DMAG

Dark Matter
Axion Group

Axion Dark Matter Search Around 23.5μeV (5.7 GHz, 250 MHz BW, ~ KSVZ sensitivity) Using a Multi-cell Microwave Cavity and Flux-driven Josephson Parametric Amplifier

Pallavi Parashar[1,2], Saebyeok Ahn[2], Boris Ivanov[2], Sergey V. Uchaikin[2], SungWoo Youn[2], Jeong Junu[2], SungJae Bae[1,2], Arjan F. van Loo[3,4], Yasunobu Nakamura[3,4], Yannis K.[1,2] Semertzidis

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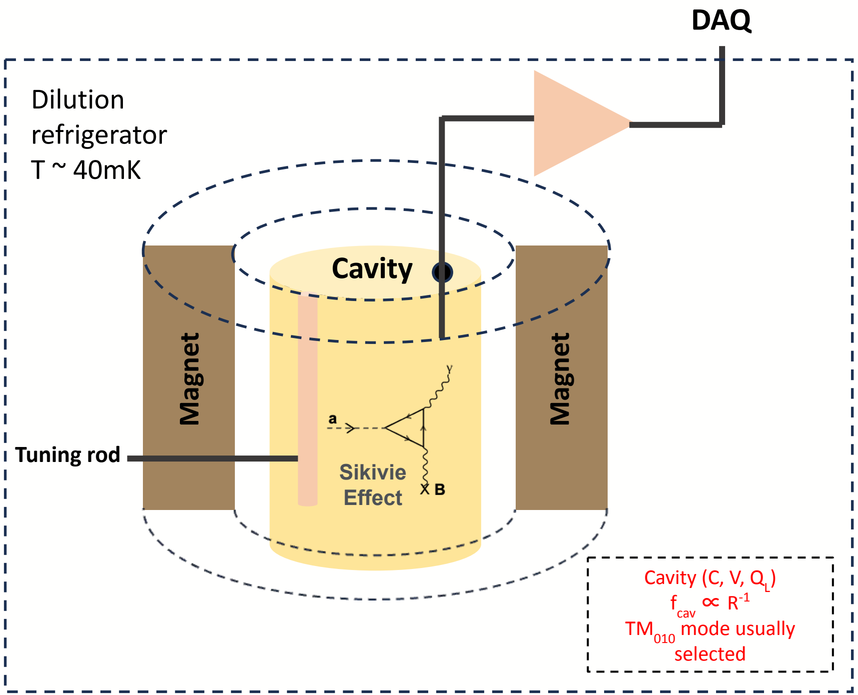
Contents

Axion Haloscope



Sikivie effect: Axion -> photon in the presence of another photon

$$\mathcal{L}_{a\gamma\gamma} = -g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$$

- QCD axions: solution to the strong CP problem [1].
- Constitute cold dark matter if $1\mu\text{eV} < m_a < 10\text{meV}$[2].
- Axion haloscope : detect the axions in the galaxy by leveraging the Sikivie effect (a–γ interaction).
- Utilize resonant cavity to enhance conversion power.
  - When $f_a = f_{cav}$, resonant conversion
  - Tune cavity resonant frequency to find unknown m_a.

Axion to photon conversion power [3]

$$P_{\text{conv.}} = \frac{g_{a\gamma\gamma}^2 \rho_{dm}}{m_a} \langle \mathbf{B}^2 \rangle V_c C \frac{Q_l Q_a}{Q_l + Q_a}$$

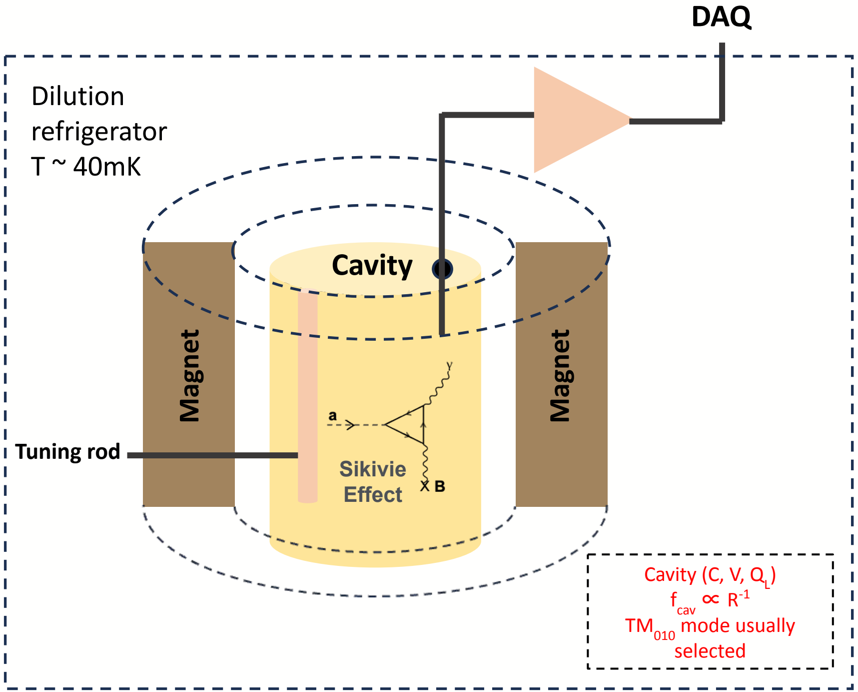
Scanning rate [3]

$$\frac{df}{dt} \propto \frac{1}{\text{S.N.R.}^2} \frac{1}{T_{\text{sys}}^2} g_{a\gamma\gamma}^4 \langle \mathbf{B}^2 \rangle^2 V_c^2 Q_l C^2$$

$g_{a\gamma\gamma}$ model-dependant (KSVZ) coupling constant
ρ_{dm} local dark matter axion density in the galactic halo
m_a mass of axion
B is the ext. magnetic field strength
V_c is the cavity volume
C is cavity form factor
Q_a is axion quality factor
Q_l is loaded cavity quality factor
T_{sys} is the system noise temperature and
SNR is Signal to Noise Ratio.

1. R. D. Peccei and H. R. Quinn, CP conservation in the presence of pseudoparticles, Phys. Rev. Lett. 38, 1440, (1977)
2. G. Raffelt, Axions, in Matter in the Universe: Proceedings of an ISSI Workshop 19–23 March 2001, Bern, Switzerland , edited by P. Jetzer, K. Pretzl, and R. Von Steiger (Springer Netherlands, Dordrecht, 2002)pp. 153–158
3. D. Kim, J. Jeong, S. Youn, Y. Kim, and Y. K. Semertzidis, Revisiting the detection rate for axion horoscopes, Journal of Cosmology and Astroparticle Physics, 2020 (03), 066
4. J. E. Kim, Weak-interaction singlet and strong CP invariance, Phys. Rev. Lett. 43, 103 (1979)

Axion Haloscope



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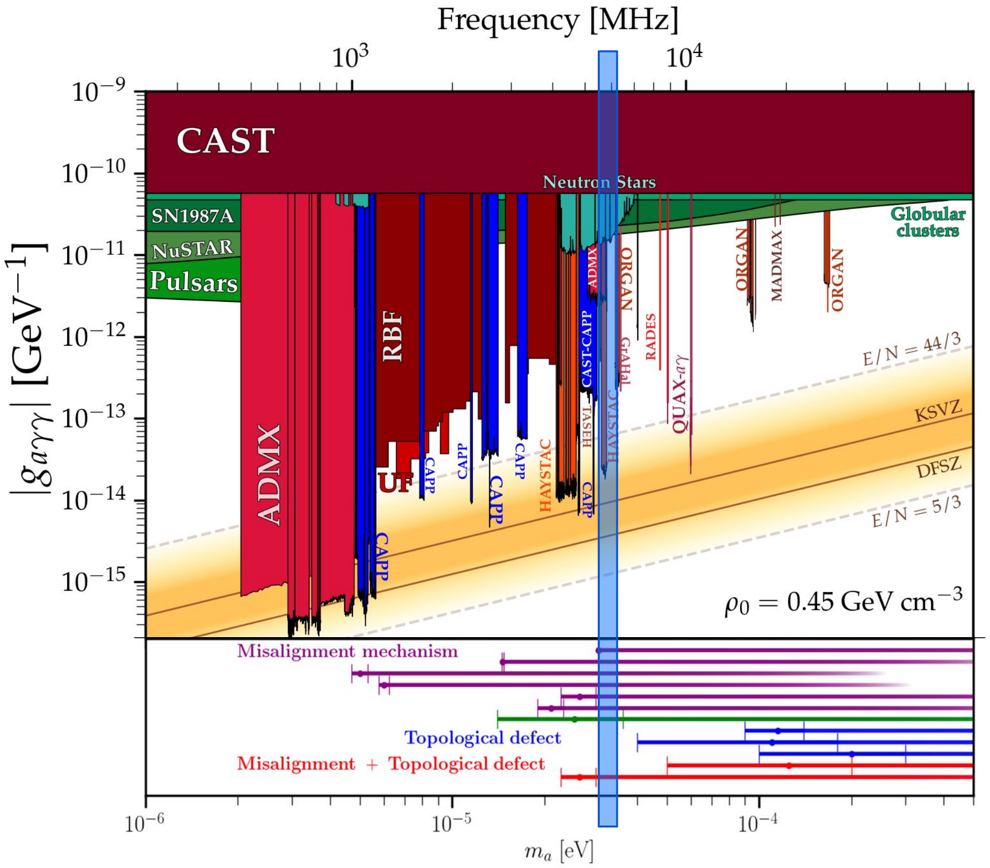
T_{sys} is the system noise temperature and
SNR is Signal to Noise Ratio.

Low noise amplifier gives low system noise → Enhances $\frac{df}{dt}$

High B and greater cavity Q, V, C → Enhances P_{conv} and $\frac{df}{dt}$

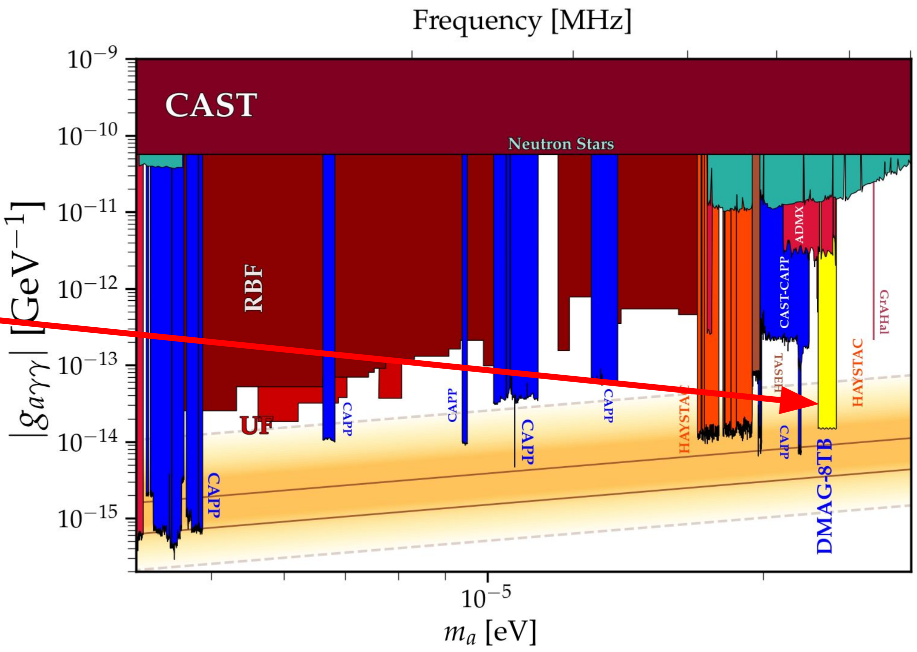
Experiment Motivation



Experiment Plan

Projected target for this experiment

5.56 GHz - 5.81 GHz

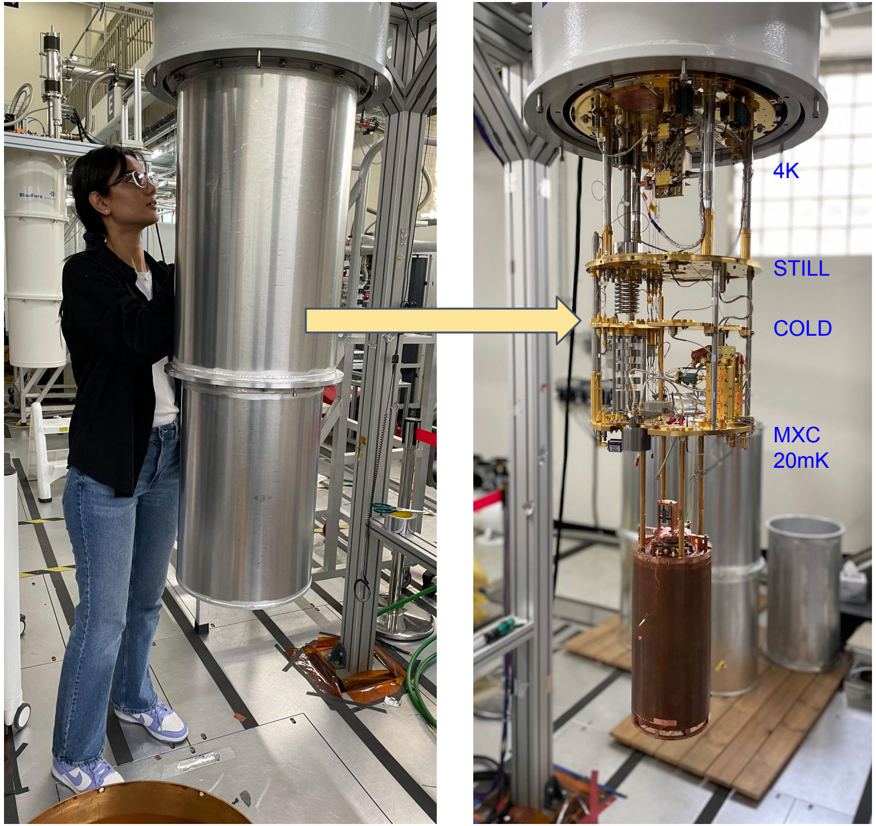


Parameters for this experiment :

$\lvert g_{a\gamma\gamma}\rvert$	ρ_{dm}	m_a	B	V_c	C	Q_a	Q_0	T_{sys}	SNR
1.5 x g_{KSVZ} (KSVZ model [4])	0.45 GeV/cm^3	~23.5 μeV	~7.2 T	3.1 L	~0.6	~10^6	~50000	~0.5 K Due to Quantum noise limited JPAs	5

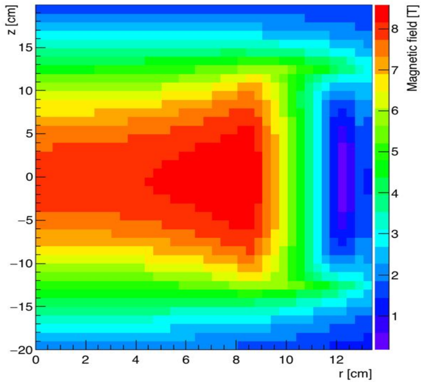
Estimated Output signal power is ~10^{-24} W, and scanning rate is ~3 MHz/day.

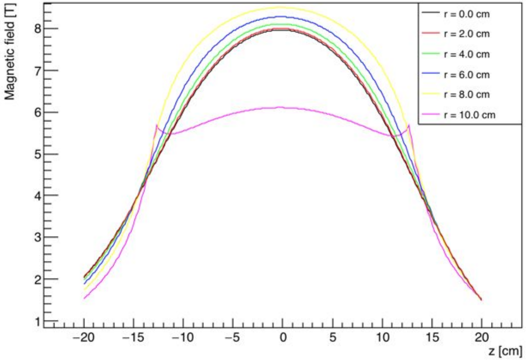
Experiment Setup



Cavity and RF Chain arrangements inside BlueFors dilution refrigerator

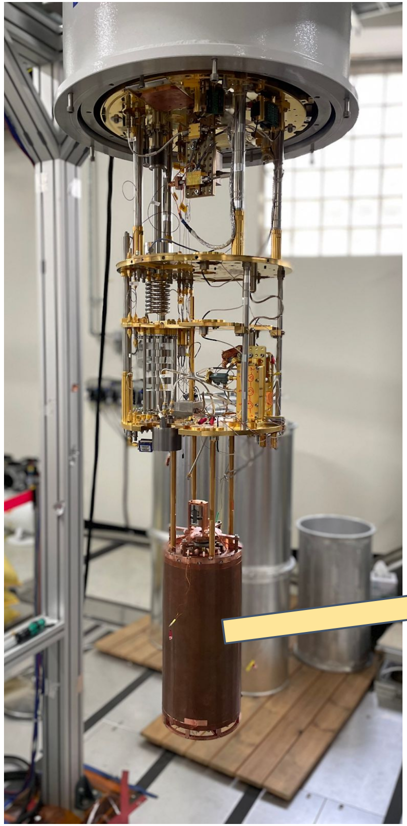
Bore diameter = 165 mm

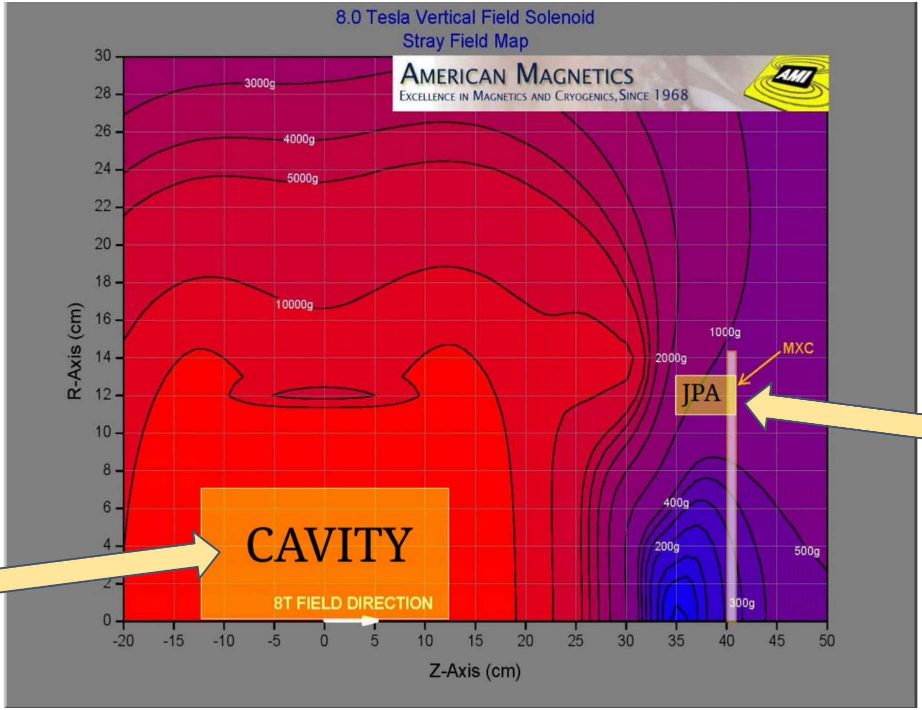




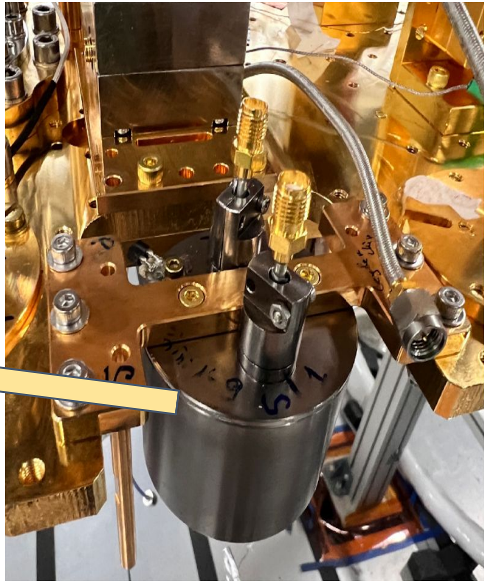
NbTi 8T solenoid magnet

Experiment Setup



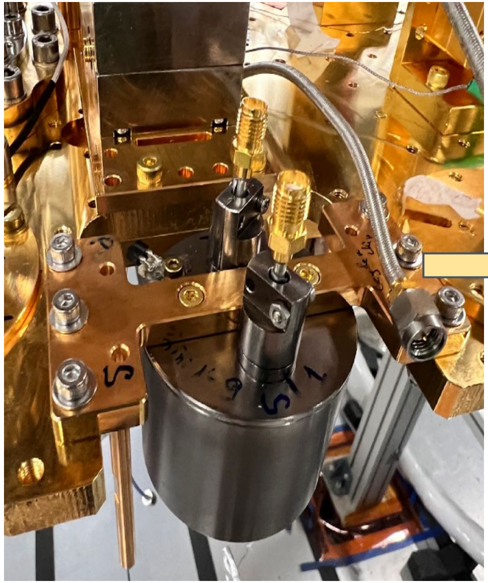


Location of components in the magnetic field inside the fridge

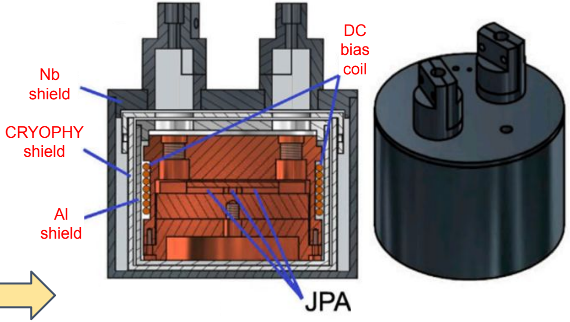


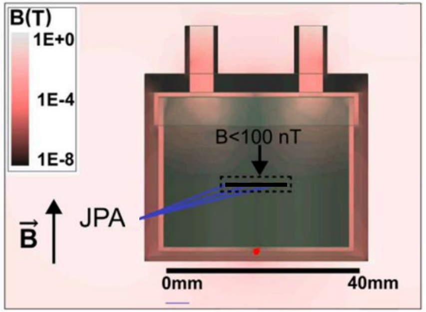
JPA provided by Prof. Nakamura's group.

Experiment Setup

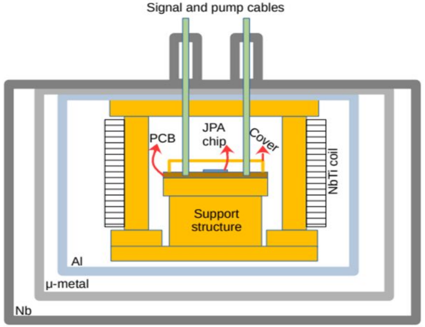


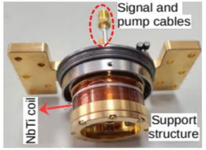
JPA provided by Prof. Nakamura's group. Shielding protects it from effects of ext. magnetic field
Shielding factor ~ 10^5

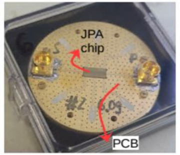


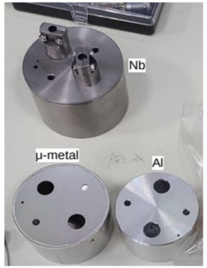


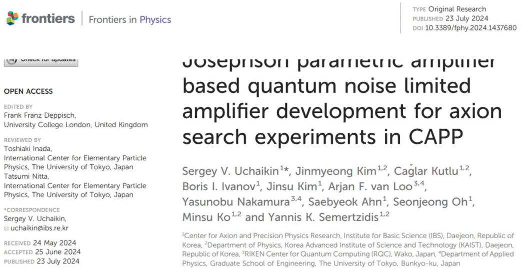
Three layer JPA shield design developed at CAPP, now DMAG [5]







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Josephson parametric amplifier based quantum noise limited amplifier development for axion search experiments in CAPP

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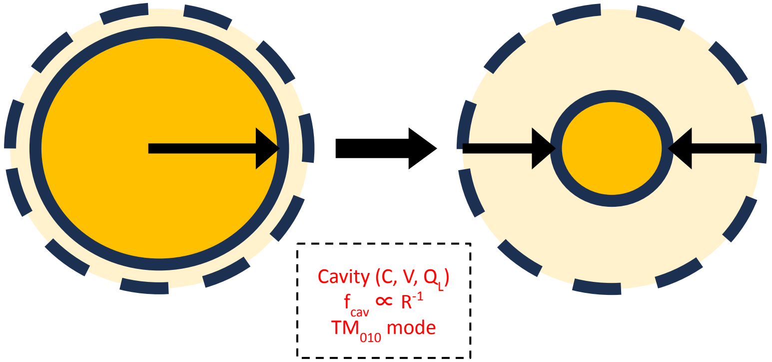
5. Sergey V. Uchaikin, Jinmyeong Kim, Calar Kutlu, Boris I. Ivanov, Jinsu Kim, Arjan F. van Loo, Yasunobu Nakamura, Saebyeok Ahn, Seonjeong Oh, Minsu Ko, Yannis K. Semertzidis, Josephson parametric amplifier based quantum noise limited amplifier development for axion search experiments in CAPP, Front. Phys., 23 July 2024, Sec. High-Energy and Astroparticle Physics, Volume 12 - 2024

Experiment Setup - 8 cell cavity

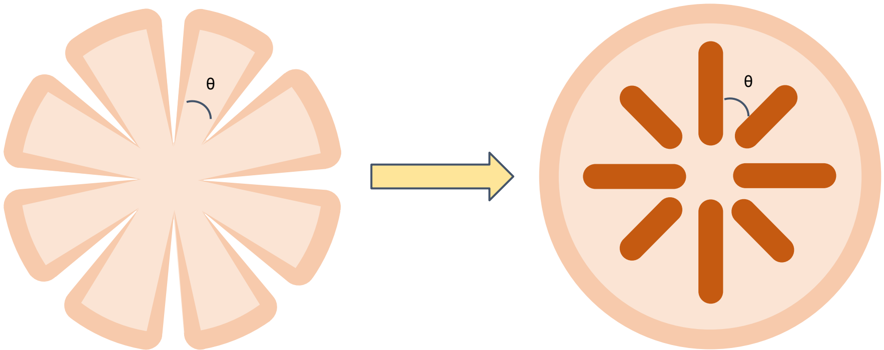


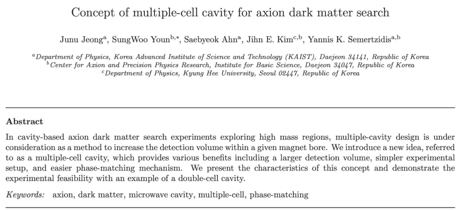
Magnet bore size is fixed, so better cavity design is needed at higher frequencies for efficient use of space.

Multiple cell cavity design [6]

- Single cavity partitioned into multiple equi-angular sections
- Antenna (RF coupler) inserted into the central gap for signal combination and power readout

Updated 8-cell cavity design from CAPP-8TB PR2, easy to assemble & better fabrication tolerances





Concept of multiple-cell cavity for axion dark matter search

Junu Jeong[a], SungWoo Youn[b,*], Saebyeok Ahn[a], Jihn E. Kim[c,b], Yannis K. Semertzidis[a,b]

[a] Department of Physics, Korea Advanced Institute of Science and Technology (KAIST), Daejeon 34141, Republic of Korea
[b] Center for Axion and Precision Physics Research, Institute for Basic Science, Daejeon 34047, Republic of Korea
[c] Department of Physics, Kyung Hee University, Seoul 02447, Republic of Korea

Abstract

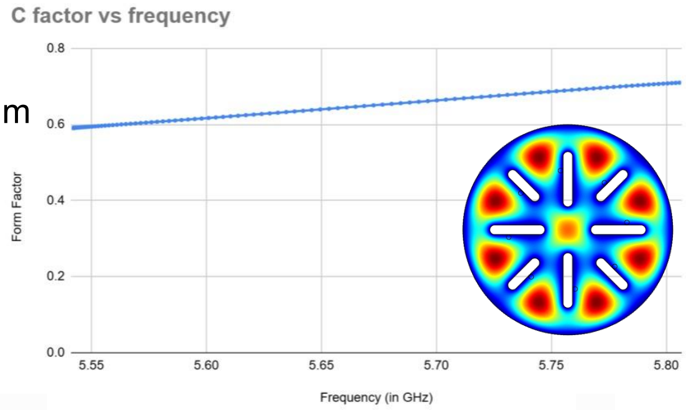
In cavity-based axion dark matter search experiments exploring high mass regions, multiple-cavity design is under consideration as a method to increase the detection volume within a given magnet bore. We introduce a new idea, referred to as a multiple-cell cavity, which provides various benefits including a larger detection volume, simpler experimental setup, and easier phase-matching mechanism. We present the characteristics of this concept and demonstrate the experimental feasibility with an example of a double-cell cavity.

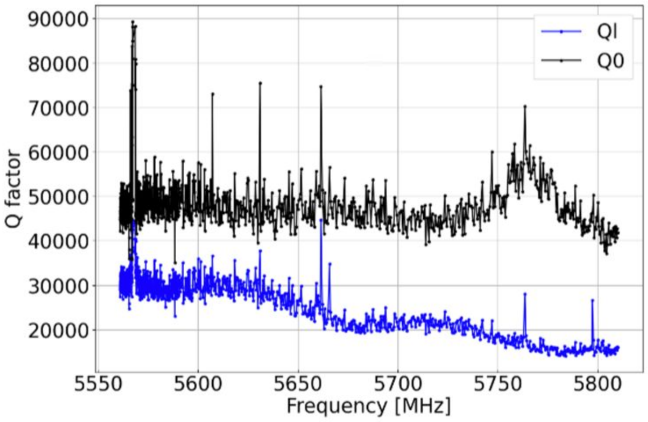
Keywords: axion, dark matter, microwave cavity, multiple-cell, phase-matching

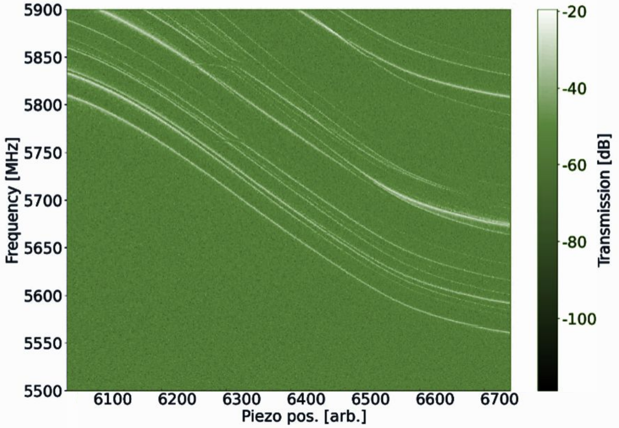
6. J. Jeong, S. Youn, S. Ahn, J. E. Kim, and Y. K. Semertzidis, Concept of multiple-cell cavity for axion dark matter search, Physics Letters B 777, 412 (2018).

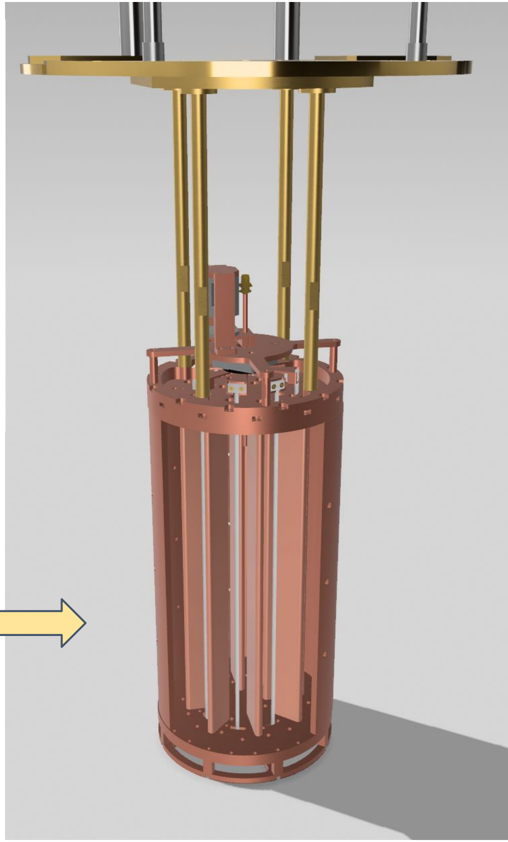
Experiment Setup - 8 cell cavity

- OFHC copper cavity
  - Inner Diameter: 128 mm
  - Inner Height: length of 270 mm
  - Volume: 3.1 L
  - Alumina tuning rod
- The tuning mechanism (carousel geometry) is moved with the help of piezo actuator.



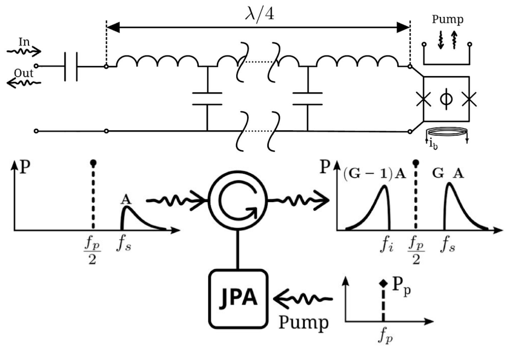




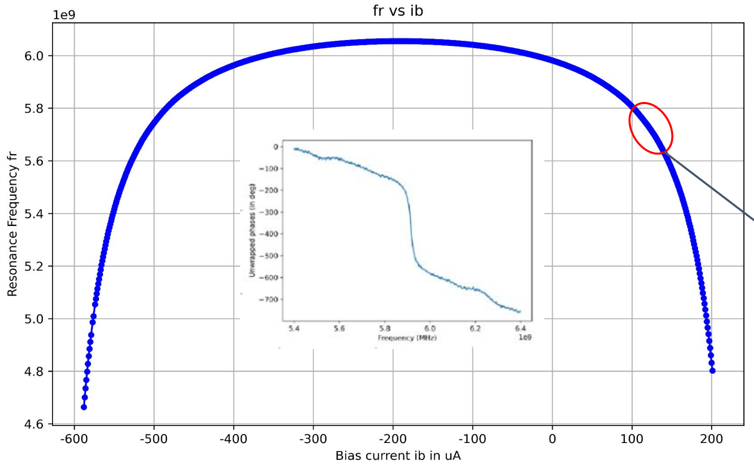


Experiment Setup - JPA operation and characterization

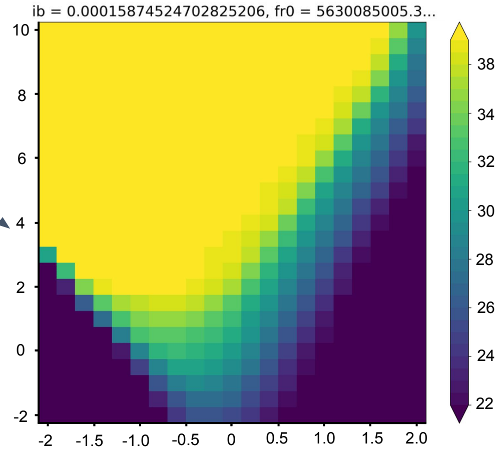
- λ/4 resonator grounded via a DC-SQUID.
- Central frequency (f_r) tuning -> DC flux through SQUID loop using a superconducting coil.
- Operated in three-wave mixing mode. Parametric amplification is achieved by modulating the flux through the SQUID using a pump signal(P_p). $f_p = 2\ f_r$.



JPA Amplification in 3 wave mixing mode



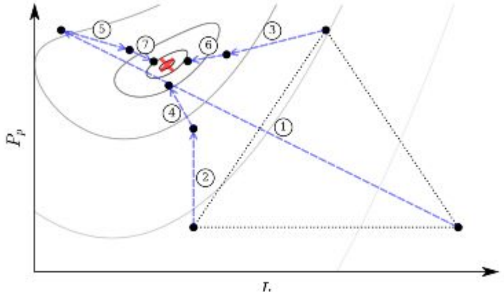
DC flux bias current (i_b) vs resonant frequency (f_r)

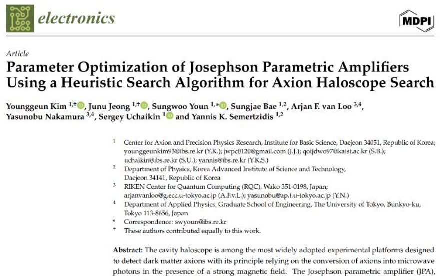


JPA gain paramaps for different i_b and P_p

Experiment Setup - JPA working point

- Methods to find least noisy JPA working points :
  - Lookup table (LUT) -
    - Scan of all combinations of pump power and bias current.
    - Straightforward, but takes too long and power saturates the JPA.
  - Nelder-Mead Method [7] [8] -
    - Numerical method to find local minimum of a function.
    - Direct search method (derivative-free).
    - Takes less time; dependin only on number of iterations.




electronics

MDPI

Article

Parameter Optimization of Josephson Parametric Amplifiers Using a Heuristic Search Algorithm for Axion Haloscope Search

Younggeun Kim [1,†], Junu Jeong [1,†], Sungwoo Youn [1,*], Sungjae Bae [1,2], Arjan F. van Loo [3,4], Yasunobu Nakamura [3,4], Sergey Uchaikin [1] and Yannis K. Semertzidis [1,2]

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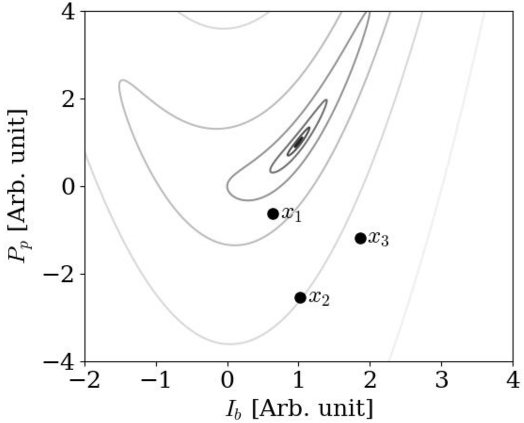
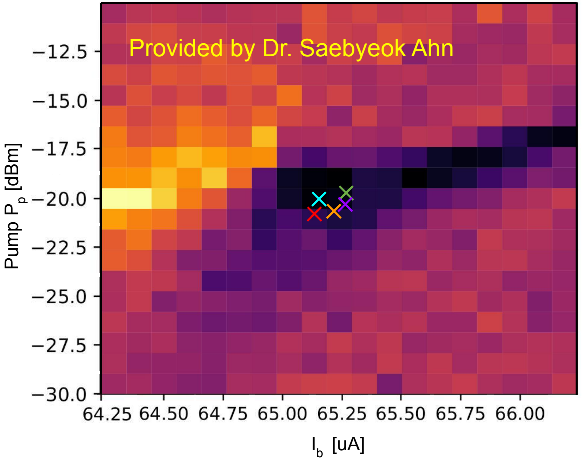
Abstract: The cavity haloscope is among the most widely adopted experimental platforms designed to detect dark matter axions with its principle relying on the conversion of axions into microwave photons in the presence of a strong magnetic field. The Josephson parametric amplifier (JPA),



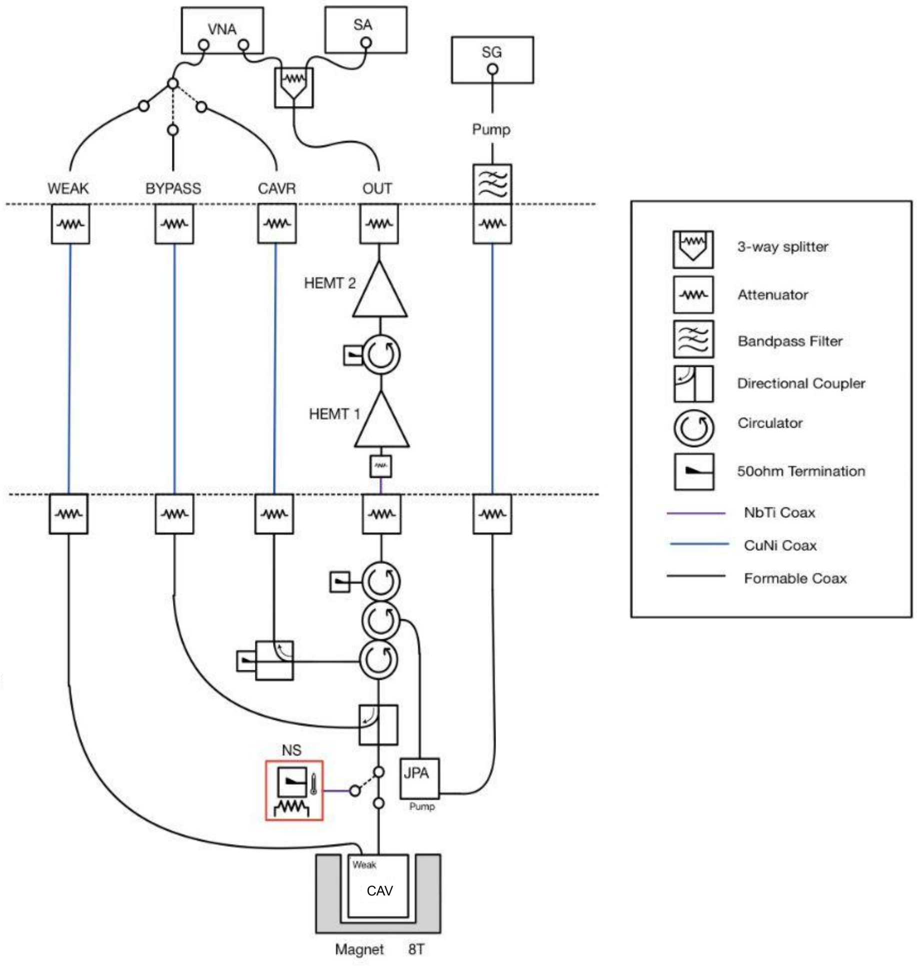
Nelder–Mead search for min noise temperature point in the 2D JPA parameter space (i_b, P_p).



Total system noise map with points picked by the NM algorithm.

7. Nelder, J.A.; Mead, R. A Simplex Method for Function Minimization. Comput. J. 1965, 7, 308–313.
8. Kim, Y., Jeong, J., Youn, S., Bae, S., van Loo, A. F., Nakamura, Y., Uchaikin, S., & Semertzidis, Y. K. (2024). Parameter Optimization of Josephson Parametric Amplifiers Using a Heuristic Search Algorithm for Axion Haloscope Search. Electronics, 13(11), 2127. https://doi.org/10.3390/electronics13112127

Experiment Setup - RF Chain



1. $T_{sys} \leq 50$ mK provided by cryogen-free dilution refrigerator, BlueFors LD400.
2. JPA used as 1st amplifier after cavity (lowest noise amplifier)
3. Cavity coupling measurements done through the output chain.
4. Cavity resonance frequency and quality factor are measured through the weak port.
5. Total system gain is measured via bypass line.
6. Total system noise temperature is measured using the cryogenic noise source.

Conclusion and Future Plans

- Presented the design and commissioning status of CAPP 8TB now DMAG 8TB axion haloscope experiment targeting 23.5 μeV mass range (~5.7 GHz) with ~ KSVZ sensitivity.
- The experiment integrates an 8-cell copper microwave cavity with high form factor, a low-noise flux-driven JPA, and a cryogen-free dilution refrigerator operating <50 mK.
- We implemented fast and effective JPA characterization protocol using the Nelder-Mead optimization algorithm, significantly reducing the time and power overhead compared to brute-force LUT scans.
- We will scan 250 MHz bandwidth between 5.56–5.81 GHz at a rate of ~ 3 MHz/day, achieving an expected signal power ~ 10^{-24} W.
- We will begin data collection for the 250 MHz range supported by the cavity in May 2025.

THANK YOU!