



Superconducting Cavities for Quantum Computers

Alexander Romanenko

NAPAC'2019

6 Sep 2019

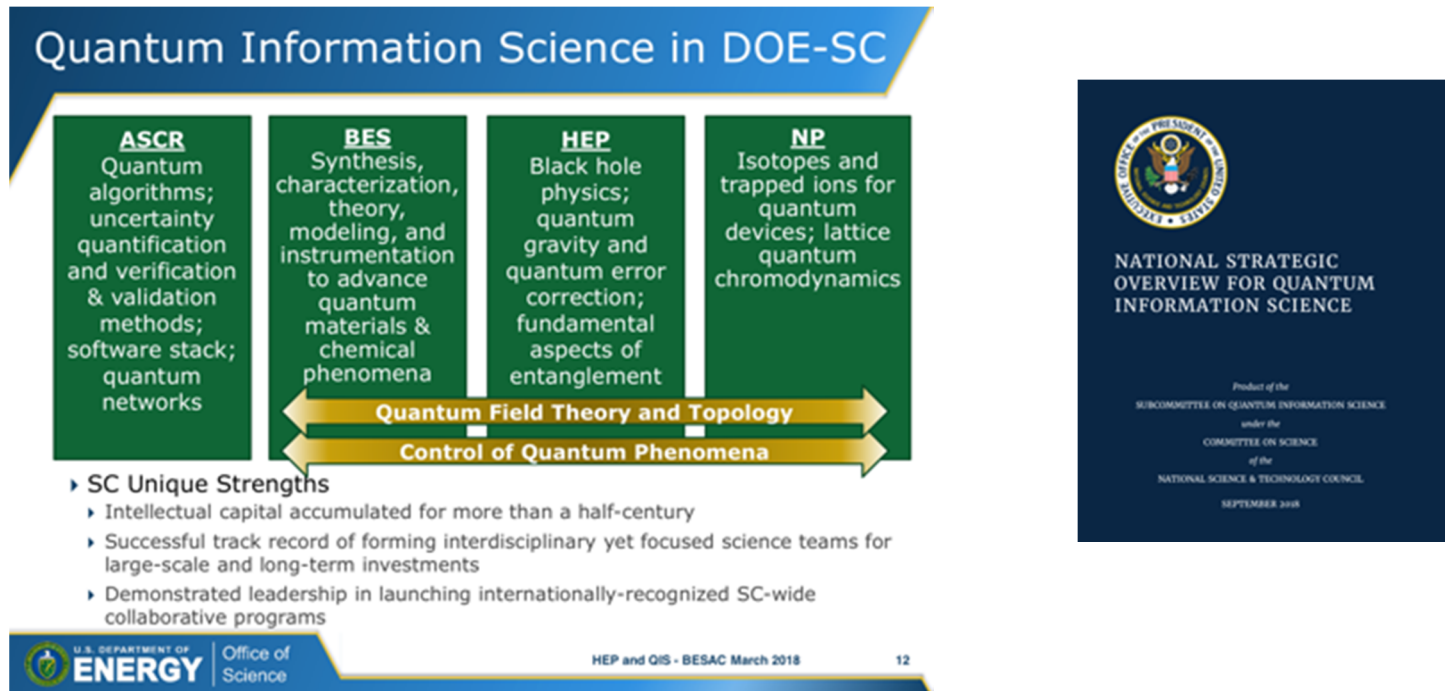
Outline

- 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 ($|0\rangle$, $|1\rangle$), 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 startups (e.g. Rigetti)
 - Trapped ions
 -

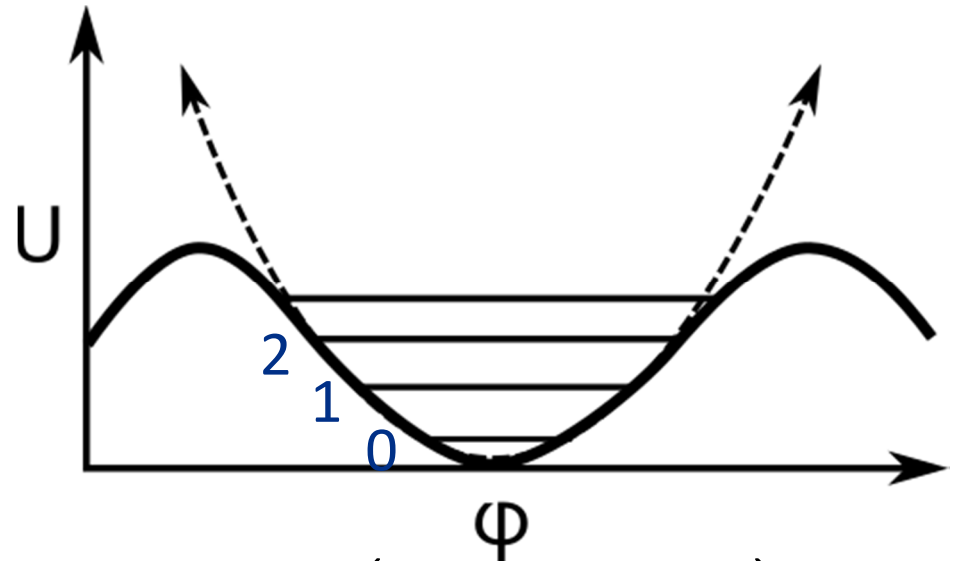
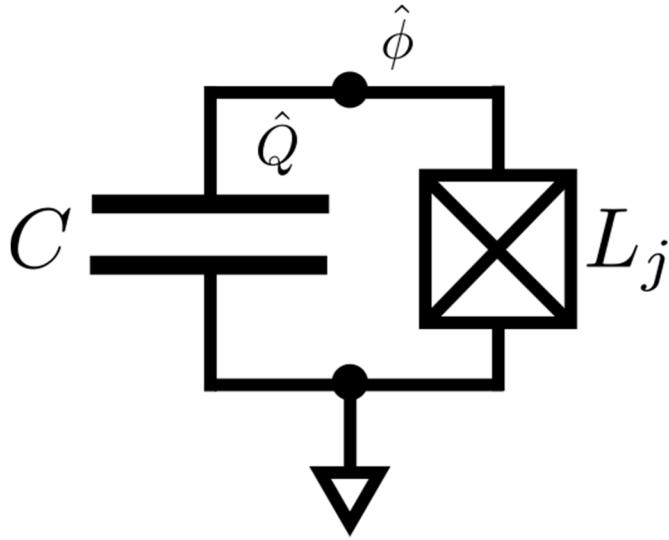
Department of Energy Enters Quantum



Fermilab: to date, 15 DOE awards and developing strategic partnerships for a DOE NQI center

Artificial Atom by a Josephson Junction

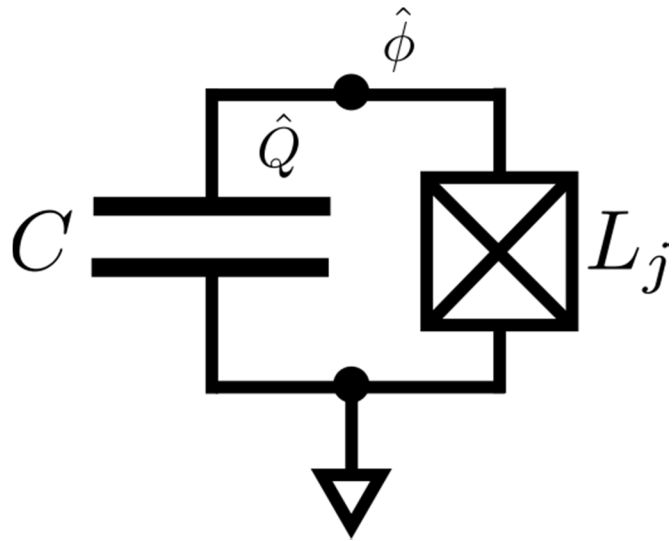
Courtesy of E. Holland



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

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

Artificial atom: Transmon

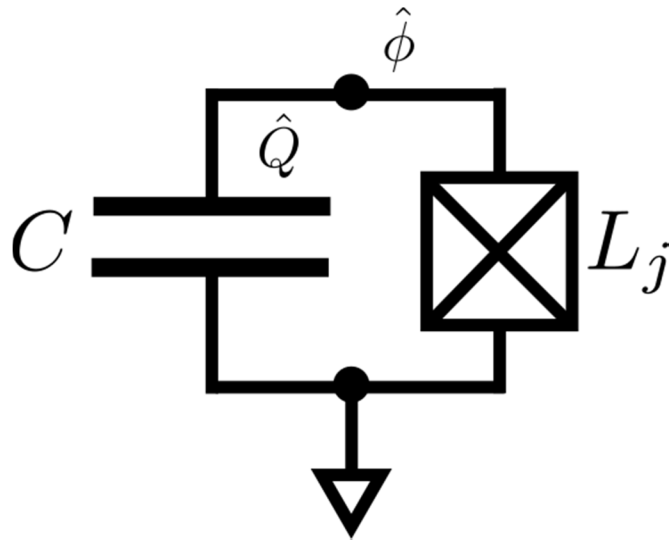


300 microns



Courtesy of E. Holland

Artificial atom: Transmon

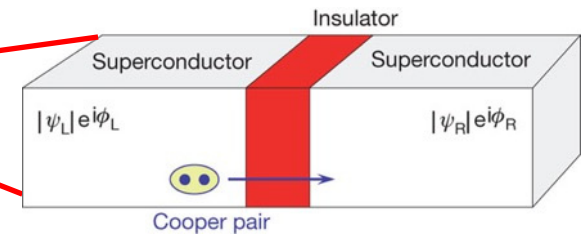


300 microns

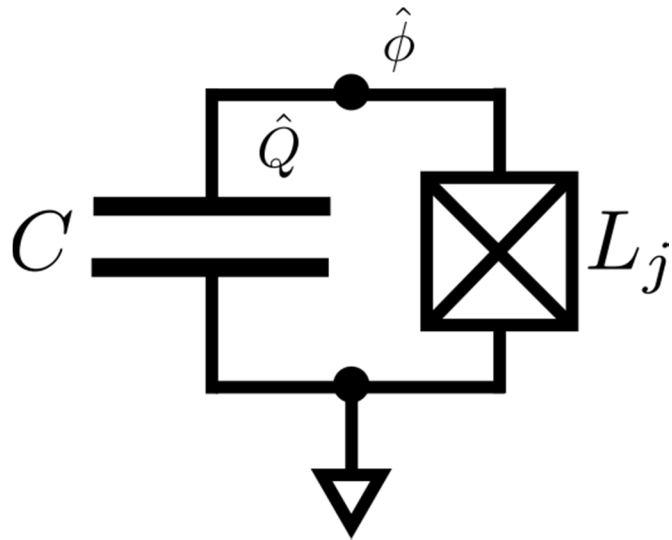
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Josephson Junction



Artificial atom: Transmon

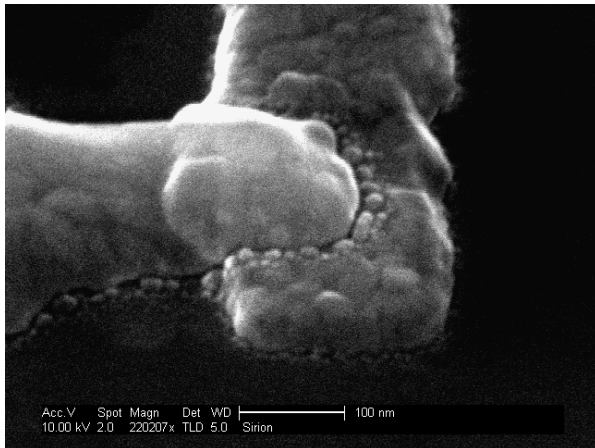
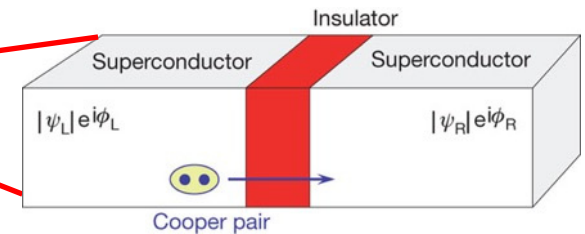


300 microns

Courtesy of E. Holland



Josephson Junction



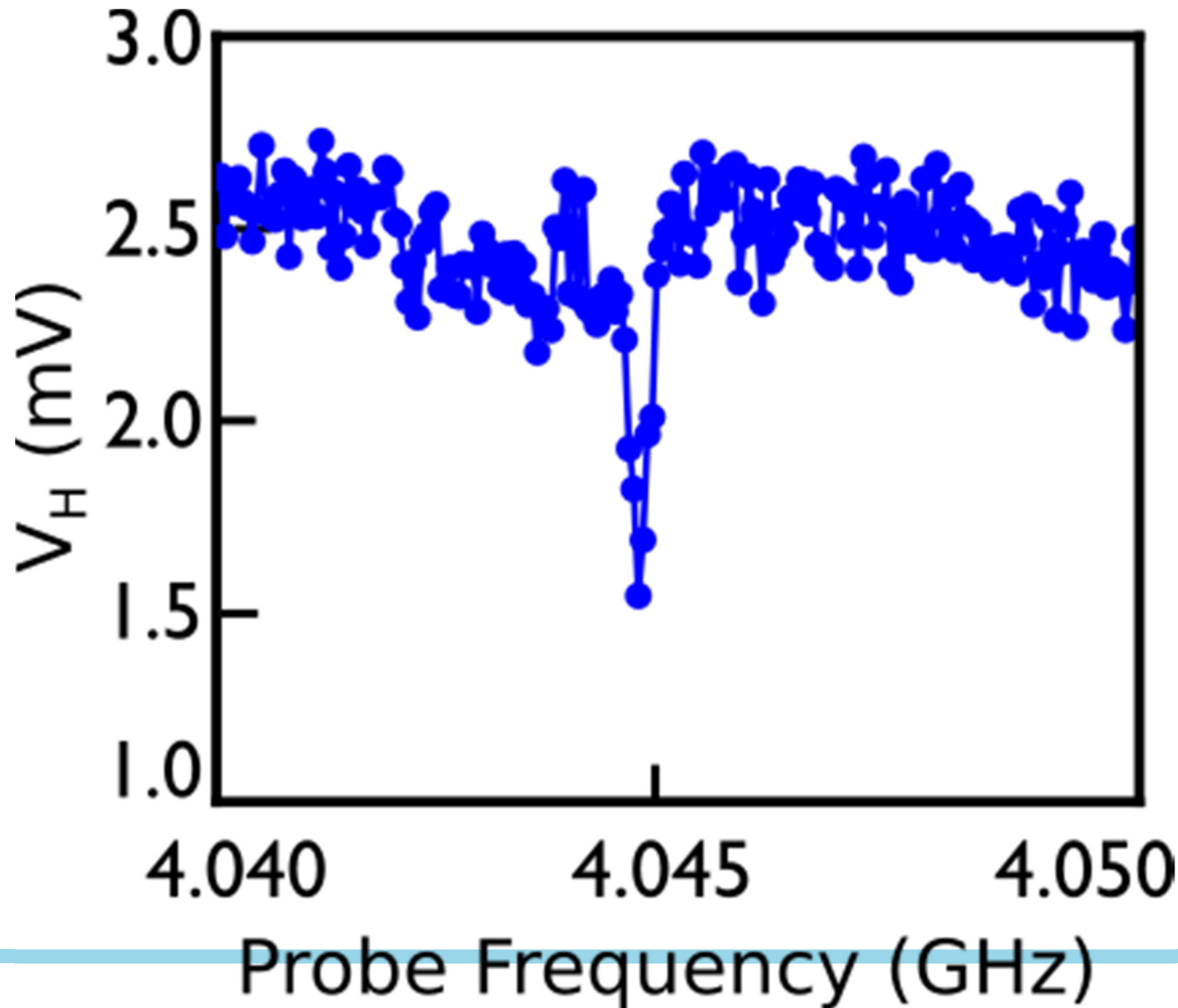
~10 trillion atoms

~1000 times Earth population

100 nanometers

Spectroscopy for First Energy Transition

Courtesy of E. Holland

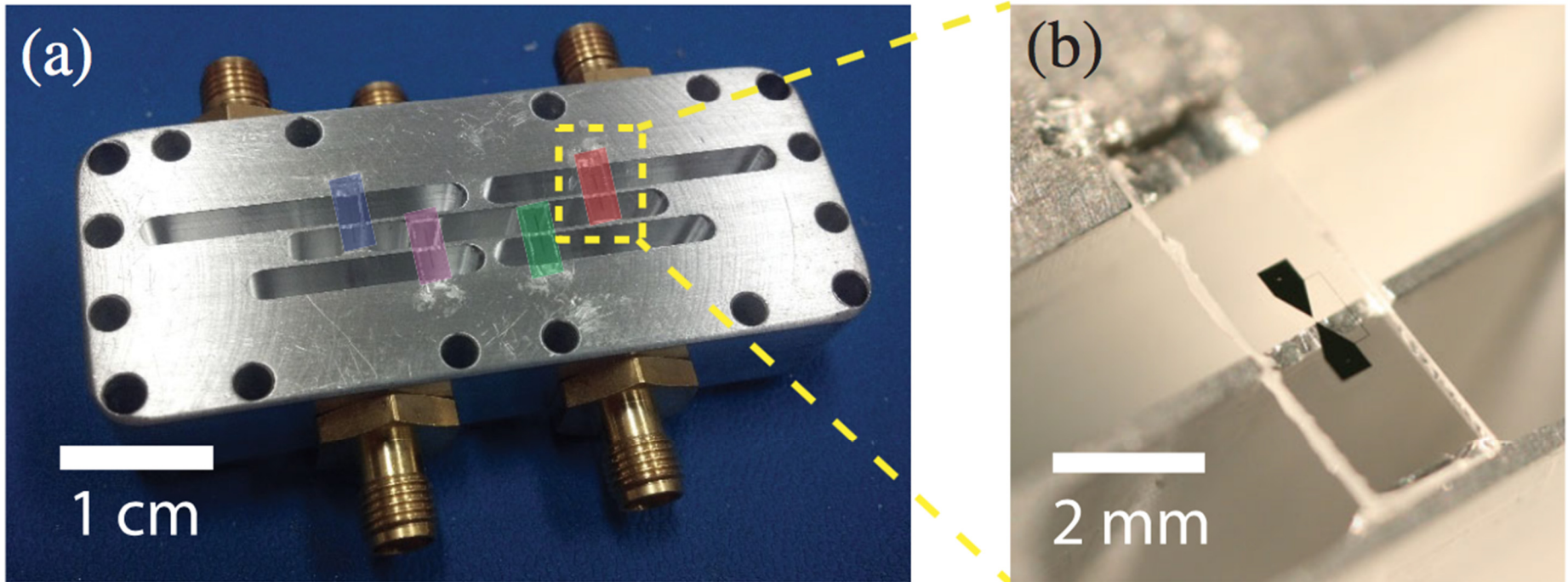


$$\omega a^\dagger a$$

Quantum Computing: 3D circuit QED architecture

State-of-the-art quality factors Q in quantum computing are $\sim 10^8$

Machined Aluminum host cavity



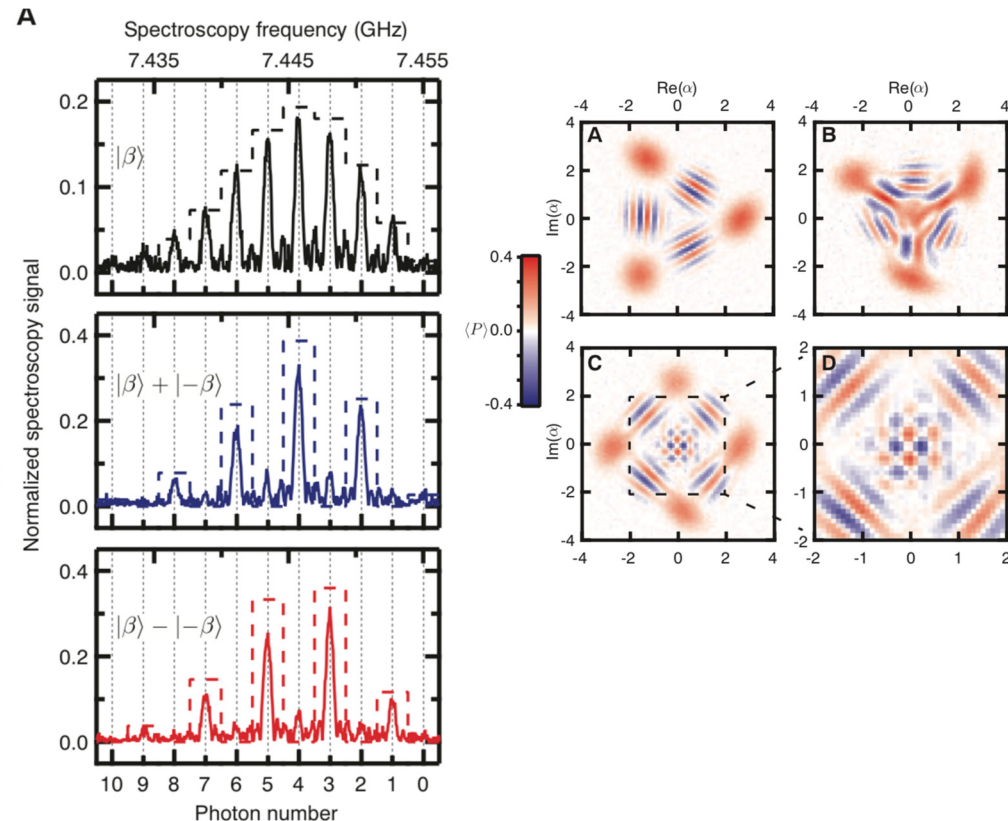
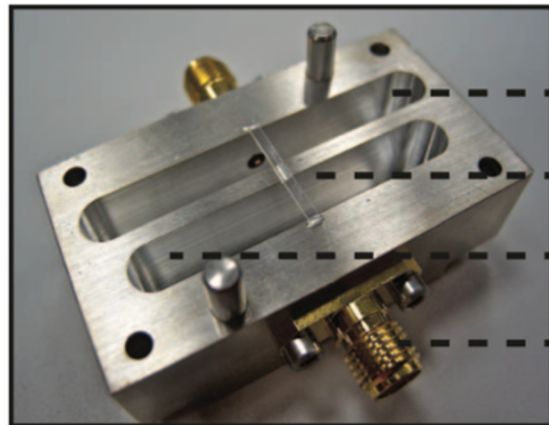
H. Paik et al, Phys. Rev. Lett. 117, 251502 (2016)

“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 Mazhar Mirrahimi,^{1,2} M. H. Devoret,¹ R. J. Schoelkopf¹



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

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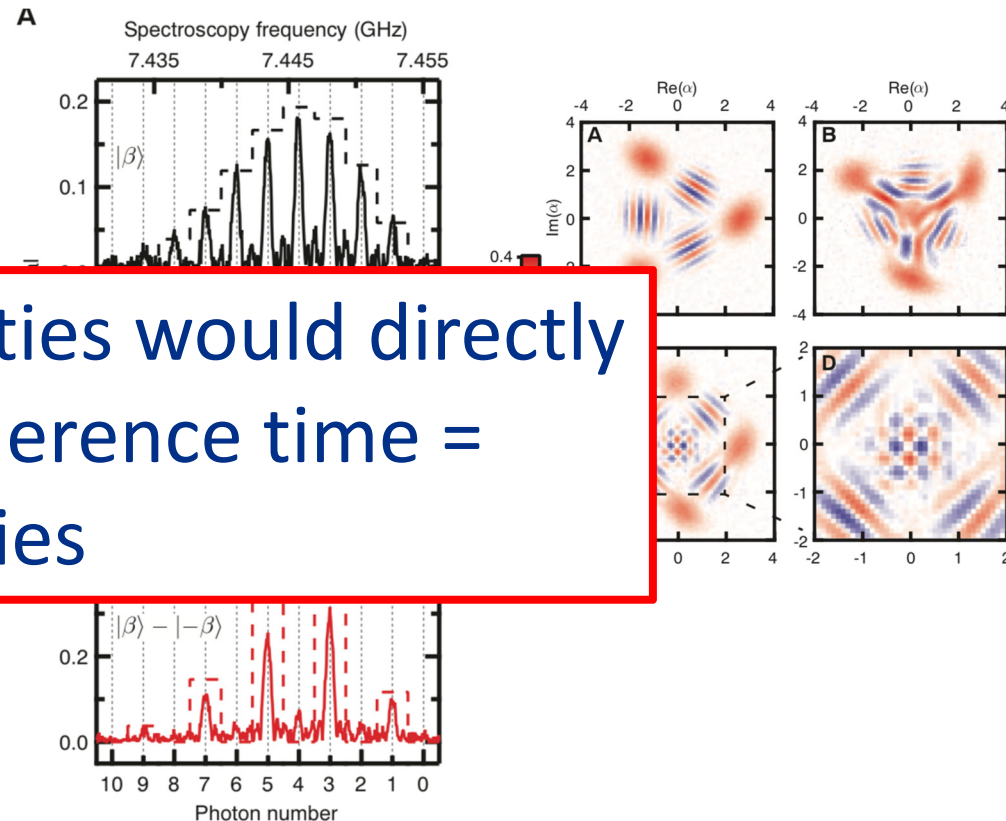
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— cavity coupler

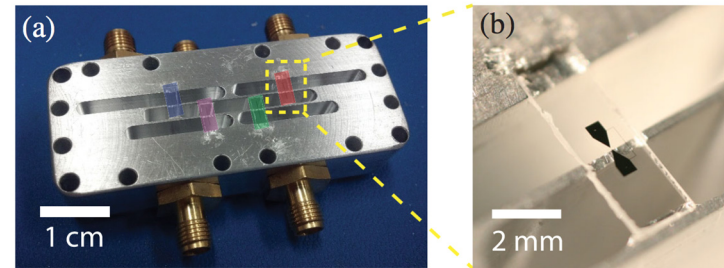
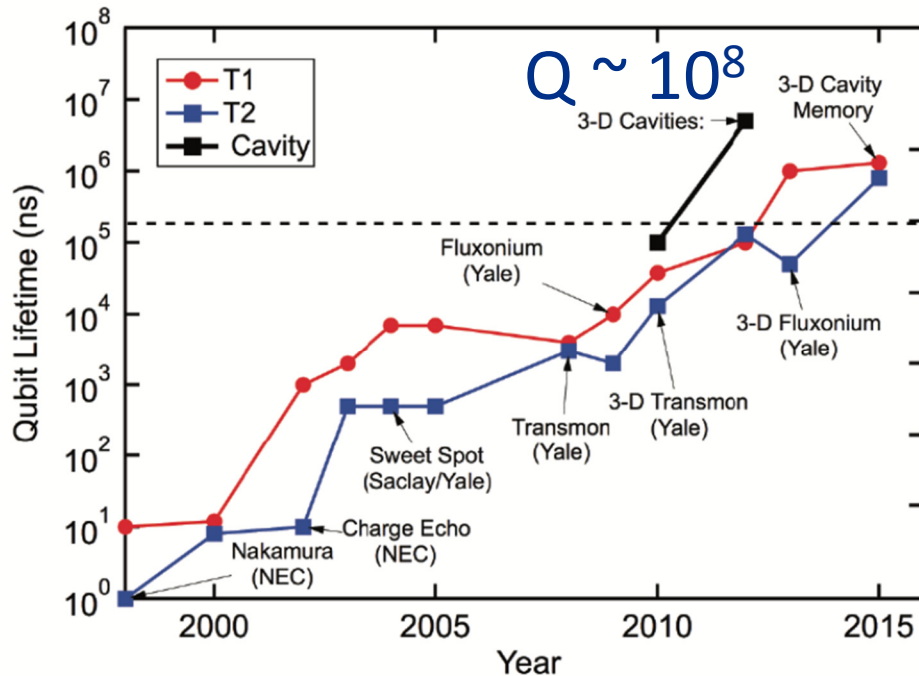
Higher Q cavities would directly boost the coherence time = new capabilities



- 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

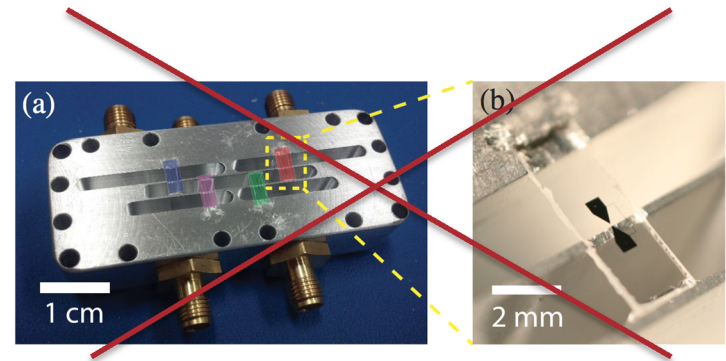
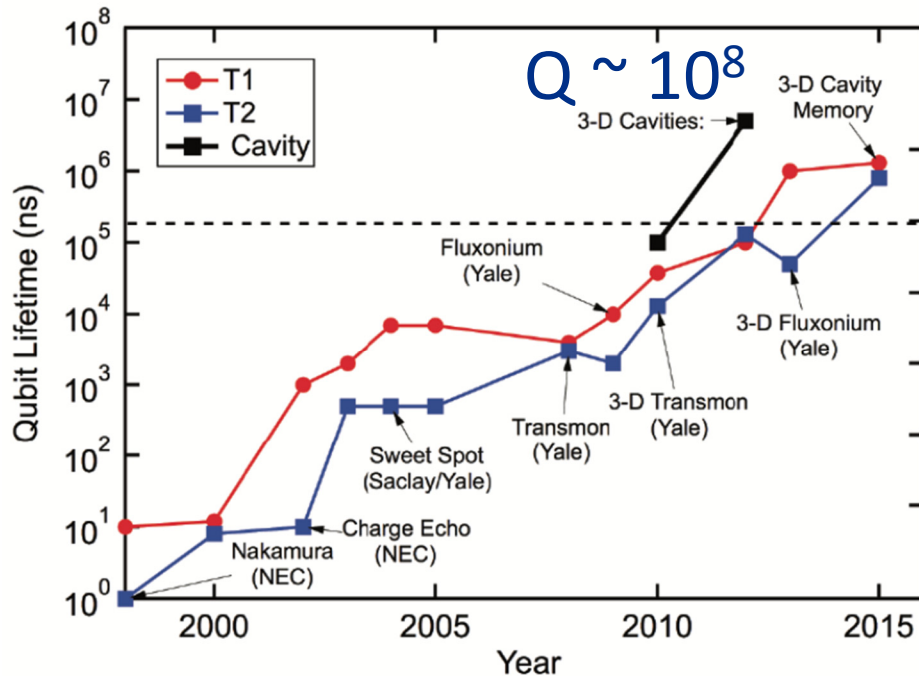
~10 msec photon lifetime/coherence is a record



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

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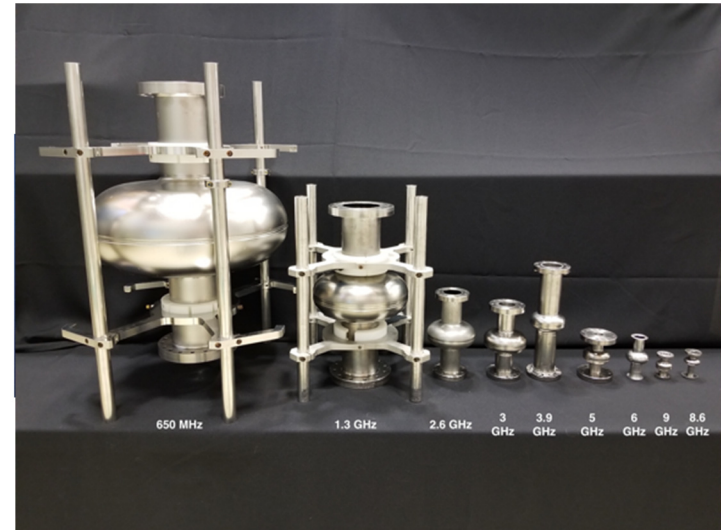
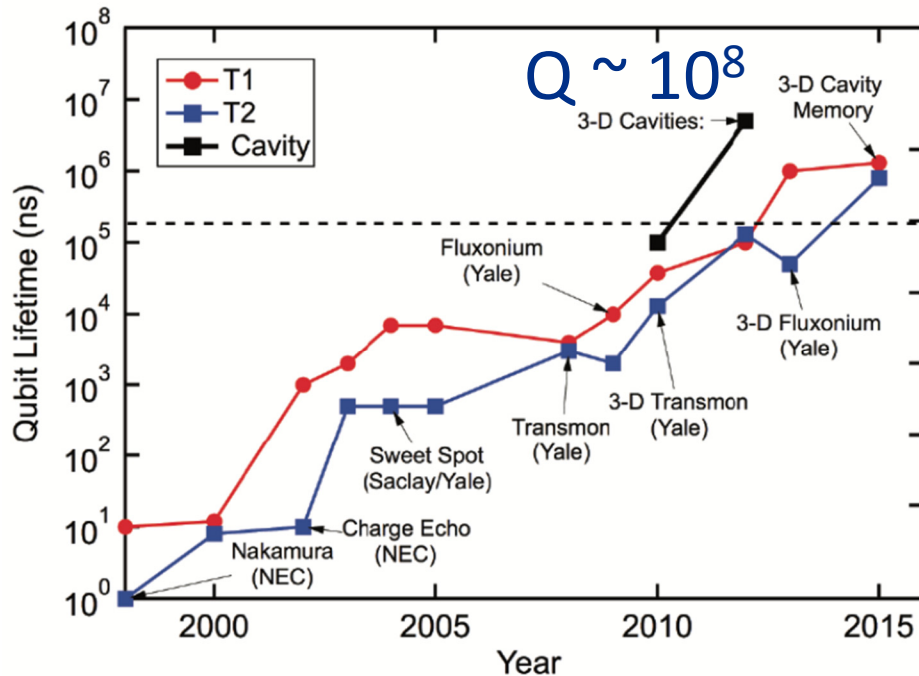
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1-cell Fermilab cavities of various frequencies

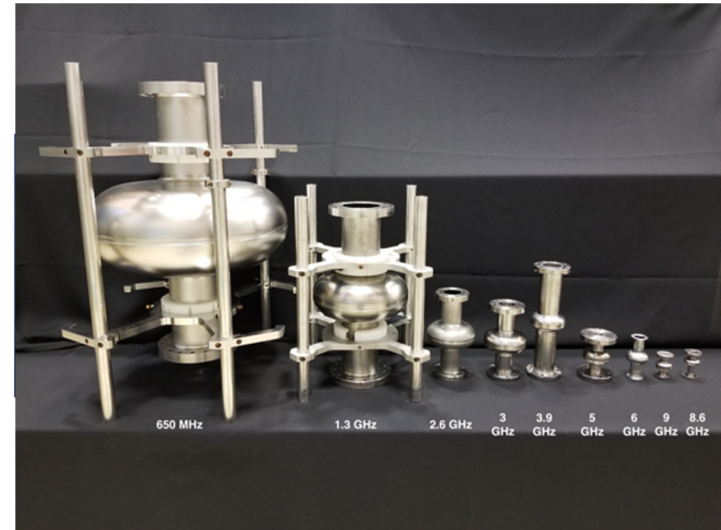
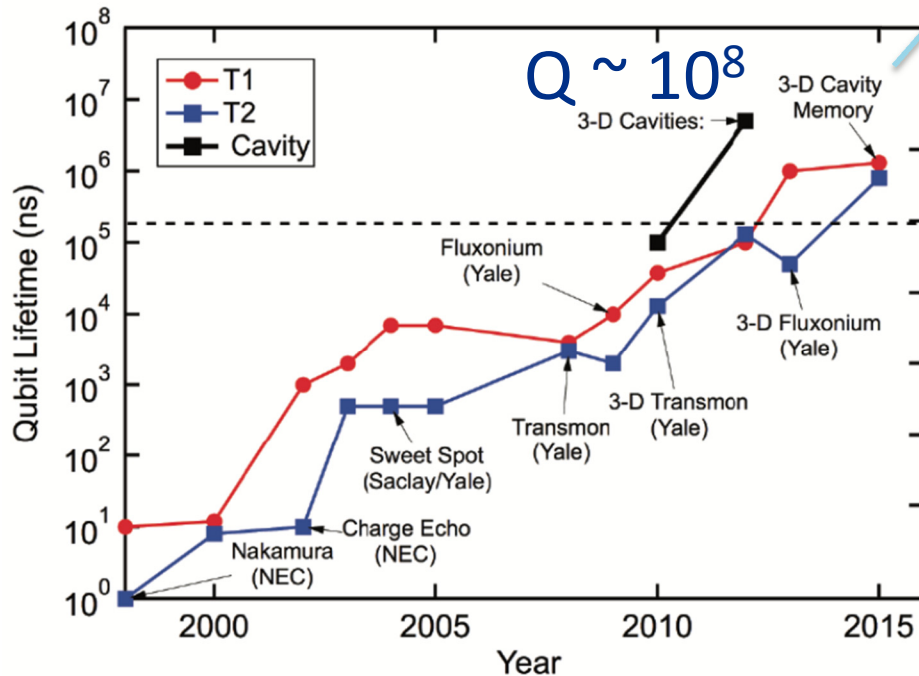
M. H. Devoret and R. J. Schoelkopf,
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High Q SRF 3D cavities for improved coherence



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

~10 msec photon lifetime/coherence is a record



1-cell Fermilab cavities of various frequencies

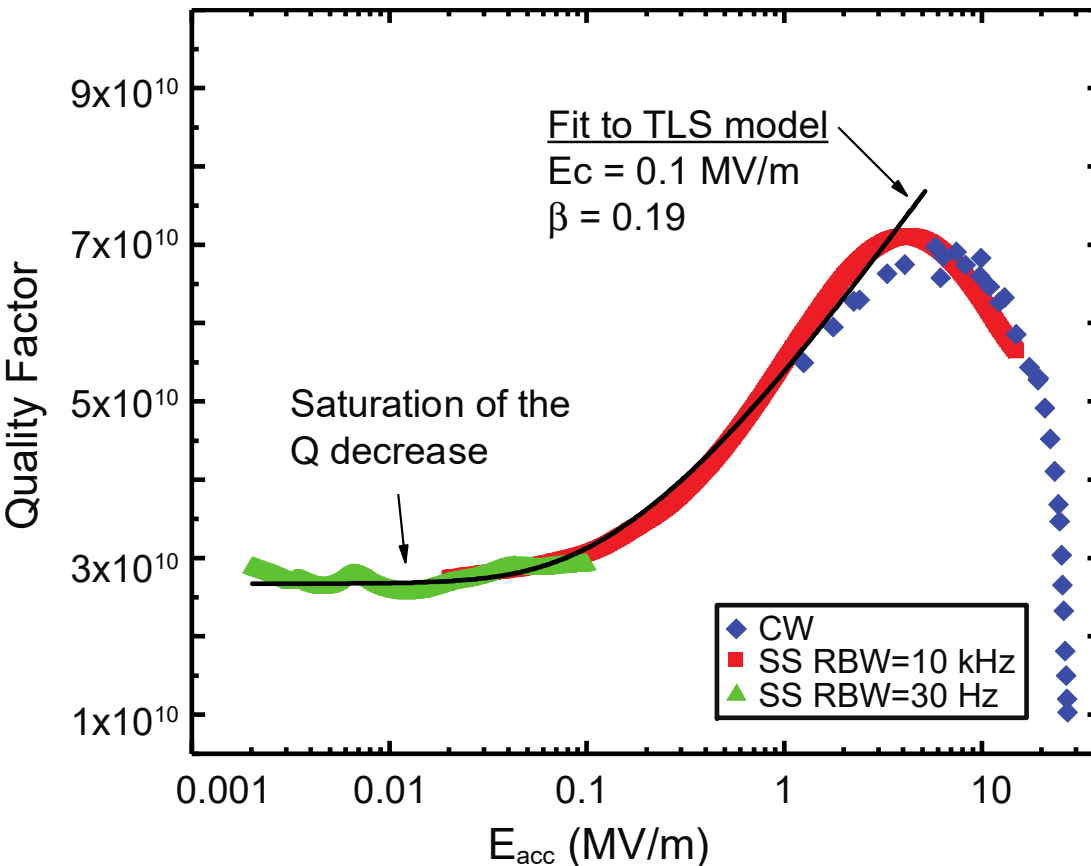
M. H. Devoret and R. J. Schoelkopf,
Science 339, 1169–1174 (2013) [SEP]

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 $T=1.5\text{K}$



Good news: low field Q saturates at $Q > 3 \times 10^{10}$

Now measured down to $\langle N \rangle < 1000$ photons

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

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

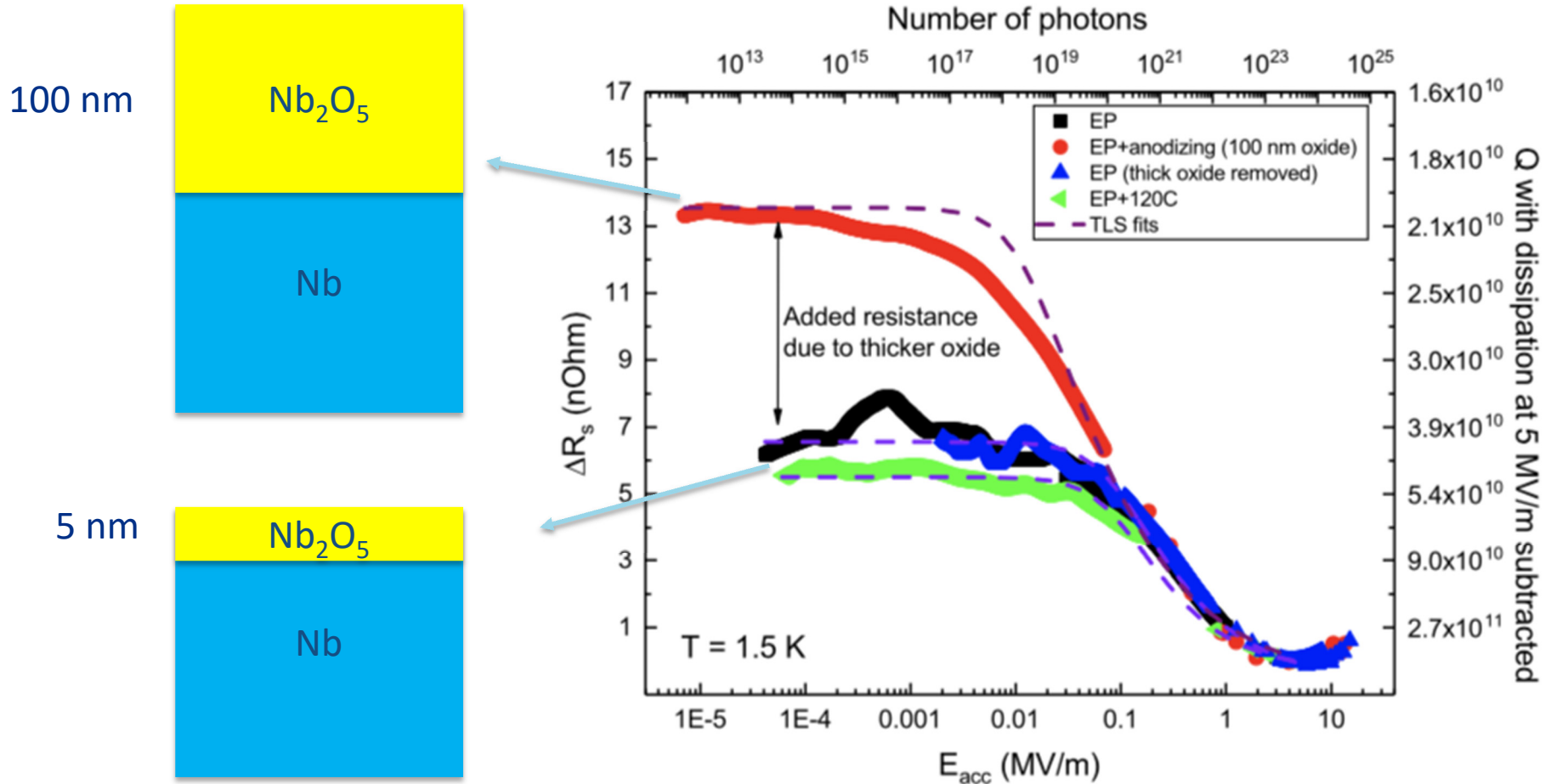
TABLE I. Summary of results for investigated 1.3 GHz elliptical shape cavities.

Cavity	Treatment	R_s (n Ω)		ΔR_s (n Ω)	TLS fit	
		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 μ m	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

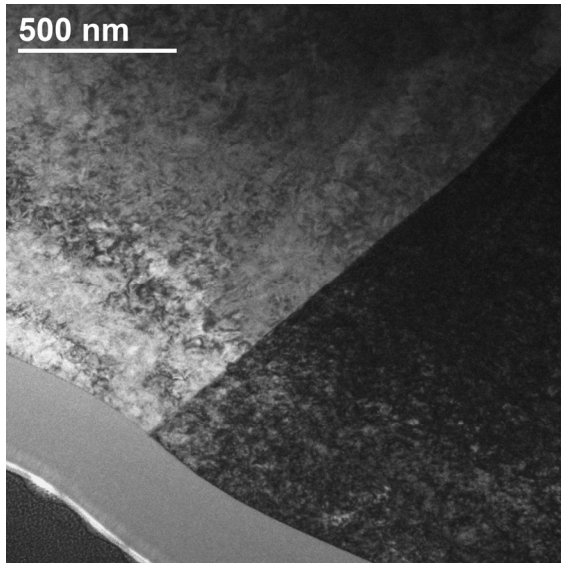
Oxide growth/change -> strong increase in very low field dissipation

Growing natural niobium oxide -> low field Q degrades

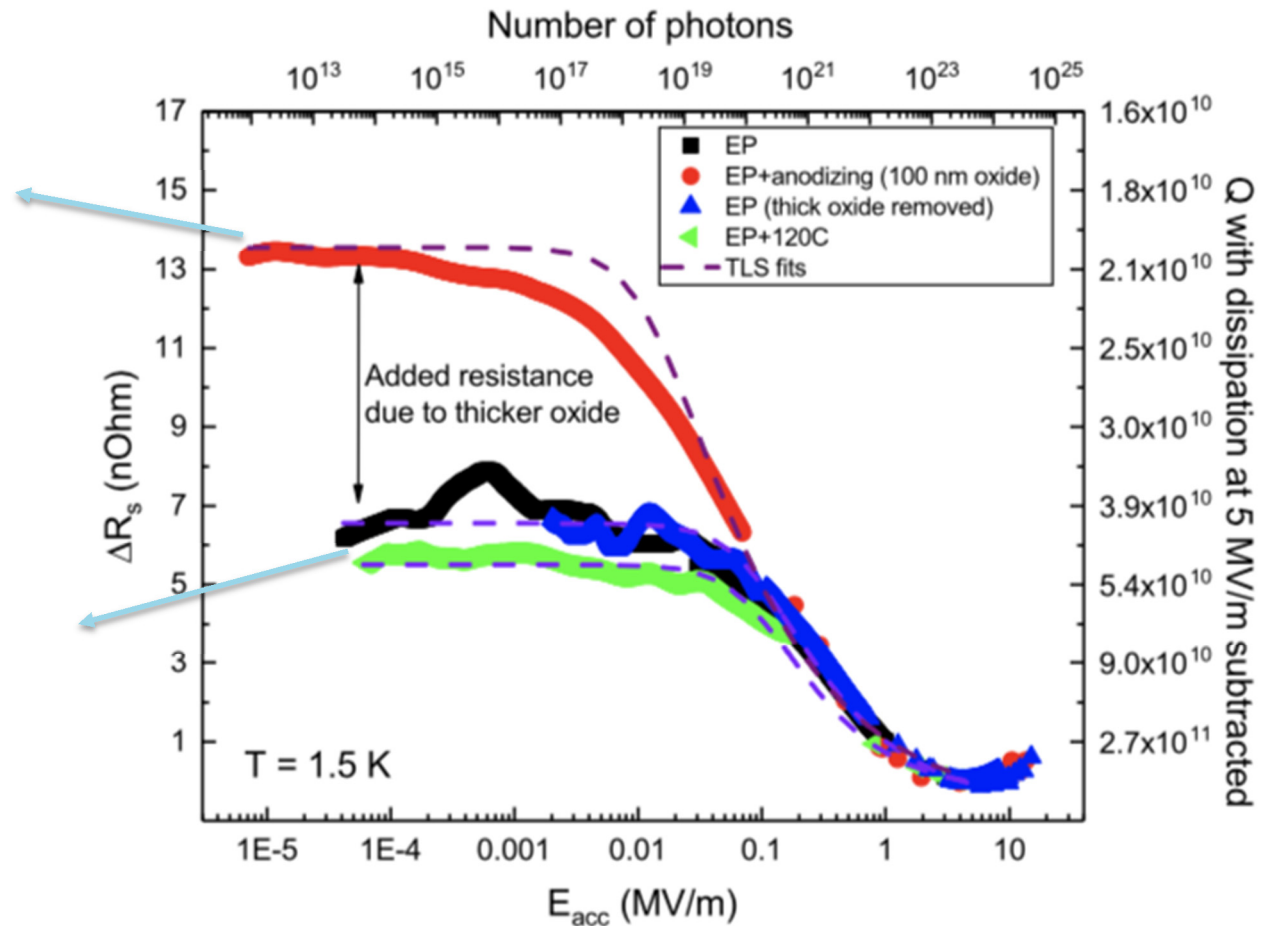
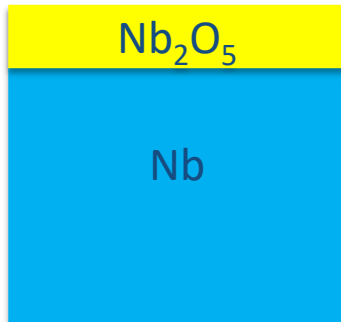


A. Romanenko and D. I. Schuster, Phys. Rev. Lett. **119**, 264801 (2017)

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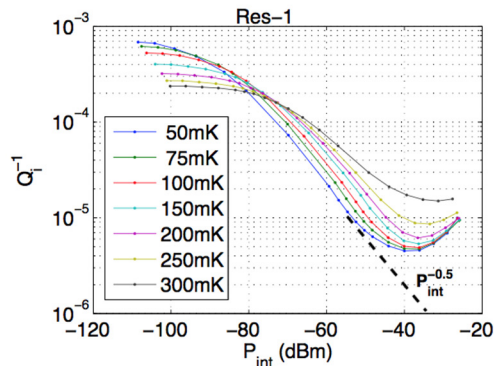


5 nm

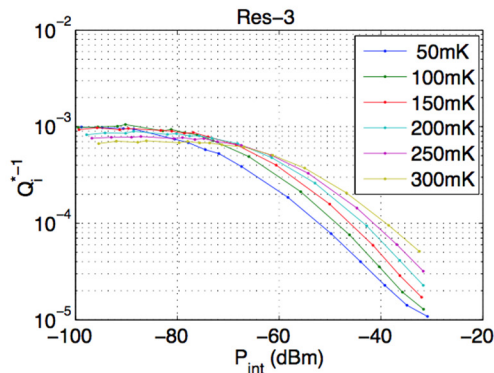


A. Romanenko and D. I. Schuster, Phys. Rev. Lett. **119**, 264801 (2017)

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

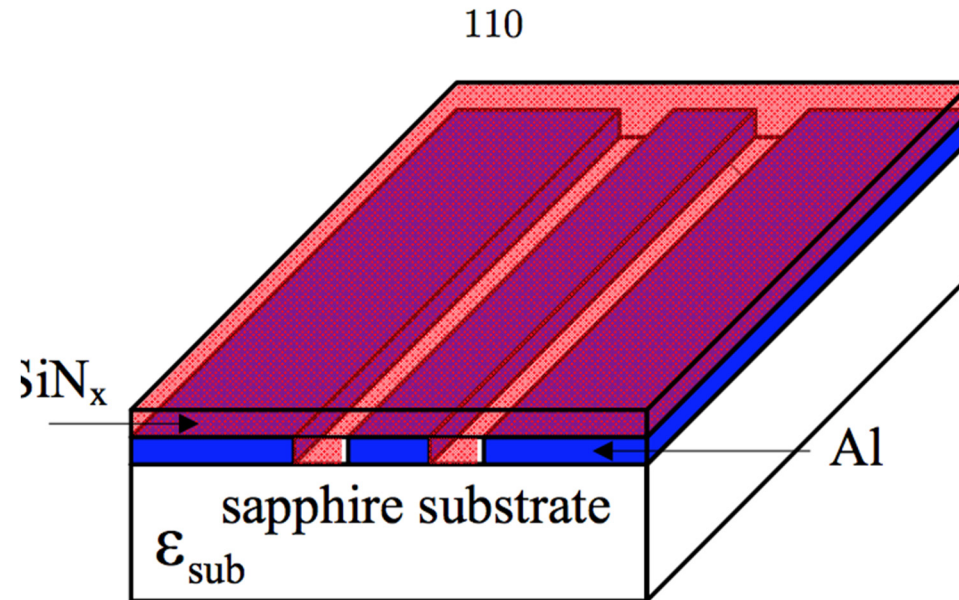


(a)



(c)

Two level systems in the dielectric as a cause

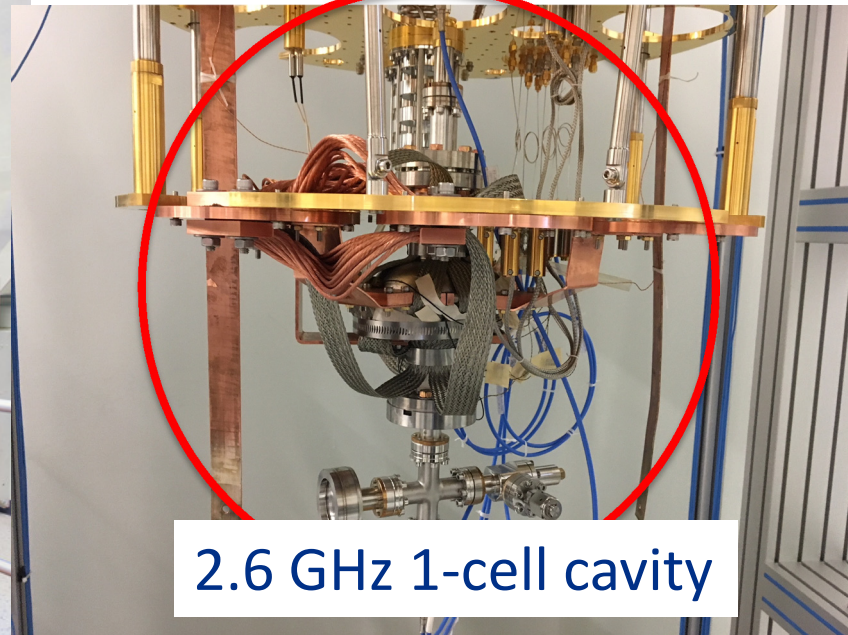
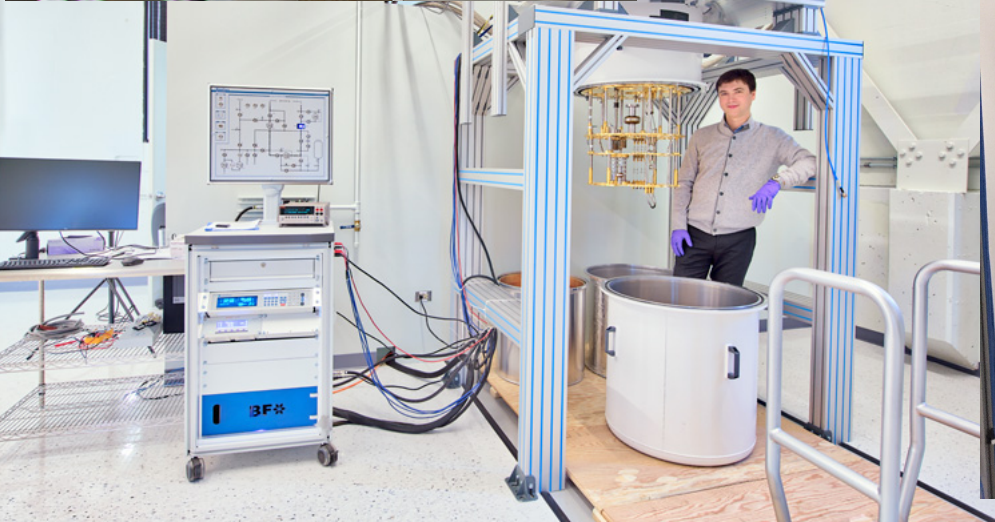


J. Martinis et al, Phys. Rev. Lett. 95, 210503 (2005)

J. Gao, PhD Thesis, Caltech, 2008

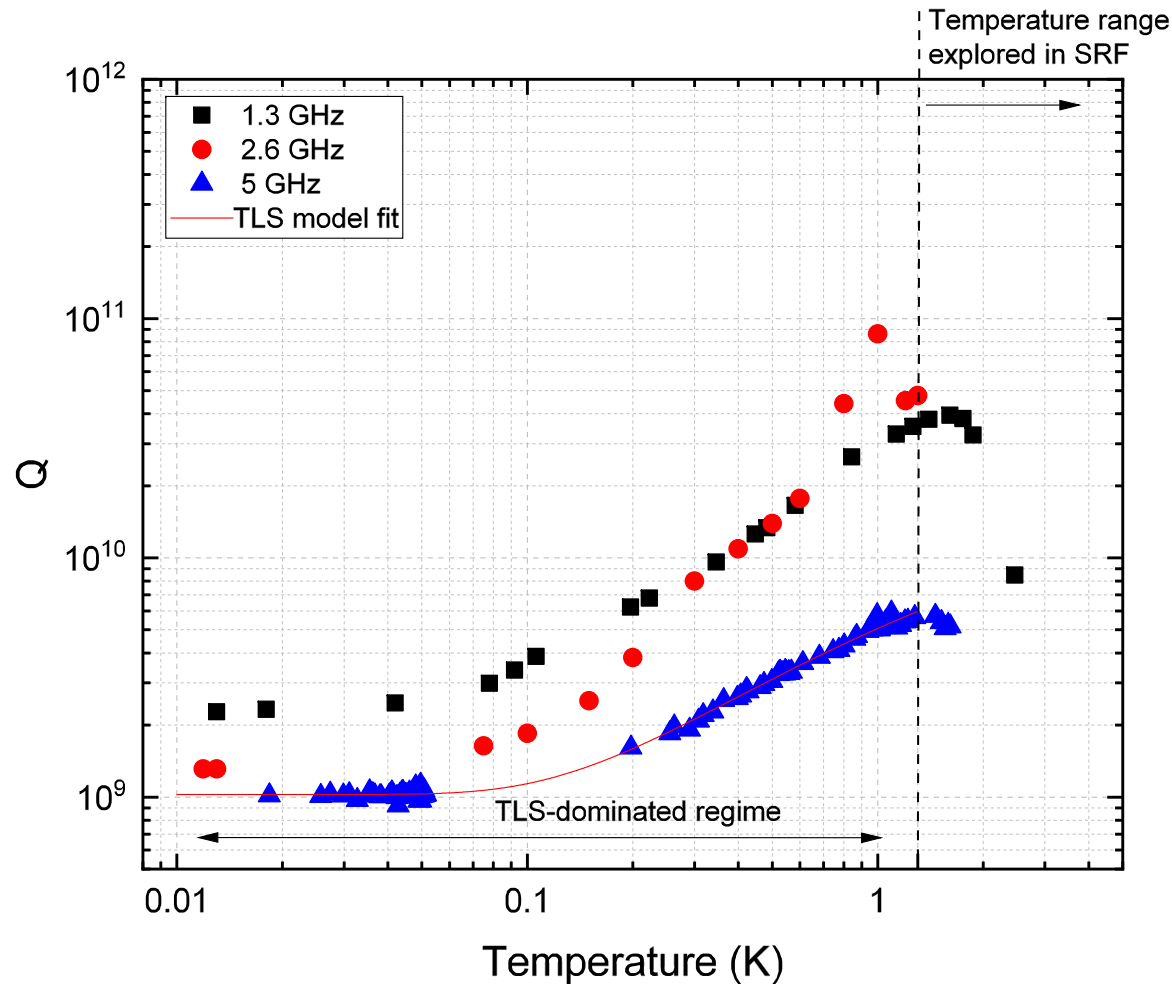
J. Zmuidzinas, Annu. Rev. Condens. Matter Phys. 2012

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



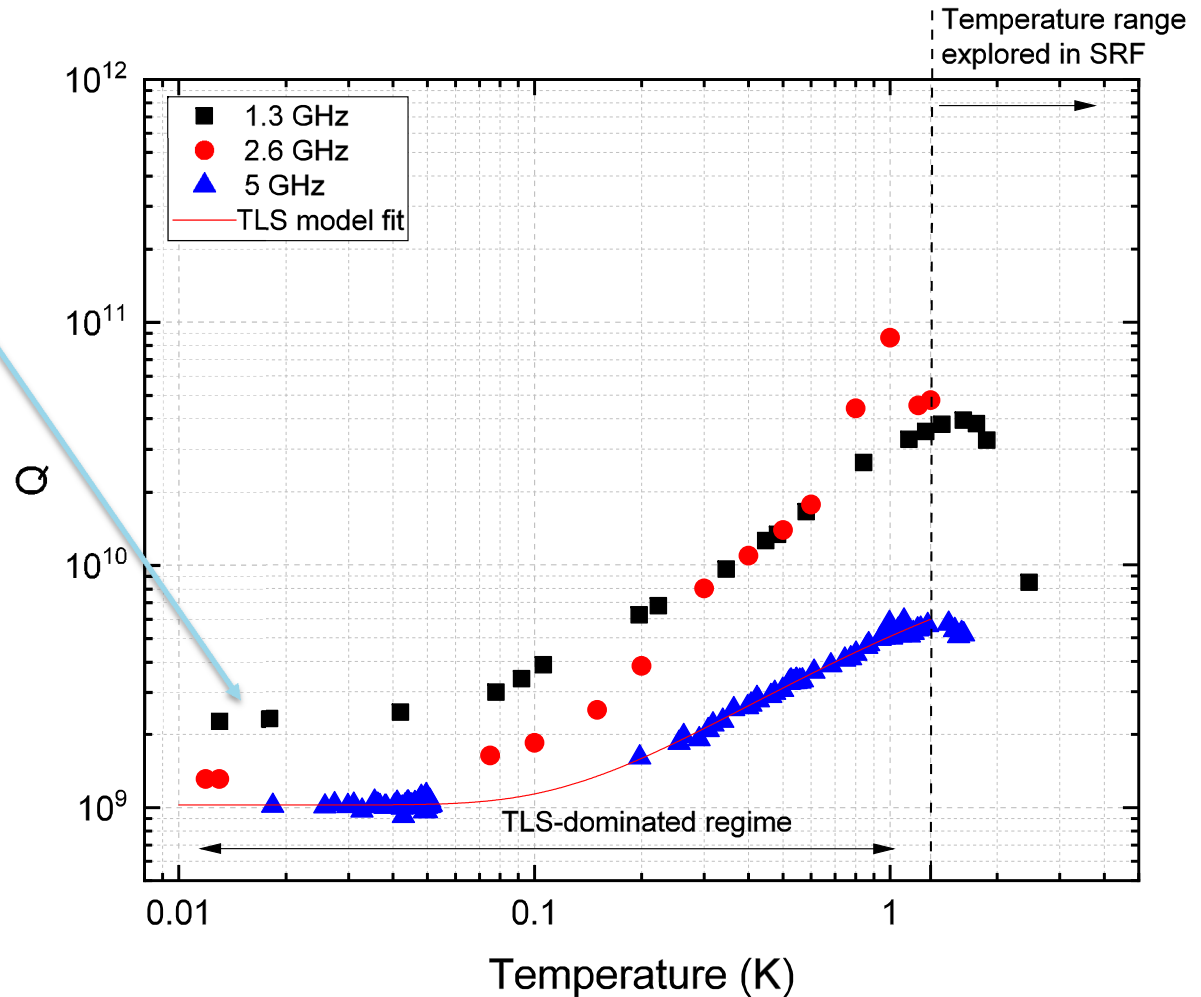
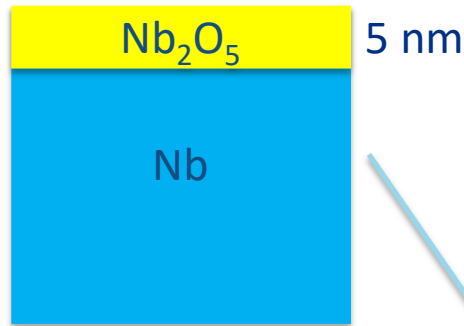
2.6 GHz 1-cell cavity

Record high Q in quantum regime at first run



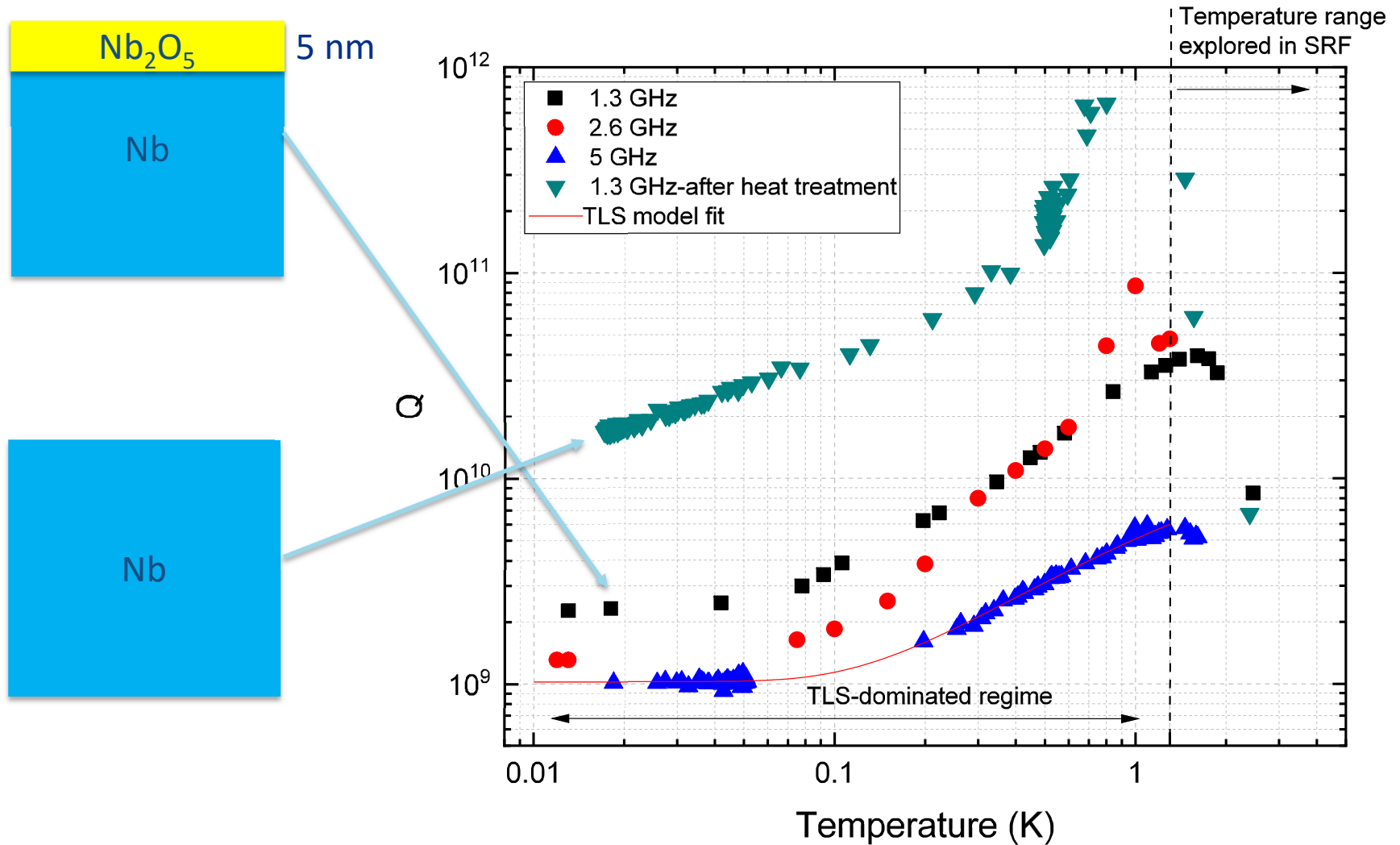
A. Romanenko, R. Pilipenko, S. Zorzetti, D. Frolov, M. Awida, S. Posen, A. Grassellino, arXiv:1810.03703

Material treatment to suppress TLS dissipation



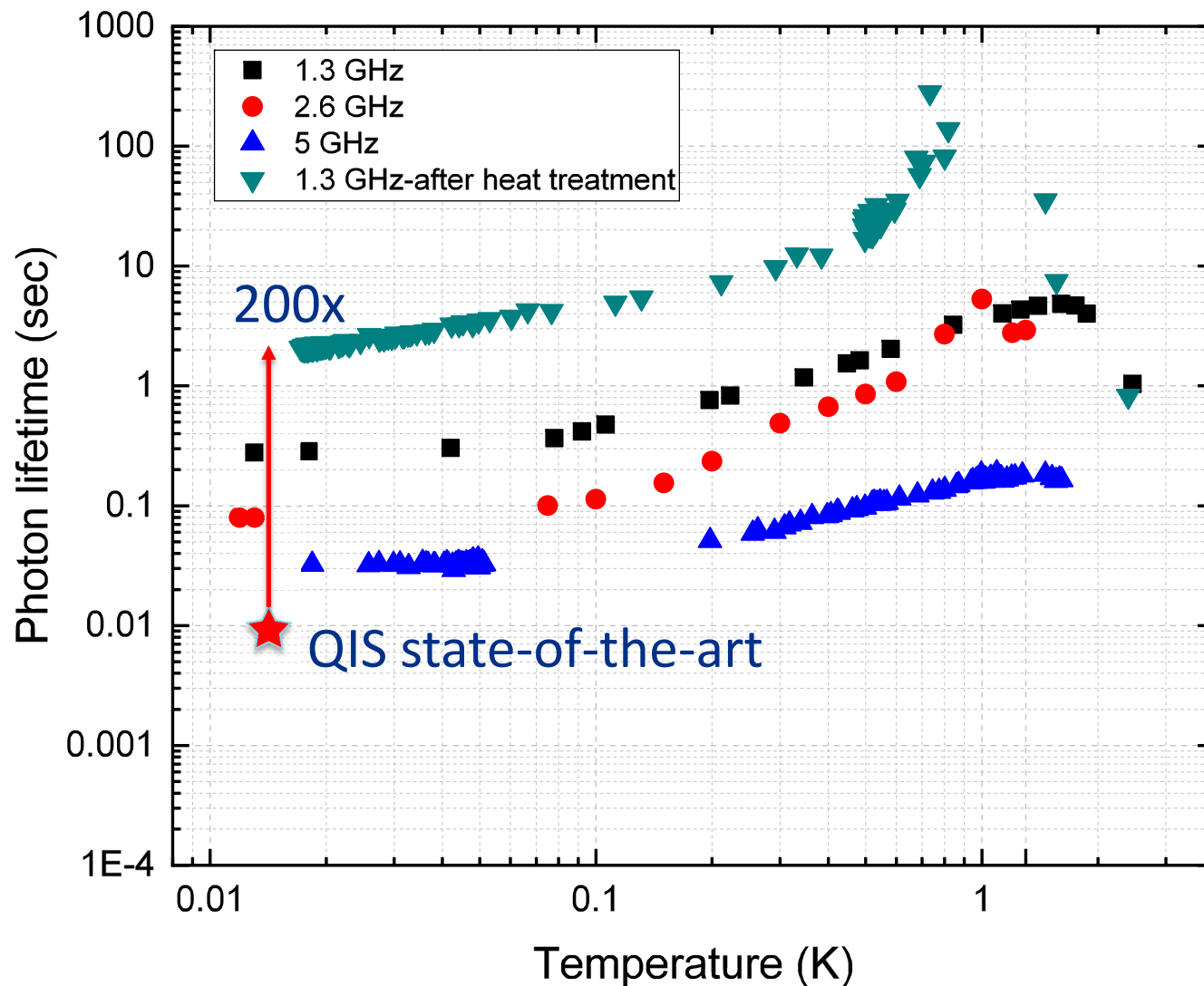
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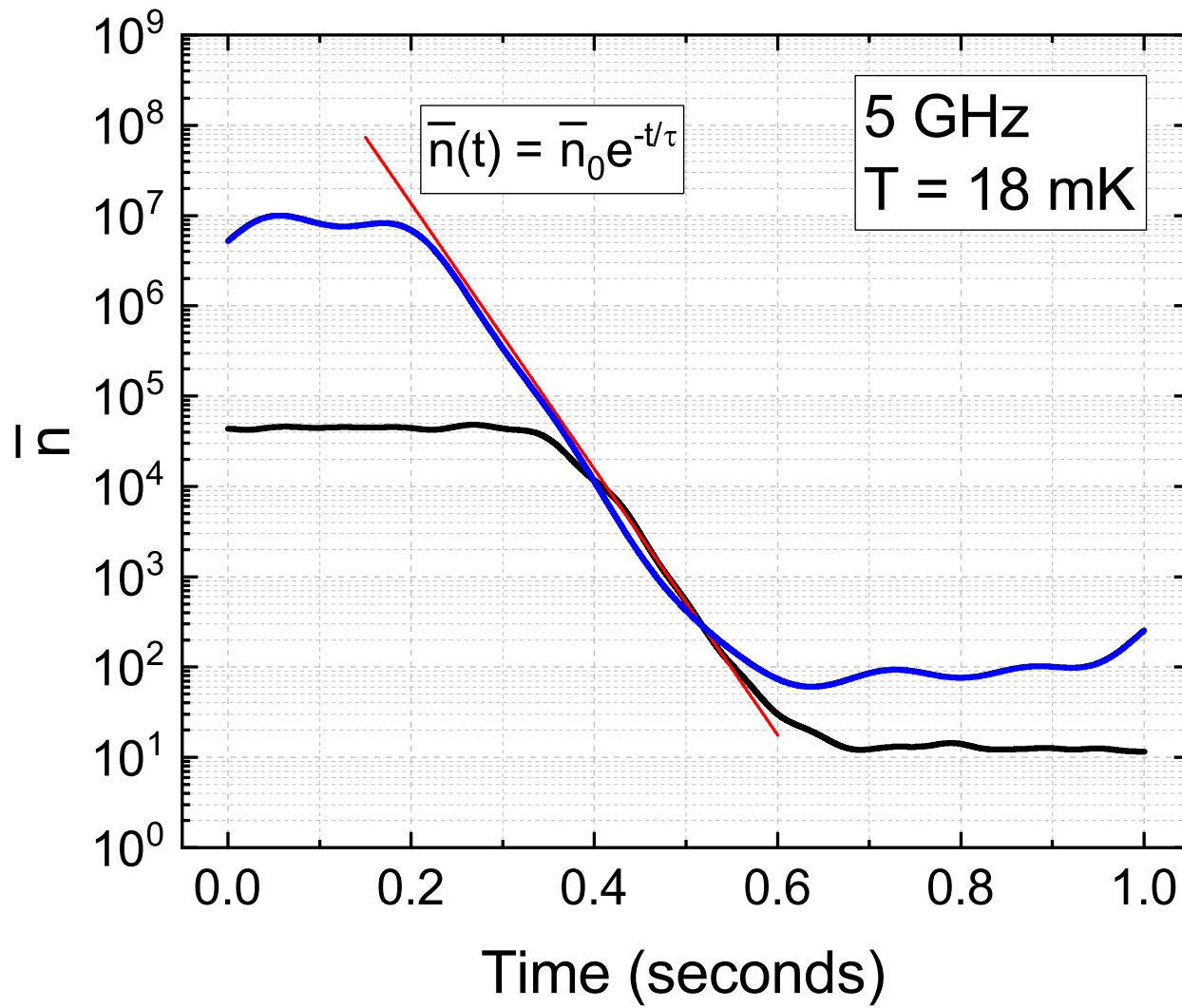
A. Romanenko, R. Pilipenko, S. Zorzetti, D. Frolov, M. Awida, S. Posen, A. Grassellino, arXiv:1810.03703

Record high photon lifetimes achieved



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

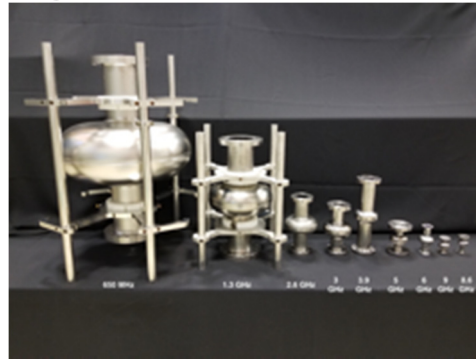
Decays show no $Q(n)$ dependence



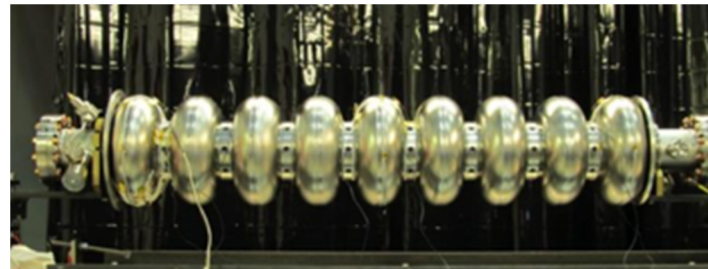
- Immediate applications

Cross Cutting: Quantum to Classical Transition

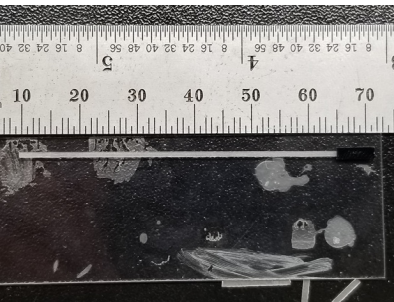
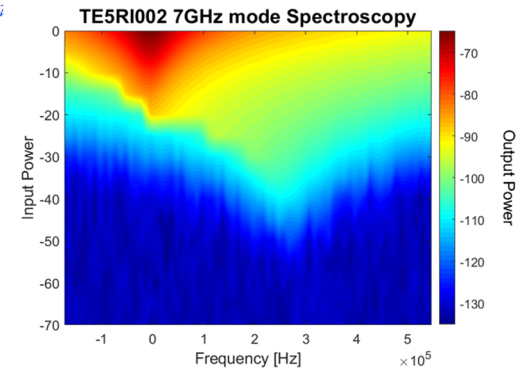
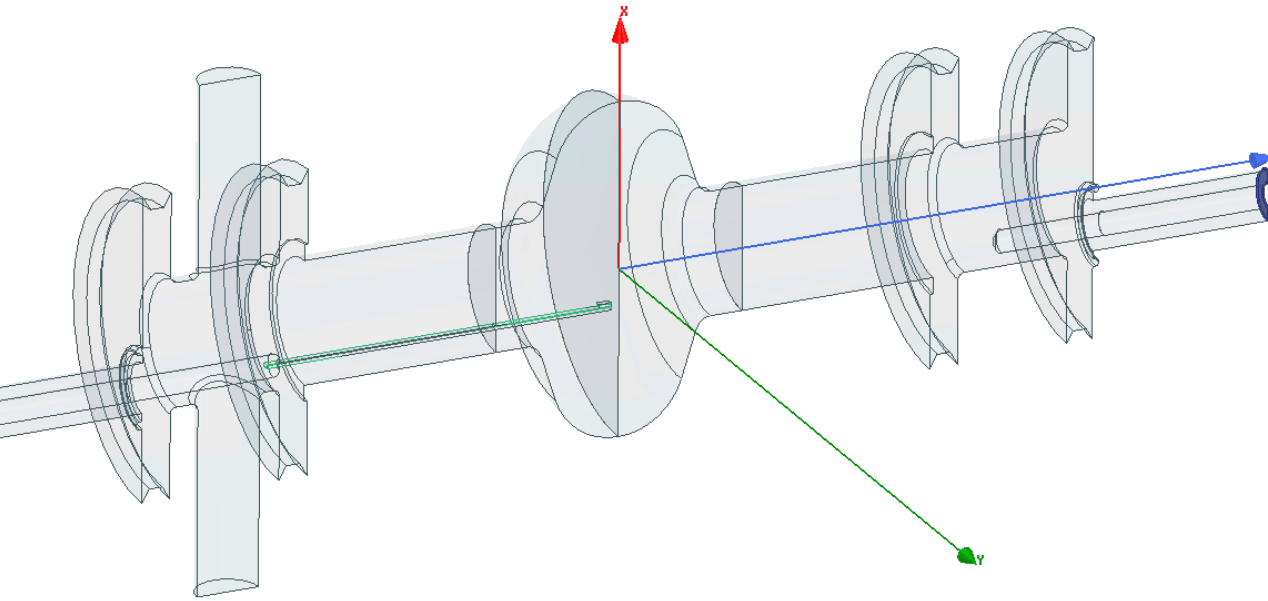
- How large of a quantum superposition state can we make in a single SRF cavity?
 - Consequence: largest effective number of qubits per module.



- How large of a macroscopic system can we make quantum?
 - Consequence: determine the physical size limits for quantum technologies (computers/processors/networks).



Integration with the transmon qubit



Prof. Robert McDermott
Chris Wilen

NIST

Dr. David Pappas



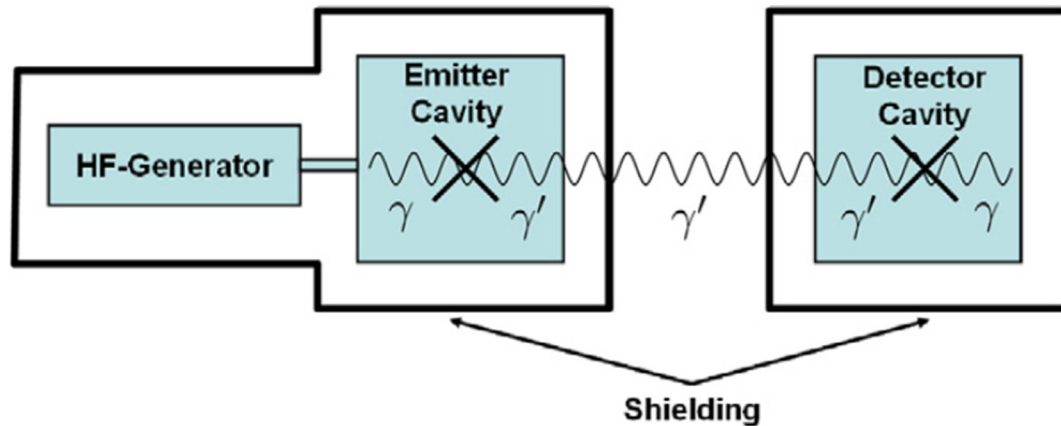
Dark sector search

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)

Looking for hidden paraphotons



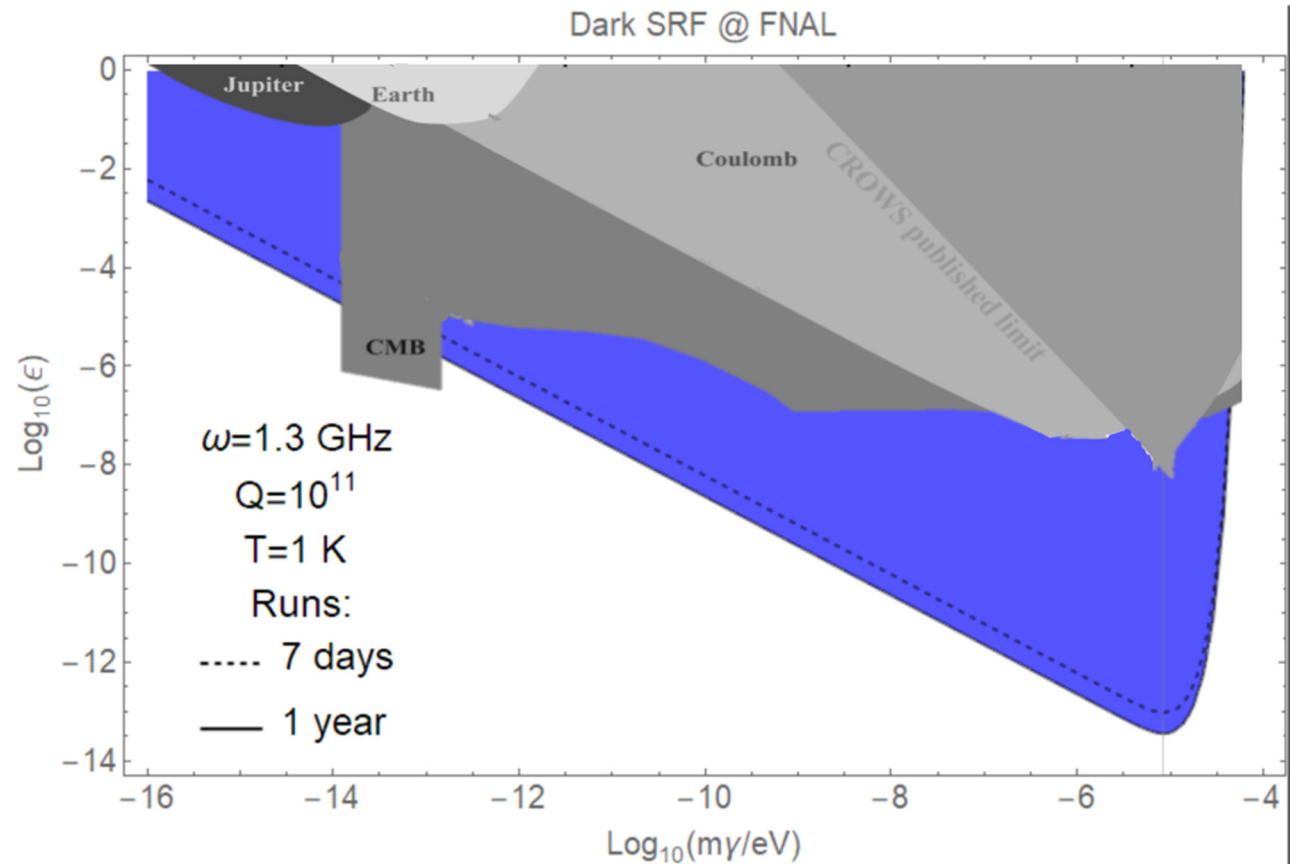
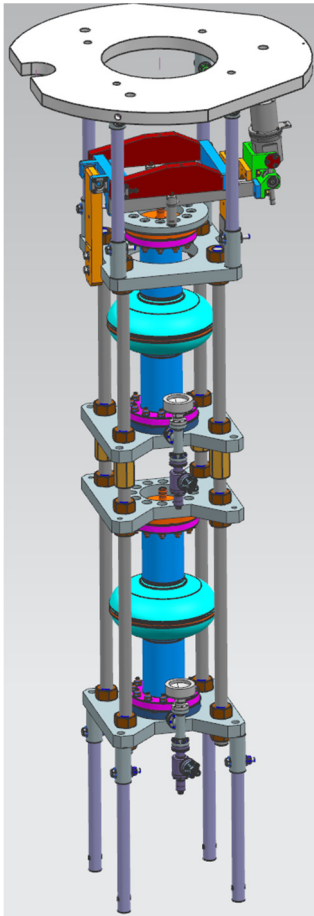
$Q_{\text{DET}}, Q_{\text{EM}} < 10^5$ so far used

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

$Q_{\text{DET}}, Q_{\text{EM}} > 10^{10}$ 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

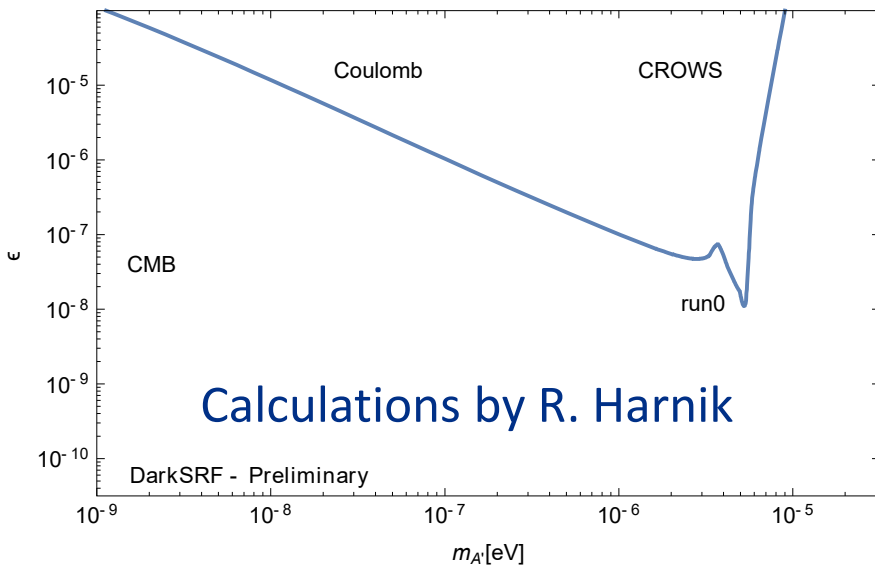


First test run has been accomplished

Dark SRF: “Run 0” has been successful

Everything worked!

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



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 **$Q > 3 \times 10^{10}$** , **$\tau \sim 2$ 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