Non-relativistic leptogenesis

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Leptogenesis - Basics

- Theory to explain the baryon asymmetry of the universe
- Proposed by Yanagida and Fukugita in 1986
- Standard Model extended by heavy right-handed Majorana-neutrinos
- Their decays $N \rightleftharpoons \varphi + \ell$ and $N \rightleftharpoons \overline{\varphi} + \overline{\ell}$ can fulfill the Sakharov conditions
  - L violation, cf. $B - L$ violation
  - CP violation
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  - CP violation
  - Departure from thermal equilibrium
- Sphaleron processes convert $B - L$ into B - asymmetry

Outline

1. Leptogenesis in the non-relativistic limit
2. Relativistic corrections
3. Radiative corrections
4. Summary

Outline

Motivation

- Measure for the washout strength: $K = \Gamma_0 / H(T = M_N)$
  - $K \gg 1$: "Strong washout"
  - $K \ll 1$: "Weak washout"

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- Δm^2_{atm} and Δm^2_{sol} imply: $7 \lesssim K \lesssim 46$

$\Rightarrow$ **Final asymmetrie was created at $T < M_N$, i.e. in the non-relativistic regime**

Rate equations in the non-relativistic regime

$$\left(\frac{d}{dt} + 3H\right) n_N = -\Gamma_N \left(n_N - n_N^{\rm eq}\right)$$

$$\left(\frac{d}{dt} + 3H\right) n_{B-L} = \Gamma_{B-L,N} \left(n_N - n_N^{\rm eq}\right) - \Gamma_{B-L}\, n_{B-L}$$

These equations are valid to all orders in the SM couplings!

Determining Γ_N at leading order

- Boltzmann equation

$$(\partial_t - Hp\partial_p)\, f_N = \frac{M_N \Gamma_0}{E_N} \left(e^{-E_N/T} - f_N \right)$$

- Yukawa interaction

$$\mathcal{L}_{N\mathrm{Yuk}} = h_{ij} \overline{N_{\mathrm{R}}}_i \widetilde{\varphi}^\dagger \ell_{\mathrm{L}j} + \text{ h.c.} \quad \Rightarrow \boxed{\Gamma_0 = \frac{|h_{11}|^2 M_N}{8\pi}}$$

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Rate equations in the non-relativistic regime

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$$\left(\frac{d}{dt} + 3H\right) n_{B-L} = \Gamma_{B-L,N} \, \left(n_N - n_N^{\mathrm{eq}}\right) - \Gamma_{B-L} \, n_{B-L}$$

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LO coefficients:

$$\boxed{\Gamma_N = \Gamma_0} \qquad \boxed{\Gamma_{B-L,N} = \epsilon\,\Gamma_0}$$

$$\boxed{\Gamma_{B-L} = \frac{3}{\pi^2}\left(c_\ell + \frac{c_\varphi}{2}\right) z^2 K_1(z)\Gamma_0}$$

Outline

Adding relativistic corrections

- Boltzmann equation

$$\left(\partial_t - Hp\partial_p\right) f_N = \frac{M_N \Gamma_0}{E_N} \left(e^{-E_N/T} - f_N\right)$$

- Yukawa interaction

$$\mathcal{L}_{N\mathrm{Yuk}} = h_{ij} \overline{N_{\mathrm{R}}}_i \widetilde{\varphi}^\dagger \ell_{\mathrm{L}j} + \text{ h.c.} \quad \Rightarrow \boxed{\Gamma_0 = \frac{|h_{11}|^2 M_N}{8\pi}}$$

- integrate Boltzmann equation over $\vec{p}$

- therefor expand $1/E_N$ $\qquad \frac{1}{E_N} \approx \frac{1}{M_N} + \frac{\vec{p}^2}{2M_N^3}$

Relativistic corrections

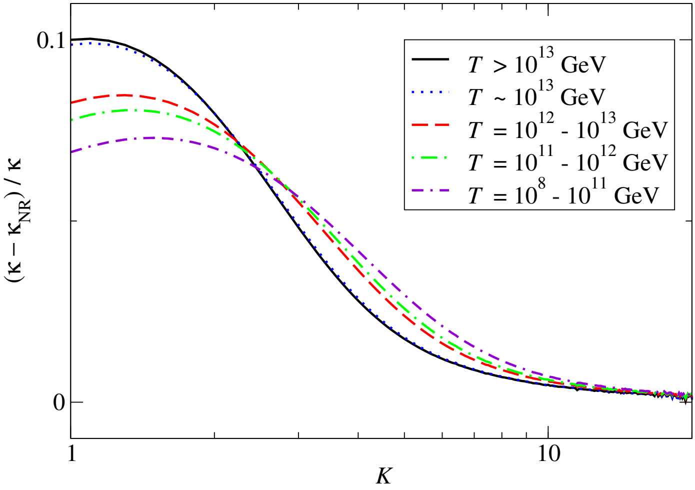
$$\left(\frac{d}{dt} + 5H\right) u = -\Gamma_u \left(u - u^{\rm eq}\right)$$

$$u \equiv \frac{1}{M_N} \cdot 2 \int \frac{d^3p}{(2\pi)^3} \frac{\vec{p}^2}{2M_N} f_N$$

$$\left(\frac{d}{dt} + 3H\right) n_N = -\Gamma_N \left(n_N - n_N^{\rm eq}\right) + \Gamma_{N,u} \left(u - u^{\rm eq}\right)$$

$$\left(\frac{d}{dt} + 3H\right) n_{B-L} = \Gamma_{B-L,N} \left(n_N - n_N^{\rm eq}\right) + \Gamma_{B-L,u} \left(u - u^{\rm eq}\right) - \Gamma_{B-L}\, n_{B-L}$$

$$\boxed{\Gamma_u = \Gamma_0} \qquad \boxed{\Gamma_{N,u} = \Gamma_0} \qquad \boxed{\Gamma_{B-L,u} = \epsilon\, \Gamma_0}$$


0.1
0
1
10
K
(κ − κNR) / κ
T > 10^13 GeV
T ~ 10^13 GeV
T = 10^12 - 10^13 GeV
T = 10^11 - 10^12 GeV
T = 10^8 - 10^11 GeV

Outline

Radiative corrections

- Before: LO
  - Decays $(1 \to 2)$
- Now: NLO
  - $2 \to 2$
  - $1 \to 3$
  - $1 \to 2$ virtual corrections

$$\boxed{\left.\frac{\partial f_N}{\partial t}\right|_{n_N=0} = f_{\mathrm{F}}(E_N)\,\Gamma_0\,\frac{M_N}{E_N}\left\{ a + \frac{\vec{p}^2}{M_N^2}\, b + O\left(g^4, \frac{g^3 T^2}{M_N^2}, \frac{g^2 T^6}{M_N^6}\right)\right\}}$$

- $a = 1 - \frac{\lambda T^2}{M_N^2} - |h_t|^2\left[\frac{21}{2(4\pi)^2} + \frac{7\pi^2}{60}\frac{T^4}{M_N^4}\right] + (g_1^2 + 3g_2^2)\left[\frac{29}{8(4\pi)^2} - \frac{\pi^2}{80}\frac{T^4}{M_N^4}\right]$
- $b = -\left[|h_t|^2\frac{7\pi^2}{45} + (g_1^2 + 3g_2^2)\frac{\pi^2}{60}\right]\frac{T^4}{M_N^4}$

A. Salvio, P. Lodone and A. Strumia, *Towards leptogenesis at NLO: the right-handed neutrino interaction rate*, JHEP **1108** (2011) 116 [arXiv:1106.2814 [hep-ph]]

M. Laine and Y. Schröder, *Thermal right-handed neutrino production rate in the non-relativistic regime*, JHEP **1202** (2012) 068 [arXiv:1112.1205 [hep-ph]]

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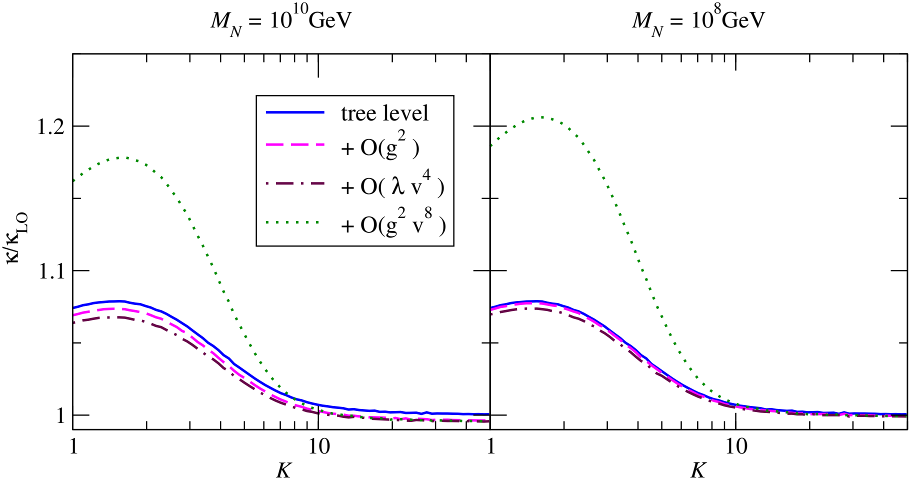
$$\left(\frac{d}{dt} + 3H\right) n_{B-L} = \Gamma_{B-L,N} \left(n_N - n_N^{\mathrm{eq}}\right) + \Gamma_{B-L,u} \left(u - u^{\mathrm{eq}}\right) - \Gamma_{B-L}\, n_{B-L}$$

NLO coefficients:

$$\boxed{\Gamma_u = a\,\Gamma_0} \qquad \boxed{\Gamma_N = a\,\Gamma_0} \qquad \boxed{\Gamma_{N,u} = (a - 2b)\,\Gamma_0}$$

Radiative corrections - Numerical results



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Summary

The non-relativistic expansion is a convenient tool for computing the lepton asymmetry!

- Relativistic corrections are small
- Accuracy can be easily controlled
- Rate equations are simple
- Radiative corrections can be included
- Only works in the (favoured) strong washout regime

Summary

The non-relativistic expansion is a convenient tool for computing the lepton asymmetry!

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- More work to do
  - Include radiative corrections in the $B - L$ rate equation
  - Include flavor effects

Thank you for your attention!

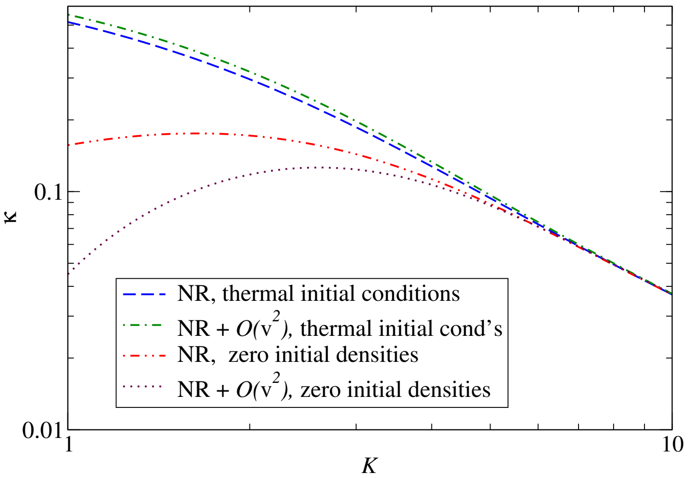
Washout strength and effective light neutrino mass

$$K = \frac{\Gamma_0}{H(T = M_N)} = \frac{\frac{|h_{11}|^2 M_N}{8\pi}}{\sqrt{\frac{8\pi^3 g_*}{90}} \frac{M_N^2}{M_{Pl}}}$$

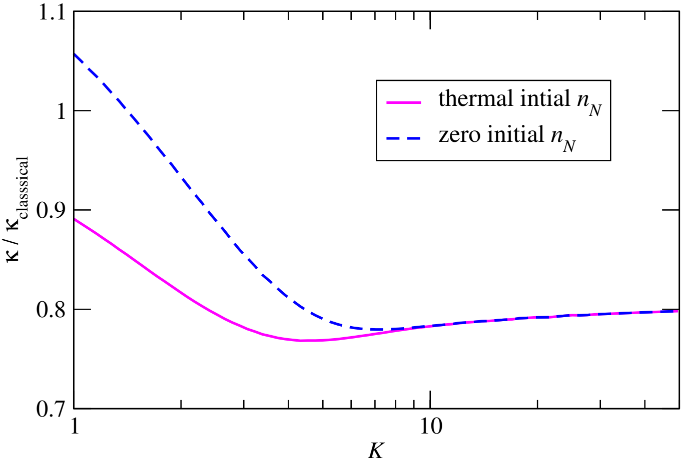
$$= \frac{M_{Pl}}{8\pi \cdot 1.66\sqrt{g_*} \cdot v^2} \cdot \frac{|h_{11}|^2 v^2}{M_N}$$

$$= \text{const.} \cdot \tilde{m}_1$$

Dependence on initial conditions



Dependence on statistics



Ratio of reaction rates and the Hubble rate