TeV scale Leptogenesis with Dark Matter in Non-standard Cosmology

D. Mahanta and D. Borah (in preparation)

Devabrat Mahanta

Indian Institute of Technology Guwahati

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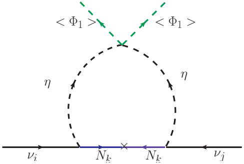
Introduction

1. Lack of experimental signature for the **WIMP miracle**. This leads to think different production mechanism of dark matter or different cosmological histories. [Francesco D'Eramo et. al JCAP 2017, Nicolás Bernal et. al Eur. Phys. J. C 2019, Paola Arias et. al JCAP 2019]
2. Viable low scale leptogenesis in different cosmological histories?
3. Unified framework of Leptogenesis and dark matter in non-standard cosmological models in the context of **Scotogenic model**.

Dark matter and Leptogenesis in the Scotogenic Model

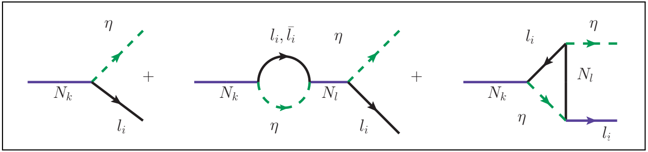
1. **The model content:**
   $N_i \to -N_i, \quad \eta \to -\eta, \quad \Phi_1 \to \Phi_1, \quad \Psi_{\rm SM} \to \Psi_{\rm SM}$



2. Leptogenesis from the decay of N_1 with η to be the dark matter [Thomas Hugle et. al PRD 2018].
3. Leptogenesis from N_2 decay with N_1 to be the dark matter. [D. Mahanta, D. Borah JCAP 2019]
4. Dark matter in modified cosmological histories [F. D'Eramo et. al JCAP 2017, Ni. Bernal et. al Eur. Phys. J. C 2019, P. Arias et. al JCAP 2019].
5. Leptogenesis and dark matter in Scotogenic model in modified cosmological histories..

N_1 Leptogenesis in scotogenic model

1. CP asymmetry



$$\epsilon_i = \frac{\sum_\alpha \Gamma(N_i \to l_\alpha \eta) - \Gamma(N_i \to \bar{l_\alpha} \bar{\eta})}{\sum_\alpha \Gamma(N_i \to l_\alpha \eta) + \Gamma(N_i \to \bar{l_\alpha} \bar{\eta})}.$$

2. Washout from inverse decay and $\Delta L = 2$ processes.

Non-standard cosmological histories

1. The universe was dominated by a species ϕ, the energy density of which falls faster than the radiation, $\rho_\phi \propto a^{-(4+n)}$ with $n = 1, 2, 3..$ **From Friedman equations n can be identified to be** $\omega = (n+1)/3$. $\Longrightarrow$ **A fast expansion.**

2. In this case we assume that the early universe was dominated by a field which behaves like matter. $\Longrightarrow$. **A slow expansion and entropy injection**

A fast expanding universe

1. The energy density of the universe is, $\rho(T) = \rho_{rad}(T) + \rho_\phi(T)$.
2. The expansion rate of the universe is, $H(T) = \sqrt{\frac{\rho(T)}{3M_{Pl}^2}}$
3. At $T = T_r$, $\rho_{rad}(T_r) = \rho_\phi(T_r)$.
4. From **BBN** constraints $T_r \gtrsim (15.4)^{1/n}$ MeV. [F. D'Eramo et. al JCAP 2017]
5. $H(T) \simeq \frac{\pi g_*^{1/2}(T) T^2}{3\sqrt{10} M_{Pl}} \left[1 + \left(\frac{g_*(T)}{g_*(T_r)}\right)^{(1+n)/3} \left(\frac{T}{T_r}\right)^n\right]^{1/2}$

Leptogenesis in a fast expanding universe

The Boltzmann equations for Leptogenesis

$$\frac{dN_{N_1}}{dz} = D_1'(N_{N_1} - N_{N_1}^{eq})$$

$$\frac{dN_{B-L}}{dz} = -\epsilon_1 D_1'(N_{N_1} - N_{N_1}^{eq}) - W_{tot}' N_{B-L}$$

where,

$$D_1' = K_1 \frac{\kappa_1(z)}{\kappa_2(z)} \frac{1}{L[n, z, z_r]}$$

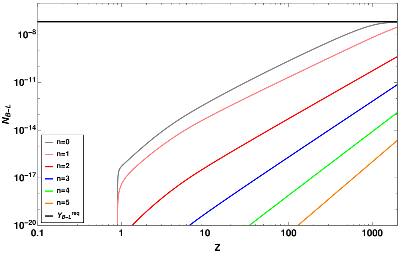
$$W_{tot}' = W_1' + \Delta W'$$

$$W_1' = \frac{1}{4} K_1 \kappa_1(z) \frac{1}{L[n, z, z_r]}$$

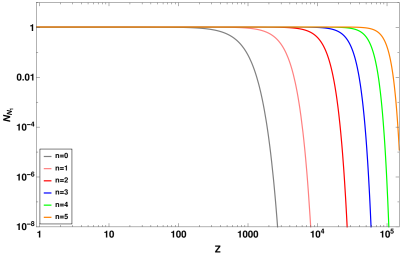
$$\Delta W' = \frac{36\sqrt{5} M_{Pl}}{\pi^{1/2} g_l g_*^{1/2} v^4} \frac{1}{z^3 L[n, z, z_r]} \frac{1}{\lambda_5^2} M_1 \bar{m}_\zeta^2$$

$$K_1 = \frac{\Gamma_1}{H(z=1)}$$

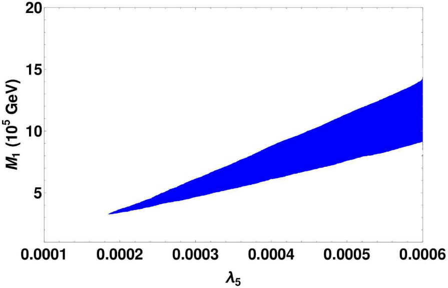
$$L[n, z, z_r] = (n+4) \left[\frac{1}{z^4} + \left(\frac{g_*(z)}{g_*(z_r)}\right)^{(1+n)/3} \frac{z_r^n}{z^{n+4}}\right]^{3/2} \left[\frac{4}{z^5} + (4+n)\left(\frac{g_*(z)}{g_*(z_r)}\right)^{(1+n)/3} \frac{z_r^n}{z^{n+5}}\right]^{-1}$$



N_{B-L}
10^{-8}
10^{-11}
10^{-14}
10^{-17}
10^{-20}
0.1
1
10
100
1000
z
n=0
n=1
n=2
n=3
n=4
n=5
Y_{B-L}^{req}



N_{N_1}
1
0.01
10^{-4}
10^{-6}
10^{-8}
1
10
100
1000
10^4
10^5
z
n=0
n=1
n=2
n=3
n=4
n=5



M_1 (10^5 GeV)
20
15
10
5
0.0001
0.0002
0.0003
0.0004
0.0005
0.0006
λ_5

Dark Matter in a fast expanding universe

The Boltzmann equation to find the dark matter relic

$$\frac{dY}{dz} = -A\frac{< \sigma v_{rel} >}{z^3 L\left[n, z, z_r\right]}\left[Y^2 - Y_{eq}^2\right]$$

where, $$A = \frac{s(z=1)}{H_{rad}(z=1)} = \frac{2\sqrt{2}\pi}{3\sqrt{5}} g_*^{1/2} m_{DM} M_{Pl}.$$

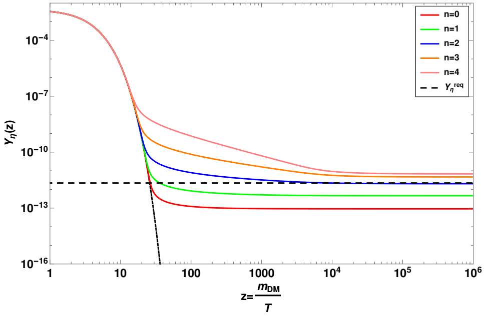
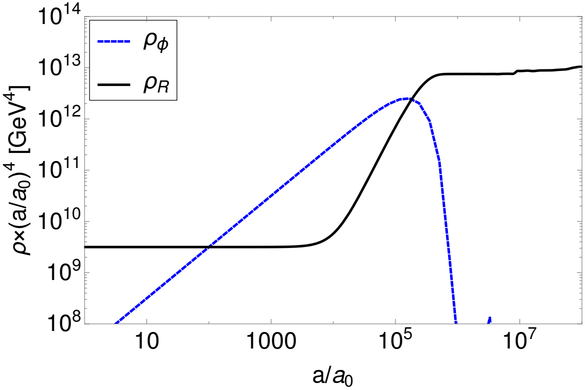


Figure: $m_{DM} = 200$ GeV, $m_{A_0} = 200.076$ GeV ($\lambda_5 = 0.0005$), $m_{H^\pm} = 205$ GeV, $T_r = 20$ MeV and $\lambda_L = 10^{-8}$.

An early matter dominated universe

1. If the early universe was dominated by a matter like field Φ, the expansion rate of the universe will be slower compared to the standard radiation untill it decays.
2. This field can decay to both dark sector and visible sector particles.
3. This cosmological model can be characterised by two parameters, T_{end} and $k = \dfrac{\rho_\phi(T = M_1)}{\rho_{rad}(T = M_1)}$.
4. $T_{end}^4 = \dfrac{90}{\pi^2 g_*(T_{end})} M_{Pl}^2 \Gamma_\Phi^2$
5. **BBN constraints** , $T_{end} \gtrsim 4$ MeV [M. Kawasaki et. al 2000].



ρ_ϕ
ρ_R
$\rho\times(a/a_0)^4$ [GeV^4]
a/a_0
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10
1000
10^5
10^7

Leptogenesis in an early matter dominated universe

$$x\frac{d\rho_\phi}{dx} + 3(1+\omega)\rho_\phi = -\frac{\Gamma_\phi \rho_\phi}{m_{DM} H}$$

$$x\frac{ds}{dx} + 3(1+\omega)s = \frac{x\Gamma_\phi \rho_\phi}{m_{DM} H}$$

$$\frac{dn_{N_1}}{dx} + \frac{n_{N_1}}{s}\frac{ds}{dx} + \frac{3n_{N_1}}{x} = -D(n_{N_1} - n_{N_1}^{eq})$$

$$\frac{dn_{B-L}}{dx} + \frac{n_{B-L}}{s}\frac{ds}{dx} + \frac{3n_{B-L}}{x} = -\epsilon D(n_{N_1} - n_{N_1}^{eq}) - W^{tot} n_{B-L}$$

$$D = K_1 z \frac{\kappa_1(z)}{\kappa_2(z)} \frac{H_{rad}(z)}{H(z)}$$

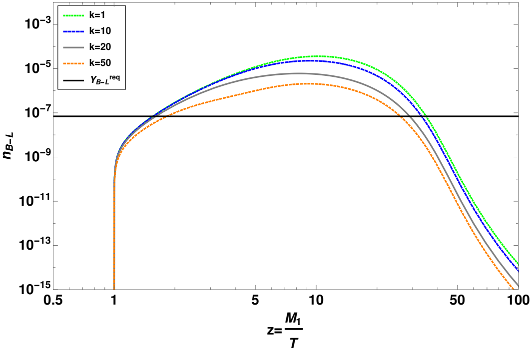
$$W = W_{ID} + \Delta W$$

$$W_{ID} = \frac{1}{4} K_1 z^3 \kappa_1(z) \frac{H_{rad}(z)}{H(z)}$$

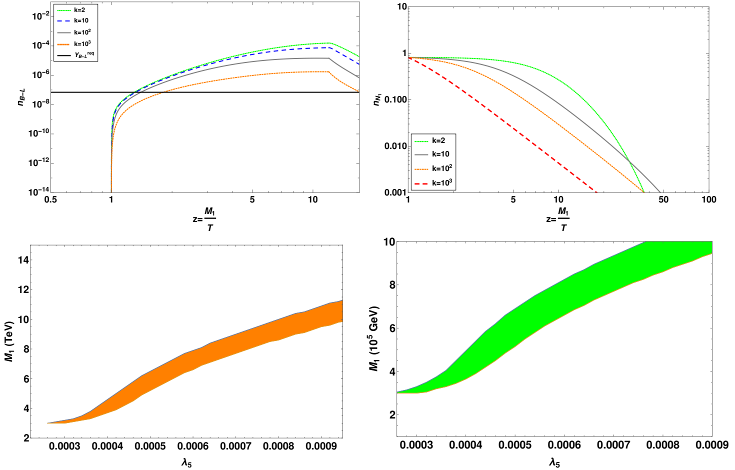
$$\Delta W = \frac{36\sqrt{5} M_{Pl}}{\pi^{1/2} g_l \sqrt{g_*} v^4} \frac{1}{z^2} \frac{1}{\lambda_5^2} M_1 \bar{m}_\xi^2 \frac{H_{rad}(z)}{H(z)}$$

$$\boxed{H(z) = \sqrt{\frac{\rho_\Phi(z) + \rho_{rad}(z)}{3M_{Pl}^2}}}$$

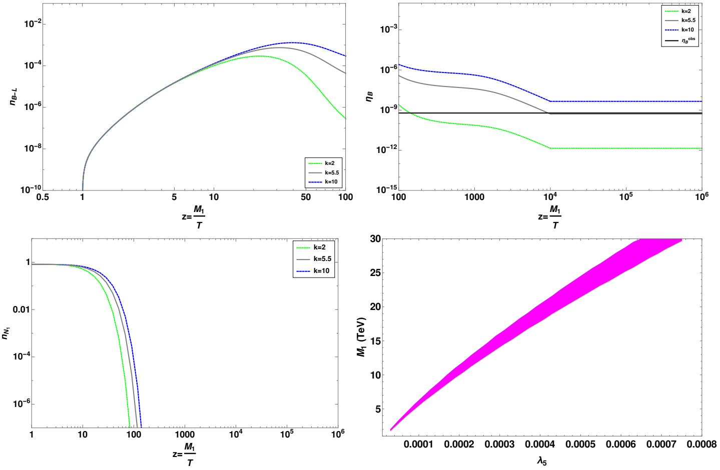
1. **Case 1:** $T_{Sphaleron} << T_{end} << T_{eq}$ $T_{end} = 10^3$ GeV, $M_1 = 2 \times 10^4$ GeV



1. **Case 2:** $T_{Sphaleron} \lesssim T_{end} << T_{eq}$ $\quad T_{end} = 250$ GeV, $M_1 = 3 \times 10^3$ GeV



1. **Case 3:** $T_{end} << T_{Sphaleron} << T_{eq}$ $\quad T_{end} = 1$ GeV, $M_1 = 10^4$ GeV



Dark matter in early matter dominated universe

$$\frac{dY}{dx} = -\frac{\langle \sigma v \rangle s}{Hx}\left(Y^2 - Y_{eq}^2\right)$$

Case 2: $T_{Sphaleron} \lesssim T_{end} << T_{eq}$

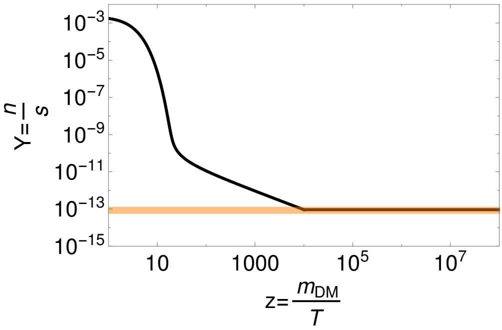


Figure: Cosmological parameters $T_{end} = 250$ GeV and $k = 10^3$. Particle physics parameters $m_{DM} = 2500$ GeV, $m_{A_0} = 2500.01$ ($\lambda_5 = 0.0005$) GeV, $m_{H^\pm} = 2500.02$ GeV $\lambda_L = 10^{-8}$ and $\lambda_2 = 10^{-2}$.

Case 3: $T_{Sphaleron} \lesssim T_{end} << T_{eq}$

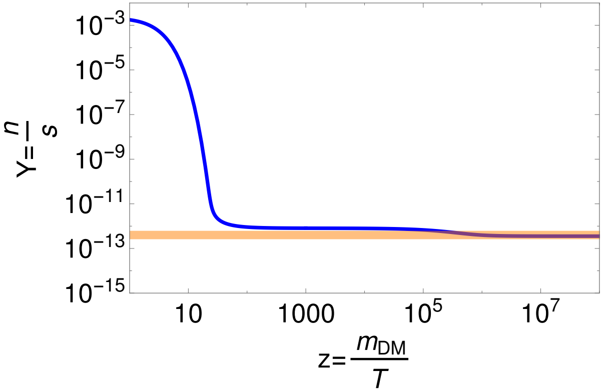


Figure: Cosmological parameters $T_{end} = 1$ GeV and $k = 5.5$. The particle physics parameters $m_{DM} = 1000$ GeV, $m_{A_0} = 1000.01$ GeV ($\lambda_5 = 0.0002$), $m_{H^\pm} = 1000.02$ GeV $\lambda_L = 10^{-8}$ and $\lambda_2 = 10^{-2}$.

Conclusions

1. The Leptogenesis scale is pushed up in a fast expanding universe, while a new parameter space which is usually forbidden, opens up for Dark Matter.

2. In an early matter dominated universe we found two possible cases for the cosmological history where the scale of Leptogenesis can be lower than the standard radiation case. In both these two cases the correct Dark Matter relic can be satisfied kepping the Dark Matter mass on the higher side.