Nucleophobic Axions

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based on arXiv: 1712.04940, with L. Di Luzio, F. Mescia, E. Nardi, P. Panci

Outline

- (Flavor-Universal) DFSZ Models
- Why Nucleophobia?
- Nucleophobia in Non-Universal DFSZ Models

Axion Models

Specify anomalous breaking of PQ (fermion sector)
and spontaneous PQ breaking (scalar sector)

$$U(1)_{\rm PQ} \times SU(3)_c^2$$

SM fermions — BSM fermions

2Higgs	2Higgs+Singlet	Higgs+Singlet
PQWW	**DFSZ**	**KSVZ**
[Peccei, Quinn, Wilczek, Weinberg '78]	[Dine, Fischler, Srednicki, Zhitnitsky '80]	[Kim, Shifman, Vainshtein, Zakharov '80]

excluded

$J/\psi \to \gamma a$

see however 1710.03764

$\langle \text{Singlet} \rangle \gg v$: "Invisible" axion models

DFSZ Models

SM fermions + 2Higgs + Singlet $\left\{ \begin{array}{c} \langle H_1 \rangle = c_\beta v \qquad \langle H_2 \rangle = s_\beta v \\ \langle \Phi \rangle = v_{\rm PQ} \gg v \end{array} \right.$

Construct 2HDM Lagrangian invariant under single U(1)

$\mathcal{L}_{\rm yuk} = y^u_{ij} \overline{Q}_i U_j \left\{ \begin{array}{l} H_1 \\ H_2 \end{array} \right.$ flavor-universal, U(1) charges $\Rightarrow$ $\begin{array}{l} \overline{Q}_i U_j \; H_1 \\ \overline{Q}_i D_j \; \tilde{H}_2 \\ \overline{L}_i E_j \; \tilde{H}_{1 \text{ or } 2} \end{array}$

Break residual U(1) by H-Singlet couplings $\mathcal{L} \sim H_1^\dagger H_2 \Phi^2$

Ensure $\text{GB}_{\rm PQ} \perp \text{GB}_{\rm Z}$

$0 = X_1 c_\beta^2 + X_2 s_\beta^2$

All PQ charges fixed in terms of vacuum angle

Axion Couplings

Higgs contain GB: axion-fermion couplings from Yukawas

$$H_i \sim v_i \, e^{i X_i a(x)/v_{\rm PQ}}$$

Can remove by PQ transformation acting only on fermions

$$f \to f e^{i X_f a(x)/v_{\rm PQ}}$$

Anomalous: generate axion couplings to field strengths

$$\mathcal{L}_{\rm anon} \sim N \frac{a}{v_{\rm PQ}} \frac{\alpha_s}{4\pi} G\tilde{G} + E \frac{a}{v_{\rm PQ}} \frac{\alpha_{\rm em}}{4\pi} F\tilde{F}$$

Local: generate derivative axion couplings to fermions

$$\mathcal{L}_{\rm ferm} \sim \frac{\partial_\mu a}{v_{\rm PQ}} \overline{u}_i \gamma^\mu P_R X_{u_i} u_i + \ldots$$

[mass basis: $X_u \to V_{UR}^\dagger X_u V_{UR}$]

DFSZ Predictions

Anomaly coefficients only depend on charge differences

$$\left.\begin{aligned} 2N &= \mathrm{Tr}\,(X_{q_L} - X_{q_R}) = 3\,(X_1 - X_2) \\ E &= \quad \ldots \quad \ldots \quad = 4X_1 - X_2 - 3X_{1\,\mathrm{or}\,2} \end{aligned}\right\} \begin{aligned} &\to 6 \\ &\to 8\,\mathrm{or}\,2 \end{aligned}$$

Fermion couplings flavor-universal & depend only on t_β

$$X_u = -\underbrace{X_1}_{2s_\beta^2}\mathbb{1}_{3\times3} \qquad X_d = \underbrace{X_2}_{-2c_\beta^2}\mathbb{1}_{3\times3} \qquad X_e = X_{1\,\mathrm{or}\,2}\mathbb{1}_{3\times3}$$

Also u+d and u+e sums depend only on charge differences

$$X_u + X_d \propto X_1 - X_2 \qquad X_u + X_e \propto X_1 - X_{1\,\mathrm{or}\,2}$$

[standard normalization is $v_{\mathrm{PQ}} = 2N f_a$]

The Bound from SN1987A

Supernova neutrino burst duration constrains
energy loss from nucleon bremsstrahlung

$$N + N \to N + N + a$$

Bounds axion-nucleon couplings $\mathcal{L}_{a-N} = C_N \frac{\partial_\mu a}{2f_a} \overline{N} \gamma^\mu \gamma_5 N$

$$f_a \gtrsim 10^9\,\mathrm{GeV} \sqrt{C_p^2 + C_n^2} \qquad m_a \lesssim 4\,\mathrm{meV} / \sqrt{C_p^2 + C_n^2}$$

[from PDG 2017; Chang, Essig, McDermott arXiv:1803.00993 find slightly weaker bound

The Heavy Axion Window

Usual Axion models (DFSZ, KSVZ)
constrained at level of ~0.01 eV

Roughly 2 orders of magnitude
until bound from Hot DM ~1 eV

To reach heavy axion window [0.01 - 1] eV
need to suppress nucleon couplings at *%* level

[same for electron couplings: bound from WDs similar to SN; but quite easy]

Heavy Axion Cosmology

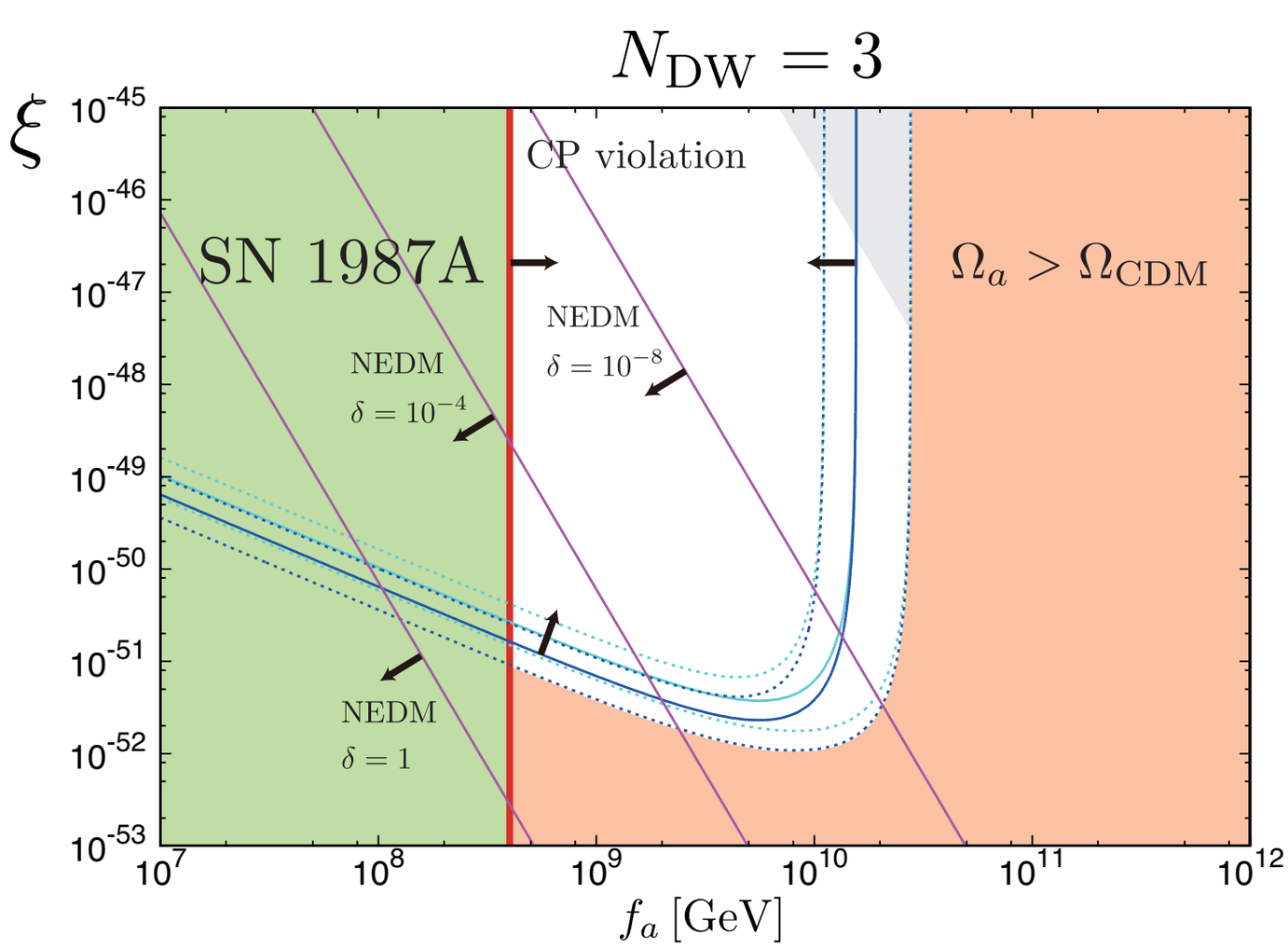
If PQ broken after inflation need to take into account axion production from topological defects:

Need larger axion masses wrt pure misalignment

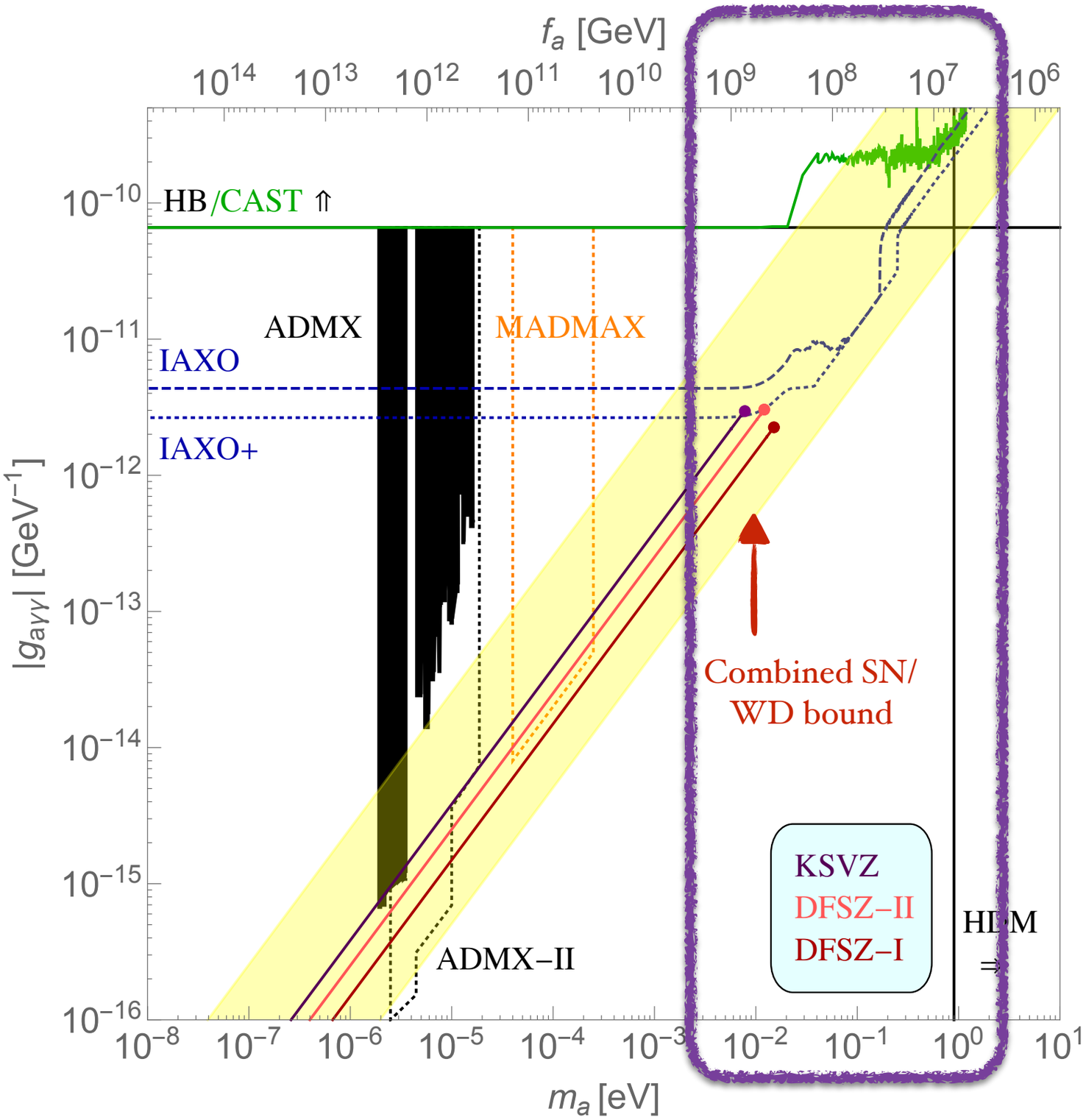
Need explicit PQ breaking term

$$\Delta V \sim -\xi f_a^3 \Phi e^{-i\delta} + \text{h.c.}$$

Kawasaki, Saikawa, Sekiguchi
arXiv:1412.0789



Heavy Axion Phenomenology



- Standard axions barely visible even at IAXO upgrade

- If SN bound relaxed can easily fit stellar coolings anomalies:

$$g_{a\gamma\gamma} \to 1.4 \cdot 10^{-11}\mathrm{GeV}^{-1}$$

$$f_a/C_e \to 3.4 \cdot 10^{9}\mathrm{GeV}$$

Ringwald & al, arXiv:1708.02111

Nucleophobic Axions

$$C_p + C_n = 0.50(5)\,(C_u + C_d - 1) - 2\delta$$

UV quark couplings — $G\tilde{G}$ — RG contrib from heavy quark couplings $\sim 5\%$

Villadoro & al, arXiv:1511.02867

$$C_p - C_n = 1.273(2)\left(C_u - C_d - \frac{1-z}{1+z}\right)$$

isospin breaking contrib
$z = m_u/m_d \approx 1/2$

Nucleon (and pion) couplings suppressed at % for

$$C_u + C_d = 1 \qquad C_u = 1/(1+z) \approx 2/3$$

can realize with PQ charges — **-in DFSZ-like models-** — need to tune Higgs vevs

Nucleophobia $\Rightarrow$ Flavor-Violation

Flavor-universal PQ charges imply $C_u + C_d = 1/3$

$$C_u = \frac{X_q - X_u}{2N} \qquad C_d = \frac{X_q - X_d}{2N}$$

$$2N = N_{\rm fam} \times (2X_q - X_u - X_d)$$

$$\Rightarrow \quad C_u + C_d = \frac{1}{N_{\rm fam}}$$

Flavor non-universal PQ charges imply FV axion couplings

$$\left[\mathrm{PQ}_u, Y_u^\dagger Y_u\right] \neq 0 \quad \Rightarrow \quad C_{a u_i u_j} \propto (V_u^\dagger \mathrm{PQ}_u V_u)_{I \neq j} \neq 0$$

Non-universal DFSZ Models

Study generalized DFSZ-type models:
PQ charges universal for two generations

Have non-trivial transition to mass basis

$$X_f = \mathrm{diag}(X_1, X_1, X_3) \to V_f^\dagger X_f V_f = X_1 \delta_{ij} + (X_3 - X_1)\, \epsilon_{ij}^f$$

$$\epsilon_{ij}^f \equiv (V_f)_{i3}^* (V_f)_{j3} \qquad\qquad f = u_L, u_R, d_L, d_R$$

Depend on 2 misalignment parameters in each sector

$$0 \leq \epsilon_{ii}^f \leq 1 \qquad\qquad \sum_i \epsilon_{ii}^f = 1$$

$$C_{ii}^f = X_1 + (X_3 - X_1)\epsilon_{ii}^f \qquad\qquad |C_{i\neq j}^f| = |X_3 - X_1| \sqrt{\epsilon_{ii}^f \epsilon_{jj}^f}$$

Nucleophobic Models

Can construct 4 nucleophic models:
non-universal in q **or** u/d sector

$$\underline{\text{Ex.}} \qquad \mathcal{L} \sim \begin{matrix} \overline{f}_{L3} f_{R3} \\ \overline{f}_{L3} f_{Ra} \end{matrix} \begin{cases} h_1 & u \\ \tilde{h}_2 & d \end{cases} + \begin{matrix} \overline{f}_{La} f_{Rb} \\ \overline{f}_{La} f_{R3} \end{matrix} \begin{cases} h_2 & u \\ \tilde{h}_1 & d \end{cases}$$

$$C^A_{u_i u_i} = c_\beta^2 - \epsilon^{u_L}_{ii} \qquad C^{V,A}_{u_i \neq u_i} = \pm \epsilon^{u_L}_{ij}$$
$$C^A_{d_i d_i} = s_\beta^2 - \epsilon^{d_L}_{ii} \qquad C^{V,A}_{d_i \neq d_i} = \pm \epsilon^{d_L}_{ij}$$

$$\frac{\partial_\mu a}{2 f_a} \overline{f}_i \gamma^\mu (C^V_{ij} + C^A_{ij} \gamma_5) f_j$$

Assume at most CKM like rotations in LH quark sector

$$\epsilon^{u_L, d_L}_{11} \lesssim \lambda^6, \qquad \epsilon^{u_L, d_L}_{22} \lesssim \lambda^4, \qquad \epsilon^{u_L, d_L}_{33} \simeq 1$$

$\epsilon^{u_L}_{ij} \equiv (V_{UL})^*_{i3} (V_{UL})_{j3}$

Nucleophobic Models

$$C_u = c_\beta^2 \qquad \text{nucleophobic for} \quad c_\beta^2 \simeq 2/3$$
$$C_d = s_\beta^2 \qquad C_N/C_{\rm KSVZ} \approx 0.08 - 1.5(c_\beta^2 - 2/3)$$

SN bound relaxed by factor 10 for 10% tuning

Can look for axion in 2-body Kaon decays

$$\mathcal{B}_{K^+\to\pi^+ a} = 1.0 \cdot 10^{-9} \left(\frac{m_a}{0.2\,\text{eV}}\right)^2 \left(\frac{\epsilon_{11}^{d_L}\epsilon_{22}^{d_L}}{\lambda^{10}}\right)$$

$\mathcal{B}^{\rm exp}_{K^+\to\pi^+ a} < 7.3 \cdot 10^{-11}$ **to be improved by ~70 at NA62**

Electrophobia

2HDM models can be extended to lepton sector

$$C_e = -c_\beta^2 + \epsilon_{11}^{e_L}$$

Need extra tuning $\epsilon_{11}^{e_L} \approx 2/3$ to relax also WD bound, but predict

$$\mathcal{B}_{\tau\to ea} = 6.7 \cdot 10^{-6} \left(\frac{m_a}{0.2\,\mathrm{eV}}\right)^2$$

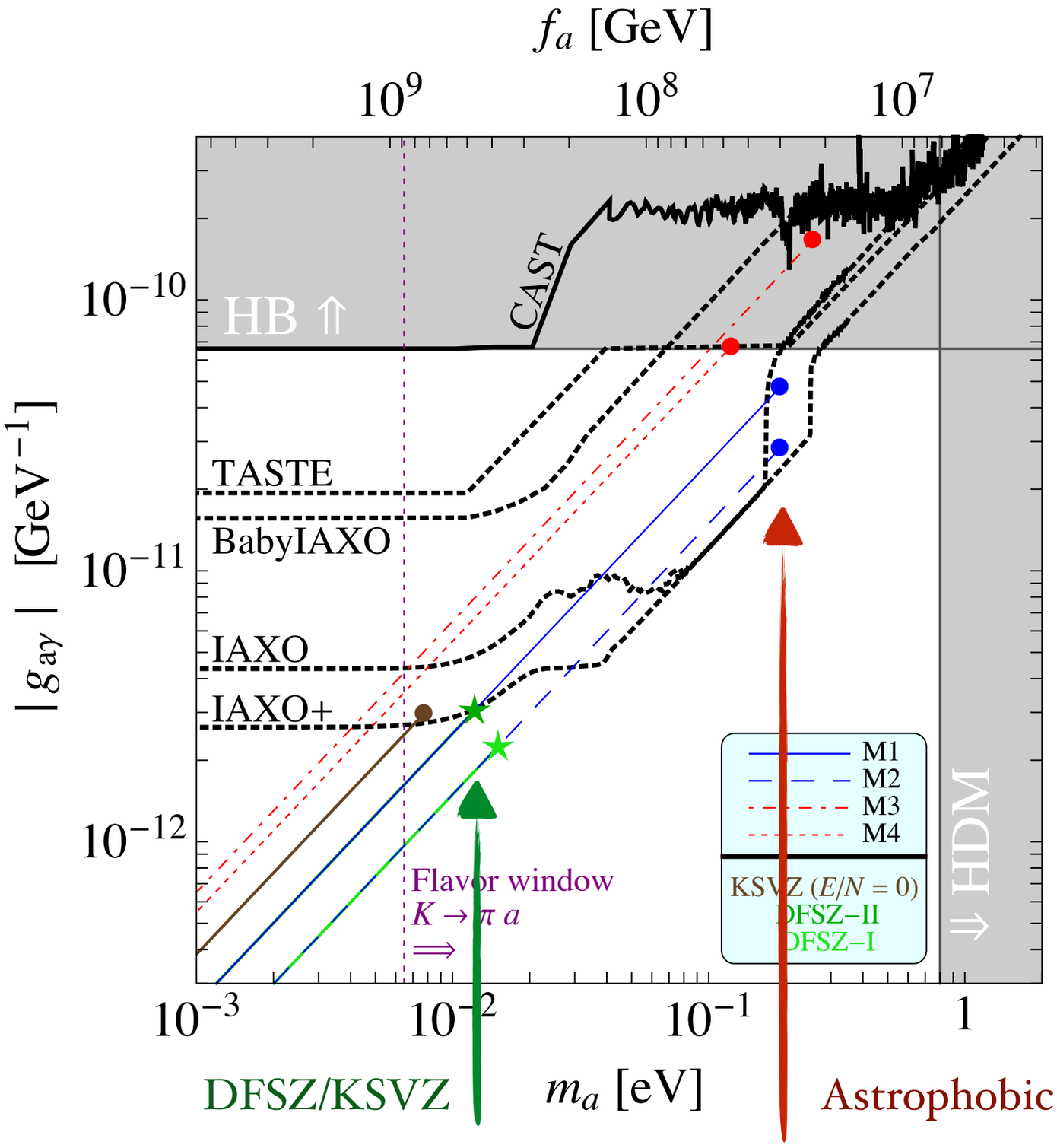
[No tuning needed in 3HDM $\quad C_e = -c_\beta^2 + 2/3$]

4 "Astrophobic" 2HDM models

	N_{DW}	E/N	$\lvert C_\gamma\rvert$	C_u	C_d	C_e	$C_{u_i\neq u_j}^{V,A}$	$C_{d_i\neq d_j}^{V,A}$	$C_{e_i\neq e_j}^{V,A}$
M1	Δ_{12}	$2/3$	1.3	$c_\beta^2 - \epsilon_{11}^{u_L}$	$s_\beta^2 - \epsilon_{11}^{d_L}$	$-c_\beta^2 + \epsilon_{11}^{e_L}$	$\pm\epsilon_{ij}^{u_L}$	$\pm\epsilon_{ij}^{d_L}$	$\mp\epsilon_{ij}^{e_L}$
M2	Δ_{12}	$8/3$	0.75	$c_\beta^2 - \epsilon_{11}^{u_L}$	$s_\beta^2 - \epsilon_{11}^{d_L}$	$s_\beta^2 - \epsilon_{11}^{e_L}$	$\pm\epsilon_{ij}^{u_L}$	$\pm\epsilon_{ij}^{d_L}$	$\pm\epsilon_{ij}^{e_L}$
M3	Δ_{12}	$-4/3$	3.3	$-s_\beta^2 + \epsilon_{11}^{u_R}$	s_β^2	$-c_\beta^2 + \epsilon_{11}^{e_L}$	$\epsilon_{ij}^{u_R}$	0	$\mp\epsilon_{ij}^{e_L}$
M4	Δ_{12}	$14/3$	2.7	c_β^2	$-c_\beta^2 + \epsilon_{11}^{d_R}$	$s_\beta^2 - \epsilon_{11}^{e_L}$	0	$\epsilon_{ij}^{d_R}$	$\pm\epsilon_{ij}^{e_L}$
DFSZ-II	$3\Delta_{12}$	$2/3$	1.3	$c_\beta^2/3$	$s_\beta^2/3$	$-c_\beta^2/3$	0	0	0
DFSZ-I	$3\Delta_{12}$	$8/3$	0.75	$c_\beta^2/3$	$s_\beta^2/3$	$s_\beta^2/3$	0	0	0

1 or 2: can get trivial domain wall number in contrast to usual DFSZ

Astrophobic Phenomenology



Allows for heavy axions ~0.2 eV

(with 5% x 5% tuning)

Testable at IAXO and NA62

Summary

- To suppress axion couplings to nucleons need flavor non-universal PQ charges

- Generalized DFSZ models with free flavor alignment parameters allow for heavy axions

- No tuning for electrophobia needed in 3HDM