Thermal Leptogenesis

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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:

\( \nu \) 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
Introduction

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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) $m_\nu \sim \nu^2 / M$

$\nu \sim 100\text{GeV}$: SM mass scale; $M$: mass of $N$.

Observed light neutrino masses yield clues on $M$

$$m_\nu \gtrsim 0.05\text{eV} \implies M \lesssim 10^{14}\text{GeV}$$

Second prediction: lepton number $L$ is violated

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

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

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A free lunch: Leptogenesis in type I seesaw

Right-handed neutrinos can also give rise to $\eta_B$ (Fukugita and Yanagida '86)

Yukawa couplings:

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

- $N$s are unstable, decay to lepton-Higgs pairs:

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

- $N$ interactions violate $L \to L \neq 0$, partially converted to $B \neq 0$ by sphalerons

- $\lambda_\nu$ complex $\Rightarrow$ CP violation $\varepsilon_i$
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 $\propto \tilde{m}_1$

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

Challenge #2: $L$ violating scatterings can destroy $\eta_B$

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

Two contributions to reaction rate:

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

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

Two conflicting requirements

$\rightarrow$ network of Boltzmann equations
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Baryon asymmetry determined by four parameters

1. \( CP \) asymmetry \( \varepsilon_1 \)
2. Mass of decaying neutrino \( M_1 \)
3. Effective light neutrino mass \( \tilde{m}_1 \) \((\propto\) decay width of \( N_1 \))
4. Light neutrino masses \( \bar{m} = \sqrt{m_{\nu_1}^2 + m_{\nu_2}^2 + m_{\nu_3}^2} \)

Final baryon asymmetry

\[ \eta_B \simeq 10^{-2} \varepsilon_1 \kappa(\tilde{m}_1, M_1\bar{m}^2) \]

need to know:

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Leptogenesis

**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 \( \varepsilon_1 \) in terms of light \( \nu \) masses:

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

\[ \varepsilon_1^{\text{max}} = \frac{3}{16\pi} \frac{M_1 m_{\nu_3}}{v^2} f(m_{\nu_i}, \tilde{m}_1) \]

two limiting cases:

- hierarchical light vs: \( m_{\nu_1} \to 0 \) \( \Rightarrow \) \( \varepsilon_1^{\text{max}} = \frac{3}{16\pi} \frac{M_1 m_{\nu_3}}{v^2} \)

- degenerate light vs: \( m_{\nu_3} = m_{\nu_1} \) \( \Rightarrow \) \( \varepsilon_1^{\text{max}} = 0 \)

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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 vs
- $\tilde{m}_1 \geq m_{\nu_1}$

$\Rightarrow$ upper bound on $\overline{m}$
Constraints on neutrino parameters

(Buchmüller, Di Bari & M.P. '03, '04)

light ν masses: \( \bar{m} < 0.22 \text{ eV} \quad \Rightarrow \quad m_{\nu_i} < 0.13 \text{ eV} \)

RHN masses: \( T_B \sim M_1 \gtrsim 10^9 \text{ GeV} \)
Resonant Leptogenesis

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

Almost no effect on bound on light $\nu$ 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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Resummation of self-energies

regularizes resonant propagator \( \Rightarrow \) mixing effects

\[
(S^{-1})_{ij} = \not p - M_i - \Sigma_{ij}
\]

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:

\[
\mathcal{M} (l_r \rightarrow \bar{l}_s) \propto h_{ri} S^{LL}_{ij} h_{sj} \\
\mathcal{M} (\bar{l}_r \rightarrow l_s) \propto h_{ri}^* S^{RR}_{ij} h_{sj} \\
\mathcal{M} (l_r \rightarrow l_s) \propto h_{ri}^* S^{RL}_{ij} h_{sj} \\
\mathcal{M} (\bar{l}_r \rightarrow \bar{l}_s) \propto h_{ri} S^{LR}_{ij} h_{sj}
\]

Contributions of different \( N_i \) mass eigenstates?
**Factorization** (Anisimov, Broncano & M.P. ’05):

Different methods:

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

\[
M(\ell_r \rightarrow \bar{\ell}_s) \propto \lambda_{r1} \frac{1}{p^2 - \hat{M}_1^2} \lambda_{s1} + \lambda_{r2} \frac{1}{p^2 - \hat{M}_2^2} \lambda_{s2} + \ldots
\]

\(\lambda_{ri}\): resummed effective \(N_i\) Yukawa coupling

Consistency: all 4 amplitudes can be factorized simultaneously.

2. Diagonalization of propagators, e.g.:

\[
U S^{LL} U^T = S^{\text{diag}}
\]

\[
M(\ell_r \rightarrow \bar{\ell}_s) \propto (hU^T)_{ri} S^{\text{diag}}_{ii} (hU^T)_{si}
\]

\((hU^T)_{ri}\): 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:** $\Gamma(N_i \rightarrow \bar{l}_r) \propto |\lambda_{ri}|^2 = \left|(hU^T)_{ri}\right|^2$, 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 $\Sigma_{jj}$ of intermediate neutrino $N_j \Rightarrow$ regulator: $\Gamma_j$ (Pilaftsis & Underwood '04)

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

Different neutrino flavours are treated differently!
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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

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

Both the position of the resonance and the maximum value for $\varepsilon_1$ 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 $\nu$ masses are incompatible with leptogenesis:
  \[ m_{\nu_i} < 0.13 \text{ eV} \]

- Lower bound on the baryogenesis temperature:
  \[ T_B \gtrsim 10^9 \text{ GeV} \text{,} \quad t_B \sim 10^{-25} \text{ s} \]

  - possible way out: resonant leptogenesis
  - leptogenesis works best in neutrino mass window
    \[ 10^{-3} \text{ eV} \lesssim m_{\nu_i} \lesssim 0.1 \text{ eV} \]

  consistent with neutrino oscillations
Conclusions

COSMOLOGY MARCHES ON

Where did it all come from?

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