SUSY02

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CMB constraints on seesaw parameters via leptogenesis

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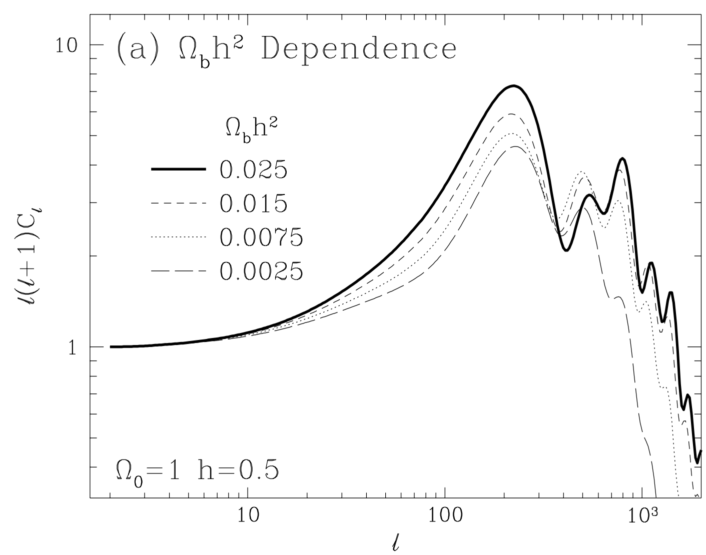
Reference paper:

W.Buchmüller, PDB, M. Plümacher, hep-ph/0205349

Baryon asymmetry from CMB

Baryons enhance the odd peaks of the power spectrum of temperature anisotropies :



- BOOMERanG and DASI find the same result $(1\,\sigma)$:

$$\Omega_b\, h^2 \;=\; 0.022^{+0.004}_{-0.003} \Rightarrow \eta_{10}^{CMB} = 6.0^{+1.1}_{-0.8}$$

$(\eta_{10} \equiv (n_N/n_\gamma)\, 10^{10} \simeq 273.6\, \Omega_b\, h^2)$

We adopt the following 3σ range:

$$\eta_B^{CMB} = (3.6 - 9.3) \times 10^{-10}$$

- Future: MAP, PLANCK

$$\Rightarrow \Delta\eta_B^{CMB}/\eta_B^{CMB} \simeq 10\%,\;\; 1\%$$

(Zaldarriaga,Spergel and Seljak 1997)

Seesaw

(Yanagida'79; Gell-Mann, Ramond and Slansky '79; Mohapatra,Senjanovic '80 and '81; Wetterich '81;. . .)

$$\boxed{\mathbf{m}_\nu = -m_D \frac{1}{\mathbf{M}} m_D^T}$$

$m_\nu \equiv$ light neutrino mass matrix

$M \equiv$ heavy neutrino mass matrix

If $M \gg m_D \Rightarrow m_\nu \ll m_D$

the corresponding mass eigenstates are Majorana fermions:

$\nu = \nu^c$ (light); $N = N^c$ (heavy)

Note: in general the mass matrices are complex and this is a possible source of CP violation

Thus it predicts three new particle species:

$$N_1, N_2, N_3$$

which cosmological consequences ?

Thermal leptogenesis: basics

(Fukugita, Yanagida, '86)

decays:

$$N_i \begin{cases} \xrightarrow{\Gamma_i} & l, \bar{\phi} \\ \xrightarrow{\bar{\Gamma}_i} & \bar{l}, \phi \end{cases}$$

CP asymmetry:

$$\epsilon_i \equiv \frac{\Gamma_i - \bar{\Gamma}_i}{\Gamma_i + \bar{\Gamma}_i}$$

effective neutrino mass:

$$\tilde{m}_i \equiv \frac{(m_D^\dagger\, m_D)_{ii}}{M_i}$$

total decay rate:

$$\Gamma_{Di} \equiv \Gamma_i + \bar{\Gamma}_i = \frac{G_F}{2\sqrt{2}\pi} \frac{K_1(M_i/T)}{K_2(M_i/T)} \;\; \tilde{m}_i \; M_i^2$$

sphalerons:

(Kuzmin,Rubakov,Shaposhnikov '85; Klebnikov,Shaposhnikov '88)

$$N_B^{\rm fin} = -\frac{a}{1-a} N_L^{\rm fin} = a\, N_{(B-L)}^{\rm fin}, \quad a \simeq \frac{1}{3}$$

Assumptions:

- $N_B^{\rm fin}$ is not influenced by N_2 and N_3 decays;
- $T_{\rm in}(= T_{\rm Reheating}(?)\ ) \gg M_1$.

Normalization. Particle and charge numbers are normalized to the number of photons **before** the onset of leptogenesis:

$$N_X(t) = n_X(t)\; R_\star^3(t)$$

$$T(t_\star) \gg M_1, \qquad N_\gamma(t_\star) \equiv 1, \qquad N_{N_1}^{\rm eq}(t_\star) = \frac{3}{4}$$

Dilution. The baryon asymmetry is measured compared to the number of photons at present $\Rightarrow$ the photon production dilutes $N_B^{\rm fin}$:

$$\boxed{\eta_{B0} = \frac{N_B^{\rm fin}}{f} = \frac{a\, N_{B-L}^{\rm fin}}{f}}\,, \qquad f \equiv \frac{N_\gamma^0}{N_\gamma^\star} \quad \text{dilution factor}$$

Minimal assumptions:

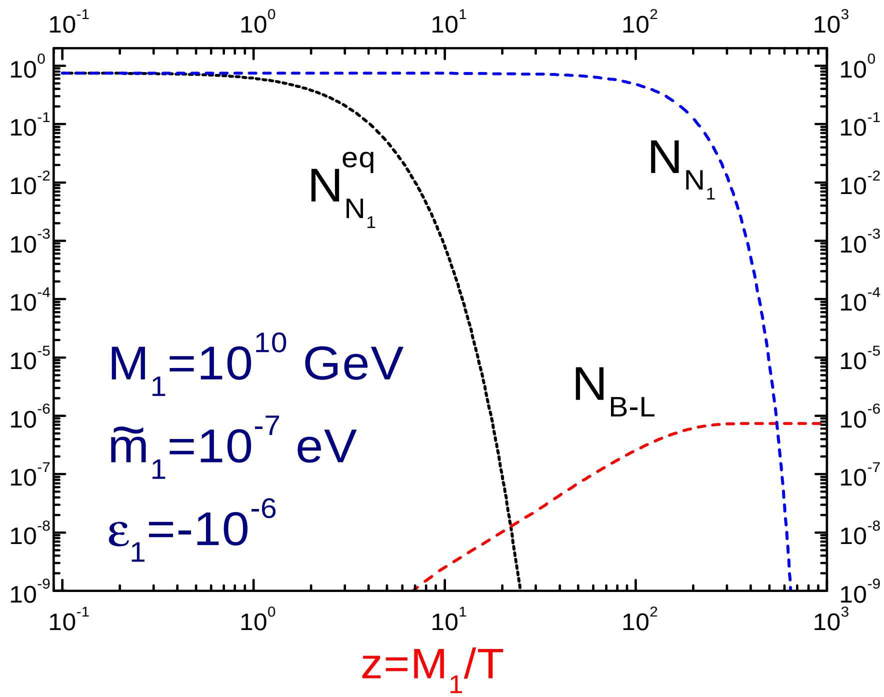
- entropy is conserved between leptogenesis and present $\Rightarrow f = g_\star/g_0$,
- $g_\star = g_{SM} + g_{N_1} = 434/4$

$$\Rightarrow \qquad \frac{a}{f} \simeq 0.013$$

Fully out of equilibrium decays

The simplest case is when the N_1's start to decay very far from equilibrium ($T_D <<< M_1$) and all other processes are frozen:

$$\begin{cases} \dfrac{dN_{N_1}}{dz} = -D\,(N_{N_1} - N_{N_1}^{\rm eq}) \\ \dfrac{dN_{B-L}}{dz} = -\epsilon_1\,D\,(N_{N_1} - N_{N_1}^{\rm eq}) \end{cases}$$



$$N_{B-L}(z) = -\epsilon_1\,N_{N_1}(z) \Rightarrow N_{B-L}^{\rm fin} = -\frac{3}{4}\epsilon_1$$

How the N_1's are initially produced ?

Wash-out and N_1's production

(Fukugita,Yanagida '86; Luty '92; Plümacher '97; Buchmüller,Plümacher'00)

Wash-out processes tend to destroy the lepton asymmetry arising from decays. In the **limit of thermal equilibrium** there is an exact compensation.

- inverse decays $\Rightarrow \Gamma_{ID} = \Gamma_D \, n_{N_1}^{\rm eq}/n_l$
- Higgs scatterings $\Rightarrow \Gamma_{\Delta L=2}$
- N_i scatterings $\Rightarrow \Gamma_{\Delta L=1}$,$\Gamma_S$

total washout rate

$$\Gamma_W = \frac{1}{2}\Gamma_{ID} + \Gamma_{\Delta L=1} + \Gamma_{\Delta L=2}$$

Boltzmann Equations

(Luty '92; Plumacher '97; Barbieri,Creminelli,Strumia,Tetradis '00; Buchmüller,PDB,Plümacher '02)

$$D,\, W,\, S \;\equiv\; \frac{\Gamma_D,\, \Gamma_W,\, \Gamma_S}{H\, z}$$

$H \equiv \dot{R}/R$ is the expansion rate

$$\begin{cases} \dfrac{dN_{N_1}}{dz} &=& -(D+S)\,(N_{N_1} - N_{N_1}^{\rm eq}) \\ \dfrac{dN_{B-L}}{dz} &=& -\epsilon_1\, D\,(N_{N_1} - N_{N_1}^{\rm eq}) - W\, N_{B-L} \end{cases}$$

efficiency factor κ:

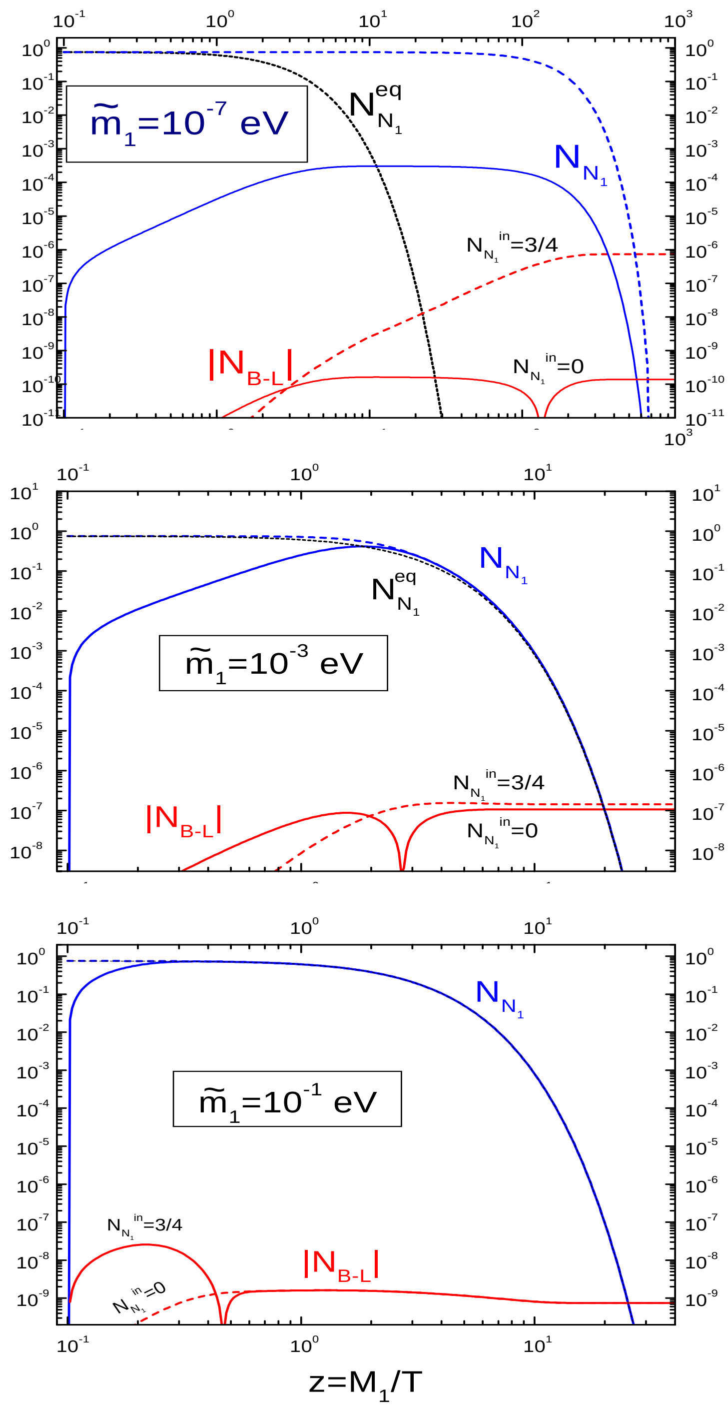
$N_{B-L}^{\rm in} = 0 \Rightarrow N_{B-L}(z) = \frac{3}{4}\,\epsilon_1\;\kappa(z;\epsilon_1,?)$

one always has: $D, S = f_{D,S}(z)\;\tilde{m}_1$

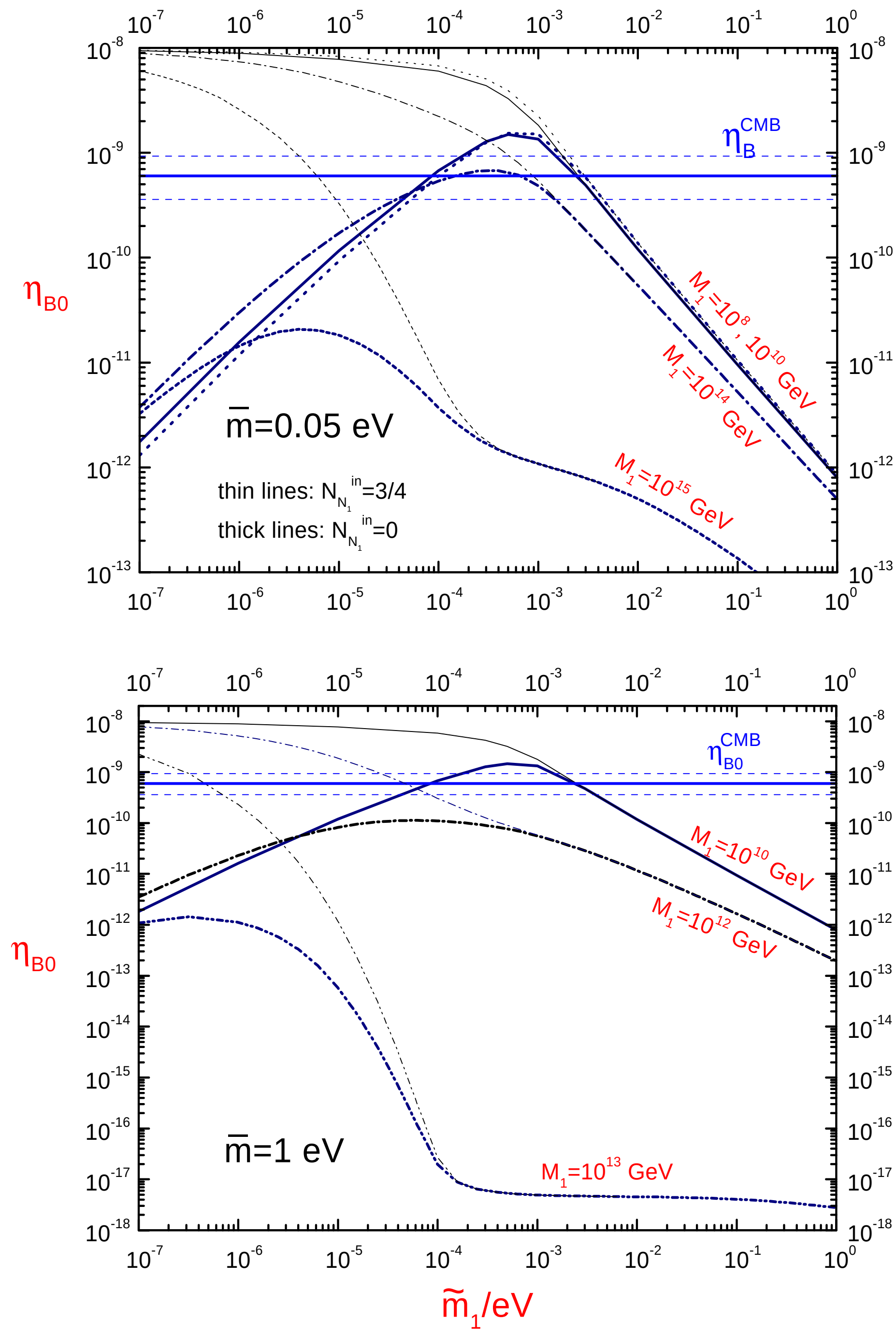
$M_1 < 10^{13}\,\mathrm{GeV}\,(0.1\,\mathrm{eV}/\bar{m})^2 \Rightarrow\; W = f_W(z)\,\tilde{m}_1$

$$\Rightarrow \boxed{\kappa\big|_{\text{small } M_1} = \kappa(z;\tilde{m}_1)}$$

$$\epsilon_1 = -10^{-6}, \quad M_1 = 10^{10}\,\text{GeV}, \quad \bar{m} = 0.05\ eV$$



$$\epsilon_1 = -10^{-6}$$



Where the dependence on M_1 (and $\bar{m}$) comes from (at large values of M_1) ?

- $D, S \propto \tilde{m}_1 \Rightarrow$ NO

$$W = \frac{1}{2} W_{ID} + W_{\Delta L=1} + W_{\Delta L=2}$$

- $W_{ID}, W_{\Delta L=1} \propto \tilde{m}_1 \Rightarrow$ NO

$$W_{\Delta L=2} = W_{\Delta L=2}^{\text{res}} + W_{\Delta L=2}^{\text{nonres}}$$

- $W_{\Delta L=2}^{\text{res}} \propto \tilde{m}_1 \ \Rightarrow$ NO

$$W_{\Delta L=2}^{\text{nonres}} = M_1 \left[\sum_i \frac{(m_D^\dagger \, m_D)_{ii}^2}{M_i^2} g_{ii}(z) + 2 \sum_{i<j} \frac{\mathcal{R}e(m_D^\dagger \, m_D)_{ij}^2}{M_i \, M_j} g_{ij}(z) \right]$$

for $z \gg 1 \Rightarrow g_{ii}(z) = g_{ij}(z) \propto z^{-2} \Rightarrow$

- $W_{\Delta L=2}^{\text{nonres}} \propto M_1 \, \bar{m}^2 / z^2 \Rightarrow$ YES

$$\boxed{\bar{m}^2 \equiv \text{tr}[m_\nu^\dagger \, m_\nu] = \sum_i m_{\nu_i}^2}$$

Bound on the CP asymmetry and surface of maximum baryon asymmetry

(Buchmüller,Yanagida '99; Barbieri et al. '00; Davidson,Ibarra '02; Buchmüller,PDB,Plümacher '02)

$M_{2,3}^2 \gg M_1^2 \Rightarrow \boxed{g \equiv \epsilon_1/\epsilon^{\max} \leq 1}$

- hierarchical $(m_{\nu_3} \gg m_{\nu_2} \gg m_{\nu_1})$

$$\epsilon^{\max} = \frac{3\,M_1}{16\,\pi}\frac{(\Delta m^2_{\rm atm})^{1/2}}{v^2} \simeq 10^{-6}\,\frac{M_1}{10^{10}\,\rm GeV}$$

(inverted hierarchy $[m_{\nu_3} \simeq m_{\nu_2} \gg m_{\nu_1}]$: factor 2 looser)

- quasi-degenerate $(m_{\nu_i} \simeq \bar{m}/\sqrt{3})$

$$\epsilon^{\max} = \frac{3\,M_1}{16\,\pi}\frac{\Delta m^2_{\rm atm}}{v^2\,m_{\nu_i}} \simeq 10^{-7}\,\frac{M_1}{10^{10}\,\rm GeV}$$

$$\boxed{\eta_{B0} \leq \eta_{B0}^{\max} = \frac{3}{4}\frac{a}{f}\,\epsilon^{\max}\,\kappa_0(\tilde{m}_1, M_1; \bar{m})}$$

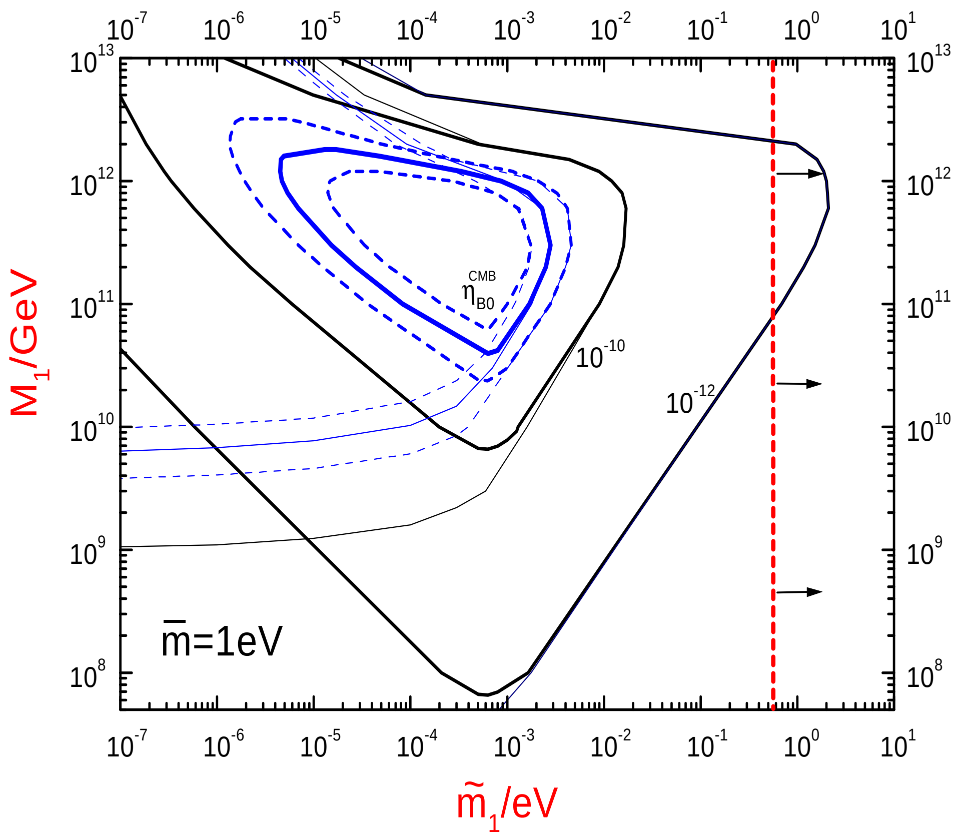
Note: if $M_{2,3} \lesssim 3\,M_1$ the CP asymmetry is enhanced and one can have $g > 1$ but until $|M_{2,3} - M_1| \ll |\Gamma_i - \Gamma_1|$ the enhancement is mild (Covi,Roulet,Vissani '96; Buchmüller, Plümacher '98; Pilaftsis '99; Davidson,Ibarra '02)

Bound on $\tilde{m}_1$: $\tilde{m}_1 \geq m_{\nu_1}$

(Fujii,Hamaguchi,Yanagida '02)

Quasi-degenerate neutrinos

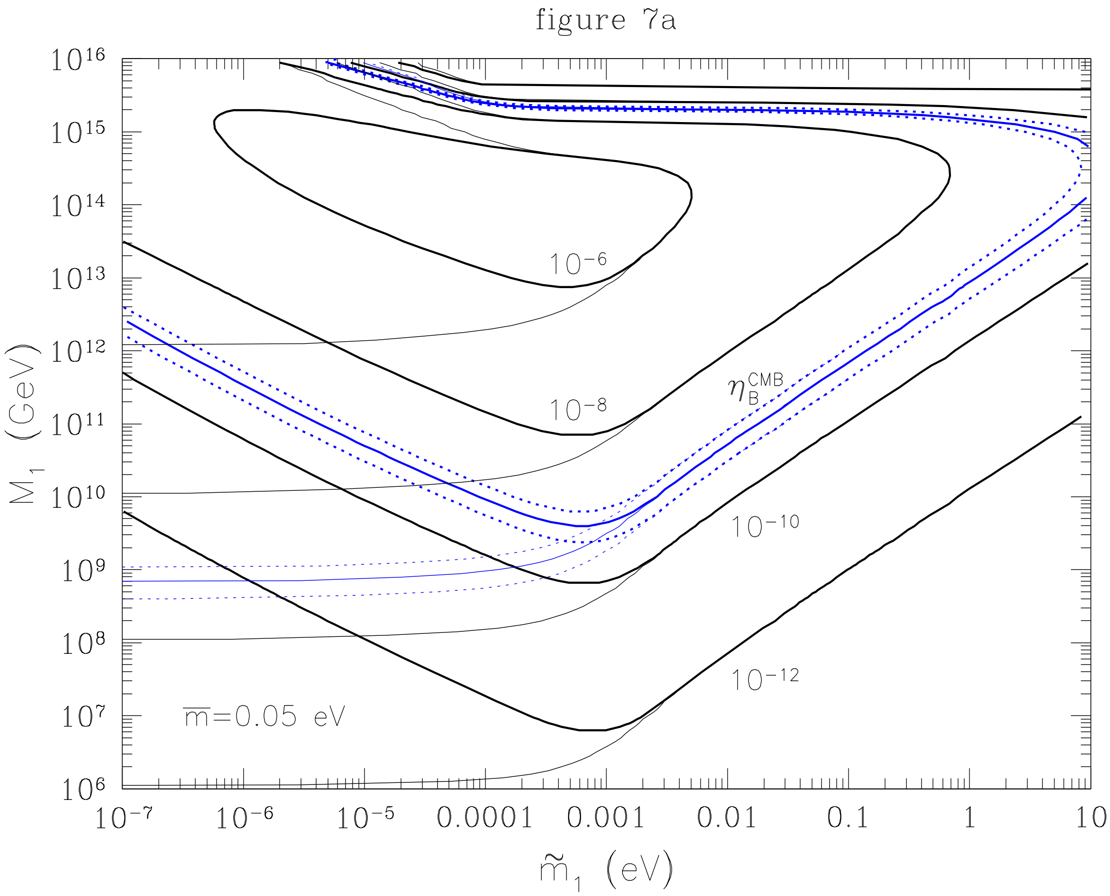
iso-η_{B0}^{max} curves



Quasi-degenerate neutrinos are incompatible with thermal leptogenesis (unless $g \gtrsim 100$) !

Hierarchical neutrinos

iso-$\eta_{B0}^{\max}$ curves



- $M_1 \gtrsim 2.4\,(0.4) \times 10^9$ GeV
- for $g \simeq 1$ and

$$10^{-3}\,\text{eV} \simeq 0.1\,\sqrt{\Delta m^2_{LMA}} \leq \tilde{m}_1 \leq \sqrt{\Delta m^2_{\text{atm}}} \simeq 5 \times 10^{-2}\,\text{eV}$$

$$\Rightarrow \boxed{T_L \simeq M_1 = \mathcal{O}(10^{10}\,\text{GeV})}$$

Conclusions

- the predictions on the baryon asymmetry can be described in a model independent way in terms of 4 parameters $\Rightarrow$ specific calculations are not necessary, one has just to extract from the model ϵ_1, M_1, $\tilde{m}_1$, $\bar{m}$;

- thermal leptogenesis predicts no evidence for $m_{\nu_i} \gtrsim (0.5\,\text{eV})$;

- with reasonable (though model dependent) assumptions one is led to the conclusion that $T_L \simeq M_1 = \mathcal{O}(10^{10}\,\text{GeV})$.