Superconducting Quantum Materials and Systems Center

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New Perspectives

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What is SQMS?

Superconducting Quantum Materials and Systems Center

A DOE National Quantum Information Science Research Center

20 Institutions
>275 Collaborators

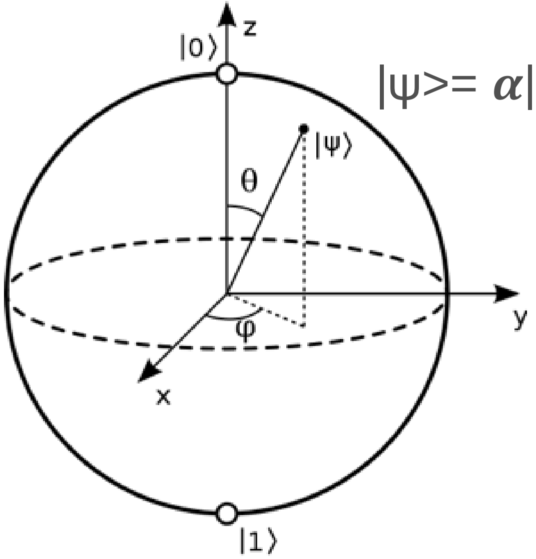
Tasked to produce dramatic advancements in quantum technologies for computing and sensing and to build the first quantum computer at Fermilab

How Do We Realize a Quantum Computer?

Basics of Quantum Computing

Utilizes **qubits**: basic unit of quantum information → Two (energy) level system

Superposition



$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$

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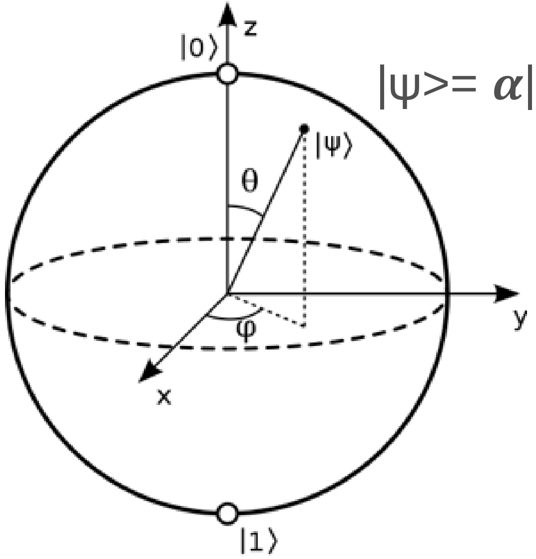

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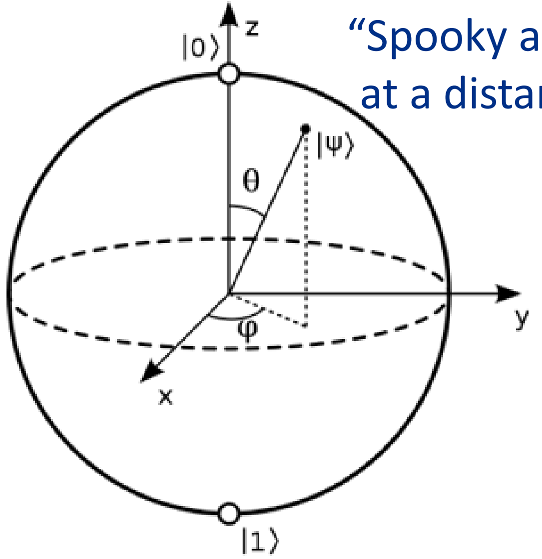
Entanglement

"Spooky action at a distance"



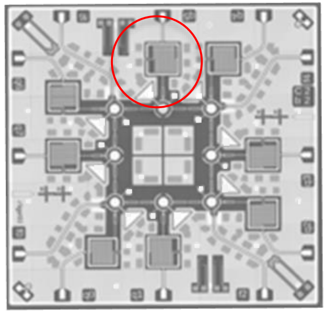
Phenomena give a quantum computer the potential to provide computational capacity for dramatic speedups in several high impact areas:

- Simulating molecule dynamics & particle collisions, modelling financial markets

Promising Way of Realizing a Qubit: Superconducting Qubits

1. Resonators (cavities)

2D



Rigetti 8-qubit processor

3D

Fermilab SRF resonators

M. Reagor et al, Science Advances, Vol.4, no. 2, (2018)

A. Romanenko et al, Phys. Rev. Appl. 13, 134052 (2020)

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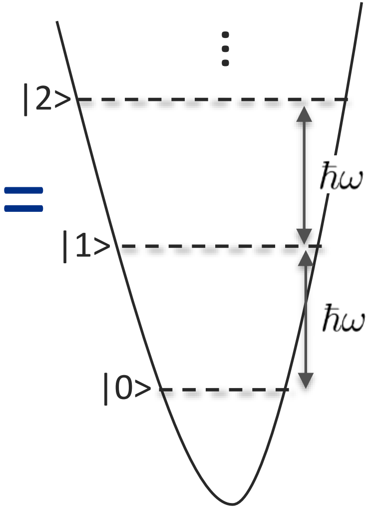

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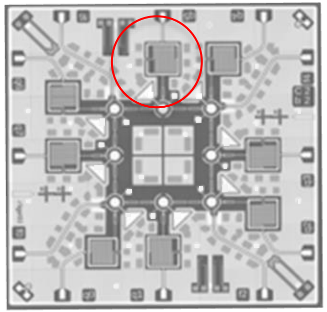

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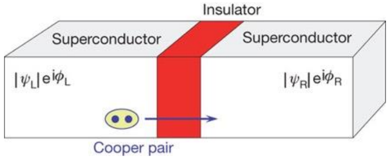
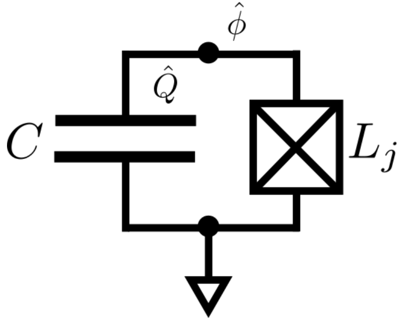
2. LC circuit with Josephson junction





"Transmon" qubits

J. Koch et al, Phys. Rev. **A** 76, 042319 (2007)

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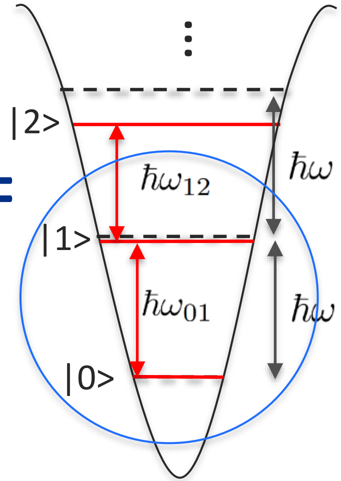
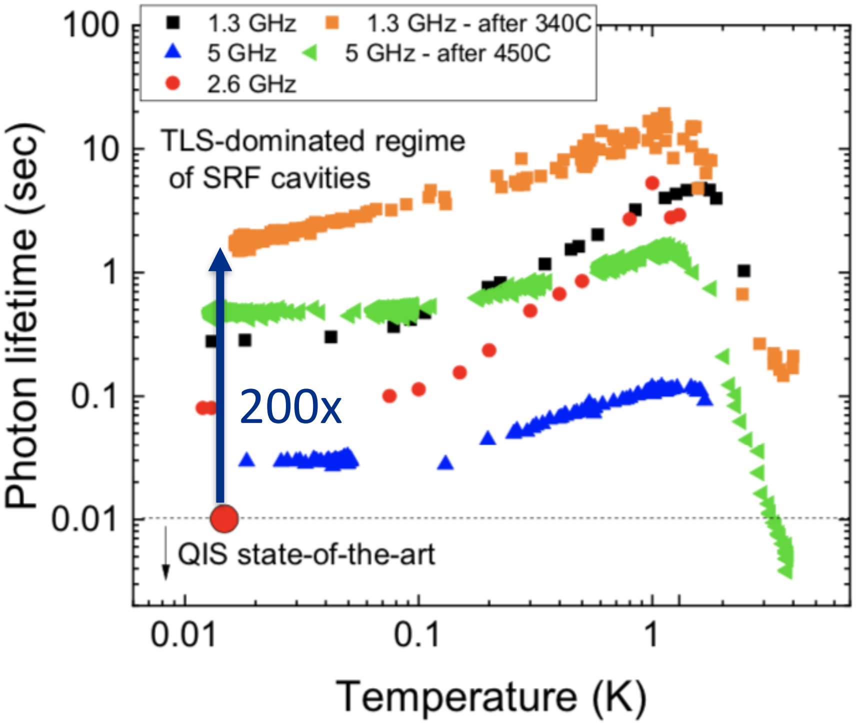


Two Level System!

Need long **quantum coherence** of superpositions for both resonator and JJ

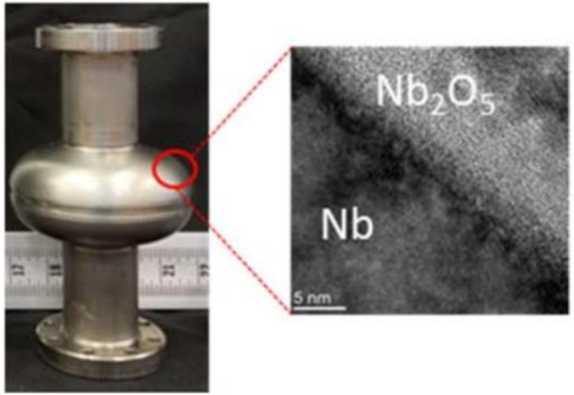
→ Need a qubit that you can manipulate and not confuse with other states

Fermilab SRF Resonators in Quantum Regime for 3D: Highest Coherence Quantum Resonators Ever Demonstrated



A. Romanenko *et al*, Phys. Rev. Applied **13**, 034032 (2020)

- Technology originally developed for particle accelerators
- Demonstrated 2 s of coherence
- Excellent starting point for SQMS



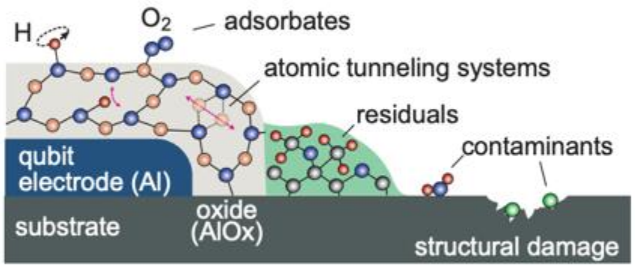
SQMS Technology Thrust:
How Do We Test and Improve Our Qubits?

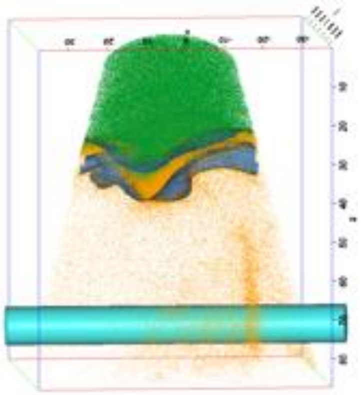
Focus Area: Materials

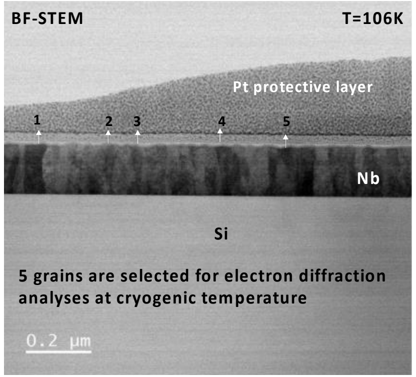
- Decoherence comes from materials used to fabricate qubits/resonators
  - Loss tangent, adsorbates, TLS,…

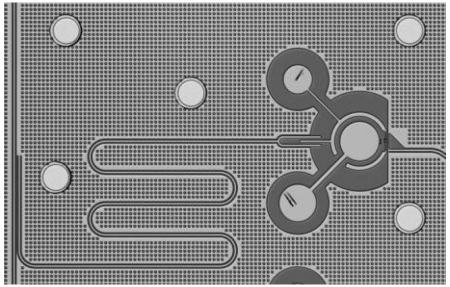
- <u>Goal:</u> Understand and mitigate the key mechanisms of decoherence to improve coherence times

- Utilizing material science techniques to study possible origins of loss
  - TEM, SEM, SIMS, XPS, XRD, PPMS, APT, EELS, AFM, …



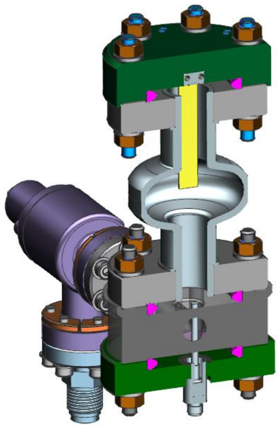


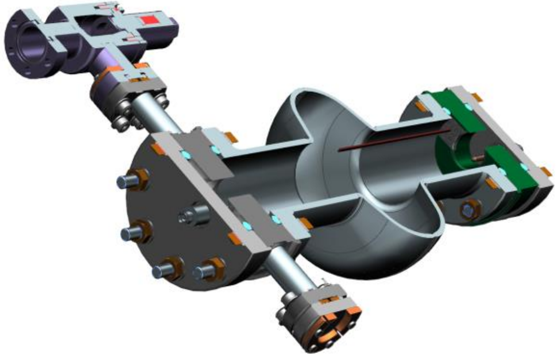




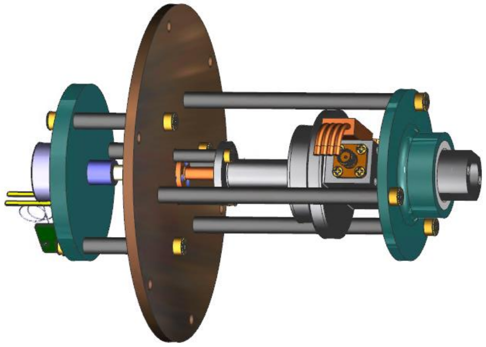
Test-Bed Devices for mK Characterization of Materials

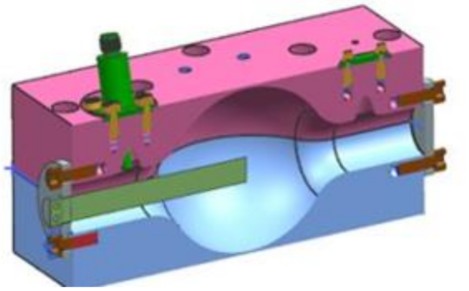
- Developing new devices to test RF performance of materials in quantum regime
  - New geometries
  - Frequency tunable cavities





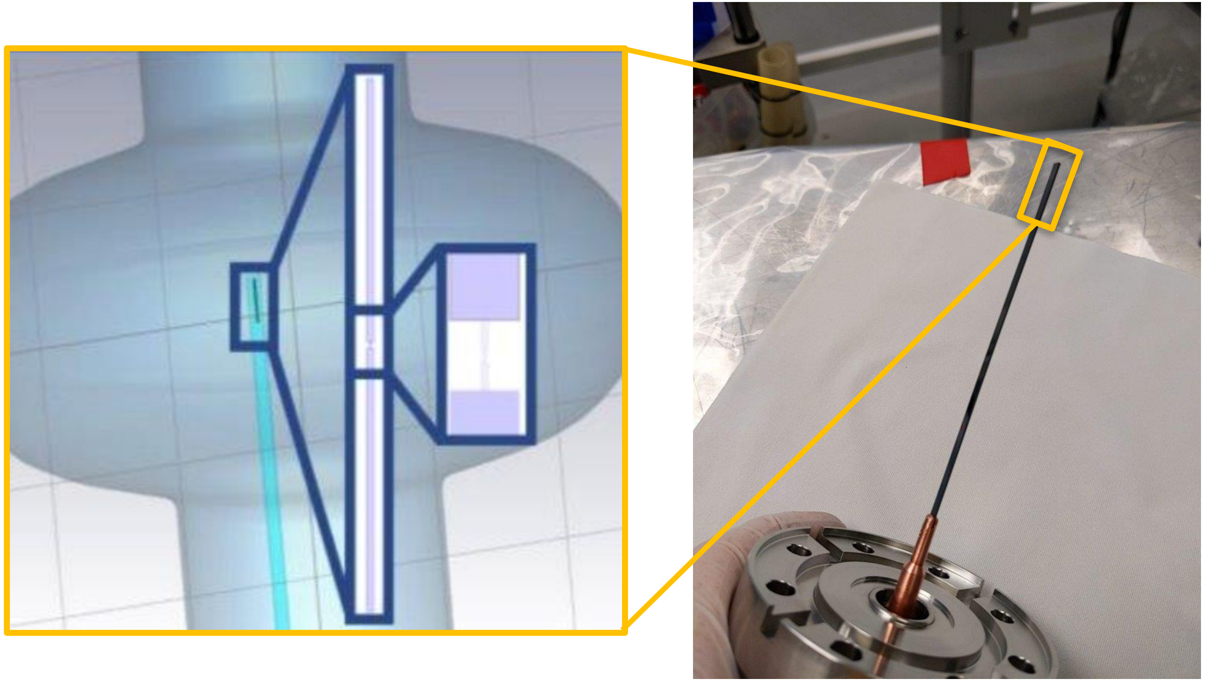
- Connecting RF performance to material differences will drive the optimization of qubit fab for longer coherence times





Focus Area: Devices

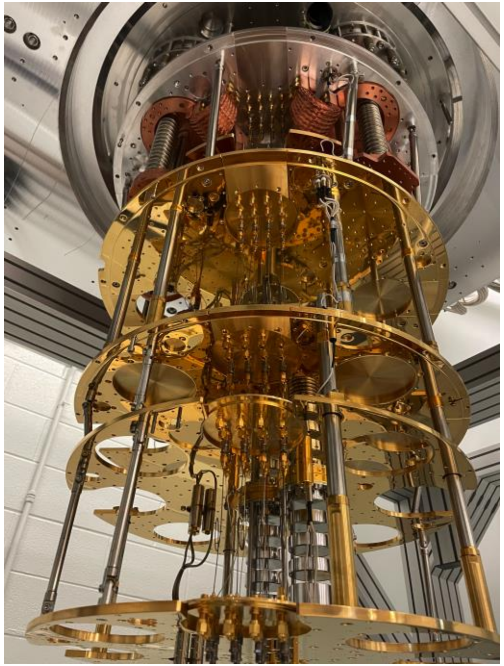
Goal: Develop methods for 2D and 3D superconducting device performance testing, benchmarking, integration, and quantum controls

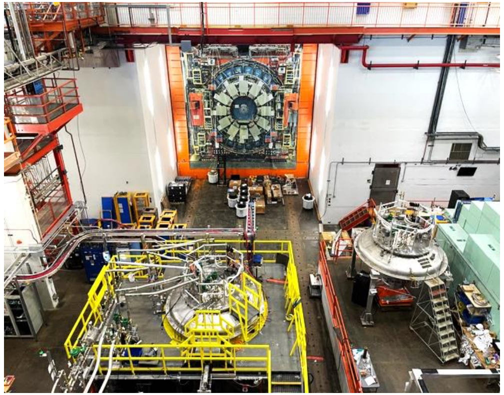


- Incorporating Rigetti transmons into 3-D SRF cavities
- Initial results are record-breaking for the photon lifetimes

Enabling Testing at Ultra-Low Temperatures

- Quantum measurements require minimal thermal noise
  - Drives decoherence
- **Dilution refrigerator**
  - Cools to ~20 mK via conduction
- Complex RF equipment
- SQMS plans to make a record size DR at FNAL!





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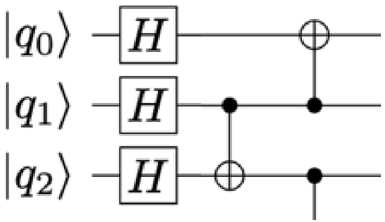
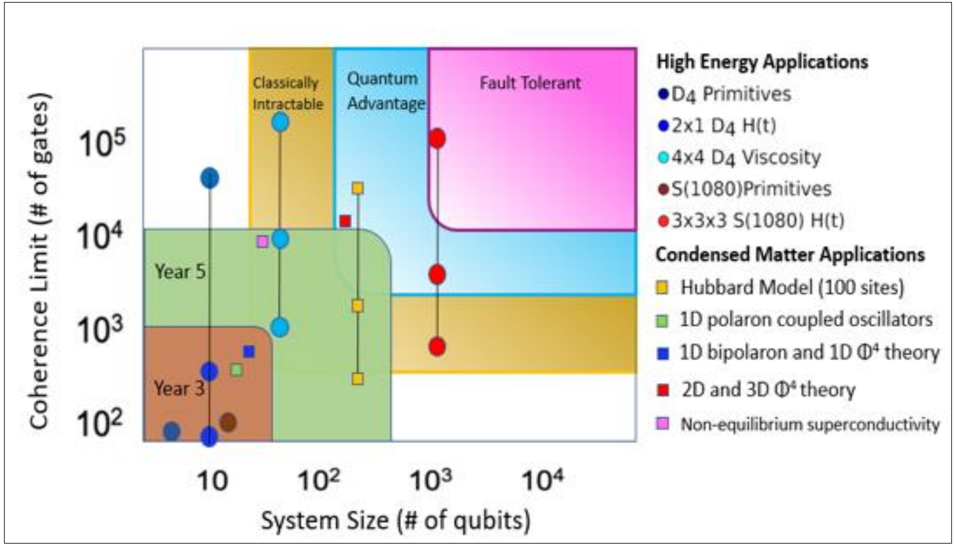
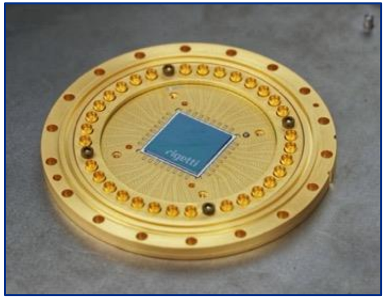
SQMS Science Thrust:
What Can we Do with These Cavities and Qubits in the Quantum Regime?

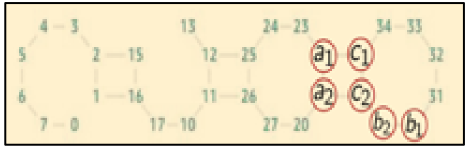
Focus Area: Algorithms, Simulations, and Benchmarking

Goal: Investigate and develop quantum algorithms and simulations enabled by the groundbreaking SQMS 3D and 2D prototypes through co-design principles







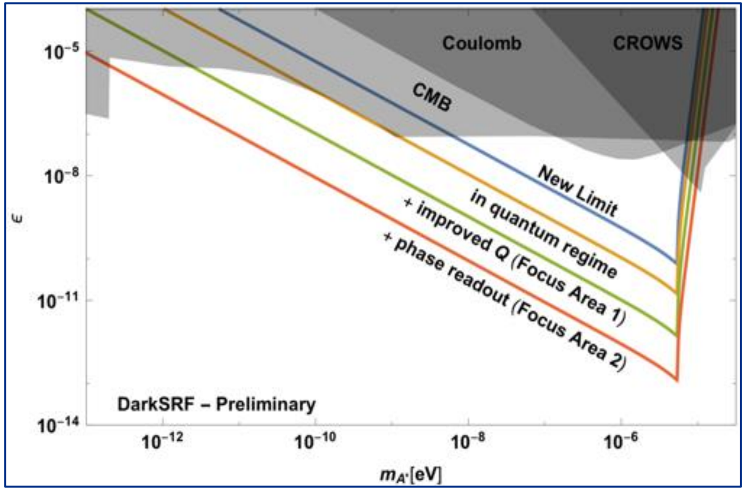


Qubits considered for a D4 gauge field theory test simulation on Rigetti hardware.

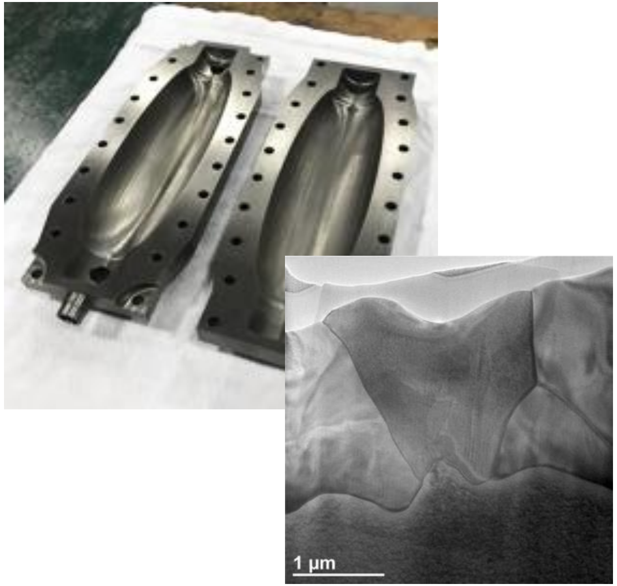
Focus Area: Physics and Sensing

Goal: Exploit the center technological advancements for fundamental physics

DarkSRF experiment:
A dark photon search



Orders of magnitude in sensitivity reach improvement via the SQMS advancements



Cavity and Nb_3Sn materials advancements for axion searches

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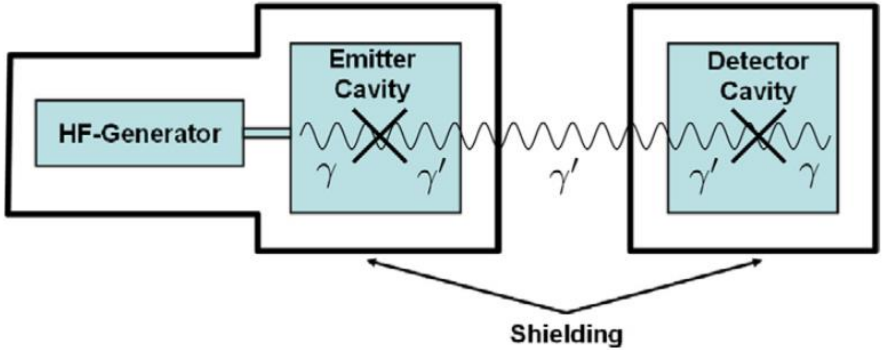
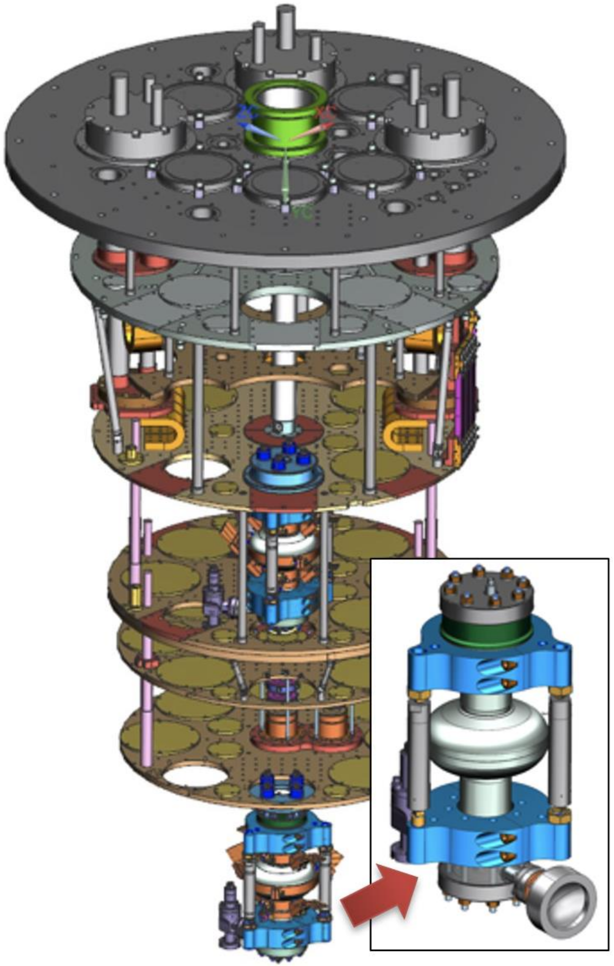
DarkSRF: The Search for Dark Photons

- Looking for BSM physics: dark photons
- “Light shining through wall” experiment
- SRF cavities will offer many orders of magnitude improvement in sensitivity



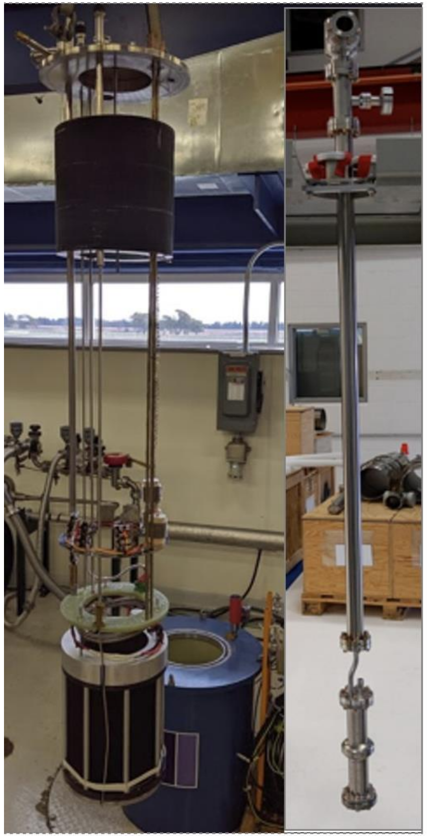
S. R. Parker *et al*, Phys. Rev. D 88, 112004 (2013)
J. Hartnett *et al*, Phys. Lett. B 698 (2011) 346
J. Jaeckel and A. Ringwald, Phys. Lett. B 659, 509 (2008)



Axion Detection with SRF Cavities

- Searching for cold dark matter candidates: axions
- Designing and manufacturing SRF resonators capable of allowing high-Q in multi-Tesla fields for axion detection.
  - Utilizing Nb_3Sn coated SRF cavities
- Currently setting up a proof-of-principle experiment at Fermilab and a second one in collaboration with INFN

New cavity shape optimized for low flux losses



6 T solenoid (left) and Nb_3Sn cavity insert (right) at Fermilab high field magnet test facility

Conclusion

- Exciting time to be a part of such a world-wide effort in the field of QIS
- SQMS has the potential of making dramatic advancements in many thrusts in the QIS field:
  - Superconducting qubits and sensors
  - Materials
  - Algorithms
  - Quantum communication
  - Hardware development
  - Cryogenics
  - RF design and engineering
- We look forward to bringing the first SRF quantum computer to life in the next few years!

*Thank you to Anna Grassellino for providing many of the slides in this talk

Thank You for Your Attention