Axion-like dark matter search using ferromagnetic toroids

Alexander Gramolin, Deniz Aybas, Dorian Johnson,
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BOSTON
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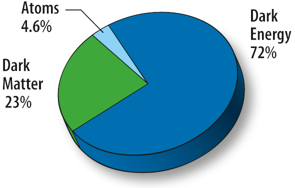
Northeastern University
Boston, MA

Ultralight axion dark matter

- Dark matter (DM) accounts for $\approx 1/4$ of the total energy density of the Universe



- The local DM energy density is

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

- QCD axions and axion-like particles are excellent DM candidates
- The number density of axions per de Broglie volume is large: $n_a/\lambda^3 \gg 1$
- As a result, axions form an oscillating classical field

$$a(t) = a_0 \sin\left(m_a t\right), \qquad a_0 \approx \sqrt{2\rho_{\mathrm{DM}}}/m_a \qquad (\text{in natural units, i.e., } \hbar = c = 1)$$

- Coherence time of these oscillations is limited by the virial velocity $v_{\mathrm{vir}} \approx 10^{-3}c$:

$$\frac{\Delta\omega_a}{m_a} \approx v_{\mathrm{vir}}^2 \approx 10^{-6}, \qquad \tau_c \approx 10^6\,\frac{2\pi}{m_a}$$

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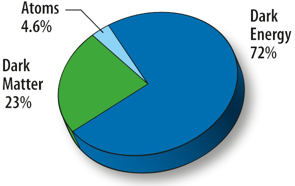

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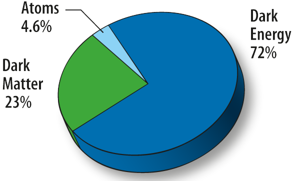

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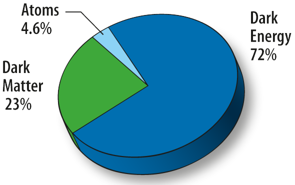

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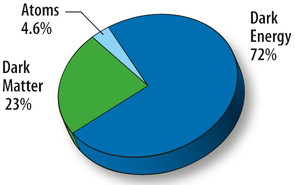

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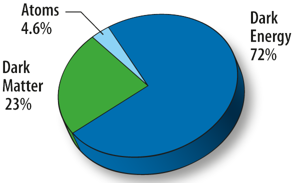

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Axion electrodynamics

- In the presence of a background axion field

$$a(t) = a_0 \sin(m_a t),$$

inhomogeneous Maxwell's equations take the form (in natural units, i.e., $\varepsilon_0 = \mu_0 = 1$)

$$\nabla \cdot \mathbf{E} = \rho - g_{a\gamma\gamma} \nabla a \cdot \mathbf{B} \qquad \text{(Gauss's law)},$$

$$\nabla \times \mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} + \mathbf{J} + g_{a\gamma\gamma} \left(\frac{\partial a}{\partial t} \mathbf{B} + \nabla a \times \mathbf{E} \right) \qquad \text{(Ampère's law)}.$$

- Under static magnetic field $\mathbf{B}_0$, DM axions source an effective current density

$$\mathbf{J}_{\text{eff}} = g_{a\gamma\gamma} \frac{\partial a}{\partial t} \mathbf{B}_0 = g_{a\gamma\gamma} \sqrt{2\rho_{\text{DM}}}\, \mathbf{B}_0 \cos(m_a t).$$

P. Sikivie, PRL **51**, 1415 (1983)

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- Axion field $a(t)$ sources an azimuthal effective current $\mathbf{J}_{\text{eff}}$
- $\mathbf{J}_{\text{eff}}$ generates an axial oscillating magnetic flux $\mathbf{\Phi}_a$
- $\mathbf{\Phi}_a$ can be detected by a SQUID coupled to a pickup coil
- Similar to ABRACADABRA, but we use ferromagnetic core material to enhance $\mathbf{B}_0$: $\mathbf{B}_0 = \mathbf{H}_0 + \mathbf{M}$ (natural units)
- We tried two core materials: gadolinium-iron garnet (GdIG) and Fe-Ni alloy powder

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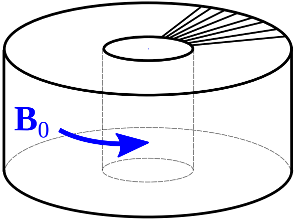

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S. Chaudhuri et al., Phys. Rev. D **92**, 075012 (2015) — DM Radio proposal

Y. Kahn, B. R. Safdi, J. Thaler, PRL **117**, 141801 (2016) — ABRACADABRA proposal

A. V. Gramolin, D. Aybas, D. Johnson, J. Adam, A. O. Sushkov, arXiv:1811.03231 (2018) — our GdIG results

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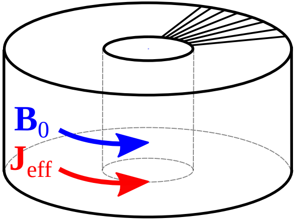

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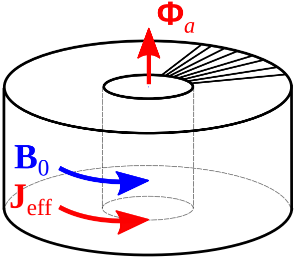

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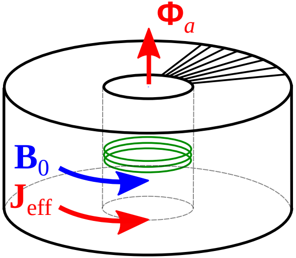

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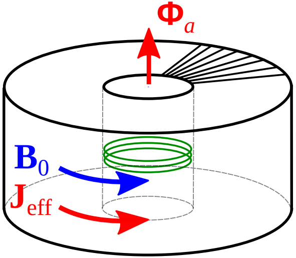

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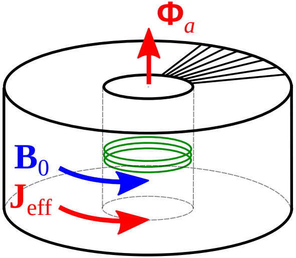

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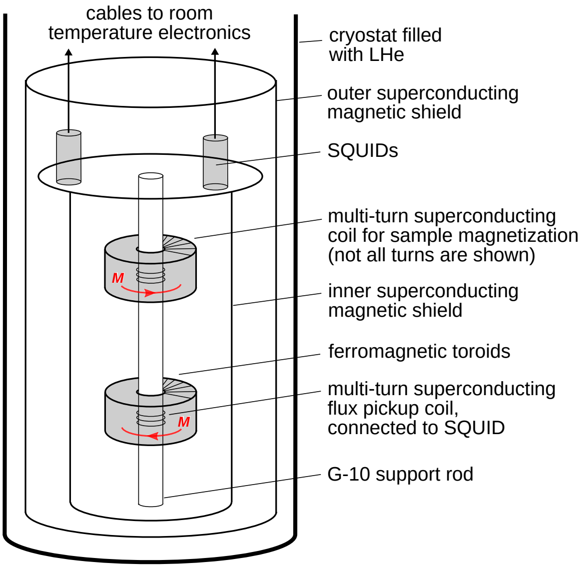
Experimental apparatus



cables to room temperature electronics

cryostat filled with LHe

outer superconducting magnetic shield

SQUIDs

multi-turn superconducting coil for sample magnetization (not all turns are shown)

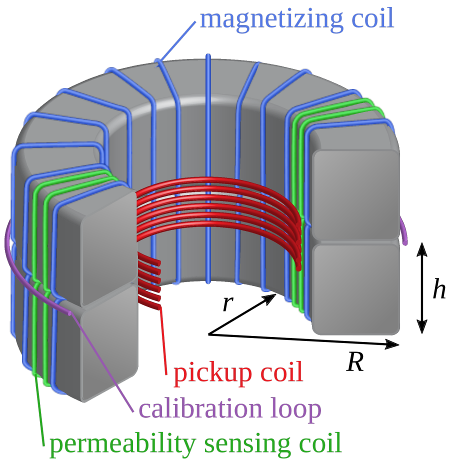
inner superconducting magnetic shield

ferromagnetic toroids

multi-turn superconducting flux pickup coil, connected to SQUID

G-10 support rod

Fe-Ni alloy powder core toroids:

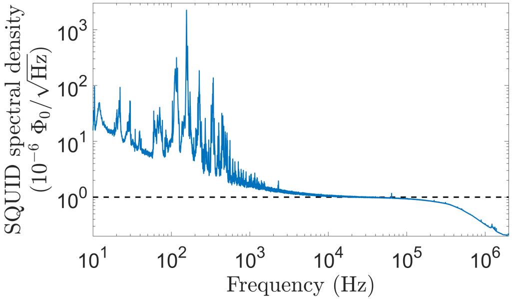


$$r = 24\ \text{mm},\ R = 39\ \text{mm},\ h = 16\ \text{mm}$$

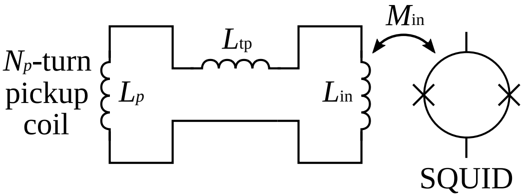
SQUID magnetometers

SQUIDS from Magnicon GmbH (Germany)

Flux noise at 4 K: $\approx 1\ \mu\Phi_0/\sqrt{\text{Hz}}$



Broadband readout circuit

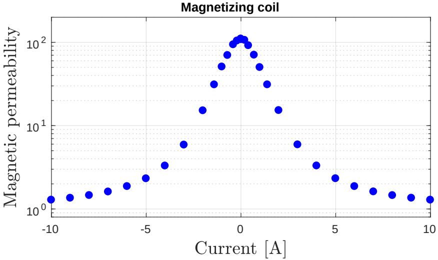


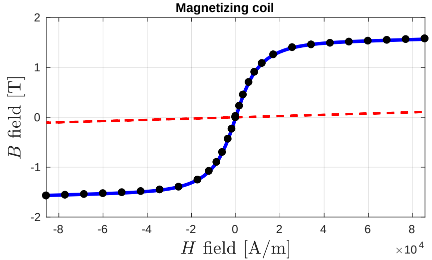
$$\Phi_{\text{SQUID}} = \frac{N_p M_{\text{in}}}{L_p + L_{\text{tp}} + L_{\text{in}}} \Phi_a$$

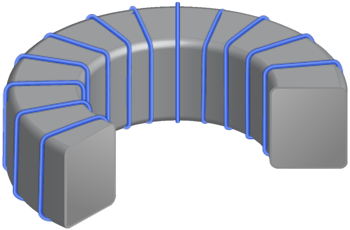
$$M_{\text{in}} = 9\ \text{nH},\ L_{\text{in}} = 1.8\ \mu\text{H},\ L_p = 3\ \mu\text{H}$$

Optimal number of turns: $N_p = 6$

Magnetization measurements







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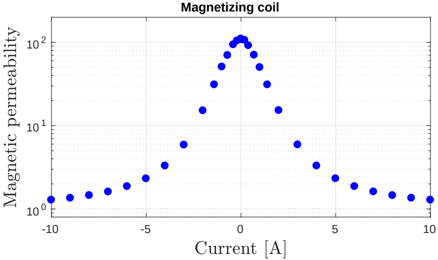
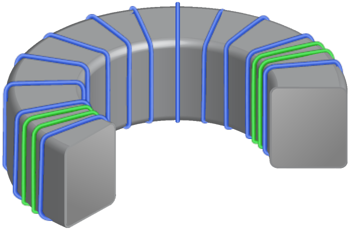
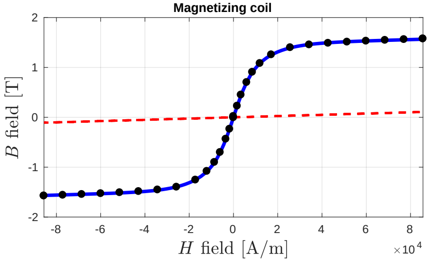

Magnetizing coil

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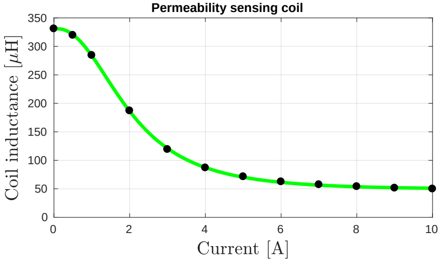
Permeability sensing coil

Sensitivity scaling

- Axion flux scales with the static magnetic field and the toroid effective volume as

$$\Phi_a = g_{a\gamma\gamma}\sqrt{2\rho_{\mathrm{DM}}}H_{\mathrm{min}}V$$

- For 6 A current in the magnetizing coil:

$$H_{\mathrm{min}} = 41\ \mathrm{kA/m}, \quad V = 396\ \mathrm{cm}^3$$

- A factor of 30 enhancement compared to an air-core toroid ($V = 13.4\ \mathrm{cm}^3$)
- Sensitivity scales with the integration time, t, as

$$\text{sensitivity} \propto \begin{cases} \sqrt{t}, & \text{if } t \ll \tau_c \text{ (coherent averaging)}, \\ \sqrt[4]{\tau_c t}, & \text{if } t \gg \tau_c \text{ (incoherent averaging)}, \end{cases}$$

where τ_c is the axion coherence time ($\tau_c \approx 10^3$ s for $f_a = 1$ kHz)

D. Budker et al., Phys. Rev. X **4**, 021030 (2014) — CASPEr proposal

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$$H_{\mathrm{min}} = 41\ \mathrm{kA/m}, \quad V = 396\ \mathrm{cm}^3$$

- A factor of 30 enhancement compared to an air-core toroid ($V = 13.4\ \mathrm{cm}^3$)
- Sensitivity scales with the integration time, t, as

$$\text{sensitivity} \propto \begin{cases} \sqrt{t}, & \text{if } t \ll \tau_c \text{ (coherent averaging)}, \\ \sqrt[4]{\tau_c t}, & \text{if } t \gg \tau_c \text{ (incoherent averaging)}, \end{cases}$$

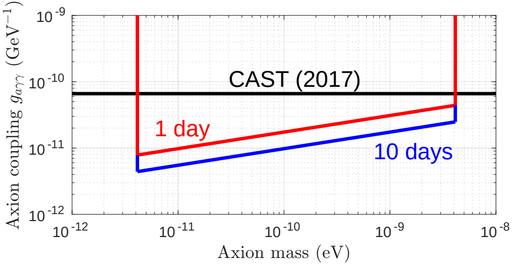
where τ_c is the axion coherence time ($\tau_c \approx 10^3$ s for $f_a = 1$ kHz)

D. Budker et al., Phys. Rev. X **4**, 021030 (2014) — CASPEr proposal

Sensitivity reach of the experiment

$$\Phi_{\mathrm{SQUID}} < \frac{1\ \mu\Phi_0/\sqrt{\mathrm{Hz}}}{\sqrt[4]{\tau_c t}}$$

$$g_{a\gamma\gamma} < \frac{1\ \mu\Phi_0/\sqrt{\mathrm{Hz}}}{\sqrt[4]{\tau_c t}} \times \frac{L_p + L_{\mathrm{tp}} + L_{\mathrm{in}}}{N_p M_{\mathrm{in}}} \times \frac{1}{\sqrt{2\rho_{\mathrm{DM}}} H_{\mathrm{min}} V}$$



V. Anastassopoulos et al. (CAST Collaboration),

Nature Physics **13**, 584 (2017)

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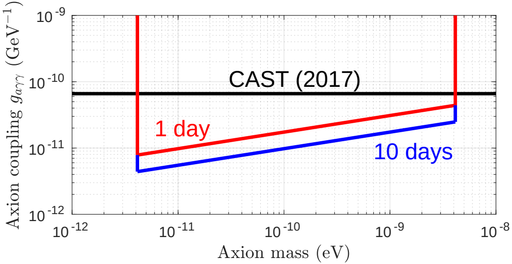

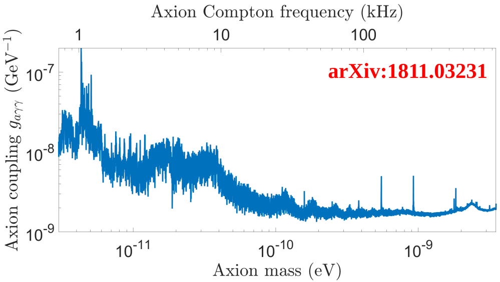

Summary and outlook

- Ultralight axion DM behaves like an oscillating classical field
- It generates an oscillating magnetic field in the presence of a static one
- Using SQUIDs we can search for axion DM in peV–neV mass range
- We enhance the static magnetic field with ferromagnetic toroidal cores
- Fe-Ni alloy powder cores provide a factor of 30 increase in sensitivity
- Projected sensitivity of the experiment surpasses the existing laboratory limits
- Work in progress: reduction of electromagnetic interference and data analysis

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Thank you for your attention!