Extra-dimensional Axions:

Axion Quality & Phenomenology

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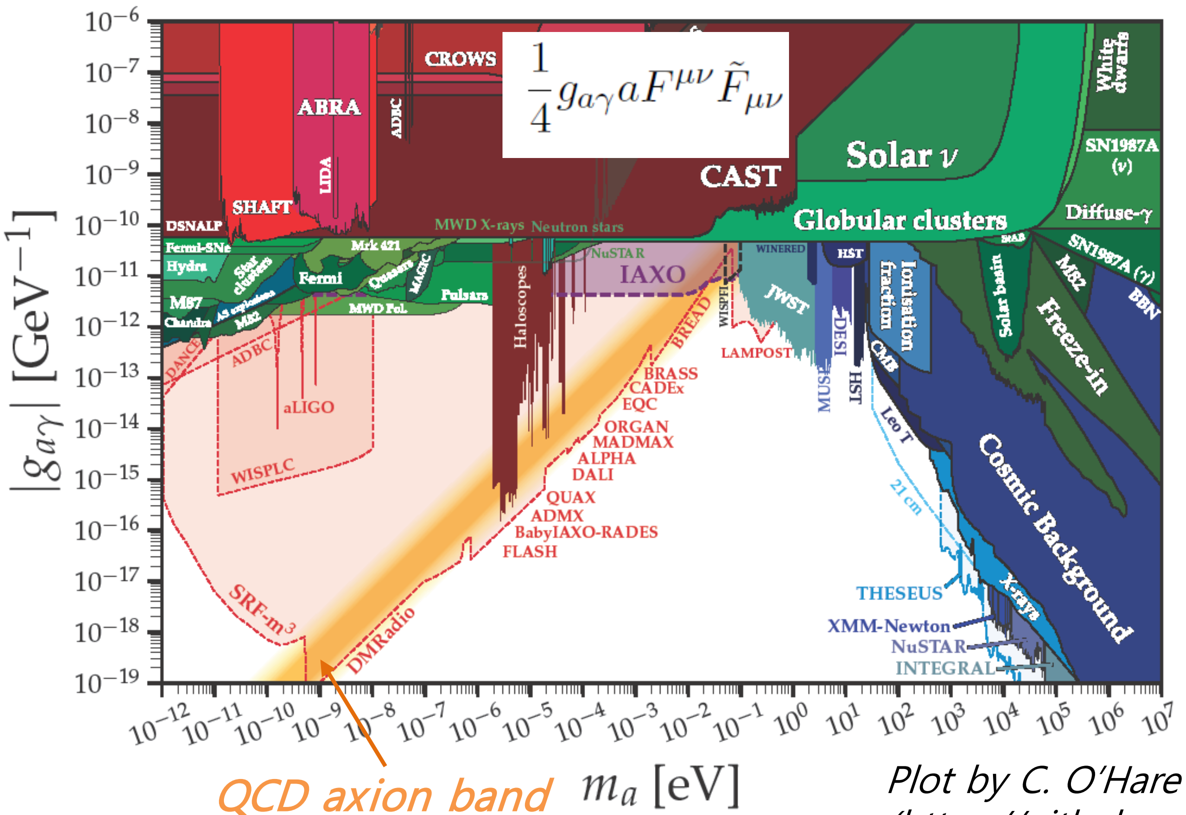
Axions are light pseudo-scalar bosons motivated by various considerations in particle physics and cosmology, notably as a solution to the strong CP problem and as a candidate for dark matter.

Axions also arise naturally in string theory, which is widely regarded as the leading theoretical framework unifying the SM of particle physics with quantum gravity.

Various laboratory experiments have been proposed or employed to search for axions, as well as astrophysical and cosmological probes, which may be able to detect axions in the foreseeable future.

Experimental Probes of the Axion–Photon Coupling
(Present Constraints and Future Reach)

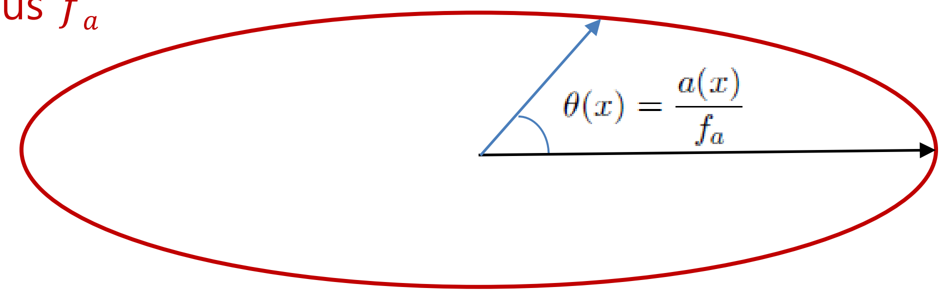


Plot by C. O'Hare
(https://github.com/cajohare)

Axions are described by an angular field variable, so characterized by a mass scale f_a called the axion decay constant or the axion scale defining the radius of the circular field space:

Circular axion field space
with radius f_a

$$a(x) \cong a(x) + 2\pi f_a$$



Angular nature of the axion field implies that axion couplings are suppressed by $1/f_a^N$ (N = # of the involved axions).

Two types of axions

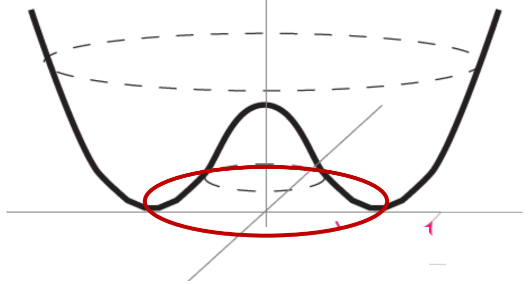
Field-theoretic axion (FTA) from the phase of complex scalar fields (either elementary or composite)

Peccei & Quinn '77; Weinberg '78; Wilczek '78

KSVZ '79-80, DFSZ '80-81, Composite '85, ...

$$\sigma(x) = \rho(x) e^{ia(x)/f_a}$$

$$\left(\frac{f_a}{\sqrt{2}} = \langle \rho \rangle \right)$$



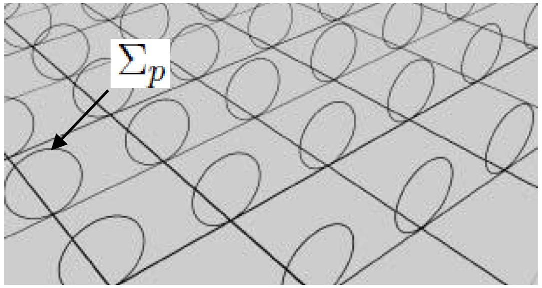
Extra-dimensional axion (EDA) from a higher-dim (p-form valued) gauge field C_p on compact internal space involving a closed p-dim surface Σ_p, e.g. string-theoretic axions:

Witten '84; KC & Kim '85; Barr '85, ...

Svrcek & Witten '06; ....

$$e^{i \int_{\Sigma_p} C_p} = e^{ia(x)/f_a}$$

$$\left(C_p = \frac{1}{p!} C_{[M_1 M_2 \dots M_p]} \, dx^{M_1} \wedge dx^{M_2} \dots \wedge dx^{M_p} \right)$$



For each axion, one can consider the associated global Peccei-Quinn (PQ) U(1) symmetry non-linearly realized in low energy limit (<< f_a) as

$$U(1)_{\rm PQ}: \quad \frac{a(x)}{f_a} \to \frac{a(x)}{f_a} + \alpha \quad (\alpha = \text{constant})$$

FTA & EDA have different UV realization of the PQ symmetry:

* FTA: $\sigma(x) = \rho(x) e^{ia(x)/f_a} \ \left(\frac{f_a}{\sqrt{2}} = \langle\rho\rangle\right)$

$$U(1)_{\rm PQ}: \quad \Phi_i \to e^{iq_i\alpha}\Phi_i \quad \left(q_i \in \mathbb{Z}\right)$$

(Linearly realized phase rotation)

* EDA: $e^{i\int_{\Sigma_p} C_p} = e^{ia(x)/f_a}$

$$U(1)_{\rm PQ}: \quad C_p \to C_p + \alpha\omega_p \quad \left(\int_{\Sigma_p} \omega_p = 1\right)$$

(Higher-dim p-form symmetry generated by a harmonic p-form ω_p associated with the p-dim surface Σ_p)

Due to their different UV realizations of the PQ symmetry, FTA and EDA can exhibit very different cosmological evolutions.

Axion couplings to the SM fields at scales below f_a (but above the weak scale):

Georgi, Kaplan, Randall '86

$$\mathcal{L}_{\text{eff}}(v_{\text{EW}} < \mu < f_a) = \frac{1}{32\pi^2}\frac{a}{f_a}\left(c_G G^{a\mu\nu}\tilde{G}^a_{\mu\nu} + c_W W^{i\mu\nu}\tilde{W}^i_{\mu\nu} + c_B B^{\mu\nu}\tilde{B}_{\mu\nu}\right)$$

$$\left(c_{G,W} \in \mathbb{Z},\ c_B \in \mathbb{Q}\ \text{ for }\ \{G^a_{\mu\nu}, W^i_{\mu\nu}, B_{\mu\nu}\} \in SU(3)_c \times SU(2)_W \times U(1)_Y\right)$$

$$+\frac{\partial_\mu a}{f_a}\sum_\psi c_\psi \bar{\psi}\sigma^\mu \psi + \ldots$$

$$\left(c_\psi \in \mathbb{R}\ \text{ for }\ \psi = q_i, u^c_i, d^c_i, \ell_i, e^c_i\right)$$

The QCD axion, a particular type of axion whose PQ symmetry is broken predominantly by the low energy QCD anomaly, offers a compelling solution to the strong CP problem and simultaneously provides an attractive candidate for dark matter. Preskill, Wise, Wilczek '83; Abbott, Sikivie '83; Dine, Fischler '83

Strong CP problem

$$\mathcal{L}_{\rm QCD} \ni (\bar{q}_L M_q q_R + {\rm h.c}) + \frac{1}{32\pi^2}\theta_{\rm QCD} G^{a\mu\nu}\tilde{G}^a_{\mu\nu}$$

$$\Rightarrow \quad d_n \sim 10^{-16}\,\bar{\theta}\,e\cdot{\rm cm} \quad \left(\bar{\theta} = \theta_{\rm QCD} + \arg({\rm Det}(M_q))\right)$$

$$|d_n| < 10^{-26}\,e\cdot{\rm cm} \quad \Rightarrow \quad |\bar{\theta}| < 10^{-10}$$

Why is this CP angle combination so small?

Axion solution

Peccei & Quinn '77; Weinberg '78; Wilczek '78

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm QCD} + \frac{1}{2}\partial_\mu a \partial^\mu a + c_G \frac{1}{32\pi^2}\frac{a}{f_a} G^{a\mu\nu}\tilde{G}^a_{\mu\nu} + \Delta\mathcal{L}$$

$$\left(U(1)_{\rm PQ}: \ a \to a + {\rm constant}\right)$$

PQ-breaking by QCD anomaly with $c_G \in \mathbb{Z}$
(necessary to solve the strong CP problem)

Additional PQ-breaking non-derivative axion interactions

$$\Rightarrow \quad d_n \sim 10^{-16}\,\theta_{\rm eff}\, e\cdot{\rm cm}$$

$$\left(\theta_{\rm eff} = \bar\theta + c_G\frac{\langle a\rangle}{f_a}\right)$$

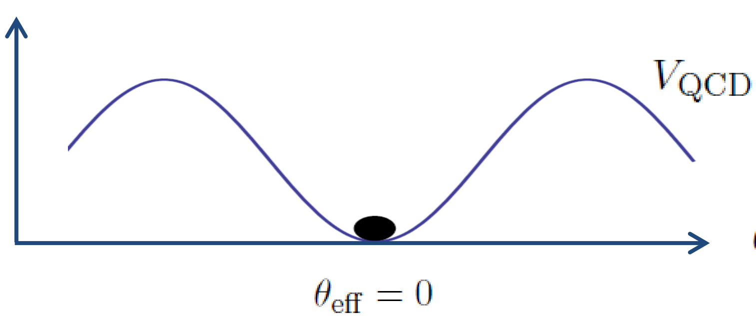
Bias axion potential

$$V_{\rm axion} = V_{\rm QCD} + \Delta V$$

$$\left(V_{\rm QCD}(a) \sim -m_\pi^2 f_\pi^2 \cos\left(\bar\theta + c_G\frac{a}{f_a}\right)\right)$$

QCD axion potential

Original proposal simply assumes that the bias potential is negligible, yielding $\theta_{\rm eff} = 0$ obtained by minimizing the QCD axion potential:

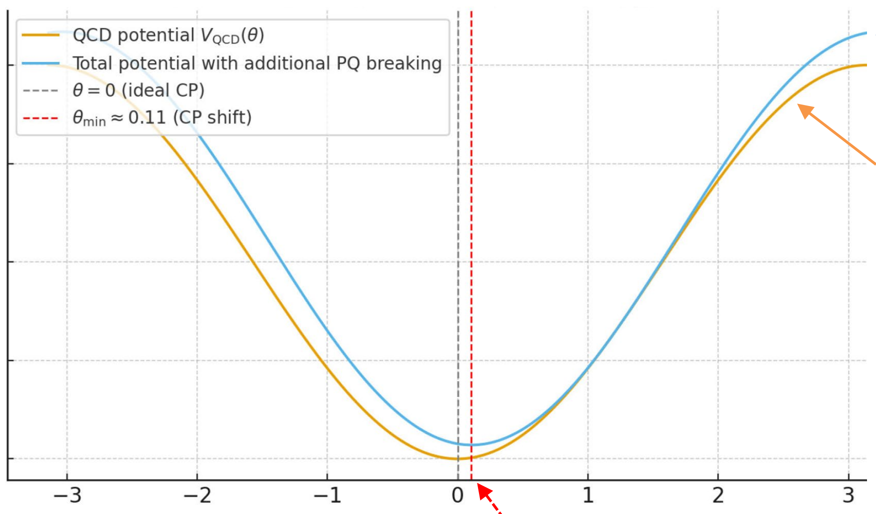


Axion quality problem

From a modern perspective, such an assumption requires justification, particularly in view of the fact that global symmetries are generically expected to be broken by quantum-gravity effects. Barr, Seckel '92; Holman et al '92; Kamionkowski, March-Russell '92

Bias potential induced by short-distance non-QCD PQ-breaking effects such as quantum gravity effects:

$$\Delta V(a) = \Lambda_{\rm UV}^4 \cos\left(\frac{a}{f_a} + \delta_{\rm UV}\right)$$



Total axion potential $V_{\rm axion}$ including the bias potential ΔV induced by short-distance non-QCD PQ-breaking

QCD axion potential $V_{\rm QCD}$ induced by the PQ-breaking long-distance QCD effects

$$\theta_{\rm eff} = \bar{\theta} + c_G \frac{\langle a \rangle}{f_a} \sim \frac{\Delta V}{V_{\rm QCD}} \sim \frac{\Lambda_{\rm UV}^4}{m_\pi^2 f_\pi^2}$$

To solve the strong CP problem without fine-tuning, the short-distance non-QCD contribution to the axion potential must be suppressed relative to the QCD potential by at least 10^{-10} :

$$\frac{\Delta V}{V_{\rm QCD}} < 10^{-10}$$

This is in sharp contrast with the expectation from simple dimensional analysis, raising a question:

"What underlying feature of the theory suppresses all UV PQ-breaking effects sufficiently to ensure that PQ symmetry breaking is dominated by the low-energy QCD anomaly?"

Extra-dim axions (EDA) provide a robust solution to the axion quality problem. KC '03; Reece '24; Craig & Kongsore '24

For EDA, $U(1)_{PQ}$ is locally equivalent to a higher-dim gauge symmetry in the limit where charged objects coupled to the p-form gauge field C_p are integrated out.

* Higher-dim gauge symmetry:

$$U(1)_C: \quad C_p \to C_p + d\Lambda_{p-1} \quad \left(\int_{\Sigma_p} d\Lambda_{p-1} = 0\right)$$

* PQ symmetry as a higher-dim p-form symmetry:

$$U(1)_{\rm PQ}: \quad C_p \to C_p + \alpha\omega_p \quad \left(\int_{\Sigma_p} \omega_p = 1\right)$$

$\alpha\omega_p = d\Lambda_{p-1}$ (locally, but not globally)

➔ Low-energy PQ breaking arises from ***nonlocal effects*** mediated by $U(1)_C$-charged (p-1)-branes coupled to C_p , and is exponentially suppressed when the charged branes are heavier than the extra-dimensional scale set by the volume of the p-dim surface Σ_p .

Implication for the axion quality problem

$$\frac{1}{g^2(M_{\rm GUT})} \propto {\rm Vol}(\Sigma_p)$$ for gauge fields coupled to EDA

$$\Rightarrow \quad V_{\rm QCD} \propto \Lambda_{\rm QCD}^3 \propto e^{-b/g^2_{\rm QCD}(M_{\rm GUT})} \propto e^{-\lambda {\rm Vol}(\Sigma_p)}$$

Bias axion potential generated by non-QCD effects including those of charged (p-1)-branes & other quantum gravity effects:

$$\Delta V \propto e^{-\lambda' {\rm Vol}(\Sigma_p)}$$

$$\Rightarrow \quad \frac{\Delta V}{V_{\rm QCD}} \propto e^{-(\lambda'-\lambda){\rm Vol}(\Sigma_p)}$$

In the regime where the charged branes are heavier than the extra-dim scale, the model-dependent coefficients λ, λ' can be parametrically larger than Vol(Σ_p), which results in a large exponential suppression of $\Delta V/V_{\rm QCD}$.

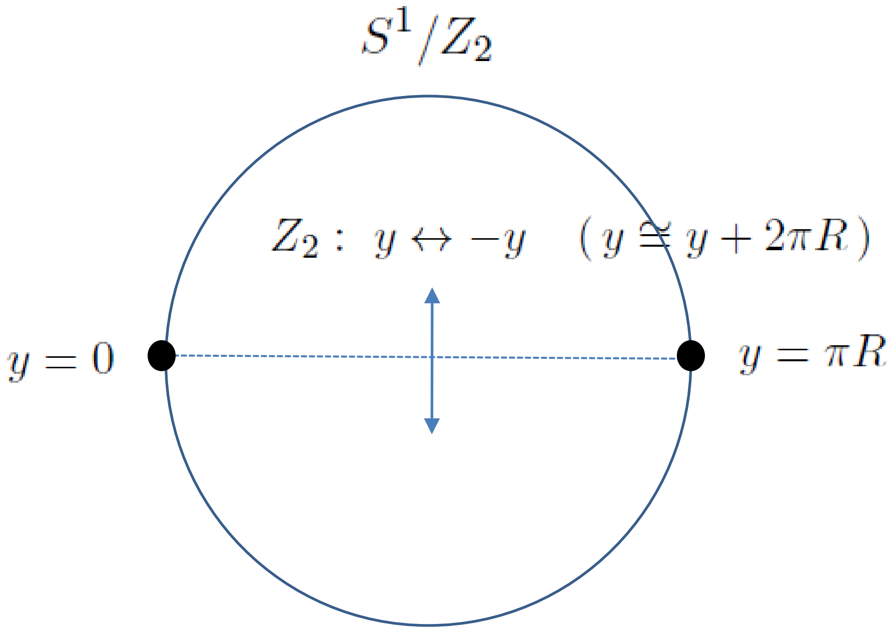
Some (more detailed & model-dependent) questions on the extra-dim axion quality:

KC, Lee, Shin arXiv:2604.08700

* Effects of singular structures in extra-dim such as branes, boundaries, or orbifold fixed points

* Effects of warped geometry

EDA from 1-form gauge field in 5-dim theory on warped $S^1/\mathbb{Z}_2$
(a slice of AdS_5)



$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2 \qquad (0 \leq y \leq \pi R)$$

Randall, Sundrum '99

$$\frac{a}{f_a} = \oint dy C_y \quad \left(C = C_\mu dx^\mu + C_y dy\right)$$

Charged matter-fields (0-branes) coupled to the 1-form gauge field, which are characterized by the 5-dim mass and appropriate Z_2 orbifold boundary conditions:

$*$ P-type mattter $\tilde{\Phi} = (\tilde{\phi}, \tilde{\psi})$ with 5-dim mass M, satisfying the orbifold BC

$$\tilde{\phi}(x,-y) = \eta_{\tilde{\phi}}\tilde{\phi}(x,y), \quad \tilde{\psi}(x,-y) = \eta_{\tilde{\psi}}\gamma^5\tilde{\psi}(x,y) \qquad (\eta_{\tilde{\phi},\tilde{\psi}} = \pm 1)$$

$*$ C-twisted matter $\Phi = (\phi, \psi)$ with 5-dim mass M, satisfying the orbifold BC

$$\phi(x,-y) = \eta_{\phi}\phi^*(x,y), \quad \psi(x,-y) = \eta_{\psi}\psi^c(x,y) \qquad (\eta_{\phi,\psi} = \pm 1)$$

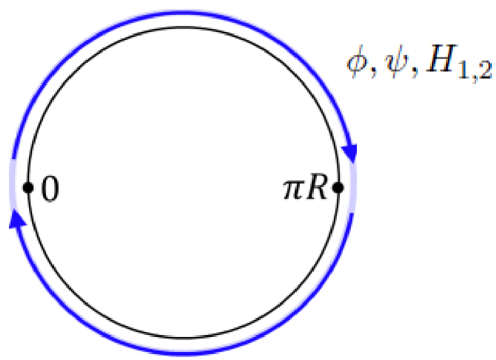
$*$ Hypermultiplet scalar $H_{1,2}$ with $\mathbb{Z}_2$-even mass M_0 and $\mathbb{Z}_2$-odd mass μ, satisfying the orbifold BC

$$H_1(x,-y) = H_2^*(x,y)$$

Bias axion potential induced by non-local effects mediated by charged matter fields (0-branes) coupled to the 1-form gauge field C:

KC, Lee, Shin arXiv:2604.08700

Worldline instanton of C-twisted matter wrapping the covering S[1] (Loop)



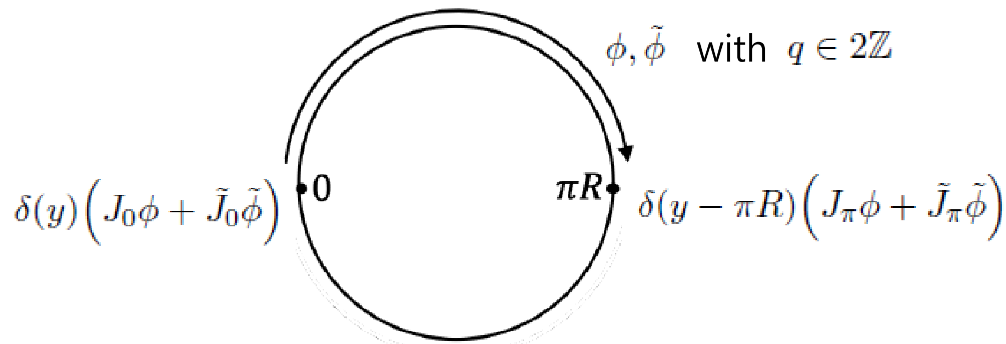
$$\Delta V \sim \frac{1}{4\pi^2} M^2 k^2 e^{-4k\pi R} e^{-2M_{\rm eff}\pi R} \cos(q\theta)$$

$$M_{\rm eff}(\phi) = \sqrt{M^2 + 4k^2}$$

$$M_{\rm eff}(\psi) = M$$

$$M_{\rm eff}(H_\alpha) = \frac{1}{2}(m_+ + m_-) \quad m_\pm = \sqrt{M_0^2 \pm \mu^2 + 4k^2}$$

Worldline instanton of P-type or C-twisted scalar stretched across the interval (Tree)



$$\Delta V \sim \Lambda^4_{\phi,\tilde{\phi}} e^{-2k\pi R} e^{-\pi R\sqrt{M^2+4k^2}} \cos(q\theta/2)$$

$$\Lambda^4_\phi = \frac{|J_0 J_\pi|}{M} \qquad \Lambda^4_{\tilde{\phi}} = \frac{|\tilde{J}_0 \tilde{J}_\pi|}{M}$$

Warping generically improves EDA quality through an additional suppression of short-distance non-QCD PQ-breaking effects.

Phenomenology: Low energy couplings of EDA

Axion couplings at scales below f_a , but above the weak scale:

$$\mathcal{L}_{\rm eff}(v_{\rm EW} < \mu < f_a) = \frac{1}{32\pi^2}\frac{a}{f_a}\left(c_G G^{a\mu\nu}\tilde{G}^a_{\mu\nu} + c_W W^{i\mu\nu}\tilde{W}^i_{\mu\nu} + c_B B^{\mu\nu}\tilde{B}_{\mu\nu}\right)$$

$$\left(c_{G,W} \in \mathbb{Z},\ c_B \in \mathbb{Q}\ \text{ for }\ \{G^a_{\mu\nu}, W^i_{\mu\nu}, B_{\mu\nu}\} \in SU(3)_c \times SU(2)_W \times U(1)_Y\right)$$

$$+\ \frac{\partial_\mu a}{f_a}\sum_\psi c_\psi \bar{\psi}\sigma^\mu\psi + \ldots$$

$$\left(c_\psi \in \mathbb{R}\ \text{ for }\ \psi = q_i, u^c_i, d^c_i, \ell_i, e^c_i\right)$$

Experimentally measurable couplings at the laboratory scale ~ m_a:

$$\frac{1}{4} g_{a\gamma} a \vec{E} \cdot \vec{B} + \partial_\mu a \left[\frac{g_{ae}}{2m_e} \bar{e} \gamma^\mu \gamma_5 e + \frac{g_{an}}{2m_n} \bar{n} \gamma^\mu \gamma_5 n + \frac{g_{ap}}{2m_p} \bar{p} \gamma^\mu \gamma_5 p \right]$$

For QCD axions solving the strong CP problem,

$$m_a \simeq 5.7 c_G \left(\frac{10^{12}\,\mathrm{GeV}}{f_a} \right) \mu\mathrm{eV}$$

$$g_{a\gamma} \simeq \frac{\alpha_{\rm em}}{\pi} \frac{1}{f_a} \left(c_B + c_W - 1.92 c_G \right)$$

$$g_{an} \simeq \frac{m_n}{f_a} \left(0.9 C_d - 0.38 C_u - 0.04 c_G \right)$$

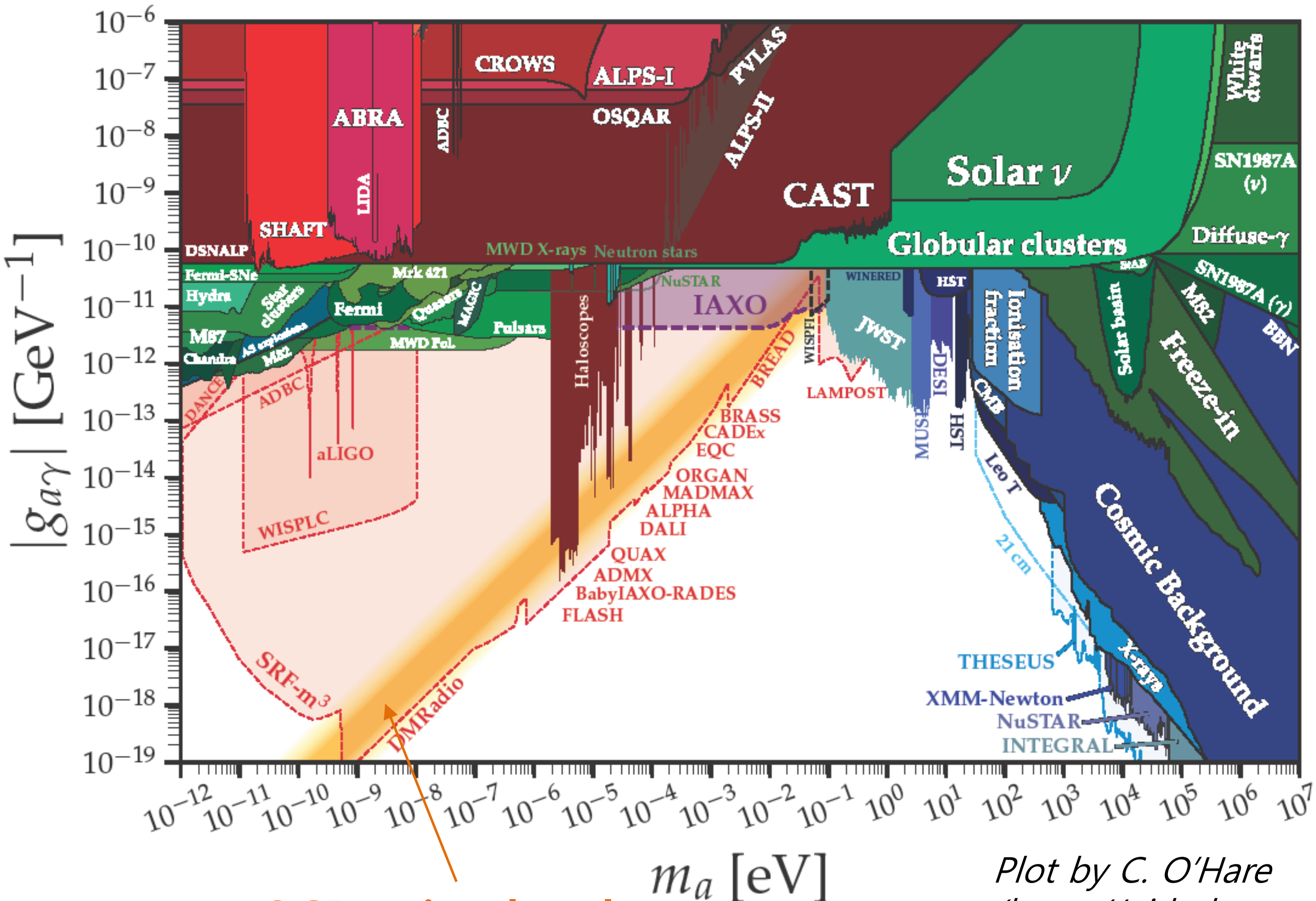
$$g_{ap} \simeq \frac{m_p}{f_a} \left(0.9 C_u - 0.38 C_d - 0.48 c_G \right)$$

$$g_{ae} \simeq \frac{m_e}{f_a} C_e$$

$$(C_u = c_q + c_{u^c} + \Delta C_u, \quad C_d = c_q + c_{d^c} + \Delta C_d, \quad C_e = c_\ell + c_{e^c} + \Delta C_e)$$

$$\Delta C_{u,d,e} = \text{radiative corrections}$$

Present status & future projection for experimental detection of $g_{a\gamma}$



QCD axion band

Plot by C. O'Hare (https://github.com/cajohare)

$$\frac{g_{a\gamma}}{m_a} \simeq \frac{\alpha_{\rm em}}{2\pi}\frac{R}{(75\,{\rm MeV})^2} \quad \left(R = \frac{c_B + c_W}{c_G} - 1.92 = \mathcal{O}(1)\right)$$

Benchmark models

* FTA: $U(1)_{\rm PQ}: \quad \Phi_i \to e^{iq_i\alpha}\Phi_i \quad \left(q_i \in \mathbb{Z}\right)$

$$\text{KSVZ-type}: \quad q_i = 0 \;\; \text{for the SM matter fields}$$

Kim '79; Shifman, Vainshtein, Zakharov '80

$$\text{DFSZ-type}: \quad q_i = \mathcal{O}(1) \;\; \text{for the SM matter fields}$$

Dine, Fischler, Srednicki '81; Zhitnitsky '81

* String-theoretic (Heterotic, Type I, IIA, IIB) EDA in
N=1 SUSY preserving compactifications such as Calabi-Yau, orbifolds, …

Witten '84; KC & Kim '85; Barr '85,…
Svrcek, Witten '06, …

* Distinctive high-scale axion couplings to the SM matter fields

KC, Im, Kim, Seong   arXiv:2106.05816

$$\text{KSVZ-type FTA :}\quad c_\psi(f_a) = 0 \qquad (\psi = \text{SM quarks and leptons})$$

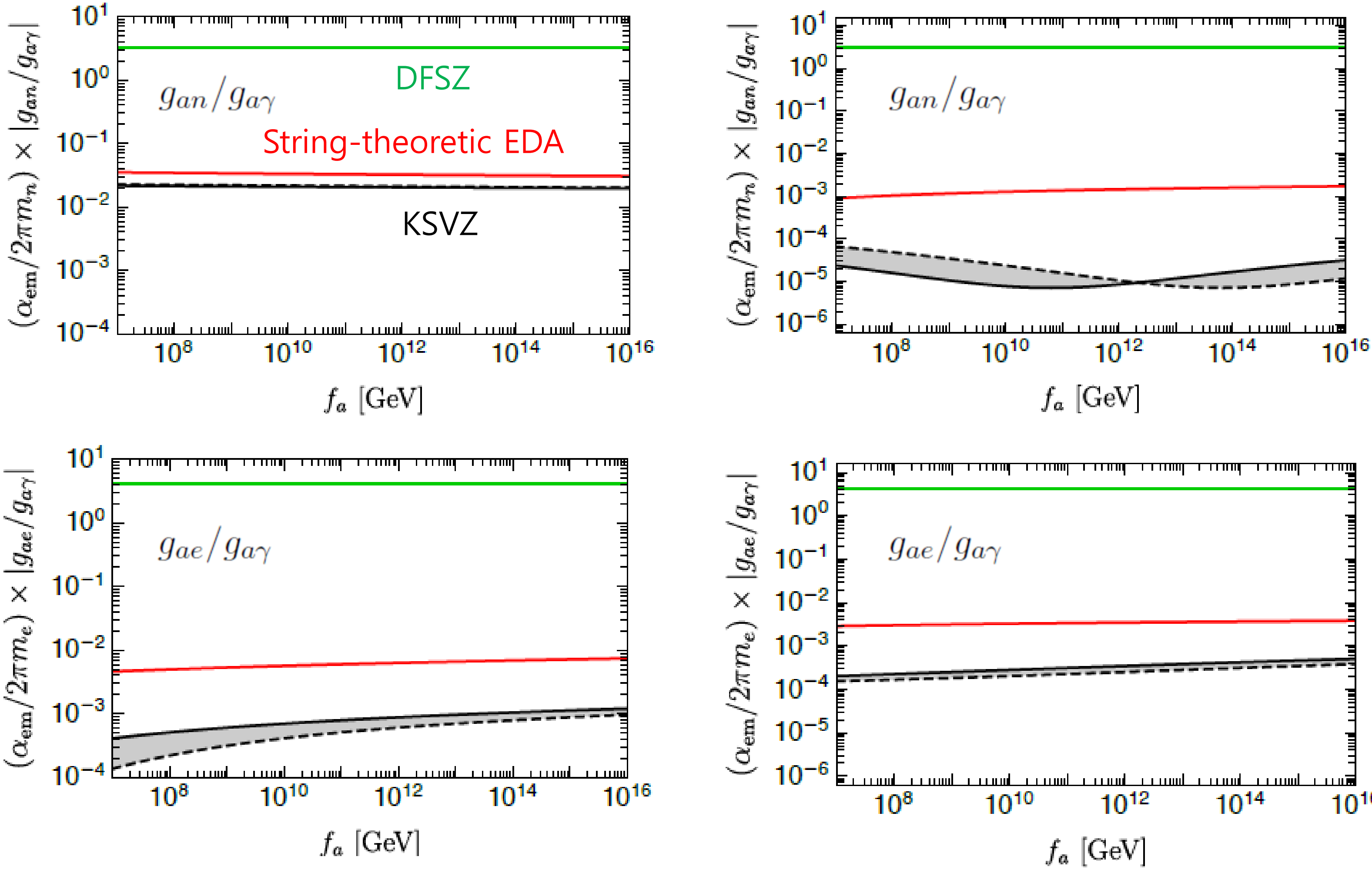
$$\text{DFSZ-type FTA :}\quad c_\psi(f_a) = \mathcal{O}(1)$$

$$\text{String-theoretic EDA :}\quad c_\psi(f_a) = \mathcal{O}\left(\frac{8\pi^2}{g_{\rm GUT}^2}\right) = \mathcal{O}(10^{-2})$$

This distinction may lead to observable differences in low-energy axion couplings, particularly in channels that are relatively insensitive to strong QCD effects:

QCD axion

Axion-like-particle w/o gluonic coupling



KC, Im, Kim, Seong arXiv:2106.05816

* Predictions for $\frac{g_{a\gamma}}{m_a} \simeq \frac{\alpha_{\rm em}}{2\pi} \frac{R}{(75\,{\rm MeV})^2} \quad \left(R = \frac{c_B + c_W}{c_G} - 1.92\right)$

$$\text{GUT FTA, Minimal non-SUSY DFSZ}: \; c_G = c_W = \frac{3}{5} = c_B \quad \Rightarrow \quad R \simeq 0.75$$

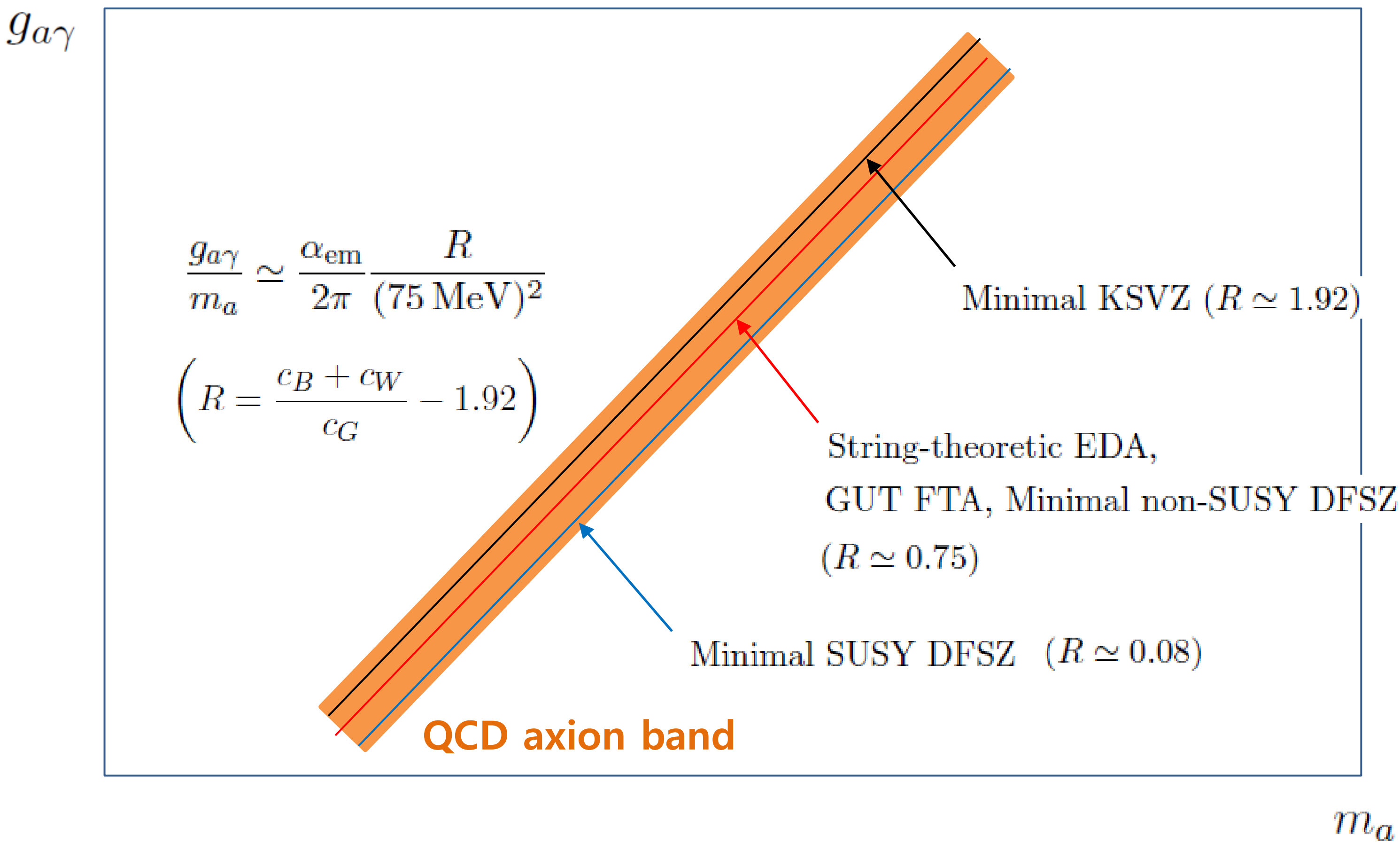
$$\text{Minimal KSVZ}: \; c_W = c_B = 0 \quad \Rightarrow \quad R \simeq -1.92$$

$$\text{Minimal SUSY DFSZ}: \; c_G = 6, \; c_W = 4, \; c_B = 8 \quad \Rightarrow \quad R \simeq 0.08$$

String-theoretic EDA :

$$\left(\frac{g_3^2}{g_2^2}\right)_{M_{\rm GUT}} \simeq \frac{c_W}{c_G}, \quad \left(\frac{g_2^2}{g_1^2}\right)_{M_{\rm GUT}} \simeq \frac{c_B}{c_W} \quad \Rightarrow \quad R \simeq 0.75 \pm \mathcal{O}\Big(\frac{1}{4} - \frac{1}{20}\Big)$$

(This result for EDA holds regardless of whether the SM gauge group is embedded in a simple GUT group at $M_{\rm GUT}$.)



$g_{a\gamma}$
$\frac{g_{a\gamma}}{m_a} \simeq \frac{\alpha_{\rm em}}{2\pi}\frac{R}{(75\,{\rm MeV})^2}$
$\left(R = \frac{c_B + c_W}{c_G} - 1.92\right)$
Minimal KSVZ ($R \simeq 1.92$)
String-theoretic EDA,
GUT FTA, Minimal non-SUSY DFSZ
($R \simeq 0.75$)
Minimal SUSY DFSZ ($R \simeq 0.08$)
QCD axion band
m_a

Conclusion

Extra-dimensional axions provide a particularly robust solution to the axion quality problem associated with the QCD axion, while arising naturally in string theory.

Warping generically improves extra-dimensional axion quality through additional suppression of short-distance non-QCD PQ-breaking effects.

Extra-dimensional axions predict distinctive patterns of low-energy couplings, potentially distinguishable from field-theoretic axions in future axion experiments.