Probing BSM CP violation and the axion quality with electric dipole moments

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High 1 workshop on Particle, String and Cosmology
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KC, Im, Jodlowski, arXiv: 2308.01090 (to appear at JHEP)

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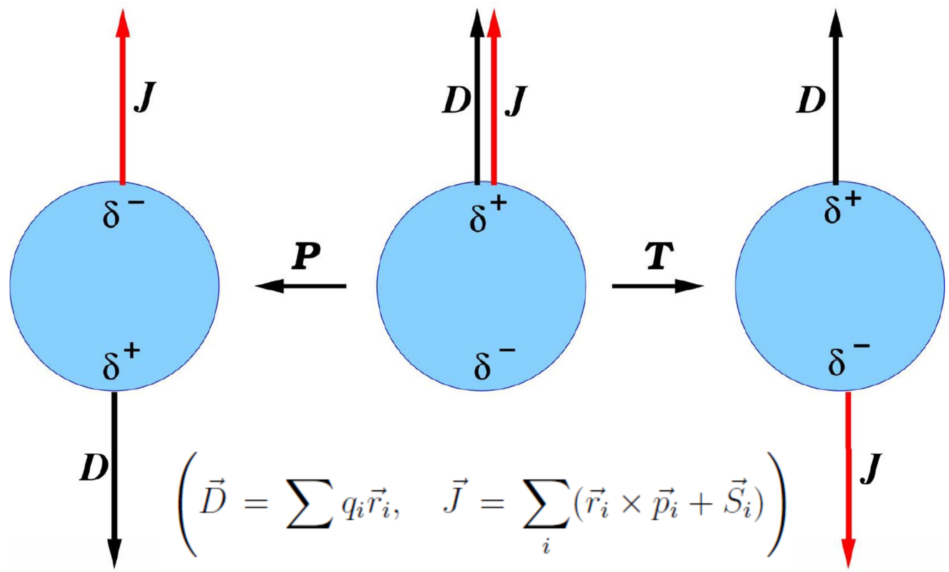
Why Electric Dipole Moments (EDM) are interesting?

Nonzero static EDM of non-degenerate quantum system means the violation of P and T (=CP) symmetry.



Historically the violation of these discrete spacetime symmetries have played important role for the progress in fundamental physics.

CP violation is one of the key conditions to generate the asymmetry between matter and antimatter in our universe. Sakharov '67

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

Standard Model (SM) prediction: $(Y_B)_{\mathrm{SM}} \lesssim 10^{-15}$

(See for instance hep-ph/0309291)

We need "CP-violating new physics beyond the SM" to explain the observed matter-antimatter asymmetry, and EDM may provide a clue about those new physics.

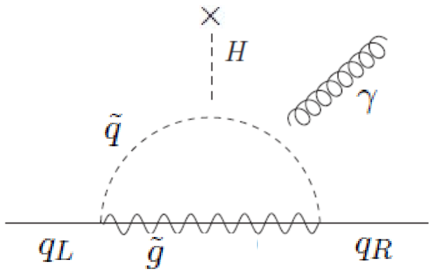
More generally EDMs can provide a hint on the scale where "new physics beyond the SM (BSM physics)" appears.

BSM CP violation

Suppression by loop, Yukawa, …

Nucleon EDM: $d_N = \sin\alpha \, \dfrac{\mu^2}{\Lambda_{\rm BSM}^2} \dfrac{e}{m_N} \quad \Big(\mu = \mu(g^2, y, v_H, m_N, ..)\Big)$

BSM mass scale



Quark EDM induced by SUSY particles

$$\mu^2 \sim \frac{g_s^2(\Lambda_{\rm BSM})}{8\pi^2} m_q m_N$$

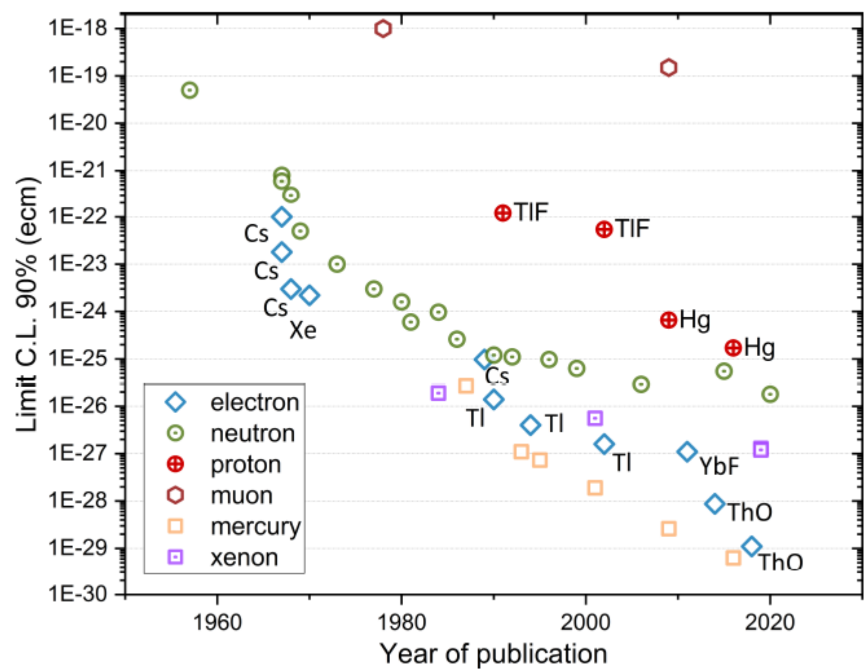
$$\Rightarrow \quad \Lambda_{\rm BSM} \sim 10\sqrt{\sin\alpha}\, \left(\frac{10^{-26}\, e\cdot{\rm cm}}{d_N}\right)^{1/2} {\rm TeV}$$

There are many ongoing experiments searching for EDMs of different systems.

Although nonzero EDM is not observed yet in any of those experiments, experimental sensitivity is expected to be improved by more than one order of magnitude over the coming ~ 10 years.

	Result	95% u.l.	
	Paramagnetic systems		
Xe^m	$d_A = (\ \ 0.7 \pm 1.4) \times 10^{-22}$	3.1×10^{-22}	e cm
Cs	$d_A = (-1.8 \pm 6.9) \times 10^{-24}$	1.4×10^{-23}	e cm
	$d_e = (-1.5 \pm 5.7) \times 10^{-26}$	1.2×10^{-25}	e cm
	$C_S = (2.5 \pm 9.8) \times 10^{-6}$	2×10^{-5}	
	$Q_m = (3 \pm 13) \times 10^{-8}$	2.6×10^{-7}	$\mu_N R_{\mathrm{Cs}}$
Tl	$d_A = (-4.0 \pm 4.3) \times 10^{-25}$	1.1×10^{-24}	e cm
	$d_e = (\ \ 6.9 \pm 7.4) \times 10^{-28}$	1.9×10^{-27}	e cm
YbF	$d_e = (-2.4 \pm 5.9) \times 10^{-28}$	1.2×10^{-27}	e cm
ThO	$d_e = (-2.1 \pm 4.5) \times 10^{-29}$	9.7×10^{-29}	e cm
	$C_S = (-1.3 \pm 3.0) \times 10^{-9}$	6.4×10^{-9}	
HfF^+	$d_e = (0.9 \pm 7.9) \times 10^{-29}$	1.6×10^{-28}	e cm
	Diamagnetic systems		
$^{199}\mathrm{Hg}$	$d_A = (2.2 \pm 3.1) \times 10^{-30}$	7.4×10^{-30}	e cm
$^{129}\mathrm{Xe}$	$d_A = (0.7 \pm 3.3) \times 10^{-27}$	6.6×10^{-27}	e cm
$^{225}\mathrm{Ra}$	$d_A = (4 \pm 6) \times 10^{-24}$	1.4×10^{-23}	e cm
TlF	$d\ = (-1.7 \pm 2.9) \times 10^{-23}$	6.5×10^{-23}	e cm
n	$d_n = (-0.21 \pm 1.82) \times 10^{-26}$	3.6×10^{-26}	e cm
	Particle systems		
μ	$d_\mu = (0.0 \pm 0.9) \times 10^{-19}$	1.8×10^{-19}	e cm
τ	$Re(d_\tau) = (1.15 \pm 1.70) \times 10^{-17}$	3.9×10^{-17}	e cm
Λ	$d_\Lambda = (-3.0 \pm 7.4) \times 10^{-17}$	1.6×10^{-16}	e cm

arXiv:1710.02504

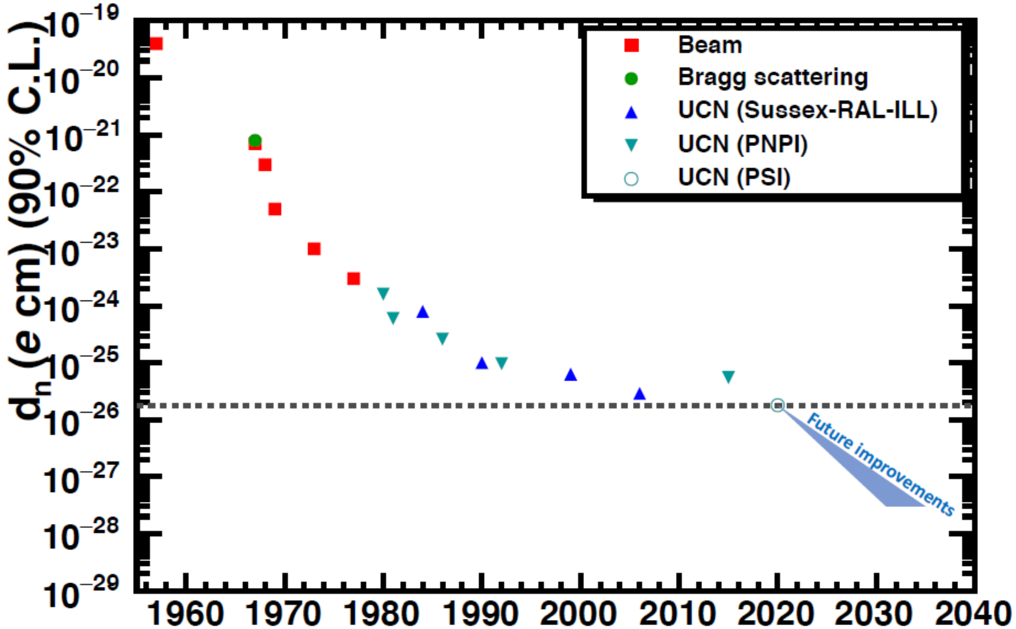


arXiv:2003.00717

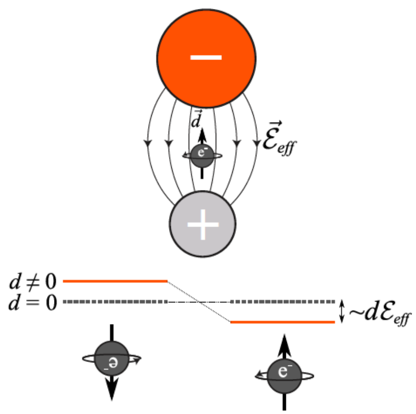
Future prospects

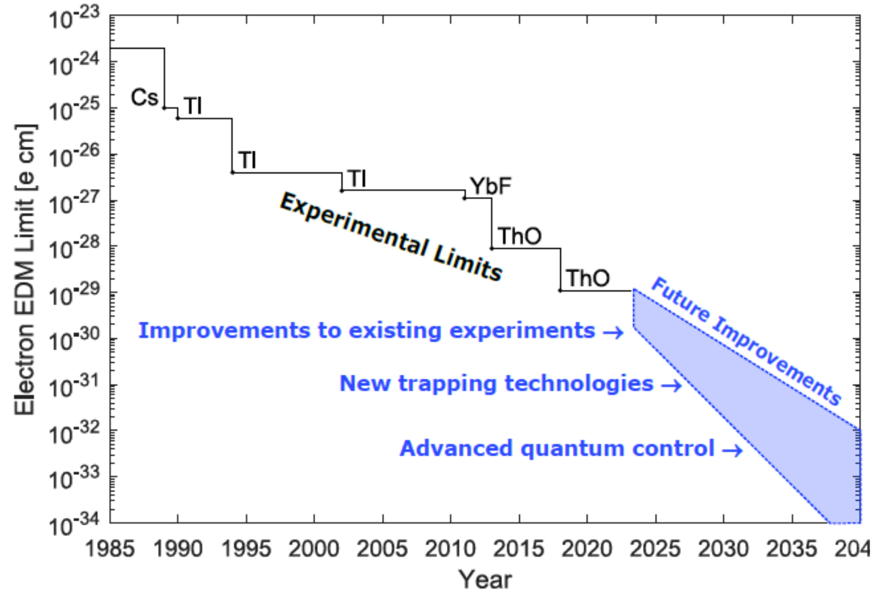
arXiv:2203.08103

Neutron EDM

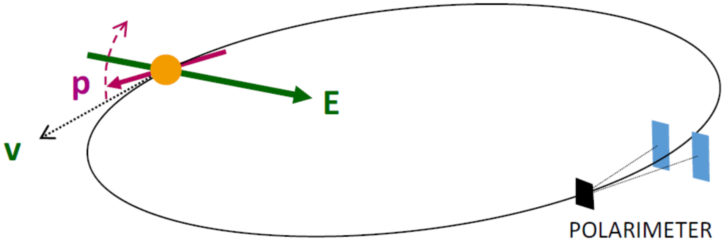


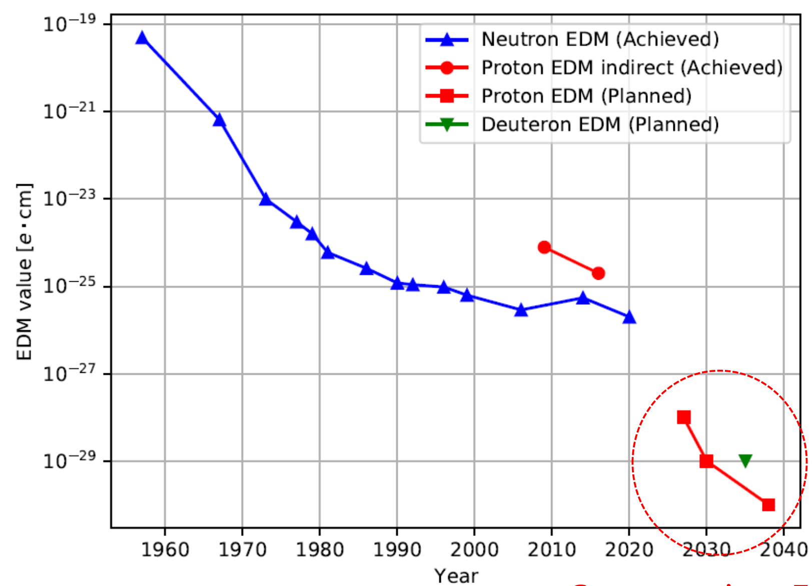
Polar molecules sensitive to electron EDM and P,T-odd e-N contact interaction





Proton, deuteron, helion EDMs
(Storage ring EDM experiments)





Storage ring EDM

There are many ongoing and planned experiments searching for EDM signal of a variety of systems (nucleons, leptons, light nuclei, atoms, molecules).

For many of those experiments, the sensitivity will be improved by more than one order of magnitude over the coming ~ 10 years:

d_n ~ 10^{-28} e.cm (1.8 x 10^{-26})

d_p ~ 10^{-29} – 10^{-30} e.cm (10^{-25})

d_D ~ 10^{-29} e.cm (possibly also **d_{He}**)

d_e ~ few x 10^{-31} – 10^{-32} e.cm (4 x 10^{-30})

C_S ~ 5 x 10^{-11} – 10^{-12} (5 x 10^{-10})

$$\left(C_S \frac{G_F}{\sqrt{2}} \bar{e} i \gamma_5 e \, \bar{N} N \right)$$

SM prediction for EDMs

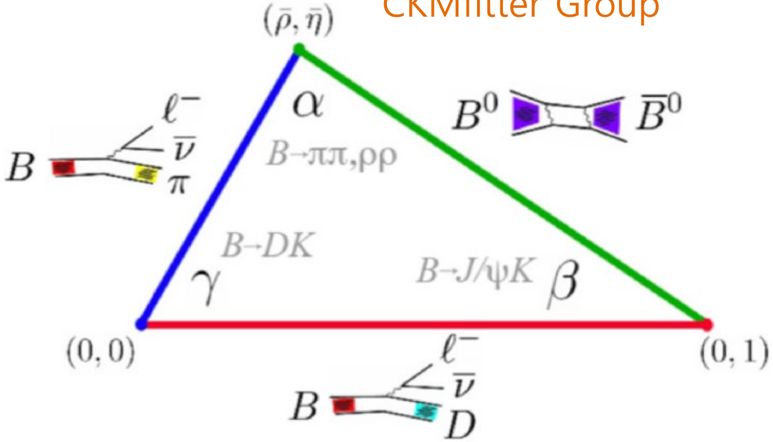
Two CP-odd angle parameters in the SM (up to dim=4 operators):

$\delta_{\rm KM} = \arg \cdot \det([y_u y_u^\dagger, y_d y_d^\dagger])$ for CP violation in the weak interactions

$\bar{\theta} = \theta_{\rm QCD} + \arg \cdot \det(y_u y_d)$ for CP violation in the strong interactions

Weak meson mixings and decays

CKMfitter Group



$\Rightarrow \quad \sin\delta_{\rm KM} = \mathcal{O}(1)$

Nucleon & electron EDMs:

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

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

De Vries et al '01 Mannel, Uraltsev '12

$$\Rightarrow \quad |\bar\theta| < 10^{-10}$$ (Strong CP problem)

$$\frac{d_e}{e\cdot\mathrm{cm}} = -(2.2-8.6)\times 10^{-28}\sin\bar\theta \;+\; \mathcal{O}(10^{-44})\times\sin\delta_{\mathrm{KM}} \lesssim \mathcal{O}(10^{-37})$$

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

P,T-odd electron-nucleon contact interaction: $C_S\frac{G_F}{\sqrt{2}}\bar{e}i\gamma_5 e\,\bar{N}N$

$$C_S \sim 3\times 10^{-2}\sin\bar\theta \;+\; 7\times 10^{-16}\sin\delta_{\mathrm{KM}}$$

Flambaum et al '19 Ema et al '22

Many of these results can be understood by simple dimensional analysis incorporating

* QCD axial anomaly implies CPV by $\bar{\theta}$ is suppressed by the lightest quark mass.

* Flavor conserving CPV by $\delta_{\rm KM}$ should contain all flavor mixing angles, therefore it is at least second order in the weak interactions.

* (Semi-)Leptonic CPV by $\delta_{\rm KM}$ involves additional loops of EM interactions, as well as the change of the lepton chirality.

$$\Rightarrow \qquad \frac{d_N(\bar{\theta})}{2\times 10^{-14}\, e\cdot {\rm cm}} \propto \frac{m_u}{m_N} \sim 4\times 10^{-3}, \qquad \frac{d_N(\delta_{\rm KM})}{2\times 10^{-14}\, e\cdot {\rm cm}} \propto G_F^2 m_N^4 \mathcal{J} \sim 10^{-15}$$

$$\frac{d_e}{d_N} \propto \left(\frac{\alpha_{\rm em}}{4\pi}\right)^3 \frac{m_e}{m_N} \sim 10^{-12}, \qquad C_S \propto \left(\frac{\alpha_{\rm em}}{4\pi}\right)^2 \frac{m_e}{f_\pi}\frac{1}{G_F m_\pi^2} \sim 10^{-1}$$

EDMs from δ_{KM} are all well below the experimental sensitivity achievable in foreseeable future, while the hadronic EDMs from $\bar{\theta}$ can have any value below the current experimental bounds.

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

Therefore, if some hadronic EDM is experimentally discovered in near future, it might be due to either BSM CPV or $\bar{\theta}$.

In such situation, discriminating between these two possibilities is the first step toward a clue about BSM physics.

Apparently, for this we need

(i) Measurement of multiple EDMs in experiment side,

(ii) Quantitative understanding of the EDM contributions from BSM CPV and $\bar{\theta}$ in theory side.

Lebedev et al '04; Dekens et al '14, de Vries et al '21

EFT approach for EDMs

BSM physics at E > 1 TeV

Integrate out all massive BSM particles
and consider the resulting SMEFT

$$\mathcal{L}_{\rm CPV}(\mu=\Lambda) = c_{\widetilde{G}} f^{abc} G^{a\mu}_{\alpha} G^{b\delta}_{\mu} \widetilde{G}^{c\alpha}_{\delta} + c_{\widetilde{W}} \epsilon^{abc} W^{a\mu}_{\alpha} W^{b\delta}_{\mu} \widetilde{W}^{c\alpha}_{\delta} + |H|^2 \left(c_{H\widetilde{G}} G^a_{\mu\nu} \widetilde{G}^{a\mu\nu} + c_{H\widetilde{W}} W^a_{\mu\nu} \widetilde{W}^{a\mu\nu} + c_{H\widetilde{B}} B_{\mu\nu} \widetilde{B}^{\mu\nu} \right) + c_{H\widetilde{W}B} H^\dagger \tau^a H \widetilde{W}^a_{\mu\nu} B^{\mu\nu} + \sum_{X=G,W,B} i (c_{qX})_{ij} \bar{Q}_{Li} \sigma^{\mu\nu} X_{\mu\nu} q_{Rj} H^{(*)} + \ldots$$

Integrate out all massive SM particles and
scale down the theory to the QCD scale

$\bar{\theta}$ BSM CPV

$$\mathcal{L}_{\rm CPV}(\mu = \mathcal{O}(1)\,\mathrm{GeV}) = \frac{1}{32\pi^2}\bar{\theta} G\tilde{G} + \sum_i \lambda_i \mathcal{O}_i$$

$$\{\mathcal{O}_i\} = \left(GG\tilde{G},\ i\bar{q}\gamma_5\sigma_{\mu\nu}G^{\mu\nu}q,\ i\bar{\psi}\gamma_5\sigma_{\mu\nu}F^{\mu\nu}\psi,\ \bar{\psi}\gamma_5\psi\bar{\psi}\psi, \ldots\right) \quad (\psi = q, \ell)$$

(gluon & quark Chromo-EDMs, quark/lepton EDMs, 4-fermion operators, ...)

Use the relevant QCD, nuclear
& atomic physics results

Experimentally measurable nucleon, nuclei, atomic, molecular EDMs

Smallness of $\bar{\theta}$ (Strong CP problem) calls for an explanation, and the QCD axion is regarded as the most appealing solution to this problem.

Peccei, Quinn '77

* QCD axion can provide the dark matter in our Universe,
* Axions or axion-like particles are generic feature of the low energy limit of string/M theory, ….

Discriminating $\bar{\theta}$ from BSM CPV in the presence of QCD axion is even more interesting.

KC Im, Jodlowski, arXiv: 2308.01090

It can provide not only a clue about BSM CPV, but also information on the axion quality which might be associated with quantum gravity.

We are primarily concerned with

Experimentally measured EDMs $\rightarrow$

* BSM CPV vs $\bar{\theta}$ w/ or w/o axion

* Axion (PQ) quality:
PQ-breaking other than the QCD anomaly, e.g. quantum gravity effect

In this talk I will discuss only the case with axion.

Axion solution of the strong CP problem

The axion solution is based on a global U(1) symmetry:

Peccei & Quinn '77

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

which is dominantly broken by <u>the QCD anomaly</u>:

Effective lagrangian at E ~ 1 GeV:

PQ-breaking by the QCD anomaly

Additional interactions

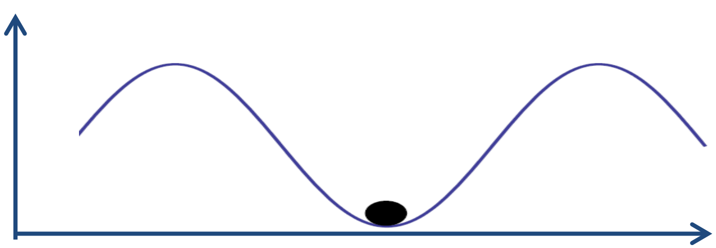
$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm QCD} + \frac{1}{2}\partial_\mu a \partial^\mu a + \boxed{\frac{1}{32\pi^2}\frac{a}{f_a} G^{a\mu\nu}\tilde{G}^a_{\mu\nu}} + \Delta\mathcal{L}$$

Additional axion potential

$$\Rightarrow \quad V_{\rm QCD}(a) \simeq -\frac{f_\pi^2 m_\pi^2}{(m_u+m_d)}\sqrt{m_u^2+m_d^2+2m_u m_d\cos(a/f_a)}$$

$$\delta V(a)$$

Shift of the axion VEV



$$\langle a \rangle = 0$$

$$\Rightarrow \quad \bar{\theta} \equiv \frac{\langle a \rangle}{f_a} = 0 + \ldots$$

Full axion potential: $V(a) = V_{\rm QCD}(a) + \delta V(a)$

* PQ-breaking by $aG\tilde{G}$ combined with the conventional low energy QCD

$$\Rightarrow \quad V_{\rm QCD}(a) \simeq -\frac{f_\pi^2 m_\pi^2}{(m_u+m_d)}\sqrt{m_u^2+m_d^2+2m_u m_d\cos(a/f_a)}$$

* Two potentially dominant origins of $\delta V(a)$ generating nonzero $|\bar{\theta}| = \langle a\rangle/f_a$

i) PQ-breaking by $aG\tilde{G}$ combined with CP-violating (but PQ and flavor conserving) low energy effective interactions induced by BSM physics:

$$\Delta\mathcal{L}_{\rm BSM-CPV} = \sum_i \lambda_i \mathcal{O}_i \quad \left(\mathcal{O}_i = GG\tilde{G},\ \bar{q}\gamma_5\sigma\cdot Gq,\ \bar{q}q\bar{q}\gamma_5 q,\ ...\right)$$

(gluon chromo-EDM, quark chromo-EDM, four-quark operators, ...)

ii) PQ-breaking other than $aG\tilde{G}$, most notably quantum gravity effects such as string/brane instantons or gravitational wormholes, generating

$$\delta V_{\rm UV} = \Lambda_{\rm UV}^4 e^{-S_{\rm ins}}\cos(a/f_a + \delta_{\rm UV})$$

$$\delta V = \delta V_{\rm SM} + \delta V_{\rm BSM} + \delta V_{\rm UV}$$

$$\delta V_{\rm SM} \sim 10^{-19} f_\pi^2 m_\pi^2 \sin\delta_{\rm KM} \sin(a/f_a)$$

Axion potential induced by $aG\tilde{G}$ & SM CPV:

Georgi, Randall '86

$$\delta V_{\rm BSM} \sim \sum_i \lambda_i \int d^4x \left\langle \frac{g_s^2}{32\pi^2} G\tilde{G}(x) \mathcal{O}_i(0) \right\rangle \sin(a/f_a)$$

Axion potential induced by $aG\tilde{G}$ & BSM CPV:

$$\delta V_{\rm UV} = \Lambda_{\rm UV}^4 e^{-S_{\rm ins}} \cos(a/f_a + \delta_{\rm UV})$$

Axion potential induced by PQ-breaking other than $aG\tilde{G}$,e.g. quantum gravity effects

$$\Rightarrow \quad \bar{\theta} = \frac{\langle a \rangle}{f_a} = \bar{\theta}_{\rm SM} + \bar{\theta}_{\rm BSM} + \bar{\theta}_{\rm UV}$$

$\bar{\theta}_{\rm SM} \sim 10^{-19}$ (too small to be interesting)

$$\bar{\theta}_{\rm BSM} \sim \frac{\sum_i \lambda_i \int d^4x \, \langle \frac{1}{32\pi^2} G\tilde{G}, \mathcal{O}_i \rangle}{f_\pi^2 m_\pi^2}$$

Axion VEV induced by $aG\tilde{G}$ & BSM CPV, which can have any value below 10^{-10}

$$\bar{\theta}_{\rm UV} \sim \frac{e^{-S_{\rm ins}} \Lambda_{\rm UV}^4 \sin\delta_{\rm UV}}{f_\pi^2 m_\pi^2}$$

Axion VEV induced by high scale PQ-breaking, which also can have any value below 10^{-10}

Axion (PQ) quality problem

In modern viewpoint, PQ-breaking by quantum gravity is considered to be inevitable:

Black hole evaporation? Gravitational Euclidean wormholes?
String world-sheet or brane instantons?, …

We then need an explanation for why PQ-breaking by quantum gravity is so suppressed that the resulting $|\bar{\theta}_{\rm UV}| = \langle a \rangle / f_a < 10^{-10}$, which has been dubbed the axion (PQ) quality problem.

There have been many theoretical studies on the axion quality problem:

Accidental PQ-symmetry, $U(1)_{PQ}$ from higher dimensional gauge symmetry, …

On the other hand, there has been no discussion about how to discriminate $\bar{\theta}_{\rm UV}$ from $\bar{\theta}_{\rm BSM}$ with experimental data, or more generically how to identify the origin of the axion VEV with experimental data.

EDM might be able to distinguish $\bar{\theta}_{\rm UV}$ from $\bar{\theta}_{\rm BSM}$:

$$\Delta\mathcal{L}_{\rm BSM-CPV} = \sum_i \lambda_i \mathcal{O}_i$$

$$\delta V_{\rm UV} = \Lambda_{\rm UV}^4 e^{-S_{\rm ins}} \cos(a/f_a + \delta_{\rm UV})$$

$$\bar{\theta} = \bar{\theta}_{\rm BSM} + \bar{\theta}_{\rm UV} = \sum_i \lambda_i \frac{\partial\bar{\theta}}{\partial\lambda_i} + \bar{\theta}_{\rm UV}$$

EDMs

$$\boxed{d_I = \sum_i \lambda_i \frac{\partial d_I}{\partial\lambda_i} + \bar{\theta}_{\rm UV}\frac{\partial d_I}{\partial\bar{\theta}} \quad (I = n, p, D, He, Ra, Xe, Hg, ...)}$$

In the presence of a QCD axion, BSM CPV affects EDMs both directly and through the induced axion VEV, while PQ breaking by quantum gravity affects EDMs only through the induced axion VEV.

As a first attempt, we may focus on relatively simple BSM scenario that BSM CPV at low energy scales appears dominantly in the form of the gluon chromo-EDM (CEDM), quark CEDMs, quark EDM with minimal flavor violation (MFV):

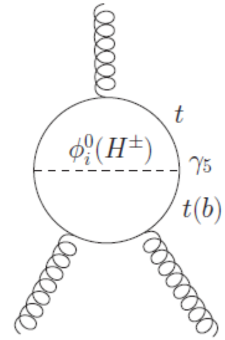
$$\mathcal{L}_{\rm CPV}(\mu) = \frac{1}{3} w f^{abc} G^{a\mu}_{\alpha} G^{b\delta}_{\mu} \widetilde{G}^{c\alpha}_{\delta} - \frac{i}{2}\sum_q \tilde{d}_q g_s \bar{q}\sigma^{\mu\nu} G_{\mu\nu}\gamma_5 q - \frac{i}{2}\sum_q d_q \bar{q}\sigma^{\mu\nu} F_{\mu\nu}\gamma_5 q$$

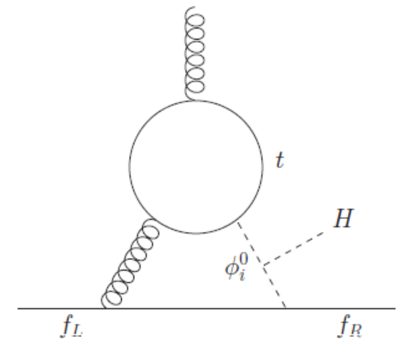
Gluon CEDM (Weinberg operator) — Quark CEDM — Quark EDM

$$d_q = m_q Q_q C_1, \quad \tilde{d}_q = m_q C_2 \quad \left(C_{1,2} = \text{flavor-universal}\right)$$

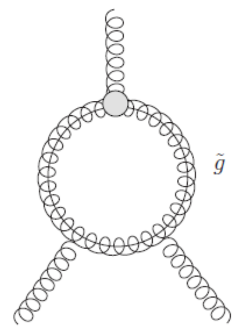
Two-Higgs doublets, SUSY (with MFV), Vector-like quarks, ...

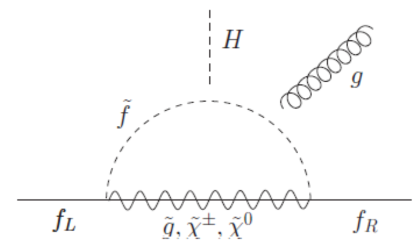
Two-Higgs doublets



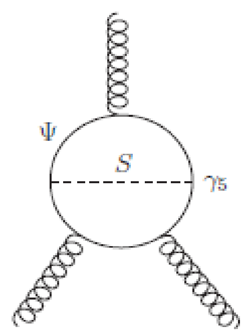


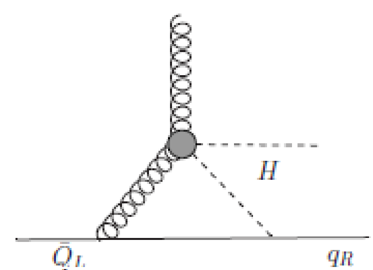
SUSY





Vector-like quarks





Gluon CEDM
(Weinberg operator)

Quark CEDM

EDM inverse problem

$$d_n,\ d_p,\ d_D,\ d_{He}, \ldots \longrightarrow \begin{array}{c} \bar{\theta}_{\mathrm{UV}}, \\ w(\mu = \Lambda_{\mathrm{BSM}}), \\ C_2(\mu = \Lambda_{\mathrm{BSM}}), \\ C_1(\mu = \Lambda_{\mathrm{BSM}}) \end{array}$$

RG evolution from the BSM scale (~ TeV) to 1 GeV

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

$$\frac{d\mathbf{C}}{d\ln\mu} = \frac{g_s^2}{16\pi^2}\gamma\,\mathbf{C},$$

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

$$C_F = (N_c^2 - 1)/2N_c = 4/3 \qquad \beta_0 \equiv (33 - 2n_f)/3$$

Nucleon EDMs

Applying the hadronic matrix elements obtained from the QCD sum rule and chiral perturbation theory for the CEDMs and EDMs renormalized at 1 GeV:

$$\bar{\theta} = \frac{\langle a \rangle}{f_a} = \bar{\theta}_{\rm BSM} + \bar{\theta}_{\rm UV}$$

$$\bar{\theta}_{\rm BSM} = \frac{m_0^2}{2} \sum_{q=u,d,s} \frac{\tilde{d}_q}{m_q} + \mathcal{O}(4\pi f_\pi^2 w) \quad (m_0^2 \simeq 0.8\,{\rm GeV}^2)$$

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

$$d_p(\bar{\theta}_{\rm UV}, \tilde{d}_q, d_q, w) = -0.46 \times 10^{-16} \bar{\theta}_{\rm UV}\, e\,{\rm cm} - e\left(0.58\tilde{d}_u + 0.073\tilde{d}_d\right) + 0.36 d_u - 0.089 d_d - 18 w\, e\,{\rm MeV},$$

$$d_n(\bar{\theta}_{\rm UV}, \tilde{d}_q, d_q, w) = 0.31 \times 10^{-16} \bar{\theta}_{\rm UV}\, e\,{\rm cm} + e\left(0.15\tilde{d}_u + 0.29\tilde{d}_d\right) - 0.089 d_u + 0.36 d_d + 20 w\, e\,{\rm MeV},$$

for $w, \tilde{d}_q, d_q$ renormalized at $\mu = 1$ GeV

Light nuclei (D, He) EDMs

Light nuclei EDMs are determined dominantly by

$$-2d_0 N^\dagger S^\mu v^\nu N F_{\mu\nu} - 2d_1 N^\dagger \tau_3 S^\mu v^\nu N F_{\mu\nu} \quad (d_0 = d_p + d_n,\ d_1 = d_p - d_n)$$

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

$$+\bar{C}_1 N^\dagger N D_\mu (N^\dagger S^\mu N) + \bar{C}_2 N^\dagger \vec{\tau} N \cdot D_\mu (N^\dagger S^\mu \vec{\tau} N)$$

Bsaisou et al '15

$$d_D = 0.94(1)(d_n + d_p) + 0.18(2)\bar{g}_1\, e\,\mathrm{fm},$$

$$d_{\mathrm{He}} = 0.9 d_n - 0.05 d_p + [0.10(3)\bar{g}_0 + 0.14(3)\bar{g}_1]\ e\,\mathrm{fm}$$

$$+\left[(0.04\pm 0.02)\bar{C}_1 - (0.09\pm 0.02)\bar{C}_2\right]\, e\cdot\mathrm{fm}^{-2}$$

CPV pion-nucleon couplings induced by $\bar{\theta}$ and the gluon and quark CEDMs:

QCD sum rule, ChPT, Lattice

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

$$\bar{g}_0(\bar{\theta}) = (15.7 \pm 1.7) \times 10^{-3}\bar{\theta},$$

$$\bar{g}_1(\bar{\theta}) = -(3.4 \pm 2.4) \times 10^{-3}\bar{\theta}$$

$$\bar{g}_0(\tilde{d}_q) \simeq -0.004(5)\, C_2\, \mathrm{GeV}^2 \quad (C_2 = \tilde{d}_q/m_q)$$

$$\bar{g}_1(\tilde{d}_q) \simeq -0.095(31)\, C_2\, \mathrm{GeV}^2$$

$$\bar{g}_1(w) \simeq \pm(2.6 \pm 1.5) \times 10^{-3} w\, \mathrm{GeV}^2$$

Larger than the naïve dimensional analysis estimation by about one order of magnitude, which is mainly due to the accidentally large value of

$$\sigma_{\pi N} = \frac{(m_u + m_d)}{4m_N}\langle N|(\bar{u}u + \bar{d}d)|N\rangle \simeq 60\,\mathrm{MeV}$$

$\bar{C}_{1,2}(\tilde{d}_q, \bar{\theta})$ give only sub-leading corrections to the nuclei EDMs.

There is no existing calculation of $\bar{g}_0(w), \bar{C}_{1,2}(w)$, therefore we use the naive dimensional analysis estimation for those low energy parameters.

(For some nuclei and atoms, this is the origin of large uncertainty in the gluon CEDM-induced EDMs.)

As warm up example, we consider the following 4 particular scenarios.

(work in preparation for more general situations)

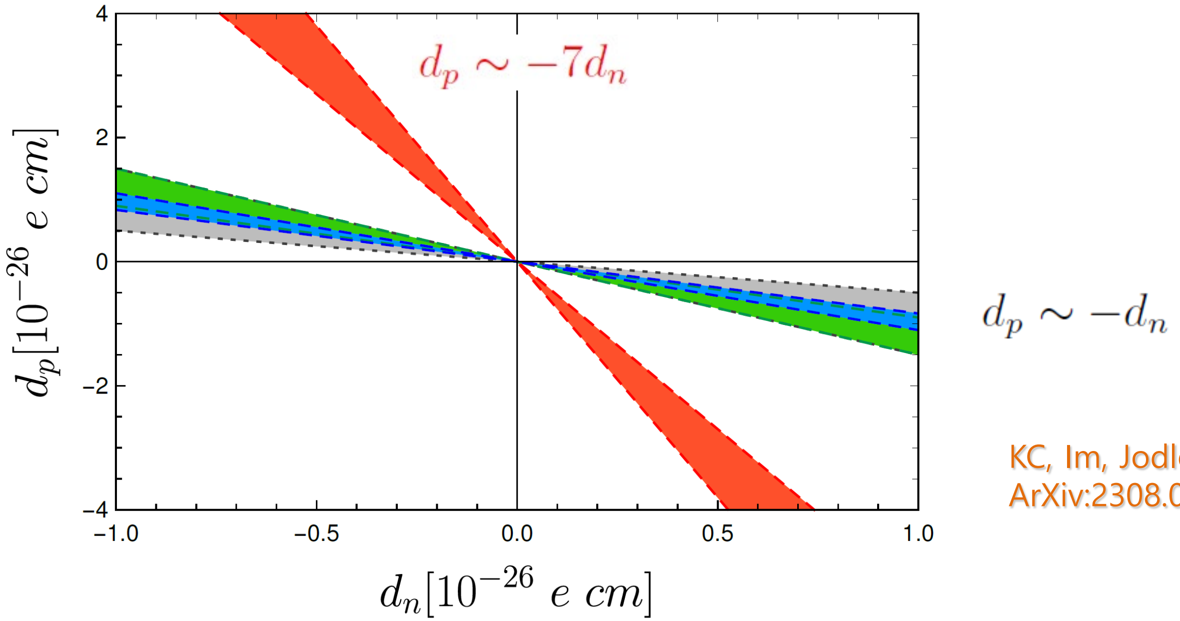
(I) Quark CEDM domination at the BSM scale with $|\bar{\theta}_{\rm UV}| \ll |\bar{\theta}_{\rm BSM}|$

(II) Quark CEDM domination at the BSM scale with $|\bar{\theta}_{\rm UV} + \bar{\theta}_{\rm BSM}| \ll |\bar{\theta}_{\rm BSM}|$

(III) Gluon CEDM domination at the BSM scale with $|\bar{\theta}_{\rm UV}| \lesssim \mathcal{O}(|\bar{\theta}_{\rm BSM}|)$

(IV) $\bar{\theta}_{\rm UV}$ domination (negligible BSM CPV)

Nucleon EDMs



KC, Im, Jodlowski, ArXiv:2308.01090

(I) Quark CEDM domination with $|\bar{\theta}_{\rm UV}| \ll |\bar{\theta}_{\rm BSM}|$

(II) Quark CEDM domination with $|\bar{\theta}_{\rm UV} + \bar{\theta}_{\rm BSM}| \ll |\bar{\theta}_{\rm BSM}|$

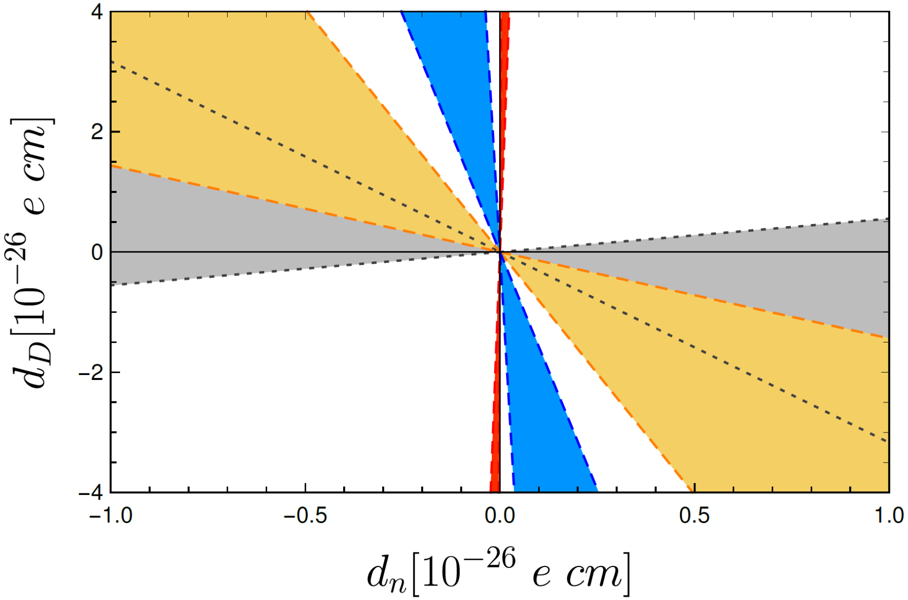
(III) Gluon CEDM domination

(IV) $\bar{\theta}_{\rm UV}$ domination

With d_p/d_n , only the unusual BSM scenario (II) can be distinguished from others, while the other three are not distinguishable from each other.

(This is due to the numerical coincidence in the BSM-induced axion VEV, so the story for the case w/o axion is quite different.)

Deuteron EDM



(I) Quark CEDM domination with $|\bar{\theta}_{\rm UV}| \ll |\bar{\theta}_{\rm BSM}|$

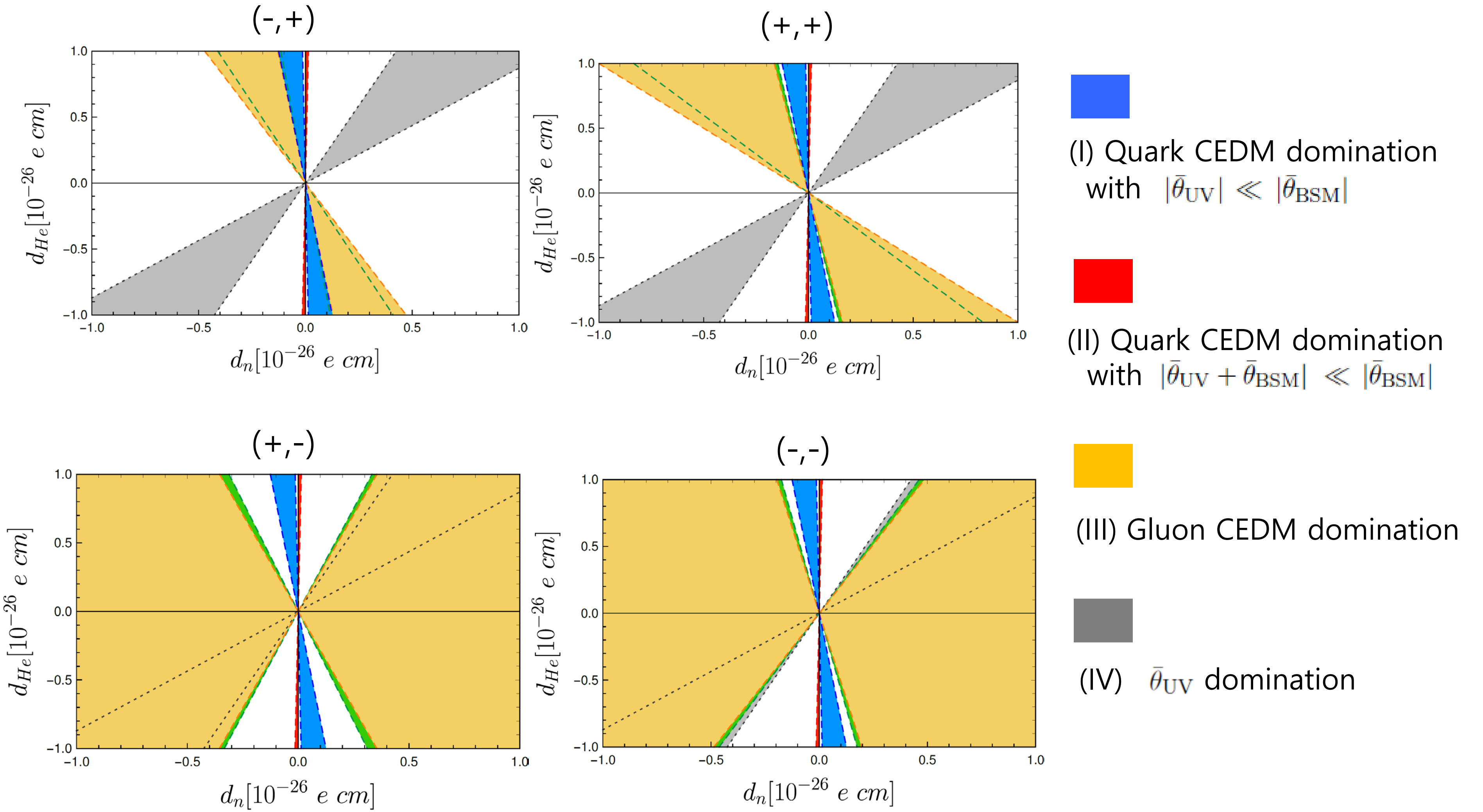
(II) Quark CEDM domination with $|\bar{\theta}_{\rm UV} + \bar{\theta}_{\rm BSM}| \ll |\bar{\theta}_{\rm BSM}|$

(III) Gluon CEDM domination

(IV) $\bar{\theta}_{\rm UV}$ domination

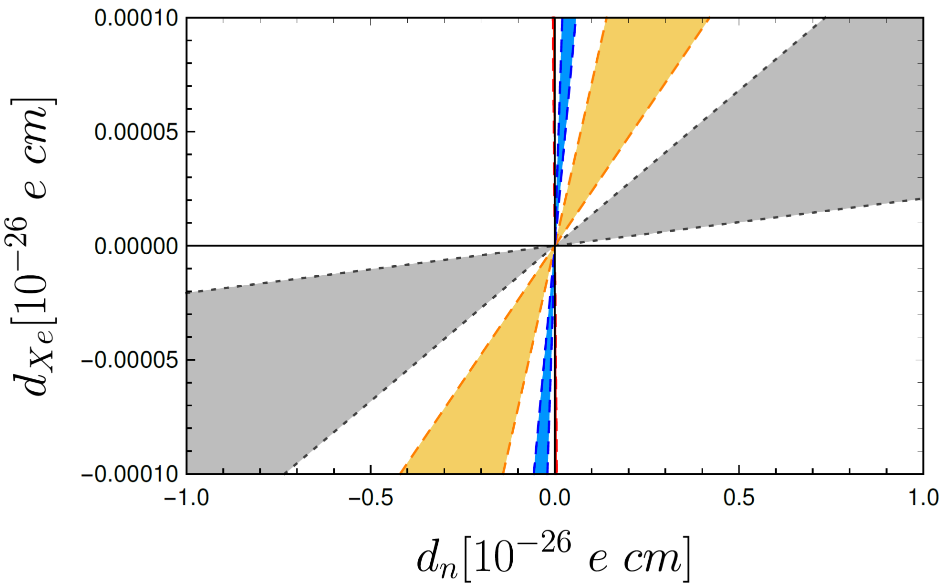
The quark CEDM scenarios (I) & (II) can be distinguished from the gluon CEDM scenario and the $\bar{\theta}_{\rm UV}$ scenario.

Helion EDM for different sign combinations of $\bar{C}_{1,2}(w)$



If $\bar{C}_2(w)$ is positive, the gluon CEDM domination can be distinguished from the $\bar{\theta}_{\rm UV}$ domination.

Xe EDM assumed to be dominantly induced by $\bar{g}_{0,1}$



Conclusion

EDMs may provide not only information on BSM CP violation, but also additional information on the QCD axion including the origin of the axion VEV (the axion quality).

As warm up examples, we performed an analysis examining if the following 4 simple scenarios with a QCD axion can be discriminated from each other, based on the EDM data:

(I) Quark CEDM domination with $|\bar{\theta}_{\rm UV}| \ll |\bar{\theta}_{\rm BSM}|$
(II) Quark CEDM domination with $|\bar{\theta}_{\rm UV} + \bar{\theta}_{\rm BSM}| \ll |\bar{\theta}_{\rm BSM}|$
(III) Gluon CEDM domination without axion $|\bar{\theta}_{\rm UV}| \lesssim \mathcal{O}(|\bar{\theta}_{\rm BSM}|)$
(IV) $\bar{\theta}_{\rm UV}$ domination (negligible BSM CPV)

To discriminate the gluon CEDM domination from other scenarios, better understanding of the involved QCD and nuclear physics parameters appears to be necessary.

It will also be crucial for extending the analysis to more general cases.