Flavored Axion Models

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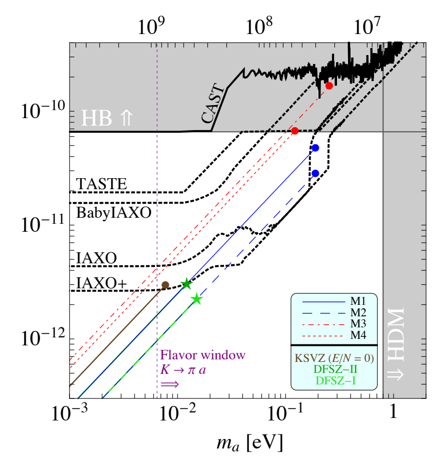
Outline

- The QCD Axion; DFSZ Models; Axion Couplings

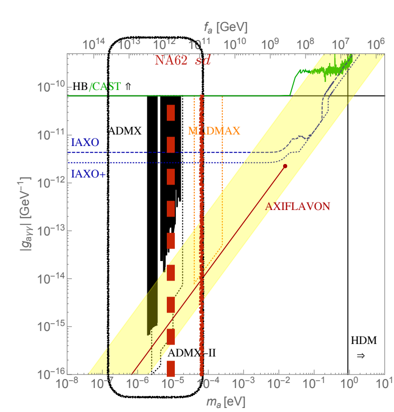
- Non-Universal DFSZ Models: The Astrophobic Axion

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



- Peccei-Quinn = Froggatt-Nielsen: The Axiflavon

arXiv: 1612.08040, with L. Calibbi,
F. Goertz, D. Redigolo, J. Zupan



The Strong CP Problem

Why don't we observe CPV in strong interactions

$$\bar{\theta} \equiv \theta + \arg\det(M_u M_d) < 10^{-10} \quad ?$$

- Can impose CP and break it spontaneously such that large CKM phase induced but determinants stay real

  Nelson-Barr solution [pure UV, difficult to test]

- If $\bar{\theta}$ would be dynamical field without any other potential, non-perturbative dynamics would generate potential for $\bar{\theta}(x)$ with trivial minimum

  Axion solution [new ultra-light, decoupled, stable particle]

The Peccei-Quinn Mechanism

[Peccei, Quinn '77]

Introduce new global $U(1)_{PQ}$ symmetry with fermion charges such that have QCD anomaly

Break global $U(1)_{PQ}$ symmetry spontaneously at scale f by vev of complex scalar field Φ

$U(1)_{PQ}$ breaking scale

radial mode

$$\Phi = \frac{f + \phi(x)}{\sqrt{2}} e^{ia(x)/f}$$

axion

$U(1)_{PQ}$ non-linearly realized as shift symmetry of axion

The Peccei-Quinn Mechanism

Effective Lagrangian at scales $\ll f$ contains only Goldstone boson $a(x)$, all other fields take mass at f

$$\mathcal{L}_{\rm eff} = \overline{\theta}\frac{\alpha_s}{8\pi}G^{\mu\nu}_a\tilde{G}_{a,\mu\nu} + \mathcal{L}_{\rm a,int}[\frac{\partial_\mu a}{f}, \psi_{\rm SM}] + \frac{a}{f}\xi\frac{\alpha_s}{8\pi}G^{\mu\nu}_a\tilde{G}_{a,\mu\nu} + \mathcal{L}_{\rm anom}[\frac{a}{f}F\tilde{F}]$$

Interactions with SM fermions [respects shift symmetry]

ABJ term for QCD anomaly [breaks shift symmetry]

ABJ term for other anomalies [cf. $\frac{\pi^0}{f_\pi}F\tilde{F}$]

Depends on $\overline{\theta}$ only through $\frac{\overline{a}(x)}{f_a} \equiv \overline{\theta} + \frac{a(x)}{f}\xi$

[have essentially made $\overline{\theta}$ dynamical field]

The Axion

Effective Lagrangian induces axion potential

$$V_{\text{eff}} = -\frac{\overline{a}(x)}{f_a}\frac{\alpha_s}{8\pi}G_a^{\mu\nu}\tilde{G}_{a,\mu\nu} \xrightarrow[\text{effects}]{\text{non-PT}} V(a) \sim -m_\pi^2 f_\pi^2 |\cos\frac{\overline{a}(x)}{f_a}|$$

Potential minimized at CP-conserving point $\langle\overline{a}(x)\rangle = 0$

QCD θ-term dynamically relaxed to zero

Axion gets mass $m_a \sim m_\pi f_\pi / f_a$ and couples to photons and SM fermions $\propto 1/f_a \propto m_a$

For large f_a axion is ultra-light and decoupled

Axion Models

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

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

SM fermions → 2Higgs; 2Higgs+Singlet

BSM fermions → Higgs+Singlet

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

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

DFSZ Models

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

Construct 2HDM Lagrangian invariant under single U(1)

$$\mathcal{L}_{\rm yuk} = y^u_{ij} \overline{Q}_i U_j \begin{cases} H_1 \\ H_2 \end{cases}$$

flavor-universal U(1) charges →

$\overline{Q}_i U_j \, H_1$

$\overline{Q}_i D_j \, \tilde{H}_2$

$\overline{L}_i E_j \, \tilde{H}_{1 \text{ or } 2}$

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

Ensure $\mathrm{GB_{PQ}} \perp \mathrm{GB_Z}$ $0 = X_1 c_\beta^2 + X_2 s_\beta^2$

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

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

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

DFSZ Predictions

Anomaly coefficients only depend on charge differences

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

Fermion couplings flavor-universal & depend only on t_β

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

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 $v_{\mathrm{PQ}} = 2N f_a$]

DFSZ Predictions

Anomaly coefficients only depend on charge differences

$$2N = \mathrm{Tr}\,(X_{q_L} - X_{q_R}) = 3\,(X_1 - X_2) \quad \rightarrow 6$$

$$E = \quad \ldots \quad \ldots \quad = 4X_1 - X_2 - 3X_{1\,\mathrm{or}\,2} \quad \rightarrow 8 \text{ or } 2$$

Fermion couplings fla… & depend only on t_β

$$X_u = -X_1 \mathbb{1} \ldots {}_{3\times 3} \qquad X_e = X_{1\,\mathrm{or}\,2} \mathbb{1}_{3\times 3}$$

$$\underbrace{\quad}_{-2c_\beta^2}$$

only 2 parameters!
(& 1 discrete choice)

Also u+d a… …e sums depend only on charge differences

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

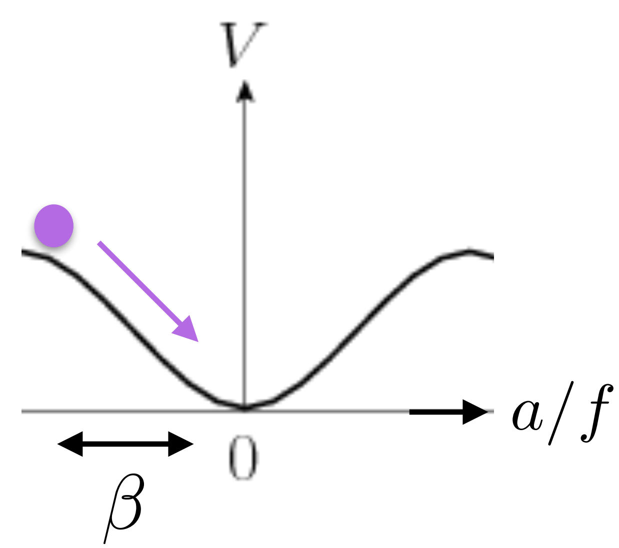
[standard normalization is $v_{\mathrm{PQ}} = 2N f_a$]

Axions as Dark Matter

[axion essentially stable for $m_a \lesssim 20\,\text{eV}$]

When PQ breaking before inflation axion can be dark matter through "misalignment mechanism"

At QCD phase transition axion starts oscillating around minimum: energy stored in oscillations contributes to DM relic density



$$\Omega_{\rm DM} h^2 \approx 0.1 \left(\frac{10^{-5}\text{eV}}{m_a}\right)^{1.18} \beta^2$$

Correct abundance for $10^{-7}\,\text{eV} \lesssim m_a \lesssim 10^{-4}\,\text{eV}$

Axion Searches

Axion searches typically rely on axion-photon coupling

$$\mathcal{L} \supset g_{a\gamma\gamma} a\, \vec{E} \cdot \vec{B} \qquad g_{a\gamma\gamma} \sim \frac{E}{N} \frac{1}{10^{16}\mathrm{GeV}} \frac{m_a}{\mu\mathrm{eV}}$$

Haloscopes: DM axion $\xrightarrow{\text{static B-field}}$ photon $E_\gamma \sim m_a$

ADMX

resonantly detected by microwave cavities of size $1/m_a$

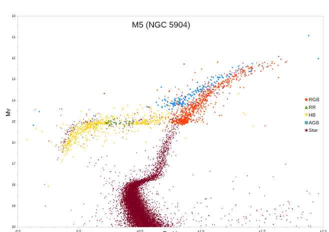
Helioscopes: Solar photon $\xrightarrow{\text{nuclear E-field}}$ axion $E_a \sim \mathrm{keV}$

CAST/IAXO

converted back to X-ray photons with static B-fields

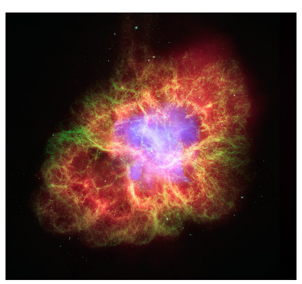
Astrophysical Bounds

Large axion couplings to matter would allow to radiate off energy in astrophysical objects



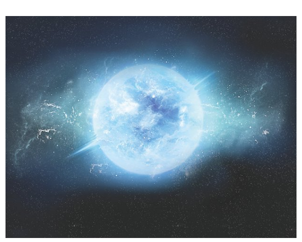
Evolution of Horizontal Branch stars: constrain photon couplings

$$m_a < \frac{3 \cdot 10^{-1}\,\mathrm{eV}}{C_\gamma}$$



Supernova neutrino burst duration: constrain nucleon couplings

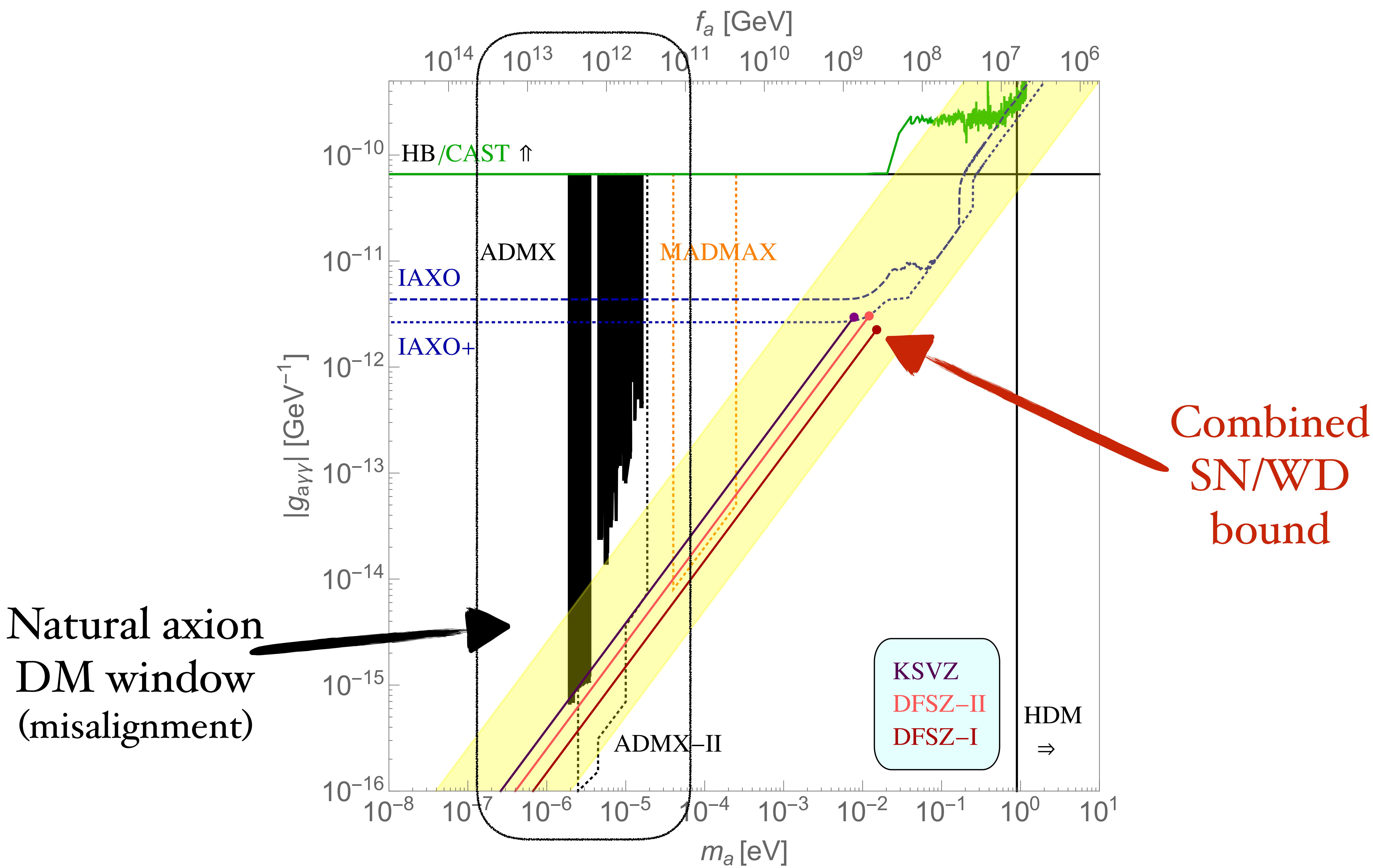
$$m_a < \frac{4 \cdot 10^{-3}\,\mathrm{eV}}{|C_N|}$$



White Dwarf cooling: constrain electron couplings

$$m_a < \frac{3 \cdot 10^{-3}\,\mathrm{eV}}{|C_e|}$$

Status of Axion Searches



Flavored Axions

Tree-level flavor-violating axion couplings are strongly constrained

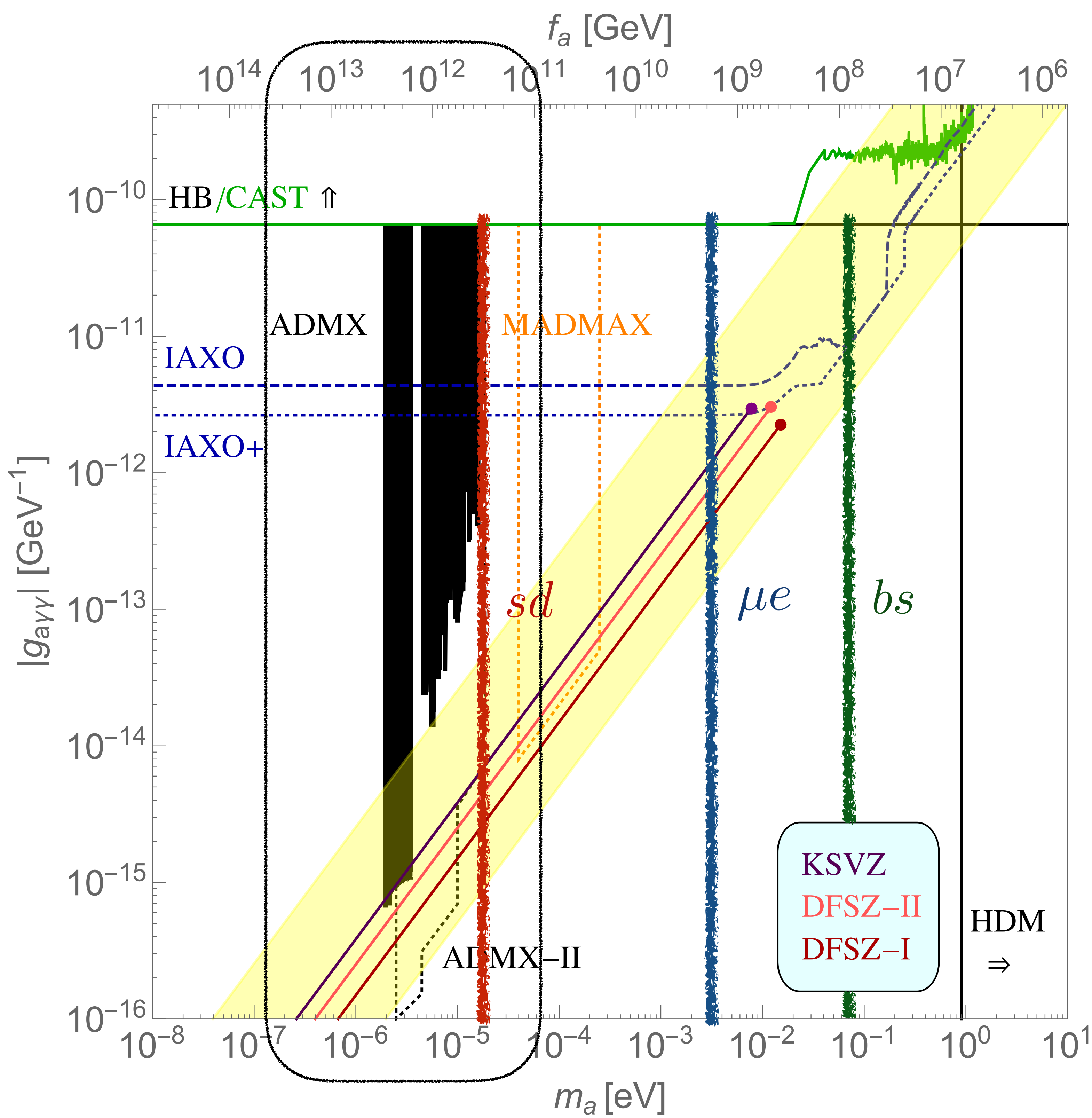
$$\frac{\partial_\mu a}{2f_a}\bar{f}_i\gamma^\mu(C^V_{ij}+C^A_{ij}\gamma_5)f_j$$

$\mu \to e a \gamma$ (Crystal Box, '88) $\qquad m_a < \dfrac{3\cdot 10^{-3}\,\mathrm{eV}}{|C_{\mu e}|}$ $\xrightarrow{?}$ **MEG, Mu3e**

$K \to \pi a$ (E787+E949, '08) $\qquad m_a < \dfrac{2\cdot 10^{-5}\,\mathrm{eV}}{|C^V_{sd}|}$ $\xrightarrow{\times 1/8}$ **NA62**

$B \to K a$ (CLEO, '01) $\qquad m_a < \dfrac{9\cdot 10^{-2}\,\mathrm{eV}}{|C^V_{bs}|}$ $\xrightarrow{\times 1/10}$ **BELLE II**

Flavor Bounds



(for $C_{i\neq j} = 1$)

Flavor Violation in DFSZ

In DFSZ flavor-violating axion couplings vanish at tree-level since Yukawas and PQ aligned

$$\left[\mathrm{PQ}_u, Y_u^\dagger Y_u\right] = 0$$

Flavor Violation loop&CKM suppressed (MFV)

$$C_{sd}^V \sim C_t \frac{y_t^2}{16\pi^2} V_{ts}^* V_{td} \sim C_t \frac{y_t^2}{16\pi^2} \lambda^5 \longrightarrow m_a \lesssim 10\,\mathrm{eV}$$

Flavored Axion Models

In general get flavor-violating axion couplings at tree-level from misalignment of PQ charges and Yukawas

$$[\mathrm{PQ}_u, Y_u^\dagger Y_u] \neq 0$$

Here discuss two examples:

2+1 DFSZ
misalignment is free parameter

PQ = FN
misalignment from fermion masses

Non-universal DFSZ Models

Generalized DFSZ-type models with 2Higgs
PQ charges universal for two generations

$$X_f = \text{diag}(X_1, X_1, X_3) \to V_f^\dagger X_f V_f = X_1 \delta_{ij} + (X_3 - X_1)\,\epsilon^f_{ij}$$

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

Depend on 2 misalignment parameters in each sector

$$0 \leq \epsilon^f_{ii} \leq 1 \qquad\qquad \sum_i \epsilon^f_{ii} = 1$$

$$C^f_{ii} = X_1 + (X_3 - X_1)\epsilon^f_{ii} \qquad\qquad |C^f_{i\neq j}| = |X_3 - X_1| \sqrt{\epsilon^f_{ii}\epsilon^f_{jj}}$$

Can have large flavor violation in all sectors!

Nucleophobic DFSZ Models

Can e.g. use to construct **nucleophobic** axion models

$$C_p + C_n = 0.50(5)\,(C_u + C_d - 1) - 2\delta \qquad C_p - C_n = 1.273(2)\left(C_u - C_d - \frac{1-z}{1+z}\right)$$

UV couplings

$G\tilde{G}$

RG contrib from heavy quark couplings $\sim 5\%$

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

Nucleon (and pion) couplings suppressed for

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

The SN bound relaxed by factor ~20;
can relax also WD bound when $C_e \ll 1$

An Astrophobic Axion Model

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

Only PQ charges of RH fields universal: couplings depend on misalignment parameters (LH rotations)

$$C^A_{u_i u_i} = c^2_\beta - \epsilon^{u_L}_{ii} , \qquad C^{V,A}_{u_i u_j} = \pm \epsilon^{u_L}_{ij}$$
$$C^A_{d_i d_i} = s^2_\beta - \epsilon^{d_L}_{ii} , \qquad C^{V,A}_{d_i d_j} = \pm \epsilon^{d_L}_{ij}$$
$$C^A_{e_i e_i} = -c^2_\beta + \epsilon^{e_L}_{ii} , \qquad C^{V,A}_{e_i e_j} = \mp \epsilon^{e_L}_{ij} ;$$

Assume at most CKM like rotations in LH quark sector

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

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

Astrophobic Axion Models

$$C_u = c_\beta^2 \qquad C_d = s_\beta^2$$

nucleophobic for
$c_\beta^2 \simeq 2/3$ (5% tuning)

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

electrophobic for
$\epsilon_{11}^{e_L} \simeq 2/3$ (5% tuning)

Note that in 3HDM 2/3 of **astrophobic** conditions

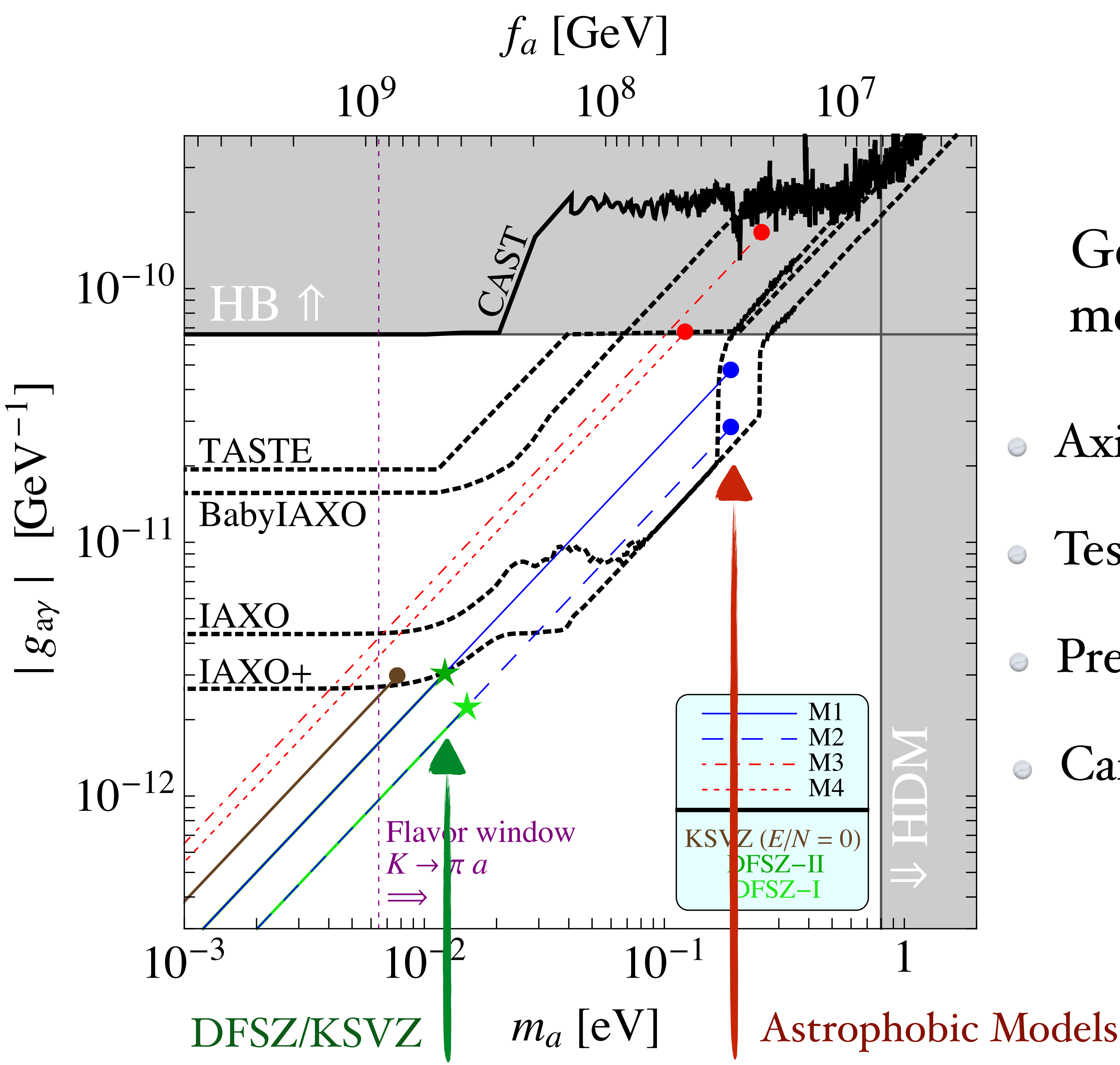
$$C_u + C_d = 1 \qquad\qquad C_u + C_e = 2/3$$

can be realized by charge assignment (no tuning), while

$$C_u \approx 2/3$$

only with adjustment of vacuum alignment angle

Astrophobic Phenomenology



Get 4 astrophobic 2HDM models with different E/N

- Axion can be **as heavy as 0.2 eV**
- Testable at IAXO and e.g. NA62
- Predict $\mathcal{B}_{\tau \to ea} = 6.7 \cdot 10^{-6} \left(\frac{m_a}{0.2\,\text{eV}} \right)^2$
- Can fit stellar cooling anomalies

arXiv: 1712.04940

PQ as a Flavor Symmetry

PQ could be subgroup of flavor symmetry that explains Yukawa hierarchies [F. Wilczek '82]

Smallness of Yukawas arise from spontaneously broken global flavor symmetry, associated Goldstone can be identified with QCD axion

$$\Phi = \frac{1}{\sqrt{2}}(V_\Phi + \phi)e^{ia/V_\Phi}$$

flavon (Φ)

$V_\Phi \sim f_a \gg v$

decouples (ϕ)

axion (a)

Simplest realization: PQ = U(1)$_{\mathbf{FN}}$

[1612.08040, see also 1612.05492]

Flavor Symmetries

SM fields charged under flavor symmetry G, which is spontaneously broken by **“flavon” field** Φ

Effective Yukawa Lagrangian needs flavon insertions in order to be invariant under G

from G selection rules

$$\mathcal{L}_{\text{eff}} \sim a_{ij} \left(\frac{\Phi}{\Lambda_F} \right)^{x_{ij}} h \bar{q}_i u_j$$

O(1) coefficients

cutoff scale

Yukawas given by powers of small order parameter $\epsilon \equiv \frac{\langle \Phi \rangle}{\Lambda_F}$

U(1) Flavor Symmetry

Simplest U(1) symmetry works: Froggatt-Nielsen

	ϕ	$\overline{q}_i$	u_i	d_i	h
U(1)	-1	q_i	u_i	d_i	0

$$y^U_{ij} = a^U_{ij}\epsilon^{q_i+u_j} \qquad y^D_{ij} = a^D_{ij}\epsilon^{q_i+d_j}$$

Can easily reproduce all hierarchies, e.g.

$u_i = (4,2,0)$ $\quad$ $q_i = (3,2,0)$ $\quad$ $d_i = (4,3,3)$

$$y^U \sim \begin{pmatrix} \epsilon^7 & \epsilon^5 & \epsilon^3 \\ \epsilon^6 & \epsilon^4 & \epsilon^2 \\ \epsilon^4 & \epsilon^2 & 1 \end{pmatrix} \quad y^D \sim \begin{pmatrix} \epsilon^7 & \epsilon^6 & \epsilon^6 \\ \epsilon^6 & \epsilon^5 & \epsilon^5 \\ \epsilon^4 & \epsilon^3 & \epsilon^3 \end{pmatrix} \qquad \epsilon \approx 0.2$$

Get unitary rotations as $V_f \sim \epsilon^{|f_i - f_j|}$

Axion-Photon Couplings

Although have considerable freedom in fermion U(1) charges **can sharply predict E/N**

$$\frac{E}{N} \in [2.4, 3.0]$$

as direct consequence of fermion mass hierarchies

$$\underbrace{\det m_u \det m_d / v^6}_{\approx 10^{-20}} = \underbrace{[\det a_u \det a_d]}_{\mathcal{O}(1)}\, \epsilon^{2N}$$

$$\underbrace{\det m_d / \det m_e}_{\approx 0.7} = \underbrace{[\det a_d / \det a_e]}_{\mathcal{O}(1)}\, \epsilon^{\frac{8}{3}N - E}$$

$$\boxed{\frac{E}{N} = \frac{8}{3} - 2\delta}$$

$$\delta = \frac{\overbrace{\log \frac{\det m_d}{\det m_e}}^{\approx -0.4} - \overbrace{\log \alpha_{de}}^{\approx 0}}{\underbrace{\log \frac{\det m_u \det m_d}{v^6}}_{\approx -44} - \underbrace{\log \alpha_{ud}}_{\approx 0}}$$

Axion-Fermion Couplings

Axion-fermion couplings determined by fermion masses and mixings up to $\mathcal{O}(1)$ coefficients

$$X_f = \mathrm{diag}(f_1, f_2, f_3) \to V_f^\dagger X_f V_f \qquad V_f \sim \epsilon^{|f_i - f_j|}$$

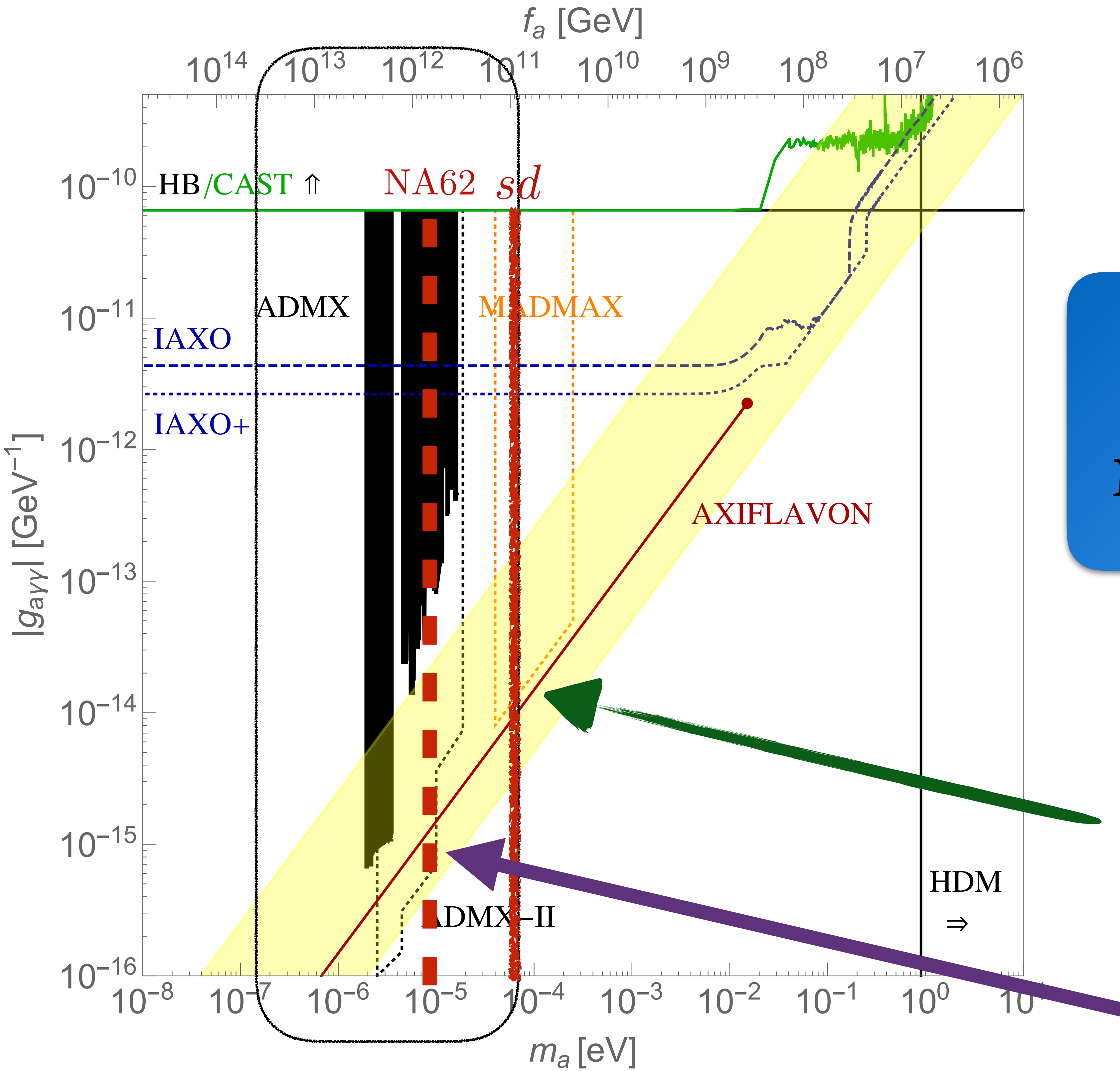
Flavor-violating couplings governed by CKM

$$C^q_{ij} \sim V^{\mathrm{CKM}}_{ij} \qquad C^u_{i<j} \sim \frac{m_i}{m_j V^{\mathrm{CKM}}_{ij}}$$

Get large a-s-d couplings of order Cabibbo angle

$$C^V_{sd} \sim \lambda \approx 0.2$$

The Axiflavon



Natural axion DM window testable at NA62 (and ADMX-II)

Present bound from E787+E949

Expected future bound from NA62

Summary

- Flavored Axion models allow for complementary axion searches with precision flavor experiments
- Generalized 2+1 DFSZ models with free flavor alignment parameters can realize nucleophobic & electrophobic axions up to 0.2 eV
- Well-motivated axion model from PQ = FN, giving flavor alignment parameters in terms of fermion masses and mixings