The Large Scale U.S. Dark-Matter Axion Search

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Talk Outline

• Brief review of the axion
• The Sikivie microwave cavity technique
• The U.S. large-scale experiment
• R&D on SQUID amplifiers
• Summary
Brief summary of the Axion

- The Axion is a light pseudoscalar resulting from the PQ-mechanism to enforce strong-CP conservation

- $f_a$, the SSB scale of PQ-symmetry, is the one important parameter in the theory

<table>
<thead>
<tr>
<th>Mass and Couplings</th>
<th>Cosmological Abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_a \sim 6 \mu eV \cdot \left( \frac{10^{12} \text{ GeV}}{f_a} \right)$</td>
<td>$\Omega_a \sim \left( \frac{5 \mu eV}{m_a} \right)^{7/6}$</td>
</tr>
<tr>
<td>$g_{a\gamma\gamma} = \frac{\alpha g_\gamma}{\pi f_a}$; $g_\gamma = \begin{cases} 0.97 \text{ KSVZ} \ -0.36 \text{ DFSZ} \end{cases}$</td>
<td>(Vacuum misalignment mechanism)</td>
</tr>
</tbody>
</table>

**Axion Mass ‘Window’**

$10^{-5 \text{ to } 6} \text{ eV} < m_a < 10^{-2 \text{ to } 3} \text{ eV}$

(Overclosure) (SN1987a)

With lower end of window preferred if $\Omega_{CDM} \sim 1$
How to detect dark-matter axions (Sikivie, 1983)

**Primakoff Conversion**

![Diagram of Primakoff Conversion]

**Resonant Conversion:**

\[
\nu = m_a c^2 [1 + O(\beta^2)]
\]

\[
P_{\text{sig}} \sim (5 \times 10^{-22} \text{W}) \cdot \left( \frac{B}{7.6 \text{T}} \right)^2 \cdot \left( \frac{V}{220 \text{eV}} \right) \cdot \left( \frac{g_\gamma}{0.97} \right)^2 \cdot \left( \frac{\rho_a}{0.45 \text{ GeV/cm}^3} \right) \cdot \left( \frac{m_a}{3 \mu \text{eV}} \right)
\]

**Dicke’s Radiometer Eqn. → Integration Time**

\[
\frac{s}{n} = \frac{P_{\text{sig}}}{kT_S} \cdot \sqrt{\frac{t}{\Delta \nu}}
\]

**Present exp’t:**

\[T \sim T_N \sim 1.5 \text{ K}\]

**Scaling Laws**

\[
\frac{d\nu}{dt} \propto B^4 V^2 \cdot \frac{1}{T_S^2}
\]

\[
g_\gamma^2 \propto \left( B^2 V \cdot \frac{1}{T_S} \right)^{-1}
\]

For fixed model \(g^2\)

For fixed scan rate \(\frac{d\nu}{dt}\)

**This is a narrow-band experiment. There is no other way to get the required sensitivity!**
Layout of the Axion Experiment

- Vacuum Pump
- Stepping motors
- Cryostat vessel
- Magnet support
- Cavity LHe reservoir
- Magnet LHe reservoir
- 1.3K J-T refrigerator
- Cavity vacuum chamber
- Amplifiers
- Tuning mechanism
- Microwave Cavity
- Dielectric tuning rod
- Metal tuning rod
- Superconducting magnet
Axion Detector Electronics

SWEEP GENERATOR

RF

T.R

I.R. MIXER

10.7 MHz IF

CRystal Filter

MIXER #2

35 kHz AF

L.O. #1

L.O. #2

Cs Clock

10 MHz Timebase

L.O. #3

125 Hz Bin FFT

0.02 Hz Bin FFT

DISK

MAGNET

CAVITY & TUNING RODS

HFET AMP.

DIR. COUPLER

SWITCH SETTINGS:
D = Data Taking
T = Transmission Measurement
R = Reflection Measurement

Power

\[ \frac{\Delta E}{E} = 10^{-6} \]

Expected Signal

\[ \frac{\Delta E}{E} = 10^{-17} \]
Brief outline of analysis

- Each frequency appears in >45 subspectra
- Weighted and co-added to produce spectrum
- 800,000 bins (125 Hz)/100 MHz

→ 6535 candidates > 2.25 $\sqrt{6} \sigma$ (95% C.L.)
→ Rescan all to same sensitivity
→ 23 candidates (Net 90% C.L.)
→ Each examined: radio peaks

For a persistent peak, the ultimate test is to turn off the magnet!
Sample data and candidates

- High-resolution data analyzed similarly
- Also looked for ‘coincidences’ between high and medium resolution data

**Environmental**

<table>
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<th>Power</th>
<th>Subspectra</th>
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<td>Total</td>
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Frequency (MHz)

- Signal maximizes off-resonance: Radio peak

**Statistical**

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Frequency (MHz)

- Signal distributed over many sub-spectra: a good threshold candidate (but did not persist in rescan)
New twist — ultrafine structure to axion signal?

- Main axion signal expected to be Maxwellian with $\Delta E/E \sim 10^{-6}$

- Sikivie et al have recently predicted non-thermalized fine-structure with $\Delta E/E \sim 10^{-17}$!
  - ‘Last-infall’ lines could contain several percent of total signal
  - May greatly improve our sensitivity

- We have instrumented independent parallel Fast Fourier Transform streams for both medium ($10^{-7}$) and high ($10^{-11}$) resolution spectra
**Cosmic axion exclusion plot**

**Phase I Upgrade:** SQUIDs at 1.3 K will allow us to run at KSVZ 4 times faster than with HEMTs

**Phase II Upgrade:** SQUIDs at 200 mK will give us sensitivity to DFSZ axions even if they only constitute 50% of the halo

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Multiple Cavities

- Exploring higher mass (frequency) range requires smaller cavities
  \[ f_{010} \propto R^{-1} \]

- Placing a single, smaller cavity inside the magnet volume would be inefficient.

- One solution is to fill the magnet volume with multiple cavities.

\[ \lambda_d - 10 - 100 \text{ m.} \]

- Since the axion signal is coherent over the magnet volume, the power from the individual cavities can be combined in phase.

- Four cavities with \( R = 20 \text{ cm} \) will be used to cover the frequency range of 800 - 2000 MHz.
Multiple Cavities/Piezoelectric Tuning
Power Combining Test

- Power Combining Test
- Measured
- Combined in Phase
- Simple Sum

Frequency (MHz)

809.8 809.9 810.0 810.1 810.2

Transmitted Power

809.8 809.9 810.0 810.1 810.2

Transmitted Power

809.8 809.9 810.0 810.1 810.2

Graphs showing transmitted power versus frequency with measured, combined in phase, and simple sum data points.
The precision of the piezos

**Stepping Motors and Gears**

- Piezos: $\Delta f = 1.99$ kHz, $\sigma = 0.46$
- Stepping motors

**Piezo Motors**

- $\Delta f = 94.4$ Hz, $\sigma = 13.6$

**Piezos — Step #0**

**Piezos — Step #200 (w/o Feedback)**
First Four-Cavity Exclusion Plot

\[ m_a (\mu eV) \]

\[ \frac{g_{\text{ar}}}{m_a}^2 [\text{GeV}^2/\text{eV}^2] \]

Frequency (MHz)

KSVZ
R&D towards 100 µeV (25 GHz) — Resonators

- Single cavity TM$_{010}$:
  - Number $\propto f^3$ in fixed volume
  - To minimize TE, TEM intruders
- Periodic Post Resonators can have very high TM$_{010}$ frequencies
  - Number $\propto f$
    - Height $\propto f^{-1}$ to minimize mode crossings
    - Tuned by global shift of alternate posts
    - Stacked as pans
- Modeling begun; first warm prototype being designed

We believe this is a promising avenue to the next decade in mass
The system noise temperature is the sum of the physical temperature of the cavity and the noise temperature of the first amplification stage.

\[ T_S = T_{\text{cav}} + T_N \]

1.3 K for Phase I

The present experiment uses GaAs HFET amplifiers supplied by NRAO with noise temperatures from 1.7 to 4.0 K.
The dc Superconducting Quantum Interference Device

- **DC SQUID**
  - two resistively shunted Josephson junctions on a superconducting ring

\[ I \rightarrow \Phi \rightarrow V \]

- Current-voltage (I-V) characteristic modulated by magnetic flux \( \Phi \):
  - period one flux quantum \( \Phi_0 = h/2e = 2 \times 10^{-15} \text{ Tm}^2 \)

\[ I \rightarrow \Phi \rightarrow V \]

\[ \Phi \rightarrow \Phi_0 \]

\[ \delta \Phi \rightarrow \delta V \]

\[ \Delta V \rightarrow 0, 1, 2 \]

\[ I_b \rightarrow n\Phi_0, (n+1/2)\Phi_0 \]
Square Washer dc SQUID

- superconducting input coil
- shunt
- counter-electrode
- washer
What the devices look like

Shunt

20 µm

Josephson Junction

1000 µm
Gain Measurements

- Gain of 11-turn microstrip SQUID with the washer grounded
Gain vs. Coil Length

![Graph showing gain vs. coil length]
Gain of 6-turn Microstrip SQUID

![Graph showing the gain of a 6-turn microstrip SQUID over a range of frequencies. The graph plots gain (in dB) against frequency (in MHz). The gain increases with frequency up to a peak at approximately 1600 MHz and then decreases.](image_url)
Varactor Tuning of Microstrip SQUID

Input

220 Ω

56 Ω 56 Ω

20 dB, 50 Ω Attenuator

SQUID

IΦ

Output

Varactor

1 - 9 pF for 20 - 0 V

Gain (dB)

-1 V 0 1 2 3 4 6 9 22 V

No Varactor

Gain (dB)

Frequency (MHz)

100 120 140 160 180 200 220
Noise Temperature Measurements

\[ P_{out} = k_B (T_i + T_N) G_S G_A + k_B T_N^p G_A \]

\[ \text{Vacuum can} \]
\[ \text{Heater} \]
\[ 50 \Omega \]
\[ \text{Thermometer} \]

\[ T_{\text{bath}} \leq 4.2 \text{ K} \]
\[ G_A \approx 17 \text{ dB} \]
\[ T_N^p \approx 8 \text{ K} \]

\[ \text{Amp. @ 295 K} \]
\[ G_A \approx 40 \text{ dB} \]
\[ T_N^p \approx 80 \text{ K} \]

\[ k_B T_S G_S G_A \]

\[ T_1 \quad T_2 \quad T_3 \quad T_i \]

slope: \( k_B G_S G_A \)
Noise Temperature of 31-turn SQUID with Cooled HEMT Postamplifier

\[ T_{N}^{\text{min}} = 0.25 \text{ K} \]

SQUID power gain \( G \approx 200 \)

Noise temperature of cooled HEMT postamplifier \( T_{N}^{P} \approx 8 \text{ K} \)

\[ T_{N}^{P} / G \approx 0.04 \text{ K} \]
Postamplifier Noise

\[ T_N^{sys} = T_N + \frac{T_N^p}{G} \quad (G = A^2) \]

Thus, require \( T_N^p \ll GT_N \)
SQUID Postamplifier

![Diagram of SQUID Postamplifier](image)

Gain (dB)

Frequency (MHz)
Noise Temperature at 519 MHz vs. Bath Temperature: Resonant Source
Noise Energy at 140 kHz vs. Bath Temperature

![Graph showing the relationship between noise energy at 140 kHz and bath temperature. The graph plots $S_\Phi (140 \text{ kHz})/2L (\text{h})$ on the y-axis and temperature (mK) on the x-axis. The data points are represented with error bars, and a trend line is drawn through the data points.](image-url)
Summary

- The axion is well-motivated in particle physics and a very credible dark-matter candidate.

- The parameter space (mass, coupling) is bounded and present experiments have already scanned well into this region.

- Near-quantum-limited SQUID amplifiers are an enabling technology for a truly definitive search.

- R&D effort underway to extend the search into the second decade in frequency.