# Thermal leptogenesis in the type-I Dirac seesaw extension to the DFSZ axion model for dark matter


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**Abstract**

The type-I Dirac seesaw extension is made to the DFSZ axion model, where light active neutrinos are Dirac particles and acquire mass through the canonical seesaw mechanism after the Peccei-Quinn and electroweak symmetry breaking, finding that neutrino mass is given by $m_\nu \approx v f_a/\Lambda_{UV}$, result which relates the three energy scales involved in the model: the mass of the heavy sterile Dirac fermions introduced ($\Lambda_{UV}$), Peccei-Quinn scale ($f_a$), and electroweak scale ($v$). As a consequence, it was found that $10^3 f_a \sim \Lambda_{UV}$, hence neutrino Yukawa coupling associated to the QCD axion, candidate to dark matter, is highly (up to $10^{-10}$) suppressed in comparison to the Higgs. Dirac neutrino effective mass matrix is computed explicitly, whose components depend on active-sterile mixing parameters, the latter being new sources of CP violation. Therefore, the CP asymmetry factor and the baryon-antibaryon density are computed for the unflavoured leptogenesis, linking neutrino physics, QCD axion, and cosmological parameters into a same physical framework.


## Introduction

Neutrino masses [1], baryon asymmetry of the universe [2], and dark matter [3] are three of the biggest problems in theoretical and particle physics. Neutrino mass generation mechanisms can lead to the introduction of new sources of CP violation [4], and due to Sakharov conditions [5], it leads to a lepton symmetry which can be transform into a baryon asymmetry [6]. This is known as leptogenesis and relates the first two problems. On the other hand, as a consequence of Peccei-Quinn mechanism, a massive and weakly coupled scalar particle, the QCD axion, emerges as a good candidate to be dark matter [7]. In this work the three problems are covered in the same framework: The DFSZ axion model is extended through the type-I Dirac seesaw model [8].

## Methodology: The model

The Standard Model of particle physics is extended to the two-Higgs-doublet model, in order to impose the Peccei-Quinn symmetry [7]. Also, a sterile scalar is introduced to separate the spontaneous symmetry breaking energy scales [8]. Dirac extension for light active neutrinos emerges from Peccei-Quinn invariance, as well as the introduction of three heavy sterile Dirac fermions through the type-I Dirac seesaw model [8].

$$-\mathcal{L}_Y = y^u_{ij}\overline{Q}_i H_u u_j + y^d_{ij}\overline{Q}_i H_d d_j + y^l_{ij}\overline{E}_{L,i} H_d e_j + h.c. + \mathcal{L}_{Type-I}$$

With:

$$-\mathcal{L}_{Type-I} = y^h_{\alpha\beta}\overline{E}_{L,\alpha} H_u N_{R,\beta} + y^\chi_{\alpha\beta}\overline{N}_{L,\alpha}\chi\nu_{R,\beta} + \frac{1}{2}\overline{N}_{L,\alpha} M^N_{\alpha\beta} N_{R,\beta} + h.c.$$

Thus, the Yukawa interactions associated to the type-I seesaw model looks like:

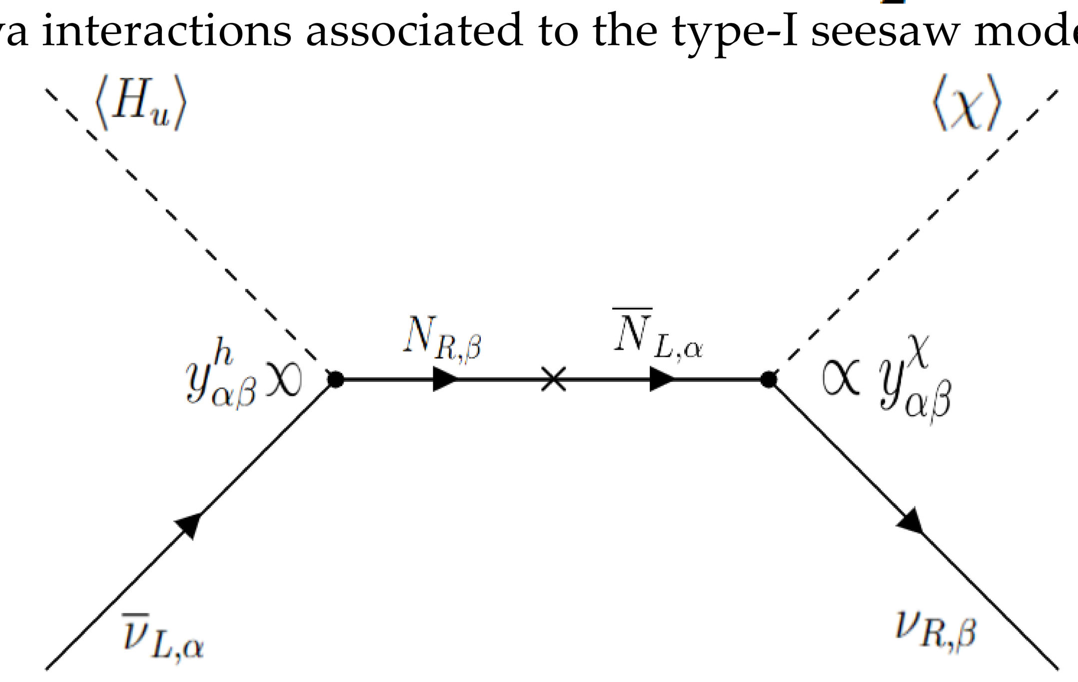


**Figure 1: Feynmann diagram for neutrino mass generation at tree-level.**

### Mass generation mechanism

Neutrino mass is generated via the Peccei-Quinn mechanism, where spontaneous Peccei-Quinn symmetry $U(1)_{PQ}$ and Standard Model gauge symmetry take place, where each corresponds to a different energy scale. A QCD axion emerges since $U(1)_{PQ}$ is a global symmetry [7].

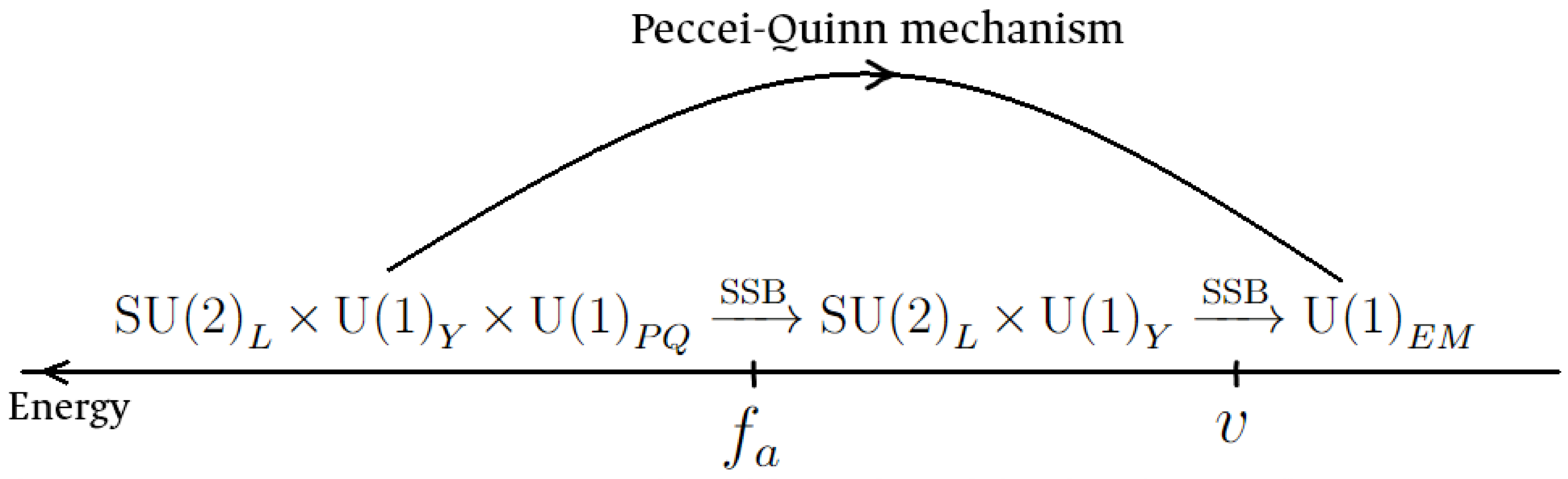


**Figure 2: Spontaneous symmetry breakings (SSB) in the Peccei-Quinn mechanism.**

## Results

In the (1+1)-scheme the light active neutrino mass is found to be [8]:

$$m_\nu \approx \frac{v f_a}{\Lambda_{UV}}$$

Consequently, from experimental measures of neutrino mass and bounds of $f_a$, it is found that:

$$10^3\,\mathrm{GeV}\, f_a \sim \Lambda_{UV}$$

Therefore, the heavy sterile fermion mass scale is bounded to $10^9 GeV \leq \Lambda_{UV} \leq 10^{15} GeV$, and leptogenesis mechanism is guaranteed in the model [9].

In the (3+3)-scheme, the light active neutrino mass matrix $m_\nu = diag(m_1, m_2, m_3)$ is given by:

$$m_\nu \approx -M^D \left(M^N\right)^{-1} \left(M^D\right)^\dagger$$

Where $M^N = diag(M_1, M_2, M_3) \sim \Lambda_{UV}$ is the mass matrix for the heavy sterile fermions, and $M^D$ is the Dirac neutrino effective mass matrix, which was found to be:

$$M^D = U^\dagger_{PMNS}\begin{pmatrix} (m_1 - M_1)\hat{S}^*_{14} & (m_1 - M_2)\hat{S}^*_{15} & (m_1 - M_3)\hat{S}^*_{16} \\ (m_2 - M_1)\hat{S}^*_{24} & (m_2 - M_2)\hat{S}^*_{25} & (m_2 - M_3)\hat{S}^*_{26} \\ (m_3 - M_1)\hat{S}^*_{34} & (m_3 - M_2)\hat{S}^*_{35} & (m_3 - M_3)\hat{S}^*_{36} \end{pmatrix}$$

With $\hat{S}^*_{ij} = e^{\delta_{ij}} \sin\theta_{ij}$, where $\theta_{ij}$ is the mixing angle, and $\delta_{ij}$ the CP-violating phase, and $U_{PMNS}$ the leptonic flavour-mixing matrix.

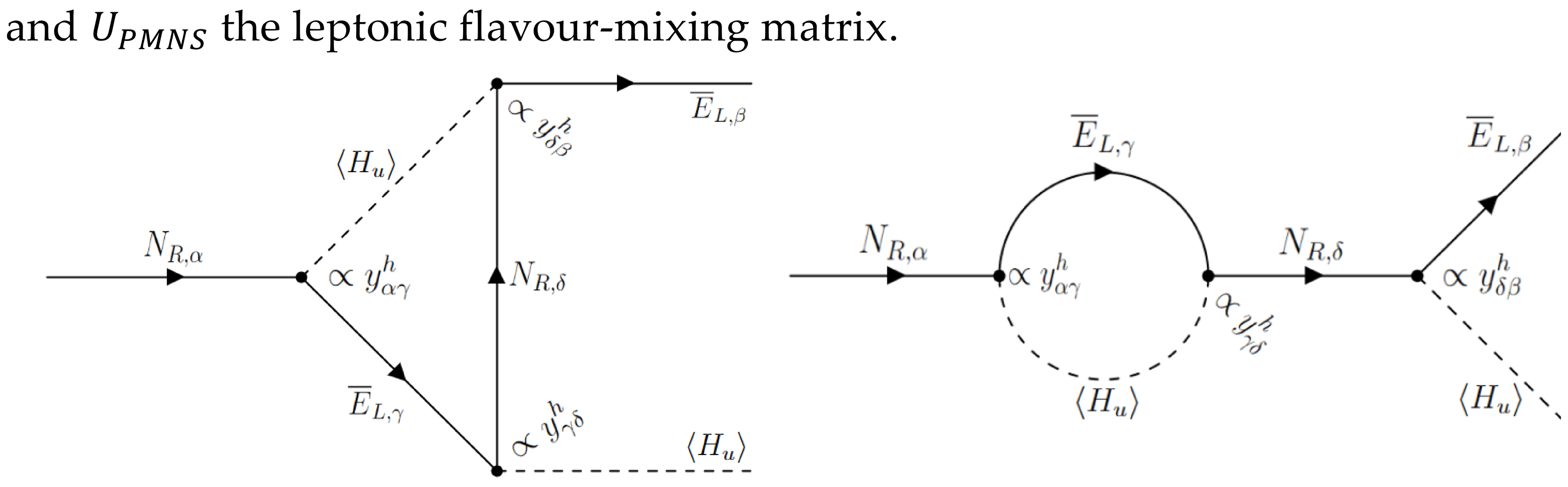


**Figure 3: Decays of the heavy sterile Dirac fermion $N_{R,\alpha}$ at one-loop.**

Decays of the heavy sterile fermions $N_{R,\alpha}$ lead to a lepton-number asymmetry, which can be estimated via the CP-violation parameter for unflavored leptogenesis [9]:

$$\epsilon_1 = \frac{1}{32\pi \sin^2\beta v^2 f_a^2 (M^D(M^D)^\dagger M^D(M^D)^\dagger)_{11}} \sum_{j\neq 1}^{3} \mathrm{Im}\left[(M^D(M^D)^\dagger M^D(M^D)^\dagger)^2_{1j}\right] f(x_{j1})$$

And the lepton-number asymmetry is transformed into a baryon asymmetry through the sphaleron processes. Thus, the baryon-antibaryon density can be computed as [9]:

$$Y_{\Delta B} = -C Y_{\Delta L} \approx -C\frac{k}{g_{*s}}\epsilon_1 \approx -(0{,}0904)k\epsilon_1$$

Where the efficiency factor satisfies $10^{-3} \leq k \leq 1$.

## Conclusion

Peccei-Quinn invariance condition leads to Dirac light active neutrinos, and the seesaw extension must be type-I Dirac. The light active neutrino mass was found to be $m_\nu \approx v f_a/\Lambda_{UV}$, implying that $10^3 f_a \sim \Lambda_{UV}$, which leads to impose upper and lower boundaries in the mass scale for heavy sterile fermions $10^9 GeV \leq \Lambda_{UV} \leq 10^{15} GeV$. The Dirac neutrino effective mass matrix was computed explicitly, and there were found expressions to compute the CP asymmetry factor and the baryon-antibaryon density.

## References


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