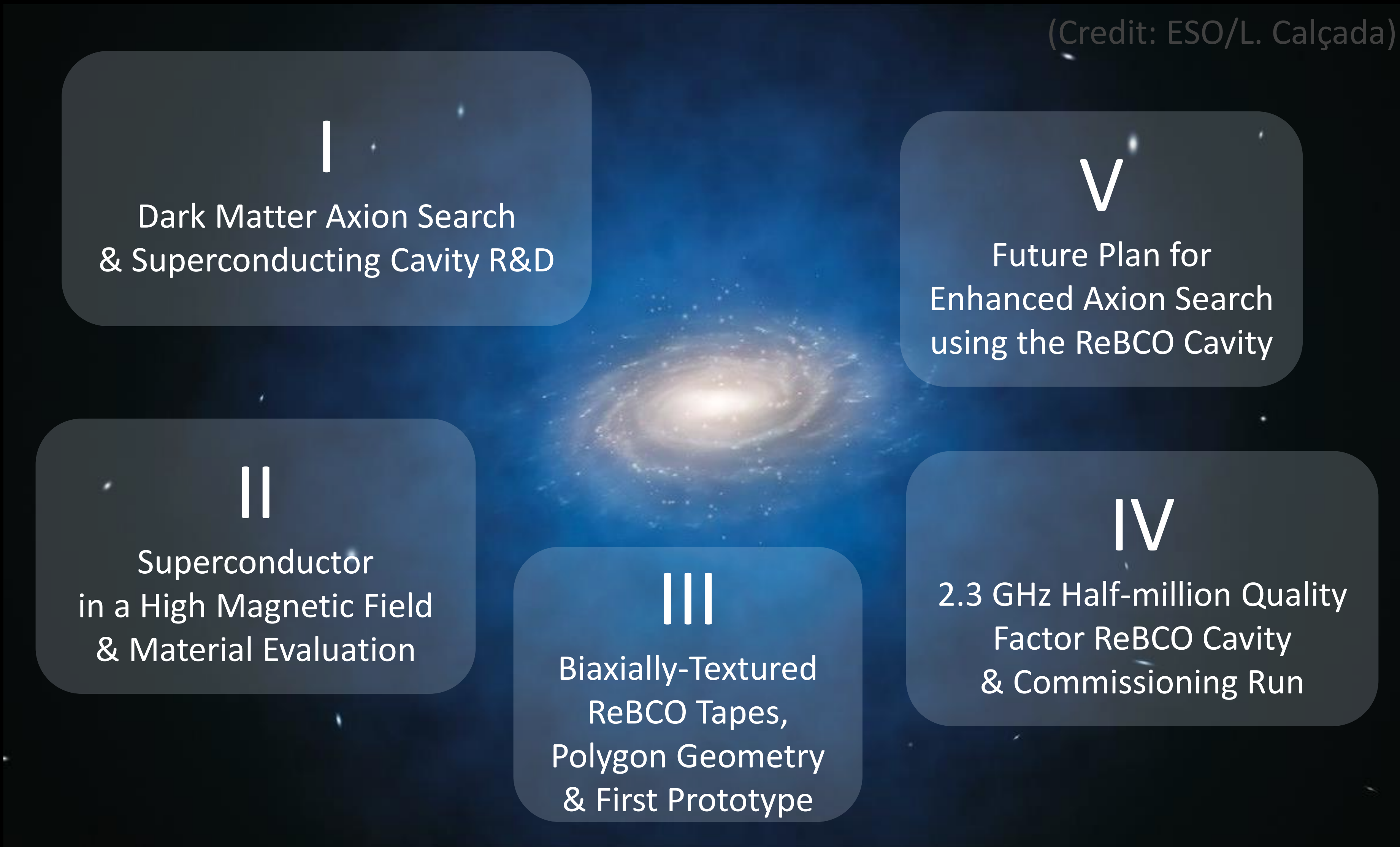
Superconducting Cavity for Dark Matter Axion Search

Danho Ahn,[1,2] Seongtae Park,[2] Ohjoon Kwon,[2] Heesu Byun,[2] Jinsu Kim,[1,2] Andrei N. Matlashov,[2] Woohyun Chung,[2] Dojun Youm,[1] Yannis K. Semertzidis.[2,1]

[1]Department of Physics, Korea Advanced Institute of Science and Technology, Daejeon 34141, Republic of Korea

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

Outline



(Credit: ESO/L. Calçada)

I

Dark Matter Axion Search
& Superconducting Cavity R&D

II

Superconductor
in a High Magnetic Field
& Material Evaluation

III

Biaxially-Textured
ReBCO Tapes,
Polygon Geometry
& First Prototype

IV

2.3 GHz Half-million Quality
Factor ReBCO Cavity
& Commissioning Run

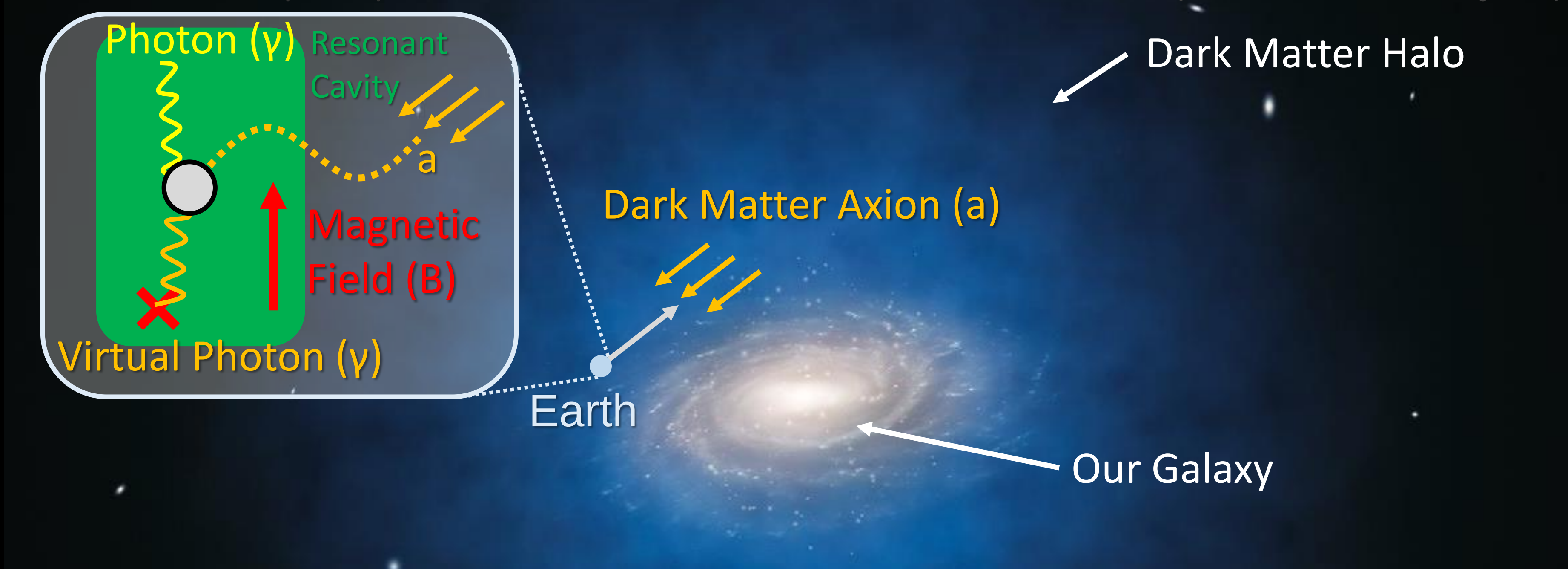
V

Future Plan for
Enhanced Axion Search
using the ReBCO Cavity

Dark Matter Axion Search (Axion Haloscope)

Sikivie PRL(1983)1415

(Credit: ESO/L. Calçada)



Coupling Constant

Dark Matter Axion Density

Conversion Power

Resonant Frequency

$$P_{a\gamma\to\gamma} = g^2_{a\gamma\gamma}\frac{\rho_a}{m_a^2} B^2 V \omega_0 C \frac{Q_a Q_c}{Q_a + Q_c}$$

Cavity Quality Factor

Axion Mass

Axion Quality Factor

Kim *et al*. JCAP03(2020)066

Revisiting Quality Factor

- Definition of Quality Factor

Angular Frequency

Internal Energy

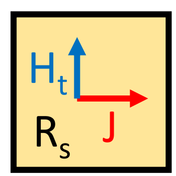
Quality Factor

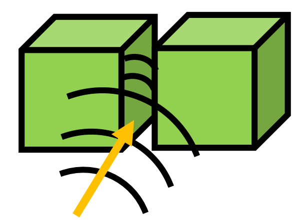
$$Q = \frac{\omega_0 U}{P_{loss}}$$

Total Energy Loss

- Decomposing Origins of Energy Loss

$$P_{surf} \propto R_s$$



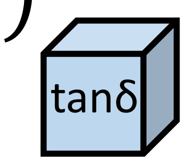


Surface Current Loss

Wave Propagation (Radiation)

$$\frac{1}{Q} = \frac{P_{loss}}{\omega_0 U} = \frac{1}{\omega_0 U}\left(P_{surf} + P_{vol} + P_{rad}\right)$$

Volume Loss



Revisiting Quality Factor

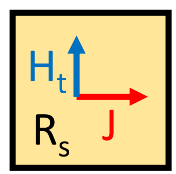
- Definition of Quality Factor

Angular Frequency   Internal Energy

Quality Factor $$Q = \frac{\omega_0 U}{P_{loss}}$$ Total Energy Loss

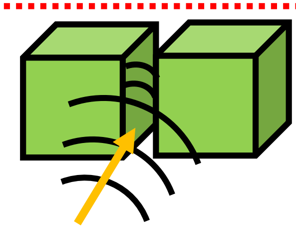
- Decomposing Origins of Energy Loss

$$P_{surf} \propto R_s$$



Surface Current Loss

Controlled by Geometric Design

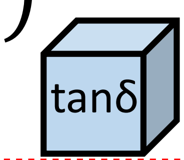


Wave Propagation (Radiation)

Low Loss

High Q $$\frac{1}{Q} = \frac{P_{loss}}{\omega_0 U} = \frac{1}{\omega_0 U}\left(P_{surf} + P_{vol} + P_{rad}\right)$$

Volume Loss



Low Loss Tangent

Revisiting Quality Factor

- Definition of Quality Factor

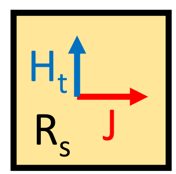
Angular Frequency   Internal Energy

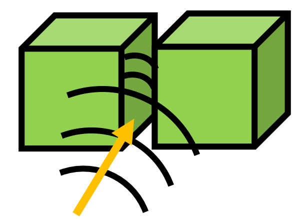
Quality Factor $$Q = \frac{\omega_0 U}{P_{loss}}$$ Total Energy Loss

- Decomposing Origins of Energy Loss

$$P_{surf} \propto R_s$$

Low Surface Resistance
→ Superconductor (SC)

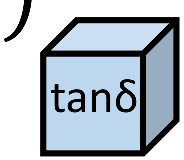




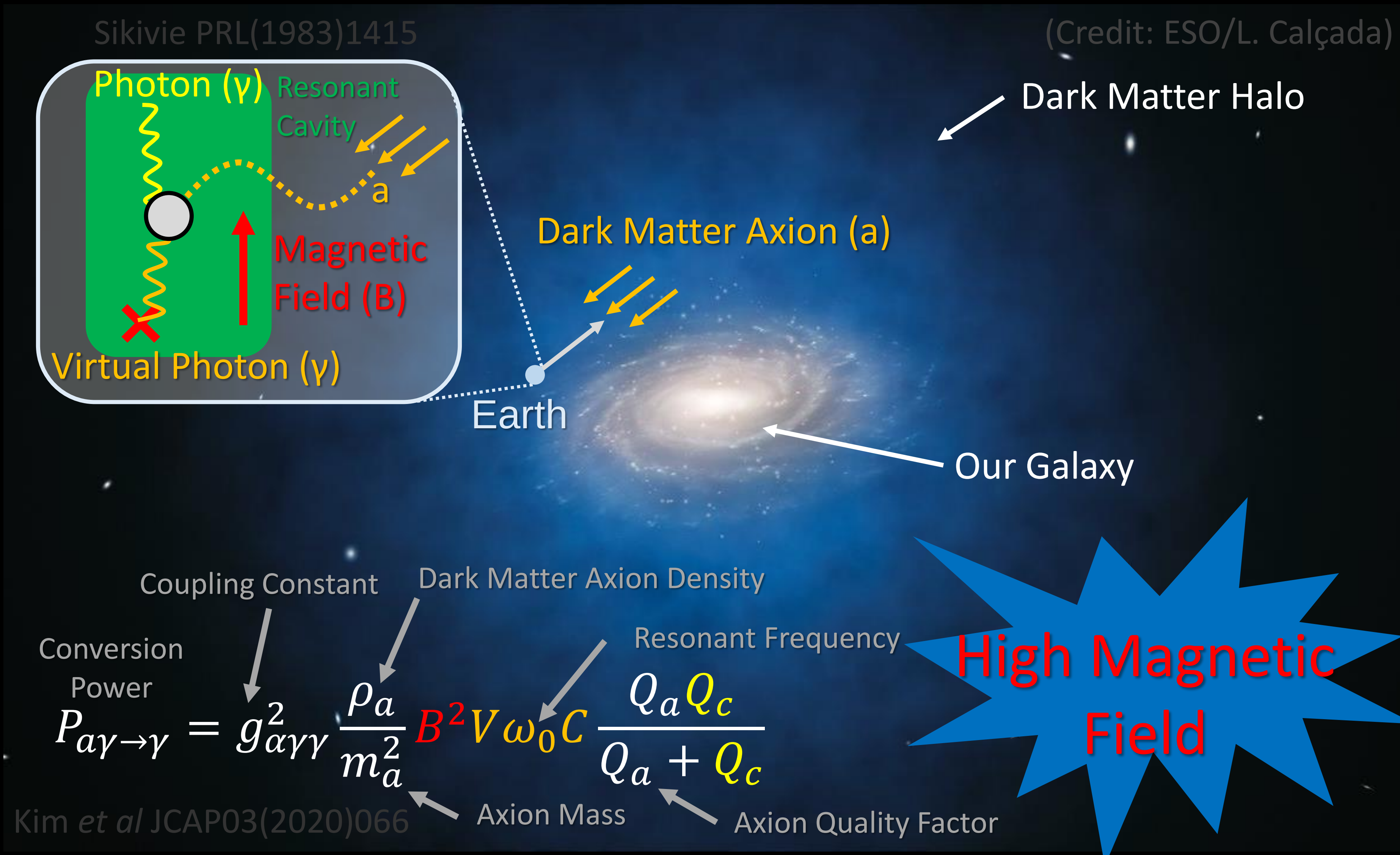
Surface Current Loss   Wave Propagation (Radiation)

High Q $$\frac{1}{Q} = \frac{P_{loss}}{\omega_0 U} = \frac{1}{\omega_0 U}\left(P_{surf} + P_{vol} + P_{rad}\right)$$

Volume Loss



Dark Matter Axion Search (Axion Haloscope)

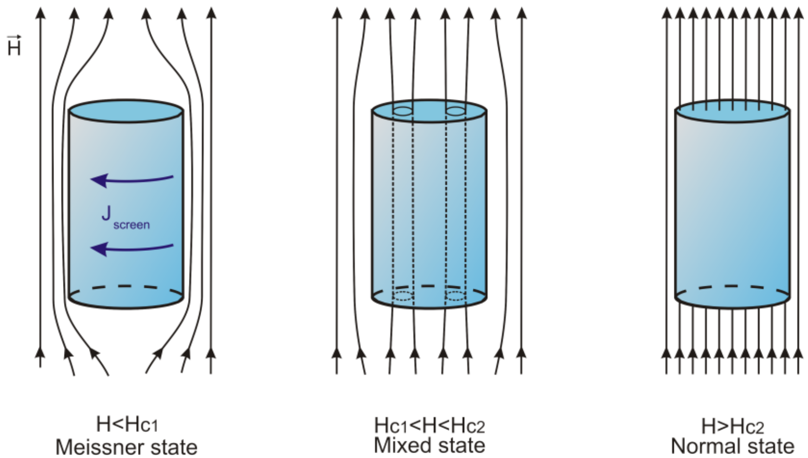


$$P_{a\gamma\to\gamma} = g^2_{a\gamma\gamma} \frac{\rho_a}{m_a^2} B^2 V \omega_0 C \frac{Q_a Q_c}{Q_a + Q_c}$$

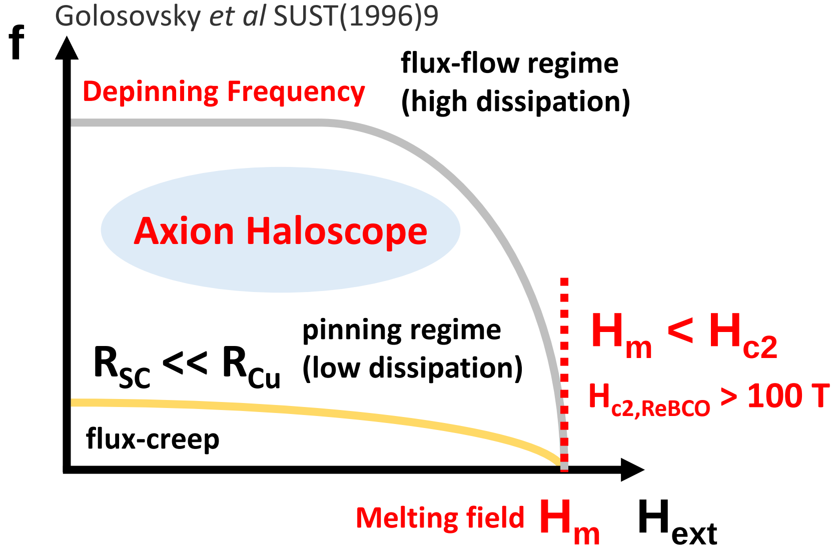
Superconductor in a High Magnetic Field

Three Phases of Type II Superconductor

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



Golosovsky *et al* SUST(1996)9



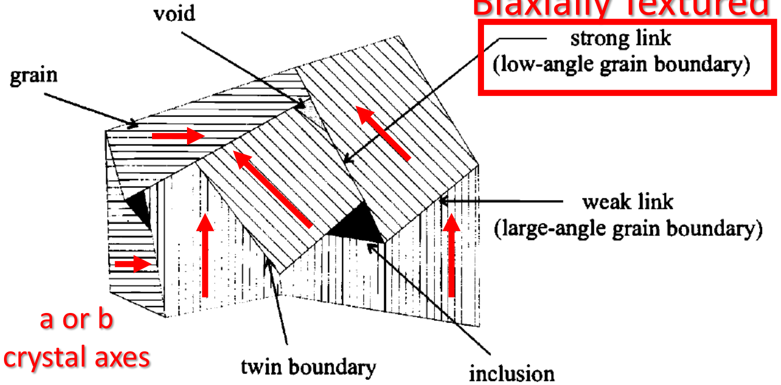
- An external magnetic field can degrade Superconductivity.
- In a mixed state, type 2 SCs make vortices inside.
- Vortex pinning can make a low dissipative surface. (low R_s)
- SC Materials with a higher upper critical field (H_{c2}) have higher melting field (H_m) of vortices.
- High-temperature superconductors (HTS) are promising for making high Q factor cavities for axion haloscope.

Material Evaluation

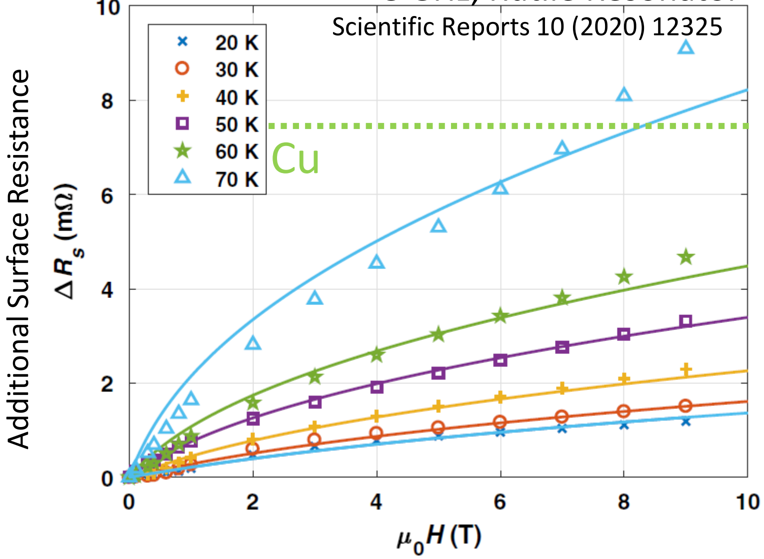
100 mK 8 GHz	R_s (B = 0 T) (Ohm)	R_s (B = 8 T, ∥ c) (Ohm)	Critical Field (H_{c2})	Depinning Frequency	Film Fabrication Method	Cavity Fabrication
OFHC Cu (Metal)	~ 7E-3	~ 7E-3	None	None	Yes	Machining
NbTi (LTS) Gatti *et al.* PRD(2019)	~ 1E-6	~ 4e-3	~ 13 T	~ 45 GHz	Deposition (No Texture Requirement)	Deposition
Bi-2212 (HTS) Bi-2223 (HTS)	~ 1E-5	?	> 100 T (∥ ab) Larbalestier *et al.* Nature(2001)	Weak Pinning ?	Deposition (No Texture Requirement)	Deposition
Tl-1223 (HTS)	~ 1E-5	~ 1e-4 Calatroni *et al.* SUST(2017)	> 100 T (∥ ab) Larbalestier *et al.* Nature(2001)	12 – 480 MHz Calatroni *et al.* SUST(2017)	Deposition (No Texture Requirement)	Deposition
ReBCO (HTS)	~ 1E-5 Ormeno *et al.* PRB(2001)	**~ 1e-4** Romanov *et al.* Scientific Reports(2020)	**> 100 T (∥ ab)** Larbalestier *et al.* Nature(2001)	Strong Pinning **10 – 100 GHz** Romanov *et al.* Scientific Reports(2020)	Deposition (Biaxial Texture)	1. Deposition **2. Using Tapes**

Biaxially Textured ReBCO Tape

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

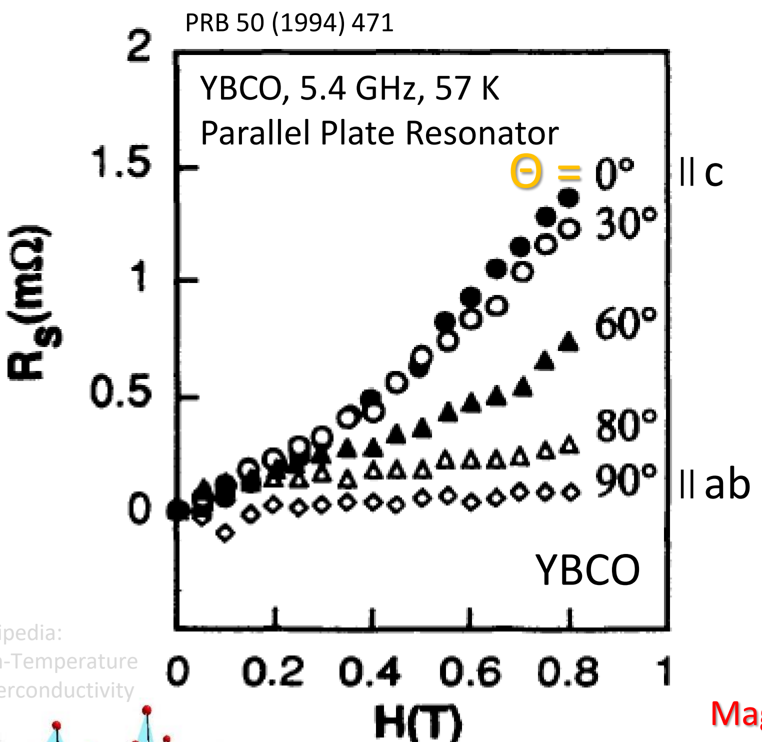


8 GHz, Rutile Resonator

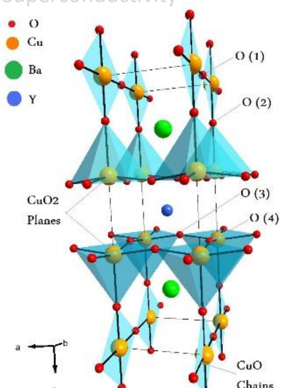


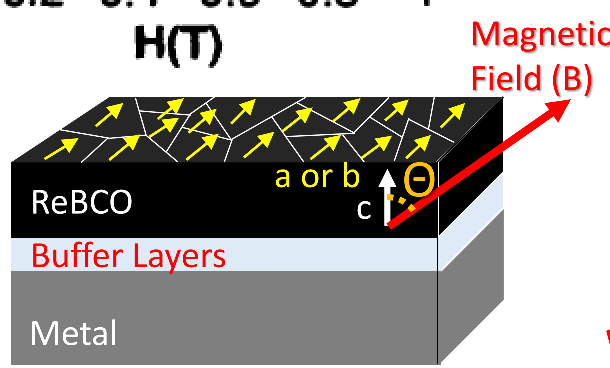
- Biaxially-textured Rare-earth Barium Copper Oxide (ReBCO) films consist of strong links.
- It shows good performance of surface resistance in a high magnetic field at low temperature.
- Its depinning frequency is also high enough. (> 10 GHz)
- There are many providers that fabricate biaxially-textured ReBCO tapes.

Biaxially Textured ReBCO Tape



Wikipedia:
High-Temperature
Superconductivity





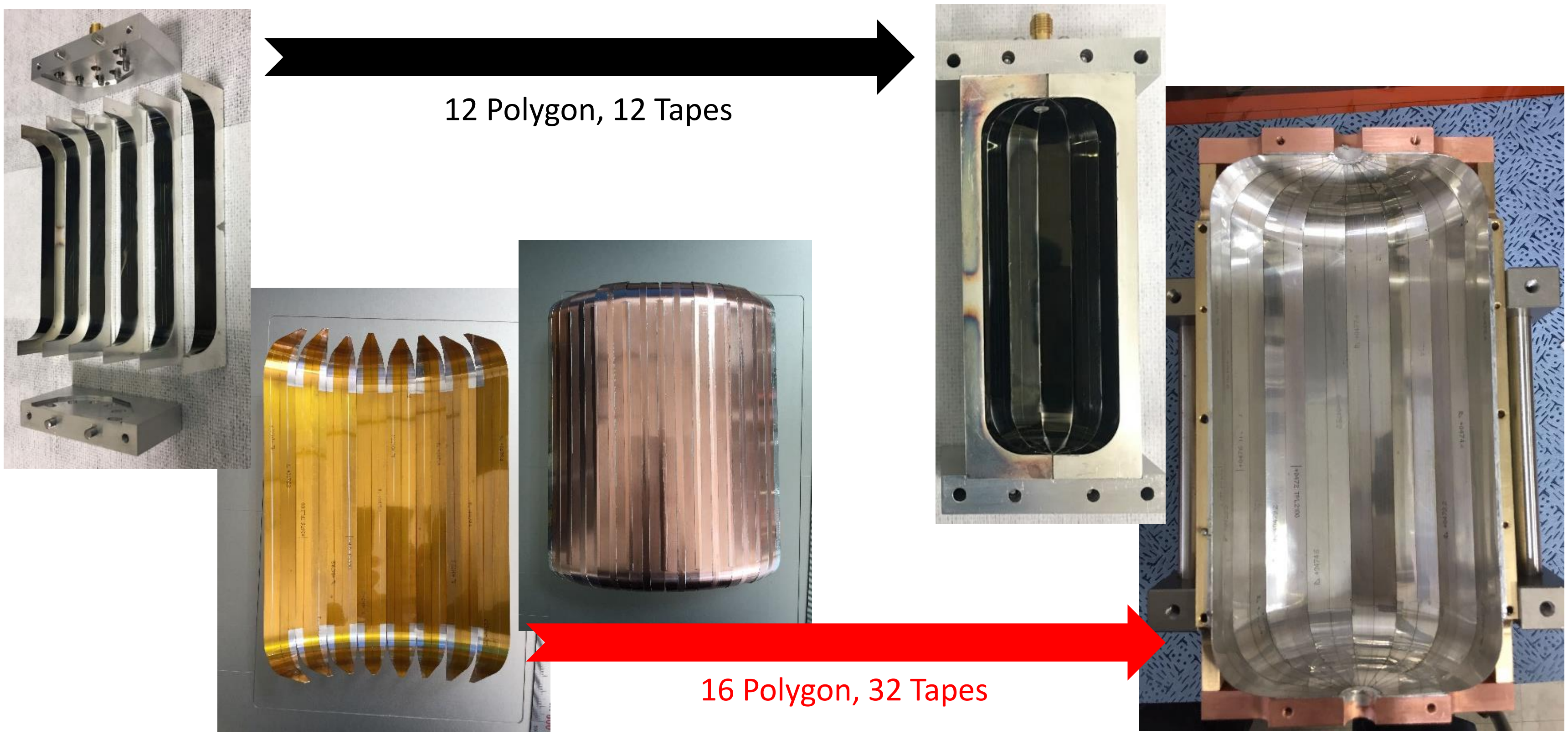
- Biaxially-Textured ReBCO films have anisotropy of surface resistance due to their crystal structure.
- The surface resistance of a film is maximized when the c axis of a crystal and the direction of an external magnetic field is parallel to each other.
- Directions of a ReBCO crystal should be considered to design a cavity.

How to make 3D surface with tapes?

Making 3D Surfaces with Tapes

CAPP's Solution

Polygon Shape: From Planar Surfaces to a 3D Surface

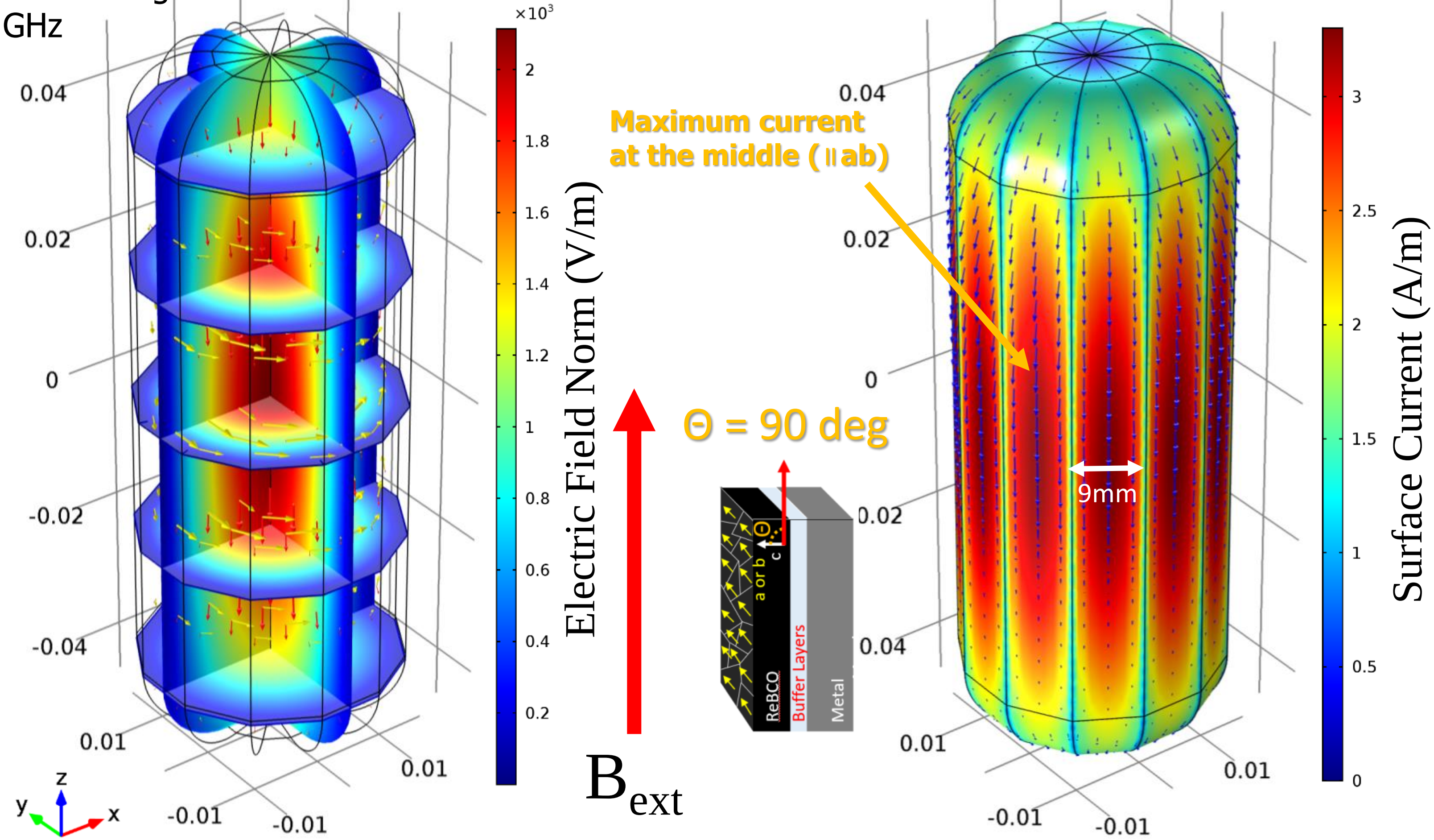


The Advantages of the Polygon Cavity

Tape Direction: Mimimized Surface Resistance
Vertical Cut: Avoiding Contact Problem

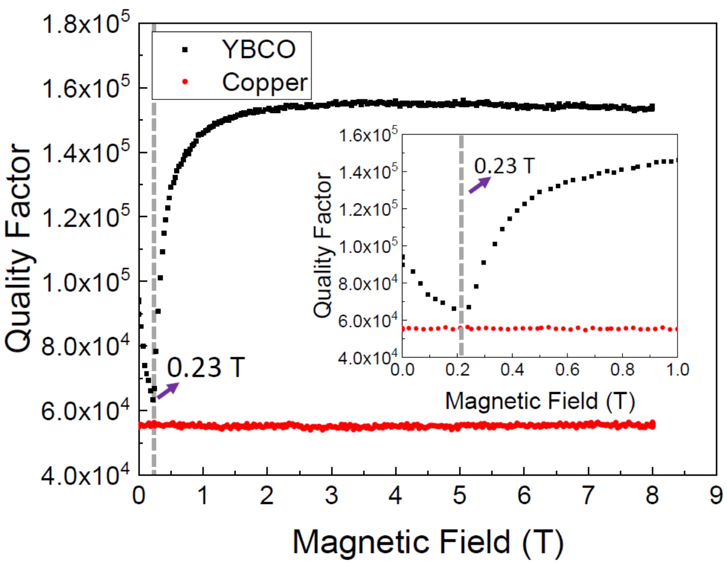
- Electric and Magnetic Field
- 6.85 GHz

- Surface Current

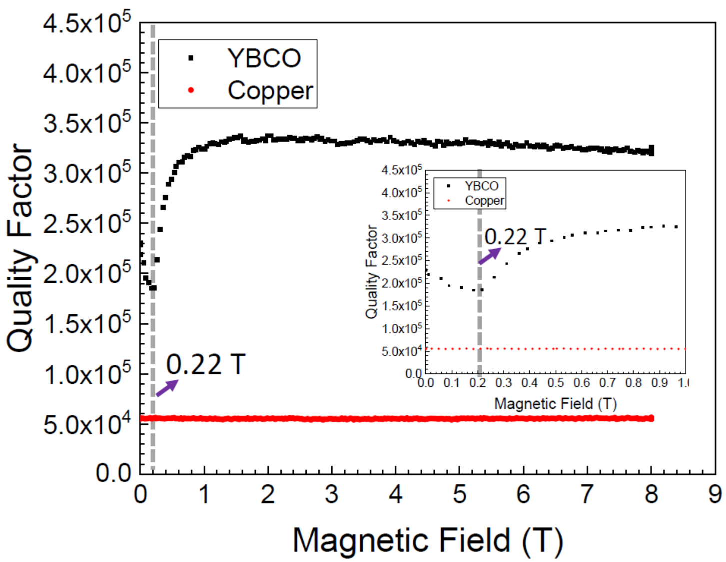


First Prototype Cavity

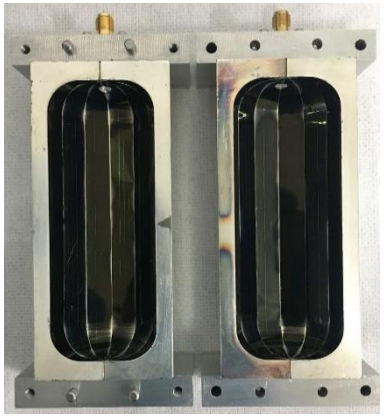
- (2019) First Prototype HTS Cavity (with Prof. Dojun Youm)
  - ✓ (March 8th) Q ~ 150,000 at 8 T
  - ✓ (August 15th) Q ~ 330,000 at 8 T (Improved Tape Edge)



ArXiv: 1904.05111

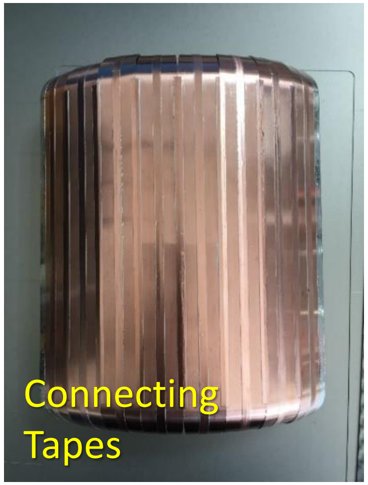


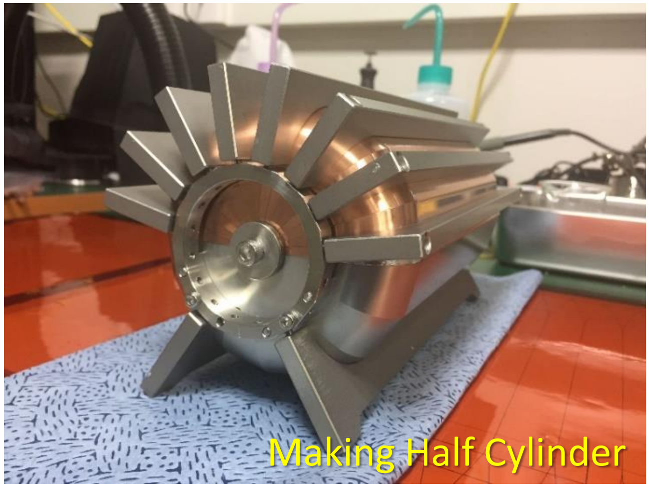
ArXiv: 2103.14515
PRApplied Submitted

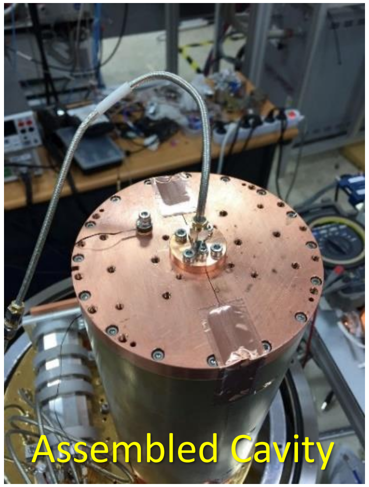


2.3 GHz Axion Search Cavity

➢ (2019 – 2020) 2.3 GHz ReBCO Cavity (Dr. Seongtae Park)

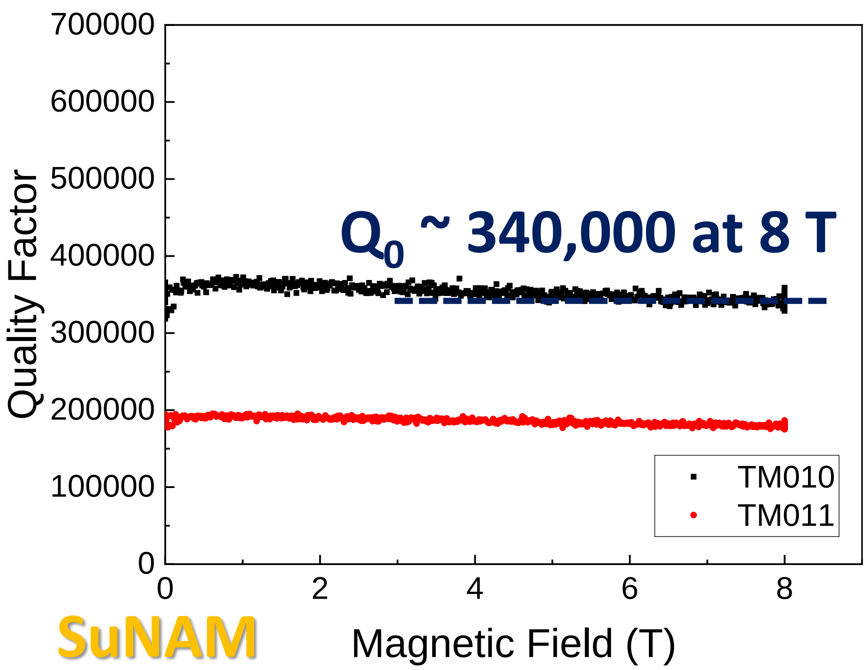


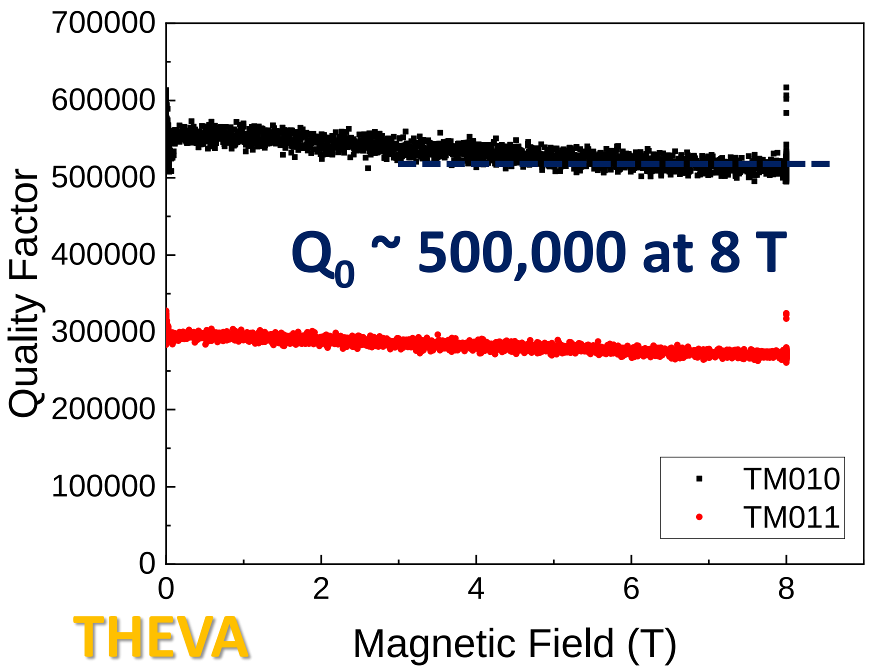




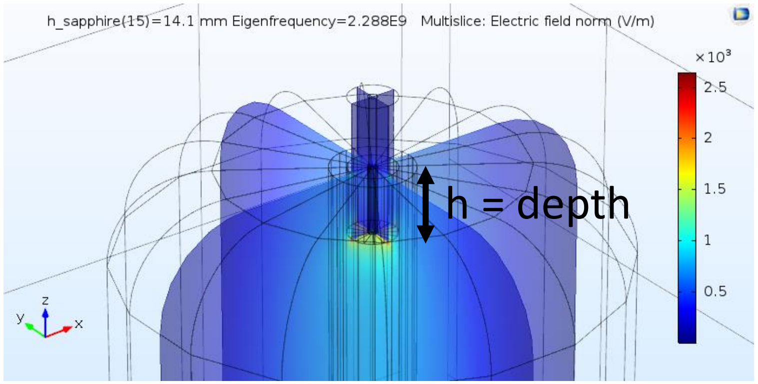
2.3 GHz Axion Search Cavity

- 2.3 GHz ReBCO Cavity (Dr. Seongtae Park)
  - ✓ (December 8th, 2019) Q ~ 340,000 at 8 T
  - ✓ (January 18th, 2020) Q ~ 500,000 at 8 T (Using Different Tape)

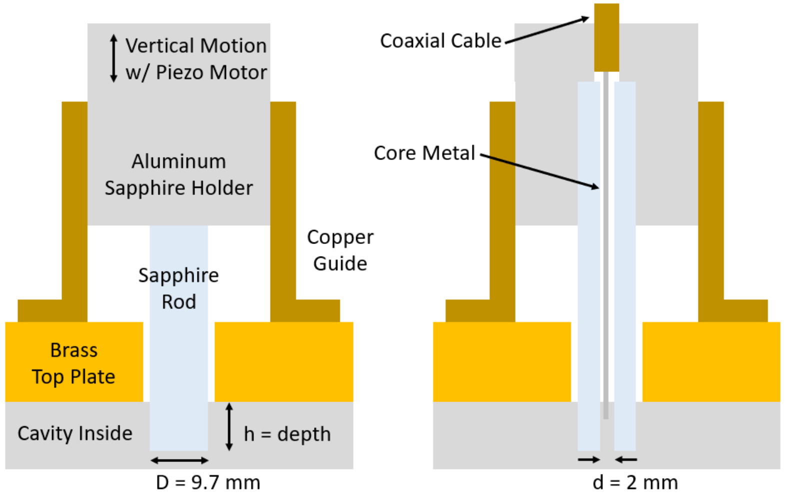


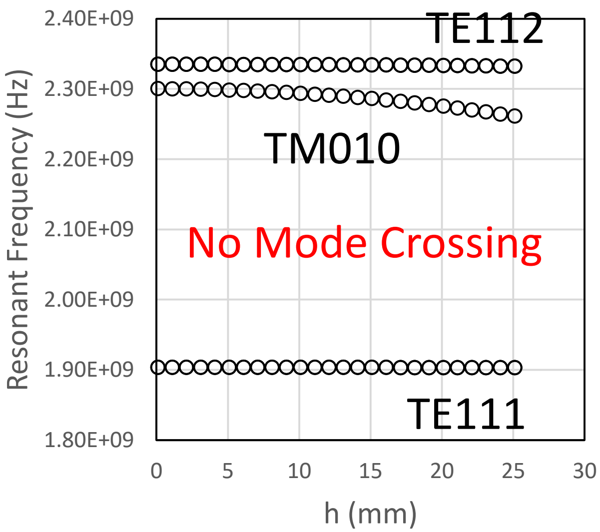


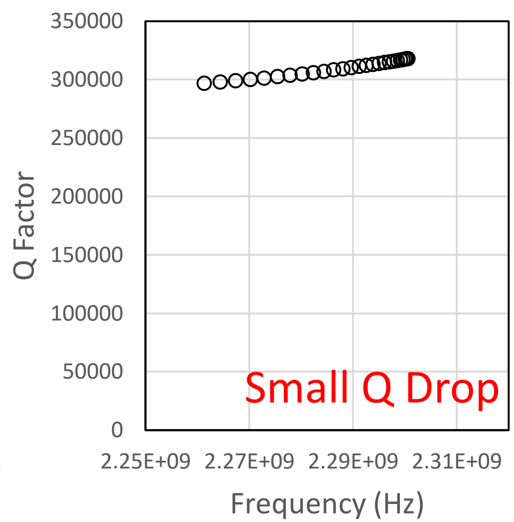
Tuning System

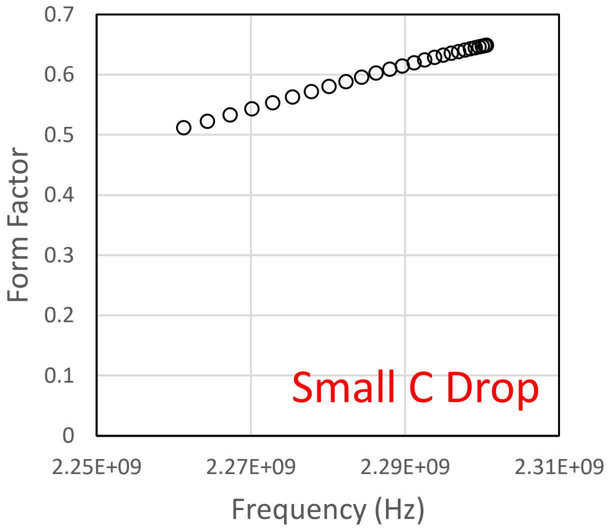


Simplified Tuning Simulation







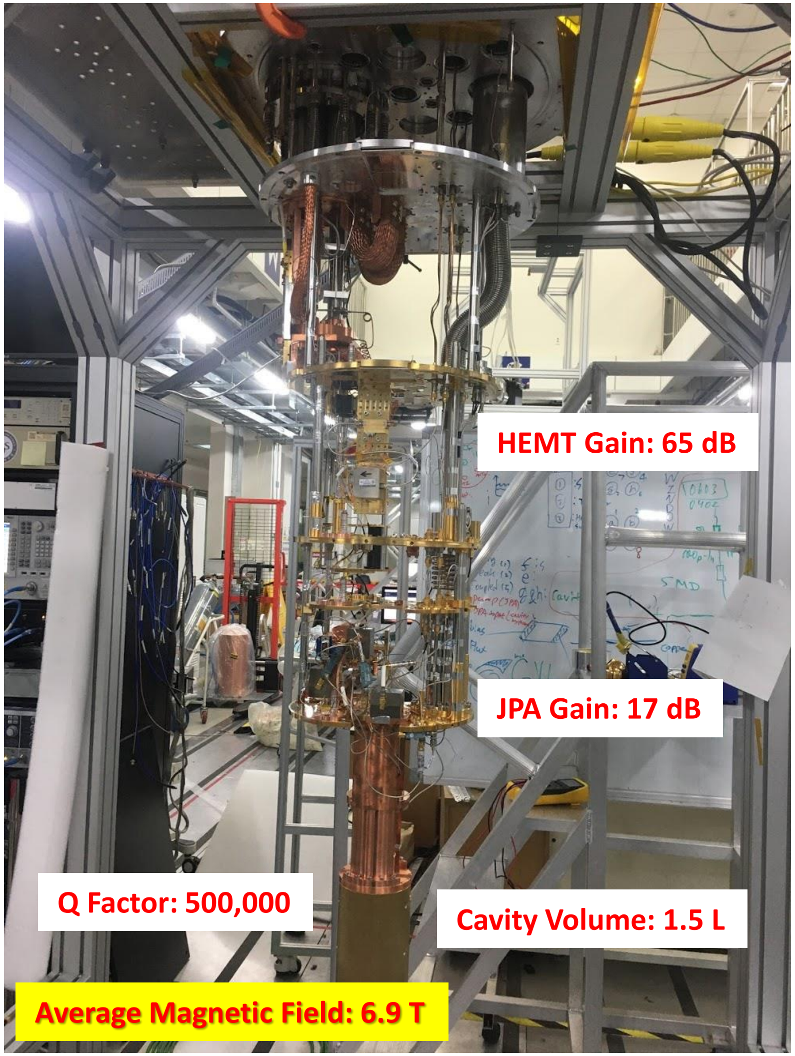


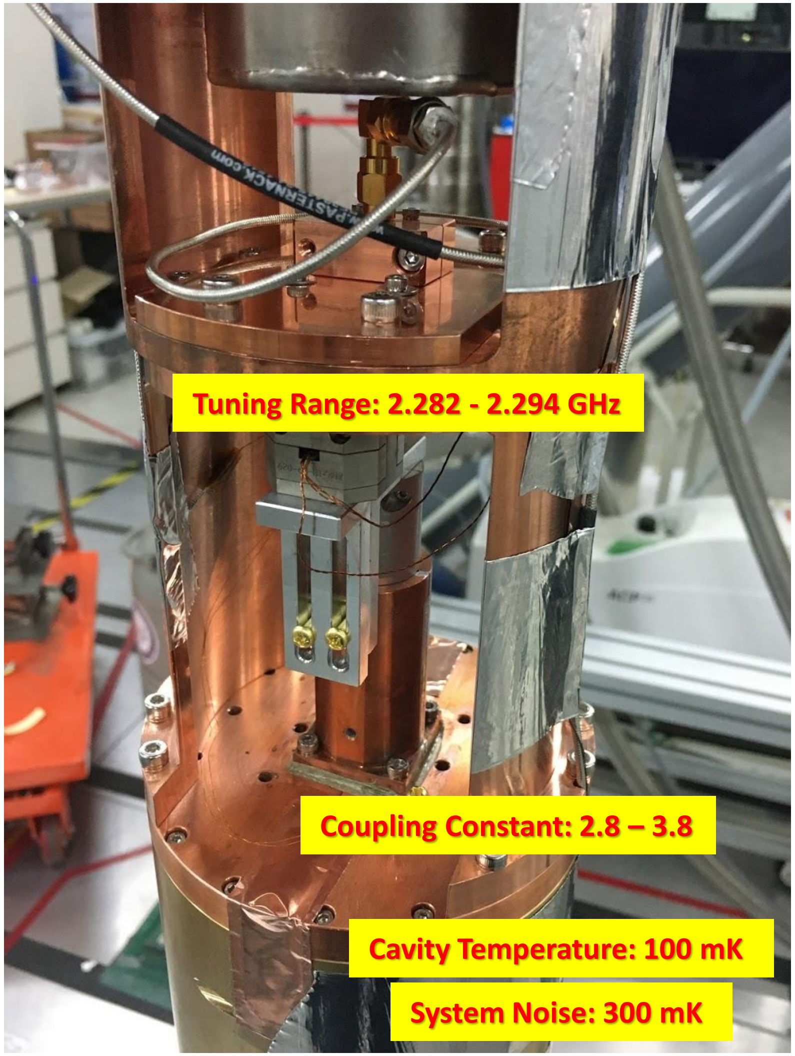
Testing in a CAPP-PACE Chain

	HEMT Run Phys. Rev. Lett. 126 (2021) 191802	**JPA Run** About to Submit (Mr. Jinsu Kim *et al.*)	**SC Run (Plan)**
Frequency Range	2.457 – 2.749 GHz	2.27 – 2.30 GHz	2.27 – 2.30 GHz
Magnetic Field (B)	7.2 T	7.2 T	7.2 T
Volume (V)	1.12 L	1.12 L	1.5 L
Quality Factor (Q_0)	100,000	100,000	**500,000 – 1,000,000**
Geometrical Factor (C)	0.51 – 0.66	0.45	0.51 – 0.65
System Noise (T_{sys})	1.1 K	**200 mK**	**200 mK**
Scan Rate (Arb.)	**1**	**18**	**150 – 300**

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

Commissioning Run Parameters



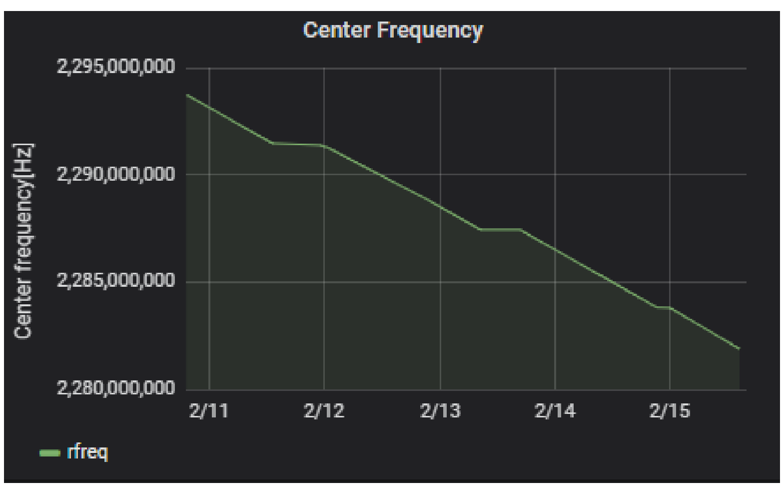


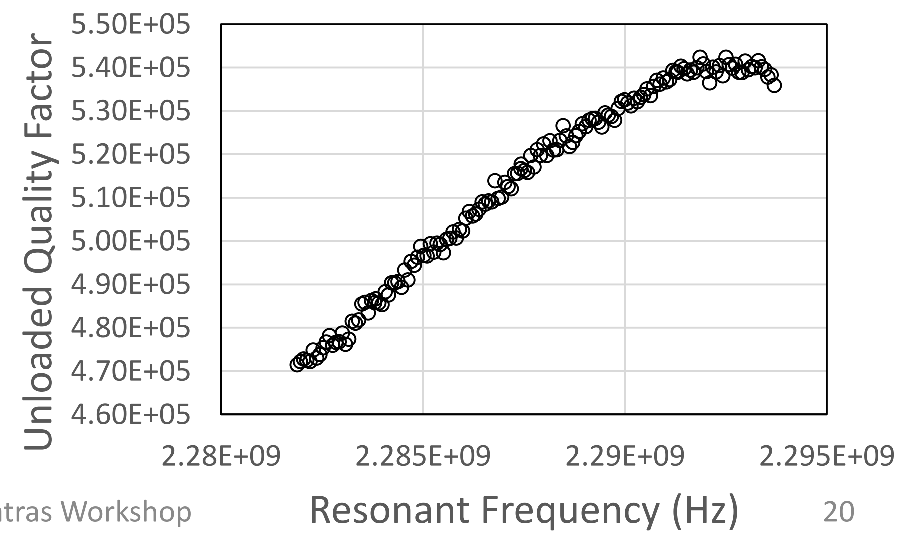
Commissioning Run

- Commissioning run is successfully finished.
  - ✓ Period: (2021) Feb 10th 19:30 ~ Feb 15th 14:30
  - ✓ Experiment Parameters

1.9 min / step

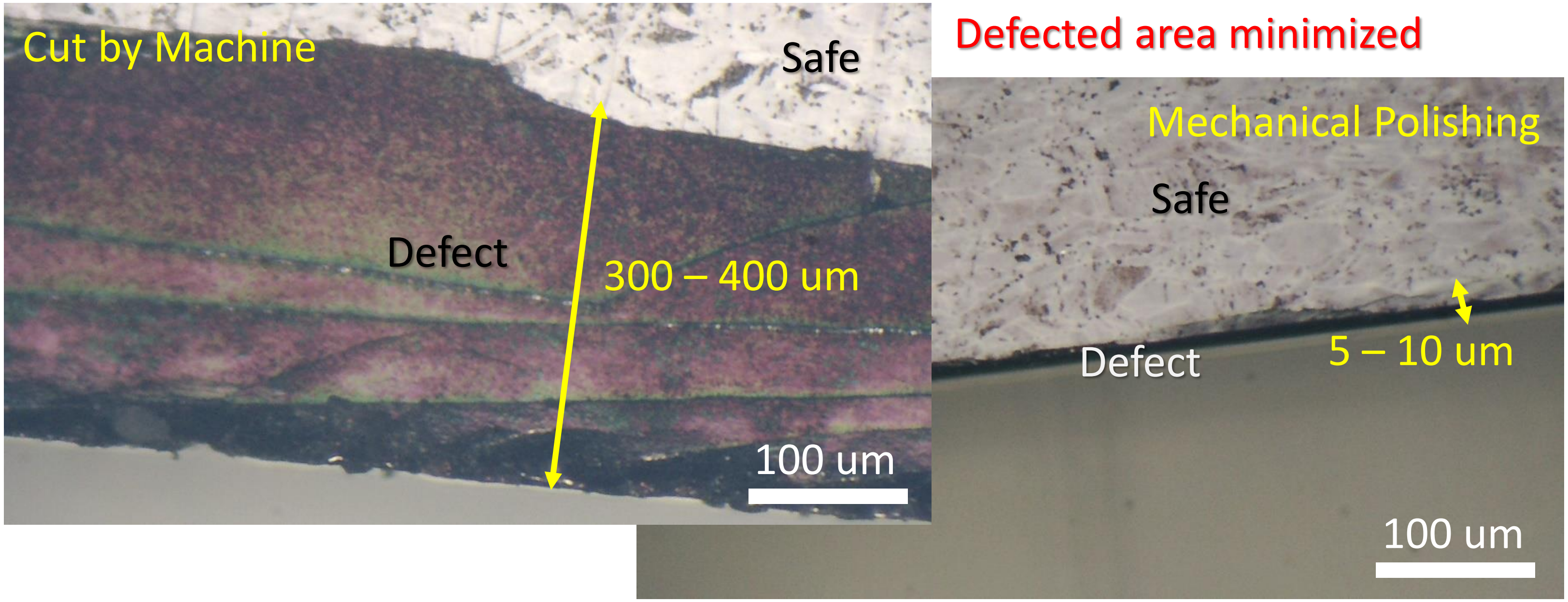
- JPA Noise Measurement (Every 1 MHz)
- NA (Span 50 kHz, IFBW 100 Hz, 501 points): Q_L, β, Every 20 steps
- SA (60 sec, Span 100 kHz, RBW 100 Hz, 1000 points)
- Cavity Tuning (5 kHz), JPA Tuning (17 dB Gain, Every 10 times)





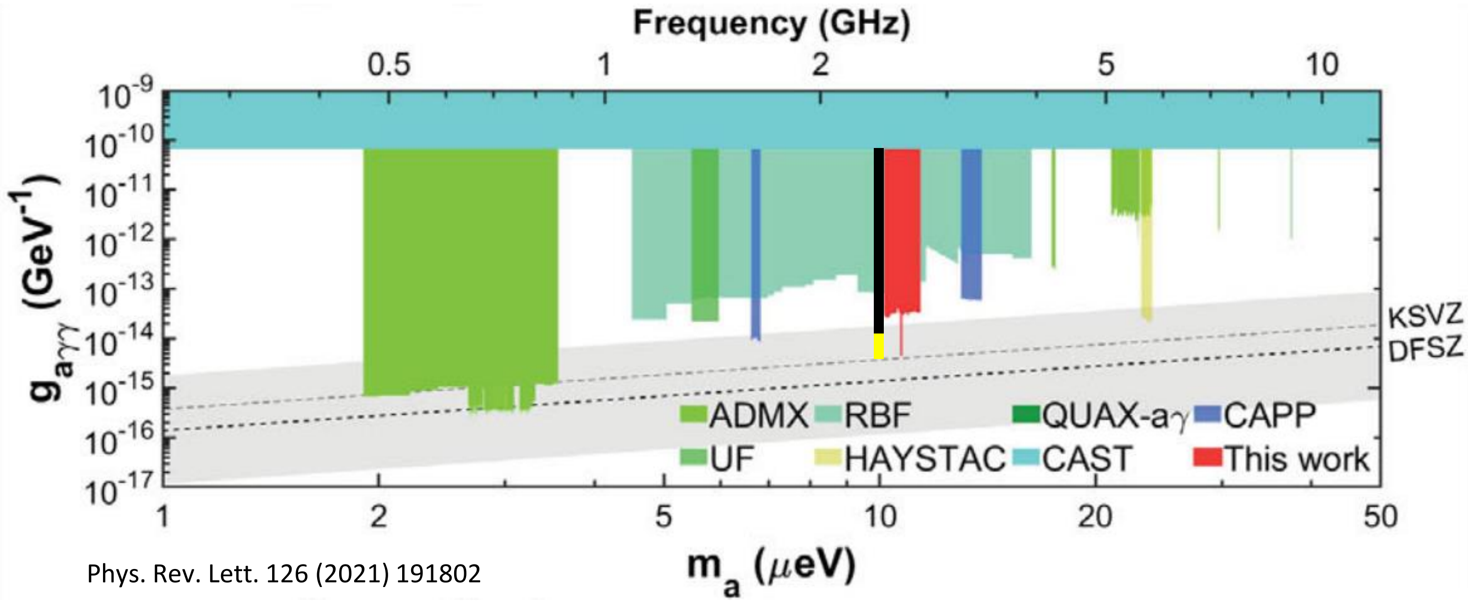
Plan for Improving 2.3 GHz ReBCO Cavity

- Next Version Cavity
  - Quality Control of Tapes (targeting $Q_0 \sim 1{,}000{,}000$)



  - Cavity Temperature Reduction: 100mK → 50mK
    - ✓ Brass Body → Copper Body (Improving Thermalization)

Target Sensitivity



Phys. Rev. Lett. 126 (2021) 191802

- HEMT Run Target: 9 KSVZ (Published)
- JPA Run Target: 2.8 KSVZ (About to Submit)
- Superconducting Cavity Run Target: 1 KSVZ

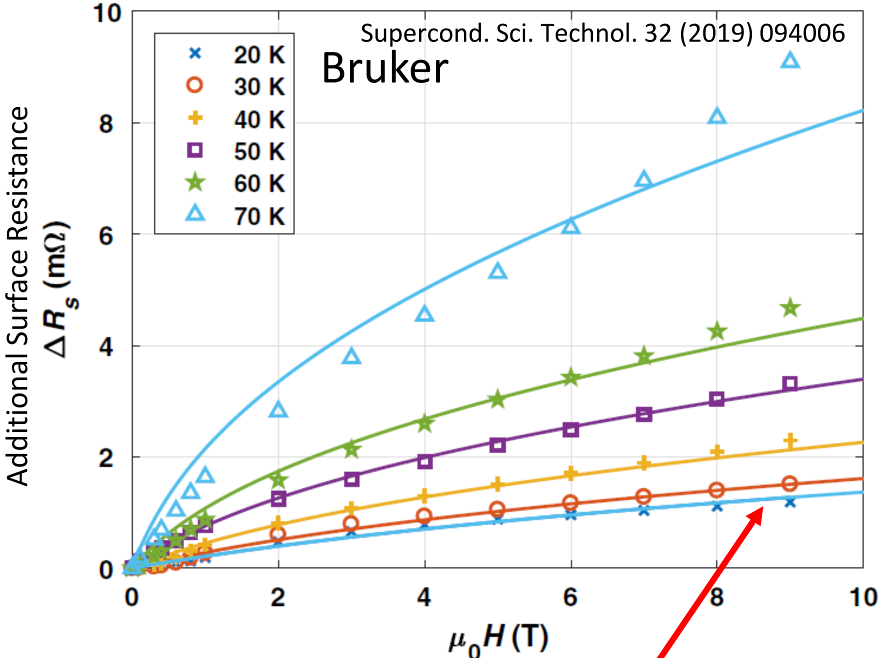
Summary

(Credit: ESO/L. Calçada)

- Superconducting Cavity R&D at CAPP aims to enhance axion search with a high Q factor cavity using superconductors.
- ReBCO is one of the most promising materials for realizing a high Q cavity in a high magnetic field.
- CAPP successfully developed a half-million Q factor ReBCO cavity with a 2.3 GHz resonance frequency working in an 8 T magnetic field.
- The commissioning run with the 2.3 GHz ReBCO cavity was successfully finished.
- CAPP-PACE team is now planning to take 1 KSVZ data with the next version of the 2.3 GHz ReBCO cavity.

Superconductivity in a High Magnetic Field

8 GHz, Rutile Resonator



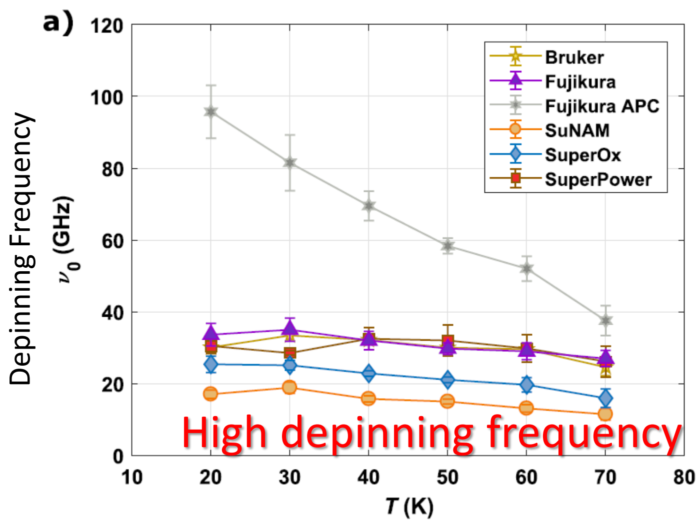
Lower Surface Resistance at Low Temperature

Gittleman & Rosenblum Model

$$\eta \dot{\mathbf{x}} + k_p \mathbf{x} = \mathbf{J} \times \Phi_0 \, \mathbf{n}_c .$$

$$\rho_v = \rho_{ff} \frac{1}{1 + i\nu_0/\nu} = \frac{B\Phi_0}{\eta} \frac{1}{1 + i\nu_0/\nu} .$$

$$Z_{fl} = Z(T, B) - Z(T, 0) = \Delta Z = \sqrt{i 2\pi \nu \mu_0 \rho_v} .$$



High depinning frequency

Biaxially textured ReBCO tapes has good properties for high Q cavity for axion Search

ReBCO Film at mK temperature

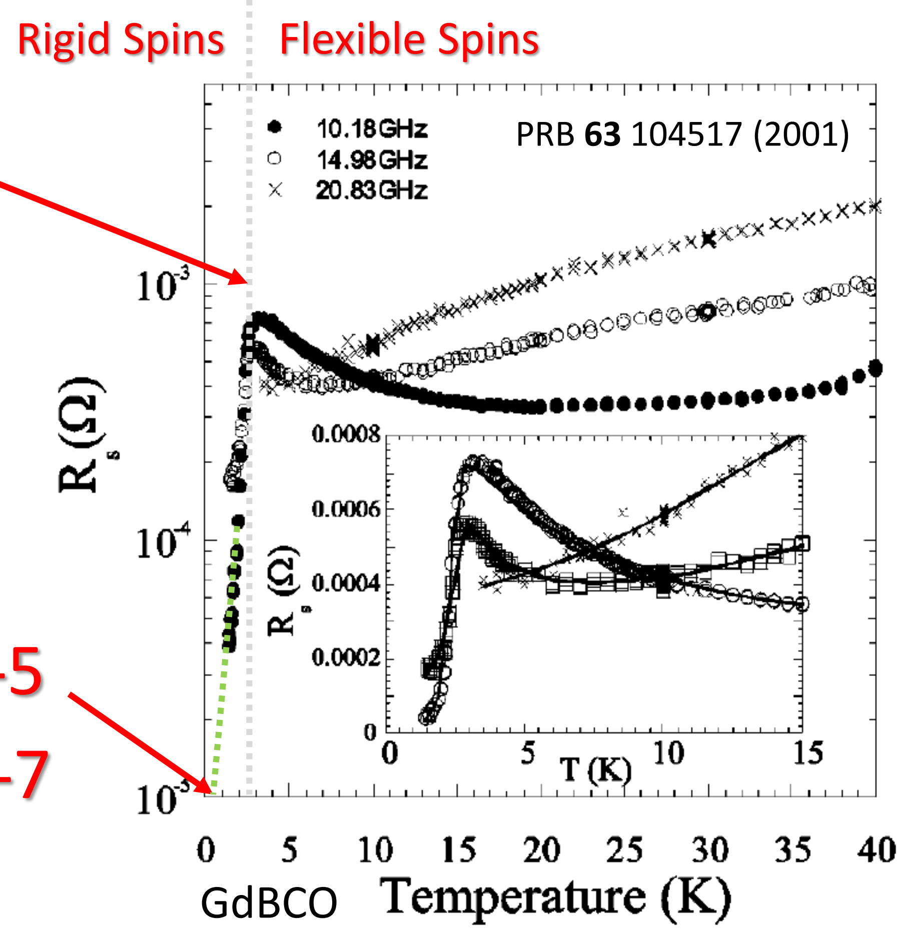
- Surface Resistance Study

Anti-ferromagnetism (AFM)
Gd Atom Spins
Néel Temperature ~ 2.2 K

$R_{s,\,0\,T,\,100\,mK,\,10.18\,GHz}$ ~ 1e-5

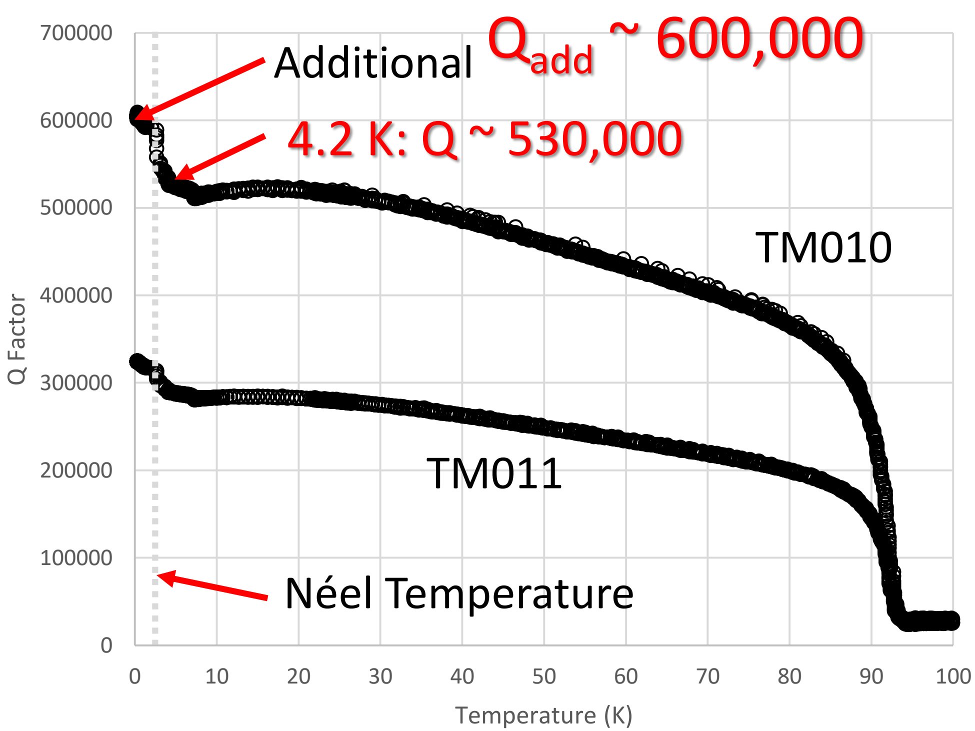
$R_{s,\,0\,T,\,100\,mK,\,2.3\,GHz}$ ~ 5.1e-7

$Q_{idealBBQ,\,100\,mK}$ ~ 7.83e8

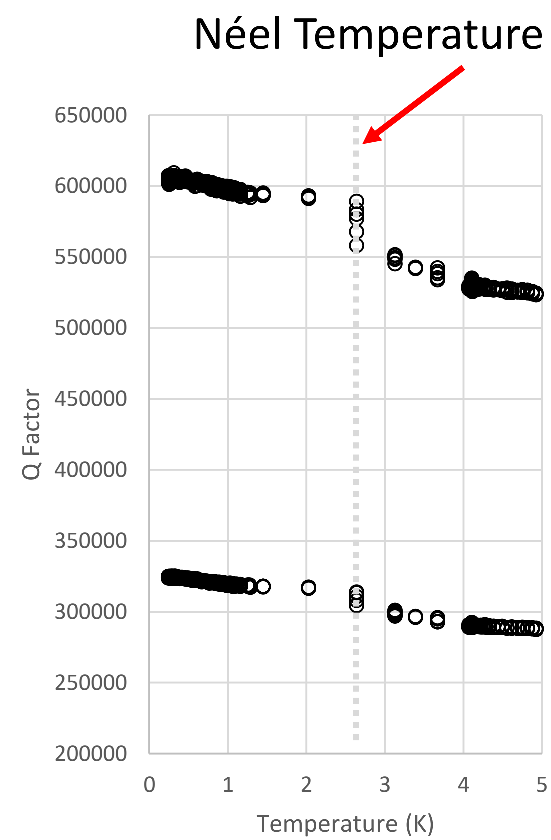


Cavity Q Factor Analysis

- Surface Resistance Study



$Q_{ReBCO,\ 4.2\ K}$ ~ 4,500,000

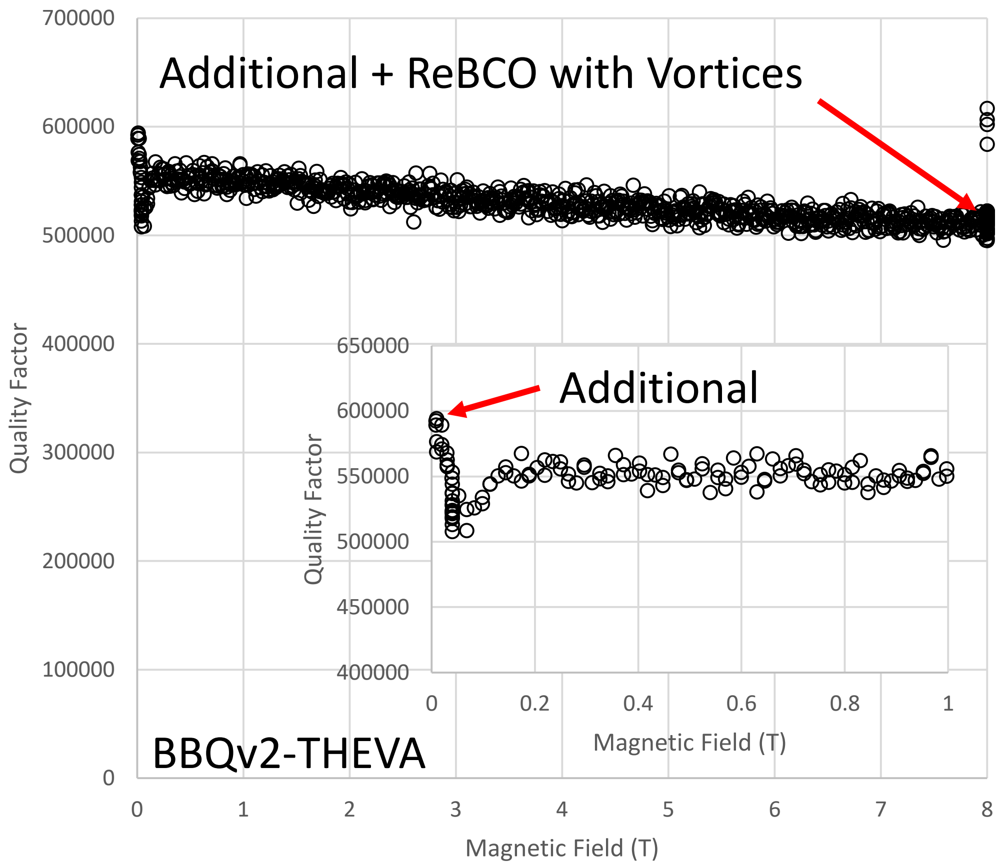


From Rutile Resonator

$Q_{idealBBQ,\ 0\ T,\ 4.2\ K}$ ~ 3,200,000

Cavity Q Factor Analysis

➢ Surface Resistance Study



at 8 T

Q_{ReBCO} ~ 3,000,000

ReBCO loss can be reduced
by additional pinning center (APC).
Ex) Fujikura APC, THEVA APC

Q_{add} ~ 600,000

Additional loss can be reduced
by improved delamination,
and polishing tapes mechanically.