Connecting paramagnetic EDM observables to the EDMs of nucleons

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Collaborators: Jordy de Vries, **Heleen Mulder**, Wouter Dekens, Javier Menéndez, Beatriz Romeo

Nucleon Electric Dipole Moments in Paramagnetic Molecules through Effective Field Theory

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EDMs 2026 : Complementary Experiments and Theory Connections

06-03-26

Outline

- Quiz (Motivation)
- Particle Theory side
  (Wouter Dekens, Jordy de Vries, Lemonia Gialidi, Heleen Mulder)
- Nuclear Theory Side
  (Javier Menéndez, Beatriz Romeo)
- Results
- Outlook

Match the following:

1 Paramagnetic systems

non-zero total electron spin

2 Diamagnetic systems

zero total electron spin
non-zero nucleon/nuclear spin

Electron EDM — d_e

Semi-leptonic e-N operator — C_{SP}

Hadronic CP Violation — d_p, d_n, $\bar{g}_{0,1}$

QCD θ

higher-dimensional operators

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QCD θ

higher-dimensional operators

non-zero EDM measurement

SM CP Violation

CKM-phase

QCD θ term

Y. Ema et al. (2022)

BSM sources of CP Violation

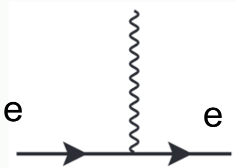
Paramagnetic systems

What do they measure?

[See Anastasia's talk]

Atomic/Molecular structure coefficients

$$d_e \times \frac{-i}{2}\,\overline{\psi}\sigma_{\mu\nu}\gamma_5 F_{\mu\nu}\psi$$



Electron EDM
purely leptonic operator

$$\text{Paramagnetic EDM} = W_{SP}\,\boldsymbol{C_{SP}} + W_d\,\boldsymbol{d_e}$$

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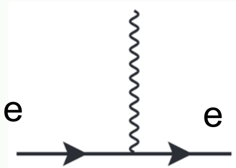

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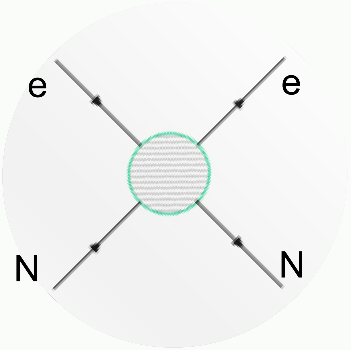


Semi-leptonic operator
Effective electron-Nucleon interactions

$$\mathcal{L} = \frac{G_F}{\sqrt{2}}\bar{e}i\gamma_5 e\,\bar{N}\left(C^0_{\mathrm{SP}} + C^1_{\mathrm{SP}}\tau^3\right)N\,.$$

Effective e-N interactions

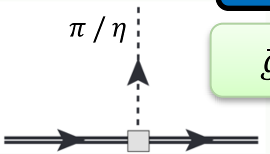
[See Heleen's talk]

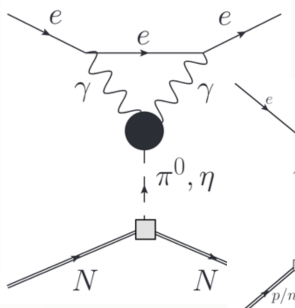
H. Mulder, R. Timmermans, and J. de Vries (2025).
Flambaum, Pospelov, Ritz, Stadnik, '19

How are they induced by hadronic CPV?

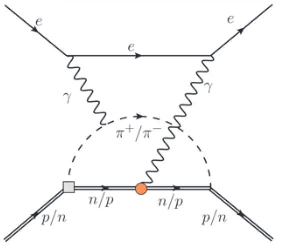
QCD θ

$\bar{g}_{\pi/\eta}$





Meson Exchange



Pion Loops

$$\mathcal{L}_\chi = \bar{g}_0 \bar{N}\tau^a N \pi^a + \bar{g}_1 \bar{N} N \pi^0 + \bar{g}_{0\eta} \bar{N} N \eta$$
$$+ 2\bar{N}(d_0 + d_1 \tau^3) v^\mu S^\nu N F_{\mu\nu} \,,$$

Effective e-N interactions

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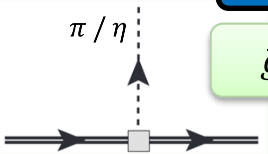
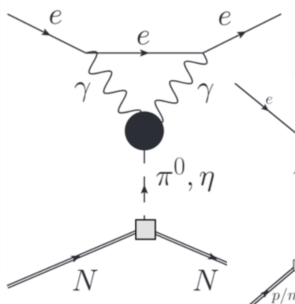


$\bar{g}_{\pi/\eta}$



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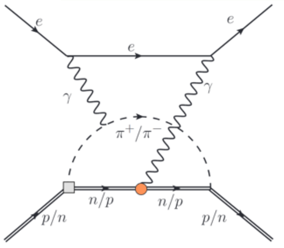

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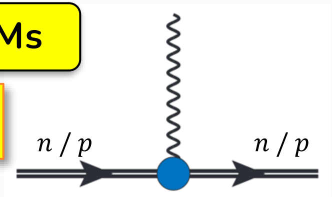
$$\mathcal{L}_\chi = \bar{g}_0 \bar{N}\tau^a N\pi^a + \bar{g}_1 \bar{N}N\pi^0 + \bar{g}_{0\eta}\bar{N}N\eta$$
$$\boxed{+2\bar{N}(d_0 + d_1\tau^3)v^\mu S^\nu N F_{\mu\nu}\,,}$$

Nucleon EDMs

d_n / d_p



C_{SP} induced by nucleon EDMs

We need both the **nucleon EDM** and the **nucleon MDM** here!!

Potential

Photon Momenta

$q_\gamma^\mu = (q_\gamma^0, \overrightarrow{q_\gamma})$

Ultrasoft

C_{SP} induced by nucleon EDMs

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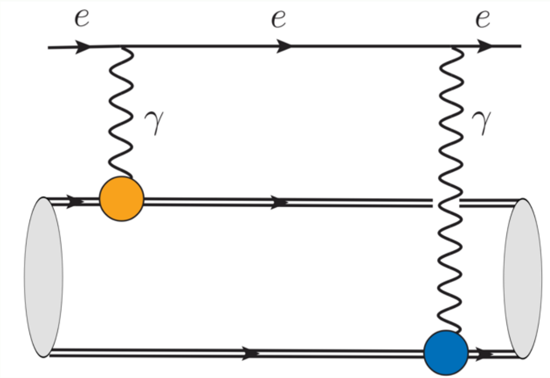
Potential



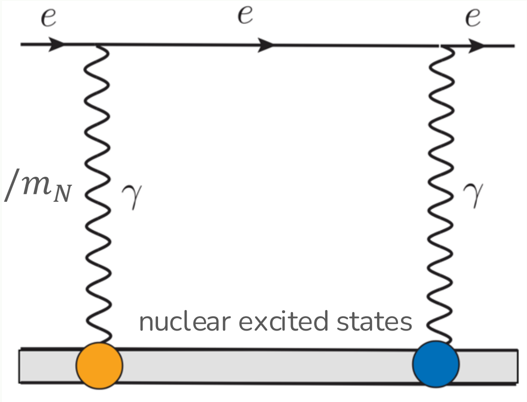
Photon Momenta

$$q_\gamma^\mu = (q_\gamma^0, \overrightarrow{q_\gamma})$$

$$q_\gamma^0 \sim \overrightarrow{q_\gamma}^2/m_N$$
$$|\overrightarrow{q_\gamma}| \sim m_\pi$$

$$q_\gamma^0 \sim |\overrightarrow{q_\gamma}| \sim {m_\pi}^2/m_N$$

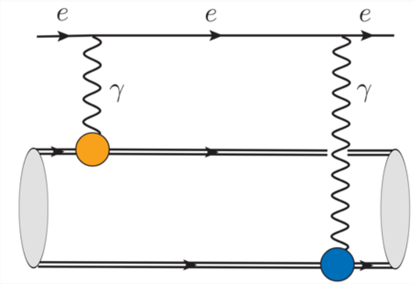
Ultrasoft



Flambaum, Pospelov, Ritz, Stadnik, ‘19
Dekens, JdV, Gialidi, Menendez, Mulder, Romeo ‘25

Potential Region

Sensitive to nuclear scales



expand in small scales like $q_\gamma^0/|\overrightarrow{q_\gamma}|$ → Two-nucleon effects

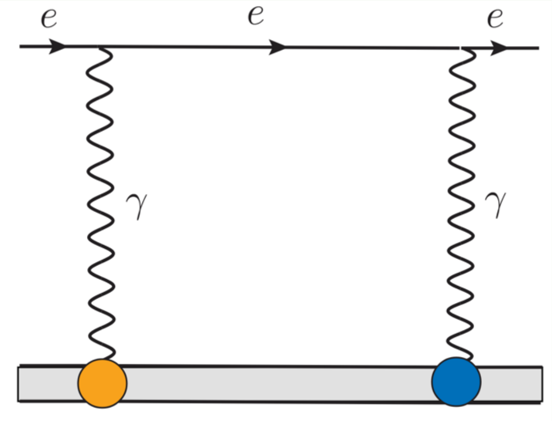
$$\mathcal{A}_{\text{pot}} = -\boxed{\langle h_f|V|h_i\rangle}\,\bar{u}(p_e')\left(1 - \frac{v\cdot(p_e'-p_e)}{2m_e}\not{v}\right) i\gamma_5 u(p_e)$$

Nuclear Matrix Element (NME) of the two-body potential V

Ultrasoft

What changes here?

$q_\gamma^0 \sim |\vec{q_\gamma}| \sim {m_\pi}^2/m_N$



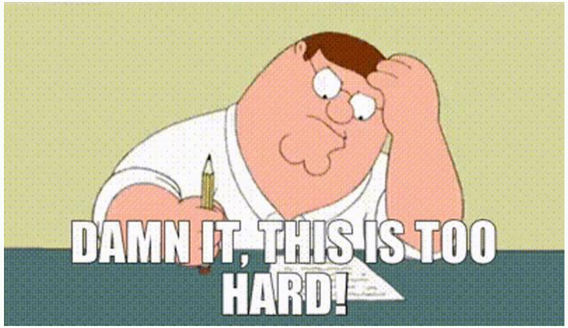
E_n: nuclear excited states

A lot of scales enter this diagram:

$m_e, p_e\ , m_\gamma\ , E_n$

⇓

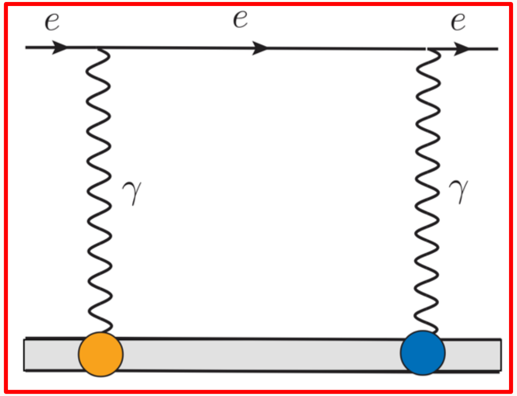
Scary Integrals

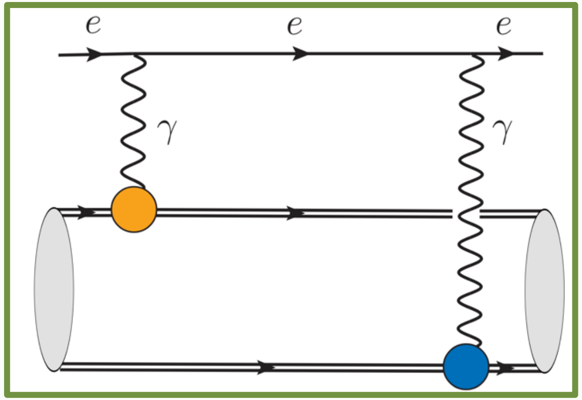


BUT!!! EFT saves us

$\boxed{E_n \gg m_e}$

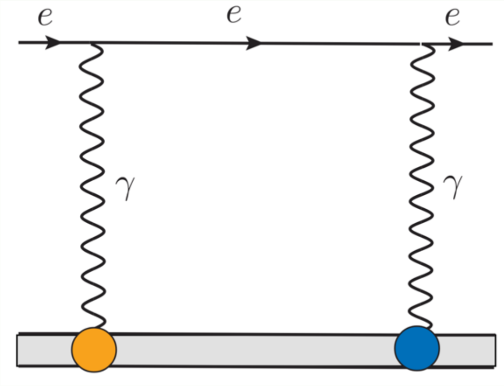
So far so good!

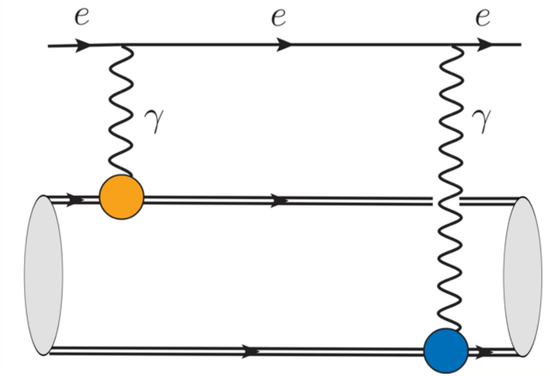




$$\bar{C}_{\mathrm{SP}}^{\mathrm{eff}} = -\frac{\sqrt{2}}{G_F}\left[\boxed{\frac{4\alpha^2 m_e}{m_N}\sum_n \frac{A_n}{\Delta_n}\left(3\ln\frac{m_e^2}{4\Delta_n^2}-1\right)} + \boxed{\langle h_i|V|h_i\rangle}\right]$$

So far so good!





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Paramagnetic EDM measurements

Nucleon EDMs

Compute NMEs

Ultrasoft

Nuclear side

$$\bar{C}_{SP}^{\text{usoft}} = -\frac{\sqrt{2}\alpha^2 m_e}{3 m_N G_F} \boxed{M_{SP}^{\text{usoft}}} \Rightarrow \sum_n \frac{\langle h_f | D^{(i)} \vec{\sigma} | n \rangle \cdot \langle n | \mu^{(i)} \vec{\sigma} | h_i \rangle}{\Delta_n} \left(1 + 3 \ln \frac{4\Delta_n^2}{m_e^2} \right)$$

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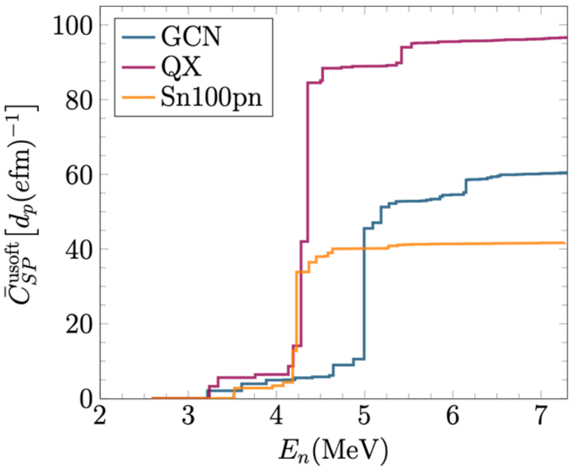
Excitation energies

$\Delta_n = E_n - E_i$

Transition elements

$\boldsymbol{E_n \gg m_e}$ ✔



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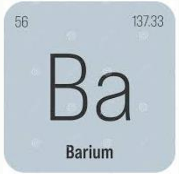
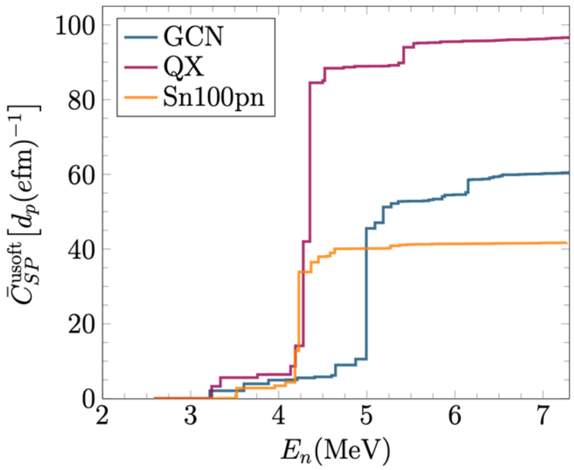
magic neutron number





$$\boxed{\bar{C}_{SP}^{\mathrm{usoft}} = (67 \pm 28)\ d_p\,(e\,\mathrm{fm})^{-1}}$$

~40% nuclear uncertainty!!

only d_p contributes!

Potential

Nuclear side

Coordinate space potential

$$\bar{C}_{SP}^{\mathrm{pot}} = -\frac{\sqrt{2}}{G_F}\langle h_i|V|h_i\rangle$$

$$V(\vec{r}) = -\frac{e^4 m_e}{18\pi m_N}\sum_{i\neq j}\mu^{(i)}D^{(j)}\,|\vec{r}|\left[\underline{\sigma^{(i)}\cdot\sigma^{(j)}} + \frac{1}{16}S^{(ij)}(r)\right]$$

Potential

Nuclear side

DOMINANT CONTRIBUTION

Coordinate space potential

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56 137.33
Ba
Barium

$$\boxed{\bar{C}_{SP}^{\mathrm{pot}} = \left[(-433\pm 5)\,d_p + (387\pm 0.4)\,d_n\right]\,(e\,\mathrm{fm})^{-1}}$$

- Both core and valence nucleons contribute to the potential NME
- Coherent structure

- NME scales with A
- Potential NMEs > Ultrasoft NMEs
- Smaller uncertainties

*NMEs computed using modified Shell Model codes for 0vbb

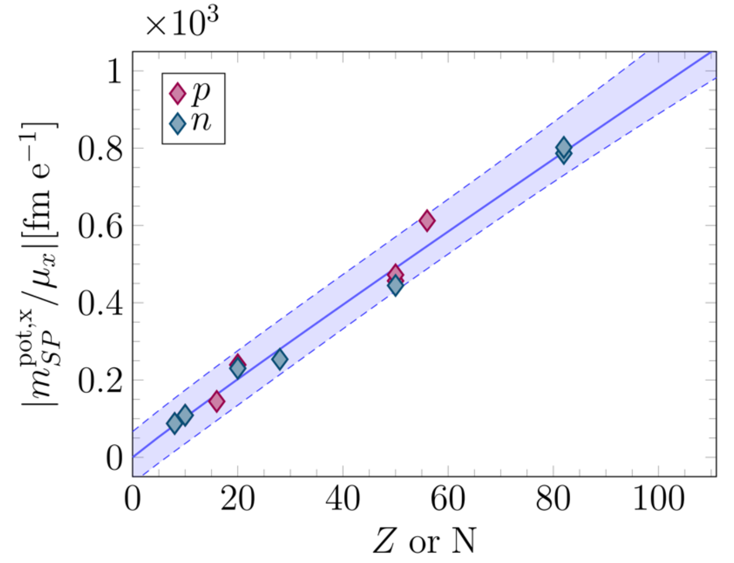
Can we go heavier?

$$M_{SP}^{\mathrm{pot}} = m_{SP}^{\mathrm{pot,p}}\, d_p + m_{SP}^{\mathrm{pot,n}}\, d_n \,.$$

Lighter nuclei confirm linear Z/N scaling

$$\boxed{m_{SP}^{\mathrm{pot,X}} = -9.74\, X\, \mu_X (\mathrm{fm}/e)}$$

$X = (Z, p)$ or (N, n)



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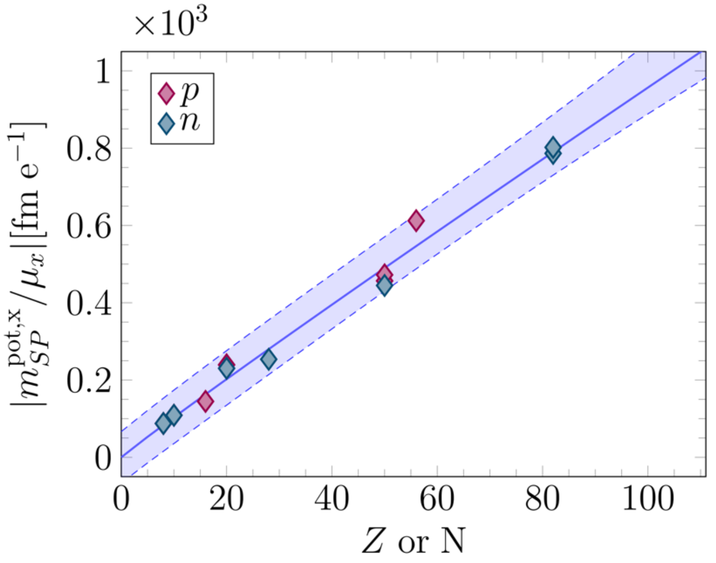


$$d_e^{\mathrm{equiv}} \equiv r_{\mathrm{mol}} \bar{C}_{\mathrm{SP}}/A$$

$$\boxed{d_e^{\mathrm{equiv}}} = \frac{\sqrt{2}e^4 m_e}{18\pi G_F m_N} \frac{r_{\mathrm{mol}}}{A} (-9.74) \left[Z\, \mu_p \boxed{d_p} + N\, \mu_n \boxed{d_n} \right] \frac{\mathrm{fm}}{e}$$

Experimental Limit → Limit on d_p or d_n

Our limits

1 Recall the best current limit from paramagnetic molecules

Roussy et al. 2023 $|d_e|_{\mathrm{HfF}^+} < 4.1 \cdot 10^{-30}\ e\ \mathrm{cm}$

2 Use scaling function

$$|d_p|_{\mathrm{HfF}^+} < 1.6 \cdot 10^{-23}\ e\ \mathrm{cm} \quad , \quad |d_n|_{\mathrm{HfF}^+} < 1.6 \cdot 10^{-23}\ e\ \mathrm{cm}$$

x100 weaker than

$|d_p|_{\mathrm{Hg}} < 2.0 \times 10^{-25}\ e$ cm

Graner et al. 2016

x1000 weaker than

$|d_n| < 1.8 \times 10^{-26}\ e$ cm

PSI 2020

Our limits

1 Recall the best current l

$|d_e|_{\mathrm{HfF}^+}$

$|d_p|_{\mathrm{HfF}^+} <$

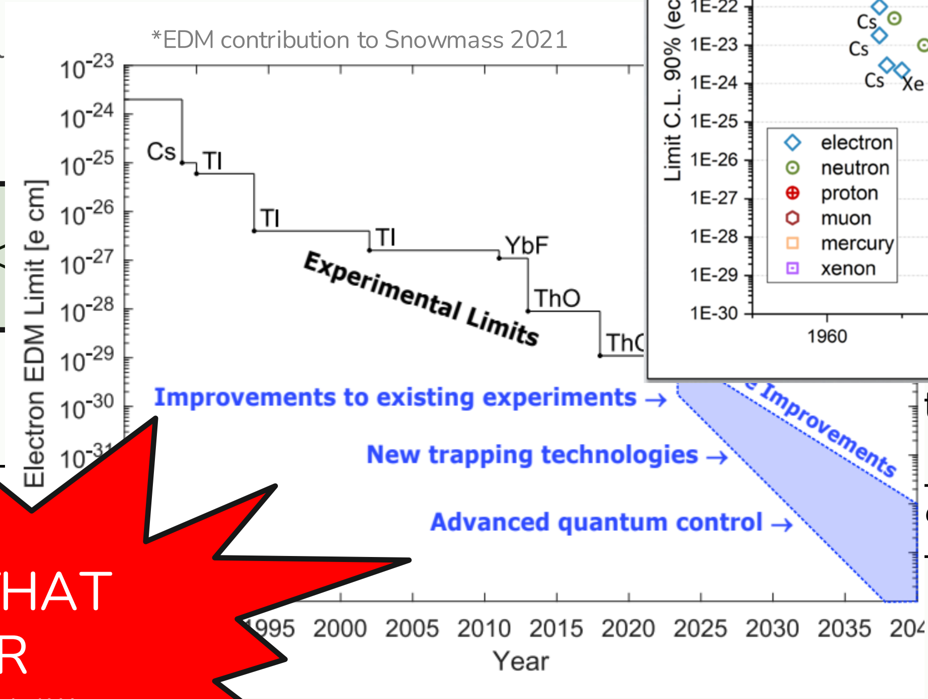
x100

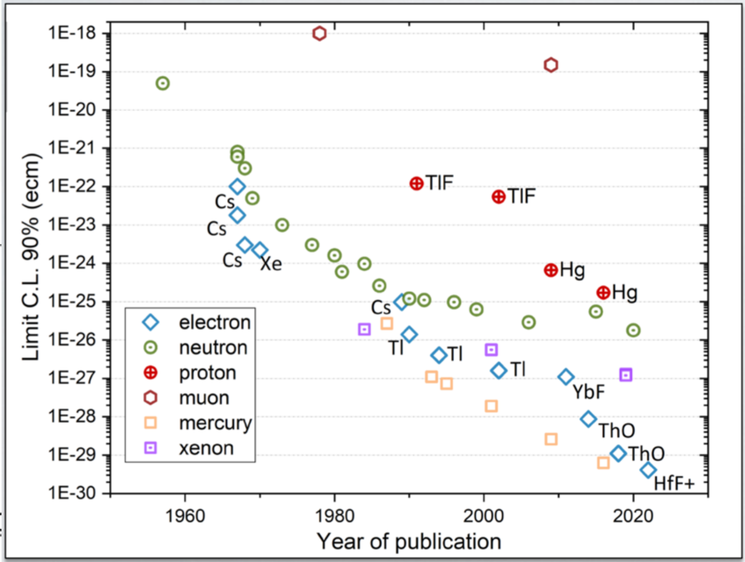
than

Bennett et al. 2009

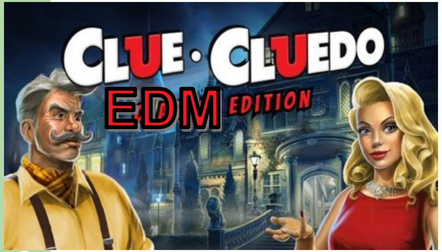
$|d_p|_{\mathrm{H}}$

$^6\ e$





NOT THAT FAR AWAY!!!



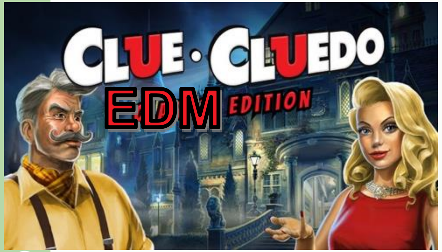
Which source did it?

PART 3

Quark EDM

Quark chromo EDM

QCD θ



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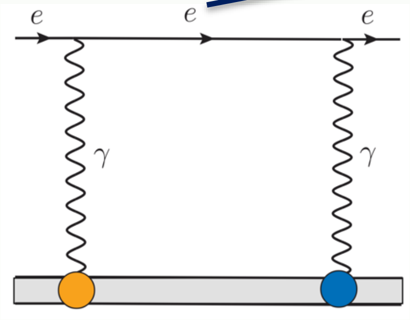
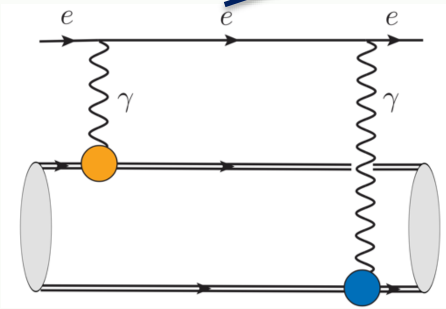
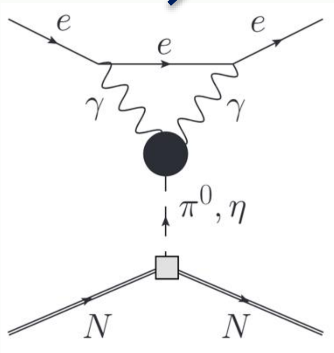
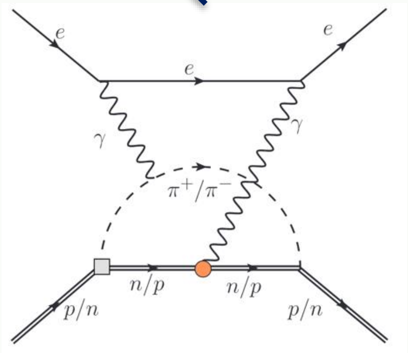
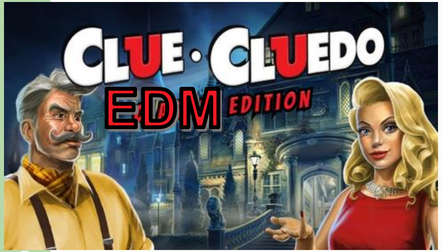








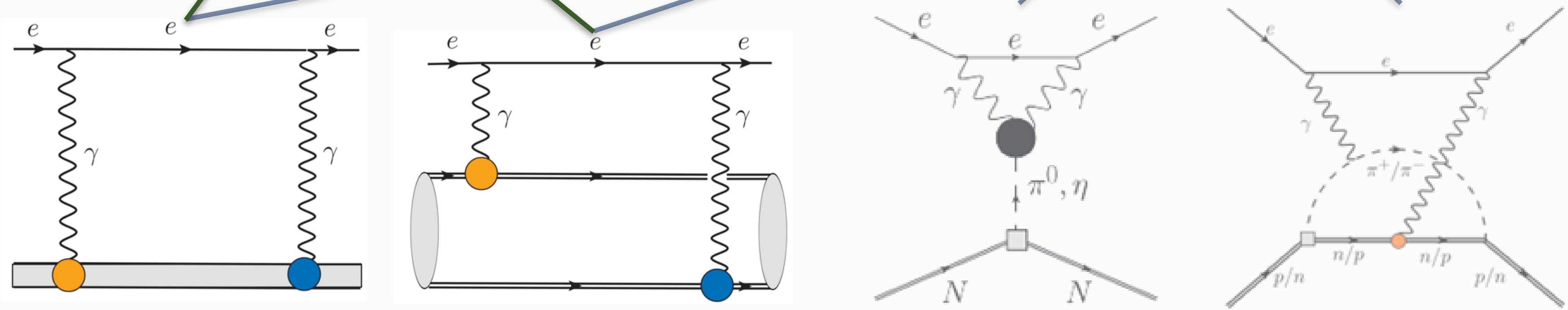


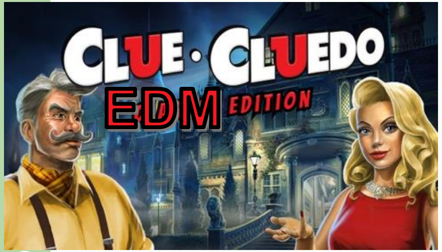
Which source did it?

Quark chromo EDM

QCD θ

Quark EDM





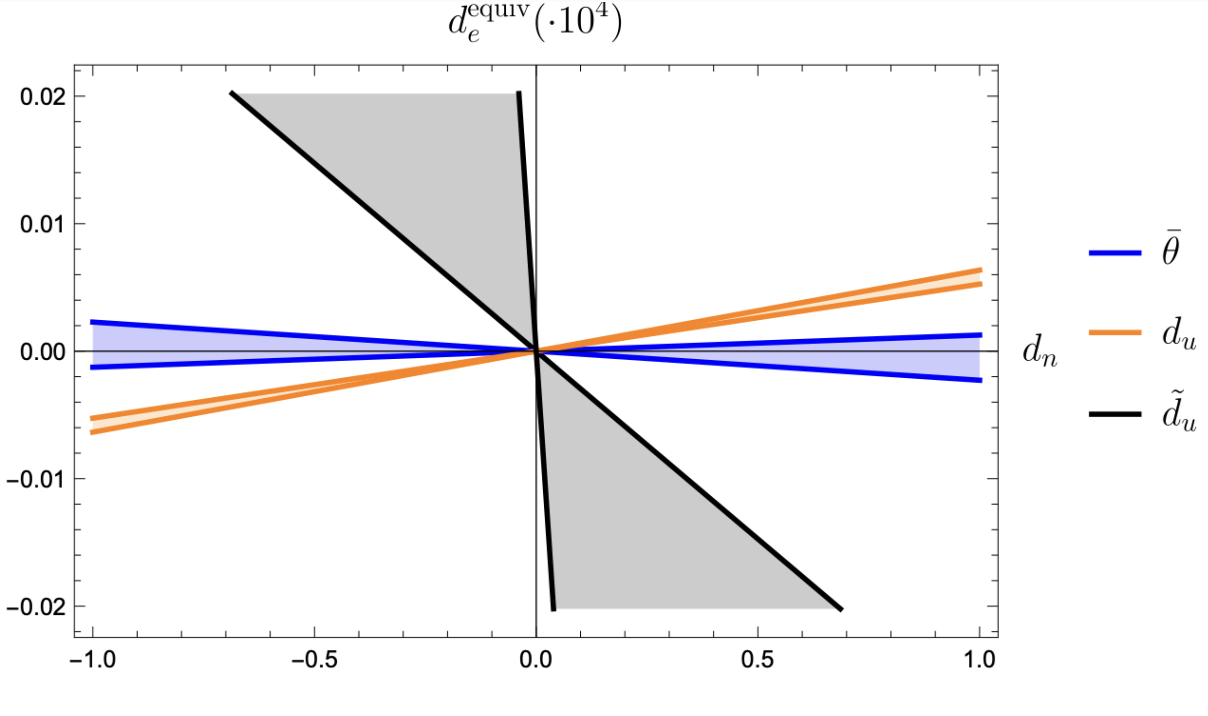
Which source did it?

Suppose QCD θ or quark (color) operators as the underlying CPV source:

$$d_n = \#_1\,\bar{\theta} \text{ and } d_e^{\text{equiv}} = \#_2\,\bar{\theta}$$

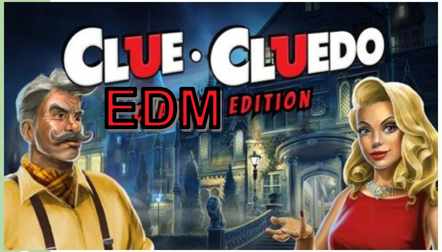
$$d_n = \#_3\,d_q \text{ and } d_e^{\text{equiv}} = \#_4\,d_q$$

$$d_e^{\text{equiv}}/d_n$$



Ratio Plot

Helps to solve the mystery



Which source did it?

Example:

Say we measure

$$d_n = 10^{-27}\text{e cm}$$

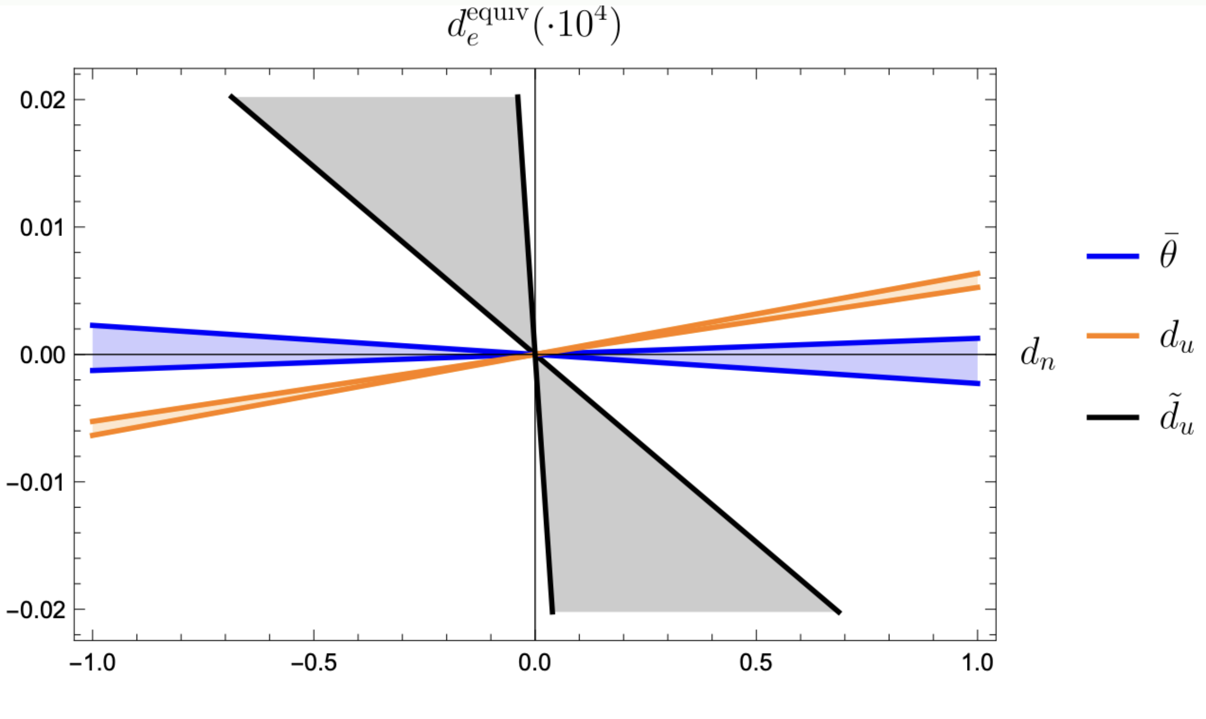
Then we expect:

for up color EDM

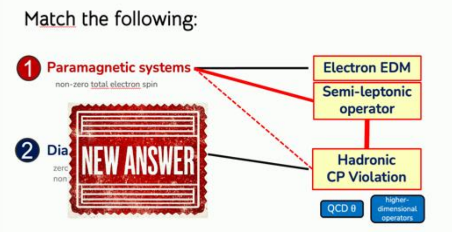
$$\boldsymbol{d_e^{equiv} \sim -\left(10^{-32} - 10^{-33}\right)\ \text{e cm}}$$

$$\boldsymbol{d_e^{equiv} \sim +10^{-34}}\ \textbf{e cm for up EDM}$$

$\boldsymbol{d_e^{equiv}}$ **even smaller for $\boldsymbol{\bar{\theta}}$**



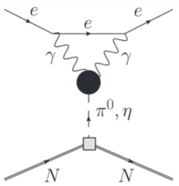
Summary

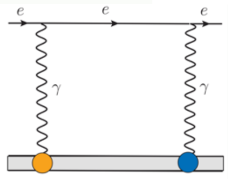


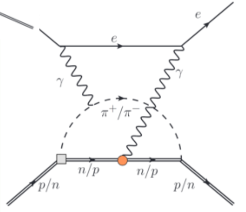
- ❖ Connect paramagnetic EDM measurements to nucleon EDMs and hadronic CPV.

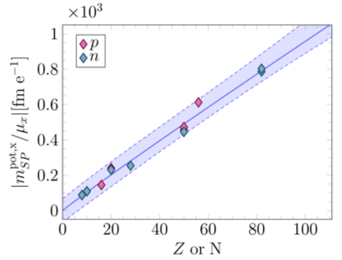
  - ❖ Meson exchange and pion loop diagrams.

  - ❖ Potential and ultrasoft diagrams.



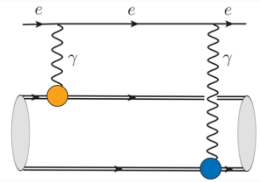




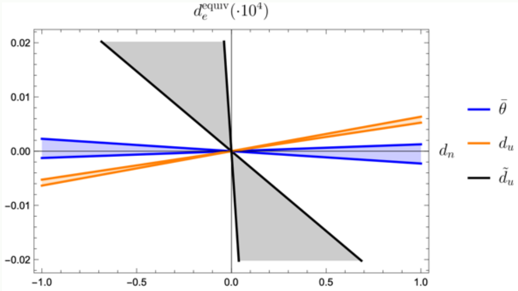


- ❖ Nuclear model calculations and use of EFT.

- ❖ Potential dominates: linear scaling



- ❖ If there is a measurement, help to solve the CPV source mystery.



- ❖ What next? …

Questions?

Thanks for listening!

The magic of matching

Full Theory above ω

$\mathrm{I}_F(\omega)$

IR scale ω

EFT just below ω

$\mathrm{I}_{EFT}(\omega)$

Same IR behaviour

$$C(\mu \sim \omega) = \mathrm{I}_F(\omega) - \mathrm{I}_{EFT}(\omega) \longrightarrow \text{IR SAFE}$$

RGE

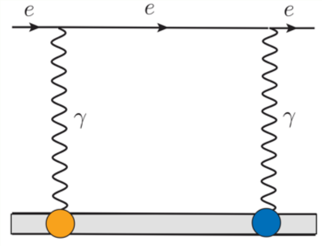
Low energy EFT at m << ω

Contributions from the Low energy EFT at m + $C(\mu \sim m)$ = FINAL ANSWER

*Introduction to EFT , Manohar 2018

Ultrasoft Region

Energy scales



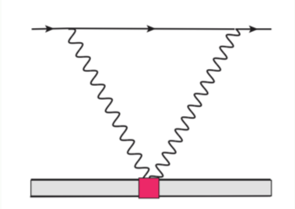
E_n

Integrate out nuclear excited states

Matching:

$$\bar{C}_{SP}(\mu \sim E_n) = \text{Box} - \text{Matching Triangle } \beta_v$$

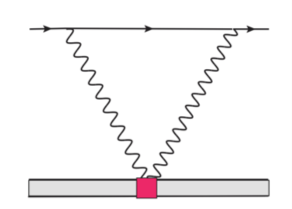
$E_n \gg m_e$



β_v:Nuclear Polarizability

Run down to $\mu \sim m_e$

m_e

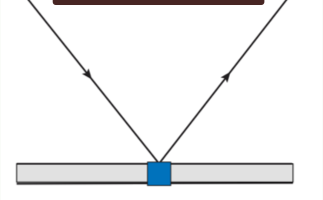


“physical low-energy triangle”

(keep low-energy scales me,pe)

+

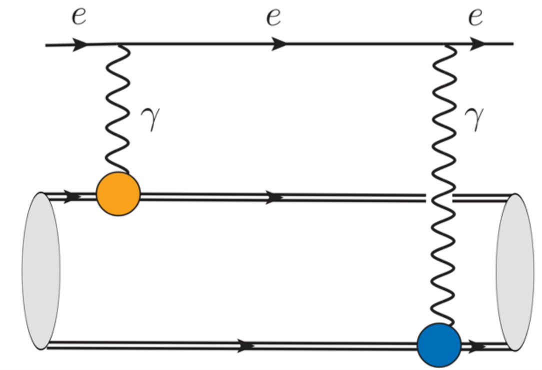
$\bar{C}_{SP}(\mu \sim m_e)$



=

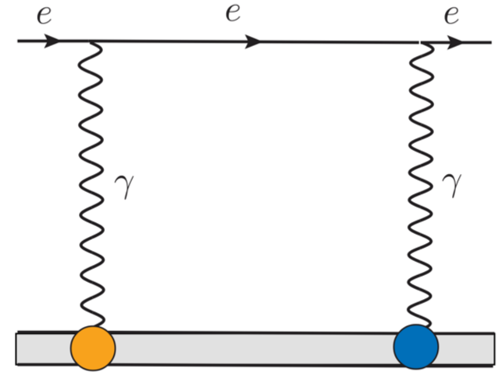
$\mathcal{A}_{usoft}$

Power counting



$$G_F\, C_{\text{SP}}(\text{pot}) \sim \frac{\alpha^2 \mu_i}{m_N \mu_N}\,\frac{d_i}{e}\,\frac{m_e}{q}\,\frac{4\pi q}{Q}$$

$$\sim \frac{\alpha^2 \mu_i}{m_N \mu_N}\,\frac{d_i}{e}\,\frac{m_e}{q}$$



$$G_F\, C_{\text{SP}}(\text{usoft}) \sim \frac{\alpha^2 \mu_i}{m_N \mu_N}\,\frac{d_i}{e}\,\frac{m_e}{q}$$