Superconducting High Coherence Platforms for Sensing and Computing

Alexander Romanenko

ECFA Task Force 5: Quantum and Emerging Technologies

12 Apr 2021

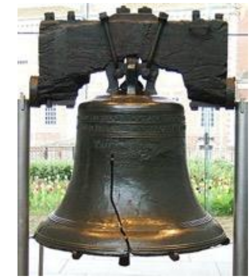
Overview

- Enabling superconducting technologies
  - Superconducting radio frequency (SRF) cavities
  - 2D and 3D superconducting qubits

- Some applications
  - Dark sector searches
    - Dark photon
    - Axions

- Future outlook
- SQMS Center – first quantum computer at FNAL

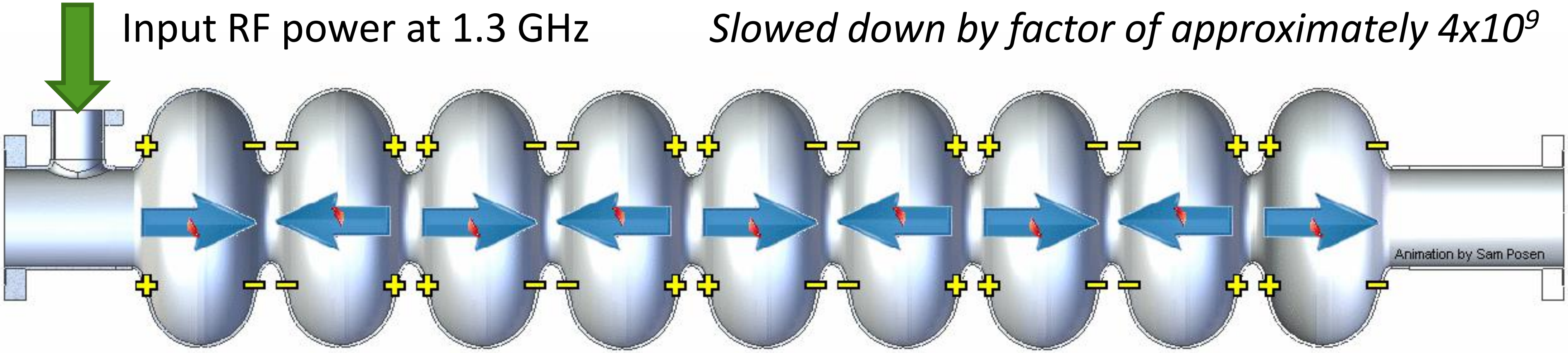
How are Particles Accelerated in Modern Machines?



- **Superconducting radiofrequency (SRF) cavities**
- High quality EM resonators: $Q_0 > 10^{10}$
- Over billions of cycles, large electric field generated (>**10^{25}** photons stored)
- Particle beam gains energy as it passes through

Input RF power at 1.3 GHz

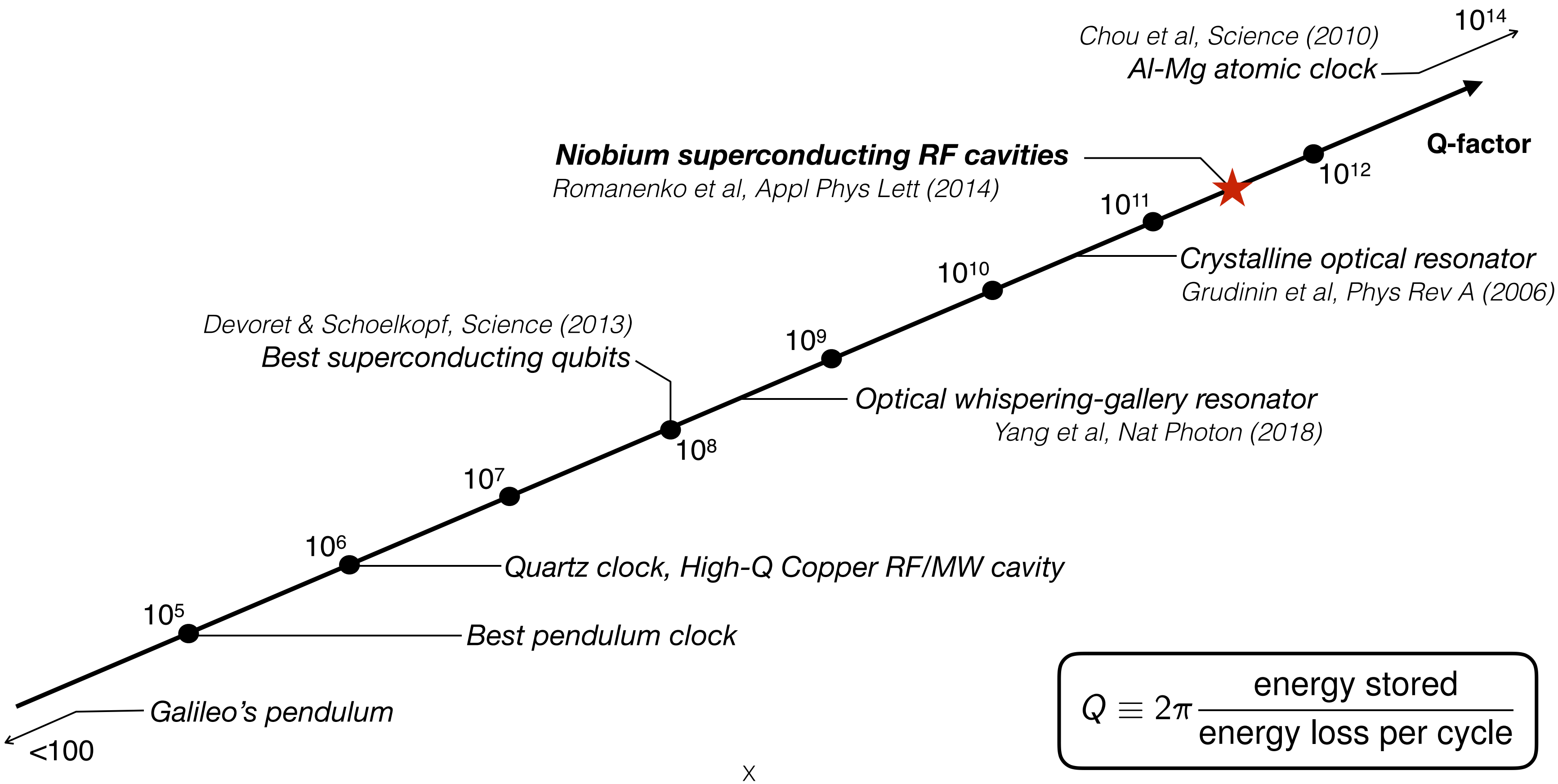
Slowed down by factor of approximately $4x10^9$



~1 m

Why SRF cavities for quantum sensing?

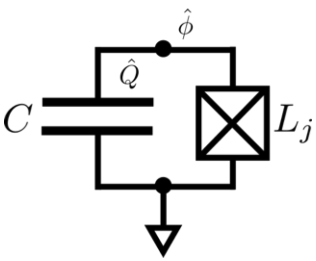
SRF cavities are the most efficient engineered oscillators

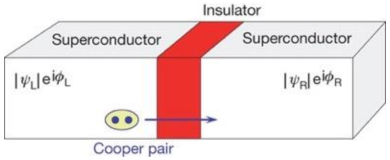


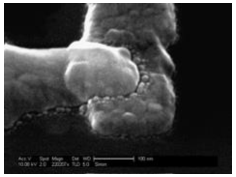
$$Q \equiv 2\pi \frac{\text{energy stored}}{\text{energy loss per cycle}}$$

Advancing Superconducting Qubits for QIS, two main components

1. LC circuit with Josephson junction







"Transmon" qubits

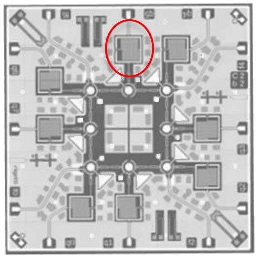
J. Koch et al, Phys. Rev. **A** 76, 042319 (2007)

+

2. Resonators (cavities)

2D

3D

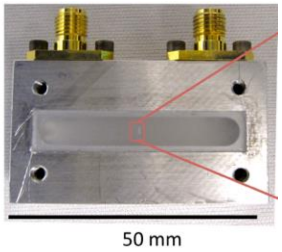


Rigetti 8-qubit processor

Q ~ 10^5

$T_{coherence}$ ~ 0.000001 s

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



3D transmon

Q ~ 10^8

$T_{coherence}$ ~ 0.001 s

H. Paik et al, Phys. Rev. Lett. 107, 240501 (2011)

Fermilab SRF resonators

Q > 10^{10}

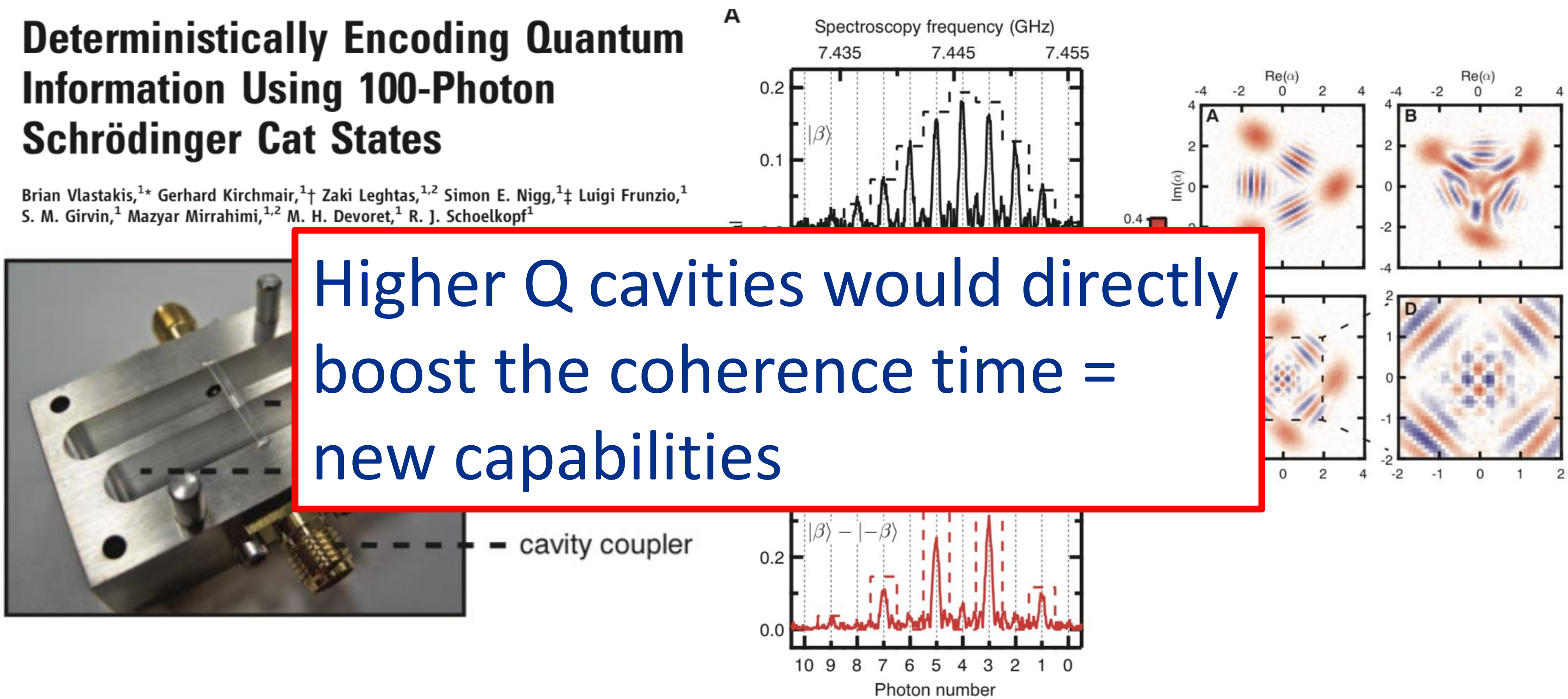
$T_{coherence}$ > 1 s

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

The main challenge is improving the **coherence** of both key components while also **scaling up** to larger combined systems

"Schrodinger cat" states as a computational/sensing resource

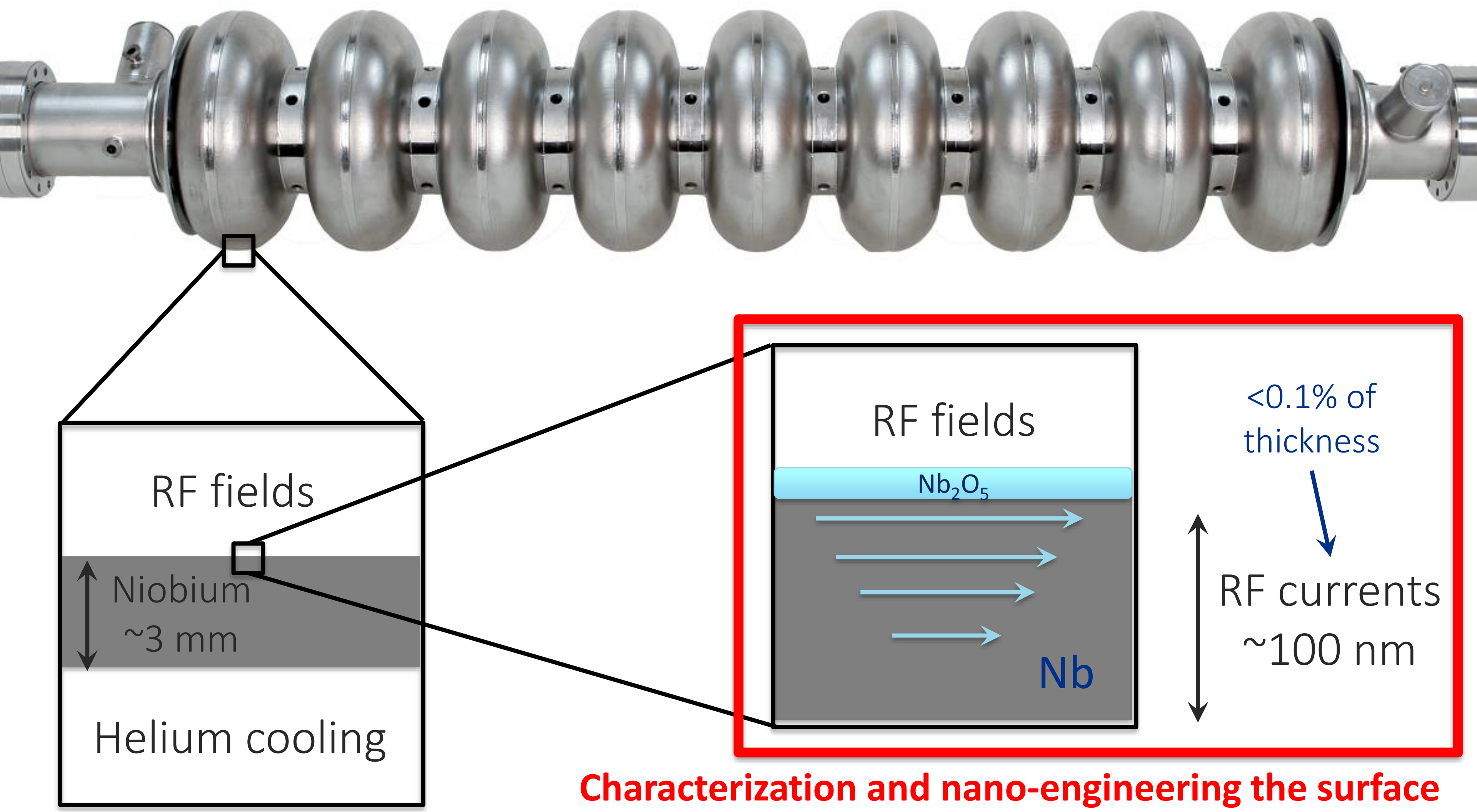
- M. Mirrahimi et al, New Journal of Physics 16 (2014) 045014



Higher Q cavities would directly boost the coherence time = new capabilities

- Error correction: N. Ofek et al, Nature 536 (2016), 441
- CNOT gate: S. Rosenblum et al, Nature Communications 9 (2018)

Nanometric RF Penetration Layer drives the performance



Characterization and nano-engineering the surface layer is crucial to performance

Modern large scale accelerators: large and complex high coherence SRF systems

European XFEL

~1000 cavities

Specification:

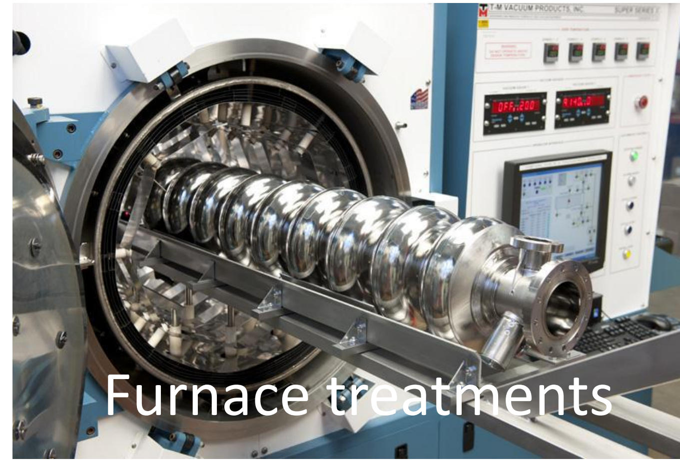
Q > 10^{10} @ 2K, 23.6 MV/m

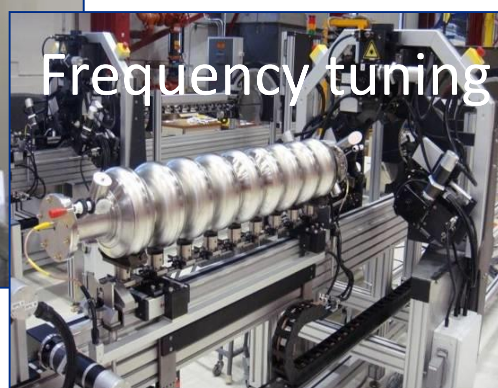
LCLS-II at SLAC

Fermilab has built half (30+) of cryomodules

Q > 2.7 x 10^{10} @ 2K, 16 MV/m

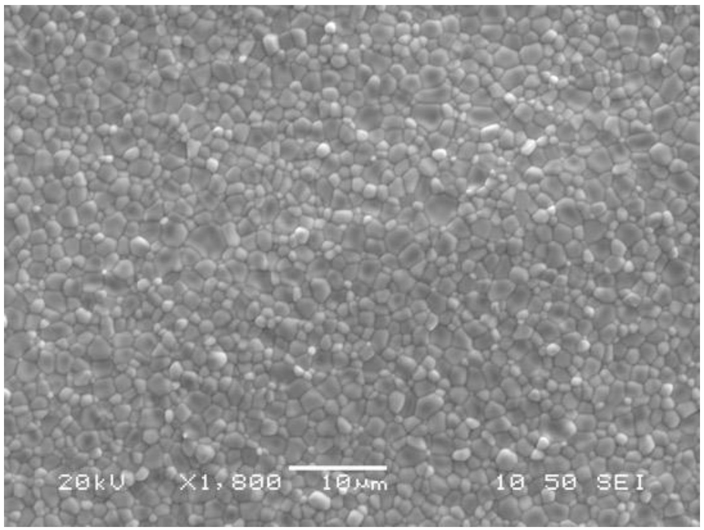
Major SRF infrastructure and expertise at Fermilab, enabling highest Q ever achieved, in low and high photon count regimes

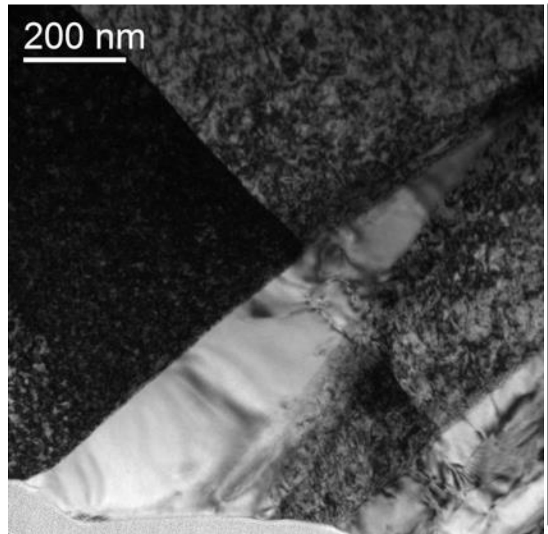


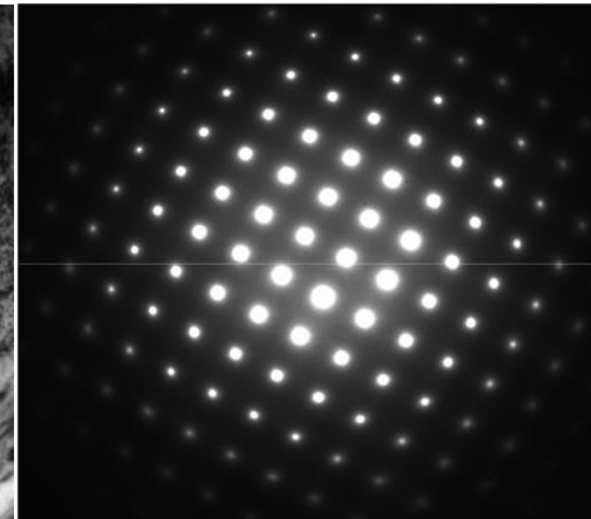


Material science and superconducting characterization

- Cavity surface undergoes a series of delicate chemical and heat treatments
- Material science tools are <u>essential</u> to understand the surface nanostructural changes that lead to dramatic changes in performance







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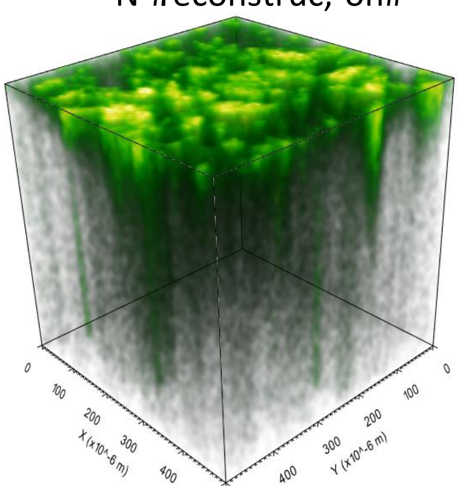
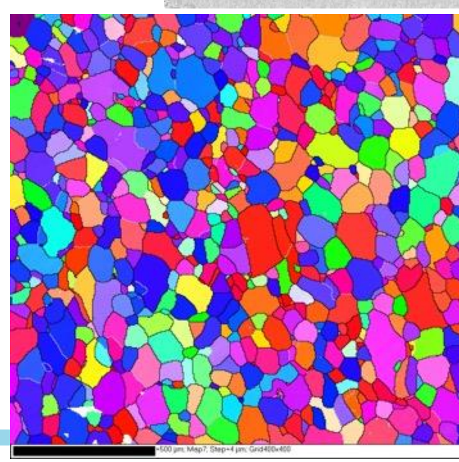
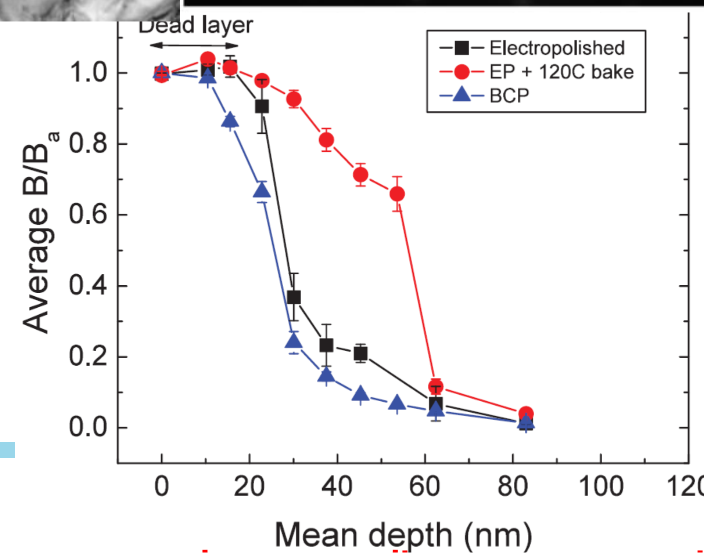
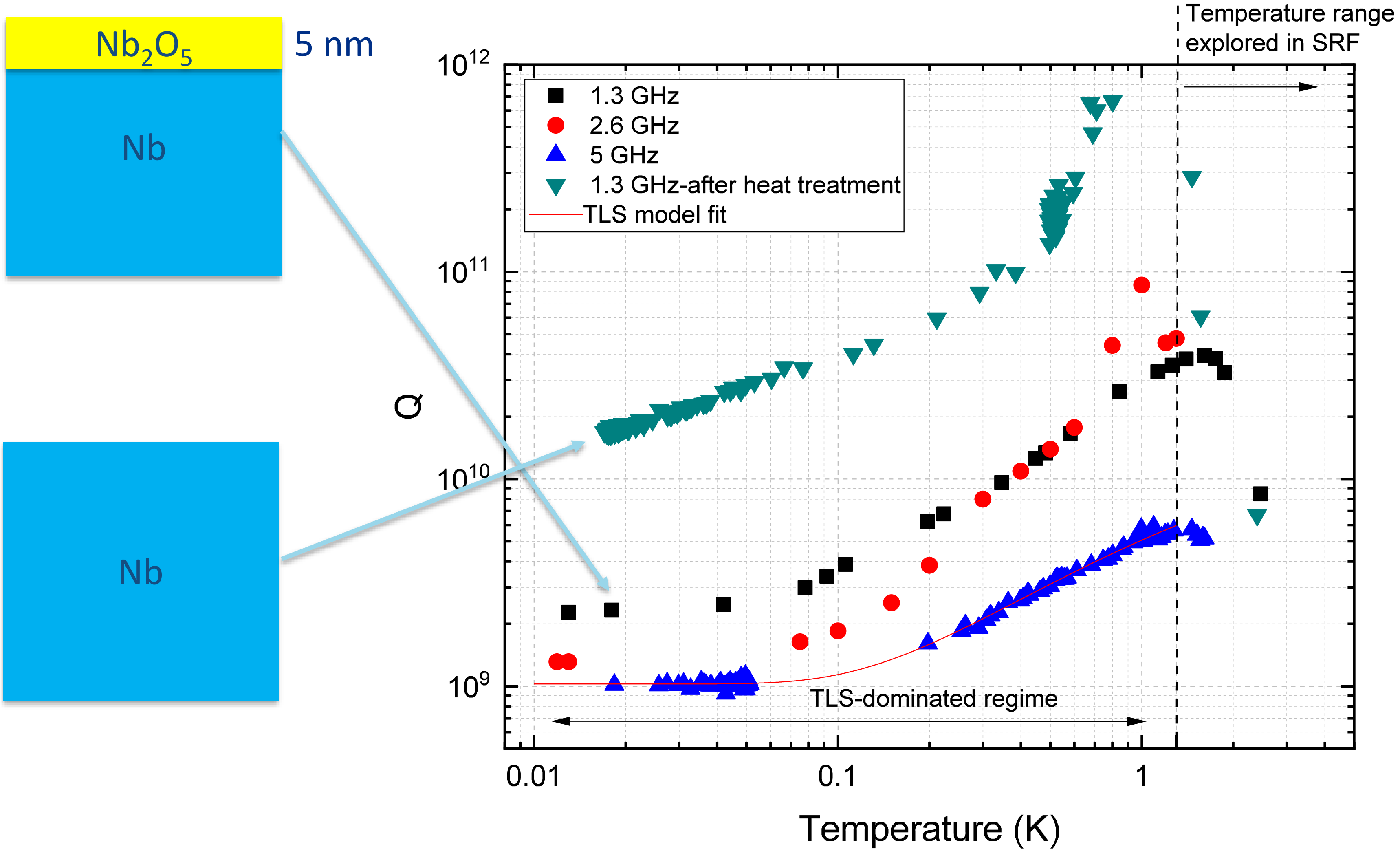




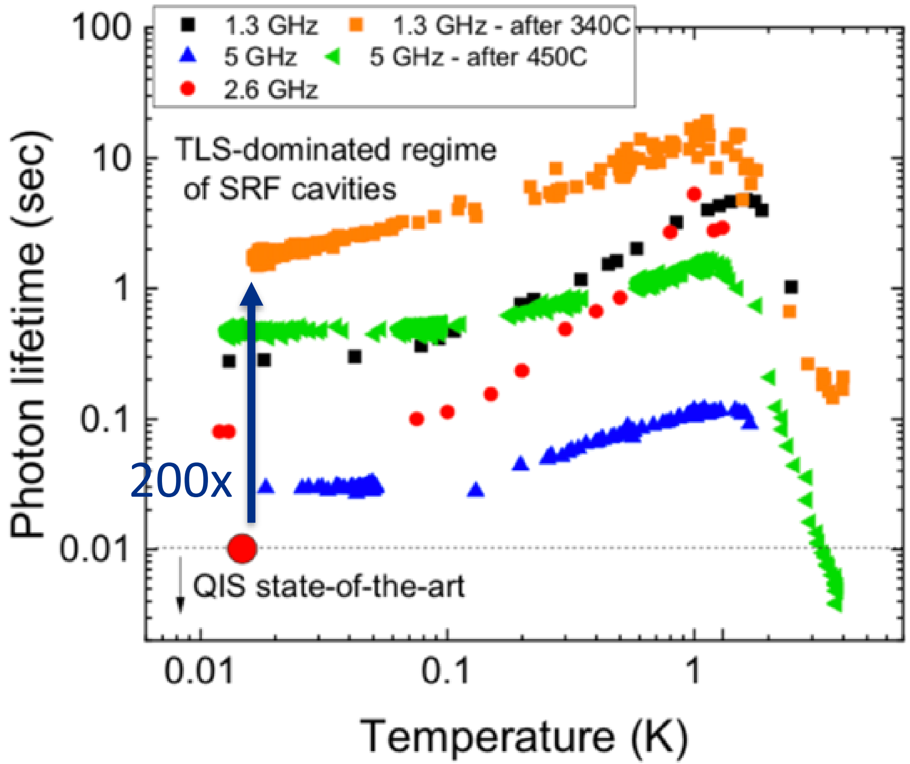


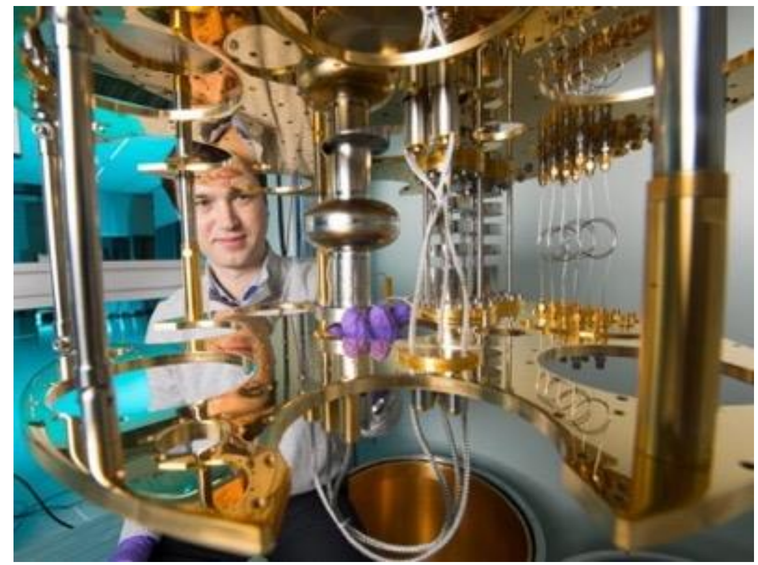
Material treatment to suppress TLS dissipation



A. Romanenko and D. I. Schuster
Phys. Rev. Lett. **119**, 264801 – Published 28 December 2017

Fermilab superconducting cavities: highest coherence (high Q) quantum microwave resonators



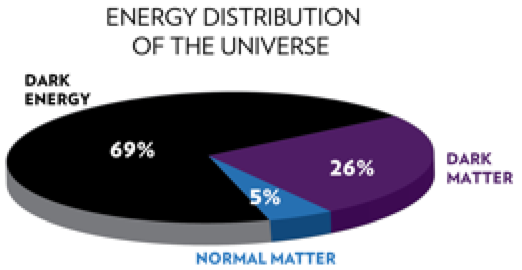


- Demonstrated record values of 2 seconds of coherence in quantum regime

A. Romanenko, R. Pilipenko, S. Zorzetti, D. Frolov, M. Awida, S. Belomestnykh, S. Posen, and A. Grassellino Phys. Rev. Applied **13**, 034032, 2020

Applications: Longer Range Interactions and Wave-like Dark Matter

- New light particles are theoretically well motivated. e.g.
  - Axion like particles (including the QCD axion)
  - Dark photons



- For such light particles two hypotheses can be tested:

New particle:

$$\mathcal{L} \supset$$

dark photons?
axions?
long range force?

Dark matter (and new particle):

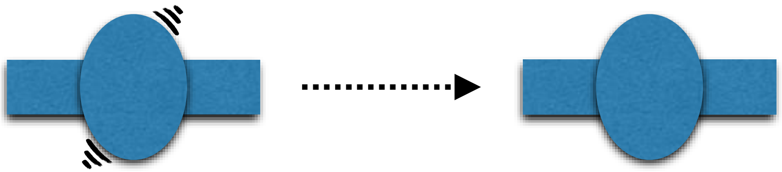
$\supset$

dark photons?
axions?

Basic search schemes

Light Shining through wall:

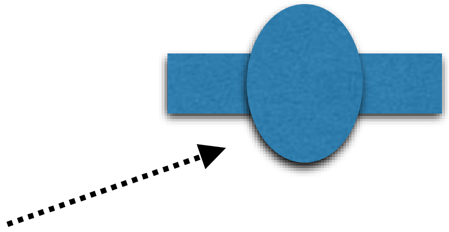
Emitter Receiver



a search for a mediator.

A dark matter search:

Receiver



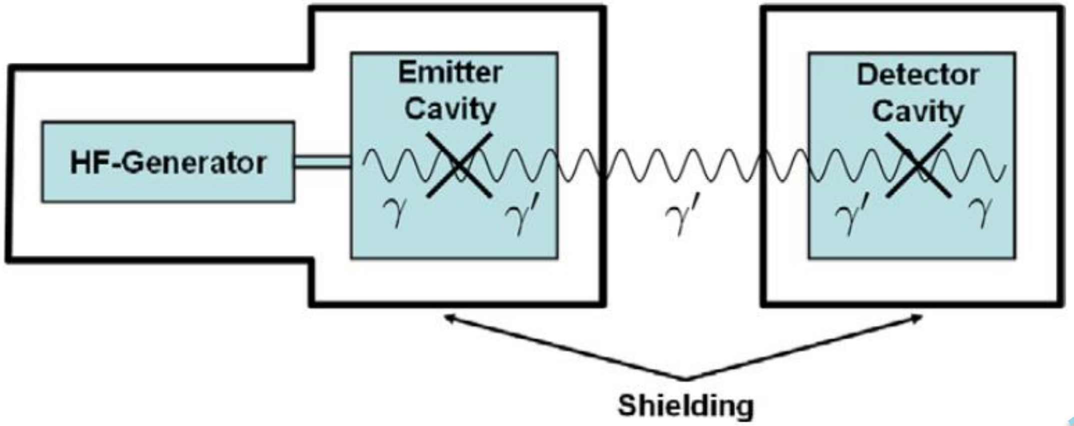
the DM filled Universe
is the emitter

Dark sector search

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)

Q_{DET}, Q_{EM} < 10^5 so far used

Looking for hidden paraphotons



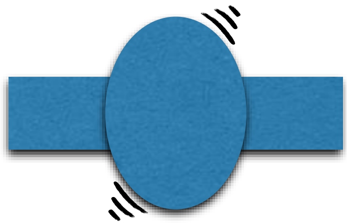
$$\frac{P_{DET}}{P_{EM}} = \chi^4 Q_{DET} Q_{EM} \left(\frac{m_{\gamma'} c^2}{\hbar\omega_\gamma}\right)^8 |G|^2$$

Q_{DET}, Q_{EM} > 10^{10} SRF can offer several orders of magnitude improvement in sensitivity to χ

Fermilab

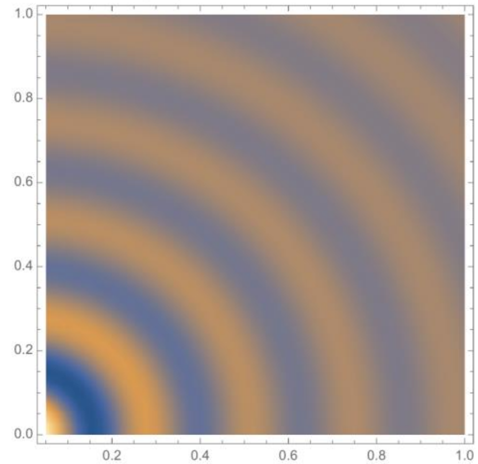
Dark Photon Search

Q> 1e9



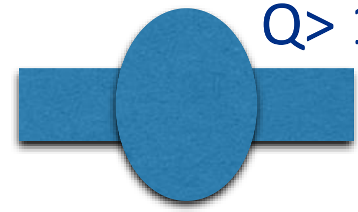
Emitter Cavity

Frequency of 1.3 GHz, excited to ~ 35 MV/m. Thats ~ 10^{25} Photons!



a dark photon field is radiated at 1.3 GHz.

Q> 1e10

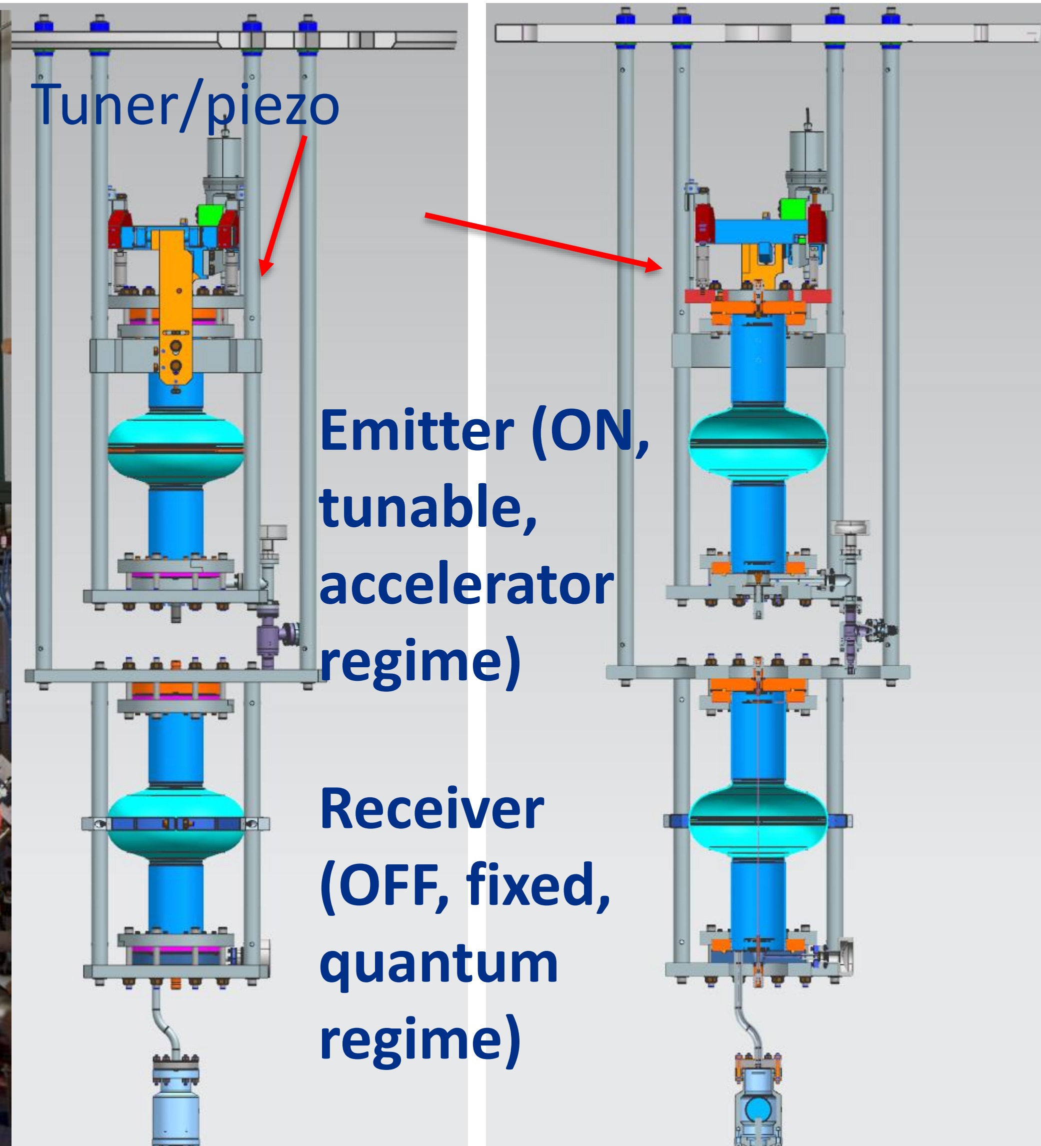


Receiver Cavity

Tuned to 1.3 GHz. Responds to dark field. Contains only thermal noise (T=1.4 K).

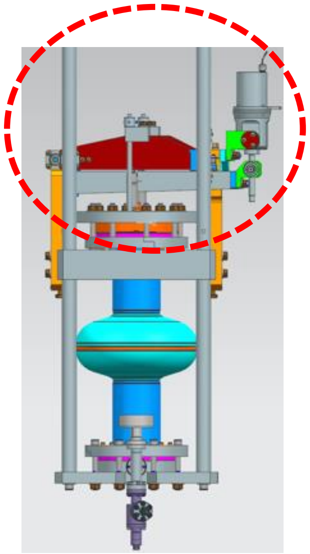
For correct cavity positioning $P_{rec} \leftarrow G^2 \, 4 \left(\frac{m_{\gamma^0}}{!} \right)^4 Q_{rec} Q_{em} P_{em}$

DarkSRF experiment @ Fermilab

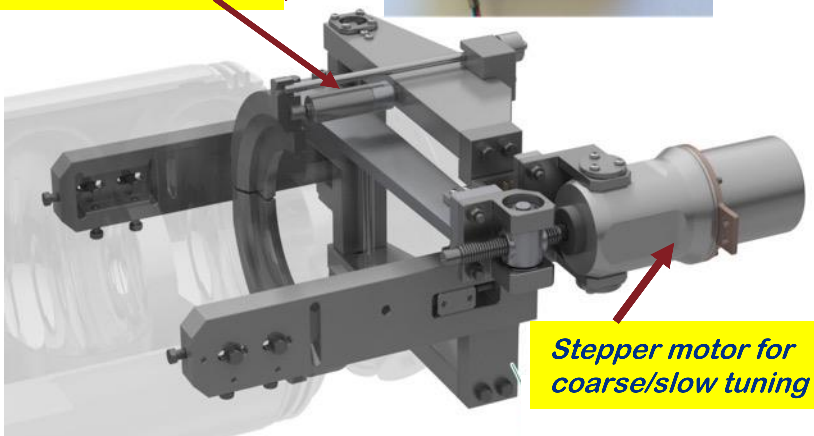


Controlling cavity frequency with sub-Hz resolution

SRF Cavity Tuner (LCLS II double lever tuner) to tune “transmitter” cavity



Piezo-actuator for fine/fast tuning



Stepper motor for coarse/slow tuning

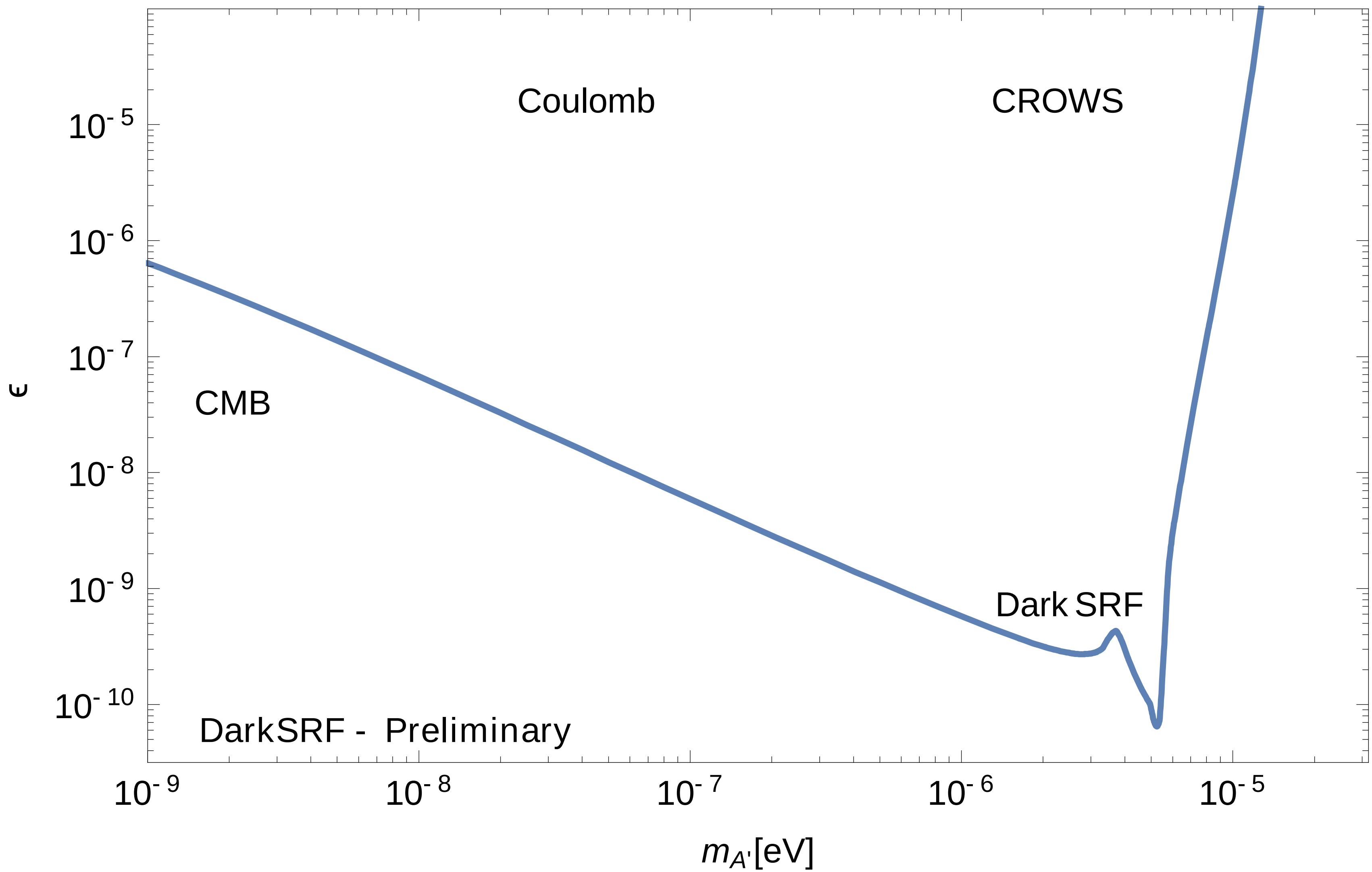
Coarse Tuner
- Range up to ΔX=2mm or ΔF=5MHz
- Resolution δx=5nm or δF=12Hz
- Hysteresis ~ 300Hz

Fine/Fast Tuner
- Range up to ΔX=3um or ΔF=8kHz
- Resolution δx=0.05nm or δF=0.1Hz (*)

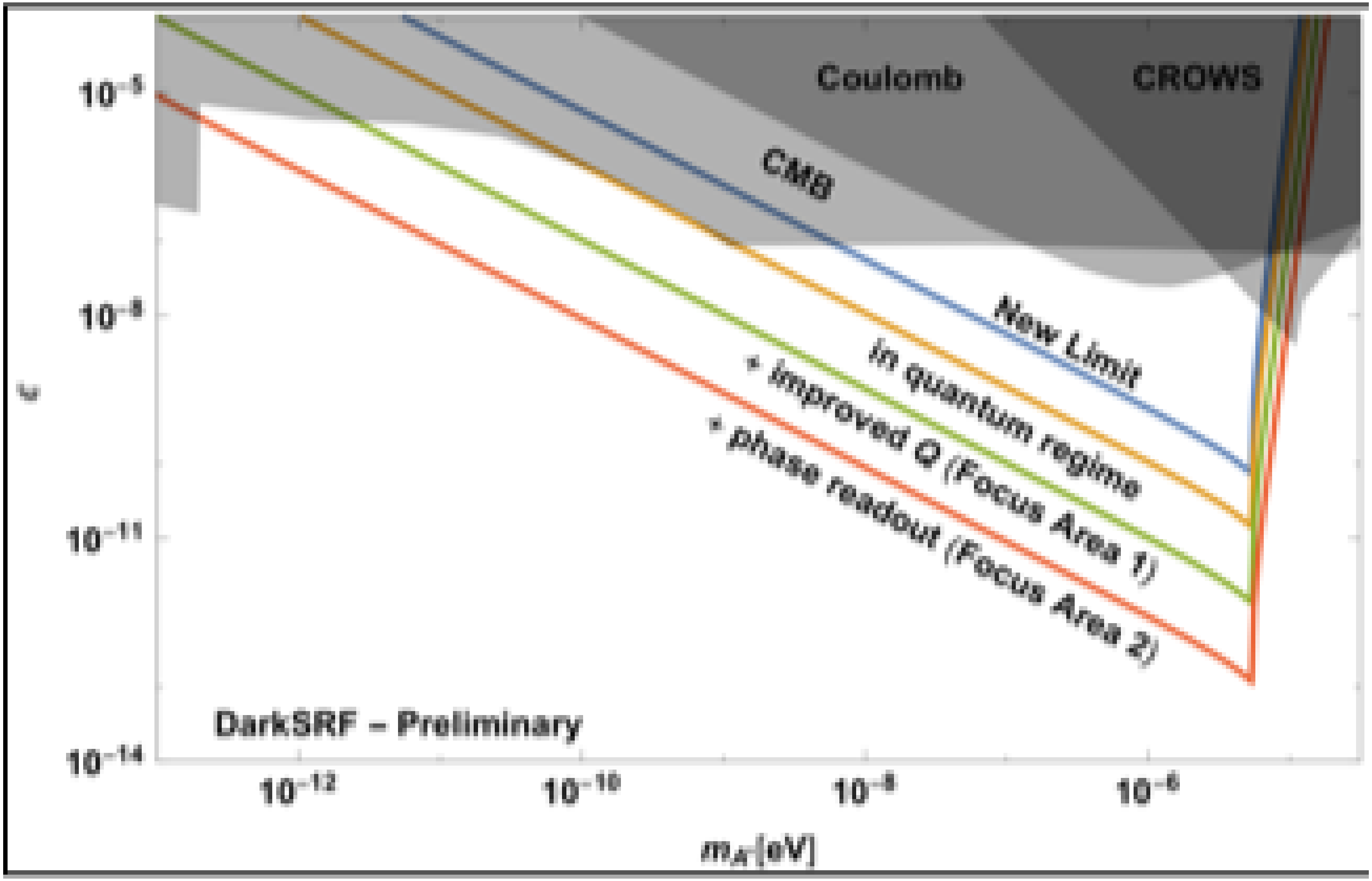
(resolution will be limited by electrical noise of the piezo amplifier)

(*) Piezo tuner resolution measured with LCLS II cavity ~0.15Hz was limited by noise at HTS

Results from run 2 – exclusion boundary pushed up to 3 orders of magnitude compared to state of the art

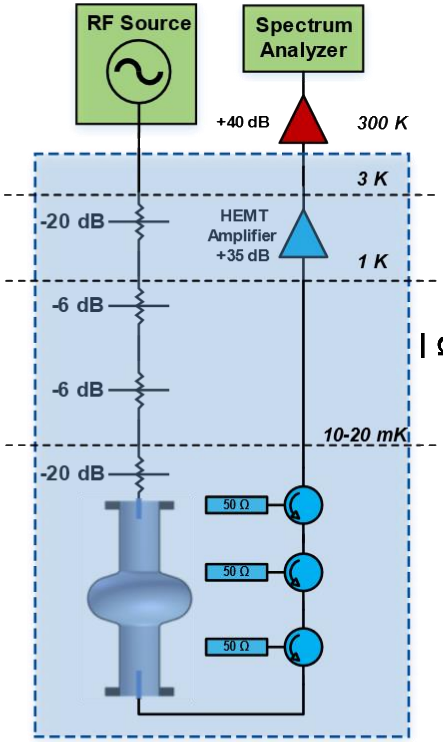


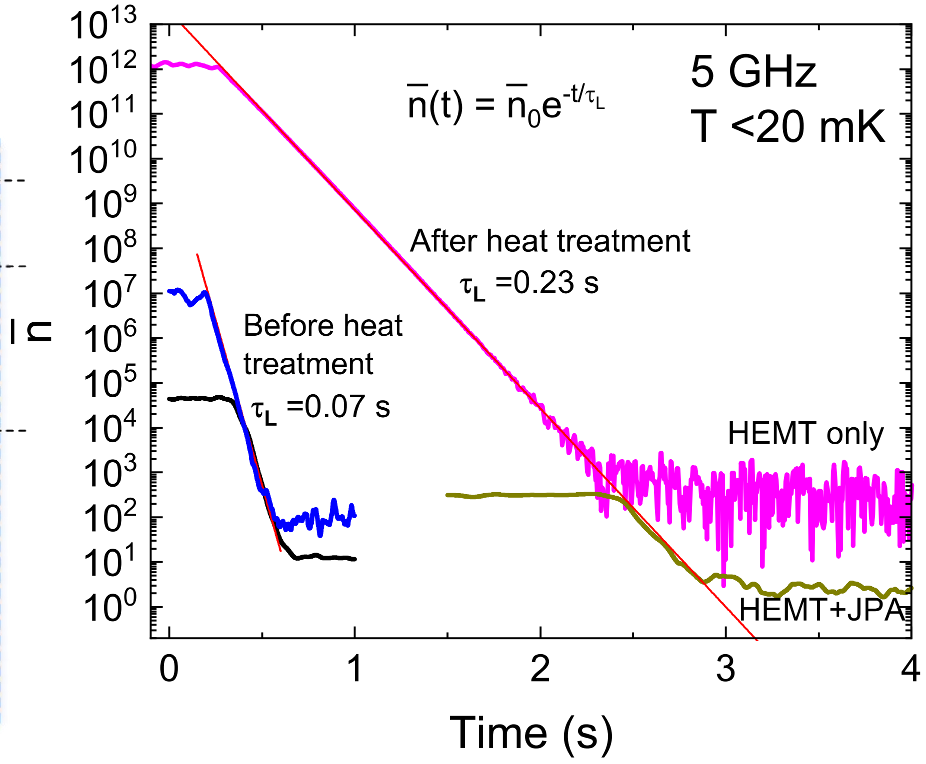
Extending DarkSRF reach



Further insight from measurements in quantum regime

- Exclusion of dark photons floating around in the galaxy at one specific frequency
- Could extend experiment by scanning





A. Romanenko, R. Pilipenko, S. Zorzetti, D. Frolov, M. Awida, S. Belomestnykh, S. Posen, and A. Grassellino Phys. Rev. Applied **13**, 034032, 2020

Lots of new exciting ideas on very high Q SRF cavities for axion searches and more – we need to implement

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Probing Axionlike Particles and the Axiverse with Superconducting Radio-Frequency Cavities

Zachary Bogorad, Anson Hook, Yonatan Kahn, and Yotam Soreq
Phys. Rev. Lett. **123**, 021801 – Published 9 July 2019

PHYSICAL REVIEW D
covering particles, fields, gravitation, and cosmology

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Axion production and detection with superconducting rf cavities

Ryan Janish, Vijay Narayan, Surjeet Rajendran, and Paul Riggins
Phys. Rev. D **100**, 015036 – Published 23 July 2019

Axion Dark Matter Detection by Superconducting Resonant Frequency Conversion

Asher Berlin
Center for Cosmology and Particle Physics, Department of Physics, New York University, New York, NY 10003, USA.

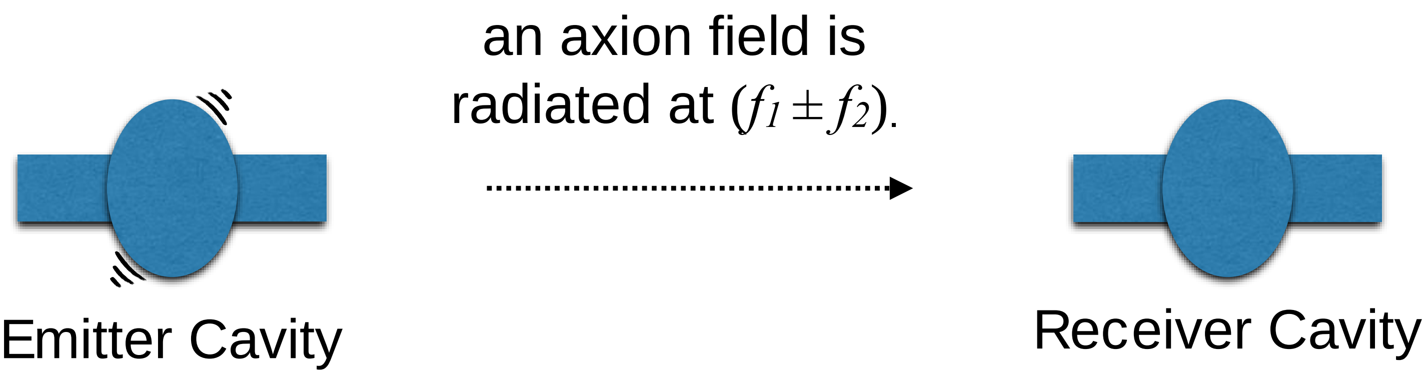
Raffaele Tito D'Agnolo
Institut de Physique Théorique, Université Paris Saclay, CEA, F-91191 Gif-sur-Yvette, France

Sebastian A. R. Ellis, Christopher Nantista, Jeffrey Neilson, Philip Schuster, Sami Tantawi, Natalia Toro, and Kevin Zhou
SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, CA 94025, USA

Searching for Millicharged Particles with Superconducting Radio-Frequency Cavities

Asher Berlin[1] and Anson Hook[2]
[1]*Center for Cosmology and Particle Physics, Department of Physics, New York University, New York, NY 10003, USA*
[2]*Maryland Center for Fundamental Physics, University of Maryland, College Park, MD 20742, USA*

Extending DarkSRF to axions searches



Excite *two* modes, with a non-zero (oscillating) $E_1 \cdot B_2$

or

search for cosmic DM.

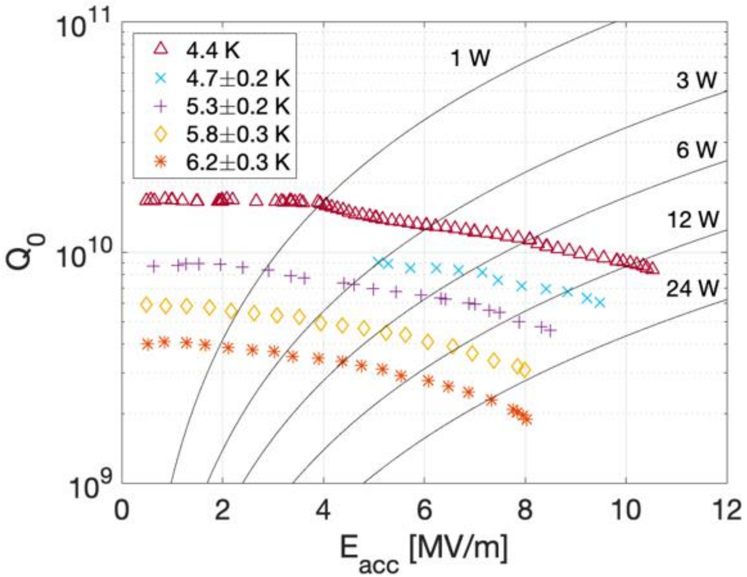
Several possibilities to explore:

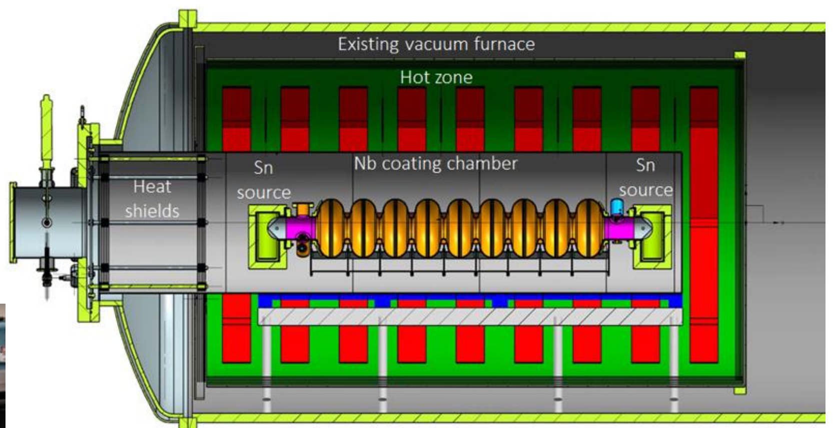
- One excited and one quiet mode.
- Inserting a region of static B field.
- .... R&D is required

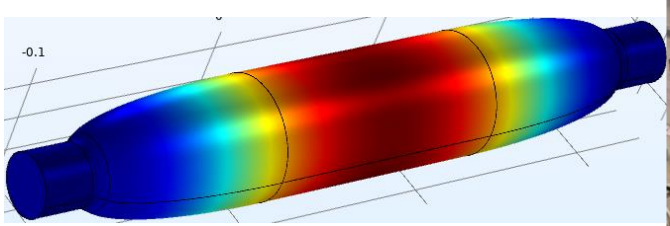
- Harnik, Romanenko, Grassellino, PAC 2018 DarkSRF presentation, Fermilab
- Kahn et al: Searching for axions and for the SM light-by-light interaction at low energies in a single cavity.
- Rajendran et al: Suggestion for light-shining-through-wall axion search using a quiet receiver cavity and a static B-field adjacent to the cavity.

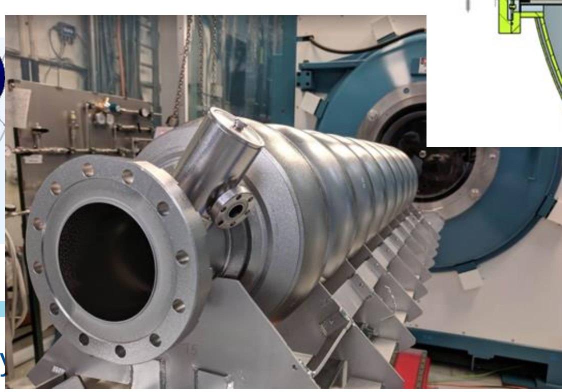
SRF Cavities for Axion Searches in Tesla fields?

- FNAL SRF group has an active research program in Nb_3Sn and other new materials
- World record Nb_3Sn cavities in the range 650MHz - 4 GHz with Q ranging from **1e9 to 1e11**
- **Will now test them in Tesla fields**
- Nb_3Sn is excellent candidate – H_{c2} ~ 30 T and we know how to make high quality films
- Optimize geometry for parallel fields to minimize Lorentz force (F~IxB)
- Several other new materials to be studied with our new CVD/ALD furnace









Sam Posen, FNAL

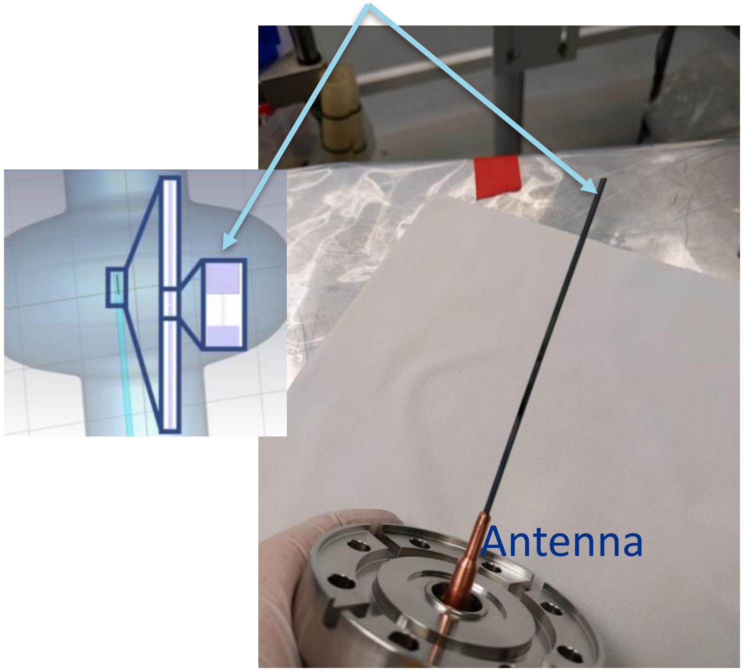
SRF cavity-qubit coupled system for quantum computing and sensing

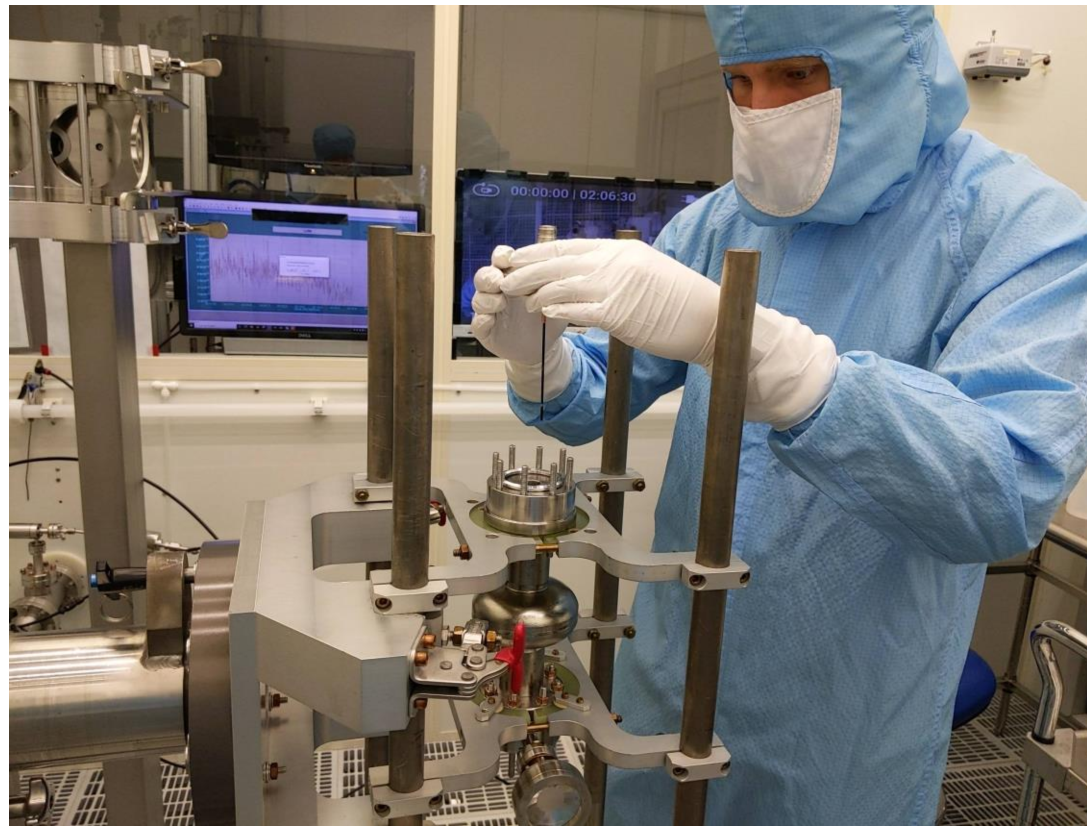
- Taking full advantage of ultra-high Q SRF cavities requires converting them to quantum nonlinear resonators
  - Achieved by integrating with the Josephson-junction based transmon qubits
  - High coherence integration => multilevel cavity mode utilization - **qudits**

- First set of Rigetti transmons has been integrated with SRF cavities
  - Combined system photon lifetimes of **~35 ms** achieved
  - Quantum measurements underway

Integration of SRF cavities with Rigetti transmons

Transmon at the end of Si rod

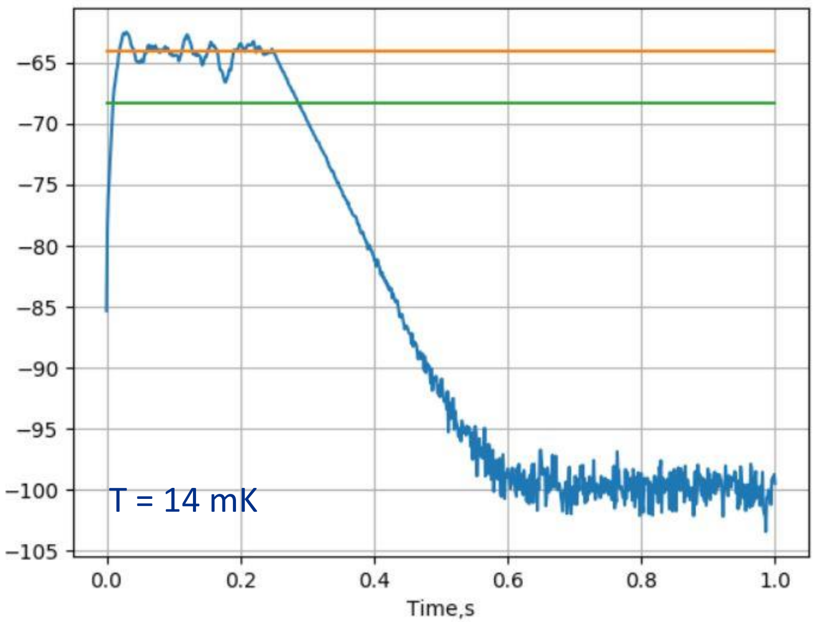




Photon lifetimes in integrated resonators in quantum regime

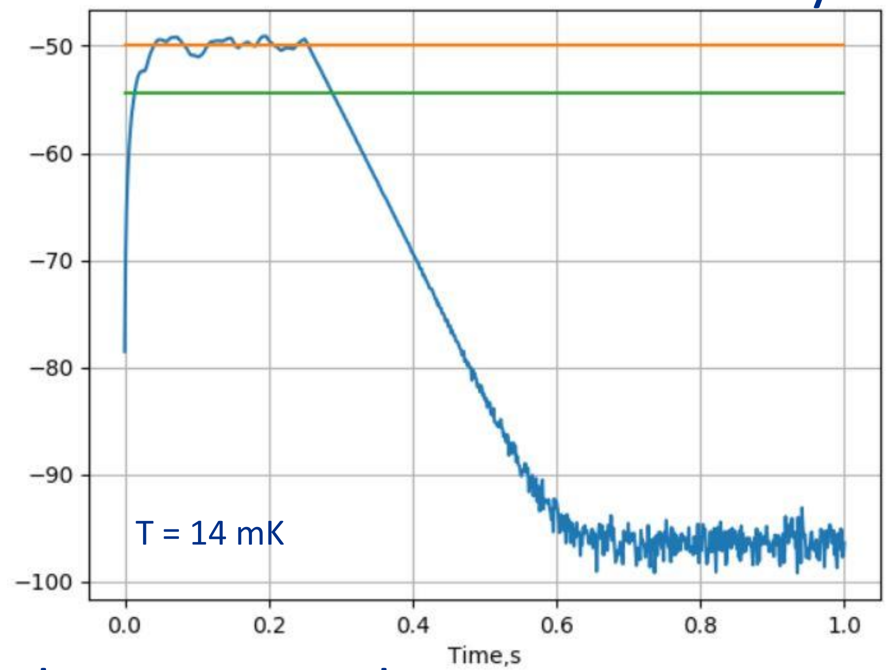
τ ~ 32 ms

Cavity 1



τ ~ 39 ms

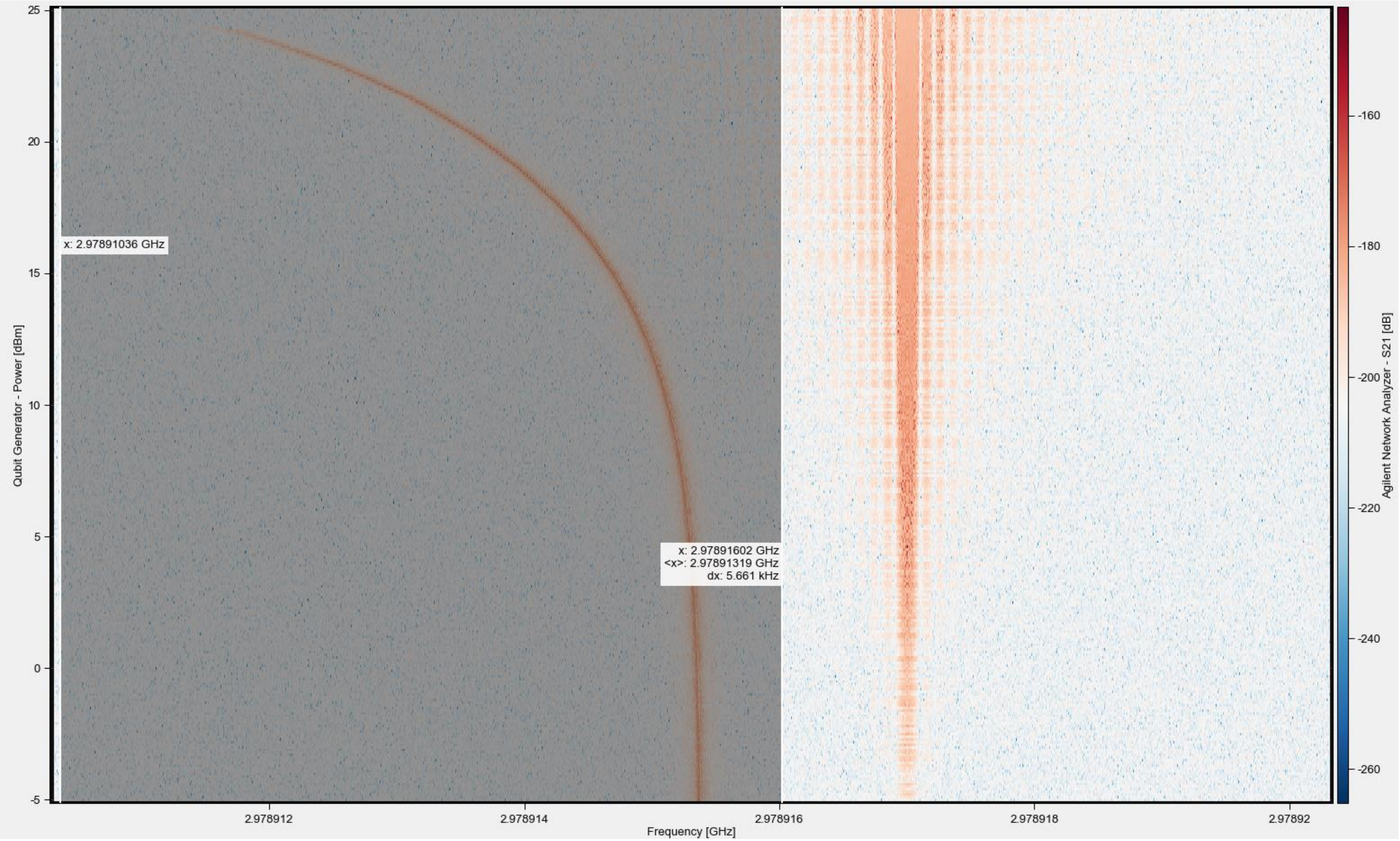
Cavity 2



Energy decay in cavity-transmon system

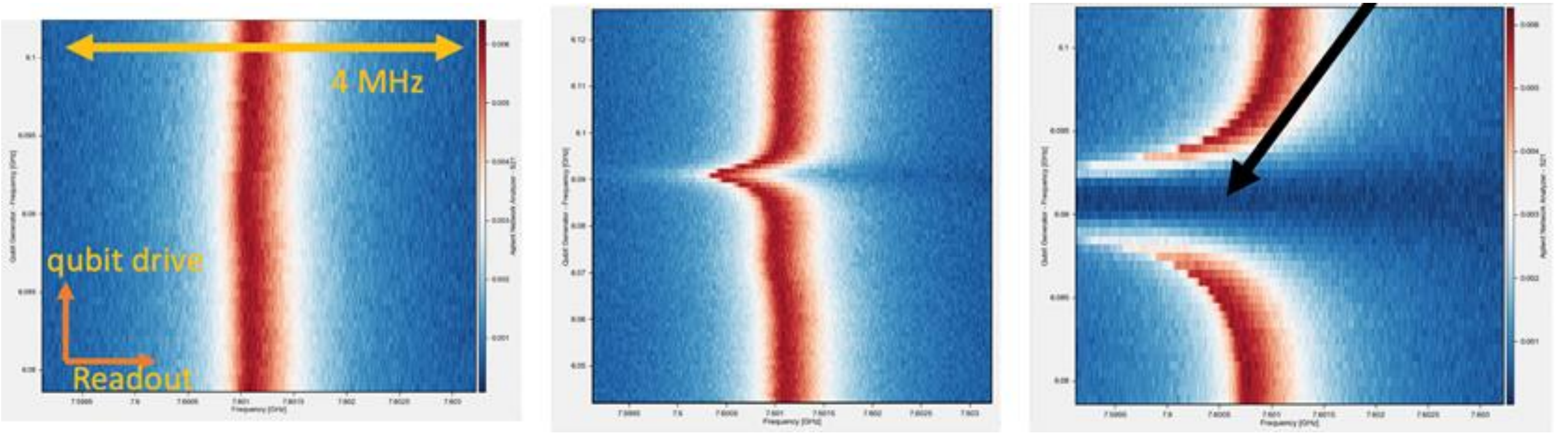
NB: Adding the transmon makes the system non-linear but drags down the Q

Fundamental SRF cavity mode shift for different photon numbers



Cross-Kerr nonlinearity in SRF cavities

- Modes hybridize/talk to each other via the qubit



Future Outlook

- Exciting new opportunities with SRF cavities for QIS and dark sector searches
  - Eg – DarkSRF excludes existence of dark photons in mass range 10^{-8}-10^{-5} eV by > 3 order of magnitude improvement from previous searches
  - Progressing to implementing various other schemes – **technology is ready**

- 2D qubits coupled to 3D SRF cavities can provide more ”handles” for detecting the dark sector-originating photons (eg photon counting)
  - But - introducing a lower Q transmon inside the cavity may lower the integrated Q somewhat (still by far the highest)
    - This is a common task for both 3D SRF quantum computing and sensing, best architectures/coupling is being worked out

August 2020: Fermilab will lead a DOE National Quantum Center

"With the **Superconducting Quantum Materials and Systems** Center (SQMS), we propose to bring the power of DOE laboratories, together with industry, academia and other federal entities, to "achieve transformational advances in quantum technologies for computing and sensing"

"We have the ambitious goal of building the first quantum computer at Fermilab"

SQMS 3D approach – unique benefits of the world's best coherence

Novel QPU architectures

- Long coherence allows going from qubit to "qu**d**it" approach

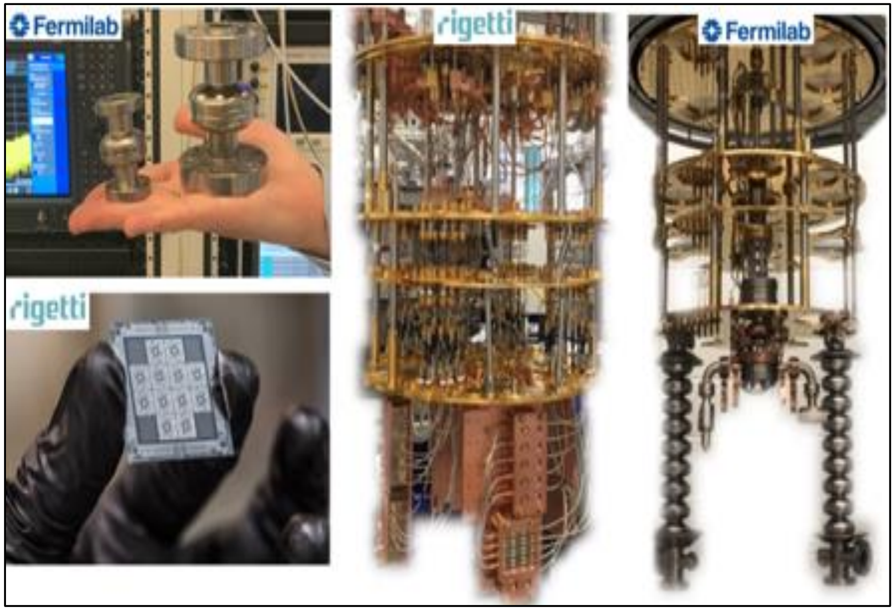
Scalability

- > 100 qubits with just few input/output lines

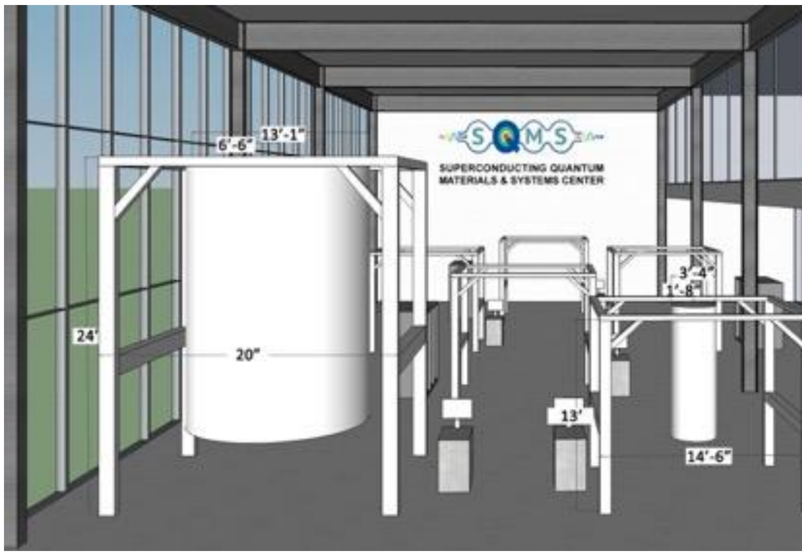
Science

- Long coherence and all-to-all connectivity offer new computation/simulation capabilities
- Probing microscopic to macroscopic boundary
- Searching for dark sector particles

ONE nine cell SRF cavity + **ONE** transmon =
SQMS 100+ qubits processor



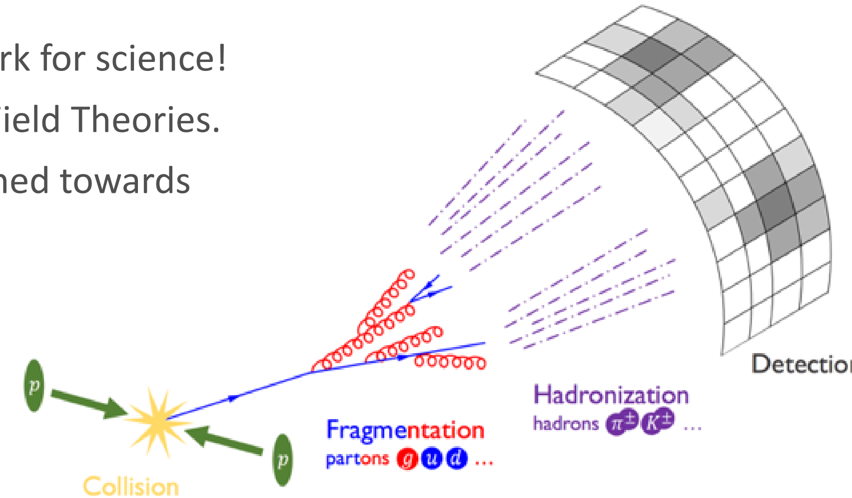
Scale up, integration capabilities and plans for the first quantum computer at Fermilab

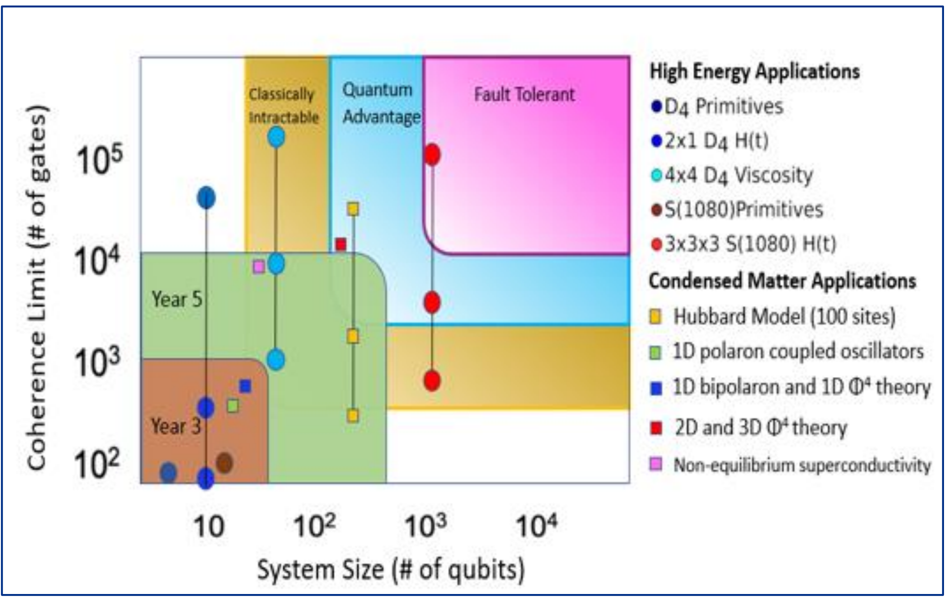


- We plan to build the largest dilution fridge ever constructed, to host hundreds of qubits, to be hosted in the IARC building
- Under design to also host large array of quantum sensors

Science and Discovery with SQMS

- We are excited to put SQMS quantum computer to work for science!
- High connectivity is well-suited to simulate Quantum Field Theories.
- Ladders of simulations (progression of toy-models) aimed towards ambitious science goals.





HEP:

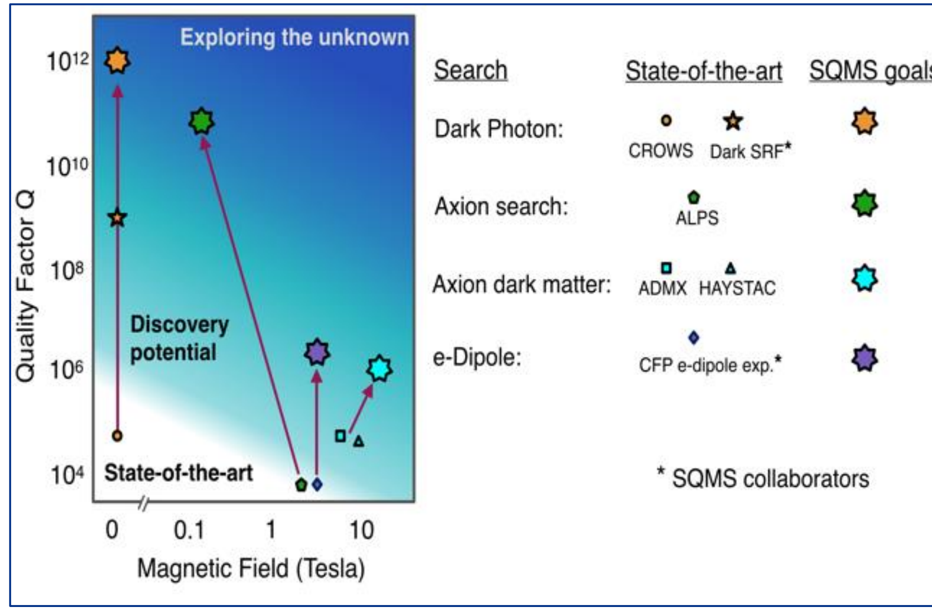
QCD dynamics: least understood parts of LHC collisions and early Universe (Hadronization, viscosity of gluon plasma)

Condensed matter:

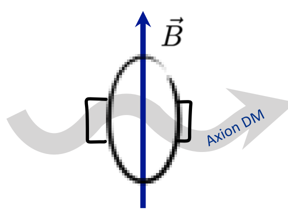
Many body states with high entanglement (aided by connectivity), many body localization. polaron system dynamics.

Science and Discovery with SQMS Technology - Sensing

- We are excited to use SQMS technology for direct exploration:
  - *Are there new long range forces?*
  - *What is the Dark Matter (DM)?*
  - *Can we probe single electrons more precisely?*



- High coherence also allows to pick up fainter signals, search for elusive particles.



e.g. Axion DM Search -
High Q in high B field (FNAL+INFN)

Orders of magnitude in sensitivity to new physics!

Summary

- Exciting new opportunities with SRF cavities for QIS and dark sector searches
  - Eg – DarkSRF excludes existence of dark photons in mass range 10^{-8}-10^{-5} eV by > 3 order of magnitude from previous searches
- Exciting progress with SQMS in the years ahead