The Axiflavon

A Minimal Axion Model from Flavor

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based on arXiv: 1612.08040 with
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General Idea

Identify PQ symmetry with U(1) flavor symmetry: the phase of the flavon is the QCD axion = axiflavon

Can obtain pretty sharp prediction for axion-photon coupling E/N [in contrast to broad range in usual axion models]

Get predictions for axion-fermion couplings, which in general are flavor-violating [up to O(1) uncertainties]

Very predictive framework that is testable both at axion and flavor experiments

see also 1612.05492

Outline

- **The Axion**

- **The Flavon**

- **The Axiflavon**

The QCD θ-term

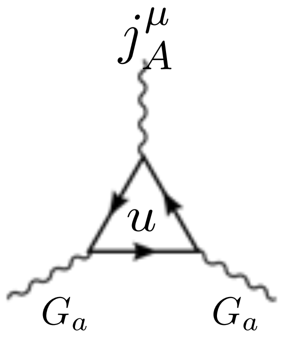
Gauge and Lorentz invariance allow QCD θ-term

$$\boxed{\mathcal{L} = \theta \frac{\alpha_s}{8\pi} G_a^{\mu\nu} \tilde{G}_{a,\mu\nu} = \theta \frac{\alpha_s}{16\pi} \epsilon_{\mu\nu\rho\sigma} G_a^{\mu\nu} G_a^{\rho\sigma}}$$

Shifts under anomalous axial U(1) transformations that control complex phases in quark masses

$$q_i \to e^{\frac{i}{2}\alpha_i^q \gamma_5} q_i \quad \Rightarrow \quad m_i^q \to e^{i\alpha_i^q} m_i^q \ , \quad \theta \to \theta - \underbrace{\sum_{i,q}}_{\uparrow} \alpha_i^q$$

consequence of ABJ anomaly



Only invariant combination can be physical

$$\bar{\theta} \equiv \theta + \arg\det\left(m^u m^d\right)$$

The Strong CP Problem

Eff. θ-term violates CP and contributes to neutron EDM

$d_n \approx 4 \times 10^{-16} \overline{\theta}\, e\,\mathrm{cm}$ ⟷ $|d_n|_{\mathrm{exp}} < 3 \times 10^{-26}\, e\,\mathrm{cm}$

Why $\overline{\theta} \equiv \theta + \arg\det\left(m^u m^d\right) < 10^{-10}$ **?**

Would expect both θ-term and complex Yukawa matrices to be present in Lagrangian and $\overline{\theta} \sim \mathcal{O}(1)$

[note: cannot impose CP since need complex Yuks for (large) CKM phase]

The Axion Solution

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

I. Field without potential is Goldstone boson: need new global symmetry that is spontaneously broken

[remains as shift symmetry $a \to a + \alpha$]

II. Want to couple Goldstone to gluons: need also anomalous breaking of global symmetry

[shift symmetry broken by $aG\tilde{G}$]

QCD Axion: Goldstone boson of new global symmetry with QCD anomaly

The Peccei-Quinn Mechanism

[Peccei, Quinn ’77]

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

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

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

radial mode

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

axion

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

$$\mathcal{L}_{\text{eff}} = \overline{\theta}\frac{\alpha_s}{8\pi}G_a^{\mu\nu}\tilde{G}_{a,\mu\nu} + \mathcal{L}_{\text{a,int}}\underbrace{[\frac{\partial_\mu a}{f}, \psi_{\text{SM}}]}_{\substack{\textbf{Interactions with}\\ \textbf{SM fermions}\\ \text{[respects shift}\\ \text{symmetry]}}} + \underbrace{\frac{a}{f}\xi\frac{\alpha_s}{8\pi}G_a^{\mu\nu}\tilde{G}_{a,\mu\nu}}_{\substack{\textbf{ABJ term for}\\ \textbf{QCD anomaly}\\ \text{[breaks shift}\\ \text{symmetry]}}} + \mathcal{L}_{\text{anom}}\underbrace{[\frac{a}{f}F\tilde{F}]}_{\substack{\textbf{ABJ term for}\\ \textbf{other anomalies}\\ \text{[cf. } \frac{\pi^0}{f_\pi}F\tilde{F}\text{]}}}$$

Depends on $\overline{\theta}$ only through PQ invariant combination

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

[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 vev $\langle\overline{a}(x)\rangle = 0$

θ-term dynamically relaxed to zero

axion gets mass $m_a \sim m_\pi f_\pi / f_a$

couples to photons and SM fermions $\sim 1/f_a$

is natural DM candidate for $1/100\,\mu\text{eV} \lesssim m_a \lesssim 100\,\mu\text{eV}$

Axion Models

Choose PQ charges of SM/BSM fermions for QCD anomaly

Models characterised by axion-photon couplings E/N and PQ breaking scale/axion mass $f_a \leftrightarrow m_a$

- **PQWW axion** [Peccei, Quinn, Wilczek, Weinberg '78]

  2HDM model without new fermions, $f_a \sim v, m_a \sim 30\,\mathrm{keV}$

  excluded

- **DFSZ axion** [Dine, Fischler, Srednicki, Zhitnitsky '80]

  2HDM model without new fermions but extra singlet scalar that breaks PQ at scale f_a much above electroweak scale; $|E/N| \in [0.3, 2.7]$

- **KSVZ axion** [Kim, Shifman, Vainshtein, Zakharov '80]

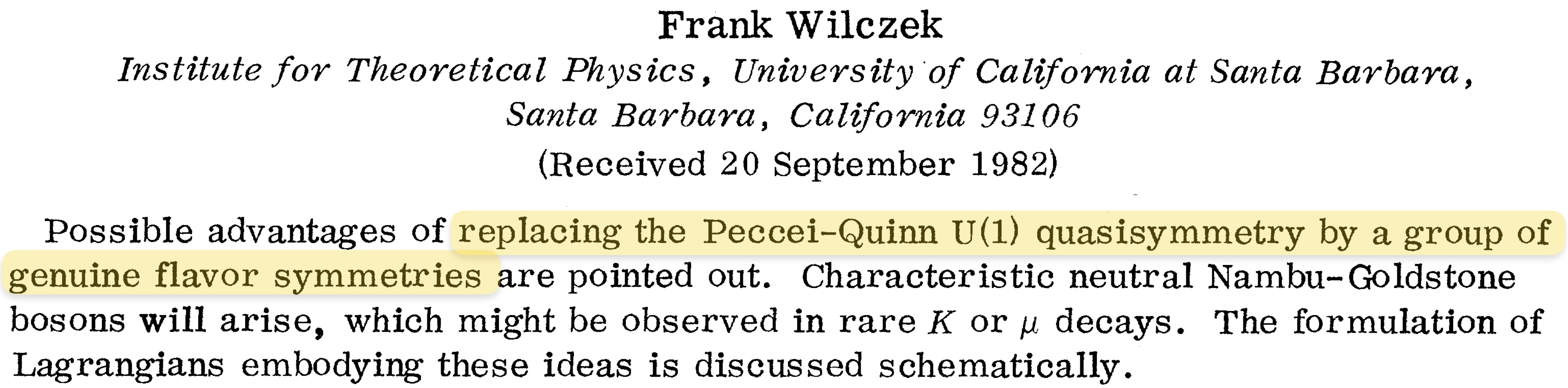
  SM model with new (heavy) fermions and extra singlet scalar that breaks PQ at scale f_a much above electroweak scale; $|E/N| \in [0, 6]$

Axions and Flavor

In usual axions solution PQ symmetry and quantum numbers are ad-hoc and serve no other purpose than to solve strong CP problem

Interesting to connect PQ to other global symmetries, e.g. **flavor symmetries** that explain Yukawa hierarchies

PQ = subgroup of $U(3)^5 \overset{\text{yuks}}{\rightarrow} U(1)_B \times U(1)_{L_i}$



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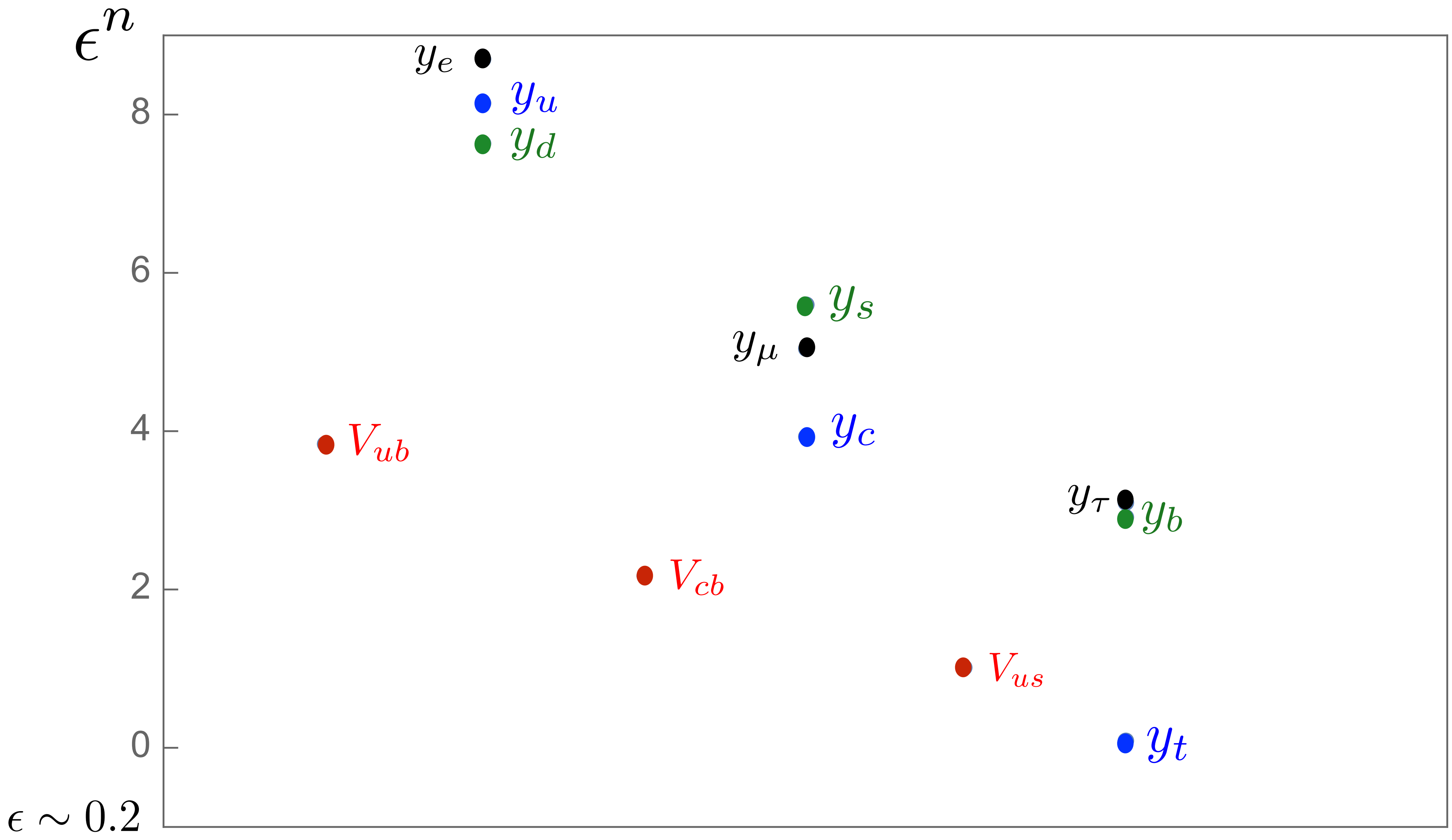
Possible advantages of replacing the Peccei-Quinn U(1) quasisymmetry by a group of genuine flavor symmetries are pointed out. Characteristic neutral Nambu-Goldstone bosons will arise, which might be observed in rare K or μ decays. The formulation of Lagrangians embodying these ideas is discussed schematically.

The SM Flavor Puzzle

Explain large hierarchies in SM Yukawas



Flavor Symmetries

Light 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 $\epsilon \equiv \dfrac{\langle \Phi \rangle}{\Lambda_F}$

U(1) Flavor Symmetry

Simplest symmetry works

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

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

Can easily reproduce all hierarchies, e.g.

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

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

Anomalous U(1) Flavor Symmetry

Charge assignments are not unique because of
O(1) coefficients and order parameter ~1/5

Still can show that **U(1) is necessarily anomalous**

[Binetruy, Ramond '94]

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

↑ **QCD anomaly coefficient**

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

↑ **EM anomaly coefficient**

Identify U(1)$_{\text{Flavor}}$ = U(1)$_{\text{PQ}}$

Work with effective U(1) flavor model

$$\mathcal{L} \sim a^u_{ij} \left(\frac{\Phi}{\Lambda}\right)^{q_i+u_j} Q_i U^c_j H + \ldots \qquad \Phi = \frac{1}{\sqrt{2}}(V_\Phi + \phi)e^{ia/V_\Phi}$$

$V_\Phi \sim f_a \gg v$

decouples

axion

SM Yukawas

$$y^u_{ij} = a^u_{ij}\epsilon^{q_i+u_j}$$

Axion-fermion couplings

$$g_{au_iu_j} \sim \frac{v}{f_a}(q_i+u_j)y^u_{ij}$$

Axion mass

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

usual QCD axion relations

Axion-photon couplings

$$g_{a\gamma\gamma} \sim \frac{E}{N}\frac{1}{10^{16}\text{GeV}}\frac{m_a}{\mu\text{eV}}$$

Axion-photon couplings

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

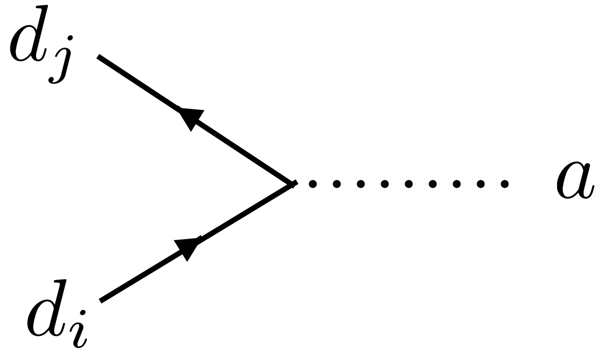
$$\boxed{\frac{E}{N} \in [2.4, 3.0]}$$

Direct consequence of fermion mass hierarchies

$$\boxed{\frac{E}{N} = \underset{\mathbf{2.7}}{\frac{8}{3}} - 2\,\frac{\overset{\mathbf{-0.4}}{\log\frac{\det m_d}{\det m_e}} - \overset{\mathbf{\sim 0}}{\log \alpha_{de}}}{\underset{\mathbf{-44}}{\log\frac{\det m_u \det m_d}{v^6}} - \underset{\mathbf{\sim 0}}{\log \alpha_{ud}}}}$$

Axion-fermion couplings

Predicted with somewhat larger [but O(1)] uncertainties



$$\sim \frac{\sqrt{m_i m_j}}{f_a} \sim \frac{m_a}{\mu\mathrm{eV}} \frac{\sqrt{m_i m_j}}{10^{12}\mathrm{GeV}}$$

Strong bounds from flavor-violating meson decays with invisible massless particle

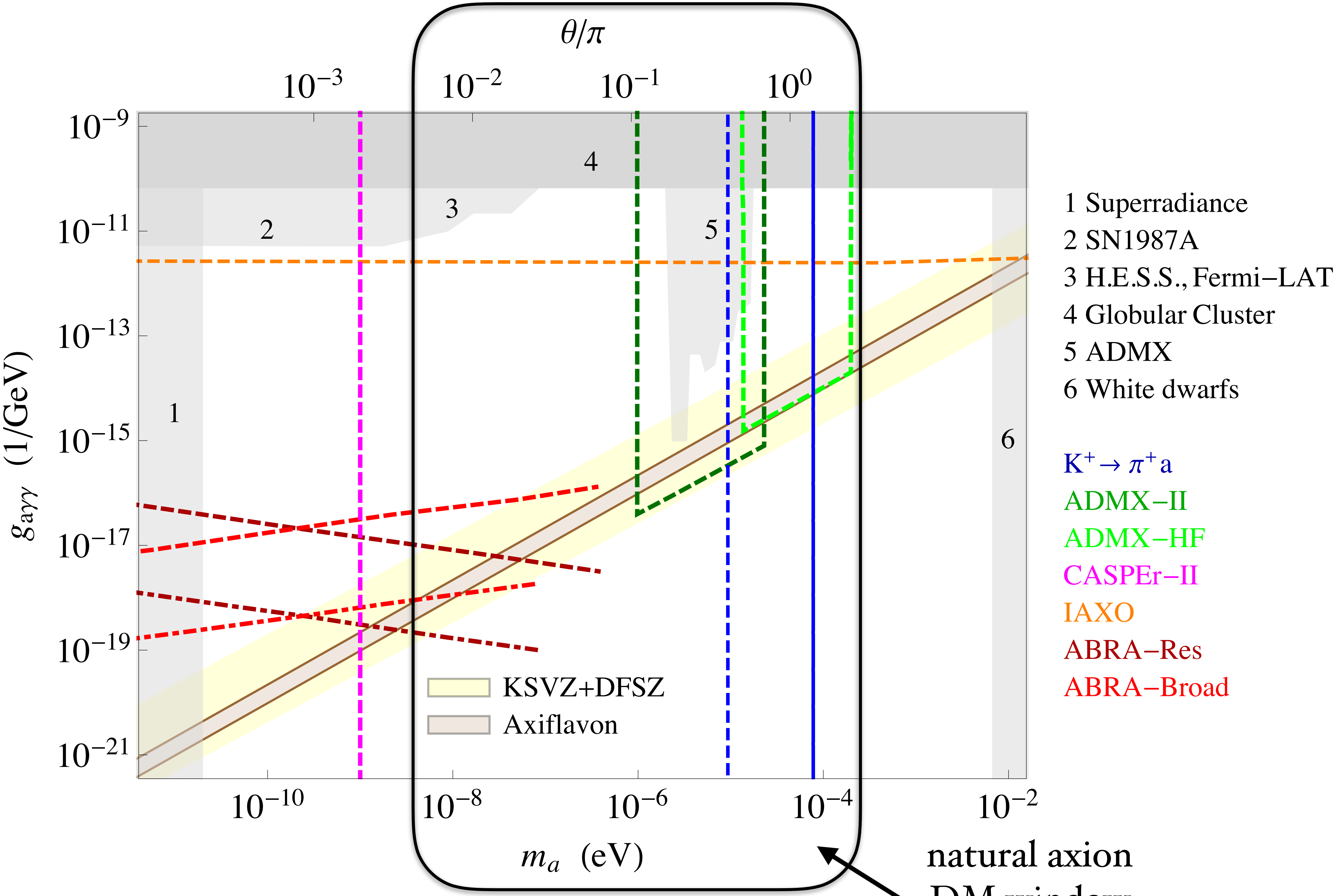
$$\mathrm{BR}(K^+ \to \pi^+ a) < 7.3 \cdot 10^{-11} \quad \Rightarrow \quad m_a \lesssim 0.08\,\mathrm{meV}$$

E787 + E949

$f_a \gtrsim 7 \times 10^{10}\,\mathrm{GeV}$

Expected improvement at NA62 by factor ~70

Summary Plot



natural axion
DM window