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Quintessential Kination and Leptogenesis

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Abstract. We show how thermal leptogenesis induced by the CP-violating decay of a right-handed neutrino (RHN) can be compatible to the assumption of quintessential kination, i.e., to a cosmological background model where the energy density of the early Universe is assumed to be dominated by the kinetic term of a quintessence field during some epoch of its evolution. The phenomenology depends on the temperature T_r above which kination dominates over radiation. For instance, when kination stops to dominate when $M/100 \lesssim T_r \lesssim M$ (where M is the RHN mass) the efficiency of the process η, defined as the ratio between the produced lepton asymmetry and the amount of CP violation in the RHN decay, can be even larger than in the standard scenario of radiation domination. On the other hand, a super–weak wash–out regime is obtained ($\eta \ll 1$) for $T_r << M/100$. In this latter situation the lower bound $T_r \gtrsim 5$ MeV $\times(M/\mathrm{TeV})(0.05\,\mathrm{eV}/\tilde{m})$ can be found, where $\tilde{m}$ is the effective neutrino mass scale.

The dark energy component in the present universe can be explained by modifying the standard cosmology with the introduction of a slowly evolving scalar field called quintessence [1]. In this case, an open possibility is the existence of an early era of kination domination, during which the Universe is dominated by the kinetic energy of the quintessence field. During this era, the expansion rate of the Universe is larger compared to the usual radiation domination case, modifying the predictions of the standard cosmological picture. Kination has been discussed in different contexts, such as dark matter and inflation[2].

In this talk we investigate the impact of the quintessential kination scenario on the properties of the thermal leptogenesis induced by the CP-violating decay of a right-handed neutrino (RHN), N [3]. As discussed in detal in [4] and summarized in the following, leptogenesis and kination can indeed be compatible with each other, although the faster expansion rate in the early Universe due to kination dominance can modify the predictions of the standard leptogenesis scenario even by several orders of magnitude.

The kination regime is attained when, in the energy–momentum tensor of the quintessence field ϕ (assumed here as spatially constant): $T_{\mu\nu} = \partial_\mu \phi \frac{\partial \mathcal{L}}{\partial \partial^\nu \phi} - g_{\mu\nu}\mathcal{L}$, the kinetic term $\dot{\phi}^2/2$ dominates over the potential term $V(\phi)$, so that

$$w \equiv \frac{p}{\rho} = \frac{\frac{\dot{\phi}^2}{2} - V(\phi)}{\frac{\dot{\phi}^2}{2} + V(\phi)} \rightarrow 1. \tag{1}$$

In this case the energy density of the Universe, which scales like $\rho \propto a^{-3(1+w)}$, is given by $\rho_{kin} \propto a^{-6}$, instead of $\rho_{rad} \propto a^{-4}$ for the case of radiation domination. In the following, we will assume that, in the epoch after reheating which is relevant to thermal leptogenesis, the energy density of the Universe is dominated by the sum of these two components, $\rho = \rho_{rad} + \rho_{kin}$, with the boundary condition $\rho_{kin}(T_r) = \rho_{rad}(T_r)$. The kination–radiation equality temperature T_r is in principle a free parameter, with the only constraint: $T_r \gtrsim$ 1 MeV, in order not to spoil big-bang nucleosynthesis. This implies that:

$$H(z) = \sqrt{\frac{z^2 + z_r^2}{1 + z_r^2}} \frac{H_1}{z^3}, \tag{2}$$

where $z \equiv M/T$ with M the mass of the RHN, $H_1 \equiv H(z = 1)$, $z_r \equiv \sqrt{\frac{g_*}{g_{*r}}} M/T_r$, g_* is the number of relativistic degrees of freedom, and $g_{*r} = g_*(T_r)$.

Let's discuss now thermal leptogenesis in a Minimal Supersymmetric extension of the Standard Model (MSSM) supplemented by right–handed neutrino supermultiplets, i.e. the model described by the following superpotential:

$$\mathcal{W} = \mathcal{W}_{MSSM} + \frac{1}{2} N^c M N^c + y H_2 L N^c. \tag{3}$$

In this case the decay rate of the RHN is given by $\Gamma_d = |y|^2 M/4\pi$ where y is the neutrino Yukawa coupling, with $g_{*r} = 10.75$ and $g_*(T) = 228.75$. This scenario has been extensively studied in the literature [5] in a conventional cosmological setup where the energy density of the early Universe is dominated by radiation.

In our case, introducing as usual the effective neutrino mass scale given by $\tilde{m} \equiv |y|^2 \langle H_2 \rangle^2 / M$, we can get the wash–out parameter, given by the ratio $K \equiv \Gamma_d / H(z = 1)$:

$$K = \frac{63.78}{\sqrt{1 + z_r^2}} \left(\frac{\tilde{m}}{0.05 \text{ ev}} \right). \tag{4}$$

The above equation shows that, depending on z_r, one can have $K >> 1$ (strong wash–out) or $K << 1$ (super–weak wash–out) at fixed $\tilde{m}$. In the general case ($z_r << 1$ corresponds to radiation domination and $z_r >> 1$ to kination domination) the Boltzmann equations that drive leptogenesis are given by:

$$\frac{d\hat{N}}{dz}(z) = -K \sqrt{\frac{1 + z_r^2}{z^2 + z_r^2}} z^2 (\hat{N} - \hat{N}_{eq}) \left[\gamma_d(z) + 2\gamma_s(z) + 4\gamma_t(z) \right] \tag{5}$$

$$\begin{aligned} \frac{d\hat{L}}{dz}(z) &= K \sqrt{\frac{1 + z_r^2}{z^2 + z_r^2}} z^2 \Big[(\gamma_d(z)\epsilon + 2\gamma_s(z)\epsilon_s + 4\gamma_t(z)\epsilon_t)(\hat{N} - \hat{N}_{eq}) \\ &\quad - \frac{\gamma_d(z)\hat{N}_{eq}\hat{L}}{4} - \frac{1}{2}\gamma_s(z)\hat{L}\hat{N} - \gamma_t(z)\hat{L}\hat{N}_{eq} \Big], \end{aligned} \tag{6}$$

where $\hat{N}(z)$ is the combined comoving number density, normalized to its equilibrium value at $z = 0$, of RH neutrinos and sneutrinos, while $\hat{L}(z)$ is the combined asymmetry of leptons and sleptons normalized in the same way. In the above equations we include the dominant $\Delta L = 1$ lepton–number violating scattering amplitudes $\gamma_{s,t}$ proportional to the top Yukawa coupling λ_t and driven by Higgs exchange in the s and t channel [5]. Moreover, the ϵ parameter is the amount of CP–violating in decays, while $\epsilon_{s,t}$ is the CP violation for $\gamma_{s,t}$.

The result of our calculation is shown in Fig. 1, where the efficiency $\eta \equiv \hat{L}(z = \infty)/\epsilon$ is calculated with the boundary condition $\hat{N}(0) = 0$ (vanishing initial RHN density) as a function

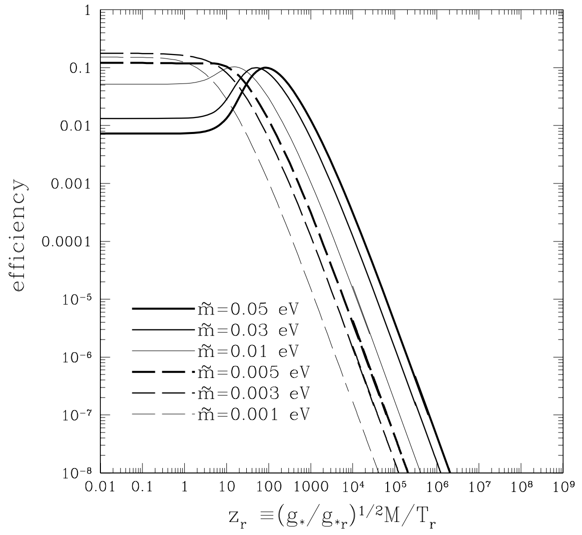

Figure 1. The efficiency as a function of $z_r \equiv \sqrt{g_*/g_{*r}} M/T_r$, for $N(0) = 0$ and for several values of $\tilde{m}$.

of z_r. In this plot a smooth transition between radiation domination (the plateau at $z_r \lesssim 1$) and kination-domination ($z_r \gtrsim 100$) is clearly visible. In particular, one can see than when $z_r >> 1$ and $K << 1$ the efficiency is strongly suppressed, so that a resonant CP violation $\epsilon \simeq 1$ is necessary in order to achieve succesful leptogenesis. For this reason in the calculation we have taken $\epsilon_{s,t} = \epsilon$. In fact, while $\epsilon \neq \epsilon_{s,t}$ is possible[6], in the case of resonant CP violation $\epsilon_{s,t}/\epsilon \to 1$ is expected to a very high level of accuracy. On the other the values of $\epsilon_{s,t}$ are irrelevant when $K \gtrsim 1$ and $z_r \lesssim 50$ since in this case scattering can be neglected in the first place. Including CP violation in scattering implies that in the super–weak wash–out regime, $K << 1$, one has aproximately $\eta \simeq 10.5K^2$. So the condition for a successful leptogenesis $Y_{\hat{L}} = 4 \times 10^{-3}\epsilon\eta \approx 10^{-10}$, which requires $\eta \gtrsim 5 \times 10^{-8}$ when $\epsilon \simeq 1$, implies the lower bound $T_r \gtrsim 5\ \text{MeV} \left(\frac{M}{\text{TeV}}\right)\left(\frac{0.05\ \text{eV}}{\tilde{m}}\right)\left(\frac{g_*/g_{*r}}{228.75/10.75}\right)^{1/2}$. This means that, depending on the parameters, T_r can be as low as the nucleosynthesis temperature. On the other hand, for $M/100 \lesssim T_r \lesssim M$ the efficiency η can be even larger than in the standard scenario of radiation domination. In this case thermal leptogenesis can proceed for a hierarchical spectrum of heavy neutrino masses, and for this scenario the usual lower bound on the RHN mass M can be relaxed up to a factor of 30 compared to the standard case.

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