Sterile Neutrinos

from Leptogenesis to NSI

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Outline

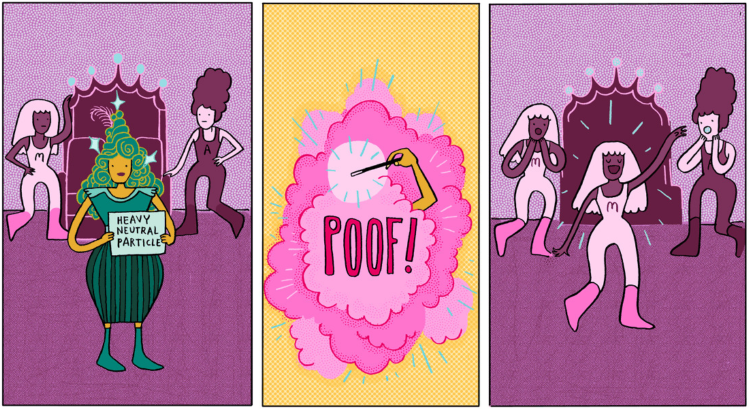
- Leptogenesis
  - Thermal leptogenesis in the presence of hypermagnetic fields
  - Nonextensive cosmology effect on thermal leptogenesis
  - Anisotropic cosmology effect on thermal leptogenesis
- Non-Standard Interaction
  - Axial NC DIS of neutrino-nucleus in the presence of NSI

Bachelor of science in physics

Master of science in particle physics

Leptogenesis

Thermal leptogenesis

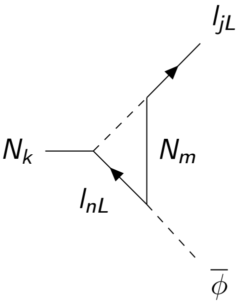


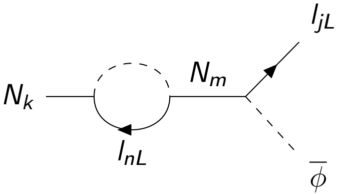
Through extension of the standard model by adding at least two right-handed neutrinos.

M.A. Luty, Phys.Rev.D 45 (1992) 455-465

CP violation

$$\epsilon_1 \equiv \frac{\Gamma_1 - \overline{\Gamma}_1}{\Gamma_1 + \overline{\Gamma}_1}$$





$$\epsilon_1 = \sum_{k \neq 1} \frac{1}{8\pi} \frac{\Im\left(yy^\dagger\right)^2_{1k}}{(yy^\dagger)_{11}} \left[f\left(\frac{M_k^2}{M_1^2}\right) + \frac{M_1 M_k}{M_1^2 - M_k^2} \right]$$

Davidson-Ibarra bound

$$M_1 > 10^9 \text{ GeV}$$

S. Davidson et al., Phys.Lett.B 535 (2002) 25-32

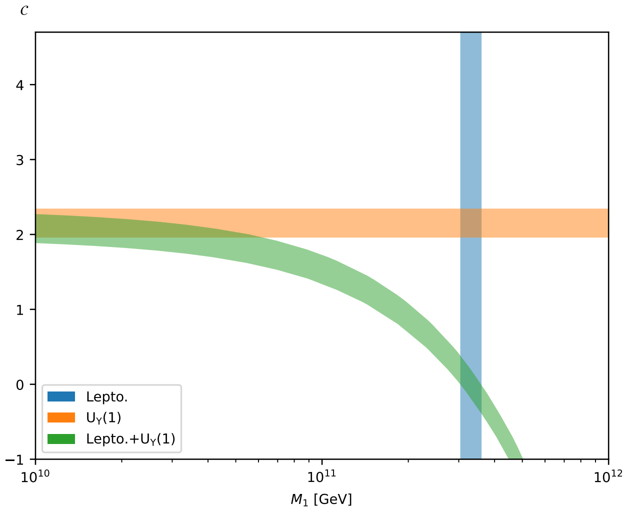
Thermal leptogenesis in the presence of hypermagnetic fields

S. Safari, MD, S. Abbaslu, S. S. Gousheh, arXiv:2401.01105

Baryogenesis through $U_Y(1)$ anomaly and RHN decay

$$\nabla_\mu j_r^\mu \propto \begin{cases} F_{\mu\nu}\tilde{F}^{\mu\nu} & \\ G_{\mu\nu}\tilde{G}^{\mu\nu}, & \sum 2q_L \rightleftarrows u_R + d_R, \\ W_{\mu\nu}\tilde{W}^{\mu\nu}, & \sum 3q_L \rightleftarrows -l_L \\ f_L \rightleftarrows f_R + \phi & \\ N \rightleftarrows l_L + \phi & \end{cases}$$

Numerical results



Nonextensive cosmology effect on thermal leptogenesis

MD, Eur.Phys.J.C 84 (2024) 3, 340

Modified distribution function

The generalized distribution function is parameterized by a real number $q \in [0, 2]$ known as the Tsallis parameter

$$f^q = \left[e_q^{\left(\frac{E-\mu}{T}\right)} + \xi \right]^{-1}$$

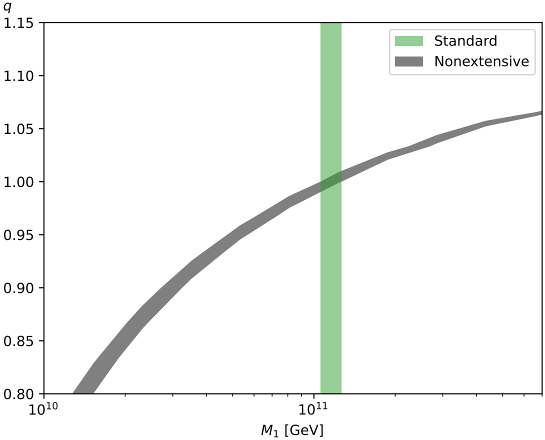
$$e_q^x \equiv \left[1 + (q-1)\,x\right]^{\frac{1}{1-q}}$$

C. Tsallis, J.Statist.Phys. 52 (1988) 479-487

In this way, the Hubble expansion rate, entropy density, and equilibrium amount of particles will be modified.

M.E. Pessah et al., Physica A 297 (2001) 164-200

Numerical results



Anisotropic cosmology effect on thermal leptogenesis

MD, Int.J.Mod.Phys.A 38 (2023) 35n36, 2350181

Bianchi type-I metric and Friedmann equation

$$ds^2 = -dt^2 + a_1^2(t)dx^2 + a_2^2(t)dy^2 + a_3^2(t)dz^2$$

$$H^2 = \frac{8\pi G}{3}\epsilon_r + \frac{1}{3}\sigma^2$$

$$a \equiv (a_1 a_2 a_3)^{1/3}, \quad H \equiv \dot{a}/a = \frac{1}{3}(H_1 + H_2 + H_3)$$

$$\sigma^2 \equiv \frac{1}{6}\left[(H_1 - H_2)^2 + (H_2 - H_3)^2 + (H_3 - H_1)^2\right]$$

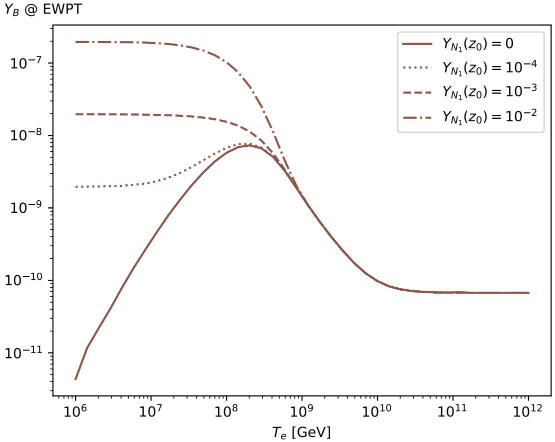
E. Russell et al., Mon.Not.Roy.Astron.Soc. 442 (2014) 3

Modified Hubble expansion rate

$$H = \frac{1.66}{M_{\mathrm{Pl}}}(g_\star)^{1/2}\,T^2\sqrt{1+\frac{g_\star}{g_\star^e}\frac{T^2}{T_e^2}}$$

M. Kamionkowski et al., Phys. Rev. D 42 (1990) 3310

Numerical results



Non-Standard Interaction

Origin of NSI

The seesaw mechanism may lead the NSI!

M. Malinsky et al., Phys.Rev.D 79 (2009) 011301

Effective lagrangian

$$\mathcal{L}_{\mathrm{NSI}}^{\mathrm{CC}} = -2\sqrt{2}G_{\mathrm{F}} \sum_{f,f',P} \epsilon_{\alpha\beta}^{ff'P} \left[\overline{\nu}_\alpha \gamma_\rho L l_\beta\right] \left[\overline{f}\gamma^\rho P f'\right]$$

$$\mathcal{L}_{\mathrm{NSI}}^{\mathrm{NC}} = -2\sqrt{2}G_{\mathrm{F}} \sum_{f,P} \epsilon_{\alpha\beta}^{fP} \left[\overline{\nu}_\alpha \gamma_\rho L \nu_\beta\right] \left[\overline{f}\gamma^\rho P f\right]$$

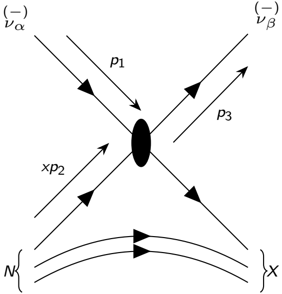
Y. Farzan et al., Front.in Phys. 6 (2018) 10

Postmaster

Axial NC DIS of neutrino-nucleus in the presence of NSI

S. Abbaslu, MD, S. Safari, Y. Farzan, JHEP 04 (2024) 038

X.S.



$$\frac{d^2\sigma(\overset{(-)}{\nu}_\alpha + N \to \overset{(-)}{\nu}_\beta + X)}{dxdy} = \sigma_0 \left\{ \frac{1}{2}\left(xy^2 + 2x - 2xy - \frac{M_N}{E_\nu} x^2 y \right) \right.$$
$$\times \left[\sum_q f_N^q(x) \left(\left| f_{\alpha\beta}^{Vq} \right|^2 + \left| f_{\alpha\beta}^{Aq} \right|^2 \right) + \sum_{\bar{q}} f_N^{\bar{q}}(x) \left(\left| f_{\alpha\beta}^{Vq} \right|^2 + \left| f_{\alpha\beta}^{Aq} \right|^2 \right) \right]$$
$$\left. \pm 2xy\left(1 - \frac{y}{2}\right) \left[\sum_q f_N^q(x) \Re\left[f_{\alpha\beta}^{Vq} (f_{\alpha\beta}^{Aq})^* \right] - \sum_{\bar{q}} f_N^{\bar{q}}(x) \Re\left[f_{\alpha\beta}^{Vq} (f_{\alpha\beta}^{Aq})^* \right] \right] \right\}$$

Oscillation corrections

$$(\sigma_{n/p})_{\overset{(-)}{\nu}_{\mathrm{far}}} = \sum_{\alpha \in \{\mathrm{far}, \perp, T\}} \sigma_{n/p}(\overset{(-)}{\nu}_{\mathrm{far}} + N \to \overset{(-)}{\nu}_{\alpha} + X)$$

$$\begin{pmatrix} \nu_{\mathrm{far}} \\ \nu_{\perp} \\ \nu_T \end{pmatrix} = \begin{pmatrix} \mathcal{A}_e & \mathcal{A}_\mu & \mathcal{A}_\tau \\ 0 & -\mathcal{A}_\tau^*/\mathcal{A} & \mathcal{A}_\mu^*/\mathcal{A} \\ \frac{\mathcal{A}\mathcal{A}_e}{|\mathcal{A}_e|} & -\frac{\mathcal{A}_\mu |\mathcal{A}_e|}{\mathcal{A}} & -\frac{\mathcal{A}_\tau |\mathcal{A}_e|}{\mathcal{A}} \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

$$|\mathcal{A}_\beta|^2 = P(\nu_\mu \to \nu_\beta)$$

Number of events in the DUNE experiment

$$\mathcal{N}^{\rm ND}_{\overset{(-)}{\nu}} = \int \phi^{\rm ND}_{\overset{(-)}{\nu}}(E) \left[(\sigma_n)_{\overset{(-)}{\nu}_\mu} N_n^{\rm ND} + (\sigma_p)_{\overset{(-)}{\nu}_\mu} N_p^{\rm ND} \right] dE$$

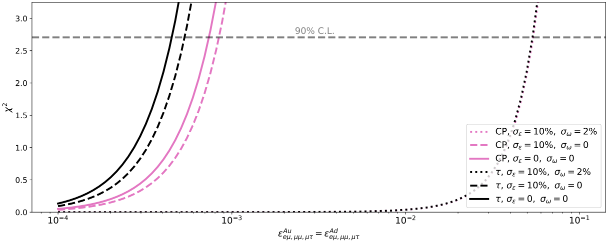
$$\mathcal{N}^{\rm FD}_{\overset{(-)}{\nu}} = \int \phi^{\rm FD}_{\overset{(-)}{\nu}}(E) \left[(\sigma_n)_{\overset{(-)}{\nu}_{\rm far}} N_n^{\rm FD} + (\sigma_p)_{\overset{(-)}{\nu}_{\rm far}} N_p^{\rm FD} \right] dE$$

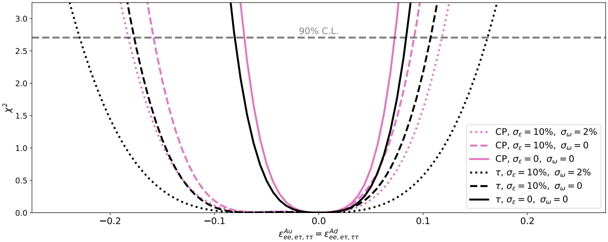
$$N_p^{\rm ND/FD} = \frac{18}{40} \frac{M_{\rm fid}^{\rm ND/FD}}{M_p} \quad \text{and} \quad N_n^{\rm ND/FD} = \frac{22}{40} \frac{M_{\rm fid}^{\rm ND/FD}}{M_p}$$

$$\mathcal{B}^{\rm ND/FD}_{\nu/\overline{\nu}} = \epsilon_{\rm CC} (\mathcal{N}^{\rm ND/FD}_{\rm CC})_{\nu/\overline{\nu}} + \epsilon_{\rm Res} (\mathcal{N}^{\rm ND/FD}_{\rm Res})_{\nu/\overline{\nu}}$$

Bound forecasting in the DUNE experiment

$$\chi^2 = \left[\sum_{Y=\nu,\overline{\nu}} \left(\frac{\left[\xi \mathcal{N}_Y(\epsilon^{Aq}_{\rm test}) - \epsilon \mathcal{N}_Y(\epsilon^{Aq}=0) + \omega_Y \mathcal{B}_Y \right]^2}{\epsilon \mathcal{N}_Y(\epsilon^{Aq}=0) + \mathcal{B}_Y} + \frac{\omega_Y^2}{\sigma_\omega^2} \right) + \frac{(\xi-\epsilon)^2}{\sigma_\epsilon^2} \right]_{\rm min}$$





Thanks for your attention!