Leptogenesis

Pasquale Di Bari

(Max Planck, Munich)

in collaboration with W. Buchmüller and M. Plümacher

Thermal Leptogenesis

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Baryon asymmetry of the Universe

- CMB acoustic peaks (WMAP) + large scale structure (SLOAN):

$$\eta_B^{CMB} = \left.\frac{n_B - n_{\bar{B}}}{n_\gamma}\right|_{t_{\rm rec}} = (6.3 \pm 0.3) \times 10^{-10}$$

(Tegmark et al. 2003)

- very good agreement with SBBN + primordial Deuterium determination :

$$\eta_B^{SBBN} = \left.\frac{n_B - n_{\bar{B}}}{n_\gamma}\right|_{t_{\rm BBN}} = (6.1 \pm 0.5) \times 10^{-10}$$

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

Baryogenesis from heavy particle decays

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($\Delta_{B-L} = +1$)

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2. Leptogenesis (Fukugita,Yanagida '86)

$$N_i \xrightarrow{\Gamma} l\, \bar{\Phi} \qquad N_i \xrightarrow[\bar{\Gamma}]{} \bar{l}\, \Phi$$

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

(Kuzmin,Rubakov,Shaposhnikov'85;Khlebnikov,Shaposhnikov'88;Harvey,Turner'90):

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(Kuzmin,Rubakov,Shaposhnikov'85;Khlebnikov,Shaposhnikov'88;Harvey,Turner'90):

- CP asymmetry parameter:

$$\varepsilon = \frac{\Gamma - \bar\Gamma}{\Gamma + \bar\Gamma}\,\Delta_{B-L} > 0$$

- Total decay parameter:

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

Out of equilibrium decays

Out of equilibrium decays

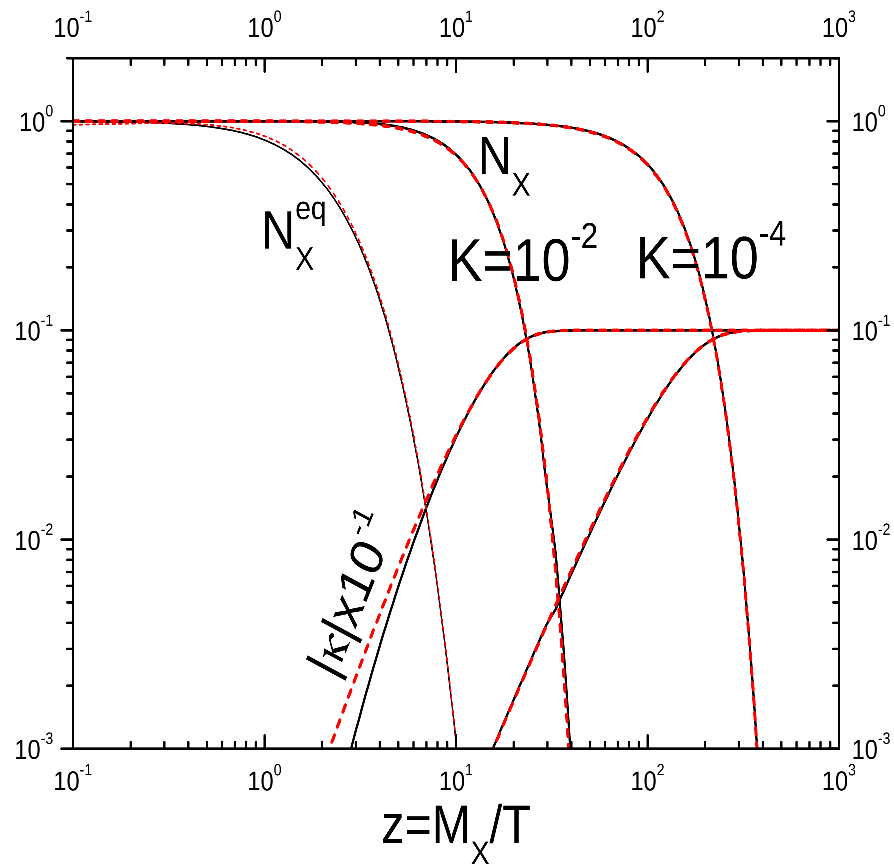
- Decay parameter

$$K = \frac{\Gamma_D^{\rm rest}}{H|_{z=1}} = \frac{2\,t_U(z=1)}{\tau_X}$$

$$z = \frac{M_X}{T}, \quad D = \frac{\Gamma_D}{H\,z}, \quad N = n\,R^3$$

$$\frac{dN_X}{dz} = -D(z)\,N_X(z)$$

$$\frac{dN_{B-L}}{dz} = -\varepsilon\,\frac{dN_X}{dz}$$



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$$\frac{dN_{B-L}}{dz} = -\varepsilon\,\frac{dN_X}{dz}$$

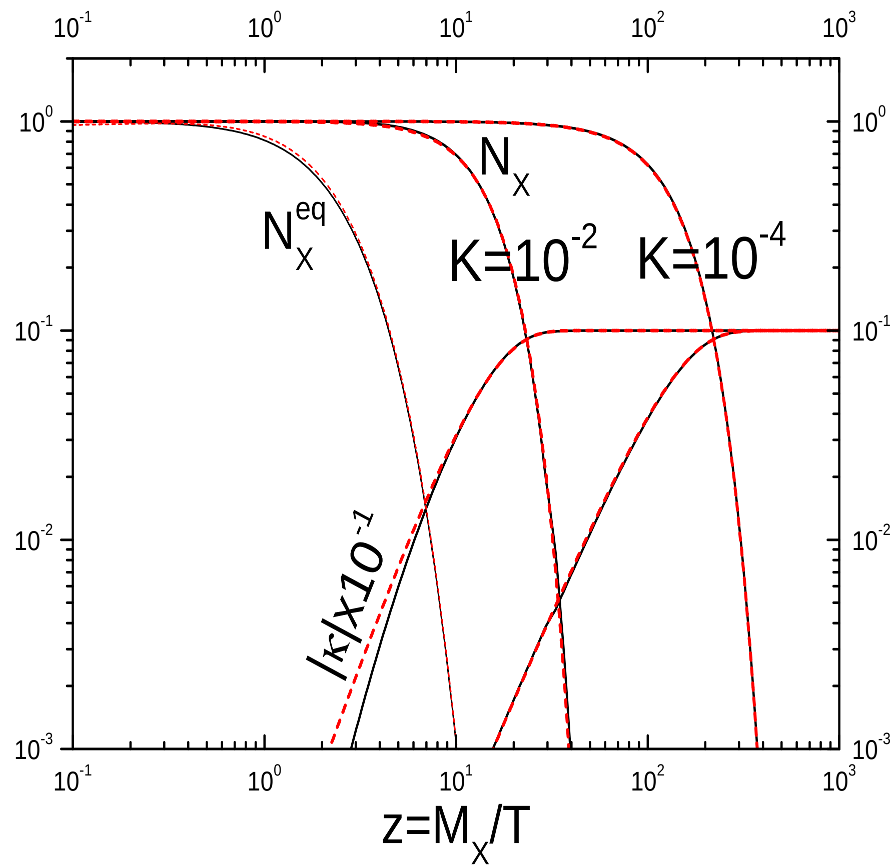
- $N^{\rm f}_{B-L} = N^{\rm i}_{B-L} + \varepsilon\,N^{\rm i}_X$

- Efficiency factor:

$$\kappa(z) \equiv \frac{N_{B-L}(z)}{\varepsilon} \quad \Rightarrow \kappa_{\rm f} = N^{\rm i}_X = 1$$

- Decay parameter

$$K = \frac{\Gamma_D^{\rm rest}}{H|_{z=1}} = \frac{2\,t_U(z{=}1)}{\tau_X}$$



Decays and Inverse Decays

$$\frac{dN_X}{dz} = -D\,N_X + D\,N_X^{\rm eq}$$

$$\frac{dN_{B-L}}{dz} = -\varepsilon\,\frac{dN_X}{dz} - W_{ID}\,N_{B-L}$$

$$W_{ID} = m\,\frac{N_X^{\rm eq}}{N_{b,l}^{\rm eq}}\,D \propto K$$

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$$N_{B-L}(z;K,z_i) = N_{B-L}^{\rm in}\,e^{-\int_{z_{\rm i}}^{z}\,dz'\,W_{ID}(z')} + \varepsilon\,\kappa(z)$$

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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 $K \gtrsim 1$

Strong wash-out regime

(Kolb,Turner'90;Buchmüller,PDB,Plümacher'04)

$$\Delta(z) \equiv N_X(z) - N_X^{\rm eq}(z) \ll 1$$

Close-to-equilibrium approximation

$$\frac{dN_X}{dz} \simeq \frac{dN_X^{\rm eq}}{dz}$$

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writing $\kappa_{\rm f} = \int_0^\infty dz' \, e^{-\psi(z',\infty)}$

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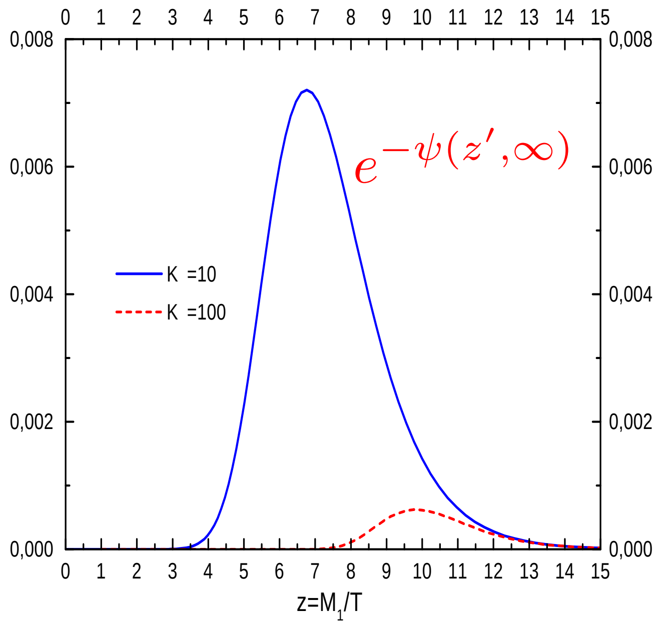
Baryogenesis temperature $T_B = M_X / z_B$



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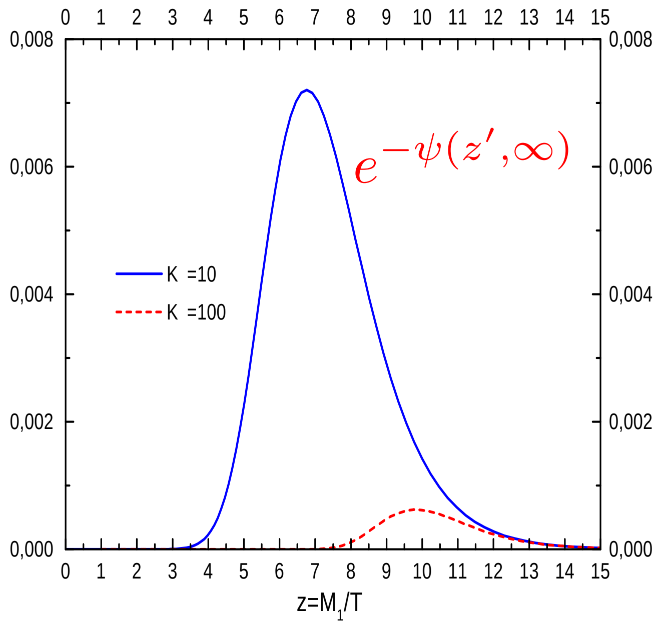
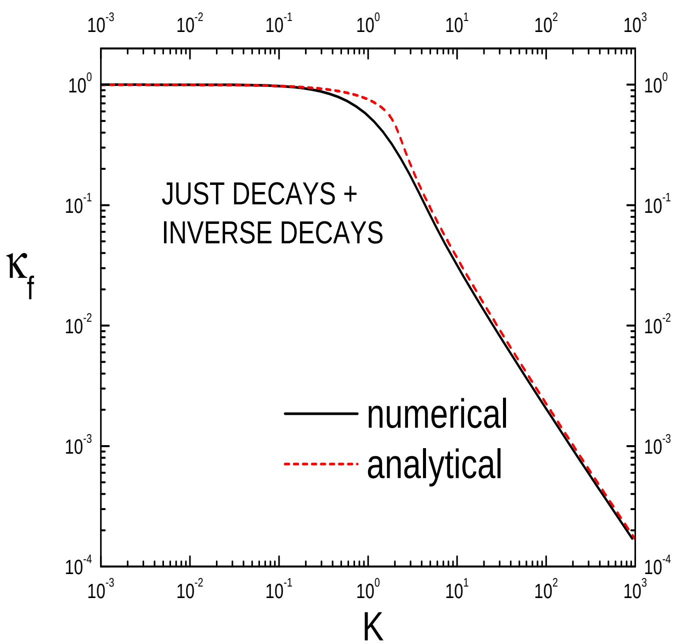
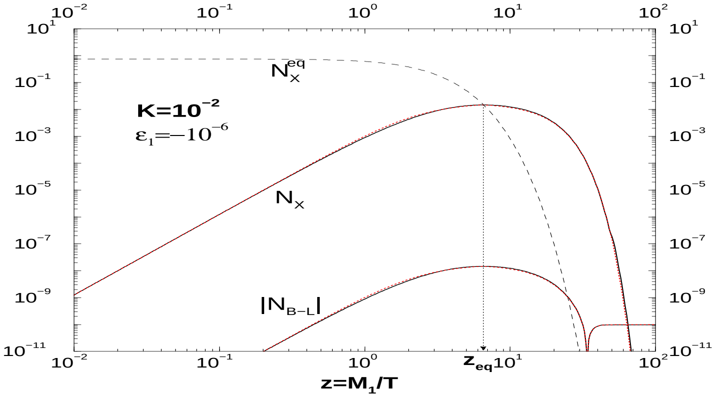


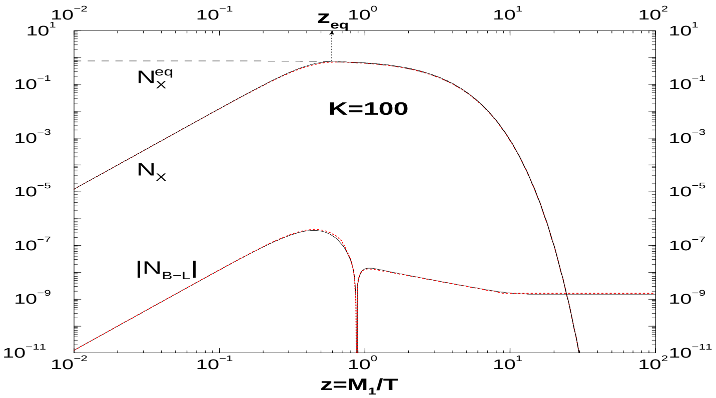
- only non relativistic stage matters
- $\kappa_{\rm f}(z_i = 0) \simeq \kappa_{\rm f}(z_i = z_B - \Delta z_B)$
- $$\kappa_{\rm f} \simeq \frac{2}{K\, z_B}\left(1 - e^{-\frac{K\, z_B}{2}}\right)$$



Neutrino production

(Fry,Turner ’81; Buchmüller,PDB,Plümacher ’04)





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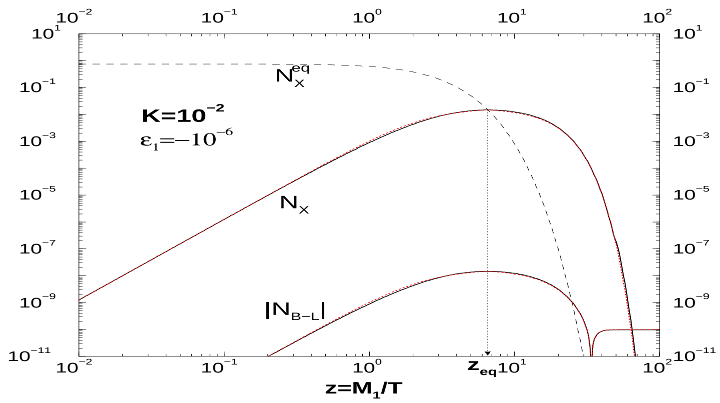
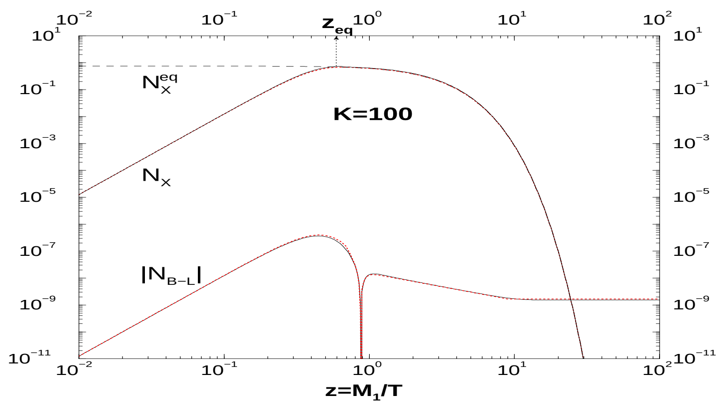
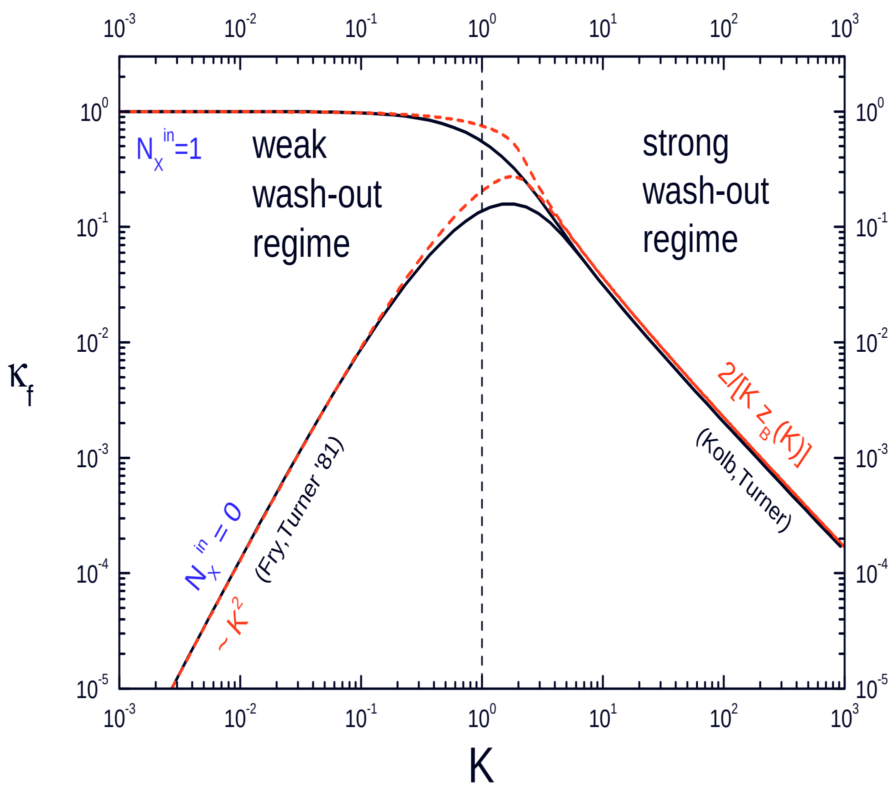




Final efficiency factor

DECAYS+INVERSE DECAYS



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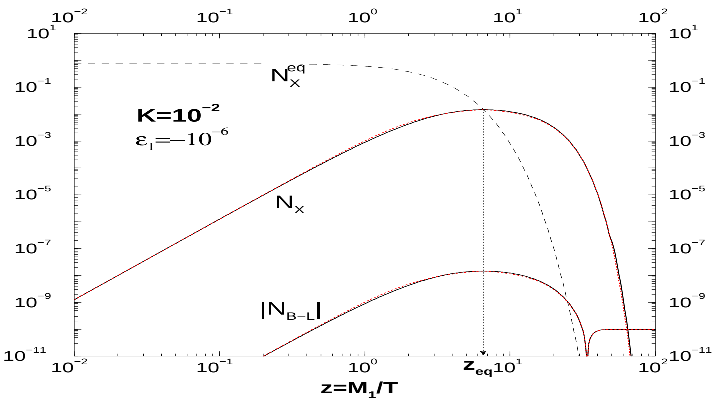

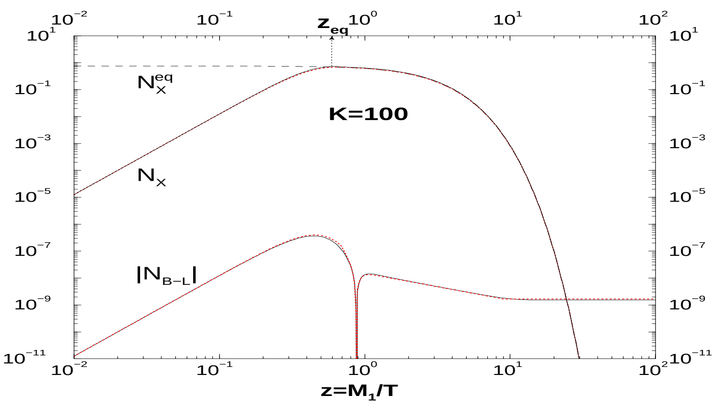

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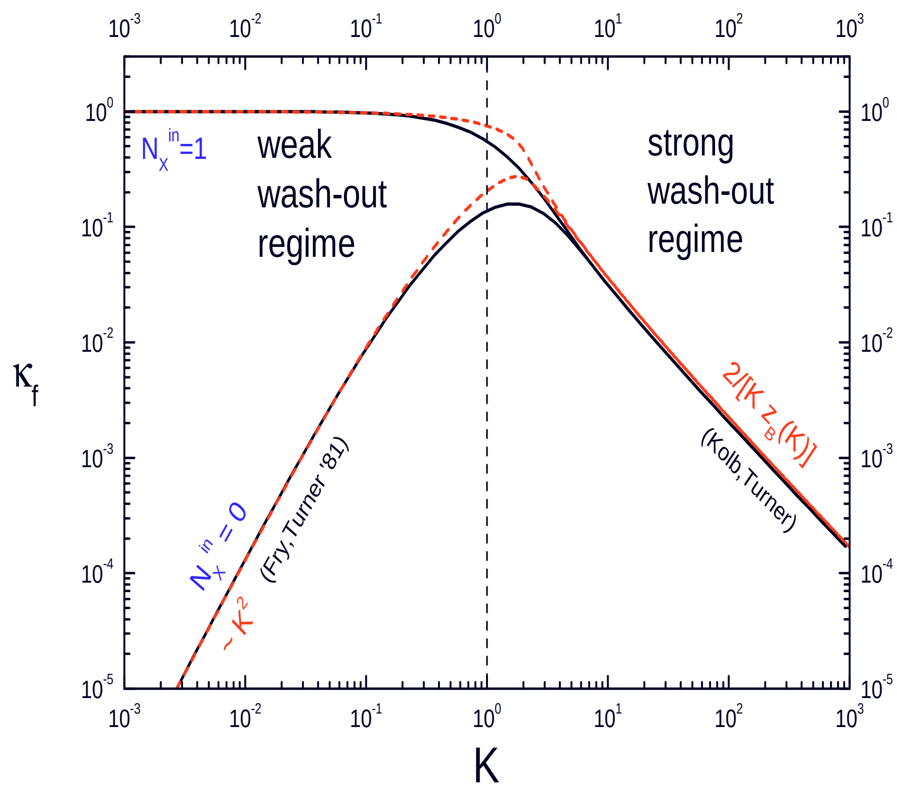

Negligible dependence on the initial conditions in the strong wash-out regime

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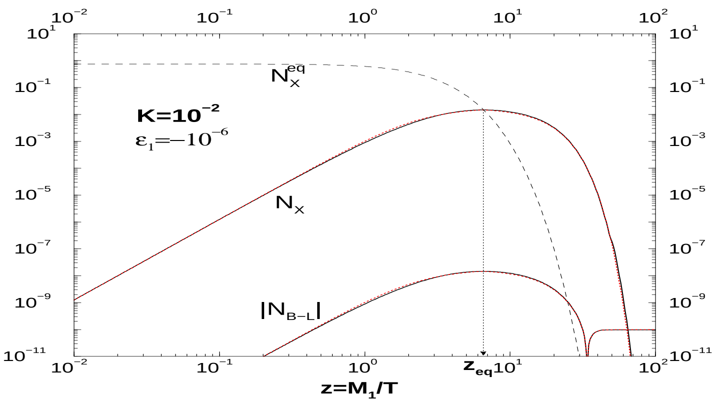

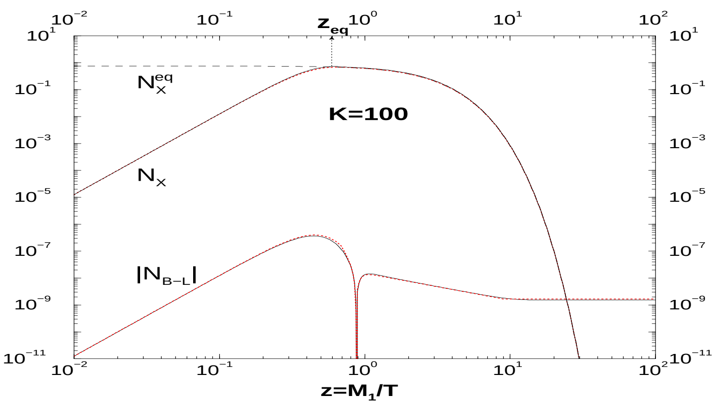

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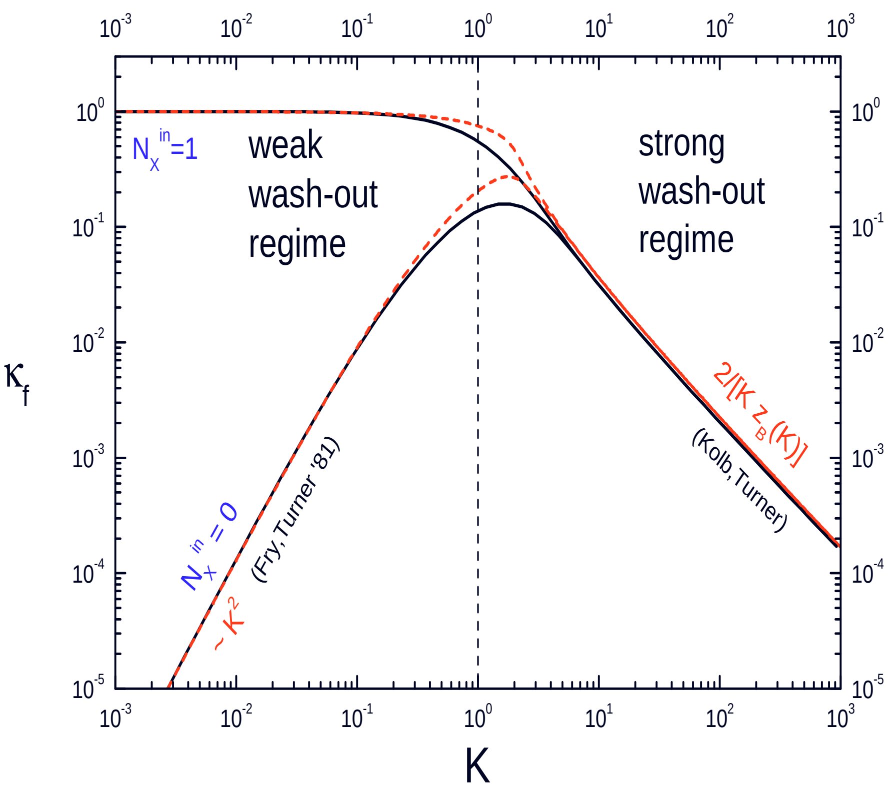

Negligible (strong) dependence on the initial conditions in the strong (weak) wash-out regime

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

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- seesaw formula

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m_D, m_ν and M are complex matrices $\Rightarrow$ 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 $M_{\rm ew} \ll M_1 \leq M_2 \leq M_3$
- lightest RH neutrinos play the role of the decaying particles $X \rightarrow N_1\,,\ \ \varepsilon \rightarrow \varepsilon_1$
- total decay rate $$\Gamma_D^{\rm rest} = \frac{\widetilde{m}_1\,M_1^2}{8\,\pi\,v^2}$$
- effective neutrino mass $$\widetilde{m}_1 \equiv \frac{(m_D^\dagger\,m_D)_{11}}{M_1}$$
- decay parameter and equilibrium neutrino mass

$$K = \frac{\Gamma_D^{\rm rest}}{H|_{z=1}} = \frac{\widetilde{m}_1}{m_\star} \qquad m_\star = {\rm const}\,\frac{v^2\,\sqrt{g_\star}}{M_{Pl}} \simeq 10^{-3}\,{\rm eV}$$

Range of $\widetilde{m}_1$

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- Seesaw orthogonal matrix (Casas, Ibarra ’01):

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(Fujii,Hamaguchi,Yanagida '02):

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(Fujii,Hamaguchi,Yanagida '02):

- for fully hierarchical neutrinos ($m_1 \ll m_{\rm sol}$):

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

$$m_{\rm atm,sol} \equiv \sqrt{\Delta m^2_{\rm atm,sol}}$$

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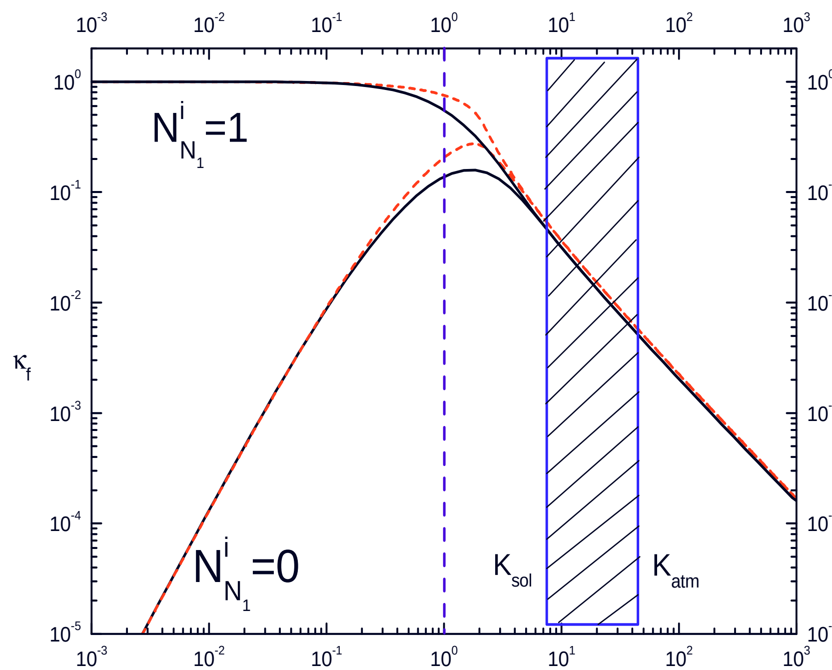
Leptogenesis K range

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

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

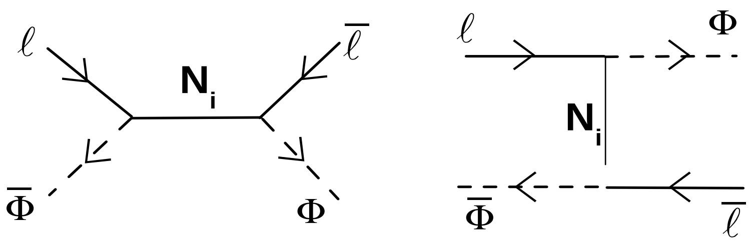


Neutrino mixing data favor leptogenesis

to lie in the strong wash-out regime

$\Delta L = 2$ processes

(Fukugita,Yanagida'86; Luty'92;Plumacher'97;Buchmüller,PDB,Plümacher'02; Pilaftsis,Underwood'03;Giudice et al.'03)



$\Rightarrow \quad W = W_{ID} + \Delta W$

- ΔW dominates at low temperatures:

$$\Delta W(z \ll 1) \propto M_1\, \bar{m}^2/z^2$$

$$\boxed{\bar{m}^2 \equiv \sum_i m_{\nu_i}^2}$$

- contributes to determine an upper bound

on the absolute neutrino mass scale

- in the case of hierarchical neutrinos is

negligible for $\boxed{M_1 \ll 10^{14}\,\mathrm{GeV}}$

$\Delta L = 2$ processes Scatterings

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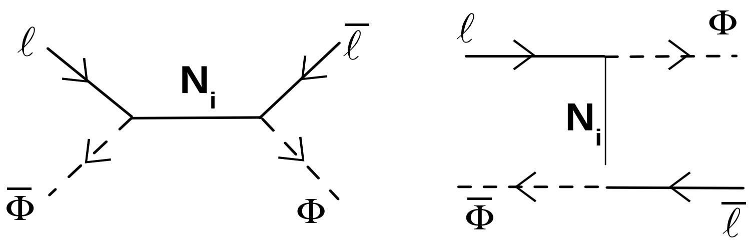

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- contributes to determine an upper bound on the absolute neutrino mass scale
- in the case of hierarchical neutrinos is negligible for $M_1 \ll 10^{14}\,\mathrm{GeV}$

1. involving the top quark (Higgs mediated):
   $N_1\, l \leftrightarrow t\, q + \dots$
2. involving the g. bosons (Higgs mediated):
   $N_1\, A \leftrightarrow H + \bar{l} + \dots$

$$\frac{dN_X}{dz} = -(D+S)\,(N_X - N_X^{\rm eq})$$
$$\frac{dN_{B-L}}{dz} = \varepsilon\, D\,(N_X - N_X^{\rm eq}) - (W_{ID} + W_S)\, N_{B-L}$$

1. in the weak wash-out regime:
   enhance the neutrino production
   source of large theoretical uncertainties
2. in the strong wash-out regime: contribute (sub-dominantly) to the wash-out

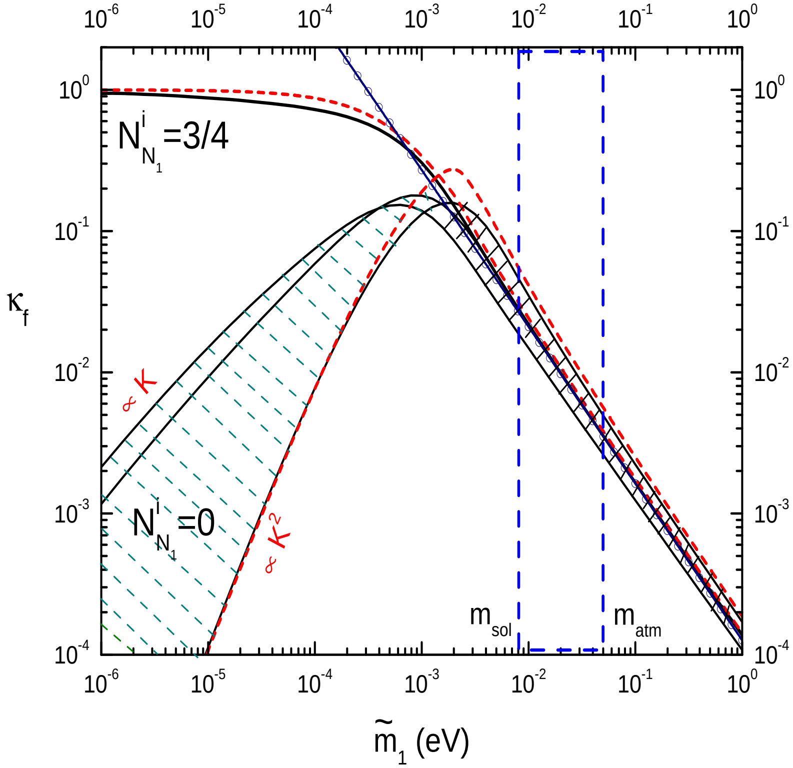
Theoretical uncertainties on $\kappa_{\rm f}$

unstable results in the weak wash-out regime:

- I.R. cut-off on the Higgs mass $\Rightarrow \kappa_{\rm f} \propto K$
  (Luty'92,Plumacher'96,Barbieri et. al.'00, Buchmuller,PDB,Plumacher '02,'03)
- thermal corrections to the Higgs mass+ running Yukawa coupling $\Rightarrow \kappa_{\rm f} \propto K^2$
  (Barbieri et. al.'03;Giudice et.al.'03)
- addition of scatterings involving gauge bosons $\Rightarrow \kappa_{\rm f} \propto K$
  (Pilaftsis,Underwood'03;Giudice et.al.'03)
- 'spectator processes' $\Rightarrow \mathcal{O}(1)$ factor suppression (Buchmuller,Plumacher'01)

$\sim 50\%$ uncertainties in the strong wash-out regime

$$\kappa_{\rm f}^{\rm sw} = (2 \pm 1)\, 10^{-2} \left(\frac{10^{-2}\,{\rm eV}}{\widetilde{m}_1}\right)^{1.1\pm 0.1}$$



CP asymmetry

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

$$\Rightarrow \varepsilon_1 \quad \simeq \quad -\frac{1}{8\pi\, v^2\, (m_D\, m_D^\dagger)_{11}} \sum_{i=2,3} \mathrm{Im}\left[(m_D\, m_D^\dagger)_{i1}^2\right] \times \left[f_V\left(\frac{M_i^2}{M_1^2}\right) + f_S\left(\frac{M_i^2}{M_1^2}\right)\right]$$

(Flanz,Paschos,Sarkar'95; Covi,Roulet,Vissani'96; Buchmüller,Plümacher'98)

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- barring RH neutrino mass degeneracies and strong phase cancellations:

(Hamaguchi,Murayama,Yanagida '01; Davidson,Ibarra '02; Hambye,Lin,Notari,Papucci,Strumia '04)

$$\varepsilon_1 \simeq \varepsilon_{\max}(M_1, m_1, \widetilde{m}_1)\,\sin\delta_L(m_1, \widetilde{m}_1, \Omega^2_{j1})$$

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$$\varepsilon_1^{\max}(M_1, m_1, \widetilde{m}_1) = \varepsilon_1^{\max}(M_1)\,\beta(m_1, \widetilde{m}_1), \quad \beta(m_1, \widetilde{m}_1) \leq 1$$

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$\beta(m_1 = 0, \widetilde{m}_1) = 1 \;\Rightarrow$ **ε_1 maximum for fully hierarchical neutrinos**

CP asymmetry

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

$$\Rightarrow \varepsilon_1 \simeq -\frac{1}{8\pi\, v^2\, (m_D\, m_D^\dagger)_{11}} \sum_{i=2,3} \mathrm{Im}\left[(m_D\, m_D^\dagger)^2_{i1}\right] \times \left[f_V\left(\frac{M_i^2}{M_1^2}\right) + f_S\left(\frac{M_i^2}{M_1^2}\right)\right]$$

(Flanz,Paschos,Sarkar'95; Covi,Roulet,Vissani'96; Buchmüller,Plümacher'98)

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

CMB constraints in the full hierarchical case

(Buchmuller,PDB,Plumacher '02)

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

$$\eta_B^{\max}(M_1,\widetilde{m}_1)|_{m_1=0} \propto M_1\,e^{-\frac{M_1}{10^{14}\,{\rm GeV}}}$$

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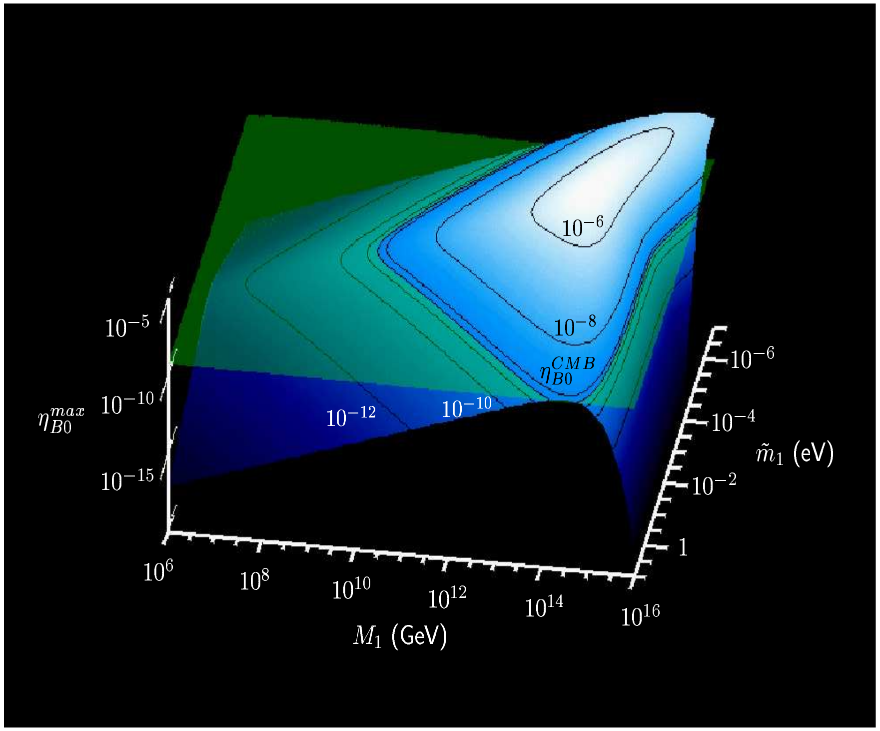

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Lower bound on M_1 and on T_i

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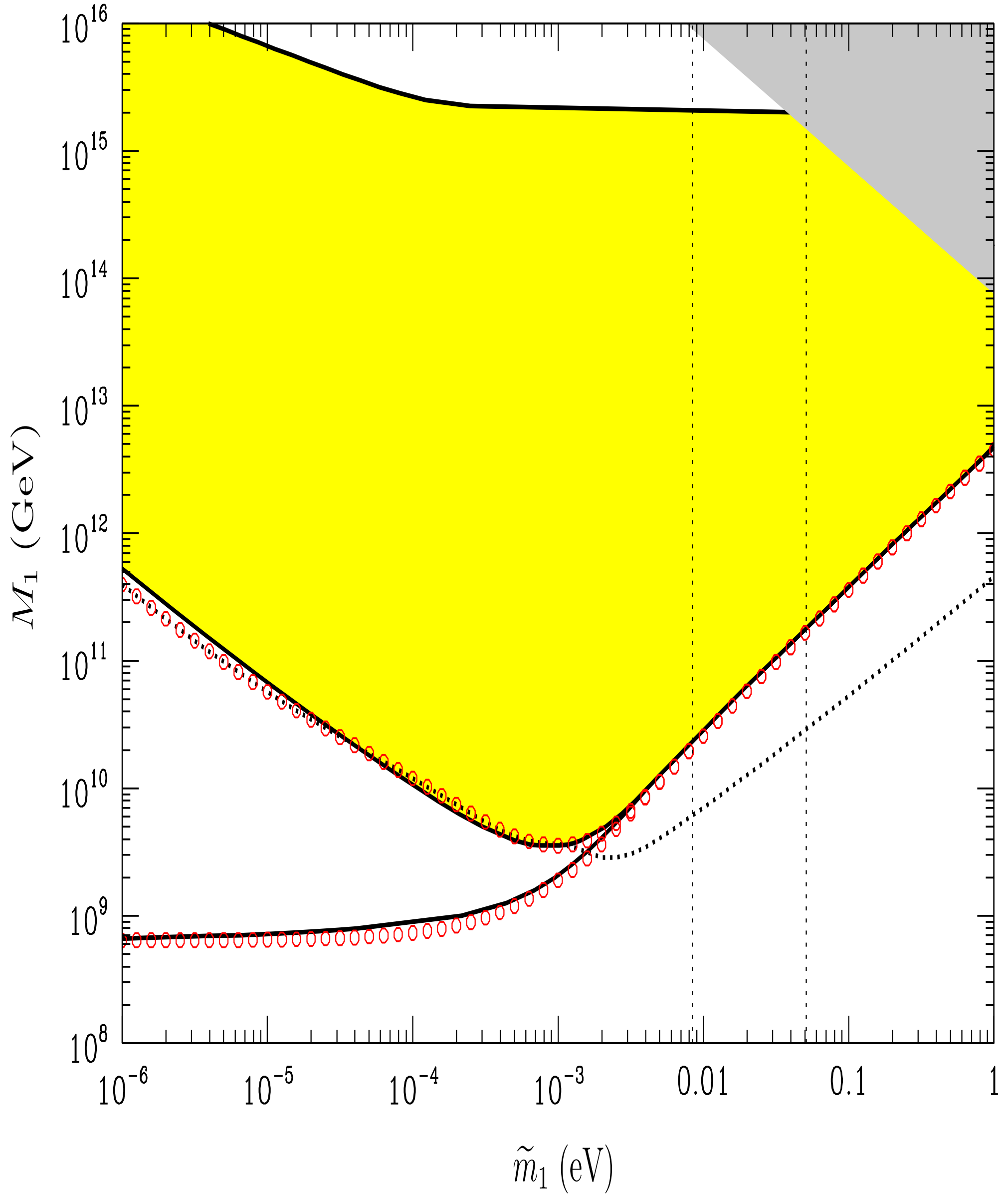

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Strong wash-out regime ($\widetilde{m}_1 \gtrsim 10^{-3}\,\mathrm{eV}$)

$$M_1, T_\mathrm{i} \gtrsim 2 \times 10^9\,\mathrm{GeV}$$

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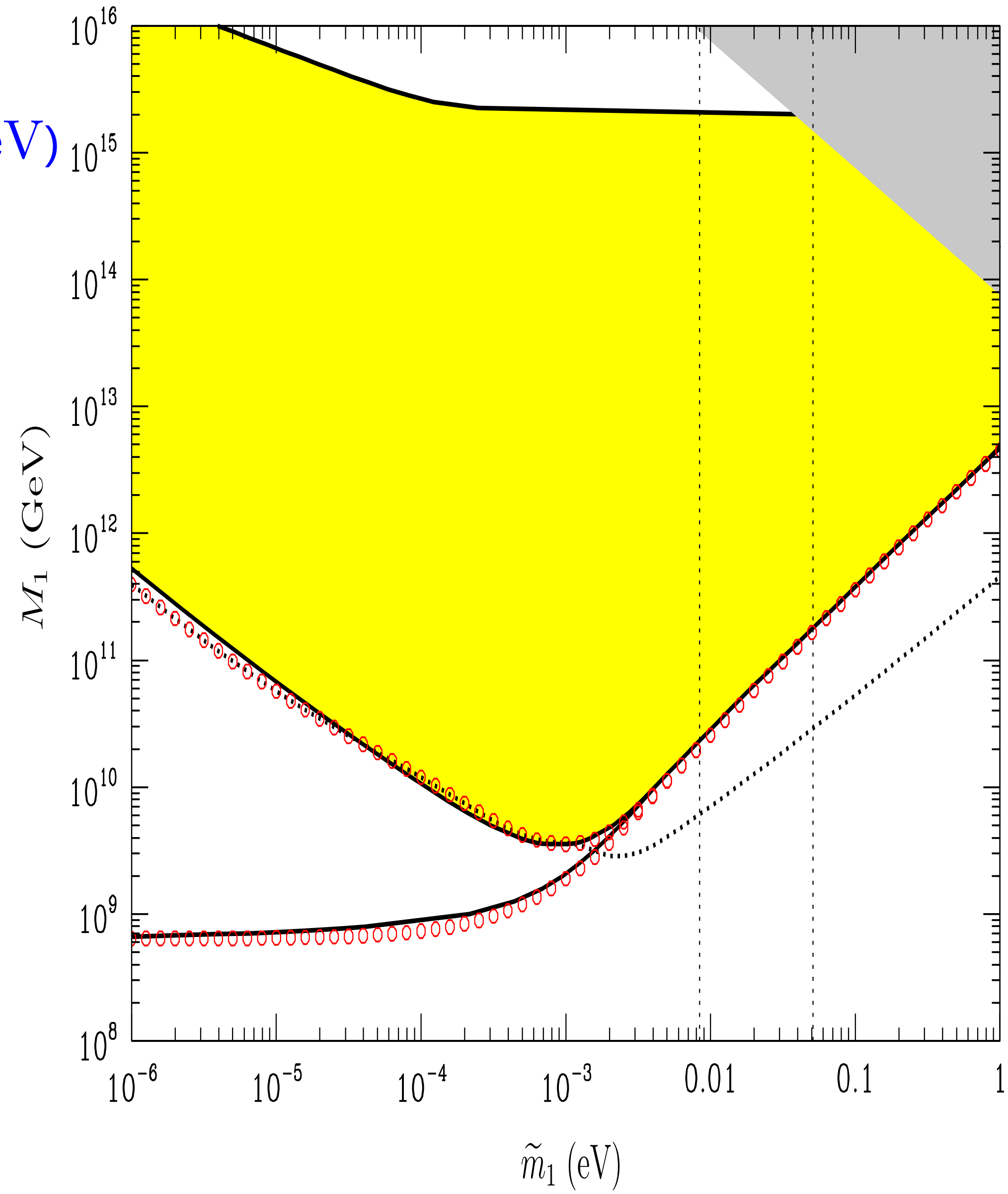

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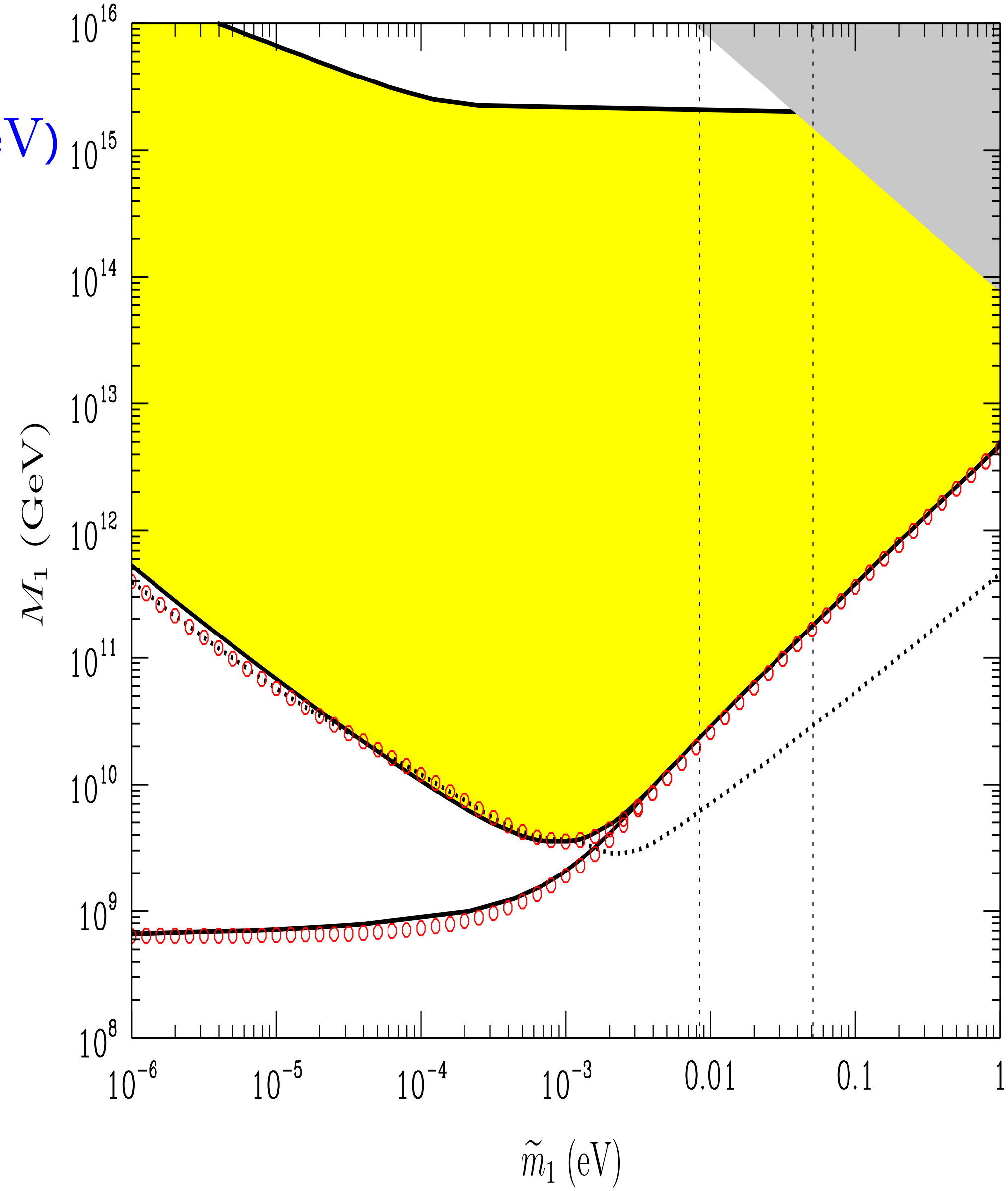
For $\widetilde{m}_1$ between m_sol and m_atm:

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

$\Rightarrow$ problem for many neutrino models !

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

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



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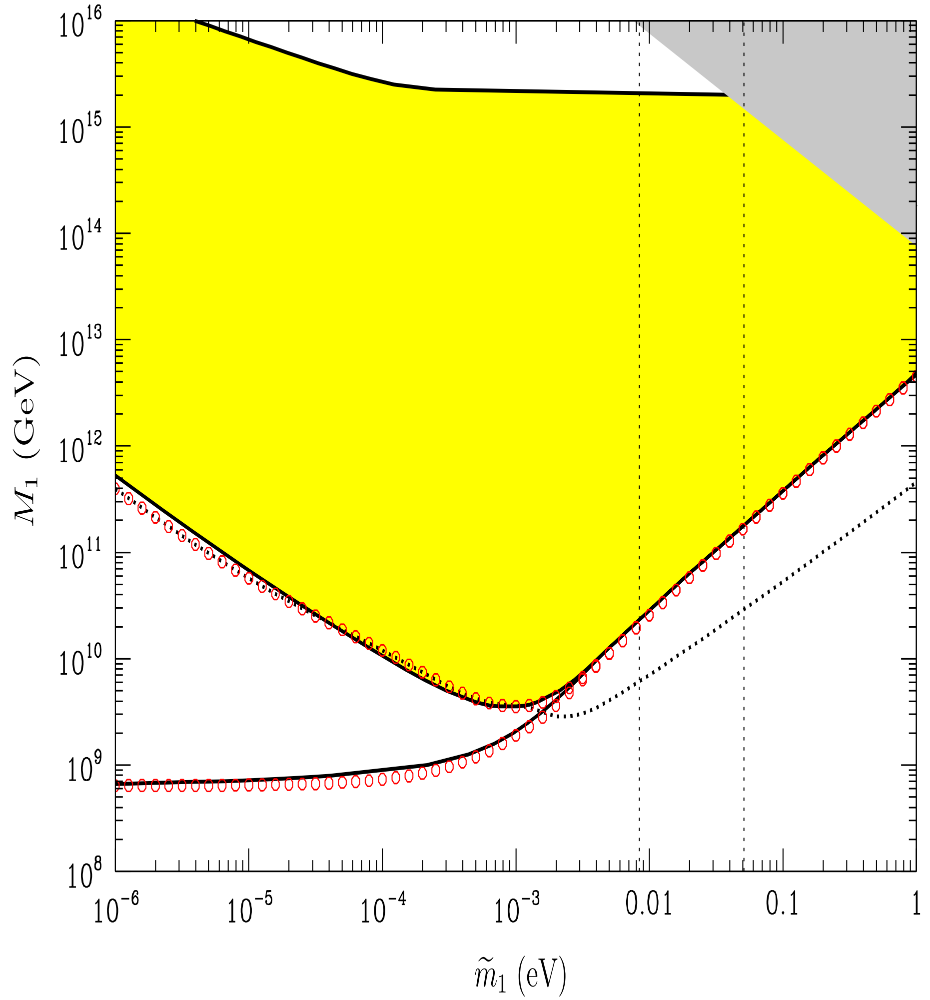

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What if we do not use $m_3^{\rm min} = m_{\rm atm}$?

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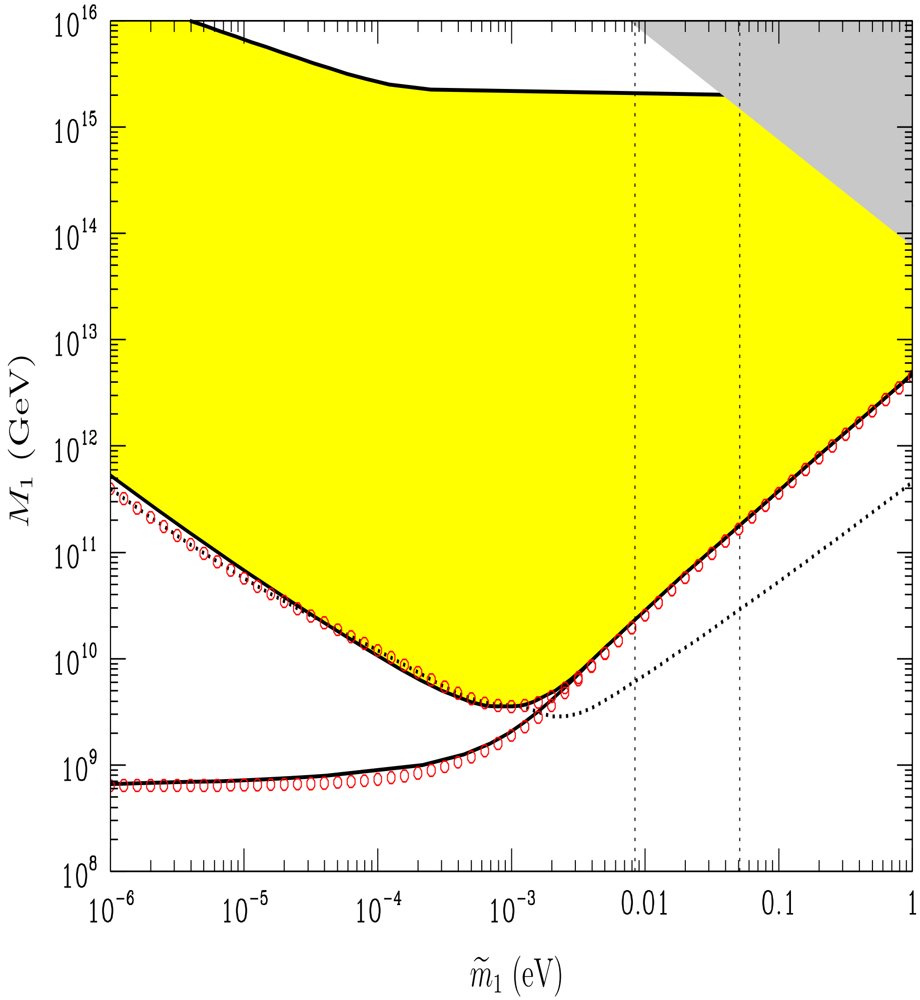

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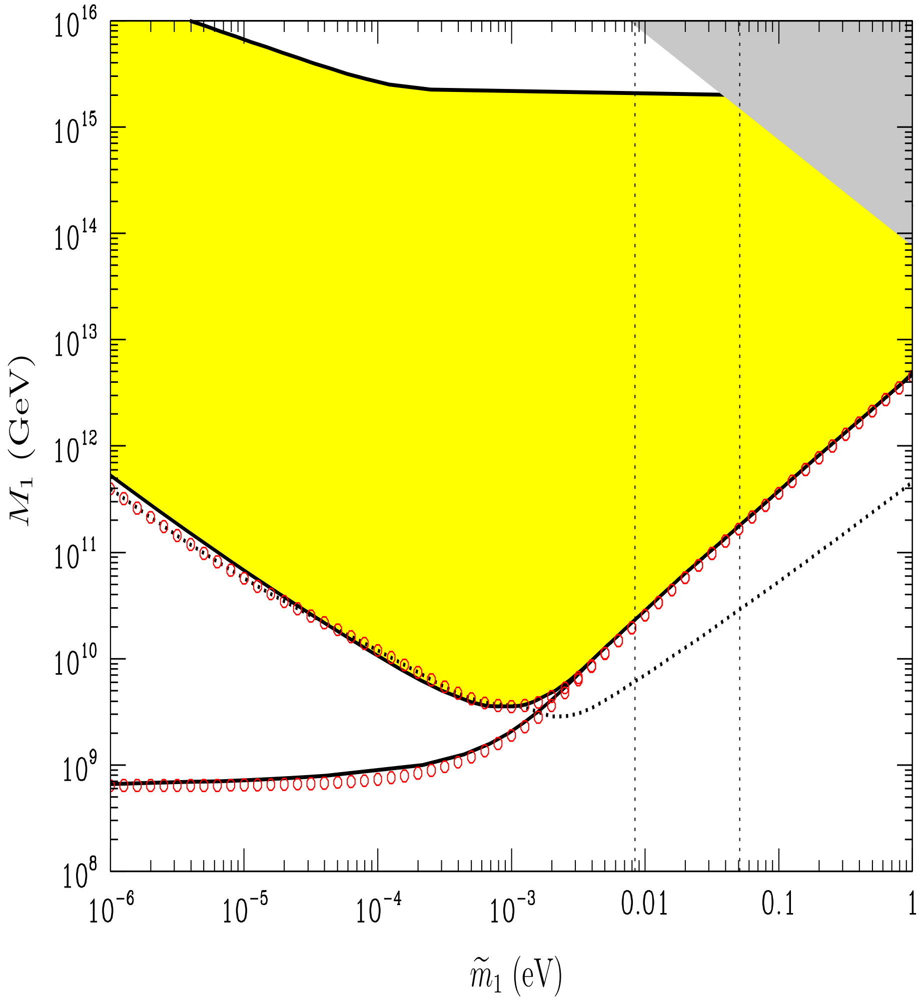

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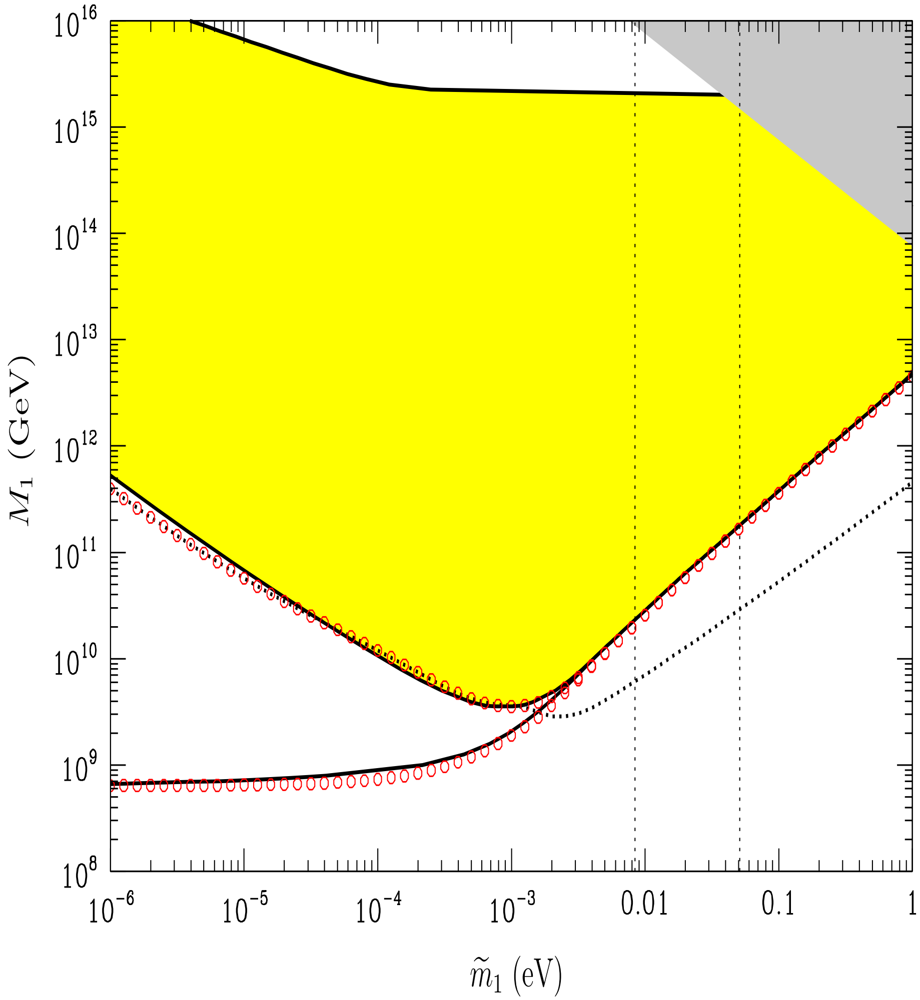

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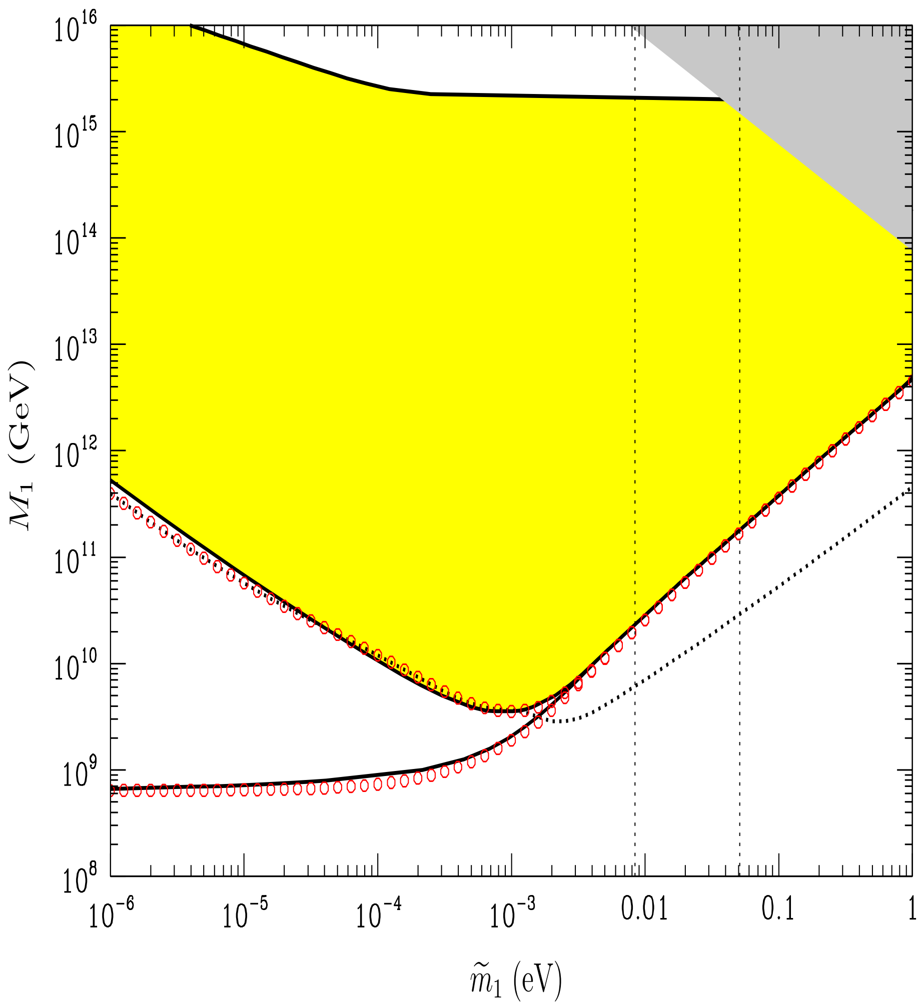
$\Rightarrow$ the experimental result:

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

is a successful test for thermal leptogenesis !



CP asymmetry bound for arbitrary m_1

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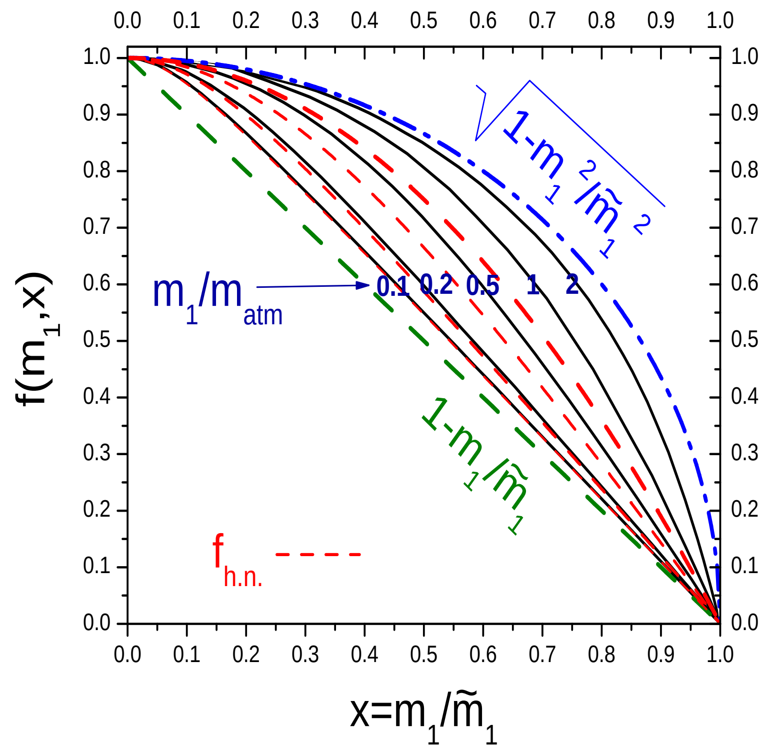

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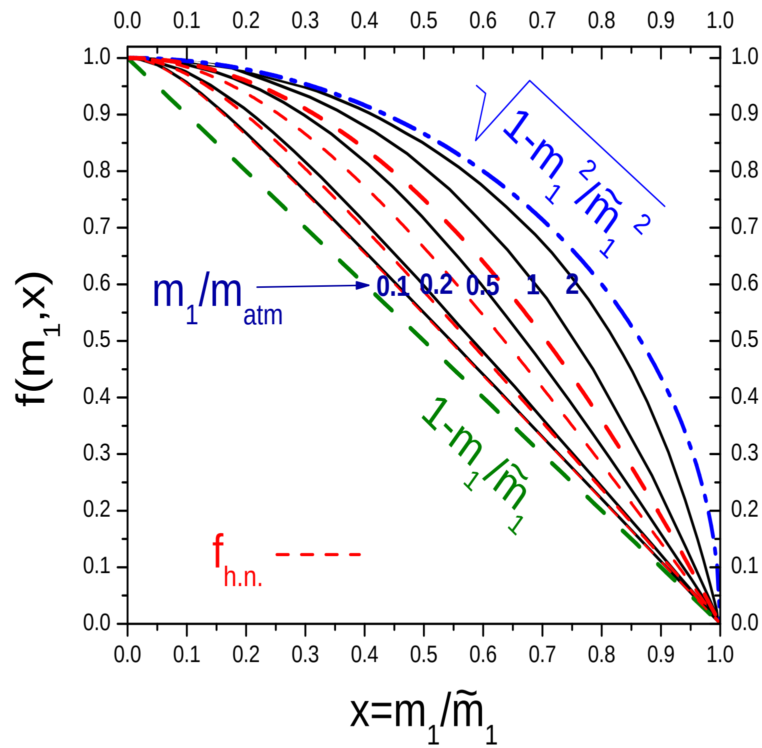

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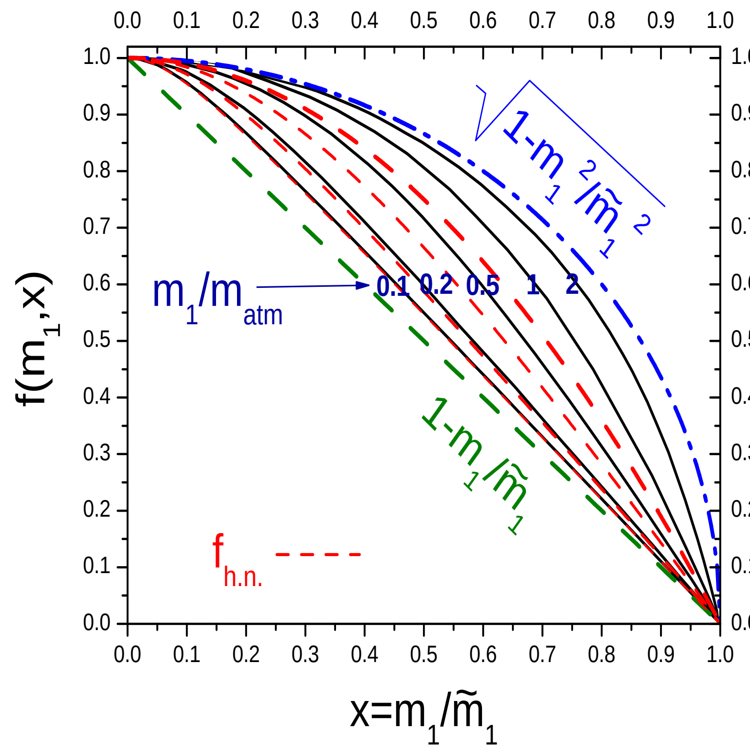

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(Hambye, Lin, Notari, Papucci, Strumia'04; PDB '04)

Upper bound on the absolute neutrino mass scale

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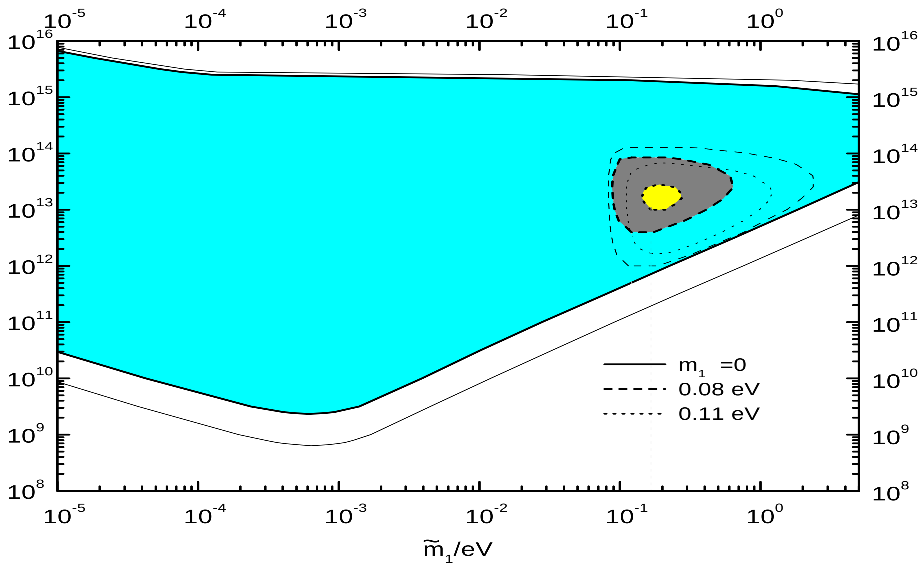

Analytically one can maximize $\eta_B^{\rm max}$ and using $f \simeq f_{hn}$ and central values of η_B^{CMB}, $m_{\rm atm}$ $\Rightarrow$

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

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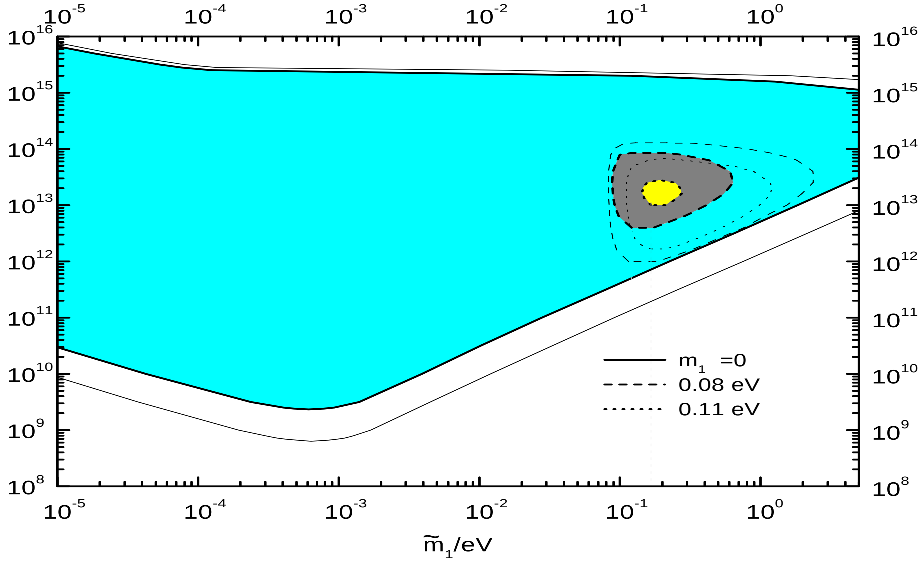

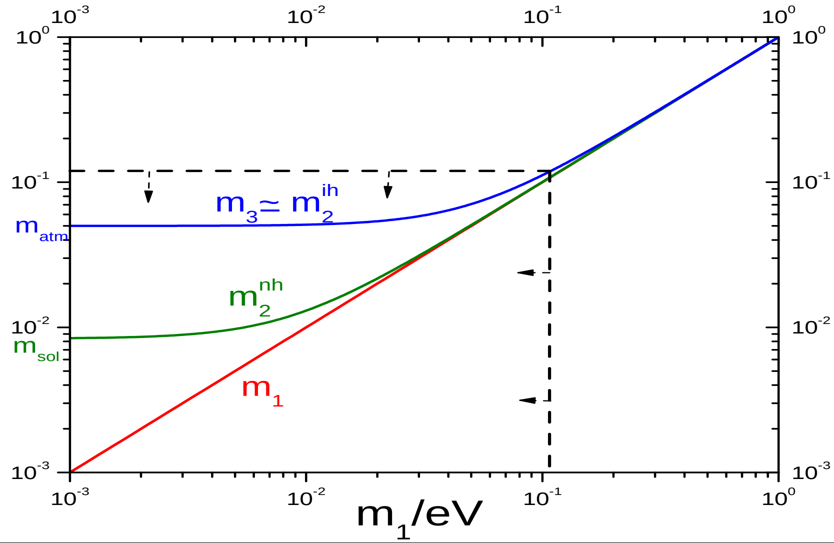

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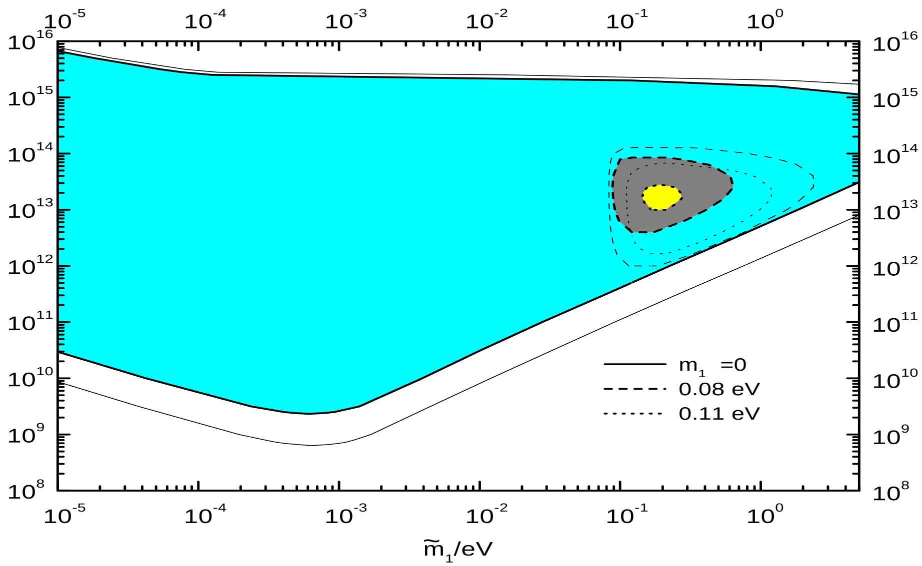

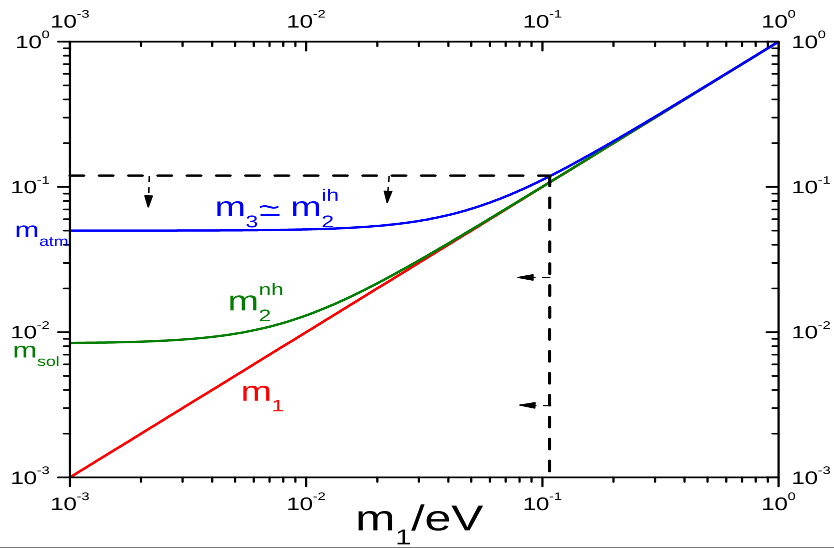

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accounting for : (i) more precise bound on f (Hambye et al. 04), (ii) statistical errors (3σ bound),

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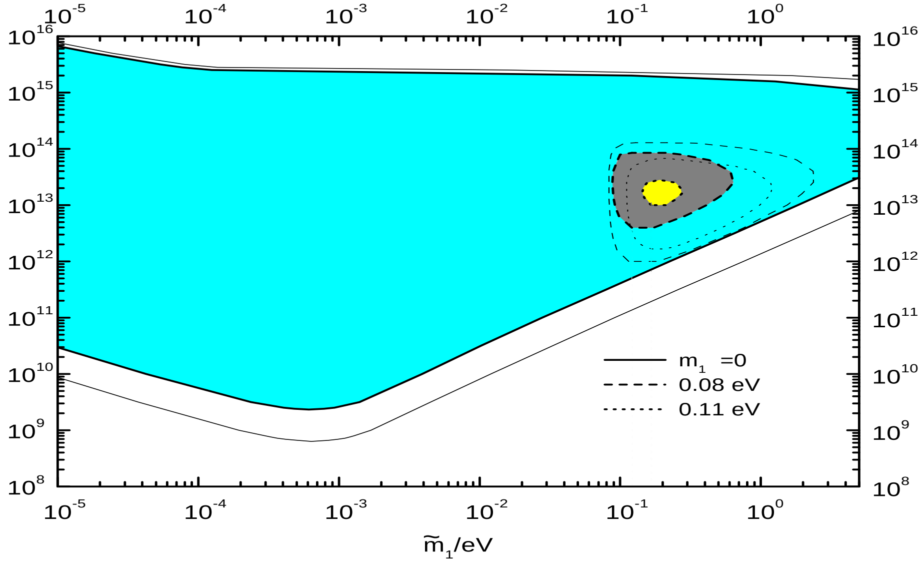

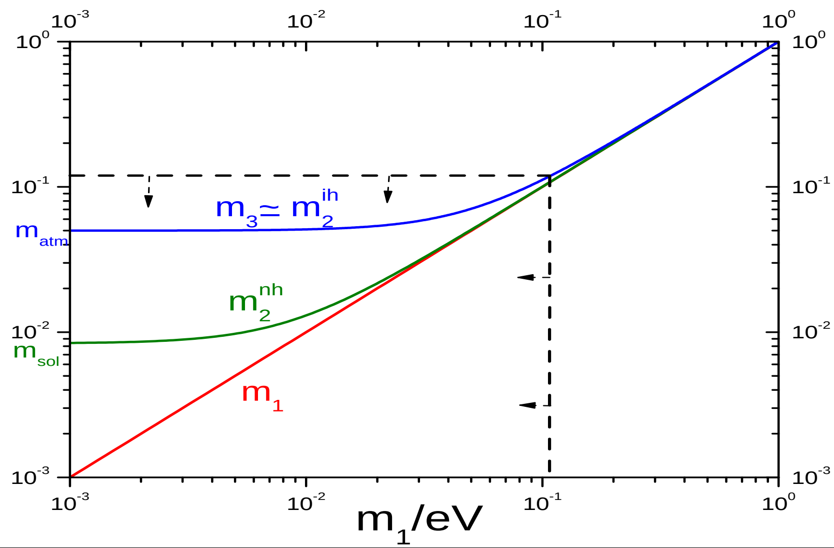

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Stability of neutrino mass bounds

(Buchmuller,PDB,Plumacher ’03)

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$$\eta_B^{\max} \longrightarrow \xi\, \eta_B^{\max}$$

How the bounds change ?

$$M_1^{\min}, T_i^{\min} \longrightarrow \frac{M_1^{\min}, T_i^{\min}}{\xi}$$

$$m_1^{\text{bound}} \longrightarrow m_1^{\text{bound}}\, \xi^{1/4}$$

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. $N_1 \longrightarrow N_1, \widetilde{N}_1^c$
2. $N_\gamma^{\rm rec} \longrightarrow \sim 2\, N_\gamma^{\rm rec}$
3. $\varepsilon_1^{\rm max} \longrightarrow 2\, \varepsilon_1^{\rm max}$
4. $g_\star \longrightarrow 2\, g_\star \Rightarrow H(1) \longrightarrow \sqrt{2}\, H(1)$
5. $\Gamma_D^{\rm rest} \longrightarrow 2\, \Gamma_D^{\rm rest}$
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1+2+3+4+5+6+7$\Rightarrow$ $\boxed{m_i^{MSSM} < 0.15\,{\rm eV}}$

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$\Rightarrow$ it seems that the bound can be 'easily' evaded ....but the BBN+CMB constraints on the extra number of neutrinos 'protect' the leptogenesis neutrino mass bound:

$$g_{\rm rec}^{\rm dec} \lesssim 1 \Rightarrow \xi_{g_\star}^{1/8} \lesssim 2$$

Degenerate leptogenesis

What if one relaxes the approximation of a hierarchical RH neutrino spectrum ?

- $\varepsilon_1^{\rm max} \longrightarrow \xi_\varepsilon \, \varepsilon_1 \Rightarrow \eta_B^{\rm max} \longrightarrow \xi_\varepsilon \, \eta_B^{\rm max}$
- dependence on all other seesaw parameters $\Rightarrow$ great model dependence
- extreme situation: resonant leptogenesis (Pilaftsis, Underwood '04): no bounds at all !

Assuming equal degeneracies of light and heavy neutrinos:

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

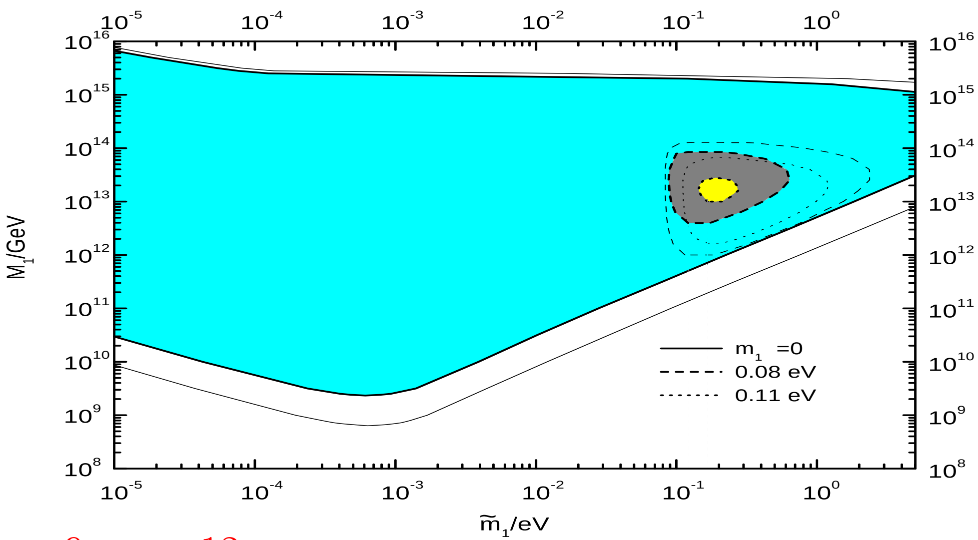
  (PDB '04)

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

  (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):

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

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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  - triplet Higgs seesaw leptogenesis
  - non thermal leptogenesis
  - ...
- Smoking gun ? Very difficult, but the problem becomes somehow easier if leptogenesis is studied in connection with the other seesaw phenomenologies and it is important to have in mind that the seesaw mechanism predicts neutrinoless double beta decay.