Leptogenesis

Alejandro Ibarra
Technische Universität München

Warsaw
February 2010

Outline

- Recapitulation
- Connection leptogenesis-neutrino masses
- The role of flavours in leptogenesis
- Supersymmetric leptogenesis
- Implications of SUSY leptogenesis

Recipe to calculate the BAU in leptogenesis

1- Take your favourite neutrino model (h_ν, M)

Recipe to calculate the BAU in leptogenesis

1- Take your favourite neutrino model (h_ν,M)

2- Calculate ϵ, $K = \dfrac{\widetilde{m}_1}{m_*}$

$$\epsilon = \frac{3}{16\pi} \frac{1}{(h_\nu h_\nu^\dagger)_{11}} \sum_i \mathrm{Im}\left[(h_\nu h_\nu^\dagger)^2_{1i}\right] \frac{M_1}{M_i}$$

$$\widetilde{m}_1 = (hh^\dagger)_{11} \frac{v^2}{M_1} \qquad m_* \simeq 10^{-3}\,\mathrm{eV}$$

Recipe to calculate the BAU in leptogenesis

1- Take your favourite neutrino model (h_ν, M)

2- Calculate ϵ, $K = \frac{\widetilde{m}_1}{m_*}$

$$\epsilon = \frac{3}{16\pi} \frac{1}{(h_\nu h_\nu^\dagger)_{11}} \sum_i \mathrm{Im}\left[(h_\nu h_\nu^\dagger)^2_{1i}\right] \frac{M_1}{M_i}$$

$$\widetilde{m}_1 = (hh^\dagger)_{11} \frac{v^2}{M_1} \qquad\qquad m_* \simeq 10^{-3}\,\mathrm{eV}$$

3- Solve the Boltzmann equations to obtain $N_{B-L}^{T=0}$

$$\frac{dN_{B-L}}{dz} = -\epsilon \;\; D\,(N_{N_1} - N_{N_1}^{\mathrm{eq}}) - W_{ID} N_{B-L}$$

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

Recipe to calculate the BAU in leptogenesis

1- Take your favourite neutrino model (h_ν,M)

2- Calculate ϵ, $K = \frac{\widetilde{m}_1}{m_*}$

$$\epsilon = \frac{3}{16\pi} \frac{1}{(h_\nu h_\nu^\dagger)_{11}} \sum_i \mathrm{Im}\left[(h_\nu h_\nu^\dagger)^2_{1i} \right] \frac{M_1}{M_i}$$

$$\widetilde{m}_1 = (hh^\dagger)_{11} \frac{v^2}{M_1} \qquad m_* \simeq 10^{-3}\,\mathrm{eV}$$

3- Solve the Boltzmann equations to obtain $N_{B-L}^{T=0}$

$$\frac{dN_{B-L}(z)}{dz} = -\epsilon\, K\, z \frac{K_1(z)}{K_2(z)} (N_{N_1}(z) - N_{N_1}^{\mathrm{eq}}(z)) - \frac{1}{2} K\, z \frac{K_1(z)}{K_2(z)} \frac{N_{N_1}^{\mathrm{eq}}(z)}{N_l^{\mathrm{eq}}} N_{B-L}(z)$$

$$\frac{dN_{N_1}(z)}{dz} = -K\, z \frac{K_1(z)}{K_2(z)} (N_{N_1}(z) - N_{N_1}^{\mathrm{eq}}(z))$$

Recipe to calculate the BAU in leptogenesis

1- Take your favourite neutrino model (h_ν,M)

2- Calculate ϵ, $K = \frac{\widetilde{m}_1}{m_*}$

$$\epsilon = \frac{3}{16\pi} \frac{1}{(h_\nu h_\nu^\dagger)_{11}} \sum_i \mathrm{Im}\left[(h_\nu h_\nu^\dagger)_{1i}^2\right] \frac{M_1}{M_i}$$

$$\widetilde{m}_1 = (hh^\dagger)_{11} \frac{v^2}{M_1} \qquad m_* \simeq 10^{-3}\,\mathrm{eV}$$

3- Solve the Boltzmann equations to obtain $N_{B-L}^{T=0}$

$$\frac{dN_{B-L}(z)}{dz} = -\epsilon\, K\, z \frac{K_1(z)}{K_2(z)}(N_{N_1}(z) - N_{N_1}^{\mathrm{eq}}(z)) - \frac{1}{2} K\, z \frac{K_1(z)}{K_2(z)} \frac{N_{N_1}^{\mathrm{eq}}(z)}{N_l^{\mathrm{eq}}} N_{B-L}(z)$$

$$\frac{dN_{N_1}(z)}{dz} = -K\, z \frac{K_1(z)}{K_2(z)}(N_{N_1}(z) - N_{N_1}^{\mathrm{eq}}(z))$$

4-Calculate the baryon-to-photon ratio

$$\eta_B = \frac{c}{f} N_{B-L}^{T=0}$$

Recipe to calculate the BAU in leptogenesis

1- Take your favourite neutrino model (h_ν, M)

2- Calculate ϵ, $K = \frac{\widetilde{m}_1}{m_*}$

$$\epsilon = \frac{3}{16\pi} \frac{1}{(h_\nu h_\nu^\dagger)_{11}} \sum_i \mathrm{Im}\left[(h_\nu h_\nu^\dagger)^2_{1i}\right] \frac{M_1}{M_i}$$

$$\widetilde{m}_1 = (hh^\dagger)_{11} \frac{v^2}{M_1} \qquad m_* \simeq 10^{-3}\,\mathrm{eV}$$

3- Solve the Boltzmann equations to obtain $N_{B-L}^{T=0}$

$$\frac{dN_{B-L}(z)}{dz} = -\epsilon\, K\, z \frac{K_1(z)}{K_2(z)} (N_{N_1}(z) - N_{N_1}^{\mathrm{eq}}(z)) - \frac{1}{2} K\, z \frac{K_1(z)}{K_2(z)} \frac{N_{N_1}^{\mathrm{eq}}(z)}{N_l^{\mathrm{eq}}} N_{B-L}(z)$$

$$\frac{dN_{N_1}(z)}{dz} = -K\, z \frac{K_1(z)}{K_2(z)} (N_{N_1}(z) - N_{N_1}^{\mathrm{eq}}(z))$$

4-Calculate the baryon-to-photon ratio

$$\eta_B = \frac{c}{f} N_{B-L}^{T=0}$$

5-Compare with the experimental value! $\eta_B = (6.11 \pm 0.19) \times 10^{-10}$

Connection leptogenesis-neutrino masses

The leptogenesis predictions depend on the high energy see-saw parameters h_ν, M. On the other hand, these same parameters give rise to neutrino masses and mixing angles:

$$-\mathcal{L}_{lep} = \nu_R^{c\,T} h_\nu L \cdot H - \frac{1}{2}\nu_R^{c\,T}\, M\, \nu_R^c + \text{h.c.}$$

$$\Big\downarrow \quad M \gg \langle H^0 \rangle$$

$$-\mathcal{L}_{\text{eff}} = -\frac{1}{2}(L \cdot H)^T \left[h_\nu^T M^{-1} h_\nu\right](L \cdot H) + \text{h.c.}$$

$$\boxed{\mathcal{M}_\nu = h_\nu^T M^{-1} h_\nu \langle H^0 \rangle^2}$$

What can are the implications for leptogenesis of the observed neutrino masses and mixing angles?

The connection is not simple...

- The high energy leptonic Lagrangian contains 12+6 new parameters

One can always choose a basis where the right-handed mass matrix is diagonal and real (but not the Yukawa coupling):

M has 3 real parameters

h_ν has 9 real parameters and 6 phases

- The effective Lagrangian contains 6+3 new parameters

$\mathcal{M}_\nu$ has six real parameters (3 masses, 3 angles) and three phases

Half of the parameters have been lost in the decoupling process (six real parameters and three phases).

There is, compatible with the observed neutrino parameters, an infinite set of Yukawa couplings!

Parametrization of the “lost” parameters:

Work in the basis where the right-handed neutrino mass matrix is diagonal:

$$\mathcal{M}_\nu = h_\nu^T \, D_M^{-1} \, h_\nu \, \langle H^0 \rangle^2 = U_{\rm lep}^* \, D_m \, U_{\rm lep}^\dagger$$

The most general Yukawa coupling which solves this equation is:

$$\boxed{h_\nu = \frac{1}{\langle H^0 \rangle} \sqrt{D_M} \, R \, \sqrt{D_m} \, U_{\rm lep}^\dagger}$$

Casas, AI

Orthogonal matrix: $R^T R = 1$

Parametrization of the "lost" parameters:

Work in the basis where the right-handed neutrino mass matrix is diagonal:

$$\mathcal{M}_\nu = h_\nu^T \, D_M^{-1} \, h_\nu \, \langle H^0 \rangle^2 = U_{\rm lep}^* \, D_m \, U_{\rm lep}^\dagger$$

The most general Yukawa coupling which solves this equation is:

$$\boxed{h_\nu = \frac{1}{\langle H^0 \rangle} \sqrt{D_M} \, R \, \sqrt{D_m} \, U_{\rm lep}^\dagger}$$

Casas, AI

Check: $\mathcal{M}_\nu = U_{\rm lep}^* \sqrt{D_m} \, R^T \sqrt{D_M} \, D_M^{-1} \sqrt{D_M} \, R \sqrt{D_m} \, U_{\rm lep}^\dagger$

Parametrization of the "lost" parameters:

Work in the basis where the right-handed neutrino mass matrix is diagonal:

$$\mathcal{M}_\nu = h_\nu^T \, D_M^{-1} \, h_\nu \, \langle H^0 \rangle^2 = U_{\rm lep}^* \, D_m \, U_{\rm lep}^\dagger$$

The most general Yukawa coupling which solves this equation is:

$$\boxed{h_\nu = \frac{1}{\langle H^0 \rangle} \sqrt{D_M} \, R \, \sqrt{D_m} \, U_{\rm lep}^\dagger}$$

Casas, AI

Check: $\mathcal{M}_\nu = U_{\rm lep}^* \sqrt{D_m} \, R^T \cancel{\sqrt{D_M}} \, \cancel{D_M^{-1}} \, \cancel{\sqrt{D_M}} \, R \sqrt{D_m} \, U_{\rm lep}^\dagger$

$$U_{\rm lep}^* \sqrt{D_m} \, R^T \, R \sqrt{D_m} \, U_{\rm lep}^\dagger$$

Parametrization of the “lost” parameters:

Work in the basis where the right-handed neutrino mass matrix is diagonal:

$$\mathcal{M}_\nu = h_\nu^T \, D_M^{-1} \, h_\nu \, \langle H^0 \rangle^2 = U_{\rm lep}^* \, D_m \, U_{\rm lep}^\dagger$$

The most general Yukawa coupling which solves this equation is:

$$\boxed{h_\nu = \frac{1}{\langle H^0 \rangle} \sqrt{D_M} \, R \, \sqrt{D_m} \, U_{\rm lep}^\dagger}$$

Casas, AI

Check: $\mathcal{M}_\nu = U_{\rm lep}^* \sqrt{D_m} \, R^T \cancel{\sqrt{D_M}} \, \cancel{D_M^{-1}} \, \cancel{\sqrt{D_M}} \, R \sqrt{D_m} \, U_{\rm lep}^\dagger$

$R^T R = 1$

$$U_{\rm lep}^* \sqrt{D_m} \, \cancel{R^T} \, \cancel{R} \sqrt{D_m} \, U_{\rm lep}^\dagger$$

$$U_{\rm lep}^* \, D_m \, U_{\rm lep}^\dagger$$

Parametrization of the "lost" parameters:

Work in the basis where the right-handed neutrino mass matrix is diagonal:

$$\mathcal{M}_\nu = h_\nu^T\, D_M^{-1}\, h_\nu\, \langle H^0 \rangle^2 = U_{\rm lep}^*\, D_m\, U_{\rm lep}^\dagger$$

The most general Yukawa coupling which solves this equation is:

$$\boxed{h_\nu = \frac{1}{\langle H^0 \rangle} \sqrt{D_M}\, R\, \sqrt{D_m}\, U_{\rm lep}^\dagger}$$

Casas, AI

Right-handed neutrino masses

3 real parameters

"Fixed" by experiments

$$R = \begin{pmatrix} \hat{c}_2 \hat{c}_3 & -\hat{c}_1 \hat{s}_3 - \hat{s}_1 \hat{s}_2 \hat{c}_3 & \hat{s}_1 \hat{s}_3 - \hat{c}_1 \hat{s}_2 \hat{c}_3 \\ \hat{c}_2 \hat{s}_3 & \hat{c}_1 \hat{c}_3 - \hat{s}_1 \hat{s}_2 \hat{s}_3 & -\hat{s}_1 \hat{c}_3 - \hat{c}_1 \hat{s}_2 \hat{s}_3 \\ \hat{s}_2 & \hat{s}_1 \hat{c}_2 & \hat{c}_1 \hat{c}_2 \end{pmatrix}$$

3 real parameters and 3 phases

Does leptogenesis make any prediction?

How to test/rule-out leptogenesis?

Does leptogenesis make any prediction?

How to test/rule-out leptogenesis?

Even though the connection between leptogenesis and low energy neutrino data is very vague, this parametrization allows to extract very valuable information about leptogenesis.

1) Upper bound on the CP asymmetry ($\Rightarrow$Lower bound on the lightest right-handed neutrino mass)

2) Upper bound on the overall neutrino mass scale (*)

(*) Or may be not

1- Upper bound on the CP asymmetry

Consider the scenario with hierarchical right-handed neutrinos. In this limit, the CP asymmetry produced in the decay of the lightest right-handed neutrino is:

$$\epsilon_1 = \frac{1}{8\pi} \frac{1}{(h_\nu h_\nu^\dagger)_{11}} \sum_{i=2,3} \mathrm{Im}\left[(h_\nu h_\nu^\dagger)^2_{1i}\right] \left[f\left(\frac{M_i^2}{M_1^2}\right) + g\left(\frac{M_i^2}{M_1^2}\right)\right]$$

In the limit of hierarchical right-handed neutrinos $M_1 \ll M_2, M_3$

$$\epsilon_1 = \frac{3}{16\pi} \frac{1}{(h_\nu h_\nu^\dagger)_{11}} \sum_i \mathrm{Im}\left[(h_\nu h_\nu^\dagger)^2_{1i}\right] \frac{M_1}{M_i}$$

$$\epsilon_1 = \frac{3}{16\pi} \frac{M_1}{\langle H^0\rangle^2} \frac{1}{(h_\nu h_\nu^\dagger)_{11}} \sum_i \mathrm{Im}\left[(h_\nu \mathcal{M}_\nu^\dagger h_\nu^T)_{1i}\right]$$

Substituting the previous parametrization of the neutrino Yukawa coupling:

$$\epsilon_1 = \frac{3}{16\pi} \frac{M_1}{\langle H^0\rangle^2} \frac{\sum_j m_j^2 \mathrm{Im}(R_{1j}^2)}{\sum_j m_j |R_{1j}|^2}$$

which is bounded from above by: $\boxed{|\epsilon_1| \leq \frac{3}{16\pi} \frac{M_1}{\langle H^0\rangle^2}(m_3 - m_1)}$ Davidson, AI

Very important! The bound becomes more strict if the neutrino masses are large.

$$|\epsilon_1| \le \frac{3}{16\pi}\frac{M_1}{\langle H^0\rangle^2}(m_3 - m_1) = \frac{3}{16\pi}\frac{M_1}{\langle H^0\rangle^2}\frac{(m_3^2 - m_1^2)}{m_3 + m_1} = \frac{3}{16\pi}\frac{M_1}{\langle H^0\rangle^2}\frac{\Delta m^2_{atm}}{m_3 + m_1}$$

Fixed by experiments

More later about this!

- However, if neutrinos are hierarchical. Then

$$\boxed{|\epsilon_1| \le \frac{3}{16\pi}\frac{M_1\sqrt{\Delta m^2_{\rm atm}}}{\langle H^0\rangle^2}}$$

The CP asymmetry is bounded from above by the mass of the lightest right-handed neutrino and the square root of the atmospheric mass splitting.

Direct window on the scale at which neutrino masses are generated, from the requirement of successful leptogenesis.

The baryon asymmetry from leptogenesis can be approximated by:

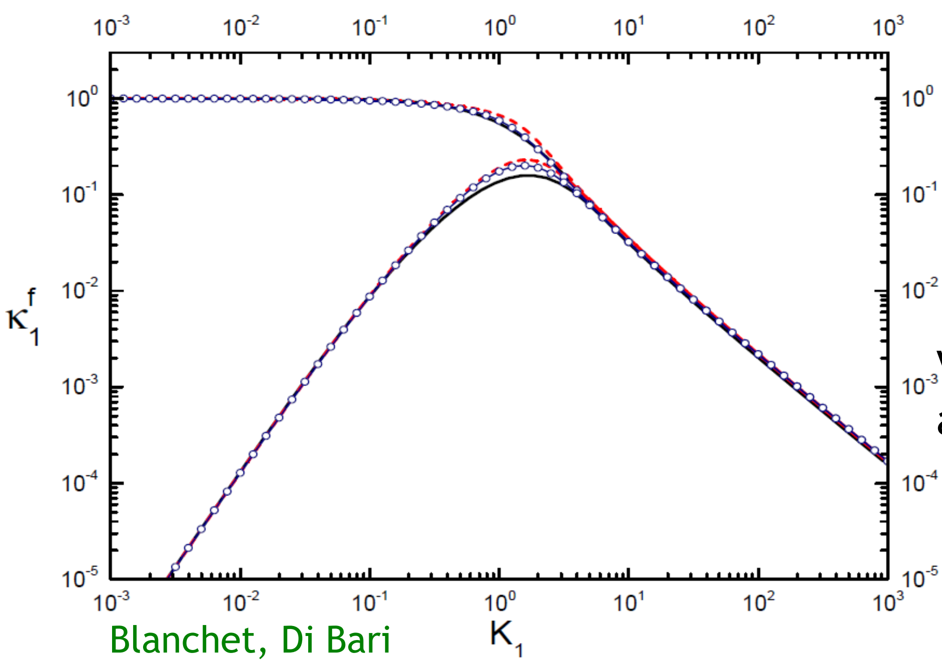
$$\eta_B \simeq 0.96 \times 10^{-2}\, \epsilon_1 \kappa$$

where $\eta_B = (6.11 \pm 0.19) \times 10^{-10}$ (WMAP)

From the upper bound on the CP asymmetry $|\epsilon_1| \leq \frac{3}{16\pi} \frac{M_1 \sqrt{\Delta m^2_{\rm atm}}}{\langle H^0 \rangle^2}$

A lower bound on the lightest right-handed neutrino mass follows:

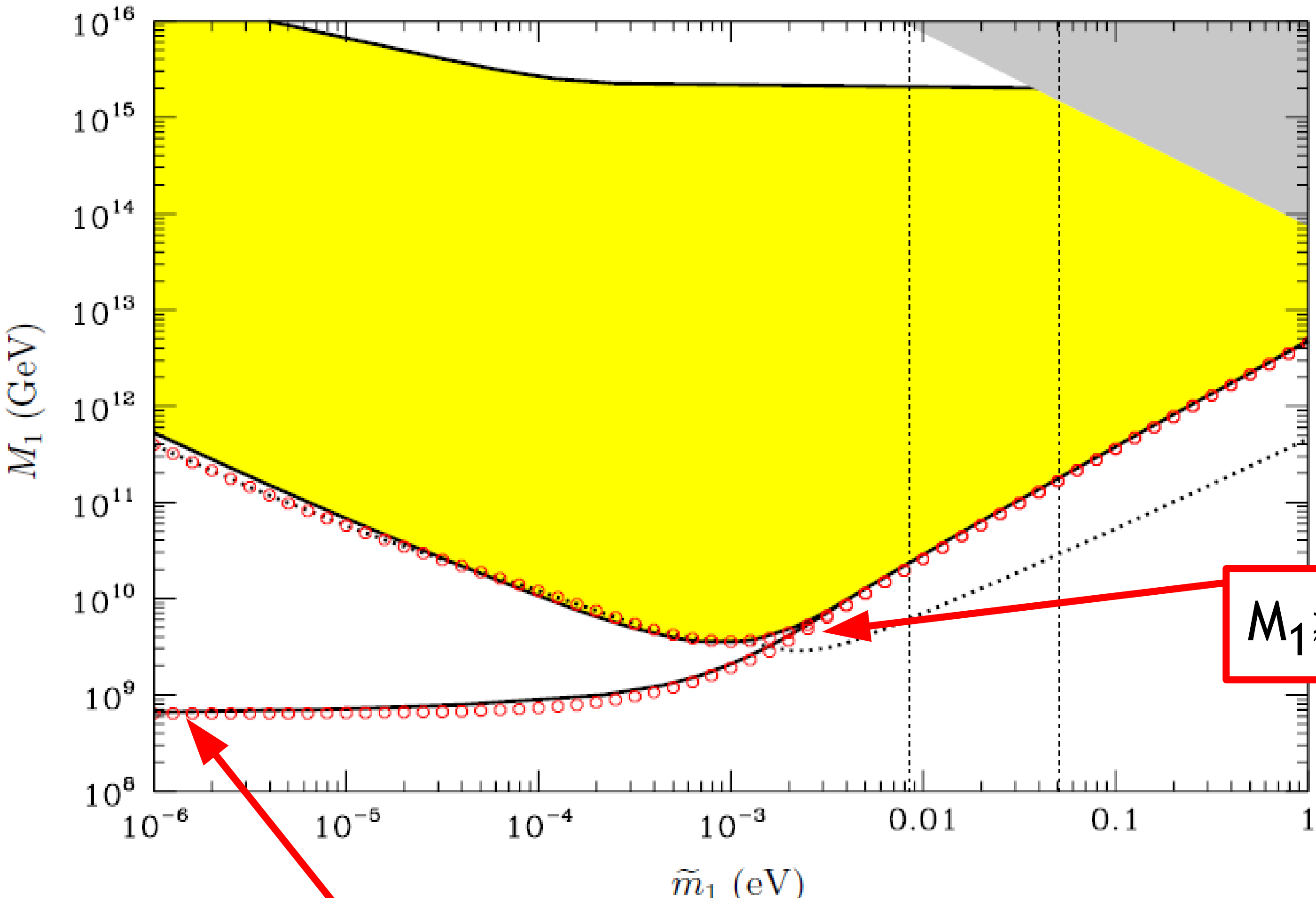
$$M_1 \gtrsim \frac{6 \times 10^8\ \mathrm{GeV}}{\kappa}$$



Blanchet, Di Bari

thermal initial abundance $\kappa \lesssim 1$ ➡ $\boxed{M_1 \gtrsim 6 \times 10^8\ \mathrm{GeV}}$

Vanishing initial abundance $\kappa \lesssim 0.2$ ➡ $\boxed{M_1 \gtrsim 3 \times 10^9\ \mathrm{GeV}}$



Buchmüller, Di Bari, Plümacher

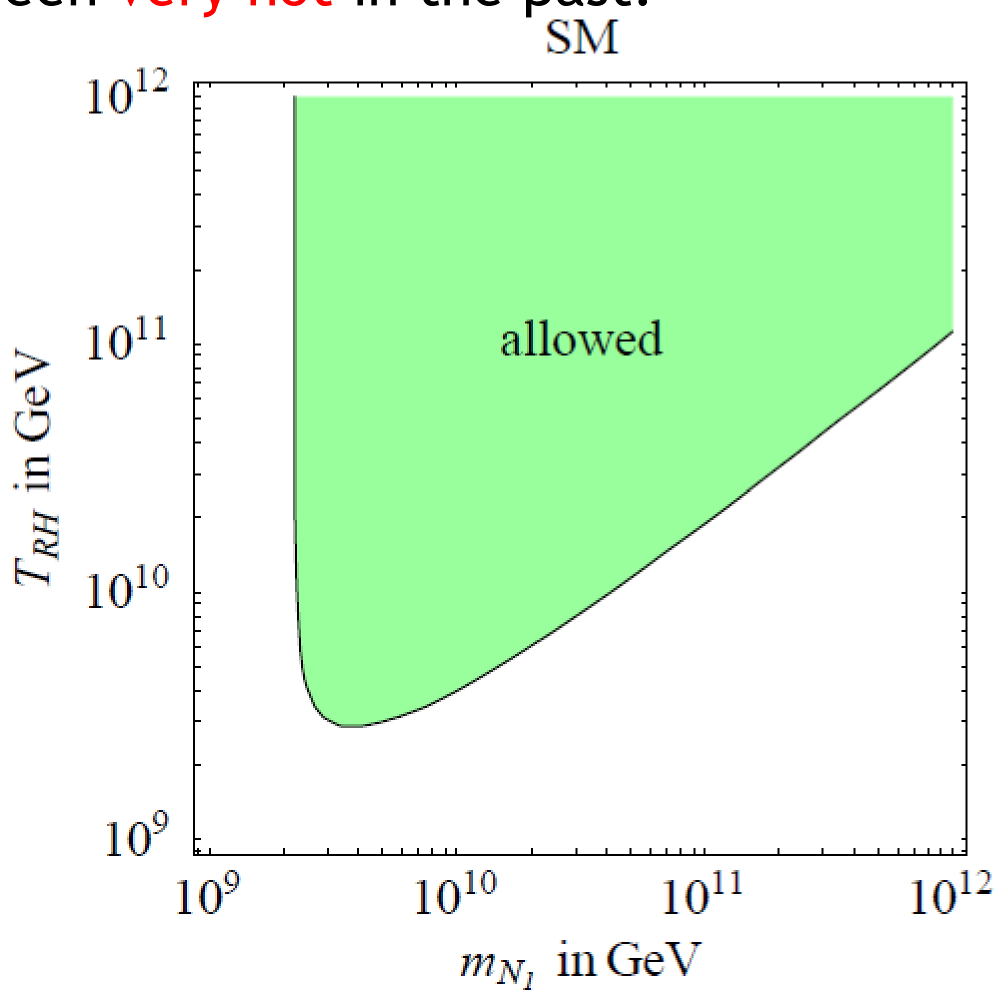
$M_1 \gtrsim 3\times10^9$ GeV

$M_1 \gtrsim 6\times10^8$ GeV

Neutrino masses are generated at VERY high energies

Implications for inflation

To produce thermally the right-handed neutrinos the Universe must have been very hot in the past:



Giudice et al.

Inflation must have reheated the Universe to temperatures larger than 10^9–10^{10} GeV $\Rightarrow$ constraint on inflationary models

Implications for SUSY scenarios

DRAMATIC!

The leptogenesis requirement that the lightest right-handed neutrino mass has to be larger than 10^9 GeV rules out many SUSY scenarios (among them, many scenarios with neutralino dark matter!)

More details later...

2- Upper bound on the neutrino mass

- The upper bound on the CP asymmetry can be rewritten as:

$$|\epsilon_1| \leq \frac{3}{16\pi}\frac{M_1}{\langle H^0\rangle^2}(m_3 - m_1) = \frac{3}{16\pi}\frac{M_1}{\langle H^0\rangle^2}\frac{(m_3^2 - m_1^2)}{m_3 + m_1} = \frac{3}{16\pi}\frac{M_1}{\langle H^0\rangle^2}\frac{\Delta m_{atm}^2}{m_3 + m_1}$$

Neutrino experiments fix the atmospheric mass splitting. Then, if the scale of neutrino masses increases, the CP asymmetry produced is smaller. It is more difficult to generate a BAU!

- Furthermore, the washout rate due to ΔL=2 scatterings goes as:

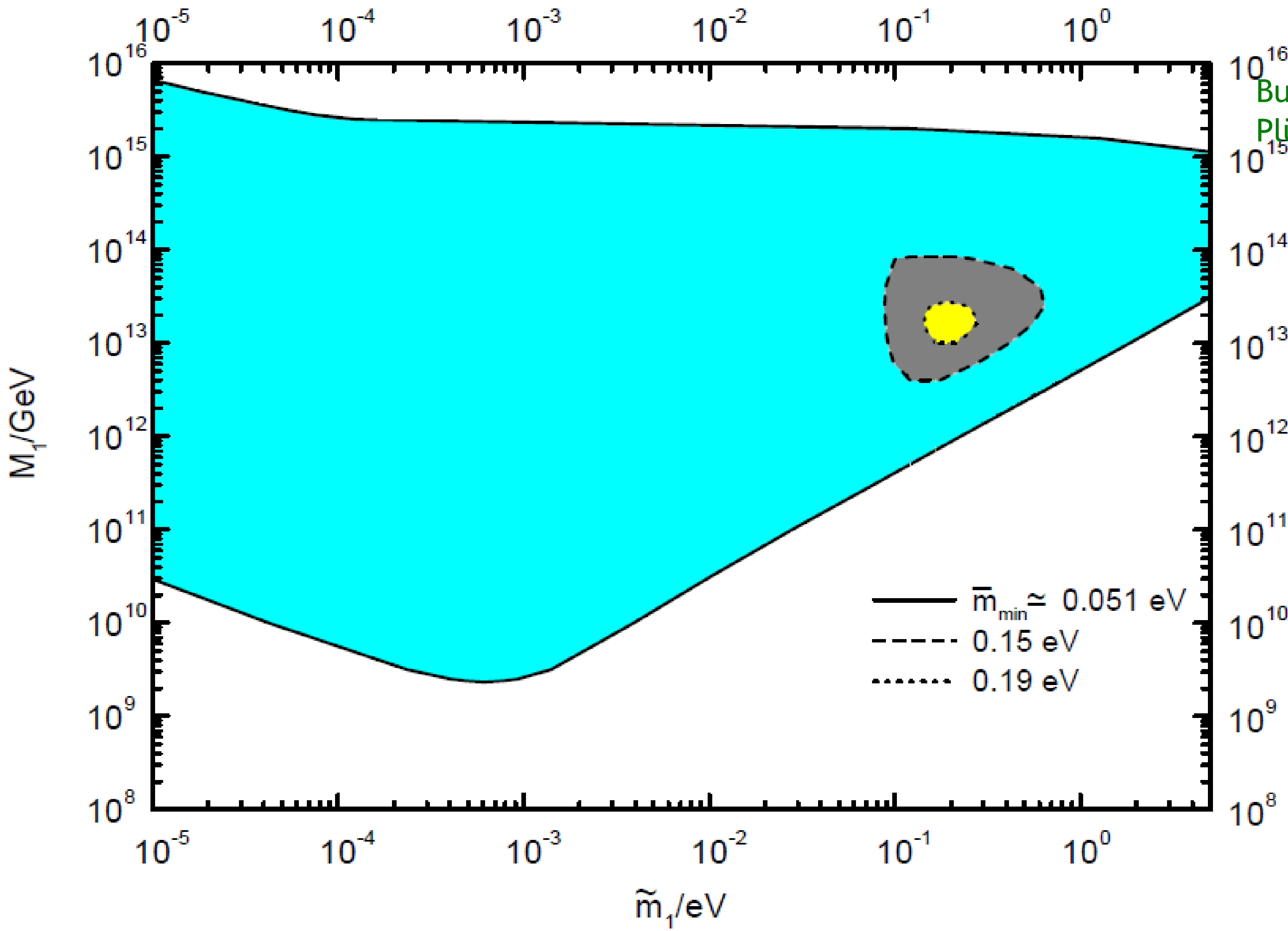
$$\Delta W \propto M_1 \overline{m}^2$$

$$\overline{m}^2 = m_1^2 + m_2^2 + m_3^2$$

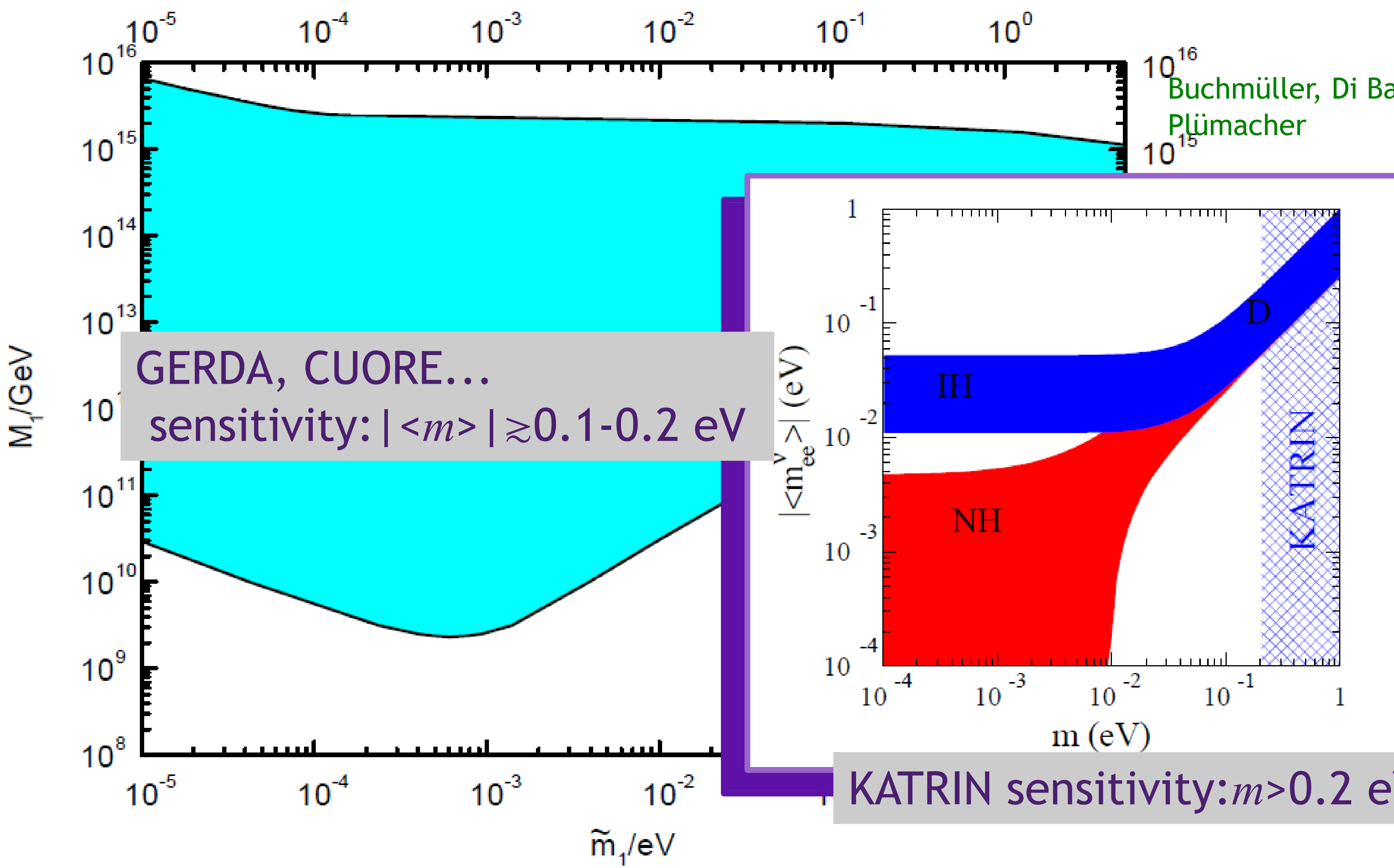
The larger the scale of neutrino masses, the larger the washout.

Is there a neutrino mass at which leptogenesis just doesn't work?

Buchmüller, Di Bari, Plümacher



For $\overline{m}$>0.20 eV, leptogenesis is no longer possible.
This corresponds to m_i>0.11 eV



Buchmüller, Di Bari, Plümacher

GERDA, CUORE…
sensitivity: $|\langle m\rangle| \gtrsim 0.1$-$0.2$ eV

KATRIN sensitivity: $m > 0.2$ eV

For $\overline{m} > 0.20$ eV, leptogenesis is no longer possible.
This corresponds to $m_i > 0.11$ eV

If $\nu 0 2\beta$ or tritium β decay experiments find a signal in the near future, leptogenesis will be disfavoured.

The role of flavour on leptogenesis

So far we have calculated the lepton asymmetry. Is it justified to talk about a lepton asymmetry, when we know that there are three leptonic flavours?

YES, but only when T$\gtrsim 10^{12}$ GeV.

The lepton Yukawa coupling $e_{R\alpha}^{T} h_{\ell\alpha} (L_\alpha \cdot H)$ can be strong enough to keep processes as $e_{L\alpha} e_{R\alpha} \to H \quad e_{L\alpha} e_{R\alpha} \to HV$ in equilibrium

The interaction rate is: $\Gamma_\alpha \simeq 5 \times 10^{-3} h_{\ell_\alpha}^2 T$

Therefore, the tau Yukawa interactions enter equilibrium at T$\sim 10^{12}$ GeV and the muon Yukawa interactions at T$\sim 10^{9}$ GeV.

What happens at $10^9 \lesssim T \lesssim 10^{12}$ GeV?

The tau Yukawa interactions are in equilibrium, while the muon and electron Yukawa interactions are out of equilibrium. The flavour of the lepton in the decay $N_1 \to H\, L_\alpha$ matters!!

The charged lepton Yukawa interactions break the coherent evolution of the lepton doublets, L_α, between the decay and the inverse decay→ below $T \sim 10^{12}$ GeV flavours are distinguishable.

Every leptonic flavour asymmetry evolves differently, and we have to deal with different flavour asymmetries, a set of Boltzmann equations, etc.

The total lepton asymmetry in the one flavour approximation is:

$$\eta_B = \frac{c^{\rm sph}}{f} N^{\rm f}_{B-L} = -\frac{3}{4f}\, c^{\rm sph}\, \epsilon_1\, \kappa$$

If flavours are propertly taken into account,

$$\eta_B = \sum_\alpha \frac{c^{\rm sph}_\alpha}{f} N^{\rm f}_{\Delta_\alpha} \sim -\frac{3}{4f} \left[c^{\rm sph}_e\, \epsilon_{1e}\, \kappa_e + c^{\rm sph}_\mu\, \epsilon_{1\mu}\, \kappa_\mu + c^{\rm sph}_\tau\, \epsilon_{1\tau}\, \kappa_\tau \right]$$

$$\Delta_\alpha \equiv B/3 - L_\alpha$$

Different scenarios depending on the temperature:

$T \gtrsim 10^{12}$ GeV

- One flavour approximation valid. Boltzmann equations:

$$\frac{dN_{B-L}(z)}{dz} = -\epsilon\, K\, z \frac{K_1(z)}{K_2(z)}(N_{N_1}(z) - N_{N_1}^{\rm eq}(z)) - \frac{1}{2} K\, z \frac{K_1(z)}{K_2(z)} \frac{N_{N_1}^{\rm eq}(z)}{N_l^{\rm eq}} N_{B-L}(z)$$

$$\frac{dN_{N_1}(z)}{dz} = -K\, z \frac{K_1(z)}{K_2(z)}(N_{N_1}(z) - N_{N_1}^{\rm eq}(z))$$

- One CP asymmetry

$$\epsilon_1 = \frac{3}{16\pi} \frac{1}{(h_\nu h_\nu^\dagger)_{11}} \sum_i \mathrm{Im}\left[(h_\nu h_\nu^\dagger)^2_{1i}\right] \frac{M_1}{M_i}$$

- One wash-out factor

$$K = \frac{\Gamma_{D_1}|_{T=0}}{H|_{T=M_1}} = \frac{\widetilde{m}_1}{m_*}$$

where $\widetilde{m}_1 = (hh^\dagger)_{11} \dfrac{v^2}{M_1} \qquad m_* = 8\pi\, 1.66 g_*^{1/2} \dfrac{v^2}{M_P} \simeq 10^{-3}\,\mathrm{eV}$

Different scenarios depending on the temperature:

$T \gtrsim 10^{12}$ GeV

- One flavour approximation valid. Boltzmann equations:

$$\frac{dN_{B-L}(z)}{dz} = -\epsilon\, K\, z \frac{K_1(z)}{K_2(z)}(N_{N_1}(z) - N_{N_1}^{\rm eq}(z)) - \frac{1}{2}\, K\, z \frac{K_1(z)}{K_2(z)} \frac{N_{N_1}^{\rm eq}(z)}{N_l^{\rm eq}} N_{B-L}(z)$$

$$\frac{dN_{N_1}(z)}{dz} = -K\, z \frac{K_1(z)}{K_2(z)}(N_{N_1}(z) - N_{N_1}^{\rm eq}(z))$$

The baryon asymmetry produced is

$$\boxed{\eta_B = \frac{c^{\rm sph}}{f}\, N_{B-L}^{\rm f}}$$

Different scenarios depending on the temperature:

$10^9 \lesssim T \lesssim 10^{12}$ GeV

One flavour approximation not valid. Tau Yukawa couplings in equilibrium
⇒ tau flavour distinguishable. Electron and muon flavour indistinguishable

- Two Boltzmann equations: $\alpha = \tau$, "$e+\mu \equiv 2$"

$$\frac{dN_{\Delta_\alpha}(z)}{dz} = -\epsilon_\alpha\, K\, z\frac{K_1(z)}{K_2(z)}(N_{N_1}(z) - N_{N_1}^{\mathrm{eq}}(z)) - \frac{1}{4}\, K_\alpha\, z^3 K_1(z) N_{\Delta_\alpha}(z)$$

$$\frac{dN_{N_1}(z)}{dz} = -K\, z\, \frac{K_1(z)}{K_2(z)}(N_{N_1}(z) - N_{N_1}^{\mathrm{eq}}(z))$$

- Two CP asymmetries: ϵ_τ, $\epsilon_2 = \epsilon_e + \epsilon_\mu$.

$$\epsilon_{1\alpha} = \frac{\Gamma(N_1 \to l_\alpha H) - \Gamma(N_1 \to l_\alpha^c H^c)}{\Gamma(N_1 \to l_\alpha H) + \Gamma(N_1 \to l_\alpha^c H^c)}$$
$$\simeq \frac{3}{16\pi}\frac{1}{(h_\nu h_\nu^\dagger)_{11}} \sum_{i=2,3} \mathrm{Im}\left[h_{\nu 1\alpha}(h_\nu h_\nu^\dagger)_{1i} h^*_{\nu i\alpha}\right] \frac{M_1}{M_i}$$

- Two wash-out factors: K_τ, $K_2 = K_e + K_\mu$.

$$K_\alpha = \frac{\Gamma_D(N_1 \to l_\alpha H)|_{T=0}}{H|_{T=M_1}} = \frac{\widetilde{m}_{1\alpha}}{m_*} \quad \text{where} \quad \widetilde{m}_{1\alpha} = h_{1\alpha} h^*_{1\alpha}\frac{v^2}{M_1}$$

Different scenarios depending on the temperature:

$10^9 \lesssim T \lesssim 10^{12}$ GeV

One flavour approximation not valid. Tau Yukawa couplings in equilibrium
$\Rightarrow$ tau flavour distinguishable. Electron and muon flavour indistinguishable

- Two Boltzmann equations: $\alpha = \tau$, "$e+\mu \equiv 2$"

$$\frac{dN_{\Delta_\alpha}(z)}{dz} = -\epsilon_\alpha \, K \, z \frac{K_1(z)}{K_2(z)} (N_{N_1}(z) - N_{N_1}^{\text{eq}}(z)) - \frac{1}{4} K_\alpha \, z^3 K_1(z) N_{\Delta_\alpha}(z)$$

$$\frac{dN_{N_1}(z)}{dz} = -K \, z \, \frac{K_1(z)}{K_2(z)} (N_{N_1}(z) - N_{N_1}^{\text{eq}}(z))$$

The baryon asymmetry produced is

$$\boxed{\eta_B = -\frac{1}{f} \frac{12}{37} \left[N_{\Delta_2} \left(\epsilon_2, \frac{417}{589} K_2 \right) + N_{\Delta_\tau} \left(\epsilon_\tau, \frac{390}{589} K_\tau \right) \right]}$$

Different scenarios depending on the temperature:

$T \lesssim 10^9$ GeV

Tau and muon Yukawa couplings in equilibrium ⇒ all lepton flavours are distinguishable

- Three Boltzmann equations: $\alpha = e, \mu, \tau$,

$$\frac{dN_{\Delta_\alpha}(z)}{dz} = -\epsilon_\alpha\, K\, z \frac{K_1(z)}{K_2(z)}(N_{N_1}(z) - N_{N_1}^{\rm eq}(z)) - \frac{1}{4}\, K_\alpha\, z^3 K_1(z) N_{\Delta_\alpha}(z)$$

$$\frac{dN_{N_1}(z)}{dz} = -K\, z\, \frac{K_1(z)}{K_2(z)}(N_{N_1}(z) - N_{N_1}^{\rm eq}(z))$$

- Three CP asymmetries

$$\epsilon_{1\alpha} = \frac{\Gamma(N_1 \to l_\alpha H) - \Gamma(N_1 \to l_\alpha^c H^c)}{\Gamma(N_1 \to l_\alpha H) + \Gamma(N_1 \to l_\alpha^c H^c)}$$

$$\simeq \frac{3}{16\pi} \frac{1}{(h_\nu h_\nu^\dagger)_{11}} \sum_{i=2,3} \mathrm{Im}\left[h_{\nu 1\alpha}(h_\nu h_\nu^\dagger)_{1i} h^*_{\nu i\alpha})\right] \frac{M_1}{M_i}$$

- Three wash-out factors

$$K_\alpha = \frac{\Gamma_D(N_1 \to l_\alpha H)|_{T=0}}{H|_{T=M_1}} = \frac{\widetilde{m}_{1\alpha}}{m_*}$$ where $$\widetilde{m}_{1\alpha} = h_{1\alpha} h^*_{1\alpha} \frac{v^2}{M_1}$$

Different scenarios depending on the temperature:

$T \lesssim 10^9$ GeV

Tau and muon Yukawa couplings in equilibrium $\Rightarrow$ all lepton flavours are distinguishable

- Three Boltzmann equations: $\alpha = e, \mu, \tau,$

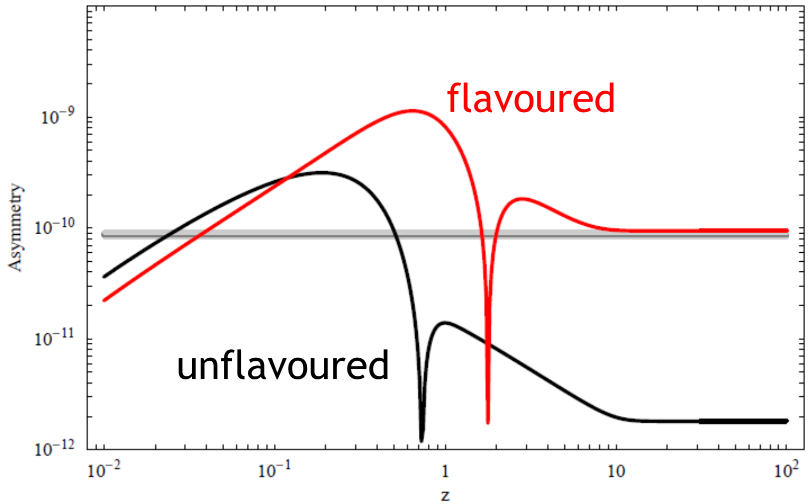
$$\frac{dN_{\Delta_\alpha}(z)}{dz} = -\epsilon_\alpha\, K\, z \frac{K_1(z)}{K_2(z)}\left(N_{N_1}(z) - N_{N_1}^{\mathrm{eq}}(z)\right) - \frac{1}{4}\, K_\alpha\, z^3 K_1(z) N_{\Delta_\alpha}(z)$$

$$\frac{dN_{N_1}(z)}{dz} = -K\, z\, \frac{K_1(z)}{K_2(z)}\left(N_{N_1}(z) - N_{N_1}^{\mathrm{eq}}(z)\right)$$

The baryon asymmetry produced is

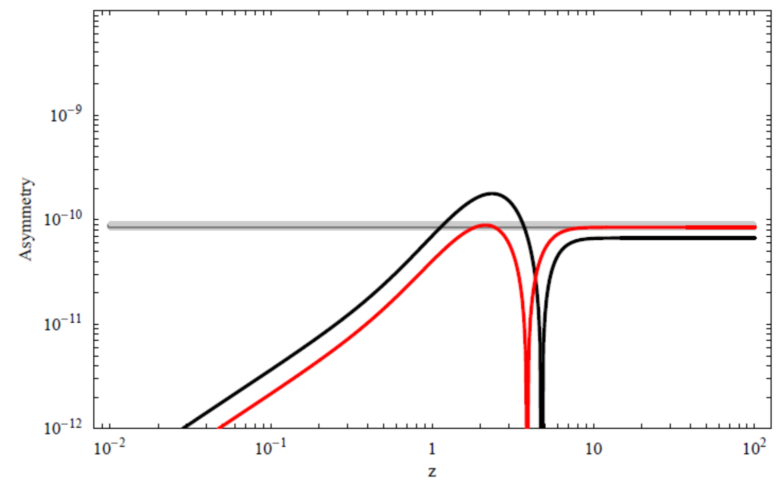
$$\boxed{\eta_B = -\frac{1}{f}\frac{12}{37}\left[N_{\Delta_e}\left(\epsilon_e, \frac{157}{179}K_e\right) + N_{\Delta_\mu}\left(\epsilon_\mu, \frac{344}{537}K_\mu\right) + N_{\Delta_\tau}\left(\epsilon_\tau, \frac{344}{537}K_\tau\right)\right]}$$

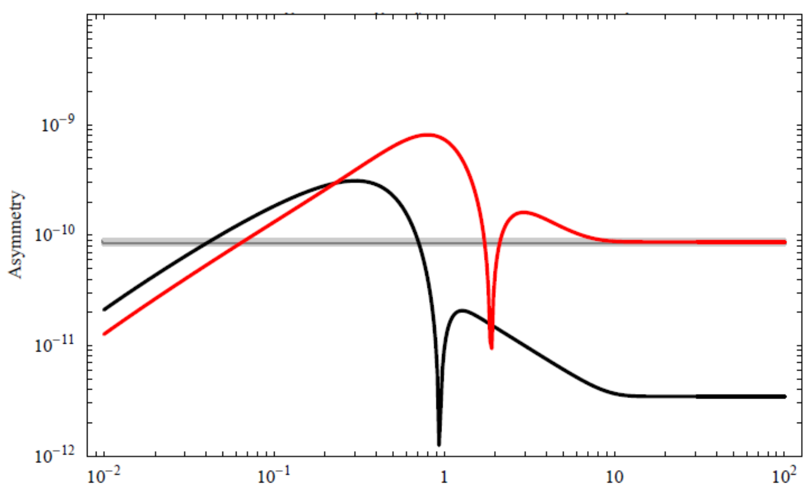
In each regime, several possibilities can occur: the asymmetry in some flavours could be strongly washed-out (K≫1), while in others could be weakly washed-out (K≪1).



$$K_\tau = 10 \qquad K_\mu = 30 \qquad K_e = 30$$
$$\epsilon_\tau = 2.5 \times 10^{-6} \qquad \epsilon_\mu = -2 \times 10^{-6} \qquad \epsilon_e = 10^{-7}$$

$$K_\tau = 0.45 \qquad K_\mu = 10^{-2} \qquad K_e = 2.5 \times 10^{-6}$$
$$\epsilon_\tau = 2.5 \times 10^{-6} \qquad \epsilon_\mu = -2 \times 10^{-6} \qquad \epsilon_e = 10^{-7}$$





$$K_\tau = 10 \qquad K_\mu = 30 \qquad K_e = 10^{-2}$$
$$\epsilon_\tau = 2.5 \times 10^{-6} \qquad \epsilon_\mu = -2 \times 10^{-6} \qquad \epsilon_e = 10^{-7}$$

What are the implications, *in practice?*

1- Flavour effects can be very important when computing the predictions in *specific* models.

For example, consider a model with two right-handed neutrinos. The most general Yukawa coupling compatible with the low energy data is:

$$\boxed{h_\nu = \frac{1}{\langle H^0 \rangle} \sqrt{D_M}\, R\, \sqrt{D_m}\, U_{\rm lep}^\dagger}$$

Right-handed neutrino masses

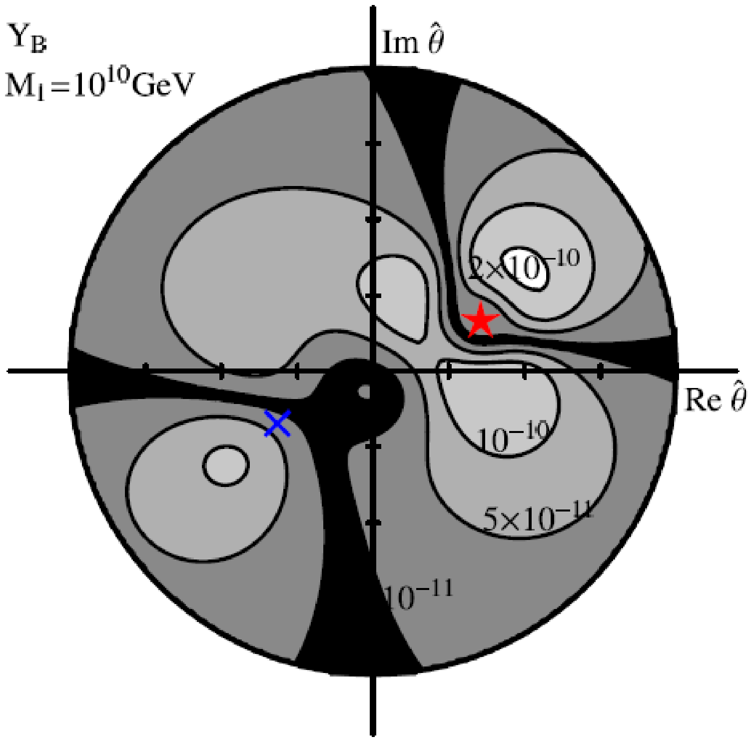
"Fixed" by experiments

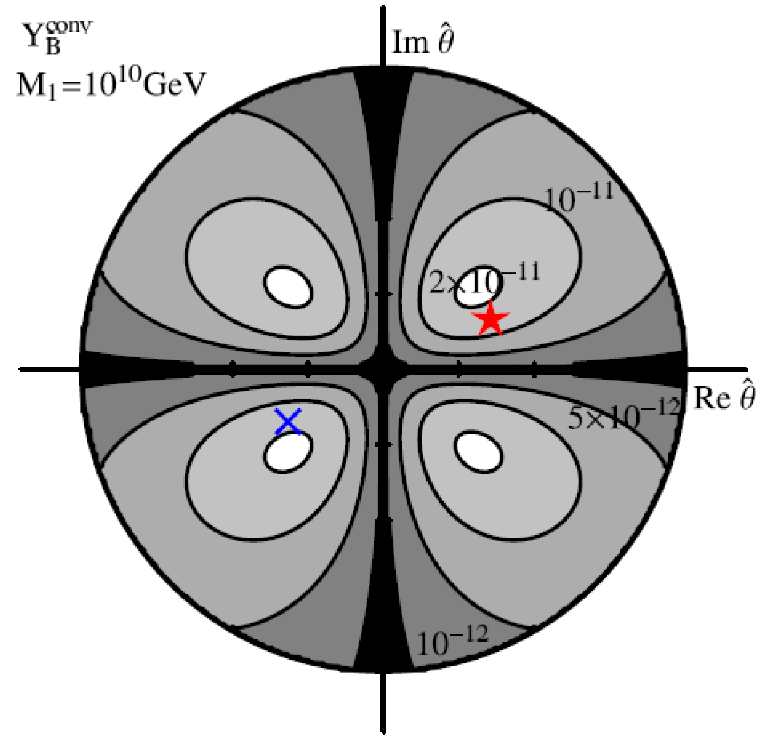
$$R = \begin{pmatrix} 0 & \cos\hat\theta & \xi \sin\hat\theta \\ 0 & -\sin\hat\theta & \xi\cos\hat\theta \end{pmatrix}$$ (normal hierarchy)

$$R = \begin{pmatrix} \cos\hat\theta & \xi \sin\hat\theta & 0 \\ -\sin\hat\theta & \xi\cos\hat\theta & 0 \end{pmatrix}$$ (inverted hierarchy)

flavoured

unflavoured





normal hierarchy , $\theta_{13} = 0.1$, $\delta = \pi/4$, $\phi = \pi/3$

The differences are maximal:

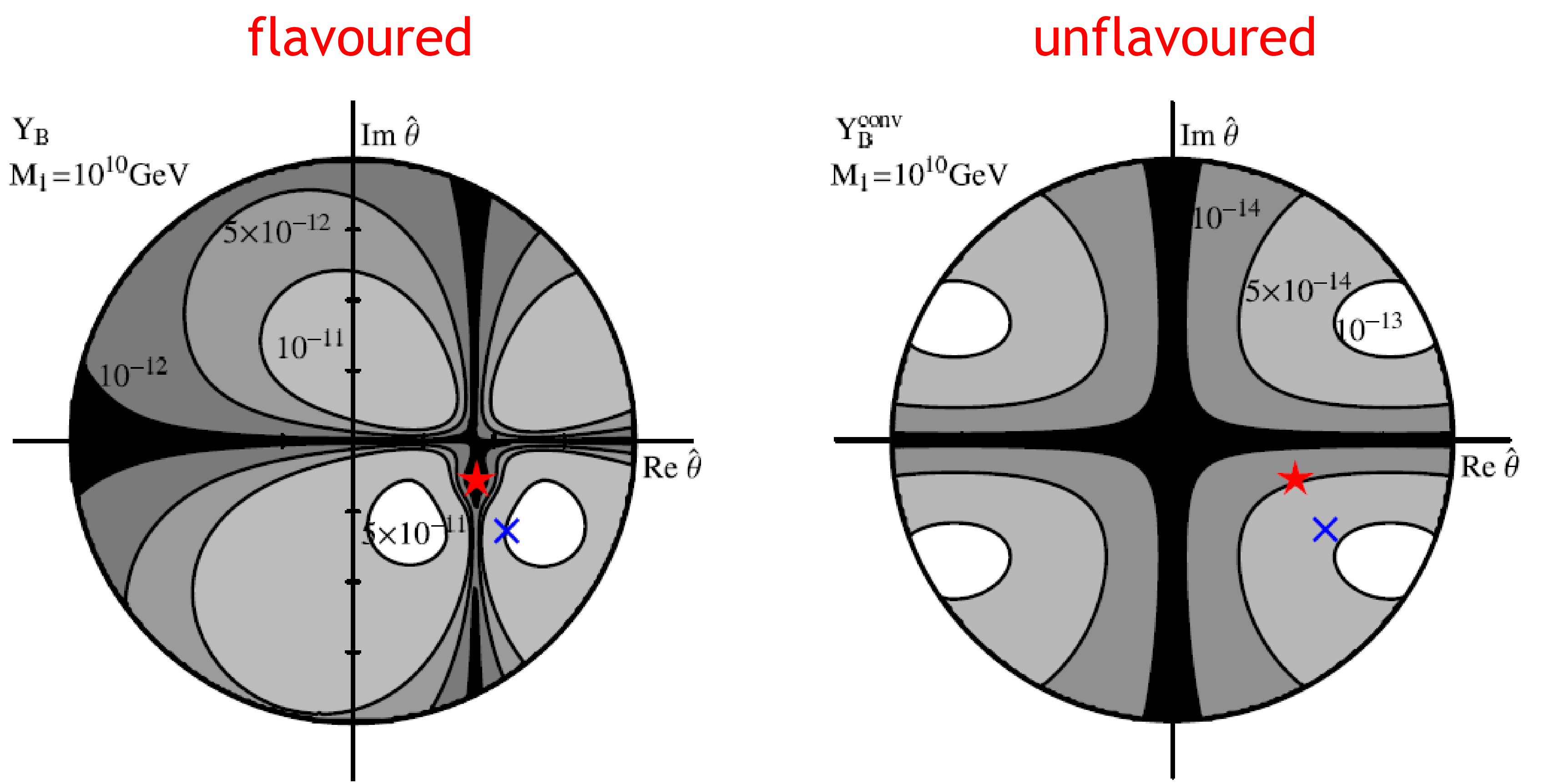
- Along the axes: R is real or pure imaginary

  In the one flavour approximation $\epsilon_1 \propto \mathrm{Im}\sin^2\hat{\theta}$

- Around texture zeros in the neutrino Yukawa matrix

★ $h_{\nu 13} = 0$

× $h_{\nu 12} = 0$



inverted hierarchy, $\theta_{13} = 0.1$, $\delta = \pi/4$, $\phi = \pi/3$

The differences are maximal:

- Along the axes: R is real or pure imaginary

  In the one flavour approximation $\epsilon_1 \propto \mathrm{Im}\sin^2\hat\theta$

- Around texture zeros in the neutrino Yukawa matrix

$\star$ $h_{\nu 13} = 0$
$\times$ $h_{\nu 12} = 0$

2- Flavour effects provide a new insight in the connection between leptogenesis and low energy CP violation.

Take the most general Yukawa coupling compatible with the low energy neutrino observations.

$$h_\nu = \frac{1}{\langle H^0 \rangle} \sqrt{D_M}\, R \sqrt{D_m}\, U_{\rm lep}^\dagger$$

In the one flavour approximation:

$$\epsilon_1 = \frac{3}{16\pi} \frac{1}{(h_\nu h_\nu^\dagger)_{11}} \sum_i \mathrm{Im}\left[(h_\nu h_\nu^\dagger)_{1i}^2\right] \frac{M_1}{M_i}$$

$$\Downarrow$$

$$\epsilon_1 = \frac{3}{16\pi} \frac{M_1}{\langle H^0 \rangle^2} \frac{\sum_j m_j^2 \mathrm{Im}(R_{1j}^2)}{\sum_j m_j |R_{1j}|^2}$$

No trace of $U_{\rm lep}$. There is no connection between leptogenesis and the low energy phases and mixing angles.

2- Flavour effects provide a new insight in the connection between leptogenesis and low energy CP violation.

Take the most general Yukawa coupling compatible with the low energy neutrino observations.

$$h_\nu = \frac{1}{\langle H^0 \rangle} \sqrt{D_M}\, R\, \sqrt{D_m}\, U_{\rm lep}^\dagger$$

Taking flavours propertly into account:

$$\epsilon_{1\alpha} \simeq \frac{3}{16\pi} \frac{1}{(h_\nu h_\nu^\dagger)_{11}} \sum_{i=2,3} \mathrm{Im}\left[h_{\nu 1\alpha} (h_\nu h_\nu^\dagger)_{1i} h^*_{\nu i\alpha} \right] \frac{M_1}{M_i}$$

$$\Downarrow$$

$$\epsilon_\alpha = -\frac{3}{16\pi} \frac{M_1}{v^2} \frac{\mathrm{Im}\left\{ \sum_{\beta,\rho} m_\beta^{1/2} m_\rho^{3/2} U^*_{\alpha\beta} U_{\alpha\rho} R_{1\beta} R_{1\rho} \right\}}{\sum_\beta m_\beta |R^2_{1\beta}|}$$

There is still a dependence on $U_{\rm lep}$! If CP violation is observed in the neutrino sector, leptogenesis will gain support.

3- Bound on the lightest right-handed neutrino mass (and on the reheating temperature)

In the one flavour approximation, the CP asymmetry is bounded from above by:

$$|\epsilon_1| \leq \frac{3}{16\pi}\frac{M_1}{\langle H^0\rangle^2}(m_3 - m_1)$$

Taking flavours properly into account, the CP asymmetries in each flavour are bounded from above by:

$$\boxed{|\epsilon_\alpha| \lesssim \frac{3}{16\pi}\frac{M_1 m_3}{\langle H^0\rangle^2} \times \sqrt{\frac{K_\alpha}{K}}}$$

Approximating the BAU by

$$\eta_B = \sum_\alpha \frac{c_\alpha^{\rm sph}}{f} N_{\Delta_\alpha}^{\rm f} \sim -\frac{3}{4f}\left[c_e^{\rm sph}\,\epsilon_{1e}\,\kappa_e + c_\mu^{\rm sph}\,\epsilon_{1\mu}\,\kappa_\mu + c_\tau^{\rm sph}\,\epsilon_{1\tau}\,\kappa_\tau\right]$$

One finds that:

$$|\eta_B| \lesssim \frac{3}{4f}\frac{3}{16\pi}\frac{M_1 m_3}{\langle H^0\rangle^2}\left[c_e^{\rm sph}\sqrt{\frac{K_e}{K}}\,\kappa_e + c_\mu^{\rm sph}\sqrt{\frac{K_\mu}{K}}\,\kappa_\mu + c_\tau^{\rm sph}\sqrt{\frac{K_\tau}{K}}\,\kappa_\tau\right]$$

3- Bound on the lightest right-handed neutrino mass (and on the reheating temperature)

In the one flavour approximation, the CP asymmetry is bounded from above by:

$$|\epsilon_1| \leq \frac{3}{16\pi} \frac{M_1}{\langle H^0 \rangle^2} (m_3 - m_1)$$

Taking flavours properly into account, the CP asymmetries in each flavour are bounded from above by:

$$\boxed{|\epsilon_\alpha| \lesssim \frac{3}{16\pi} \frac{M_1 m_3}{\langle H^0 \rangle^2} \times \sqrt{\frac{K_\alpha}{K}}}$$

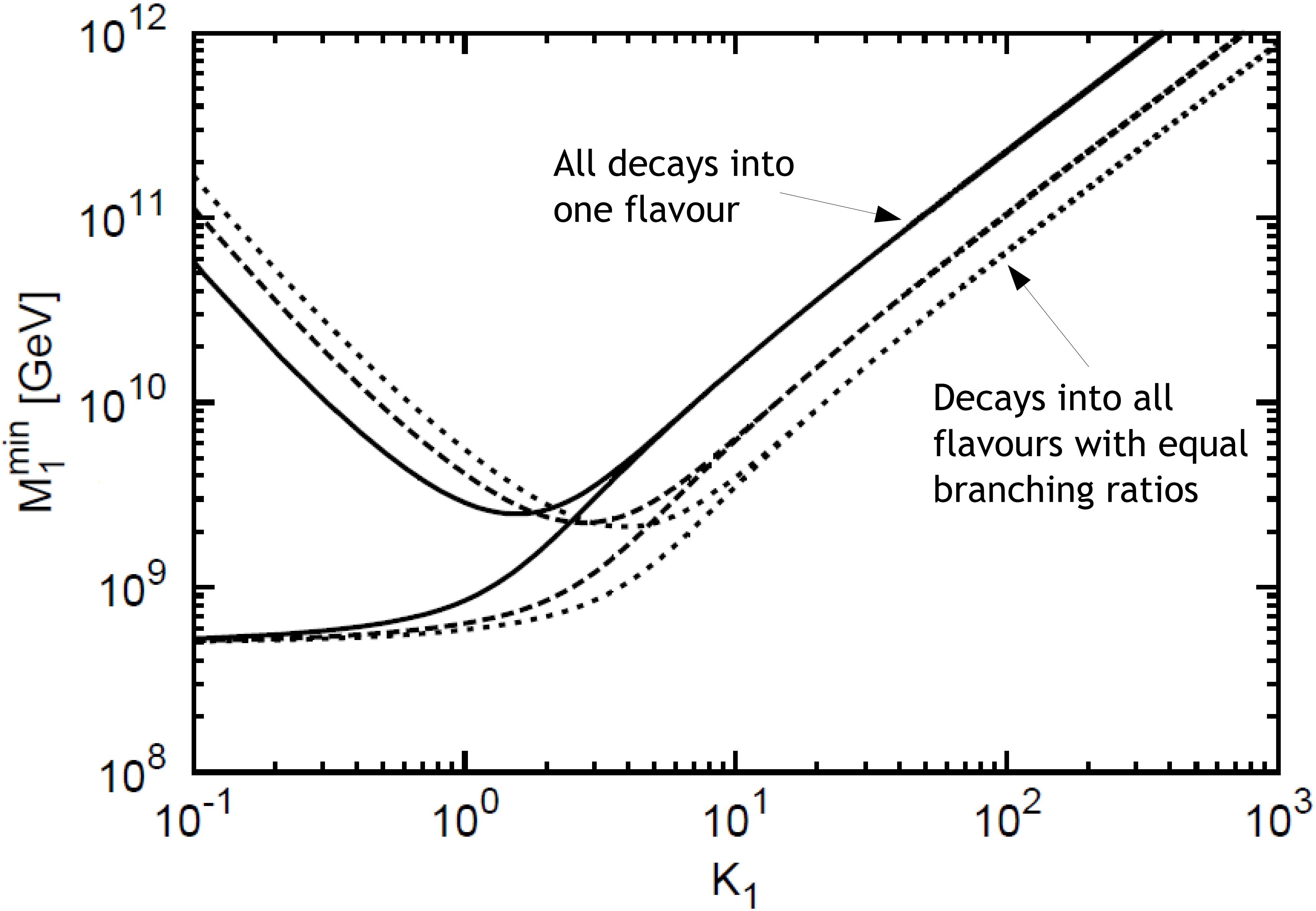
Approximating the BAU by

$$\eta_B = \sum_\alpha \ldots$$

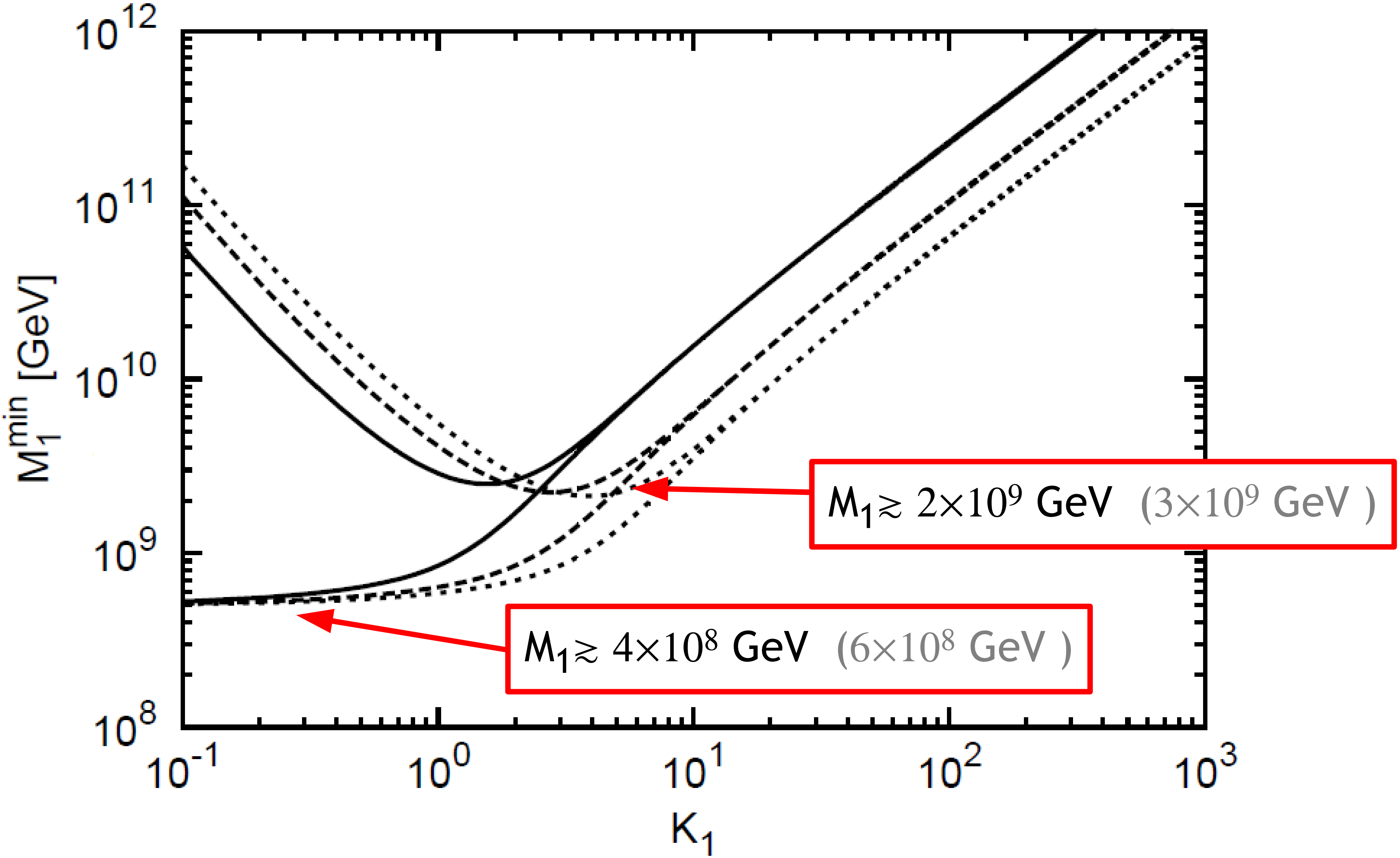
Lower bound on M_1 from the experimental value of η_B

One finds that:

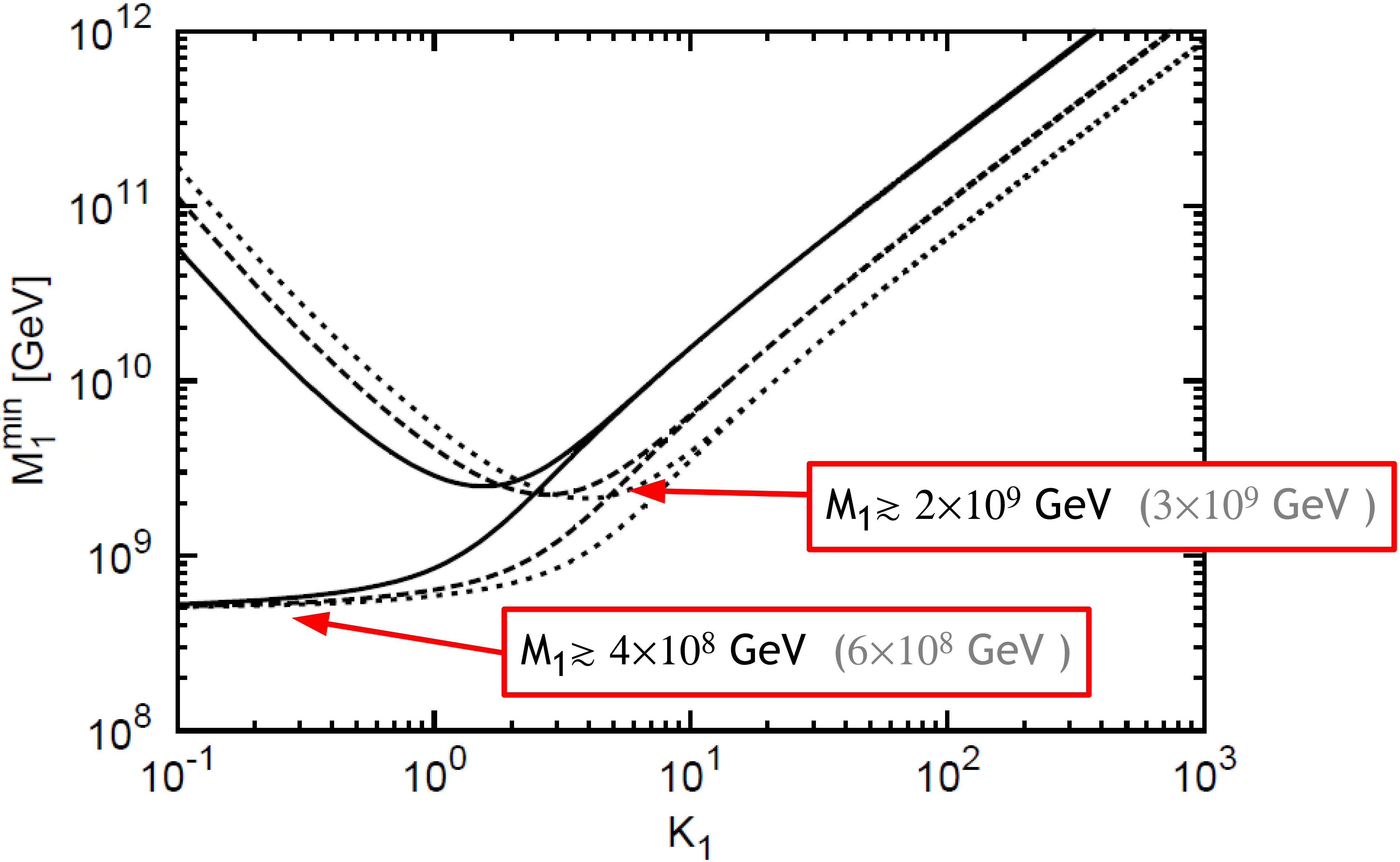
$$|\eta_B| \lesssim \frac{3}{4f} \frac{3}{16\pi} \frac{M_1 m_3}{\langle H^0 \rangle^2} \left[c_e^{\mathrm{sph}} \sqrt{\frac{K_e}{K}} \kappa_e + c_\mu^{\mathrm{sph}} \sqrt{\frac{K_\mu}{K}} \kappa_\mu + c_\tau^{\mathrm{sph}} \sqrt{\frac{K_\tau}{K}} \kappa_\tau \right]$$



10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
M_1^{min} [GeV]
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
K_1
All decays into one flavour
Decays into all flavours with equal branching ratios

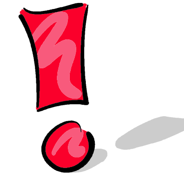


10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
M_1^{min} [GeV]
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
K_1
$M_1 \gtrsim 2\times10^9$ GeV (3×10^9 GeV)
$M_1 \gtrsim 4\times10^8$ GeV (6×10^8 GeV)



No substantial change compared to the one flavour approximation

4- Bound on the neutrino masses



In the one flavour approximation, the CP asymmetry is bounded from above by:

$$|\epsilon_1| \leq \frac{3}{16\pi}\frac{M_1}{\langle H^0\rangle^2}(m_3 - m_1) = \frac{3}{16\pi}\frac{M_1}{\langle H^0\rangle^2}\frac{\Delta m^2_{atm}}{m_3 + m_1}$$

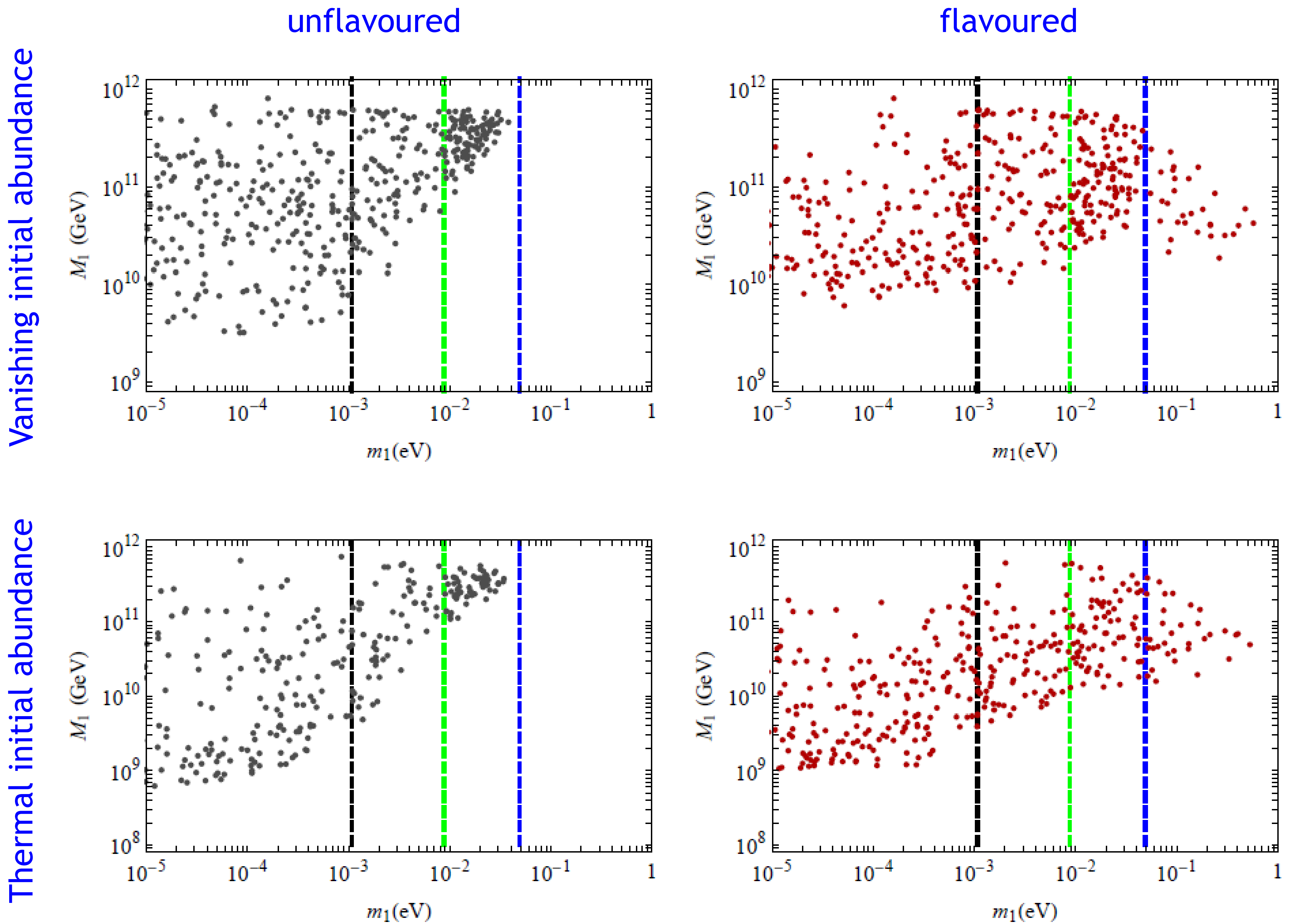
Suppressed for heavy neutrinos (degenerate neutrinos)

Taking flavours properly into account, the CP asymmetries in each flavour are bounded from above by:

$$|\epsilon_\alpha| \lesssim \frac{3}{16\pi}\frac{M_1 m_3}{\langle H^0\rangle^2} \times \sqrt{\frac{K_\alpha}{K}}$$

No suppression!!

The bound on the neutrino masses will get relaxed



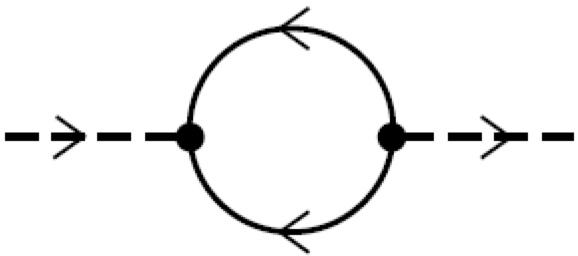
Abada, Josse-Michaux

Supersymmetric leptogenesis

The see-saw Lagrangian is:

$$-\mathcal{L}_{lep} = {\nu_R^c}^T h_\nu L \cdot H - \frac{1}{2} {\nu_R^c}^T M \, \nu_R^c + \text{h.c.}$$

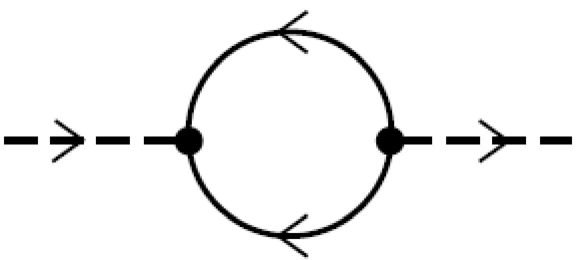
The Higgs doublet interacts with heavy degrees of freedom

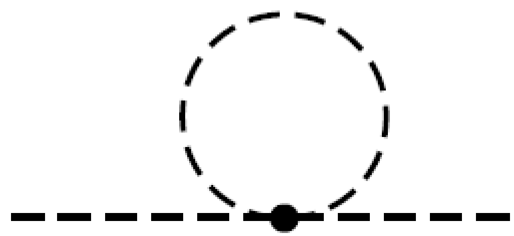


$$\delta m_H^2 \sim \frac{1}{16\pi^2} Y^2 M^2$$

Quadratic divergence!

In the SUSY version of the see-saw

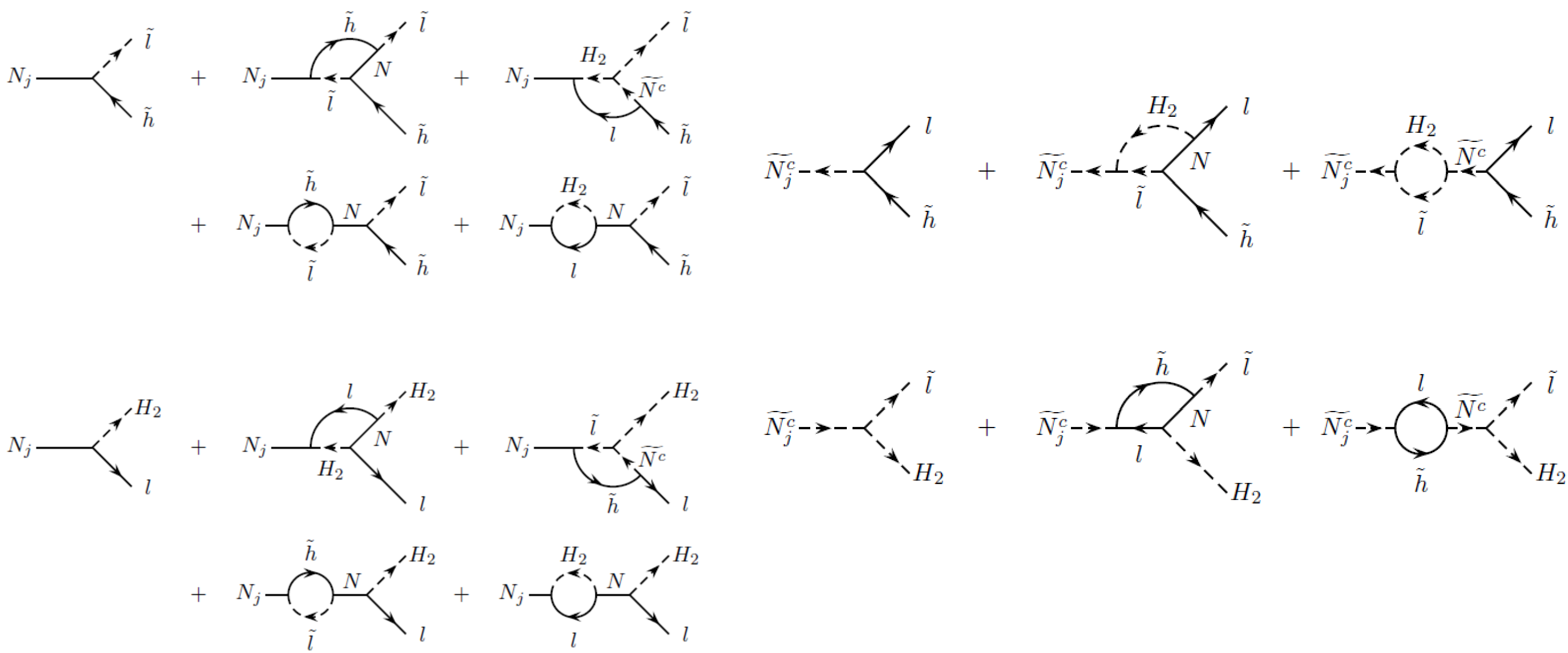




$$\delta m_H^2 \sim \frac{1}{16\pi^2} Y^2 \log \frac{M^2}{\Lambda^2}$$

SUSY solves the hierarchy problem of the see-saw mechanism.
Natural framework to implement leptogenesis.

The calculation of the baryon asymmetry in the SUSY version of leptogenesis is analogous to the non-SUSY case, but more complicated...



The calculation gives: $$\epsilon_1 = \frac{1}{8\pi}\frac{1}{(h_\nu h_\nu^\dagger)_{11}}\sum_{i=2,3}\mathrm{Im}\left[(h_\nu h_\nu^\dagger)^2_{1i}\right] f\left(\frac{M_i^2}{M_1^2}\right)$$

$$f(x) = \sqrt{x}\left[\log\left(\frac{1+x}{x}\right) + \frac{2}{x-1}\right]$$

In the limit of hierarchical right-handed neutrinos, $f(x) \simeq \frac{3}{\sqrt{x}}$

$$\epsilon_1 = \frac{3}{8\pi}\frac{1}{(h_\nu h_\nu^\dagger)_{11}}\sum_{i=2,3}\mathrm{Im}\left[(h_\nu h_\nu^\dagger)^2_{1i}\right]\frac{M_1}{M_i}$$

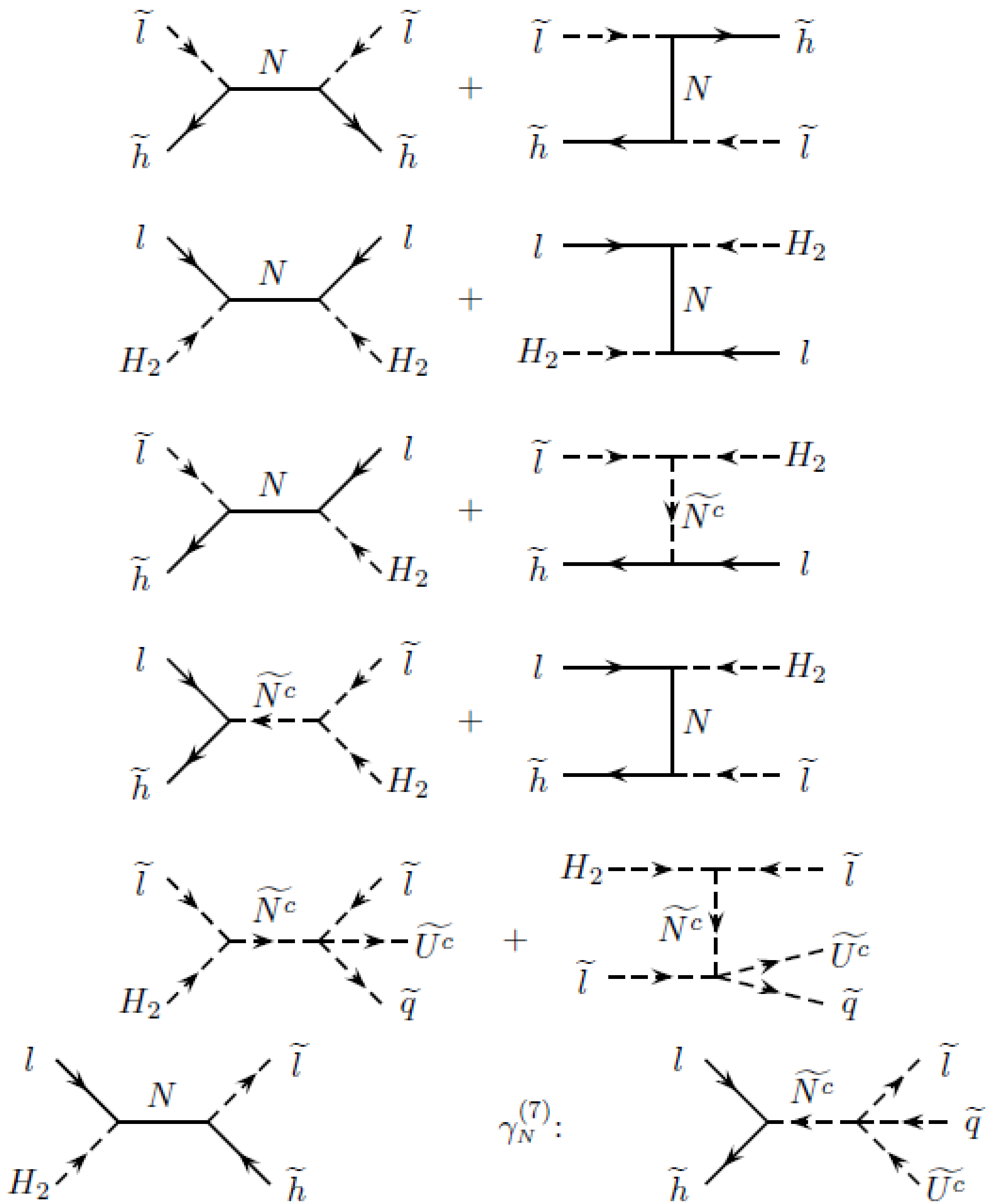
The upper bound on the CP asymmetry reads:

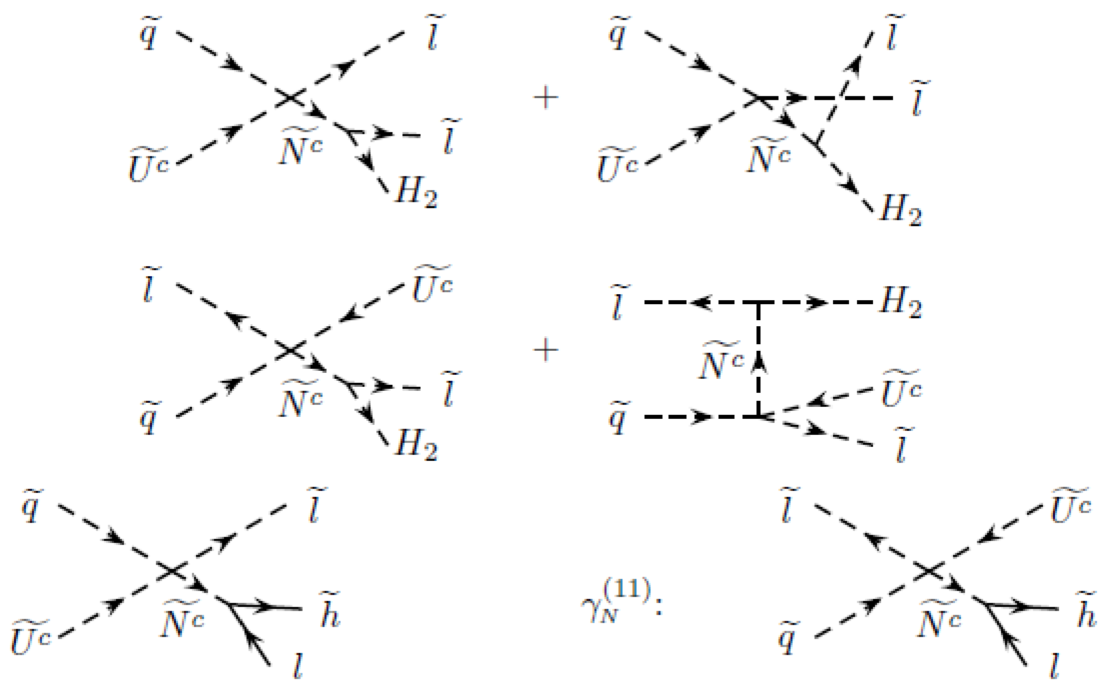
$$\boxed{|\epsilon_1| \leq \frac{3}{8\pi}\frac{M_1}{\langle H_u^0\rangle^2}(m_3 - m_1)}$$

Compare to non-SUSY case: $\epsilon_1 \leq \frac{3}{16\pi}\frac{M_1}{\langle H^0\rangle^2}(m_3 - m_1)$

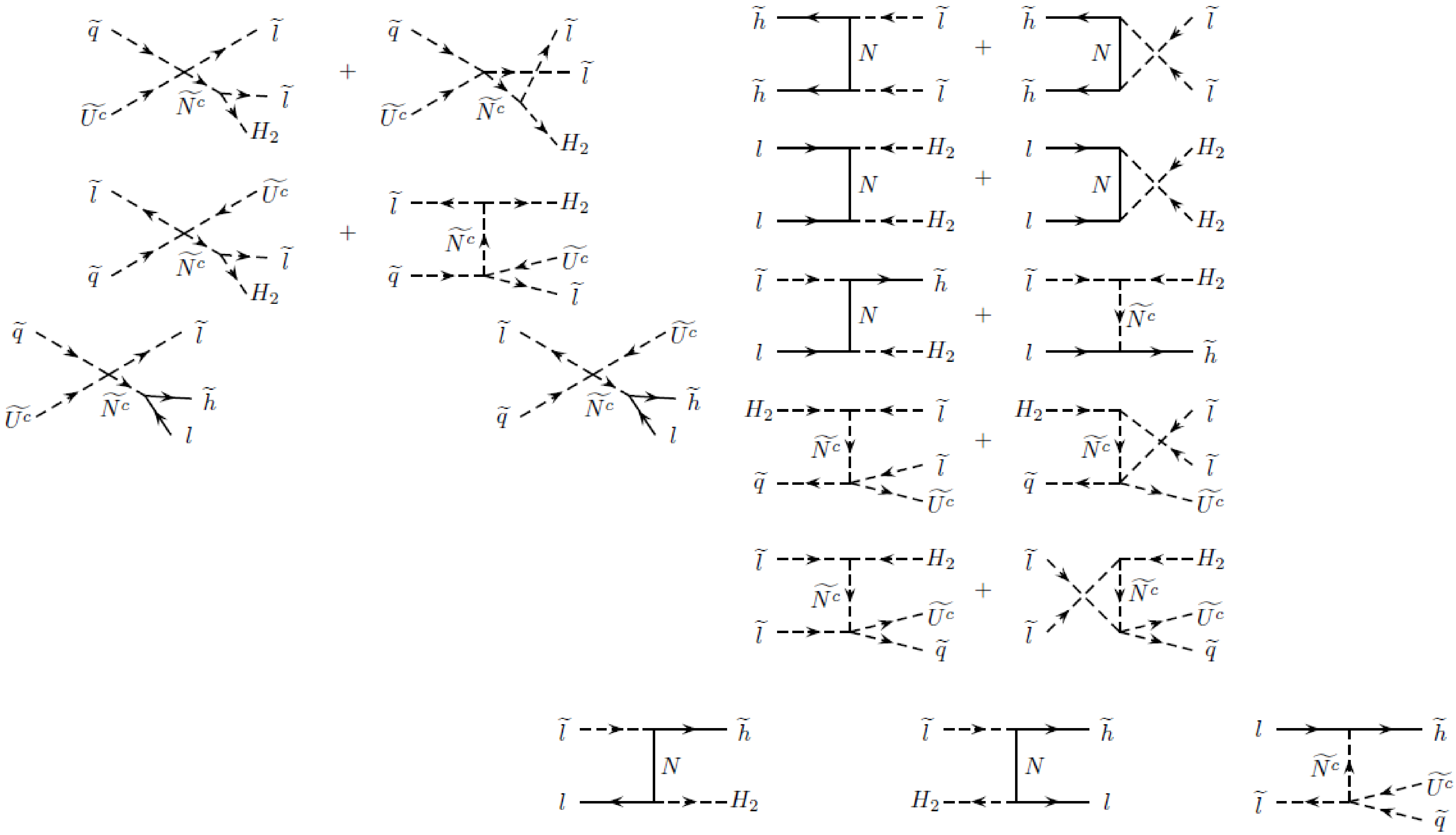
Double asymmetry, since there are two particles producing the asymmetry: right-handed neutrinos and right-handed sneutrinos

Wash-out is much more complicated than in the non-SUSY case



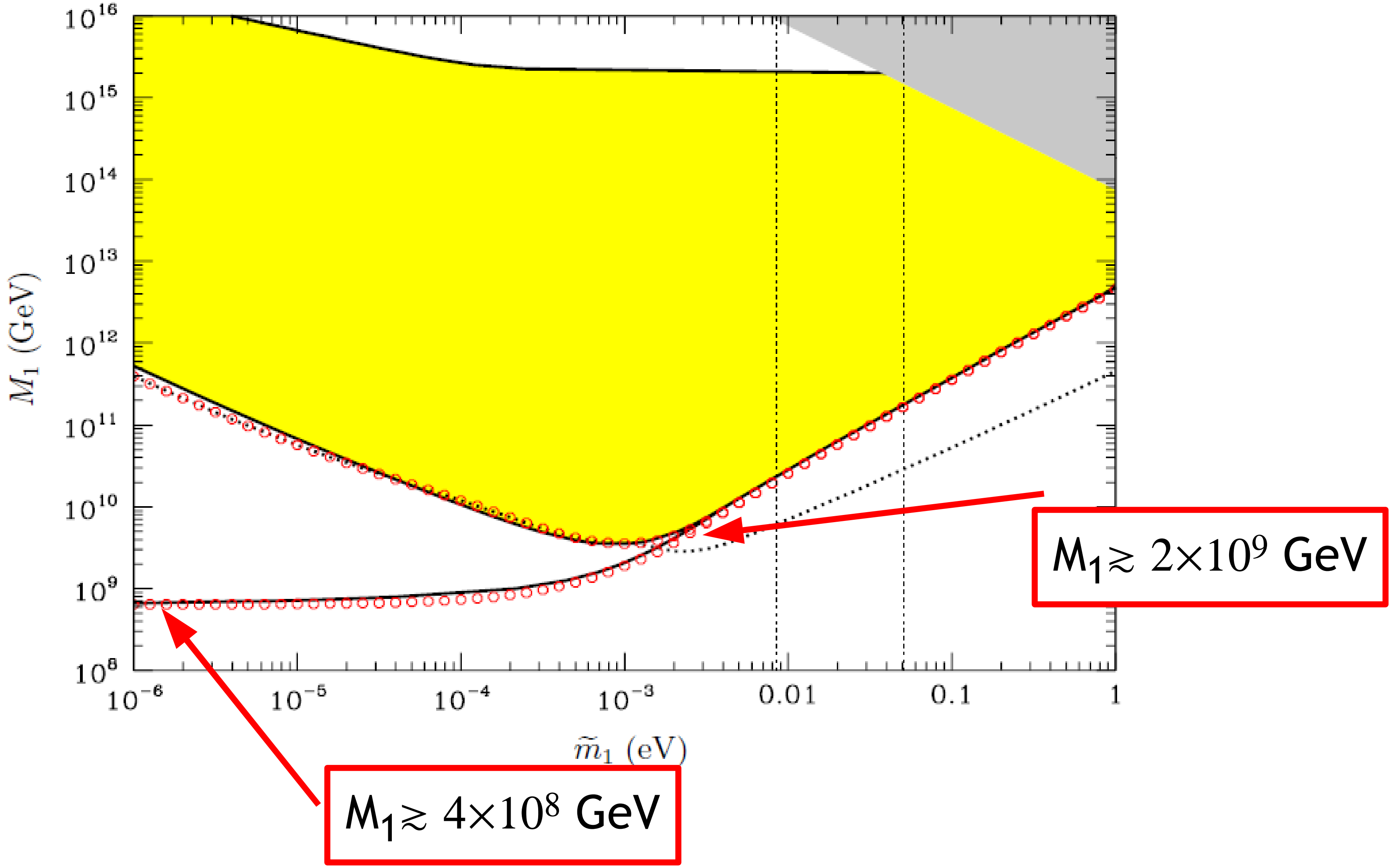


$\widetilde{q}$ $\widetilde{l}$ $\widetilde{U^c}$ $\widetilde{N^c}$ $\widetilde{l}$ H_2
+
$\widetilde{q}$ $\widetilde{l}$ $\widetilde{l}$ $\widetilde{U^c}$ $\widetilde{N^c}$ H_2
$\widetilde{l}$ $\widetilde{U^c}$ $\widetilde{q}$ $\widetilde{N^c}$ $\widetilde{l}$ H_2
+
$\widetilde{l}$ H_2 $\widetilde{N^c}$ $\widetilde{U^c}$ $\widetilde{q}$ $\widetilde{l}$
$\widetilde{q}$ $\widetilde{l}$ $\widetilde{U^c}$ $\widetilde{N^c}$ $\widetilde{h}$ l
$\gamma_N^{(11)}$:
$\widetilde{l}$ $\widetilde{U^c}$ $\widetilde{q}$ $\widetilde{N^c}$ $\widetilde{h}$ l

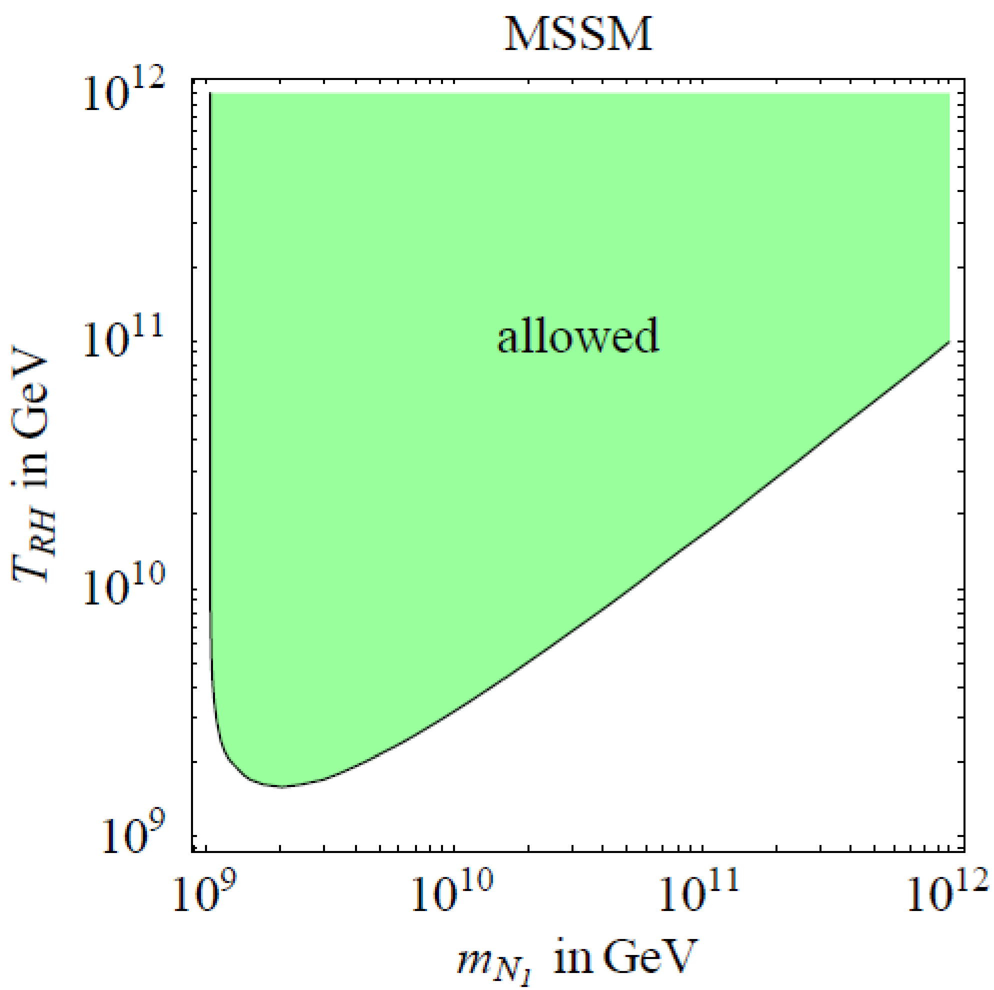


At the end of the day, the wash-out is roughly double than in the non-SUSY case.

Double asymmetry, but double wash-out. The two effects roughly compensate ⇒ the result is similar to the SM result:



Reheating temperature necessary for SUSY leptogenesis:



Giudice et al.

The Universe must have been VERY hot

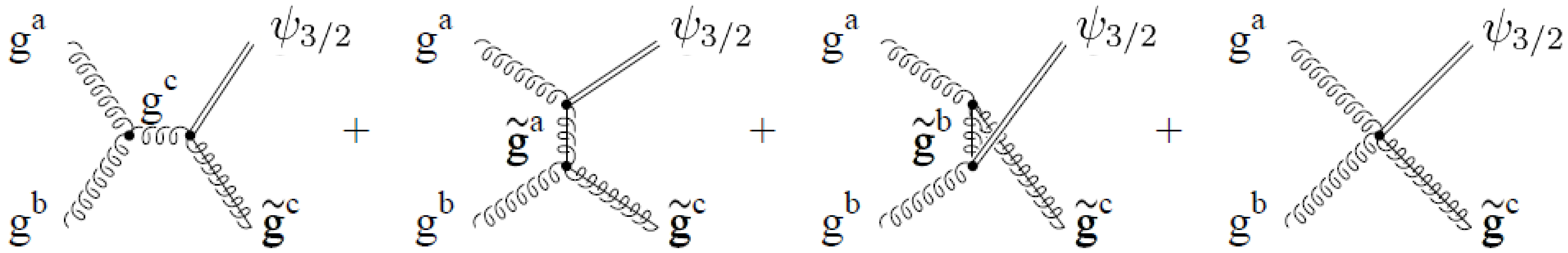
Implications of SUSY leptogenesis:

1- Dark matter

The gravitino "problems" with leptogenesis

The gravitino is the superpartner of the graviton. It is present in all models with local supersymmetry (supergravity)

It is thermally produced in the early Universe by scatterings



The relic abundace of gravitinos is:

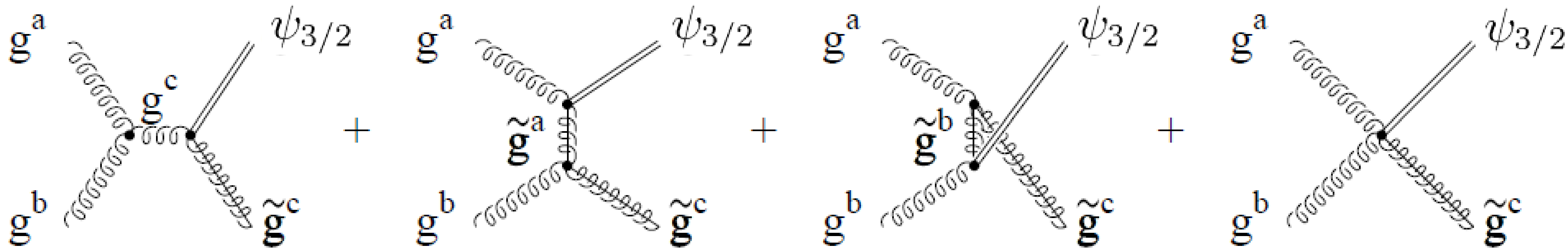
$$\boxed{\Omega_{3/2}h^2 \simeq 0.1 \left(\frac{T_R}{10^9\,\mathrm{GeV}}\right)\left(\frac{5\,\mathrm{GeV}}{m_{3/2}}\right)\left(\frac{m_{\tilde{g}}}{500\,\mathrm{GeV}}\right)^2}$$

Leptogenesis requires $T_R \gtrsim 10^9$ GeV $\Rightarrow m_{3/2} \gtrsim 5$ GeV

The gravitino "problems" with leptogenesis

The gravitino is the superpartner of the graviton. It is present in all models with local supersymmetry (supergravity)

It is thermally produced in the early Universe by scatterings



The relic abundace of gravitinos is:

$$\boxed{\Omega_{3/2}h^2 \simeq 0.1 \left(\frac{T_R}{10^9\,\mathrm{GeV}}\right)\left(\frac{5\,\mathrm{GeV}}{m_{3/2}}\right)\left(\frac{m_{\tilde{g}}}{500\,\mathrm{GeV}}\right)^2}$$

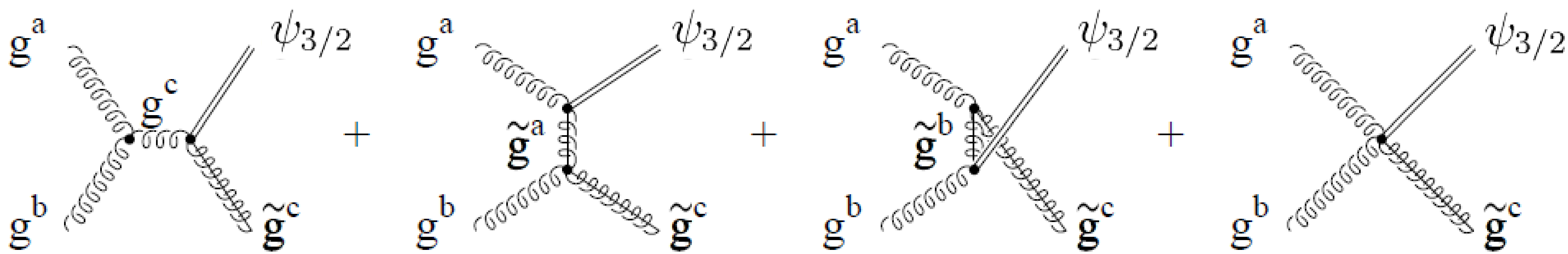
Leptogenesis requires $T_R \gtrsim 10^9$ GeV $\Rightarrow$ $m_{3/2} \gtrsim 5$ GeV

Models with low scale SUSY breaking (gauge mediation) are incompatible with leptogenesis, otherwise the density of gravitinos would be larger than the critical density. (More precisely, $M_{mes} \gtrsim 10^{16}$ GeV, for $m_{soft} \sim 1$ TeV).

The gravitino "problems" with leptogenesis

The gravitino is the superpartner of the graviton. It is present in all models with local supersymmetry (supergravity)

It is thermally produced in the early Universe by scatterings



The relic abundace of gravitinos is:

$$\boxed{\Omega_{3/2}h^2 \simeq 0.1 \left(\frac{T_R}{10^9\,\mathrm{GeV}}\right)\left(\frac{5\,\mathrm{GeV}}{m_{3/2}}\right)\left(\frac{m_{\tilde{g}}}{500\,\mathrm{GeV}}\right)^2}$$

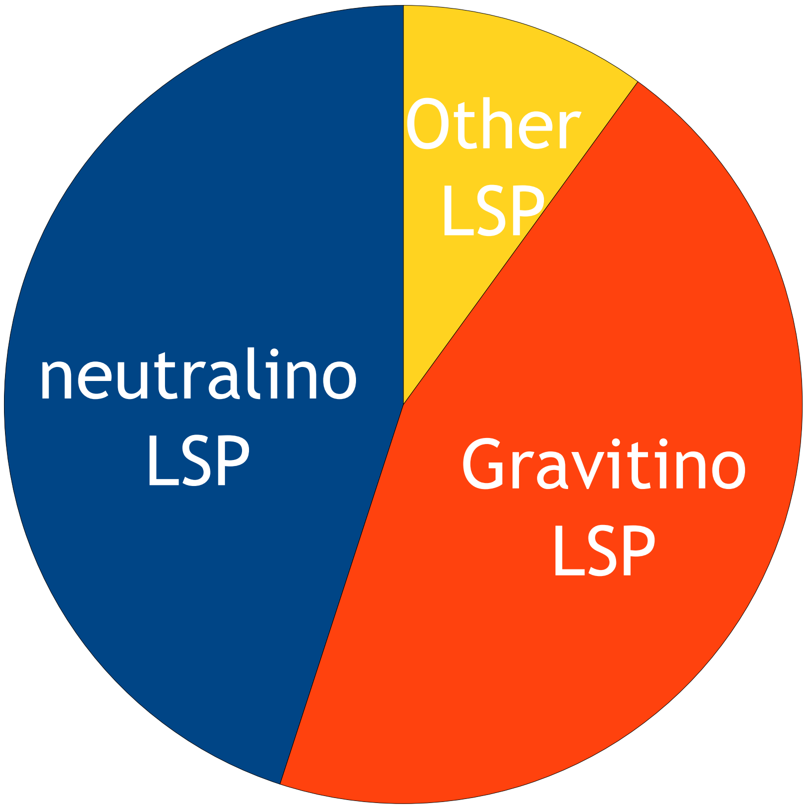
Leptogenesis requires $T_R \gtrsim 10^9$ GeV $\Rightarrow$ $m_{3/2} \gtrsim 5$ GeV

The leptogenesis clue (Nr.1)

Models with low scale SUSY breaking (gauge mediation) are incompatible with leptogenesis, otherwise the density of gravitinos would be larger than the critical density. (More precisely, $M_{\mathrm{mes}} \gtrsim 10^{16}$ GeV, for $m_{\mathrm{soft}} \sim 1$ TeV).

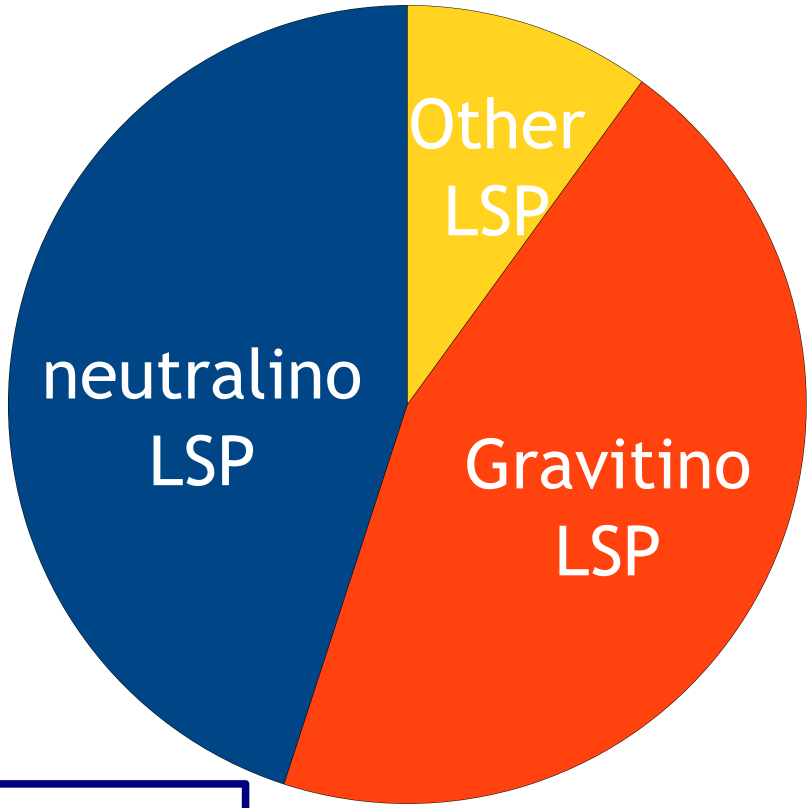
Leptogenesis requires $m_{3/2} \gtrsim 5$ GeV in order to not to overclose the Universe. This requirement seems to be easily fulfilled in models with gravity mediated SUSY breaking, $m_{3/2} \gtrsim 100\text{-}1000$ GeV.

Sketch of SUSY models



Leptogenesis requires $m_{3/2} \gtrsim 5$ GeV in order to not to overclose the Universe. This requirement seems to be easily fulfilled in models with gravity mediated SUSY breaking, $m_{3/2} \gtrsim 100\text{-}1000$ GeV.

Sketch of SUSY models



The leptogenesis requirement $T_R \gtrsim 10^9$ GeV makes this class of scenarios contrived!

Leptogenesis requires $m_{3/2} \gtrsim 5$ GeV in order to not to overclose the Universe. This requirement seems to be easily fulfilled in models with gravity mediated SUSY breaking, $m_{3/2} \gtrsim 100\text{-}1000$ GeV.

In many SUSY analyses, the neutralino is the Lightest Supersymmetric Particle (LSP), thus the gravitino decays into neutralinos and Standard Model particles:

$$\psi_{3/2} \to \gamma \, \widetilde{\gamma}$$

If R-parity is conserved, this decay can only proceed through a gravitational interaction ⇒ very suppressed decay rate:

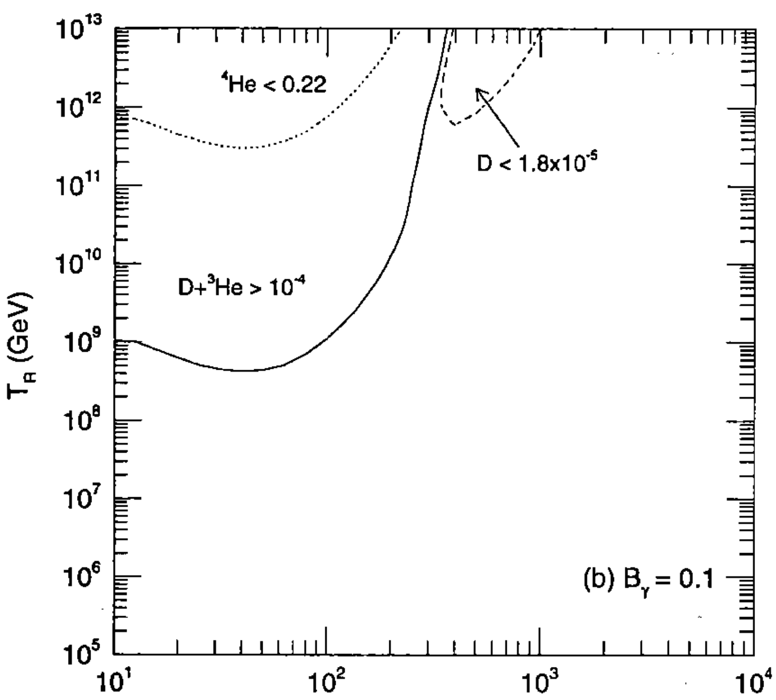
$$\Gamma = \frac{m_{3/2}^2}{32\pi M_P^2} \left\{ 1 - \left(\frac{m_{\widetilde{\gamma}}}{m_{3/2}} \right)^2 \right\}^3 \left\{ 1 + \frac{1}{3} \left(\frac{m_{\widetilde{\gamma}}}{m_{3/2}} \right)^2 \right\}$$

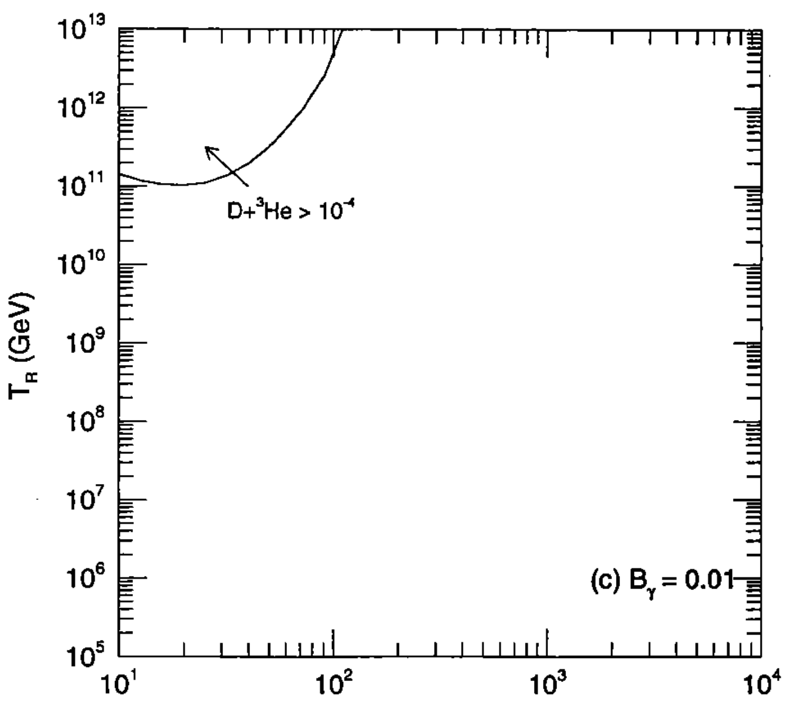
$$\boxed{\tau_{3/2}(\psi_{3/2} \to \gamma \, \widetilde{\gamma}) \simeq 3.9 \times 10^8 \left(\frac{m_{3/2}}{100\ \mathrm{GeV}} \right)^{-3} \mathrm{s}}$$

The photons are produced during or after Big Bang Nucleosynthesis, potentially jeopardizing the successful predictions of the Standard BBN scenario.

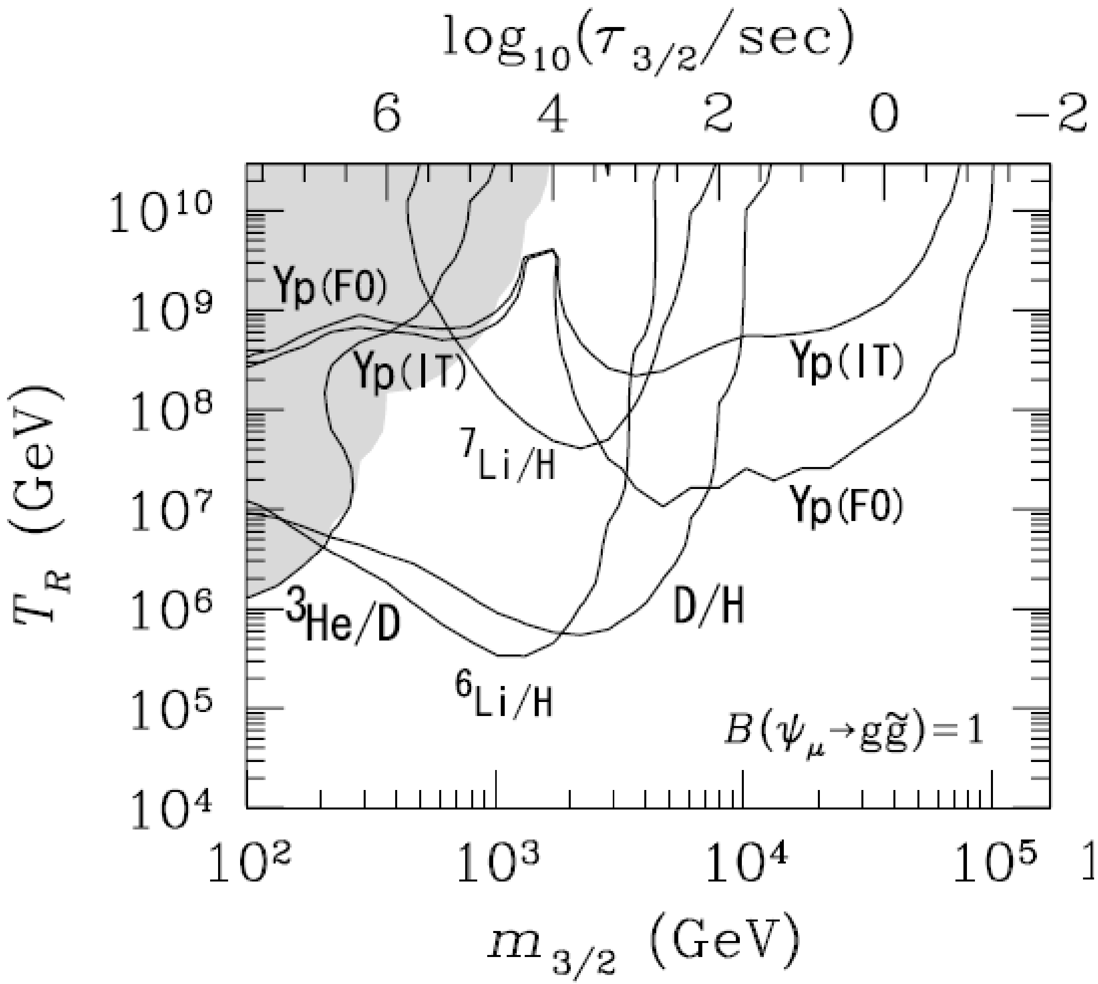
More concretely, the photons can dissociate the light elements if the photon energy is above a certain threshold. For example:

$$\mathrm{D} + \gamma \rightarrow n + p,\ E_{th} = 2.225\mathrm{MeV}$$

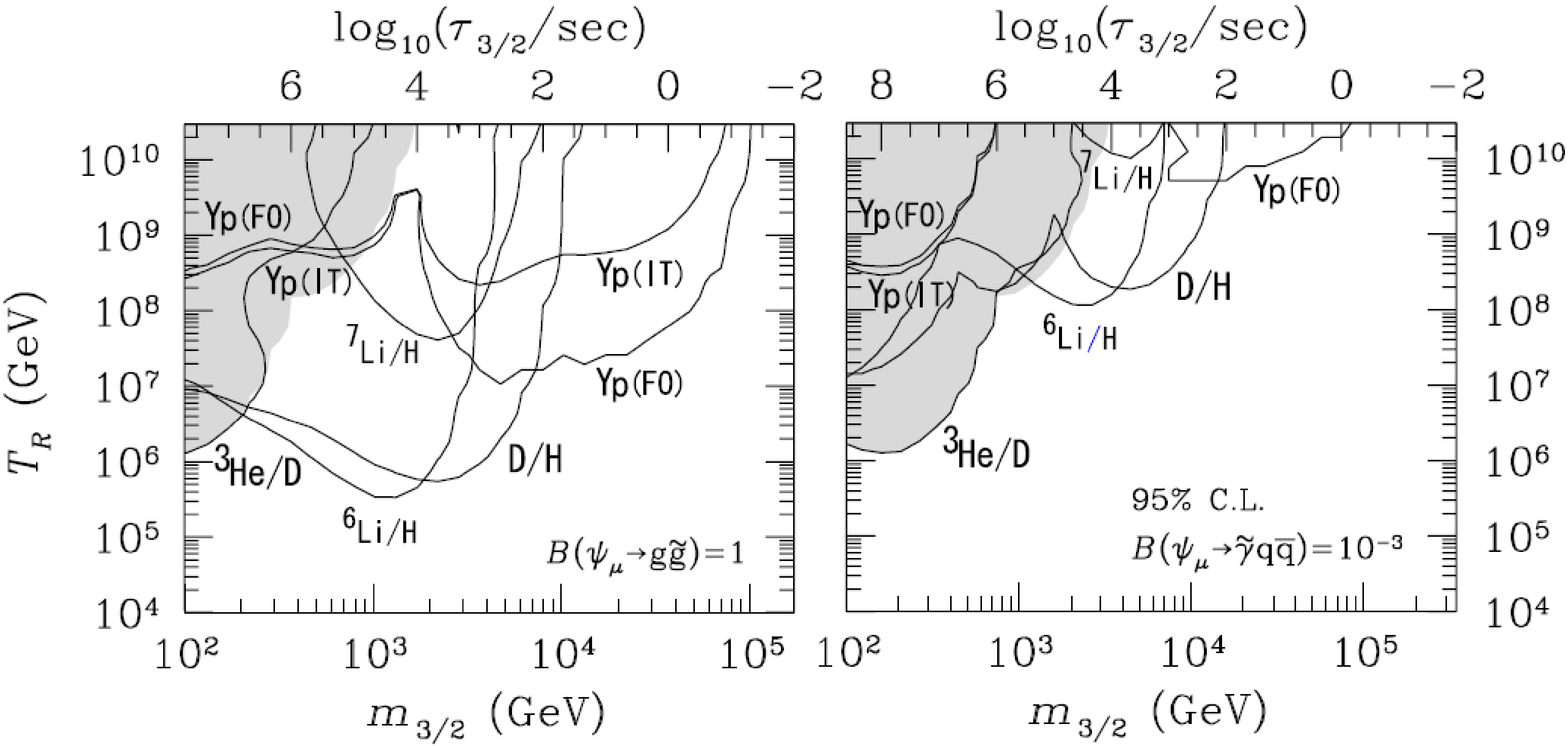




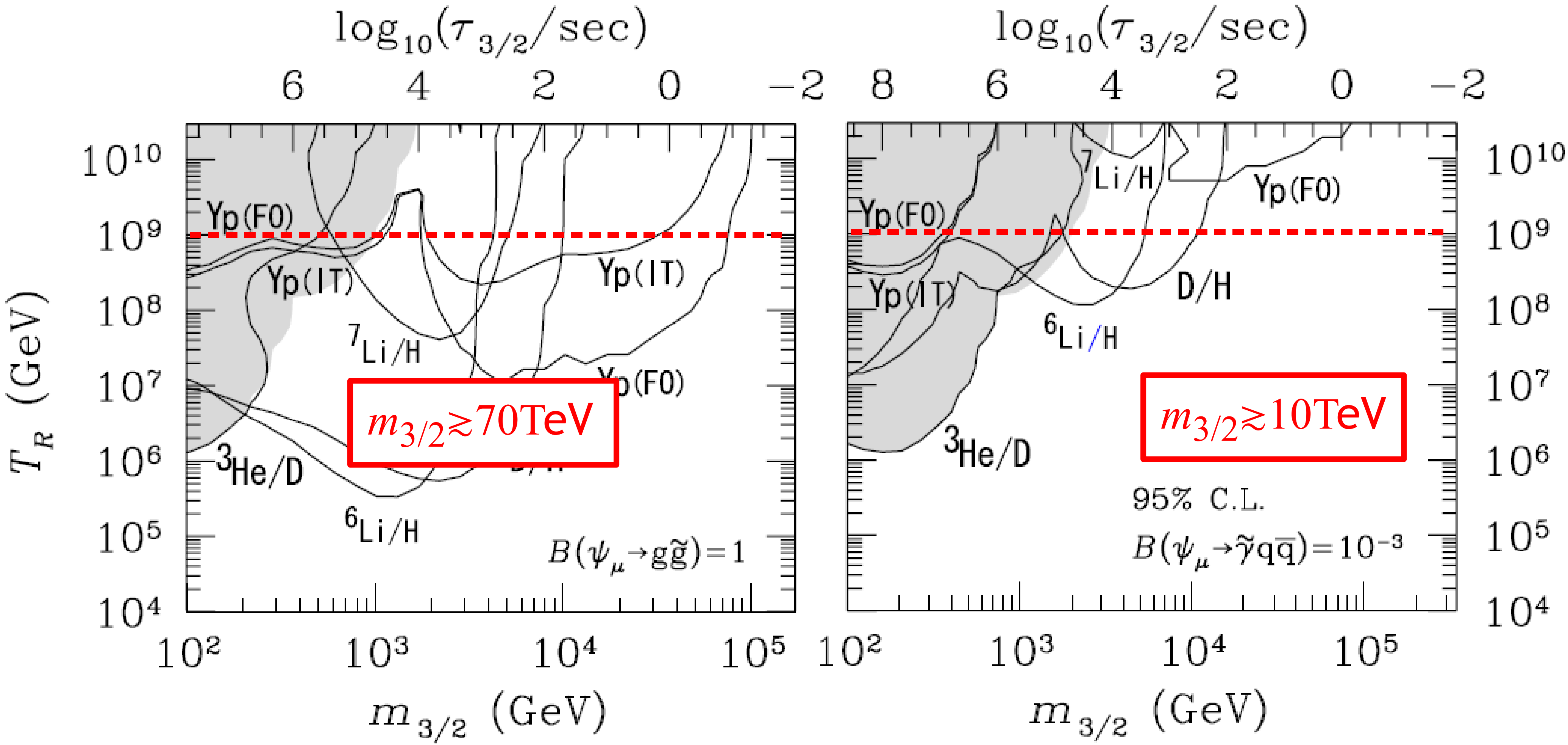
Even worst, if $m_{3/2} \gtrsim m_{\hat{g}}$, the gravitino could decay into gluon-gluino, that hadronize producing energetic hadrons $\longrightarrow$ hadrodissociation of the primordial elements.



Even worst, if $m_{3/2} \gtrsim m_{\hat{g}}$, the gravitino could decay into gluon-gluino, that hadronize producing energetic hadrons $\longrightarrow$ hadrodissociation of the primordial elements. Other hadronic channels are also dangerous.

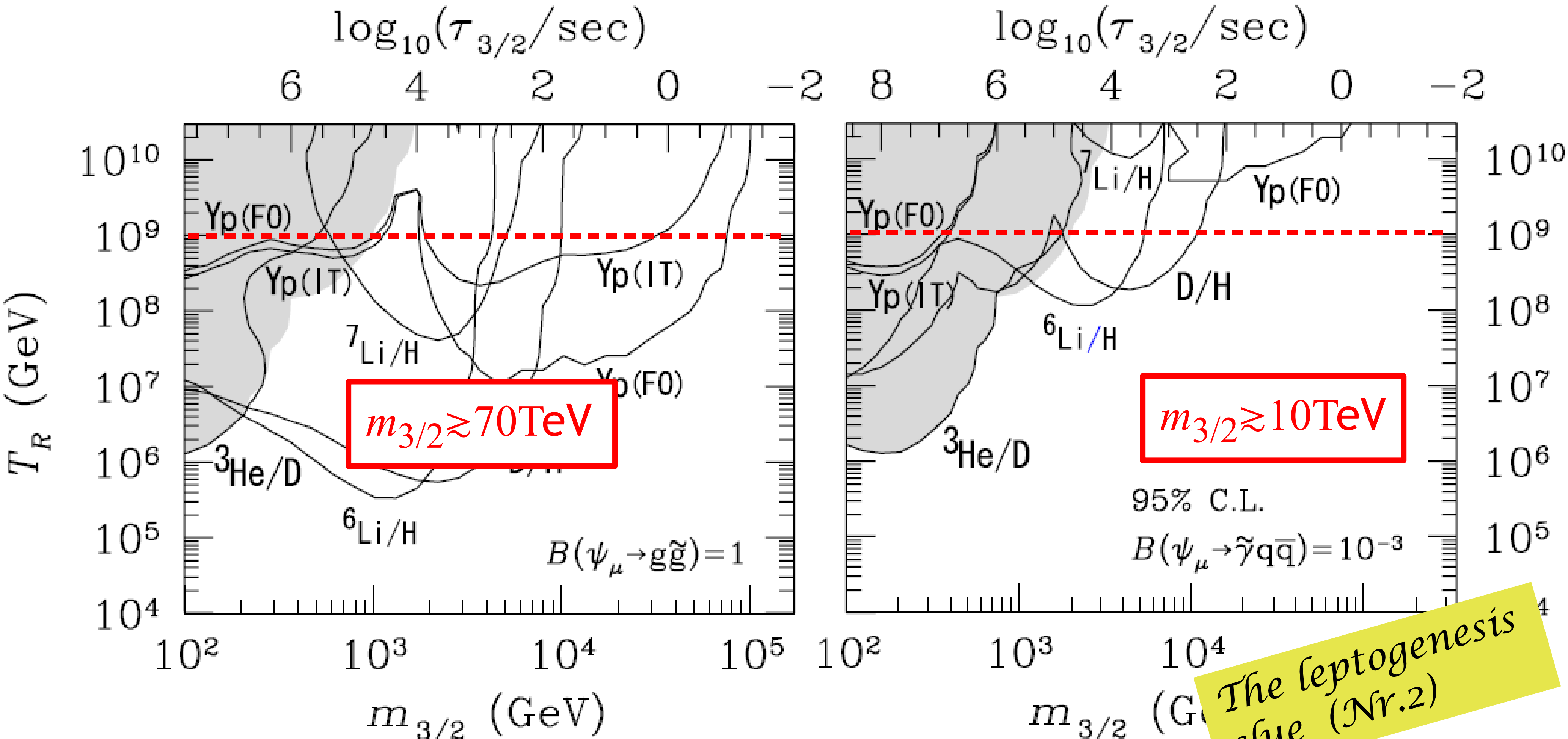


Even worst, if $m_{3/2} \gtrsim m_{\hat{g}}$, the gravitino could decay into gluon-gluino, that hadronize producing energetic hadrons $\longrightarrow$ hadrodissociation of the primordial elements. Other hadronic channels are also dangerous.



If leptogenesis is the correct mechanism to generate the BAU, successful BBN requires a very heavy gravitino (naturalness?)

Even worst, if $m_{3/2} \gtrsim m_{\hat{g}}$, the gravitino could decay into gluon-gluino, that hadronize producing energetic hadrons $\longrightarrow$ hadrodissociation of the primordial elements. Other hadronic channels are also dangerous.



The leptogenesis clue (Nr.2)

If leptogenesis is the correct mechanism to generate the BAU, successful BBN requires a very heavy gravitino (naturalness?)

Constraints on the gravitino parameters from leptogenesis

- The gravitino must be heavier than 5 GeV (overclosure)
- If it is unstable, it must be heavier than 10TeV (BBN)

Not very appealing...

Constraints on the gravitino parameters from leptogenesis

- The gravitino must be heavier than 5 GeV (overclosure)
- If it is unstable, it must be heavier than 10TeV (BBN)

Not very appealing... What if the gravitino is stable?

Very appealing possibility!! The problems with BBN can be avoided. More importantly, the gravitino could constitute the dark matter of the Universe:

- Electrically neutral, colourless.
- Non-baryonic.
- Weakly interacting.
- "Cold" ($m_{3/2} \gtrsim 5$ GeV)
- Very long lived (even with R-parity violation)
- Could have the correct relic abundance for the reheating temperature required by leptogenesis and the range of gravitino masses suggested by gravity mediation.

$$\Omega_{3/2} h^2 \simeq 0.1 \left(\frac{T_R}{10^9\,\mathrm{GeV}}\right)\left(\frac{5\,\mathrm{GeV}}{m_{3/2}}\right)\left(\frac{m_{\tilde{g}}}{500\,\mathrm{GeV}}\right)^2$$

Constraints on the gravitino parameters from leptogenesis

- The gravitino must be heavier than 5 GeV (overclosure)
- If it is unstable, it must be heavier than 10TeV (BBN)

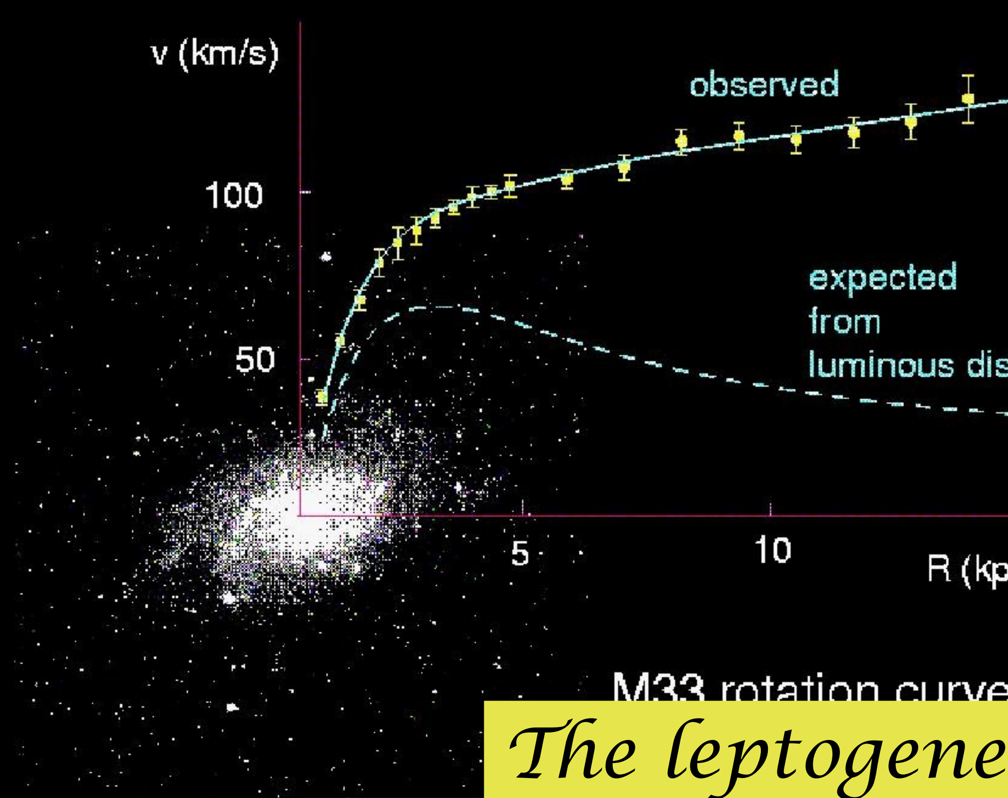
Not very appealing... What if the gravitino is stable?

Very appealing possibility!! The problems with BBN can be avoided. More importantly, the gravitino could constitute the dark matter of the Universe:

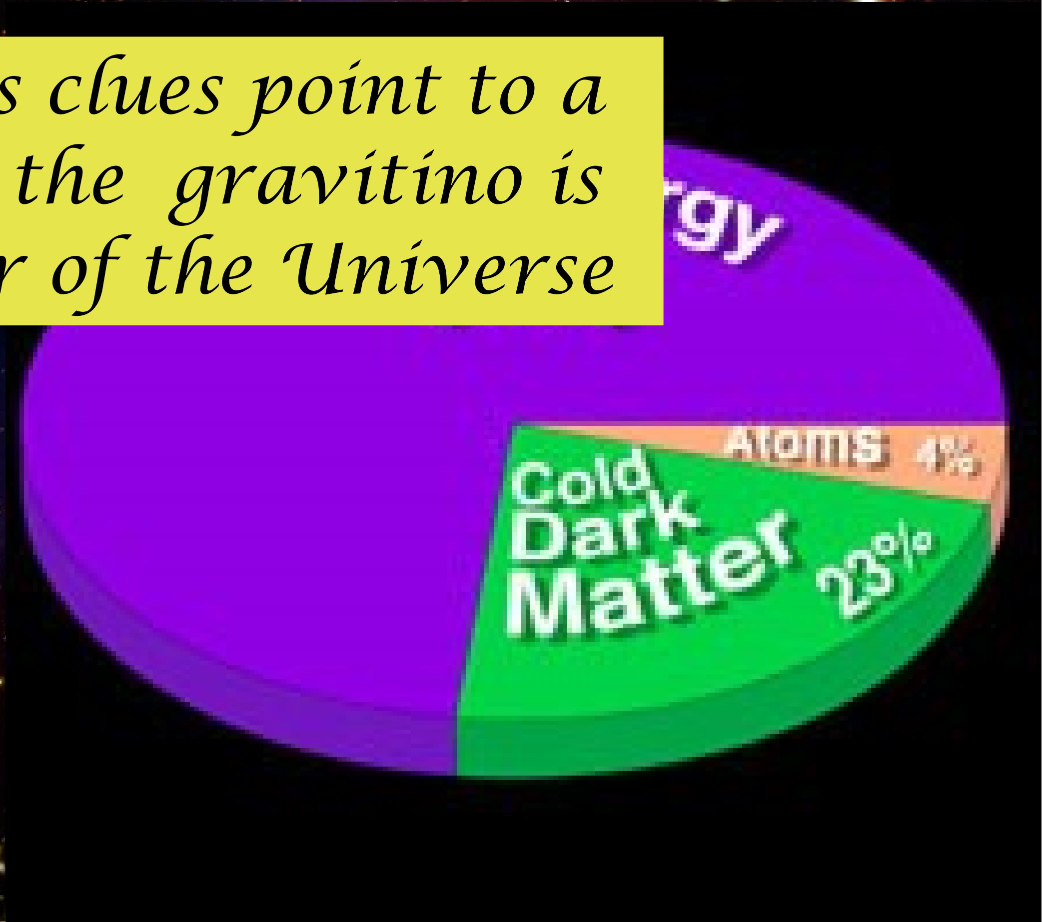
- Electrically neutral, colourless.
- Non-baryonic.
- Weakly interacting.
- "Cold" ($m_{3/2} \gtrsim 5$ GeV)
- Very long lived (even with R-parity violation)
- Could have the correct relic abundance for the reheating temperature required by leptogenesis and the range of gravitino masses suggested by gravity mediation.

$$\Omega_{3/2} h^2 \simeq 0.1 \left(\frac{T_R}{10^9\,\mathrm{GeV}} \right) \left(\frac{5\,\mathrm{GeV}}{m_{3/2}} \right) \left(\frac{m_{\tilde{g}}}{500\,\mathrm{GeV}} \right)^2$$

The leptogenesis clue (Nr.3)



The leptogenesis clues point to a scenario where the gravitino is the dark matter of the Universe



Implications of SUSY leptogenesis:

2- Lepton flavour violation

Lepton flavour violation (LFV) and leptogenesis

The branching ratio of the process $\mu \to e\,\gamma$ can be estimated to be:

$$\mathrm{BR}(\mu \to e\gamma) \sim \frac{96\pi^3\alpha^3}{G_F^2}\frac{\theta_{\mu e}^2}{M_{\mathrm{LFV}}^4}$$

Mixing parameter

Mass of the particles which induce the LFV

Right-handed neutrinos introduce new sources of flavour violation with $M_{\mathrm{LFV}}=10^{15}$ GeV and $\theta \sim 1$ (or with lower energies and smaller θ).

$$\mathrm{BR}(\mu \to e\gamma) \sim 10^{-53}$$

Unobservable!

(Present bound, $\mathrm{BR}(\mu \to e\gamma) < 1.2 \times 10^{-11}$)

Lepton flavour violation (LFV) and leptogenesis

The branching ratio of the process $\mu \to e\,\gamma$ can be estimated to be:

$$\mathrm{BR}(\mu \to e\gamma) \sim \frac{96\pi^3\alpha^3}{G_F^2}\frac{\theta_{\mu e}^2}{M_{\mathrm{LFV}}^4}$$

Mixing parameter

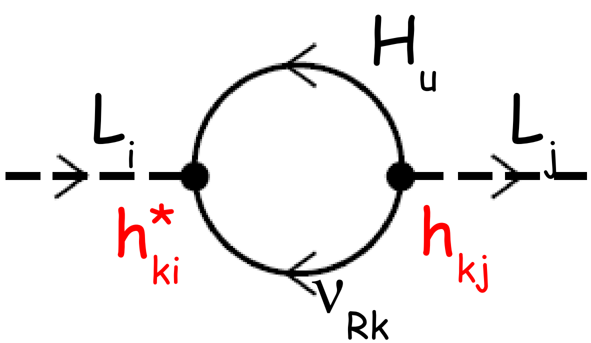
Mass of the particles which induce the LFV

Right-handed neutrinos introduce new sources of flavour violation with $M_{\mathrm{LFV}}=10^{15}$ GeV and $\theta \sim 1$ (or with lower energies and smaller θ).

$$\mathrm{BR}(\mu \to e\gamma) \sim 10^{-53}$$

Unobservable!

If the particles responsible for neutrino masses are lighter than the mediation scale, quantum corrections will generate flavour violating terms in the slepton sector: Borzumati, Masiero



$$\begin{aligned}
\left(\delta \mathbf{m}_L^2\right)_{ij} &\simeq -\frac{1}{8\pi^2}(3m_0^2+|A_0|^2)(h_\nu^\dagger h_\nu)_{ij}\log\left(\frac{\Lambda}{M_{\mathrm{maj}}}\right)\\
\left(\delta \mathbf{m}_e^2\right)_{ij} &\simeq 0\ ,\\
(\delta \mathbf{A}_e)_{ij} &\simeq \frac{-3}{8\pi^2}A_0 h_e (h_\nu^\dagger h_\nu)_{ij}\log\left(\frac{\Lambda}{M_{\mathrm{maj}}}\right)\ ,
\end{aligned}$$

Lepton flavour violation (LFV) and leptogenesis

The branching ratio of the process $\mu \to e\,\gamma$ can be estimated to be:

$$\mathrm{BR}(\mu \to e\gamma) \sim \frac{96\pi^3\alpha^3}{G_F^2}\frac{\theta_{\mu e}^2}{M_{\mathrm{LFV}}^4}$$

Mixing parameter

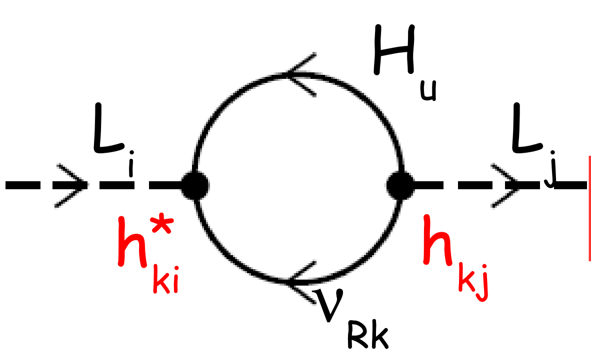
Mass of the particles which induce the LFV

Right-handed neutrinos introduce new sources of flavour violation with $M_{\mathrm{LFV}}=10^{15}$ GeV and $\theta \sim 1$ (or with lower energies and smaller θ).

$$\mathrm{BR}(\mu \to e\gamma) \sim 10^{-53}$$

Unobservable!

If the particles responsible for neutrino masses are lighter than the mediation scale, quantum corrections will generate flavour violating terms in the slepton sector: Borzumati, Masiero



$$\left(\delta \mathbf{m}_L^2\right)_{ij} \simeq -\frac{1}{8\pi^2}(3m_0^2+|A_0|^2)(h_\nu^\dagger h_\nu)_{ij}\log\left(\frac{\Lambda}{M_{\mathrm{maj}}}\right)$$

Logarithmic dependence with M

$$(\delta \mathbf{A}_e)_{ij} \simeq \frac{-3}{8\pi^2}A_0 h_e (h_\nu^\dagger h_\nu)_{ij}\log\left(\frac{\Lambda}{M_{\mathrm{maj}}}\right)$$

Lepton flavour violation (LFV) and leptogenesis

The branching ratio of the process $\mu \to e\,\gamma$ can be estimated to be:

$$\mathrm{BR}(\mu \to e\gamma) \sim \frac{96\pi^3\alpha^3}{G_F^2}\frac{\theta_{\mu e}^2}{M_{\mathrm{LFV}}^4}$$

Mixing parameter

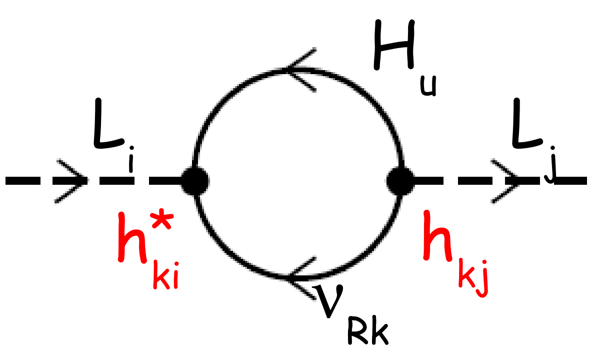
Mass of the particles which induce the LFV

Right-handed neutrinos introduce new sources of flavour violation with $M_{\mathrm{LFV}}=10^{15}$ GeV and $\theta \sim 1$ (or with lower energies and smaller θ).

$$\mathrm{BR}(\mu \to e\gamma) \sim 10^{-53}$$

Unobservable!

If the particles responsible for neutrino masses are lighter than the mediation scale, quantum corrections will generate flavour violating terms in the slepton sector: Borzumati, Masiero



$\left(\delta \mathbf{m}_L^2\right)_{ij}$

$\left(\delta \mathbf{m}_e^2\right)_{ij}$

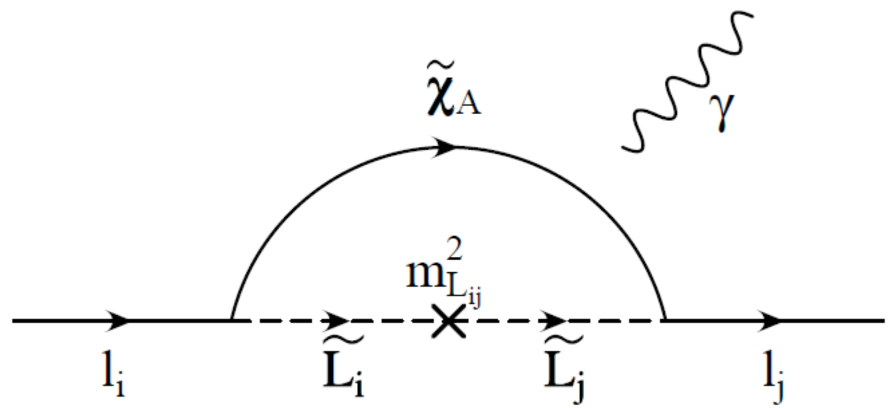
$(\delta \mathbf{A}_e)_{ij}$

$8\pi^2$ $\left(M_{\mathrm{maj}}\right)$

The scale of LFV is not the Majorana mass scale ($10^{9\text{-}15}$ GeV) but the soft mass scale (~1TeV).

Huge enhancement of the BRs

The calculation of the branching ratios is straightforward



$$\mathrm{BR}(\ell_j \to \ell_i \gamma) \simeq \frac{\alpha^3}{G_F^2} \frac{|(\mathbf{m}_L^2)_{ij}|^2}{m_S^8} \tan^2\beta \, \mathrm{BR}(\ell_j \to \ell_i \nu_j \bar{\nu}_i)$$

$$(\mathbf{m}_L^2)_{ij} \simeq \mathbf{m}_L^2(\Lambda)_{ij} - \frac{1}{8\pi^2}(3m_0^2 + |A_0|^2)(h_\nu^\dagger h_\nu)_{ij} \log\left(\frac{\Lambda}{M_{\mathrm{maj}}}\right)$$

The calculation of the rate is, however, full of uncertainties

Back of the envelope calculation of BR($l_i \to l_j \gamma$):

$$\mathrm{BR}(\ell_j \to \ell_i \gamma) \simeq \frac{\alpha^3}{G_F^2} \frac{|(\mathbf{m}_L^2)_{ij}|^2}{m_S^8} \tan^2\beta \, \mathrm{BR}(\ell_j \to \ell_i \nu_j \bar{\nu}_i)$$

$$(\mathbf{m}_L^2)_{ij} \simeq \mathbf{m}_L^2(\Lambda)_{ij} - \frac{1}{8\pi^2}(3m_0^2 + |A_0|^2)(h_\nu^\dagger h_\nu)_{ij} \log\left(\frac{\Lambda}{M_{\mathrm{maj}}}\right)$$

Cut-off scale?

Flavour structure of the soft terms at the cut-off scale?

soft-SUSY parameters?

tanβ?

Size and flavour structure of the Yukawa couplings?

Right-handed neutrino masses?

The calculation of the rate is, however, full of uncertainties

Back of the envelope calculation of BR($l_i \to l_j \gamma$):

$$\mathrm{BR}(\ell_j \to \ell_i \gamma) \simeq \frac{\alpha^3}{G_F^2} \frac{|(\mathbf{m}_L^2)_{ij}|^2}{m_S^8} \tan^2\beta \, \mathrm{BR}(\ell_j \to \ell_i \nu_j \bar{\nu}_i)$$

$$(\mathbf{m}_L^2)_{ij} \simeq \mathbf{m}_L^2(\Lambda)_{ij} - \frac{1}{8\pi^2}(3m_0^2 + |A_0|^2)(h_\nu^\dagger h_\nu)_{ij} \log\left(\frac{\Lambda}{M_{\mathrm{maj}}}\right)$$

Cut-off scale?

Flavour structure of the soft terms at the cut-off scale?

soft-SUSY parameters?

tanβ?

Size and flavour structure of the Yukawa couplings?

Right-handed neutrino masses?

The calculation of the rate is, however, full of uncertainties

Back of the envelope calculation of BR($l_i \to l_j \gamma$):

$$\mathrm{BR}(\ell_j \to \ell_i \gamma) \simeq \frac{\alpha^3}{G_F^2} \frac{|(\mathbf{m}_L^2)_{ij}|^2}{m_S^8} \tan^2\beta \, \mathrm{BR}(\ell_j \to \ell_i \nu_j \bar{\nu}_i)$$

$$(\mathbf{m}_L^2)_{ij} \simeq \mathbf{m}_L^2(\Lambda)_{ij} - \frac{1}{8\pi^2}(3m_0^2 + |A_0|^2)(h_\nu^\dagger h_\nu)_{ij} \log\left(\frac{\Lambda}{M_{\mathrm{maj}}}\right)$$

Cut-off scale?
Flavour structure of the soft terms at the cut-off scale?
soft-SUSY parameters?
tanβ?
Size and flavour structure of the Yukawa couplings?
Right-handed neutrino masses?

The calculation of the rate is, however, full of uncertainties

Back of the envelope calculation of BR($l_i \to l_j \gamma$):

$$\mathrm{BR}(\ell_j \to \ell_i \gamma) \simeq \frac{\alpha^3}{G_F^2} \frac{|(\mathbf{m}_L^2)_{ij}|^2}{m_S^8} \tan^2\beta \, \mathrm{BR}(\ell_j \to \ell_i \nu_j \bar{\nu}_i)$$

$$(\mathbf{m}_L^2)_{ij} \simeq \mathbf{m}_L^2(\Lambda)_{ij} - \frac{1}{8\pi^2}(3m_0^2 + |A_0|^2)(h_\nu^\dagger h_\nu)_{ij} \log\left(\frac{\Lambda}{M_{\mathrm{maj}}}\right)$$

Cut-off scale?
Flavour structure of the soft terms at the cut-off scale?
soft-SUSY parameters?
tanβ?
Size and flavour structure of the Yukawa couplings?
Right-handed neutrino masses?

The calculation of the rate is, however, full of uncertainties

Back of the envelope calculation of BR($l_i \to l_j \gamma$):

$$\mathrm{BR}(\ell_j \to \ell_i \gamma) \simeq \frac{\alpha^3}{G_F^2} \frac{|(\mathbf{m}_L^2)_{ij}|^2}{m_S^8} \tan^2\beta \, \mathrm{BR}(\ell_j \to \ell_i \nu_j \bar{\nu}_i)$$

$$(\mathbf{m}_L^2)_{ij} \simeq \mathbf{m}_L^2(\Lambda)_{ij} - \frac{1}{8\pi^2}(3m_0^2 + |A_0|^2)(h_\nu^\dagger h_\nu)_{ij} \log\left(\frac{\Lambda}{M_{\mathrm{maj}}}\right)$$

Cut-off scale?
Flavour structure of the soft terms at the cut-off scale?
soft-SUSY parameters?
tanβ?
Size and flavour structure of the Yukawa couplings?
Right-handed neutrino masses?

The calculation of the rate is, however, full of uncertainties

Back of the envelope calculation of BR($l_i \to l_j \gamma$):

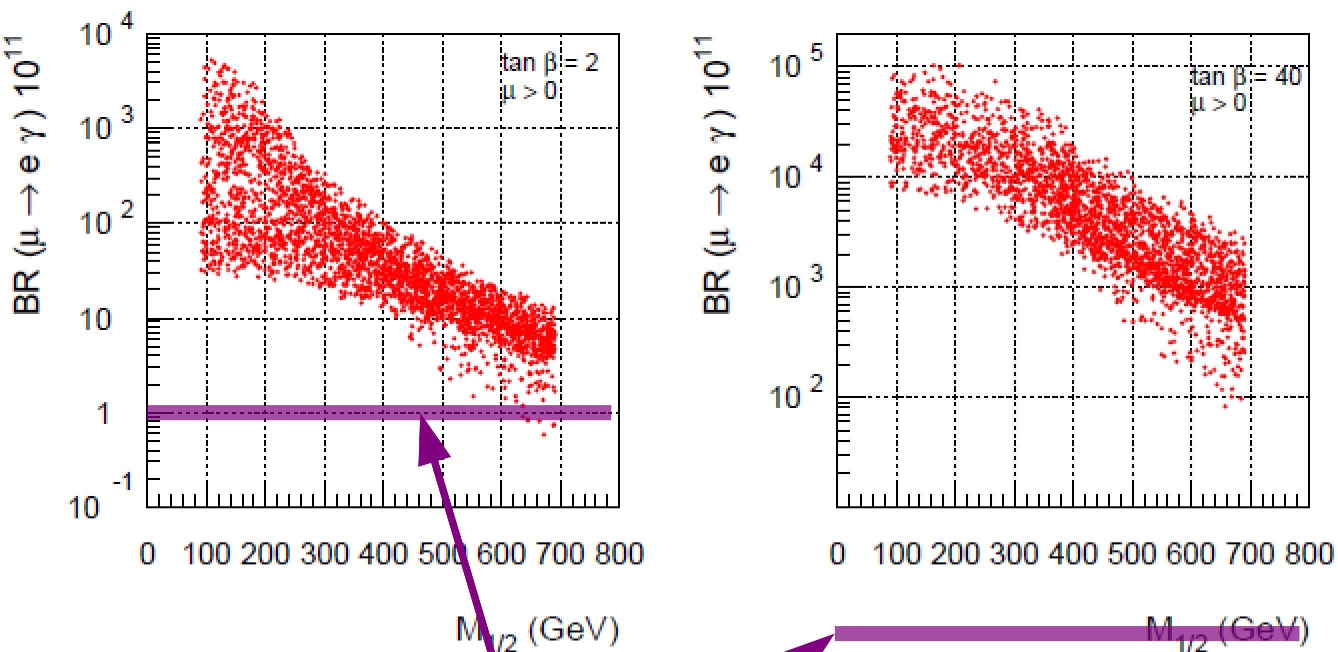
$$\mathrm{BR}(\ell_j \to \ell_i \gamma) \simeq \frac{\alpha^3}{G_F^2} \frac{|(\mathbf{m}_L^2)_{ij}|^2}{m_S^8} \tan^2\beta \, \mathrm{BR}(\ell_j \to \ell_i \nu_j \bar{\nu}_i)$$

$$(\mathbf{m}_L^2)_{ij} \simeq \mathbf{m}_L^2(\Lambda)_{ij} - \frac{1}{8\pi^2}(3m_0^2 + |A_0|^2)(h_\nu^\dagger h_\nu)_{ij} \log\left(\frac{\Lambda}{M_{\mathrm{maj}}}\right)$$

Cut-off scale?
Flavour structure of the soft terms at the cut-off scale?
soft-SUSY parameters?
tanβ?
Size and flavour structure of the Yukawa couplings?
Right-handed neutrino masses?

Example 1: SO(10) inspired model. Mixing angles in the Yukawa couplings as the leptonic mixing matrix

$$(h_\nu^\dagger h_\nu)_{21} = y_t^2 U_{\mu 3} U_{e3} + y_c^2 U_{\mu 2} U_{e2} + \mathcal{O}(y_u^2)$$



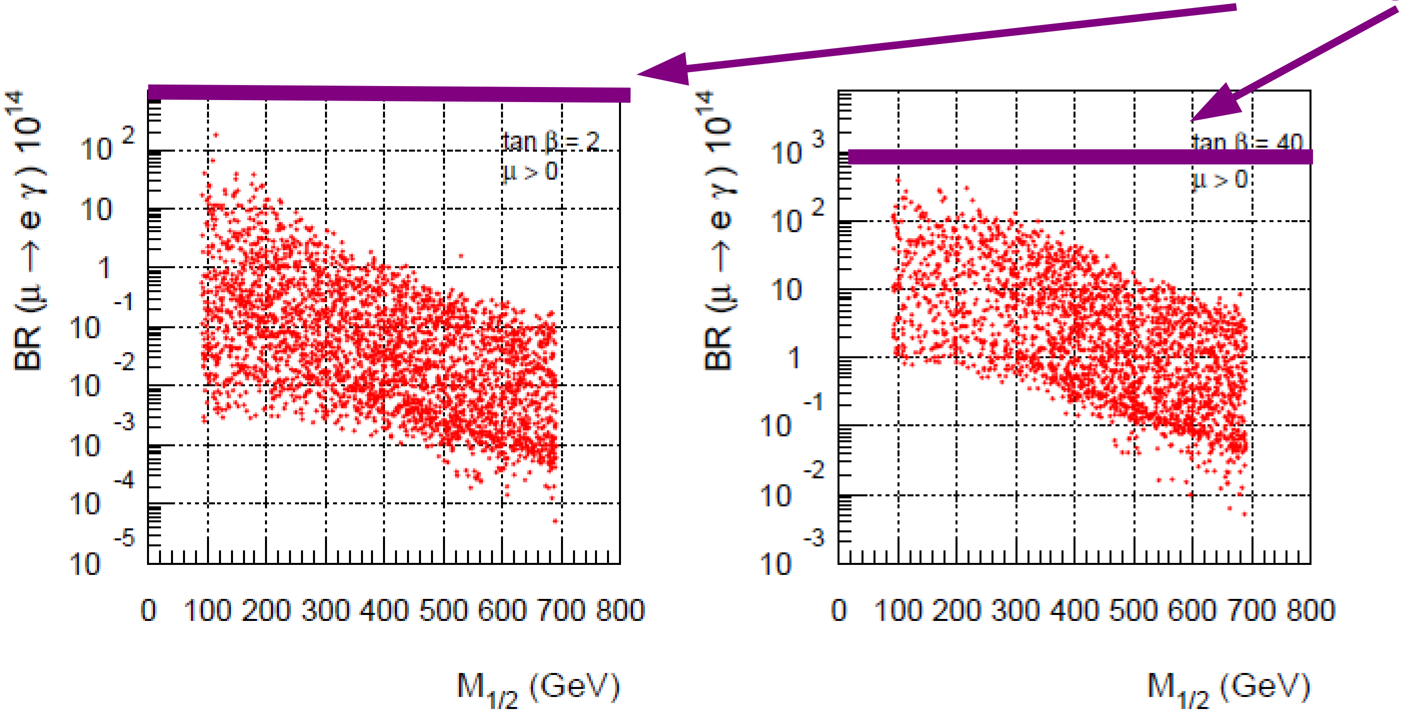
Masiero, Vempati, Vives

Present bound

<u>Example 2</u>: SO(10) inspired model. Mixing angles in the Yukawa couplings as the CKM matrix

$$(h_\nu^\dagger h_\nu)_{21} = y_t^2 V_{td} V_{ts} + \mathcal{O}(y_c^2)$$

Present bound



Masiero, Vempati, Vives

Is there any lower bound on the rate of $\mu \to e\gamma$?

Assume the worst case for the detection of $l_i \to l_j \gamma$

- $(\mathbf{m}_L^2)_{ij}$, $(\mathbf{m}_e^2)_{ij}$, $\mathbf{A}_{eij}$, $i \neq j$ vanish at high energies (no LFV in the soft terms at tree level)

AND

- $(h_\nu^\dagger h_\nu)$ diagonal

The back of the envelope calculation gives BR($l_i \to l_j \gamma$)=0

$$\mathrm{BR}(\ell_j \to \ell_i \gamma) \simeq \frac{\alpha^3}{G_F^2} \frac{|(\mathbf{m}_L^2)_{ij}|^2}{m_S^8} \tan^2\beta \, \mathrm{BR}(\ell_j \to \ell_i \nu_j \bar{\nu}_i)$$

$$(\mathbf{m}_L^2)_{ij} \simeq \mathbf{m}_L^2(\Lambda)_{ij} - \frac{1}{8\pi^2}(3m_0^2 + |A_0|^2)(h_\nu^\dagger h_\nu)_{ij} \log\left(\frac{\Lambda}{M_{\mathrm{maj}}}\right)$$

Is there any lower bound on the rate of $\mu \to e\gamma$?

Assume the worst case for the detection of $l_i \to l_j \gamma$

- $(\mathbf{m}^2_L)_{ij}$, $(\mathbf{m}^2_e)_{ij}$, $\mathbf{A}_{eij}$, $i \neq j$ vanish at high energies (no LFV in the soft terms at tree level)

AND

- $(h_\nu^\dagger h_\nu)$ diagonal

The back of the envelope calculation gives BR($l_i \to l_j \gamma$)=0

$$\mathrm{BR}(\ell_j \to \ell_i \gamma) \simeq \frac{\alpha^3}{G_F^2} \frac{|(\mathbf{m}^2_L)_{ij}|^2}{m_S^8} \tan^2\beta \, \mathrm{BR}(\ell_j \to \ell_i \nu_j \bar{\nu}_i)$$

$$(\mathbf{m}^2_L)_{ij} \simeq \mathbf{m}^2_L(\Lambda)_{ij} - \frac{1}{8\pi^2}(3m_0^2 + |A_0|^2)(h_\nu^\dagger h_\nu)_{ij} \log\left(\frac{\Lambda}{M_{\mathrm{maj}}}\right)$$

All the right-handed neutrinos decouple at the same scale M_{maj}

Strict calculation $(h_\nu^\dagger h_\nu)_{ij} \log\left(\frac{\Lambda}{M_{\mathrm{maj}}}\right) \longrightarrow \sum_k h^*_{\nu ki} \log\left(\frac{\Lambda}{M_k}\right) h_{\nu kj}$

Which is *necessarily* different from zero (unless cancellations take place)

The result of the calculation gives:

$$\boxed{\mathrm{BR}(\mu \to e\gamma) \gtrsim 1.2 \times 10^{-11} \left(\frac{M_1}{5 \times 10^{12}\mathrm{GeV}}\right)^2 \left(\frac{m_S}{200\,\mathrm{GeV}}\right)^{-4} \left(\frac{\tan\beta}{10}\right)^2}$$

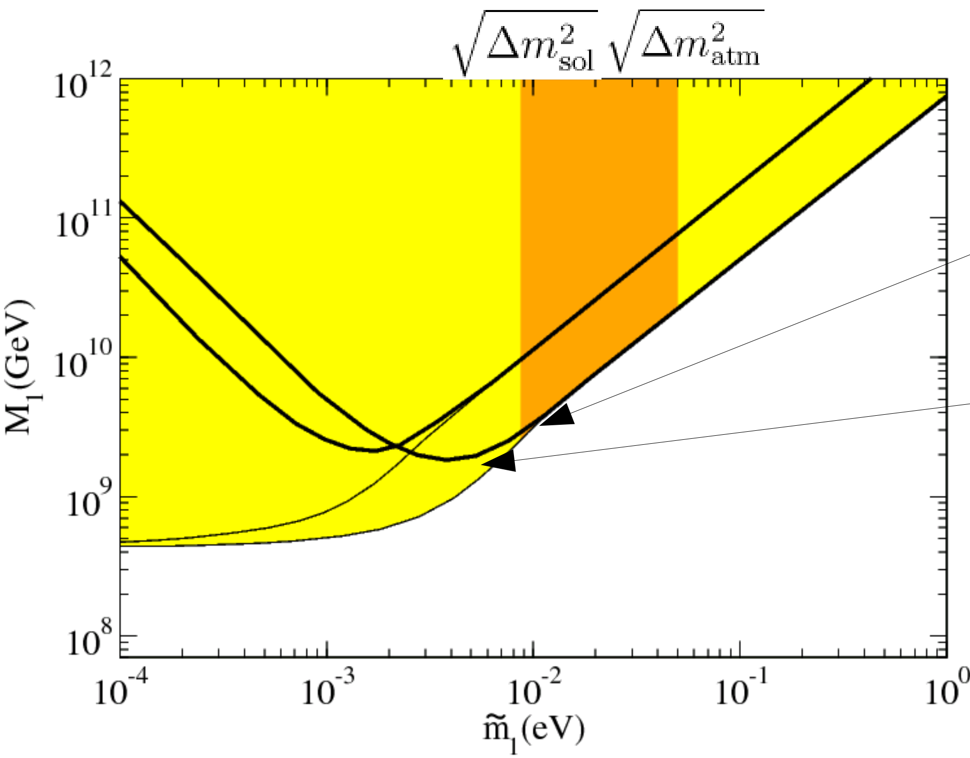
AI, Simonetto

The result of the calculation gives:

$$\mathrm{BR}(\mu \to e\gamma) \gtrsim 1.2 \times 10^{-11} \left(\frac{M_1}{5 \times 10^{12}\,\mathrm{GeV}}\right)^2 \left(\frac{m_S}{200\,\mathrm{GeV}}\right)^{-4} \left(\frac{\tan\beta}{10}\right)^2$$

AI, Simonetto

Connection to leptogenesis!



$$\mathrm{BR}(\mu \to e\gamma) \gtrsim 5 \times 10^{-18} \left(\frac{m_S}{200\,\mathrm{GeV}}\right)^{-4} \left(\frac{\tan\beta}{10}\right)^2$$

$$\mathrm{BR}(\mu \to e\gamma) \gtrsim 5 \times 10^{-19} \left(\frac{m_S}{200\,\mathrm{GeV}}\right)^{-4} \left(\frac{\tan\beta}{10}\right)^2$$

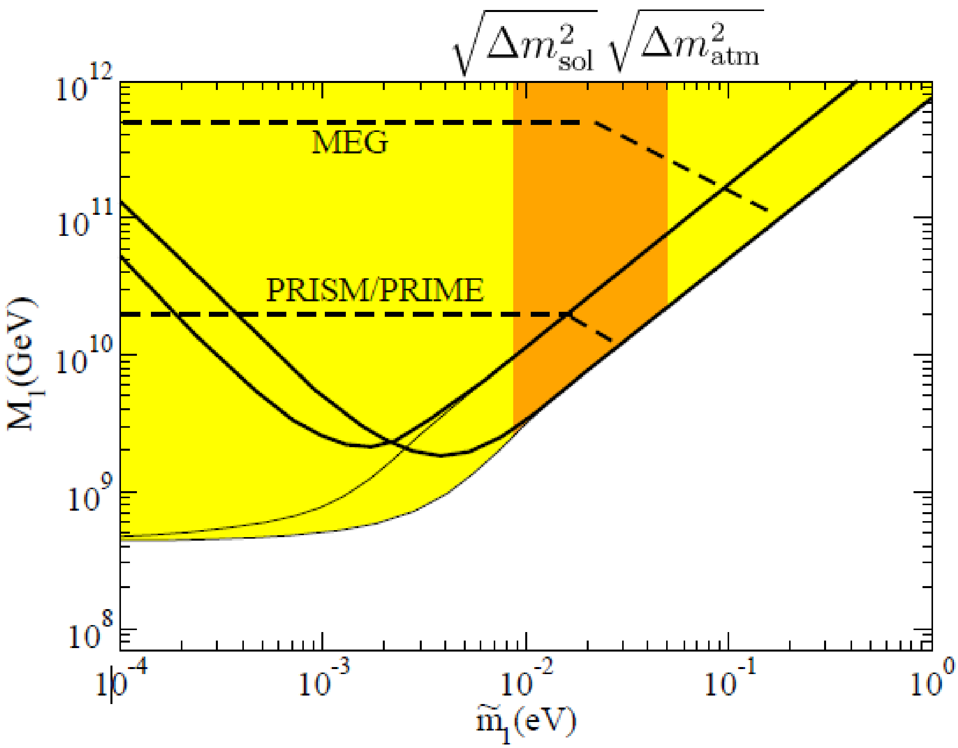
PRISM/PRIME at JPARC aims to a sensitivity to μTi-e Ti at the level of 10^{-18} (equivalent to ~10^{-16} in BR($\mu \to e\gamma$)).
Part of the parameter space can be covered

The result of the calculation gives:

$$\boxed{\mathrm{BR}(\mu \to e\gamma) \gtrsim 1.2 \times 10^{-11} \left(\frac{M_1}{5 \times 10^{12}\,\mathrm{GeV}}\right)^2 \left(\frac{m_S}{200\,\mathrm{GeV}}\right)^{-4} \left(\frac{\tan\beta}{10}\right)^2}$$

AI, Simonetto

Connection to leptogenesis!



PRISM/PRIME at JPARC aims to a sensitivity to μTi-e Ti at the level of 10^{-18} (equivalent to ~10^{-16} in BR($\mu\to e\gamma$)).
Part of the parameter space can be covered

Summary of leptogenesis predictions

Non-SUSY case

- Neutrino oscillations. Already observed!

Summary of leptogenesis predictions

Non-SUSY case

- Neutrino oscillations. Already observed!
- Lepton number violation $\Rightarrow$ neutrinoless double beta decay

Summary of leptogenesis predictions

Non-SUSY case

- Neutrino oscillations. Already observed!
- Lepton number violation $\Rightarrow$ neutrinoless double beta decay
- CP violation in the neutrino sector

Summary of leptogenesis predictions

Non-SUSY case

- Neutrino oscillations. Already observed!
- Lepton number violation $\Rightarrow$ neutrinoless double beta decay
- CP violation in the neutrino sector
- (Huge tuning)

SUSY case

Summary of leptogenesis predictions

Non-SUSY case

- Neutrino oscillations. Already observed!
- Lepton number violation $\Rightarrow$ neutrinoless double beta decay
- CP violation in the neutrino sector
- (Huge tuning)

SUSY case

- Possibly gravitino dark matter (probably not neutralino dark matter)

Summary of leptogenesis predictions

Non-SUSY case

- Neutrino oscillations. Already observed!
- Lepton number violation $\Rightarrow$ neutrinoless double beta decay
- CP violation in the neutrino sector
- (Huge tuning)

SUSY case

- Possibly gravitino dark matter (probably not neutralino dark matter)
- BR($\mu \to e\gamma$)>10^{-18} for typical SUSY parameters

Summary of leptogenesis predictions

Non-SUSY case

- Neutrino oscillations. Already observed!
- Lepton number violation $\Rightarrow$ neutrinoless double beta decay
- CP violation in the neutrino sector
- (Huge tuning)

SUSY case

- Possibly gravitino dark matter (probably not neutralino dark matter)
- $\mathrm{BR}(\mu \rightarrow e\gamma) > 10^{-18}$ for typical SUSY parameters

Still looking for a smoking gun!