Results and update from the ABRACADABRA search for sub-µeV axion dark matter
And Future Plans
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Axion as “Light” DM

\[ \Omega_a \sim \left( \frac{f_a}{10^{12} \text{ GeV}} \right)^{7/6} \]

- Gravitational Waves
- Neutrino Masses
- Light Dark Matter
- New Forces
- EDMs, g-2, Flavor Violation

Arvanitaki
QCD Axion Properties

\[ m_a \simeq 0.6 \text{eV} \frac{10^7 \text{GeV}}{f_a} \]

\( f_a \) : PQ Symmetry Breaking Scale Relationship Model-dependent

Rev.Mod.Phys. 82 (2010) 557
QCD Axion Properties

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Relationship Model-dependent

Rev. Mod. Phys. 82 (2010) 557
Context
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Pre-inflation
ABRA, DMRadio, SLIC, CASPER, ...
1Hz - 300 MHz

1801.08127
Context

\[ m_a \sim 0.6 \text{eV} \frac{10^7 \text{GeV}}{f_a} \]

GUT Scale
Microwave Cavities

- Cosmic relic axions (Dark Matter) with masses ~ microwave energies
- Resonant conversion of axion in high-Q cavity in magnetic field
- ADMX Current state of the art. HAYSTAC, CAPP, others coming online

Carosi, G. , et al, Contemporary Physics, 49: 4, 281
Alternative: Lumped Element

Tuned LC Circuit: 
*Cabrera, Thomas, 2010*
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Cabrera, Thomas, 2010

Solenoidal Magnet:  
PRL 112 (2014) 131301;  
PRD 97 (2019) 072011;  
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* PRL 112 (2014) 131301;
* PRD 97 (2019) 072011;
* 1911.05722


Toroidal Magnet:
* ABRACADABRA:  
  * PRL 117 (2016) 141801
A Search for Low-Mass Axion Dark Matter

“A Broadband or Resonant Approach to Cosmic Axion Detection with an Amplifying $B$-field Ring Apparatus”
Treat ultralight axion DM as coherent field

\[ a(t) = \frac{\sqrt{2} \rho_{\text{DM}}}{m_a} \sin(m_a t) \]
Treat ultralight axion DM as coherent field

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Generic axion modifies Ampere’s Law:

\[ \nabla \times \mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} - g_{\gamma\gamma}(\mathbf{E} \times \nabla a - \mathbf{B} \frac{\partial a}{\partial t}) \]
ABRA Concept

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Magnetooquasistatic limit  \( \mathbf{E}=0, \) DM \( \nu \sim 10^{-3} \)
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Yields axion-induced effective current:

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Induces oscillating magnetic field in torus

Measure induced field using pickup loop
DC B-field free
Dissecting ABRACADABRA-10 cm

- G10 Support structure (nylon bolts)
- Copper Thermalization Bands
- Superconducting tin coated copper shield

12cm
Assembling ABRACADABRA-10 cm

Pickup Loop
ABRA-10cm Mounted

Kevlar Support

700 mK

150 mK
Axion Limits

- Broadband Data-taking in summer 2018. No resonator.

- No $5\sigma$ excesses that were not vetoed by Magnet off or digitizer data

- Published results: PRD 99 (2019) 052012; PRL 122 (2019) 121802
ABRACADABRA-10 cm Run 1 Limits

To appear in PDG 2019 (courtesy G. Rybka)
ABRACADABRA-10 cm Run 1 Limits
Future Plans
Leading up to a Cubic Meter Experiment

- **ABRA-10cm**: Running at MIT.
- **DMRadio-Pathfinder (Vector DM)**: Running at Stanford.
- **DMRadio-50L**: Under Construction at Stanford.
- **DMRadio-m³ R&D Consortium** recently funded by DOE HEP Dark Matter Small Initiatives Program for ~$1M.
  - Includes ABRA PIs (Henning and Winslow).
  - 2 years.
  - **Goal**: Develop 30% Design, focused on magnet.
  - Develop Full Proposal for 1m³ experiment.
- Organizational kickoff meeting at MIT last month. Developing plan for merger by Summer 2020.
DM Radio Cubic Meter Consortium

Funded as part of DOE New Initiatives in Dark Matter program

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<th>Name</th>
<th>Institution</th>
<th>Role / Team Lead</th>
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<td>Consortium PI</td>
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<td>UC Berkeley</td>
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<td>Lindley Winslow</td>
<td>MIT</td>
<td>Magnetic shielding, vibration</td>
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<tr>
<td>Nadine Kurita</td>
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<td>Project Management Plan</td>
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**DM Radio Cubic Meter Science Goals**

**Cubic Meter Experiment**
- 1 m$^3$ Detection Volume
- 20 mK Temperature
- 4 Tesla Magnetic Field
- 5 MHz – 200 MHz
- dc SQUID with 20× quantum limit
- 3 years of live scan time
- Quantum Acceleration would enable QCD sensitivity at lower mass
DM Radio Cubic Meter Timeline

2020-2021: DM Radio-m³ R&D
2022-2025: DM Radio-m³ Proposed Project Build
2025-2230: DM Radio-m³ Science Scanning

New Initiatives in Dark Matter R&D Selection
DMRadio-m³ R&D
DMRadio-m³ Consortium
proto-Collaboration
DMRadio-m³ Project
DMRadio-m³ Collaboration
Construction
Operation / Science
Submit Project Proposal
Project Build Complete

Conclusion

- We have built and operated the first broadband search for Axion Dark Matter in the sub \(\mu\text{eV}\) range.
- With a 10 cm scale detector and 1 month of exposure, we are competitive with the leading limits in the field.
- Developing proposal for a \(\sim 1 \text{ m}^3\) scale experiment with resonant readout to reach QCD axion line
- Opens up other well-motivated axion mass ranges
BONUS SLIDES
DM Axions Below 1μeV

• Pre-inflation PQ symmetry breaking allows axion masses $10^{-12}$ to $10^{-4}$ eV or even beyond

• GUT Scale Axion at $\sim 1$ neV ($f_a \sim 10^{15}$ GeV) generic feature of String Theories

• Many proposals exist for removing fine tuning of $\theta$ required for $m_a \ll 1\mu$eV. Typically require new particles.

• Or can just require long-scale inflation, eg. Phys. Rev. D 98, 035017 (2018)
Axions Catching up to WIMPs

APS April Meeting Abstracts

![Graph showing Axions Catching up to WIMPs](chart)

- **WIMP Dark Matter**
- **Axion Dark Matter**

*Courtesy, J.Ouellet*
Two Readout Strategies

**Broadband**

Scan all frequencies simultaneously

$S_{\Phi,0}^{1/2} \sim 10^{-6} \Phi_0 / \sqrt{\text{Hz}}$

< ~50 Hz 1/f noise dominates

Broadband Sensitivity: > ~50 Hz

$$g_{\alpha \gamma \gamma} \propto \left( \frac{m_a}{t} \right)^{1/4} \frac{S_{\Phi,0}^{1/2}}{B_{\text{max}} G V_B \sqrt{\rho_{DM}}}$$

**Resonant**

Resonance enhancement by adding capacitor with high-Q

Scan across frequencies

Thermal noise in pickup loop dominates

Resonance Mode Sensitivity:

$$g_{\alpha \gamma \gamma} \propto \sqrt{L_T} \left( \frac{1}{m_a t} \right)^{1/4} \frac{1}{B_{\text{max}} G V_B} \sqrt{\frac{k_B T}{\rho_{DM} Q_0}}$$
• 10 kHz high-pass and 1.9MHz anti-aliasing filters before digitizer

• Digitizer-only data show spurious noise spikes that were vetoed.
Calibration

- Calibrate by injecting AC current into the calibration loop
- Fine scan from 10 kHz - 3 MHz at multiple amplitudes
- Gain lower than expected by a factor of ~6.5. Corrected for next phase
Broadband Data Collection Procedure

- Collected data with magnet on continuously for 4 weeks from July - August
- AlazarTech ATS9870 8-bit Digitizer locked to a Rb oscillator frequency standard
- 10 MS/s for $2.4 \times 10^6$ seconds (25T samples total)
- Apply FFTW on-the-fly on DAQ machine to compute Power Spectral Distributions (PSD)
- Acquisition (currently) limited to 1 cpu and 8 TB max data size

**10 MS/s Sampling**

- Compute PSDs of 10 s waveforms
- Average 80 PSDs, write to disk
- $\Delta f = 100$ mHz

**1 MS/s Sampling**

- Compute PSDs of 100 s waveforms
- Average 16 PSDs, write to disk
- $\Delta f = 10$ mHz

**100 kS/s Sampling**

- Written directly to disk
- 2,452,000 seconds total
- $\Delta f \approx 408$ nHz
Next ABRA-10 cm run

- Reduced wiring lengths — reduced parasitic inductances
- Cylindrical Pickup loop to reduce loop inductance
- Boosted gain by factor ~10
- Had to implement active feedback to reduce noise <1kHz
- Broadband run planned by end of 2019
COMSOL Simulation

Axion effective current in ABRA-10cm toroid
Simulations in COMSOL

- Geometric factor encodes the flux through the pickup loop due to the integrated effective current

- Use COMSOL simulations to calculate the coupling to the axion field (and confirm calibration coupling)
  - Simulation of ABRACADABRA-10 cm geometry and superconducting shield
  - Material properties need to be measured in the future
  - Losses in Magnet Materials
Dissecting ABRACADABRA-10 cm

Superconducting Pickup Loop  
$r_p = 2\,\text{cm}$

Superconducting Calibration Loop  
$r_c = 4.5\,\text{cm}$

Delrin Toroid Body

80×16 NbTi (CuNi) winds (counter-wound)
Assembling ABRACADABRA-10 cm

Superconducting Systems Inc. (SSI) designs and manufactures superconducting magnets for both medical applications and physics research applications. We are seeking a recent graduate with a Master of Science or Bachelor of Science degree in mechanical engineering to participate in the development of innovative magnets for human MRI applications. The candidate should:

1) Have a M.S. or B.S. degree in Mechanical Engineering
2) Be fluent in the Chinese Mandarin language
3) Have completed advanced courses in structural design and analysis
4) Have participated in practical design projects
5) Be skilled with SolidWorks software
6) Be willing to travel

The position is located at Billerica, MA. SSI offers competitive salary and benefits. Work experience of 2-5 years is desirable.

Please contact Francesca Minervini at the below email address with your resume (.pdf form if possible) attached.

Francesca Minervini
Project Engineer/ Mechanical Engineer
fminervini@ssi99.com

(SUPERCONDUCTING SYSTEMS INC.)

(Normally make MRI magnets!)
Mounting ABRA

Kevlar Support

150 mK

700 mK
SQUID Readout

- Off-the-shelf Magnicon DC SQUIDs
  - 2 Stage
  - Typical noise floor $\sim 1 \mu \Phi_0/(\text{Hz})^{1/2}$
  - Optimized for operation $< 1 \text{ K}$
  - Typical gain of $\sim 1.3 \text{ V}/\Phi_0$
- No resonator (i.e. broadband readout)
Magnet Off Data

- Collected 2 weeks of magnet off data with the same configuration
- High frequency transient noise also present. Reduced lifetime 30%
- Used for spurious signal veto
Axion Astrophysics
Axion Search Approach

- Search range to 75 kHz - 2 MHz ($m_a$ in 0.31 — 8.1 neV).
- 8.6 million mass points
- For each mass point, calculate a likelihood function
- Axion discovery search based on a log-likelihood ratio test, between the best fit and the null hypothesis
- $5\sigma$ discovery threshold: $TS>56.1$
- Accounts for Look Elsewhere Effect.

For details, see: PRD 97 (2018) 123006
Evidence for Dark Matter is Gravitational

- Galactic Rotation Curves
- Peculiar velocities of galaxies in clusters
- X-Ray emission of hot gas in clusters.
- Weak gravitational lensing
- Cosmic Microwave background (indirect)

- Big Bang Nucleosynthesis predicts it cannot be baryonic