Superconducting Quantum Memory with a Suspended Coaxial Resonator

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Normal memory VS Quantum memory

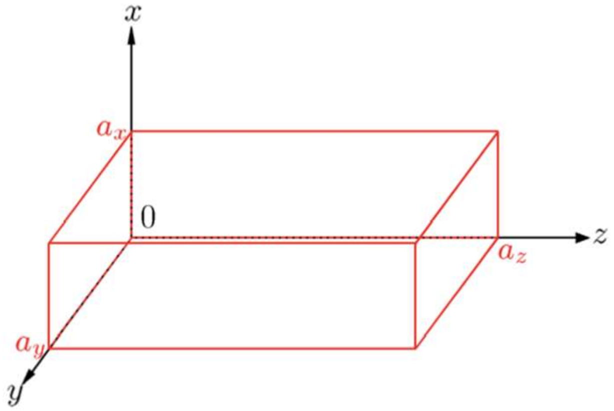
Feature	Normal Memory (e.g., RAM)	Quantum Memory
What it Stores	Classical bits (0s and 1s)	Quantum bits (qubits: superposition & entanglement)
State Preservation	Stable until power off	Must preserve fragile quantum states
Operations	Reads/writes classical data	Reads/writes quantum data (no copying due to quantum rules)
Purpose	Temporarily holds data for computation	Enables quantum computation & communication
Examples	Used in laptops, phones, servers	Found in quantum computers, quantum networks

Why is Quantum Memory Needed?

- **Quantum Communication**: Enables long-distance secure data transfer.
- **Quantum Computing**: Stores intermediate results for quantum algorithms.
- **Quantum Networks**: Links quantum devices for sharing entanglement.

Meet the classical modes of a resonator

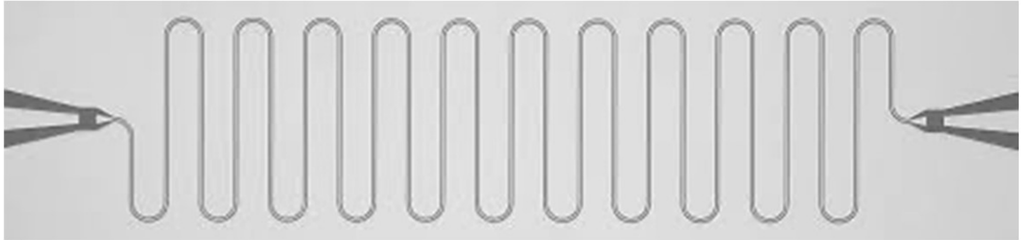
Eg. 3D cavity

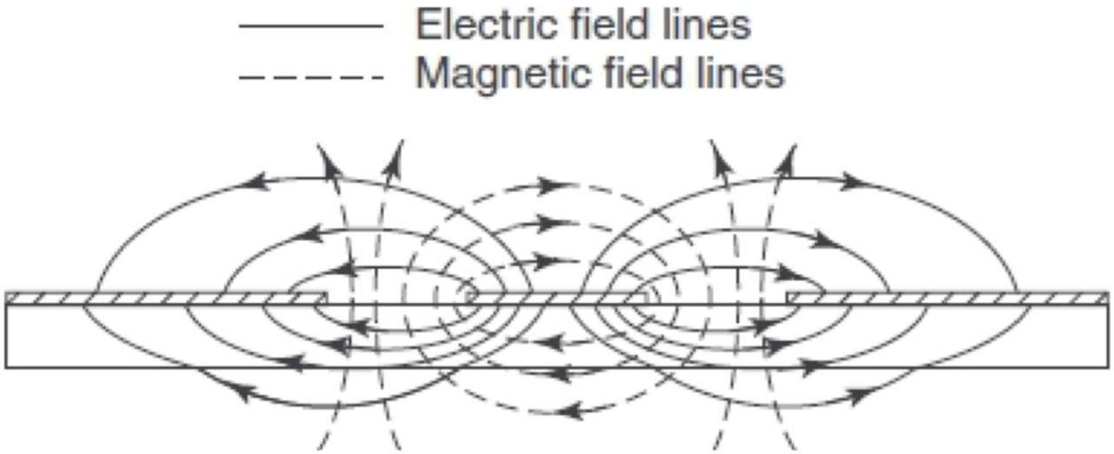


$$k_x = \frac{\pi n_x}{a_x}, \qquad k_y = \frac{\pi n_y}{a_y}, \qquad k_z = \frac{\pi n_z}{a_z}$$

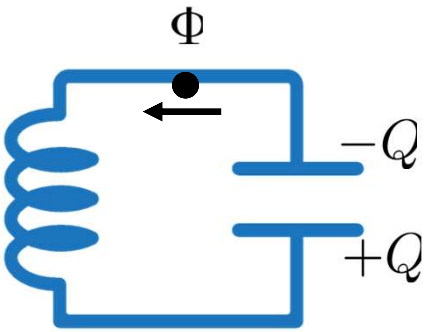
$$\omega = \pi c \sqrt{\frac{n_x^2}{a_x^2} + \frac{n_y^2}{a_y^2} + \frac{n_z^2}{a_z^2}}$$

Eg. 2D resonator





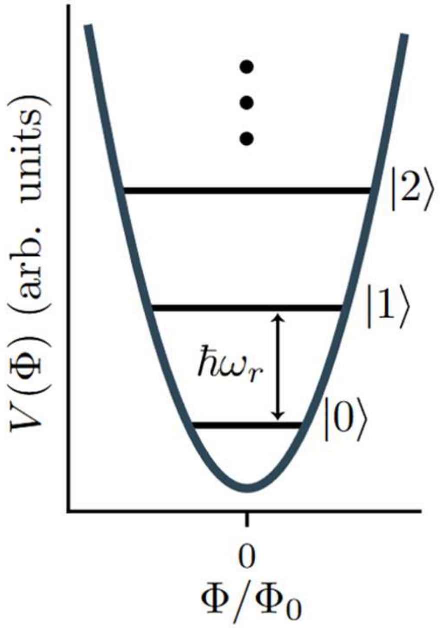
Quantizing the LC oscillator



$$\omega_r = \frac{1}{\sqrt{LC}}$$

Recipe for quantization:

- promote charge and flux to non-commuting observables
- express observables in terms of ladder operators



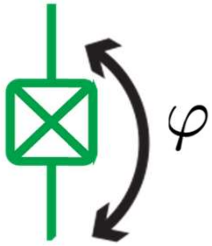
$$H = E_C + E_L = \frac{Q^2}{2C} + \frac{\Phi^2}{2L} \quad \Longrightarrow \quad \hat{H} = \omega_r(\hat{a}^\dagger \hat{a} + 1/2)$$

We cannot uniquely address the harmonic oscillator eigenstates with a classical drive.

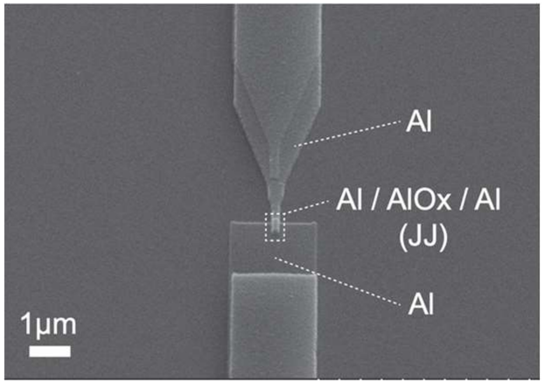
A. Blais et al., Rev. Mod. Phys. (2021)

An anharmonic LC oscillator: the transmon qubit

Nonlinearity comes from the Josephson Junction (JJ)



$$\hat{H}_{JJ} = -E_J \cos(\hat{\varphi})$$



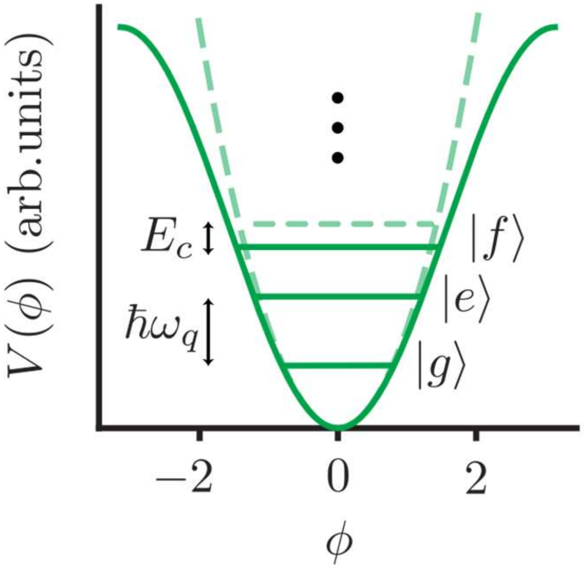
A. Blais et al., Rev. Mod. Phys. (2021)

the transmon qubit

$$\hat{H} = \frac{E_C}{4}\hat{Q}^2 - E_J \cos(\hat{\varphi})$$

expanding the cosine up to fourth order:

$$\hat{H} \approx \hbar\omega_q \hat{a}^\dagger \hat{a} - \frac{E_C}{2}\hat{a}^\dagger\hat{a}^\dagger\hat{a}\hat{a}$$

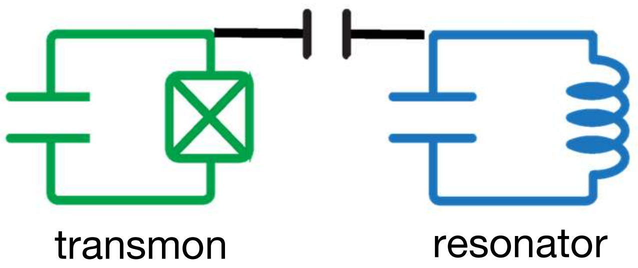


Unequally spaced levels allow us to isolate two levels as our qubit subspace.

Transmon-resonator interaction in the dispersive regime

$$\hat{H} = \underbrace{\hbar\omega_r \hat{a}^\dagger \hat{a}}_{\text{resonator}} + \underbrace{\frac{\hbar\omega_q}{2}\hat{\sigma}_z}_{\text{qubit}} + \underbrace{\hbar g(\hat{a}^\dagger\hat{\sigma}_- + \hat{a}\hat{\sigma}_+)}_{\text{coupling}}$$

- For $|\omega_r - \omega_q| \gg g$ we can make certain approximations
- This parameter regime is called the dispersive regime



$$\hat{H} \approx \hbar\omega_r \hat{a}^\dagger \hat{a} + \frac{\hbar\omega_q}{2}\hat{\sigma}_z + \hbar\chi\hat{a}^\dagger\hat{a}\hat{\sigma}_z$$

dispersive coupling

A. Blais et al., Rev. Mod. Phys. (2021)

Dispersive readout of transmon/resonator

$$\hat{H} \approx \hbar\omega_r \hat{a}^\dagger \hat{a} + \frac{\hbar\omega_q}{2}\hat{\sigma}_z + \hbar\chi \hat{a}^\dagger \hat{a}\hat{\sigma}_z$$

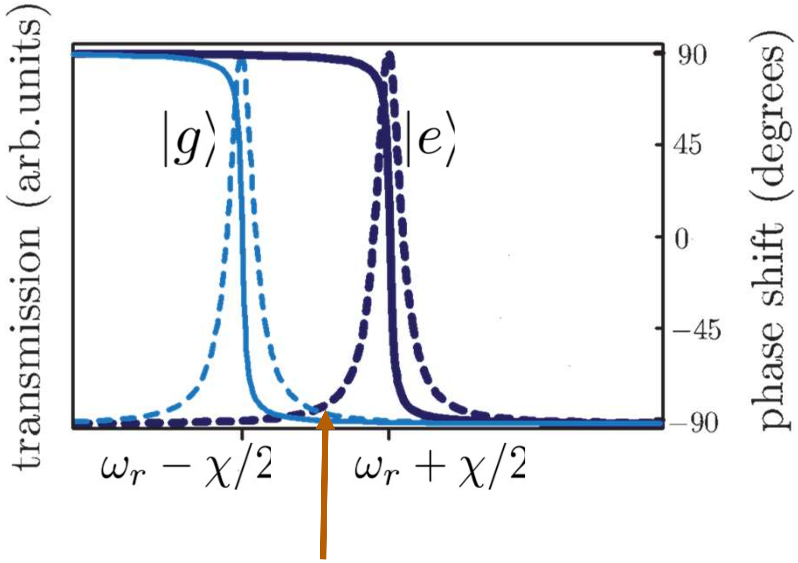
$$\hat{H} \approx \hbar \hat{a}^\dagger \hat{a}(\omega_r + \chi\hat{\sigma}_z) + \frac{\hbar\omega_q}{2}\hat{\sigma}_z$$

resonator frequency depends on the qubit state

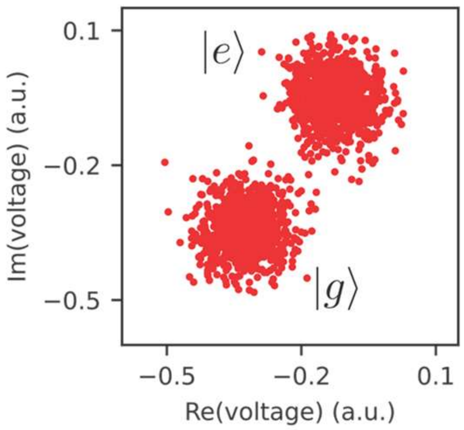
$$\hat{H} \approx \hbar\omega_r \hat{a}^\dagger \hat{a} + \frac{\hbar\hat{\sigma}_z}{2}\left(\omega_q + 2\chi\hat{a}^\dagger \hat{a}\right)$$

qubit frequency depends on the resonator state

A. Blais et al., Rev. Mod. Phys. (2021)



measure with a probe tone at this frequency



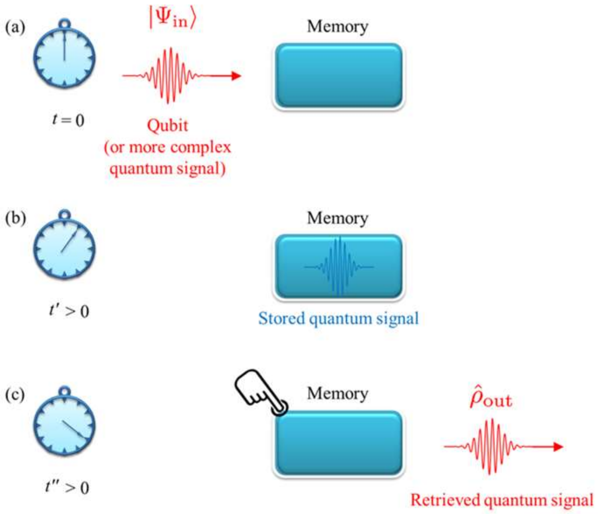
Motivation for the paper

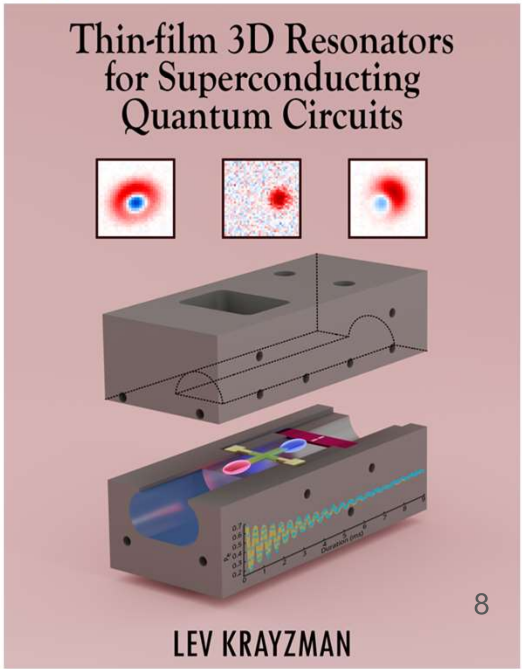
Quantum Information Storage Challenges:

- Require robust, high-coherence quantum memories for storing quantum states.
- Trade-offs between **coherence time**, **scalability**, and **ease of fabrication**.

The Surface Participation Problem:

- Conventional 3D bulk-machined resonators have low surface participation, reducing losses but are hard to integrate with qubits.
- Thin-film circuits are scalable and controllable but suffer from high losses due to surface defects.





Thin-film 3D Resonators
for Superconducting
Quantum Circuits

LEV KRAYZMAN

Summary of the paper

Proposed Solution:

- Introduces a **hybrid resonator design**:
  - Thin-film conductor supported by a **dielectric scaffold**.
  - Encased within a **3D package** for enhanced coherence.

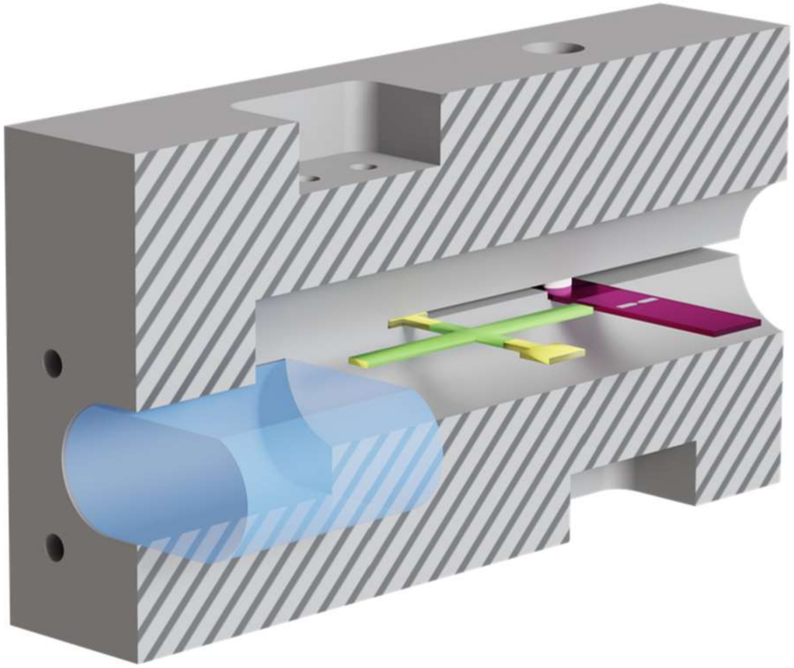
Key Results:

- Achieved **single-photon lifetimes exceeding one millisecond**
- Integration with a **transmon qubit chip**

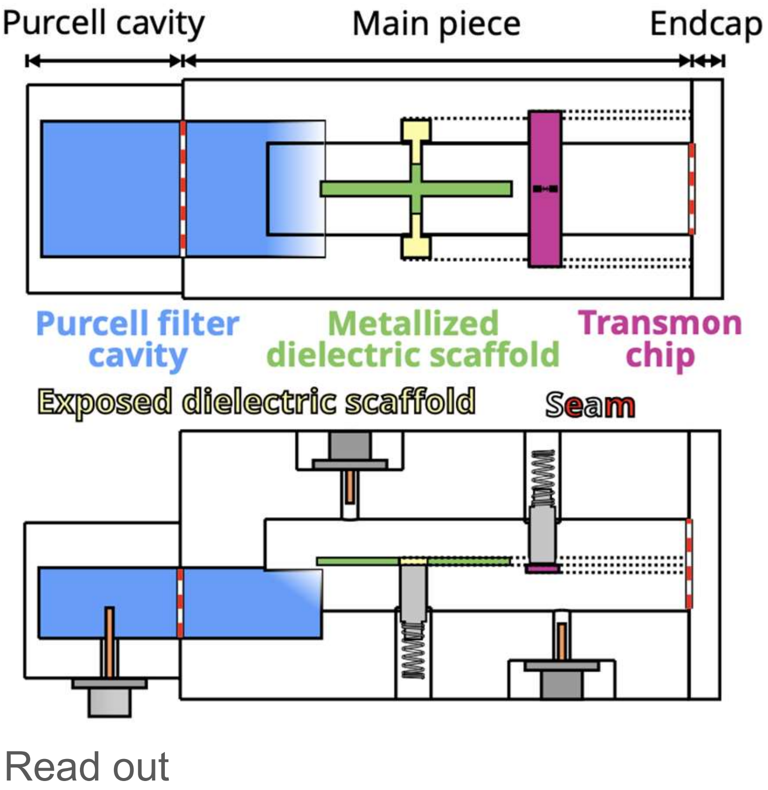
Significance:

- Both low-loss (l**ong coherence**) properties of bulk resonators and **scalability** of thin-film circuits.
- **Modularity** allows independent replacement of qubit and resonator components, essential for scalable quantum systems.

2.5D architecture of the device



3D render of the main piece of the device
(cross-section view)

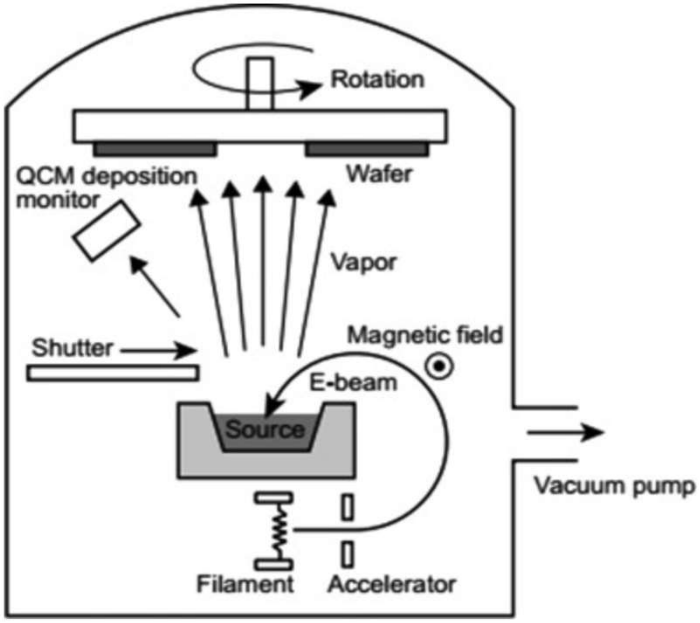


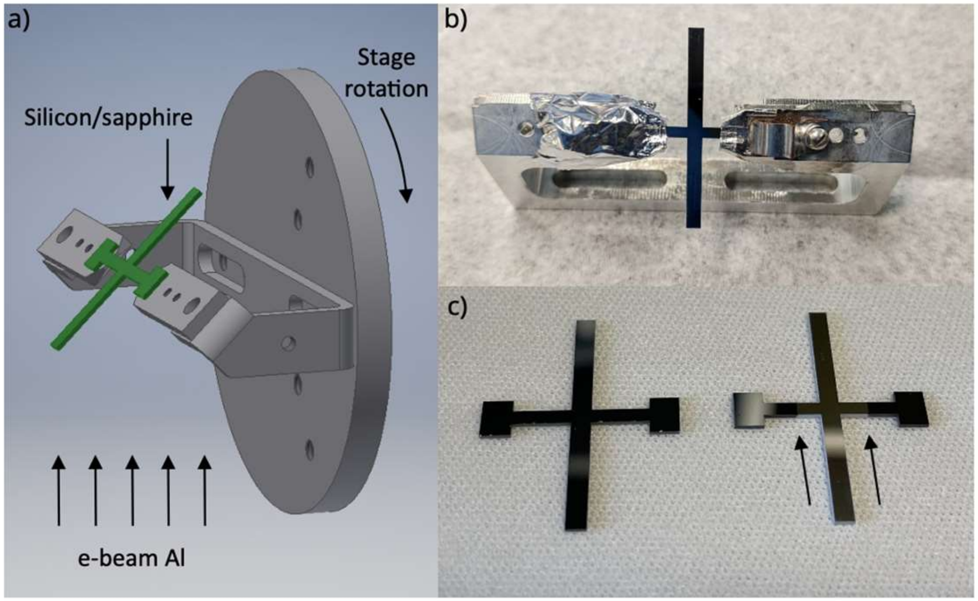
top and side view diagrams of the device

Center conductor fabrication

1.Laser cut Silicon/Sapphire into cross shape.

2. Rotational evaporation coat one stick in the cross with thin-film .





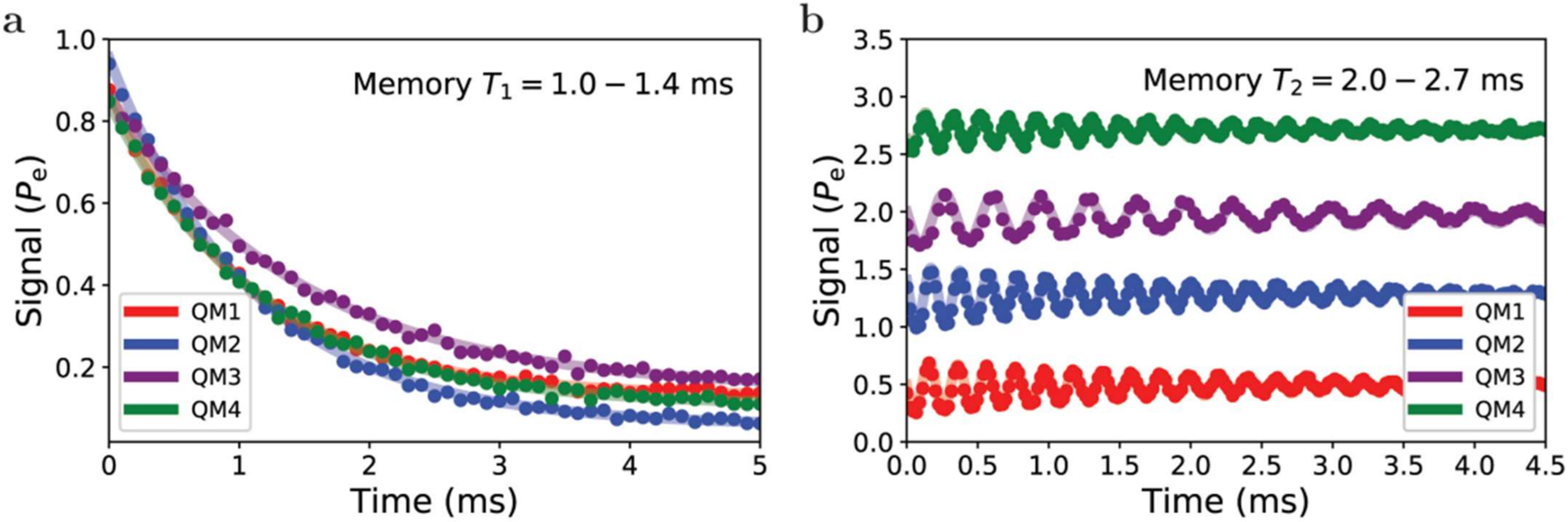
https://doi.org/10.1016/C2018-0-04648-4

Previous work: on-chip resonators

- High material quality and well-suited for integration with qubits.
- Limitation: High surface participation can lead to significant energy losses.

T_1 → Relaxation time

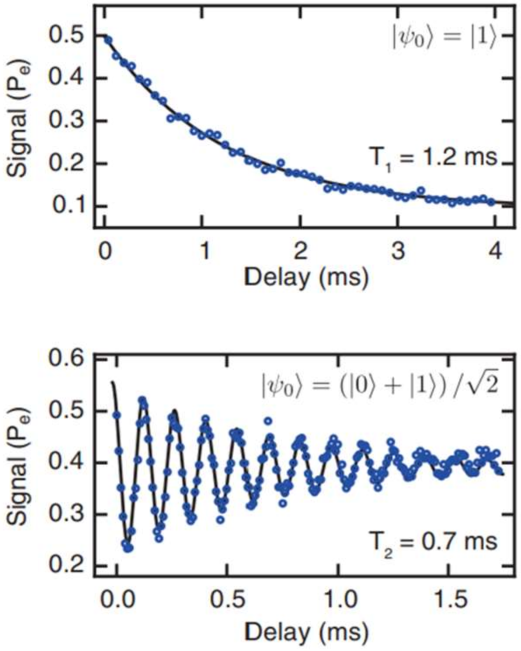
T_2 → Coherence time



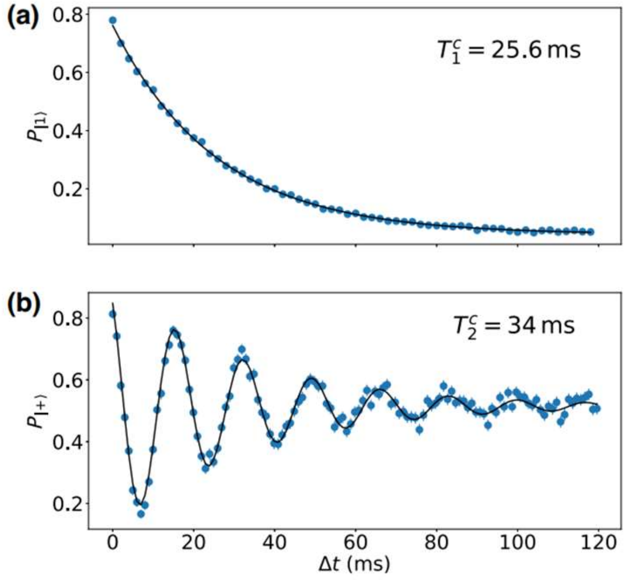
S. Ganjam et al., *Surpassing millisecond coherence times in on-chip superconducting quantum memories by optimizing materials, processes, and circuit design*, arXiv:2308.15539 [quant-ph] (2023).

Previous work: 3D cavity resonators

- Achieved long coherence times due to minimization of surface losses.
- Limitation: Complex fabrication and lack of scalability for quantum processors.



M. Reagor et al., *Quantum memory with millisecond coherence in circuit QED*, Phys. Rev. B **94**, 014506 (2016).

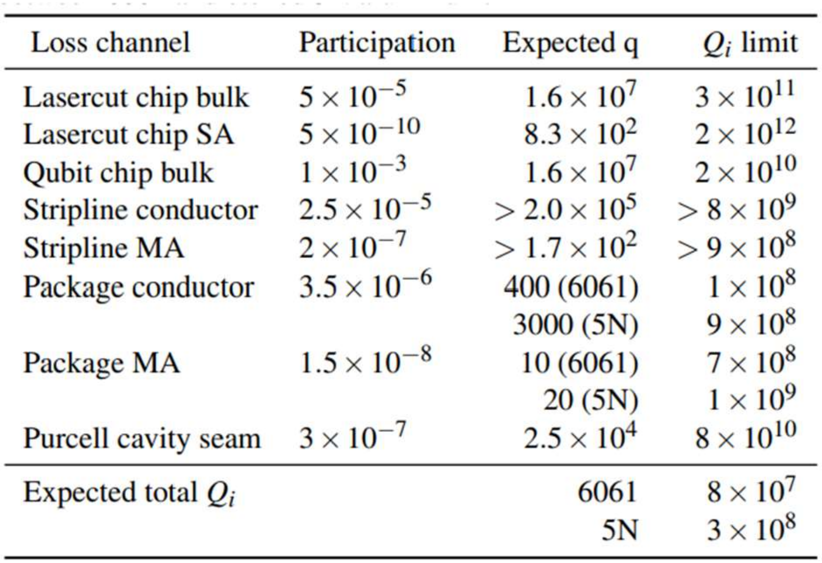


O. Milul, B. Guttel, U. Goldblatt, S. Hazanov, L. M. Joshi, D. Chausovsky, N. Kahn, E. Çiftyürek, F. Lafont, and S. Rosenblum, *Superconducting Cavity Qubit with Tens of Milliseconds Single-Photon Coherence Time*, PRX Quantum **4**, 030336 (2023).

This work: Methods

- Use the λ/2 mode for storage, since it has a node in the center of the resonator
    - Minimizes dielectric loss
- Use 3λ/2 mode for readout
- Preparation of Fock states to measure decoherence lifetimes
    - Two separate methods for measuring T_1

Limiting quality factors for different loss modes are given in the table to the right.

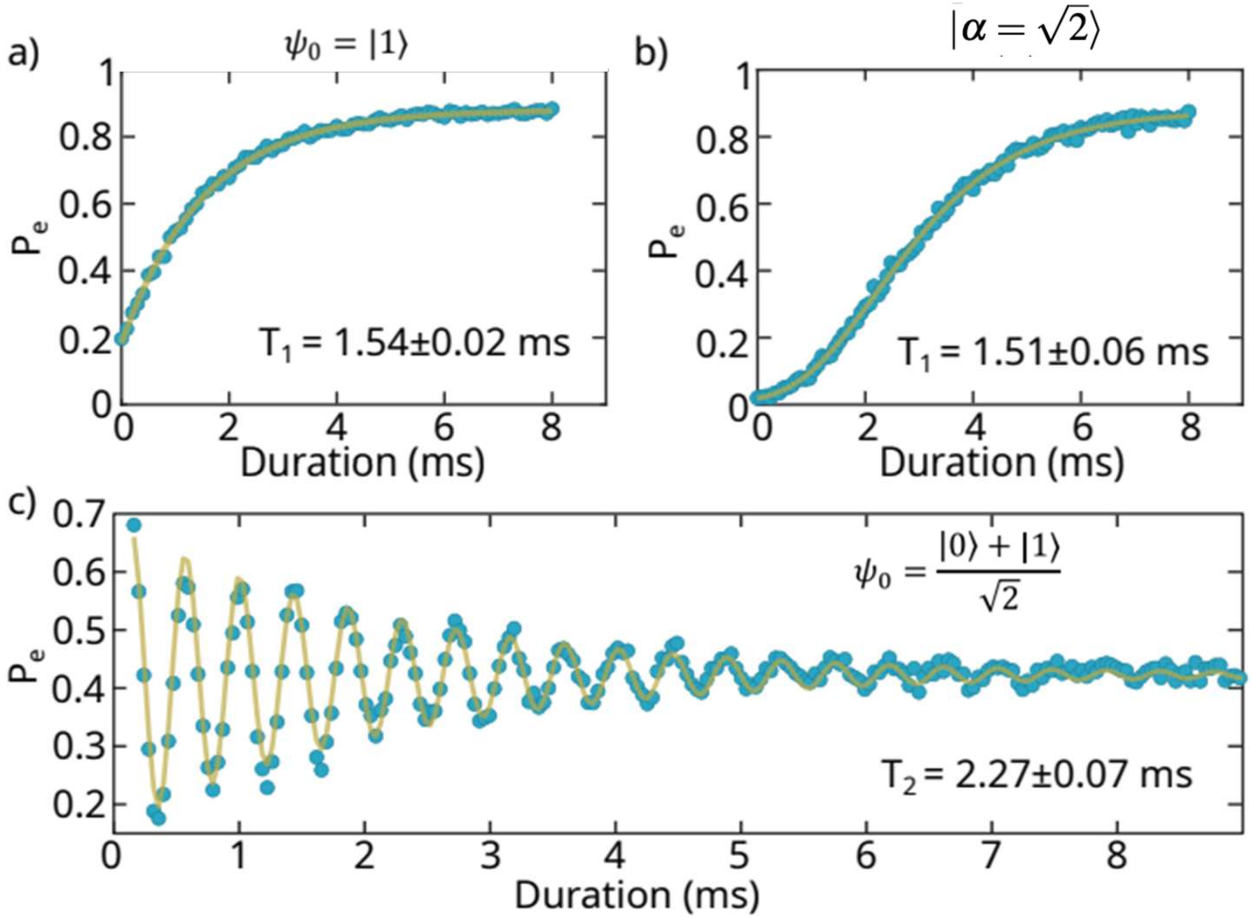


Loss channel	Participation	Expected q	Q_i limit
Lasercut chip bulk	5×10^{-5}	1.6×10^{7}	3×10^{11}
Lasercut chip SA	5×10^{-10}	8.3×10^{2}	2×10^{12}
Qubit chip bulk	1×10^{-3}	1.6×10^{7}	2×10^{10}
Stripline conductor	2.5×10^{-5}	$> 2.0 \times 10^{5}$	$> 8 \times 10^{9}$
Stripline MA	2×10^{-7}	$> 1.7 \times 10^{2}$	$> 9 \times 10^{8}$
Package conductor	3.5×10^{-6}	400 (6061)	1×10^{8}
		3000 (5N)	9×10^{8}
Package MA	1.5×10^{-8}	10 (6061)	7×10^{8}
		20 (5N)	1×10^{9}
Purcell cavity seam	3×10^{-7}	2.5×10^{4}	8×10^{10}
Expected total Q_i		6061	8×10^{7}
		5N	3×10^{8}

$$1 / Q_i \equiv \sum_i \frac{p_i}{q_i}$$

This work: Results

- Achieves millisecond lifetimes while keeping unwanted energy participations low



Citation analysis

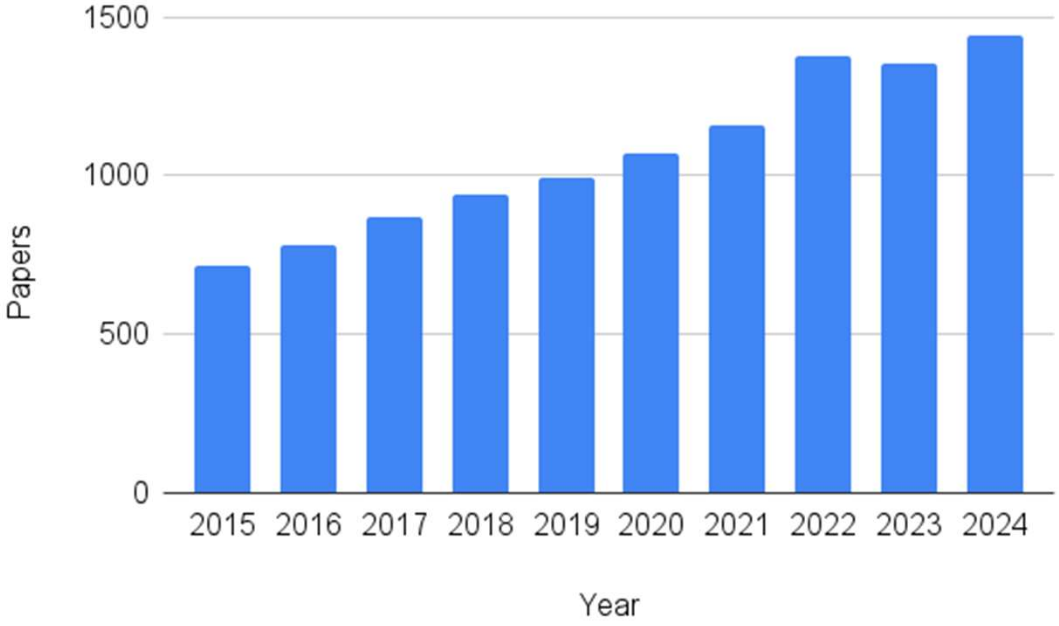
The paper was published this year, and there's no citation…

The most cited references include following works done by Schoelkopf's group at Yale:

- Reagor et al. (2016). Quantum memory with millisecond coherence in circuit QED. *Physical Review B*. [cited 397 times]
- Chou et al. (2018). Deterministic teleportation of a quantum gate between two logical qubits. *Nature*. [cited 274 times]
- Heeres et al. (2015). Cavity state manipulation using photon-number selective phase gates. *Physical review letters*. [cited 209 times]
- Brecht et al. (2016). Multilayer microwave integrated quantum circuits for scalable quantum computing. *npj Quantum Information*. [cited 180 times]

Development of the field

Quantum memory is a growing field



Papers searched with keyword “quantum memory” in Web of Science

Future directions:

- modular architecture
- better fabrication
- hybrid systems (coupling different types of elements)

Conclusion

- **Hybrid Design**: Utilizes a dielectric scaffold to support a thin-film conductor within a 3D package, merging low-loss characteristics of bulk resonators with the material quality control of thin-film circuits.

- **Enhanced Coherence**: Achieves single-photon lifetimes over one millisecond, indicating high coherence and reliability for quantum information storage.

- **Scalability and Modularity**: Allows for separate fabrication and replacement of qubit and resonator components, facilitating easier scaling and maintenance of quantum systems.

Questions?