On Exploring Leptogenesis in an Extension of the Scotogenic Model

PPC 2024 IIT Hyderabad
Parallel Session Talk
Based on: JCAP 02, 041 (2024)
In collaboration with
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Labh Singh
Central University of Himachal Pradesh

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Indian Institute of Technology Hyderabad

Introduction

- Why do all the structures in the Universe consist up of ordinary matter

  Matter-Antimatter Asymmetry $\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} = 6.1 \times 10^{-10}$

  PDG, PTEP, 2022

- Observation of BBN (T~ 1 MeV) and CMB (T~ 1eV) agree with each other

- What is the theoretical origin of matter-antimatter asymmetry?

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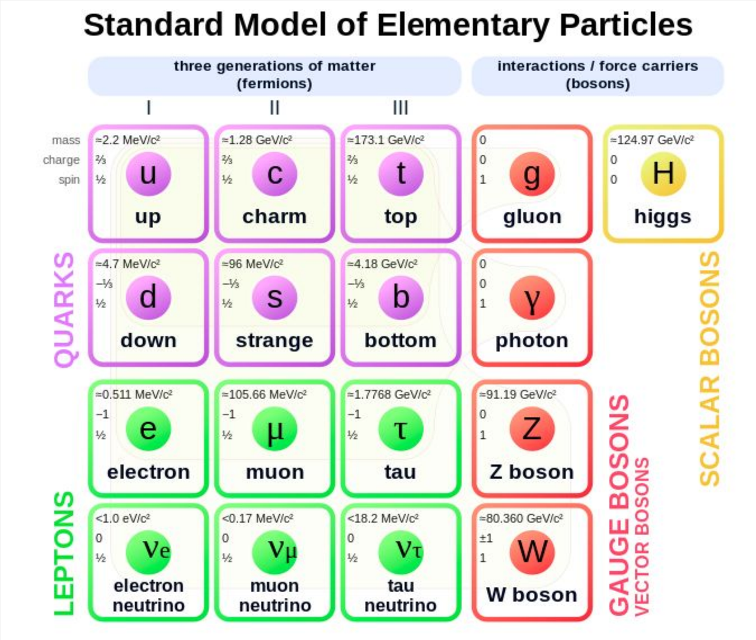
Leptogenesis

- <u>**Leptogenesis**</u>

Requirement of Leptogenesis



+ 3 (or atleast 2) Heavy Majorana fermions (N_R)

SM+3 RHN

Leptogenesis ⟷ **Type-I Seesaw**

- **Type-I seesaw + Leptogenesis**

$$\mathcal{L} = Y_\nu \nu_L \tilde{\Phi} \overline{N}_R + M_N \bar{N}_R^c N_R + h.c.$$

Fukugita and Yanagida 1986

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$$\begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix}$$

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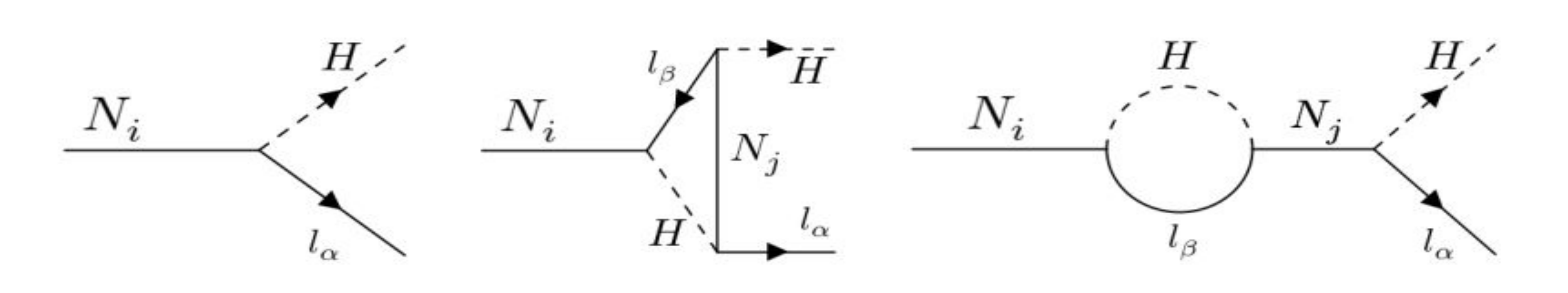

Covi, Roulet, Vissani, 1991

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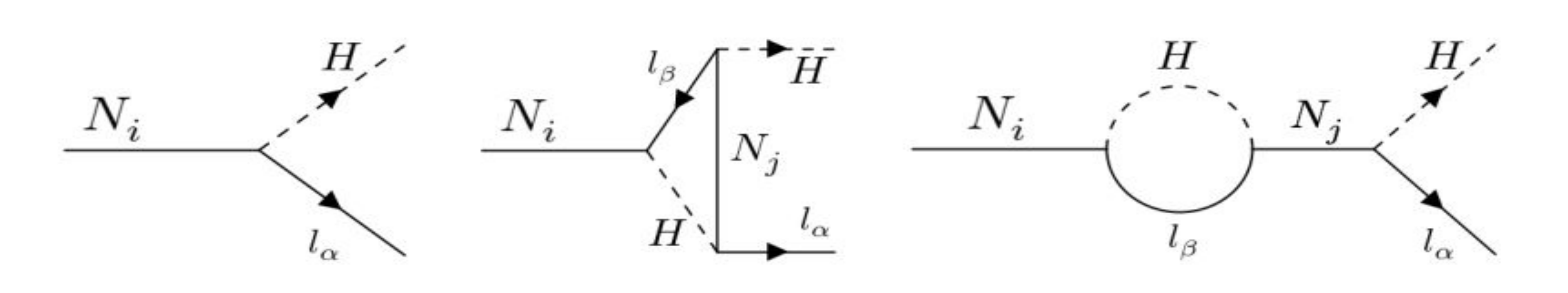
$Y^2 v^2$

Generates Neutrino mass and matter-antimatter asymmetry: Elegant



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- # Type-I seesaw + Leptogenesis

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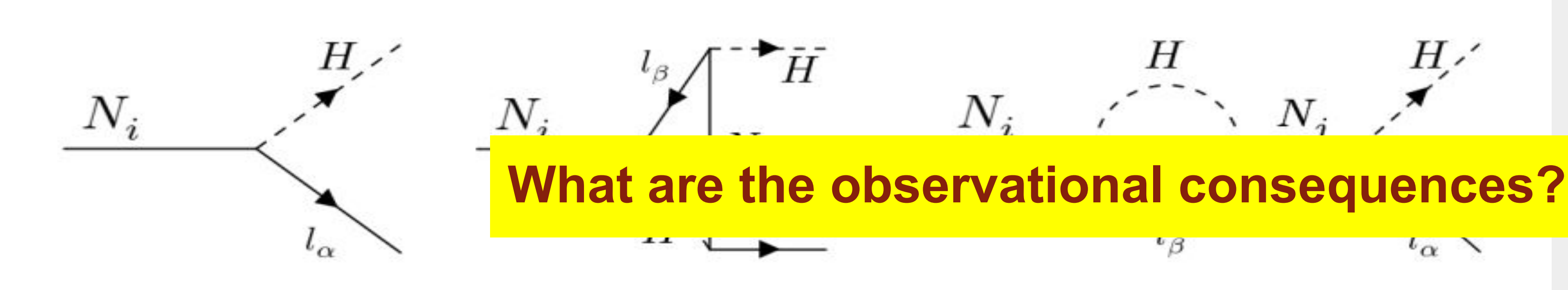

What are the observational consequences?

Covi, Roulet, Vissani, 1991

- **Type-1 seesaw + Leptogenesis**

$$\mathcal{L} = Y_\nu \nu_L \tilde{\Phi} \overline{N}_R + M_N \bar{N}_R^c N_R + h.c.$$

$$m_\nu = \frac{Y_\nu^2 v^2}{M_N} \approx 0.1eV$$ For $Y_\nu \approx \mathcal{O}(1), M_N$ have to be 10^{13}-10^{14} GeV.

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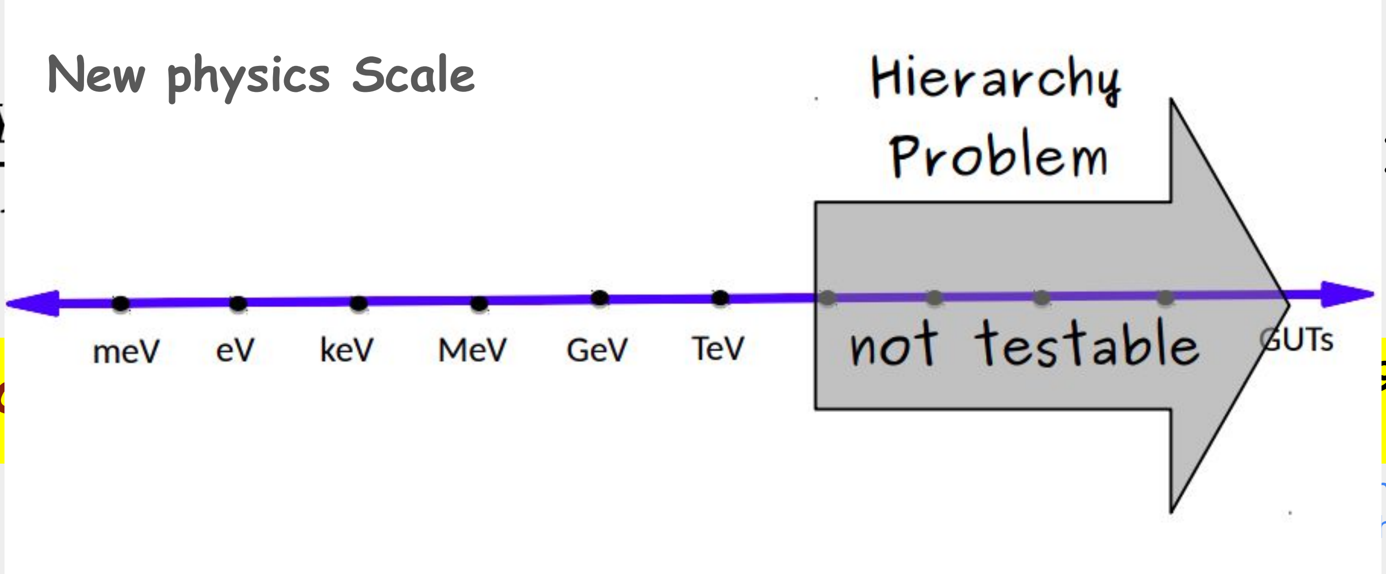
For successful leptogenesis and correct ν mass, $M_N \geq 10^9$ GeV

Davidson, Ibarra, hep-ph:0202239
Buchmuller, et. a, hep-ph:0401240l

• Type-1 seesaw + Leptogenesis

$m_\nu =$ ... 10^{13}-10^{14}



For succ ... **GeV**

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Inaccessible to conventional laboratory experiments!!

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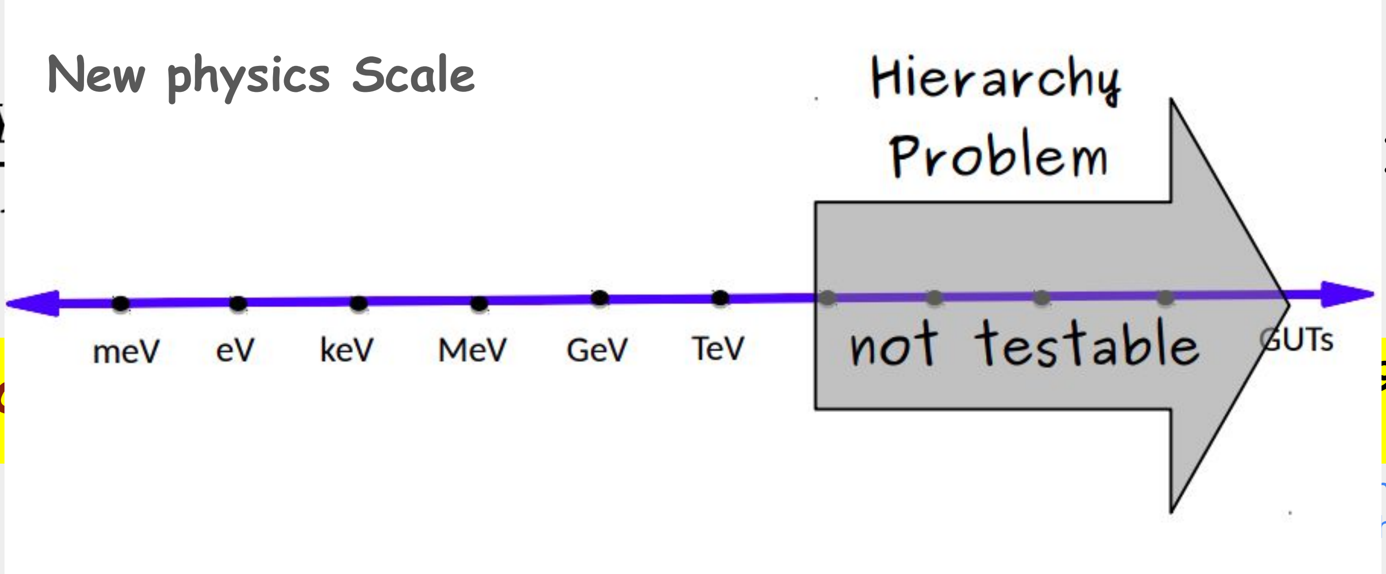

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Inaccessible to conventional laboratory experiments!!

Therefore, we are behind low scale leptogenesis scenarios

Singlet-Triplet Scoto-genic Model

Particle Content	Generations	Symmetry $(SU(2)_L \times U(1)_Y \times Z_2)$
L	3	$(2, -\frac{1}{2}, +)$
ϕ	1	$(2, \frac{1}{2}, +)$
N	1	$(1, 0, -)$
Σ	1	$(3, 0, -)$
Ω	1	$(3, 0, +)$
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Table: Particle content of the singlet-triplet scotogenic model

M. Hirsch, et. al, JHEP, 2013

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Beyond SM particle: N, Σ, Ω, η

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SM particles (L, ϕ)

Beyond SM particle (N, Σ, Ω, η)

Contribute to ν mass generation and Leptogenesis (N, Σ)

Contribute to the W-mass anomaly (Ω)

Dark-matter candidate (η)

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The relevant Yukawa Lagrangian of the model is given by

$$\begin{aligned}\mathcal{L} &= Y_L^{\alpha\beta}\overline{L_\alpha}\phi\ell_\beta + Y_N^{\alpha}\overline{L_\alpha}i\sigma_2\eta N + Y_\Sigma^{\alpha}\overline{L_\alpha}C\Sigma^\dagger i\sigma_2\eta + Y_\Omega \mathrm{Tr}(\overline{\Sigma\Omega})N \\ &+ \frac{1}{2}M_N\overline{N^c}N + \frac{1}{2}M_\Sigma \mathrm{Tr}(\overline{\Sigma^c}\Sigma) + h.c.\end{aligned}$$

The scalar potential of the model is given by

$$\begin{aligned}V &= -m_\phi^2\phi^\dagger\phi + m_\eta^2\eta^\dagger\eta + \frac{\lambda_1}{2}\left(\phi^\dagger\phi\right)^2 + \frac{\lambda_2}{2}\left(\eta^\dagger\eta\right)^2 + \frac{m_\Omega^2}{2}Tr\left(\Omega^\dagger\Omega\right) + \lambda_3\left(\phi^\dagger\phi\right)\left(\eta^\dagger\eta\right) \\ &+ \lambda_4\left(\phi^\dagger\eta\right)\left(\eta^\dagger\phi\right)\frac{\lambda_5}{2}\left[\left(\phi^\dagger\eta\right)^2 + h.c.\right] + \frac{\lambda^\eta}{2}\left(\eta^\dagger\eta\right)Tr\left(\Omega^\dagger\Omega\right) \\ &+ \frac{\lambda_1^\Omega}{2}\left(\phi^\dagger\phi\right)Tr\left(\Omega^\dagger\Omega\right) + \frac{\lambda_2^\Omega}{4}Tr\left(\Omega^\dagger\Omega\right)^2 + \mu_1\phi^\dagger\Omega\phi + \mu_2\eta^\dagger\Omega\eta.\end{aligned}$$

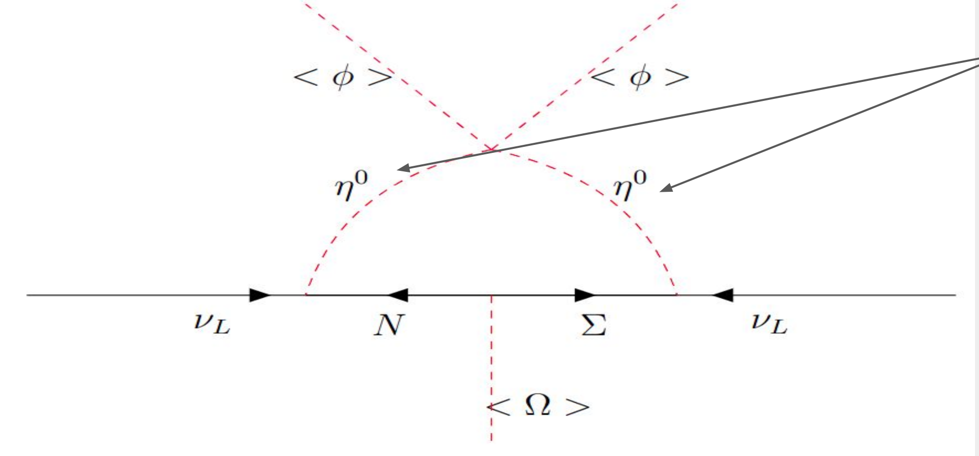
After EWSB, the masses of scalar sector

$$m_{\eta^{\pm}}^2 = m_\eta^2 + \frac{1}{2}\lambda_3 v_\phi^2 + \frac{1}{2}\lambda^\eta v_\Omega^2 + \frac{1}{\sqrt{2}} v_\Omega \mu_2,$$
$$m_{\eta^R}^2 = m_\eta^2 + \frac{1}{2}\lambda_3 v_\phi^2 + \frac{1}{2}(\lambda_4 + \lambda_5) v_\phi^2 - \frac{1}{\sqrt{2}} v_\Omega \mu_2 + \frac{1}{2}\lambda^\eta v_\Omega^2,$$
$$m_{\eta^I}^2 = m_\eta^2 + \frac{1}{2}\lambda_3 v_\phi^2 + \frac{1}{2}(\lambda_4 - \lambda_5) v_\phi^2 - \frac{1}{\sqrt{2}} v_\Omega \mu_2 + \frac{1}{2}\lambda^\eta v_\Omega^2.$$

And masses of fermion sector are

$$m_{\chi^{\pm}} = M_\Sigma,$$
$$m_{\chi^0_{1,2}} = \frac{1}{2}\left(M_\Sigma + M_N \mp \sqrt{(M_\Sigma - M_N)^2 + 4(v_\Omega Y_\Omega)^2}\right),$$

The neutrino mass generated at one-loop level



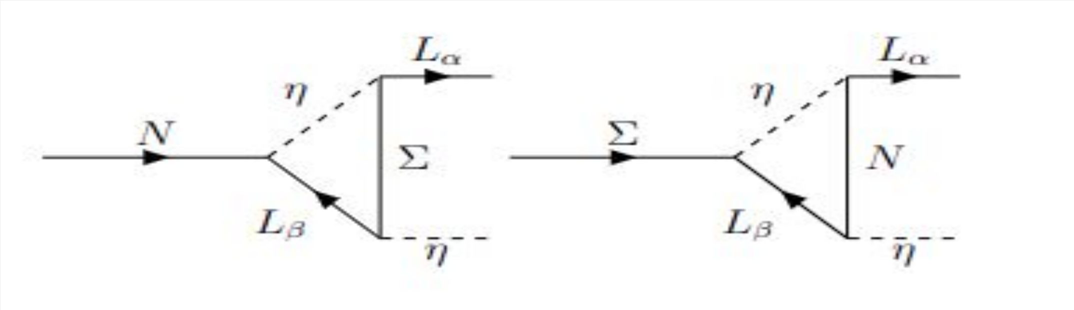
Dark-Matter contribute to neutrino mass generation

M. Hirsch, et. al, JHEP, 2013

$$(\mathcal{M}_\nu)_{\alpha\beta} = \sum_{i=1}^{2} \frac{h_{\alpha i} h_{\beta i} m_{\chi_i^0}}{2(4\pi)^2} \left[\frac{m^2_{\eta^R} \ln\left(\frac{m_i^2}{m^2_{\eta^0}}\right)}{m^2_{\chi_i^0} - m^2_{\eta^R}} - \frac{m^2_{\eta^I} \ln\left(\frac{m^2_{\chi_i^0}}{m^2_{\eta^I}}\right)}{m^2_{\chi_i^0} - m^2_{\eta^I}} \right]$$

For low scale leptogenesis in our model, we considered both the heavy fermions to be moderately hierarchical.

$M_N \gtrapprox M_\Sigma$



LS, D. Mahanta, S. Verma, JCAP, 2024

CP-Asymmetry parameter:

$$\epsilon^{F(\Sigma)} = \frac{1}{8\pi\left(Y^\dagger_{F(\Sigma)} Y_{F(\Sigma)}\right)} \sum_{j\neq i} \mathrm{Im}\left[\left(Y^\dagger_{F(\Sigma)} Y_{\Sigma(F)}\right)^2_{ij}\right] \mathcal{F}\left(\frac{M^2_{\Sigma(F)}}{M^2_{F(\Sigma)}}\right)$$

where $$\mathcal{F}(x) = \sqrt{x}\left[1 + \frac{1}{1-x} + (1+x)\ln\left(\frac{x}{1+x}\right)\right]$$

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} = 6.1 \times 10^{-10}$$

Parameters of model (Yukawa Coupling) → Boltzmann Equation → Lepton Asymmetry

Comoving number density of Σ, N and B-L asymmetry

$$\frac{dn_\Sigma}{dz} = -D_\Sigma(n_\Sigma - n_\Sigma^{eq}) - S_A(n_\Sigma^2 - (n_\Sigma^{eq})^2),$$

$$\frac{dn_N}{dz} = -D_N(n_N - n_N^{eq}),$$

$$\frac{dn_{B-L}}{dz} = -\epsilon^\Sigma D_\Sigma(n_\Sigma - n_\Sigma^{eq}) - \epsilon^N D_N(n_N - n_N^{eq}) - W_{\rm ID}^\Sigma n_{B-L} - W_{\rm ID}^N n_{B-L} - W_{\Delta L} n_{B-L}.$$

LS, D. Mahanta, S. Verma, JCAP, 2024

Due to CP- violations

⇓

More Anti-Leptons than Leptons

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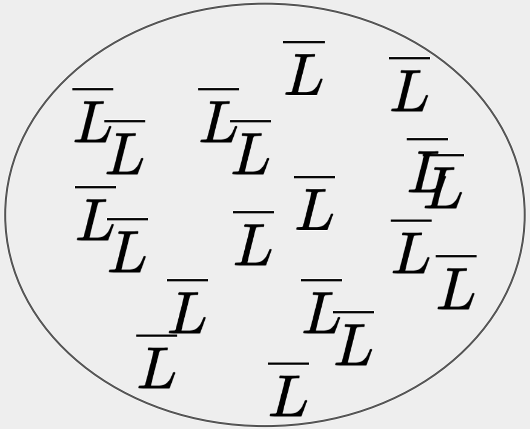
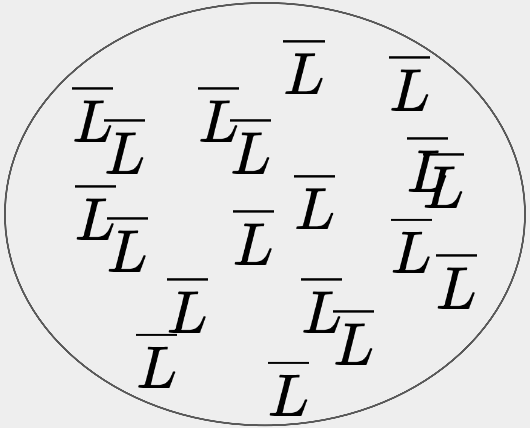


Asymmetry in the Lepton sector

Due to CP- violations

More Anti-Leptons than Leptons

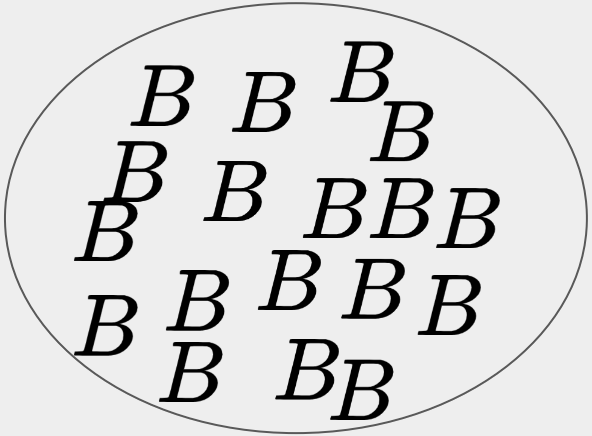
L=-1, B=0
B-L=1, **B+L=-1**



Sphaleron Process

(Converts Lepton Asymmetry into Baryon Asymmetry before EWPT)

L=0, B=1
B-L=1, **B+L=1**

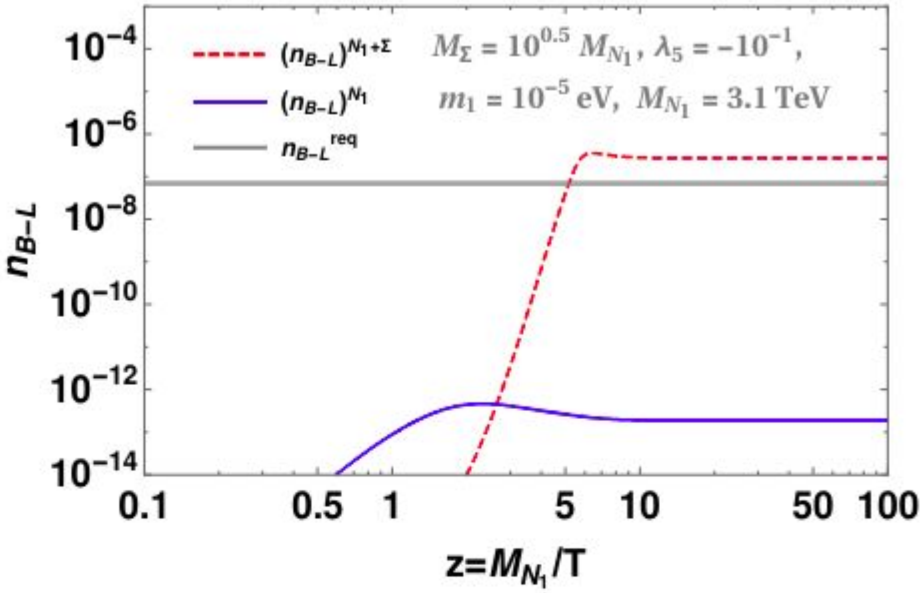


Asymmetry in the Lepton sector

Asymmetry in the Baryon sector

$$\eta_{B-L} = 9.2 \times 10^{-3}\eta$$

Results


$(n_{B-L})^{N_1+\Sigma}$
$(n_{B-L})^{N_1}$
n_{B-L}^{req}
$M_\Sigma = 10^{0.5}\, M_{N_1},\ \lambda_5 = -10^{-1},$
$m_1 = 10^{-5}$ eV, $M_{N_1} = 3.1$ TeV
n_{B-L}
10^{-4} 10^{-6} 10^{-8} 10^{-10} 10^{-12} 10^{-14}
0.1 0.5 1 5 10 50 100
$z=M_{N_1}/T$

Results

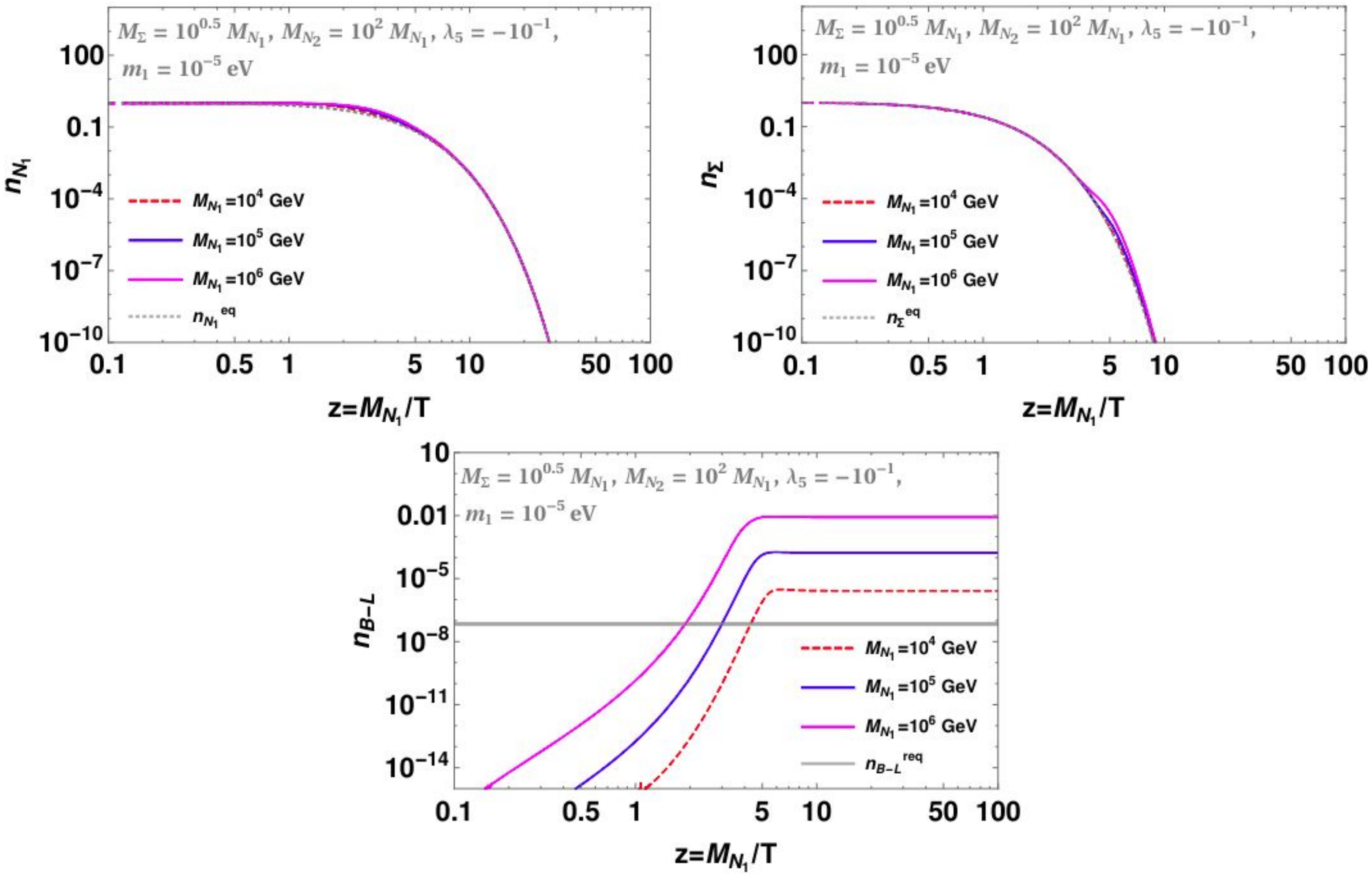


Figure 2: Evolution of comoving number density w.r.t Z.

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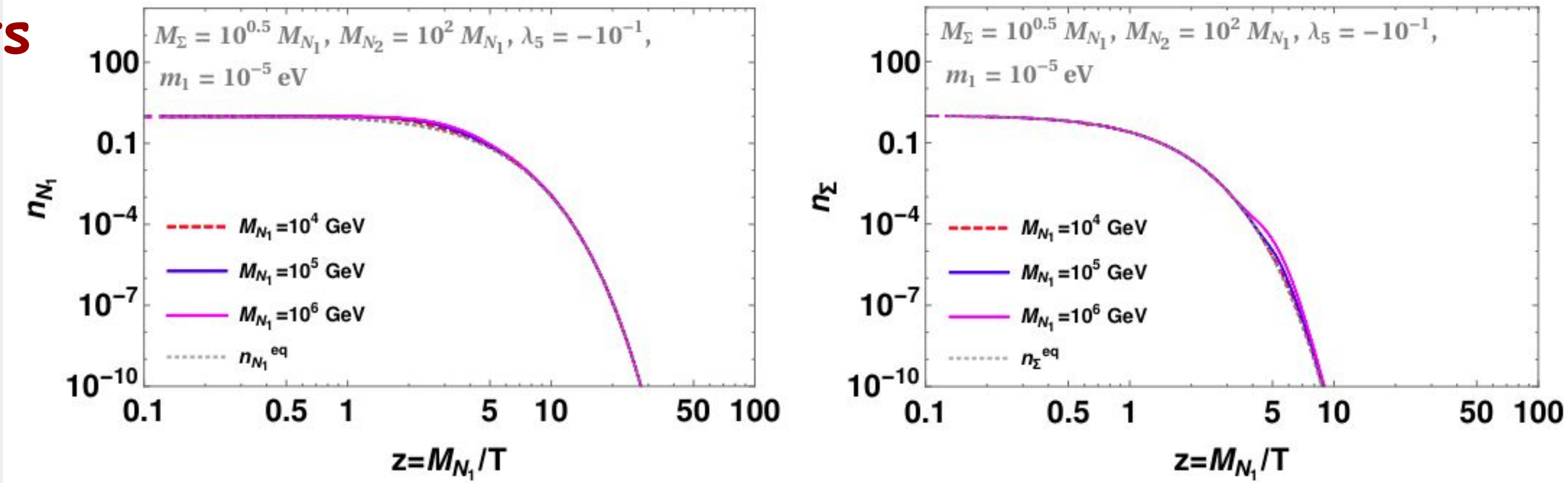

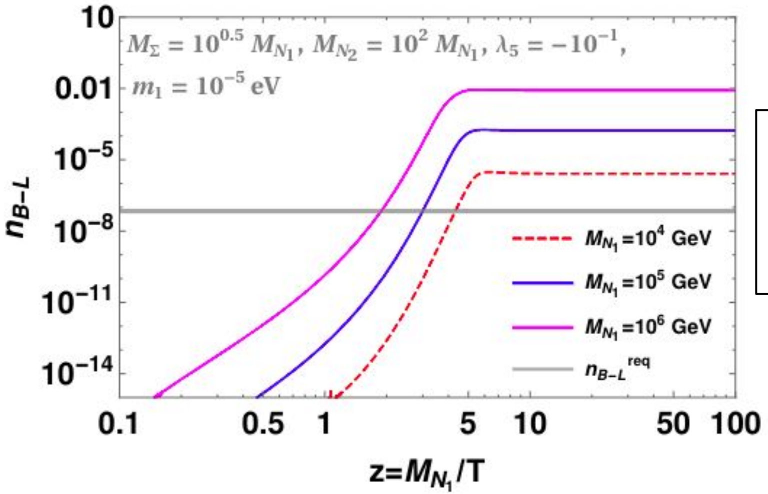

We found the scale of the leptogenesis around TeV range

Figure 2: Evolution of comoving number density w.r.t Z.

Summary

- In this work, we have realised low-scale leptogenesis in singlet-triplet scotogenic model.
- We obtained the scale of the leptogenesis in the TeV range.
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Thank You