The nEDM,
the axion,
the nEDM and the axion …

S. Roccia

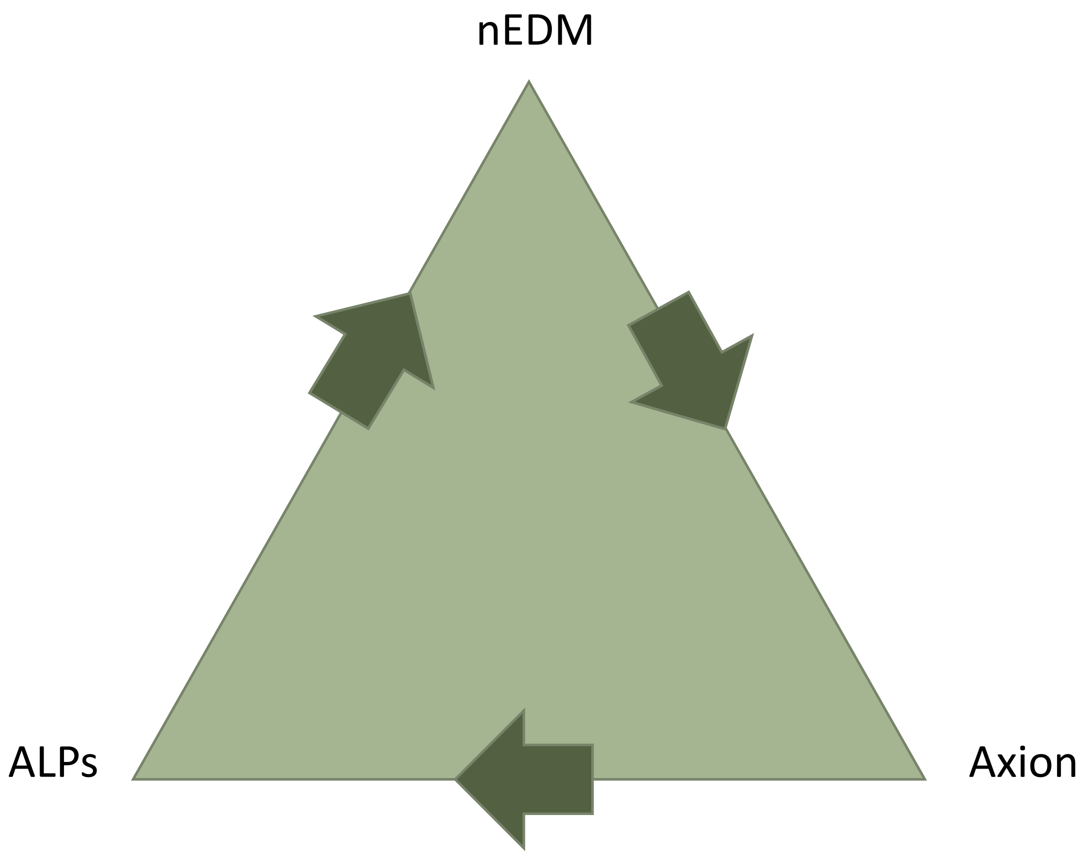
GDR - 2024

Outline

1) From the neutron Electric Dipole Moment to the Axion

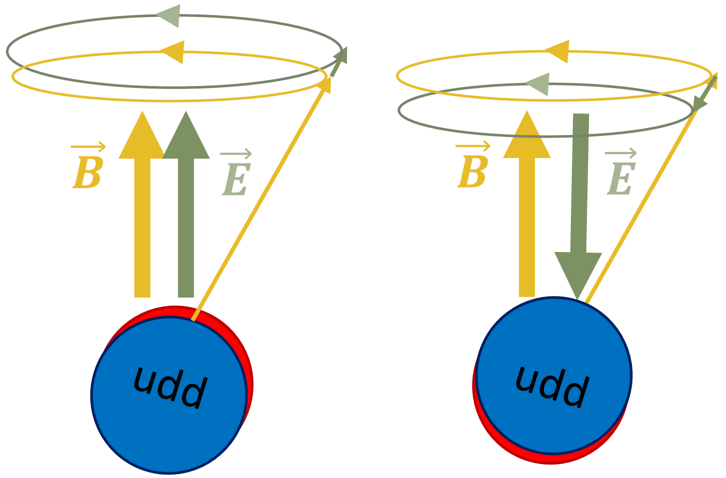
2) From the Axion to the Axion Like Particles

3) … and back to the neutron Electric Dipole Moment



What is an Electric Dipole Moment?

$$H = -\overrightarrow{\mu_n}.\vec{B} - \overrightarrow{d_n}.\vec{E} = \frac{h\, f_n}{2}$$



d_n = (0.0 ± 1.1 $_{stat}$ ± 0.2 $_{syst}$) 10^{-26} e.cm

10 years, 34 PhD thesis, 55 persons at a given time

The neutron spin as a quantum clock
- Magnetic field -> 30 turns each second
- Electric field -> 1 turn in 200 days

But the neutron lifetime is 12 minutes
-> we store neutrons for 3 minutes

What is an Electric Dipole Moment?

d_n^{CKM} d_n^{θ} d_n^{NP}

$$d_n = 10^{-32} e.cm + 10^{-16}\, e.cm\,(\theta) + 10^{-24}\, e.cm \left(\frac{200\ GeV}{M}\right)^2 \sin(\varphi_{CP})$$

-> P and T (CP) violating quantity receiving contributions from **MANY** couplings

• From the neutron Electric Dipole Moment to the Axion

What is an Electric Dipole Moment?

$$\underbrace{d_n^{CKM}}\qquad\boxed{d_n^{\theta}}\qquad\qquad\qquad d_n^{NP}$$

$$d_n = 10^{-32} e.cm + 10^{-16}\, e.cm\,(\theta) + 10^{-24}\, e.cm \left(\frac{200\ GeV}{M}\right)^2 \sin(\varphi_{CP})$$

$$L_{eff} = L_{QCD} + \theta\,\frac{\alpha_S}{8\,\pi}\,\varepsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma}$$

From lattice calculations: $d_n = -0.00152(71)\theta\ e.fm$

Experimental upper limit: $|d_n| \le\ 2.10^{-13}\ \ e.fm$ ⇒ $\theta \le 10^{-10}$


Forbes

INNOVATION • SCIENCE • EDITORS' PICK

The 'Strong CP Problem' Is The Most Underrated Puzzle In All Of Physics

Ethan Siegel Senior Contributor

Starts With A Bang Contributor Group

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What is the axion?

-> A solution to the strong CP problem

Illustration by Sandbox Studio, Chicago with Steve Shanabruch

• From the neutron Electric Dipole Moment to the Axion

What is the axion?

-> A solution to the strong CP problem

The axion is a well motivated dark matter candidate

Axion density relative to the critical density of the universe

$$\Omega_a \approx \left(\frac{6\,\mu\mathrm{eV}}{m_a}\right)^{\frac{7}{6}} \approx \Omega_m = 0.23\ (m_a \approx 20\ \mu eV)$$

Entire dark matter density

The theory is quite predictive

Essentially all of the physics of the axion depends on a large unknown energy scale f_a, at which Peccei-Quinn symmetry is broken.

$$m_a \approx 6\,\mathrm{eV}\left(\frac{10^6\,\mathrm{GeV}}{f_a}\right)$$

The axion has a two photons coupling, and g_γ is model dependant.

$$g_{a\gamma\gamma} = \frac{\alpha g_\gamma}{\pi f_a}$$

Annual Review of Nuclear and Particle Science Vol. 65:485-514 (2015)

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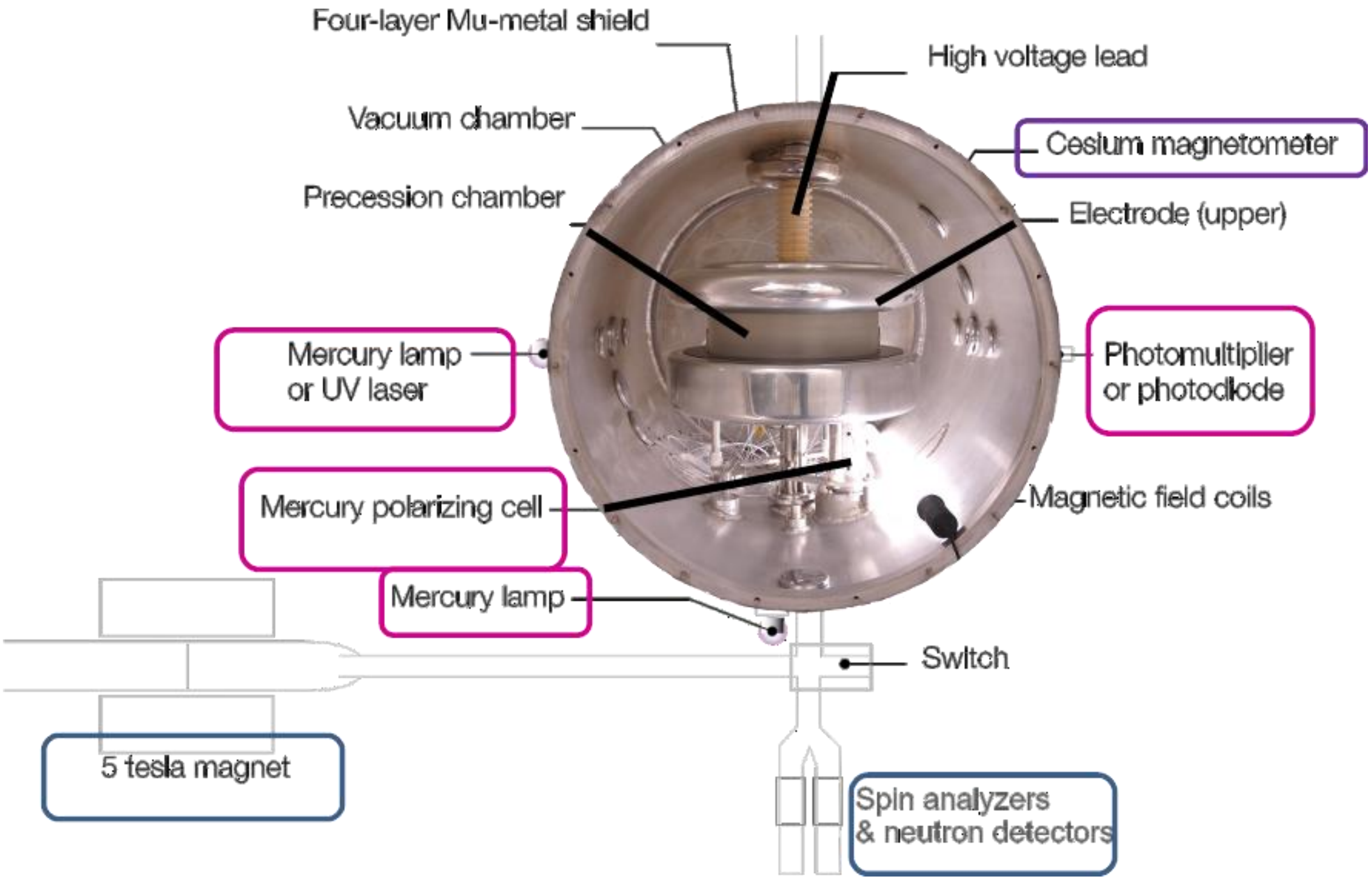
Partial breaking of the Peccei-Quinn symmetry

ALPs

Ask Less, Probe!

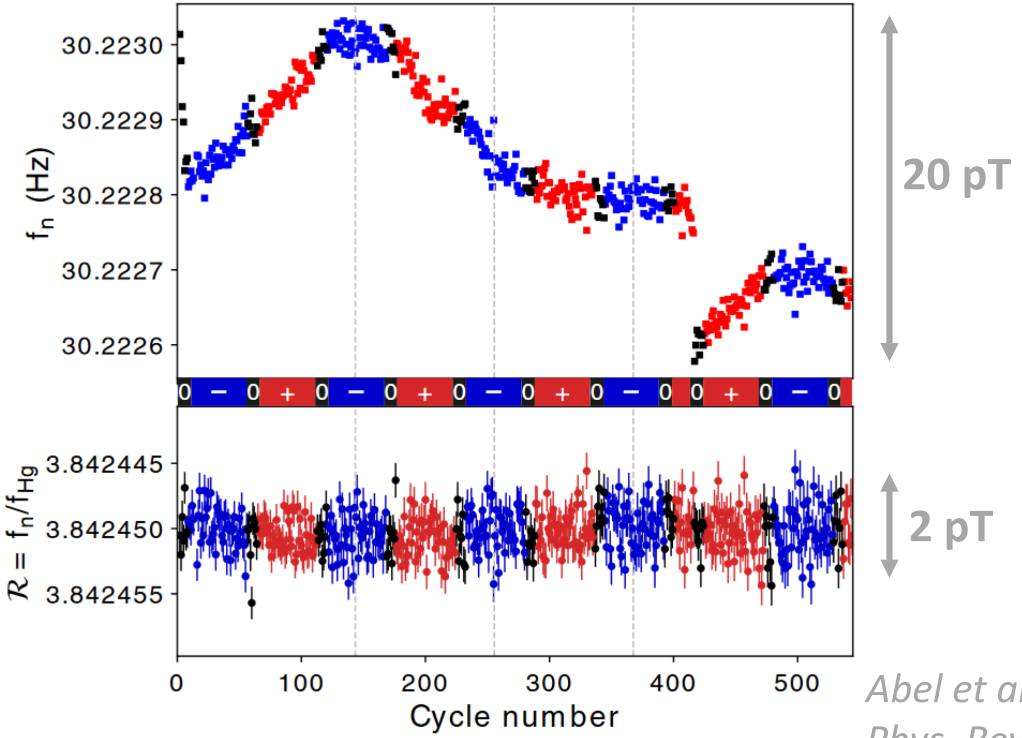
The nEDM apparatus as
a multipropose setup

nEDM setup: (1986) 2006-2010 **@ILL** and 2011-2017 **@PSI**



with one chamber: the magnetometry approach

$$
\begin{array}{lcccc}
\mathrm{h}\ f_n\ (\uparrow\uparrow) & = & 2\ \vec{\mu}_n.\vec{B}(\uparrow\uparrow) & + & 2\ \vec{d}_n.\vec{E}(\uparrow\uparrow) \\
\mathrm{h}\ f_n\ (\uparrow\downarrow) & = & 2\ \vec{\mu}_n.\vec{B}(\uparrow\downarrow) & - & 2\ \vec{d}_n.\vec{E}(\uparrow\downarrow) \\
\hline
\mathrm{h}(f_n\ (\uparrow\uparrow)\text{-}\ f_n\ (\uparrow\downarrow)) & = & 2\vec{\mu}_n.(\vec{B}(\uparrow\uparrow)-\vec{B}(\uparrow\downarrow)) & - & 2\vec{d}_n.(\vec{E}(\uparrow\uparrow)+\vec{E}(\uparrow\downarrow))
\end{array}
$$



Mercury co-magnetometer (1998)

$$\mathscr{R} \equiv \frac{f_{\mathrm{n}}}{f_{\mathrm{Hg}}} = \frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}}$$

Cesium magnetometer array (2009)

Abel et al (nEDM collab)
Phys. Rev. Lett. 124, 081803 (2020)

Let’s take advantage of everything we are avoiding for a nEDM measurement:
Clock comparison experiments

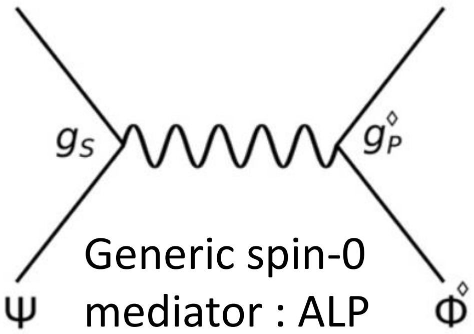
$$\mathscr{R} \equiv \frac{f_n}{f_{Hg}} = \frac{\gamma_n}{\gamma_{Hg}} \left(1 + \frac{\vec{b}.\vec{B}}{B^2} \pm \left(d_n - \frac{\gamma_n}{\gamma_{Hg}} d_{Hg}\right) \frac{2E}{h f_{Hg}}\right)$$

Applied fields

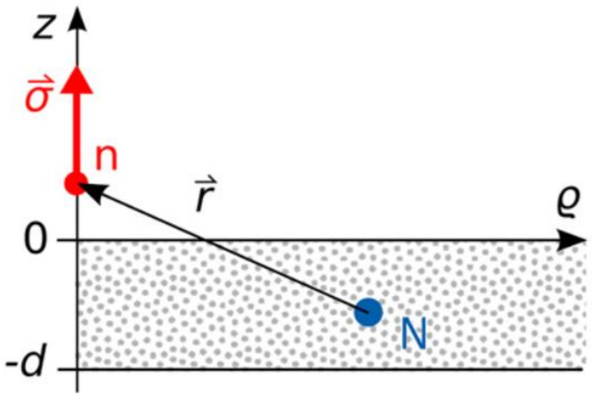
Observables

Clocks On The Wall by Setsiri Silapasuwanchai

Short range spin-dependent interaction



Generic spin-0 mediator : ALP

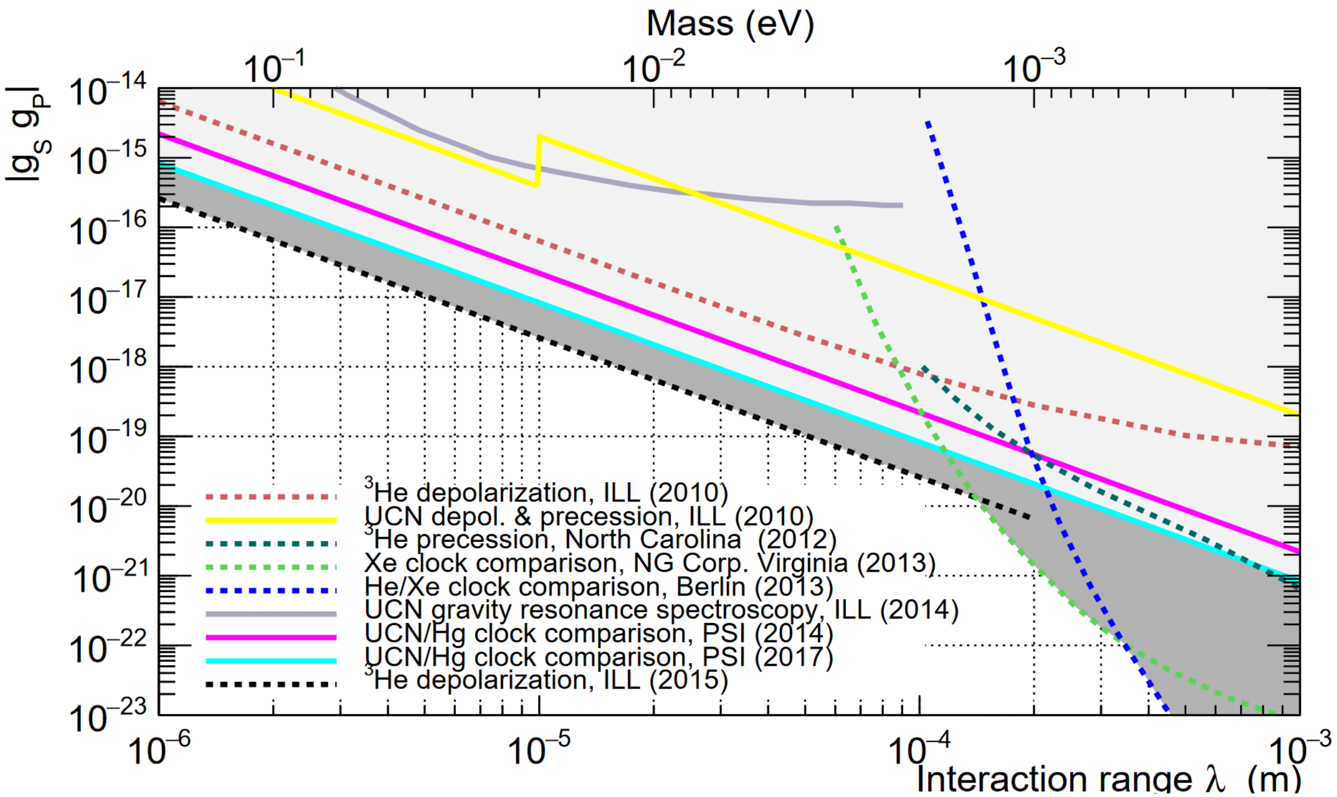


In the precession chamber

UCNs

Mercury atoms

$\downarrow \vec{g}$

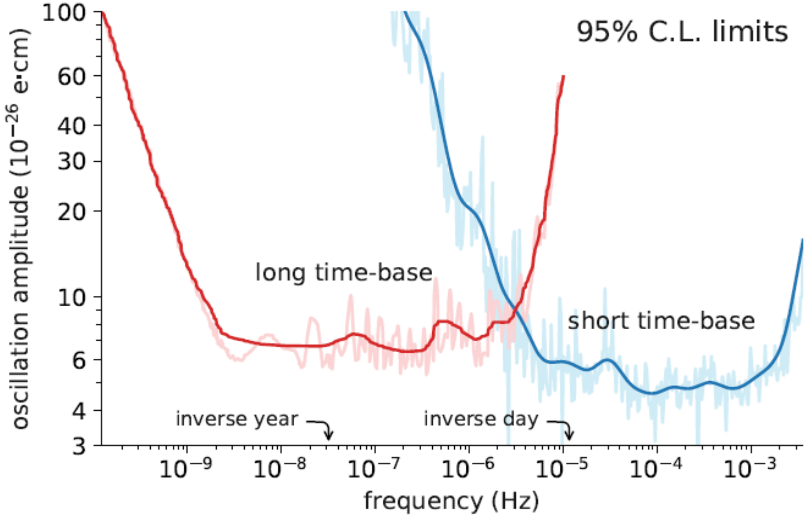


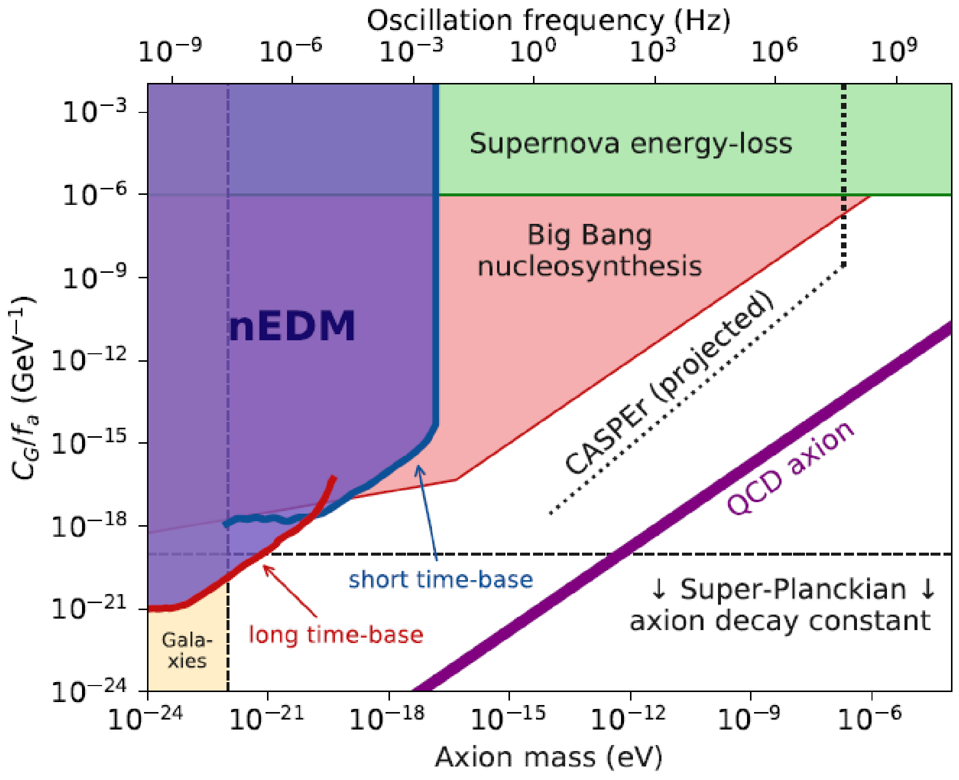
Search for the interactions of the **coherently oscillating axion** DM field with gluons and fermions
-> oscillating electric dipole moments (EDMs) of nucleons
-> anomalous spin-precession effects

$$a = a_0 \cos(\omega t)$$
$$\omega \approx m_a c^2/\hbar$$

$$\mathcal{L}_{\text{int}} = \frac{C_G}{f_a}\frac{g^2}{32\pi^2} a G^b_{\mu\nu}\tilde{G}^{b\mu\nu} - \frac{C_N}{2f_a}\partial_\mu a \bar{N}\gamma^\mu\gamma^5 N$$

$$d_n(t) \approx +2.4 \times 10^{-16} \frac{C_G a_0}{f_a} \cos(m_a t)\ e\cdot\text{cm}$$





ILL data: long data taking

PSI data: high sensitivity

C. Abel et al., Phys. Rev. X 7, 041034 (2017)

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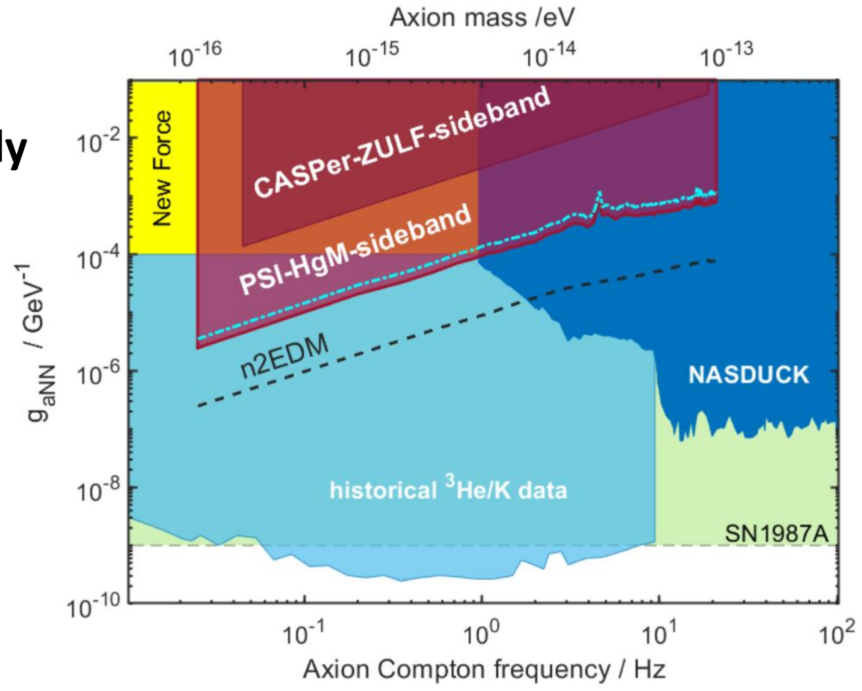
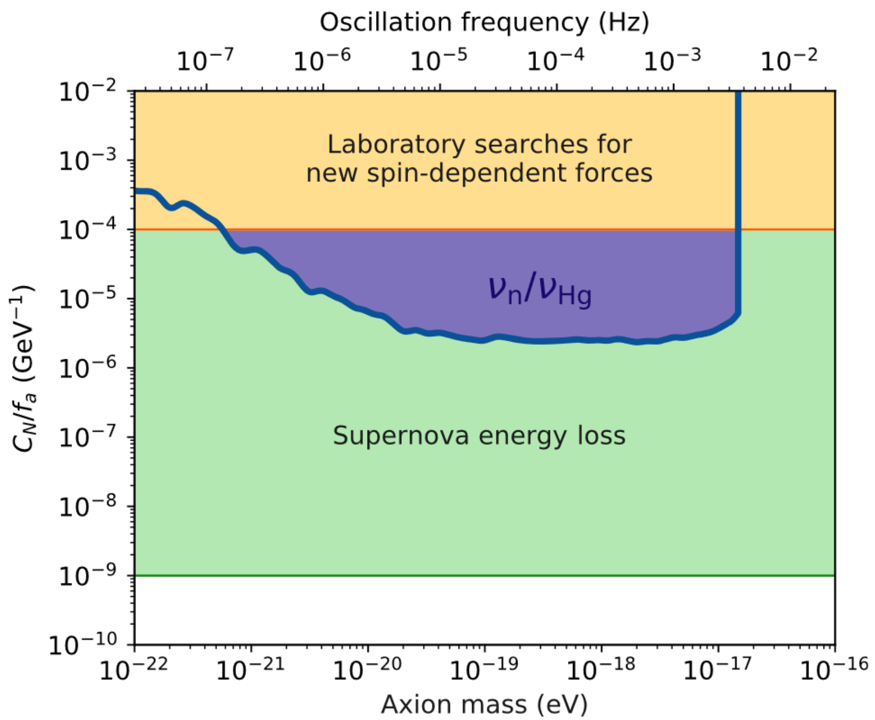
$$H_{\text{int}} = \frac{C_N}{2f_a}\sin(m_a t)\vec{\sigma}_N \cdot \vec{p}_a$$

$$\vec{\sigma}_N \cdot \vec{p}_a = \hat{m}_F f(\sigma_N) m_a |\vec{v}_a| \times [\cos(\chi)\sin(\delta) + \sin(\chi)\cos(\delta)\cos(\Omega_{\text{sid}} t - \eta)]$$

Hg only



C. Abel et al., SciPost Physics 15, 058 (2023)



C. Abel et al., Phys. Rev. X 7, 041034 (2017)

The end

Clock comparisons can probe spin-dependent interaction
nEDM setup with magnetometry can probe spin-dependent interaction with nucleons
nEDM setup has a unique window to probe Axion