

Flavored Axion Models

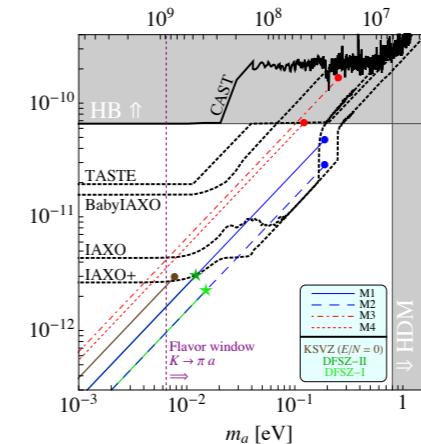


Robert Ziegler (CERN)

Outline

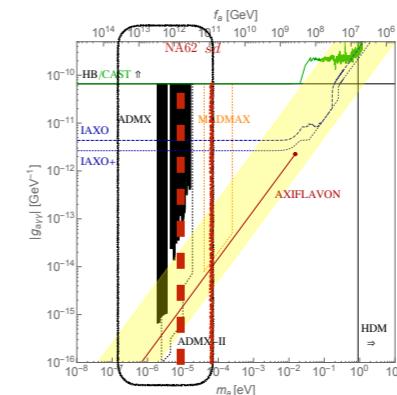
- The QCD Axion, DFSZ Models, Axion Couplings
- Non-Universal DFSZ Models: The Astrophobic Axion

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



- Peccei-Quinn = Froggatt-Nielsen: The Axiflaviton

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 $U(1)_{\text{PQ}}$ symmetry with fermion charges such that have QCD anomaly

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

The diagram illustrates the decomposition of the complex scalar field Φ at the $U(1)_{\text{PQ}}$ breaking scale f . The field Φ is given by the equation:

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

Blue arrows point from the text labels to the corresponding parts of the equation:

- A blue arrow points from "U(_IPQ breaking scale" to the term $f + \phi(x)$.
- A blue arrow points from "radial mode" to the term f .
- A blue arrow points from "axion" to the term $a(x)$.

$U(1)_{\text{PQ}}$ 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

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



**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 $\bar{\theta}$ only through $\frac{\bar{a}(x)}{f_a} \equiv \bar{\theta} + \frac{a(x)}{f} \xi$

{have essentially made $\bar{\theta}$ dynamical field}

The Axion

Effective Lagrangian induces axion potential

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

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

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 origin of QCD anomaly (**fermion sector**)
and spontaneous PQ breaking (**scalar sector**)

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



PQWW

[Peccei, Quinn,
Wilczek, Weinberg '78]

excluded

$$J/\psi \rightarrow \gamma a$$

see however 1710.03764

DFSZ

[Dine, Fischler, Srednicki,
Zhitnitsky '80]

KSVZ

[Kim, Shifman, Vainshtein,
Zakharov '80]

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

DFSZ Models

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

Construct 2HDM Lagrangian invariant under single U(I)

$$\mathcal{L}_{\text{yuk}} = y_{ij}^u \bar{Q}_i U_j \left\{ \begin{array}{l} H_1 \\ H_2 \end{array} \right. \xrightarrow[\text{U(I) charges}]{\text{flavor-universal}} \begin{array}{l} \bar{Q}_i U_j H_1 \\ \bar{Q}_i D_j \tilde{H}_2 \\ \bar{L}_i E_j \tilde{H}_1 \text{ or } 2 \end{array}$$

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



Ensure $\text{GB}_{\text{PQ}} \perp \text{GB}_Z$
 $0 = X_1 c_\beta^2 + X_2 s_\beta^2$

All PQ charges fixed in terms of vacuum angle

Axion Couplings

Higgs contain GB: axion-fermion couplings from Yukawas

$$H_i \sim v_i e^{i \textcolor{red}{X}_i a(x) / v_{\text{PQ}}}$$

Can remove by PQ transformation acting only on fermions

$$f \rightarrow f e^{i \textcolor{blue}{X}_f a(x) / v_{\text{PQ}}}$$

Anomalous: generate axion
couplings to field strengths

Local: generate derivative
axion couplings to fermions

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

$$\mathcal{L}_{\text{ferm}} \sim \frac{\partial_\mu a}{v_{\text{PQ}}} \bar{u}_i \gamma^\mu P_R \textcolor{blue}{X}_{\textcolor{blue}{u}_i} u_i + \dots$$

$$[\text{mass basis: } \textcolor{blue}{X}_u \rightarrow V_{UR}^\dagger \textcolor{blue}{X}_{\textcolor{blue}{u}} V_{UR}]$$

DFSZ Predictions

Anomaly coefficients only depend on charge differences

$$\begin{aligned} 2N &= \text{Tr} (\textcolor{blue}{X}_{q_L} - X_{q_R}) = 3 (X_1 - X_2) \\ E &= \dots \dots = 4X_1 - X_2 - 3X_{1 \text{ or } 2} \end{aligned} \quad \left. \begin{array}{l} \rightarrow 6 \\ \rightarrow 8 \text{ or } 2 \end{array} \right\}$$

Fermion couplings flavor-universal & depend only on t_β

$$X_u = -X_1 \mathbb{1}_{3 \times 3} \quad X_d = \underbrace{X_2}_{-2c_\beta^2} \mathbb{1}_{3 \times 3} \quad X_e = X_{1 \text{ or } 2} \mathbb{1}_{3 \times 3}$$

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

$$X_u + X_d \propto X_1 - X_2 \quad X_u + X_e \propto X_1 - X_{1 \text{ or } 2}$$

[standard normalization is $v_{\text{PQ}} = 2Nf_a$]

DFSZ Predictions

Anomaly coefficients only depend on charge differences

$$2N = \text{Tr} (X_{q_L} - X_{q_R}) = 3(X_1 - X_2) \quad \left. \right\} \rightarrow 6$$
$$E = \dots \dots = 4X_1 - X_2 - 3X_{1 \text{ or } 2} \quad \left. \right\} \rightarrow 8 \text{ or } 2$$

Fermion couplings flavor

$$X_u = -X_1 \mathbb{1}_{3 \times 3}$$

only 2 parameters!
(& 1 discrete choice)

$$-2c_\beta^2$$

& depend only on t_β

$$X_e = X_{1 \text{ or } 2} \mathbb{1}_{3 \times 3}$$

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

$$X_u + X_d \propto X_1 - X_2$$

$$X_u + X_e \propto X_1 - X_{1 \text{ or } 2}$$

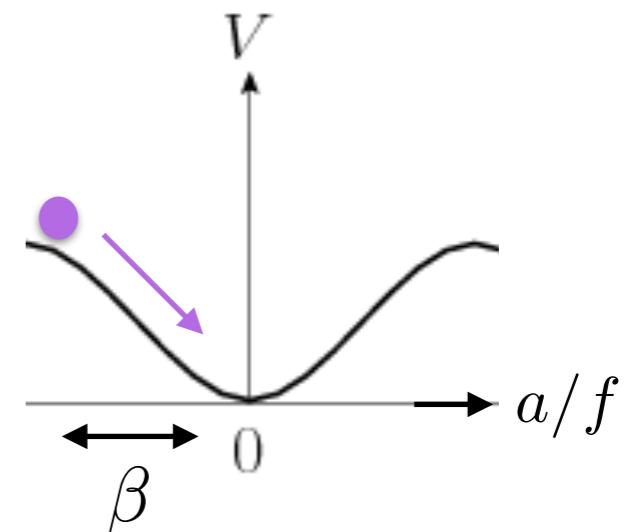
[standard normalization is $v_{\text{PQ}} = 2Nf_a$]

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



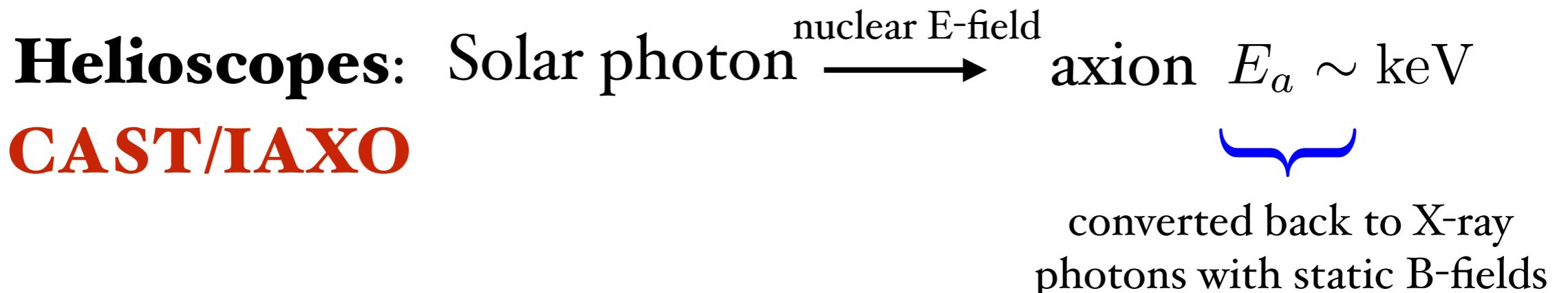
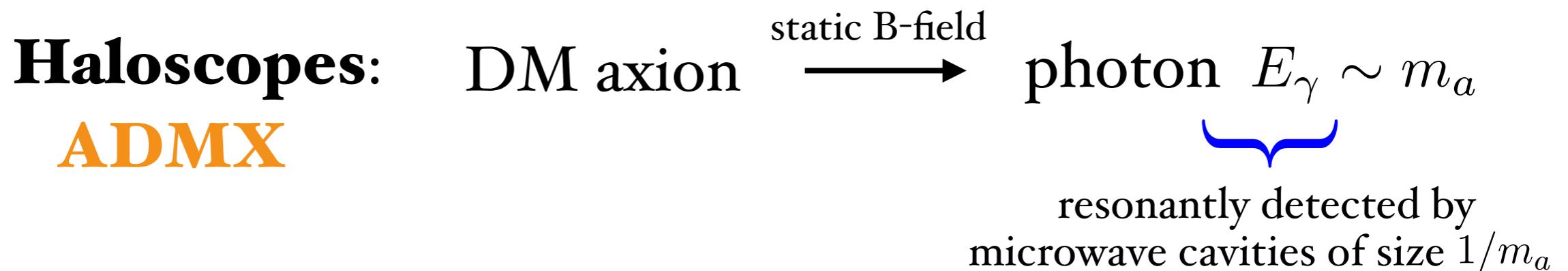
$$\Omega_{\text{DM}} h^2 \approx 0.1 \left(\frac{10^{-5} \text{ eV}}{m_a} \right)^{1.18} \beta^2$$

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

Axion Searches

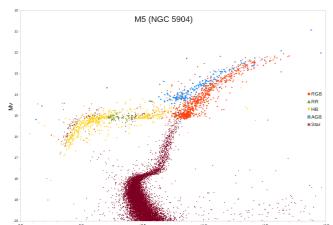
Axion searches typically rely on axion-photon coupling

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



Astrophysical Bounds

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



Evolution of Horizontal Branch stars:
constrain photon couplings

$$g_{a\gamma\gamma} < \frac{6.6 \cdot 10^{-11}}{\text{GeV}}$$



White Dwarf cooling:
constrain electron couplings

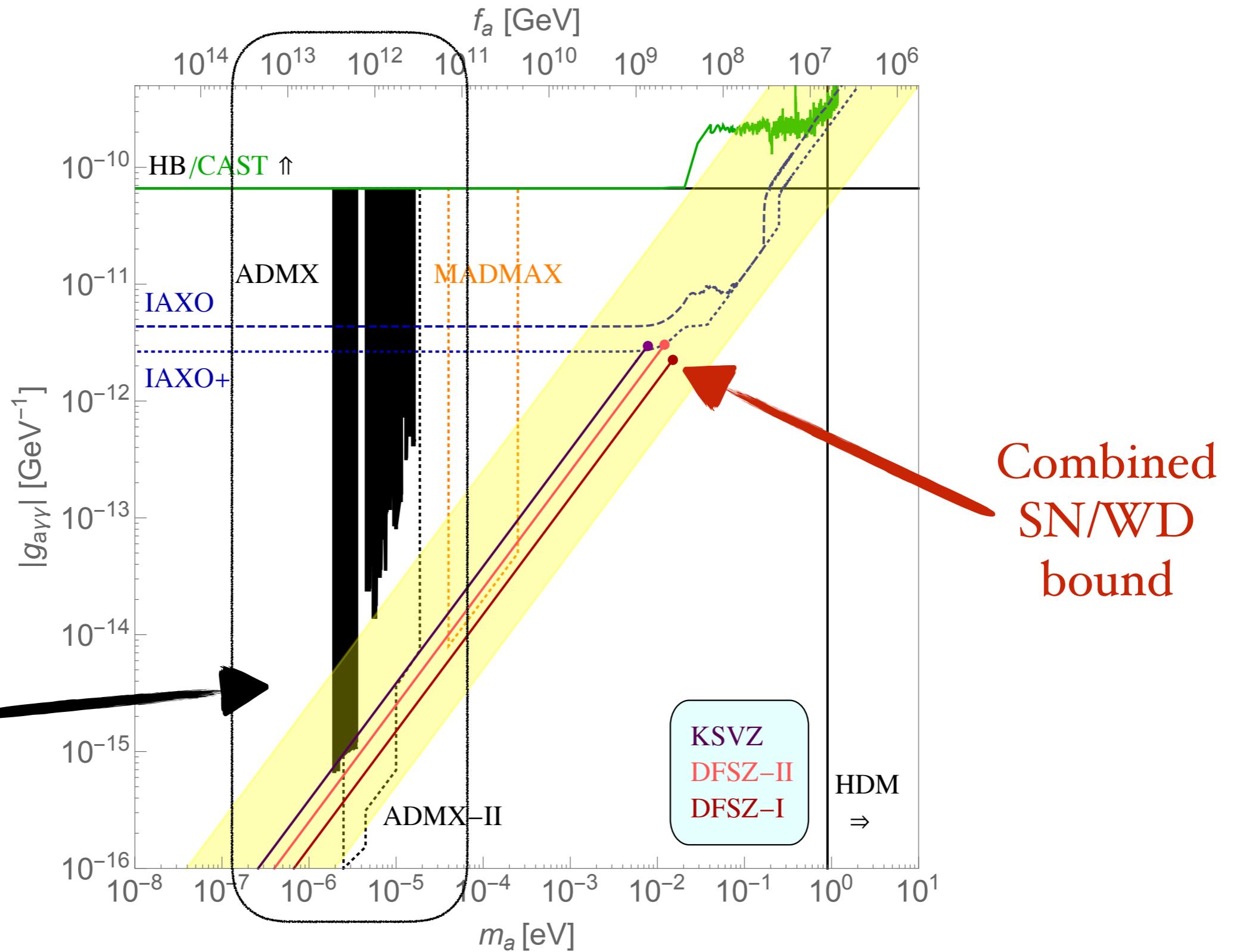
$$C_e < \frac{0.003 \text{ eV}}{m_a}$$



Supernova neutrino burst duration:
constrain nucleon couplings

$$C_N < \frac{0.004 \text{ eV}}{m_a}$$

Status of Axion Searches



Flavored Axions

Tree-level flavor-violating axion couplings are strongly constrained

$$\frac{\partial_\mu a}{2f_a} \bar{f}_i \gamma^\mu (C_{ij}^V + C_{ij}^A \gamma_5) f_j$$

$$\mu \rightarrow e a \gamma \quad m_a < \frac{2.6 \cdot 10^{-3} \text{eV}}{|C_{\mu e}|}$$

(Crystal Box, '88)

?  **MEG, Mu3e**

$$K \rightarrow \pi a \quad m_a < \frac{1.7 \cdot 10^{-5} \text{eV}}{|C_{sd}^V|}$$

(E787+E949, '08)

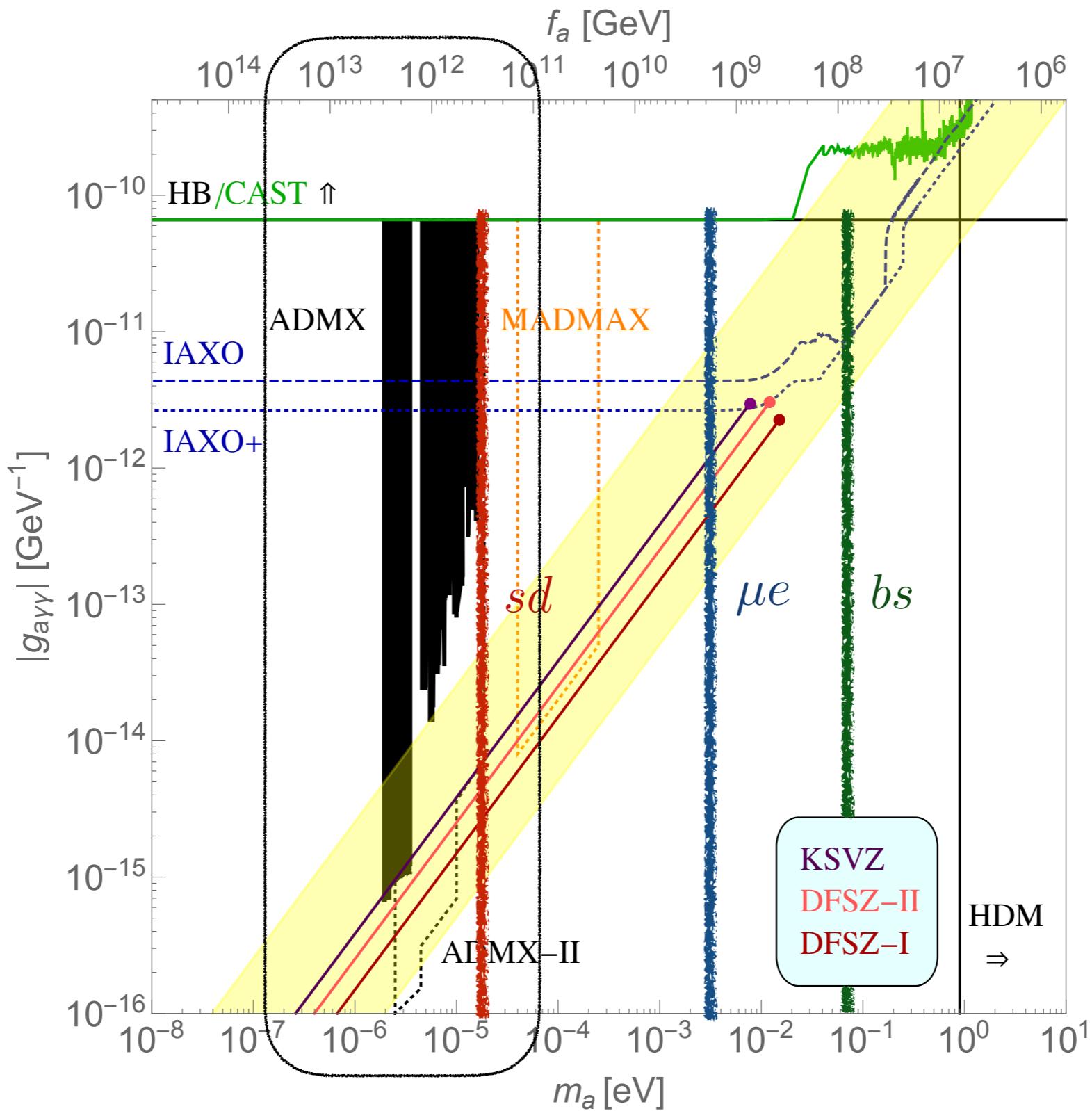
$\times 1/8$  **NA62**

$$B \rightarrow K a \quad m_a < \frac{9.4 \cdot 10^{-2} \text{eV}}{|C_{bs}^V|}$$

(CLEO, '01)

$\times 1/10$  **BELLE II**

Flavor Bounds



Flavor Violation in DFSZ

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

$$[\text{PQ}_u, Y_u^\dagger Y_u] = 0$$

loop&CKM suppressed

$$C_{sd}^V \sim C_t \frac{y_t^2}{16\pi^2} V_{ts}^* V_{td} \log \frac{f_a}{m_t} \sim C_t \frac{y_t^2}{16\pi^2} \lambda^5 \log \frac{f_a}{m_t}$$

$m_a \lesssim 0.6 \text{ eV}$ (weaker than SN/WD bound)

Flavored Axion Models

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

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

Just like Supersymmetry: flavor-violation from misalignment of sfermion masses and Yukawas $[\tilde{m}_U^2, Y_u^\dagger Y_u]$

Here consider two examples:

A) 2+1 DFSZ
misalignment is
free parameter

B) $\text{PQ} = \text{FN}$
misalignment from
fermion masses

Flavored DFSZ Models

“Next-to-minimal” DFSZ-type models:
PQ charges universal for **two** generations

Have non-trivial transition to mass basis

$$X_f = \text{diag}(X_1, X_1, X_3) \rightarrow V_f^\dagger \textcolor{blue}{X}_f V_f = X_1 \delta_{ij} + (X_3 - X_1) \epsilon_{ij}^f$$

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

Depend on 2 misalignment parameters in each sector

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

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

Nucleophobic DFSZ Models

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

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


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

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

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

An Astrophobic Axion Model

$$\mathcal{L} \sim \frac{\bar{f}_{L3} f_{R3}}{\bar{f}_{L3} f_{Ra}} \begin{cases} h_1 & \textcolor{red}{u} \\ \tilde{h}_2 & \textcolor{blue}{d} \\ \tilde{h}_1 & \textcolor{green}{e} \end{cases} + \frac{\bar{f}_{La} f_{Rb}}{\bar{f}_{La} f_{R3}} \begin{cases} h_2 & \textcolor{red}{u} \\ \tilde{h}_1 & \textcolor{blue}{d} \\ \tilde{h}_2 & \textcolor{green}{e} \end{cases}$$

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

$$\begin{aligned} C_{u_i u_i}^A &= c_\beta^2 - \epsilon_{ii}^{u_L}, & C_{u_i u_j}^{V,A} &= \pm \epsilon_{ij}^{u_L} \\ C_{d_i d_i}^A &= s_\beta^2 - \epsilon_{ii}^{d_L}, & C_{d_i d_j}^{V,A} &= \pm \epsilon_{ij}^{d_L} \\ C_{e_i e_i}^A &= -c_\beta^2 + \epsilon_{ii}^{e_L}, & C_{e_i e_j}^{V,A} &= \mp \epsilon_{ij}^{e_L}, \end{aligned}$$

Assume at most CKM like rotations in LH quark sector

$$\epsilon_{11}^{u_L, d_L} \lesssim \lambda^6, \quad \epsilon_{22}^{u_L, d_L} \lesssim \lambda^4, \quad \epsilon_{33}^{u_L, d_L} \simeq 1$$

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

Astrophobic Axion Models

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



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

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



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

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

$$C_u + C_d = 1$$

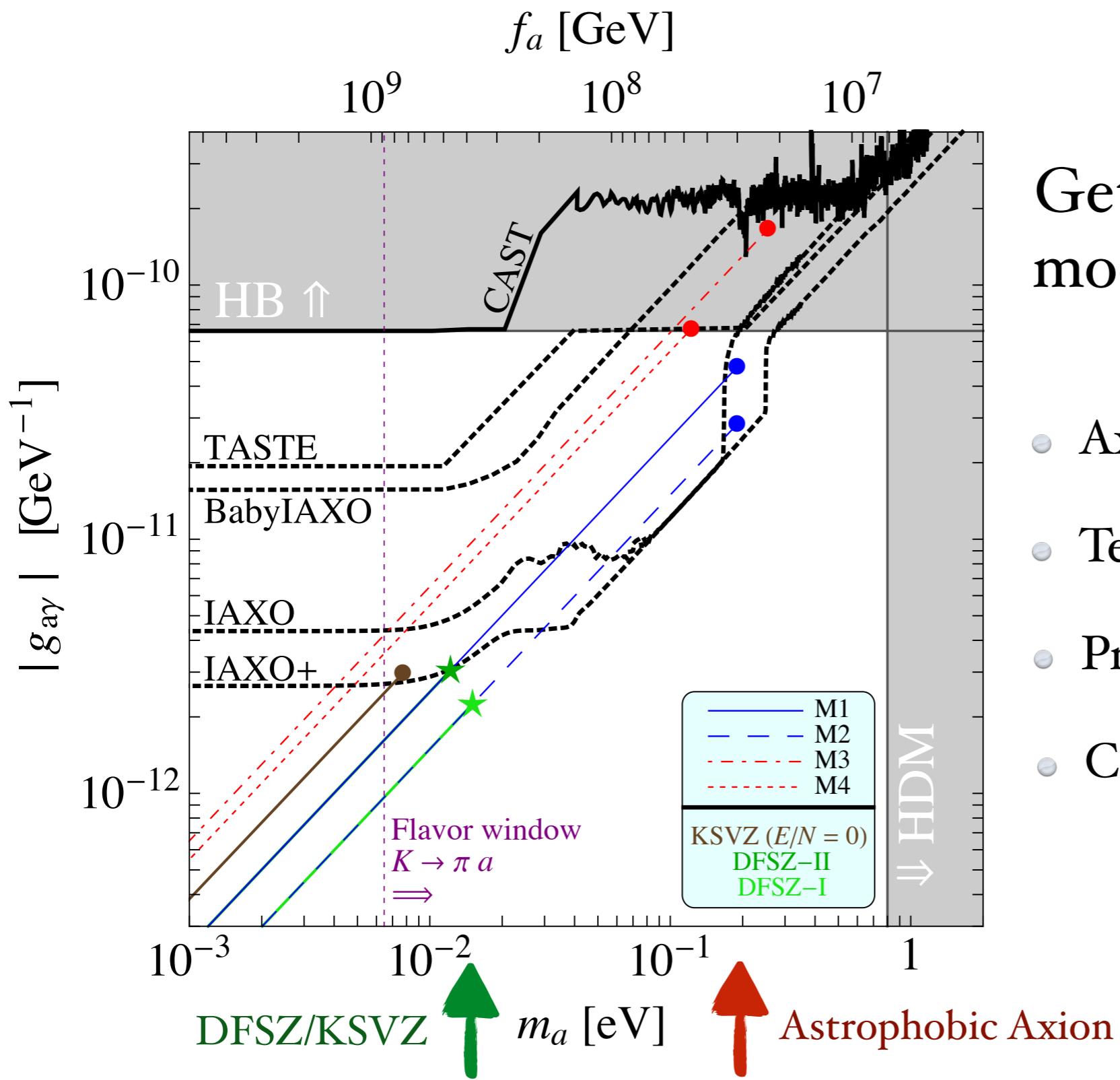
$$C_u + C_e = 2/3$$

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

$$C_u \approx 2/3$$

is always suitable 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 $\mathcal{B}_{\tau \rightarrow ea} = 6.7 \cdot 10^{-6} \left(\frac{m_a}{0.2 \text{ eV}} \right)^2$
- Can fit stellar cooling anomalies

PQ = FN (The Axiflavor)

PQ could be subgroup of flavor symmetry
responsible for Yukawa hierarchies

[Wilczek '82]

Simplest realization: $\text{PQ} = \text{U(I)}_{\text{FN}}$

[see also 1612.05492]

Work with effective U(I)_{FN} flavor model

$$\mathcal{L} \sim a_{ij}^u \left(\frac{\Phi}{\Lambda} \right)^{q_i + u_j} Q_i U_j^c H + \dots$$

$\mathcal{O}(1)$ UV cutoff flavon $V_\Phi \sim f_a \gg v$ decouples axion

SM Yukawas

SM Yukawa hierarchies from powers of $\epsilon \equiv \langle \Phi \rangle / \Lambda$

$$y_{ij}^U = a_{ij}^U \epsilon^{q_i + u_j} \quad y_{ij}^D = a_{ij}^D \epsilon^{q_i + d_j}$$

Can easily reproduce all hierarchies, e.g.

$$u_i = (4, 2, 0) \quad q_i = (3, 2, 0) \quad d_i = (4, 3, 3)$$
$$y^U \sim \begin{pmatrix} \epsilon^7 & \epsilon^5 & \epsilon^3 \\ \epsilon^6 & \epsilon^4 & \epsilon^2 \\ \epsilon^4 & \epsilon^2 & 1 \end{pmatrix} \quad y^D \sim \begin{pmatrix} \epsilon^7 & \epsilon^6 & \epsilon^6 \\ \epsilon^6 & \epsilon^5 & \epsilon^5 \\ \epsilon^4 & \epsilon^3 & \epsilon^3 \end{pmatrix} \quad \epsilon \approx 0.2$$

Axion-Photon Couplings

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

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

as direct consequence of fermion mass hierarchies

$$\det m_u \det m_d / v^6 = [\det a_u \det a_d] \epsilon^{2N}$$

$$\underbrace{\approx 10^{-20}}$$

$$\underbrace{\mathcal{O}(1)}$$



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

$$\det m_d / \det m_e = [\det a_d / \det a_e] \epsilon^{\frac{8}{3}N - E}$$

$$\underbrace{\approx 0.7}$$

$$\underbrace{\mathcal{O}(1)}$$

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

Axion-Fermion Couplings

Axion-fermion couplings through Yukawa terms

$$\Phi \sim e^{i(q_i + u_j)a(x)/V_\Phi}$$

Remove by PQ transformation acting only on fermions

$$f_i \rightarrow f_i e^{-i f_i a(x)/V_\Phi}$$

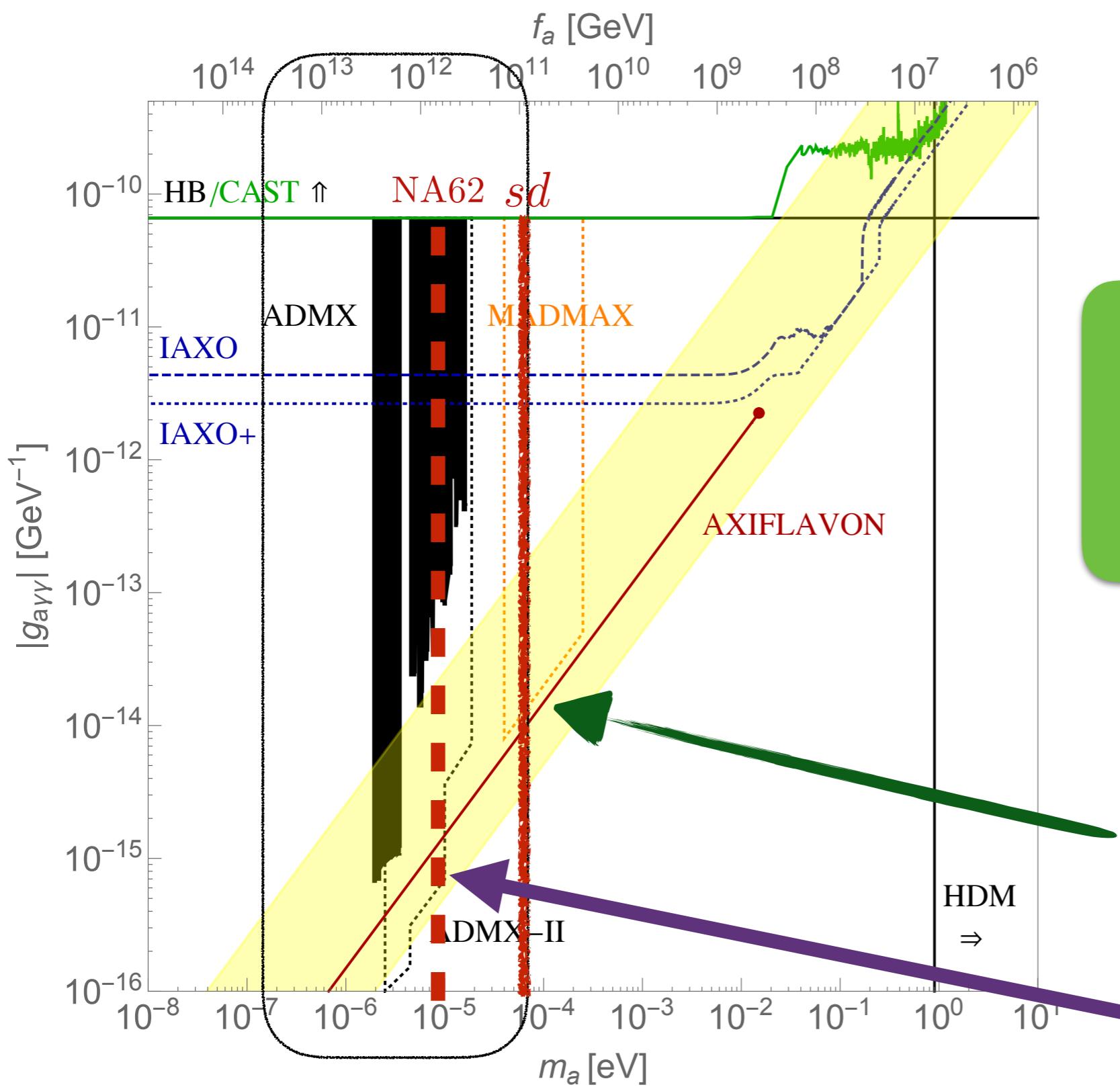
Up to $\mathcal{O}(1)$ coefficients fermion couplings
determined by fermion masses and mixings

$$\textcolor{blue}{X}_f = \text{diag}(f_1, f_2, f_3) \rightarrow V_f^\dagger \textcolor{blue}{X}_f V_f \quad V_f \sim \epsilon^{|f_i - f_j|}$$

$$C_{ij}^f \sim \epsilon^{|f_i - f_j|}$$

$$C_{ij}^q \sim V_{ij}^{\text{CKM}} \quad C_{i < j}^u \sim \frac{m_i}{m_j V_{ij}^{\text{CKM}}}$$

The Axiflavor



**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
- When $PQ = FN$ flavor alignment parameters predicted in terms of fermion masses and mixings up to $O(1)$ uncertainties; E/N in narrow range