Uncovering the microscopic features of axion with low energy observables

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Axion 2023, Xi'an

KC, Im, Seong, Kim, JHEP 08 (2021) 058 (arXiv:2106.05816)
KC, Im, Jodlowski, in preparation

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Outline

- Discriminating among different axion models with low energy axion couplings
- Exploring the quality of PQ symmetry with electric dipole moments

Axions (or axion-like particles (ALP)) are light pseudo-scalar bosons postulated in many models for physics beyond the SM:

Strong CP problem, dark matter, inflation, …

Also string theories generically predict axions in 4-dim effective theory.

Axions are angular fields: $\frac{a(x)}{f_a} \cong \frac{a(x)}{f_a} + 2\pi$

$(f_a = \text{axion decay constant or axion scale})$

Axions can be naturally light due to a global U(1) Peccei-Quinn (PQ) symmetry non-linearly realized in low energy limit, which severely constrains the possible low energy couplings:

$$U(1)_{\rm PQ}: \quad a(x) \;\rightarrow\; a(x) + \text{constant}$$

$$\mathcal{L}_{\rm axion} = \frac{1}{2}(\partial_\mu a)^2 + \sum_A c_A \frac{1}{32\pi^2}\frac{a}{f_a} F^{A\mu\nu}\tilde{F}^A_{\mu\nu} + \sum_\psi c_\psi \frac{\partial_\mu a}{f_a}\bar{\psi}\sigma^\mu\psi + \ldots.$$

Two different origins of axion fields

* **Field-theoretic axions** originating from the phase of $U(1)_{PQ}$-charged scalar fields:

$$\phi = \rho(x) e^{ia(x)/f_a} \quad \Big(f_a = \langle \rho \rangle \Big)$$

Peccei,Quinn; Weinberg; Wilczek
Kim; Shifman,Vainshtein,Zakharov (KSVZ)
Dine,Fischler,Srednicki; Zhitnitsky (DFSZ)

$$\langle QQ^c \rangle = \Lambda^3 e^{ia(x)/f_a} \quad \Big(f_a \sim \Lambda \Big)$$

Composite axion
Kim; KC, Kim; ...

Field-theoretic axions have a UV completion with a linearly realized $U(1)_{PQ}$ $(f_a = 0)$ which can be described by 4-dim EFT.

Two different type of field-theoretic axions:

DFSZ-type: SM quarks and leptons are $U(1)_{PQ}$-charged

KSVZ-type: SM quarks and leptons are neutral under $U(1)_{PQ}$
(Most of composite axions are KSVZ-type)

* **String-theoretic axions** originating from the zero modes of p-form gauge field in higher dimensional spacetime, e.g. axions in string theory:

Witten '84

$$\frac{a(x)}{f_a} = \int_{\Sigma_p} C^{(p)}_{[m_1,..,m_p]}(x,y)\, dy^{m_1}...dy^{m_p} \quad (\Sigma_p = p\text{-cycle in extra-dim})$$

or $$f_a \partial_\mu a = \epsilon_{\mu\nu\rho\sigma}\left(\partial^\nu B^{\rho\sigma} + ...\right)$$

String-theoretic axions do not have a UV completion with linear $U(1)_{PQ}$ as $f_a \to 0$ is at an infinite field distance which can not be described by 4-dim EFT.

DFSZ-type, KSVZ-type, and string-theoretic axions have different pattern of low energy couplings which might be measurable in future experiments.

KC, Im, Kim, Seong, '21

Two particularly well-motivated light axions

* QCD axion solving the strong CP problem, which is also an appealing candidate for dark matter:

U(1)$_{PQ}$ is broken dominantly by the axion coupling to the gluons:

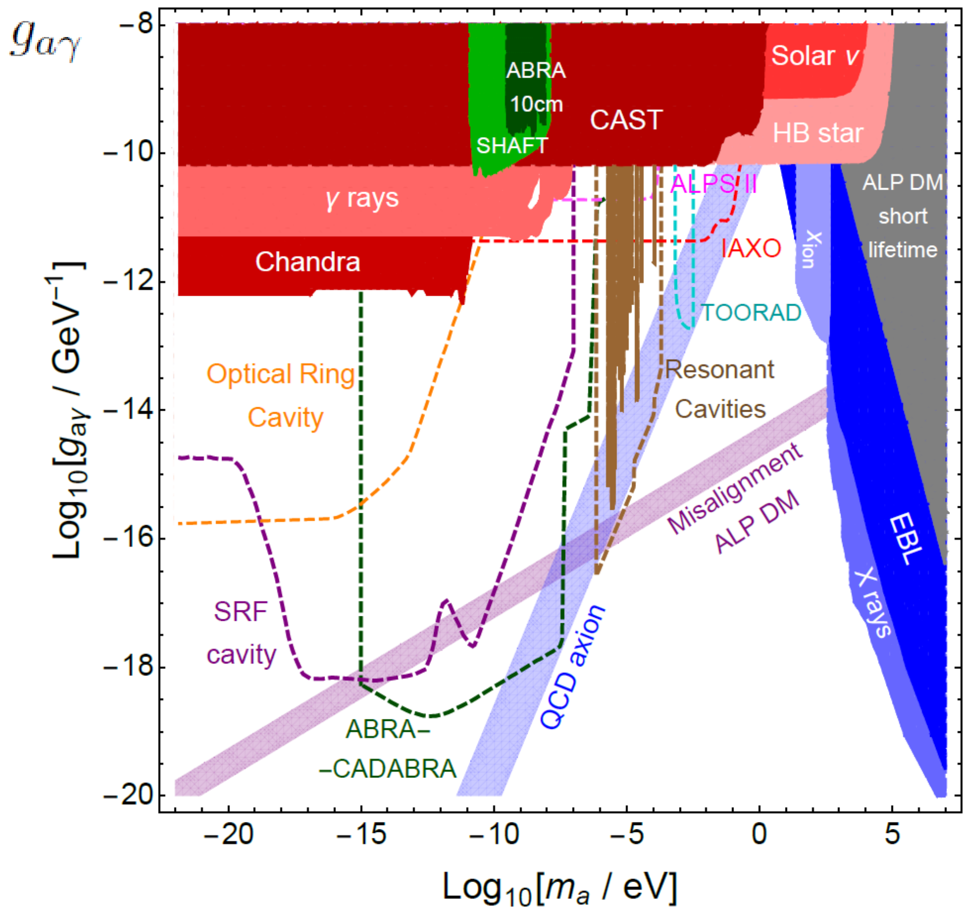
$$\frac{1}{32\pi^2}\frac{a_{\rm QCD}}{f_a}G^{a\mu\nu}\tilde{G}^a_{\mu\nu} \rightarrow \qquad \theta_{\rm QCD} \equiv \frac{\langle a_{\rm QCD}\rangle}{f_a} = 0$$

$$m_{a_{\rm QCD}} \simeq 5.7\times 10^{-6}\left(\frac{10^{12}\,{\rm GeV}}{f_a}\right)\,{\rm eV}$$

* Ultra-light ALP which does not couple to the gluons, so can be much lighter than the QCD axion, but still may constitute the dark matter, e.g. fuzzy dark matter:

$$\frac{\rho_{\rm ALP}}{\rho_{\rm DM}} \sim \left(\frac{m_a}{10^{-22}{\rm eV}}\right)^{1/2}\left(\frac{f_a}{10^{17}{\rm GeV}}\right)^2$$

Both QCD axion and ultra-light ALP have a bright prospect for experimental detection.



KC, Im and Shin (2021)

If an axion is discovered, e.g. through the coupling to photon, so its mass is known, it will be relatively easy to measure other couplings such as the couplings to the nucleons and electron.

Discriminating among different type of axions with low energy couplings

Axion couplings measurable in low energy experiments can be determined mostly by the axion couplings to the gluons and light quarks at scales around 1 GeV, as well as the couplings to the photon and electron:

photon gluons light quarks & electron

$$\frac{1}{32\pi^2}\frac{a(x)}{f_a}\left(c_\gamma F^{\mu\nu}\tilde{F}_{\mu\nu} + c_G G^{\alpha\mu\nu}\tilde{G}^{\alpha}_{\mu\nu}\right) + \sum_{\Psi=u,d,e}\frac{\partial_\mu a(x)}{2f_a}C_\Psi \bar{\Psi}\gamma^\mu\gamma_5\Psi$$

$(c_{\gamma,G} = \text{rational number})$ at $\mu = \mathcal{O}(1)$ GeV

$$\Rightarrow \quad \frac{1}{2}g_{a\gamma}a(x)\vec{E}\cdot\vec{B} + \partial^\mu a(x)\left(\frac{g_{ap}}{2m_p}\bar{p}\gamma_\mu\gamma_5 p + \frac{g_{an}}{2m_n}\bar{n}\gamma_\mu\gamma_5 n + \frac{g_{ae}}{2m_e}\bar{e}\gamma_\mu\gamma_5 e\right)$$

$$g_{a\gamma} \simeq \frac{\alpha_{\rm em}}{2\pi}\frac{1}{f_a}\left(c_\gamma - 1.92c_G\right)$$

$$g_{ap} \simeq \frac{m_p}{f_a}\left(0.94c_G + 0.88C_u - 0.39C_d\right)$$

for $C_{u,d}$ at $\mu = 2\,\text{GeV}$

$$g_{an} \simeq \frac{m_n}{f_a}\left(0.04c_G - 0.39C_u + 0.88C_d\right)$$

C_e at $\mu = m_e$

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

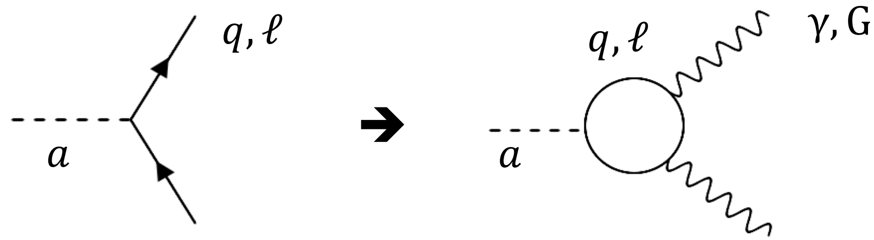
Cortona et al, arXiv:1511.02867

Different pattern of couplings for different types of axions

$$\frac{1}{4}\tilde{g}_{aA}a(x)F^{A\mu\nu}\tilde{F}^{A}_{\mu\nu} + \frac{1}{2}\tilde{g}_{a\Psi}\partial_\mu a(x)\bar{\Psi}\gamma^\mu\gamma_5\Psi \quad (A=\gamma, G;\ \Psi = u, d, e)$$

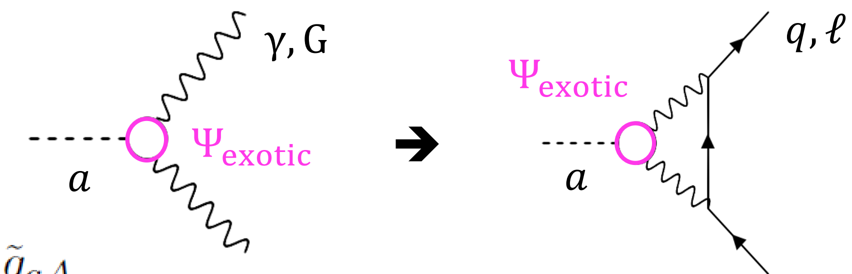
$$\left(\tilde{g}_{aA} = \frac{g_A^2}{8\pi^2}\frac{c_A}{f_a} \ \ (c_A = \text{rational number}), \quad \tilde{g}_{a\Psi} = \frac{c_\Psi}{f_a}\right)$$

* DFSZ-type axion:



$$\tilde{g}_{aA} \sim \frac{g_A^2}{8\pi^2}\tilde{g}_{a\Psi}$$

* KSVZ-type axion:



$$\tilde{g}_{a\Psi} \sim \left(\frac{g_A^2}{8\pi^2}\ln(f_a/\mu)\right)\tilde{g}_{aA}$$

* String-theoretic axion:

$$\tilde{g}_{aA} \sim \tilde{g}_{a\Psi}$$

Different types of axions have parametrically different coupling ratios controlled by the loop factor $g_A^2/8\pi^2$:

* **DFSZ-type:** $\tilde{g}_{aA} \sim \frac{g_A^2}{8\pi^2}\tilde{g}_{a\Psi}$
* **KSVZ-type:** $\tilde{g}_{a\Psi} \sim \left(\frac{g_A^2}{8\pi^2}\ln(f_a/\mu)\right)\tilde{g}_{aA}$
* **String-theoretic:** $\tilde{g}_{aA} \sim \tilde{g}_{a\Psi}$

On the other hand, experimentally measurable axion couplings are the couplings at scales below the QCD scale where $g_{\rm QCD}^2/8\pi^2 \sim 1$, so certain part of this parametric difference can become insignificant by nonperturbative QCD effects.

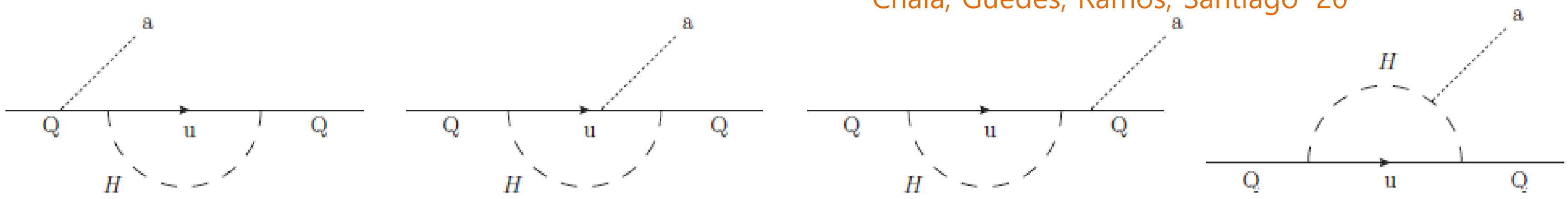
It might also be significantly diluted by perturbative radiative effects involving a large logarithmic factor $\ln(f_a/\mu) \gg 1.$

Therefore, to see if these three type of axions can be distinguished by experimentally measurable couplings, we need to include both perturbative & nonperturbative quantum corrections to low energy axion couplings.

Perturbative corrections to axion couplings

Yukawa-induced 1-loop running of axion couplings to chiral fermions and Higgs fields :

KC, Im, Park, Yun '17,
Camalich, Pospelov, Vuong, Ziegler, Zupan '20
Heiles, König, Neubert '20,
Chala, Guedes, Ramos, Santiago '20



$$\left.\frac{d\mathbf{c}_F}{d\ln\mu}\right|_{1-\text{loop}} = \frac{\xi_y}{16\pi^2}\sum_{f,\alpha}\left(\frac{1}{2}\{\mathbf{c}_F, \mathbf{y}^\dagger_{fF\alpha}\mathbf{y}_{fF\alpha}\} + \mathbf{y}^\dagger_{fF\alpha}\mathbf{c}^T_f\mathbf{y}_{fF\alpha} + c_{H_\alpha}\mathbf{y}^\dagger_{fF\alpha}\mathbf{y}_{fF\alpha}\right),$$

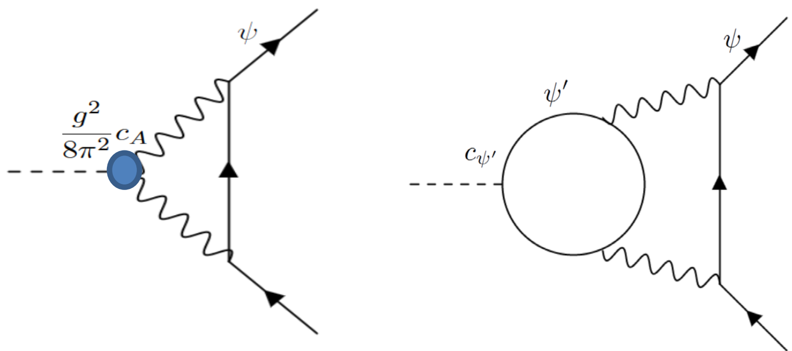
$$\left.\frac{d\mathbf{c}^T_f}{d\ln\mu}\right|_{1-\text{loop}} = \frac{\xi_y}{16\pi^2}\sum_{F,\alpha}\left(\frac{1}{2}\{\mathbf{c}^T_f, \mathbf{y}_{fF\alpha}\mathbf{y}^\dagger_{fF\alpha}\} + \mathbf{y}_{fF\alpha}\mathbf{c}_F\mathbf{y}^\dagger_{fF\alpha} + c_{H_\alpha}\mathbf{y}_{fF\alpha}\mathbf{y}^\dagger_{fF\alpha}\right),$$

$$\left.\frac{dc_{H_\alpha}}{d\ln\mu}\right|_{1-\text{loop}} = \frac{1}{8\pi^2}\sum_{f,F}\left(c_{H_\alpha}\mathrm{tr}(\mathbf{y}^\dagger_{fF\alpha}\mathbf{y}_{fF\alpha}) + \mathrm{tr}(\mathbf{y}_{fF\alpha}\mathbf{c}_F\mathbf{y}^\dagger_{fF\alpha}) + \mathrm{tr}(\mathbf{y}^\dagger_{fF\alpha}\mathbf{c}^T_f\mathbf{y}_{fF\alpha})\right),$$

$$F_i = \{q_i, \ell_i\} \qquad f_i = \{u^c_i, d^c_i, e^c_i\}$$

$$\text{non-SUSY}: \ \xi_y = 1 \qquad \text{SUSY}: \ \xi_y = 2$$

Gauge-induced 2-loop running:



Srednicki '85, Chang and KC '93
KC, Im, Shin '20,
Chala, Guedes, Ramos, Santiago '20
Bauer, Neubert, Renner, Schnubel, Thamm '20

$$\left.\frac{d\mathbf{c}_\psi}{d\ln\mu}\right|_{2-\text{loop}} = -\xi_g \sum_A \frac{3}{2}\left(\frac{g_A^2}{8\pi^2}\right)^2 \mathbb{C}_A(\psi)\Big(c_A - 2\sum_{\psi'}\text{tr}(\mathbf{c}_{\psi'})\mathbb{T}_A(\psi')\Big)\mathbb{1},$$

$$\left.\frac{dc_{H_\alpha}}{d\ln\mu}\right|_{2-\text{loop}} = -\xi_H \sum_A \frac{3}{2}\left(\frac{g_A^2}{8\pi^2}\right)^2 \mathbb{C}_A(H_\alpha)\Big(c_A - 2\sum_{\psi'}\text{tr}(\mathbf{c}_{\psi'})\mathbb{T}_A(\psi')\Big),$$

$\mathbb{C}_A(\Phi)$ = quadratic Casimir $\qquad$ $\mathbb{T}_A(\Phi)$ = Dynkin index

$\text{non-SUSY}: \ \xi_g = 1, \ \xi_H = 0$ $\qquad$ $\text{SUSY}: \ \xi_g = \xi_H = \frac{2}{3}$

For given axion model defined at UV scale, one can use these perturbative RG evolutions to get the relevant couplings at $\mu = 2\ \mathrm{GeV}$:

$$\frac{1}{32\pi^2}\frac{a(x)}{f_a}\left(c_\gamma F^{\mu\nu}\tilde{F}_{\mu\nu} + c_G G^{\alpha\mu\nu}\tilde{G}^{\alpha}_{\mu\nu}\right) + \sum_{\Psi=u,d,e}\frac{\partial_\mu a(x)}{2f_a}C_\Psi\bar{\Psi}\gamma^\mu\gamma_5\Psi$$

For relevant nonperturbative QCD effects, we use the lattice results quoted in arXiv:1511.02867 (Cortona et al)

$$\frac{1}{2}g_{a\gamma}a(x)\vec{E}\cdot\vec{B} + \partial^\mu a(x)\left(\frac{g_{ap}}{2m_p}\bar{p}\gamma_\mu\gamma_5 p + \frac{g_{an}}{2m_n}\bar{n}\gamma_\mu\gamma_5 n + \frac{g_{ae}}{2m_e}\bar{e}\gamma_\mu\gamma_5 e\right)$$

$$g_{a\gamma} \simeq \frac{\alpha_{\rm em}}{2\pi}\frac{1}{f_a}\left(c_\gamma - 1.92c_G\right)$$

$$g_{ap} \simeq \frac{m_p}{f_a}\left(0.94c_G + 0.88C_u - 0.39C_d\right)$$

$$g_{an} \simeq \frac{m_n}{f_a}\left(0.04c_G - 0.39C_u + 0.88C_d\right)$$

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

for $C_{u,d}$ at $\mu = 2\,\mathrm{GeV}$

C_e at $\mu = m_e$

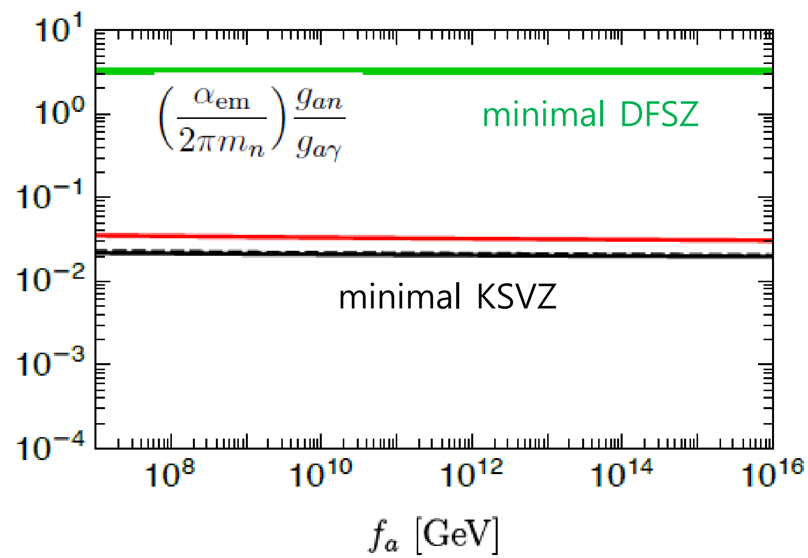
Resulting coupling ratios $g_{aX}/g_{a\gamma}\ (X = p, n, e)$

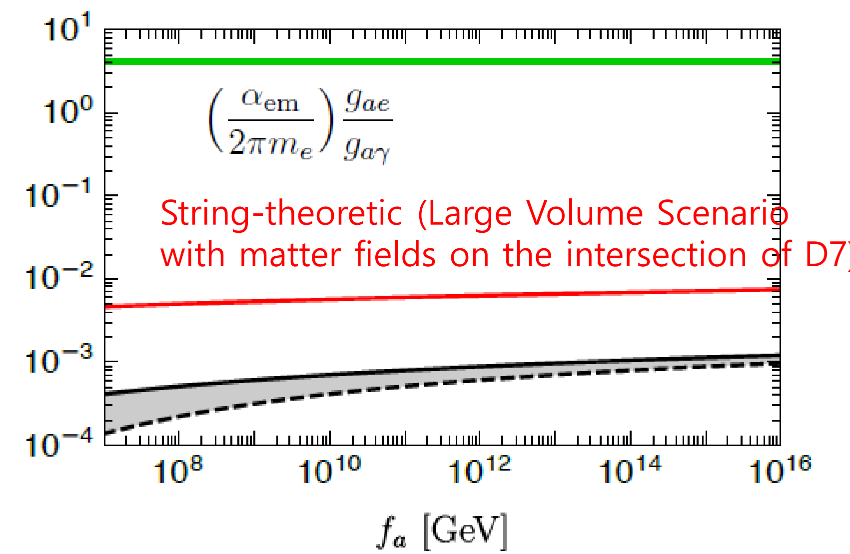
KC, Im, Seong, Kim, arXiv:2106.05816

QCD axion $(c_G \neq 0)$

1) All three types (DFSZ, KSVZ, String-theoretic) of QCD axions have similar $g_{ap}/g_{a\gamma}$ because of the nonperturbative contribution from the axion-meson mixing induced by c_G.

2) As the axion-meson mixing contribution to g_{an} & g_{ae} are small, these three types of QCD axions have distinguishable values of $g_{an}/g_{a\gamma}$ and $g_{ae}/g_{a\gamma}$.





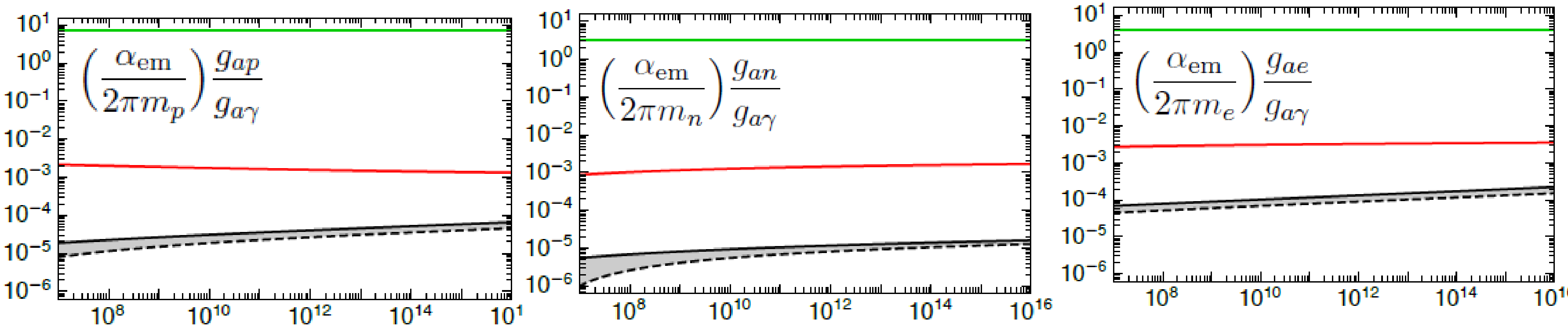
$$\left(\frac{g_{an}}{g_{a\gamma}}\right)_{\rm DFSZ} \gg \left(\frac{g_{an}}{g_{a\gamma}}\right)_{\rm string-theoretic} \simeq \left(\frac{g_{an}}{g_{a\gamma}}\right)_{\rm KSVZ}$$

$$\left(\frac{g_{ae}}{g_{a\gamma}}\right)_{\rm DFSZ} \gg \left(\frac{g_{ae}}{g_{a\gamma}}\right)_{\rm string-theoretic} \gg \left(\frac{g_{ae}}{g_{a\gamma}}\right)_{\rm KSVZ}$$

Ultra-light ALP $(c_G = 0,\ c_\gamma = 1)$

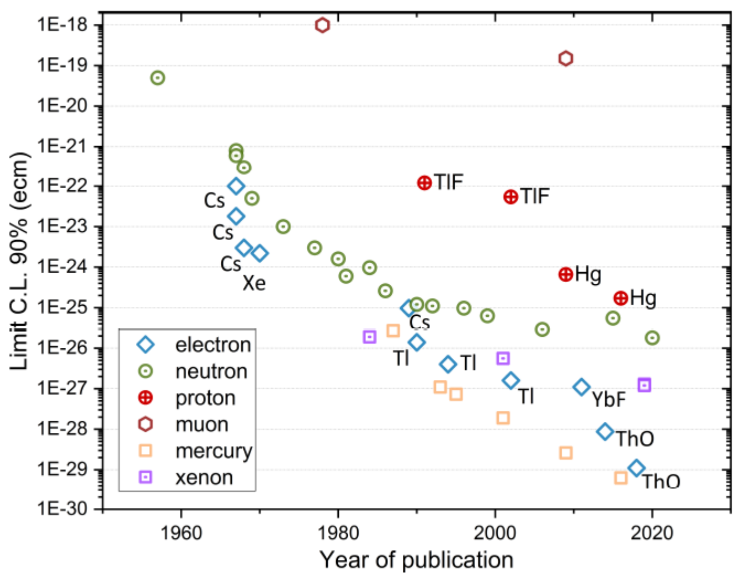
Different type of ALPs have clearly distinguishable patterns for all three coupling ratios:

$$\left(\frac{g_{aX}}{g_{a\gamma}}\right)_{\rm DFSZ} \gg \left(\frac{g_{aX}}{g_{a\gamma}}\right)_{\rm string-theoretic} \gg \left(\frac{g_{aX}}{g_{a\gamma}}\right)_{\rm KSVZ} \qquad (X = p, n, e)$$

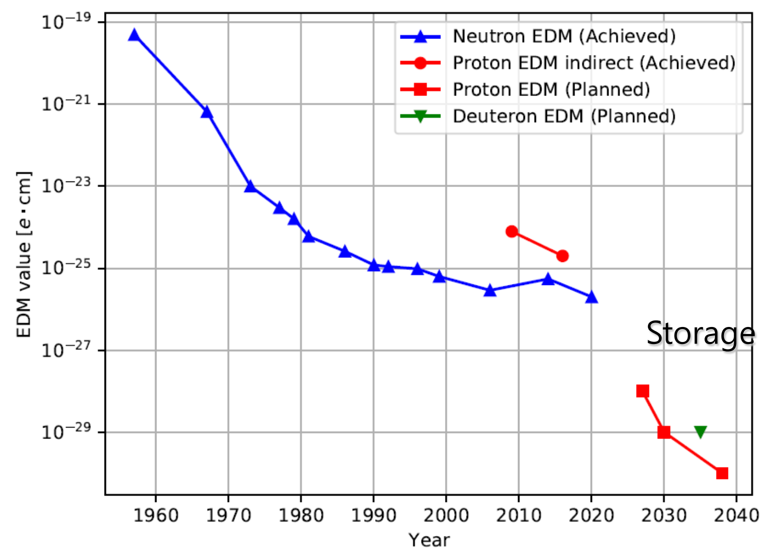


Exploring the quality of PQ symmetry with EDMs

Electric dipole moments (EDM) provide a highly sensitive tool to probe CP violation beyond the SM. They also have a bright prospect for improving the experimental sensitivity in the near future.



arXiv:2003.00717



Storage ring EDM

arXiv:2203.08103

SM predictions

$$\delta_{\rm KM} = \arg\cdot {\rm Det}([y_u y_u^\dagger, y_d y_d^\dagger]) \qquad \theta_{\rm QCD} = \theta_{\rm bare} + \arg\cdot {\rm Det}(y_u y_d)$$

$$\frac{d_n}{e\cdot{\rm cm}} = -(1.5\pm 0.7)\times 10^{-16}\sin\theta_{\rm QCD} \;+\; \mathcal{O}(10^{-31} - 10^{-32})\times \sin\delta_{\rm KM}$$

$$\frac{d_p}{e\cdot{\rm cm}} = (1.1\pm 1.0)\times 10^{-16}\sin\theta_{\rm QCD} \;+\; \mathcal{O}(10^{-31} - 10^{-32})\times \sin\delta_{\rm KM}$$

$$\frac{d_D}{e\cdot{\rm cm}} = -(0.4\pm 1.5)\times 10^{-16}\sin\theta_{\rm QCD} \;+\; \mathcal{O}(10^{-31} - 10^{-32})\times \sin\delta_{\rm KM}$$

De Vries et al '21 Mannel, Uraltsev '12

➔ $|\theta_{\rm QCD}| \lesssim 10^{-10}$

$$\frac{d_e}{e\cdot{\rm cm}} = -(2.2 - 8.6)\times 10^{-28}\sin\theta_{\rm QCD} \;+\; \mathcal{O}(10^{-44})\times \sin\delta_{\rm KM}$$

KC, Hong '91; Ghosh, Sato '18 Pospelov, Ritz '14

$$\frac{d_e^{\rm equiv}}{e\cdot{\rm cm}} \simeq\; 4.5\times 10^{-22}\sin\theta_{\rm QCD} \;+\; 10^{-35}\sin\delta_{\rm KM}$$

(due to $\bar{e}\gamma_5 e\bar{N}N$ for paramagnetic molecules)

Flambaum et al '19 Ema et al '22

EDMs from $\delta_{\rm KM}$ are all well below the current experimental bounds, while the hadronic EDMs from θ_{QCD} can have any value below the current bounds.

There can also be CP-violations (CPV) beyond the SM (BSM), which may induce EDMs at any value below the current bounds.

Therefore, if some hadronic EDM is experimentally discovered, an immediate question is

"Is it from BSM CPV or from θ_{QCD} ?

Effective theory approach provides a powerful tool to study EDMs induced by BSM CPV.

BSM model at E > 1 TeV

Integrate out all massive BSM and SM particles and scale down the theory to lower energy scale

gluon chromo-EDM quark chromo-EDM

Effective theory for EDMs at scales around the QCD scale

$$f^{abc} G^a G^b \widetilde{G}^c \quad + \quad \bar{q}\sigma^{\mu\nu} i\gamma_5 G_{\mu\nu} q$$

$$\bar{q}\sigma^{\mu\nu} i\gamma_5 F_{\mu\nu} q + \bar{e}\sigma^{\mu\nu} i\gamma_5 F_{\mu\nu} e \quad + \cdots$$

quark and lepton EDM 4-fermion operators

QCD, nuclear & atomic physics

Experimentally measurable nucleon, atomic, molecular EDMs

The smallness of θ_{QCD} demands an explanation (strong CP problem), and QCD axion associated with non-linearly realized $U(1)_{PQ}$ provides arguably the most appealing explanation.

In the presence of QCD axion, θ_{QCD} corresponds to the vacuum value of the axion field determined by the $U(1)_{PQ}$-breaking axion potential:

$$\frac{1}{32\pi^2}\frac{a(x)}{f_a}G^{\alpha\mu\nu}\tilde{G}^{\alpha}_{\mu\nu} \quad \Rightarrow \quad \theta_{\rm QCD} = \frac{\langle a \rangle}{f_a}$$

Usually it is assumed that the above axion coupling to the gluons provides the most dominant $U(1)_{PQ}$-breaking to the extent that the resulting θ_{QCD} is small enough.

However generically there can be additional $U(1)_{PQ}$-breaking other than $\mathbf{aG\tilde{G}}$ which may induce a sizable axion vacuum value.

(PQ quality problem)

Generic axion potential:

Conventional axion potential induced by $aG\tilde{G}$

$$V(a) = -\frac{m_u m_d}{(m_u+m_d)^2} f_\pi^2 m_\pi^2 \cos\left(\frac{a}{f_a}\right)$$
$$-\frac{m_u m_d}{(m_u+m_d)^2} f_\pi^2 m_\pi^2 \times \left(10^{-19} \sin\delta_{\rm KM} \sin\left(\frac{a}{f_a}\right)\right)$$
$$-\frac{m_u m_d}{(m_u+m_d)^2} f_\pi^2 m_\pi^2 \times \left(\left(\sum_i \lambda_i \epsilon_i\right) \sin\left(\frac{a}{f_a}\right)\right)$$
$$-\Lambda_{\rm UV}^4 e^{-S_{\rm ins}} \cos\left(\frac{a}{f_a} + \delta_{\rm UV}\right) + \ldots$$

Axion potential induced by $aG\tilde{G} \oplus$ SM CP-violation

Axion potential induced by $aG\tilde{G} \oplus$ BSM CP-violation

Axion potential induced by additional PQ-breaking (other than $aG\tilde{G}$) at UV scales, e.g. string/brane instantons or other quantum gravity effects

$$\mathcal{L}_{\rm BSM-CPV} = \sum_i \epsilon_i \mathcal{O}_i(x)$$

$$\{\mathcal{O}_i\} = \{GG\tilde{G}, \bar{q}\gamma_5\sigma^{\mu\nu}G_{\mu\nu}q, \bar{q}q\bar{q}\gamma_5 q, \ldots\}$$

$$\lambda_i = \frac{\int d^4x \left\langle \frac{1}{32\pi^2} G\tilde{G}(x)\mathcal{O}_i(0)\right\rangle}{\frac{m_u m_d}{(m_u+m_d)^2} f_\pi^2 m_\pi^2}$$

Quality of the PQ-symmetry
= Size of additional PQ-breaking other than $aG\tilde{G}$

Generically there can be three different sources of the axion VEV:

$$\theta_{\rm QCD} = \frac{\langle a \rangle}{f_a} = \theta_{\rm in}^{\rm SM} + \theta_{\rm in}^{\rm BSM-CPV} + \theta_{\rm in}^{\rm UV}$$

$$\theta_{\rm in}^{\rm SM} \simeq 10^{-19}$$

Axion VEV induced by $aG\tilde{G} \oplus$ SM CPV, which is too small to be interesting

Georgi & Randall '86

$$\theta_{\rm in}^{\rm BSM-CPV} \simeq \sum_i \lambda_i \epsilon_i$$

Axion VEV induced by $aG\tilde{G} \oplus$ BSM CPV, which can be as large as 10^{-10}

$$\theta_{\rm in}^{\rm UV} \simeq \frac{\Lambda_{\rm UV}^4 e^{-S_{\rm ins}} \sin\delta_{\rm UV}}{\frac{m_u m_d}{(m_u+m_d)^2} f_\pi^2 m_\pi^2} + \ldots$$

Axion VEV induced by additional PQ-breaking at UV scale such as quantum gravity effects, which also can be as large as 10^{-10}

Would it be possible to discriminate $\theta_{\rm in}^{\rm UV}$ from $\theta_{\rm in}^{\rm BSM-CPV}$ through EDMs, so extract information on the quality of the PQ-symmetry?

This might be possible since additional PQ-breaking at UV scale affects EDM only through the induced axion VEV, while BSM-CPV affects EDM both directly and through the induced axion VEV.

This question is a part of the bigger question:

"How to identify the UV origin of experimentally observed EDMs?"

The first step would be to identify the parameter region of θ_{QCD} and the Wilson coefficients in the EFT of BSM CPV at O(1) GeV, which can explain the experimentally measured nucleon, atomic, molecular EDMs:

$$\mathcal{L}_{\mathrm{BSM-CPV}} = \sum_i \epsilon_i \mathcal{O}_i(x) \qquad \{\mathcal{O}_i\} = \{GG\tilde{G}, \bar{q}\gamma_5\sigma^{\mu\nu}G_{\mu\nu}q, \bar{q}q\bar{q}\gamma_5 q, \ldots\}$$

(gluon & light quarks CEDMs, EDMs, 4-fermion operators)

The next step is to guess the underlying BSM models at higher scales, producing the corresponding Wilson coefficients at O(1) GeV.

This is a cumbersome process involving many free parameters, so we begin with certain assumptions simplifying the problem.

Here we study this question in simple scenario in which BSM CPV is dominated by the gluon and quark chromo-EDMs around the EW scale, which is often the case if BSM physics is mediated to the SM sector mainly by the gluons or the Higgs bosons:

KC, Im, Jodlowski, to appear

Vector-like quarks

Multi-Higgs

Split-SUSY with light gluinos

Certain parameter region of other BSM models

$$\mathcal{L}_{\rm BSM-CPV}(\mu = M_W) = \frac{1}{3} w f^{abc} G^{a\mu}_{\alpha} G^{b\delta}_{\mu} \widetilde{G}^{c\alpha}_{\delta} - \frac{i}{2}\sum_q \tilde{d}_q g_s \bar{q}\sigma^{\mu\nu} G_{\mu\nu}\gamma_5 q$$

Gluon CEDM
(Weinberg operator)

Quark CEDMs

More specifically we will be focusing on the following **4 simple scenarios** and examine if we can discriminate between these 4 scenarios with nucleon and diamagnetic atomic EDMs which have a good prospect to be measured in future EDM experiments:

- θ_{QCD} domination (with or without axion)

  (Axion VEV dominantly induced by additional PQ-breaking at UV scales)

- Gluon CEDM domination at the EW scale (with or without axion)

  (Axion VEV dominantly induced by the corresponding BSM CPV)

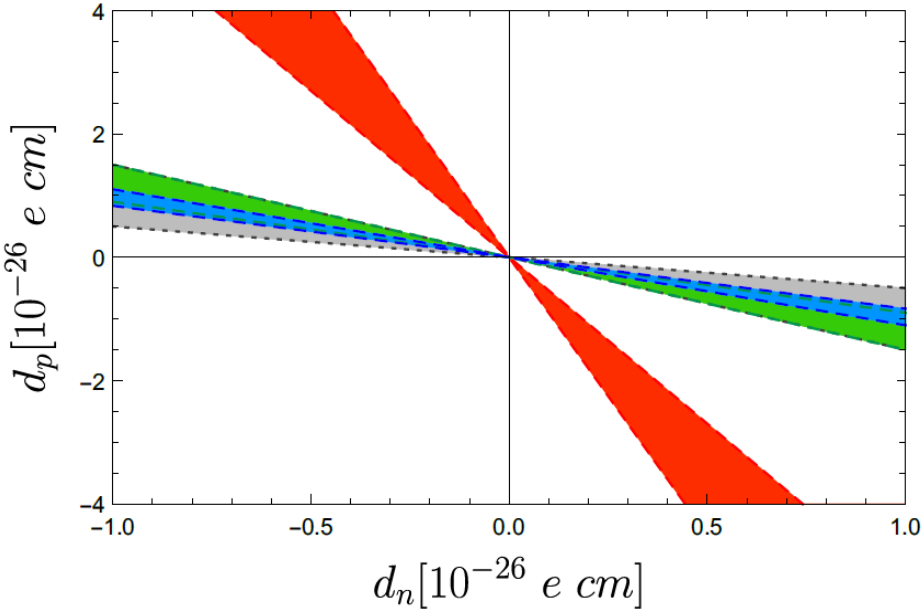
- Quark CEDM domination at the EW scale with axion

  (Axion VEV dominantly induced by the corresponding BSM CPV)

- Quark CEDM domination at the EW scale without axion

With this study, we might be able to get some insight about "to what extent EDMs can provide information on QCD axion".

Nucleon EDMs



RG evolution from the EW scale to 1 GeV and apply the existing QCD sum rule & ChPTresults:

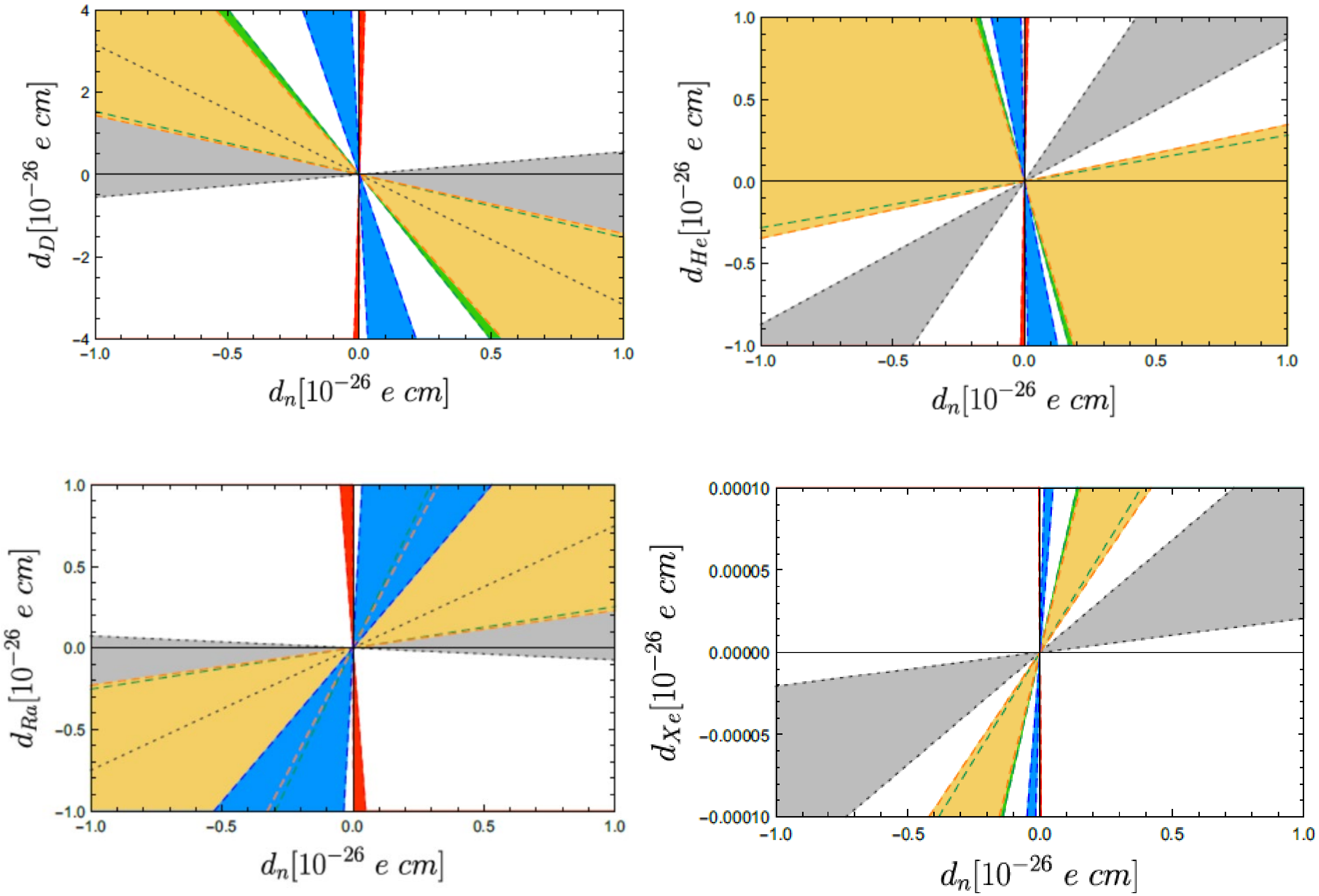
Pospelov, Ritz '99
Hisano, Lee, Nagata, Shimizu '12
Hisano, Kobayashi, Kuramoto, Kuwahara '15
Yamanaka, Hiyama '20

KC, Im, Jodlowski, to appear

- θ_{QCD} domination (with or without axion)
- Gluon CEDM domination (with or without axion)
- Quark CEDM domination with axion
- Quark CEDM domination without axion

With d_p/d_n , one can clearly distinguish "quark CEDM domination without axion" from other cases, while the other three cases are not distinguishable from each other.

Diamagnetic atomic EDMs



QCD sum rule, ChPT,
Nuclear physics results

Chupp et al '19
de Vries et al '21
Osamura et al '22

θ_{QCD} domination
with or without axion

without axion
with axion
Gluon CEDM domination

Quark CEDM domination
with axion

Quark CEDM domination
without axion

Our results implies that EDMs can provide not only the information on BSM CPV, but also additional information on QCD axion including the origin of the axion VEV (Quality of the PQ-symmetry).

To generalize our analysis to more generic case, it is crucial to reduce the uncertainties in the involved QCD, nuclear and atomic physics analysis for the nucleon, atomic, molecular EDMs.

Conclusion

- If an axion is discovered, so its mass is known, we might be able to measure multiple axion couplings, e.g.

$$g_{aX} \ \ (X = \gamma, p, n, e)$$

  and the pattern of these couplings might tell us which type of axion we have discovered among the DFSZ-type, KSVZ-type, and string-theoretic axions.

- EDMs can provide not only the information on BSM CP violation, but also information on QCD axion including the quality of the PQ symmetry.

  To extend our analysis to more generic situations, we need further improvement of the involved QCD, nuclear and atomic physics calculations.

Thank you for your attention.