Two invisible axion models with a non-minimal flavor structure

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In collaboration with: Alejandro Celis and Hugo Serôdio

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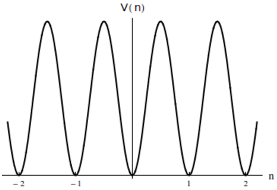
Outline

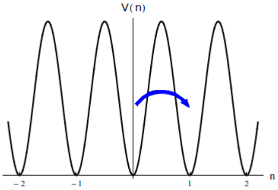
1. Introduction
2. Effective Aligned 2HDM with a DFSZ-like invisible axion
3. 3 Higgs Flavored PQ Model (3HFPQ)
4. Conclusions

Introduction: the Strong CP phase



[G. 't Hooft, 1976]

Introduction: the Strong CP phase



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$$|\theta\rangle = \sum_n e^{-i\theta n}|n\rangle$$

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

$$\bar{\theta} = \underbrace{\theta}_{\text{From QCD}} + \underbrace{\arg\left[\det\left(M_{\text{quark}}\right)\right]}_{\text{From the Yukawa sector}}$$

✓ The $U(1)_A$ problem is solved. Source for the η' mass

✗ $\mathcal{L}_\theta$ violates CP. From neutron EDM $|\bar{\theta}| \lesssim 10^{-11}$ [Baker et al., 2006] **Why??**

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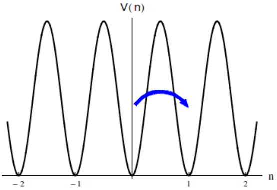

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Interesting proposal: Promote $\bar{\theta}$ to a dynamical field, the **axion**

Introduction: Axion models

General features

- PQ symmetry: global QCD anomalous and chiral $U(1)_{\mathrm{PQ}}$
- New particle: the axion

Original Peccei-Quinn implementation [Peccei, Quinn (1977)]

- Two Higgs doublets with the PQ symmetry enforcing NFC
- The PQ and the electroweak scales are the same
- ✗ Ruled out by experiment

Invisible axion models (extra scalar singlet $\langle S\rangle = v_{\mathrm{PQ}} \gg v$)

✓ Interesting features: Dark matter, neutrino masses...

- KSVZ: SM (PQ blind) + $Q_{L,R}$ + S [Kim (1979); Shifman, Vainshtein, Zakharov (1980)]
- DFSZ: 2HDM + S [Zhitnitskii (1980); Dine, Fischler, Srednicki (1981)]

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

Introduction: multi-Higgs-doublet models (MHDM)

Extend the scalar sector by adding extra doublets

- ✓ Minimal extension of the SM
- ✓ Theoretically motivated (Strong CP, SUSY...)
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- ✗ Uncontrolled FCNCs

$$-\mathcal{L}_Y = \overline{Q_L^0}\,[\Gamma_1\,\Phi_1 + \Gamma_2\,\Phi_2]\,d_R^0 + \overline{Q_L^0}\,[\Delta_1\,\widetilde{\Phi}_1 + \Delta_2\,\widetilde{\Phi}_2]u_R^0 + \text{h.c.}$$

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Warning! FCNCs!

Introduction: Natural Flavor Conservation (NFC)

Protection by symmetry [Weinberg, Glashow (1977); Pachos (1997)]

Introduce a $\mathcal{Z}_2$ symmetry that only allows one Yukawa 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

- ✓ Free of FCNCs
- ✓ Simplest implementation
- ✓ PQ symmetry: DFSZ invisible axion model
- ✗ No spontaneous CPV

Motivation: Aligned two-Higgs-doublet model (A2HDM)

Yukawa alignment [Pich, Tuzon (2009)]

Request Yukawa matrices in the same sector to be proportional

- ✓ No tree-level FCNCs
- ✓ General scalar potential
- ✓ NFC models as particular limits
- ✓ Allows spontaneous CPV
- ✗ Not imposed by a symmetry $\Rightarrow$ Unstable under RGE

[Ferreira, Lavoura, Silva (2010)]

Solution: Treat it as an effective theory of a larger scalar sector

[Medeiros Varzielas (2011); Serôdio (2011); Bae (2012)]

Opportunity: Use the enlarged scalar sector to implement the PQ mechanism [Celis, JF, Serôdio (2014)]

Effective A2HDM with an invisible

Model implementation

- Matter content: 2HDM + $\phi_{1,2}$ + S with $v_{\mathrm{PQ}} \gg v$
- PQ symmetry: like DFSZ with $\phi_{1,2}$ singlets
- The PQ symmetry enforces NFC and $\phi_{1,2}$ pasive fields

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

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✓ Neutrino masses (N_R gauge singlet charged under PQ)

Dirac:

$$\overline{\ell_L} Y_j\, \tilde{\phi}_j N_R + \text{h.c.}$$

$$m_\nu = \frac{v_j^*}{\sqrt{2}} Y_j$$

Majorana (see-saw Type I):

$$\overline{\ell_L}\, Y\, \tilde{\Phi}_k N_R + \overline{N_R^c}\, A\, N_R\, S + \text{h.c.}$$

$$m_\nu \simeq -\frac{u_k^{*2}}{2\sqrt{2} v_{\rm PQ}}\, Y\, A^{-1}\, Y^T$$

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✓ Passive and active scalar fields mix

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

A2HDM as a decoupling limit

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

Decoupling: $m_{H_3},\, m_{H_4} \ll m_{H_1},\, m_{H_2}$

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

A2HDM as a decoupling limit

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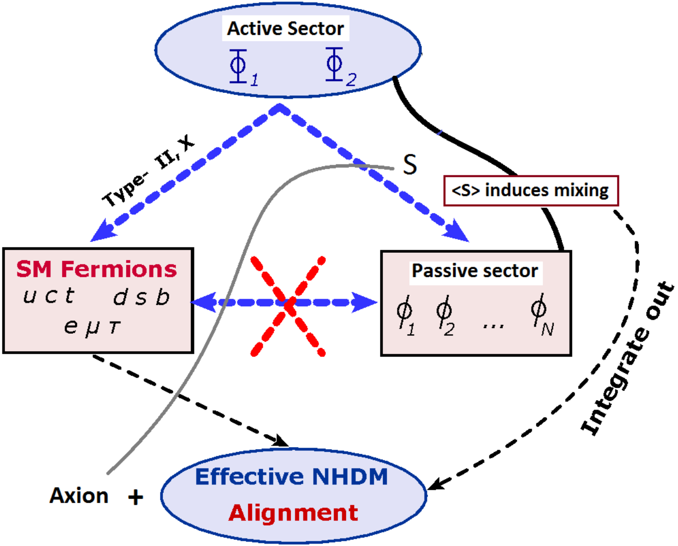
This is Yukawa alignment!

A2HDM as a decoupling limit



Axion properties

- Axion-photon coupling like in the DFSZ model

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

- The axion coupling to matter is different

$$\mathcal{L}_{ae} = g_{ee}^{A}\,\frac{\partial_\mu a}{2v_{PQ}}\,\bar{e}\,\gamma^\mu\gamma_5\,e\,, \quad g_{ee}^{A} \in \begin{cases} [0,\,1.8] & \text{for } \Phi_u \\ [0.2,\,2] & \text{for } \Phi_d \end{cases}$$

✗ Domain wall problem, like in the DFSZ model ($N_{\rm DW} = 6$)

Motivation: Branco–Grimus–Lavoura model (BGL)

Controlled FCNCs [Branco, Grimus, Lavoura (1996)]

Allow FCNCs in one sector controlled by the CKM matrix

- ✓ FCNCs under control
  [Botella, Branco, Carmona, Nebot, Pedro, Rebelo (2014); Bhattacharyya, Das, Kundu (2014)]
- ✓ Allows spontaneous CPV
- ✓ Imposed by a symmetry (discrete or continuous)
  $\Rightarrow$ Stable under RGE [Botella, Branco, Nebot, Rebelo (2011)]
- ✗ Accidental symmetry in the Higgs potential
  $\Rightarrow$ Undesired pseudo-Goldstone boson

Solutions:

- Soft breaking of the accidental symmetry
- Add extra singlets

Opportunity: The PQ symmetry is responsible of the BGL Yukawa structure and the pseudo-Goldstone boson is the axion

[Celis, JF, Serôdio (2014)]

3 Higgs Flavored PQ Model

(3HFPQ)

BGL Yukawa textures

$$-\mathcal{L}_Y = \overline{Q_L^0}\left[\Gamma_1^{BGL}\,\Phi_1 + \Gamma_2^{BGL}\,\Phi_2\right] d_R^0 + \overline{Q_L^0}\left[\Delta_1^{BGL}\,\widetilde{\Phi}_1 + \Delta_2^{BGL}\,\widetilde{\Phi}_2\right] u_R^0 + \text{h.c.}$$

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

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

- No FCNCs in the up sector, FCNCs in the down sector proportional to V_{CKM}
- Unique implementation in 2HDM [Ferreira, Silva (2011); Serôdio (2013)]

The anomalous condition for BGL-like a model

- Up sector block diagonal: $\begin{cases} \mathcal{S}_L = \mathrm{diag}\left(1, 1, e^{iX_{tL}\,\theta}\right) \\ \mathcal{S}_R^u = \mathrm{diag}\left(e^{iX_{uR}\,\theta}, e^{iX_{uR}\,\theta}, e^{iX_{tR}\,\theta}\right) \end{cases}$
- Down sector unconstrained: $\mathcal{S}_R^d = e^{iX_{dR}\theta}\,\mathbb{I}$
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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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$$X_{uR} = -X_{dR}$$

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BGL 2HDM is anomally free. We need to extend the model

Anomalous BGL-like implementation (3HPQ)

$$
\begin{aligned}
-\mathcal{L}_{\mathrm{Y}} = & \overline{Q_L^0}\,[\Gamma_1\,\Phi_1 + \Gamma_3\,\Phi_3]\,d_R^0 + \overline{Q_L^0}\,[\Delta_1\,\widetilde{\Phi}_1 + \Delta_2\,\widetilde{\Phi}_2]u_R^0 \\
& + \overline{L_L^0}\,[\Pi_2\,\Phi_2 + \Pi_3\,\Phi_3]\,l_R^0 + \overline{L_L^0}\,\Sigma_3\,\widetilde{\Phi}_3 N_R^0 + \overline{(N_R^0)^c} A N_R^0 S^* + \text{h.c.}\,,
\end{aligned}
$$

$$
\Pi_3 \sim \Gamma_1 = \begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ 0 & 0 & 0 \end{pmatrix}, \qquad \Pi_1 \sim \Gamma_2 = 0\,, \qquad \Pi_2 \sim \Gamma_3 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \times & \times & \times \end{pmatrix},
$$

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

- Two right-handed neutrinos

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

3HFPQ. Model properties

- No FCNCs in the up-quark sector
- FCNCs in the down-quark sector under control

$$\left(N_d'\right)_{ij} = (D_d)_{ij} - \frac{v^2}{v_3^2}(V_{\text{CKM}}^\dagger)_{i3}(V_{\text{CKM}})_{3j}(D_d)_{jj}$$

$$\left(N_d\right)_{ij} = \frac{v_2}{v_1}(D_d)_{ij} - \frac{v_2}{v_1}(V_{\text{CKM}}^\dagger)_{i3}(V_{\text{CKM}})_{3j}(D_d)_{jj}$$

- FCNCs in the lepton sector under control

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

$$\left(N_e\right)_{ij} = -\frac{v_1}{v_2}(U_{\text{PMNS}}^\dagger)_{i3}(U_{\text{PMNS}})_{3j}(D_e)_{jj}$$

- Neutrino masses via type I see-saw with one massless neutrino

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

3HFPQ. Axion properties and flavor bounds

Models	KSVZ	DFSZ	3HFPQ
BSM fields	$Q+S$	Φ_2+S	$\Phi_2+\Phi_3+S$
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

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$$\mathcal{L}_{\rm FCNC} = \frac{\partial_\mu a}{2 v_{\rm PQ}} \left[\bar{\mu}\gamma^\mu \left(g_{\mu e}^V + \gamma_5\, g_{\mu e}^A \right) e + \bar{s}\gamma^\mu \left(g_{sd}^V + \gamma_5\, g_{sd}^A \right) d \right] + h.c.$$

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$$\mathcal{L}_{\mathrm{FCNC}} = \frac{\partial_\mu a}{2 v_{\mathrm{PQ}}} \left[\bar{\mu}\gamma^\mu \left(g_{\mu e}^V + \gamma_5\, g_{\mu e}^A \right) e + \bar{s}\gamma^\mu \left(g_{sd}^V + \gamma_5\, g_{sd}^A \right) d \right] + h.c.$$

$$g_{\mu e}^{V,A} = U_{\tau 2}^* U_{\tau 1} \sim 2.4 \times 10^{-1}$$

$$g_{sd}^{V,A} = -2 V_{ts}^* V_{td} \sim 6.9 \times 10^{-4}$$

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

[Bolton et al. (1988)]

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

[Adler et al. E787 Collaboration (2002)]

3HFPQ. Axion astrophysical bounds

Bound from white-dwarfs (WD)

$$\mathcal{L}_{ea} = g_{ee}^{A} \frac{\partial_\mu a}{2 v_{PQ}} \bar{e}\gamma^\mu \gamma_5 e \quad \Rightarrow \quad m_a \lesssim 1.5/|g_{ee}^{A}|\,\text{meV}$$

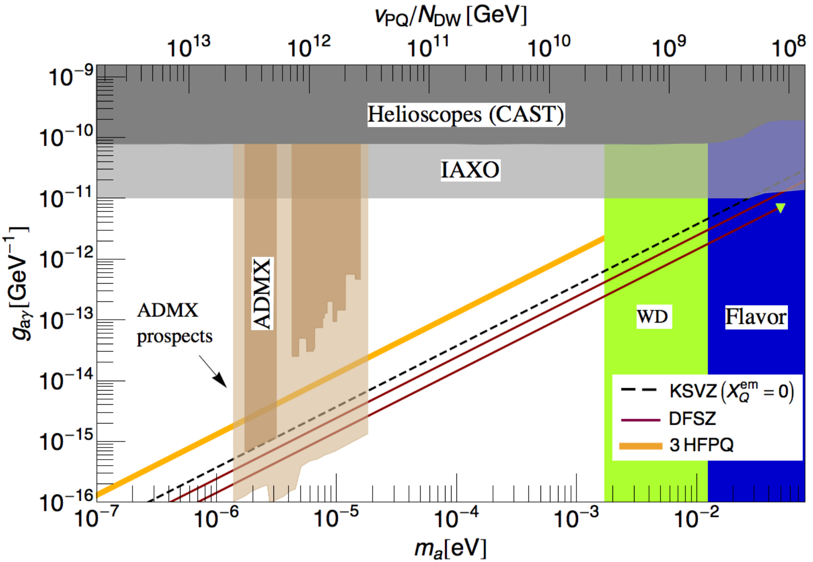
[Raffelt (2008); Bertolami et al. (2014)]

$$g_{ee}^{A} = -2 + |U_{\tau 1}|^2 + \frac{v_2^2 + 2v_3^2}{v^2} \qquad |g_{ee}^{A}| \in [0, 1.8]$$

In the top-vev dominance regime, i.e $\underline{v_2 \simeq v}$: $m_a \lesssim 1.7$ meV

Other interesting axion experiments:

- Helioscopes: CERN Axion Solar Telescope (CAST), International Axion Observatory (IAXO) [Andriamonje et al. (2007); Irastorza et al. (2011)]
- Axion Dark Matter experiment (ADMX) [Asztalos et al. (2010)]



v_{PQ}/N_{DW} [GeV]
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
$g_{a\gamma}$ [GeV^{-1}]
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
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]

3HFPQ. Model variations

- Different PQ charge implementations
- Symmetric permutations in flavor space
- Permuting the up and down Yukawa textures

Models	KSVZ	DFSZ	3HFPQ
BSM fields	$Q+S$	Φ_2+S	$\Phi_2+\Phi_3+S$
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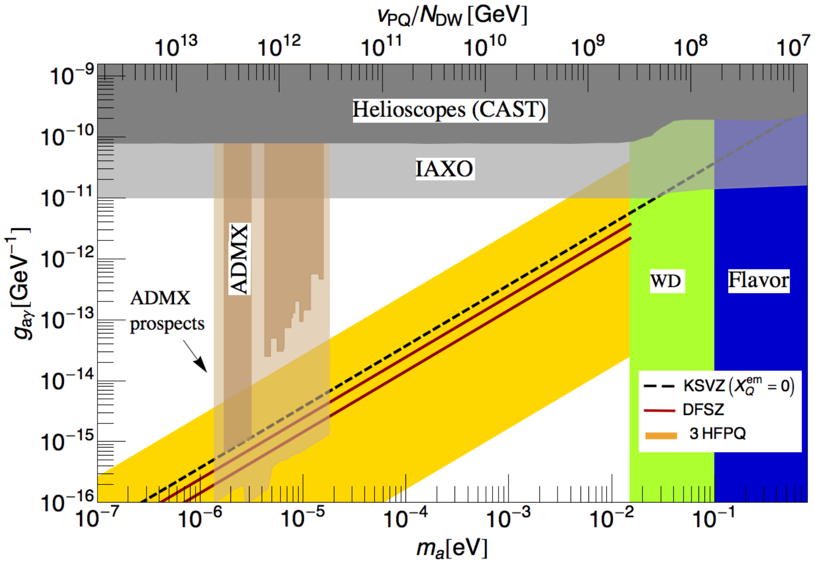
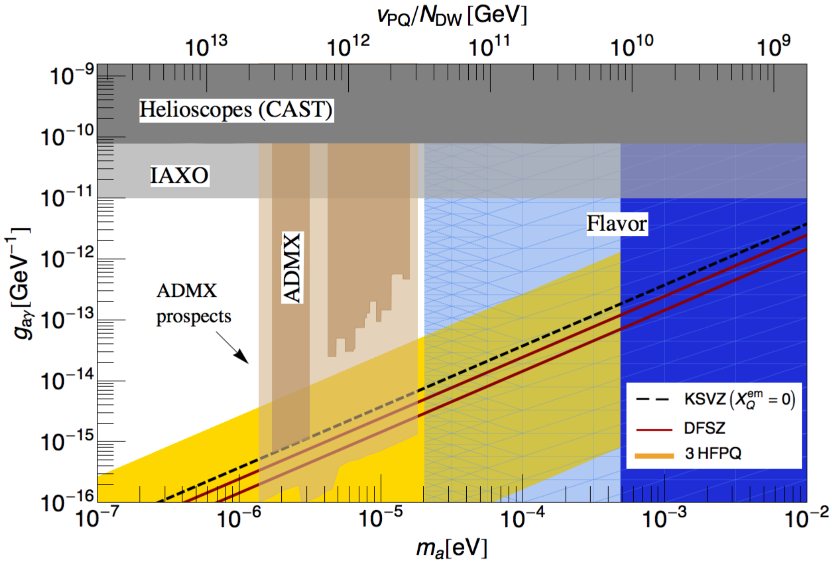
$C_{a\gamma}/C_{ag}$	$6(X_Q^{em})^2$	$2/3, 8/3$	$[-34/3, 44/3]$
Tree-level CtM	No	Yes	Yes
Tree-level FCAI	No	No	Yes
N_{DW}	1	$3, 6$	$1,\ 2,\ \cdots,\ 8$

3HFPQ. Model variations



3HFPQ. Up- and charm-quarks singled out



Conclusions

Effective A2HDM with an axion

- Same axion-photon couplings as in the DFSZ model
- Differences in the axion coupling to matter

✗ Domain wall problem ($N_{\rm DW} \neq 1$) as in the DFSZ model

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Effective A2HDM with an axion

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3HFPQ model

✓ Flavored axion. Important constraints on the PQ scale from familon searches in kaon and muon decays

  - Models where up and charm quark are singled out severely constrained ($|V_{us}^* V_{ud}| \sim |V_{cs}^* V_{cd}| \gg |V_{ts}^* V_{td}|$)
  - No important constraints in models where down-quarks are singled out

✓ No domain wall problem for a large variety of models ($N_{\text{DW}} = 1$)

- Possibility to mimic DFSZ axion-photon coupling with $N_{\text{DW}} = 1$
- Possibility to get $C_{a\gamma} = 0$ but with $N_{\text{DW}} > 1$