Two models with extra Higgs doublets and Axions

H. Serôdio (KAIST)

4^{th} KIAS Workshop Particle Physics and Cosmology, 30 October 2014.

In collaboration with: Alejandro Celis, Javier Fuentes-Martin
Works: PLB700(2011); PLB737(2014); arXiv:1410.6217 and arXiv:1410.6218

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Outline

- $U(1)_A$ is anomalous (Good η' is massive)
- A new term is introduce due to this anomaly

$$\bar{\theta}\frac{g_s^2}{32\pi^2}G_{a,\mu\nu}\tilde{G}_a^{\mu\nu}$$

- $\bar{\theta}$ violates T and P, and therefore also CP. From the neutron electric dipole moment $|\bar{\theta}| \lesssim 10^{-11}$.
- With just QCD $\bar{\theta} = 0$ as initial condition would be stable under radiative corrections. No longer true in the SM

$$\bar{\theta} = \theta_{QCD} + \text{Arg}(\text{Det}(M_q))$$

Introduction: The Strong CP Problem in a nutshell

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Problem: Why is $\bar{\theta}$ so small?

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Problem: Why is $\bar{\theta}$ so small? One interesting solution: "promote" this phase to a dynamical field, the Axion.

Introduction: Standard Axion Models

The original axion model:

- PQ: SM + Φ_2 = 2HDM.
  (axion scale = electroweak scale, ruled out)

  [Peccei, Quinn (1977)]

One way out: split both scales ($\langle S \rangle \gg \langle \phi_i \rangle$)

- KSVZ: SM (blind) + $Q_{L,R}$ + S

  [Kim (1979); Shifman, Vainshtein, Zakharov (1980)]

- DFSZ: SM + Φ_2 + S = 2HDM + S

  [Zhitnitskii (1980); Dine, Fischler, Srednicki (1981)]

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I will work on DFSZ-like extensions, i.e **NHDM + S**

Introduction: Adding scalar doublets

- New sources of **CPV**
- CP can be spontaneously generated
- **Dark** matter candidates
- New mechanisms for neutrino mass
- $\cdots$

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Natural Flavour Conservation [Weinberg, Glashow (1977); Pachos (1997)]

Idea: Allow just one Yukawa coupling in each sector

Model	up	down	lepton
Type-I	Φ_2	Φ_2	Φ_2
Type-II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

- **Pros:** No FCNCs at tree level; Easy to implement with a symmetry
- **Cons:** No spontaneous CPV
- PQ symmetry: invisible DFSZ axion model

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  - **Pros:** No FCNCs at tree level; General scalar sector; Contains the NFC cases as particular limits; Allows spontaneous CPV
  - **Cons:** Not implemented by symmetry [Ferreira, Lavoura, Silva (2010)]
  - See it as a low energy effective aligned 2HDM [Bae (2012); HS (2011)]

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- **The BGL model** [Branco, Grimus, Lavoura (1996)]
  Idea: Allow FCNCs in just one sector

$$\text{Up Yukawas:} \quad \Delta_1 = \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & 0 \end{pmatrix}, \quad \Delta_2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \times \end{pmatrix}$$

$$\text{Down Yukawas:} \quad \Gamma_1 = \begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ 0 & 0 & 0 \end{pmatrix}, \quad \Gamma_2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \times & \times & \times \end{pmatrix}$$

  - No FCNCs in the up sector, FCNCs in the down sector small
  - Unique implementation in 2HDM [Ferreira, Silva (2011); HS (2013)]

Effective A2HDM

with

an

Matter content and Lagrangian

Under the $U(1)_{PQ}$ symmetry

$$\text{Fermions:} \quad \left[\begin{array}{ll} Q_{L\alpha} \to Q_{L\alpha}, & \ell_{L\alpha} \to e^{iX_\ell\,\theta}\ell_{L\alpha}, \\ u_{R\alpha} \to e^{iX_u\,\theta}u_{R\alpha}, & e_{R\alpha} \to e^{iX_e\,\theta}e_{R\alpha}, \\ d_{R\alpha} \to e^{iX_d\,\theta}d_{R\alpha}, & \end{array} \right.$$

$$\text{Scalars:} \quad \left[S \to e^{iX_S\,\theta}S\,, \quad \Phi_j \to e^{iX_j\,\theta}\Phi_j\,, \quad \phi_j \to \phi_j \right.$$

Φ_j are active fields, i.e. they interact with fermions (*a la* **NFC**)

$$-\mathcal{L}_Y = \overline{Q_L}\,\Gamma\,\Phi_1 d_R + \overline{Q_L}\,\Delta\,\tilde{\Phi}_2 u_R + \overline{\ell_L}\,\Pi\,\Phi_k e_R + \text{h.c.}$$

ϕ_j are passive fields, i.e. they don't interact directly with fermions but they mix with the actives

$$V \supset \mu_{1,j}\Phi_1^\dagger\phi_j S + \mu_{2,j}\Phi_2^\dagger\phi_j S^* + \text{h.c.}$$

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The scalar singlet vev: $v_{\text{PQ}}^2 \simeq -2\mu_S^2/\lambda_S \gg v^2$ active-passive mixing

A decoupling limit

We have in leading order a $SU(2)_L$ conserving mixing between doublets. Defining $\varphi = (\Phi_1,\, \Phi_2,\, \phi_1,\, \phi_2)^T$, we want to diagonalize the mass terms for the doublets

$$\varphi_i^\dagger \mathcal{M}_{ij}\, \varphi_j \quad \text{with} \quad \mathcal{M} \ = \left(\begin{array}{cc} \mathcal{M}_A & \mathcal{M}_B \\ {\mathcal{M}_B}^\dagger & \mathcal{M}_C \end{array} \right).$$

The mass eigenstates are H_i, with $M_{H_1} \leq M_{H_2} \leq M_{H_3} \leq M_{H_4}$.

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$$\begin{pmatrix} \Phi_1 \\ \Phi_2 \\ \phi_1 \\ \phi_2 \end{pmatrix} = \begin{pmatrix} & & \mathcal{R}_{13} & \mathcal{R}_{14} \\ & & \mathcal{R}_{23} & \mathcal{R}_{24} \\ & & & \\ & & & \end{pmatrix} \begin{pmatrix} H_1 \\ H_2 \\ H_3 \\ H_4 \end{pmatrix}$$

since after the H_1 and H_2 decoupling

$$\begin{aligned} -\mathcal{L}_Y^{\text{eff}} &= \overline{Q_L}\, \Gamma\, (\mathcal{R}_{13} H_3 + \mathcal{R}_{14} H_4) d_R + \overline{Q_L}\, \Delta\, (\mathcal{R}_{23}^* \tilde{H}_3 + \mathcal{R}_{24}^* \tilde{H}_4) u_R \\ &\quad + \overline{\ell_L}\, \Pi\, (\mathcal{R}_{k3} H_3 + \mathcal{R}_{k4} H_4) e_R + \text{h.c.} \end{aligned}$$

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This is alignment

Axion properties

Axion-gluon coupling

$$a\frac{g_s^2|C_{ag}|}{32\pi^2 v_{PQ}}G_{a,\mu\nu}\tilde{G}_a^{\mu\nu}\,,\quad \text{with}\quad C_{ag}=6\quad N_{DW}\neq 1$$

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Axion-photon coupling

$$a\frac{\alpha}{8\pi v_{PQ}}C_{ag}C_{a\gamma}^{eff}F_{\mu\nu}\tilde{F}^{\mu\nu} \quad \text{with} \quad C_{a\gamma}^{\text{eff}}\simeq\frac{C_{a\gamma}}{C_{ag}}-\frac{2}{3}\frac{4+z}{1+z},$$

$$C_{a\gamma}/C_{ag}=\begin{cases} 8/3\,, & \Phi_d \\ 2/3\,, & \Phi_u \end{cases}$$

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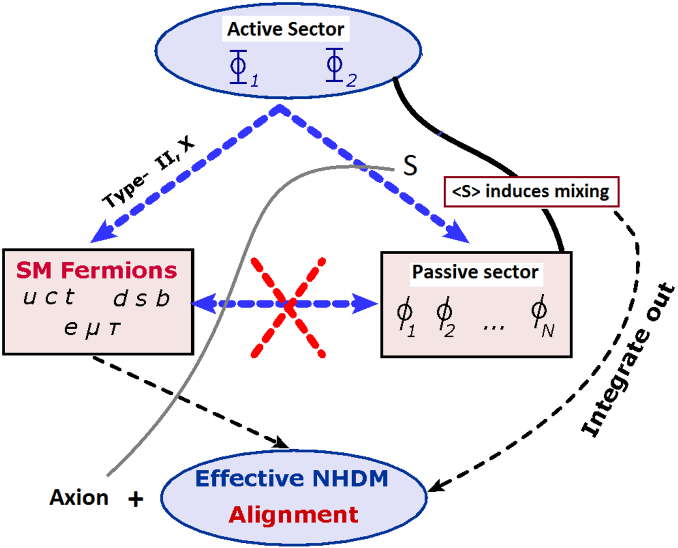
Axion-electron axial coupling

$$g_{ee}^A \frac{\partial_\mu a}{2v_{PQ}} \bar{e}\gamma^\mu\gamma_5\, e\,, \quad g_{ee}^A = \begin{cases} 2\frac{u_2^2}{v^2} + \frac{v_1^2+v_2^2}{v^2} & \text{for } \Phi_d \\ -2\frac{u_1^2}{v^2} - \frac{v_1^2+v_2^2}{v^2} & \text{for } \Phi_u \end{cases}$$

Conclusions I



3 Higgs Flavored PQ Model

(3HFPQ)

Why is BGL safe from large FCNCs?

$$\text{Up Yukawas:} \quad \Delta_1 = \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & 0 \end{pmatrix}, \quad \Delta_2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \times \end{pmatrix}$$

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In the mass basis

$$N_d = \frac{v_2}{v_1} D_d - \frac{v_2}{\sqrt{2}} \left(\frac{v_1}{v_2} + \frac{v_2}{v_1} \right) U_{dL}^{\dagger} e^{i\theta} \Gamma_2 U_{dR}$$

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$$[N_d]_{ij} = \frac{v_2}{v_1} [D_d]_{ij} - \left(\frac{v_2}{v_1} + \frac{v_1}{v_2} \right) V_{3i}^{*} V_{3j} [D_d]_{jj} \quad \rightarrow \left[\begin{array}{l} |\Delta S| = 2 \quad \text{transitions} \\ |V_{td}^{*} V_{ts}|^2 \sim \lambda^{10} \end{array} \right.$$

[Botella, Branco, Carmona, Nebot, Pedro, Rebelo (2014)]

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Can we add an axion to this setup?

Finding the anomalous implementation

- Up sector block diagonal

$$\mathcal{S}_L = \mathrm{diag}\left(1, 1, e^{iX_{tL}\,\theta}\right) \;, \quad \mathcal{S}_R^u = \mathrm{diag}\left(e^{iX_{uR}\,\theta}, e^{iX_{uR}\,\theta}, e^{iX_{tR}\,\theta}\right)$$

- Down sector unconstrained

$$\mathcal{S}_R^d = e^{iX_{dR}\theta}\,\mathbb{I}$$

Yukawa phase transformation matrix

$$\Theta_u = \theta \begin{pmatrix} X_{uR} & X_{uR} & X_{tR} \\ X_{uR} & X_{uR} & X_{tR} \\ X_{uR} - X_{tL} & X_{uR} - X_{tL} & X_{tR} - X_{tL} \end{pmatrix}$$

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Anomaly free condition: $2X_{tL} - (2X_{uR} + X_{tR} - 3X_{dR}) = 0$

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BGL 2HDM is anomaly free. We need at least 3 Higgs

$$\Gamma_1 = \begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ 0 & 0 & 0 \end{pmatrix}, \qquad \Gamma_2 = 0\,, \qquad \Gamma_3 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \times & \times & \times \end{pmatrix},$$

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Field transformations

$$X^Q_{\alpha L} = (0, 0, -2)\,, \quad X^u_{\alpha R} = (5/2, 5/2, -1/2)\,, \quad X^d_R = -5/2$$
$$X^\ell_{\alpha L} = (0, 0, 1)\,, \quad X^l_{\alpha R} = -1/2\,, \quad X^N_R = 1/2\,, \quad X_S = 1$$

Lagrangian

$$-\mathcal{L}_\mathrm{Y} = \overline{Q^0_L}\,[\Gamma_1\,\Phi_1 + \Gamma_3\,\Phi_3]\,d^0_R + \overline{Q^0_L}\,[\Delta_1\,\widetilde{\Phi}_1 + \Delta_2\,\widetilde{\Phi}_2]u^0_R$$
$$+ \overline{L^0_L}\,[\Pi_2\,\Phi_2 + \Pi_3\,\Phi_3]\,l^0_R + \overline{L^0_L}\,\Sigma_3\,\widetilde{\Phi}_3 N^0_R + \overline{(\mathbf{N^0_R})^c}\mathbf{A}\mathbf{N^0_R}\mathbf{S}^* + \mathrm{h.c.}\,,$$

$$\Pi_1 = 0\,, \quad \Pi_2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \times & \times & \times \end{pmatrix}, \quad \Pi_3 = \begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ 0 & 0 & 0 \end{pmatrix},$$

Two right-handed neutrinos

$$\Sigma_3 = \begin{pmatrix} \times & \times \\ \times & \times \\ 0 & 0 \end{pmatrix}$$

$$m_\nu \simeq -\frac{v_3^2 e^{i(\alpha_{PQ} - 2\alpha_3)}}{2\sqrt{2} v_{PQ}} \Sigma_3 A^{-1} {\Sigma_3}^T = \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

One massless light neutrino. Leptonic sector with a BGL suppression, but with CKM replaced by PMNS

$$\left(N_e'\right)_{ij} = -\frac{(v_1^2 + v_2^2)}{v_3^2} (D_e)_{ij} + \frac{v^2}{v_3^2} (U^\dagger)_{i3} (U)_{3j} (D_e)_{jj}$$

Axion properties

Axion-gluon coupling: $C_{ag} = 1, \quad N_{DW} = 1$

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Axion flavor changing interaction

$$\frac{\partial_\mu a}{2 v_{\rm PQ}} \left[\bar{\mu} \gamma^\mu \left(g^V_{\mu e} + \gamma_5 \, g^A_{\mu e} \right) e + \bar{s} \gamma^\mu \left(g^V_{sd} + \gamma_5 \, g^A_{sd} \right) d \right] +$$

with

$$g^{V,A}_{sd} = -2 V^*_{ts} V_{td} \,, \qquad g^{V,A}_{\mu e} = U^*_{\tau 2} U_{\tau 1} \,.$$

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$K^+ \to \pi^+ a \longrightarrow m_a \leq 18$ meV

$$|V_{CKM}| \simeq \begin{pmatrix} 0.974 & 0.252 & 0.00351 \\ 0.225 & 0.973 & 0.0412 \\ 0.00867 & 0.040 & 0.999 \end{pmatrix}$$

$$|V^*_{ts} V_{td}| \sim 3.5 \times 10^{-4}$$

$\mu^+ \to e^+ a \gamma \longrightarrow m_a \leq 12$ meV

$$|V_{PMNS}| \simeq \begin{pmatrix} 0.82 & 0.55 & 0.11 \\ 0.41 & 0.58 & 0.72 \\ 0.41 & 0.58 & 0.69 \end{pmatrix}$$

$$|V^*_{\tau 2} V_{\tau 1}| \sim 2.4 \times 10^{-1}$$

axion-electron axial coupling

From stellar evolution and white-dwarf cooling considerations.

$$g_{ee}^{A} = -2 + |U_{\tau 1}|^2 + \frac{v_2^2 + 2v_3^2}{v^2}, \quad m_a \lesssim 1.5/|g_{ee}^{A}|\,\text{meV}$$

We can get $|g_{ee}^{A}| \in [0, 1.8]$. In the top-vev dominance regime, i.e. when $v_2 \sim v$, one obtains an upper bound on the axion mass $m_a \lesssim 1.7$ meV

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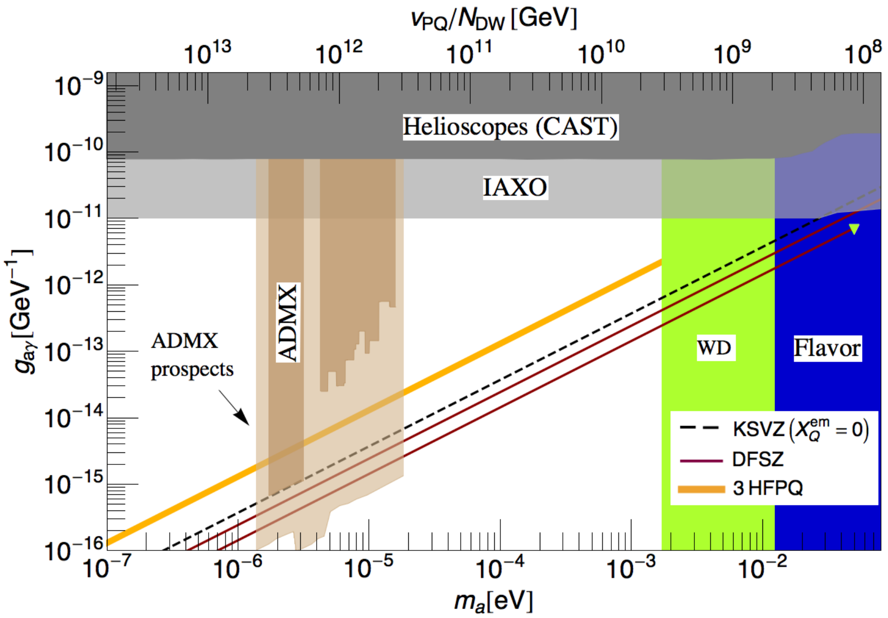
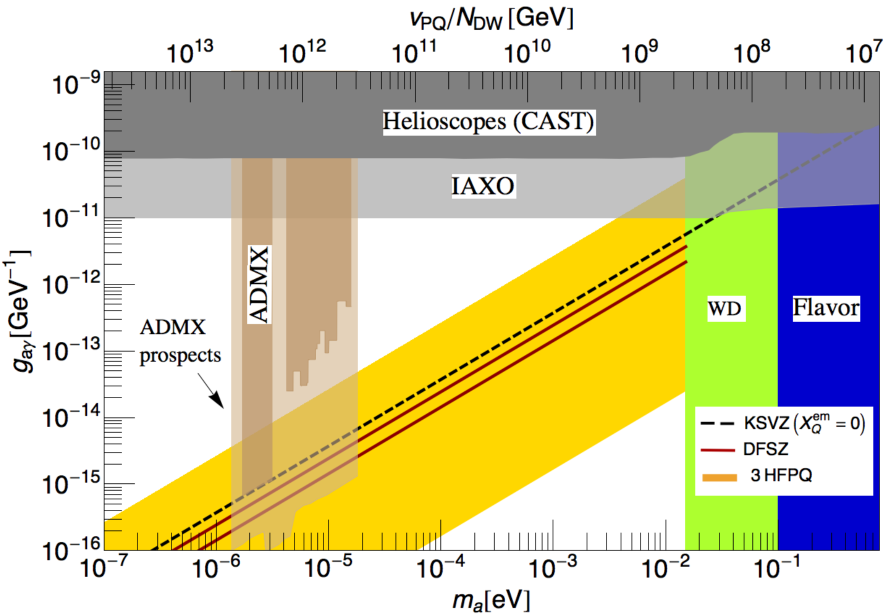
Models	KSVZ	DFSZ	3HFPQ
BSM fields	Q+S	Φ_2+S	Φ_2+Φ_3+S
PQ fields	Q, S	q, l, $\Phi_{1,2}$, S (flavor blind)	q, l, $\Phi_{1,2,3}$, S (flavor sensitive)
$C_{a\gamma}/C_{ag}$	$6(X_Q^{em})^2$	$2/3, 8/3$	$26/3$
CtM	No	Yes	Yes
FCAI	No	No	Yes
$N_{\rm DW}$	1	3, 6	1


v_{PQ}/N_{DW} [GeV]
10^{13} 10^{12} 10^{11} 10^{10} 10^{9} 10^{8}
10^{-9} 10^{-10} 10^{-11} 10^{-12} 10^{-13} 10^{-14} 10^{-15} 10^{-16}
$g_{a\gamma}$ [GeV^{-1}]
Helioscopes (CAST)
IAXO
ADMX
ADMX prospects
WD
Flavor
KSVZ ($X_Q^{em} = 0$)
DFSZ
3 HFPQ
10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2}
m_a[eV]

Model variations


v_{PQ}/N_{DW} [GeV]
10^{13} 10^{12} 10^{11} 10^{10} 10^{9} 10^{8} 10^{7}
Helioscopes (CAST)
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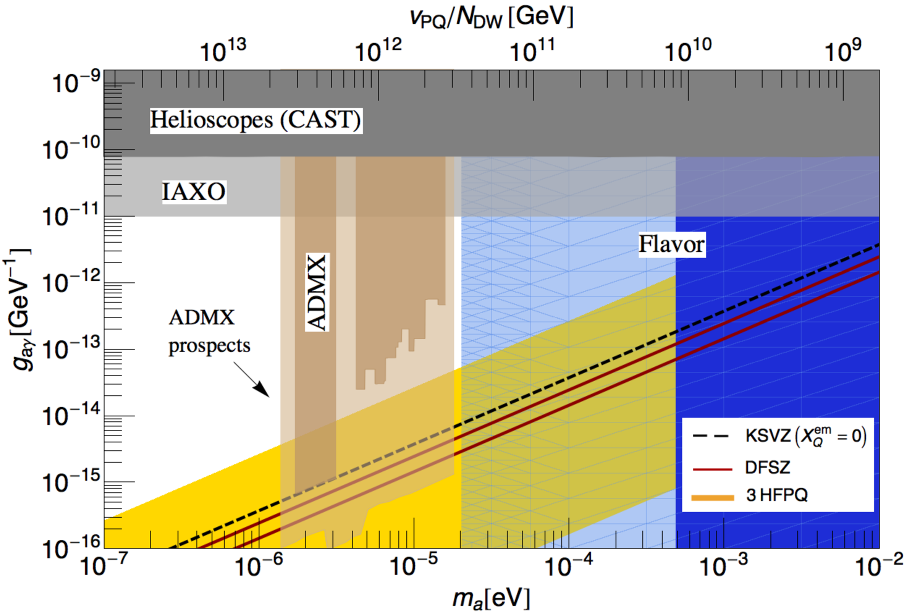
m_a [eV]

Permuting flavors



For: charm single out; up single out

Conclusions II

- Models with tree-level FCNCs in the down-quark or charged lepton sectors receive important constraints on the PQ scale from familon searches in kaon and muon decays.
- Models with tree-level FCNCs in the down-quark sector for which the up (or charm) quark is singled out receive the strongest upper bound on the axion mass from $K^+ \to \pi^+ a$ decays since in this case the flavor changing couplings are not as suppressed $|V_{us}^* V_{ud}| \sim |V_{cs}^* V_{cd}| \gg |V_{ts}^* V_{td}|$.
- A large variety of the models considered have $N_{\rm DW} = 1$. One interesting aspect is the fact that we are able to mimic the DFSZ axion coupling to photons and have at the same time $N_{\rm DW} = 1$. A zero $C_{a\gamma}$ can be achieved but only in models with $N_{\rm DW} > 1$.

Backup

- **Case I**
- Restrictions: $X_{dR} = -X_{uR}$, $X_{tL} \neq -(X_{uR} - X_{tR})$

$$\text{Texture Matching: } \begin{cases} X_{uR} \neq X_{tR}, \\ X_{tL} \neq X_{tR} - X_{uR} \end{cases}$$

$$\text{Anomaly: } X_{tL} \neq -\frac{1}{2}(X_{uR} - X_{tR})$$

- Higgs charges: $X_{\Phi 1} = X_{uR}$, $X_{\Phi 2} = X_{tR} - X_{tL}$, $X_{\Phi 3} = X_{tL} + X_{uR}$

Yukawa textures

$$\Gamma_1 = \begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ 0 & 0 & 0 \end{pmatrix}, \qquad \Gamma_2 = 0, \qquad \Gamma_3 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \times & \times & \times \end{pmatrix},$$

$$\Delta_1 = \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & 0 \end{pmatrix}, \qquad \Delta_2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \times \end{pmatrix}, \qquad \Delta_3 = 0,$$

- **Case II**
- Restrictions: $X_{tR} = 2X_{tL} - X_{dR}$, $X_{tL} \neq -(X_{uR} - X_{tR})$

$$\text{Texture Matching: } \begin{cases} X_{tL} \neq X_{uR} + X_{dR}, \\ X_{tL} \neq \frac{1}{2}\left(X_{uR} + X_{dR}\right) \end{cases}$$

$$\text{Anomaly: } X_{uR} \neq -X_{dR}$$

- Higgs charges: $X_{\Phi 1} = X_{uR}$, $X_{\Phi 2} = -X_{dR}$, $X_{\Phi 3} = X_{tL} - X_{dR}$

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$$\Gamma_1 = 0\,, \qquad \Gamma_2 = \begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ 0 & 0 & 0 \end{pmatrix}, \quad \Gamma_3 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \times & \times & \times \end{pmatrix},$$

$$\Delta_1 = \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & 0 \end{pmatrix}, \qquad \Delta_2 = 0\,, \qquad \Delta_3 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \times \end{pmatrix}.$$

The anomalous implementation

- **Case III**
- Restrictions: $X_{tR} = X_{uR} + X_{tL}$

$$\text{Texture Matching: } \begin{cases} X_{uR} \neq -X_{dR},\ X_{tL} \neq X_{uR} + X_{dR}, \\ X_{tL} \neq -\left(X_{uR} + X_{dR}\right),\ X_{tL} \neq \frac{1}{2}\left(X_{uR} + X_{dR}\right) \end{cases}$$

$$\text{Anomaly: } X_{tL} \neq 3\left(X_{uR} + X_{dR}\right)$$

- Higgs charges: same as in **Case II**

Yukawa textures

$$\Gamma_1 = 0\,, \qquad \Gamma_2 = \begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ 0 & 0 & 0 \end{pmatrix}, \quad \Gamma_3 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \times & \times & \times \end{pmatrix},$$

$$\Delta_1 = \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & \times \end{pmatrix}, \qquad \Delta_2 = 0\,, \qquad \Delta_3 = 0\,.$$

The scalar sector

- Add complex scalar singlet: $S \to e^{iX_S\,\theta} S$, with $|\langle 0| S |0\rangle| \gg |\langle 0| \Phi_i |0\rangle|$
- The scalar potential: $V(\Phi, S) = [V(\Phi, S)]_{\text{blind}} + [V(\Phi, S)]_{\text{sen}}$

$$
\begin{aligned}
[V(\Phi, S)]_{\text{blind}} =& m_i^2 \Phi_i^\dagger \Phi_i + \lambda_{ii,jj} \left(\Phi_i^\dagger \Phi_i\right) \left(\Phi_j^\dagger \Phi_j\right) + \lambda'_{ij,ji} \left(\Phi_i^\dagger \Phi_j\right) \left(\Phi_j^\dagger \Phi_i\right) \\
& + m_S^2 |S|^2 + \lambda_S |S|^4 + \lambda_i^{\Phi S} (\Phi_i^\dagger \Phi_i) |S|^2
\end{aligned}
$$

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$$[V(\Phi, S)]_{\text{blind}} = m_i^2 \Phi_i^\dagger \Phi_i + \lambda_{ii,jj} \left(\Phi_i^\dagger \Phi_i\right) \left(\Phi_j^\dagger \Phi_j\right) + \lambda'_{ij,ji} \left(\Phi_i^\dagger \Phi_j\right) \left(\Phi_j^\dagger \Phi_i\right) + m_S^2 |S|^2 + \lambda_S |S|^4 + \lambda_i^{\Phi S} (\Phi_i^\dagger \Phi_i) |S|^2$$

$[V(\Phi, S)]_{\text{blind}}$ is $U(1)^4$ invariant. We need two phase sensitive terms

$$U(1)^4 \quad \longrightarrow \quad U(1)_{PQ} \times U(1)_Y$$

The anomalous implementation

Case	Phase sensitive	Constraint
(1)	$\left(\Phi_1^\dagger\Phi_2\right)\ \left(\Phi_1^\dagger\Phi_3\right)$	$X_{\Phi 2} + X_{\Phi 3} - 2X_{\Phi 1} = 0$
(2)	$\left(\Phi_2^\dagger\Phi_1\right)\ \left(\Phi_2^\dagger\Phi_3\right)$	$X_{\Phi 3} + X_{\Phi 1} - 2X_{\Phi 2} = 0$
(3)	$\left(\Phi_3^\dagger\Phi_1\right)\ \left(\Phi_3^\dagger\Phi_2\right)$	$X_{\Phi 1} + X_{\Phi 2} - 2X_{\Phi 3} = 0$
(4)	$\left(\Phi_1^\dagger\Phi_2\right)\ \{S, S^*\}^{k_1}$	$k_1 X_S = \mp(X_{\Phi 2} - X_{\Phi 1})$
(5)	$\left(\Phi_1^\dagger\Phi_3\right)\ \{S, S^*\}^{k_2}$	$k_2 X_S = \mp(X_{\Phi 3} - X_{\Phi 1})$
(6)	$\left(\Phi_2^\dagger\Phi_3\right)\ \{S, S^*\}^{k_3}$	$k_3 X_S = \mp(X_{\Phi 3} - X_{\Phi 2})$

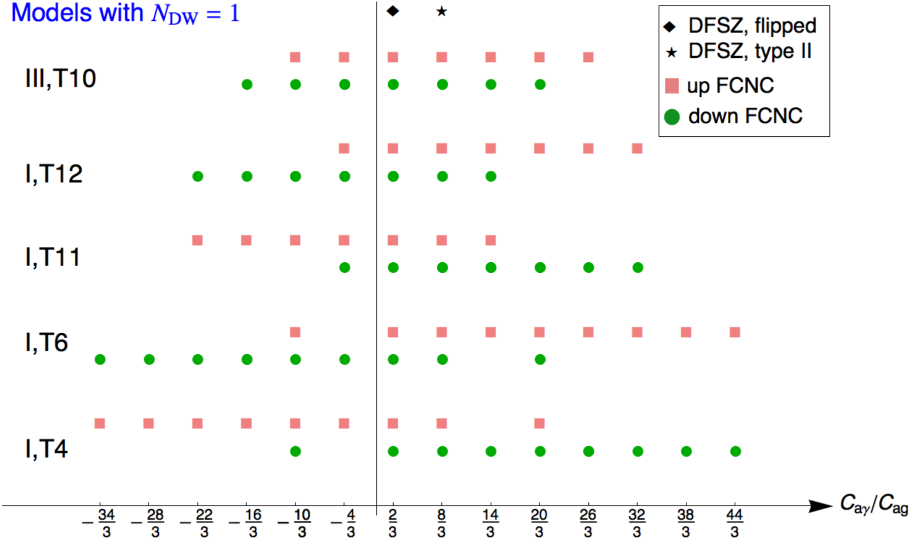
Combinations

$T_{1,2}$: (4) + (5), $T_{3,4}$: (4) + (6), $T_{5,6}$: (5) + (6),
T_7 : (4) + (5) + (1), T_8 : (4) + (6) + (2), T_9 : (5) + (6) + (3)
T_{10} : (4) + (5) + (6) + (1), T_{11} : (4) + (5) + (6) + (2),
T_{12} : (4) + (5) + (6) + (3)

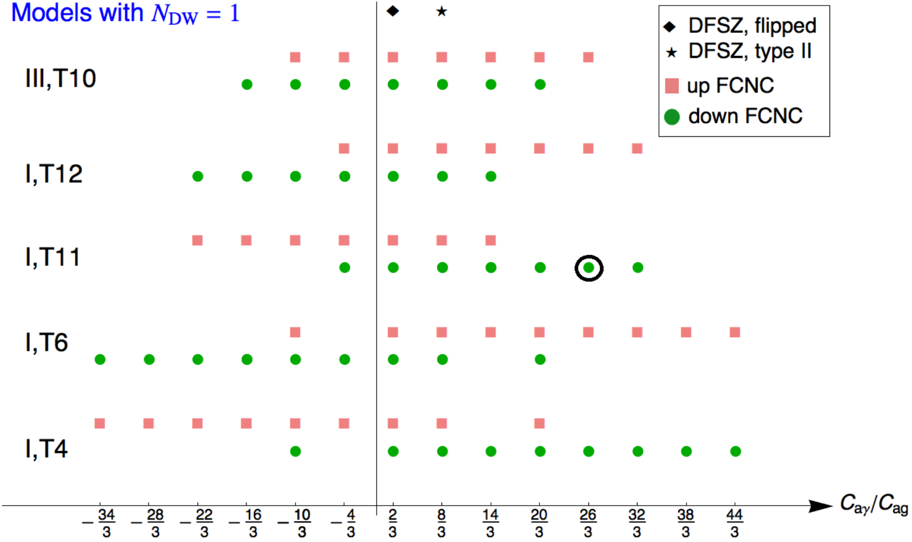
Axion properties

	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{11}	T_{12}
$N^{I}_{\rm DW}$	3	3	2	1	2	1	–	2	2	–	1	1
$N^{II}_{\rm DW}$	2	4	2	4	6	6	4	4	–	2	2	–
$N^{III}_{\rm DW}$	–	3	5	7	7	8	2	–	–	1	–	–

Models with $N_{DW} = 1$



Models with $N_{\rm DW} = 1$



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PQ fields	$Q,\ S$	$q,\ l,\ \Phi_{1,2},\ S$ (flavor blind)	$q,\ l,\ \Phi_{1,2,3},\ S$ (flavor sensitive)
$C_{a\gamma}/C_{ag}$	$6(X_Q^{em})^2$	$2/3, 8/3$	$[-34/3, 44/3]$
Tree-level CtM	No	Yes	Yes
Tree-level FCAI	No	No	Yes
N_{DW}	1	$3, 6$	$1,\ 2,\ \cdots,\ 8$