Purpose of this workshop

- Bring together...
  - Researchers in axion physics
  - Experts in microwave cavities for accelerators.
  - Experts in quantum information technologies.

Goal

- Bring students and researchers unfamiliar with axion dark matter searches up to speed on unique experimental requirements.
- Work through new concepts to address the challenge of going to higher and lower mass axion searches in an informal setting.
The Nature of Dark Matter
One of the premier unsolved mysteries in physics

- **1930s**
  Fritz Zwicky: noticed odd motion of member galaxies of the Coma Cluster (moving too quickly to be bound)

- **1980s**
  Vera Rubin: systematically surveyed a large number of galaxies. Rotation curves did not make sense without a large unseen mass → made dark matter unavoidable!

Likely new particle outside standard model
A. Baryons essentially ruled out!
B. Neutrinos likely only small fraction.

Tremendous progress in the last 20 years on searches for both!

Recently DOE has made a major investment in three “Generation 2” direct dark-matter projects
1. LZ (Liquid Zenon WIMP search)
2. SuperCDMS-Snolab (Ge/Si WIMPS search)
3. ADMX (axion dark matter search)
Pecccei and Quinn: CP conserved through a hidden symmetry

QCD CP violation should, e.g., give a large neutron electric dipole moment ($\mathcal{T} + \text{CPT} = \mathcal{CP}$); none is unobserved. (9 orders-of-magnitude discrepancy)

$$
T \left( \begin{array}{c}
\mu_n \\
|n> \\
-\mu_n
\end{array} \right) = \begin{array}{c}
d_n \\
|n> \\
-d_n
\end{array} \neq |n>
$$

Why doesn’t the neutron have an electric dipole moment?

$$d_e < 3 \cdot 10^{-26} \text{ e-cm}$$
Baker et al. 2006

This leads to the “Strong CP Problem”: Where did QCD CP violation go?

1977: Pecccei and Quinn: Posit a hidden broken U(1) symmetry $\Rightarrow$
1) A new Goldstone boson (the axion);
2) Remnant axion VEV nulls QCD CP violation.
Axion experimentally constrained parameter space

With current technology, only ADMX has reached the dark matter QCD axion band.

Graham, et.al (2016)
ADMX: Collaboration (begin in mid-1990s)

Sponsors
ADMX now DOE Gen 2 project

Recently Joined

ADMX-High Frequency
Separate collaboration sited at Yale

Primary sponsor

*in process of joining
The ADMX experimental layout (original concept from P. Sikivie)

Local Milky Way density:
\[ \rho_{\text{halo}} \sim 450 \text{ MeV/cm}^3 \]

Thus for \( m_a \sim 10 \mu\text{eV} \):
\[ \rho_{\text{halo}} \sim 10^{14} \text{ cm}^{-3} \]

“High Resolution” channel

\[ \beta_{\text{virial}} \sim 10^{-3} : \]
\[ \lambda_{\text{De Broglie}} \sim 100 \text{ m} \]

\[ \Delta \beta_{\text{flow}} \sim 10^{-11} : \]
\[ \lambda_{\text{Coherence}} \sim 1000 \text{ km} \]
Power transfer increased by time coherence between cavity E-field and axion field

Weak coupling -- takes many swings to fully transfer the wave amplitude. Number of swings = cavity Quality factor. Narrowband cavity response → iterative scan through frequency space.

*Slide from Aaron Chou (FNAL)
Microwave Cavity needs tunable resonance
Microwave Cavity needs tunable resonance

Cavity

Antennas

Tuning Rod

Transmittance between Antennas

1.5 GHz 1.6 GHz

Frequency
Frequency tuning the $\text{TM}_{010}$ mode
Example Frequency Mode Map (sidecar system)

Reference mode map in blue

Simulated mode map in yellow

Red Dots are live data taken from wide scan
Critically coupling the $\text{TM}_{010}$ mode
Typical ADMX Run Cadence

- Start by injecting a broad, swept RF signal to record cavity response. Record state data (temperatures, hall sensors, pressures, etc).

- Integrate for ~ 100 sec to 10s of minutes (final integration time dependent on experimental parameters).

- Every few days adjust the critical coupling of the antennas.

- Scan rate is a trade-off in sensitivity vs frequency (mass) coverage.

- The scan rate uses a threshold sensitivity.

- Any candidate above threshold is flagged for further study.
Sample data and candidates

### Environmental

**Subspectra**

**Total**

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<td>775.74</td>
<td>775.75</td>
<td>775.76</td>
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**Signal maximizes off-resonance:**
Radio peak

### Statistical

**Subspectra**

**Total**

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<th></th>
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<th></th>
<th></th>
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<tbody>
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<td>772.11</td>
<td>772.12</td>
<td>772.13</td>
<td>772.14</td>
<td>772.15</td>
<td>772.16</td>
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</table>

**Signal distributed over many sub-spectra:**
A good threshold candidate (but did not persist in rescan)
The Radiometer equation dictates strategy

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

* Dicke, 1946

But integration time limited to ~ 100 sec

System noise temp. now

\[T_S = T + T_N \sim 1.5 + 1.5 \text{ K}\]

But \(T_{\text{Quant}} \sim 30 \text{ mK}\)

This is where we invested to get to Gen 2

\[
P_{\text{sig}} \sim (B^2 V) Q_{\text{cav}} g^2 m_a \rho_a
\]

\[\sim 10^{-23} \text{ Watts for ADMX}\]

But magnet size, strength \(B^2 V \sim \$\)
Enabling technology: Quantum-limited amplifiers
500-1000 MHz Microstrip SQUID Amp (MSA) Devices

Gain = 20 dB
Frequency 612 MHz

Quantum limit $T_Q = 30 \text{ mK}$

At $T_{bath} = 50 \text{ mK}$
Noise temperature:
$T_{N}^{\text{opt}} = 48 \pm 5 \text{ mK}$

Noise temperatures of $48 \pm 5 \text{ mK}$ have been demonstrated at 612 MHz, within 1.7 times the quantum limit

Darin Kinion, JC

UCB produced
Prof. John Clarke
Quantum Limited Amplifiers

SQUIDs (at lower frequencies)

“JPAs” (at higher frequencies)
Cavity and thermal shielding (4 K, 1 K, 100 mK)
Currently installed Cavity & Motion Control

Dilution Fridge mounted directly to cavity top

Quality factor:
~ 70k at cryogenic temps

Rotary gearbox
1:19,600 gear reduction

Linear gearbox (coupling)
ADMX currently operational

- Initial commissioning run at 200 mK between Aug 9th – Oct 3rd
  - No evidence of vibration heating from motion in field
  - No evidence of cavity heating from motion control
- Recent upgraded heat exchangers (now operating at 160 mK)
- Currently taking data at 660 MHz and at 7 Tesla
ADMX Science Prospects: Year 1 (0.6 – 1 GHz)
Key Microwave Cavity Design Constraints

- Maximize product of $B^2 \cdot V \cdot Q_L \cdot C_{lmn}$ to maximize axion-to-photon conversion power
  - $B^2 V$ set by the magnet bore: $(8T)^2 \cdot (\sim 100 \text{ liters})$

- Loaded Quality factor $Q_L = \text{frequency/bandwidth}$
  - $(Q_L \sim 10^5$ for copper cavity $\sim 1 \text{ GHz})$

- Mode Form Factor $C_{lmn}$

- Tunability: must be able to shift resonant frequency over an appreciable range (typically 30-50%)

- Ability to determine that you are on the mode that couples to axions ($TM_{0n0}$)

- Precision & alignment tolerances (minimize spurious modes and mode crossings)
Managing mode-crossings

- Transverse Magnetic (TM) modes move up in frequency as tuning rods are rotated.

- Transverse Electric (TE) modes remain relatively static in frequency.

- When both mode’s frequencies are degenerate there’s a “mode crossing” in which the two modes “mix” and the resonant peak can disappear.

- The longer the cavity, the more TE modes there are in the tuning range.

  Keep aspect ratios: $\text{Length} / \text{radius} \sim 5$.

- We step around mode crossings by using multiple tuning rods (metal and dielectric).
Possible to instrument higher order modes

### $\text{TM}_{020}$ Mode
- Relative Frequency: 2.3
- Tuning Range: 920-2,100 MHz
- Relative Power: 0.41

### $\text{TM}_{010}$ Mode
- Relative Frequency: 1.0
- Tuning Range: 400-900 MHz
ADMX: Multi-mode readout

Ch 1: Instrumented with MSA amp & low pass filter (DFSZ sensitivity)

Ch 2: Instrumented with JPA amp & high pass filter (~KSVZ sensitivity)

Challenging due to more complicated mode structure.

Cryogenic filters are non-trivial components (provided by NRAO)
Challenge of higher frequency axion searches

- Scaling single cavity to higher frequencies ($f$) – Volume $\sim (f)^{-3}$!
- Quality factor also goes down as frequency increases ($Q_L \sim 10^5 \cdot (f)^{-2/3}$)

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Axion Mass</th>
<th>$Q_L$</th>
<th>Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>540 MHz</td>
<td>2 $\mu$eV</td>
<td>100,000</td>
<td>135 liters</td>
</tr>
<tr>
<td>2.4 GHz</td>
<td>9 $\mu$eV</td>
<td>60,000</td>
<td>2.6 liters</td>
</tr>
<tr>
<td>10 GHz</td>
<td>36 $\mu$eV</td>
<td>25,000</td>
<td>0.025 liters</td>
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</table>

16” diameter

5” diameter
R&D work underway to expand usable volume

- Photonic Bandgap Cavities

Multicavity Array's
Increasing Q of the cavity is also important.

\[ P_{\text{axion}} \sim B^2 V \cdot \min(Q_a, Q_L) \cdot (g_\gamma)^2 \rho_a m_a \]

\( Q_a = \) axion linewidth (gravitational thermalization)
\[ \sim \frac{E}{\Delta E} \sim \frac{1}{\beta^2} \sim \frac{1}{(100 \text{ km/s})^2} \sim 10^6 \]

1 GHz mass axion should be spread over 1 kHz

\( Q_L = \) loaded cavity quality factor
\[ \sim \text{resonant } f / \text{bandwidth} \]
\[ \sim 10^5 \text{ for copper cavity at 1 GHz} \]

Increasing \( Q_L \) to \( Q_a \) will increase your sensitivity
The “Hybrid” superconducting cavity concept

For typical ADMX cavity $L/R \sim 5$ giving $Q$ enhancement of 6
Conclusion

- The dark matter axion is a very compelling dark matter candidate.
- Experiments are finally getting sensitive enough to reach plausible dark matter axion model space.
- Lots of technical challenges remain to efficiently cover the rest of the parameter space... hence this workshop.

A Big Thank You the Heising-Simons Foundation, LLNL, DOE and NSF for supporting these efforts (and this workshop)!