Flavored Axions

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based on 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?

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

$\mathcal{L} = \theta \frac{\alpha_s}{8\pi} G_a^{\mu\nu} \tilde{G}_a^{\mu\nu}$

The Axion Solution

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

QCD Axion: Goldstone of spontaneously broken global U(1) symmetry with QCD anomaly

[ultra-light, decoupled, stable particle]

The QCD Axion

[Peccei, Quinn ’77, Wilczek;’78 Weinberg ’78]

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

radial mode

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

axion

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

$$\mathcal{L}_{\mathrm{eff}} = \bar{\theta}\frac{\alpha_s}{8\pi}G_a^{\mu\nu}\tilde{G}_{a,\mu\nu} + \mathcal{L}_{a,\mathrm{int}}\underbrace{[\frac{\partial_\mu a}{f}, \psi_{\mathrm{SM}}]}_{\text{Interactions with SM fermions}} + N\frac{a(x)}{f}\underbrace{\frac{\alpha_s}{4\pi}G_a^{\mu\nu}\tilde{G}_{a,\mu\nu}}_{\text{ABJ term for QCD anomaly}} + E\frac{a(x)}{f}\underbrace{\frac{\alpha_{\mathrm{em}}}{4\pi}F^{\mu\nu}\tilde{F}_{\mu\nu}}_{\text{ABJ term for EM anomaly}}$$

[can absorb $\bar{\theta}$ in $a(x)$: becomes dynamical field]

Axion-Gluon Couplings

Effective Lagrangian induces axion potential

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

Minimum at CP-conserving point $\langle a(x)\rangle = 0$

QCD θ-term dynamically relaxed to zero

Generates axion mass

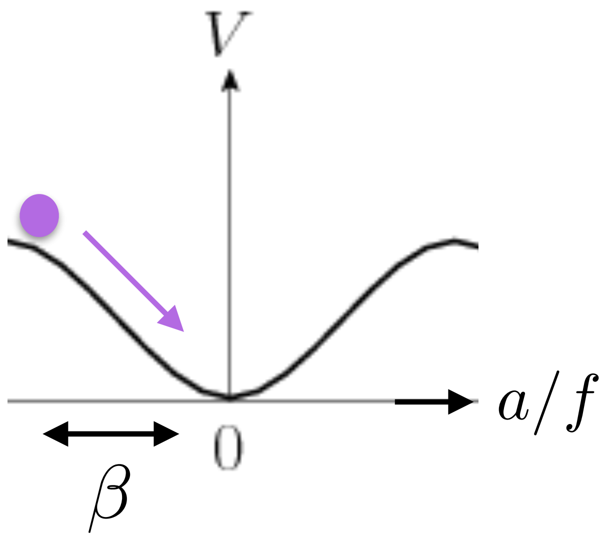
$$m_a \propto m_\pi f_\pi / f_a = 5.7\,\mu\text{eV}\left(\frac{10^{12}\,\text{GeV}}{f_a}\right)$$

Axions as Dark Matter

{axion essentially stable for $m_a \lesssim 20\,\mathrm{eV}$}

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



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

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

Axion-Photon Couplings

Axion searches 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 $\underbrace{E_\gamma \sim m_a}$

ADMX

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

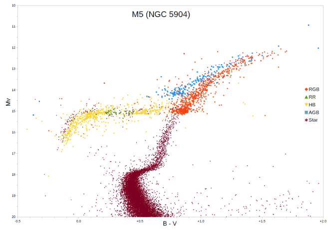
Helioscopes: Solar photon $\xrightarrow{\text{nuclear E-field}}$ axion $\underbrace{E_a \sim \mathrm{keV}}$

CAST/IAXO

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

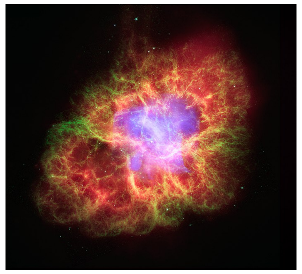
Astrophysical Constraints

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



Evolution of Horizontal Branch stars: constrain photon couplings

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



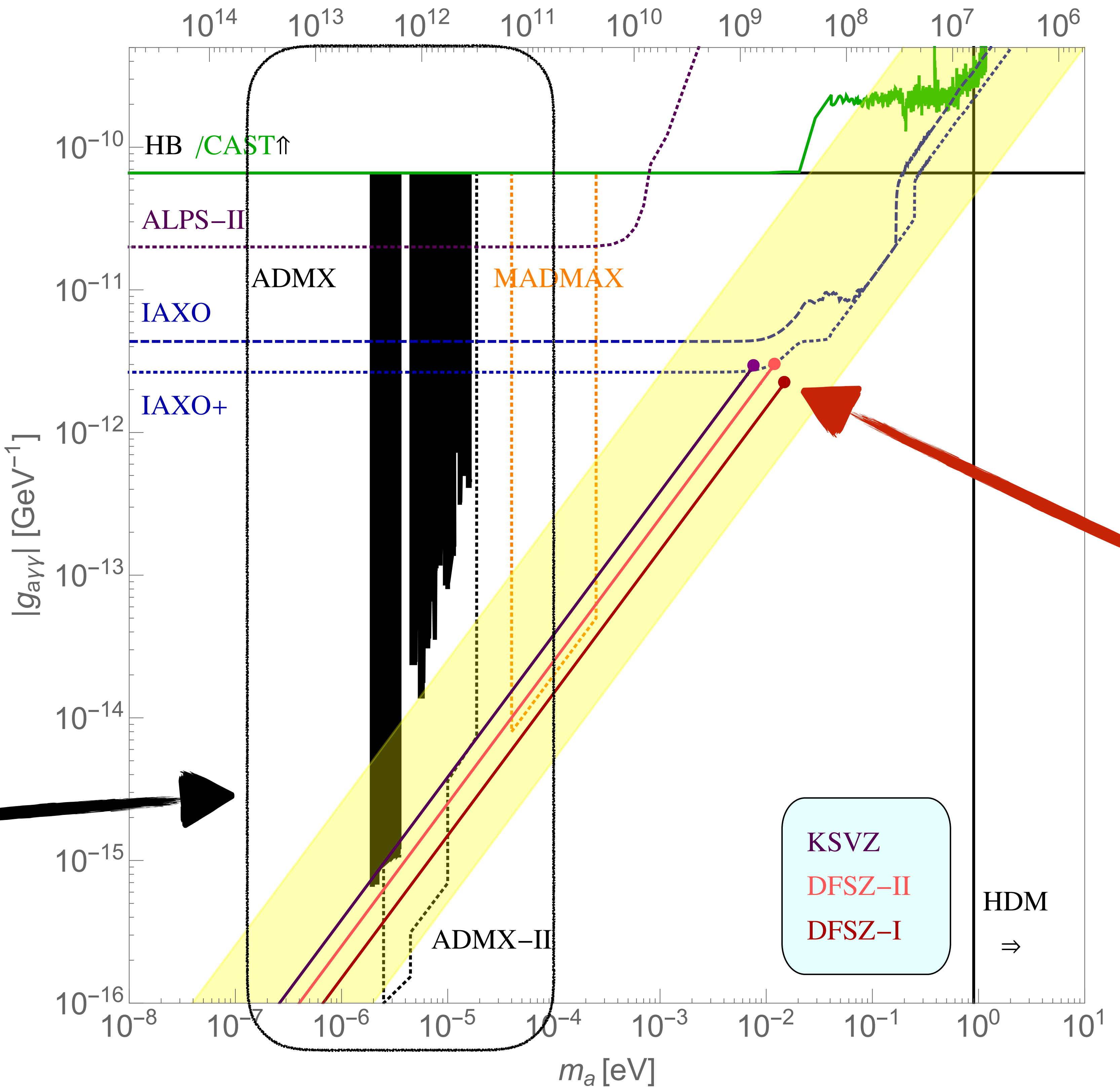
Supernova neutrino burst duration: constrain nucleon couplings

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

White Dwarf cooling: constrain electron couplings

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

Status of Axion Searches



Combined
SN/WD
bound

Natural axion
DM window
(misalignment)

Axion-Fermion Couplings

Strongly constrained by decays into invisible, massless axion

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

$\mu \to e a \gamma$

(Crystal Box, ’88)

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

$\xrightarrow{?}$ **MEG, Mu3e**

$K \to \pi a$

(E787+E949, ’08)

$$m_a < \frac{2\cdot 10^{-5}\,\mathrm{eV}}{|C^V_{sd}|}$$

$\xrightarrow{\times 1/8}$ **NA62**

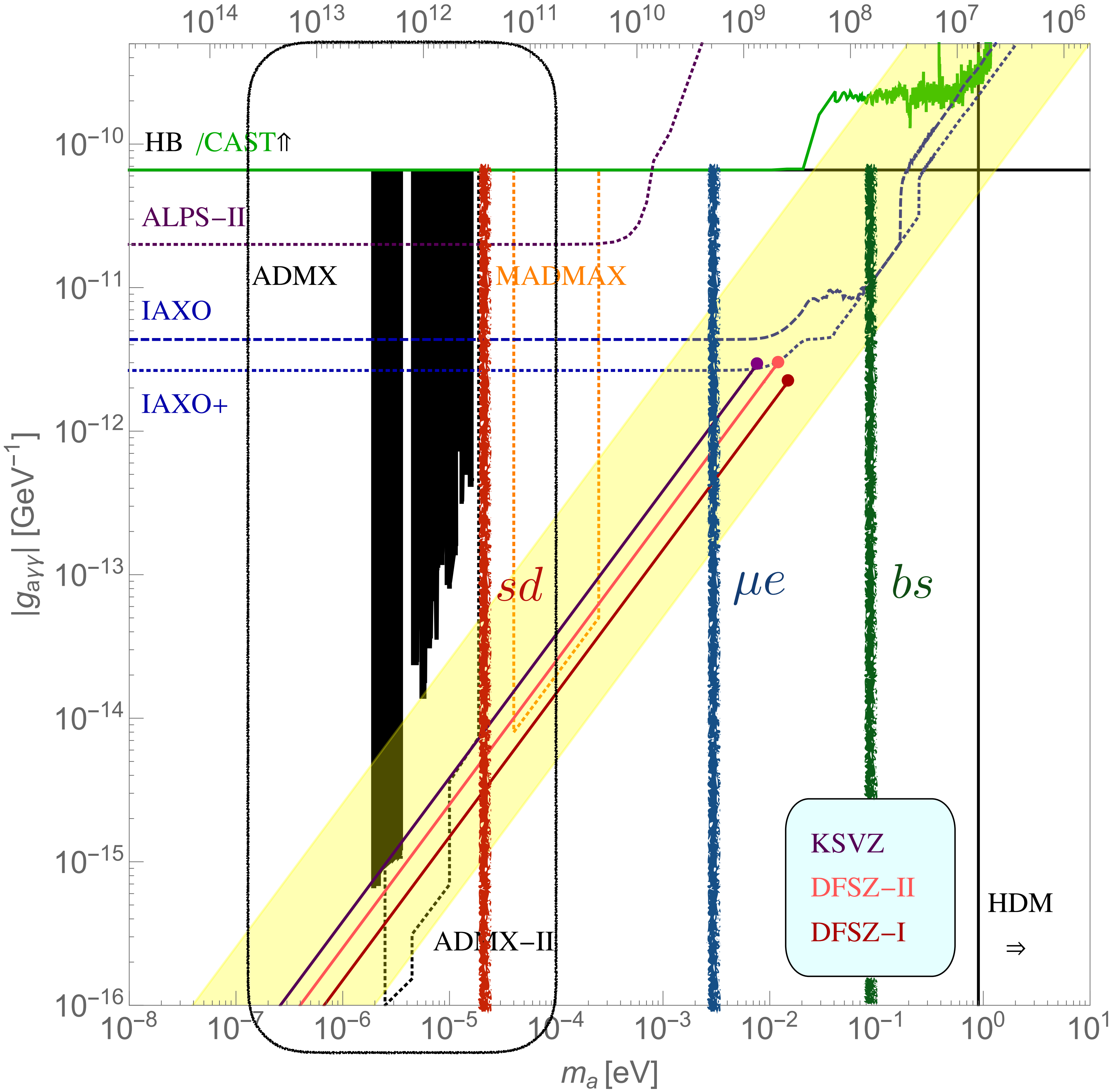
$B \to K a$

(CLEO, ’01)

$$m_a < \frac{9\cdot 10^{-2}\,\mathrm{eV}}{|C^V_{bs}|}$$

$\xrightarrow{\times 1/10}$ **BELLE II**

Flavor Constraints



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

Origin of Axion-Fermion Couplings

Axion-fermion couplings given by diagonal PQ charges **in gauge basis**

$$\tilde{C}^{V,A}_{u_i u_j} = (X_{q_i} \pm X_{u_i})\delta_{ij}$$

Folded with unitary rotations **in mass basis**

$$V^\dagger_{UL} M_u V_{UR} = M_u^{\rm diag}$$

$$\boxed{C^{V,A}_{u_i u_j} = (V^\dagger_{UL} X_q V_{UL})_{ij} \pm (V^\dagger_{UR} X_u V_{UR})_{ij}}$$

Axion Model Predictions

In general axion-fermion couplings depend on PQ charges AND unitary rotations, as PQ charge matrix constitutes new source of flavor violation beyond SM Yukawas

$$\boxed{[\mathrm{PQ}_u, Y_u^\dagger Y_u] \neq 0 \longrightarrow (V_{UR}^\dagger \mathrm{PQ}_u V_{UR})_{i\neq j} \neq 0}$$

Two possibilities to construct predictive model:

A) Take all PQ charges flavor-universal

B) Predict PQ and Yukawas simultaneously

Flavor-Universal Models

Universal PQ charges don't introduce new sources of flavor violation beyond SM (MFV)

$$\boxed{X_q \propto X_u \propto X_d \propto \mathbb{1}_{3\times 3}}$$

(assumed in usual DFSZ models)

Flavor Violation is loop & CKM suppressed

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

PQ as a Flavor Symmetry

Need model of flavor to predict Yukawas
in flavor basis where PQ diagonal

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

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

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

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

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

$V_\Phi \sim f_a \gg v$

decouples

axion

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

PQ = FN

Simplest U(1) symmetry works: Froggatt-Nielsen

[Froggatt,Nielsen ‘79]

	ϕ	$\bar{q}_i$	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 $V_f \sim \epsilon^{|f_i - f_j|}$

Axion-Photon Couplings

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

$$2N = \sum_i 2q_i + u_i + d_i$$

$$E = \sum_i \frac{5}{3} q_i + \frac{4}{3} u_i + \ldots$$

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

Direct consequence of fermion mass hierarchies

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

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

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

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

Axion-Fermion Couplings

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

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

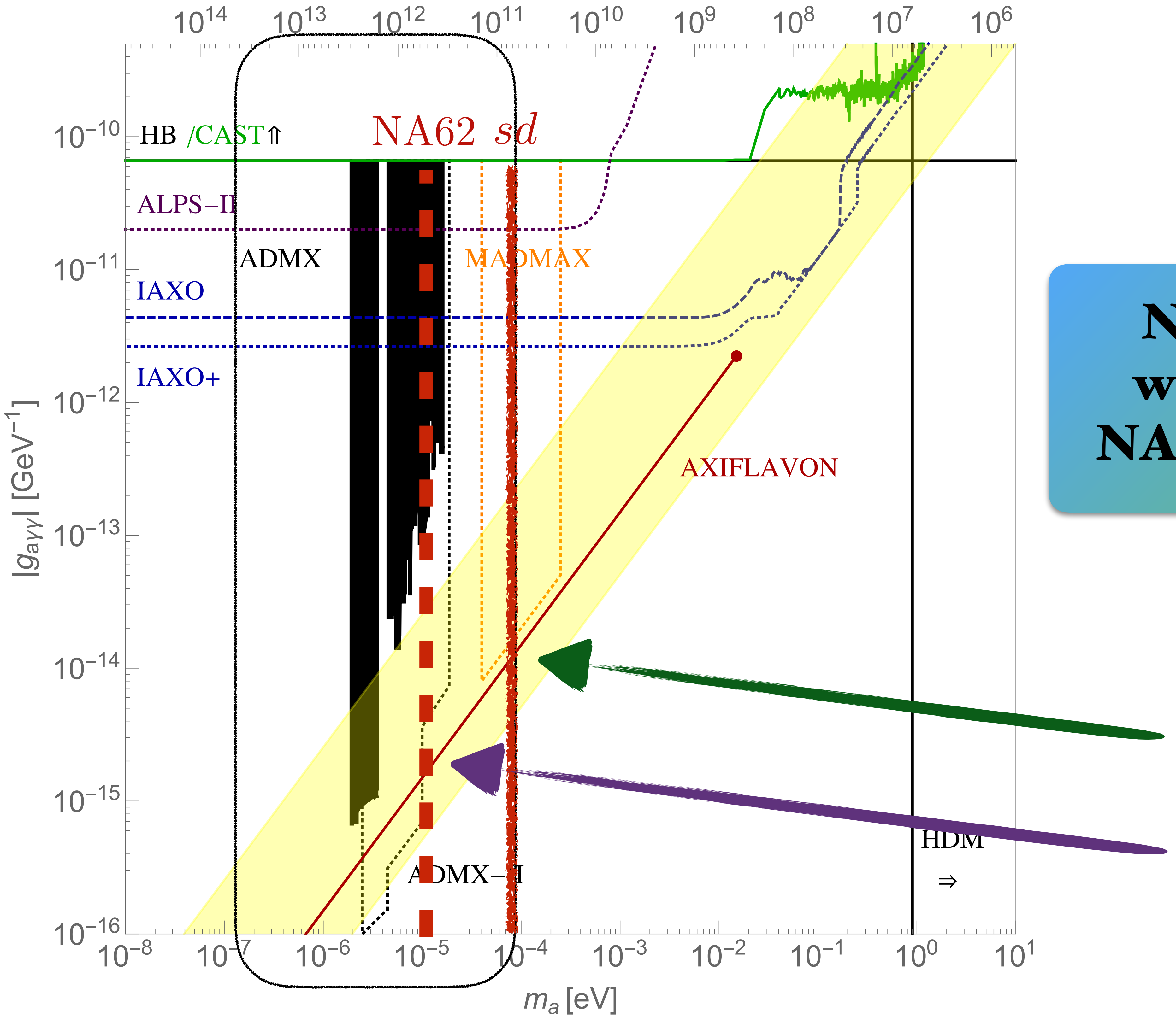
Flavor-violating couplings governed by CKM

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

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

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

The Axiflavon



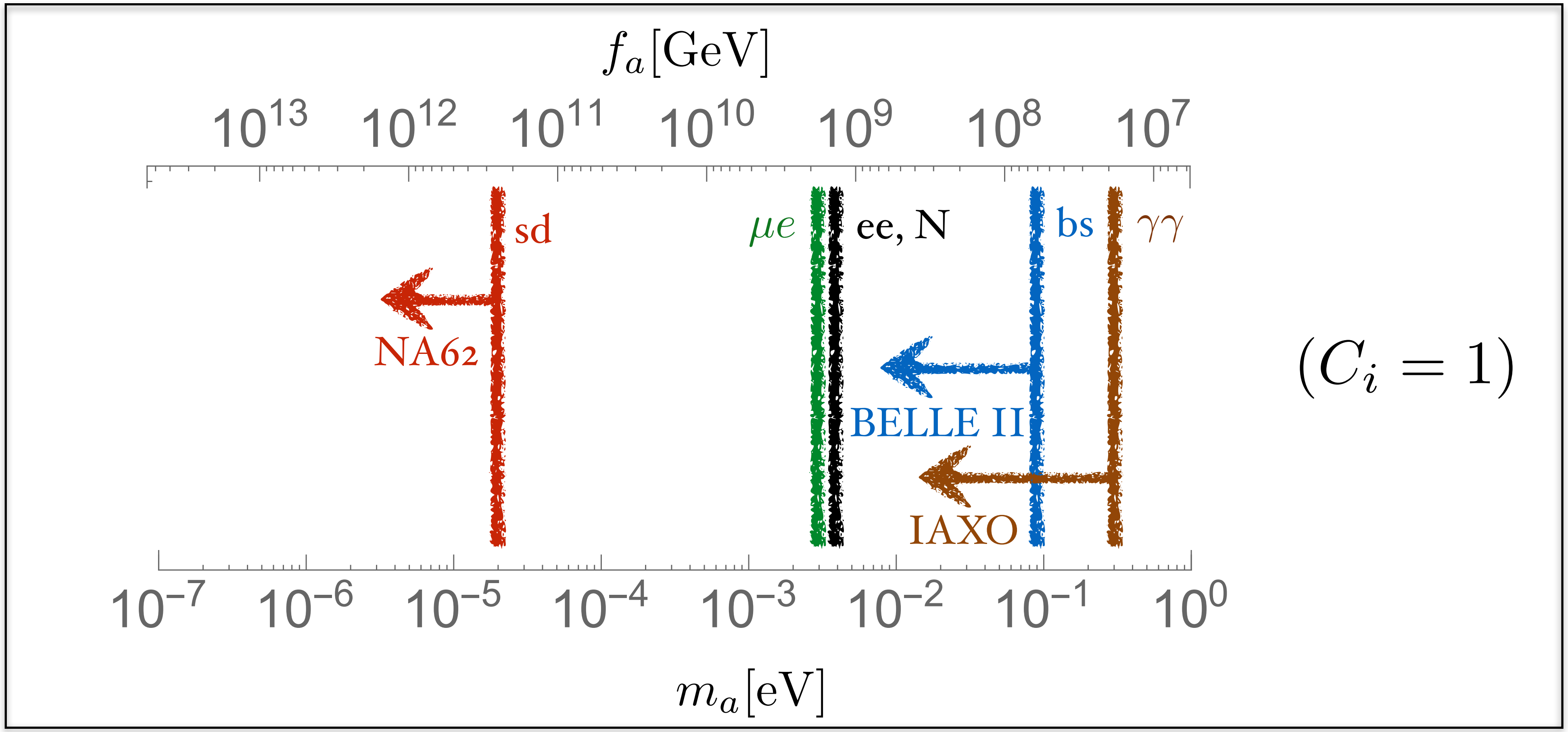
Natural axion DM window testable at NA62 (and ADMX-II)

Present bound from E787+E949

Expected future bound from NA62

Summary

- Flavored axions allow for complementary axion searches with precision flavor experiments



- Well-motivated axion model from PQ = FN, flavor-violating couplings from fermion masses and mixings