BREAD: Broadband Reflector Experiment for Axion Detection

Snowmass CF2 Wavelike Dark Matter Meeting
10 min review talks | 8 October 2021

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Science goal: broadband $m \gtrsim 10^{-4}$ eV axion & dark photon DM search

R&D supported by DOE HEP-QIS QuantISED, FNAL LDRD

See also UW Beyond Gen2 [Jan 2021], CPAD [Feb 2021] (Andrew Sonnenschein), Patras [Jun 2021] (Stefan Knirck) and Snowmass LoI CF2 No. 179
The broadband & high-mass search problem

1) Desire broadband but existing cavity haloscopes are narrowband $\Delta m/m \ll 1$

2) Desire high mass but canonical search rate* $R \sim f^{-14/3}$ impractical for $m > 50 \mu$eV

BREAD: R&D program to overcome both longstanding obstructions

*See e.g. Backes et al [2008.01853] for how to overcome this scaling in HAYSTAC
Step 1: convert DM to photons

Induce axion–photon conversion via conducting surface in B-field

Axion dark matter augments Ampère–Maxwell equation

\[ \nabla \times \mathbf{B} - \partial_t \mathbf{E} = J_{\text{DM}} \]

Boundary conditions imply \( \perp \) SM photon emission

\[ \frac{P_a}{10^{-21} \text{ W}} = 3.1 \cdot \frac{\rho_{\text{CDM}}}{0.3 \text{ GeV cm}^{-3}} \cdot \frac{A}{10 \text{ m}^2} \left( \frac{B}{10 \text{ T}} \right)^2 \times \left( \frac{g_{a\gamma\gamma}}{10^{-11} \text{ GeV}^{-1}} \frac{1 \text{ meV}}{m_a} \right)^2. \]

Dish eschews tuning to unknown DM mass
Inherently broadband ⇒ ideal for searches

Concept proposed in Horns et al [1212.2970]

Cylindrical barrel driven by standard solenoid & fridge geometries

9.4 T human MRI @ UIC
https://meml.lab.uic.edu
10.5 Tesla/88 cm bore Passively Sheilded

Fridge for ADMX science at FNAL
(photo: Kristin Dona)

See also “Ultra-High Field Solenoids and Axion Detection” Mark Bird (2020)
Step 2: collect photons

Low frequency ~ 20 GHz
numerical Maxwell eqn

High frequency ~ IR
ray limit $\lambda \ll \ell_{\text{sens}}$

Small 3D-printed
test model @ FNAL

Proposed dark photon
pilot schematic

Kate Azar, Matthew Malaker, Gabe Hoshino (summer students)
led many detailed simulation studies

↑ Parabolic reflector geometry for BREAD
→ Inverse of classical lighthouse (Bordier-Marcet 1811)
Cylindrically symmetric parallel rays from/to a point

Gabe Hoshino led in situ tests

Currently iterating with engineers to manufacture reflector for pilots

uslhs.org/reflectors
Step 3: detect photons

CANDIDATE PHOTOSENSOR CLASSES

**Heterodyne [microwave]**
Down-convert frequencies with local oscillator
High resolution for narrow spectral features
Noise limited by standard quantum limit $k_B T = h \nu$
Promising for QCD axions around $O(10)$ GHz regimes

**Bolometers [microwave to optical]**
Very broadband $\Delta m/m \gg 1$, noise limited for QCD axions
Transition Edge Sensors, Kinetic Inductance Detectors
Well-established sensors reach $\sim 10^{-19}$ W/$\sqrt{\text{Hz}}$ (TES, KID)
Recently Quantum Capacitance Detectors $\sim 10^{-20}$ W/$\sqrt{\text{Hz}}$

**Photocounters [near-IR]**
Superconducting nanowires (SNSPD) e.g. by Caltech/MIT/NIST
Low noise but present $E_{\text{threshold}}$ around near-IR for counting
Hochberg et al 1903.05101 $10^{-4}$ Hz dark count for DM search
Verma et al 2012.09979 extended up to 9.9 $\mu$m (0.12 eV)
Preparing sensor testing @ Fermilab towards pilot

Kristin Dona, Stefan Knirck, JL, Andrew Sonnenschein pictured; thanks to Israel Hernandez, David Miller, Tony Zhou et al
**Projected sensitivity**

Bottom line: next generation photosensors could decisively search QCD axion benchmarks over several mass decades motivating sensor R&D
Snowmass synergies

Particle physics
Principal goal to discover axion and/or dark photon dark matter in next decade

Astronomy
Decadal survey, sub-mm/IR science, Photosensors for future observatories

Quantum technology
Information science, sensing, telecommunications

Cosmic Frontier
CF2 wavelike dark matter

Accelerators
AF7 R&D
High field magnets

Instrumentation
IF1 quantum sensing
IF2 photon detectors

Underground
UF2 Facilities for cosmic frontier

BREAD naturally fits in high-mass CF2 whitepaper with inevitable IF1/2 synergy
E.g. synergy: different science driving similar sensor R&D

Origins space telescope demands $\sim 10^{-20} \text{ W/}\sqrt{\text{Hz}}$ sensors across mid-/far-IR

$\leftarrow$ origins.ipac.caltech.edu technology & science

Simulation of QCD NEP (blue) versus wavelength for the optical loading predicted for the OST compared with the required NEP (orange).

Example TES, KID, SNSPD discussion for OST science
**SUMMARY**

**Broadband Reflector Experiment for Axion Detection**

- **Multidecade discovery reach** of axion/dark photon DM overcoming broadband & high-mass search problem
- **Unique geometry** practical for standard solenoids & fridges with science demands driving next-gen photosensor R&D
- **Preparing sensor testing** at FNAL for nearer term pilot
  Longer term 5-10 year R&D parallelling Snowmass scope
- **Interesting synergies** crossing traditionally non-HEP communities from astronomy to quantum technology
- **Welcoming friendly** multidisciplinary group at early stages with much room for individual creativity
EXTRAS