Status of ADMX-HF
Extreme Axion Experiment

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Maria Simanovskaia
Graduate student
University of California - Berkeley
• Review of current limits on axions
• Description of our experiment
• Preliminary results
• Near-term goals
• Cavity research and development
Axion Basics

Good news – Parameter space is bounded
Bad news – All couplings are *extraordinarily* weak

Axion production quenches neutrino pulse from SN1987a if mass too big (~ meV)

Ordinary stellar burning rules out axions if coupling too big
Limits on the axion after twenty years

The graph shows the limits on the coupling constant $g_{a\gamma\gamma}^2$ (GeV$^{-2}$) as a function of the axion mass $m_a$ (μeV) for different models and experiments. The graph includes regions excluded by HEMT (<2004) and SQUID (2007-09). The models include KSVZ, DFSZ, and ADMX.
Axion detection – quantitative details

Cavity Bandwidth: \[ \frac{\Delta \nu_c}{\nu_c} = Q^{-1} \sim 10^{-4} \]

Axion Bandwidth: \[ \frac{\Delta \nu_a}{\nu_a} \sim \beta^2 \sim 10^{-6} \]

Conversion Power:

\[ P \sim g_{\alpha\gamma\gamma}^2 (\rho_a / m_a) B^2 Q V C_{nm} \sim 10^{-23} \text{ W} \]

Signal to Noise Ratio:

\[ SNR = \frac{P}{k T_S} \sqrt{\frac{t}{\Delta \nu_a}} \]
Team ADMX-HF / X3

Yale University (experiment site)
Steve Lamoreaux, Ling Zhong, Ben Brubaker, Sid Cahn

UC Berkeley
Karl van Bibber, Maria Simanovskaia, Samantha Lewis, Jaben Root, Saad Al Kenany, Kelly Backes, Nicholas Rapidis, Isabella Urdinaran

CU Boulder/JILA
Konrad W. Lehnert, Daniel Palken, William F. Kindel, Maxime Malnou

Lawrence Livermore National Lab
Gianpaolo Carosi, Tim Shokair
Microwave Cavity

- Cu body with off-axis tuning rod
- Tunable over 3.6 – 5.8 GHz
- $Q_C \sim 20,000$
- Stepping motors and Kevlar lines used for motion
Josephson Parametric Amplifiers

- Josephson Parametric Amplifier composed of SQUIDs
- Tunable from 4.4-6.5 GHz with 20 dB of gain
- Require magnetic field-free environment

Persistent coils for field cancellation

Double wall cryoperm with superconducting Pb foil inside

+ magnetic compensation coil
By looking at the shift of the JPA frequency curve between $B = 0$ T and $B = 9$ T (see interleaved points), we conclude that the field at the JPA changes $< 0.01$ flux quantum as the magnet is ramped. Thus the magnetic shielding is working very well.
Integration of the Experiment at Yale

Josephson Parametric Amplifier

Microwave Cavity (copper)

$^3$He/$^4$He Dilution Refrigerator

9.4 Tesla, 10 Liter Magnet
Integration of the Experiment at Yale

Superconducting magnet
- Made by Cryomagnetics, Inc.
- Maximum field of 9.4 T
- Large bore
- Dry system

Dilution refrigerator
- 25 mK base temperature
- Experiment operates at 100 mK to stabilize the JPA
- Thermal shield contains gantry, JPA, and cavity

Data analysis
- Two analysis sites: Yale and Berkeley
First run in $f \sim 6$ GHz range (Jan – Aug 2016)

$T_{SYS} \sim 1100$ mK ($\sim 3.5$ $T_{SQL}$; “hot rod” problem)

Reach $g_{\gamma\gamma} \sim 2.5$ KSVZ, $< 2$ KSVZ with new thermal link

The first data run should conclude by early August
Project Timeline – snow storm at Yale

- Experienced a magnet quench in early March
- Surprisingly little damage
- Repairs complete, experiment back in operation mid-May
Preliminary Data
Data quality appears very good

Candidates for rescan

Synthetic axion signals injected
Preliminary Analysis (pass 1/3)

CAST and HB star limits

ADMX-HF Exclusion (Preliminary)

$g_{\gamma\gamma}$ (GeV$^{-1}$)

$10^{-10}$

$10^{-11}$

$10^{-12}$

$10^{-13}$

$10^{-14}$

$10^{-15}$

$10^{-16}$

$m_a$ (eV)

$2.355$  $2.36$  $2.365$  $2.37$  $2.375$  $2.38$  $2.385$  $2.39$  $2.395$  $2.4$  $\times 10^{-5}$

KSVZ

DFSZ
The near-term program

- Higher frequency run with “hot rod” mitigation (early fall 2016)
- Swap in Blue Fors fridge
- Deploy, run squeezed-vacuum state receiver (early 2017)
  - Will take significant rework of exp’t
  - To reduce $T_{\text{SYS}} < T_{\text{SQL}}$
- Microwave cavity enhancements to improve quality factor and spectral cleanliness (mid-2017)
Photonic Band Gap Structures

(Samantha Lewis)

Open structure designed to trap TM modes, but allow TE modes to radiate away

Cleanses the spectrum of the forest of mode crossings, and thus dramatically accelerates the scan rate of the experiment

Applying PBG concepts can increase spectral clarity and increase cavity volume.
Distributed Bragg Reflector Concepts

• Flory and Taber used sapphire inserts to enhance $Q$ of a TE mode
  • Room temperature $Q \sim 10^6$ at $\sim 10$ GHz
• Although TE modes aren’t useful to us, we can learn from DBR concepts
  • Use just cylindrical inserts
• Place dielectric cylinders of $\lambda/4$ width (in dielectric) at natural nodes of $TM_{0m0}$ mode to confine mode away from metal wall

Can use DBR concepts to enhance $Q$ by a factor of $\sim 5$.

Superconducting Thin-Film coatings
(Maria Simanovskaia, Al Kenany)

\[ \text{Nb}_{0.30}\text{Ti}_{0.67}\text{O}_{0.03} : 280 \text{ nm} \]

Coating cavity barrel with superconducting thin films will improve cavity Q.
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The US Department of Energy
Thank you!

Questions?
Backup Slides
Hot rod solution

Improved Thermal Link of Rod to Cavity

Copper Shaft & Pin

Bearing

Thermal Link (copper helix)

Tuning Rod

Axle (alumina)
Mode map
Equations...

Radiometer equation

\[
\text{SNR} = \frac{P}{kT_s} \sqrt{\frac{t}{\Delta \nu_a}}
\]

Form factor

\[
C_{nml} = \frac{\left| \int_V d^3 x \vec{E}_\omega \cdot \vec{B}_0 \right|^2}{B_0^2 V \int_V d^3 x \epsilon \left| \vec{E}_\omega \right|^2}
\]

Scan rate

\[
\frac{dv}{dt} \propto g_{\alpha \gamma \gamma}^4 \frac{m_a^2}{T_s^2} B^4 Q_c V^2
\]
Accelerating dark-matter axion searches with quantum measurement technology

Huaixiu Zheng,1 Matti Silveri,1 R. T. Brierley,1 S. M. Girvin,1 and K. W. Lehnert2

1Department of Physics, Yale University, New Haven, Connecticut 06520-8120, USA
2JILA, University of Colorado and National Institute of Standards and Technology
Boulder, CO 80309-0440
(Dated: July 12, 2016)

The axion particle, a consequence of an elegant hypothesis that resolves the strong-CP problem of quantum chromodynamics, is a plausible origin for cosmological dark matter. In searches for axionic dark matter that detect the conversion of axions to microwave photons, the quantum noise associated with microwave vacuum fluctuations will soon limit the rate at which parameter space is searched. Here we show that this noise can be partially overcome either by squeezing the quantum vacuum using recently developed Josephson parametric devices, or by using superconducting qubits to count microwave photons.

PACS numbers: Valid PACS appear here

I. INTRODUCTION AND ORGANIZATION

The nature and origin of cosmological dark matter is an enduring puzzle of modern physics. Likewise, the charge-parity (CP) symmetry in the strong nuclear force seems implausibly well conserved. The hypothesis of Peccei and Quinn resolves this “strong CP problem” by positing a scalar field that couples to quarks and undergoes a spontaneous symmetry-breaking phase transition [1]. Excitations of this field in its low energy phase, known as axions [2, 3], would have the appropriate properties to act as a source of dark matter [4-6].

conversion rate is enhanced by the cavity quality factor. By adjusting the cavity’s resonance frequency, the range of favorable frequencies can then be scanned in a step-wise manner, tuning the cavity to a new resonance frequency and waiting to average the cavity’s thermal noise sufficiently well to resolve the presence of any excess microwave photons caused by the coupling to the axion field. To reduce the background number of thermal photons that obscure the axion signal, the cavity is cooled well below ambient temperature.

Even if the cavity temperature were cold enough to completely freeze out this thermal background, existing
Bead-pull cavity characterization

Mode crossing of $TM_{010}$ and $TE$

Graphs showing frequency changes with step number.
Bead-pull cavity characterization

Mode crossing of $TM_{010}$ and $TE$
• Application of bead-pull technique
• TFS layer on cavity barrel help improve $Q$
• DBR concepts help improve $Q$
• PBG concepts help improve $V$, spectral cleanliness

Conversion Power

$$P \sim g_{\alpha \gamma \gamma}^2 \left( \frac{\rho_\alpha}{m_\alpha} \right) B^2 Q VC_{nml} \sim 10^{-23} \text{ W}$$