Searches for Axion Dark Matter

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Why axions?

\[ \mathcal{L}_{\text{QCD}} \supset \frac{\theta}{32\pi^2} \text{Tr} \ G_{\mu\nu} \tilde{G}^{\mu\nu} \quad \Rightarrow \quad d_n \approx 3.6 \times 10^{-16} \theta \ e \ cm \]

Why so small?
\[ \theta \lesssim 10^{-10} \]
Strong CP problem

Axion can dynamically relax \( \theta \)


\[ \mathcal{L}_{\text{QCD}} \supset \left( \theta - \frac{a}{f_a} \right) \frac{1}{32\pi^2} \text{Tr} \ G_{\mu\nu} \tilde{G}^{\mu\nu} \]
Why dark matter?

Fit to CMB data is exquisitely good, and requires 26.8% of energy density in cold DM
Axion DM: one field solves two problems!

\[ \theta_i = a_i / f_a \]

initial misalignment

\[ 3H = m_a \]

solve strong CP, DM with at worst ~1% tuning

\[ a \propto T^{3/2} \cos(m_a t) \]

\[ \Omega_a h^2 \sim 0.1 \left( \frac{f_a}{10^{16} \text{GeV}} \right)^{7/6} \left( \frac{\theta_i}{5 \times 10^{-3}} \right)^2 \]

\[ m_a \sim 6 \times 10^{-10} \text{ eV} \left( \frac{10^{16} \text{ GeV}}{f_a} \right) \]

looks just like cold DM!
Axion-SM interactions

\[ \mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} - \frac{i}{2} g_{da} \bar{N} \sigma_{\mu\nu} \gamma_5 N F^{\mu\nu} + g_{aNN} (\partial_\mu a) \bar{N} \gamma^\mu \gamma_5 N + g_{ae} (\partial_\mu a) \bar{e} \gamma^\mu \gamma_5 e \]

Axion-photon conversion

Nucleon EDM

Nuclear axial moment

Electron axial moment

Note: for QCD axion, \( m_a \sim 6 \times 10^{-10} \text{ eV} \left(\frac{10^{16} \text{ GeV}}{f_a}\right) \)

All couplings of order \( 1/f_a \)

For “axion-like particles” (ALPs), couplings independent of \( m_a \)
FIG. 1. Parameter space for axions (top) and axion-like particles (ALPs) (bottom). In the bottom plot, the QCD axion models lie within an order of magnitude from the explicitly shown "KSVZ" axion line (red band). Colored regions are: experimentally excluded regions (dark green), constraints from astronomical observations (gray) or from astrophysical or cosmological arguments (blue), and sensitivity of planned and suggested experiments (light green) (ADMX [14], ALPS–II [15], IAXO [16–18], Dish antenna [19]). Shown in red are boundaries where ALPs can account for all the dark matter produced either thermally in the big bang or non-thermally by the misalignment mechanism.

QCD axion: mass $\propto$ coupling

Enormous mass range

Couples very weakly to SM
ALP parameter space

Couples very weakly to SM
good DM candidates
Enormous mass range

QCD axion: mass $\propto$ coupling

FIG. 1. Parameter space for axions (top) and axion-like particles (ALPs) (bottom). In the bottom plot, the QCD axion models lie within an order of magnitude from the explicitly shown "KSVZ" axion line (red band). Colored regions are: experimentally excluded regions (dark green), constraints from astronomical observations (gray) or from astrophysical or cosmological arguments (blue), and sensitivity of planned and suggested experiments (light green) (ADMX [14], ALPS-II [15], IAXO [16–18], Dish antenna [19]). Shown in red are boundaries where ALPs can account for all the dark matter produced either thermally in the big bang or non-thermally by the misalignment mechanism.

[Essig et al., 1311.0029]
Axion DM today: field, not particle

Useful analogy:

Light bosonic DM behaves collectively: think in terms of charges and currents, not Feynman diagrams
Properties of axion DM

\[ m_a \ll 1 \text{eV} \]

Bosonic DM + macroscopic occupation # = classical field:

\[ a(t) = a_0 \sin(m_a t) = \frac{\sqrt{2 \rho_{DM}}}{m_a} \sin(m_a t) \]

e.g. \( m_a = 10^{-9} \text{ eV} \)

\( \lambda_{\text{Comp}} \sim \text{km} \)

\( \tau_{\text{Comp}} \sim \mu \text{s} \)

Local DM velocity \( \rightarrow \) Spatial coherence \( \rightarrow \) Temporal coherence

\( \Delta v_{\text{DM}} \sim v_{\text{DM}} \sim 10^{-3} \)

\[ \lambda_{\text{dB}} = \frac{\lambda_{\text{Comp}}}{v_{\text{DM}}} \]

\[ \tau_{\text{dB}} = \frac{\lambda_{\text{Comp}}}{v_{\text{DM}}^2} \]

Experiments can exploit enhanced coherence time
Properties of axion DM

\[ m_a \ll 1\text{eV} \]

\[ a(t) = a_0 \sin(m_a t) = \frac{\sqrt{2}\rho_{\text{DM}}}{m_a} \sin(m_a t) \]

In axion DM background, get oscillating observables:


\[
\nabla \times \mathbf{B}_r = \frac{\partial \mathbf{E}_r}{\partial t} - g_{a\gamma\gamma} \left( \mathbf{E}_0 \times \nabla a - \mathbf{B}_0 \frac{\partial a}{\partial t} \right)
\]

\[
\nabla \cdot \mathbf{E}_r = -g_{a\gamma\gamma} \mathbf{B}_0 \cdot \nabla a
\]

\[ d_n = g_d a \]

\[ H_N \supset g_{aNN} \nabla a \cdot \vec{\sigma}_N \]
Properties of axion DM

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\[ \nabla \cdot \mathbf{E}_r = -g_{\alpha\gamma\gamma} \mathbf{B}_0 \cdot \nabla a \]

\[ d_n = g_d a \]

\[ H_N \supset g_{\alpha NN} \nabla a \cdot \vec{\sigma}_N \]

Note: \( \nabla a \propto v_{\text{DM}} \sim 10^{-3} \)
Axion-photon searches

\[ \nabla \times \mathbf{B}_r = \frac{\partial \mathbf{E}_r}{\partial t} + g_{a\gamma\gamma} \mathbf{B}_0 \frac{\partial a}{\partial t} \]

Cavity regime: \( \lambda_{\text{Comp}} \sim R_{\text{exp}} \)
ADMX

Quasistatic regime: \( \lambda_{\text{Comp}} \gg R_{\text{exp}} \)
ABRACADDBRA

Radiation regime: \( \lambda_{\text{Comp}} \ll R_{\text{exp}} \)
MADMAX
Figure 2

Schematic of the microwave cavity search for dark matter axions. Axions resonantly convert to a quasi-monochromatic microwave signal in a high-Q cavity in a strong magnetic field; the signal is extracted from the cavity by an antenna, amplified, mixed down to the audio range, and the power spectrum calculated by a FFT. Possible fine structure on top of the thermalized axion spectrum would reveal important information about the formation of our galaxy.

Within experimental control are the magnetic field strength $B_0$, and the volume of the cavity $V$, as well as the mode-dependent form-factor $C$, and loaded quality factor of the cavity $Q_L$. $\eta$ is the fraction of power coupled out by the antenna probe, generally adjusted to be at or near critical coupling, $\eta = 1/2$. The resonant conversion condition is that the frequency of the cavity must equal the mass of the axion, $\Delta f = m_a c^2 \times \left(1 + \frac{1}{2} O(2)\right)$, where $\Delta f \approx 10^{3}$ is the galactic virial velocity. The signal is thus monochromatic to $10^{6}$. The search is performed by tuning the cavity in small overlapping steps (Figure 2).

The expected signal power is extraordinarily tiny, of order $10^{-22}$ W for the current experiment. Actual detection of the axion is the consummate signal-processing problem, governed by the Dicke radiometer equation (42)

$$P \sim g_{a\gamma\gamma}^2 \frac{\rho_{DM}}{m_a} \frac{B_0^2 V Q}{\eta}$$

One especially important feature about the microwave cavity search for axions that strongly differentiates it from WIMP searches, is that it is a total energy detector, i.e. the signal represents the instantaneous (mass + kinetic) energy of the axion. While the majority

LITERATURE CITED

Axion astronomy with ADMX

[O'Hare and Green, Phys. Rev. D95 (2017)]

\[ a(t) = \frac{\sqrt{2\rho_{DM}}}{m_a} \int d^3v \, g(v) \cos(\omega_v(t - v \cdot x)) \]

\[ \omega_v = m_a(1 + \frac{1}{2}v^2 + O(v^4)) \]

Much easier to identify structure in \( g(v) \) for axions than WIMPS!
Quasistatic regime: ABRACADABRA

\[ \nabla \times \mathbf{B}_r = \frac{\partial E_r}{\partial t} + g_{\alpha\gamma\gamma} B_0 \frac{\partial a}{\partial t} \]

\[ \Phi_a(t) = g_{\alpha\gamma\gamma} \sqrt{2\rho_{DM}} \cos(m_a t) \times (B_{\text{max}} V G_{\text{toroid}}) \]

Volume enhancement: energy stored scales as \( B_0^2 V^2 \)
ABRACADABRA reach

Full-scale reach:

\[ \nu = \frac{m_a}{2\pi} \]

**ABRA-10cm prototype:**

[Winslow et al., ABRACADABRA collab.]

GUT-scale QCD axion

QS breaks down (detailed sim. needed)

Data by end of 2017!

\[ \nu = \frac{m_a}{2\pi} \]
Radiation regime: MADMAX


$$\nabla \times \mathbf{B}_r = \epsilon \frac{\partial \mathbf{E}_r}{\partial t} + g_{a\gamma\gamma} \mathbf{B}_0 \frac{\partial a}{\partial t} \implies \mathbf{D}_r(t) = \epsilon \mathbf{E}_r(t) = -g_{a\gamma\gamma} \mathbf{B}_0 a(t)$$

E+M boundary condition at interfaces forces radiation to cancel axion-induced $\mathbf{D}$

Best of both worlds: large volume and high Q
MADMAX reach

Broadband and resonant modes possible:

\[ P \propto g_{a\gamma\gamma}^2 \rho_{\text{DM}} B_0^2 A \beta^2 \]

\[ \int \beta(\nu_a)^2 \, d\nu_a = N_{\text{disks}} \times \text{const.} \]

3-year runtime:

= 1 if QCD axion

Excellent prospects in high-frequency regime
CASPEr: NMR with axion DM


Nuclei immersed in axion DM can have:

- Oscillating EDM
- Spin-dependent force

\[ d_n = g_d \frac{\sqrt{2\rho_{DM}}}{m_a} \cos(m_a t) \]

\[ H_N \supset g_{aNN} \sqrt{2\rho_{DM}} \cos(m_a t) \vec{v} \cdot \vec{\sigma}_N \]

Figure 6

CASPEr setup. The applied magnetic field \( B_{\text{ext}} \) is colinear with the sample magnetization, \( \vec{M} \). In CASPEr-Wind the nuclear spins precess around the local velocity of the dark matter, \( \vec{v} \), while in CASPEr-Electric the nuclear EDM causes the spins to precess around an effective electric field in the crystal \( \vec{E} \), perpendicular to \( B_{\text{ext}} \). The SQUID pickup loop is arranged to measure the transverse magnetization of the sample.

The CASPEr-Wind experiment is in fact a search for any light particle that couples to nuclear spin (a generic coupling), not just the axion. For example, any pseudo-Goldstone boson is expected to possess a coupling that would be detectable in the CASPEr-Wind experiment. It can also detect other types of dark matter, for example hidden photon dark matter (87, 26) is detectable through a nuclear dipole moment coupling.

Existing experiments may already be able to set limits on axion-like particles. Data from experiments searching for nuclear EDMs or looking at nucleon spin precession in a low background environment may be reanalyzed to search for a time-varying signal, a sign of the axion. While not ultimately as sensitive as CASPEr where the signal is resonantly enhanced, such searches may be able to probe beyond the current astrophysical limits in Figures 7 and 8.

CASPEr is a novel and highly sensitive search for a broad class of dark matter candidates in two new parameter spaces, the 'axion wind' and nuclear EDM, of which the QCD axion is the most well-known example. In particular, CASPEr has the sensitivity to detect the QCD axion over a wide range of masses from \( \sim 10^{-9} \) eV to \( 10^{-12} \) eV which are well-motivated by fundamental physics (24) and where no other experiment can detect it.

Construction is just beginning on the CASPEr experiment. Work on CASPEr is currently being carried out in several places including Stanford, Berkeley, and Mainz.

Note that the Wind coupling leads to a spin-dependent force which could be probed using NMR techniques as well e.g. (80, 81, 82, 83, 84, 85).
CASPEr: NMR with axion DM


Nuclei immersed in axion DM can have:

- Oscillating EDM
- Spin-dependent force

\[ d_n = g_d \frac{\sqrt{2} \rho_{\text{DM}}}{m_a} \cos(m_a t) \quad \text{and/or} \quad H_N \supset g_{aNN} \sqrt{2 \rho_{\text{DM}}} \cos(m_a t) \vec{v} \cdot \vec{\sigma}_N \]

Polarize some spins, watch them precess around:

- External E field
- Axion field velocity

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\[ \vec{E}^*, \vec{v} \]
**CASPEr: NMR with axion DM**


Nuclei immersed in axion DM can have:

- Oscillating EDM
- and/or
- Spin-dependent force

\[ d_n = g_d \frac{\sqrt{2} \rho_{DM}}{m_a} \cos(m_a t) \quad \quad \quad H_N \supset g_{aNN} \sqrt{2} \rho_{DM} \cos(m_a t) \vec{v} \cdot \vec{\sigma}_N \]

Polarize some spins, watch them precess around:

- External E field
- and/or
- Axion field velocity

Resonance in transverse magnetization when \( 2 \mu B_{\text{ext}} = m_a \)
The frequency must be scanned, realistically it would likely take several experiments to cover either region. Not been combined in a single experiment. Thus the phase 2 proposal may be taken as an estimate of one way to experiments. Phase 1 (upper, orange region) is a more conservative version relying on demonstrated technology.

We assume a SQUID magnetometer with sensitivity $10^{-20}$ to be covered (lighter blue) [59, 60]. Phase 1 is a modification of current solid state static EDM techniques that is optimized to the sample for phase 2. The ADMX region shows what region of the QCD axion has been covered (darker blue) [34] or will for our phase 1 and 2 proposals, set by magnetometer noise. The red dashed line shows the limit from magnetization noise of the sample for phase 2.

**FIG. 2:** Estimated constraints in the ALP parameter space in the EDM coupling is the local value of the ALP field (see [17] for a different from the usual ALP-photon coupling parameter. The purple region of Fig. 2 shows the non-decoupling signal!

The dashed (red) line in Fig. 2 shows the ultimate limit on the sensitivity of the phase 2 experiment from sample magnetization noise. The solid (orange and red) regions in Fig. 2 show estimates for the sensitivities for two phases of our proposed Figure 2 shows the ALP parameter space of the EDM coupling

The width of the purple band gives an approximation to the axion model-dependence in this

**III. SENSITIVITY**

The solid (orange and red) regions in Fig. 2 show estimates for the sensitivities for two phases of our proposed

**ALSO SIMILAR IDEA USING ELECTRON SPINS: QUAX**

CASPEr reach

CASPEr-Electric

20 T max B-field

CASPEr-Wind
[Graham and Rajendran, Phys. Rev. D88 (2013)]

fine-tuned...

non-decoupling signal!

magnetization noise

velocity suppression: can’t quite reach QCD axion

(Also similar idea using electron spins: QUAX)
Outlook for QCD axion DM detection

[adapted from Essig et al., 1311.0029]

Next decades could definitively probe QCD axion as DM!
Backup slides
SQUID magnetometry basics

Cartoon picture: extremely sensitive flux-to-voltage amplifier

change in flux induces current across junction (DC Josephson effect)

\[
\Phi_0 = \frac{\hbar}{2e} = 2.1 \times 10^{-15} \text{ Wb} = 2.1 \times 10^{-15} \text{ T} \cdot \text{m}^2
\]
Beyond vanilla QCD axion...

A “Clockwork” Axion: exponentially enhanced photon coupling

Further motivation to cover full axion parameter space!
Broadband: readout circuit

Cannot resolve thermal noise, SQUID noise dominates

Inductance matching: \( L_i \approx L_p \implies \Phi_{\text{SQUID}} \approx \frac{\alpha}{2} \sqrt{\frac{L}{L_p}} \Phi_{\text{pickup}} \)

Optimal coupling*: \( \frac{1}{2} \int B^2 \, dV = \frac{\Phi^2}{2L_p} \approx 0.01 \) huge area = amplification

*thanks to K. Irwin for pointing this out
**Resonant: readout circuit**

\[ Q = \frac{1}{R} \sqrt{\frac{L_T}{C}} \]

\[ L_T = L_p + L_i \]

Can use feedback to match circuit bandwidth to signal.

Can resolve thermal noise, SQUID noise subdominant.
Broadband: S/N and sensitivity

Take data for time $t$:

If $t < \tau$, S/N improves like $\sqrt{t}$ (random walk)

Our regime is $t \gg \tau$: $S/N \sim |\Phi_{\text{SQUID}}|(t\tau)^{1/4}/S_{\Phi,0}^{1/2}$

$S/N = 1 \quad \rightarrow \text{sensitivity to}$

$g_{\alpha\gamma} > 6.3 \times 10^{-18}$ GeV$^{-1} \left( \frac{m_a}{10^{-12} \text{ eV}} \frac{1 \text{ year}}{t} \right)^{1/4} \frac{5 \text{ T}}{B_{\text{max}}} \times \left( \frac{0.85 \text{ m}}{R} \right)^{5/2} \sqrt{\frac{0.3 \text{ GeV/cm}^3}{\rho_{\text{DM}}} \frac{S_{\Phi,0}^{1/2}}{10^{-6} \Phi_0/\sqrt{\text{Hz}}}}$

improves at low masses from coherence time

$R = r = a = h/3$: tall toroid increases B-field energy
**Resonant:** S/N and sensitivity

\[ P_S = Q_0 \frac{m_a \Phi^2_{\text{pickup}}}{2L_T}, \quad P_N = k_B T \sqrt{\frac{m_a}{2\pi t_{\text{e-fold}}}} \]

Each e-fold of frequency scanned for equal time, only take data on resonance (note: this is not optimal!)

\[ \frac{P_S}{P_N} = 1 \]

\[ \Rightarrow \text{sensitivity to} \]

\[ g_{a\gamma\gamma} > 9.0 \times 10^{-17} \text{ GeV}^{-1} \left( \frac{10^{-12} \text{ eV} \text{ 20 days}}{m_a \ t_{\text{e-fold}}} \right)^{1/4} \times \frac{5 \ T}{B_{\text{max}}} \left( \frac{0.85 \text{ m}}{R} \right)^{5/2} \sqrt{\frac{0.3 \text{ GeV/cm}^3 \ 10^6}{\rho_{\text{DM}}} \frac{T}{Q_0 \ 0.1 \text{ K}}} \]

Improves at high masses

Improves at low temp
Oxford Instruments Triton 400 dil fridge:
12 L working volume

Normally used for $0\nu\beta\beta$

Cryogen-free, can run weeks unattended
ABRACADABRA-10 cm
Superconducting pickup cylinder

Tall, thin walls: minimize inductance

Gap to force current through SQUID
Superconducting pickup cylinder

Tall, thin walls: minimize inductance

Gap to force current through SQUID
SQUIDS

**Pickup:** looking to purchase a Magnicon SQUID current sensor

Typical noise: $1.2 \times 10^{-6} \Phi_0/(\text{Hz})^{1/2} @ 4K$, with $1/f$ corner at 3 Hz

**Amplifier:** currently have a set of Magnicon SQUID amplifier arrays