Uncovering the axion and BSM CP violation with electric dipole moments

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COSMIC WISPer, Bari

KC, Im, Jodlowski, arXiv: 2308.01090

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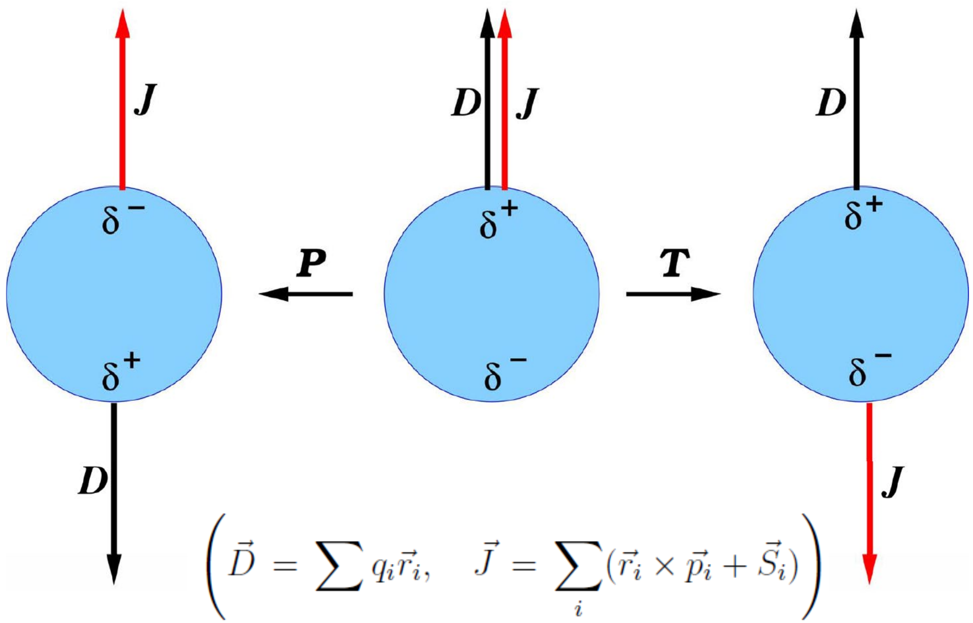
Why EDM is interesting and important?

Nonzero permanent EDM means **P** and **T (=CP)** violation.

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

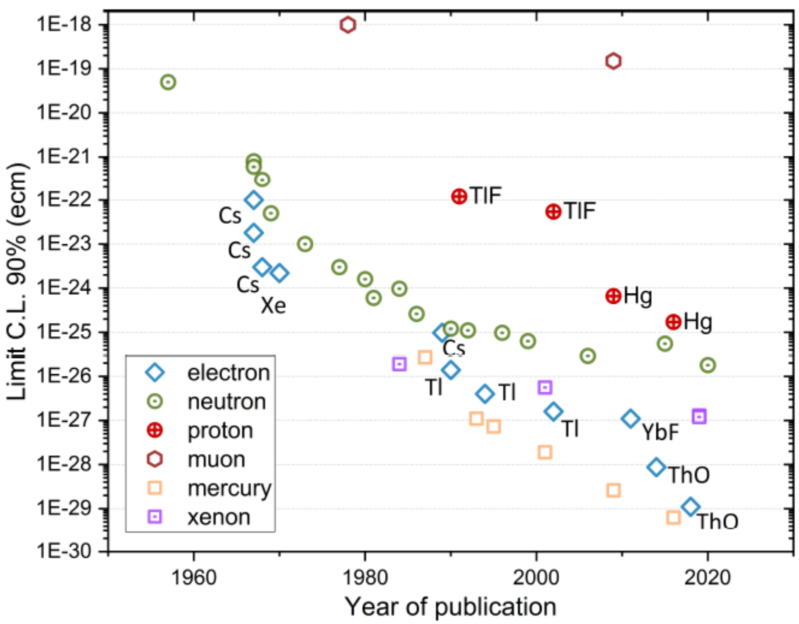
Observed asymmetry: $Y_B = \frac{n_B}{s} \sim 10^{-10}$

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

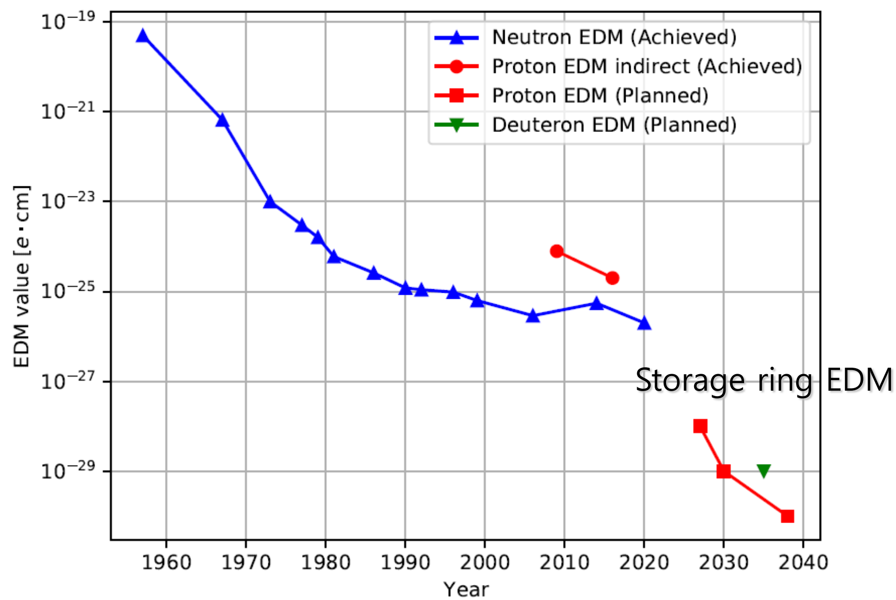
SM can provide neither an enough CP violation, nor out of equilibrium.

We need "Beyond the SM (BSM) physics involving CP violation", and EDM may provide a hint for those BSM physics.

EDMs have a bright prospect for significant experimental progress.



arXiv:2003.00717



arXiv:2203.08103

$$d_n < 1.8 \times 10^{-26} \text{ e cm}$$
$$d_e < 4.1\times10^{-30} \text{ e cm}$$
$$d_{Hg} < 7.4\times10^{-30} \text{ e cm}$$

Abel et al '20
Roussy et al '22
Graner et al '16

SM predictions

$$\delta_{\rm KM} = \arg\cdot\det([y_u y_u^\dagger, y_d y_d^\dagger])$$

$$\bar\theta = \theta_{\rm QCD} + \arg\cdot\det(y_u y_d)$$

$$\frac{d_n}{e\cdot{\rm cm}} = -(1.5\pm0.7)\times10^{-16}\sin\bar\theta \;+\; \mathcal{O}(10^{-31}-10^{-32})\times\sin\delta_{\rm KM}$$

$$\frac{d_p}{e\cdot{\rm cm}} = (1.1\pm1.0)\times10^{-16}\sin\bar\theta \;+\; \mathcal{O}(10^{-31}-10^{-32})\times\sin\delta_{\rm KM}$$

De Vries et al '01 Mannel, Uraltsev '12

$$\Rightarrow \quad |\bar\theta| \lesssim 10^{-10}$$

$$\frac{d_e}{e\cdot{\rm cm}} = -(2.2-8.6)\times10^{-28}\sin\bar\theta \;+\; \mathcal{O}(10^{-44})\times\sin\delta_{\rm KM} \lesssim \mathcal{O}(10^{-37})$$

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

$$\frac{d_e^{\rm equiv}}{e\cdot{\rm cm}} \simeq 4.5\times10^{-22}\sin\bar\theta \;+\; 10^{-35}\sin\delta_{\rm KM} \lesssim \mathcal{O}(10^{-31})$$

Flambaum et al '19 Ema et al '22

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

EDMs from $\delta_{\rm KM}$ are all well below the current experimental bounds, while the hadronic EDMs from $\bar{\theta}$ 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 if it is from BSM CPV or from $\bar{\theta}$.

To answer to this question, quantitative understanding of the contribution from $\bar{\theta}$ is essential, together with the measurement of multiple EDMs.

This question has ben studied recently, but only for a few specific models such as leptoquarks, LR-symmetric, MSSM in a limited parameter space.

de Vries, Draper, Fuyuto, Kozaczuk, Lillard '21

$\bar{\theta}$ with axion

One may think we can eliminate $\bar{\theta}$ by introducing a QCD axion which would solve the strong CP problem by the Peccei-Quinn (PQ) mechanism.

However, in modern viewpoint, even in theories with QCD axion, $\bar{\theta}$ remains to be an incalculable parameter, although its smallness might become more natural (PQ-quality problem).

The axion solution to the strong CP problem is based on a global U(1) symmetry:

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

which is dominantly broken by the axion coupling to gluons:

Peccei, Quinn

Effective lagrangian at E ~ 1 GeV:

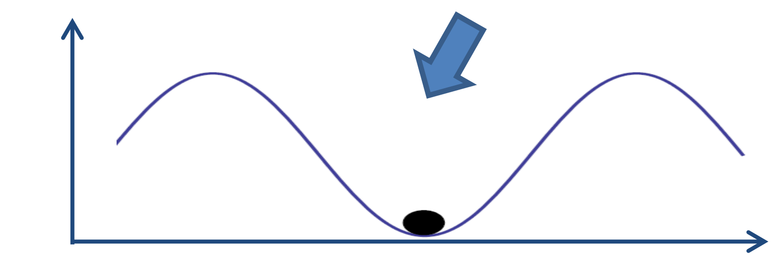
Additional interactions

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

Additional axion potential

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

Shift of axion VEV



$$\langle a \rangle = 0$$

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

$$V(a) = V_{\rm QCD}(a) + \delta V(a)$$

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

Conventional axion potential induced by low energy QCD through the PQ-breaking axion coupling $aG\tilde{G}$

$$\Delta\mathcal{L} = \{\text{SM-CPV}\} + \{\text{BSM-CPV}\} + \{\text{UV-originated additional PQ-breaking}\} + \ldots$$

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

CP-violating effective interactions of gluons and light quarks around 1 GeV where the PQ-breaking by $aG\tilde{G}$ becomes important

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

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

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

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

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

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

$$\bar{\theta}_{\rm SM} \sim 10^{-19}$$

Axion VEV induced by the SM CPV,
which is too small to be interesting

Georgi, Randall '86

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

Axion VEV induced by 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 UV-originated additional
PQ-breaking such as quantum gravity effects,
which also can have any value below 10^{-10}

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?, ...

PQ quality problem:

How to protect the PQ symmetry from quantum gravity to ensure

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

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

$$\Delta\mathcal{L}_{\rm BSM-CPV} = \sum_i \lambda_i \mathcal{O}_i \qquad\qquad \delta V_{\rm UV}(a)$$

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

EDMs

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

In the presence of axion, BSM CPV affects EDM both directly and through the induced axion VEV, while UV-originated PQ breaking affects only through the induced axion VEV.

Discriminating $\bar{\theta}_{\rm UV}$ from $\bar{\theta}_{\rm BSM}$ is a part of the bigger question:

How to identify the UV origin of experimentally observed EDMs?

Effective theory approach provides a model-independent method to study EDMs induced by generic BSM CPV:

BSM model at E > 1 TeV

↓

Integrate out all massive BSM particles and consider the resulting SMEFT

$$\begin{aligned}\mathcal{L}_{\rm CPV}(\mu=\Lambda) =& c_{\widetilde{G}} f^{abc} G^{a\mu}_{\alpha} G^{b\delta}_{\mu} \widetilde{G}^{c\alpha}_{\delta} + c_{\widetilde{W}} \epsilon^{abc} W^{a\mu}_{\alpha} W^{b\delta}_{\mu} \widetilde{W}^{c\alpha}_{\delta} \\ &+ |H|^2 \left(c_{H\widetilde{G}} G^{a}_{\mu\nu} \widetilde{G}^{a\mu\nu} + c_{H\widetilde{W}} W^{a}_{\mu\nu} \widetilde{W}^{a\mu\nu} + c_{H\widetilde{B}} B_{\mu\nu} \widetilde{B}^{\mu\nu} \right) \\ &+ c_{H\widetilde{W}B} H^\dagger \tau^a H \widetilde{W}^{a}_{\mu\nu} B^{\mu\nu}\end{aligned}$$

↓

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

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

$$\left(\mathcal{O}_i = \bar{q}\gamma_5 \sigma \cdot G q,\ GG\tilde{G},\ \bar{q}\gamma_5\sigma \cdot F q,\ \bar{q}\gamma_5 q \bar{q} q, \ldots \right)$$

(light quark and gluon CEDMs, EDMs, 4-fermion operators)

QCD, nuclear & atomic physics ↓

Experimentally measurable nucleon, atomic, molecular EDMs

The first step to identify the UV origin of the experimentally observed EDMs would be to identify the parameter region of $\bar{\theta}$ and the Wilson coefficients λ_i which can explain the measured values:

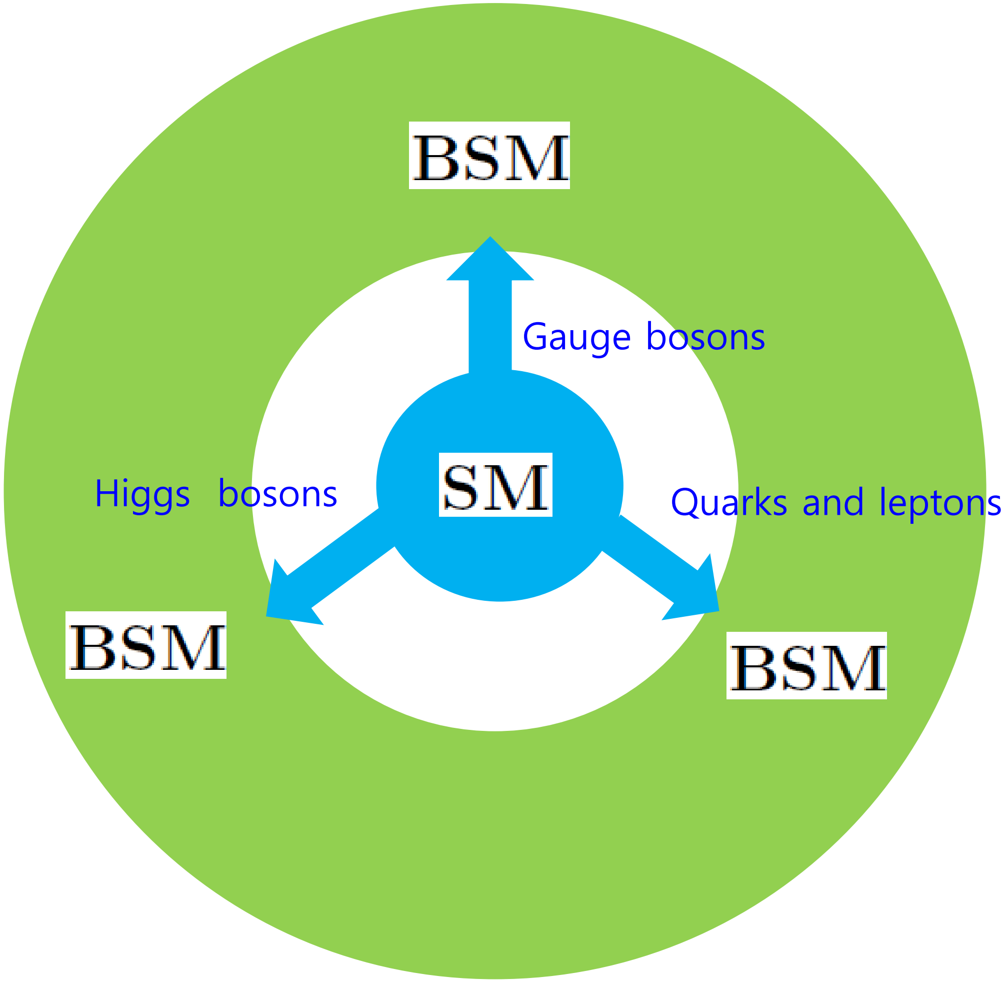
$$\Delta\mathcal{L}_{\rm BSM-CPV} = \sum_i \lambda_i \mathcal{O}_i \quad \left(\mathcal{O}_i = \bar{q}\gamma_5\sigma\cdot Gq,\ GG\tilde{G},\ \bar{q}\gamma_5\sigma\cdot Fq,\ \bar{q}\gamma_5 q\bar{q}q, ...\right)$$

(light quark and gluon 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 parameters, so we start with certain assumptions simplifying the problem.

BSM physics might be classified by how it communicates with the SM.



Certain class of BSM physics communicate with the SM mainly through the SM gauge bosons, particularly gluons, or through the Higgs boson, while being relatively sequestered from the SM quark and leptons:

Multi-Higgs doublets, Split-SUSY with light gluinos, Vector-like quarks, …

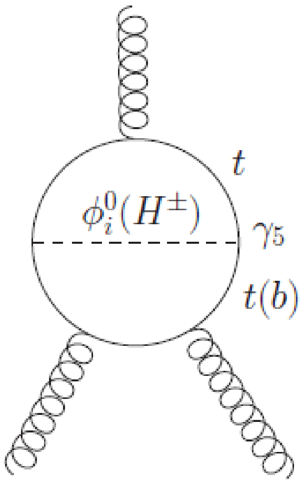
Here we focus on such BSM models in which BSM CPV is transmitted to the low energy world in the form of the gluon and quark chromo-EDMs around the EW scale, for a large portion of the parameter space:

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

Gluon CEDM
(Weinberg operator)

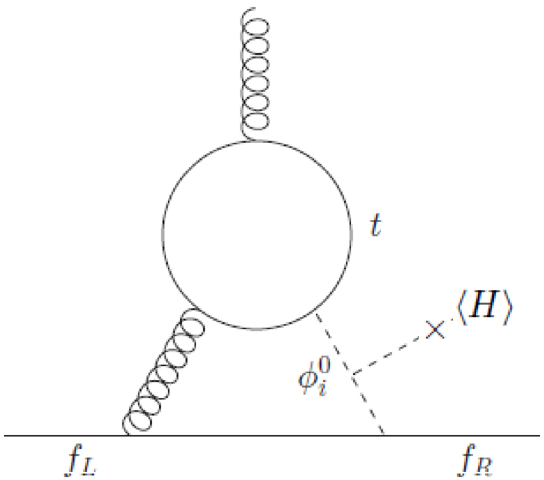
Quark CEDMs

Models of multi-Higgs doublets



$$\frac{1}{3} w f^{abc} G^{a\mu}_{\alpha} G^{b\delta}_{\mu} \widetilde{G}^{c\alpha}_{\delta}$$

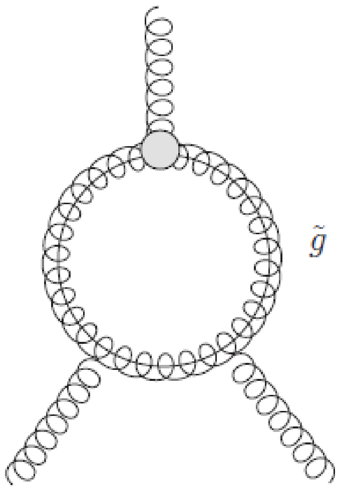
Gluon CEDM
(Weinberg operator)



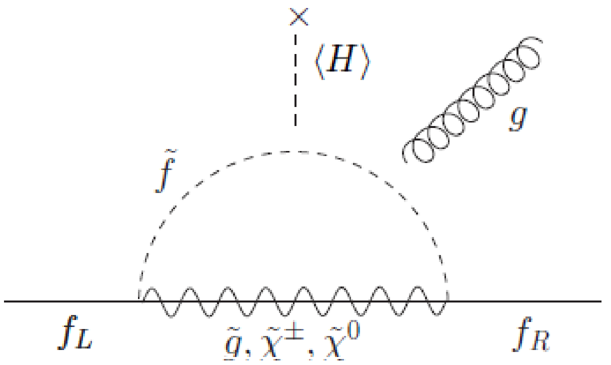
$$\frac{i}{2} \sum_q \tilde{d}_q g_s \bar{q} \sigma^{\mu\nu} G_{\mu\nu} \gamma_5 q$$

Quark CEDM

SUSY models



Gluon CEDM
(Weinberg operator)



Quark CEDM

Vector-like quarks

$$m_\psi \psi \psi^c + y_s S \psi \psi^c + \text{h.c.}$$

KC, Kim, Im, Mo ,16

$\psi + \psi^c$: vector-like quark

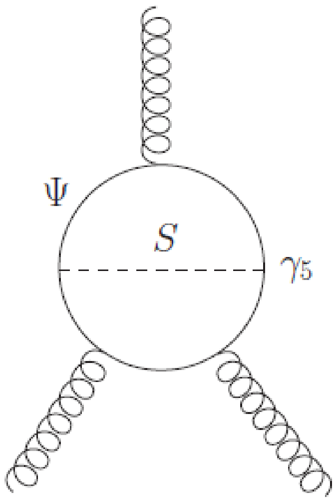
S : singlet real scalar

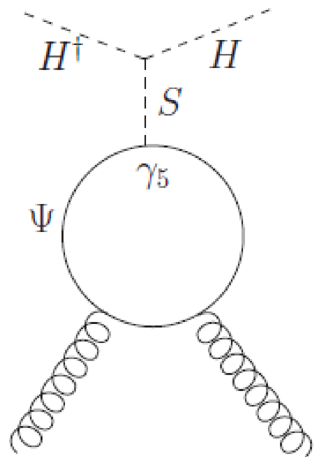
↓ m_ψ, y_S : complex

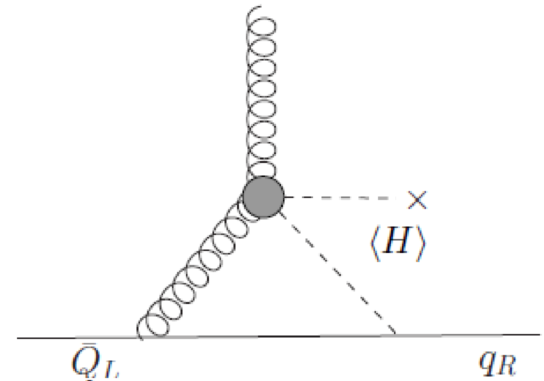
$$|m_\psi| \bar{\Psi}\Psi + |y_S| \cos\alpha \, S\bar{\Psi}\Psi + i|y_S| \sin\alpha \, S\bar{\Psi}\gamma^5\Psi$$

$$\Psi = \begin{pmatrix} \psi \\ \psi^{c*} \end{pmatrix} \qquad \alpha = \arg(m_\psi) - \arg(y_S)$$

s-h mixing







Gluon CEDM
(Weinberg operator)

Quark CEDM

Relative importance of CEDM depends on the size of s-h mixing.

1-loop RG evolution from the BSM scale ~ TeV to 1 GeV

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

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

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

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

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

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

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

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

In case with a QCD axion,

$$\bar\theta_{\rm PQ} \equiv \frac{\langle a\rangle}{f_a} = \bar\theta_{\rm UV} + \bar\theta_{\rm BSM} \qquad \bar\theta_{\rm BSM} = \frac{m_0^2}{2}\sum_{q=u,d,s}\frac{\tilde d_q}{m_q} + \mathcal{O}(4\pi f_\pi^2 w) \qquad \left(m_0^2 \simeq 0.8\,\mathrm{GeV}^2\right)$$

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

$$d_n^{\rm PQ}(\bar\theta_{\rm UV}, \tilde d_q, d_q, w) = 0.31\times 10^{-16}\bar\theta_{\rm UV}\, e\,\mathrm{cm} + e\left(0.15\tilde d_u + 0.29\tilde d_d\right) - 0.089 d_u + 0.36 d_d + 20 w\, e\,\mathrm{MeV},$$

Examine the following **4 simple scenarios** to see if the nucleon and diamagnetic atomic EDMs, which have a good prospect to be measured in future experiments, can discriminate between these 4 scenarios:

- $\bar{\theta}$ domination (with or without axion)

  (Axion VEV dominantly induced by the UV-originated PQ-breaking)

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

  (Axion VEV dominantly induced by the gluon CEDM)

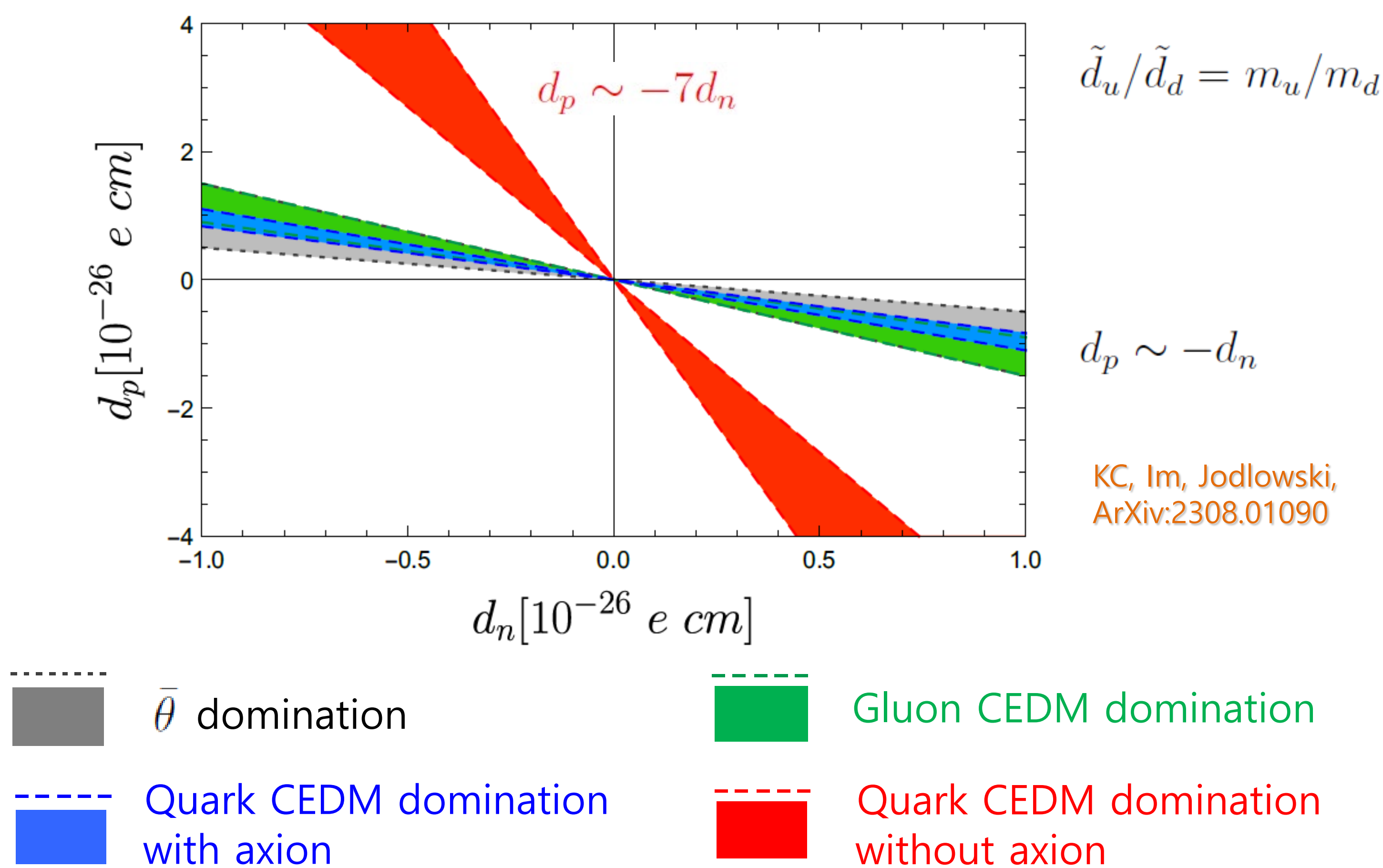
- Quark CEDM domination at the EW scale with axion

  (Axion VEV dominantly induced by the quark CEDM)

- Quark CEDM domination at the EW scale without axion

With this study, we might be able to get an insight on “to what extent EDMs can provide information on the QCD axion”.

Nucleon EDMs



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.

CPV pion-nucleon couplings provide additional nuclear physics parameters generated by the underlying $\bar{\theta}$ parameter and BSM CPV:

$$\bar{g}_0 \bar{N} \frac{\vec{\sigma}}{2} \cdot \vec{\pi} N + \bar{g}_1 \pi_3 \bar{N} N$$

EDMs of diamagnetic atoms are particularly sensitive to these CPV pion-nucleon couplings. Some are sensitive only to the isospin-violating coupling, while others are equally sensitive to the both couplings:

$$\begin{aligned}
d_D &= 0.94(1)(d_n + d_p) + 0.18(2)\bar{g}_1 \, e\,\mathrm{fm}, \\
d_{He} &= 0.9 d_n - 0.05 d_p + [0.10(3)\bar{g}_0 + 0.14(3)\bar{g}_1] \; e\,\mathrm{fm}, \\
d_{Ra} &= 7.7 \times 10^{-4} \, [(2.5 \pm 7.5)\bar{g}_0 - (65 \pm 40)\bar{g}_1] \; e\,\mathrm{fm}, \\
d_{Xe} &= 1.3 \times 10^{-5} d_n - 10^{-5} \, [1.6\bar{g}_0 + 1.7\bar{g}_1] \; e\,\mathrm{fm},
\end{aligned}$$

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

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

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

$$\bar{g}_0(\tilde{d}_q) \simeq (2.2 \pm 0.7)\mathrm{GeV}\,(\tilde{d}_u + \tilde{d}_d)$$

$$\bar{g}_1(\tilde{d}_q) \simeq (38 \pm 13)\mathrm{GeV}\,(\tilde{d}_u - \tilde{d}_d)$$

due to the accidentally large value of

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

$$\bar{g}_0(\omega) \simeq 10^{-2}\omega\,\mathrm{GeV}^2$$

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

QCD sum rule, ChPT, Lattice

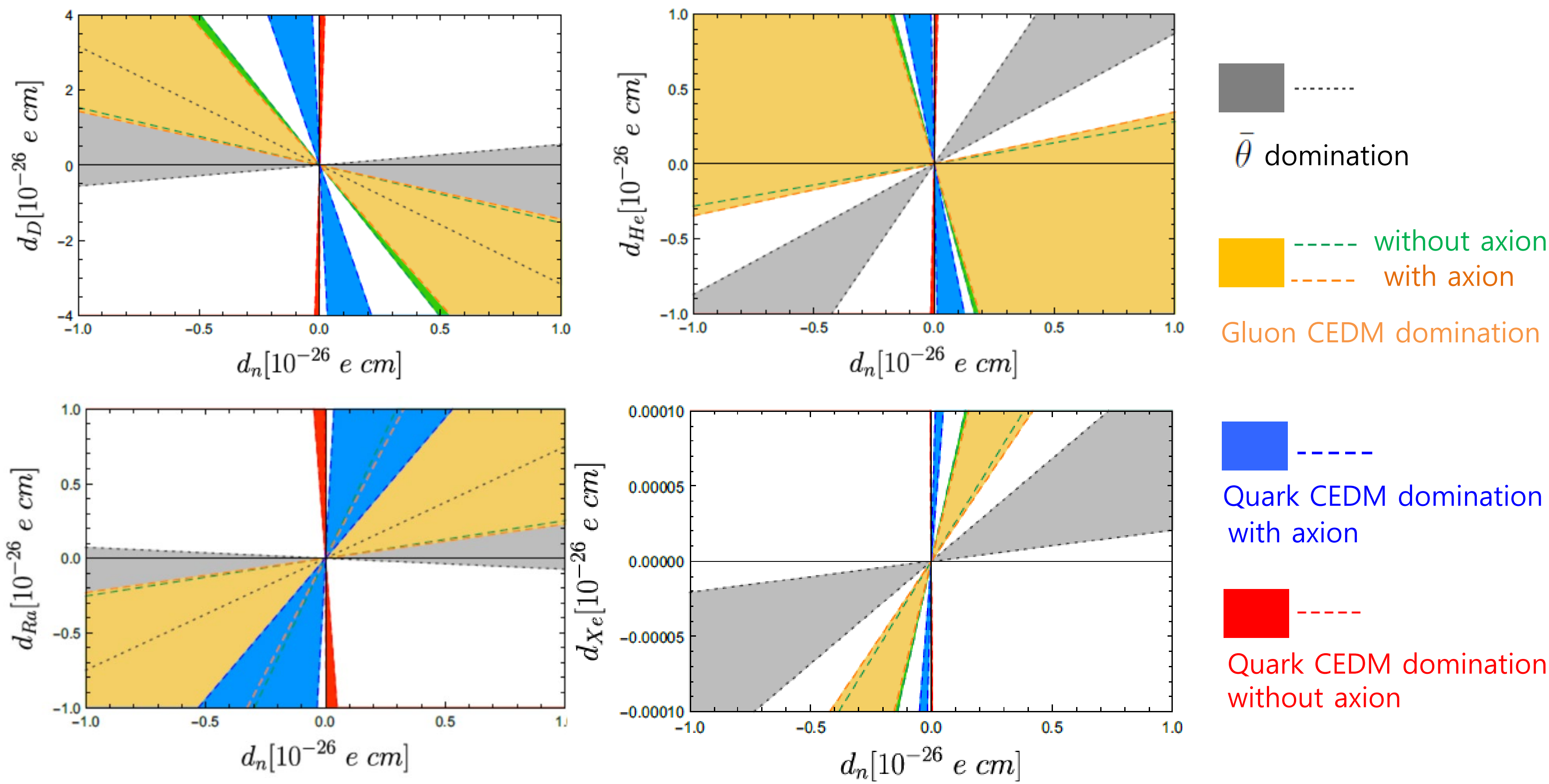
Chupp et al '19
de Vries et al '21
Osamura et al '22

$\bar{g}_{0,1}$ and $\tilde{d}_q$ break $SU(2)_L \times SU(2)_R$, while $\bar{\theta}, \omega$ do not.

Suppression from $SU(2)_L \times SU(2)_R$ breaking while (without) preserving the isospin:

$$\frac{(m_u + m_d)}{4\pi f_\pi} \sim 10^{-2} \qquad \left(\frac{(m_d - m_u)}{4\pi f_\pi} \sim 3 \times 10^{-3}\right)$$

Diamagnetic atomic EDMs



In case with axion, $\bar{\theta}$ -domination corresponds to the $\bar{\theta}_{\rm UV}$ -domination which can be discriminated from other scenarios having $|\bar{\theta}_{\rm BSM}| \gg |\bar{\theta}_{\rm UV}|$.

Conclusion

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

As simple examples, with the nucleon and diamagnetic atomic EDMs, the following 4 scenarios can be discriminated from each other:

1) $\bar{\theta}$ domination
2) Gluon CEDM domination (with or without axion)
3) quark CEDM domination without axion
4) quark CEDM domination with axion

Extending this analysis to more general situation appears to be challenging and it requires a further improvement of the involved QCD, nuclear and atomic physics calculations for EDMs.

Thank you for your attention.