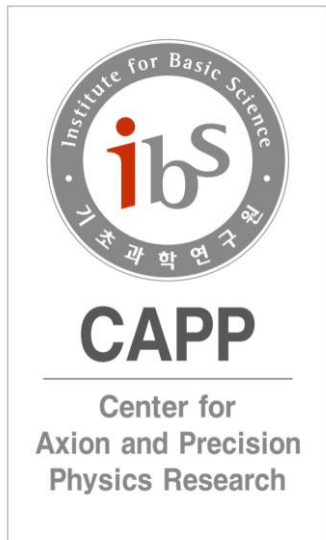




The First High-Temperature Superconducting Cavities for Axion Dark Matter Search

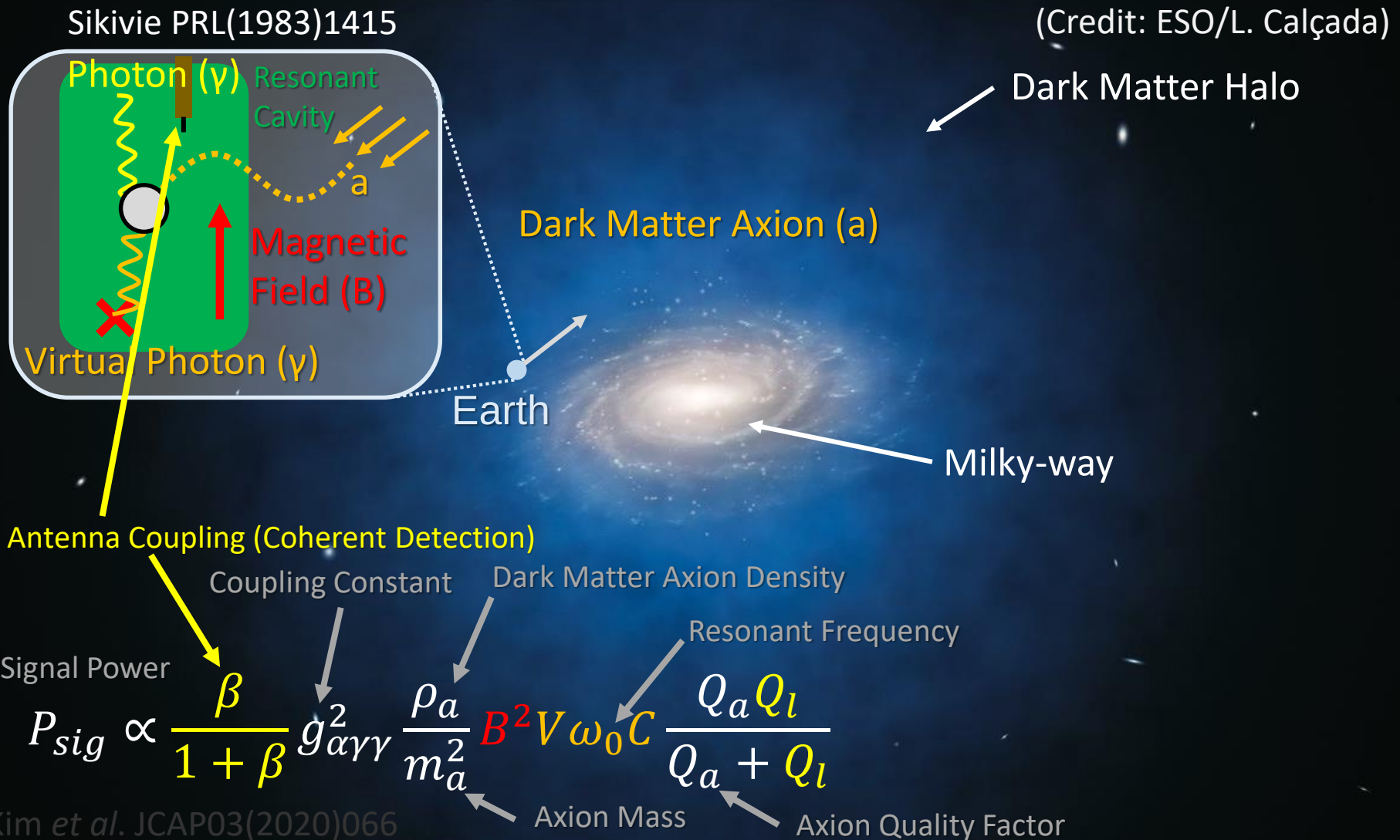
Danho Ahn¹.

¹Center for Axion and Precision Physics Research, Institute of Basic Science, Daejeon 34051, Republic of Korea

Introduction

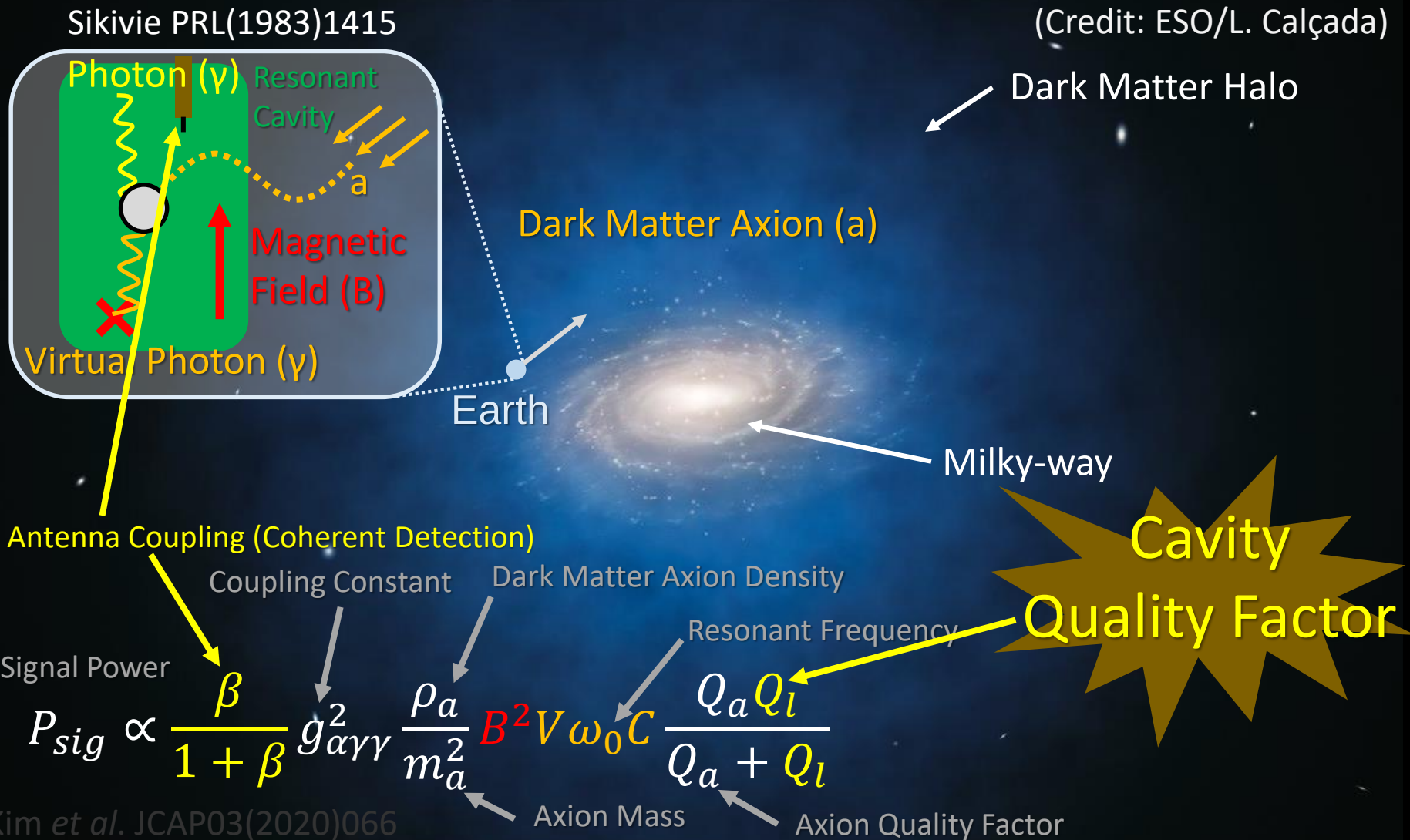
Axion Haloscope

(Credit: ESO/L. Calçada)



Axion Haloscope

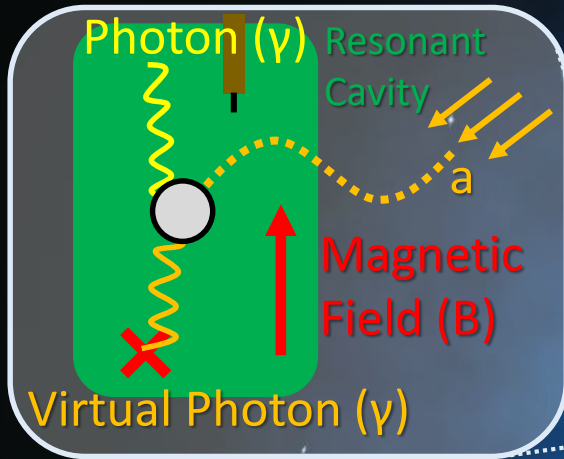
(Credit: ESO/L. Calçada)



Cavity Quality Factor in Axion Haloscope

Sikivie PRL(1983)1415

(Credit: ESO/L. Calçada)



$$Q_l \gg Q_a$$

Scan Rate

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

System Noise

Loaded Quality Factor

Axion Quality Factor (10^6)

Cervantes *et al.* arXiv:2208.03183

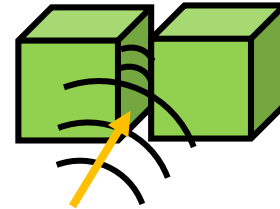
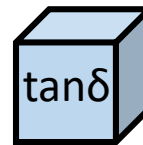
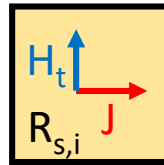
Superconducting Cavity R&D

Cavity Quality Factor

- $1/Q$ is related to the total energy loss in a cavity.

$$\frac{1}{Q} = \sum_i \frac{R_{s,i}}{G_i} + p \tan\delta + rad$$

Superconductor!

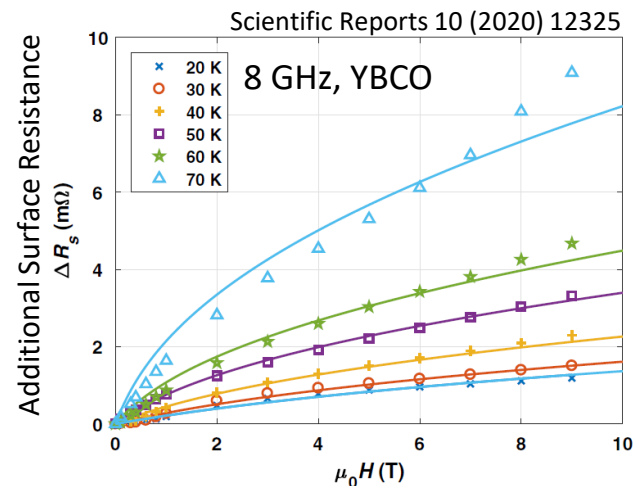
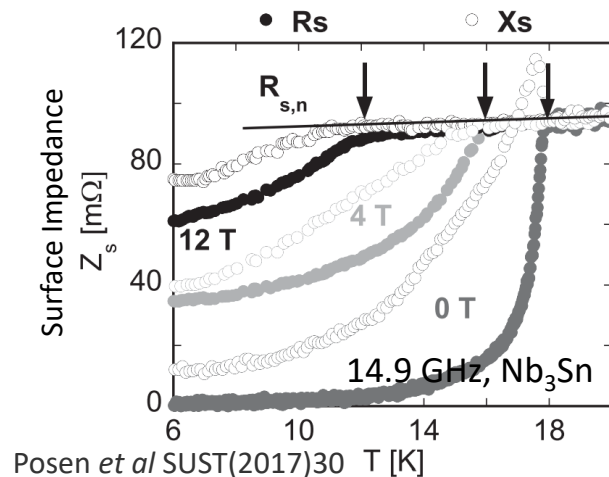


$$G_i = \frac{2\omega_0 U}{\int |H_t(r)|^2 dA_i} \quad p = \frac{1}{2U} \int \vec{D}(r) \cdot \vec{E}(r) dV_{di}$$

Superconducting Radio-frequency Cavity

➤ Material Choice?

- Most of superconductors are not working in a high magnetic field
- Biaxially-textured Rare-earth Barium Copper Oxide (ReBCO)



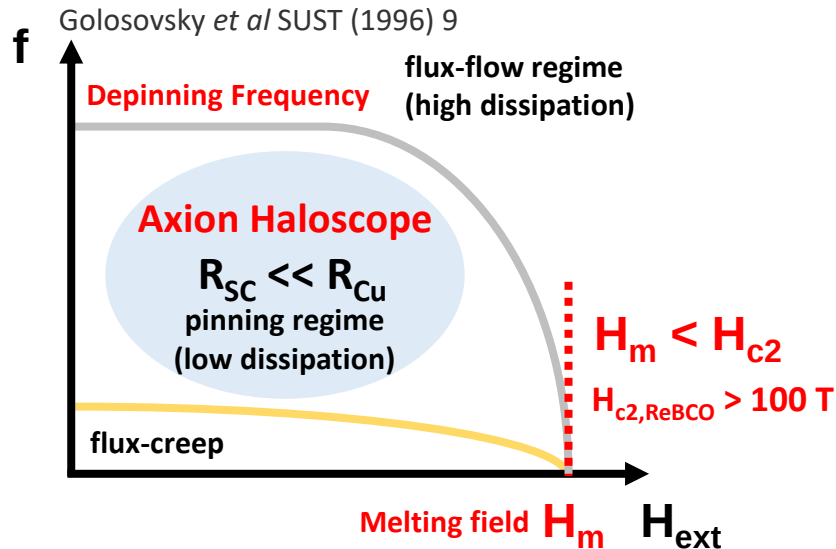
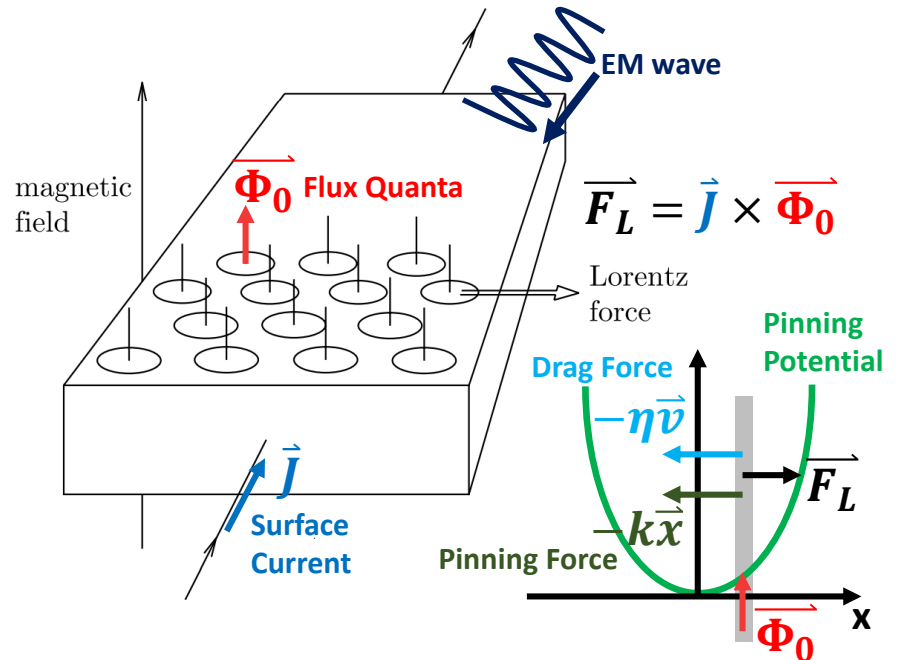
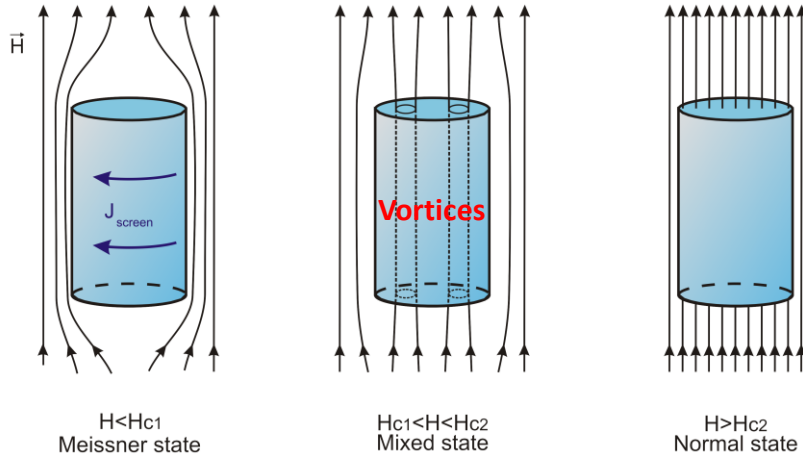
➤ How are we going to make a cavity?

- HTS tapes + 3D Surface
- Tape alignment for minimizing radiation energy loss

Vortex Pinning is Important for Low R_s

Three Phases of Type II Superconductor

<https://www.cee.elektro.dtu.dk/news/nyhed?id=E6796539-A36B-4CA5-BC31-CBDBBCA335D8>



➤ Two criteria for evaluating materials

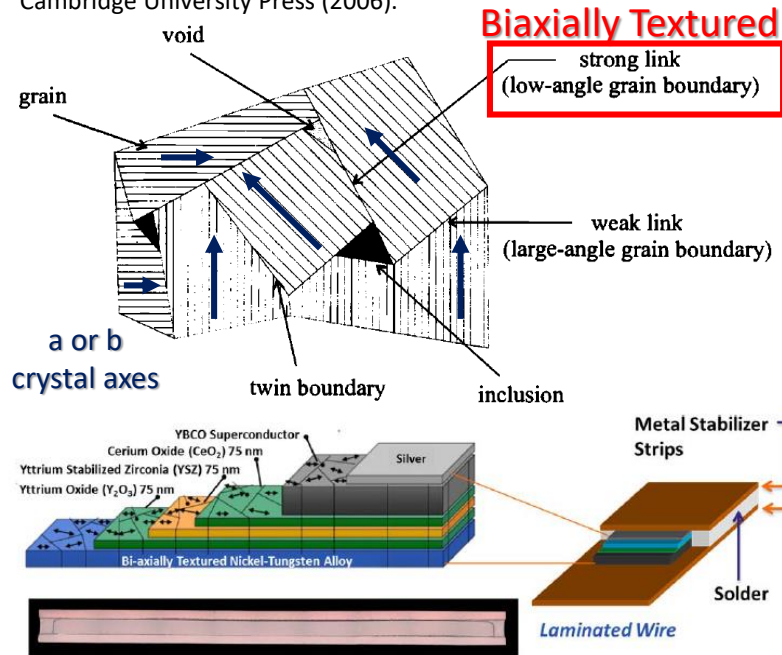
- ✓ Large upper critical field ($H_{c2} > 30 \text{ T}$)
 - Lower Vortex Density
- ✓ High depinning frequency ($\omega_0 > 1 \text{ GHz}$)
 - $\omega_0 = k / \eta$
 - $\omega \gg \omega_0$ (Drag force $\gg$ Pinning force)

Material Evaluation

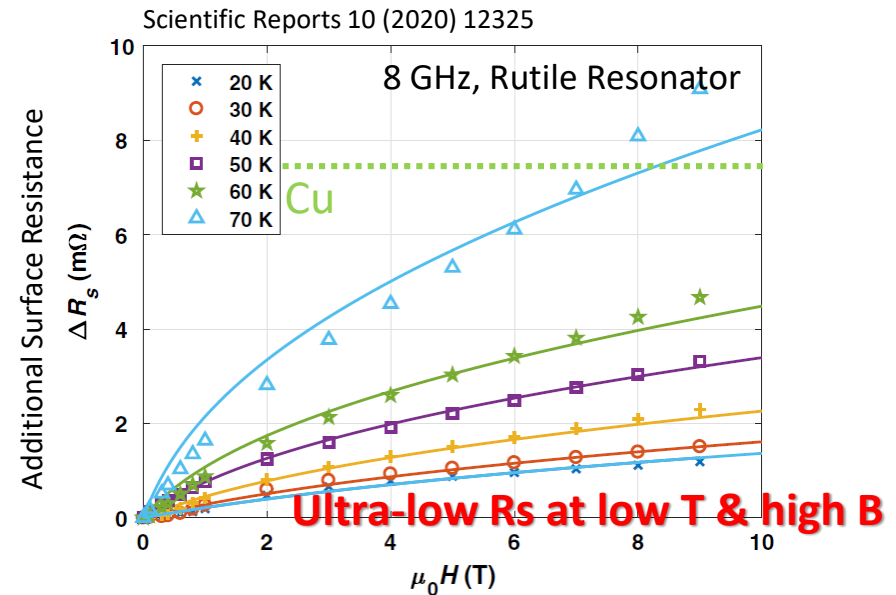
100 mK 8 GHz	R_s (B = 0 T) (Ohm)	R_s (B = 8 T, $\parallel c$) (Ohm)	Critical Field (H_{c2})	Depinning Frequency
OFHC Cu (Metal)	$\sim 7E-3$	$\sim 7E-3$	None	None
Low Temperature Superconductors (LTS)				
NbTi (LTS) Gatti <i>et al.</i> PRD(2019)	$\sim 1E-6$	$\sim 4e-3$	Small ~ 13 T	~ 45 GHz
Nb ₃ Sn (LTS) Alimenti <i>et al.</i> SUST(2020)	$\sim 1E-6$	?	~ 25 T	Small ~ 6 GHz
High Temperature Superconductors (HTS)				
Bi-2212 (HTS) Bi-2223 (HTS)	$\sim 1E-5$	?	> 100 T ($\parallel ab$) Larbalestier <i>et al.</i> Nature(2001)	Weak Pinning ?
Tl-1223 (HTS)	$\sim 1E-5$	$\sim 1e-4$ Calatroni <i>et al.</i> SUST(2017)	> 100 T ($\parallel ab$) Larbalestier <i>et al.</i> Nature(2001)	12 – 480 MHz Calatroni <i>et al.</i> SUST(2017)
ReBCO (HTS) Re = Y, Gd, Eu, ...	$\sim 1E-5$ Ormeno <i>et al.</i> PRB(2001)	$\sim 1e-4$ Romanov <i>et al.</i> Scientific Reports(2020)	> 100 T ($\parallel ab$) Larbalestier <i>et al.</i> Nature(2001)	10 – 100 GHz Romanov <i>et al.</i> Scientific Reports(2020)

Biaxially-Textured Film is Necessary for High Q

M. J. Lancaster, "Passive microwave device applications of HTS",
Cambridge University Press (2006).



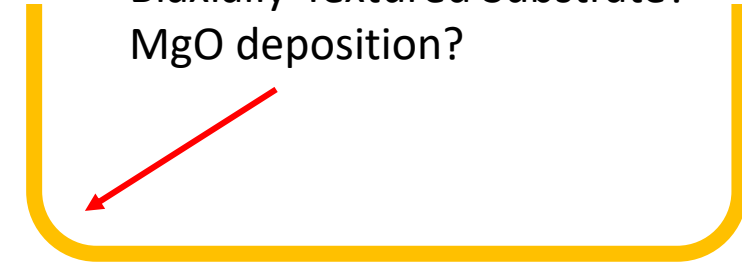
IEEE Trans. Appl. Supercond. 23 (2013) 6601205



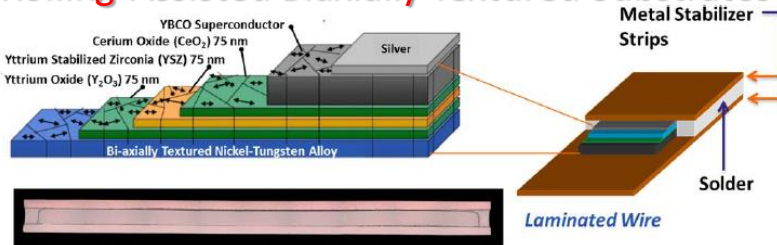
- Biaxial texture is essential to avoid weak links.
 - Weak link is a misalignment of crystal axes at grain boundaries
 - Weak links at grain boundaries degrades surface resistance.
 - Only biaxially-textured ReBCO films show low surface resistance at high magnetic field
- For high Q cavity, biaxially-textured film should be fully covered on the cavity surfaces.

Deposition on Curved Surface is Difficult

Ion-beam?
Biaxially-Textured Substrate?
MgO deposition?

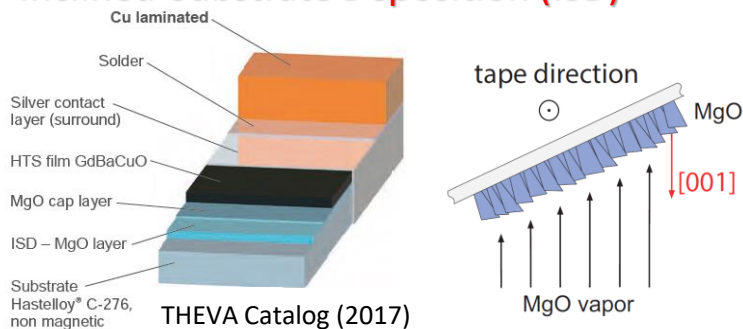


Rolling-Assisted Biaxially Textured Substrates (RABiTS)



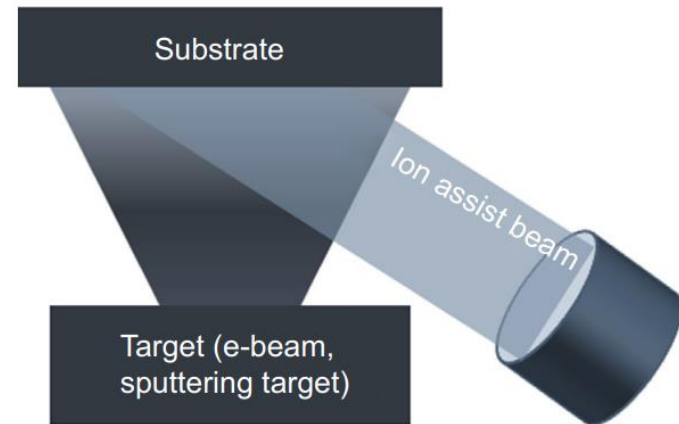
IEEE Trans. Appl. Supercond. 23 (2013) 6601205

Inclined-Substrate Deposition (ISD)



THEVA Catalog (2017)

Ion-Beam Assisted Deposition (IBAD)



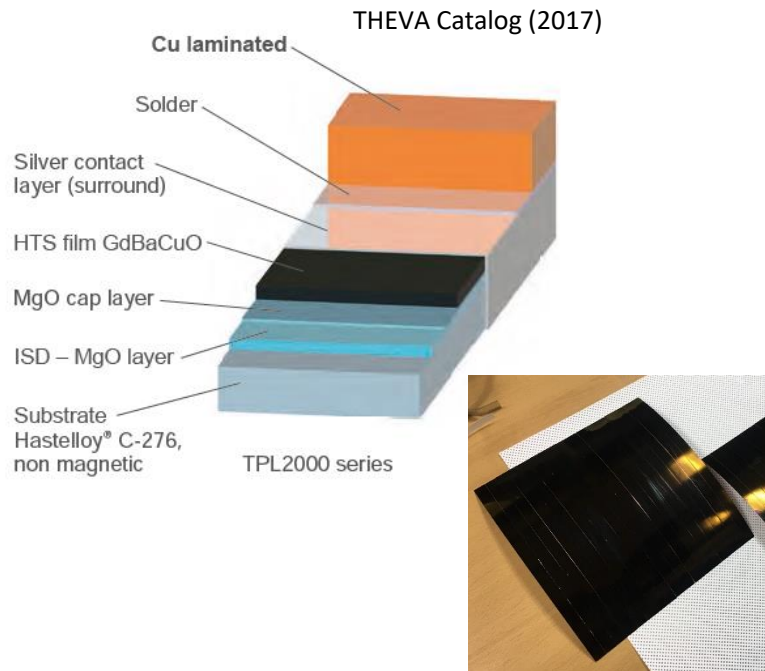
Superconductors in the Power Grid, Elsevier (2015)

- Directly forming a biaxially-textured ReBCO film on the deeply concaved inner surface of the cavities is difficult.
- **Can we make a cavity with ReBCO tapes?**

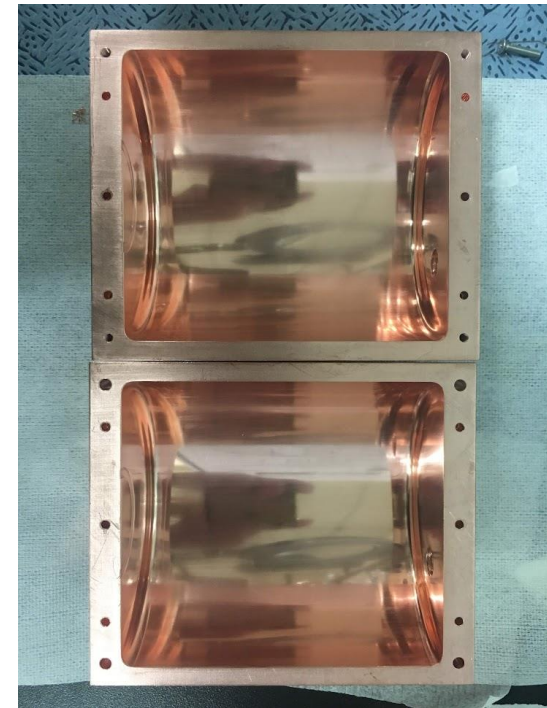
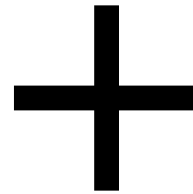
Solution: Tape Attachment on 3D Surface

Biaxially-Textured ReBCO Tapes

+ Cavity Body → 3D HTS Cavity



2D Material



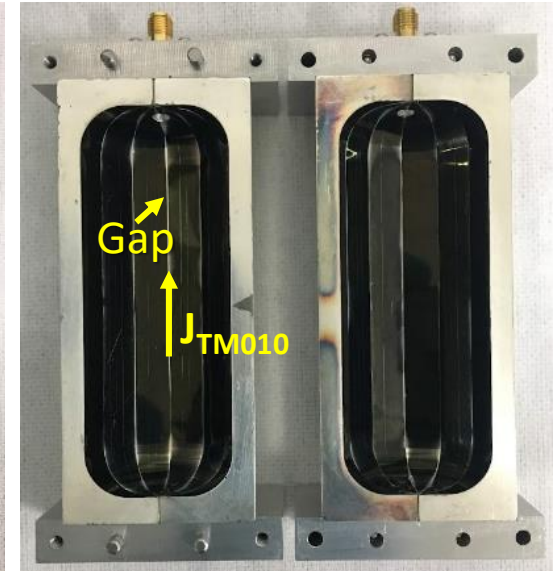
3D Surface

Radio-Frequency Design Issues

Electric Field of a Resonant Mode

$$C = \frac{\epsilon_0 \left| \int_{V_c} \mathbf{E}_r \cdot \mathbf{B}_0 \right|^2}{\int_{V_c} |\mathbf{B}_0|^2 dV \int_{V_c} \epsilon |\mathbf{E}_r|^2 dV}$$

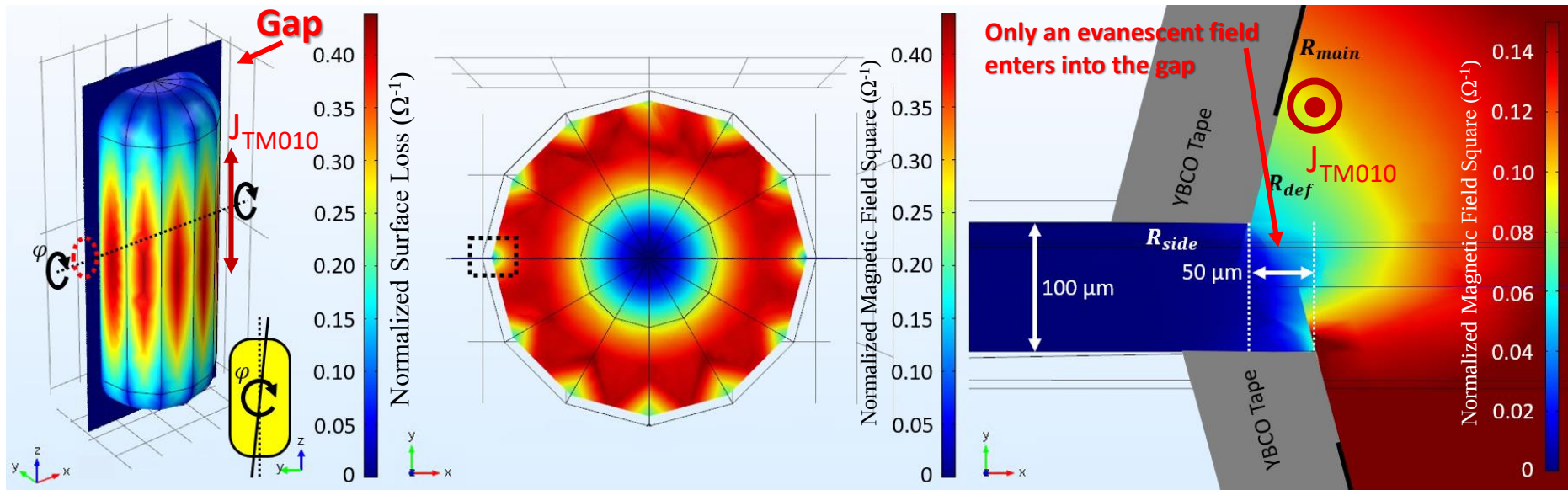
External Magnetic Field



- TM010 maximizes the form factor in the cavity haloscope.
 - Aligned directions of external magnetic field and the mode electric field makes high form factor.
- Tape alignment is necessary to prevent the electromagnetic wave propagation through the gaps.

N polygonal structure with N gaps

Polygonal Cavity Simulation with Gaps



$$\frac{1}{Q} = \frac{\overset{\text{HTS Tape}}{R_{s,HTS}}}{G_{HTS}} + \frac{\overset{\text{Fabrication}}{R_{s,defect}}}{G_{defect}} + \frac{\overset{\text{RF Design}}{1}}{Q_{gap}}$$

$Q_{gap} \sim 10^7$

1st Generation 6.9 GHz Polygon Cavity

1. Etching: Ammonia Water + Hydrogen Peroxide
2. Silver Sputtering



1st Generation 6.9 GHz Polygon Cavity

- (2019) First Prototype YBCO Cavity
 - ✓ (1st Cavity) **$Q \sim 150,000$ at 8 T**
 $1\mu\text{m}$ sputtering
 - ✓ (2nd Cavity) **$Q \sim 330,000$ at 8 T**
 $2\mu\text{m}$ sputtering + better alignment

PHYSICAL REVIEW APPLIED 17, L061005 (2022)

Letter

Biaxially Textured $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ Microwave Cavity in a High Magnetic Field for a Dark-Matter Axion Search

Danho Ahn^{1,2}, Ohjoon Kwon,² Woohyun Chung^{2,*}, Wonjun Jang,^{3,†} Doyu Lee,^{2,‡} Jinhwan Lee,⁴ Sung Woo Youn², HeeSu Byun,² Dojun Youm,¹ and Yannis K. Semertzidis^{1,2}

¹Department of Physics, Korea Advanced Institute of Science and Technology (KAIST), Daejeon 34141, Republic of Korea

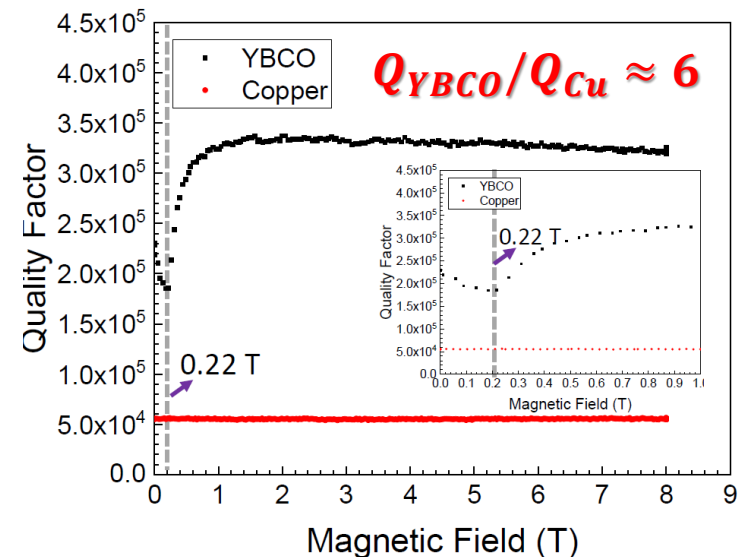
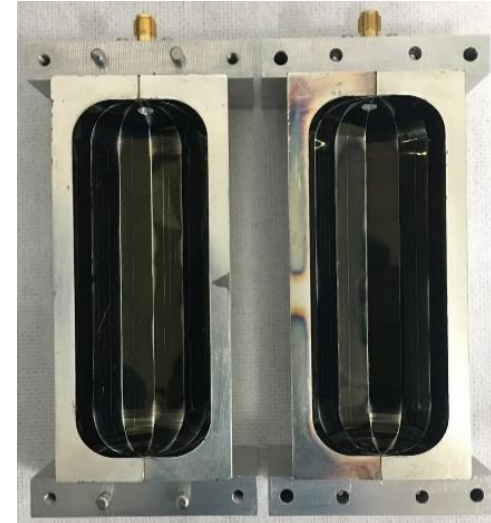
²Center for Axion and Precision Physics Research, Institute for Basic Science, Daejeon 34051, Republic of Korea

³Center for Quantum Nanoscience, Institute for Basic Science, Seoul 33760, Republic of Korea

⁴Center for Artificial Low Dimensional Electronic Systems, Institute for Basic Science, Pohang 37673, Republic of Korea

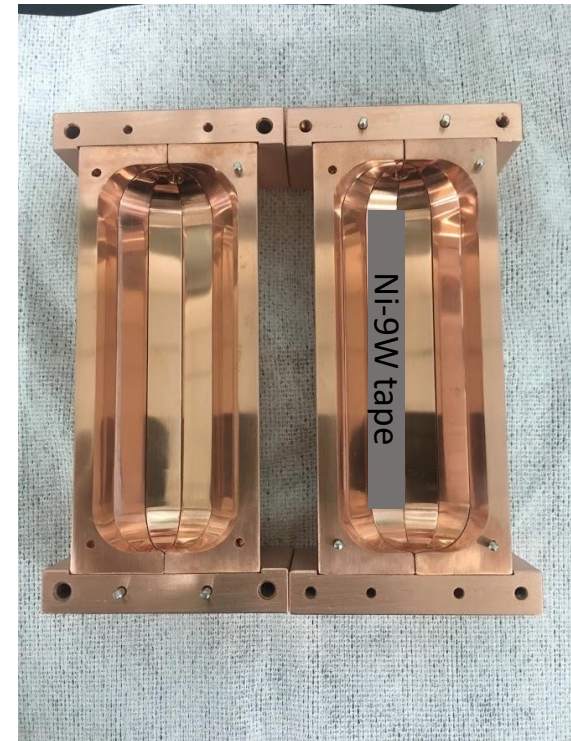
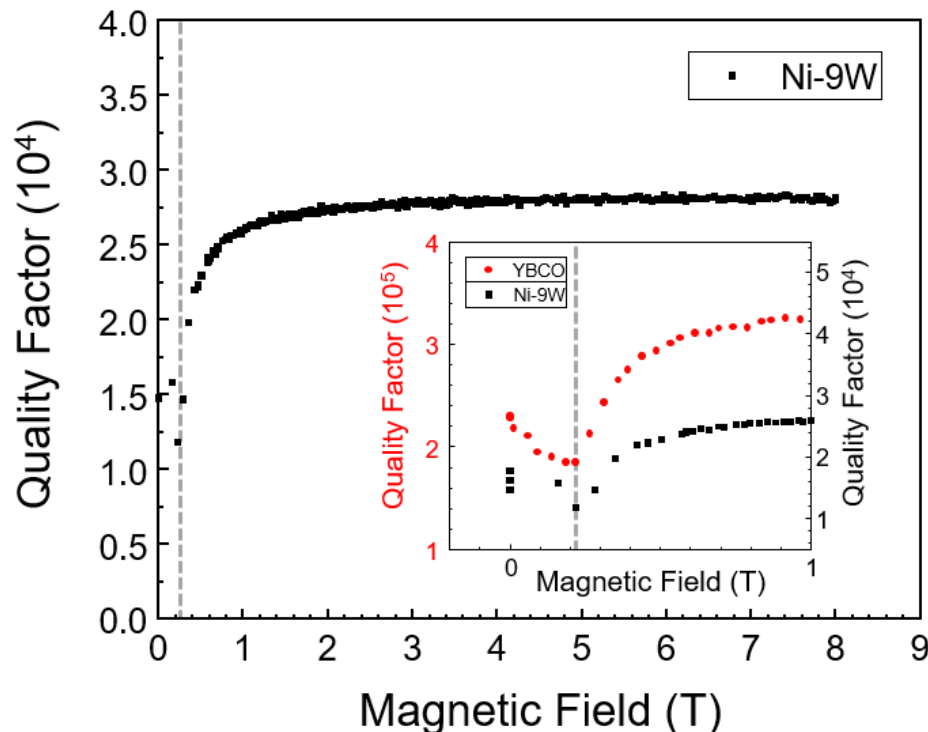
(Received 10 March 2022; accepted 5 May 2022; published 28 June 2022)

A high-quality (Q)-factor microwave resonator in the presence of a strong magnetic field can have a wide range of applications, such as in axion dark matter searches where the two aspects must coexist to enhance the experimental sensitivity. We introduce a polygon-shaped cavity design with biaxially textured $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ superconducting tapes covering the entire inner wall. Using a 12-sided polygon cavity, we obtain substantially improved Q factors of the 6.9-GHz TM_{010} mode at 4 K with respect to a copper cavity and observe no considerable degradation in the presence of magnetic fields up to 8 T.



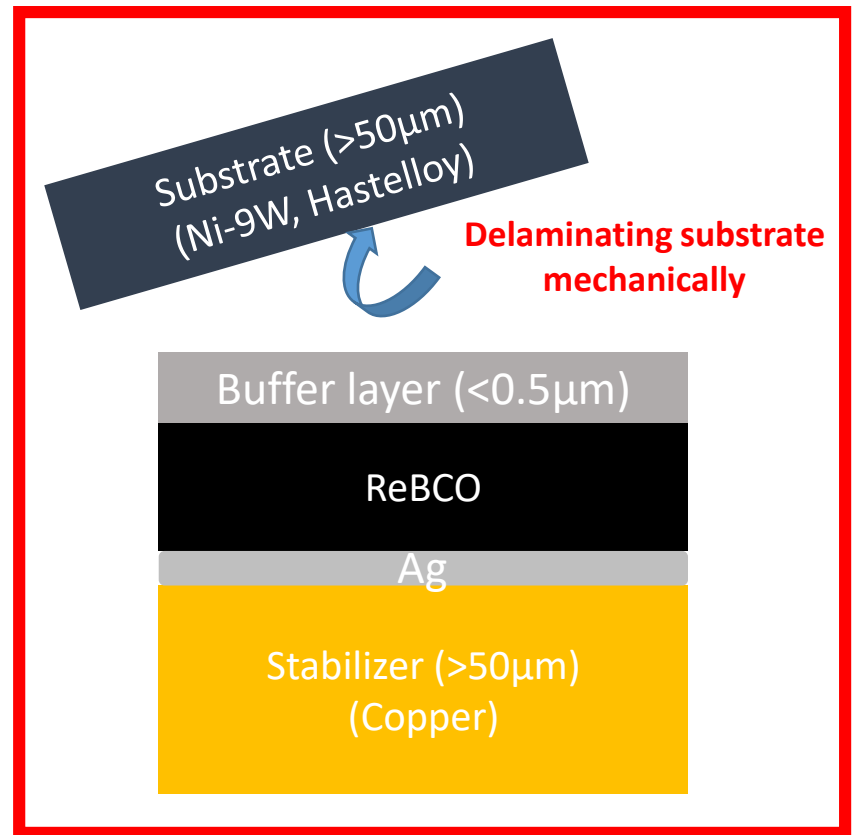
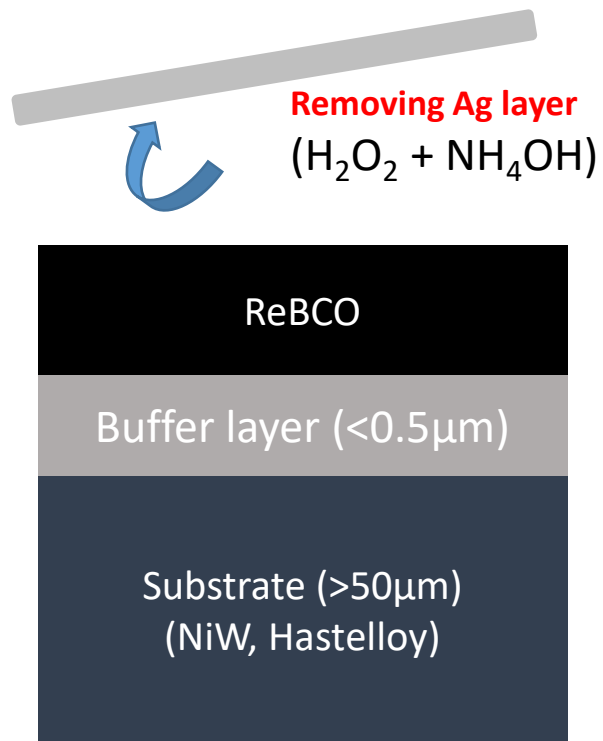
Ni-9W Still Generate Surface Loss

- The Ni-9W tape was attached on one copper cavity wedge.
- The Q factor behavior of the test cavity was similar to the YBCO cavity.

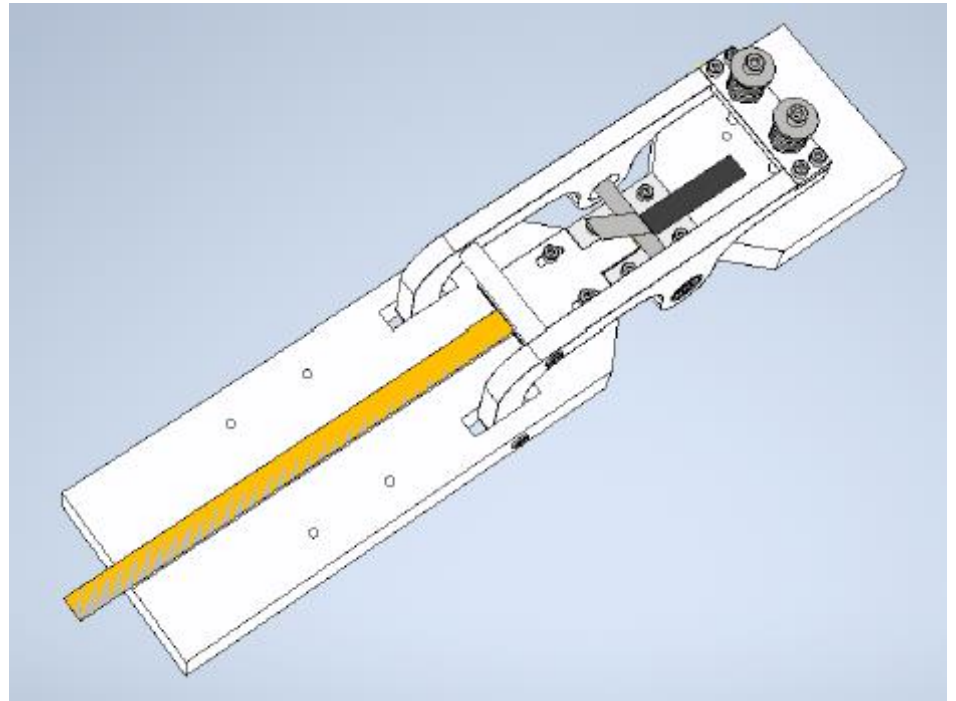
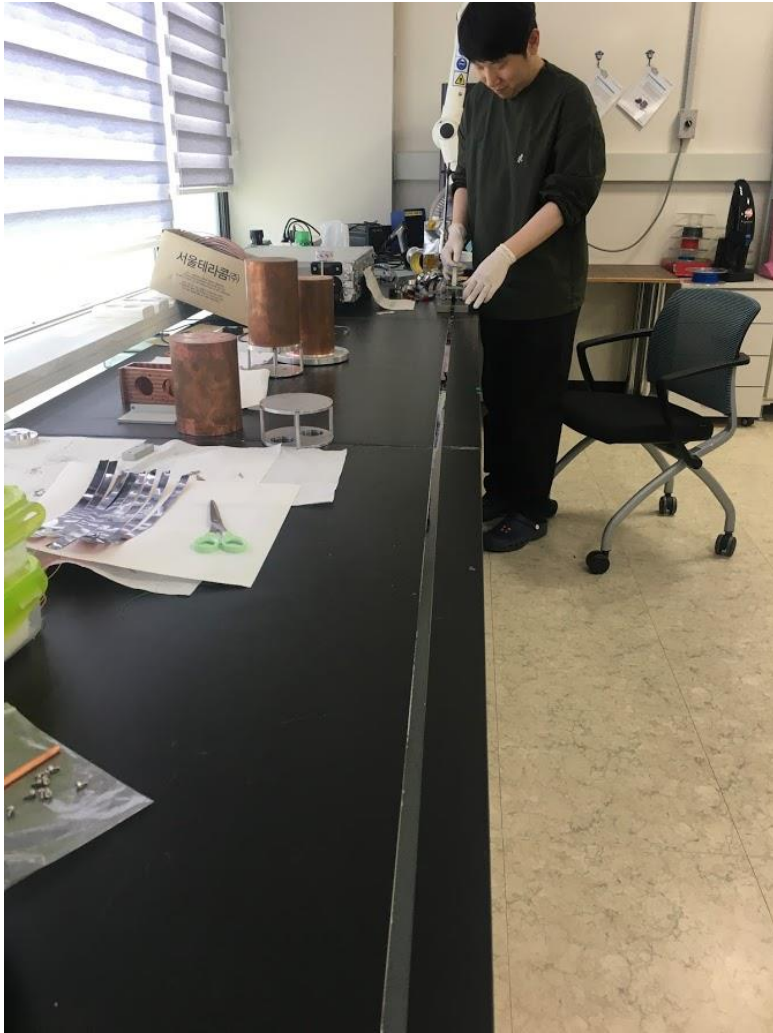


Tape Delamination for Eliminating Ni-9W

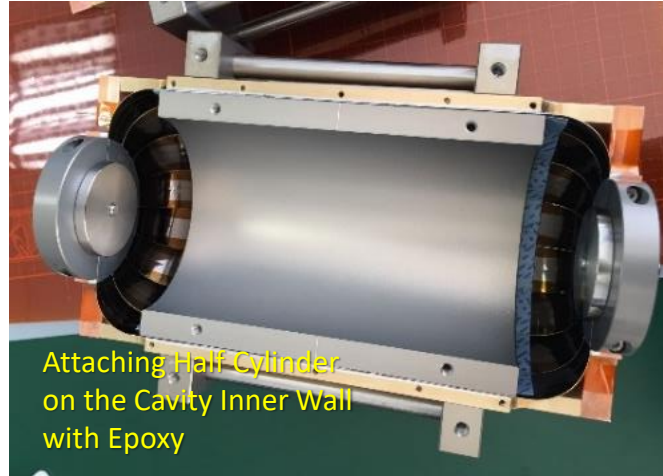
- Ni-9W layer can be removed by tape delamination.



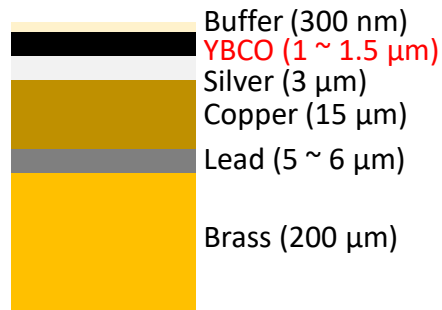
2nd Generation Cavity Development



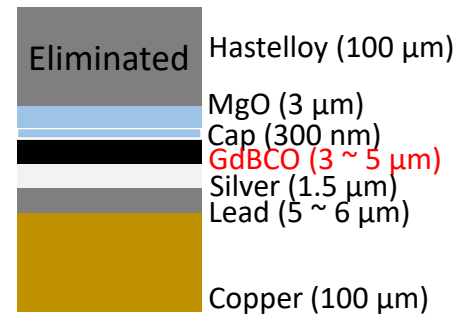
2nd Generation Cavity for Axion Haloscope



SuNAM



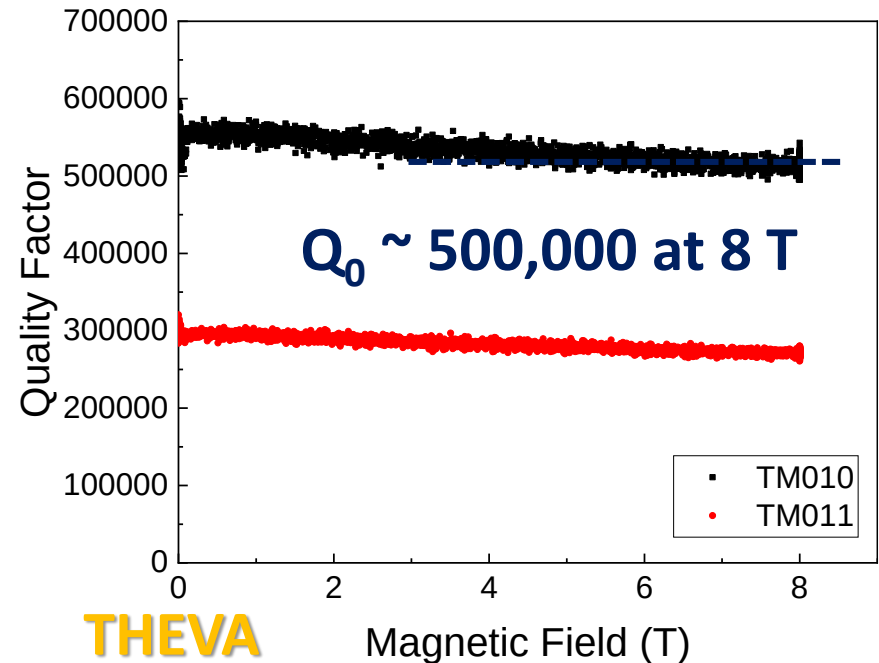
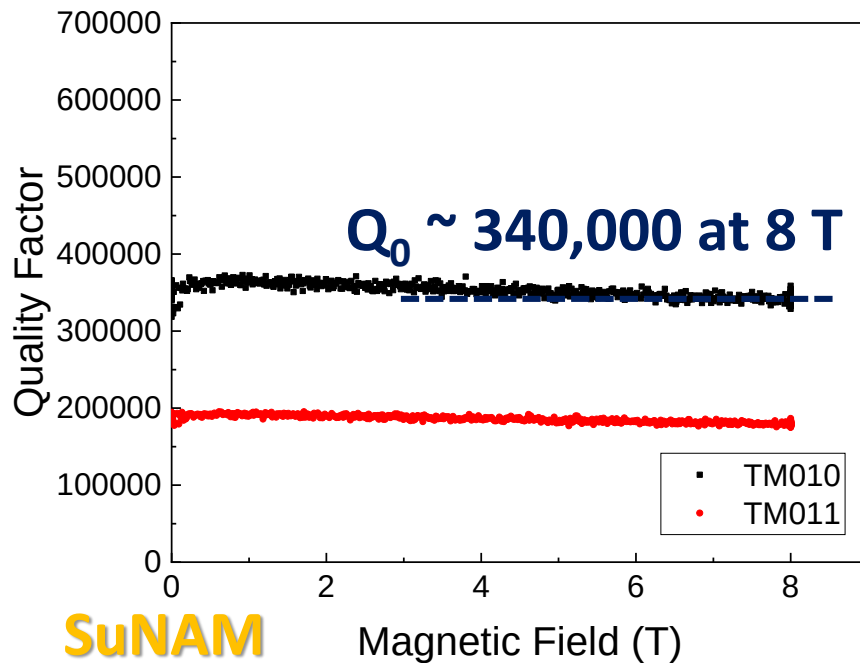
THEVA



2nd Generation Cavity for Axion Haloscope

➤ 2.3 GHz HTS Cavity

- ✓ (December 8th, 2019) $Q \sim 340,000$ at 8 T (SuNAM YBCO Tape, 1.5 L)
- ✓ (January 18th, 2020) $Q \sim 500,000$ at 8 T (THEVA GdBCO Tape, 1.5 L)



Finding Optimal ReBCO Tape

- Various tapes showed different performances.
- It is necessary to study surface resistance of different tapes.
 - AMSC, SuNAM (YBCO)
 - THEVA, Superpower (GdBCO)
 - Fujikura (EuBCO + Additional Pinning Center).

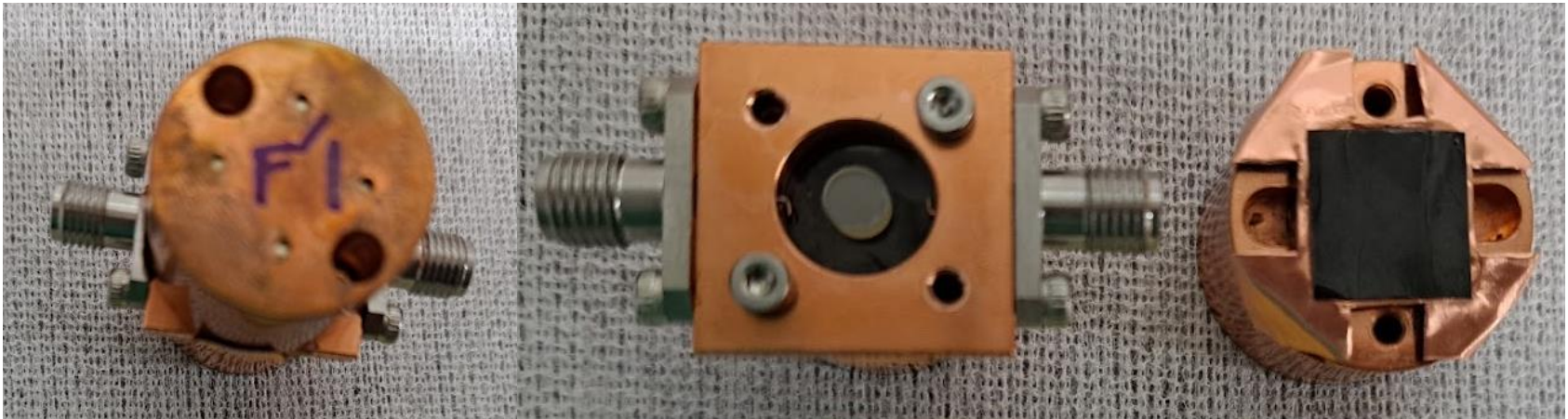
$$\frac{1}{Q} = \overset{\text{HTS Tape}}{\frac{R_{s,HTS}}{G_{HTS}}} + \overset{\text{Fabrication}}{\frac{R_{s,defect}}{G_{defect}}} + \overset{\text{RF Design}}{\frac{1}{Q_{gap}}}$$

Finding Optimal ReBCO Tape

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 - AMSC, SuNAM (YBCO)
 - THEVA, Superpower (GdBCO)
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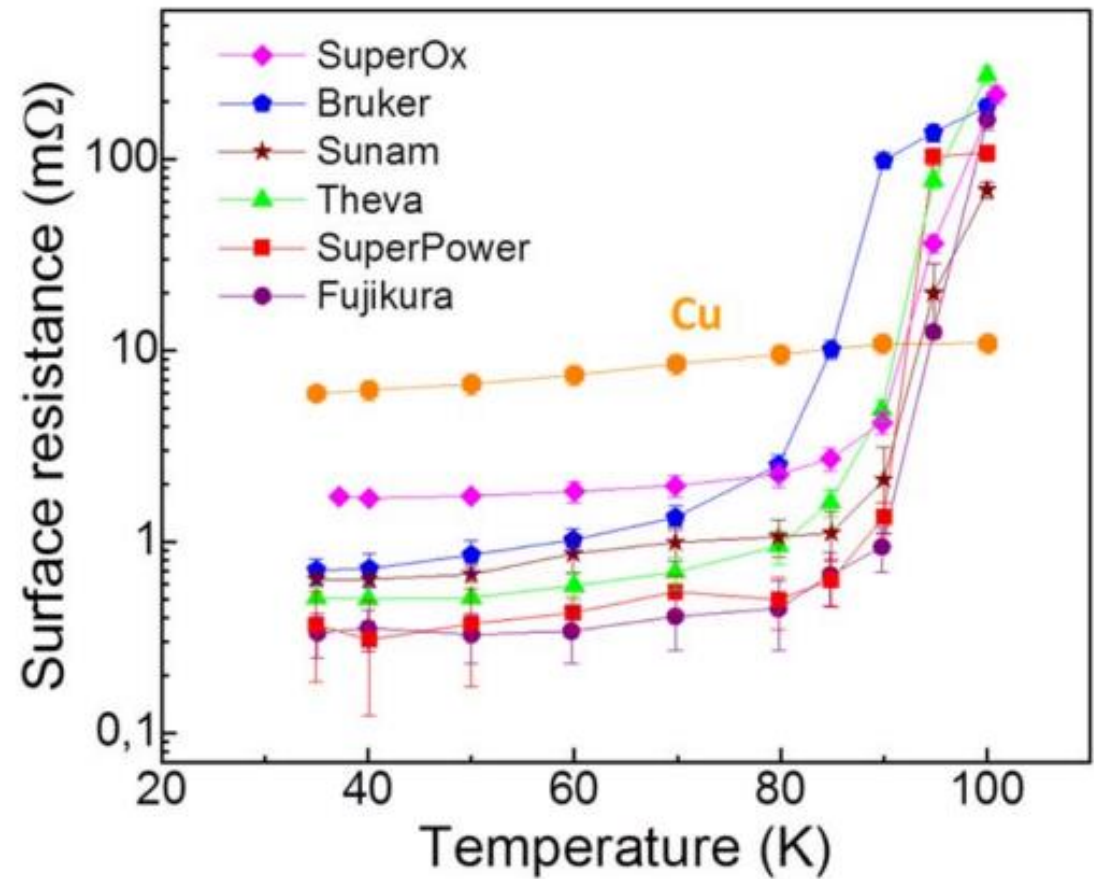
Hakki-Coleman Type Resonator using a Rutile Cylinder

$$\frac{1}{Q} = \frac{R_{s,i}}{104.8 \, \Omega} + \frac{1}{Q_{cu}} + \tan \delta$$



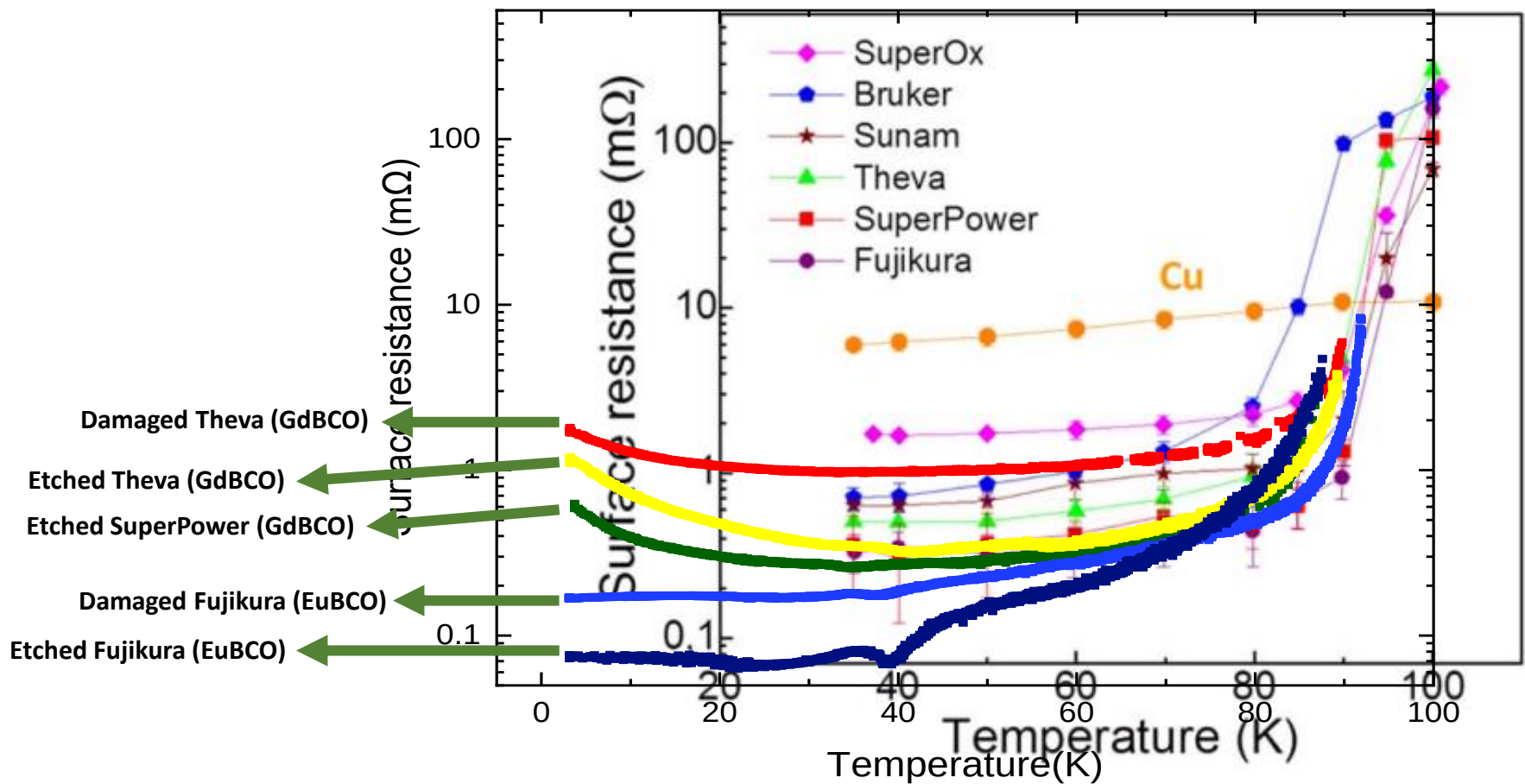
Temperature Study

T Puig et al 2019 Supercond. Sci. Technol. 32 094006

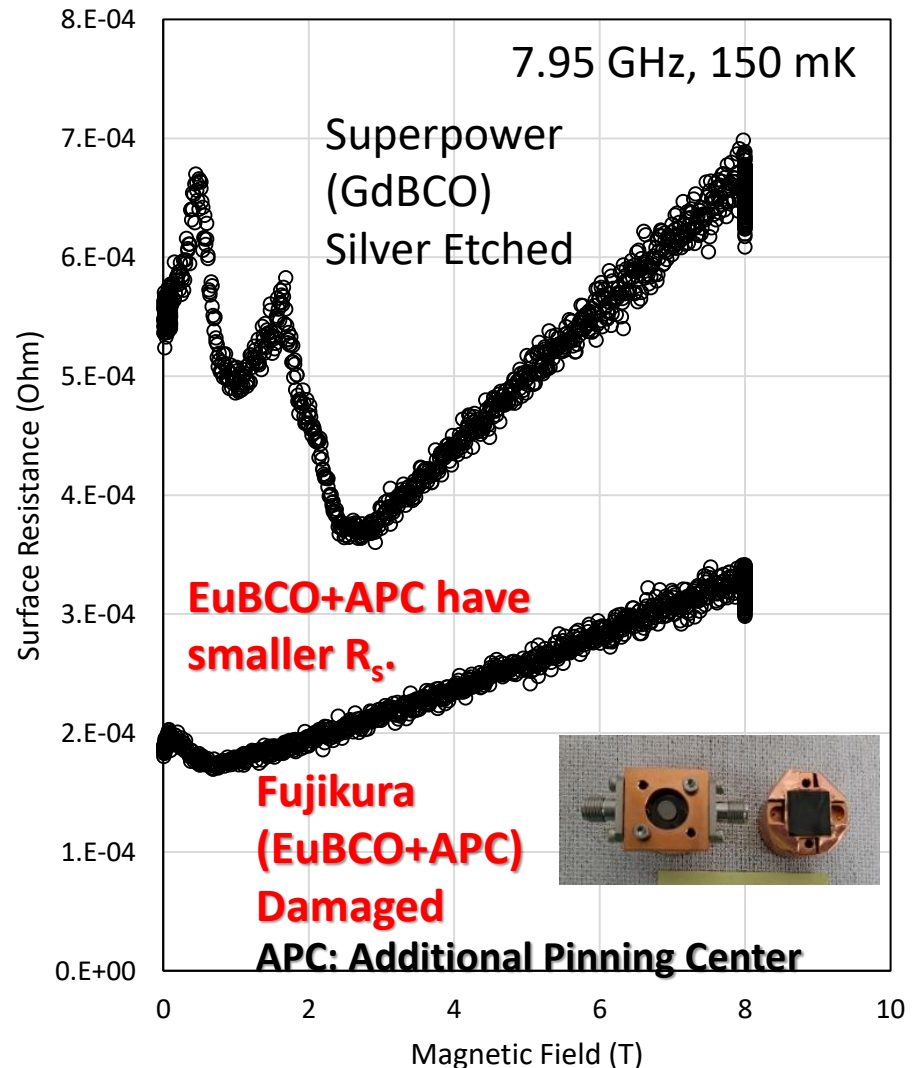
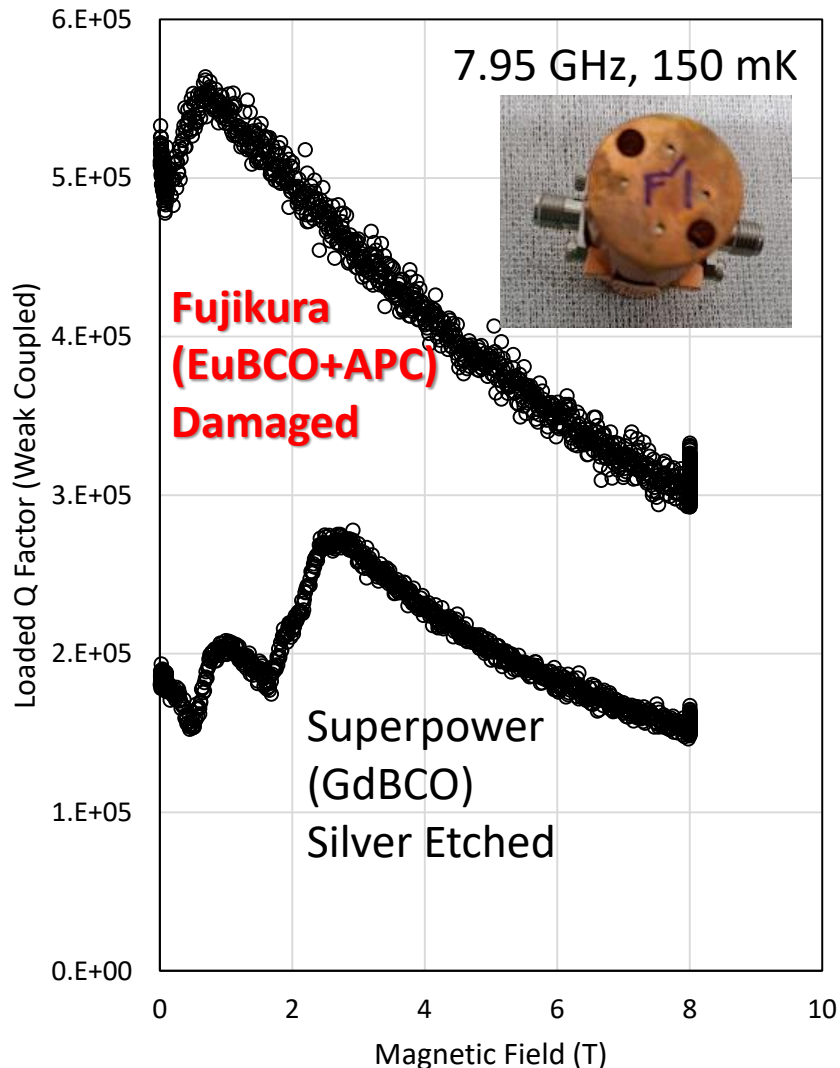


EuBCO Has the Lowest Surface Resistance

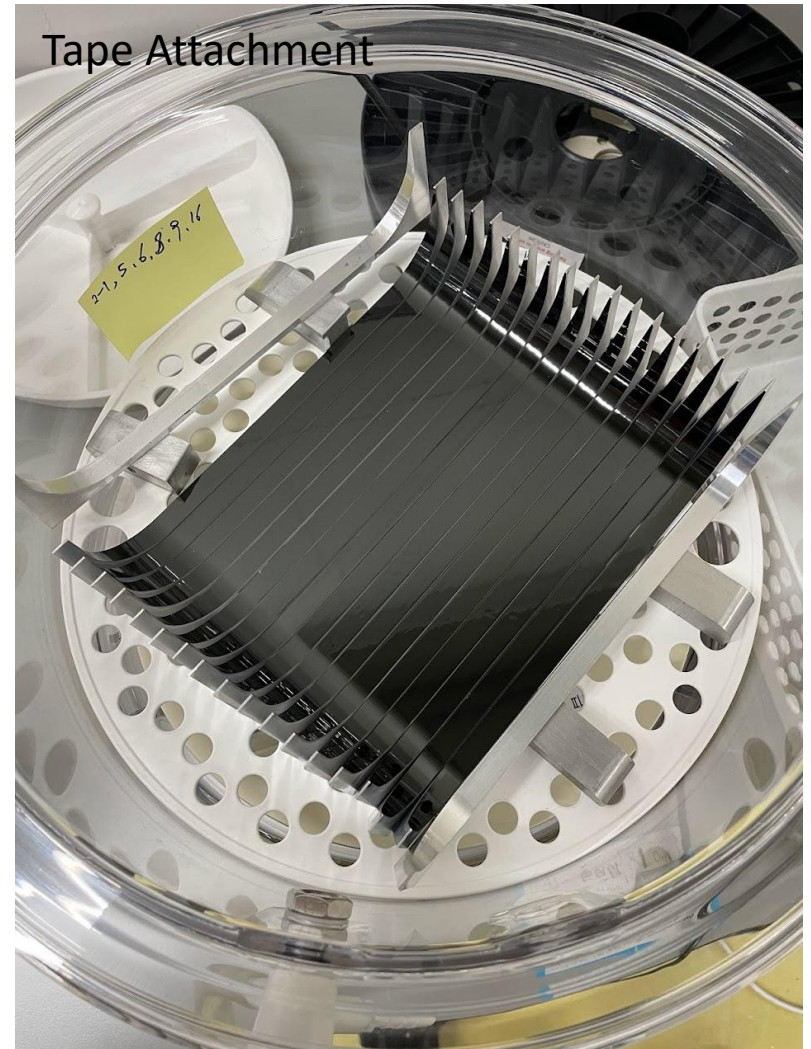
T Puig et al 2019 Supercond. Sci. Technol. 32 094006



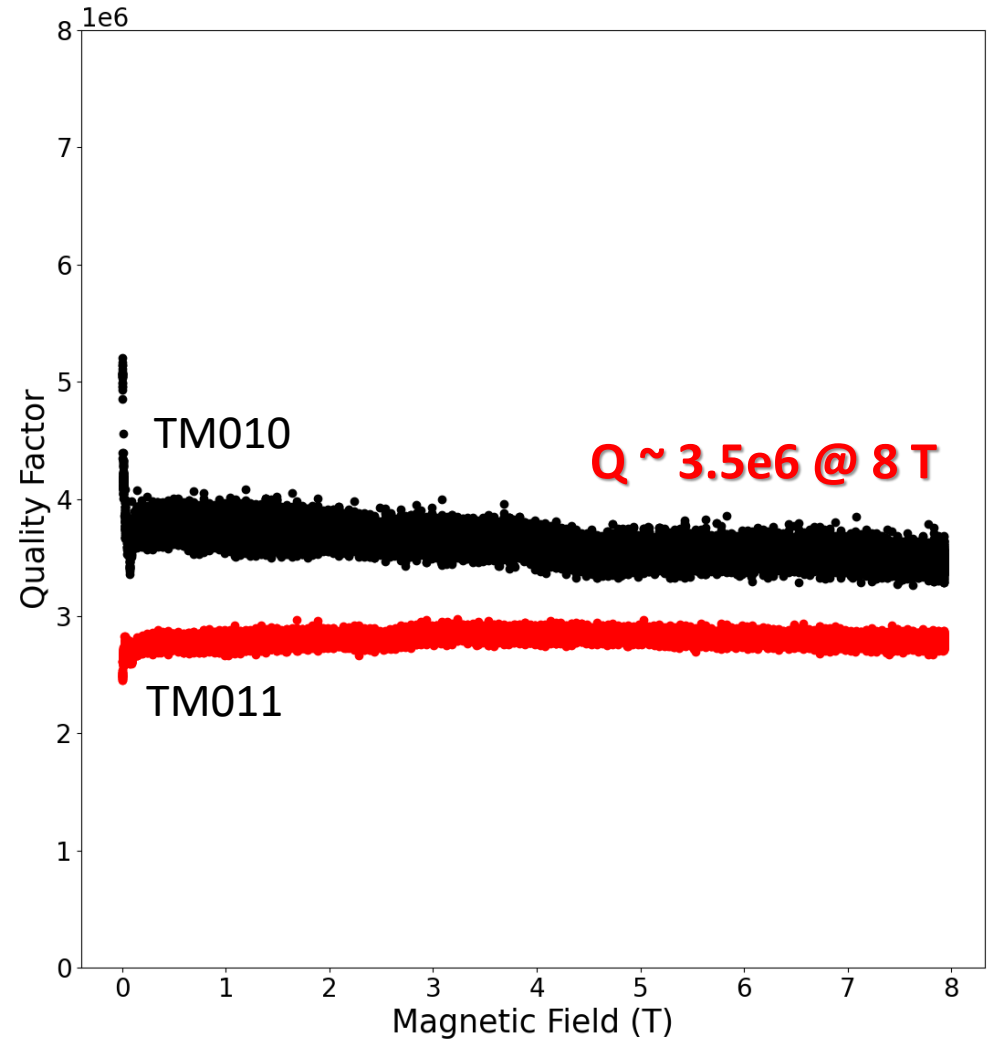
EuBCO Has the Lowest R_s in a Magnetic Field



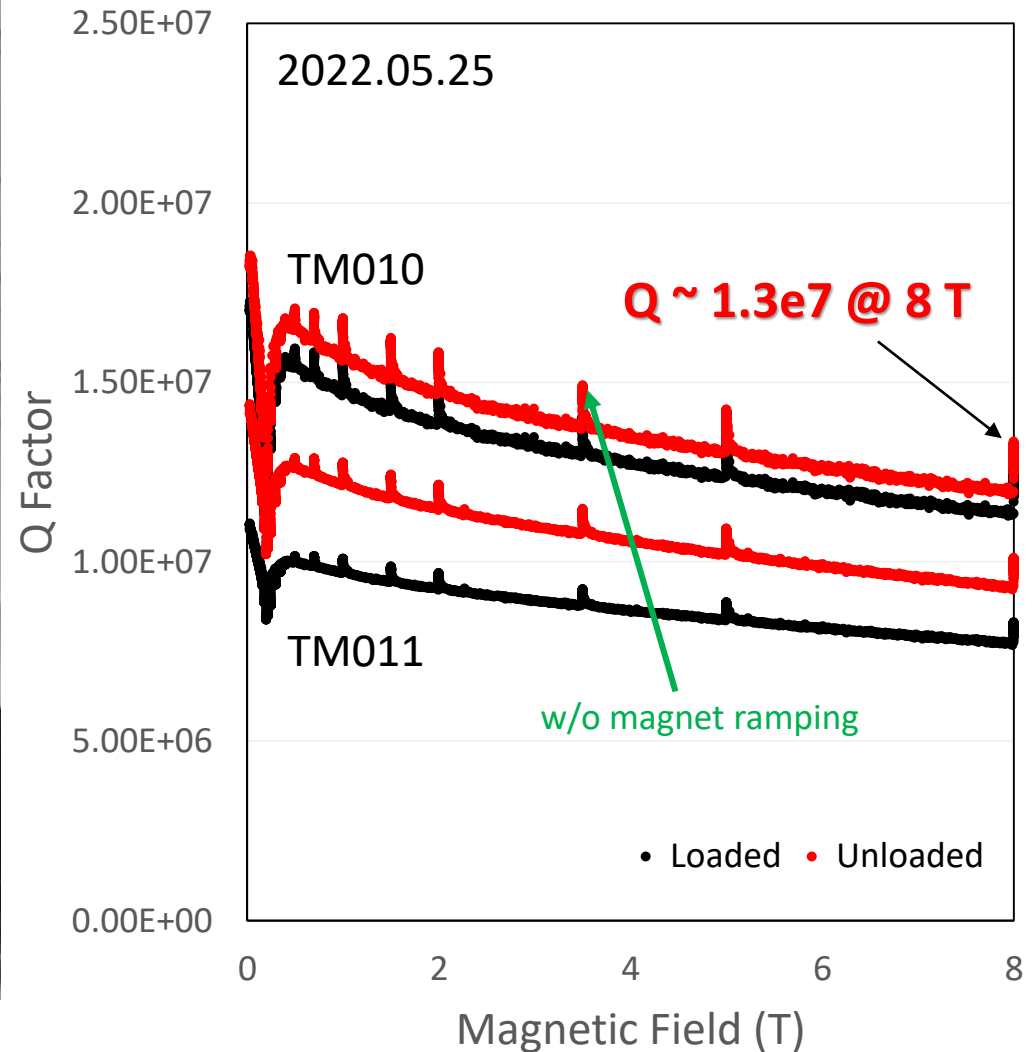
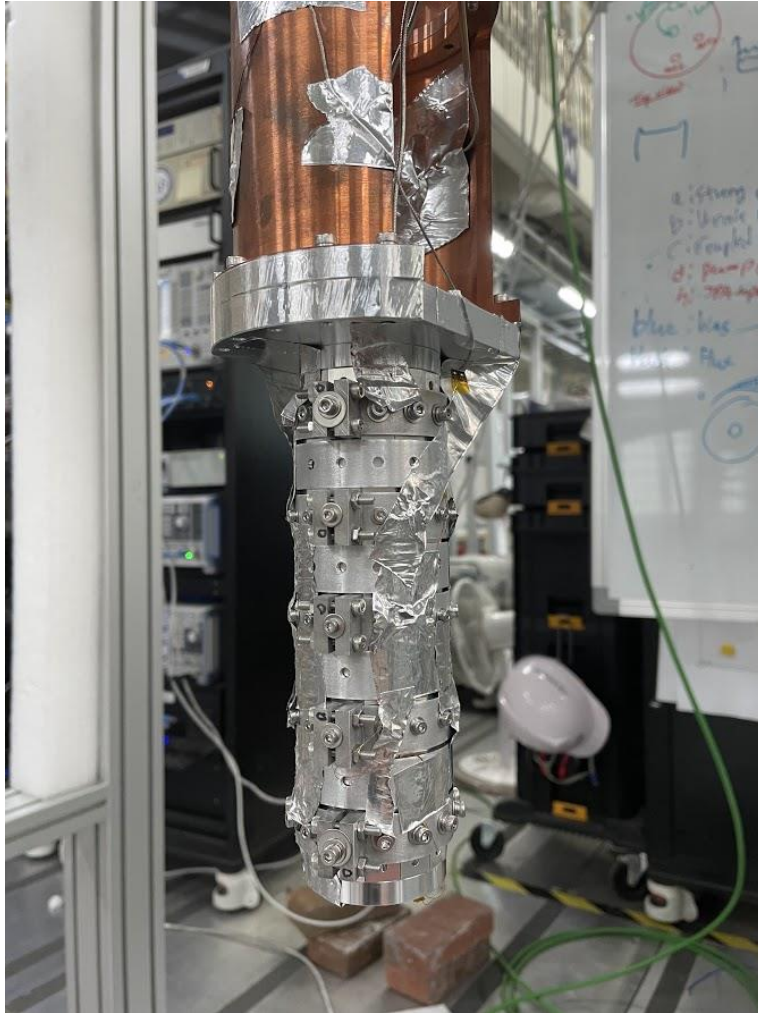
3rd Generation Cavity using EuBCO Tapes (1)



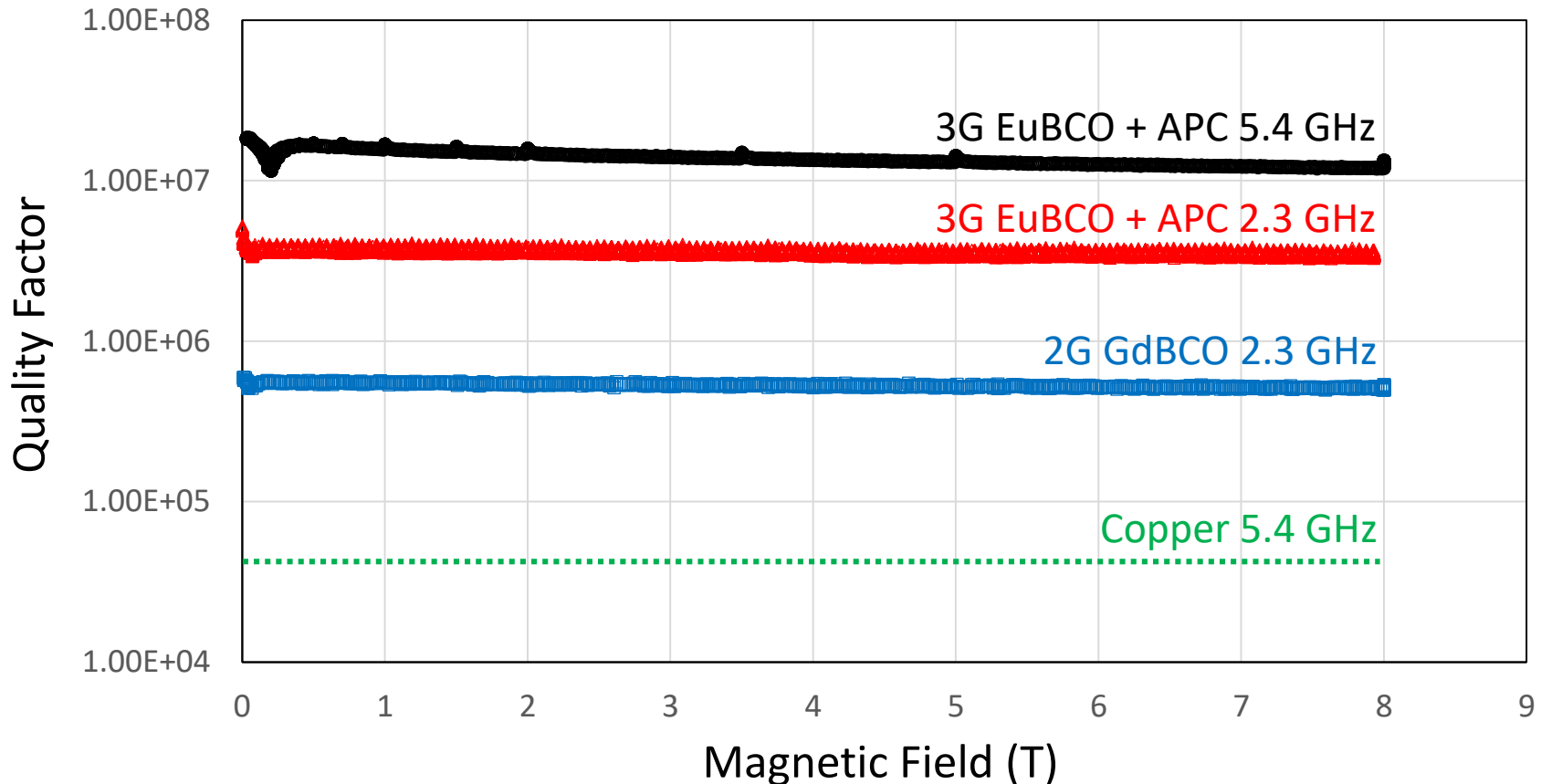
3rd Generation Cavity using EuBCO Tapes (1)



3rd Generation Cavity using EuBCO Tapes (2)



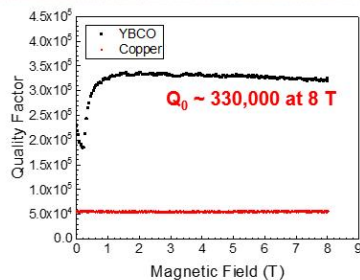
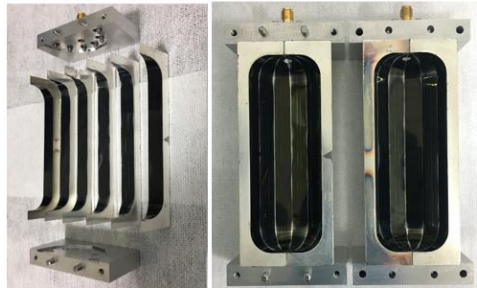
13 Million Quality Factor is Achieved



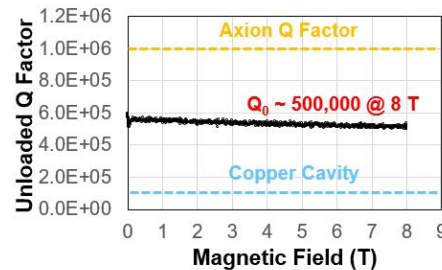
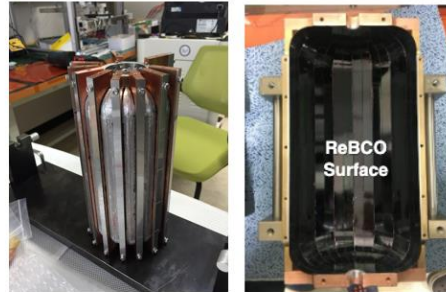
- 3rd Generation EuBCO cavity reached **two orders of magnitude bigger Q factor than copper** cavity.

Summary of HTS Cavity Development

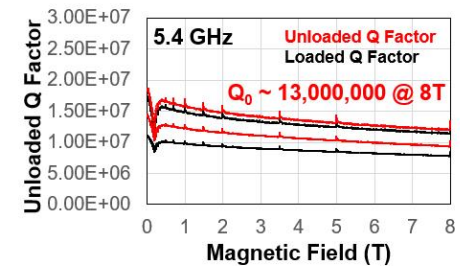
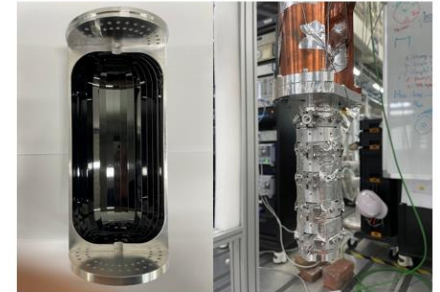
First Gen. (6.9 GHz)



Second Gen. (2.3 GHz)



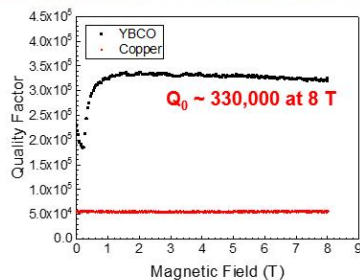
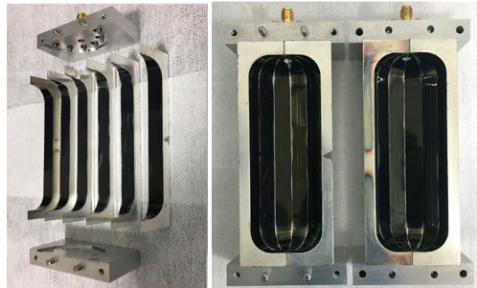
Third Gen. (2.2 GHz & 5.4 GHz)



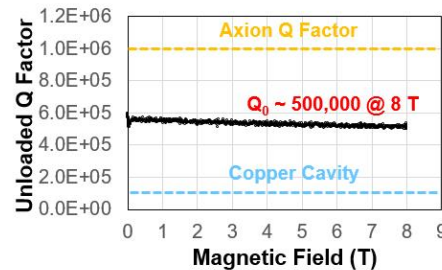
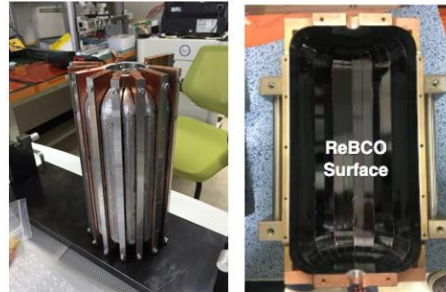
Generation	Material	Substrate	Volume [liters]	Frequency [GHz]	Q-factor
1 st Gen	YBCO	NiW	0.3	6.9	150,000 @ 8 T 330,000 @ 8 T
2 nd Gen	GdBCO	Hastelloy	1.5	2.3	500,000 @ 8 T
3 rd Gen	EuBCO + APC	Hastelloy	1.5	2.3	3,500,000 @ 8 T
	EuBCO + APC	Hastelloy	0.2	5.4	13,000,000 @ 8 T
4 th Gen	EuBCO + APC	Hastelloy	37	~ 1	?

Summary of HTS Cavity Development

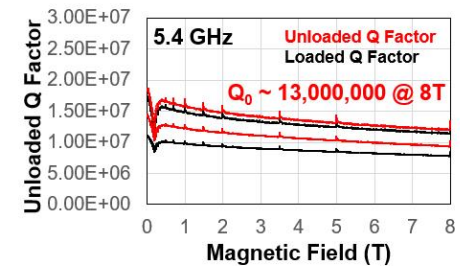
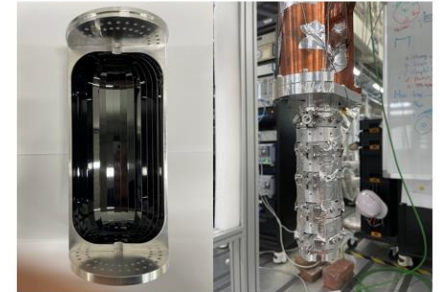
First Gen. (6.9 GHz)



Second Gen. (2.3 GHz)



Third Gen. (2.2 GHz & 5.4 GHz)

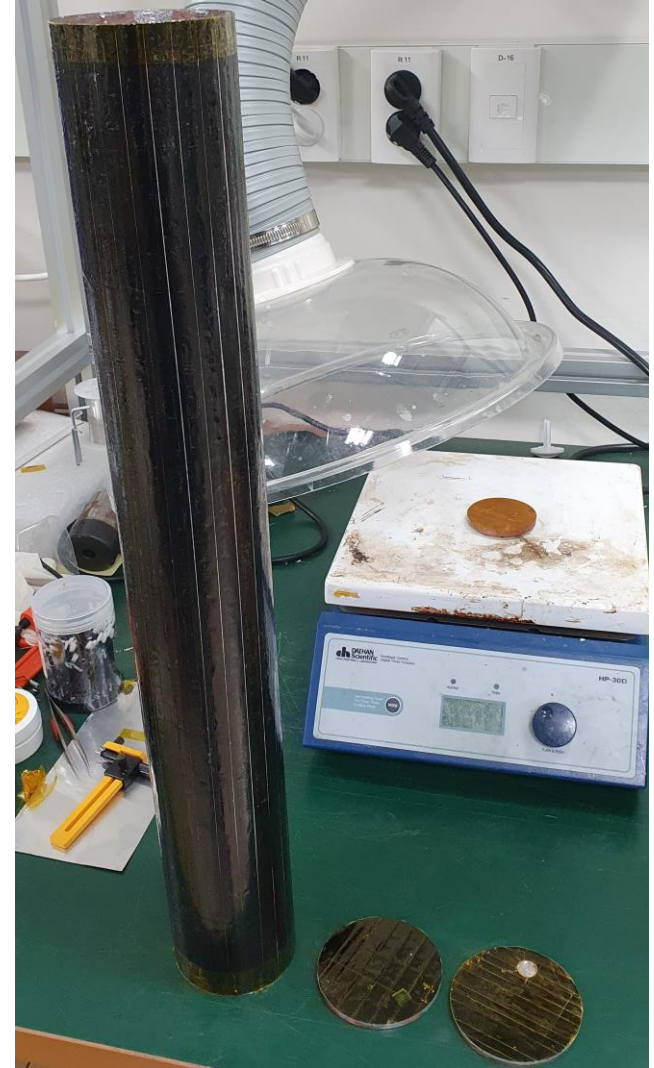


Generation	Material	Substrate	Volume [liters]	Frequency [GHz]	Q-factor
1 st Gen	YBCO	NiW	0.3	6.9	150,000 @ 8 T 330,000 @ 8 T
2 nd Gen	GdBCO	Hastelloy	1.5	Haloscope 2.3	500,000 @ 8 T
3 rd Gen	EuBCO + APC	Hastelloy	1.5	AQN 2.3	3,500,000 @ 8 T
	EuBCO + APC	Hastelloy	0.2	LHe Tuning 5.4	13,000,000 @ 8 T
4 th Gen	EuBCO + APC	Hastelloy	37	~ 1	CAPP-MAX ?

HTS Tuning Rod for CAPP-MAX Experiment



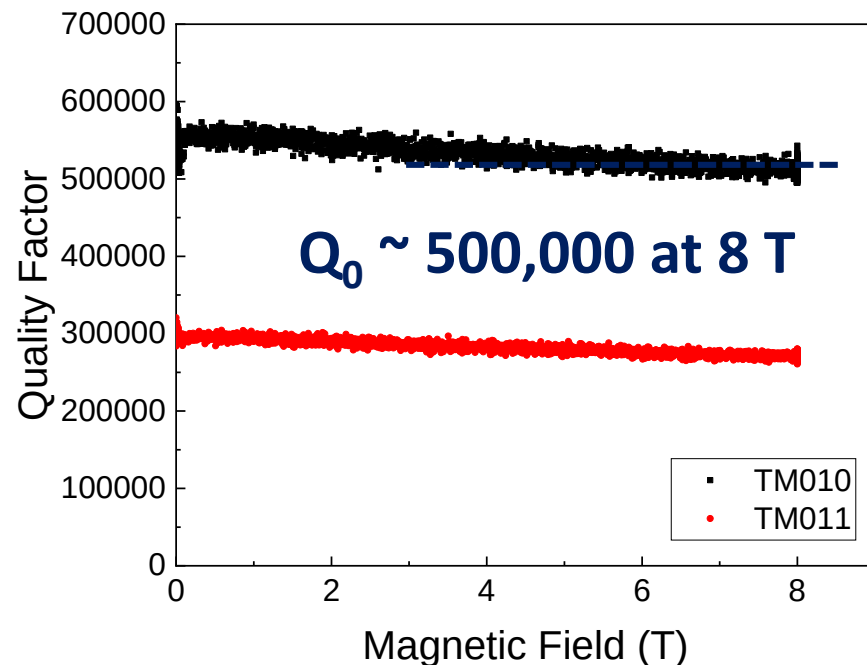
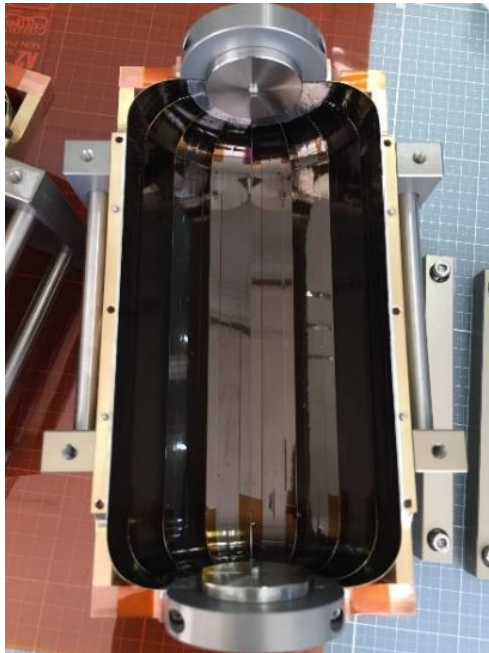
Stay Tuned!



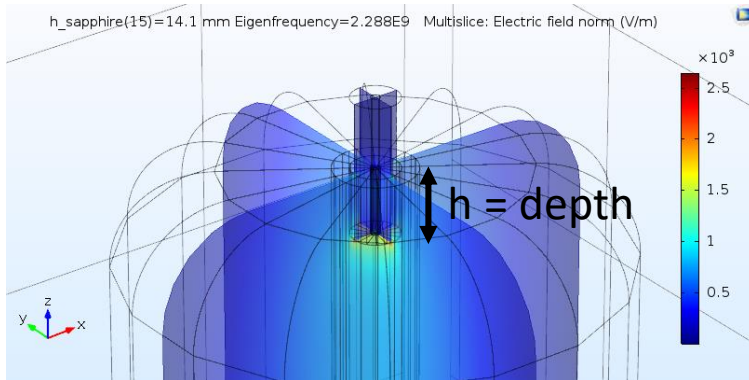
Axion Search with High-Temperature Superconducting Cavity

2nd Generation Cavity for Axion Haloscope

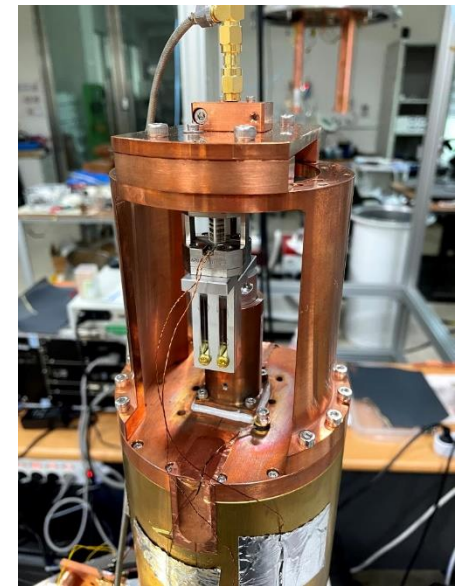
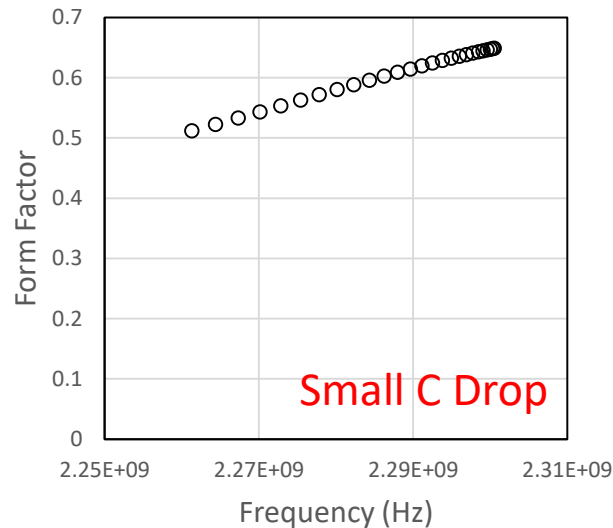
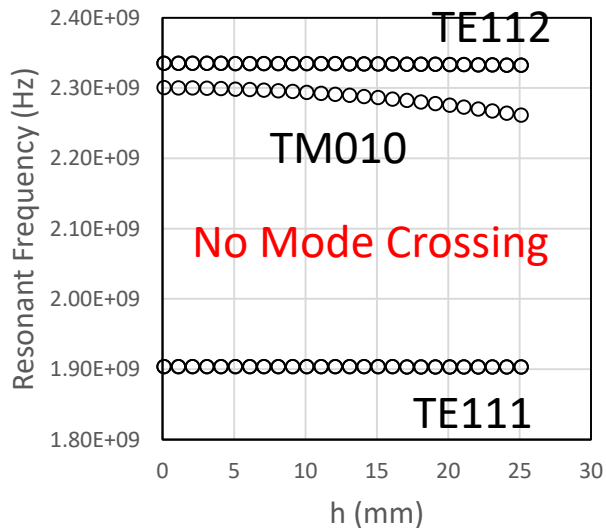
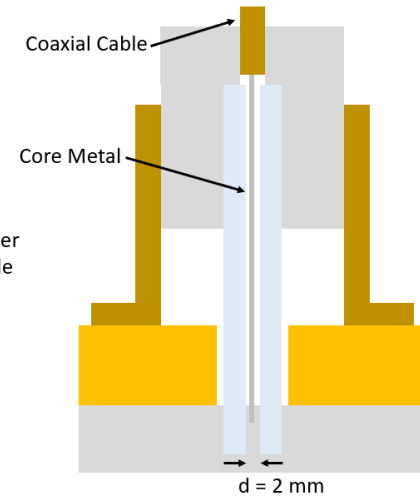
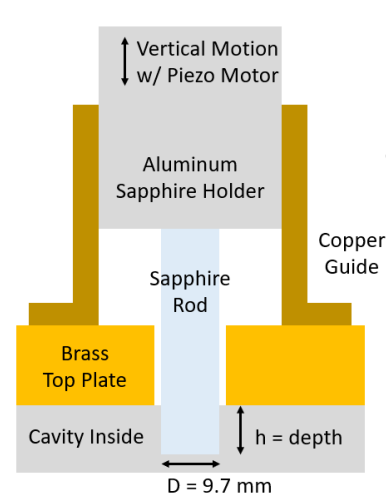
- 1.5 L large volume cavity was designed for the cavity haloscope experiment.
- 2.3 GHz resonant frequency was targeted for Josephson parametric amplifier with the same working frequency.



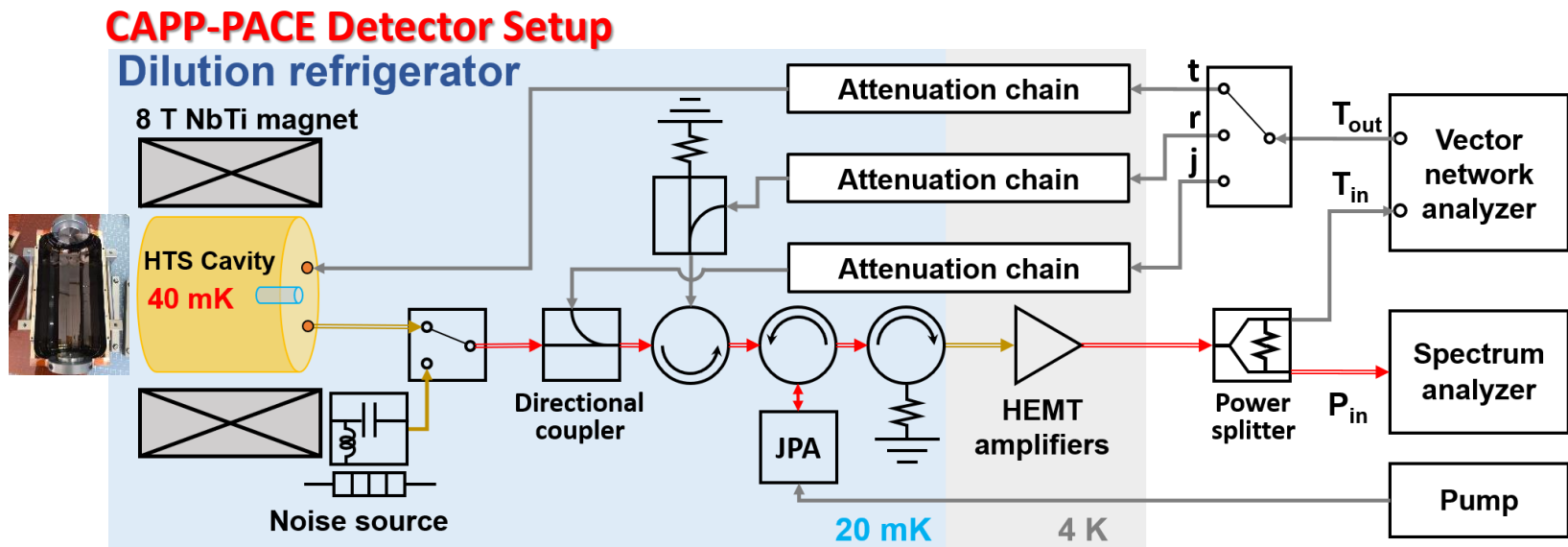
Tuning Mechanism



Tuning Simulation



Axion Search with Superconducting Cavity



➤ Total System Noise ($T_{sys} = T_{cav} + T_{add}$)

- Cavity noise temperature ($T_{cav} \approx 60\text{mK}$)

✓ $T_{cav} = \frac{h\nu}{k_B} \left(\frac{1}{e^{h\nu/k_B T_{phy}} - 1} + \frac{1}{2} \right)$, T_{phy} (cavity physical temperature $\sim 40\text{ mK}$)

- Added noise by the receiver chain ($T_{add} \approx 120\text{mK}$)

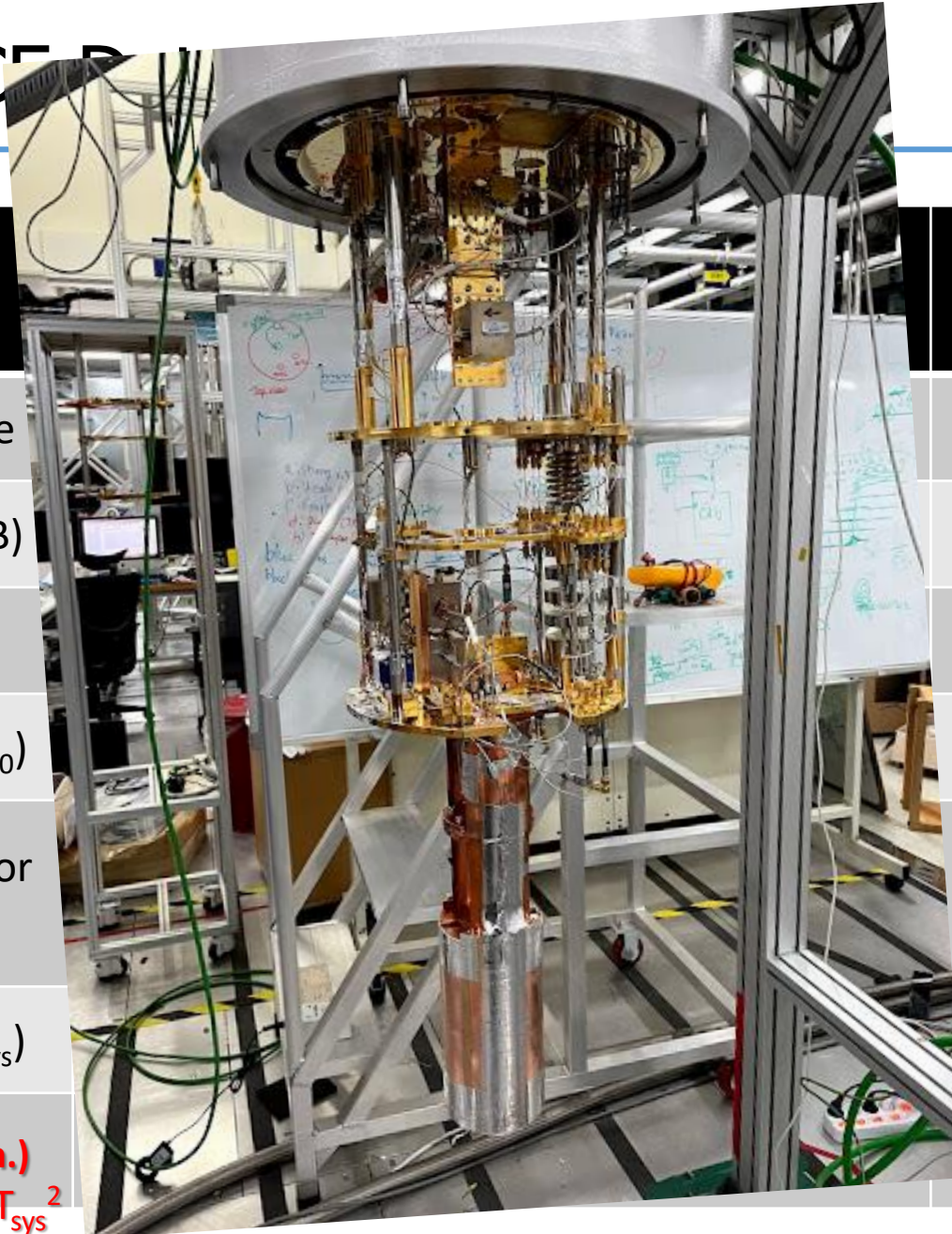
- Spectrum Analyzer Efficiency ($\eta \approx 0.7$)

$$\frac{df}{dt} = \eta \frac{4}{5} \frac{1}{SNR^2} \left(\frac{P_0}{k_B T_{sys}} \frac{\beta}{1 + \beta} \right)^2 \frac{Q_l Q_a^2}{Q_l + Q_a}$$

CAPP-PACE Detector

	HEMT Run Phys. Rev. Lett. 126 (2021)	JPA Run Phys. Rev. Lett. 130 (2023)	SC Run Analysis in process
Frequency Range	2.457 – 2.749 GHz	2.27 – 2.30 GHz	2.273 – 2.295 GHz
Magnetic Field (B)	7.2 T	7.2 T	6.95 T
Volume (V)	1.12 L	1.12 L	1.5 L
Quality Factor (Q_0)	100,000	100,000	500,000
Geometrical Factor (C)	0.51 – 0.66	0.45	0.51 – 0.65
System Noise (T_{sys})	~ 1.1 K	~ 200 mK	~ 180 mK
Scan Rate (Norm.) $\propto B^4 V^2 C^2 Q_0 / T_{\text{sys}}^2$	1	18	310

CAPP-PAC5



SC Run
Analysis in process

Frequency Range

2.273 – 2.295 GHz

Magnetic Field (B)

6.95 T

Volume (V)

1.5 L

Quality Factor (Q_0)

500,000

Geometrical Factor
(C)

0.51 – 0.65

System Noise (T_{sys})

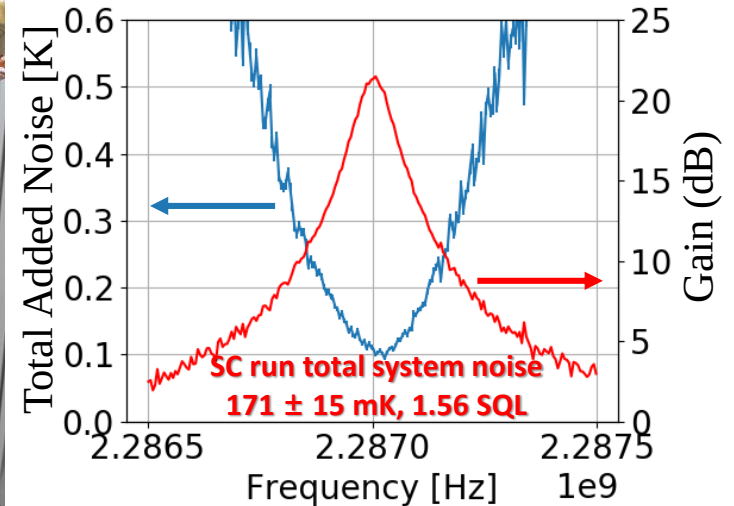
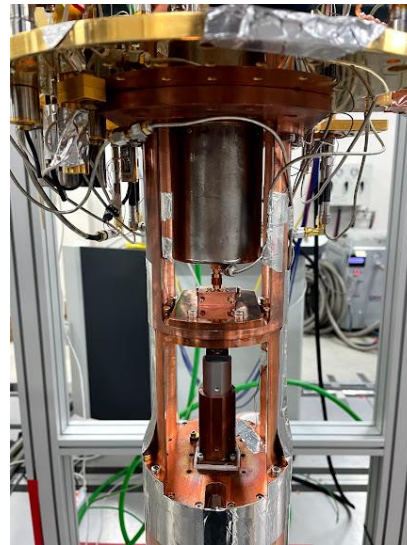
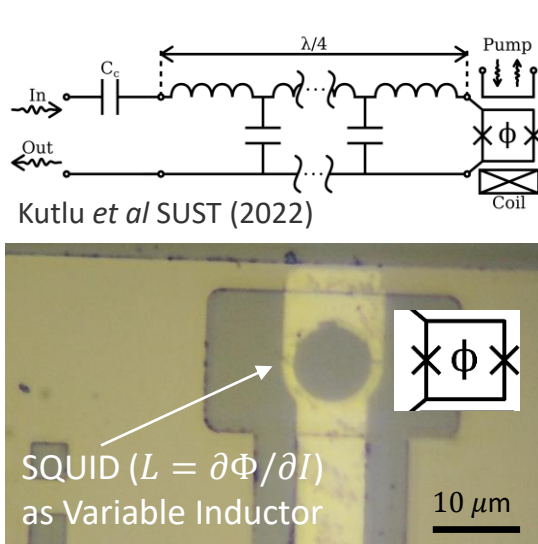
~ 180 mK

Scan Rate (Norm.)

310

$$\propto B^4 V^2 C^2 Q_0 / T_{\text{sys}}^2$$

Josephson Parametric Amplifier (JPA)



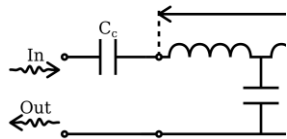
- JPA is Josephson junction based quantum-noise-limited amplifier
- CAPP Flux-driven JPA was developed in collaboration with Nakamura group at Univ. of Tokyo and RIKEN
- Operation range: 2.27 GHz – 2.30 GHz
- JPA was protected by two layer superconducting shield
- Total system noise temperature

$$T_{\text{sys}} = T_{\text{cav}} + T_{\text{add}}$$

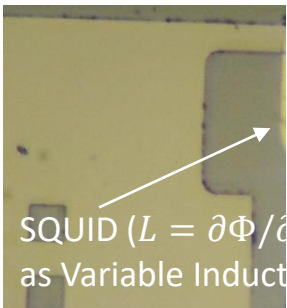
Noise from cavity
Total system noise
Chain added noise

$$T_{\text{cav}} = \frac{h\nu}{k_B} \left(\frac{1}{e^{h\nu/k_B T_{\text{phy}}} - 1} + \frac{1}{2} \right)$$

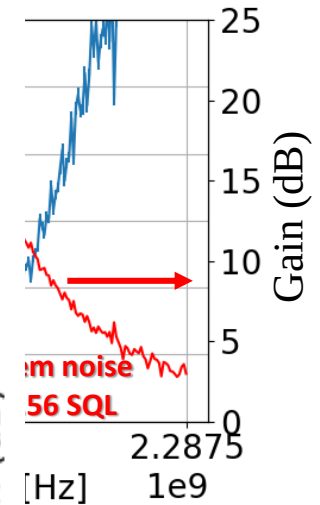
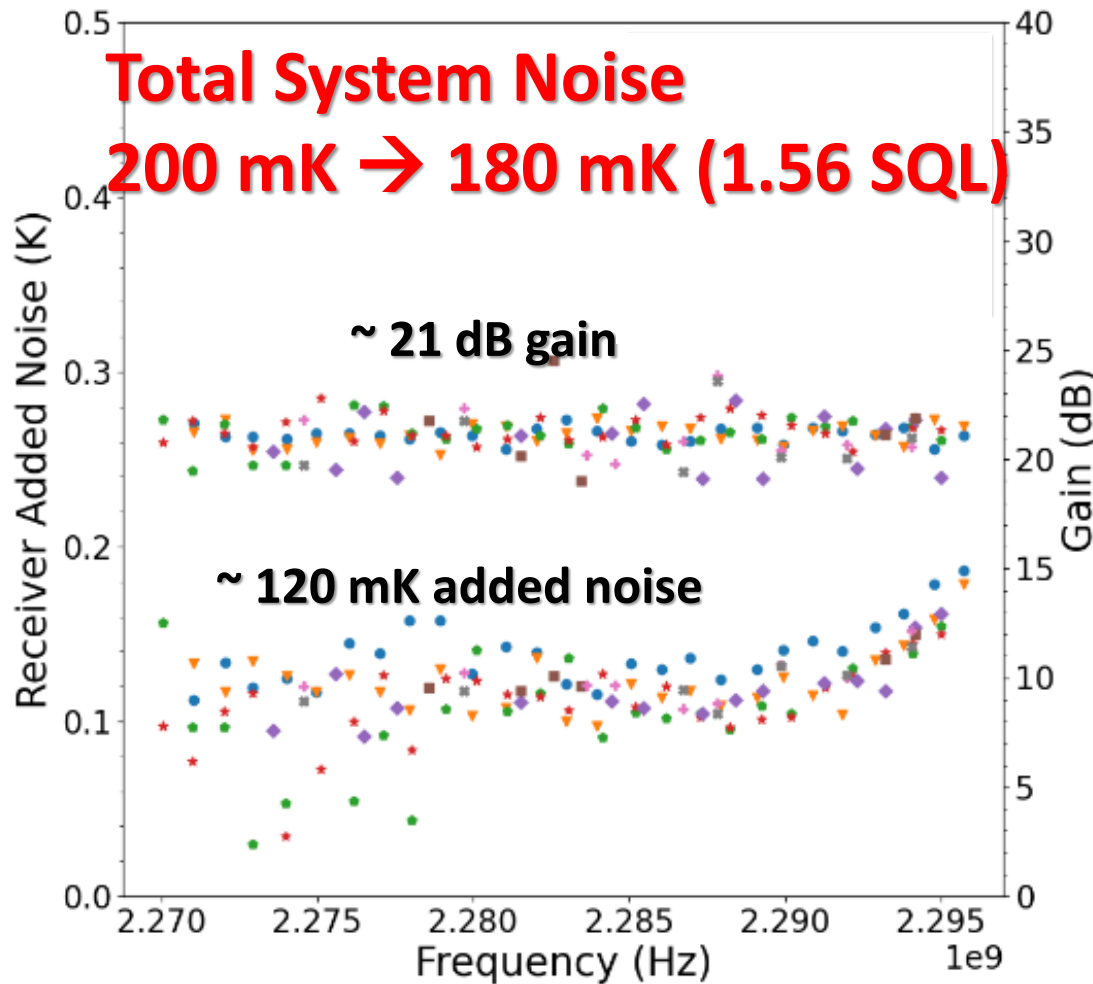
Josephson Parametric Amplifier (JPA)



Kutlu et al SUST (202



- JPA is Josephson
- CAPP Flux-coupled
- Operation range
- JPA was pre-
- Total system



kyo and RIKEN

Total system noise

Chain added noise

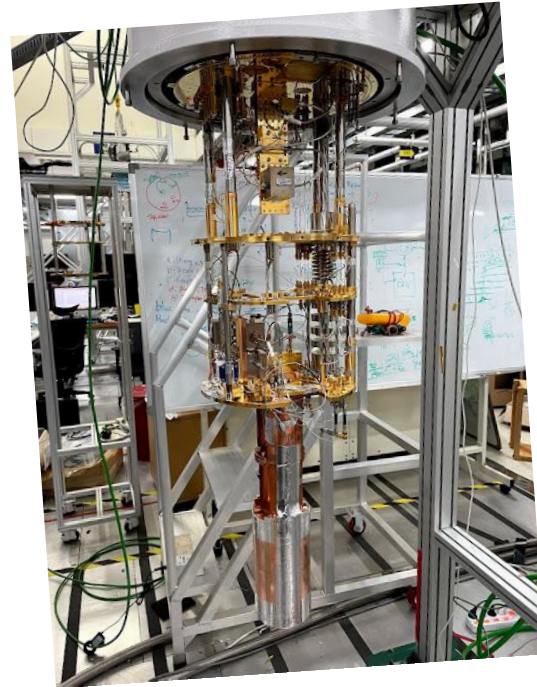
Superconducting Cavity Run Operation

- Target scan rate for $g_\gamma = 0.99 \times g_\gamma^{KSVZ}$ axion

B_0	V	C	Q_0	β	SNR	η	T_{tot}
6.95 T	1.5 L	~ 0.6	500,000	~ 1.75	5	0.7	~ 180 mK

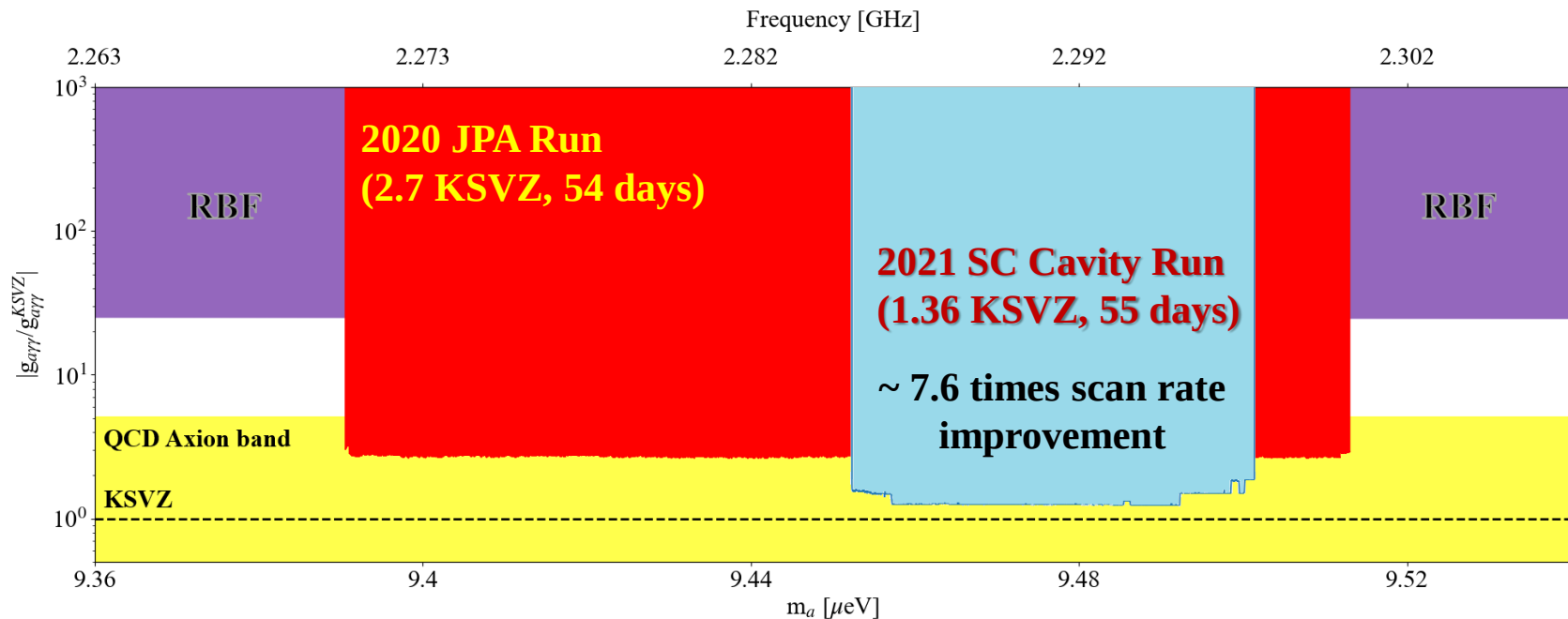
~ 0.6 MHz / day

- For 2.282 – 2.295 GHz (13 MHz)
- 1st phase (2.284 – 2.295 GHz)
- Oct 7 ~ Oct 16, 2021
 - 2nd phase (2.284 – 2.295 GHz)
- Oct 26 ~ Nov 4, 2021
 - 3rd phase (2.282 – 2.292 GHz)
- Jul 20 ~ Aug 24, 2022



Total $\sim 7,500$ spectra

Expected Exclusion Plot



	JPA Run	SC Run
Frequency Range	2.27 – 2.30 GHz	2.273 – 2.295 GHz
Magnetic Field (B)	7.2 T	6.95 T
Volume (V)	1.12 L	1.5 L
Quality Factor (Q_0)	100,000	500,000
Geometrical Factor (C)	0.45	0.51 – 0.65
System Noise (T_{sys})	~ 200 mK	~ 180 mK
SNR Efficiency	85 %	57 %
Scan Rate (Norm.)	1	7.6

Summary

- Superconducting RF technology can enhance the scan rate of axion haloscope.
- ReBCO is one of the most promising superconductors for realizing a high Q cavity in a high magnetic field.
- CAPP have achieved 13 million Q factor high-temperature superconducting (HTS) cavity working at 8 T magnetic field.
- CAPP have a plan to construct 36 liter HTS cavity for CAPP-MAX experiment.
- Physics data from the half-million Q factor 2.3 GHz GdBCO cavity was successfully taken.

Axion Cold Dark Matter

➤ Axion is a cold dark matter candidate.

- Axion cosmology suggests the misalignment production mechanism.

- Small mass invisible axions can be a cold dark matter. Marsh, Phys. Rep. 643 (2016).
Pre-inflationary: $10^{-6} < m_a < 10^{-2} \text{ eV}$
Post-inflationary: $10^{-5} \text{ eV} < m_a$

➤ Axion is considered virialized classical particles in a galactic scale.

- Axion follows Maxwell-Boltzmann distribution Turner, PRD 42 (1990).

➤ Axion is wave-like in a laboratory scale. $m_a = 10 \mu\text{eV}$, $\rho_{DM} \approx 0.45 \text{ GeV/cm}^3$

$$\lambda_a = \frac{2\pi}{m_a v_{\text{vir}}} \approx 140 \text{ m}, N_a = n_a \lambda_a^3 \approx 10^{26}, \tau_a = \frac{\lambda_a}{v_{\text{vir}}} \approx 400 \mu\text{s}$$

➤ Axion can emit electromagnetic wave

$$\mathcal{L}_{a-\gamma} = \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + g_{a\gamma\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$(\partial_t^2 - \nabla^2 + m_a^2)a = -g_{a\gamma\gamma}\mathbf{E} \cdot \mathbf{B} \quad g_{a\gamma\gamma}a\mathbf{E} \cdot \mathbf{B}$$

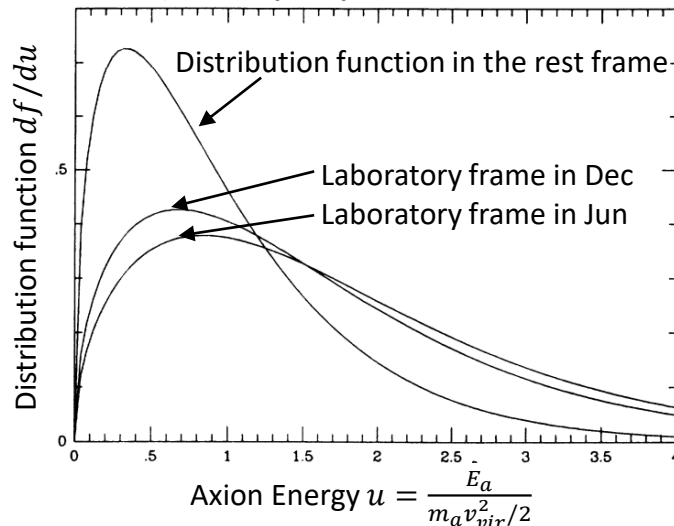
$$\nabla \cdot (\mathbf{E} - cg_{a\gamma\gamma}\mathbf{B}a) = \rho_e/\epsilon$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\partial_t \mathbf{B}$$

$$\nabla \times (c\mathbf{B} + g_{a\gamma\gamma}\mathbf{E}a) = \partial_t (\mathbf{E} - cg_{a\gamma\gamma}\mathbf{B}a) + c\mu\mathbf{J}_e$$

Turner, PRD 42 (1990).



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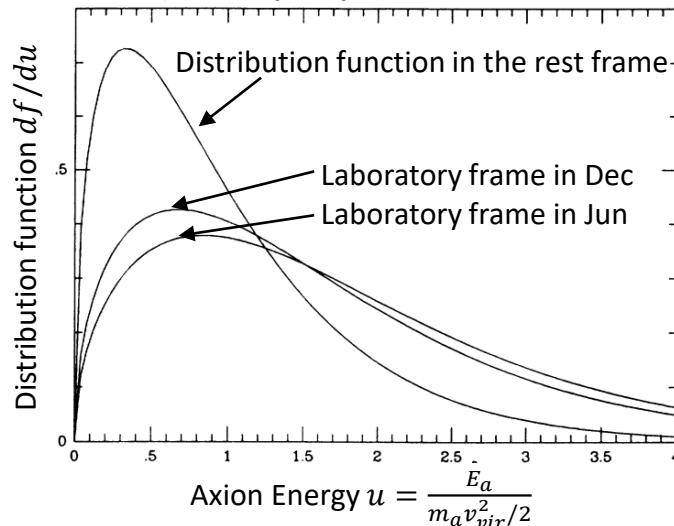
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$$\lambda_a = \frac{2\pi}{m_a v_{vir}} \approx 140 \text{ m}, N_a = n_a \lambda_a^3 \approx 10^{26}, \tau_a = \frac{\lambda_a}{v_{vir}} \approx 400 \mu\text{s}$$

➤ Axion can emit electromagnetic wave

$$\mathcal{L}_{a-\gamma} = \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + g_{a\gamma\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$(\partial_t^2 - \nabla^2 + m_a^2)a = -g_{a\gamma\gamma}\mathbf{E} \cdot \mathbf{B}$$

$$g_{a\gamma\gamma}a\mathbf{E} \cdot \mathbf{B}$$

$$\nabla \cdot (\mathbf{E} - cg_{a\gamma\gamma}\mathbf{B}a) = \rho_e/\epsilon$$

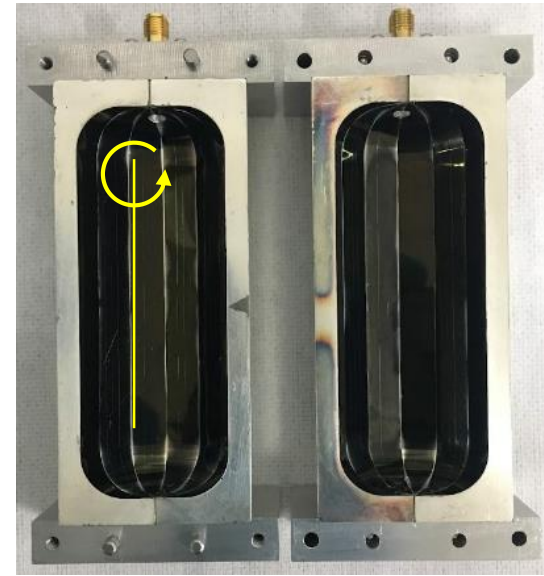
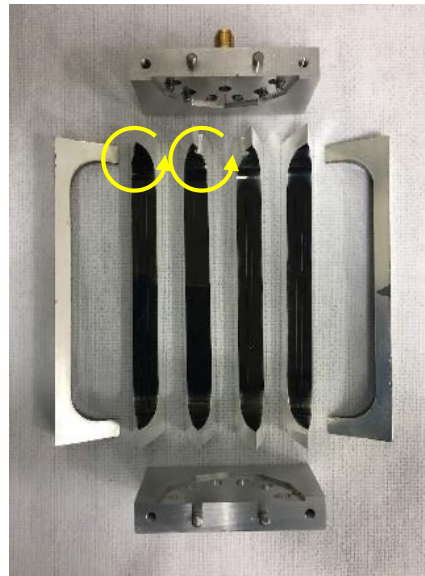
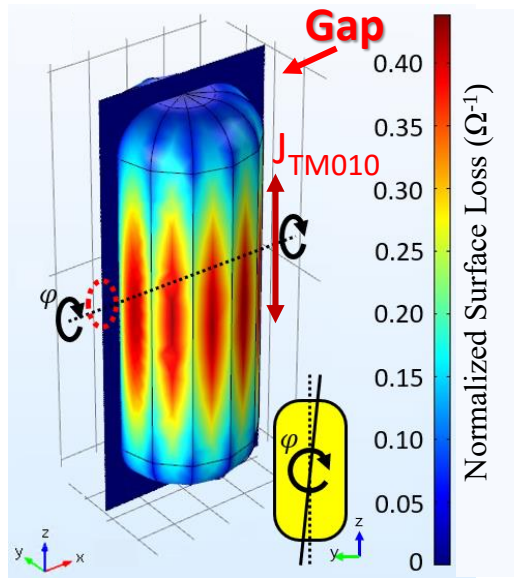
$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\partial_t \mathbf{B}$$

$$\nabla \times (c\mathbf{B} + g_{a\gamma\gamma}\mathbf{E}a) = \partial_t (\mathbf{E} - cg_{a\gamma\gamma}\mathbf{B}a) + c\mu\mathbf{J}_e$$

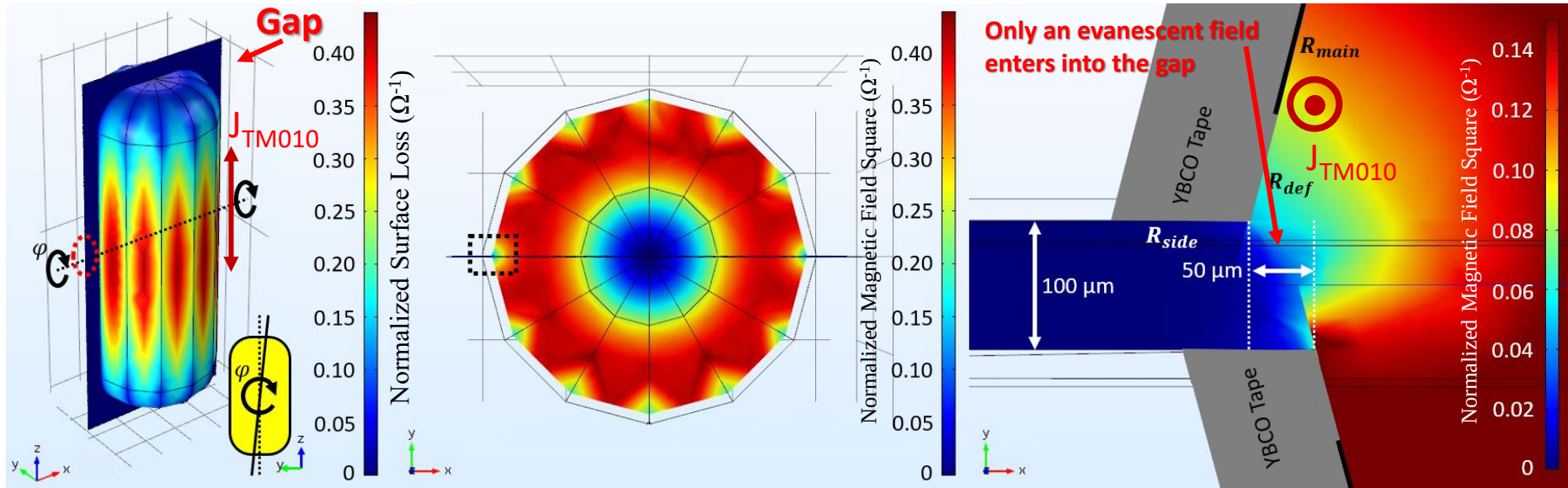
Coherent Detection?

Polygonal Cavity Simulation with Gaps



- Gap geometry is realized in the simulation.
- Misalignments and defects are considered based on fabrication error.
 - Gap geometry: Gap tilting, Step between superconducting main surfaces
 - Surface Condition: Metal on the gap sides (R_{side} Ag), Defects on the main surface (R_{defr} Ni-9W).
- Surface current direction is parallel to the in-plane direction of gaps.
- Only evanescent field enter into a gap.

Q_{TM010} Maintains 10^7 with N Gaps

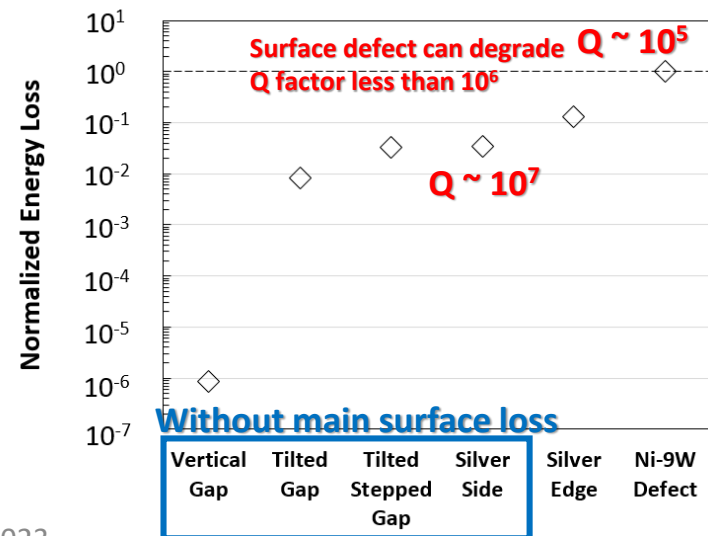
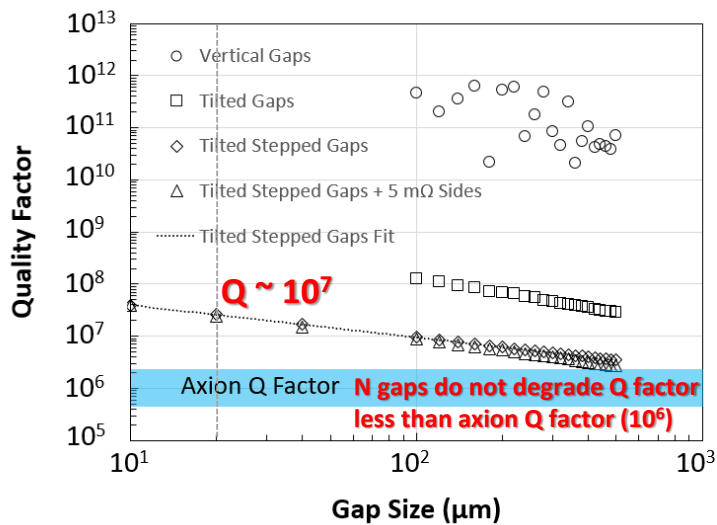
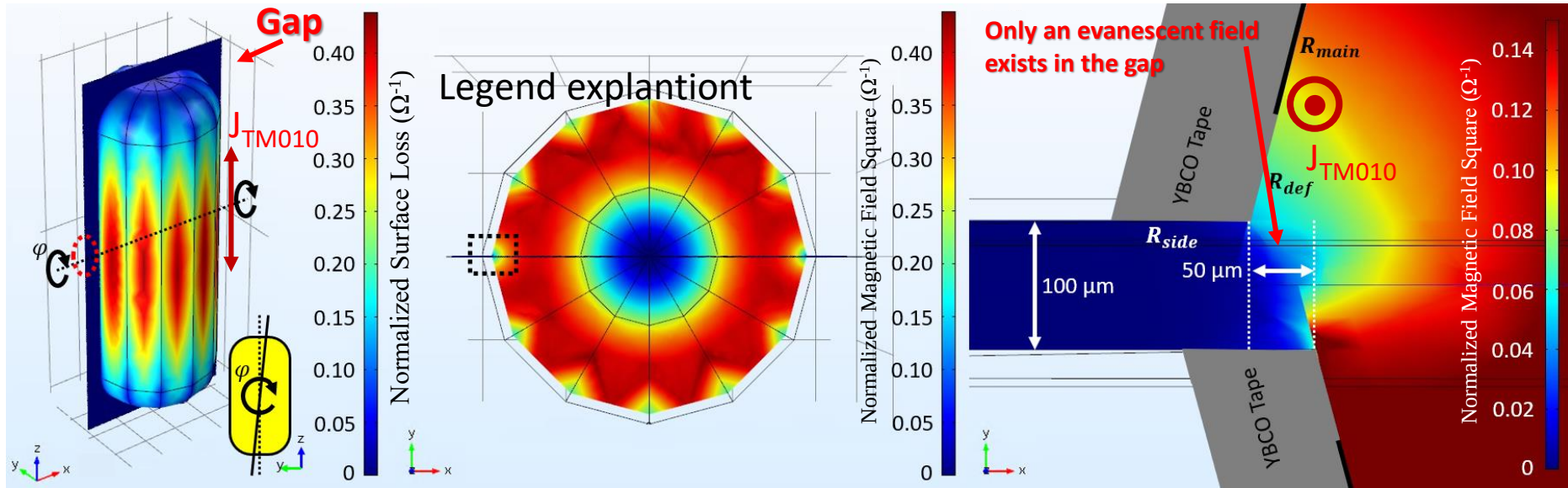


N gaps do not degrade Q factor less than axion Q factor (10^6)

Condition	R_{side} (mΩ)	R_{def} (mΩ)	Q
VGs	0	0	$\sim 10^{12}$
TGs	0	0	$\sim 10^8$
TSGs	0	0	3×10^7
TSGs + Silver Side	Ag (5 mΩ)	0	2×10^7
TSGs + Silver Side + Silver Edge	Ag (5 mΩ)	1 % Ag (5 mΩ)	5×10^6
TSGs + Silver Side + Silver Edge + Ni-9W Defect	Ag (5 mΩ)	1 - 5 % Ni-9W (50 mΩ)	$\sim 10^5$

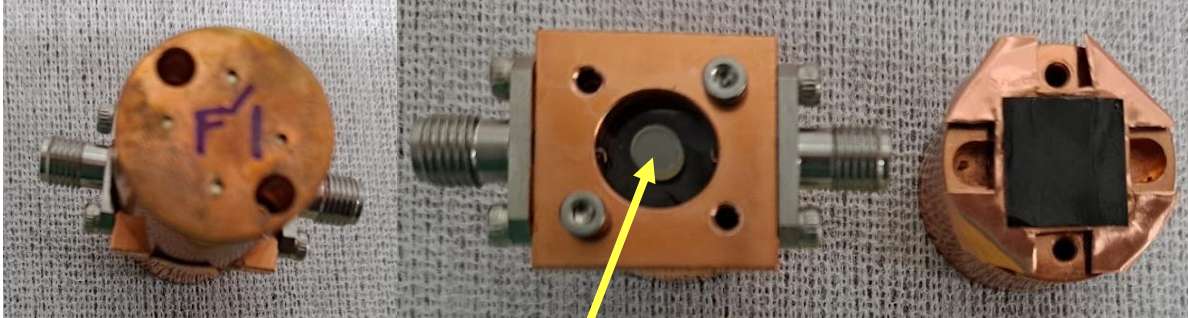
TABLE I: Quality factor results in various conditions. The Q factor values are the estimations for a case of $20 \mu\text{m}$ gaps. The first three conditions are vertical gaps (VG), tilted gaps (TG), and tilted stepped gaps (TSG).

N Gaps Do Not Degrade Q_{TM010}



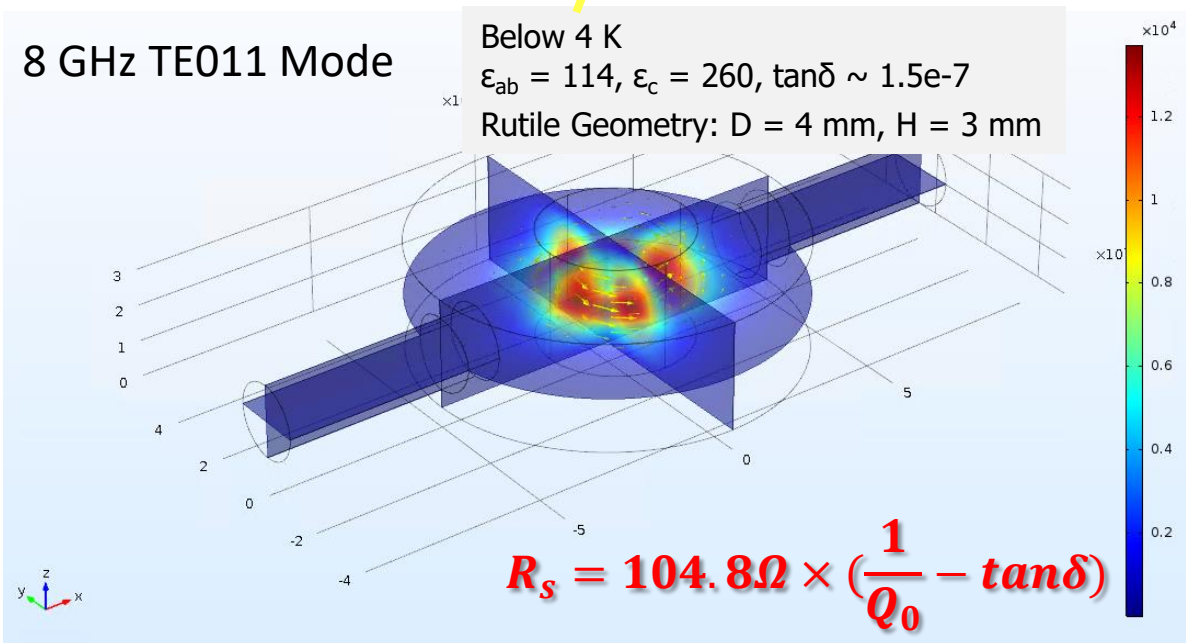
Surface Resistance Measurement

Hakki-Coleman Type Resonator using a Rutile Cylinder

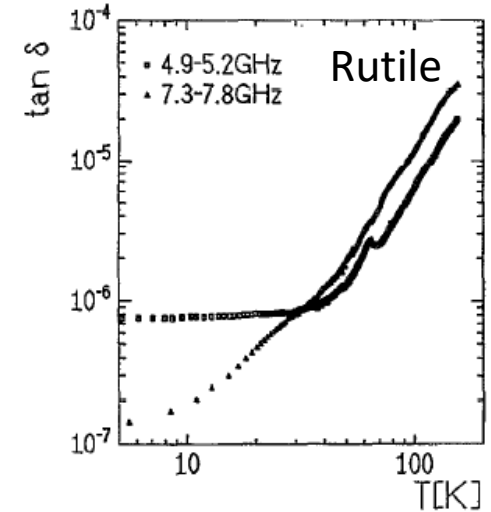


8 GHz TE₀₁₁ Mode

Below 4 K
 $\epsilon_{ab} = 114$, $\epsilon_c = 260$, $\tan\delta \sim 1.5e-7$
 Rutile Geometry: D = 4 mm, H = 3 mm



Journal of Applied Physics 78, 6683 (1995)



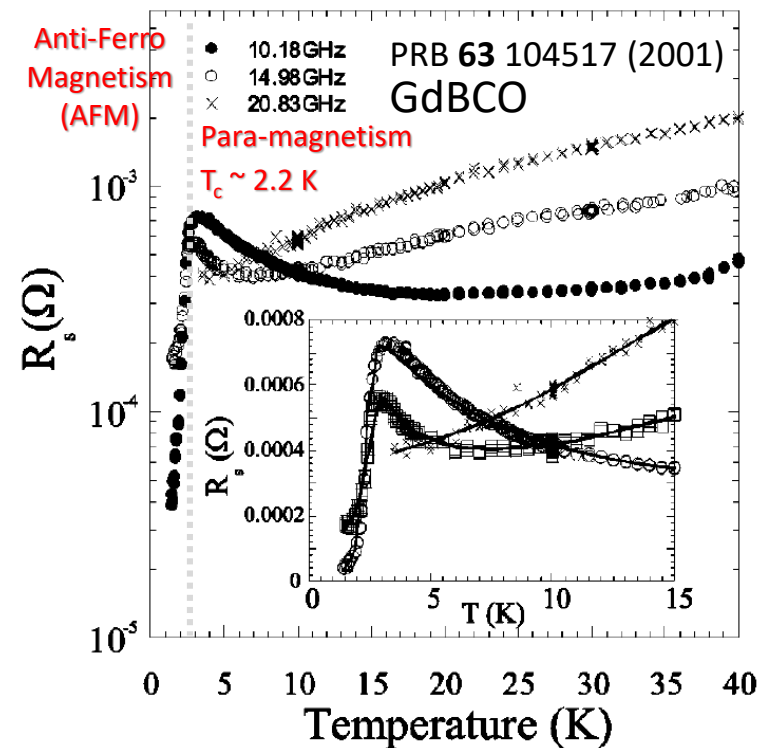
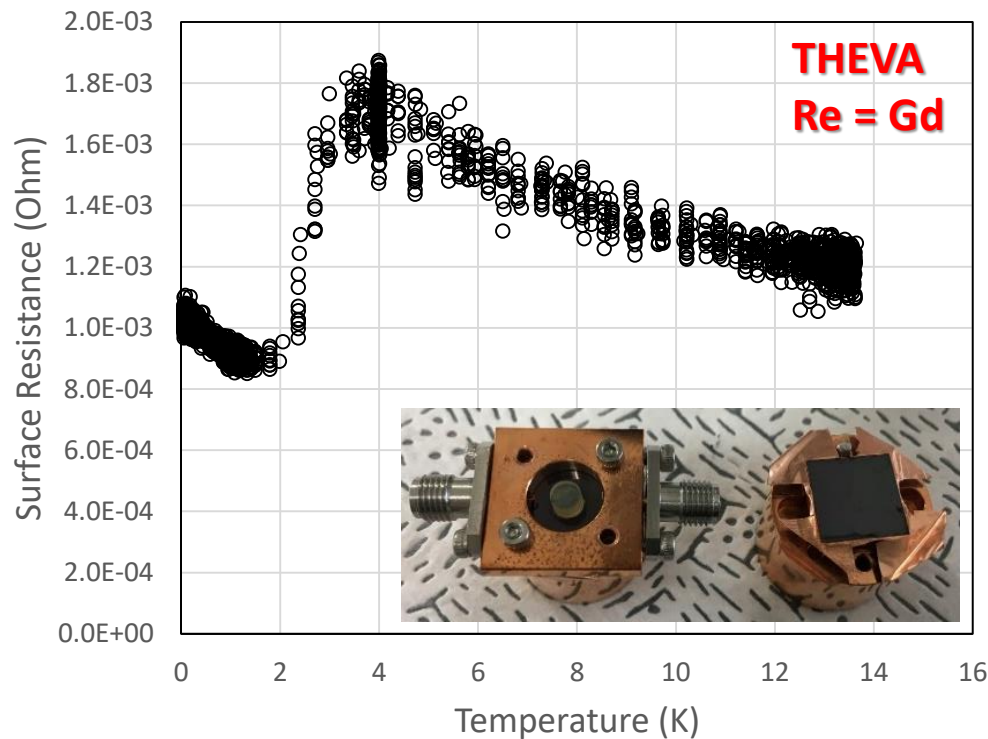
$$\frac{1}{Q} = \left(\sum_i \frac{R_{s,i}}{G_i} + p \tan\delta \right)$$

$$p = \frac{1}{2U} \int \vec{D}(r) \cdot \vec{E}(r) dV_{di} \rightarrow 1$$

$$G_i = \frac{2\omega_0 U}{\int |H_t(r)|^2 dA_i} = 104.8 \Omega$$

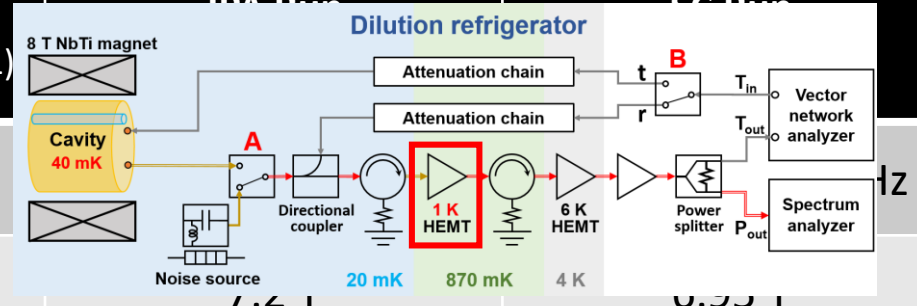
Since GdBCO Have Additional Magnetism

- Gd is a magnetic atom which gives additional R_s .
- GdBCO magnetic transition at 2.2 K was reproduced.
- EuBCO tapes do not have magnetic behavior. $R_{Eu} < R_{Gd}$



CAPP-PACE Detector

	HEMT Run Phys. Rev. Lett. 126 (2021)	IDA Run	CG Run
Frequency Range	2.457 – 2.749 GHz		
Magnetic Field (B)	7.2 T		
Volume (V)	1.12 L		
Quality Factor (Q_0)	100,000		
Geometrical Factor (C)	0.51 – 0.66		
System Noise (T_{sys})	~ 1.1 K		
Scan Rate (Norm.) $\propto B^4 V^2 C^2 Q_0 / T_{\text{sys}}^2$	1	18	310



PHYSICAL REVIEW LETTERS 126, 191802 (2021)

Lowest Physical Temperature (38mK)

First Results from an Axion Haloscope at CAPP around 10.7 μeV

Ohjoon Kwon¹, Doyu Lee^{1,*}, Woohyun Chung^{1,*}, Danho Ahn^{2,1}, HeeSu Byun¹, Fritz Caspers^{3,4},
 Hyoungsoon Choi², Jihoon Choi^{1,2}, Yonuk Chong^{5,8}, Hoyong Jeong⁶, Junu Jeong^{2,1}, Jihn E. Kim⁷, Jinsu Kim^{2,1},
 Çağlar Kutlu^{2,1}, Jinhwan Lee⁸, MyeongJae Lee¹, Soohyung Lee¹, Andrei Matlashov¹, Seonjeong Oh¹,
 Seongtae Park¹, Sergey Uchaikin¹, SungWoo Yoon¹, and Yannis K. Semertzidis^{1,2}

¹Center for Axion and Precision Physics Research (CAPP), IBS, Daejeon 34051, Republic of Korea

²Department of Physics, KAIST, Daejeon 34141, Republic of Korea

³CERN, European Organization for Nuclear Research, CH-1211 Genve 23, Switzerland

⁴ESI (European Scientific Institute) Archamps Technople, F-74160, France

⁵Korea Research Institute of Standards and Science, Daejeon 34113, Republic of Korea

⁶Department of Physics, Korea University, Seoul 02841, Republic of Korea

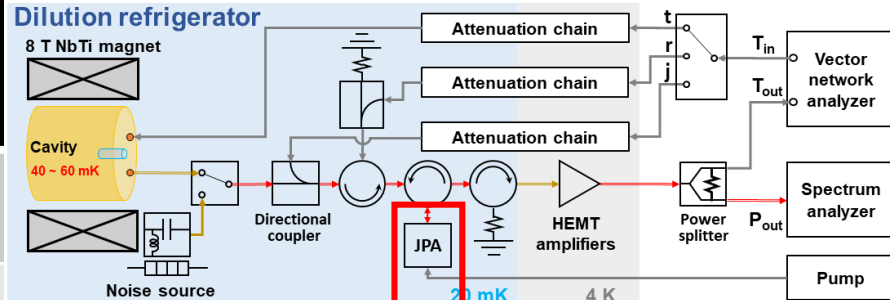
⁷Department of Physics, Kyung Hee University, Seoul 02447, South Korea

⁸Center for Artificial Low Dimensional Electronic Systems, IBS, Pohang 37673, Republic of Korea

(Received 15 January 2021; accepted 24 March 2021; published 12 May 2021; corrected 11 August 2021)

The Center for Axion and Precision Physics Research at the Institute for Basic Science is searching for axion dark matter using ultralow temperature microwave resonators. We report the exclusion of the axion mass range 10.7126–10.7186 μeV with near Kim-Shifman-Vainshtein-Zakharov (KSVZ) coupling sensitivity and the range 10.16–11.37 μeV with about 9 times larger coupling at 90% confidence level. This is the first axion search result in these ranges. It is also the first with a resonator physical temperature of less than 40 mK.

CAPP-PACE Detector



PHYSICAL REVIEW LETTERS **130**, 091602 (2023)

Lowest Noise Temperature

Near-Quantum-Noise Axion Dark Matter Search at CAPP around 9.5 μeV

Jinsu Kim^{1,2}, Ohjoon Kwon², Çağlar Kutlu^{1,2}, Woohyun Chung^{2,*}, Andrei Matlashov², Sergey Uchaikin²,
Arjan Ferdinand van Loo^{3,4}, Yasunobu Nakamura², Seonjeong Oh², HeeSu Byun,²
Danho Ahn^{1,2} and Yannis K. Semertzidis^{2,1}

¹Department of Physics, KAIST, Daejeon 34141, Republic of Korea

²Center for Axion and Precision Physics Research (CAPP), IBS, Daejeon 34051, Republic of Korea

³RIKEN Center for Quantum Computing (RQC), Wako, Saitama 351-0198, Japan

⁴Department of Applied Physics, Graduate School of Engineering, The University of Tokyo, Bunkyo-ku, Tokyo 113-8656, Japan

(Received 9 August 2022; accepted 19 January 2023; published 28 February 2023)

We report the results of an axion dark matter search over an axion mass range of 9.39–9.51 μeV . A flux-driven Josephson parametric amplifier (JPA) was added to the cryogenic receiver chain. A system noise temperature of as low as 200 mK was achieved, which is the lowest recorded noise among published axion cavity experiments with phase-insensitive JPA operation. In addition, we developed a two-stage scanning method which boosted the scan speed by 26%. As a result, a range of two-photon coupling in a plausible model for the QCD axion was excluded with an order of magnitude higher in sensitivity than existing limits.

DOI: 10.1103/PhysRevLett.130.091602

System Noise (T_{sys})

~ 1.1 K

Scan Rate (Norm.)

1

$$\propto B^4 V^2 C^2 Q_0 / T_{\text{sys}}^2$$

JPA Run
Phys. Rev. Lett. 130 (2023)

SC Run
Analysis in process

2.27 – 2.30 GHz

2.273 – 2.295 GHz

7.2 T

6.95 T

1.12 L

1.5 L

100,000

500,000

0.45

0.51 – 0.65

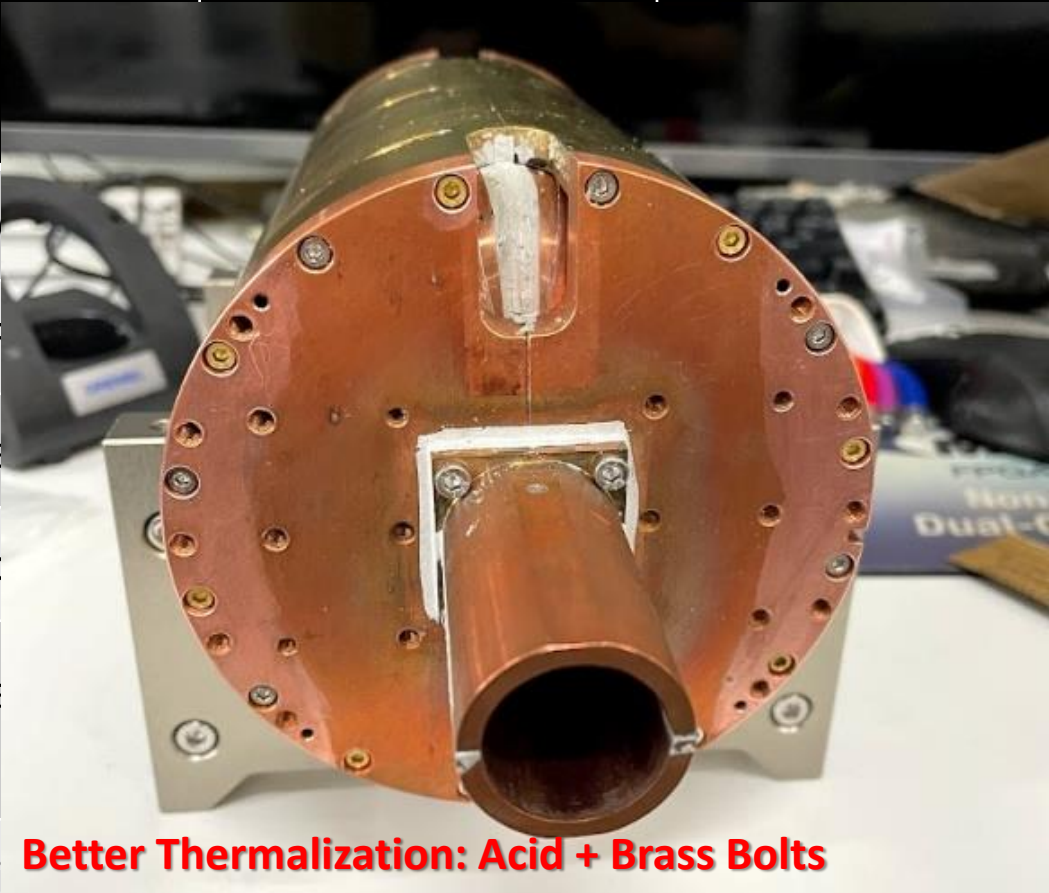
~ 200 mK

~ 180 mK

18

310

CAPP-PACE Detector

				3)	SC Run Anaysis in process
Frequency					2.273 – 2.295 GHz
Magnetic F					6.95 T
Volume					Bigger Volume 1.5 L
Quality Fac					Higher Q Factor 500,000
Geometrical (C)					0.51 – 0.65
System No	Better Thermalization: Acid + Brass Bolts				Better Noise Temperature ~ 180 mK
Scan Rate (Norm.) $\propto B^4 V^2 C^2 Q_0 / T_{sys}^2$	1	18	310		

Analysis Procedure

➤ Baseline Removal

- Raw spectrum have baseline due to frequency dependent gain.
- Savitzky-Golay filter was used to remove the baselines.

➤ Vertical combination

- Each spectrum have different cavity response and noise temperature.
- Merging spectra with same standard.

➤ Horizontal combination

- The power of axion signal is distributed over bins due to frequency dispersion
- Frequency distribution of axion signal should be merged to maximize expected axion signal.
- Selected suspicious peaks with high excess power becomes rescan candidate.

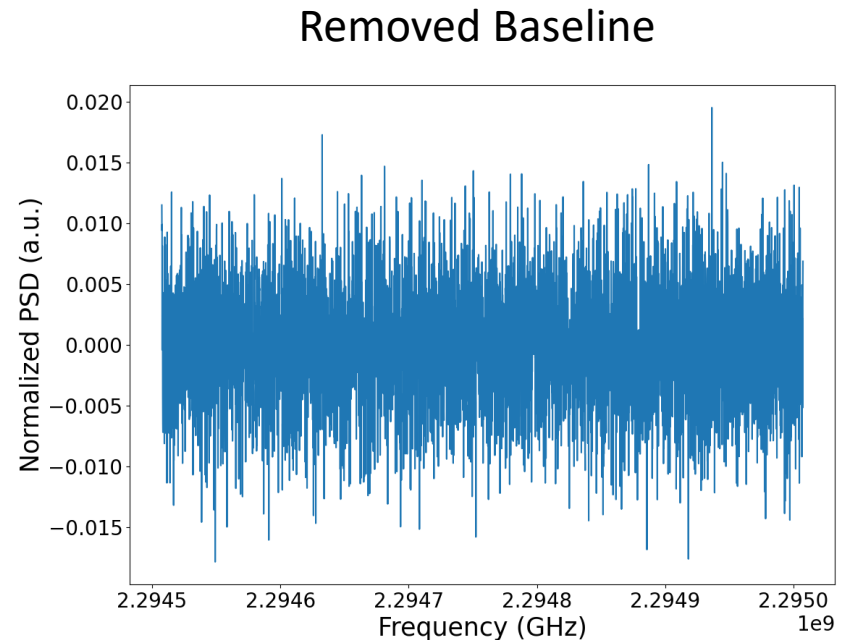
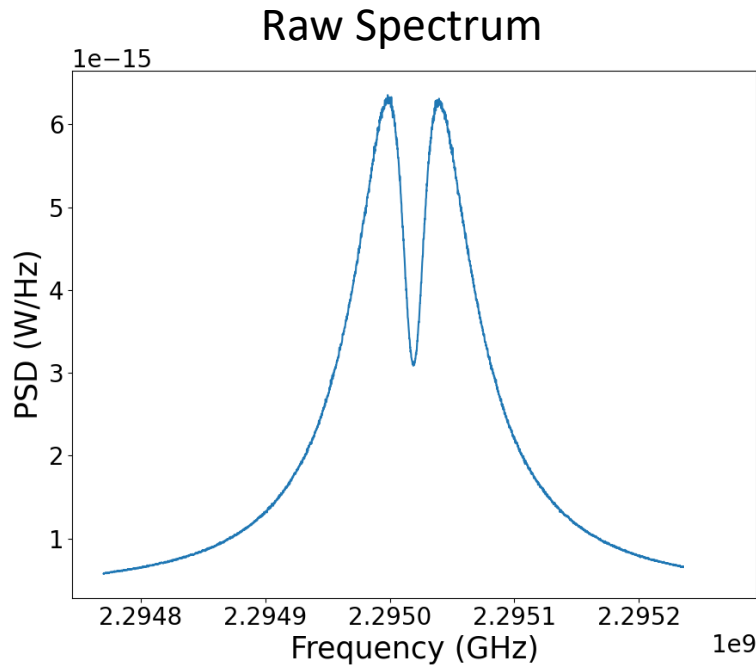
➤ Rescan

- Taking additional data for rescan candidates to test whether there is axion or not.

Analysis

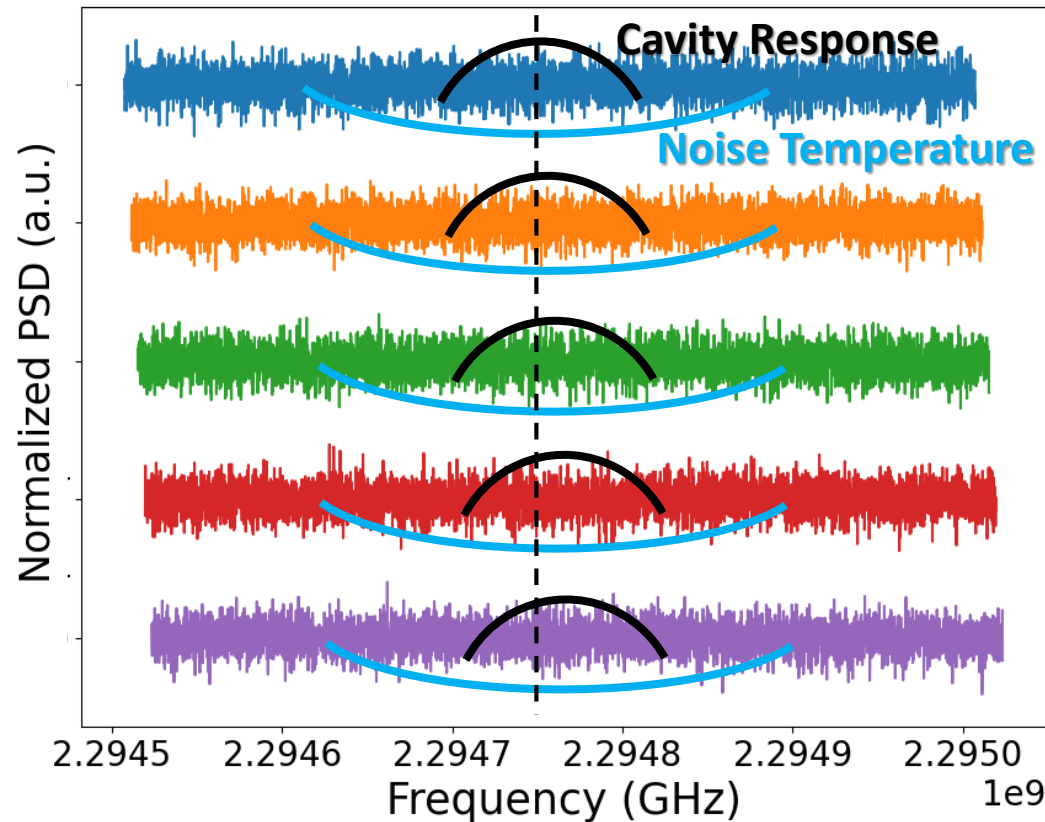
➤ Baseline Removal

- Raw spectrum have baseline due to frequency dependent gain.
- Savitzky-Golay filter was used to remove the baselines.



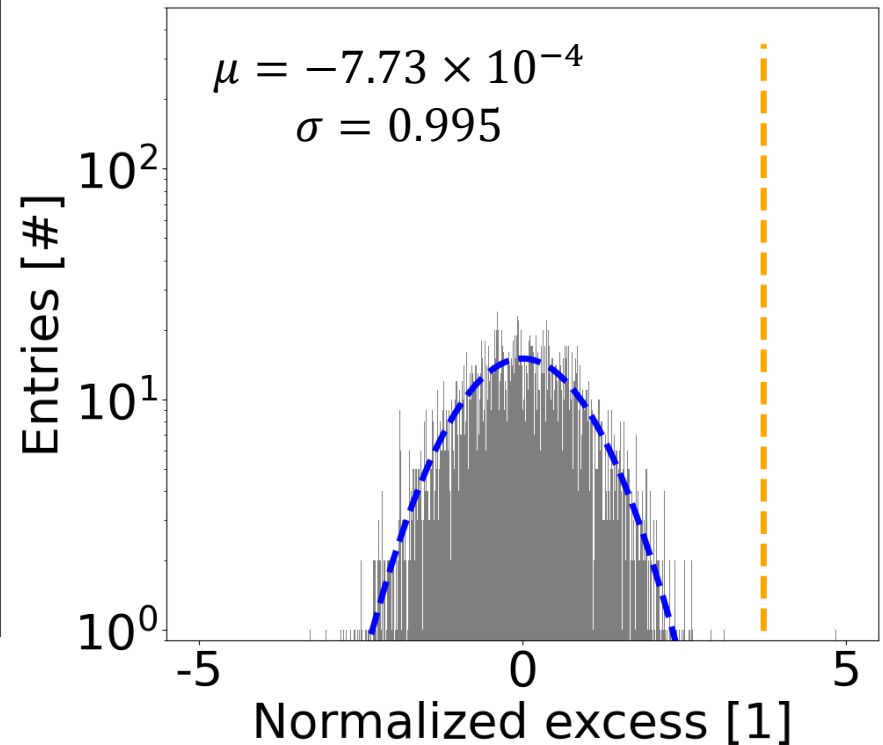
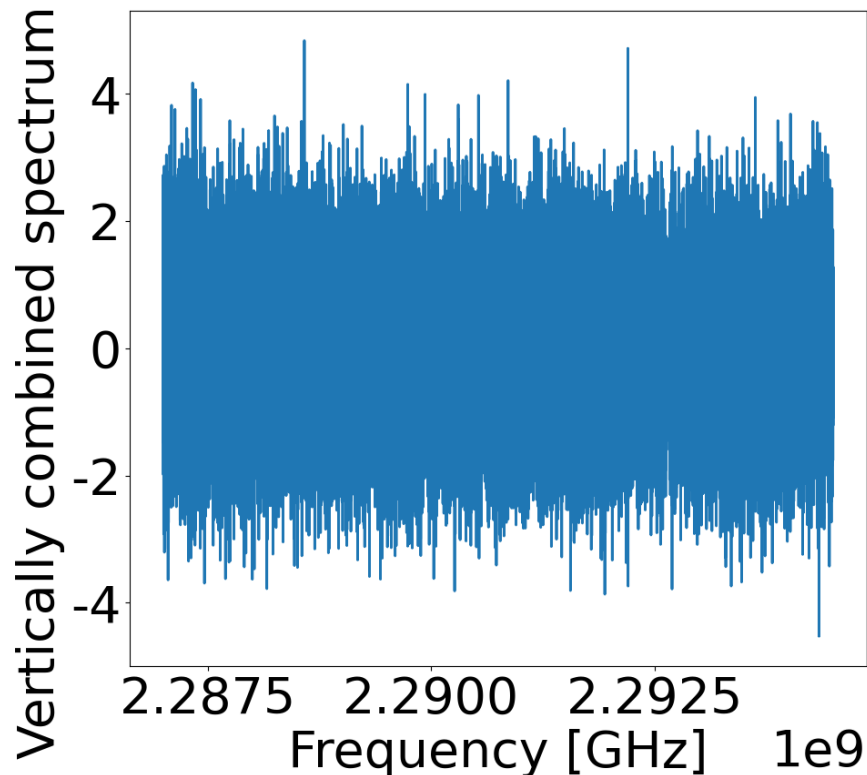
Analysis

- Vertical combination
 - Each spectrum have different cavity response and noise temperature.
 - Merging spectra with same standard.



Analysis

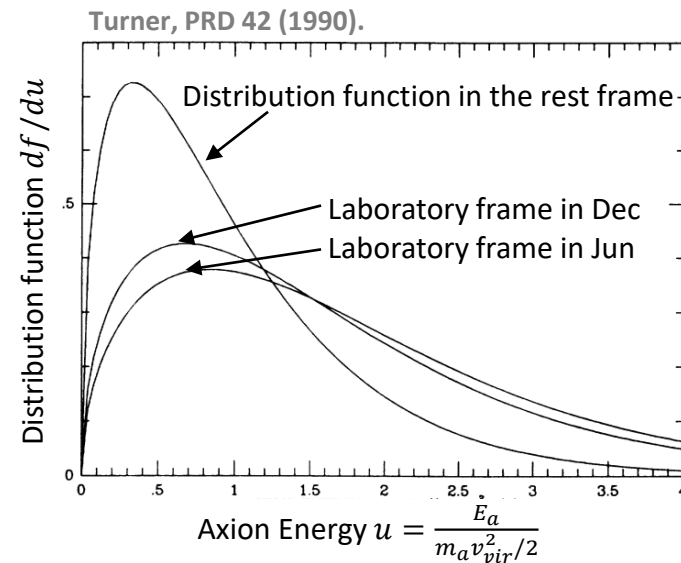
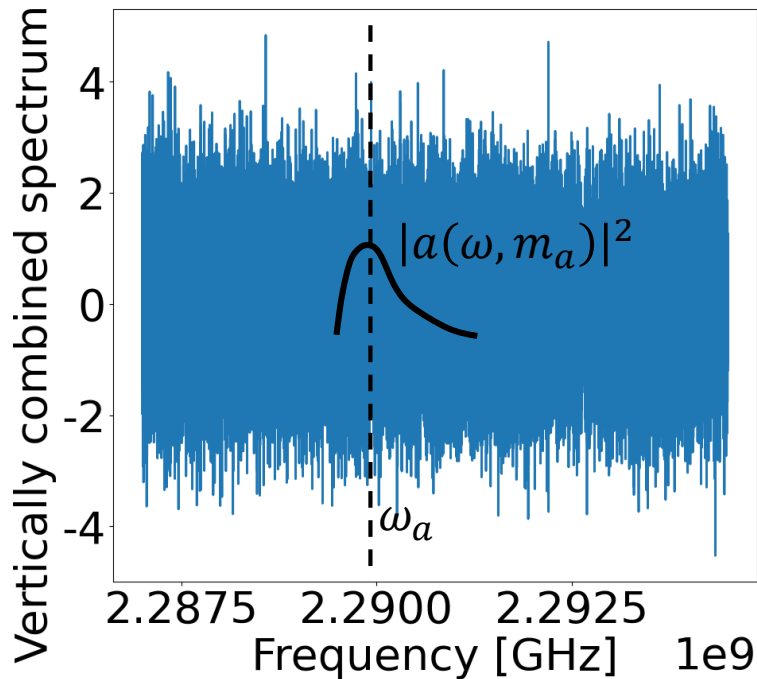
- Vertical combination
 - Each spectrum have different cavity reponse and noise temperature.
 - Merging spectra with same standard.



Analysis

➤ Horizontal combination

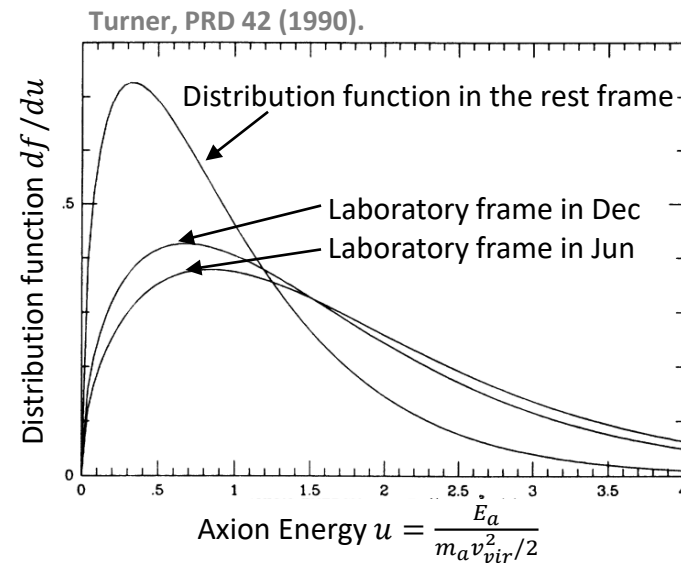
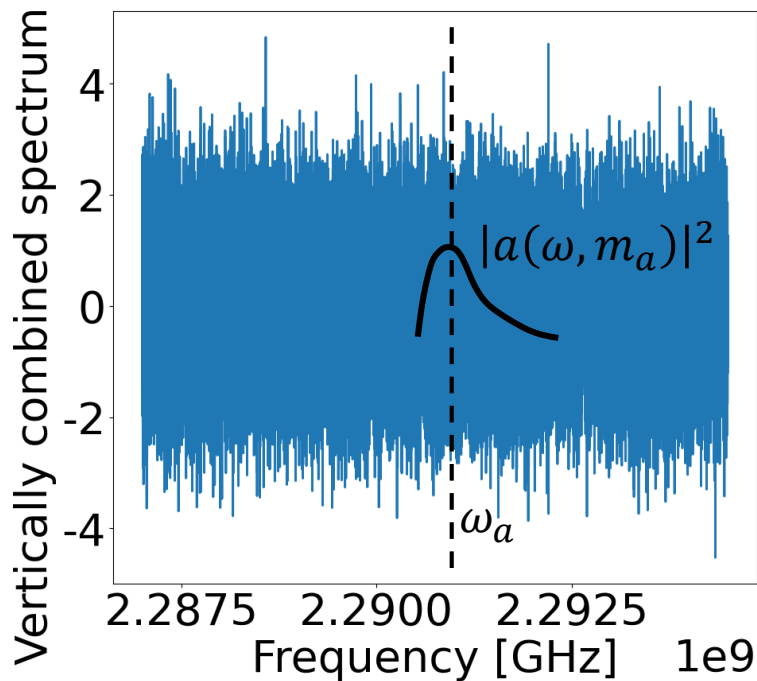
- The power of axion signal is distributed over bins due to frequency dispersion
- Frequency distribution of axion signal should be merged to maximize expected axion signal.
- Selected suspicious peaks with high excess power becomes rescan candidate.



Analysis

➤ Horizontal combination

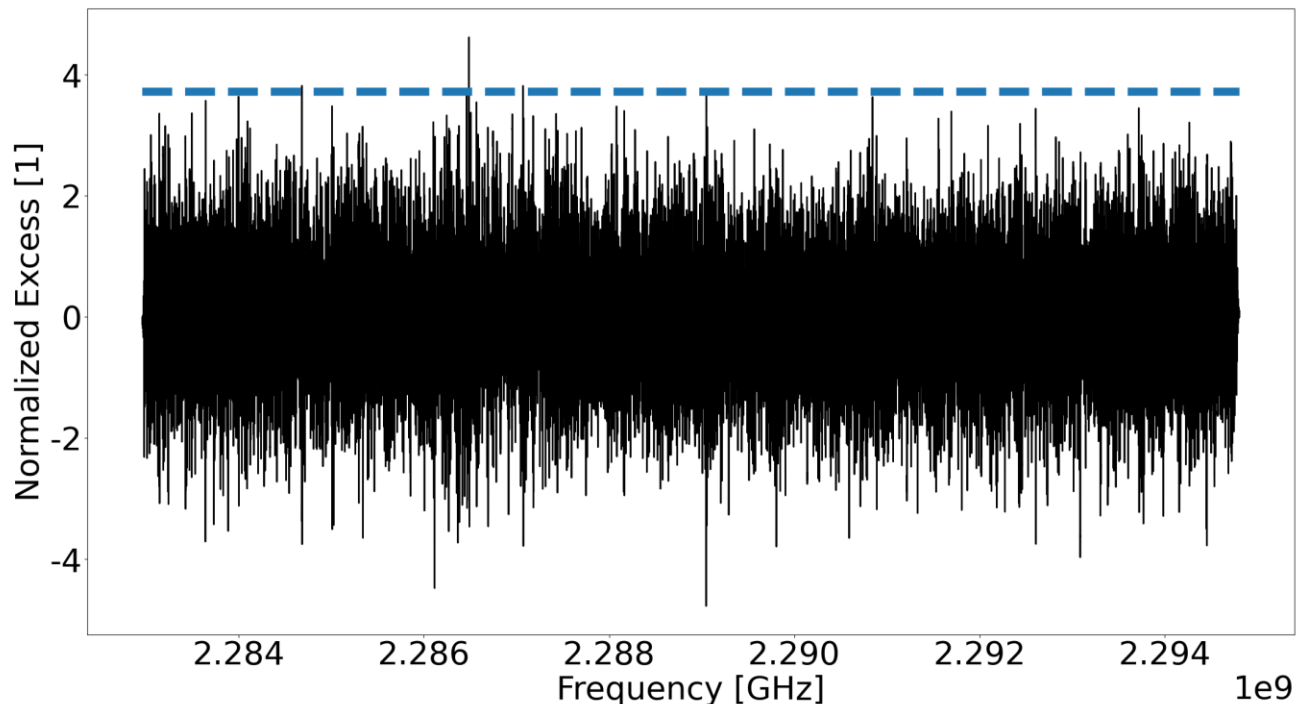
- The power of axion signal is distributed over bins due to frequency dispersion
- Frequency distribution of axion signal should be merged to maximize expected axion signal.
- Selected suspicious peaks with high excess power becomes rescan candidate.



Analysis

➤ Horizontal combination

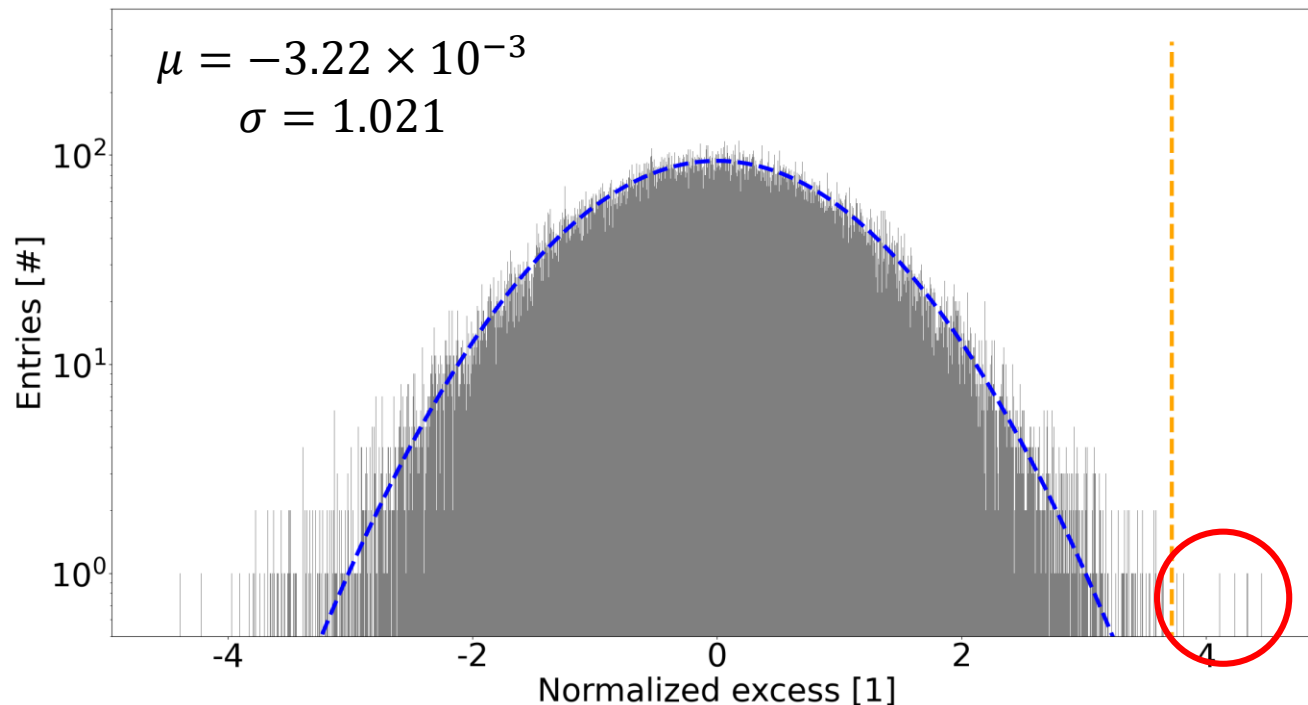
- The power of axion signal is distributed over bins due to frequency dispersion
- Frequency distribution of axion signal should be merged to maximize expected axion signal.
- Selected suspicious peaks with high excess power becomes rescan candidate.



Analysis

➤ Horizontal combination

- The power of axion signal is distributed over bins due to frequency dispersion
- Frequency distribution of axion signal should be merged to maximize expected axion signal.
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Analysis

➤ Horizontal combination

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- Frequency distribution of axion signal should be merged to maximize expected axion signal.
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