Probing the PQ (axion) quality with electric dipole moments

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KC, S.H. Im, K. Jodlowski, JHEP 04 (2024) 007

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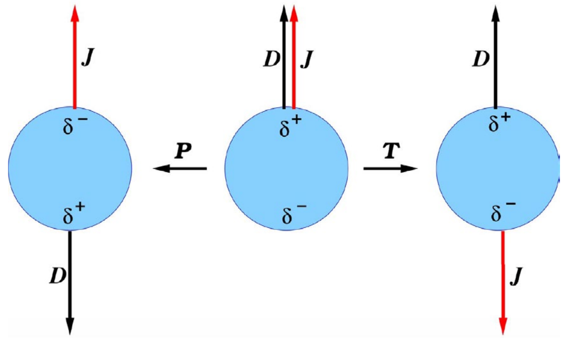
Why Electric Dipole Moments (EDM) are interesting?

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



$$\left(\vec{D} = \sum q_i \vec{r}_i, \quad \vec{J} = \sum_i (\vec{r}_i \times \vec{p}_i + \vec{S}_i)\right)$$

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: $(Y_B)_{\rm SM} \lesssim 10^{-15}$

We need "CP-violating new physics beyond the SM", and EDMs may provide a hint about such new physics.

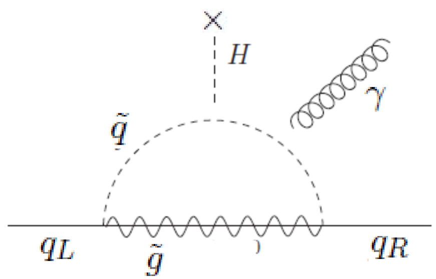
Specifically, EDMs can provide an information on the energy scale where "new physics beyond the SM (BSM physics)" appears.

BSM CP-odd angle

$$\text{EDM} \propto \frac{1}{\Lambda_{\text{BSM}}^2} \times \sin\delta_{\text{BSM}} \times (\text{Loop factors, gauge/Yukawa couplings, ...})$$

BSM mass scale

Quark EDM induced by SUSY particles



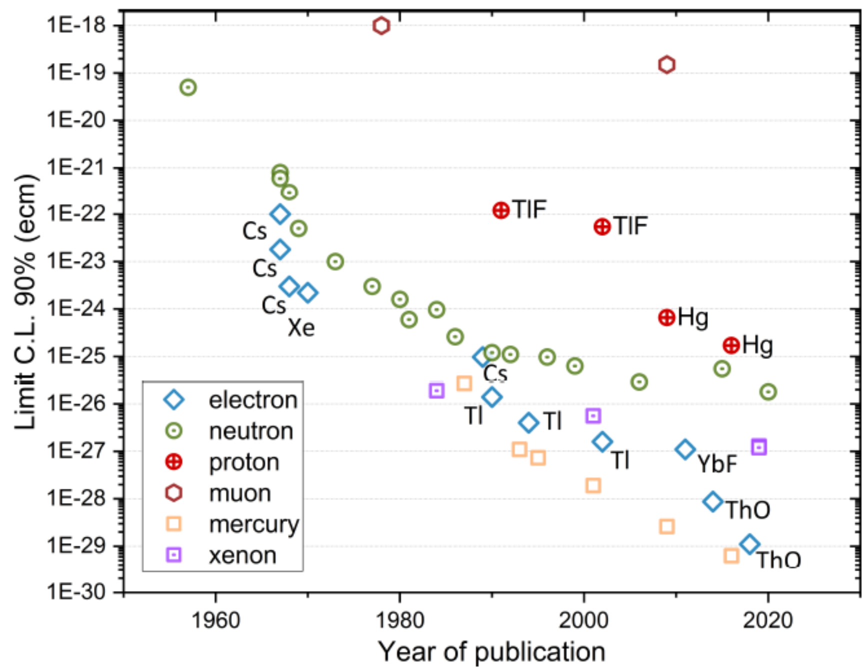
➔ neutron EDM $d_n \propto \frac{\sin\delta_{\text{SUSY}}}{M_{\text{SUSY}}^2}$

$$M_{\text{SUSY}} \sim 10\sqrt{\sin\delta_{\text{SUSY}}}\left(\frac{10^{-26} e\cdot\text{cm}}{d_n}\right)^{1/2}\ \text{TeV}$$

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

	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}	$\mu_N R_{Cs}$
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}Hg	$d_A = (2.2 \pm 3.1) \times 10^{-30}$	7.4×10^{-30}	e cm
^{129}Xe	$d_A = (0.7 \pm 3.3) \times 10^{-27}$	6.6×10^{-27}	e cm
^{225}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

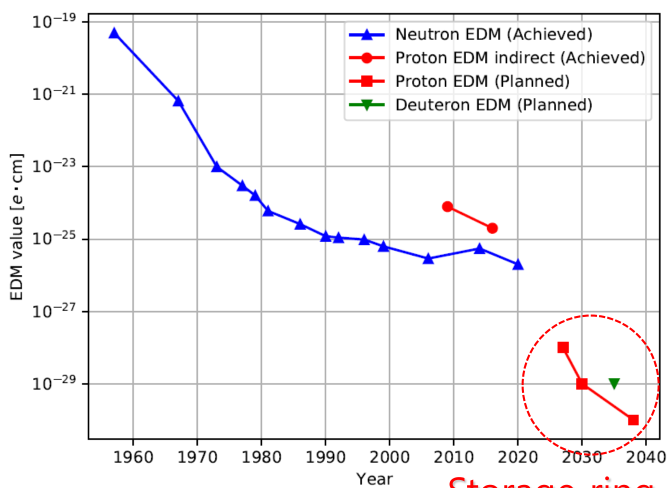


arXiv:2003.00717

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

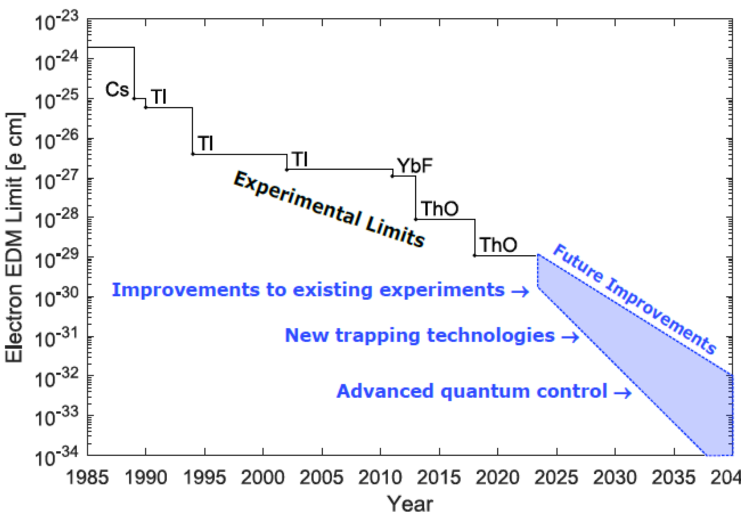
arXiv:2203.08103

Proton or Deuteron EDM from Storage ring EDM experiment



Storage ring EDM

Electron EDM or $C_S \frac{G_F}{\sqrt{2}} \bar{e} i\gamma_5 e \bar{N} N$ from polar molecules



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

$\mathbf{d_D}$ ~ 10^{-29} e.cm

$\mathbf{d_e}$ ~ 10^{-31} – 10^{-33} e.cm (4×10^{-30})

$\mathbf{C_S}$ ~ 10^{-11} – 10^{-13} (5×10^{-10})

SM predictions

Two CP-odd angles in the SM (up to d=4 terms)

$\sin\delta_{\rm KM} \propto \det([y_u y_u^\dagger, y_d y_d^\dagger])$ (CPV in the weak interactions)

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

Experimental data tell $\delta_{\rm KM} \sim 1$, while $|\bar{\theta}| < 10^{-10}$, where the upper bound on $\bar{\theta}$ comes from the neutron EDM given by

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

De Vries et al '01 Mannel, Uraltsev '12

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

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

$$C_S\frac{G_F}{\sqrt{2}}\bar{e}i\gamma_5 e\,\bar{N}N \;:\; C_S \sim 3\times 10^{-2}\sin\bar{\theta} \;+\; 7\times 10^{-16}\sin\delta_{\rm KM}$$

Flambaum et al '19 Ema et al '22

Due to the suppression from the involved flavor mixings, EDMs from δ_{KM} are all well below the experimental sensitivity which can be achieved in near future, while 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 experimental 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.

For this, we need

(i) measurement of multiple EDMs in experiment side,

(ii) quantitative understanding of the EDMs induced by BSM CPV and $\bar{\theta}$ in theory side.

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

We can then solve **the EDM inverse problem:**

Sang Hui Im's talk for more details

Discriminate BSM CPV from $\bar{\theta}$, and extract further information on BSM CPV with experimentally measurable EDMs

PQ (axion) quality problem

The smallness of $|\bar{\theta}| < 10^{-10}$ relative to $\delta_{\rm KM} \sim 1$ causes a naturalness problem called the strong CP problem.

An appealing solution to the strong CP problem is the Peccei-Quinn (PQ) mechanism based on a non-linearly realized global U(1) symmetry:

Peccei & Quinn '77

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

Associated Pseudo-Nambu-Goldstone boson "the axion"

which is dominantly broken by the QCD anomaly.

Generic effective Lagrangian involving the axion at E ~ 1 GeV

PQ-breaking by
the QCD anomaly

Additional axion interactions
including additional PQ-breaking

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

Dominant axion potential
induced by the QCD anomaly

Additional axion potential

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

PQ-mechanism

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

Non-zero axion VEV

Two possible origins of $\delta V(a)$ generating nonzero $\bar{\theta} = \langle a \rangle / f_a$:

1) PQ-breaking by $aG\tilde{G}$ combined with PQ-conserving CP-violation

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

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

- BSM CPV generically described by $\Delta\mathcal{L}_{\rm BSM} = \sum \lambda_i \mathcal{O}_i$ at E ~ 1 GeV:

$$\left(\mathcal{O}_i = \{\bar{q}\gamma_5\sigma^{\mu\nu}G_{\mu\nu}q,\, GG\tilde{G},\, \bar{q}q\bar{q}\gamma_5 q, ...\},\quad \lambda_i = \{\tilde{d}_q,\, w,\, \lambda_{4q}, ...\}\right)$$

$$\delta V_{\rm BSM} \sim \sum_i \lambda_i \int d^4x \left\langle \frac{g_s^2}{32\pi^2} G\tilde{G}(x)\mathcal{O}_i(0)\right\rangle \sin(a/f_a) \quad \left(\lambda_i \propto \left(\frac{1}{8\pi^2}\right)^L \frac{1}{\Lambda_{\rm BSM}^2}\right)$$

$$\Rightarrow \quad \bar{\theta}_{\rm BSM} \sim \frac{\sum_i \lambda_i \int d^4x \,\langle \frac{1}{32\pi^2} G\tilde{G}, \mathcal{O}_i\rangle}{f_\pi^2 m_\pi^2} \quad \propto \left(\frac{1}{8\pi^2}\right)^L \frac{f_\pi^2}{\Lambda_{\rm BSM}^2}$$

* $|\bar{\theta}_{\rm BSM}| < 10^{-10}$ can be easily achieved for $\Lambda_{\rm BSM} > 1\,{\rm TeV}$.

* Unless $\Lambda_{\rm BSM}$ is too high, the resulting $\bar{\theta}_{\rm BSM}$ can be close to 10^{-10}.

2) Additional PQ-breaking other than $aG\tilde{G}$, most notably the breaking by quantum gravity

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

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

$$\delta V_{\rm UV} \sim \frac{f_a^{4+n}}{M_{\rm Pl}^n}\cos\left(a/f_a + \delta_{\rm QG}\right) \quad \text{or} \quad m_{3/2}M_{\rm Pl}^3 e^{-S_{\rm ins}}\cos\left(a/f_a + \delta_{\rm QG}\right)$$

$$\Rightarrow \quad \bar{\theta}_{\rm UV} \sim \frac{f_a^{4+n}}{M_{\rm Pl}^n f_\pi^2 m_\pi^2}\sin\delta_{\rm QG} \quad \text{or} \quad \frac{m_{3/2}M_{\rm Pl}^3}{f_\pi^2 m_\pi^2}e^{-S_{\rm ins}}\sin\delta_{\rm QG}$$

PQ (axion) quality problem

Why PQ-breaking by quantum gravity is highly suppressed, so that

$$|\bar{\theta}_{\rm UV}| < 10^{-10} \ ?$$

$$\left(n \geq 7 \quad \text{or} \quad \text{S}_{\rm ins} \geq 200\right)$$

There have been many theoretical ideas proposed for the PQ quality problem, which may explain why $|\bar{\theta}_{\rm UV}| < 10^{-10}$: (See Ryosuke Sato's talk)

Accidental PQ-symmetry, Composite axions,
Extra-dimensional axions from higher dimensional gauge field, …

These ideas all imply that $\bar{\theta}_{\rm UV}$ can be close to the current experimental upper bound 10^{-10}.

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

EDMs can distinguish $\bar{\theta}_{\rm UV}$ from $\bar{\theta}_{\rm BSM}$, therefore determine the size of $\bar{\theta}_{\rm UV}$ which may parameterize the strength of the PQ-breaking by quantum gravity effects.

BSM CPV affects EDM both directly and through the induced axion VEV $\bar{\theta}_{\rm BSM}$, while the PQ breaking by quantum gravity affects EDM only through the induced axion VEV $\bar{\theta}_{\rm UV}$.

$$\delta V_{\rm UV} \qquad \Delta\mathcal{L}_{\rm BSM} = \sum_i \lambda_i \mathcal{O}_i \qquad \lambda_i = \{\tilde{d}_q,\, w,\, \lambda_{4q},\, ...\}$$

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

$$d_X = \frac{\partial d_X}{\partial \bar{\theta}}\bar{\theta}_{\rm UV} + \sum_i \left(\frac{\partial \langle a/f_a \rangle}{\partial \lambda_i}\frac{\partial d_X}{\partial \bar{\theta}} + \frac{\partial d_X}{\partial \lambda_i} \right)\lambda_i$$

EDM inverse problem

(See S.H Im's talk for more details)

$$d_X = \mathcal{D}_{X\theta}\,\bar{\theta}_{\rm UV} + \sum_i \mathcal{D}_{Xi}\,\lambda_i \qquad \lambda_i = \{\tilde{d}_q,\, w,\, \lambda_{4q}, \ldots\}$$

$$\left(\mathcal{D}_{X\theta} = \frac{\partial d_X}{\partial \bar{\theta}}, \quad \mathcal{D}_{Xi} = \frac{\partial d_X}{\partial \lambda_i} + \frac{\partial \langle a/f_a\rangle}{\partial \lambda_i}\frac{\partial d_X}{\partial \bar{\theta}}\right)$$

$$\rightarrow \quad \bar{\theta}_{\rm UV} = \sum_X (\mathcal{D}^{-1})_{\theta X}\, d_X, \quad \lambda_i = \sum_X (\mathcal{D}^{-1})_{iX}\, d_X$$

If we can theoretically compute $\mathcal{D}_{X\theta}$ and $\mathcal{D}_{Xi}$ for enough number of elements $\{X\} = \{\text{nucleons, nuclei, atoms, molecules}\}$ and enough number of EFT parameters $\lambda_i = \{\tilde{d}_q, w, \lambda_{4q}, ...\}$ with enough accuracy, $\bar{\theta}_{\rm UV}$ and λ_i can be unambiguously determined by experimentally measurable EDMs.

We are far from such a stage, so we will take a more modest approach assuming a specific form of BSM CPV and examine if we can discriminate a certain set of simple scenarios from each other with EDMs.

Specifically we focus on the scenarios that BSM CPV at E ~ TeV is dominated either by the light quark chromo-EDM (CEDM) or by the gluon CEDM.

This is the case in some parameter region of BSM CPV transmitted to the SM fields mainly through the SM gauge interactions and/or the SM Higgs: Multi-Higgs doublets, SUSY, Vector-like quarks, ...

Cirigliano et al '19

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

Gluon CEDM (Weinberg operator)

Quark CEDMs

We then examine if the following scenarios

- (i) $\bar{\theta}_{\rm UV}$ -domination (negligible BSM CPV)
- (ii) light-quark CEDM domination (w/ or w/o QCD axion)
- (iii) gluon CEDM domination (w/ or w/o QCD axion)

can be discriminated from each other by EDMs.

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

$$K_1(\mu) = \frac{d_q(\mu)}{m_q Q_q}, \quad K_2(\mu) = \frac{\tilde{d}_q(\mu)}{m_q}, \quad K_3(\mu) = \frac{w(\mu)}{g_s}$$

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

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

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

Low energy quark CEDM induced by the gluon CEDM through the RG evolution:

$$\frac{\Delta\tilde{d}_q}{m_q}(1\ \mathrm{GeV}) \simeq \begin{cases} 0.41\, w(1\ \mathrm{GeV}) & \Lambda = 1\ \mathrm{TeV}, \\ 0.53\, w(1\ \mathrm{GeV}) & \Lambda = 10\ \mathrm{TeV} \end{cases}$$

Nucleon EDMs

Apply the relevant hadronic matrix elements obtained from the QCD sum rules and chiral perturbation theory:

Pospelov, Ritz '01; Demir et al '02, Hisano et al '12; Hisano et al '15; Haisch et al '19; Yamanaka et al '21

* W/ QCD axion:

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

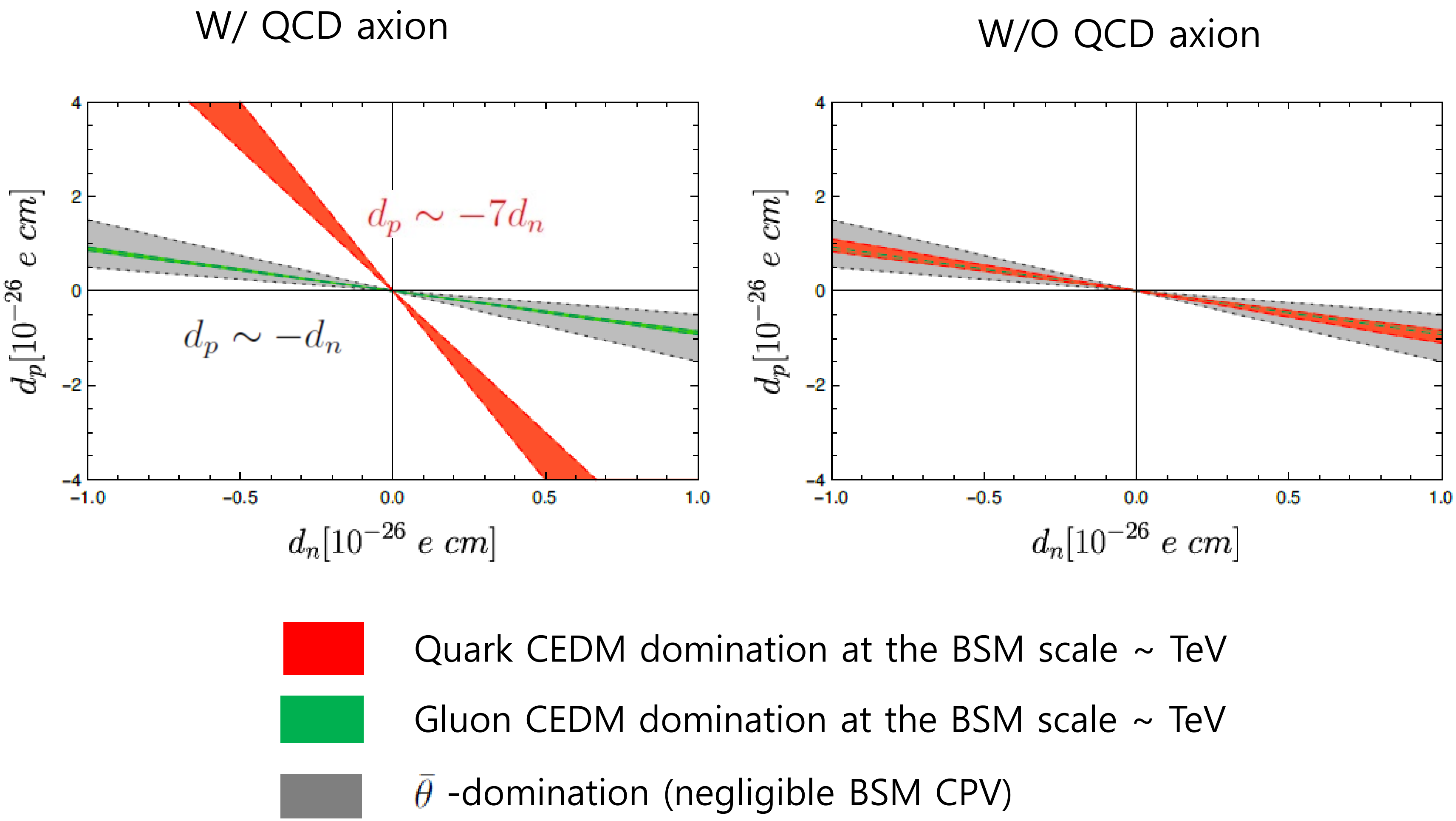
$$d_n^{\rm PQ}(\bar\theta_{\rm UV}, \tilde d_q, d_q, w) = 0.31\times 10^{-16}\bar\theta_{\rm UV}\, e\,{\rm cm} + e\left(0.15\tilde d_u + 0.29\tilde d_d\right) - 0.09 d_u + 0.36 d_d + 20 w\, e\,{\rm MeV}$$

* W/O QCD axion:

$$d_p(\bar\theta, \tilde d_q, d_q, w) = -\,0.46\times 10^{-16}\bar\theta\, e\,{\rm cm} + e\left(-0.17\tilde d_u + 0.12\tilde d_d + 0.0098\tilde d_s\right) + 0.36 d_u - 0.09 d_d - 18 w\, e\,{\rm MeV},$$

$$d_n(\bar\theta, \tilde d_q, d_q, w) = 0.31\times 10^{-16}\bar\theta\, e\,{\rm cm} + e\left(-0.13\tilde d_u + 0.16\tilde d_d - 0.0066\tilde d_s\right) - 0.09 d_u + 0.36 d_d + 20 w\, e\,{\rm MeV}$$

for $w, \tilde d_q, d_q$ renormalized at $\mu = 1$ GeV



With d_p/d_n, only the quark CEDM domination scenario without QCD axion can be discriminated from others, while the other scenarios are not distinguishable from each other.

Light nuclei (D, He) EDMs

EDMs of light nuclei are determined mainly by

Bsaisou et al '15

$$-\frac{i}{2}\bar{N}\left(d_p\frac{1+\tau_3}{2}+d_n\frac{1-\tau_3}{2}\right)\sigma^{\mu\nu}F_{\mu\nu}\gamma_5 N$$

$$m_N\Delta_\pi\pi_3\vec{\pi}\cdot\vec{\pi} \qquad \bar{g}_0\bar{N}\vec{\tau}\cdot\vec{\pi}N+\bar{g}_1\pi_3\bar{N}N$$

$$C_1(\bar{N}N)(\bar{N}i\gamma_5 N)+C_2(\bar{N}\vec{\tau}N)\cdot(\bar{N}i\gamma_5\vec{\tau}N)$$

$$\begin{aligned} d_D &= 0.94(1)(d_n+d_p)+\left[0.18(2)\bar{g}_1-0.75(14)\Delta_\pi\right]e\,\mathrm{fm}, \\ d_{\mathrm{He}} &= 0.9d_n-0.03(1)d_p \\ &\quad+\left[0.11(1)\bar{g}_0+0.14(2)\bar{g}_1-0.63(15)\Delta_\pi-(0.04(2)C_1-0.09(2)C_2)\,\mathrm{fm}^{-3}\right]e\,\mathrm{fm} \end{aligned}$$

CPV pion-nucleon couplings induced by $\bar{\theta}$ and CEDMs

QCD sum rule, ChPT, Lattice:

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

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

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

$$\bar{g}_0(\tilde{d}_q) \simeq -0.004(5) K_2\,\mathrm{GeV}^2 \quad \left(K_2 = \tilde{d}_q/m_q\right)$$

$$\bar{g}_1(\tilde{d}_q) = -0.095(31)\,K_2\,\mathrm{GeV}^2$$

$$\bar{g}_1(w) \simeq \pm(2.6 \pm 1.5) \times 10^{-3} w\,\mathrm{GeV}^2 \quad \text{for } \tilde{d}_q \text{ and } w \text{ at } \mu = 1 \text{ GeV}$$

$\bar{g}_0(\bar{\theta}, \tilde{d}_q)$, $\bar{g}_1(w)$ are compatible with the naive dimensional analysis (NDA) estimation.

Weinberg; Georgi, Manohar '84

On the other hand, $\bar{g}_1(\bar{\theta}, \tilde{d}_q)$ are larger than the NDA estimation by about one order of magnitude, which is mainly due to the large value of

$$\frac{1}{2}\langle N|\bar{u}u + \bar{d}d|N\rangle_{\mu\simeq 200\mathrm{MeV}} \simeq 8$$

which can be determined from $\sigma_{\pi \mathrm{N}} \simeq 59\,\mathrm{MeV}$.

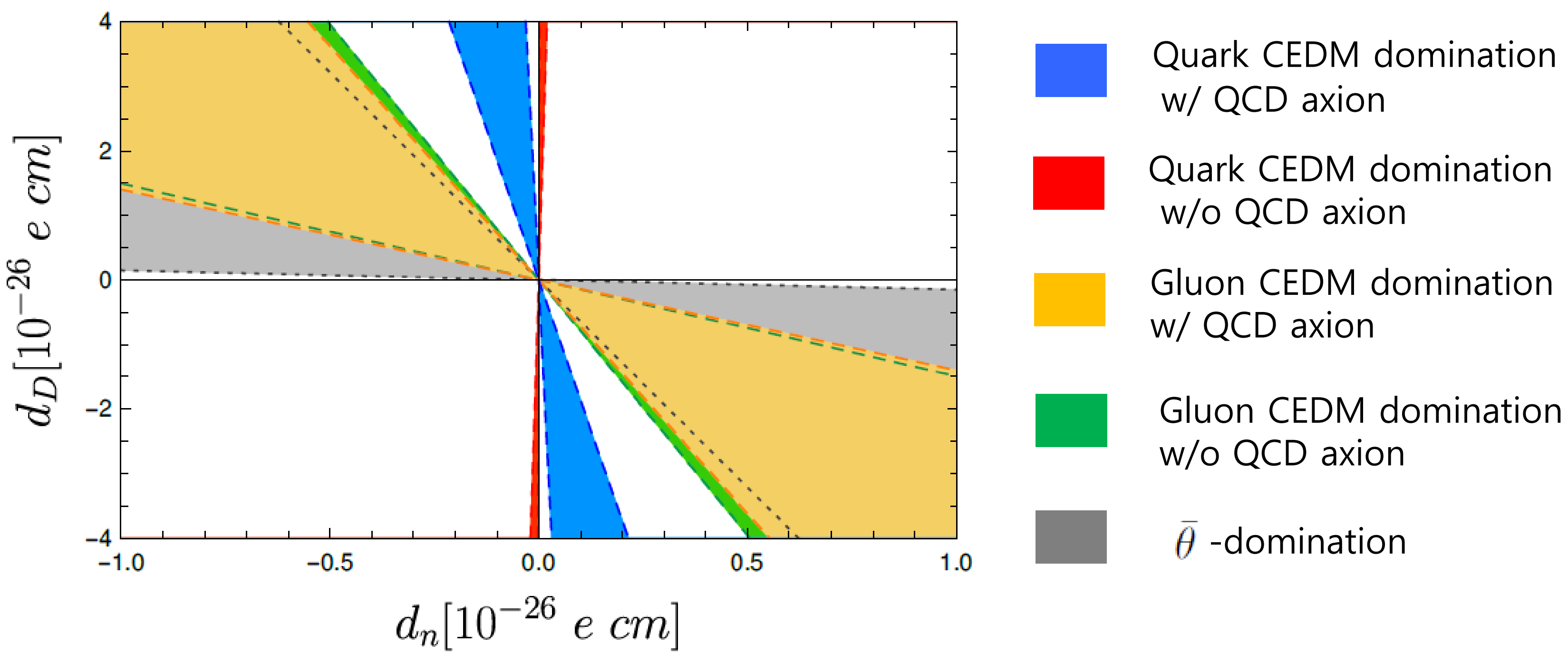
There is no existing calculation for $\bar{g}_0(w)$, $\Delta_\pi(\bar{\theta}, \tilde{d}_q, w)$, $C_{1,2}(\bar{\theta}, \tilde{d}_q, w)$.

Power counting in chiral perturbation theory implies that $C_{1,2}(\bar{\theta}, \tilde{d}_q)$ give only sub-leading effects compared to those of $\bar{g}_{0,1}(\bar{\theta}, \tilde{d}_q)$ so they can be ignored.

If $\bar{g}_0(w)$, $\Delta_\pi(\bar{\theta}, \tilde{d}_q, w)$ obey the NDA estimation, they are about one order of magnitude smaller than $\bar{g}_1(\bar{\theta}, \tilde{d}_q, \Delta\tilde{d}_q)$, and then they also can be ignored.

There can be important contributions to some EDMs from $C_{1,2}(w)$, e.g. for d_{He} . In such case, we may assume that the magnitudes of $C_{1,2}(w)$ obey the NDA estimation, and consider the four possible sign combinations.

Deuteron EDM

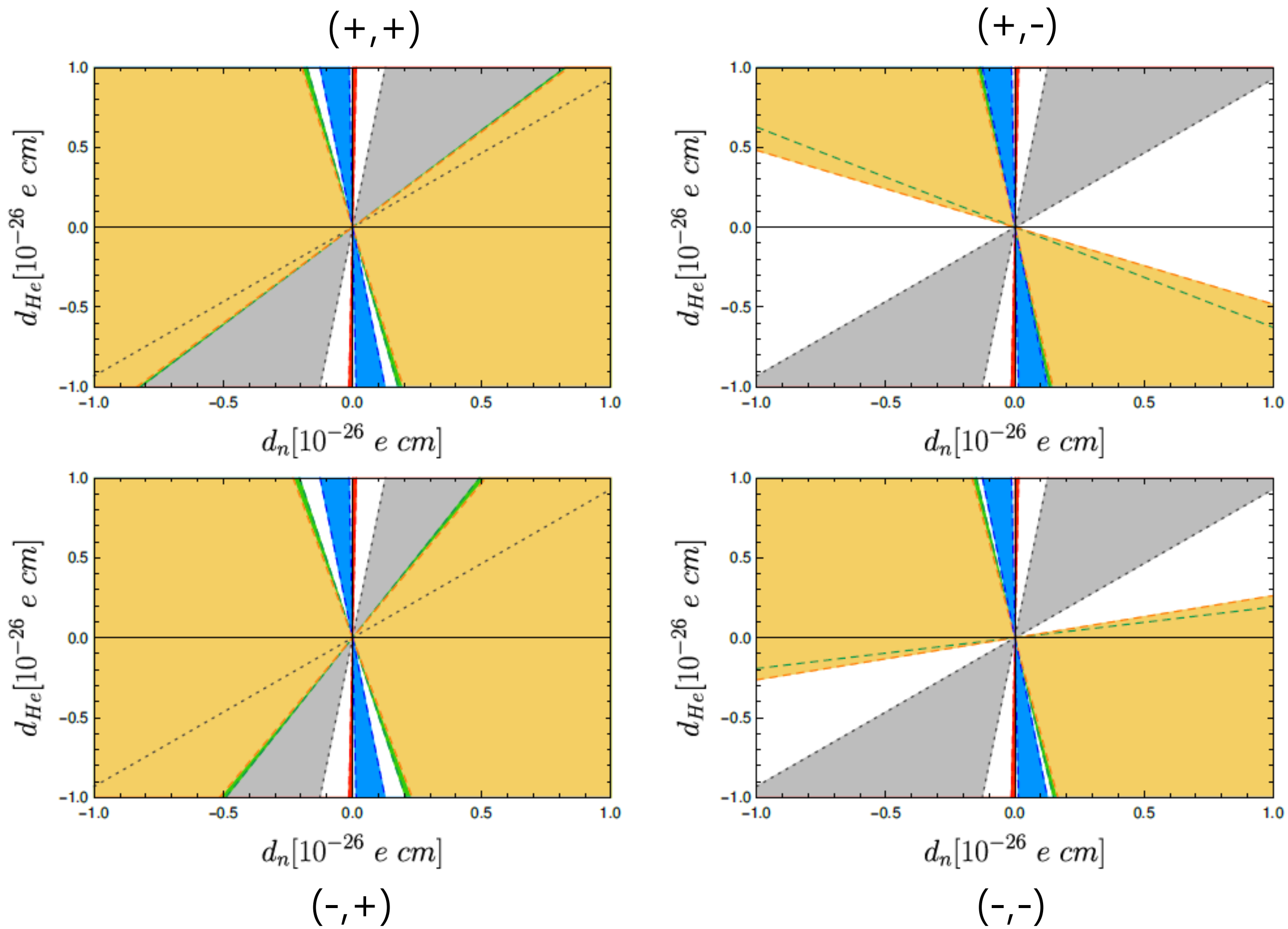


Determined mainly by $d_N(\bar{\theta}, \tilde{d}_q, w)$, $\bar{g}_1(\bar{\theta}, \tilde{d}_q, \Delta\tilde{d}_q)$ which have been evaluated by QCD sum rules.

Regardless of the presence of QCD axion, quark CEDM domination scenario can be discriminated from others.

Yet, the gluon CEDM domination is not distinguishable from the $\bar{\theta}$ domination.

Helion EDM for different sign combinations of $C_{1,2}(w)/w$ under the assumption that their magnitudes obey the NDA:



If $C_2(w)/w$ is negative, the gluon CEDM domination can be distinguished from the $\bar{\theta}$ -domination.

Conclusion

EDMs can provide not only information on BSM CP violation, but also additional information on the origin of the axion VEV, and therefore on the PQ (axion) quality problem.

As an warm up study, we performed an analysis examining if the following five scenarios can be discriminated from each other with the EDM data:

* $\bar{\theta}$-domination (negligible BSM CPV)
* Quark CEDM domination at the BSM scale (w/ or w/o QCD axion)
* Gluon CEDM domination at the BSM scale (w/ or w/o QCD axion)

To unambiguously discriminate the gluon CEDM domination from other scenarios, additional knowledge of the hadronic EFT parameters induced by the gluon CEDM is required.

More comprehensive and quantitative analysis of the hadronic effective couplings $(\bar{g}_{0,1}, C_{1,2}, ...)$ induced by BSM CPV will be essential for making progress in identifying the origin of EDMs (**the EDM inverse problem**) as well as identifying the origin of the axion VEV (**the PQ quality problem**).