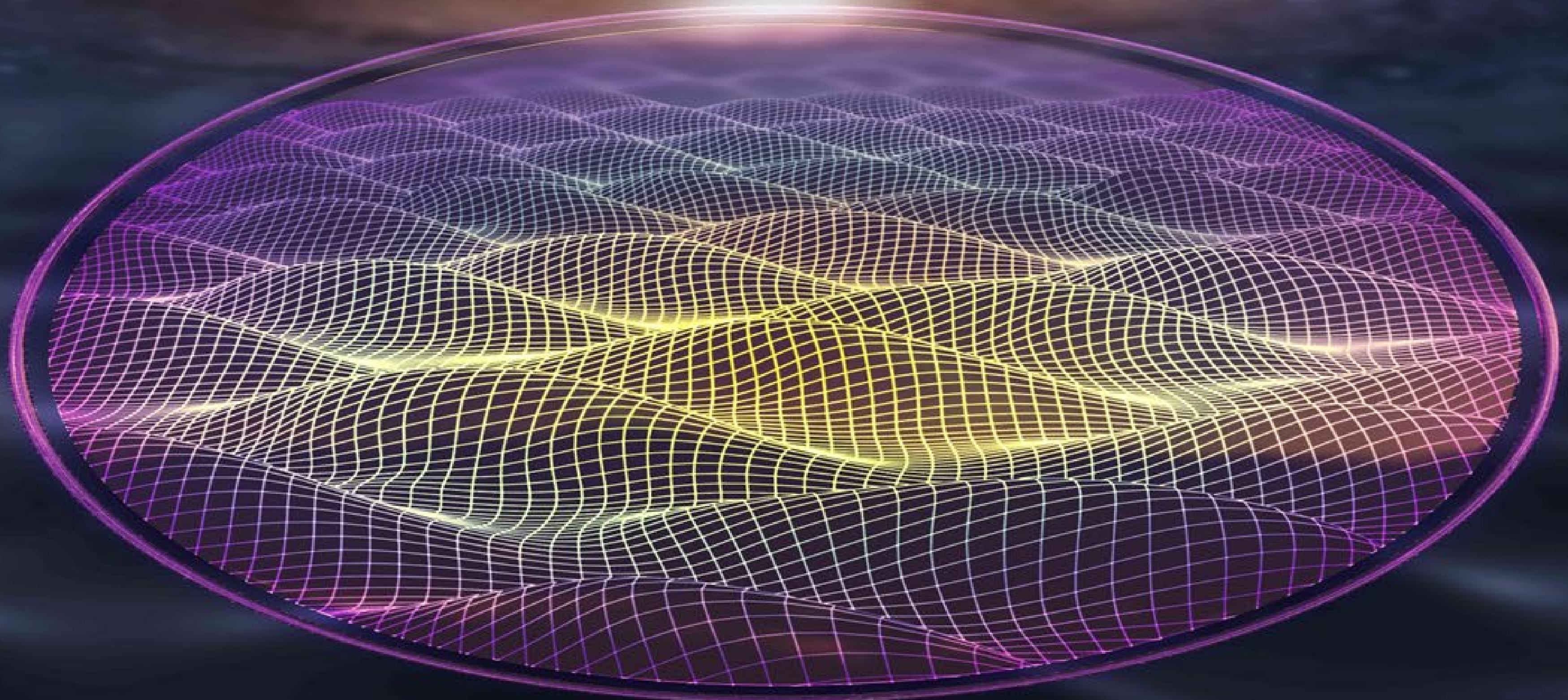
Search for axion-like dark matter with ferromagnets

Alex Sushkov
Sasha Gramolin, Deniz Aybas, Janos Adam, Dorian Johnson



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Axions and axion-like particles, axion-like dark matter

1. Pseudoscalar light particle: spin = 0, wide range of possible masses [Phys. Rev. D **98**, 035017 (2018)]
2. Proposed to solve the strong CP problem of Quantum Chromodynamics [Phys. Rev. Lett. **38**, 1440 (1977)]
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axion-like dark matter

ALP mass range $m_a c^2 < \mathrm{meV}$

+

dark matter energy density: $\rho_{\mathrm{DM}} \approx 0.4\,\frac{\mathrm{GeV}}{\mathrm{cm}^3} \approx (0.05\,\mathrm{eV})^4$

↓

large number of particles per de Bloglie wavelength

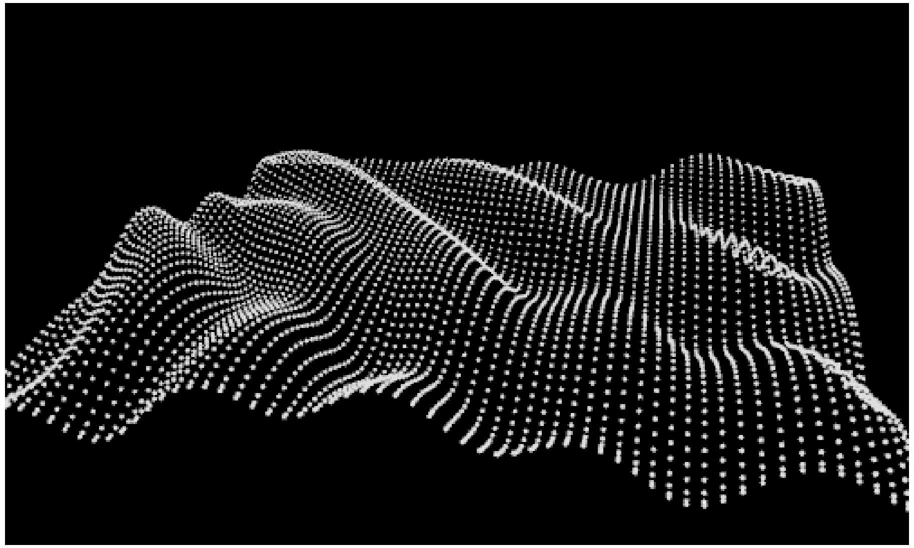
↓

ALP dark matter acts as a classical field

axion-like field: $a(t) = a_0 \cos \omega_a t$

$\omega_a = m_a c^2/\hbar$ → ALP Compton frequency

$\rho_{\mathrm{DM}} \propto a_0^2$ → dark matter density



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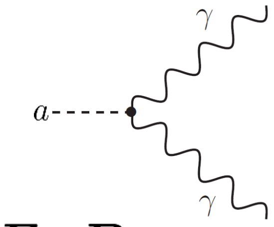
interaction with photons:

ALP field amplitude → $\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$ ← symmetry breaking scale



$$\mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma} a \boldsymbol{E} \cdot \boldsymbol{B}$$

→ ALP ↔ photon conversion in a magnetic field
→ precision electromagnetic sensors

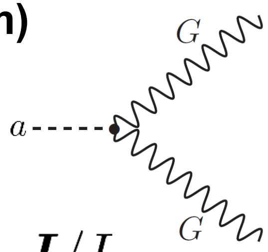
ADMX, HAYSTAC, DMradio, ABRA, ALPS, CAST, IAXO, CAPP, ORGAN, SLIC, BREAD, LC circuit, MADMAX, KLASH, BRASS, many others

SHAFT → a kHz-MHz search using SQUIDs and ferromagnetic toroidal cores

[A.Gramolin et al., *Nature Physics* **17**, 79 (2021)]

interaction with gluons: (strong-CP problem)

$$\frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu}$$



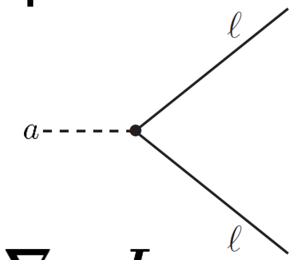
$$\mathcal{H}_{\mathrm{EDM}} = g_d a \boldsymbol{E}^* \cdot \boldsymbol{I}/I$$

→ nuclear spin $\boldsymbol{I}$ interacts with an oscillating electric dipole moment (EDM) $d_n = g_d a$ in presence of effective electric field $\boldsymbol{E}^*$.

CASPEr-electric

interaction with leptons:

$$\frac{\partial_\mu a}{f_a} \bar{\psi}_\ell \gamma^\mu \gamma_5 \psi_\ell$$



$$\mathcal{H}_{aNN} = g_{aNN} \boldsymbol{\nabla} a \cdot \boldsymbol{I}$$

→ nuclear spin $\boldsymbol{I}$ interacts with an effective magnetic field $\boldsymbol{\nabla} a$.

force mediator → ARIADNE
electron spin → QUAX

CASPEr-gradient

CASPEr (Cosmic Axion Spin Precession Experiments) search for experimental signatures of these interactions using precision magnetic resonance

[D. Aybas et al., *Phys. Rev. Lett.* **126**, 160505 (2021)]
[D. Aybas et al., *Quant. Sci. Tech.* (2021)]
[D. Budker et al., *Phys. Rev. X* **4**, 021030 (2014)]
[A. Garcon et al., Sci. Adv. **5**, eaax4539 (2019)]

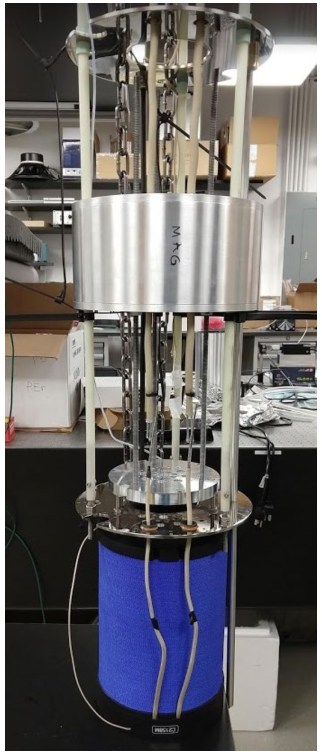
CASPEr-e experimental results

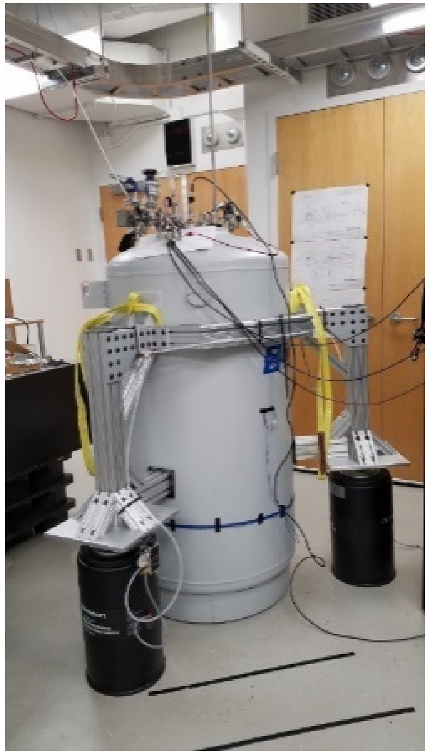
search for EDM and gradient couplings →

$$\mathcal{H}_{\rm EDM} = g_d a \boldsymbol{E}^* \cdot \boldsymbol{I}/I$$

$$\mathcal{H}_{aNN} = g_{aNN} \boldsymbol{\nabla} a \cdot \boldsymbol{I}$$

talks by Deniz Aybas and Janos Adam





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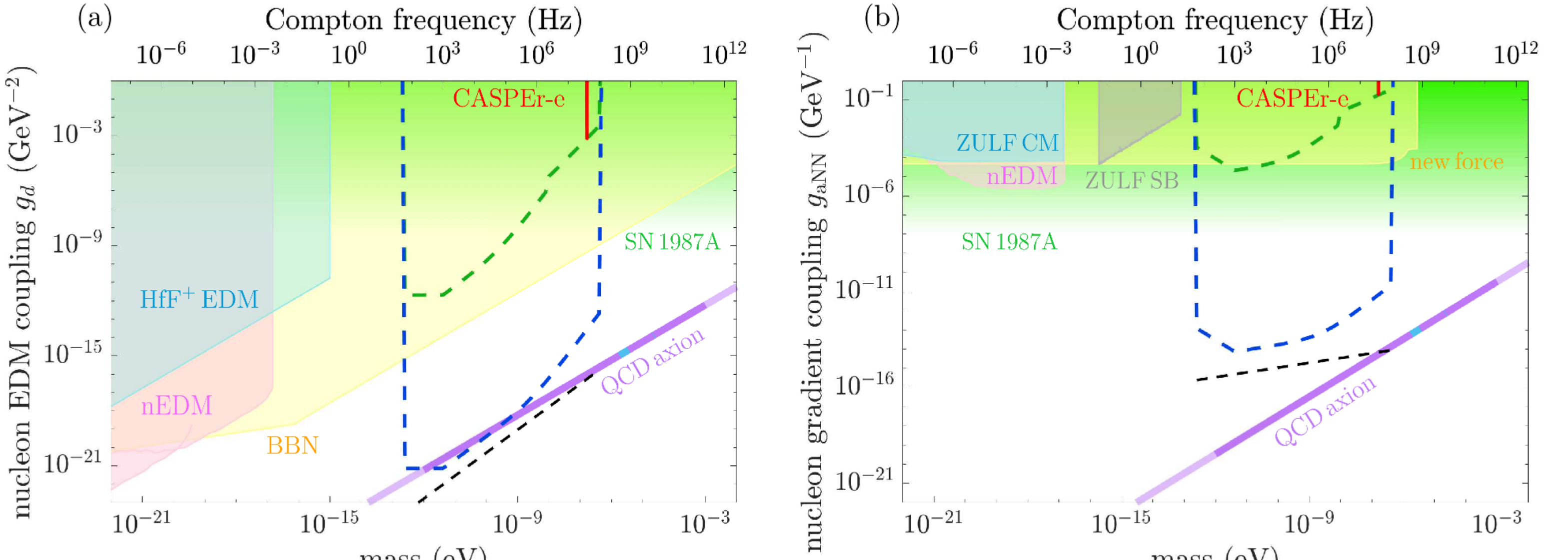
- precision magnetic resonance experiment using ^{207}Pb nuclear spin ensemble in a solid with broken inversion symmetry
- sensor → cryogenic RF amplifier, voltage noise: 0.05 nV/√Hz
  → magnetic field sensitivity @ 40 MHz: 2 fT/√Hz
- ALP search in the 162 neV to 166 neV mass range
- Limits (at 5σ level):

$$|g_d| < 9.5 \times 10^{-4}\,\mathrm{GeV}^{-2} \Leftrightarrow |d_n| < 1.0 \times 10^{-21}\,\mathrm{e\cdot cm}, \quad |\theta| < 4.3 \times 10^{-6}$$

$$|g_{aNN}| < 2.8 \times 10^{-1}\,\mathrm{GeV}^{-1}$$

↑ amplitudes of oscillations near 40 MHz

- goal: probe the QCD axion band for mass ≈ 10^{-12} to 10^{-9} eV



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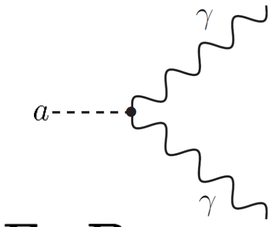
ALP field amplitude → a

symmetry breaking scale → f_a

$$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$$



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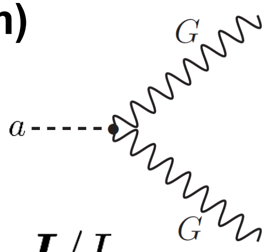

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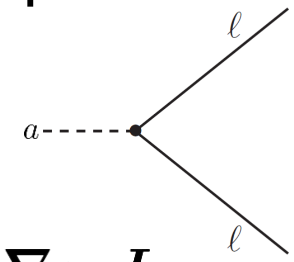

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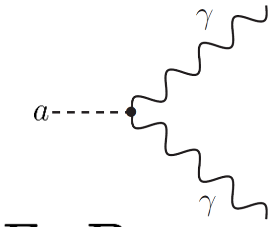

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approach → additional term in Ampere's law

$$\vec{\nabla} \times \vec{H} = \vec{J}_f$$

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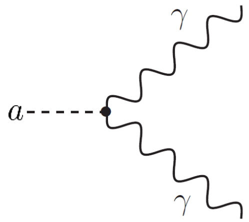

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$$\vec{\nabla} \times \vec{H} = \vec{J}_f + \frac{g_{a\gamma\gamma}}{\mu_0 c} \frac{\partial a}{\partial t} \vec{B}$$

azimuthal static magnetic field B_0

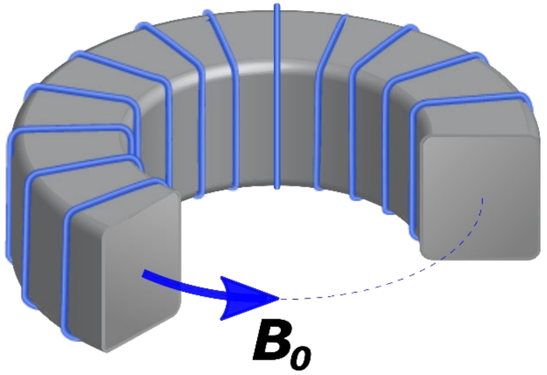
+

axion field
$$a(t) = a_0 \cos \omega_a t$$

⇓

azimuthal effective current

$$\vec{J}_{\text{eff}} = \frac{g_{a\gamma\gamma}}{\mu_0 c} \frac{\partial a}{\partial t} \vec{B}_0$$



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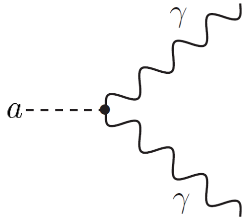

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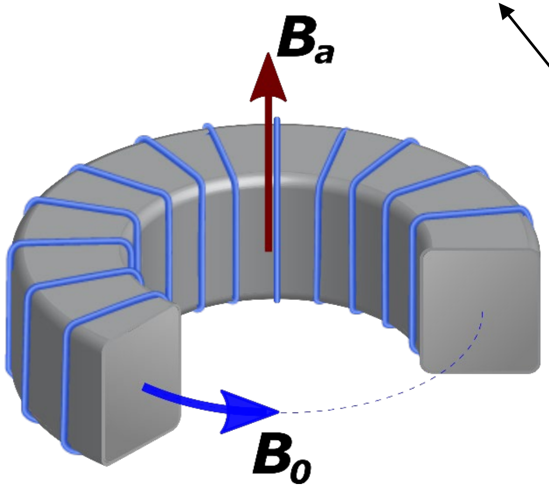

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axial oscillating magnetic field B_a

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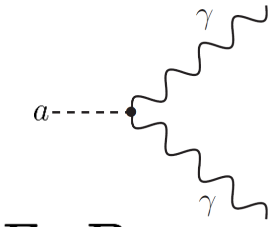

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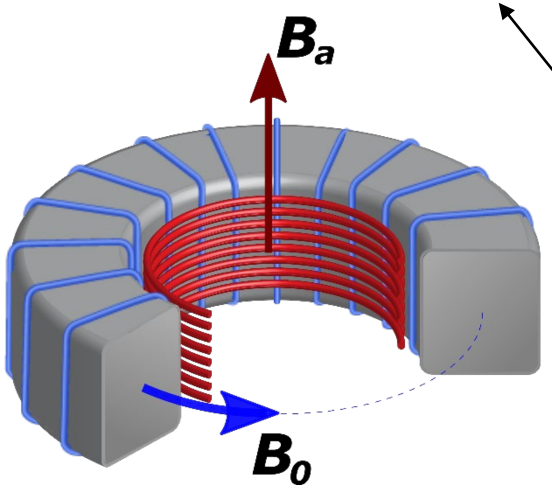

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axial oscillating magnetic field B_a

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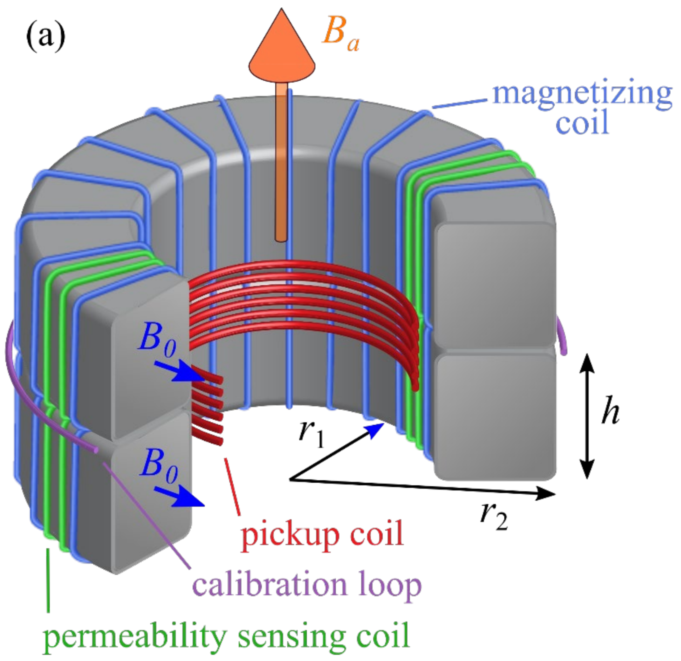
detected by SQUID

Experimental setup



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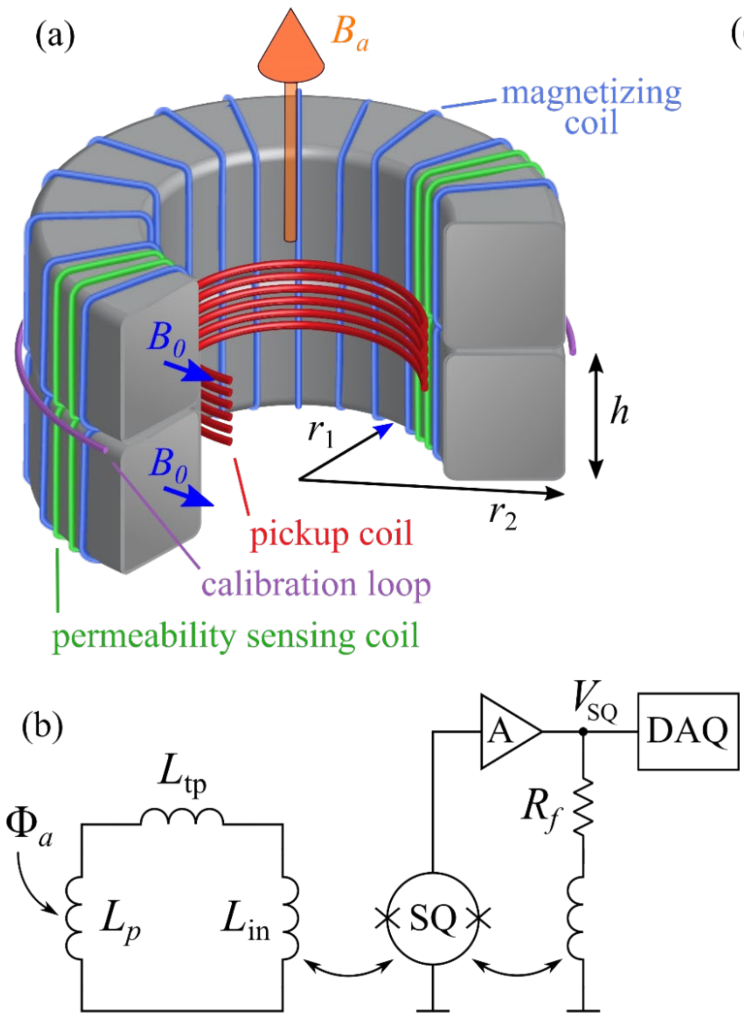

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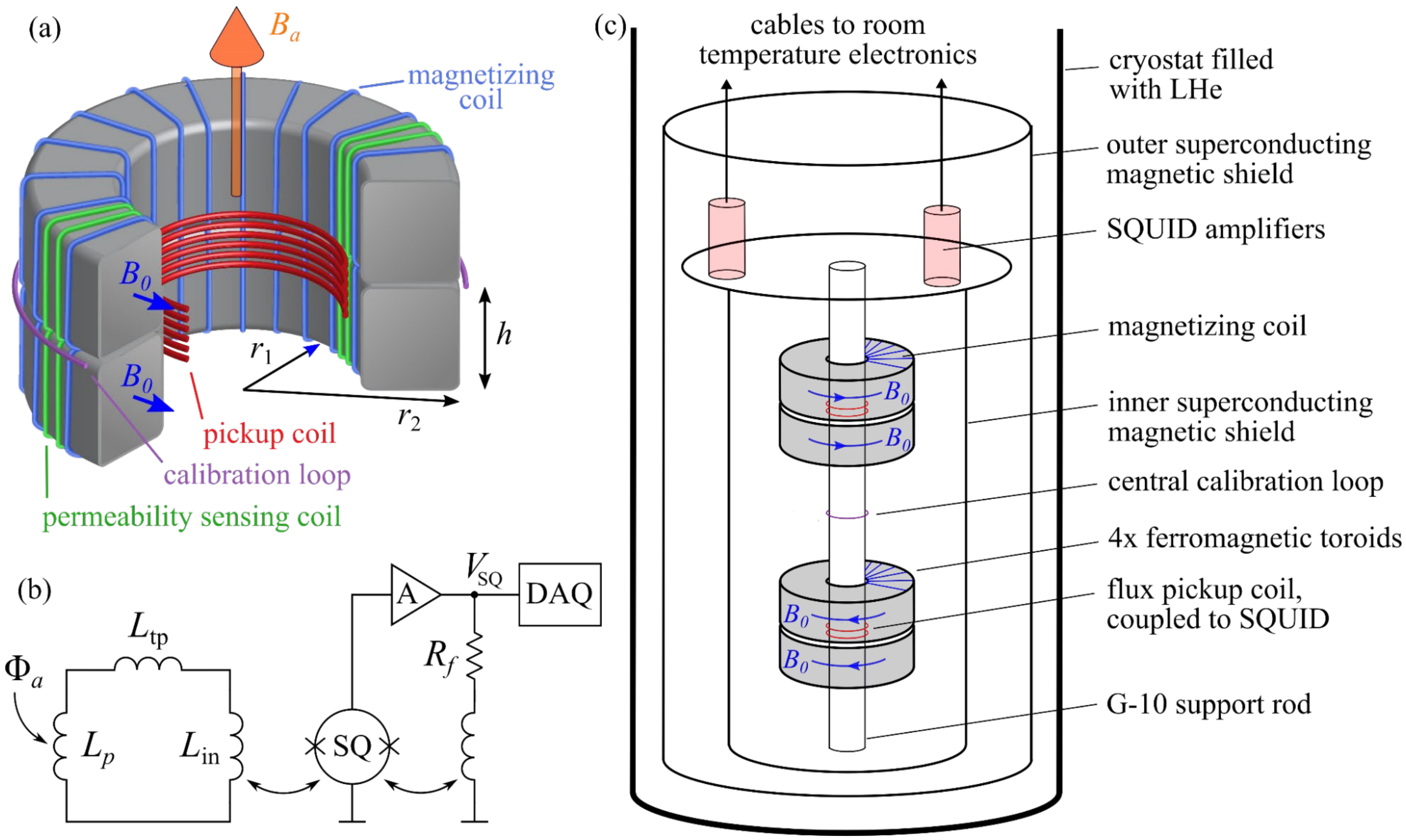

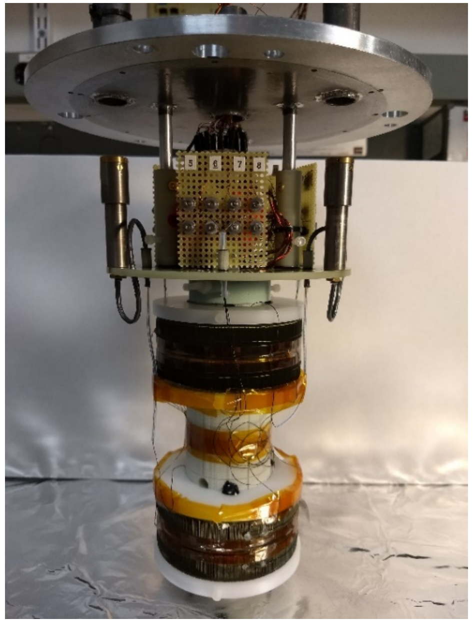

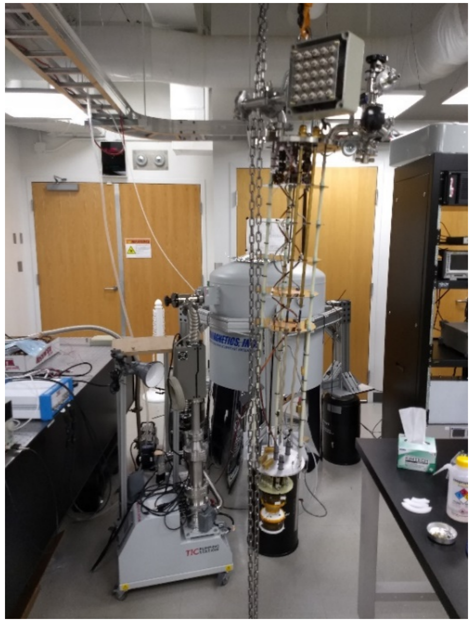

two detection channels, RF pickup appears in phase but ALP signal appears out of phase → **systematic rejection**

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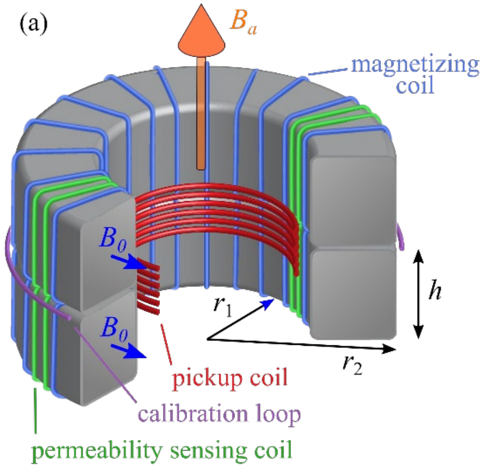
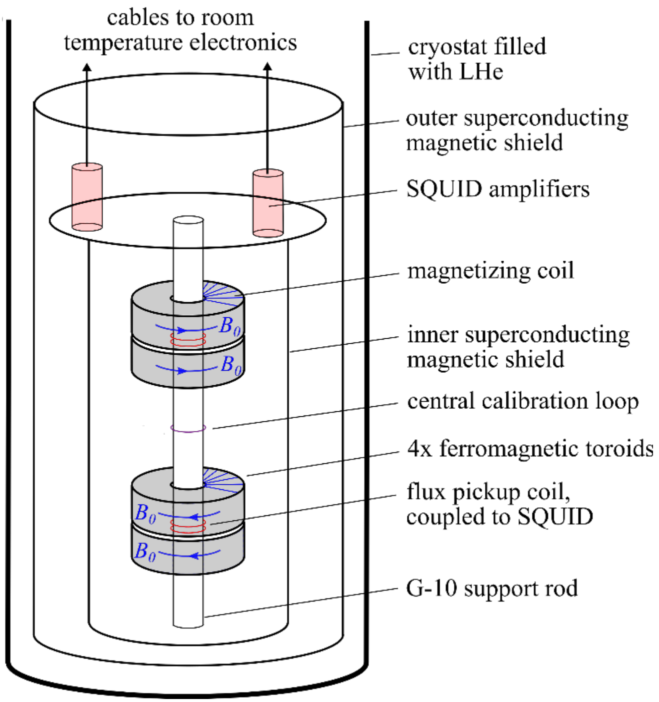
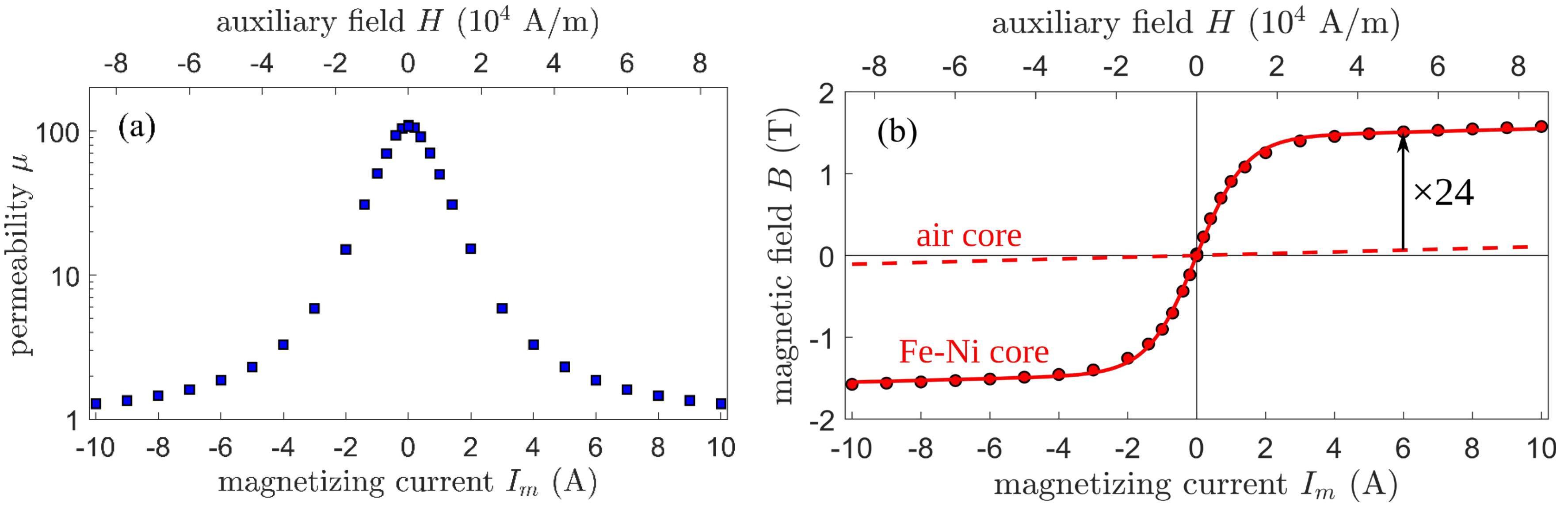
Measurements of magnetization of ferromagnetic toroids





toroid material: powdered iron-nickel alloy



- a factor of 24 enhancement of magnetic field B_0
- B_0 = 1.5 T achieved at 6 A current

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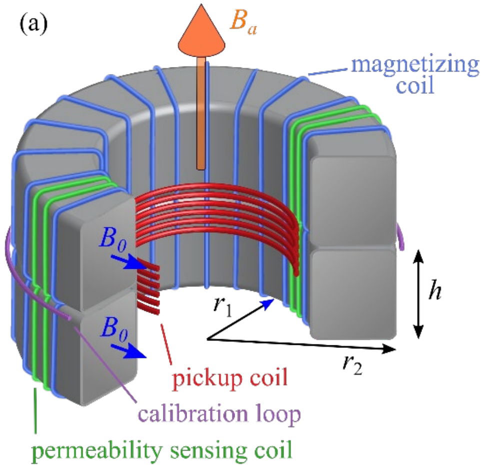
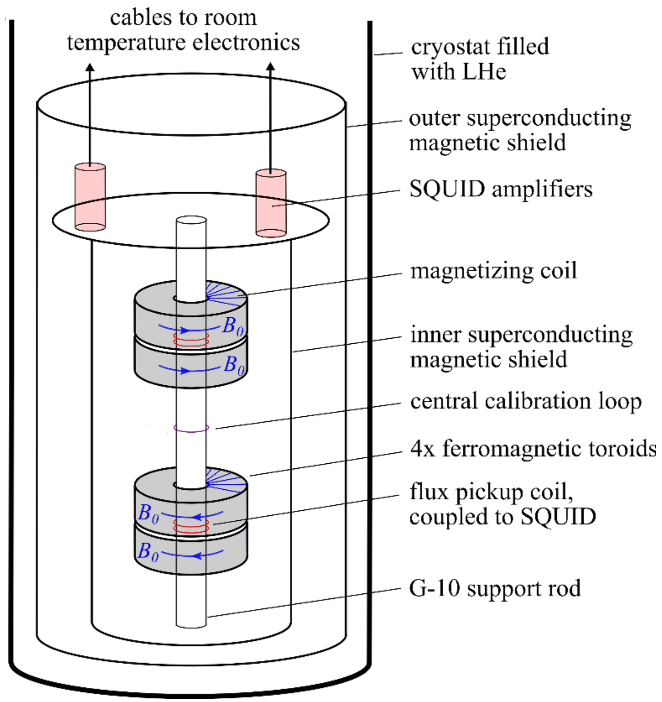
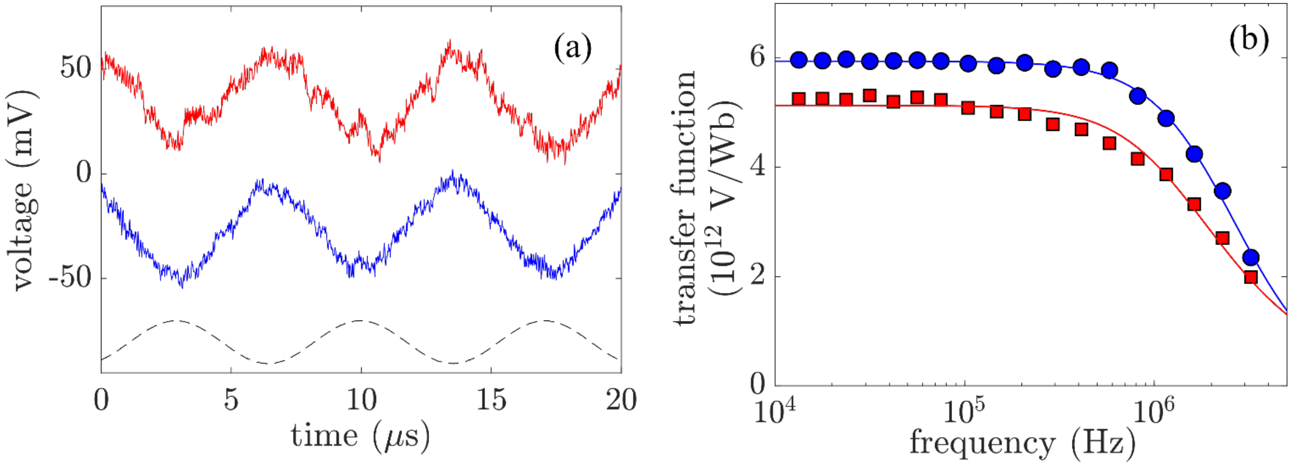
Performance of SQUID magnetic field sensors





sensor calibration



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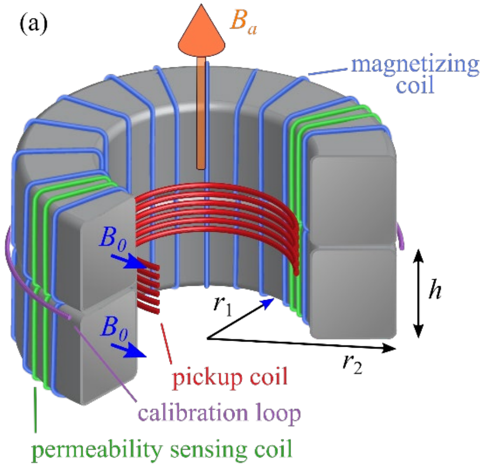

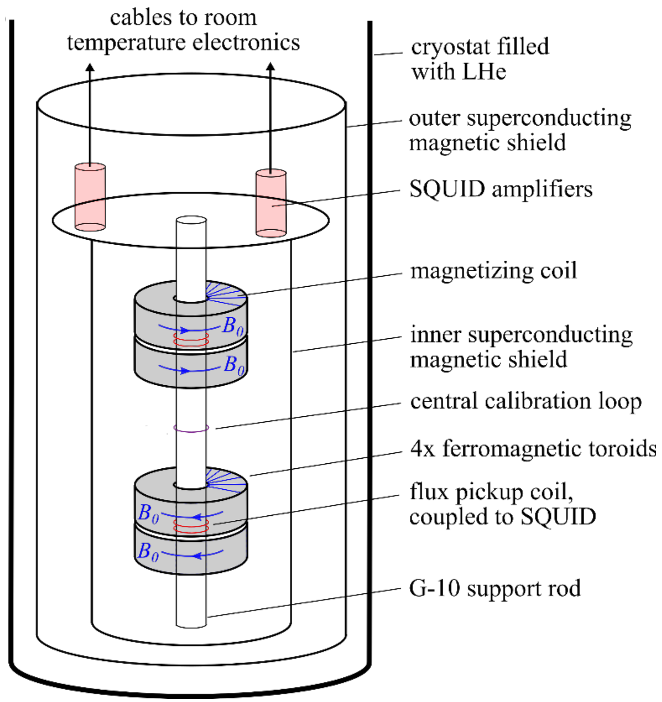

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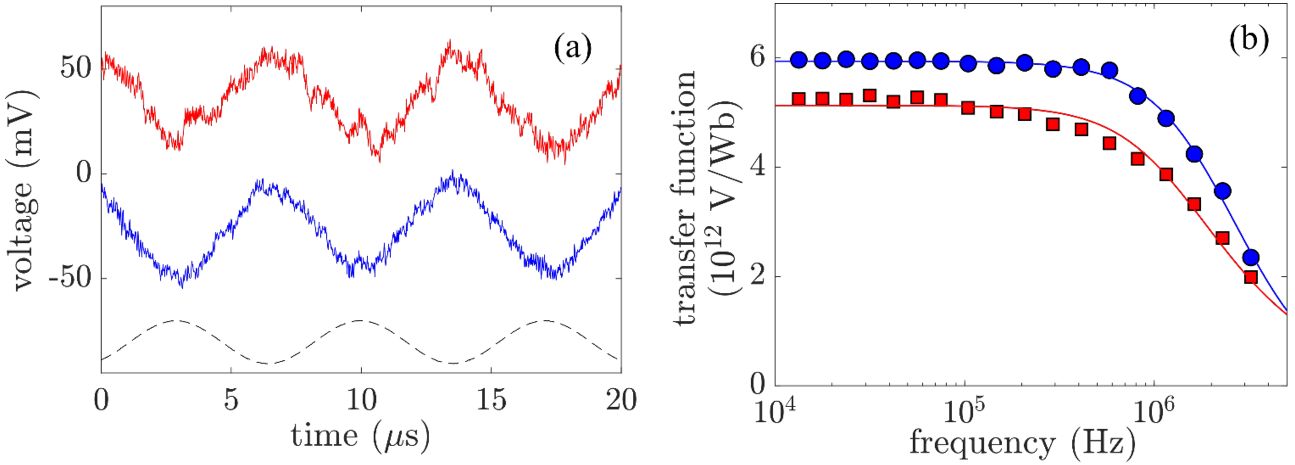

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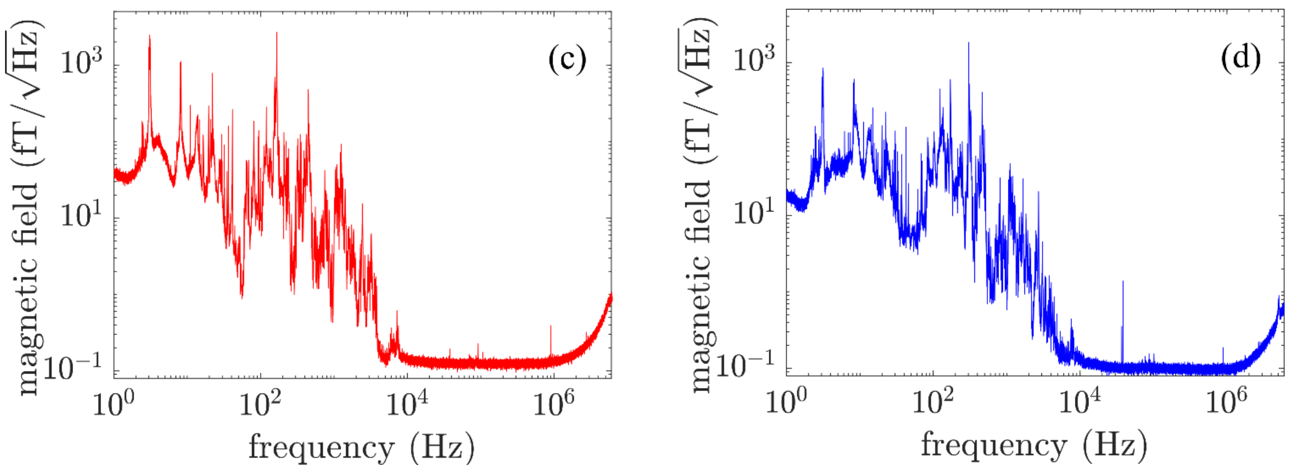
sensitivity →



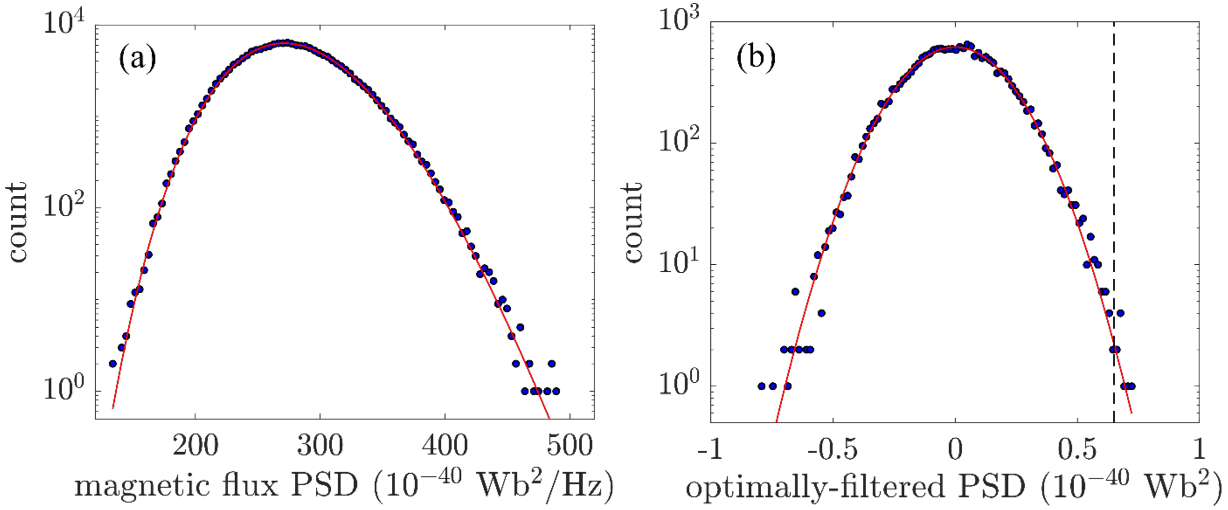
- magnetic field sensitivity → $150\,\mathrm{aT}/\sqrt{\mathrm{Hz}}$ ≈ **broadband record**

[A. Gramolin et al., *Nature Physics* **17**, 79 (2021)]

Data analysis

data statistics
(standard halo model)

- analyze data in 3-decade range: 12 peV to 12 neV, 2×10^7 possible ALP masses
- gaussian statistics; ≈ 13×10^3 candidates flagged (8×10^3 expected based on normal distribution)
- all candidates rejected by requiring detection in antisymmetric channel combination



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New limits of electromagnetic interaction of axion-like particles

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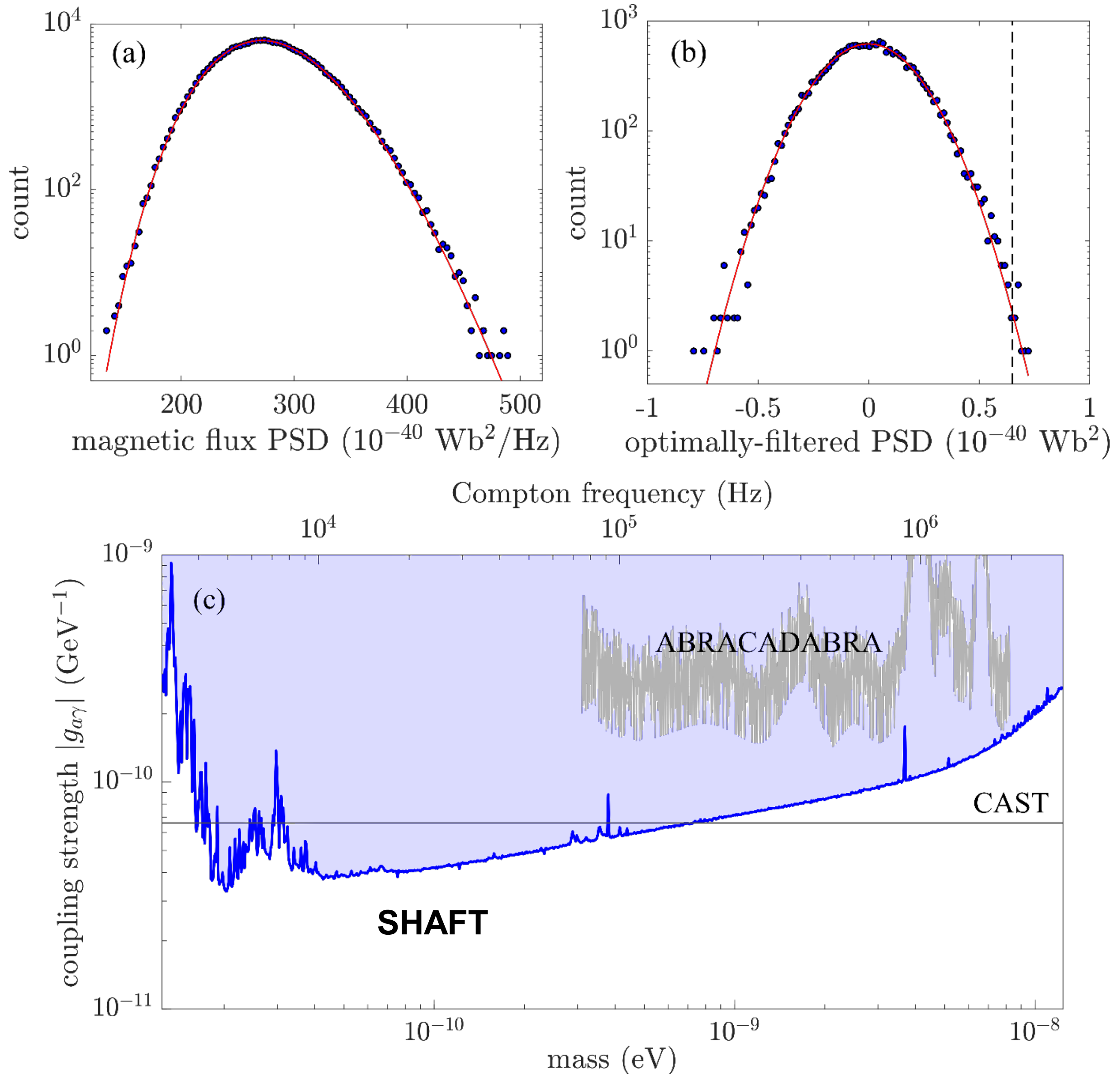
result: limit on electromagnetic
interaction of axion-like dark matter →

5σ limits reach $3.3 \times 10^{-11}\ \mathrm{GeV}^{-1}$ near 20 peV



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[new ABRA results, *arXiv:2102.06722* (2021)]

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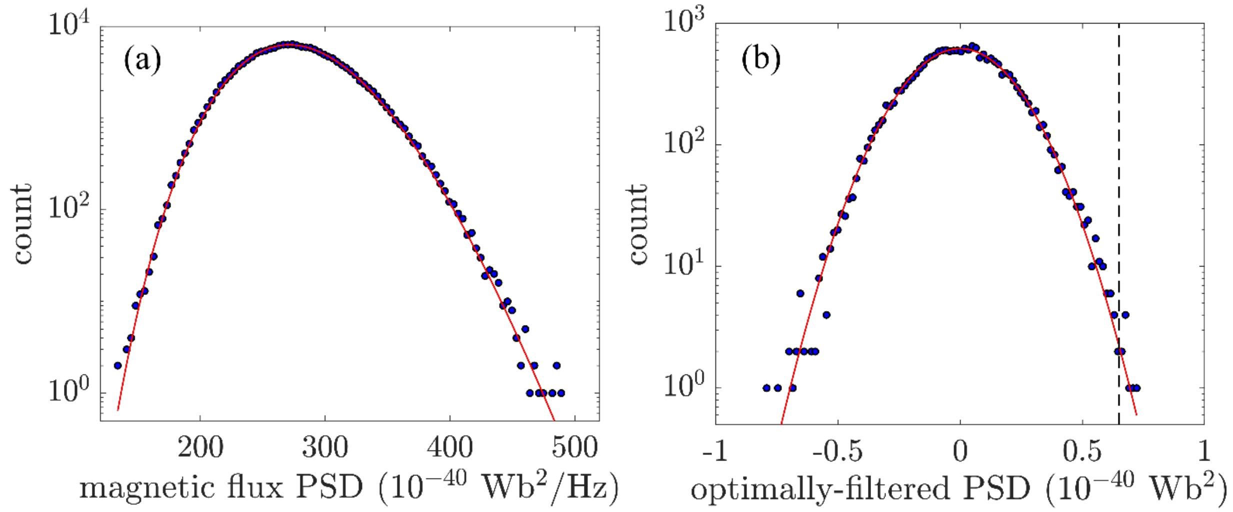
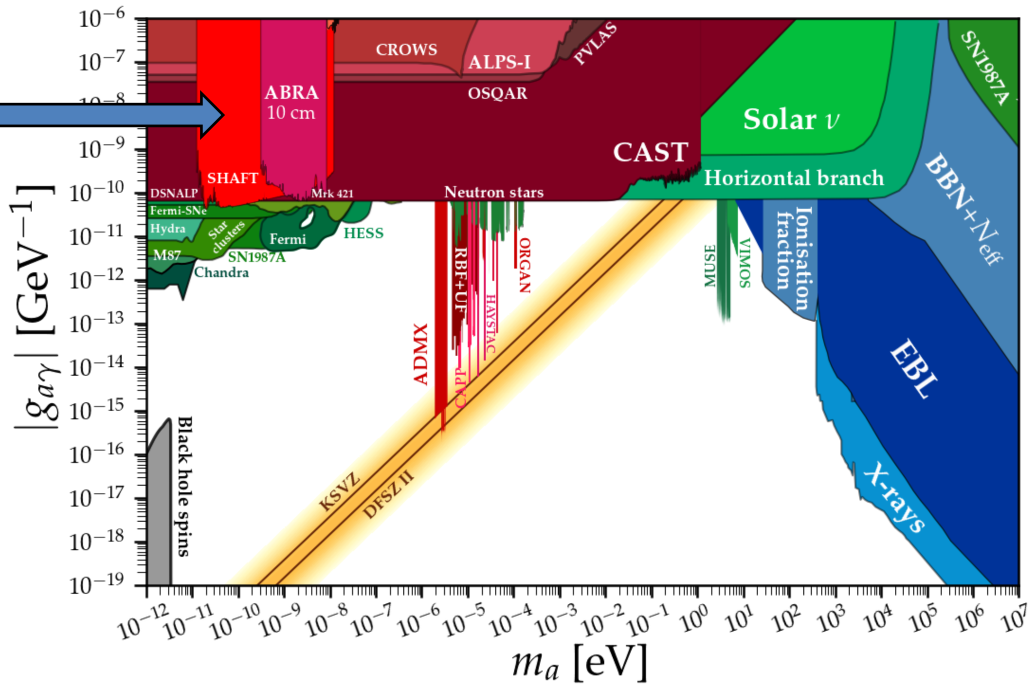
data statistics
(standard halo model)



- analyze data in 3-decade range: 12 peV to 12 neV, 2×10^7 possible ALP masses
- gaussian statistics; ≈ 13×10^3 candidates flagged (8×10^3 expected based on normal distribution)
- all candidates rejected by requiring detection in antisymmetric channel combination

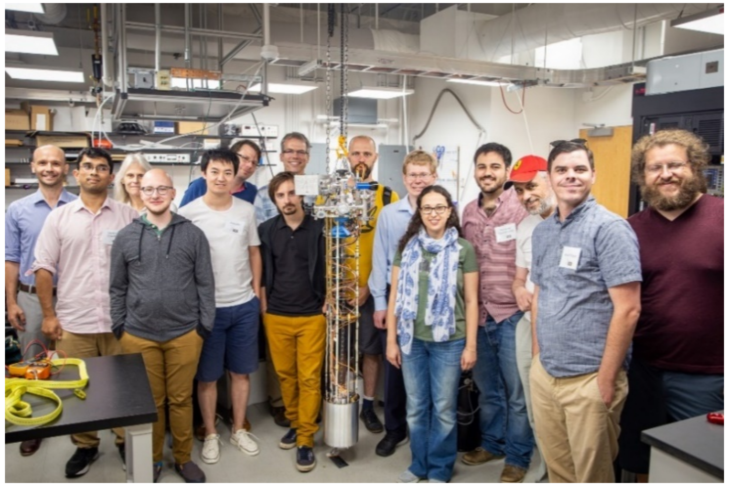
result: limit on electromagnetic interaction of axion-like dark matter



5σ limits reach $3.3\times10^{-11}\,\mathrm{GeV}^{-1}$ near 20 peV

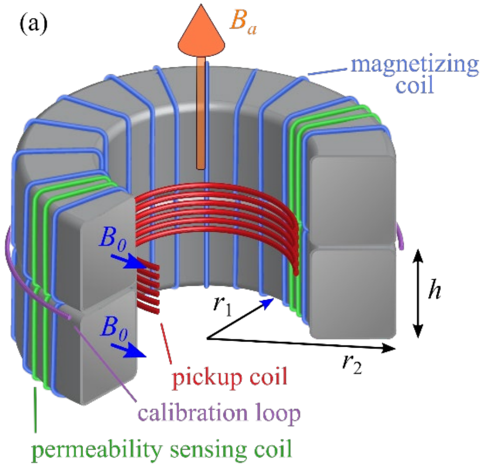
[A. Gramolin et al., *Nature Physics* **17**, 79 (2021)]

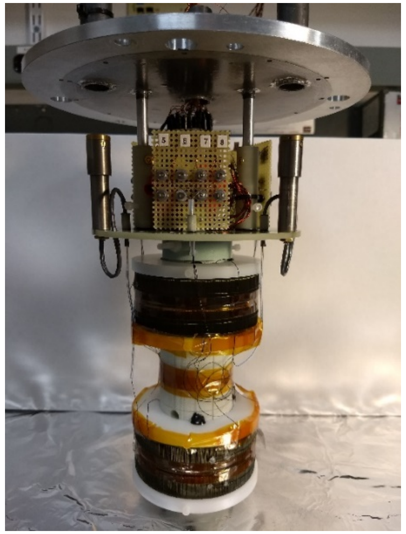
Alex Sushkov (Boston University): Search for axion-like dark matter with ferromagnets



CASPEr
+
DM-radio

team SHAFT:
Sasha Gramolin,
Deniz Aybas,
Janos Adam,
Dorian Johnson





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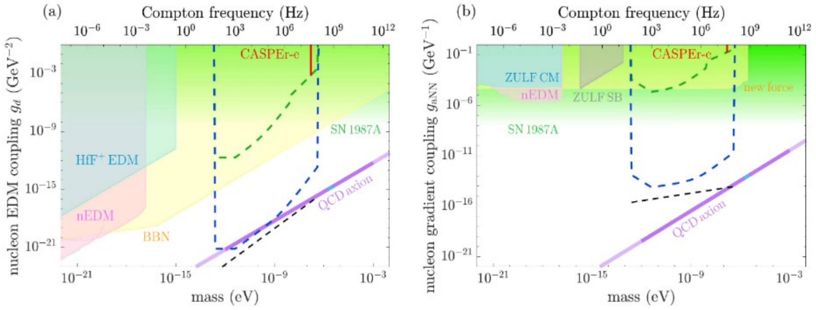
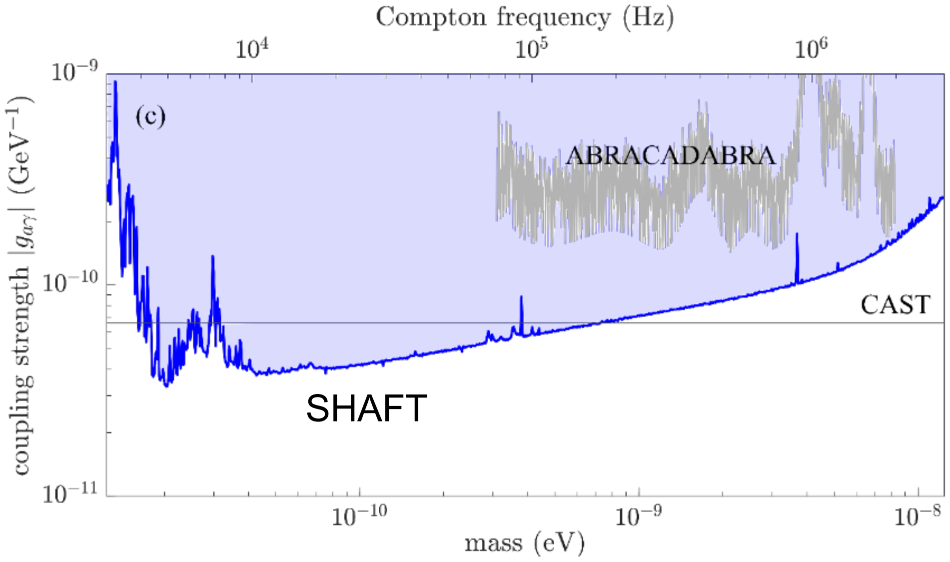


Thank you!



[D. Aybas et al., *Phys. Rev. Lett.* **126**, 160505 (2021)]
[D. Aybas et al., *Quant. Sci. Tech.* (2021)]

[D. DeMille et al., *Science* **357**, 990 (2017)]

[A.Gramolin et al., *Nature Physics* **17**, 79 (2021)]