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

第11回「極低放射能技術」研究会

March 6, 2026

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Low-magnetic-background environment for neutron EDM experiment

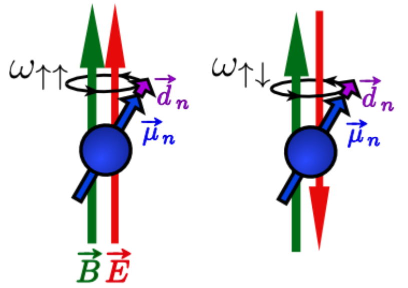
- **Neutron Electric Dipole Moment (nEDM)**
  - Constrains Time-reversal violation in strong interaction
  - Limit obtained by comparing spin precession frequencies of neutrons under electric and magnetic fields
  - Use Ultracold neutrons (UCNs) that can be stored for ~100 s
- **Stability requirement**
  - 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

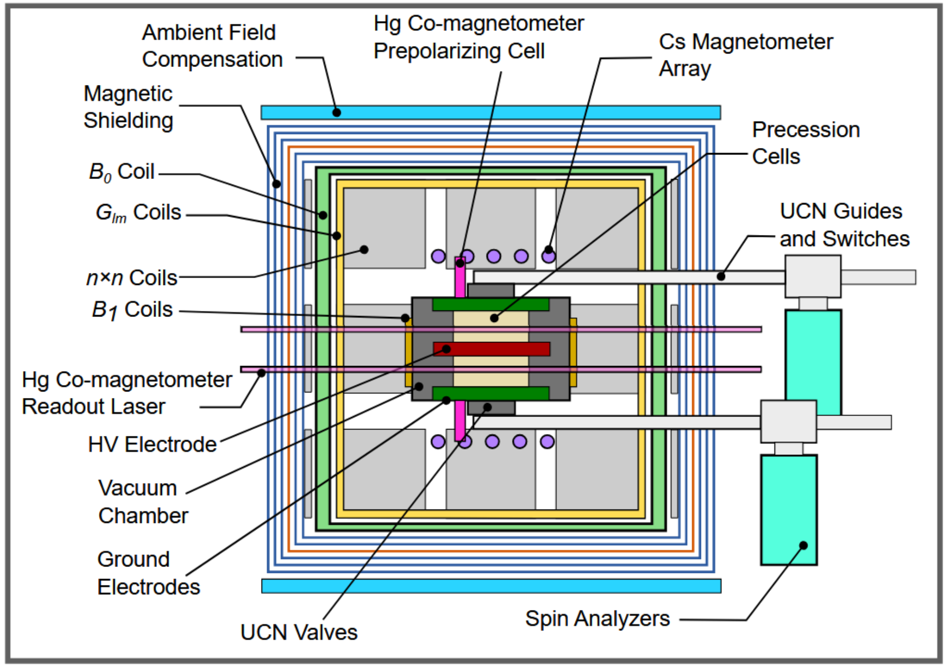
$$H = -\mu_n \vec{B} \cdot \frac{\vec{S}}{S} - d_n \vec{E} \cdot \frac{\vec{S}}{S}$$

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

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

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

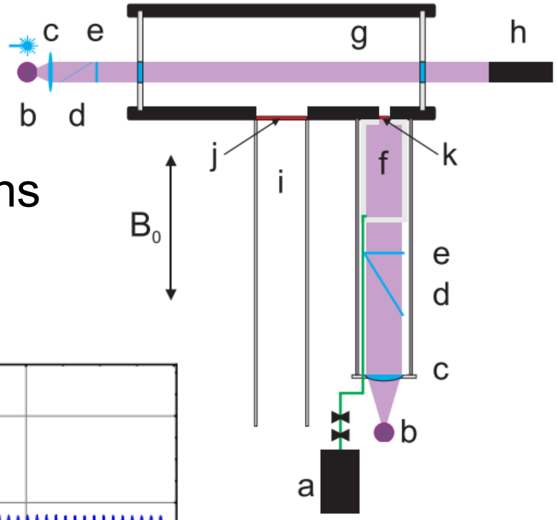




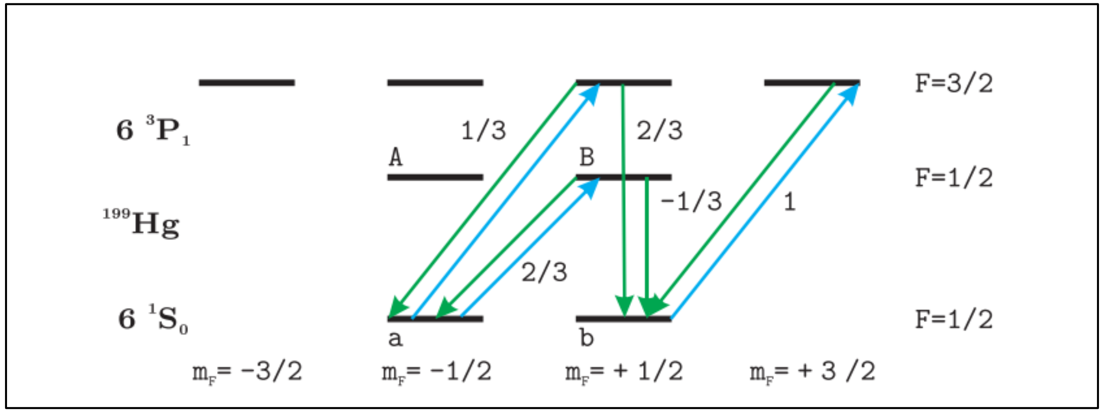
S. Vanbergen, PhD thesis, University of British Columbia (2025)

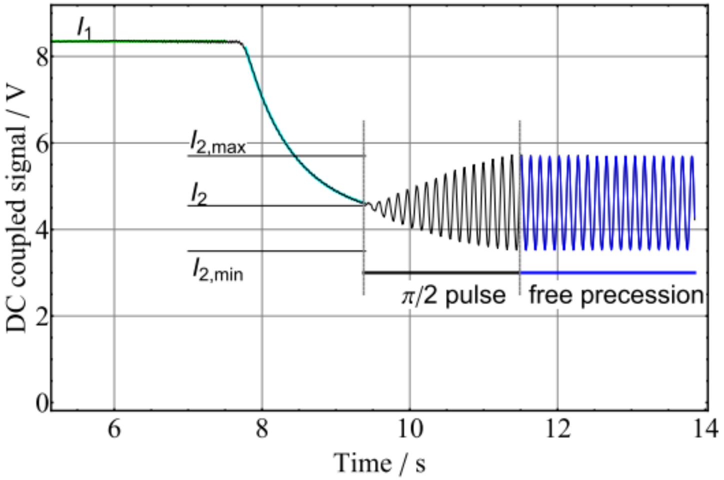
Motivation: can we use this for non-neutron experiments to search for new physics?

Tool — Hg atomic magnetometer as nEDM co-magnetometer



- 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: $\nu_n \approx$ 30 Hz, $\nu_{199\mathrm{Hg}} \approx$ 8 Hz, $\nu_{\mathrm{Cs}} \approx$ 7 kHz

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

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 $m_a = 5.70(7)\mu\mathrm{eV}\left(\frac{10^{12}\mathrm{GeV}}{f_a}\right)$

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

- **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

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axion-gluon coupling

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axion-nucleon coupling

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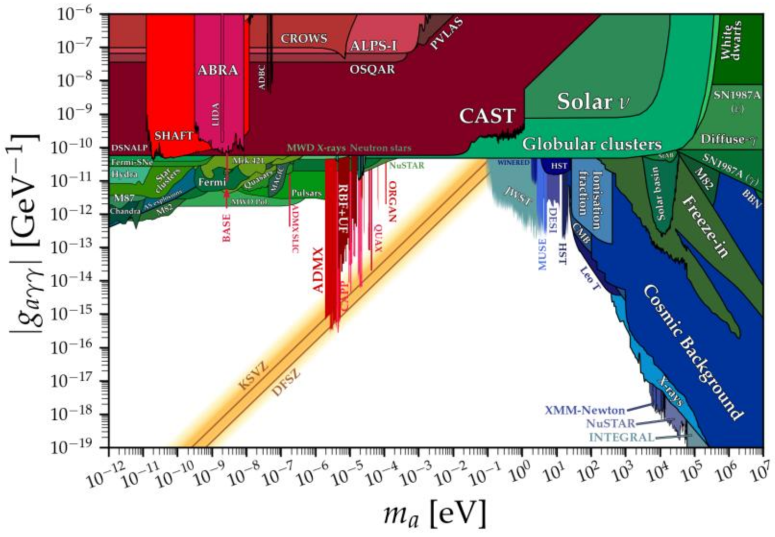
➡ axion-EDM coupling

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

axion-photon coupling



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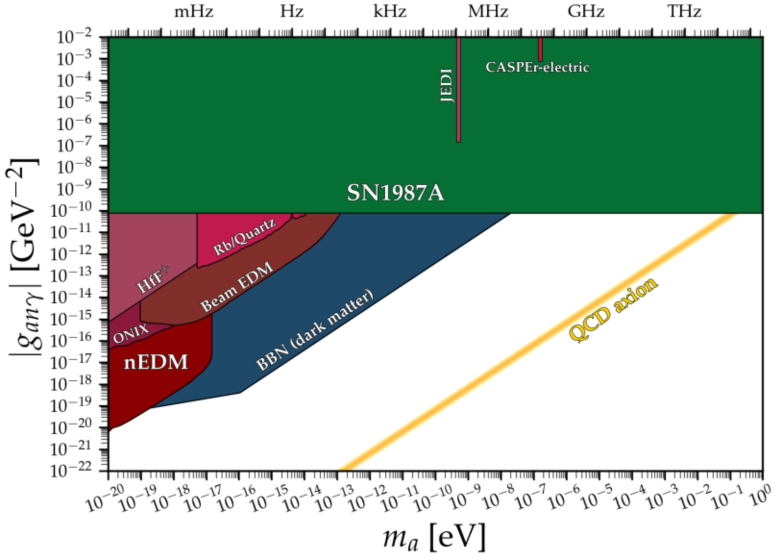

axion-neutron coupling

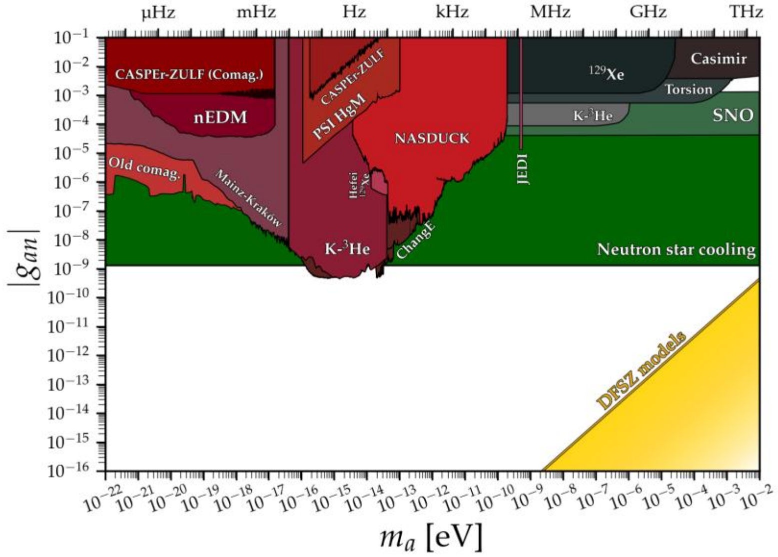

Figure: "Axion Limits", C. O'Hare

Accessible interactions

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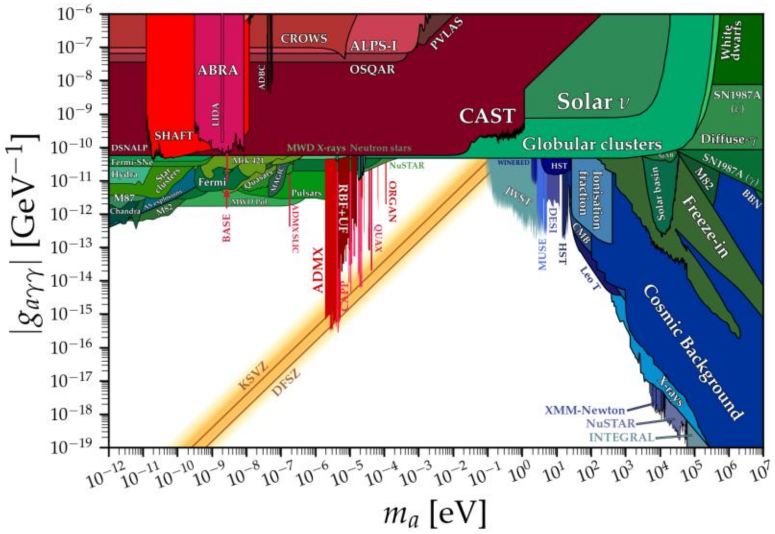

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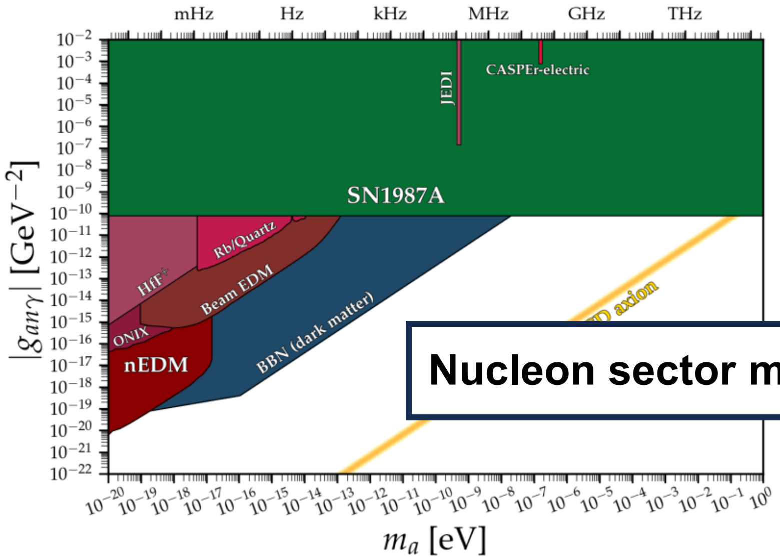

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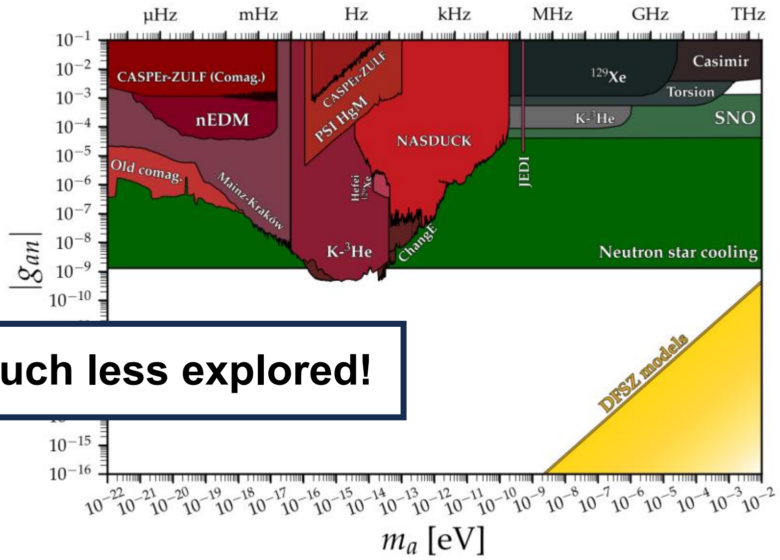

Nucleon sector much less explored!

Figure: “Axion Limits”, C. O’Hare

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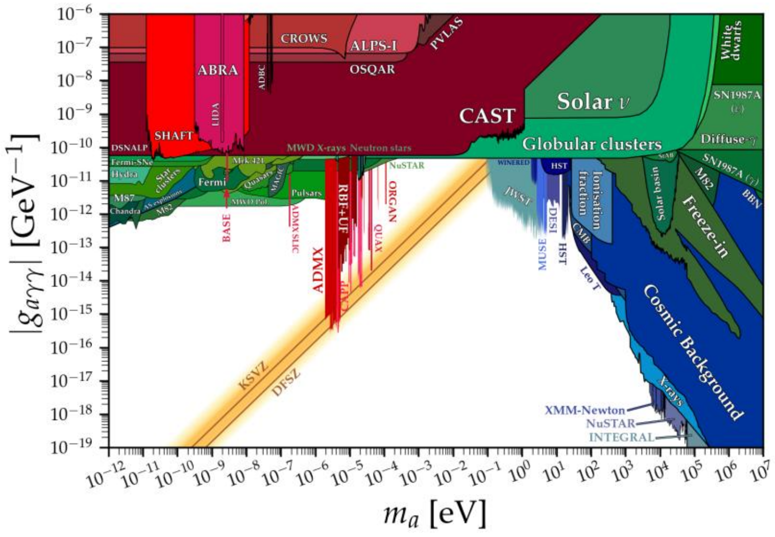

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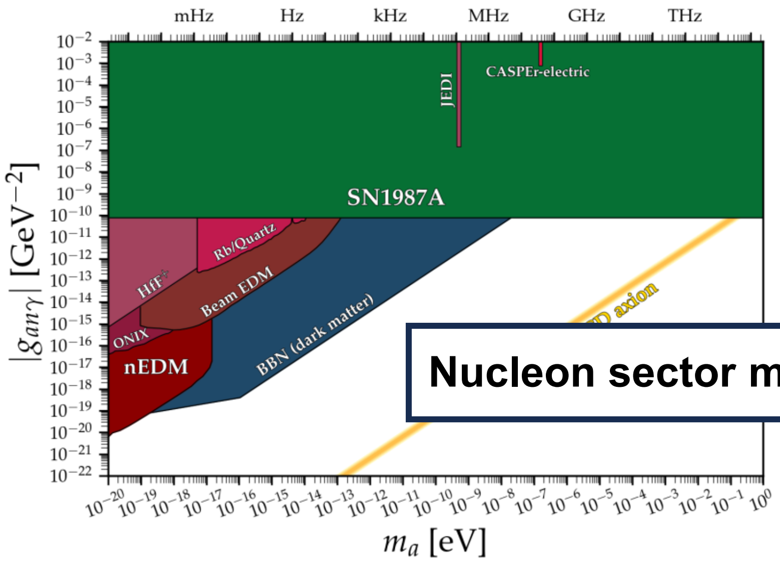

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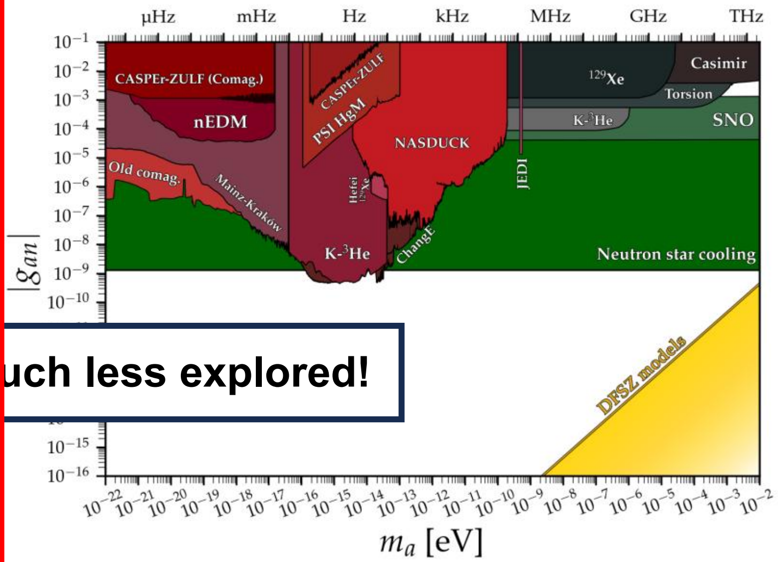

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Figure: "Axion Limits", C. O'Hare

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

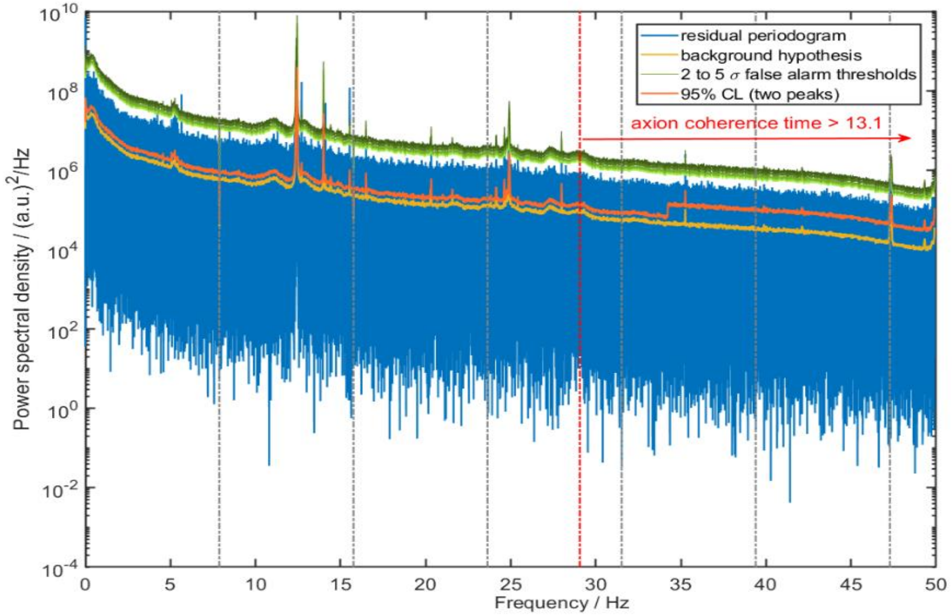
$$\mathcal{L}_{aNN} = -\frac{C_N}{2f_a}\partial_\mu a \bar{N}\gamma^\mu\gamma_5 N \Rightarrow H_{\text{int}}(t) = \frac{C_N}{2f_a}\sin(m_a t)\boldsymbol{\sigma}_N\cdot\boldsymbol{p}_a \qquad \left(g_{aNN} = \frac{C_N m_N}{2f_a}\right)$$

→ Axion induces pseudomagnetic field

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

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)

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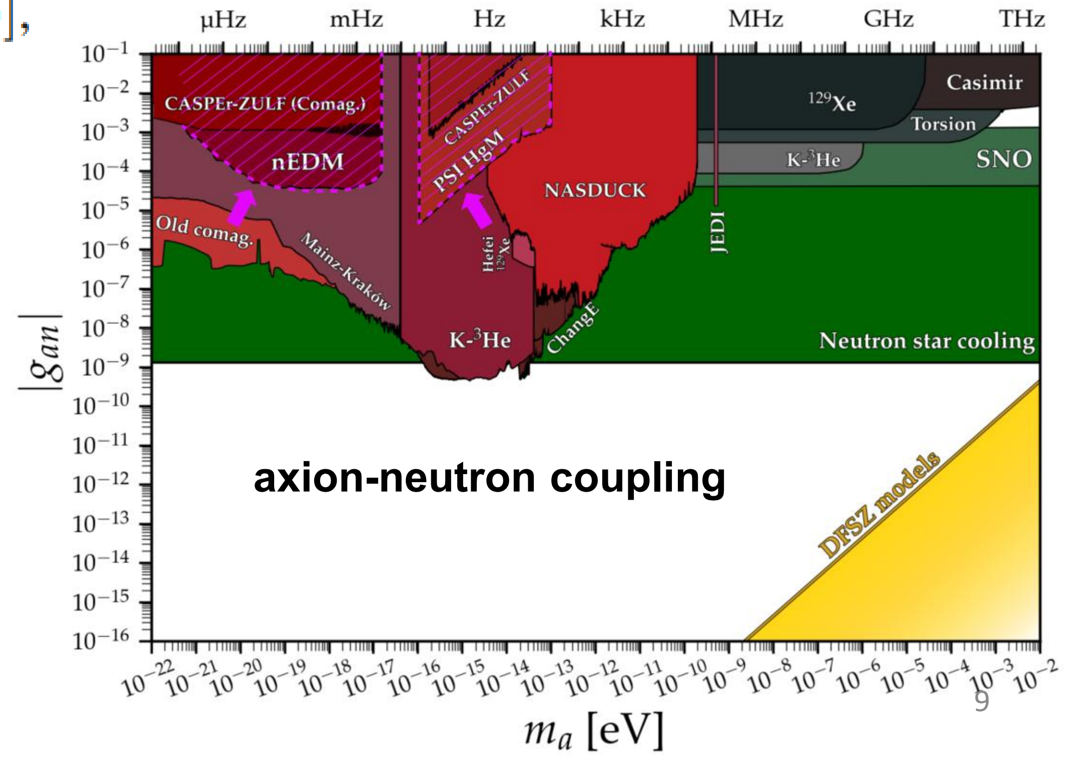

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New approach: axion wind on ^{199}Hg/^{201}Hg comagnetometer

$$H = -\mu \cdot B + \frac{C_i\sqrt{2\rho}|v_a|}{2f_a}\sin(m_a t)\boldsymbol{\sigma}\cdot\hat{\boldsymbol{v}}_\alpha$$

$$\frac{f_{201}}{f_{199}} = \frac{\mu_{201}B - (C_N/2f_a)\sqrt{2\rho}|v_a|\sin(m_a t)\,\boldsymbol{\sigma}_{N,201}\cdot\hat{\boldsymbol{v}}_a}{\mu_{199}B - (C_N/2f_a)\sqrt{2\rho}|v_a|\sin(m_a t)\,\boldsymbol{\sigma}_{N,199}\cdot\hat{\boldsymbol{v}}_a}$$

$$\approx \frac{\mu_{201}}{\mu_{199}} - \boxed{\frac{(C_N/2f_a)\sqrt{2\rho}|v_a|\sin(m_a t)}{\mu_{199}B}\boldsymbol{\sigma}_{N,201}\cdot\hat{\boldsymbol{v}}_a\left(1 - \frac{\mu_{201}}{\mu_{199}}\frac{\sigma_{N,199}}{\sigma_{N,201}}\right)}$$

varying term

Nucleus	Magnetic moment μ	Schmidt $\langle s_z\rangle^0$	Minimal model $\langle s_n^z\rangle$	Minimal model $\langle s_p^z\rangle$	Preferred model $\langle s_n^z\rangle$	Preferred model $\langle s_p^z\rangle$
^{3}He	−2.127	0.500	0.500	0.000	0.500	0.000
^{129}Xe	−0.778	0.500	0.379	0.121	0.365	0.135
^{131}Xe	0.691	−0.300	−0.252	−0.048	−0.246	−0.054
^{135}Ba	0.838	−0.300	−0.267	−0.033	−0.263	−0.037
^{137}Ba	0.937	−0.300	−0.278	−0.022	−0.275	−0.025
^{171}Yb	0.494	−0.167	−0.151	−0.015	−0.150	−0.017
^{173}Yb	−0.648	−0.357	−0.140	−0.217	−0.114	−0.243
^{199}Hg	0.506	−0.167	−0.151	−0.014	−0.151	−0.016
^{201}Hg	−0.560	0.500	0.356	0.144	0.339	0.161

Stadnik, Y. V., & Flambaum, V. V. (2015) EPJ C **75**, 110
Stones, N.J. (2005), Atomic Data and Nuclear Data Tables **90**, 75

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

$$H = -\mu \cdot B + \frac{C_i \sqrt{2\rho}|v_a|}{2 f_a} \sin(m_a t) \boldsymbol{\sigma} \cdot \hat{\boldsymbol{v}}_\alpha$$

$$\frac{f_{201}}{f_{199}} = \frac{\mu_{201} B - (C_N/2f_a)\sqrt{2\rho}|v_a| \sin(m_a t)\, \boldsymbol{\sigma}_{N,201} \cdot \hat{\boldsymbol{v}}_a}{\mu_{199} B - (C_N/2f_a)\sqrt{2\rho}|v_a| \sin(m_a t)\, \boldsymbol{\sigma}_{N,199} \cdot \hat{\boldsymbol{v}}_a}$$

$$\approx \frac{\mu_{201}}{\mu_{199}} - \frac{(C_N/2f_a)\sqrt{2\rho}|v_a| \sin(m_a t)}{\mu_{199} B} \boldsymbol{\sigma}_{N,201} \cdot \hat{\boldsymbol{v}}_a \left(1 - \frac{\mu_{201}}{\mu_{199}} \frac{\sigma_{N,199}}{\sigma_{N,201}}\right)$$

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Nucleus	Magnetic moment μ	Schmidt $\langle s_z \rangle^0$	Minimal model		Preferred model	
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~> 1 ⇒ sensitive

$$\delta\left(\frac{C_N}{2f_a}\right) = \left(\frac{\sqrt{2\rho}|v_a| \sin(m_a t)}{\mu_{199}} \hat{\boldsymbol{v}}_a \cdot \boldsymbol{\sigma}_{N,201} \left(1 - \frac{\mu_{201}}{\mu_{199}} \frac{\sigma_{N,199}}{\sigma_{N,201}}\right)\right)^{-1} \delta B$$

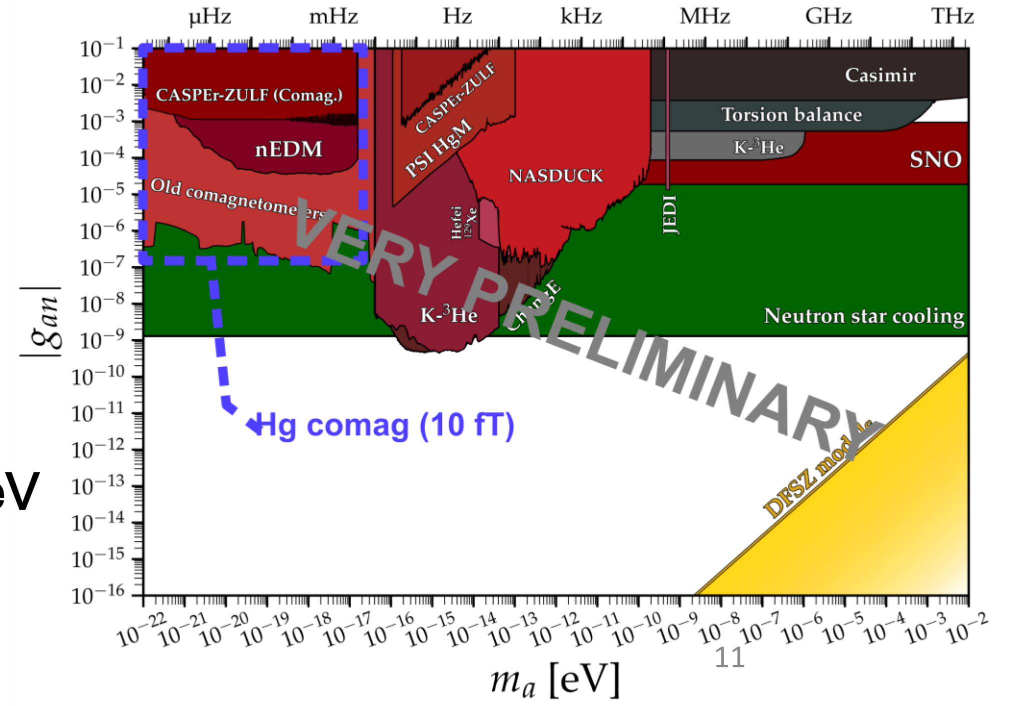
$$\rho_{\mathrm{DM}} = 0.4\,\mathrm{GeV/cm^3}$$

$$|v_a| \approx v_0 \approx 10^{-3} c$$

$$|\sin(m_a t)| \approx 1$$

~2x10^{2} eV*T

= 0.6 (Schmidt model)



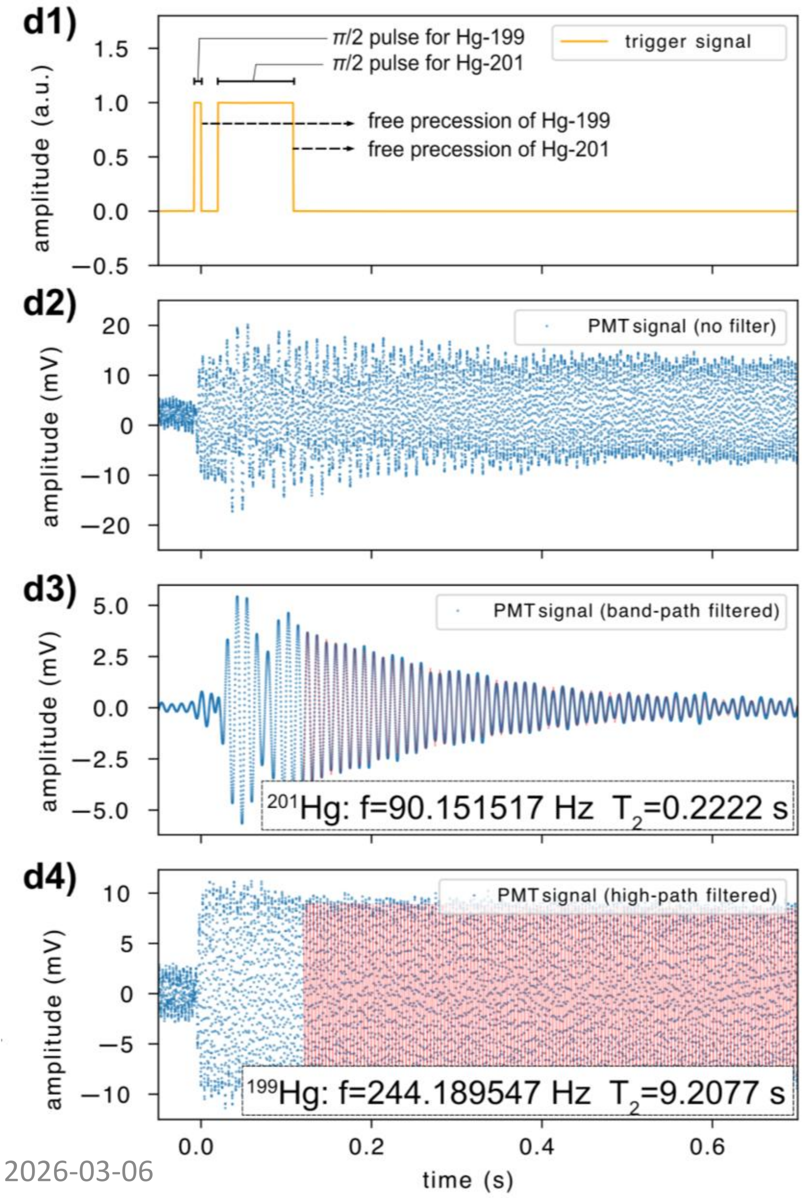
$$\delta\left(\frac{C_n}{2f_a}\right)/\delta B \sim 10^{-2}\text{–}10^{-1}\,\mathrm{eV/T}$$

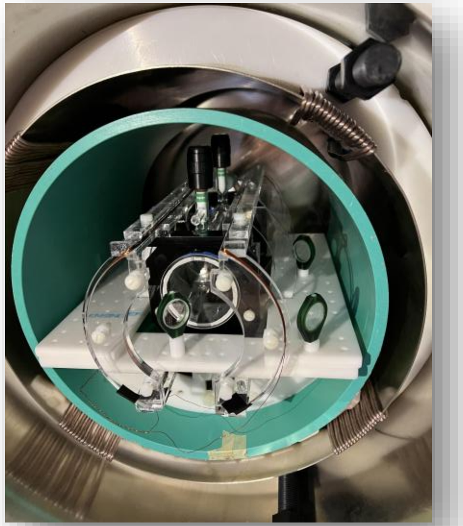
➡ δB ~10 fT → δ($C_n/2f_a$) ~ 10^{-16} eV (g_{an}~ 10^{-7})

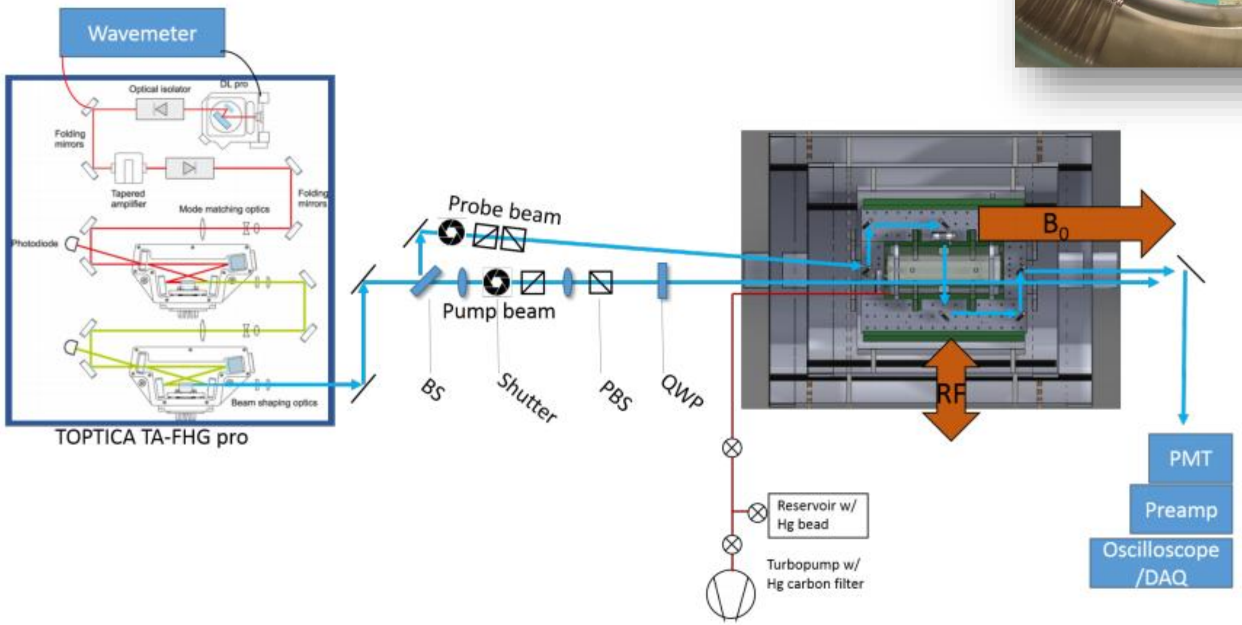
Stadnik, Y. V., & Flambaum, V. V. (2015) EPJ C **75**, 110

Stones, N.J. (2005), Atomic Data and Nuclear Data Tables **90**, 75

Experiment with a test setup (40 h measurement in August 2024)







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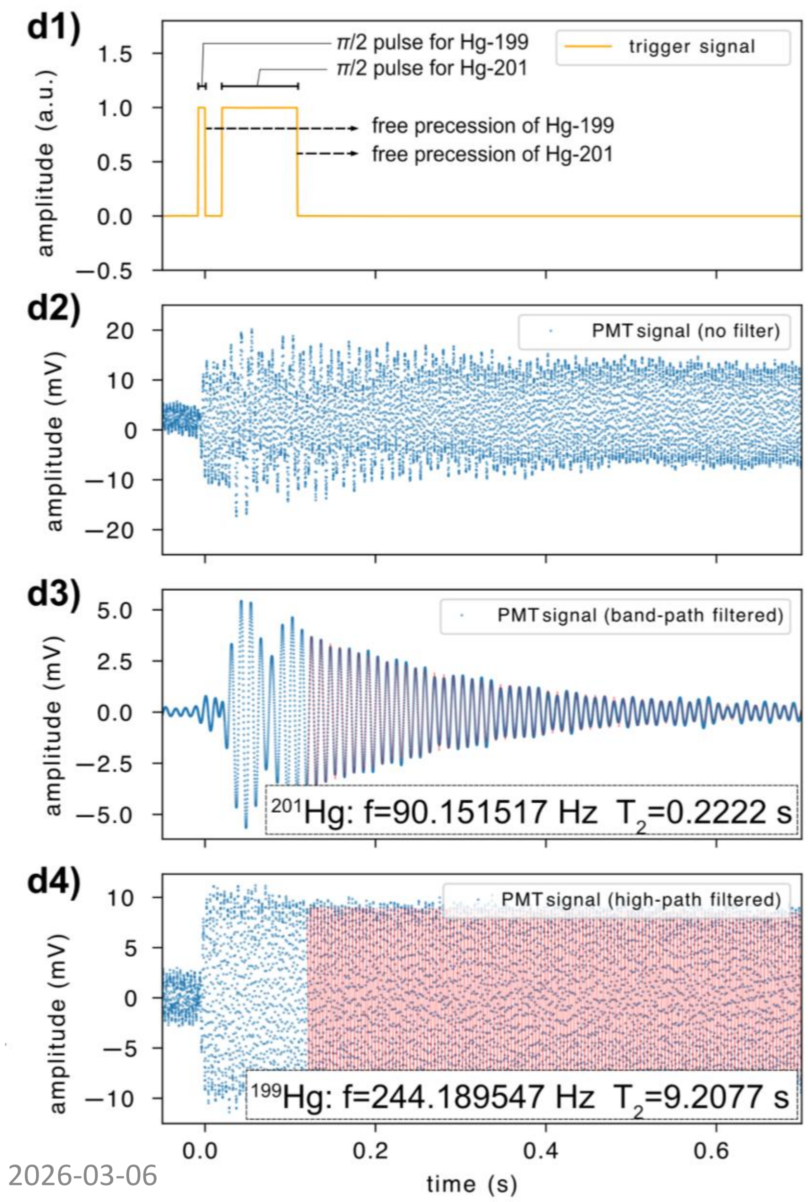
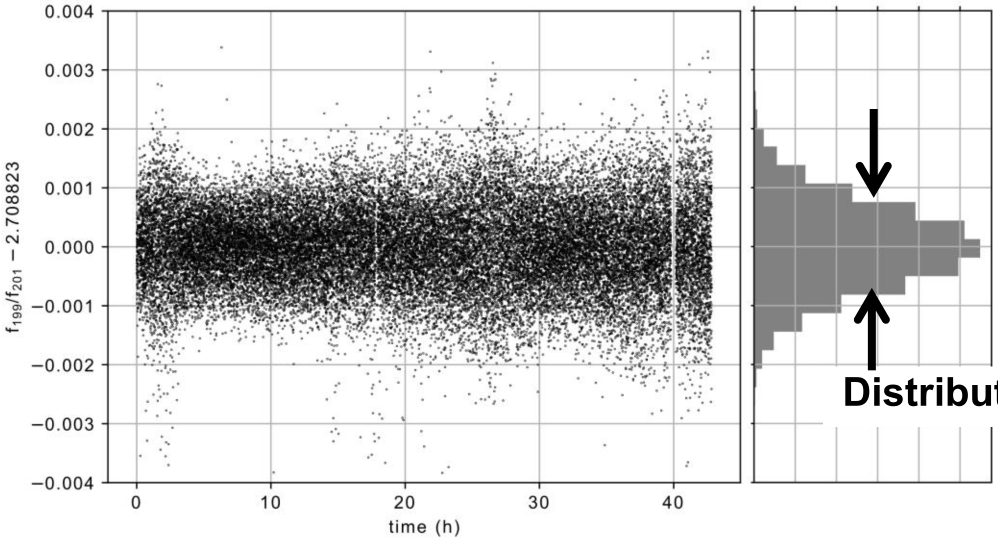
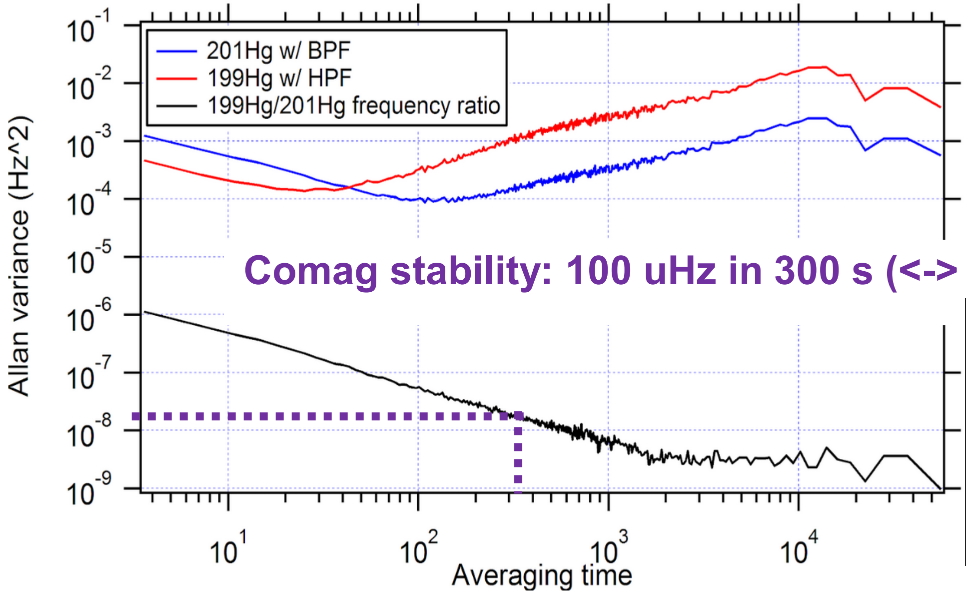


Frequency ratio f_{199}/f_{201}



Distribution width ~1 mHz (<-> 1 nT)



Comag stability: 100 uHz in 300 s (<-> 100 pT)

Limitation (relaxation time):

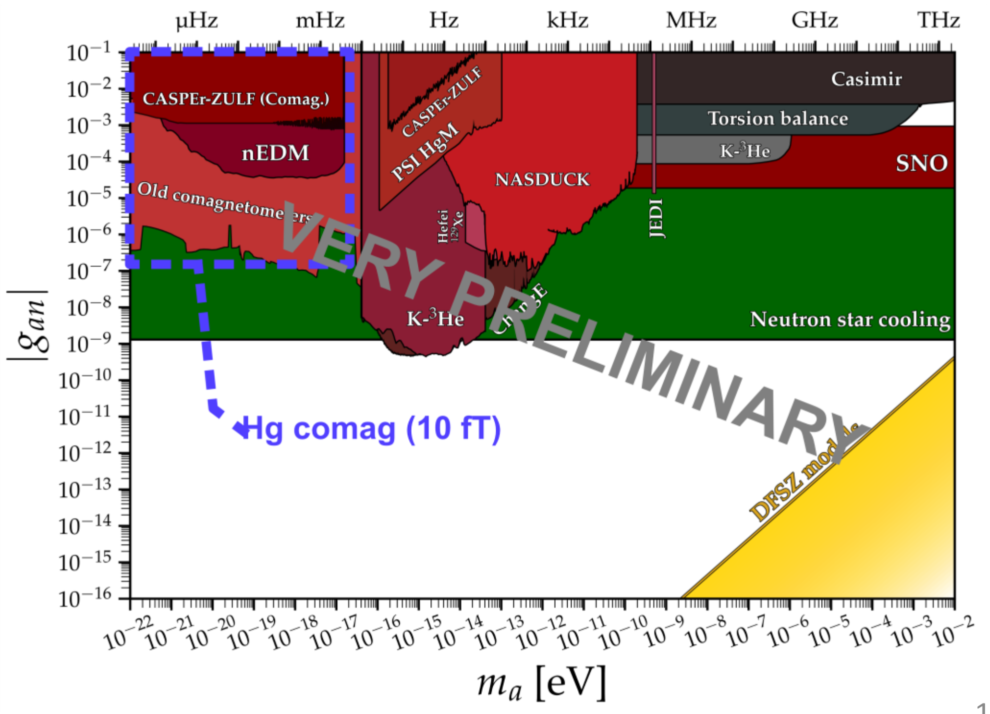
- Wall collisions (^{201}Hg)
- Magnetic field inhomogeneity

Analysis of test measurement

- Obtained Lomb-Scargle periodogram (used astropy package) → up to 1 nT amplitudes
- To evaluate the CL:
  - Generate simulation data with the same statistical properties → Evaluate CLs for each frequency bin
- Three orders of magnitude for the precedent work, five orders of magnitudes to go to the final goal ($\Delta B \sim 1$ nT → 10 fT)
- Strategies for improvement:
  - Improvement in T_2 by ~x100
  - Smaller B_0 by x30
  - Improvement on S/N
  - Measurement time x10-100

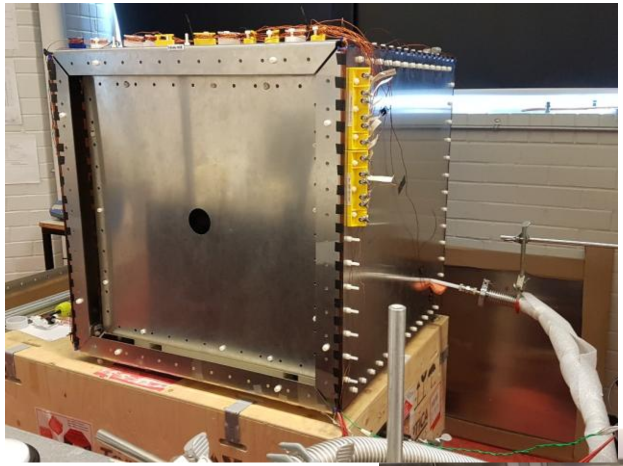
Cramer-Rao lower bound (CRLB)

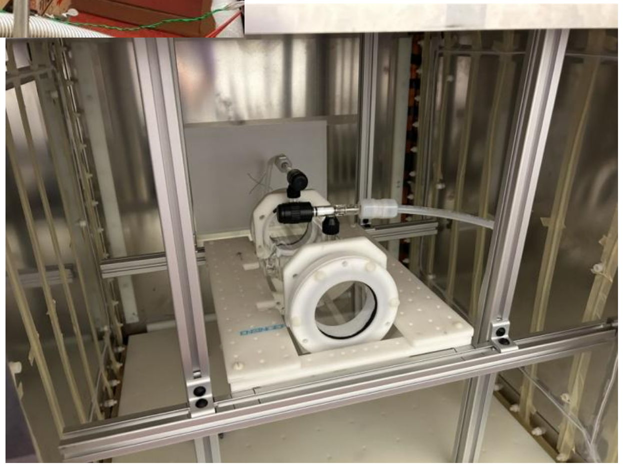
$$\delta B \geq \frac{\sqrt{12}}{\gamma_{\mathrm{Hg}} \frac{a_s}{\rho} T^{3/2}} \sqrt{C(r = T/\tau)}$$



Upgrades during 2025

- Improved magnetic shielding → smaller magnetic gradient → better T_2
- Coating for reducing depolarization by wall collisions
- Development of non-magnetic valve





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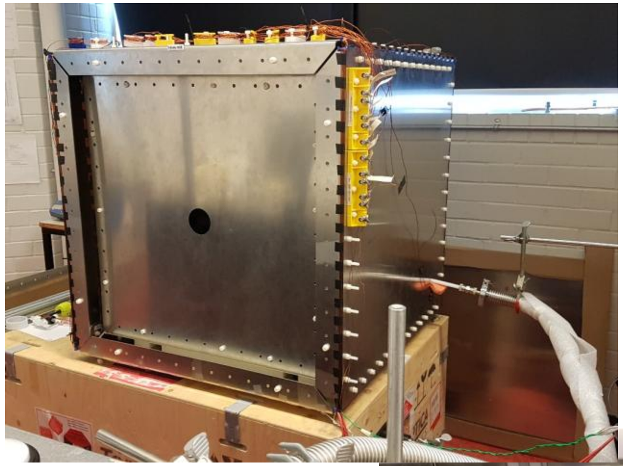

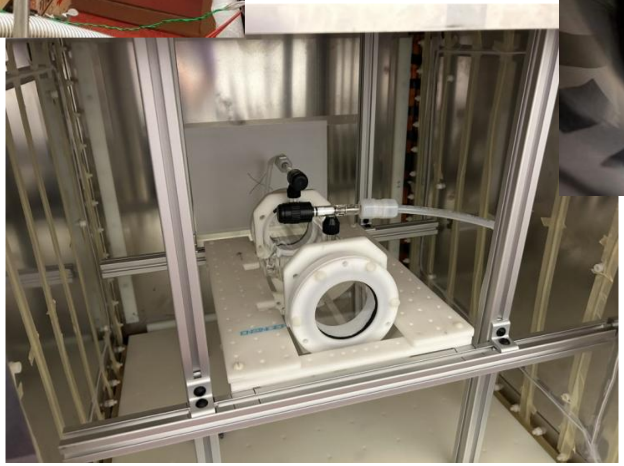

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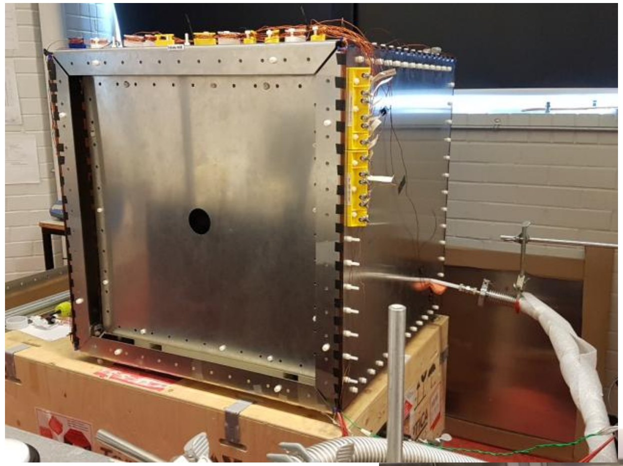
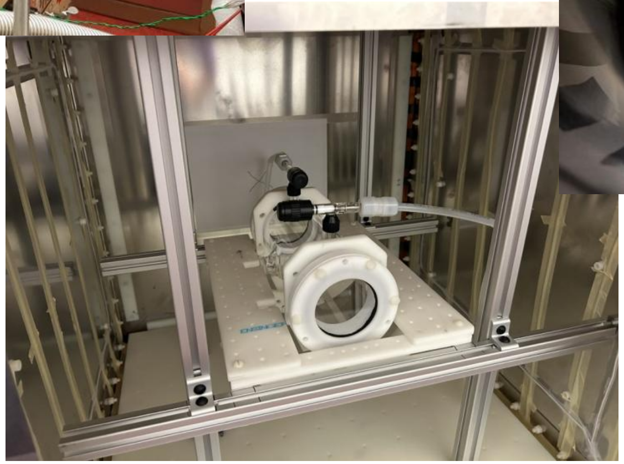
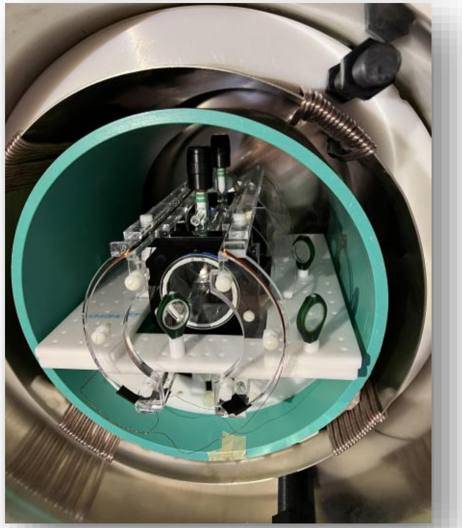
- Coating for reducing depolarization by wall collisions
- Development of non-magnetic valve

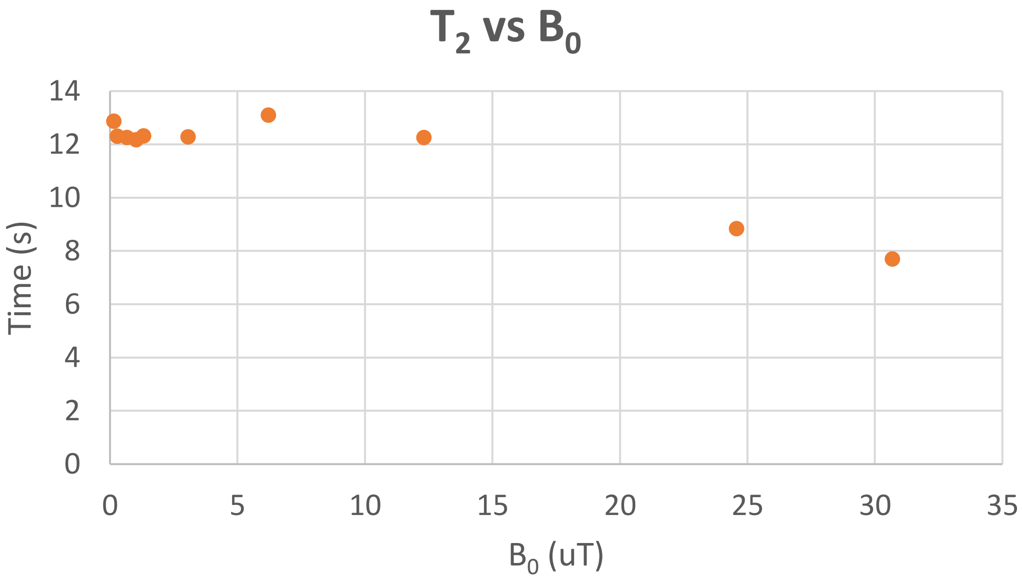


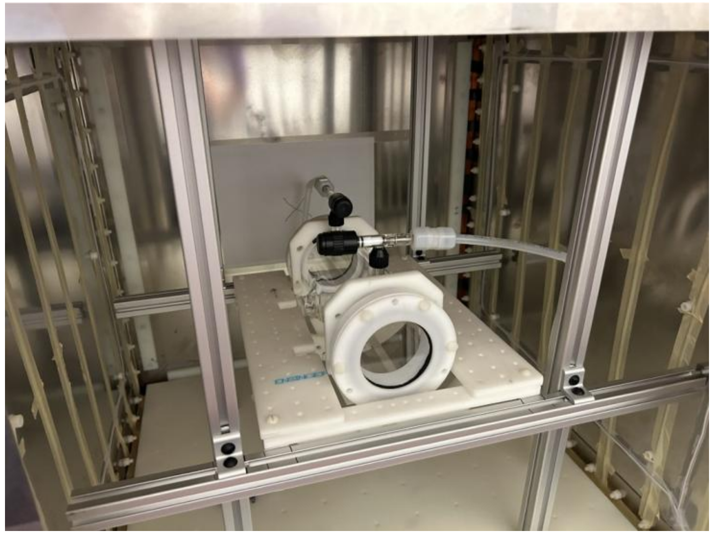


Upgrades during 2025: magnetic shielding

- 3-layer cylindrical shield OD~300 mm → 2-layer cubic shield ~$(1m)^3$
- T_2 under B_0=1 uT, improved by 30%

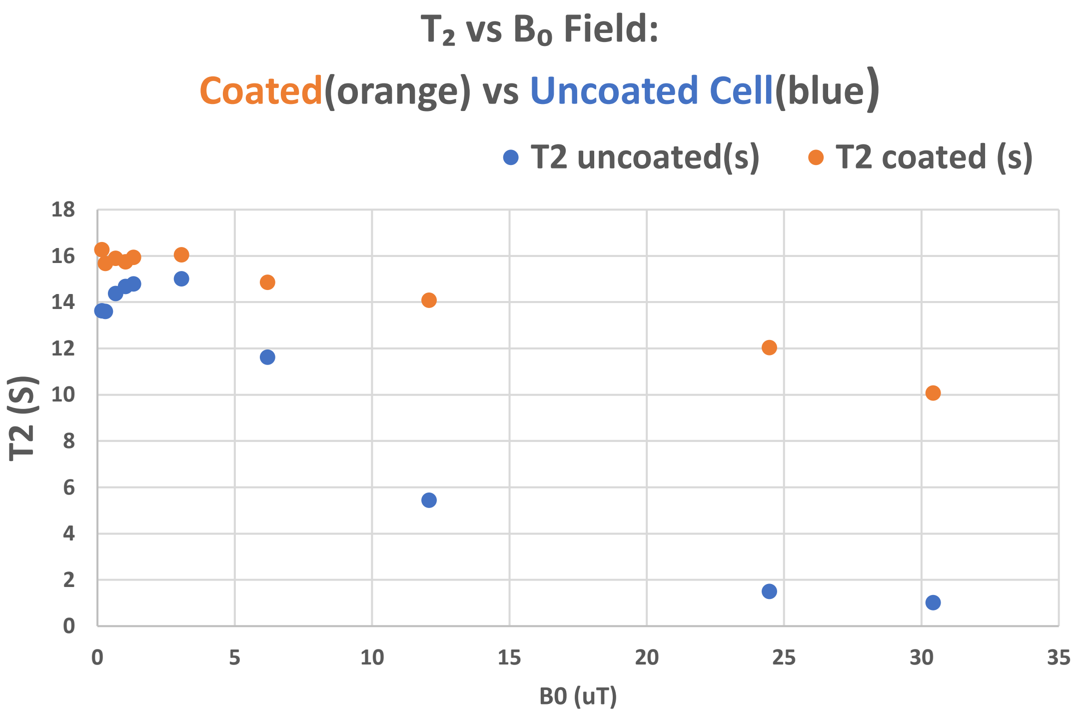






Upgrades during 2025: cell coating

- Long-chain paraffin coatings (e.g. C32H66) applied to the cell walls via PVD evaporation (in the future, neutron-friendly dPS)
- T_2 under B_0=1 uT, improved by 14%



Summary

- Introduced ^{199}Hg/^{201}Hg isotope comagnetometer as a new approach to search for axion-nucleon coupling in an ultralow mass range of < **10^{-17} eV**
- Status 2025:
  - Establishing the procedure of data analysis
  - Marginal improvements to achieve longer T_2 to increase stability
- Dramatic improvement anticipated by moving to the 6-layer 3.5-m magnetically shielded room for nEDM

Acknowledgements

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Thank you for your attention!