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

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What is this work about?

- Four of the biggest problems in cosmology and theoretical physics:
  1. Neutrino masses
  2. Baryon asymmetry of the universe
  3. Strong CP problem
  4. Dark matter

- These problems will be **linked together into a same model**, in which the following are the proposed solutions:
  1. Type-I Dirac seesaw model
  2. Thermal leptogenesis
  3. Peccei-Quinn symmetry
  4. Scalar and weakly coupled massive particle: DFSZ axion model

Outline

Motivation and relevance

1. Type-I Dirac seesaw model
   - It explains neutrino mass generation [1, 2].
   - New sterile heavy fermions are introduced.
   - This allows the introduction of new sources of CP violation in the lepton sector [3].
2. Thermal leptogenesis
   - It is guaranteed due to the Sakharov conditions [4].
   - CP violation in the lepton sector leads to a lepton asymmetry [3].
   - Lepton asymmetry can be converted into a baryon asymmetry thanks to sphaleron processes [5].

Motivation and relevance

3. Peccei-Quinn symmetry
   - In the Standard Model is imposed a new global U(1) broken symmetry through chiral transformations of the fermions, requiring the introduction of a new Higgs doublet [6].
   - It solves the Strong CP problem since this symmetry allows to make the CP-violating topological term equals zero [6].
   - After the spontaneous symmetry breaking, a new pseudo-scalar particle appears [7], the QCD axion [8].
   - Experiments has ruled out that the electroweak and Peccei-Quinn symmetries energy scales are the same [9].
4. Scalar and weakly coupled massive particle: DFSZ axion model
   - It introduces a new gauge-singlet scalar field whose vacuum expectation value sets the Peccei-Quinn symmetry breaking energy scale above the electroweak energy scale [10, 11].
   - This model could explain dark matter existence as weakly interacting massive scalar particles [12].

Neutrino mass generation

- The **Weinberg operator** is the only possible effective Lagrangian which generates a neutrino mass term assuming only left-handed neutrino fields and without spoiling up the Standard Model symmetry [13]:

$$\mathcal{L}_{eff}^{W} = -\frac{1}{\Lambda_{UV}} \sum_{i,m} \overline{E}_{L,i} \tilde{H} X'_{i,m} \tilde{H}^{T} E^{c}_{L,m} + h.c. \qquad (1)$$

  Where $i, m = e, \mu, \tau$ the flavour indices, and $\tilde{H} = i\gamma^2 H^*$ is the charge conjugated Higgs doublet, and X a non-diagonal complex symmetrical 3×3 matrix.

- It is a five-dimension operator, which means:

$$[\Lambda_{UV}] = [M]$$

- After the Higgs mechanism, neutrino masses are found to be [13]:

$$m_i = \frac{v^2}{\Lambda_{UV}} x_i = \frac{v}{\Lambda_{UV}} (v x_i) \qquad (2)$$

  With x_i the eigenvalues of X.

- $\Lambda_{UV} \lesssim 1 \times 10^{14}$ GeV [14].

Neutrino mass generation

At tree-level, the Feymann diagram for the effective Weinberg lagrangian looks like:

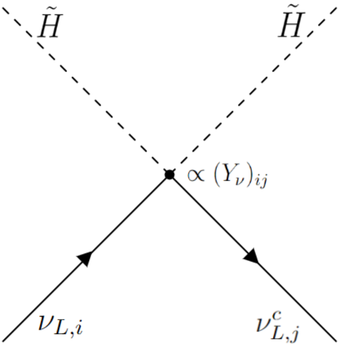

Figure: Feynman diagram for the Weinberg effective operator in the Majorana extension.

Neutrino mass generation in the type-I seesaw model

The $SU(2)_L \times U(1)_Y$ gauge invariant lagrangian for the type-I seesaw model is given by [2, 3]:

$$\mathcal{L}_{type-I} = -\overline{E}_{L,\alpha} y_{\alpha\beta} \tilde{H} N_{\beta,R} - \frac{1}{2} \overline{N}_{R,\alpha} M^R_{\alpha\beta} N^c_{\beta,R} + h.c. \tag{3}$$

- New sterile heavy Majorana fields $N_{i,R}$ (with $i = 1, 2, 3$) are introduced.
- Extra terms violate lepton-number [2, 3].
- At second order in perturbation theory it leads to Weinberg effective operator [14].
- $M^R \sim \Lambda_{UV}$

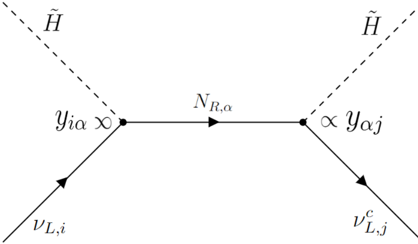

Figure: Feynman diagram for the neutrino mass generation in the type-I seesaw model.

Neutrino mass generation in the type-I seesaw model

Thus, small neutrino masses are generated through heavy sterile fermion exchanges.

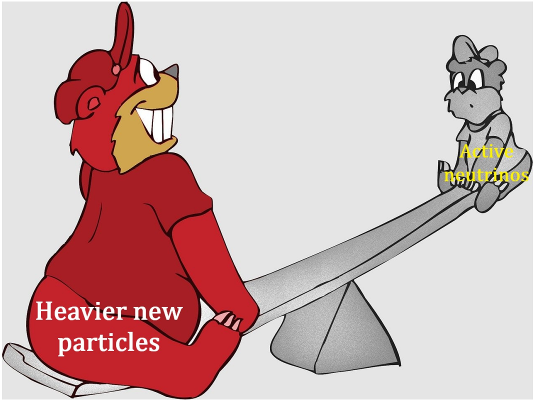

Figure: Artistic illustration of neutrino mass generation through the typer-I seesaw model (adaptation from a free license image).

Peccei-Quinn symmetry and the DFSZ axion model

- In this model the Yukawa interaction is given by:

$$\mathcal{L}_Y = -y_u \bar{Q}_L H_u u_R - y_d \bar{Q}_L \Phi_2^c d_R - y_e \bar{E}_L H_d^c e_R + h.c. \tag{4}$$

Where:

$$H_u = \sin\beta H + \cos\beta H' \tag{5}$$

$$H_d = \cos\beta H - \sin\beta H' \tag{6}$$

Being H the Standard Model Higgs field, and H' a massless doublet field.

- The particle content of the DFSZ axion model is:

	Q_i	u_i^c	d_i^c	$E_{L,l}$	e_l^c	H_u	H_d	χ
$\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$	(2,1/6)	(1,-2/3)	(1,1/3)	(2,-1/2)	(1,1)	(2,-1/2)	(2,1/2)	(0,0)
$\mathrm{U}(1)_{PQ}$	1	1	1	1	1	2	2	4

Figure: Particle content and associated charges for the DFSZ axion model.

Peccei-Quinn mechanism

The following energy scale relation is found:

$$f_a^2 = v_x^2 + \sin^2(2\beta)v^2 \tag{7}$$

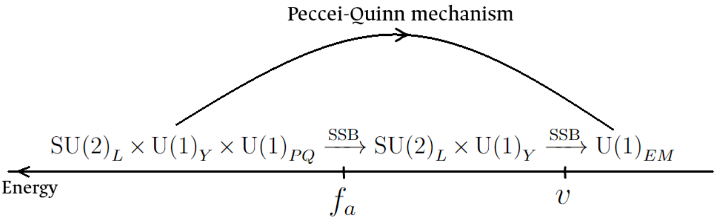

Figure: Peccei-Quinn mechanism illustration.

Matching both models

It is possible to match both models through the following Weinberg effective operator whose is gauge and Peccei-Quinn invariant [15]:

$$\mathcal{L}_W^D = \frac{y^{\nu}_{\alpha\beta}}{\Lambda_{UV}} \overline{E}_{L,\alpha} H_u \nu_{R,\beta} \chi + h.c. \tag{8}$$

Where the Peccei-Quinn charge associated to the right-handed light neutrino $\nu_{R,\beta}$ must be -5.

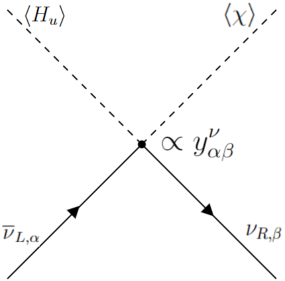

Figure: Feynman diagram for the Weinberg effective operator in the Dirac extension.

Matching both models

The UV-completion of the above Weinberg effective operator is given by the type-I Dirac seesaw extension [15]:

$$-\mathcal{L}_Y = y^u_{ij}\overline{Q}_i H_u u_j + y^d_{ij}\overline{Q}_i H_d d_j + y^l_{ij}\overline{E}_{L,i} H_d e_j + h.c. + \mathcal{L}_{Type-I} \quad (9)$$

With:

$$-\mathcal{L}_{Type-I} = y^h_{\alpha\beta}\overline{E}_{L,\alpha} H_u N_{R,\beta} + y^\chi_{\alpha\beta}\overline{N}_{L,\alpha}\chi\nu_{R,\beta} + \frac{1}{2}\overline{N}_{L,\alpha} M^N_{\alpha\beta} N_{R,\beta} + h.c. \quad (10)$$

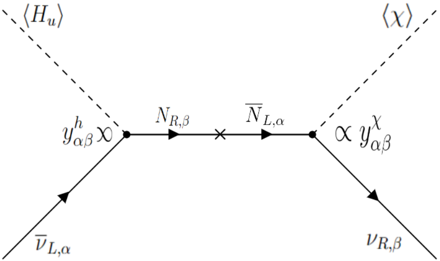

Figure: Feynman diagram for the type-I Dirac seesaw extension to the DFSZ axion model.

Results: (1+1)-scheme

- After the Higgs mechanism it is found that:

$$m_\nu = -\frac{m^{D1}m^{D2}}{m^N} = -\frac{2\sin\beta v\sqrt{f_a^2 - \sin^2(2\beta)v^2}}{m^N}y^h y^\chi \tag{11}$$

Which can be approximated to [16]:

$$m_\nu \approx \frac{vf_a}{\Lambda_{UV}} \tag{12}$$

- Taking the current upper limit for neutrino mass found in experiments [17, 18], it is found that:

$$10^3\,\mathrm{GeV}\,f_a \sim \Lambda_{UV} \tag{13}$$

- Then, spontaneous Peccei-Quinn symmetry breaking occurs at lower energies than the mass of the heavy sterile particles N_i.
- Thus, the decays of N_i take place before the spontaneous $\mathrm{U}(1)_{PQ}$ symmetry breaking.
- From the current experimental boundaries on f_a [12], it follows that:

$$10^9\,\mathrm{GeV} \leq \Lambda_{UV} \leq 10^{15}\,\mathrm{GeV} \tag{14}$$

Results: Cosmological timeline

1. The universe cools down enough until it reaches the energy Λ_{UV}, meanwhile the heavy sterile fermions N_i decay to lighter particles, taking place a cosmological phase transition.
2. CP-violating processes generate the baryon asymmetry of the universe [19].
3. Then, the universe continues cooling down and when it decreases by approximately 10^3 GeV it reaches the scale energy f_a, where the spontaneous $U(1)_{PQ}$ symmetry breaking occurs, taking place a cosmological phase transition.
4. A real scalar field (the axion $a(x)$) candidate to dark matter appears in the spectrum and adquires mass in this process [12].
5. Finally, the universe cools down so much that it reaches the Higgs vacuum expectation value v, giving rise to the Higgs mechanism [20].
6. All particles (except the axion) adquire mass, including light active neutrinos because of the seesaw mechanism, and going through the electroweak cosmological phase transition [21].

Results: (3+3)-scheme

After the Higgs mechanism, the type-I Dirac seesaw lagrangian leads to:

$$\mathcal{L}_m^{\nu} = -\frac{1}{2}\overline{\nu}_{L,\alpha} M_{\alpha\beta}^{D1} N_{R,\beta} - \frac{1}{2}\overline{N}_{L,\alpha} M_{\alpha\beta}^{D2} \nu_{R,\beta} - \frac{1}{2}\overline{N}_{L,\alpha} M_{\alpha\beta}^{N} N_{R,\beta} + h.c. \quad (15)$$

With the **Dirac mass matrices** defined as:

$$M_{\alpha\beta}^{D1} = \sqrt{2}\sin\beta v y_{\alpha\beta}^{h} \quad (16)$$

$$M_{\alpha\beta}^{D2} = \sqrt{2\left(f_a^2 - \sin^2(2\beta) v^2\right)} y_{\alpha\beta}^{\chi} \quad (17)$$

The above mass lagrangian can be written in a more simplified matrix form:

$$\mathcal{L}_m^{\nu} = -\frac{1}{2}\begin{pmatrix}\overline{\nu}_L & \overline{N}_L\end{pmatrix}\begin{pmatrix}0 & M^{D1} \\ M^{D2} & M^{N}\end{pmatrix}\begin{pmatrix}\nu_R \\ N_R\end{pmatrix} + h.c. \quad (18)$$

Results: (3+3)-scheme

- Dirac neutrino effective masses:

$$\begin{pmatrix} 0 & M^{D1} \\ M^{D2} & M^{N} \end{pmatrix} = U^{\dagger} \begin{pmatrix} D_\nu & 0 \\ 0 & D_N \end{pmatrix} U \tag{19}$$

With $D_\nu = \mathrm{diag}(m_1, m_2, m_3)$ and $D_N = \mathrm{diag}(M_1, M_2, M_3)$, and being the matrices D_ν and D_N real and positive definited.

- The 6×6 unitary matrix U can be parameterized as:

$$U = \begin{pmatrix} U_{PMNS} & R \\ Q & U'_{PMNS} \end{pmatrix} \tag{20}$$

- Because of the smallness of this mixing, the following approximation is performed:

$$R \approx= \begin{pmatrix} \hat{S}^*_{14} & \hat{S}^*_{15} & \hat{S}^*_{16} \\ \hat{S}^*_{24} & \hat{S}^*_{25} & \hat{S}^*_{26} \\ \hat{S}^*_{34} & \hat{S}^*_{35} & \hat{S}^*_{36} \end{pmatrix} \tag{21}$$

Where $\hat{S}^*_{ij} = e^{i\delta_{ij}} \sin\theta_{ij}$.

Results: (3+3)-scheme

- From the matrix equation (19) the following equations are found:

$$0 = U^{\dagger}_{PMNS} D_{\nu} U_{PMNS} + \left(R^{\dagger} U_{PMNS}\right)^{\dagger} D_N \left(R^{\dagger} U_{PMNS}\right) \tag{22}$$

$$M^{D1} = U^{\dagger}_{PMNS} \left(D_{\nu} R - R D_N\right) \tag{23}$$

$$M^{D2} = \left(R^{\dagger} D_{\nu} - D_N R^{\dagger}\right) U_{PMNS} \tag{24}$$

$$M^{N} = R^{\dagger} D_{\nu} R + D_N \tag{25}$$

- Notice that from (23) and (24) follows that:

$$M^{D1} = \left(M^{D2}\right)^{\dagger} \equiv M^{D} \tag{26}$$

- The above result leads to:

$$y^{\chi}_{\alpha\beta} = \frac{\sin\beta v}{\sqrt{f_a^2 - \sin^2(2\beta) v^2}} (y^{h}_{\beta\alpha})^{*} \tag{27}$$

- In consequence:

$$|y^{\chi}_{\alpha\beta}| \approx \frac{v}{f_a} |y^{h}_{\alpha\beta}| \Leftrightarrow \qquad 10^{-10} |y^{h}_{\alpha\beta}| \leq |y^{\chi}_{\alpha\beta}| \leq 10^{-4} |y^{h}_{\alpha\beta}| \tag{28}$$

Results: (3+3)-scheme

- In (23) it was found that the Dirac mass matrix $M^{D1} = (M^{D2})^\dagger = M^D$ can be computed as:

$$M^D = U^\dagger_{PMNS}\left(D_\nu R - R D_N\right)$$

$$M^D = U^\dagger_{PMNS}\begin{pmatrix} (m_1 - M_1)\hat{S}^*_{14} & (m_1 - M_2)\hat{S}^*_{15} & (m_1 - M_3)\hat{S}^*_{16} \\ (m_2 - M_1)\hat{S}^*_{24} & (m_2 - M_2)\hat{S}^*_{25} & (m_2 - M_3)\hat{S}^*_{26} \\ (m_3 - M_1)\hat{S}^*_{34} & (m_3 - M_2)\hat{S}^*_{35} & (m_3 - M_3)\hat{S}^*_{36} \end{pmatrix} \tag{29}$$

- Also, notice that if this Dirac neutrino effective mass matrix is hermitian, then the lepton mixing matrix U_{PMNS} is exactly unitary in this model.
- The effective neutrino mass matrix is found to be:

$$m_\nu \approx M^D \left(M^N\right)^{-1} (M^D)^\dagger \tag{30}$$

Results: Thermal leptogenesis

CP-violating processes lead to a lepton asymmetry which can be converted into a baryon asymmetry through sphaleron processes.

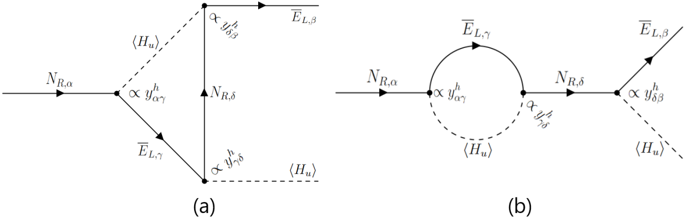

Figure: Feynman diagrams for the decay of N_i through the Yukawa coupling with the $SU(2)_L$ leptonic and Higgs doublets.

$$\Gamma_{\alpha\beta} \propto \frac{1}{8\left(f_a^2 - \sin^2(2\beta)v^2\right)^3} |(M^D)^\dagger_{\alpha\gamma}(M^D)^\dagger_{\gamma\delta}(M^D)^\dagger_{\delta\beta}|^2 M_i^N \qquad (31)$$

Results: Thermal leptogenesis

- CP-violation parameter is defined as:

$$\epsilon_{i\alpha} = \frac{\Gamma(N_{R,i} \to \overline{E}_{L,\alpha} + \langle H_u \rangle) - \Gamma(N^c_{R,i} \to \overline{E}^c_{L,\alpha} + \langle H^c_u \rangle)}{\Gamma_{N_i}} \quad (32)$$

- The majority of the baryon asymmetry will be produced in the out-of-equilibrium decay of the lightest sterile fermion N_1 [19].
- Therefore, only one CP asymmetry factor will be relevant to thermal leptogenesis [22]:

$$\epsilon_1 = \frac{1}{32\pi \sin^2 \beta v^2 f_a^2 (M^D(M^D)^\dagger M^D(M^D)^\dagger)_{11}} \sum_{j\neq 1}^{3} \mathrm{Im}\left[(M^D(M^D)^\dagger M^D(M^D)^\dagger)^2_{1j}\right] f(x_{j1}) \quad (33)$$

Where $x_{ji} = M_j^N / M_i^N$, and $f(x)$ the so-called “one-loop function”, which are given by [19]:

$$f(x) = x\left[1 + \frac{1}{(1-x^2)} + (1+x^2)\ln\left(1+\frac{1}{x^2}\right)\right] \quad (34)$$

Results: Thermal leptogenesis

- The Boltzmann equation for the lepton asymmetry is given by [23]:

$$\frac{dY_{\Delta L}}{dt} + 3H(t)Y_{\Delta L} = \frac{\Gamma_{N_1}\epsilon_1}{s} \tag{35}$$

- The solution can be estimated to [24, 25, 26]:

$$Y_{\Delta L} \approx (0.26) \cdot k\epsilon_1 \tag{36}$$

With the efficiency factor k expected to be about $10^{-3} \leq k \leq 1$ [27].

- And in consequence, the baryon asymmetry can be computed as [28, 29]:

$$\begin{aligned} Y_{\Delta B} &= -CY_{\Delta L} \\ &\approx -C\frac{k}{g_{*s}}\epsilon_1 \\ &\approx -(0.0904)k\epsilon_1 \end{aligned} \tag{37}$$

With the coefficient C given by:

$$C = \frac{8N_f + 4N_H}{22N_f + 13N_H} \approx 0.347 \tag{38}$$

Conclusions

- Peccei-Quinn symmetry 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 $10^3\text{GeV}\ f_a \sim \Lambda_{UV}$, which leads to impose upper and lower boundaries in the mass scale for heavy sterile fermions $10^9\text{GeV} \leq \Lambda_{UV} \leq 10^{15}\text{GeV}$.
- The Dirac neutrino effective mass matrix was computed explicitly.
- There were found expressions to compute the CP asymmetry factor and the baryon-antibaryon density.
- Most of the results depend on yet unknown parameters of neutrino and QCD axion physics, but precisely **this aspect links both research fields** into a same model.

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Thank you