Fermion mass, Axion dark matter, and Leptogenesis in SO(10) GUT

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1. Motivation
2. Model
3. Leptogenesis
4. Axion DM
5. Numerical analysis
6. Summary

Outline

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Motivation

- Grand Unified Theories (GUTs) aim to unify the strong, weak, and electromagnetic forces into a single force at a high energy scale.
- $\mathrm{SO}(10)$-based GUTs can encompass all Standard Model fermions of each generation into a single 16-dimensional representation

(H. Fritzsch and P. Minkowski 1975)

- This 16_F contains the SM singlet right-handed neutrino. These models can explain tiny masses of the SM neutrinos through the type-I seesaw mechanism
- Higgs representations that can contribute to fermion masses and mixing

$$16 \times 16 = 10_s + 120_a + 126_s,$$
$$\mathcal{L}_{yuk} = 16_F(Y_{10}10_H + Y_{120}120_H + Y_{126}\overline{126}_H)16_F.$$

Y_{10}, Y_{126} are symmetric, Y_{120} is antisymmetric in the family space.

(K.S Babu and R. N. Mohapatra 1993)

Motivation

- Extending $\mathrm{SO}(10)$ gauge symmetry with global Peccei-Quinn (PQ) symmetry is well-motivated as it solves the strong CP problem.

  (R. Peccei and H. R. Quinn 1977)
- In the minimal scenario, with a complex 10_H and a $\overline{126}_H$ Higgs representations, the Yukawa sector consists of the minimum number of parameters as the PQ symmetry forbids one of the two Yukawa terms with 10_H.

$$\mathcal{L}_{yuk} \supset 16_F(Y_{10}10_H + Y_{126}\overline{126}_H)16_F.$$

- Due to the many orders of difference between EW and GUT scales, RGEs running of necessary Yukawa couplings during the fitting must be carefully considered.

  (A. Dueck and W. Rodejohann 2013)
- Minimal Yukawa sector with Y_{10} and Y_{126} is unable to fit all observables in charged fermion and neutrino sectors within 2σ ranges once RGE running is incorporated.

  (T. Ohlsson and M. Pernow 2019)

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Model

- We introduce a fermion in the fundamental representation, 10_F, and a scalar in the spinorial representation, 16_H.
- 54_H breaks the GUT symmetry to an intermediate symmetry
- PQ charges

$$\begin{aligned} \text{Fermions}: &\quad 16^i_F \rightarrow e^{+i\alpha} 16^i_F, \quad 10_F \rightarrow 10_F. \\ \text{Scalars}: &\quad 10_H \rightarrow e^{-2i\alpha} 10_H, \quad \overline{126}_H \rightarrow e^{-2i\alpha} \overline{126}_H, \quad 54_H \rightarrow 54_H, \quad 16_H \rightarrow e^{-i\alpha} 16_H. \end{aligned}$$

- Mass of the quark-like states (D, D^c) and lepton-like states $(E, E^c$ and $N, N^c)$ residing in 10_F have independent masses,

$$\begin{aligned} \mathcal{L}_Y \supset &\; 10_F 10_F \left(m_F + y\; 54_H\right) \\ = &\; \underbrace{\left(2m_F + 2\sqrt{2} y v_{54}\right)}_{\equiv m'_F} D^c D + \underbrace{\left(2m_F - 3\sqrt{2} y v_{54}\right)}_{\equiv m''_F} \left(E E^c + N N^c\right) \;. \end{aligned}$$

Model

- Once the 16_H obtains VEV, the fermion 10_F mixes with 16_i, which modifies the mass matrices of light SM-like fermions and help to obtain better fits. Mixings between 16_F and 10_F

$$\mathcal{L}_Y \supset z_i 16_i 10_F 16_H = \underbrace{-\sqrt{2} z_i v_{16}}_{\equiv \mu_i} \left(d_i^c D + e_i E^c - \nu_i N^c \right) .$$

- The 4×4 Dirac mass matrices,

$$\mathcal{L}_Y \supset \begin{pmatrix} d_i & D \end{pmatrix} M_D \begin{pmatrix} d_i^c \\ D^c \end{pmatrix} + \begin{pmatrix} e_i & E \end{pmatrix} M_E \begin{pmatrix} e_i^c \\ E^c \end{pmatrix} + \begin{pmatrix} \nu_i & N \end{pmatrix} M_N^D \begin{pmatrix} \nu_i^c \\ N^c \end{pmatrix}$$

$$M_D = \begin{pmatrix} M_d & 0_{3\times 1} \\ \mu_{1\times 3} & m'_F \end{pmatrix}, \quad M_E = \begin{pmatrix} M_e & \mu^T_{3\times 1} \\ 0_{1\times 3} & m''_F \end{pmatrix}, \quad M_N^D = \begin{pmatrix} M_\nu^D & -\mu^T_{3\times 1} \\ 0_{1\times 3} & m''_F \end{pmatrix} .$$

Symmetry breaking

- The symmetry breaking chain in our model is given by

$$
\begin{aligned}
SO(10) \times U(1)_{\rm PQ} &\xrightarrow[54_H]{M_{\rm GUT}} SU(4)_C \times SU(2)_L \times SU(2)_R \times D \times U(1)_{\rm PQ} \\
&\xrightarrow[16_H + \overline{126}_H]{M_{\rm int}} SU(3)_C \times SU(2)_L \times U(1)_Y \\
&\xrightarrow[10_H + \overline{126}_H]{M_{EW}} SU(3)_C \times U(1)_{\rm em} \,.
\end{aligned}
$$

- The first (and the second) symmetry breaking produces superheavy monopoles

(T W B Kibble 1976)

- Spontaneous breaking of PQ symmetry (along with non-perturbative QCD effects) leads to multiple distinct degenerate vacua resulting in $N_{\rm DW}$ number of domain walls, leading to axion domain wall problem

(P. Sikivie 1982)

- We assume inflation to take place after the scale $M_{\rm int}$ (but before the leptogenesis scale), which gets rid of all unwanted topological defects.

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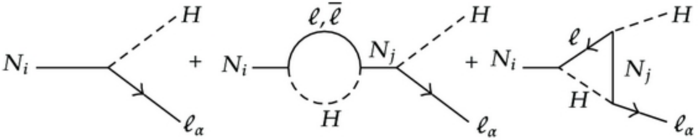
Leptogenesis

- 1. ΔL generated by CP violating out-of-equilibrium decays of RH neutrinos.
  2. Partial washout by inverse decay (and scatterings)
  3. Lepton asymmetry is converted into baryon asymmetry by EW sphaleron



(S. Davidson, E. Nardi, Y. Nir 2008)

- For $M_{N_i} \geqslant 10^{13}\,\mathrm{GeV}$, the leptons $|L_i\rangle$ and anti-lepton $|\bar{L}_i\rangle$ quantum states produced via the decay of N_i can be written as pure states between their production at decay and absorption at inverse decay.

(S. Blanchet, P.D Bari, D A. Jones and L Marzola 2012)

Flavor Leptogenesis

- Charged-lepton interactions occuring between decays and inverse decays could disrupt coherent propagation of leptons created in N_i decays prior to their inverse decays.

$$-\mathcal{L}_Y \supset h_\alpha \bar{\ell}_\alpha \phi e_{R\alpha}, \qquad \Gamma_\alpha \simeq 5 \times 10^{-3} h_\alpha T$$

$$\begin{array}{rl} \text{unflavored regime} & T > 5 \times 10^{12}\mathrm{GeV} \\ \text{two-flavor regime} & 10^{8}\mathrm{GeV} < T < 5 \times 10^{12}\mathrm{GeV} \\ \text{three-flavor regime} & T < 10^{8}\mathrm{GeV} \end{array}$$

(P.S.B. Dev, P.D Bari, B. Garbrecht, S. Lavignac, P. Millington, D. Teresi 2018)

- $|L_i\rangle$ and $|\bar{L}_i\rangle$ states coupling with N_i written in flavour eigenstates $(\alpha = e, \mu, \tau)$

$$|L_i\rangle = \sum_\alpha \mathcal{C}_{i\alpha} |L_\alpha\rangle, \quad \mathcal{C}_{i\alpha} \equiv \langle L_\alpha | L_i \rangle \quad \text{and} \quad |\bar{L}_i\rangle = \sum_\alpha \bar{\mathcal{C}}_{i\bar{\alpha}} |\bar{L}_\alpha\rangle, \quad \bar{\mathcal{C}}_{i\bar{\alpha}} \equiv \langle \bar{L}_\alpha | \bar{L}_i \rangle .$$

$$CP\, |\bar{L}_i\rangle = \sum_\alpha \bar{\mathcal{C}}_{i\alpha} |L_i\rangle, \quad \text{with} \quad \bar{\mathcal{C}}_{i\alpha} = \mathcal{C}^*_{i\bar{\alpha}}.$$

- $\mathcal{C}_{i\alpha} \neq \bar{\mathcal{C}}_{i\alpha}$ due to one-loop CP violating correction

Density matrix equations

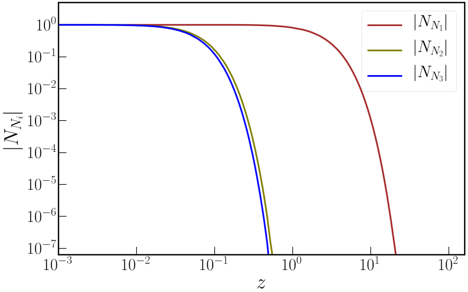
- Yukawa interactions and charged lepton interactions compete with each other in the determination of the average properties of the lepton quantum states.

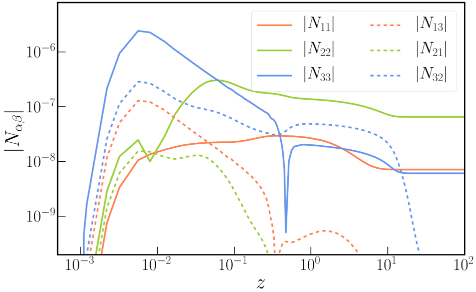
$$\begin{aligned}
\frac{dN_{N_j}}{dz} &= -D_j\left(N_{N_j} - N_{N_j}^{eq}\right)\\
\frac{dN_{\alpha\beta}^{B-L}}{dz} &= \sum_j\left[\varepsilon_{\alpha\beta}^{(j)}D_j\left(N_{N_j} - N_{N_j}^{eq}\right) - \frac{1}{2}W_j\left\{P^{(j)0}, N^{B-L}\right\}_{\alpha\beta}\right]\\
&\quad - \frac{\mathrm{Im}(\Lambda_\tau)}{Hz}\left(\delta_{\alpha 1}N_{1\beta} + \delta_{\beta 1}N_{\alpha 1} - 2\delta_{\alpha 1}\delta_{\beta 1}N_{11}\right)\\
&\quad - \frac{\mathrm{Im}(\Lambda_\mu)}{Hz}\left(\delta_{\alpha 2}N_{2\beta} + \delta_{\beta 2}N_{\alpha 2} - 2\delta_{\alpha 2}\delta_{\beta 2}N_{22}\right).
\end{aligned}$$

- $P_{\alpha\beta}^{i}$ describes how a particular combination of flavor asymmetry gets washed out via N_i

$$P_{\alpha\beta}^{(i)0} = C_{i\alpha}^{0}C_{i\beta}^{*0} = \frac{Y_{\alpha i}Y_{\beta i}^{*}}{(Y^\dagger Y)_{ii}}.$$

Evolution of number densities





$$(M_1, M_2, M_3) = (0.0564, 2.13, 2.37) \times 10^{11}\ \text{GeV}.$$

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Axion Dark Matter

- Spontaneous symmetry breaking of global symmetry leaves a Goldstone, axion A

$$A = \sum_k c_k A_k, \quad A_k = \underbrace{\left(\frac{q_k v_k}{f_{\rm PQ}}\right)}_{\equiv c_k} A + \text{orthogonal exciations}; \qquad f_{\rm PQ} = \left(\sum_k q_k^2 v_k^2\right)^{1/2}$$

- The fields that acquire VEVs and carry PQ charges in our model are given by,

$$10_H \supset (1,2,2) \supset \underbrace{H_u}_{\phi_3} (1,2,1/2) + \underbrace{H_d}_{\phi_4} (1,2,-1/2)\ ,$$

$$\overline{126}_H \supset (15,2,2) + (10,1,3) \supset \underbrace{\Sigma_u}_{\phi_1} (1,2,1/2) + \underbrace{\Sigma_d}_{\phi_2} (1,2,-1/2) + \underbrace{\Delta_R}_{\phi_5} (1,1,0)\ ,$$

$$16_H \supset (4,2,1) + (\overline{4},1,2) \supset \underbrace{\xi_d}_{\phi_6} (1,2,-1/2) + \underbrace{\xi_s}_{\phi_7} (1,1,0)\ .$$

Axion Dark Matter

1. Axion must be orthogonal to Goldstone bosons of broken gauge symmetries.

$$\sum_k c_k q_k^X v_k = 0, \qquad X = R \text{ or } X = B - L$$

2. At the perturbative level, the axion remains massless.

- PQ symmetry is broken at intermediate symmetry scale, axion decay constant $f_A \sim M_{\text{int}}$. (Domain wall number is found to be $N_{\text{DW}} = 6$)

$$m_A \sim 6\mu\text{eV} \left(\frac{10^{12}\text{GeV}}{M_{\text{int}}} \right).$$

  Require $v_R \sim 10^{12-13}\text{GeV}$ for correct neutrino mass scale, $m_A \sim \mathcal{O}(1-100)\mu\text{eV}$

- The relic abundance of the axion field today can be obtained from

$$\Omega_A h^2 \approx 0.7 \left(\frac{M_{\text{int}}}{10^{12}\text{GeV}} \right)^{1.16} \left(\frac{\Theta_i}{\pi} \right)^2, \quad \text{initial misalignment angle } |\Theta_i| \in (0.09, 1.3)$$

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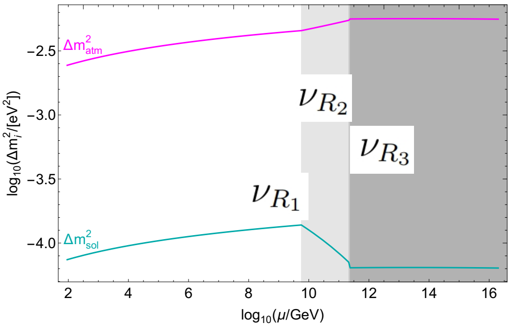
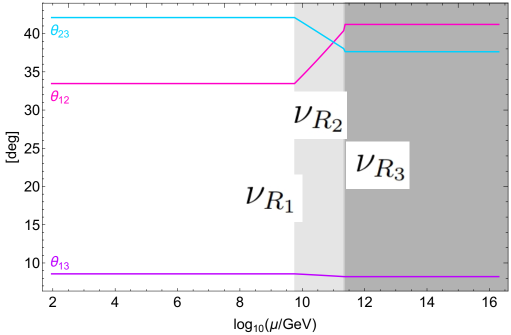
Fitting procedure

- All running effects within type-I seesaw extended SM are taken into account
- All fermion masses and mixings are fitted only at the low energy scale where experimental values are measured
- Any corrections to RGEs from intermediate scale to GUT scale due to presence of additional states other than right-handed neutrinos are not considered.





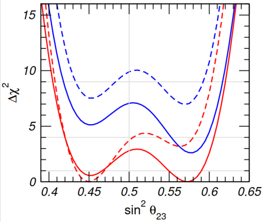
Benchmark fit

Observables (Δm^2_{ij} in eV^2)	Values at M_Z scale		
	Input	Fit	pull^2
$y_u/10^{-6}$	6.65±2.25	6.55	1.95×10^{-3}
$y_c/10^{-3}$	3.60±0.11	3.59	2.79×10^{-6}
y_t	0.986±0.0086	0.986	3.11×10^{-3}
$y_d/10^{-5}$	1.645±0.165	1.646	6.23×10^{-5}
$y_s/10^{-4}$	3.125±0.165	3.126	3.87×10^{-5}
$y_b/10^{-2}$	1.639±0.015	1.639	3.34×10^{-3}
$y_e/10^{-6}$	2.7947±0.02794	2.7944	1.32×10^{-4}
$y_\mu/10^{-4}$	5.8998±0.05899	5.8962	3.79×10^{-3}
$y_\tau/10^{-2}$	1.0029±0.01002	1.0028	7.80×10^{-5}

$$\chi^2 = \sum_{\text{all observs}} \left(\frac{\text{theoretical prediction} - \text{experimental central value}}{\text{experimental } 1\sigma \text{ error}} \right)^2 = \sum \text{pull}^2 .$$

Benchmark fit

Observables (Δm^2_{ij} in eV^2)	Values at M_Z scale		
	Input	Fit	pull^2
$\theta_{12}^{\mathrm{CKM}/10^{-2}}$	22.735±0.072	22.732	1.65×10^{-3}
$\theta_{23}^{\mathrm{CKM}/10^{-2}}$	4.208±0.064	4.210	1.25×10^{-3}
$\theta_{13}^{\mathrm{CKM}/10^{-3}}$	3.64±0.13	3.64	1.62×10^{-4}
δ^c_{CKM}	1.208±0.054	1.207	2.92×10^{-4}
$\Delta m^2_{21}/10^{-5}$	7.425±0.205	7.417	1.31×10^{-3}
$\Delta m^2_{31}/10^{-3}$	2.515±0.028	2.515	7.41×10^{-5}
$\sin^2\theta_{12}$	0.3045±0.0125	0.3041	1.14×10^{-3}
$\sin^2\theta_{23}$	0.5705±0.0205 ‡	0.4494	0.59
$\sin^2\theta_{13}$	0.02223±0.00065	0.02223	3.31×10^{-5}
$\eta_B/10^{-10}$	6.12±0.004	6.12	1.81×10^{-4}



$$(m_1, m_2, m_3) = (0.285, 0.907, 5.02) \times 10^{-11}\ \mathrm{GeV}, \qquad \chi^2 = 0.6$$

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Summary

- The minimal $SO(10) \times U(1)_{\mathrm{PQ}}$ is extensively explored in literature. It gives a bad fit for fermion masses and mixing when renormalization group equations governing the Yukawa couplings are incorporated.
- We proposed an extension (with lower dimensional representations) of the minimal setup by introducing only a few new parameters.
- The particle content is enlarged to include a fermion 10_F in the fundamental representation and a scalar 16_H in the spinorial representation.
- Out-of-equilibrium decays of right-handed neutrinos generate matter-antimatter symmetry observed in the Universe.
- PQ symmetry solves strong CP problem, and the axion plays role of dark matter.

Thank you!