Thermal Leptogenesis

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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

Problem #2:

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

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Standard Model:

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

Introduce right-handed neutrinos N

First prediction: neutrino masses (type I seesaw) $m_\nu \sim v^2/M$
$v \sim 100\,\mathrm{GeV}$: 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

B and L not independent at $T \gtrsim 100\,\mathrm{GeV}$ (sphalerons)

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

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Leptogenesis

A free lunch: Leptogenesis in type I seesaw

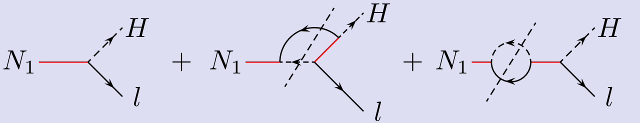
Right-handed neutrinos can also give rise to η_B (Fukugita and Yanagida '86)
Yukawa couplings:

$$\mathcal{L}_Y \simeq \overline{N}\lambda_\nu l H - \overline{N} M N$$

- Ns are unstable, decay to lepton-Higgs pairs:

$$\Gamma_D \propto \widetilde{m}_1 = \frac{v^2}{M_1}(\lambda_\nu^\dagger \lambda_\nu)_{11}$$

- N interactions violate $L \to L \neq 0$, partially converted to $B \neq 0$ by sphalerons
- λ_ν complex $\Rightarrow$ CP violation ε_i



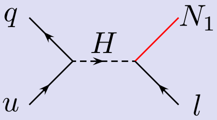
Challenge #1: How do the N get produced?

(Luty ’92; M.P. ’96; Pilaftsis and Underwood ’03)

N scattering processes are important

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

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



Challenge #2: L violating scatterings can destroy η_B

(Fukugita & Yanagida ’90; Buchmüller, Di Bari & M.P. ’02; Giudice et al. ’03)

Two contributions to reaction rate:

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

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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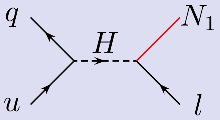

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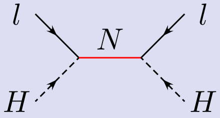

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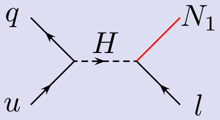

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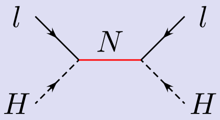

Two conflicting requirements

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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 $\widetilde{m}_1$ ($\propto$ decay width of N_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:

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- efficiency factor κ parametrizes N interactions (from integration of Boltzmann eqs.)

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CP asymmetry

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

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

(Davidson & Ibarra ’02; Buchmüller, Di Bari & M.P. ’03; Hambye et al. ’03)

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

two limiting cases:

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

→ *CP* asymm. suppressed if light ν spectrum quasi-degenerate

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Constraints on neutrino parameters

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

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

   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 $\eta_B \propto \varepsilon_1$

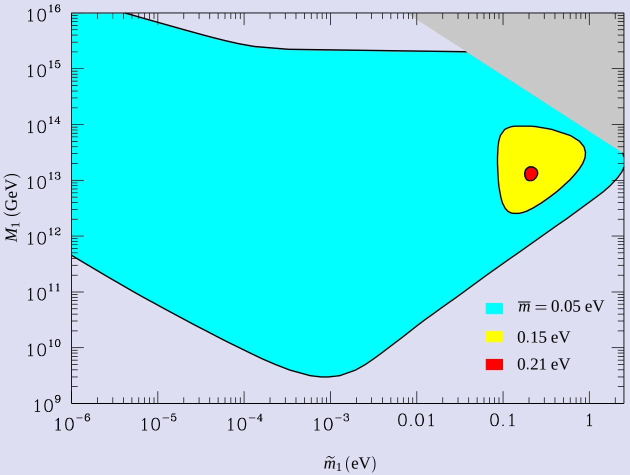
for fixed $\overline{m} \Rightarrow$ allowed region in $(\widetilde{m}_1, M_1)$ plane

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

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

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

(Buchmüller, Di Bari & M.P. ’03, ’04)

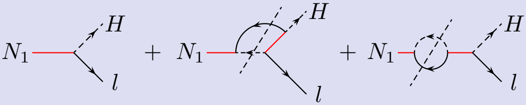


light ν masses: $\overline{m} < 0.22\,\text{eV} \quad \Rightarrow \quad m_{\nu_i} < 0.13\,\text{eV}$

RHN masses: $T_B \sim M_1 \gtrsim 10^9$ GeV

Resonant Leptogenesis

Resonant enhancement of CP-asymmetry for $M_{2,3} - M_1 \ll M_1$:



Almost no effect on bound on light ν masses, but lower limit on T_B, M_1 can be evaded.
However: many different results in literature !?

Problem: N_i unstable, i.e. cannot appear as in- or out-states of S-matrix elements

Solution: scattering amplitudes of stable particles with N_i as intermediate states

Factorisation: effective one-loop couplings of N_i

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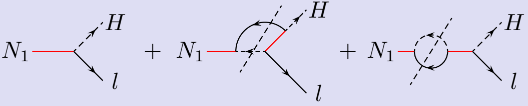

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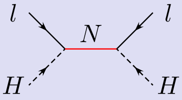

Factorisation: effective one-loop couplings of N_i

Resummation of self-energies

regularizes resonant propagator ⇒ mixing effects

$$\left(S^{-1}\right)_{ij} = \not{p} - M_i - \Sigma_{ij}$$

Renormalization known (Kniehl & Pilaftsis '96)

Chiral decomposition of propagator:

$$S = P_R S^{RR} + P_L S^{LL} + P_L \not{p} S^{LR} + P_R \not{p} S^{RL}$$

Contribute to different scattering processes:

$$\mathcal{M}\left(l_r \to \bar{l}_s\right) \propto h_{ri} S_{ij}^{LL} h_{sj} \qquad \mathcal{M}\left(\bar{l}_r \to l_s\right) \propto h_{ri}^* S_{ij}^{RR} h_{sj}^*$$

$$\mathcal{M}\left(l_r \to l_s\right) \propto h_{ri}^* S_{ij}^{RL} h_{sj} \qquad \mathcal{M}\left(\bar{l}_r \to \bar{l}_s\right) \propto h_{ri} S_{ij}^{LR} h_{sj}^*$$

Contributions of different N_i mass eigenstates?

Factorization (Anisimov, Broncano & M.P. ’05):

Different methods:

1. Decompose scattering ampl. into partial fractions, e.g.:

   $$\mathcal{M}\left(l_r \to \bar{l}_s\right) \propto \lambda_{r1}\,\frac{1}{p^2-\hat{M}_1^2}\,\lambda_{s1}+\lambda_{r2}\,\frac{1}{p^2-\hat{M}_2^2}\,\lambda_{s2}+\ldots$$

   λ_{ri}: resummed effective N_i Yukawa coupling

   Consistency: all 4 amplitudes can be factorized simultaneously.

2. Diagonalization of propagators, e.g.: $U\,S^{LL}\,U^T = S^{\text{diag}}$

   $$\mathcal{M}\left(l_r \to \bar{l}_s\right) \propto \left(hU^T\right)_{ri} S_{ii}^{\text{diag}} \left(hU^T\right)_{si}$$

   $\left(hU^T\right)_{ri}$: resummed effective N_i Yukawa coupling

   Consistency: for $p^2 = M_i^2$ all 4 amplitudes can be factorized simultaneously.

Results:

Both methods yield identical results for physical quantities:

1. Decay widths: $\Gamma(N_i \to \bar{l}_r) \propto |\lambda_{ri}|^2 = \left|\left(hU^T\right)_{ri}\right|^2$, for $p^2 = M_i^2$
2. CP-asymmetries, e.g.:

$$\varepsilon_1 \propto \frac{M_2^2 - M_1^2}{\left(M_2^2 - M_1^2\right)^2 + \left(M_2\Gamma_2 - M_1\Gamma_1\right)^2} \,,$$

Previous approaches, e.g., resum only self-energy Σ_{jj} of intermediate neutrino $N_j \Rightarrow$ regulator: Γ_j (Pilaftsis & Underwood '04)

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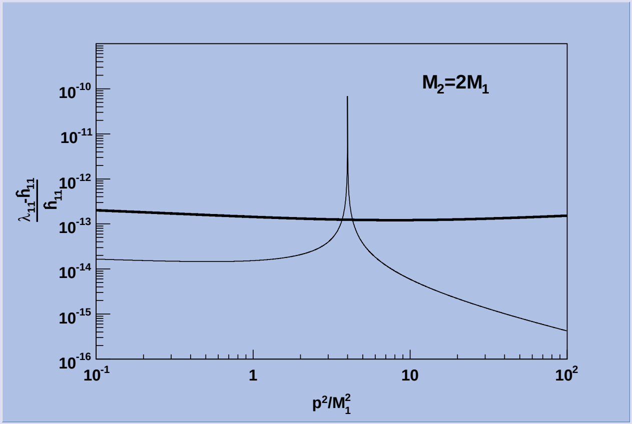
Relative one-loop correction to couplings of N_1

Our result (thick line) compared to the one of Pilaftsis et al.:



thin line has resonance at $p^2 = M_2^2$, i.e. contributions from different neutrino mass eigenstates not properly separated in previous approaches.

CP asymmetry

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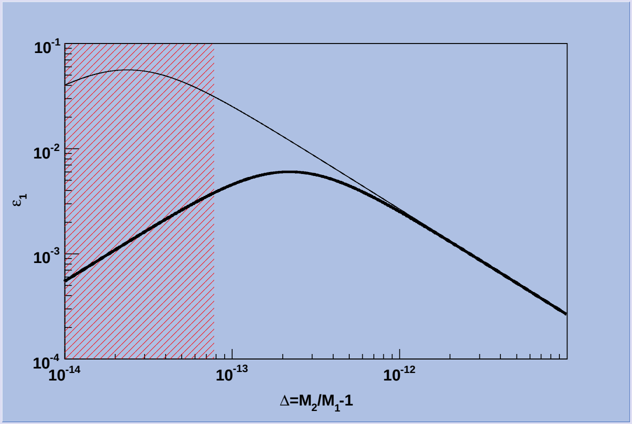

Both the position of the resonance and the maximum value for ε_1 have shifted by an order of magnitude (details depend on neutrino mass model used).

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:

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

  possible way out: resonant leptogenesis
- leptogenesis works best in neutrino mass window

$$10^{-3}\,\mathrm{eV} \lesssim m_{\nu_i} \lesssim 0.1\,\mathrm{eV}$$

  consistent with neutrino oscillations


COSMOLOGY MARCHES ON
where did it all come from?
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s. harris