Search for axion-like dark matter with ferromagnets

Alex Sushkov
Sasha Gramolin, Deniz Aybas, Janos Adam, Dorian Johnson
**Axions and axion-like particles, axion-like dark matter**

3. Axion-like particles (ALPs) arise naturally in string theories, symmetries broken up to GUT (10^{16} \text{ GeV}), Planck (10^{19} \text{ GeV}) scales

**axion-like dark matter**

- **ALP mass range**
  \[m_a c^2 < \text{meV}\]

- **dark matter energy density:**
  \[\rho_{\text{DM}} \approx 0.4 \frac{\text{GeV}}{\text{cm}^3} \approx (0.05 \text{ eV})^4\]

- **large number of particles per de Broglie wavelength**

- **ALP dark matter acts as a classical field**

**axion-like field:**
\[a(t) = a_0 \cos \omega_a t\]

\[\omega_a = \frac{m_a c^2}{\hbar} \rightarrow \text{ALP Compton frequency}\]

\[\rho_{\text{DM}} \propto a_0^2 \rightarrow \text{dark matter density}\]
Axions and axion-like particles, axion-like dark matter

1. Pseudoscalar light particle: spin = 0, wide range of possible masses \[ a(t) = a_0 \cos \omega_t \]
2. Proposed to solve the strong CP problem of Quantum Chromodynamics \[ \text{[Phys. Rev. Lett. 38, 1440 (1977)]} \]
3. Axion-like particles (ALPs) arise naturally in string theories, symmetries broken at GUT (10^{16} \text{ GeV}) or Planck (10^{19} \text{ GeV}) scales
4. Possible interactions with standard model particles:

**interaction with photons:**

\[ \mathcal{L}_{\alpha\gamma\gamma} = g_{\alpha\gamma\gamma} a E \cdot B \]

→ ALP ↔ photon conversion in a magnetic field

→ precision electromagnetic sensors

**interaction with gluons:**

(strong-CP problem)

\[ \mathcal{H}_{\text{EDM}} = g_{\alpha} a E^* \cdot I / I \]

→ nuclear spin \( I \) interacts with an oscillating electric dipole moment (EDM) \( d_n = g_\alpha a \) in presence of effective electric field \( E^* \)

**interaction with leptons:**

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

→ nuclear spin \( I \) interacts with an effective magnetic field \( \nabla a \).

force mediator → ARIADNE

electron spin → QUAX

**CASPEr-electric**

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


**CASPEr-gradient**

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

\[ \text{[A. Gramolin et al., Nature Physics 17, 79 (2021)]} \]
search for EDM and gradient couplings →
\[ \mathcal{H}_{\text{EDM}} = g_d a E^* \cdot I / I \]
\[ \mathcal{H}_{aNN} = g_{aNN} \nabla a \cdot I \]

talks by Deniz Aybas and Janos Adam

- precision magnetic resonance experiment using $^{207}\text{Pb}$ nuclear spin ensemble in a solid with broken inversion symmetry
- sensor → cryogenic RF amplifier, voltage noise: 0.05 nV/$\sqrt{\text{Hz}}$
  → magnetic field sensitivity @ 40 MHz: 2 fT/$\sqrt{\text{Hz}}$
- ALP search in the 162 neV to 166 neV mass range
- Limits (at 5σ level):
  \[ |g_d| < 9.5 \times 10^{-4} \text{ GeV}^{-2} \]
  \[ |d_n| < 1.0 \times 10^{-21} \text{ e} \cdot \text{ cm} \]
  \[ |\theta| < 4.3 \times 10^{-6} \]
  \[ |g_{aNN}| < 2.8 \times 10^{-1} \text{ GeV}^{-1} \]
- amplitudes of oscillations near 40 MHz
- goal: probe the QCD axion band for mass $\approx 10^{-12}$ to $10^{-9}$ eV

[D. Aybas et al., Phys. Rev. Lett. 126, 160505 (2021)]
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[A. Garcon et al., *Sci. Adv.*, eaax4539 (2019)]

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

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

**CASPEr-gradient**

[D. Budker et al., *Phys. Rev. X* 4, 021030 (2014)]

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

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

[D. Aybas et al., *Phys. Rev. Lett.* 126, 160505 (2021)]
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Search for Halo Axions with Ferromagnetic Toroids (SHAFT)

\[ a(t) = a_0 \cos \omega_a t \]

**goal:** search for electromagnetic coupling of axion-like dark matter in a broad mass (frequency) range: kHz - MHz

interaction with photons:

\[ \mathcal{L}_{\alpha \gamma \gamma} = g_{\alpha \gamma \gamma} a \mathbf{E} \cdot \mathbf{B} \]

\[ \nabla \times \mathbf{H} = \mathbf{J}_f \]

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[Phys. Rev. D 92, 075012 (2015)]
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**approach** → additional term in Ampere’s law

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

azimuthal static magnetic field \( B_0 \)

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**interaction with photons:**
- ALP field amplitude
- symmetry breaking scale
- \( \mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma} a E \cdot B \)
- \( \frac{a}{f_a} F_{\mu
\nu} \tilde{F}^{\mu\nu} \)
- \( a \leftrightarrow \) photon conversion in a magnetic field
- precision electromagnetic sensors

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

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**interaction with photons:**

- ALP field amplitude: $a / f_a$
- Symmetry breaking scale: $\mathcal{L}_{\alpha \gamma \gamma} = g_{\alpha \gamma \gamma} a E \cdot B$

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

- a factor of 24 enhancement of magnetic field $B_0$
- $B_0 = 1.5 \text{ T}$ achieved at 6 A current

[A. Gramolin et al., *Nature Physics* 17, 79 (2021)]
Performance of SQUID magnetic field sensors

- two detection channels, RF pickup appears in phase, but ALP signal appears out of phase → **systematic rejection**
- SQUID sensor bandwidth → 2 MHz

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Performance of SQUID magnetic field sensors

- two detection channels, RF pickup appears in phase, but ALP signal appears out of phase → systematic rejection
- SQUID sensor bandwidth → 2 MHz

- magnetic field sensitivity → 150 aT/√Hz ≈ broadband record
Data analysis

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

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 × 10^{-11} GeV^{-1} near 20 peV

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

Thank you!

[A. Gramolin et al., Nature Physics 17, 79 (2021)]
[D. DeMille et al., Science 357, 990 (2017)]
[D. Aybas et al., Quant. Sci. Tech. (2021)]
[D. Aybas et al., Phys. Rev. Lett. 126, 160505 (2021)]