Baryon asymmetry from leptogenesis

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Third priority question

- Dark Energy -- 74%
- Dark Matter -- 22%
- Normal Matter -- 4%
    - Only <0.1% visible

Sakharov's conditions

$$\frac{n_B}{n_\gamma} = 6.1^{+0.3}_{-0.2} \times 10^{-10}$$

- B violation
- C and CP violation
- out of equilibrium condition

Fourth condition: B-L violation

- B, L are not conserved in the SM, violated non-perturbatively by sphalerons which convert

  B ⇔ L

  with certain selection rules
- B+L anomalous, washed out by sphalerons
- B-L anomaly free, conserved by sphalerons

$$\frac{n_{\mathcal{B}}}{s} = \frac{24 + 4n_H}{66 + 13n_H} \frac{n_{\mathcal{B}-\mathcal{L}}}{s}$$

How to create the baryon asymmetry?

- GUT-s: NO, generate B+L
- EW phase transition:

  NO, requires m_H<40 GeV
- Leptogenesis: out-of-equilibrium decays of heavy neutrinos (Fukugita&Yanagida)

Related to neutrino masses via seesaw mechanism

Singlet neutrinos are Majorana particles

$N = N^c$ $\qquad$ $L = \frac{1}{2} M_N NN + L_i Y^{ij} N_j H + h.c.$

- $N \Rightarrow L\, H$
- $N \Rightarrow L^c H^\dagger$

9 param. $\qquad \mathcal{M}_\nu = Y_\nu^T (M_N)^{-1} Y_\nu v^2 \sin^2\beta \qquad$ 18 param.

$\Delta m^2_{sol} = 7\text{x}10^{-5}\ eV^2$

$\Delta m^2_{atm} = 2\text{x}10^{-3}\ eV^2$

- 1 TeV $< M_N < 10^{13}$ GeV
- requires at least 2 neutrinos N

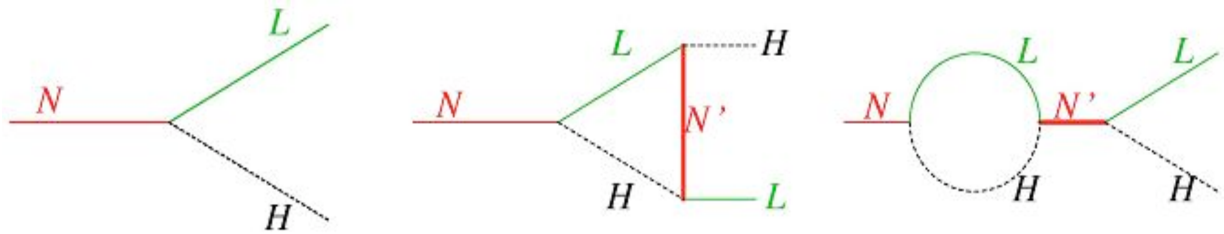
Calculating baryon asymmetry requires

$$Y_{\mathcal{B}-\mathcal{L}} = -\epsilon_{N_1}\ \eta\ Y_{N_1}^{\mathrm{eq}}(T \gg m_{N_1})$$

- CP asymmetry ε
- efficiency (washout effects) η
- initial conditions ?????

CP asymmetry in N_1 decays

- $N_1 \Rightarrow L\ H$
- $N_1 \Rightarrow L^c H^\dagger$



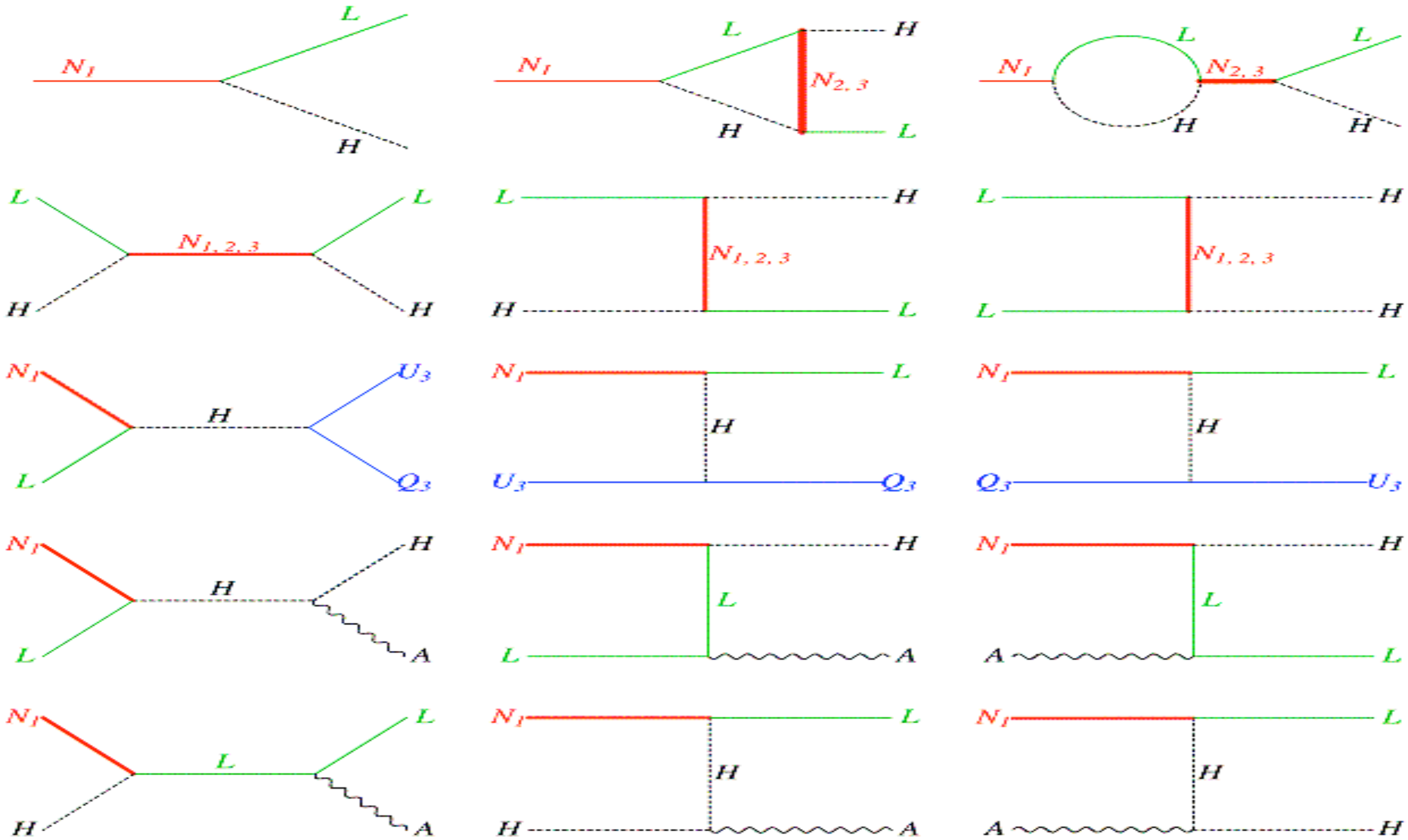
$$\epsilon_{N_1}(0) = \frac{1}{8\pi} \sum_{j \neq 1} \frac{\mathrm{Im}\left[(Y^\dagger Y)^2_{j1}\right]}{[Y^\dagger Y]_{11}} f\left(\frac{m^2_{N_j}}{m^2_{N_1}}\right)$$

$$f(x) = \sqrt{x}\left[\frac{x-2}{x-1} - (1+x)\ln\left(\frac{1+x}{x}\right)\right] \xrightarrow{x \gg 1} -\frac{3}{2\sqrt{x}}$$

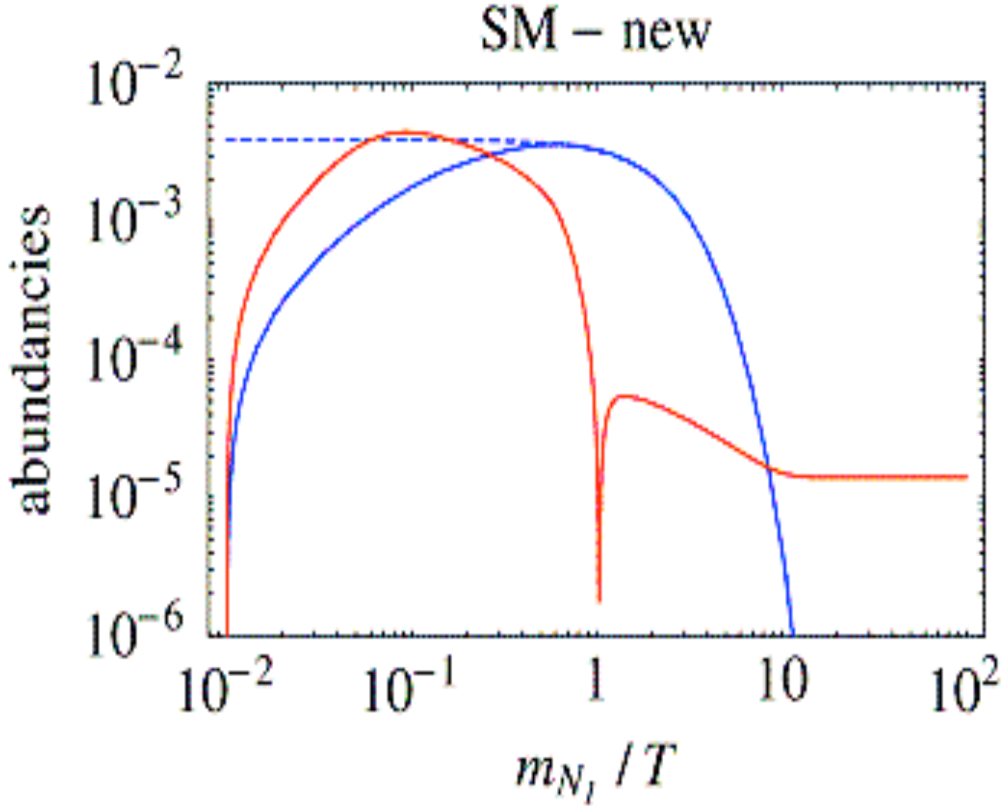
$$|\epsilon_{N_1}| \leq \frac{3}{16\pi} \frac{m_{N_1}(m_3 - m_1)}{v^2}$$

CP violation requires at least 2 generations of N

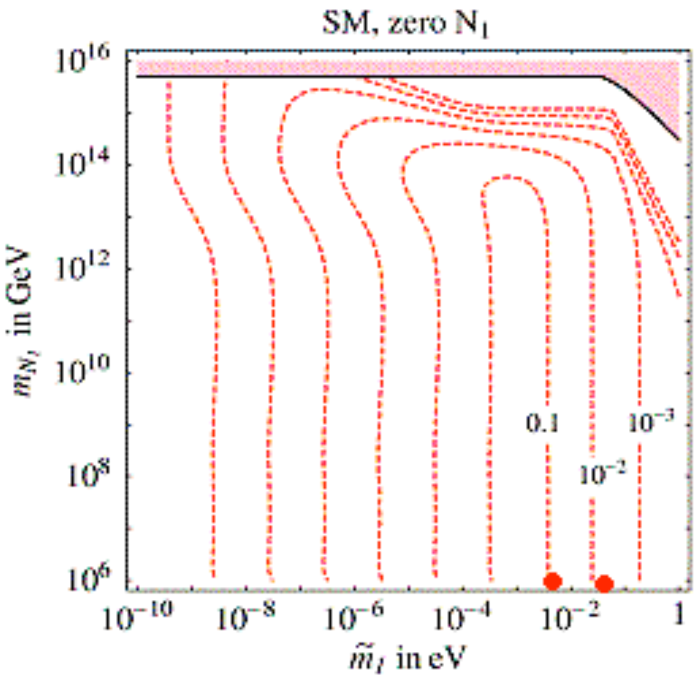
Solve Boltzmann equations to find the baryon asymmetry



Evolution of abundances for vanishing initial N abundance



Results for the efficiency



Efficiency depends on a single parameter

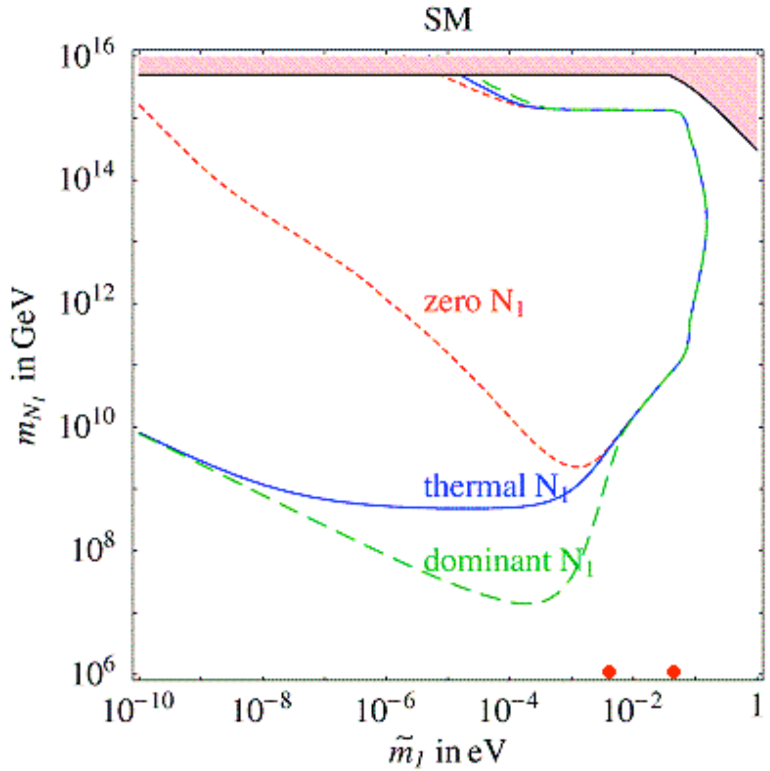
$$\tilde{m}_1 \equiv (Y_\nu Y_\nu^\dagger)_{11} v^2 / m_{N_1}$$

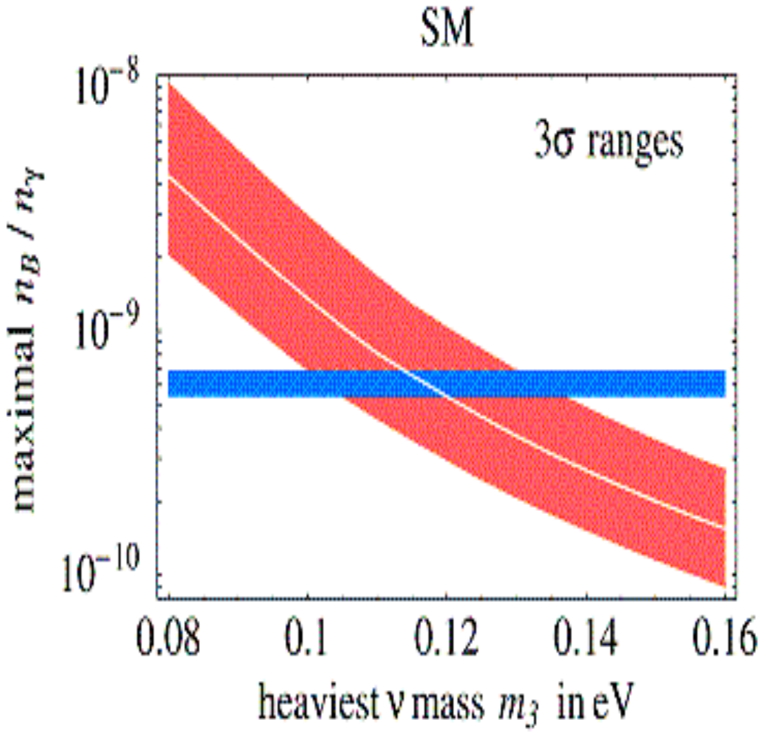
$$\Gamma_{N_1} = \frac{1}{8\pi} (Y_\nu Y_\nu^\dagger)_{11} \, m_{N_1}$$

$$\frac{1}{\eta} \approx \frac{3.3 \times 10^{-3}\,\mathrm{eV}}{\tilde{m}_1} + \left(\frac{\tilde{m}_1}{0.55 \times 10^{-3}\,\mathrm{eV}} \right)^{1.16}$$

Implications for neutrino physics

From ε_{max} and η





Alternative: Soft leptogenesis

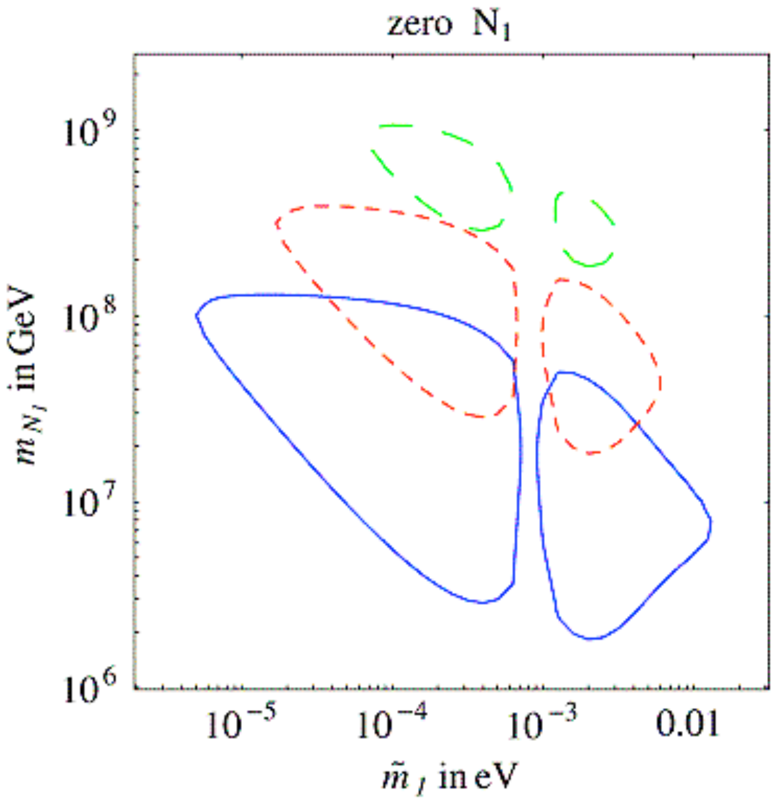
- Only one generation of N needed
- Mass splitting on sneutrinos from the soft terms

$$-\mathcal{L}_{soft} = \tilde{m}^2_{ij}\tilde{N}^\dagger_i\tilde{N}_j + \left(A_{ij}Y_{ij}\tilde{N}_i\tilde{\ell}_j H + \frac{1}{2}B_{ij}M_{ij}\tilde{N}_i\tilde{N}_j + \text{h.c.}\right)$$

- Situation exactly as in K^0 meson system
- CP violation comes from complex soft A terms

$$\epsilon_{\tilde{N}\to\tilde{L}H}(T=0) = -\epsilon_{\tilde{N}\to L\tilde{H}}(T=0) = \frac{4\Gamma_{\tilde{N}_1}B}{4B^2+\Gamma^2_{\tilde{N}_1}}\frac{\text{Im}A}{m_{N_1}}$$

Soft leptogenesis



- B=100 GeV, 1 TeV, 10 TeV
- Lowers the scale of thermal leptogenesis

Conclusions

- Thermal leptogenesis is related to KNOWN physics, thus predictive, technical details have been worked out
- Still too many free parameters, especially if relating them to neutrino masses m_ν (LFV)
- Wait for LHC to learn more