Winds of change in wave-like dark matter

Rising Stars Symposium
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What is dark matter?

‘Invisible’ matter that would be able to explain:
• Anisotropies in the cosmic microwave background
• Rotation curves of galaxies
• Behavior of galaxy cluster collisions
• Matter Radiation Fluctuations
• Primordial nucleosynthesis
• Gravitational lensing
• Baryon Acoustic Oscillations

Characteristics of the dark matter:
• Cold (non-relativistic)
• Feebly-interacting
• Non-baryonic
• Gravitationally-interacting
• Very stable
Axions as Dark Matter

• 1-100 µeV mass range to constitute entirety of dark matter

• Two classes of models:
  
  • **KSVZ (Kim-Shifman-Vainshtein-Zakharov):**
    • couples to leptons
    • Range of $g_\gamma$ values, typically $g_\gamma=-0.97$ used
  
  • **DFSZ (Dine-Fischler-Srednicki-Zhitnitsky):**
    • couples to quarks and leptons
    • Range of $g_\gamma$ values, typically $g_\gamma=0.36$ used
strong CP problem

Neutron electric dipole moment

EDM would violate T (CP) symmetry
Peccei-Quinn Mechanism

- Peccei-Quinn devised solution that upgraded theta to dynamical variable
- Tips the wine-bottle potential so that lowest energy configuration precludes existence of neutron EDM
- ‘PQ’ mechanism —> pseudo scalar boson (axion)
The Axion 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.
Axion Dark Matter eXperiment

- Resonant cavity in a magnetic field (‘haloscope’)
- Relying on inverse Primakoff effect
- High-Q → Higher probability of axion to photon conversion
- Have reached DFSZ benchmark sensitivity with the ADMX detector
• 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
Data-taking operations 2019-2021

Medium-res

- 100 Hz bin width
- Saved as power spectra
- Isothermal halo model
- Bin width optimized for expected axion lineshape

High-res

- 10 mHz native bin width
- Saved as time-series
- Non-virialized axions
- Sensitive to frequency modulation from orbital and rotational motion
Driving the data-taking operations!

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Axion Doppler Shift

ADMX Run 1C data-taking?

- bias quantum amplifier
- transmission measurement
- reflection measurement
- possibly inject synthetic axion signals
- digitize
- move rods
- couple antenna
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![Graph showing last transmission scan with gain in dB vs frequency in MHz.](image-url)
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Synthetic Axion Generator

Type 1:
Injections that we use to verify the integrity of the receiver chain and sensitivity

- Turned off in final sweep through frequency range; verified as synthetics.
- 10-12 per 10 MHz.

Type 2:
Injection used to practice full axion detection procedure

- Stay on until the ADMX operators determine that they are not real signals.
- 1-2 per run.

Upgrades made to Synthetic Axion Generator (SAG) for Run 1C
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Two factors here are inextricably linked…

Small volume

Smaller wavelength of TM010 mode

Higher frequency (mass) of axion you can detect

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

- Higher Frequencies
- Smaller Volumes
- Slower Scan Rate
Where do we go from here?

Smaller Cavities → Multi-Cavity Systems → Something Completely Different?

Near-Term → Longer-Term → Future
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
Traveling Wave Parametric Amplifier

- 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)
Multi-cavity arrays

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

- 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!
ADMX Extended Frequency Range

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)
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\]

\[ C_{010} = \frac{\left| \int dV B_{\text{ext}}^{-} \cdot \vec{E}_\alpha \right|^2}{B_{\text{ext}}^2 \int dV \epsilon_r |\vec{E}_\alpha|^2} \]

“Form Factor”
Resonant Feedback Concept

Cavity

Resonant feedback

https://arxiv.org/abs/1805.11523
Closed Loop Gain Configuration

- Generated resonances on the FPGA board.
- Shape from FPGA filter is Lorentzian.
- Can see resonances in a VNA measurement across the cavity.
• The injected tone is enhanced when on resonance, and diminished when off resonance.

• Behaves like cavity resonance.

• Further studies to ensue (noise studies, feedback controls).
Conclusions

- ADMX has completed the first half of Run 1C data-taking
- Will resume second half at DFSZ sensitivity after upgrades
- First implementation of a TWPA in a dark matter axion search
- Progress is being made towards higher frequency searches
- Discovery could happen at any moment.
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