# Nonlinear coupling in circuit QED for quantum optomechanics

Summit Quantum Limits — Dokkum

**Jels van Arragon — 9/9/2026**

Precision and Microsystems Engineering

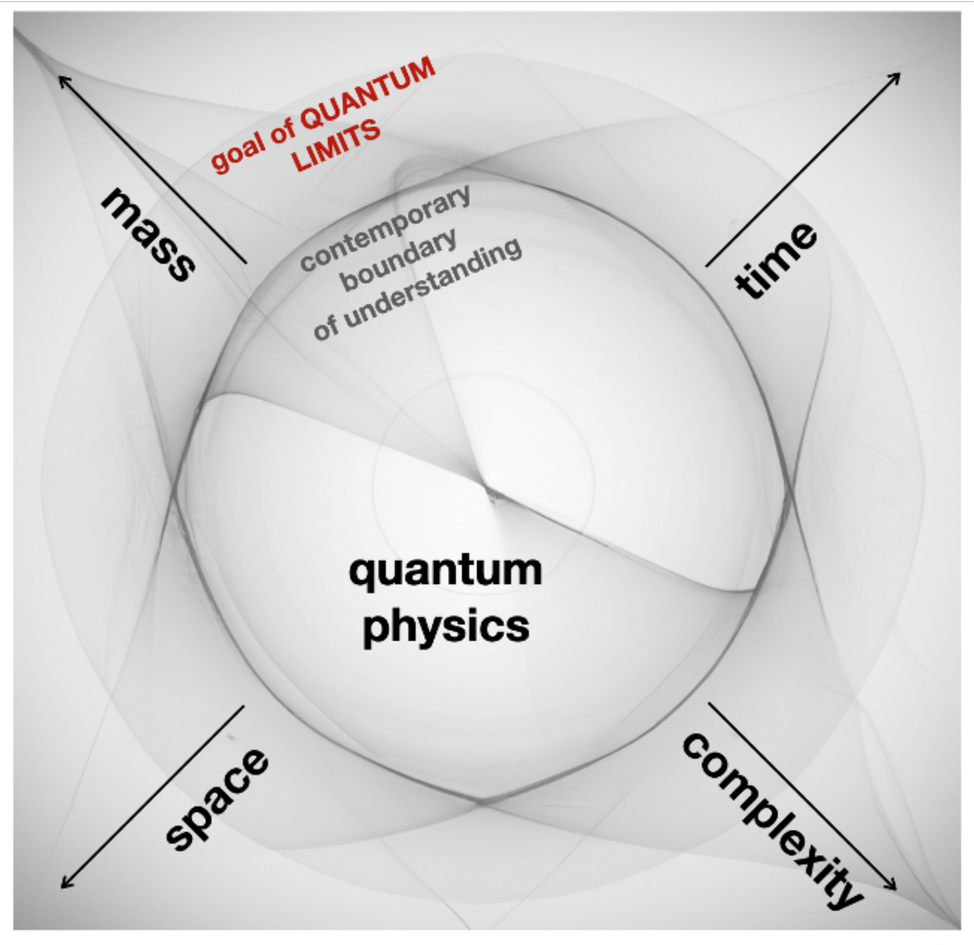
Department of Quantum Nanoscience
Opening the quantum world for innovation

SteeleLab

TU Delft

QUANTUM LIMITS

# Interferometric tests of quantum gravity




My project:

*Steele Lab*

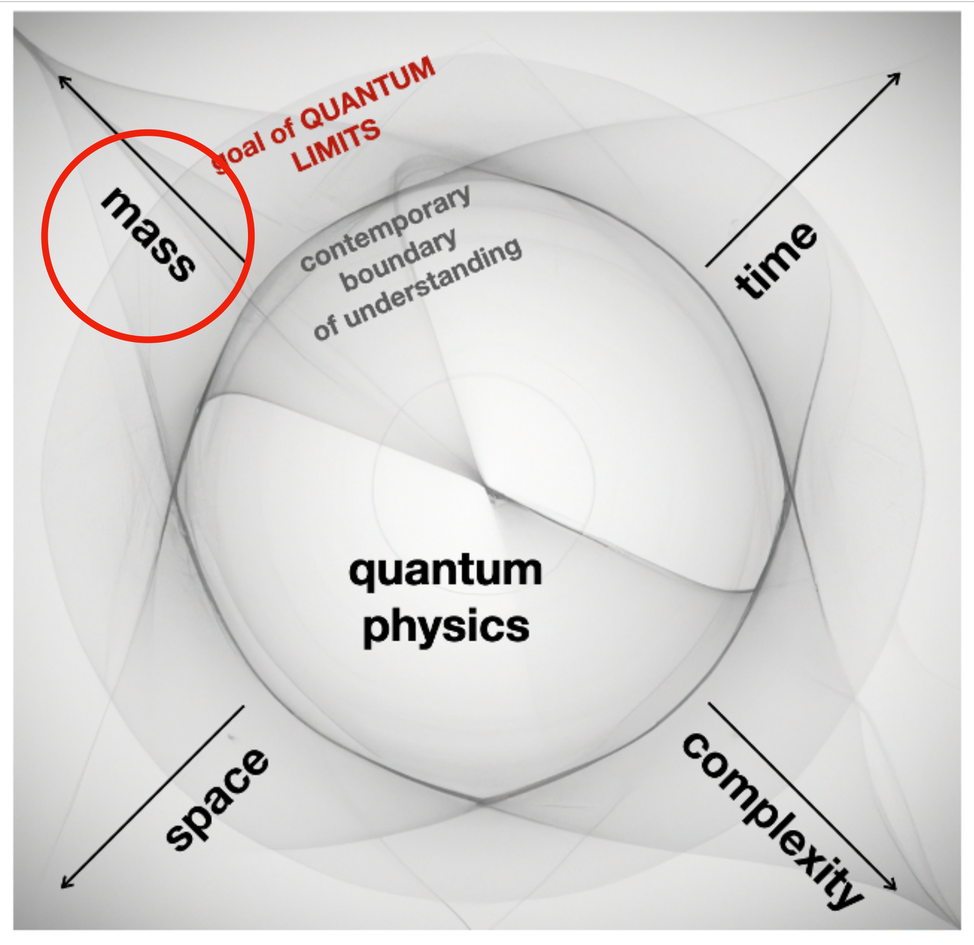
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# Interferometric tests of quantum gravity




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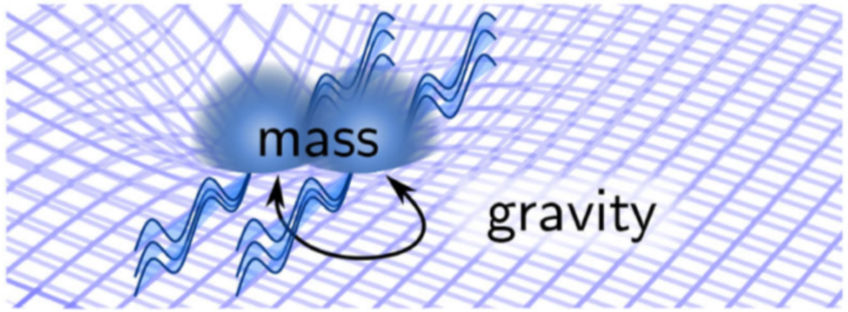
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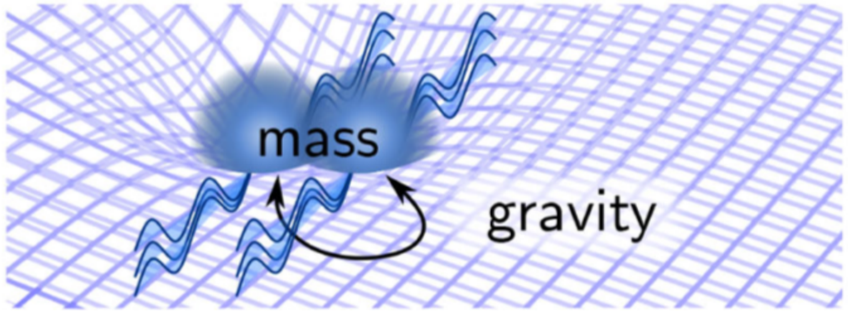
**Is gravity classical?**

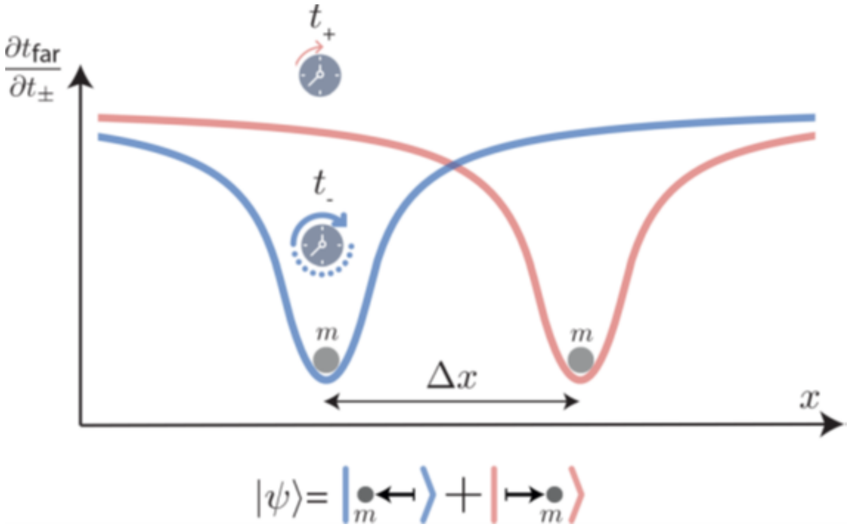
# Testing Diosi-Penrose collapse




Bose et al., 2025, Rev. Mod. Phys.

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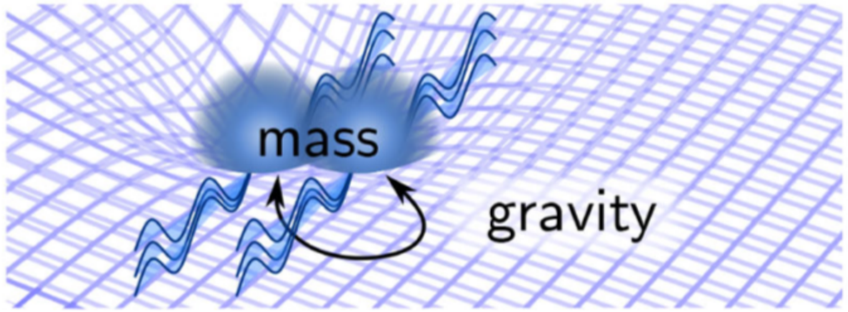


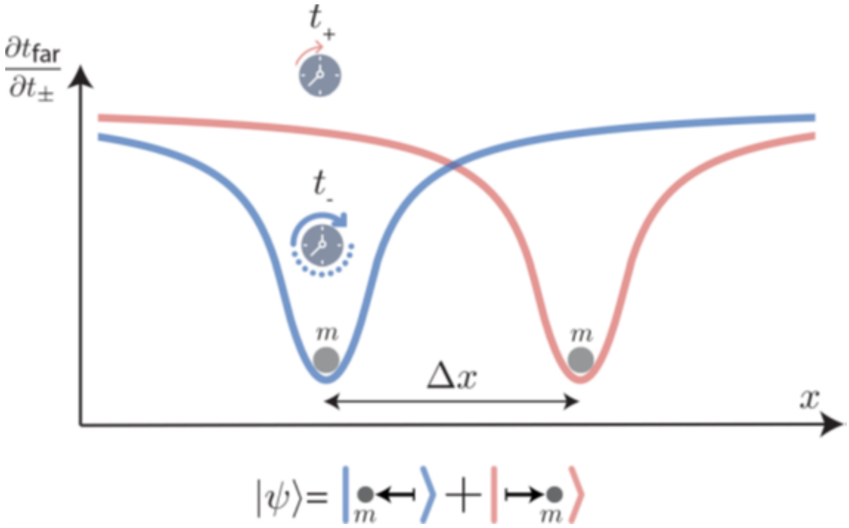

Bose et al., 2025, Rev. Mod. Phys.

Gely and Steele, 2021, AVS Quantum Sci.

# Testing Diosi-Penrose collapse




$$t_G \propto \hbar \frac{R}{Gm^2}$$

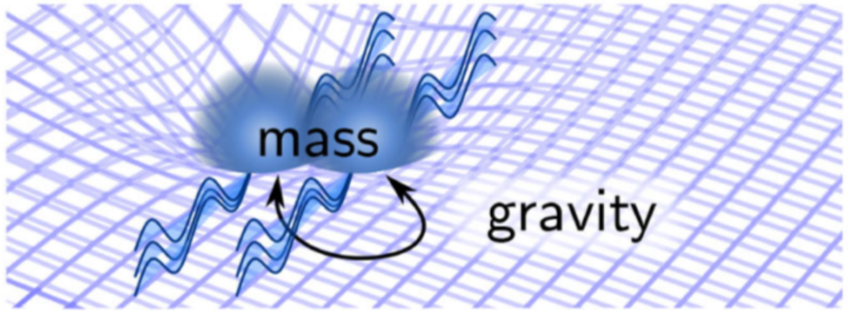





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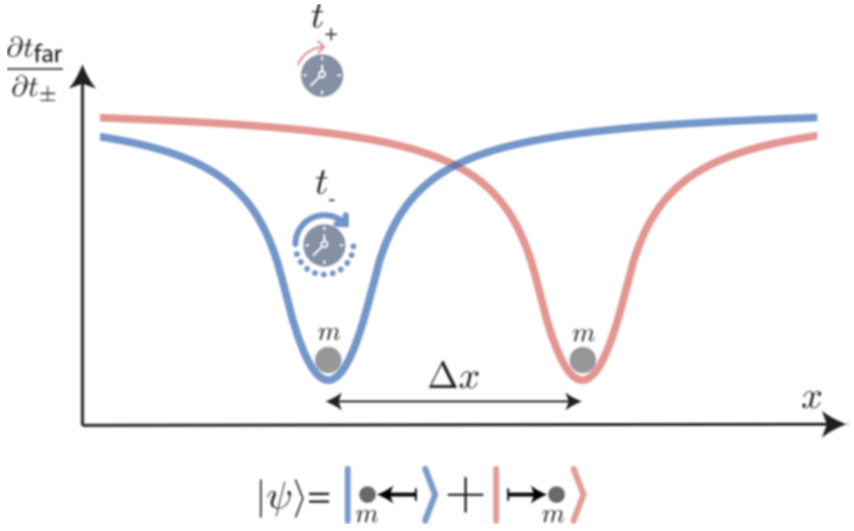
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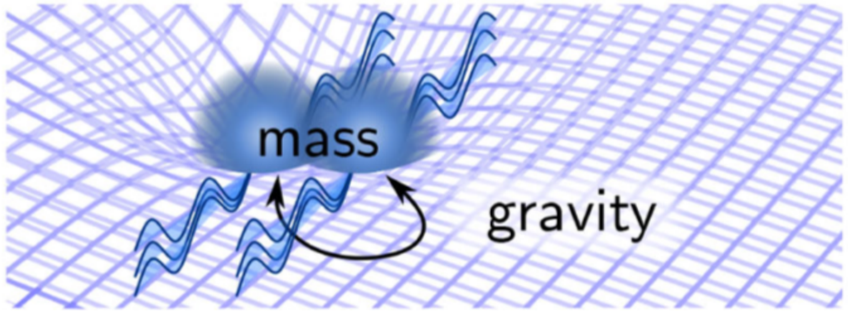

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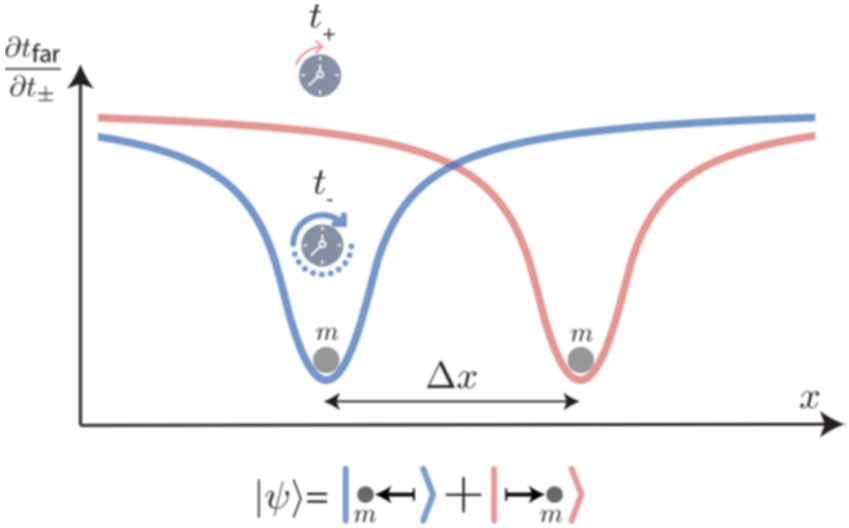
Heavy resonator




Bose et al., 2025, Rev. Mod. Phys.
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# Testing Diosi-Penrose collapse




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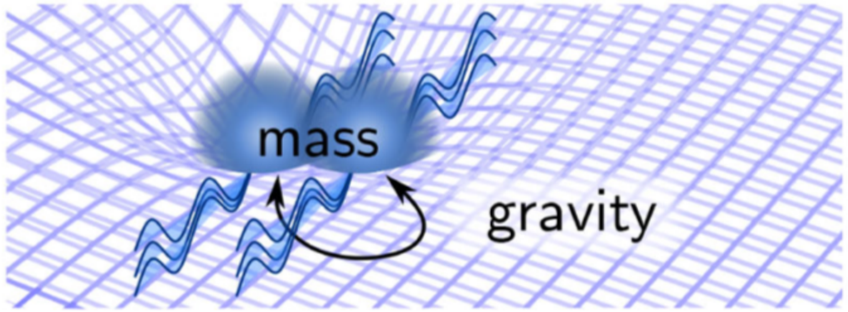
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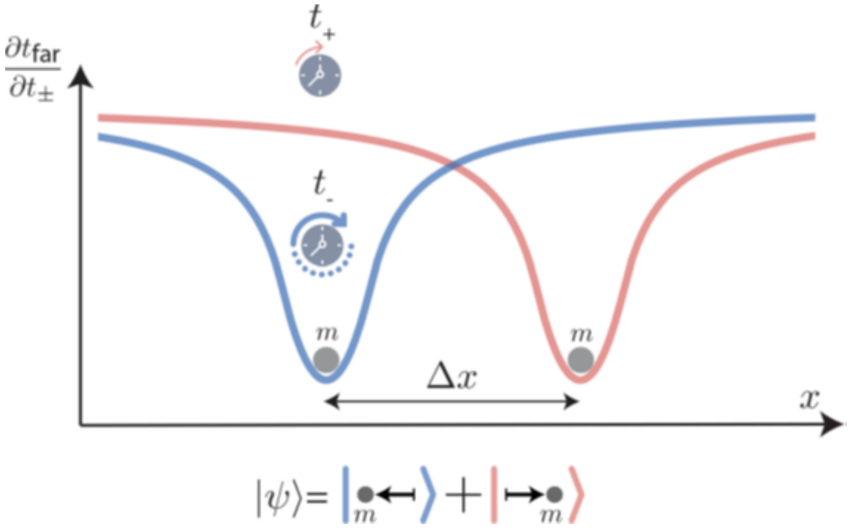
Long coherence time
→ High Q



Bose et al., 2025, Rev. Mod. Phys.
Gely and Steele, 2021, AVS Quantum Sci.

# Testing Diosi-Penrose collapse

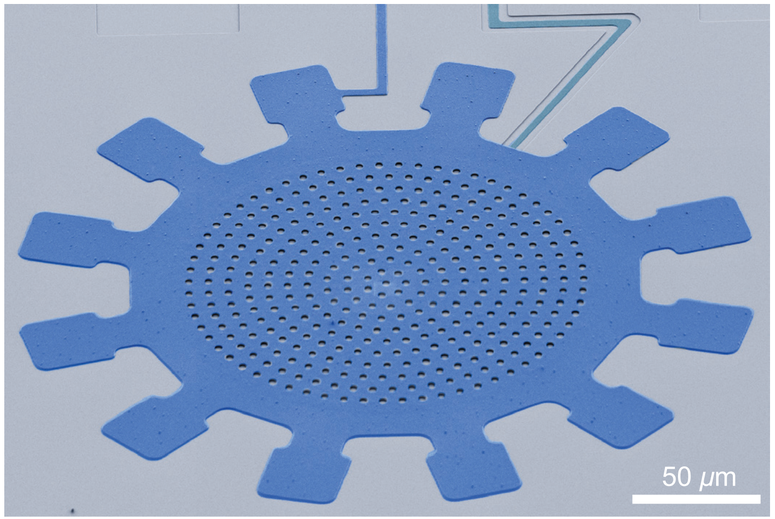



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Heavy resonator

Long coherence time
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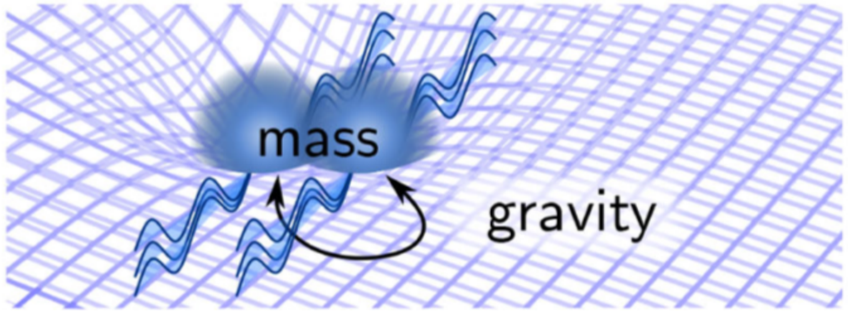



Bose et al., 2025, Rev. Mod. Phys.

Gely and Steele, 2021, AVS Quantum Sci.

Youssefi et al., 2023, Nature Physics

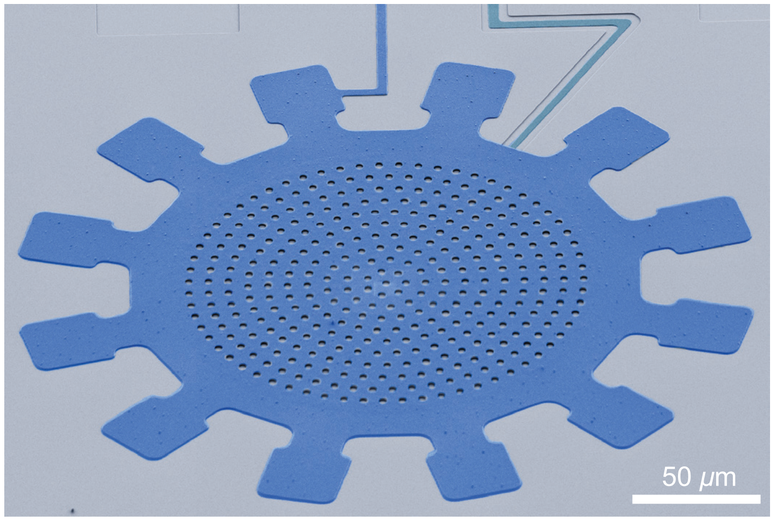
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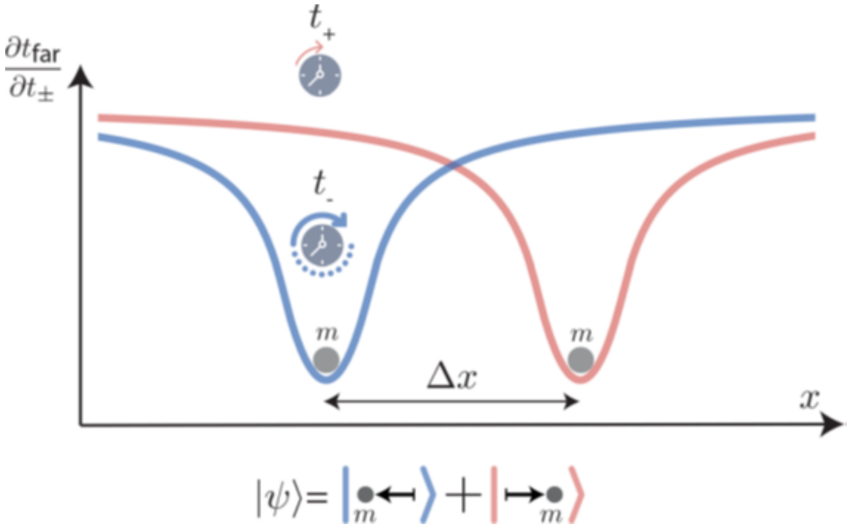



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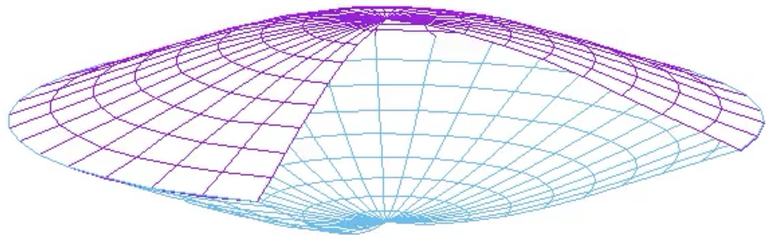
Long coherence time
→ High Q




Make a cat!

*How?*



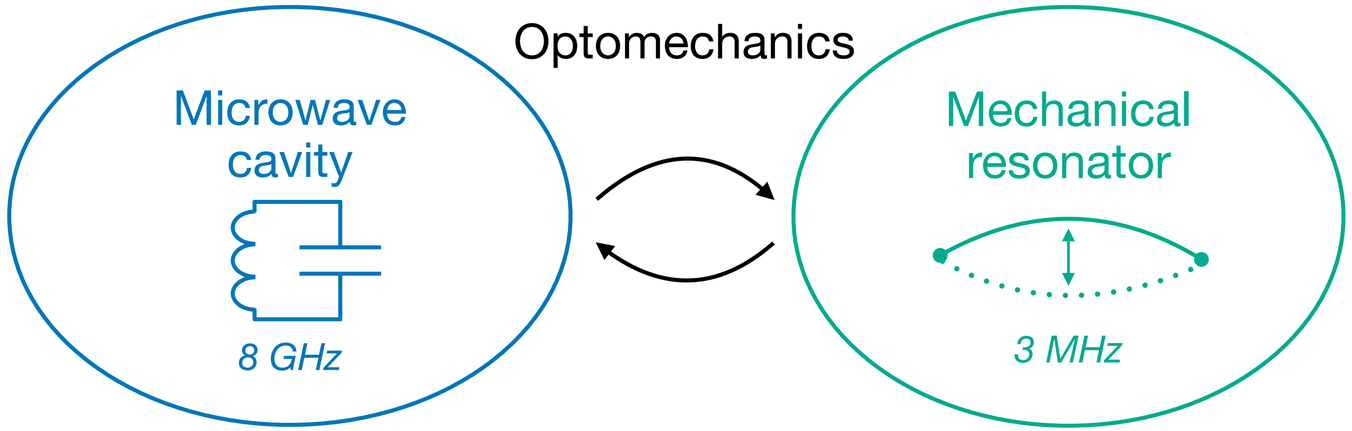
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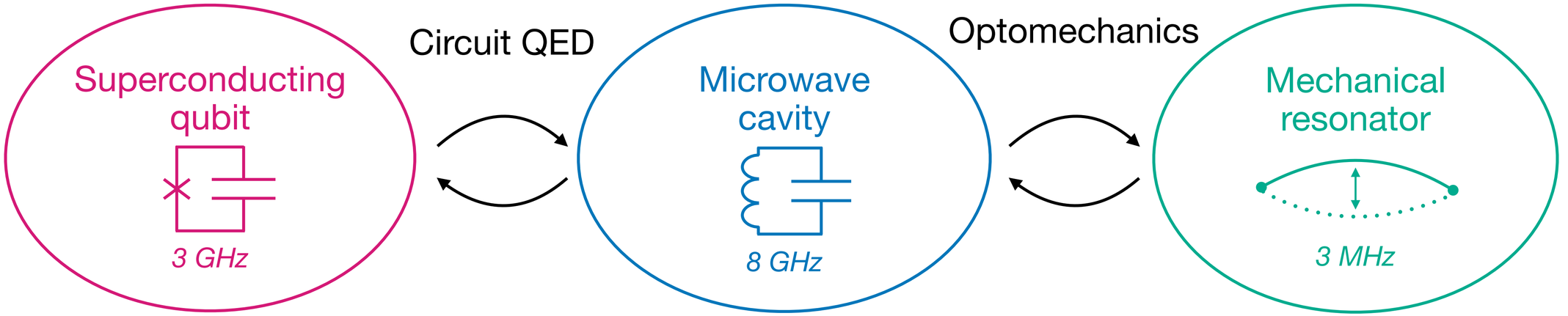
Youssefi et al., 2023, Nature Physics

# Making superpositions in drums with circuit QED

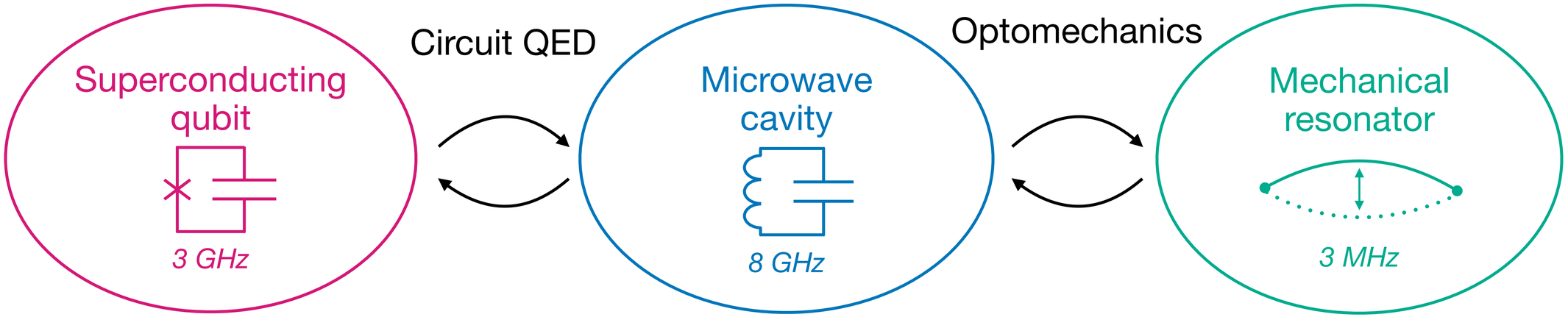
# Recipe for a mechanical cat

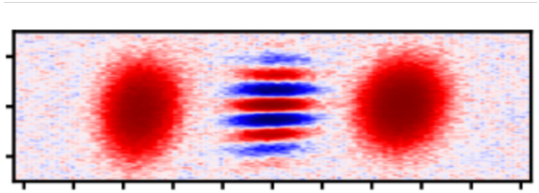


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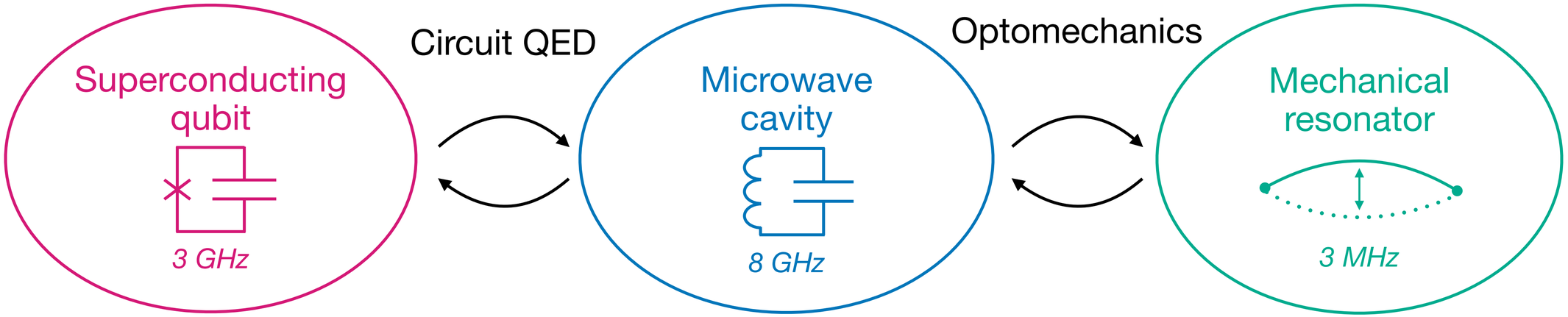
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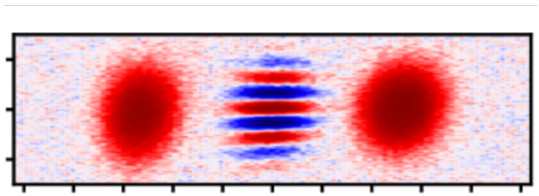


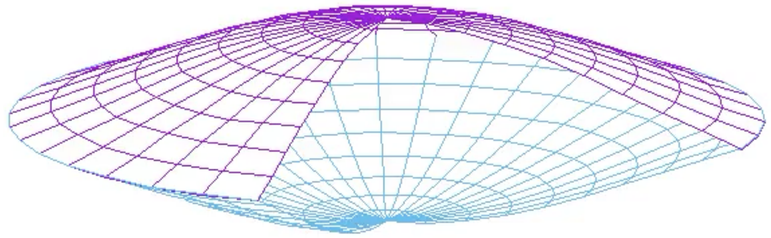
Microwave cat

# Recipe for a mechanical cat



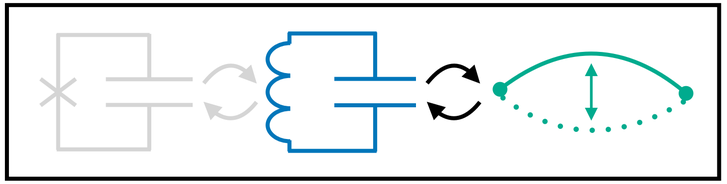



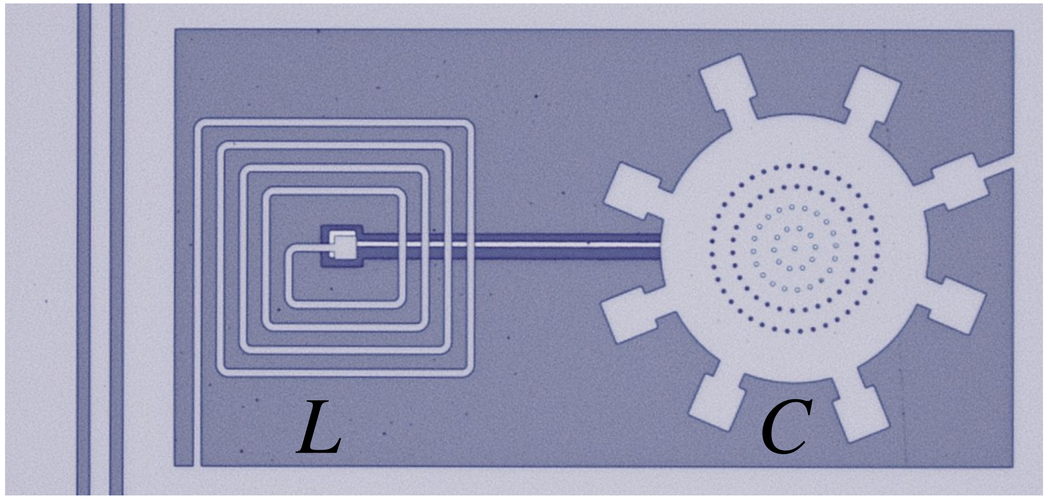
Microwave cat



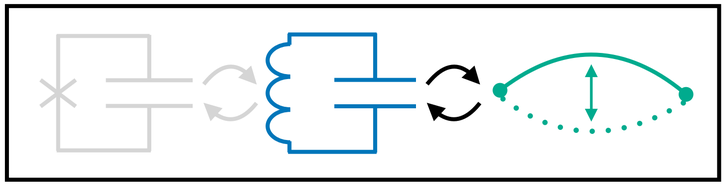
Mechanical cat

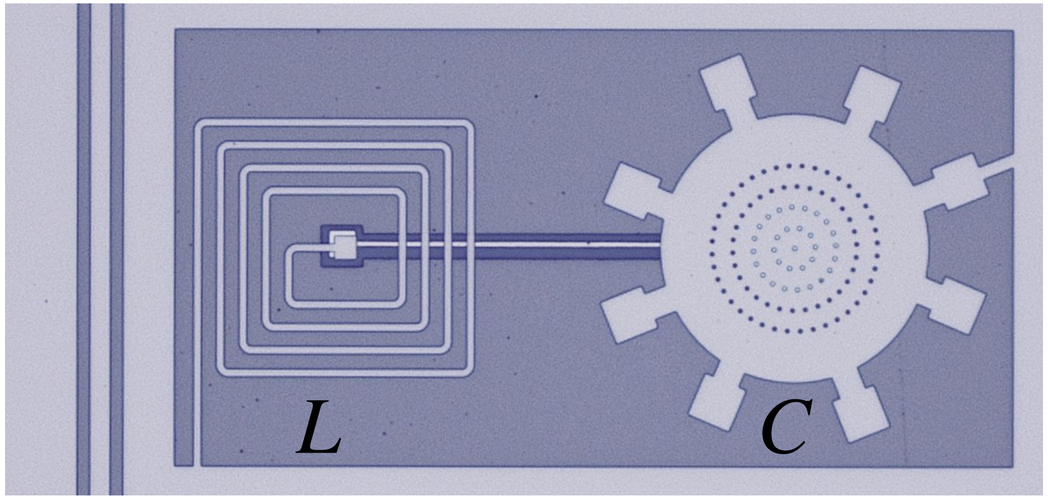
# Controlling the drum

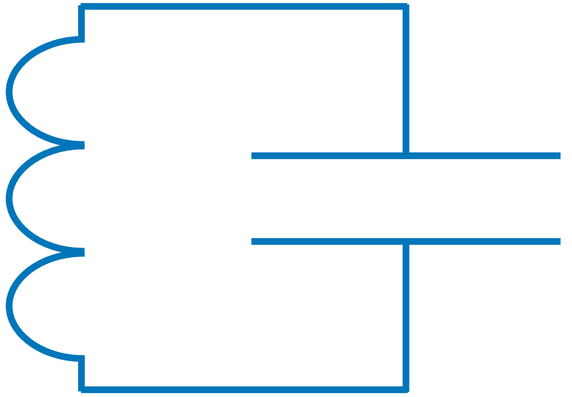




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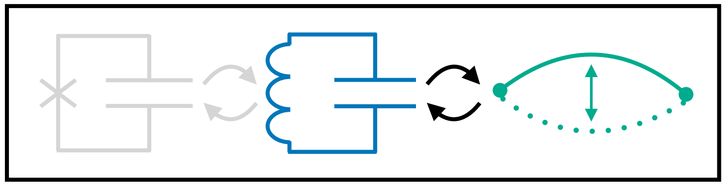


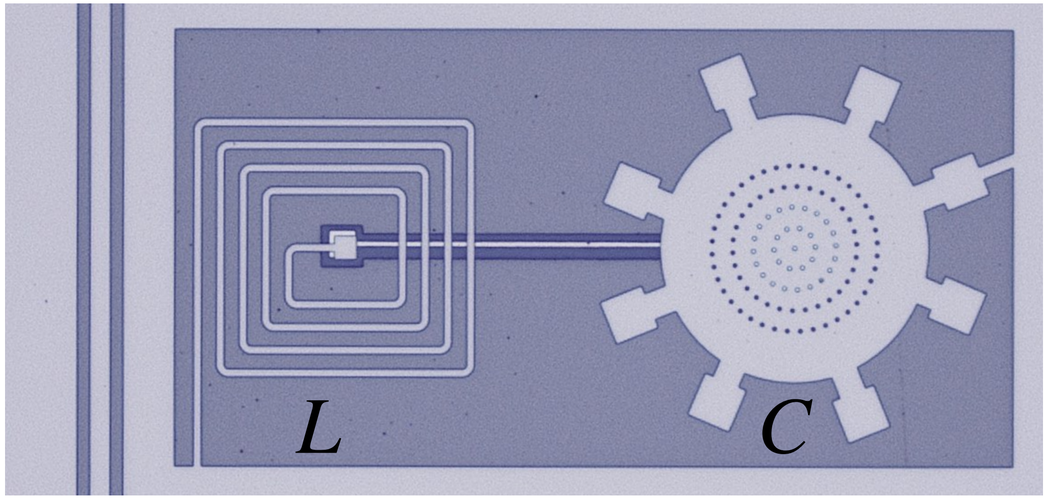


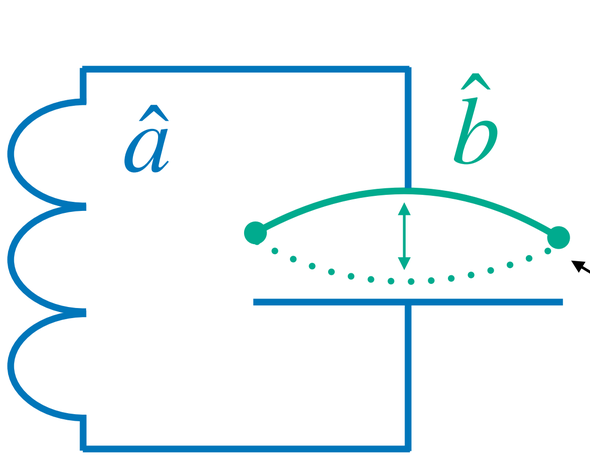



$$\omega_c = \sqrt{\frac{1}{LC}}$$

# Controlling the drum



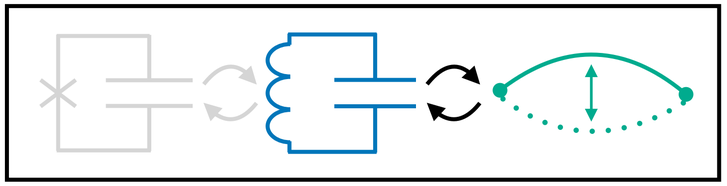


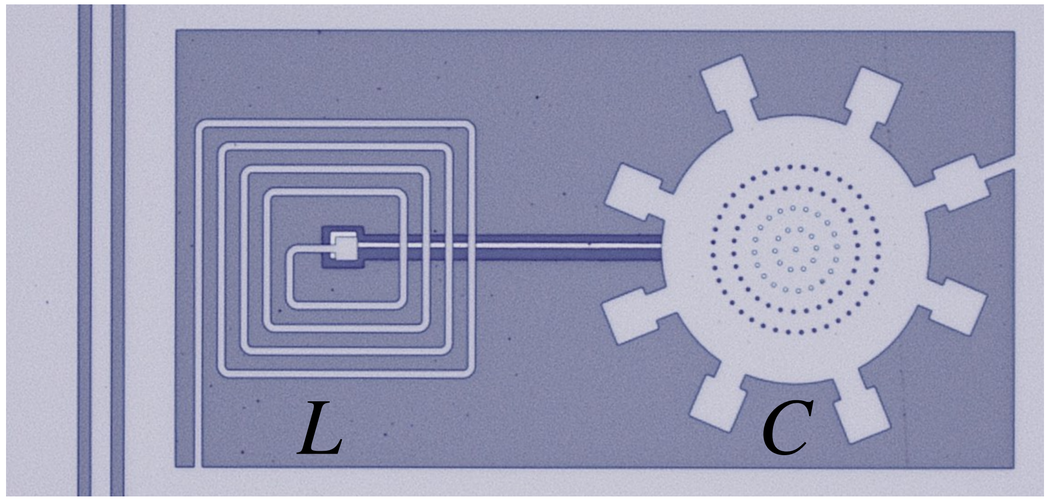



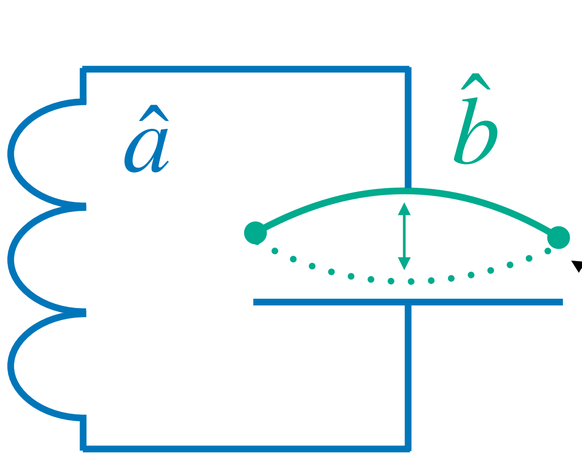

$$\omega_c = \sqrt{\frac{1}{LC}}$$

$C(x)$

# Controlling the drum






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

$C(x)$

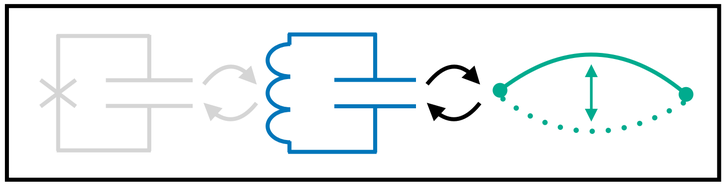
*Interaction:*

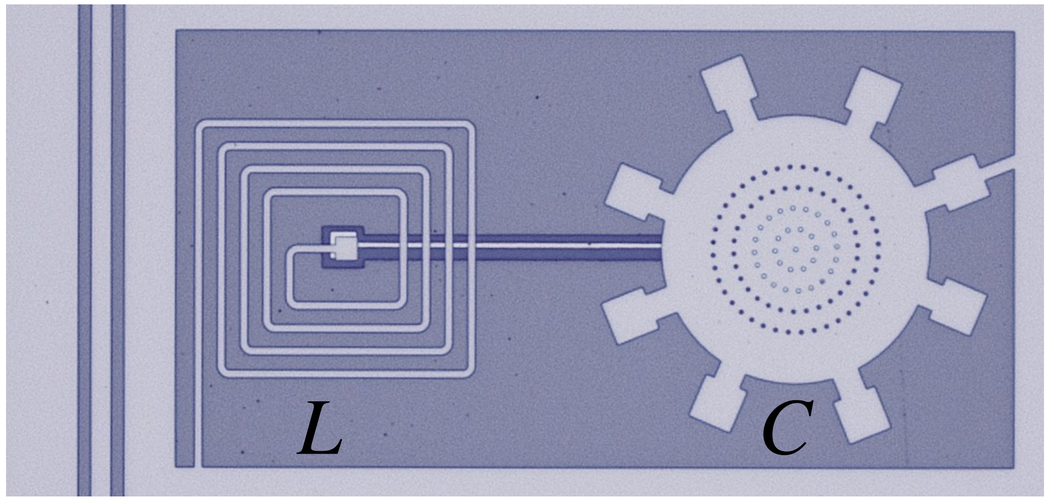
$$\hbar g_0 \hat{a}^\dagger \hat{a} (\hat{b} + \hat{b}^\dagger)$$

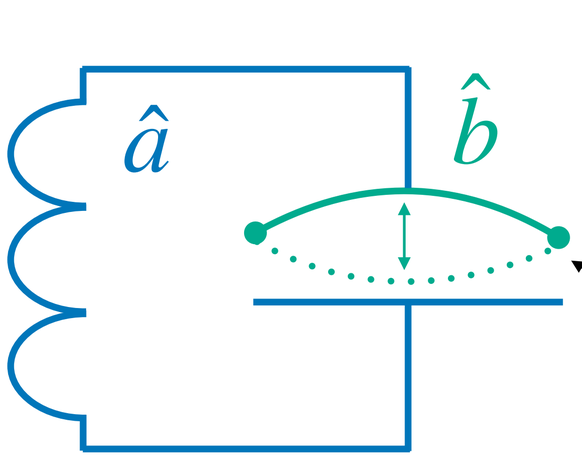
(Voltage)²

Position

# Controlling the drum






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

$C(x)$

Coupling rate $g_0 = x_{zpf}\dfrac{d\omega_c}{dx}$ ~ 10 Hz

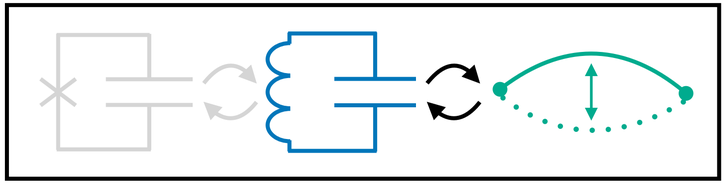
**Very small!**

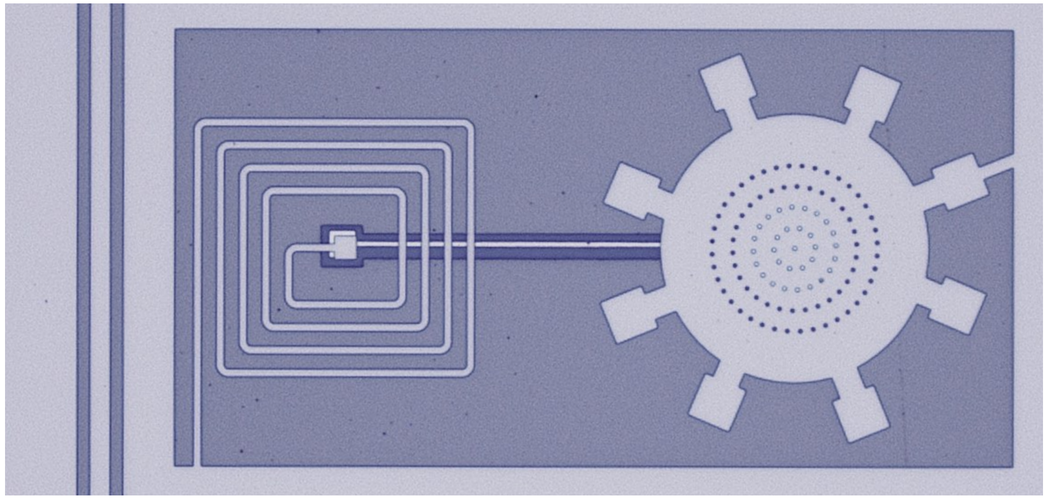
*Interaction:*

$$\hbar g_0 \hat{a}^\dagger \hat{a}(\hat{b} + \hat{b}^\dagger)$$

(Voltage)²  Position

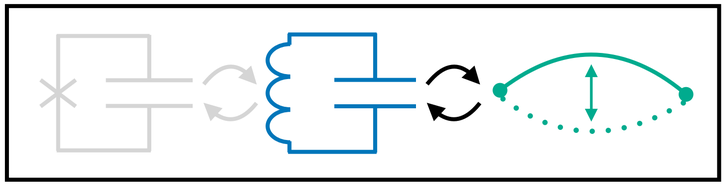
# Strong driving for strong coupling

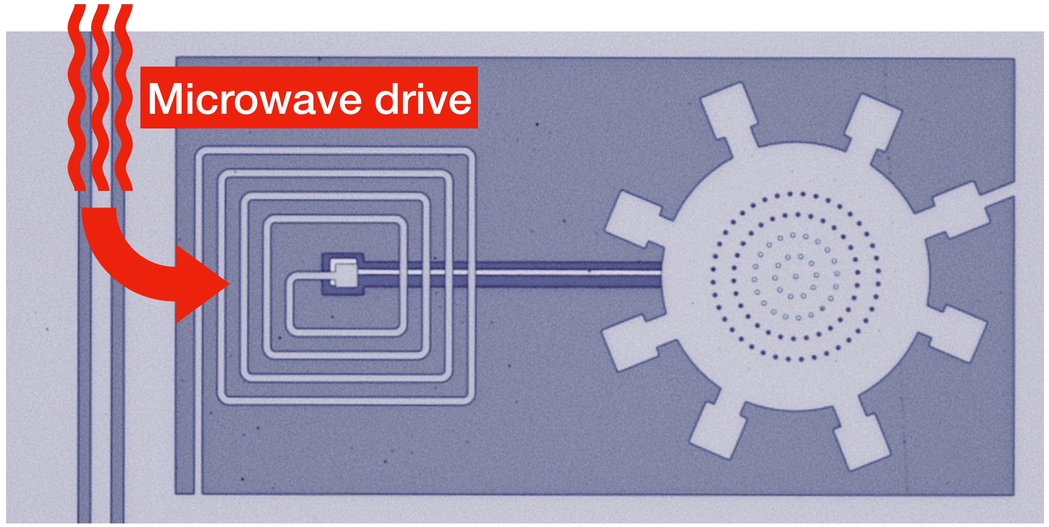




*No driving:* $\hbar g_0 \hat{a}^\dagger \hat{a}(\hat{b} + \hat{b}^\dagger)$

# Strong driving for strong coupling






*No driving:* $\hbar g_0 \hat{a}^\dagger \hat{a}(\hat{b} + \hat{b}^\dagger)$

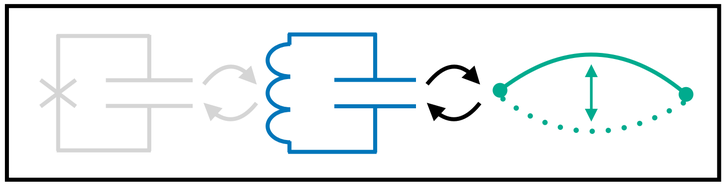
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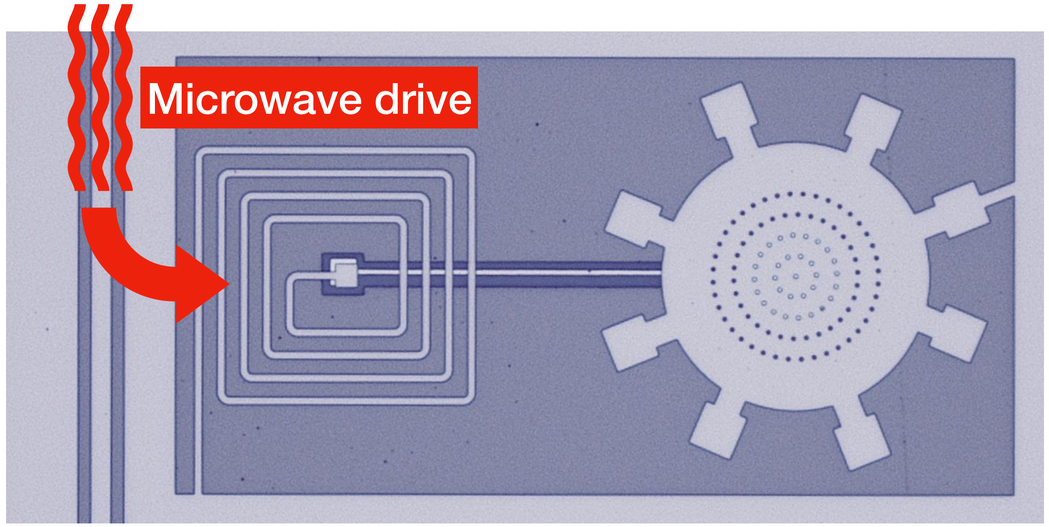
Write $\hat{a} \rightarrow \alpha + \delta\hat{a}$ and linearize

↓

**Strongly driven:** $\hbar g(\delta\hat{a} + \delta\hat{a}^\dagger)(\hat{b} + \hat{b}^\dagger)$

# Strong driving for strong coupling






*No driving:* $\hbar g_0 \hat{a}^\dagger \hat{a}(\hat{b} + \hat{b}^\dagger)$

↓

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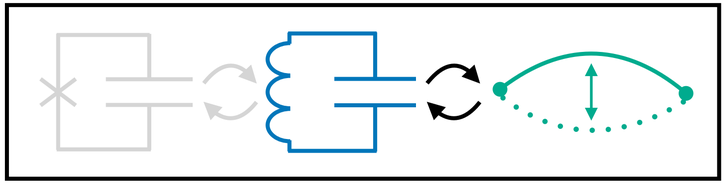
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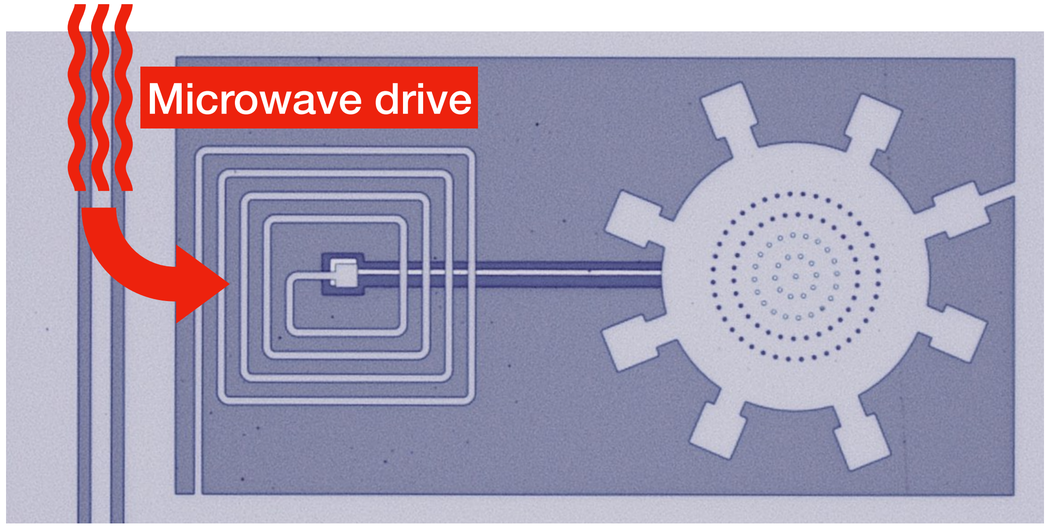
**Strongly driven:** $\hbar g(\delta\hat{a} + \delta\hat{a}^\dagger)(\hat{b} + \hat{b}^\dagger)$

$$g = \sqrt{N} g_0$$

Enhanced coupling!

# Strong driving for strong coupling





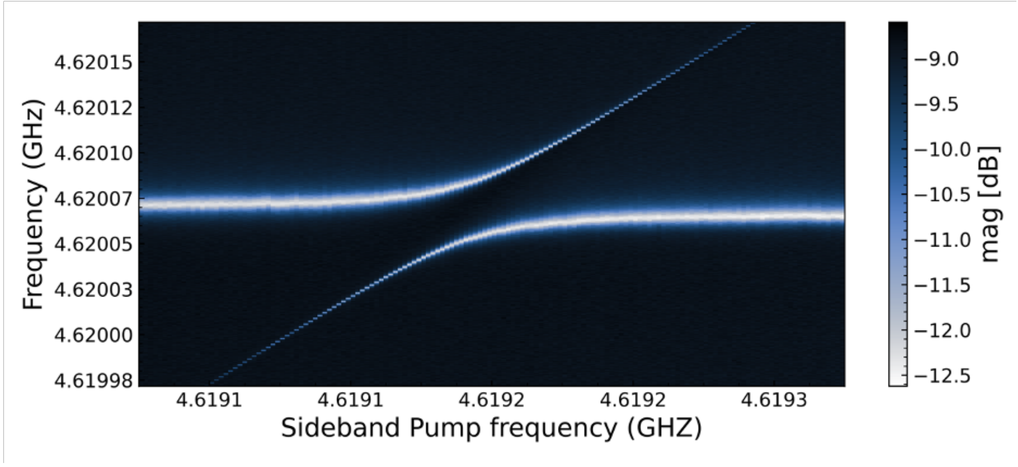

*No driving:* $\hbar g_0 \hat{a}^\dagger \hat{a}(\hat{b} + \hat{b}^\dagger)$

↓

Write $\hat{a} \rightarrow \alpha + \delta\hat{a}$ and linearize

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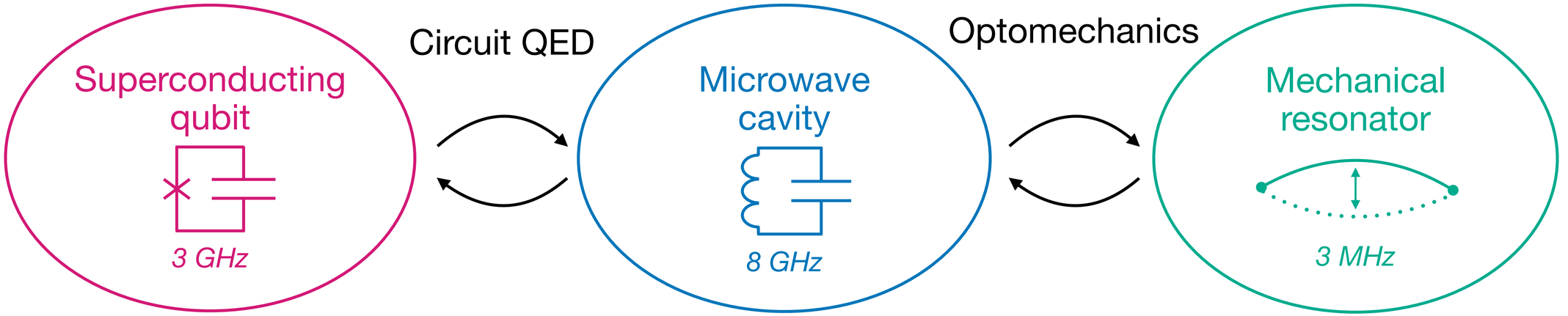
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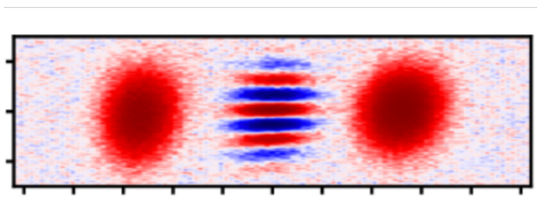


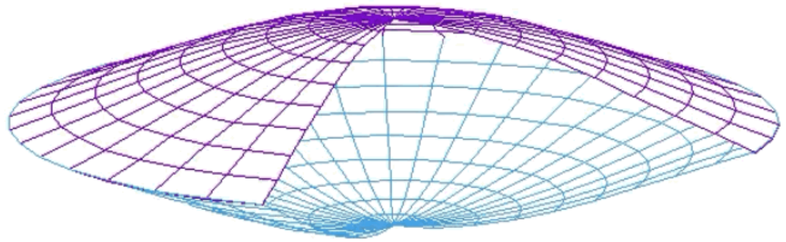

$$g = \sqrt{N} g_0$$

Enhanced coupling!

# Recipe for a mechanical cat



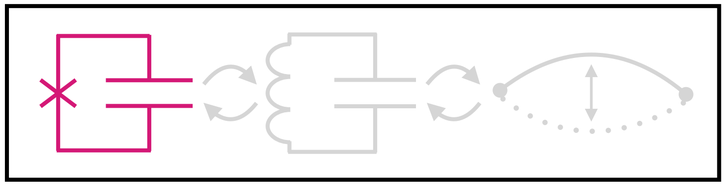





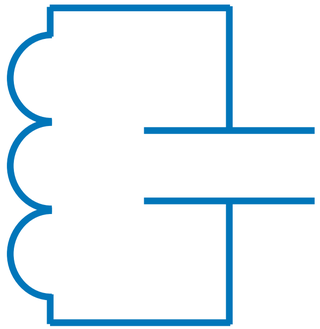
Microwave cat

Mechanical cat

# How to get a superpositon?

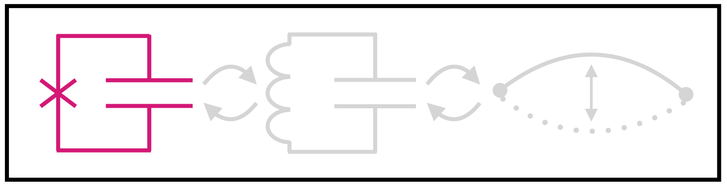


Linear resonator



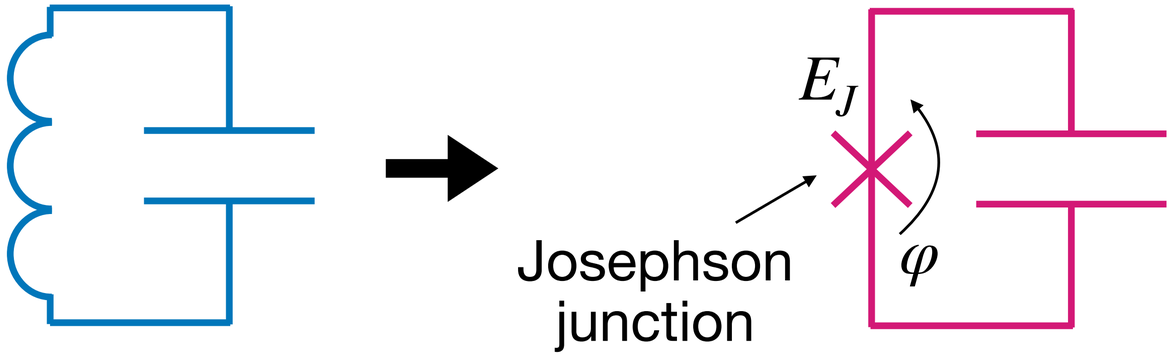
*Harmonic potential*

# How to get a superpositon?



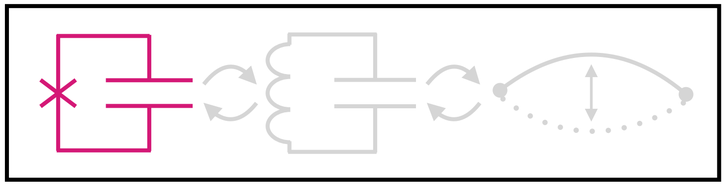
Linear resonator

**Superconducting qubit**



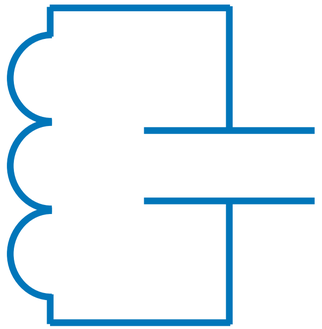

*Harmonic potential*

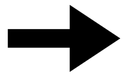
# How to get a superpositon?

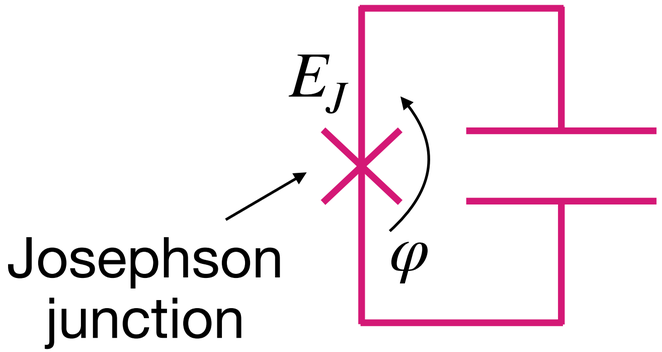


Linear resonator

**Superconducting qubit**





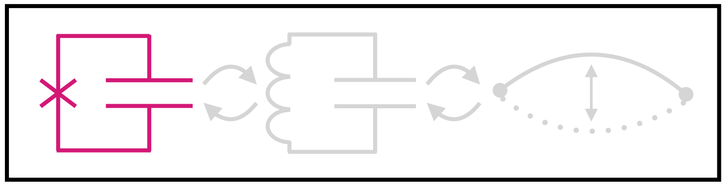



*Harmonic potential*

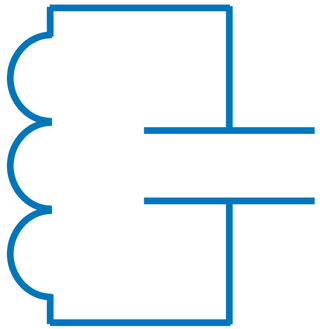
*= nonlinear inductor*

Potential = $-E_J \cos(\varphi)$

# How to get a superpositon?

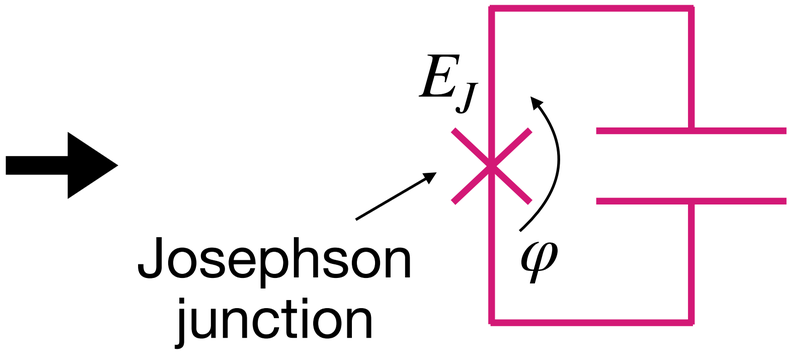


Linear resonator



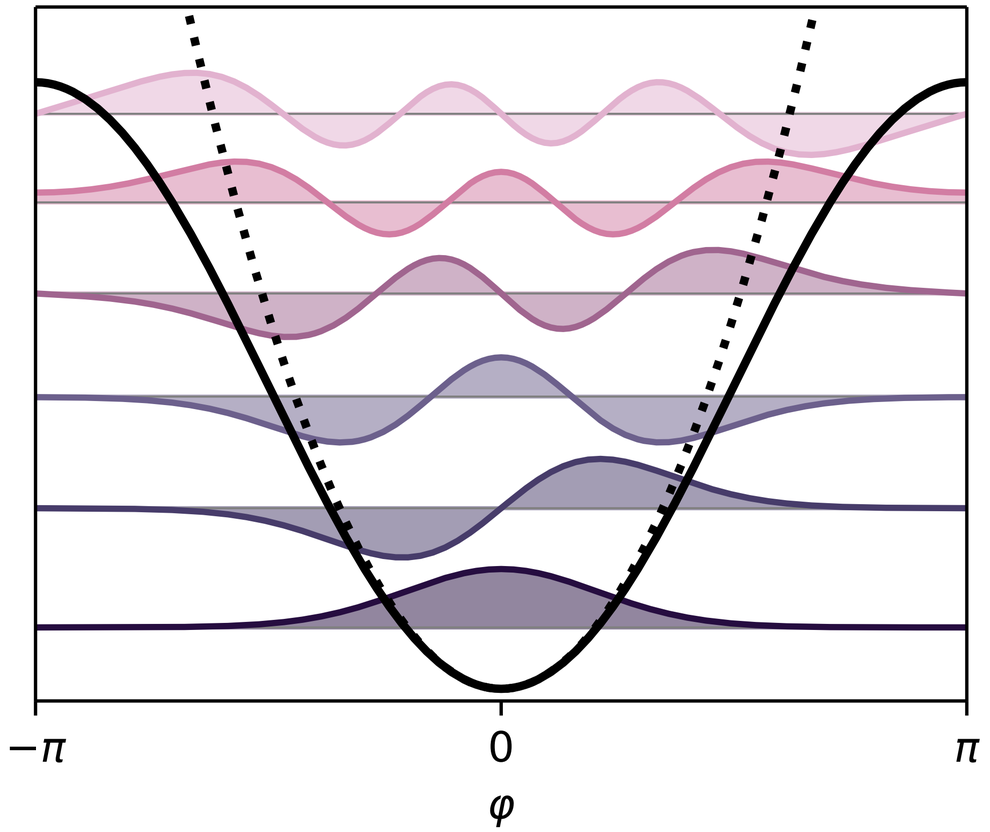
*Harmonic potential*

**Superconducting qubit**

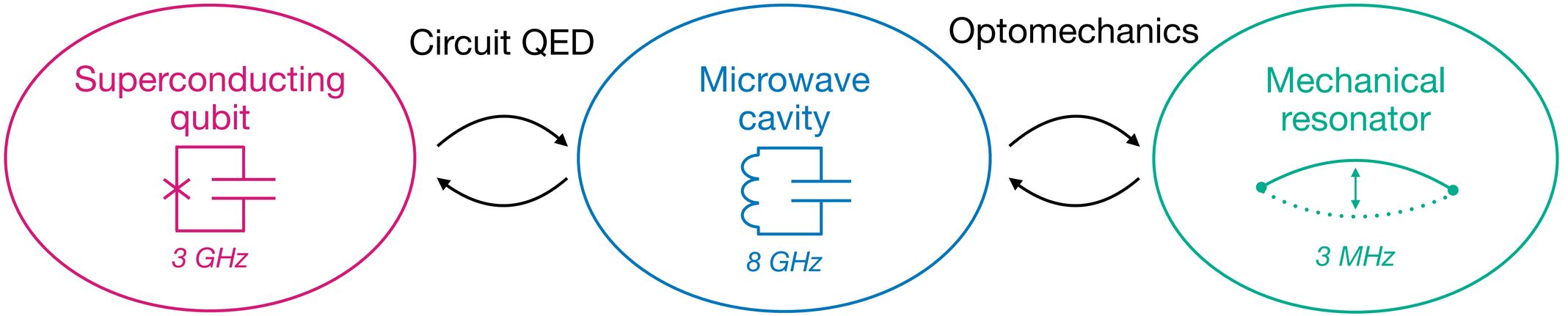



*= nonlinear inductor*

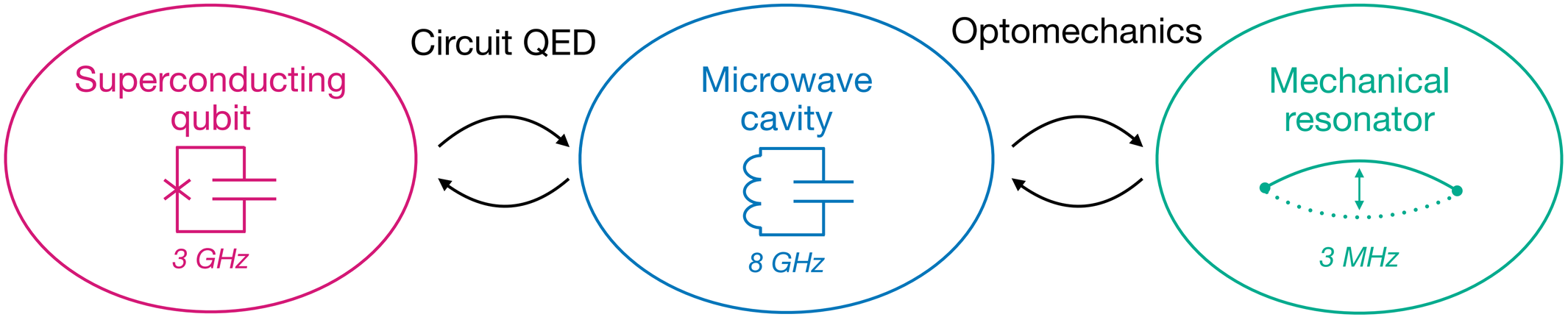
Potential = $-E_J \cos(\varphi)$

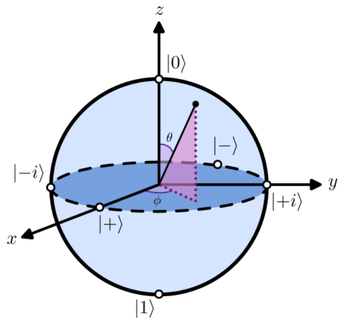


# Recipe for a mechanical cat

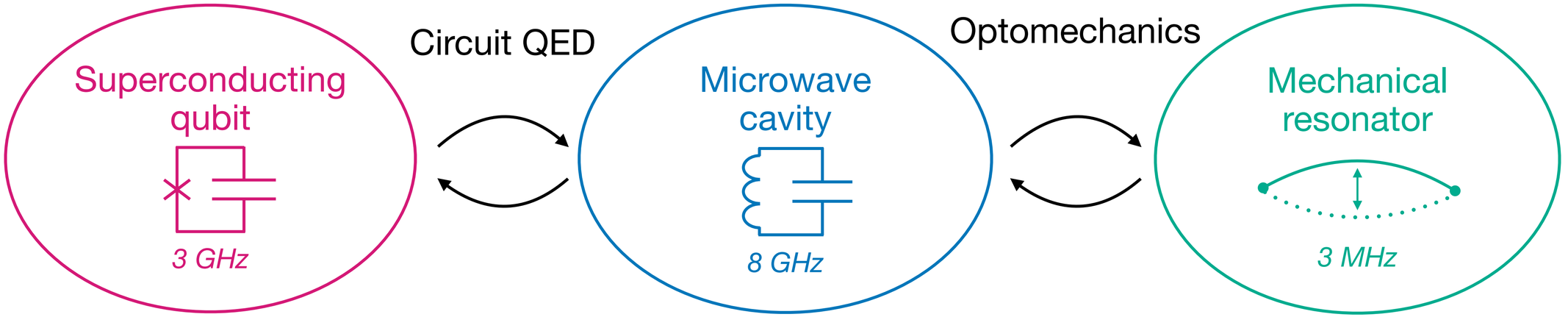


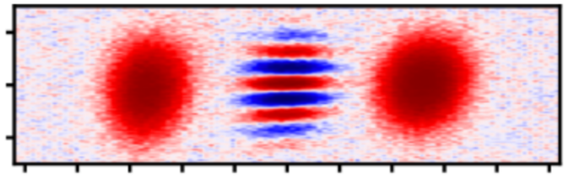
# Recipe for a mechanical cat



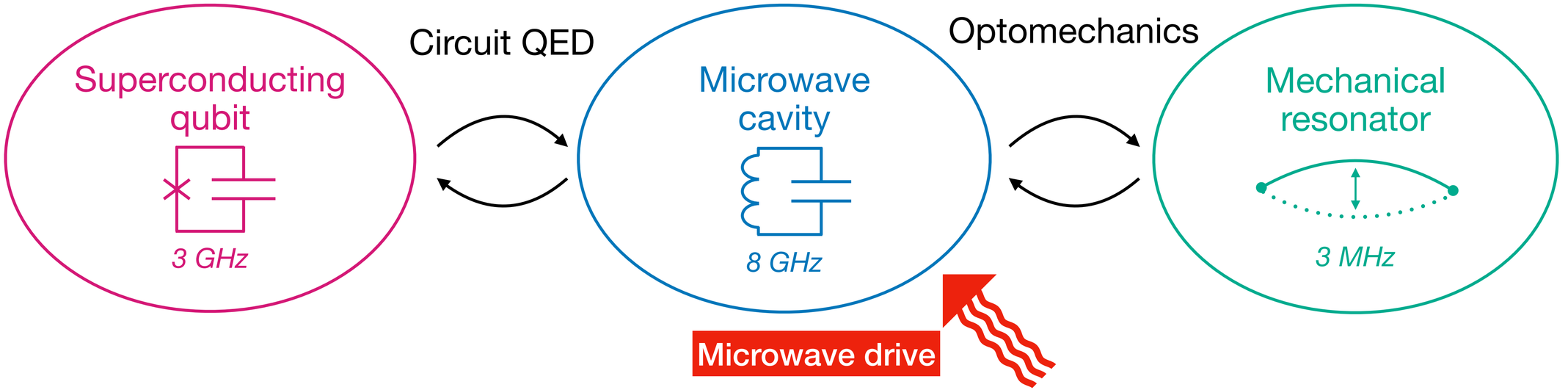



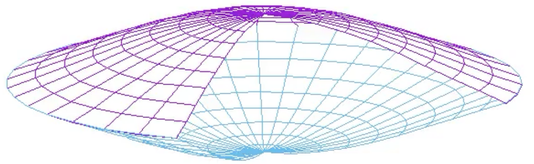
# Recipe for a mechanical cat



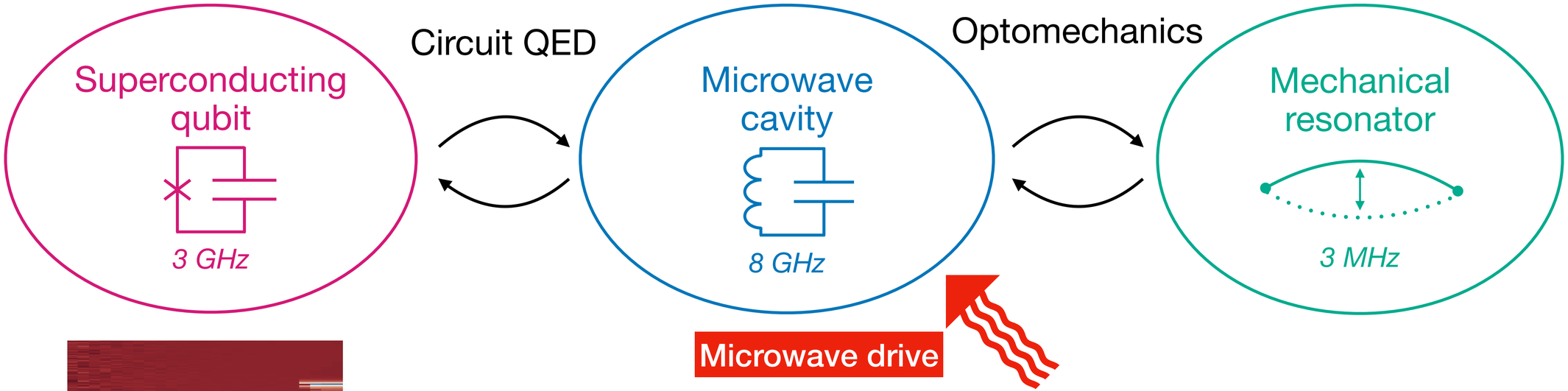



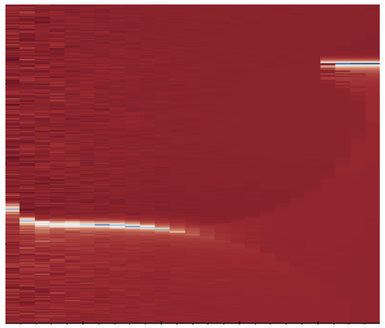
# Recipe for a mechanical cat



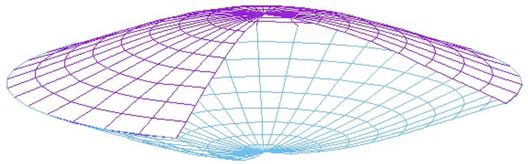



# Recipe for a mechanical cat

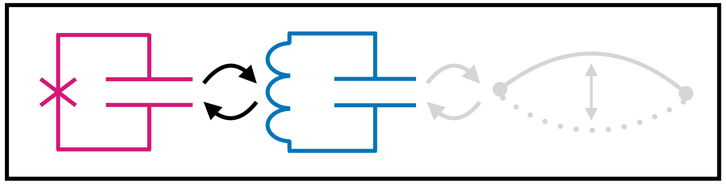


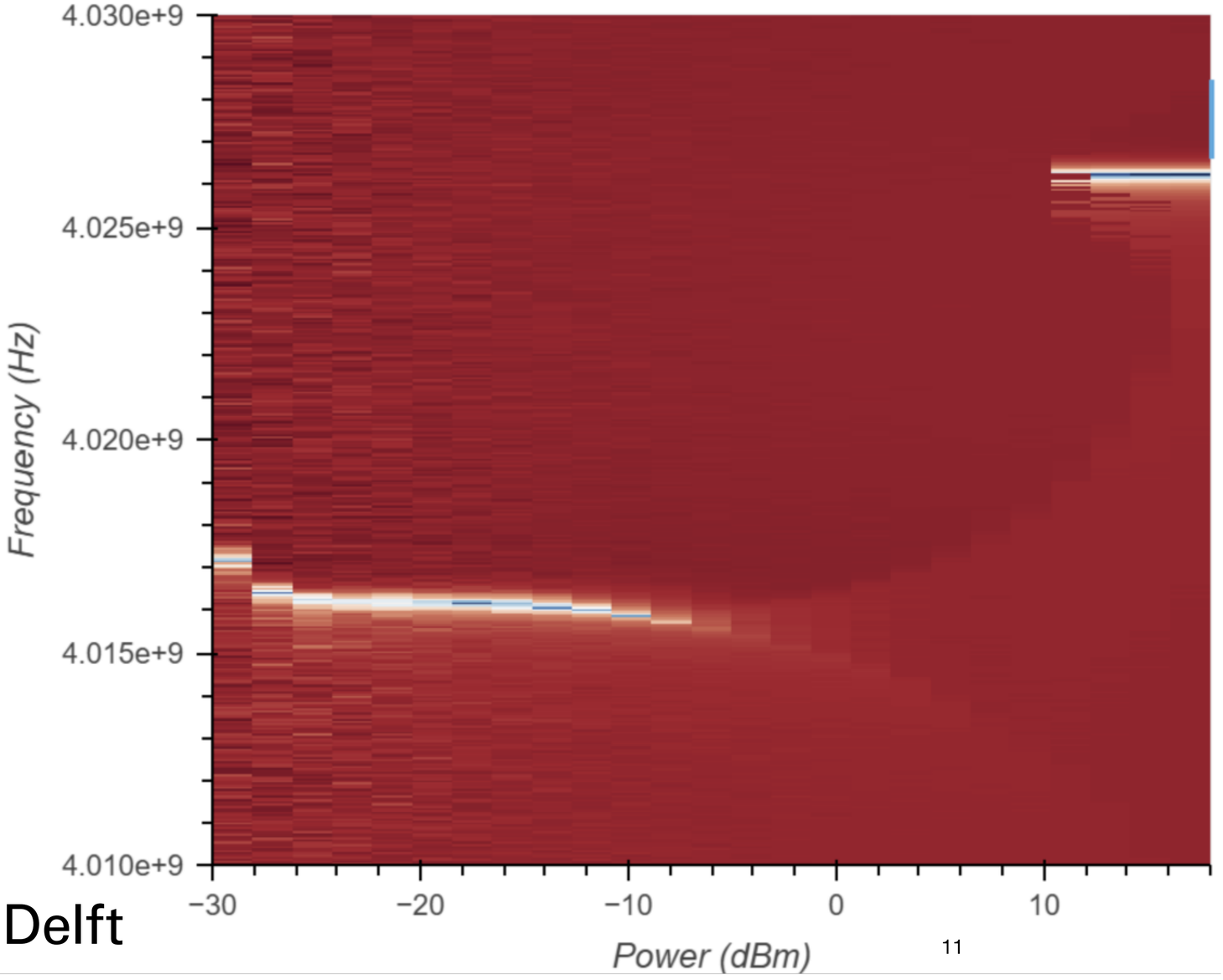





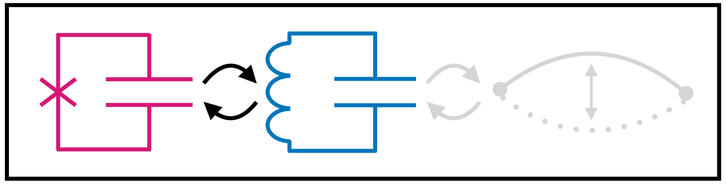


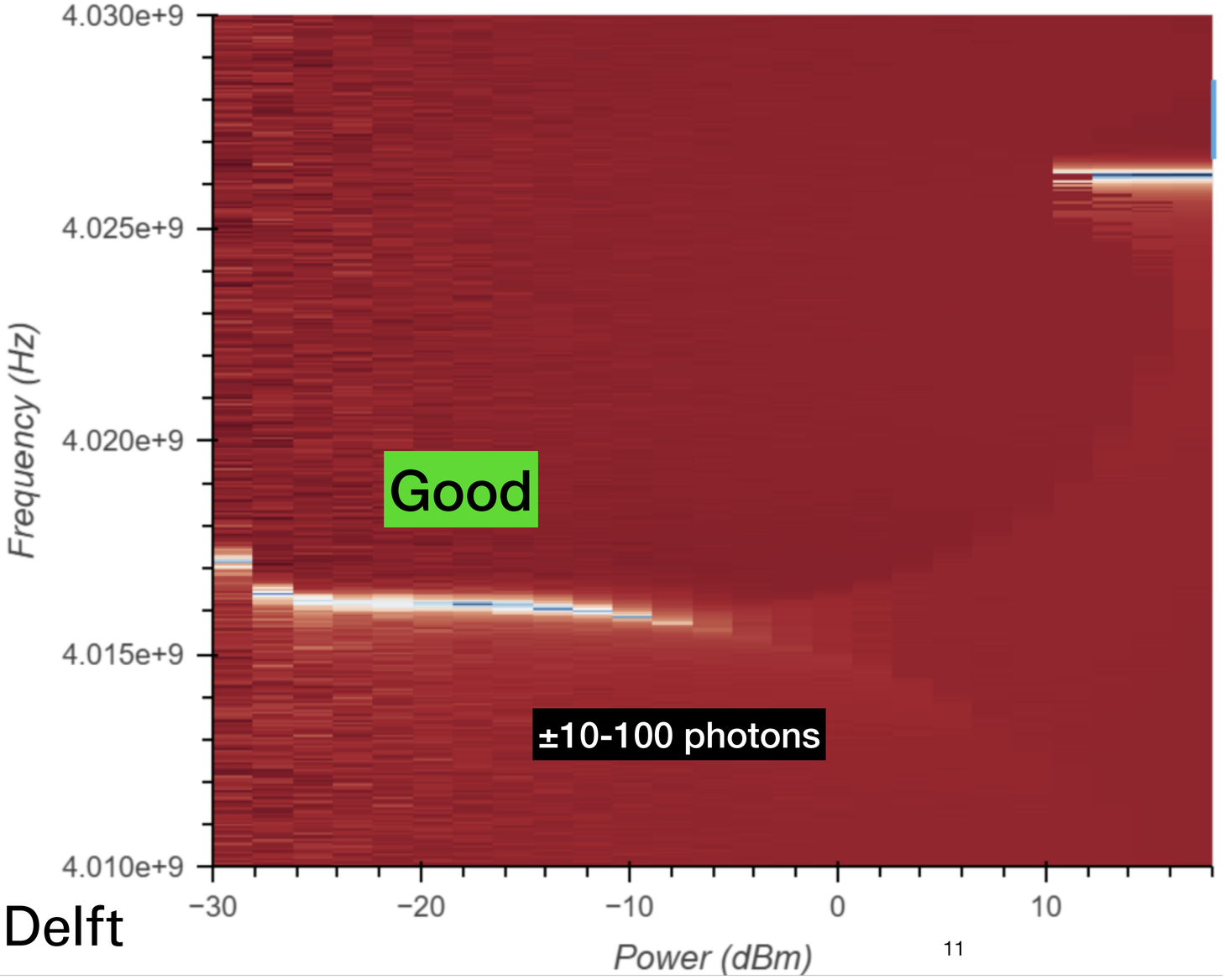
# Qubit ‘punch out’



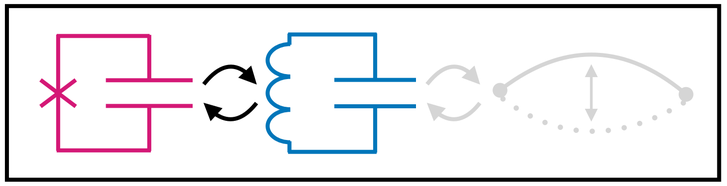


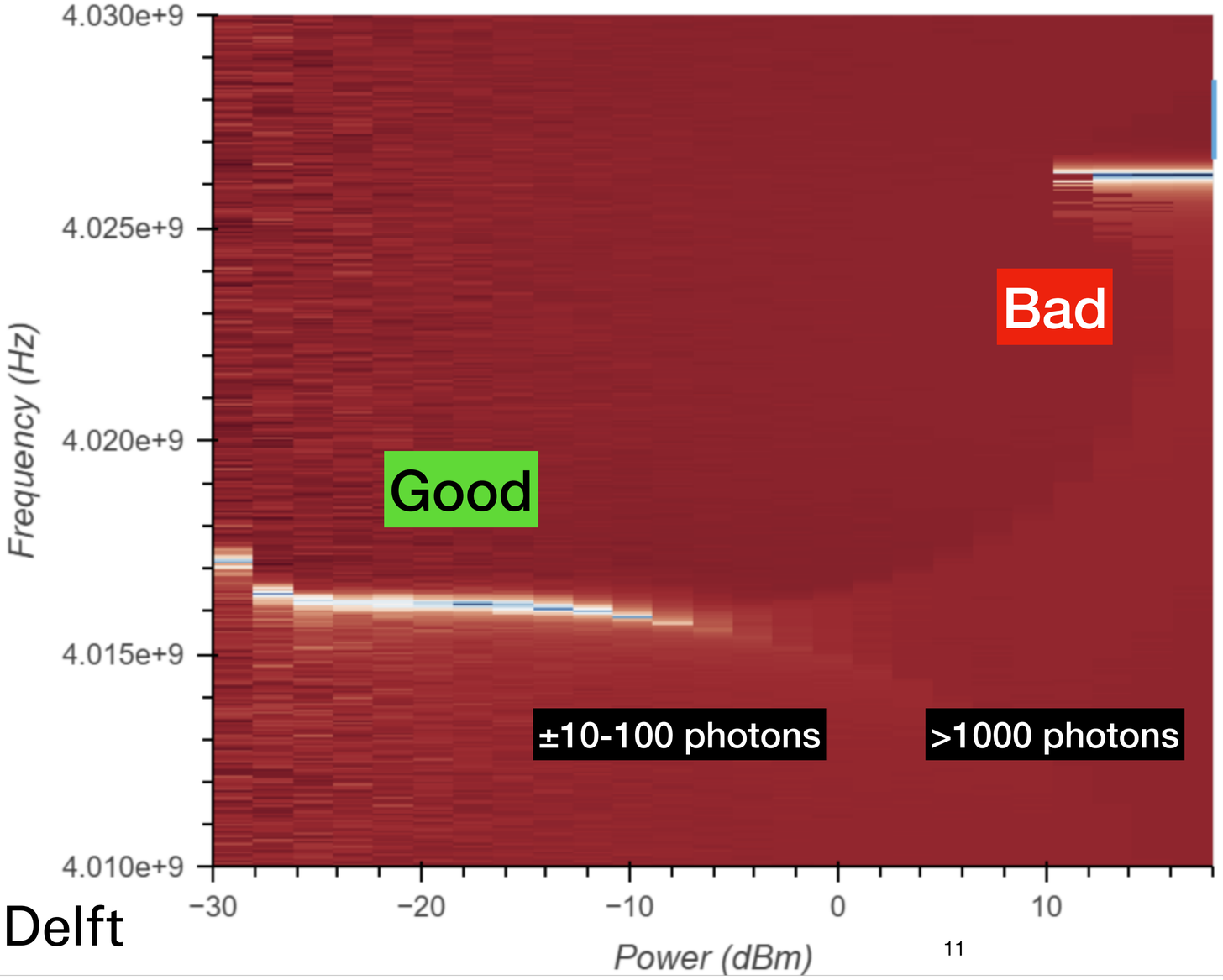
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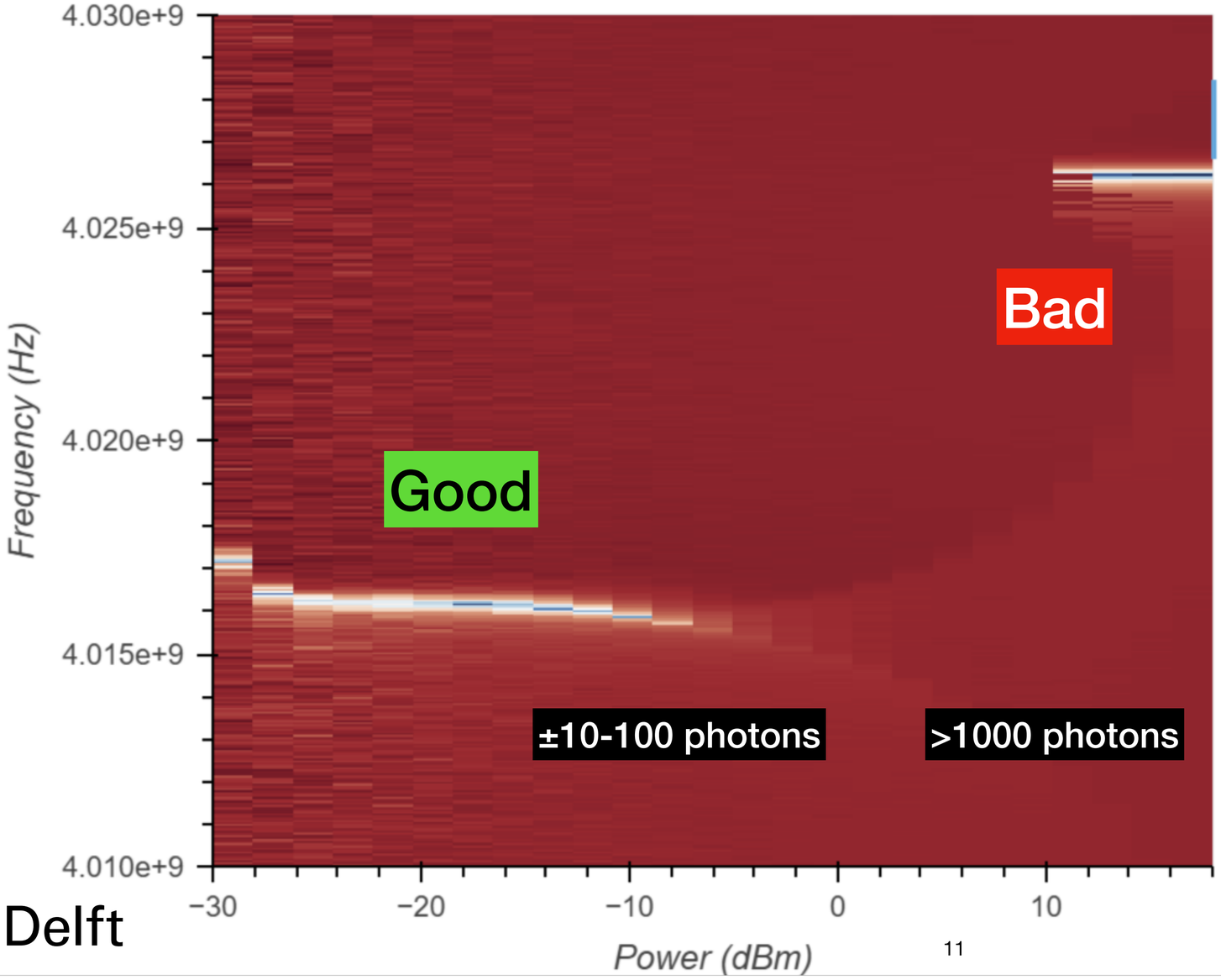


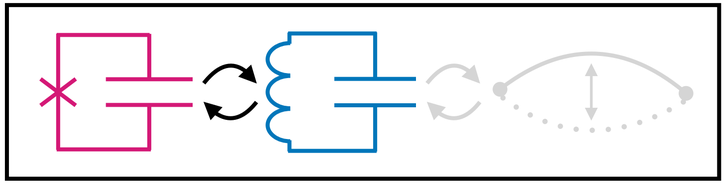
# Qubit ‘punch out’

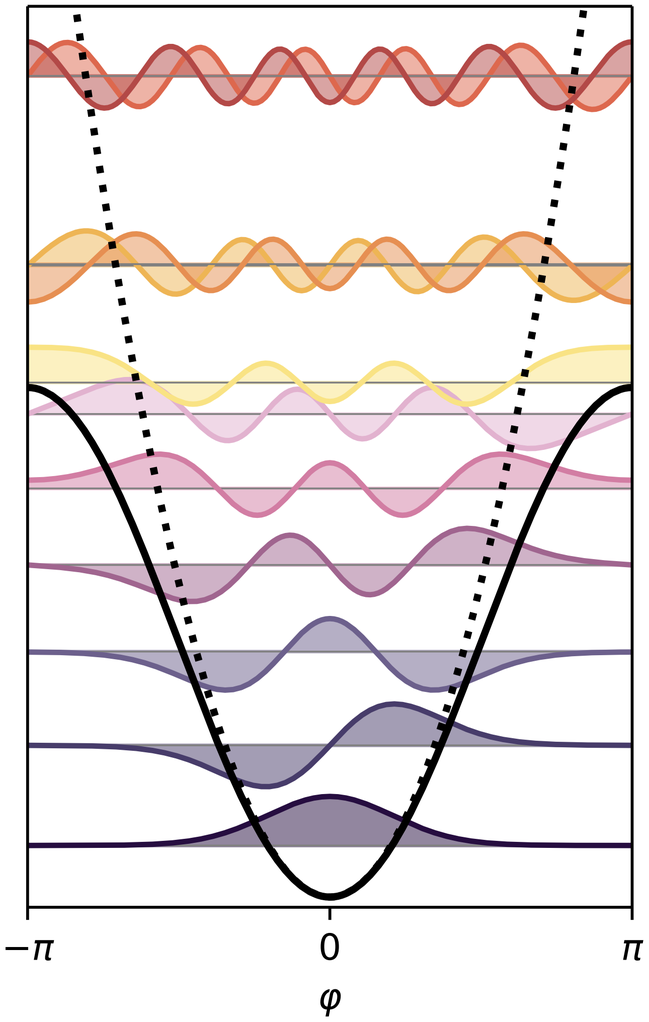




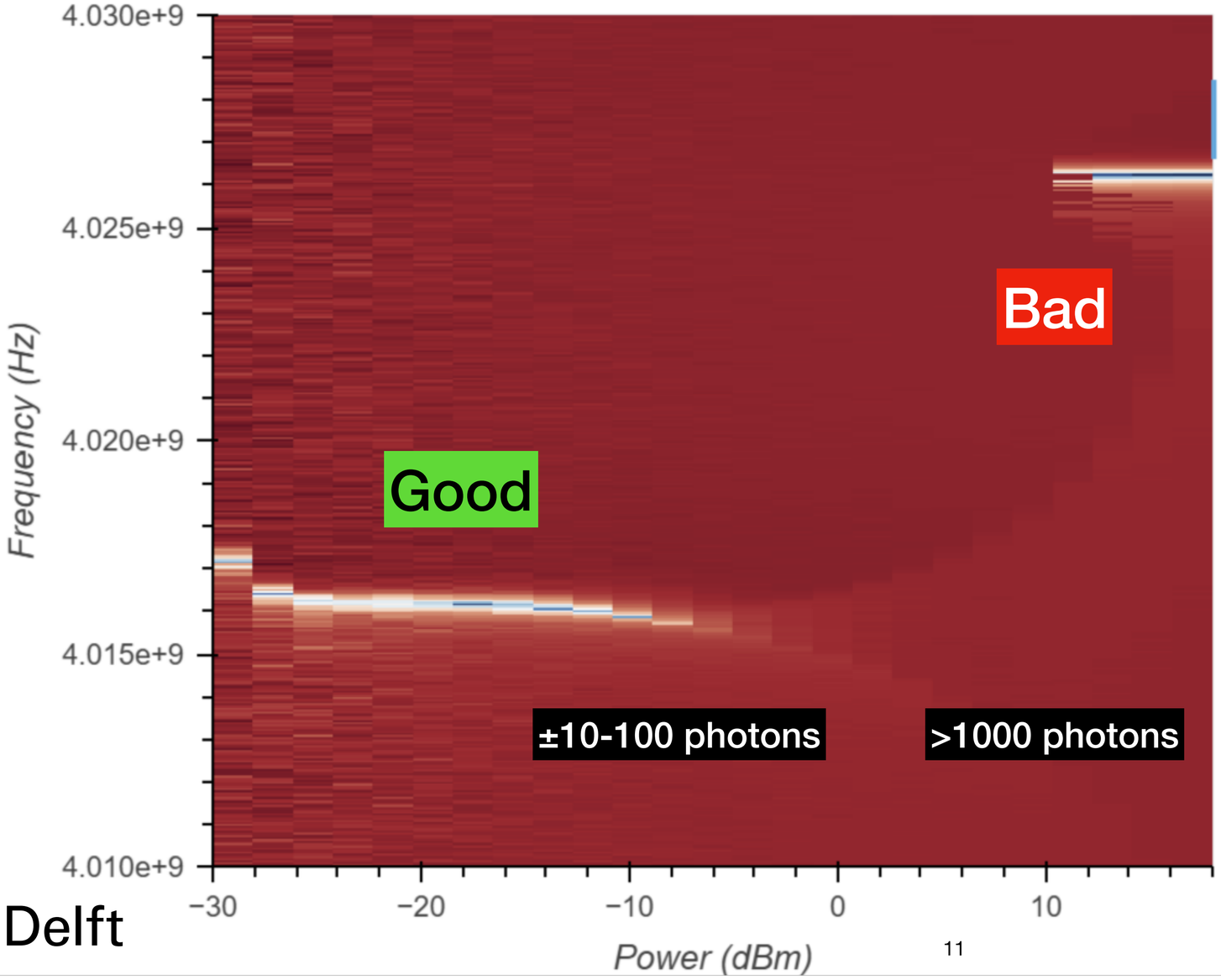
# Qubit ‘punch out’

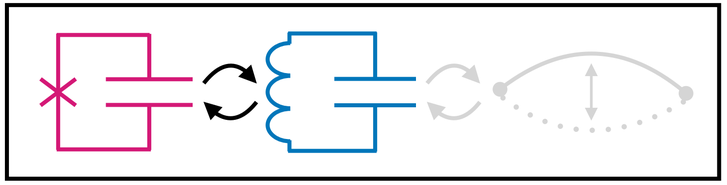


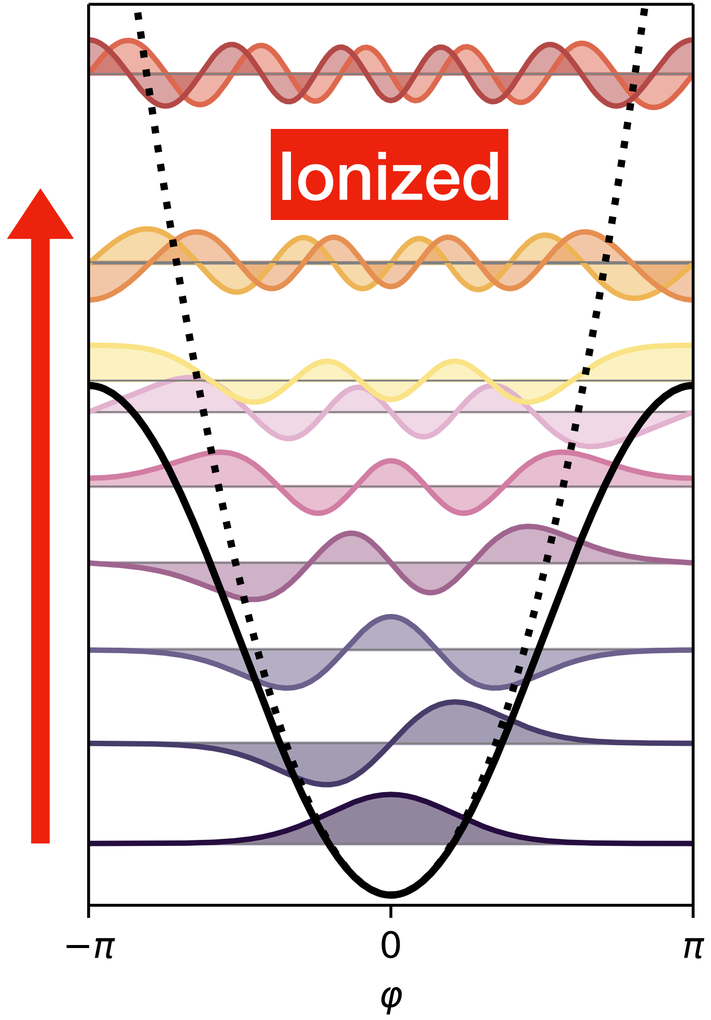





# Qubit ‘punch out’

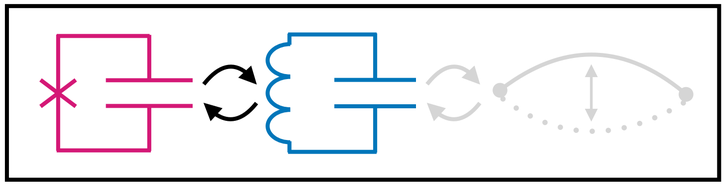


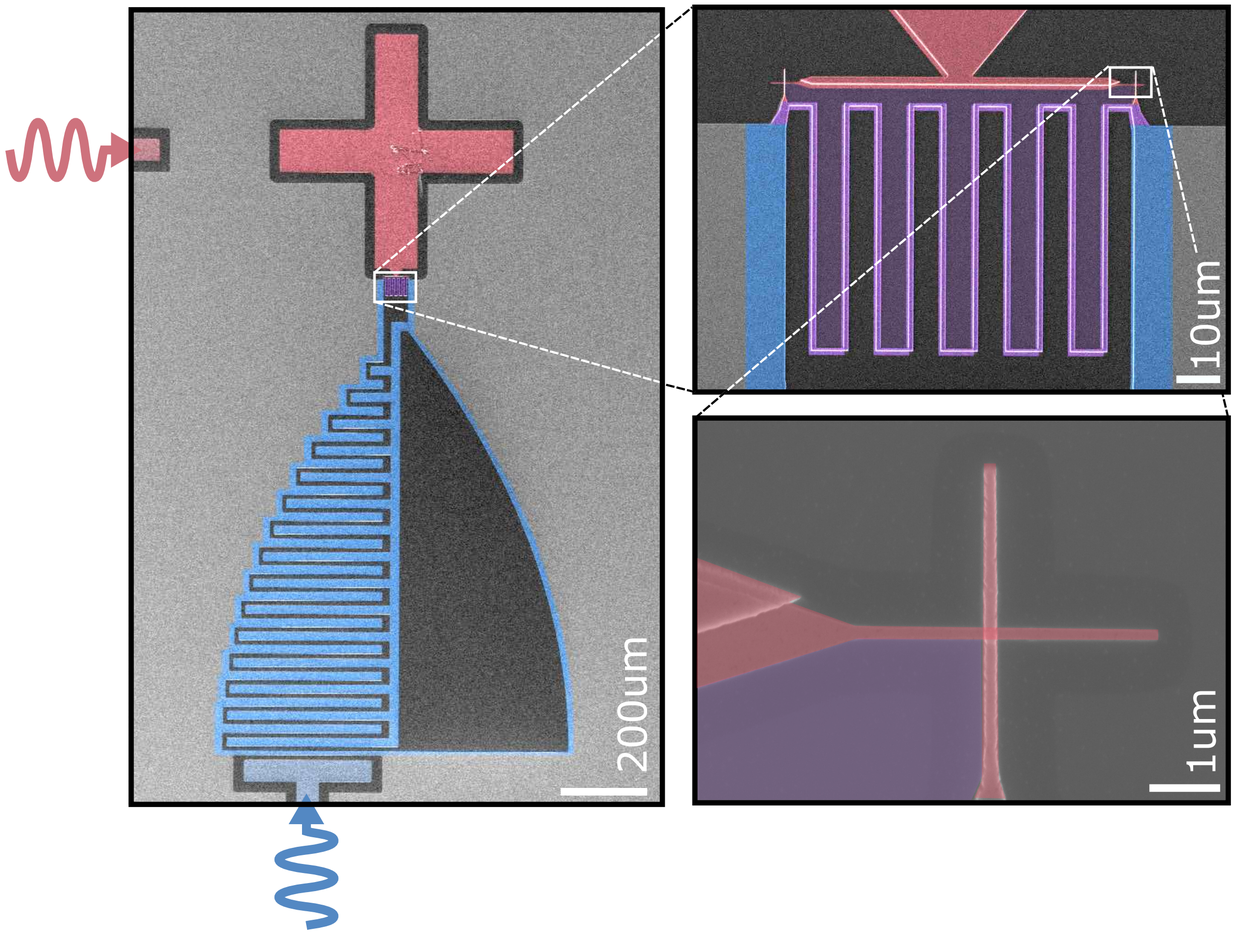





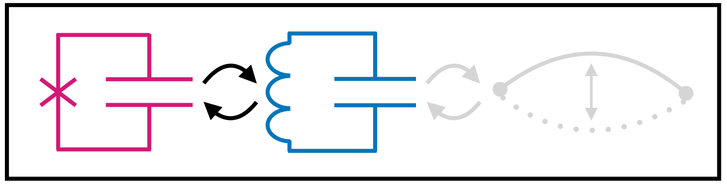
# cQED with more photons

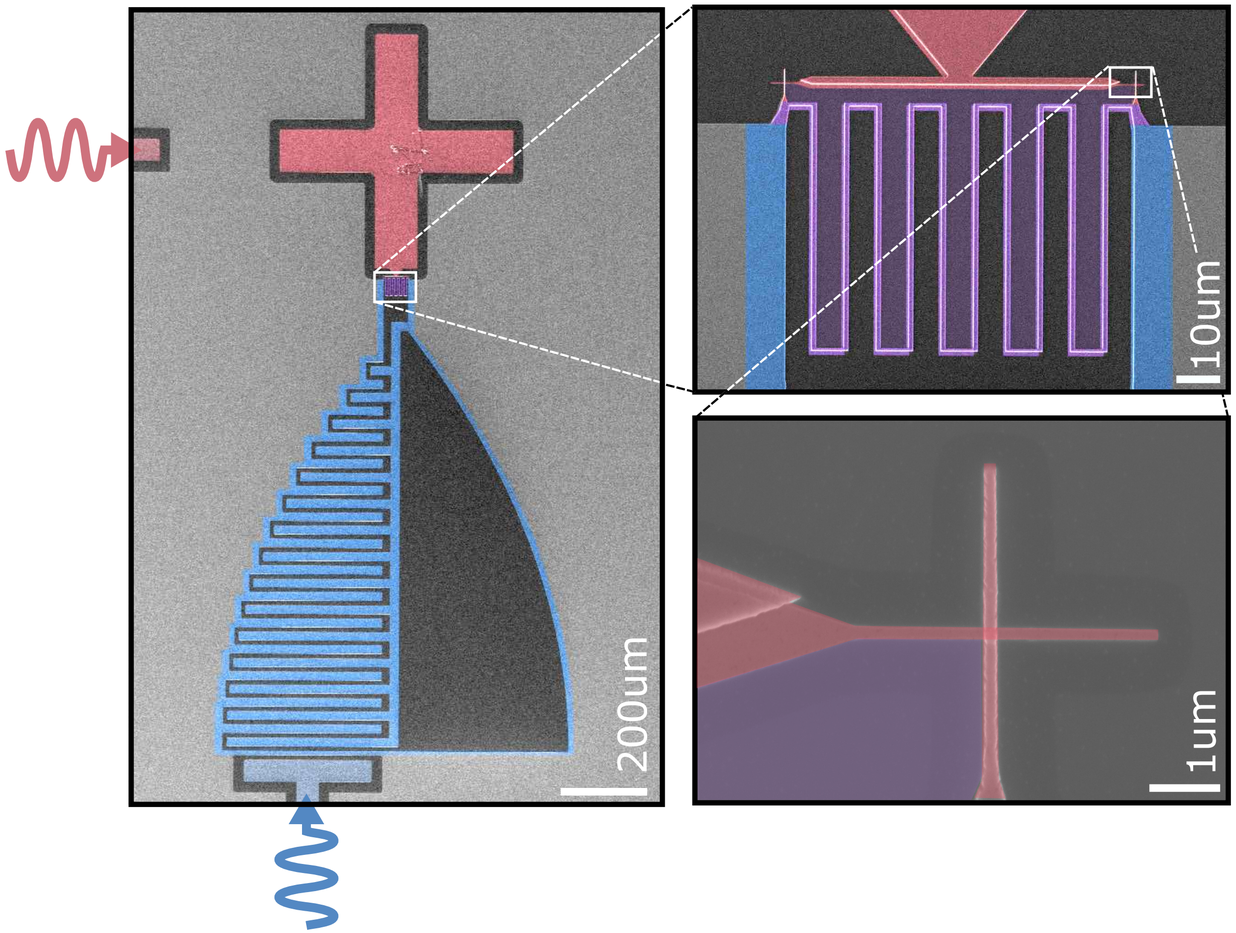
# Large photon number

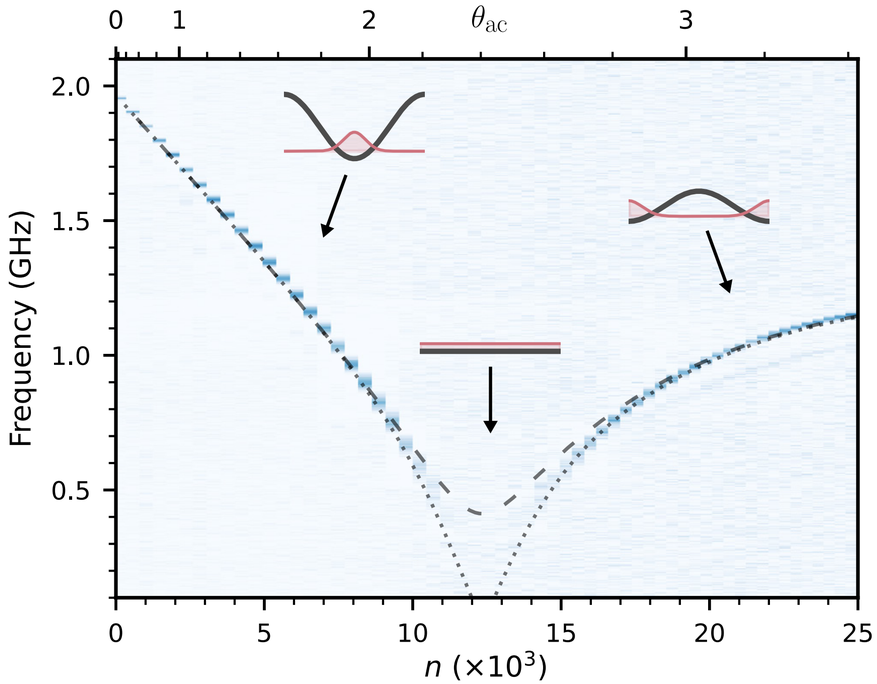




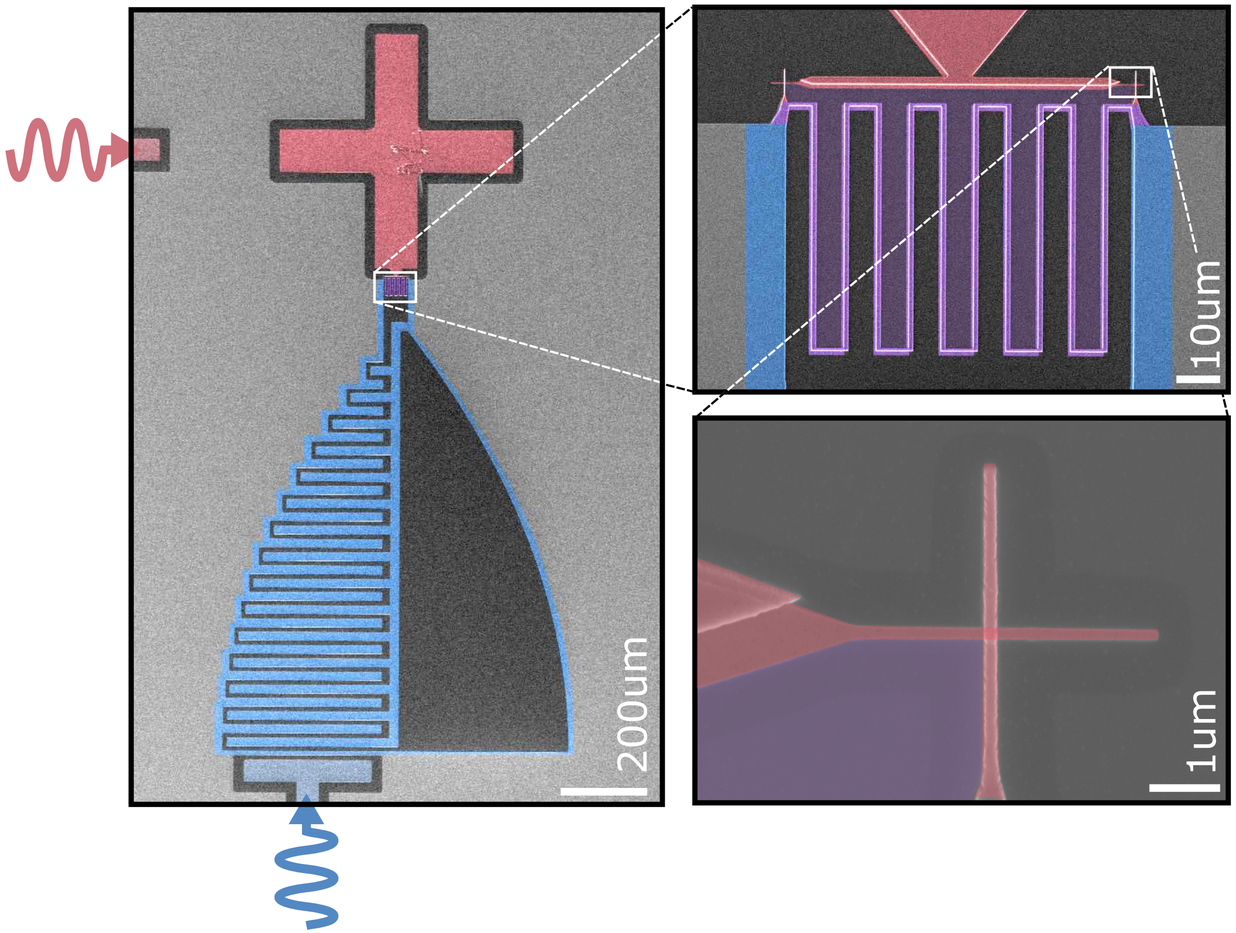
# Large photon number

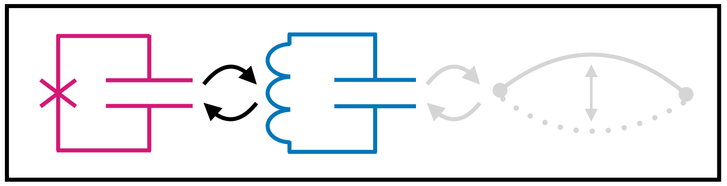


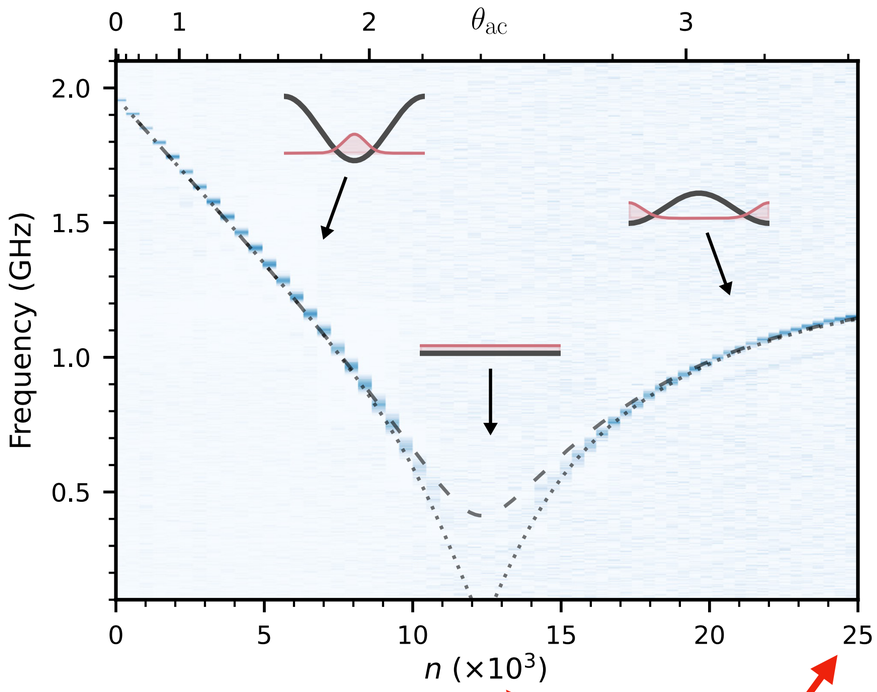


# Large photon number

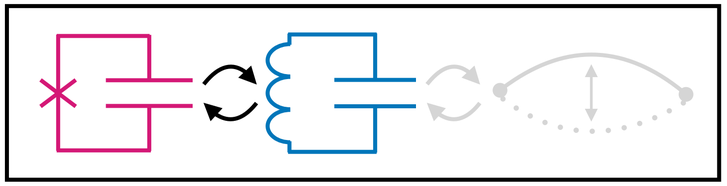


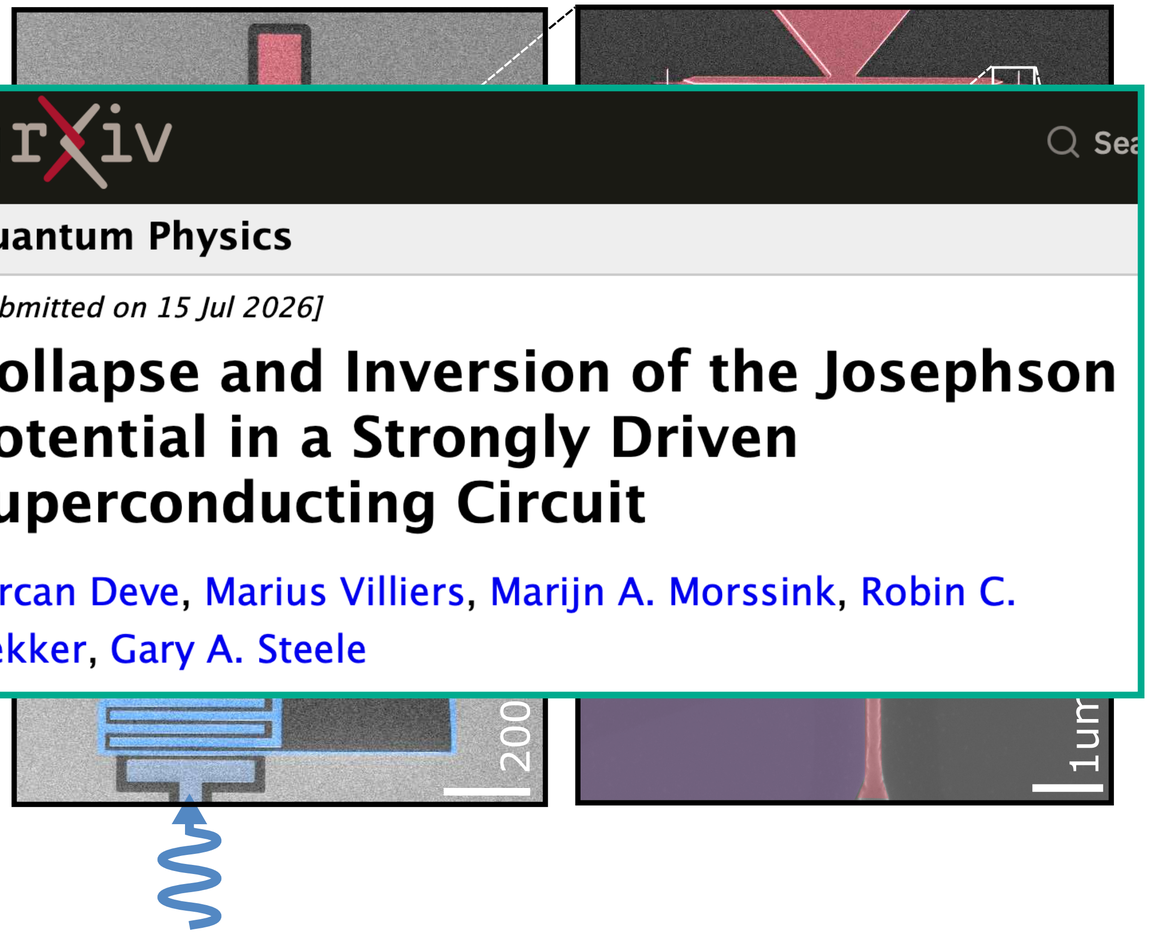






> 25.000 photons!

# Large photon number





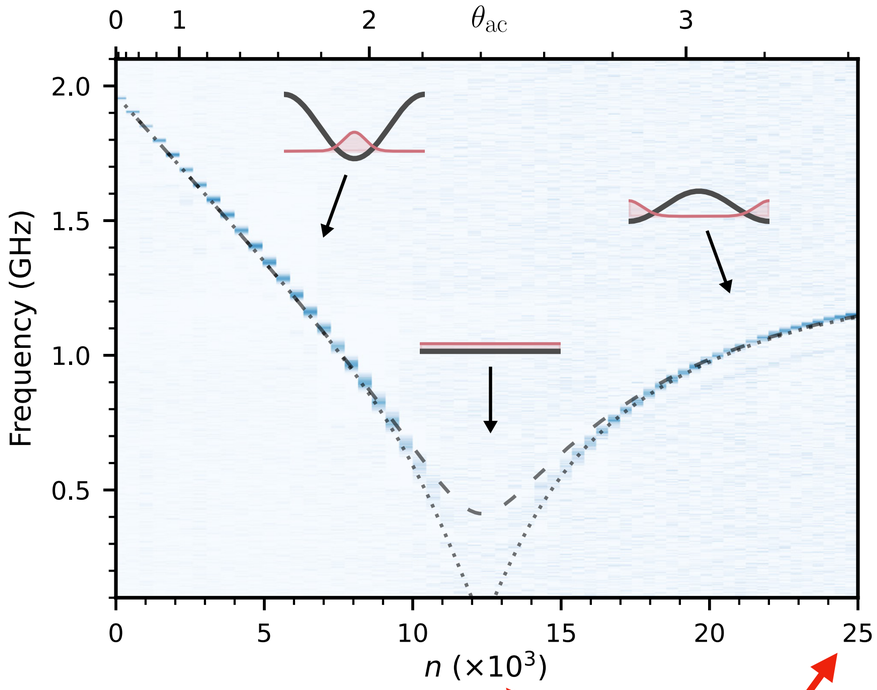

arXiv

Quantum Physics

*[Submitted on 15 Jul 2026]*

**Collapse and Inversion of the Josephson Potential in a Strongly Driven Superconducting Circuit**

Sercan Deve, Marius Villiers, Marijn A. Morssink, Robin C. Dekker, Gary A. Steele




> 25.000 photons!

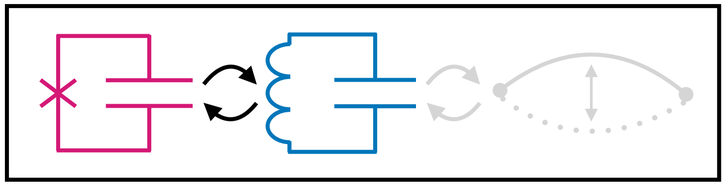


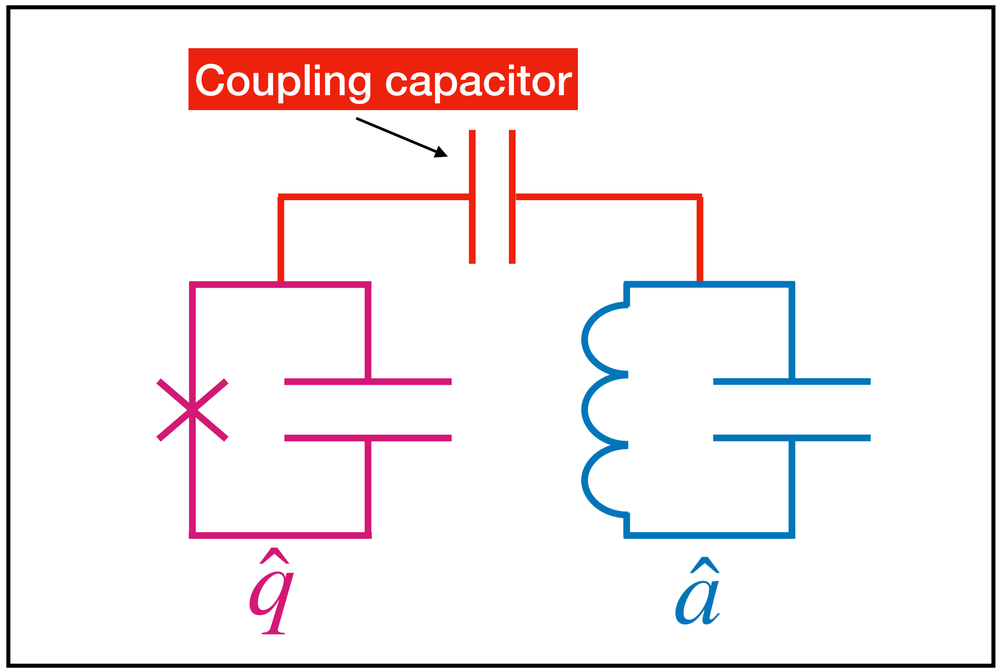
*Sercan*



*Marius*

# Cosine-cosine coupling

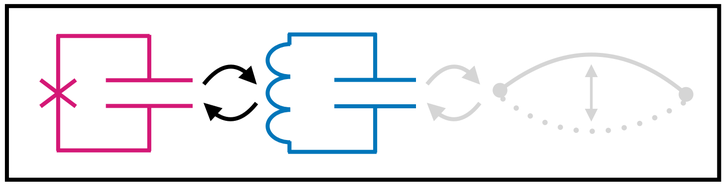


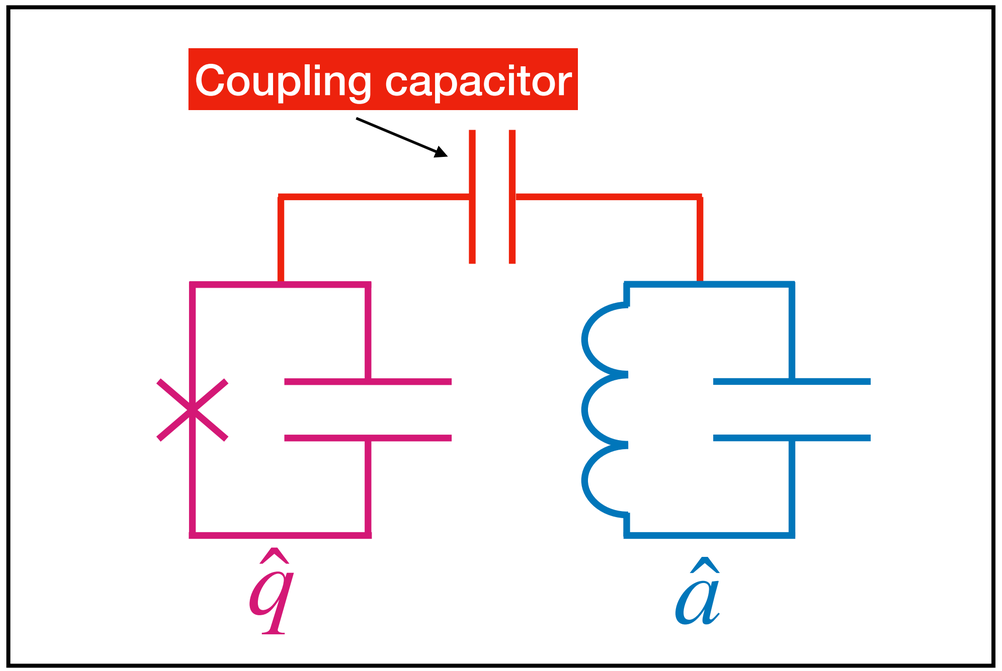


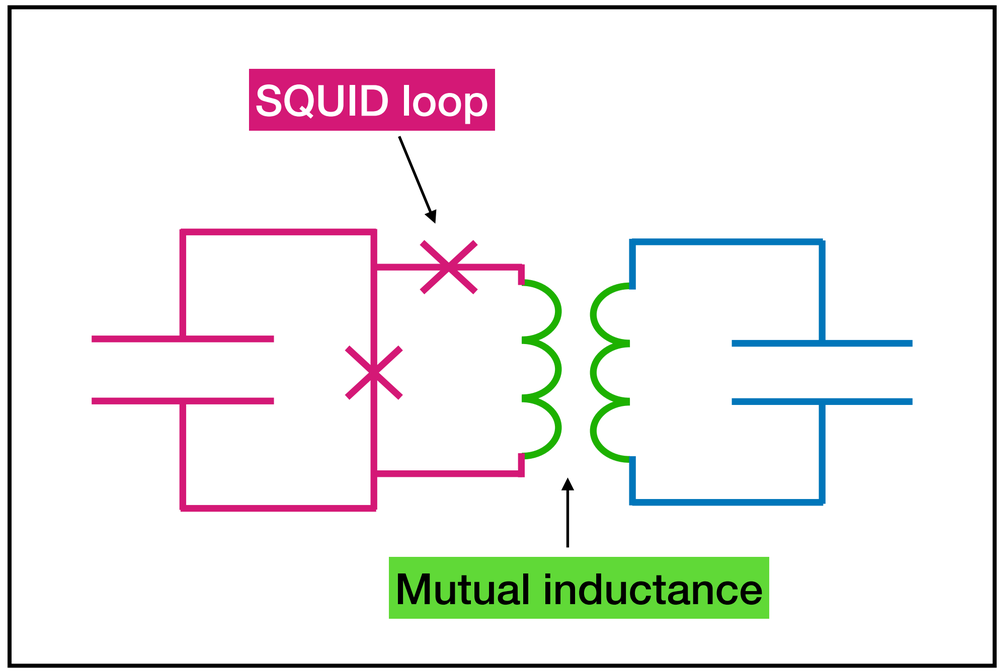

Jaynes-Cummings interaction

$$\propto \hat{a}\hat{q}^{\dagger} + \hat{a}^{\dagger}\hat{q}$$

# Cosine-cosine coupling



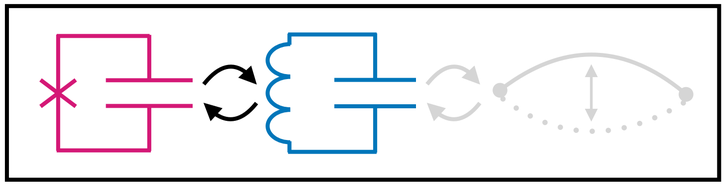


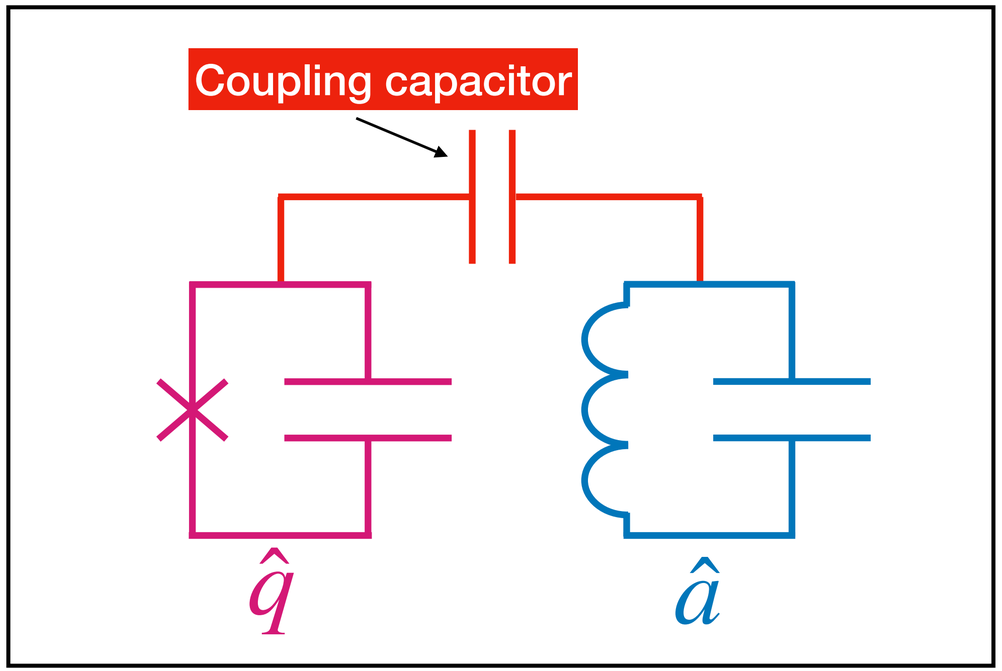



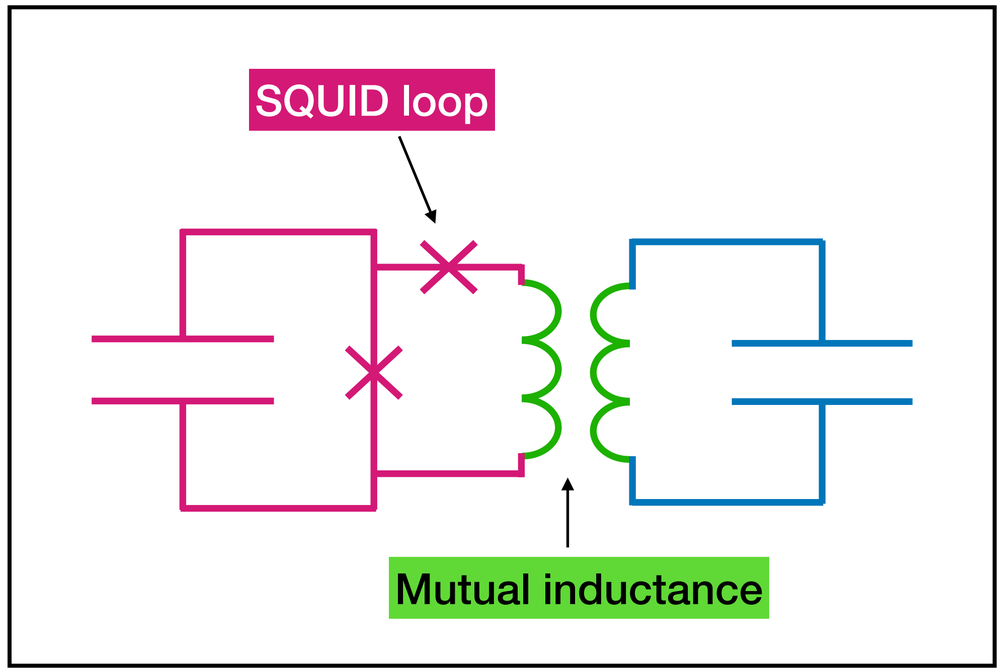

Jaynes-Cummings interaction

$$\propto \hat{a}\hat{q}^{\dagger} + \hat{a}^{\dagger}\hat{q}$$

# Cosine-cosine coupling






Jaynes-Cummings interaction

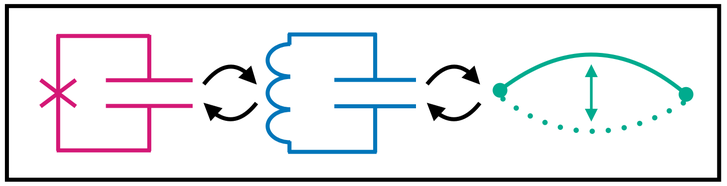
$$\propto \hat{a}\hat{q}^{\dagger} + \hat{a}^{\dagger}\hat{q}$$

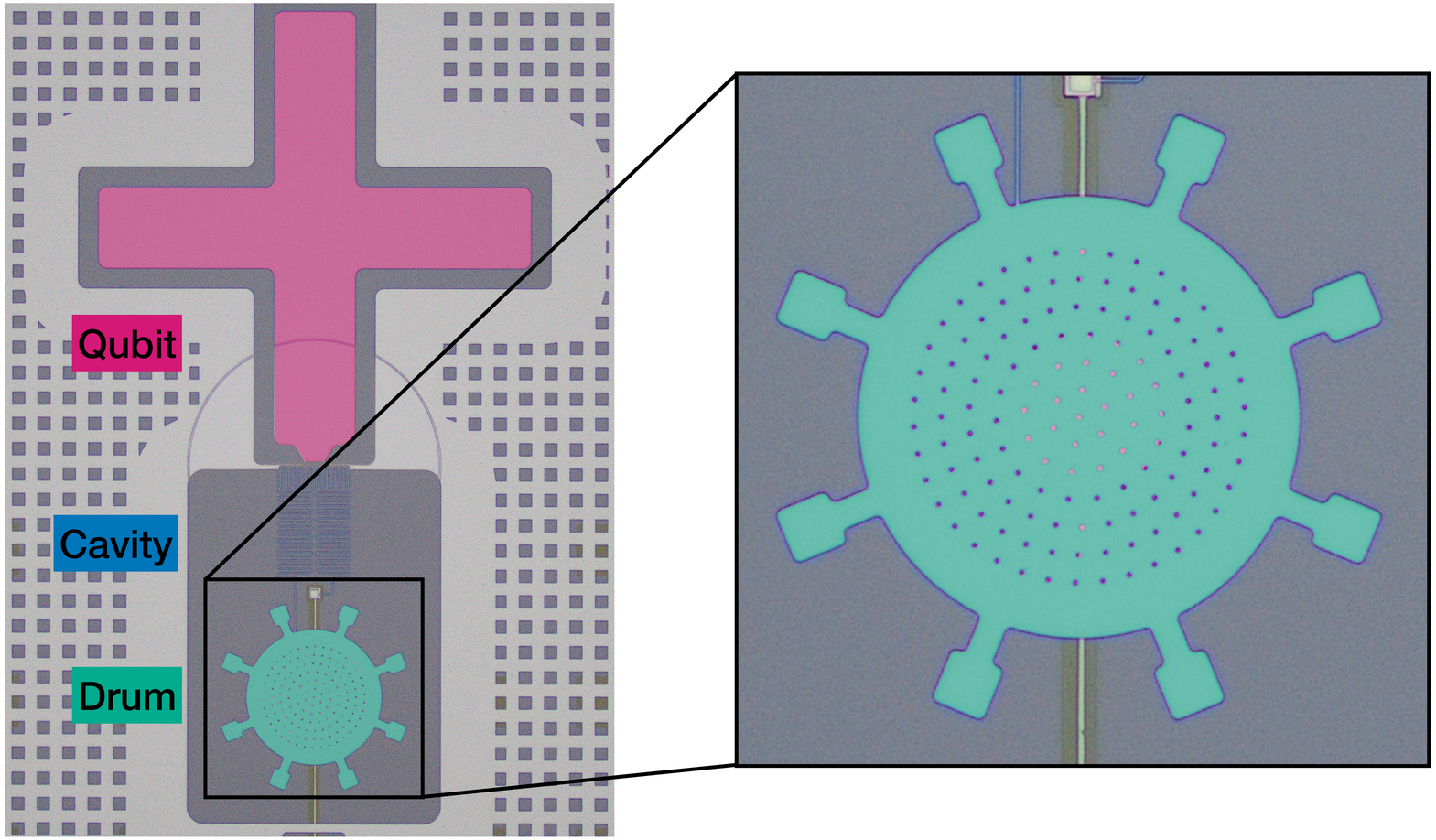
$$\propto \cos[\varphi_a(\hat{a} + \hat{a}^{\dagger})]\cos[\varphi_q(\hat{q} + \hat{q}^{\dagger})]$$

$$\sim \hat{a}^{\dagger}\hat{a}\hat{q}^{\dagger}\hat{q}$$

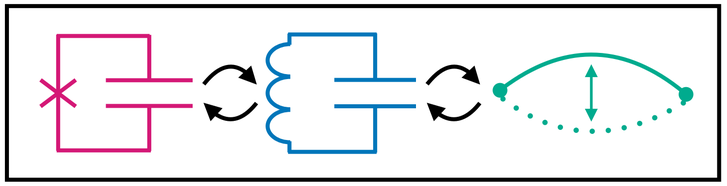
TU Delft

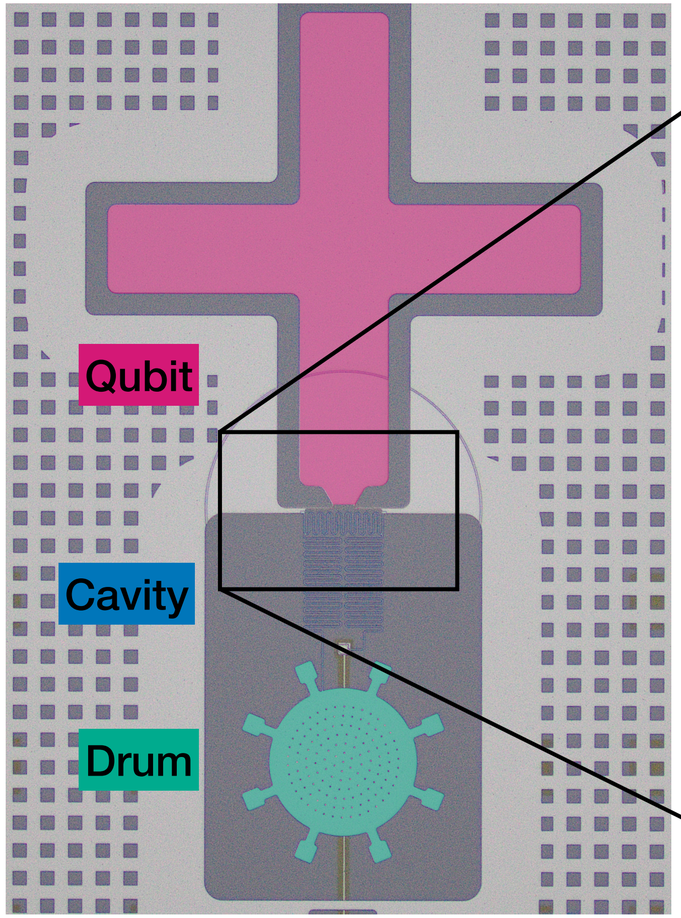
# Putting it all together

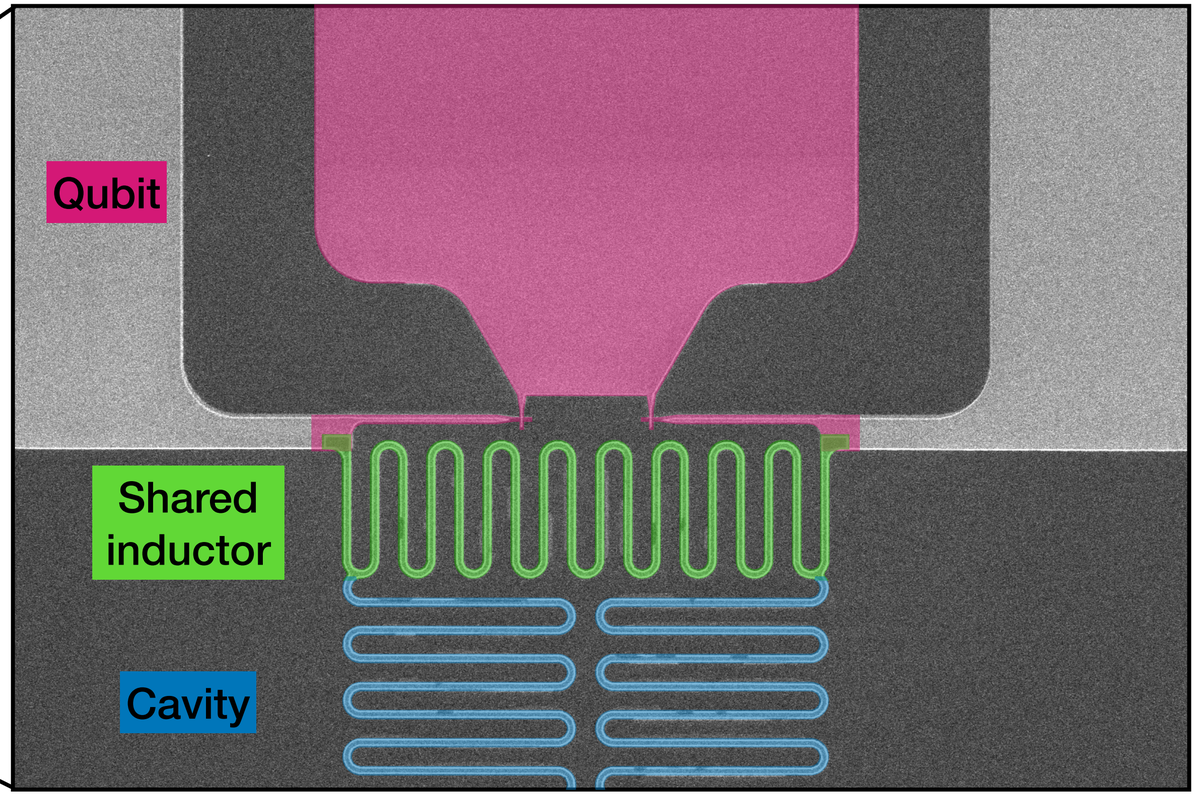


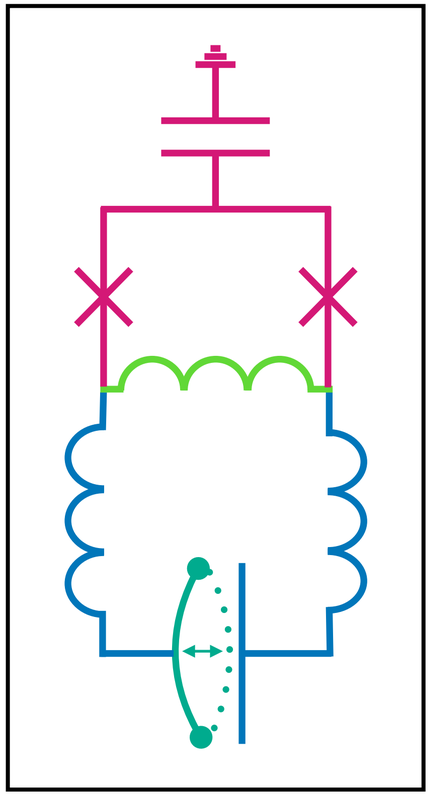


# Putting it all together

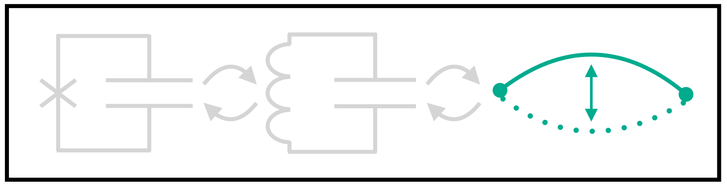




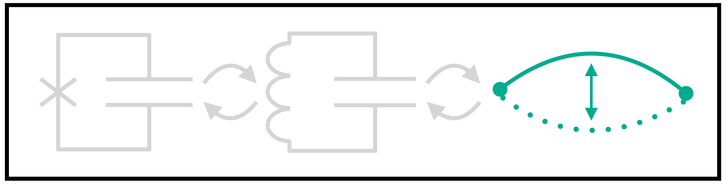



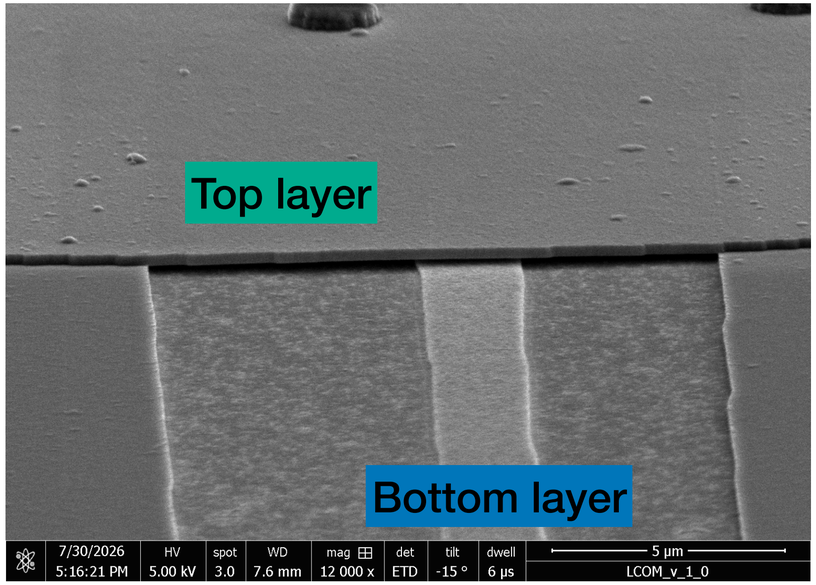



# Fabricating the drums

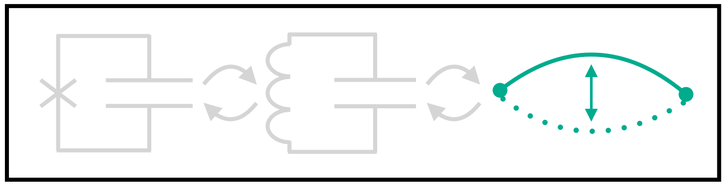


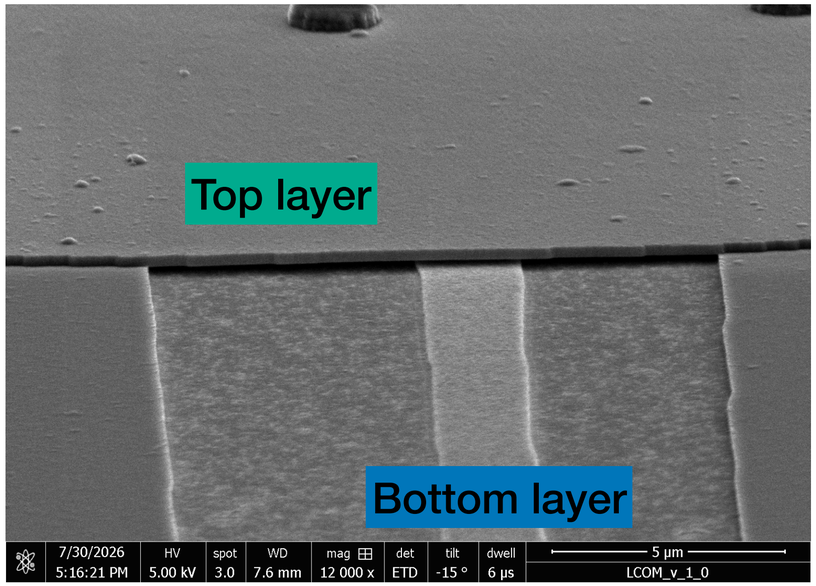
# Fabricating the drums

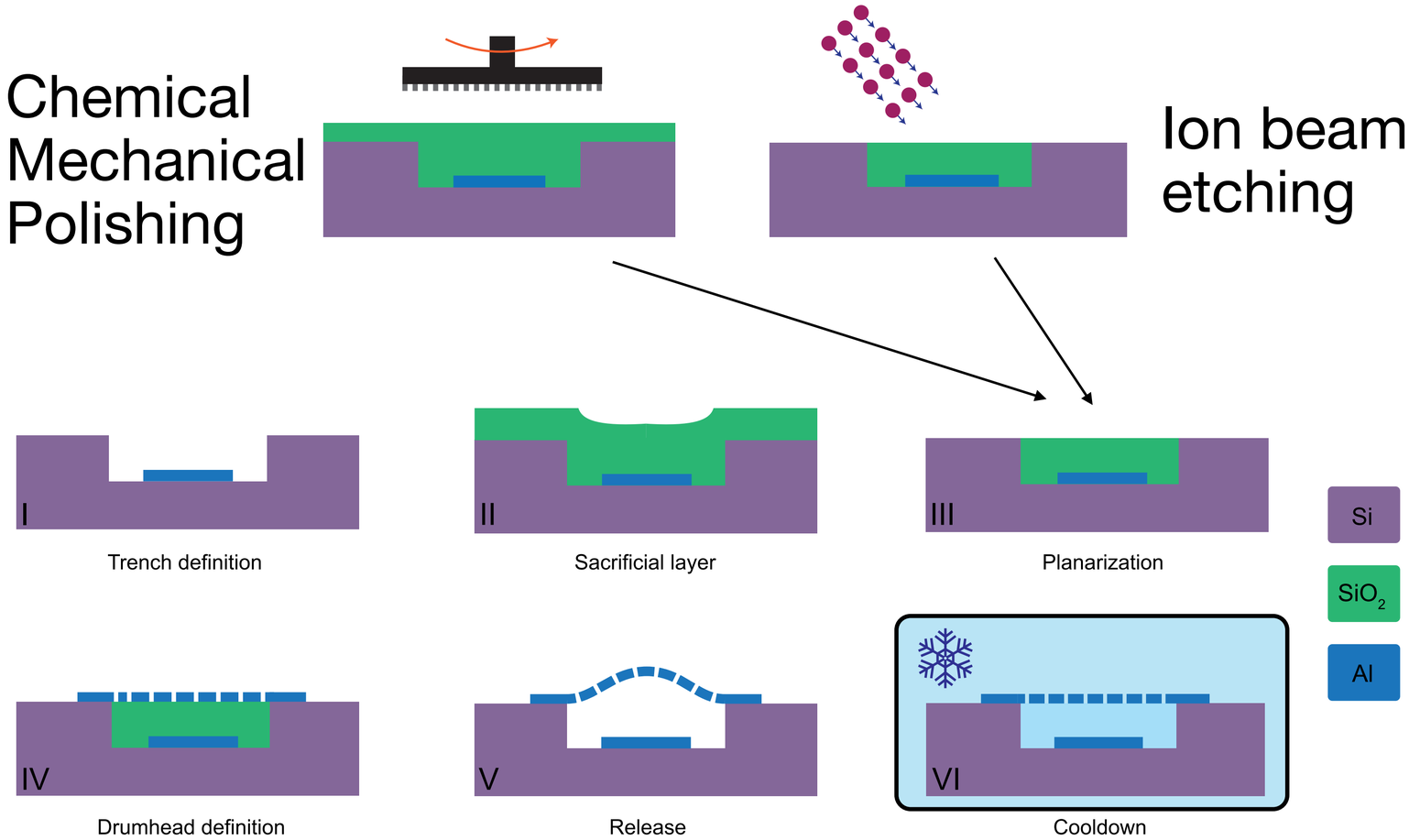




# Fabricating the drums





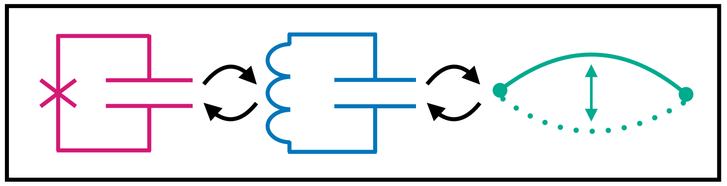



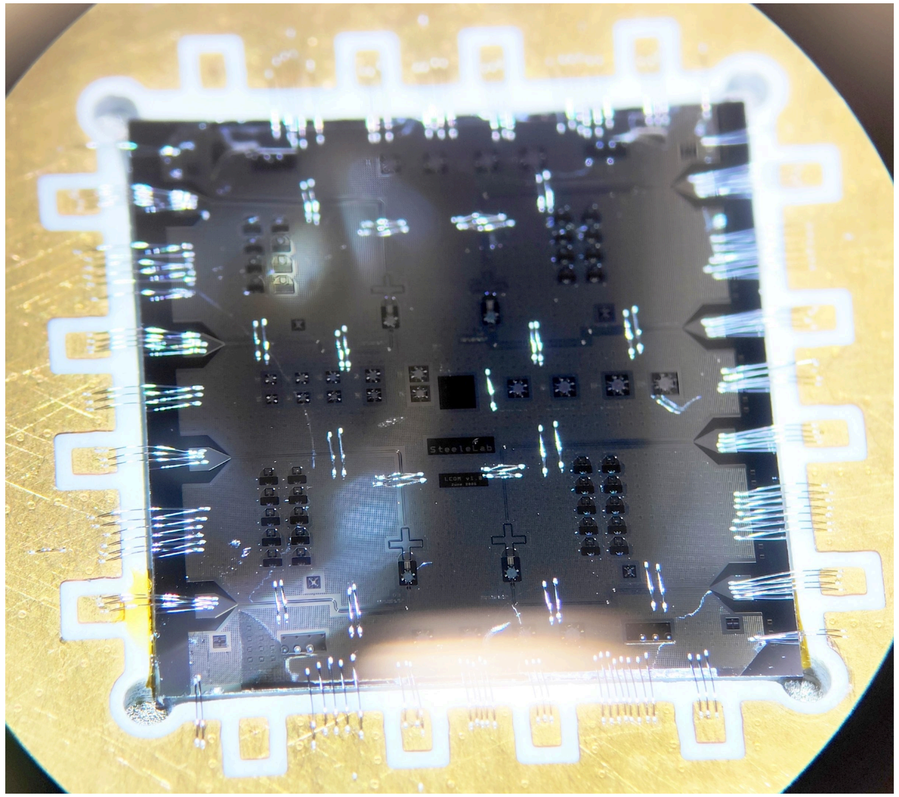

EPFL

TU Delft

Youssefi et al., 2025, Phys. Rev. Applied

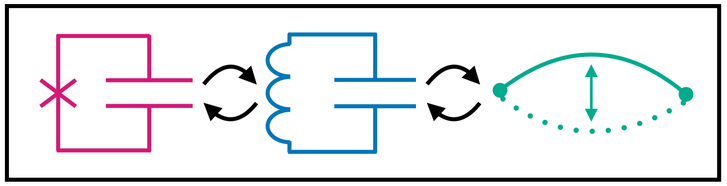
# First cooldown of the chip

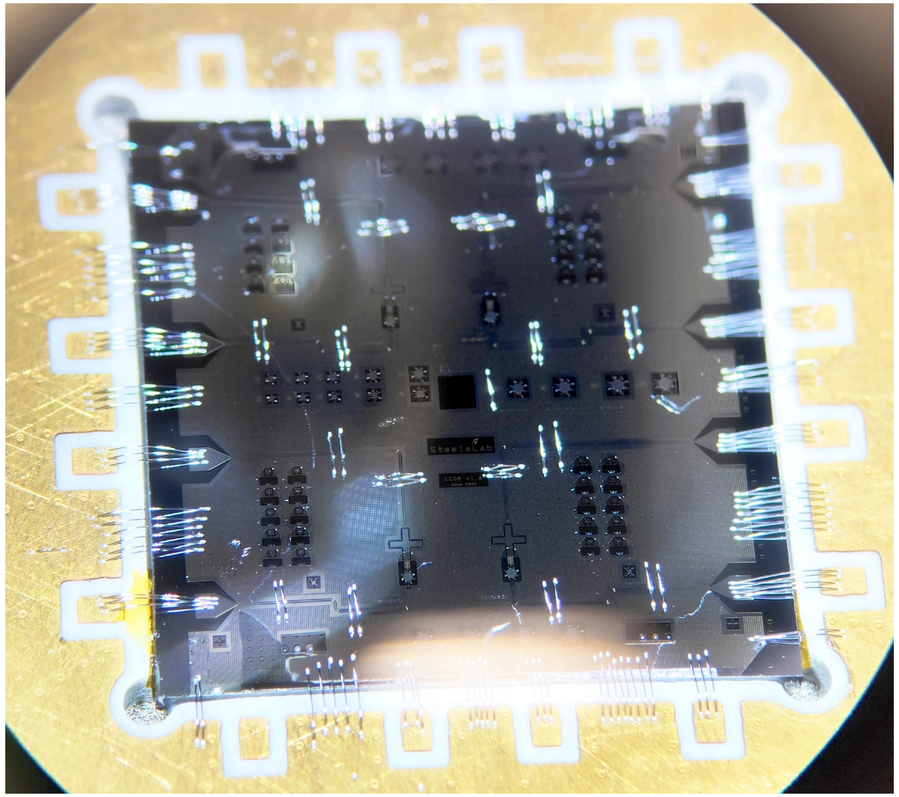




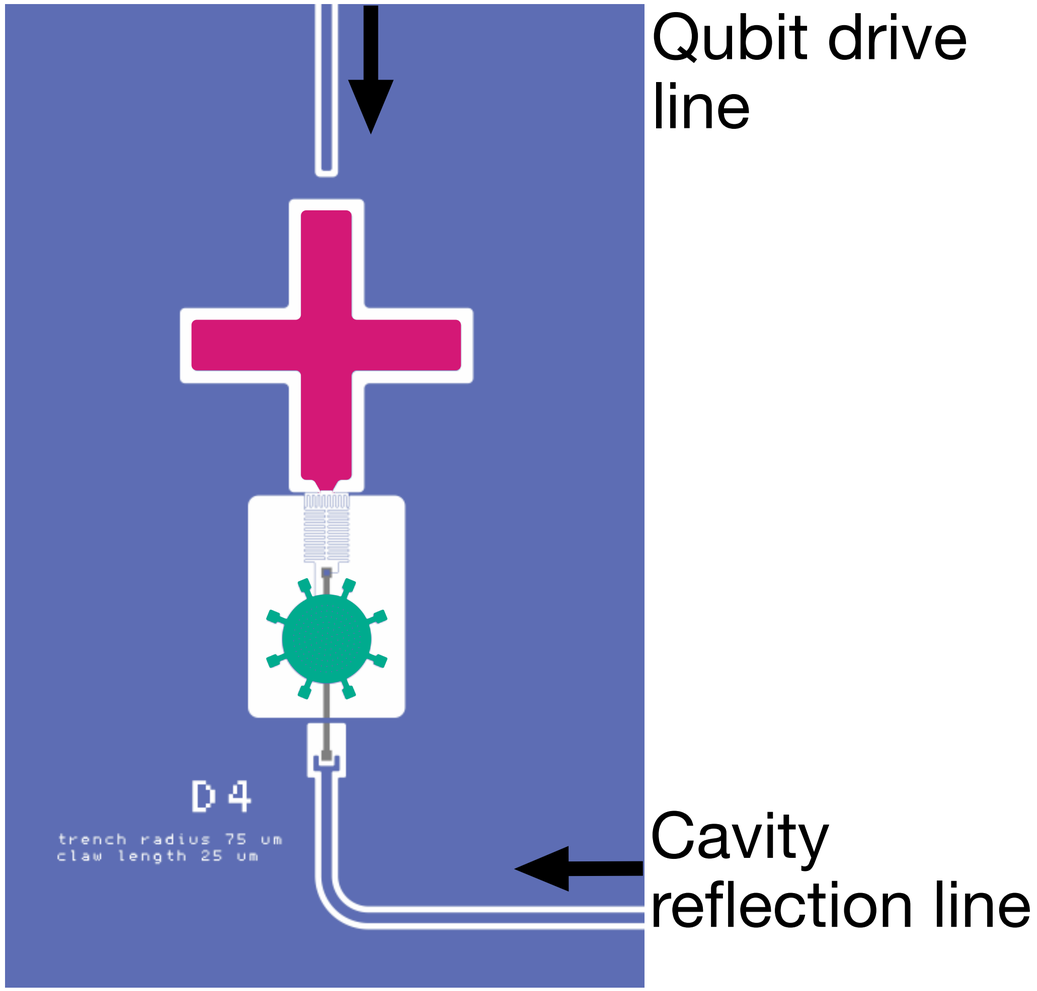
First iteration!

# First cooldown of the chip

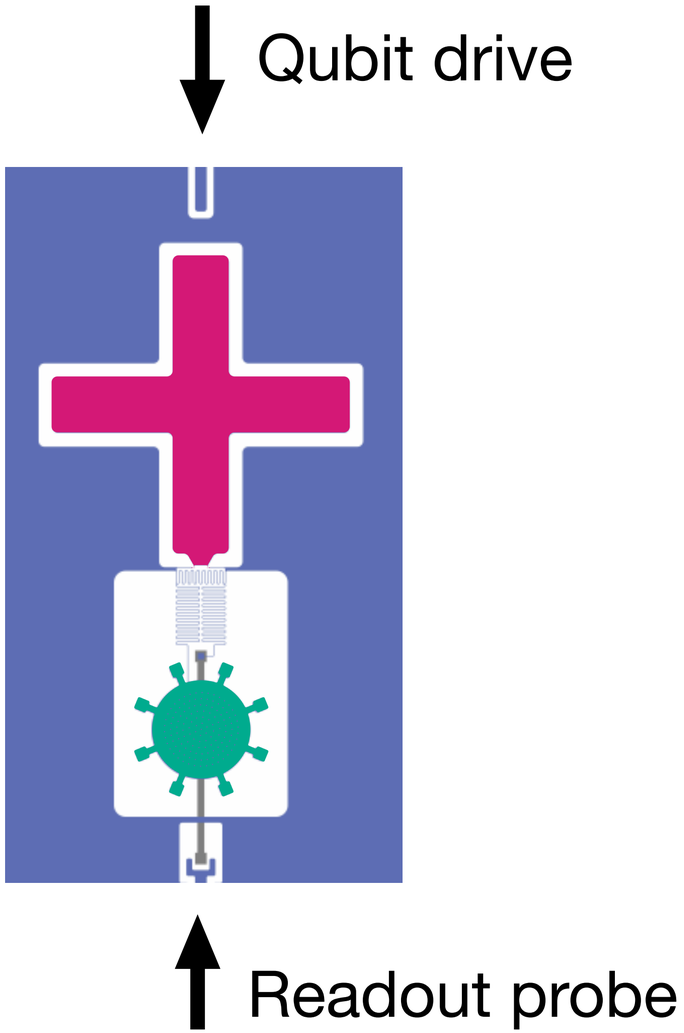


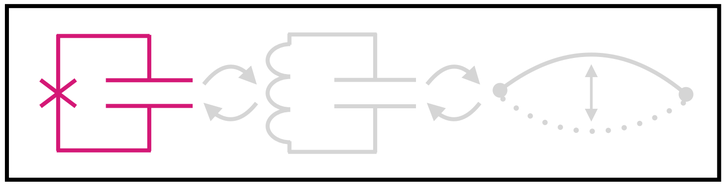


First iteration!

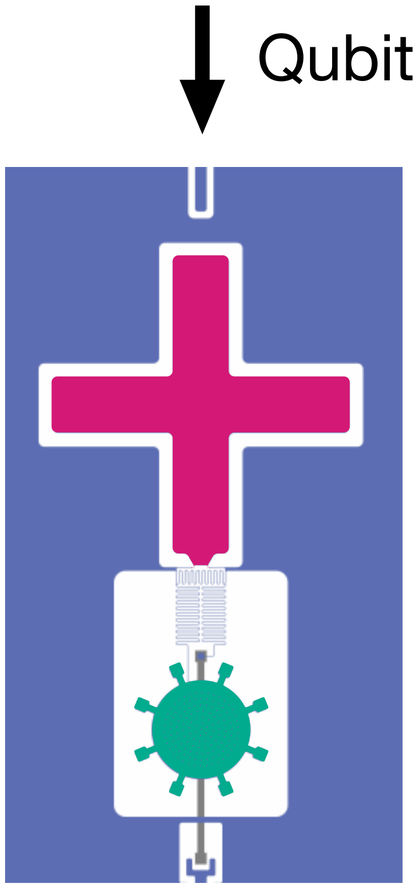


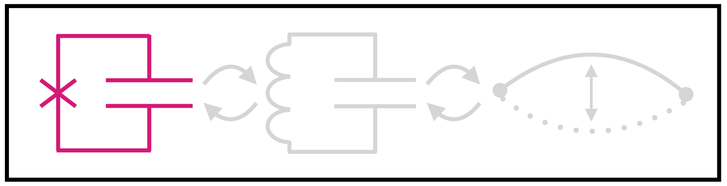
# Qubit is alive

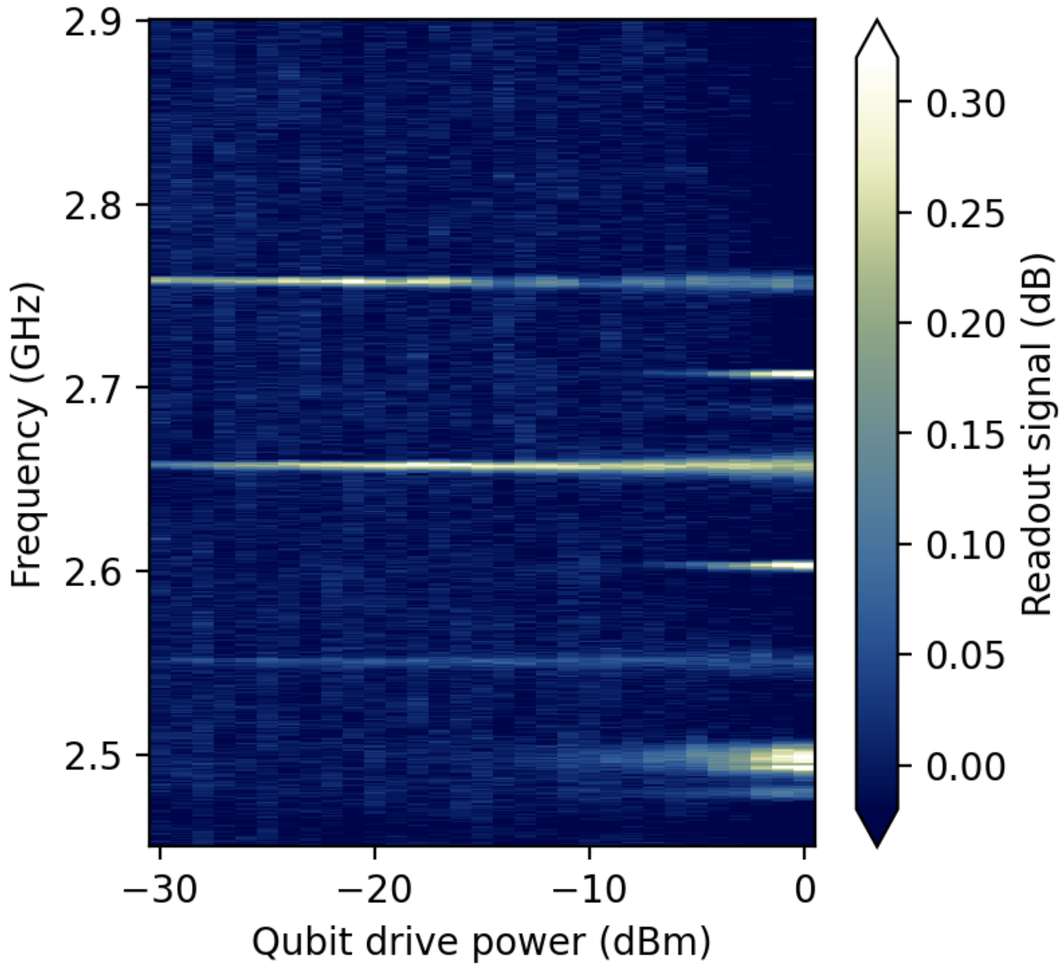


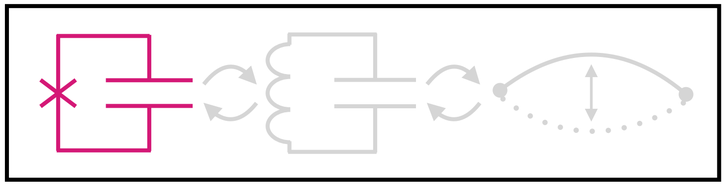
# Qubit is alive



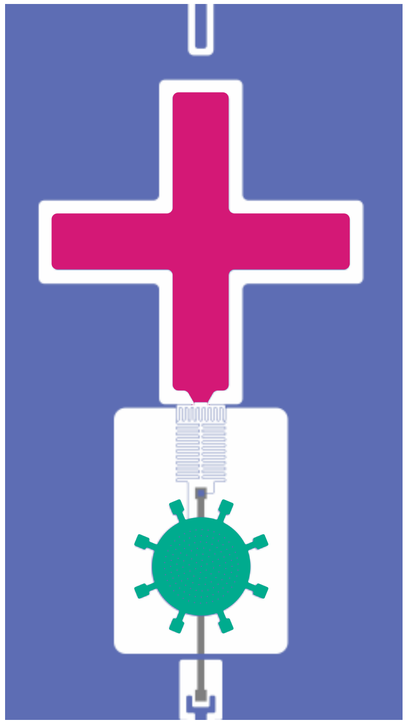





# Characterizing the qubit

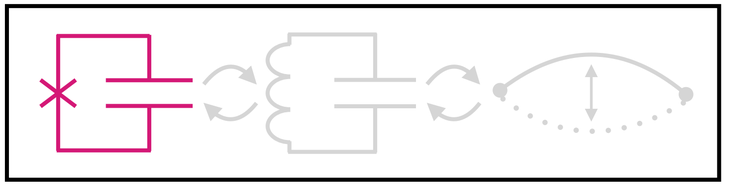


Qubit drive

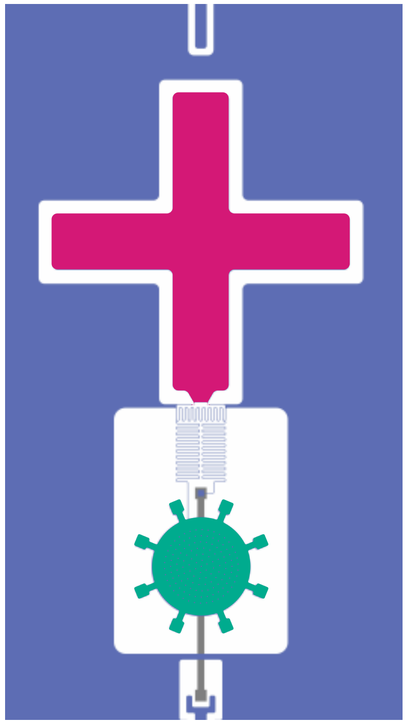


Readout probe

# Characterizing the qubit

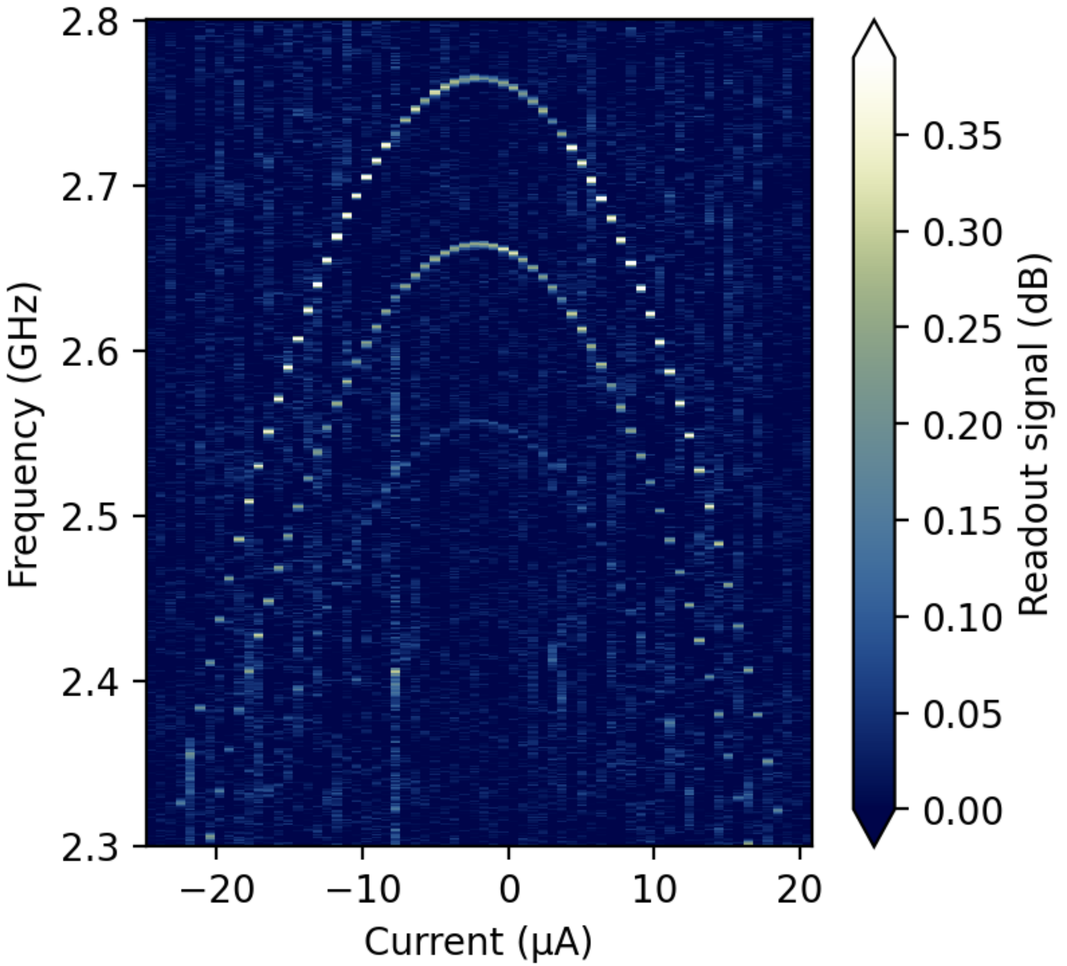


Qubit drive



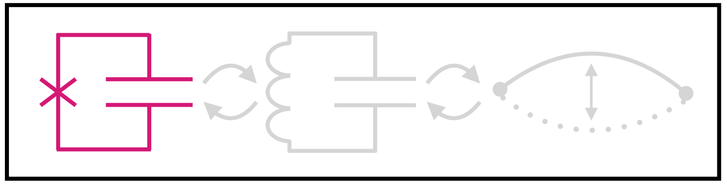
*Sweep external flux*

Readout probe

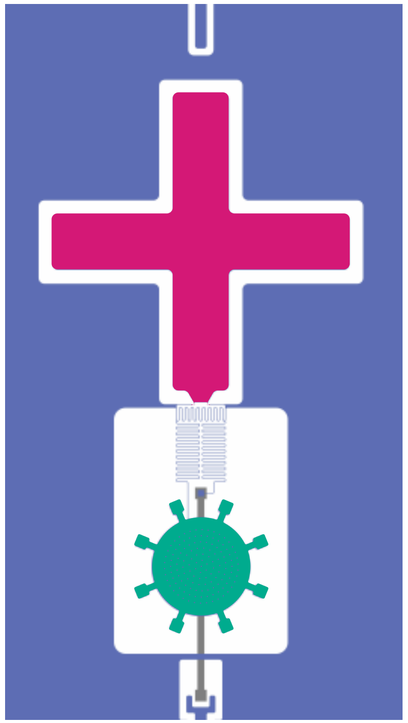



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# Characterizing the qubit



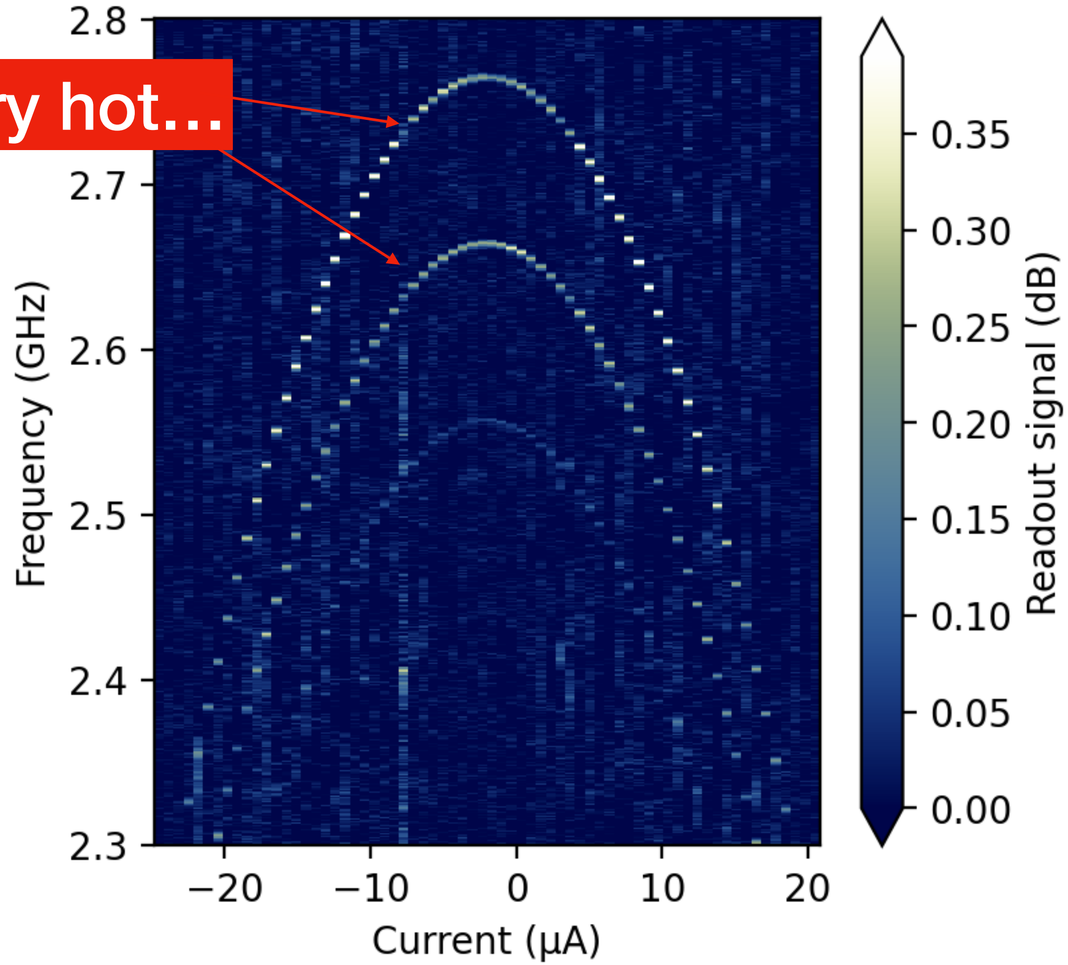
Qubit drive



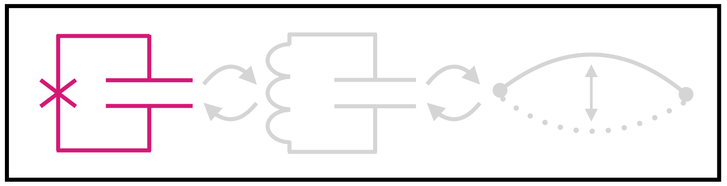
Readout probe

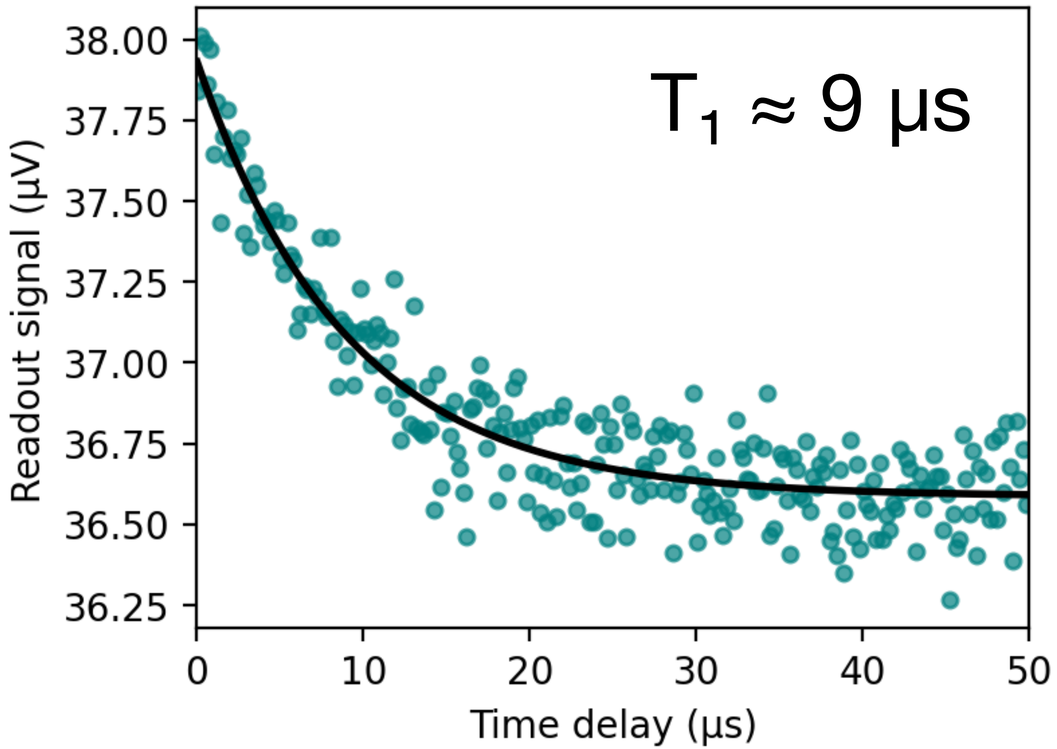
*Sweep external flux*

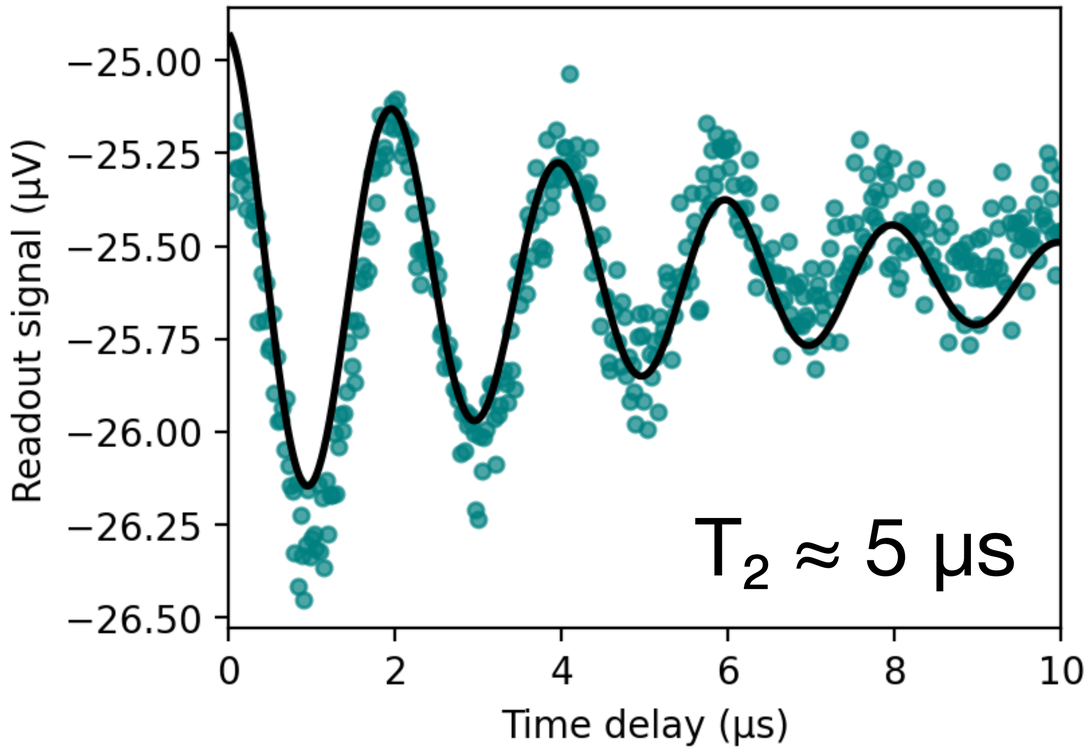
Qubit is very hot…



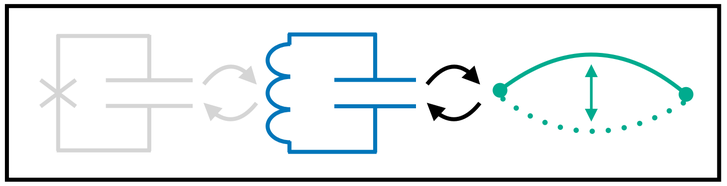
# Coherence times are decent

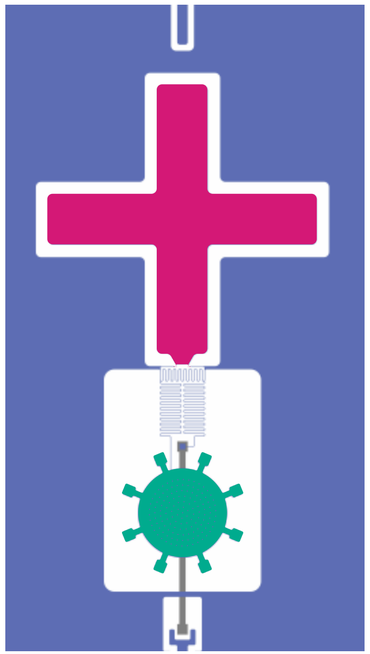


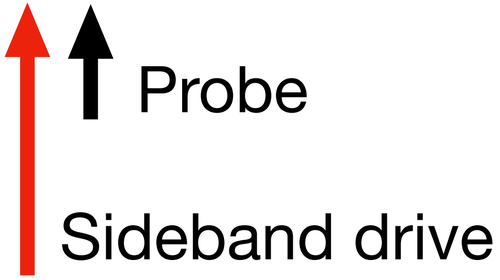


# Can we see the drums?

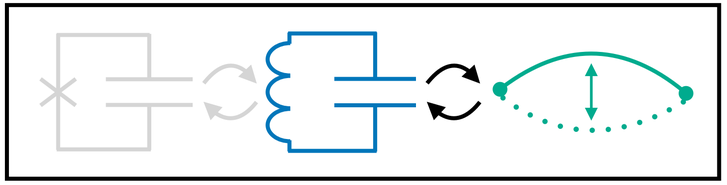


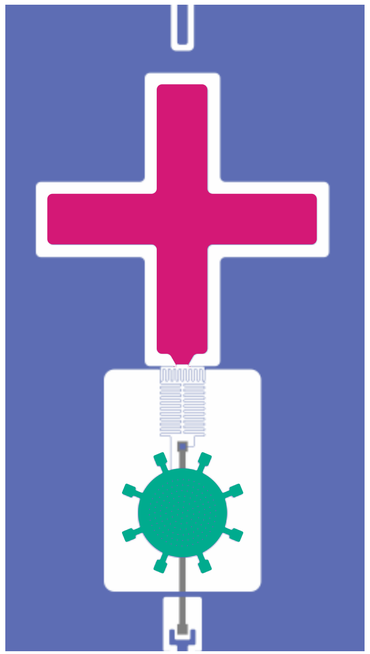


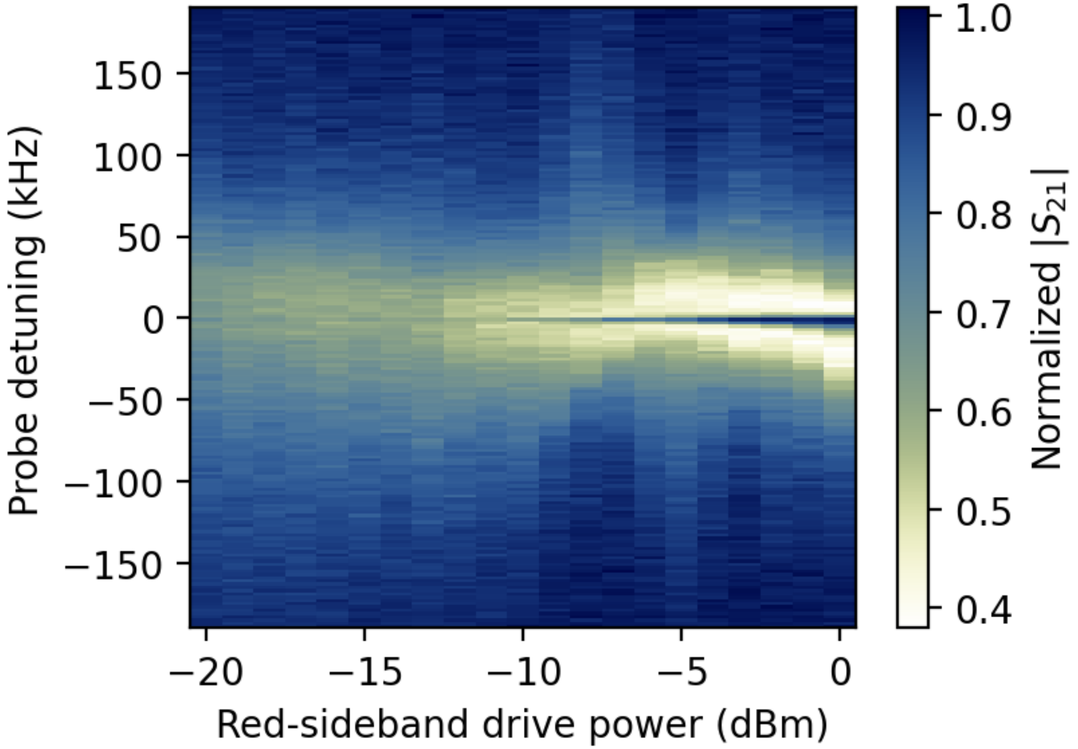


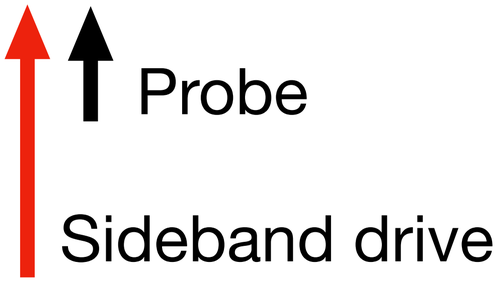



# Can we see the drums?







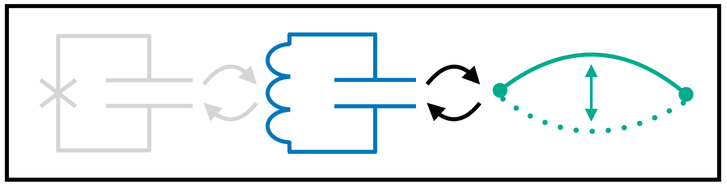



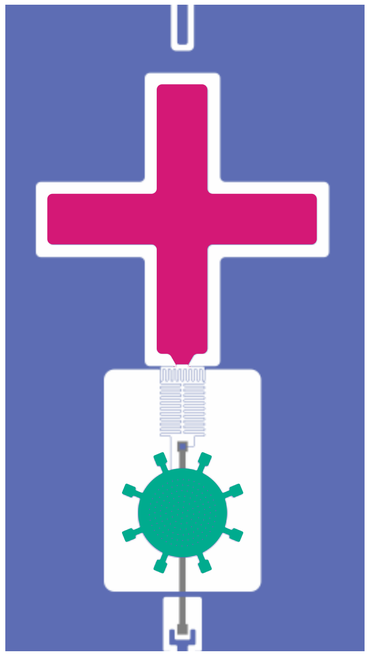




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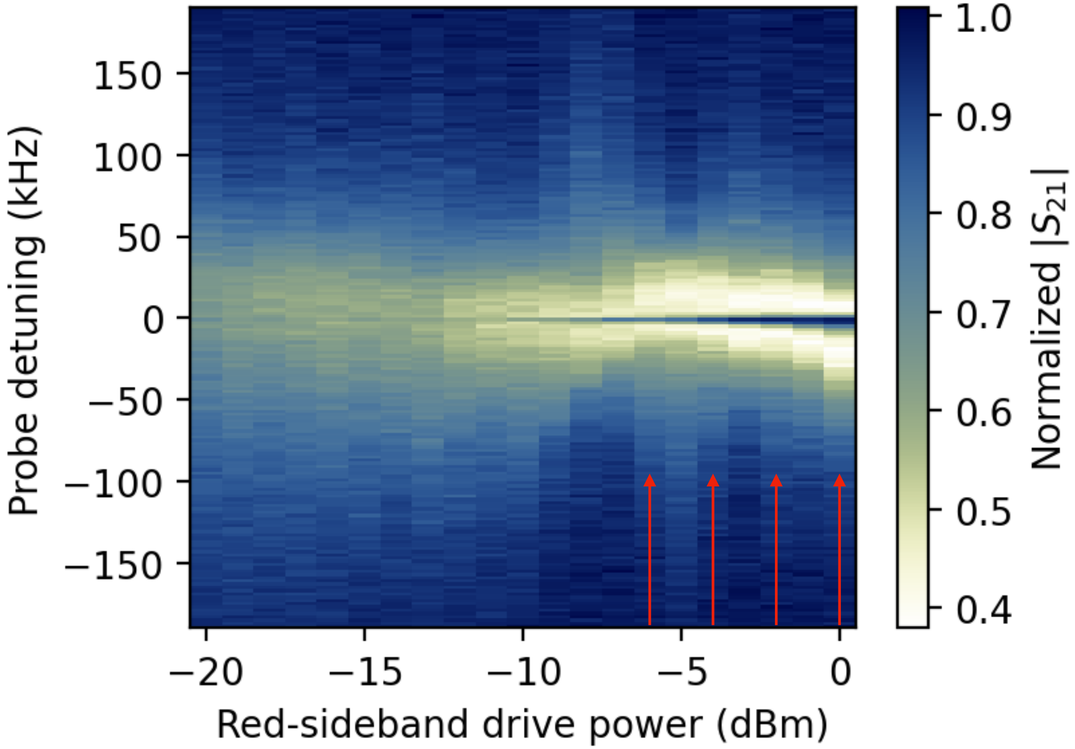
# Can we see the drums?





Probe

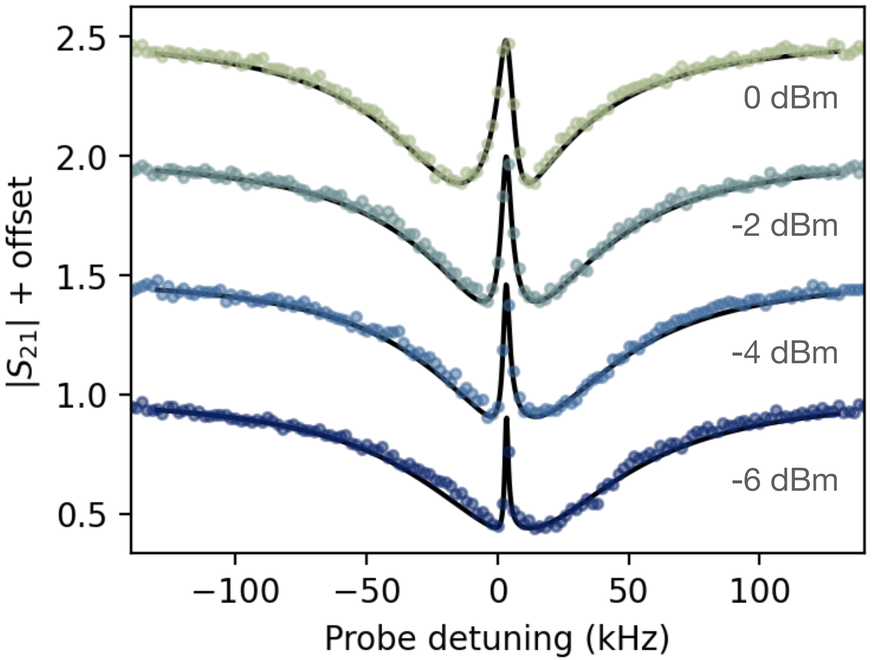
Sideband drive





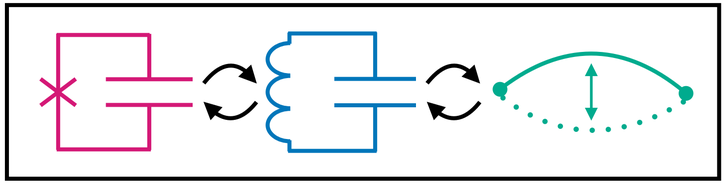


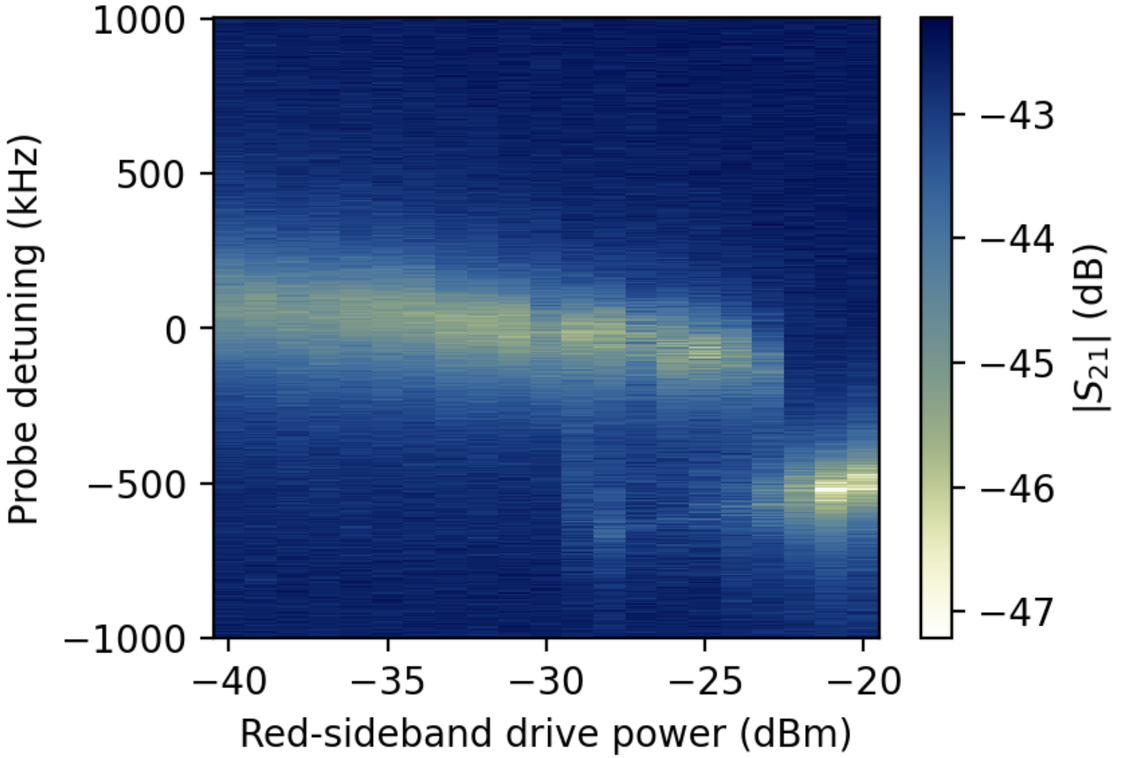
Optomechanically-induced transparency



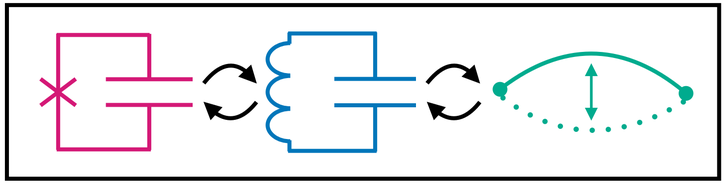

TU Delft

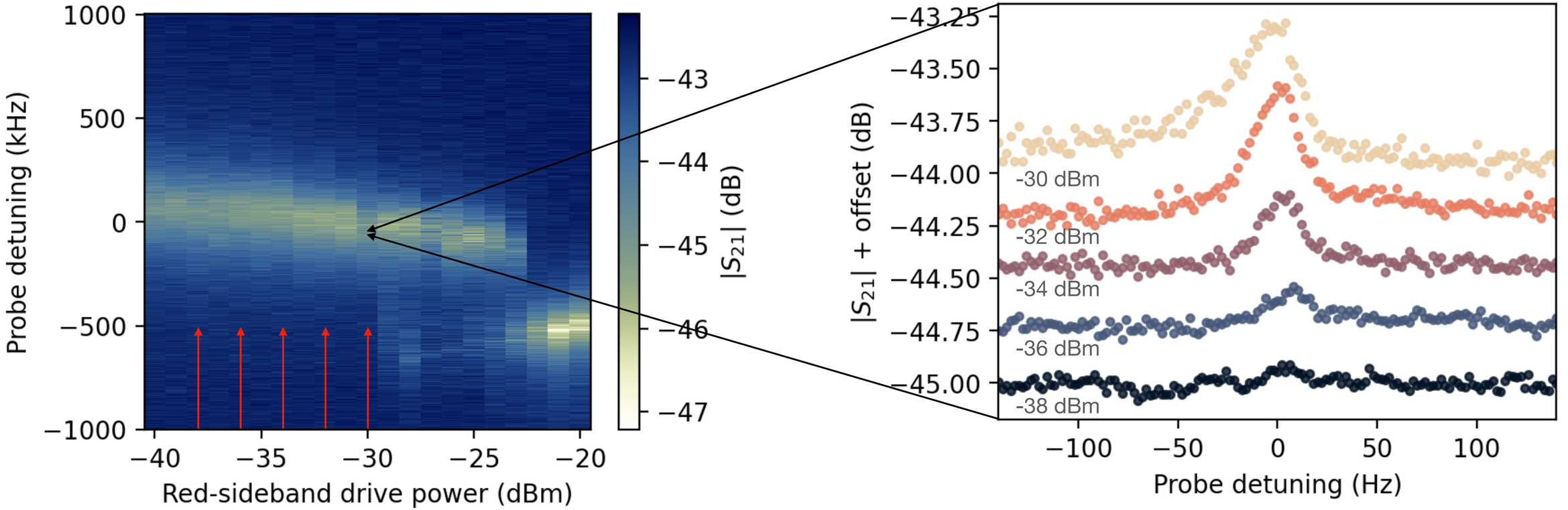
# OMIT before punch-out



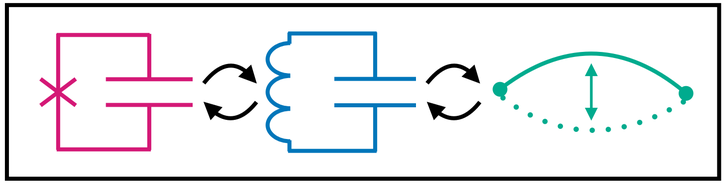


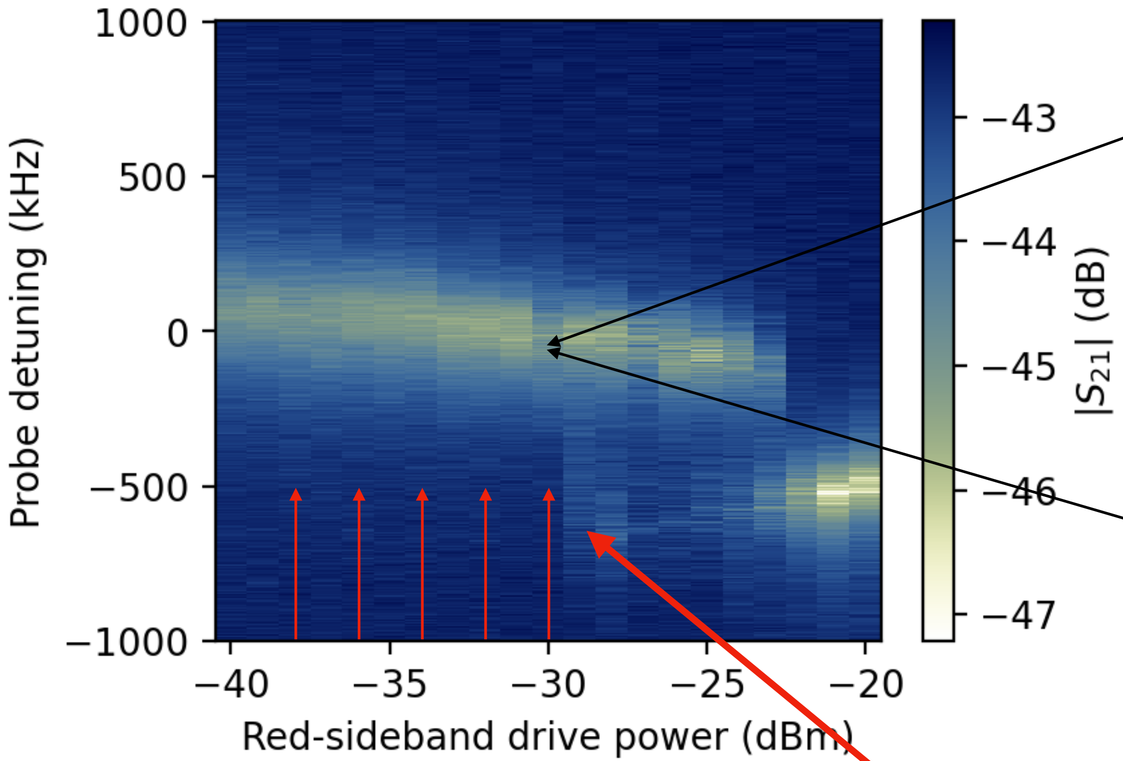
# OMIT before punch-out

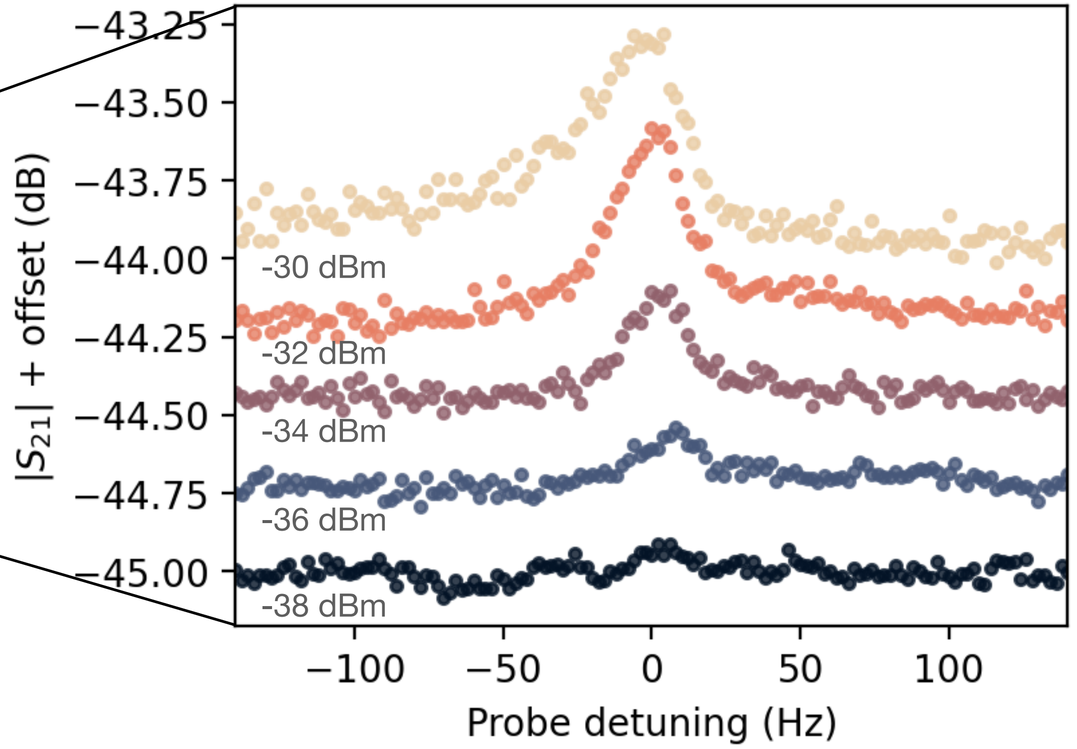




# OMIT before punch-out

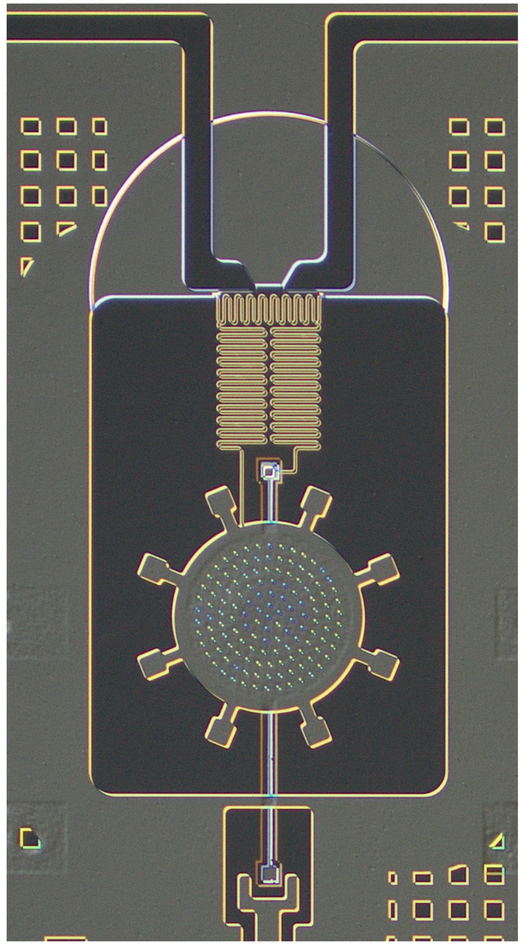




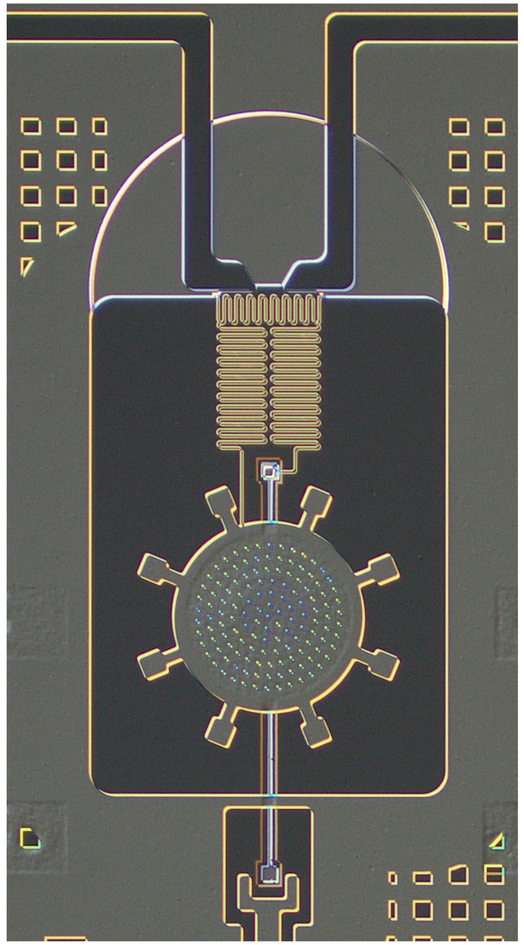

Only ±10-100 photons…

# What’s next?



Qubit and drum both work!

# What's next?

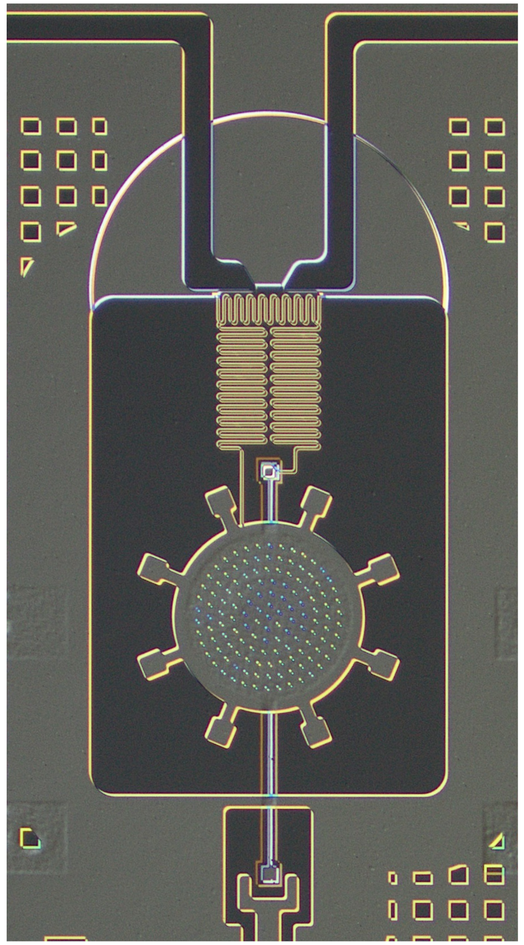


Qubit and drum both work!

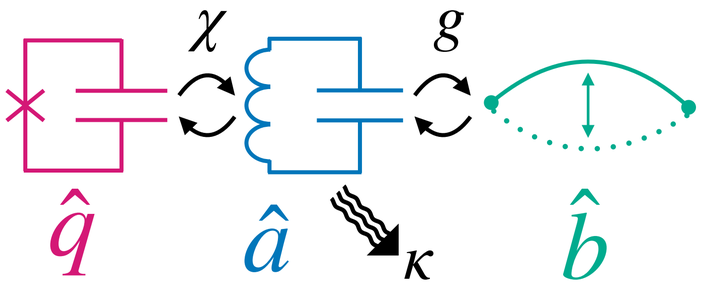
Improvements:

- Fix setup issues
- Lower qubit frequency

# What's next?



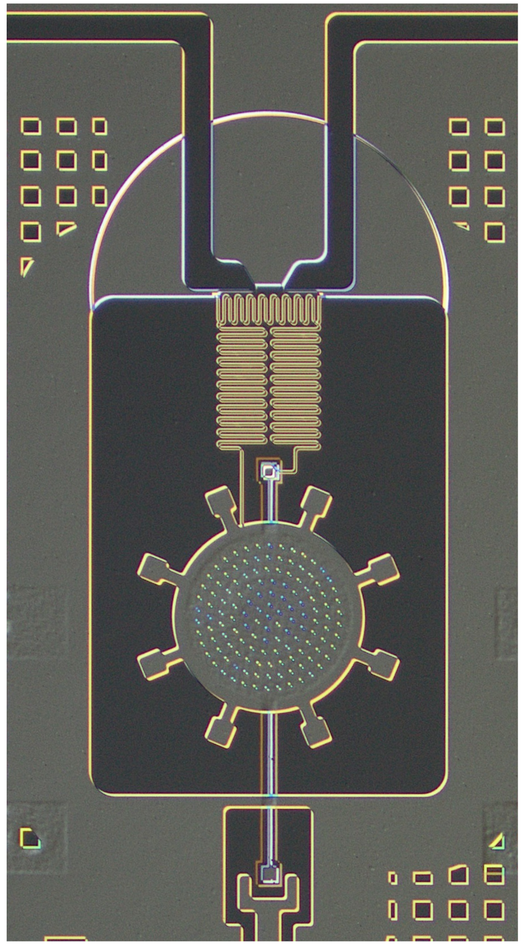
Qubit and drum both work!



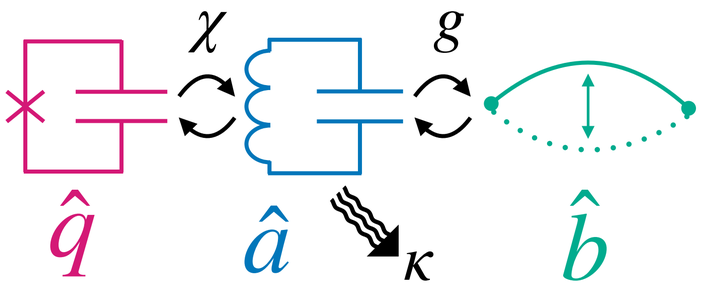

Improvements:

- Fix setup issues
- Lower qubit frequency

# What's next?



Qubit and drum both work!

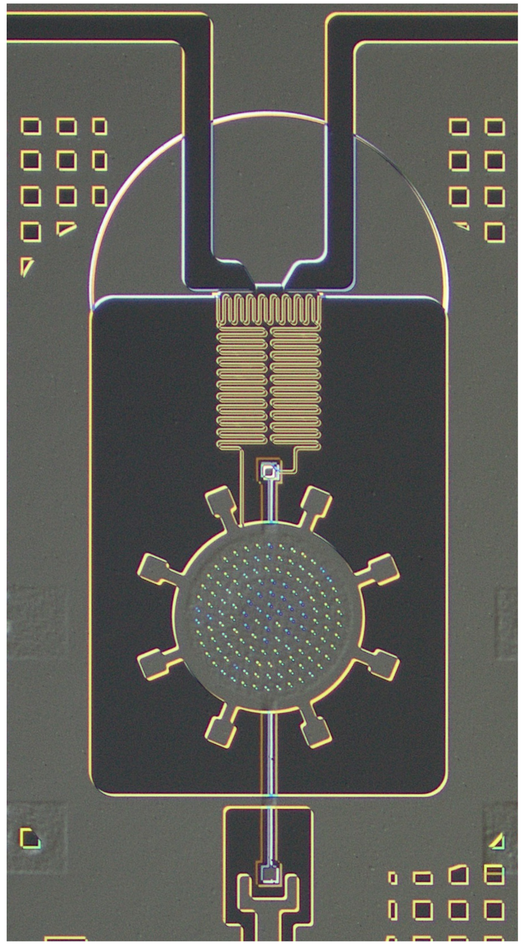



$$\chi \hat{a}^\dagger \hat{a} \hat{q}^\dagger \hat{q} + g(\hat{a} + \hat{a}^\dagger)(\hat{b} + \hat{b}^\dagger)$$

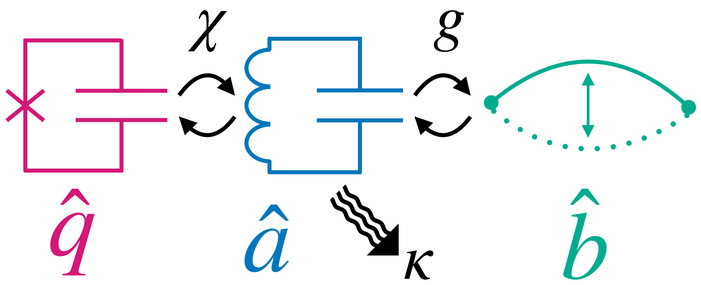
Improvements:

- Fix setup issues
- Lower qubit frequency

# What's next?



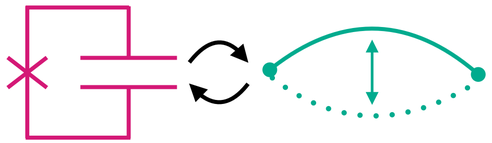
Qubit and drum both work!




$$\chi \hat{a}^\dagger \hat{a} \hat{q}^\dagger \hat{q} + g(\hat{a} + \hat{a}^\dagger)(\hat{b} + \hat{b}^\dagger)$$

↓ Trace out the cavity

Effective qubit-mechanics interaction:

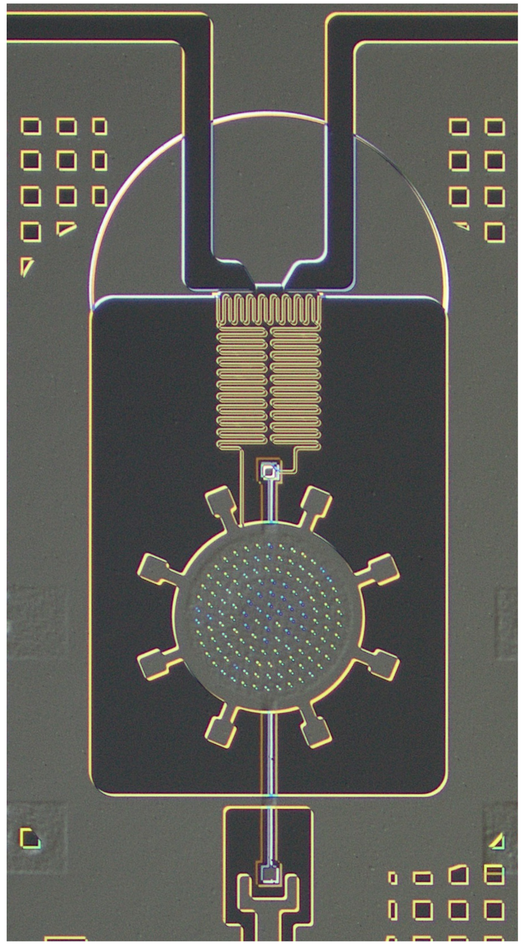


$$\chi \left( \frac{2g}{\kappa} \right)^2 \hat{q}^\dagger \hat{q} \hat{b}^\dagger \hat{b}$$

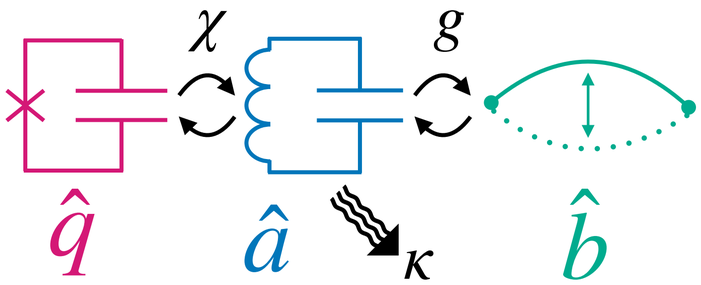
Improvements:

- Fix setup issues
- Lower qubit frequency

# What's next?



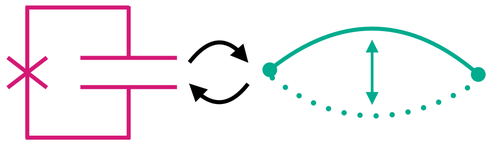
Qubit and drum both work!




$$\chi \hat{a}^\dagger \hat{a} \hat{q}^\dagger \hat{q} + g(\hat{a} + \hat{a}^\dagger)(\hat{b} + \hat{b}^\dagger)$$

↓ Trace out the cavity

Effective qubit-mechanics interaction:



$$\chi \left( \frac{2g}{\kappa} \right)^2 \hat{q}^\dagger \hat{q} \hat{b}^\dagger \hat{b}$$

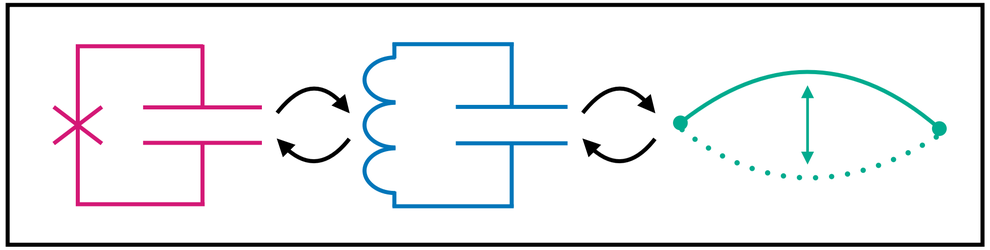
*Radiation-pressure induced dephasing*

Improvements:

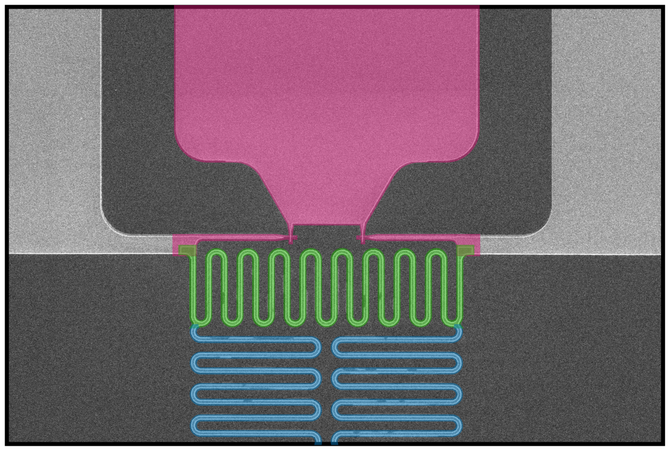
- Fix setup issues
- Lower qubit frequency

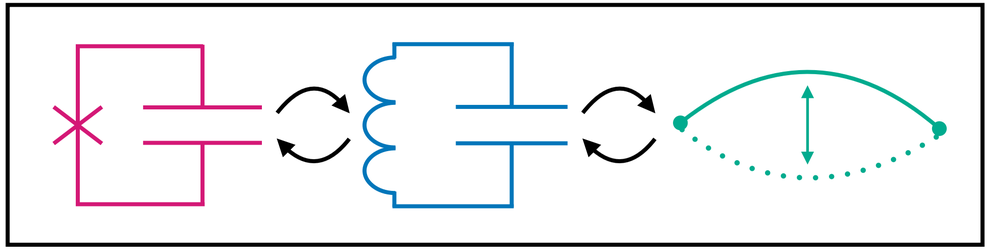
TU Delft

# Nonlinear coupling in circuit QED for quantum optomechanics



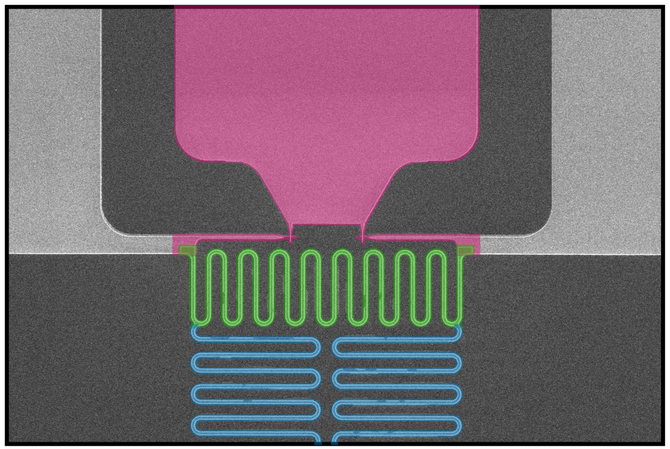
# Nonlinear coupling in circuit QED for quantum optomechanics

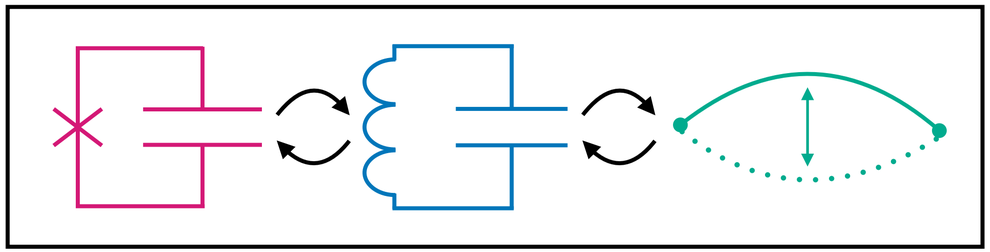




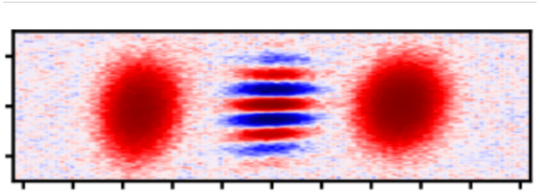
Photon-number resilient coupling

# Nonlinear coupling in circuit QED for quantum optomechanics

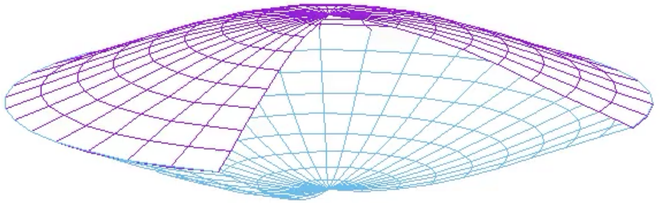




Photon-number resilient coupling

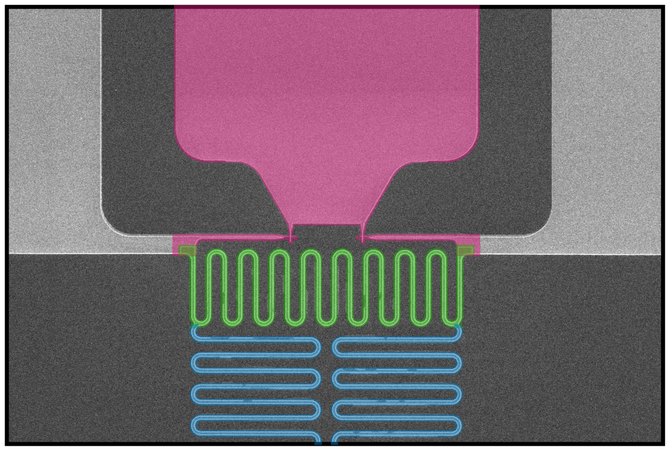


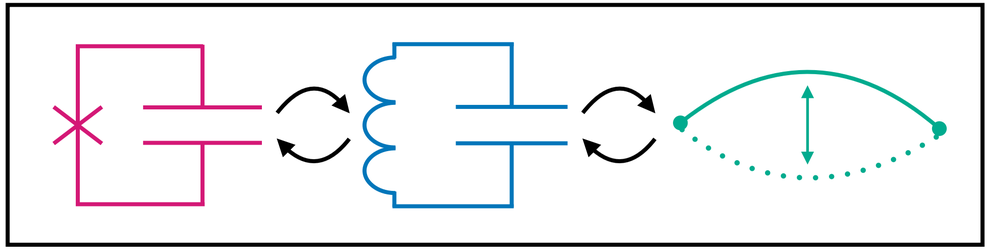
Microwave cat



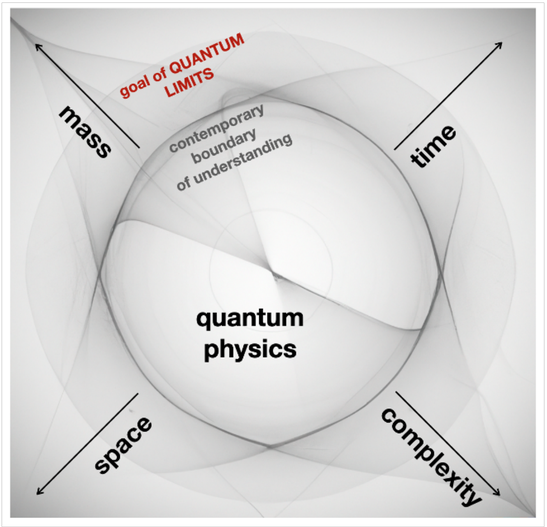
Massive superposition

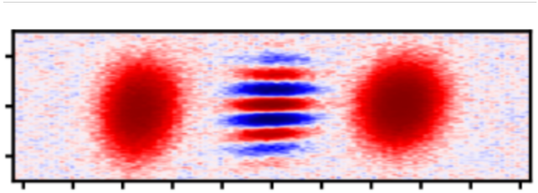
# Nonlinear coupling in circuit QED for quantum optomechanics



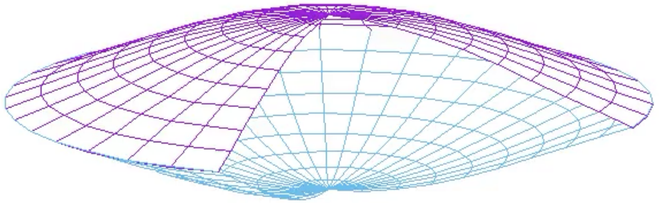


Photon-number resilient coupling



Microwave cat



Massive superposition

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# Acknowledgments

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Matteo



*Marius*



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Matteo



*Marius*





Gary



Richard

Department of Quantum Nanoscience
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# Appendix: branch analysis

