Imprints of Non-standard cosmology on Leptogenesis

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Outlines

1. Introduction
2. Expansion of Univesre under modified cosmology
3. Leptogenesis Boltzmann equations in Non-standard cosmology
4. Non-standard Leptogenesis
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Introduction

- Matter $\sim$ 5%, Dark matter $\sim$ 27%, Dark energy 68%.
- Matter antimatter asymmetry in the Universe

  $$Y_B = \frac{n_B}{s} \sim 10^{-11}$$

- Leptogenesis:
  M. Fukugita, T. Yanagida; Phys. Lett. B174 (1986) 45
- Sakharov conditions; Pisma Zh. Eksp. Teor. Fiz. 5 (1967) 32

  1. Baryon or Lepton number violation
  2. CP violation
  3. Out of equilibrium dynamics.

- Origin of light neutrino mass via seesaw mechanism.

Expansion of Univesre under modified cosmology

- Influence of a scalar field φ, F. D'Eramo . *et. al* : JCAP 1705, no. 05, 012 (2017).

$$\rho_{rad} = \frac{\pi^2}{30} g_* T^4 \qquad s = \frac{2\pi^2}{45} g_{*s} T^3$$

$$H = \sqrt{\frac{8\pi G \rho_{rad}}{3}} = 1.66\sqrt{g_*}\frac{T^2}{M_P} .$$

Consider that a scalar field φ is also present at the early Universe and its energy density depends on the scale factor a

$$\rho_\varphi \sim a^{-(4+n)}, \qquad n > 0 .$$

- Total entropy $S = sa^3$ is conserved, $g_{*s} T^3 a^3 = \text{Constant}$.
- Temperature T_r when energy density of φ becomes equal to energy density of radiation, i.e., at $T = T_r$, $\rho_\varphi = \rho_{rad}$.

Total energy density is expressed as

$$\rho_{Tot} = \rho_{rad} + \rho_{\varphi} = \rho_{rad}\left[1 + \frac{g_*(T_r)}{g_*(T)}\left(\frac{g_{*s}(T)}{g_{*s}(T_r)}\right)^{(4+n)/3}\left(\frac{T}{T_r}\right)^n\right].$$

At large T, $g_* \simeq g_{*s}$ are constant.

$$\rho_{Tot} = \rho_{rad}\left[1 + \left(\frac{T}{T_r}\right)^n\right].$$

The Hubble parameter can be redefined as

$$H' = 1.66\sqrt{g_*}\frac{T^2}{M_P}\left[1 + \left(\frac{T}{T_r}\right)^n\right]^{1/2} = H\left[1 + \left(\frac{T}{T_r}\right)^n\right]^{1/2}.$$

Effect of multiple scalar fields with sequential domination

$$n_i > 0, \quad n_i < n_{i+1}$$

where

$$\rho_{\phi_i} > \rho_{\phi_{i-1}} \text{ for } T > T_i,$$
$$\rho_{\phi_i} = \rho_{\phi_{i-1}} \text{ for } T = T_i,$$
$$\rho_{\phi_i} < \rho_{\phi_{i-1}} \text{ for } T < T_i.$$

$$\rho_{\phi_i}(T) = \rho_{\phi_i}(T_i) \left(\frac{g_{*S}(T)}{g_{*S}(T_i)} \right)^{\frac{4+n_i}{3}} \left(\frac{T}{T_i} \right)^{4+n_i}$$

For two scalar fields

$$\rho_{tot}(T) = \rho_{rad}(T) \left\{ 1 + \left(\frac{T}{T_r} \right)^{n_1} \left[1 + \left(\frac{T}{T_2} \right)^{(n_2-n_1)} \right] \right\}$$

$$H_{new} = H \left\{ 1 + \left(\frac{T}{T_r} \right)^{n_1} \left[1 + \left(\frac{T}{T_2} \right)^{(n_2-n_1)} \right] \right\}^{1/2}$$

Leptogenesis Boltzmann equations in Non-standard cosmology

- Leptogenesis with right handed neutrinos, Type-I seesaw mechanism
- Interaction Lagrangian is given as

$$\mathcal{L} = -Y_{ij}\bar{l}_i\tilde{\Phi}N_j - \frac{1}{2}M_j\bar{N^c}_jN_j + h.c. \ .$$

- Neutrino mass: $M_\nu = -m_D^T M^{-1} m_D$.
- CP asymmetry parameter ε :

$$\varepsilon = -\frac{3}{16\pi}\frac{1}{(Y^\dagger Y)_{11}}\sum_{j=2,3}\mathrm{Im}[(Y^\dagger Y)^2_{1j}]\frac{M_1}{M_j} \ .$$

- Casas-Ibarra (CI) parametrization:

$$|\varepsilon| < \frac{3}{16\pi v^2}M_1 m_\nu^{\max} \ ,$$

for $|\varepsilon| \sim 10^{-6}$, $M_1 \geq 10^{10}$ GeV with $m_\nu^{\max} = \sqrt{\Delta m^2_{31}}$.

- Modified Boltzmann equations for Leptogenesis
  BE for RHN decay

$$\frac{dY_{N_1}}{dz} = -z\frac{\Gamma_1}{H_1}\frac{1}{\mathcal{J}}\frac{K_1(z)}{K_2(z)}\left(Y_{N_1} - Y_{N_1}^{\rm eq}\right),$$

BE for lepton asymmetry in the modified framework

$$\frac{dY_L}{dz} = -\frac{\Gamma_1}{H_1}\frac{1}{\mathcal{J}}\left(\varepsilon z\frac{K_1(z)}{K_2(z)}(Y_{N_1}^{eq} - Y_{N_1}) + \frac{z^3 K_1(z)}{4}Y_L\right).$$

with $H_1(T = M_1) = 1.66 g_*^{1/2} M_1^2/M_P = Hz^2$ and $z = M_1/T$.

$$\mathcal{J} = \left\{1 + \left(\frac{M_1}{T_r z}\right)^{n_1}\left[1 + \left(\frac{M_1}{T_r x z}\right)^{(n_2-n_1)}\right]\right\}^{1/2}$$

with $x = \frac{T_2}{T_r}$.

- Transfer of asymmetry:

$$Y_B = \frac{28}{79} Y_L \, .$$

$$Y_B^{\rm expt} = (8.24 - 9.38) \times 10^{-11}.$$

- Initial conditions: $Y_L(z = 0) = 0$
- RHN initial abundance: I) $Y_{N_1}^{in} = Y_{N_1}^{eq}$ and II) $Y_{N_1}^{in} = 0$

Study with single scalar field: S. L. Chen, A. D. Banik and Ze-kun Liu; JCAP 03 (2020) 009

Non-standard Leptogenesis

Two scalar field:
Case I : $Y_{N_1}^{in} = Y_{N_1}^{eq}$, $\varepsilon = 10^{-5}$, $\Gamma_1/H_1 = 600$, $T_r = 10^{-3} M_1$

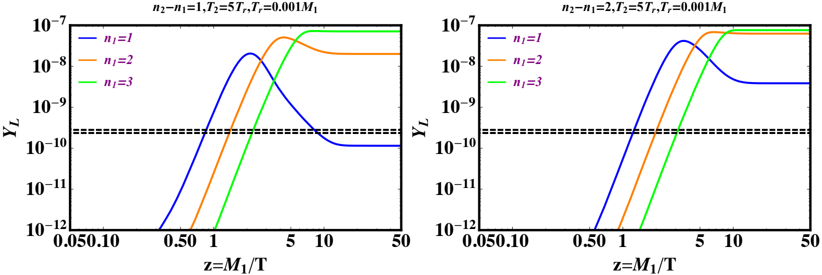

Figure: 1. *Evolution of Y_L versus z for initial equilibrium RHN abundance, $T_2 = 5\,T_r$ and different n_1 values, with $n_2 - n_1 = 1$ (left panel) and $n_2 - n_1 = 2$ (right panel). The double black line(s) describe the baryogenesis threshold.*

Two scalar field:

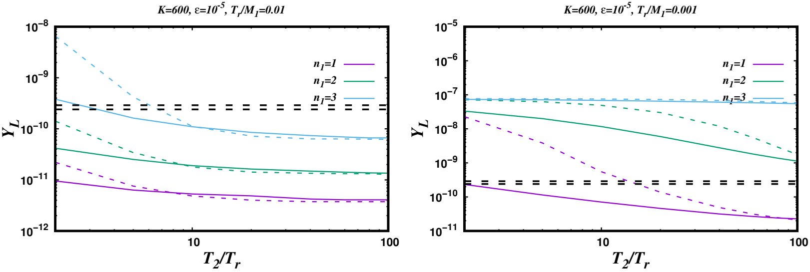

Figure: 2. *Y_L versus T_2/T_r for $T_r/M_1 = 0.01$ (left panel) and $T_r/M_1 = 0.001$ (right panel), with different n_1. Solid (dashed) lines refer to $n_2 - n_1 = 1$ ($n_2 - n_1 = 2$). The double black line(s) describe the baryogenesis threshold.*

Case II : $Y_{N_1}^{in} = 0$ (same parameter set)

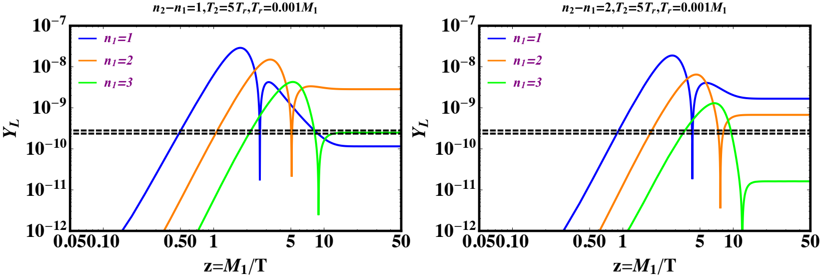

Figure: 3. *Same as Fig. 1 for zero RHN abundance.*

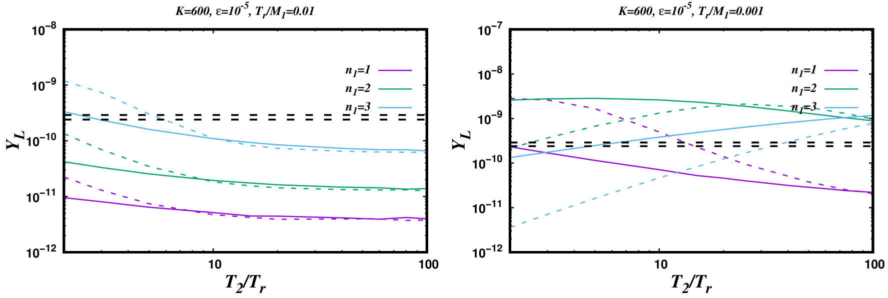

Figure: 4. *Same as Fig. 2 with zero RHN initial abundance. The double black line(s) describes the baryogenesis threshold.*

Three scalar field:

$$\mathcal{J} = \left\{ 1 + \left(\frac{M_1}{T_r z} \right)^{n_1} \left[1 + \left(\frac{M_1}{T_r x z} \right)^{(n_2 - n_1)} \left(1 + \left(\frac{M_1}{T_r y z} \right)^{(n_3 - n_2)} \right) \right] \right\}^{1/2}$$

where $y = T_3 / T_r$.

Case I : $Y_{N_1}^{in} = Y_{N_1}^{eq}$

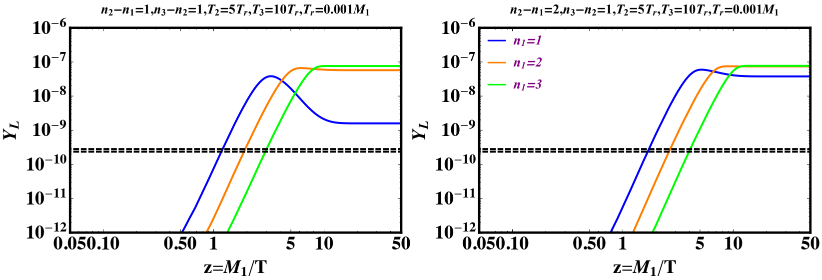

Figure: 5. *Effect of three scalar fields on Y_L versus z plots for initial equilibrium RHN abundance and different n_1 values with $n_2 - n_1 = 1$ (left panel) and $n_2 - n_1 = 2$ (right panel) with $T_3 = 10T_r$ and $n_3 - n_2 = 1$. The double black line(s) describes the baryogenesis threshold.*

Case I : $Y_{N_1}^{in} = 0$

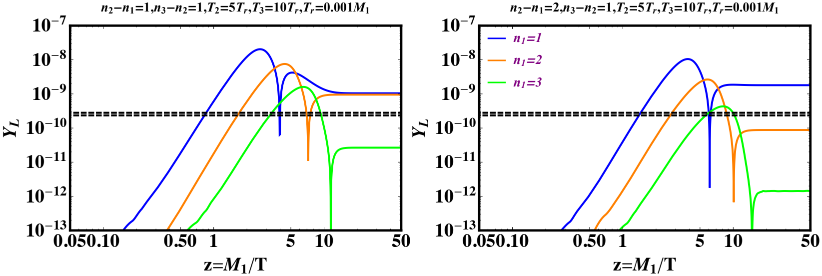

Figure: 6. *Same as Fig. 5 for zero initial RHN abundance. The double black line(s) describe the baryogenesis threshold.*

Conclusions

- Typically, with the increasing of n_i, Y_L increases while the washout decreases. This is due to the fact that the faster the expansion is, the higher is the departure from thermal equilibrium.
- The relevance of the ϕ_{i+1} with respect to ϕ_i depends upon the difference $n_{i+1} - n_i$. It clearly grows if $n_{i+1} - n_i$ increases, but n_i must not be too high, otherwise the dominance of the ϕ_{i+1} enters too early, in an epoch where the RHN N_1 has not been produced in a sufficient quantity. In other words, if ϕ_i already absorbs the whole washout, the ϕ_{i+1} action ceases to be significant.
- With the $Y_{N_1}^{in} = Y_{N_1}^{EQ}$ initial conditions, the production of asymmetry Y_L is typically monotonic and after a washout the value of Y_L saturates at a certain value. To evaluate if leptogenesis is so efficient to generate the requested amount of baryon asymmetry, one has to analyze the balance between the values of the exponents n_i and the ratios of the temperatures T_i to the radiation temperature T_r.

Conclusions

- With the $Y_{N_1}^{in} = 0$ initial conditions, there is an oscillation due to the strong initial washout, since the inverse decay of the produced RHN N_1 is large at the beginning and starts with a vanishing initial abundance. The saturation of Y_L at a certain value is thus slower and the amount of asymmetry Y_L can be small. As in the previous case, in order to understand if leptogenesis can generate baryogenesis, one has to evaluate the dipendence of Y_L upon the n_i and the temperatures T_i.
- We have studied in details the case with two scalar fields, where it is indeed possible to satisfy Baryon asymmetry in the universe within the range $0.001 \leq T_r/M_1 \leq 0.01$ for thermal leptogenesis with a chosen set of parameters $M_1 = 10^{11}$ GeV, $\epsilon = 10^{-5}$ and $\Gamma_1/H_1 = 600$ for a large interval of T_2/T_r values.
- In the case of three scalar fields, also studied in details, it is important to analyze the behavior of the system with initial conditions $Y_{N_1}^{in} = 0$ in comparison with the $Y_{N_1}^{in} = Y_{N_1}^{EQ}$ initial conditions. Again, as in the presence of two-scalar fields, a decreasing of the washout accompanied by a decreasing of the Y_L values can be observed.

THANK YOU FOR YOUR ATTENTION!