Neutrino Masses and the Baryon Asymmetry

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Outline

- Introduction
- Baryon and Lepton Number Violation in the SM
- Baryogenesis through Lepton Number Violation
- Supersymmetric Leptogenesis
- Neutrino Masses
- Summary

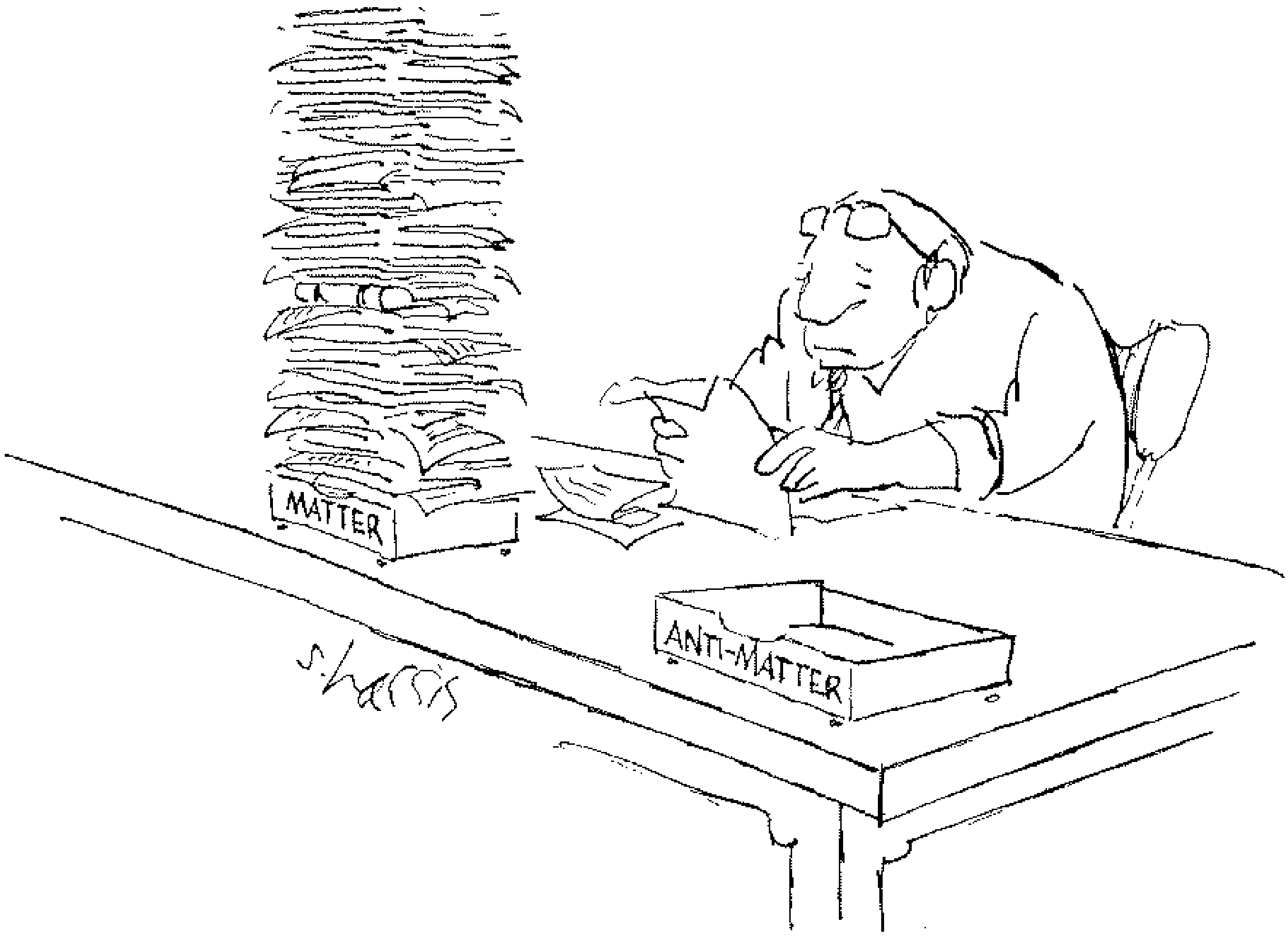
Baryogenesis

The universe is made of matter.

Baryon asymmetry (from nucleosynthesis and CMB):

$$\eta_B \equiv \frac{n_b - n_{\bar{b}}}{n_\gamma} \sim 6 \times 10^{-10}$$

η_B must have been dynamically generated:

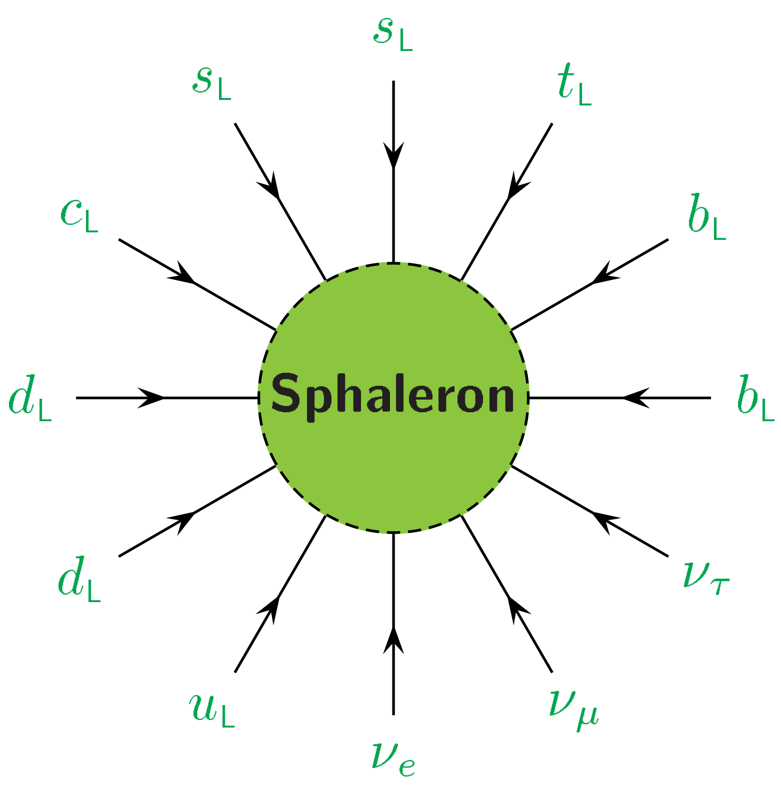


Necessary ingredients (Sakharov, 1967):

- Baryon number violation
- C and CP violation
- Deviation from thermal equilibrium

Baryogenesis and lepton number violation

Standard model: $B+L$ is violated by sphalerons 't Hooft '76



in thermal equilibrium at $T \gtrsim 100$ GeV Kuzmin, Rubakov & Shaposhnikov '85

$$\Longrightarrow \qquad \eta_B \quad = \quad c\,\eta_{B-L}$$

(SM: $c = \frac{28}{79}$; MSSM: $c = \frac{8}{23}$)

Baryogenesis requires breaking of $B - L$

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Simplest realization: SM + right-handed neutrinos

(Fukugita and Yanagida '86)

Yukawa interactions:

$$\mathcal{L}_Y = \overline{l_\mathsf{L}}\, H\, \lambda_l^*\, e_\mathsf{R} + \overline{l_\mathsf{L}} \epsilon H^\dagger\, \lambda_\nu^*\, \nu_\mathsf{R} - \frac{1}{2}\, \overline{\nu_\mathsf{R}^c}\, M\, \nu_\mathsf{R} + \text{ h.c.}$$

Dirac masses $m_l = \lambda_l\, v$ and $m_\mathsf{D} = \lambda_\nu\, v$

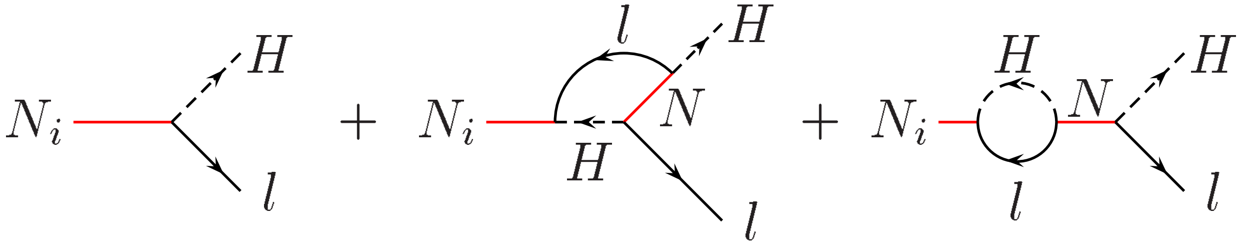
natural assumption: $M \gg m_\mathsf{D}$

$\rightarrow$ seesaw mechanism: 6 Majorana mass eigenstates

$$N \simeq \nu_\mathsf{R} + \nu_\mathsf{R}^c \qquad \nu \simeq K^\dagger\, \nu_\mathsf{L} + \nu_\mathsf{L}^c\, K$$

$$m_N \simeq M \qquad m_\nu \simeq -K^\dagger\, m_\mathsf{D}\, \frac{1}{M}\, m_\mathsf{D}^T\, K^*$$

Generation of a lepton asymmetry



CP asymmetry

$$\varepsilon_1 = \frac{\Gamma(N_1 \to l + H) - \Gamma(N_1 \to \bar{l} + \bar{H})}{\Gamma(N_1 \to l + H) + \Gamma(N_1 \to \bar{l} + \bar{H})}$$

for $M_{2,3} \gg M_1$:

$$\varepsilon_1 \simeq -\frac{3}{16\pi} \sum_i \frac{\mathrm{Im}\left[(\lambda_\nu^\dagger \lambda_\nu)^2_{i1}\right]}{(\lambda_\nu^\dagger \lambda_\nu)_{11}} \frac{M_1}{M_i}$$

in terms of light neutrino masses: Davidson & Ibarra '02

$$\varepsilon_1 = \frac{3}{16\pi} \frac{M_1}{v^2} \sum_{i \neq 1} \frac{\Delta m^2_{i1}}{m_i} \frac{\mathrm{Im}\left(h^2_{i1}\right)}{(h^\dagger h)_{11}}, \qquad h = K^\dagger \lambda_\nu$$

$\Longrightarrow$ upper bound on the CP asymmetry

hierarchical neutrinos

$m_3 \simeq (\Delta m^2_{atm})^{1/2} \gg m_2 \simeq (\Delta m^2_{sol})^{1/2} \gg m_1$

$$|\varepsilon_1| \leq \frac{3}{16\pi} \frac{M_1 (\Delta m^2_{atm})^{1/2}}{v^2}$$

quasi-degenerate neutrinos

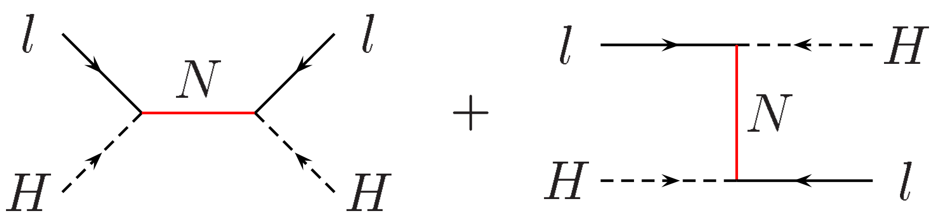
$m_1 \simeq m_2 \simeq m_3 \simeq \bar{m}/\sqrt{3} \gg (\Delta m^2_{atm})^{1/2}$

$$|\varepsilon_1| \leq \frac{3\sqrt{3}}{16\pi} \frac{M_1 \Delta m^2_{atm}}{v^2 \bar{m}}$$

Potential problems

1. Washout due to Neutrino mediated L violating scatterings

(Fukugita & Yanagida '90)



$\longrightarrow$ low energy effective interaction

$$\mathcal{L}_{\Delta L=2} = \frac{1}{2v^2}(m_D \frac{1}{M} m_D^T)_{ij} (l_{Li} H) C (l_{Lj} H) + \text{h.c.}$$

Reaction rate:

$$\Gamma_{\Delta L=2}(T) = \frac{1}{\pi^3} \frac{T^3}{v^4} \sum_{i=e,\mu,\tau} m_{\nu_i}^2$$

If all SM interactions + $\Gamma_{\Delta L=2}$ + sphalerons are in thermal equilibrium

$$\Rightarrow B = L = 0$$

$\eta_B \neq 0 \Rightarrow$ necessary condition $\Gamma_{\Delta L=2}(T) < H(T)$
$\Rightarrow$ bound on light neutrino masses

$$\sum_{i=e,\mu,\tau} m_{\nu_i}^2 < (2 \text{ eV})^2 \, \frac{10^{10} \text{ GeV}}{T_B}$$

2. How do the N_i get produced?

CP asymmetry ε_i: mean lepton asymmetry per neutrino decay.

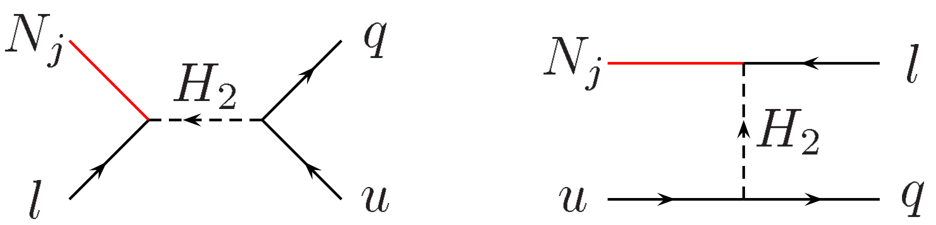
$\Rightarrow$ simple approximation

$$N_L \sim N_{N_1}\varepsilon_1$$

Heavy right-handed neutrinos have to be numerous before decaying.

Thermal equilibrium has to be established at high temperatures $T > M_1$.

Solution: Neutrino-Top scatterings: (Luty '92; M.P. '96)



$\longrightarrow$ in a consistent analysis all lepton number violating and conserving processes have to be taken into account

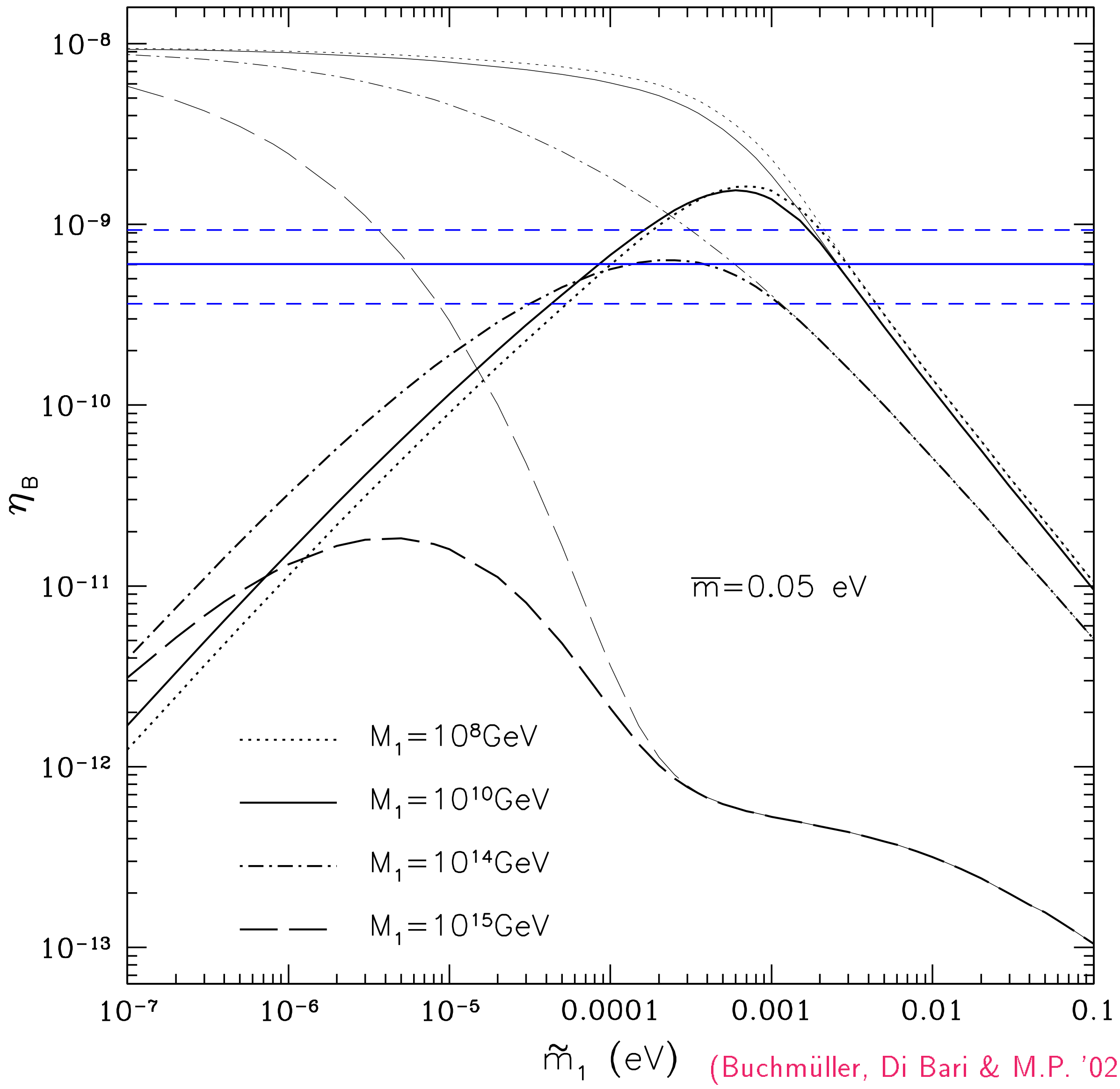
$\longrightarrow$ Network of Boltzmann equations

η_B depends essentially on $\widetilde{m}_1 = \dfrac{(m_D^\dagger m_D)_{11}}{M_1}$ (M.P. '96)

for hierarchical light neutrinos: $\bar{m} = 0.05\,\text{eV}$

naive expectation:

$\varepsilon_1 = 10^{-6} \;\rightarrow \eta_B^{\max} \sim 10^{-2}\varepsilon_1 = 10^{-8}$



(Buchmüller, Di Bari & M.P. '02)

initial conditions:

$N_{N_1} = N_{N_1}^{\text{eq}}$ at $T \gg M_1$ (thin lines)

$N_{N_1} = 0$ at $T \gg M_1$ (thick lines)

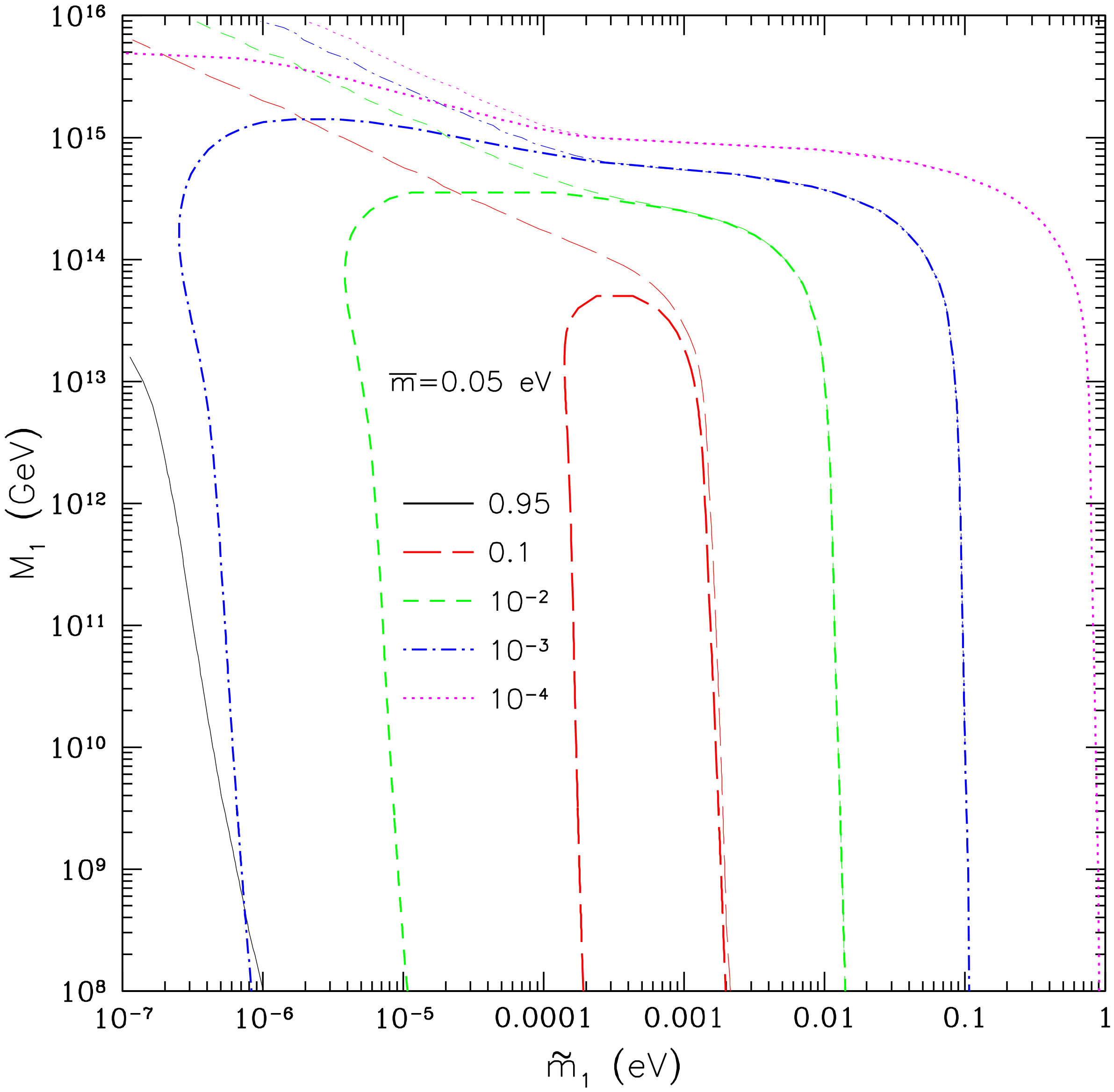
Baryogenesis is possible if

$$10^{-5}\text{ eV} \lesssim \widetilde{m}_1 \lesssim 5 \cdot 10^{-3}\text{ eV}$$

Efficiency factor: κ

(Barbieri et al. '00; Buchmüller, Di Bari & M.P. '02)

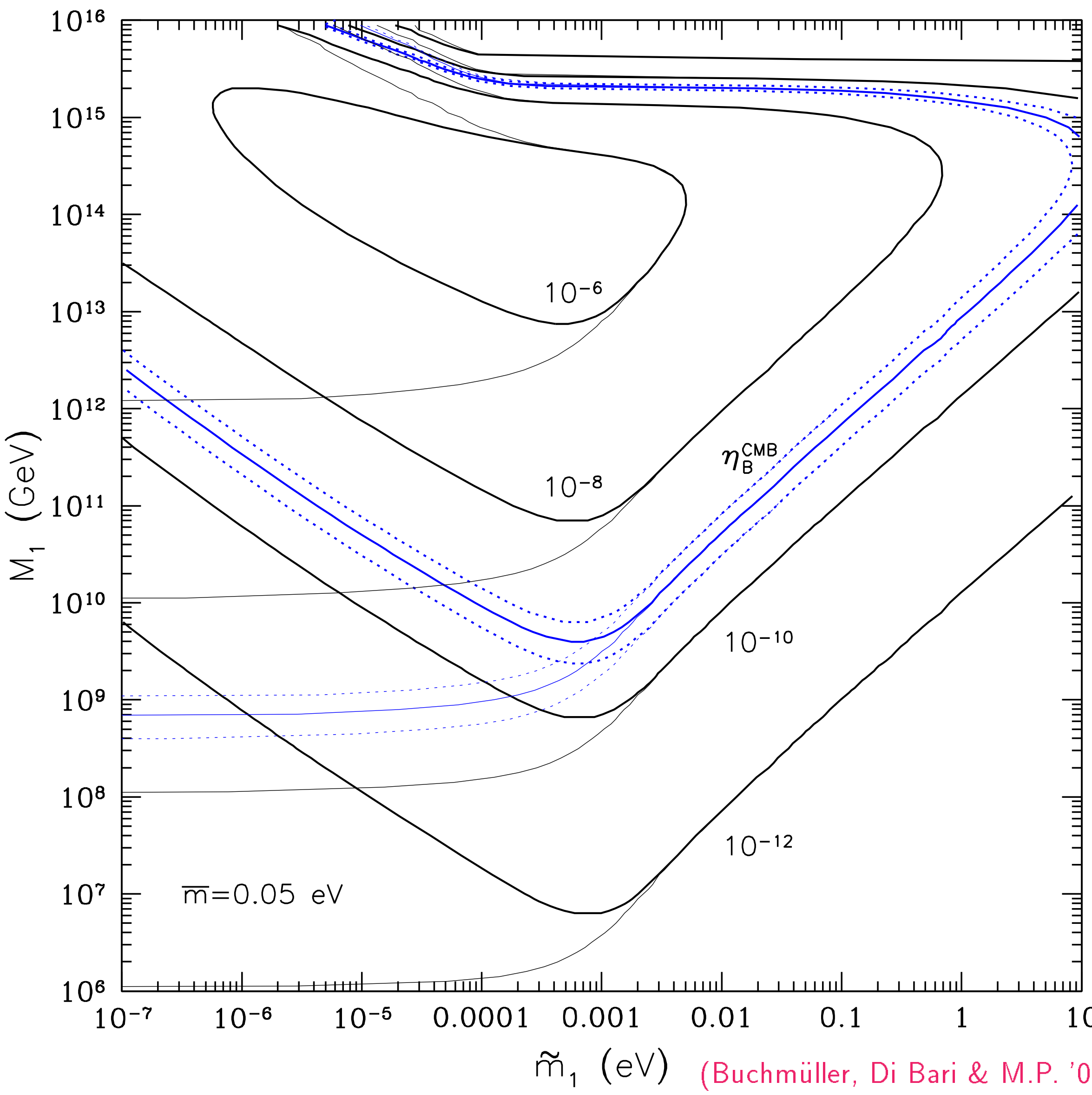
$$\eta_B = 10^{-2}\,\varepsilon_1\,\kappa$$



Maximal baryon asymmetry:

$$|\varepsilon_1| \quad \leq \quad \frac{3}{16\pi}\frac{M_1(\Delta m^2_{atm})^{1/2}}{v^2}$$

$$\Rightarrow \quad \eta_B^{\max} \quad = \quad 10^{-2}\,\frac{3}{16\pi}\frac{M_1(\Delta m^2_{atm})^{1/2}}{v^2}\,\kappa$$



(Buchmüller, Di Bari & M.P. '02)

lower bound on the baryogenesis temperature:

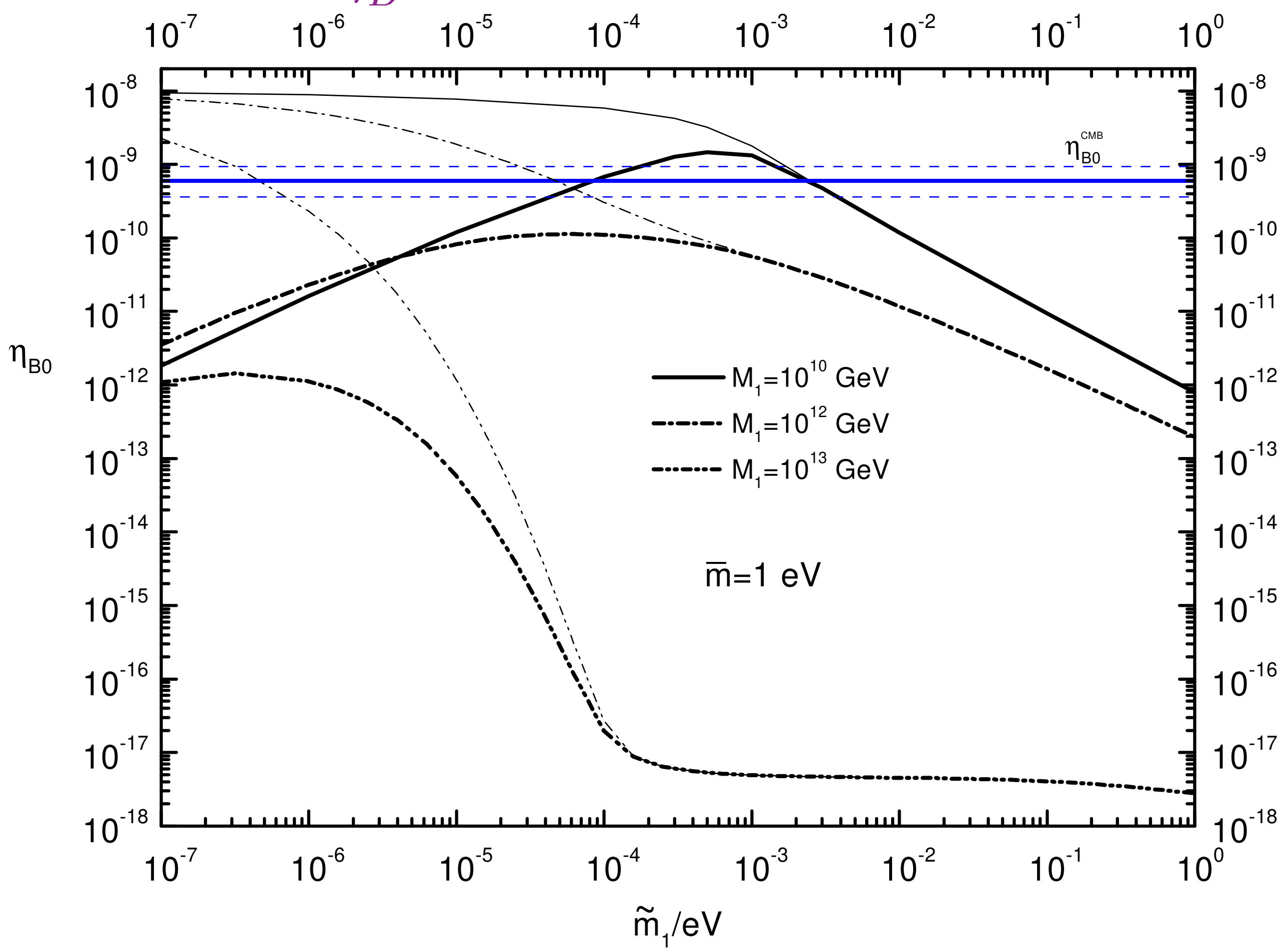
$$T_B \sim M_1 \gtrsim 2\times 10^9\ \mathrm{GeV}$$

η_B depends essentially on $\widetilde{m}_1 = \dfrac{(m_D^\dagger m_D)_{11}}{M_1}$

for quasi-degenerate light neutrinos: $\bar{m} = 1\,\mathrm{eV}$

naive expectation:

$\varepsilon_1 = 10^{-6} \;\rightarrow\; \eta_B^{\max} \sim 10^{-2}\varepsilon_1 = 10^{-8}$



initial conditions:

$N_{N_1} = N_{N_1}^{\mathrm{eq}}$ at $T \gg M_1$ (thin lines)

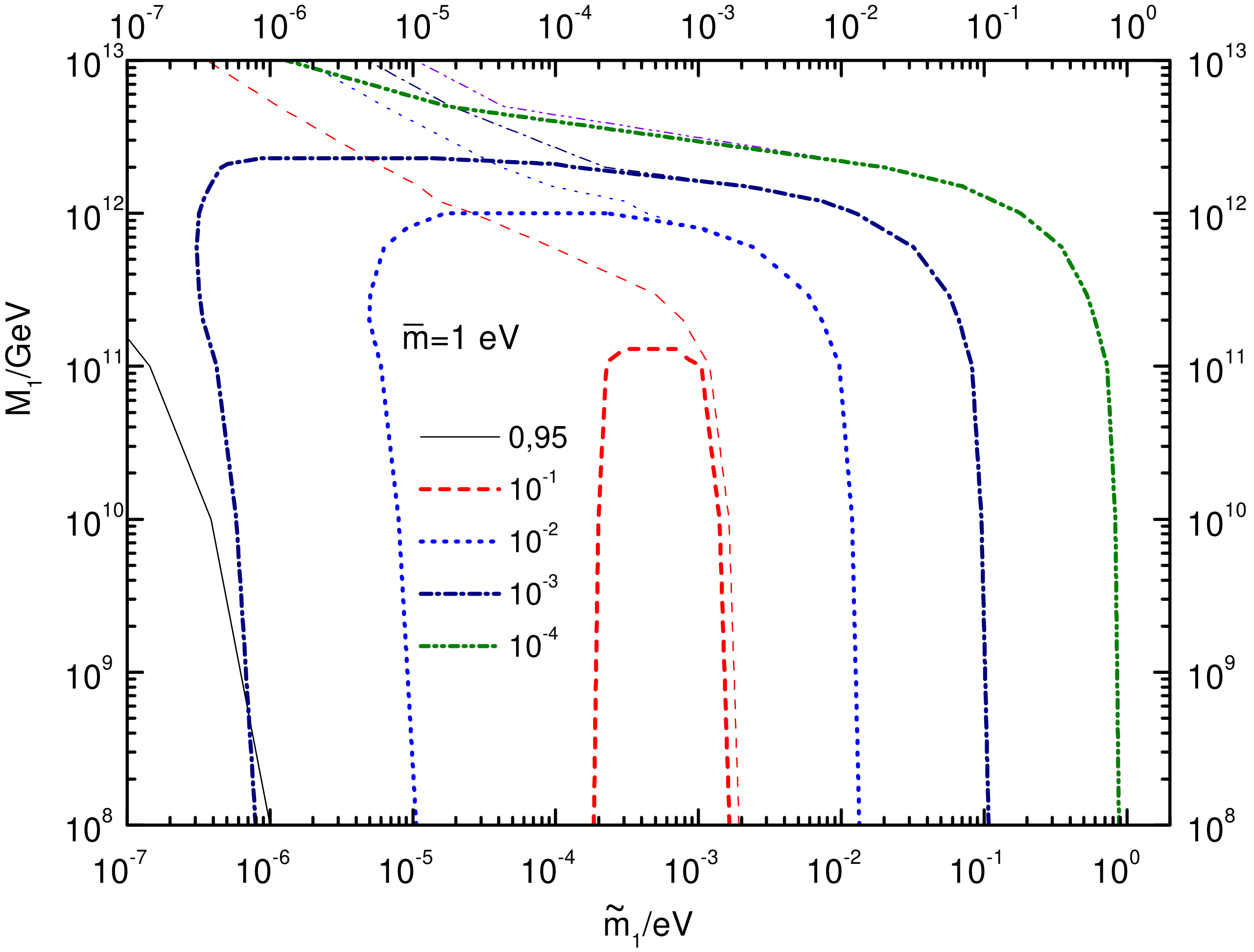
$N_{N_1} = 0$ at $T \gg M_1$ (thick lines)

Baryogenesis is possible if

$$10^{-4}\ \mathrm{eV} \lesssim \widetilde{m}_1 \lesssim 10^{-3}\ \mathrm{eV}$$

Efficiency factor: κ

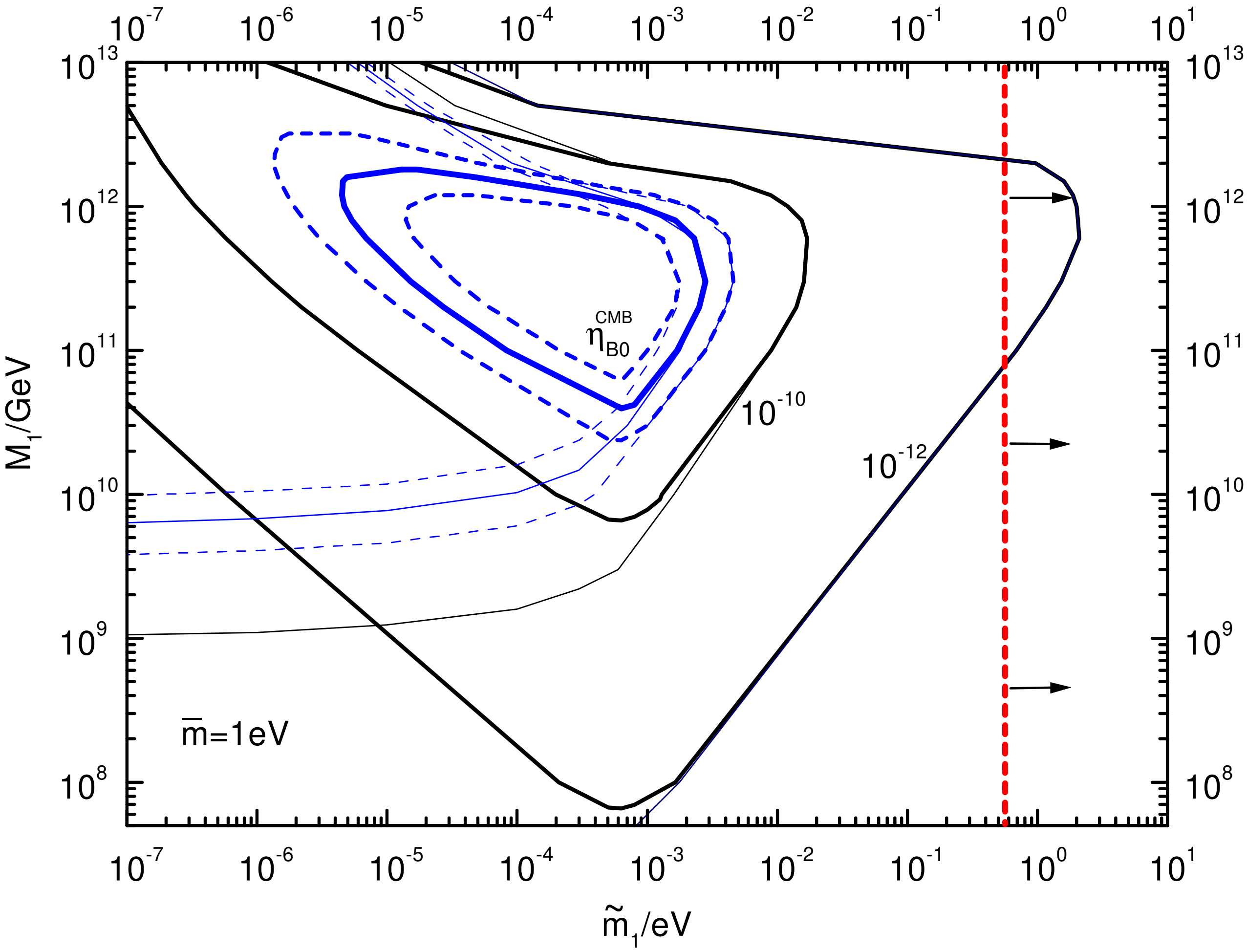
$$\eta_B = 10^{-2}\, \varepsilon_1\, \kappa$$



Maximal baryon asymmetry:

$$|\varepsilon_1| \quad \leq \quad \frac{3}{16\pi}\frac{M_1(\Delta m^2_{atm})^{1/2}}{v^2}$$

$$\Rightarrow \quad \eta_B^{\max} \quad = \quad 10^{-2}\,\frac{3}{16\pi}\frac{M_1(\Delta m^2_{atm})^{1/2}}{v^2}\,\kappa$$



$$\tilde{m}_1 \gtrsim m_1 \simeq \frac{\bar{m}}{\sqrt{3}} \simeq 0.6\,\mathrm{eV}$$

quasi-degenerate light neutrinos are incompatible with leptogenesis!

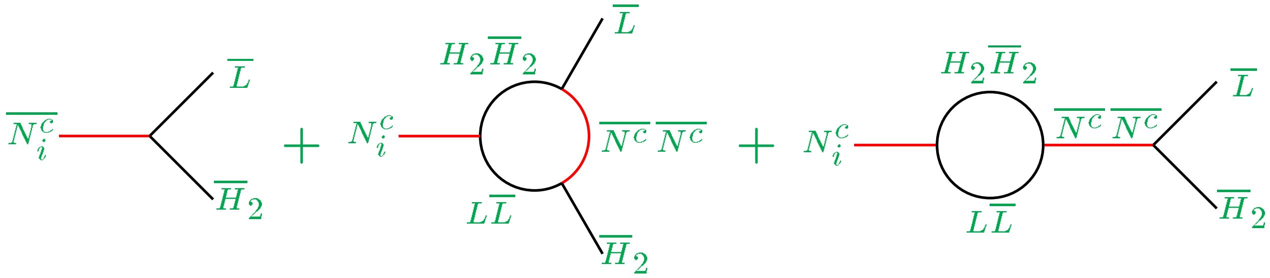
Supersymmetric Leptogenesis

(Campbell et al. '93; Covi et al. '96; M.P. '97)

Superpotential

$$W = \mu H_1 \epsilon H_2 + H_1 \epsilon L \lambda_l E^c + H_2 \epsilon L \lambda_\nu N^c + \frac{1}{2} N^c M N^c$$

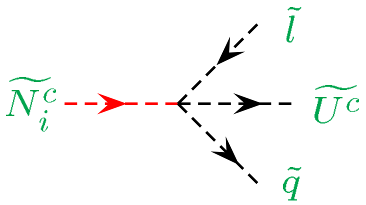
Many new decay channels and scattering processes have to be considered $\rightarrow$ Superfield techniques (M.P. '97)



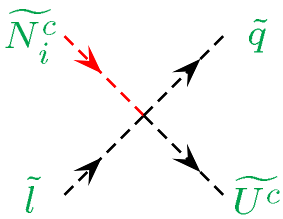
CP asymmetry:

$$\varepsilon_i \approx -\frac{3}{8\pi v_2^2} \sum_j \frac{\mathrm{Im}\left[(m_\mathrm{D}^\dagger m_\mathrm{D})^2_{ji}\right]}{(m_D^\dagger m_D)_{ii}} \frac{M_i}{M_j}$$

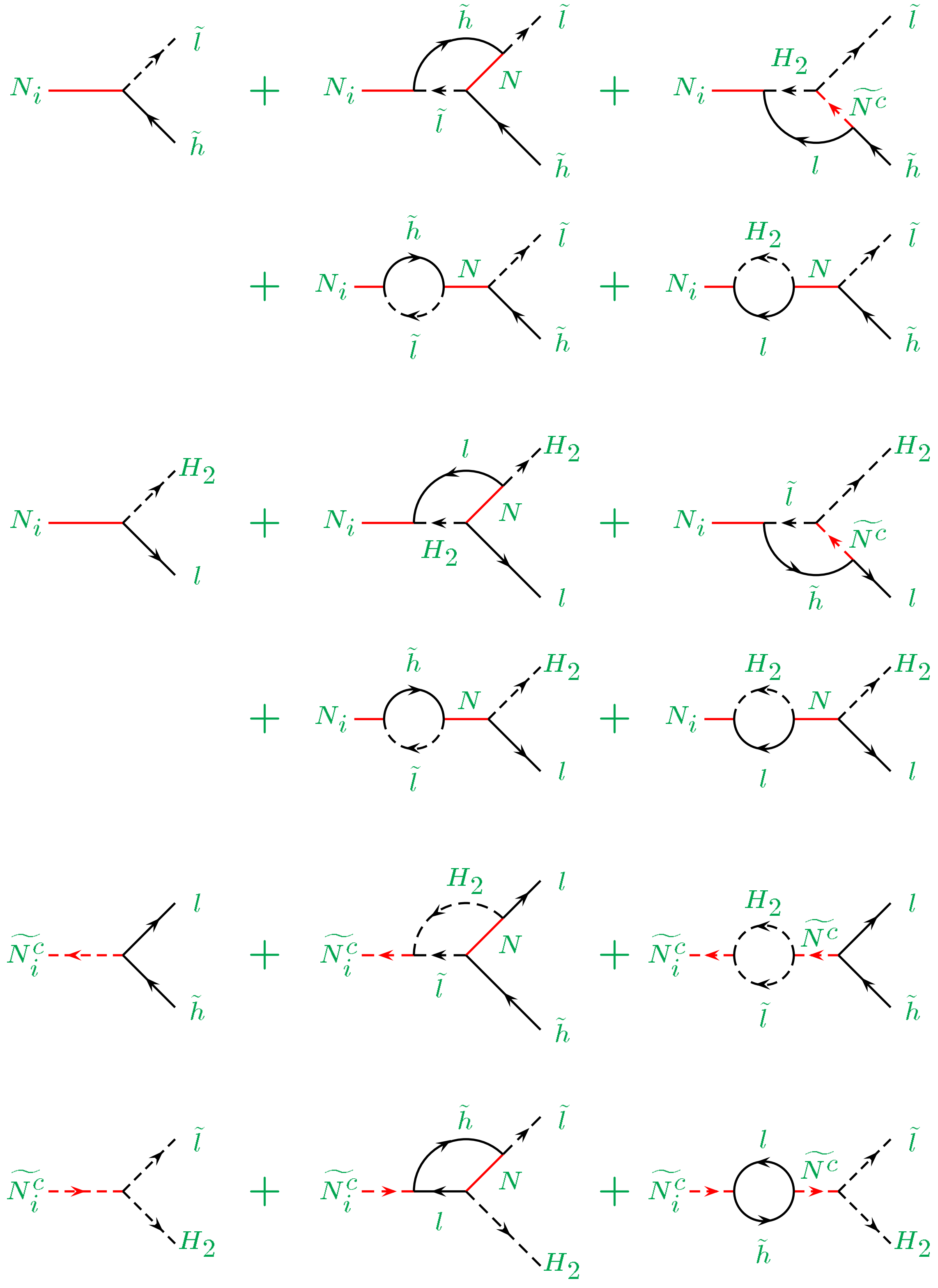
Further decay channels

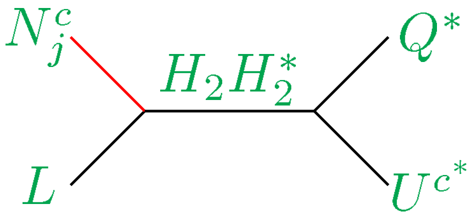


Stop Sneutrino scattering



In component fields





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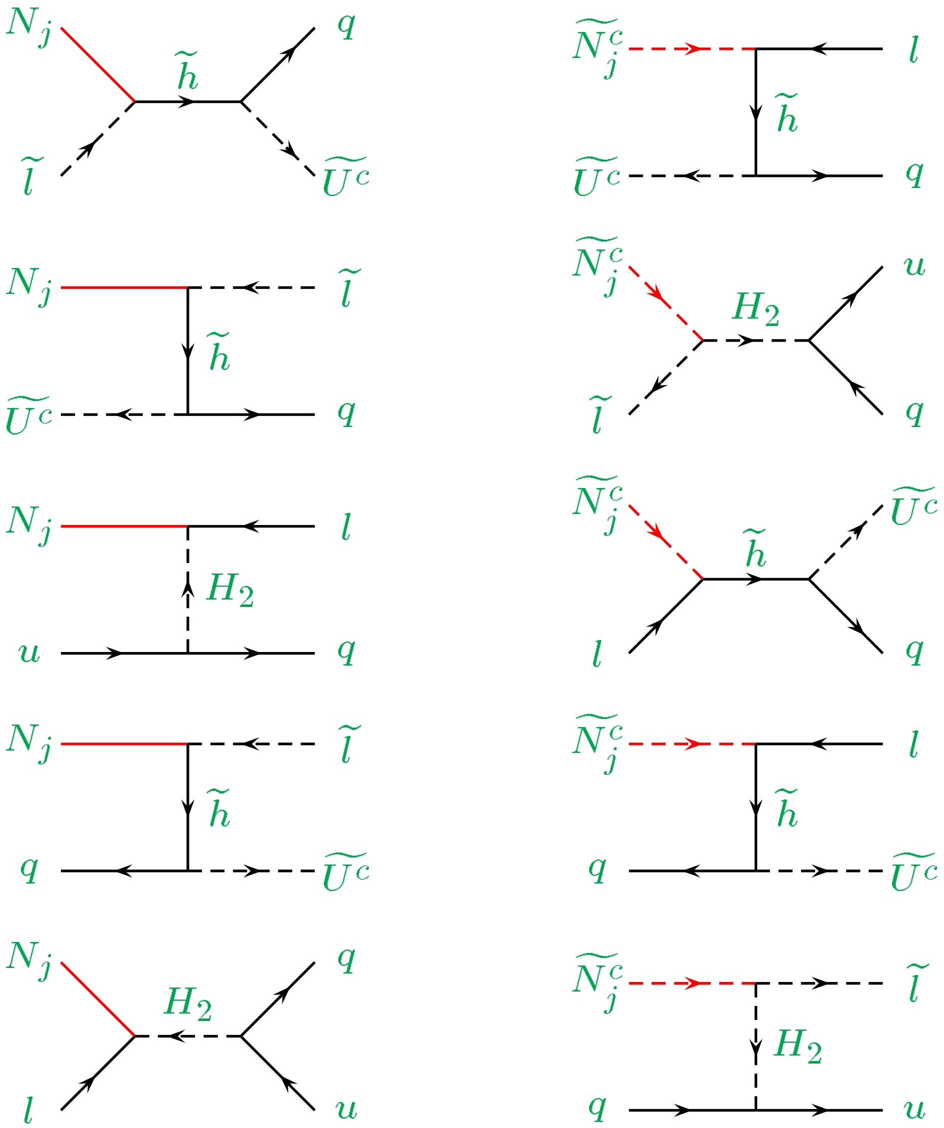
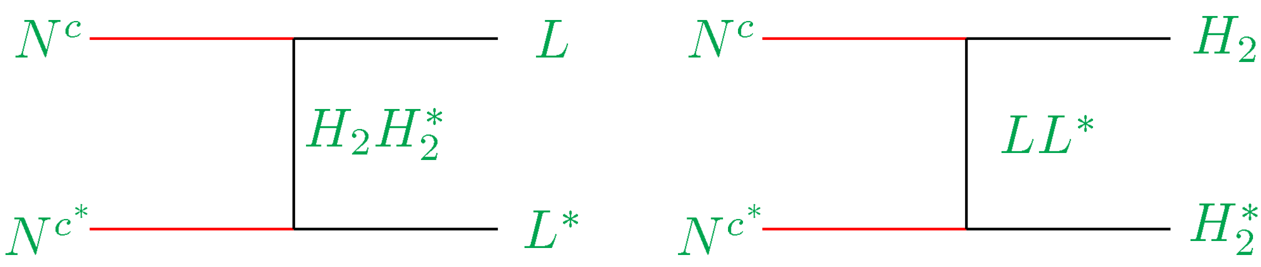


$2 \to 3$ processes are phase space suppressed

these processes bring the heavy neutrinos into thermal equilibrium at $T > M_1$

(S)neutrino pair creation and annihilation

Superfields in configuration space:



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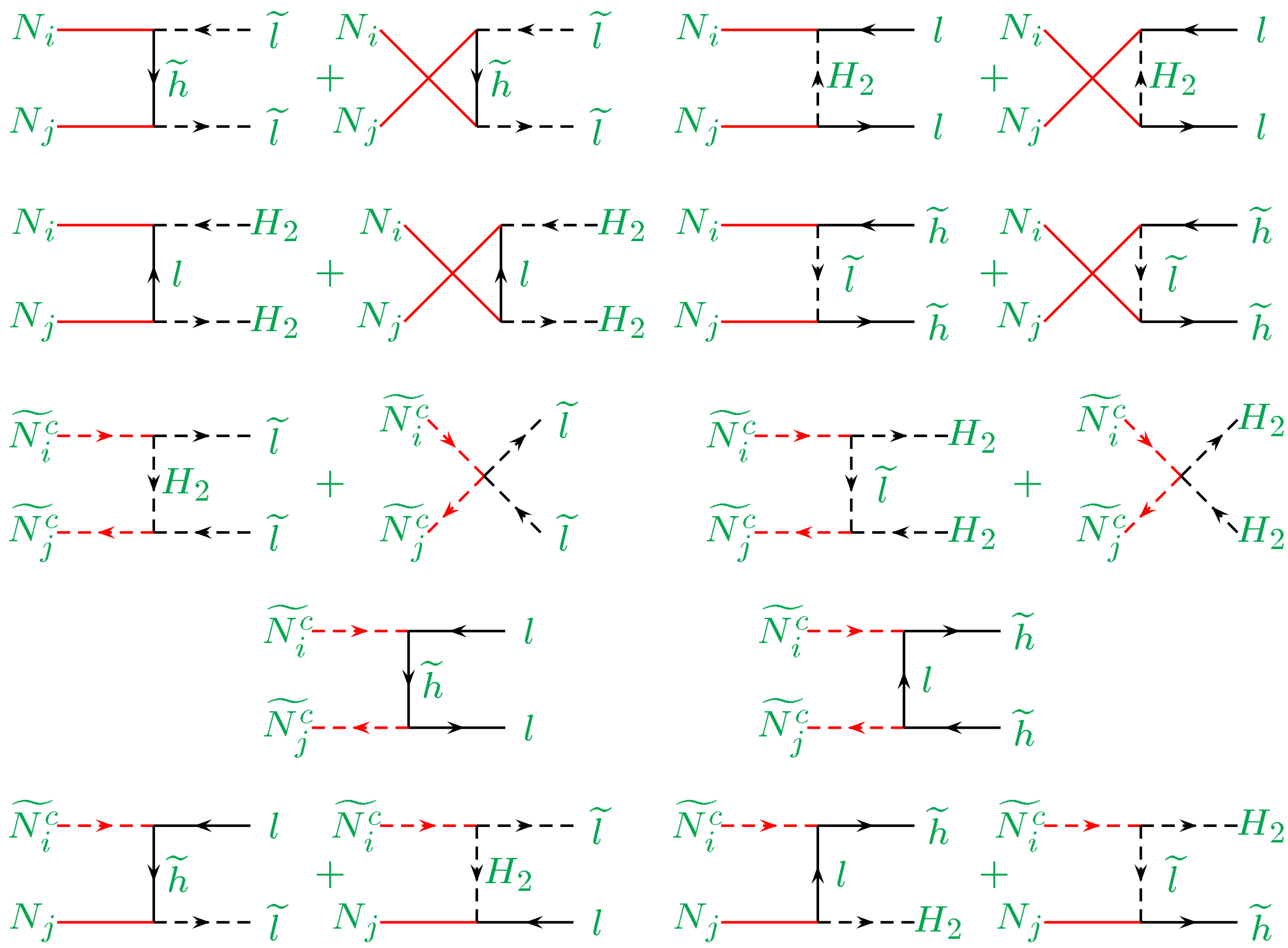
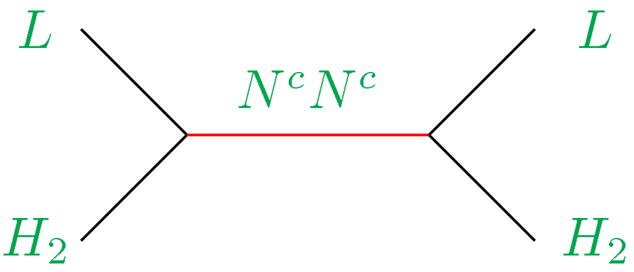
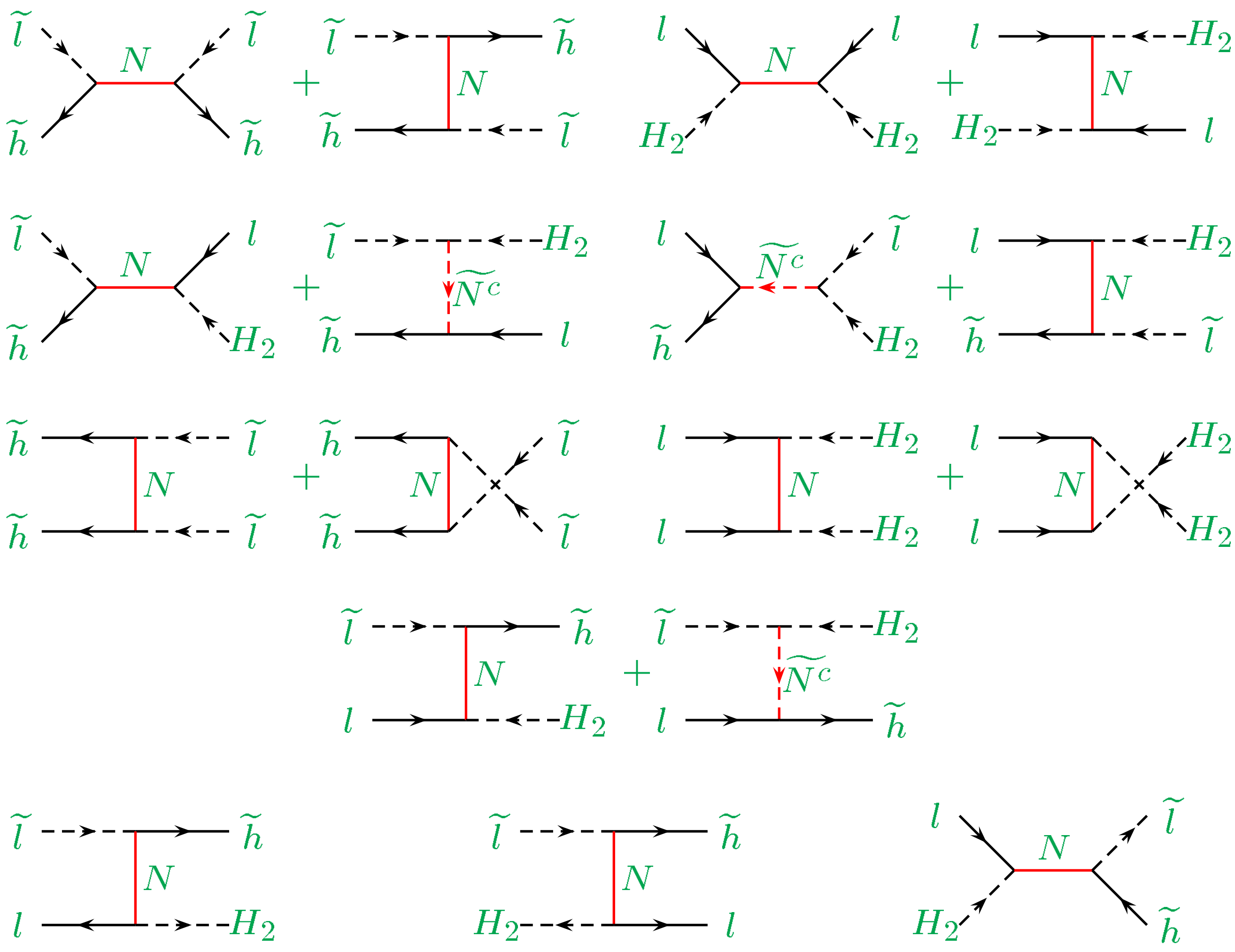


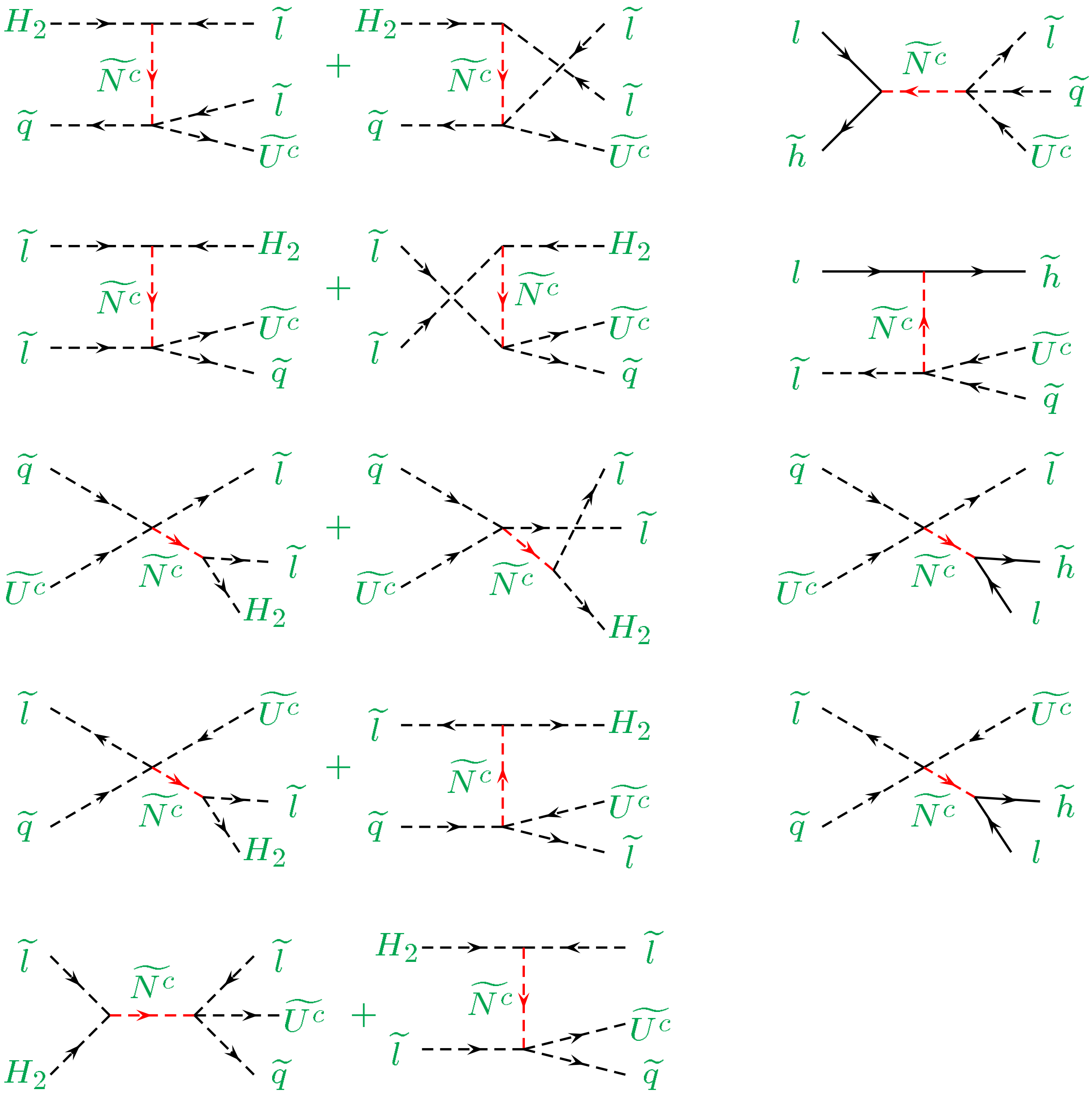
L violating scatterings

Superfields in configuration space:



In component fields:



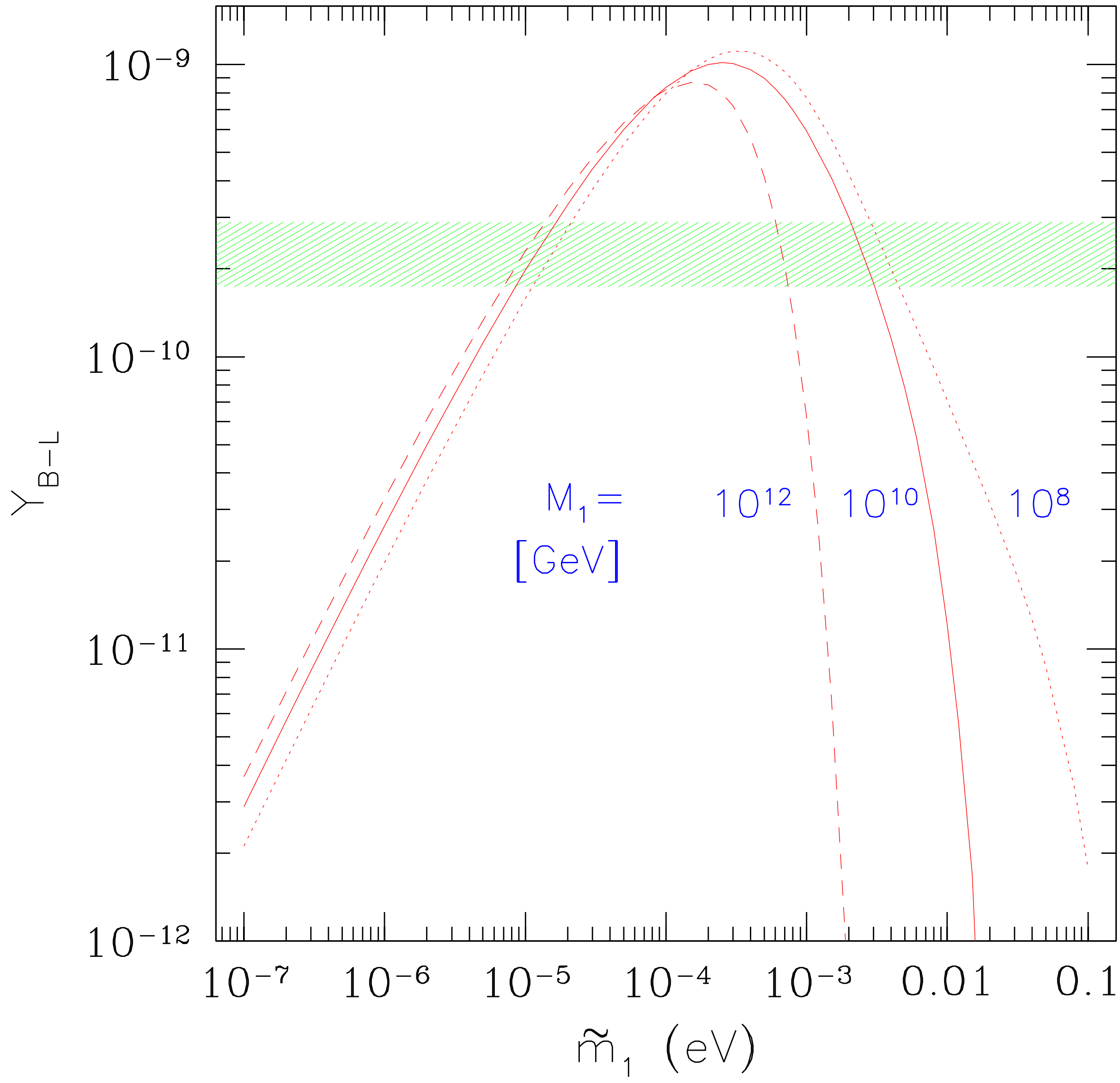


These processes can easily reduce the generated asymmetry by several orders of magnitude compared to the rough estimate

$$N_L \sim N_{N_1}\varepsilon_1$$

Y_{B-L} depends essentially on $\widetilde{m}_1 = \dfrac{(m_D^\dagger m_D)_{11}}{M_1}$

$$\varepsilon_1 = 10^{-6} \;\rightarrow Y_{B-L} \sim \frac{\varepsilon_1}{g*} = 4 \cdot 10^{-9}$$



Baryogenesis is possible if

$$10^{-5}\ \text{eV} \lesssim \widetilde{m}_1 \lesssim 5 \cdot 10^{-3}\ \text{eV}$$

Neutrino Masses

Most general case:

mass matrices:
$$M = \begin{pmatrix} M_1 & 0 & 0 \\ 0 & M_2 & 0 \\ 0 & 0 & M_3 \end{pmatrix}$$

$$m_{\mathrm{D}} = V \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix} U^\dagger$$

U is the mixing matrix in $m_{\mathrm{D}}^\dagger m_{\mathrm{D}}$.

mixing matrix in the leptonic charged current depends on the parameters of V and U.

$\Rightarrow$ no model independent connection between mixing and CP violation at high and at low energies

$\rightarrow$ additional theoretical input is needed
(cf. talks of T. Morozumi and A. Ibarra in WG2)

- Flavour symmetries

  (Sato & Yanagida '98; Buchmüller & Yanagida '98; Lola & Ross '99; Buchmüller & M.P. '99; Achiman '99; Kang, Kang & Sarkar '99; Berger '99; Nielsen & Takanishi '01; Hirsch & King '01)

- Texture zeroes

  (Ellis, Lola & Nanopoulos '99; Berger & Brahmachari '99; Goldberg '99)

Froggatt-Nielsen Mechanism

(Froggatt & Nielsen '79; Bijnens & Wetterich '87; Sato & Yanagida '99; Buchmüller & Yanagida '99; Buchmüller & M.P. '99)

spontaneously broken U(1)$_F$ symmetry
singlet field Φ, $Q_\Phi = -1$ $\rightarrow$ Yukawa couplings via non-renormalizable interactions

$$h_{ij} = g_{ij} \left(\frac{\langle\Phi\rangle}{\Lambda}\right)^{Q_i+Q_j} \qquad \Lambda > \Lambda_{\mathrm{GUT}}$$

SU(5)×U(1)$_F$ symmetry

ψ_i	e^c_{R3}	e^c_{R2}	e^c_{R1}	l_{L3}	l_{L2}	l_{L1}	ν^c_{R3}	ν^c_{R2}	ν^c_{R1}
Q_i	0	1	2	0	0	1	0	1	2

Yukawa matrices

$$h_e \sim h_\nu \sim \begin{pmatrix} \epsilon^3 & \epsilon^2 & \epsilon^2 \\ \epsilon^2 & \epsilon & \epsilon \\ \epsilon & 1 & 1 \end{pmatrix} \qquad h_N \sim \begin{pmatrix} \epsilon^4 & \epsilon^3 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & \epsilon \\ \epsilon^2 & \epsilon & 1 \end{pmatrix}$$

Mass matrix of the light neutrinos

$$m_\nu \sim \begin{pmatrix} \epsilon^2 & \epsilon & \epsilon \\ \epsilon & 1 & 1 \\ \epsilon & 1 & 1 \end{pmatrix} \frac{v_2^2}{\langle R\rangle}$$

Mass ratios $\quad m_e : m_\mu : m_\tau \sim \epsilon^3 : \epsilon : 1 \quad \Rightarrow \epsilon \sim \frac{1}{17}$

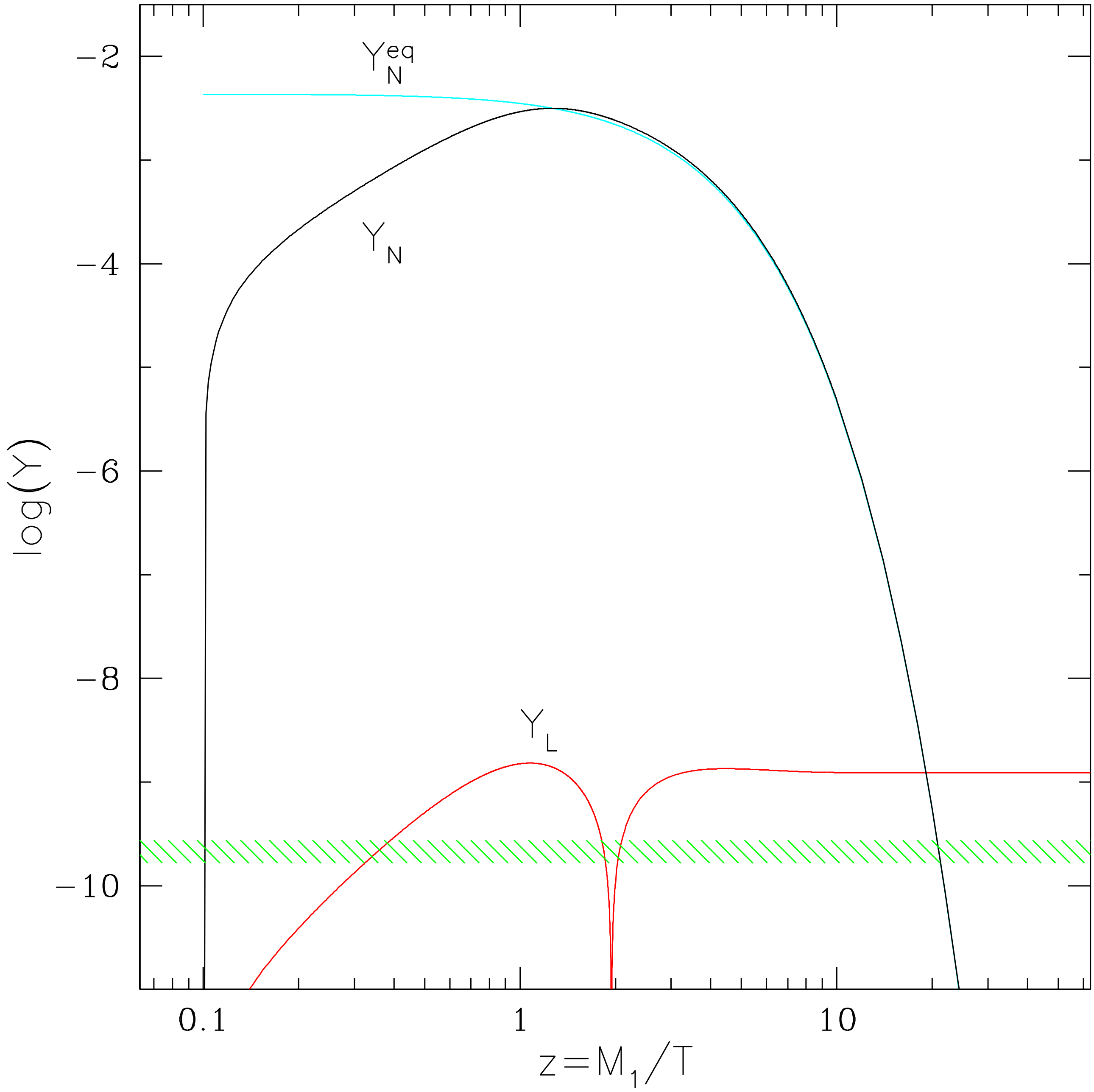
$$M_1 : M_2 : M_3 \sim \epsilon^4 : \epsilon^2 : 1 \qquad m_1 : m_2 : m_3 \sim \epsilon^2 : 1 : 1$$

CP asymmetry $\quad \varepsilon_1 \sim \frac{3}{16\pi}\epsilon^4 \sim 10^{-6}$

Mass scales

$v_2 \sim 174\,\text{GeV} \qquad \overline{m_\nu} = \sqrt{m_{\nu_\mu} m_{\nu_\tau}} \sim 10^{-2}\,\text{eV}$

$M_3 \sim \frac{v_2^2}{\overline{m_\nu}} \sim 10^{15}\,\text{GeV} \qquad M_1 \sim \epsilon^4 M_3 \sim 10^{10}\,\text{GeV}$



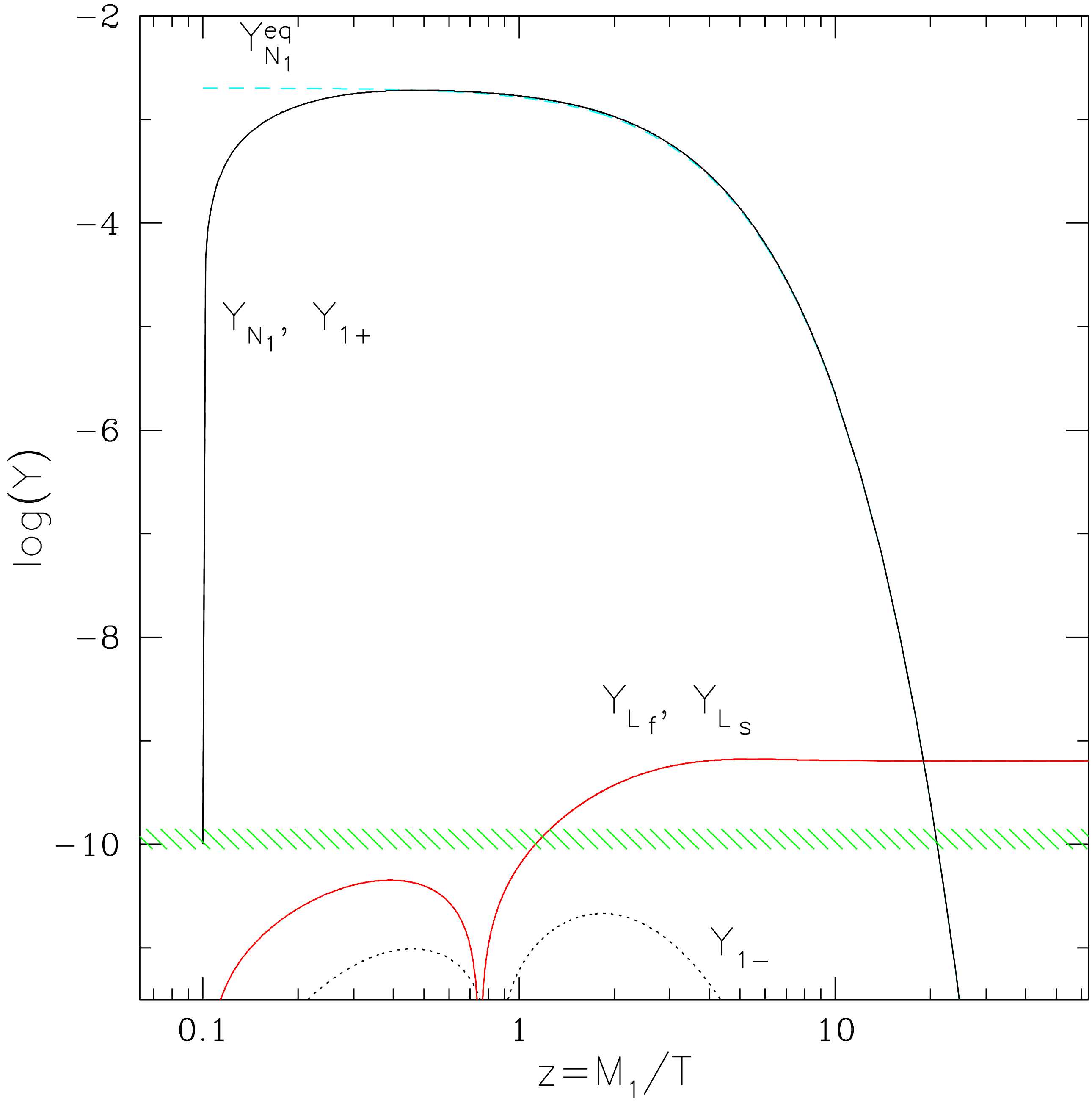
$\frac{1}{7}\eta_L \simeq Y_L \sim 10^{-9}$

CP asymmetry $\varepsilon_1 \sim \frac{3}{8\pi}\epsilon^4 \sim 10^{-6}$

Mass scales

$v_2 \sim 174\,\text{GeV}$ $\overline{m_\nu} = \sqrt{m_{\nu_\mu} m_{\nu_\tau}} \sim 10^{-2}\,\text{eV}$

$M_3 \sim \frac{v_2^2}{\overline{m_\nu}} \sim 10^{15}\,\text{GeV}$ $M_1 \sim \epsilon^4 M_3 \sim 10^{10}\,\text{GeV}$



$\frac{1}{7}\eta_L \simeq Y_L \sim 10^{-9}$

Low-energy phases

Parametrize in terms of low-energy observables
(Davidson & Ibarra, hep-ph/0206304)
Neutrino Yukawa couplings:

$$\lambda_\nu = V_R^\dagger D_Y V_L$$

$\Rightarrow$ use m_ν, D_Y, V_L as independent input parameters.
light neutrino masses:

$$U^T m_\nu U = \mathrm{diag}(m_{\nu_1}, m_{\nu_2}, m_{\nu_3})$$

MNS matrix:

$$U = V \cdot \mathrm{diag}(e^{-i\phi/2}, e^{-i\phi'/2}, 1)$$

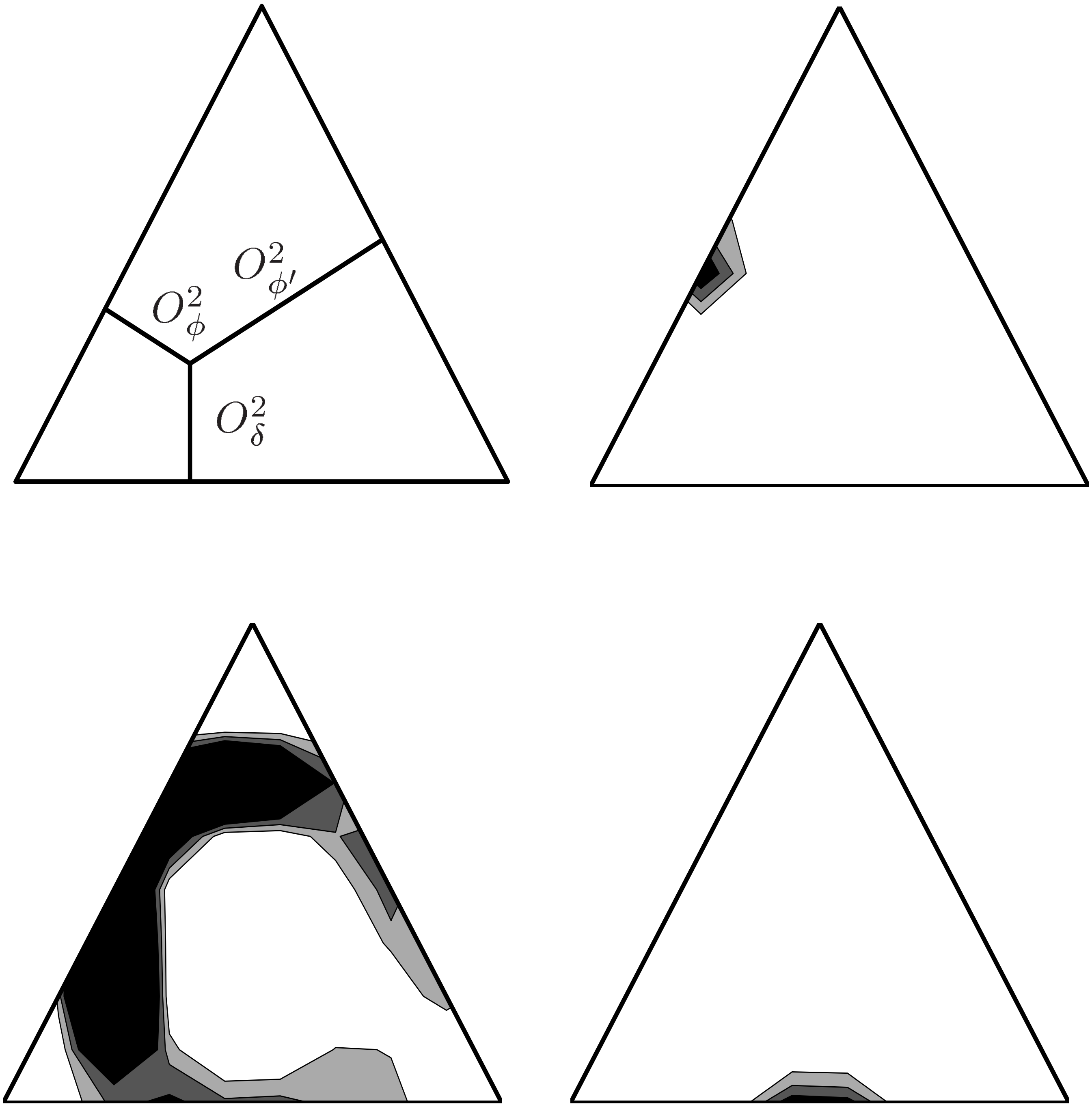
where V is CKM-like:

- one 'Dirac'-phase δ
  ($\rightarrow$ CP violation in neutrino oscillations).

- two 'Majorana' phases: ϕ, ϕ'; ($\rightarrow \beta\beta_{0\nu}$)

simple example: $V_L = 1$
$\Rightarrow$ only δ, ϕ and ϕ' enter in leptogenesis

Phase overlaps:



$V_L = 1$, $\theta_{\mathrm{Chooz}} = 0.1,\ 0.01,\ 0.001$

The Gravitino 'Problem'

(Khlopov & Linde '84; Ellis, Kim & Nanopoulos '84; Ellis, Nanopoulos & Sarkar '85; Moroi, Murayama & Yamaguchi '93; Kawasaki and Moroi '95; Bolz, Buchmüller & M.P. '98; Bolz, Brandenburg & Buchmüller '00)

Production of gravitinos in the early universe

$$\Omega_{\tilde{G}} h^2 \simeq 0.21 \left(\frac{T_R}{10^{10}\,\text{GeV}}\right) \left(\frac{100\,\text{GeV}}{m_{\tilde{G}}}\right) \left(\frac{m_{\tilde{g}}(\mu)}{1\,\text{TeV}}\right)^2$$

BBN constraints on unstable relics (Ellis et al. '92)

$$\text{(I)} \quad m_X Y_X(T) < 4 \cdot 10^{-10}\,\text{GeV}, \quad \tau < 2 \cdot 10^6\,\text{sec}$$

$$\text{(II)} \quad m_X Y_X(T) < 4 \cdot 10^{-12}\,\text{GeV}, \quad \tau \text{ arbitrary}$$

$\Rightarrow$ unstable gravitino is inconsistent with reheating temperature of $\mathcal{O}(10^{10})$ GeV

viable scenario:

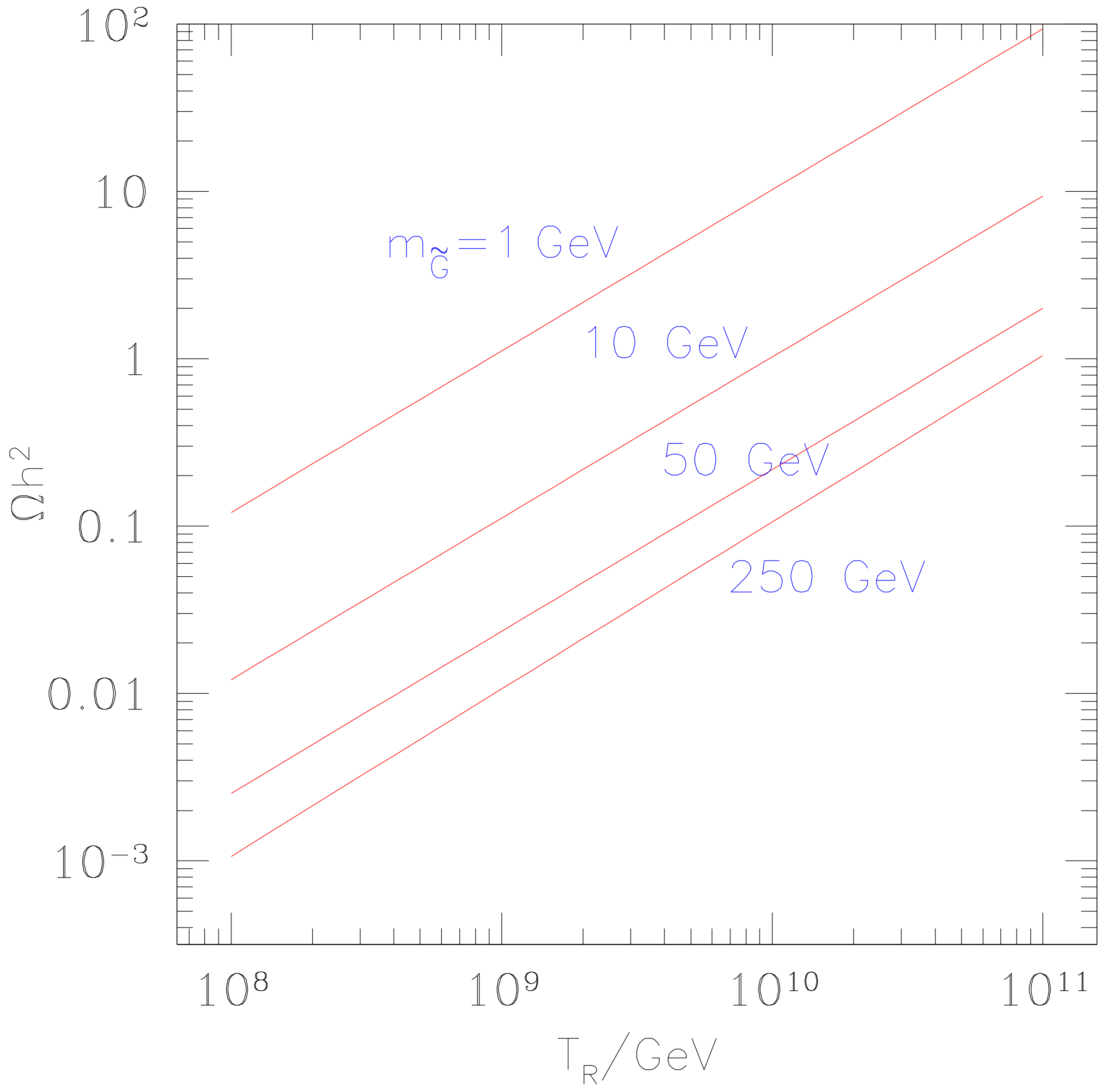
- gravitino is the LSP: $\Omega_{\tilde{G}} < 1$
- NLSP decays before BBN

$$\tau_{NSP} = 48\pi \frac{m_{\tilde{G}}^2 M^2}{m_{NSP}^5} < 2 \cdot 10^6\,\text{sec}$$

Gravitinos as cold dark matter ?

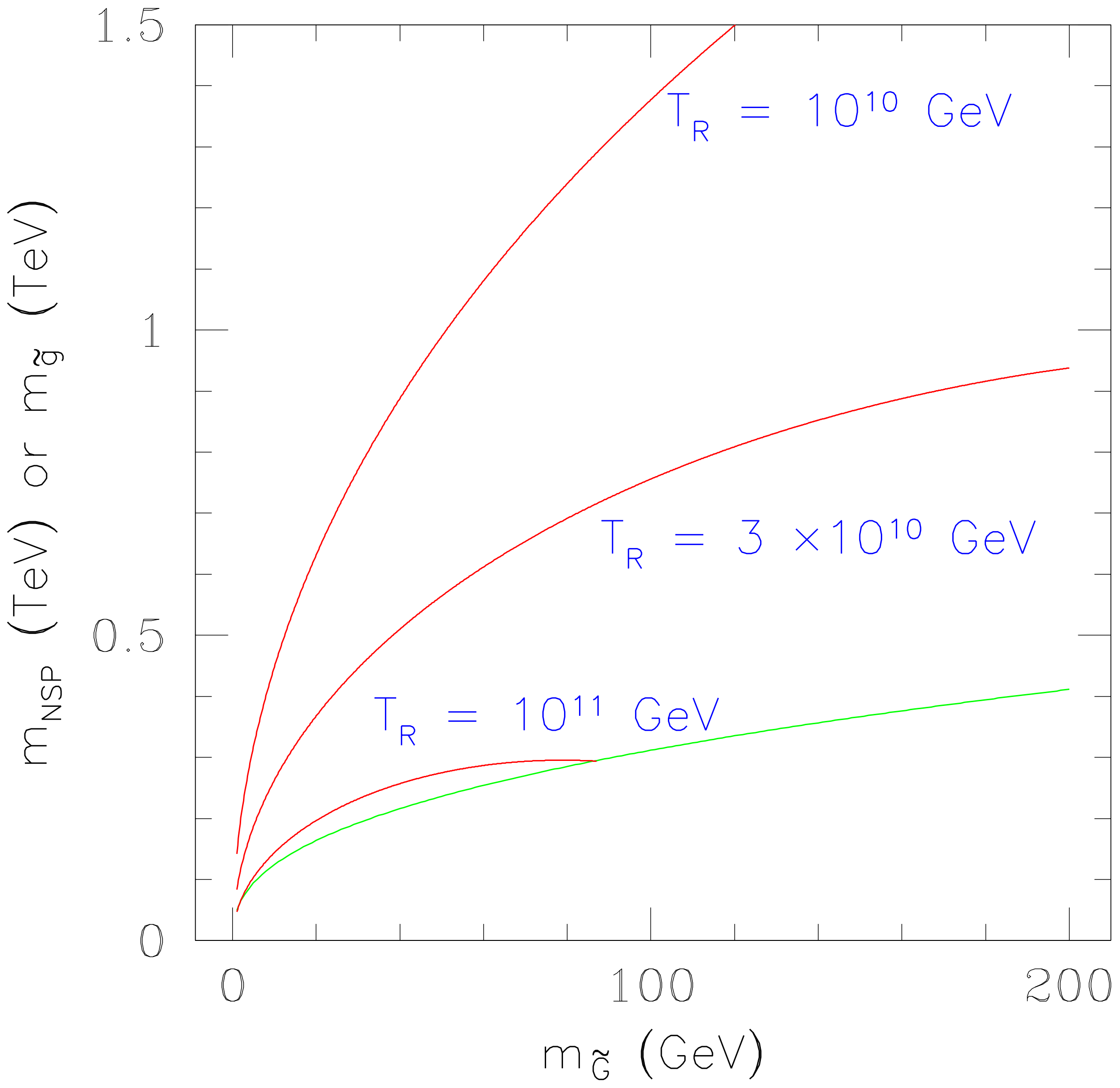
Leptogenesis: $T_R \sim 10^8 - 10^{10}$ GeV

Gluino mass: $m_{\tilde{g}} = 700$ GeV



$\Omega_{\tilde{G}} < 1 \Rightarrow$ upper bound on the gluino mass

$\tau_{NSP} < 2 \cdot 10^6\,\mathrm{sec} \Rightarrow$ lower bound on the NSP mass



Summary

- The existence of a baryon asymmetry suggests the existence of lepton number violation and right-handed neutrinos

- L violating scatterings are of crucial importance

- Cosmological baryon asymmetry is related to light neutrino properties

- Quasi-degenerate light neutrino masses are incompatible with leptogenesis

- lower bound on the baryogenesis temperature:

$$T_B \sim M_1 \gtrsim 2 \times 10^9 \text{ GeV}$$

- Natural framework: GUT broken into the SM gauge group at $\Lambda_{\text{GUT}} \sim 10^{16}$ GeV

- no model-independent constraints on CP violation in neutrino oscillations

The theory of the baryon asymmetry will yield new information about physics beyond the standard model