Implications of
FLAVOR in LEPTOGENESIS

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A. Abada, S. Davidson, A. Ibarra, M. Losada, A. Riotto, F.X. J.M. : work in progress

also :

E. Nardi, Y. Nir, E. Roulet, J. Racker : hep-ph/0601084

Summary

Baryon Asymmetry of the Universe

Observed Baryon asymmetry in the Universe $Y_B = \frac{n_B - n_{\bar{B}}}{s}$

$$3.4 \times 10^{-10} \leq Y_B^{BBN} \leq 6.9 \times 10^{-10}$$

$$6.0 \times 10^{-10} \leq Y_B^{CMB} \leq 6.6 \times 10^{-10}$$

Sakharov's conditions : Sakharov, `67

Baryon number violation
C & CP violation
Departure from equilibrium

Problem of S.M. : smallness of neutrinos masses

Necessity to go beyond the SM

Beyond the SM

Minimal Extension of S.M. with right-handed neutrinos of Majorana type

$$\mathcal{L} = \mathcal{L}_{SM} + \left(\frac{Mi}{2} N_i^2 + \lambda_{i\alpha} N_i \ell_\alpha H + h_\alpha H \overline{e}_{R\alpha} \ell_\alpha + h.c. \right)$$

Generation of the light neutrino mass by the See-Saw mechanism

$$m_\nu = U^* D_{m_\nu} U^\dagger = \lambda^T M^{-1} \lambda v^2$$

Explain their smallness :

$$\lambda v = 0.1\ GeV, M = 10^{10} GeV \Rightarrow m_\nu = 10^{-2} eV$$

Leptogenesis

Baryon asymmetry via Lepton asymmetry

Fukugita&Yanadiga, `86

Sakharov's conditions are fulfilled in the context of leptogenesis :

CP asymmetry from the complex couplings λ

B violation by reprocessing the dynamically generated L number

Out-of-equilibrium decays of the right handed neutrinos

Leptogenesis without flavor :
the 1 flavor approximation

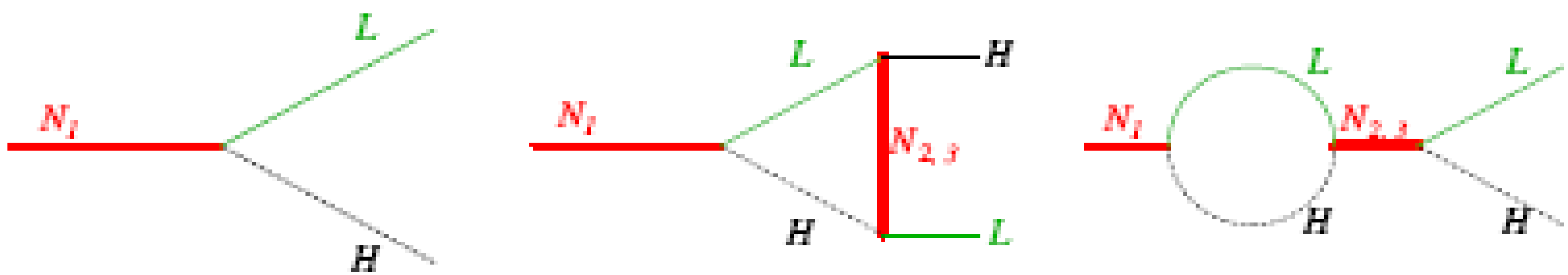
Total CP asymmetry for the lightest heavy neutrino

Dynamical generation a total Lepton asymmetry $Y_L = \frac{n_L - n_{\bar{L}}}{s}$

Global out-of-equilibrium condition : $K \equiv \left. \frac{\Gamma(N_1 \rightarrow H\, l)}{H} \right|_{T=M_1}$

Total CP asymmetry

Arise from interference between the decay tree level and 1-loop correction.
For the lightest heavy neutrino :



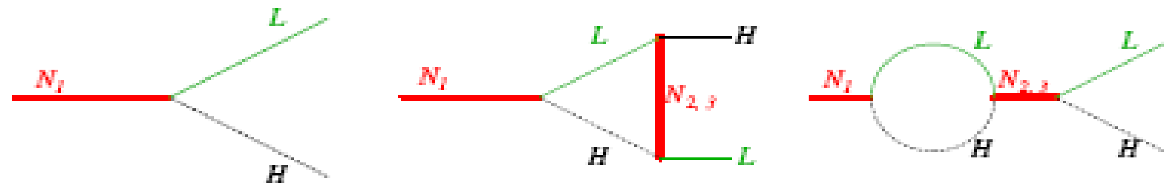
$$\epsilon_1 = \frac{\Sigma_\alpha \left(\Gamma(N_1 \to H\ell_\alpha) - \Gamma(N_1 \to \overline{H\ell_\alpha})\right)}{\Sigma_\alpha \left(\Gamma(N_1 \to H\ell_\alpha) + \Gamma(N_1 \to \overline{H\ell_\alpha})\right)}$$

$$= \frac{1}{8\pi} \sum_{j\neq 1} \frac{\Im[(\lambda\lambda^\dagger)^2_{j\,1}]}{(\lambda\lambda^\dagger)_{1\,1}} f\left(\frac{M_j^2}{M_1^2}\right)$$

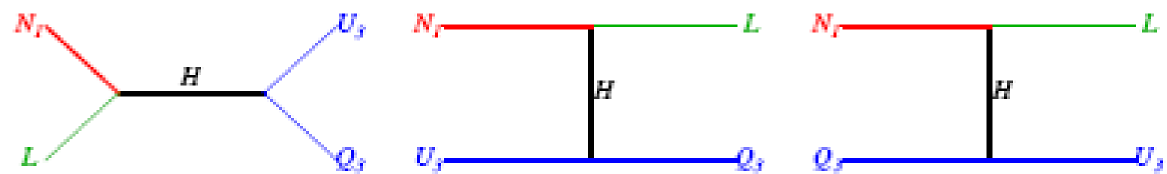
Boltzmann Equations in the 1fa

$$
\begin{aligned}
Y'_{N_1}(z) &= -\left(D(z)+S(z)\right)\left(Y_{N_1}(z)-Y^{eq}_{N_1}(z)\right)\\
Y'_{L}(z) &= \epsilon_1 D(z)\left(Y_{N_1}(z)-Y^{eq}_{N_1}(z)\right)-W(z)Y_L(z)
\end{aligned}
$$

D : decay&inverse decays :

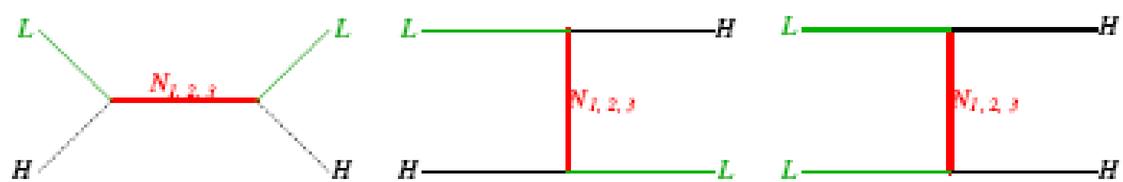


S : ΔL=1 scattering



+ terms involving gauges bosons

W : D, S and ΔL=2 scattering



Giudice & *al*, hep-ph/03010123

Boltzmann Equations in the 1fa

The produced Lepton asymmetry is converted to a Baryon asymmetry via sphaleron interactions :

$$Y_B = -\left(\frac{8n_G + 4n_H}{14n_G + 9n_H}\right) Y_L$$

The Baryon asymmetry is related to the total CP asymmetry and to the strength of the wash-out term

This strength is parametrize by $$K = \frac{(\lambda\lambda^\dagger)_{11} v^2}{M_1 m_\star}$$

$$W(z) \propto K$$

Boltzmann Equations in the 1fa

Solutions of B.E. :

$$
\begin{aligned}
Y_L(z) &= \epsilon_1 \int_{z_i}^{z} dz' D(z')(Y_{N_1} - Y_{N_1}^{eq}) e^{-\int_{z'}^{z} dz'' W(z'')} \\
&= \epsilon_1 \kappa(z)
\end{aligned}
$$

$$Y_L \propto \varepsilon_1 \Rightarrow Y_B \propto \varepsilon_1$$

Lepton and Baryon asymmetries are proportional to CP asymmetry

Boltzmann Equations in the 1fa

In the case of <u>degenerate light neutrino spectrum :</u>

$$m_{\nu 1} = m_{\nu 2} = m_{\nu 3} \Rightarrow \varepsilon_1 = 0$$

$$\varepsilon_1 = 0 \Rightarrow Y_L = 0 \Rightarrow Y_B = 0$$

No Baryon asymmetry can be generated

Degenerated spectrum is excluded by Leptogenesis in the 1fa

Boltzmann Equations in the 1fa

Constraint on the light neutrino mass : for $m_{\nu 1} \simeq m_{\nu 2} \simeq m_{\nu 3} \simeq m_{\nu}$

$$\varepsilon_1 \leq \varepsilon_1^{max} = \frac{3 M_1}{8 \pi v^2} \frac{\Delta m^2_{atm}}{m_\nu}$$

Davidson, Ibarra '02

$$Y_B \leq Y_B^{max} \propto \frac{\Delta m^2_{atm}}{m^2_\nu}$$

$$\Rightarrow m_\nu \leq 0.15\, eV$$

Buchmuller & *al*, `04

What about flavor ?

YL total asymmetry
CP asymmetry } sum of individual asymmetries

$$Y_L = Y_{ee} + Y_{\mu\mu} + Y_{\tau\tau}$$
$$\epsilon_1 = \epsilon_{ee} + \epsilon_{\mu\mu} + \epsilon_{\tau\tau}$$

The 1fa deals only with the total asymmetries :
some information is missing

When flavor is taken into account

Individual CP asymmetries

$$\epsilon_{\alpha\alpha} = \frac{\Gamma(N_1 \to \ell_\alpha H) - \Gamma(N_1 \to \overline{\ell_\alpha} H^c)}{\Gamma(N_1 \to \ell H) - \Gamma(N_1 \to \overline{\ell} H^c)}$$

The Boltzmann equations are modified :

$$\begin{aligned} Y'_{N_1}(z) &= -(D(z)+S(z))\left(Y_{N_1}(z) - Y^{eq}_{N_1}(z)\right) \\ Y'_{\alpha\alpha}(z) &= \epsilon_{\alpha\alpha} D(z)\left(Y_{N_1}(z) - Y^{eq}_{N_1}(z)\right) - W_{\alpha\alpha}(z) Y_{\alpha\alpha}(z) \end{aligned}$$

Flavored wash-out parameters

$$W_{\alpha\alpha}(z) \propto K_{\alpha\alpha} \equiv \frac{\lambda_{1\alpha}\lambda^*_{1\alpha} v^2}{M_1 m_*}$$

Boltzmann Equations : flavored case

For the total Lepton number :

$$Y_L^{'} = \sum_\alpha Y_{\alpha\alpha}^{'} = \left(\sum_\alpha \epsilon_{\alpha\alpha}\right) D(z) \left(Y_{N_1}(z) - Y_{N_1}^{eq}(z)\right) - \left(\sum_\alpha W_{\alpha\alpha}(z) Y_{\alpha\alpha}(z)\right)$$

It differs from the 1fa :

$$\sum_\alpha W_{\alpha\alpha}(z) Y_{\alpha\alpha}(z) \neq \sum_\alpha W_{\alpha\alpha}(z) \sum_\beta Y_{\beta\beta}(z) = W(z)\, Y_L(z)$$

Boltzmann Equations : flavored case

We numerically solve the different set of B. E. with hierarchical spectrum for both light and heavy neutrinos :

$$M_3 : M_2 : M_1 = m_\tau : m_\mu : m_e$$

$$m_3^2 = m_1^2 + \Delta m_{atm}^2 , m_2^2 = m_1^2 + \Delta m_{sol}^2$$

and for the mixing angles :

$$\sin(\theta_{12})^2 \simeq 0.314$$

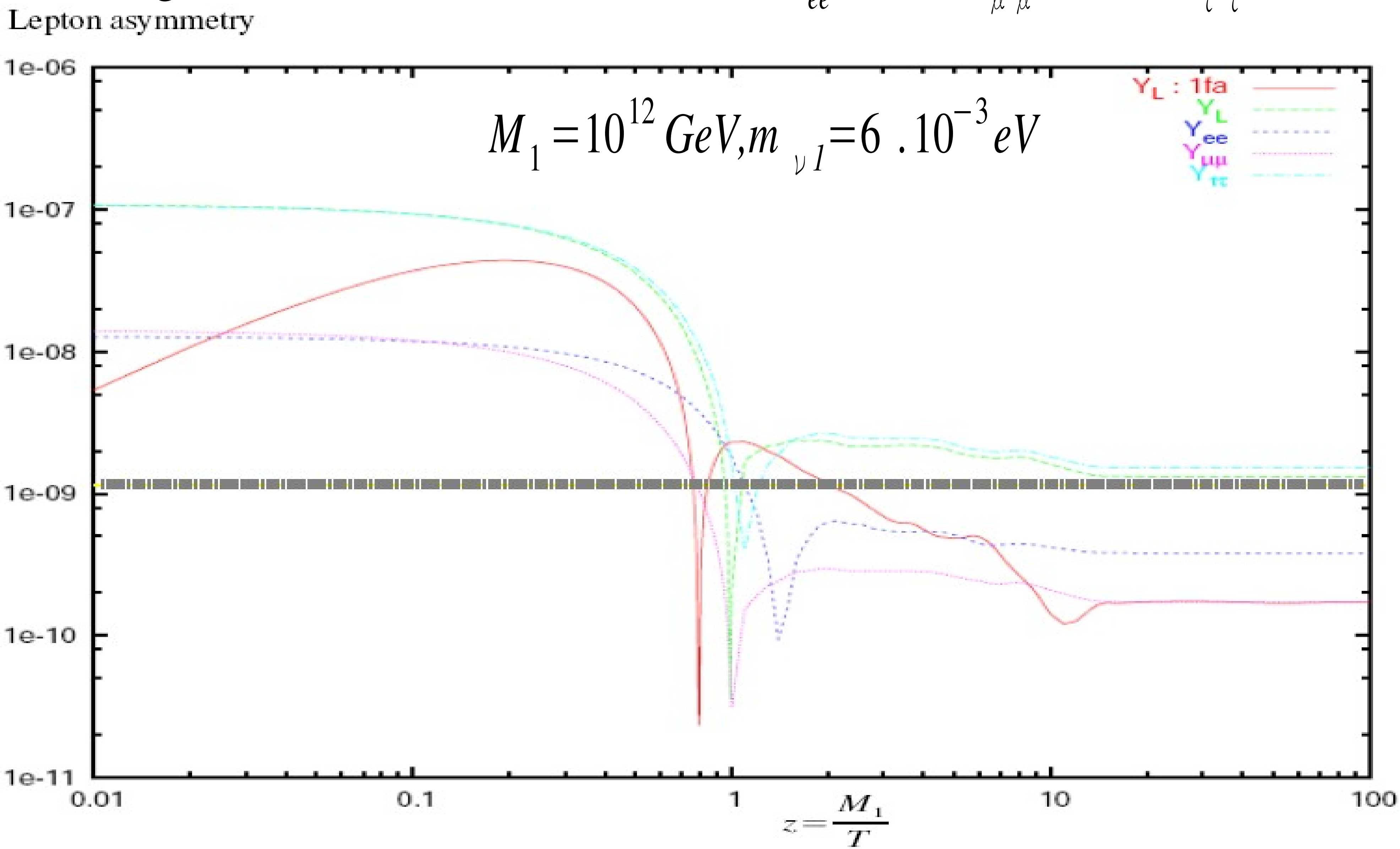
$$\sin(\theta_{23})^2 \simeq 0.44$$

$$\sin(\theta_{13})^2 \simeq 0.9\mathrm{x}10^{-2}$$

Fogli & *al*, '05

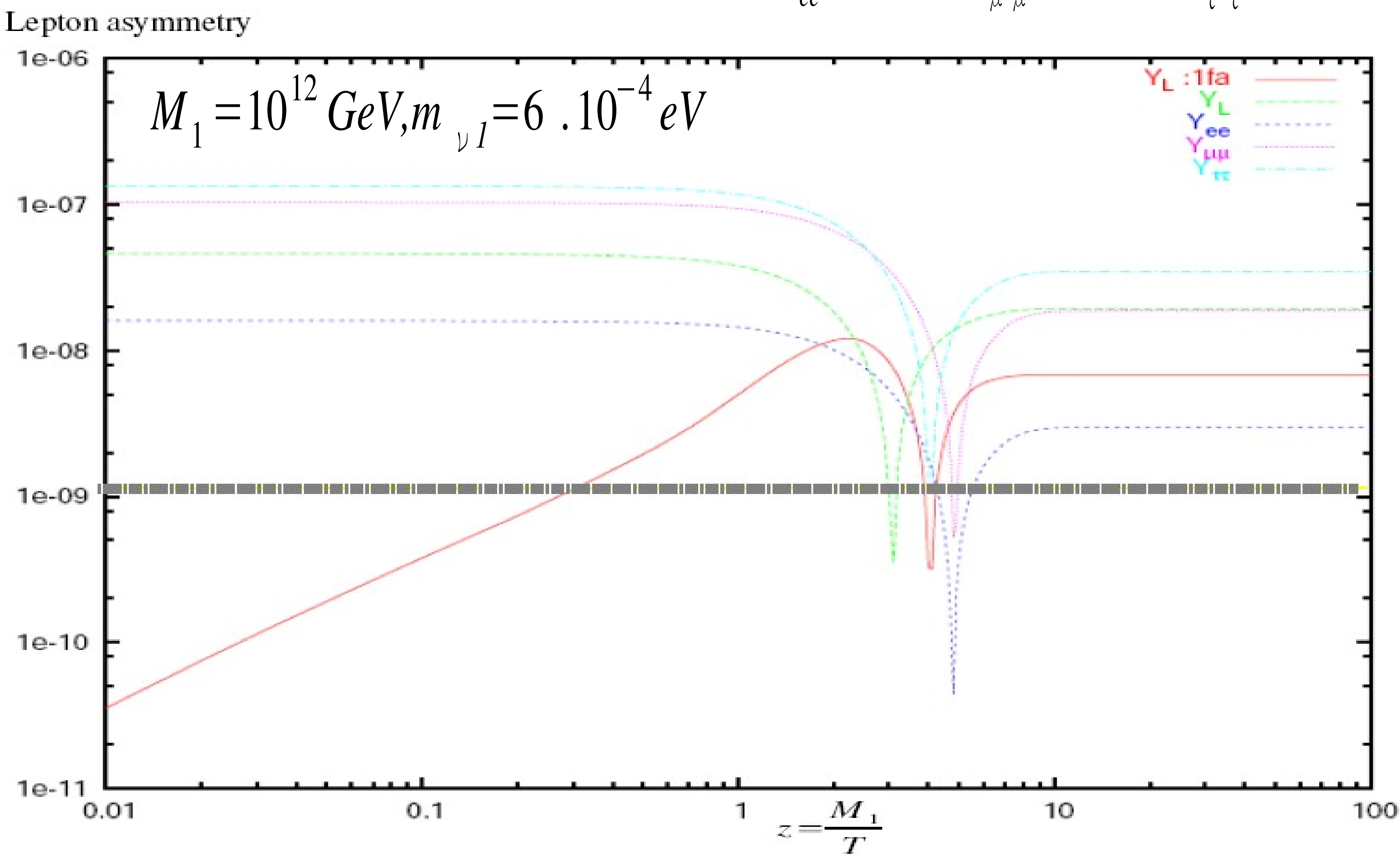
Boltzmann Equations : flavored case

For strong wash-out case K >> 1 $K \simeq 50,\ K_{ee} \simeq 10,\ K_{\mu\mu} \simeq 21,\ K_{\tau\tau} \simeq 19$



Boltzmann Equations : flavored case

For weak wash-out case K << 1 $K \simeq 0.7, K_{ee} \simeq 0.2, K_{\mu\mu} \simeq 0.2, K_{\tau\tau} \simeq 0.3$



Boltzmann Equations : flavored case

Non flavor-symmetric Lepton to Baryon number conversion :

$$\begin{aligned} Y_B &\neq c\,(Y_{ee} + Y_{\mu\mu} + Y_{\tau\tau}) \\ Y_B &= c_e Y_{ee} + c_\mu Y_{\mu\mu} + c_\tau Y_{\tau\tau} \end{aligned}$$

The conversion factors depends whether an interaction is in equilibrium or not, and so depend on M1.

For exemple, with $M1 \leq 10^9\ GeV$, one has :

$$Y_B = -\frac{12}{37}\left(\frac{40}{13}Y_{ee} + \frac{51}{13}Y_{\mu\mu} + \frac{51}{13}Y_{\tau\tau}\right)$$

Consequences for the degenerate spectrum

Even if the total CP asymmetry vanishes, individual ones do not

$$\epsilon_1 = 0 = \sum_\alpha \epsilon_{\alpha\alpha}$$

$$\epsilon_{\alpha\alpha} \neq 0$$

From the flavored B.E.

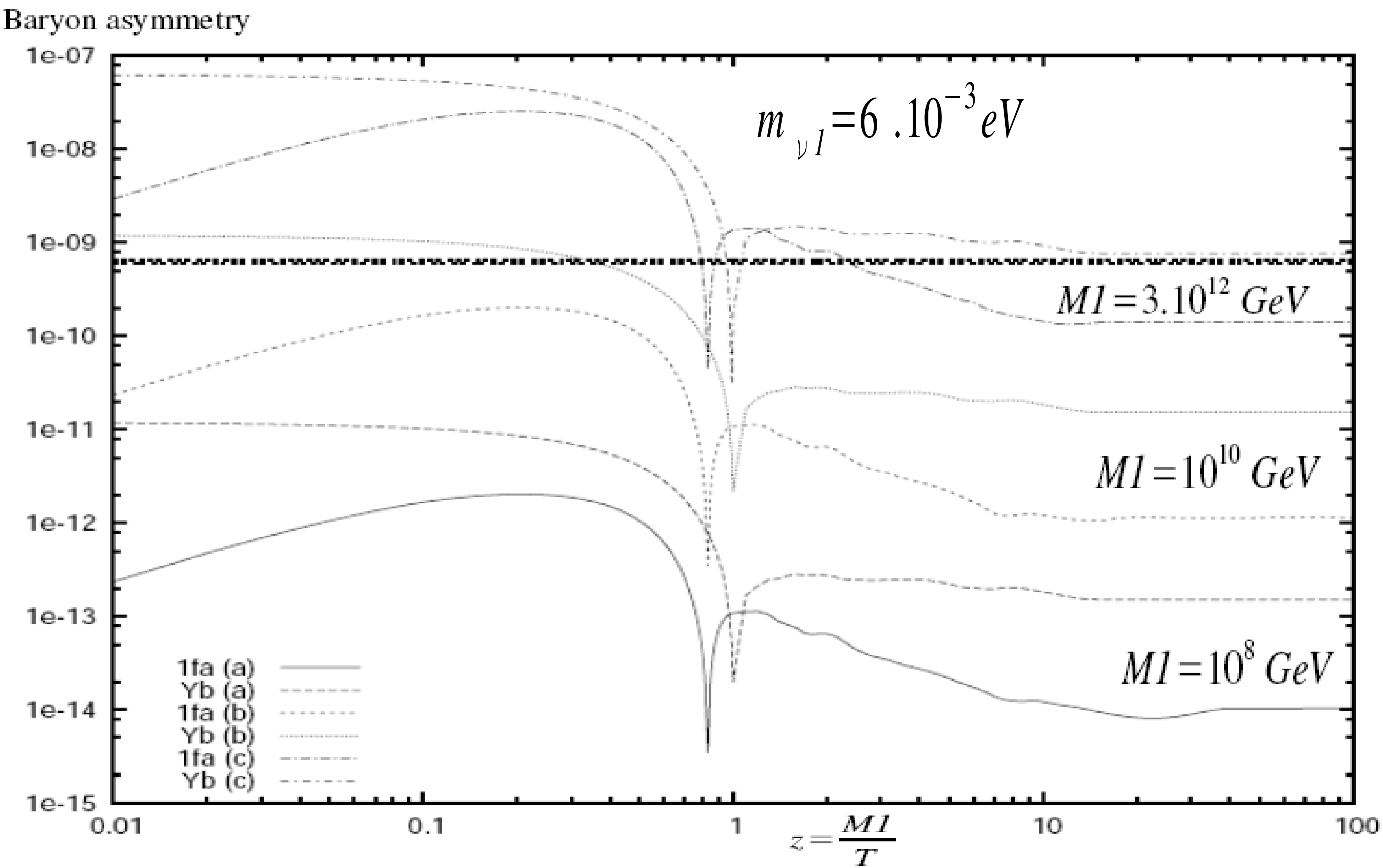
→ Non-zero Lepton asymmetry $Y_{\alpha\alpha} \propto \varepsilon_{\alpha\alpha} \neq 0$

→ Non-zero Baryon asymmetry $Y_B \neq 0$

Degenerate spectrum is no more excluded when flavor is taken into account

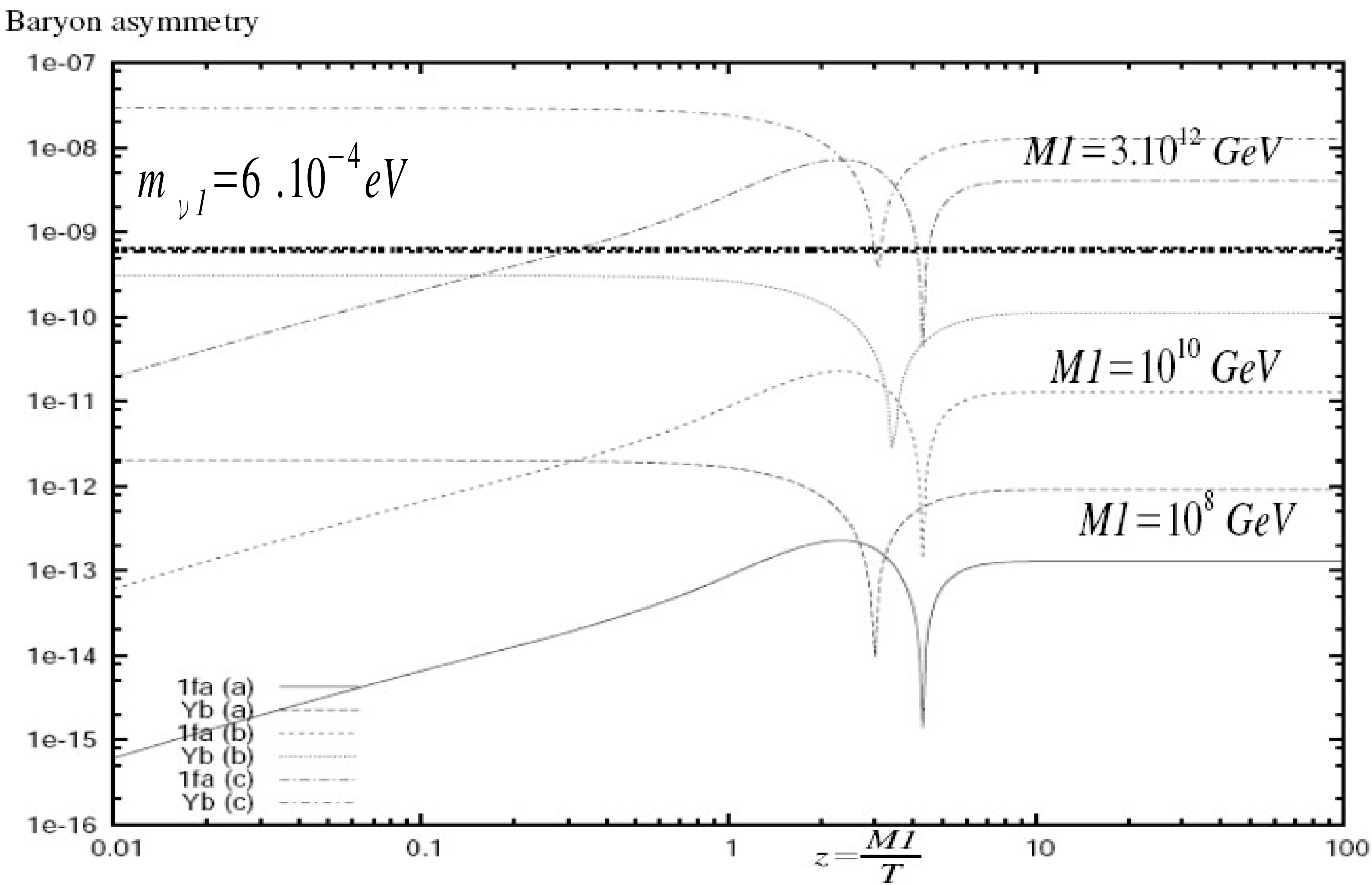
Boltzmann Equations : flavored case

For all flavor in strong wash-out K~50



Boltzmann Equations : flavored case

For all flavor in weak wash-out K~0.7



Constraint on the masses

- Including flavor, for $m_{\nu 1} \simeq m_{\nu 2} \simeq m_{\nu 3} \simeq m_{\nu}$

$$|\epsilon_{\alpha\alpha}| \leq \frac{3 M_1 m_\nu}{8 \pi v^2} \qquad \sum_\alpha \epsilon_{\alpha\alpha} \simeq 0$$

But Y_B^{max} independent of m_ν ⟶ no upper bound on m_ν

- Taking account of flavor *slightly* increase the Baryon asymmetry
Constraint on Min(M1) that allows successful BAU are weakened

Conclusion

1 flavor approximation :

forbidden degenerate spectra

upper bound on light neutrino masses

need LARGE M1

Flavored Leptogenesis :

<u>allowed</u> degenerate spectra

<u>no</u> upper bound on light neutrino masses

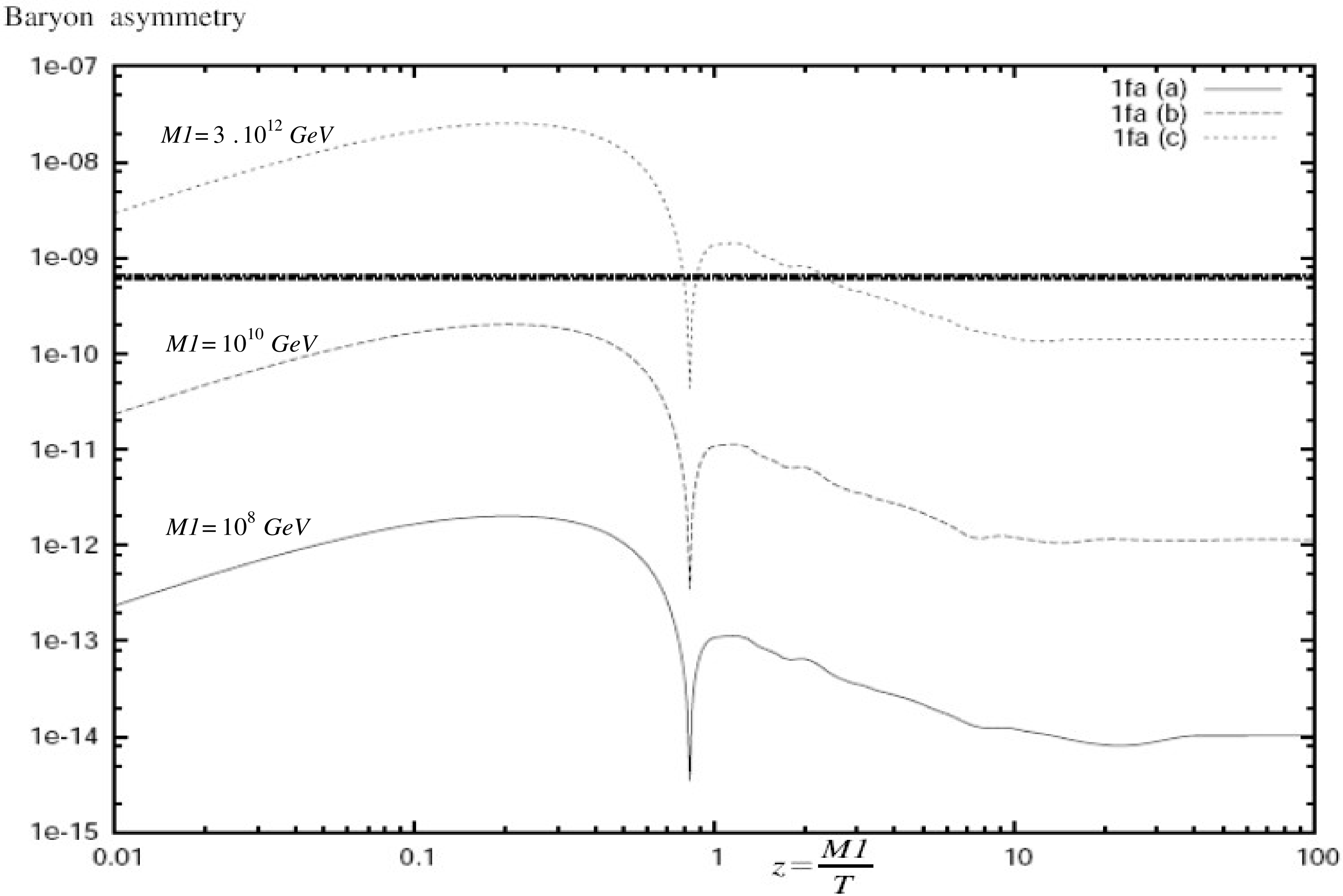
need large M1

Inclusion of flavor is relevant in Leptogenesis.

merci de votre attention

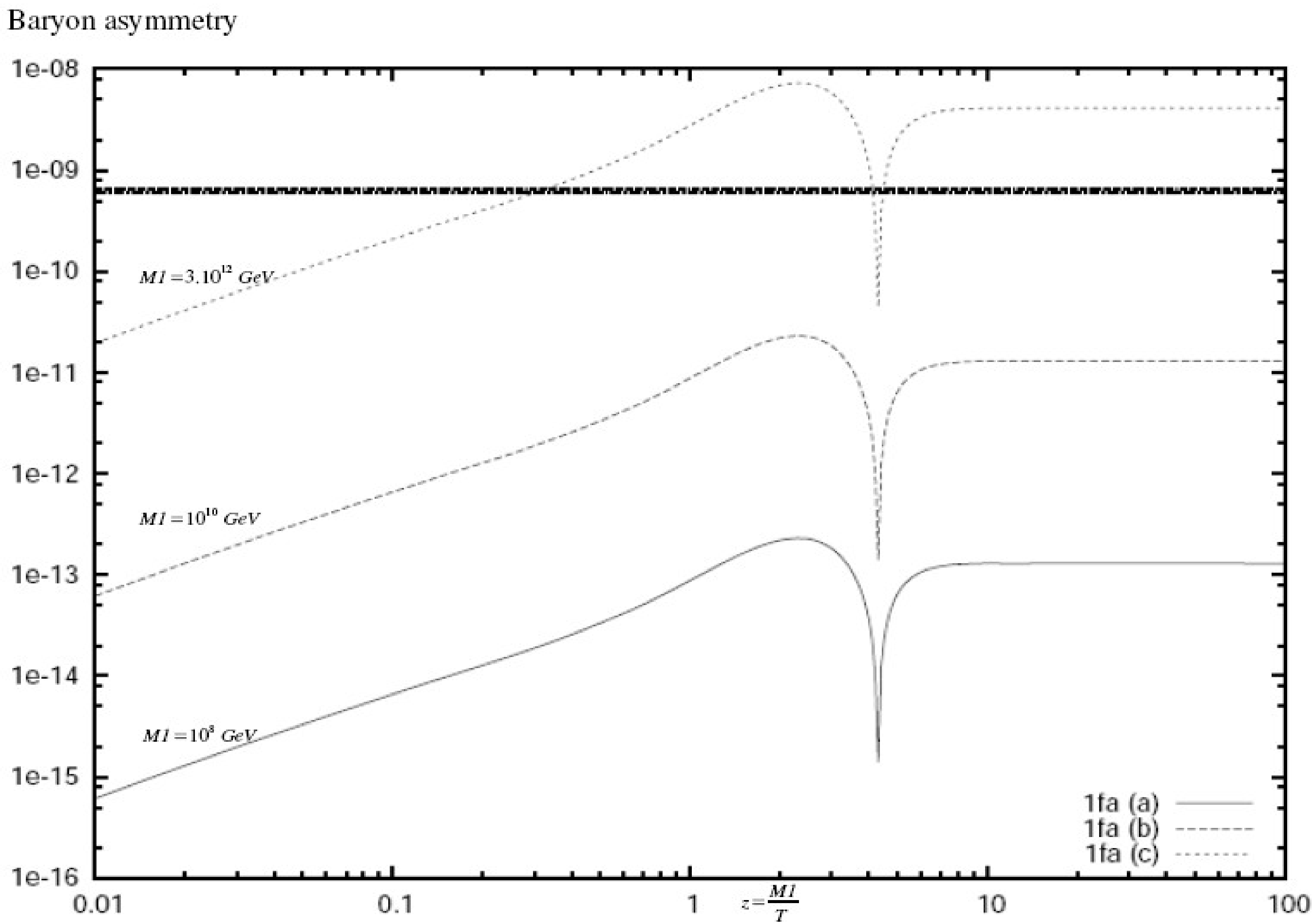
Boltzmann Equations in the 1fa

In the strong wash-out regime K >> 1



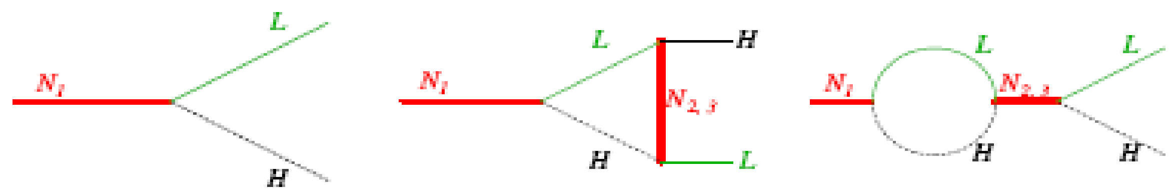
Boltzmann Equations in the 1fa

In the weak wash-out regime K << 1



$$m_{\nu 1} = m_{\nu 2} = m_{\nu 3}$$
$$\Downarrow$$
$$\epsilon_1 = 0$$

$$K_{\alpha\alpha} = \frac{\lambda_{1\alpha}\lambda^{\star}_{1\alpha} v^2}{M_1 m_{\star}}$$



$$Y_B \leq Y_B^{max} \sim \alpha \frac{\Delta m^2_{atm}}{(\sum m_\nu)^2}$$