Baryogenesis and Leptogenesis

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Outline

- Introduction
- Baryon and Lepton Number Violation in the SM
- Electroweak Baryogenesis
- Affleck-Dine Baryogenesis
- Leptogenesis
- Summary

Baryogenesis

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

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

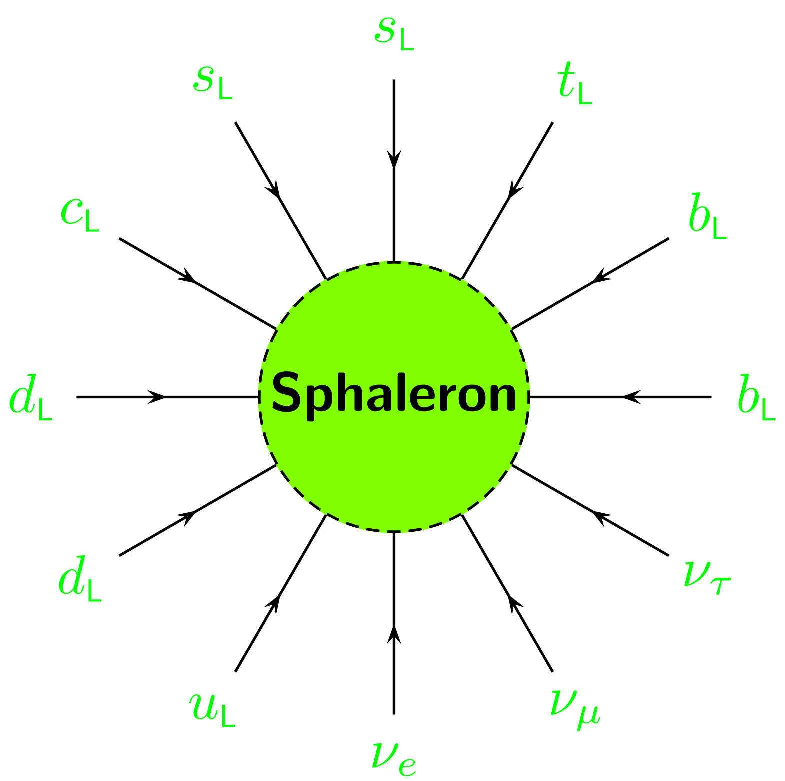
η_B must have been dynamically generated:

Necessary ingredients (Sakharov, 1967):

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

Baryon and lepton number violation

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



Transition rate

$$T = 0 : \qquad e^{-4\pi/\alpha_w} \sim 10^{-170}$$

$$T_c > T > 0 : \qquad e^{-E_{sph}/T} \quad \text{with} \quad E_{sph} \sim \frac{8\pi v(T)}{g}$$

$$T > T_c : \qquad \alpha_w^5 T^4$$

Bödeker '98

in thermal equilibrium at $T \gtrsim 100$ GeV

Kuzmin, Rubakov & Shaposhnikov '85

Electroweak Baryogenesis

Electroweak phase transition

for $T > T_c \sim 100$ GeV the Higgs VEV "evaporates" and the EW symmetry is "restored".

1st order phase transition $\longrightarrow$ deviation from thermal equilibrium

$\Rightarrow$ generate η_B if sphalerons are strongly suppressed in the broken phase

$$\frac{\Delta v(T_c)}{T} \geq 1 \quad \Rightarrow \quad m_H \leq 40\,\mathrm{GeV}$$

Baryogenesis is not possible in the SM!

Also: not enough CP violation in the SM.

What is needed:

- new bosons to strengthen the phase transition
- new sources of CP violation

MSSM?

Huet & Nelson; Carena et al.; Cline et al.; and many others

Maybe, but:

Derivation of the source term controversial
Most optimistic case:

- $m_h \lesssim 117\,\mathrm{GeV}$ and $m_{\tilde{t}} < m_t$ (Tevatron!)
- $A_t \gtrsim 0.2 m_Q$
- chargino masses small ~ 100 GeV
- $arg(M_i \mu)$ large
- $\tan\beta > 5$
- all other squarks and sleptons heavy, $m \gtrsim 2\,\mathrm{TeV}$

NMSSM?

Davies et al. '96; Huber & Schmidt '00

- need fundamental μ term

Electroweak baryogenesis at preheating?

might work, if $T_R < 100$ GeV

Affleck-Dine Baryogenesis

Basic idea: Affleck & Dine '84

During inflation a condensate carrying baryon and/or lepton number forms along flat direction of effective potential

condensate is static until late times $H \sim m_{3/2}$

SUSY breaking lifts flat direction $\longrightarrow$ condensate decays $\longrightarrow$ B and L transferred to matter particles

Potential problem: Allahverdi et al. '00

thermal plasma coupled to flat directions

$\longrightarrow$ induces effective SUSY breaking terms

$\longrightarrow$ lifts flat directions

$\longrightarrow$ condensate decays much earlier

$\longrightarrow$ substantially reduced B asymmetry

Alternative: Kusenko et al.; Enqvist et al.

condensate fragments into long-lived baryonic Q-balls decay into matter fields at late times

Baryogenesis before EW phase transition?

Sphalerons $\Rightarrow$ breaking of $B-L$ needed

not possible in SM and $SU(5)$!

Possible low energy operator that breaks $B-L$:

$$\frac{1}{M}(l_L H)(l_L H)$$

What is the scale M ?

Neutrino masses

$B-L$ violation predicts non vanishing ν masses

after SM symmetry breaking:

$$\langle H \rangle = v \qquad \Rightarrow \qquad m_\nu \sim \frac{v^2}{M}$$

$$m_\nu \sim 0.05\,\mathrm{eV} \qquad \Rightarrow \qquad M \sim 10^{14}\,\mathrm{GeV}$$

$\rightarrow$ GUT scale

Origin of $B-L$ violating operator?

heavy right-handed neutrinos!

Leptogenesis

Right-handed neutrinos naturally explain the smallness of light neutrino masses

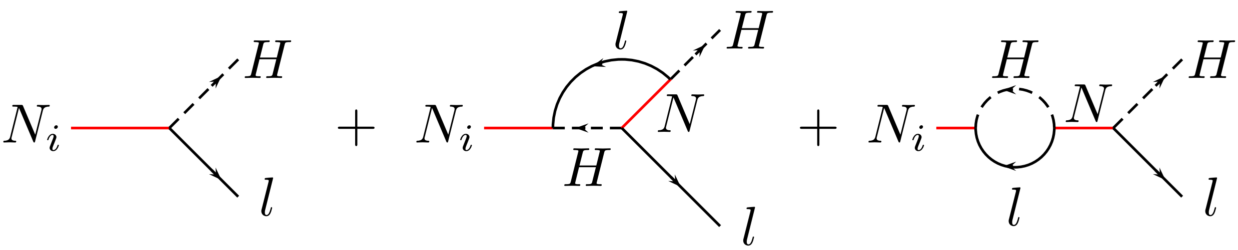
Right-handed neutrinos can also be the origin of the cosmological baryon asymmetry:
(Fukugita and Yanagida '86)

Yukawa couplings:

$$\mathcal{L}_Y = \overline{l_{\mathsf{L}}}\, H\, \lambda_l^*\, e_{\mathsf{R}} + \overline{l_{\mathsf{L}}} \epsilon H^\dagger\, \lambda_\nu^*\, \nu_{\mathsf{R}} - \frac{1}{2}\, \overline{\nu_{\mathsf{R}}^c}\, M\, \nu_{\mathsf{R}} + \text{ h.c.}$$

- $M \neq 0 \Rightarrow N$'s are unstable
- λ_ν complex $\Rightarrow CP$ violation

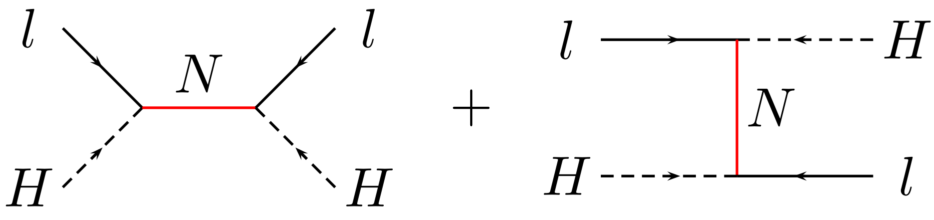
Generation of a lepton asymmetry



Connection between the properties of light neutrinos and the cosmological baryon asymmetry?

Potential problems

1. Washout due to Neutrino mediated L violating scatterings (Fukugita & Yanagida '90)



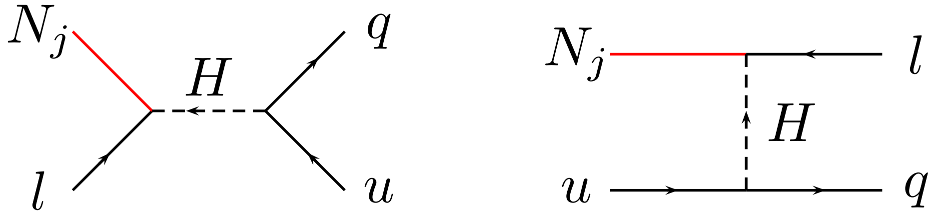
Reaction rate:

$$\Gamma_{\Delta L=2}(T) = \frac{1}{\pi^3}\frac{T^3}{v^4}\sum_{i=e,\mu,\tau} m_{\nu_i}^2$$

$\Rightarrow$ upper bound on light neutrino masses

2. How do the N_i get produced?

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



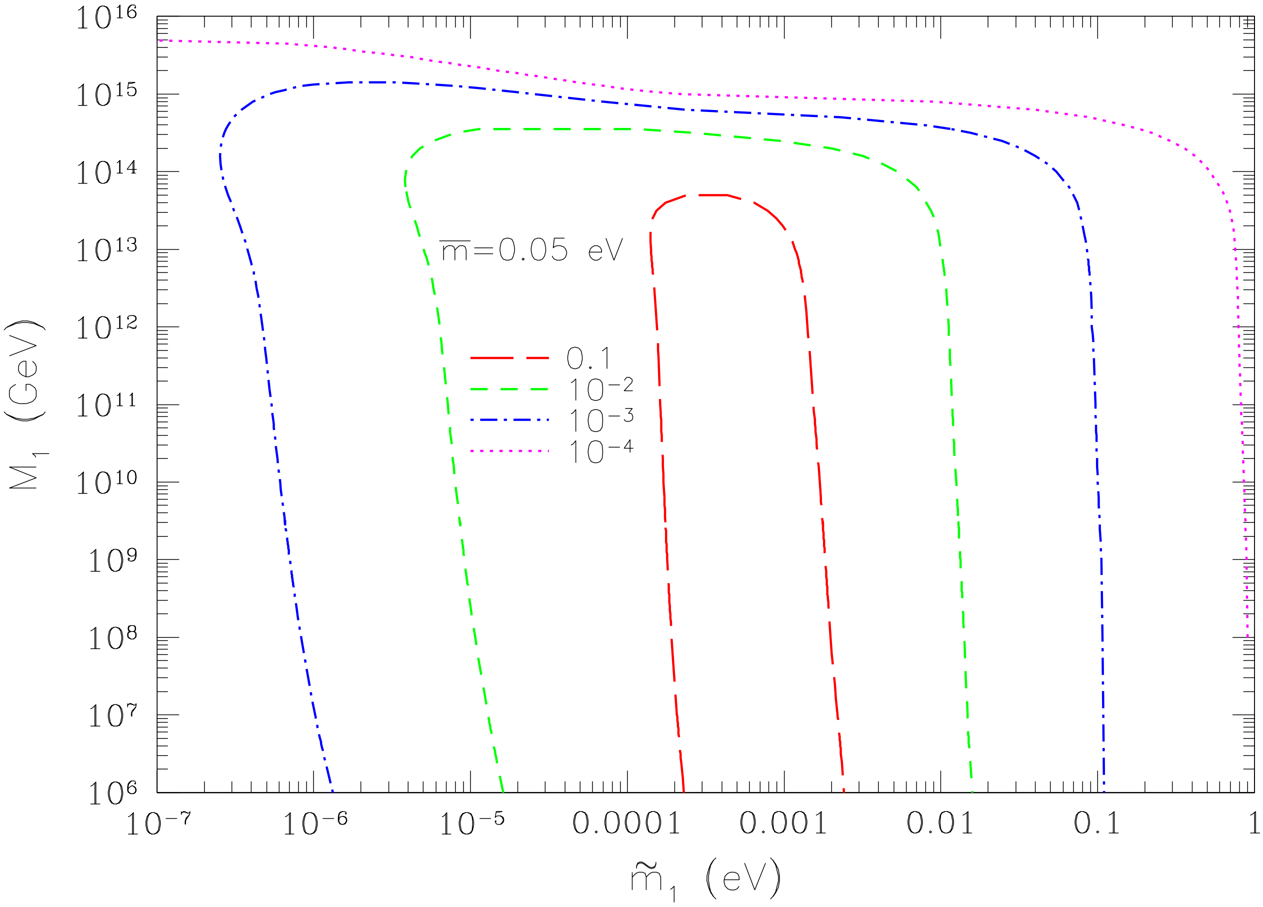
$\longrightarrow$ in a consistent analysis all lepton number violating and conserving processes have to be taken into account

$\longrightarrow$ Network of Boltzmann equations

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: $\widetilde{m}_1 = v^2 \frac{(\lambda^\dagger\lambda)_{11}}{M_1}$

preferred mass range for leptogenesis:

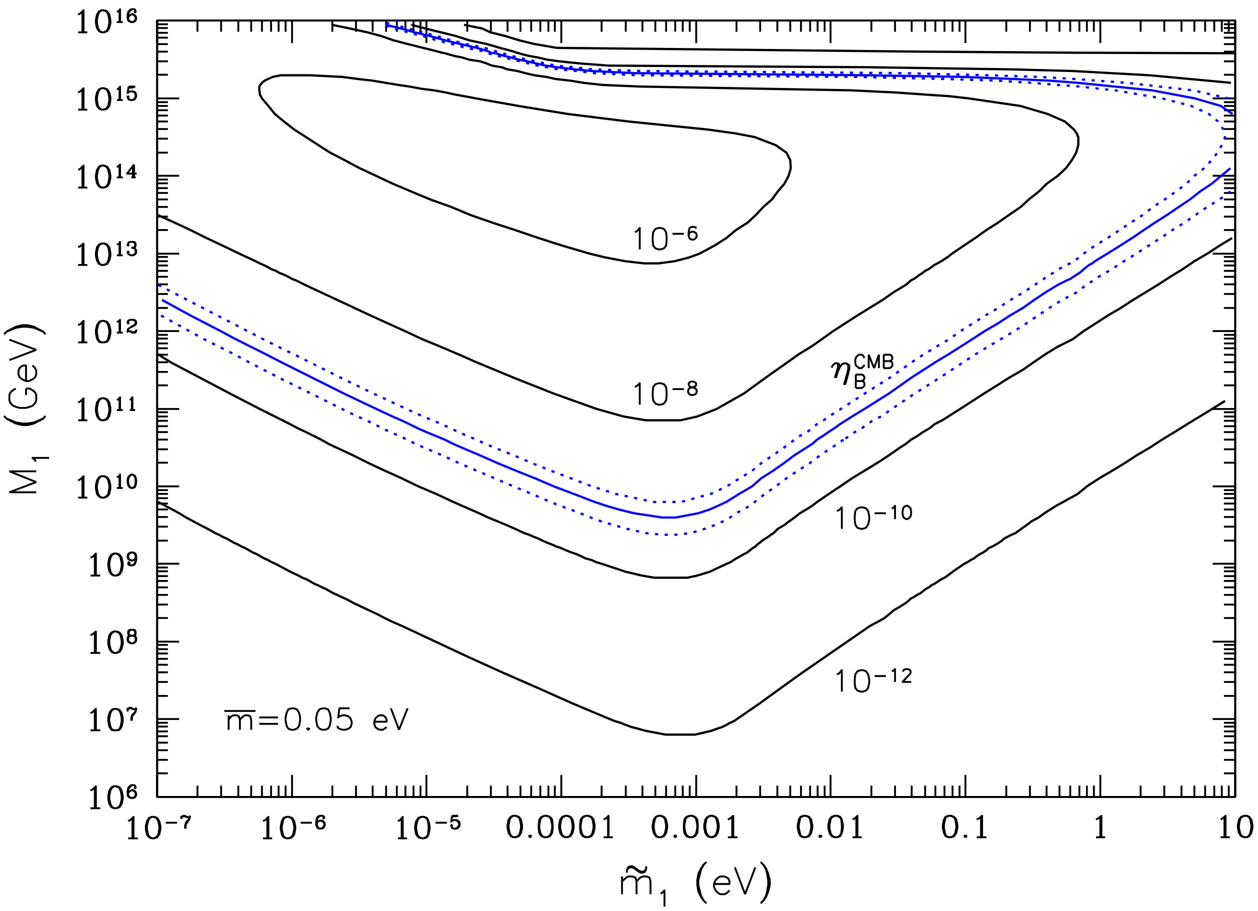
$$10^{-4}\,\mathrm{eV} \lesssim \widetilde{m}_1 \lesssim 10^{-2}\,\mathrm{eV}$$

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:

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

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 $\overline{m}$, M_1

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 $\overline{m}$

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

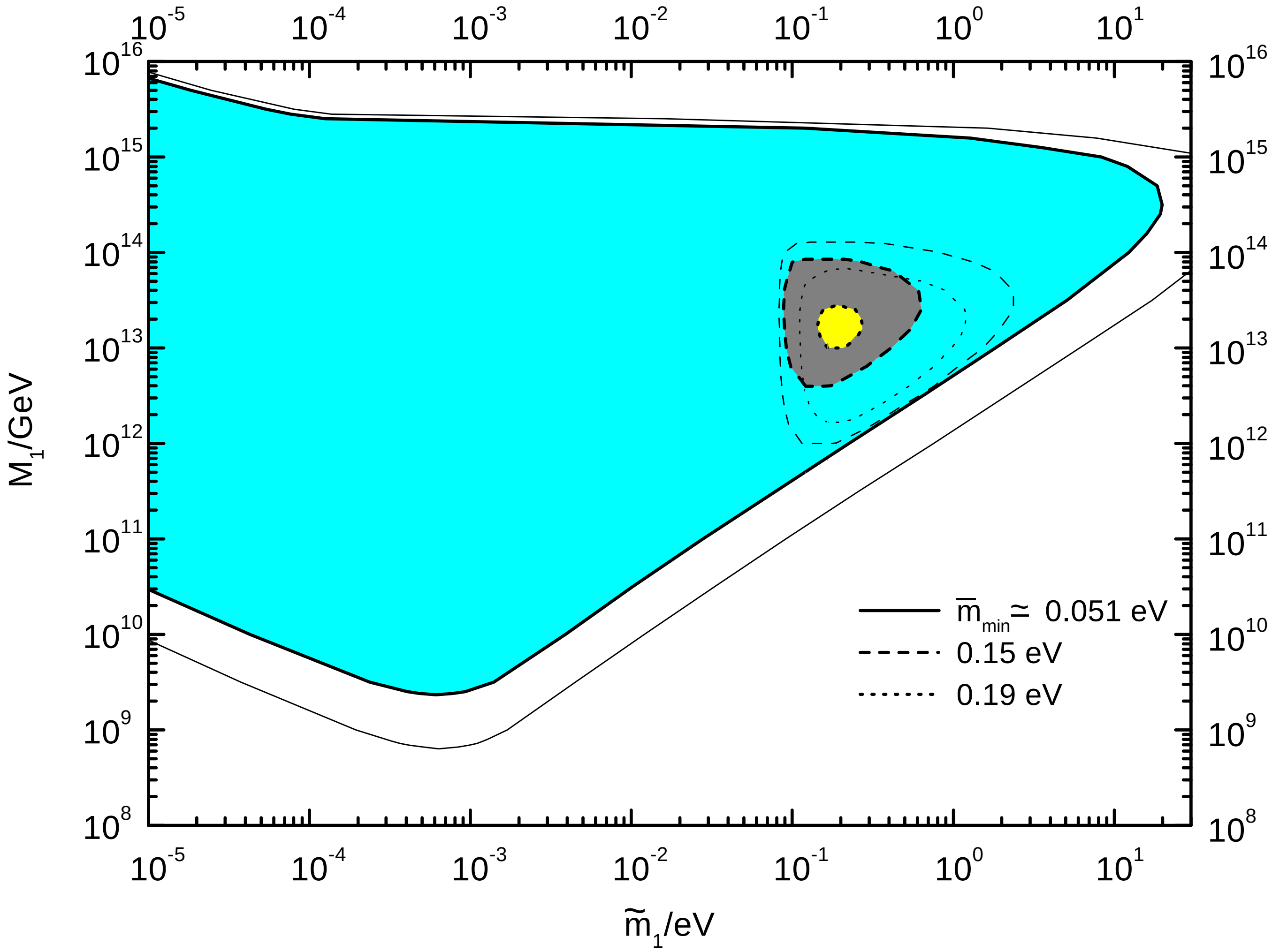
$\Delta L = 2$ scatterings at low temperature:

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

$\Rightarrow$ upper bound on light neutrino masses

normal hierarchy:

Buchmüller, Di Bari & M.P. '03

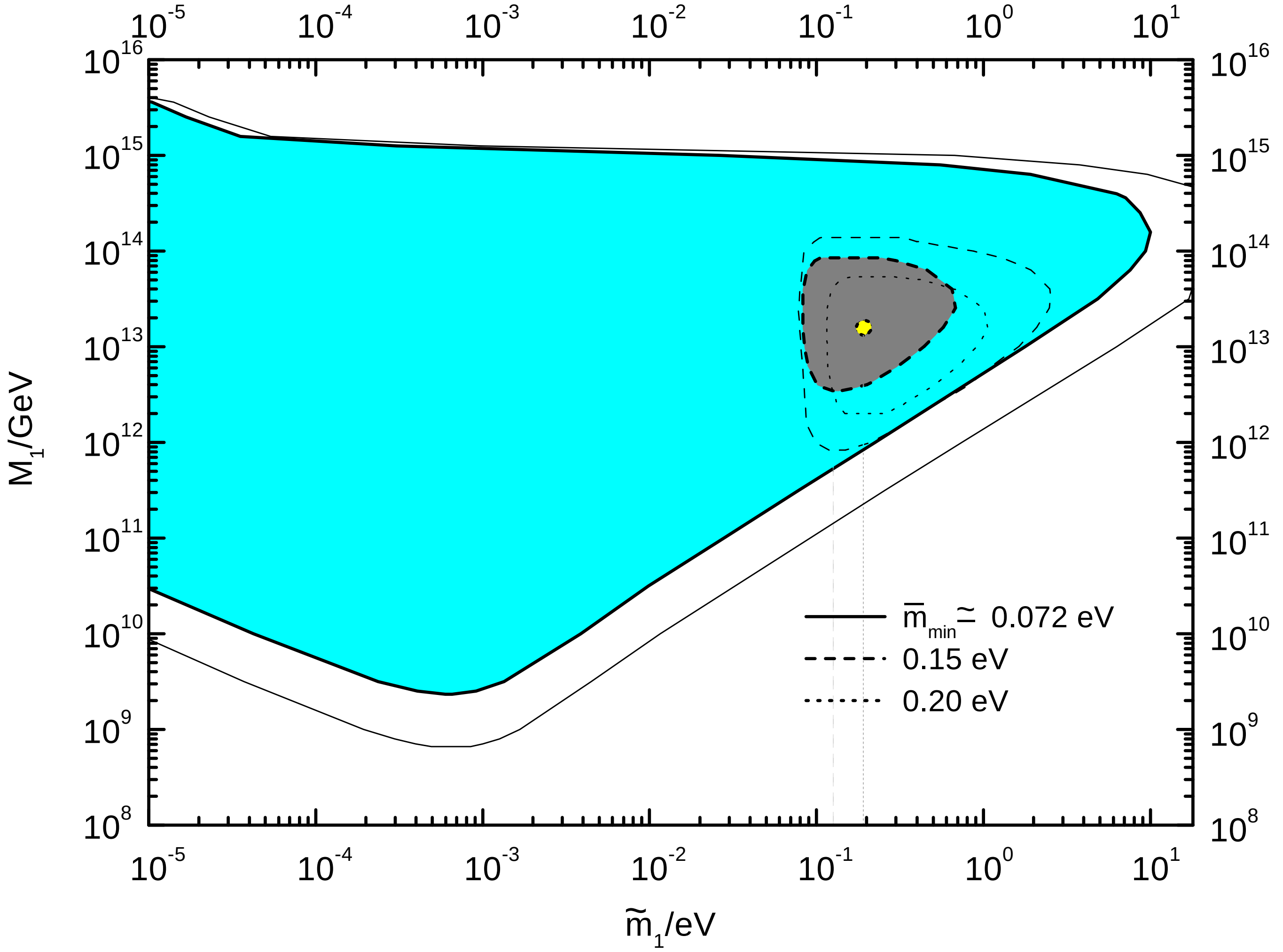


$$\Rightarrow \qquad \overline{m} < 0.20\,\mathrm{eV}$$

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

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

inverted hierarchy:



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

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

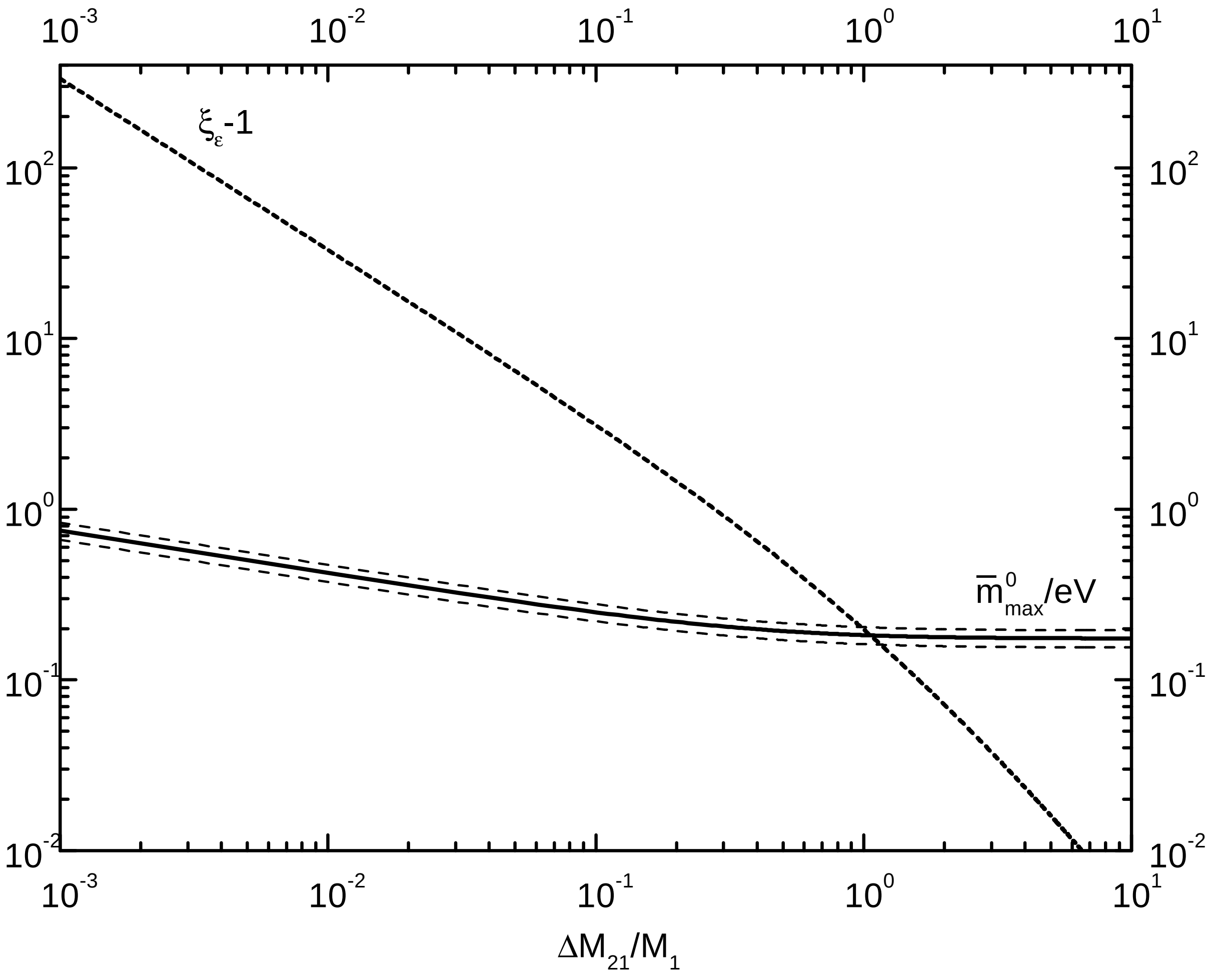
Loop holes?

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 $x \gg 1$



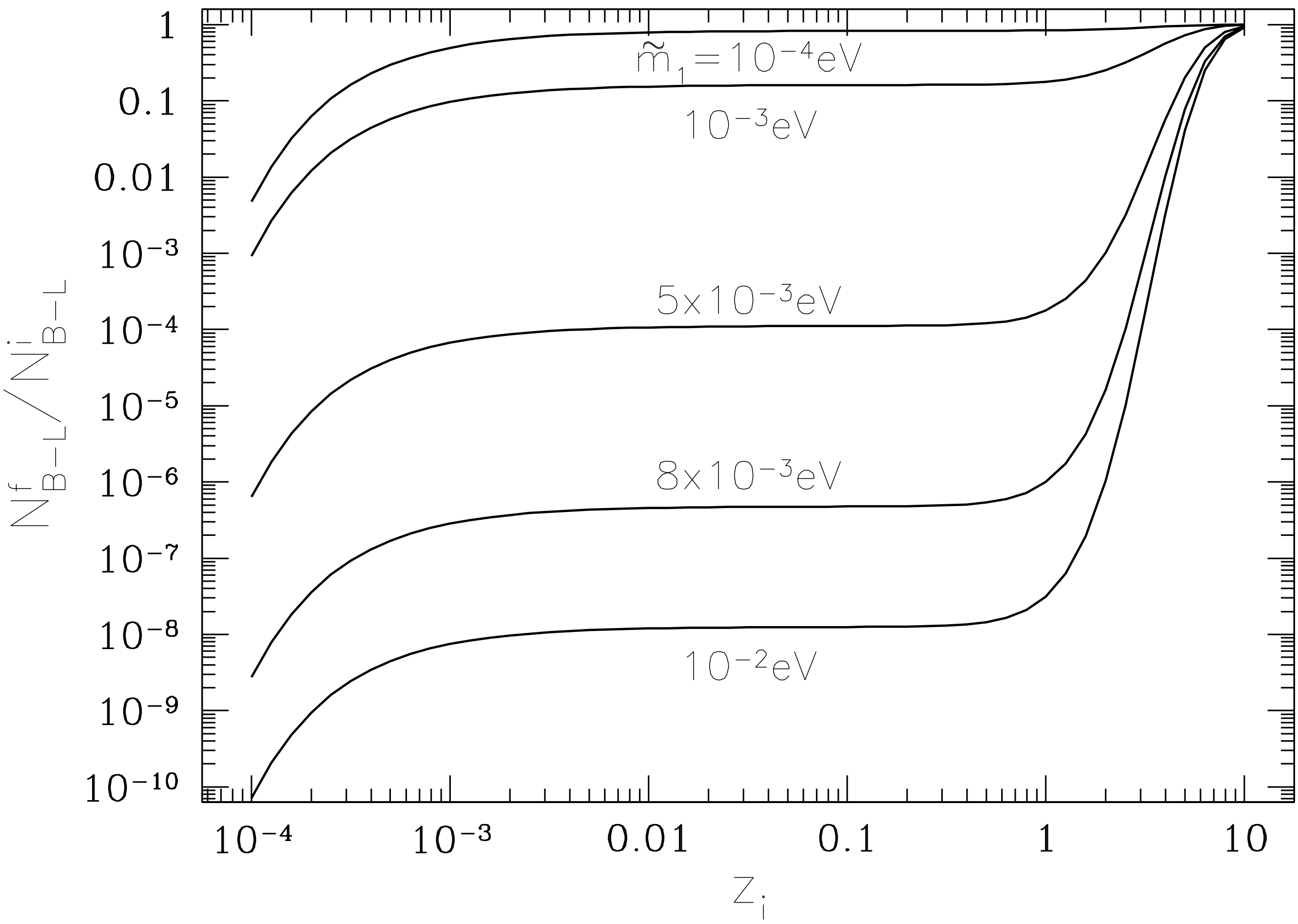
However: $\overline{m}_{\max} \propto \xi^{1/4}$

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

Initial conditions?

assume: initial asymmetry
effect of washout?

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



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

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

Summary

Baryogenesis requires physics beyond the SM

many different explanations have been proposed

natural scenario: Leptogenesis

- Quasi-degenerate light neutrino masses are incompatible with leptogenesis:

$$m_i \lesssim 0.1\ \mathrm{eV}$$

- lower bound on the baryogenesis temperature:

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

The theory of the baryon asymmetry will yield new information about physics beyond the standard model