Seesaw

and

Leptogenesis

Pasquale Di Bari

(Max Planck, Munich)

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- as a probe of very early Universe history and 'new' physics, like BBN (future ?)

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- . . . in very good agreement with the determination from SBBN + primordial Deuterium measurements :

$$\eta_B^{SBBN} = (6.1 \pm 0.5) \times 10^{-10}$$

  (Cyburt et al. 2001, Kirkman et al. 2003)

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$$N_B^{\mathrm{f}} \simeq \frac{1}{3}\, N_{B-L}^{\mathrm{f}} \simeq -\frac{1}{2}\, N_L^{\mathrm{f}}$$

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- Total decay parameter:

$$\Gamma_D = \Gamma + \bar{\Gamma} = \Gamma_D^{\mathrm{rest}} \left\langle \frac{1}{\gamma} \right\rangle$$

Seesaw $\Rightarrow$ Leptogenesis (Fukugita,Yanagida '86)

$$\mathcal{L}^{\nu}_{\rm mass} = -\frac{1}{2}\left[(\bar{\nu}^c_L, \bar{\nu}_R)\begin{pmatrix} m_T & {m_D}^T \\ m_D & M_R \end{pmatrix}\begin{pmatrix} \nu_L \\ \nu^c_R \end{pmatrix}\right] + h.c.$$

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m_D, m_ν and M are complex matrices ⇒ natural source of CP violation

- 3 new heavy RH neutrinos N_1,N_2,N_3 with masses $M_{\rm ew} \ll M_1 \leq M_2 \leq M_3$

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- 3 new heavy RH neutrinos N_1,N_2,N_3 with masses $M_{\rm ew} \ll M_1 \leq M_2 \leq M_3$
- approximation: only the decays of the N_1's contribute to the final asymmetry
  - it typically works well for $M_2 \gtrsim 2\,M_1$ but with some interesting exception !
  - within this approximation the final asymmetry depends only on a few seesaw parameters

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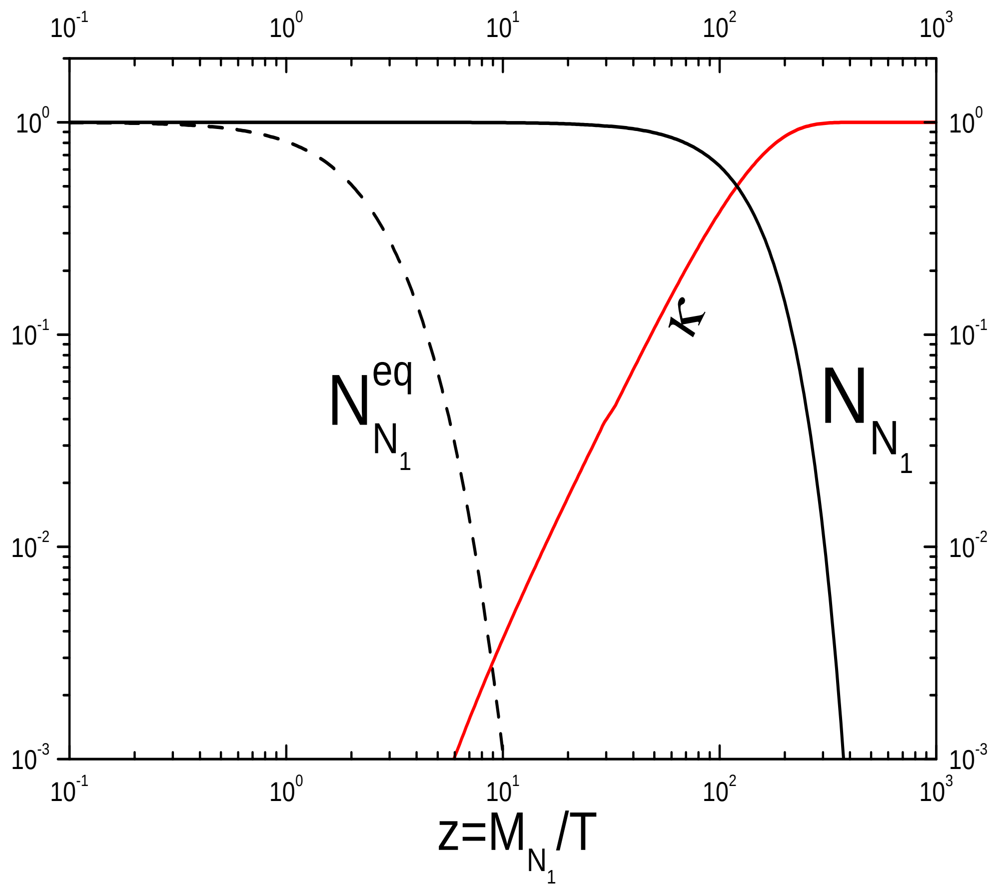

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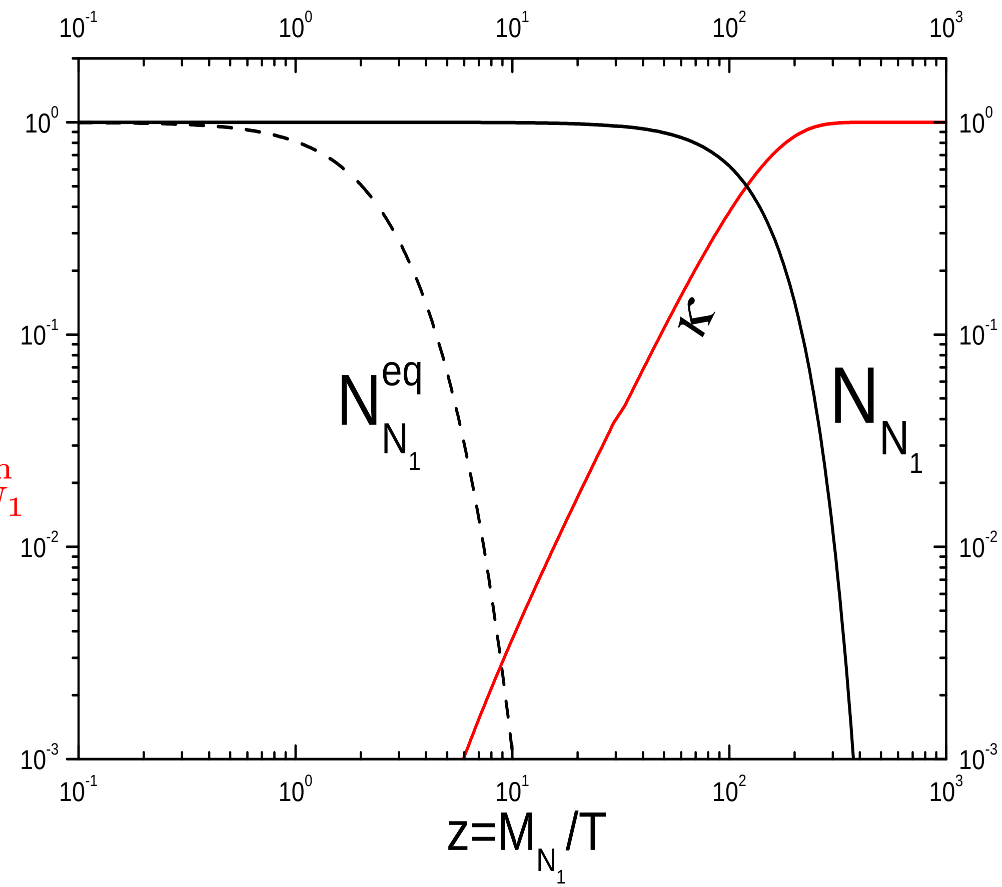

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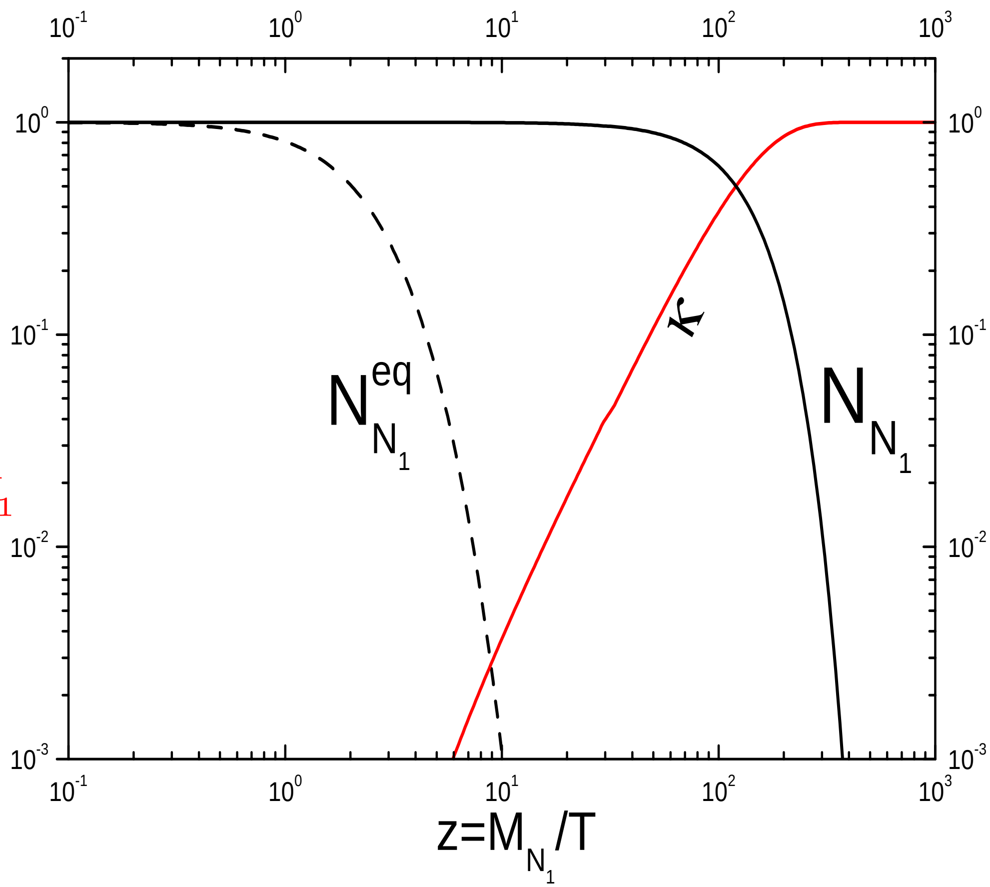

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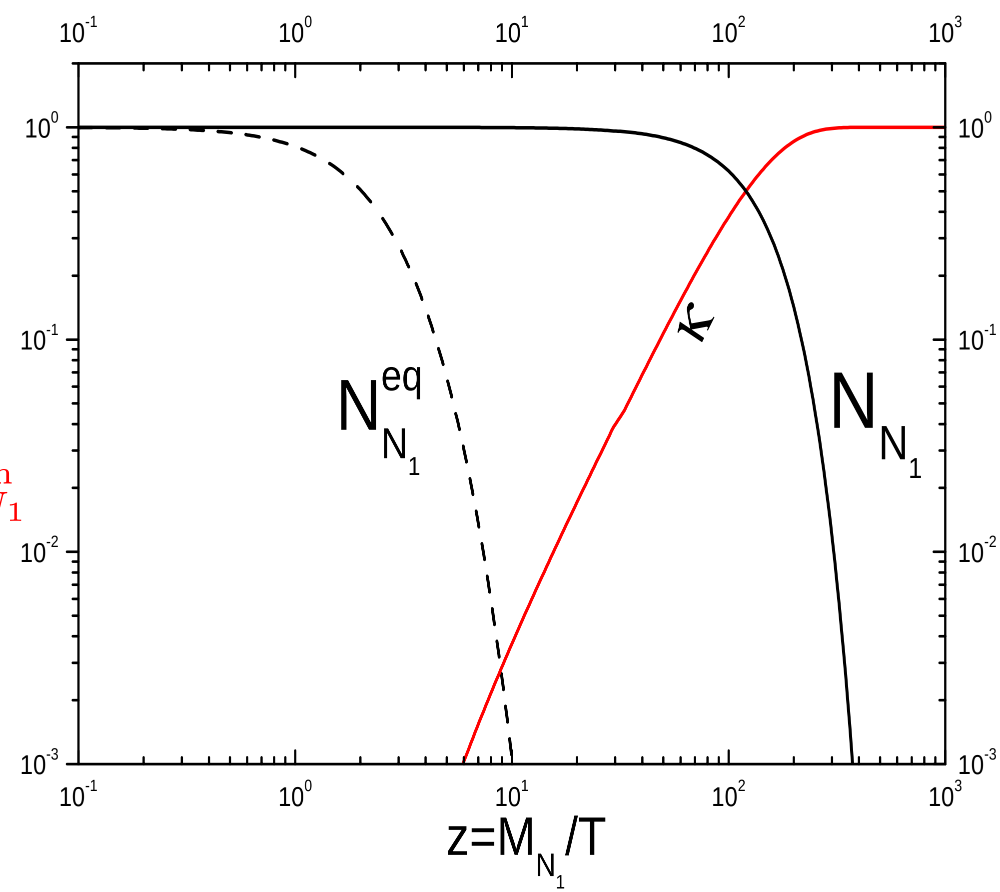

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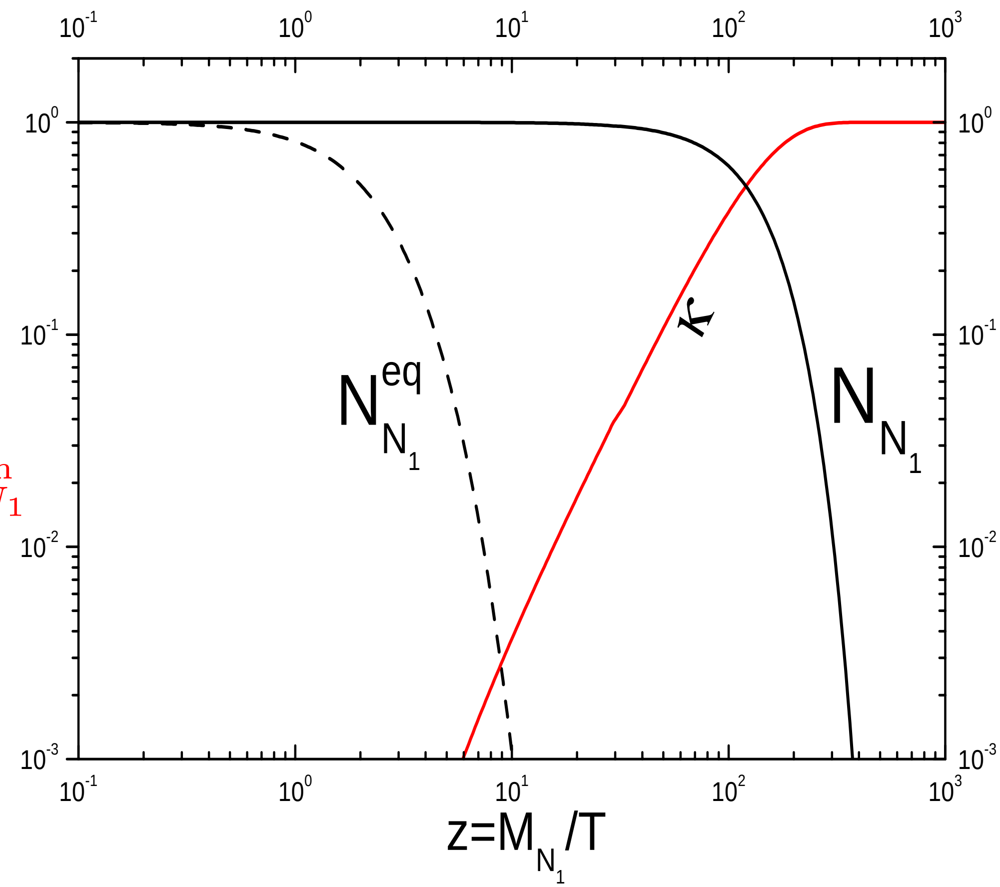

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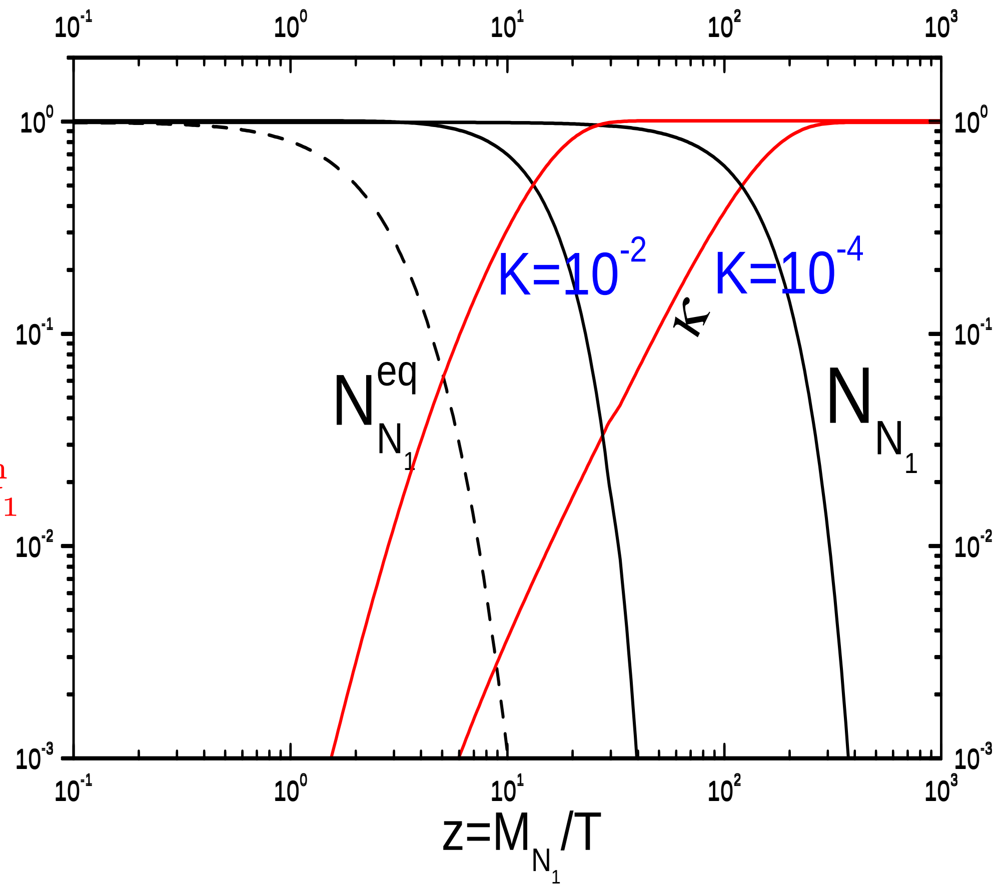

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- Weak wash-out regime for $K \lesssim 1$ (out-of-equilibrium picture recovered for $K \rightarrow 0$)
- Strong wash-out regime for $K \gtrsim 1$

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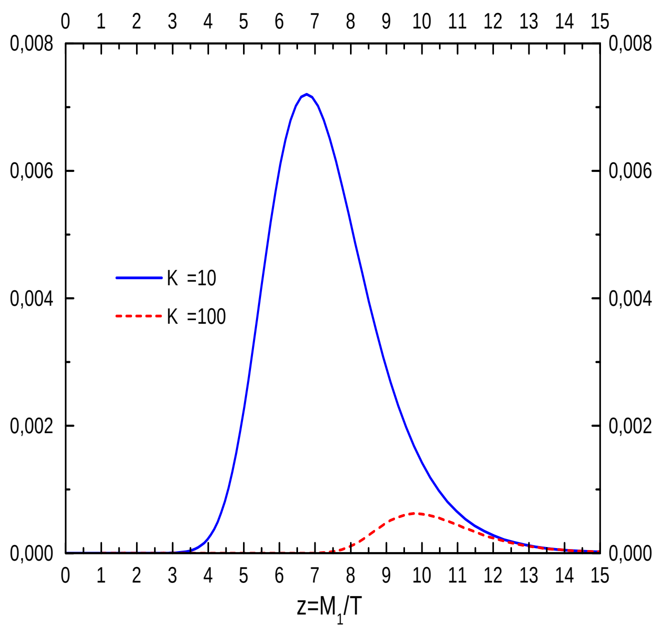

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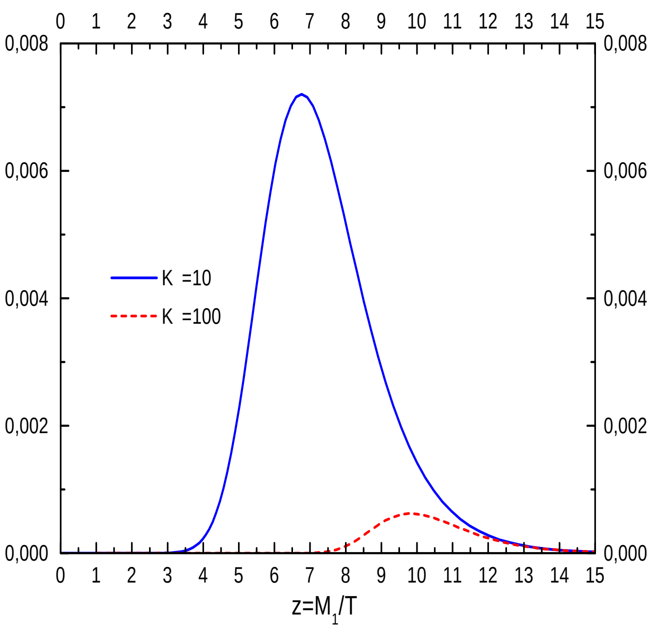

- only non relativistic stage matters
- $\kappa_{\rm f}(z_i=0) \simeq \kappa_{\rm f}(z_i = z_B - \Delta z_B)$
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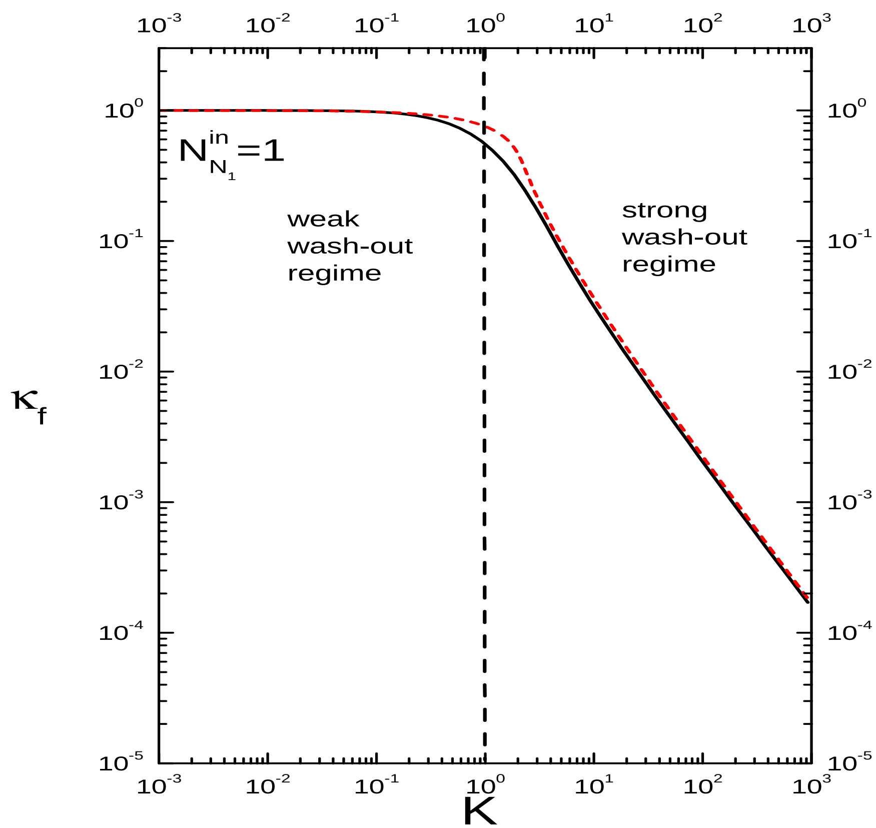

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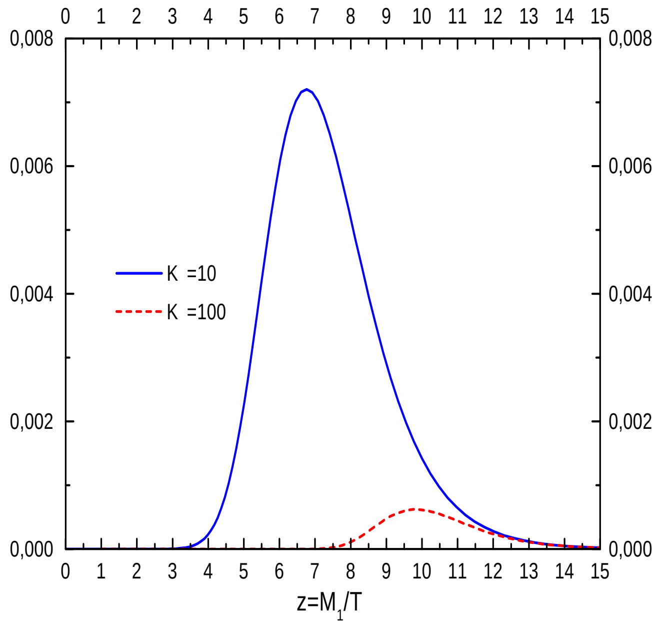

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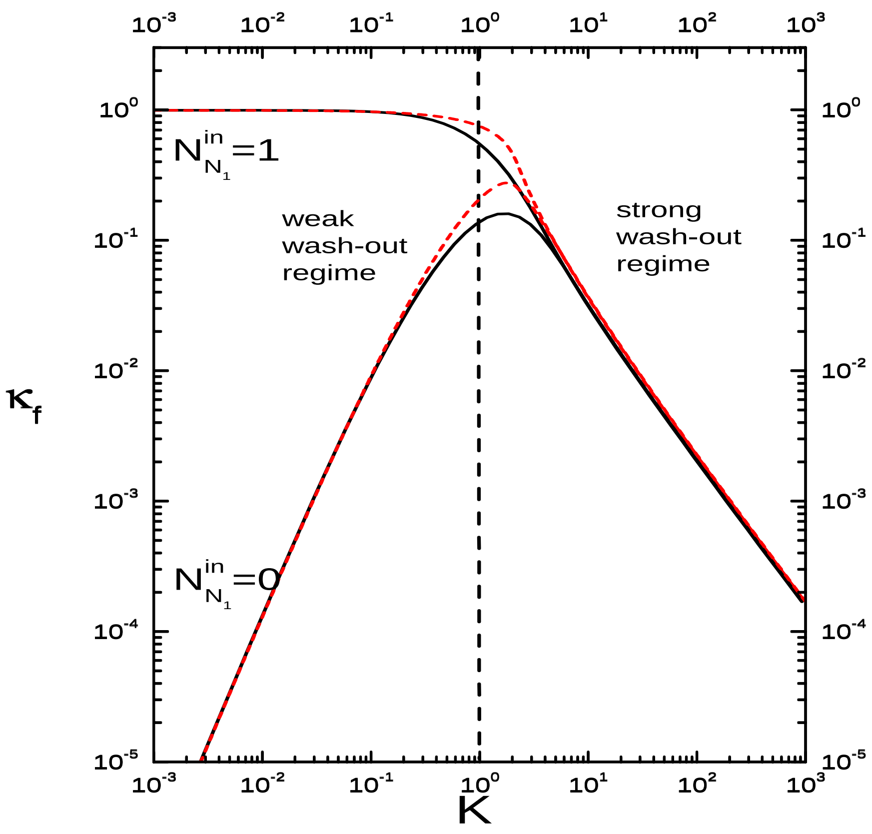

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- equilibrium neutrino mass

$$m_\star = {\rm const}\, \frac{v^2\,\sqrt{g_\star}}{M_{Pl}} \simeq 10^{-3}\,{\rm eV}$$

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$$\Omega = D_m^{-1/2} \, U^\dagger \, m_D \, D_M^{-1/2} \Rightarrow \Omega_{ij} = \frac{(U^\dagger \, m_D)_{ij}}{\sqrt{m_i \, M_j}}$$

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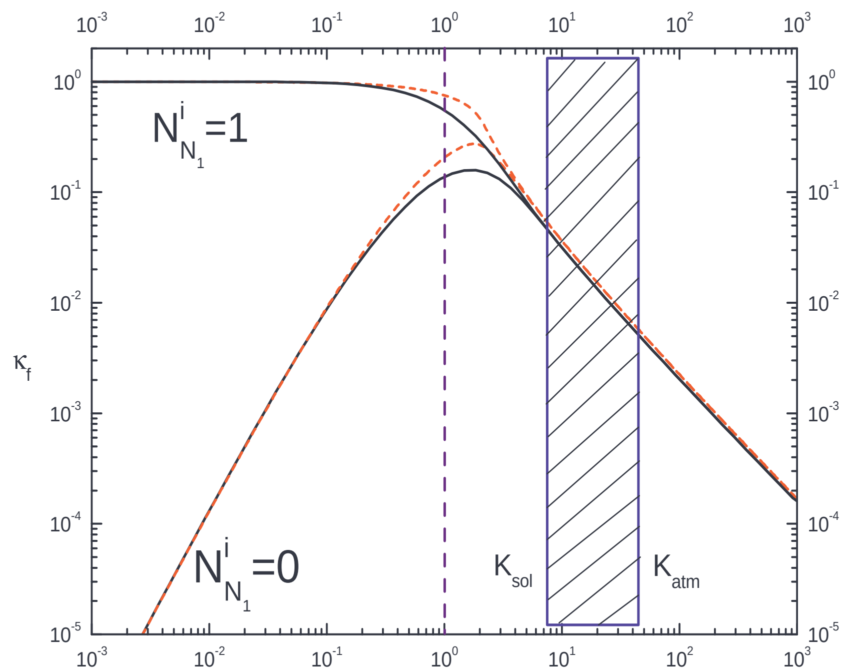
$\mathcal{O}(m_{\rm sol} \simeq 0.008\,\mathrm{eV}) < \widetilde{m}_1 < \mathcal{O}(m_{\rm atm} \simeq 0.05\,\mathrm{eV})$

Leptogenesis K range

Translating $\widetilde{m}_1$ in terms of $K = \widetilde{m}_1 / m_\star$:

$$8 \simeq K_{\rm sol} \lesssim K \lesssim K_{\rm atm} \simeq 50$$



Neutrino mixing data favor leptogenesis

to lie in the strong wash-out regime

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- conditions for weak wash-out:

1. fully hierarchical neutrinos
2. $m_1 \leq \widetilde{m}_1 \ll m_\star \ll m_{\rm sol} \Rightarrow$

$$\Omega \simeq R_{23} \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & \Omega_{22} & \sqrt{1-\Omega_{22}^2} \\ 0 & -\sqrt{1-\Omega_{22}^2} & \Omega_{22} \end{pmatrix}$$

3. $\widetilde{m}_1 \simeq m_1 \Rightarrow \varepsilon_1 \simeq 1 - m_1/\widetilde{m}_1 \Rightarrow$

$\widetilde{m}_1 \gg m_1 \Rightarrow \Omega \neq R_{23}$

$\Rightarrow$ fine-tuned conditions !

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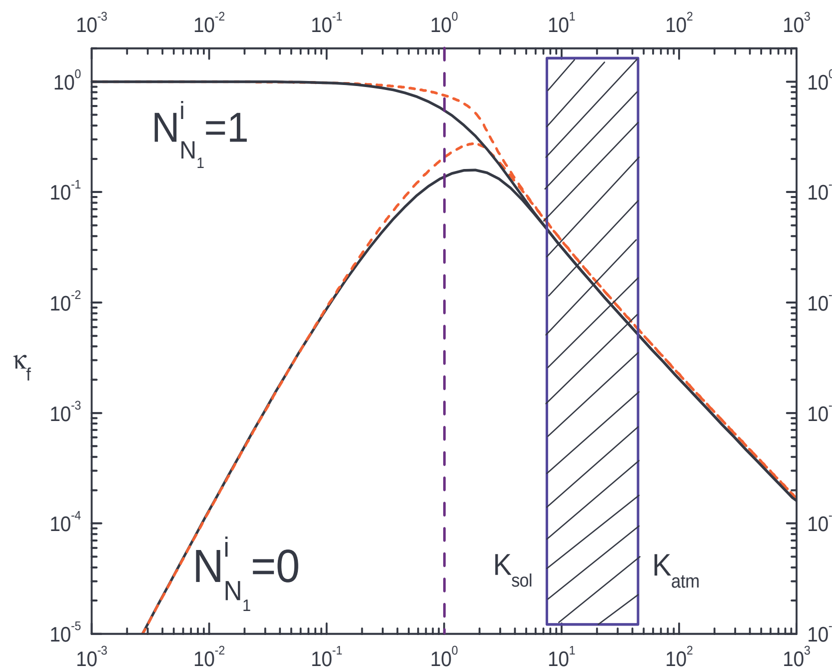

Neutrino mixing data favor leptogenesis

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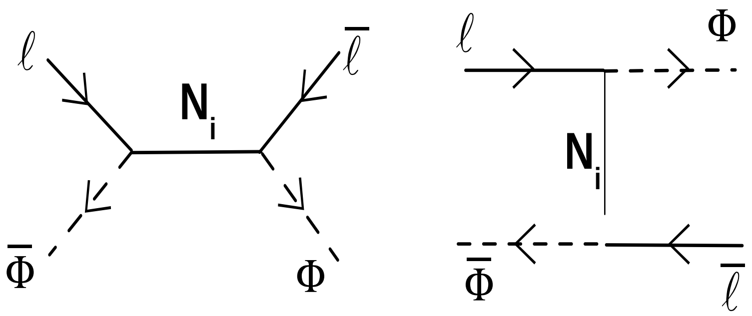
$\Delta L = 2$ processes



$$W_{\Delta L=2}(z) = \not{W}^{\rm res}_{\Delta L=2}(z) + \Delta W(z)$$

- ΔW is important only in the non relativistic regime

$$\Delta W(z \ll 1) \propto \frac{M_1\, \bar{m}^2}{z^2}\,, \quad \boxed{\bar{m}^2 \equiv \sum_i m_{\nu_i}^2}$$

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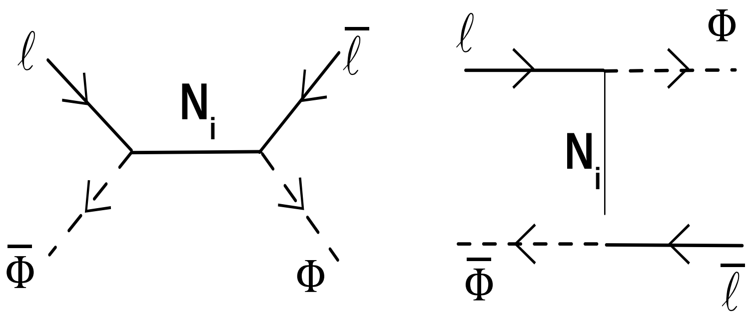

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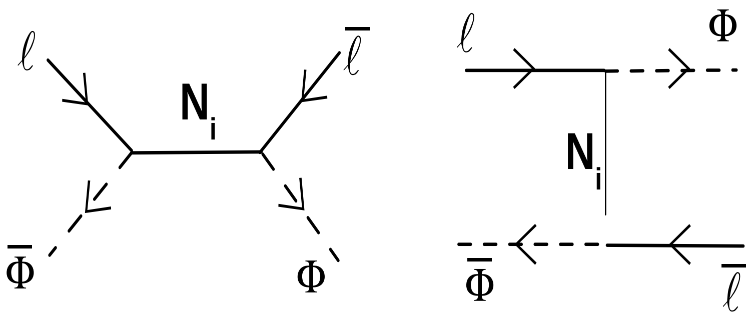

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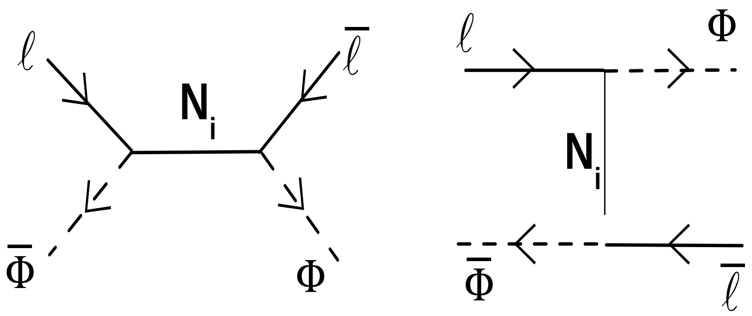

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- in the case of hierarchical neutrinos is negligible for $\boxed{M_1 \ll 10^{14}\,{\rm GeV}}$

CP asymmetry

- Interference between tree level and (vertex + self energy) one-loop diagrams

$$\Rightarrow \varepsilon_1 \quad \simeq \quad \frac{1}{8\pi\, v^2\, (m_D^\dagger\, m_D)_{11}} \sum_{i=2,3} \mathrm{Im}\left[(m_D^\dagger\, m_D)^2_{1i}\right] \times \left[f_V\left(\frac{M_i^2}{M_1^2}\right) + f_S\left(\frac{M_i^2}{M_1^2}\right)\right]$$

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$$\varepsilon_1^{\max}(M_1) \equiv \frac{3}{16\pi}\, \frac{M_1\, m_{\mathrm{atm}}}{v^2} \simeq 10^{-6} \left(\frac{M_1}{10^{10}\,\mathrm{GeV}}\right)$$

CMB constraints in the full hierarchical case

(Buchmuller,PDB,Plumacher '02)

$$\eta_B^{\max}(M_1,\widetilde{m}_1)|_{m_1=0} \simeq d\;\varepsilon_1^{\max}(M_1)\,\kappa_{\rm f}(M_1,\widetilde{m_1})$$

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$$d \simeq \frac{1}{3\,N_\gamma^{\rm rec}} \simeq 10^{-2}$$

CMB bound:

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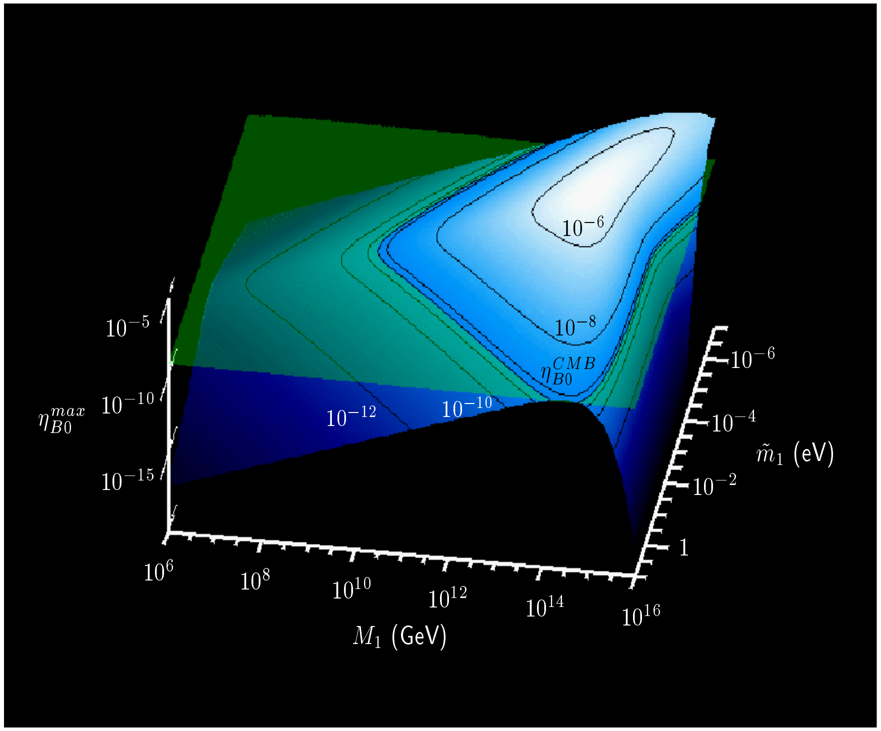
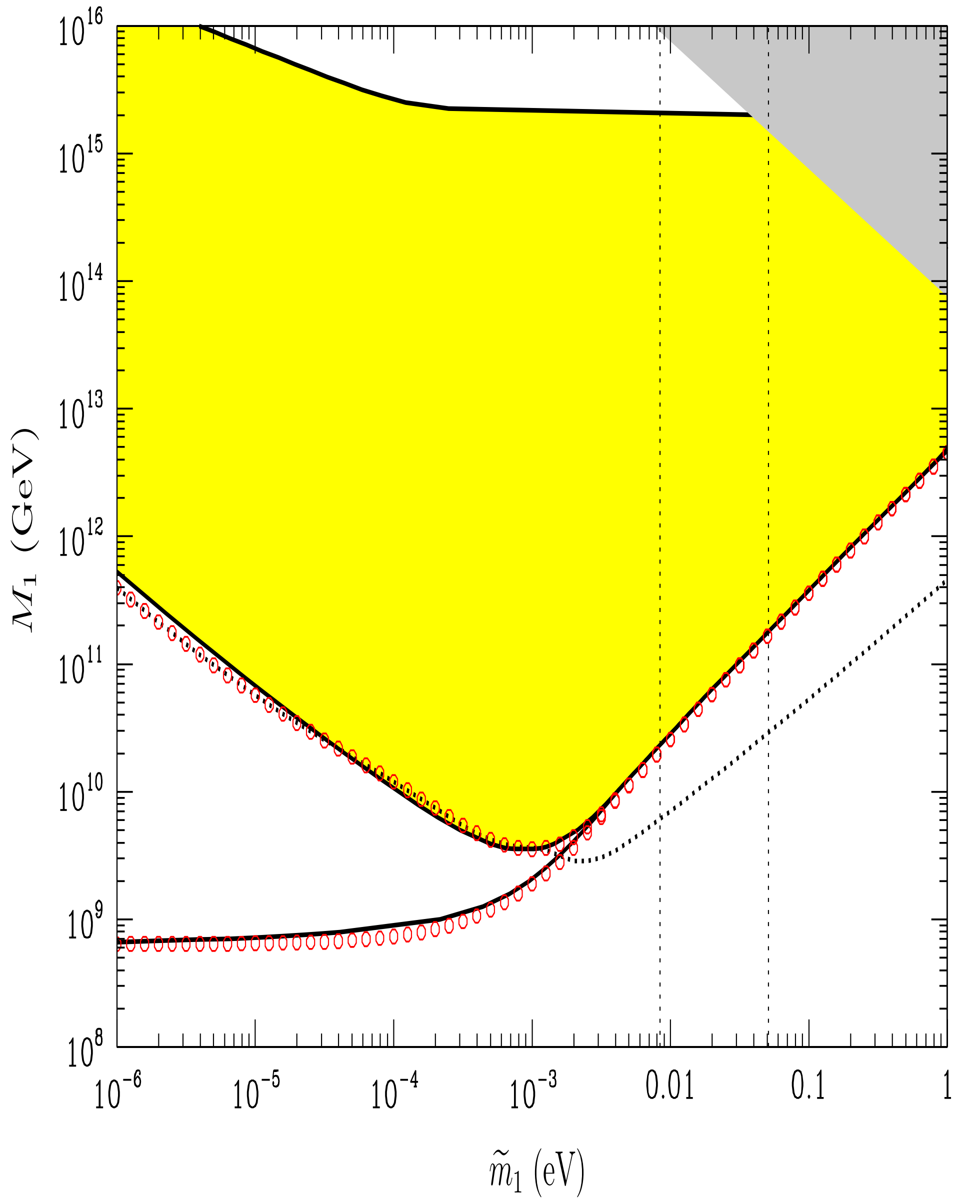


Lower bound on M_1 and on $T_{\rm in}$

(Davidson,Ibarra '02; Buchmuller,PDB,Plumacher '02,'04; Giudice,Notari,Raidal,Riotto,Strumia,'03)



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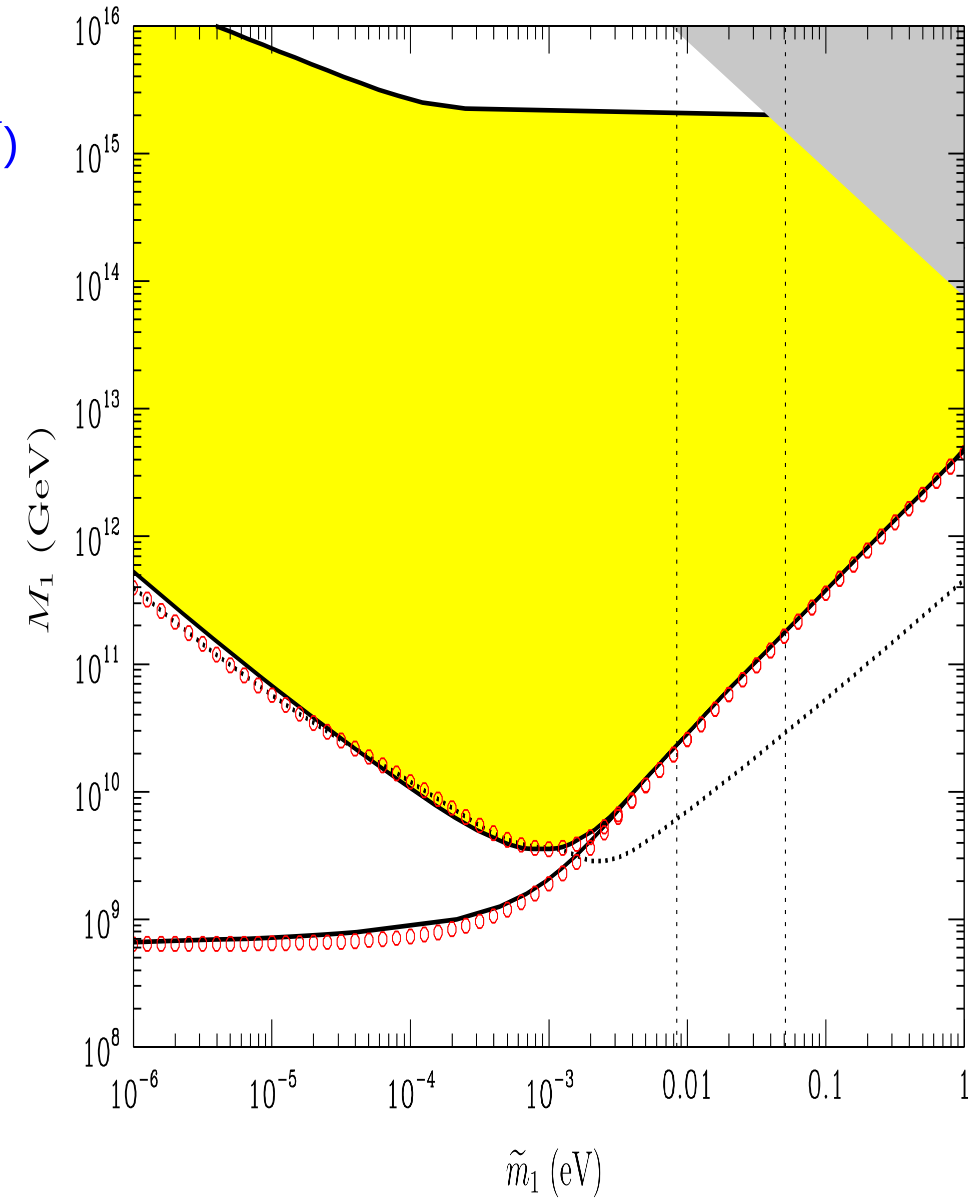

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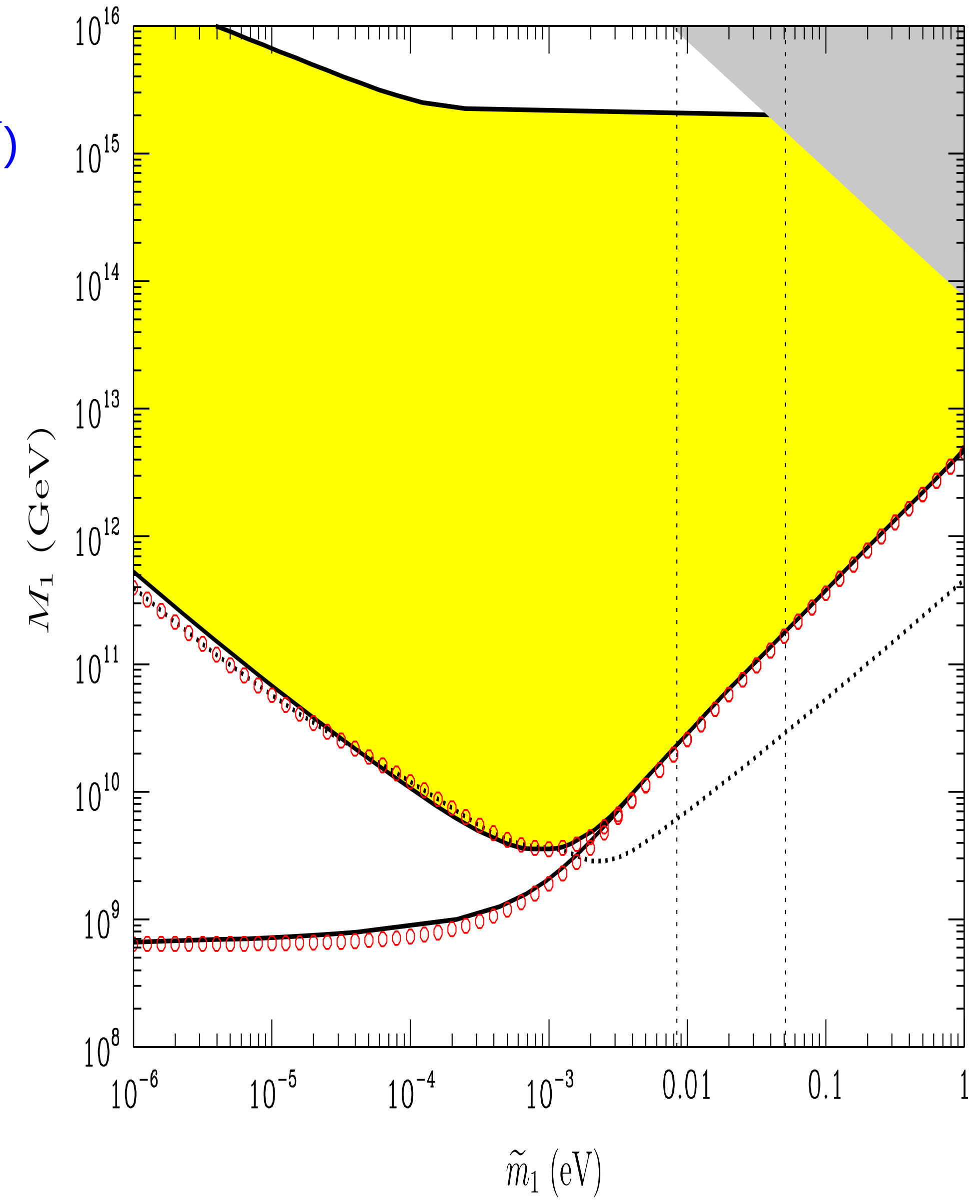
For $\widetilde{m}_1$ between $m_{\rm sol}$ and $m_{\rm atm}$:

$$M_1 \gtrsim (10^{10} - 10^{11})\,{\rm GeV}$$

$\Rightarrow$ problem for many neutrino models !

(Branco et al.'02, Davidson'02, Akhmedov er al. '03,. . .)

$$T_{\rm reh} \gtrsim \frac{M_1^{\rm min}(\widetilde{m}_1)}{z_B(\widetilde{m}_1)-2} \simeq \frac{M_1^{\rm min}}{5}$$



Leptogenesis ‘conspiracy’

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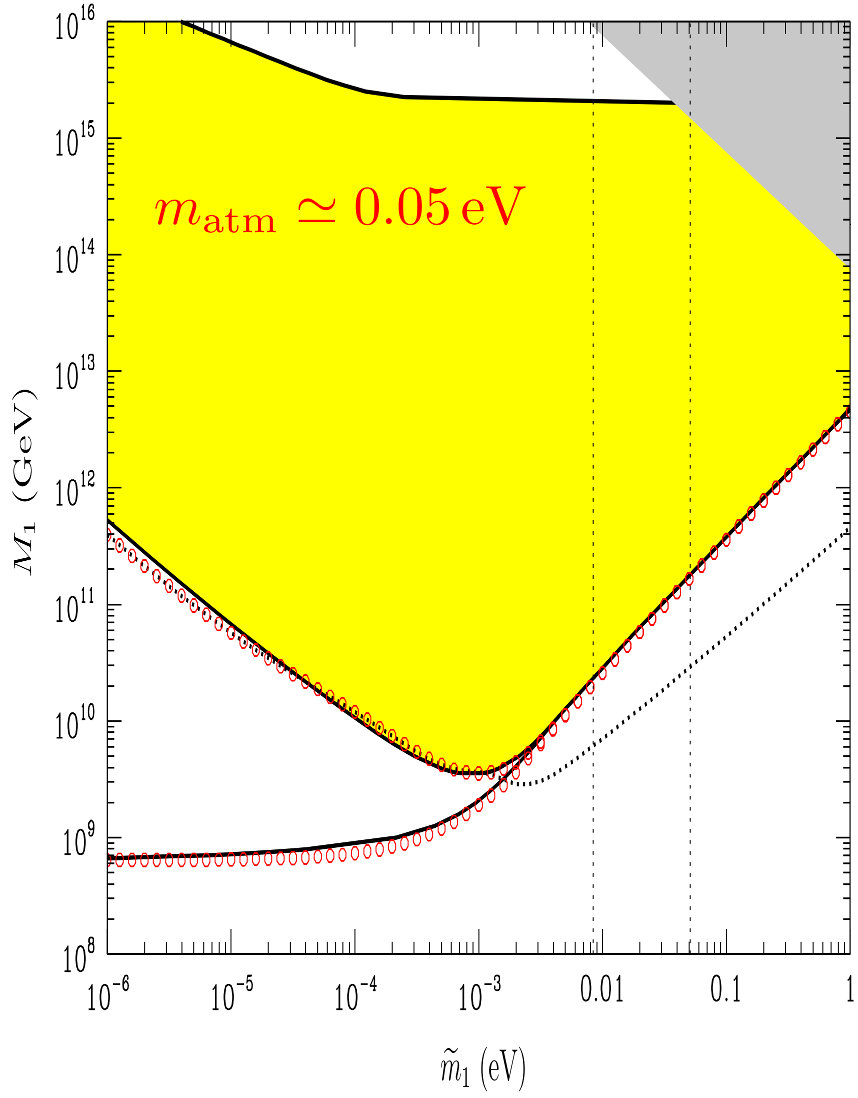

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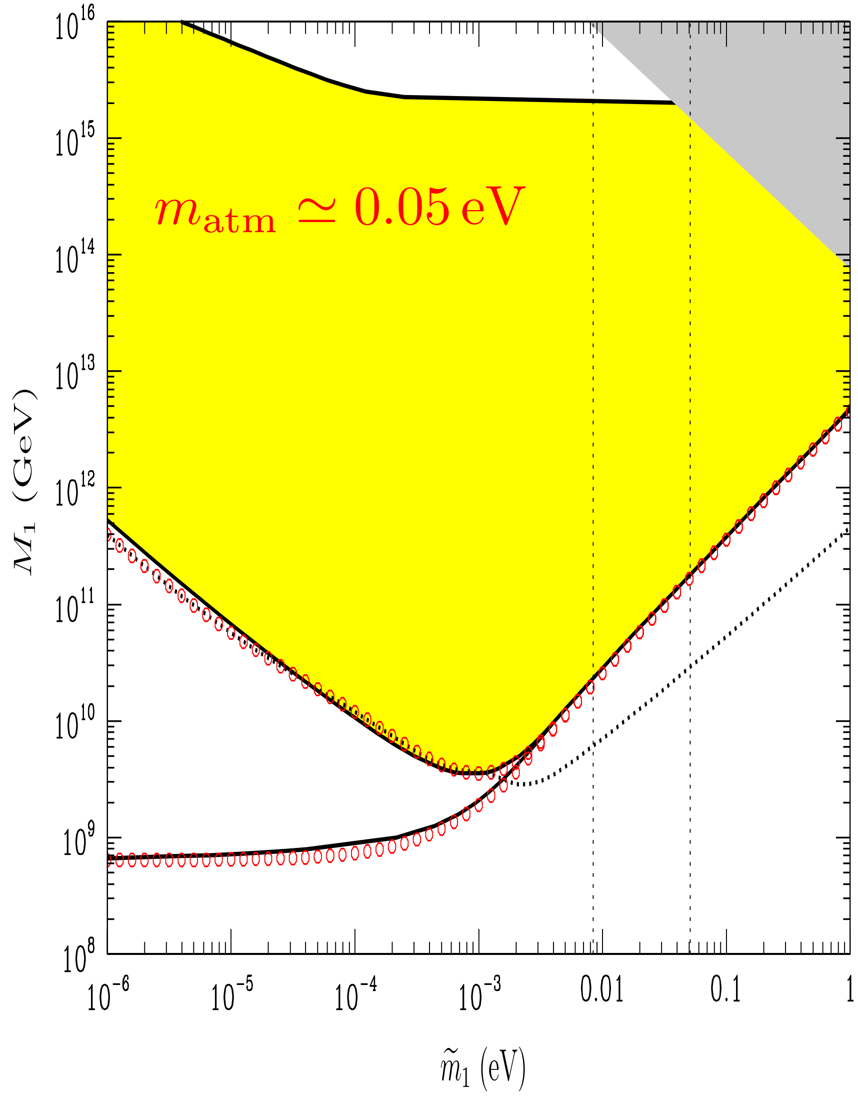

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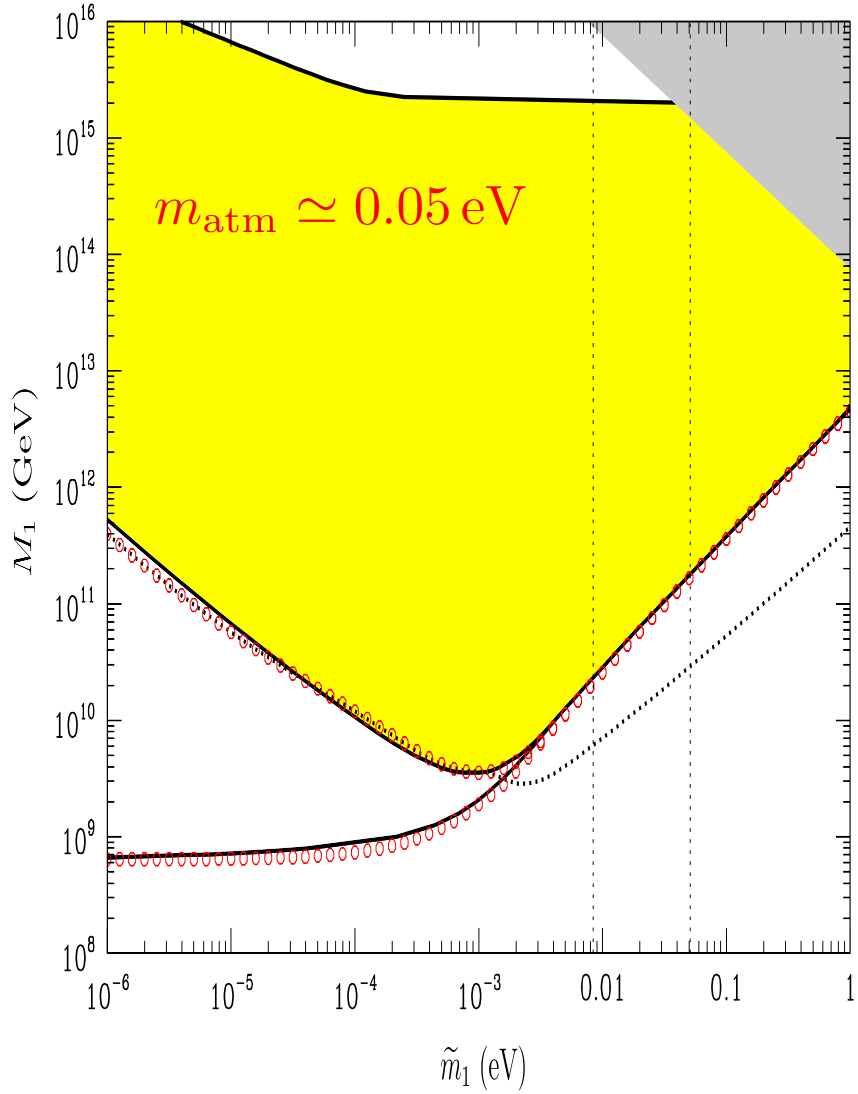

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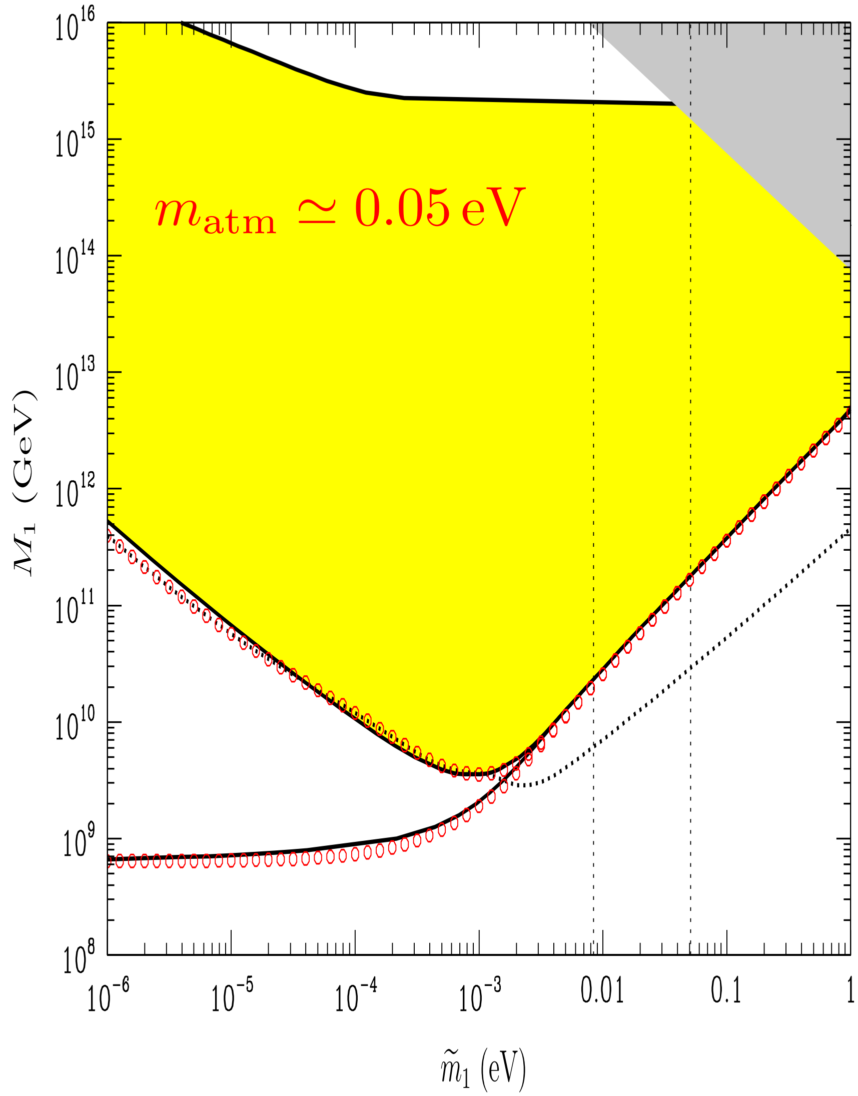

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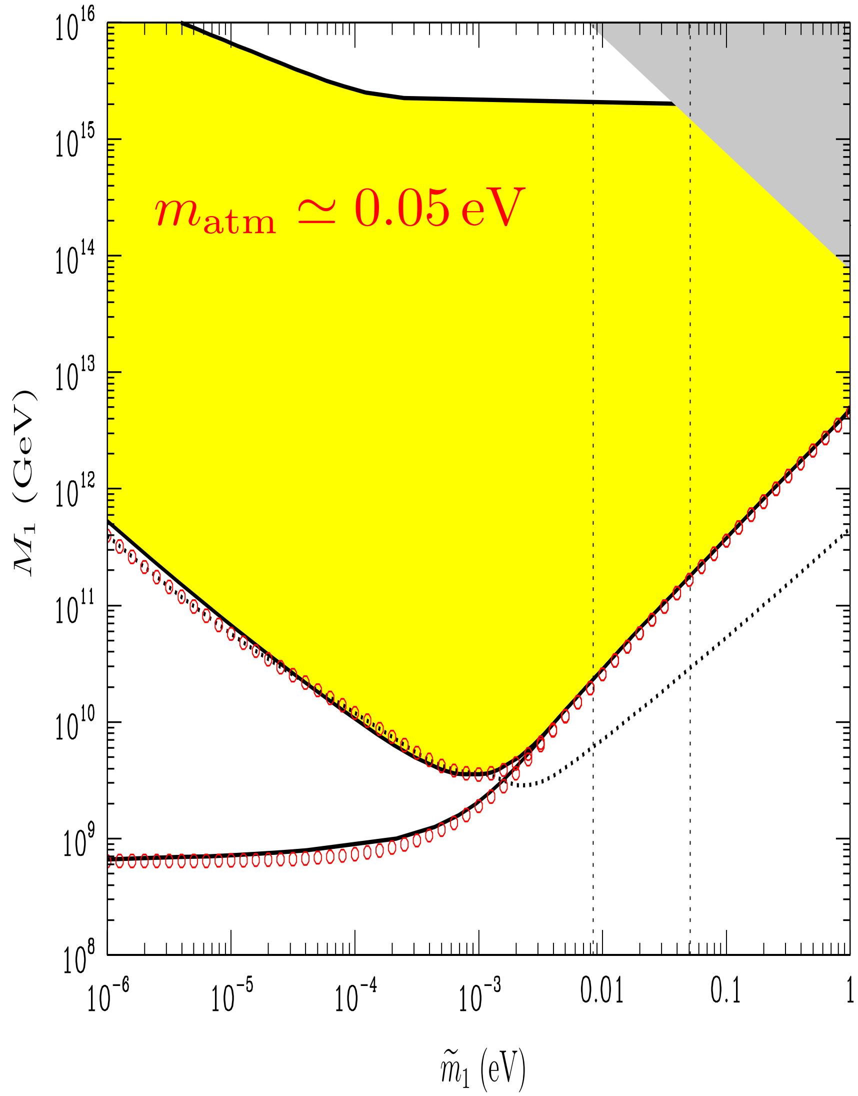

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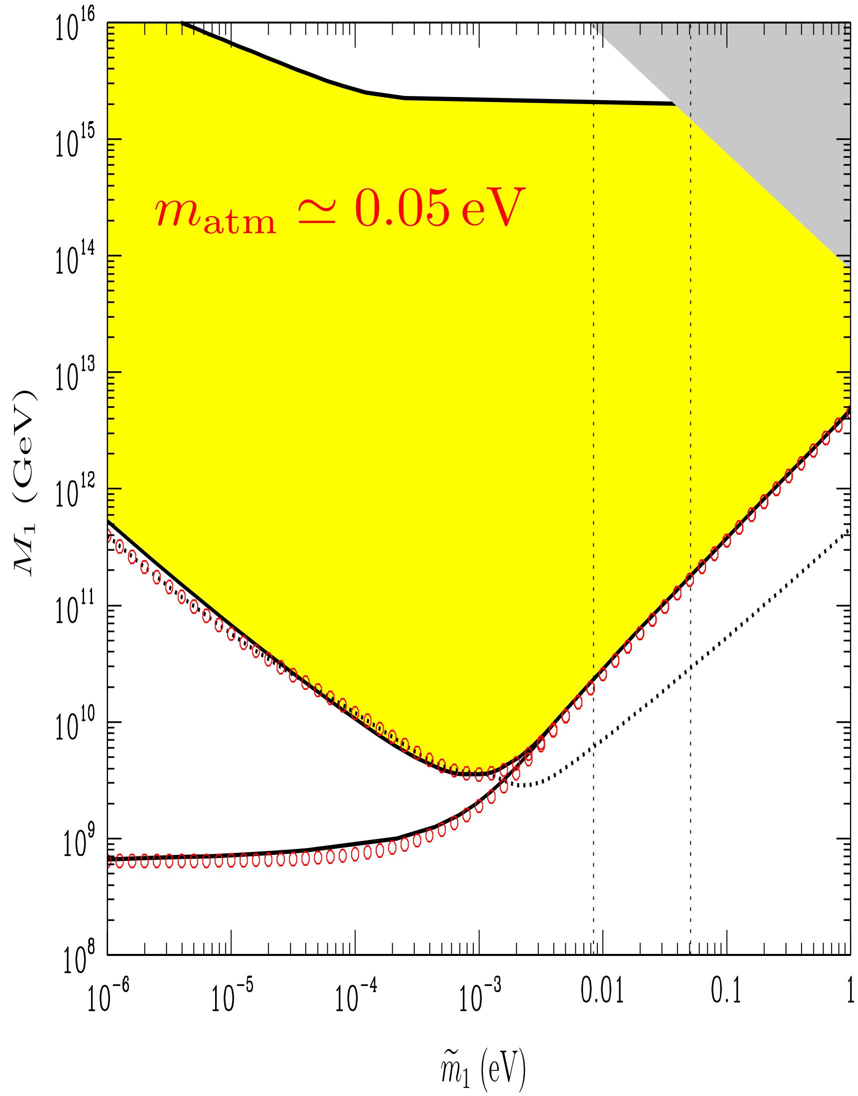
⇒ the experimental result:

$$\mathcal{O}(10^{-3}\,{\rm eV}) < m_{\rm atm} < \mathcal{O}(1\,{\rm eV})$$

is a successful test for thermal leptogenesis !



Testing the seesaw mechanism with leptogenesis

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$$m_D = U \begin{pmatrix} \sqrt{m_1} & 0 & 0 \\ 0 & \sqrt{m_2} & 0 \\ 0 & 0 & \sqrt{m_3} \end{pmatrix} \Omega \begin{pmatrix} \sqrt{M_1} & 0 & 0 \\ 0 & \sqrt{M_2} & 0 \\ 0 & 0 & \sqrt{M_3} \end{pmatrix} \qquad \begin{pmatrix} U^\dagger U & = & I \\ \Omega\,\Omega^T & = & I \end{pmatrix}$$

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$$\uparrow \qquad\qquad \uparrow$$

theory “*observables*”

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$$\textit{theory} \qquad\qquad\qquad\qquad \textit{“observables”}$$

- parameter counting: 6 + 3 + 6 + 3 = 18
- some of them we measure: $\theta_{12}, \theta_{23}, m_{\rm sol}, m_{\rm atm}$

future experiments could measure or constraint: $m_1, \theta_{13}, \delta, \varphi_1, \varphi_2$

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Testing the seesaw mechanism with leptogenesis

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- leptogenesis $\Rightarrow$ information on Ω, M_i (but also on m_1 !)
- $\varepsilon_i = \varepsilon_i(m_D^\dagger\, m_D) \Rightarrow U$ cancels out

$\Rightarrow$ in general only Ω is the source of the CP violation necessary for leptogenesis

$\Rightarrow$ (no) CP violation in neutrino mixing does not imply $\varepsilon_i \neq 0$ $(\varepsilon_i = 0)$

however with extra theoretical input U and Ω can be related

Seesaw geometry

(PDB '04)

For hierarchical RH neutrinos the dependence on many parameters is marginal and the predicted asymmetry depends approximately only on 6 parameters

$$\eta_B \simeq -\,10^{-2}\,\kappa_{\rm f}(m_1,\widetilde{m}_1,M_1)\,\varepsilon_1(M_1,m_1,\widetilde{m}_1,\Omega^2_{j1})$$

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We have seen that:

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For hierarchical RH neutrinos the dependence on many parameters is marginal and the predicted asymmetry depends approximately only on 6 parameters

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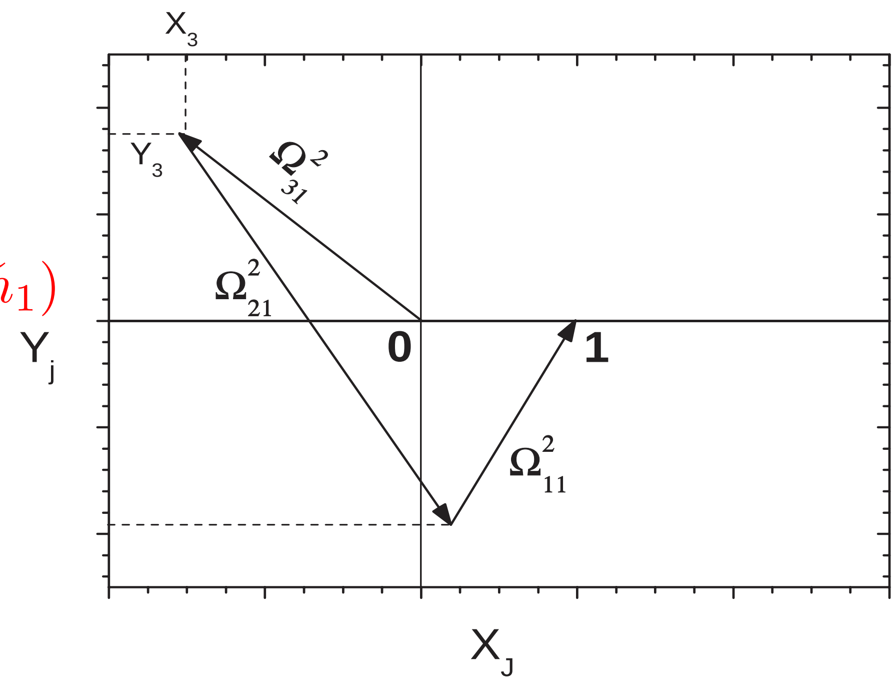

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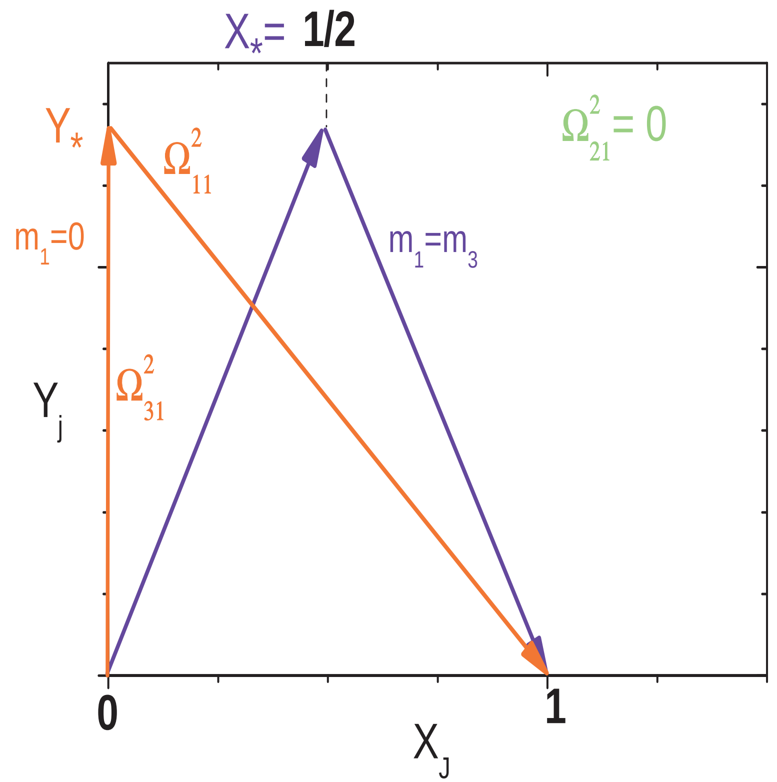

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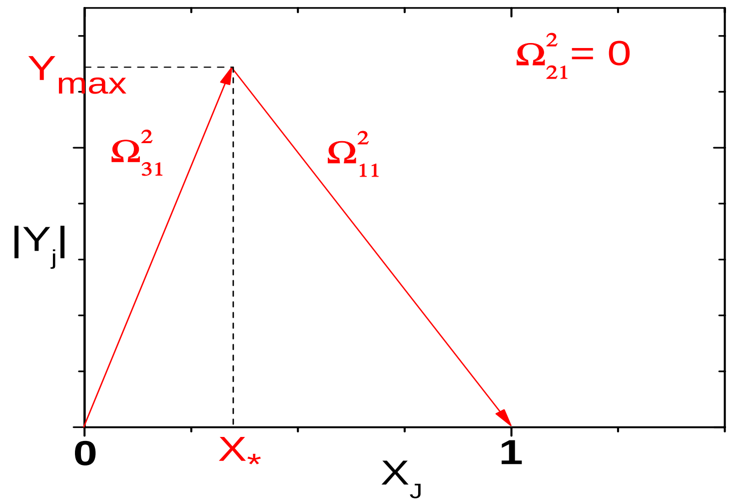

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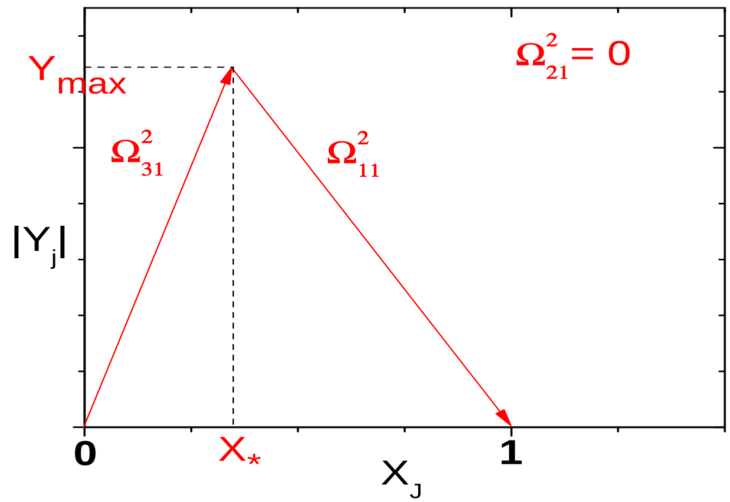

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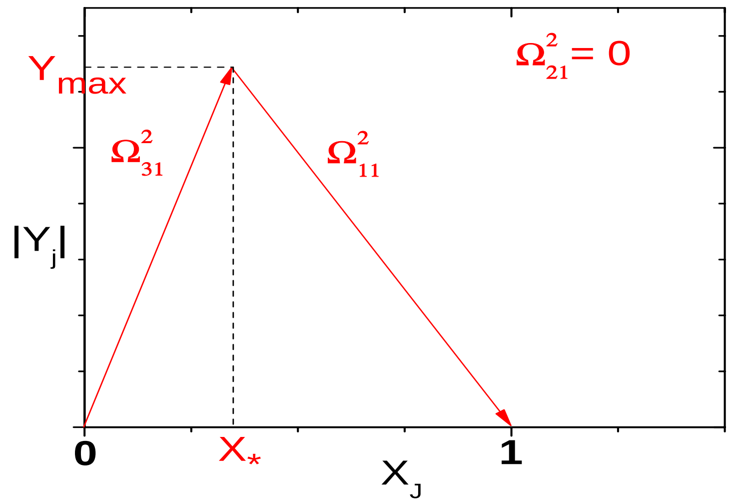

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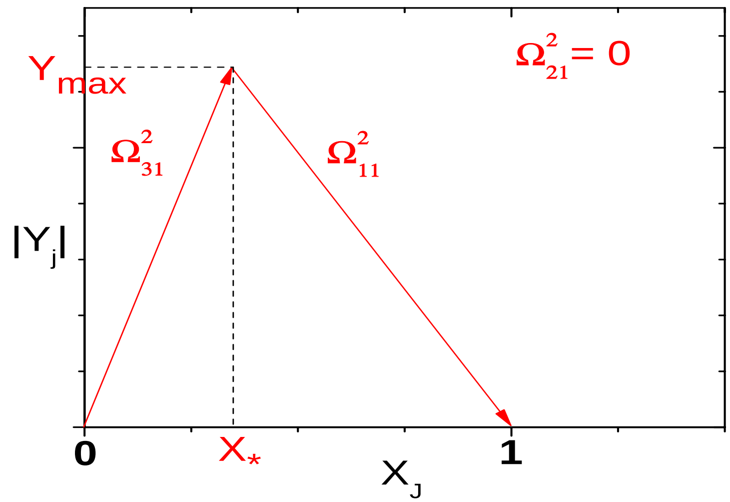

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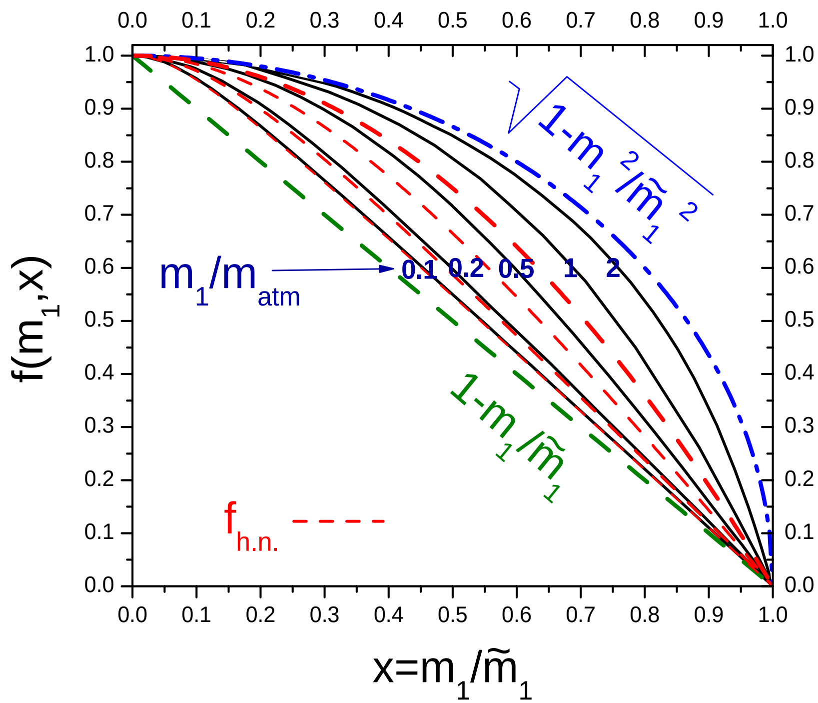

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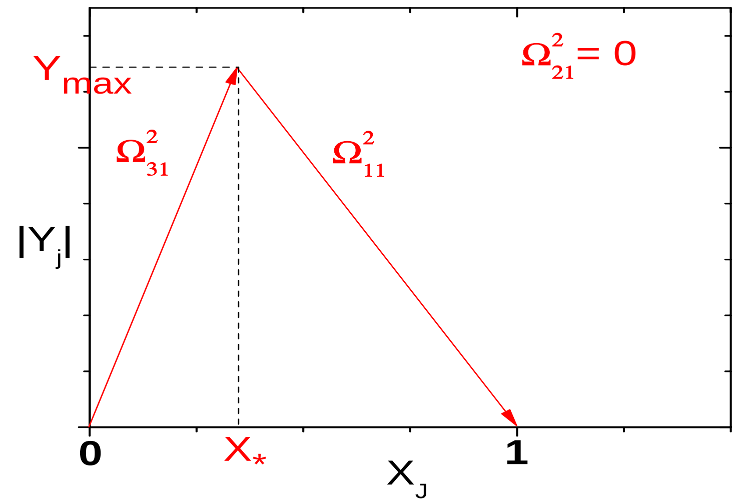

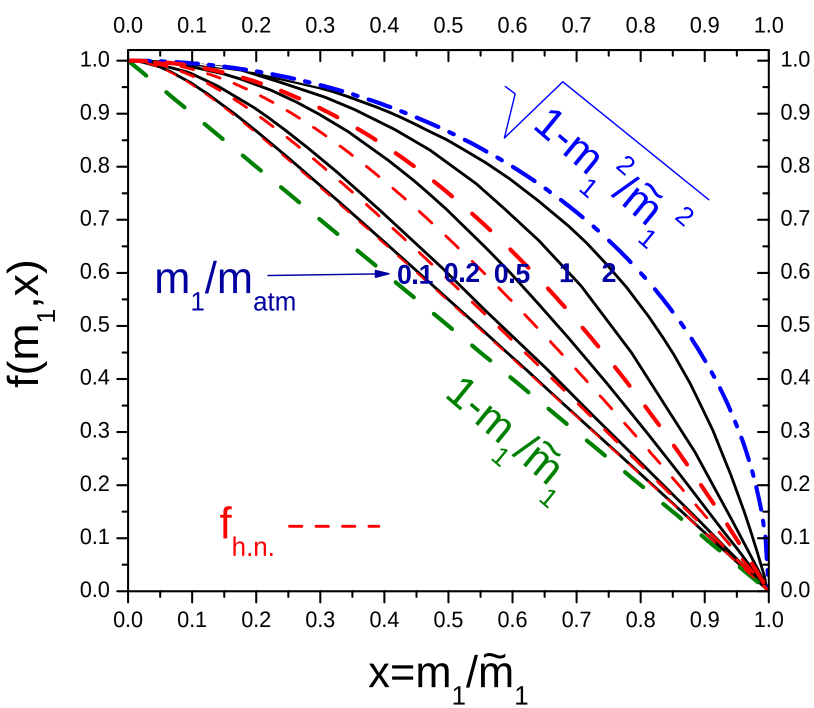

Upper bound on the absolute neutrino mass scale

(Buchmüller,PDB,Plümacher ’02,’03,’04)

$$\eta_B^{\max}(m_1,\widetilde{m}_1,M_1) \simeq 10^{-2}\,\varepsilon_1^{\max}(M_1)\,\frac{m_{\rm atm}}{m_3+m_1}\,f(m_1,\widetilde{m}_1)\,\kappa_{\rm f}(\widetilde{m_1})\,e^{-w\,M_1\,\sum_i\,m_i^2} \geq \eta_B^{CMB}$$

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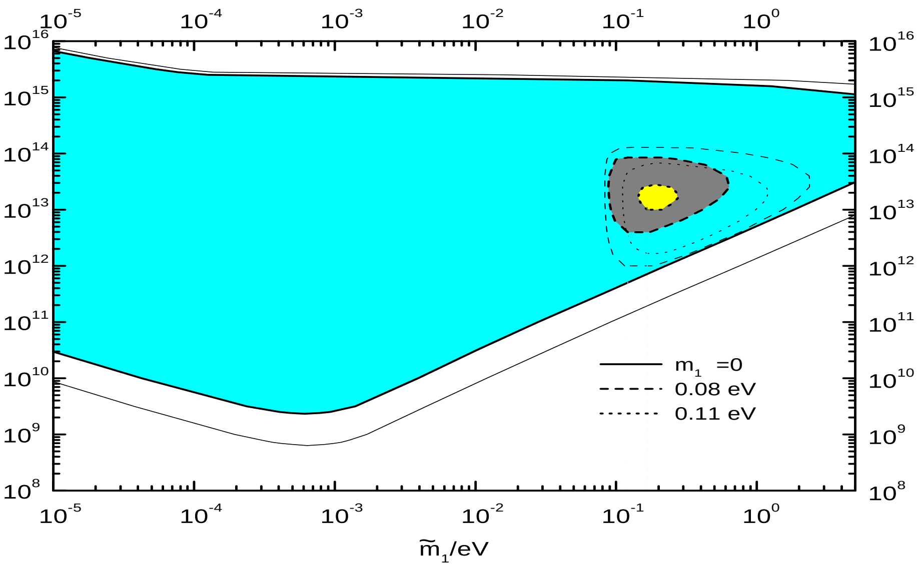

Analytically one can maximize $\eta_B^{\max}$ and using

$f \simeq f_{hn}$ and central values of η_B^{CMB}, $m_{\rm atm}$ $\Rightarrow$

$$m_i < \left(\frac{10^{25}\,g_{\rm rec}\,a_{\rm sph}\,\pi^6\,v^4}{3^{9/2}\,e\,M_{\rm Pl}^2\,{\rm GeV}^2}\right)^{1/4}{\rm eV} \simeq 0.12\,{\rm eV}$$

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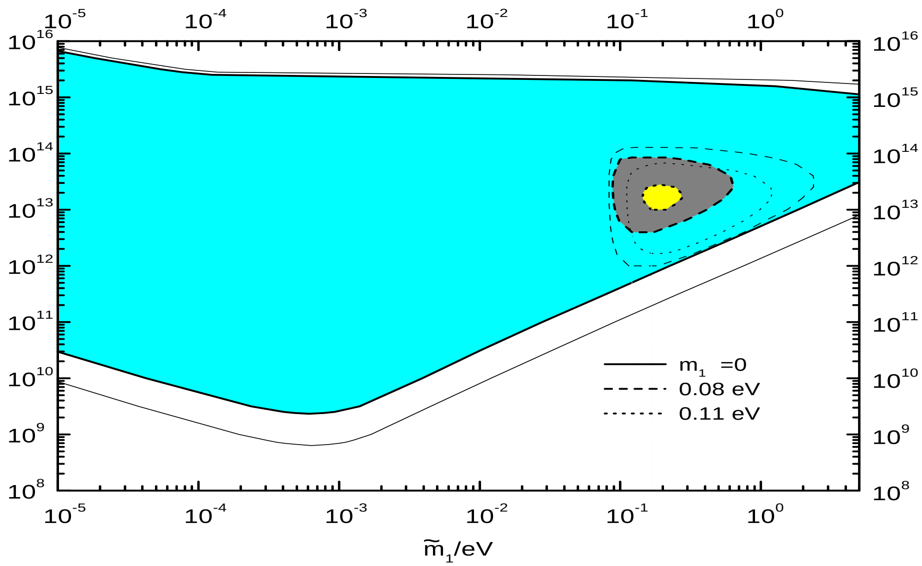

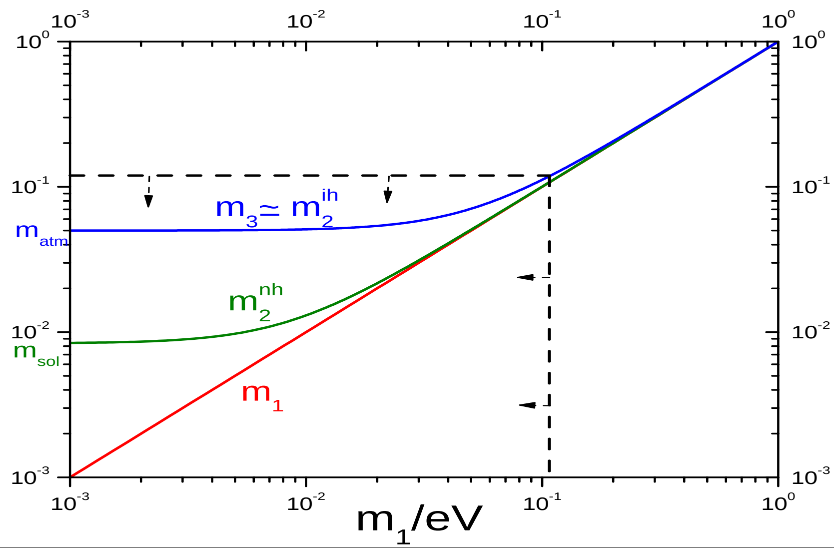

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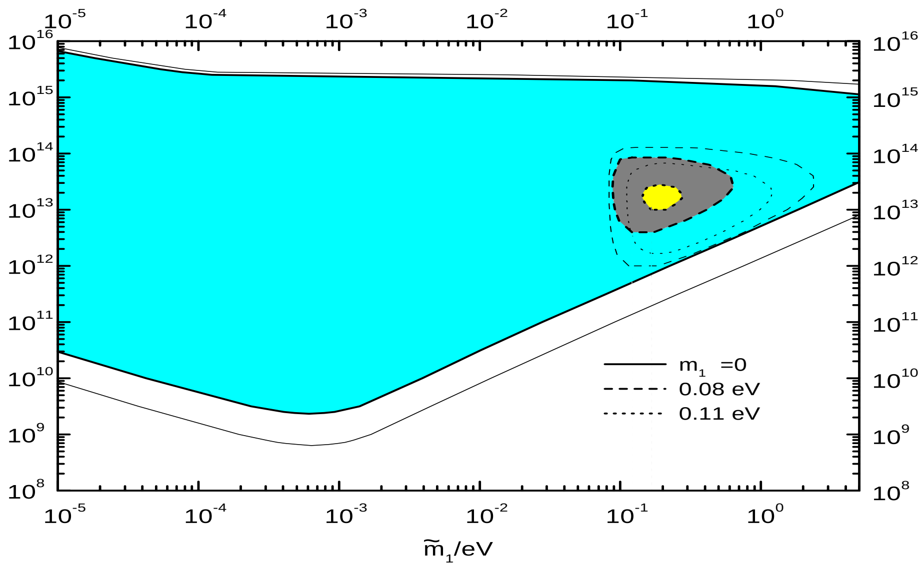

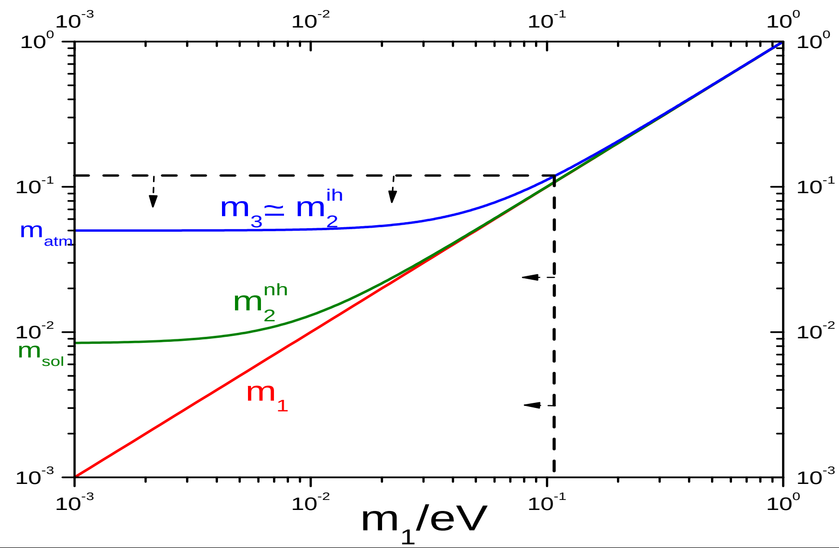

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accounting for : (i) more precise bound on f (Hambye et al. 04), (ii) statistical errors (3σ bound),

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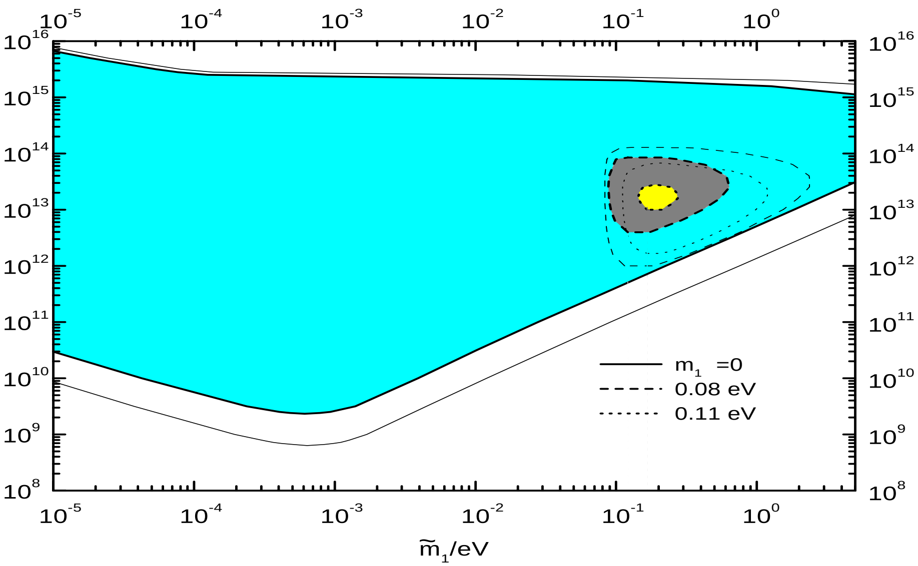

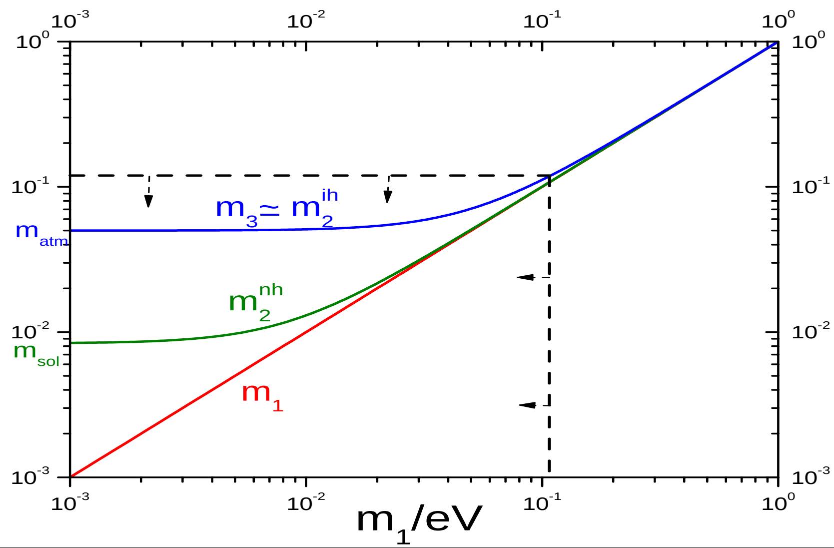

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The lower bound on the RH neutrino mass is much more sensitive to some variation than the upper bound on the light neutrino masses

The supersymmetric (MSSM) case

(Davidson et al. '92; Covi,Roulet,Vissani '96; Plumacher '97; Giudice et al. '03; PDB '04)

1. $N_1 \longrightarrow N_1 \, , \widetilde{N}_1^c$
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6. $\Gamma_{\Delta L=2} \longrightarrow 5\, (\Gamma_{\Delta L=2})/3$
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tension with the upper bound on $T_{\rm reh}$ from gravitino problem

$\Rightarrow$ motivation for models of non thermal leptogenesis

(Lazarides,Shafi'91;Murayama,Yanagida'94; Giudice,Peloso,Riotto,Tkachev'99)

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6. $\Gamma_{\Delta L=2} \longrightarrow 5\, (\Gamma_{\Delta L=2})/3$
7. running of neutrino masses halved

$$1+2+3+4+5 \Rightarrow (T_{\rm reh}^{\rm min})^{\rm MSSM} \simeq (1/\sqrt{2})\, (T_{\rm reh}^{\rm min})^{\rm SM} \simeq 1.5 \times 10^9\ {\rm GeV}$$

tension with the upper bound on $T_{\rm reh}$ from gravitino problem

$\Rightarrow$ motivation for models of non thermal leptogenesis

(Lazarides,Shafi’91;Murayama,Yanagida’94; Giudice,Peloso,Riotto,Tkachev’99)

$$1{+}2{+}3{+}4{+}5{+}6{+}7 \Rightarrow \boxed{m_i^{MSSM} < 0.15\, {\rm eV}}$$

Phase suppression

$$\boxed{\sin\delta_L = \frac{\rho_3 \sin\varphi_3 + (m_{\rm sol}^2/m_{\rm atm}^2)\,\rho_2 \sin\varphi_2}{\rho_3 + (m_{\rm sol}/m_{\rm atm})\,\rho_2}} \Rightarrow M_1 \gtrsim \frac{4\times 10^8\,{\rm GeV}}{\kappa_{\rm f}\,\sin\delta_L}$$

- $\sin\delta_L = 1 \Rightarrow$

$\rho_2 = 0, {\rm Re}[\Omega_{11}^2] \simeq 1, \phi_3 = \frac{\pi}{2}$

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- models with m_3 dominated by N_1:

$\widetilde{m}_1 \geq m_{\rm atm}, \sin\delta_L < 1$:

$M_1 \gtrsim 1.5\times 10^{11}\,{\rm GeV}$,

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$\widetilde{m}_1 \geq m_{\rm sol}, \quad \sin\delta_L \lesssim m_{\rm sol}/m_{\rm atm}$

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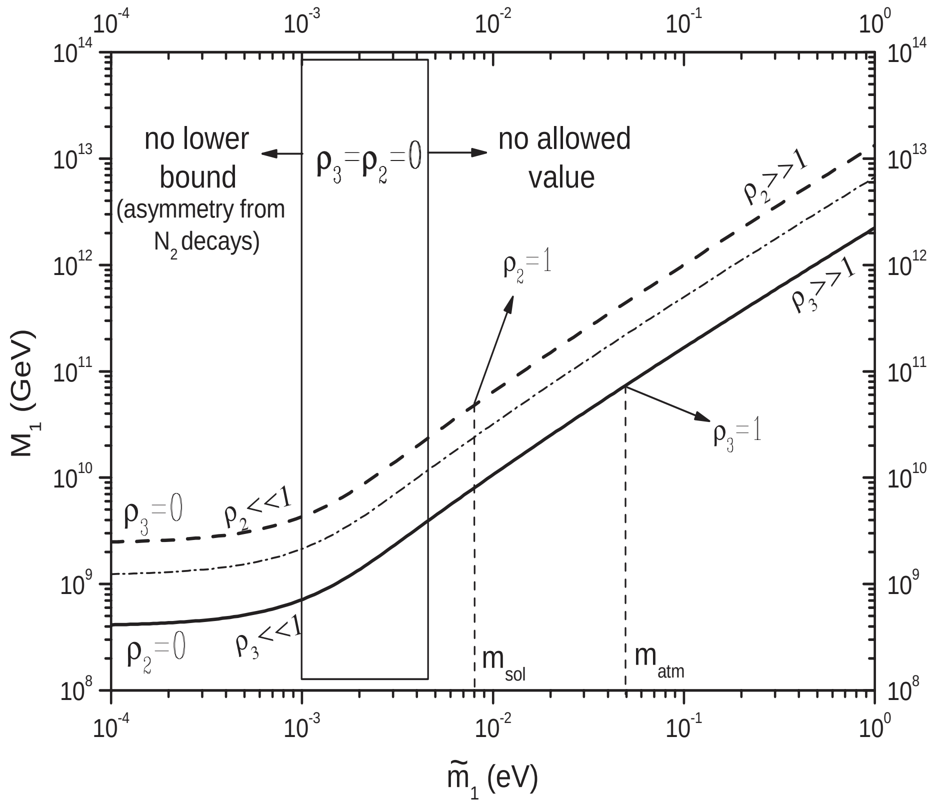

A new scenario of thermal leptogenesis

$$\Omega \simeq \begin{pmatrix} 1 & 0 & 0 \\ 0 & \Omega_{22} & \sqrt{1-\Omega_{22}^2} \\ 0 & -\sqrt{1-\Omega_{22}^2} & \Omega_{22} \end{pmatrix} \Rightarrow \widetilde{m}_1 = m_1, \varepsilon_1 = 0 \quad \text{but...}$$

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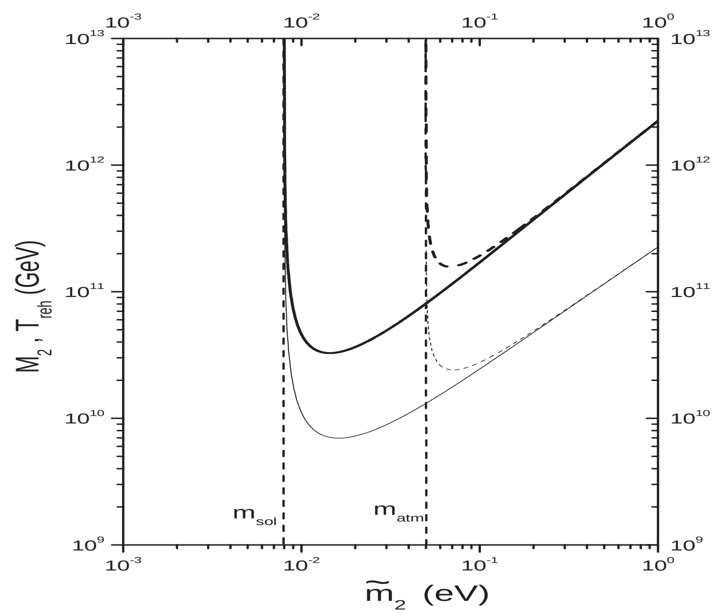

Beyond a hierarchical heavy neutrino spectrum

Two conditions for the validity of the hierarchical heavy neutrino (below 10%):

$1)\ \frac{M_2}{M_1} \geq \frac{z_B(K_2)+2}{z_B(K_1)-2} \gtrsim 5 \qquad 2)\ \xi_\varepsilon \equiv \frac{\varepsilon_1}{\varepsilon_{\max}(M_1)} \lesssim 0.1$

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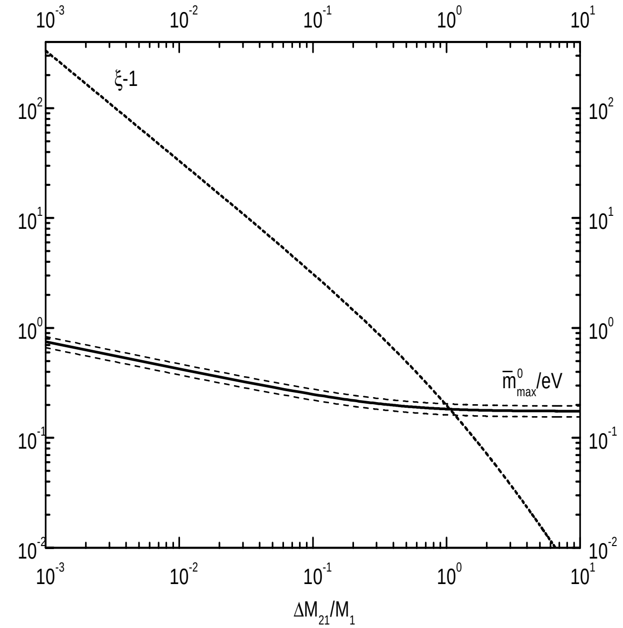

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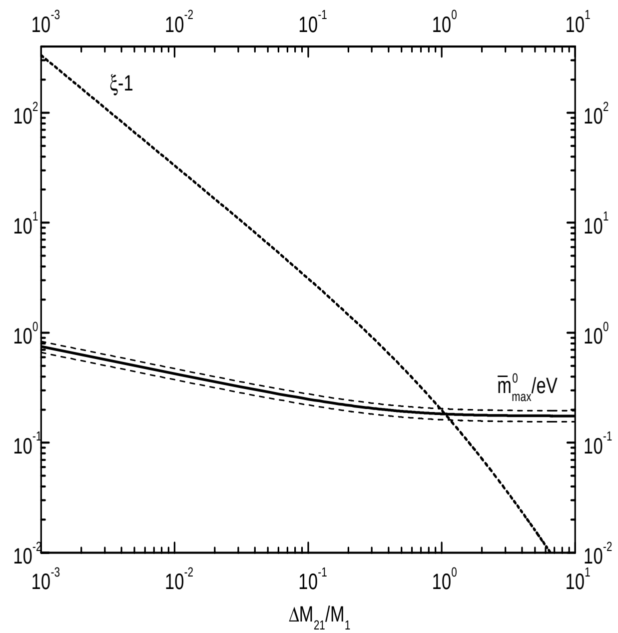
- $M_2 \gtrsim 5\,M_1 \Rightarrow \xi_\varepsilon \ll 0.1$ unless huge values of the imaginary parts i.e. fine-tuned phase cancellations
- second term disappears for $M_2 = M_3$ ('inverted' heavy neutrino spectrum) maximum for $M_3 \gg M_1, M_2$ ('normal' h.n.s.)
- the second term can become important for quasi-degenerate neutrinos



‘Degenerate’ leptogenesis

- $\varepsilon_1^{\max} \longrightarrow \xi_\varepsilon\,\varepsilon_1 \Rightarrow \eta_B^{\max} \longrightarrow \xi_\varepsilon\,\eta_B^{\max}$
- dependence on the other seesaw parameters $\Rightarrow$ great model dependence
- extreme situation: resonant leptogenesis :almost no bounds at all !

  (Pilaftsis, Underwood ’04)

Assuming equal degeneracies of light and heavy neutrinos:

- ‘normal’ heavy neutrino spectrum $\Rightarrow m_i^{\rm bound} \lesssim 0.2\,{\rm eV}$

  (PDB ’04)

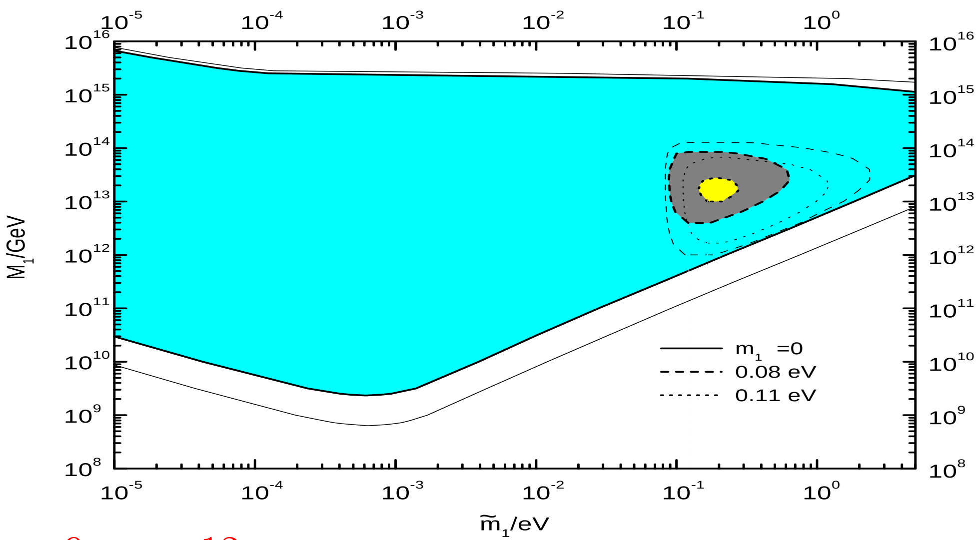
- ’inverted’ heavy neutrino spectrum $\Rightarrow m_i^{\rm bound} \lesssim 0.6\,{\rm eV}$

  they use the resonant regime !

  (Hambye,Lin,Notari,Papucci,Strumia ’04)

A 'too-short-blanket' problem

(Buchmüller,PDB,Plümacher'03,PDB '04)



For $T_{\rm reh}^{\rm max} \sim (5\times 10^9 - 10^{12})\ {\rm GeV}$ (MSSM case):

$$\frac{m_1}{m_{\rm atm}} \lesssim \frac{A}{\sqrt{1+2\,A}} \qquad \text{with} \qquad A \simeq 0.2\,\frac{T_{\rm reh}^{\rm max}}{10^{10}\ {\rm GeV}} \qquad (M_1^{\rm max} \simeq 5\,T_{\rm reh}^{\rm max})$$

Example: $T_{\rm reh}\,(M_1) \lesssim 3\,(15)\ \times 10^{10}\ {\rm GeV} \Rightarrow m_{1(3)} \lesssim 0.02\,(0.055)\,{\rm eV}$

The assumption of hierarchical heavy neutrino spectrum seems to be reasonable for the most interesting region of the allowed parameter space ! More investigation is needed.

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- Seesaw geometry: nice and simple tool to study leptogenesis and make connections with neutrino mass models :
  - CP asymmetry bound for any m_1;
  - expression for the effective leptogenesis phase;
  - useful correspondence with neutrino mass models

- lower bounds on M_1 and on $T_{\rm reh}$ more severe for typically considered neutrino SD mass models; models with m_1 dominated by M_1 allow $T_{\rm reh} \ll 10^{10}\,{\rm GeV}$ but do not have connections with quark masses;

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- new scenario of thermal leptogenesis: asymmetry generated by N_2 $\Rightarrow$ no lower bound on M_1;
- for $M_2 \gtrsim 5\,M_1$ the assumption of hierarchical heavy neutrinos works very well for hierarchical light neutrinos; the quasi-degenerate case is more subtle.