Results and Status of the Axion Dark Matter Experiment

Nicole Crisosto
17/7/2019
DSU 2019
Buenos Aries, Argentina
Outline

• Background
• Haloscope Detectors
• ADMX Design
• ADMX Results
• Future Work
Why we look for axions

• There is compelling evidence for dark matter, but we don’t know what it is

• Axions may make up the dark matter

• Axions are a well motivated dark matter candidate because they arise from solving the strong CP problem
Invisible axions

- For QCD axions that solve strong CP, coupling and mass are interdependent
- Strongly coupled axions are not observed
- Weakly coupled axions make up the dark matter window
- Elusive invisible axions in μeV mass range

How we look for axions

- Detection through the Sikivie Haloscope
- An external magnetic field stimulates conversion to real photons
- The photon signature of axion conversion is faint
- Resonant enhancement is needed
- Axion mass is unknown so we must scan possible resulting photon frequencies
Cavity Tuning

- Antennas
- Tuning Rod
- Cavity

Transmittance between Antennas

Graph showing transmittance with a peak at 1.5 GHz.

Frequency

1.5 GHz
Cavity Tuning

Antennas

Tuning Rod

Cavity

Transmittance between Antennas

Frequency

1.5 GHz  1.6 GHz
Power

\[ P_{\text{axion}} = 1.9 \times 10^{-22} \text{ W} \left( \frac{V}{136 \text{ L}} \right) \left( \frac{B}{6.8 \text{ T}} \right)^2 \left( \frac{C}{0.4} \right) \left( \frac{g_\gamma}{0.97} \right)^2 \left( \frac{\rho_a}{0.45 \text{ GeV cm}^{-3}} \right) \left( \frac{f}{650 \text{ MHz}} \right) \left( \frac{Q}{50,000} \right) \]

- V is cavity volume
- B magnetic field
- \( C_{nl} \) is a form factor, overlap of cavity mode and applied magnetic field
- \( g_\gamma \sim 0.36 \) (DFSZ) while \( g_\gamma \sim -0.97 \) (KSVZ)
- \( \rho \) is local axion halo density
- 650 MHz \( \Leftrightarrow \) 2.7 \( \mu \text{eV} \)
- Q resonator quality factor, how long cavity rings coherently with conversion photon
Radiometer

- Signal to Noise Ratio from the radiometer equation
  \[ \frac{s}{n} = \frac{P}{k T_n} \sqrt{\frac{t}{\Delta f}} \]

- System temperature
  \[ T_n = T_{phys} + T_{amp} \]

- Scan rate
  \[ \frac{df}{dt} \approx 750 \text{ MHz/year} \left( \frac{g_\gamma}{0.36} \right)^4 \left( \frac{5}{\text{SNR}} \right)^2 \left( \frac{f}{1 \text{ GHz}} \right)^2 \left( \frac{B_0}{8 \text{ T}} \right)^4 \left( \frac{V}{100 \text{ L}} \right)^2 \left( \frac{Q_L}{10^5} \right) \left( \frac{C_{010}}{0.5} \right)^2 \left( \frac{\rho_a}{0.45 \text{ GeV cm}^{-3}} \right)^4 \left( \frac{0.2 \text{ K}}{T_{sys}} \right)^2 \]
Engineering Parameters

• High quality factor resonator -> copper plated microwave cavity resonator

• Strong magnetic field -> large superconducting solenoid magnet

• Low system noise temperature
  • Low physical temperature -> dilution refrigerator
  • Low amplifier noise temperature -> quantum electronics
ADMX Site

Cleanroom (with insert hanging)

ADMX Magnet

ADMX DAQ & Controls

Helium Liquefier
Experiment Layout

- Field Cancellation Coil
- Squidadel
- Dilution Refrigerator
- Antennas
- 8 Tesla Magnet
- Microwave Cavity
- Tuning Rods

Warm Space
Liquid Helium Reservoir
Cold Space
Magnet

- Superconducting solenoid magnet
- 53 cm bore
- 100 cm height
- Up to 8 Telsa
- 230 Amps
Helium Plant

- Major $^4$He consumption
  - Magnet fills
  - Insert reservoir fills
- Capture and re-liquify $^4$He
- Recent Plant Upgrades
  - Mother Dewar volume increase
  - Production rate increase
  - Autofill System
Dilution Refrigerator

• Cooling through of mixing $^3$He and $^4$He
• Allows persistent milliKelvin temperatures
• Substantial cooling power 800 $\mu$watts @ 100 mK
• Physical noise becomes lower than noise temperature of classically limited amplifiers
• Sets the stage for quantum limited amplifiers
Quantum Electronics

- Superconducting Quantum Interference Devices (SQUIDs)
  - Flux to voltage transducers
- Josephson Parametric Amplifiers (JPAs)
  - “pumped” oscillator
- Amplifiers that approach the quantum limit
- Allow for low noise temperature
- Live in a field free region “squidadel”

*SQUID Φ vs. V

SQUID Φ vs. V

ω = \frac{1}{\sqrt{LC}}

*JPA figures courtesy of Shahid Nawaz
Receiver Chain

- Receiver chain progress through warmer regions
- Additional HEMT amplification
- Double heterodyne mixing
- FFT to digitize and record
Synthetic Axion Injection

- How do we know we are capable of detection?
- Synthetic test signals are periodically injected
- Confirm in live analysis and remove from actual search data
Synthetic signal candidate for ADMX Run1b
Run 1a

- Operated from January- June 2017

- Scanned frequency range: 645-680 MHz (2.66-2.81 µeV)

- Magnetic field: 6.8 T

- Temperature: ~150 mK

- DFSZ sensitivity attained for the first time!
Run 1a Limits

Search for Invisible Axion Dark Matter with the Axion Dark Matter Experiment
PRL 120, 151301 (2018)
Run 1b

- Operated from January - October 2018
- Higher magnetic field 7.6 T
- Colder temperature ~90 mK
- Extended searched mass frequency range 680 - 800 MHz (2.81 - 3.31 μeV)
Run 1c: On-going search

- An axion has not yet been found, the search continues
- Tuning Rod and Quantum Electronics Changed
- Planned Frequency Range: 800 - 1,000 Mhz
Run 1c: On-going search

- Expected Improvements
  - smaller mode crossings
  - better cryogenics and noise temperature
  - lower dead time/more efficient operation
  - wider tuning range
- Stay tuned for progress updates!
Searching Higher Masses

• Smaller cavity radius for higher frequency

• Loss of volume => less power out

• Combine an array of cavities!
Run 2

Cavity Frequency (GHz)

Axion Coupling $|g_{a\gamma}|$ (GeV$^{-1}$)

Axion Mass μeV

ADMX G2 Discovery Potential

DFSZ
Four-Cavity Array Prototype
ADMX Sidecar Cavity
4-6 GHz $\text{TM}_{010}$ & 6-7 GHz $\text{TM}_{020}$

Completely separate system installed above main cavity

Cavity Frequency (GHz)

Axion Coupling $|g_{\alpha\gamma}| \ (\text{GeV}^{-1})$

- $10^{-9}$
- $10^{-10}$
- $10^{-11}$
- $10^{-12}$
- $10^{-13}$
- $10^{-14}$
- $10^{-15}$
- $10^{-16}$
- $10^{-17}$

Axion Mass $\mu\text{eV}$

- 1
- 10
- 100

- ADMX G2 Discovery Potential
- DFSZ
Future Prospectus
Conclusion

- Axions are a well motivated dark matter candidate, especially of in light of the Strong CP problem

- Axions are hard to detect

- Orchestration of a tuned resonator, large magnet, cryogenics, and quantum electronics gives us a chance at detection!

- ADMX is the first and only experiment to attain DFSZ sensitivity thus far

- Data-taking is to be continued in the near future

- Other resonators are under development to extend searchable axion mass range
Acknowledgements

• This work was supported by the U.S. Department of Energy through Grants No. DE-SC0009723, No. DE-SC0010296, No. DE-SC0010280, No. DE-SC0010280, No. DEFG02-97ER41029, No. DE-FG02-96ER40956, No. DEAC52-07NA27344, and No. DE-C03-76SF00098.

• Fermilab is a U.S. Department of Energy, Office of Science, HEP User Facility. Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DE-AC02-07CH11359.

• Additional support was provided by the Heising-Simons Foundation and by the Lawrence Livermore National Laboratory and Pacific Northwest National Laboratory LDRD offices.

• Thank you ADMX collaborators at:
  • UW, UF, LLNL, FNAL, UCB, PNNL, LANL, NRAO, WU, UWA, & Sheffield
Backup Slides
Fridge Improvement

![Graph showing fridge temperature over months from February to April, with peaks in March 2017 and 2018.](graph_image)
Axions and Maxwell’s Equations

• Axion field alters Maxwell’s Equations

\[ \nabla \cdot \vec{E} = g\vec{B} \cdot \nabla a \]
\[ \nabla \times \vec{B} - \frac{\partial \vec{E}}{\partial t} = g(\vec{E} \times \nabla a - \vec{B} \frac{\partial a}{\partial t}) \]

• In the presence of an external magnetic field \( \vec{B}_0 \),

\[ \nabla \times \vec{B}_a = \vec{j}_a = -g\vec{B}_0 \frac{\partial a}{\partial t} \]
Searches to Date
Design and R&D 2

Cavities

- **ADMX Gen2** has used a single cavity with metal tuning rods
- **Plans to use a 4 cavity array**
  - Tuned in concert to a single frequency
  - Output amplitudes added
  - Use metal and dielectric tuning