Axion Search in the Neutron Sector with Highly-Sensitive Atomic Magnetometers

UGRP2025 (B01)

June 25, 2025

Takashi Higuchi

(KURNS, Kyoto U., RCNP, U. Osaka)

Background: magnetic subsystems of a neutron EDM experiment

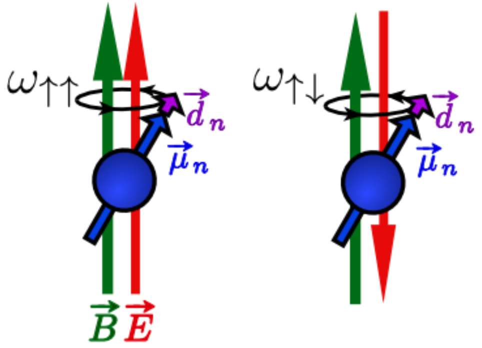
- **TUCAN** (TRIUMF Ultracold Advanced Neutron) experiment
  - Aiming at a neutron electric dipole moment (nEDM) measurement with **10^{-27} ecm** precision
    - Sensitive probe for T- and hence CP-violation in strong interaction
- Principle of the nEDM measurement:

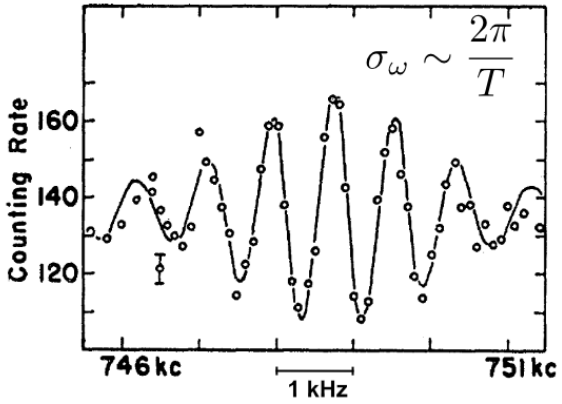
$$H = -\mu_n \vec{B} \cdot \frac{\vec{S}}{S} - d_n \vec{E} \cdot \frac{\vec{S}}{S}$$

$\uparrow\uparrow$: $\vec{B} \parallel \vec{E}$

$\uparrow\downarrow$: $\vec{B} \parallel -\vec{E}$

$$d_n = \frac{\hbar(\omega_{\uparrow\uparrow} - \omega_{\uparrow\downarrow})}{4|E|}$$





J.H. Smith, E.M. Purcell & N.F. Ramsey, Phys. Rev. **108**, 120 (1957)

C. Abel et al., Phys. Rev. Lett. **124**, 081803 (2020)

- Key 1 (statistics): high-intensity ultracold neutron source, now under commissioning at TRIUMF

  → Enable a measurement with x200 statistics over the current best measurement
- Key 2 (systematics): control of magnetic field stability and homogeneity

Background: magnetic subsystems of a neutron EDM experiment

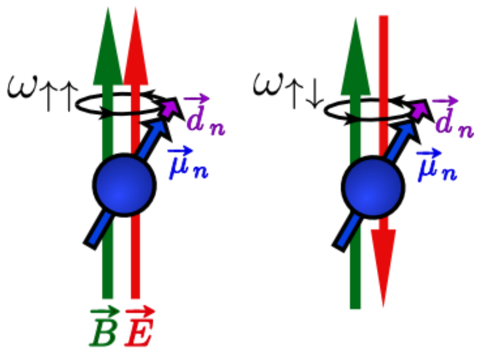
- **TUCAN** (<u>T</u>RIUMF <u>U</u>ltra<u>c</u>old <u>A</u>dvanced <u>N</u>eutron) experiment
  - Aiming at a neutron electric dipole moment (nEDM) measurement with **10^{-27} ecm** precision
    - Sensitive probe for T- and hence CP-violation in strong interaction
- Principle of the nEDM measurement:

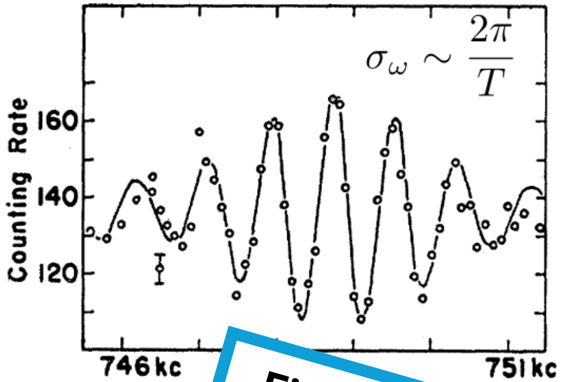
$$H = -\mu_n \vec{B} \cdot \frac{\vec{S}}{S} - d_n \vec{E} \cdot \frac{\vec{S}}{S}$$

$\uparrow\uparrow$: $\vec{B} \parallel \vec{E}$

$\uparrow\downarrow$: $\vec{B} \parallel -\vec{E}$

$$d_n = \frac{\hbar(\omega_{\uparrow\uparrow} - \omega_{\uparrow\downarrow})}{4|E|}$$





J.H. Smith, E.M. Purcell & N.F. Ramsey, ... (1957)

C. Abel et al., Phys. Rev. Lett. **124**, 081...

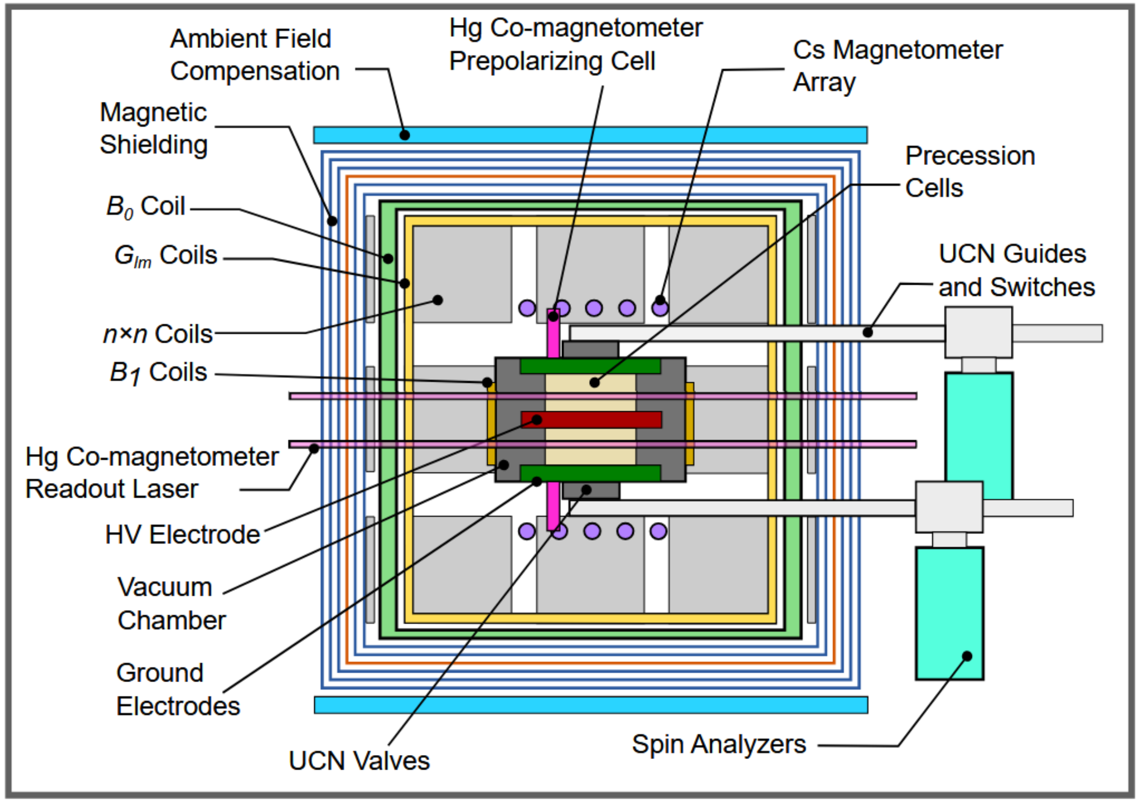
First UCNs from the TUCAN source! (June 13, 2025)

- <u>Key 1 (statistics)</u>: high-intensity ultracold neutron source, now under commissioning a...

  → Enable a measurement with x200 statistics over the current best measurement
- <u>Key 2 (systematics)</u>: control of magnetic field stability and homogeneity

Magnetic-field related subsystems

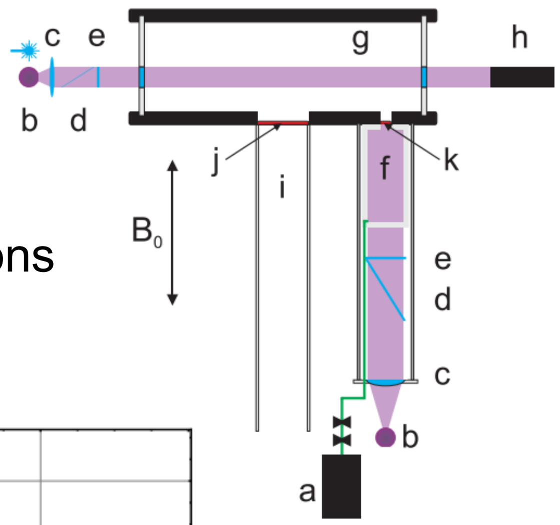
- **Stability requirement**
  - Required stability: ~10 fT (out of $B_0 \approx$ 1uT)
  - Solution:
    - Magnetic shielding at the level of < **10 pT/cycle**
    - Use optically-read ^{199}Hg atoms as cohabiting magnetometer, sensitive to 10 fT order (80 nHz) → effective x100 reduction
- **Homogeneity requirement**
  - Leading order systematic shift ∝ E x (dB/dz)
  - Required homogeneity: < 1 nT/m
  - Solution:
    - Magnetic shielding: residual field <|1 nT|
    - Self-shielded B_0 coil, shim coils
    - Distributed optically-read Cs magnetometers



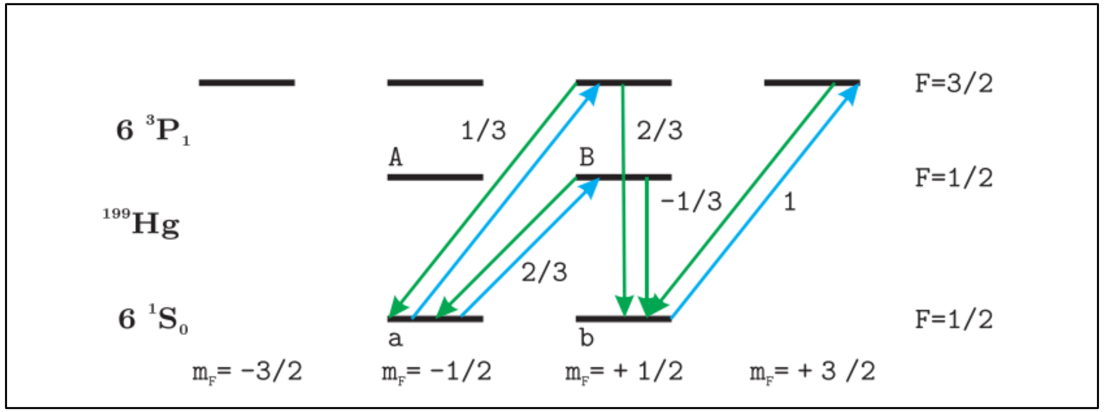
S. Vanbergen, PhD thesis, University of British Columbia (2025)

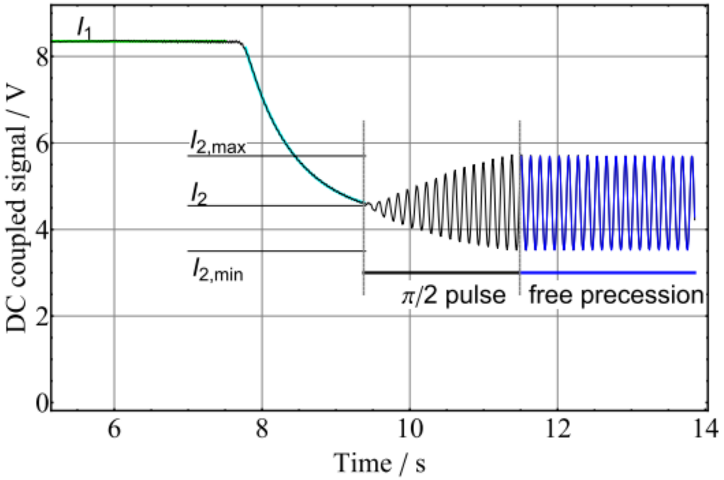
Motivation: can we use this for non-neutron experiments to search for new physics?

Magnetic-field related subsystems



- **Hg comagnetometer**
  - Optically-pumped atomic magnetometer cohabits the same volume as neutrons
  - Used intercombinational transition: $6^1S_0 \rightarrow 6^3P_1$ polarize/probe the nuclear spin





M.C. Fertl, PhD thesis, ETH Zürich (2013)

$\gamma_n = -29.16$ MHz/T, $\gamma_{199\mathrm{Hg}} = 7.7162$ MHz/T
→ at $B_0 \approx$ 1uT: $v_n \approx$ 30 Hz, $v_{199\mathrm{Hg}} \approx$ 8 Hz, $v_{\mathrm{Cs}} \approx$ 7 kHz

- TUCAN Hg magnetometer: prototype setup developed at the University of British Columbia (UBC)

Outline

1. **Background**
   - Relation to the TUCAN EDM experiment
   - Physics motivations: Axion
2. **Review of the previous work**
3. **New approach using ^{199}Hg/^{201}Hg comagnetometer**
4. **Experiment Status**

Motivations — Axion

- **Axion**:
  - Proposed as a solution of the strong CP problem (small θ value) → a new U(1) symmetry (Peccei-Quinn symmetry) → pseudoscalar NG boson (spin=0) "axion"
  - Original QCD axion $$m_a = 5.70(7)\mu\text{eV}\left(\frac{10^{12}\text{GeV}}{f_a}\right)$$

D. Peccei and H. R. Quinn, Phys. Rev. D. **16**, 1791 (1977)
di Cortona, G.G., Hardy, E., Vega, J.P. *et al. J. High Energ. Phys.* **2016**, 34 (2016).

    - Now searched in a wide parameter space as candidate of dark matter
    - Interests in ultralight axion ($<10^{-10}$ eV):
      - compatibility with ΛCDM dark matter
      - "fuzzy" axion in the context of quantum gravity

Marsh, David J.E., Physics Reports. **643**: 1–79.(2016)

Arvanitaki, A. et al., Phys. Rev. D 81, 123530 (2010)

  - Low-energy, long wavelength ($\sim R_\oplus, R_\odot$), wavefunction expressed as classical oscillation with a long period

axion-photon coupling	**axion-gluon coupling**	**axion-nucleon coupling**
$\mathcal{L}_{a\gamma\gamma} = \frac{g_{a\gamma\gamma}}{4} aF_{\mu\nu}\tilde{F}^{\mu\nu}$	$\mathcal{L}_{agg} = \frac{C_G}{f_a} a \frac{g_s^2}{32\pi^2} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$	$\mathcal{L}_{aNN} = -g_{aNN}\partial_\mu a\bar{N}\gamma^\mu\gamma_5 N$

- **Search methods:**
  - Axion-photon coupling:
    - Optical/RF/Microwave cavities
    - Light-shining-through a wall
    - Solar axion searches
    - …
  - Axion-gluon coupling:
    - Search for oscillating EDMs
  - Axion-nucleon coupling:
    - Atomic magnetometers

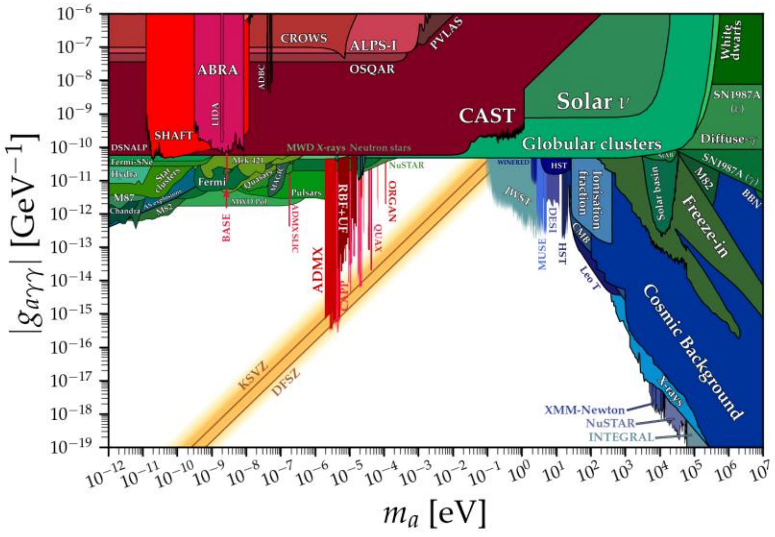
Accessible interactions

axion-photon coupling	axion-gluon coupling	axion-nucleon coupling
$\mathcal{L}_{a\gamma\gamma} = \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$	$\mathcal{L}_{agg} = \frac{C_G}{f_a} a \frac{g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$	$\mathcal{L}_{aNN} = -g_{aNN} \partial_\mu a \bar{N} \gamma^\mu \gamma_5 N$

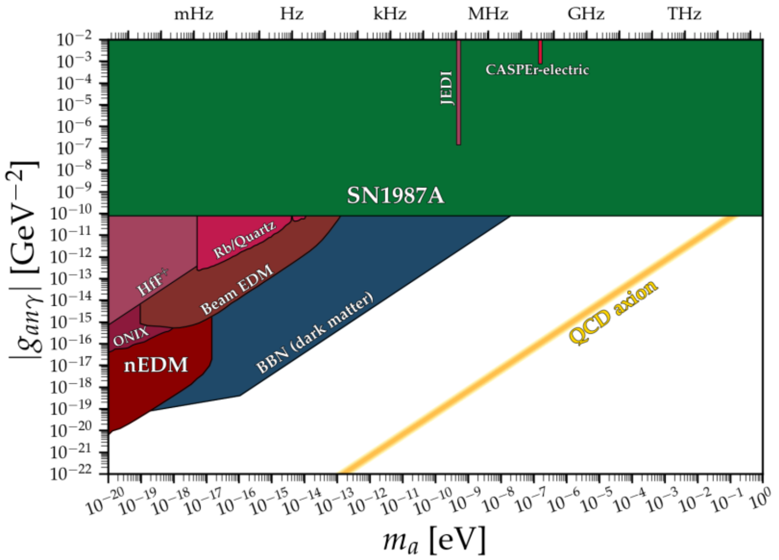
axion-EDM coupling

$$\mathcal{L}_{aN\gamma} = -\frac{i}{2} g_{aN\gamma}\, a \bar{N} \sigma^{\mu\nu} \gamma_5 N F_{\mu\nu}$$

axion-photon coupling



axion-EDM coupling



axion-neutron coupling

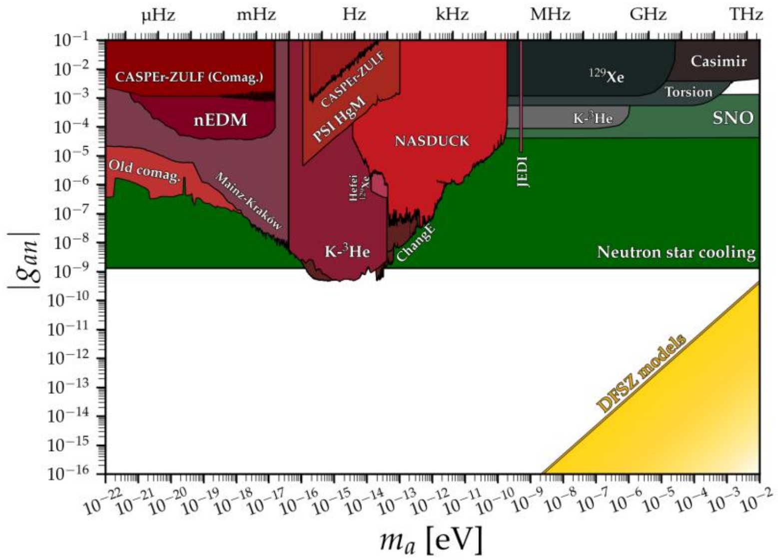


Figure: “Axion Limits”, C. O’Hare

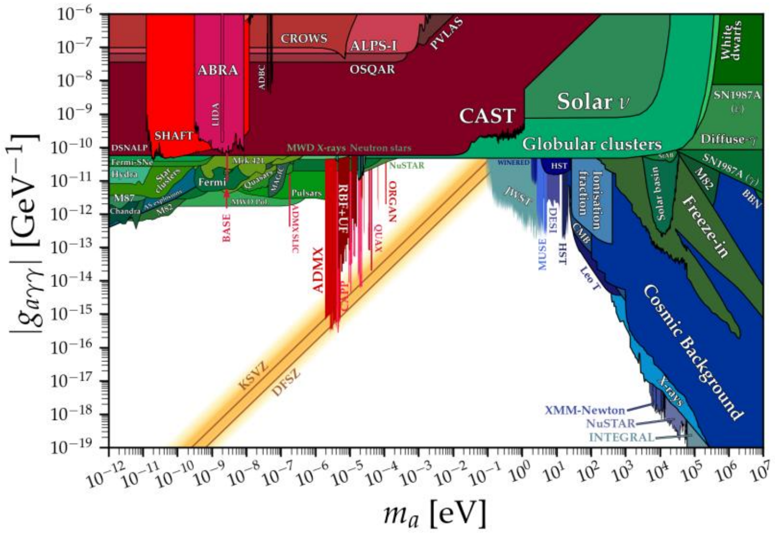
Accessible interactions

axion-photon coupling	axion-gluon coupling	axion-nucleon coupling
$\mathcal{L}_{a\gamma\gamma} = \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$	$\mathcal{L}_{agg} = \frac{C_G}{f_a} a \frac{g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$	$\mathcal{L}_{aNN} = -g_{aNN} \partial_\mu a \bar{N} \gamma^\mu \gamma_5 N$

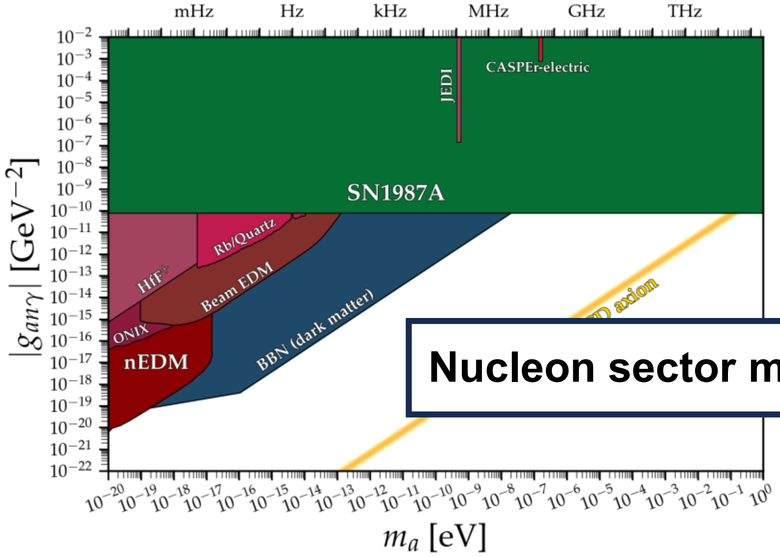
➡ axion-EDM coupling

$$\mathcal{L}_{aN\gamma} = -\frac{i}{2} g_{aN\gamma}\, a \bar{N} \sigma^{\mu\nu} \gamma_5 N F_{\mu\nu}$$

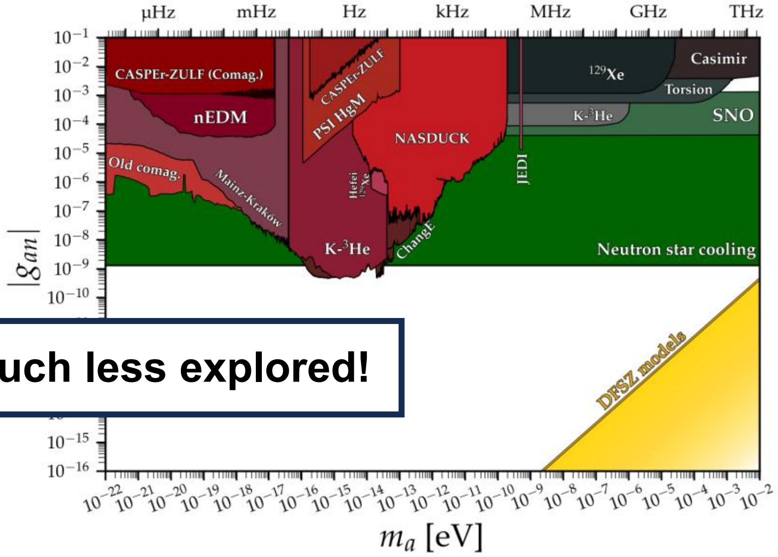
axion-photon coupling



axion-EDM coupling



axion-neutron coupling



Nucleon sector much less explored!

Figure: "Axion Limits", C. O'Hare

Accessible interactions

axion-photon coupling

$$\mathcal{L}_{a\gamma\gamma} = \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

axion-gluon coupling

$$\mathcal{L}_{agg} = \frac{C_G}{f_a} a \frac{g_s^2}{32\pi^2} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

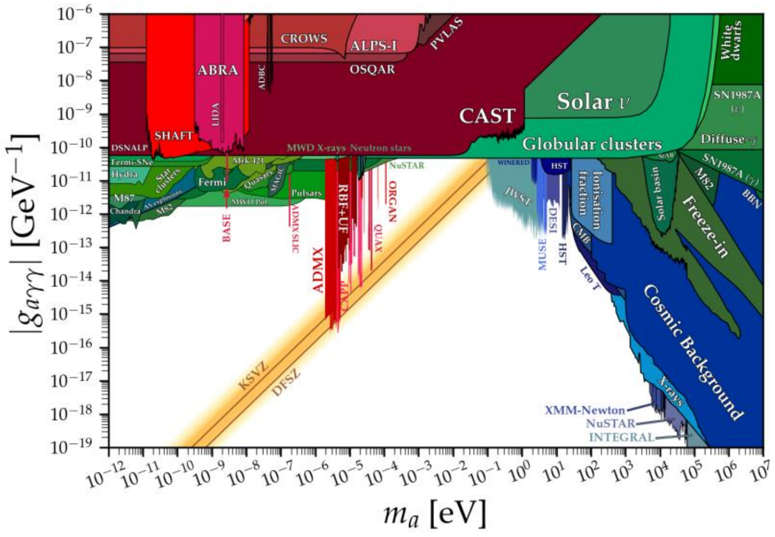
axion-nucleon coupling

$$\mathcal{L}_{aNN} = -g_{aNN}\partial_\mu a \bar{N}\gamma^\mu\gamma_5 N$$

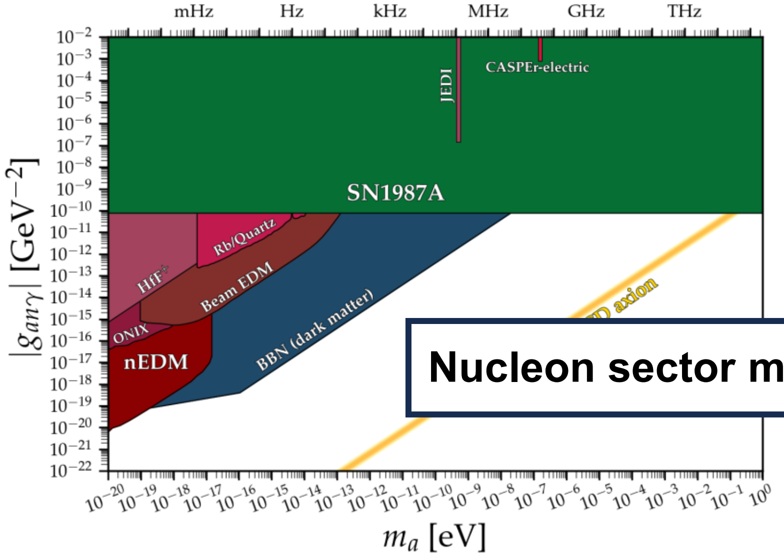
➡ axion-EDM coupling

$$\mathcal{L}_{aN\gamma} = -\frac{i}{2} g_{aN\gamma}\, a\bar{N}\sigma^{\mu\nu}\gamma_5 N F_{\mu\nu}$$

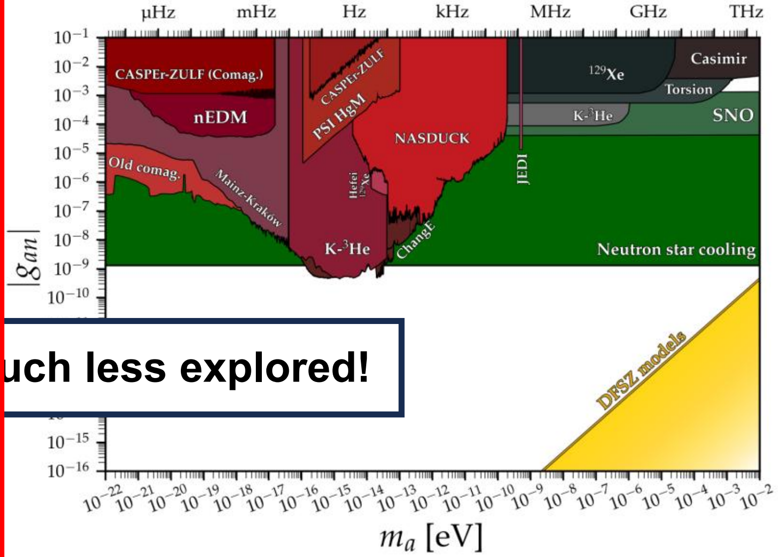
axion-photon coupling



axion-EDM coupling



axion-neutron coupling



Nucleon sector much less explored!

Figure: "Axion Limits", C. O'Hare

PSI nEDM collaboration 2017 (axion-neutron coupling)

- Axion-nucleon coupling searched by *axion wind* effect on the neutron/^{199}Hg or ^{199}Hg system :
  - From

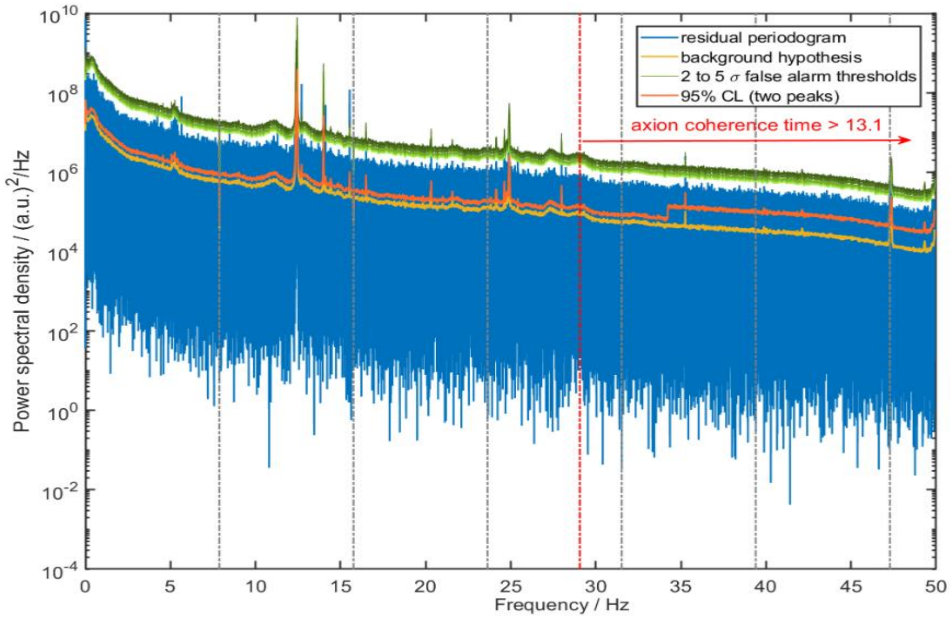
$$\mathcal{L}_{aNN} = -\frac{C_N}{2f_a}\partial_\mu a \bar{N}\gamma^\mu\gamma_5 N \Rightarrow H_{\text{int}}(t) = \frac{C_N}{2f_a}\sin(m_a t)\boldsymbol{\sigma}_N \cdot \boldsymbol{p}_a \quad \left(g_{aNN} = \frac{C_N m_N}{2f_a}\right)$$

→ Axion induces pseudomagnetic field

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

χ: angle between B_0 and the earth's rotation axis
δ, η: angle between B_0 and the galactic DM flux (from theory)
Ω_{sid}=7.29x10^{-5} s^{-1} sidereal frequency

→ The axion-induced pseudomagnetic field has frequency components: m_a, $m_a \pm \Omega_{sid}$



  - Used nEDM data $R=f_n/f_{Hg}$ or ^{199}Hg time transient data
  - Looked for peaks: 3 σ peaks found in subset data, but not consistent with the expected phase relation → discarded

Abel, C., et al, Physical Review X **7**, 041034 (2017)
Abel, C. et al., SciPost Phys. **15**, 058 (2023)

PSI nEDM collaboration 2017 (axion-neutron coupling)

- Axion-nucleon coupling searched by *axion wind* effect on the neutron/^{199}Hg or ^{199}Hg system :
  - From

$$\mathcal{L}_{aNN} = -\frac{C_N}{2f_a}\partial_\mu a \bar{N}\gamma^\mu\gamma_5 N \Rightarrow H_{\text{int}}(t) = \frac{C_N}{2f_a}\sin(m_a t)\boldsymbol{\sigma}_N \cdot \boldsymbol{p}_a \qquad \left(g_{aNN} = \frac{C_N m_N}{2f_a}\right)$$

→ Axion induces pseudomagnetic field

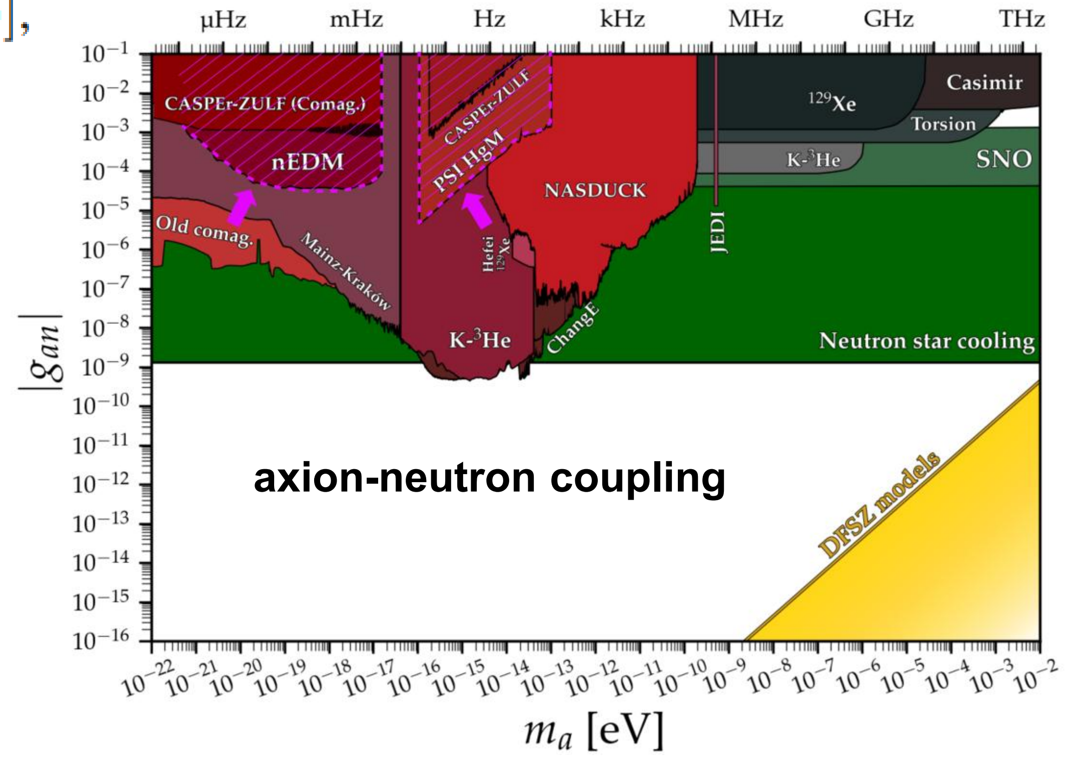
$$\boldsymbol{\sigma}_N \cdot \boldsymbol{p}_a = \hat{m}_F f(\boldsymbol{\sigma}_N) m_a |\boldsymbol{v}_a| \times [\cos(\chi)\sin(\delta) + \sin(\chi)\cos(\delta)\cos(\Omega_{\text{sid}} t - \eta)],$$

→ The axion-induced pseudomagnetic field has frequency components: m_a, $m_a \pm \Omega_{sid}$

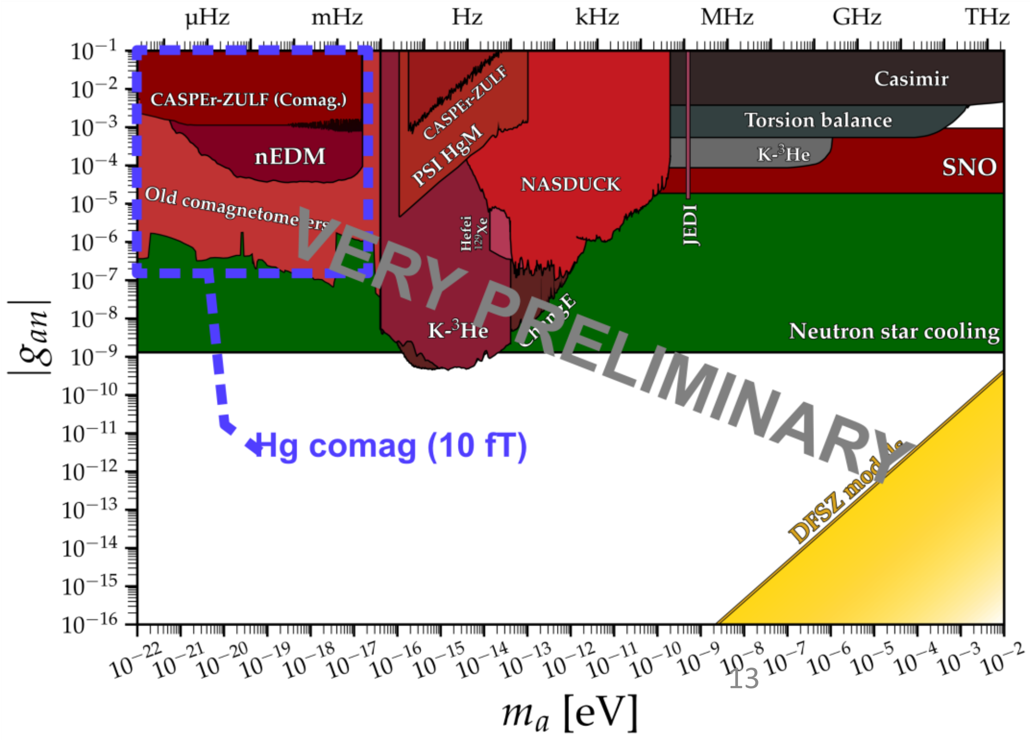
- Used nEDM data $R=f_n/f_{Hg}$ or ^{199}Hg time transient data
- Looked for peaks: 3 σ peaks found in subset data, but not consistent with the expected phase relation → discarded

Abel, C., et al, Physical Review X **7**, 041034 (2017)
Abel, C. et al., SciPost Phys. **15**, 058 (2023)

X: angle between B_0 and the earth's rotation axis
δ, η: angle between B_0 and the galactic DM flux (from theory)
Ω_{sid}=7.29x10^{-5} s^{-1} sidereal frequency

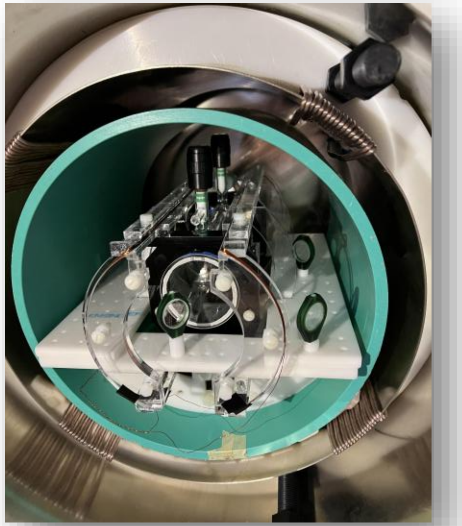


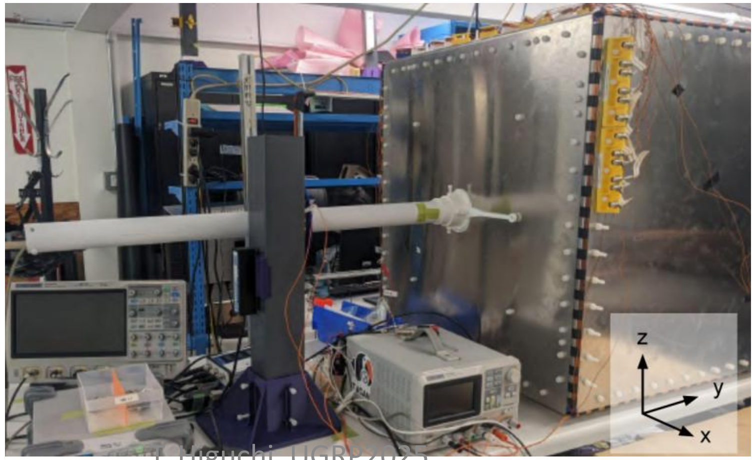
New approach: axion wind on $^{199}Hg/^{201}Hg$ comagnetometer



Future plans

- 2025:
  - Develop analysis framework
  - Upgrade magnetic shield of the UBC setup
  - (Physics run at the UBC?)
- 2026 (1-year accelerator shutdown of TRIUMF):
  - Integrate the system to the Magnetically Shielded Room at TRIUMF
    - Improve the magnetic homogeneity by a factor of 70
    - (Potentially) Integrate the neutron EDM cell (x60 larger volume) → reduced wall collision
  - Physics run at TRIUMF
- (Installation of dedicated laser for ^{201}Hg)





Summary

- Introduced ^{199}Hg/^{201}Hg isotope comagnetometer as a new approach to search for nucleon-axion coupling in an ultralow mass range of < $\mathbf{10^{-17}}$ **eV**
- Advanced magnetic shielding and highly sensitive Hg magnetometer developed for the TUCAN EDM experiment allows an experimental search competitive to the existing best comagnetometer data
- Experiment status: reaching 1 pT stability in the prototype setup, aiming at x100 improvement

Acknowledgements

TUCAN
TRIUMF Ultracold Advanced Neutron Collaboration

UBC team:

W. Klassen, K. Madison, Z. Mao, E. Miller, T. Momose, Q. Ye

& Y.V. Stadnik (U. Sydney), W. Yin (TMU)

Thank you for your attention!