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R&D of High-coherence Superconducting Quantum Systems

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Introduction

✓ At Fermilab we build and we operate accelerators for HEP

✓ Lately we started developing technology for quantum information science

✓ Accelerator technology can be applied to other scientific areas
  → **High-coherence superconducting devices**

✓ <u>A similar model can be adopted by ILC laboratory as well!</u>

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Quantum computing and qubits

Quantum computing

- Basic idea is to use "qubits" instead of bits
  - 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
  - …..

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Resonators: not yet qubits

* If we take a single resonant mode of any resonator, it looks like a harmonic oscillator
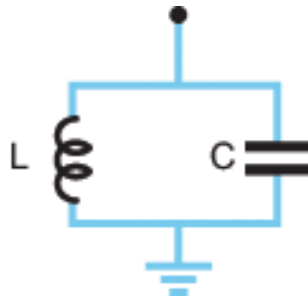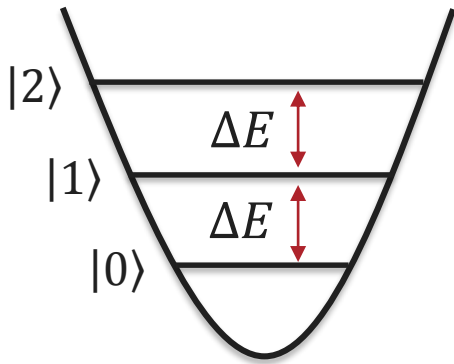
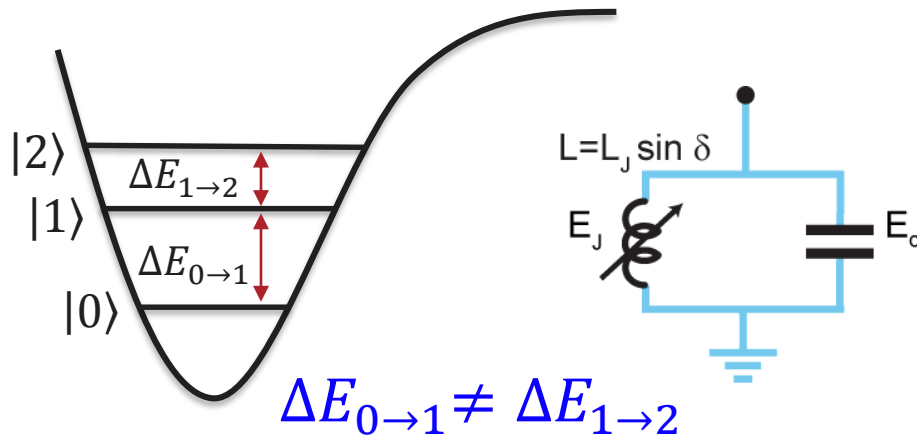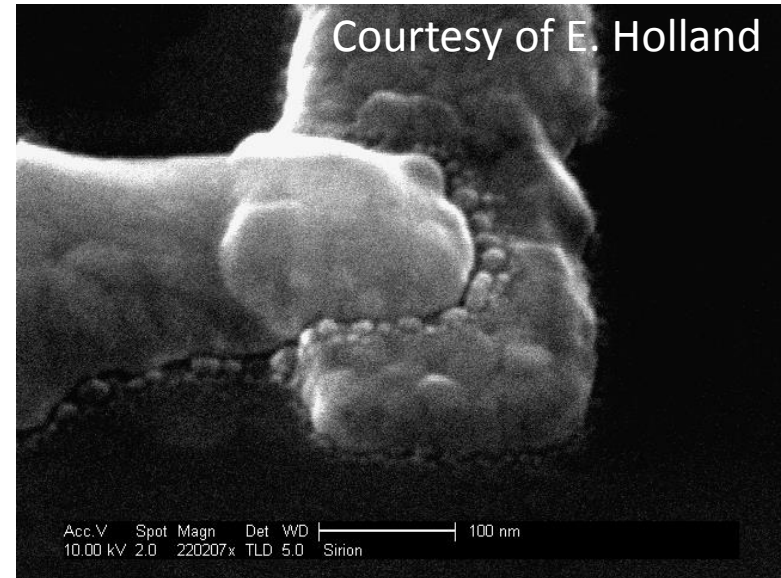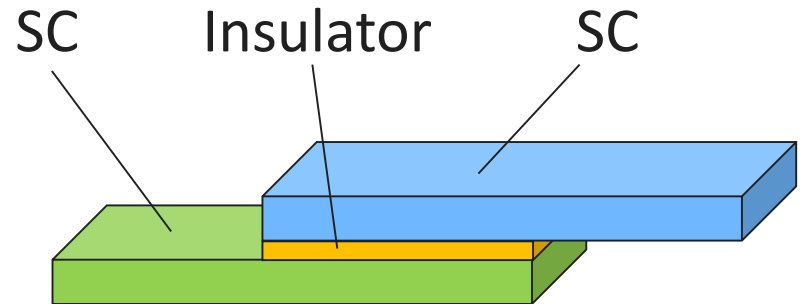* <u>HOWEVER</u>, the energy separation between levels is even ⇒ I cannot select a specific transition

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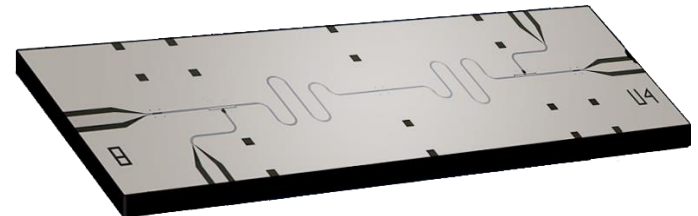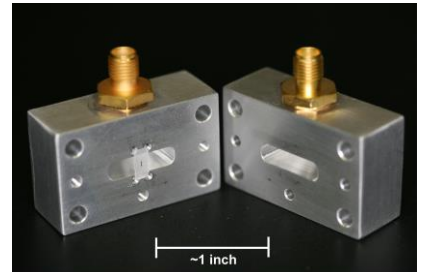
Superconducting qubits

* Based on Josephson junctions: non-linear inductors

$|2\rangle$

$\Delta E_{1\to2}$

$|1\rangle$

$\Delta E_{0\to1}$

$|0\rangle$

$L = L_J \sin \delta$

E_J E_c

$\Delta E_{0\to1} \neq \Delta E_{1\to2}$

* Behaves as an anharmonic LC resonator, transitions can be tuned in the microwave spectra ⇒ **a perfect artificial atom!**

Schematics of a Josephson junction
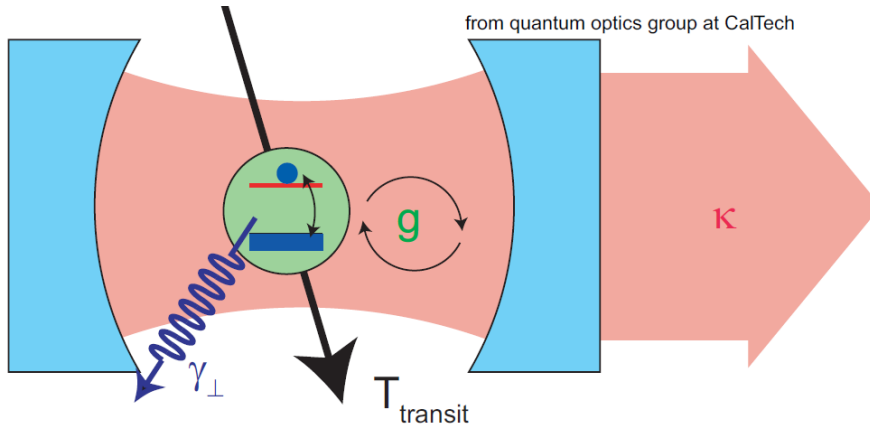
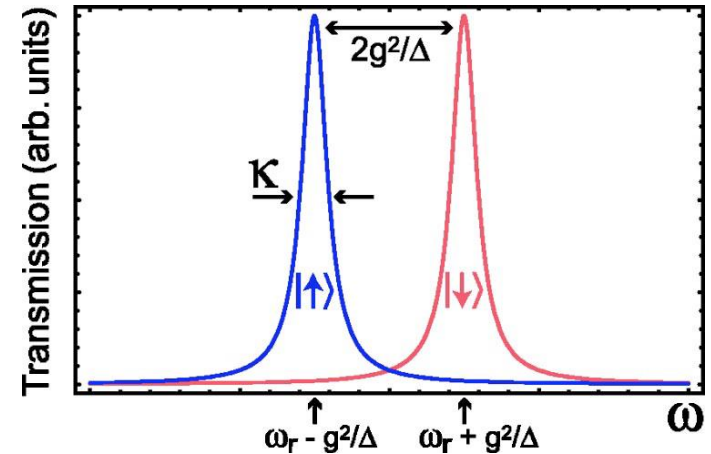SC   Insulator   SC

Courtesy of E. Holland

Acc.V   Spot   Magn   Det   WD   100 nm
10.00 kV 2.0   220207x TLD 5.0   Sirion

100 nanometers

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Cavity Quantum Electrodynamics (QED)

✱ Qubit read-out based on frequency shift of coupled resonator
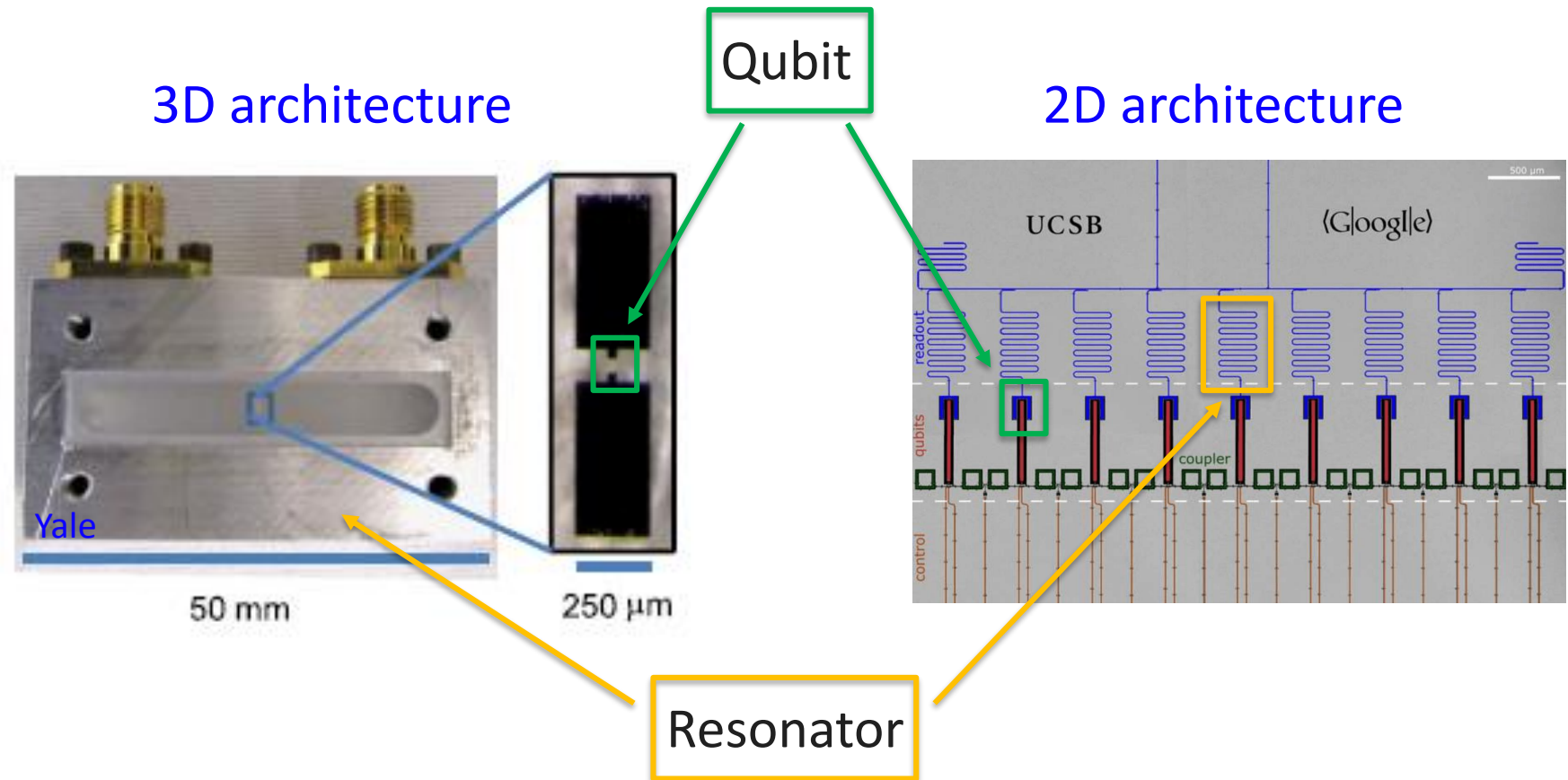
A. Blais et al., PRA 69, 062320 (2004)

from quantum optics group at CalTech

$$\mathcal{H} = \hbar\omega_r\left(a^\dagger a + \frac{1}{2}\right) + \frac{\hbar\omega_{eg}}{2}\sigma^z + \hbar g(a^\dagger\sigma^- + \sigma^+ a) + \mathcal{H}_\kappa + \mathcal{H}_\gamma$$

cavity   qubit/atom   interaction term

Serge Haroche and David Wineland Nobel Prize 2012

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Cavity-QED architecture for SC qubits

* Resonator coupled to a qubit
   →Coupling through capacitance or mutual inductance

3D architecture

Qubit

2D architecture

Yale

50 mm

250 μm

UCSB

(Google)

500 μm

readout

qubits

coupler

control

Resonator

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Typical layout of a quantum computation experiment

* Very low temperature (milli-Kelvin) is mandatory to avoid thermal excitation: $\kappa_B T < \hbar \omega$

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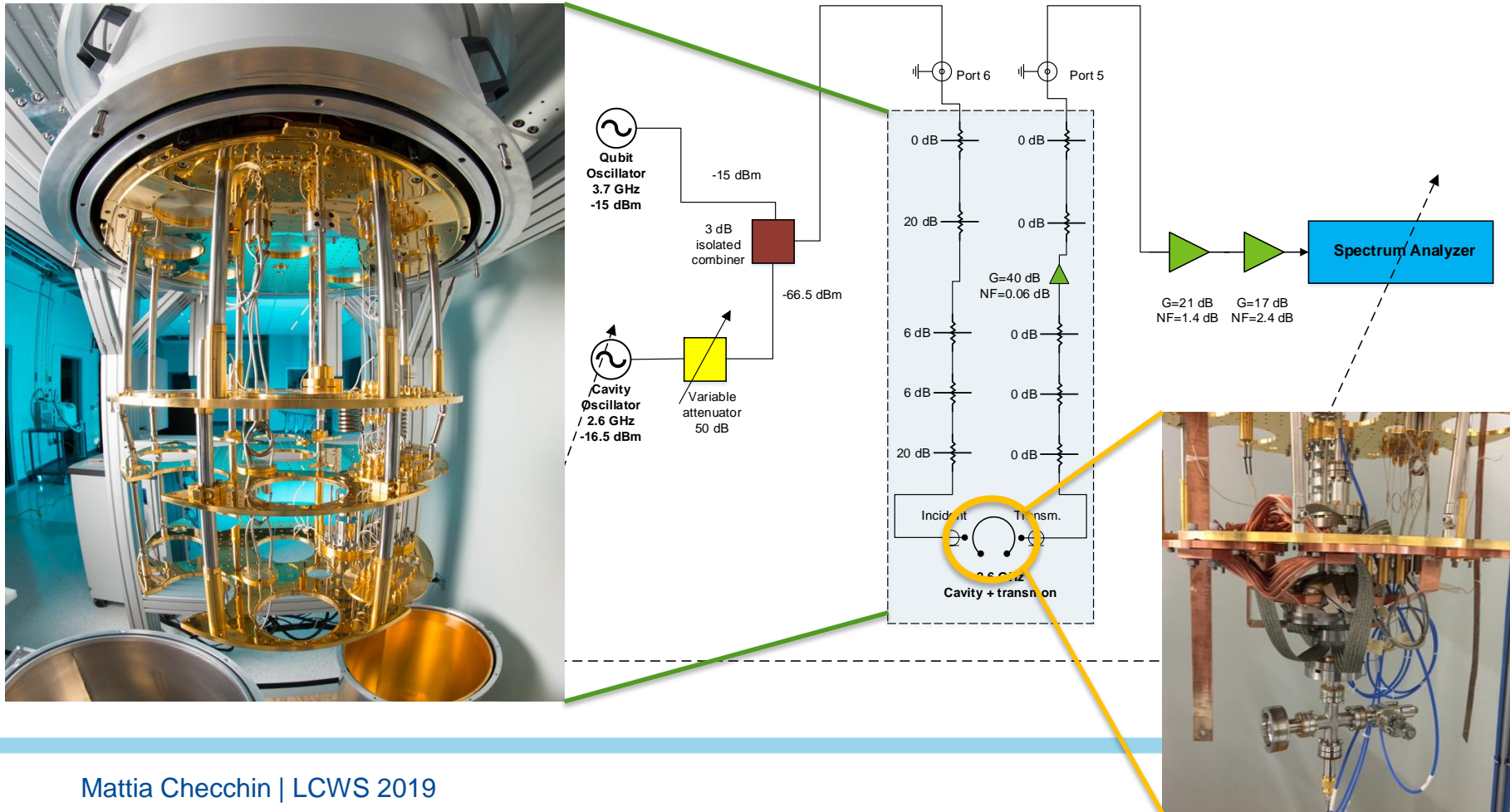
High-coherence quantum systems R&D

Qubit decoherence

- Decoherence = tendency of a quantum system to loose information

- We can beat decoherence by developing:
  - Better qubits
    - Protect qubit against sources of noise (flux and charge)
    - Minimize spurious two-level systems (TLS)
  - Better resonators
    - Increasing Q-factor
    - Minimize TLS
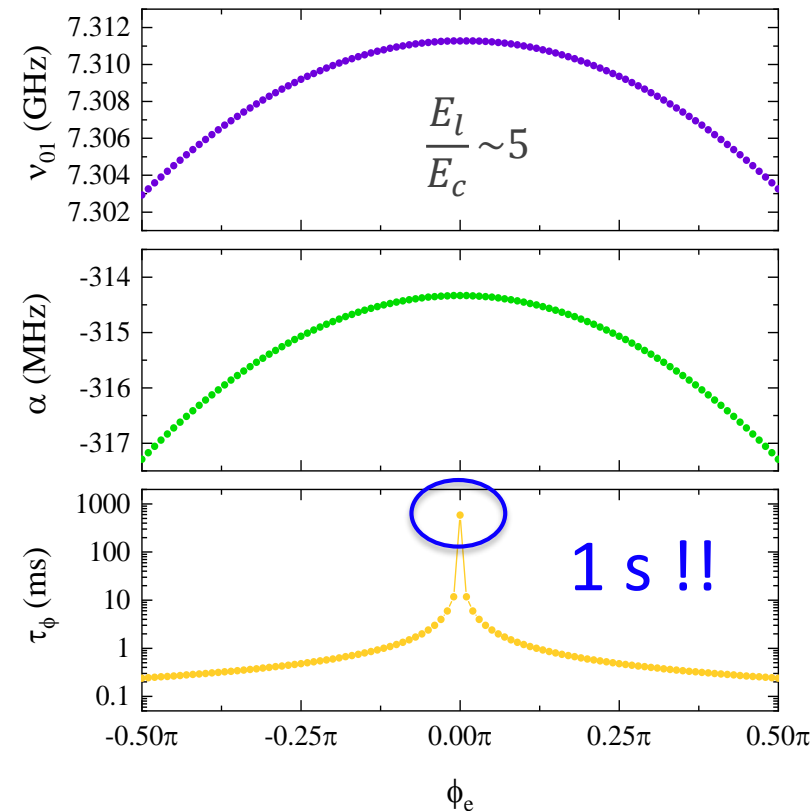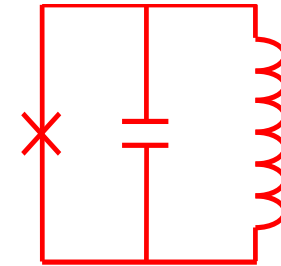   - **We can take advantage of High-Q SRF technology!**

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Flux- and charge-insensitive qubit

Design: $E_{j0} \gg E_c, E_l \sim E_c$

Pure dephasing time τ_ϕ **up to 1 s!**

- Shunt inductance → **no charge noise**
- **The larger L, the smaller the flux noise**
  - **In-line kinetic inductors**

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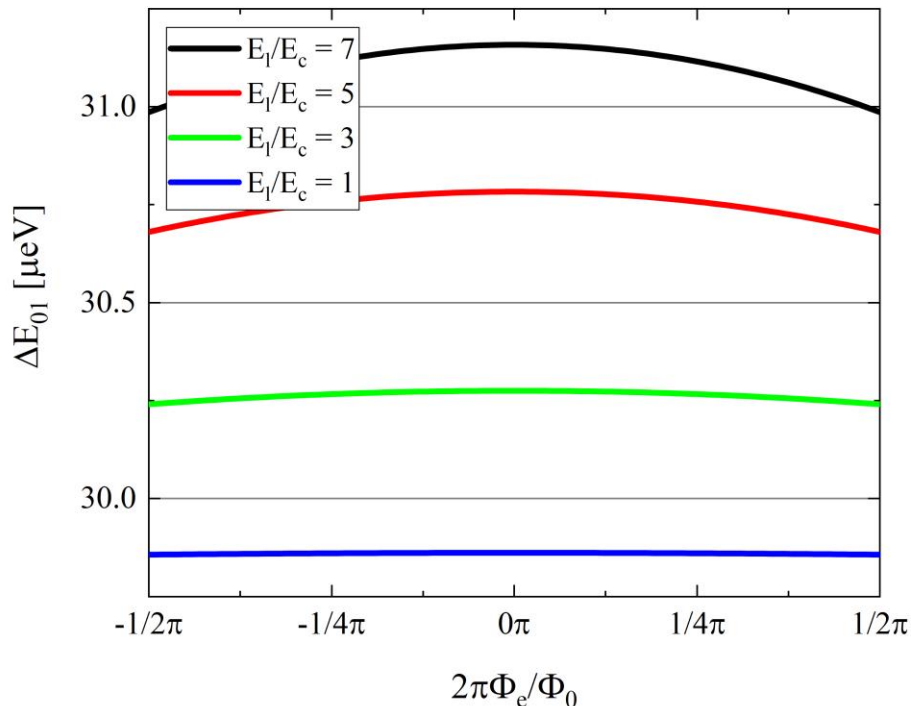
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"Schrodinger cat" states as a computational resource

- 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]

— cavity coupler

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

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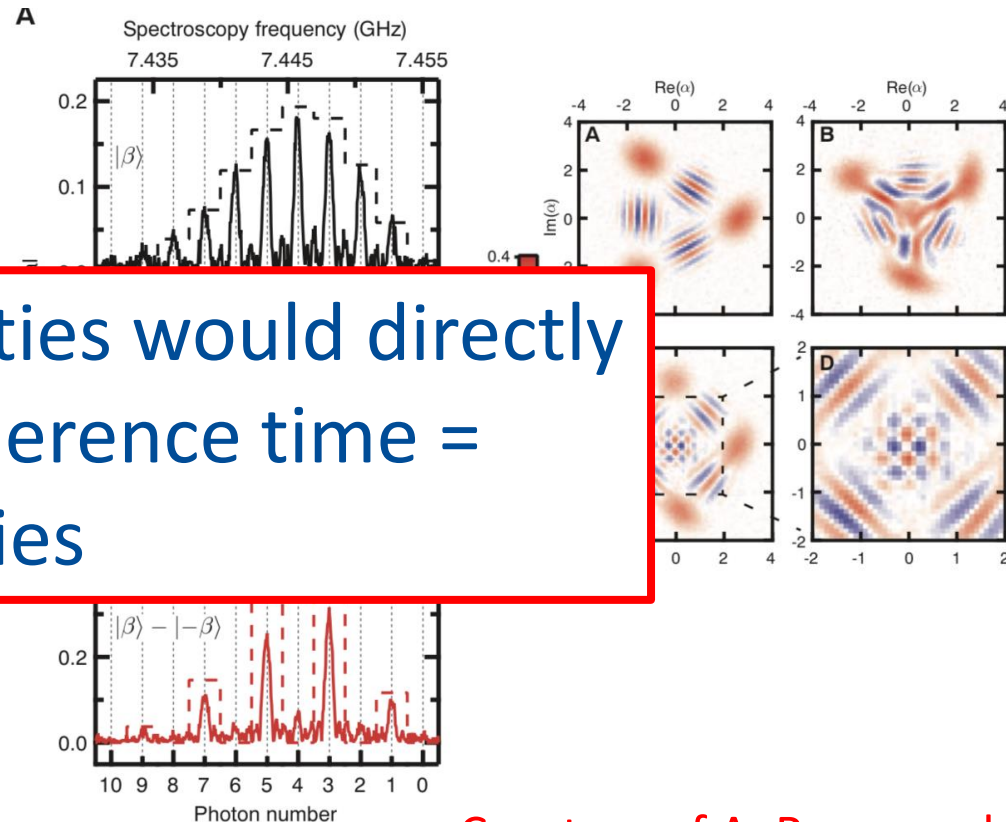
- Error correction: N. Ofek et al, Nature 536 (2016), 441
- CNOT gate: S. Rosenblum et al, Nature Communications 9 (2018)

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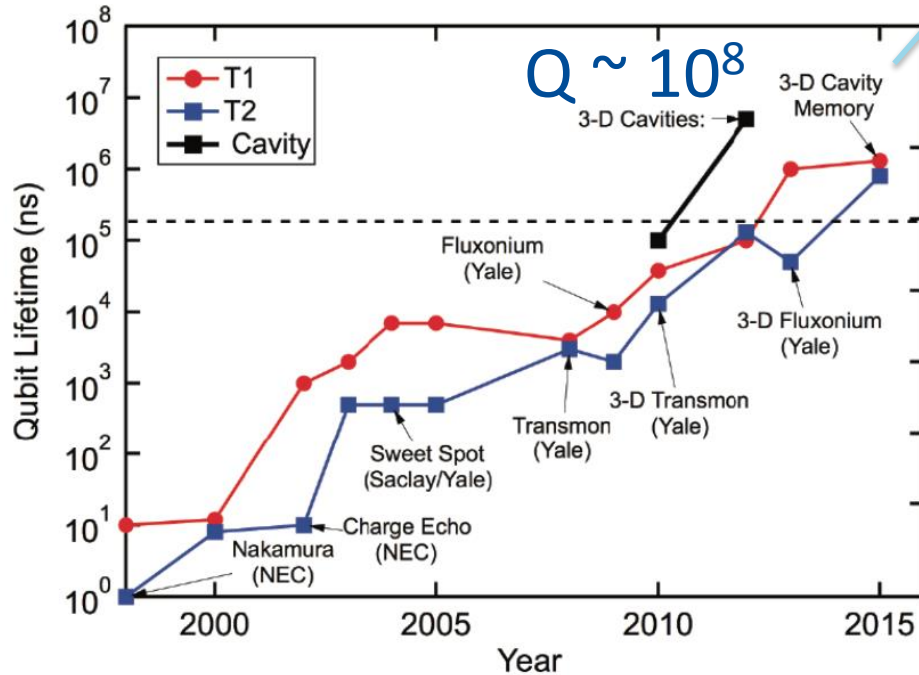
High Q SRF 3D cavities for improved coherence

$Q > 10^{11}$

~10 seconds of coherence

~10 msec photon lifetime/coherence is a record

$Q \sim 10^8$
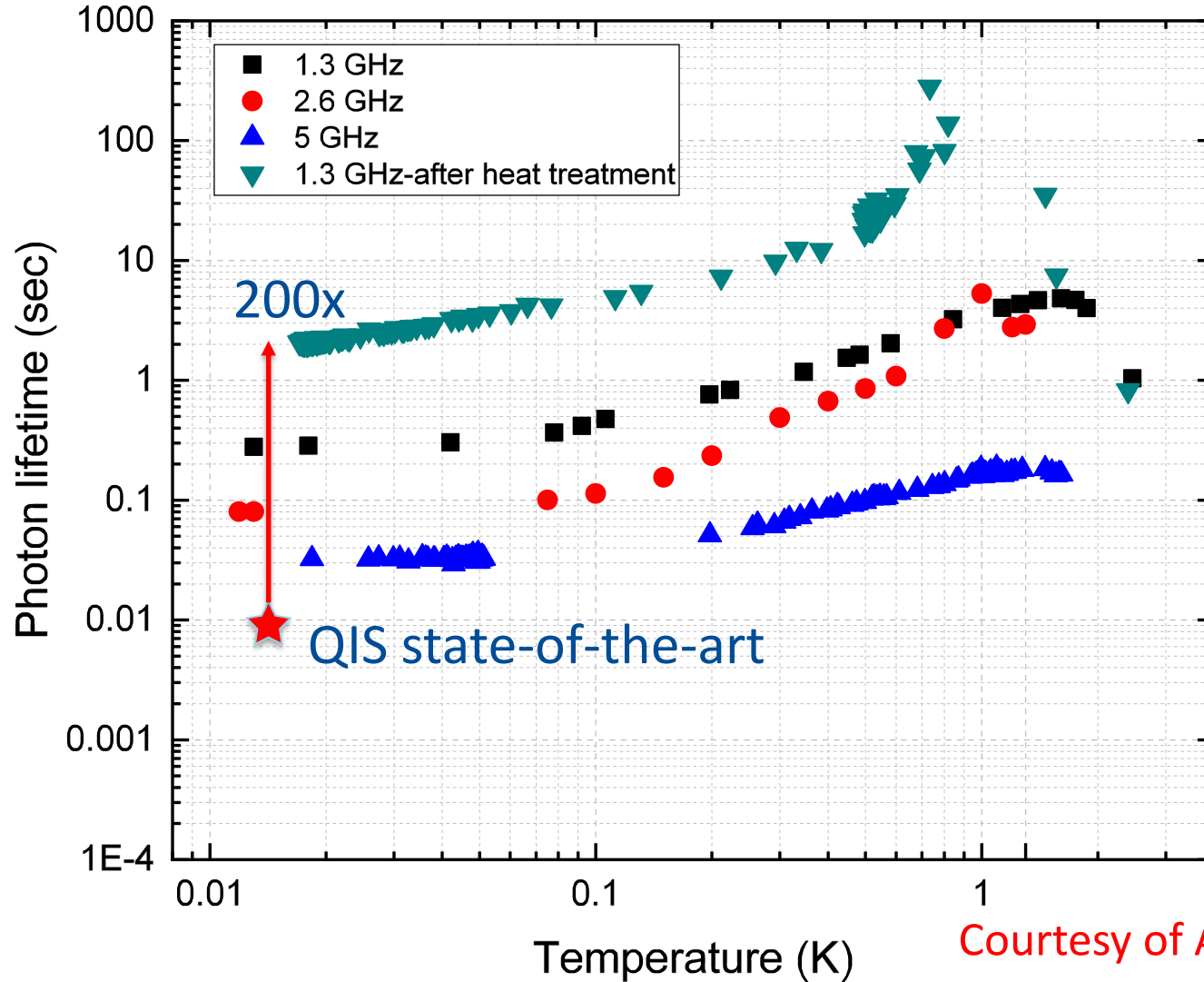

M. H. Devoret and R. J. Schoelkopf, *Science* 339, 1169–1174 (2013)

1-cell Fermilab cavities of various frequencies
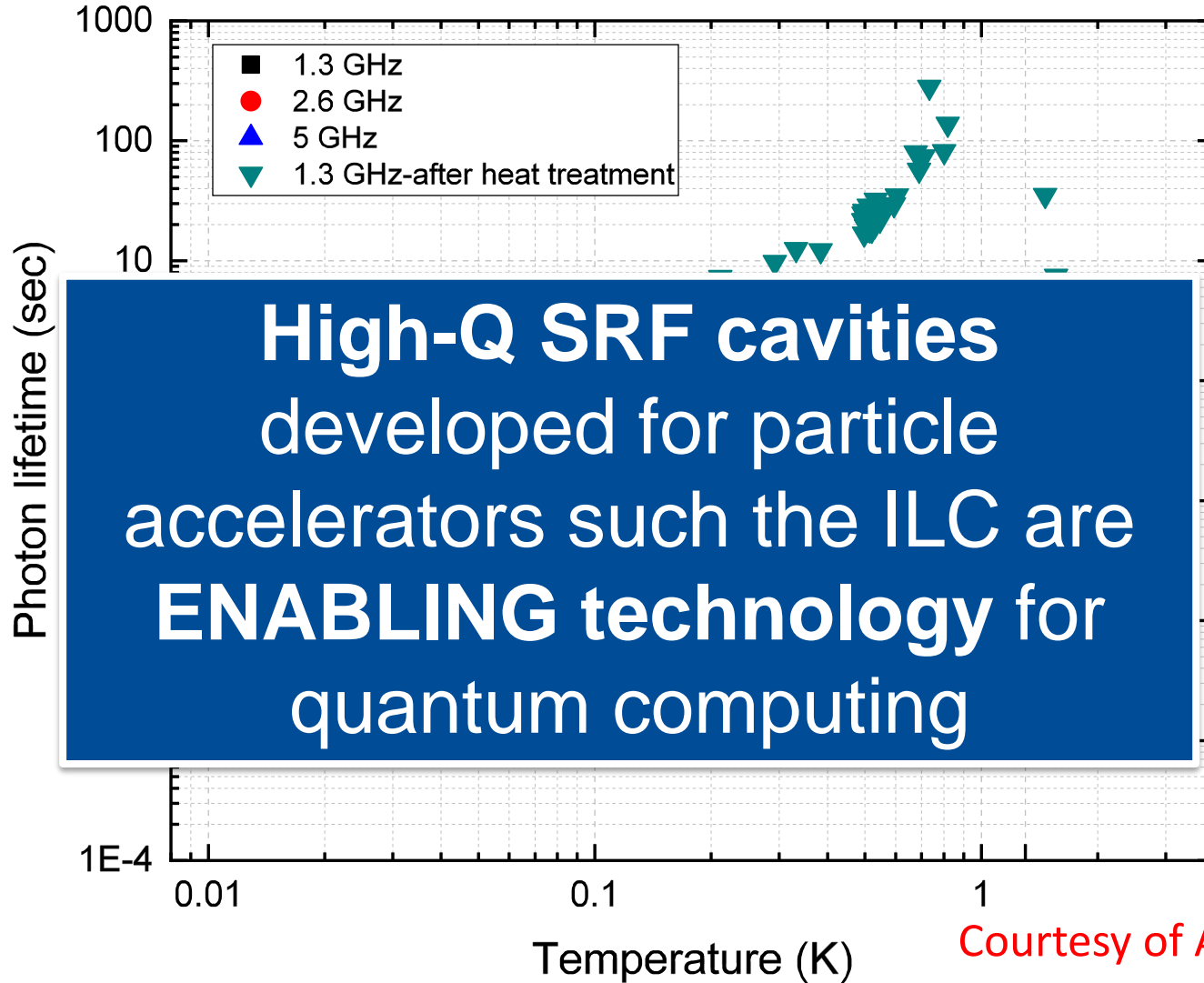
Courtesy of A. Romanenko

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Record high photon lifetimes achieved

Courtesy of A. Romanenko

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

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Record high photon lifetimes achieved

High-Q SRF cavities developed for particle accelerators such the ILC are **ENABLING technology** for quantum computing

Courtesy of A. Romanenko

A. Romanenko, R. Pilipenko, S. Zorzetti, D. Frolov, M. Awida, S. Posen, A. Grassellino, arXiv:1810.03703
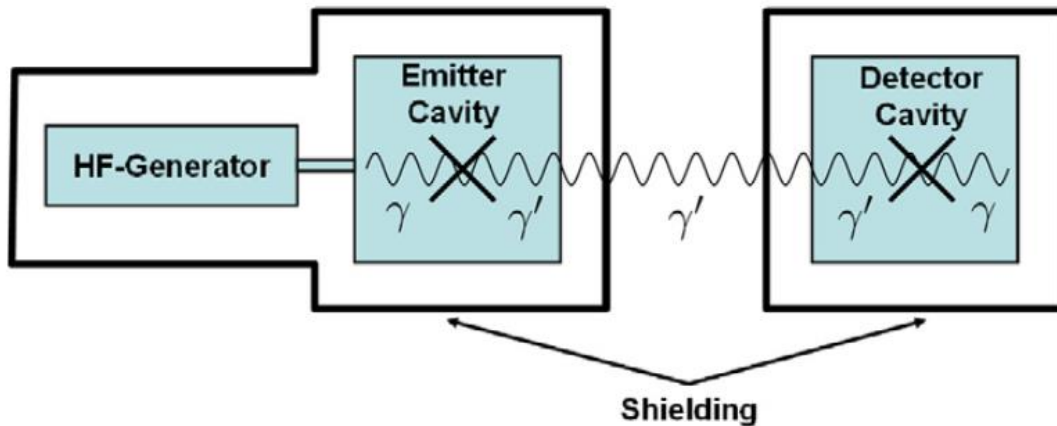
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Dark matter search with SRF technology

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

$$\frac{P_{DET}}{P_{EM}} = \chi^4 Q_{DET} Q_{EM} \left(\frac{m_{\gamma'}c^2}{\hbar\omega_\gamma}\right)^8 |G|^2$$
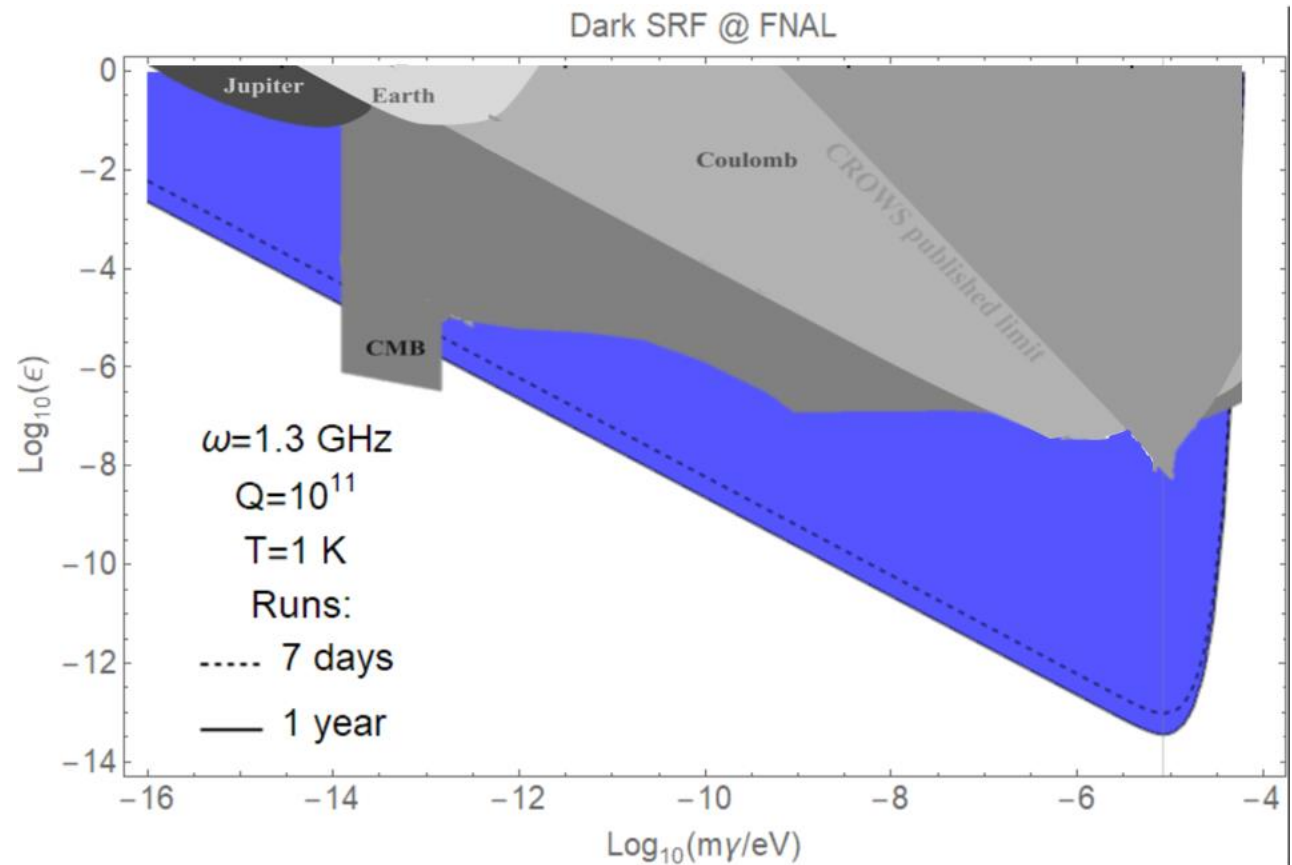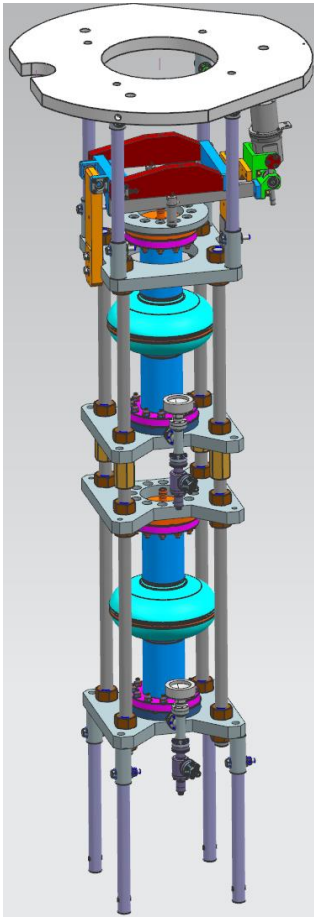
Q_{DET}, Q_{EM} > 10^{10} SRF can offer several orders of magnitude improvement in sensitivity to χ

Courtesy of A. Romanenko

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"Dark SRF" experiment at Fermilab

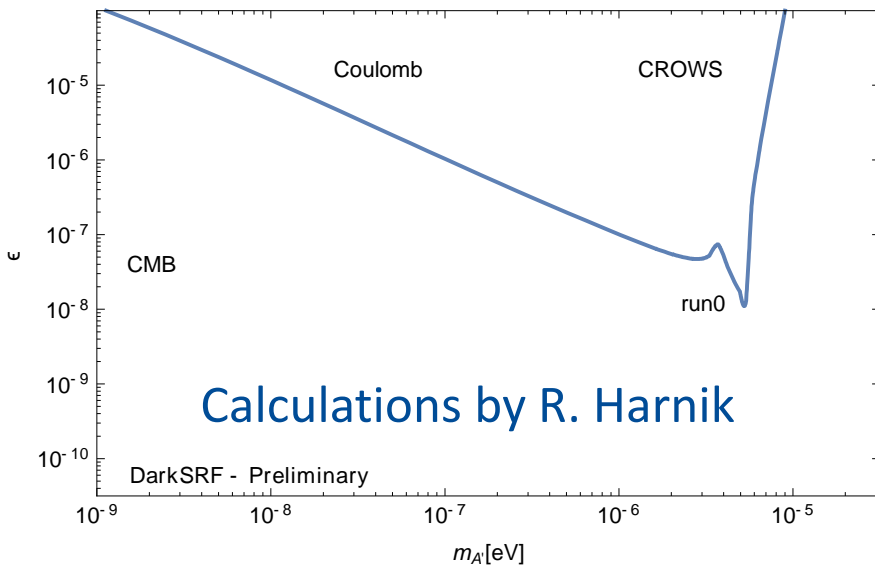- First search for dark photons with SRF cavities

First test run has been accomplished

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Dark SRF: "Run 0" has been successful

Everything worked!

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

Calculations by R. Harnik

Courtesy of A. Romanenko

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Conclusions

Conclusions

* Coherence time in quantum devices can be boosted by improving qubit performance or by increasing the quality factor of the coupled resonator
    → **High-Q SRF cavities enabling technology for high-coherent quantum systems**

* High-Q SRF cavities provide a solid platform for developing high sensitive microwave photon detectors for dark matter searches

* Fermilab's R&D on high-coherence quantum systems based on high-Q SRF cavities provides solid ground to develop a similar program at the future ILC laboratory

Thank you for the attention

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