The Axion-Photon Coupling

Prateek Agrawal
University of Oxford

CERN
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PA, Platschorre [2309.03934]
Choi, Forslund, Lam, Shao [2309.03937]
Reece [2309.03939]
Cordova, Hong, Wang [2309.05636]
Heidenreich, McNamara, Reece [2309.07951]

Some Broad Take-Aways

Discovery of the axion will be much more than discovering a particle

The scale of the axion couplings will give us a new UV scale, F_a

Axion couplings to gauge bosons are topological in nature, contain deep insights about the structure of the Standard Model

Does electron have the smallest unit of electric charge?
What is the global structure of the SM gauge group?
Are the SM forces unified?

Effects such as mixing and mass are captured in a very interesting way while being compatible with the quantization

Several of our conclusions apply to any compact field, such as pions or new pseudo-Goldstone bosons

The Axion-Maxwell Lagrangian

Axion-Photon interactions are very promising experimentally

At long distances described by Axion - Maxwell Lagrangian

$$\mathscr{L}_{\text{axMax}} = -\frac{1}{4e^2} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} F_a^2 \partial_\mu a \partial^\mu a + \mathscr{A} a \frac{1}{16\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu} + V(a)$$

The QCD Axion

One of the most compelling candidates for new physics

Peccei, Quinn [1977]
Weinberg [1978]
Wilczek [1978]
Vafa, Witten [1984]

$$\mathscr{A} = E - 1.92N \quad \rightarrow \quad g_{a\gamma\gamma} = \frac{\alpha_{\text{em}}}{\pi(F_a/N)} \left(\frac{E}{N} - 1.92 \right)$$

The String Axiverse

[0905.4720]
Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell

Hyperlight axions are ubiquitous in string compactifications

Axion potentials from instantons can be naturally exponentially suppressed

"hundreds of axions, some of them massless"

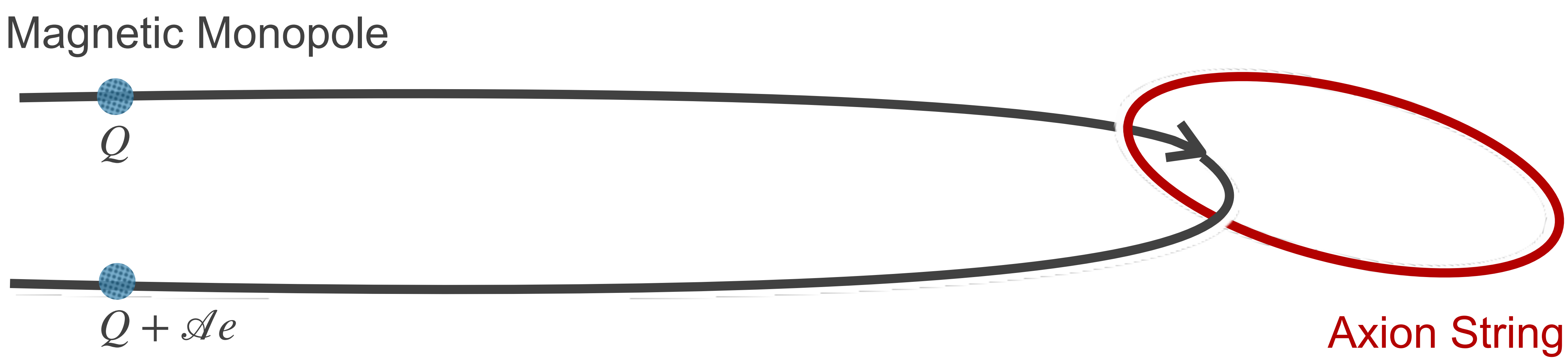
[1808.01282]
Demirtas, Long, McAllister, Stillman

For nearly massless axiverse axions, $\mathscr{A} \in \mathbb{Z}$

(Assuming the electron to have the fundamental quantum of electric charge)

See Shu-Heng's talk for generalizations

Axion Strings and Monopoles



Sikivie
[Phys.Lett.B 137 (1984) 353-356]

The monopole experiences $\Delta\theta = \dfrac{\Delta a}{F_a} = 2\pi\mathscr{A}$

Picks up an extra electric charge $\Delta Q = e\mathscr{A}$ due to the Witten effect

Charge flows on to the axion string through the Goldstone-Wilczek current
Anomaly inflow $\Rightarrow$ charge flow!

Dirac-Schwinger-Zwanziger Quantization $\Rightarrow \mathscr{A} \in \mathbb{Z}$

Applies to massive / massless axions

Sokolov, Ringwald [2205.02605]
Heidenreich, McNamara, Reece [2309.07951]
See Matt's talk for assumptions and caveats

Grand Unification and Axions

In GUTs the axion couples to the full GUT $\mathcal{G}\tilde{\mathcal{G}}$

PA, Nee, Reig [2206.07053]

The relative couplings to photons and gluons of the QCD axion are fixed

For simple embeddings in a GUT $E/N = 8/3$

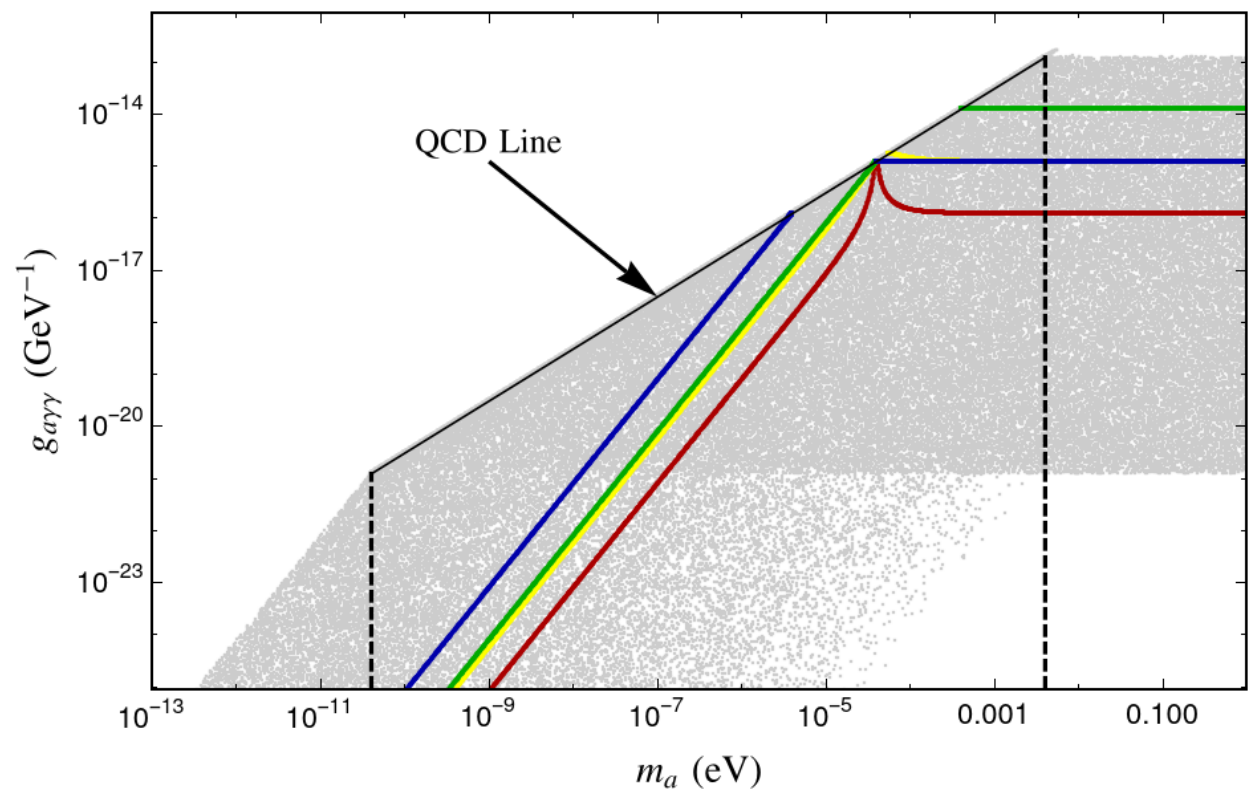
$$g_{a\gamma\gamma} = \frac{\alpha_{\rm em}}{\pi(F_a/N)}\left(\frac{E}{N} - 1.92\right)$$

Other axions are decoupled in simple GUTS !

Can couple to the SM gauge bosons through mixing effects

$$V(a_1, a_2) = \left(\frac{a_1}{f_1} + \frac{a_2}{f_2}\right)\mathcal{G}\widetilde{\mathcal{G}} + \frac{1}{2}m_2^2 a_2^2$$

An explicit mass for a_1 will spoil the solution to strong-CP



see also Gendler, Marsh, McAllister, Moritz [2309.13145]

A Small Puzzle

For the QCD axion, an irrational correction from mixing with the pion

$$g_{a\gamma\gamma} = \frac{\alpha_{\rm em}}{\pi(F_a/N)}\left(\frac{E}{N} - 1.92\right)$$

Quantization argument did not rely on absence of mass mixing terms

Axion-Maxwell Lagrangian EFT is valid for all values of the axion

A more general form of Axion-Maxwell

$$\mathscr{L}_{\rm axMax} = -\frac{1}{4e^2}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}F_a^2\partial_\mu a\partial^\mu a + \frac{g(a)}{16\pi^2}F_{\mu\nu}\tilde{F}^{\mu\nu} + V(a)$$

PA, Fan, Reece, Wang [1709.06085]
Fraser, Reece [1910.11349]
PA, Platschorre [2309.03934]

The function $g(a)$ is a monodromic function

$$g(a+2\pi) - g(a) = 2\pi\mathscr{A}, \quad \mathscr{A} \in \mathbb{Z}$$

(Assuming the electron to have the fundamental quantum of electric charge)

See Shu-Heng's talk for generalizations

For a massless axion, $g(a) = \mathscr{A}a$

Non-linear $g(a)$ is a spurion for axion continuous shift symmetry

General properties of $g(a)$

A prototypical example

$$g(a) = 2\arctan\left(\frac{1-z}{1+z}\tan\frac{a}{2}\right) + 2\pi \mathrm{sign}(1-z)\Theta(a-\pi)$$

PA, Platschorre [2309.03934]

Linearized coupling around $a = 0$

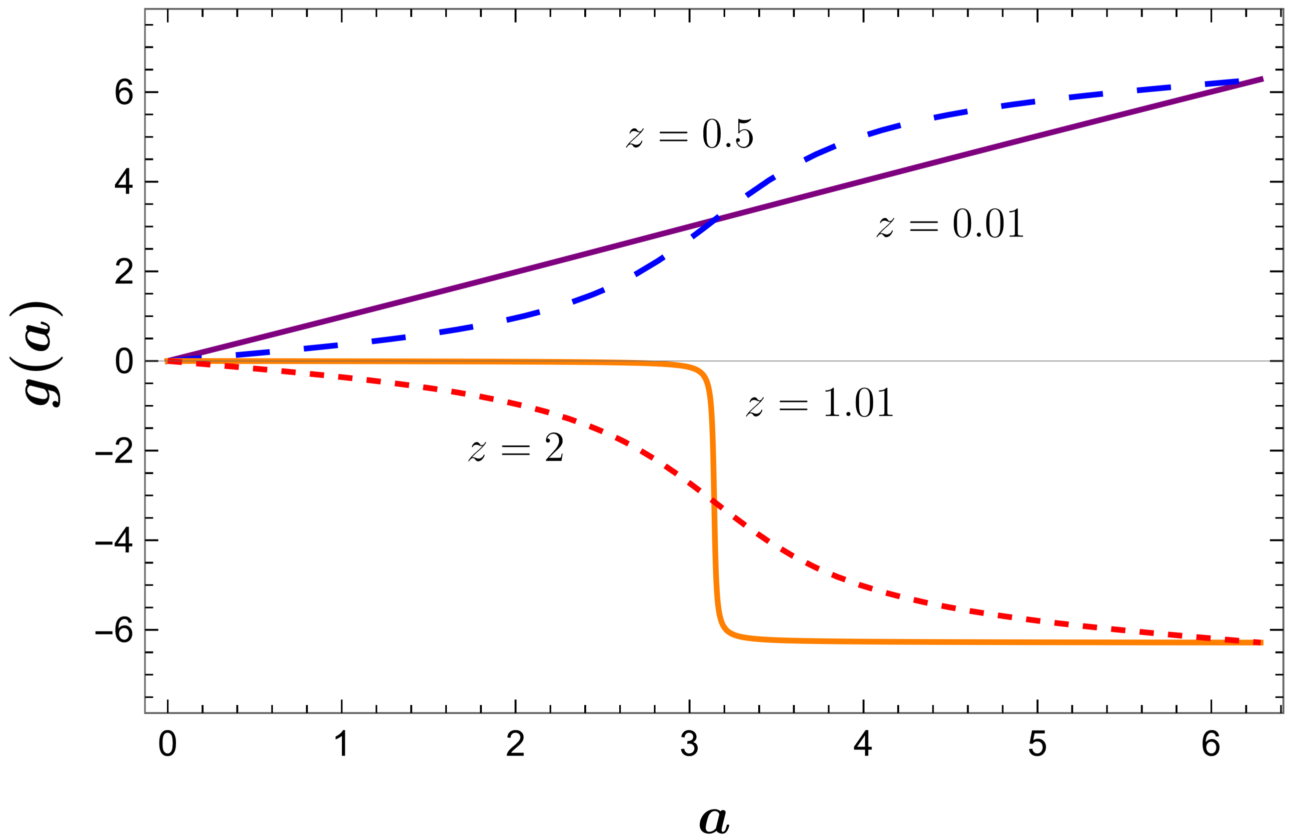
$$g'(0) = \frac{1-z}{1+z}$$

z is a real parameter. E.g. $z = m_u/m_d$

A symmetry $z \to \frac{1}{z}$

Interesting values: $z = \{0,1,\infty\}$

$V(a)$ and $g(a)$ depend on $\mathcal{Z} = ze^{ia}$



For nearly quantized coupling, $z \ll 1$, the potential for the axion $m_a^2 F_a^2 \sim z\Lambda^4$

Example 1: The QCD Axion

$$\mathscr{L} = \frac{Na}{8\pi^2}\mathrm{Tr}\left(G\widetilde{G}\right) + \frac{Ea}{16\pi^2}F\widetilde{F}$$

Axion potential using the chiral Lagrangian, integrating out pion

$$\pi^0 = -\arctan\left(\frac{1-z}{1+z}\tan\frac{2Na}{2}\right) - \pi\mathrm{sign}(1-z)\sum_{k=1}^{N}\Theta\left(a-(2k-1)\frac{\pi}{2N}\right)$$

$$V(a) = -f_\pi^2 m_\pi^2\sqrt{1-\frac{4z}{(1+z)^2}\sin^2\left(\frac{2Na}{2}\right)} \qquad z = \frac{m_u}{m_d}$$

The pion Wess-Zumino-Witten term corrects the axion-photon coupling

$$g(a) = Ea - \frac{5}{3}Na - \arctan\left(\frac{1-z}{1+z}\tan\frac{2Na}{2}\right) - \pi\mathrm{sign}(1-z)\sum_{k=1}^{N}\Theta\left(a-(2k-1)\frac{\pi}{2N}\right)$$

$$g_{a\gamma\gamma} = \frac{\alpha_{\mathrm{em}}}{\pi F_a}\left(E - \frac{5N}{3} - \frac{1-z}{1+z}N\right)$$

The monodromy $E - \dfrac{2N}{3} - 2N\,\mathrm{sign}(1-\mathrm{z}) \in \mathbb{Z}$, vanishes for $\dfrac{E}{N} = \dfrac{8}{3}$!

[Shu-Heng's talk]

Example 2: Perturbative PQ breaking

$$\mathscr{L} = i\bar{\Psi}\gamma^\mu D_\mu \Psi - f\bar{\Psi}e^{ia\gamma_5}\Psi - m_\Psi \bar{\Psi}\Psi$$

In this case $z = \dfrac{f}{m_\Psi}$

The Coleman - Weinberg potential

$$V(a) = -c_1 m(a)^2 - \frac{m(a)^4}{16\pi^2}\ln\frac{m(a)^2}{c_2^2}$$

$$m(a)^2 = (m_\Psi + f)^2\left(1 - \frac{4z}{(1+z)^2}\sin^2\left(\frac{a}{2}\right)\right)$$

The axion-photon coupling from integrating out Ψ

$$g(a) = \frac{1}{2}a - \arctan\left(\frac{1-z}{1+z}\tan\frac{a}{2}\right) - \mathrm{sign}(1-z)\pi\Theta(a-\pi)$$

Notice at $z \to \{0,\infty\}$, the potential for axion vanishes, and $g(a) \to a\mathbb{Z}$

Example 3: Axions from Extra Dimensions

A 5D theory compactified on a circle with a U(1) gauge field and a fermion

$$S = \int d^4x \int dy \left[-\frac{1}{4e^2} F_{MN}F^{MN} - \Psi^\dagger \left(\gamma^\mu D_\mu + m \right) \Psi \right]$$

The axion is the Wilson loop around the extra dimension

$$\oint dy A_5(x, y) = a(x) \qquad\qquad z = e^{-2\pi R m}$$

Fermion decomposes into a 4D fermion + a compact QM dof coupled to the axion

$$\mathscr{L} = \frac{1}{2}\dot{q}^2 + i\dot{q}\frac{a}{2\pi}, \qquad q \sim q + 2\pi$$

See also Fan, Fraser, Reece, Stout [2105.09950]

This generates a potential $V(a)$ and a monodromic coupling $g(a)$

$$V(a) = \frac{m^2}{(2\pi R)^2} \sum_{n=1}^{\infty} \frac{1}{\pi^2 n^3} e^{-n2\pi|Rm|}(-1)^n \cos(na)(1 + \ldots)$$

$$g(a) = \frac{1}{2}a + \arctan\left(\frac{1-z}{1+z} \tan\left(\frac{a}{2} \right) \right) + \pi \mathrm{sign}(1-z)\Theta(a-\pi) \qquad \mathcal{Z} = ze^{ia}$$

Take-Away Message

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The scale of the axion couplings will give us a new UV scale, F_a

Axion couplings to gauge bosons are topological in nature, contain deep insights about the structure of the Standard Model

> Does electron have the smallest unit of electric charge?
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Extra: Measuring Axion-Photon couplings

A very important physics target post discovery

Measuring the QCD axion coupling precisely faces some challenges

Axion haloscope cavities measure the combination $\rho_{\text{DM}} g_{a\gamma\gamma}$

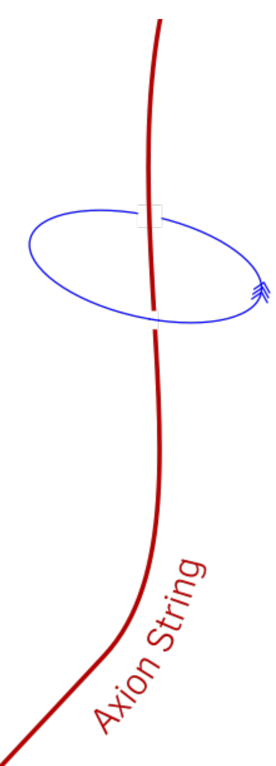
- local DM density ρ_{DM} is not known to high precision

Other haloscopes using time-varying EDM can measure $\rho_{\text{DM}}(1/f_a)$

- theory calculations are only good to about 30%

PA, Berghaus, Fan, Hook, Marques-Tavares, Rudelius [2203.08026]

Hyperlight axions can lead to cosmic birefringence in the CMB



Axiverse string networks can persist in the sky today

PA, Hook, Huang [1912.02823]

Yin, Dai, Ferraro [2111.12741]

Jain, Long, Amin [2103.10962], [2208.08391]

See also

Minami, Komatsu [2011.11254]

Eskilt, Komatsu [2205.13962]

CMB photons get a polarization rotation

$$\Delta\Phi = \mathscr{A}\alpha_{\text{em}}\frac{\Delta a}{2\pi F_a}$$

Polarization rotation jumps across axion strings in the sky by $\mathscr{A}\alpha_{\text{em}}$

Extra: Comments on $\mathbb{Z}_6$

SM gauge group has a global ambiguity

$$SU(3)_c \times SU(2)_w \times U(1)_Y / \Gamma$$

Usually it is said $\Gamma = \mathbb{Z}_2, \mathbb{Z}_3, \mathbb{Z}_6$, but it may be $\mathbb{Z}_{6000}$

There are statements in the literature that local experiments cannot tell us about this Γ

These examples and talks by Shu-Heng and Matt explicitly show how we may be able to at least rule out possibilities

Another simple example: The LHC finds a vectorlike color/EW singlet with hypercharge 1/6