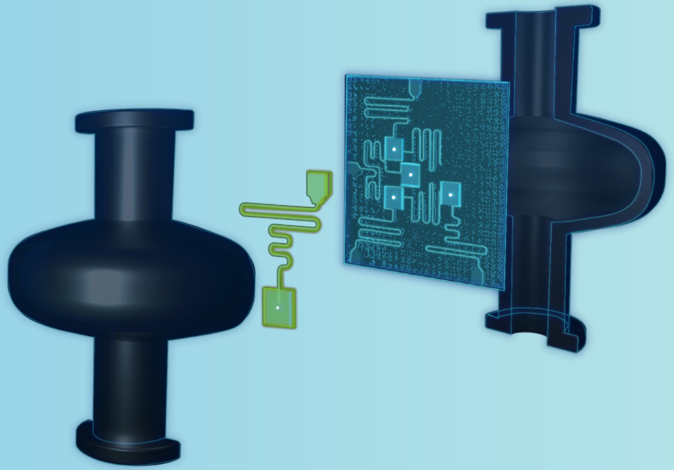
SQMS Fermilab U.S. DEPARTMENT OF ENERGY Office of Science



Superconducting Quantum Computing and Sensing Boosted by the Accelerator Technology Research in SRF

Alexander Romanenko

Chief Technology Officer, Fermilab

SQMS Technology Thrust Leader

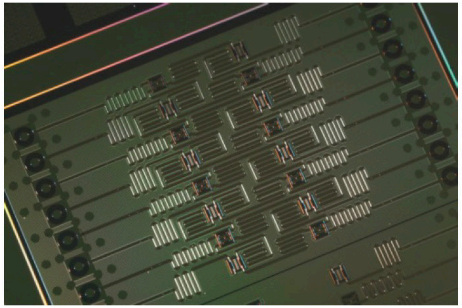
Quantum computing

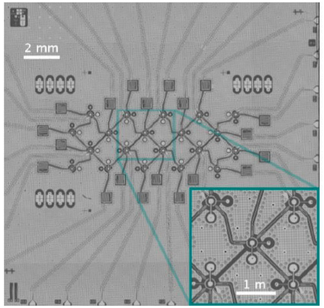
- Basic idea is to use “qubit” instead of a bit
  - Utilize two states of the quantum system (|0>, |1>), which can be also prepared in any superpositions
  - Also utilize entanglement between the qubits
  - Provides computational capacity for dramatic speedups in several areas
    - Finding large prime number multipliers, database search etc

- Many architectures
  - **Superconducting qubits** => most pursued currently
    - Google, IBM, Intel, several new startups
  - Trapped ions
  - …..

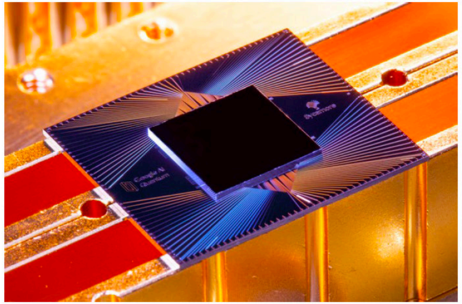
Quantum computing with superconducting circuits

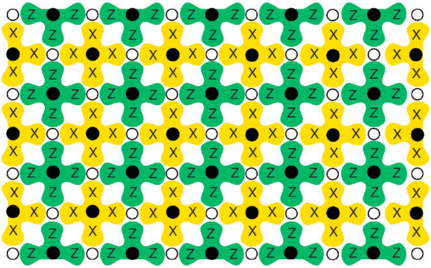
- Recent demonstration of quantum supremacy
- Josephson-junction based qubits
- 2D architectures use nearest neighbor coupling
  - Coherence ~20-40 us in multiqubit chips
- 3D architectures
  - Coherence can be significantly enhanced


IBM Q Experience



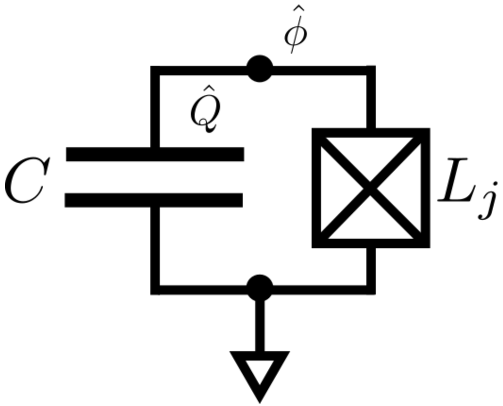
Rigetti

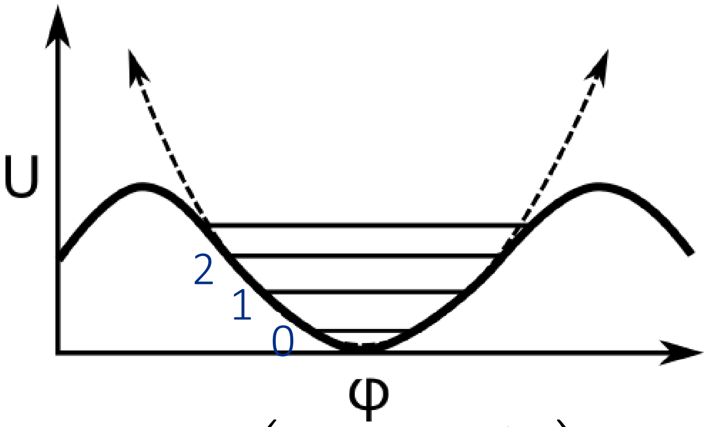

Google/UCSB



Fermilab SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

Artificial Atom by a Josephson Junction



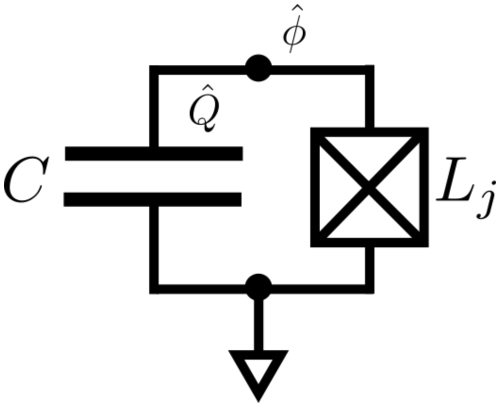


$$\hat{H}_T = \hbar\omega_{LC}\hat{a}^\dagger\hat{a} - E_j\left(\cos\hat{\phi} + \frac{\hat{\phi}^2}{2}\right)$$

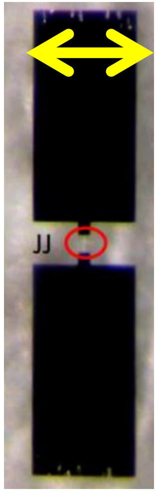
$$\hat{H}_T \approx \hbar\omega'\hat{a}^\dagger\hat{a} - \frac{\alpha}{2}\hat{a}^{\dagger 2}\hat{a}^2$$

Fermilab SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

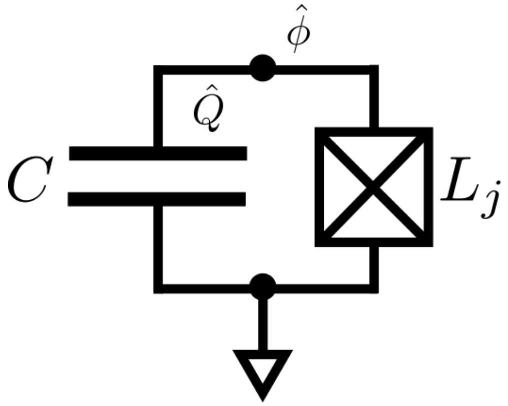
Artificial atom: Transmon



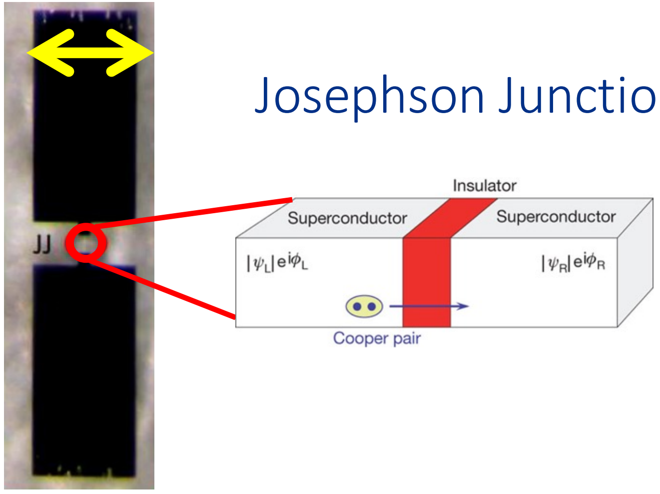
300 microns



Artificial atom: Transmon



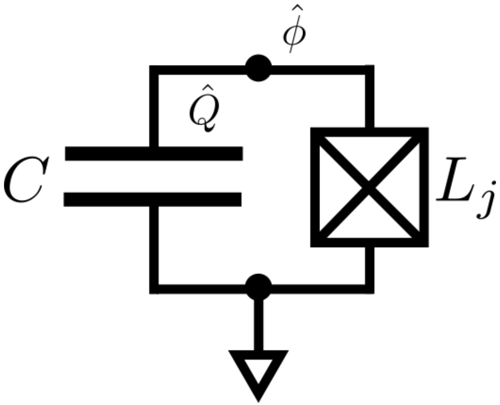
300 microns



Josephson Junction

Fermilab SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

Artificial atom: Transmon



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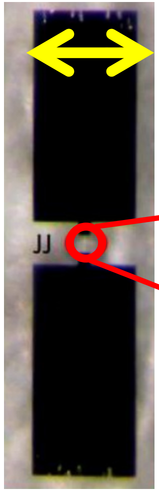
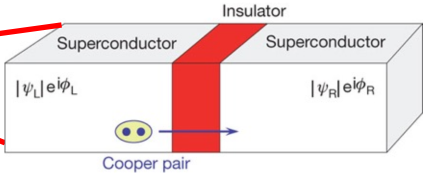
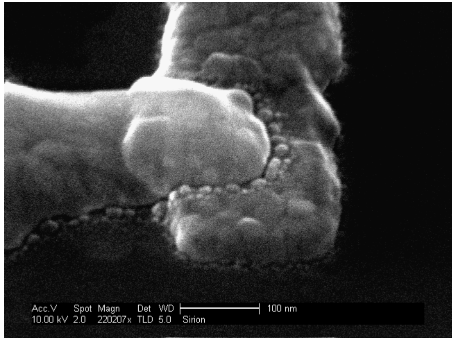


Josephson Junction



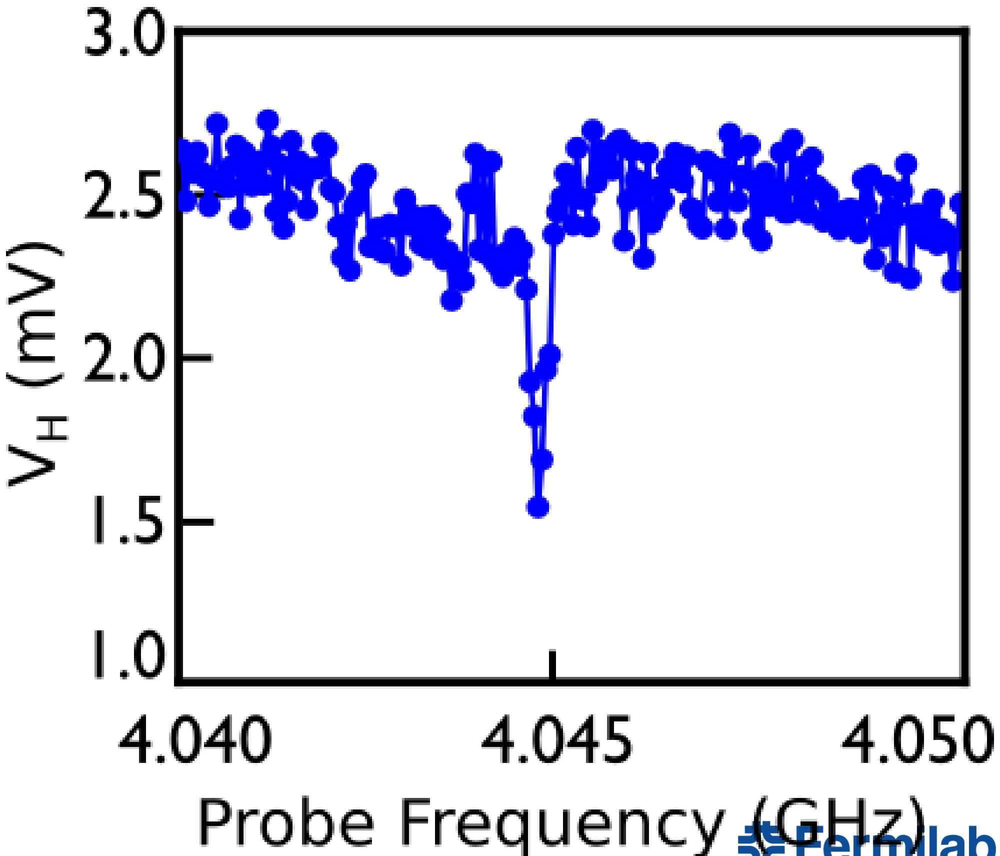


100 nanometers

~10 trillion atoms

~1000 times Earth population

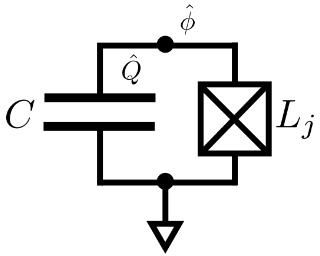
Spectroscopy for First Energy Transition

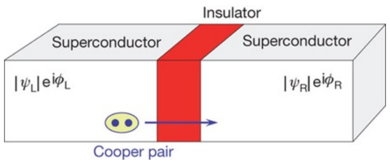


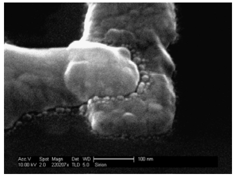
$$\omega a^\dagger a$$

Superconducting Qubits have two main components

1. LC circuit with Josephson junction







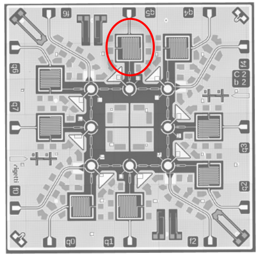
"Transmon" qubits

+

2. Resonators (cavities)

2D

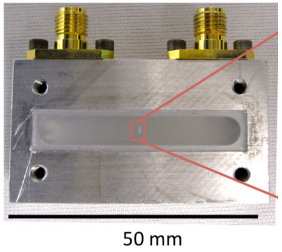
3D



Rigetti 8-qubit processor

$Q \sim 10^5$

$T_{coherence} \sim 1$ us



3D transmon

$Q \sim 10^8$

$T_{coherence} \sim 1$ ms

Fermilab SRF resonators

$Q > 10^{10}$

$T_{coherence} > 1$ s

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

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

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

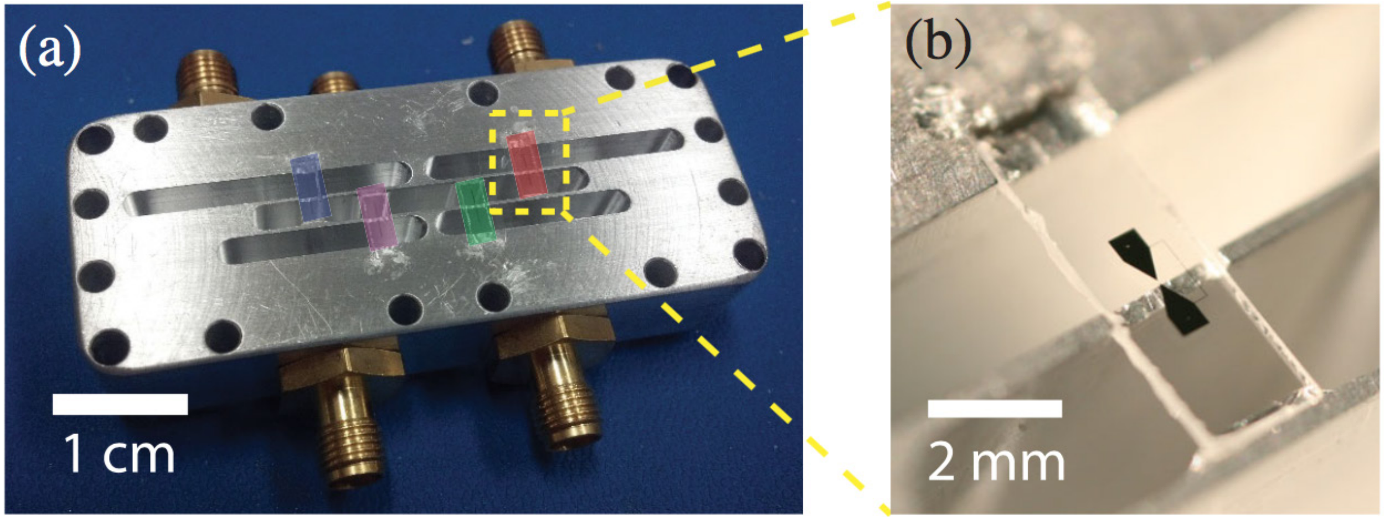
A. Romanenko et al, Phys. Rev. Appl. 13, 134052 (2020)

Improving the **coherence** of both key components => transformational advances in the fundamental QIS building blocks, leading to quantum computing scalability and quantum sensing potential for discovery

Quantum Computing: 3D circuit QED architecture

State-of-the-art quality factors Q in quantum computing are ~**10^8**

Machined Aluminum host cavity



H. Paik et al, Phys. Rev. Lett. 117, 251502 (2016)

Fermilab
SQMS
SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

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

Deterministically Encoding Quantum Information Using 100-Photon Schrödinger Cat States

Brian Vlastakis,[1*] Gerhard Kirchmair,[1†] Zaki Leghtas,[1,2] Simon E. Nigg,[1‡] Luigi Frunzio,[1]
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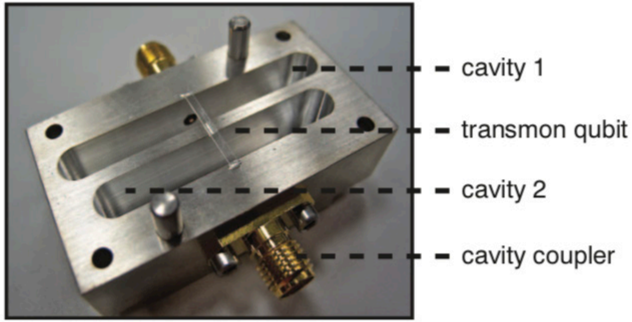

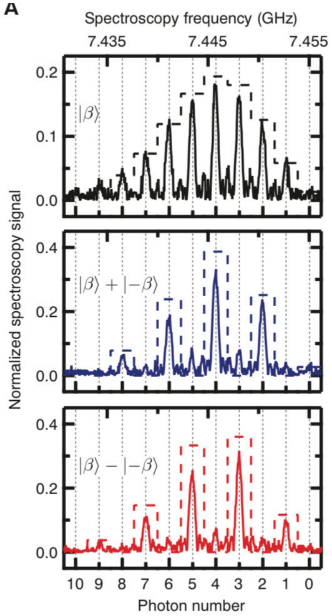

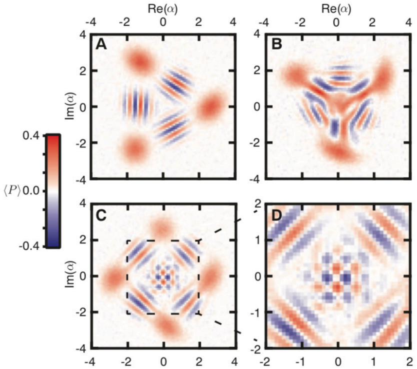

- Error correction: N. Ofek et al, Nature 536 (2016), 441
- CNOT gate: S. Rosenblum et al, Nature Communications 9 (2018)

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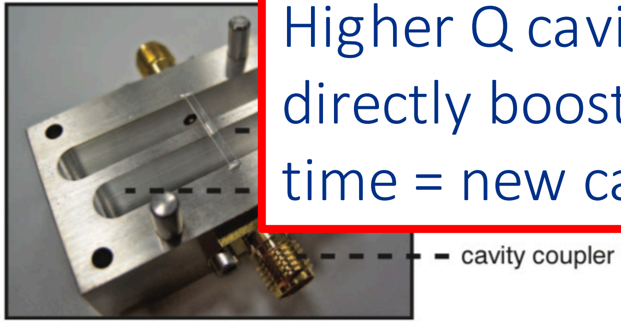

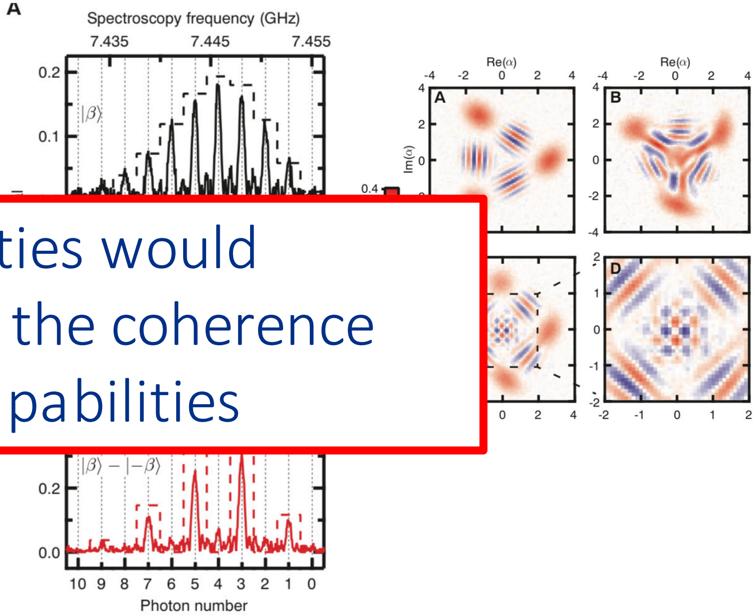

Higher Q cavities would directly boost the coherence time = new capabilities

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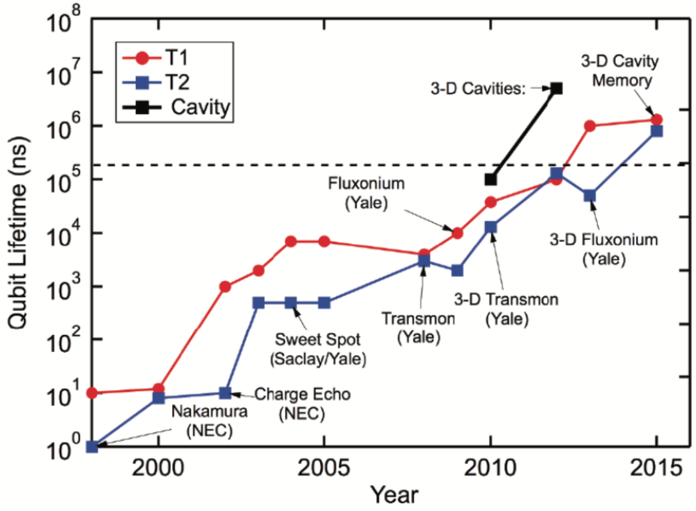
- CNOT gate: S. Rosenblum et al, Nature Communications 9 (2018)

High Q SRF 3D cavities for improved coherence



M. H. Devoret and R. J. Schoelkopf, *Science* 339, 1169–1174 (2013)

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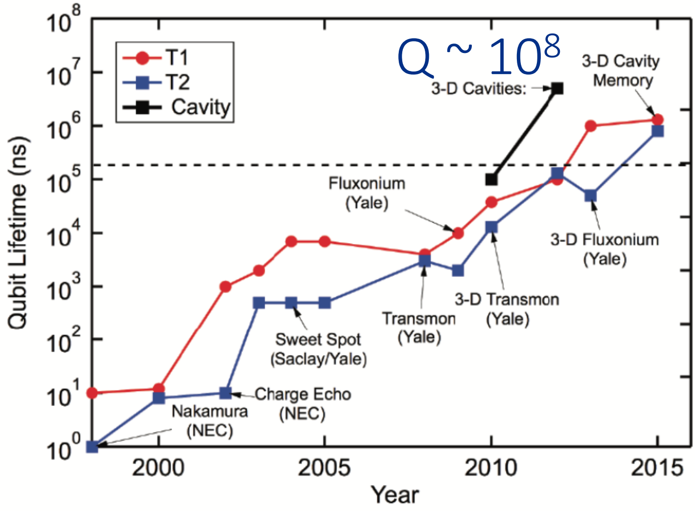

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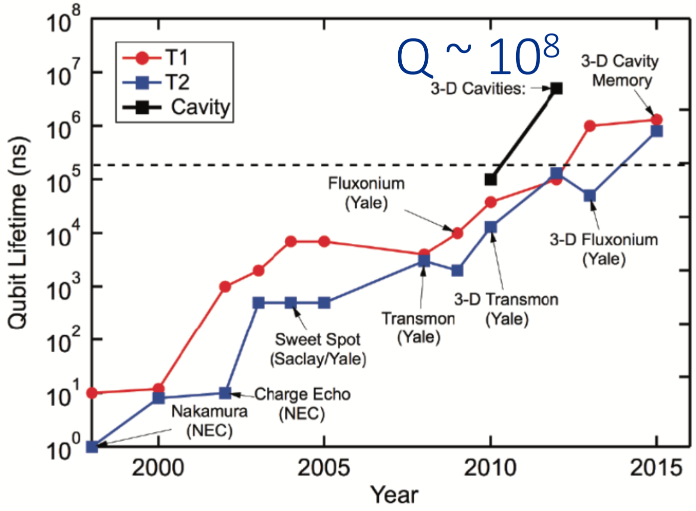
~10 msec photon lifetime/coherence is a record



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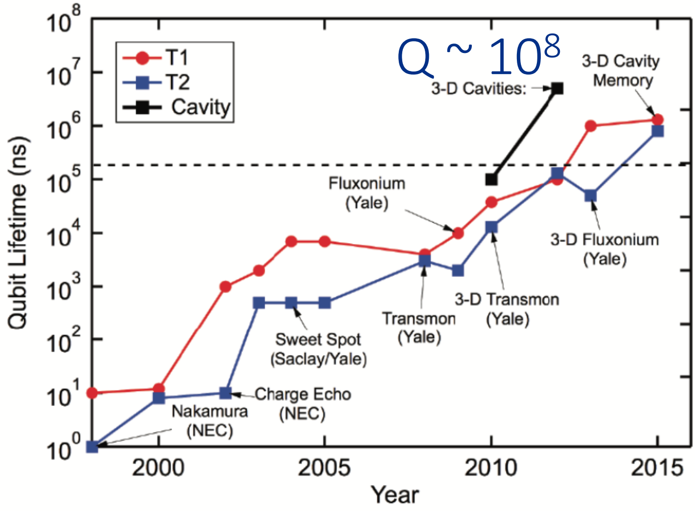

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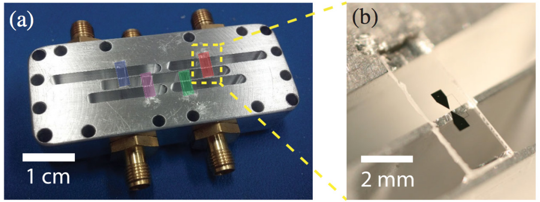

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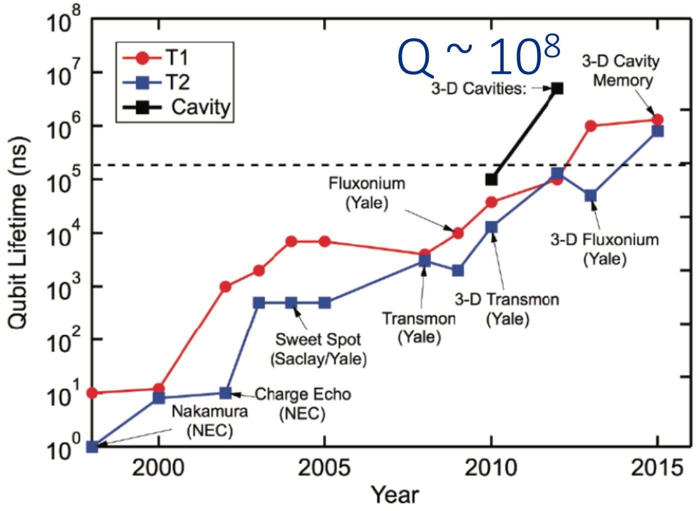

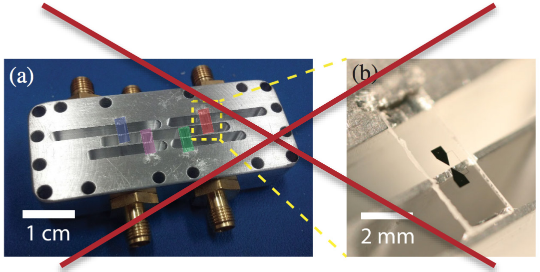

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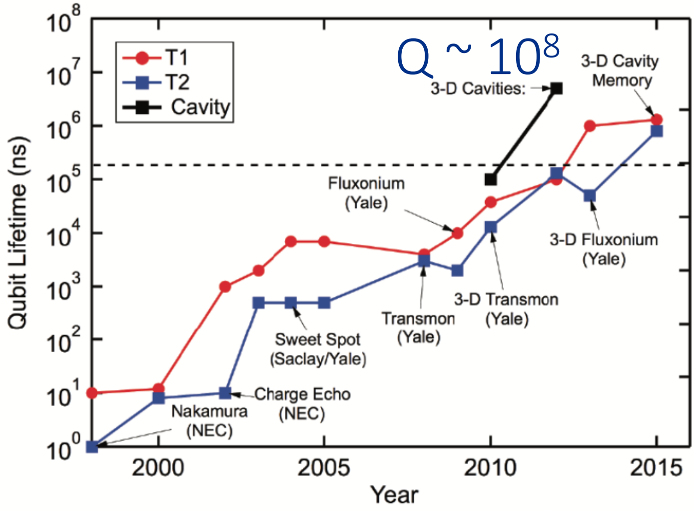

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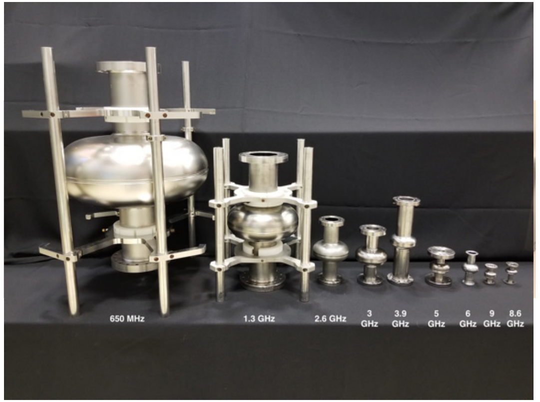

1-cell Fermilab cavities of various frequencies

High Q SRF 3D cavities for improved coherence

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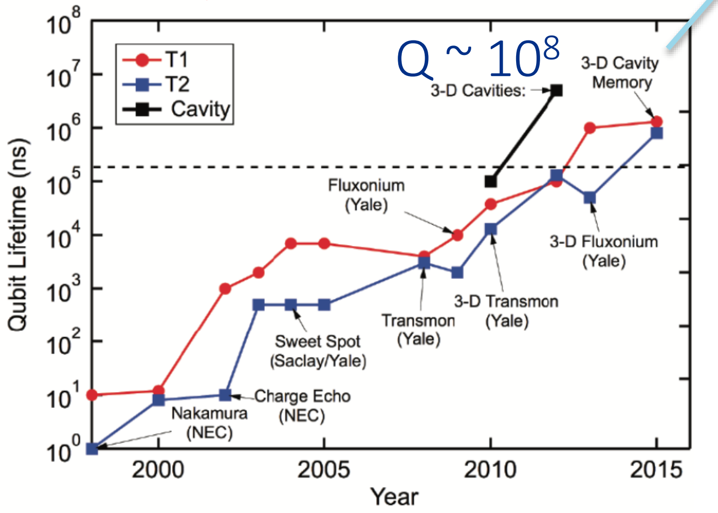
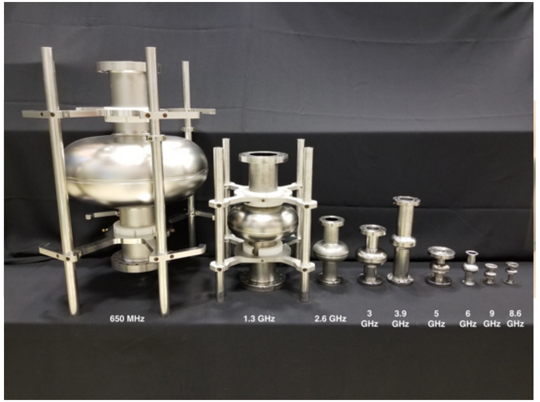


M. H. Devoret and R. J. Schoelkopf, *Science* 339, 1169–1174 (2013)

Q > 10^{11}

~10 seconds of coherence



1-cell Fermilab cavities of various frequencies

H. R. 6227

(Bill Passed Dec 2018)

One Hundred Fifteenth Congress
of the
United States of America

AT THE SECOND SESSION

Begun and held at the City of Washington on Wednesday, the third day of January, two thousand and eighteen

An Act

To provide for a coordinated Federal program to accelerate quantum research and development for the economic and national security of the United States.

Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled,

SECTION 1. SHORT TITLE; TABLE OF CONTENTS.

National Quantum Initiative Act

This bill directs the President to implement a National Quantum Initiative Program to, among other things, establish the goals and priorities for a 10-year plan to accelerate the development of quantum information science and technology applications.

The bill defines "quantum information science" as the storage, transmission, manipulation, or measurement of information that is encoded in systems that can only be described by the laws of quantum physics.

The National Science and Technology Council shall establish a Subcommittee on Quantum Information Science, including membership from the National Institute of Standards and Technology (NIST) and the National Aeronautics and Space Administration (NASA), to guide program activities.

The President must establish a National Quantum Initiative Advisory Committee to advise the President and subcommittee on quantum information science and technology research and development.

NIST shall carry out specified quantum science activities and convene a workshop to discuss the development of a quantum information science and technology industry.

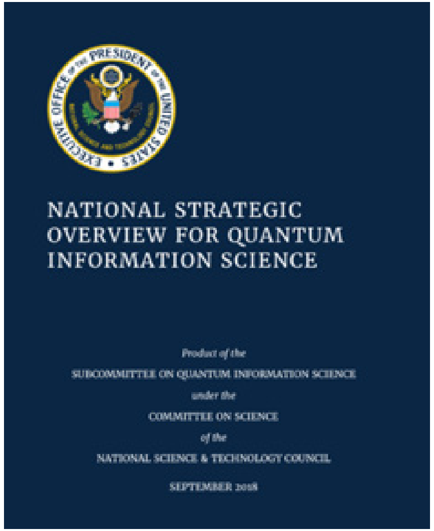
The National Science Foundation shall: carry out a basic research and education program on quantum information science and engineering, and award grants for the establishment of Multidisciplinary Centers for Quantum Research and Education.

The Department of Energy (DOE) shall carry out a basic research program on quantum information science. The Office of Science of DOE shall establish and operate National Quantum Information Science Research Centers to conduct basic research to accelerate scientific breakthroughs in quantum information science and technology.

U.S. National Quantum Initiative

https://www.quantum.gov

https://science.osti.gov/Initiatives/QIS/QIS-Centers

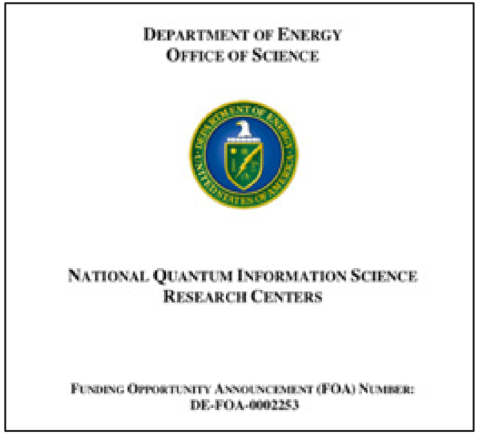

NATIONAL STRATEGIC OVERVIEW FOR QUANTUM INFORMATION SCIENCE

Product of the
SUBCOMMITTEE ON QUANTUM INFORMATION SCIENCE
under the
COMMITTEE ON SCIENCE
of the
NATIONAL SCIENCE & TECHNOLOGY COUNCIL
SEPTEMBER 2018

In 2019 Congress mandated the creation of **five Dept. of Energy national quantum centers** (initiative across Office of Science)

$575M over five years , renewable for another five years, to develop quantum computers, quantum sensors, and quantum communications

- Goal is transformational advances in quantum science and technology
- Create a quantum economy
- Work in coordination with other agencies
- DOE Centers first five years funded through 2025, with potential renewal up to 2030


DEPARTMENT OF ENERGY
OFFICE OF SCIENCE

NATIONAL QUANTUM INFORMATION SCIENCE RESEARCH CENTERS

FUNDING OPPORTUNITY ANNOUNCEMENT (FOA) NUMBER:
DE-FOA-0002253

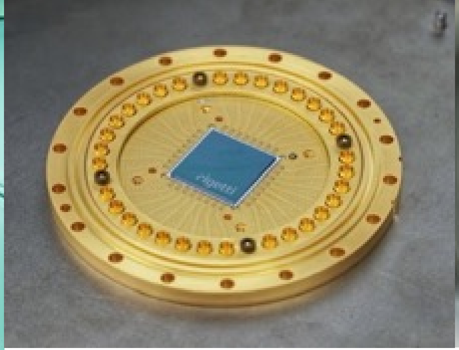
Led by FNAL, $115M
Awarded August 2020

Superconducting Quantum Materials and Systems Center

A DOE National Quantum Information Science Research Center

23 Institutions
> 350 Researchers
> 100 students/postdocs

Fermilab, rigetti, Northwestern University, Ames Laboratory, NASA Ames Research Center, NIST, INFN Istituto Nazionale di Fisica Nucleare, Stanford University, University of Illinois Urbana-Champaign, Rutgers, Università di Pisa, University of Colorado Boulder, Illinois Institute of Technology, Johns Hopkins University, Temple University, Colorado School of Mines, The University of Arizona, University of Minnesota, NYU, Goldman Sachs, Lockheed Martin, JANIS, Unitary Fund

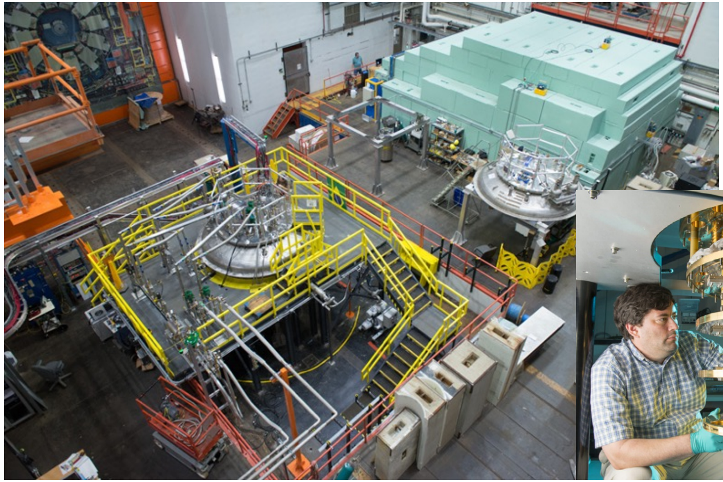
SQMS Mission Statement: “bring together the power of national labs, industry and academia to achieve transformational advances in the major cross-cutting challenge of understanding and eliminating **quantum decoherence** in superconducting 2D and 3D devices, with the goal of enabling construction and deployment of superior quantum systems for computing and sensing."



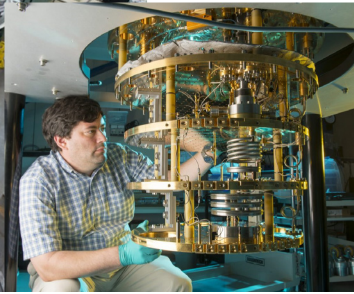
Foundational Strengths: large accelerators, R&D to large scale integration

FNAL expertise and facilities critical for success in scale up of 3D QIS technologies

- Vacuum systems
- Superconducting Materials
- Microwave SC devices
- Cryogenics
- High precision frequency control
- LLRF, controls
- Magnetic shielding



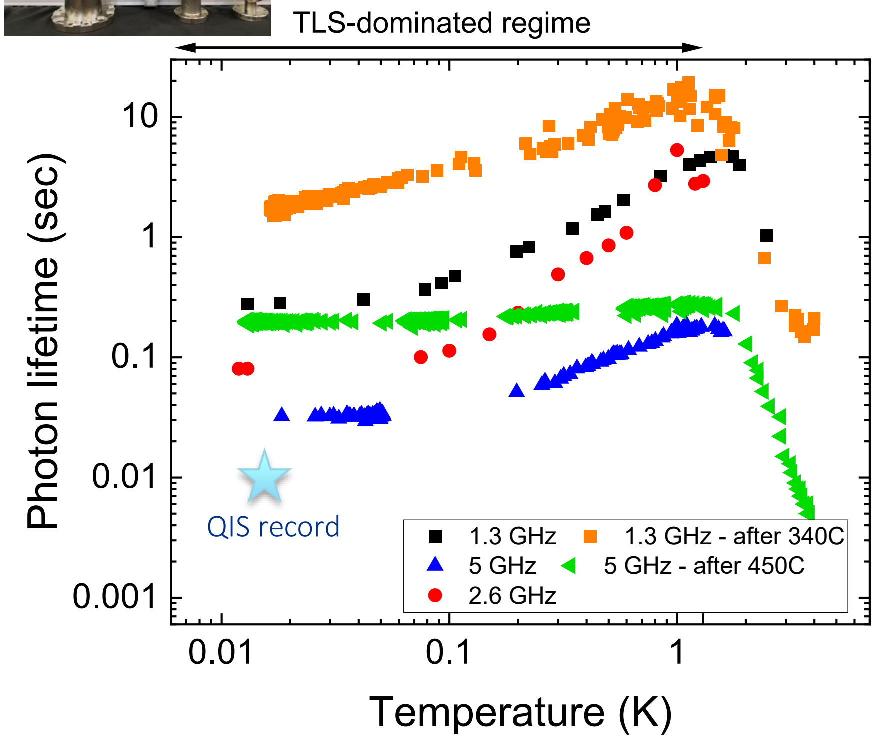
M. Hollister



Fermilab SQMS is constructing a world record sized DR capable of hosting thousands of qubits

Modern accelerators are like quantum computers and sensors: large and complex high coherence (Q) superconducting microwave systems controlled with the highest precision

Record long coherence 3D SRF cavities



A. Romanenko, R. Pilipenko, S. Zorzetti, D. Frolov, M. Awida, S. Belomestnykh, S. Posen, A. Grassellino, Phys. Rev. Appl. 13, 034032 (2020)

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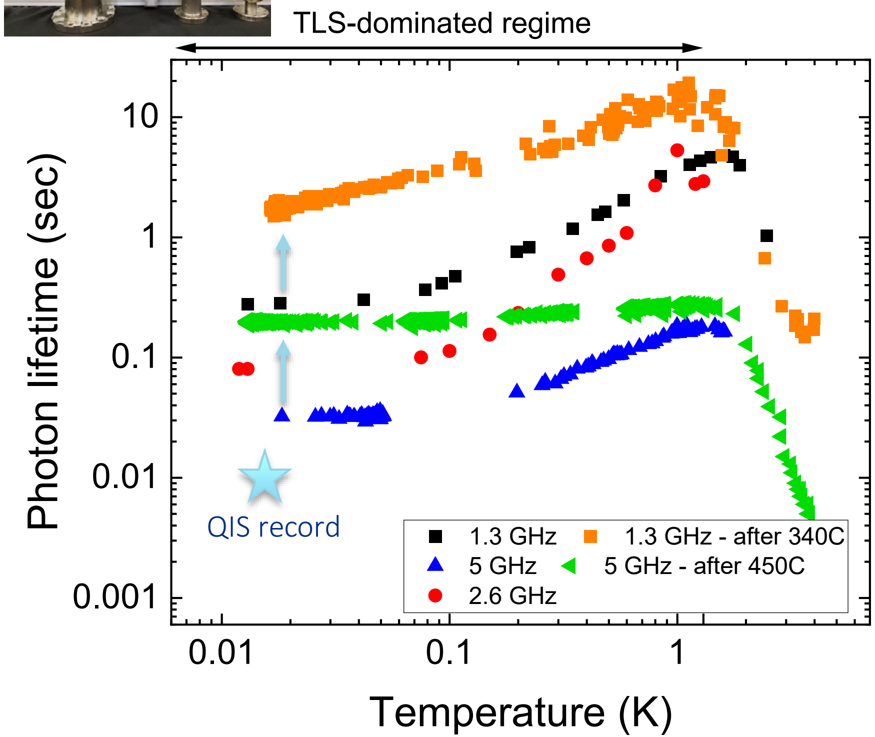

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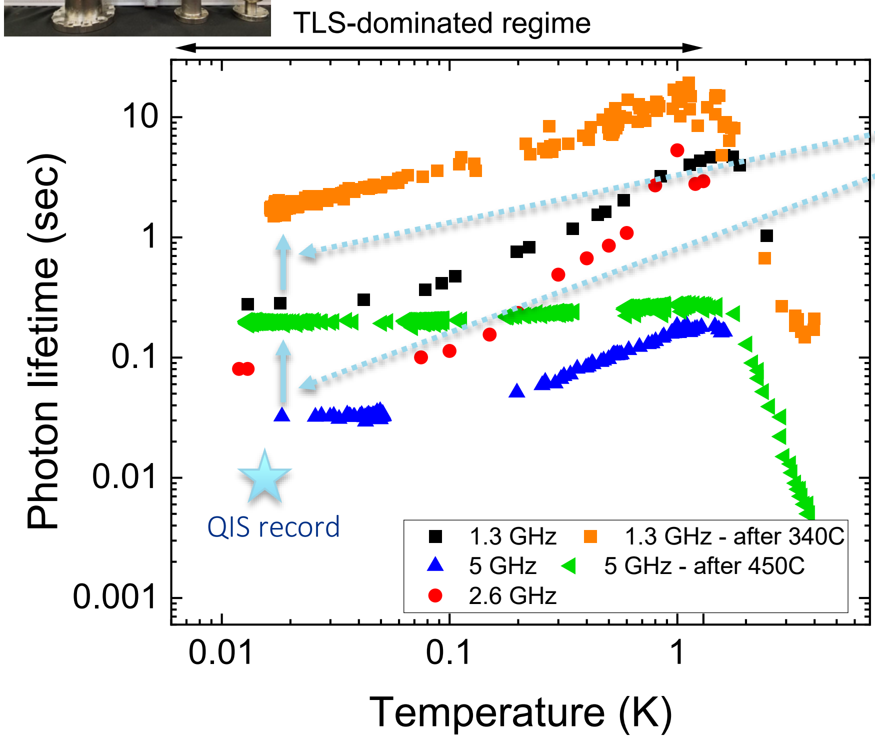
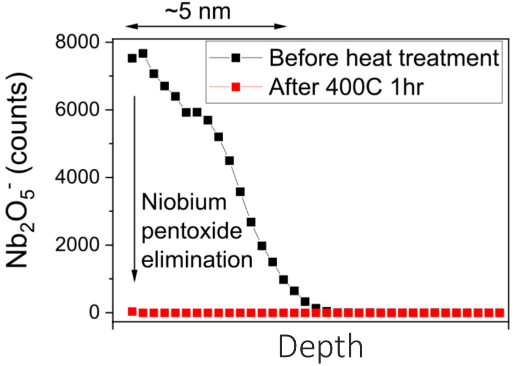


340-450C treatments remove amorphous Nb_2O_5 hosting TLS



TOF-SIMS data on cavity cutouts

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Scientific and Technological Goals – quantum computing

Develop and deploy a prototype quantum computer at Fermilab

Based on our own SRF technology for QIS

Explore and demonstrate advantage for HEP (and more)

1. FROM ELEMENTS TO STRUCTURE AND FROM STRUCTURE TO ELEMENTS

An unfamiliar computer from far away stands at the center of
ibition hall. Some of the onlookers marvel at its unprecedented pc
ers gather in animated knots trying, but so far in vain, to make ou

"Computer science and basic physics mark two of the frontiers of the civilization of this age. One seeks to build complexity out of simplicity. The other tries to unravel complexity into simplicity. No one, it has been said, is better at taking a puzzle apart than the person who put it together and no one is better at putting a puzzle together than the one who took it apart"

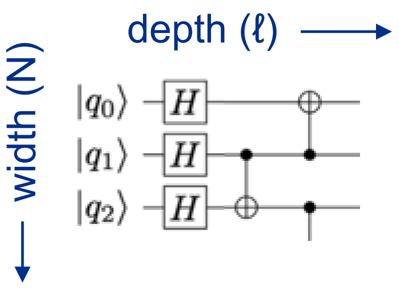
SQMS processors performance goals compared to leading systems →

Processor metrics	Leading systems	Center prototypes (3 yr)		Center device goals (5 yr)	
		2D-Alpha (estimate)	SRF-Alpha (estimate)	SQMS-2D (estimate)	SQMS-3D (estimate)
Number of qubits	53	128	>100	256	>200
Connectivity graph (qubit:neighbors)	1:4	1:3	1:10	1:3	1:200
Qubit T_1 lifetime, μs (median)	70	200	400,000	400	1,000,000
Gate time, ns (median)	20	50	2000	40	100
Coherence/gate time ratio	1,000	4,000	20,000	10,000	10,000,000
Single qubit gate fidelity (%)	99.85	99.6	99.5	99.95	99.95
Two qubit gate fidelity (%)	99.65	99.2	99.5	99.9%	99.95
Achievable circuit depth (1/error)	300	100	200	1,000	2,000

SQMS key goals and estimated performance parameters.

SQMS Quantum Computing 10-year Roadmap - technology

Quantum algorithms:



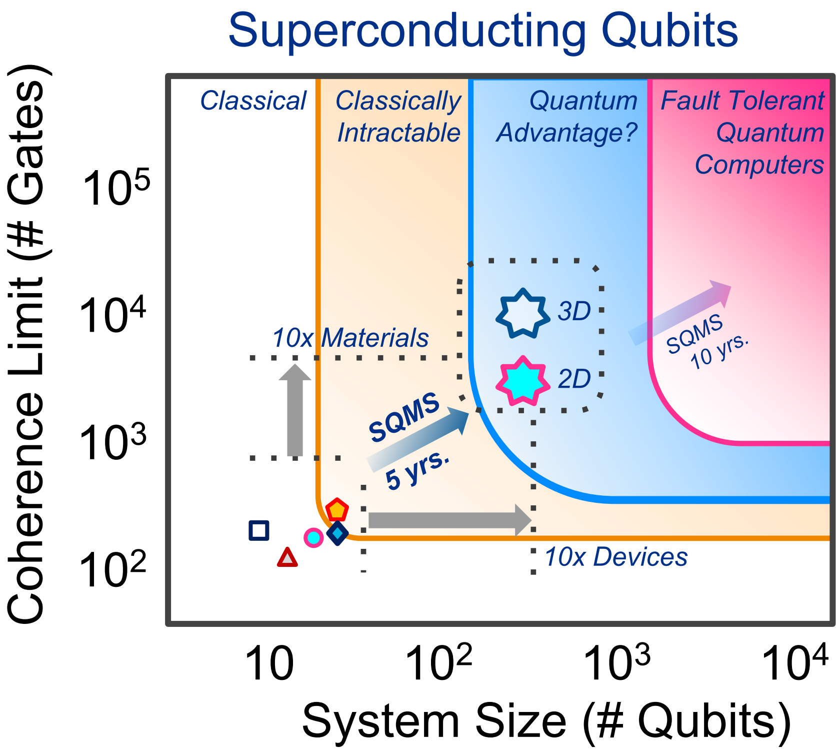
Ultimate limits to depth:

$\max(\ell) \propto T_1 / t_{gate}$

For SC qubits, typical:

t_{gate} = [20-1000] ns

$\max(N^*\ell) \sim 10^4$



SQMS Consequences:

- SQMS-3D
- SQMS-2D

Leading US testbeds:

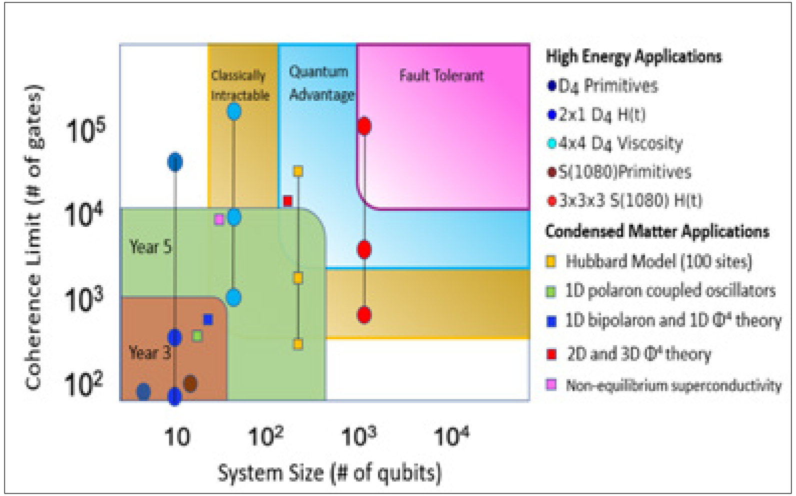
- *Google Sycamore*
- *IBM Hexagonal*
- *Rigetti Aspen*
- *Yale Single-mode*
- *UChicago Multi-mode*

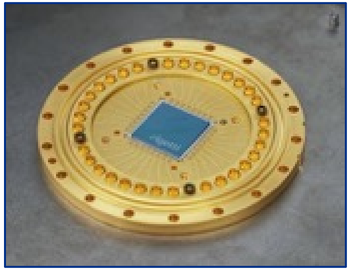
SQMS Quantum Computing Roadmap - science

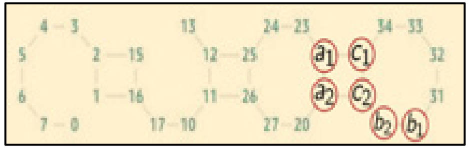
Goal: Investigate and develop quantum algorithms and simulations enabled by the groundbreaking SQMS 3D and 2D prototypes through co-design principles

Deliverables/metrics: simulations of the dynamics of theories approximating QCD, simulate LHC physics, plasma early universe conditions, quantum materials far from equilibrium, intermediate electron/phonon SC…

SQMS computational and simulation science goals mapped to prototypes







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

Scientific and Technological Goals – quantum sensing

Develop and deploy new quantum sensors at Fermilab

Push superconducting sensors at the frontier of coherence and frequency control technologies

From technology R&D to experimental prototypes, informing future large experiments

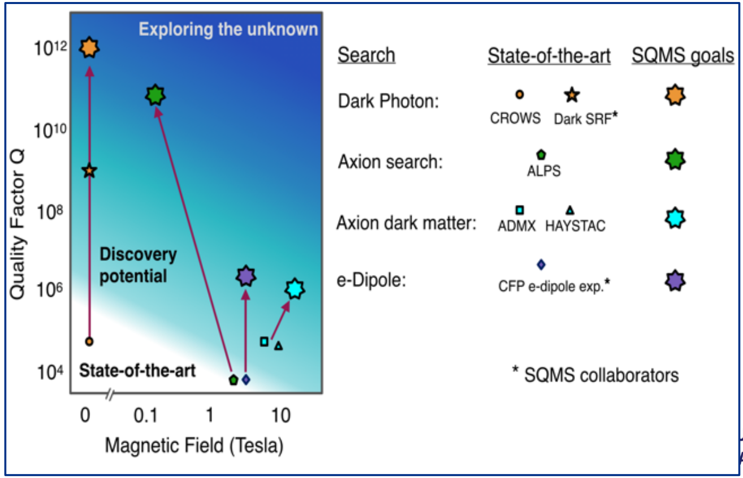
THE 2021 ECFA DETECTOR RESEARCH AND DEVELOPMENT ROADMAP

The European Committee for Future Accelerators Detector R&D Roadmap Process Group

Chapter 5

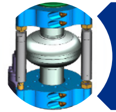
Quantum and Emerging Technologies Detectors

"The unprecedented sensitivity and precision of quantum systems enables the investigation of questions of fundamental concern to particle physics. These include the nature of dark matter, the existence of new forces, the earliest epochs of the universe at T >> 1TeV and the possible dynamics of dark energy, the possible existence of dark radiation and the cosmic neutrino background, the violation of fundamental symmetries, and even the nature of interaction and space-time at scales as high as $M_{Planck} \sim 10^{19}$ GeV"



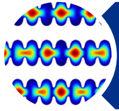
Physics and Sensing 5-year Roadmap

	Year 1	Year 2	Year 3	Year 4	Year 5



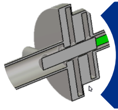
DarkSRF

- Measure in LHe, 1st DarkSRF publication
- Phase sensitive readout
- Implement in DR, quantum regime!
- Improve Q_0 towards 1e12



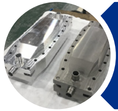
Multimode Cavity Axion Search

- Nonlinearity studies
- 2-cavity multimode design
- 2-cavity 1st test
- 2- and 3- mode 1-cavity design
- 2- and 3- mode 1-cavity 1st test



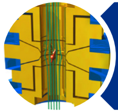
Tunable Dark Photon Search

- Design and fabricate cavity
- Trial runs, feedback
- Study heterodyne vs photon counting
- Data taking runs



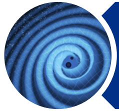
High B-Field Axion Search

- Co-design w/ materials & devices
- Searches w/ best cavities and qubits
- Evaluate Nb_3Sn, NbTi Q_0 in high B
- Evaluate search w/ AC B-field



Single Particle Penning Trap

- Design high Q cavity geometry
- Testing optimized cavities/squids
- Prototype cavities & squids
- 1st next gen e- μ/μ_B measurements

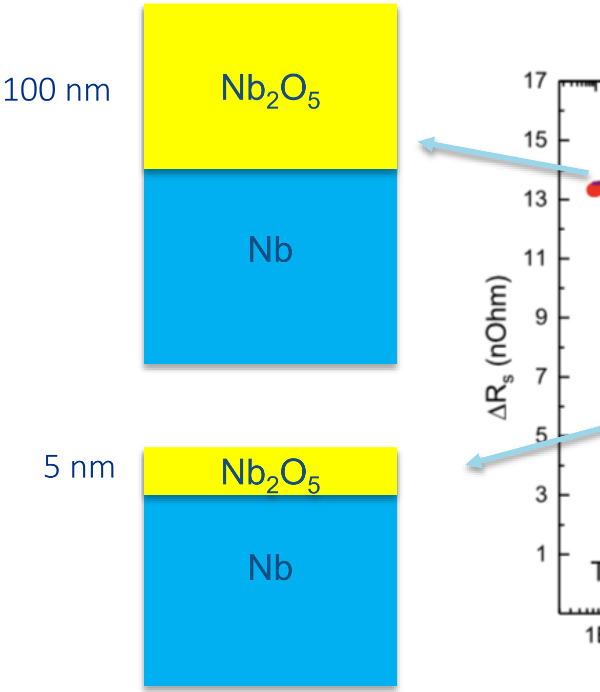


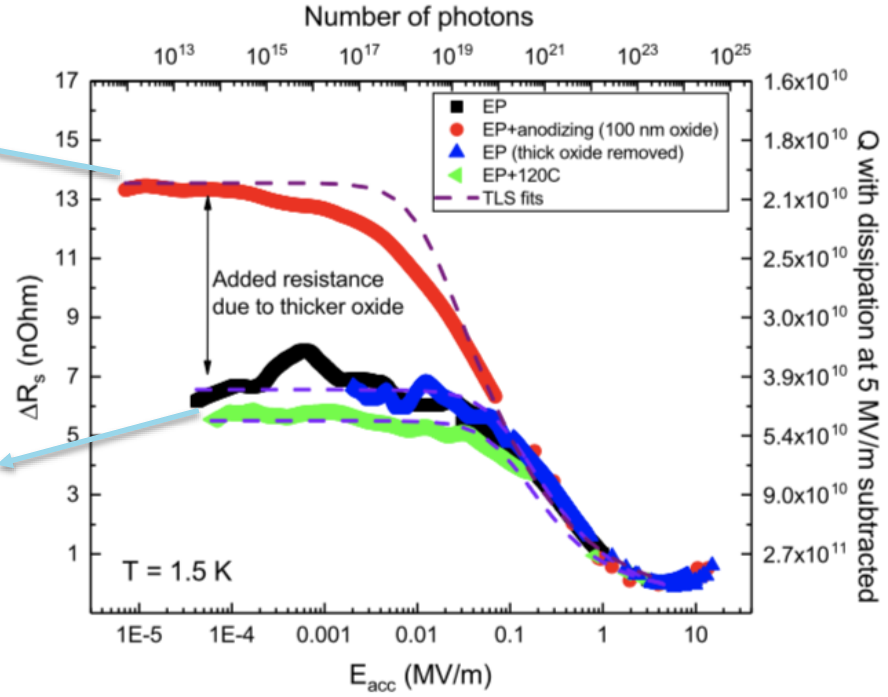
Other Quantum Sensing Schemes

- Theory study of QIS for dark radiation detection, Quantum Sensor Network, Evaluate SRF cavities for gravitational wave detection, DM with traps.

- Niobium oxide – primary TLS source, its mitigation, impact on the 2D qubits achievable coherence times

Niobium oxide is the main limiting factor in 3D cavities





A. Romanenko and D. I. Schuster, Phys . Rev. Lett. **119**, 264801 (2017)

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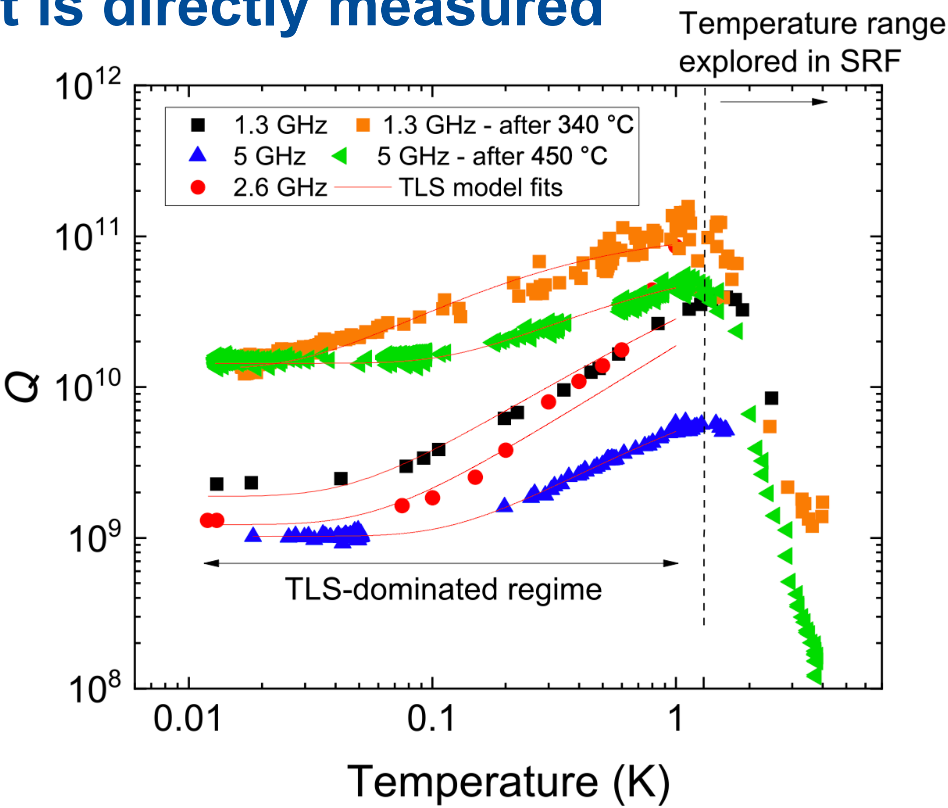
Niobium oxide – TLS loss tangent is directly measured

A. Romanenko, R. Pilipenko, S. Zorzetti, D. Frolov, M. Awida, S. Belomestnykh, S. Posen, A. Grassellino, Phys. Rev. Appl. 13, 034032 (2020)

- High Q 3D SRF cavities are limited by the two-level-systems in niobium oxide

TABLE I. Summary of TLS model fitting results.

f_0 (GHz)	Oxide treatment	$F\delta_0$	F	δ_0
1.3	No	5.2×10^{-10}	1.0×10^{-7}	0.17
2.6	No	8.2×10^{-10}	2.4×10^{-8}	0.13
5	No	9.1×10^{-10}	1.2×10^{-8}	0.08
1.3	340°C 3 h	6.7×10^{-11}	...	...
5	450°C 3 h	5.6×10^{-11}	...	...



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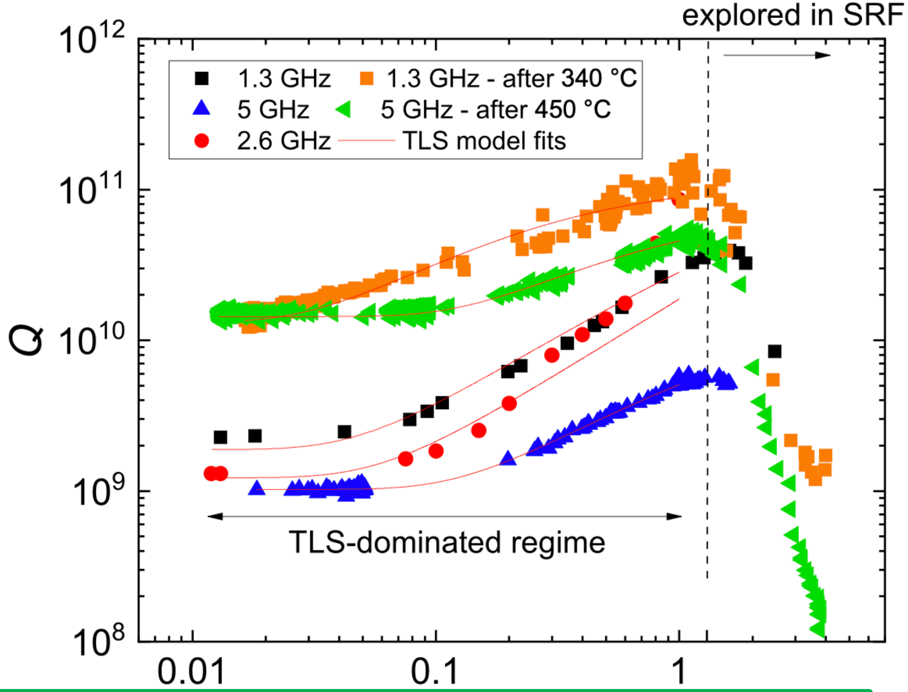
Temperature range explored in SRF



E.g. take p~10^{-5} participation ratio for a 2D qubit mode of ~5 GHz => niobium oxide caps 2D qubit at Q~1.3e6 or **T_1~40 us**

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- Minimal effect of the conductive niobium losses in niobium films

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Nb film deposited on the inside of the high Q bulk Nb cavity

- Check if the Nb film would behave differently from Nb bulk in the quantum regime

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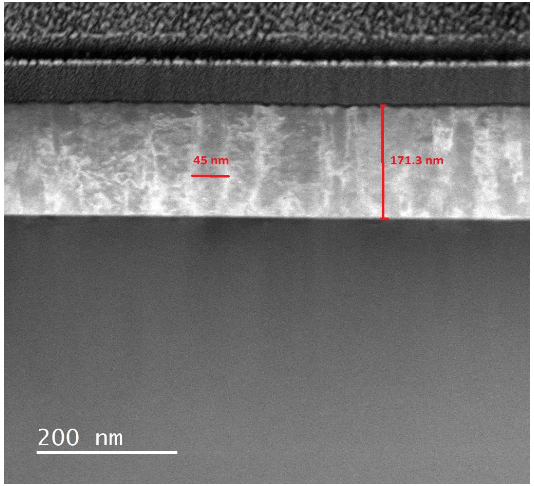

TEM of the typical HIPIMS produced film quality

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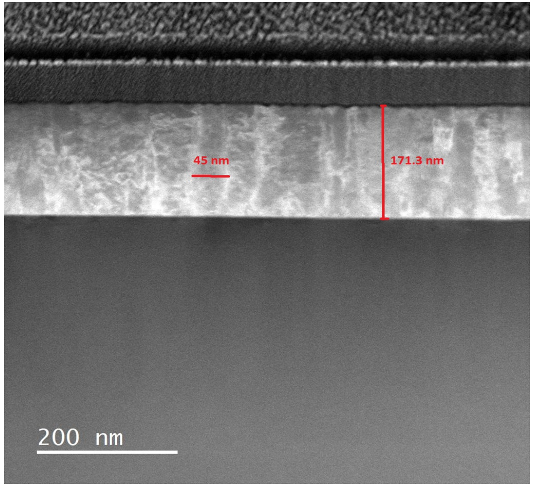

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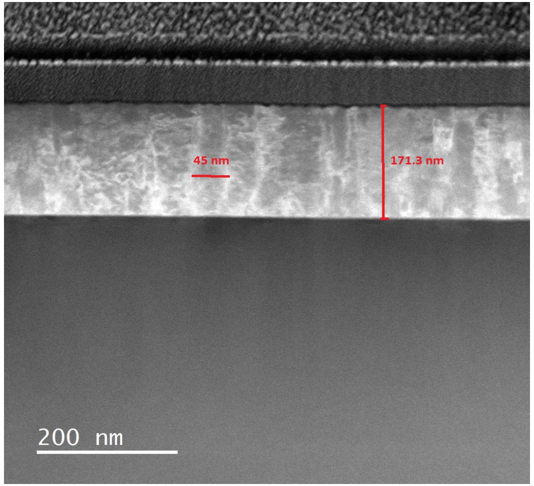

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HIPIMS cavity deposition system at CERN

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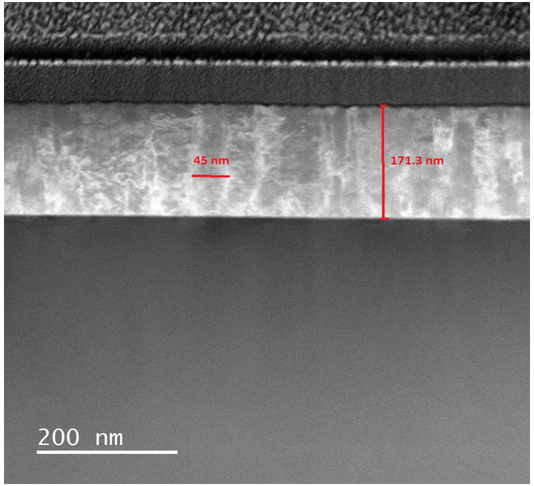

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HIPIMS cavity deposition system at CERN

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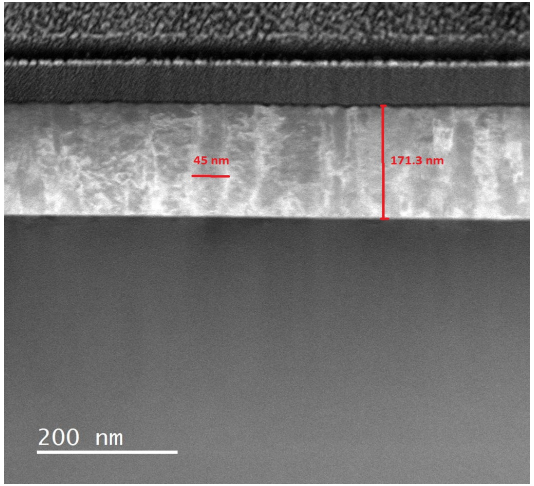
Nb film deposited on the inside of the high Q bulk Nb cavity

Dilution refrigerator Q measurements

- Check if the Nb film would behave differently from Nb bulk in the quantum regime



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HIPIMS cavity deposition system at CERN

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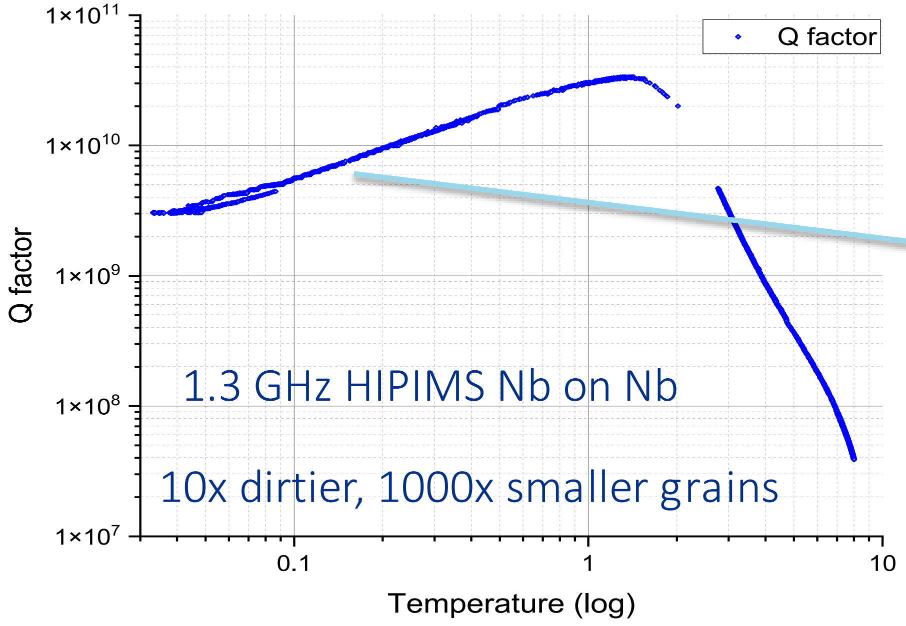
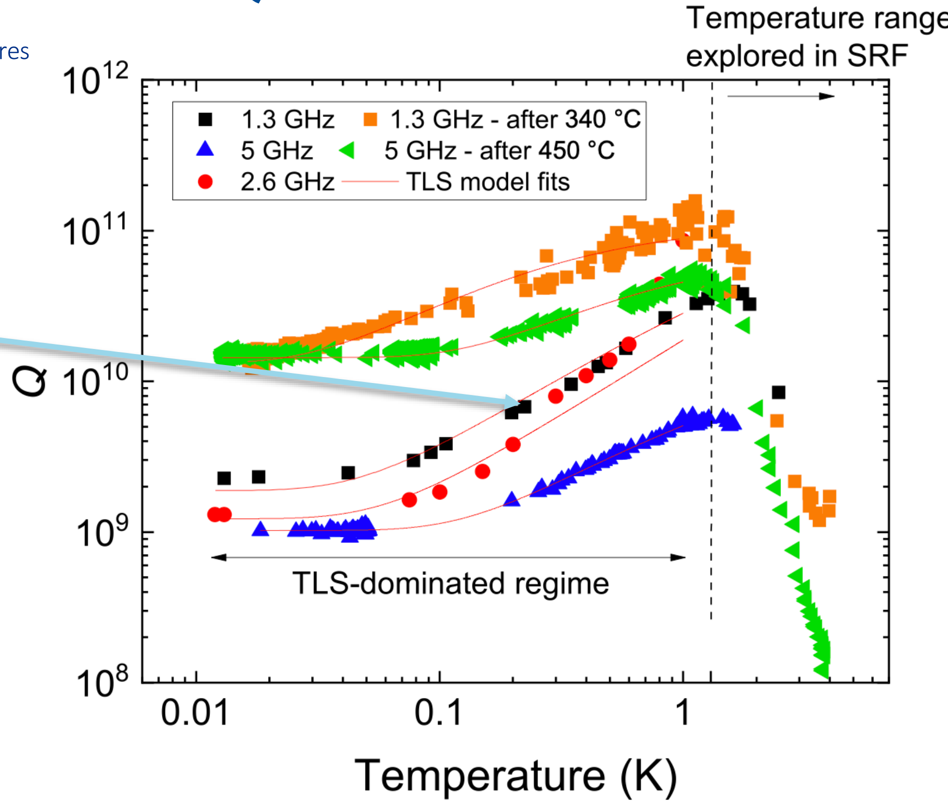
HIPIMS Nb film on Nb cavity -> the same Q as bulk Nb

T00.119: Characterization of niobium films with varying RRR values at low temperatures





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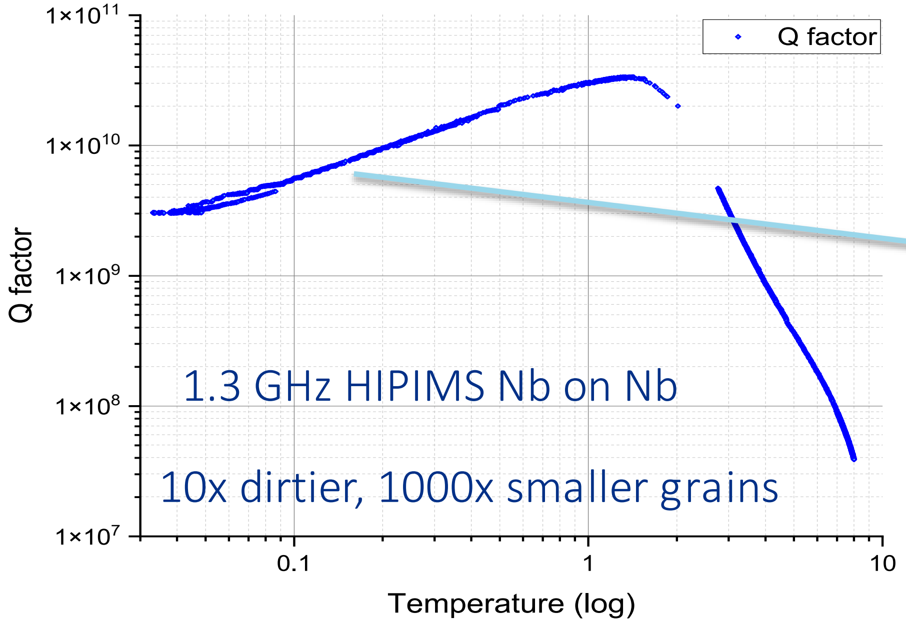

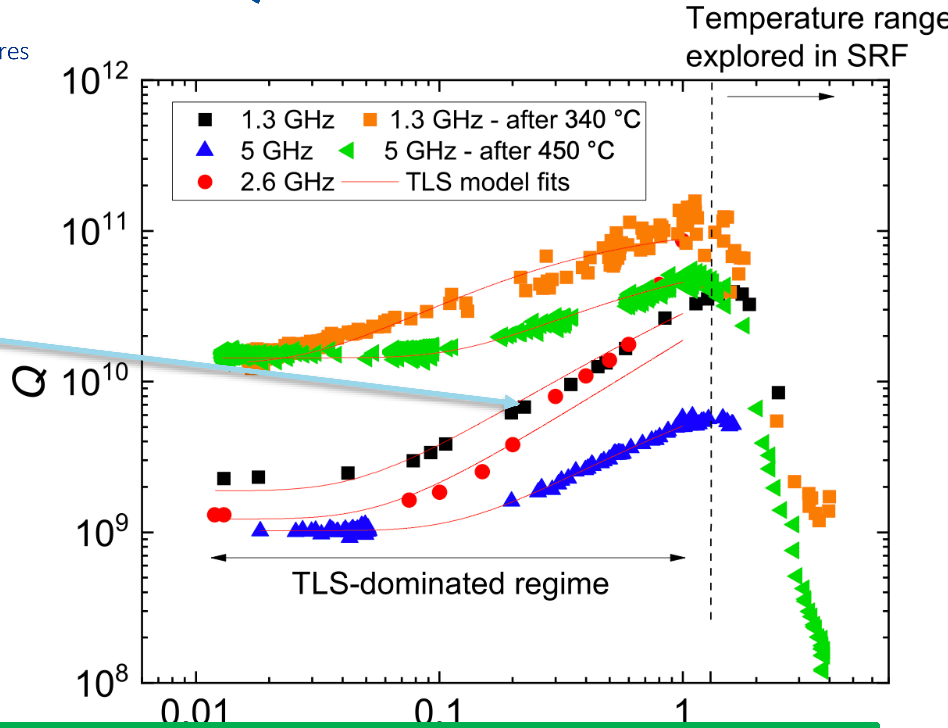

Different grain size, impurity content of the HIPIMS film <u>lead to the same high Q as bulk Nb</u> => Nb oxide is the main target to increase the coherence times of 2D qubits

TUM
NTER

- Operation of the current 3D SRF Cavity-Transmon system
  - Fermilab SRF cavity + Rigetti transmon

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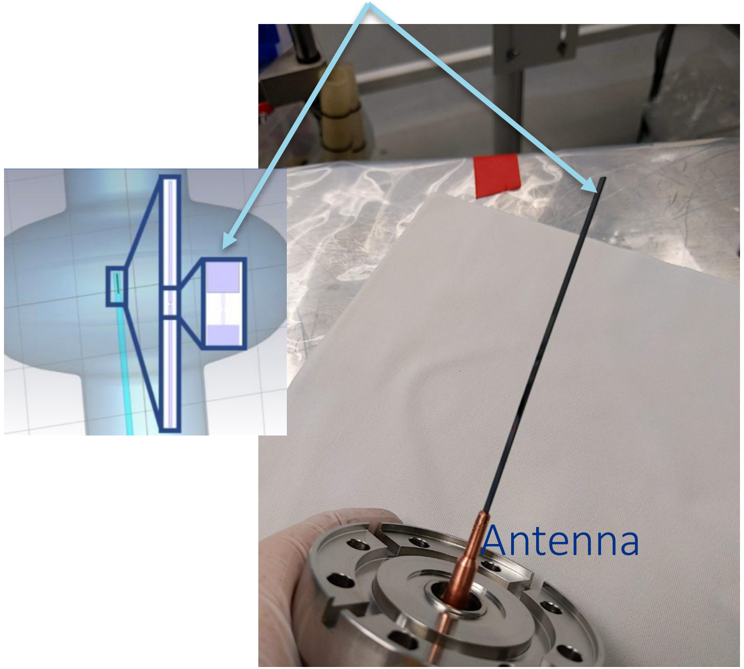
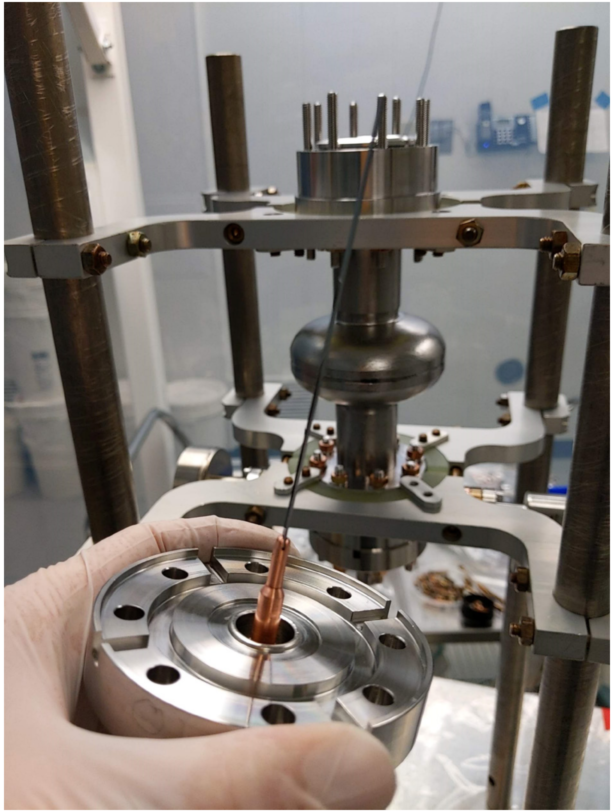
Integration of SRF cavities with Rigetti transmons

Transmon at the end of Si rod





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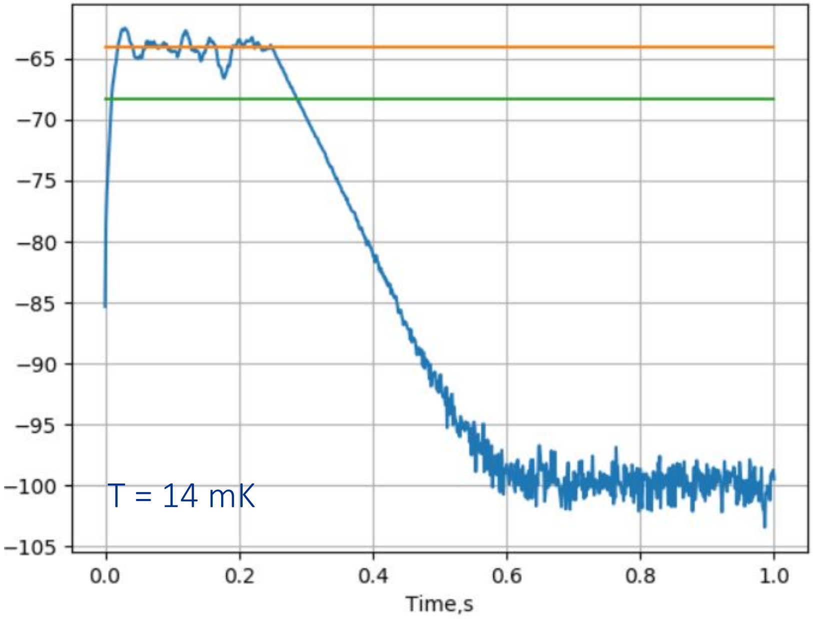
Photon lifetimes in integrated resonators in quantum regime

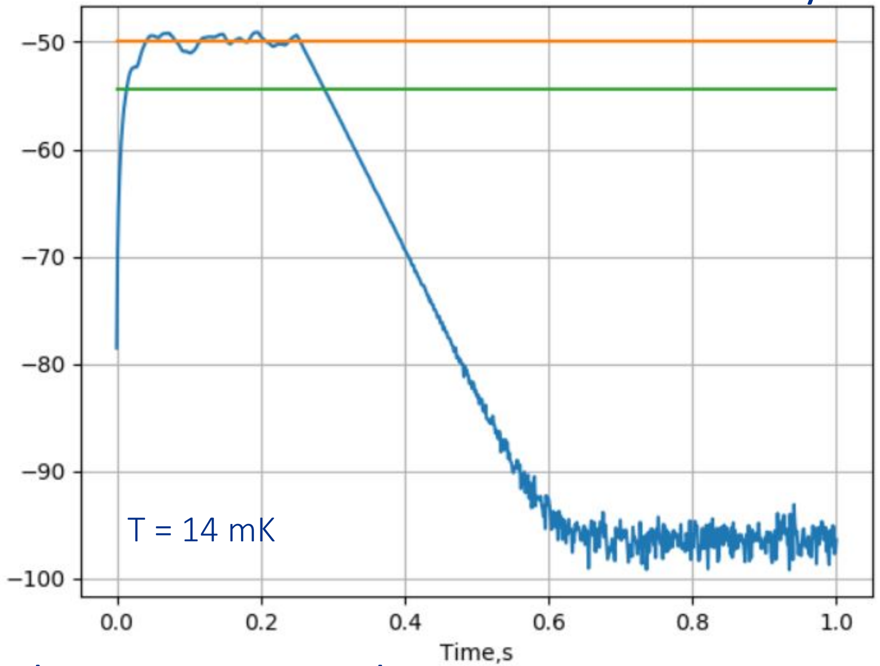
t ~ 32 ms

Cavity 1



t ~ 39 ms

Cavity 2



Energy decay in cavity-transmon system

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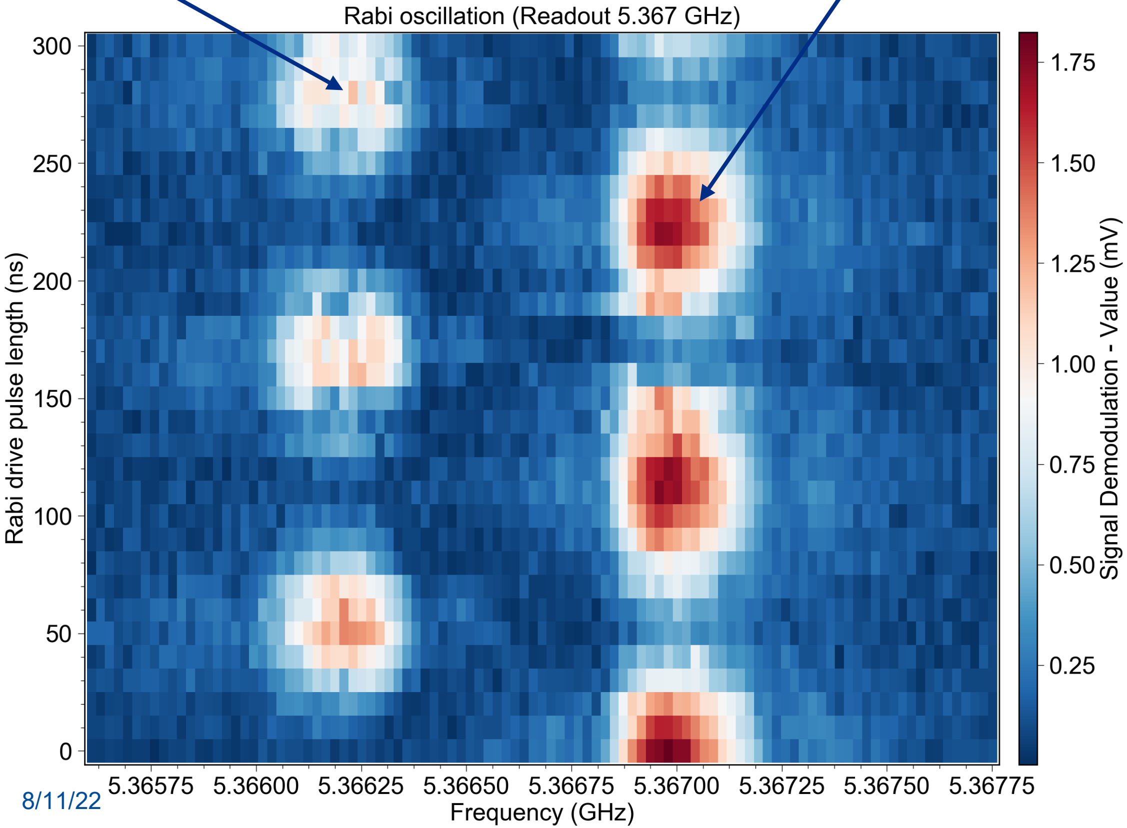
Example of Rabi oscillations – qubit driven inside the cavity

Qubit is $|e\rangle$

Qubit is $|g\rangle$



The readout mode (5.367 GHz) frequency is oscillating by the qubit Rabi oscillation and dispersive interaction

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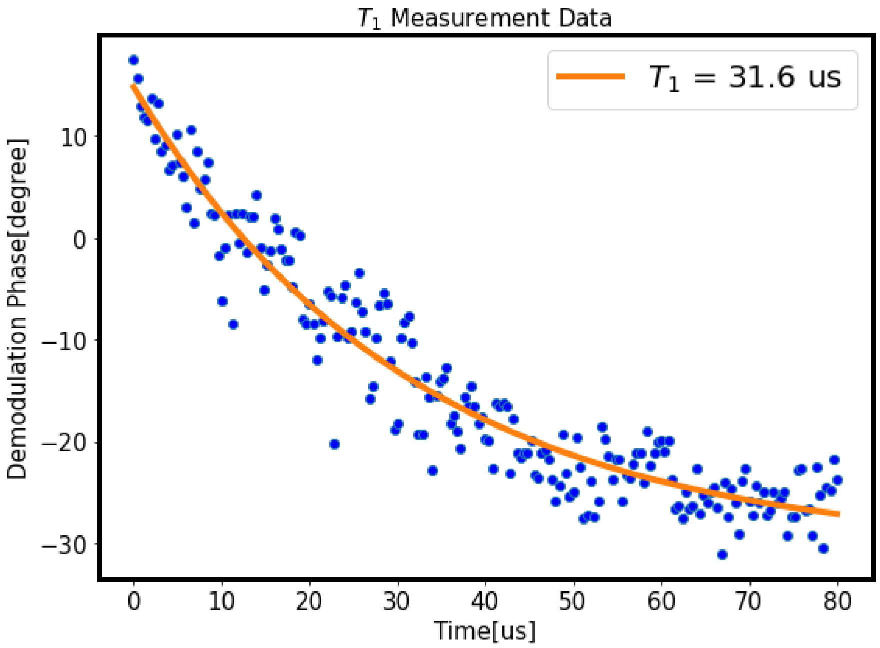
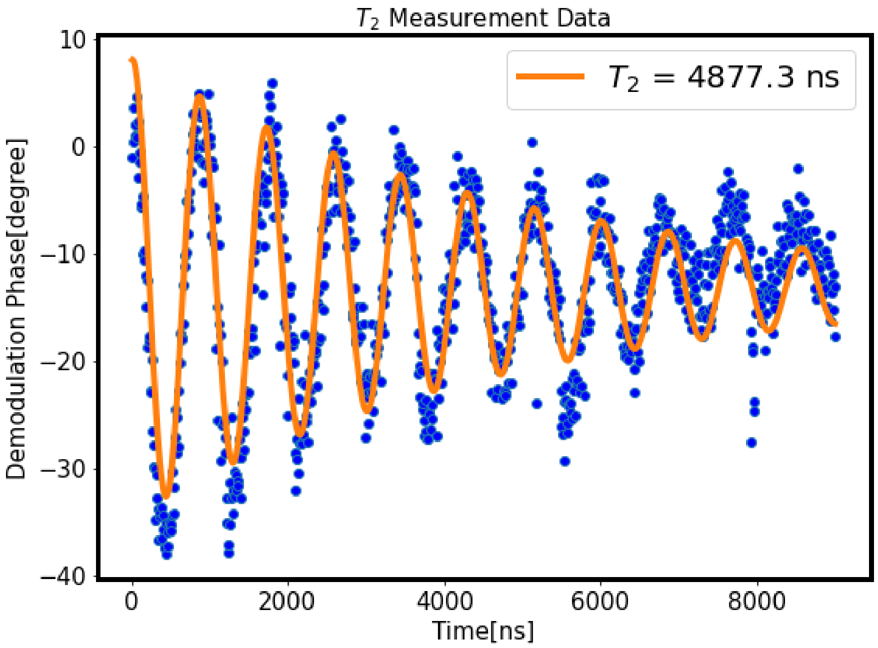
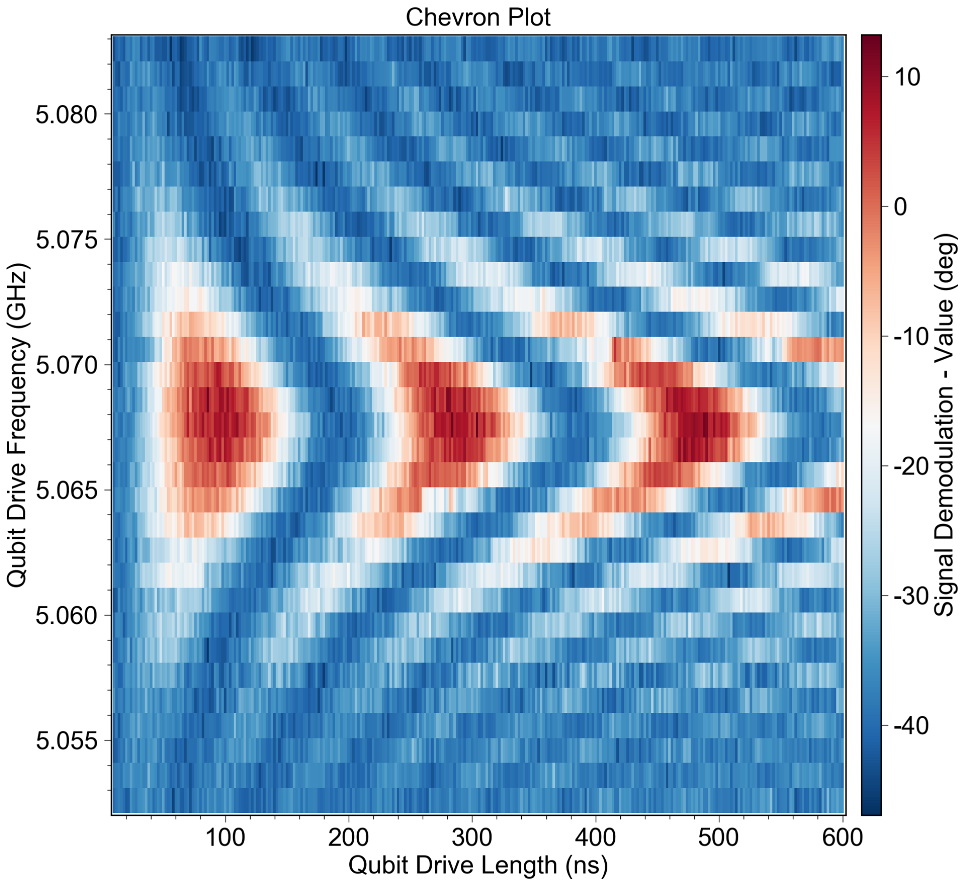
Example - measure coherence times T1 and T2 of the transmon inside the SRF cavity





Example - varying frequency and drive length for the Rabi oscillations



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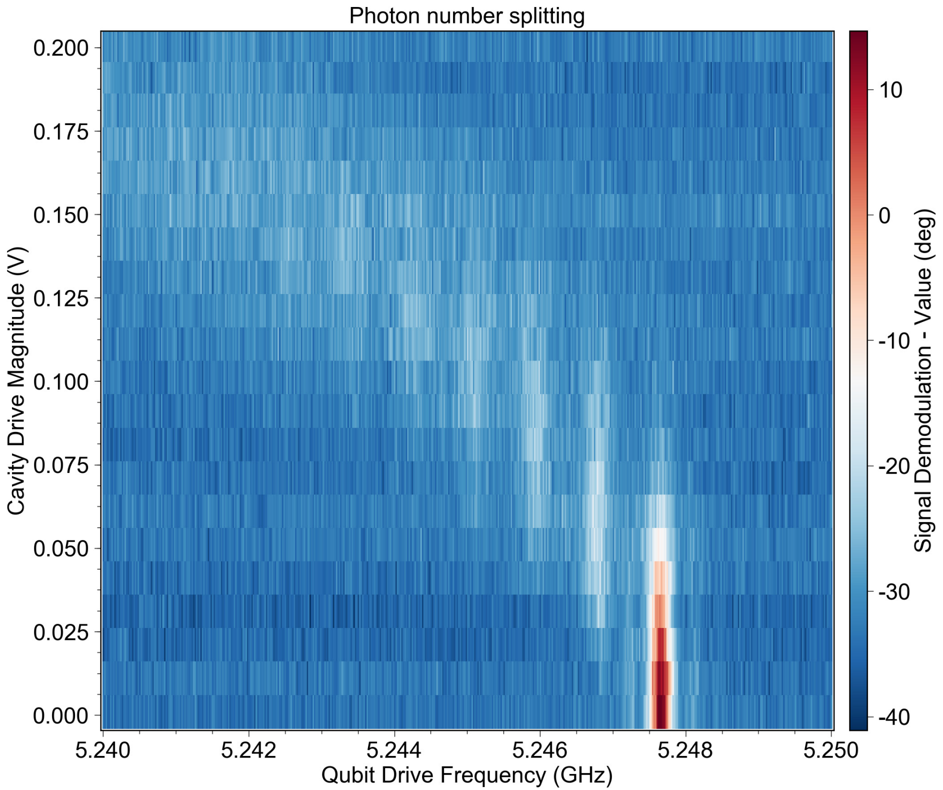
Example – change of transmon frequency depending on the number of photons in the SRF cavity



Cavity frequency : 5.366 GHz

Cavity Q : 1.4e5

$$\frac{\kappa_C}{2\pi} = 120.166\ kHz$$

$$\frac{\chi_C}{2\pi} = 775.6\ kHz$$

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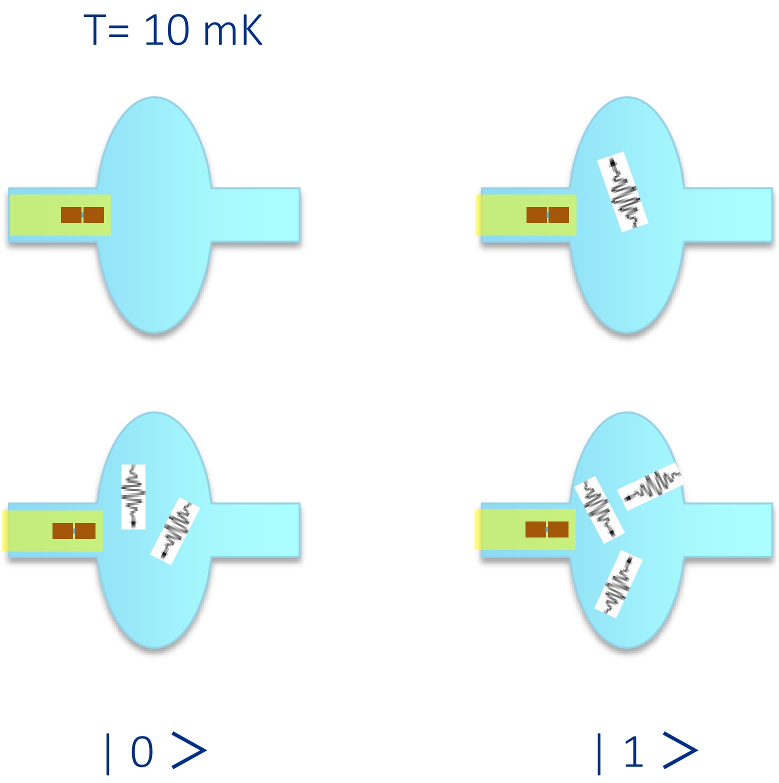
SRF Quantum Computing – where are the “bits”?

- How to encode a qubit (|0> and |1>) inside the cavity?
  - Example 1: Call the ground state (**no photons**) as |0>, one **single photon** present as |1> (Fock state)
  - Example 2: Call an **even** number of photons as |0>, **odd** number as |1>
- NOTE: Josephson-junction based transmon is used for state creation and quantum operations



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One step further = Qudit approach

- Qubit approach = two states used

- In the qudit approach, more than 2 (d>2) levels are used for quantum computing

- Example (let's take d = N energy levels in a single mode of SRF cavity):
  - $|\text{ qudit state } \rangle = a_0 |0\rangle + a_1 |1\rangle + a_2 |2\rangle + \ldots + a_N |N\rangle$, $|a_0|^2 + \ldots + |a_N|^2 = 1$
  - Qudits allow fast scale-up and to have the "all-to-all" connectivity
    - Open up further options for quantum algorithms and simulations

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SRF is the unique platform for qudit implementation

- In order to store and manipulate many multiphoton states they must live long enough – **coherence** is key
  - Even if just **1** photon is absorbed, the state is destroyed
  - Example: each photon in SRF cavity lives ~t = Q/w = 1 sec, then state of precisely 1000 photons |1000 > lives t/1000 = 1/1000 sec – still long enough!

- Current 2D and 3D platforms (non-SRF) do not have enough coherence for taking the qudit approach beyond several photon states
  - Single photons live <~ 1 ms

- With SRF we are targeting to control **~10000 photons** per mode – equivalent to ~13 qubits

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What does SRF buy us?

- Long coherence makes multiphoton states of a large size and **qudit** approach viable

- Very minimal wiring – 1 transmon to convert the 9-cell into a **100+ qubit**-equivalent QPU
  - The more levels can be controlled in each SRF cavity mode (qudit), the less wiring is needed

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Summary

- Superconducting quantum computing receives a tremendous boost from Accelerator Technology expertise

- One of the National Quantum Initiative QIS Research centers is based on the SRF Technology – SQMS led by Fermilab

- Superconducting qubits are both being advanced and employed to build the QPUs by SQMS
  - Taking advantage of the coherence using the qudit approach

- First ever integration of high Q SRF cavity with Rigetti transmon has been achieved
  - Optimization of the coupling parameters etc is ongoing
  - Proceeding to manipulation of the various quantum states in the high Q fundamental mode