Gauged 2HDM with Axion-Dirac Neutrino Interplay

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Motivation

Problems to solve beyond the SM:

$$\boxed{\begin{array}{ccccc} \text{Small neutrino masses} & & \text{Nature of dark matter} & & \\ \Big\Uparrow & & \Big\Uparrow & & \\ \text{Dirac seesaw mechanism} & \Longleftrightarrow & \text{Axion} & \Longrightarrow & \text{Strong CP problem} \end{array}}$$

Framework: 2HDM with extra $U(1)_X$ and $U(1)_{PQ}$ symmetries.

Model building

	$\mathcal{G}_{SM}$	$U(1)_{global}$	$U(1)_{afree}$
L_{aL}	$(\mathbf{1},\mathbf{2},-1/2)$	$q'_{n_L}-q'_{\Phi_u}-2q'_\sigma-q'_\varphi$	$-3l_{Q_L}$
e_{aR}	$(\mathbf{1},\mathbf{1},-1)$	$q'_{n_L}-2q'_{\Phi_u}-2q'_\sigma-q'_\varphi$	$-3l_{Q_L}-l_{\Phi_u}$
ν_{aR}	$(\mathbf{1},\mathbf{1},0)$	$q'_{n_L}-q'_\varphi$	$-3l_{Q_L}+l_{\Phi_u}$
n_{aL}	$(\mathbf{1},\mathbf{1},0)$	q'_{n_L}	$-3l_{Q_L}+l_{\Phi_u}+l_\varphi$
n_{aR}	$(\mathbf{1},\mathbf{1},0)$	$q'_{n_L}-q'_\sigma$	$-3l_{Q_L}+l_{\Phi_u}+l_\varphi$
Q_{aL}	$(\mathbf{3},\mathbf{2},1/6)$	q'_{Q_L}	l_{Q_L}
u_{aR}	$(\mathbf{3},\mathbf{1},2/3)$	$q'_{Q_L}+q'_{\Phi_u}$	$l_{Q_L}+l_{\Phi_u}$
d_{aR}	$(\mathbf{3},\mathbf{1},-1/3)$	$q'_{Q_L}-q'_{\Phi_u}-q'_\sigma-q'_\varphi$	$l_{Q_L}-l_{\Phi_u}-l_\varphi$
k_{aL}	$(\mathbf{3},\mathbf{1},-1/3)$	$q'_{Q_L}-q'_{\Phi_u}-q'_\sigma-q'_\varphi$	$l_{Q_L}-l_{\Phi_u}-l_\varphi$
k_{aR}	$(\mathbf{3},\mathbf{1},-1/3)$	$q'_{Q_L}-q'_{\Phi_u}-q'_\sigma$	$l_{Q_L}-l_{\Phi_u}$
Φ_u	$(\mathbf{1},\mathbf{2},1/2)$	q'_{Φ_u}	l_{Φ_u}
Φ_d	$(\mathbf{1},\mathbf{2},1/2)$	$q'_{\Phi_u}+q'_\sigma+q'_\varphi$	$l_{\Phi_u}+l_\varphi$
φ	$(\mathbf{1},\mathbf{1},0)$	q'_φ	l_φ
σ	$(\mathbf{1},\mathbf{1},0)$	q'_σ	0

Scalar sector

The scalar potential has only one non-Hermitian term:

$$V = V_{\text{Hermitian}} - \left[\lambda_4(\Phi_d^\dagger \Phi_u)(\sigma\varphi) + \mathrm{h.c.}\right] \tag{1}$$

Anomaly cancellation:

$$\begin{aligned} I &: [SU(3)_C]^2 \times U(1)_{global}\,; & II &: [SU(2)_L]^2 \times U(1)_{global}\,; \\ III &: [U(1)_Y]^2 \times U(1)_{global}\,; & IV &: U(1)_Y \times [U(1)_{global}]^2\,; \\ V &: [Grav]^2 \times U(1)_{global}\,; & VI &: [U(1)_{global}]^3 \end{aligned} \tag{2}$$

Polar decomposition:

$$\Phi_{u,d} = \begin{pmatrix} \phi^+_{u,d} \\ \phi^0_{u,d} \end{pmatrix}, \quad \text{with} \quad \phi^0_{u,d} = \frac{v_{u,d} + s_{u,d}}{\sqrt{2}} \exp\left(i \frac{a_{u,d}}{v_{u,d}} \right)$$
$$\varphi = \frac{v_\varphi + s_\varphi}{\sqrt{2}} \exp\left(i \frac{a_\varphi}{v_\varphi} \right) \quad \text{and} \quad \sigma = \frac{v_\sigma + s_\sigma}{\sqrt{2}} \exp\left(i \frac{a_\sigma}{v_\sigma} \right) \tag{3}$$

SSB pattern:

$$\begin{array}{c} \mathcal{G}_{SM} \otimes U(1)_X \otimes U(1)_{PQ} \otimes U(1)_B \otimes U(1)_L \\ \Big\downarrow \; v_\sigma \sim 10^{12}\ \text{GeV} \\ \mathcal{G}_{SM} \otimes U(1)_X \otimes U(1)_B \otimes U(1)_L \\ \Big\downarrow \; v_\varphi \sim 10^{4}\ \text{GeV} \\ \mathcal{G}_{SM} \otimes U(1)_B \otimes U(1)_L \\ \Big\downarrow \; v \sim 246\ \text{GeV} \\ SU(3)_C \otimes U(1)_{EM} \otimes U(1)_B \otimes U(1)_L \end{array} \tag{4}$$

CP-odd potential:

$$V(a_i) = -\frac{\lambda_4}{2} v_u v_d v_\varphi v_\sigma \cos\left(\frac{a_u}{v_u} - \frac{a_d}{v_d} + \frac{a_\varphi}{v_\varphi} + \frac{a_\sigma}{v_\sigma}\right) \tag{5}$$

Massive field:

$$A = \frac{v_d v_\varphi v_\sigma a_u - v_u v_\varphi v_\sigma a_d + v_u v_d v_\sigma a_\varphi + v_u v_d v_\varphi a_\sigma}{\sqrt{v_\sigma^2 (v_\varphi^2 v^2 + v_u^2 v_d^2) + v_\varphi^2 v_u^2 v_d^2}}, \quad m_A^2 \approx \frac{\lambda_4 v_\sigma v_\varphi}{v_u v_d} v^2 \tag{6}$$

Massless fields:

$$G_c = \frac{1}{f_G} \sum_\phi c_\phi v_\phi a_\phi, \quad c = X, Y, PQ \tag{7}$$

$$\boxed{a = \frac{-\frac{v_d^2 v_\varphi^2 v_u}{v_u^2 v_d^2 + v_\varphi^2 v^2} a_u + \frac{v_u^2 v_\varphi^2 v_d}{v_u^2 v_d^2 + v_\varphi^2 v^2} a_d - \frac{v_u^2 v_d^2 v_\varphi}{v_u^2 v_d^2 + v_\varphi^2 v^2} a_\varphi + v_\sigma a_\sigma}{\sqrt{v_\sigma^2 + \frac{v_u^2 v_d^2 v_\varphi^2}{v_u^2 v_d^2 + v_\varphi^2 v^2}}}, \quad m_a = 0 \quad (8)}$$

Gauge sector: Unmixed $U(1)_X$ gauge boson

In the basis $(W_3^\mu, B_Y^\mu, B_X^\mu)$:

$$M^2_{NGB} = \frac{1}{4}\begin{pmatrix} g_L^2 v^2 & -g_L g_Y v^2 & 0 \\ -g_L g_Y v^2 & g_Y^2 v^2 & 0 \\ 0 & 0 & 4g_X^2\left(v_\varphi^2 + \frac{v_u^2 v_d^2}{v^2}\right) \end{pmatrix} \tag{9}$$

Neutral gauge boson masses:

$$\begin{aligned} m_\gamma &= 0\,, \\ m_Z &= v\left(g_L^2 + g_Y^2\right)^{1/2}\,, \\ m_{Z'} &= g_X\left(v_\varphi^2 + \frac{v_u^2 v_d^2}{v^2}\right)^{1/2} \end{aligned} \tag{10}$$

Fermion sector

Flipped (Type-Y) 2HDM Yukawa Lagrangian:

$$
\begin{aligned}
-\mathcal{L}_y = {} & y^u_{ab}\, \overline{Q_{aL}}\, \widetilde{\Phi_u}\, u_{bR} + y^d_{ab}\, \overline{Q_{aL}}\, \Phi_d\, d_{bR} + y^e_{ab}\, \overline{L_{aL}}\, \Phi_u\, e_{bR} + y^n_{ab}\, \overline{L_{aL}}\, \widetilde{\Phi_d}\, n_{bR} \\
& + y^\alpha_{ab}\, \varphi\, \overline{n_{aL}}\, \nu_{bR} + y^\beta_{ab}\, \sigma\, \overline{n_{aL}}\, n_{bR} + y^k_{ab}\, \varphi^*\, \overline{k_{aL}}\, k_{bR} + \frac{y^\mu_{ab}\mu}{\sqrt{2}}\, \overline{k_{aL}} d_{bR} + \mathrm{h.c.}
\end{aligned}
\tag{11}
$$

Charged lepton and up-type quark mass matrices:

$$
M^F = \frac{y^F v_u}{\sqrt{2}}\,, \quad F = e, u \tag{12}
$$

Down-type quark mass matrix in the basis $D = (d, k)$:

$$
M^D = \frac{1}{\sqrt{2}} \begin{pmatrix} y^d v_d & 0 \\ y^\mu \mu & y^k v_\varphi \end{pmatrix} \tag{13}
$$

Diagonalisation of M^D:

$$
(U^D_L)^\dagger M^D U^D_R = \mathrm{diag}(m_d, m_s, m_b, M_1, M_2, M_3) \tag{14}
$$

Neutral lepton mass matrix in the basis $N = (\nu, n)$:

$$M^N = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & y^n v_d \\ y^\alpha v_\varphi & y^\beta v_\sigma \end{pmatrix} \tag{15}$$

Dirac seesaw mechanism:

$$m_\nu \simeq \frac{y^n (y^\beta)^{-1} (y^\alpha)^T}{\sqrt{2}} \frac{v_d v_\varphi}{v_\sigma} = \frac{Y^\nu_{eff}}{\sqrt{2}} \frac{v_d v_\varphi}{v_\sigma} \tag{16}$$

$Y^\nu_{eff} \sim 10^{-4}$ implies $v_\varphi / v_\sigma \ll 1$. Intermediate scale physics?

FCNC mediated by Z:

$$\mathcal{L}^{Z}_{FCNC} \simeq \frac{g_L}{2\cos\theta_W} Z^{\mu}\, \overline{d'_{iL}} \gamma_{\mu} \left(V_L^{d\dagger} B_L^{D} B_L^{D\dagger} V_L^{d} \right)_{ij} d'_{jL} \tag{17}$$

$B_L^D \sim 10^{-3}$ suppresses the FCNC below experimental limit.

Axion Physics

Axion-photon and axion-gluon anomaly coefficients:

$$
\begin{aligned}
C_{a\gamma} &\equiv 2 \sum_{f=fermions} (PQ_{f_L} - PQ_{f_R})(Q_f)^2 = 2PQ_\sigma \, , \\
C_{ag} &\equiv \sum_{q=quarks} (PQ_{q_L} - PQ_{q_R}) = 3PQ_\sigma
\end{aligned} \tag{18}
$$

Axion-photon coupling:

$$
g_{a\gamma} \approx \frac{\alpha}{2\pi f_a} \left(\frac{C_{a\gamma}}{C_{ag}} - 1.95 \right) \tag{19}
$$

Axion mass from nonperturbative QCD effects [Weinberg, 1978]:

$$
m_a \simeq 5.7 \left(\frac{10^{12}\ \text{GeV}}{f_a} \right) \mu\text{eV} \tag{20}
$$

$f_a \simeq \frac{v_\sigma}{3} \sim 10^{12}$ GeV, implies $m_a \simeq 17\,\mu$eV.

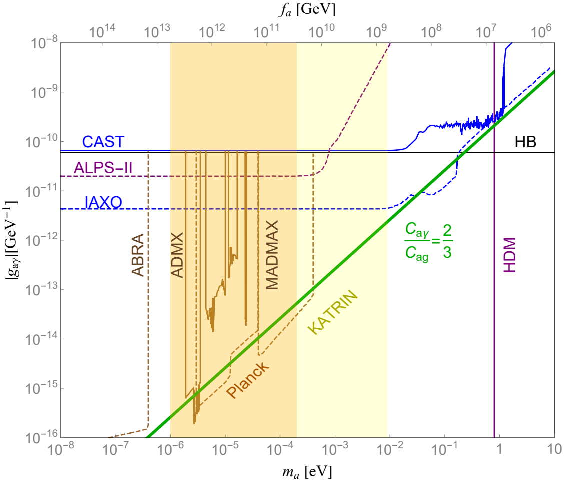

Figura 1: The green line shows our model prediction for $|g_{a\gamma}|$ vs m_a. Constraints from experiments, cosmology and astrophysics are also displayed.

Flavour-violating process [Adler et al., 2008, Björkeroth et al., 2018]:

$$\mathrm{Br}(K^+ \to \pi^+ a) = 9.77 \times 10^{11} \frac{1}{f_a^2} \left(\frac{\mu \sin\theta}{v_\varphi} \right)^4 \mathrm{GeV}^2 \lesssim 7.3 \times 10^{-11} \tag{21}$$

$\frac{\mu \sin\theta}{v_\varphi} \simeq 9.1 \times 10^{-4}$ implies that $f_a \gtrsim 10^5$ GeV. [Ema et al., 2017]: $f_a \gtrsim 10^{10}$ GeV

Conclusions

Solution to the neutrino masses, nature of dark matter and strong CP problem may arise from the axion-neutrino interplay;

Imposition of orthogonality of the Goldstone bosons fixes the physical charges of $U(1)_{PQ}$ and $U(1)_X$ charges;

The preferred region for neutrino masses and axion dark matter may be tested by forthcoming axion experiments looking for axion-photon interactions

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