Cosmic Axion Detection with an Amplifying B-field Ring Apparatus

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Two important facts to keep in mind in any dark matter talk (at least, today)
Fact 1: we know a lot about dark matter
Fact 2: we know almost nothing about dark matter
Fact 2: we know almost nothing about dark matter

- No evidence for non-gravitational interactions
- No evidence for particular dark-matter mass
Over 20 orders of magnitude in DM mass!

\[ \log_{10}(m_{a}/\text{eV}) \]
Dark-matter: BSM physics exists

- Clear evidence that dark-matter (BSM physics) exists
- Well motivated dark-matter models (WIMPs, axions, …)
## Dark matter models

<table>
<thead>
<tr>
<th>Name</th>
<th>What is it?</th>
<th>Motivation</th>
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<tr>
<td>Axion</td>
<td>( \left( \bar{\theta} + \frac{a}{f_a} \right) G_{\mu\nu} \tilde{G}^{\mu\nu} )</td>
<td>Strong CP</td>
</tr>
<tr>
<td>Neutralino (WIMP)</td>
<td>( \tilde{B}, \tilde{W}_3, \tilde{H}_u, \tilde{H}_d )</td>
<td>Hierarchy Problem (why Higgs mass so light)</td>
</tr>
</tbody>
</table>
How can we probe axion dark matter?

- **Laboratory experiments**: ADMX (resonant cavity), CAST (axion helioscope)
- **New proposal**: *PRL* 117, Sept. 2016 (Y. Kahn, B.S., J. Thaler): A broadband approach to axion dark matter detection
Outline

- Axion particle physics (review)
- Axion cosmology (review and work in progress)
- ABRACADABRA: Cosmic axion detection (theory)
- ABRACADABRA-10 cm at MIT (experiment)
Why axions and what are they?
Strong CP: the other naturalness problem ($|\bar{\theta}| < 10^{-10}$)

- Problem: CP-violating $\delta_{\text{CKM}} \sim O(1)$, but $|\bar{\theta}| < 10^{-10}$
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    - Light pseudo-goldstone boson “the axion” removes $|\bar{\theta}|$
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    - Axion can be dark matter
The axion solves the strong CP problem

\[ \mathcal{L}_{QCD}^{CP} = -\frac{\theta g^2}{32\pi^2} G_{\mu\nu} \tilde{G}^{\mu\nu} - \sum_q \bar{q} m_q e^{-i\phi_q} \gamma_5 q \]

- **U(1)\textsubscript{A} anomaly:** \( q \rightarrow e^{-i\alpha_q} \gamma_5 q \)
  \( \theta \rightarrow \theta + 2 \sum q \alpha_q \)

- **U(1)\textsubscript{A} invariant:** \( \bar{\theta} \equiv \theta - \sum_q \phi_q \)

Peccei, Quinn 1977; Weinberg 1978; Wilczek 1978
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- **Calculation:** \( d_n \approx 2.4 \times 10^{-16} \bar{\theta} \text{ e} \cdot \text{cm} \)

- **Measurement:** \( |\bar{\theta}| < 10^{-10} \)

- **No anthropic argument for why \( \bar{\theta} \) is so small!**

Peccei, Quinn 1977; Weinberg 1978; Wilczek 1978
The axion solves the strong CP problem

\[ \mathcal{L}_{\text{axion}} = - \left( \bar{\theta} + \frac{a}{f_a} \right) \frac{g^2}{32\pi^2} G_{\mu\nu} \tilde{G}^{\mu\nu} \]

QCD generates axion mass:

\[ V(a) \approx \frac{1}{2} f_a^2 m_a^2 \left( \bar{\theta} + \frac{a}{f_a} \right)^2 \]

\[ m_a \approx \frac{f_\pi}{f_a} m_\pi \approx 10^{-9} \text{ eV} \left( \frac{10^{16} \text{ GeV}}{f_a} \right) \]

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\[ \mathcal{L} = - \frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} \quad g_{a\gamma\gamma} \propto \frac{\alpha_{\text{EM}}}{f_a} \]

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Axion dark matter is a classical field

- **Axions**
  - **WIMPS**

![Graph showing log10(m_a/eV) vs de Broglie wavelength]

- **Dark Matter Models**
  - de Broglie wavelength: \( \lambda_{dB} = \frac{2\pi}{p} \approx \frac{2\pi}{mv} \)
  - **Axion** \( (m = 10^{-9} \text{ eV}) \): \( \lambda_{dB} \approx 8 \times 10^3 \text{ km} \)
  - **WIMP** \( (m = 100 \text{ GeV}) \): \( \lambda_{dB} \approx 8 \times 10^{-17} \text{ km} \)

Local DM energy density: \( \rho_{DM} \approx 0.4 \text{ GeV/cm}^3 \)

Local occupancy number: \( N \approx (\rho_{DM}/m) \times 3 \lambda_{dB} \)

- **Axion** \( \approx 10^{44} \)
  - **WIMP** \( \approx 10^{36} \)
Axion dark matter is a classical field

- **DM field**: Axions
- **DM particles**: WIMPS

**de Broglie wavelength**: \( \lambda_{dB} = \frac{2\pi}{p} \approx \frac{2\pi}{m v} \)

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**Local occupancy number**: \(N \approx (\rho_{DM}/m) \times \lambda_{dB}^3\)

- \(N_{\text{axion}} \approx 10^{44}\)
- \(N_{\text{WIMP}} \approx 10^{-36}\)
The axion as dark matter \((f_a > H_I/2\pi)\)

\[
\ddot{a} + 3H\dot{a} + m_a^2 a = 0 \quad (H = T^2/m_{\text{pl}})
\]
The axion as dark matter \( (f_a > H_1/2\pi) \)

\[
\ddot{a} + 3H\dot{a} + m_a^2 a = 0 \\
(H = T^2/m_{pl})
\]

\[
\theta_i = a_i / f_a
\]

initial misalignment

\( 3H = m_a \)

\( a \propto T^{3/2} \cos(m_a t) \)
The axion as dark matter ($f_a > H_1/2\pi$)

\[ \ddot{a} + 3H\dot{a} + m_a^2 a = 0 \quad (H = T^2/m_{pl}) \]

\[ \theta_i = a_i/f_a \]

- After $3H = m_a$, coherent oscillations $\sim$ NR matter

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Initial misalignment
The axion as dark matter \((f_a > \frac{H_1}{2\pi})\)
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- After \(3H = m_a\), coherent oscillations \(\sim\) NR matter

- Today: \(\Omega_a h^2 \sim 0.1 \left(\frac{f_a}{10^{12} \text{ GeV}}\right)^{7/6} \theta_i^2\)
The axion as dark matter \((f_a > H_1/2\pi)\)

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- After \(3H = m_a\), coherent oscillations \(\sim\) NR matter

- Today: \(\Omega_a h^2 \sim 0.1 \left( \frac{f_a}{10^{12} \text{ GeV}} \right)^{7/6} \theta_i^2\)

- \(f_a = 10^{16} \text{ GeV} \rightarrow |\theta_i| \lesssim 10^{-3} - 10^{-2}\) (e.g., Tegmark, Aguirre, Rees, Wilczek ’05)
Is QCD damping relevant at small $f_a$?

Preliminary! In progress with Andrey Katz

\[ \ddot{a} + (3H + \gamma_{\text{QCD}})\dot{a} + m^2_a a = 0 \]
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- **QCD Damping rate** (McLerran et. al. 1990):

\[
\gamma_{\text{QCD}} = \frac{1}{f_a^2 T} \int d^4 x \left\langle \frac{\alpha_s}{4\pi} \text{tr}[G_{\mu\nu} \tilde{G}^{\mu\nu}(x)] \frac{\alpha_s}{4\pi} \text{tr}[G_{\mu\nu} \tilde{G}^{\mu\nu}(0)] \right\rangle_T \\
= \frac{\Gamma_{\text{sphaleron}}}{f_a^2 T} \\
\propto \text{(large coefficient)} \times \frac{T^3}{f_a^2} 
\]
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  \]

  \[
  = \frac{\Gamma_{\text{sphaleron}}}{f_a^2 T}
  \]

  \[
  \propto (\text{large coefficient}) \times \frac{T^3}{f_a^2}
  \]

- **Important if** $\gamma_{QCD} \sim H$ at $T \sim 1$ GeV:

  \[
  \frac{(1 \text{ GeV})^3}{f_a^2} \sim \frac{(1 \text{ GeV})^2}{10^{18} \text{ GeV}}
  \]

- **Important for** $f_a \lesssim 10^{10}$ GeV (with the $\mathcal{O}(1)$ numbers)
Is QCD damping relevant at small $f_a$?

Probably not if $f_a \gtrsim 10^{11}$ GeV

![Graph showing the behavior of $a(t)$ with and without QCD damping at $f_a = 10^{11}$ GeV]
Is QCD damping relevant at small $f_a$?

Likely yes if $f_a \lesssim 10^{10}$ GeV

The graph shows two cases:
- $f_a = 10^{10}$ GeV
  - Black line: with QCD damping
  - Orange line: no QCD damping

The black line damps out more rapidly than the orange line, indicating QCD damping is relevant.
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How can we probe axion dark matter?

- IAXO Projected (Axions from the Sun)
- ADMX Limit (axion-DM resonant cavity)
- ADMX Projected
- QCD axion (theory)

Graph with axes:
- $g_{a\gamma\gamma}$ (GeV$^{-1}$)
- $m_a$ (eV)
- $f_a$ (GeV)
- $\nu = \frac{m_a}{2\pi}$

Scale for $g_{a\gamma\gamma}$:
- $10^{-10}$ Hz
- $10^{-12}$ kHz
- $10^{-14}$ MHz
- $10^{-16}$ GHz

Scale for $m_a$:
- $10^{-13}$
- $10^{-11}$
- $10^{-9}$
- $10^{-7}$
- $10^{-5}$

Scale for $f_a$:
- $10^{13}$
- $10^{15}$
- $10^{17}$
- $10^{19}$
How can we probe axion dark matter?

IAXO Projected (Axions from the Sun)

ADMX Limit (axion-DM resonant cavity)

BH Superradiance?

e.g., Arvanitaki, Baryakhtar, Huang 2014
How can we probe axion dark matter?

- IAXO Projected (Axions from the Sun)

- ADMX Limit (axion-DM resonant cavity)

- ADMX Projected

- String/GUT inspired axion DM models

- Naturally Live Here!

- e.g., Svrcek, Witten 2006
Axion dark matter modifies Maxwell’s equations

- Recall axions also couple to QED:

\[
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- Magnetoquasistatic approximation: new electric current that follows B-field lines

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

Scott Thomas and Blas Cabrera (2010), Sikivie et. al. (2013)
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- Magnetoquasistatic approximation: new electric current that follows \( B \)-field lines
  \[ \nabla \times B = g_{a\gamma\gamma} B \frac{\partial a}{\partial t} \]

- Locally: \( a(t) \approx a_0 \sin(m_a t) \) and \( \frac{1}{2} m_a^2 a_0^2 = \rho_{\text{DM}} \)

- \( J_{\text{eff}} = g_{a\gamma\gamma} \sqrt{2} \rho_{\text{DM}} B \sin(m_a t) \)

Scott Thomas and Blas Cabrera (2010), Sikivie et. al. (2013)
Axion dark matter generates magnetic flux

Superconducting pickup loop
Axion dark matter generates magnetic flux

Estimate $B$-field induced through pickup loop

$(r = a = h = R)$
Axion dark matter generates magnetic flux

- Estimate $B$-field induced through pickup loop 
  $(r = a = h = R)$
- Axion effective current: $I_{\text{eff}} \sim R^2 J_{\text{eff}}$
- \[ B \sim \frac{I_{\text{eff}}}{R} \sim R g_{\alpha\gamma\gamma} \sqrt{2} \rho_{\text{DM}} B_0 \sin(m_a t) \]
- $f_a = 10^{16}$ GeV, $B_0 \sim 5$ T, $R \sim 4$ m: $B \sim 10^{-22}$ T (KSVZ)
Two readout strategies

Broadband

Better at low frequency

Resonant

Better at high frequency
Two readout strategies

Broadband

Resonant

Thermal noise dominates

Capacitors bring resistance ->

Better at low frequency

Better at high frequency

$\omega_{\text{res}} = 1/\sqrt{LC}$
Two readout strategies

Broadband

- Pickup loop
- SQUID noise dominates
- Better at low frequency

Resonant

- \( \Delta \omega \)
- Better at high frequency
Broadband estimate

Example from MRI application: (Myers et. al. 2007)

- $B$-field sensitivity: $S_B^{1/2} \approx 6.4 \times 10^{-17} \text{ T}/\sqrt{\text{Hz}}$
- $R \approx 3.3 \text{ cm}$
Broadband estimate

- Example from MRI application: (Myers et. al. 2007)
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- Scale to $R \approx 4$ m
  - $S_B^{1/2} \approx 5 \times 10^{-20}$ T/√Hz
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- Scale to $R \approx 4 \text{ m}$
  - $S_B^{1/2} \approx 5 \times 10^{-20} \text{ T/\sqrt{Hz}}$
- $t = 1$ year interrogation time for GUT scale axion
  - Coherence time: $\tau \sim 2\pi/(m_a v^2) \sim 10 \text{ s} \ (v \sim 10^{-3})$
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- $t = 1$ year interrogation time for GUT scale axion
  - Coherence time: $\tau \sim \frac{2\pi}{(m_a v^2)} \sim 10 \, \text{s} \,(v \sim 10^{-3})$
  - $S/N = 1$ for $B = S_B^{1/2} (t\tau)^{-1/4} \sim 10^{-22} \, \text{T}$
Axion dark matter projected reach

$t = 1$ year

$B_{\text{max}} = 5$ T

$R \sim 1 \text{ m}$

$R \sim 4 \text{ m}$

Broadband

$T < 60 \text{ mK}$
Axion dark matter projected reach

- Broadband: $T < 60 \text{ mK}$
- $t = 1 \text{ year}$
- $B_{\text{max}} = 5 \text{ T}$

- Resonant: $T = 10 \text{ mK}, \ Q \sim 10^6$
- $R \sim 1 \text{ m}$

- $R \sim 4 \text{ m}$

Graph showing $g_{a\gamma}$ vs. $m_a$ with different frequency bands.
Axion dark matter projected reach

$t = 1 \text{ year}$

$B_{\text{max}} = 5 \text{ T}$

MQS approximation breaks down

Resonant $T = 10 \text{ mK, } Q \sim 10^6$

Broadband $T < 60 \text{ mK}$

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The MIT prototype: ABRACADABRA-10 cm

- **ABRACADABRA**: A Broadband/Resonant Approach to Cosmic Axion Detection with an Amplifying B-field Ring Apparatus
- **Dimensions**: $12 \times 12 \text{ cm}^2$ ($R = 3 \text{ cm}$, $h = 12 \text{ cm}$), $B = 1 \text{ T}$
- **People (LNS+CTP, PSFC, +1 Princeton)**: Janet Conrad, Joe Formaggio, Sarah Heine, Yoni Kahn, Joe Minervini, **Jonathan Ouellet**, Kerstin Perez, Alexey Radovinsky, **B.S.**, Jesse Thaler, Daniel Winklehner, **Lindley Winslow**
- **Lindley’s dilution refrigerator** ($< 100 \text{ mK}$)
  - **Workable space**: $R \sim 25 \text{ cm}$, $h \sim 25 \text{ cm}$
The MIT prototype: ABRACADABRA-10 cm

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- **Lindley’s dilution refrigerator** ($< 100 \text{ mK}$)
  - Workable space: $R \sim 25 \text{ cm}$, $h \sim 25 \text{ cm}$
- **Funded by the NSF** (as of this week)
Thanks Daniel Winklehner for CAD model and slides.
ABRA-10 cm: vertical cut

test wire
ABRA-10 cm: pickup cylinder

Superconducting pickup cylinder

Pickup loop leads

Cut cylinder so current returns through leads
ABRA-10 cm: reach after 1 month
Complementary proposals for axion dark matter experiments
CASPER: oscillating neutron EDM

\[ \mathcal{L}_{\text{axion}} = - \left( \bar{\theta} + \frac{a}{f_a} \right) \frac{g^2}{32\pi^2} G_{\mu\nu} \tilde{G}^{\mu\nu} \]

\[ d_n(t) = g_d a(t), \quad g_d \approx \frac{2.4 \times 10^{-16}}{f_a} \text{ e} \cdot \text{cm} \]

\[ \mathcal{L}_{\text{axion}} \]

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(Budker, Graham, Ledbetter, Rajendran, and Sushkov '13)
Light bosonic dark matter future

- **MIT**: ABRA-10 cm followed by ABRA-1 m ($B \sim 10$ T)

- **ABRA-1 m**: multiple experiments at different locations
  - Preliminary discussions with Korean Center for Axion and Precision Physics (Yannis Semertzidis)

- Axions and light bosonic dark matter well motivated by high-scale physics (e.g., compactified string theory)

- Detection may provide window to high-scale physics (GUT scale, inflation, . . .)

- New ideas to search for ultra-light scalars, dark-photons, etc. (laboratory experiments + astrophysics)
  - e.g., CASPEr experiment
  - Black Hole superradiance
Questions?
Axion Backup Slides
Magnetic field sensitivity calculation

- $B(t) = B_0 \sin[\omega_0 t + \phi(t)] + B_n(t)$
- $\phi(t)$: evolves over coherence time $\tau$
Magnetic field sensitivity calculation

- $B(t) = B_0 \sin[\omega_0 t + \phi(t)] + B_n(t)$
- $\phi(t)$: evolves over coherence time $\tau$

\[
P(\omega) \equiv \frac{1}{\sqrt{T}} \int_0^T dt B(t) \sin(\omega t) = P_0(\omega) + P_n(\omega)
\]
Magnetic field sensitivity calculation

- \( B(t) = B_0 \sin[\omega_0 t + \phi(t)] + B_n(t) \)
- \( \phi(t) \): evolves over coherence time \( \tau \)

\[
P(\omega) \equiv \frac{1}{\sqrt{T}} \int_0^T dt B(t) \sin(\omega t) = P_0(\omega) + P_n(\omega)
\]

- Spectral density: \( \lim_{T \to \infty} |P_n(\omega)|^2 \to S_B^{1/2}(\omega) \) [T / \( \sqrt{\text{Hz}} \)]
Magnetic field sensitivity calculation

- $B(t) = B_0 \sin[\omega_0 t + \phi(t)] + B_n(t)$

- $\phi(t)$: evolves over coherence time $\tau$

$$ P(\omega) \equiv \frac{1}{\sqrt{T}} \int_0^T dt B(t) \sin(\omega t) = P_0(\omega) + P_n(\omega) $$

- Spectral density: $\lim_{T \to \infty} |P_n(\omega)|^2 \to S_B^{1/2}(\omega) \ [T \ / \sqrt{\text{Hz}}]$ 

- $T < \tau$:
  - $|P_0(\omega_0)|^2 \propto B^2 T \to B^2 = S_B^{1/2}(\omega_0) / T$
Magnetic field sensitivity calculation

- $B(t) = B_0 \sin[\omega_0 t + \phi(t)] + B_n(t)$
- $\phi(t)$: evolves over coherence time $\tau$

$$P(\omega) \equiv \frac{1}{\sqrt{T}} \int_0^T dt B(t) \sin(\omega t) = P_0(\omega) + P_n(\omega)$$

- Spectral density: $\lim_{T \to \infty} |P_n(\omega)|^2 \to S_B^{1/2}(\omega) \ [T/\sqrt{\text{Hz}}]$

- $T < \tau$:  
  - $|P_0(\omega_0)|^2 \propto B^2 T \to B^2 = S_B^{1/2}(\omega_0)/T$

- $T > \tau$  
  - $|P_0(\omega_0)|^2 \propto \frac{B^2}{T} \times T\tau = B^2 \tau$
Magnetic field sensitivity calculation

- $B(t) = B_0 \sin[\omega_0 t + \phi(t)] + B_n(t)$
- $\phi(t)$: evolves over coherence time $\tau$
  
  $$P(\omega) \equiv \frac{1}{\sqrt{T}} \int_0^T dt B(t) \sin(\omega t) = P_0(\omega) + P_n(\omega)$$

- Spectral density: \( \lim_{T \to \infty} |P_n(\omega)|^2 \to S_B^{1/2}(\omega) \text{ [T }/\sqrt{\text{Hz}}]\)
- $T < \tau$:
  - $|P_0(\omega_0)|^2 \propto B^2 T \rightarrow B^2 = S_B^{1/2}(\omega_0)/T$
- $T > \tau$
  - $|P_0(\omega_0)|^2 \propto \frac{B^2}{T} \times T \tau = B^2 \tau$
  - But, line-width is broad and can resolve $N = T/\tau$ different frequencies
Magnetic field sensitivity calculation

- \( B(t) = B_0 \sin[\omega_0 t + \phi(t)] + B_n(t) \)
- \( \phi(t) \): evolves over coherence time \( \tau \)

\[
P(\omega) \equiv \frac{1}{\sqrt{T}} \int_0^T dt B(t) \sin(\omega t) = P_0(\omega) + P_n(\omega)
\]

- Spectral density: \( \lim_{T \to \infty} |P_n(\omega)|^2 \to S_{B}^{1/2}(\omega) \ [T / \sqrt{\text{Hz}}] \)
- \( T < \tau \):
  - \( |P_0(\omega_0)|^2 \propto B^2 T \to B^2 = S_{B}^{1/2}(\omega_0)/T \)
- \( T > \tau \):
  - \( |P_0(\omega_0)|^2 \propto \frac{B^2}{T} \times T \tau = B^2 \tau \)
  - But, line-width is broad and can resolve \( N = T/\tau \) different frequencies
  - \( B^2 = S_{B}^{1/2}(\omega_0)/\tau / \sqrt{N} = S_{B}^{1/2}(\omega_0)/\sqrt{T \tau} \)
Axion DM: Broadband Readout

\[ \Phi_{\text{pickup}} = (L_p + L_i)I \]

\[ \Phi_{\text{SQUID}} = MI \]

- \( L_i \approx L_p \) and \( M \approx \sqrt{L/L_i} \)

\[ \Phi_{\text{SQUID}} \approx \frac{1}{2} \sqrt{\frac{L}{L_p}} \Phi_{\text{pickup}} \approx 0.01 \Phi_{\text{pickup}} \]
**CASPEr: BBN and tuning bounds**

\[ \mathcal{L}_{\text{axion}} = - \left( \bar{\theta} + \frac{a}{f_a} \right) \frac{g^2}{32\pi^2} G_{\mu\nu} \tilde{G}^{\mu\nu} \]

- QCD generates minimum \( m_a \)

![Graph showing bounds on axion mass and QCD effects](attachment:image.png)