Imprints of string theory in low energy observables via axions

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- K Choi, SHI, HJ Kim, H Seong, *JHEP 08 (2021) 058, 2106.05816*
- K Choi, SHI, K Jodlowski, in preparation

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Outline

- Imprints of microscopic origins of axions in *low energy axion couplings*

- Testing the origin of CP and PQ breaking with *electric dipole moments of nucleons and atoms*

Strong CP problem and QCD axion

$$y_u H Q_L u_R^c + y_d H^* Q_L d_R^c + \frac{g_s^2}{32\pi^2}\theta G\tilde{G}$$

CPV in the QCD sector

$$\bar{\theta} = \theta + \arg\det(y_u y_d) < 10^{-10}$$

Non-observation of neutron EDM

[Abel et al '20]

while $\delta_{\mathrm{CKM}} = \arg\det\left[y_u y_u^\dagger, y_d y_d^\dagger\right] \sim \mathcal{O}(1)$

The QCD vacuum energy is minimized at the CP-conserving point ($\bar{\theta} = 0$).

[Vafa, Witten '84]

$$V_{QCD} \sim -\Lambda_{QCD}^4 \cos\bar{\theta}$$

Promote $\bar{\theta}$ to a dynamical field (=QCD axion) : $\frac{g_s^2}{32\pi^2}\left(\theta + \frac{a}{f_a}\right)G\tilde{G}$

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

QCD axion lagrangian

$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)^2 + \frac{g_s^2}{32\pi^2} c_G \frac{a}{f_a} G^{\mu\nu}\tilde{G}_{\mu\nu}$$
$$+ \frac{a}{f_a} \sum_{A=W,B,\ldots} \frac{g_A^2}{32\pi^2} c_A F^{A\mu\nu}\tilde{F}^A_{\mu\nu} + \frac{\partial_\mu a}{f_a}\left(\sum_{\psi=q,\ell,\ldots} c_\psi \psi^\dagger \bar{\sigma}^\mu \psi + \sum_{\phi=H,\ldots} c_\phi \phi^\dagger i\overleftrightarrow{D}^\mu \phi \right)$$

$$U(1)_{PQ}: \quad a(x) \to a(x) + \alpha$$

broken by $c_G \neq 0$ non-perturbatively

$$m_a^2 \simeq c_G^2 \frac{m_u m_d}{(m_u + m_d)^2} \frac{m_\pi^2 f_\pi^2}{f_a^2}$$

The axion couplings to the other SM particles $c_W, c_B, c_q, c_\ell, c_H$ depend on UV physics.

Axion-Like Particles (ALPs)

- Cousins of the QCD axion, while not being necessarily involved in solving the strong CP problem (so c_G can be 0)
- Ubiquitous in many BSM scenarios, in particular, string theory

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

$$\frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2 + \frac{a}{f_a}\sum_A \frac{g_A^2}{32\pi^2} c_A F^{A\mu\nu}\tilde{F}^A_{\mu\nu} + \frac{\partial_\mu a}{f_a}\left(\sum_\psi c_\psi \psi^\dagger \bar{\sigma}^\mu \psi + \sum_\phi c_\phi \phi^\dagger i \overleftrightarrow{D}^\mu \phi\right)$$

i) approximate shift symmetry $U(1)_{PQ}$ $\quad a(x) \rightarrow a(x) + c \;\; (c \in \mathbb{R})$

: ALP can be naturally light.

ii) periodicity $\quad \dfrac{a(x)}{f_a} \equiv \dfrac{a(x)}{f_a} + 2\pi$

: f_a characterizes typical size of ALP couplings up to the dimensionless parameters c_A, c_ψ, c_ϕ which depend on UV physics.

Axions in string theory

Witten '84

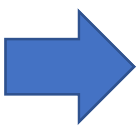
4D axions from p-form gauge fields

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

Ω : harmonic p-form on the compact internal space

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

Model-independent axion from 2-form field



SUSY-preserving compactification

$$T = \tau + ia$$

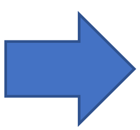
Axion chiral superfield
(τ : volume modulus of the p-cycle dual to Ω)

$U(1)_{PQ}$: $T \to T + ic$

From a gauge symmetry

Periodicity : $T \equiv T + 2\pi i$

$$\delta A_{[M_1 M_2 \ldots M_p]} = \partial_{[M_1}\Lambda_{M_{2,\ldots}M_p]}$$



4D SUGRA effective lagrangian

$$K = K_0(T + T^*) + Z_I(T + T^*)\Phi_I^* e^{g_A V_A}\Phi_I + \cdots$$

$$\mathcal{F}_A = \frac{c_A}{8\pi^2}T + \cdots \qquad Z_I \propto (T + T^*)^{\omega_I}$$

c_A , ω_I : $O(1)$ rational numbers

For $\tau \gg 1$, the matter field normalization is proportional to a simple scaling of the internal space volume.

Conlon, Cremades, Quevedo '06

$$K = K_0(T+T^*) + Z_I(T+T^*)\Phi_I^* e^{g_A V_A}\Phi_I + \cdots$$

$$\mathcal{F}_A = \frac{c_A}{8\pi^2}T + \cdots \qquad Z_I \propto (T+T^*)^{\omega_I}$$

c_A , ω_I : $O(1)$ rational numbers

$$T = \tau + ia$$

$$\mathcal{L}_{\rm eff} = \frac{M_P^2}{4}\partial_\tau^2 K_0\,(\partial_\mu a)^2 + \frac{\omega_I}{2\tau}\partial_\mu a\left(\psi_I^\dagger\bar\sigma^\mu\psi_I + \phi_I^\dagger i\overleftrightarrow{D}^\mu\phi_I\right) - \frac{1}{4}\left(\frac{c_A\tau}{8\pi^2} + \cdots\right)F^{A\mu\nu}F^A_{\mu\nu} + \frac{c_A}{32\pi^2}aF^{A\mu\nu}\widetilde{F}^A_{\mu\nu}$$

Value of τ ?

i) $\dfrac{c_A\tau}{8\pi^2} \lesssim \dfrac{1}{g_A^2}$

ii) Contribution to axion potential from brane instantons

$$\delta V(a) \sim e^{-\tau} m_{3/2} M_P^3 \cos a \lesssim \mathcal{O}(m_a^2 f_a^2)$$

$$\Rightarrow \quad \tau \gtrsim \ln(m_{3/2}M_P/m_a^2) \sim \frac{8\pi^2}{g^2_{\rm GUT}} + \ln\left(\frac{m_{3/2}}{1\,{\rm TeV}}\right) + 2\ln\left(\frac{10^{-5}\,{\rm eV}}{m_a}\right)$$

From i) and ii), $\boxed{\mathcal{O}\left(\dfrac{8\pi^2}{g^2_{\rm GUT}}\right) \lesssim \tau \lesssim \dfrac{1}{c_A}\dfrac{8\pi^2}{g_A^2}}$

$$\mathcal{L}_{\text{eff}} = -\frac{1}{4g_A^2} F^{A\mu\nu} F^A_{\mu\nu} + \frac{M_P^2}{4} \partial_\tau^2 K_0 \left(\partial_\mu a\right)^2 + \frac{\omega_I}{2\tau} \partial_\mu a \left(\psi_I^\dagger \bar{\sigma}^\mu \psi_I + \phi_I^\dagger i \overleftrightarrow{D}^\mu \phi_I \right) + \frac{c_A}{32\pi^2} a F^{A\mu\nu} \widetilde{F}^A_{\mu\nu}$$

$$\frac{c_A g_A^2}{8\pi^2} \lesssim \frac{1}{\tau} \lesssim \mathcal{O}\left(\frac{g_{\text{GUT}}^2}{8\pi^2} \right)$$

$$\mathcal{L}_{\text{eff}} = -\frac{1}{4g_A^2} F^{A\mu\nu} F^A_{\mu\nu} + \frac{M_P^2}{4} \partial_\tau^2 K_0 \left(\partial_\mu a\right)^2 + \omega_I \mathcal{O}\left(\frac{c_A g_A^2}{16\pi^2} \right) \partial_\mu a \left(\psi_I^\dagger \bar{\sigma}^\mu \psi_I + \phi_I^\dagger i \overleftrightarrow{D}^\mu \phi_I \right) + \frac{c_A}{32\pi^2} a F^{A\mu\nu} \widetilde{F}^A_{\mu\nu}$$

Axions from p-form gauge fields have comparable strength for axion-matter and axion-gauge couplings.

Canonical normalization $a \to \frac{a}{f_a}$ $\quad f_a = M_P \sqrt{\frac{\partial_\tau^2 K_0}{2}}$

$$\boxed{\mathcal{L}_{\text{eff}} = -\frac{1}{4g_A^2} F^{A\mu\nu} F^A_{\mu\nu} + \frac{1}{2} (\partial_\mu a)^2 + \omega_I \mathcal{O}\left(\frac{c_A g_A^2}{16\pi^2} \right) \frac{\partial_\mu a}{f_a} \left(\psi_I^\dagger \bar{\sigma}^\mu \psi_I + \phi_I^\dagger i \overleftrightarrow{D}^\mu \phi_I \right) + \frac{c_A}{32\pi^2} \frac{a}{f_a} F^{A\mu\nu} \widetilde{F}^A_{\mu\nu}}$$

KSVZ axion

Kim '79, Shifman, Vainshtein, Zakharov '80

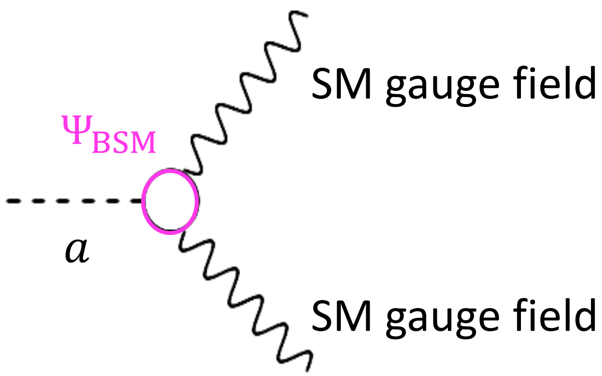
The axion *couples to SM fields via a heavy BSM fermion* charged under the SM gauge group.

$$\boxed{y\Phi\Psi_{\rm BSM}\Psi^c_{\rm BSM} + {\rm h.c.}}$$

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

$$\langle\Phi\rangle = \frac{1}{\sqrt{2}}f_a$$

$$m_\Psi = \frac{y}{\sqrt{2}}f_a$$



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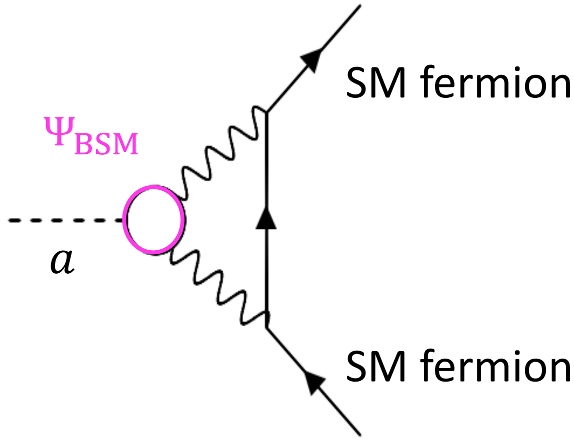


"KSVZ-like axions"

: *no tree-level couplings* to the SM fermions

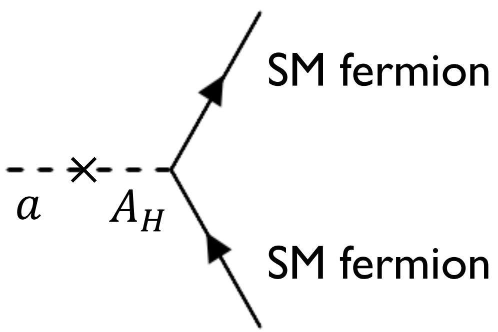
DFSZ axion

Dine, Fischler, Srednicki '81, Zhitnitsky '80

The axion *couples to the SM sector at tree-level* through the Higgs portal.

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

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



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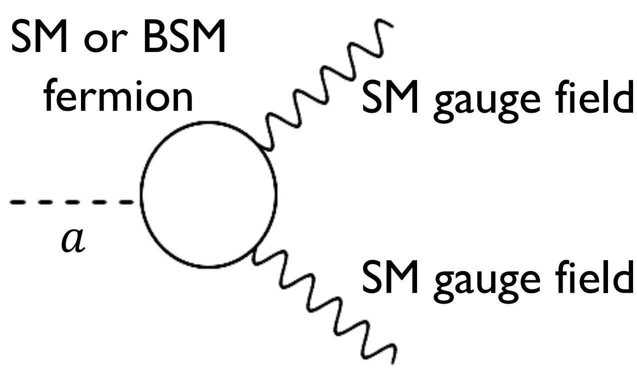
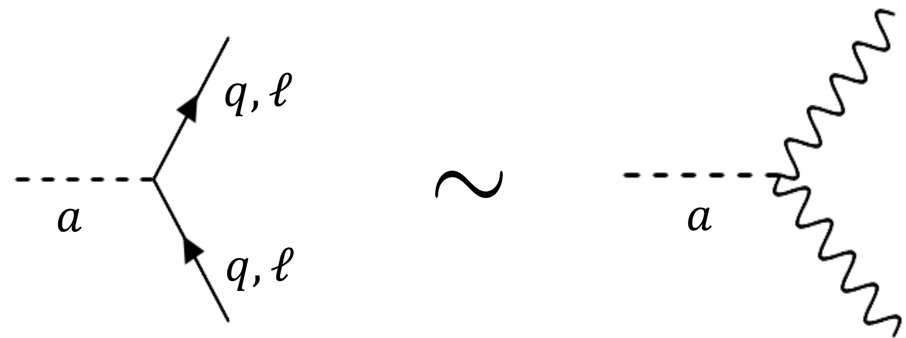


"DFSZ-like axions"

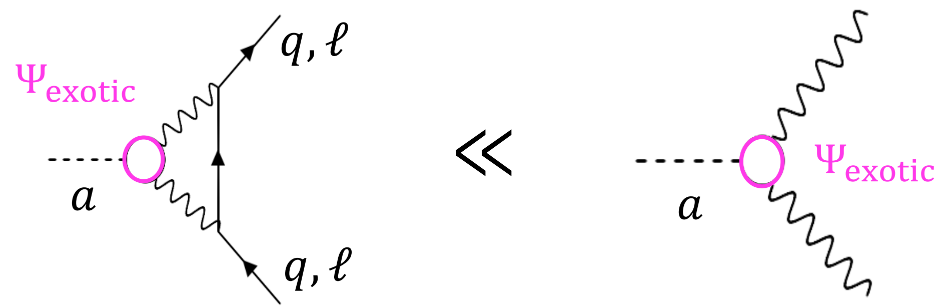
: $O(1)$ *tree-level couplings* to the SM fermions

Summary: characteristic patterns of axion couplings to the SM depending on the microscopic origins

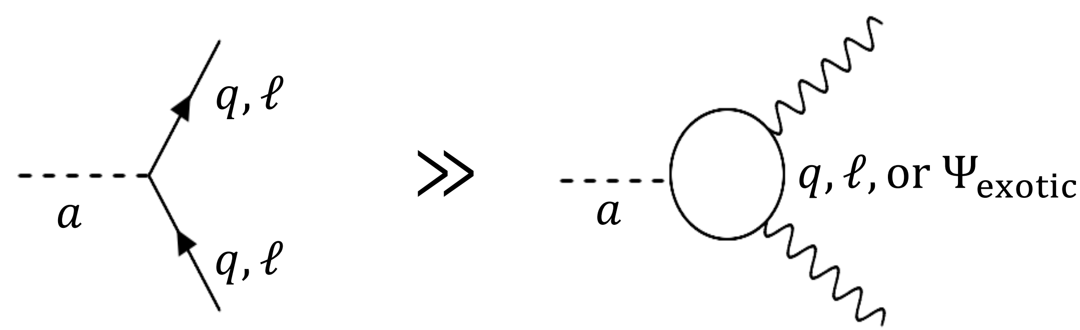
String-theoretic axions



KSVZ-like axions

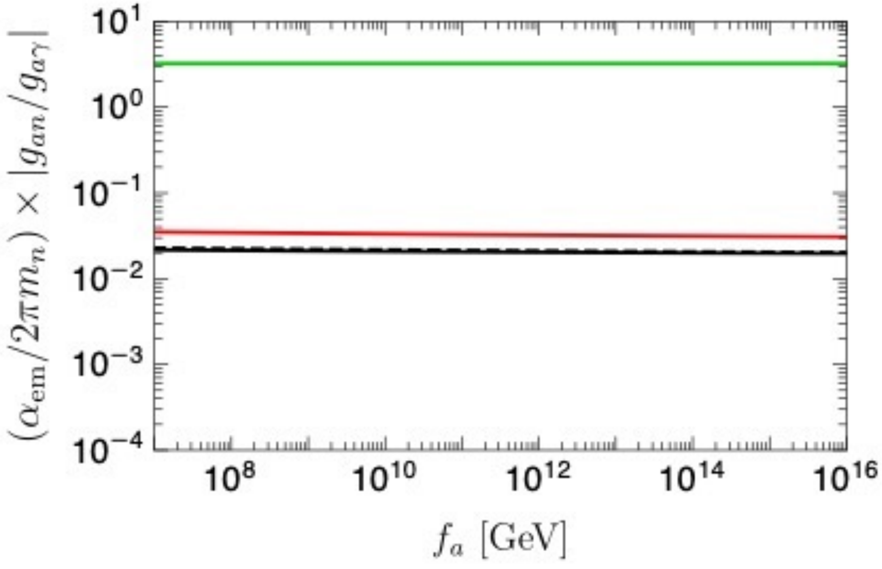


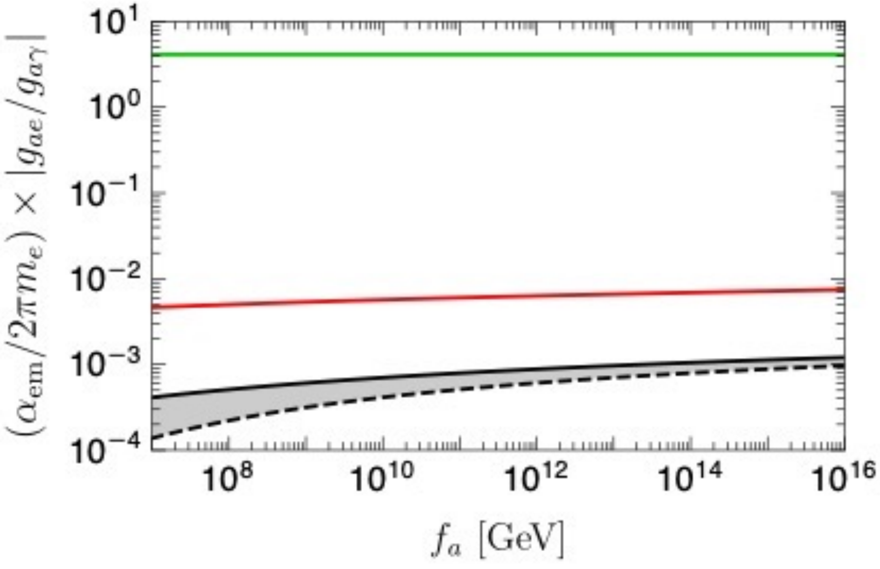
DFSZ-like axions



Uncovering UV physics for axions by coupling ratios

For QCD axion ($c_G \neq 0$), $g_{ap} \sim \frac{\mathrm{m_p}}{\mathrm{f_a}}$ regardless of the classes of models



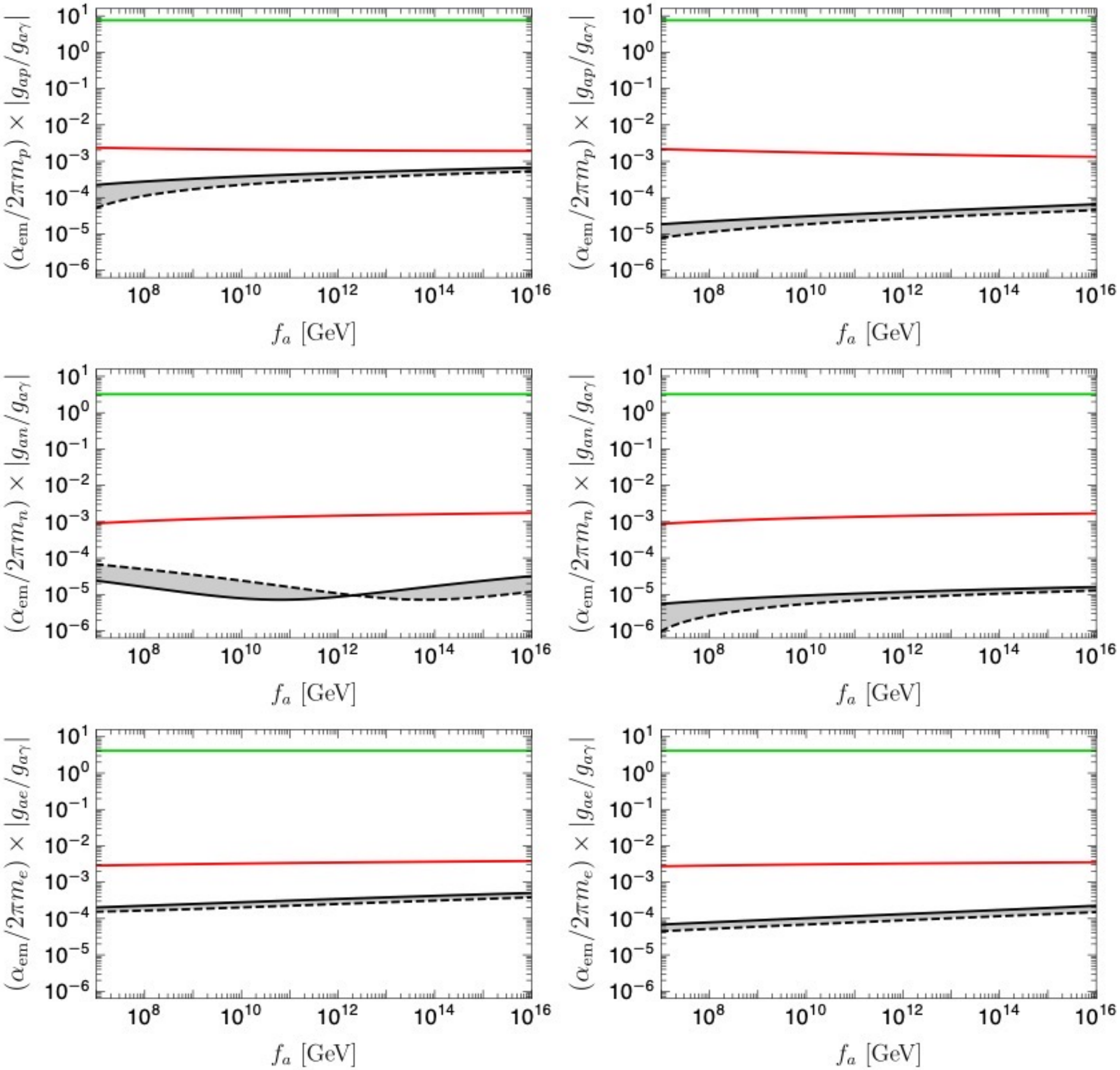


Green : DFSZ-like axion (DFSZ-1 with $\tan\beta = 10$ and $m_{H^{\pm}} = 10$ TeV)

Red : String-theoretic axion

Black : KSVZ-like axion (dashed : $m_Q = 10^{-3} f_a$, solid : $m_Q = f_a$)

For ALPs with ($c_G = 0$),



Green : DFSZ-like axion

Red : String-theoretic axion

Black : KSVZ-like axion

(dashed : $m_Q = 10^{-3} f_a$,

solid : $m_Q = f_a$)

$c_W = 1$ ($c_G = c_B = 0$) $\quad$ $c_B = 1$ ($c_G = c_W = 0$)

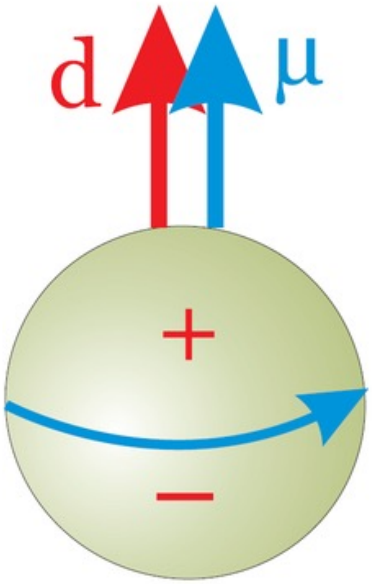
Outline

- Imprints of microscopic origins of axions in *low energy axion couplings*

- Testing the origin of CP and PQ breaking with *electric dipole moments of nucleons and atoms*

EM dipole moments of a particle

A fundamental particle or an atom can have electric dipole moment (d) and magnetic dipole moment (μ) along the direction of its spin.



$$H = -\mu\, \mathbf{B} \cdot \frac{\mathbf{S}}{S} - d\, \mathbf{E} \cdot \frac{\mathbf{S}}{S}$$

$$P : \mathbf{E} \to -\mathbf{E},\ \ \mathbf{B} \to +\mathbf{B},\ \ \mathbf{S} \to +\mathbf{S}$$
$$T : \mathbf{E} \to +\mathbf{E},\ \ \mathbf{B} \to -\mathbf{B},\ \ \mathbf{S} \to -\mathbf{S}$$

A non-zero electric dipole moment breaks the P and $T(= CP)$ invariance, while a magnetic dipole moment does not.

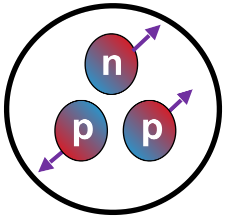
CP violation is an important condition to generate the asymmetry between matter and antimatter.

Observed asymmetry : $Y_B = \frac{n_B}{s} \sim 10^{-10}$

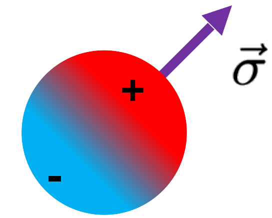
SM prediction : $Y_{B,SM} \lesssim 10^{-15}$

e.g. Konstandin, Prokopec, G. Schmidt '03

SM does not provide an enough CP violation, and we need new physics beyond the SM involving additional CP violation.



EDM probe for New Physics



None of electric dipole moments (EDMs) of any fundamental particles and atoms has been observed so far.

SM prediction

$$d_N \sim (10^{-32}\delta_{\mathrm{CKM}} + 10^{-16}\,\bar{\theta})\ \text{e cm}$$
$$d_e \sim (10^{-44}\,\delta_{CKM} + 10^{-27}\,\bar{\theta})\ \text{e cm}$$

$\delta_{\mathrm{CKM}} \sim O(1)$

Experimental status

$$d_n < 1.8 \times 10^{-26}\ \text{e cm}$$
$$d_e < 4.1{\times}10^{-30}\ \text{e cm}$$

Abel et al '20

Roussy et al '22

$\bar{\theta} \lesssim 10^{-10} \leftarrow$

Typical BSM prediction

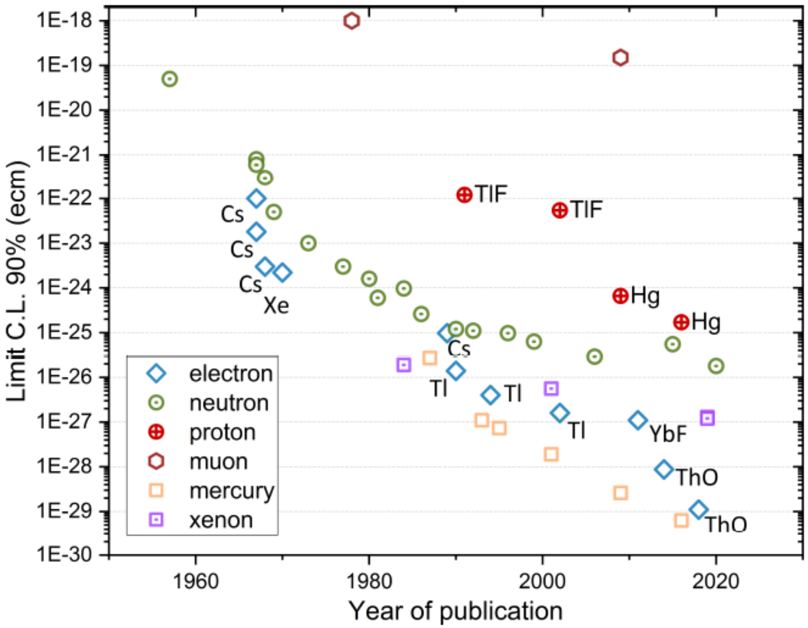
$$d_N \sim \frac{1}{16\pi^2}\frac{f_\pi}{\Lambda^2}$$
$$d_e \sim \frac{1}{16\pi^2}\frac{m_e}{\Lambda^2}$$

$\Lambda \gtrsim O(10{\sim}100)$ TeV

Powerful probe for new physics!

Experimental prospect

2003.00717



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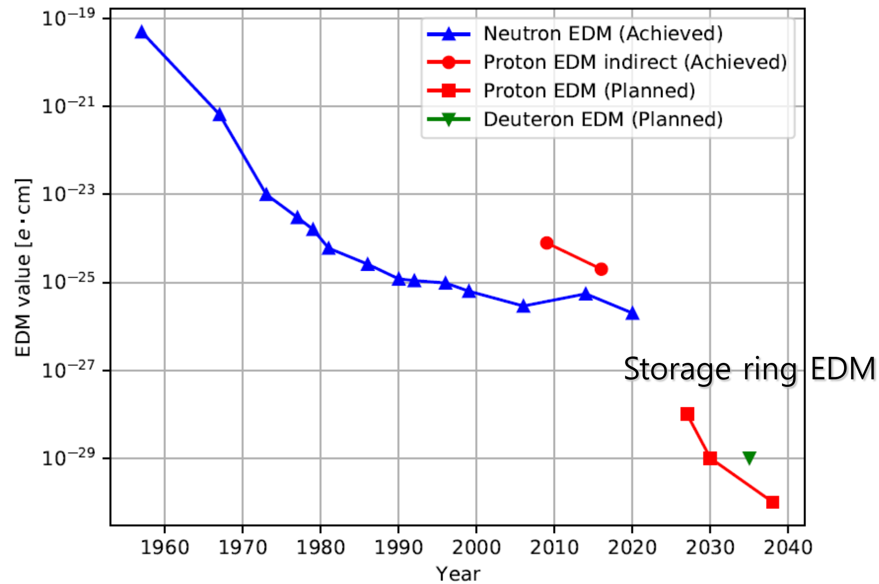


Within a decade, the experimental sensitivity on nuclear and atomic EDMs is going to be improved by several orders of magnitude.

CPV effective operators from New Physics

CPV dimension-6 operators of SM fields

$$f^{abc}G^aG^b\widetilde{G}^c + |H|^2 G\widetilde{G} + H\bar{Q}_L\sigma^{\mu\nu}G_{\mu\nu}d_R$$

$$+ H\bar{Q}_L\sigma^{\mu\nu}B_{\mu\nu}d_R + \bar{L}_L e_R \bar{d}_R Q_L + \cdots$$

⬇ EWSB

: this work!

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

Gluon and Quark Chromo-EDMs

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

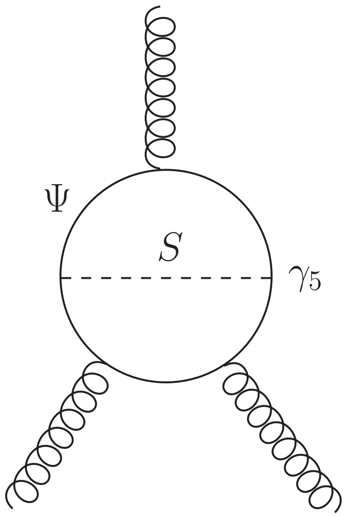
Quark and Electron EDMs

4-Fermi operators

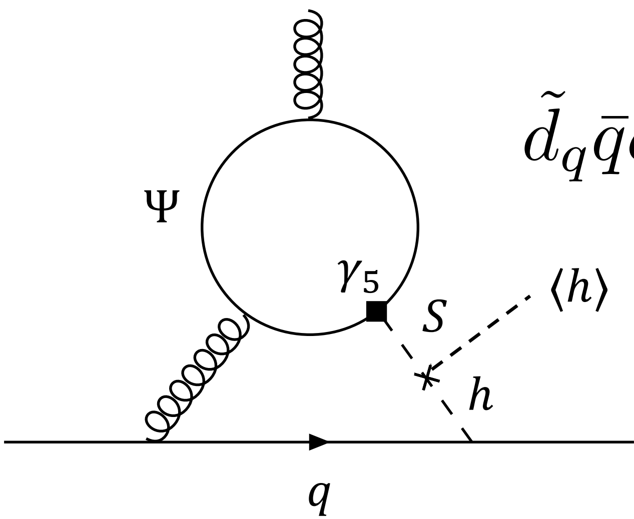
e.g.) Split SUSY (Giudice and Romanino ‘05)

e.g.) LR symmetric model, Leptoquark (de Vries et al ‘21)

BSM scenarios



$$d_w G G \tilde{G}$$



$$\tilde{d}_q \bar{q} \sigma \cdot G i \gamma^5 q$$

- Vector-like Quarks

  K Choi, SHI, H Kim, DY Mo '16

- MSSM
- Split SUSY with light gluinos

  Hisano, Kobayashi, Kuramoto, Kuwahara '15

- 2-Higgs doublet models

  S. Weinberg '89
  Gunion, Wyler '90
  Chang, Keung, Yuan '90
  Jung, Pich '14

Characteristic CPV signal of string theory?

A large QCD θ-parameter from QG correction to the QCD axion potential

$$V(\bar{\theta}) \simeq V_{\rm QCD}(\bar{\theta}) + V_{\rm QG}(\bar{\theta})$$

$$V_{\rm QCD}(\bar{\theta}) \sim -m_\pi^2 f_\pi^2 \cos\bar{\theta}$$

$$V_{\rm QG}(\bar{\theta}) \sim -m_{3/2} M_{\rm Pl}^3 \exp(-\tau) \cos(\bar{\theta} + \delta_{\rm CP})$$

e.g. D3-brane instantons in Type IIB string

$$\langle\bar{\theta}\rangle \sim \frac{m_{3/2} M_{\rm Pl}^3}{m_\pi^2 f_\pi^2} e^{-\tau} \delta_{\rm CP}$$

Demirtas, Gendler, Long, McAllister, Moritz '21

$$-N_{\rm axion}^4 \lesssim \ln\langle\bar{\theta}\rangle \lesssim 0$$

Nearly flat logarithmic distribution over the landscape

A sizable $\bar{\theta} \sim 10^{-10}$ is easily realized in string theory.

BSM contribution to $\langle\bar{\theta}\rangle$

$$V(\bar{\theta}) \simeq V_{\rm QCD}(\bar{\theta}) + V_{\rm QG}(\bar{\theta}) + V_{\rm BSM}(\bar{\theta})$$

$$V_{\rm BSM}(\bar{\theta}) \sim -m_\pi^2 f_\pi^2 \left(\frac{\Lambda_{\rm QCD}}{\Lambda_{\rm BSM}}\right)^N \cos(\bar{\theta} + \delta_{\rm CP,BSM})$$

: CPV by $\delta_{\rm CP,BSM}$ & PQ breaking by the QCD instantons

$$\Rightarrow \quad \langle\bar{\theta}\rangle \sim \frac{m_{3/2} M_{\rm Pl}^3}{m_\pi^2 f_\pi^2} e^{-\tau} \delta_{\rm CP,string} + \left(\frac{\Lambda_{\rm QCD}}{\Lambda_{\rm BSM}}\right)^N \delta_{\rm CP,BSM}$$

The BSM contribution can also easily give rise to $\bar{\theta} \sim 10^{-10}$.

[e.g. For $N = 2$ (dimension 6 operator), $\Lambda_{\rm BSM} \sim 100$ TeV]

Can we experimentally distinguish string-induced $\langle\bar{\theta}\rangle$ from BSM-induced $\langle\bar{\theta}\rangle$?

Do they predict different EDM signals?

String

$$\theta G\tilde{G}$$

θ-parameter

vs

BSM

$$d_w G G \tilde{G}$$

Gluon CEDM

$$\tilde{d}_q \bar{q} \sigma \cdot G i \gamma^5 q$$

Quark CEDMs

Estimation of the nucleon EDMs

Naïve dimensional analysis (NDA)

$$d_N \sim \frac{e}{\Lambda_\chi}\left(\frac{m_*}{\Lambda_\chi}\bar{\theta} + \frac{\Lambda_\chi^2}{4\pi} d_w + \frac{\Lambda_\chi}{4\pi}\tilde{d}_q\right)$$

$$\Lambda_\chi = 4\pi f_\pi$$

$$m_* \equiv \left(trM_q^{-1}\right)^{-1} \simeq \frac{m_u m_d}{m_u + m_d}$$

Agrees more or less

QCD sum rules

$$d_p = -0.46\times 10^{-16}[e\ cm]\ \bar{\theta} - e(18\ \mathrm{MeV})d_w + e(-0.17\ \tilde{d}_u + 0.12\ \tilde{d}_d + 0.0098\ \tilde{d}_s)$$

$$+e(1.1\ \mathrm{MeV})C_2 \qquad \tilde{d}_q \equiv m_q C_2$$

$$d_n = 0.31\times 10^{-16}[e\ cm]\ \bar{\theta} + e(20\ \mathrm{MeV})d_w + e(-0.13\ \tilde{d}_u + 0.16\ \tilde{d}_d - 0.0066\ \tilde{d}_s)$$

$$-e(0.15\ \mathrm{MeV})C_2$$

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

➡ $d_p(\bar{\theta}, d_w) \approx -d_n(\bar{\theta}, d_w)$ while $d_p(\tilde{d}_q) \approx -7 d_n(\tilde{d}_q)$

If there exists the QCD axion (i.e. dynamical $\bar{\theta}$),

$$\langle\bar{\theta}\rangle = \bar{\theta}_{QG} + \frac{\Lambda_\chi^2}{4\pi} d_W + \frac{0.8\ \mathrm{GeV}^2}{2}\sum_q \frac{\tilde{d}_q}{m_q}$$

NDA

QCD sum rule (Pospelov, Ritz '00)

$$d_p^{PQ} = -0.46\times10^{-16}[e\ cm]\ \bar{\theta}_{QG} - e(18\ \mathrm{MeV})d_w - \underbrace{e(0.58\ \tilde{d}_u + 0.073\ \tilde{d}_d)}_{-e(1.7\ \mathrm{MeV})C_2}$$

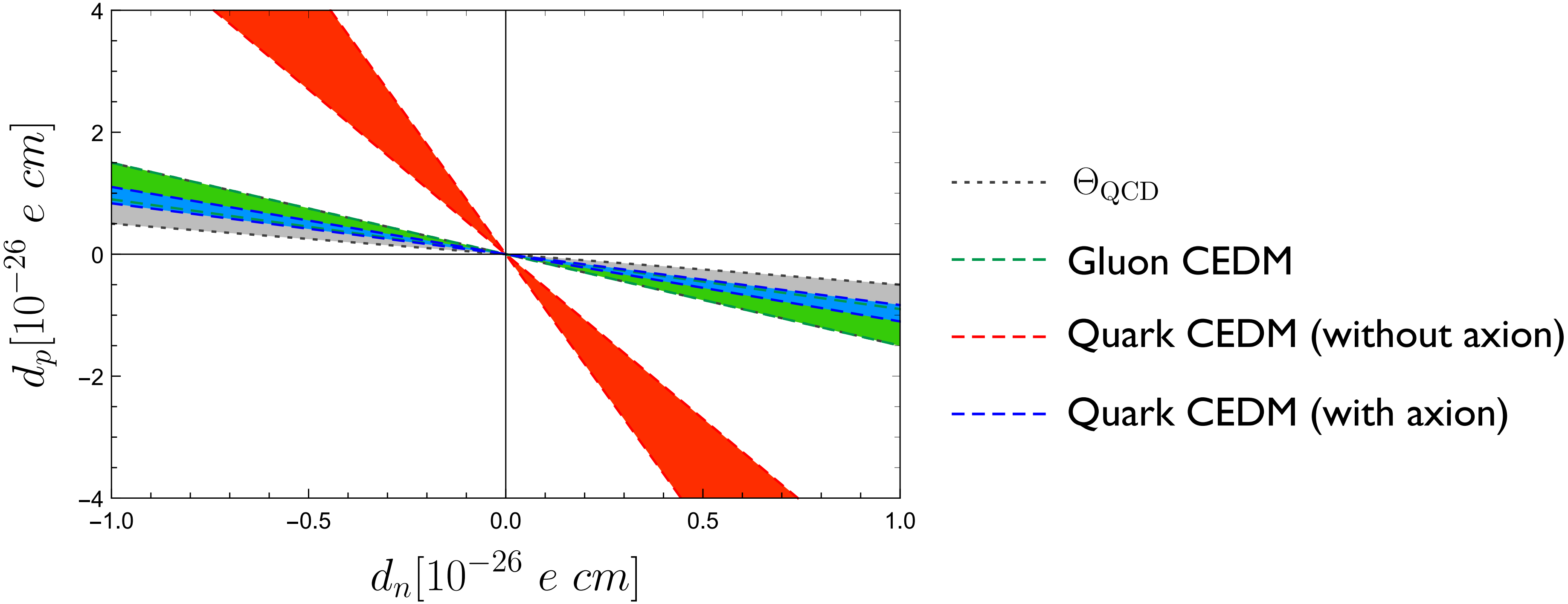
$$\tilde{d}_q \equiv m_q C_2$$

$$d_n^{PQ} = 0.31\times10^{-16}[e\ cm]\ \bar{\theta}_{QG} + e(20\ \mathrm{MeV})d_w + \underbrace{e(0.15\ \tilde{d}_u + 0.29\ \tilde{d}_d)}_{+e(1.7\ \mathrm{MeV})C_2}$$

➡ $d_p^{PQ} \approx -d_n^{PQ}$ regardless of the CPV sources

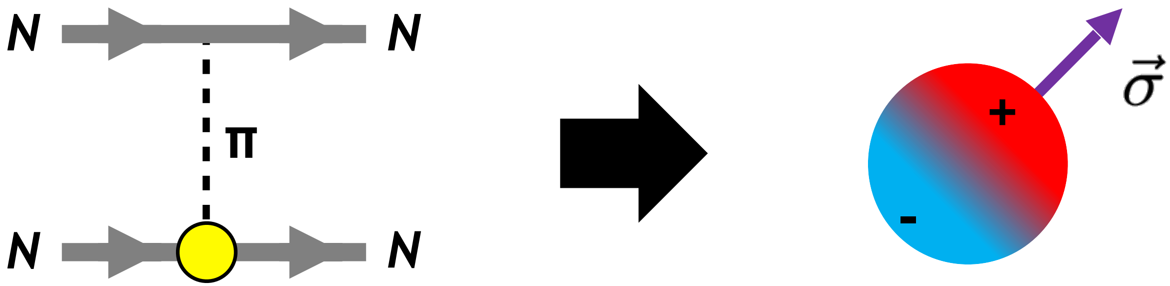
Nucleon EDM profile

Choi, SHI, Jodlowski in preparation



- If the QCD axion exists, the nucleon EDM profile is hard to distinguish the θ-dominant CPV (string scenario) from the BSM CPV scenarios.
- If the large ratio d_p/d_n (red band) is observed, it implies that *the QCD axion may not really exist.*

Aids from CP-odd nuclear force



P, CP-odd nuclear force

Polarization of nucleus
→ *Atomic electric dipole moment*

CP-odd nuclear forces are dominated by CPV pion-nucleon couplings.

$$\bar{g}_0 \bar{N} \tau \cdot \pi N + \bar{g}_1 \bar{N} \pi_3 N$$

Isospin-singlet   Isospin-breaking

Atomic EDMs from CP-odd nuclear force

$$\bar{g}_0 \bar{N} \tau \cdot \pi N + \bar{g}_1 \bar{N} \pi_3 N$$

Isospin-singlet　　Isospin-breaking

Diamagnetic atomic EDMs are particularly sensitive to CP-odd forces.

$$d_{\mathrm{Ra}} = (7.7 \times 10^{-4}) \times [(2.5 \pm 7.5)\bar{g}_0 - (65 \pm 40)\bar{g}_1] e \ \mathrm{fm}$$

$$d_D = (0.94 \pm 0.01)(d_n + d_p) + [(0.18 \pm 0.02)\bar{g}_1] e \ \mathrm{fm}$$

de Vries, Draper, Fuyuto, Kozaczuk, Lillard ’21
Osamura, Gubler, Yamanaka ‘22

Storage ring experiment is going to measure the EDMs of such light nuclei.

F. Abusaif et al. (CPEDM Collaboration) ‘19

$$\boxed{\bar{g}_1 \bar{N} \pi_3 N}$$

NDA $\quad \bar{g}_1 \sim 4\pi \frac{(m_u - m_d) m_*}{\Lambda_\chi^2} \bar{\theta} + (m_u - m_d)\Lambda_\chi d_w + \Lambda_\chi (\tilde{d}_u - \tilde{d}_d)$

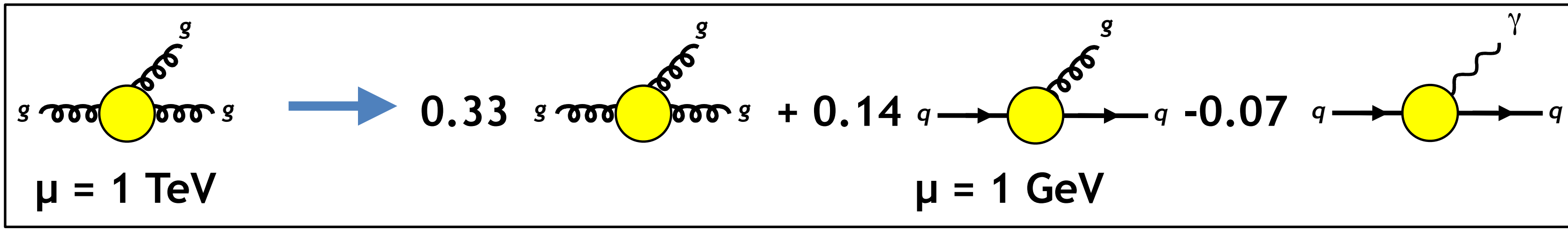
ChPT & QCD sum rules;
agrees with NDA
(Osamura, Gubler, Yamanaka '22)

$$\bar{g}_1 = (3.4 \pm 2.4)\times 10^{-3} \bar{\theta} \pm (2.2 \pm 1.6)\times 10^{-3} \mathrm{GeV}^2 d_W$$
$$+ (28 \pm 12)\mathrm{GeV}\, (\tilde{d}_u - \tilde{d}_d) \qquad \tilde{d}_q \equiv m_q C_2$$
$$-(0.7 \pm 0.3)\times 10^{-1} \mathrm{GeV}^2 C_2$$

ChPT & baryon spectrum;
larger than $4\pi\times$NDA
(de Vries, Mereghetti, Walker-Loud '15)

ChPT & QCD sum rules;
enhanced by $\frac{\sigma_{\pi N}}{\bar{m}} \sim 4\pi$
(de Vries et al '21)

RGE effect



(Adapted from Nodoka Yamanaka)

$$\Delta\tilde{d}_q(1\ \mathrm{GeV}) \simeq -r\, m_q\, d_W(1\ \mathrm{GeV})$$

$$r = 0.41\ (\Lambda_{\mathrm{BSM}} = 1\ \mathrm{TeV}),\ 0.54\ (\Lambda_{\mathrm{BSM}} = 10\ \mathrm{TeV})$$

The radiatively induced quark-CEDM from the gluon CEDM is important (even dominant) for $\bar{g}_1$, while not for d_N :

NDA

$$\bar{g}_1 \sim 4\pi \frac{(m_u - m_d)m_*}{\Lambda_\chi^2}\,\bar{\theta} + (m_u - m_d)\Lambda_\chi d_w + \Lambda_\chi\,(\tilde{d}_u - \tilde{d}_d)$$

$$d_N \sim \frac{e}{\Lambda_\chi}\left(\frac{m_*}{\Lambda_\chi}\,\bar{\theta} + \frac{\Lambda_\chi^2}{4\pi} d_w + \frac{\Lambda_\chi}{4\pi}\,\tilde{d}_q\right)$$

Nuclear and Atomic EDMs' profile

$$\frac{e\bar{g}_1(\bar{\theta})}{m_n d_n(\bar{\theta})} \approx -(3.7 \pm 3.4),$$

$$\frac{e\bar{g}_1(C_2)}{m_n d_n(C_2)} \approx (2.3 \pm 2.2) \times 10^3, \qquad \tilde{d}_q = m_q C_2$$

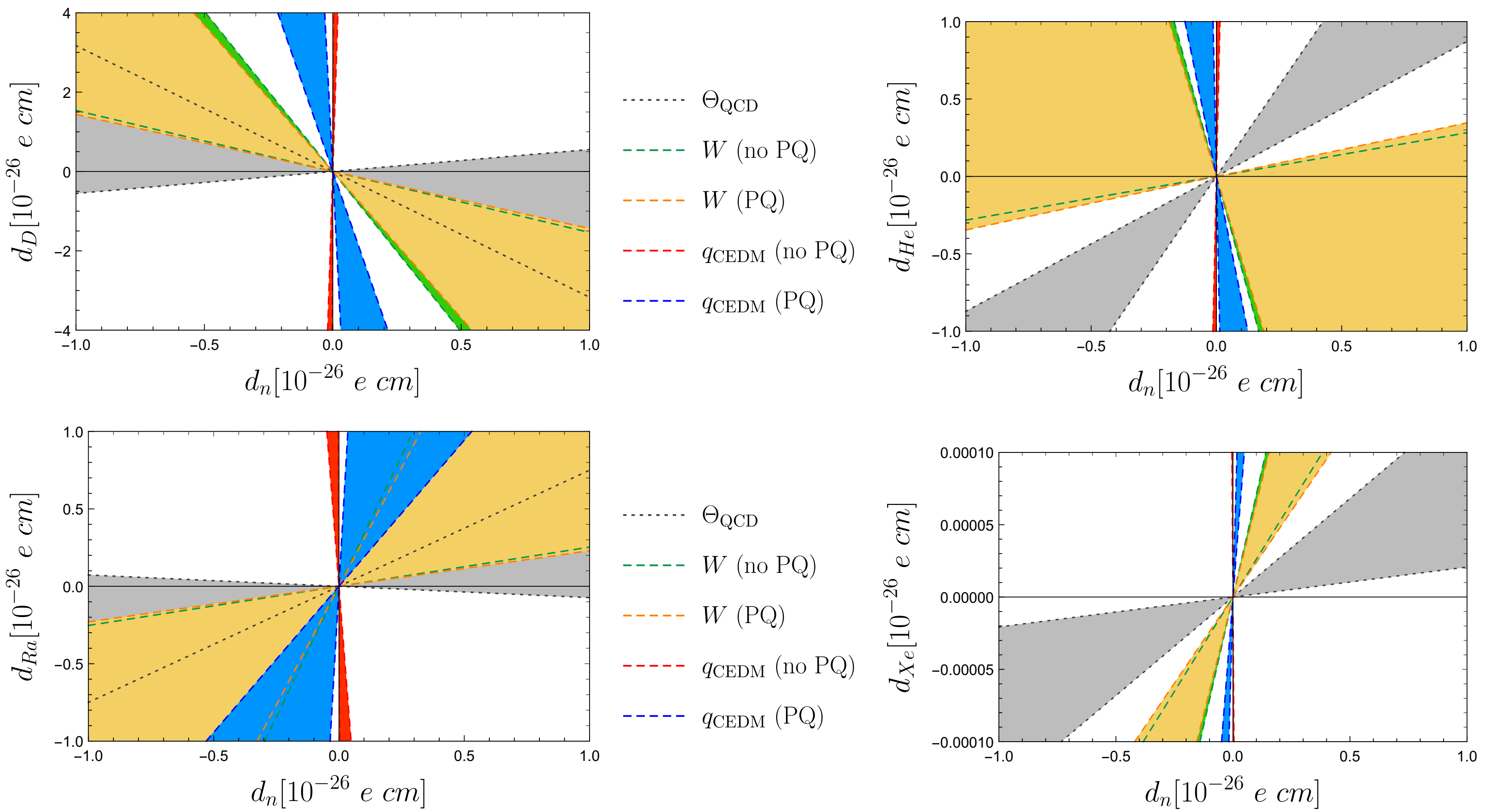
$$\frac{e\bar{g}_1^{\mathrm{PQ}}(C_2)}{m_n d_n^{\mathrm{PQ}}(C_2)} \approx -(1.00 \pm 0.89) \times 10^2,$$

$$\frac{e\bar{g}_1(\Delta C_2, w)}{m_n d_n(\Delta C_2, w)} \simeq \frac{e\bar{g}_1^{\mathrm{PQ}}(\Delta C_2, w)}{m_n d_n^{\mathrm{PQ}}(\Delta C_2, w)} \approx -(5.1 \pm 2.5)\, r(\Lambda),$$

- The ratio $\bar{g}_1/d_n$ can clearly distinguish quark CEDM-dominant CPV (with / without axion) from the others including the θ-dominant CPV.
- For the gluon CEDM-dominant CPV, on the other hand, $\bar{g}_1$ is not enough, and one may need $\bar{g}_0$.

Nuclear and Atomic EDMs' profile

Choi, SHI, Jodlowski in preparation



- d_D has no limit yet but to be probed up to 10^{-29} e cm in a storage ring experiment
  F. Abusaif et al. (CPEDM Collaboration) '19
- $d_{Ra} < 1.4\times10^{-23}$ e cm (to be improved up to 1×10^{-28} e cm) M Bishof et al '16

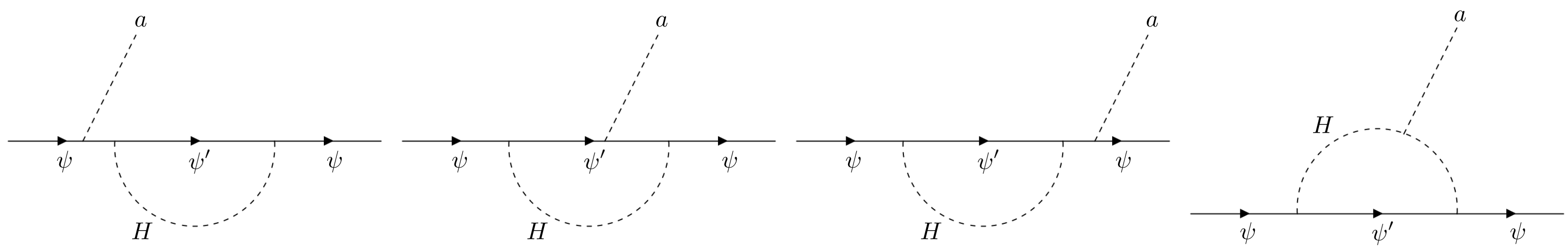
Conclusions

- Axions, once discovered, may give us a clue of UV physics including string theory by the characteristic pattern of low energy couplings to SM particles.
- The measurement of the axion-electron coupling is particularly important for pinning down the microscopic origin of the QCD axion.
- Nuclear and atomic EDMs are powerful probes for BSM above TeV scale and/or string theory.
- CPV from string theory may be imprinted in a large QCD θ-parameter if there exists the QCD axion.
- We find that the CPV from BSM scenarios dominated by gluon or quark CEDMs can be experimentally discriminated from the θ-dominant CPV by characteristic EDM profiles.
- Interestingly, quark CEDMs may tell us whether the QCD axion really exists or not.

Back-up slides

Running of axion couplings by Yukawa interactions

K Choi, SHI, CB Park, S Yun '17, Camalich, Pospelov, Vuong, Ziegler, Zupan '20
Heiles, König, Neubert '20, Chala, Guedes, Ramos, Santiago '20



$$\frac{\partial_\mu a}{f_a}\left(\sum_\psi c_\psi \psi^\dagger \bar{\sigma}^\mu \psi + \sum_{\alpha=1,2} c_{H_\alpha} H_\alpha^\dagger i\overleftrightarrow{D}^\mu H_\alpha\right) + \sum_A \frac{g_A^2}{32\pi^2} c_A \frac{a}{f_a} F^{A\mu\nu}\widetilde{F}^A_{\mu\nu}$$

$y_t u_3^c Q_3 H_\alpha$

$$\frac{dc_{Q_3}}{d\ln\mu} \approx \frac{\xi_y}{16\pi^2} y_t^2 n_t$$

$$\frac{dc_{u_3^c}}{d\ln\mu} \approx \frac{\xi_y}{8\pi^2} y_t^2 n_t$$

$$\frac{dc_{H_u}}{d\ln\mu} \approx \frac{3}{8\pi^2} y_t^2 n_t$$

$n_t = c_{u_3^c} + c_{Q_3} + c_{H_\alpha}$

$= 0$ for KSVZ-like models

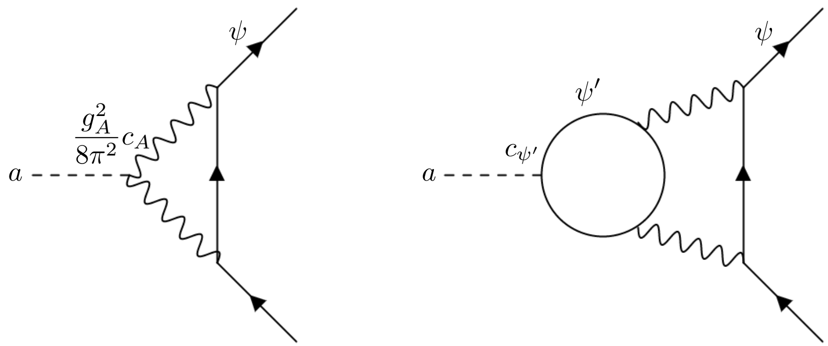
$\neq 0$ for the DFSZ model

below $\mu = m_{H^\pm}$

$$\xi_y = \begin{cases} 1 & \text{for non-SUSY models} \\ 2 & \text{for SUSY models} \end{cases}$$

Running of axion couplings by gauge interactions

Srednicki '85, S Chang and K Choi '93
K Choi, SHI, CS Shin '20,
Chala, Guedes, Ramos, Santiago '20
Bauer, Neubert, Renner, Schnubel, Thamm '20



$$\frac{\partial_\mu a}{f_a}\left(\sum_\psi c_\psi \psi^\dagger \bar{\sigma}^\mu \psi + \sum_{\alpha=1,2} c_{H_\alpha} H_\alpha^\dagger i \overleftrightarrow{D}^\mu H_\alpha\right) + \sum_A \frac{g_A^2}{32\pi^2} c_A \frac{a}{f_a} F^{A\mu\nu}\widetilde{F}^A_{\mu\nu}$$

$$\left.\frac{dc_\psi}{d\ln\mu}\right|_{\rm gauge} = -\xi_g \sum_A \frac{3}{2}\left(\frac{g_A^2}{8\pi^2}\right)^2 \mathbb{C}_A(\psi)\,\tilde{c}_A$$

$$\left.\frac{dc_{H_\alpha}}{d\ln\mu}\right|_{\rm gauge} = -\xi_H \sum_A \frac{3}{2}\left(\frac{g_A^2}{8\pi^2}\right)^2 \mathbb{C}_A(H_\alpha)\,\tilde{c}_A$$

$$\tilde{c}_A \equiv c_A - \sum_{\psi'} c_{\psi'}$$

$\neq 0$ for field-theoretic axions below the mass scale of the heaviest ψ'

$$\xi_g = \begin{cases} 1 & \text{for non-SUSY models} \\ 2/3 & \text{for SUSY models}\end{cases}, \quad \xi_H = \begin{cases} 0 & \text{for non-SUSY models} \\ 2/3 & \text{for SUSY models}\end{cases}$$

$\mathbb{C}_A(\Phi)$: quadratic Casimir

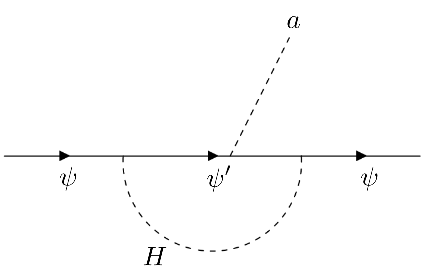
Numerical results

For $m_{BSM} = 10^{10}$ GeV and $\tan\beta = 10$,

$$
\begin{aligned}
C_u(2\,\mathrm{GeV}) &\simeq C_u(f_a) - 0.28\, n_t(f_a) + [17.7\, \tilde{c}_G(f_a) + 0.52\, \tilde{c}_W(f_a) + 0.036\, \tilde{c}_B(f_a)] \times 10^{-3}\,, \\
C_d(2\,\mathrm{GeV}) &\simeq C_d(f_a) + 0.31\, n_t(f_a) + [19.4\, \tilde{c}_G(f_a) + 0.23\, \tilde{c}_W(f_a) + 0.0047\, \tilde{c}_B(f_a)] \times 10^{-3}\,, \\
C_e(m_e) &\simeq C_e(f_a) + 0.29\, n_t(f_a) + [0.81\, \tilde{c}_G(f_a) + 0.28\, \tilde{c}_W(f_a) + 0.10\, \tilde{c}_B(f_a)] \times 10^{-3}\,.
\end{aligned}
$$

$$\frac{y_t^2}{8\pi^2} n_t(f_a) \ln\frac{m_{BSM}}{m_t} \sim 0.3\, \mathrm{n_t(f_a)}$$

$$\left(\frac{g_A^2}{8\pi^2}\right)^2 \tilde{c}_A(f_a) \ln\frac{m_{BSM}}{\mu} \sim (10^{-4} - 10^{-2})\tilde{c}_A(f_a)$$



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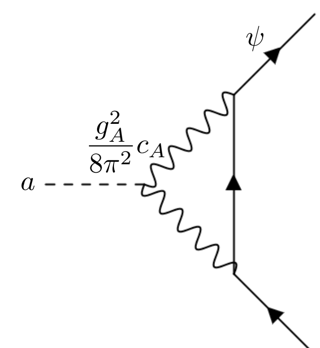
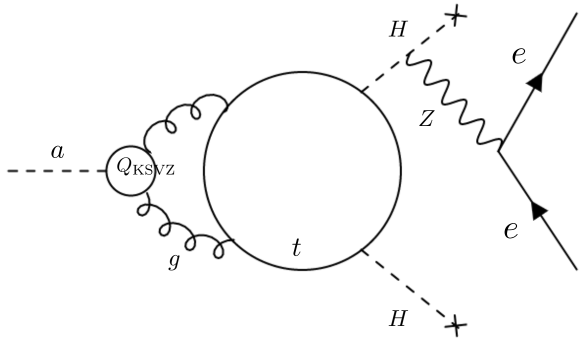
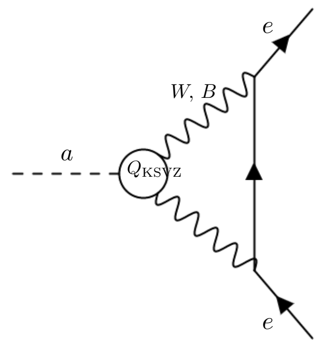
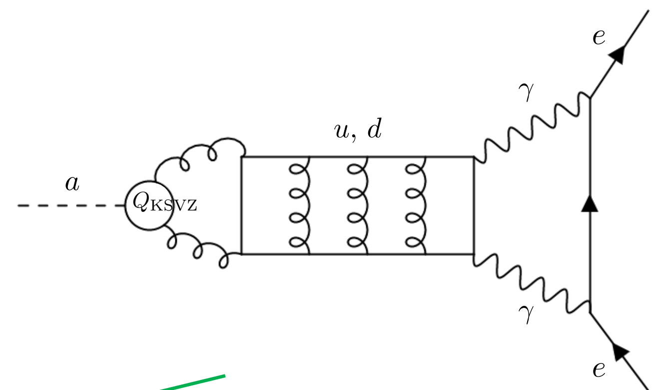


ΔC_e in KSVZ-like models

Srednicki '85
S Chang and K Choi '93
Bauer, Neubert, Renner, Schnubel, Thamm '20







$$C_e(m_e) \simeq \left[0.84\, c_G - 0.03\, c_G + 0.28\, c_W + 0.10\, c_B\right] \times 10^{-3} \quad \text{(KSVZ with MSSM)}$$

$$C_e(m_e) \simeq \left[0.83\, c_G - 0.03\, c_G + 0.54\, c_W + 0.13\, c_B\right] \times 10^{-3} \quad \text{(KSVZ with SM)},$$

Previously ignored because it is at three-loop level.

$$\left(\frac{\alpha_s}{2\pi}\right)^3 y_t^2 c_G \ln\left(\frac{f_a}{m_t}\right) \sim 10^{-3} c_G$$

Consequences in low energy observables

Axion couplings to the photon, electron, neutron, and proton below GeV

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

$$g_{a\gamma} \simeq \frac{\alpha_{\rm em}}{2\pi} \frac{1}{f_a} \left(c_W + c_B - \frac{2}{3} \frac{m_u + 4m_d}{m_u + m_d} c_G \right) \simeq \frac{\alpha_{\rm em}}{2\pi} \frac{1}{f_a} \left(c_W + c_B - 1.92 c_G \right),$$

$$g_{ap} \simeq \frac{m_p}{f_a} \left(C_u \Delta u + C_d \Delta d - \left(\frac{m_d}{m_u + m_d} \Delta u + \frac{m_u}{m_u + m_d} \Delta d \right) c_G \right),$$

$$\simeq \frac{m_p}{f_a} \left(0.90(3)\, C_u(2\,{\rm GeV}) - 0.38(2)\, C_d(2\,{\rm GeV}) - 0.48(3)\, c_G \right),$$

$$g_{an} \simeq \frac{m_n}{f_a} \left(C_d \Delta u + C_u \Delta d - \left(\frac{m_u}{m_u + m_d} \Delta u + \frac{m_d}{m_u + m_d} \Delta d \right) c_G \right),$$

$$\simeq \frac{m_n}{f_a} \left(0.90(3)\, C_d(2\,{\rm GeV}) - 0.38(2)\, C_u(2\,{\rm GeV}) - 0.04(3)\, c_G \right),$$

$$g_{ae} \simeq \frac{m_e}{f_a} C_e(m_e),$$

$$\underbrace{\langle p | \bar{u} \gamma^\mu \gamma_5 u | p \rangle}_{s^\mu \Delta u}$$

$$\underbrace{\langle p | \bar{d} \gamma^\mu \gamma_5 d | p \rangle}_{s^\mu \Delta d}$$

Cortona, Hardy, Vega, Villadoro '15

Taking into account the radiative corrections with the choice of parameters $f_a = 10^{10}$ GeV, $t_\beta = 10$, and $m_{SUSY} = 10$ TeV,

$$g_{ap} \simeq \frac{m_p}{f_a} \begin{cases} \mathcal{O}(1), & \text{DFSZ-like} \\ -0.48c_G + (0.5c_W + 0.05c_B) \times 10^{-3}, & \text{KSVZ-like} \\ -0.48c_G + 0.7\omega_I g^2_{\rm GUT} \times 10^{-2}, & \text{String} \end{cases}$$

$$g_{an} \simeq \frac{m_n}{f_a} \begin{cases} \mathcal{O}(1), & \text{DFSZ-like} \\ -0.03c_G + (0.5c_W - 0.15c_B) \times 10^{-4}, & \text{KSVZ-like} \\ -0.03c_G + 0.63\,\omega_I g^2_{\rm GUT} \times 10^{-2}, & \text{String} \end{cases}$$

$$g_{ae} \simeq \frac{m_e}{f_a} \begin{cases} \mathcal{O}(1), & \text{DFSZ-like} \\ (c_G + 0.4c_W + 0.15c_B) \times 10^{-3}, & \text{KSVZ-like} \\ (c_G + 0.4c_W + 0.15c_B) \times 10^{-3} + \omega_I g^2_{\rm GUT} \times 10^{-2}, & \text{String} \end{cases}$$

For the string-theoretic model, a universal scaling weight ω_I is assumed.

Ex) $\omega_I = \frac{1}{2}$, $\omega_I g^2_{GUT} \sim 0.25$ in a type-IIB string Large Volume Scenario

Laboratory searches for axion DM -photonic probes

$$\frac{g_{a\gamma}}{4} a F\tilde{F} \quad \Rightarrow \quad \nabla \times \vec{B} = \frac{\partial \vec{E}}{\partial t} \underbrace{- g_{a\gamma} \vec{B} \partial_t a}_{\vec{J}_{\rm eff}}$$

$\vec{J}_{\rm eff}$ effective current

Background axion DM field

$$a \approx a_0 \cos\left[m_a(t - \vec{v}\cdot\vec{x})\right]$$

$$\rho_a = \frac{1}{2} m_a^2 a_0^2 \qquad |\vec{v}| \sim 10^{-3} c$$

$$\Rightarrow \quad \vec{J}_{\rm eff} \approx g_{a\gamma} \sqrt{2\rho_a} \vec{B} \sin m_a t$$

The best experimental sensitivity on $g_{a\gamma}$ is obtained when $\rho_a = \rho_{DM}$.

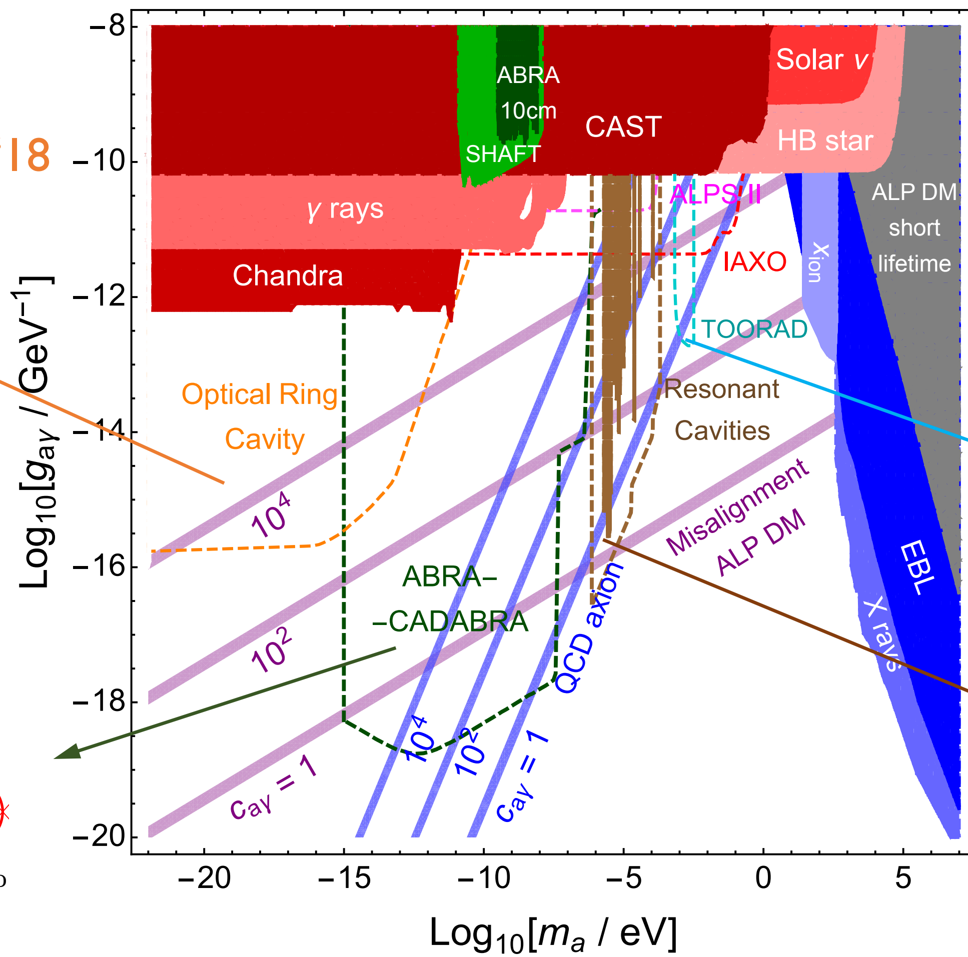
Misalignment axion DM

$$f_a \simeq 10^{17}\,\mathrm{GeV} \left(\frac{10^{-22}\,\mathrm{eV}}{m_a}\right)^{1/4} \sqrt{\frac{\rho_a}{\rho_{\rm DM}}} \quad \Rightarrow \quad g_{a\gamma} = \frac{e^2}{8\pi^2} \frac{1}{f_a} c_{a\gamma}$$

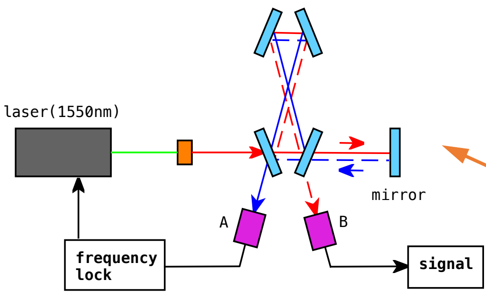
Given axion DM mass,
$g_{a\gamma}$ is determined for $c_{a\gamma} \sim O(1)$.

Current and future limits on $g_{a\gamma}$

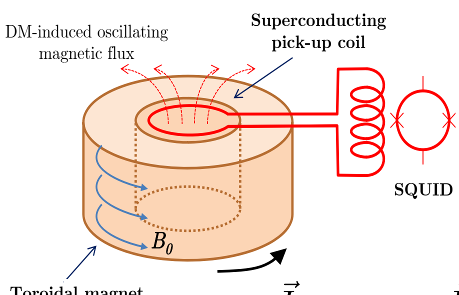
Choi, SHI, Shin '20



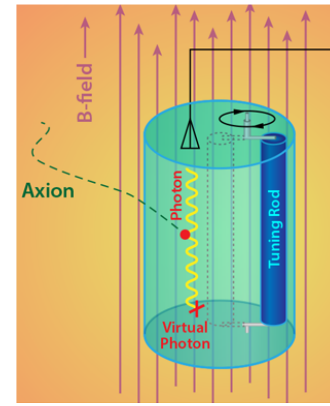
Obata, Fujita, Michimura '18



Kahn, Safdi, Thaler '16



$$\vec{J}_{\rm eff} = -g_{a\gamma}\vec{B}_0\partial_t a$$



Marsh, Fong, Lentz, Smejkal, Ali '18

ADMX, IBS-CAPP, MADMAX…

Laboratory searches for axion DM -nucleonic probes

$$g_{aN}\frac{\partial_\mu a}{2m_N}\bar{N}\gamma^\mu\gamma^5 N \quad \Rightarrow \quad \underbrace{g_{aN}\frac{\nabla a}{\gamma_N m_N}}_{\vec{B}_{\rm eff}}\cdot\gamma_N\vec{S}_N$$

γ_N : nucleon gyromagnetic ratio

Background axion DM field

$$a \approx a_0\cos\left[m_a(t-\vec{v}\cdot\vec{x})\right]$$

$$\rho_a = \frac{1}{2}m_a^2 a_0^2 \qquad |\vec{v}| \sim 10^{-3}c$$

$$\Rightarrow \quad \vec{B}_{\rm eff} \approx g_{aN}\frac{\sqrt{2\rho_a}}{\gamma_N m_N}\vec{v}_a\sin m_a t$$

The best experimental sensitivity on g_{aN} is obtained when $\rho_a = \rho_{DM}$.

Misalignment axion DM

$$f_a \simeq 10^{17}\,{\rm GeV}\left(\frac{10^{-22}\,{\rm eV}}{m_a}\right)^{1/4}\sqrt{\frac{\rho_a}{\rho_{\rm DM}}} \quad \Rightarrow \quad g_{aN} = \frac{m_N}{f_a}c_{aq}\times\mathcal{O}(1)$$

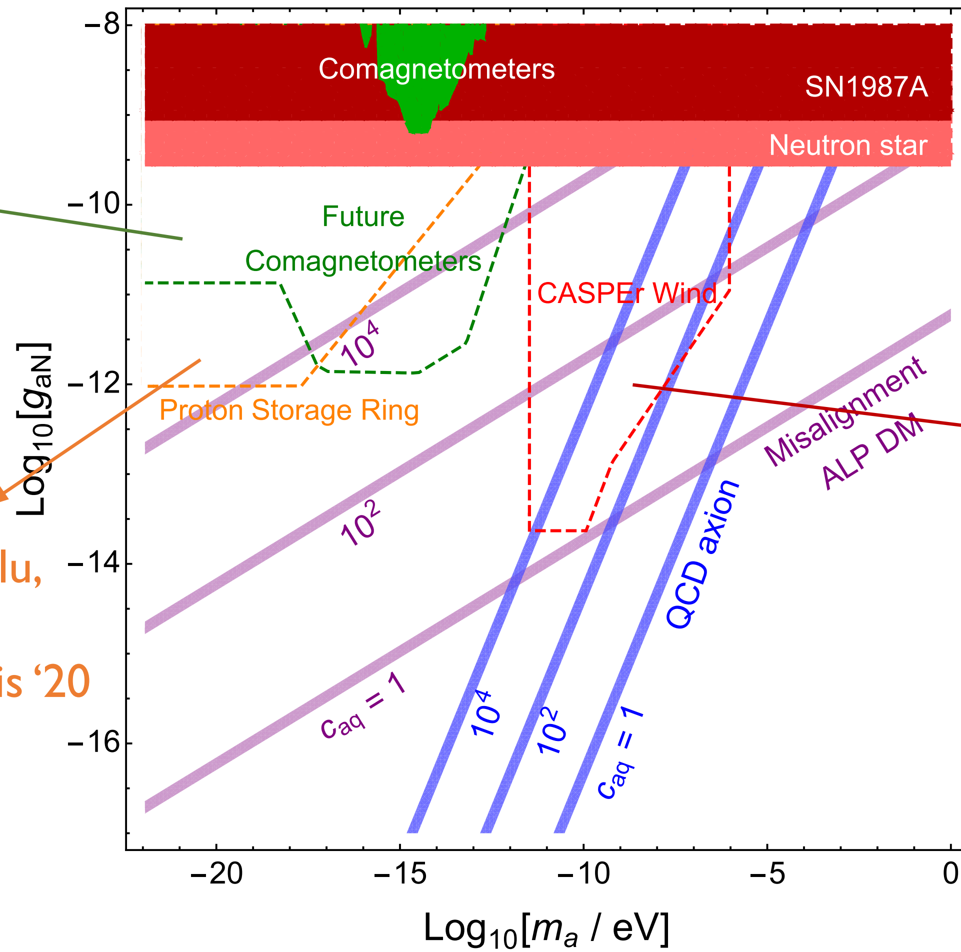
Given axion DM mass, g_{aN} is determined for $c_{aq}\sim O(1)$.

Current and future limits on g_{aN}

Choi, SHI, Shin '20

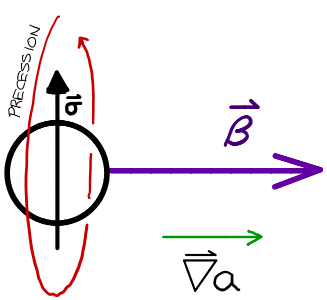
Bloch, Hochberg, Kuflik, Volansky '19

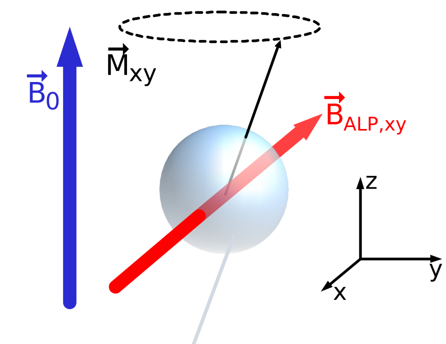
$$\frac{B^e_{\rm eff}}{B^N_{\rm eff}} \sim \frac{c_{ae} m_e}{c_{aN} m_N} \neq 1$$



Kimball et al '17

Graham, Haciomeroglu, Kaplan, Omarov, Rajendran, Semertzidis '20





NMR

Effect of the QCD axion

$$\theta G\tilde{G} + (m_q q_L q_R^c + \text{h.c.}) \longrightarrow \left(|m_q| e^{i\bar{\theta}} q_L q_R^c + \text{h.c.}\right) \qquad \bar{\theta} = \theta + \arg(m_q)$$

$q_L \to q_L e^{-i\theta}$ (chiral rotation)

$$\left(|m_q| e^{i\bar{\theta}} q_L q_R^c + \text{h.c.}\right) + V_{\text{QG}}(\bar{\theta}) + \left(i\tilde{d}_q q_L \sigma^{\mu\nu} G_{\mu\nu} q_R^c + \text{h.c.}\right) + d_W GG\tilde{G}$$

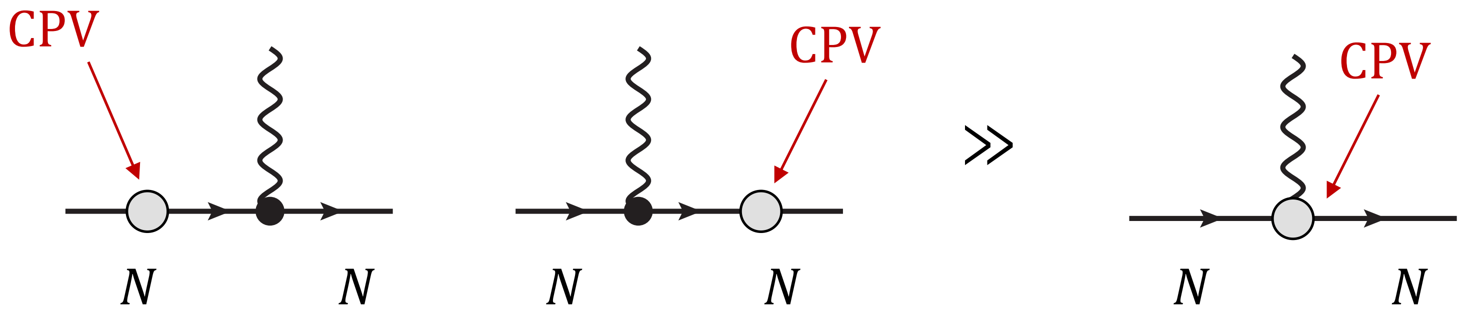
QCD confinement (NDA estimation)

$$V(\bar{\theta}) \approx -\frac{\Lambda_\chi^3}{(4\pi)^2}|m_q|\cos\bar{\theta} + V_{\text{QG}}(\bar{\theta}) \pm \frac{\Lambda_\chi^5}{(4\pi)^3}\tilde{d}_q \sin\bar{\theta} \pm \frac{\Lambda_\chi^5}{(4\pi)^3}|m_q| d_W \sin\bar{\theta}$$

When the PQ mechanism is working (i.e. $\bar{\theta}$ dynamical),

$$\partial_{\bar{\theta}} V = 0 \quad \Rightarrow \quad \langle\bar{\theta}\rangle \approx (4\pi)^2 \frac{\partial_{\bar{\theta}} V_{\text{QG}}}{|m_q|\Lambda_\chi^3} \pm \frac{\Lambda_\chi^2}{4\pi}\frac{\tilde{d}_q}{|m_q|} \pm \frac{\Lambda_\chi^2}{4\pi} d_W$$

Demir, Pospelov, Ritz '02
Haisch, Hala '19
Yamanaka, Hiyama '21



The QCD sum rules indicate that the nucleon EDMs are dominated by the CP phase of the nucleon mass.
(Maybe due to the isospin-singlet nature of the CPV sources)

$$|m_N|\bar{N}e^{i\gamma_5\alpha}N + \frac{1}{2}\mu_N g_s \bar{N}\sigma^{\mu\nu}NF_{\mu\nu} \qquad \mu_p \approx -\mu_n$$

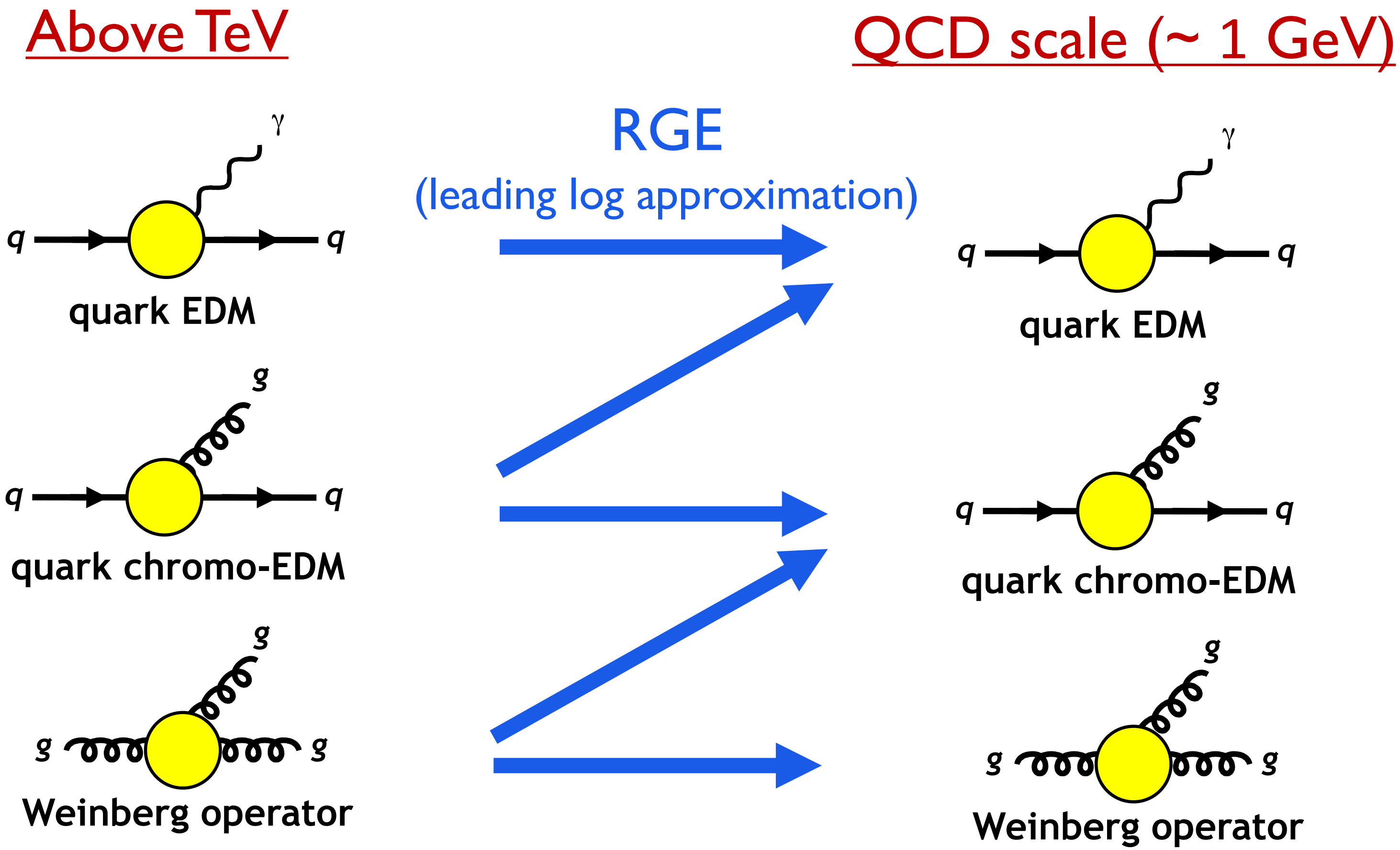
: isovector nature of nucleon g-2

$$N \to N e^{-i\gamma_5\alpha/2}$$

⬇

$$|m_N|\bar{N}N + \frac{1}{2}\mu_N g_s \bar{N}\sigma^{\mu\nu}NF_{\mu\nu} - \frac{1}{2}\underbrace{\alpha\mu_N}_{d_N} g_s \bar{N}\sigma^{\mu\nu}i\gamma_5 N F_{\mu\nu}$$

RG mixing among CPV operators



(Adapted from Nodoka Yamanaka's slide)

RGE at 1-loop

$$C_1(\mu) = \frac{d_q(\mu)}{m_q Q_q}, \quad C_2(\mu) = \frac{\tilde{d}_q(\mu)}{m_q}, \quad C_3(\mu) = \frac{d_W(\mu)}{g_3}$$

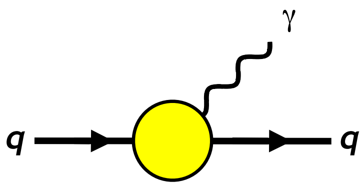
$$\mu \frac{\partial \mathbf{C}}{\partial \mu} = \frac{g_3^2}{16\pi^2} \gamma \, \mathbf{C}$$

$$\gamma \equiv \begin{pmatrix} \gamma_e & \gamma_{eq} & 0 \\ 0 & \gamma_q & \gamma_{Gq} \\ 0 & 0 & \gamma_G \end{pmatrix} = \begin{pmatrix} 8C_F & 8C_F & 0 \\ 0 & 16C_F - 4N_c & 2N_c \\ 0 & 0 & N_c + 2n_f + \beta_0 \end{pmatrix}$$

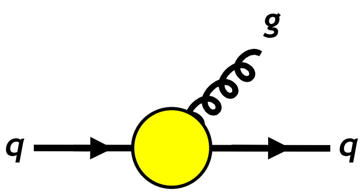
- $C_F = \frac{4}{3}$ (quadratic Casimir)
- $N_c = 3$
- n_f = number of light quarks
- $\beta_0 = (33 - 2nf)/3$

From QCD scale to nuclear CPV observables

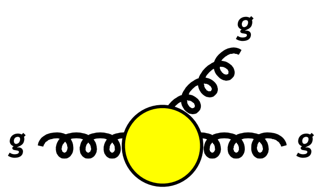
QCD scale (~ 1 GeV)



quark EDM



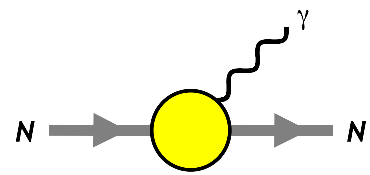
quark chromo-EDM



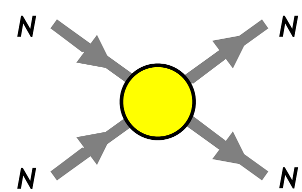
Weinberg operator

- Chiral EFT
- Naïve Dimensional Analysis (NDA)
- QCD sum rules
- Lattice inputs

CPV at nuclear level



Nucleon EDM

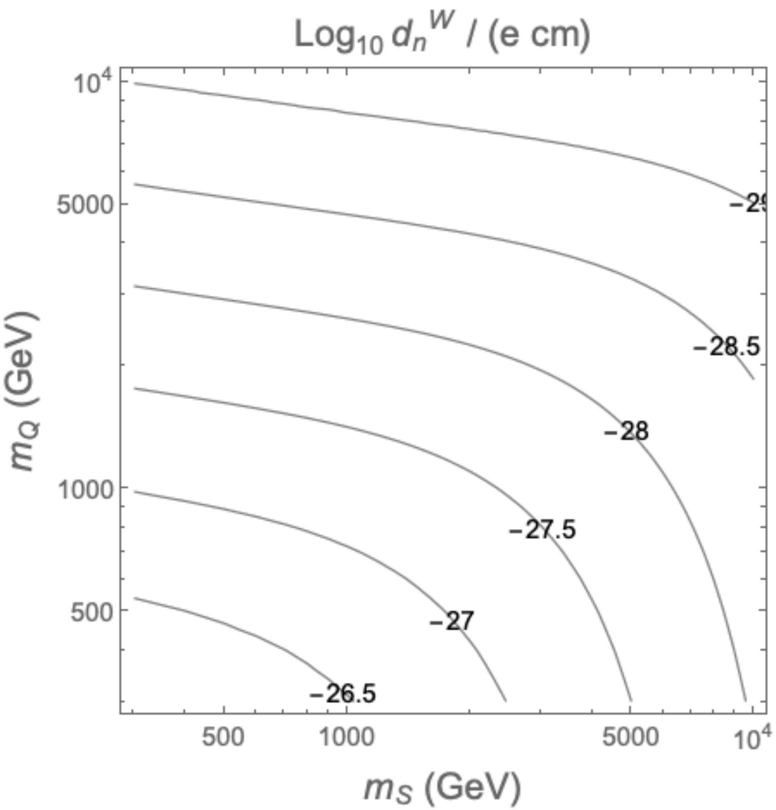


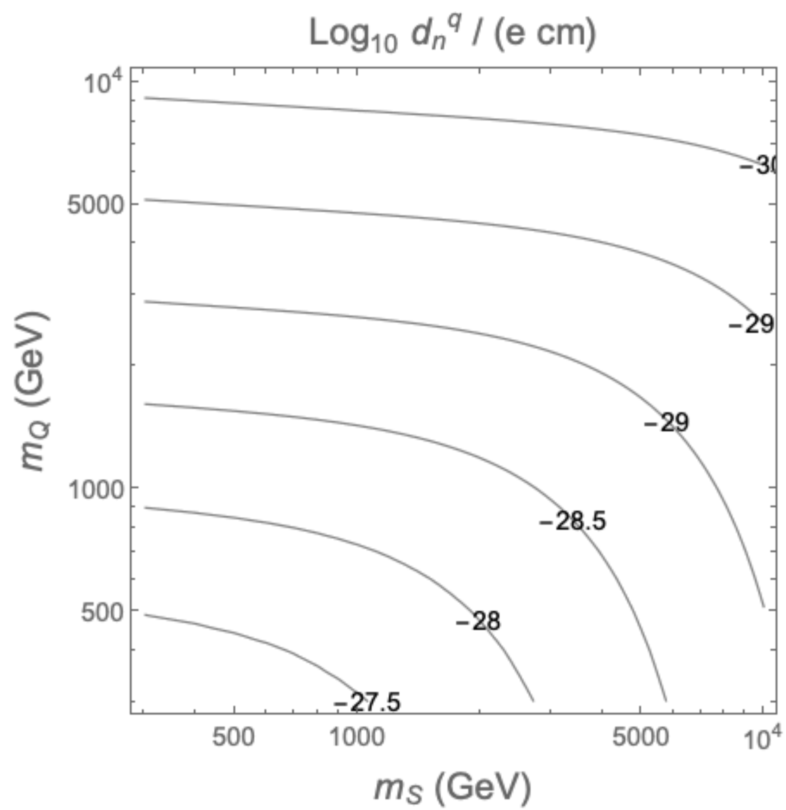
CP-odd nuclear force

Neutron EDM from VLQs

I) Weinberg operator dominance (no s-h mixing)

$$y_S = \alpha = 1$$



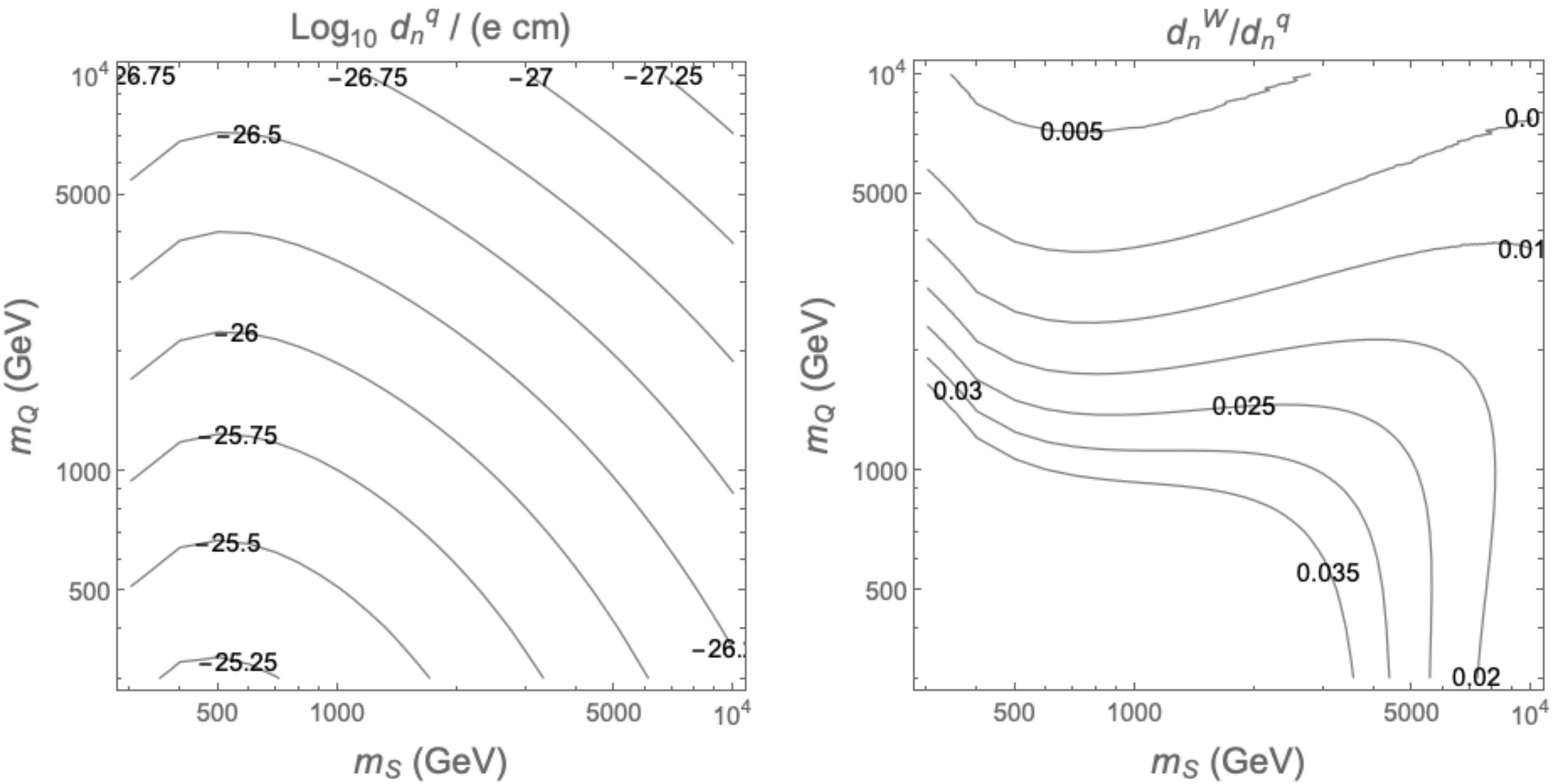


$|d_n| < 1.8{\times}10^{-26}$ e cm   Abel et al '20

Neutron EDM from VLQs

II) quark CEDM dominance (with a sizable s-h mixing)

$$y_S = \alpha = 1 \qquad S^2|H|^2 \rightarrow \theta_{sh} \sim \langle S\rangle\langle H\rangle/m_S^2 \sim v/m_S$$



$|d_n| < 1.8{\times}10^{-26}$ e cm Abel et al ‘20