



Accelerated Search for **Axion Dark Matter** in the 15.30–15.85 μeV Range Using a **Seamless High-Temperature Superconducting Cavity**

Jiwon Lee^{1,2}

(on behalf of DMAG-8T)

¹Department of Physics, KAIST / ²Dark Matter Axion Group, IBS

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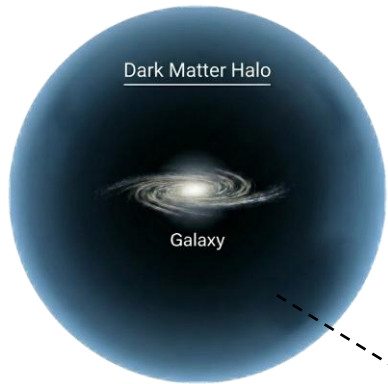
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Introduction: Axion Haloscope

- Cavity Axion Haloscope

Invented by Pierre Sikivie in 1983.



Axion dark matter in the galactic halo

External magnetic field

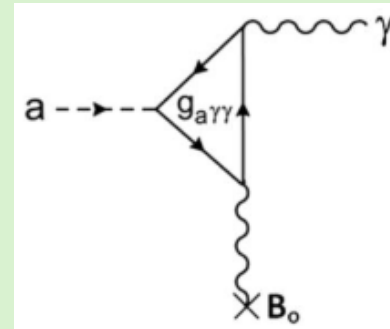
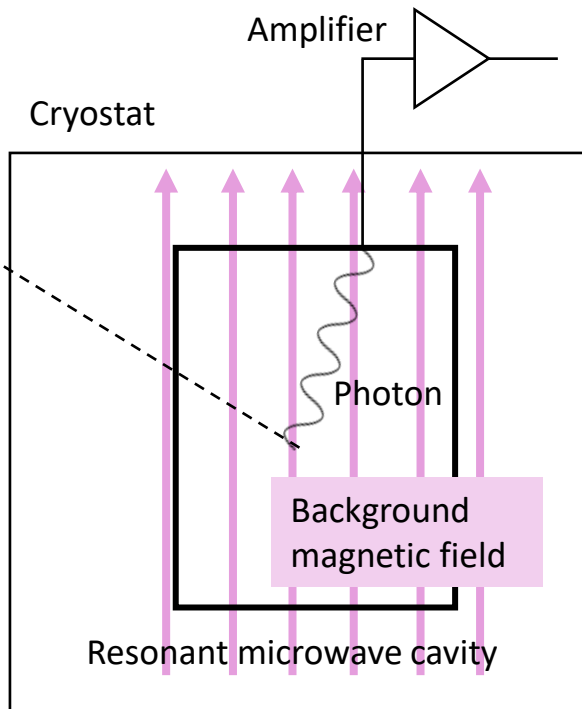
$$\mathbf{B}_0 \hat{\mathbf{z}}$$

Axion effective current

$$\mathbf{J}_0 \hat{\mathbf{z}}$$

E-field of TM_{010} mode

$$\mathbf{E}_0 \hat{\mathbf{z}}$$



Axion-photon interaction

$$\mathcal{L} \supset g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$

The axion field couples to the electric and magnetic fields.

Modified Ampere's Law

$$\nabla \times \mathbf{B} - \frac{\partial \mathbf{E}}{\partial t} = -g_{a\gamma\gamma} \mathbf{B}_0 \frac{\partial a}{\partial t}$$

Axion effective current density ($\mathbf{J}_a$) excites the $\mathbf{E}_0 \hat{\mathbf{z}}$ field of the TM_{010} mode.

$$\mathbf{J}_a = -g_{a\gamma\gamma} B_0 \frac{\partial a}{\partial t} \hat{\mathbf{z}}$$

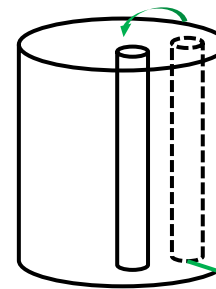
$$f_{\text{axion}} = \frac{m_{\text{axion}} c^2}{h}$$

When $f_{\text{axion}} = f_{\text{cavity}}$

→ Resonant conversions of axions to photons

Unknown mass

→ Frequency tuning via an off-axis rod is essential.

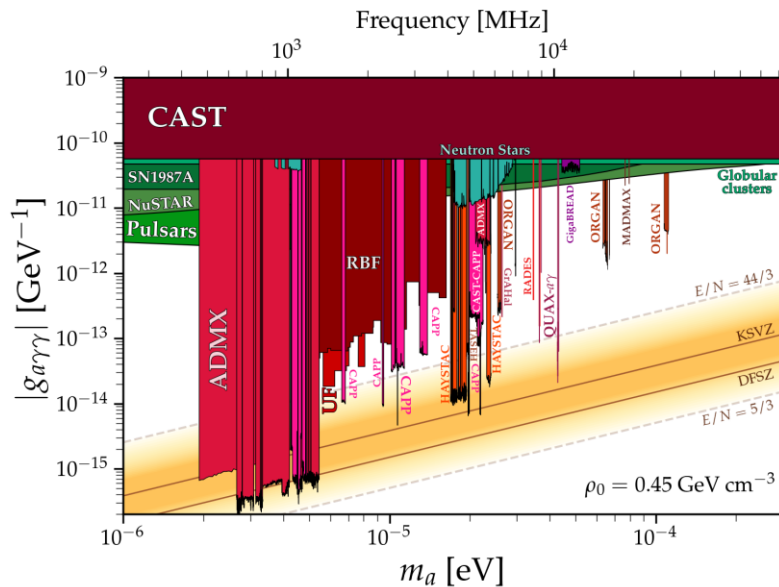


Dielectric or metal rod

- $g_{a\gamma\gamma}$: Axion photon coupling
- ρ_a : Axion density in the local dark-matter halo
- B : Externally applied B-field
- V : Cavity volume
- C : Cavity form factor
- Q_l : Loaded Cavity Q-factor
- Q_a : Axion Q-factor
- β : antenna coupling coefficient
- T_{sys} : system noise temperature

- Exclusion limit

Extensive global efforts, including ADMX, DMAG, and HAYSTAC, are underway to probe the vast axion parameter space.



The axion parameter space is vast, and a significant portion remains unexplored. Accelerating the scanning speed ($\frac{df}{dt}$) is the most critical challenge.

Axion conversion power

$$P_{a\gamma\gamma} = g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a} B^2 V C \frac{\beta}{1 + \beta} \frac{Q_l Q_a}{Q_l + Q_a}$$

Scan rate

$$\frac{df}{dt} \propto \frac{B^4 V^2 C^2}{T_{\text{sys}}^2} Q_l Q_a$$

To improve the scan rate,

- Magnetic field B^4

High cost

Cavity Volume V^2

Predetermined by commercially available SC magnets

Cavity form factor C^2

Maximized by utilizing the TM_{010} mode ($C \sim 0.69$)

System Noise Temperature T_{sys}^2

Josephson Parametric Amplifiers (JPA)

Near-quantum-limited amplifier

$$T_{\text{sys}} = T_1 + \frac{T_2}{G_1} + \dots \text{ (Friis' formula)}$$

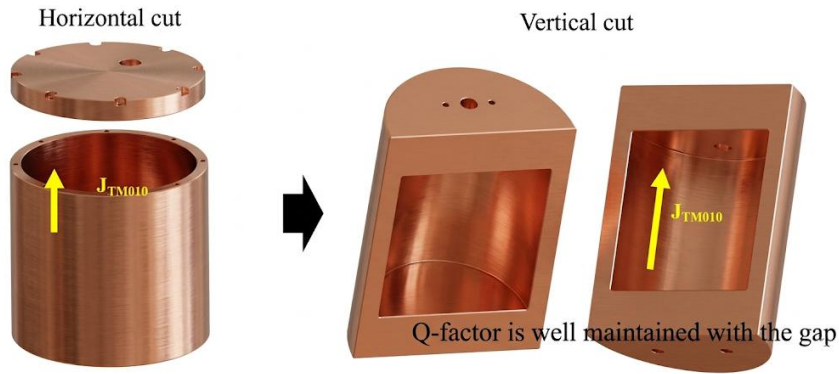
Loaded cavity Q-factor Q_l

Copper: Limited by the anomalous skin effect at cryogenic temperatures ($Q_0 \lesssim 10^5$).

LTS (e.g., NbTi): Vulnerable to high magnetic fields.

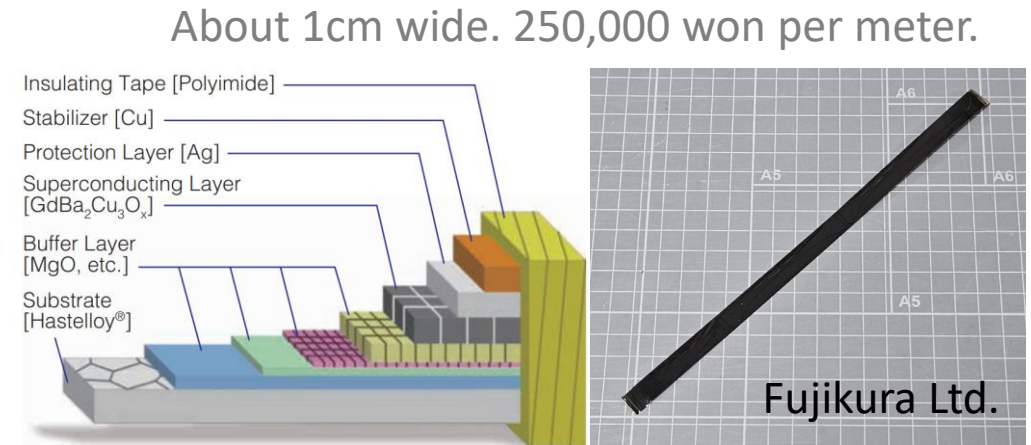
HTS (e.g., ReBCO): Maintains ultra-high Q-factor in multi-tesla fields.

Overcoming the 2D Limit: The Polygon Cavity Concept

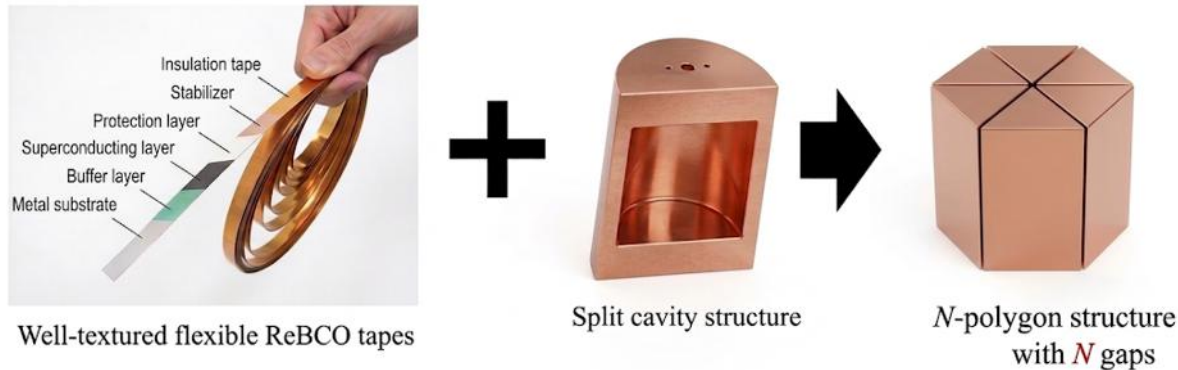


Compatibility with Vertical Division

- Surface current (J_{TM010}) flows purely parallel to the vertical gaps.
- No interruption of current lines → Negligible Q-factor degradation

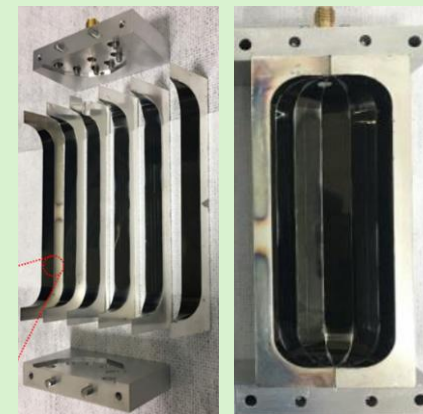


Commercially available HTS tapes



Conceptual Breakthrough:

- Constructing a 3D cavity by tiling multiple 2D HTS tapes.
- *(Original concept proposed by Dr. Woohyun)*



The 1st HTS Polygon Cavity
Constructed by attaching tapes to melon-shaped wedges.

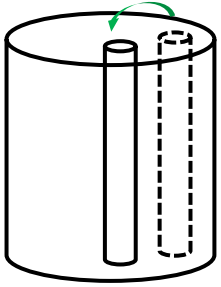
$$Q_0 \approx 3.0 \times 10^5 \text{ at } 8 \text{ T}$$

(~6 times higher than Cu)

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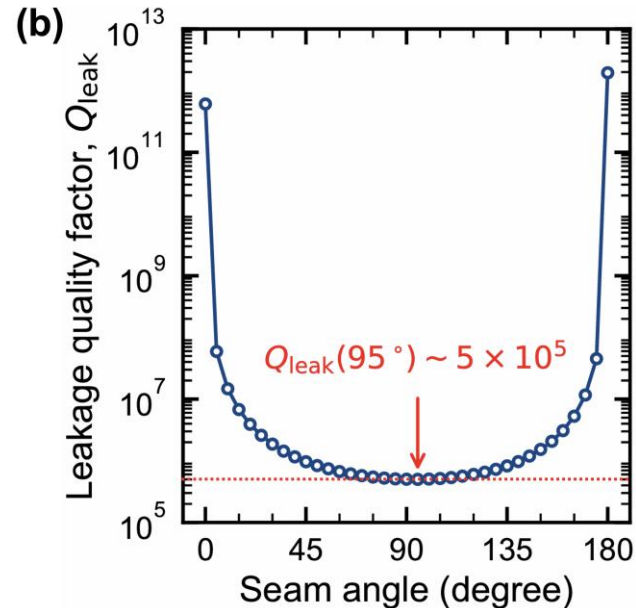
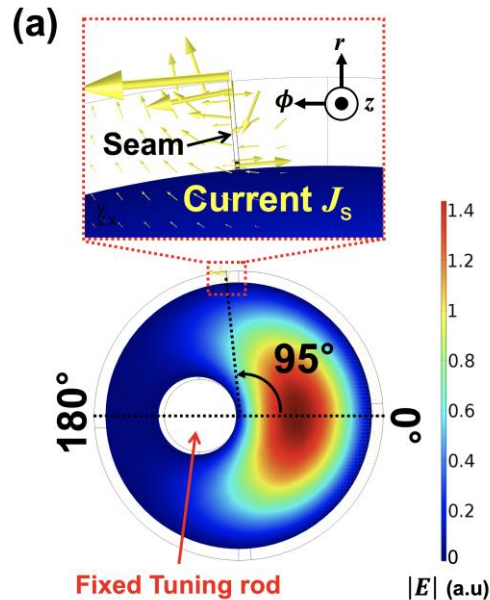
Azimuthal Symmetry Breaking & Solution

- Gap simulation



Conventional tuning method
→ Rotation of an off-axis rod.
→ Dielectric or metal rod.

A rotating vertical gap + fixed tuning rod + perfect conductor



- Indium Soldering Method

- Concept: Connecting tapes with indium to form an electrically closed surface. → Enables the use of conventional rotating tuning rods, making the system highly practical for real axion searches.

Why Indium?

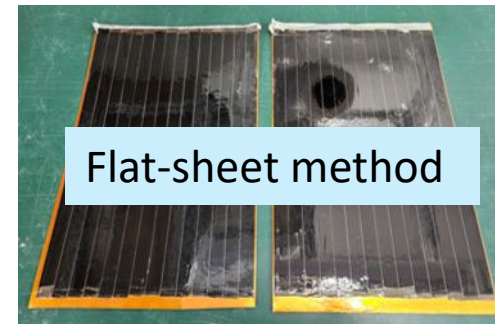
Thermal Constraint: HTS tapes suffer critical I_c degradation when heated above 200°C

Material Selection:

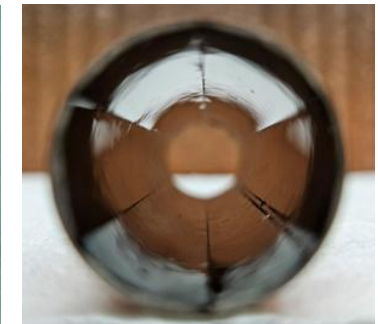
Melting point: $\sim 157^\circ\text{C}$

Low electrical resistivity at cryogenic temperature

- Development of Soldering Technology



Flat-sheet method

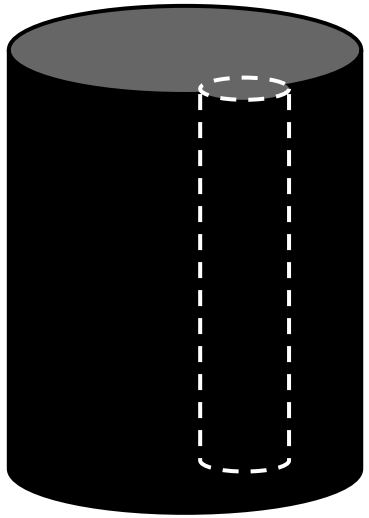


Pipe-soldering method

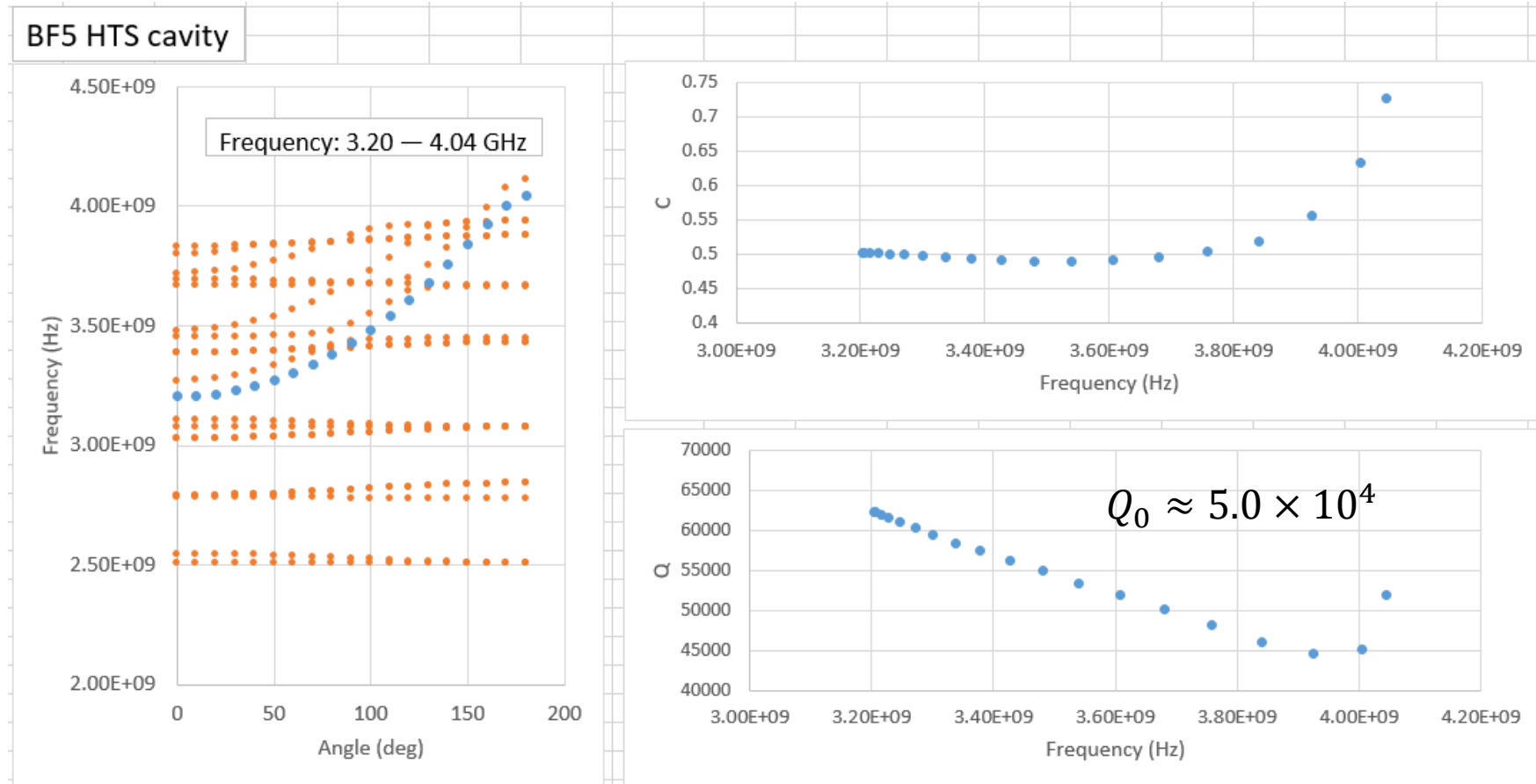
HTS Cavity Fabrication for DMAG-8T

Details on later slides

- Design optimization via COMSOL



Cavity
D103mm, H220mm
Tuning rod
※ tuning radius: 8 mm

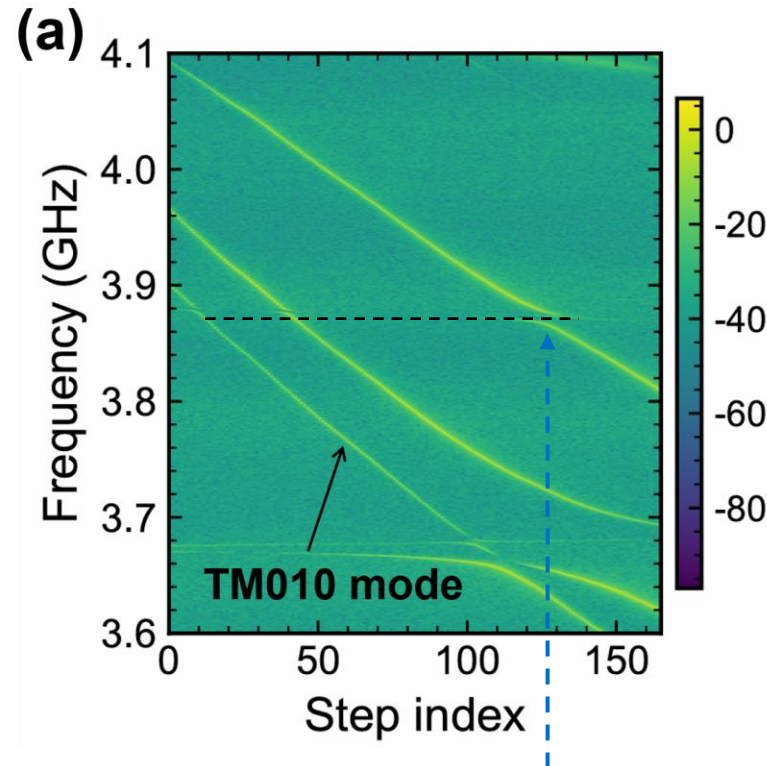
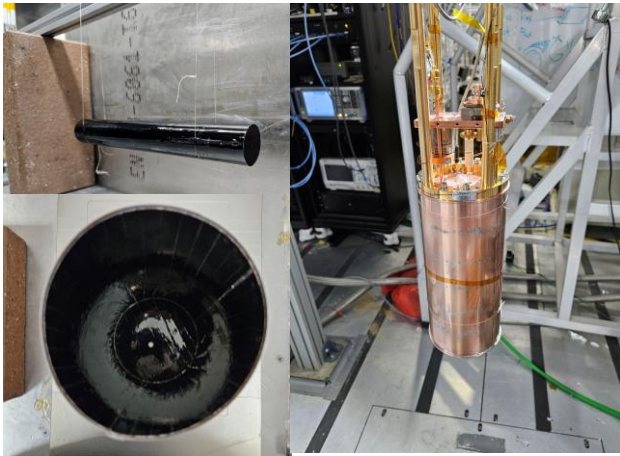
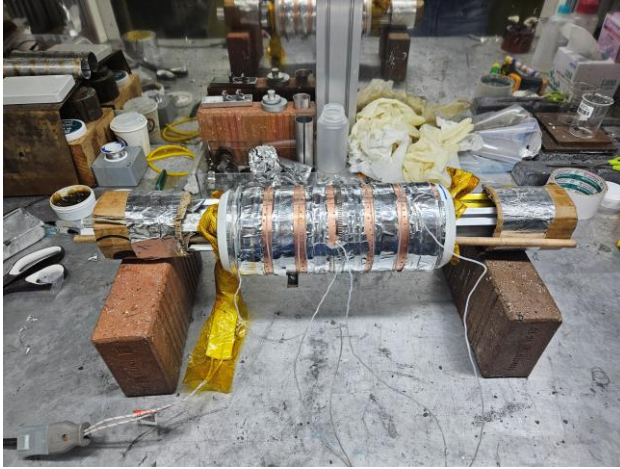


Material: Low-temperature copper
Reference for benchmarking HTS performance

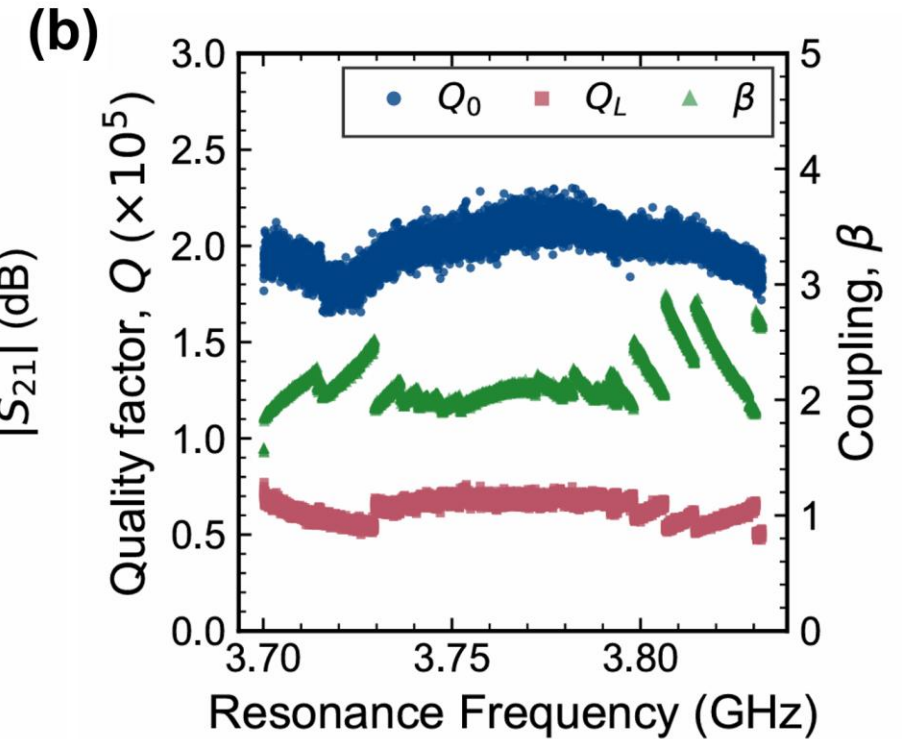
HTS Cavity Fabrication for DMAG-8T

Details on later slides

- Measure performance: Mode Map & Q-factor



Axion search region: 3.7 – 4.0 GHz
Mode crossing region (~ 3.88 GHz)
should be excluded from analysis

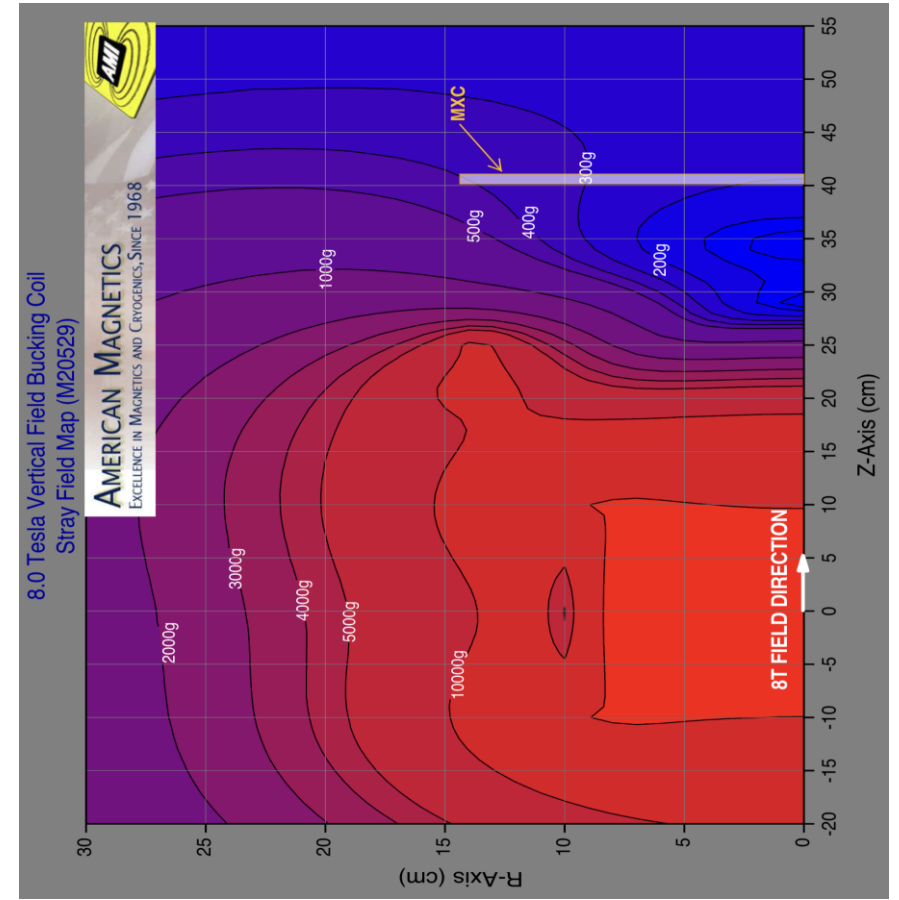
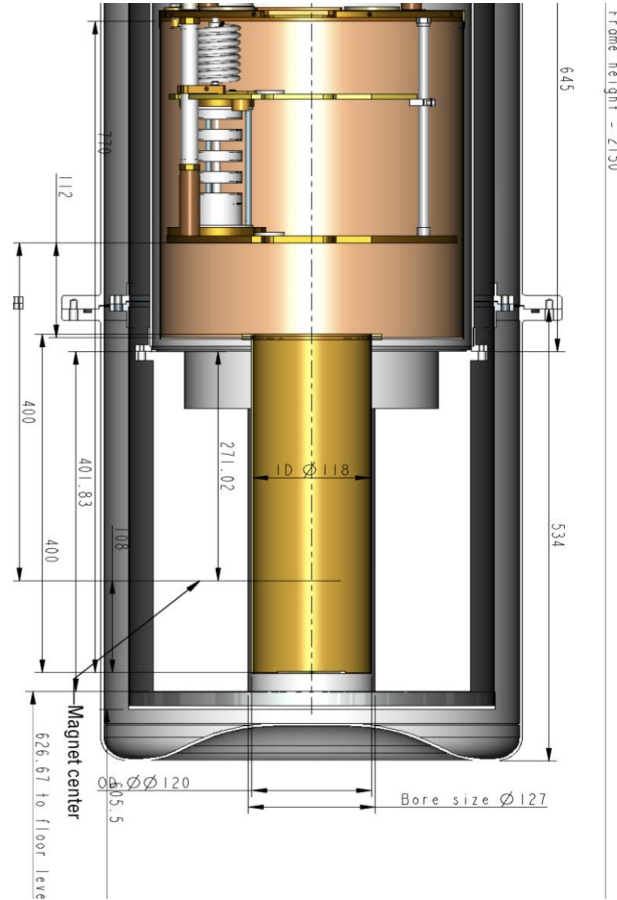
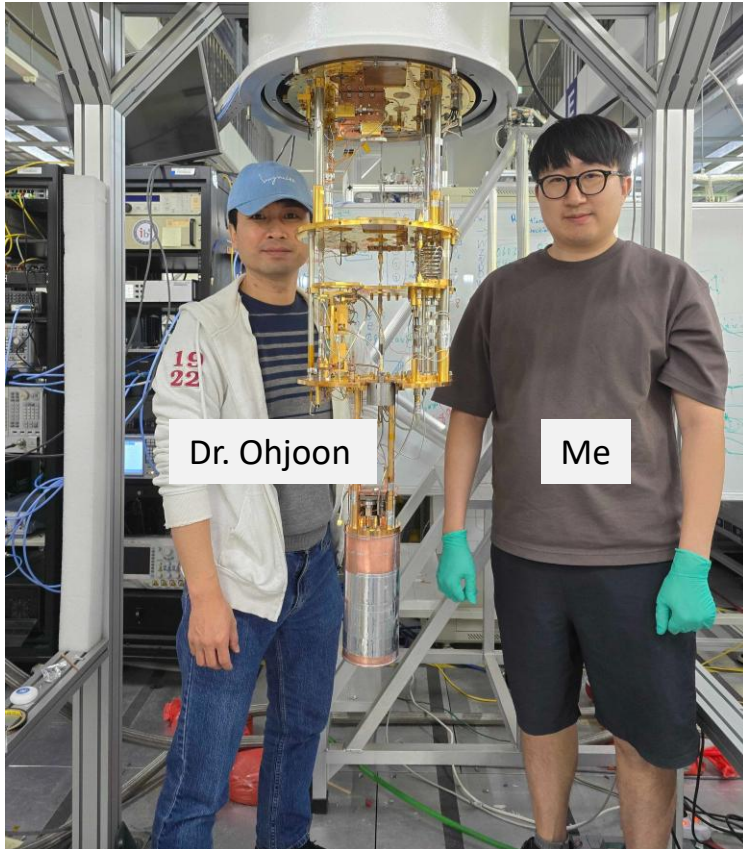


$Q_0 \approx 2.0 \times 10^5$ at 40 mK, 8 T

A four-fold enhancement compared to the Cu cavity

Experimental Setup: DMAG-8T

- Bluefors dilution refrigerator LD400 & AMI 8T (12 cm bore magnet)

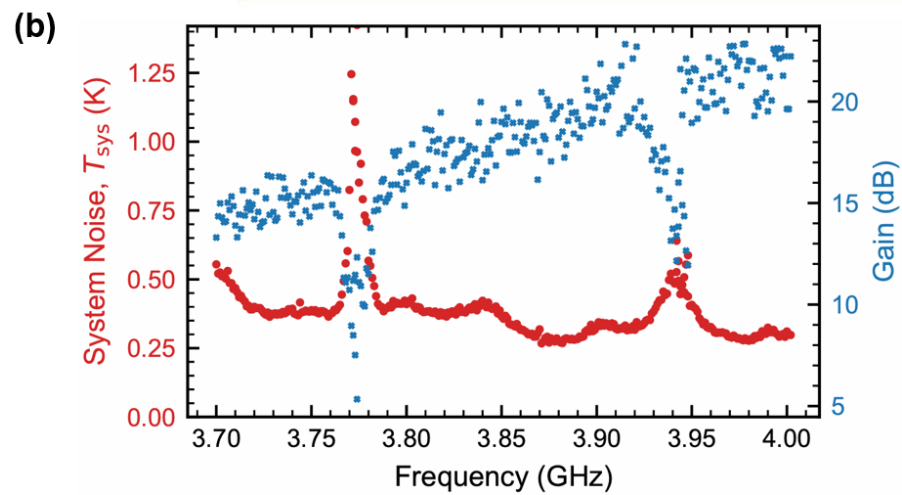
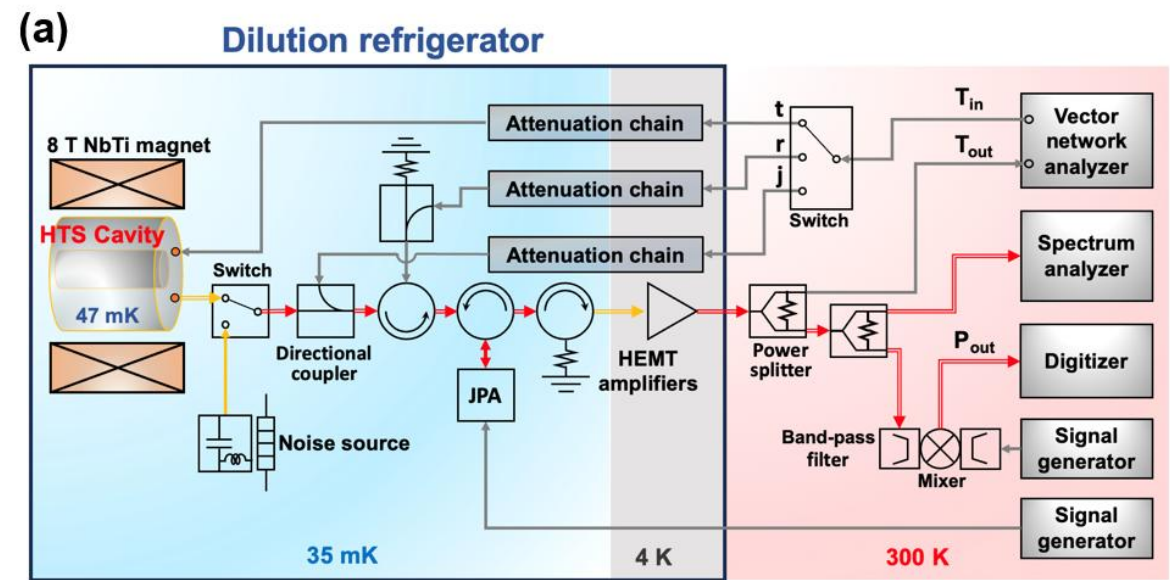
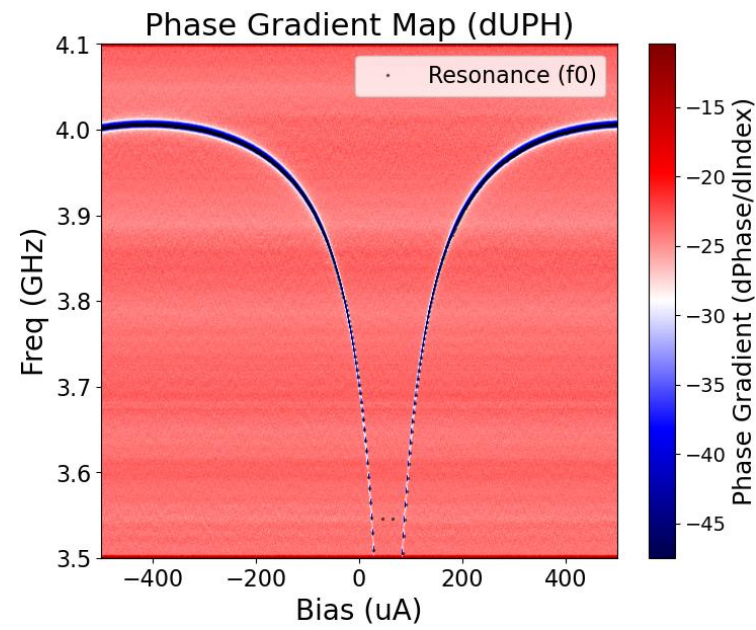


It allows us to perform sub-Kelvin measurements in a high B-field environment.

Experimental Setup: DMAG-8T

- Josephson parametric amplifier (JPA)

Int'l collaboration w/ Nakamura's group



Number of Quanta	Formula	3.7 GHz	4.0 GHz
0.5 quanta (SQL)	$T = \frac{hf}{2k_B}$	88.8 mK	96.0 mK
1.0 quantum	$T = \frac{2hf}{2k_B}$	177.6 mK	192.0 mK
1.5 quanta	$T = \frac{3hf}{2k_B}$	266.4 mK	288.0 mK

Working range of JPA (3.7 – 4.0 GHz, total 300 MHz) → determined the axion search range

DAQ for 3.700 – 3.833 GHz

Step 1. Cavity tuning

1. Automated stuck tuning rod detection
2. Magnetic field ramping and precision frequency alignment

Step 2. Cavity characterization (Per Run)

1. Parameter extraction (f_0, Q_L, β)
 2. Full S-parameter traces (S21, S22) recorded
- ※ Temporarily detunes JPA bias during VNA sweeps

Step 3. JPA optimization (Per 5 Runs)

1. Lookup table assistance
2. Autonomous minimum T_{sys} search: re-optimizes bias and pump power to minimize T_{sys}

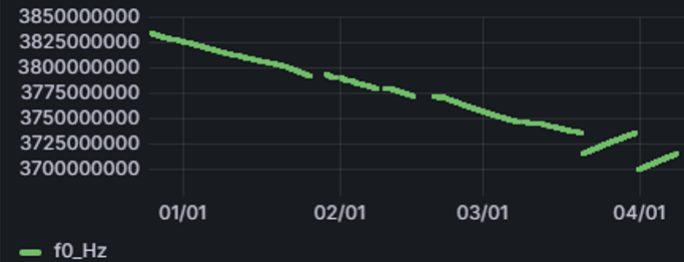
Step 4. Axion data acquisition

1. Digitizer acquisition: 780s
2. Parallel processing: Asynchronous background processing and storage to eliminate dead time

Step 5. Real-time monitoring & logging

1. MySQL & Grafana
2. Independent Multi-Stage Safety: Monitoring thermal stability ($T < 51.4$ mK) and hardware limits.

Cavity f_0 vs time



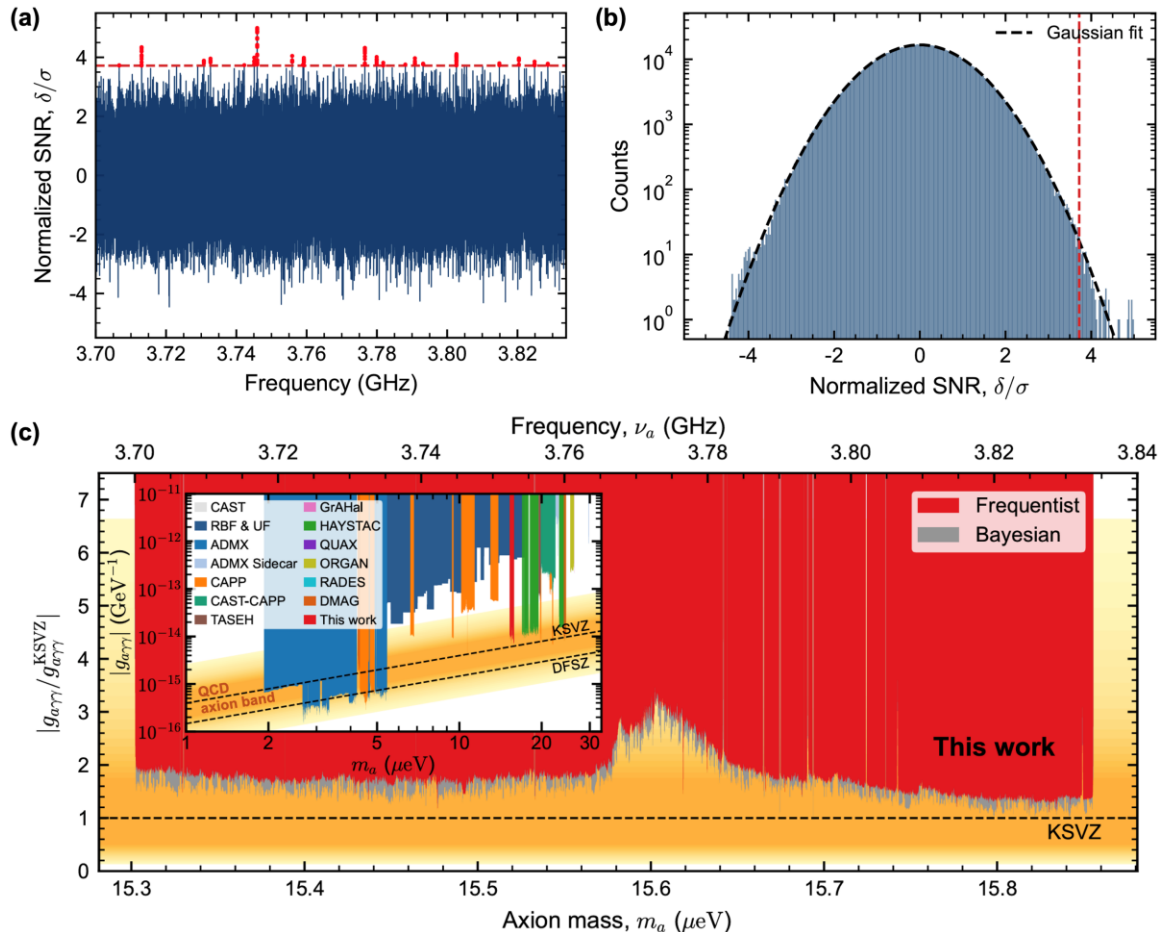
• Data-taking period:

- 2025.12.25 17:13 – 2026.04.08 10:37
- Frequency coverage: 3.700 – 3.833 GHz (Total 133 MHz)

Frequency	Axion Mass	Magnetic Field	Effective Volume	Unloaded Q	Loaded Q	System Noise Temp.	Average Scan rate
3.700–3.833 GHz	15.30–15.85 μ eV	8.0 T ($B_{avg} \approx 7.20$ T)	1.68 L	2.0×10^5	1.5×10^5	280–400 mK	1.28 MHz/day

Data Analysis

- Data analysis process: Baseline subtraction → RFI / Spurious masking → Vertical combination → Horizontal combination → Candidate rescan → Exclusion limit

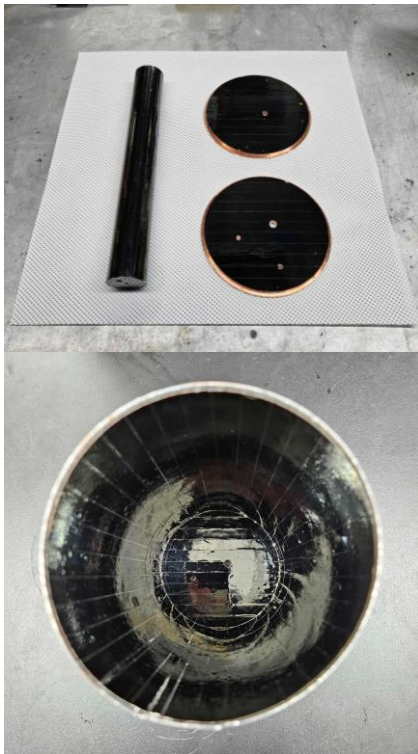
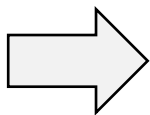
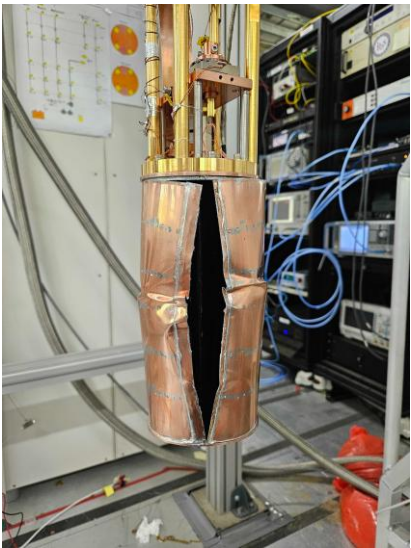


- 4th order (> 3.74 GHz) & 5th order (< 3.74 GHz) Savitzky-Golay filter baseline subtraction
- Average SNR efficiency $\langle \eta \rangle = 76.04 \%$
- 21 candidate clusters ($> 3.718\sigma$) systematically rescanned → All resolved as statistical fluctuations.

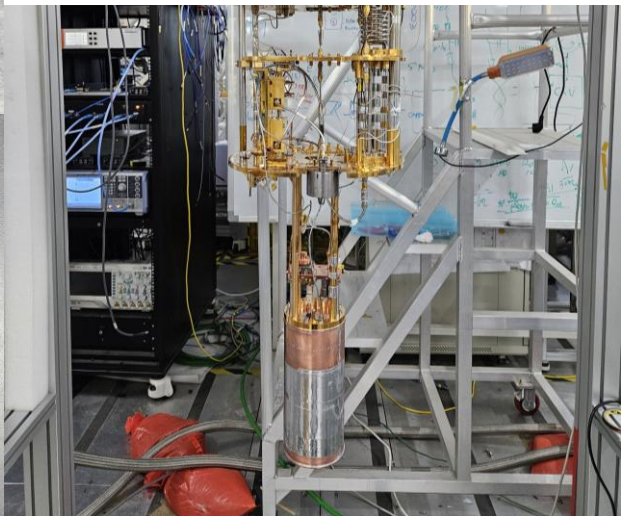
- Frequentist 90% C.L. (5.0σ): Median limit $1.7 \times$ KSVZ, peak sensitivity $1.3 \times$ KSVZ
- Bayesian Framework (10% Prior Update): Peak sensitivity reaches the benchmark KSVZ line.
- Systematic error bounded to 3.1%.
- Submitted to PRL (arXiv: 2609.08144).

Replacement HTS Cavity (3.833 – 4.000 GHz)

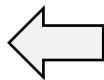
- Magnet quench occurred after the rescan process on July 30.
- Severe mechanical rupture on the cavity sidewall → We fabricated the replacement cavity.



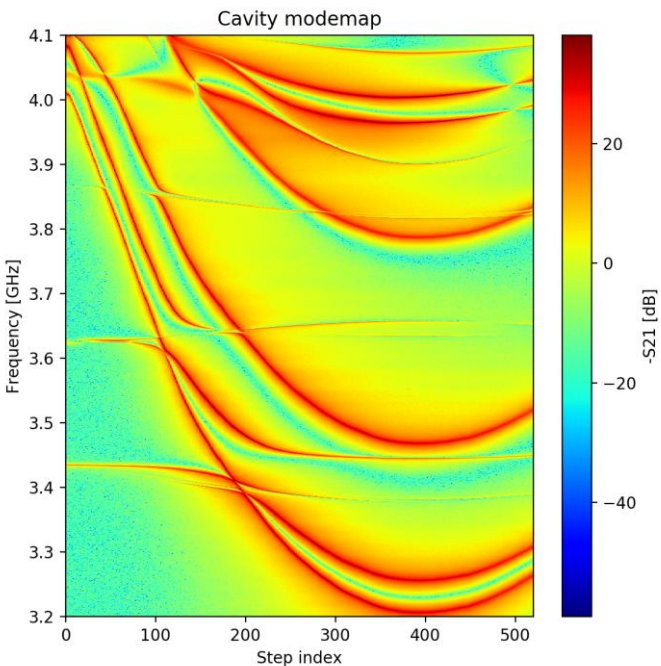
Zero-Field Cavity Performance
($B = 0$ T)
✖ Indium $T_c \approx 3.41$ K, $H_c \approx 0.03$ T



Room-temperature cavity mode mapping
was performed over 3.21 – 4.01 GHz.



T_cav	f_0 (GHz)	Q_0
5.02 K	3.838886	1.56×10^5
32.4 mK	3.935195	2.90×10^5



Summary

- Technological Breakthrough:
 - Successfully developed a seamless HTS cavity via face-to-face indium soldering, completely eliminating symmetry-breaking TEM radiation leakage.
 - Maintained $Q_0 \approx 2.0 \times 10^5$ at 8 T / 40 mK across a 300 MHz tuning range (3–4 x higher than Cu).
- Axion Search Results (3.700 – 3.833 GHz):
 - Completed 133 MHz physics run using a near-quantum-noise JPA ($T_{\text{sys}} \approx 280\text{--}400$ mK).
 - Established 90% C.L. exclusion limits reaching $1.3 \times \text{KSVZ}$ (Frequentist) and successfully probed the benchmark KSVZ coupling line (Bayesian).
- Current Status & Future Roadmap:
 - Fabricated and assembled the upgraded replacement HTS cavity for the 3.833–4.000 GHz band.
 - Cryogenic integrity fully validated at base temperature ($Q_0 \approx 2.9 \times 10^5$ at 32.4 mK, $B = 0$ T).
 - Plan to initiate 8 T axion data acquisition within this month to complete the remaining sweep.

Thank you for your attention! / Questions & Answers