The Axiflavon

A Minimal Axion Model from Flavor

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based on arXiv: 1612.08040 with
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Outline

- **The Axion**

- **The Flavon**

- **The Axiflavon**

The Axion

The QCD θ-term

Gauge and Lorentz invariance allow QCD θ-term

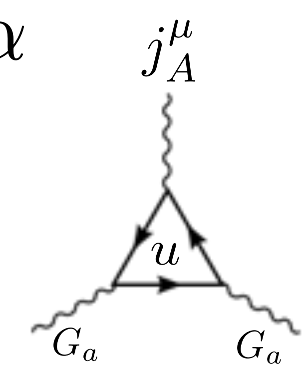
$$\mathcal{L} = \theta \frac{\alpha_s}{8\pi} G_a^{\mu\nu} \tilde{G}_{a,\mu\nu} = \theta \frac{\alpha_s}{16\pi} \epsilon_{\mu\nu\rho\sigma} G_a^{\mu\nu} G_a^{\rho\sigma}$$

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

for 1 quark generation: $\mathcal{L}_{\text{mass}} = -\overline{u}_L M_u u_R + \text{h.c.}$

$$\left.\begin{array}{c} u_{L,R} \to e^{\mp \frac{i\alpha}{2}} u_{L,R} \\ u \to e^{\frac{i\alpha}{2}\gamma_5} u \end{array}\right\} \Rightarrow \begin{array}{c} M_u \to e^{i\alpha} M_u \\ \theta \to \theta - \alpha \end{array}$$

consequence of ABJ anomaly



The Physical QCD θ -term

for 3 SM quark generations:

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

Can use axial U(1) transformations to move phases arbitrarily between quark mass terms and θ -term

Only invariant combination can be physical

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

[Note: if up-quark would be massless could set $\overline{\theta} = \theta \to 0$]

The Strong CP Problem

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

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

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]

Solving the Strong CP Problem

- Massless up-quark would be solution, but **ruled out**

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

  Axion solution {new ultra-light, decoupled, stable particle}

The Axion Solution

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

[non-conserved Noether current $\partial_\mu j^\mu_{\rm PQ} \sim \frac{\alpha_s}{4\pi} G\tilde{G}$]

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

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

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

$$\Phi \to e^{i\alpha}\Phi \quad \Longrightarrow \quad a \to a + \alpha f$$

The Peccei-Quinn Mechanism

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

$$\mathcal{L}_{\rm eff} = \overline{\theta}\frac{\alpha_s}{8\pi}G_a^{\mu\nu}\tilde{G}_{a,\mu\nu} + \frac{1}{2}\partial_\mu a \partial^\mu a + \mathcal{L}_{\rm a,int}[\frac{\partial_\mu a}{f}, \psi_{\rm SM}] + \frac{a}{f}\xi\frac{\alpha_s}{8\pi}G_a^{\mu\nu}\tilde{G}_{a,\mu\nu} + \mathcal{L}_{\rm anom}[\frac{a}{f}F\tilde{F}]$$

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 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 Peccei-Quinn Mechanism

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

Generates also axion mass $m_a \sim m_\pi f_\pi / f_a$

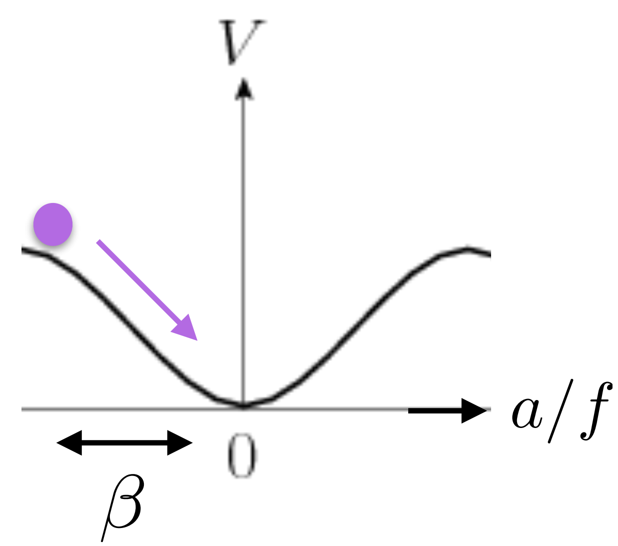
couples to photons and SM fermions $\sim 1/f_a$

For large f_a axion is ultra-light and decoupled

Axions as Dark Matter

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

In early universe axion displaced from minimum



As universe expands axion rolls down and starts oscillating around minimum: energy stored in oscillations contributes to DM relic density

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

Right abundance for $10^{-8}\,\mathrm{eV} \lesssim m_a \lesssim 10^{-4}\,\mathrm{eV}$

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; $|E/N| \in [0, 6]$

Axion Searches

Axion searches typically rely on axion-photon coupling

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

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

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

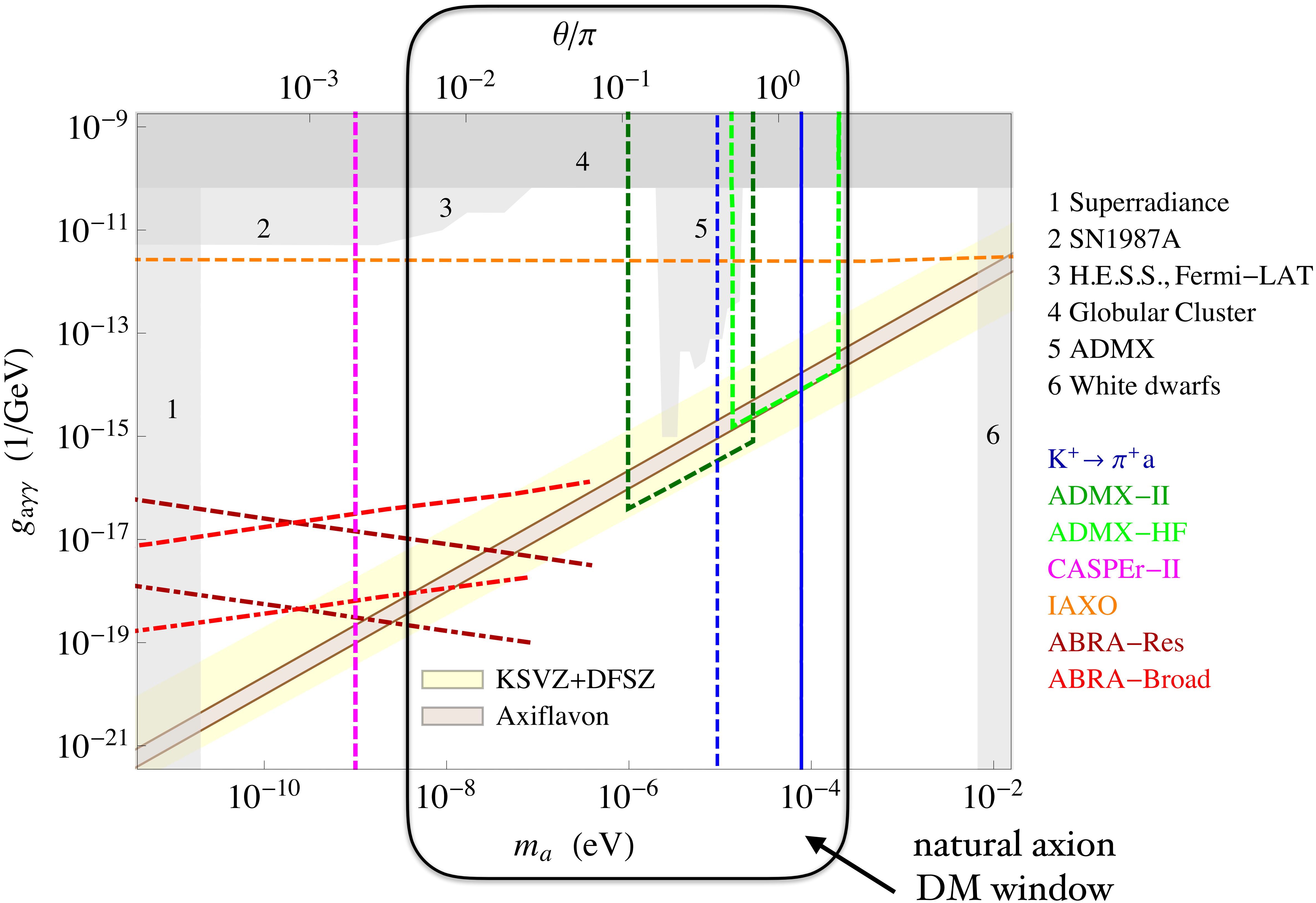
ADMX

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

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

CAST/IAXO

Axion Searches



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 $U(3)^5 \stackrel{\text{yuks}}{\to} U(1)_B \times U(1)_{L_i}$

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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 Flavon

The SM Flavor Puzzle

Matter fields come in 3 families
with same gauge quantum numbers

Accounts for most parameters of SM:
fermion masses and mixings that are
strongly hierarchical

$y_u \sim \epsilon^{7\div 8}$	$y_d \sim \epsilon^7$	$V_{ub} \sim \epsilon^3$
$y_c \sim \epsilon^{3\div 4}$	$y_s \sim \epsilon^5$	$V_{cb} \sim \epsilon^2$
$y_t \sim 1$	$y_b \sim \epsilon^3$	$V_{us} \sim \epsilon$

$\epsilon \approx 0.2$

Why are these numbers so small ?

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

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

from G selection rules

O(1) coefficients

cutoff scale

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

U(1) Flavor Symmetries

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

U(1) selection rule gives sum of charges

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

Simple pattern can reproduce all hierarchies, e.g.

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

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

$\epsilon \approx 0.2$

U(1) Flavor Symmetries

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]

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

↑ QCD anomaly coefficient

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

↑ EM anomaly coefficient

Predictivity of Flavor Symmetries

All BSM effects suppressed by messenger scale

$$\mathcal{L}_{eff} \sim \frac{1}{\Lambda_F^2} \left(\frac{\phi}{\Lambda_F} \right)^{y_{ij}} \left(\overline{q}_i \gamma^\mu q_j \right)^2 + \ldots$$

Overall cutoff scale/symmetry breaking scale is not determined, since explain *dimensionless* Yukawa couplings

No measurable effects if very large messenger scale: need to combine with new low-energy dynamics

The Axiflavon

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 [but O(1) uncertainties]

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

see also 1612.05492

Setup

Effective U(1) flavor model

$$\mathcal{L} \sim a^u_{ij} \left(\frac{\Phi}{\Lambda}\right)^{q_i+u_j} Q_i U^c_j H + \dots$$

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

$V_\Phi \sim f_a \gg v$

decouples

axion

SM Yukawas

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

axion-fermion couplings

$$g_{af_if_j} \sim \frac{v}{V_\Phi} y_{ij}$$

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

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

Photon couplings

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

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

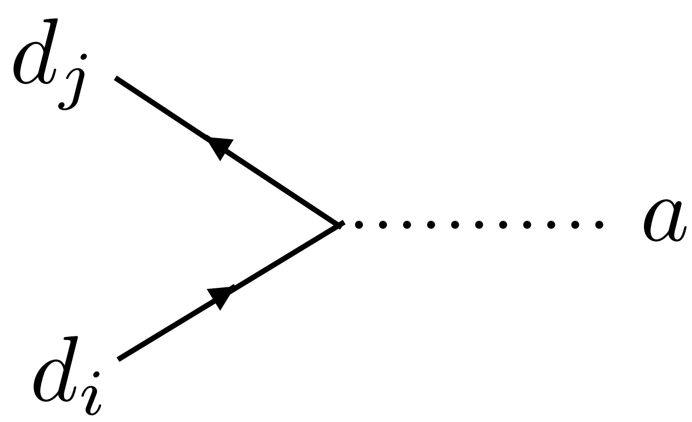
Direct consequence of fermion mass hierarchies

$$\frac{E}{N} = \frac{8}{3} - 2\,\frac{\overbrace{\log \frac{\det m_d}{\det m_e}}^{-0.4} - \overbrace{\log \alpha_{de}}^{\sim 0}}{\underbrace{\log \frac{\det m_u \det m_d}{v^6}}_{-44} - \underbrace{\log \alpha_{ud}}_{\sim 0}}$$

2.7

Fermion couplings

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



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

Axiflavon essentially massless [< meV] and stable

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

Probing the Axiflavon

Kaon Sector

$$\mathrm{BR}(K^+ \to \pi^+ a) \simeq 1.2 \cdot 10^{-10} \left(\frac{m_a}{0.1\,\mathrm{meV}}\right)^2 \underbrace{\left(\frac{\kappa_{sd}}{N}\right)^2}_{\mathcal{O}(1)}$$

90% CL combined bound from E787 + E949

$$\mathrm{BR}(K^+ \to \pi^+ a) < 7.3 \cdot 10^{-11}$$

$\Rightarrow$ $m_a \lesssim 0.08\,\mathrm{meV}$

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

Expected improvement for NA62 is factor ~70

will probe up to $m_a \sim 9\,\mu\mathrm{eV}$

Summary Plot