Scoping out the axion parameter space

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PATRAS
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Can explain *all* the dark matter

Wave-like Dark Matter
de Broglie wavelength
~100s of meters

Solve the Strong CP Problem

QCD Axion
The QCD Axion

KSVZ
(Kim-Shifman-Vainshtein-Zakharov)

DFSZ
(Dine-Fischler-Srednicki-Zhitnitsky)
The QCD Axion

DFSZ

KSVZ
Resonant Cavity Haloscope

Axion wavelength is ~100 m long

Axion to photon production \( \propto E \cdot B \)

This axion lineshape has been exaggerated. A real signal would hide beneath the noise in a single digitization. An axion detection requires a very cold experiment and an ultra low noise receiver-chain.

Unknown axion mass requires a tunable resonator.
Scan Rate

\[
\frac{df}{dt} \approx 543 \ \text{MHz/yr} \left( \frac{B}{7.6 \ T} \right)^4 \left( \frac{V}{136 \ \ell} \right)^2 \left( \frac{Q_l}{30000} \right) \left( \frac{C}{0.4} \right) \left( \frac{g_\gamma}{0.36} \right)^4 \left( \frac{f}{740 \ \text{MHz}} \right)^2 \left( \frac{\rho}{0.45 \ \text{GeV/cm}^3} \right)^2 \left( \frac{0.2 \ K}{T_{\text{sys}}} \right)^2 \left( \frac{3.5}{\text{SNR}} \right)^2
\]

Maximize

- B Field
- Volume
- Quality Factor
- Form Factor

Defined by nature

- Frequency
- Coupling
- Dark Matter Density

Minimize

- System noise:
  - Amplifier Noise
  - Physical Noise
Axion Dark Matter eXperiment (ADMX)

• Built and operated at Livermore (1994-2010)
• Operating at CENPA, University of Washington (2010-Now)
• Most sensitive resonant cavity haloscope experiment. Sensitive to DFSZ axions.
• One of 3 “Gen-2” Dark Matter Projects
• Global collaboration of 11 institutions

Primary Sponsor

Sponsors
Run 1C Science Goals

• Target Frequency (Mass) Range: 800-1020 MHz (3.3—4.2 μeV)

• Medium Resolution and High Resolution data sets

• Goal of DFSZ sensitivity
  • Improve quality factor.
  • Improved understanding and operation of quantum amplifiers.
  • Improved noise temperature.

• Other upgrades:
  • New digitizer
  • Upgraded RF software
  • Improved synthetic axion capabilities
- Dil Fridge: Reaches ~100 mK
- Superconducting magnet: ~can reach up to 8 T
- Quantum electronics: Josephson Parametric Amplifier (JPA)
- Field cancellation coil
- Microwave cavity and electronics
ADMX-G2 Run 1C

Period

- Commissioning at UW started March 2019
- October 2019 - May 2021 —> $2 \times g_{\text{avv}}$ DFSZ
- Fall 2021 - ? —> $1 \times g_{\text{avv}}$ DFSZ

Frequency Range

- 800-1020 MHz
- Widest run period for a DFSZ search

Typical System Noise

- 600 mK (includes cavity->JPA attenuation)
Optimizing the JPA rebiasing

Adjust coupling to cavity (beta = 2): 20% scan rate increase
Analysis

- Data set of > 100,000 spectra.
- Spectra are processed by removing the receiver shape.
- Obtain roughly Gaussian noise centered around zero in the absence of an axion signal.
- Combine individual spectra into grand spectrum and apply line-shape filter.
- Search for candidates.
- In general, rescan for 3 conditions:
  - Too low SNR (need more data)
  - 3-sigma excess
  - Excess at DFSZ axion power or above.
**Persistence Checks**

- Virialized axion signal is persistent.
- RFI that comes and goes is clearly not an axion.
- Time between scans typically 2 weeks or less. Important details for high-res search.
- Distinguish between synthetic axion signals and real signal.
Synthetic Axion Detection (SAG)

Upgrades made to Synthetic Axion Generator (SAG) for Run 1C

- Extra stage of mixing/filtering to improve signal purity
- New enclosure separate from the main DAQ
- New 0-90 dB programmable attenuator for increased automation. Fully automated and integrated with dripline/lua.
- Axion line shape is simulated but not perfect. Will be improved in future runs.
Synthetic Axion Detection

Check on our ability to detect axions + understanding of experiment

Example candidate that proceeded to the detection committee for rigorous evaluation.

- Candidate Evaluation Sequence:
  - Persistence checks
  - RFI test with lab antenna + spectrum analyzer
  - On-off resonance test
  - Mode Test
  - Field ramp (final step!)
Run 1C Sensitivity

• Sensitive to KSVZ: 800-970 MHz
• Sensitive to DFSZ 970-1020 MHz
• Covered 2x prior frequency range

For analysis details

• Results for Run 1C Forthcoming
Sidecar Cavity and Receiver Chain

• Sidecar is a small prototyping cavity that sits on top of the main cavity.

• This iteration of sidecar is testing:
  • Traveling Wave Parametric Amplifier (TWPA)
  • Clamshell cavity design
  • Piezo motors for antenna and tuning rod

These are possible features of the future data-taking operations.
Demonstration of a Axion Search with TWPA

- Benefits of TWPA include
  - Broadband gain spans several GHz.
  - Eliminates need for an additional circulator (Less loss, more space)
  - Reasonable noise performance
- ADMX Sidecar Demonstration
  - Operated TWPA for several weeks in magnetic field
  - Reasonable performance (achieved ~8 dB SNR)
• Exploring higher frequency axions
• Using squeezed state receiver
  • Phys. Rev. X 9, 021023 (2019)
• Exploring Bayesian techniques:

Recent publication from earlier this year
Axion Mass (µeV)

1-2 GHz
(ADMX-G2)
(Target: DFSZ)

Preliminary

Model
Preinflationary

Frequency (MHz)

10^1
10^2
10^3
10^4
1-2 GHz (ADMX-G2) (Target: DFSZ)

2-4 GHz Extended Frequency Range (EFR) (Target: DFSZ)

Preliminary
4-cavity array planned for University of Washington

- 1.4-2.2 GHz
- Amplitude-combine cavities in phase for improved SNR.
- Scan rate $\sim (N)^2$: $N$ cavities in phase allows factor of $N$ increase in scan rate relative to power combining after the fact
- Setup has common rotor with coarse tuning rods.
- Fine-tuning done by perturbing fields with sapphire mounted to linear stage.
ADMX Extended Frequency Range (EFR)

2-4 GHz prototype cavity assembly at University of Florida
Cylindrical cavity formed from two clamshell halves

Possibly ~18 cavities
Simulations underway
9.4 T MRI Magnet at UIUC

- Scan rate goes as $B^4 = \text{High field critical for future axion searches.}$
- Scan rate goes as $V^2 = \text{Large volume critical for future axion searches.}$
- ADMX Collaboration plans to use large-bore 9.4 T magnet currently at UIUC.
- Room for R&D work in this magnet as well!
New Features

- Horizontal magnet bore
- Extra modularity: cavity electronics are separate from magnet bore
- Large magnet volume: 258 liters
- Preferred site for ADMX-EFR: PW8 Hall at Fermilab
- Other: Squeezing? Superconducting cavities?

(ADMX EFR Design)
Conclusions

• First pass through Run 1C excludes axion dark matter at roughly half the DFSZ coupling in the mass range of 3.2—4.2 μeV (780—1010 MHz).

• Second pass through this region in the coming months will bring us to DFSZ.

• ADMX is on track to continue its search for axions. Discovery could happen at any moment!

• Progress being made towards higher frequency searches.
Acknowledgements
Backup Slides
Resonant cavity axion haloscope

• Proposed by Pierre Sikivie.

• Uses the Inverse Primakoff effect.

• High quality factor $\longrightarrow$ higher chance of axion to photon conversion.

• High overlap of magnetic and electric fields.

“Form Factor”

$$ C_{010} = \frac{|\int dV \mathbf{B}_{\text{ext}} \cdot \mathbf{E}_a|}{B_{\text{ext}}^2 \int dV \epsilon_r |\mathbf{E}_a|^2} $$
Main cavity (x4)  

No Sidecar

Weak port (x4)  
Bypass (x4)

Ch output (x1)  
JPA Pump (x1)  
Hot load (x1)?
Theoretical Constraints

Lower bound set by size of dark matter halo size of dwarf galaxies

Upper bound set by SN1987A and white dwarf cooling time

- Pre-inflation PQ phase transition

- Post-inflation PQ phase transition


Adaptation of L. Winslow DPF Slide
Demonstration of a Axion Search with TWPA

- Benefits of TWPA include
  - Broadband gain spans several GHz.
  - Eliminates need for an additional circulator to separate incoming and outgoing modes (less loss, more space for us)
  - Peaks and troughs every 50-MHz could enable new scanning and optimization strategies
  - Reasonable noise performance

- ADMX Sidecar Demonstration
  - Operated TWPA for several weeks in magnetic field
  - Reasonable performance (achieved ~8 dB SNR)
  - System noise meets expectations
  - Definitive results coming soon in paper.