Neutrinos and the Cosmic Baryon Asymmetry

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(based on collaboration with W. Buchmüller and P. Di Bari)

Outline

- Introduction: two problems
- Leptogenesis: one solution
- Constraints on neutrino parameters
- Conclusions

Introduction

Problem #1: the universe is made of matter.

Baryon asymmetry (from nucleosynthesis and CMB):

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

must have been generated during the evolution of the universe

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Necessary ingredients (Sakharov, 1967)

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

Neutrino masses

- direct mass searches: $m_\nu \lesssim 2\,\mathrm{eV}$
- Neutrino oscillations:

  atmospheric ν oscillations: $\Rightarrow m_{\nu_i} \gtrsim 0.05\,\mathrm{eV}$

  solar ν oscillations: $\Rightarrow m_{\nu_j} \gtrsim 0.008\,\mathrm{eV}$

Problem #2:

ν masses are $\neq 0$ but orders of magnitude smaller than any other known masses

Both problems cannot be solved in the Standard Model
$\Rightarrow$ need extended model

Standard Model:

- left- and right-handed quarks and charged leptons
- neutrinos only left-handed. Why?

Introduce right-handed neutrinos N

First prediction: neutrino masses

$$m_\nu \sim \frac{v^2}{M}$$

$v \sim 100\,$GeV: SM mass scale; M: mass of N.
Observed light neutrino masses yield clues on M

$$m_\nu \gtrsim 0.05\,\mathrm{eV} \quad \Rightarrow \quad M \lesssim 10^{14}\,\mathrm{GeV}$$

Second prediction: lepton number L is violated

Baryon and lepton number violation

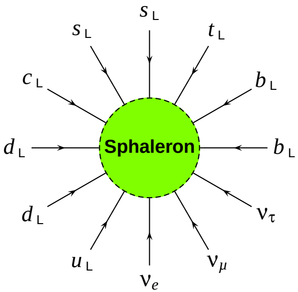
SM: $B+L$ is violated by instantons

('t Hooft '76; Klinkhammer & Manton '84; Kuzmin et al. '85)

Sphalerons are in thermal equilibrium above electroweak 'phase transition':

$$T_{ew} \sim 100\ \text{GeV} \lesssim T \lesssim 10^{12}\ \text{GeV}$$

$B+L$ violated, $B-L$ conserved.



B and L are not independent at $T \gtrsim 100\,\text{GeV}$

$$\eta_B = c\,\eta_{B-L} = \frac{c}{c-1}\eta_L\,, \quad \text{with} \quad c \sim \frac{1}{3}$$

L violating processes can generate η_B!

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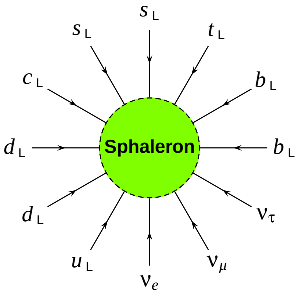

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Leptogenesis

A free lunch:

Right-handed neutrinos can also give rise to η_B
(Fukugita and Yanagida '86)
Yukawa couplings:

$$\mathcal{L}_Y = \overline{N}\lambda_\nu l H - \frac{1}{2}\overline{N} M N$$

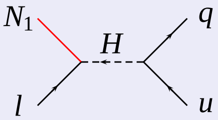
- N's are unstable: $\Gamma_D \propto \widetilde{m}_1 = \frac{v^2}{M_1}\left(\lambda_\nu^\dagger \lambda_\nu\right)_{11}$
- N interactions violate $L \to L \neq 0$, partially converted to $B \neq 0$ by sphalerons
- λ_ν complex $\Rightarrow$ CP violation ε_i

Connection between properties of light neutrinos and η_B?

Challenge #1: How do the N get produced?

N scattering processes are important
all production processes $\propto \widetilde{m}_1$

need large $\widetilde{m}_1$ for efficient production



Challenge #2: washout due to N mediated L violating scatterings

Two contributions to reaction rate:

- resonant contribution from N_1: $\propto \widetilde{m}_1$
- remainder: $\propto M_1 \overline{m}^2$, $\overline{m}^2 = \sum m^2_{\nu_i}$

need small $\widetilde{m}_1$ and $M_1 \overline{m}^2$ to avoid washout

Two conflicting requirements

$\longrightarrow$ network of Boltzmann equations

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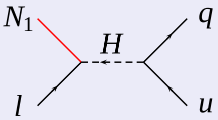

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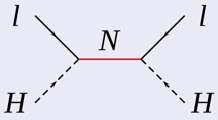

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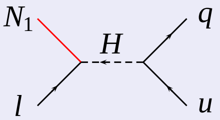

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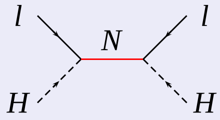

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Baryon asymmetry determined by four parameters

1. CP asymmetry ε_1
2. mass of decaying neutrino M_1
3. effective light neutrino mass $\widetilde{m}_1 = v^2 \frac{(\lambda_\nu^\dagger \lambda_\nu)_{11}}{M_1}$
4. light neutrino masses $\overline{m} = \sqrt{m_{\nu_1}^2 + m_{\nu_2}^2 + m_{\nu_3}^2}$

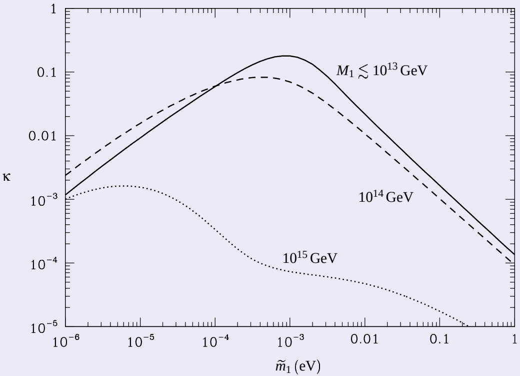
Final baryon asymmetry

$$\eta_B \simeq 10^{-2}\, \varepsilon_1\, \kappa(\widetilde{m}_1, M_1 \overline{m}^2)$$

need to know:

- CP asymmetry ε_1 (from neutrino mass model)
- efficiency factor κ parametrizes N interactions (from integration of Boltzmann eqs.)

Efficiency factor κ as function of $\widetilde{m}_1$



hierarchical light ν's: $\overline{m} = 0.05\,$eV

maximal efficiency:

$\kappa^{\max} \simeq 0.18$

for $\widetilde{m}_1 \simeq 10^{-3}\,$eV and $M_1 \lesssim 10^{13}\,$GeV

$\rightarrow$ N interactions reduce efficiency:

- for $\widetilde{m}_1 \ll 10^{-3}\,$eV: N production inefficient
- for $\widetilde{m}_1 \gg 10^{-3}\,$eV: washout too strong
- for $M_1 \gtrsim 10^{13}\,$GeV: $\Gamma_{\Delta L=2} \propto M_1 \overline{m}^2$ becomes important

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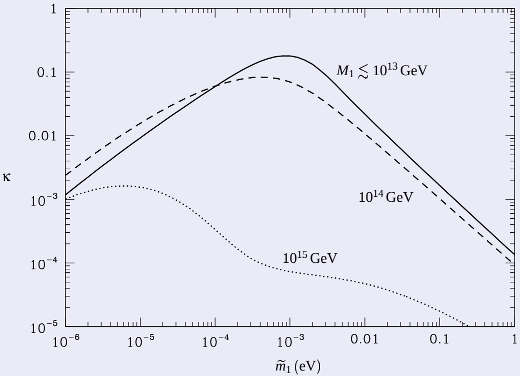

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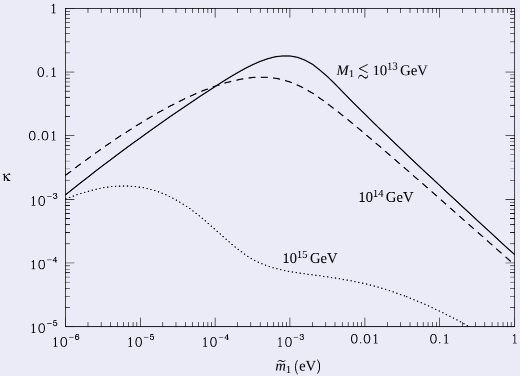

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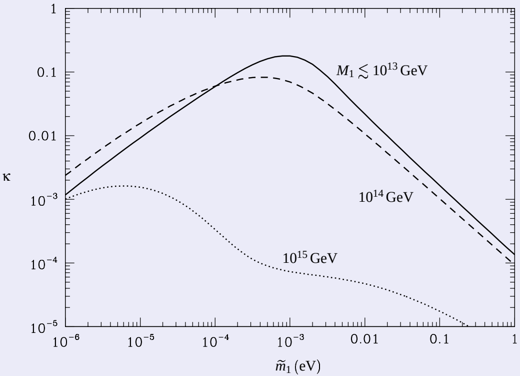

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CP asymmetry

$$\varepsilon_1 = \frac{\Gamma(N \to l) - \Gamma(N \to \bar{l})}{\Gamma(N \to l) + \Gamma(N \to \bar{l})}$$

for $M_{2,3} \gg M_1$: upper bound on ε_1 in terms of light ν masses:

$$\varepsilon_1^{\max} = \frac{3}{16\pi} \frac{M_1 m_{\nu_3}}{v^2} f\left(m_{\nu_i}, \widetilde{m}_1\right)$$

two limiting cases:

- hierarchical light νs: $m_{\nu_1} \to 0 \quad \Rightarrow \quad \varepsilon_1^{\max} = \frac{3}{16\pi} \frac{M_1 m_{\nu_3}}{v^2}$
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Constraints on neutrino parameters

1. N_1 production processes $\propto \tilde{m}_1 \Rightarrow$ lower limit on $\tilde{m}_1$
2. Washout processes:

   res. contrib. from $N_1 \propto \tilde{m}_1 \Rightarrow$ upper limit on $\tilde{m}_1$

   remainder $\propto M_1 \overline{m}^2 \Rightarrow$ upper limit on M_1 for fixed $\overline{m}$
3. maximal CP asymmetry $\propto M_1 \Rightarrow$ lower limit on M_1 since $\eta_B \propto \varepsilon_1$

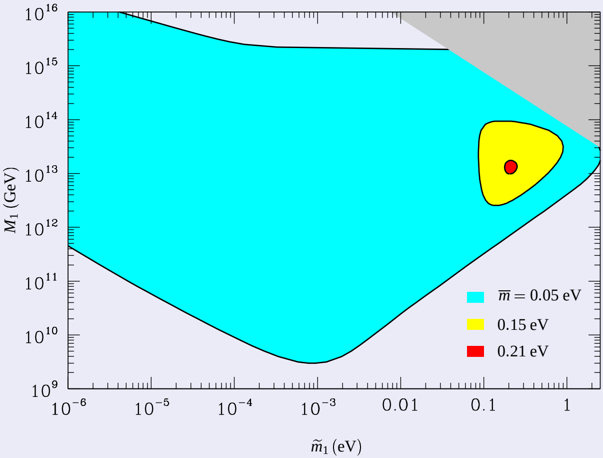
for fixed $\overline{m} \Rightarrow$ allowed region in $(\tilde{m}_1, M_1)$ plane

Size of allowed region depends on $\overline{m}$ since:

- max. CP asymm. suppressed for quasi-degenerate light νs
- $\tilde{m}_1 \geq m_{\nu_1}$

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

Upper bound on light neutrino masses



- light ν masses: $\overline{m} \geq m_{\rm atm} = 0.05\,{\rm eV} \Rightarrow$ lower bound on the baryogenesis temperature $T_B \sim M_1 \gtrsim 10^9\,{\rm GeV}$
- $\overline{m} < 0.22\,{\rm eV} \quad \Rightarrow \quad m_{\nu_i} < 0.13\,{\rm eV}$

Conclusions

- Type I seesaw naturally explains the cosmological baryon asymmetry and the smallness of neutrino masses
- Quasi-degenerate light ν masses are incompatible with leptogenesis:

$$m_{\nu_i} < 0.13\ \mathrm{eV}$$

- lower bound on the baryogenesis temperature:

$$T_B \gtrsim 10^9\ \mathrm{GeV}\,, \qquad t_B \sim 10^{-25}\,\mathrm{s}$$