Employing SRF to Boost Coherence of 3D Quantum Systems

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SRF’2019

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Outline

- Quantum computing and systems
- Appeal of SRF cavities for quantum systems
  - Ultra-high Q > 10^{10} factors are routine
  - Decades of expertise in surface engineering and underlying superconducting RF science
- 3D SRF quantum system implementation at FNAL
  - Proof-of-principle demonstrations of τ up to 2 seconds at T < 20 mK and low photon numbers
  - Clarification of the TLS role
- Applications of the new capability
  - Quantum computing
  - Fundamental physics

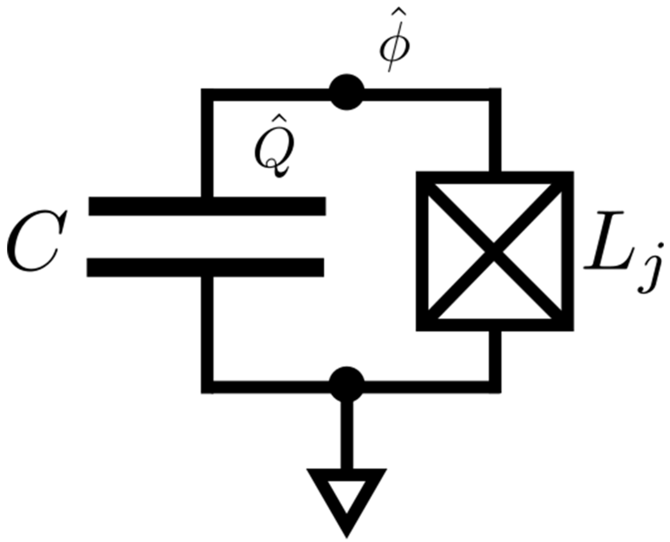
Quantum computing

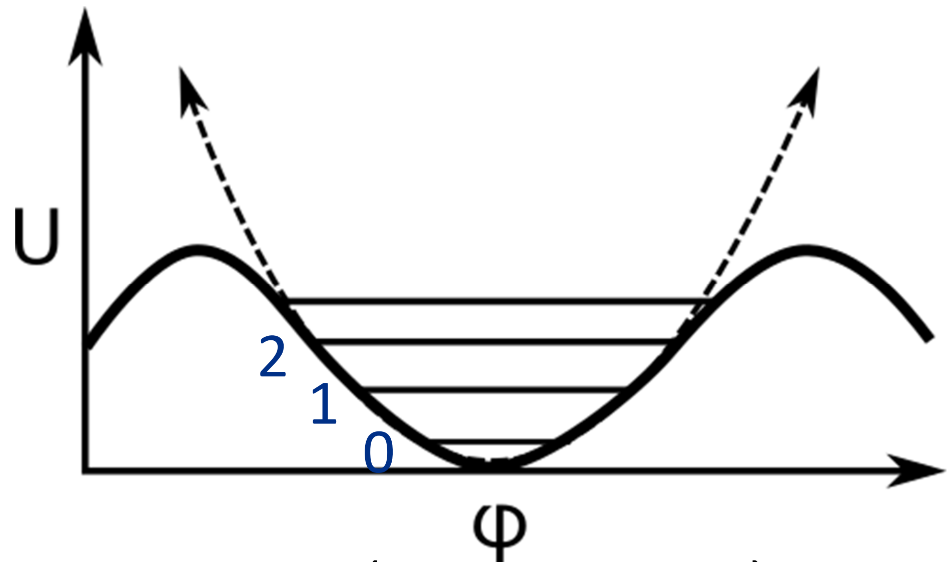
- Basic idea is to use “qubit” instead of a bit
  - Utilize two states of the quantum system (|0>, |1>), which can be also prepared in any superpositions
  - Also utilize entanglement between the qubits
  - Provides potentially computational capacity for dramatic speedups in several areas
    - Finding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

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

Artificial Atom by a Josephson Junction

Courtesy of E. Holland

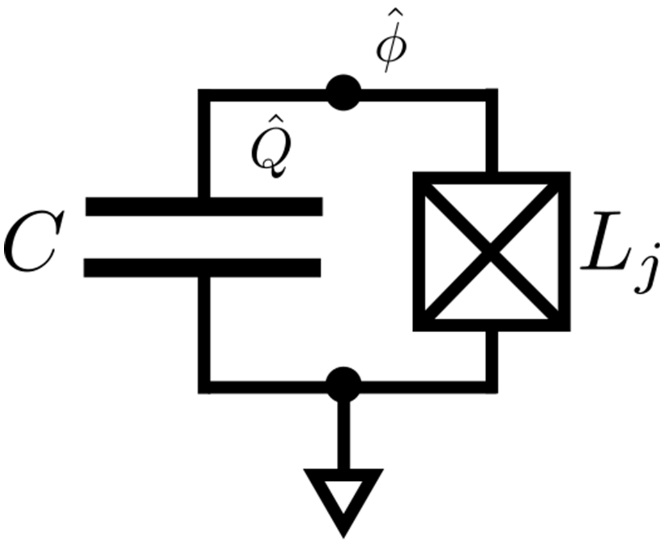




$$\hat{H}_T = \hbar\omega_{LC}\hat{a}^\dagger\hat{a} - E_j\left(\cos\hat{\phi} + \frac{\hat{\phi}^2}{2}\right)$$

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

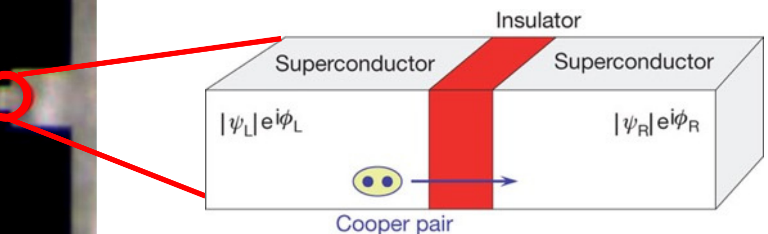
Artificial atom: Transmon

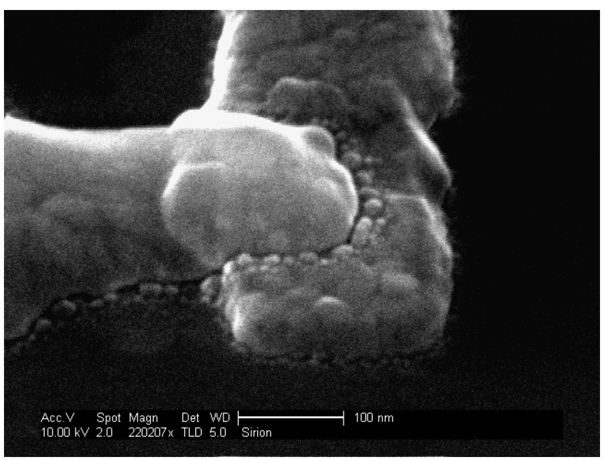


300 microns

Courtesy of E. Holland

Josephson Junction





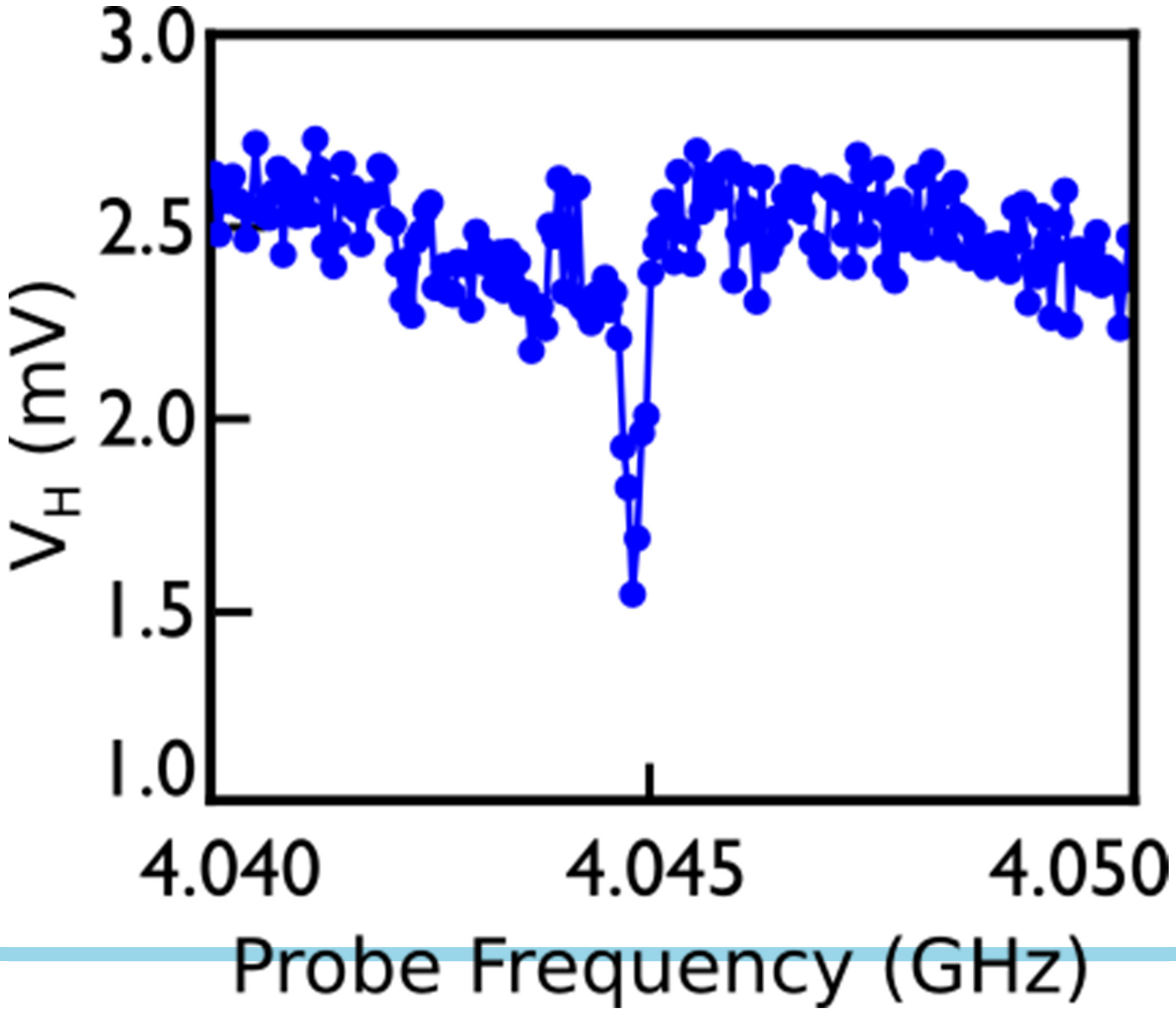
~10 trillion atoms
~1000 times Earth population

100 nanometers

Fermilab

Spectroscopy for First Energy Transition

Courtesy of E. Holland

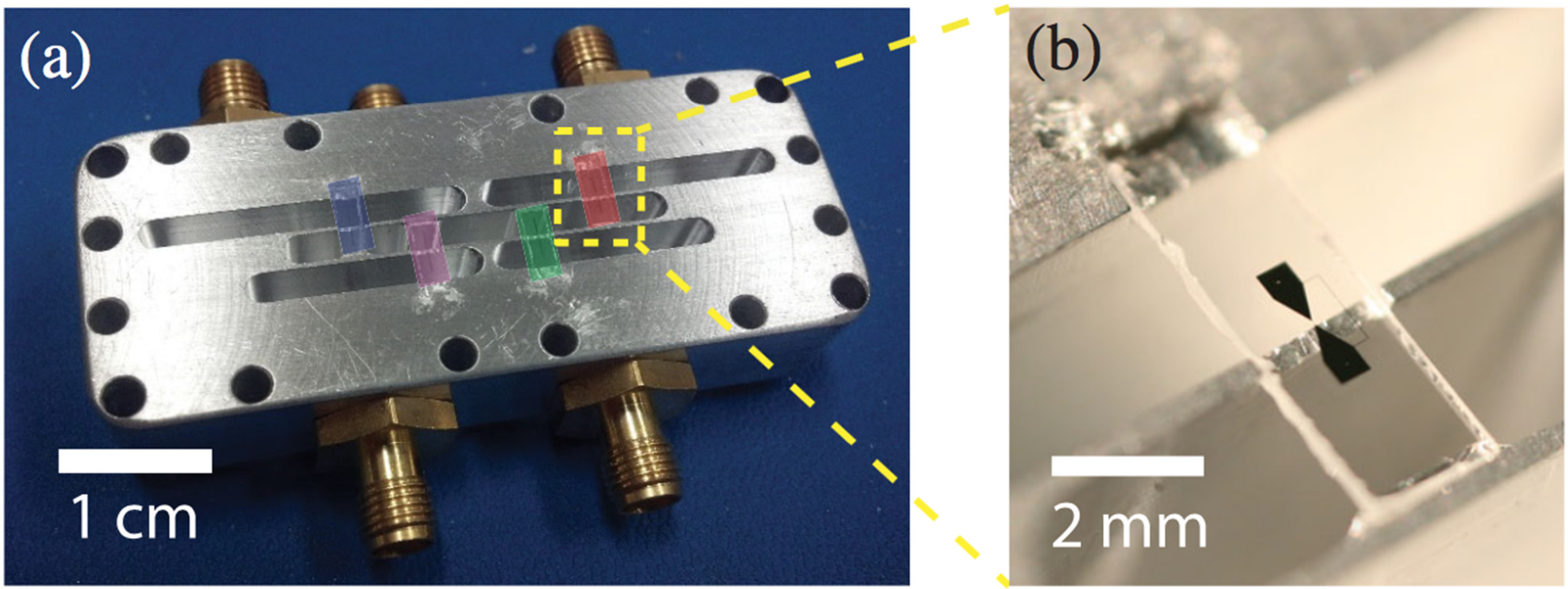


$$\omega a^\dagger a$$

Quantum Computing: 3D circuit QED architecture

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

Machined Aluminum host cavity



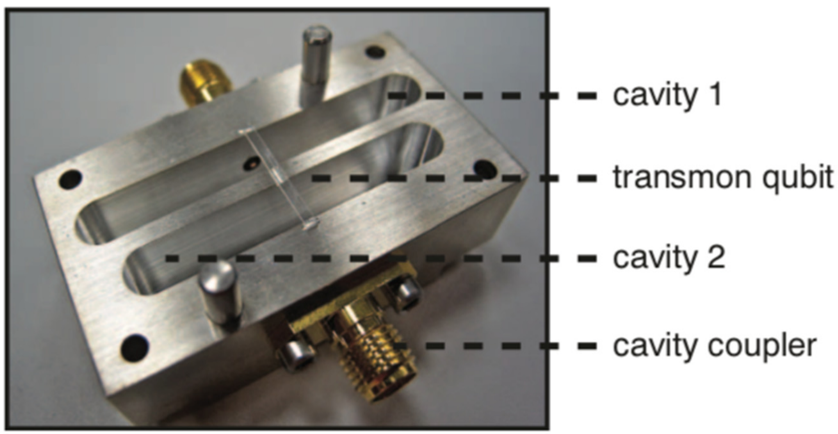
H. Paik et al, Phys. Rev. Lett. 117, 251502 (2016)

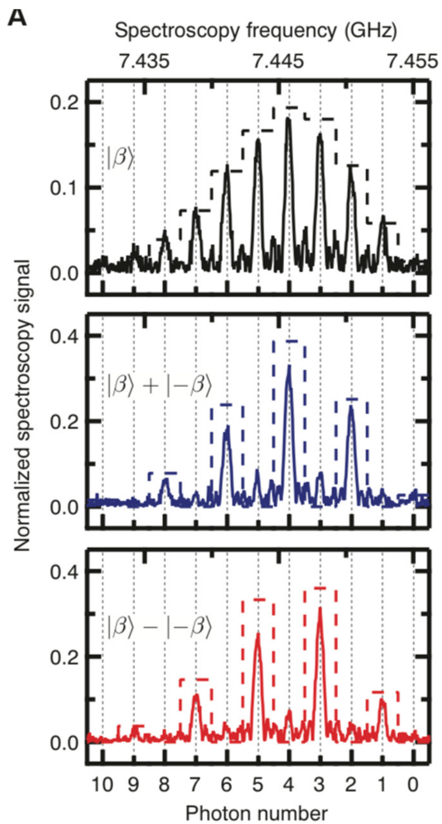
“Schrodinger cat” states as a computational resource

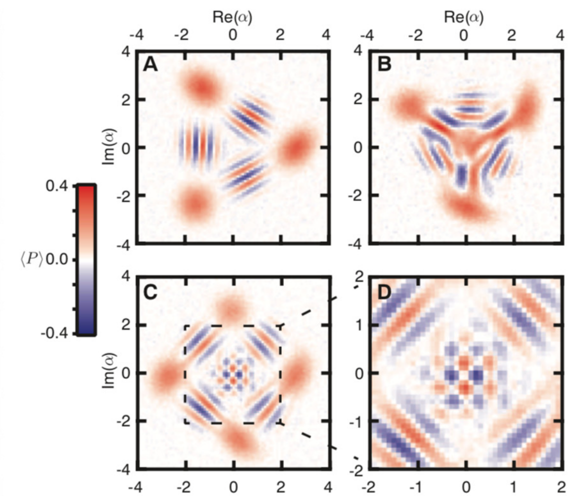
- M. Mirrahimi et al, New Journal of Physics 16 (2014) 045014

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] S. M. Girvin,[1] Mazyar Mirrahimi,[1,2] M. H. Devoret,[1] R. J. Schoelkopf[1]







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

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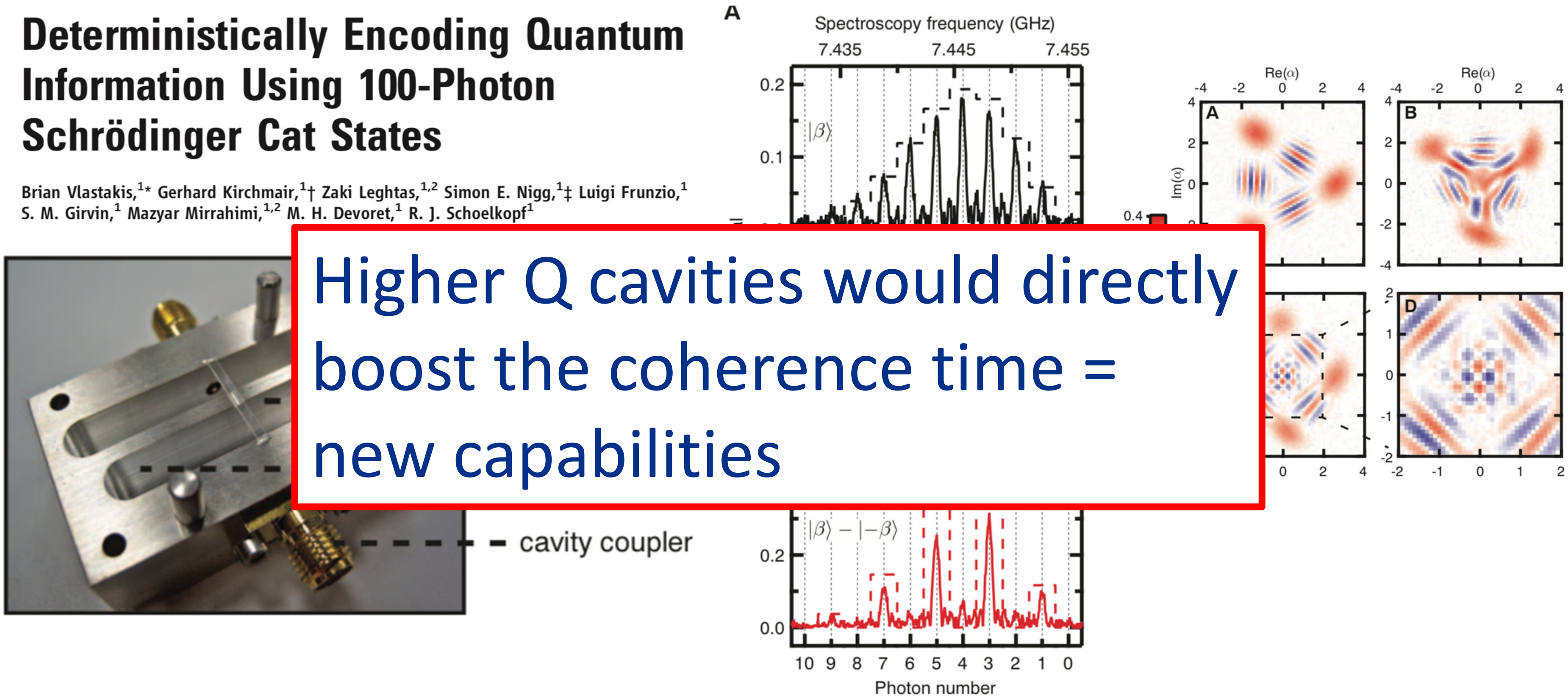
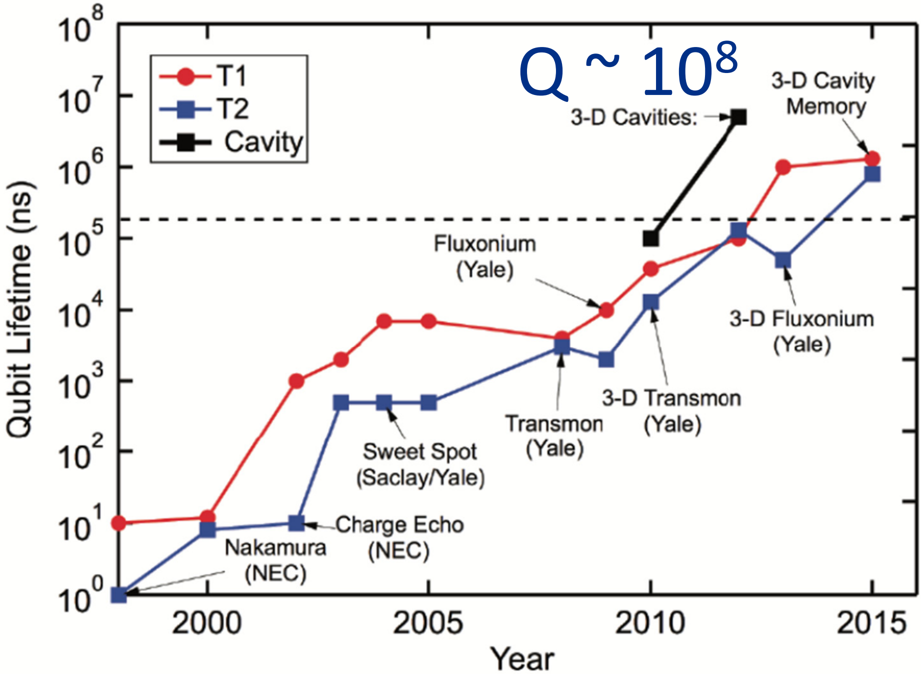


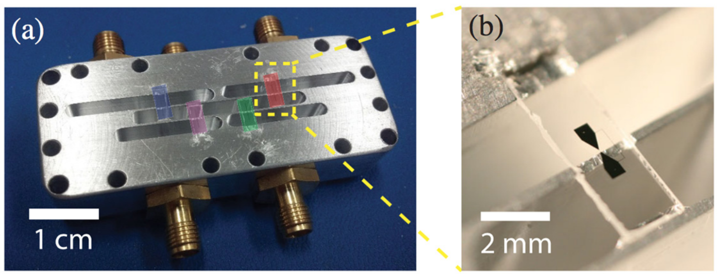
Higher Q cavities would directly boost the coherence time = new capabilities

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

High Q SRF 3D cavities for improved coherence

~10 msec photon lifetime/coherence is a record





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

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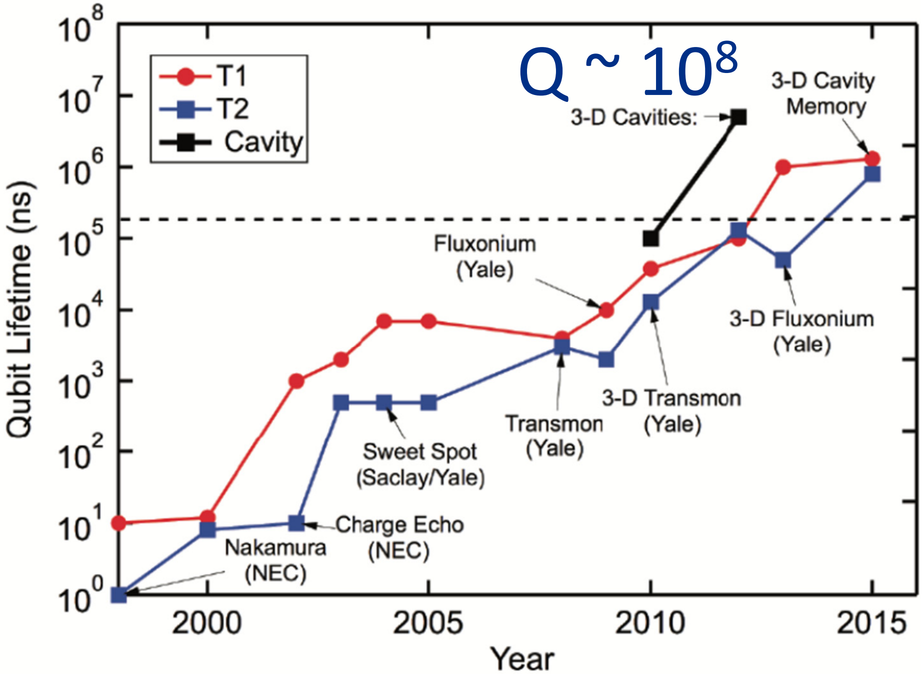

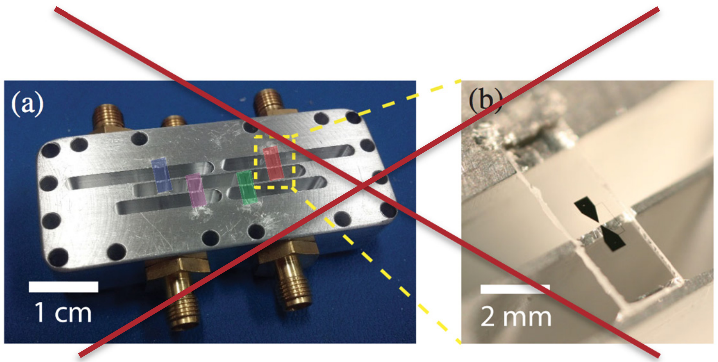

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High Q SRF 3D cavities for improved coherence

Q > 10^{11} ~10 seconds of coherence

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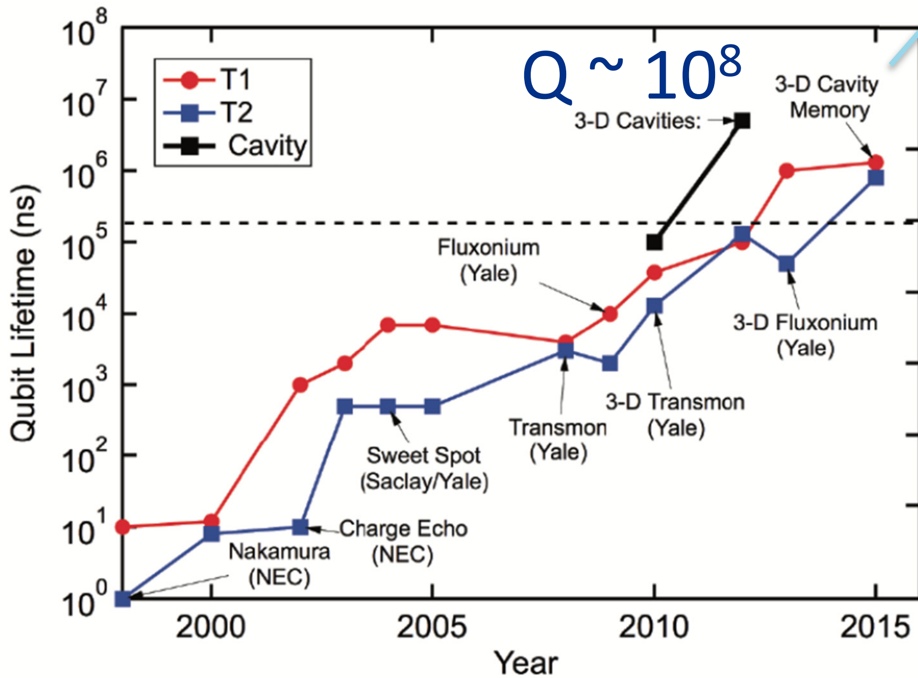

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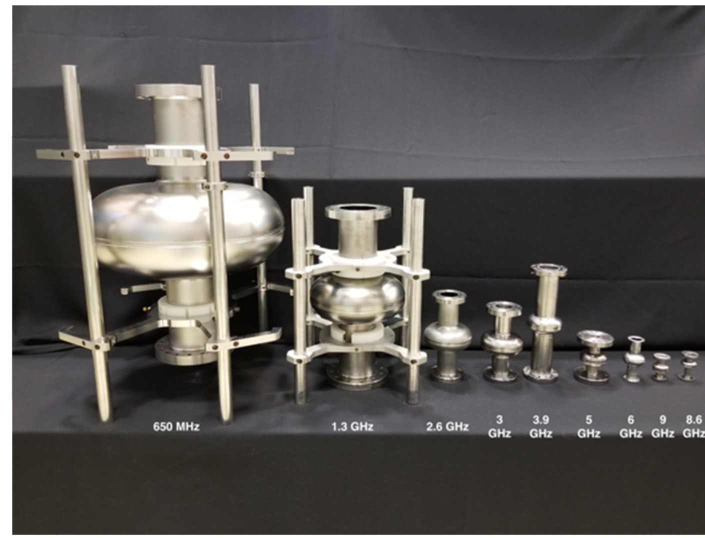


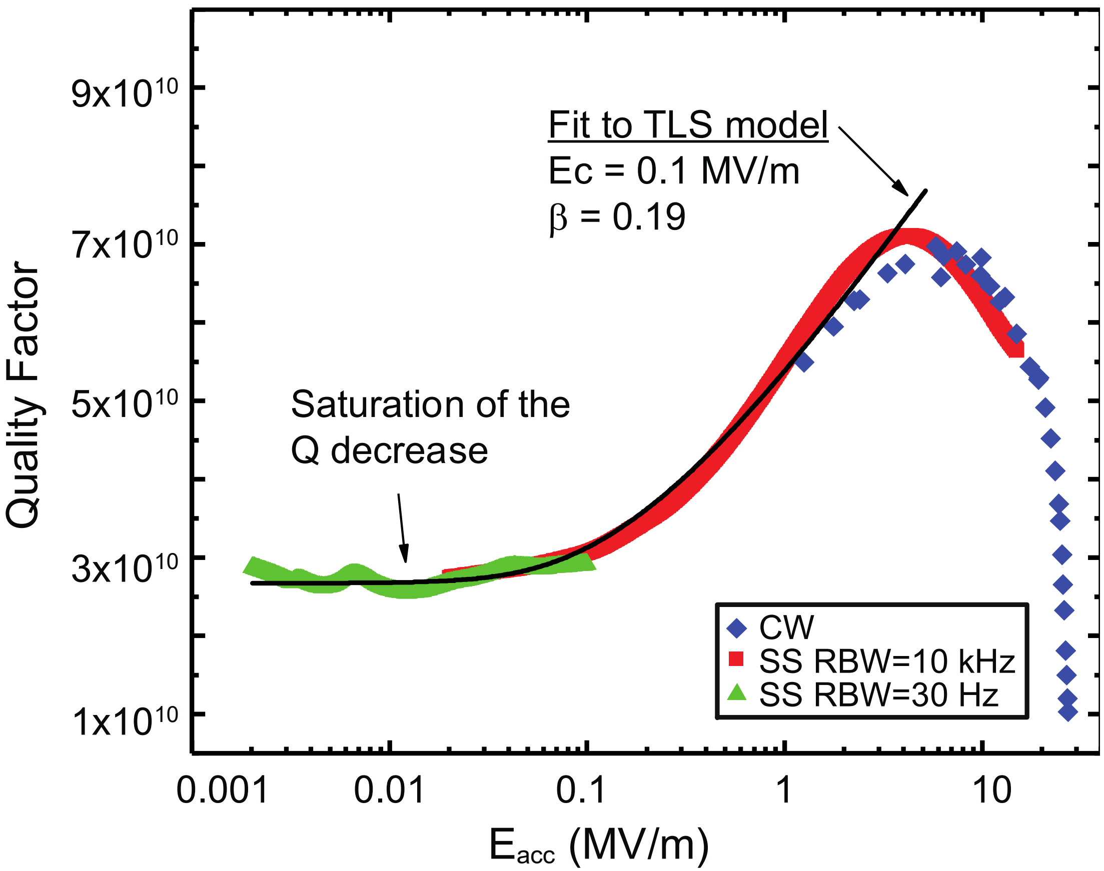
1-cell Fermilab cavities of various frequencies

Can we translate high Q expertise in SRF cavities to ‘quantum regime’?

- First question: what is the cause of the low field Q slope and what happens with Q as we decrease the field further?
- Second question: what happens at lowest T < 20 mK and at low photon numbers?

First experiment: extend the measured fields to record low

1.3 GHz T=1.5K



Good news: low field Q saturates at Q>**3 x 10^{10}**

Now measured down to <N> < 1000 photons

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

What is the effect of surface treatments on low field Q?

TABLE I. Summary of results for investigated 1.3 GHz elliptical shape cavities.

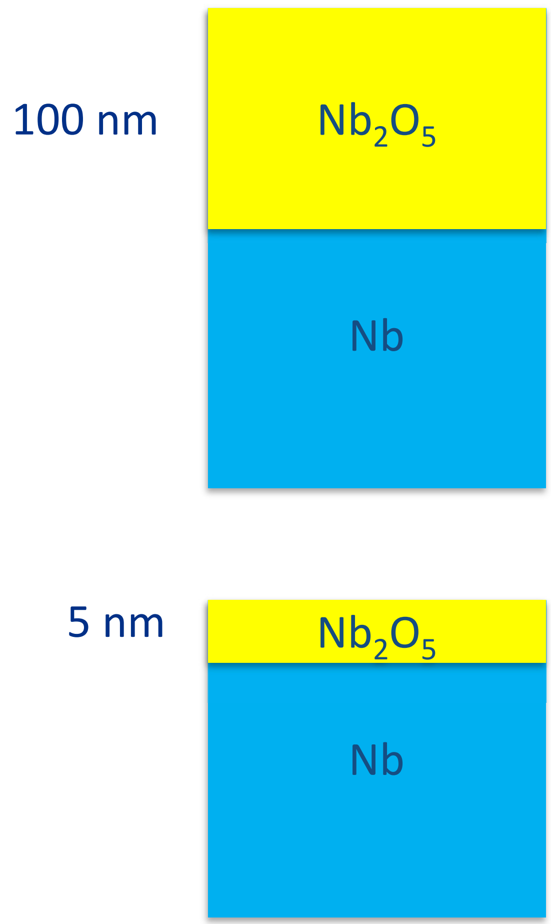
		R_s (nΩ)		ΔR_s (nΩ)	TLS fit	
Cavity	Treatment	5 MV/m	< 0.001 MV/m		E_c(MV/m)	β
AES012	Bulk EP	2.7	9.0	6.3	0.19	0.38
AES012	+100 nm oxide by anodizing	5.0	17.0	12.0	0.02	0.25
AES012	+EP 5 μm	3.0	7.0	4.0	0.19	0.38
AES014	Bulk EP + 120 °C 48 hrs	2.6	8.6	6.0	0.14	0.41
AES015	N infusion 800/120 °C 48 hrs	2.0	5.2	3.2	0.21	0.33
AES015	N infusion 800/160 °C 48 hrs	1.8	4.4	2.6	0.18	0.29
RDTTD004[a]	N doping + condensed 10^{-4} Torr of N_2	1.5	6.6	5.1	0.09	0.28
AES011	800 °C 2 hrs +120 °C 48 hrs	1.4	5.5	4.1	0.17	0.35
AES011	N infusion 800/160 °C 96 hrs	2.3	5.2	2.9	0.11	0.26
AES016[a]	800 °C 2 hrs +120 °C 48 hrs	1.7	5.6	3.9	0.10	0.28
PAV008[b]	800 °C 3 hrs +120 °C 48 hrs	9.8	17.0	7.2	0.12	0.37
PAV010	N infusion 800/120 °C 48 hrs	2.1	6.7	4.6	0.26	0.35
PAV010	N infusion 800/200 °C 48 hrs	6.6	10.8	4.2	0.20	0.42

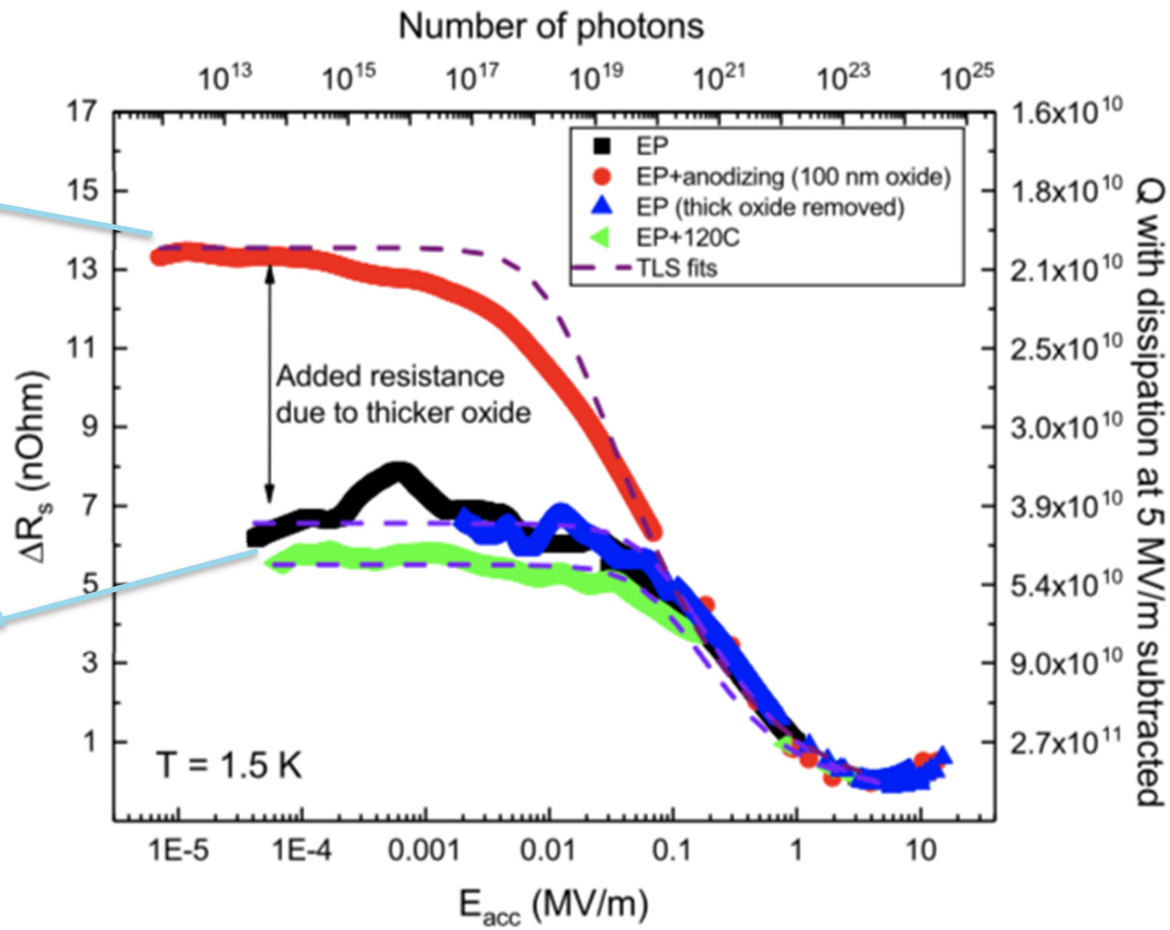
Changes within penetration depth have little effect

Oxide growth/change -> strong increase in very low field dissipation

Fermilab

Growing natural niobium oxide -> low field Q degrades





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

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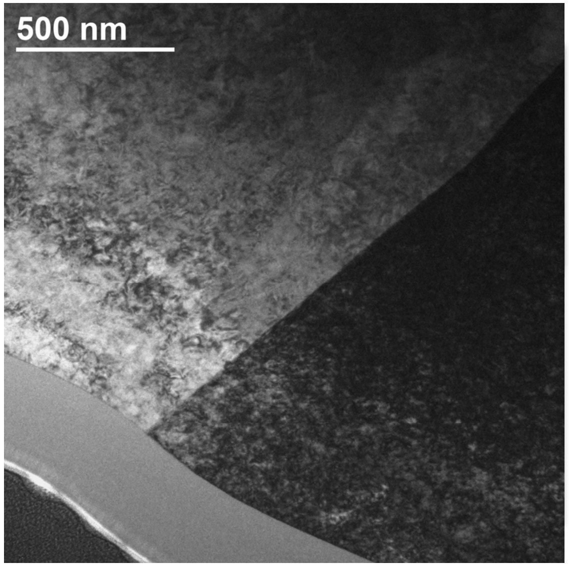
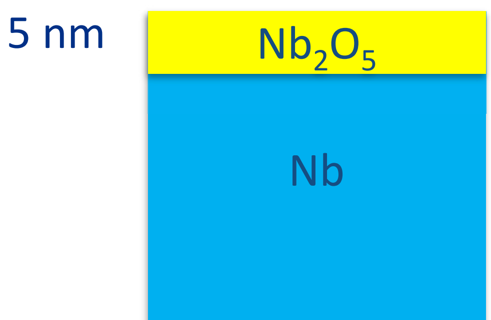
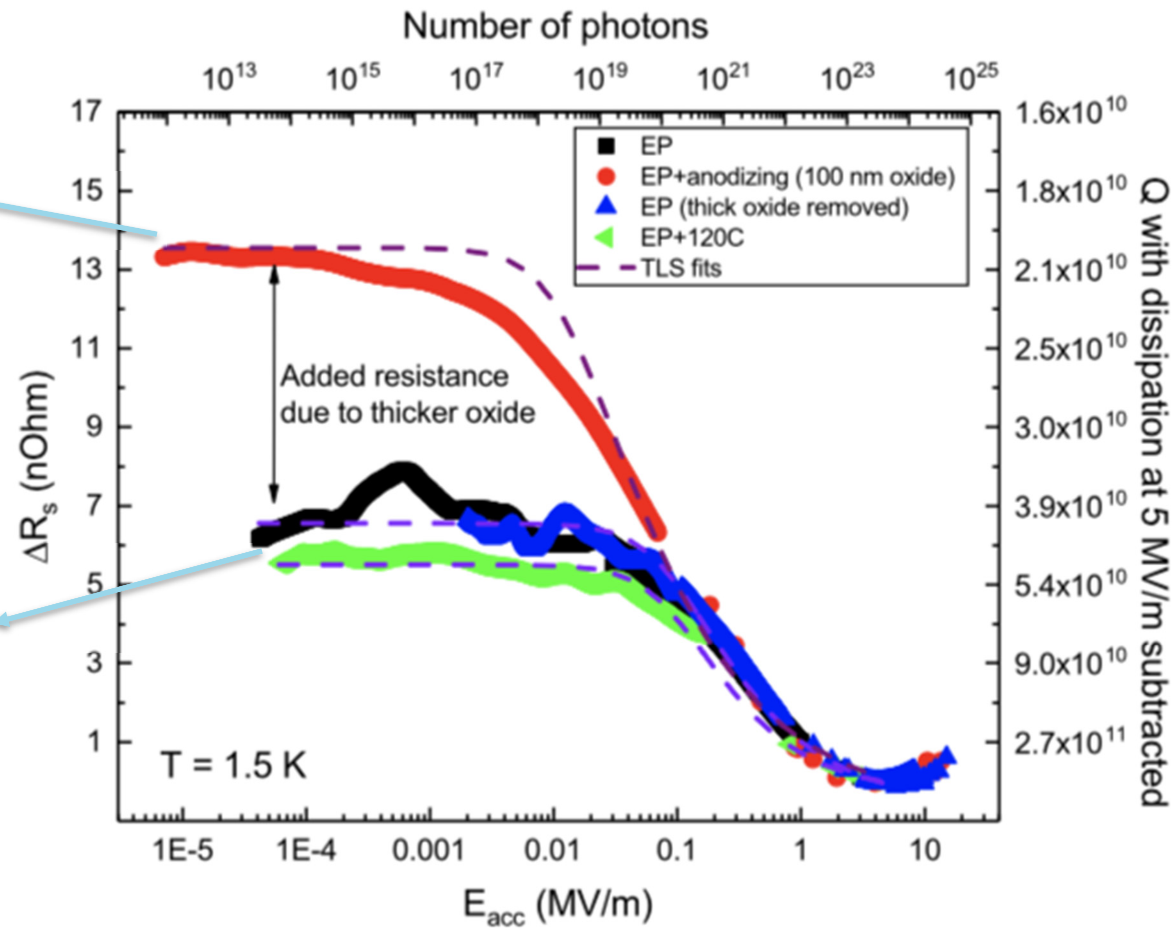
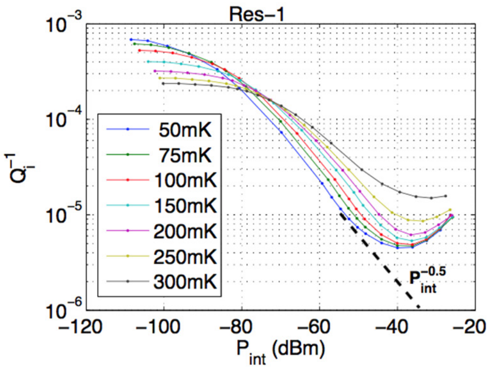




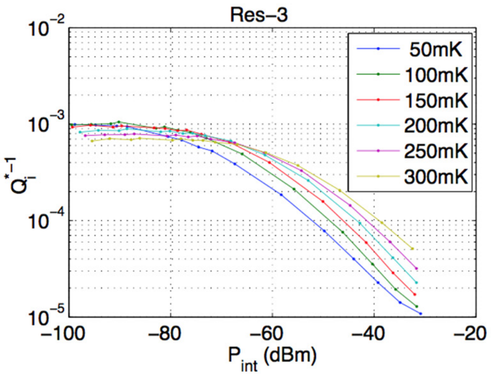


A. Romanenko and D. I. Schuster, Phys . Rev. Lett. **119**, 264801 (2017)

From 2D resonator world -> low-field increased losses

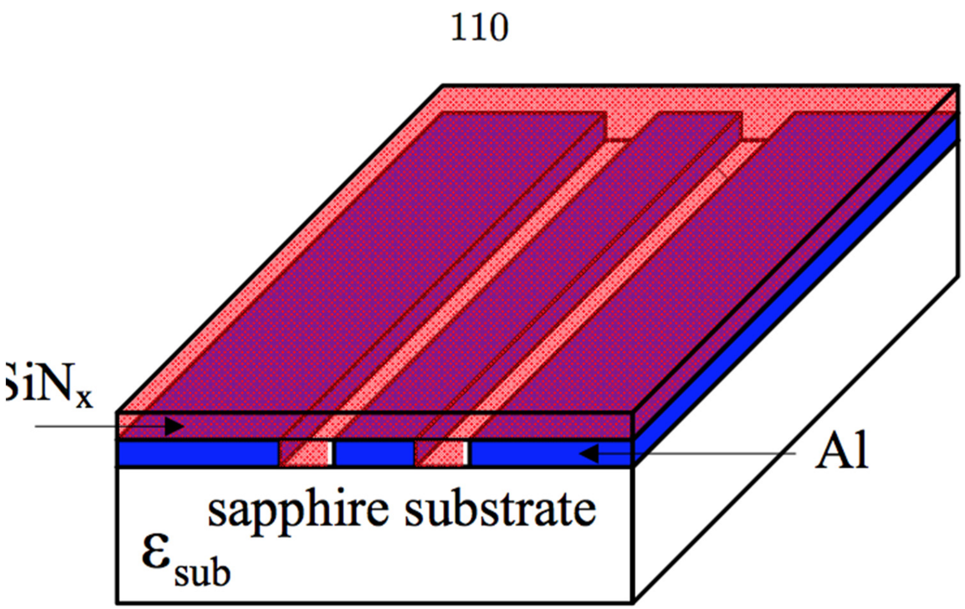


(a)



(c)

Two level systems in the dielectric as a cause



J. Martinis et al, Phys. Rev. Lett. 95, 210503 (2005)

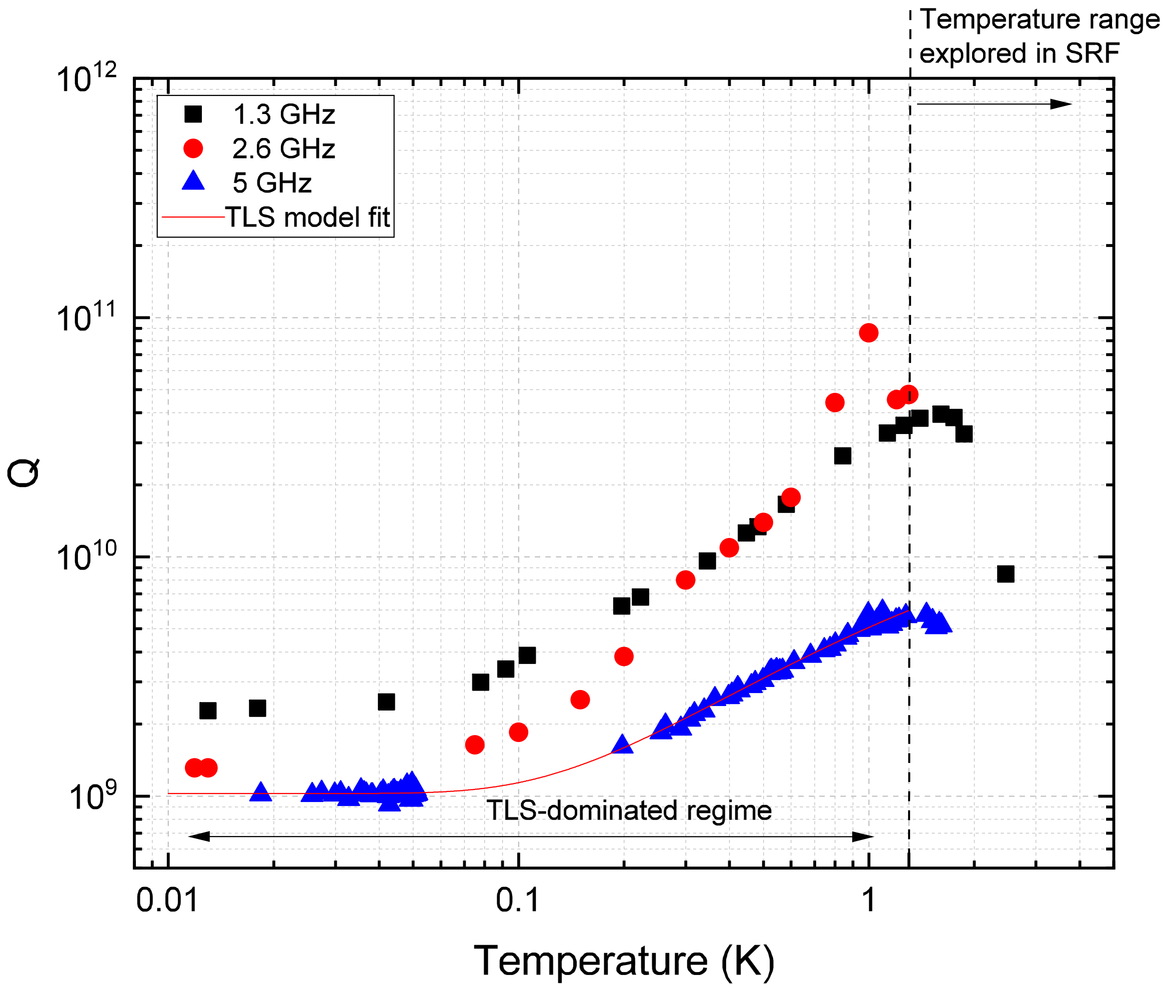
J. Gao, PhD Thesis, Caltech, 2008

J. Zmuidzinas, Annu. Rev. Condens. Matter Phys. 2012

- What happens in the “quantum regime”? ($T < 20mK$, low photon number)

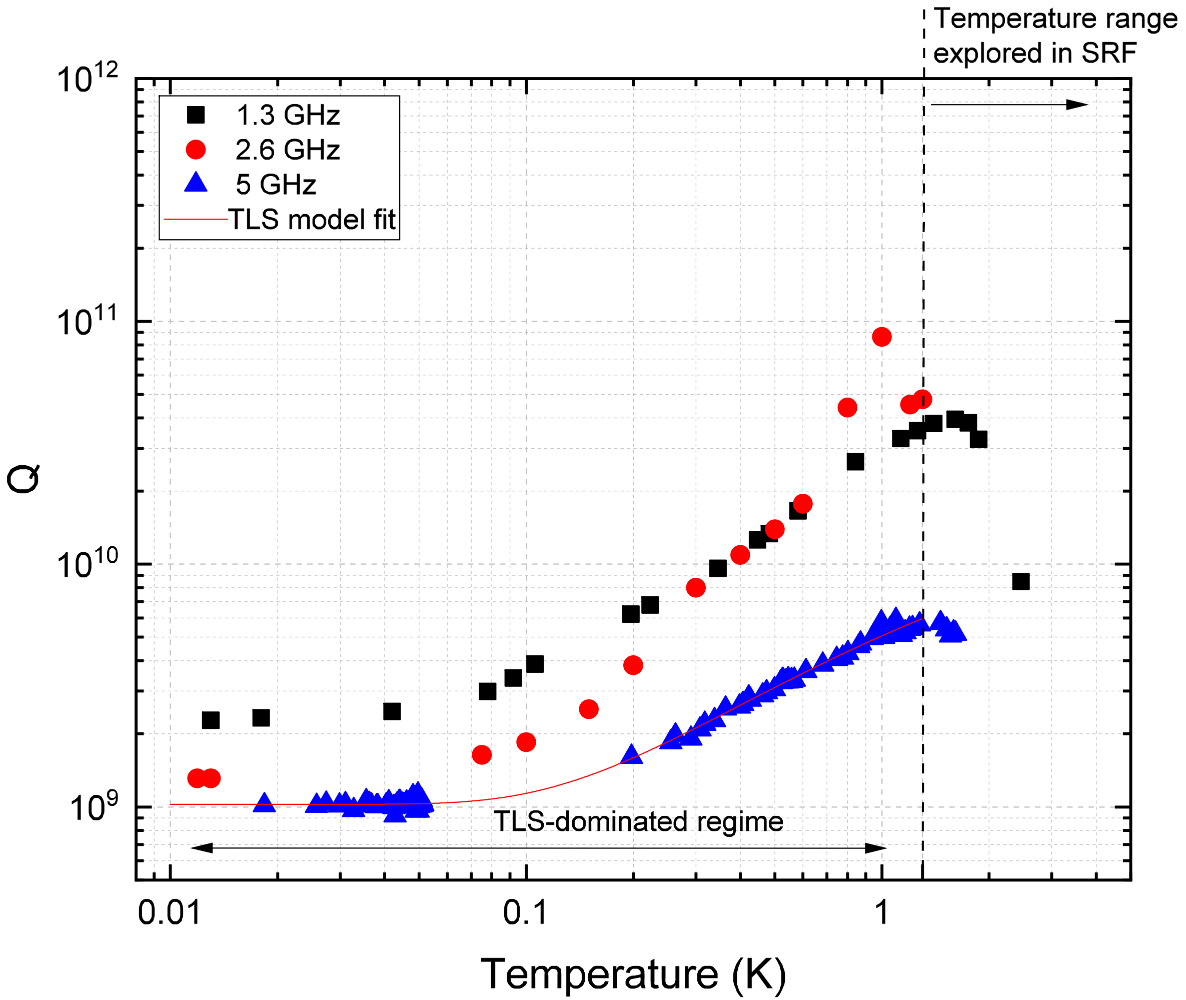

2.6 GHz 1-cell cavity

Record high Q in quantum regime at first run



A. Romanenko, R. Pilipenko, S. Zorzetti, D. Frolov, M. Awida, S. Posen, A. Grassellino, arXiv:1810.03703

Material treatment to suppress TLS dissipation



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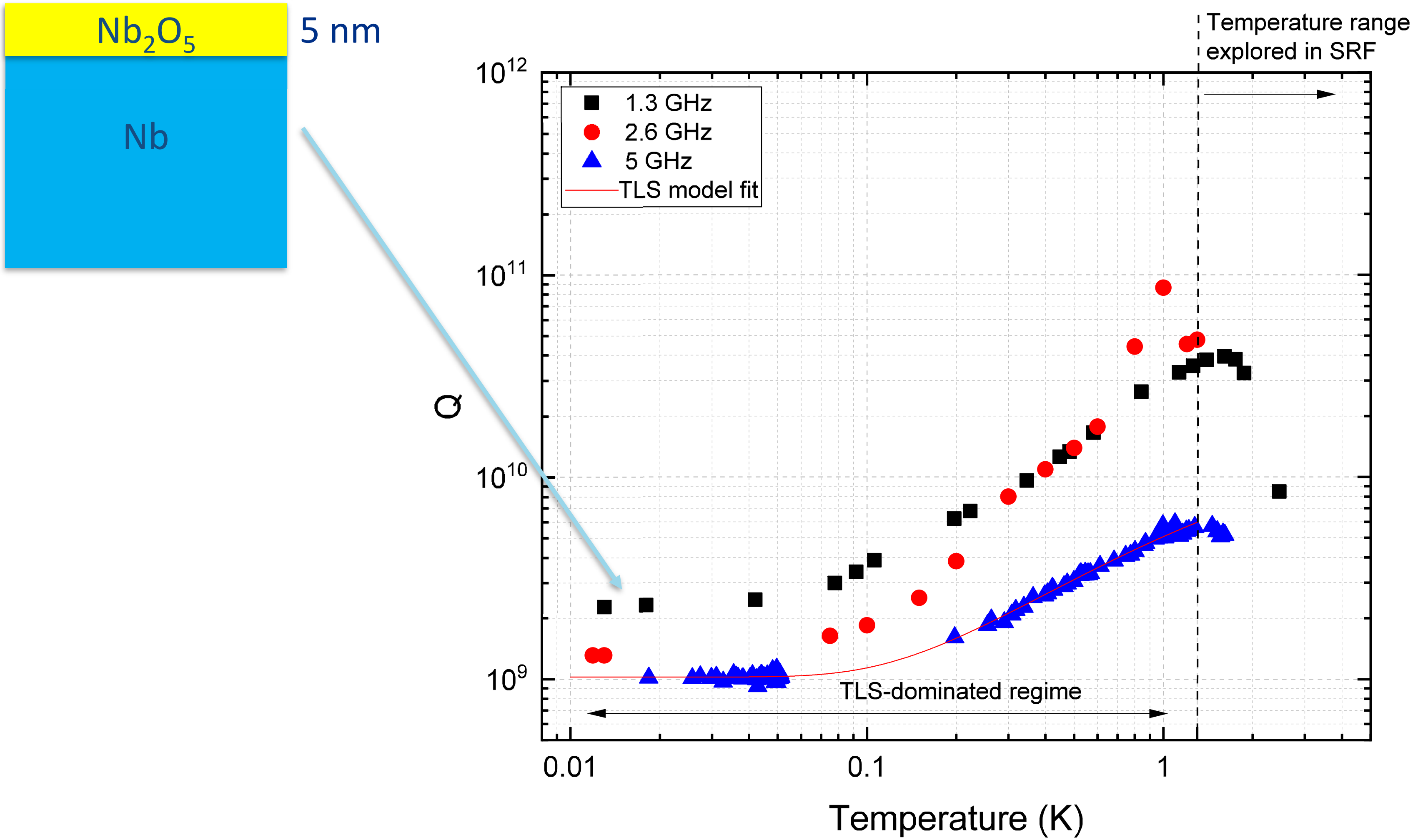

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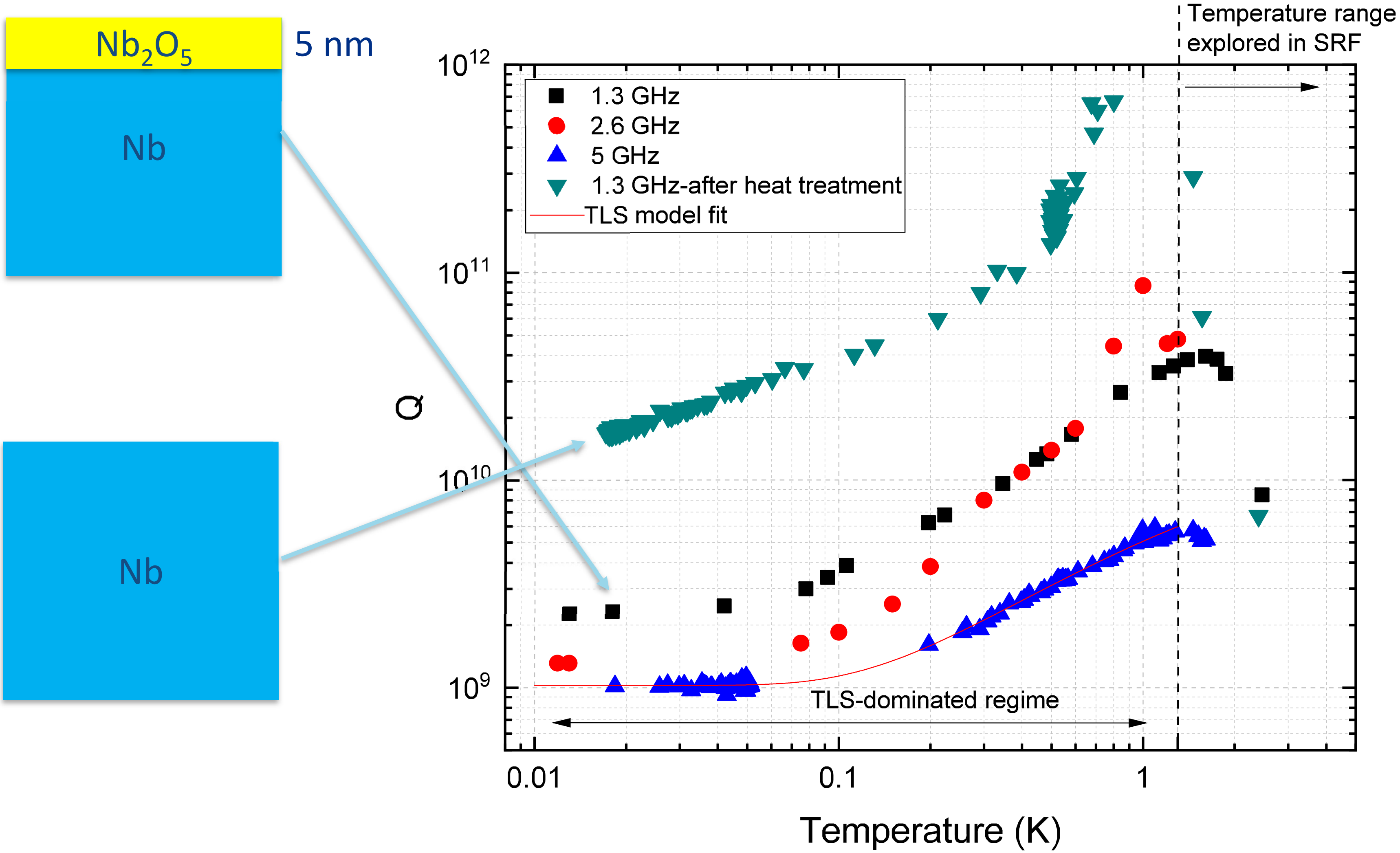
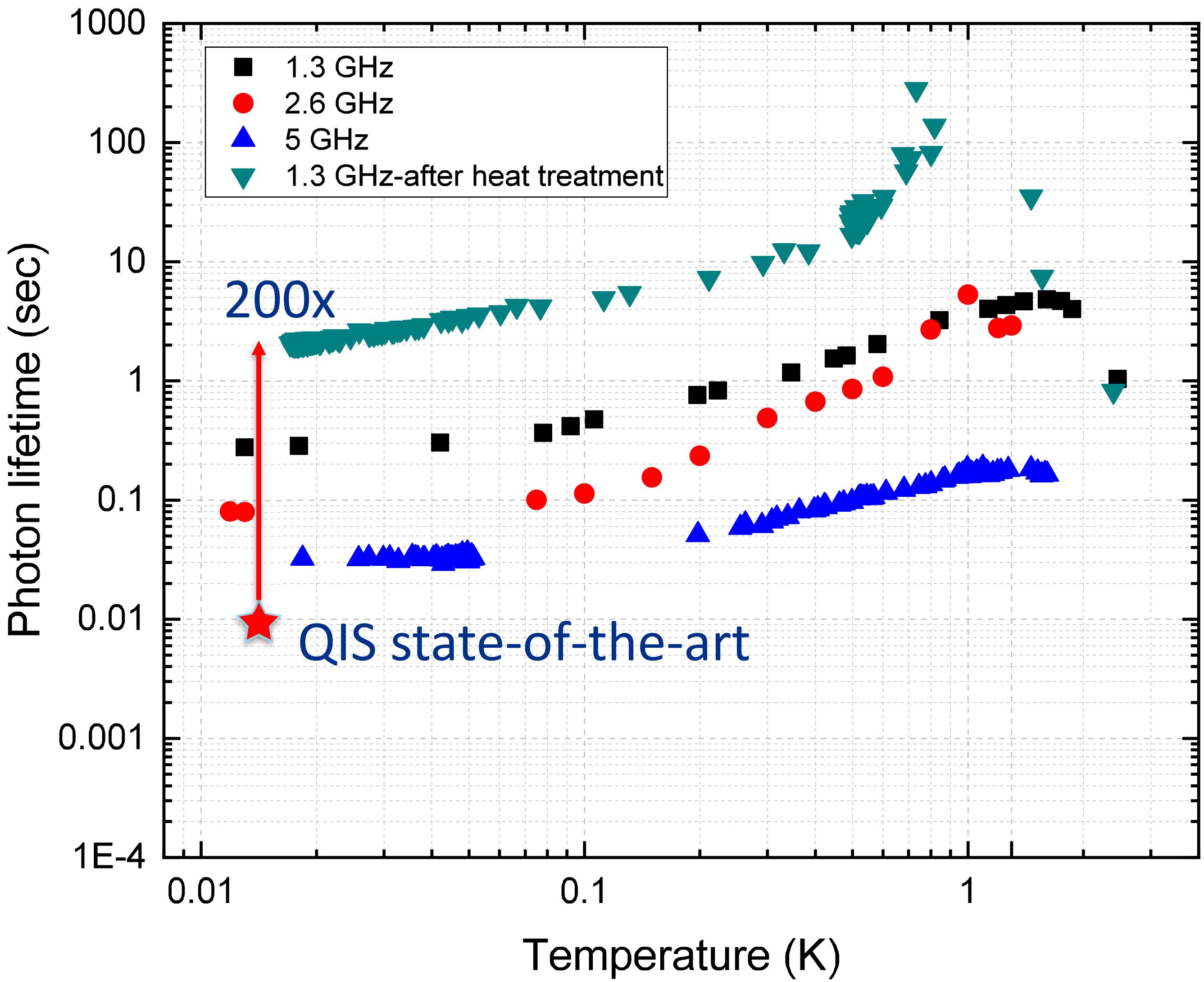


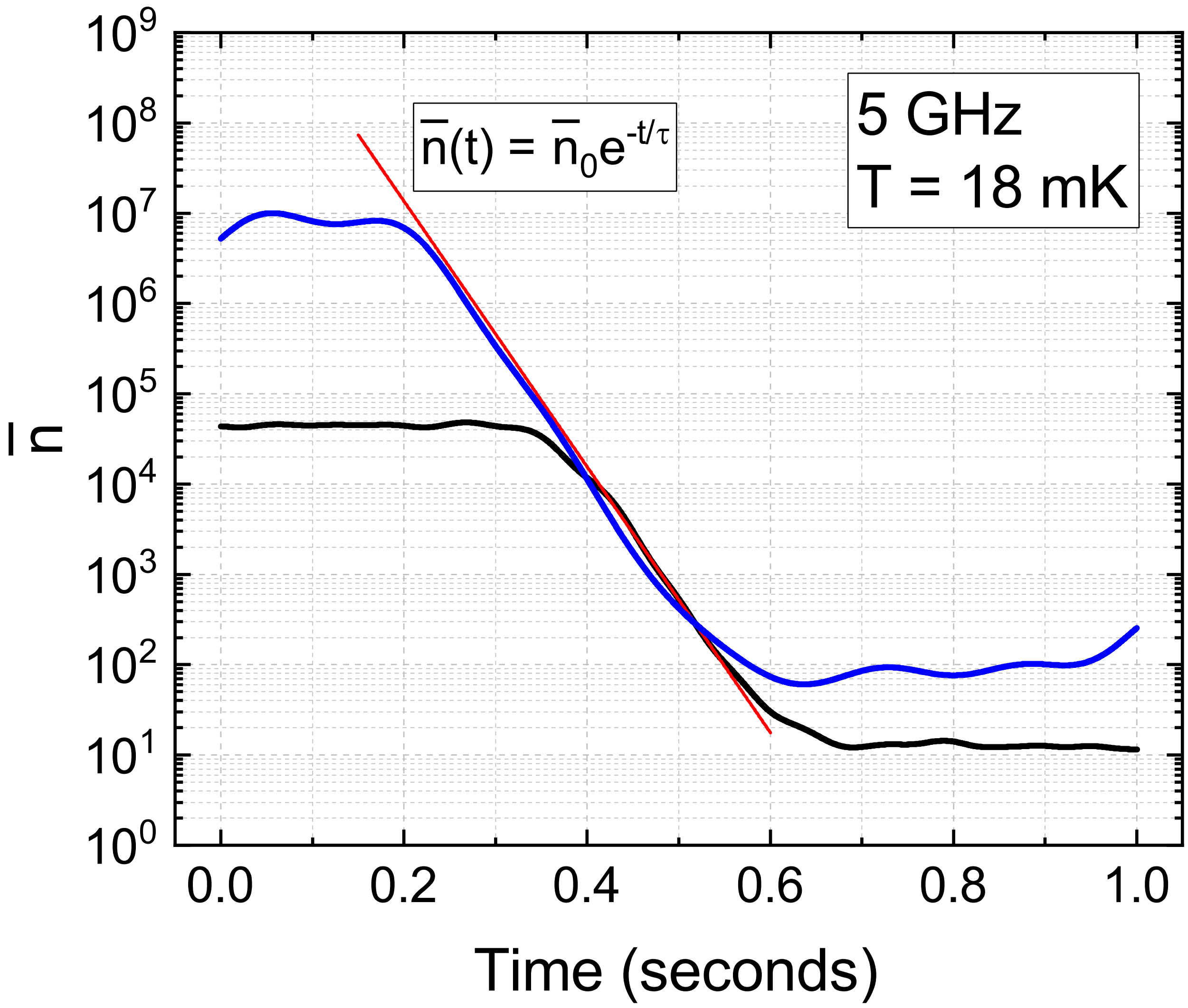
A. Romanenko, R. Pilipenko, S. Zorzetti, D. Frolov, M. Awida, S. Posen, A. Grassellino, arXiv:1810.03703

Record high photon lifetimes achieved



A. Romanenko, R. Pilipenko, S. Zorzetti, D. Frolov, M. Awida, S. Posen, A. Grassellino, arXiv:1810.03703

Decays show no Q(n) dependence



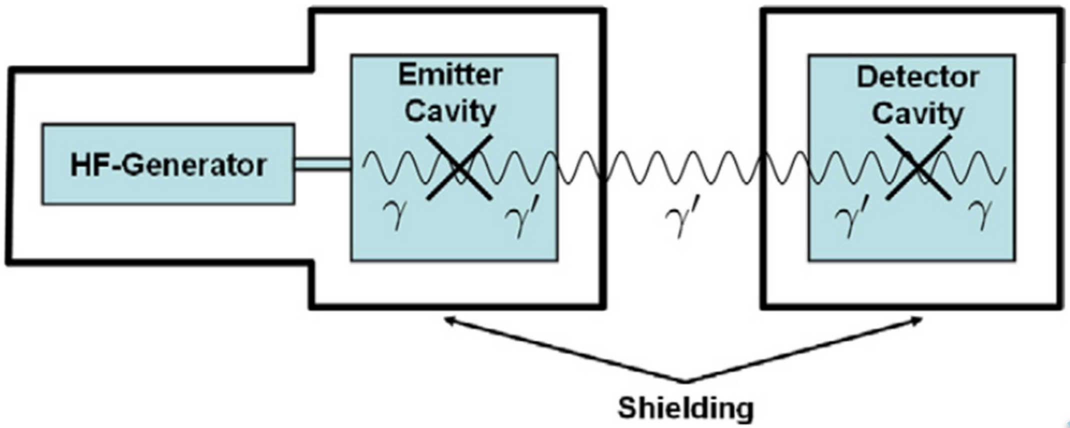
- Immediate applications

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

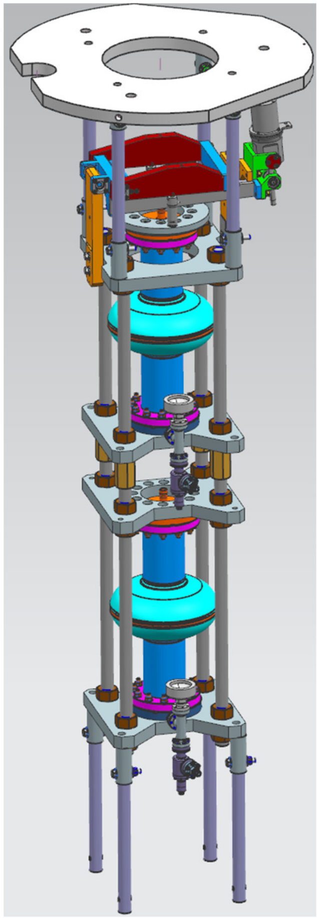


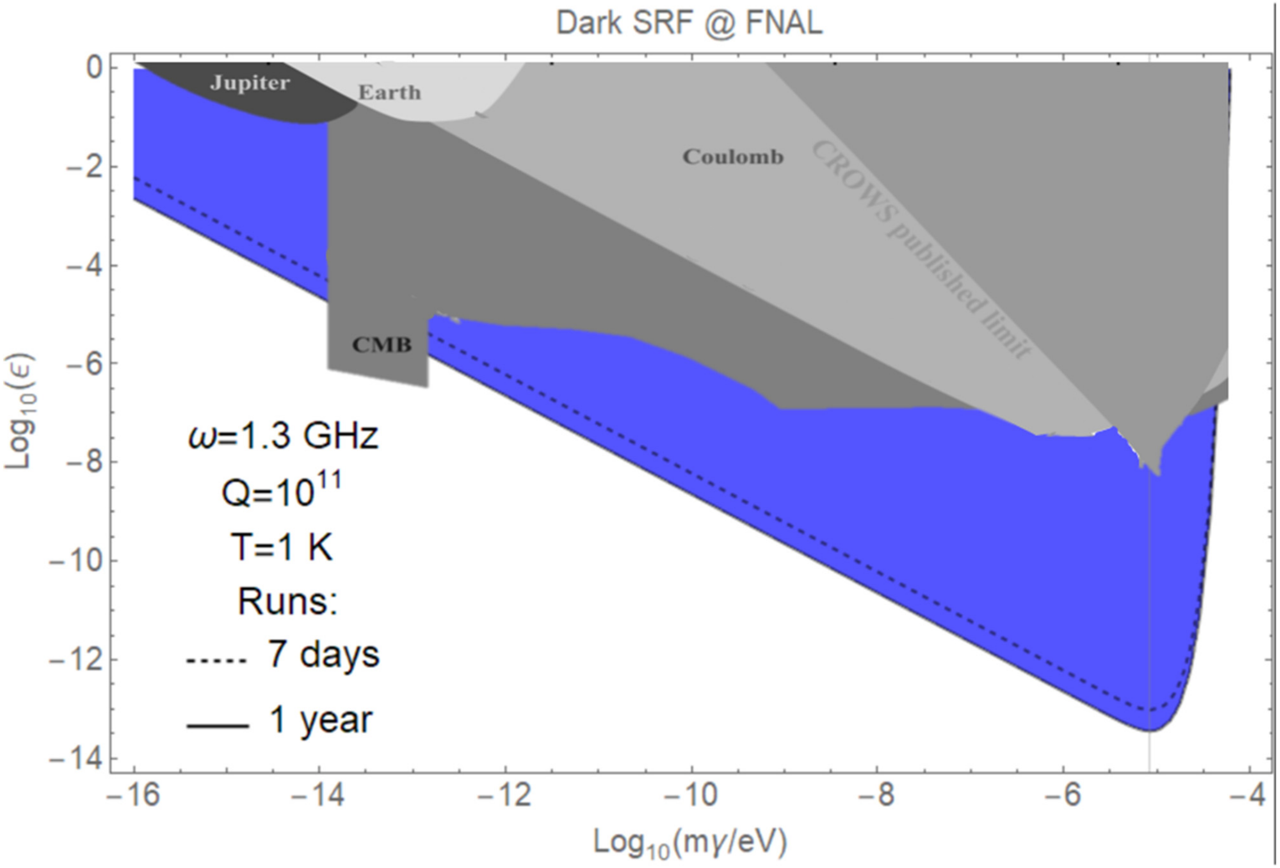
$$\frac{P_{DET}}{P_{EM}} = \chi^4 Q_{DET} Q_{EM} \left(\frac{m_{\gamma'} c^2}{\hbar\omega_\gamma}\right)^8 |G|^2$$

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

“Dark SRF” experiment at Fermilab

- First search for dark photons with SRF cavities



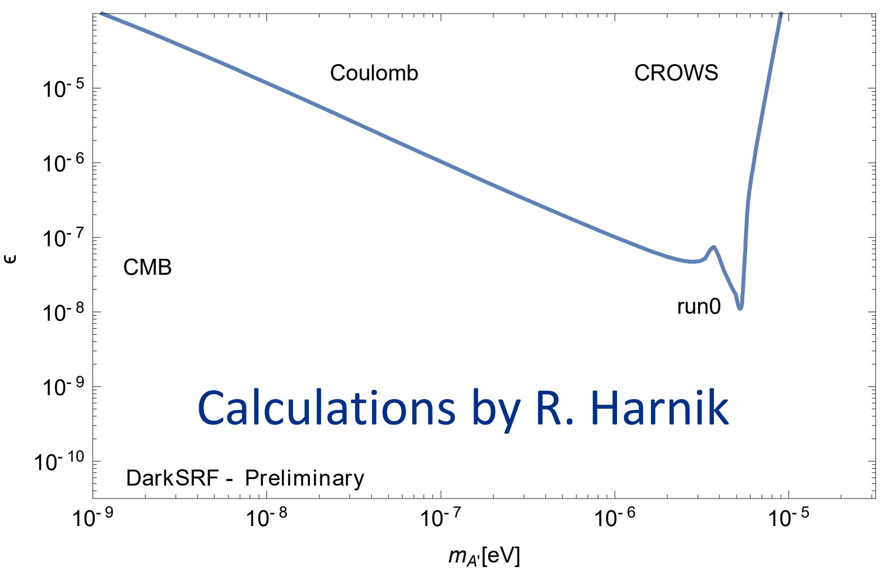


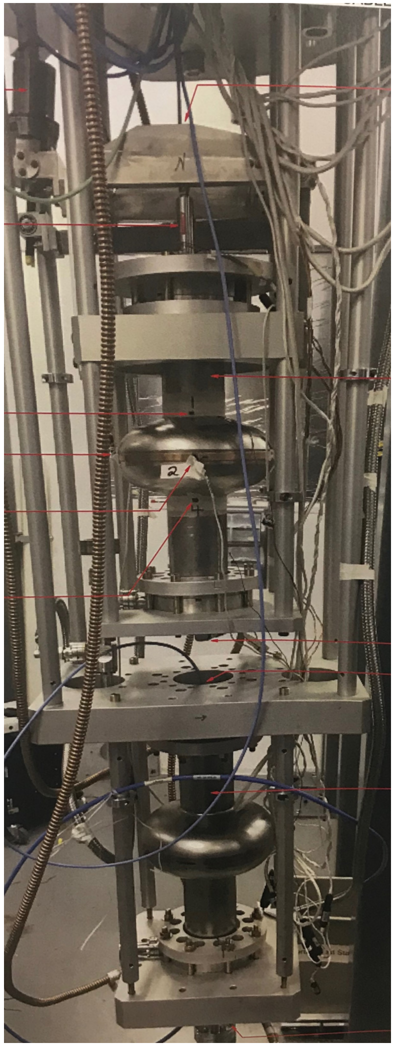
First test run has been accomplished

Dark SRF: “Run 0” has been successful

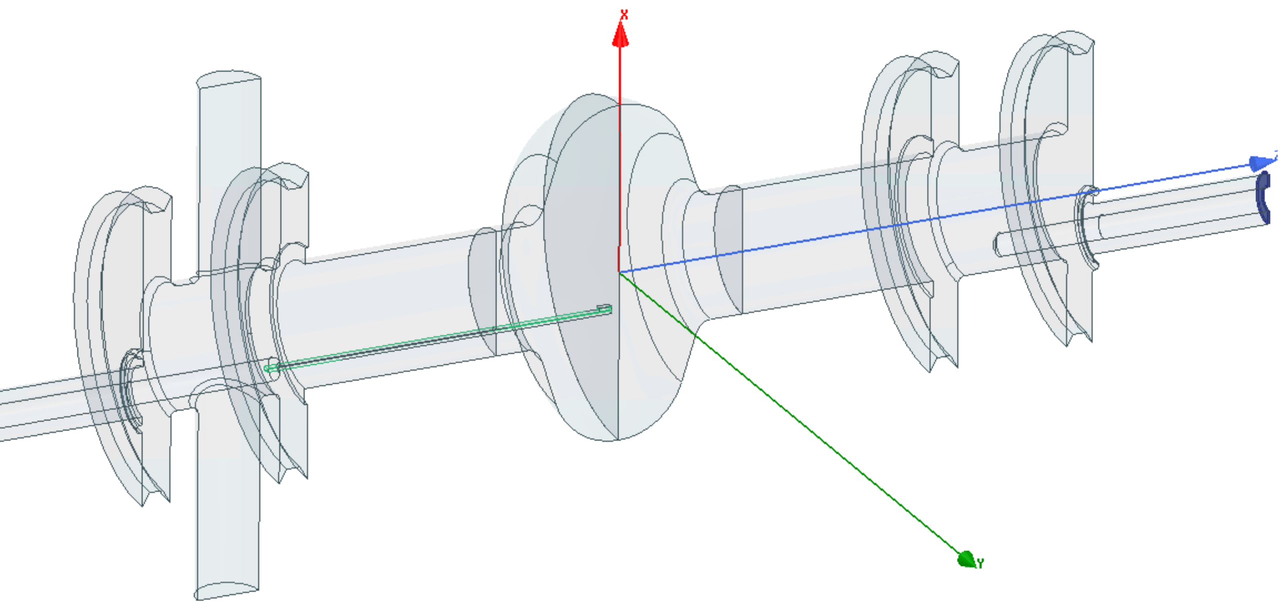
Everything worked!

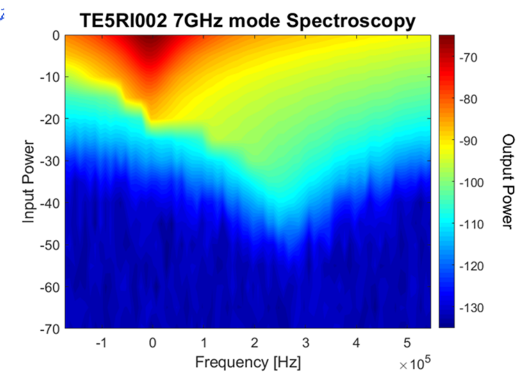
- ✓ Design
- ✓ Tuner operation
- ✓ Microwave scheme for matching the frequencies
- ✓ Actual data – first acquisition

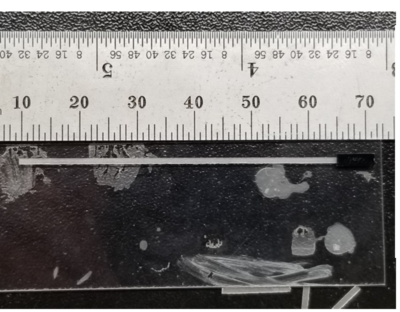




Integration with the transmon qubit







Prof. Robert McDermott

Chris Wilen

Dr. David Pappas

Applications: Quantum computing/physics

- 3D transmon - further coherence enhancement

- Quantum memory
  - Store the states longer (Fock and/or coherent states)

- Schrodinger cat-state based logical encoding
  - Photon lifetime increase directly improves coherence and achievable size and error rate (photon loss)

- How big of a ”cat” state can we create?

Summary

- Accelerator ultra-high Q microwave 3D cavity expertise can enable a qualitative jump on achievable photon lifetimes/coherence
  - Complex accelerators with hundreds of $Q > 10^{10}$ cavities are routine, $Q > 10^{11}$ is the state-of-the-art
- Very high Qs can be translated to ”quantum” regime
  - Demonstrated $\mathbf{Q > 3 \times 10^{10}}$, τ **~ 2 sec** at <20 mK, low photons
- Developing first immediate applications
  - Quantum physics – micro/macro boundary
  - 3D microwave quantum memory/qubits
  - Dark photon search with orders of magnitude improved sensitivity