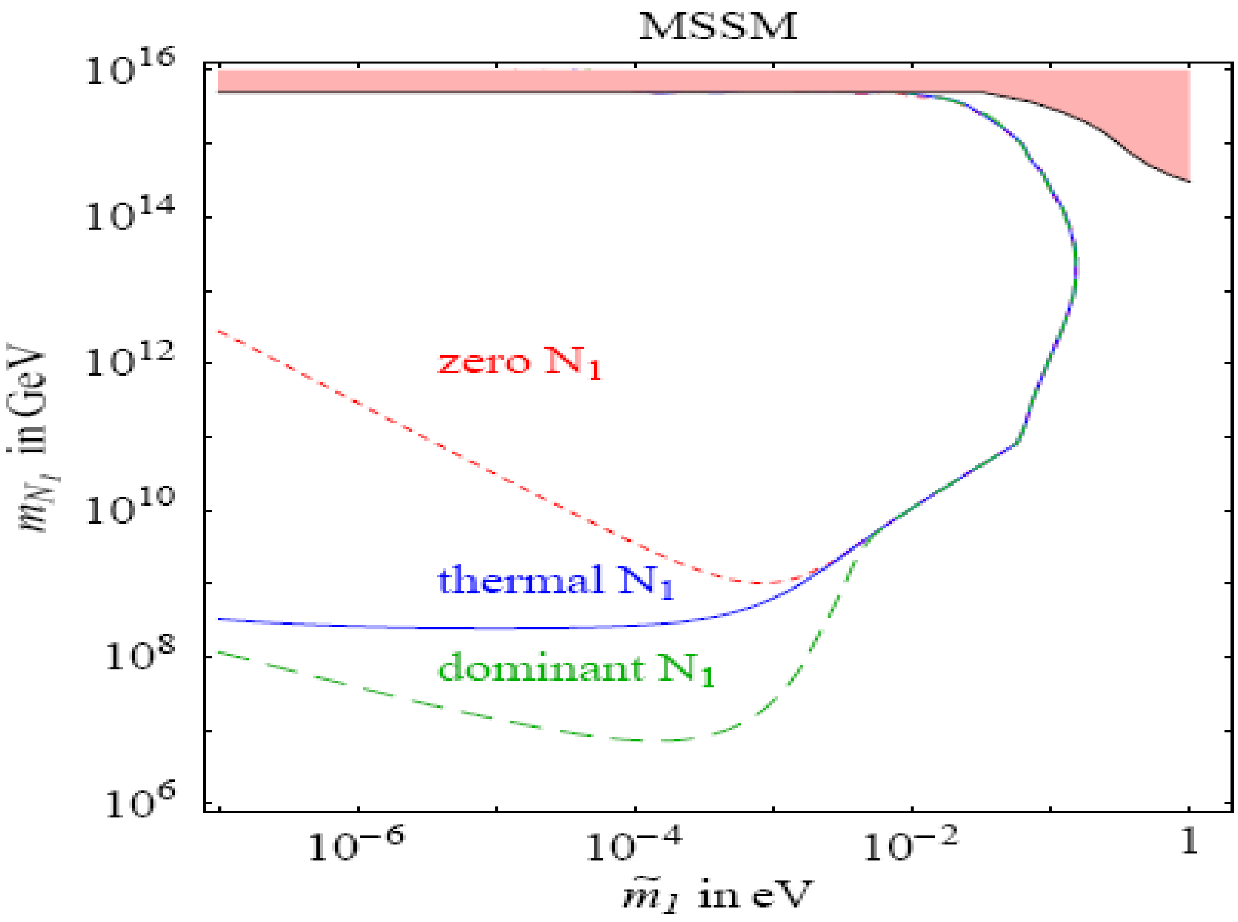


Figure 10: Analytical lower bounds on M_1 (circles) and T_i (dotted line) for $m_1 = 0$, $\eta_B^{CMB} = 6 \times 10^{-10}$ and $m_{\rm atm} = 0.05\,$eV. The analytical results are compared with the numerical ones (solid lines). The vertical dashed lines indicate the range $(m_{\rm sol}, m_{\rm atm})$. The gray triangle at large M_1 and large $\widetilde{m}_1$ is excluded by theoretical consistency (cf. appendix A).

G. F. Giudice et al., hep-ph/0310123



Bottomline

- There is a lower bound on the values of

The mass of the lightest right-handed neutrino and on thus, in the context of thermal leptogenesis, on the reheating temperature.

This the famous Ibarra-Dadidson bound

Gravitino overproduction

- Bolz et al., Nucl Phys. **B606** (2001) 518

$$\Omega_{3/2}h^2 \simeq 0.44\alpha_3(T_R)\left[1+\frac{1}{3}\left(\frac{\alpha_3(T_R)}{\alpha_3(\mu)}\right)^2\left(\frac{m_{\tilde{g}}(\mu)}{m_{3/2}}\right)^2\right]\left(\frac{T_R}{10^{10}\mathrm{GeV}}\right)\left(\frac{m_{3/2}}{100\mathrm{GeV}}\right)$$

- WMAP constraint

$$\Omega_{DM}h^2 = 0.1126^{+0.0161}_{-0.0181}$$

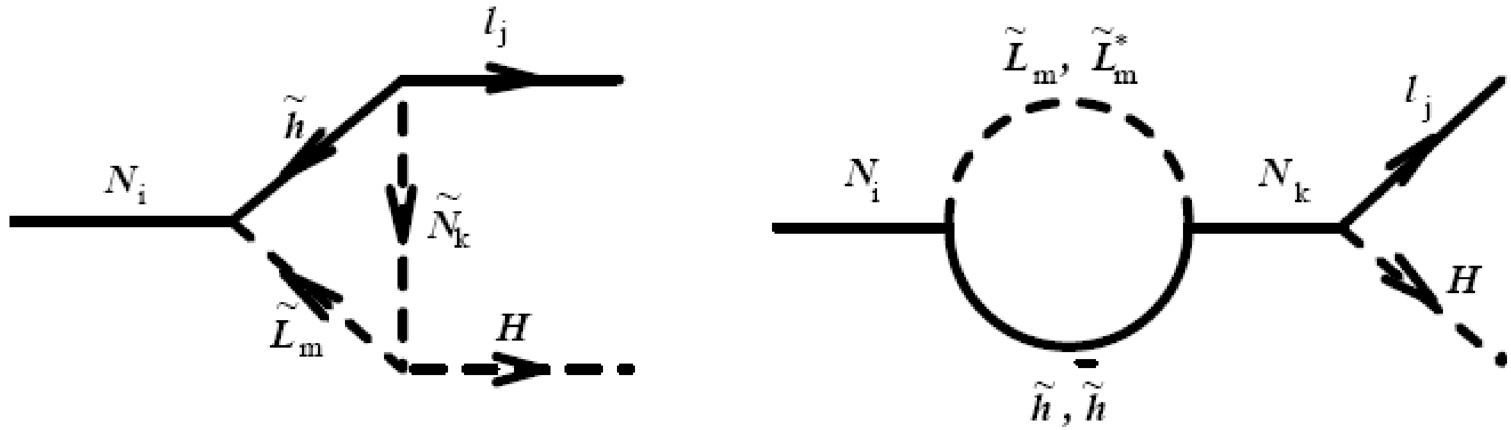
Unstable Gravitino

If gravitino has hadronic decay

Modes, to prediction BBN prediction

$$T_R < 10^{6-7}\ \mathrm{GeV}$$

Kawasaki et al, astro-ph/0408426



l_j
$\tilde{h}$
N_i
$\tilde{N}_k$
$\tilde{L}_m$
H
$\tilde{L}_m, \tilde{L}_m^*$
N_i
N_k
l_j
H
$\tilde{h}, \tilde{h}$

Several solutions to gravitino overproduction

- Pilaftis, PR **D56 (**1997**)** 5431

$$M_1 \simeq M_2$$

- Stable gravitino: M. bolz, PL **B443 (**1998**)** 209
- Gravitino decays before BBN: $m_{3/2} > 100\ \mathrm{TeV}$

$T_R < 10^{11}\ \mathrm{GeV}$ Kitano et al, PR **D70 (**04**)** 75012

R-Parity

- Ordinary particle: electron, neutrino, right-handed neutrino, Higgs, etc R=1

Selectron, sneutrino, Higgsino, R=-1

There is nothing sacred about R-parity and it can be violated.

R-Parity violation as a solution

$$W_{\mathrm{RPV}} = \sum_i \epsilon_{\alpha\beta} \lambda_i \hat{N}_i \hat{H}_d^\alpha \hat{H}_u^\beta$$

D. E. López-Fogliani and C. Muñoz, hep-ph/0508297

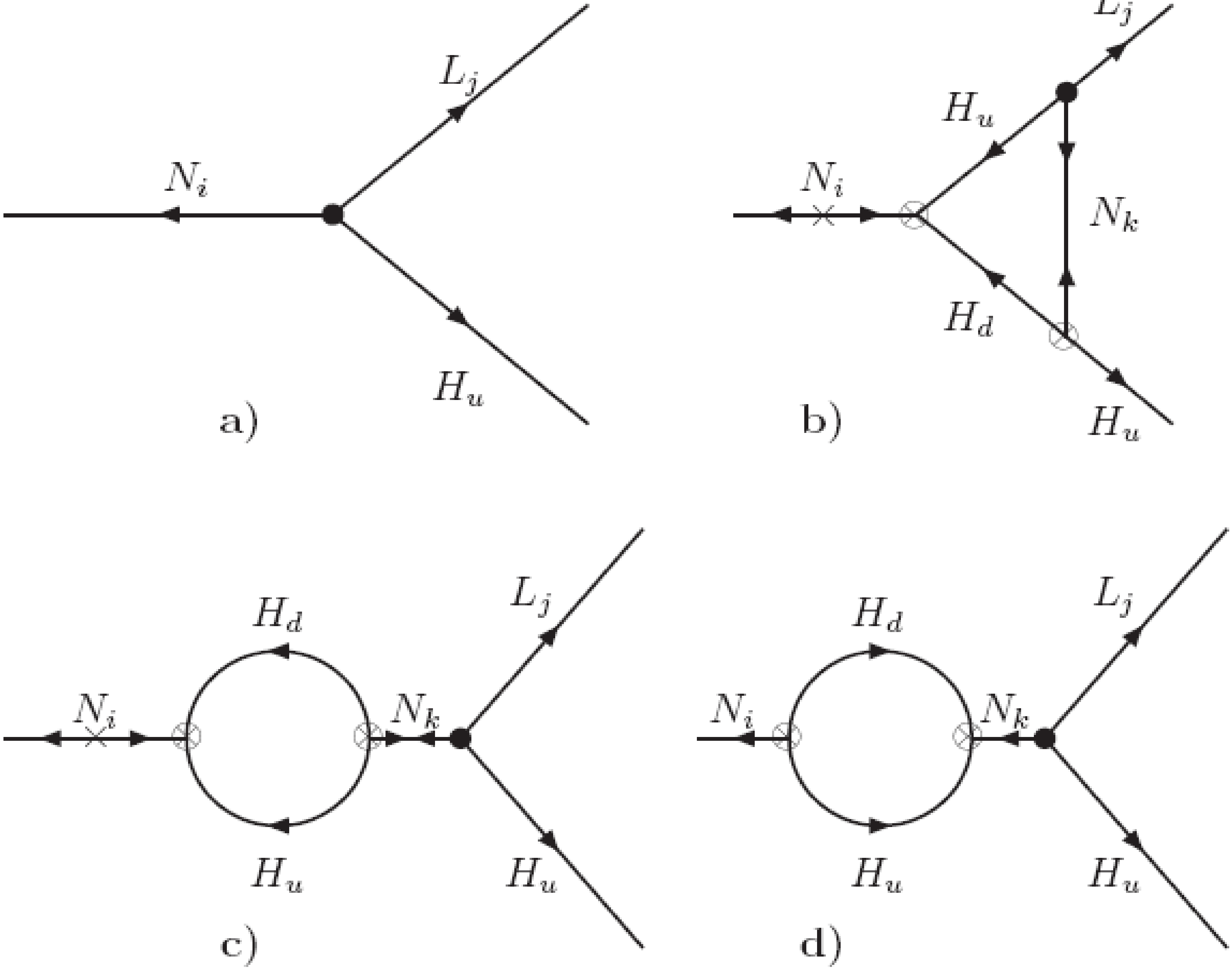
Attention

- R-parity violation as a source of neutrino masses

$$W = mL \cdot H_u$$

- However, in our case

Origin of neutrino masses in this model is the seesaw mechanism $m_\nu = \langle H_u \rangle^2 Y_\nu^T \frac{1}{M} Y_\nu$



N_i
L_j
H_u
a)
L_j
H_u
N_i
N_k
H_d
H_u
b)
H_d
N_i
N_k
L_j
H_u
H_u
c)
H_d
N_i
N_k
L_j
H_u
H_u
d)

We have to redefine ϵ_{N_1}

$$\frac{dN_{N_1}}{dz} = -(D+S)(N_{N_1} - N_{N_1}^{eq}),$$

and

$$\frac{dN_{B-L}}{dz} = -\epsilon_{N_1} D(N_{N_1} - N_{N_1}^{eq}) - W N_{B-L},$$

$$\begin{aligned}\epsilon_{N_1} &= -\sum_i \left[\frac{\Gamma(N_1 \to \bar{l}_i \bar{H}_u) - \Gamma(N_1 \to l_i H_u)}{\Gamma_{\mathrm{tot}}(N_1)/2} \right. \\ &+ \left. \frac{\Gamma(N_1 \to \bar{\tilde{l}}_i \bar{\tilde{H}}_u) - \Gamma(N_1 \to \tilde{l}_i \tilde{H}_u)}{\Gamma_{\mathrm{tot}}(N_1)/2} \right]\end{aligned}$$

- Since the rates of interactions of right-handed neutrino and sneutrino are the same we do not need study their evolution,

  separately.

Di Bari, hep-ph/0406115.

$$\epsilon = \frac{1}{2\pi}\sum_{k\neq 1}\left[[g(\frac{M_k^2}{M_1^2}) + \frac{2\frac{M_k}{M_1}}{\frac{M_k^2}{M_1^2}-1}]\mathcal{I}_{k1} - \frac{2\mathcal{J}_{k1}}{\frac{M_k^2}{M_1^2}-1}\right]$$

$$g(x) = \sqrt{x}\ln[(1+x)/x]$$

$$\mathcal{I}_{k1} = \frac{\sum_j \mathrm{Im}[(Y_\nu^*)_{1j}\lambda_1^*\lambda_k(Y_\nu)_{kj}]}{(Y_\nu Y_\nu^\dagger)_{11} + |\lambda_1|^2}$$

$$\mathcal{J}_{k1} = \frac{\sum_j \mathrm{Im}[(Y_\nu^*)_{1j}\lambda_1\lambda_k^*(Y_\nu)_{kj}]}{(Y_\nu Y_\nu^\dagger)_{11} + |\lambda_1|^2}$$

Out of equilibrium

$$\Gamma_{\rm tot}(N_i) = \Gamma_{\rm tot}(\tilde{N}_i) = \frac{(Y_\nu Y_\nu^\dagger)_{ii} + |\lambda_i|^2}{4\pi} M_i$$

$$\Gamma_{\rm tot}(N_1) = \Gamma_{\rm tot}(\tilde{N}_1) < H|_{T=M_1}$$

$$|\lambda_1|^2 \sim (Y_\nu Y_\nu^\dagger)_{11}$$

$$(Y_\nu)_{ij} \lesssim \sqrt{(\Delta m^2_{atm})^{1/2} M_i/(v^2 \sin^2\beta)} \;\sim$$

$$10^{-5}\sqrt{M_i/(10^6\ \mathrm{GeV})}$$

$$\epsilon = \frac{1}{2\pi} \sum_{k \neq 1} \left[[g(\frac{M_k^2}{M_1^2}) + \frac{2\frac{M_k}{M_1}}{\frac{M_k^2}{M_1^2} - 1}] \mathcal{I}_{k1} - \frac{2\mathcal{J}_{k1}}{\frac{M_k^2}{M_1^2} - 1} \right]$$

$$\mathcal{I}_{k1} = \frac{\sum_j \mathrm{Im}[(Y_\nu^*)_{1j} \lambda_1^* \lambda_k (Y_\nu)_{kj}]}{(Y_\nu Y_\nu^\dagger)_{11} + |\lambda_1|^2}$$

Decay of heavier right-handed neutrinos can be in equilibrium.

$$M_2^2/M_1^2 \sim 10$$

$$\epsilon_{N_1} + \epsilon_{\tilde{N}_1} \approx 10^{-6}\sqrt{\frac{M_1}{10^6\ \mathrm{GeV}}}\lambda_2 \sin\phi$$

$\lambda_2 \sim 1$ is allowed

Contrasting two cases

$$\epsilon = \frac{1}{2\pi}\sum_{k\neq 1}\left[[g(\frac{M_k^2}{M_1^2}) + \frac{2\frac{M_k}{M_1}}{\frac{M_k^2}{M_1^2}-1}]\mathcal{I}_{k1} - \frac{2\mathcal{J}_{k1}}{\frac{M_k^2}{M_1^2}-1}\right]$$

$$\mathcal{I}_{k1} = \frac{\sum_j \mathrm{Im}[(Y_\nu^*)_{1j}\lambda_1^*\lambda_k(Y_\nu)_{kj}]}{(Y_\nu Y_\nu^\dagger)_{11} + |\lambda_1|^2}$$

$$\mathcal{I}_{k1} = \frac{\sum_{jm} \mathrm{Im}[(Y_\nu^*)_{1j}(Y_\nu^*)_{1m}(Y_\nu)_{km}(Y_\nu)_{kj}]}{(Y_\nu Y_\nu^\dagger)_{11}}$$

Wash-out processes

- S and D in R-parity conserving case are given by

$$\tilde{m}_1 = \frac{(Y_\nu Y_\nu^\dagger)_{11} v^2}{M_1}$$

- S and D in R-parity violating case are given

Are given by

$$\tilde{m}_1 = \frac{(Y_\nu Y_\nu^\dagger)_{11} + |\lambda_1|^2}{M_1} v^2$$

- Inverse decay $\ell H_u \to N_1$ and $N_1 \ell \to \bar{t} q$ in both R-parity conserving and violating cases are given by $(Y_\nu Y_\nu^\dagger)_{11}/M_1$

Wash-out processes are more significant.

- The rate of $\ell\ell \to H_u H_u$ is given by

$$W \propto M_1 \left| Y_\nu^T \frac{1}{M} Y_\nu \right|^2$$

- The rate of $\ell H \to HH$ is enhanced by λ_2

$$\propto M_1 |\lambda_2 (Y_\nu)_{21} / M_2|^2$$

$$\text{replace } M_1 \text{ with } M_1[\lambda_2/(Y_\nu)_{2i}]^2$$

- **For given values of** $\widetilde{m}_1$ **and** $\overline{m} = \sqrt{m_1^2 + m_2^2 + m_3^2}$

Wash-out processes for $\lambda_2 = 0 \text{ and } M_1 \sim 10^{15} \text{ GeV}$

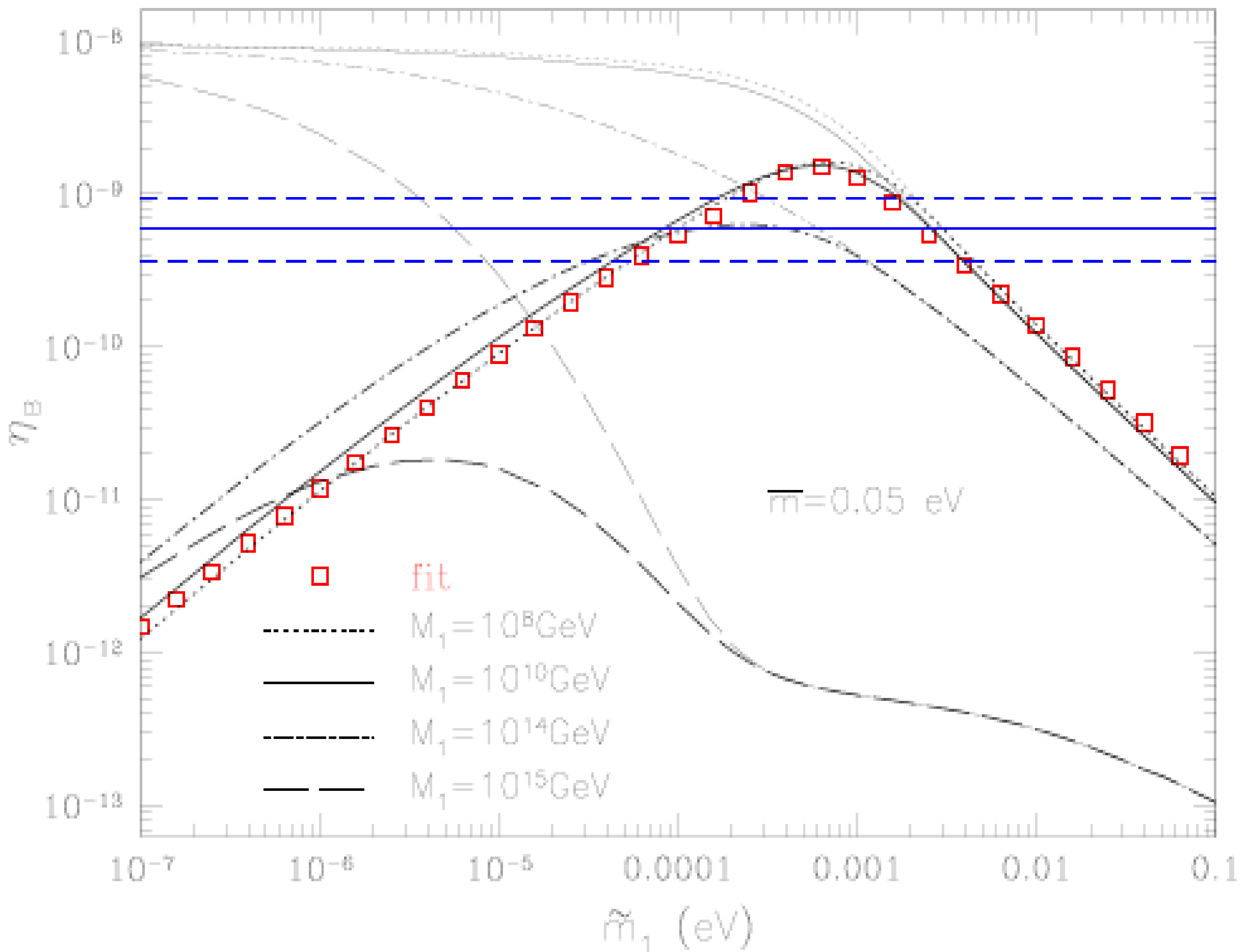
Will be equivalent to wash-out processes for

$$\lambda_1 \sim (Y_\nu)_{1i},\ \lambda_2 \sim 1 \text{ and } M_1 \sim 10^6 \text{ GeV}$$

Which results in $\epsilon_{N_1} \sim 10^{-6}$

- W. Buchmuller, P. Di Bari and M. Plumacher, ``Cosmic microwave background, matter-antimatter asymmetry and neutrino masses,'' Nucl. Phys. **B643**, 367 (2002) [arXiv:hep-ph/0205349].

figure 5a



10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
η_B
10^{-7}
10^{-6}
10^{-5}
0.0001
0.001
0.01
0.1
$\tilde{m}_1$ (eV)
$\bar{m}$=0.05 eV
fit
$M_1=10^8$GeV
$M_1=10^{10}$GeV
$M_1=10^{14}$GeV
$M_1=10^{15}$GeV

Thermal Distribution

$$W^{N^3} = \lambda_{221}^{N^3} \hat{N}_2 \hat{N}_2 \hat{N}_1$$

$$|M_2 - M_1|/M_1 \sim 1$$

$$T \sim M_2$$

$\tilde{N}$-dependant part of Lagrangian

$$\sum_i |M_i \tilde{N}_i + (Y_\nu)_{ij} \tilde{L}_j H_u + \lambda_i H_d H_u + \sum_{jk} \lambda^{N^3}_{ijk} \tilde{N}_j \tilde{N}_k|^2 +$$

$$\sum_{ij} \Big[m_0^2 |\tilde{N}_i|^2 + B_\nu M_i (\tilde{N}_i^2 + \mathrm{H.c.})$$

$$+ \left[A^i_\lambda \tilde{N}_i H_d H_u + (A_\nu)_{ij} \tilde{N}_i \tilde{L}_j H_u + \mathrm{H.c.} \right] \Big]$$

$$\left| \left\langle \tilde{N}_i \right\rangle \right| \simeq \frac{\lambda_i v^2 \sin\beta \cos\beta}{M_i} \ll v$$

tiny correction to the μ term

bilinear R-parity violating term

$$(Y_\nu)_{ij}\epsilon_{\alpha\beta}\frac{\lambda_i v^2 \sin\beta\cos\beta}{M_i}\hat{L}_j^\alpha \hat{H}_u^\beta$$

- Contribution of the R-parity violating bilinear term to the neutrino mass

$$(Y_\nu \lambda v^2 \sin\beta \cos\beta / M)^2 / m_{susy}$$

Which is negligible in comparison to

$$Y_\nu^2 v^2 \sin^2 \beta / M$$

Down side of the model

$$\Gamma(\chi \longrightarrow \nu_i + e^- + e^+) \sim 10\ \mathrm{sec}^{-1}\ \lambda_2^2 \times$$
$$\frac{\cos^2\beta}{0.01}\,\frac{\mathrm{Max}[(Y_\nu)^2_{2i},(Y_\nu)^2_{2e}]}{10^{-9}}\left(\frac{10^6\mathrm{GeV}}{M_2}\right)^2\left(\frac{m_\chi}{100\mathrm{GeV}}\right)^3$$

- Berezinsky et al., PL **B266** (1991) 382; PR **D57** (1998) 147

- Neutralino cannot be a dark matter candidate. However its signature in colliders is the same as in the R-Parity parity conserved MSSM.

- Can its late decay destroy BBN?

(IT HAS HADRONIC DECAY MODES.)

- J. R. Ellis, G.B. Gelmini, J.L. Lopez, D.V. Nanopoulos and S. Sarkar, ``Astrophysical Constraints On Massive Unstable Neutral Relic Particles,'' Nucl. Phys. **B373** (1992) 399.

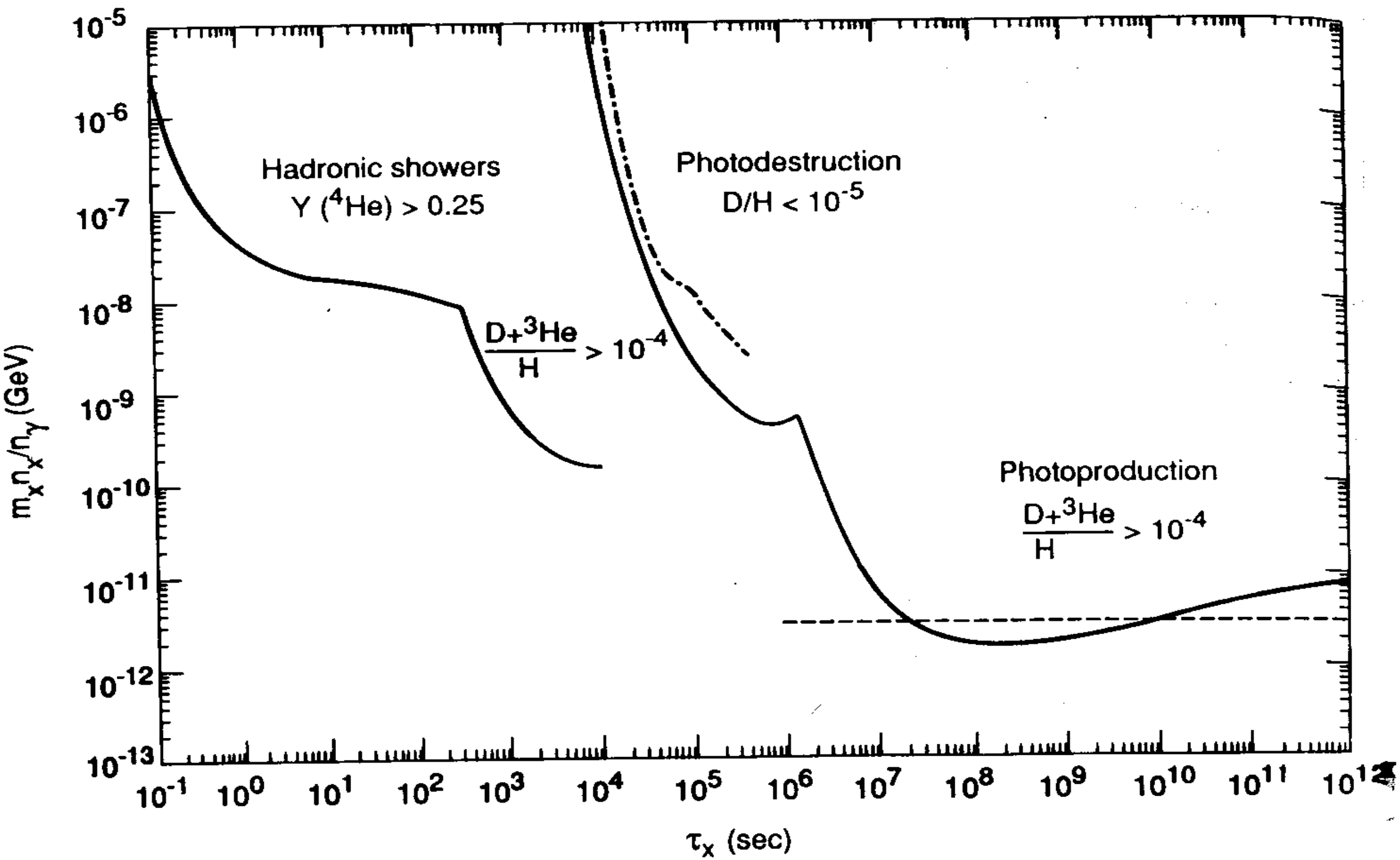


Fig. 3. Upper bounds on the decaying-particle abundance as a function of its lifetime from the effects of electromagnetic and hadronic cascades on primordial elemental abundances. For decays occurring after nucleosynthesis, the most severe constraints are from photoproduction of $D+{}^3He$ (eq. (18)) and photodestruction of D (eq. (19)). All these bounds apply for $m_x \gtrsim 10$–50 MeV. The horizontal dashed line is the approximate bound given earlier [18] while the dot-dashed line is the bound obtained in ref. [27]. For shorter lifetimes, the best bounds come from consideration of the production of ^4He and $D+{}^3He$ by hadronic cascades for $m_x \gtrsim 1$ GeV [25].

Conclusions

- R-parity violating term

$$W_{\mathrm{RPV}} = \sum_i \epsilon_{\alpha\beta} \lambda_i \hat{N}_i \hat{H}_d^\alpha \hat{H}_u^\beta$$

can enhance the lepton-antilepton asymmetry, making thermal leptogenesis possible.

- However in this model, neutralino is not stable but not in a dangerous way.

Lifetime of neutralinos is large, so for LHC it is practically stable.