Thermal Leptogenesis

Michael Plümacher
CERN

Outline

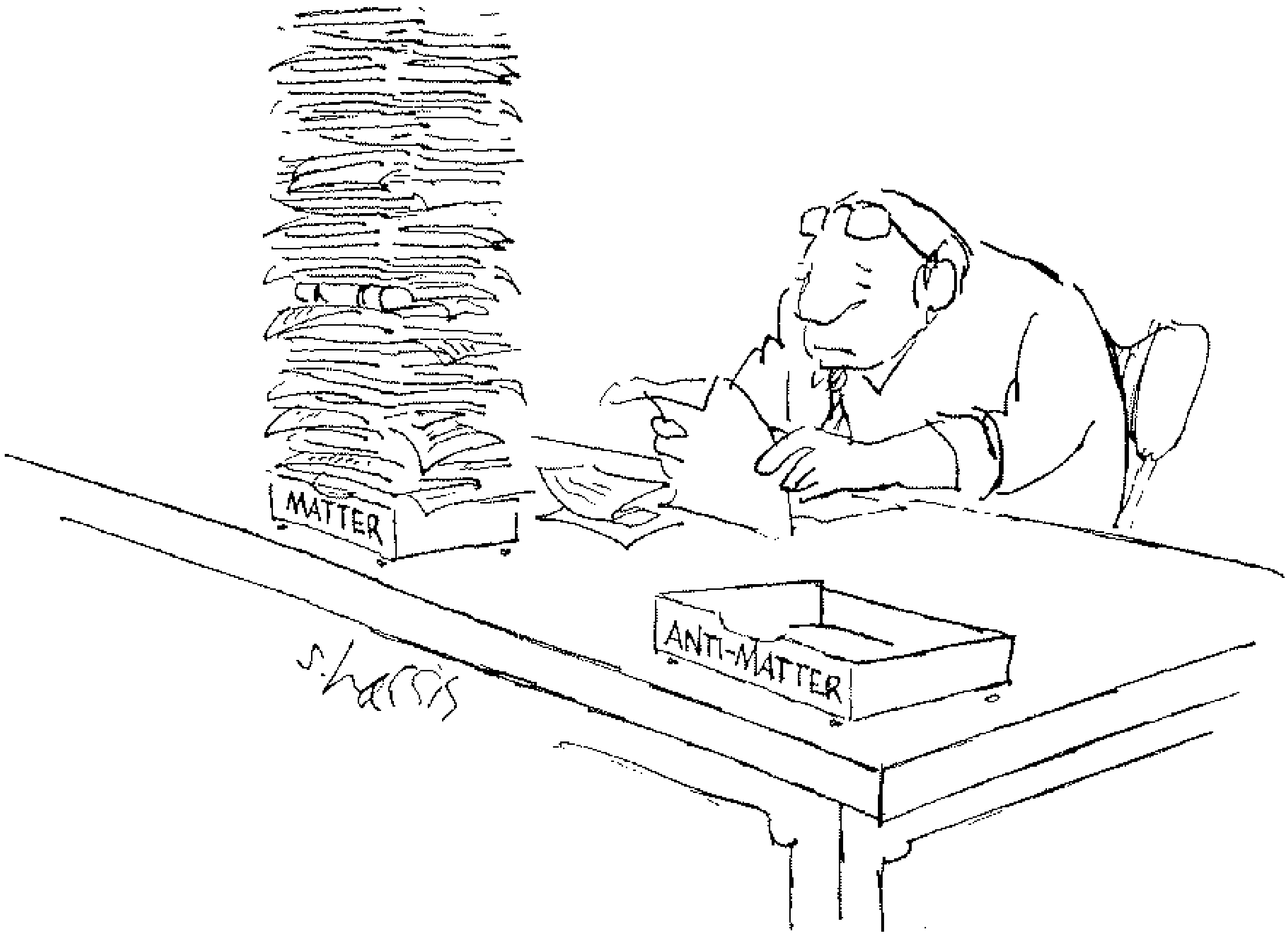
- Introduction
- Baryogenesis through Lepton Number Violation
- Constraints on Neutrino Parameters
- Initial Conditions and Potential Loopholes
- Summary

Baryogenesis

The universe is made of matter.
Baryon asymmetry (from nucleosynthesis and CMB):

$$\eta_B \equiv \frac{n_b - n_{\bar{b}}}{n_\gamma} \sim 6 \times 10^{-10}$$

η_B must have been dynamically generated:

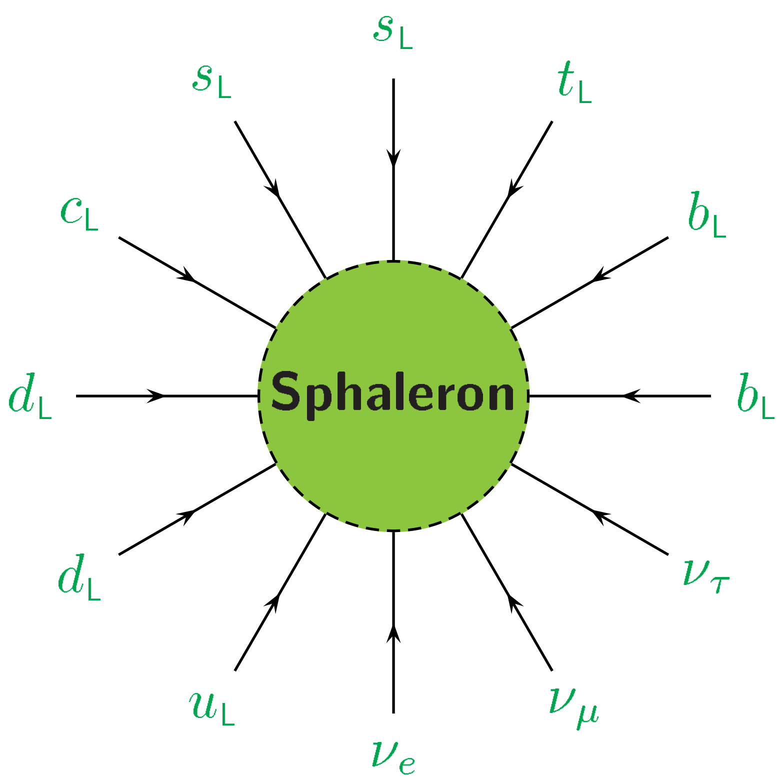


Necessary ingredients (Sakharov, 1967):

- Baryon number violation
- C and CP violation
- Deviation from thermal equilibrium

Baryogenesis and lepton number violation

Standard model: $B + L$ is violated by instantons 't Hooft '76



in thermal equilibrium at $T \gtrsim 100$ GeV

Kuzmin, Rubakov & Shaposhnikov '85

$$\Longrightarrow \qquad \eta_B \;=\; c\,\eta_{B-L}$$

(SM: $c = \frac{28}{79}$; MSSM: $c = \frac{8}{23}$)

Baryogenesis requires breaking of $B - L$

Potential loophole :

if Yukawa interactions not in thermal eq. for $T \gtrsim 100$ GeV

$\Rightarrow$ "hide" asymmetry in right-handed fields

(Cline et al. '93; Dick et al '00; . . .)

Baryogenesis requires breaking of $B - L$

Simplest realization: SM + singlet neutrinos
(Fukugita and Yanagida '86)

Yukawa interactions:

$$\mathcal{L}_Y = \overline{l_{\mathrm{L}}} H^\dagger h_\nu \nu_{\mathrm{R}} - \frac{1}{2} \overline{\nu_{\mathrm{R}}^c} M \nu_{\mathrm{R}} + \text{ h.c.}$$

$\rightarrow$ seesaw mechanism: 6 Majorana mass eigenstates

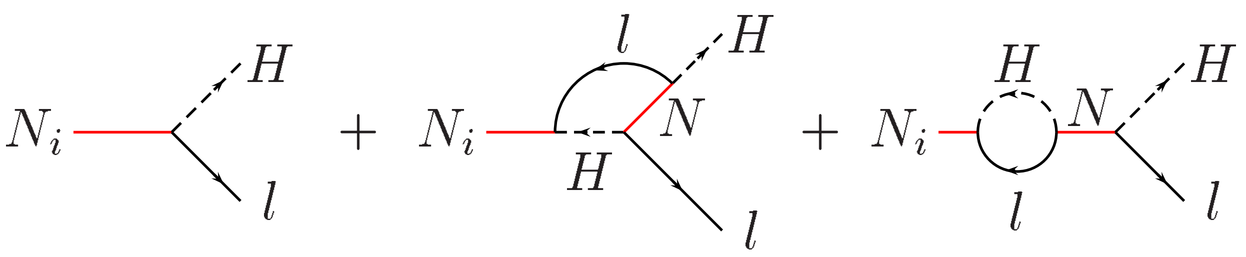
$$N \simeq \nu_{\mathrm{R}} + \nu_{\mathrm{R}}^c \qquad \nu \simeq U_\nu^\dagger \nu_{\mathrm{L}} + \nu_{\mathrm{L}}^c U_\nu$$

$$m_N \simeq M \qquad m_\nu \simeq -U_\nu^\dagger m_{\mathrm{D}} \frac{1}{M} m_{\mathrm{D}}^T U_\nu^*$$

Seesaw naturally explains η_B:

- N's are unstable: $\Gamma_D \propto \widetilde{m}_1 = \frac{1}{M_1}\left(m_D^\dagger m_D\right)_{11}$
- h_ν complex $\Rightarrow$ CP violation ε_1

Generation of a lepton asymmetry



Out-of-Equilibrium Decay

at $T \gg M_N$

$$\Gamma_N \gg H$$

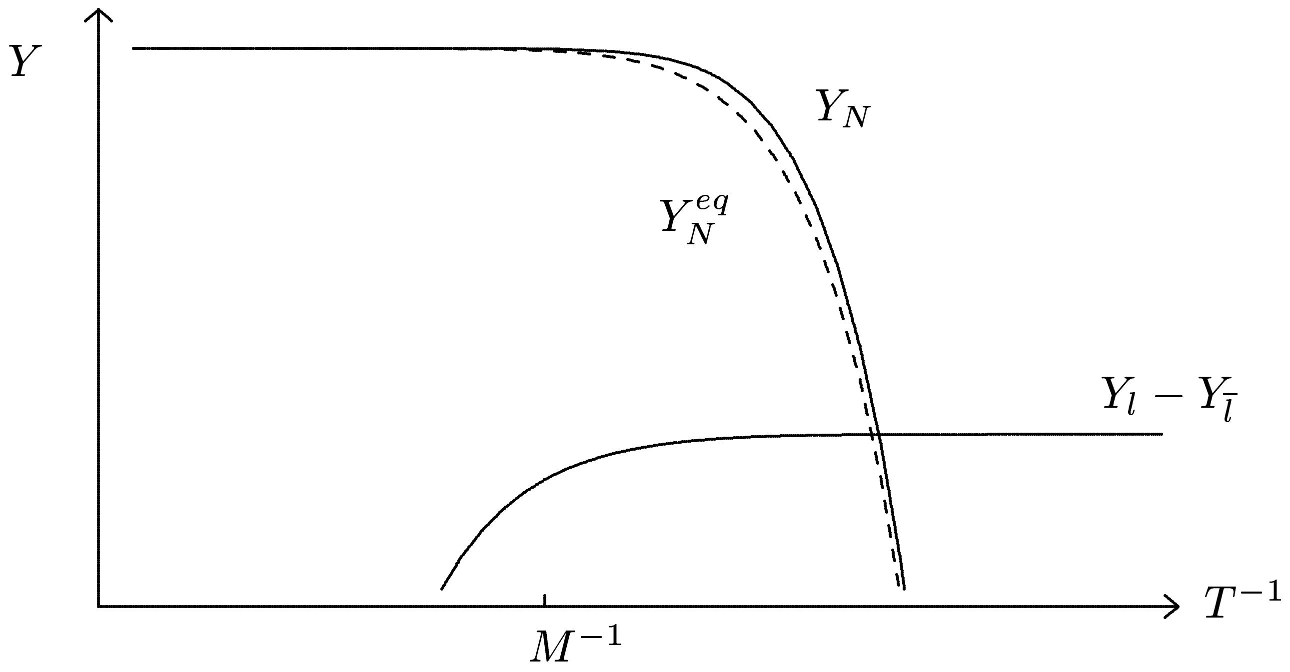
the heavy neutrinos are in thermal equilibrium

when $T \sim M_N$

$$\Gamma_N \ll H$$

$\Rightarrow$ the neutrinos do not decay fast enough to follow the equilibrium distribution

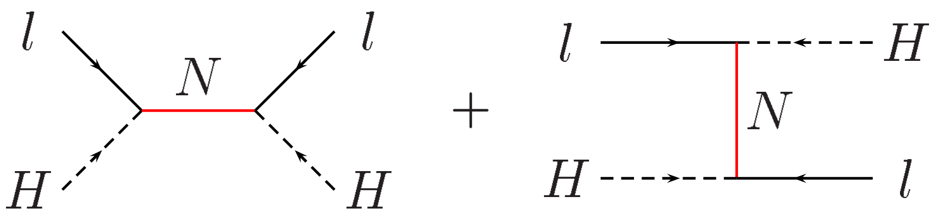
$\Rightarrow$ deviation from thermal equilibrium: there is an excess of neutrinos



Scattering processes

1. Washout due to Neutrino mediated L violating scatterings

(Fukugita & Yanagida '90)



$\longrightarrow$ low energy effective interaction at $T \ll M_1$

$$\mathcal{L}_{\Delta L=2} \sim \frac{1}{2v^2}(m_D \frac{1}{M} m_D^T)_{ij}\,(l_{Li}H)\,(l_{Lj}H)$$

Reaction rate:

$$\Gamma_{\Delta L=2}(T) \propto \sum_{i=e,\mu,\tau} m_{\nu_i}^2 = \overline{m}^2$$

$\rightarrow$ Bound on light neutrino masses!

Two contributions at $T \sim M_1$:

- resonance contribution from N_1: $\propto \widetilde{m}_1$
- non-res. contrib. from N_i, $i = 1,2,3$: $\propto M_1 \overline{m}^2$

$\Rightarrow$ $\widetilde{m}_1$ and $M_1 \overline{m}^2$ should be small to avoid washout!

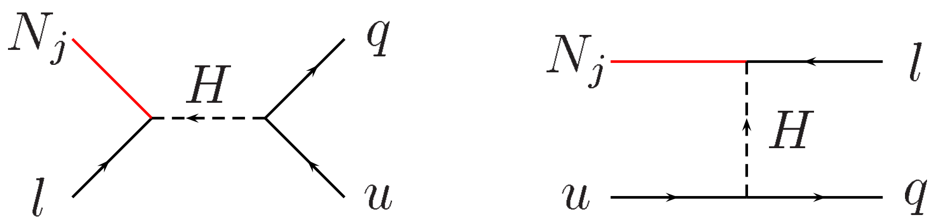
CP asymmetry ε_1 :
mean lepton asymmetry per neutrino decay.

$\Rightarrow$ simple approximation

$$N_L \sim N_{N_1} \varepsilon_1$$

2. How do the right-handed neutrinos get produced?

Important contribution:
Neutrino-Top scatterings: (Luty '92; M.P. '96)



N_1 production processes $\propto \widetilde{m}_1$

$\Rightarrow$ $\widetilde{m}_1$ should be large for successful leptogenesis!

can both conditions on $\widetilde{m}_1$ be reconciled?

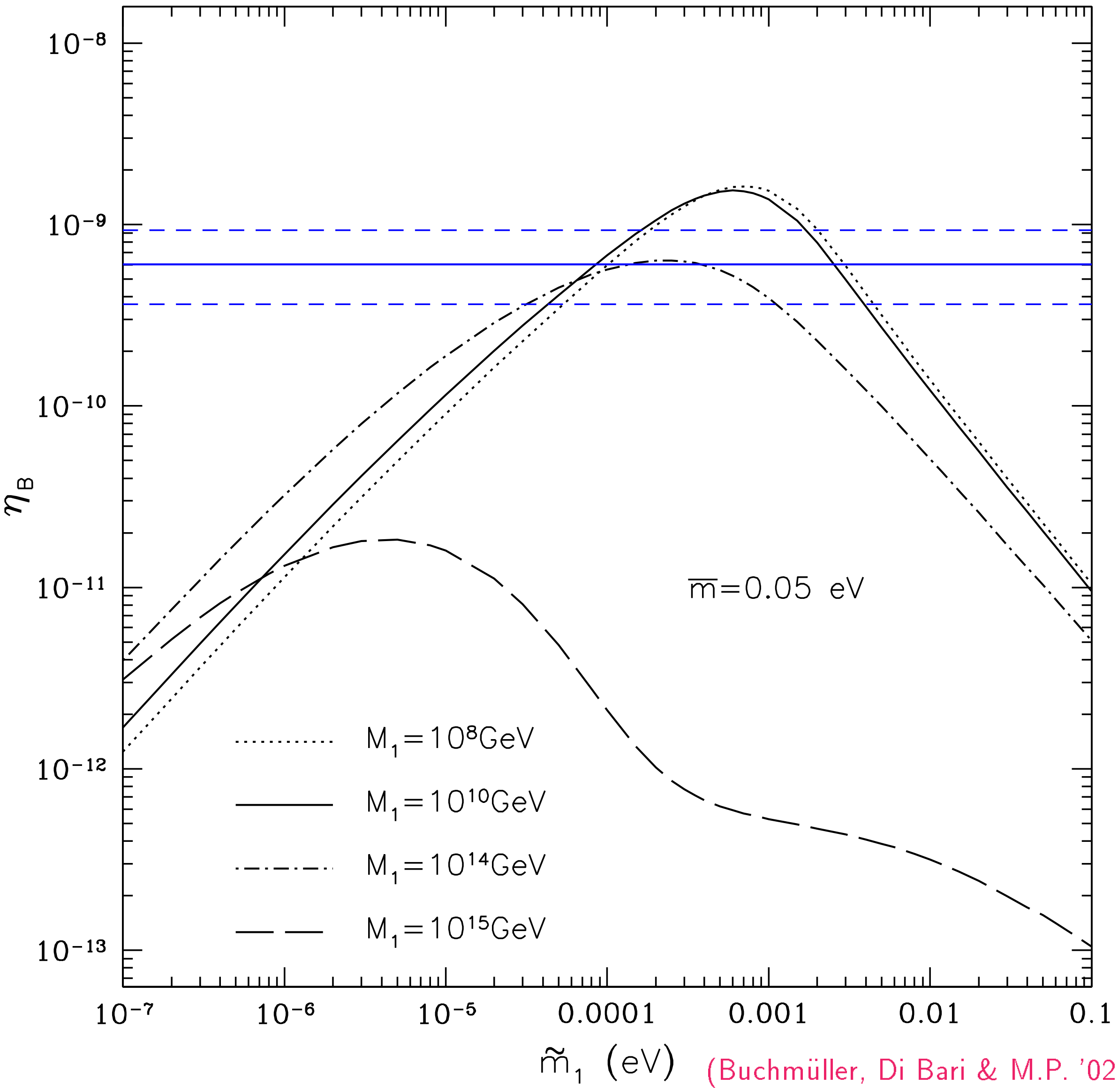
$\rightarrow$ Network of Boltzmann equations

η_B as a function of $\widetilde{m}_1$ (M.P. '96)

for hierarchical light neutrinos: $\overline{m} = 0.05\,\mathrm{eV}$

naive expectation:

$\varepsilon_1 = 10^{-6} \;\rightarrow\; \eta_B^{\max} \sim 10^{-2}\varepsilon_1 = 10^{-8}$



(Buchmüller, Di Bari & M.P. '02)

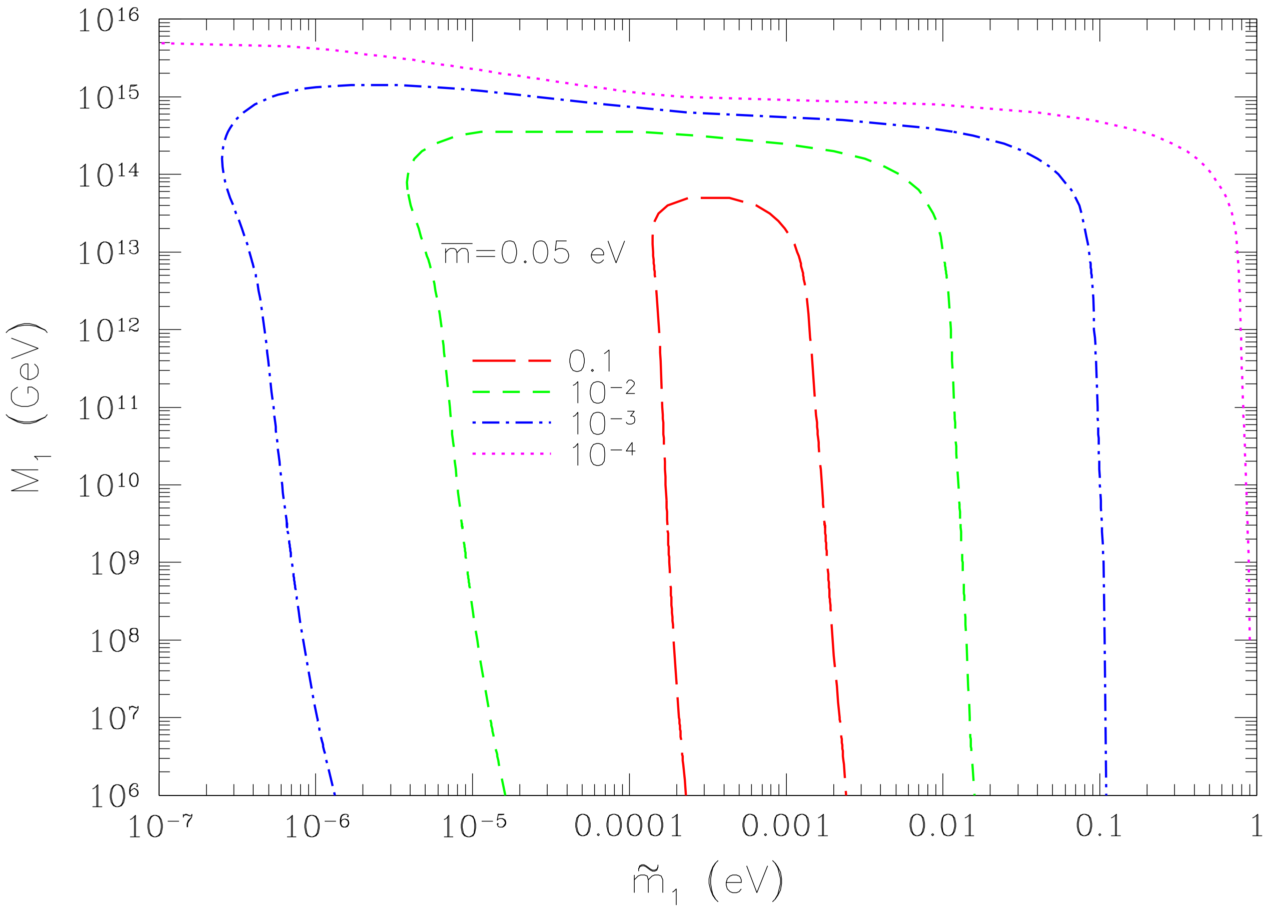
Baryogenesis is possible if

$$10^{-4}\ \mathrm{eV} \lesssim \widetilde{m}_1 \lesssim 10^{-2}\ \mathrm{eV}$$

Effect of scatterings can be parametrized by an efficiency factor: κ

(Barbieri et al. '00; Buchmüller, Di Bari & M.P. '02)

$$\eta_B = 10^{-2}\, \varepsilon_1\, \kappa$$



effective light neutrino mass: $\widetilde{m}_1 = v^2 \frac{\left(h_\nu^\dagger h_\nu\right)_{11}}{M_1}$

preferred mass range for leptogenesis:

$$10^{-4}\,\mathrm{eV} \lesssim \widetilde{m}_1 \lesssim 10^{-2}\,\mathrm{eV}$$

CP asymmetry for $M_{2,3} \gg M_1$:

$$\varepsilon_1 \simeq -\frac{3}{16\pi} \sum_i \frac{\mathrm{Im}\left[(h_\nu^\dagger h_\nu)_{i1}^2\right]}{(h_\nu^\dagger h_\nu)_{11}} \frac{M_1}{M_i}$$

→ upper bound on the CP asymmetry in terms of light neutrino masses:

(Davidson & Ibarra '02, Buchmüller, Di Bari & M.P. '03)

$$\varepsilon_1^{\max} = \frac{3}{16\pi} \frac{M_1 m_3}{v^2} \left(1 - \frac{m_1}{m_3} \sqrt{1 + \frac{m_3^2 - m_1^2}{\widetilde{m}_1^2}} \right)$$

effective light neutrino mass

$$\widetilde{m}_1 = v^2 \frac{(h_\nu^\dagger h_\nu)_{11}}{M_1} \quad \Rightarrow \quad m_1 \leq \widetilde{m}_1 \lesssim m_3$$

hierarchical neutrinos:

$$m_3 \gg m_1 \to 0 \quad \Rightarrow \quad \varepsilon_1^{\max} = \frac{3}{16\pi} \frac{M_1 m_3}{v^2}$$

degenerate neutrinos:

$$m_3 = m_1 \quad \Rightarrow \quad \varepsilon_1^{\max} = 0$$

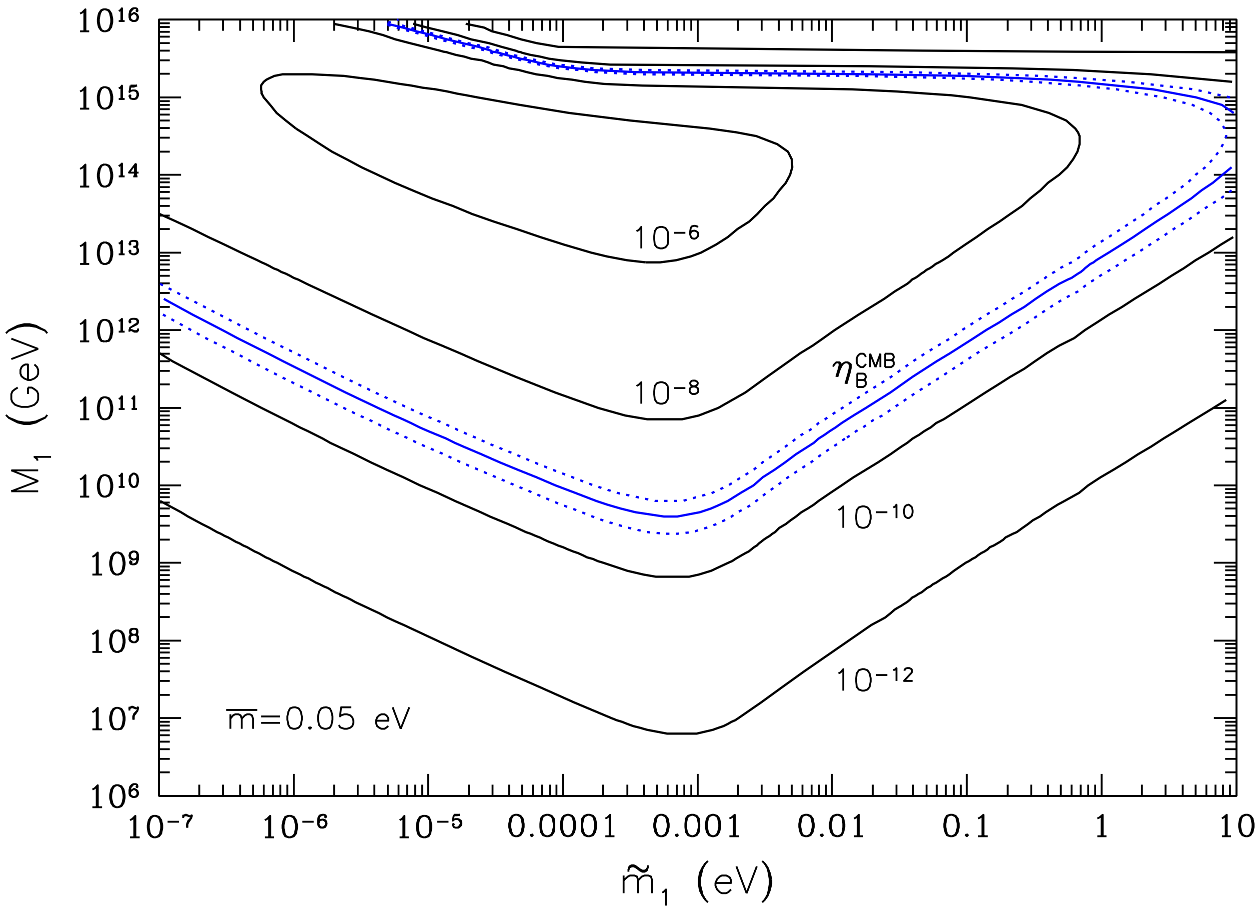
→ CP asymmetry suppressed if light ν spectrum quasi degenerate

Maximal baryon asymmetry:

Davidson & Ibarra '02; Buchmüller, Di Bari & M.P. '03

$$|\varepsilon_1| \leq \frac{3}{16\pi}\frac{M_1(\Delta m^2_{atm})^{1/2}}{v^2}$$

$$\Rightarrow \quad \eta_B^{\max} = 10^{-2}\,\frac{3}{16\pi}\frac{M_1(\Delta m^2_{atm})^{1/2}}{v^2}\,\kappa$$



lower bound on the baryogenesis temperature:

$$T_B \sim M_1 \gtrsim 10^9\ \mathrm{GeV}$$

Leptogenesis and light ν's

Neutrino Yukawa couplings:

$$\mathcal{L}_Y = \bar{l} H^\dagger \, h_\nu \, N - \frac{1}{2} \overline{N} \, M \, N$$

in basis where M is diagonal

light ν masses

$$m_\nu = -m_D \frac{1}{M} m_D^T \quad \Rightarrow \quad m_\nu^{\rm diag} = U_\nu^\dagger m_\nu U_\nu^*$$

go to basis where M and m_ν are diagonal

$$h_\nu \to \tilde{h}_\nu = U_\nu^\dagger h_\nu$$

Leptogenesis depends only on

$$\tilde{h}_\nu^\dagger \tilde{h}_\nu = h_\nu^\dagger h_\nu$$

Leptogenesis not related to mixings and CP violation in light neutrinos!

Constraints on Neutrino Parameters

N_1 production processes $\propto \widetilde{m}_1$
$\Rightarrow$ lower limit on $\widetilde{m}_1$

Washout processes:
resonance contribution from $N_1 \quad \propto \widetilde{m}_1$
$\Rightarrow$ upper limit on $\widetilde{m}_1$
non-res. contrib. from N_i , $i = 1, 2, 3 \quad \propto M_1 \overline{m}^2$
$\Rightarrow$ upper limit on M_1 for fixed $\overline{m}$

maximal CP asymmetry $\propto M_1$
$\Rightarrow$ lower limit on M_1

for fixed $\overline{m}$ $\Rightarrow$ allowed region in $(\widetilde{m}_1, M_1)$ plane
size of allowed region depends on $\overline{m}$

maximal CP asymmetry $\propto \left(1 - \frac{m_1}{m_3}\sqrt{1 + \frac{m_3^2 - m_1^2}{\widetilde{m}_1^2}}\right)$
suppressed for quasi-degenerate neutrinos

$\Rightarrow$ upper limit on $\overline{m}$

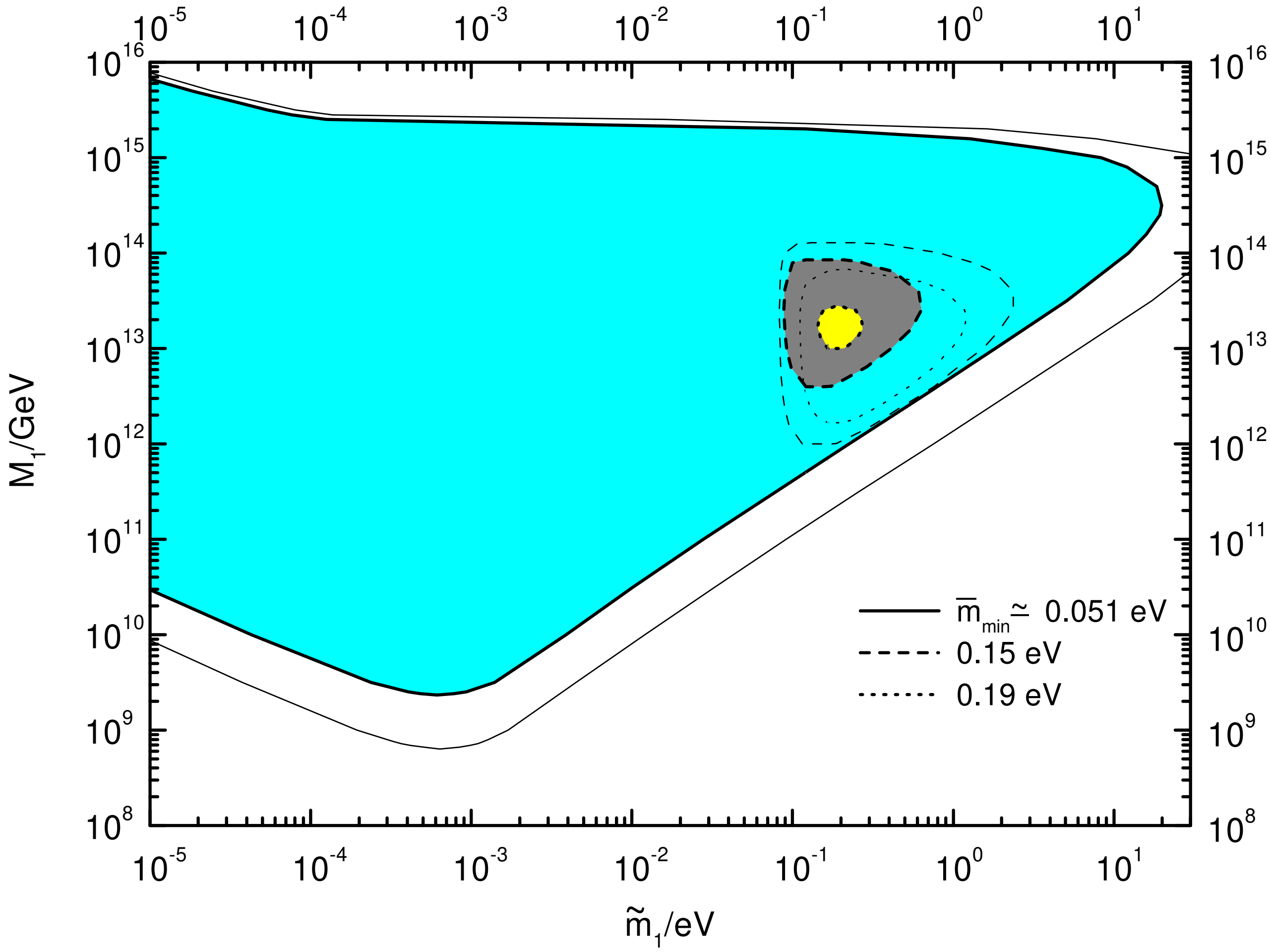
upper limit on $\overline{m}$:

$$\overline{m}^2 = \sum_{i=1,2,3} m_{\nu_i}^2$$

$\Rightarrow$ upper bound on light neutrino masses

normal hierarchy:

Buchmüller, Di Bari & M.P. '03

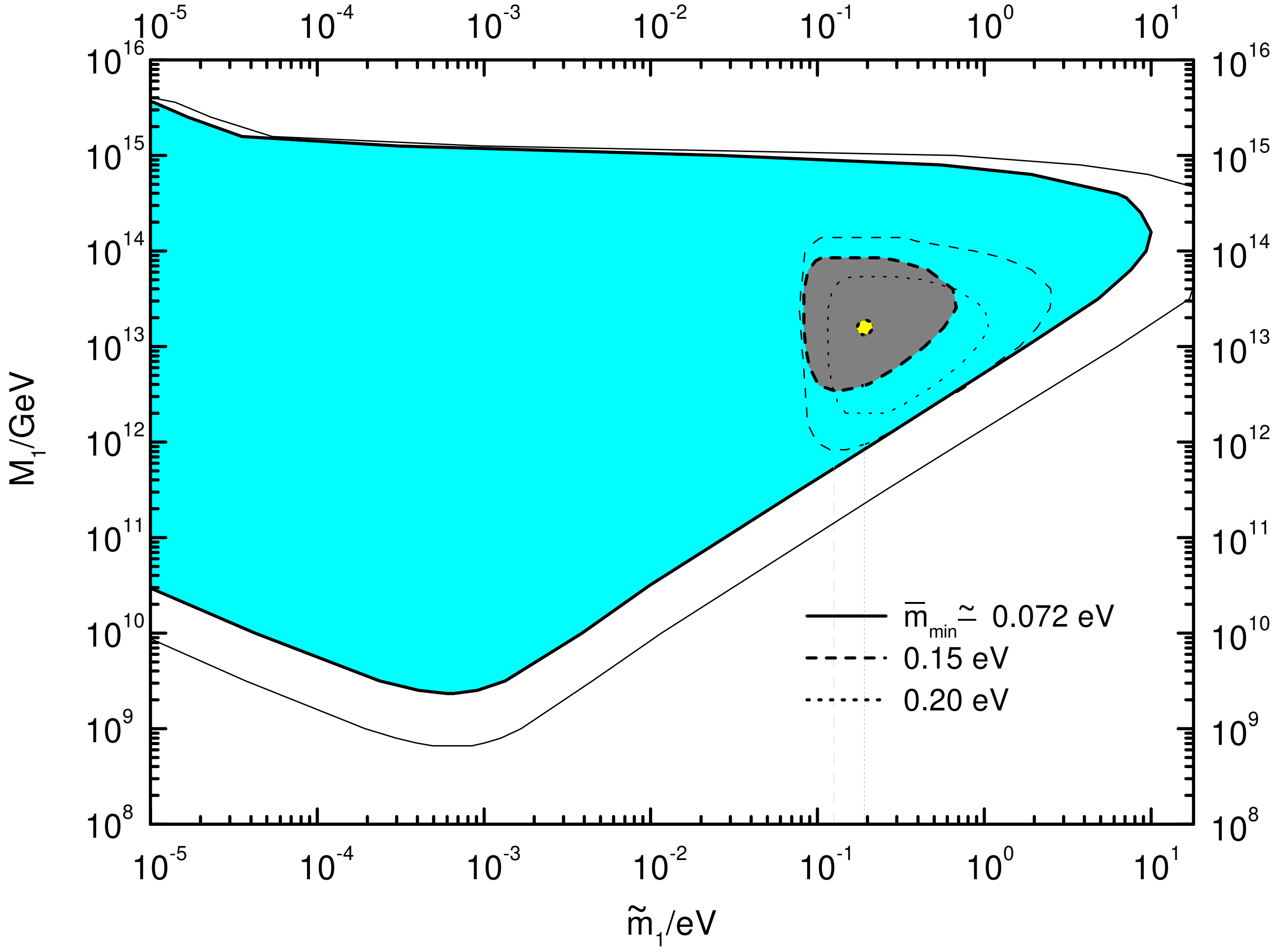


$$\Rightarrow \qquad \overline{m} < 0.20\,\mathrm{eV}$$

$$\Rightarrow \qquad m_1, m_2 < 0.11\,\mathrm{eV}\ , \quad m_3 < 0.12\,\mathrm{eV}$$

$$\mathrm{WMAP} + \mathrm{2dFGRS}: \quad m_i < 0.23\,\mathrm{eV}$$

inverted hierarchy:

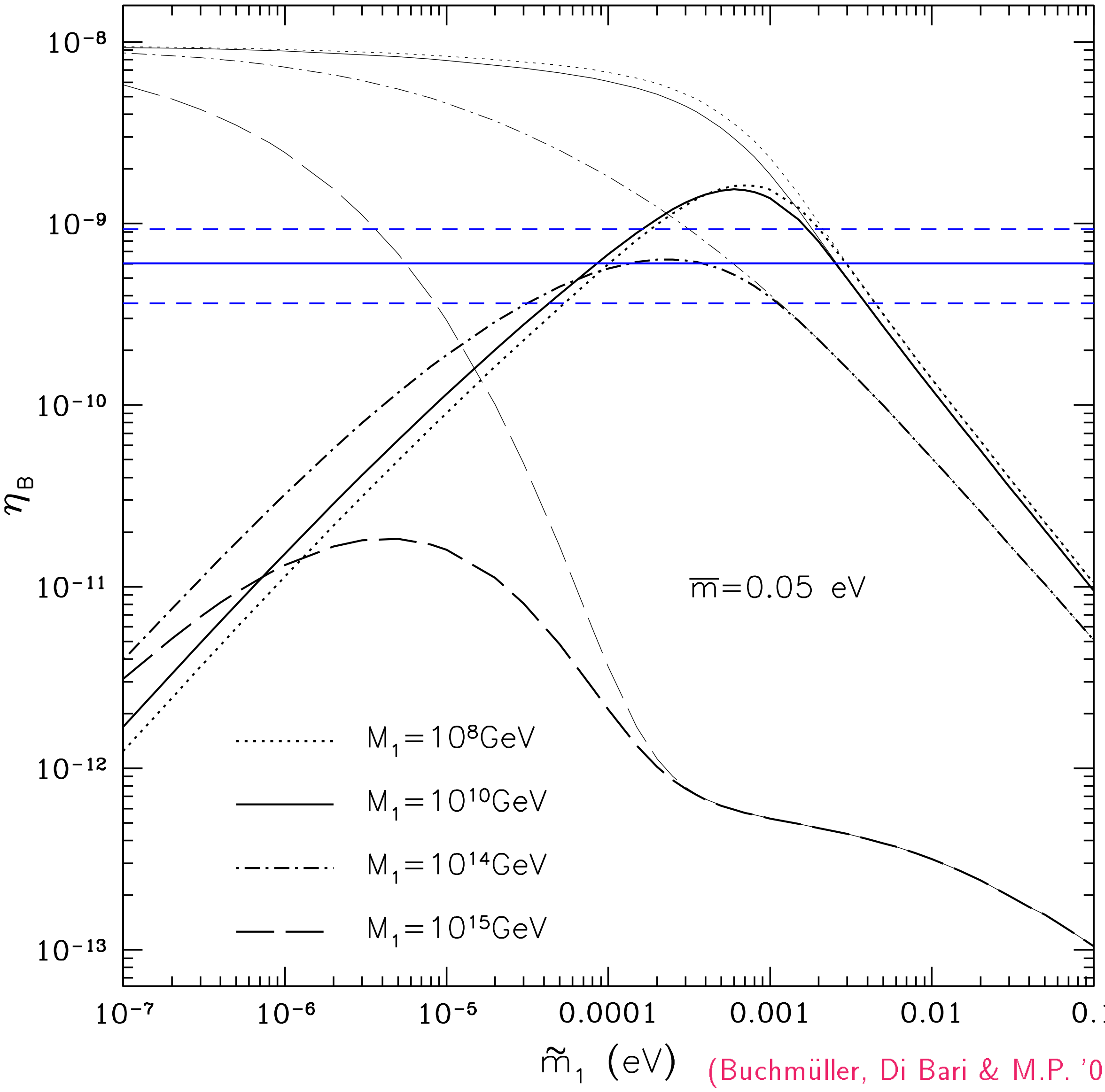


$$\Rightarrow \qquad \overline{m} < 0.21\,\mathrm{eV}$$

$$\Rightarrow \qquad m_1, m_2 < 0.11\,\mathrm{eV}\ , \quad m_3 < 0.12\,\mathrm{eV}$$

Initial conditions?

η_B as a function of $\widetilde{m}_1$ for $\overline{m} = 0.05$ eV



(Buchmüller, Di Bari & M.P. '02)

initial conditions:

$N_{N_1} = N_{N_1}^{eq}$ at $T \gg M_1$ (thin lines)

$N_{N_1} = 0$ at $T \gg M_1$ (thick lines)

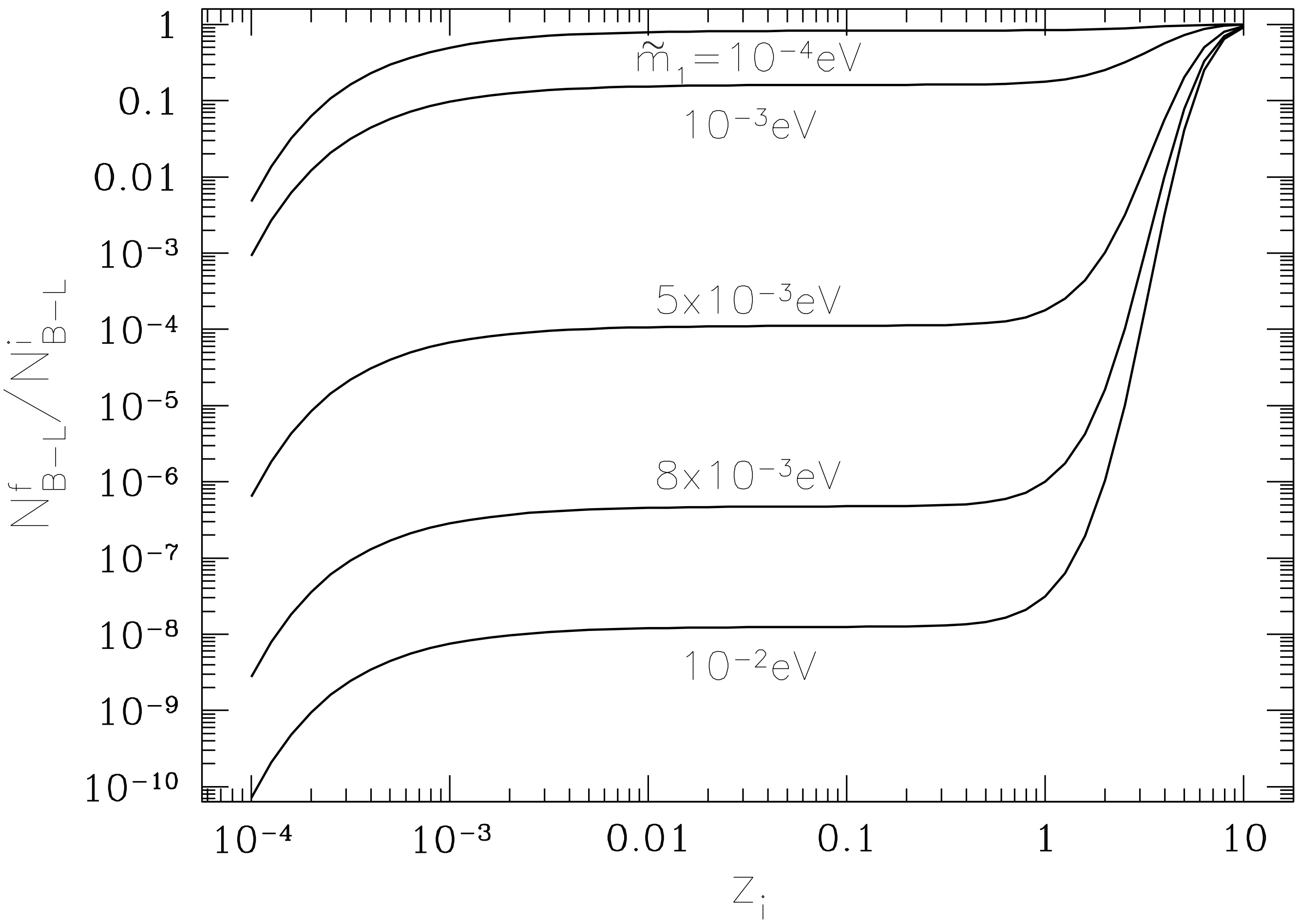
$\Rightarrow$ no dependence on initial conditions for

$$\widetilde{m}_1 \gtrsim 10^{-3}\,\text{eV}$$

Initial conditions?

assume: initial asymmetry
effect of washout?

example: ratio of final (after washout) to initial asymmetry for $\overline{m} = 0.05\,\text{eV}$, $M_1 = 10^{10}\,\text{GeV}$



very efficient washout of initial asymmetry at $z_i \sim 1$ for $\widetilde{m}_1 \gtrsim 10^{-3}\,\text{eV}$

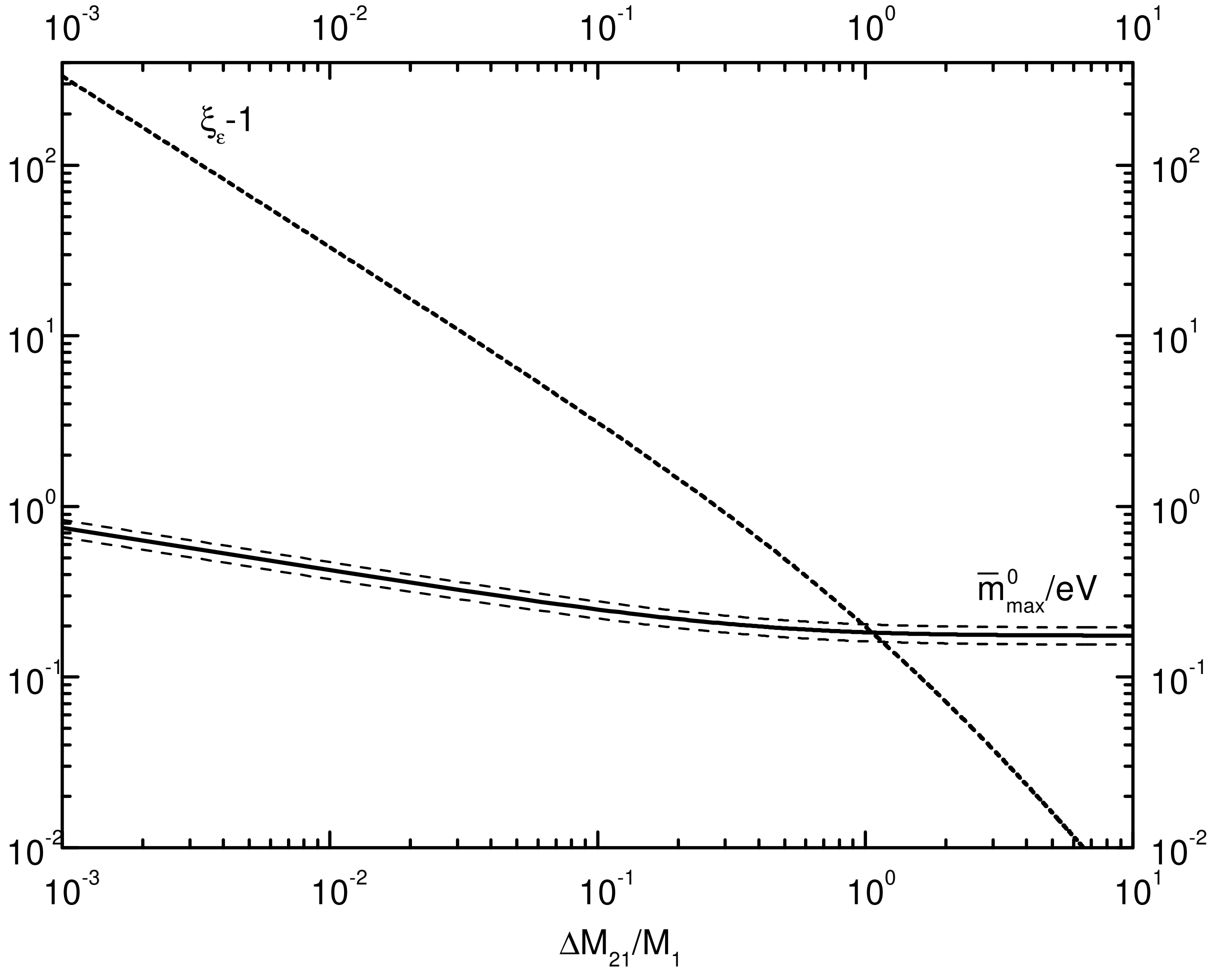
$\Rightarrow$ no dependence on initial conditions for
$$\widetilde{m}_1 \gtrsim 5 \times 10^{-3}\,\text{eV}$$

Loopholes?

Quasi-degenerate heavy neutrinos?
if $\Delta M_{21} = M_2 - M_1 \lesssim M_1$ maximal CP asymmetry is enhanced by a factor

$$\xi(x) = \frac{2}{3}x\left[(1+x)\ln\left(\frac{1+x}{x}\right) - \frac{2-x}{1-x}\right] \;, x = \frac{M_2^2}{M_1^2}$$

note: $\xi(x) \to 1$ for $x \gg 1$



However: $\overline{m}_{\max} \propto \xi^{1/4}$

$$\Rightarrow \text{for } \frac{\Delta M_{21}}{M_1} \sim 10^{-3}\,, \quad \xi^{1/4} \sim 4$$

Summary

- Type I seesaw naturally explains the cosmological baryon asymmetry
- L violating scatterings are of crucial importance
- Cosmological baryon asymmetry is related to light neutrino properties
- Quasi-degenerate light neutrino masses are incompatible with leptogenesis:

$$m_i < 0.12 \text{ eV}$$

- lower bound on the baryogenesis temperature:

$$T_B \sim M_1 \gtrsim 4 \times 10^8 \text{ GeV}$$