Can electric dipole moment experiments distinguish sources of BSM CP violation?

Seminar “Theory of elementary particles and cosmology”
3 October 2024, Faculty of Physics, University of Warsaw

Krzysztof Jodłowski
Institute for Basic Science
Center for Theoretical Physics of the Universe
Particle Theory and Cosmology Group
Daejeon, S. Korea

Based on:
Kiwoon Choi, Sang Hui Im, KJ
JHEP 04 (2024) 007

Outline

- Motivation
  - CP violation in the SM
  - QCD axion and the PQ quality problem
  - *BSM CPV* dim. 6 operators

- Electric dipole moments
  - mapping high energy BSM to nuclear/atomic EDMs
  - *Can sources of BSM CP violation be distinguished?*

- Summary

Standard Model and Beyond

SM is the EFT validated up to $E \sim 100's$ GeV but going beyond is needed

$$\mathcal{L}_{SM} = \mathcal{L}_{kin} + gA_\mu \bar{F}\gamma_\mu F + Y_{ij}\bar{F}_i H F_j + \lambda(H^\dagger H)^2 + \ldots + O_{\text{Weinberg}} + O_{d=6} + \ldots$$

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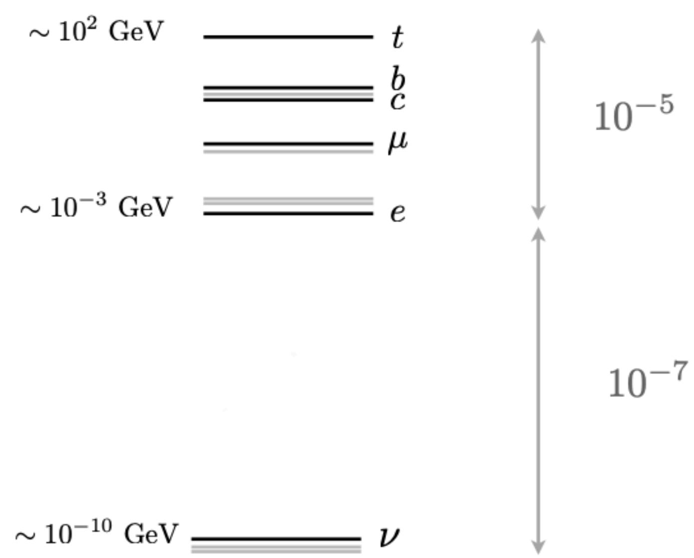
- cosmological constant: $+ c_0\, \Lambda_{UV}^4 \sqrt{g}$ $\qquad c_0 \sim -10^{-60} \left(\frac{\mathrm{TeV}}{\Lambda_{UV}}\right)^4$ $\qquad$ d=0
- EW hierarchy problem: $+ c_2\, \Lambda_{UV}^2\, H^\dagger H$ $\qquad c_2 \simeq 0.008 \left(\frac{\mathrm{TeV}}{\Lambda_{UV}}\right)^2$ $\qquad$ d=2
- strong CP problem: $+ \theta\, G_{\mu\nu} \tilde{G}^{\mu\nu}$ $\qquad \theta \lesssim 10^{-10}$ $\qquad$ d=4
- neutrino masses



Coefficients of these renormalizable and super-renormalizable operators are fine tuned; *c_n is natural if $c_n \to 0$* leads to enhanced symmetry.

't Hooft: Naturalness, Chiral Symmetry, and Spontaneous Chiral Symmetry Breaking

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• *strong CP problem*	$+\,\theta\,G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\theta \lesssim 10^{-10}$	d=4

New Physics

- hierarchy problem (UV): SUSY, GUT, extra dim., string theory
- *strong CP problem* (IR): axion from global $U(1)_{\mathrm{PQ}}$ which is anomalous, spontaneously broken at high scale f_a, and explicitly broken by QCD instantons

  strong CP problem (UV): P-invariance in UV (Left-Right sym.);

  CP-invariance in UV but spont. broken (Nelson-Barr, modular-invariance, ...)

CP violation in QCD

- Yukawa quark couplings
  - mass matrix after EWSB is neither Hermitian nor diagonal
    $\mathscr{L} \supset \bar{q}_i M_{ij} q_j + \mathrm{h.c.}$
  - from flavor to mass basis: (large) mixing in the CKM matrix $\delta_{\text{CKM}} \sim 1$.

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- Theta term

$$\mathscr{L} \supset \theta G\tilde{G} = \partial_\mu K^\mu, \quad K_\mu = \theta\, \epsilon_{\mu\nu\rho\sigma}\left(A_a^\nu G_a^{\rho\sigma} - \frac{f^{abc}}{3} A_a^\nu A_b^\rho A_c^\sigma\right)$$

This is CP odd *topological* term - it's a total derivative but i) K_μ not gauge-inv and ii) its integral is nonzero. It measures the change of winding number of gauge configurations; θ is a global property of the state (θ vacuum).

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- Chiral rotations of the quark fields
  - the mass matrix M_{ij} is diagonalized by transformations $SU(N_f)_A \times SU(N_f)_V$
  - to remove the overall phase, rotate $q_{R/L} \to e^{\pm i\alpha/2} q_{R/L}$
  - the physical theta is the rotation invariant combination: $\bar{\theta} = \theta - \arg\det M$

Consequences of CPV

- Electric dipole moments
  - $d^{\text{EDM}}\bar{\psi}\sigma_{\mu\nu}\gamma^5\psi F^{\mu\nu} \rightarrow d^{\text{EDM}}\overrightarrow{S}\cdot\overrightarrow{E};$
  - Under T: $\overrightarrow{E} \rightarrow \overrightarrow{E}$, $\overrightarrow{\sigma} \rightarrow -\overrightarrow{\sigma}$

    $$\frac{e}{2}F_{\mu\nu}\sigma^{\mu\nu} = -e\begin{pmatrix} (\vec{B}+i\vec{E})\vec{\sigma} & \\ & (\vec{B}-i\vec{E})\vec{\sigma} \end{pmatrix}$$

  - $d^{\text{EDM}} \propto \bar{\theta} \neq 0$ indicates T violation, which by the CPT theorem, is equivalent to CPV
  - The non-observation of d_N^{EDM} implies that $|\bar{\theta}| \lesssim 10^{-10} \rightarrow$ fine-tuning! (strong CP problem)

    The anthropic bound is weak: $0 \lesssim \bar{\theta} \lesssim 0.1$

    Ubaldi Phys.Rev.D81 025011, 2010; Lee et al. Phys. Rev. Research 2, 033392 (2020)

- Sakharov conditions for baryogenesis $\frac{N(B)}{N(\gamma)} \approx 10^{-9} \gg 10^{-20}$
  - C and CP violation
  - Baryon number violation
  - Departure from thermal equilibrium

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- Sakharov conditions for baryogenesis $\dfrac{N(B)}{N(\gamma)} \approx 10^{-9} \gg 10^{-20}$ SM
  - C and CP violation
  - Baryon number violation (sphelarons)
  - Departure from thermal equilibrium (electroweak and QCD phase transitions are smooth crossovers)

  SM

  BSM

- BSM with CPV is expected
  - We will study patterns of d^{EDM} induced by some dim-6 CPV operators predicted by
    - BSM that *solves* the strong CP problem by introducing axion
    - other solution

Towards the Axion

- Digression
  - what about $\theta_{\rm EM} F\tilde{F}$ and $\theta_{\rm weak} F_a \tilde{F}^a$?
    - the first is unphysical since it always integrates to zero for finite-energy configurations (no abelian instantons)
    - the second can be *rotated away* due to the chiral anomaly; since the weak force involves only the left-handed quarks, this is $U(1)_B$
    - For QCD with $m_u = 0$: $\bar{\theta} = \theta - \arg\det M = \theta$ and the same applies.

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- Let's compute the QCD vacuum energy using CHPT
  - WLOG $\bar{\theta} = \theta - \arg\det M = -\arg\det M$ (complex masses); $\mathscr{L} \supset \bar{q}_i M_{ij} q_j + \text{h.c.}$

$$V(\bar{\theta}) = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4m_u m_d}{(m_u+m_d)^2}\sin^2\left(\frac{\bar{\theta}}{2}\right)} \approx \frac{1}{2} m_\pi^2 f_\pi^2 \frac{m_u m_d}{(m_u+m_d)^2}\bar{\theta}^2.$$ Di Vecchia, Veneziano 80

$V(\bar{\theta})$ is periodic with minimum at the origin — Vafa, Witten 84

"Promote" $\bar{\theta}(x) = a(x)/f_a$, $m_a = 5.7 \times \left(\frac{10^{12}\,\text{GeV}}{f_a}\right) \mu\text{eV}$ — Peccei, Quinn 77; Weinberg 78; Wilczek 78

(a got mass from the QCD anomaly: $m_a \sim \Lambda_{\text{QCD}}^2/f_a$)

Peccei–Quinn Axion

- There is a new global, chiral symmetry $U(1)_{\mathrm{PQ}}$ Peccei, Quinn 77; Weinberg 78; Wilczek 78
    - the quarks have non-zero charges e_i and transform as $q_{R_i/L_i} \to e^{\pm i e_i \alpha/2} q_{R_i/L_i}$
    - Assigning the charges such that $\sum_i e_i \neq 0$, the $U(1)_{\mathrm{PQ}} \times SU(3)^2$ current is anomalous and θ can be rotated away like in the $m_u = 0$ solution.

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    - Actually, this is impossible in the SM if $U(1)_{\mathrm{PQ}}$ is not broken
        - Normalizing $\sum_i e_i = 1$, $\bar{Q}_L H D_R$ implies $H \to H e^{i\alpha/6}$, while $\bar{Q}_L H^c U_R$: $H \to H e^{-i\alpha/6}$
        - Evaded if $U(1)_{\mathrm{PQ}}$ is spontaneously broken; the <u>pseudo</u>Goldstone boson $a(x)$ has approximate shift symmetry (<u>anomaly</u> indicates there is explicit breaking by <u>instantons</u>)
        - SSB does not spoil the physical $\bar{\theta}_{ph} = \bar{\theta} + a/f_a \simeq 0$. The shift symmetry is broken by $a(x)G(x)\tilde{G}(x)$ and condition $\bar{\theta}_{ph} \simeq 0$ is equivalent to $\langle a/f_a \rangle \simeq -\bar{\theta}$.

Peccei–Quinn Axion

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- Since $U(1)_{\rm PQ}$ is chiral, the axion a is a pseudoscalar, and the $aG\tilde{G}$ term is CP even.
- What is the scale f_a?
  - $f_a = v_{\rm SM}$ Peccei, Quinn 77; Weinberg 78; Wilczek 78 — Excluded by $K \to \pi a$
  - $f_a \gg v_{\rm SM}$ KSVZ (1979) and DFSZ (1980) "invisible axions" — The targets of Primakoff effect searches, helioscopes, etc.

The Invisible QCD Axion

- DFSZ Dine, Fischler, Srednicki; Zhitnitsky (1980)
  - Repeat the PQWW axion:
    - add a second Higgs doublet H_2 and a scalar Φ

      $H_1 \to e^{i\alpha/6} H_1, \quad H_2 \to e^{-i\alpha/6} H_2, \quad \Phi \to e^{i\alpha/6}\Phi$
    - The axion field is a linear combination of the phases
    - The PQ scale $$f_a = \frac{\sqrt{v_1^2 + v_2^2 + v_\Phi^2}}{6}$$

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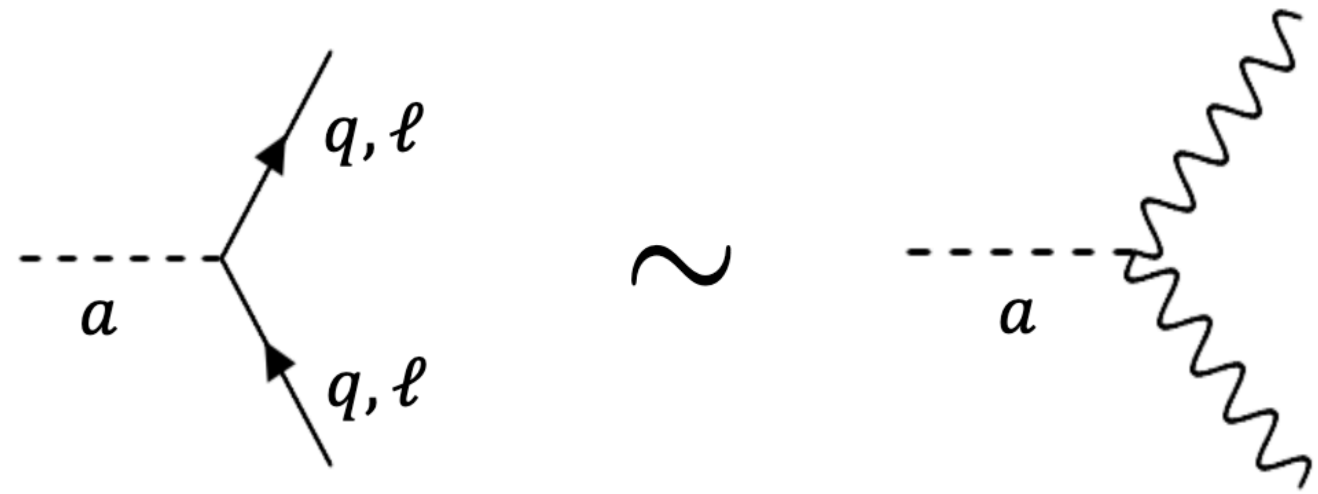
- KSVZ Kim; Shifman–Vainshtein, Zakharov (1979)
  - quarks have $e_i = 0$; instead, add heavy quark $\Psi \sim (3,1,0)$ with $e_\Psi = e_\Phi/2$
  - We also introduce a singlet field Φ, whose vev will give m_Ψ

    $$\mathcal{L}_{\text{PQ-inv}} \supset \lambda \Phi \overline{\Psi}_L \Psi_R + \text{h.c.} \qquad |\langle \Phi \rangle| = v_\Phi/\sqrt{2}.$$

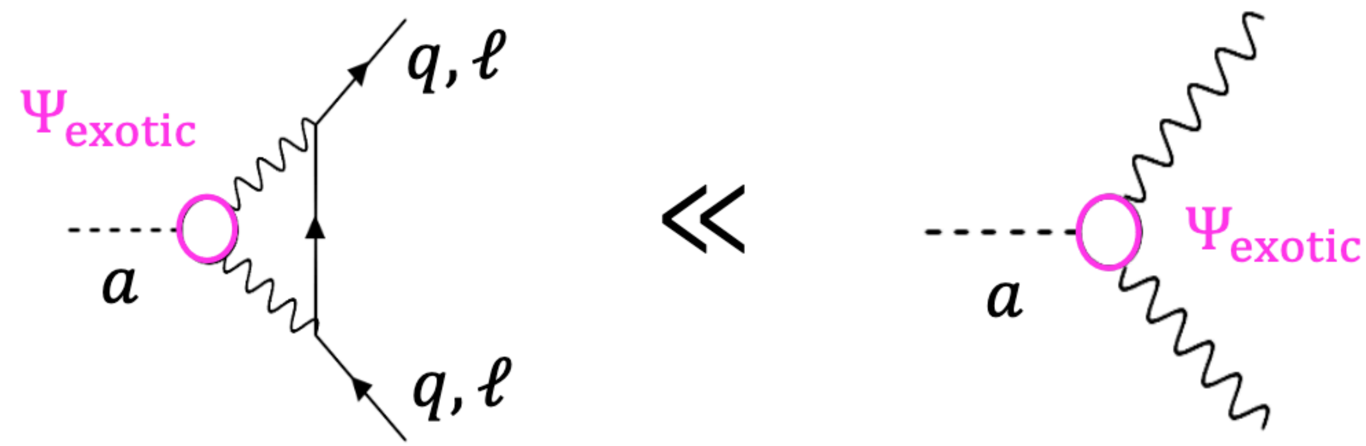
    $$\Phi = (f_a + \sigma(x)) e^{i a(x)/\sqrt{2} f_a}$$
    - Often called a "hadronic axion" - leptons through photon loops
- Axion or ALP? discrete shift symmetry $a \to a + 2\pi f_a$ and coupling to gluons $G^{\mu\nu} \tilde{G}_{\mu\nu}$

The Invisible QCD Axion

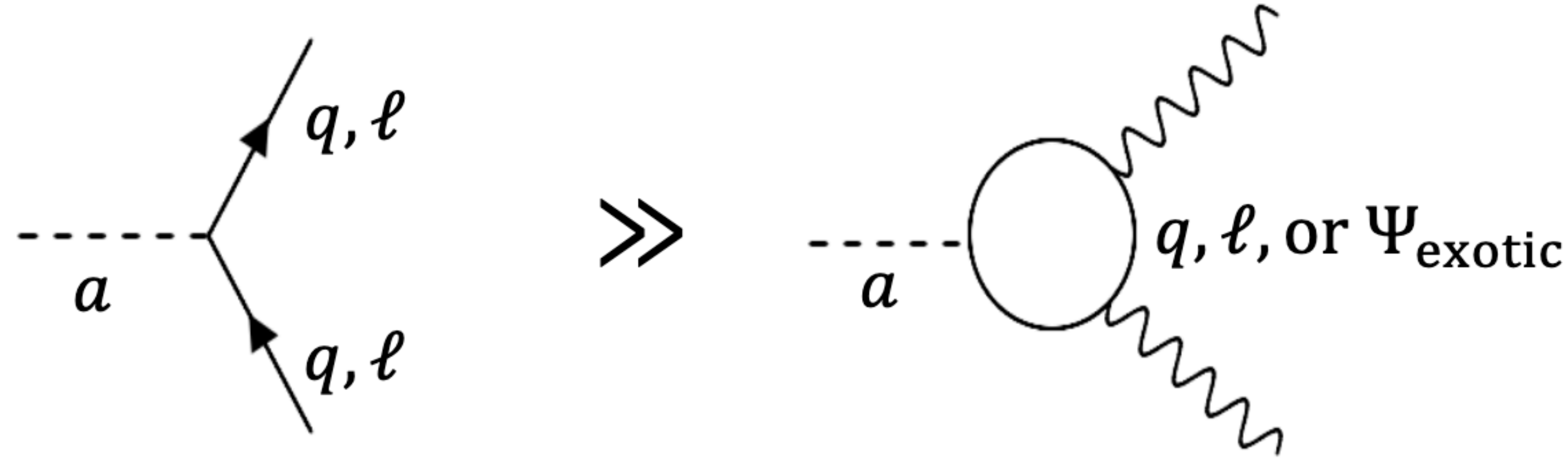
String-theoretic axions



KSVZ-like axions

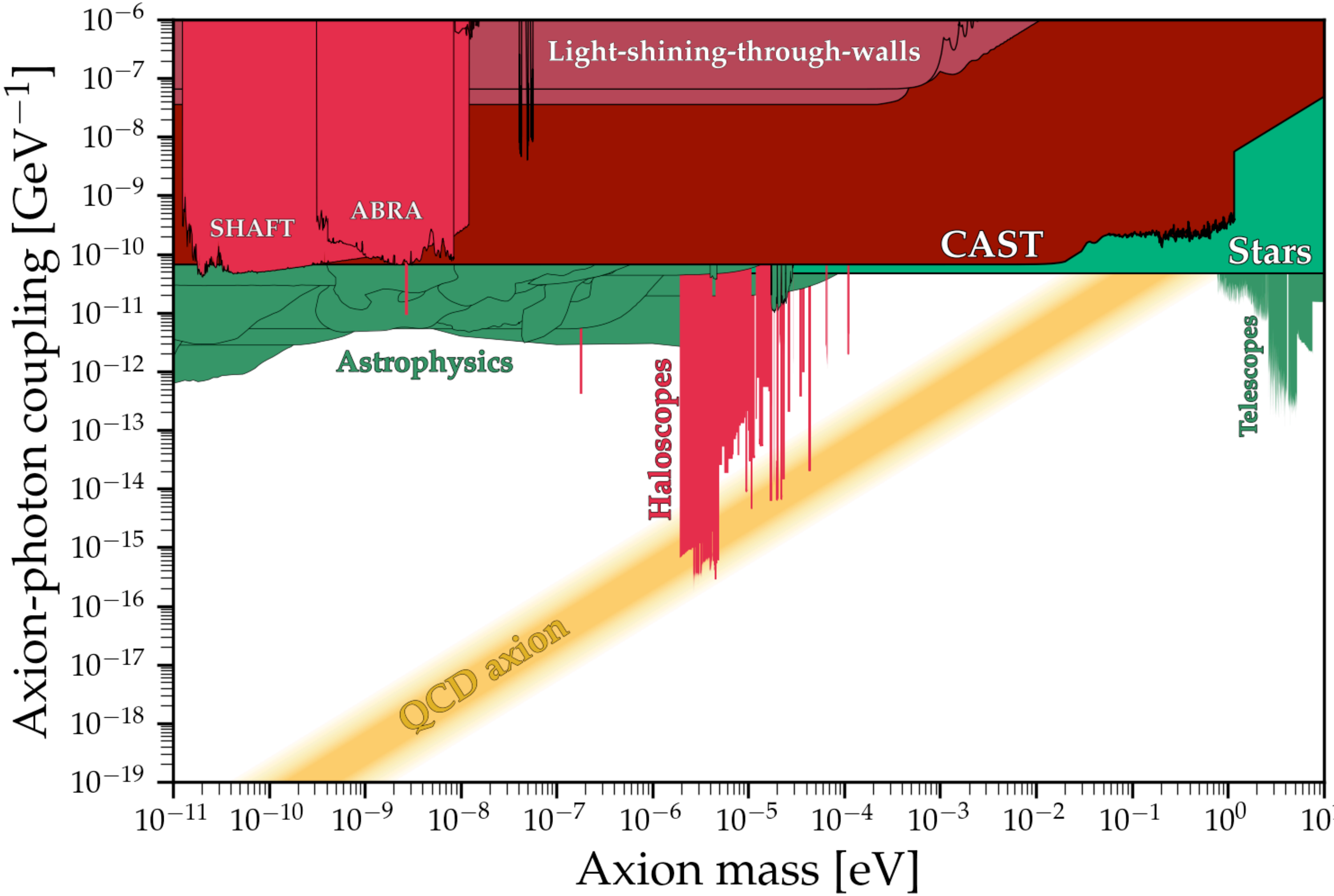


DFSZ-like axions



Slide by Sang Hui Im

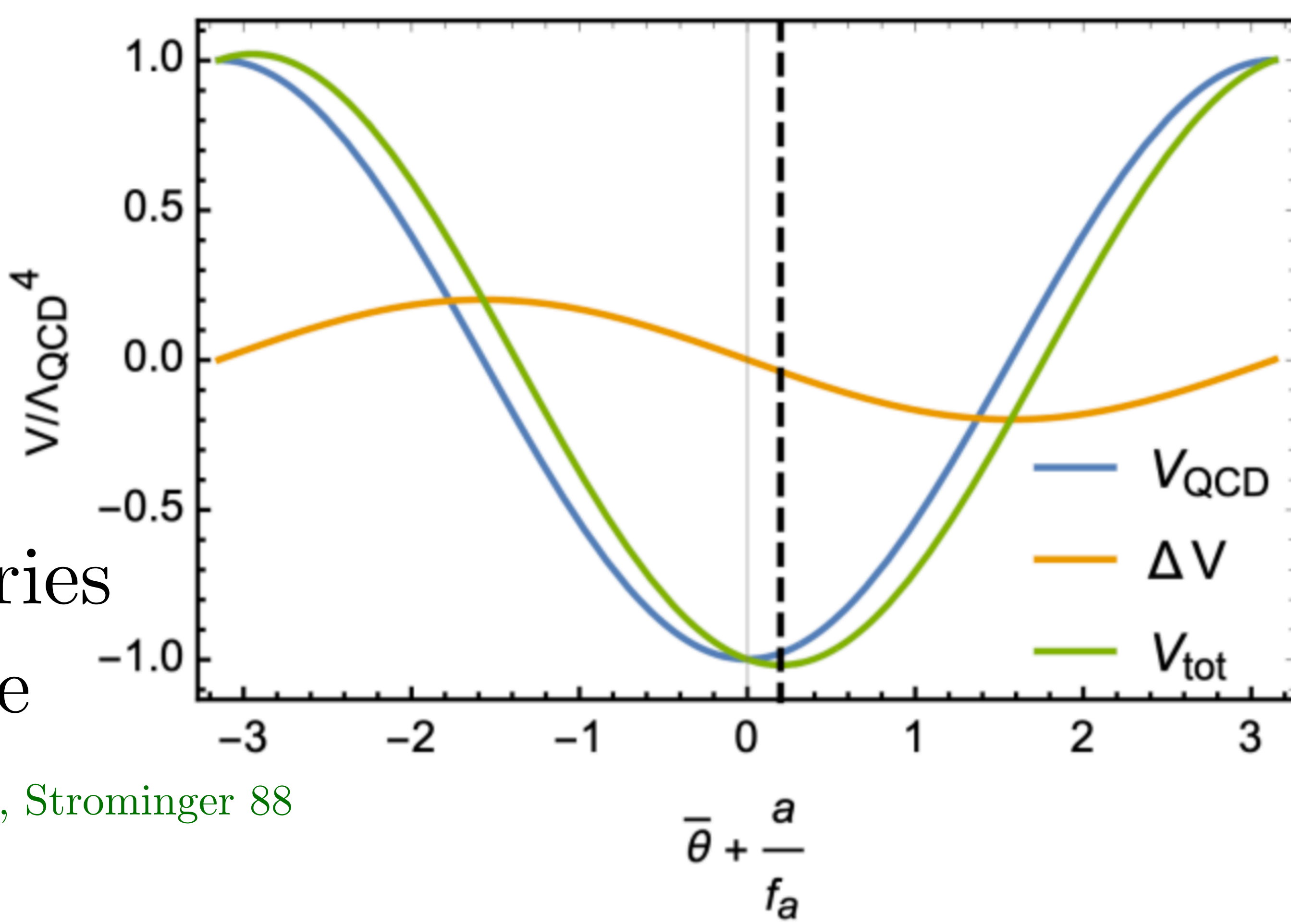
The Invisible QCD Axion



Ciaran O'Hare https://cajohare.github.io/AxionLimits

PQ quality problem

- The $U(1)_{\rm PQ}$ was assumed to be nearly exact, broken only by non-perturbative QCD effects or by very high-dimension irrelevant operators
- For PQ field $\Phi = \frac{f_a}{\sqrt{2}} e^{ia/f_a}$ a PQ-violating operator $\frac{c_n}{M_{Pl.}^{n-4}} \Phi^n + \mathrm{h.c.}$ induces $V(a) \simeq -2|c_n| M_{Pl.}^4 \left(\frac{f_a}{\sqrt{2} M_{Pl.}}\right)^n \cos\left(\frac{na}{f_a} + \delta_n\right)$. This shifts the axion field from the CP-conserving minimum by
$$\frac{|\Delta a|}{f_a} \simeq 2n|c_n \sin\delta_n| \left(\frac{M_{Pl.}}{\Lambda_{\rm QCD}}\right)^4 \left(\frac{f_a}{\sqrt{2} M_{Pl.}}\right)^n$$
Barr, Seckel 92, Kamionkowski, March-Russel 92



- In particular, (quantum) gravity is expected to violate any global symmetries *e.g.*, gravitational instanton potential due to wormhole induce $\theta_{eff} \simeq \frac{e^{-S_{wh}}}{(\Lambda_{QCD} R_0)^4}$ Giddings, Strominger 88

PQ quality problem

The physical QCD angle receives three independent contributions:

$\bar{\theta}_{ph} = \bar{\theta}_{\rm SM} + \bar{\theta}_{\rm BSM/PQ} + \bar{\theta}_{\rm QG}$, where $\bar{\theta}_{\rm SM} \simeq 10^{-19}$, $\bar{\theta}_{\rm BSM/PQ} \lesssim 10^{-10}$, $\bar{\theta}_{\rm QG} \sim ?$

- The global anomalous $U(1)_{\rm PQ}$
    - is an accidental symmetry, e.g., discrete gauge symmetries

      Kraus, Wilczek 89
    - comes from 5D gauge symmetry

      Cheng, Kaplan 01; Izawa, Watari, Yanagida 02; Arkani-Hamed, Cheng, Creminelli, Randall 03
    - predicted by $SO(32)$ superstring theory (zero modes of p-form gauge field)

      Witten 84
    - is actually gauged
        - by introducing second sector which cancels the anomaly

          Barr, Seckel 92; Suzuki, Yanagida, Ibe 18
        - using the dual description: two-form axionic gauged shift symmetry

          Dvali 05

Can we distinguish $\bar{\theta}_{\rm BSM/PQ}$ from $\bar{\theta}_{\rm QG}$? The latter only influences $\langle a \rangle$.

Electric dipole moments

- $d^{\text{EDM}}\,\bar{\psi}\,\sigma_{\mu\nu}\,\gamma^5\,\psi\,F^{\mu\nu} \rightarrow d^{\text{EDM}}\,\overrightarrow{S}\cdot\overrightarrow{E}$; $\quad \frac{e}{2}F_{\mu\nu}\sigma^{\mu\nu} = -e\begin{pmatrix} (\vec{B}+i\vec{E})\vec{\sigma} & \\ & (\vec{B}-i\vec{E})\vec{\sigma} \end{pmatrix}$
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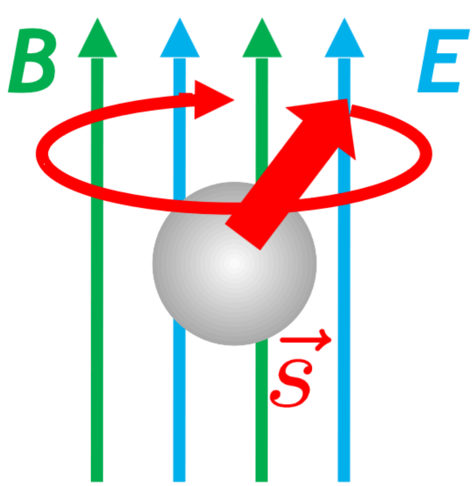
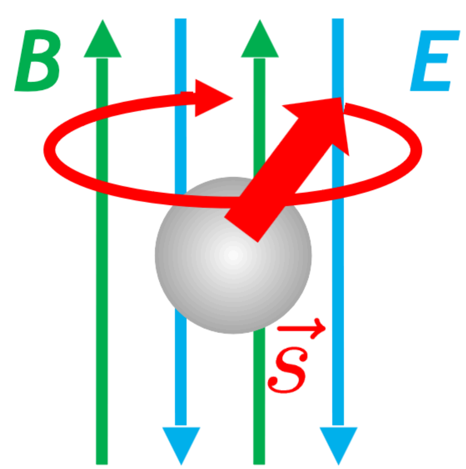


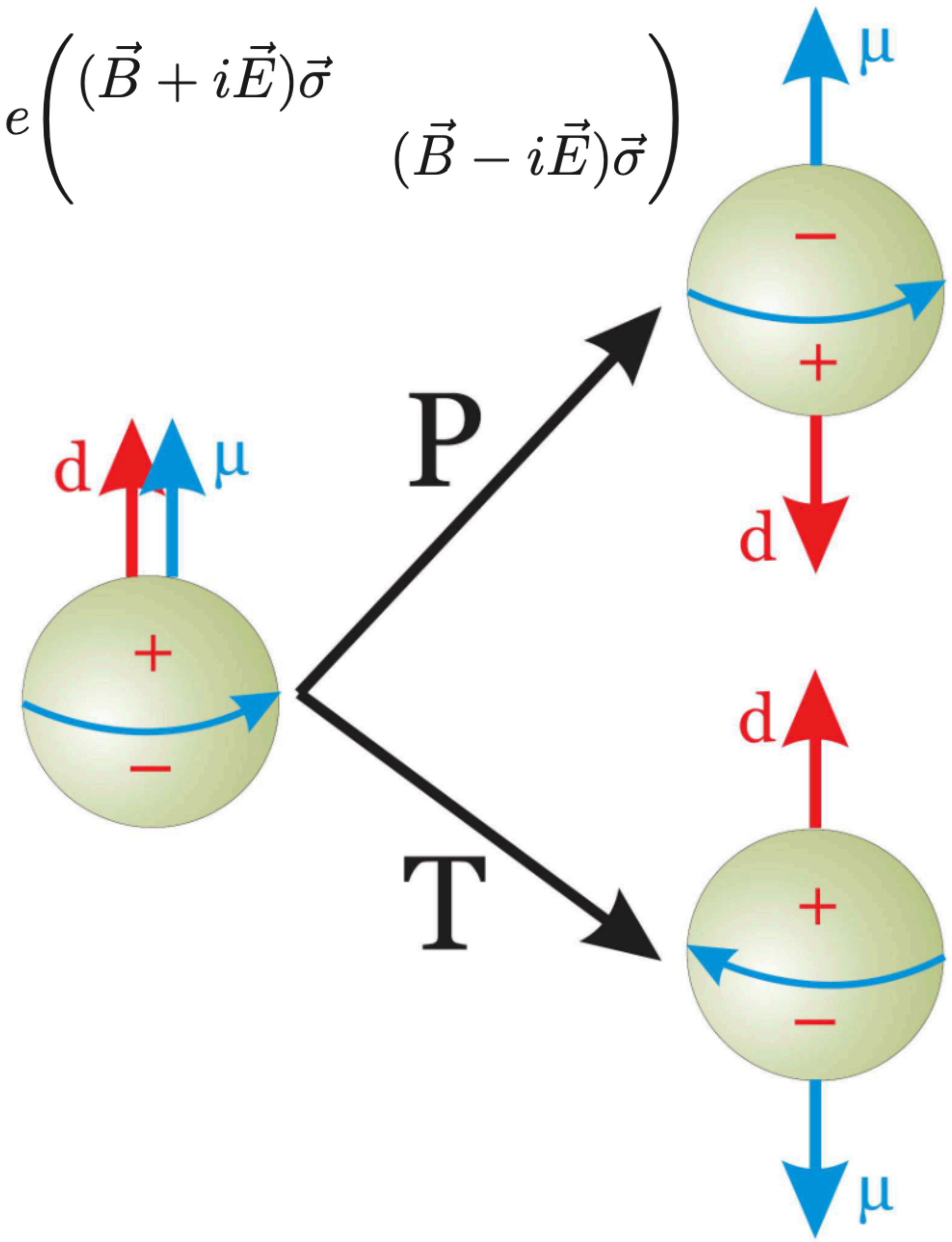


$\omega_{\uparrow\uparrow} = 2(\mu B + dE)/\hbar \qquad \omega_{\uparrow\downarrow} = 2(\mu B - dE)/\hbar$

$$d^{\text{EDM}} = \frac{\hbar}{4E}(\omega_{\uparrow\uparrow} - \omega_{\uparrow\downarrow})$$

"Never measure anything but frequency!"

Arthur Schawlow 81



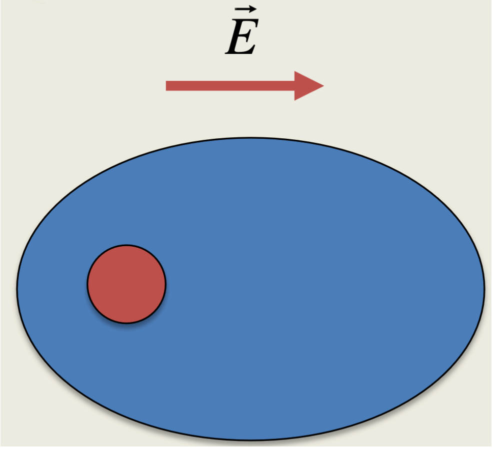
No EDM was detected since in the SM

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

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

Electric dipole moments

$$d^{\text{EDM}}\vec{S}\cdot\vec{E}$$



Schiff's Theorem

EDM of nucleus is screened (assuming non-relativistic, point-like EM constituents).

$d_n^{\text{EDM}} \lesssim 2\times10^{-26}\,\text{e}\cdot\text{cm}$ Abel et. al. 20

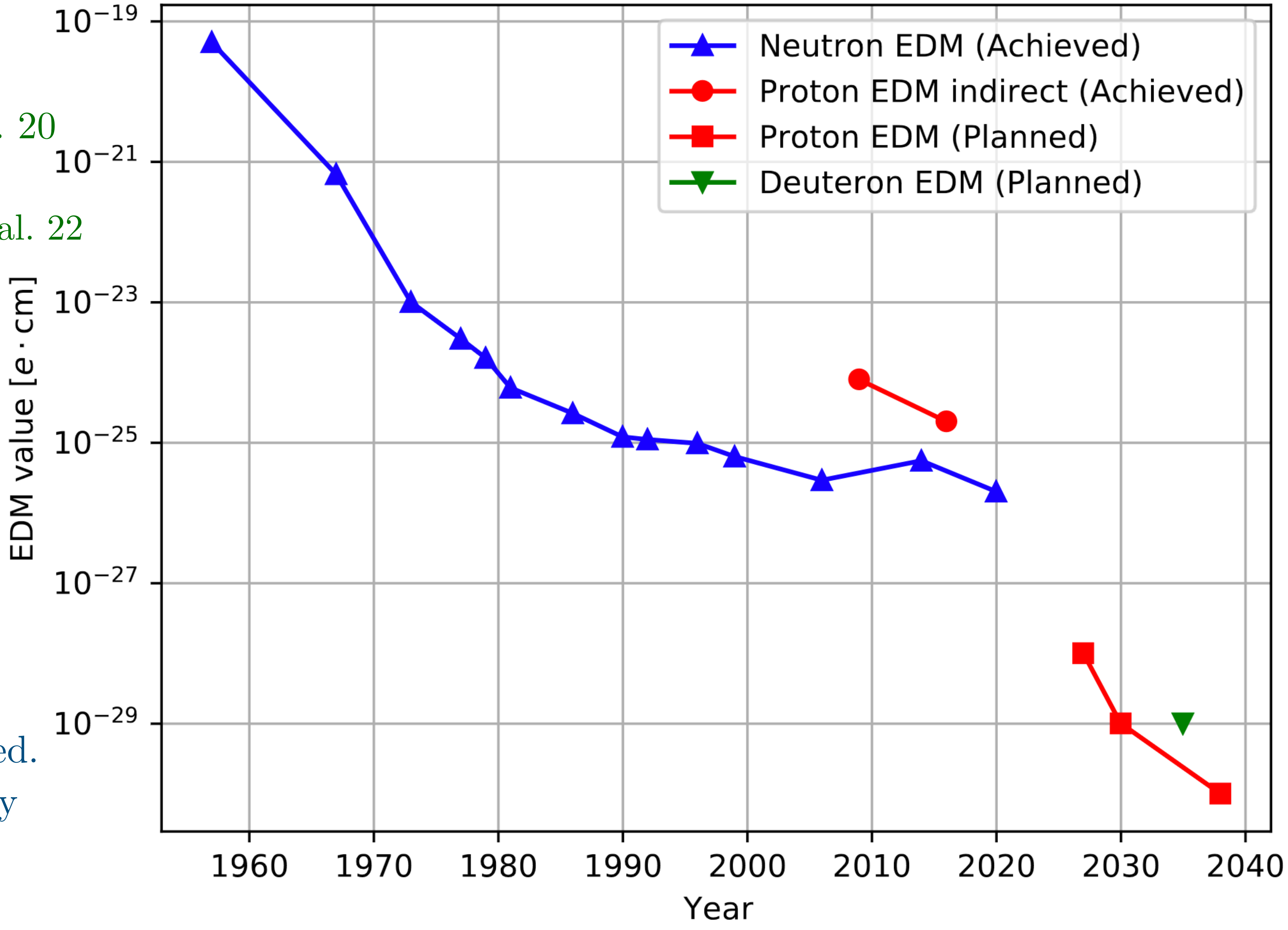
$d_e^{\text{EDM}} \lesssim 4.1\times10^{-30}\,\text{e}\cdot\text{cm}$ Roussy et. al. 22

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

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

$\rightarrow \Lambda \sim 10 - 100\,\text{TeV}$

EDM Snowmass 2203.08103



Nuclear and atomic EDMs will be significantly improved. We focus on nucleons and diamagnetic atoms since they are the most sensitive to hadronic CPV.

Connecting Λ_{BSM} to EDM

Λ

$\Lambda_{\mathrm{BSM}} \sim 10 - 100\,\mathrm{TeV}$ — perturbative QFT

$\Lambda_{\mathrm{EWSB}} \sim 200\,\mathrm{GeV}$

$\Lambda_{\mathrm{QCD\,nonpert.}} \sim 1\,\mathrm{GeV}$

non-perturbative QFT

$\Lambda_{\mathrm{CHPT}} \sim 100\,\mathrm{MeV}$ — Hadronic and nuclear EDMs

many body QM problem

$\Lambda \sim \alpha m_e \simeq 1\,\mathrm{keV}$ — Atomic/Molecular observables

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

↓ EWSB

$$f^{abc}G^aG^b\widetilde{G}^c + \bar{q}\sigma^{\mu\nu}i\gamma_5G_{\mu\nu}q + \bar{q}\sigma^{\mu\nu}i\gamma_5F_{\mu\nu}q + \bar{e}\sigma^{\mu\nu}i\gamma_5F_{\mu\nu}e + \bar{q}q\bar{q}q + \bar{e}e\bar{q}q$$

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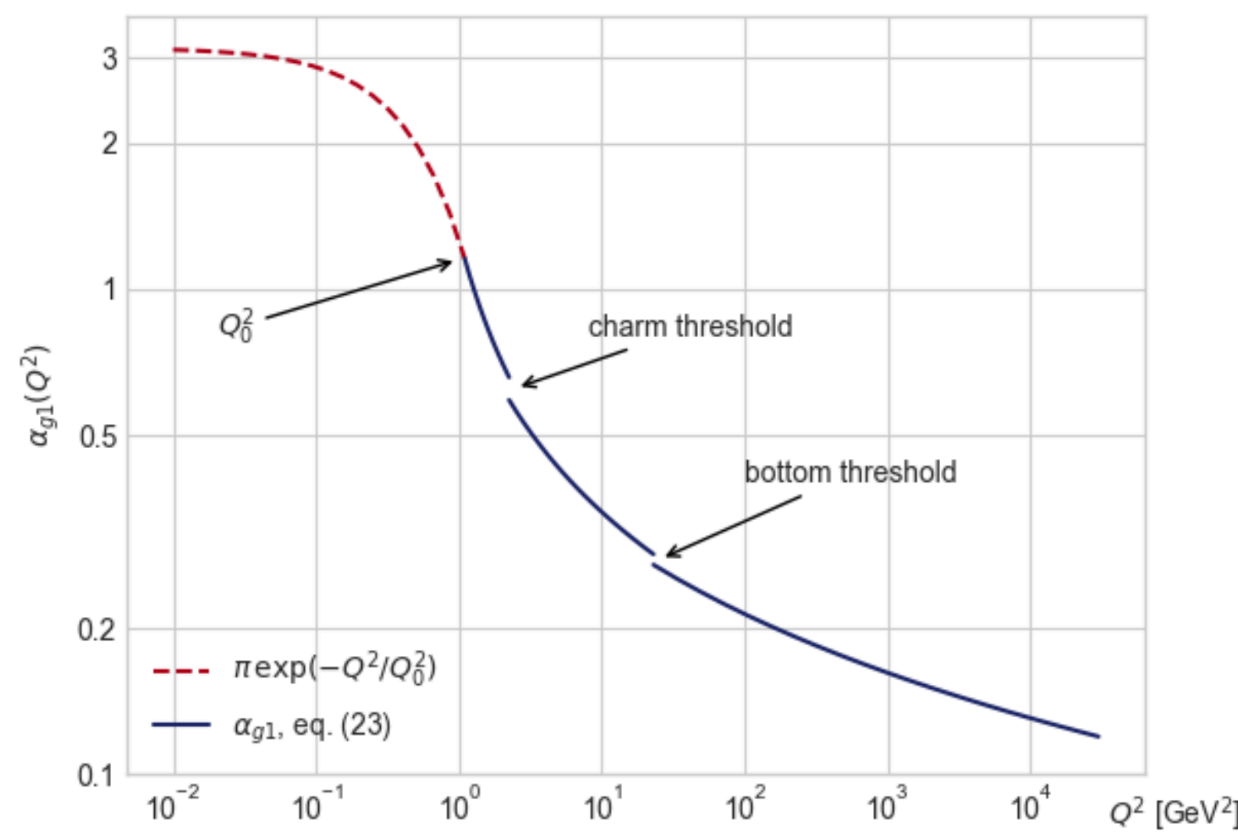
$\downarrow$ EWSB

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

m_b $\downarrow$ m_c



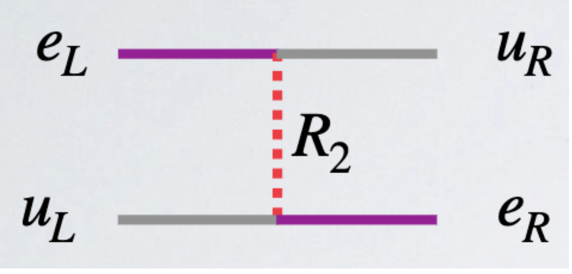
BSM scenarios with CPV

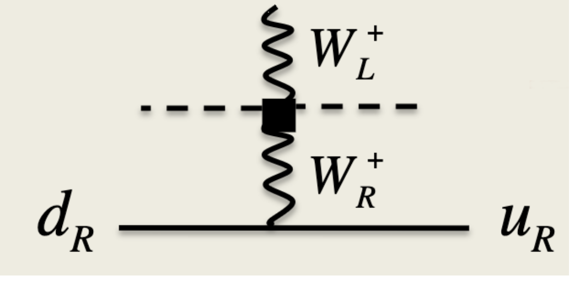
$$f^{abc}G^aG^b\widetilde{G}^c + \bar{q}\sigma^{\mu\nu}i\gamma_5 G_{\mu\nu}q + \bar{q}\sigma^{\mu\nu}i\gamma_5 F_{\mu\nu}q + \bar{e}\sigma^{\mu\nu}i\gamma_5 F_{\mu\nu}e + \bar{q}q\bar{q}q + \bar{e}e\bar{q}q$$

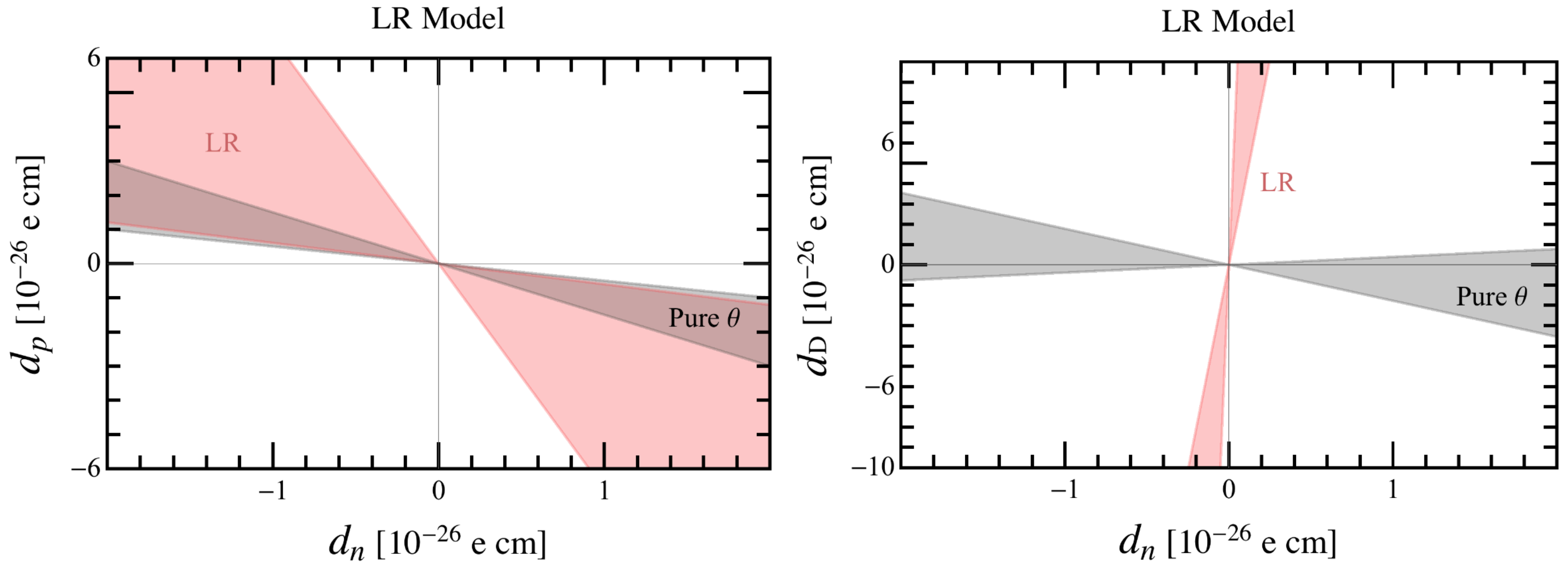
Leptoquarks; LR-symmetric; MSSM in certain parameter region

de Vries, Draper, Fuyuto, Kozaczuk, Lillard 21

No Weinberg operator!







de Vries, Draper, Fuyuto, Kozaczuk, Lillard 21

Weinberg operator impact on EDMs studied recently Yamanaka, Hiyama 20; Osamura, Gubler, Yamanaka 22.
Sizable contribution to $\bar{g}_{0,1}$, d_n, etc.

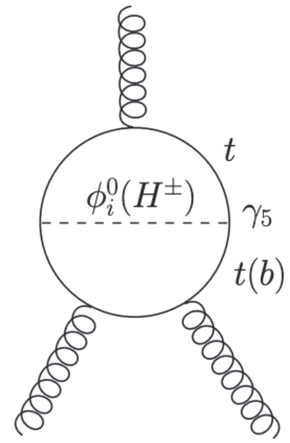
BSM scenarios with CPV

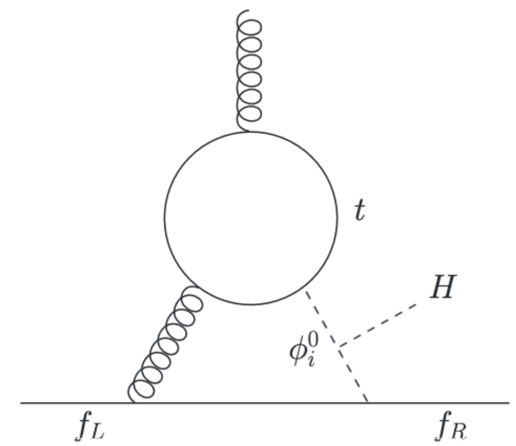
$$f^{abc}G^aG^b\widetilde{G}^c + \bar{q}\sigma^{\mu\nu}i\gamma_5 G_{\mu\nu}q + \bar{q}\sigma^{\mu\nu}i\gamma_5 F_{\mu\nu}q + \bar{e}\sigma^{\mu\nu}i\gamma_5 F_{\mu\nu}e + \bar{q}q\bar{q}q + \bar{e}e\bar{q}q$$

Kiwoon Choi, Sang Hui Im, KJ JHEP 04 (2024) 007

2HDM

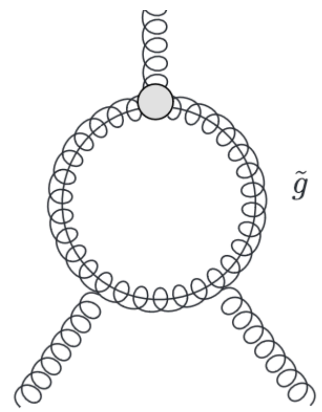
Weinberg 89
Gunion, Wyler 90
Jung, Pich 14

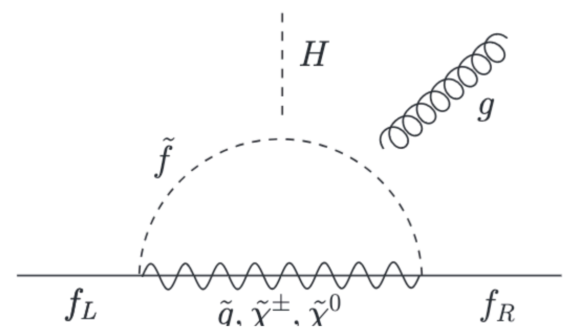




MSSM

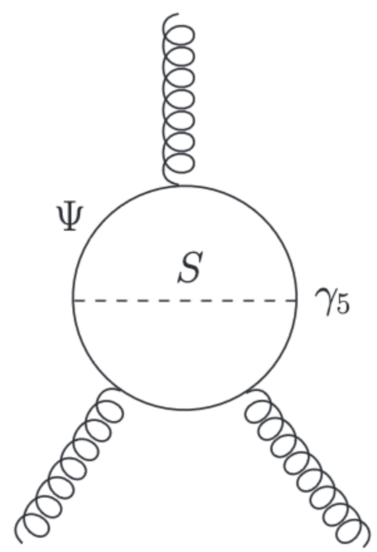
Giudice, Romanino 04
Hisano, et al. 15

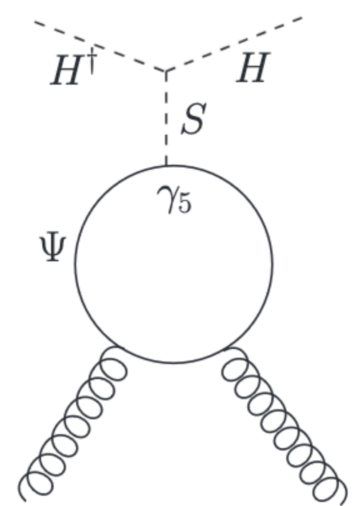


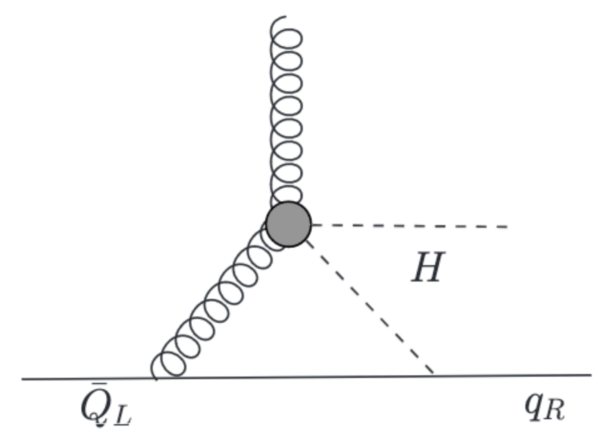


VLQ + singlet

Choi et al. 16







QCD Sum Rules vs NDA

NDA: $\overset{\text{PQ/no PQ}}{d_N} \sim \frac{\pm e}{\Lambda_\chi}\left(\frac{m_*}{\Lambda_\chi}\bar{\theta} + \frac{\Lambda_\chi^2}{4\pi}d_w + \frac{\Lambda_\chi}{4\pi}\tilde{d}_q\right)$

Weinberg 91

$$\Lambda_\chi = 4\pi f_\pi, \quad 1/m_* = 1/m_u + 1/m_d$$

consistent with sum rules (with large uncertainty)

QCD Sum Rules

Shifman, Vainshtein, Zakharov 79

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

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

$$\overset{\text{no PQ}}{d_p}(\bar{\theta}, \tilde{d}_q, d_q, w) = -0.46\times 10^{-16}\bar{\theta}\, e\,{\rm cm} + e\left(-0.17\tilde{d}_u + 0.12\tilde{d}_d + 0.0098\tilde{d}_s\right) + 0.36 d_u - 0.09 d_d - 18 w\, e\,{\rm MeV},$$

$$\overset{\text{no PQ}}{d_n}(\bar{\theta}, \tilde{d}_q, d_q, w) = 0.31\times 10^{-16}\bar{\theta}\, e\,{\rm cm} + e\left(-0.13\tilde{d}_u + 0.16\tilde{d}_d - 0.0066\tilde{d}_s\right) - 0.09 d_u + 0.36 d_d + 20 w\, e\,{\rm MeV}.$$

Pospelov, Ritz 99; Hisano, Lee, Nagata, Shimizu 12; Hisano, Kobayashi, Kuramoto, Kuwahara 15; Yamanaka, Hiyama 20 Kaneta et. al., 23

With QCD axion/Without QCD axion

$\overset{\text{PQ}}{d_p}(\bar{\theta}, d_w) \approx -\overset{\text{PQ}}{d_n}(\bar{\theta}, d_w)$ while $\overset{\text{no PQ}}{d_p}(\tilde{d}_q) \approx -7\overset{\text{no PQ}}{d_n}(\tilde{d}_q)$

EDMs

- Diamagnetic atoms
  - closed-shells → atomic EDM vanishes in ground state, but nuclear effects reintroduce EDM
    - nuclear polarization due to CPV nuclear forces - Fig. 1
    - nucleon EDMs
    - Schiff moments (shape deformation)

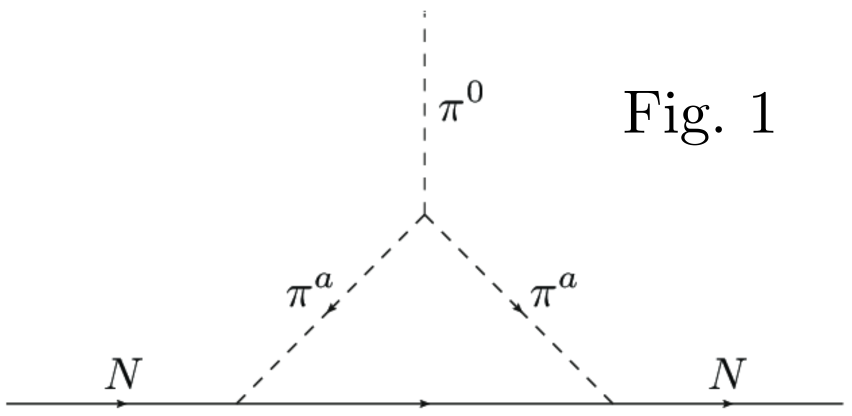


Fig. 1

$$\mathcal{L}_{\pi N} = \bar{g}_0 \bar{N}\vec{\tau}\cdot\vec{\pi}N + \bar{g}_1\pi_3\bar{N}N$$

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

$$d_{He} = 0.9\, d_n - 0.05\, d_p + [(0.1 \pm 0.03)\bar{g}_0 + (0.14 \pm 0.03)\bar{g}_1]\, e\text{fm}$$

Chupp et al. 1710.02504

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

de Vries, et al. 2107.04046

$$d_{Xe} = 1.3 \cdot 10^{-5}\, d_n - 1.7 \cdot 10^{-5}\, \bar{g}_1\, e\text{fm} - 1.6 \cdot 10^{-5}\, \bar{g}_0\, e\text{fm}$$

Osamura, Gubler, Yamanaka, 2203.06878

$\theta_{QCD}\, G\tilde{G}$

$$d_n = (1.5 \pm 0.7) \cdot 10^{-16}\, \bar{\theta}\, e\text{cm} \qquad \bar{g}_0 = (14.7 \pm 2.3) \cdot 10^{-3}\, \bar{\theta}$$

$$d_p = -(1 \pm 0.5)\, d_n \qquad \bar{g}_1 = -(3.4 \pm 2.4) \cdot 10^{-3}\, \bar{\theta}$$

de Vries, et al. 2107.04046

cEDM

$$\bar{g}_0 = [1.1, 3.8]\ GeV\ (\tilde{d}_u + \tilde{d}_d) \qquad \bar{g}_1 = [21.5, 60.5]\ GeV\ (\tilde{d}_u - \tilde{d}_d)$$

de Vries, et al. 2107.04046

Weinberg operator

$$d_n = (w \times \text{GeV}^2)(20 \pm 12) \times 2 \cdot 10^{-17} e\text{cm}$$

$$d_p = (w \times \text{GeV}^2)(-18 \pm 11) \times 2 \cdot 10^{-17} e\text{cm}$$

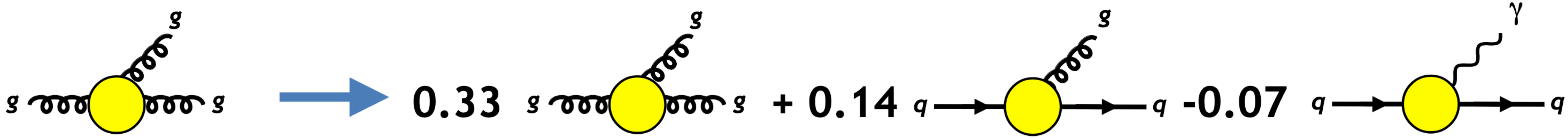
$$\bar{g}_1 = \pm\, (w \times \text{GeV}^2)[1.1, 4] \cdot 10^{-3}$$

Yamanaka, Oka 2208.03920   Osamura, Gubler, Yamanaka, 2203.06878

Patterns of Nucleon EDMs

$\Lambda_{\mathrm{BSM}} \to \Lambda_{\mathrm{QCD\,nonpert.}}$

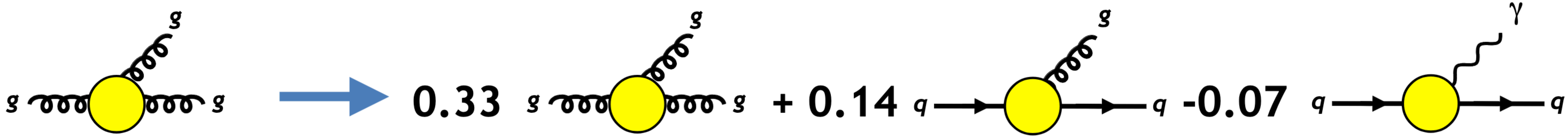
$1\,\mathrm{TeV} \to 1\,\mathrm{GeV}$

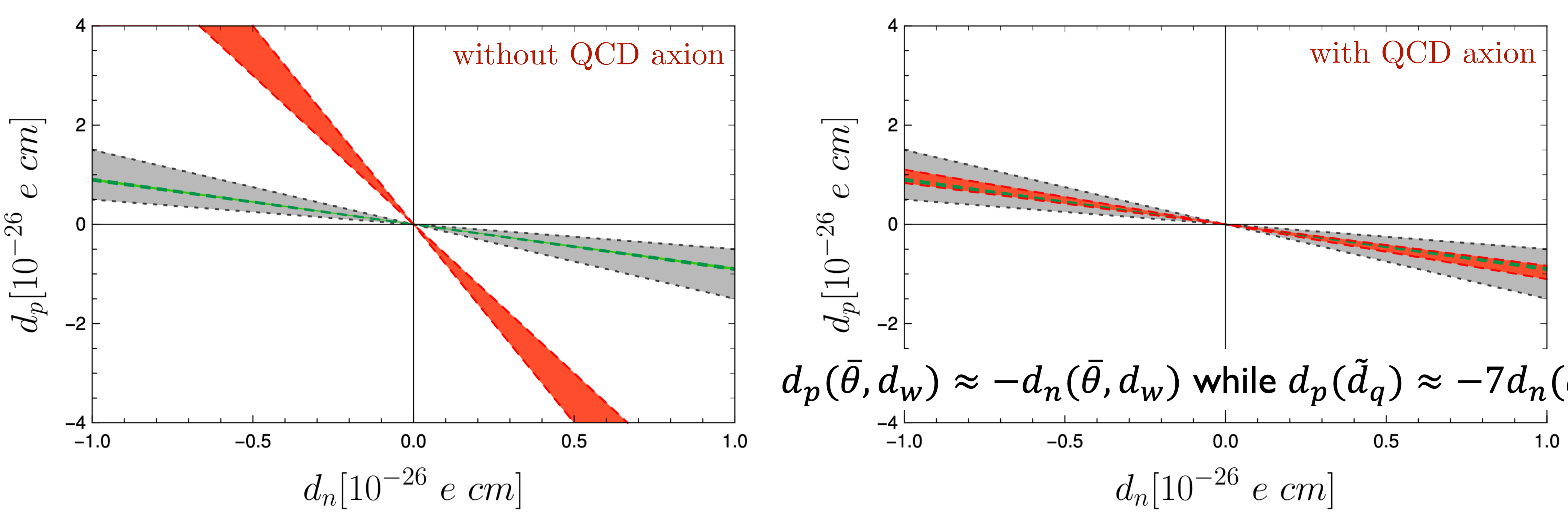


Patterns of Nucleon EDMs

$\Lambda_{\rm BSM} \rightarrow \Lambda_{\rm QCD\,nonpert.}$

1 TeV → 1 GeV

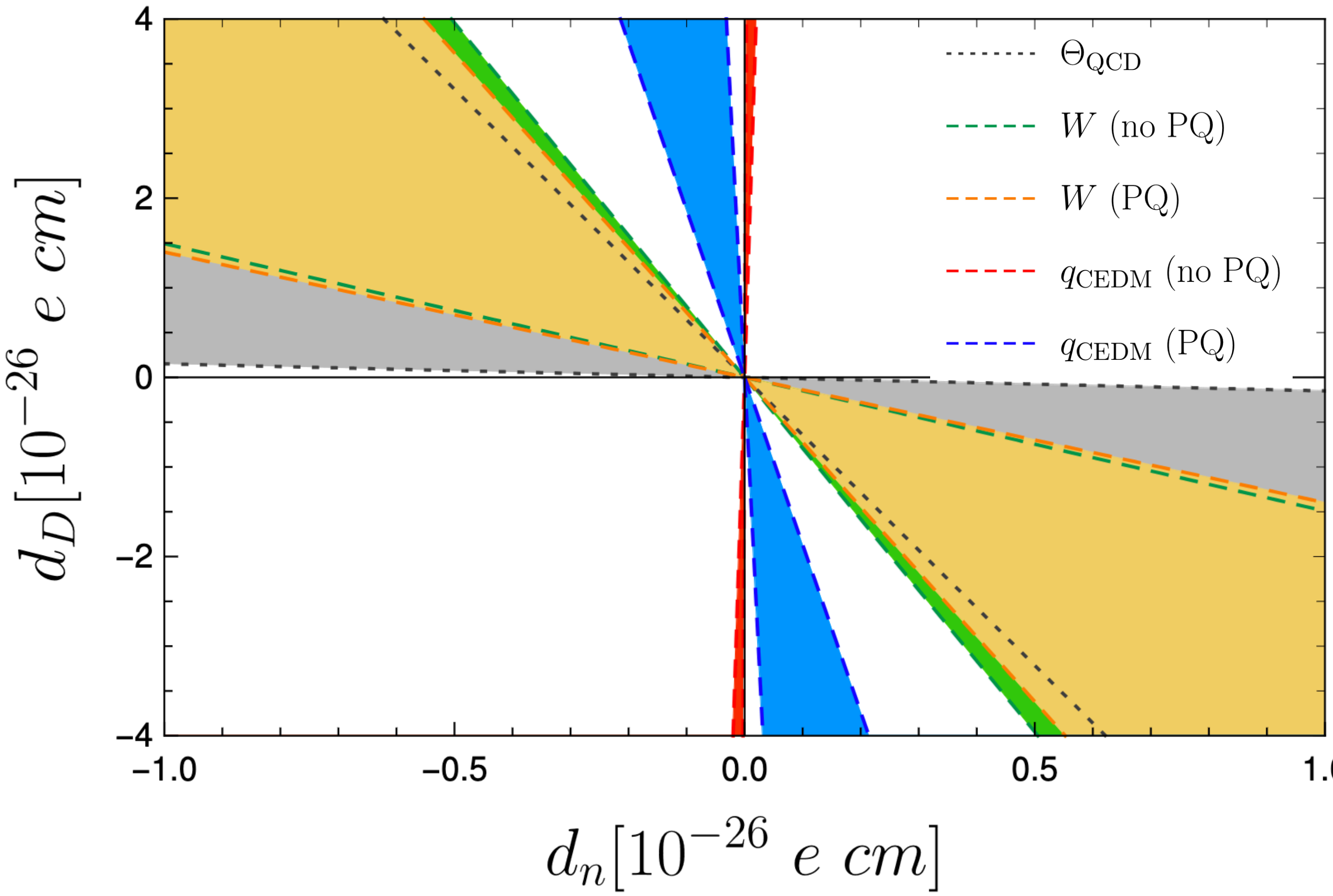


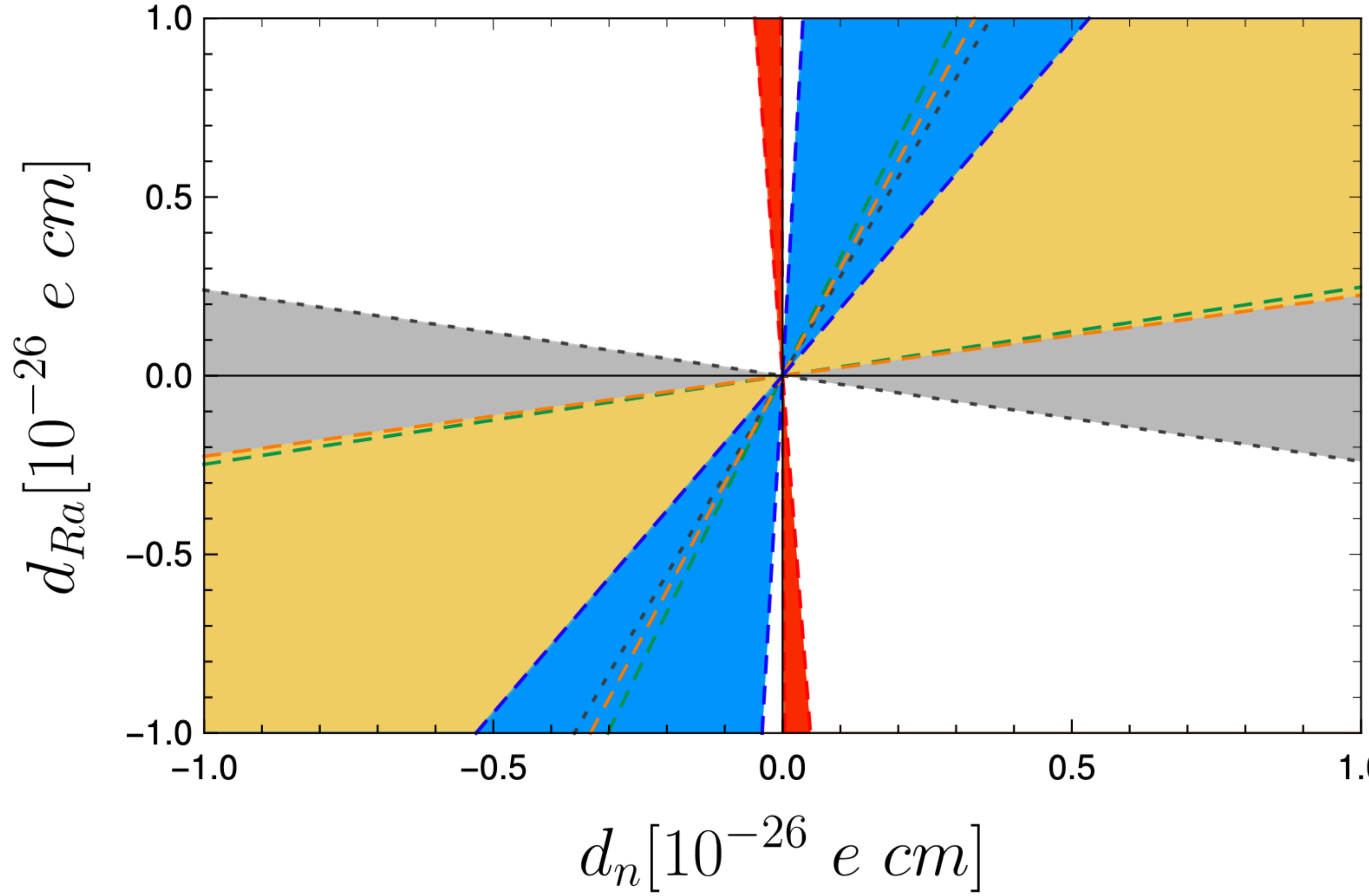


$$d_p(\bar\theta, d_w) \approx -d_n(\bar\theta, d_w) \text{ while } d_p(\tilde d_q) \approx -7 d_n(\tilde d_q)$$

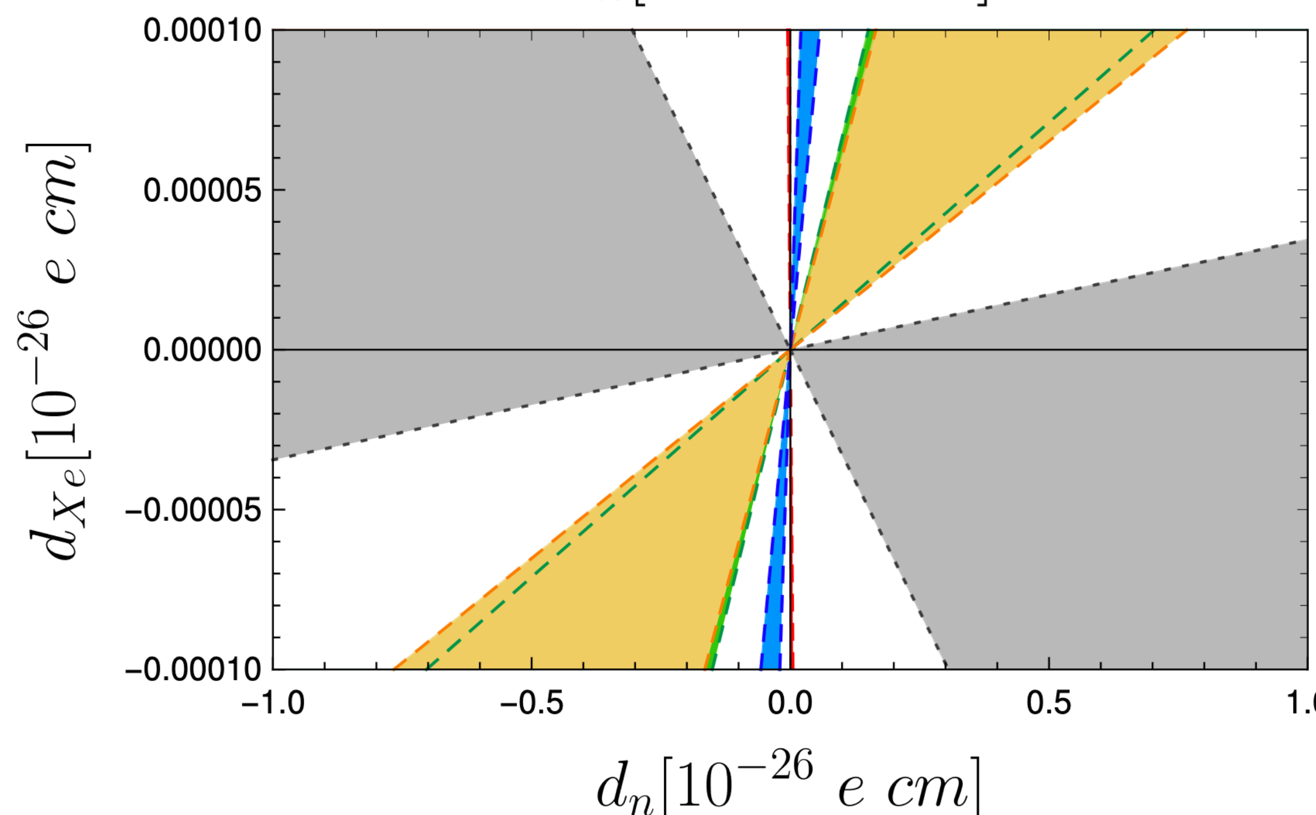
- The *radiatively* induced quark-CEDM from the gluon CEDM is the dominant contribution to $\bar g_1$ and subdominant to d_n.
- The ratio d_p/d_n can clearly *distinguish quark CEDM*-dominant CPV *without axion* from the others, including the θ-dominant CPV. However, it is a fine-tuned scenario with $\bar\theta = \bar\theta_{bare} + \bar\theta_{rad.} + \bar\theta_{UV} \simeq 0$.
- For other models, the $d_p/d_n \sim -1$ within uncertainties regardless of the source.

Results



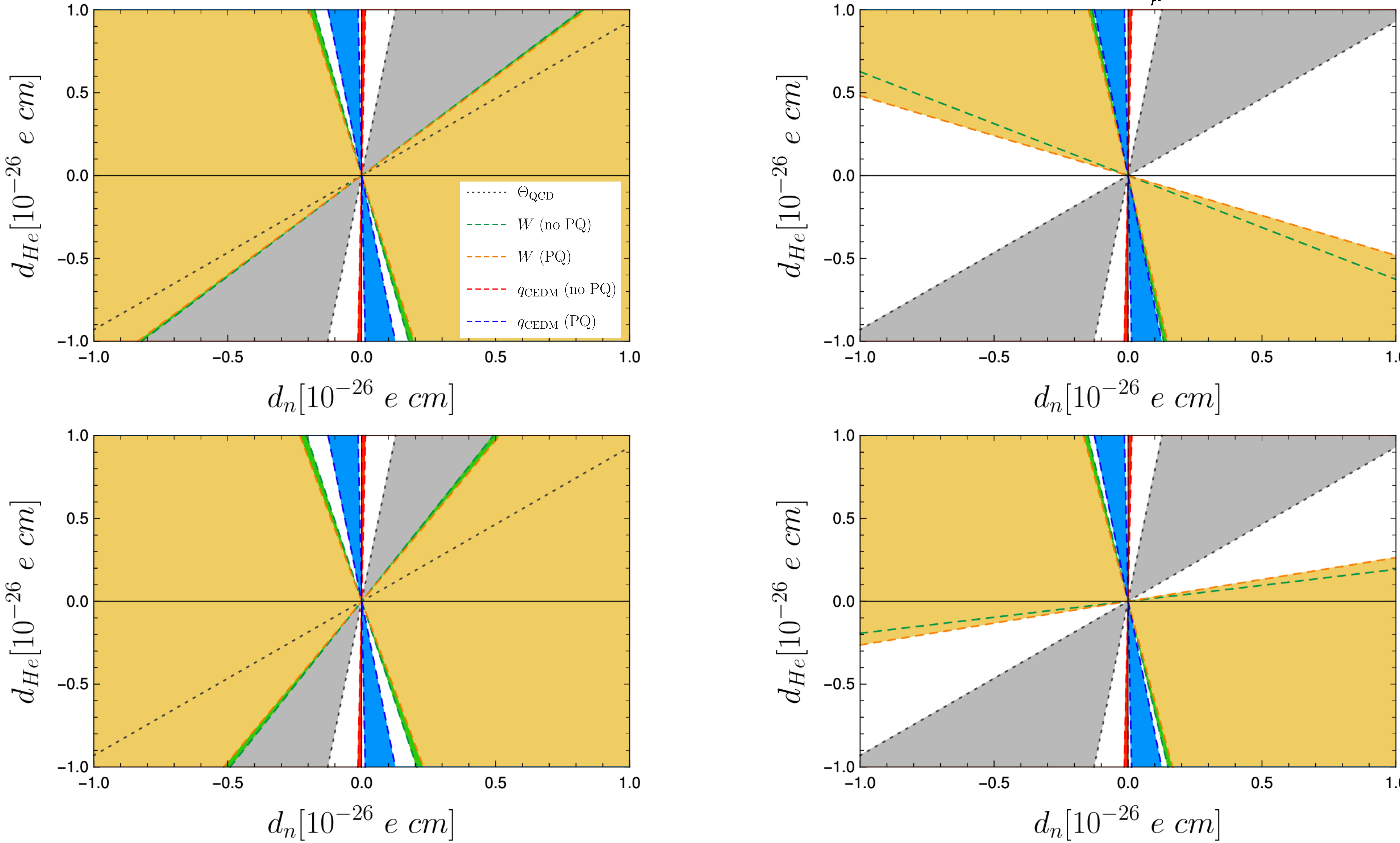


- d_D (no present limit)
  - will be probed up to $\sim 10^{-29}$ $\mathrm{e \cdot cm}$ in storage ring experiments CPEDM Collaboration 19
  - quark CEDM domination scenario can be discriminated from others (generic)
  - gluon CEDM domination (Weinberg) is not distinguishable from the $\bar{\theta}$ domination
- $d_{Ra} \lesssim 1 \times 10^{-23}\,\mathrm{e \cdot cm}$
  - will be probed up to $\sim 10^{-28}$ $\mathrm{e \cdot cm}$ Bishof et al. 16
- d_{Xe} may distinguish $\bar{\theta}$ from other sources

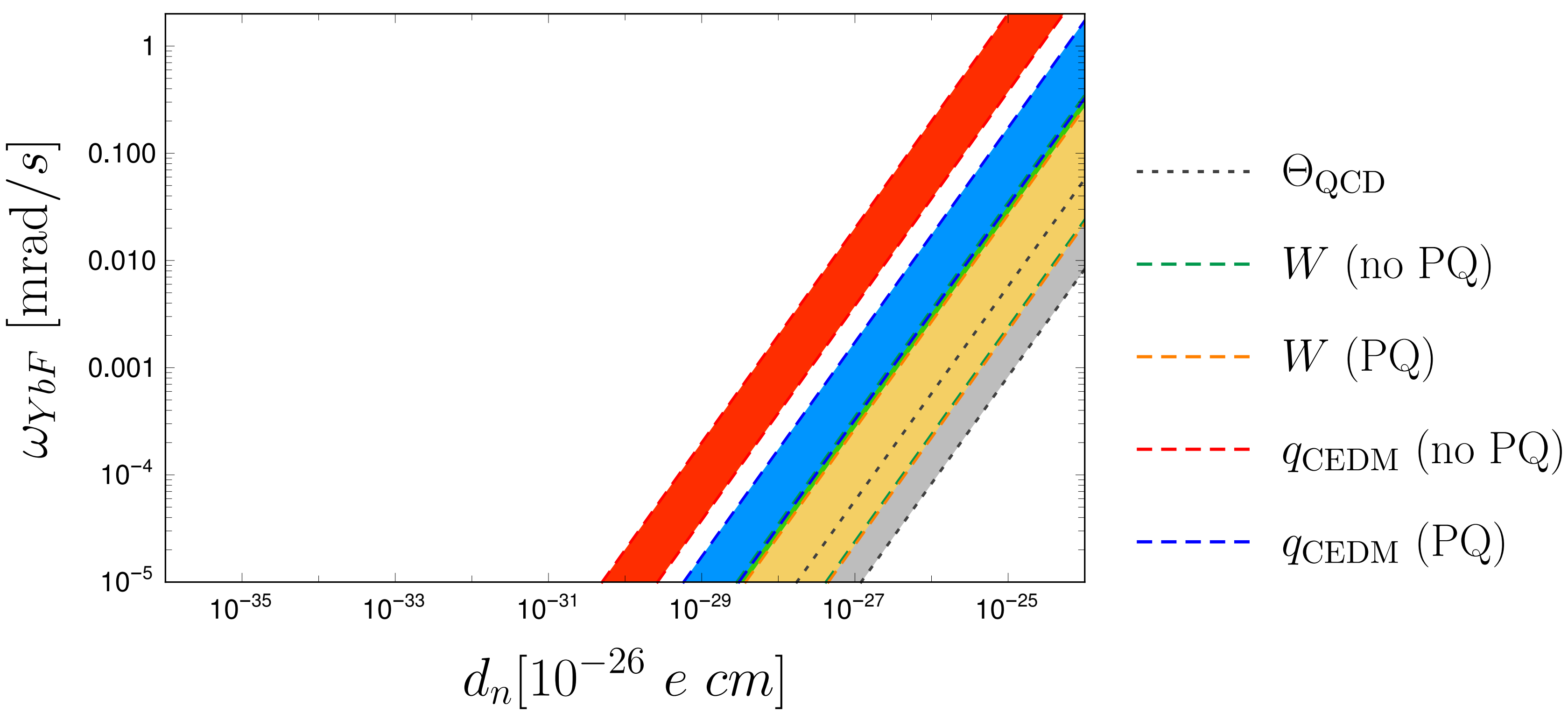


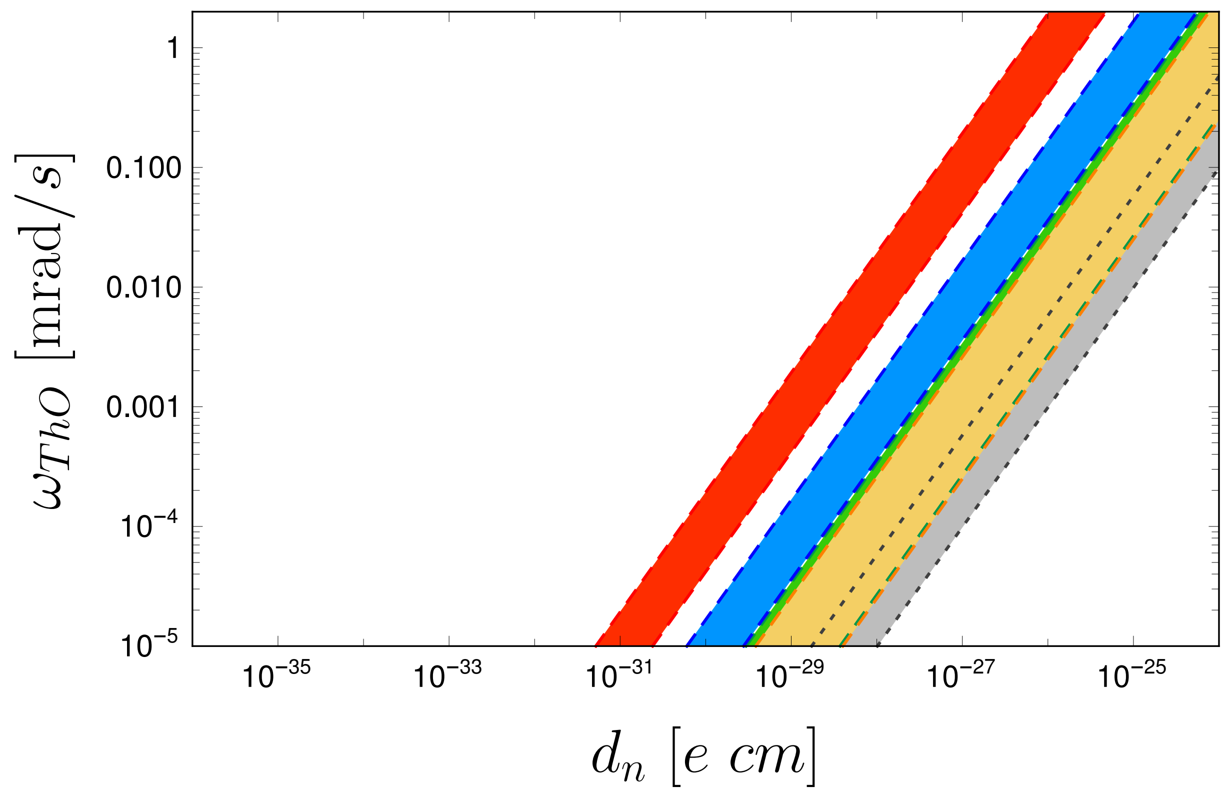
Results

Helion EDM depends on the *unknown* sign of dim-7 operator $\bar{N}N \cdot D_\mu(\bar{N}S^\mu N)$

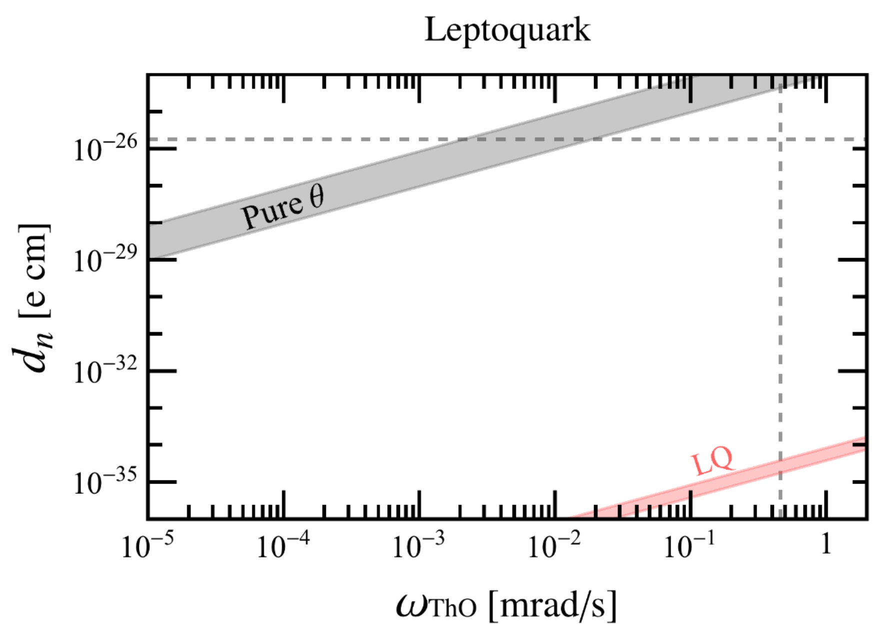


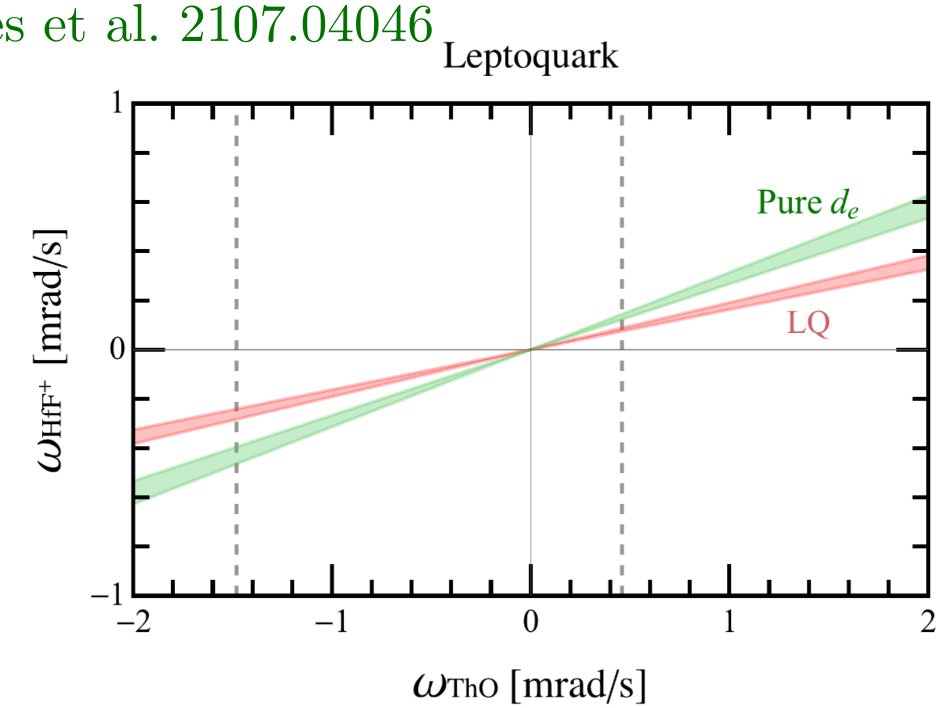
Results

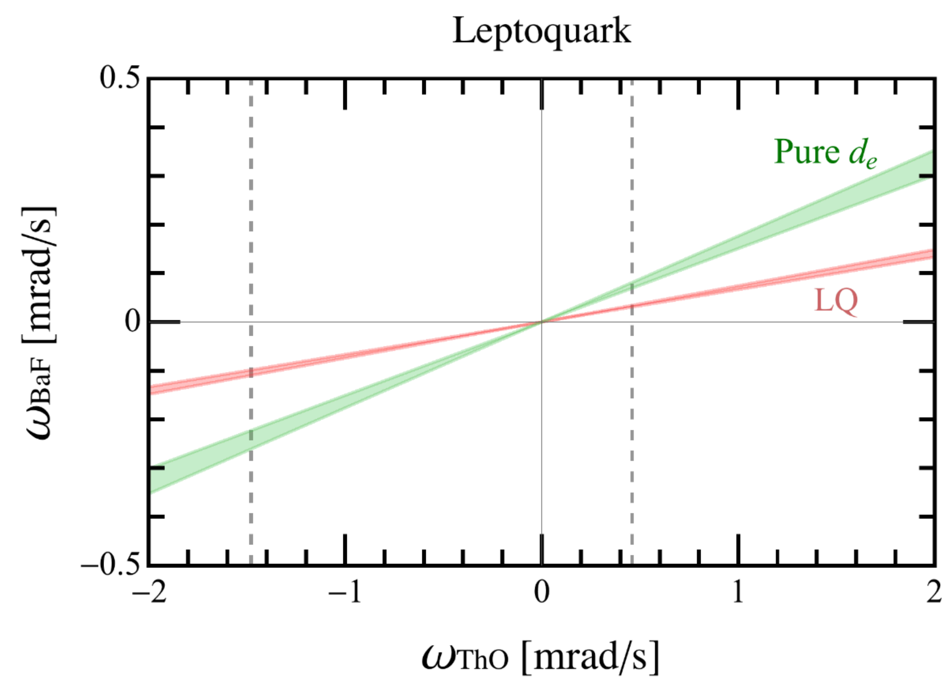




- Paramagnetic atoms
  - quantitatively similar results regardless of the molecule
  - consistent with de Vries et al. 2107.04046







Conclusions

- EDMs may provide not only the information on BSM CP violation, but also additional information on QCD axion including the *origin of the axion VEV* (the PQ quality). Future experimental progress will allow to probe some well-motivated BSM physics up to $\Lambda \sim 10 - 100\,\mathrm{TeV}$.

- We analyzed if the following scenarios can be discriminated from each other based on the EDM data in both cases with and without the PQ mechanism:

  1) $\bar{\theta}$ domination
  2) Weinberg operator domination
  3) quark CEDM domination

- Currently, the analysis is quite limited due to the lack of knowledge of precise values of certain hadronic parameters - further knowledge of the hadronic parameters induced by BSM CPV will be crucial for extending the analysis to more general cases. However, certain BSM scenarios result in clearly distinguishable patterns of EDMs. In particular, if d_n and d_p will be measured and $|d_p/d_n| \gg 1$, QCD axion likely does not exist.

Dziękuję!

Thank you!

감사합니다

Shameless plug

- My other talks at FUW :)

  - October 8th **Tuesday** 11:00 - B2.38
    Clockwork inspired extra dimension models at future lepton colliders, beam dumps, and SN1987
    Seminar "High-Energy, Cosmology and Astro-particle physics"

  - October 11th **Friday** 14:15 - 1.40,
    Covariant quantum field theory of tachyons is unphysical
    Seminar "Exact Results in Quantum Physics and Gravitation"