A Theoretical Overview of EDMs

The Low-Energy Frontier of Particle Physics
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*special thanks to A. Masiero and P. Paradisi for inspiring discussions that shaped this talk

Outline

1. Introduction on EDMs
2. EDMs from CP violation in the quark sector (CKM)
3. EDMs from CP violation in strong interactions (theta term)
4. EDMs from CP violation in the neutrino sector
5. EDMs & baryogenesis
6. EDMs sensitivity to New Physics (NP): Heavy vs. Light
7. Oscillating EDMs

Electric & Magnetic Dipole Moments

- Interaction of a particle with spin $\overrightarrow{S}$ with with an electric/magnetic field

$$\mathcal{H} = -\mu \frac{\vec{S}}{|S|} \cdot \vec{B} - d \frac{\vec{S}}{|S|} \cdot \vec{E}$$

Magnetic dipole moment (MDM) μ

Electric dipole moment (EDM) d

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Electric dipole moment (EDM) d

- properties under Time Reversal T and Parity P

$$\begin{array}{llll} T: & \vec{E} \to +\vec{E} & \vec{B} \to -\vec{B} & \vec{S} \to -\vec{S} \\ P: & \vec{E} \to -\vec{E} & \vec{B} \to +\vec{B} & \vec{S} \to +\vec{S} \end{array}$$

- MDMs are P and T even

- EDMs are P and T odd (CP violating, assuming CPT = locality + Lorentz + spin-statistics)

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  - translates into EDM sensitivity

$$d \sim \frac{\Delta E}{\textbf{Electric field}} \sim 10^{-25}\,\mathbf{e\,cm} \qquad \text{for} \qquad \textbf{Electric field} \sim 10^{4}\,\mathbf{V/cm}$$

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  - theoretically inferring scaling of EDMs (see later)

$$d \sim \frac{1}{16\pi^2} \times \frac{1\,\text{MeV}}{\Lambda^2} \quad \longrightarrow \quad \Lambda \gtrsim 1\,\text{TeV}$$

Relativistic generalization

- Interaction of a fermion with the photon field

$$-d_f \frac{\vec{S}}{|S|} \cdot \vec{E} \qquad \rightarrow$$

$$-\mu_f \frac{\vec{S}}{|S|} \cdot \vec{B} \qquad \rightarrow \qquad e(\bar{f}\gamma_\mu f)A^\mu$$

- minimal coupling of fermions with photon gives rise to MDM with gyromagnetic ratio $g = 2$

$$\mu_f = g_f \frac{e}{2m_f}$$

Relativistic generalization

- Interaction of a fermion with the photon field

$$-d_f \frac{\vec{S}}{|S|} \cdot \vec{E} \quad \to \quad d_f \frac{i}{2} (\bar{f} \sigma_{\mu\nu} \gamma_5 f) F^{\mu\nu}$$

$$-\mu_f \frac{\vec{S}}{|S|} \cdot \vec{B} \quad \to \quad e(\bar{f} \gamma_\mu f) A^\mu + a_f \frac{e}{4m_f} (\bar{f} \sigma_{\mu\nu} f) F^{\mu\nu}$$

- minimal coupling of fermions with photon gives rise to MDM with gyromagnetic ratio $g = 2$

$$\mu_f = g_f \frac{e}{2m_f} \quad , \qquad (g_f - 2) = 2a_f$$

- dimension 5 operators induce an EDM d_f and a MDM a_f

- absent for elementary particles at the classical level, but can be induced by loop corrections

Experimentally accessible EDMs

1. EDM of paramagnetic systems: atoms (Tl, Fr, ...) and molecules (ThO, YbF, ...)

2. EDM of diamagnetic atoms (Hg, Ra, Rn, ...)

3. EDM of the neutron, proton, deuteron

4. EDM of the muon/tau

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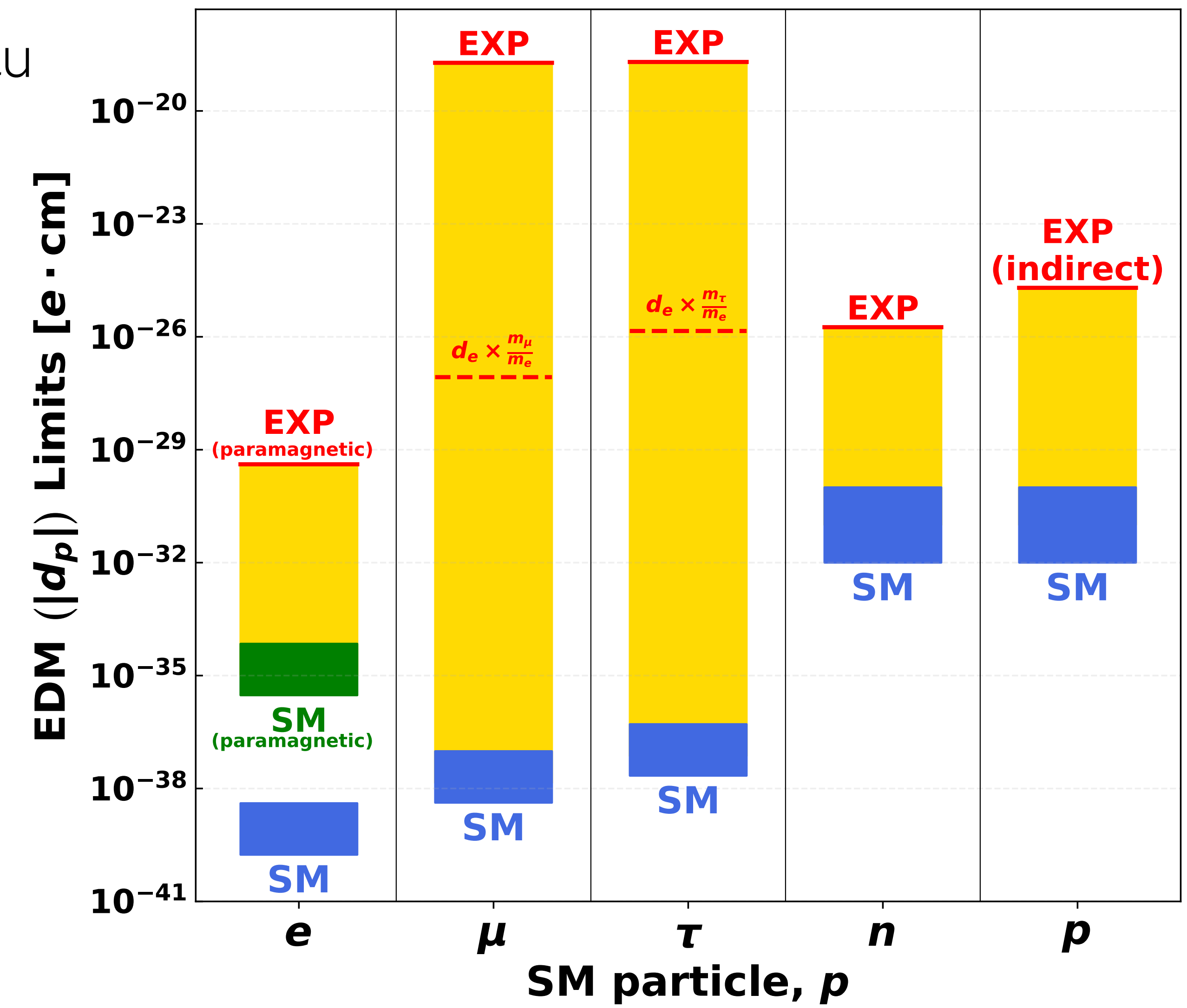
[Courtesy of A. Keshavarzi]



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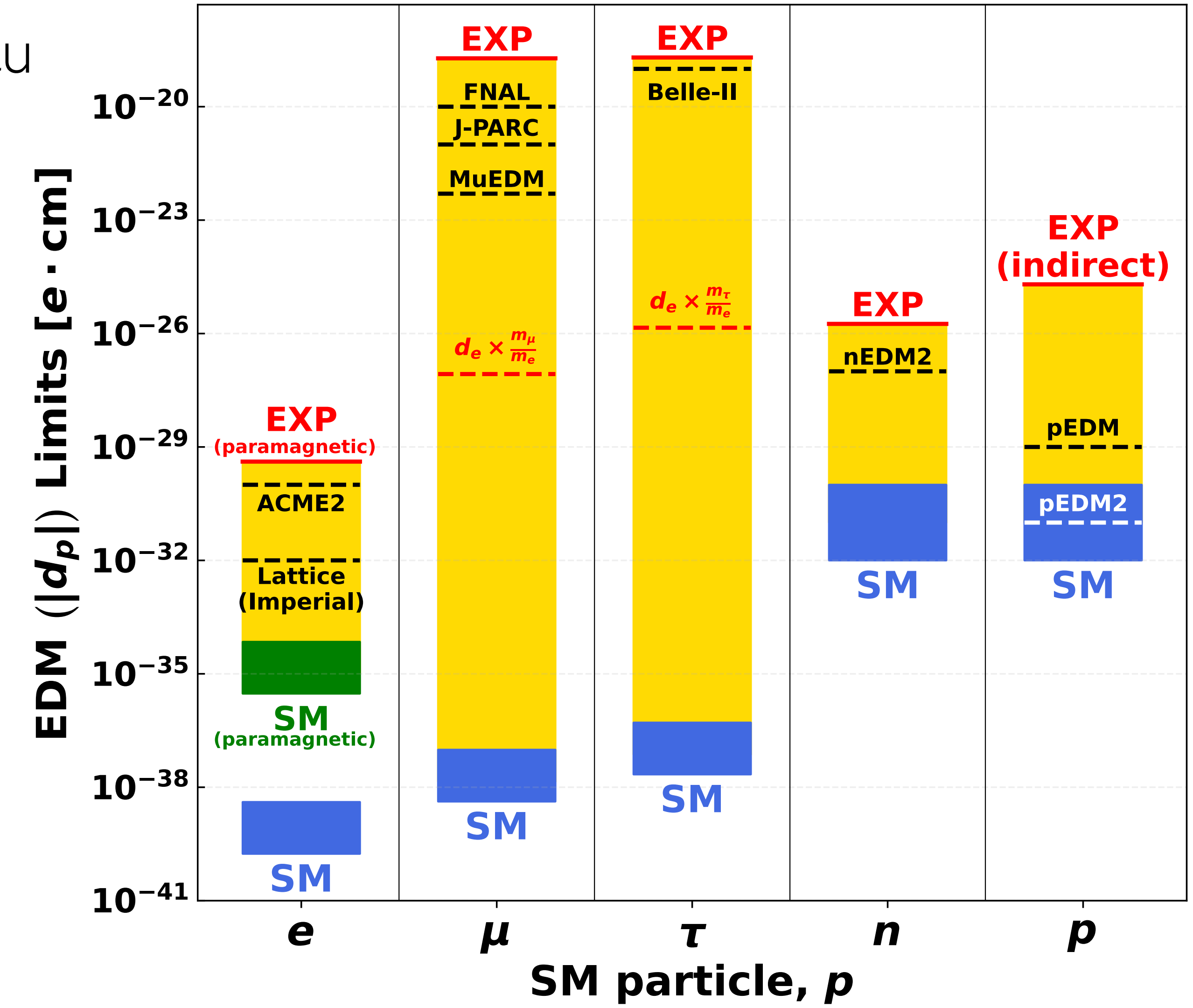
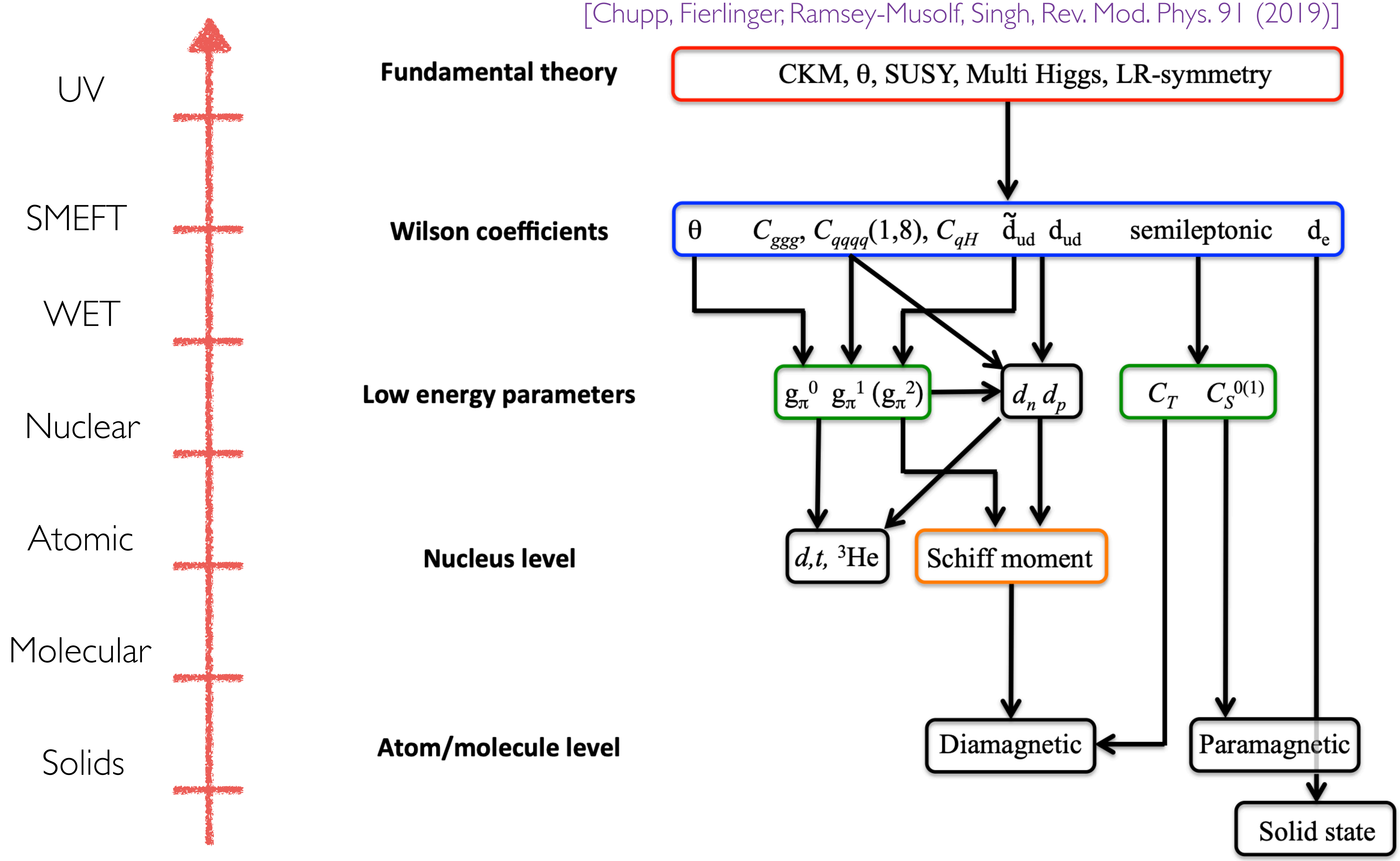


A tower of EFTs

- Need to predict EDMs of composite systems in terms of CP-violating sources

[Chupp, Fierlinger, Ramsey-Musolf, Singh, Rev. Mod. Phys. 91 (2019)]



CP violating operators

- CP-odd Lagrangian at the GeV scale

$$\frac{g_s^2}{32\pi^2}\bar{\theta}G^A_{\mu\nu}\tilde{G}^{\mu\nu,\,A}$$ QCD theta term

- terms at dimension 4

CP violating operators

- CP-odd Lagrangian at the GeV scale

$\frac{g_s^2}{32\pi^2}\bar{\theta}G^A_{\mu\nu}\tilde{G}^{\mu\nu,\,A}$	QCD theta term
$d_f\frac{i}{2}(\bar{f}\sigma_{\mu\nu}\gamma_5 f)F^{\mu\nu}$	EDMs of quarks and leptons
$d^c_q\frac{ig_s}{2}(\bar{q}_\alpha\sigma^{\mu\nu}T^A_{\alpha\beta}\gamma_5 q_\beta)G^A_{\mu\nu}$	chromo EDMs (CEDMs) of quarks

- terms at dimension 4, dimension 5

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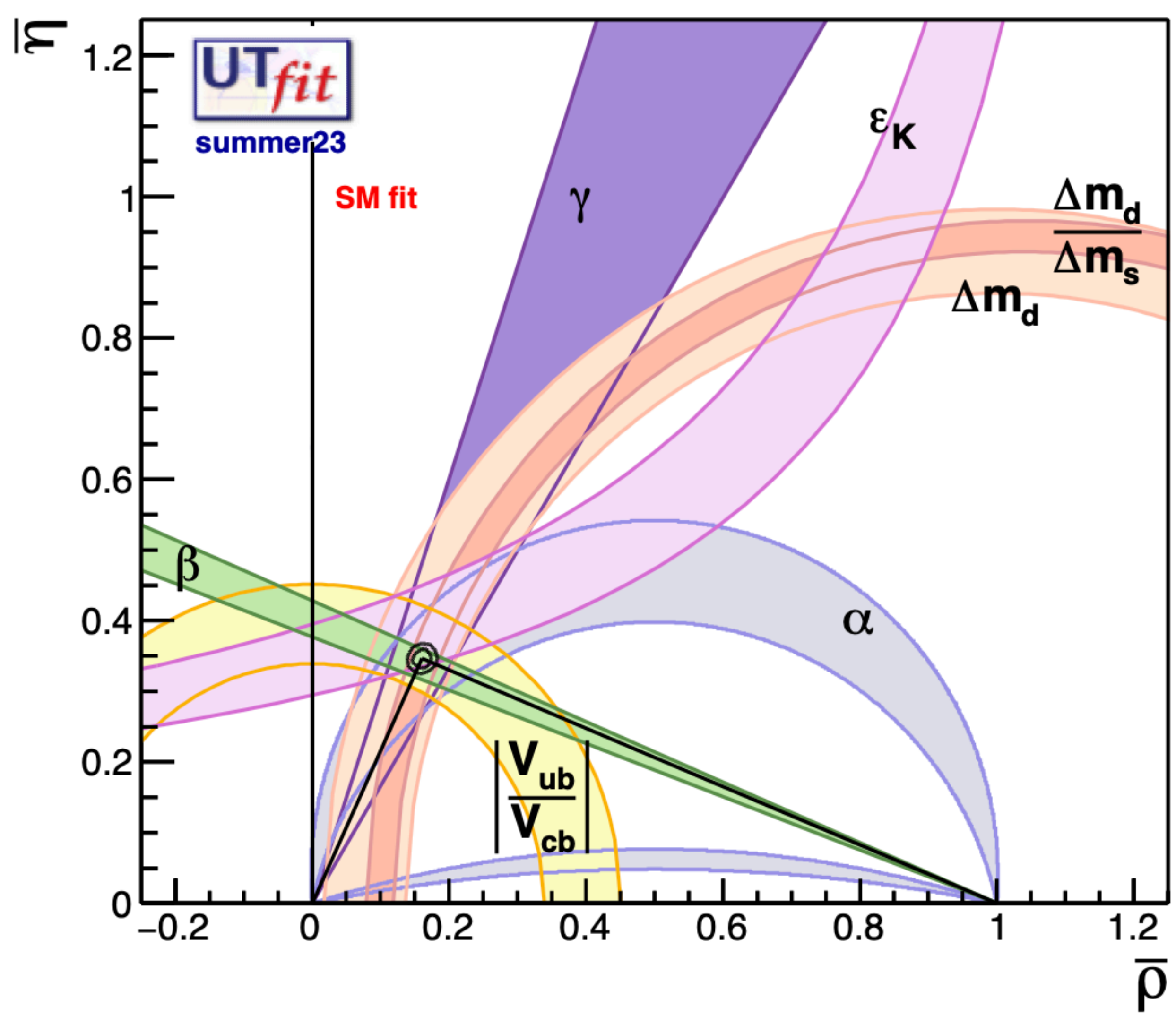
$d_q^c \frac{ig_s}{2}(\bar{q}_\alpha \sigma^{\mu\nu} T^A_{\alpha\beta}\gamma_5 q_\beta)G^A_{\mu\nu}$	chromo EDMs (CEDMs) of quarks
$\frac{w}{3} f^{ABC} G^A_{\mu\nu}\tilde{G}^{\nu\rho,\, B} G_\rho^{\mu,\, C}$	Weinberg three gluon operator
$C_{ij}(\bar{f}_i f_i)(\bar{f}_j i\gamma_5 f_j)$	CP violating 4 fermion operators

- terms at dimension 4, dimension 5, dimension 6

CP violation in the quark sector

- CP violation observed in K and B physics
  - parametrized by the Jarlskog invariant: $\mathrm{Im}\left[V_{ij}V_{kl}V_{i\ell}^{*}V_{kj}^{*}\right] = J\sum_{mn}\epsilon_{ikm}\epsilon_{j\ell n}$

$$J = c_{12}c_{23}c_{13}^{2}s_{12}s_{23}s_{13}\sin\delta$$
$$= (3.08^{+0.15}_{-0.13}) \times 10^{-5}$$



EDMs from CKM

- CKM power-counting rules for CP-violating & flavour-singlet observables:

  1. EDM operator breaks chirality, hence in perturbation theory $d_f \propto m_f$

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  4. the <u>anti-symmetric</u> structure of J in flavour space leads to additional loop suppressions

$$d_q^{\text{CKM}}(\text{2-loop}) = 0$$

[Shabalin Sov. J. Nucl. Phys. 28 (1978)]

$$d_e^{\text{CKM}}(\text{3-loop}) = 0$$

[Pospelov, Khriplovich, Sov. J. Nucl. Phys. 53 (1991)]

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- we will consider CKM contributions to:

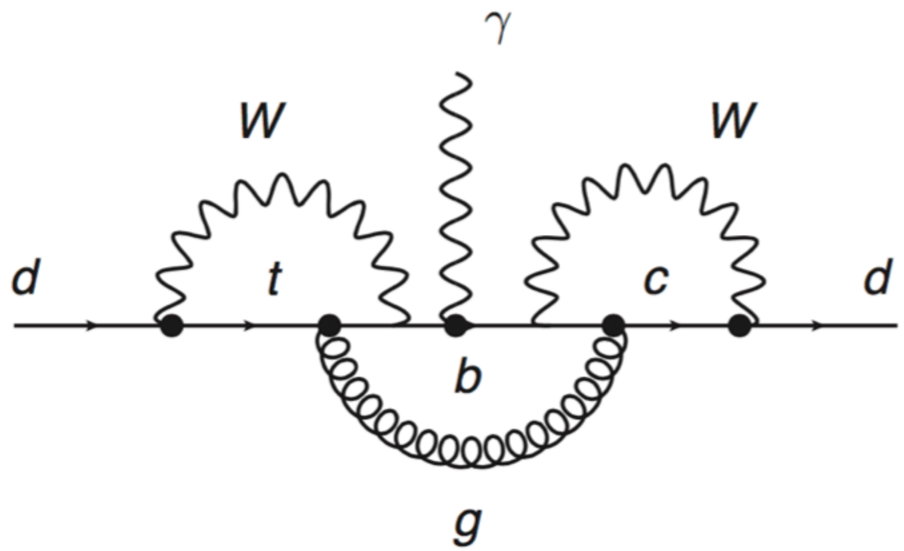
  - i) fundamental EDMs, ii) nucleon EDMs, iii) diamagnetic EDMS, iv) paramagnetic EDMs
  - contributions are usually classified in short-distance and long-distance

Fundamental EDMs from CKM

- quark EDM (for nucleon EDM see later)

$$d_d^{(\mathrm{est})}(\mathcal{J}) \sim e\mathcal{J}\frac{\alpha_s\alpha_W^2}{(4\pi)^3}\frac{m_d}{m_W^2}\frac{m_c^2}{m_W^2} < 10^{-34}e\mathrm{cm}$$

[Khriplovich, Phys. Lett. B 173, 193 (1986)
Czarnecki, Krause, Phys. Rev. Lett. 78 (1997)]



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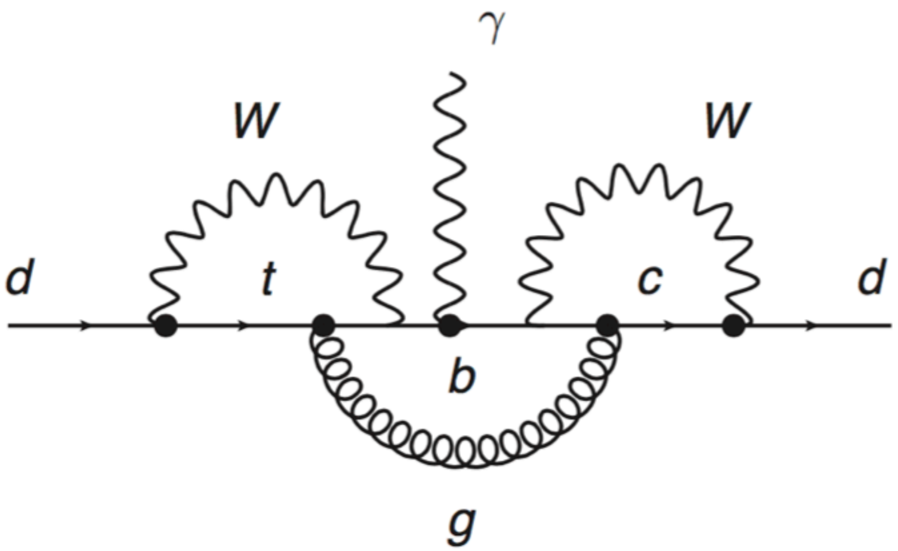
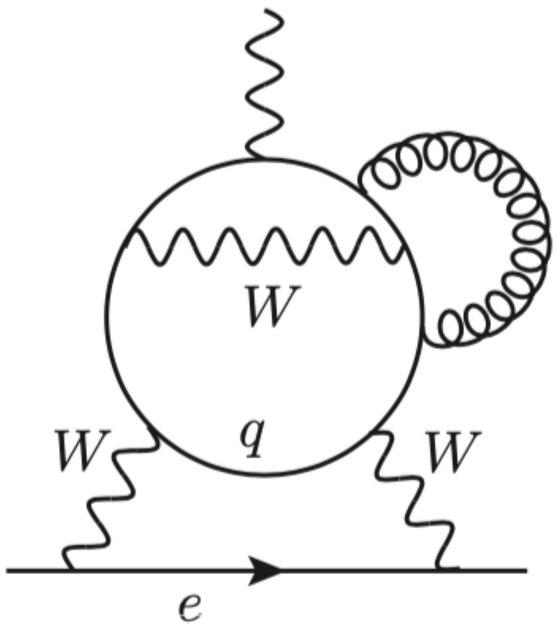


- electron EDM (for paramagnetic EDM see later)

$$d_e(\mathcal{J}) \sim e\mathcal{J}\frac{m_e m_c^2 m_s^2}{m_W^6}\frac{\alpha_W^3\alpha_s}{(4\pi)^4} \sim O(10^{-44})\ e\mathrm{cm}$$

[Pospelov, Khriplovich, Sov. J. Nucl. Phys. 53 (1991),
Pospelov, Ritz, Phys. Rev. D89 no. 5 (2014)]



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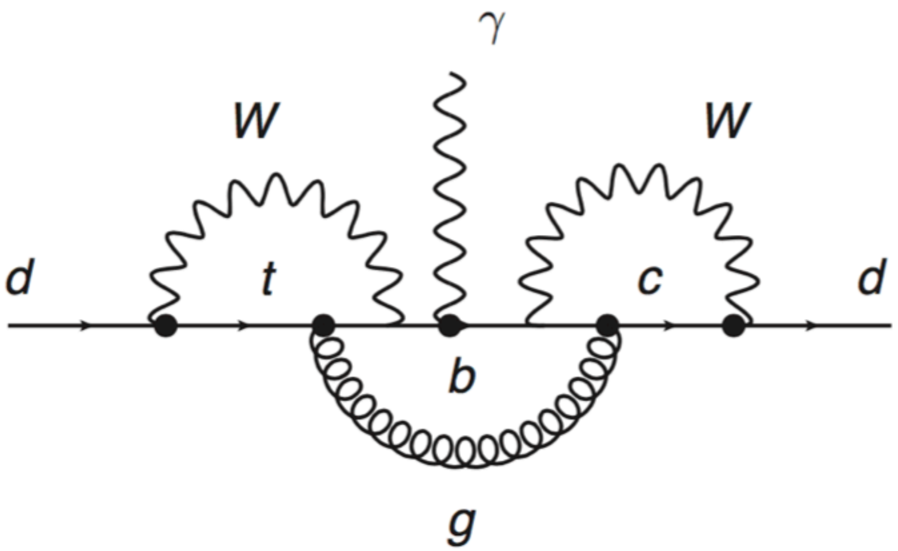

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- large long-distance contribution

$$d_e \sim 6\times 10^{-40}\, e\, cm$$

[Yamaguchi, Yamanaka, Phys. Rev. Lett. 125 (2020)]

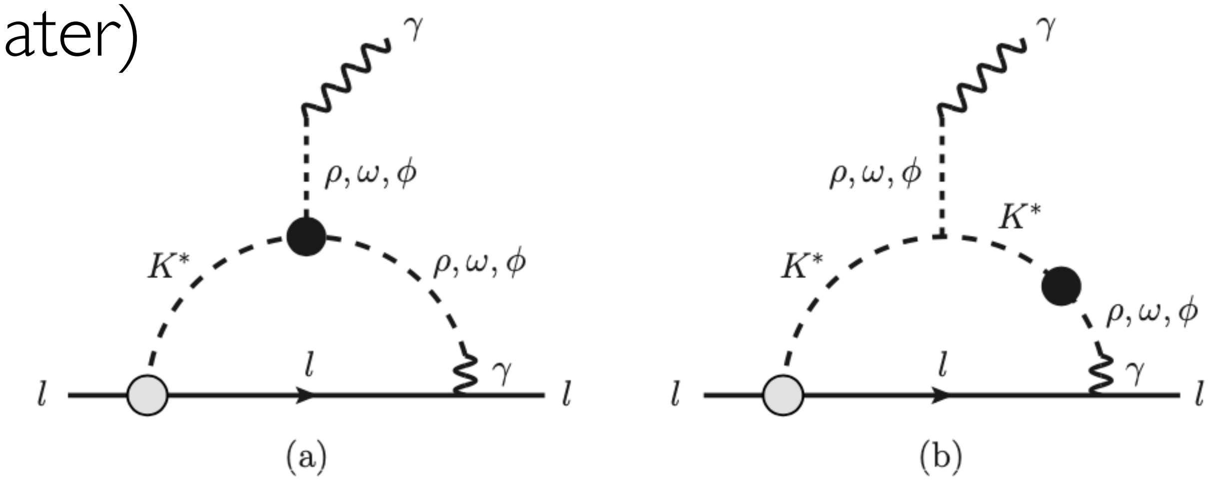

FIG. 2. Long-distance contribution to the charged lepton EDM generated in the SM, with the (a) strong and (b) weak three-vector meson interactions. Other symmetric diagrams are not displayed. The $|\Delta S| = 1$ semileptonic interaction (gray blob) and the $|\Delta S| = 1$ hadronic interaction (black blob) are chosen so as to form the Jarlskog invariant.

Nucleon EDMs from CKM

- qEDM is <u>not</u> the dominant source of the CKM-induced EDM of nucleons
  - 4-quark CP-odd operators + chirally enhanced contributions

$$
\begin{aligned}
d_N^{(\mathrm{lim})}(\mathcal{J}) &\sim e c_n \mathcal{J} G_F^2 m_{\mathrm{had}}^3 \\
&< 10^{-29} e\mathrm{cm} \times c_n \left(\frac{m_{\mathrm{had}}}{300\,\mathrm{MeV}}\right)^3
\end{aligned}
$$

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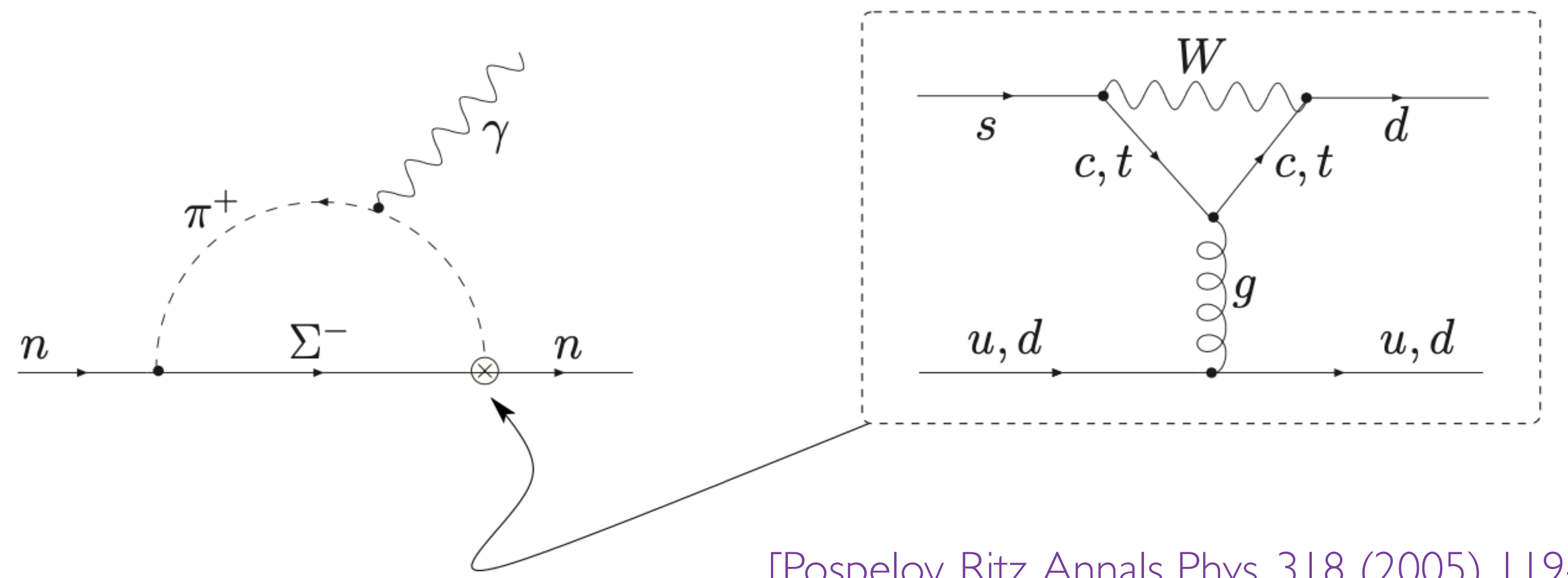
$$\longrightarrow \quad d_N \sim 10^{-(32\div31)}\, e\, cm$$

[Khriplovich, Zhitnitsky, Phys. Lett. B 109 (1982)
Gavela, Le Yaouanc, Oliver, Pene, Raynal, Pham, Phys. Lett. B 109 (1982)
McKellar, Choudhury, He, Pakvasa, Phys. Lett. B 197 (1987)
Mannel, Uraltsev, Phys. Rev. D 85 (2012)]



[Pospelov, Ritz, Annals Phys. 318 (2005) 119-169]

Fig. 6. A leading contribution to the neutron EDM in the Standard Model, arising via a four-quark operator generated by a strong penguin, and then a subsequent enhancement via a chiral π^+ loop.

Schiff theorem

- EDM of a neutral atom vanishes at LO [Schiff, Phys. Rev. 132 (1963)]

within a neutral atom (in the non-relativistic limit and treating the nucleus as point-like) the atomic EDM vanishes due to screening of the applied electric field

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- Proof: [See e.g. Engel, Ramsey-Musolf, van Kolck, Prog. Part. Nucl. Phys. 71 (2013)]

  i) consider a system of point-like particles (nucleons + electrons) interacting with a Coulomb pot.

$$H = \sum_k \frac{p_k^2}{2m_k} + \sum_k V(\vec{r}_k) - \sum_k \vec{d}_k \cdot \vec{E}_k = H_0 + i \sum_k (1/e_k) \underbrace{\left[\vec{d}_k \cdot \vec{p}_k, H_0\right]}_{H_d}$$

  ii) perturbed ground state

$$|\tilde{0}\rangle = |0\rangle + \sum_m \frac{|m\rangle \langle m| H_d |0\rangle}{E_0 - E_m} = |0\rangle + \sum_m \frac{|m\rangle \langle m| i \sum_k (1/e_k) \vec{d}_k \cdot \vec{p}_k |0\rangle (E_0 - E_m)}{E_0 - E_m} = \left(1 + i \sum_k (1/e_k) \vec{d}_k \cdot \vec{p}_k\right) |0\rangle$$

  iii) induced EDM in perturbed ground state is zero

$$\vec{d}' = \langle\tilde{0}| \sum_j e_j \vec{r}_j |\tilde{0}\rangle = i \langle 0| \left[\sum_j e_j \vec{r}_j, \sum_k (1/e_k) \vec{d}_k \cdot \vec{p}_k\right] |0\rangle = -\sum_k \vec{d}_k = -\vec{d}$$

Diamagnetic EDMs from CKM

- Diamagnetic = paired electrons (e.g. ^{199}Hg)

  - Schiff theorem evaded thanks to finite-size of the nucleus

  - atomic EDM is <u>suppressed</u> w.r.t. EDM of the nucleus (by an $(R_{\rm nucl}/R_{\rm atom})^2 \sim O(10^3)$ factor)

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- Leading contribution arises from Schiff moment $H = 4\pi \vec{S} \cdot \vec{\nabla}\delta^3(\vec{r})$

  - CKM contribution via CP-odd nucleon potential somewhat larger than nucleon EDM one

$$\mathcal{L}_{\rm nuc} = \frac{1}{\sqrt{2}} G_F \eta_{np} \bar{N} N \bar{N} i\gamma_5 N$$

[Flambaum, Khriplovich, Sushkov, Sov. Phys. JETP 60 (1984)
Donoghue, Holstein, Musolf, Phys. Lett. B 196 (1987)
Ginges and V.V. Flambaum, Phys. Rept. 397 (2004)
Ban et al., Phys. Rev. C 82 (2010)]

$$\begin{aligned} d_{\rm Hg}(\mathcal{J}) &\sim -10^{-17} \left(\frac{S(\mathcal{J})}{e{\rm fm}^3} \right) e{\rm cm} \\ &\sim 10^{-25} \eta_{np}(\mathcal{J}) e{\rm cm}, \end{aligned}$$

$$\longrightarrow \quad d_{\rm Hg}(\mathcal{J}) < 10^{-35} e{\rm cm}$$

$$\eta_{np}^{(\rm lim)}(\mathcal{J}) \sim c_{\rm Schiff} \mathcal{J} G_F m_{\rm had}^2$$

Paramagnetic EDMs

- Paramagnetic = unpaired electrons (e.g. ThO)
  - Schiff theorem evaded thanks to relativistic electrons
  - atomic/molecular EDM is <u>enhanced</u> w.r.t. EDM of the electron

Paramagnetic EDMs

- Paramagnetic = unpaired electrons (e.g. ThO)

- Receives contributions from both eEDM and semi-leptonic CP-odd operators

$$\mathcal{L}_{CP} = -\frac{i}{2} d_e \bar{e} F \sigma \gamma_5 e - \frac{G_F}{\sqrt{2}} C_{SP} \bar{N} N \bar{e} i \gamma_5 e$$

- C_{SP} does not depend on the spin of the nucleus, coherently enhanced by A (# of nucleons)

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- shift of atomic/molecular energy levels (under external E field)

$$\boxed{\frac{\Delta E}{\mathcal{E}_{\rm ext}} = f_d (d_e + r C_{SP})}$$

- $f_d \simeq \frac{10\, Z^3 \alpha_{\rm em}}{J(J+1/2)(J+1)^2}$ ~ $O(10^{2 \div 3})$ enhancement factor due to relativistic violation of Schiff th.

- r : ratio of atomic matrix elements of C_{SP} and d_e operators ($r_{\rm ThO} = 1.33 \times 10^{-20} e\mathrm{cm}$)

- Equivalent EDM : $d_e^{\rm equiv} \equiv r C_{SP}$

Paramagnetic EDMs from CKM

- CKM-induced C_{SP} contribution dominates w.r.t. the direct contribution from d_e

$$d_e^{\text{equiv}}(\mathcal{J}) \sim 10^{-38} e\text{cm}$$

[Pospelov, Ritz, Phys. Rev. D89 no. 5 (2014)]

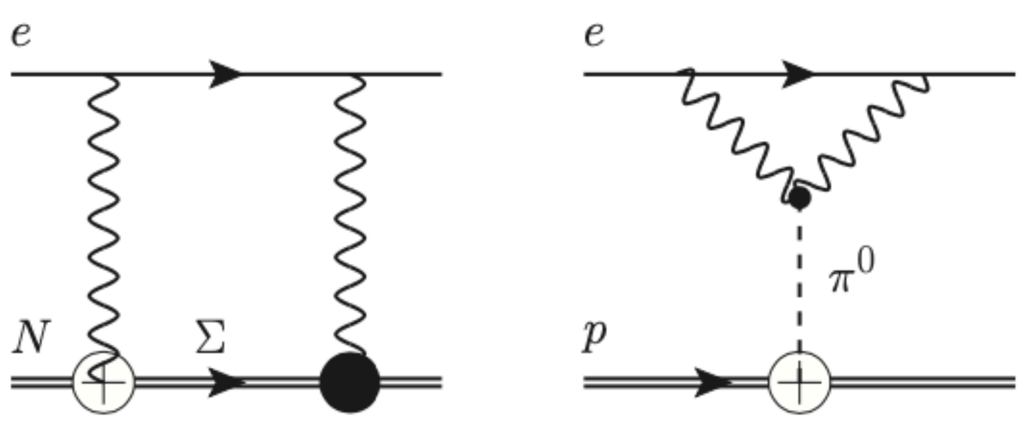

FIG. 3. Examples of the 2PE mechanism, leading to $\bar{e}i\gamma_5 e\bar{N}N$ interactions. Left panel (Fig. 3a): a combination of two weak transitions changing strangeness by ± 1. The crossed and filled circles stand for the CP-odd and CP-even $\Sigma N\gamma$ vertices; the CP-odd vertex is induced by an EM penguin as in Fig. 2. Right panel (Fig. 3b): a diagram involving π^0 mediation. The crossed vertex in this case represents the CP-odd $\pi^0 NN$ coupling.

- to be compared with $d_e \sim 6 \times 10^{-40}\, e\, cm$

[Yamaguchi, Yamanaka, Phys. Rev. Lett. 125 (2020)]

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- Breakthrough result in 2022

[Ema, Gao, Pospelov, Phys. Rev. Lett. 128 (2022)]

$$G_F C_{SP} \propto \mathcal{J} G_F^3 m_t^2 m_e m_s^{-1} \Lambda_{\rm hadr}^2$$

$$\boxed{d_e^{\rm equiv} \simeq 1.0 \times 10^{-35}\, e\,{\rm cm}}$$

- with O(30%) accuracy

- Equivalent EDM : $d_e^{\rm equiv} \equiv r C_{SP}$

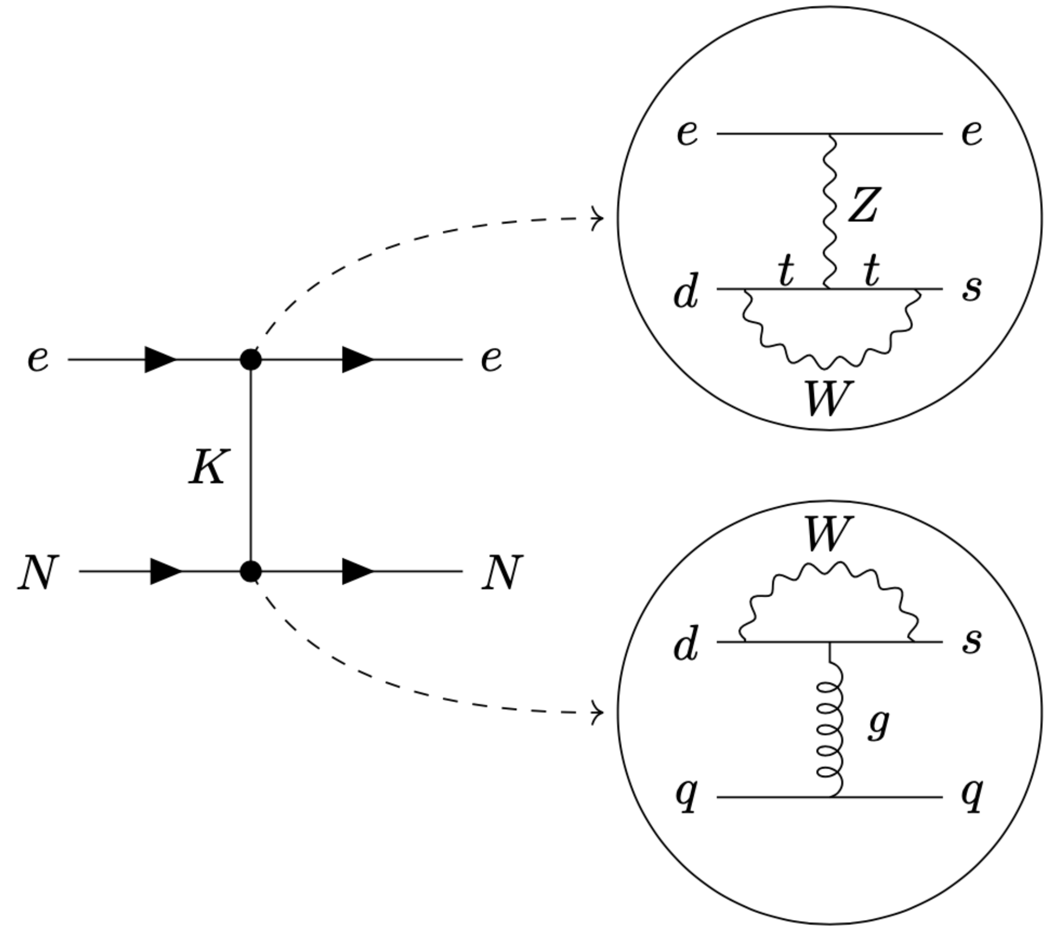


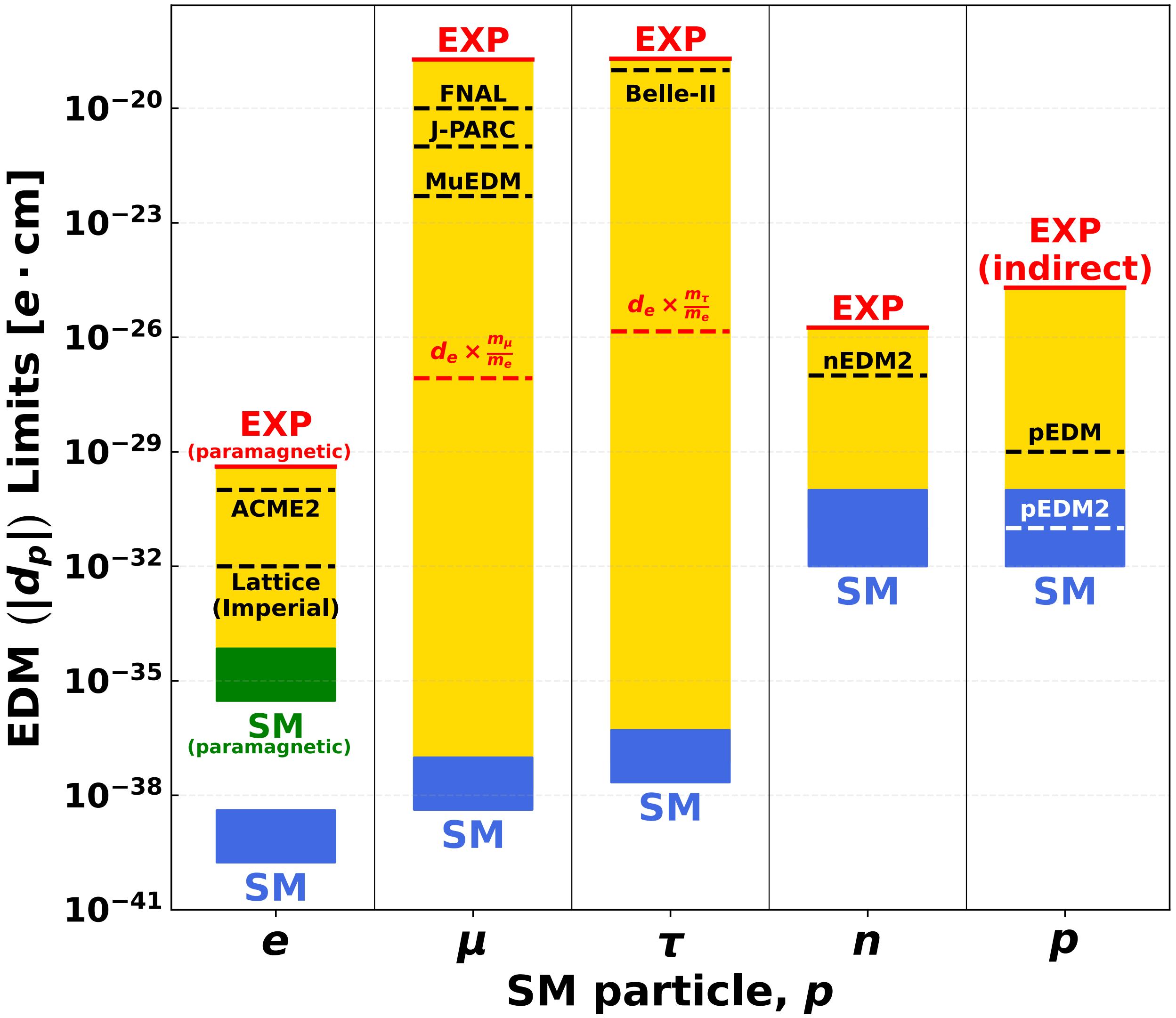
FIG. 1: EW^3 order diagram that dominates in the chiral limit. The top vertex is the CP-odd, P-even $K_S \bar{e} i\gamma_5 e$ generated in EW^2 order, and the bottom vertex is CP-even, P-odd $K_S \bar{N} N$ coupling generated at EW^1 order.

CKM benchmarks

- Set the maximal sensitivity to NP (like neutrino floor for Direct Detection)

  - below that, any signal would be polluted by SM-CKM uncertainties

[Courtesy of A. Keshavarzi]



EDMs beyond CKM

- Motivated CP-violating sources beyond the CKM

  - theta term

  - neutrino mixing

  - baryogenesis

  - axion DM background

  - …

Strong CP

- CP violation from strong interactions: $\bar{\theta} = \theta -$ arg det $Y_U Y_D$

$$\delta\mathcal{L}_{\rm QCD} = \theta \frac{g_s^2}{32\pi^2} G\tilde{G} \qquad |\bar{\theta}| \lesssim 10^{-10} \qquad \text{(bound from nEDM)}$$

- Naive Dimensional Analysis:

$$H = -d_n \, \mathbf{E} \cdot \hat{\mathbf{S}} \qquad \Longleftrightarrow \qquad \mathcal{L} = -d_n \, \frac{i}{2} \overline{n} \sigma^{\mu\nu} \gamma_5 n F_{\mu\nu}$$

$$\left(1 - c\frac{m_q}{2m_n} e^{i\overline{\theta}}\right) \frac{e}{m_n} \overline{n} \sigma^{\mu\nu} \gamma_5 n F_{\mu\nu} + \text{h.c.} \qquad \longrightarrow \qquad d_n = c \frac{m_q}{m_n} \frac{e}{m_n} \overline{\theta}$$

Strong CP

- CP violation from strong interactions: $\bar{\theta} = \theta -$ arg det $Y_U Y_D$

$$\delta\mathcal{L}_{\mathrm{QCD}} = \theta \frac{g_s^2}{32\pi^2} G\tilde{G} \qquad |\bar{\theta}| \lesssim 10^{-10} \qquad \text{(bound from nEDM)}$$

- Naive Dimensional Analysis:

$$H = -d_n\, \mathbf{E} \cdot \hat{\mathbf{S}} \qquad \Longleftrightarrow \qquad \mathcal{L} = -d_n\, \frac{i}{2} \overline{n} \sigma^{\mu\nu} \gamma_5 n F_{\mu\nu}$$

$$\left(1 - c\frac{m_q}{2m_n} e^{i\overline{\theta}}\right) \frac{e}{m_n} \overline{n} \sigma^{\mu\nu} \gamma_5 n F_{\mu\nu} + \text{h.c.} \quad \longrightarrow \quad d_n = \overbrace{c\frac{m_q}{m_n}}^{10^{-2}} \overbrace{\frac{e}{m_n}}^{e\;\mathrm{GeV}^{-1}} \overline{\theta} \sim 10^{-2}\, \overline{\theta}\, e\, \mathrm{GeV}^{-1}$$

$$\simeq 2 \times 10^{-16} \bar{\theta}\, e\, cm$$

Paramagnetic EDM from theta term

- Competitive bound on theta term from paramagnetic EDMs

$$(d_e)_{m_\pi} \simeq \frac{3e\alpha_{em} m_e}{\pi^3 f_\pi^2} A_1 C_1 \left[\ln\left(\frac{4\pi f_\pi}{m_\pi}\right)\right]^2$$

$$\simeq 5\times 10^{-26}\theta \frac{m_u m_d}{(m_u+m_d)m_\pi} e\mathrm{cm}\,.$$

$\rightarrow$ $|\bar{\theta}| \lesssim 10^{-2}$

[Choi, Hong, Phys. Lett. B 259 (1991)
Ghosh, Sato, Phys. Lett. B 777 (2018)]

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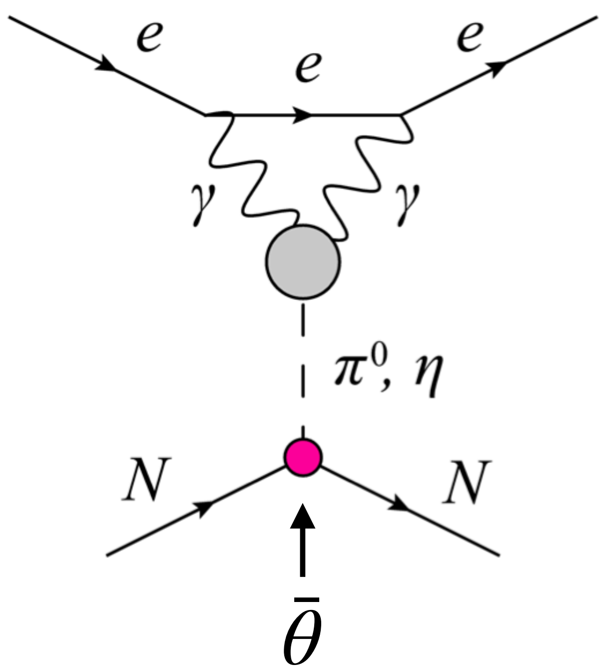
[Choi, Hong, Phys. Lett. B 259 (1991)
Ghosh, Sato, Phys. Lett. B 777 (2018)]

- better sensitivity through C_{SP}

$$d_e^{\text{equiv}} \sim 4\times 10^{-22}\bar{\theta} \quad \longrightarrow \quad |\bar{\theta}|_{\text{ThO}} \lesssim 3\times 10^{-8}$$

[Flambaum, Pospelov, Ritz, Stadnik, Phys. Rev. D 102 (2020)]



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[Flambaum, Pospelov, Ritz, Stadnik, Phys. Rev. D 102 (2020)]

- even after accounting for nEDM bound, theta contribution can be larger than CKM

- future sensitivity from paramagnetic EDMs could surpass present nEDM limit on theta

What should we expect for $\bar{\theta}$?

- In the SM, theta is a free parameter

  - divergent (7-loops), but very stable under radiative corrections

[Ellis, Gaillard NPB 150 (1979)
Khriplovich, Vainshtein NPB 414 (1994)]

$$\bar{\theta}_{\text{div.}} \sim \frac{1}{(4\pi)^{14}} g'^2 \left[Y^2(u_R) - Y^2(d_R)\right] J_{\text{CKM}} \log \Lambda_{\text{UV}} \sim 10^{-46} \log \Lambda_{\text{UV}}$$

$$\uparrow$$

$$\text{Im}\,\text{Det}\left[Y_U Y_U^\dagger, Y_D Y_D^\dagger\right] \approx 10^{-29}$$

What should we expect for $\bar{\theta}$?

- In the SM, theta is a free parameter

- Theta is calculable in theories beyond the SM (addressing the strong CP problem)

1. QCD axion: new spin-0 boson with a pseudo-shift symmetry $a \to a + \kappa f_a$

broken by $\frac{a}{f_a} \frac{g_s^2}{32\pi^2} G\tilde{G}$ $\longrightarrow$ $E(0) \leq E(\langle a \rangle)$ [Vafa, Witten, Phys. Rev. Lett. 53 (1984)]

$$\theta_{\text{eff}} = \frac{\langle a \rangle}{f_a}$$

$$\begin{aligned} e^{-V_4 E(\theta_{\text{eff}})} &= \int \mathcal{D}\varphi \, e^{-S_0 + i\theta_{\text{eff}} \int G\tilde{G}} \\ &= \left| \int \mathcal{D}\varphi \, e^{-S_0 + i\theta_{\text{eff}} \int G\tilde{G}} \right| \\ &\leq \int \mathcal{D}\varphi \left| e^{-S_0 + i\theta_{\text{eff}} \int G\tilde{G}} \right| = e^{-V_4 E(0)} \end{aligned}$$

**path-integral measure positive definite for a vector-like theory (e.g. QCD)*

What should we expect for $\bar{\theta}$?

- In the SM, theta is a free parameter
- Theta is <u>calculable</u> in theories beyond the SM (addressing the strong CP problem)

1. QCD axion: does the axion really relax to zero ?

→ $$\theta_{\rm eff}^{\rm SM} = \frac{\langle a \rangle}{f_a} \sim G_F^2 f_\pi^4 j_{\rm CKM} \approx 10^{-18}$$ [Georgi, Randall, NPB276 (1986)]

A <u>no-lose theorem</u> for the "SM axion":

$$d_n^{\rm axion} \sim \underbrace{10^{-16}\, \theta_{\rm eff}^{\rm SM}}_{10^{-34}} \, e\,{\rm cm} \qquad d_n^{\rm SM} \simeq 10^{-32} \, e\,{\rm cm} \qquad |d_n^{\rm exp}| \lesssim 10^{-26} \, e\,{\rm cm}$$

→ better way to test the axion ground state, via axion mediated forces

[See backup slides + talk by P. Sørensen tomorrow]

What should we expect for $\bar{\theta}$?

- In the SM, theta is a free parameter

- Theta is calculable in theories beyond the SM (addressing the strong CP problem)

2. P or CP as spontaneously broken symmetries

[… Nelson, Phys. Lett. B 136 (1984)
Barr, Phys. Rev. Lett. 53 (1984) …]

- finite contributions to $\bar{\theta}$, from the CP-violating sources responsible for the CKM

- strong model-dependency, but models typically live at the nEDM boundary

CP violation in the neutrino sector

- 1 Dirac phase + 2 Majorana phases

$$|\nu_\alpha\rangle = \sum_{i=1}^{n} U^*_{\alpha i} |\nu_i\rangle$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\rm CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\rm CP}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- $\delta_{\rm CP}$ from 3ν oscillations

- $\eta_{1,2}$ from $0\nu\beta\beta$

CP violation in the neutrino sector

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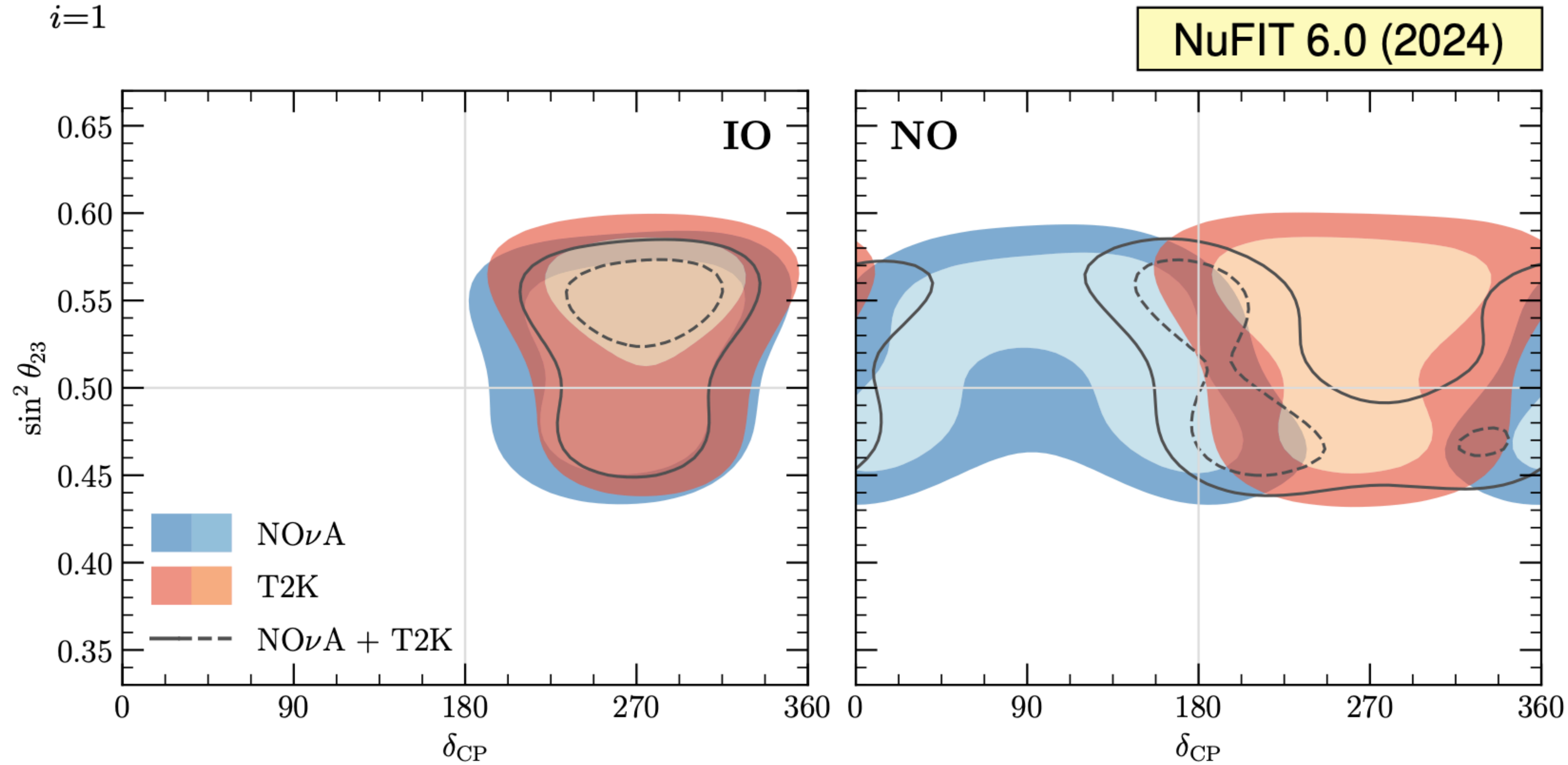


- $\delta_{\rm CP}$ from 3ν oscillations

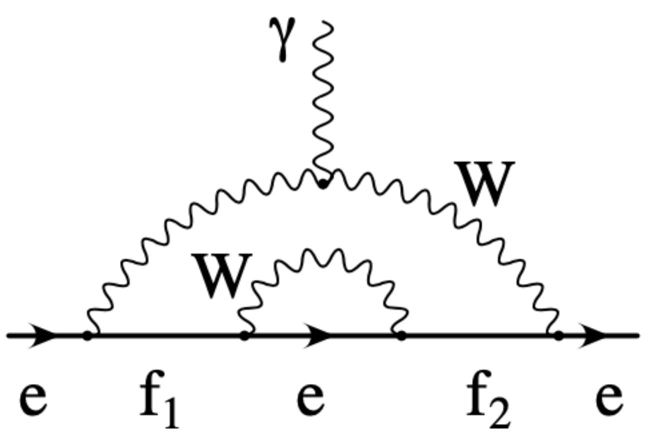
- $\eta_{1,2}$ from $0\nu\beta\beta$

eEDM from neutrinos

- Typically too small and model-dependent

[Ng Ng, Mod. Phys. Lett. A 11 (1996)
Archambault, Czarnecki, Pospelov, Phys. Rev. D 70 (2004).
de Gouvea, Gopalakrishna Phys. Rev. D 72 (2005)]

- Pure Dirac neutrino contribution vanishes at 2-loops (as for qEDM)



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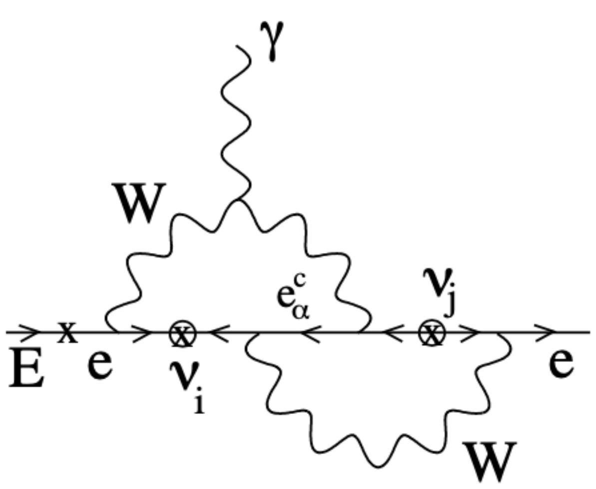
  - Pure Dirac neutrino contribution vanishes at 2-loops (as for qEDM)

  - Pure Majorana contribution utterly small (as for $\mu \to e\gamma$)



$$|d_e| \propto m_\nu^4 \lesssim 10^{-72}\, e\, cm$$

eEDM from neutrinos

- Typically too small and model-dependent

[Ng Ng, Mod. Phys. Lett. A 11 (1996)
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- Pure Dirac neutrino contribution vanishes at 2-loops (as for qEDM)

- Pure Majorana contribution utterly small (as for $\mu \to e\gamma$)

- SMEFT expectation very small

$$\mathscr{L}_{\mathrm{SMEFT}} \supset -\frac{\lambda}{2\Lambda}\ell\ell HH - \frac{ig}{\Lambda^2}\bar{\ell}\gamma_5\sigma_{\mu\nu}eF^{\mu\nu}$$

$$\rightarrow \quad m_\nu = \frac{\lambda v^2}{\Lambda} = \lambda\,\mathrm{eV}\left(\frac{10^{14}\,\mathrm{GeV}}{\Lambda}\right)$$

$$d_e = \frac{gv}{\Lambda^2} \sim \frac{em_e}{\Lambda^2} = 10^{-45}\,e\,cm\left(\frac{10^{14}\,\mathrm{GeV}}{\Lambda^2}\right)^2$$

eEDM from neutrinos

- Typically too small and model-dependent

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  - Pure Dirac neutrino contribution vanishes at 2-loops (as for qEDM)

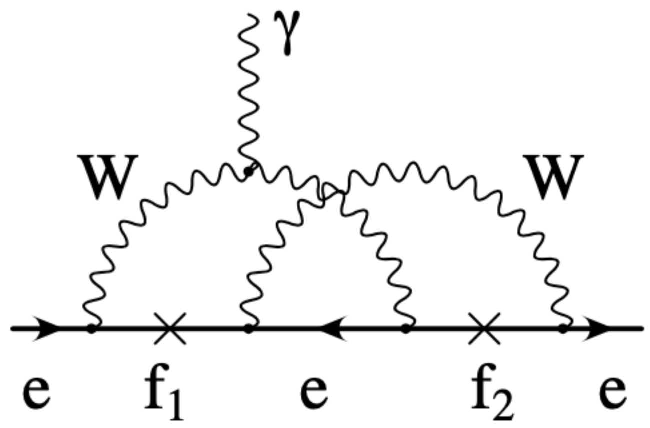
  - Pure Majorana contribution utterly small (as for $\mu \to e\gamma$)

  - SMEFT expectation very small

  - Type-I seesaw contribution also small (but model-dependent)

$$|d_e| \lesssim e \left(\frac{G_F}{16\pi^2}\right)^2 m_e \,\frac{\Delta M}{M}\frac{m_1^2}{M}\frac{m_2^2}{M} \quad < 1.5 \times 10^{-43} e \text{ cm}, \quad \text{see-saw case}$$

$$\lesssim 10^{-33}\; e \text{ cm}, \quad \text{fine-tuned case}$$



$$m_\nu = \left|\frac{m_1^2 e^{2i\eta}}{M_1} + \frac{m_2^2}{M_2}\right|$$

eEDM from neutrinos

- Typically too small and model-dependent

[Ng Ng, Mod. Phys. Lett. A 11 (1996)
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- Pure Majorana contribution utterly small (as for $\mu \to e\gamma$)

- SMEFT expectation very small

- Type-I seesaw contribution also small (but model-dependent)

→ do not expect (generically) a measurable effect,
but not entirely ruled out in certain neutrino mass models

EDMs & baryogenesis

- Sakharov criteria for matter-antimatter asymmetry: [Sakharov, JETP Letters 5 (1967)]

1. Baryon number violation
2. C and CP violation
3. Departure from thermal equilibrium

EDMs & baryogenesis

- Sakharov criteria for matter-antimatter asymmetry: [Sakharov, JETP Letters 5 (1967)]

  1. Baryon number violation

  2. C and CP violation

  3. Departure from thermal equilibrium

  - CP violation from CKM not sufficient

$$\frac{\text{Im Det}\,[M_U M_U^\dagger, M_D M_D^\dagger]}{(100\,\text{GeV})^{12}} \simeq 10^{-20} \ll \eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq 6 \times 10^{-10}$$

$$\downarrow$$

$$T_{\text{sphal.}} \gtrsim 100\,\text{GeV}$$

EDMs & baryogenesis

- Sakharov criteria for matter-antimatter asymmetry: [Sakharov, JETP Letters 5 (1967)]

  1. Baryon number violation

  2. C and CP violation

  3. Departure from thermal equilibrium

  - CP violation from CKM not sufficient

  - new sources of CP violation are required (leptogenesis, EW baryogenesis, …)

EDM sensitivity to heavy NP

- EDMs are secretly d=6 operators

  - helicity flipping

$$d_f \frac{i}{2}(\bar{f}\sigma_{\mu\nu}\gamma_5 f)F^{\mu\nu} = d_f \frac{i}{2}(\bar{f}_L\sigma_{\mu\nu}f_R - \bar{f}_R\sigma_{\mu\nu}f_L)F^{\mu\nu}$$

  - above the EW scale need to add a Higgs doublet to restore $SU(2)_L$ invariance

$$\frac{1}{\Lambda^2}H(\bar{f}_L\sigma_{\mu\nu}f_R)F^{\mu\nu} \quad \to \quad \frac{v}{\Lambda^2}(\bar{f}_L\sigma_{\mu\nu}f_R)F^{\mu\nu} \quad , \quad d_f \sim \frac{v}{\Lambda^2}$$

EDM sensitivity to heavy NP

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  - helicity flipping

$$d_f \frac{i}{2}(\bar{f}\sigma_{\mu\nu}\gamma_5 f)F^{\mu\nu} = d_f \frac{i}{2}(\bar{f}_L\sigma_{\mu\nu}f_R - \bar{f}_R\sigma_{\mu\nu}f_L)F^{\mu\nu}$$

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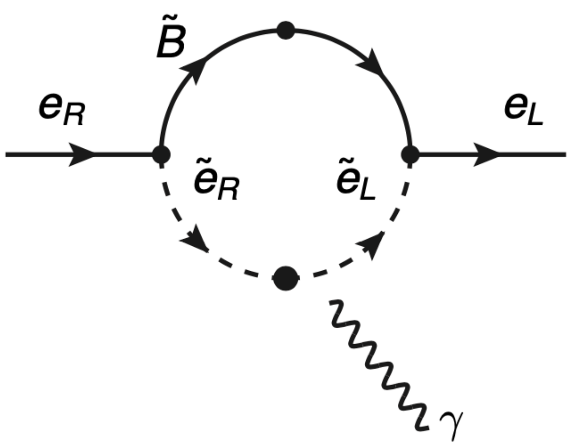
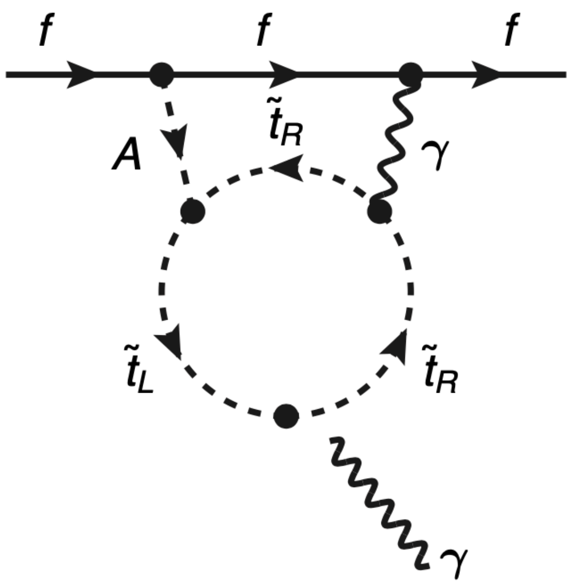
  - typical NP contributions at 1- and 2-loops

$$\frac{|d_e|}{e} \sim \begin{cases} \frac{eg^2}{16\pi^2}\frac{m_e}{\Lambda^2}\sin\phi_{\rm CPV} \sim 10^{-29}\, e\, cm \left(\frac{50\ \text{TeV}}{\Lambda}\right)^2 \sin\phi_{\rm CPV} & \text{(1-loop)} \\ e\left(\frac{g^2}{16\pi^2}\right)^2 \frac{m_e}{\Lambda^2}\sin\phi_{\rm CPV} \sim 10^{-29}\, e\, cm \left(\frac{2.5\ \text{TeV}}{\Lambda}\right)^2 \sin\phi_{\rm CPV} & \text{(2-loops)} \end{cases}$$

EDM sensitivity to heavy NP

- EDMs are secretly d=6 operators





- typical NP contributions at 1- and 2-loops (e.g. from SUSY)

$$\frac{|d_e|}{e} \sim \begin{cases} \dfrac{eg^2}{16\pi^2}\dfrac{m_e}{\Lambda^2}\sin\phi_{\rm CPV} \sim 10^{-29}\, e\, cm \left(\dfrac{50\,\text{TeV}}{\Lambda}\right)^2 \sin\phi_{\rm CPV} & \text{(1-loop)} \\ e\left(\dfrac{g^2}{16\pi^2}\right)^2 \dfrac{m_e}{\Lambda^2}\sin\phi_{\rm CPV} \sim 10^{-29}\, e\, cm \left(\dfrac{2.5\,\text{TeV}}{\Lambda}\right)^2 \sin\phi_{\rm CPV} & \text{(2-loops)} \end{cases}$$

EDM sensitivity to light NP

- CP-violating axion-like particles (ALPs)

[Marciano, Masiero, Paradisi, Passera, Phys. Rev. D 94 (2016)
Di Luzio, Gröber, Paradisi, Phys. Rev. D 104 (2021)
Di Luzio, Levati, Paradisi, JHEP 02 (2024)]

$$\mathcal{L}_\phi = e^2 \frac{\tilde{C}_\gamma}{\Lambda} \phi F \tilde{F} + g_s^2 \frac{\tilde{C}_g}{\Lambda} \phi G \tilde{G} + i \frac{v}{\Lambda} y_P^{ij} \phi \bar{f}_i \gamma_5 f_j$$
$$+ e^2 \frac{C_\gamma}{\Lambda} \phi F F + g_s^2 \frac{C_g}{\Lambda} \phi G G + \frac{v}{\Lambda} y_S^{ij} \phi \bar{f}_i f_j$$

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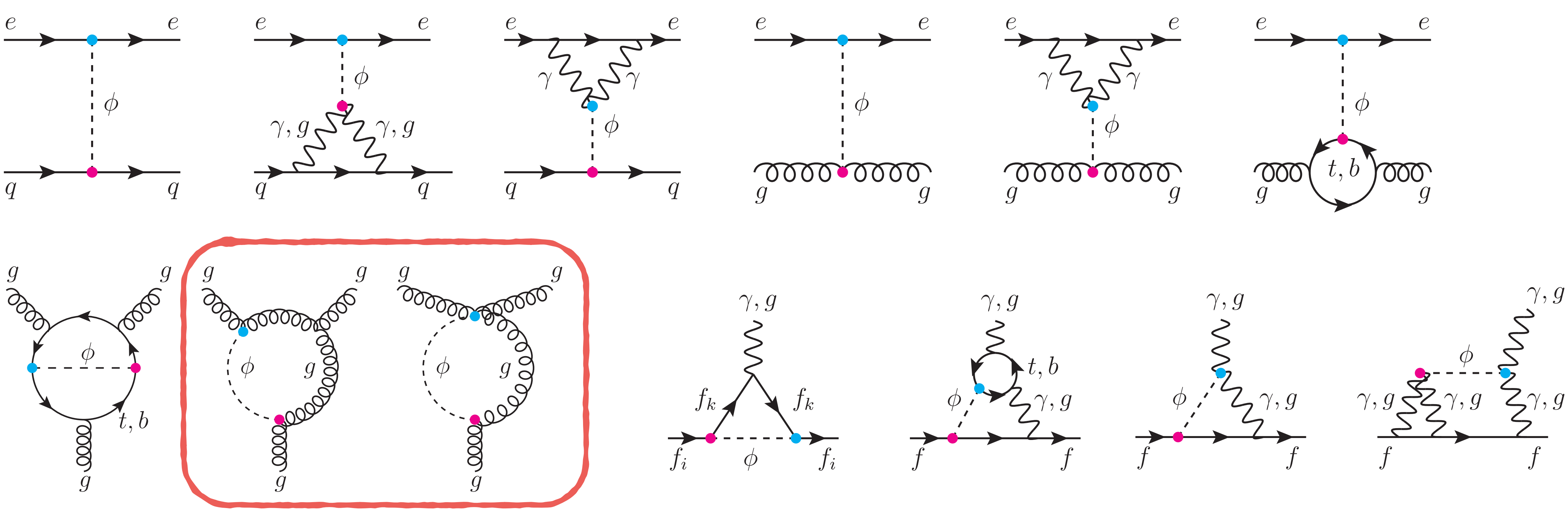
$$+ e^2 \frac{C_\gamma}{\Lambda} \phi F F + g_s^2 \frac{C_g}{\Lambda} \phi G G + \frac{v}{\Lambda} y_S^{ij} \phi \bar{f}_i f_j$$

- different scaling/sensitivity w.r.t. heavy NP + new short-distance contributions to EDMs



Axion-induced oscillating EDM

- Axion DM background is CP-violating $\longrightarrow$ induces an oscillating EDM

$$\mathscr{L} \supset \frac{g_s^2}{32\pi^2}\frac{a}{f_a}G\tilde{G} \longrightarrow \mathscr{L} \supset -\frac{i}{2}g_{an\gamma}\, a\bar{n}\sigma_{\mu\nu}\gamma_5 n F^{\mu\nu}$$

Axion-induced oscillating EDM

- Axion DM background is CP-violating $\longrightarrow$ induces an oscillating EDM

$$\mathscr{L} \supset \frac{g_s^2}{32\pi^2}\frac{a}{f_a}G\tilde{G} \longrightarrow \mathscr{L} \supset -\frac{i}{2}\underbrace{g_{an\gamma}}\, a\bar{n}\sigma_{\mu\nu}\gamma_5 n F^{\mu\nu}$$

$$a(t) \simeq \sqrt{\frac{2\rho_{\rm DM}}{m_a^2}}\cos(m_a t)$$

$$d_n(t) = g_{an\gamma}\sqrt{\frac{2\rho_{\rm DM}}{m_a^2}}\cos(m_a t) \simeq 10^{-34}\, e\, cm\, \cos(m_a t)$$

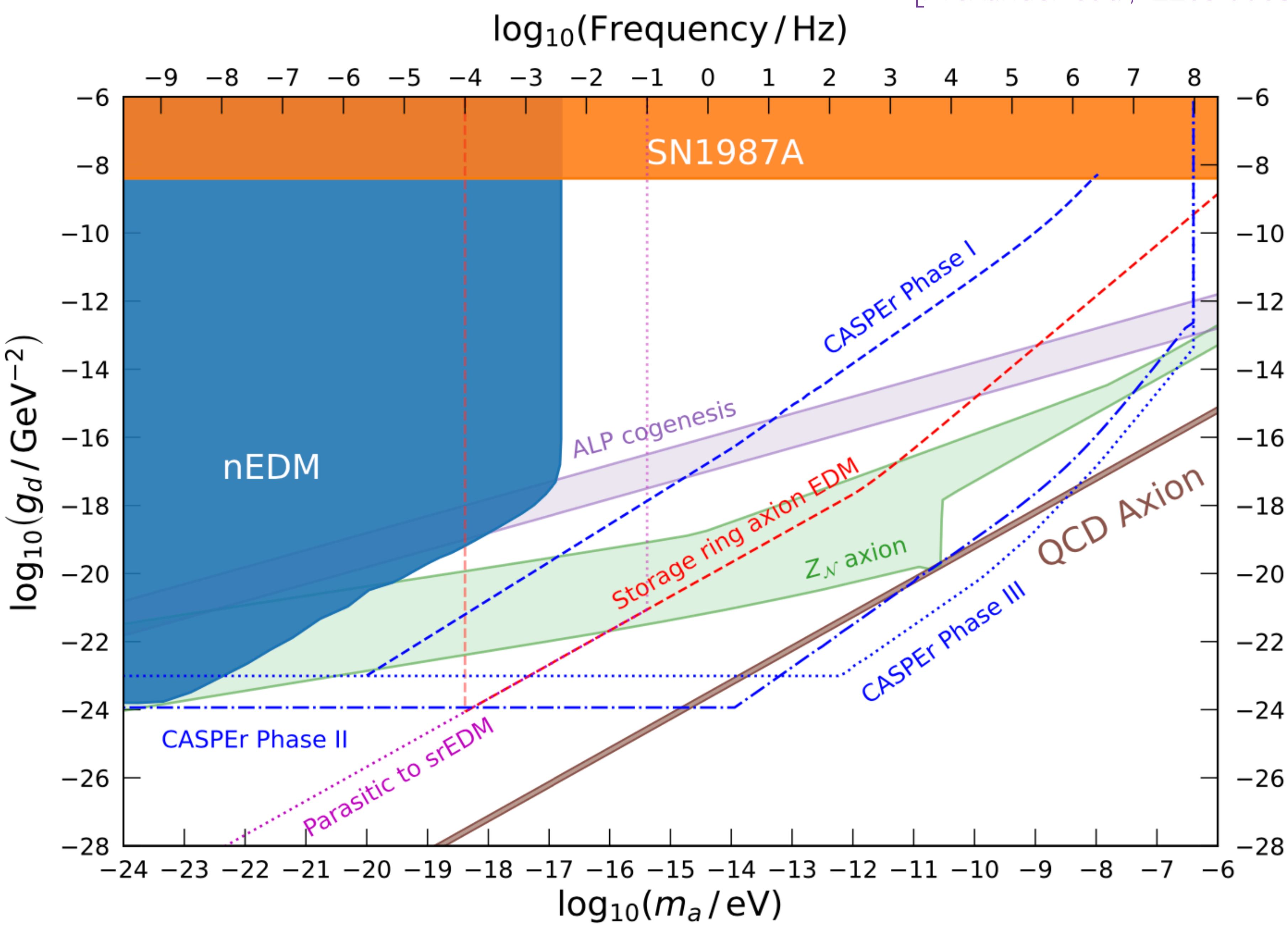
- NMR techniques (CASPEr-electric) [Graham, Rajendran Phys. Rev. D 88 (2013), Budker, Graham, Ledbetter, Rajendran, Sushkov, Phys. Rev. X 4 (2014)]

- proton storage rings [Graham et al, Phys. Rev. D 103 (2021) Kim, Semertzidis, Phys. Rev. D 104 (2021)]

Axion-induced oscillating EDM

- Axion DM background is CP-violating → induces an oscillating EDM

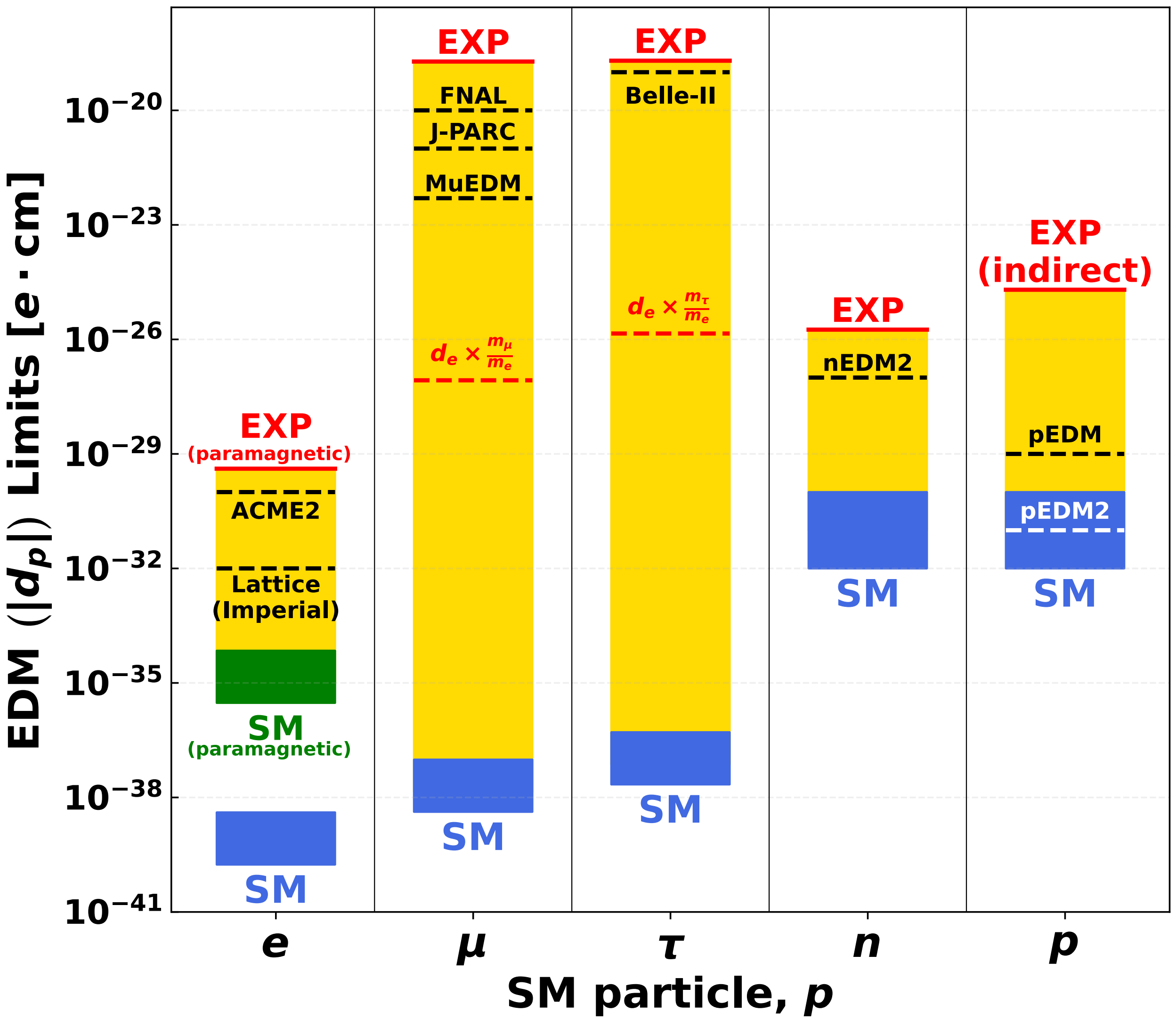
[Alexander et al, 2205.00830]



Conclusions

- EDMs are powerful probes of NP
- SM-CKM background negligible in the foreseeable future: signal = discovery of NP

[Courtesy of A. Keshavarzi]



Conclusions

- EDMs are powerful probes of NP
- SM-CKM background negligible in the foreseeable future: signal = discovery of NP
- Motivated CP-violating sources to be probed by EDMs:

  - non-zero theta term
  - CP-violation related to baryogenesis (strongly model-dependent)
  - TeV scale NP addressing the EW Hierarchy Problem (SUSY, …)

- New ideas with oscillating EDMs to probe CP-violating axion DM background

Backup slides

Open questions

- Ultimate EDM experiments (electron and/or proton) to reach SM-CKM sensitivity ?
- Complementarity of EDMs to disentangle origin of CP violation ?
- What insights into baryogenesis can be gained from the observation of an EDM ?
- EDM connections with other leptonic dipoles (MDM, LFV, …) ?
- EDM interplay with high-energy observables (LHC, …) ?

On leptonic dipoles: $\ell \to \ell' + \gamma$

- **NP effects are encoded in the effective Lagrangian**

$$\mathcal{L} = e\frac{m_\ell}{2}\left(\bar{\ell}_R\sigma_{\mu\nu}A_{\ell\ell'}\ell'_L + \bar{\ell}'_L\sigma_{\mu\nu}A^{\star}_{\ell\ell'}\ell_R\right)F^{\mu\nu} \qquad \ell,\ell' = e,\mu,\tau\,,$$

  - **Branching ratios of $\ell \to \ell'\gamma$**

$$\frac{\mathrm{BR}(\ell \to \ell'\gamma)}{\mathrm{BR}(\ell \to \ell'\nu_\ell\bar{\nu}_{\ell'})} = \frac{48\pi^3\alpha}{G_F^2}\left(|A_{\ell\ell'}|^2 + |A_{\ell'\ell}|^2\right).$$

  - **Δa_ℓ and leptonic EDMs**

$$\Delta a_\ell = 2m_\ell^2\,\mathrm{Re}(A_{\ell\ell}), \qquad \frac{d_\ell}{e} = m_\ell\,\mathrm{Im}(A_{\ell\ell})\,.$$

  - **"Naive scaling":** a broad class of NP theories contributes to Δa_ℓ and d_ℓ as

$$\frac{\Delta a_\ell}{\Delta a_{\ell'}} = \frac{m_\ell^2}{m_{\ell'}^2}, \qquad \frac{d_\ell}{d_{\ell'}} = \frac{m_\ell}{m_{\ell'}}\,.$$

On leptonic dipoles: $\ell \to \ell' + \gamma$

- $\mathbf{BR(\ell_i \to \ell_j\gamma)}$ **vs.** $\mathbf{(g-2)_\mu}$

[Giudice, Paradisi, Passera, JHEP 11 (2012)]

$$\mathrm{BR}(\mu \to e\gamma) \approx 3 \times 10^{-13} \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right)^2 \left(\frac{\theta_{e\mu}}{10^{-5}}\right)^2$$

$$\mathrm{BR}(\tau \to \mu\gamma) \approx 4 \times 10^{-8} \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right)^2 \left(\frac{\theta_{\mu\tau}}{10^{-2}}\right)^2$$

- **EDMs vs.** $\mathbf{(g-2)_\mu}$

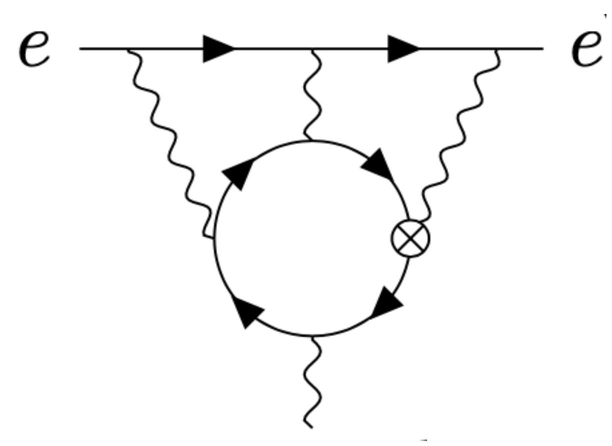
$$d_e \simeq \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right) 10^{-29} \left(\frac{\phi_e^{CPV}}{10^{-5}}\right) e\,\mathrm{cm}\,,$$

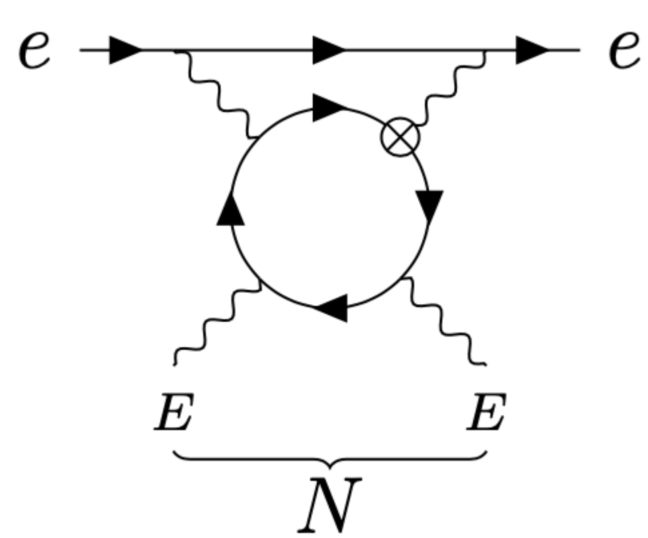
$$d_\mu \simeq \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right) 2 \times 10^{-22}\, \phi_\mu^{CPV}\ e\,\mathrm{cm}\,,$$

- **Main messages:**
  - $\mathbf{\Delta a_\mu \approx (3 \pm 1) \times 10^{-9}}$ **requires a nearly flavor and CP conserving NP**
  - **Large effects in the muon EDM** $\mathbf{d_\mu \sim 10^{-22}\ e\,\mathrm{cm}}$ **are still allowed!**

Model-independent relations

- Muon/tau EDM inside a loop generates d_e and C_{SP} [Ema, Gao, Pospelov Phys. Rev. Lett. 128 (2022)]





→ $|d_\mu| < 1.7 \times 10^{-20}\, e\,\mathrm{cm}$

- stronger than direct limit at BNL $|d_\mu| < 1.8 \times 10^{-19}\, e\,\mathrm{cm}$

→ $|d_\tau| < 1.6 \times 10^{-18}\, e\,\mathrm{cm}$

- stronger than direct limit at Belle $|d_\tau| < 3.9 \times 10^{-17}\, e\,cm$

EDM bounds

[Chupp, Fierlinger, Ramsey-Musolf, Singh, Rev. Mod. Phys. 91 (2019) 1, 015001]

	Result	95% u.l.	ref.
	Paramagnetic systems		
Xe^m	$d_A = (\ \ 0.7 \pm 1.4) \times 10^{-22}$	3.1×10^{-22} e cm	a
Cs	$d_A = (-1.8 \pm 6.9) \times 10^{-24}$	1.4×10^{-23} e cm	b
	$d_e = (-1.5 \pm 5.7) \times 10^{-26}$	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	c
	$d_e = (\ \ 6.9 \pm 7.4) \times 10^{-28}$	1.9×10^{-27} e cm	
YbF	$d_e = (-2.4 \pm 5.9) \times 10^{-28}$	1.2×10^{-27} e cm	d
ThO	$d_e = (-2.1 \pm 4.5) \times 10^{-29}$	9.7×10^{-29} e cm	e
	$C_S = (-1.3 \pm 3.0) \times 10^{-9}$	6.4×10^{-9}	
HfF^+	$d_e = (0.9 \pm 7.9) \times 10^{-29}$	1.6×10^{-28} e cm	f
	Diamagnetic systems		
$^{199}\mathrm{Hg}$	$d_A = (2.2 \pm 3.1) \times 10^{-30}$	7.4×10^{-30} e cm	g
$^{129}\mathrm{Xe}$	$d_A = (0.7 \pm 3.3) \times 10^{-27}$	6.6×10^{-27} e cm	h
$^{225}\mathrm{Ra}$	$d_A = (4 \pm 6) \times 10^{-24}$	1.4×10^{-23} e cm	i
TlF	$d\ \ = (-1.7 \pm 2.9) \times 10^{-23}$	6.5×10^{-23} e cm	j
n	$d_n = (-0.21 \pm 1.82) \times 10^{-26}$	3.6×10^{-26} e cm	k
	Particle systems		
μ	$d_\mu = (0.0 \pm 0.9) \times 10^{-19}$	1.8×10^{-19} e cm	l
τ	$Re(d_\tau) = (1.15 \pm 1.70) \times 10^{-17}$	3.9×10^{-17} e cm	m
Λ	$d_\Lambda = (-3.0 \pm 7.4) \times 10^{-17}$	1.6×10^{-16} e cm	n

TABLE I Systems with EDM results and the most recent results as presented by the authors. When d_e is presented by the authors, the assumption is $C_S = 0$, and for ThO, the C_S result assumes $d_e = 0$. Q_m is the magnetic quadrupole moment, which requires a paramagnetic atom with nuclear spin $I > 1/2$. (μ_N and R_{Cs} are the nuclear magneton and the nuclear radius of ^{133}Cs, respectively.) We have combined statistical and systematic errors in quadrature for cases where they are separately reported by the experimenters. References; a (Player and Sandars, 1970); b (Murthy *et al.*, 1989); c (Regan *et al.*, 2002b); d (Hudson *et al.*, 2011); e (Baron *et al.*, 2014); f (Cairncross *et al.*, 2017); g (Graner *et al.*, 2017); h (Rosenberry, 2001); i (Parker *et al.*, 2015); j (Cho *et al.*, 1991); k (Pendlebury *et al.*, 2015); l (Bennett *et al.*, 2009); m (Inami *et al.*, 2003); n (Pondrom *et al.*, 1981).

CP-violating axions

- $\mathscr{L} \supset g_s^N a\overline{N}N + g_p^N a\overline{N}i\gamma_5 N$

$$g_{aN}^S \sim \frac{f_\pi}{f_a}\theta_{\rm eff}$$

from UV sources of CP-violation or PQ breaking

[Moody, Wilczek, Phys. Rev. D 30 (1984)
Barbieri, Romanino, Strumia, Phys. Lett. B 387 (1996)
Pospelov Phys. Rev. D 58 (1998)
Bertolini, Di Luzio, Nesti, Phys. Rev. Lett. 126 (2021)
Okawa, Pospelov, Ritz, Phys. Rev. D 105 (2022)
Dekens, de Vries, Shain, JHEP 07 (2022)]

CP-violating axions

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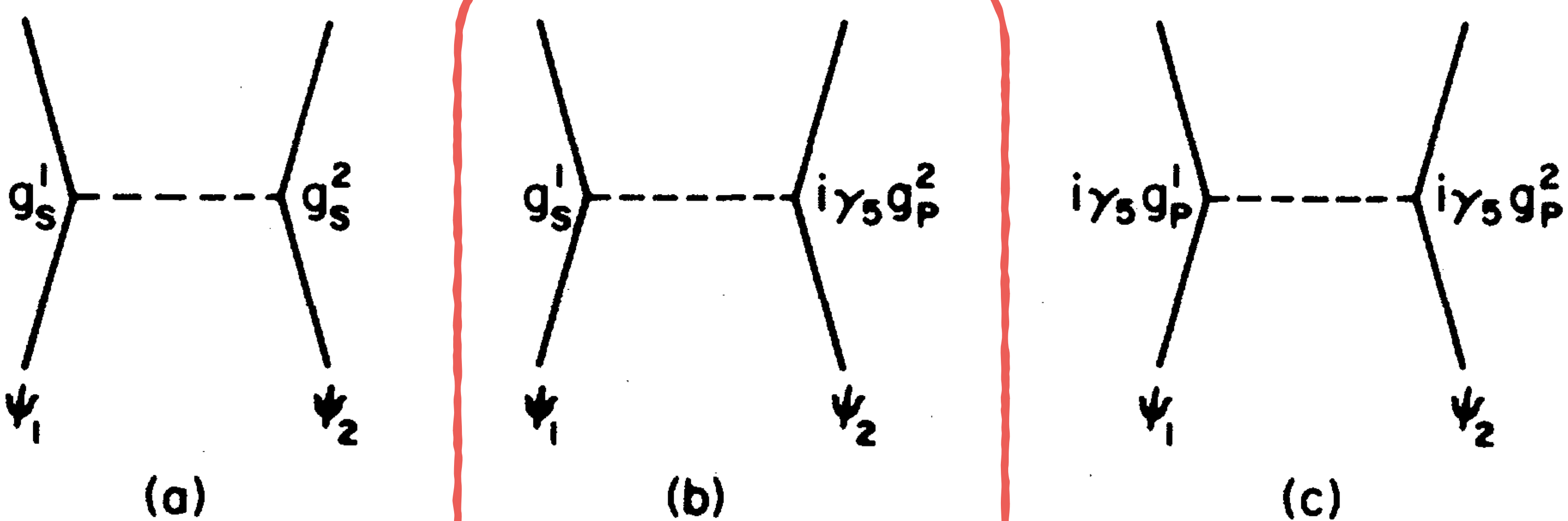
from UV sources of CP-violation or PQ breaking

New macroscopic forces from non-relativistic potentials [Moody, Wilczek, Phys. Rev. D 30 (1984)]



monopole-monopole

double θ_{eff} suppression

monopole-dipole

ARIADNE, QUAX-gpgs, …

dipole-dipole

spin suppression + bkgd from ordinary magnetic forces

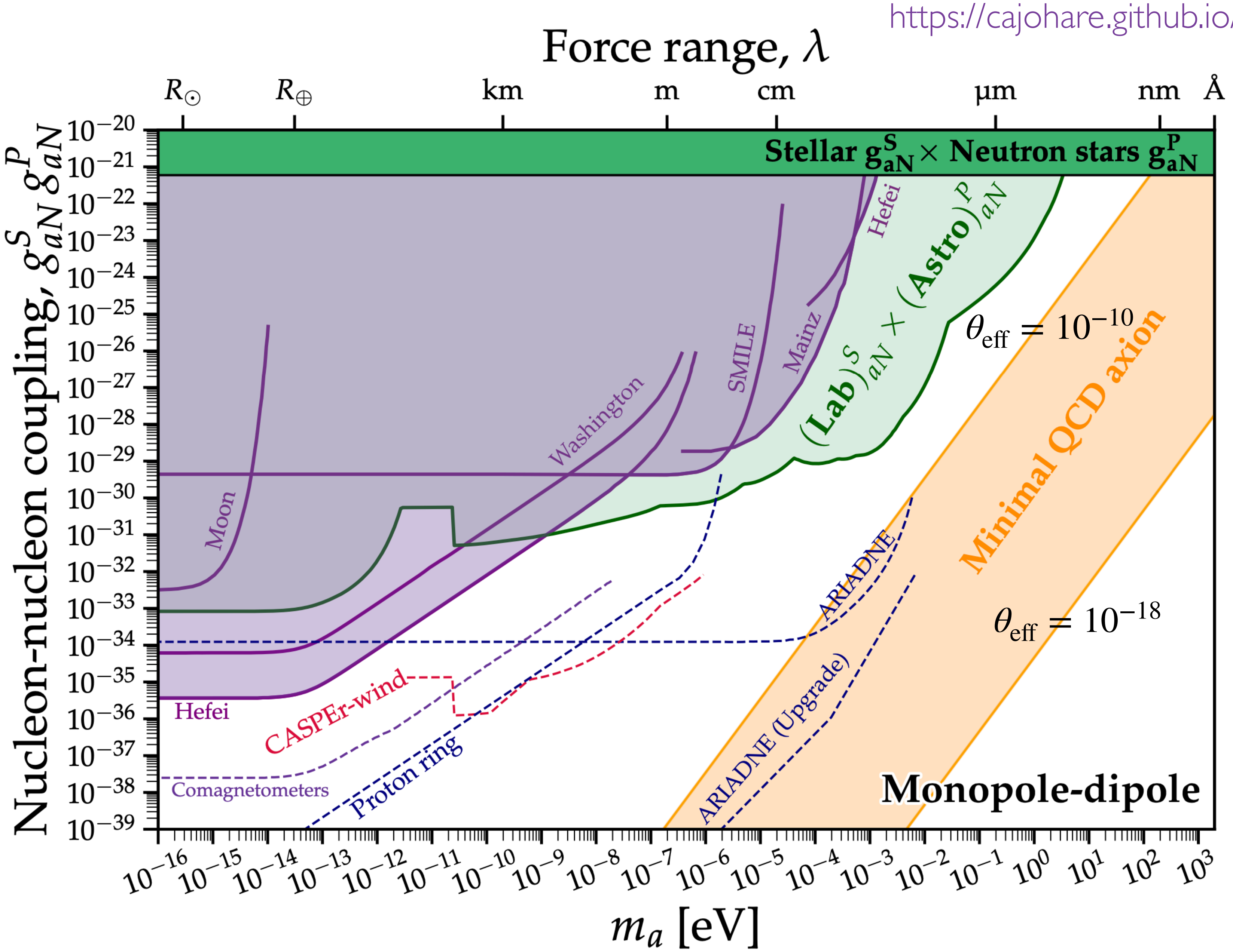
CP-violating axions

- $\mathscr{L} \supset g_s^N a\overline{N}N + g_p^N a\overline{N}i\gamma_5 N$

$$g_{aN}^S \sim \frac{f_\pi}{f_a}\theta_{\text{eff}}$$

from UV sources of CP-violation or PQ breaking

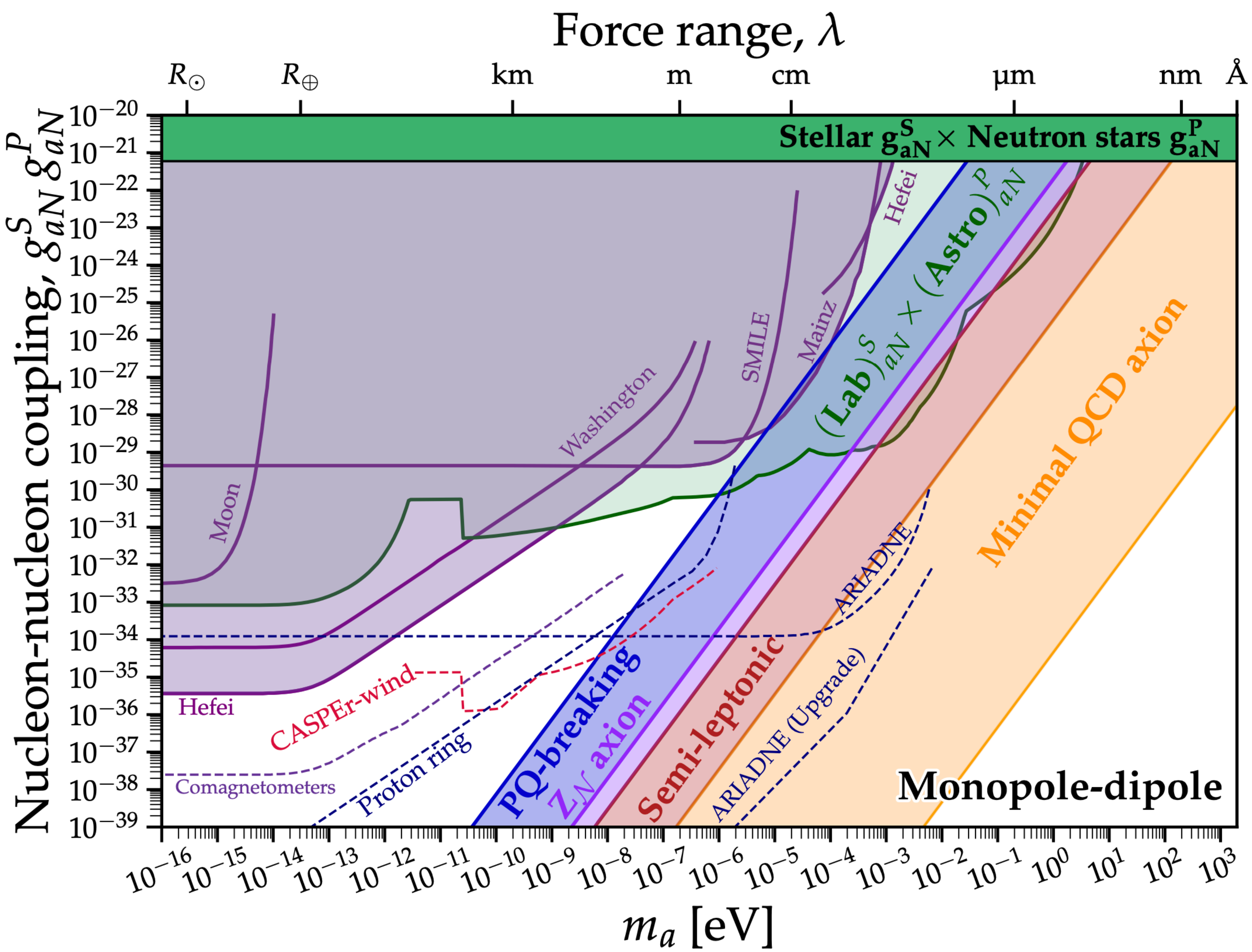
[O'Hare, Vitagliano, Phys. Rev. D 102 (2020)
https://cajohare.github.io/AxionLimits]



CP-violating axions

- $\mathscr{L} \supset g_s^N a \overline{N} N + g_p^N a \overline{N} i \gamma_5 N$ $\qquad g_{aN}^S \sim \frac{f_\pi}{f_a} \theta_{\text{eff}}$ ← from UV sources of CP-violation or PQ breaking

[Di Luzio, Gisbert, Nesti, Sørensen, Phys. Rev. D 110 (2024)]



CP-violating axions

- $\mathscr{L} \supset g_s^N a \bar{N} N + g_p^e a \bar{e} i \gamma_5 e$

$$g_{aN}^S \sim \frac{f_\pi}{f_a} \theta_{\text{eff}}$$

from UV sources of CP-violation or PQ breaking

[Di Luzio, Gisbert, Nesti, Sørensen, Phys. Rev. D 110 (2024)]