Superconductors for Dark Matter Detection (and maybe Accelerators)

Applied Superconductivity Center
National High Magnetic Field Laboratory
Florida State University

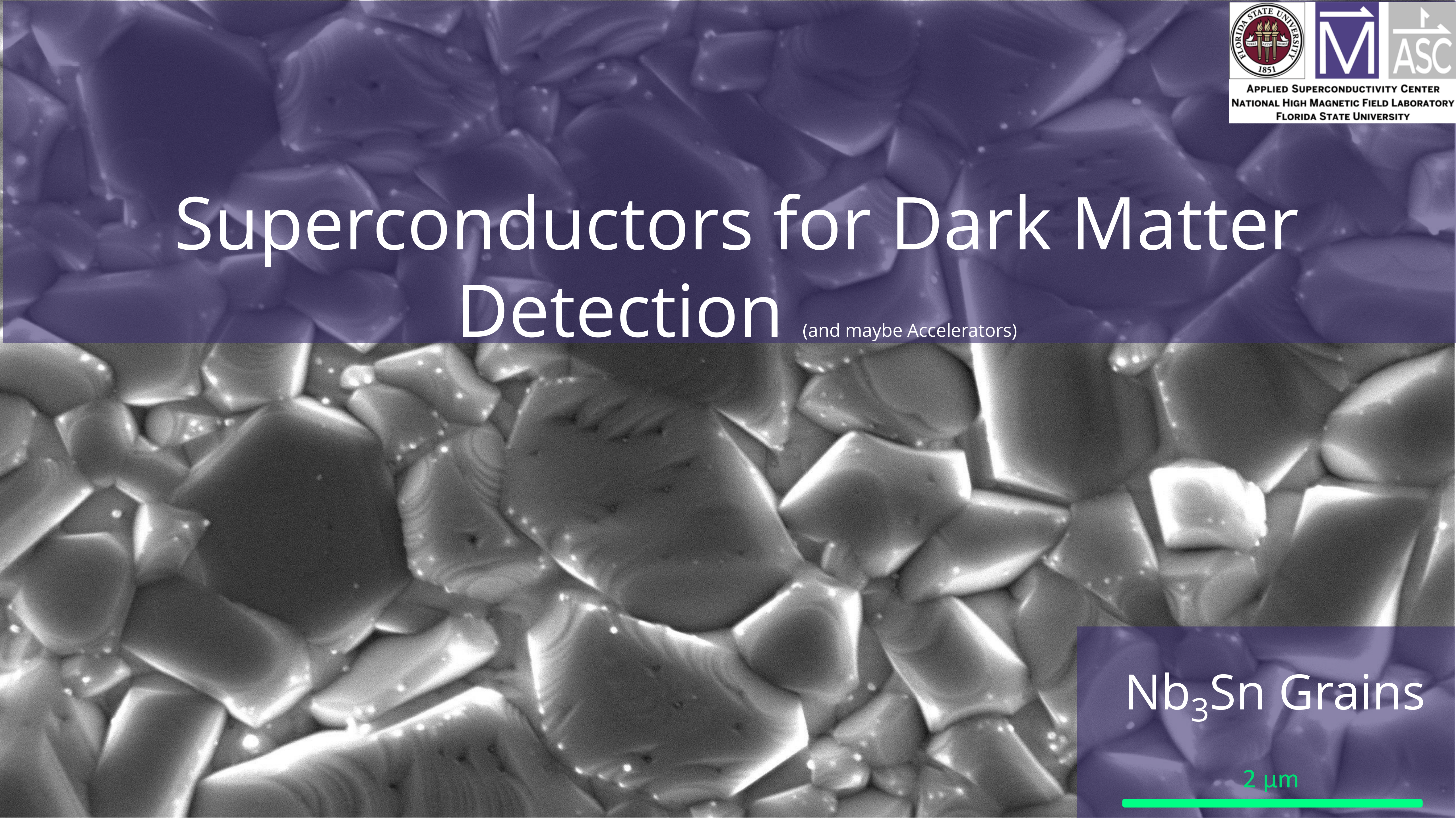
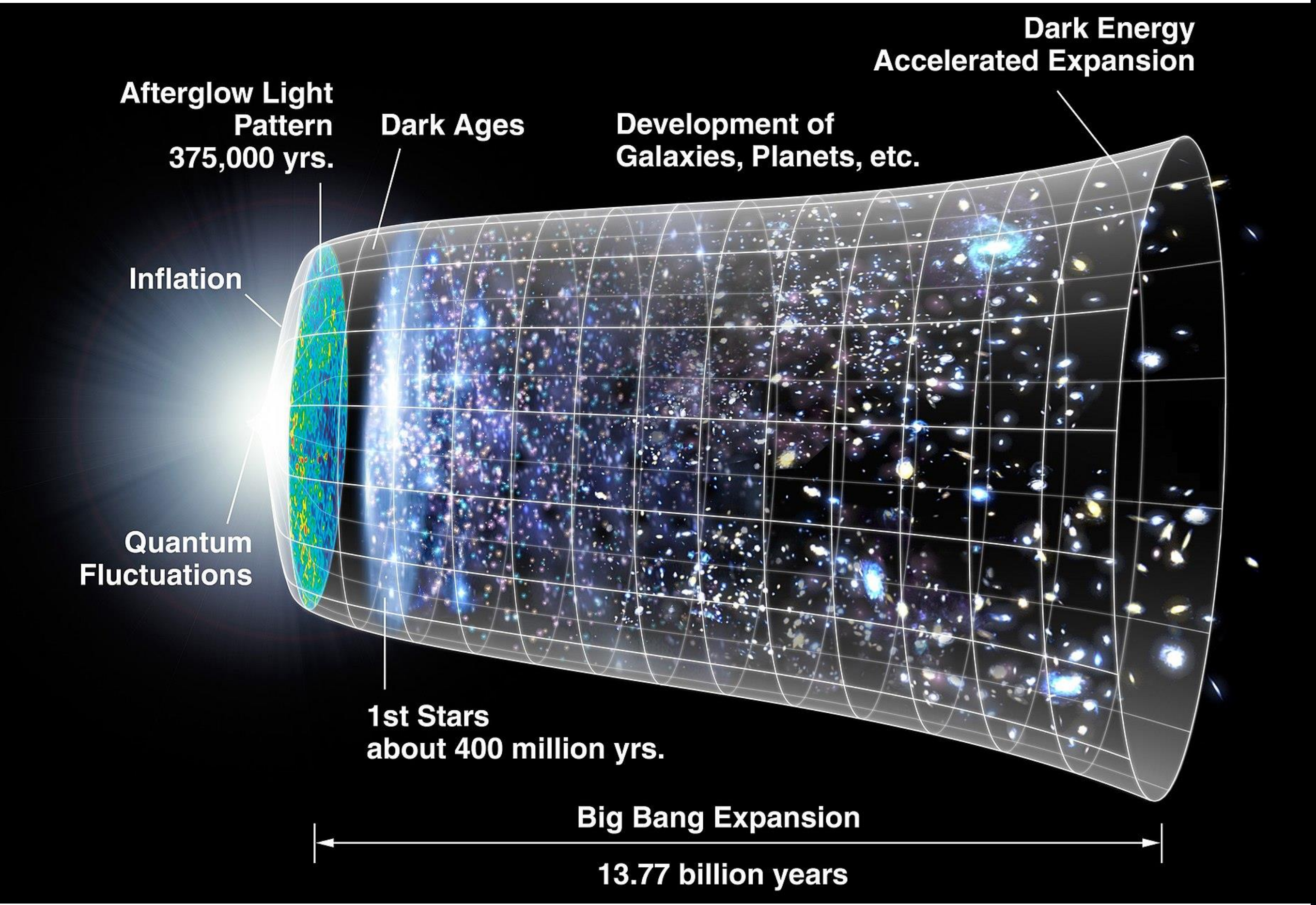


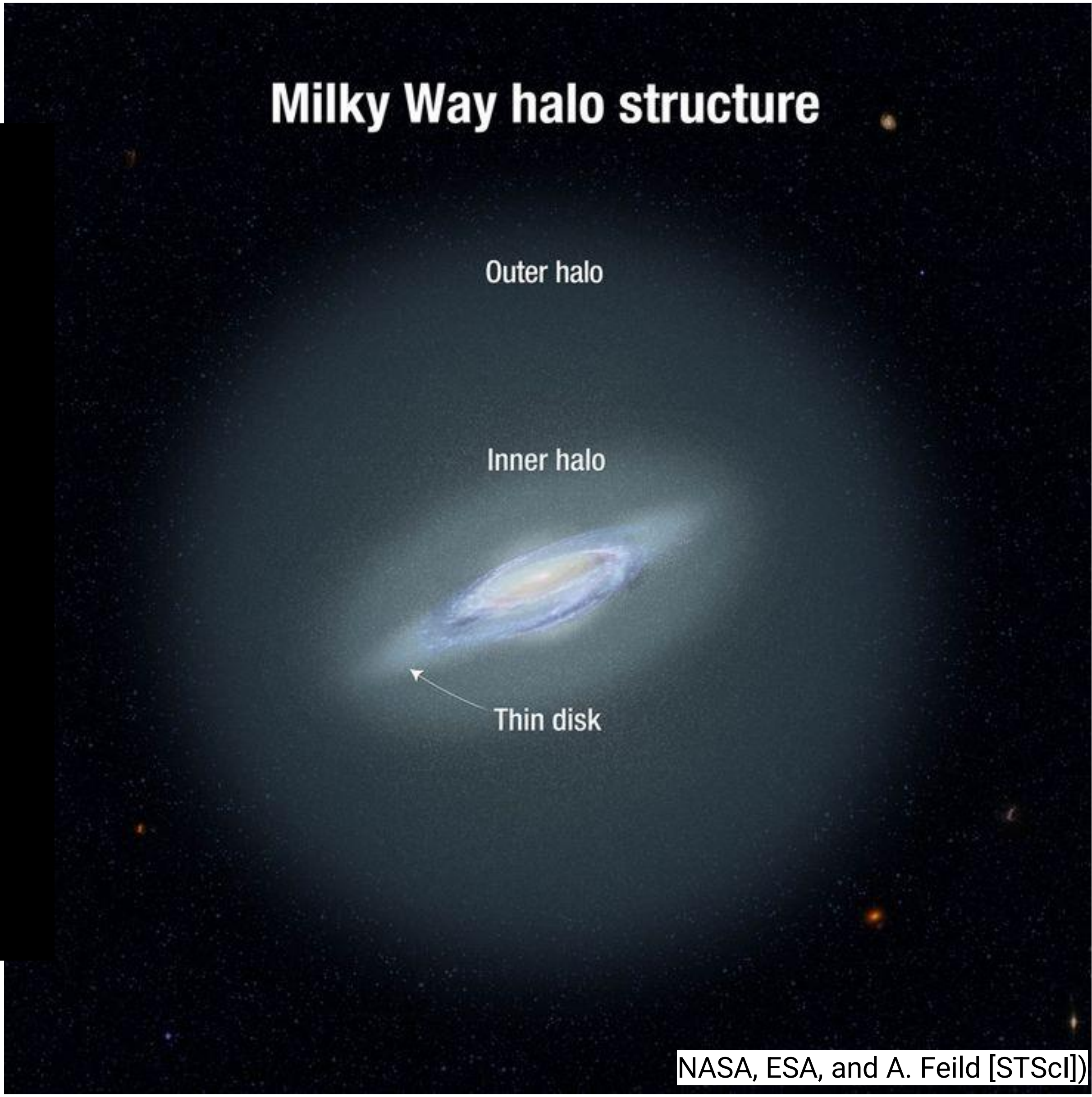
Table of Contents

- Axions
- Detecting the Axion
- Nb_3Sn for Axion Detection
- Making a resonator
- Healing Seams for Axion Detectors (and maybe SRF cavities)

Baryogenesis and Dark Matter



[CMB Timeline300 no WMAP - Cosmological constant - Wikipedia]



NASA, ESA, and A. Feild [STScI])

NATIONAL MAGLAB

Axion comes to clean up!

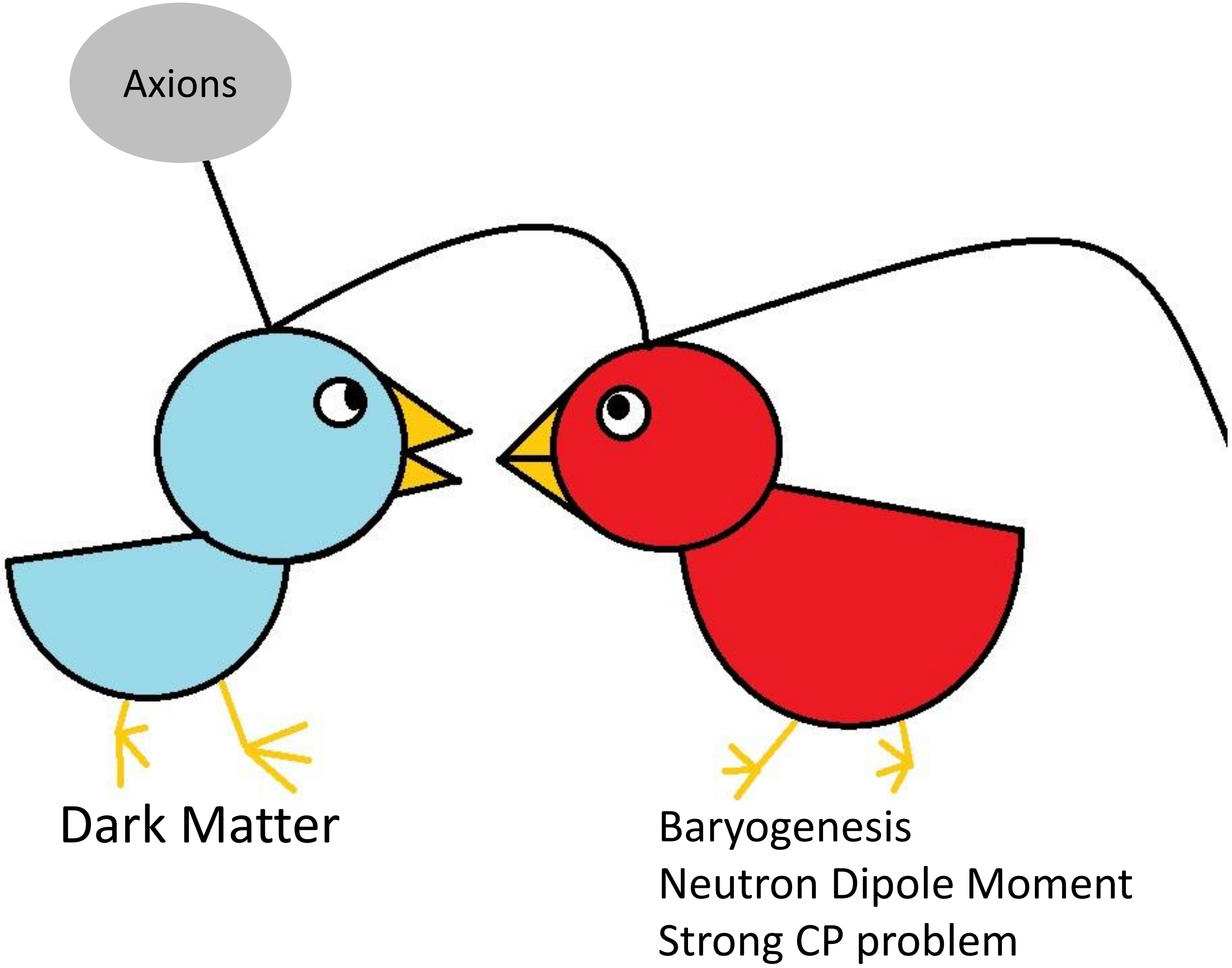
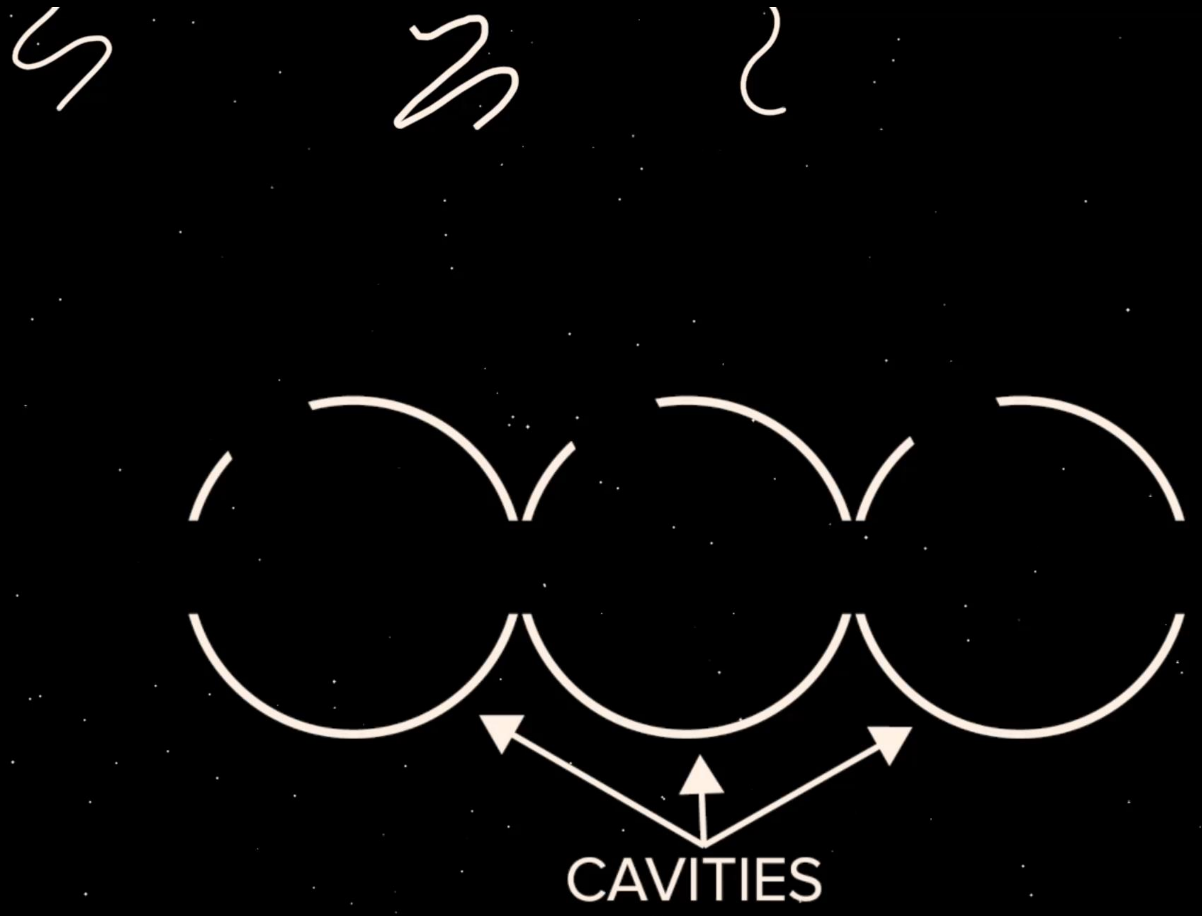


Table of Contents

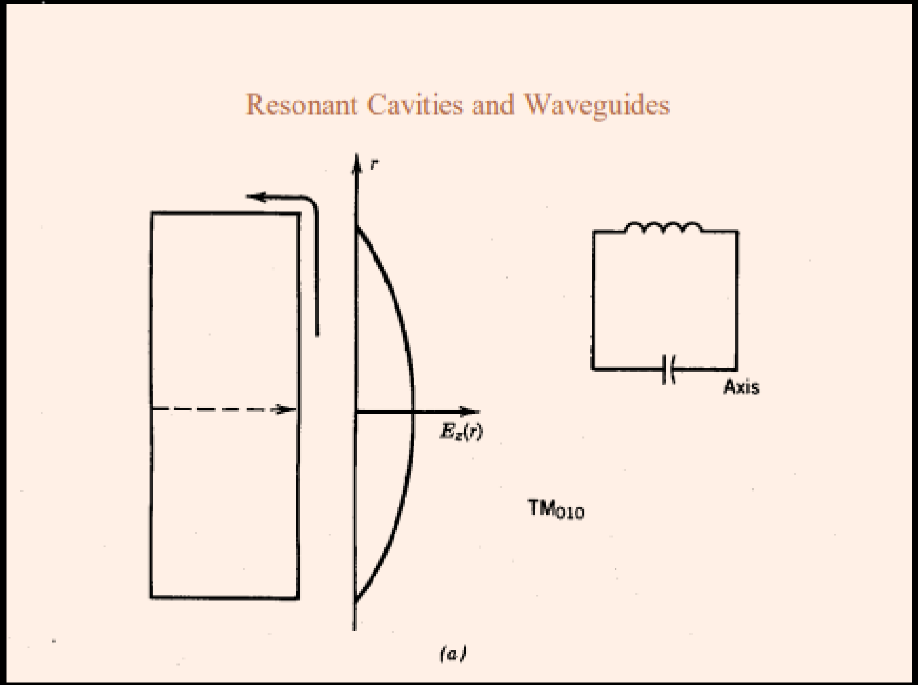
- Axions
- Detecting the Axion
- Nb_3Sn for Axion Detection
- Making a resonator
- Healing Seams for Axion Detectors (and maybe SRF cavities)

NATIONAL MAGLAB ASC

Resonance behavior of a cavity



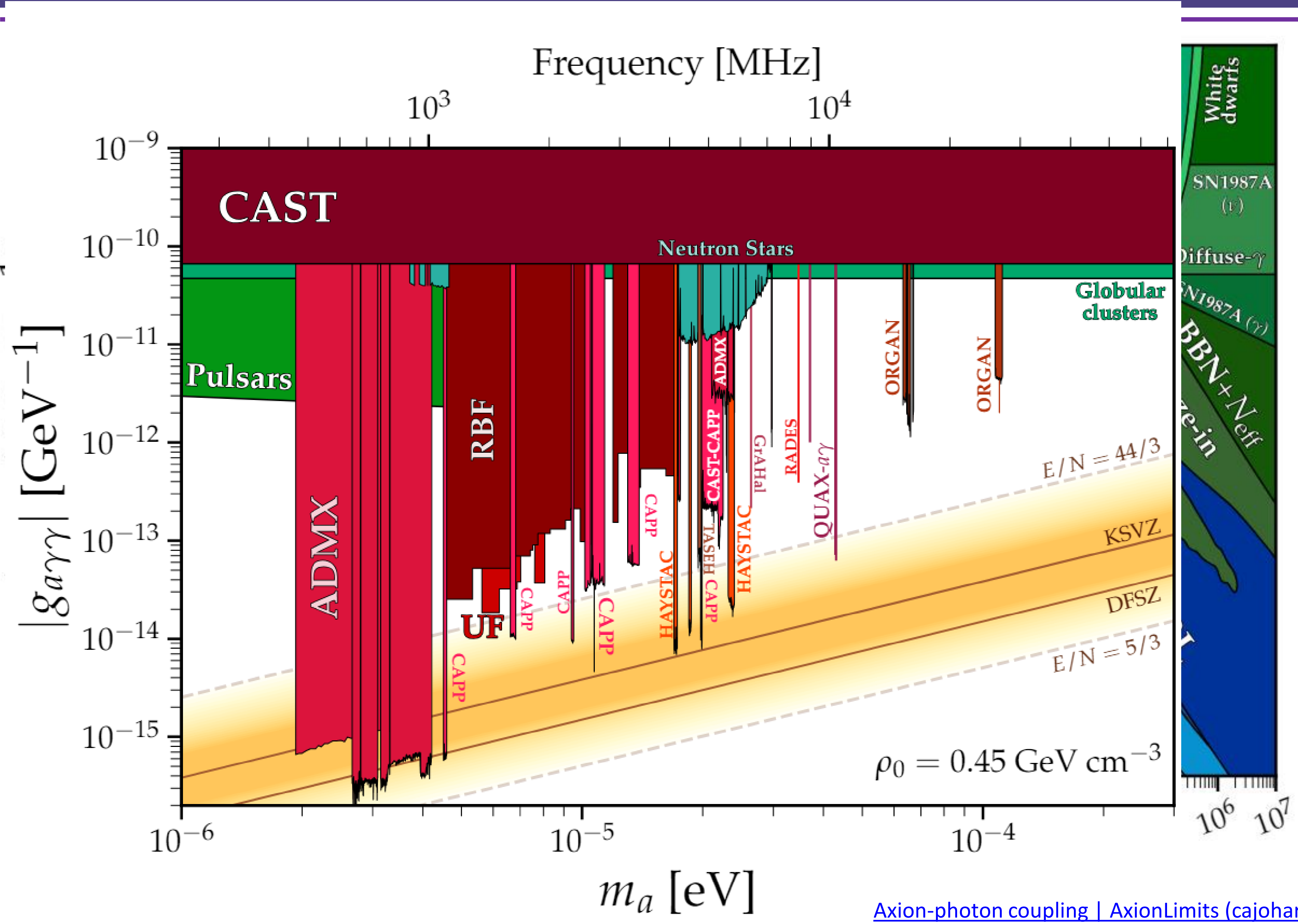
- Microwave at Resonant frequency depends on geometry of cavity
- Resonates at TM_{010} mode

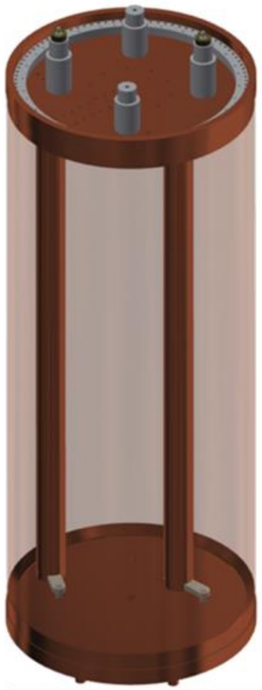


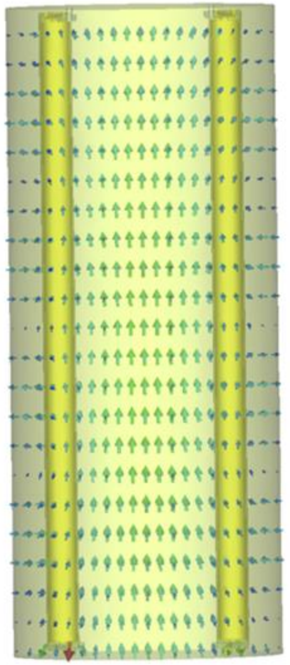
Accelerator Science: Why RF? (youtube.com)

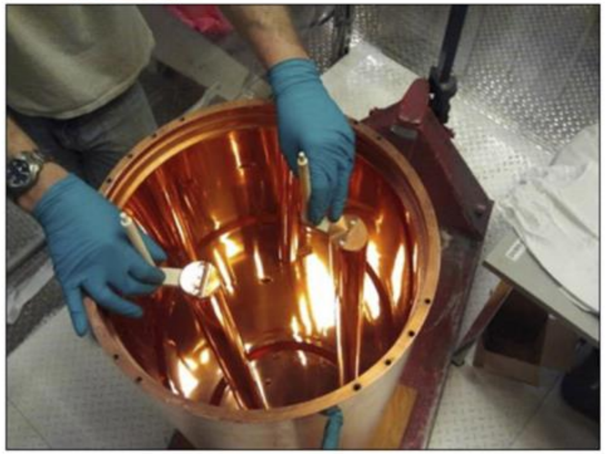
Resonant cavity and circuit analysis (physicsforums.com)

Detecting the Axion









[Axion-photon coupling | AxionLimits (cajohare.github.io)]

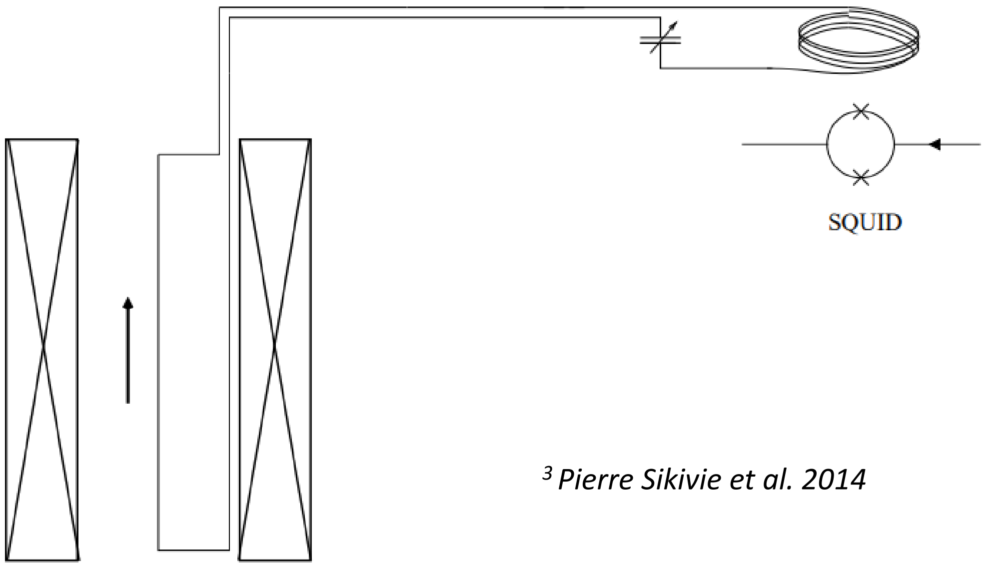
[2] C. Bartram, 2018

Measuring the Axion

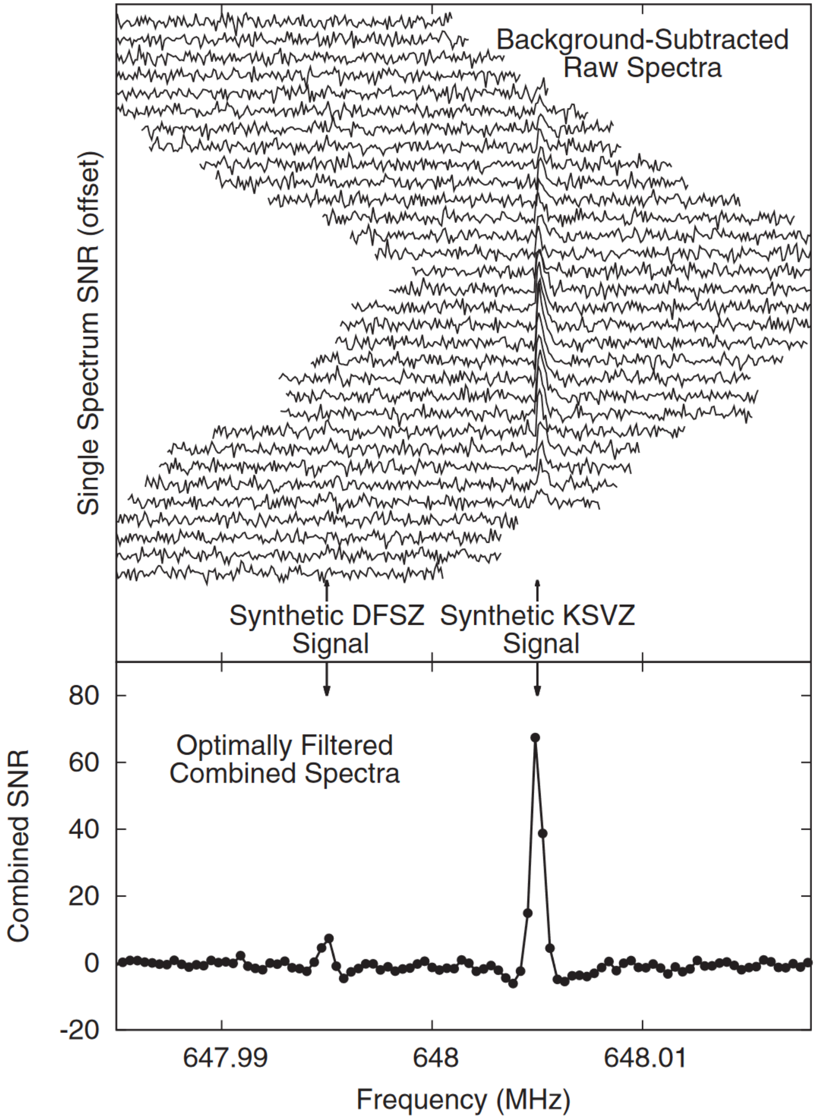
Power input from Axion Decay

$$P_{axion} = 1.9 \times 10^{-22}\ \mathrm{W} \left(\frac{V}{136\ \mathrm{l}}\right)\left(\frac{B}{6.8\ \mathrm{T}}\right)^2\left(\frac{C}{0.4}\right)\left(\frac{g_\gamma}{0.97}\right)^2 \times \left(\frac{\rho_a}{0.45\ \mathrm{GeV\ cm^{-3}}}\right)\left(\frac{f}{650\ \mathrm{MHz}}\right)\left(\frac{Q_\alpha}{50{,}000}\right).$$

Nick Du et al. 2018



[3] *Pierre Sikivie et al. 2014*



[4] *Nick Du et al. 2018*

Power from Axion Decay

$$P_{axion} = 1.9 \times 10^{-22}\ \mathrm{W} \left(\frac{V}{136\ \mathrm{l}}\right)\left(\frac{B}{6.8\ \mathrm{T}}\right)^2\left(\frac{C}{0.4}\right)\left(\frac{g_\gamma}{0.97}\right)^2 \times \left(\frac{\rho_a}{0.45\ \mathrm{GeV\ cm^{-3}}}\right)\left(\frac{f}{650\ \mathrm{MHz}}\right)\left(\frac{Q_\alpha}{50{,}000}\right).$$

Cavity Geometry

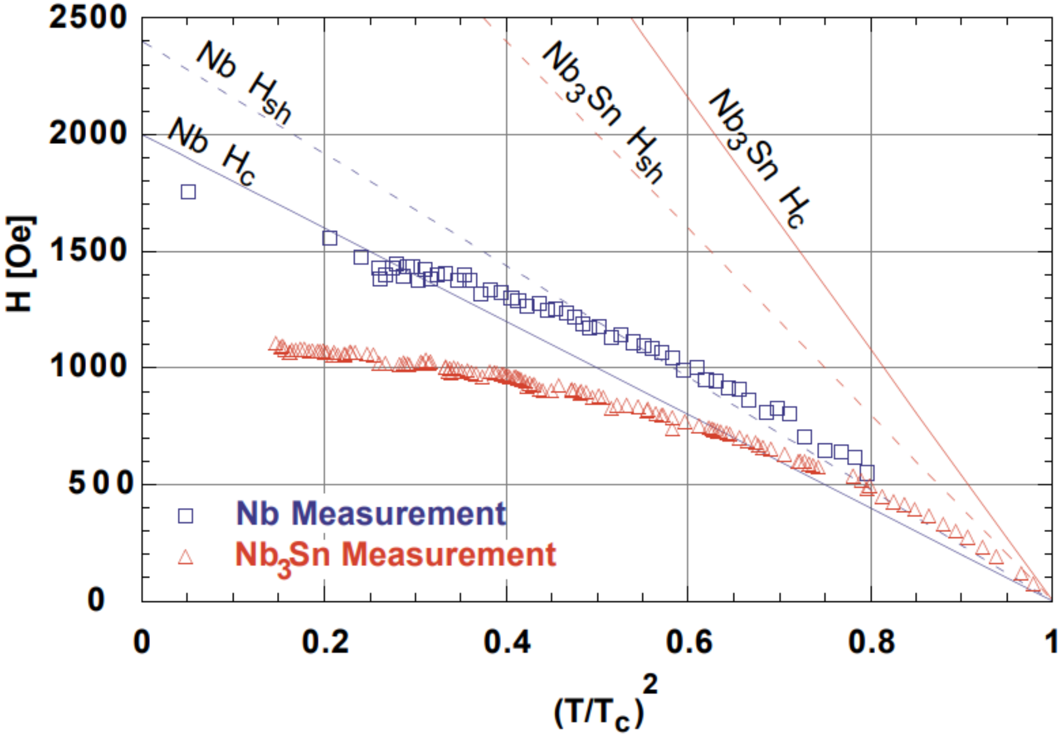
Dependent on Axion model

Maximize these!

[4] Nick Du et al. 2018

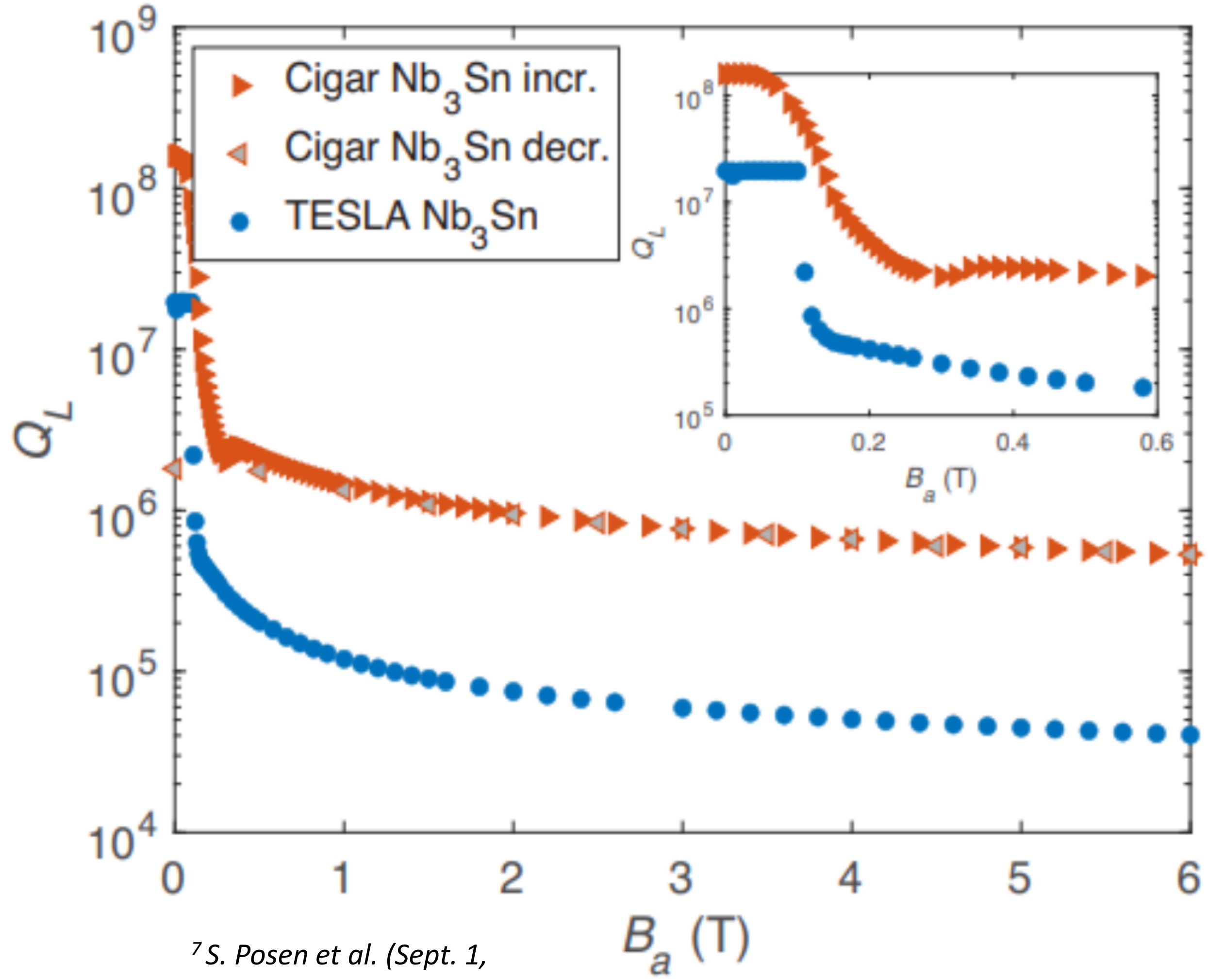
Quality factor and Superconductors

Low Field



[5] *Posen, S., and D. L. Hall., 2017*

High Field



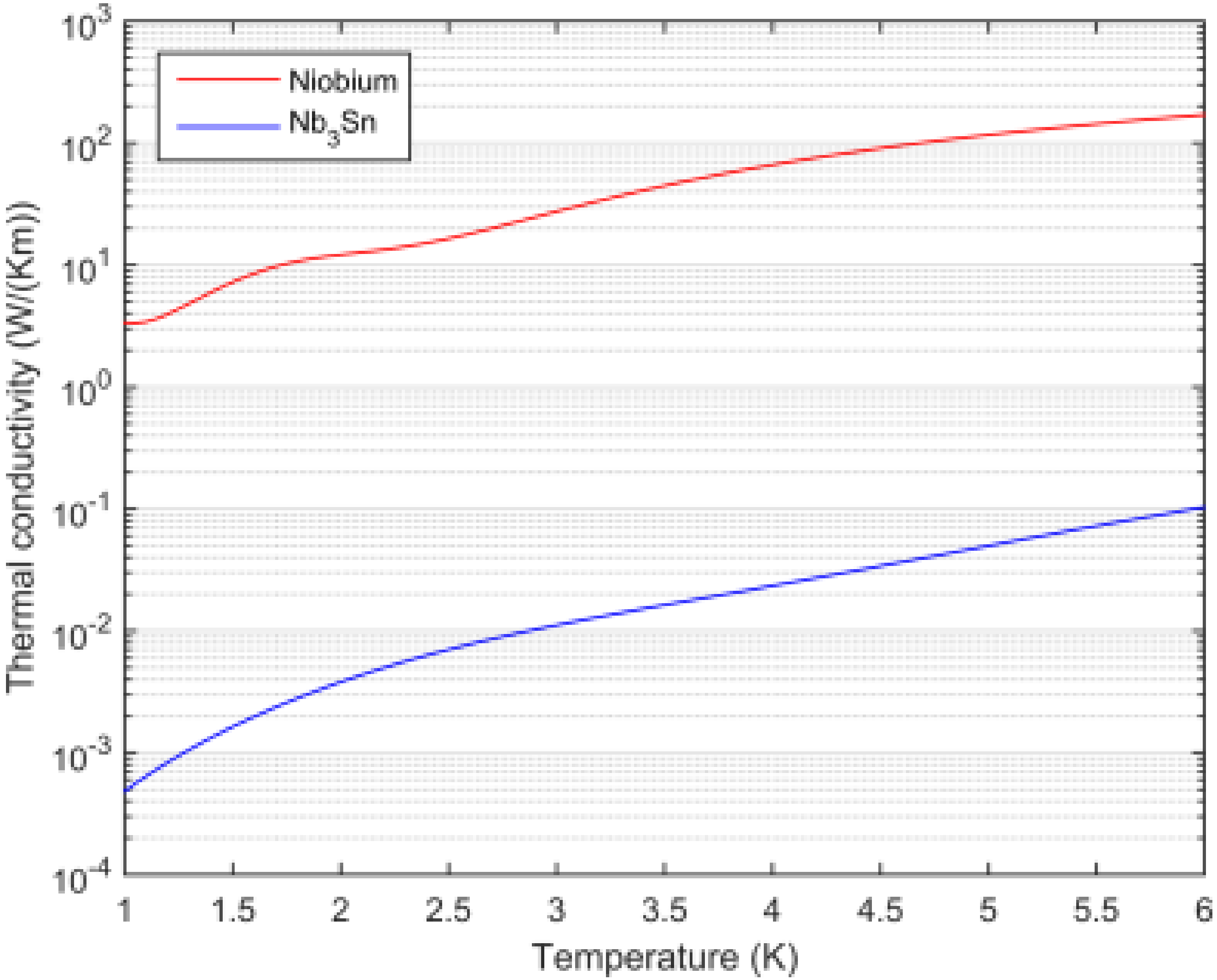
[7] *S. Posen et al. (Sept. 1, 2023)*

NATIONAL MAGLAB

Why Nb_3Sn on Cu?

- Copper has good thermal conductivity; this suppresses hot spot formation in the Nb_3Sn and allows for high Q factor at low E_{acc}

- Needed due to Nb_3Sn's low thermal conductivity



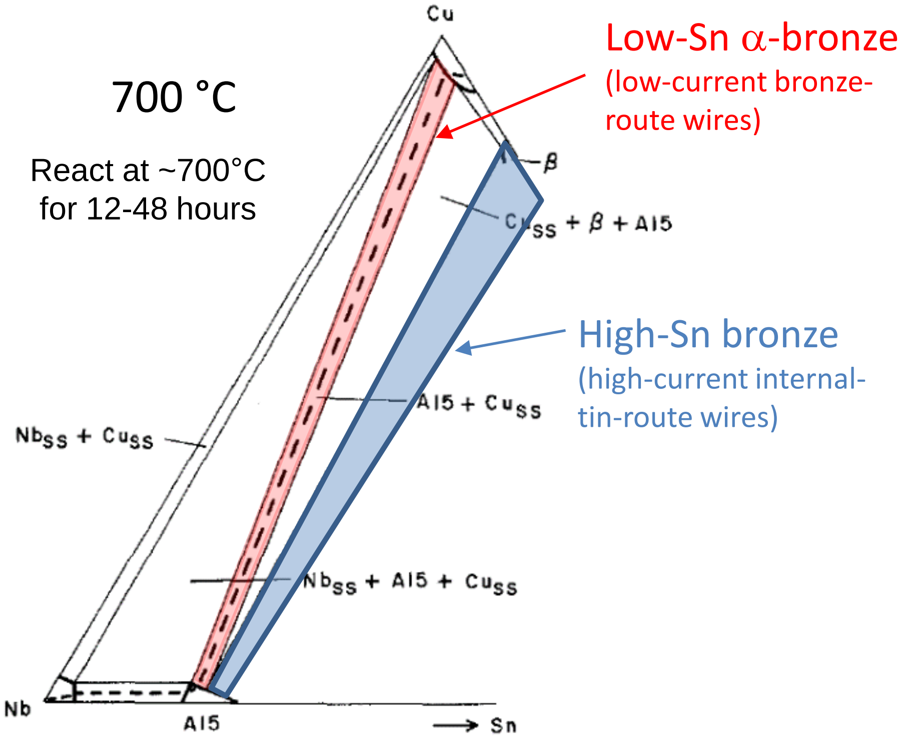
Daniel Hall PhD, F Koechlin 1996, G D 1964

Table of Contents

- Axions
- Detecting the Axion
- Nb_3Sn for Axion Detection
- Making a resonator
- Healing Seams for Axion Detectors (and maybe SRF cavities)

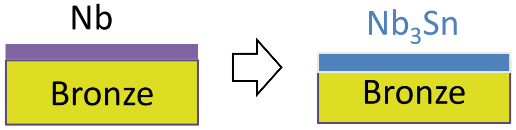
We’ve succeeded making Nb_3Sn films in multiple ways

- Bronze route reaction temperature of ~700°C is compatible with Cu cavities
  - Cu melts at 1085°C, below the ~1100°C tin vapor method
  - Cu cavities facilitate conduction cooling and goals of DOE Accelerator Stewardship.
- We recently used a high-Sn alloy instead of the usual α-bronze to increase tin activity.
  - Increased tin activity is the key to success of Nb_3Sn wires for high-field magnets
  - Increased tin activity is vital to avoid tin-poor A15 with degraded superconducting properties
- Experiments began with Nb substrates then moved on to Cu substrates

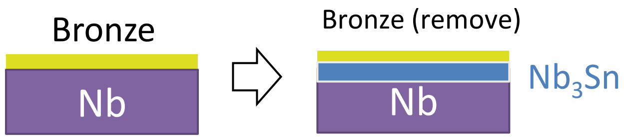


D. Dew-Hughes & T. S. Luhman Journal of Materials Science volume 13, pages1868–1876(1978)

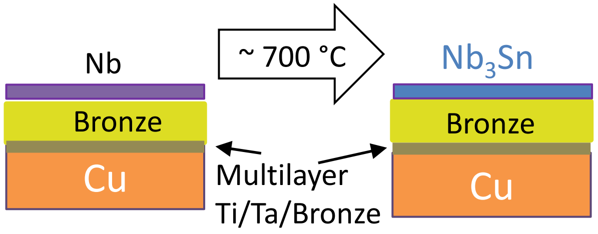
[8] *Withanage et al., 2021*



[9] *This work*



[10] *This work*

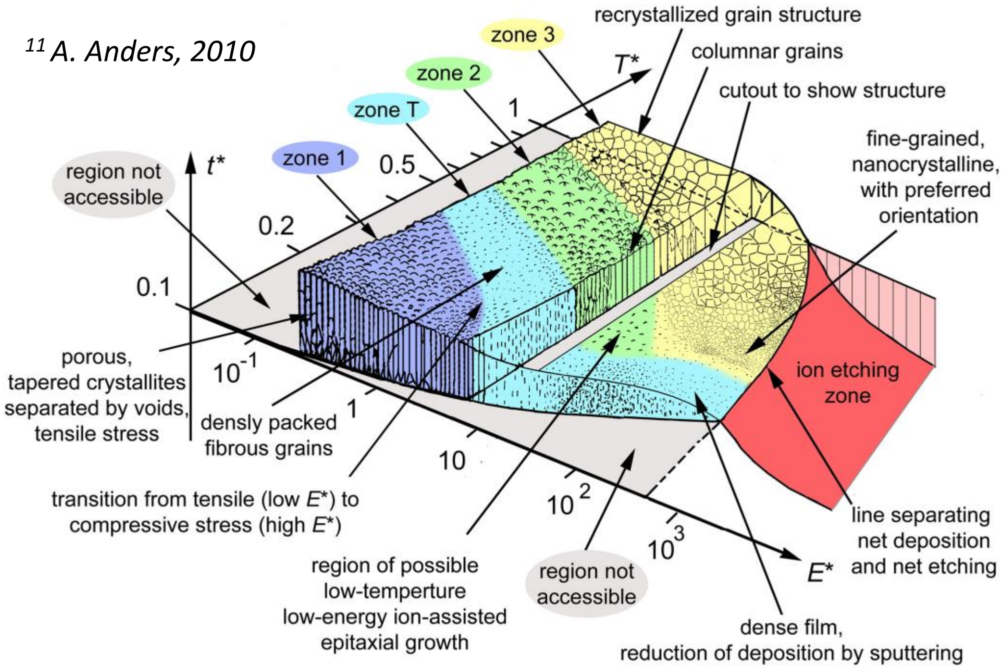


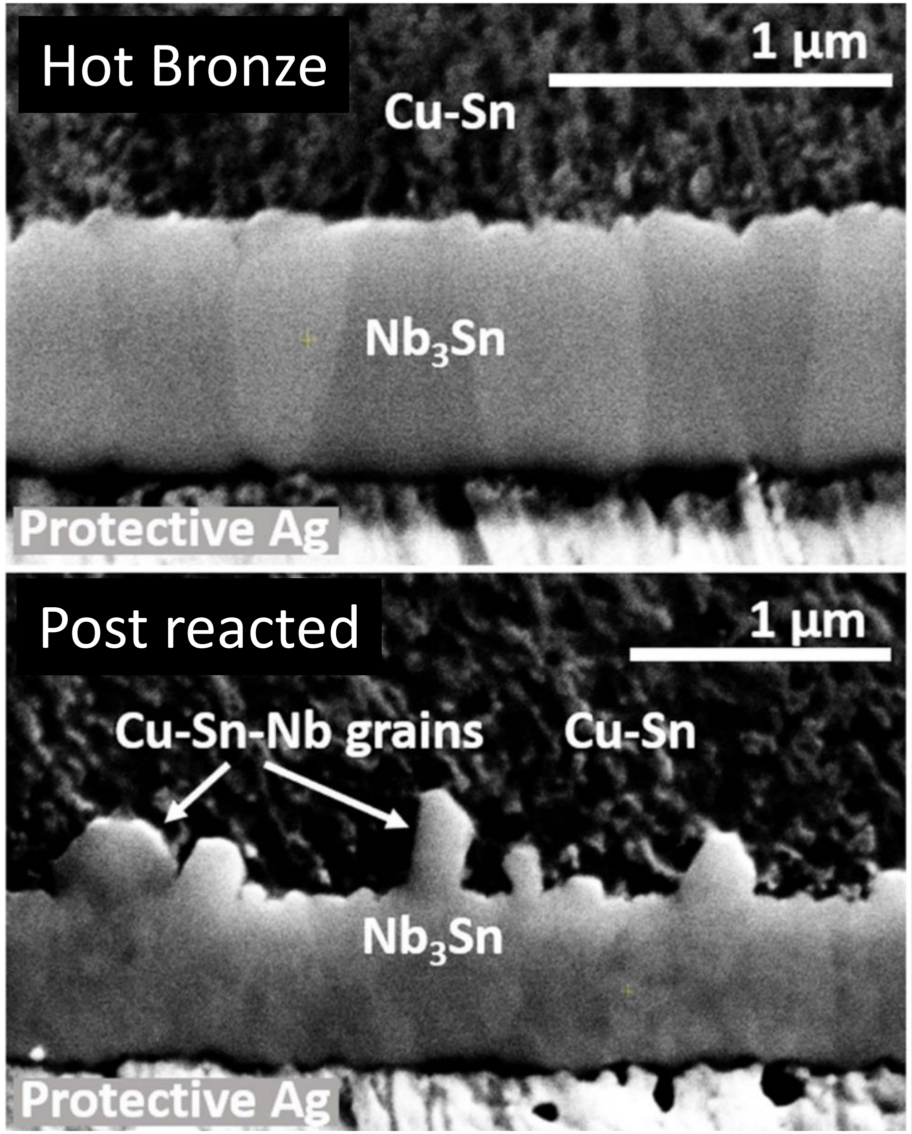
NATIONAL MAGLAB ASC

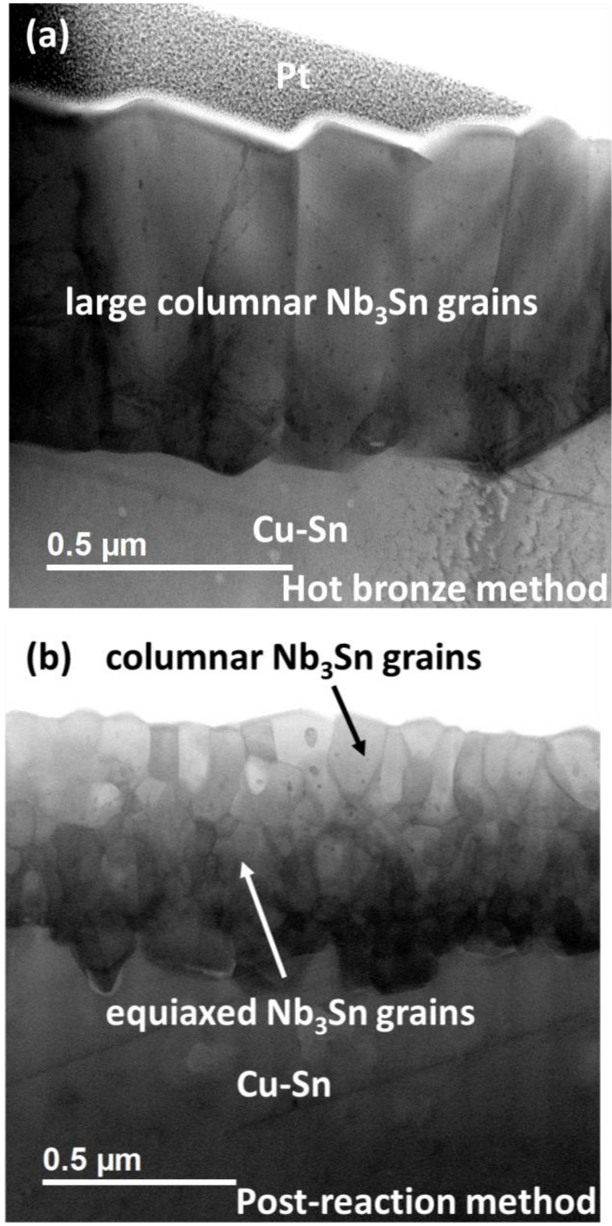
Bronze substrate

Hot Bronze reminiscent of zone T sputtered microstructure

[11] *A. Anders, 2010*





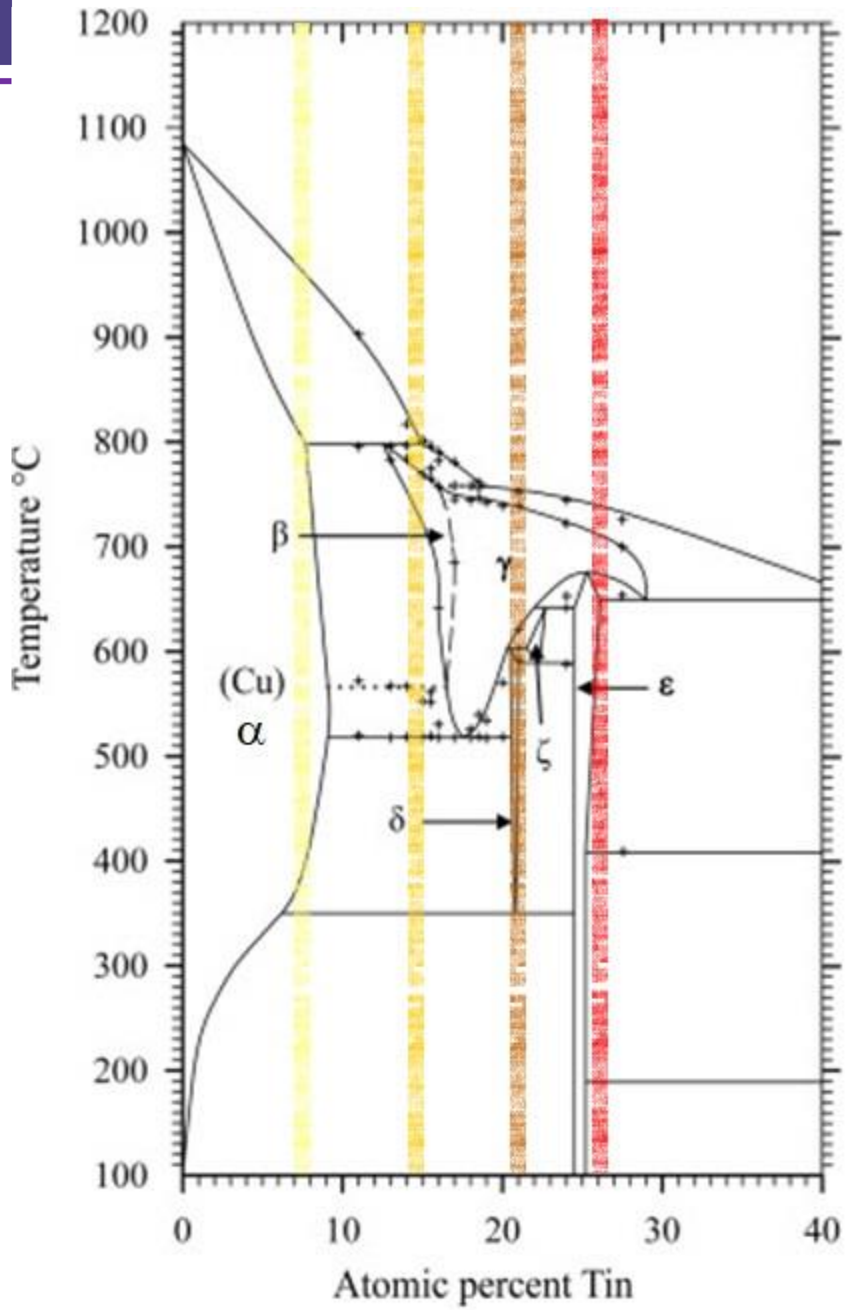


[7] *Withanage et al., 2021*

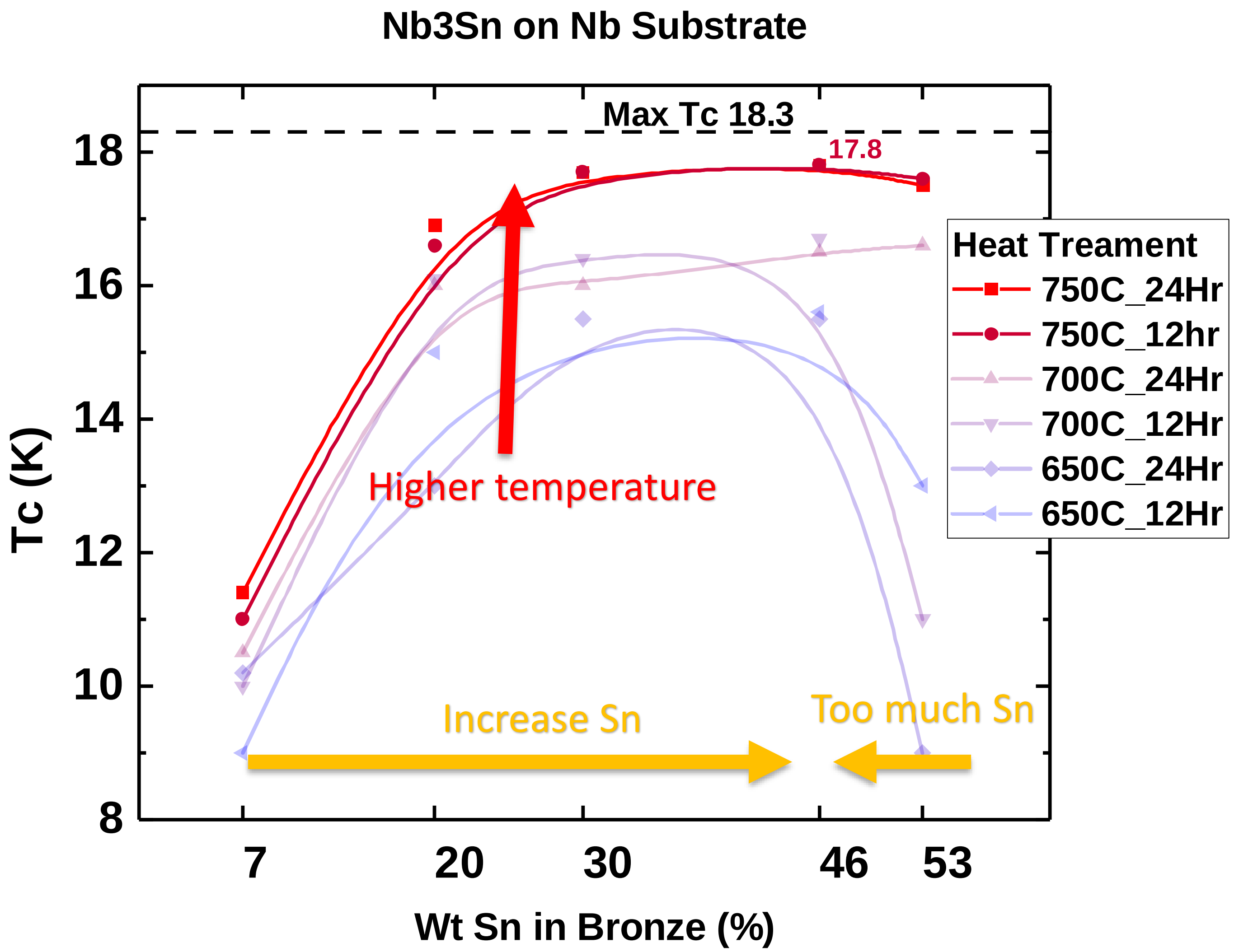
High Sn "Bronze"

- Maybe we can increase Sn activity using High Sn "Bronze"
- We aim to make α, β, γ, and ε single phases in the Cu-Sn phase diagram

Cu – Sn Alloy Name	Wt% Sn	At% Sn
α	13%	~7%
β	24%	~14%
γ	33%	~21%
ε	40%	~26%



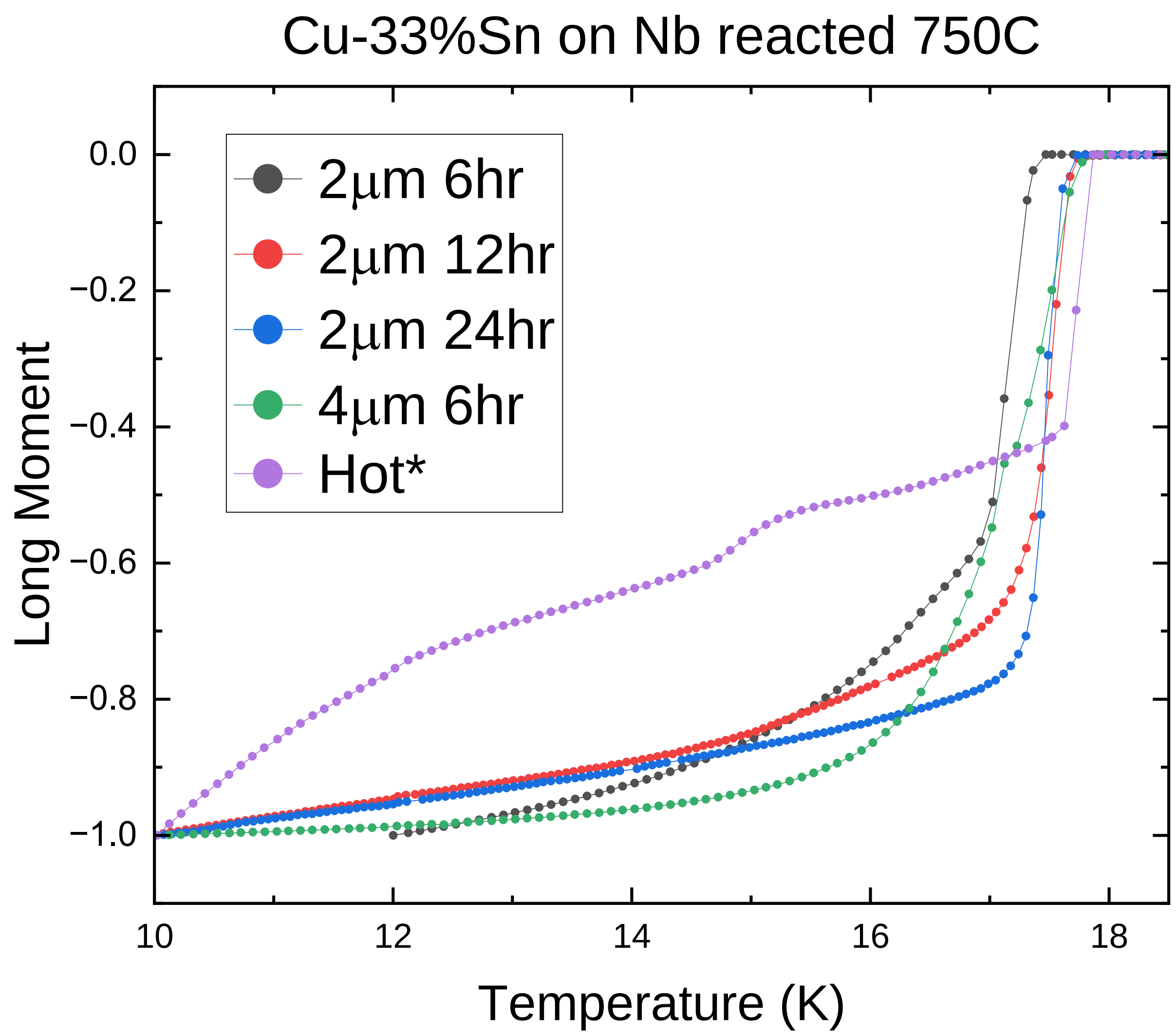
Results: Nb_3Sn via bronze on Nb



[9] *A. Juliao et al. TBD*

NATIONAL MAGLAB

Nb substrates: Sn Activity and Reaction Time



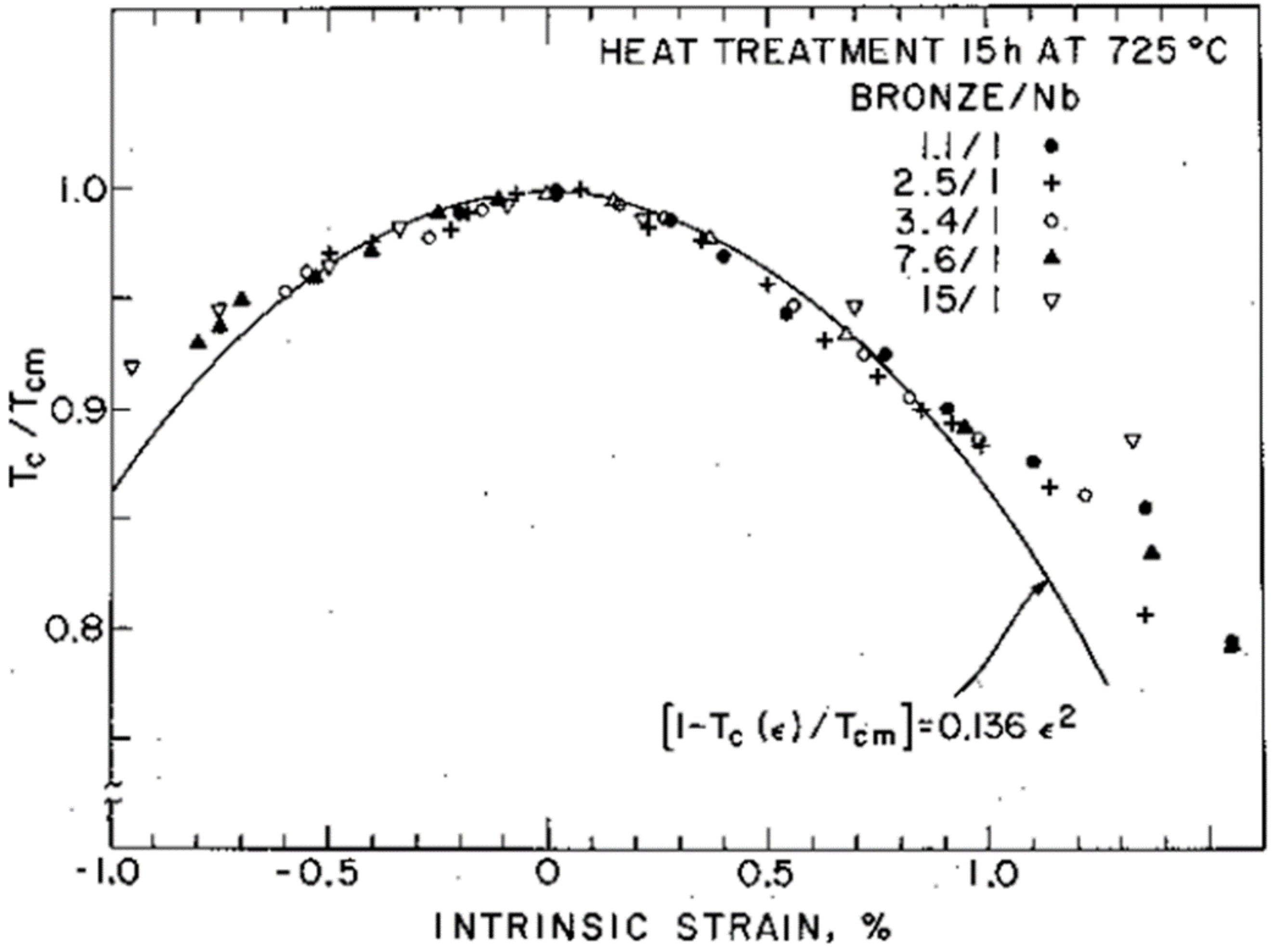
- Black has the lowest Tc
- Least Sn and Time

- Red, Blue, and Green ≈ Tc onset
- Balance between reaction time and Sn volume.

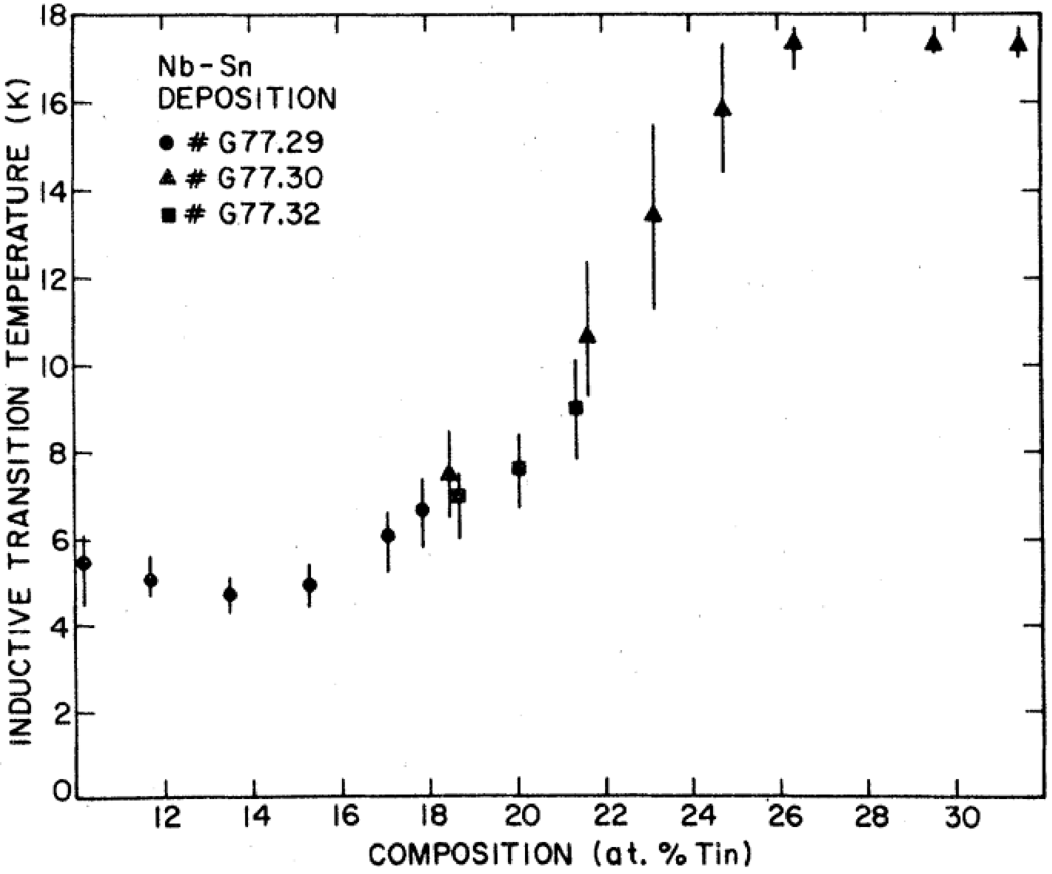
- Purple has the highest Tc with the sharpest transition
- Hot deposition has best Tc and sharpest transition

What effects Tc for Nb_3Sn?

Strain

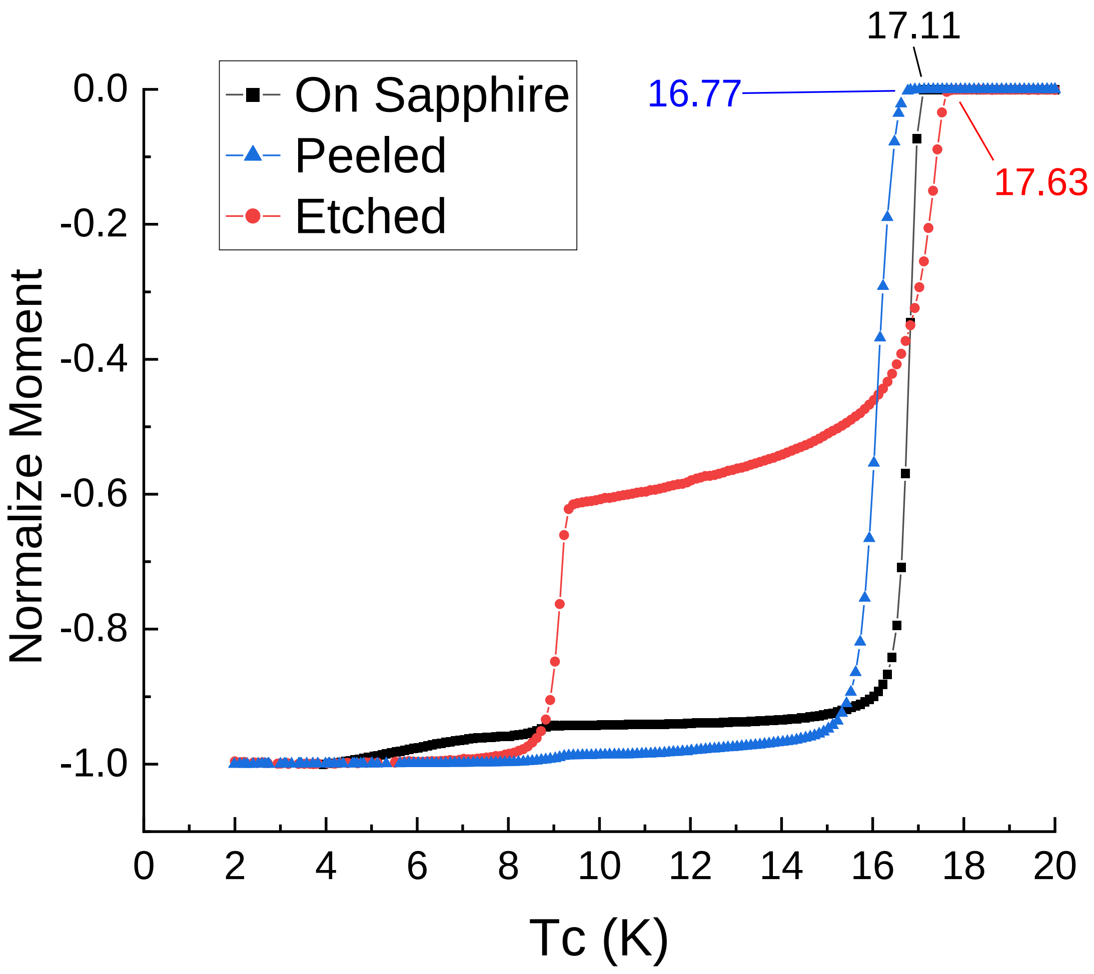


At % Sn



[13] *D. F. Moore et al. 1979*

Strain Experiment Sapphire

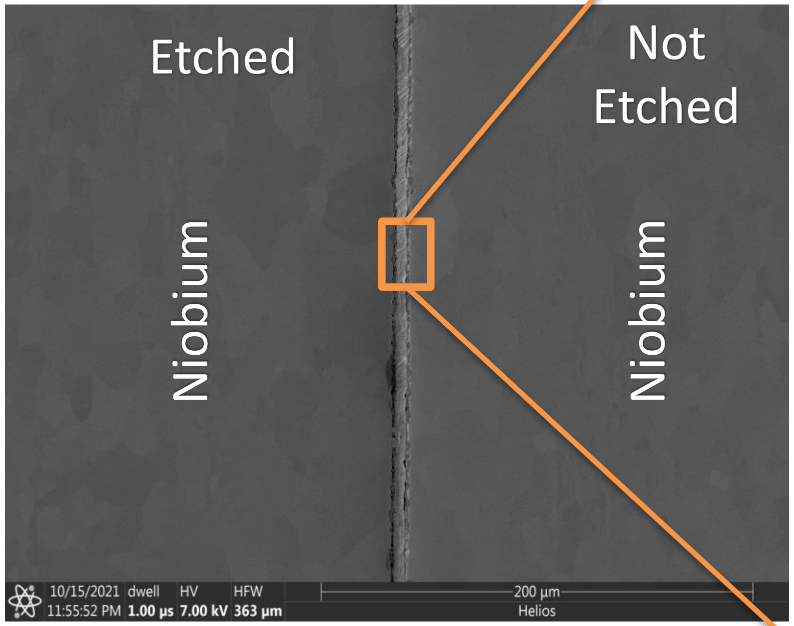


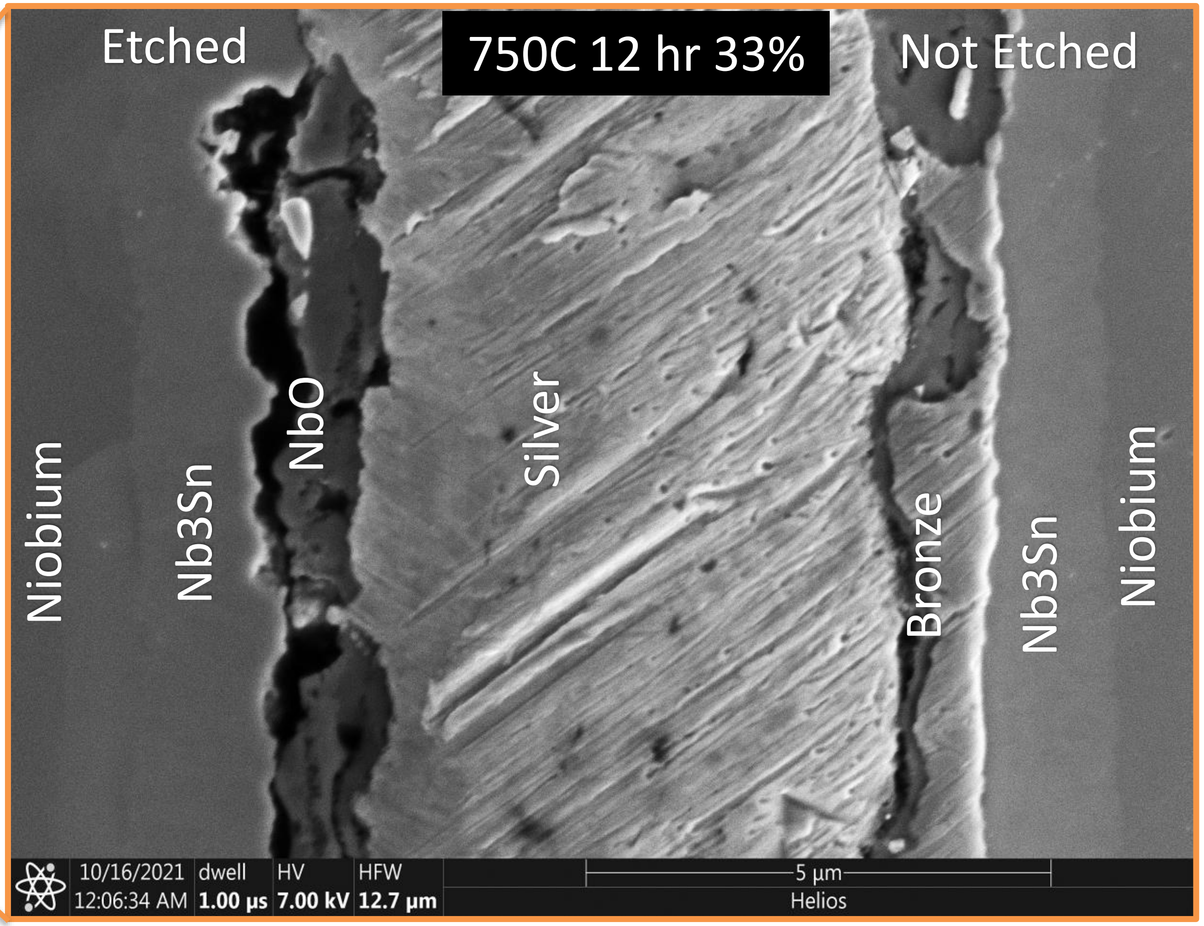
2 µm Cu-13%Sn 680C Nb 500nm deposition

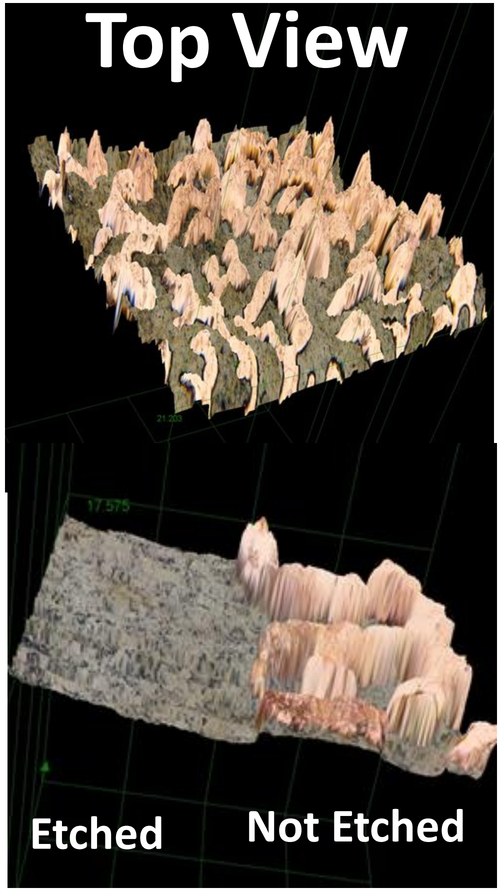
- **Film confined to sapphire has a sharp transition**
- **Film peeled off sapphire relieves the tensile strain but increases strain felt by the Nb_3Sn from the CuSn**
- **Compressive strain from Cu-Sn is relieved after etch and increases Tc ~ 1K ($\epsilon \sim .5\%$)**

Nb substrate with Cu-Sn Etch

Sample cut in half, one side etched, and pasted together for polish

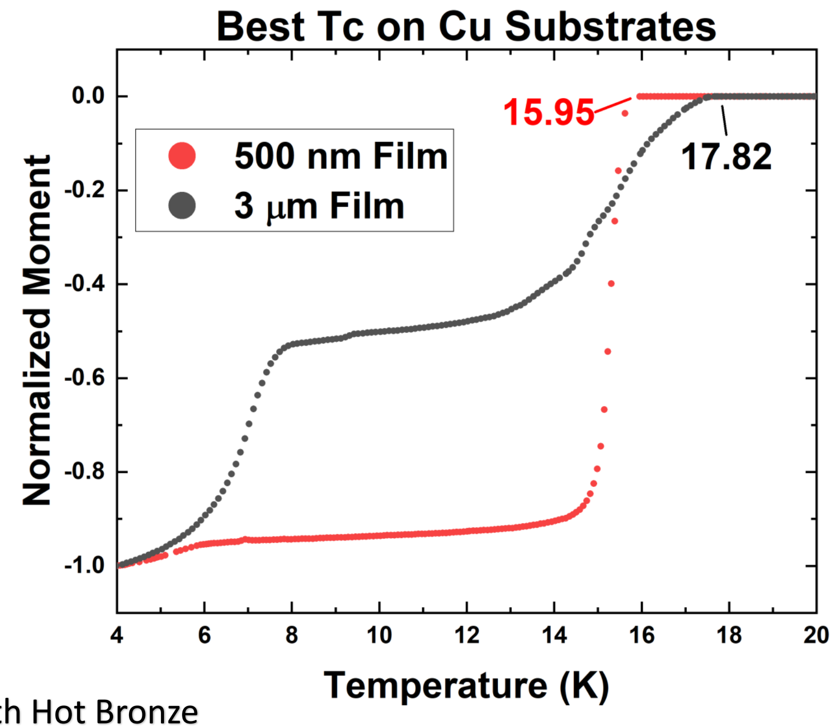






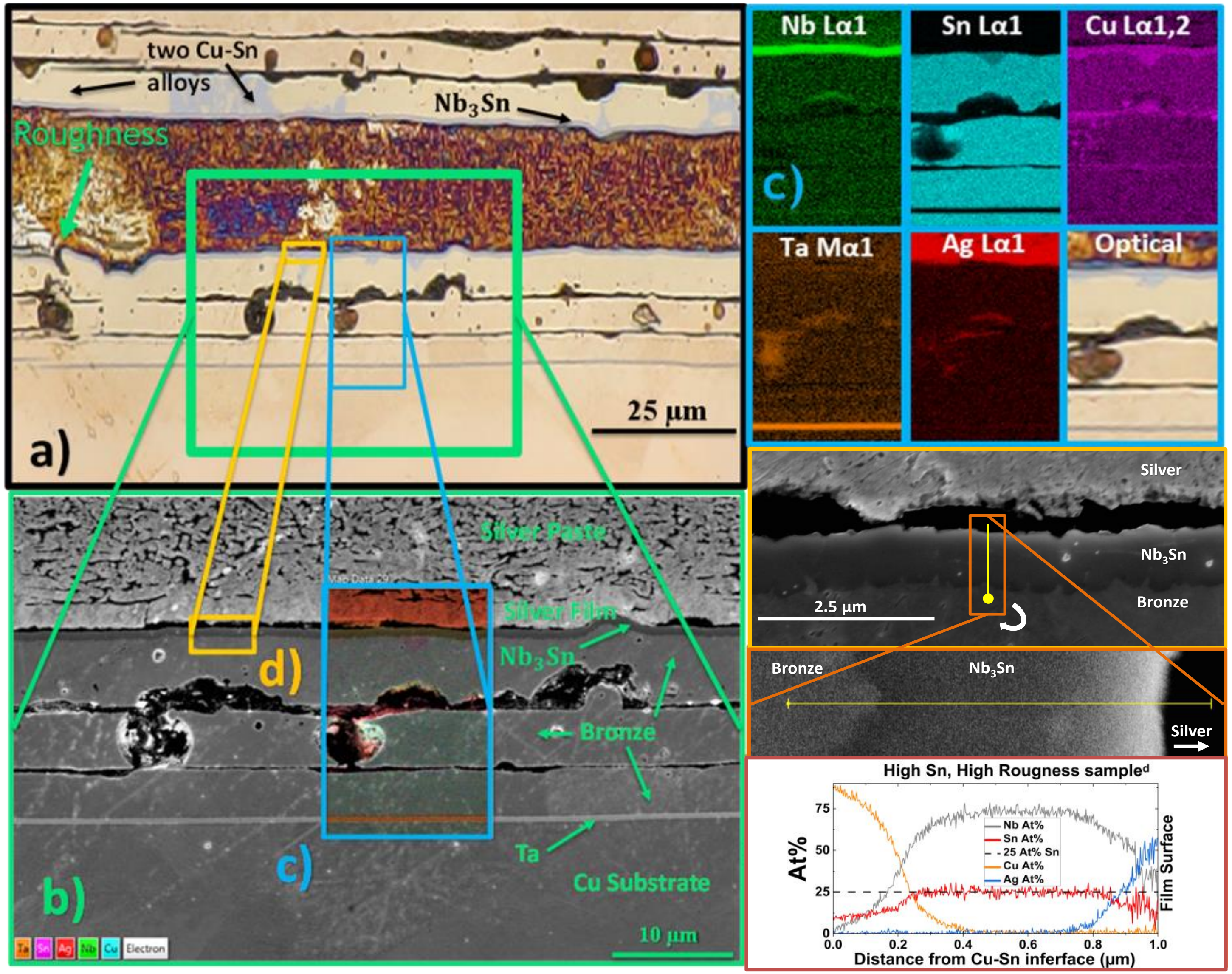
[9] *A. Juliao et al. TBD*

How can we analyze these films?



*Both Hot Bronze

Critical Temperature Tc

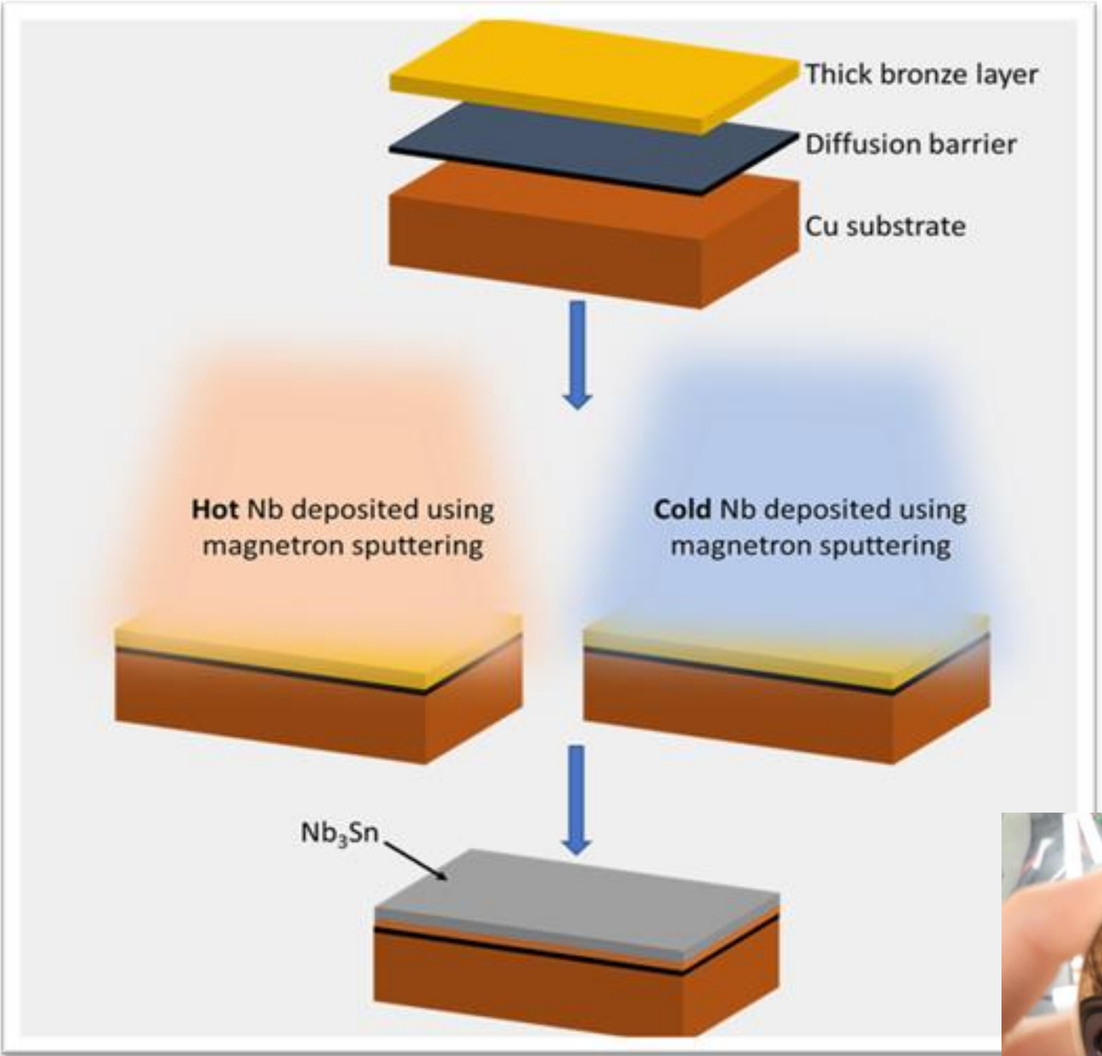


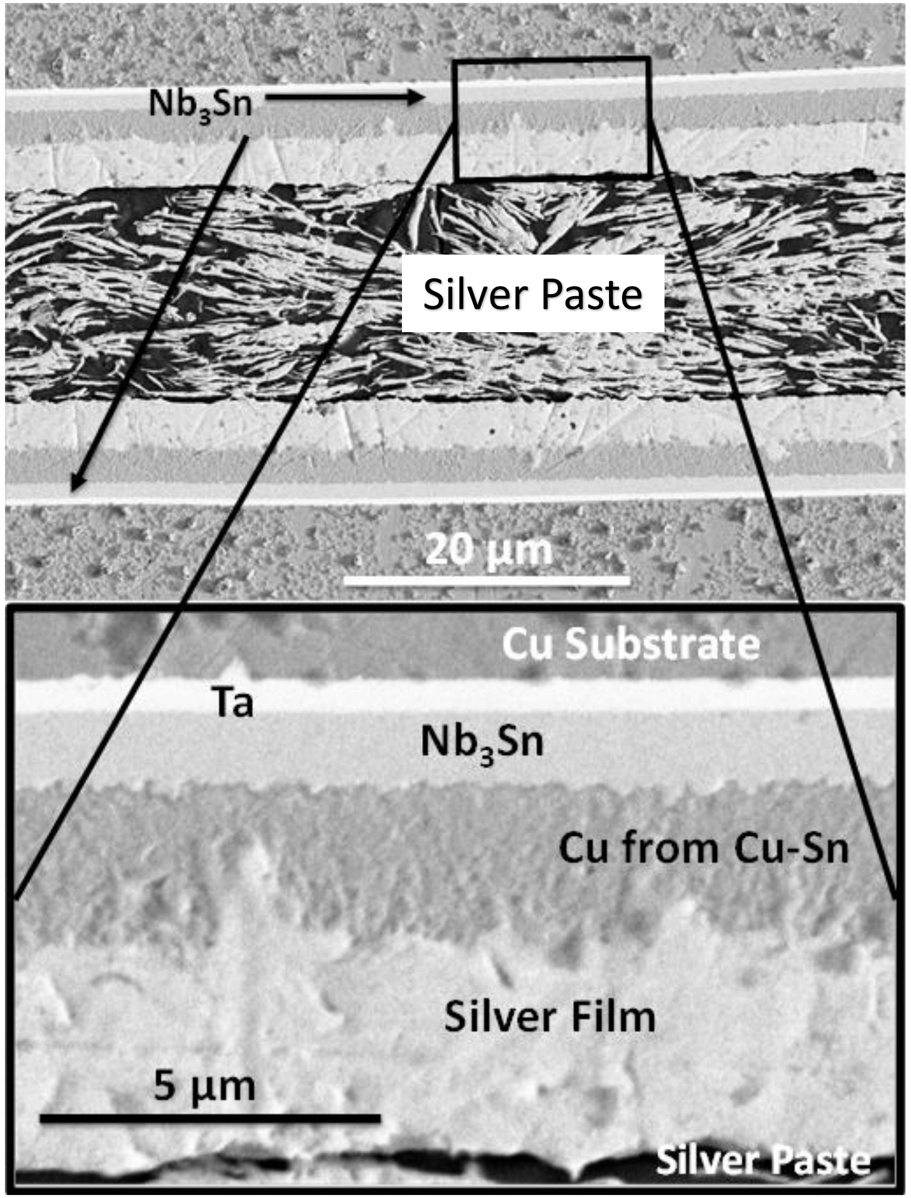
Optical, SEM

EDS

[10] *A. Juliao et al. TBD*

Cu substrates

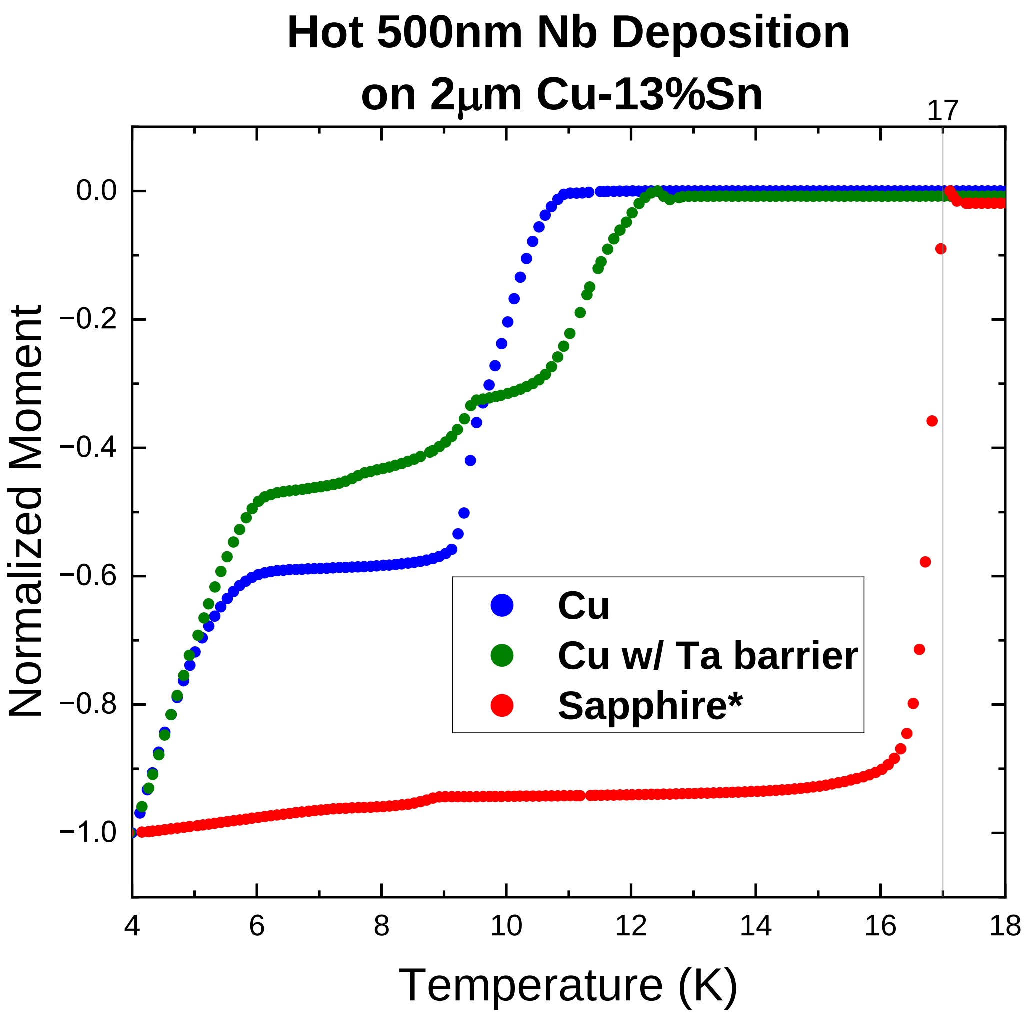




Mechanically polish Cu

[10] A. Juliao et al. TBD

Substrate effects



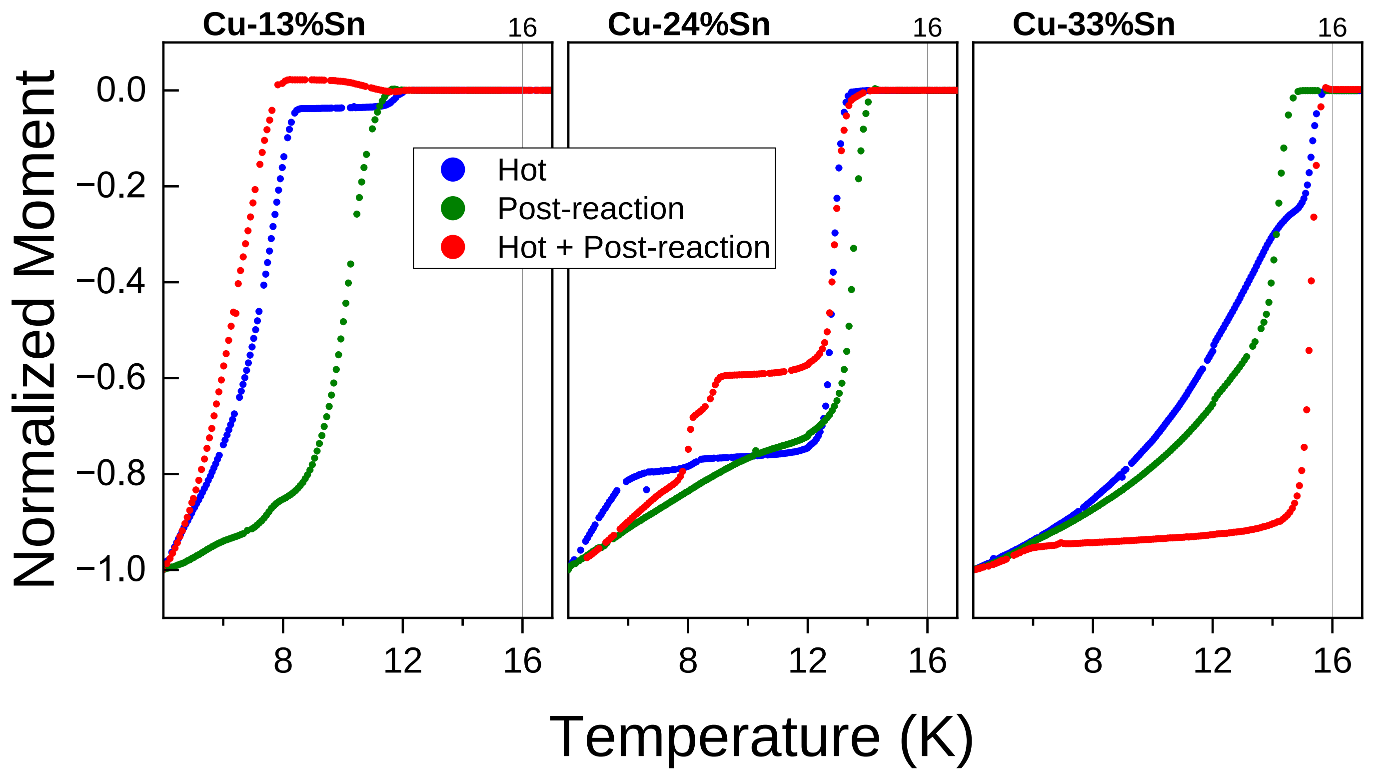
The sapphire film has low CTE mismatch and high Sn content.

Sn diffuses into Cu substrate, and a Low Sn% thin CuSn layer will give bad Tc.

300nm Ta diffusion layer is not enough for this case.

Optimize CuSn layer?

Nb_3Sn on (Cu/Ta/5μm Cu-Sn)



We are losing Sn, with 300nm Ta diffusion barrier.

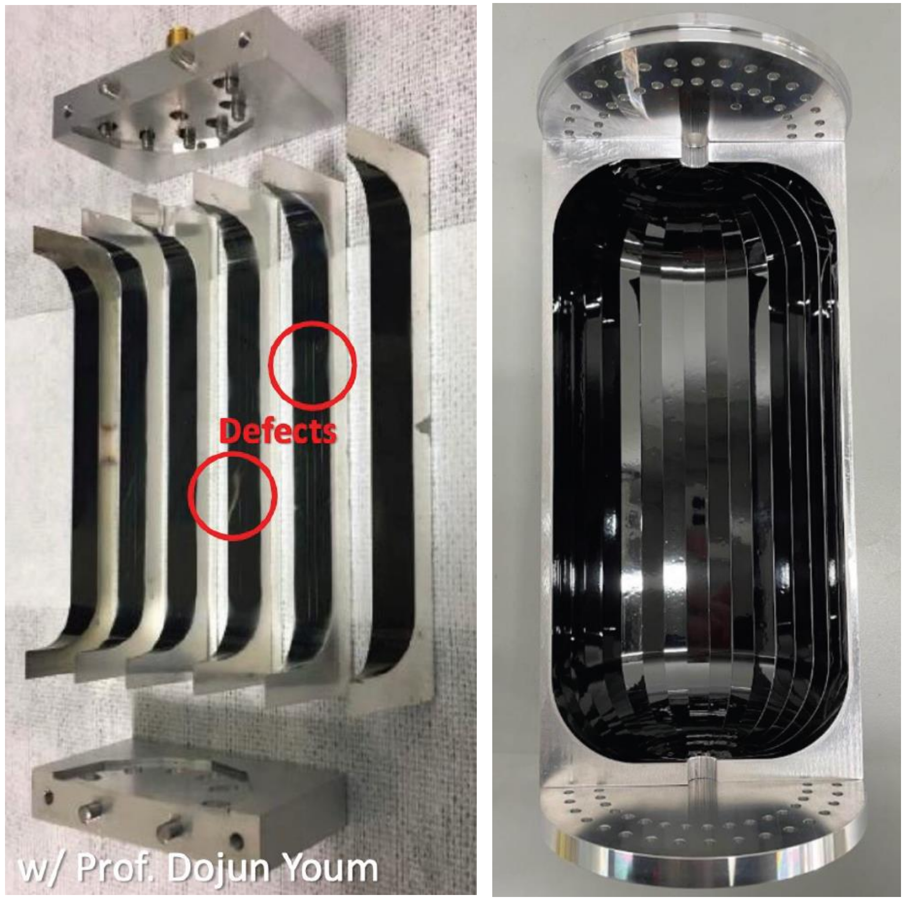
Can mitigate the effects of Sn loss with a higher Sn% film, though a thicker film doesn't give the same effect.

Table of Contents

- Axions
- Detecting the Axion
- Nb_3Sn for Axion Detection
- Making a resonator
- Healing Seams for Axion Detectors (and maybe SRF cavities)

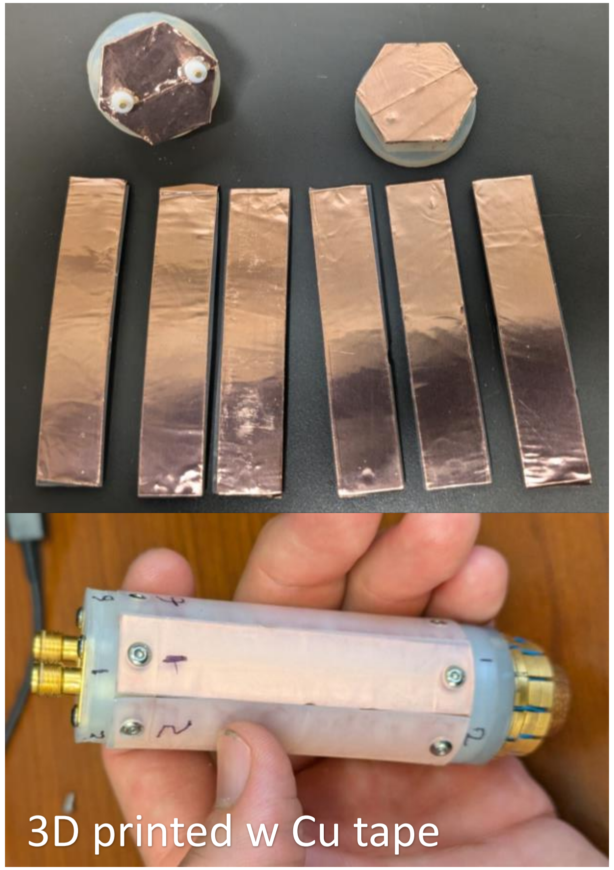
RF Test Resonators

South Korean HTS cavity



O. Kwon SQMS 2024

FSU 3D printed Cu tape hexagonal cavity



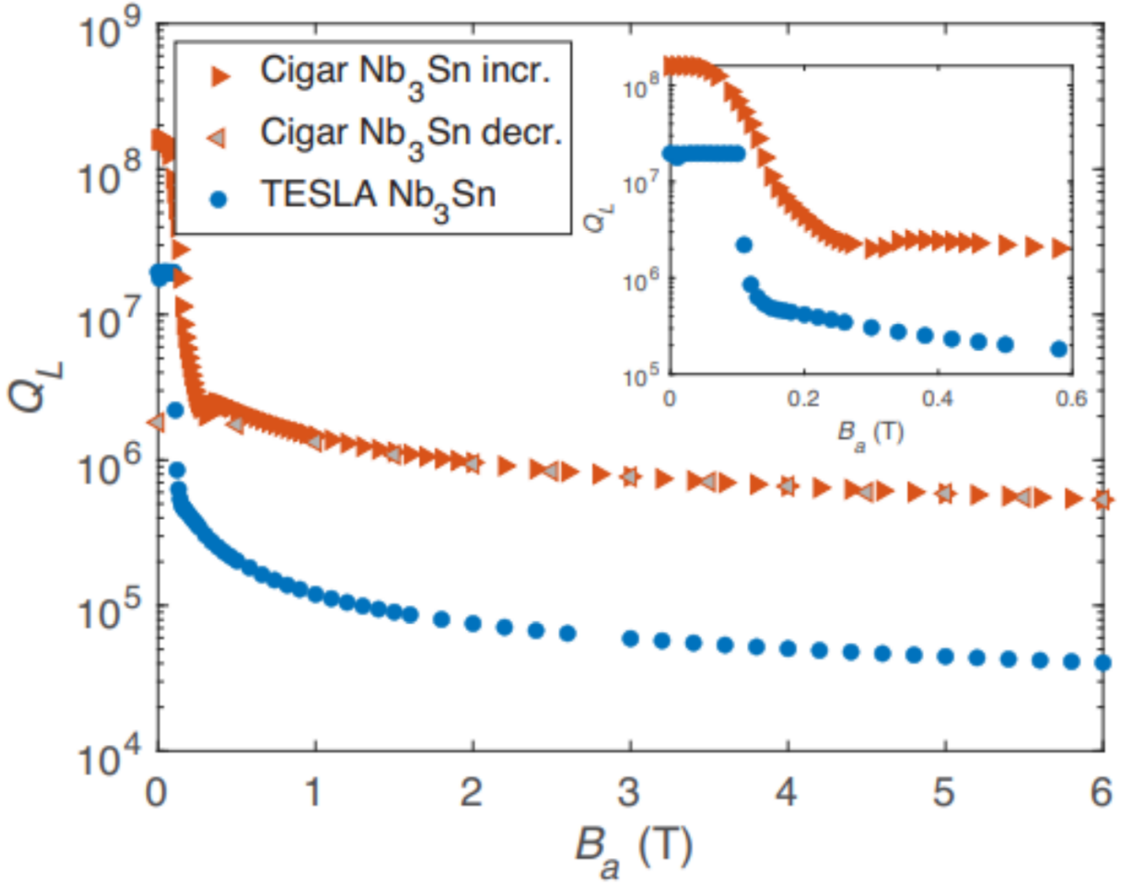
UW ADMX PPMS NbTi Cavity

T. Braine arxiv 2022

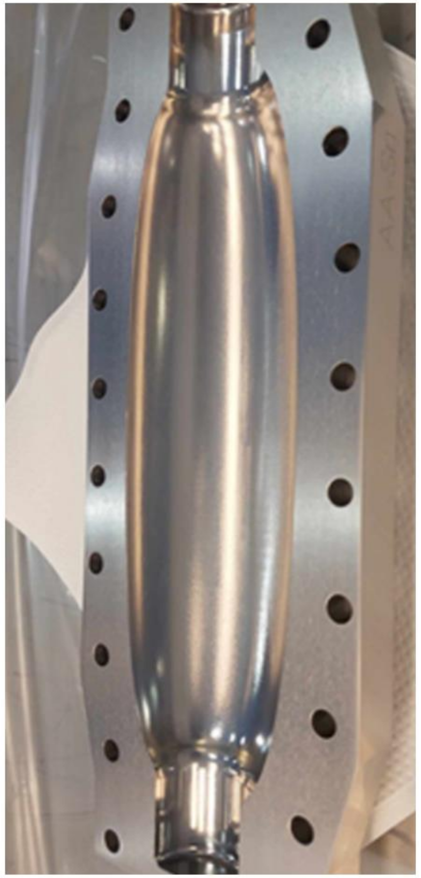
Yes Hexagon, Yes it has seams…

Geometry and Orientation matters

[16] *Tao Jiang et al Nov. 12, 2013*



Quality factor vs Magnetic field



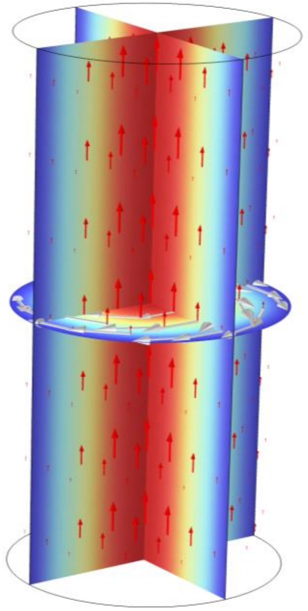
a) cigar-shaped cavity optimized for high-field
b) TESLA cavity for particle accelerators

[7] *S. Posen et al. (Sept. 1, 2023)*

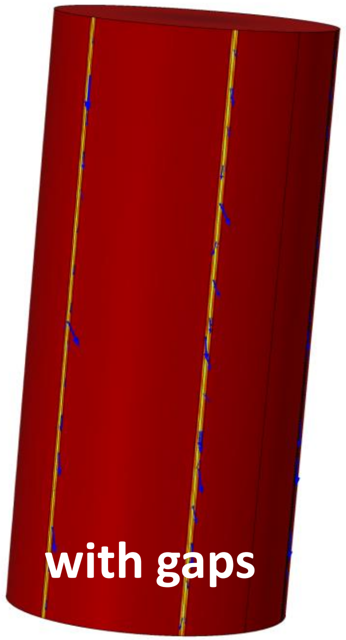
Geometry Simulations

- **Modeling TM010 mode with COMSOL EM physics**
- **Using Conductivity of Cu at T ~ 4K**
- **Gaps between conducting walls reduces Q by ~ 30%**
- **Hexagon increases Frequency by ~2Ghz and reduces Q ~ 65%**

Cylindrical



f ~ 9.97 GHz
Q ~ 1.779×10^5



f ~ 9.978 GHz
Q ~ 1.28×10^5

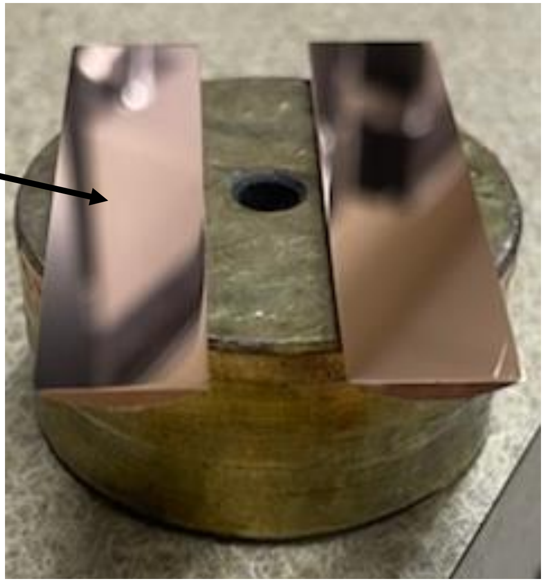
Hexagonal

f ~ 11.12 GHz
Q ~ 5.981×10^4

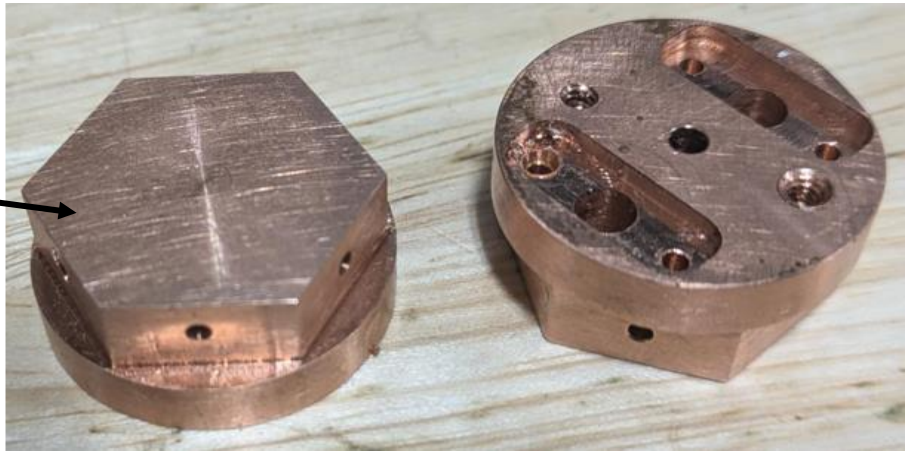
Start with 1 Nb_3Sn surface

Side walls

Nb_3Sn coating

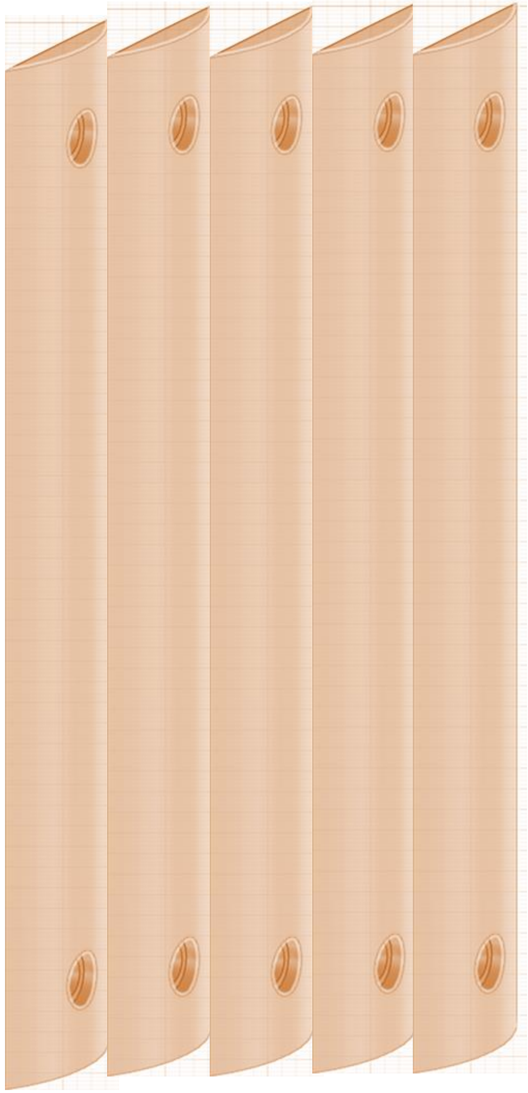


Bulk Cu



Keep Top and Bottom caps Cu

5 walls: Bulk Cu

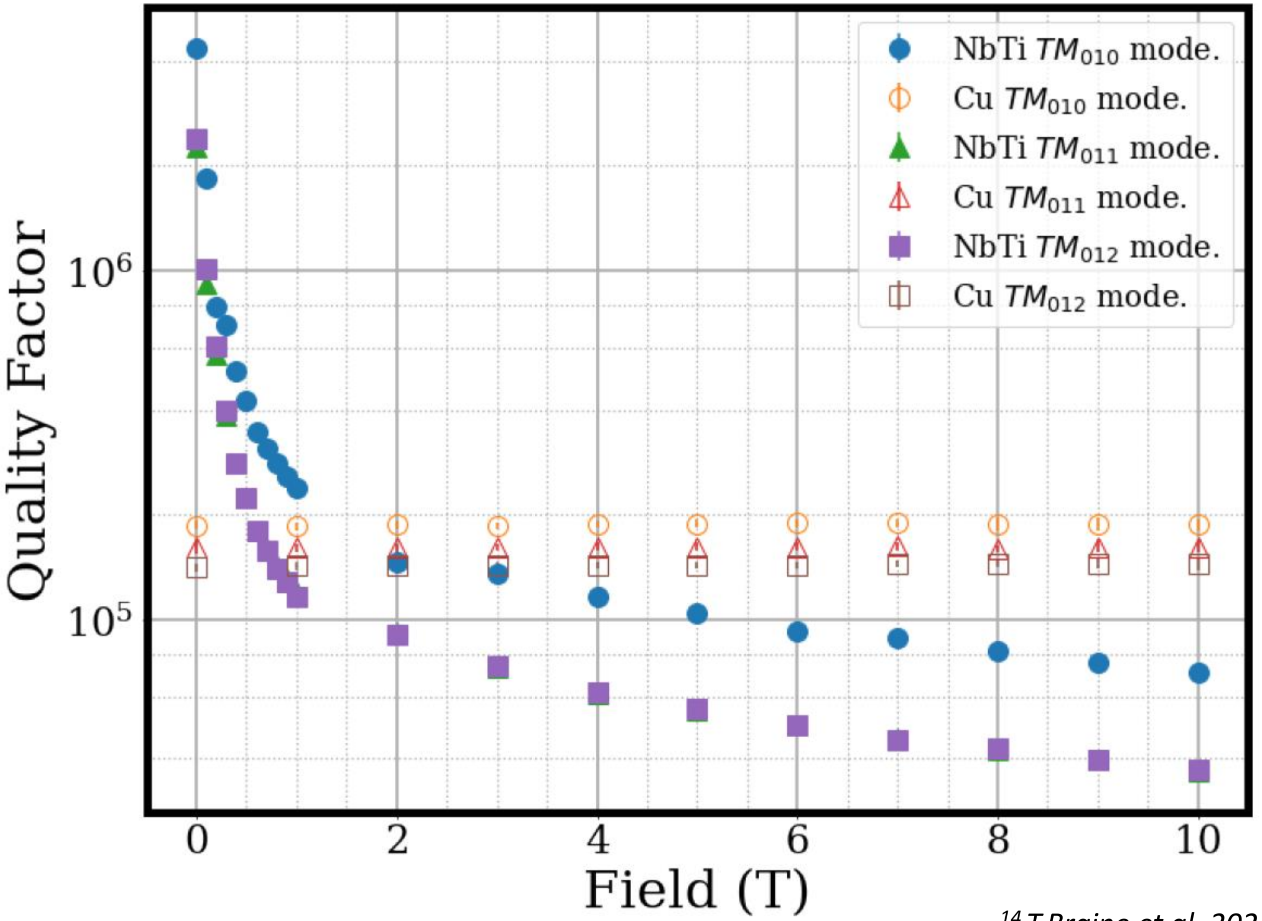


Nb_3Sn coating recipe on 1 Cu wall

Have not measured Q yet!!??!?

We will try to recreate mode decomposition measurement our collaborators did with NbTi.

Everything is set up, will measure soon!!!



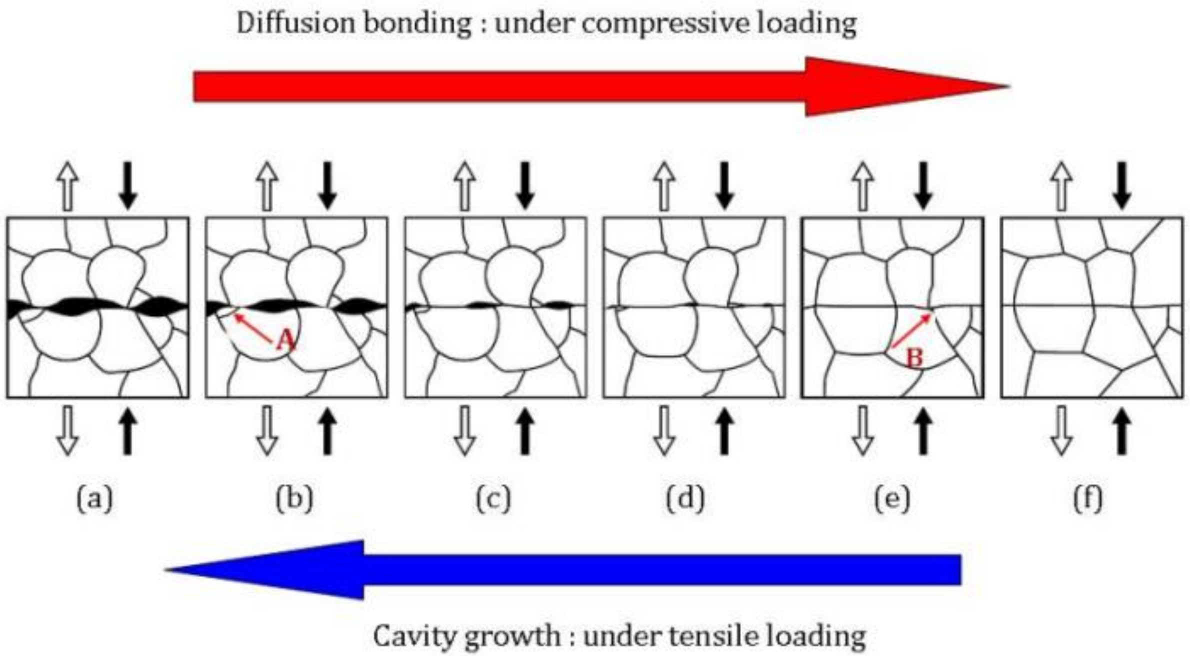
[14] T.Braine et al. 2023

Table of Contents

- Axions
- Detecting the Axion
- Nb_3Sn for Axion Detection
- Making a resonator
- Healing Seams for Axion Detectors (and maybe SRF cavities)

Diffusion Bonding Seams

Formation mechanism of the diffusion bonding



Successful diffusion bonding has:

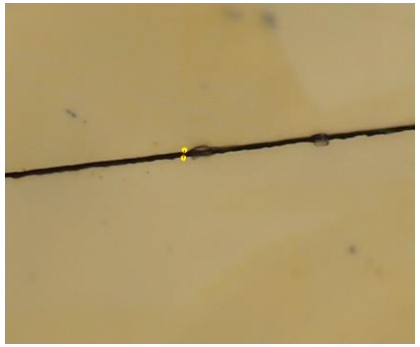
1. **Close contact between the surface planes of the two materials being combined.**

2. **Enough driving force being applied to the materials to supply enough diffusion coefficient.**

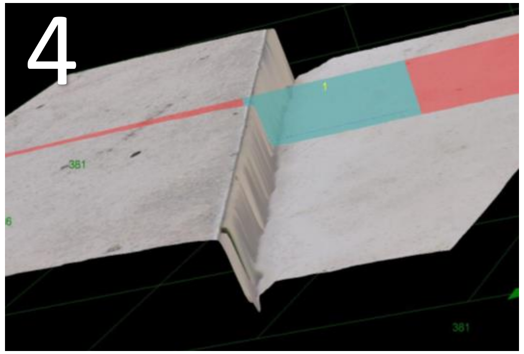
Healing Recipes

#	Recipe	Substrate	Pre-heat Bolted	Bolted Deposition	Deposition Temp (C°)	Post-Heat	Comments	Continuous Film
1	Hot	CuSn	✓	✓	715	✓	High Surface Mobility	✓
2	Hot Ti	CuSnTi	✓	✓	715	✓	Ti Precipitates	-
3	Cold Pre	CuSn	✓	✓	200	✓	Low Surface Mobility	-
4	Cold	CuSn	-	✓	200	✓	Interface Stress	-
5	Separate	CuSn	-	-	200	✓	Nb in Interface	-

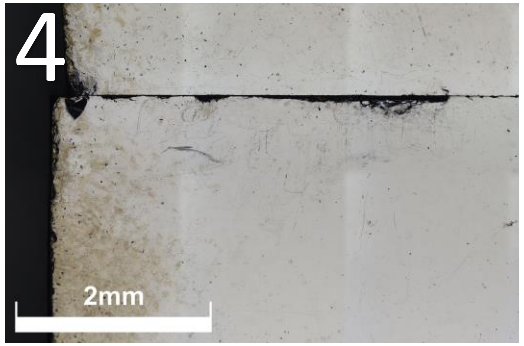
Challenges



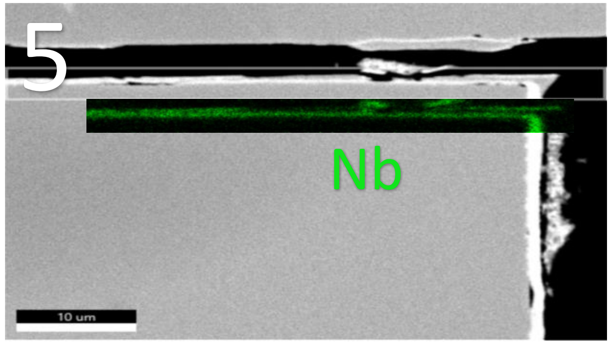
1 µm gap



24 µm offset above



Stress at interface

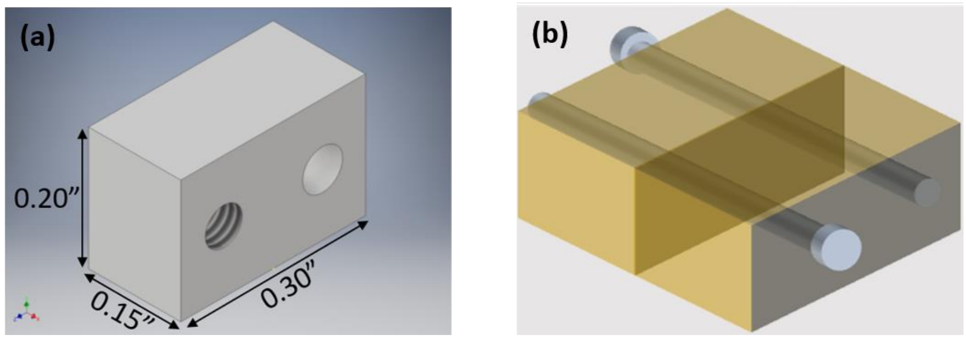


Nb coating interface

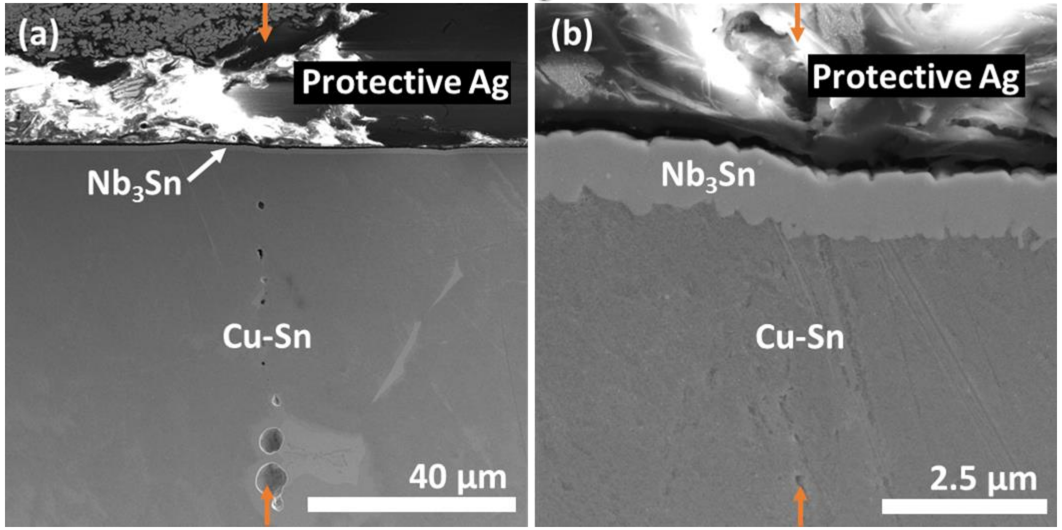
[15]Andre ASC 2024

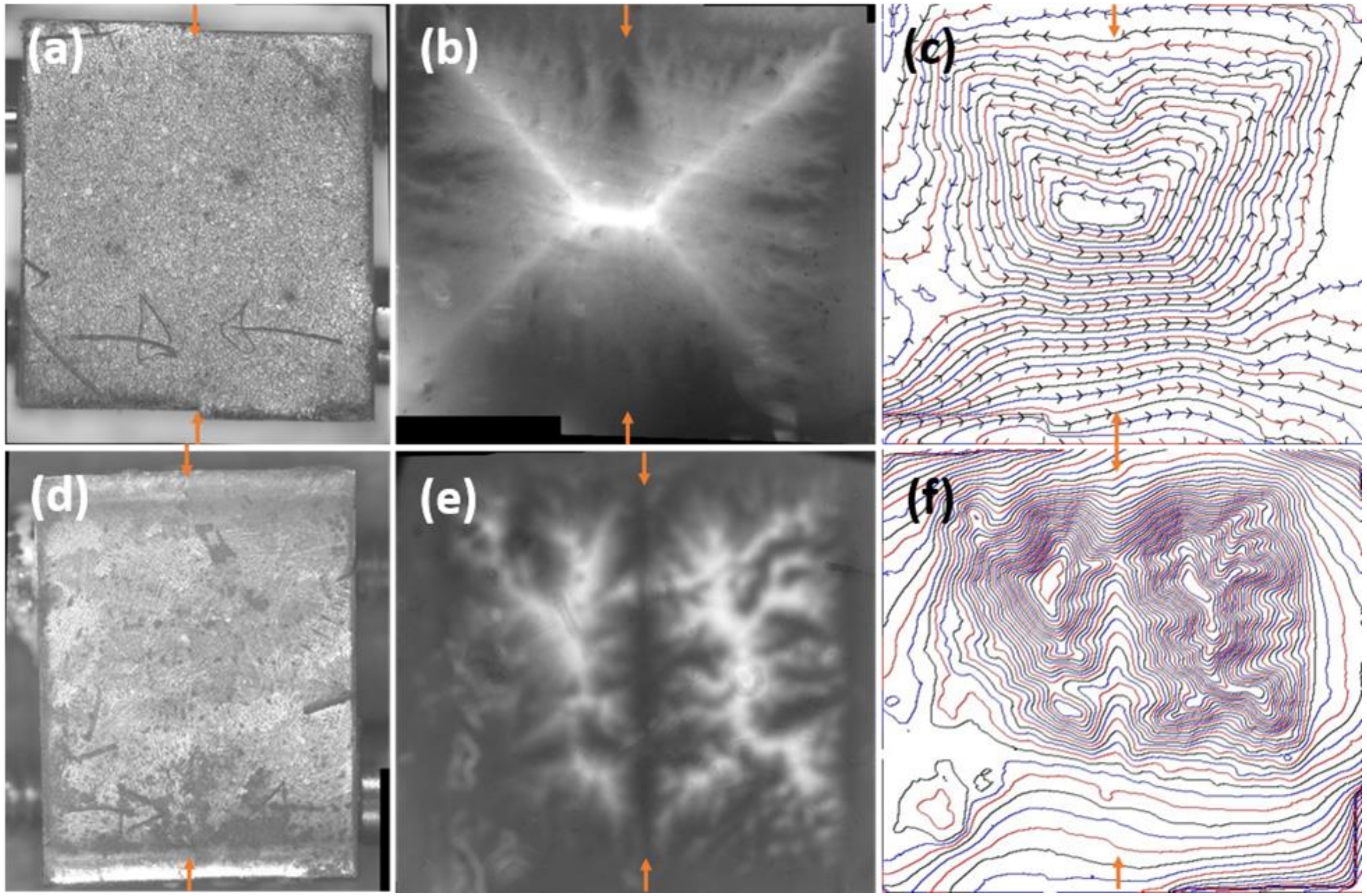
Continuous Seam Across Joint

Two bronze blocks



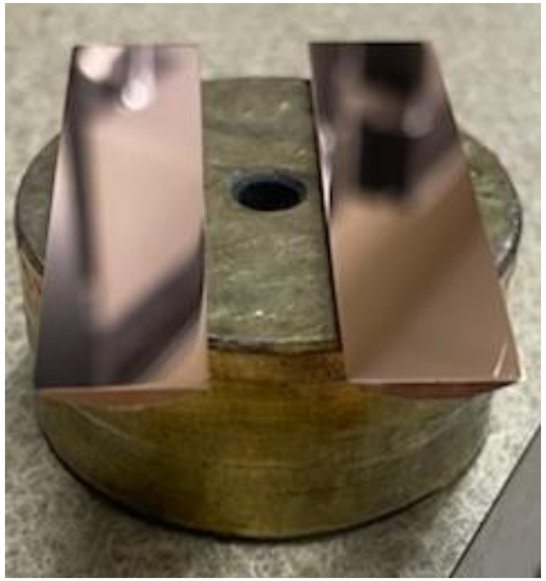
Continuous Nb_3Sn across seam





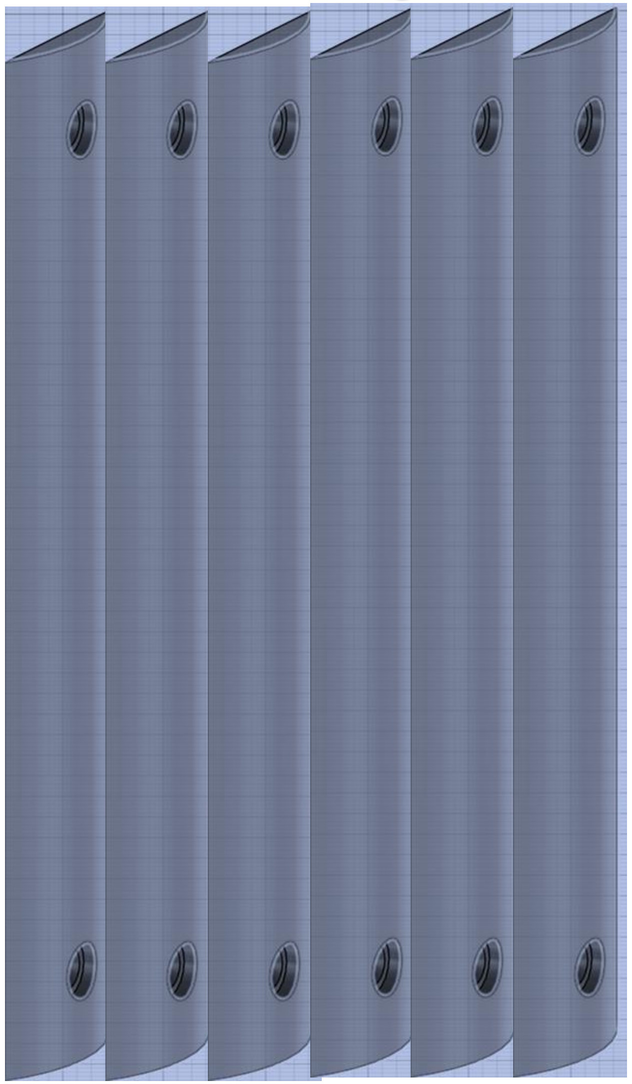
Magneto Optical Imaging (MOI)
Continuous superconductivity in a, b, c
discontinuous superconductivity in d, e, f

To End with...

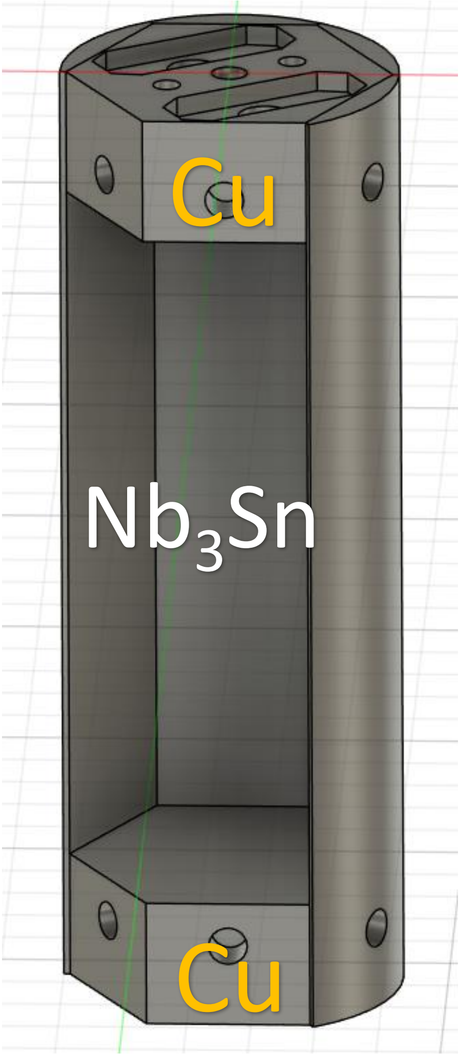


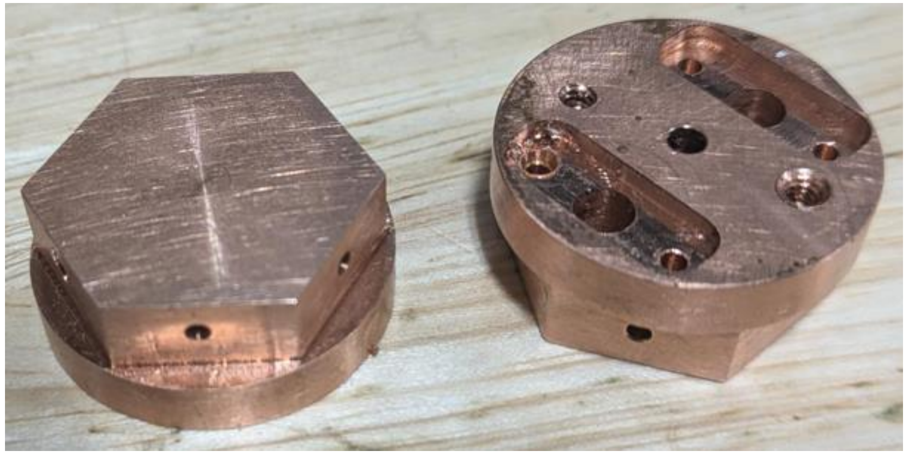
Nb_3Sn coating recipe →

6 wall: Nb_3Sn



Heat Treat to heal →



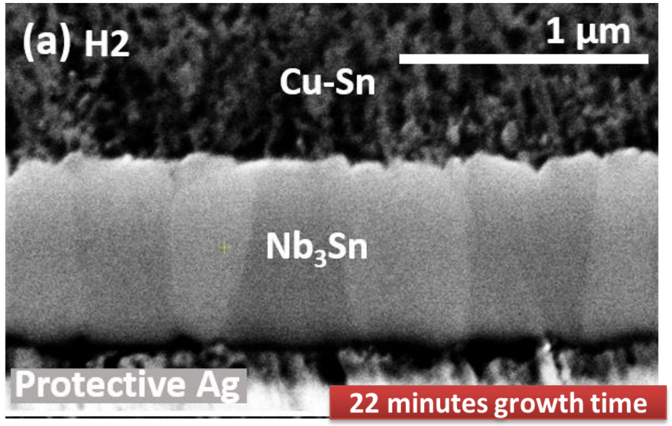


Keep Cu Bulk

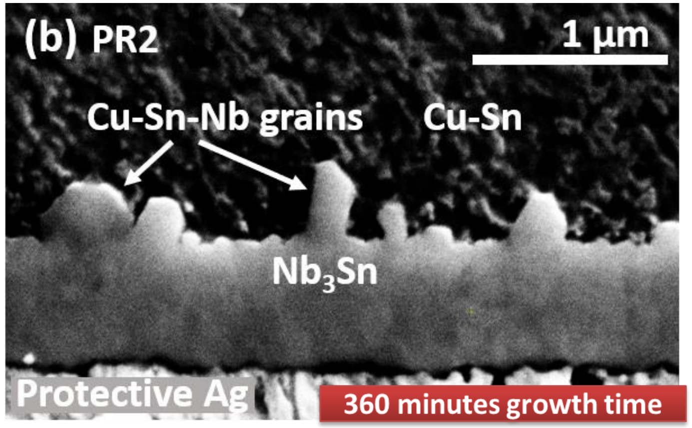
Conclusion

- Optimizing recipes for Nb_3Sn on Cu.
- Analyzed strain effects from Cu-Sn layer on Nb_3Sn.
- By exchanging one wall of a hexagonal cavity, we will have fast throughput relative measurements for our recipes. (can compare with 2-inch disk samples SLAC/Barcelona)
- Looking forward to Q testing in B and T for our Cu-Sn method (Cu in GB's) and our unique microstructure.

a) Hot Bronze

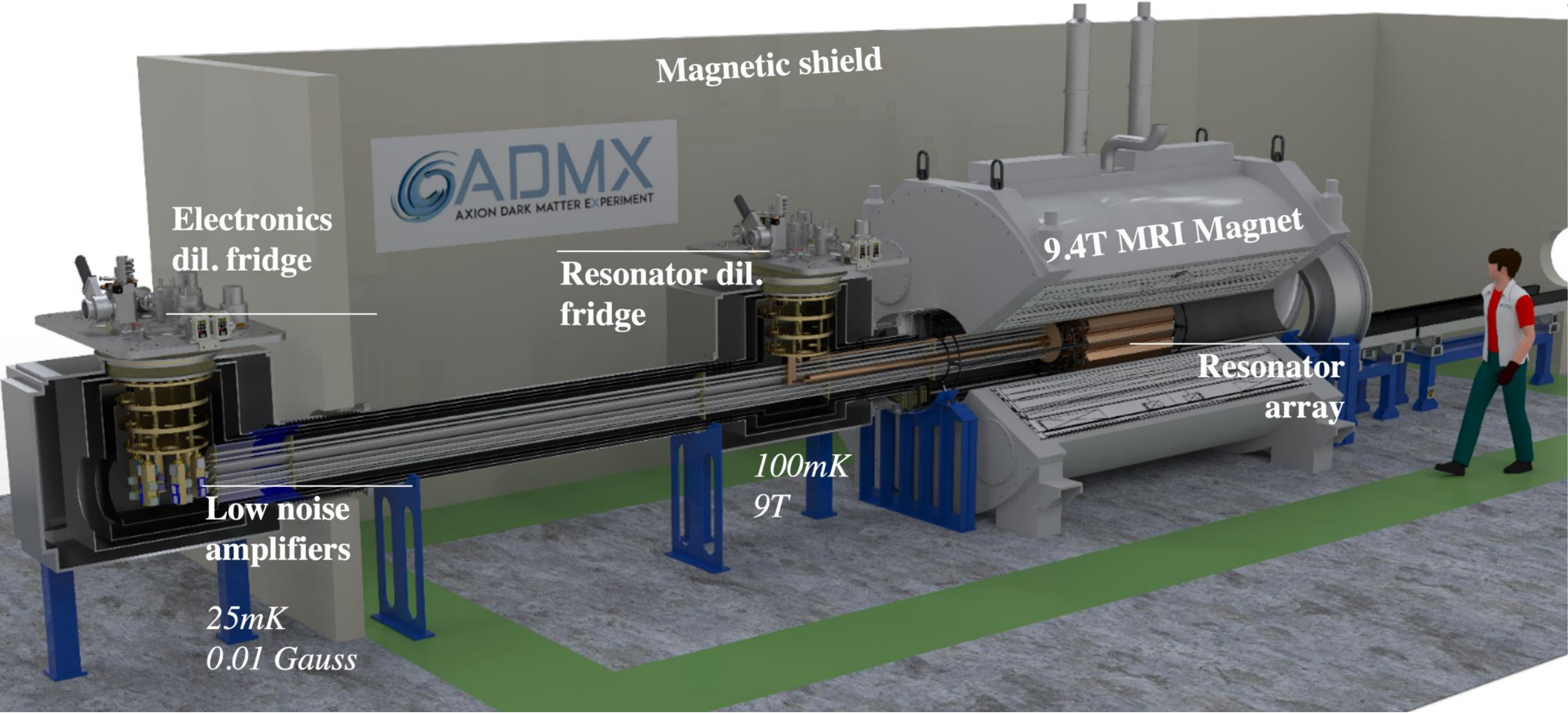


b) Post-reacted



W. Withanage, SS&T 2021

Future Experiments



ADMX Fermilab Collaborators

Acknowledgements

- The Applied Superconductivity Center

- ADMX Collaborators at Fermilab, Lawrence Livermore National Lab, University of Washington, University of Florida

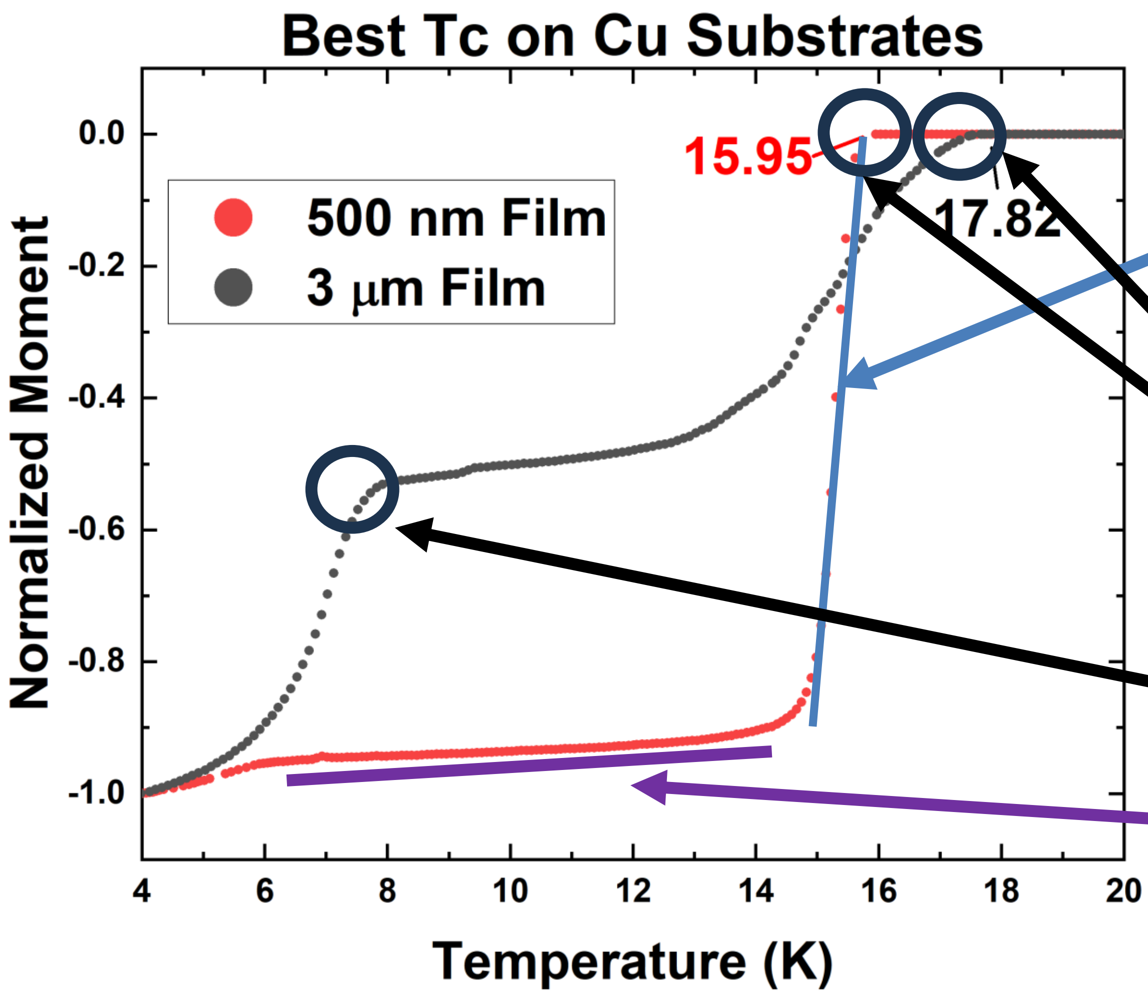
- High Energy Physics – Department of Energy: High-field Cavities for Axion Dark Matter

References

1. Sikivie, Pierre. "Invisible Axion Search Methods." *Reviews of Modern Physics* 93, no. 1 (February 18, 2021): 015004. https://doi.org/10.1103/RevModPhys.93.015004.
2. Boutan, Christian. "A Piezoelectrically Tuned RF-Cavity Search for Dark Matter Axions." *Ph.D. Thesis*, 2017. https://ui.adsabs.harvard.edu/abs/2017PhDT........24B.
3. Sikivie, P., N. Sullivan, and D. B. Tanner. "Proposal for Axion Dark Matter Detection Using an L C Circuit." *Physical Review Letters* 112, no. 13 (March 31, 2014): 131301. https://doi.org/10.1103/PhysRevLett.112.131301.
4. Nick Du et al. "Search for Invisible Axion Dark Matter with the Axion Dark Matter Experiment." In: Phys. Rev. Lett. 120.15 (Apr. 9, 2018), p. 151301. issn: 0031-9007, 1079-7114. doi: 10 . 1103 / PhysRevLett . 120 . 151301. arXiv: 1804 . 05750 [hep-ex]. url: https : //link.aps.org/doi/10.1103/PhysRevLett.120.151301
5. Posen, S., and D. L. Hall. "Nb3Sn Superconducting Radiofrequency Cavities: Fabrication, Results, Properties, and Prospects." *Superconductor Science and Technology* 30, no. 3 (January 2017): 033004. https://doi.org/10.1088/1361-6668/30/3/033004.
6. Di Gioacchino, Daniele, Claudio Gatti, David Alesini, Carlo Ligi, Simone Tocci, Alessio Rettaroli, Giovanni Carugno, et al. "Microwave Losses in a DC Magnetic Field in Superconducting Cavities for Axion Studies." *IEEE Transactions on Applied Superconductivity* 29, no. 5 (August 2019): 1–5. https://doi.org/10.1109/TASC.2019.2897267.
7. S. Posen et al. "High-Quality-Factor Superconducting Cavities in Tesla-Scale Magnetic Fields for Dark-Matter Searches." In: Phys. Rev. Applied 20.3 (Sept. 1, 2023), p. 034004. doi: 10.1103/PhysRevApplied.20.034004. arXiv: 2201.10733 [physics.acc-ph]. url: https: //link.aps.org/doi/10.1103/PhysRevApplied.20.034004 (visited on 01/19/2024).
8. Wenura Withanage, Andre Juliao, and Lance Cooley. "Rapid Nb 3 Sn Film Growth by Sputtering Nb on Hot Bronze." In: Superconductor Science and Technology 34 (Apr. 9, 2021). doi: 10.1088/1361-6668/abf66f.
9. A. Juliao et al., Nb3Sn on Nb substrates using Cu-Sn alloys, TBD
10. A. Juliao et al., Nb3Sn on Cu substrates using Cu-Sn alloys, TBD
11. Andre Anders. "A Structure Zone Diagram Including Plasma-Based Deposition and Ion Etching." In: Thin Solid Films 518.15 (May 31, 2010), pp. 4087–4090. issn: 0040-6090. doi:10.1016/j.tsf.2009.10.145. url: https://www.sciencedirect.com/science/article/pii/S0040609009018288
12. D. O. Welch. "Alteration of the Superconducting Properties of A15 Compounds and Elementary Composite Superconductors by Nonhydrostatic Elastic Strain." In: Advances in Cryogenic Engineering Materials: Volume 26. Ed. by A. F. Clark and R. P. Reed. Boston, MA: Springer US, 1980, pp. 48–65. isbn: 978-1-4613-9859-2. doi: 10.1007/978-1-4613-9859-2_4. url: https://doi.org/10.1007/978-1-4613-9859-2_4
13. Moore, D. F., R. B. Zubeck, J. M. Rowell, and M. R. Beasley. "Energy Gaps of the A − 15 Superconductors Nb 3 Sn, V 3 Si, and Nb 3 Ge Measured by Tunneling." *Physical Review B* 20, no. 7 (October 1, 1979): 2721–38. https://doi.org/10.1103/PhysRevB.20.2721.
14. Braine et al. "Multi-Mode Analysis of Surface Losses in a Superconducting Microwave Resonator in High Magnetic Fields." In: Rev. Sci. Instrum. 94.3 (Mar. 1, 2023), p. 033102. issn: 0034-6748, 1089-7623. doi: 10.1063/5.0122296. arXiv: 2208.11799 [physics.acc-ph]. url: http://arxiv.org/abs/2208.11799
15. A. Juliao et al., Bronze healing blocks for SRF cavities, TBD
16. Jiang, Tao, Feisi He, Fei Jiao, Fa He, Xiangyang lu, and Kui Zhao. "Feasibility Study on SRF Cavity Improvement by Doping Method," November 12, 2013.

Thank you for your time!

What do these Tc curves mean?



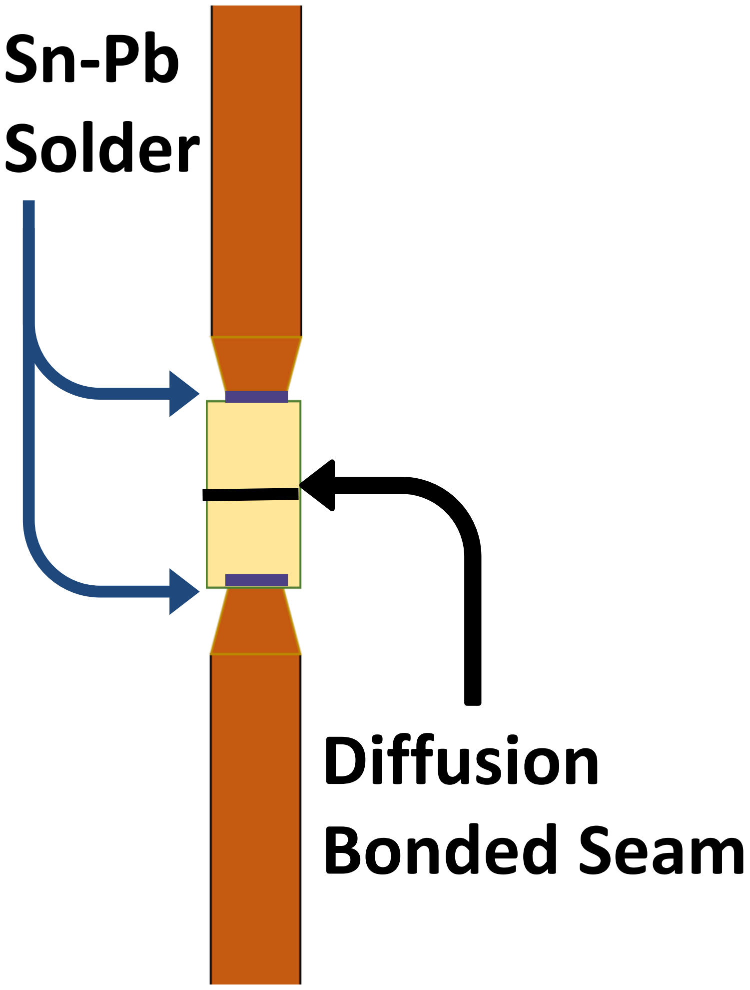
Sharp Transition = Constant Sn%

Tc onset = Best Nb_3Sn

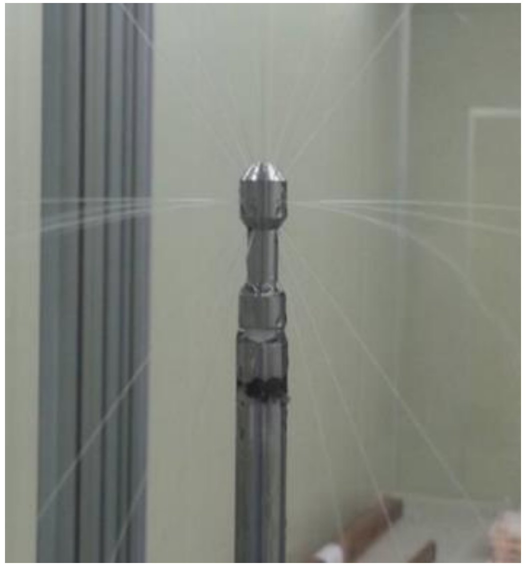
2nd transition = 2nd phase (Nb?)

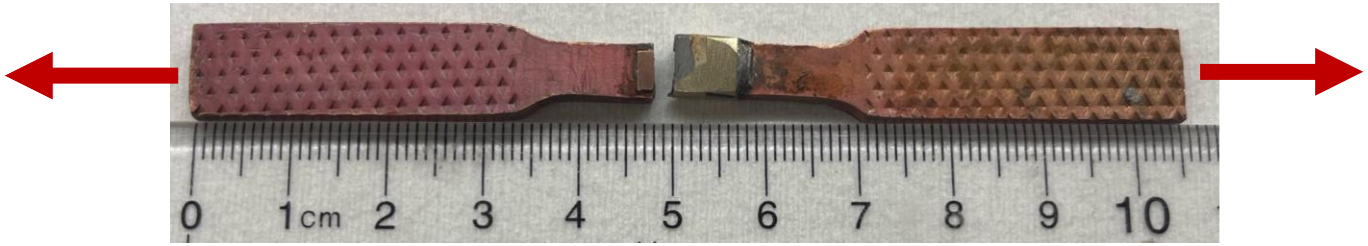
Zero Slope = Uniform

Tensile Testing the Seam



Tensile test simulates the need for cavity seams to withstand a high pressure rinse (HPR) at 140 bar.





Axion field and Maxwell's Laws

Maxwell's Laws → Modified Maxwell's Laws

$$\vec{\nabla} \cdot \vec{E} = \rho_{\rm el} \quad \longrightarrow \quad \vec{\nabla} \cdot \vec{E} = \underline{g\vec{B} \cdot \vec{\nabla} a} + \rho_{\rm el}$$

$$\vec{\nabla} \times \vec{B} - \frac{\partial \vec{E}}{\partial t} = \vec{j}_{\rm el} \quad \longrightarrow \quad \vec{\nabla} \times \vec{B} - \frac{\partial \vec{E}}{\partial t} = \underline{g(\vec{E} \times \vec{\nabla} a - \vec{B}\frac{\partial a}{\partial t})} + \vec{j}_{\rm el}$$

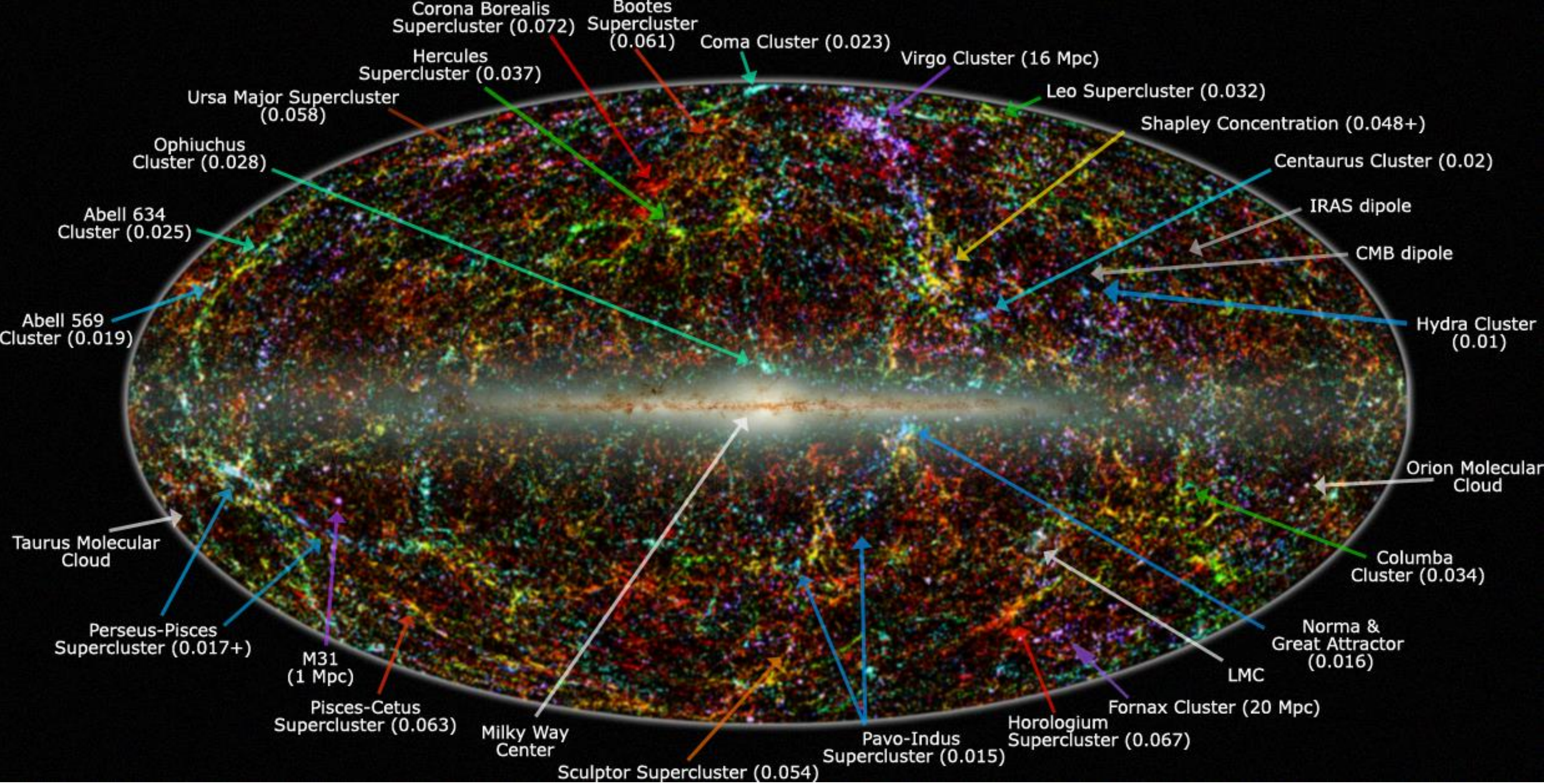
Axons cause an oscillating current.

$$\vec{j}_a = -g\vec{B}_0\dot{a}$$ where $$\dot{a} \equiv \frac{\partial a}{\partial t}$$

This current creates a magnetic field, which can be measured.

$$\vec{\nabla} \times \vec{B}_a = \vec{j}_a$$

[1] Pierre Sikivie, 2021


Corona Borealis Supercluster (0.072)
Bootes Supercluster (0.061)
Coma Cluster (0.023)
Virgo Cluster (16 Mpc)
Hercules Supercluster (0.037)
Leo Supercluster (0.032)
Ursa Major Supercluster (0.058)
Shapley Concentration (0.048+)
Ophiuchus Cluster (0.028)
Centaurus Cluster (0.02)
IRAS dipole
Abell 634 Cluster (0.025)
CMB dipole
Abell 569 Cluster (0.019)
Hydra Cluster (0.01)
Orion Molecular Cloud
Taurus Molecular Cloud
Columba Cluster (0.034)
Perseus-Pisces Supercluster (0.017+)
M31 (1 Mpc)
Norma & Great Attractor (0.016)
LMC
Pisces-Cetus Supercluster (0.063)
Fornax Cluster (20 Mpc)
Milky Way Center
Horologium Supercluster (0.067)
Pavo-Indus Supercluster (0.015)
Sculptor Supercluster (0.054)

PhD Timeline

Spring 2024

1. How good is good enough?
2. Choose a route Nb_3Sn on Cu

Prospectus

Spring 2024

3. Test RF of Cu

- Prepare Cu cavity
- Test Cu at RT
- Test Cu at 4.2K and 6T

Summer 2024

4. Make and test Nb_3Sn Cavity

- Prepare Substrate
- Prepare deposition
- Prepare Nb_3Sn
- Measure Cavity

Fall 2025

5. Post analysis

- Microstructure
- Electromagnetic
- Crystal structure

Repeat 4?

Spring 2025

6. SCGSR at LLNL

Defend PhD

Future research

Larger cavity

Other applications for SRF (Qubits, electron beam, etc.)

Replacing One Wall

- We replace one of the 6 sides with a superconducting film, and we simulate this by increasing the conductivity of the wall by 10x.

- We change the conductivity in various steps to see the impact of this conductivity change.