A strange contribution to the neutron EDM

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Motivation

EDMs provide among the most stringent constraints on new physics

Neutron
Electric Dipole Moment

Electron
Electric Dipole Moment

$$\frac{\langle n|\Delta H|n\rangle}{\langle n|n\rangle} = -d_n E_{\rm el}$$

Within the SM:

$$|\sin\bar{\theta}| \lesssim 10^{-10}$$

$10^{-32}\, e$ cm !!

$$d_n = ce\frac{m_u}{m_n^2}\sin\bar{\theta} + c'e\frac{G_F^2 f_\pi^4}{m_n} J < 10^{-26}\, e\,\text{cm}$$

Abel et al. (2020)

Bounds will improve by 10-100 (proton up to 1000)!!!

Strong sensitivity to new physics

Virtually all BSM scenarios predict more CP-violation

$$\mathcal{L} \supset c_W \frac{g_s^3}{g_*^2 m_*^2} G G \widetilde{G} + c_{ijkl} \frac{g_*^2}{m_*^2} \overline{q_i} \Gamma q_k \, \overline{q_i} \Gamma q_l + c_{ij} \frac{g_*}{m_*^2} \overline{q_i} H \sigma^{\mu\nu} q_j \, g_V V_{\mu\nu}$$

Usually less relevant
(after flavor constraints)

My focus

EFT for the light flavors ($i,j = u,d,s$) at $\Lambda_{\mathbf{UV}} < m_c$

Real

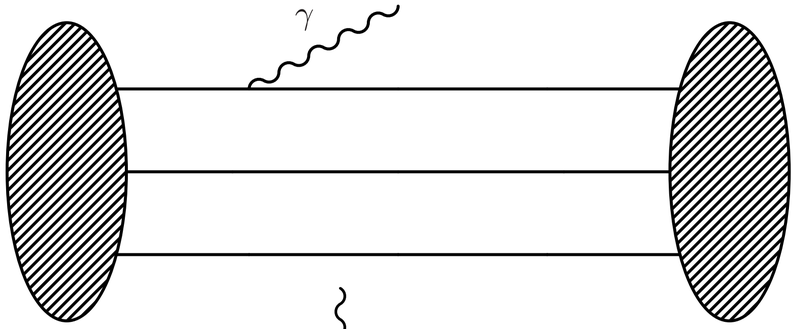
$$\mathcal{L}_{\Lambda_{\rm UV}} = -\frac{1}{4} G^A_{\mu\nu} G^{A\,\mu\nu} + \overline{q_i} i\gamma^\mu D_\mu q_i - (\overline{q_i} m_{ij} P_R q_j + \text{hc})$$

$$+ \frac{d_{ij}}{2} \overline{q_i} i\sigma^{\mu\nu} \gamma_5 q_j \, F_{\mu\nu}$$

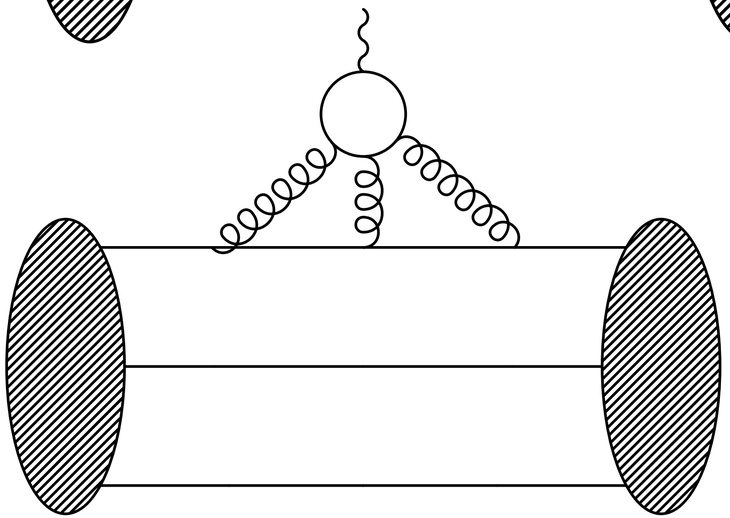
$$d_n = g^u_{Tn} d_u + g^d_{Tn} d_d + g^s_{Tn} d_s$$

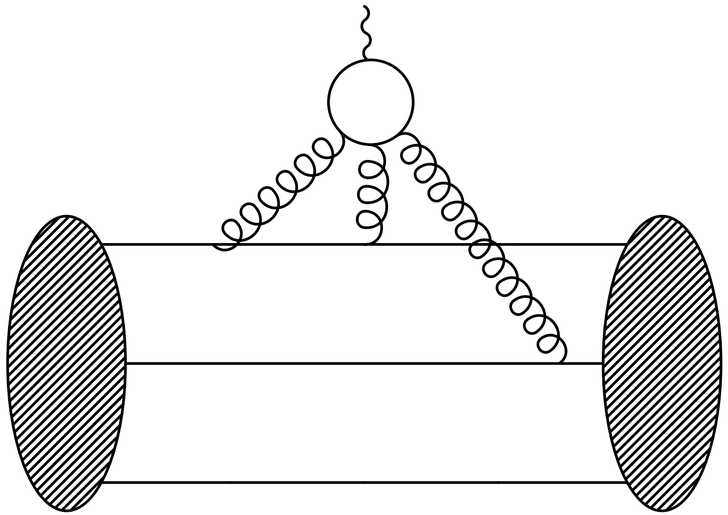
Single insertion of quark EDM, all orders in QCD

Valence quark



Sea quark





NDA: $\dfrac{g^s_{Tn}}{g^{u,d}_{Tn}} \sim 1 \quad \text{if} \quad \dfrac{g_s^2}{16\pi^2} \sim 1$ (At large N one has 1/N)

However…

$$d_n^{\rm PQ}(d_q,\tilde{d}_q) = (1\pm 0.5)\frac{|\langle\bar{q}q\rangle|}{(225{\rm MeV})^3}\left[1.1e(\tilde{d}_d+0.5\tilde{d}_u)+1.4(d_d-0.25\tilde{d}_u)\right]$$

Pospelov-Ritz (2005)

$$d_n(d_q) = g_T^d d_d + g_T^u d_u.$$

Pospelov-Ritz (2025)

Strange quark?

	Final results		
q	g_A^q	g_T^q	g_S^q
u	0.781(25)	0.782(28)	9.39(88)
d	−0.440(39)	−0.195(10)	8.84(93)
s	−0.055(9)	−0.0016(12)	0.37(14)

Bhattacharya et al (2025)

g_T	u	d	s	c
B64	0.739(23)	-0.207(11)	-0.00259(64)	-0.0012(17)
C80	0.741(14)	-0.1976(73)	-0.0004(12)	-0.0014(21)
D96	0.756(16)	-0.1989(72)	-0.00149(62)	-0.0027(16)
$a=0$	0.756(29)	-0.196(12)	-0.0009(11)	-0.0028(26)

Alexandrou et al (2025)

$$\begin{aligned} d_n = &-(1.5\pm 0.7)\cdot 10^{-3}\ \bar{\theta}\, e\,{\rm fm} \\ &-(0.20\pm 0.01)d_u\ +\ (0.78\pm 0.03)d_d\ +\ (0.0027\pm 0.016)d_s \\ &-(0.55\pm 0.28)e\tilde{d}_u\ -\ (1.1\pm 0.55)e\tilde{d}_d\ +\ (50\pm 40)\,{\rm MeV}\, e\,\tilde{d}_G \end{aligned}$$

Alarcon et al (2022)

$$d_n = g_{Tn}^u d_u + g_{Tn}^d d_d + g_{Tn}^s d_s$$

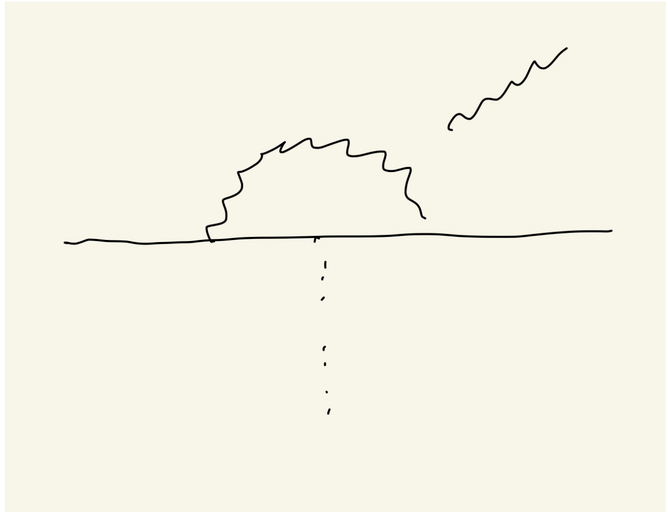
Current status

- Theory models (non-relativistic quark model, QCD sum-rules)
  $g_{Tn}^d = -4 g_{Tn}^u,\ g_{Tn}^s = 0$
- Lattice
  $g_{Tn}^d = -3.8 g_{Tn}^u,\ g_{Tn}^s = \mathcal{O}(10^{-3})$ (numerical noise)

In both:
$g_{Tn}^d / g_{Tn}^u \approx -4$
& $g_{Tn}^s \approx 0.$

Does NDA fail?!

In typical scenarios beyond the Standard Model



$$d_{ij} \sim \frac{g_*^2}{16\pi^2} \frac{y_{ij} v}{m_*^2} e$$

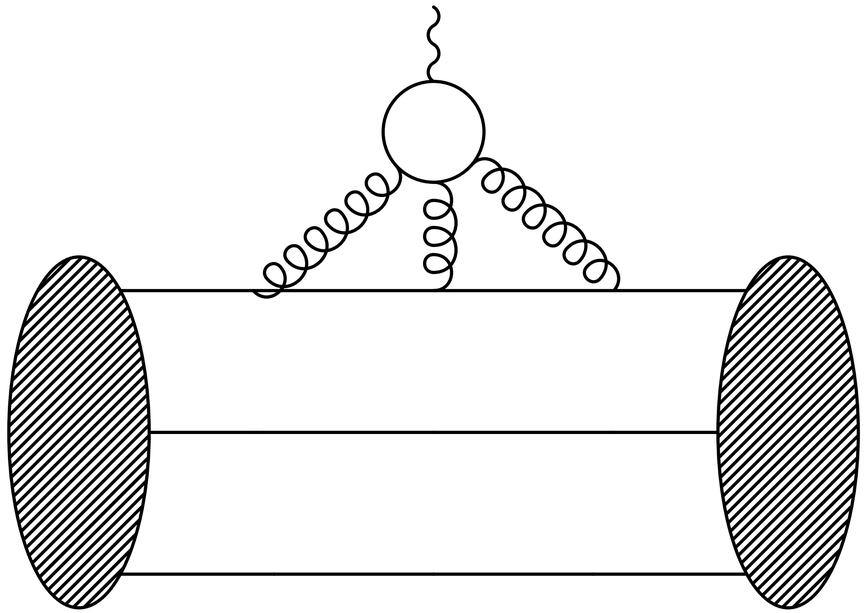
m_{ij}

$$|d_n| \leq 1.8 \times 10^{-26}\ e\,\mathrm{cm} \begin{cases} m_* \gtrsim 4 g_* \sqrt{g^u_{Tn}}\ \mathrm{TeV} \\ m_* \gtrsim 5 g_* \sqrt{g^d_{Tn}}\ \mathrm{TeV} \\ m_* \gtrsim 24 g_* \sqrt{g^s_{Tn}}\ \mathrm{TeV} \end{cases} \leftarrow \frac{m_s}{m_u} \sim 40$$

Strange dominates if $g^s_{Tn}/g^{u,d}_{Tn} \gtrsim 0.05$!!!

What is going on?!

In QCD, all diagrams involving d_s are strongly IR-sensitive.



Example: the loop requires a chirality-flip…

$$d_n \propto \mathrm{Tr}[dm^\dagger] \times \frac{1}{\Lambda_{\mathrm{IR}}}$$

Two types of contributions of d_s

$$\propto \mathrm{Tr}[dm^\dagger]$$

Visible within perturbation theory with IR cutoff

$$\propto \mathrm{Tr}[dU^\dagger]$$

Genuine non-perturbative: chiral condensate

Not included in matching lattice to continuum (only multiplicative renormalization)

A Wilsonian view

$\Lambda_{\rm UV}$

$$\mathcal{L}_{\Lambda_{\rm UV}} \supset \frac{d_{ij}}{2}\overline{q_i} i\sigma^{\mu\nu}\gamma_5 q_j\, F_{\mu\nu}$$

Hadronic scale
$\Lambda < \Lambda_{\rm UV}$

$$\mathcal{L}_{\Lambda} \supset \frac{d_{ij}}{2}\overline{q_i} i\sigma^{\mu\nu}\gamma_5 q_j\, F_{\mu\nu}$$

$$+\frac{g^4}{\Lambda^6}\left(\frac{g^2}{16\pi^2}\right)^n [d_{mn}\overline{q}_m P_R q_n][\overline{q}_j P_L q_i][\overline{q}_i i\sigma^{\mu\nu} P_R q_j]\, F_{\mu\nu} + \text{hc}$$

$$+\cdots$$

$$\propto \text{Tr}[dU^\dagger]\text{Tr}[\overline{q}_L i\sigma^{\mu\nu} U q_R]$$

SU(3)-universal EDM proportional to d_s

$$d_n \sim d_s \frac{g_s^4}{\Lambda^6}\left(\frac{g_s^2}{16\pi^2}\right)^n \langle\overline{q}q\rangle^2 \underset{\Lambda \to \Lambda_{\rm QCD}}{\to} \mathcal{O}(1) d_s$$

NDA (need to check)

More quantitative approach: the Non-Relativistic Quark Model

Non-relativistic Quark Model

Quarks are non-relativistic ⇔ Constituent quarks!

$$|n;\mathrm{NR}\rangle = \frac{1}{3\sqrt{2}}\left[|ddu\rangle\left(2|++-\rangle - |+-+\rangle - |-++\rangle\right)\right] + \mathrm{sym}$$

$$d_n|_{\mathrm{NRQM}} = \langle n;\mathrm{NR}|d_\psi \otimes \sigma_3|n;\mathrm{NR}\rangle = -\frac{1}{3}d_\psi^u + \frac{4}{3}d_\psi^d$$

Need a map between d_ψ (constituent) and d_{ij} (bare)…

The Chiral Quark Model

Georgi-Manohar (1984)

$$SU(3)_L \times SU(3)_R \to SU(3)_V$$

$$\Lambda_\chi \equiv 4\pi f_\pi \sim 1\text{GeV}$$

$$m_\psi \sim 300 \div 400 \text{ MeV}$$

Constituent quarks

$$\mathcal{L}_{\chi\text{QM}} = -\frac{1}{4} G^A_{\mu\nu} G^{A\,\mu\nu} + \overline{\psi} i\gamma^\mu \nabla_\mu \psi - m_\psi \overline{\psi}\psi$$

$$+ \frac{f_\pi^2}{4} \text{Tr}[\partial_\mu U \partial^\mu U^\dagger] + b\Lambda_\chi f_\pi^2 \text{Tr}[mU^\dagger + \text{hc}] + g_A \overline{\psi}\gamma^\mu\gamma_5 A_\mu \psi + \cdots$$

$$U = \xi\xi$$

$$A_\mu = \frac{i}{2}\left(\xi\partial_\mu\xi^\dagger - \xi^\dagger\partial_\mu\xi\right).$$

Dipoles for the Chiral Quarks, compatible with the full chiral symmetry

$$\mathcal{L}_{\chi\mathrm{QM}} \supset -\frac{i}{2}\,\overline{\psi}\hat{d}_\psi\sigma^{\mu\nu}\gamma_5\psi\,F_{\mu\nu}$$

$$[\hat{d}_\psi]_{ij} = c_1[\hat{d}]_{ij} + c_2\mathrm{Tr}[\hat{d}]\,\delta_{ij}$$

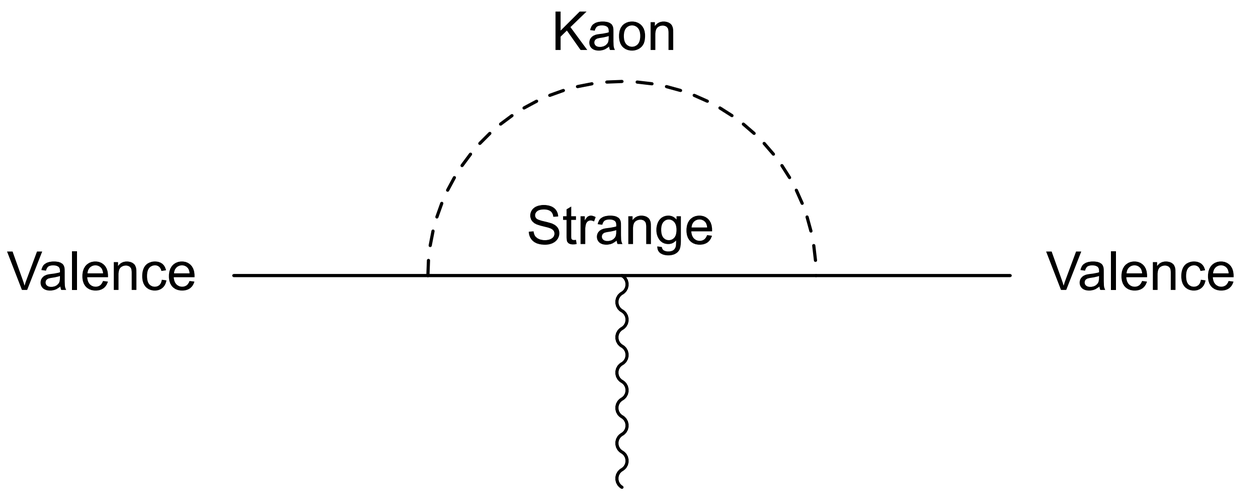
Obvious valence quark contribution

$$\propto \mathrm{Tr}[\overline{q}_L\sigma^{\mu\nu}d\,q_R]$$

Flavor-universal contribution proportional to the condensate

$$\propto \mathrm{Tr}[dU^\dagger]\mathrm{Tr}[\overline{q}_L i\sigma^{\mu\nu}U q_R]$$

$$\hat{d} = \frac{1}{2}\left(\xi^\dagger d\xi^\dagger + \xi d^\dagger\xi\right) = d - \Pi d\Pi - \frac{1}{2}\left(\Pi^2 d + d\Pi^2\right) + \cdots$$



$$\delta c_2|_{\rm LL} = c_1 \frac{g_A^2}{16\pi^2 f_\pi^2} \left[\frac{7}{12} m_{\psi_s}^2 \ln \frac{\mu^2}{m_{\psi_s}^2} + \frac{1}{2} M_K^2 \ln \frac{\mu^2}{M_K^2} \right] .$$

If there is a valence-quark contribution, there must be a strange contribution

$$\frac{|g_{Tn}^s|}{|g_{Tn}^{u,d}|} \sim 0.1 \div 0.3$$

Chiral perturbation theory

Two types of contributions

$$\propto \mathrm{Tr}[dU^\dagger]$$

Leading-order counterterm

$$\propto \mathrm{Tr}[dm^\dagger]$$

NLO counterterm

$$\propto \mathrm{Tr}[dm^\dagger]\ \ln(m^\dagger m)$$

Calculable

$$\mathcal{L}_{\rm EFT} = \frac{f_\pi^2}{4}\mathrm{Tr}\left[\partial_\mu U \partial^\mu U^\dagger\right] - B\mathrm{Tr}\left[mU^\dagger + m^\dagger U\right]$$
$$+\mathrm{Tr}\left[\overline{\Psi} v^\mu i\nabla_\mu \Psi\right] + (D+F)\mathrm{Tr}\left[\overline{\Psi}\gamma^\mu\gamma_5 A_\mu \Psi\right] + (D-F)\mathrm{Tr}\left[\overline{\Psi}\gamma^\mu\gamma_5 \Psi A_\mu\right]$$
$$+\cdots$$
$$-\frac{i}{2}\left\{\kappa_1\mathrm{Tr}[\hat{d}\overline{\Psi}\sigma^{\mu\nu}\gamma_5\Psi] + \kappa_2\mathrm{Tr}[\overline{\Psi}\sigma^{\mu\nu}\gamma_5\hat{d}\Psi] + \kappa_3\mathrm{Tr}[\hat{d}]\mathrm{Tr}[\overline{\Psi}\sigma^{\mu\nu}\gamma_5\Psi]\right\}F_{\mu\nu}$$

Jenkins-Manohar (1991)

$D \sim 0.8, \quad F \sim 0.5$

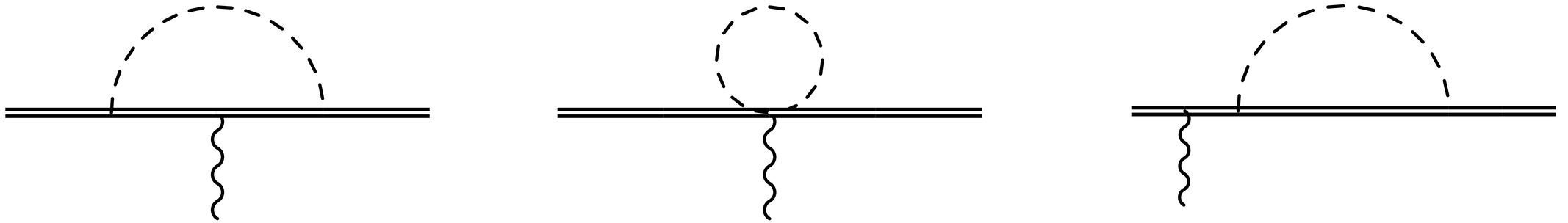
Electric Dipoles

Neutron EDM at LO:

$$d_n^{\rm LO} = \kappa_1 d_s + \kappa_2 d_d + \kappa_3(d_u + d_d + d_s)$$

$$\begin{cases} g^u_{Tn,\rm LO} = \kappa_3 \\ g^d_{Tn,\rm LO} = \kappa_2 + \kappa_3 \\ g^s_{Tn,\rm LO} = \kappa_1 + \kappa_3 \end{cases}$$

At first non-trivial order



$$d^{\rm NLO}_{a'b'} = d^{\rm LO}_{a'b'} + A^{\Pi}_{a'b'} \frac{M^2_{\Pi}}{16\pi^2 f^2_{\pi}} \ln \frac{M^2_n}{M^2_{\Pi}} + B^{\Pi}_{a'b'} \frac{M^2_{\Pi}}{16\pi^2 f^2_{\pi}}$$

A is calculable in terms of D,F, but …

— The analytic terms B must be matched to data (not known)

— Diagrams in B also depend on the dipoles of the excited states (not known)

— The strange mass is not small: the non-analytic part is of the same order as the B-term.

$$\frac{M^2_K}{\Lambda^2_\chi} = 0.2$$

$$g^s_{Tn,\mathrm{NLO}} = 0.14\, g^u_{Tn,\mathrm{LO}} + 0.048\, g^d_{Tn,\mathrm{LO}} + 1.7\, g^s_{Tn,\mathrm{LO}} + 0.18\, B^K_{nn,s}$$

Compatible with the non-analytic terms of the Chiral Quark Model

Barring accidental cancellations we should expect

$$g^s_{Tn} \gtrsim \mathcal{O}\left(\frac{M_K^2}{16\pi^2 f_\pi^2}\right)$$

If a much smaller value is measured, then a M_K-dependent cancellation must take place.

The lattice results do not reveal any such dependence…

Conclusions

- ☑ The neutron EDM provides very stringent constraints on new physics.
- ☑ NRQM + Large N QCD + Chiral PT paint a consistent picture:
  - NDA works and g_{Tn}^{s} is unsuppressed of order 0.1-0.3
  - A contribution $g_{Tn}^{s} \lesssim 0.1$ would be evidence of a M_K-dependent cancellation
- ☑ **BEWARE: the strange EDM dominates in many new physics scenarios.**