Roles of Peccei-Quinn symmetry in an effective model for dark matter and neutrino mass

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Motivation and basic idea

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- Several problems unsolved in the standard model require some extension of it. ⇒ How to solve these in a simple and unified way ?
- As such an example, we propose a model which has Peccei-Quinn symmetry and results in the scotogenic model in lepton sector at low energy regions.
- Strategy adopted in this study is summarized in the right table .

Peccei-Quinn (PQ) symmetry is imposed to satisfy the following nature :

- it realizes $N_{DW}=1$ so as to escape the domain wall problem
- it plays a role of Frogatt-Nielsen symmetry.
- its spontaneous breaking leaves Z_2 in the leptonic sector.

◆ Strong CP problem
◆ Mass and mixing of quarks

$U(1)$

● Peccei-Quinn (PQ) mechanism
● Frogatt-Nielsen mechanism

SSB

◆ Neutrino mass
◆ Dark matter
◆ Baryon number asymmetry

Z_2

Scotogenic model as leptonic sector

PQ symmetry which satisfies the above requirements

PQ symmetry and domain wall problem

$$\mathcal{L}^{PQ} \supset \sum_{i,j}(y^f_{ij}\Phi \bar{f}_{L_i} f_{R_j} + \mathrm{h.c.}) + i\frac{\theta_{\rm QCD}}{32\pi^2}F^a_{\mu\nu}\tilde{F}^{a\mu\nu}$$

Strong CP problem can be solved through PQ mechanism

$$f^i_L \to e^{i\alpha X_{f^i_L}} f^i_L, \quad f^i_R \to e^{i\alpha X_{f^i_R}} f^i_R, \quad \Phi \to e^{i\alpha X_\Phi}\Phi, \quad -X_{f^i_L} + X_{f^j_R} + X_\Phi = 0$$

$$\theta_{\rm QCD} \to \theta_{\rm QCD} + \frac{\alpha}{2}\sum_{i=1}^{n_f}\left(X_{f^i_R} - X_{f^i_L}\right) = \theta_{\rm QCD} - \frac{\alpha}{2}\sum_{i=1}^{n_f} X_\Phi \qquad \theta_{\rm QCD} : \text{period } 2\pi$$

$$\alpha = 2\pi\frac{k}{N_{\rm DW}}, \quad k = 1, \cdots, N_{\rm DW} \ \left(\equiv \left|\sum_{i=1}^{n_f}\frac{X_\Phi}{2}\right|\right)$$

degenerate $N_{\rm DW}$ vacua

$\langle\Phi\rangle$ ➡ Spontaneous breaking of $Z_{N_{\rm DW}}$

Domain wall problem
Its energy density over-closes the universe.

A promising possibility to escape domain wall problem is $N_{DW}=1$.

- Flavor independent quark's PQ charge with no extra colored fermion (DFSZ)

  ➡ $N_{\rm DW} = \sum_{i=1}^{3}\frac{|X_{H_u}+X_{H_d}|}{2} = 3|X_S| \neq 1$
- Extra colored fermion (KSVZ) ➡ $N_{DW}=1$ for $n_f=1, X_\Phi=2$

Flavor dependent PQ charge allows $N_{DW}=1$ without introducing colored fermions.

Frogatt-Nielsen charge

$$N_{\rm DW} = \frac{1}{2}\left|\sum_q (X_{q_R} - X_{q_L})\right| = 1 \ \Rightarrow \ \left|\sum_q (X_{q_R} - X_{q_L})\right| = 2$$

An example of this realization

	q_{L_1}	q_{L_2}	q_{L_3}	u_{R_1}	u_{R_2}	u_{R_3}	d_{R_1}	d_{R_2}	d_{R_3}	ϕ	S	ℓ_{L_i}	N_{R_i}	η
X_f	-4	-2	0	4	2	0	-10	-8	2	0	-2	0	1	-1
Z_2	$+$	$+$	$+$	$+$	$+$	$+$	$+$	$+$	$+$	$+$	$+$	$+$	$-$	$-$

ϕ, η doublet scalars $\quad S$ singlet scalar

Assumed vacuum $\langle\phi\rangle, \ \langle S\rangle \neq 0, \quad \langle\eta\rangle = 0$

No QCD instanton effect in lepton sector.
⇒ Z_2 is a remnant good symmetry there.

Axion physics

- Astrophysical/cosmological constraints ⇒ $10^9 \text{ GeV} < \langle S\rangle < 10^{12}\text{GeV}$
- Flavor changing neutral process $(K^\pm \to \pi^\pm a)$ ⇒ $\langle S\rangle \gtrsim 8\times 10^{10}$ GeV
- Axion-photon coupling predicted for this PQ charge assignment

$$g_{a\gamma\gamma} = \frac{m_a}{\rm eV}\frac{2.0}{10^{10}\rm GeV}\times 1.75.$$

Quark sector with Frogatt-Nielsen mechanism based on PQ symmetry

Yukawa couplings for quarks allowed by the imposed $U(1)$

$$-\mathcal{L}^q_y = \sum_{i=1}^{3}\left[\sum_{j=1}^{3} y^u_{ij}\left(\frac{S}{M_*}\right)^{\frac{1}{2}(X_{u_{R_j}}-X_{q_{L_i}})}\bar{q}_{L_i}\phi u_{R_j} + \sum_{j=1}^{2} y^d_{ij}\left(\frac{S^*}{M_*}\right)^{\frac{1}{2}(X_{d_{R_j}}-X_{q_{L_i}})}\bar{q}_{L_i}\tilde{\phi} d_{R_j} + y^d_{i3}\left(\frac{S}{M_*}\right)^{\frac{1}{2}(X_{d_{R_3}}-X_{q_{L_i}})}\bar{q}_{L_i}\tilde{\phi} d_{R_3} + \mathrm{h.c.}\right]$$

$\langle S\rangle \neq 0$

M_* cut-off scale which could be determined by the stability and the perturbativity of the model. See the discussion below.

$$\mathcal{M}_u = \begin{pmatrix} y^u_{11}\,\epsilon^4 & y^u_{12}\,\epsilon^3 & y^u_{13}\,\epsilon^2 \\ y^u_{21}\,\epsilon^3 & y^u_{22}\,\epsilon^2 & y^u_{23}\,\epsilon \\ y^u_{31}\,\epsilon^2 & y^u_{32}\,\epsilon & y^u_{33}\end{pmatrix}\langle\phi\rangle, \quad \mathcal{M}_d = \begin{pmatrix} y^d_{11}\,\epsilon^3 & y^d_{12}\,\epsilon^2 & y^d_{13}\,\epsilon^3 \\ y^d_{21}\,\epsilon^4 & y^d_{22}\,\epsilon^3 & y^d_{23}\,\epsilon^2 \\ y^d_{31}\,\epsilon^5 & y^d_{32}\,\epsilon^4 & y^d_{33}\,\epsilon\end{pmatrix}\langle\phi\rangle, \qquad \varepsilon \equiv \frac{\langle S\rangle}{M_*}$$

$$y^u_{11}=y^u_{23}=y^u_{32}=y^u_{33}=1, \quad y^u_{13}=y^u_{22}=y^u_{31}=0.1, \quad y^u_{12}=y^u_{21}=0.7,$$
$$y^d_{21}=y^d_{22}=y^d_{31}=y^d_{32}=1, \quad y^d_{11}=y^d_{13}=y^d_{23}=0.1, \quad y^d_{12}=0.022, \quad y^d_{33}=0.3.$$

Mass eigenvalues and CKM mixing matrix for $\varepsilon = 0.08$

$$m_u = 2.6 \text{ MeV}, \quad m_c = 1.1 \text{ GeV}, \quad m_t = 174 \text{ GeV},$$
$$m_d = 6.7 \text{ MeV}, \quad m_s = 92 \text{ MeV}, \quad m_b = 4.2 \text{ GeV},$$
$$V_{\rm CKM} = \begin{pmatrix} 0.974 & -0.226 & -0.00515 \\ 0.226 & 0.974 & -0.0184 \\ 0.00918 & 0.0168 & 0.9998\end{pmatrix}.$$

Leptonic sector reduced to Scotogenic neutrino mass model

Leptonic sector invariant under the imposed $U(1)$

$$-\mathcal{L}^\ell_y = \sum_{\alpha=e,\mu,\tau}\sum_{i=1}^{3} h_{\alpha i}\bar{\ell}_\alpha \eta N_i + \sum_{i=1}^{3} y_i S \bar{N}^c_i N_i + \mathrm{h.c.},$$
$$V = m_S^2 S^\dagger S + \kappa_1(S^\dagger S)^2 + \kappa_2(S^\dagger S)(\phi^\dagger\phi) + \kappa_3(S^\dagger S)(\eta^\dagger\eta)$$
$$+ m_\phi^2\phi^\dagger\phi + m_\eta^2\eta^\dagger\eta + \lambda_1(\phi^\dagger\phi)^2 + \lambda_2(\eta^\dagger\eta)^2 + \lambda_3(\phi^\dagger\phi)(\eta^\dagger\eta) + \lambda_4(\phi^\dagger\eta)(\eta^\dagger\phi)$$
$$+ \frac{\lambda_5}{2}\left[\frac{S}{M_*}(\eta^\dagger\phi)^2 + \mathrm{h.c.}\right],$$

$\langle S\rangle \neq 0$

$$\tilde{\lambda}_1 = \lambda_1 - \frac{\kappa_2^2}{4\kappa_1}, \quad \tilde{\lambda}_2 = \lambda_2 - \frac{\kappa_3^2}{4\kappa_1}, \quad \tilde{\lambda}_3 = \lambda_3 - \frac{\kappa_2\kappa_3}{2\kappa_1}, \tilde{\lambda}_5 = \lambda_5\frac{\langle S\rangle}{M_*},$$
$$M_i = y_i\langle S\rangle, \quad \tilde{m}_\phi^2 = m_\phi^2 + \kappa_2\langle S\rangle^2, \quad \tilde{m}_\eta^2 = m_\eta^2 + \kappa_3\langle S\rangle^2,$$

Scotogenic model invariant under Z_2

$$-\mathcal{L}^\ell_y = \sum_{\alpha=e,\mu,\tau}\sum_{i=1}^{3} h_{\alpha i}\bar{\ell}_\alpha \eta N_i + \sum_{i=1}^{3} M_i \bar{N}^c_i N_i + \mathrm{h.c.}$$
$$V_{\rm eff} = \tilde{m}_\phi^2(\phi^\dagger\phi) + \tilde{m}_\eta^2(\eta^\dagger\eta) + \tilde{\lambda}_1(\phi^\dagger\phi)^2 + \tilde{\lambda}_2(\eta^\dagger\eta)^2 + \tilde{\lambda}_3(\phi^\dagger\phi)(\eta^\dagger\eta) + \lambda_4(\phi^\dagger\eta)(\eta^\dagger\phi) + \frac{\tilde{\lambda}_5}{2}\left[(\eta^\dagger\phi)^2 + \mathrm{h.c.}\right]$$

✓ One-loop neutrino mass generation
✓ Existence of stable dark matter ⇒ Lightest component of η^0
✓ Stability conditions

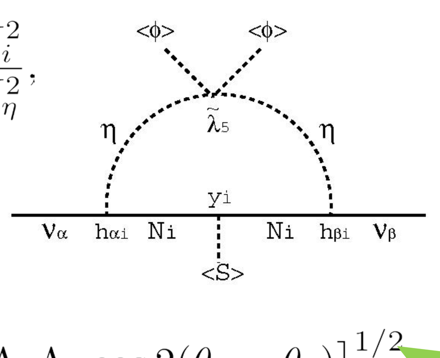
$$\tilde{\lambda}_1 > 0, \quad \tilde{\lambda}_2 > 0, \quad \tilde{\lambda}_3 > -2\sqrt{\tilde{\lambda}_1\tilde{\lambda}_2}, \quad \tilde{\lambda}_3 + \lambda_4 - |\tilde{\lambda}_5| > -2\sqrt{\tilde{\lambda}_1\tilde{\lambda}_2}.$$

Low energy phenomena could be described in the same way as the scotogenic model.

Neutrino mass

Neutrino mass is generated by one-loop effect.

$$\mathcal{M}_{\alpha\beta} = \sum_i h_{\alpha i}h_{\beta i}\Lambda_i, \qquad \Lambda_i \simeq \frac{\tilde{\lambda}_5\langle\phi\rangle^2}{8\pi^2 M_i}\ln\frac{M_i^2}{\bar{M}_\eta^2},$$
$$h_{ej} = 0, \quad h_{\mu j} = h_{\tau j} \equiv h_j \quad (j = 1, 2);$$
$$h_{e3} = h_{\mu 3} = -h_{\tau 3} \equiv h_3,$$



$$m_1 = 0, \qquad m_2 = 3|h_3|^2\Lambda_3,$$
$$m_3 = 2\left[|h_1|^4\Lambda_1^2 + |h_2|^4\Lambda_2^2 + 2|h_1|^2|h_2|^2\Lambda_1\Lambda_2\cos 2(\theta_1 - \theta_2)\right]^{1/2}$$

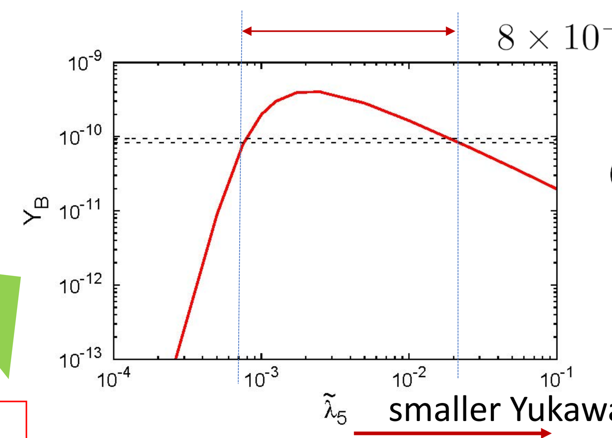
If model parameters are taken to be

$$M_1 = 10^8 \text{ GeV}, \quad M_2 = 4\times 10^8 \text{ GeV}, \quad M_3 = 10^9\text{GeV},$$
$$|h_1| = 10^{-4.5}, \quad |h_2| \simeq 7.2\times 10^{-4}\tilde{\lambda}_5^{-0.5}, \quad |h_3| \simeq 3.1\times 10^{-4}\tilde{\lambda}_5^{-0.5},$$

Neutrino oscillation data are explained consistently.

Leptogenesis

Baryon number asymmetry could be explained through the out-of-equilibrium decay of N_1



$$8\times 10^{-4} \lesssim \tilde{\lambda}_5 \lesssim 2\times 10^{-2}$$
$$\varepsilon = 0.08$$
$$0.01 \lesssim \lambda_5 \lesssim 0.25$$

✓ Maximal CP phase is assumed.
✓ N_i 's are assumed to be produced only through Yukawa interactions. ➡ $M_1 \geq 10^8$ GeV

Dark matter

Axion energy density $\quad \Omega_a h^2 = 2\times 10^4\left(\frac{\langle S\rangle}{10^{16}\text{ GeV}}\right)^{7/6}\langle\theta_i^2\rangle,$

$\langle S\rangle < 10^{11}$ GeV

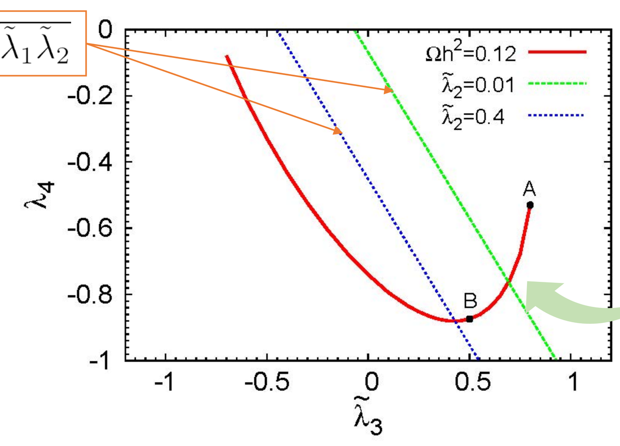
Axion could not be a dominant component of DM.

Components of η are degenerate for $m_\eta^2 \sim 1$ TeV

$$M^2_{\eta^\pm} = \tilde{m}_\eta^2 + \tilde{\lambda}_3\langle\phi\rangle^2, \qquad M^2_{\eta_{R,I}} = \tilde{m}_\eta^2 + \left(\tilde{\lambda}_3 + \lambda_4 \pm \tilde{\lambda}_5\right)\langle\phi\rangle^2.$$

Their coannihilation reduces the abundance effectively.

$$\tilde{\lambda}_3 + \lambda_4 = |\tilde{\lambda}_5| - 2\sqrt{\tilde{\lambda}_1\tilde{\lambda}_2}$$



DM abundance can be explained by relic η^0_R for suitable $\tilde{\lambda}_3, \ \lambda_4$

Stability constrains allowed region.
For example,
A is allowed for $\tilde{\lambda}_2 = 0.01, 0.4$,
but B is allowed for $\tilde{\lambda}_2 = 0.4$.

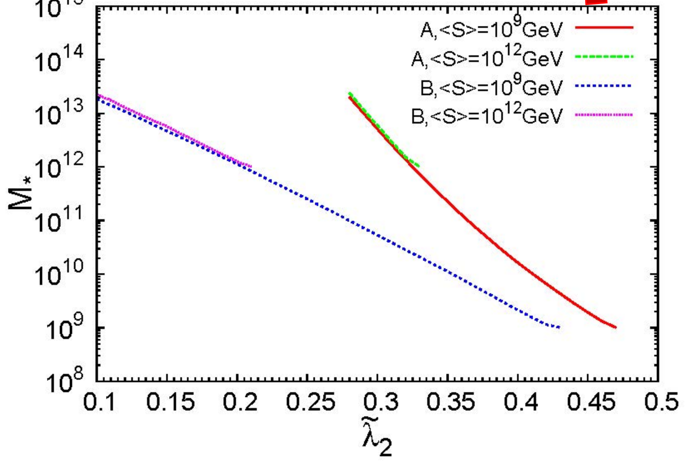
Consistency of model parameters with vacuum stability and perturbativity

Model parameters used to explain the above issues should be consistent with the vacuum stability and the perturbativity up to the cut-of-scale M_*.

RGE study for $\tilde{\lambda}_{1,2,3,5}, \ \lambda_4$ to find M_*

Initial values at M_W

✓ Higgs mass ⇒ $\tilde{\lambda}_1$
✓ neutrino mass, leptogenesis ⇒ $\tilde{\lambda}_5$
✓ DM abundance ⇒ $\tilde{\lambda}_3, \ \lambda_4$
a free parameter ⇒ $\tilde{\lambda}_2$



$$\langle S\rangle \sim 10^{11} \text{ GeV}, \quad \varepsilon = 0.08 \Rightarrow M_* \sim 1.25\times 10^{12} \text{ GeV}$$

If $\tilde{\lambda}_2$ is set to an appropriate value at M_W, M_* could take a consistent value which is used in the above study.

This model could explain several unsolved problems in the standard model in a simple and unified way, as long as the global symmetry has sufficient goodness even in the gravitational effect. Some theory at high energy regions might give an answer to this point.