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Patterns of Axion Couplings and Experimental Tests

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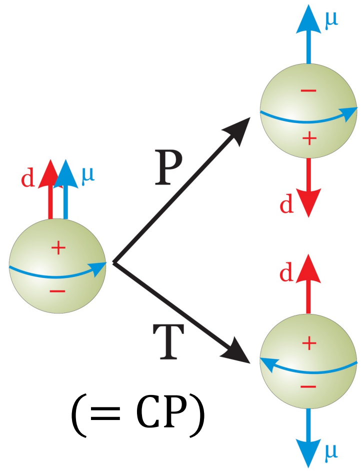
Quantum Chromodynamics (QCD) Axion

Motivated by non-observation of the electric dipole moment (EDM) of nucleons : "the strong CP problem"



$$\frac{\alpha_s}{4\pi}\theta_{\rm QCD} G^{\mu\nu}\widetilde{G}_{\mu\nu}$$ QCD θ-term (P, T-violating)

predicts a non-zero neutron EDM

$$d_n \simeq 2.4 \times 10^{-16} \theta_{\rm QCD}\, e\,{\rm cm}$$

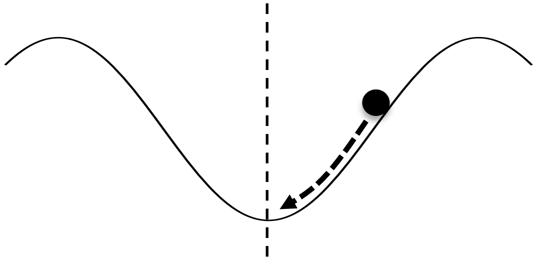
$$|d_n^{\rm exp}| < 1.8 \cdot 10^{-26}\ e\ {\rm cm}\ (90\%\ {\rm CL})$$

$|\theta_{QCD}| < 10^{-10}$ Why so small?

Promote θ_{QCD} to a dynamical field (= QCD axion)

$$\theta_{\rm QCD} \ \rightarrow \ \theta_{\rm QCD}(x) \equiv \frac{a(x)}{f_a}$$

[Peccei, Quinn '77, Weinberg '78, Wilczek '78]



$\langle \theta_{QCD} \rangle = 0$

Axion-Like Particles (ALPs)

New physics scenarios for the QCD axion can easily incorporate other "axion-like particles" which do not participate in solving the strong CP problem.

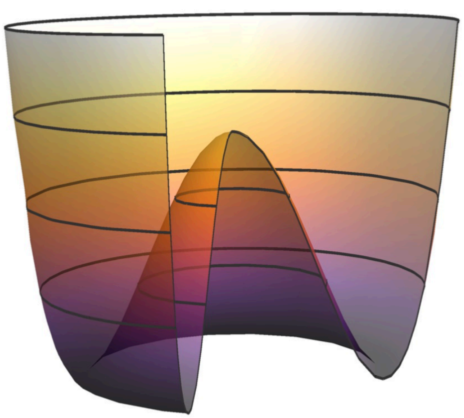
Candidates :

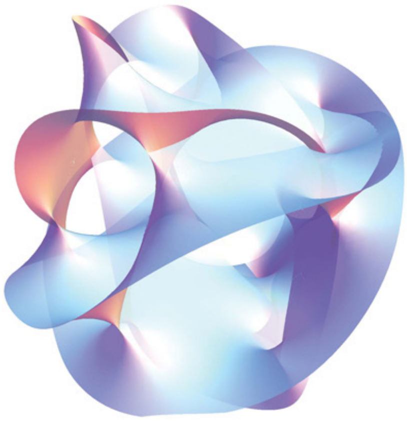
- Pseudo Nambu-Goldstone bosons in field theory
- Zero modes of higher-dimensional gauge fields in string theory

"string axiverse" [Arvanitaki, Dimopoulos, Dubovsky, Kaloper, Marsh-Russell, '09]

$$\Phi(x) = \rho(x) e^{i\theta(x)}$$

$$A_{[m_1 \ldots m_p]}(x^\mu, y^m) = \theta(x) \omega_{[m_1 \ldots m_p]}(y)$$





Effective Field Theory of Axions and ALPs

$$\frac{1}{2}f_a^2\partial^\mu\theta\partial_\mu\theta - V(\theta) + \theta\sum_A \frac{g_A^2}{32\pi^2}c_A A^{\mu\nu}\widetilde{A}_{\mu\nu} + \partial_\mu\theta\sum_f c_f f^\dagger\bar{\sigma}^\mu f$$

i) Periodicity $\theta(x) \equiv \theta(x) + 2\pi$

- $V(\theta)$ is a periodic potential.
- c_A has to be an integer number, while c_f does not have to.

ii) Global $U(1)$ *softly* broken by $V(\theta)$ $\theta(x) \to \theta(x) + \alpha$

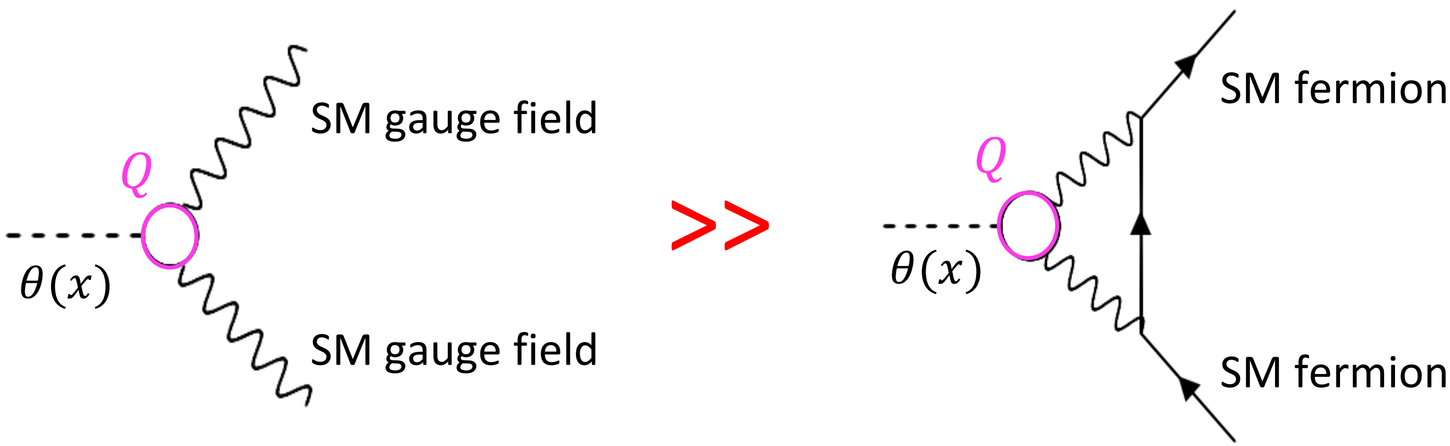
- It allows a naturally small mass for $\theta(x)$.

KSVZ axion

Kim '79, Shifman, Vainshtein, Zakharov '80

The axion couples to SM particles via a heavy BSM fermion Q which carries SM gauge charges.

$$y\Phi Q Q^c \qquad \Phi(x) = \frac{1}{\sqrt{2}}\rho(x)e^{i\theta(x)}$$



$\sim \dfrac{g_A^2}{16\pi^2}\times$ $c_A = 2\mathrm{tr}\left(T_A^2(Q)\right)$ Dynkin index

: $O(1)$ integer number

$$c_f = c_A \cdot O\left(\frac{g_A^2}{16\pi^2}\right)^2$$

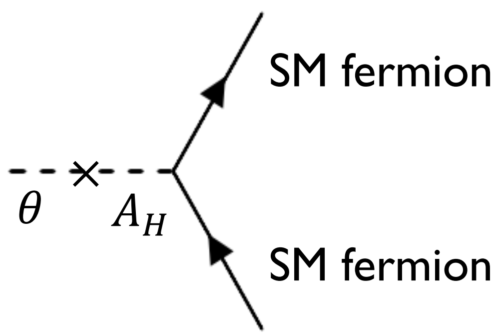
DFSZ axion

Dine, Fischler, Srednicki '81, Zhitnitsky '80

The axion couples to SM particles through the Higgs portal.

$$y_u u_R^c Q_L H_u + y_d d_R^c Q_L H_d + y_e e_R^c L H_d + \lambda \Phi^2 H_u H_d + \text{h.c.}$$

$$\Phi(x) = \frac{1}{\sqrt{2}} \rho(x) e^{i\theta(x)}$$



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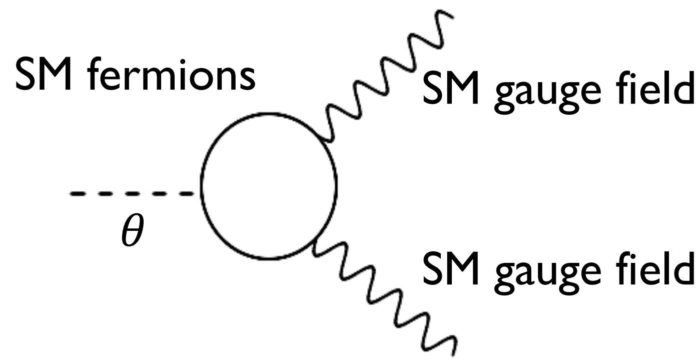


$c_f = O(1)$ real number

$\sim \frac{g_A^2}{16\pi^2} \times$

$c_g = 6,$	$O(1\sim10)$
$c_\gamma = 16$	integer numbers

Axions from string theory or extra dimensions

4D axions from p-form gauge fields — Witten '84

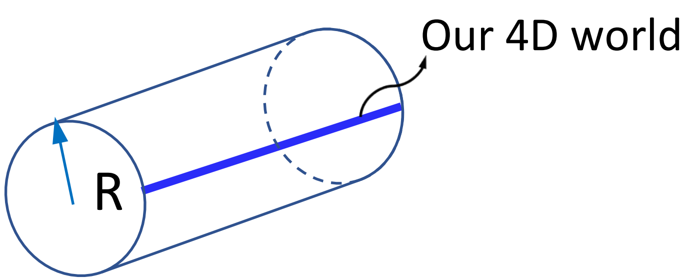
$$A_{[m_1 m_2 .. m_p]}(x^\mu, y^m) = \theta(x^\mu)\Omega_{[m_1 m_2 .. m_p]}(y^m)$$

Ω : zero mode wavefunction over the extra dimensional space

$$\epsilon_{\mu\nu\rho\sigma}\partial^\nu B^{\rho\sigma}(x) = \partial_\mu \theta(x)$$

Axion from 2-form field

- 5D toy example



Compact extra dimension

$$A_M(x^\mu, y) \qquad M = 0, 1, 2, 3, 5$$

$$\Rightarrow \quad A_5(x^\mu, y) = \theta(x^\mu)\Omega_5(y)$$

$$F_{MN} = \partial_M A_N - \partial_N A_M$$

M_5: 5D Planck mass (String scale)

$$S = \int d^5x \sqrt{-g} \left(-\frac{1}{4g_5^2} F^{MN} F_{MN} + c_1 \frac{\epsilon^{MNPQR}}{\sqrt{-g}} A_M G^a_{NP} G^a_{QR} + \frac{c_2}{M_5} F_{MN} \bar{\Psi} \gamma^M \gamma^N \Psi + \cdots \right)$$

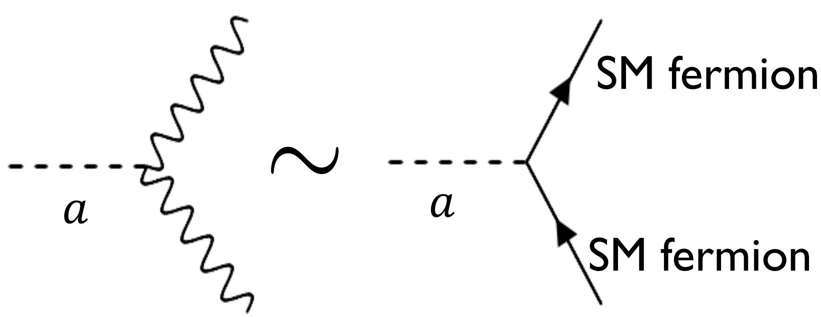
5D Chern-Simon term (axion-gauge field coupling)

5D gauge-matter coupling (axion-matter coupling)

$c_1 \sim c_2 \sim O(1)$

Integrating out the extra dimension

$$S_{\rm eff} = \int d^4x \left(-\frac{1}{4g^2} F^{\mu\nu} F_{\mu\nu} + \frac{1}{2} g^2 M_5^2 \partial^\mu \theta \partial_\mu \theta + c_1 \theta G^{a\mu\nu} \widetilde{G}^a_{\mu\nu} + c_2 g^2 \partial_\mu \theta \bar{\Psi} \gamma^\mu \gamma^5 \Psi + \cdots \right)$$

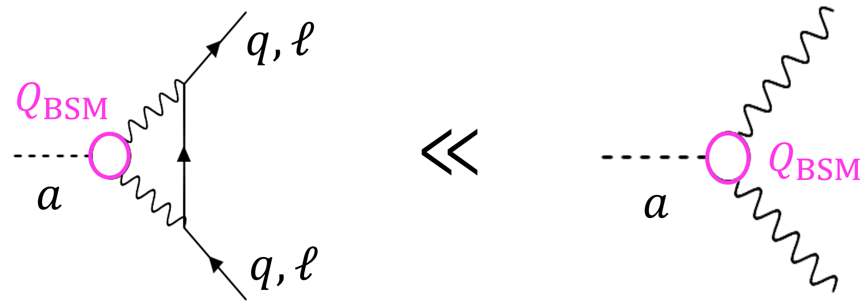


Comparable!

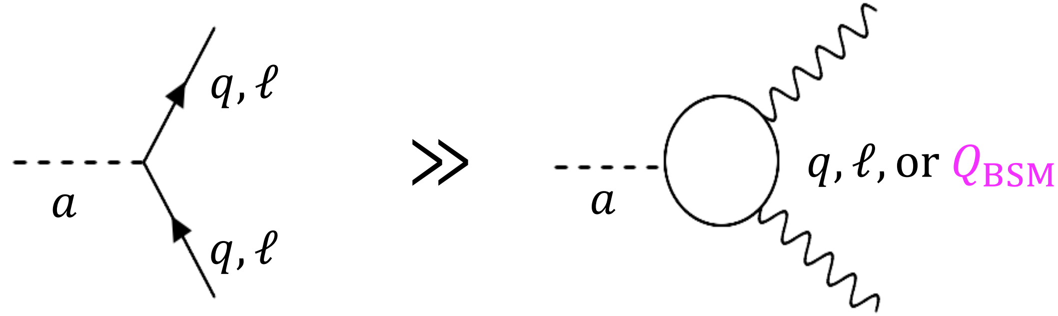
K Choi, SHI, HeeJung Kim, H Seong, '21

Characteristic patterns of axion couplings to the SM depending on the UV origins

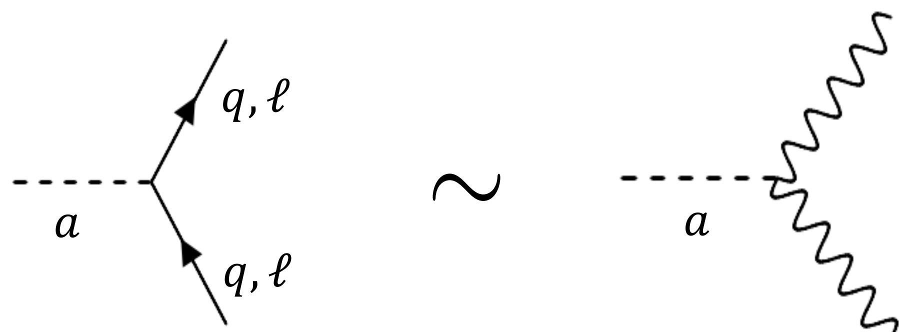
KSVZ-type axions



DFSZ-type axions



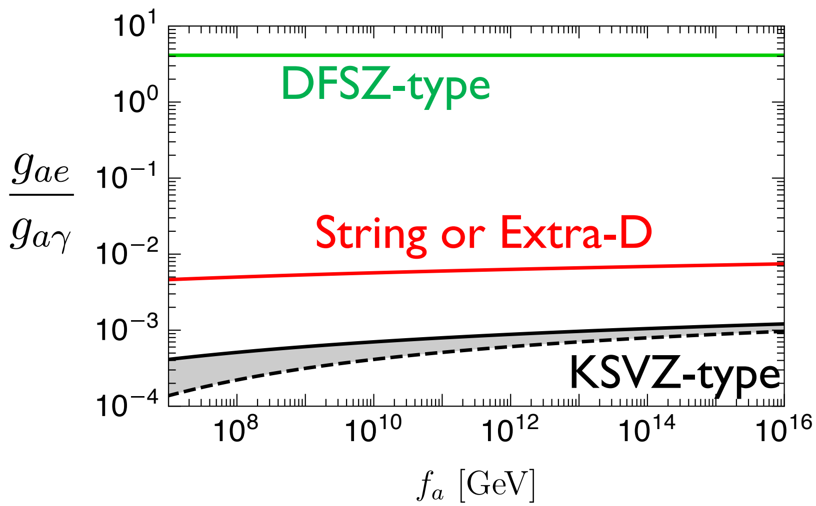
String or Extra-D axions



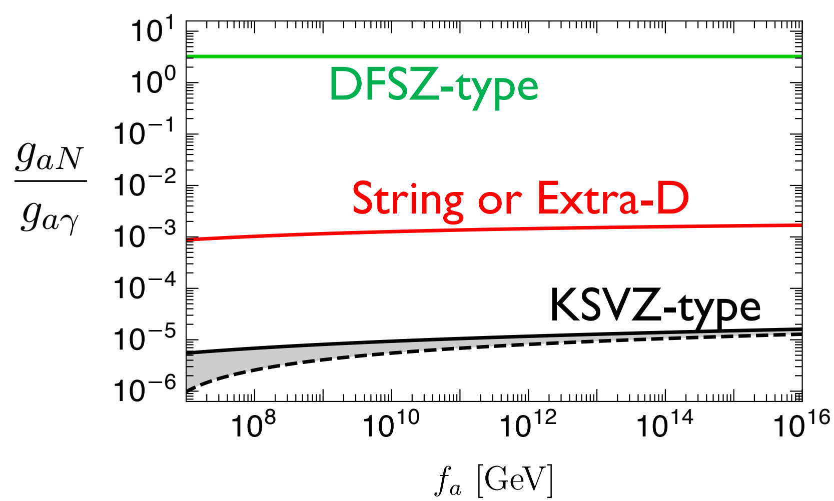
Low energy imprint of string theory or extra dimensions in axion couplings

K Choi, SHI, HeeJung Kim, H Seong, '21

- We have shown that the pattern of axion couplings is robust against quantum corrections.
- For QCD axion, the axion-electron coupling is important to distinguish the three types of UV physics.

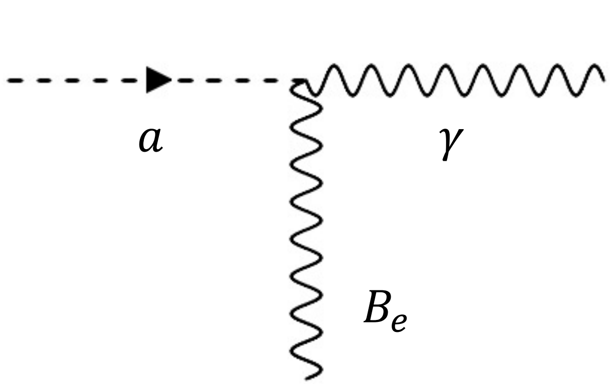


QCD axion and ALPs

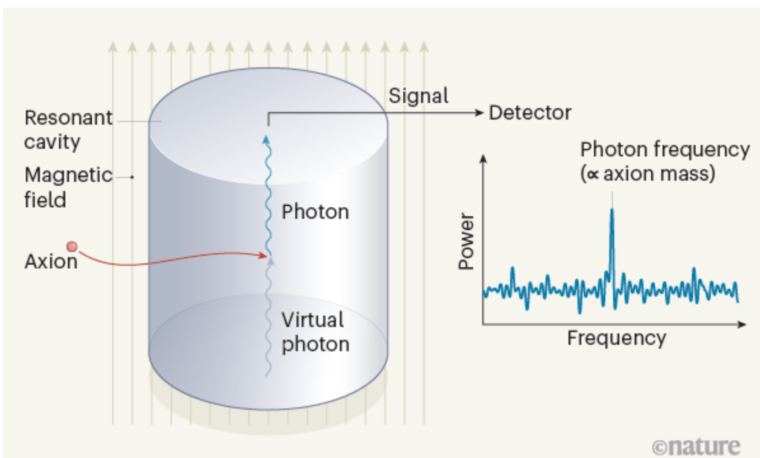


ALPs without a coupling to gluons

Experimental programs to detect axion dark matter

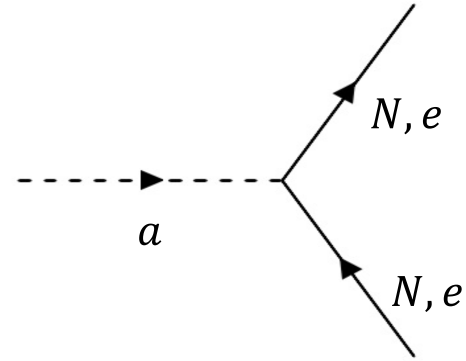


Axion-photon conversion

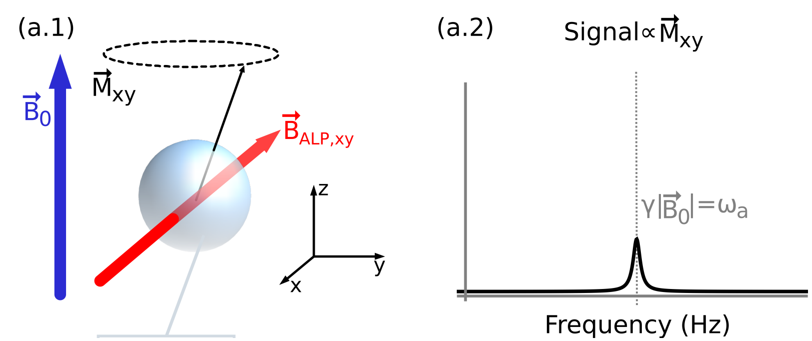


Microwave EM cavity

: ADMX(US), IBS-CAPP(Korea), QUAX(Italy), …



Axion-nucleon or electron spin interaction ($\nabla\theta \sim B_{\mathrm{eff}}$)



NMR technique

: CASPEr(US), QUAX(Italy)

Physical effects of the axion-electron coupling

$$c_e \partial_\mu \theta \bar{e} \gamma^\mu \gamma^5 e$$

Spatial components

$$\underbrace{c_e \nabla \theta}_{\vec{B}_{eff}} \cdot \bar{e} \vec{\sigma} e$$

Axion-induced small B-field
: QUAX experiment

Time component

$$c_e \dot{\theta} (e_R^\dagger e_R - e_L^\dagger e_L)$$

Axion-induced chiral chemical potential

$$\vec{p} \cdot \vec{\sigma} \rightarrow \vec{p} \cdot \vec{\sigma} - c_e \dot{\theta}$$

Momentum shift along the electron spin direction causing asymmetry between different helicity eigenstates

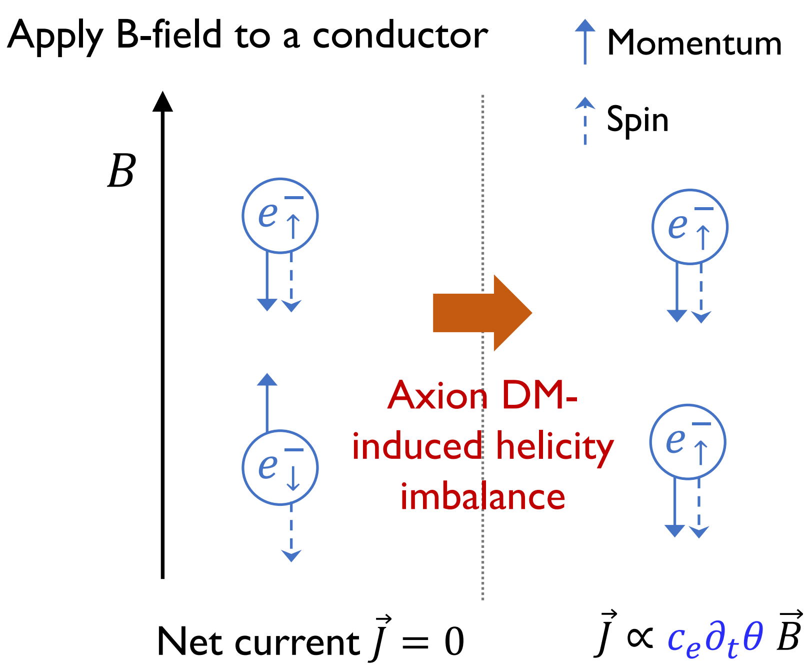
DK Hong, SHI, KS Jeong, D Yeom, '24

Nonrelativistic Chiral Magnetic Effect (CME)

DK Hong, SHI, KS Jeong, D Yeom, '24

Axion dark matter background gives a chiral chemical potential to electrons yielding helicity imbalance of electrons.

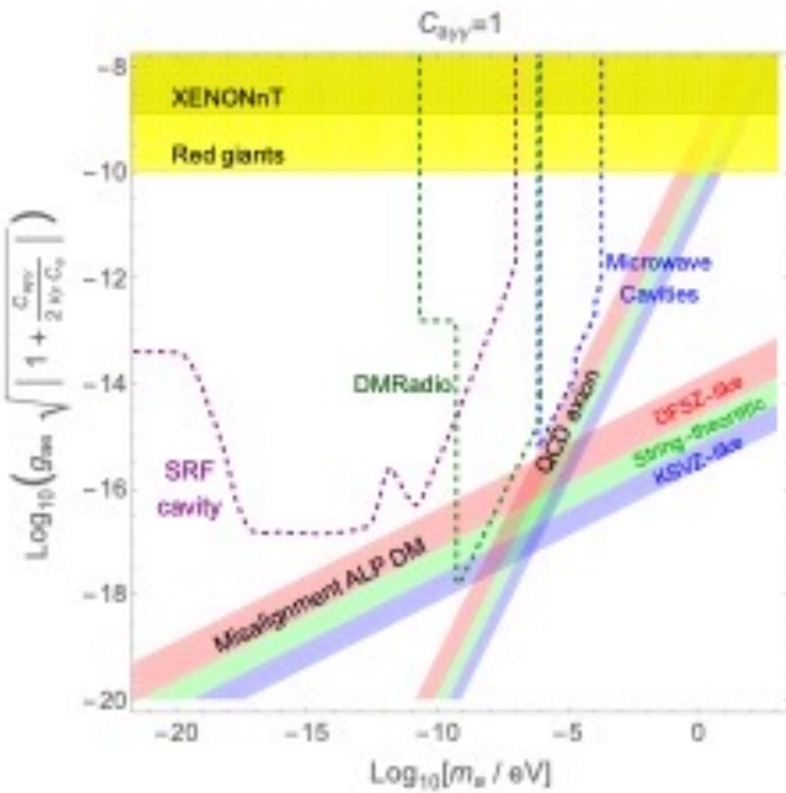
When the electrons are polarized (e.g. by an applied B-field), the helicity imbalance gives rise to an electric current along the polarized direction, called the "chiral magnetic effect" (Fukushima, Kharzeev, Warringa '08).

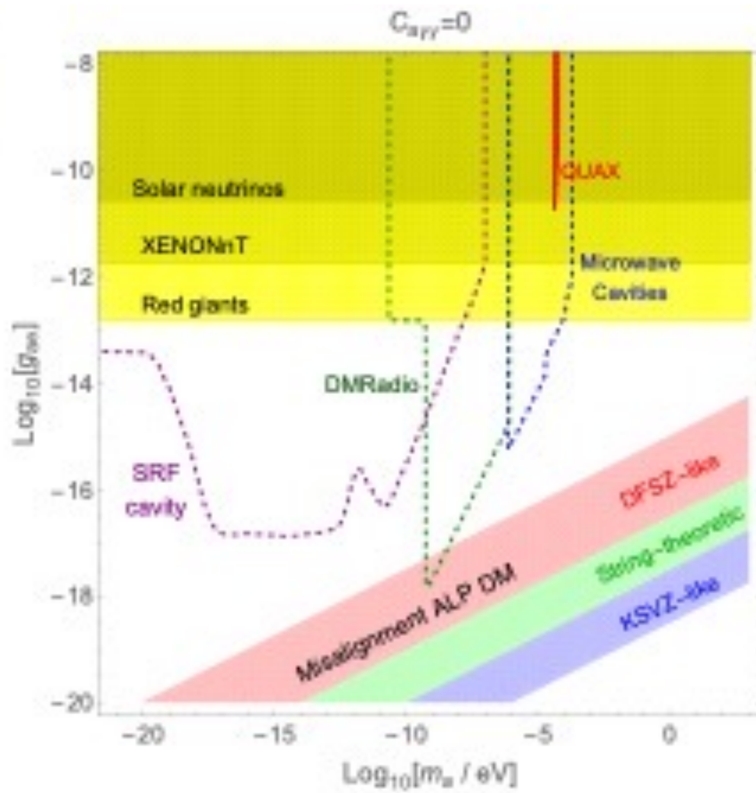


Precision measurements of the axion-electron coupling by CME

DK Hong, SHI, KS Jeong, D Yeom, '24

By repurposing the existing or planned axion haloscopes originally designed for probing the axion-photon coupling, we may be able to detect the axion DM-induced CME current!





Constraint on axion interactions from periodicity

Periodic nature of the axion field $\theta(x) \equiv \theta(x) + 2\pi$

Because of the periodicity, the axion interaction strengths are *quantized.*

e.g.) $\mathcal{L}_{\rm int} \supset c_g \theta(x) G^{\mu\nu}\tilde{G}_{\mu\nu} + c_\gamma \theta(x) F^{\mu\nu}\tilde{F}_{\mu\nu}$

Axion-gluon interaction Axion-photon interaction

$$c_g, c_\gamma \in \mathbb{Z}$$

➡ $$c_g \sim c_\gamma \sim \mathcal{O}(1)$$

unless there is a large integer number in the underlying fundamental theory.

Clockwork axion

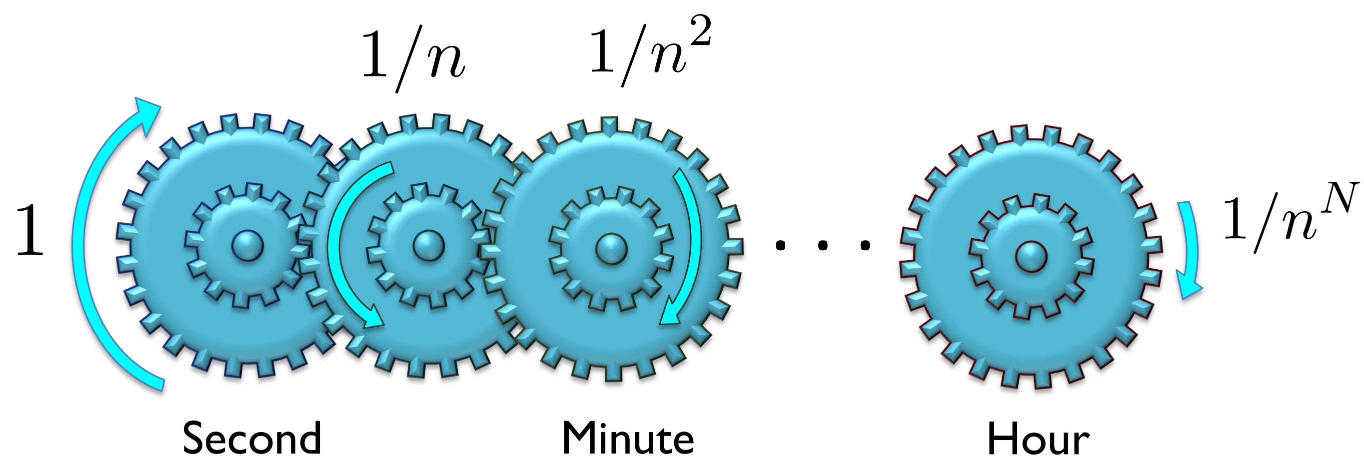
Choi, H Kim, S Yun '14
Choi, SHI '16
DE Kaplan, Rattazzi '16

Even without a large integer number in the fundamental theory, a large integer number can be generated if there are multiple axions interacting with each other in a particular way.

$n \in \mathbb{Z}$

$$\mathcal{H}(\theta_1, ..., \theta_N) = \Lambda_1^4 \cos(\theta_1 - n\theta_2) + \Lambda_2^4 \cos(\theta_2 - n\theta_3) + \cdots + \Lambda_{N-1}^4 \cos(\theta_{N-1} - n\theta_N)$$

Lightest mass eigenstate $\theta_L \propto \theta_1 + \frac{1}{n}\theta_2 + \frac{1}{n^2}\theta_3 + ... + \frac{1}{n^{N-1}}\theta_N$



Lightest mass eigenstate

$$\theta_L \propto \theta_1 + \frac{1}{n}\theta_2 + \frac{1}{n^2}\theta_3 + \ldots + \frac{1}{n^{N-1}}\theta_N$$

$$\mathcal{L}_{\rm int} \supset \theta_N(x) G^{\mu\nu}\tilde{G}_{\mu\nu} + \theta_1(x) F^{\mu\nu}\tilde{F}_{\mu\nu}$$
$$\simeq \frac{1}{n^N}\theta_L(x) G^{\mu\nu}\tilde{G}_{\mu\nu} + \theta_L(x) F^{\mu\nu}\tilde{F}_{\mu\nu}$$

$$\frac{c_\gamma}{c_g} \simeq n^N = e^{N \ln n}$$

N = number of axions
n = $O(1)$ integer parameter

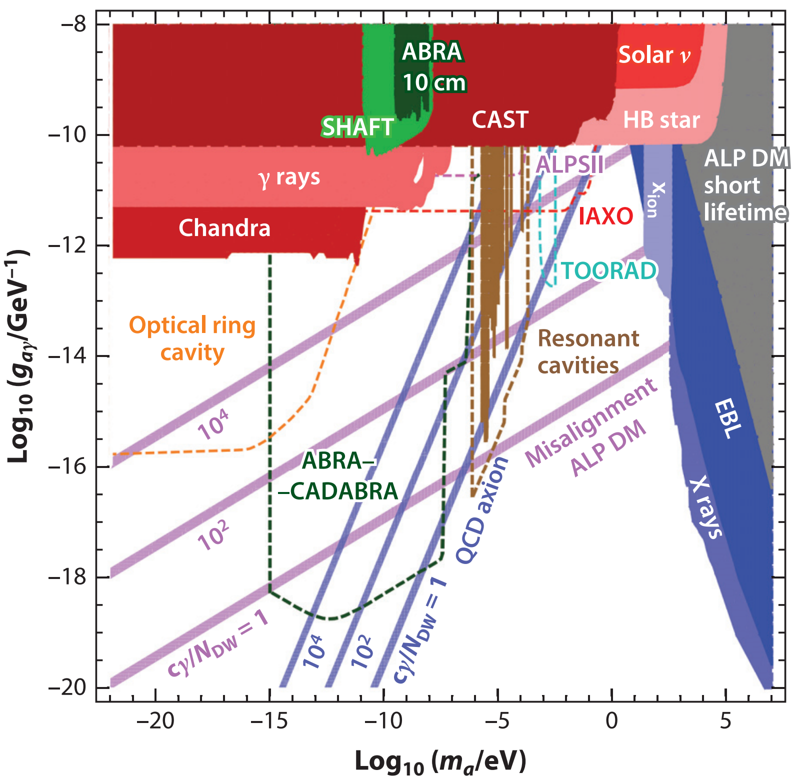
Multiple axions can give rise to a large hierarchy between different axion interaction strengths (e.g. axion-photon vs. axion-gluon).

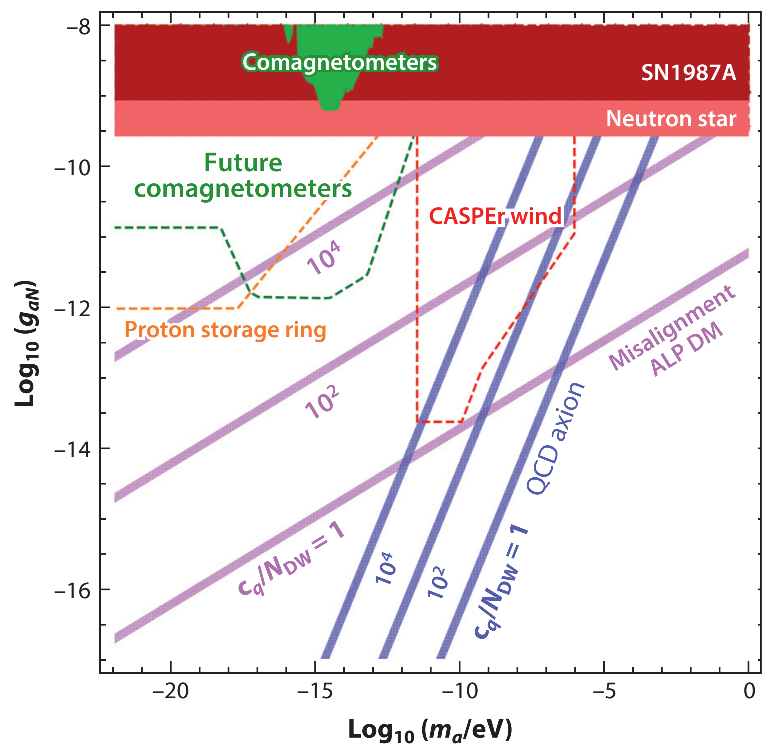
"clockwork mechanism"

Photo-, Nucleo-, or Electro-philic clockwork axions

Clockwork QCD axion or ALPs can have much stronger interactions than conventional axions, and so they can be examined in the upcoming experiments.

M Farina, D Pappadopulo, F Rompineve, A Tesi '17
P Agrawal, J Fan, M Reece, LT Wang,'18
K Choi, SHI, CS Shin, Ann.Rev.Nucl.Part.Sci. 71 (2021) 225





Key messages

- Conventionally UV physics for axions or ALPs has been classified into two types: KSVZ or DFSZ.
- We have shown that axions from string theory or extra dimensions can have different characteristics for axion couplings to SM particles.
- For QCD axion, the precision measurement of the axion-electron coupling is crucial to distinguish the three types of UV physics.

- Exploiting the chiral magnetic effects has a great potential to significantly improve experimental sensitivity on the axion-electron coupling.

- Multiple axion mixings can give rise to large integer numbers for axion couplings at low energies, which can yield axion couplings much stronger than conventional ones from a single axion.