University of Padova

Probing Axion Dark Matter with Electric Dipole Moments

Matteo Verzeletti – 17/07/2025

Theoretical preliminaries

1) Strong CP problem: Peccei-Quinn solution

Starting lagrangian: $\mathcal{L}_{QCD} + \vartheta \frac{g_s^2}{32\pi^2} G\tilde{G}$

Add the axion: a pseudo-NGB associated to the spontaneous breaking of a global $U(1)_{PQ}$ with pseudo-shift-symmetry

$$\mathcal{L}_a = \frac{1}{2}\left(\partial_\mu a\right)^2 + \mathcal{L}_{int}(\partial a, q) + \frac{g_s^2}{32\pi^2}\frac{a}{f_a} G\tilde{G}$$

$$\Downarrow \quad a \to a + \alpha f_a$$

Removed ϑ-term, left with an axion EFT

Theoretical preliminaries

After a chiral field redefinition: $q \to e^{i\frac{a}{2f_a}\gamma_5} q$

Removed $aG\tilde{G}$ due to chiral anomaly

$$\mathcal{L} \supset -m\, e^{i\frac{a}{f_a}} \overline{q}_L q_R + h.c.$$

2) U(1) toy model

$$\mathcal{L}_E \supset -m\, \bar{\psi}_{E,L}\psi_{E,R} e^{i\frac{g}{m}a} + h.c.$$

Similarly: $\psi_D = e^{ig\frac{a}{2m}\gamma_5}\psi_E$

$$\mathcal{L}_D \supset -m\, \bar{\psi}_D\psi_D + \frac{g}{2m}\partial_\mu a\ \bar{\psi}_D\gamma^\mu\gamma_5\psi_D + \frac{e^2}{16\pi^2}\frac{g}{2m}aF\tilde{F}$$

Theoretical preliminaries

3) Axion as DM candidate

From axion potential in χPT: $m_a \propto \frac{m_\pi f_\pi}{f_a} \approx \mathrm{meV}\left(\frac{10^9\mathrm{GeV}}{f_a}\right)$

Smallness of mass and couplings due to astrophysical bounds $f_a \gtrsim 10^9\mathrm{GeV}$

$$\Downarrow$$

Motivated DM candidate, thus Non-Relativistic:

$$a = a_0 \cos(m_a t) \qquad \rho_a = \frac{1}{2} a_0^2 m_a^2 \approx 0.3\,\frac{\mathrm{GeV}}{\mathrm{cm}^3}$$

Oscillating EDMs

Axion interactions would induce P and T violation, in particular:

$$H \supset -d\, \boldsymbol{S} \cdot \boldsymbol{E}$$

The semiclassical axion DM background would cause the EDM to oscillate in time

Neutron EDM case

$$d_n\big(a(t)\big) \approx 10^{-34} e \text{ cm} \cos(m_a t)$$

$\Rightarrow$

CASPEr-Electric Experiment

The SM contribution to EDM would constitute a baseline:

Oscillating Signal $\Leftrightarrow$ New Physics

Di Luzio, Gisbert, Sørensen, 2024 [2308.16135]

- Derivation of NR hamiltonian for the two basis.
- Proof of equivalence of state evolution.
- Effective electron EDM in time-dependent perturbation theory:

$$U(t,0) \supset 1 + i \boxed{\frac{g}{2m^2} \int^t dt' \, a \, \boldsymbol{\sigma} \cdot e\boldsymbol{E}} + i \frac{g}{2m^2} [a \, \boldsymbol{\sigma} \cdot (\boldsymbol{p} + e\boldsymbol{A})]^t + \mathcal{O}\left(\int dt'^2\right)$$

$$V_{EDM} = -d(a) \, \boldsymbol{\sigma} \cdot \boldsymbol{E} \quad \Leftarrow \quad \not{C}\not{P} \text{ test}$$

Key points:

- Shift-symmetry restored through the boundary term
- No static EDM

Need of Relativistic origin: Schiff's Theorem

Hypotheses:

- Non-relativistic limit
- Point-like nucleus

$\Rightarrow$

Vanishing total EDM due to internal shielding

$$H = H_0 + H_d = \sum_k \left[\left(-\frac{1}{2m} \nabla_k^2 + e_k U(r_k) \right) + \left(\boldsymbol{d}_k \cdot \frac{1}{e_k} \boldsymbol{\nabla}_k U(r)_{r=r_k} \right) \right]$$

$$= \sum_k \left[\left(-\frac{1}{2m} \nabla_k^2 + e_k U(r_k) \right) + \left(\frac{i}{e_k} \boldsymbol{d}_k \cdot [\boldsymbol{p}_k, H_0] \right) \right]$$

$$|\tilde{n}\rangle = |n\rangle + \sum_m \frac{\langle m|H_d|n\rangle}{E_n - E_m} |m\rangle$$

$$= \left(1 + i \sum_k \frac{1}{e_k} \boldsymbol{d}_k \cdot \boldsymbol{p}_k \right) |n\rangle$$

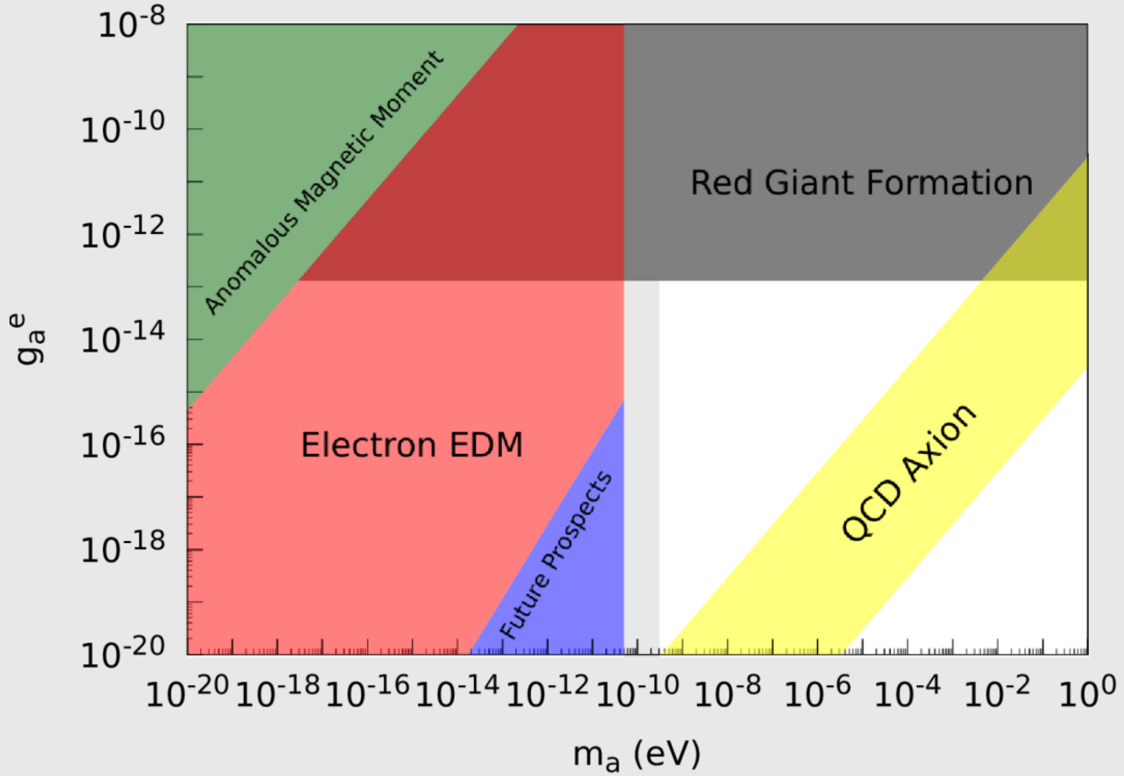
$$\boldsymbol{d}_e^{int} = \langle \tilde{n} | \textstyle\sum e_l \boldsymbol{r}_l | \tilde{n} \rangle = \underbrace{\langle n | \textstyle\sum e_l \boldsymbol{r}_l | n \rangle}_{=0} + i \langle n | [\textstyle\sum e_l \boldsymbol{r}_l, \textstyle\sum e_k^{-1} \boldsymbol{d}_k \cdot \boldsymbol{p}_k] | n \rangle = -\langle n | \textstyle\sum \boldsymbol{d}_k | n \rangle = -\boldsymbol{d}_e^{bare}$$

Evans, 2024 [2412.14664]

Electron EDM by 1-loop matching of the $\gamma a \bar{e} e$ 4-point function to
$\mathcal{L}_{EDM} = i\frac{d(a)}{2}\bar{\psi}\sigma^{\mu\nu}\gamma_5\psi F_{\mu\nu}$, claiming

$$d(a) = e\frac{\alpha}{2\pi}\frac{g}{m^2}a(t)$$

10^{11} factor improvement on g constraints!

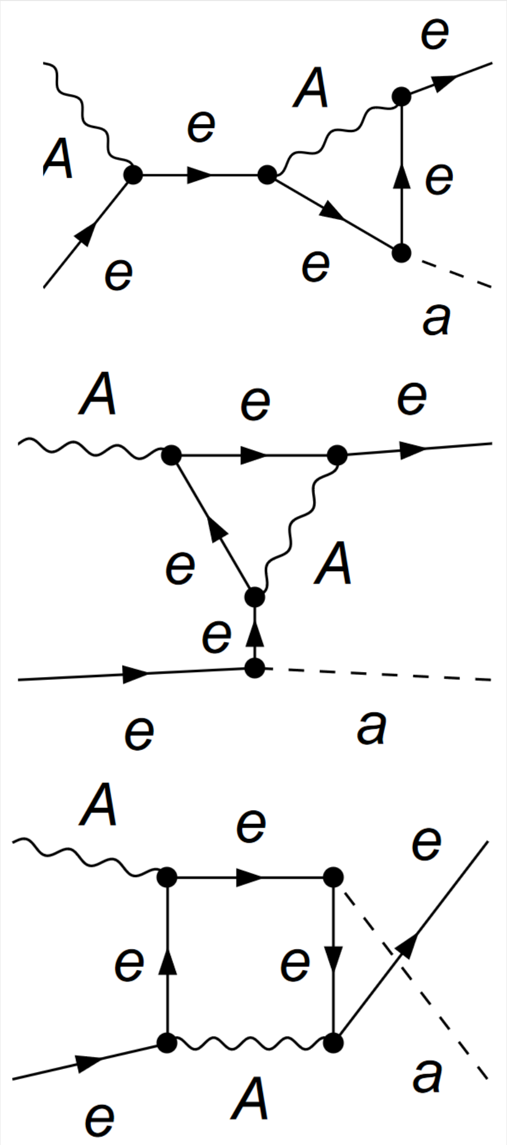


Thesis Objectives

- Test independently such a claim
- If falsified, look for a non-spurious EDM contribution

Current state of development

- Preliminar study of $\gamma e \to a e$ tree-level amplitude
- Implementation of the models into FeynCalc package of Wolfram Mathematica (FeynRules interface)
- 1-loop automated calculation



Under study:

- $p_a^\mu \ll m_e$ limit for tree-level and 1-loop to match on the effective theory
- Atomic physics calculation of axion induced EDM in paramagnetic system, via analogy with semi-leptonic operators

Backup Slides

Paramagnetic systems’ EDM [e.g. ThO]

- Schiff’s Theorem evaded: heavy atoms ⇒ Non-relativistic electrons
- Unpaired external shell electron ⇒ vicinity of opposite parity states

$$H \supset -\frac{i}{2} d_e \bar{e}\, \sigma^{\mu\nu}\gamma_5\, e\, F_{\mu\nu} - \frac{G_F}{\sqrt{2}} C\, \bar{N} N \bar{e}\, i\gamma_5 e$$

We aim to estimate the contribution of the axion interaction term in analogy with the semi-leptonic operator.