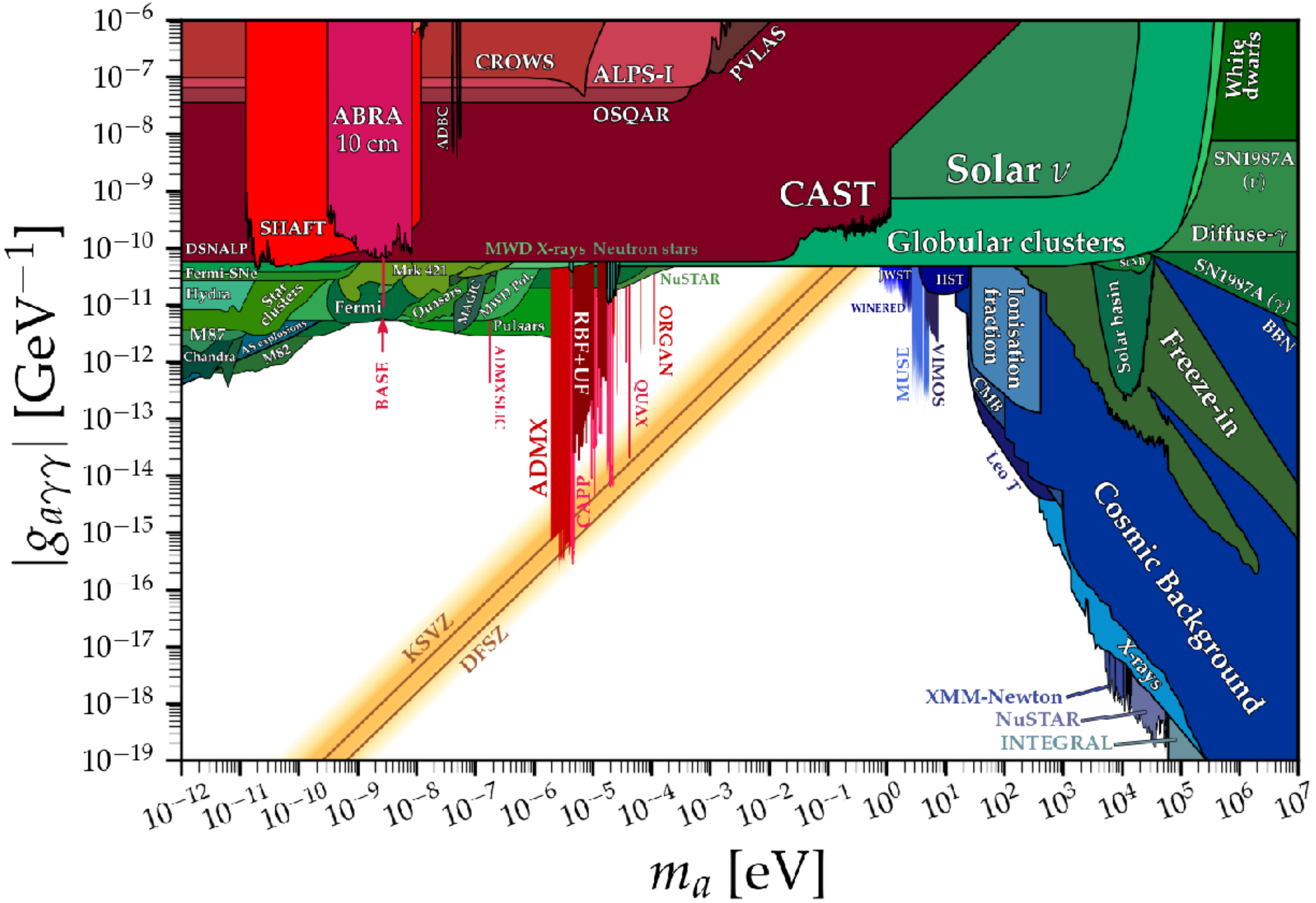
Searches for wavelike dark matter utilizing superconducting qubits

Oct 16, 2024

The University of Tokyo, ICEPP Tatsumi Nitta

for DarQ experiment

Axion Hunting So Far



DFSZ sensitivity

- ADMX
- CAPP

→ Probability of discovery is too low, so far

Big money (huge magnet etc) “partially” solves problems

New ideas and technologies are necessary for discovery

We are investigating possibilities of **superconducting qubits**

Basic Properties Superconducting Qubits

As Quantum Computer …

✓Large EDM

-> 10^6 × atoms

✓Fast Readout

-> $O(10)\ ns$

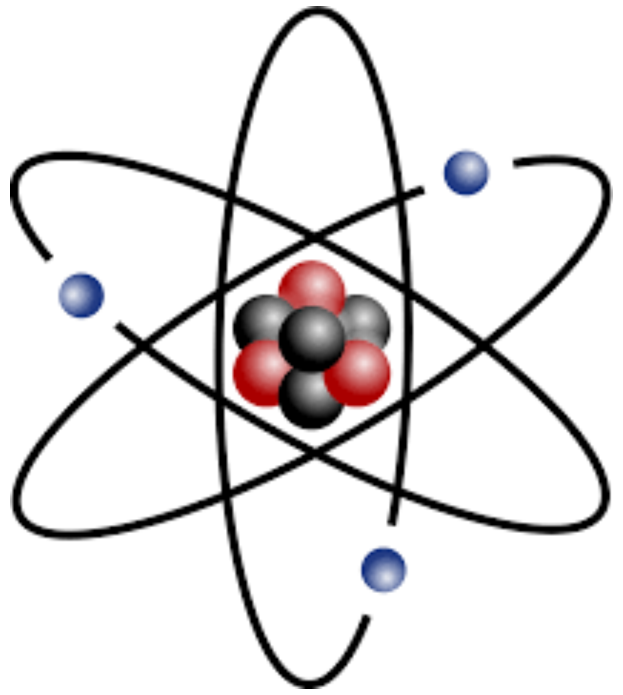
✓Long Lifetime

-> $O(100)\ \mu s$

✓Low Noise

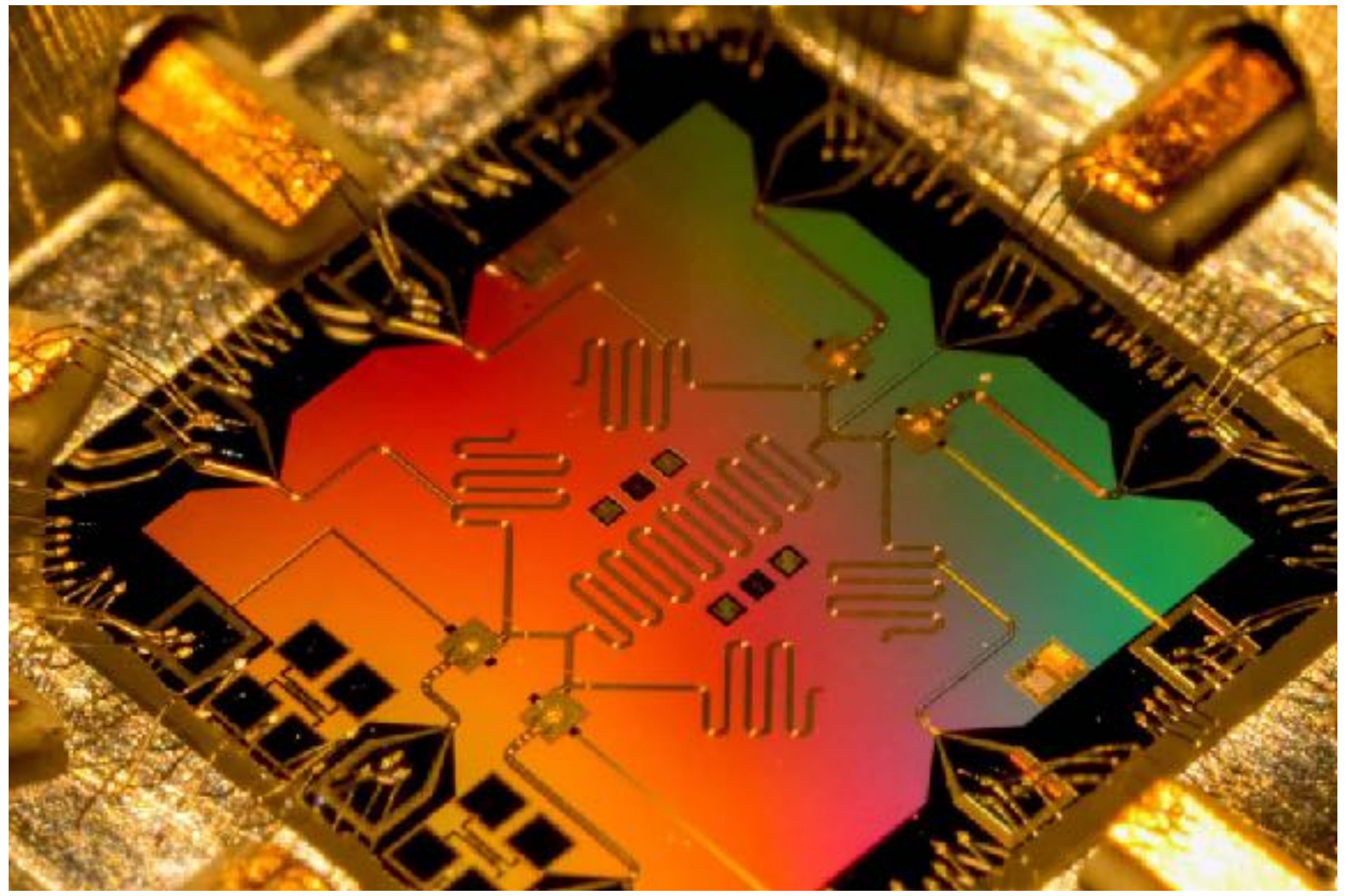
-> mK & shield

0.1 nm



$N_{\text{electron}} < O(100)$

100 μm



Many copper pairs behaves coherently

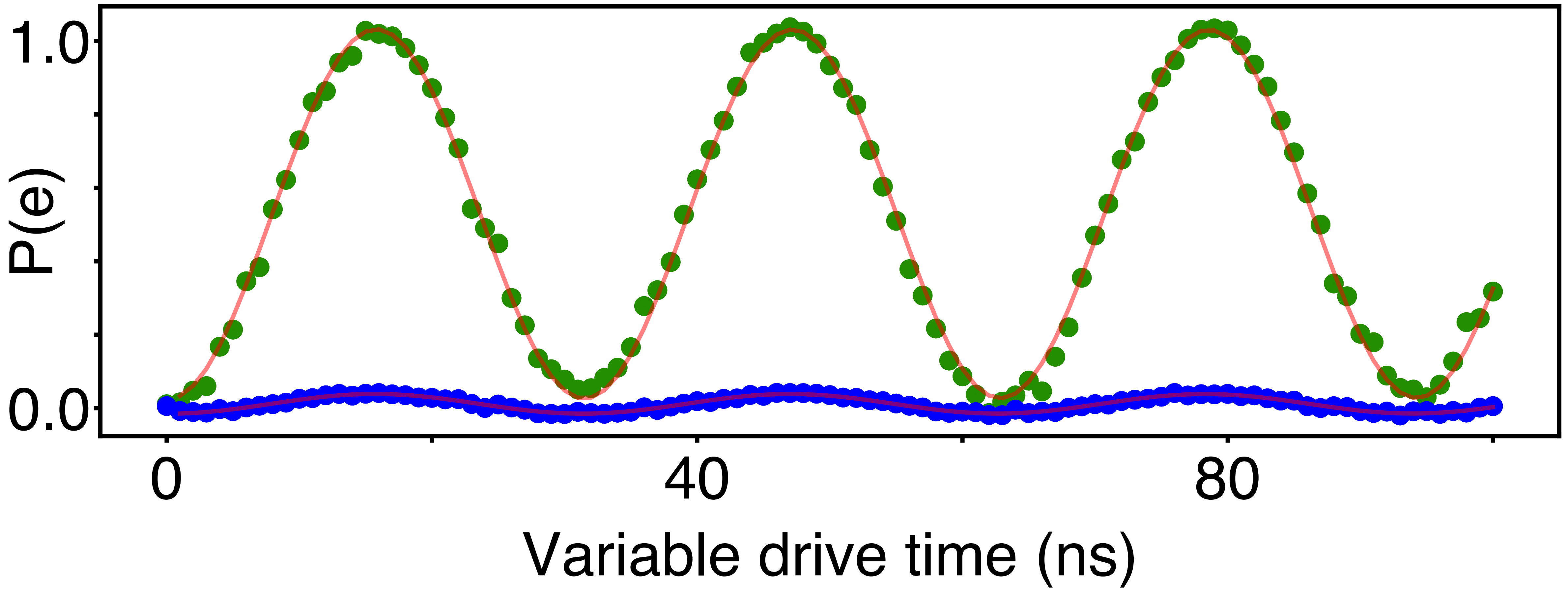
Qubit is a giant artificial atom

Basic Properties Superconducting Qubits

As Quantum Computer …

- ✓Large EDM
  - -> $10^6 \times$ atoms
- ✓Fast Readout
  - -> $O(10)\ ns$
- ✓Long Lifetime
  - -> $O(100)\ \mu s$
- ✓Low Noise
  - -> mK & shield

Driving $|0\rangle \rightarrow |1\rangle$ takes only 10 ns



Qubit is so fast

Basic Properties Superconducting Qubits

As Quantum Computer …

- ✓Large EDM
  - -> $10^6 \times$ atoms
- ✓Fast Readout
  - -> $O(10)\ ns$
- ✓Long Lifetime
  - -> $O(100)\ \mu s$
- ✓Low Noise
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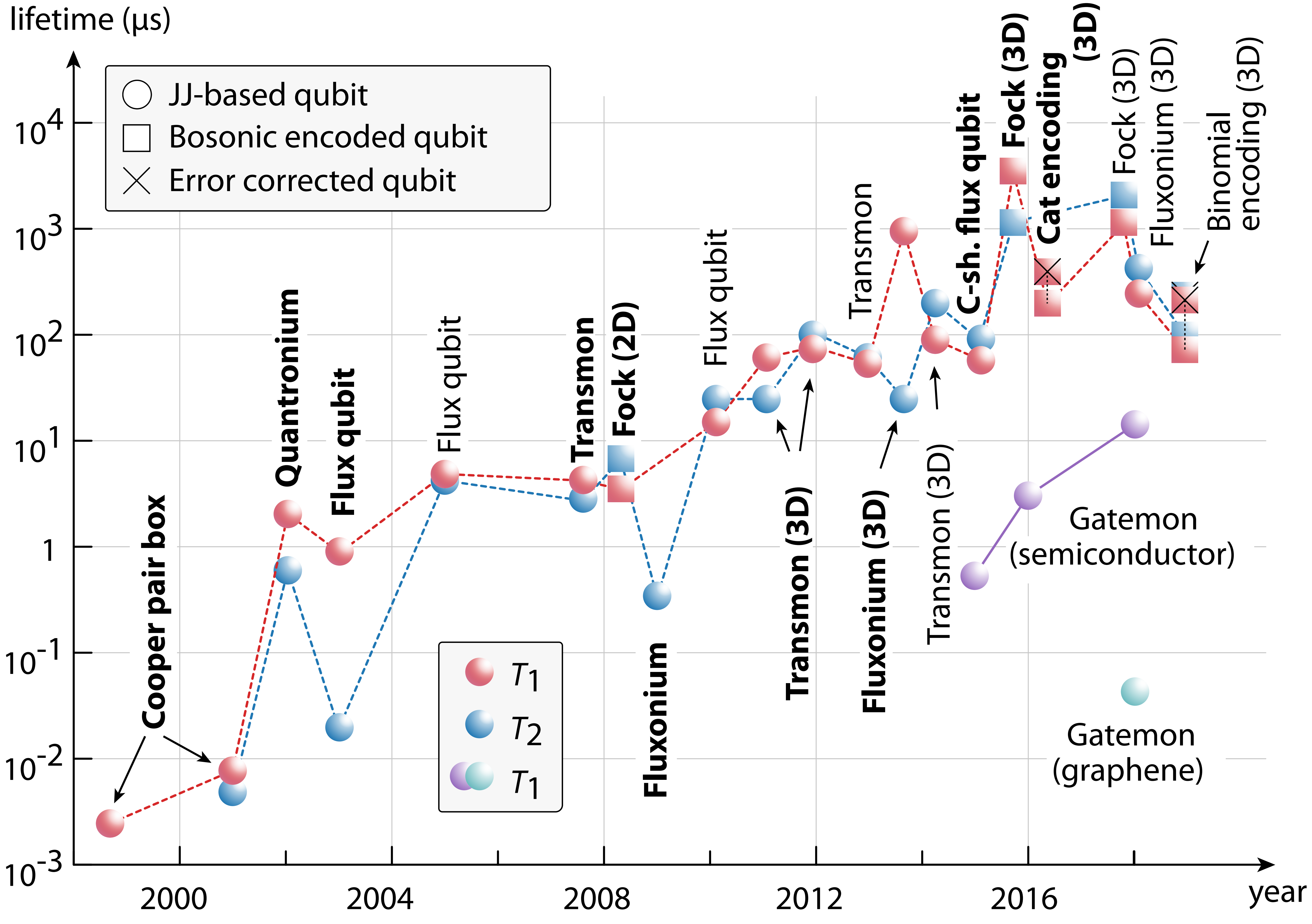


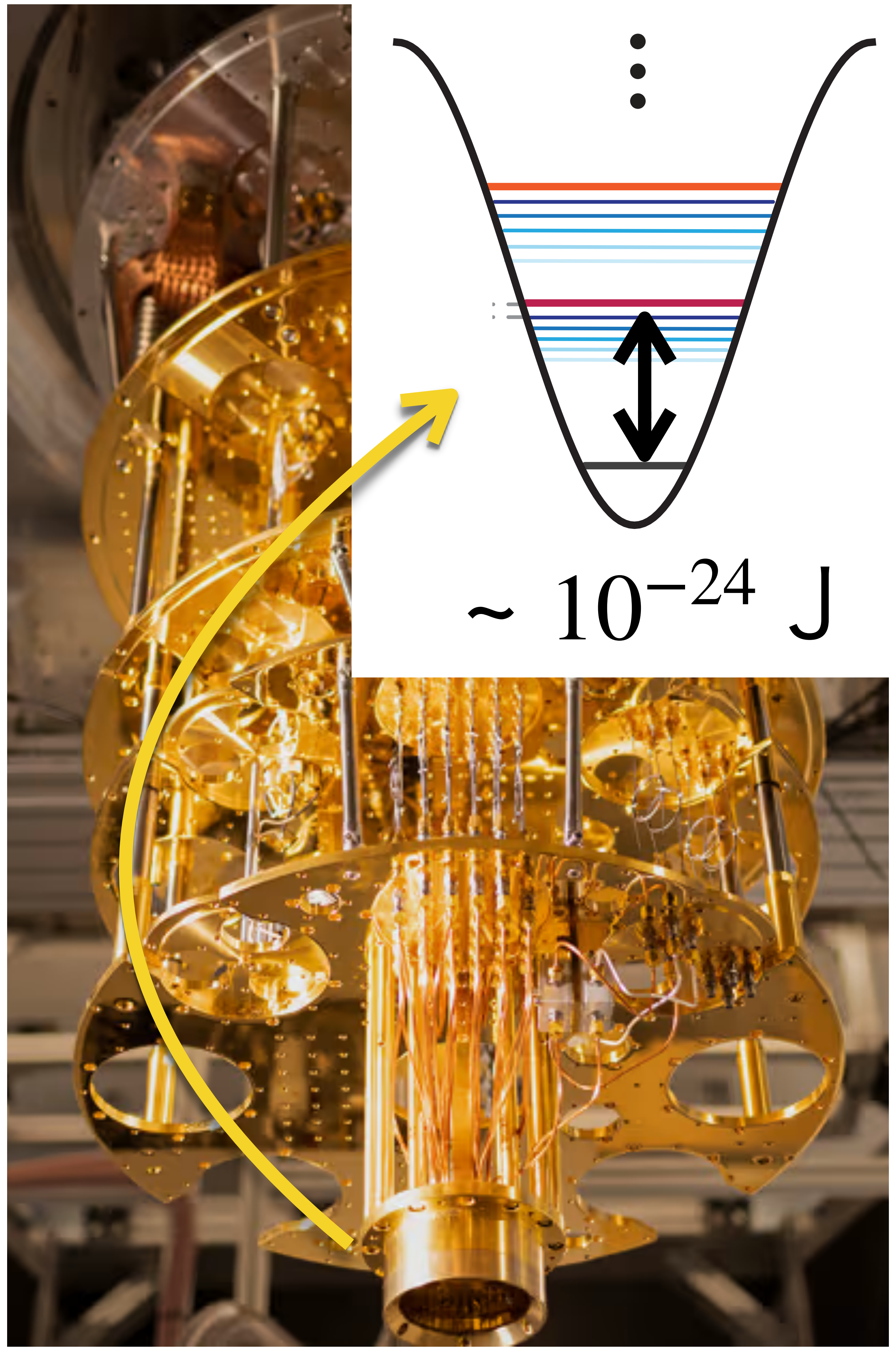
Relatively long coherence time

Basic Properties Superconducting Qubits

As Quantum Computer …

- ✓Large EDM
  - -> $10^6 \times$ atoms
- ✓Fast Readout
  - -> $O(10)\ ns$
- ✓Long Lifetime
  - -> $O(100)\ \mu s$
- ✓Low Noise
  - -> mK & shield

~ 10^{-13} W



~ 10^{-24} J

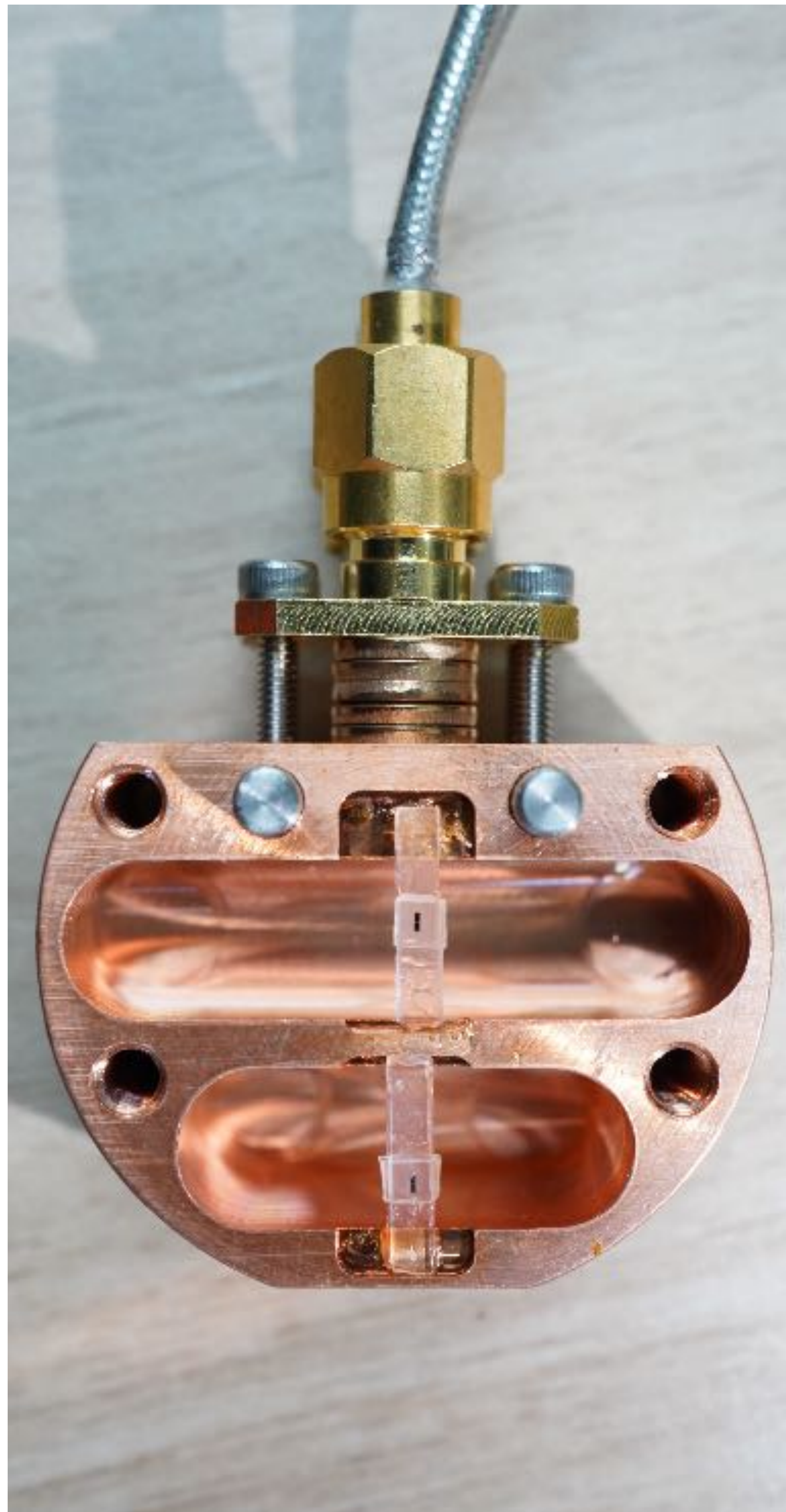
~ 10^{-19} W

@100 Hz帯域

Qubit is in ultra low noise environment

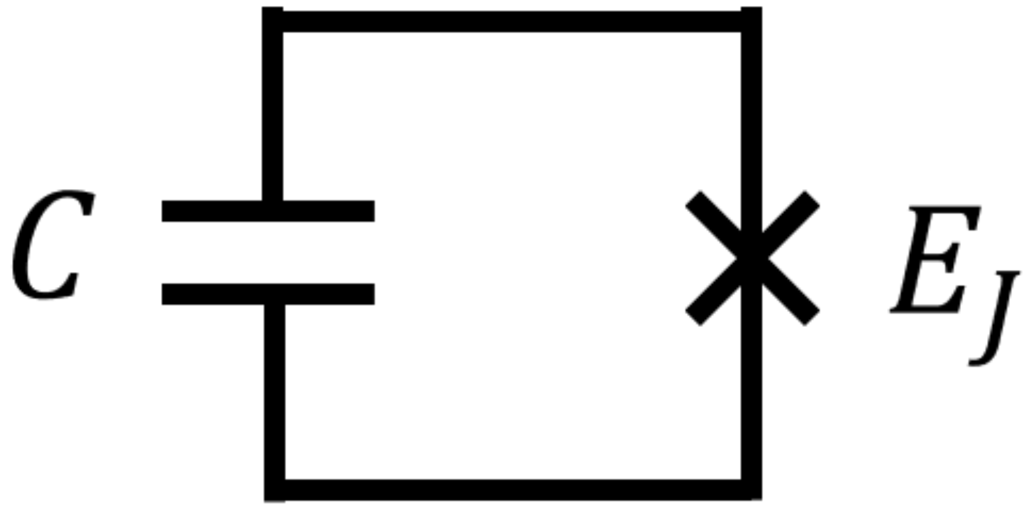
Basic Properties Superconducting Qubits

As Quantum Computer …		As Quantum Sensor …
✓Large EDM -> $10^6 \times$ atoms	↔	✓Strong coupling to signals
✓Fast Readout -> $O(10)$ ns	↔	✓Low readout error
✓Long Lifetime -> $O(100)$ μs	↔	✓Easier operation
✓Low Noise -> mK & shield	↔	✓Don’t miss tiny signals

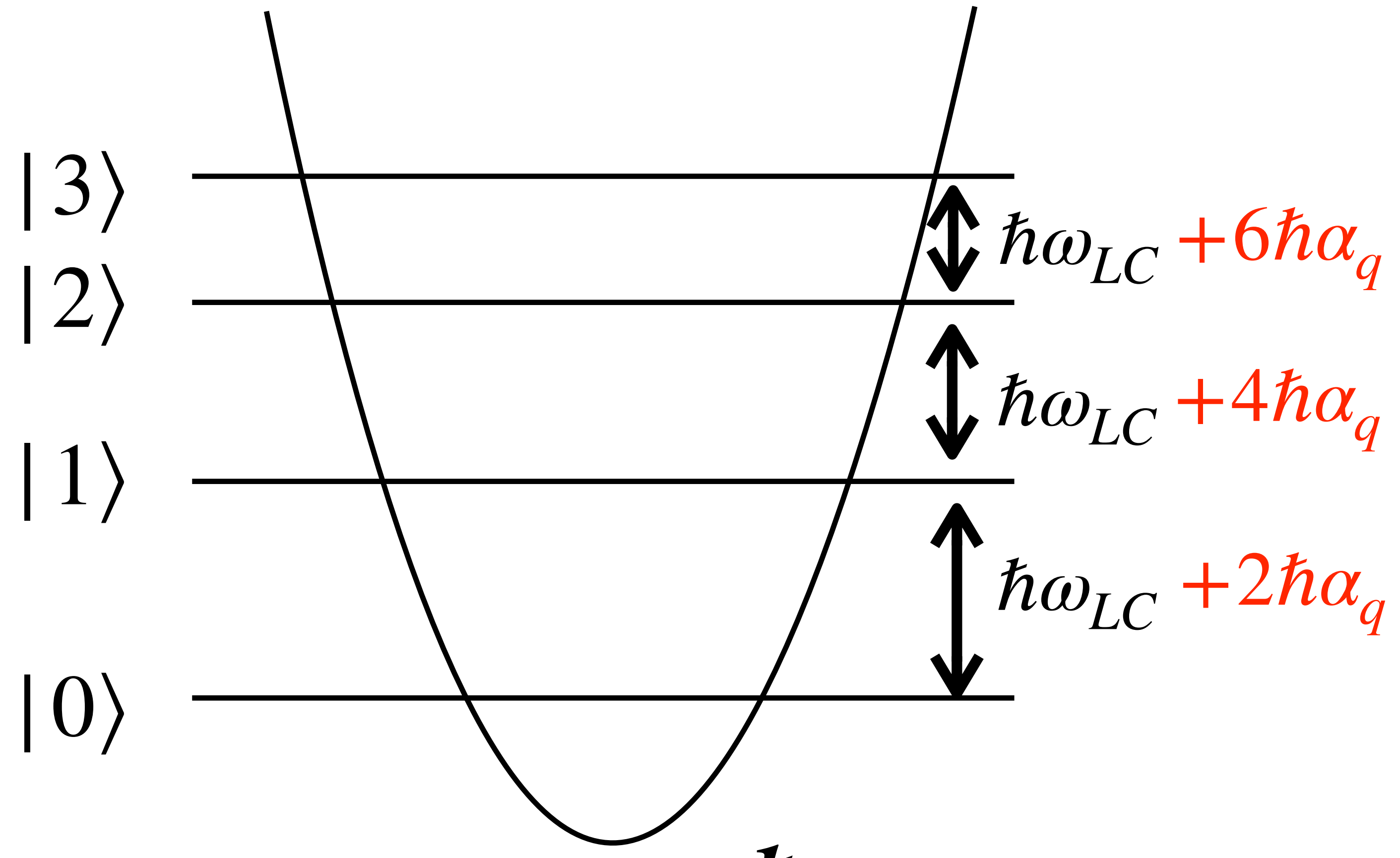


Superconducting Qubits

Circuit diagram of Qubit



Energy level

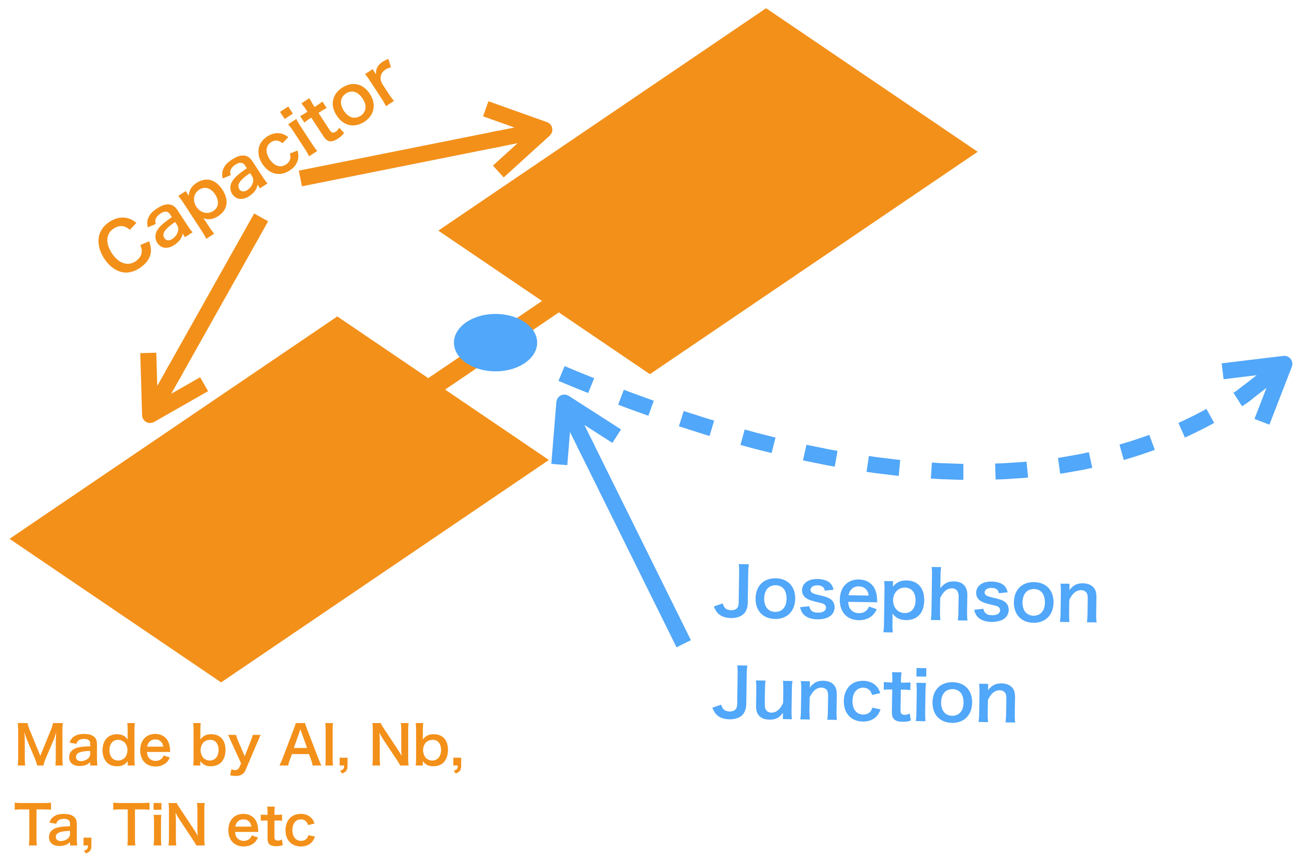


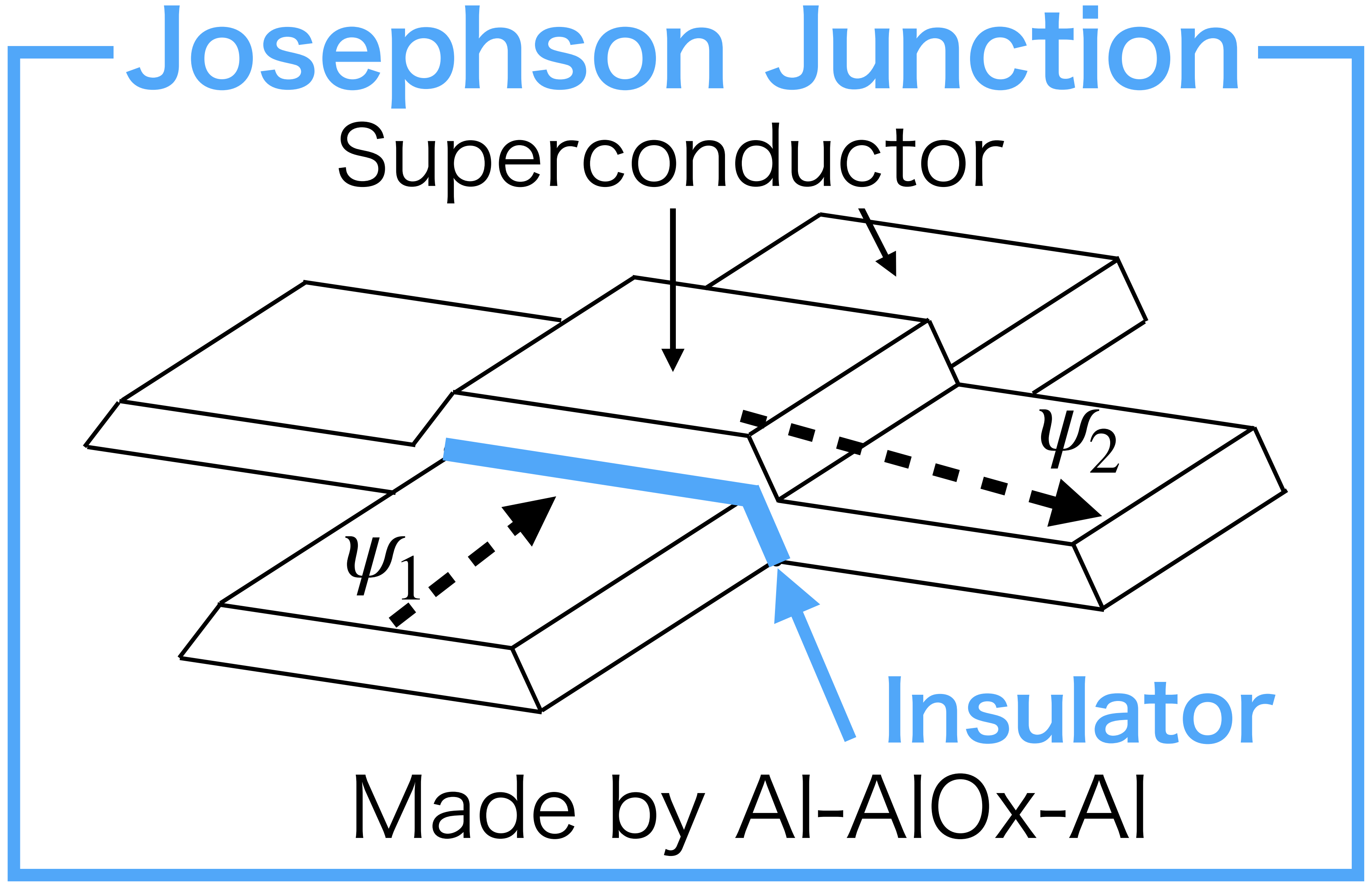
$$\mathscr{H} = \hbar\omega_q a^\dagger a + \frac{\hbar\alpha_q}{2} a^\dagger a^\dagger a a$$

- LC resonator which L is nonlinear
  Nonlinearity makes anharmonicity (α_q)

  → Easy control from $|0\rangle \rightarrow |1\rangle$
- Nonlinearity comes from **Josephson junction**

Qubit in real

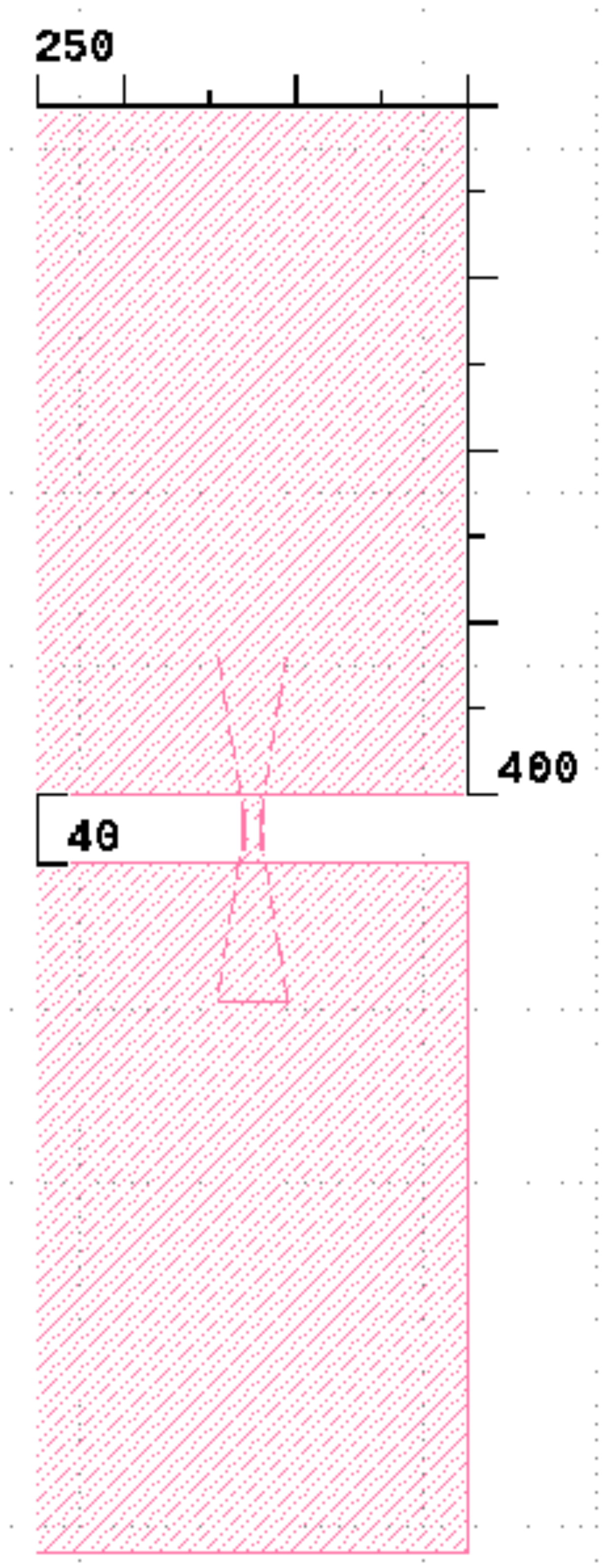




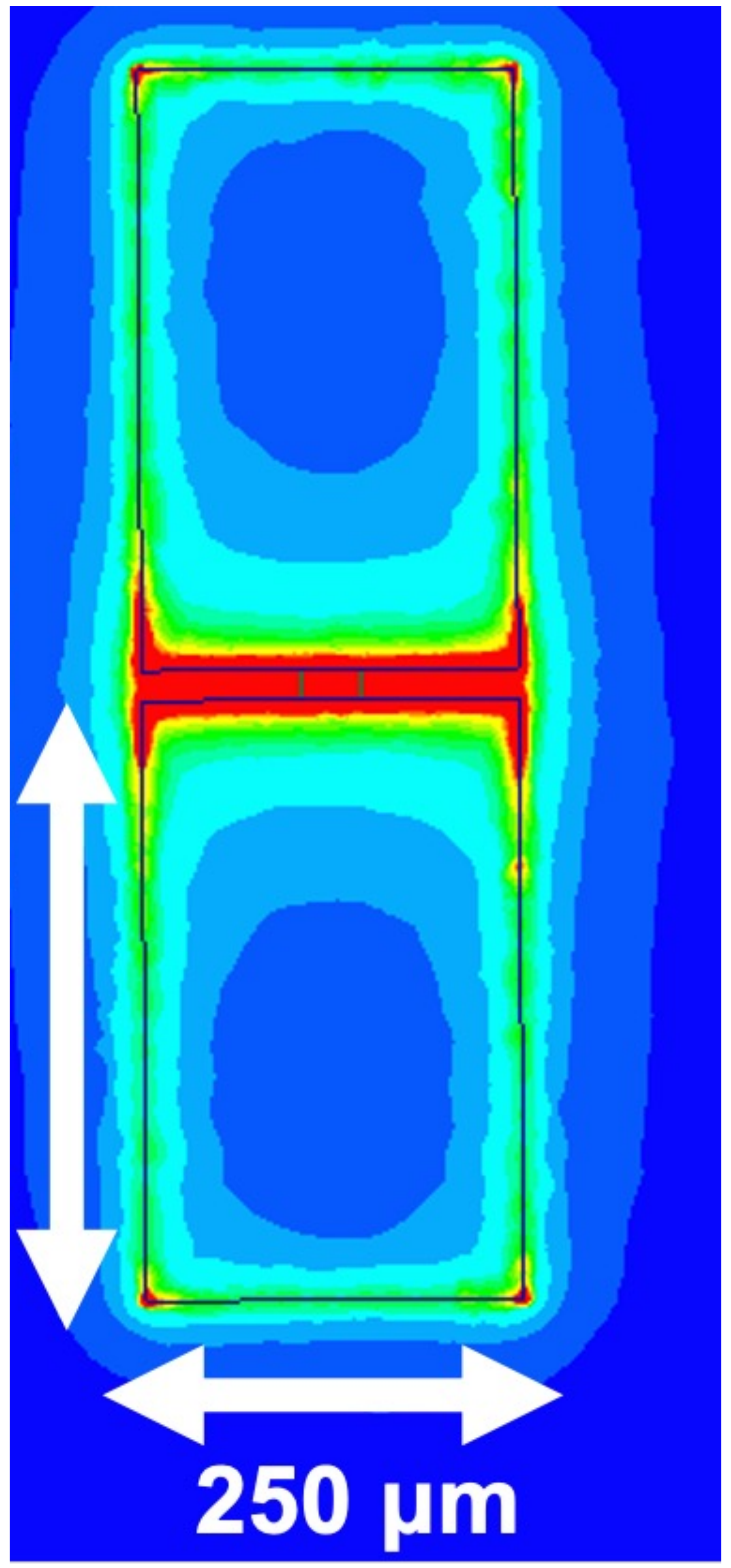
We are making qubit ourself

Qubits for
quantum computing ≠ Qubits for
quantum sensing

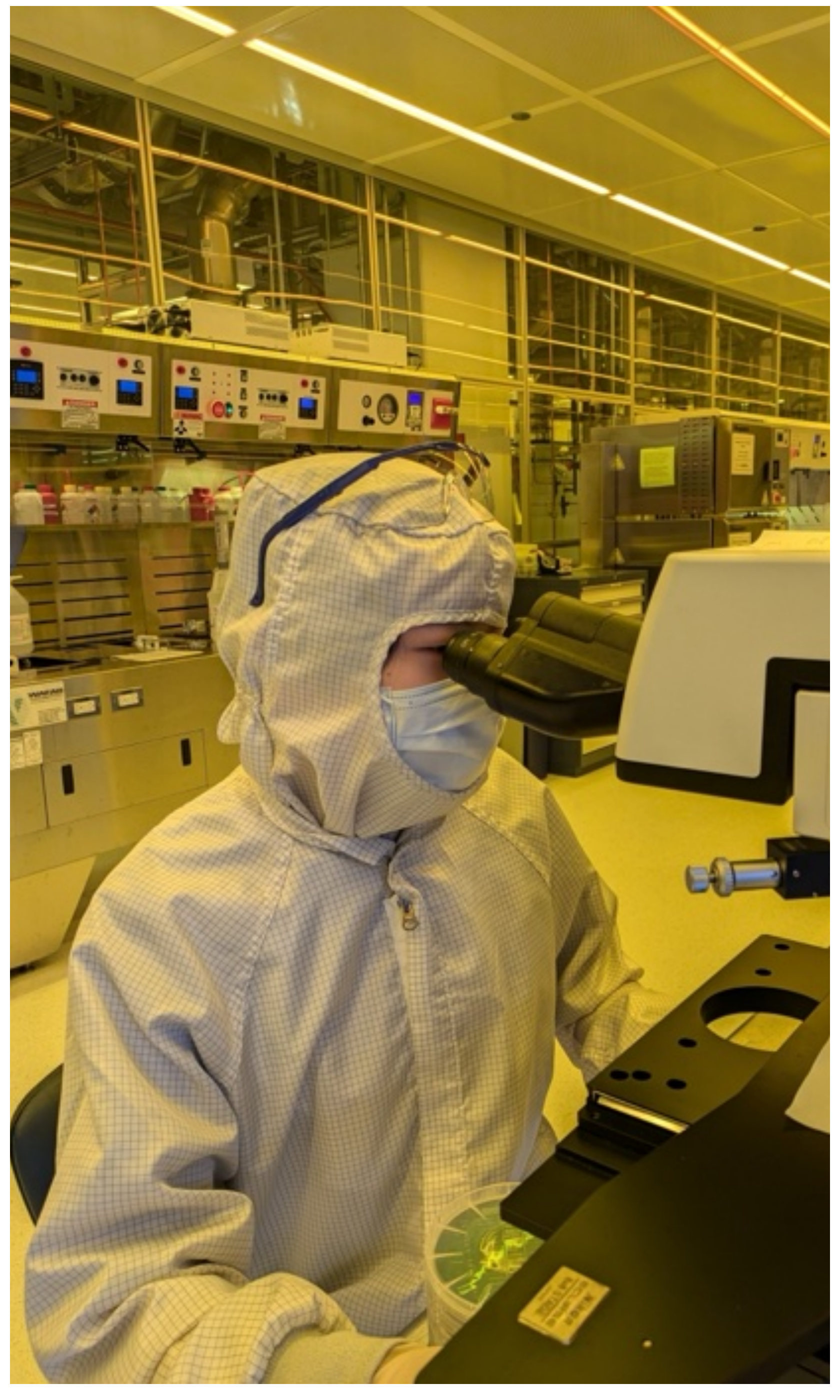
Design



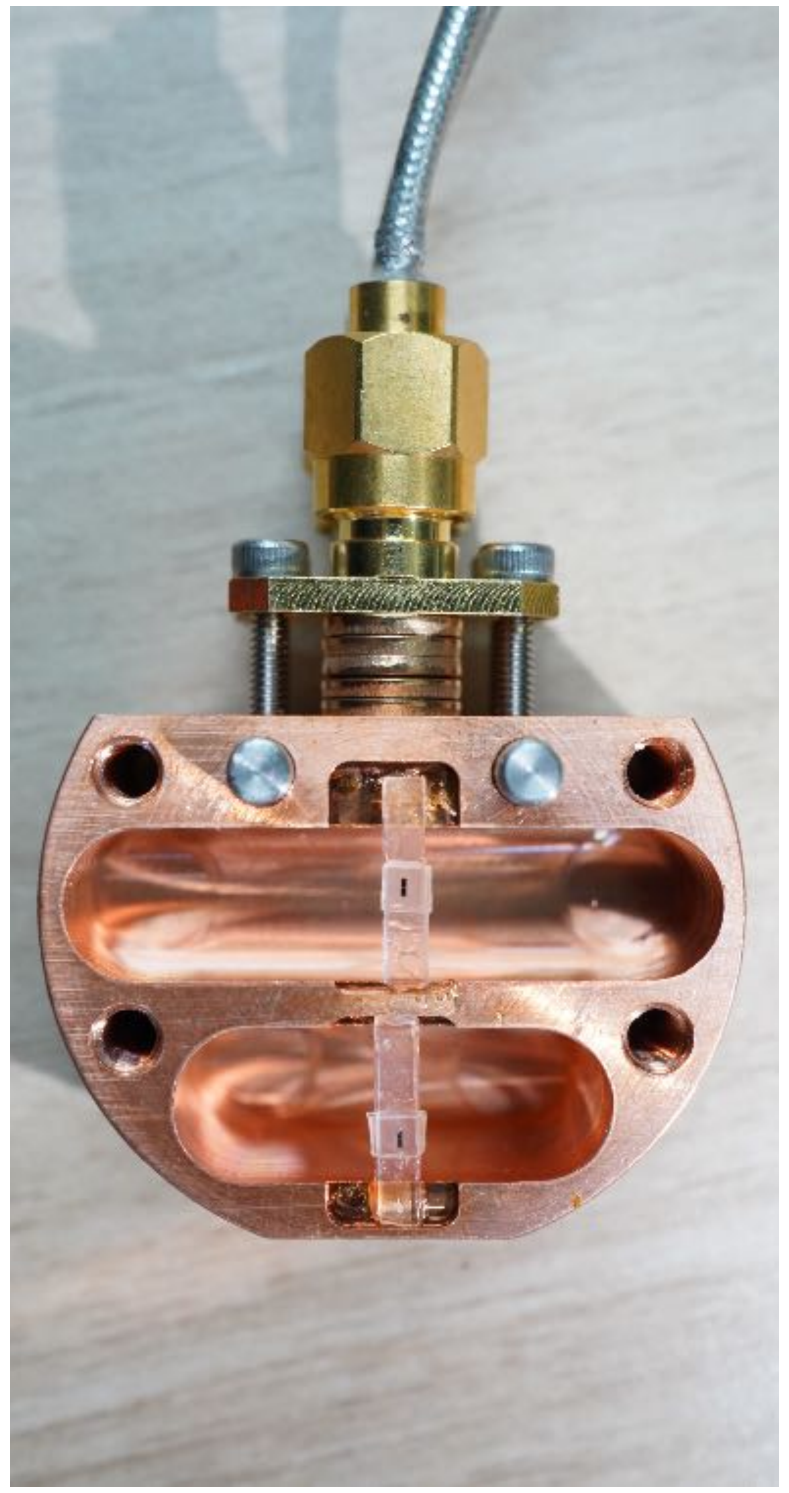
Simulation



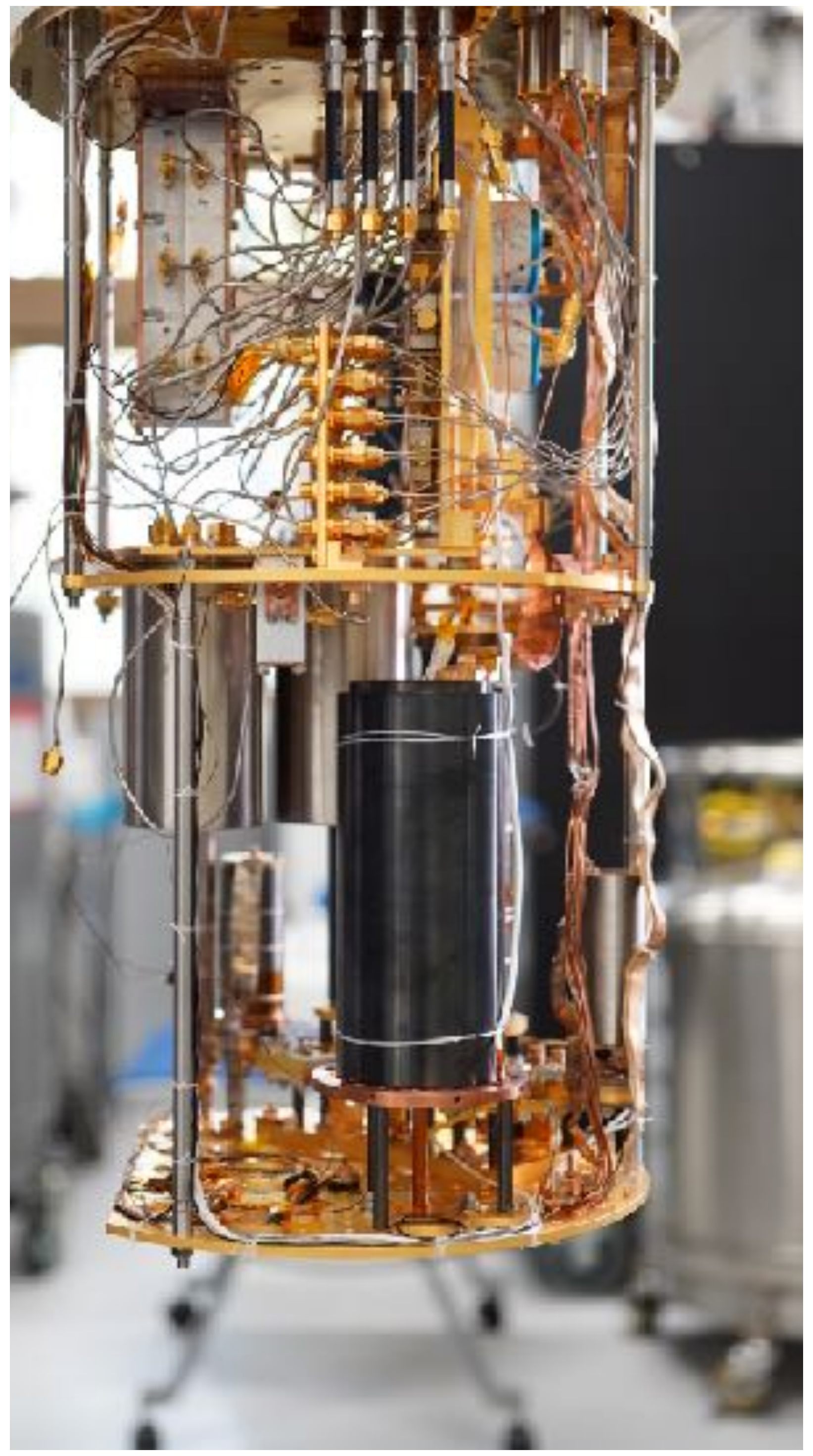
Fabrication



Packaging



Measurement

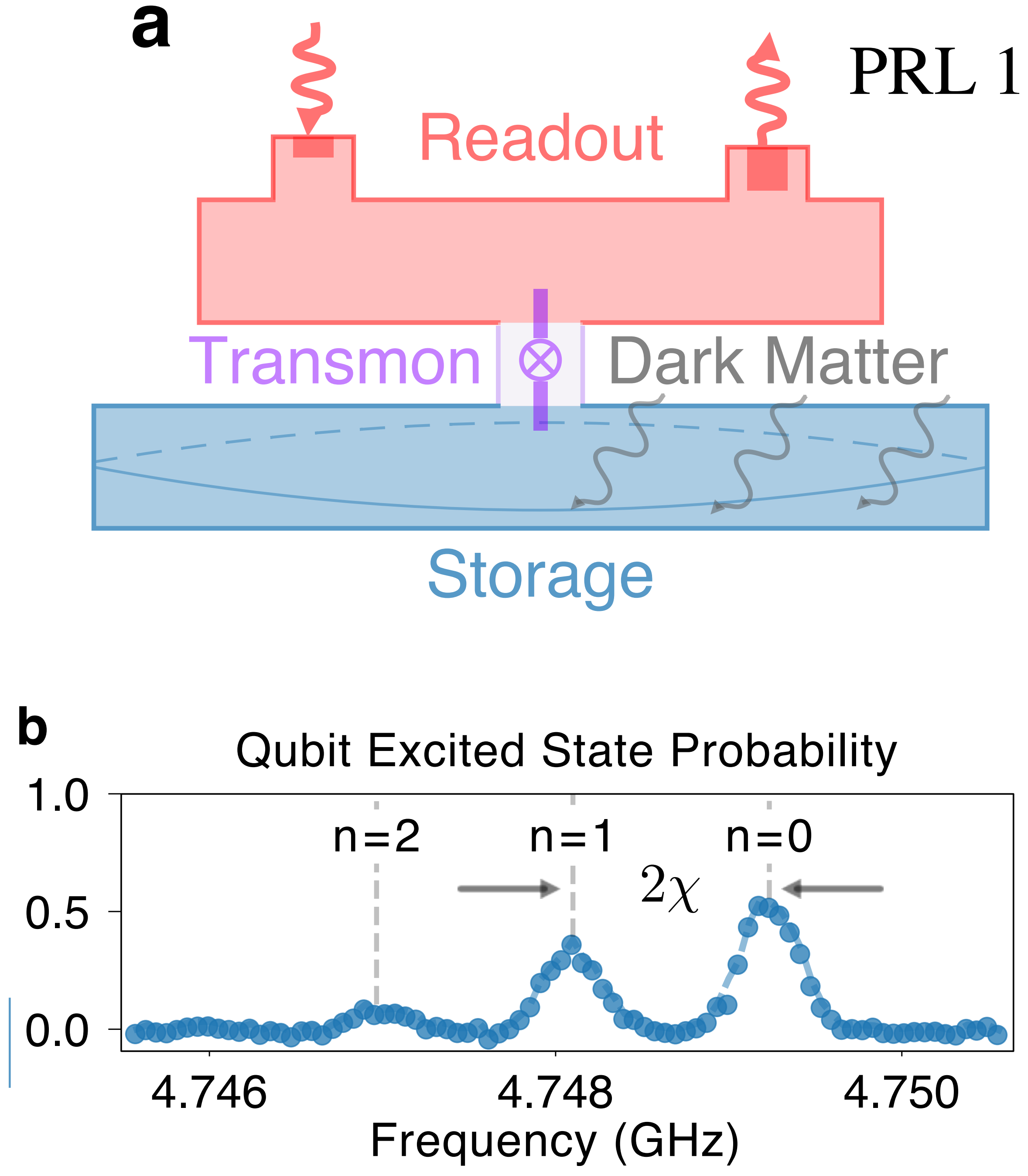


Qubits are utilized for DM searches

Single photon counting

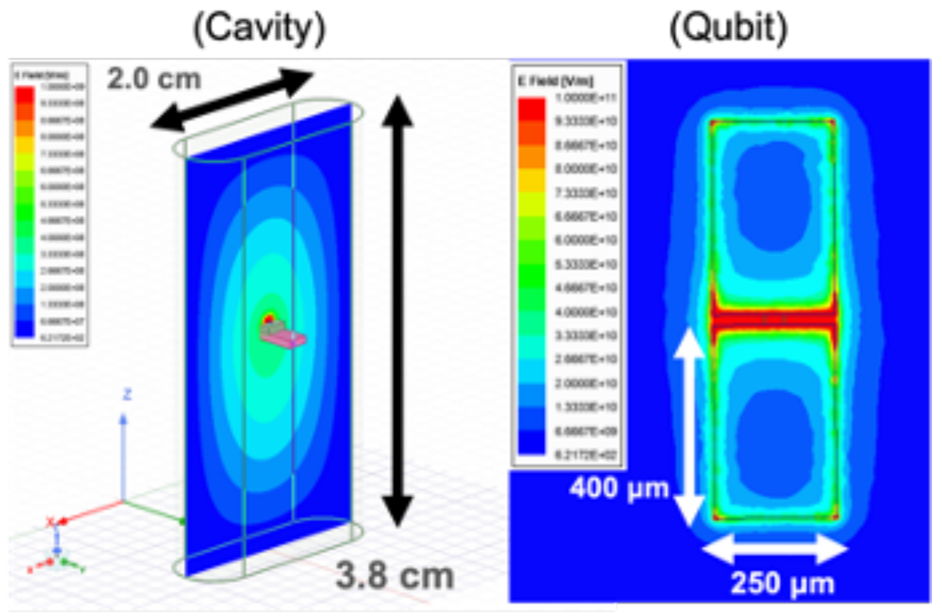
Aaron et.al.

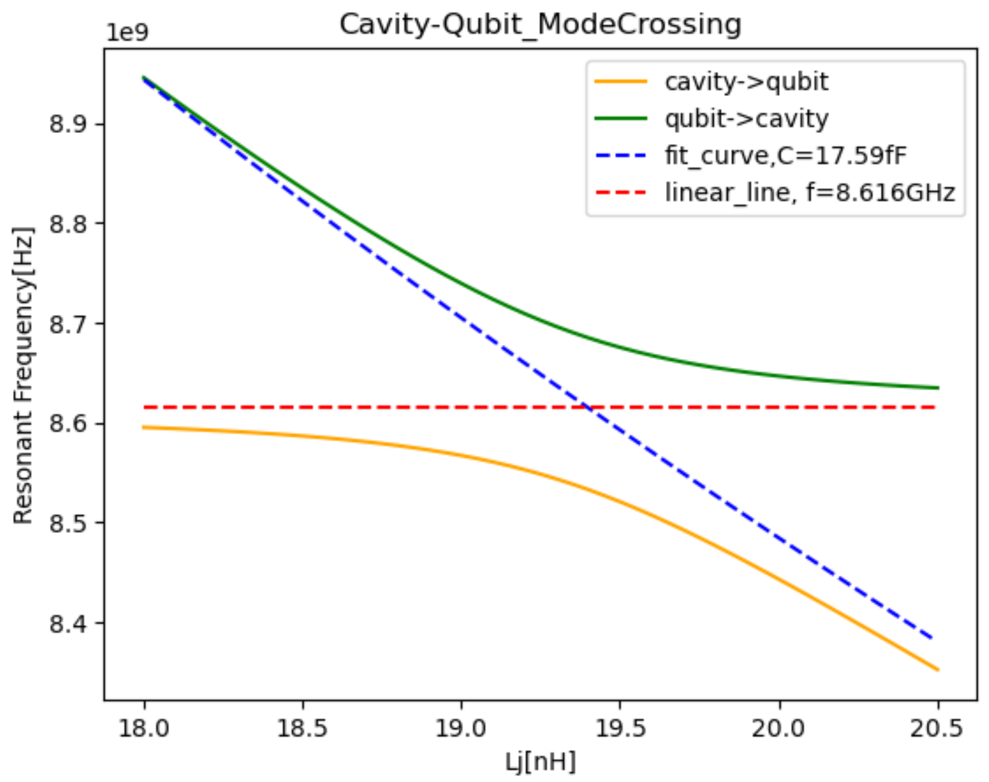
PRL 126 141302 (2021)



Highest sensitivity

Cavity tuning by Lamb shift

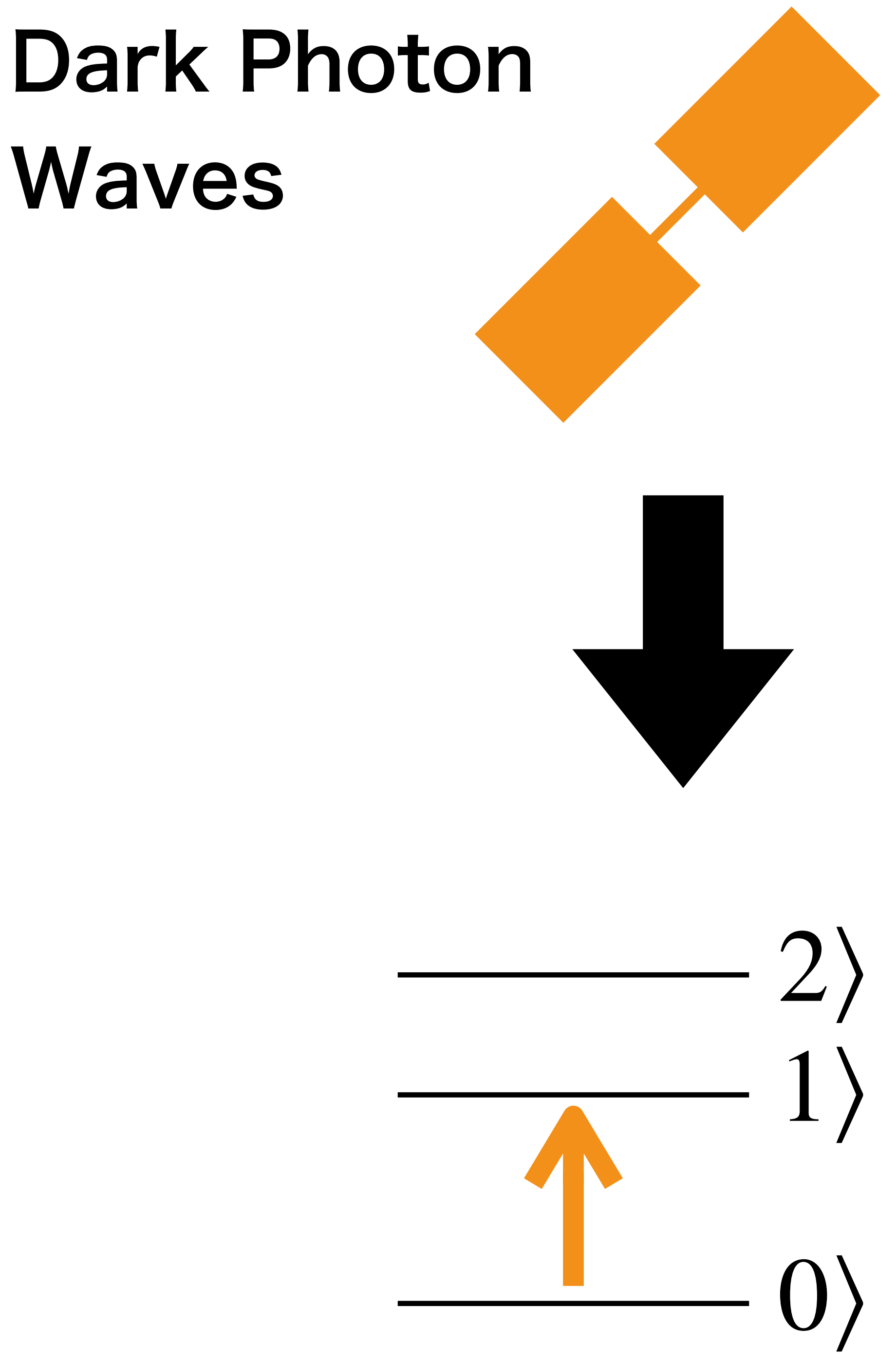




For easier scanning

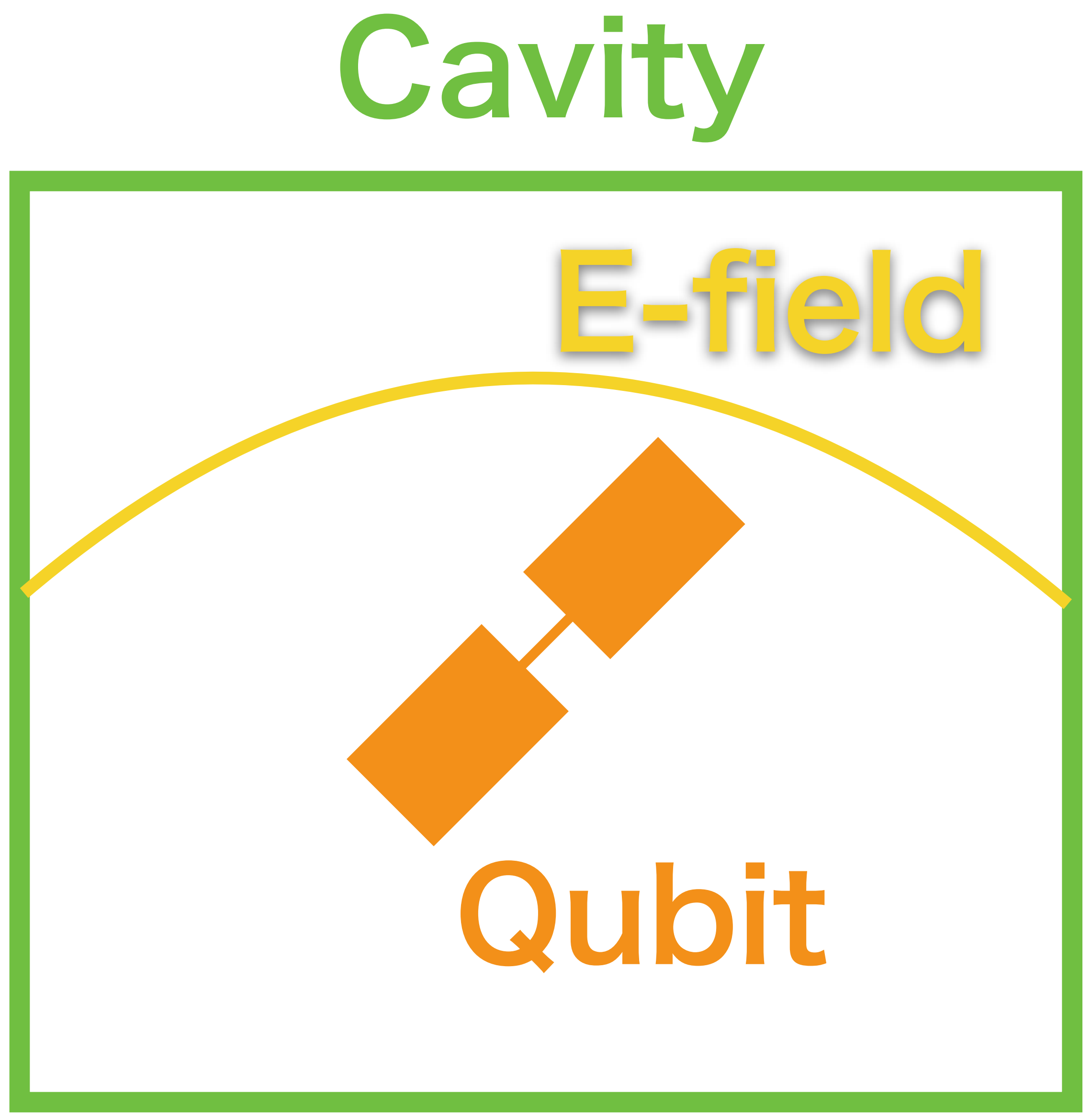
Direct excitation

Moroi+ PRL **131**, 211001



Easier scanning

Cavity QED

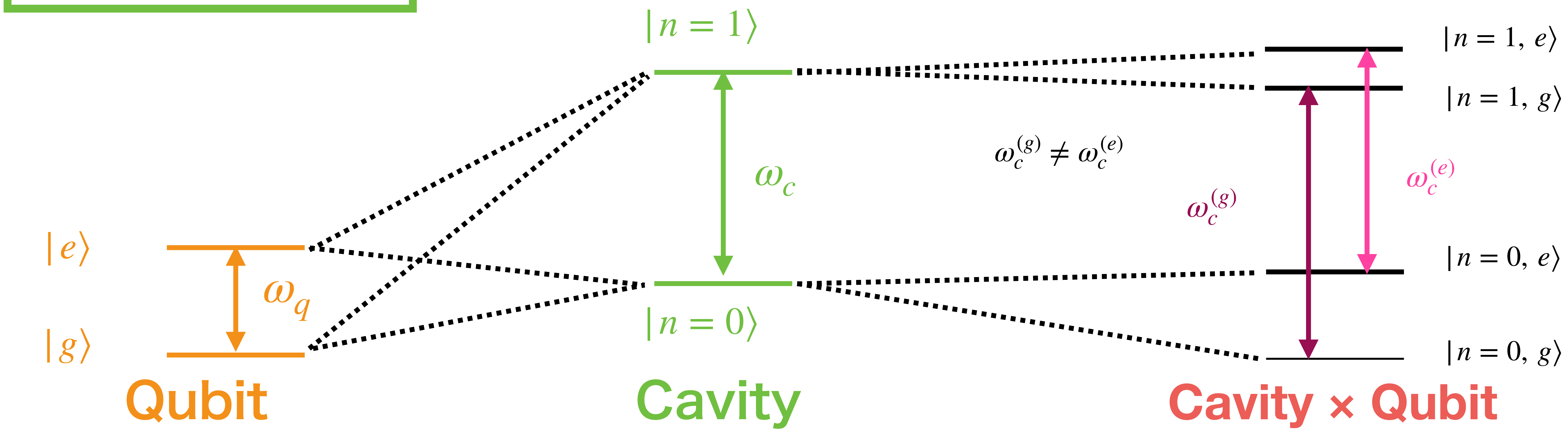


Cavity Qubit Interaction

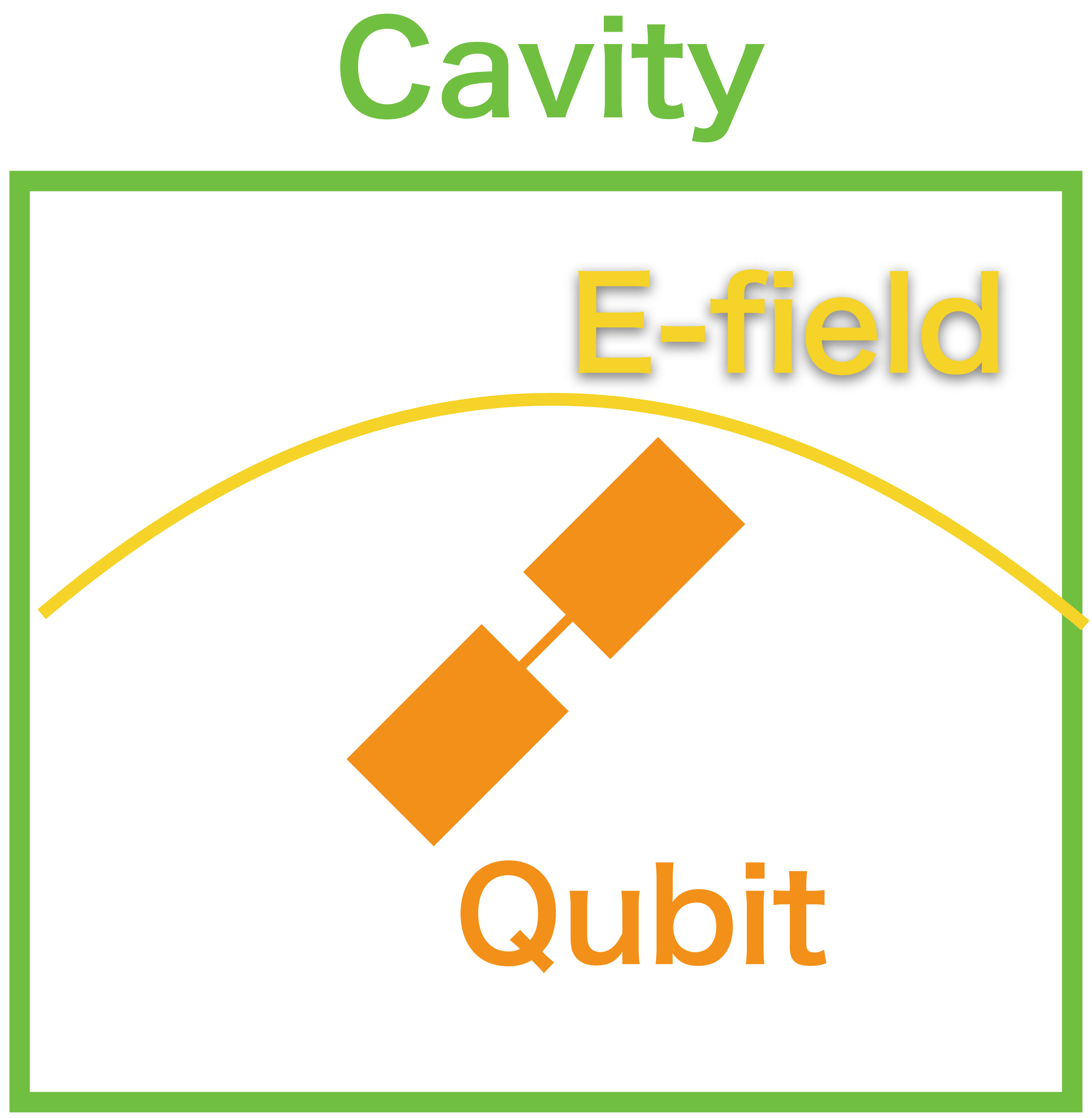
$$\mathscr{H}/\hbar = \boxed{\frac{\omega_q}{2}\sigma_z} + \boxed{\omega_c a^\dagger a} + \boxed{g(\sigma_+ a + a^\dagger \sigma_-)}$$

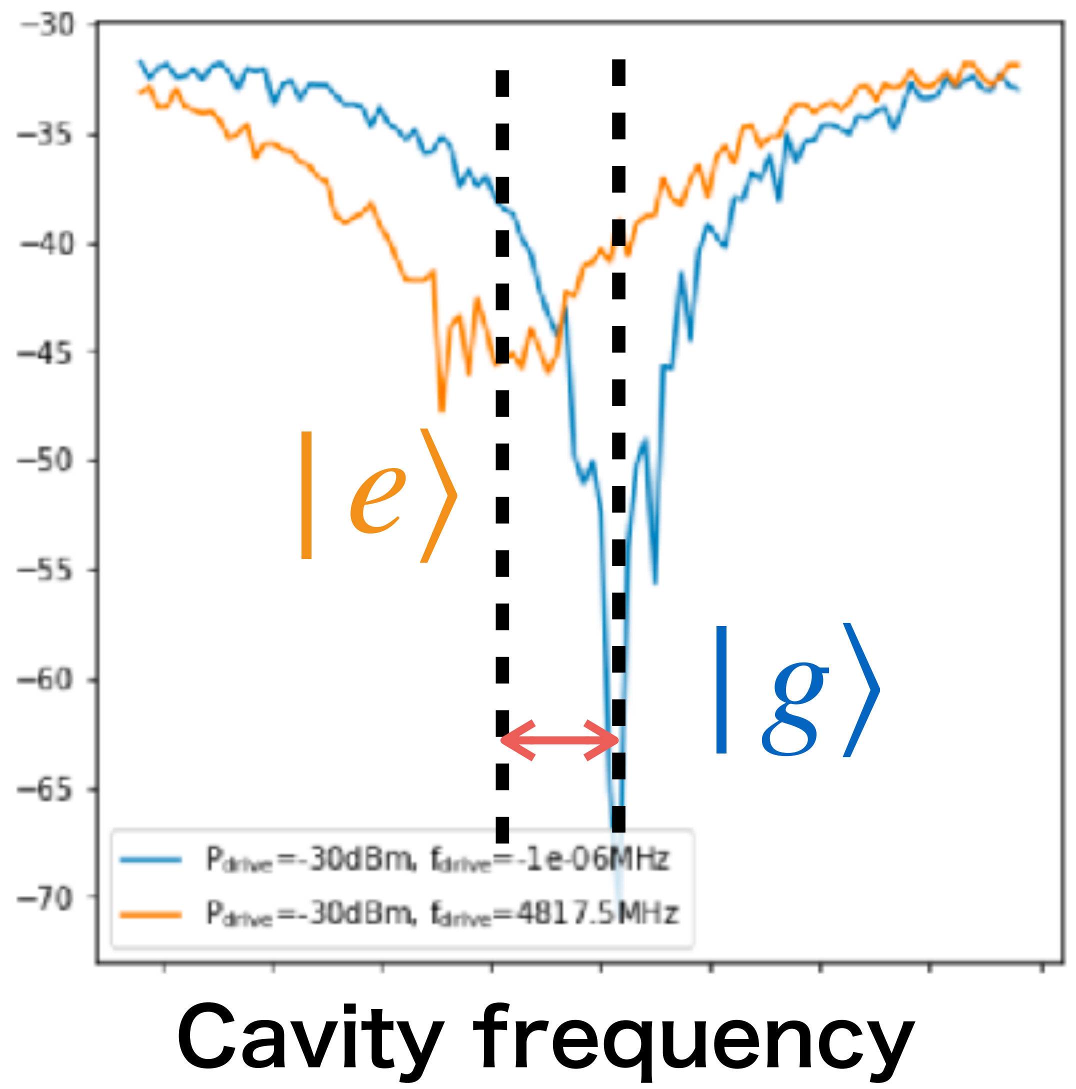
$$\Delta = \omega_c - \omega_q$$

$$\mathscr{H}/\hbar = \left(\omega_c + g^2/\Delta\right)\sigma_z/2 + \left(\omega_q + g^2/\Delta\sigma_z\right)a^\dagger a$$



Dispersive readout





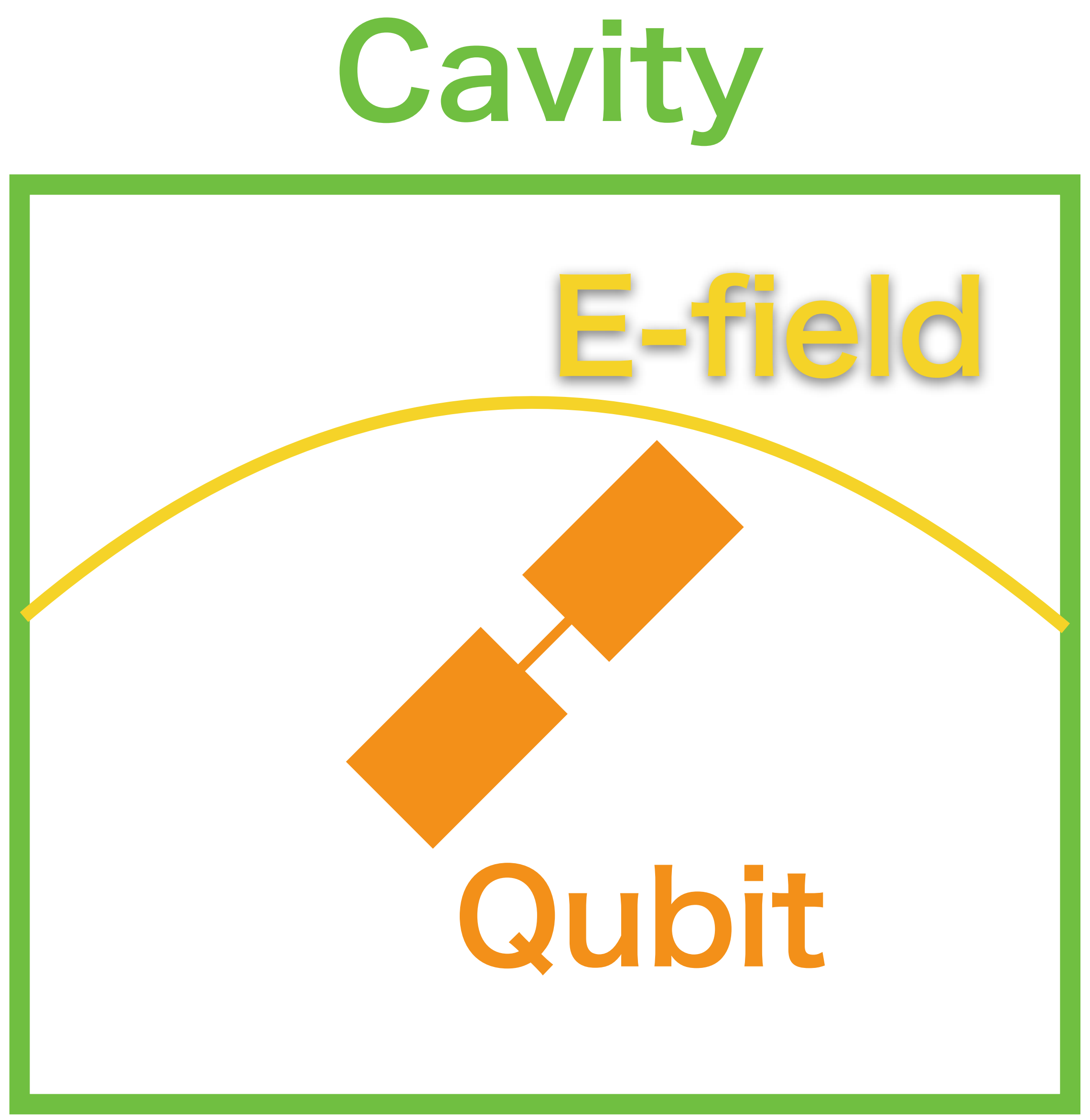
$$\mathscr{H}/\hbar = \frac{\omega_q}{2}\sigma_z + \omega_c a^\dagger a + g(\sigma_+ a + a^\dagger \sigma_-)$$

$$\mathscr{H}/\hbar = \left(\omega_c + g^2/\Delta\right)\sigma_z/2 + \left(\omega_q + g^2/\Delta\sigma_z\right)a^\dagger a$$

- **Dispersive readout**
  the standard method for quantum computing

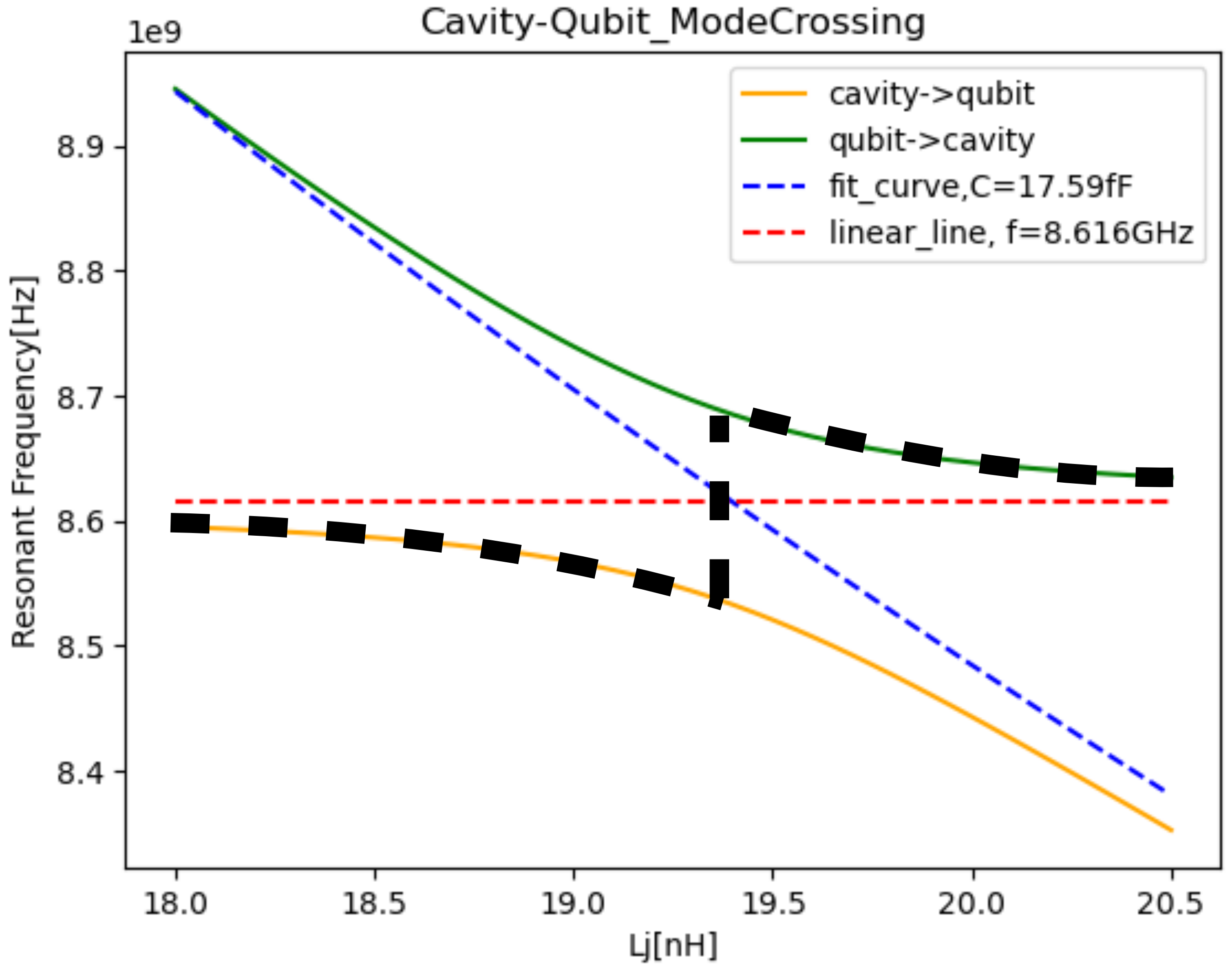
- **Direct excitation experiments utilize this interaction**

Lamb shift



$$\mathcal{H}/\hbar = \frac{\omega_q}{2}\sigma_z + \omega_c a^\dagger a + g(\sigma_+ a + a^\dagger \sigma_-)$$

$$\mathcal{H}/\hbar = \left(\omega_c + g^2/\Delta\right)\sigma_z/2 + \left(\omega_q + g^2/\Delta\sigma_z\right)a^\dagger a$$

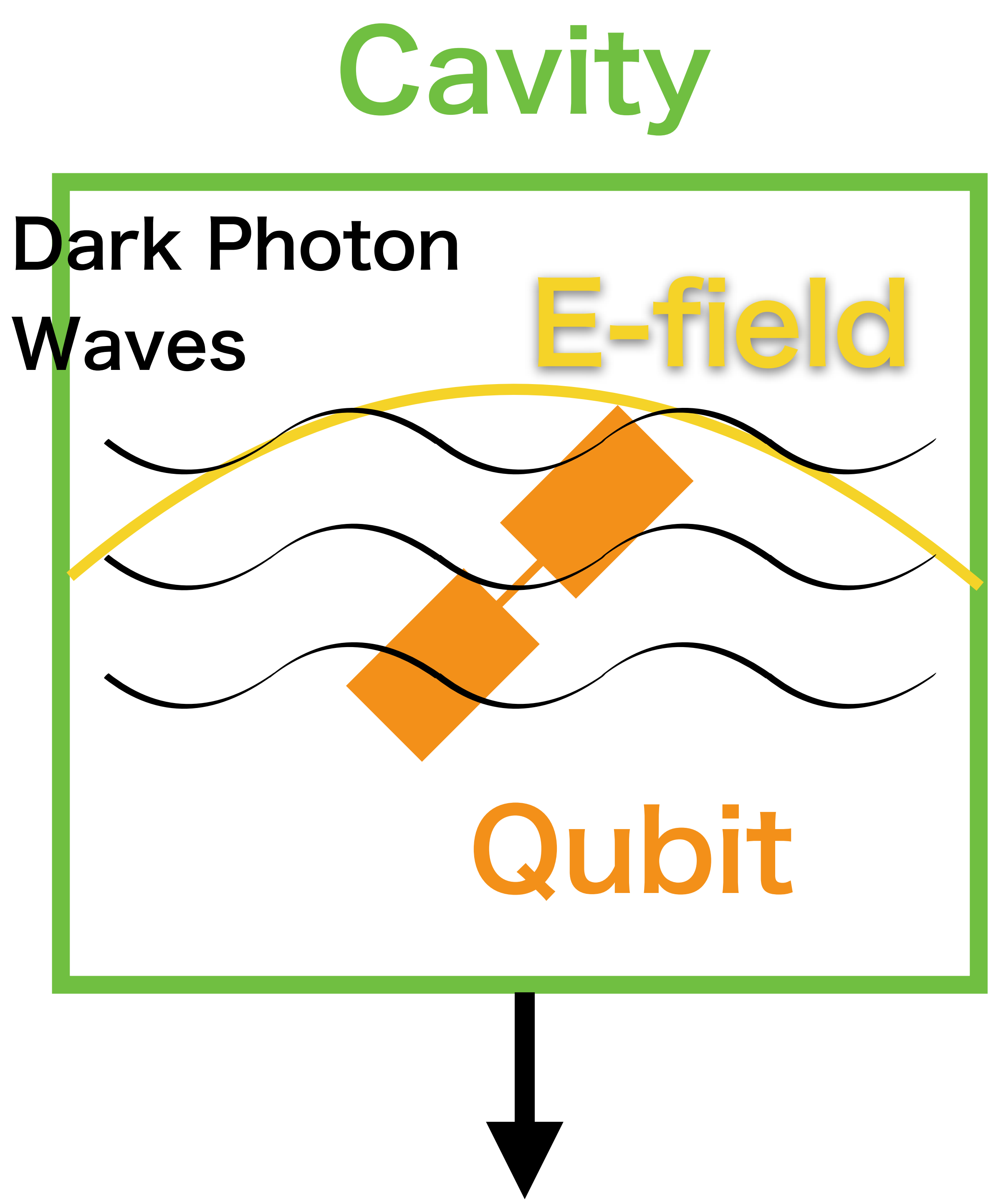


$\Delta = \omega_c - \omega_q$ changes ω_c

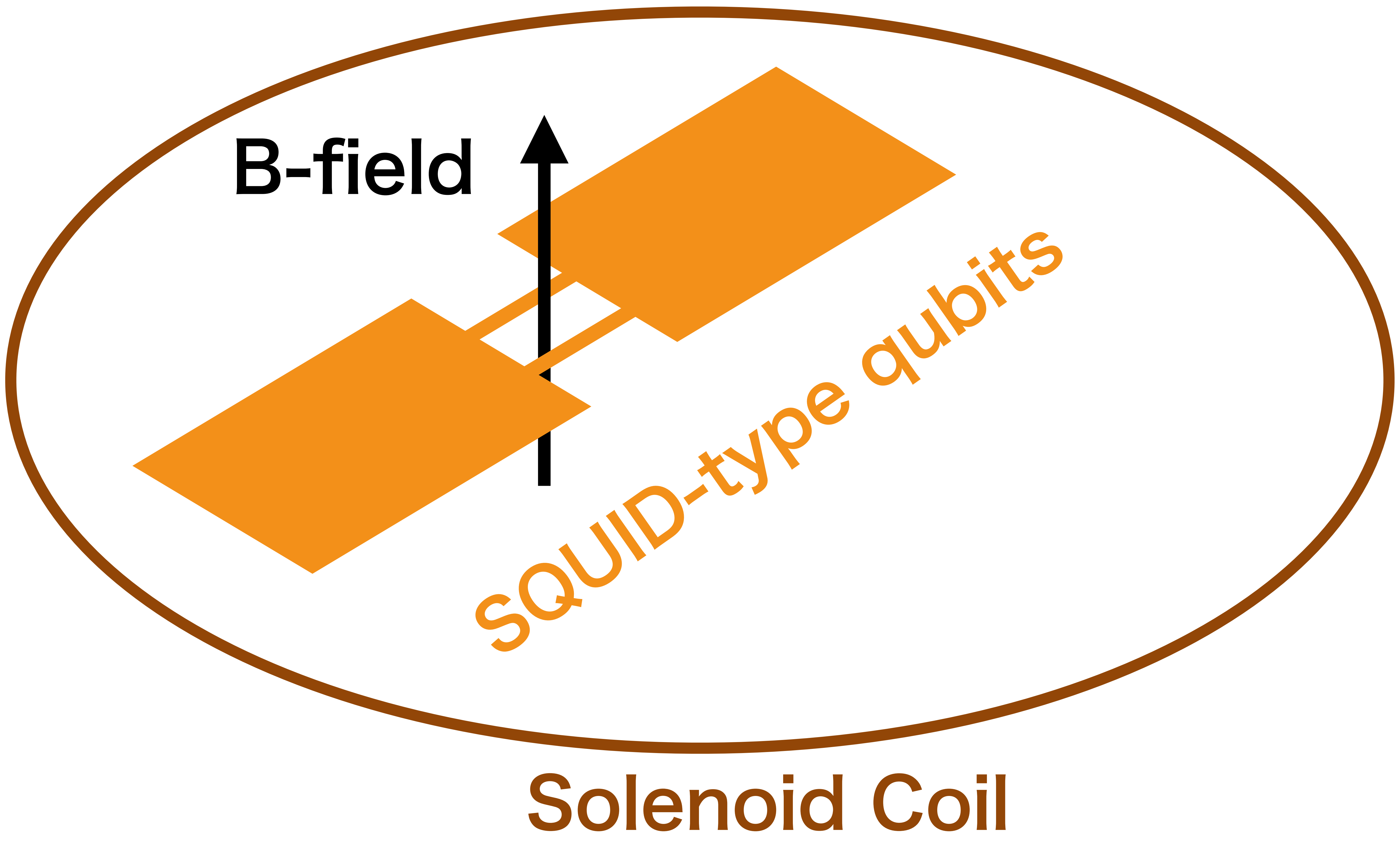
→ ω_c can tune by tuning ω_q

The tuning range is determined by g

Lamb shift experiment



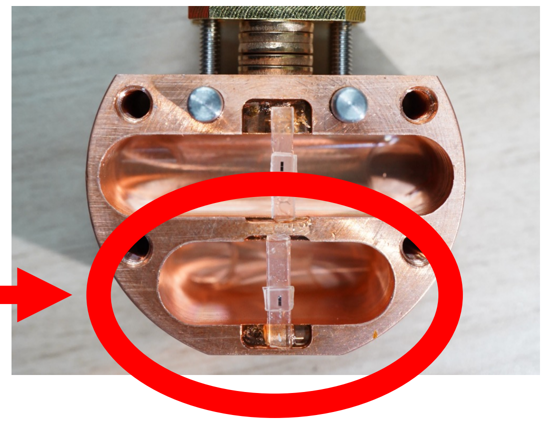
Readout by like a standard DM experiments



Tuning of qubit frequency is easy
Just applying external small magnetic field to the squid loop

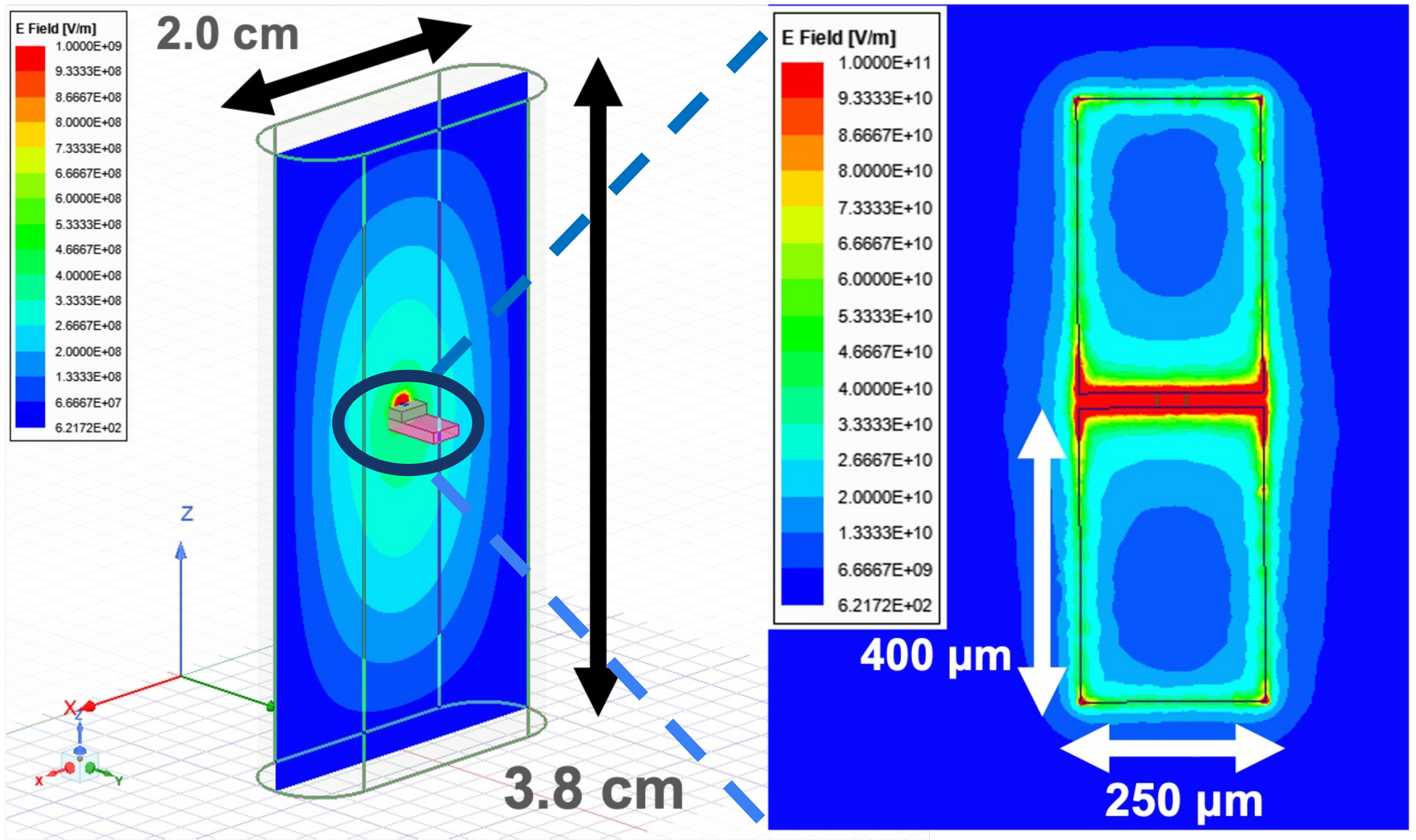
Lamb shift simulation

The same design and material of the actual cavity and qubit



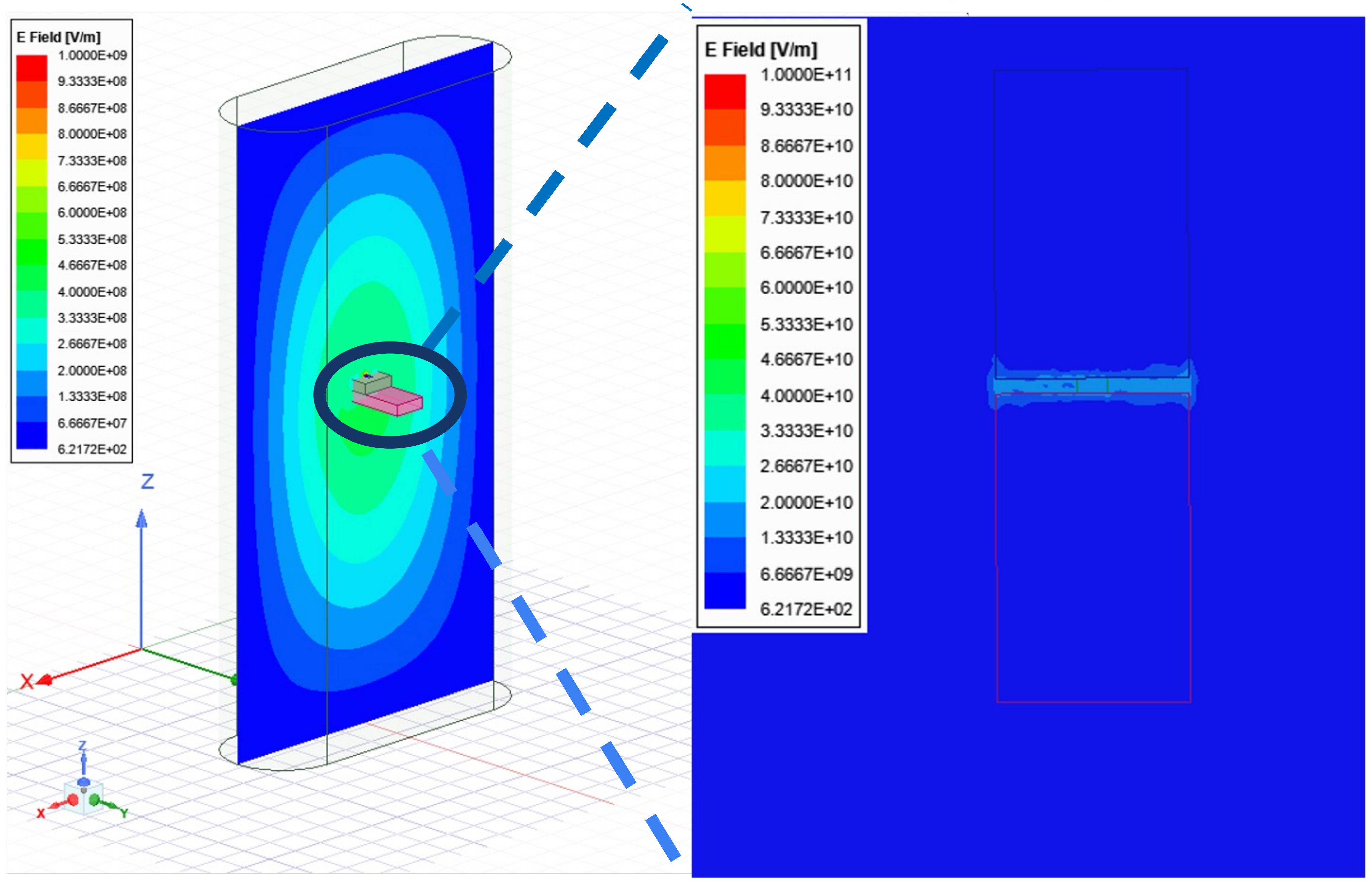
here!

(Cavity) (Qubit)



Interaction Maximum

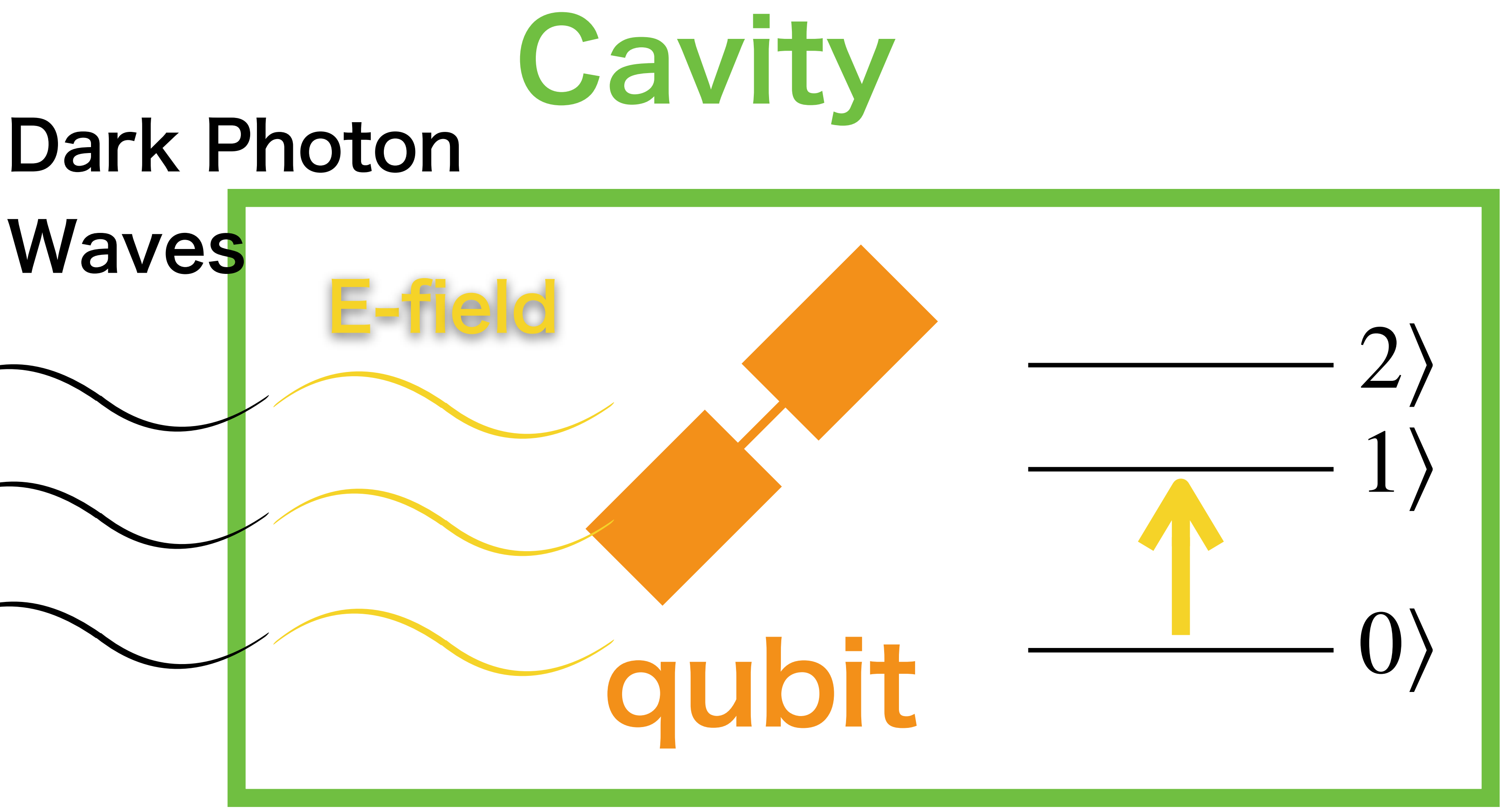
(Cavity) (Qubit)

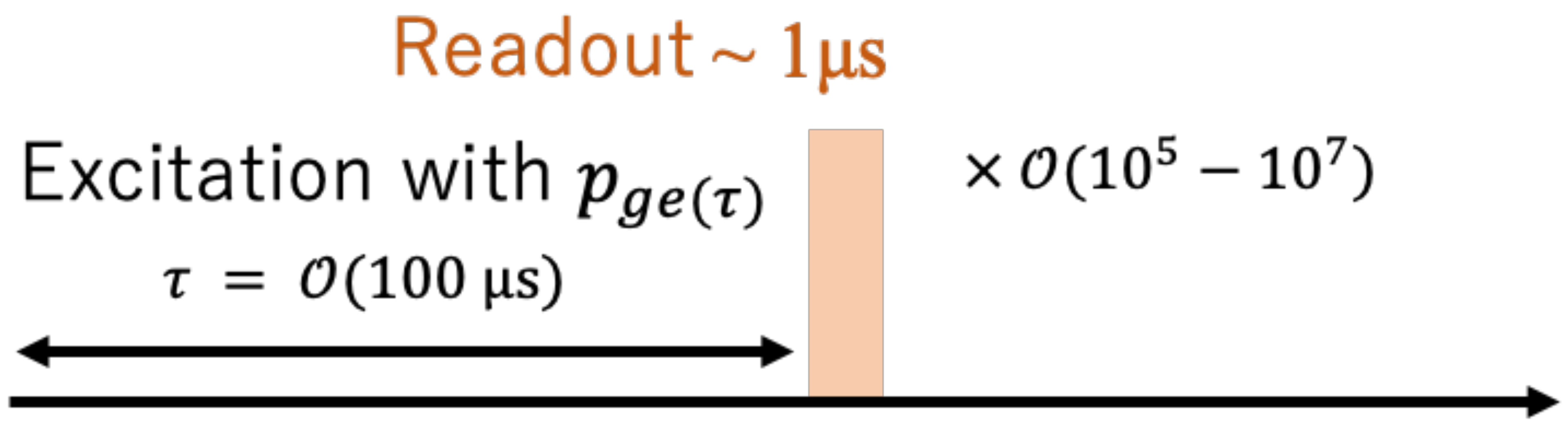


Interaction Minimum

Courtesy of Kan Nakazono

Direct Excitation





$$p_{ge} \cong 0.12 \times \kappa^2 cos^2\Theta \left(\frac{\epsilon}{10^{-11}}\right)^2 \left(\frac{f_{01}}{1\ \mathrm{GHz}}\right)\left(\frac{\tau}{100\ \mu\mathrm{s}}\right)^2 \left(\frac{C}{0.1\ \mathrm{pF}}\right)\left(\frac{d}{100\ \mu\mathrm{m}}\right)^2 \left(\frac{\rho_{DM}}{0.45\ \mathrm{GeV/cm^3}}\right)$$

idea from Moroi +, PRL 131.211001

1. Dark photon converts to E-field by any metal surfaces (ex. shield of qubits)

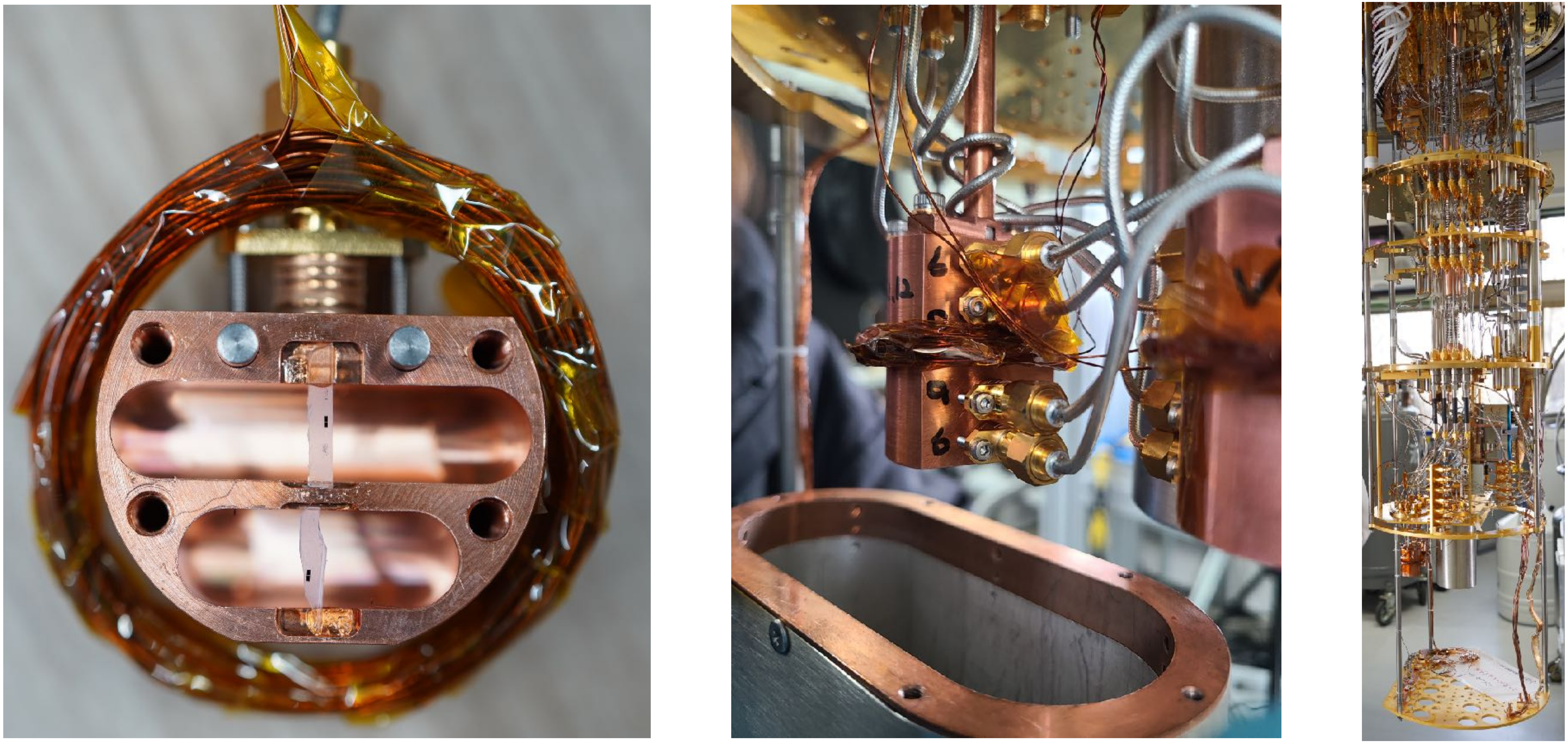
2. Qubit state is driven from |0> to |1> by the E-field if the qubit frequency matched to the E-field frequency ~ Dark photon Compton frequency

3. The state is read out by dispersive readout (exactly the same way as quantum computing)

Courtesy of Karin Watanabe

Setup

We can do both experiment with the same setup!



Setup

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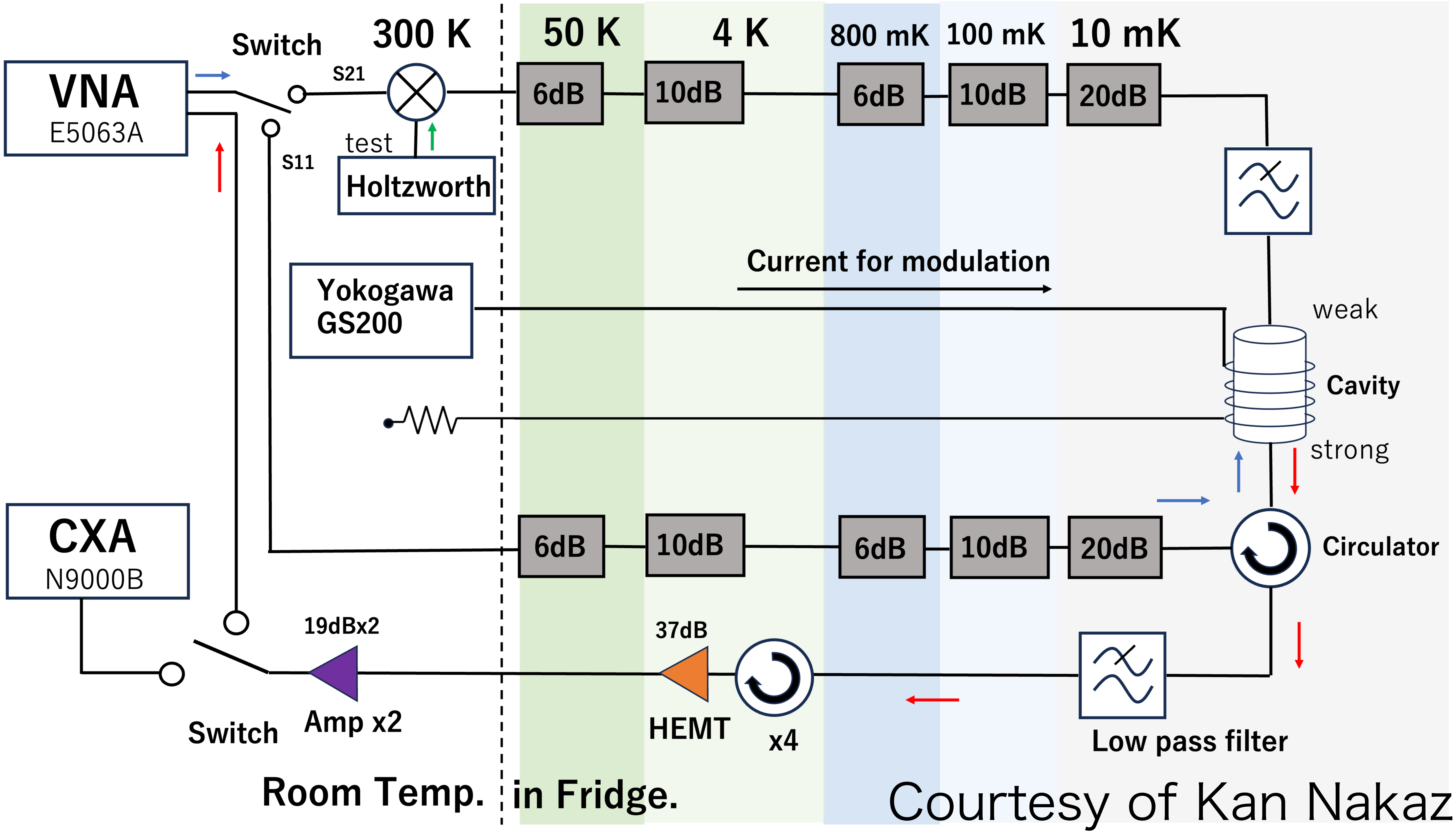
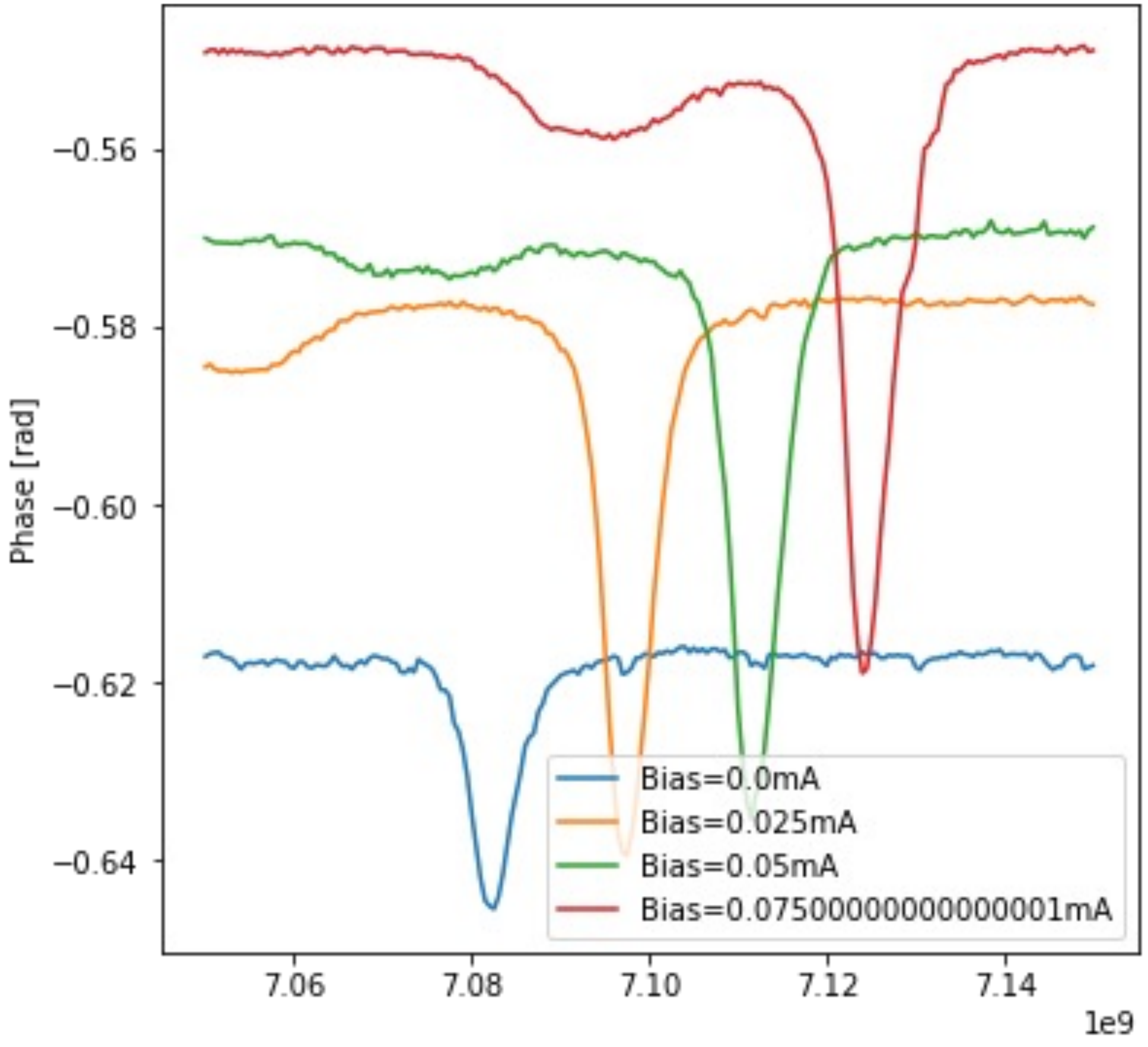


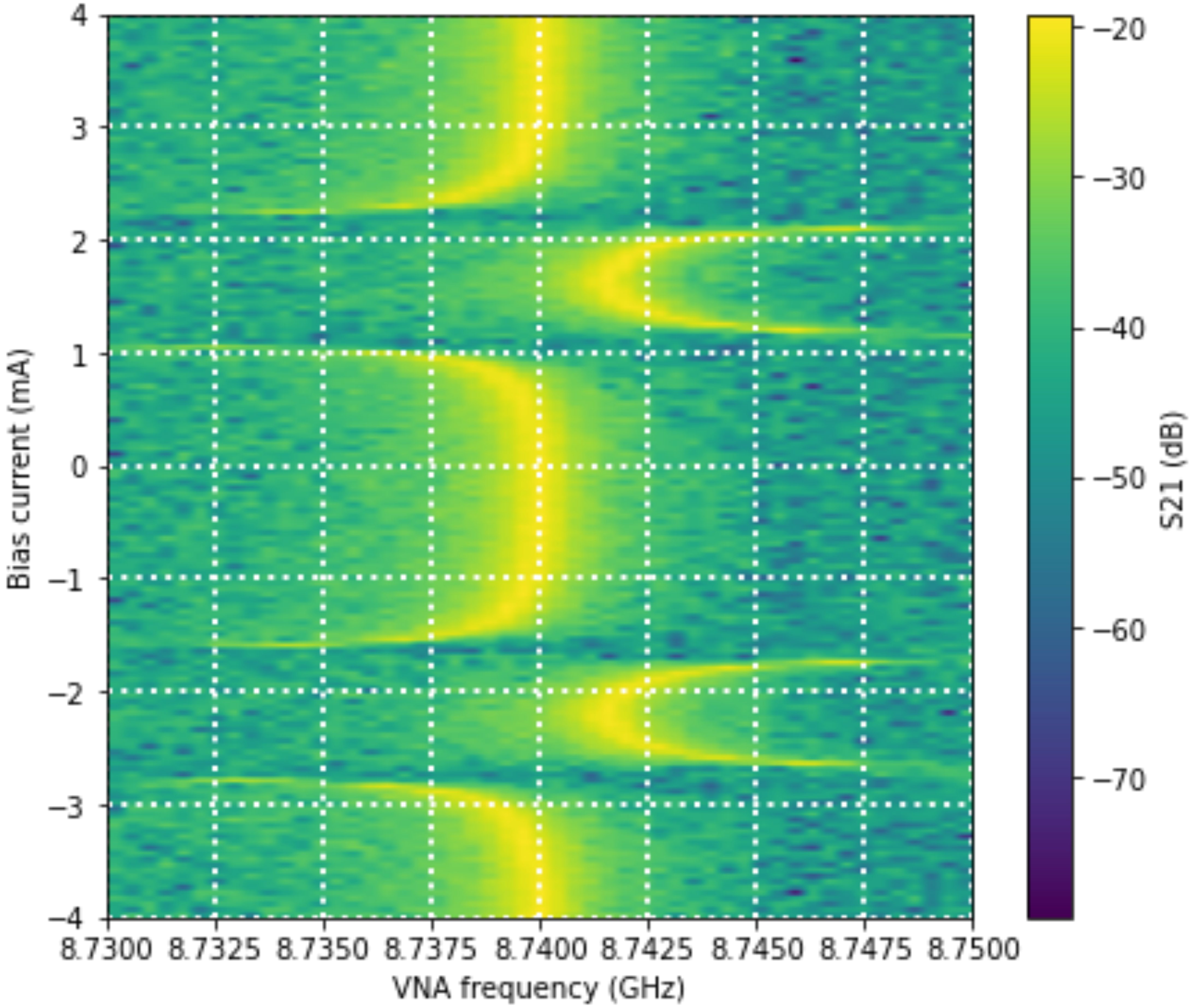
Courtesy of Kan Nakazono

Lamb shift experiments

Tunable qubit frequency



Qubit Frequency



Cavity frequency

Courtesy of Kan Nakazono

Lamb shift experiments

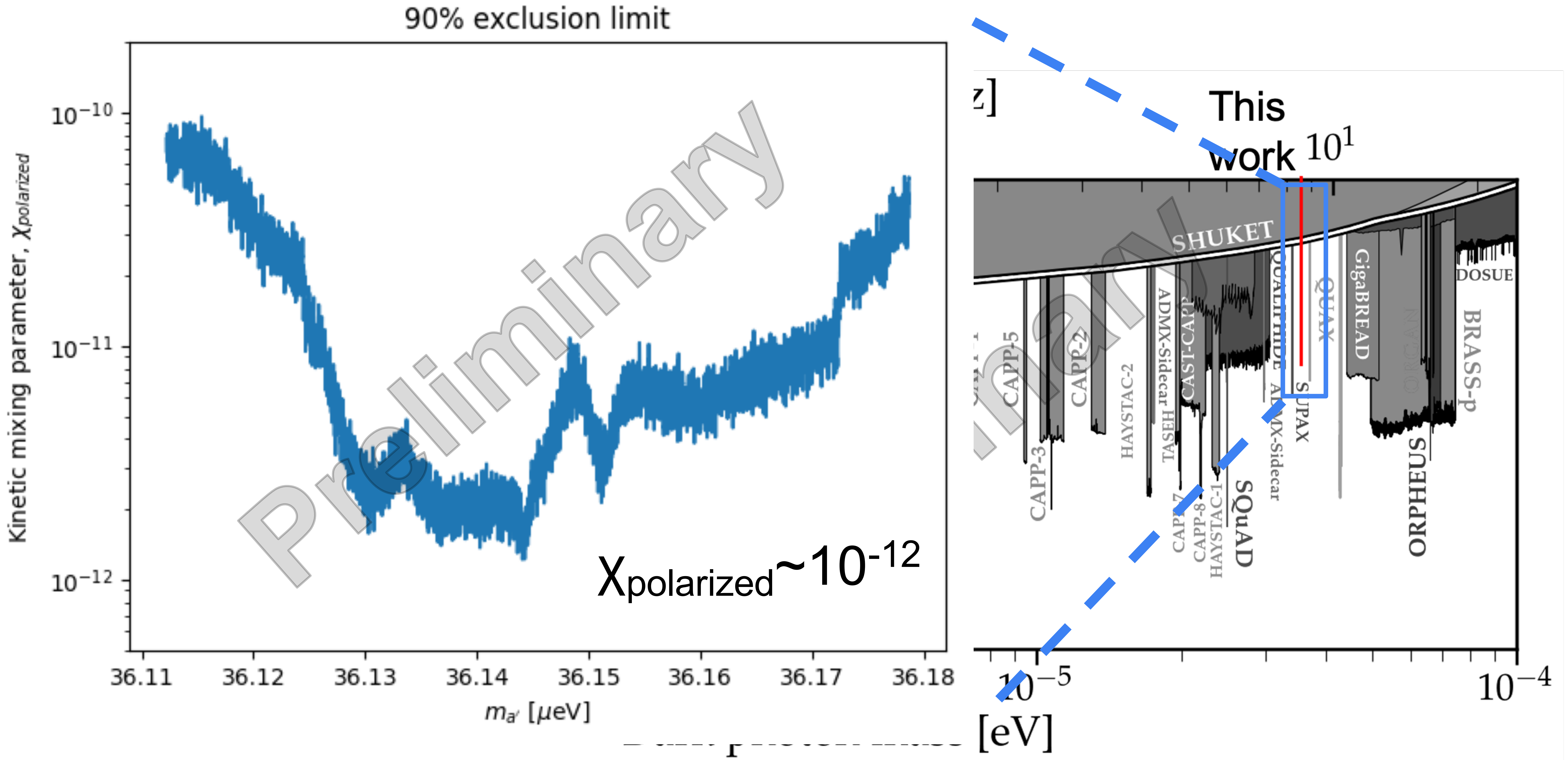
parameter	value	explanation	others
$m_{A'}$	Resonant frequency	dark photon mass	8.733 GHz$=36.1$ µeV
$\rho_{A'}$	0.45 GeV/cm^3	dark photon density	SJ Asztalos et al. (2001)
β	measured	antenna coupling	
b	200 Hz	bandwidth	setting of spectrum analyzer
T_{sys}	3.76 K	system noise	extrapolate hotload measurement
V_{eff}	3.15 cm^3	effective volume	$V \times \mathrm{formfactor}$
Q_L	measured	(loaded) quality factor	
η	0.98	attenuation factor	
N	100	sample number	

$$P_{A'} = \eta\chi^2 m_{A'}\rho_{A'}V_{eff}Q_L\frac{\beta}{\beta+1}$$

$$P_{noise} \sim \frac{k_b b T_{sys}}{\sqrt{N}}$$

Courtesy of Kan Nakazono

Lamb shift experiments

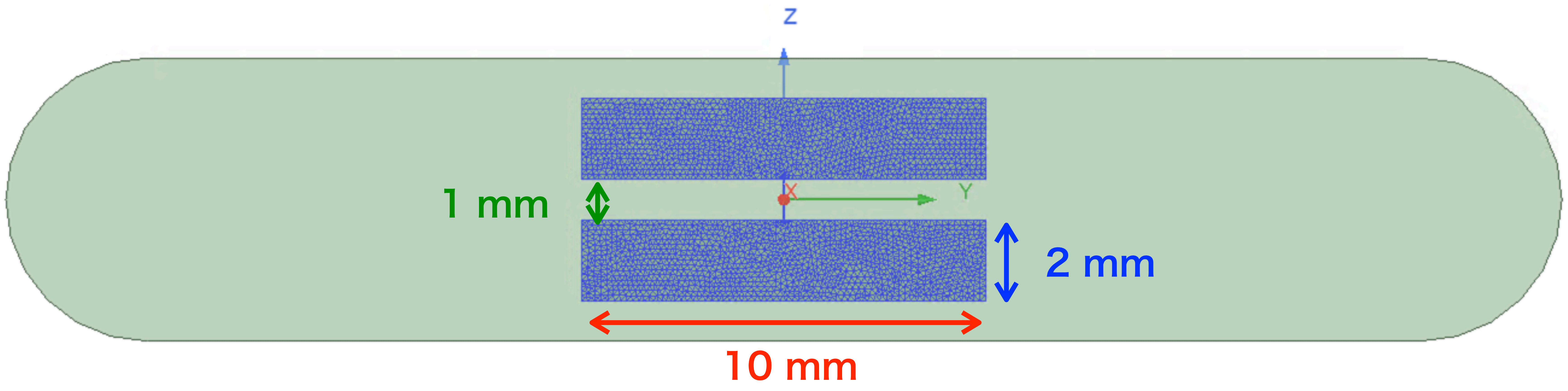


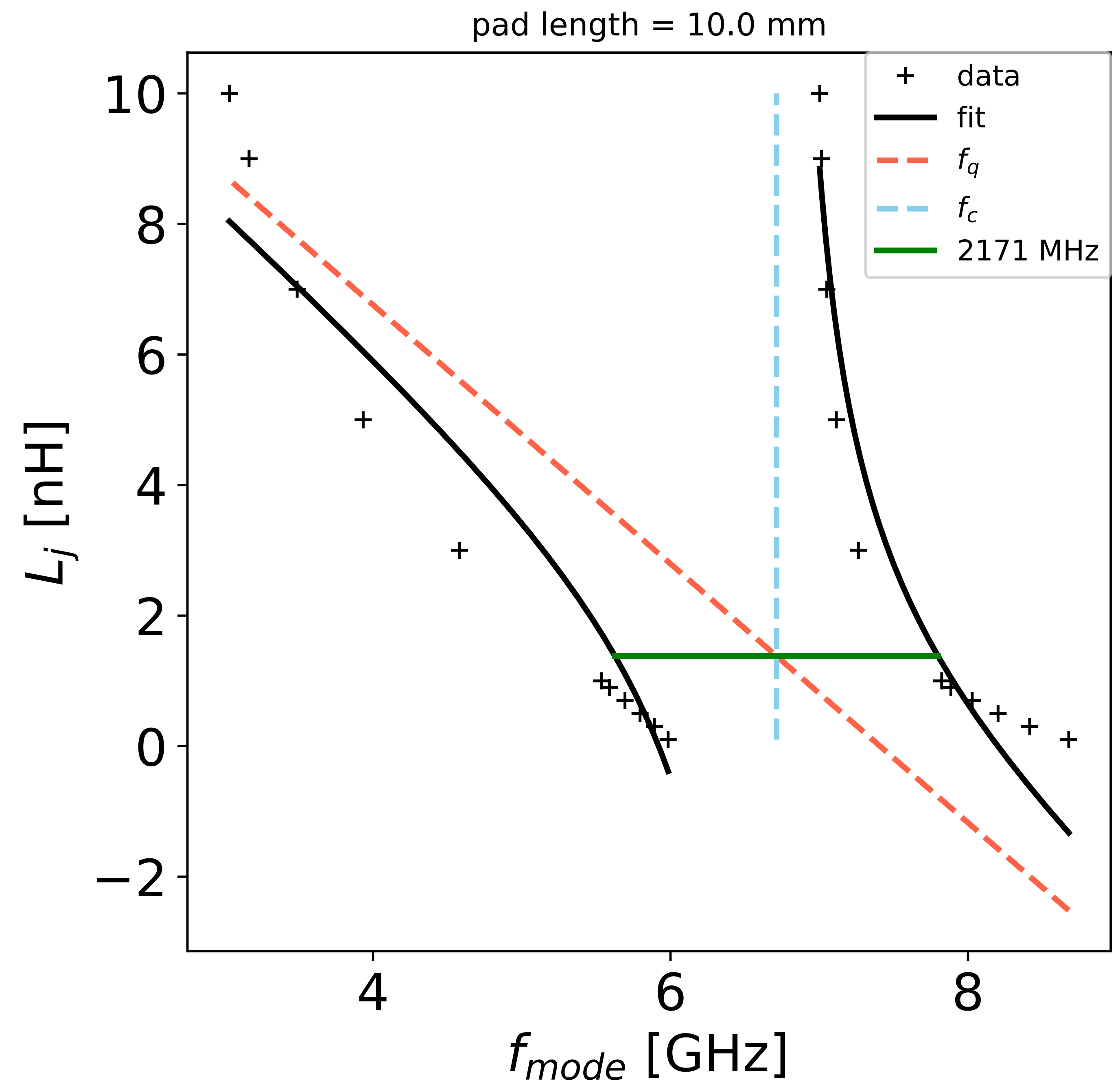
This work

$\chi_{polarized} \sim 10^{-12}$

Courtesy of Kan Nakazono

Future plan for Lamb shift





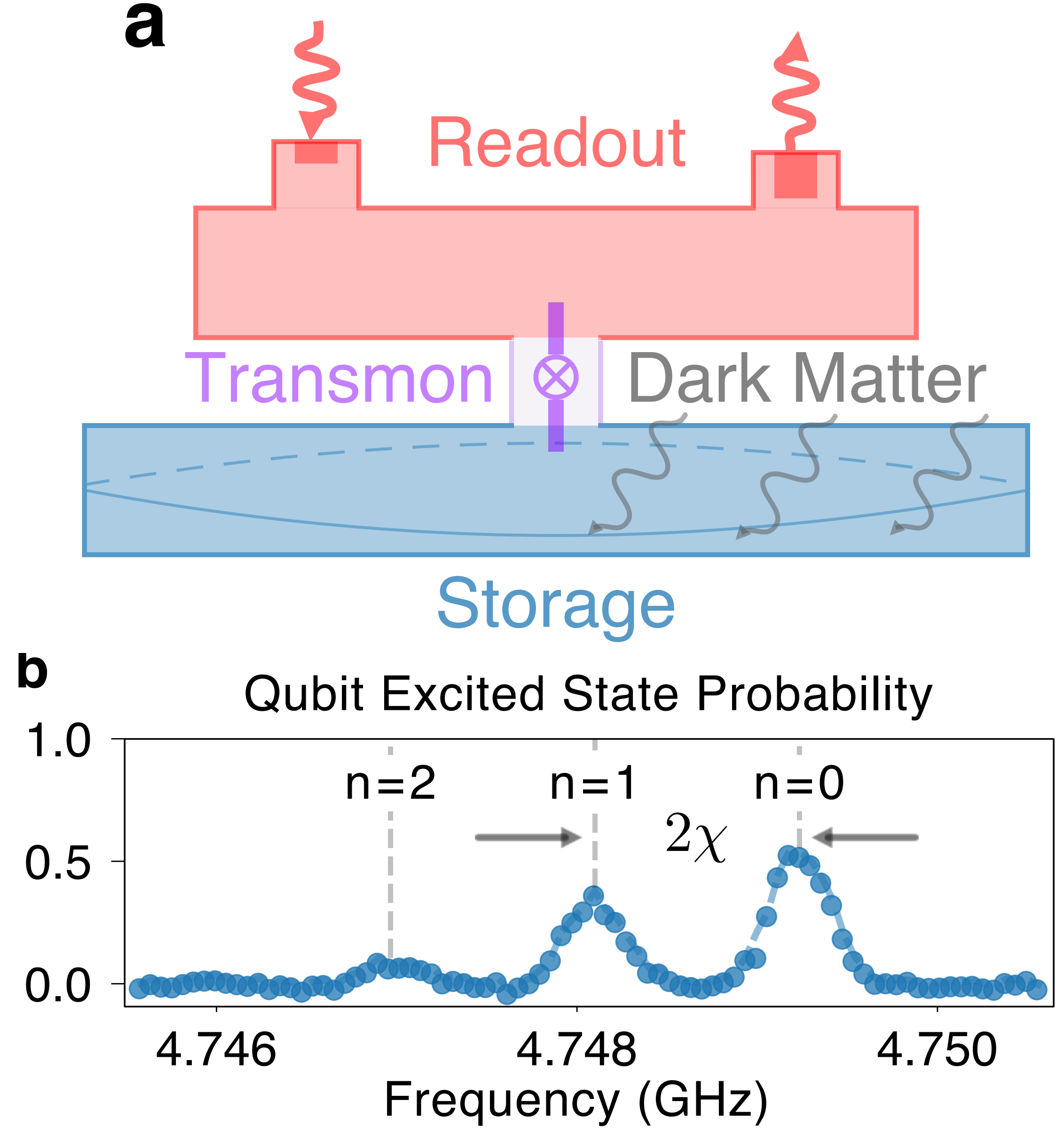
Increasing the size of pads lead further strong coupling (g)

→ **1-2 GHz tuning** is possible at least in the simulation

Ultimate coupling could be realized by galvanic contact [Noguchi+ 2016]

Aaron et.al.

PRL 126 141302 (2021)

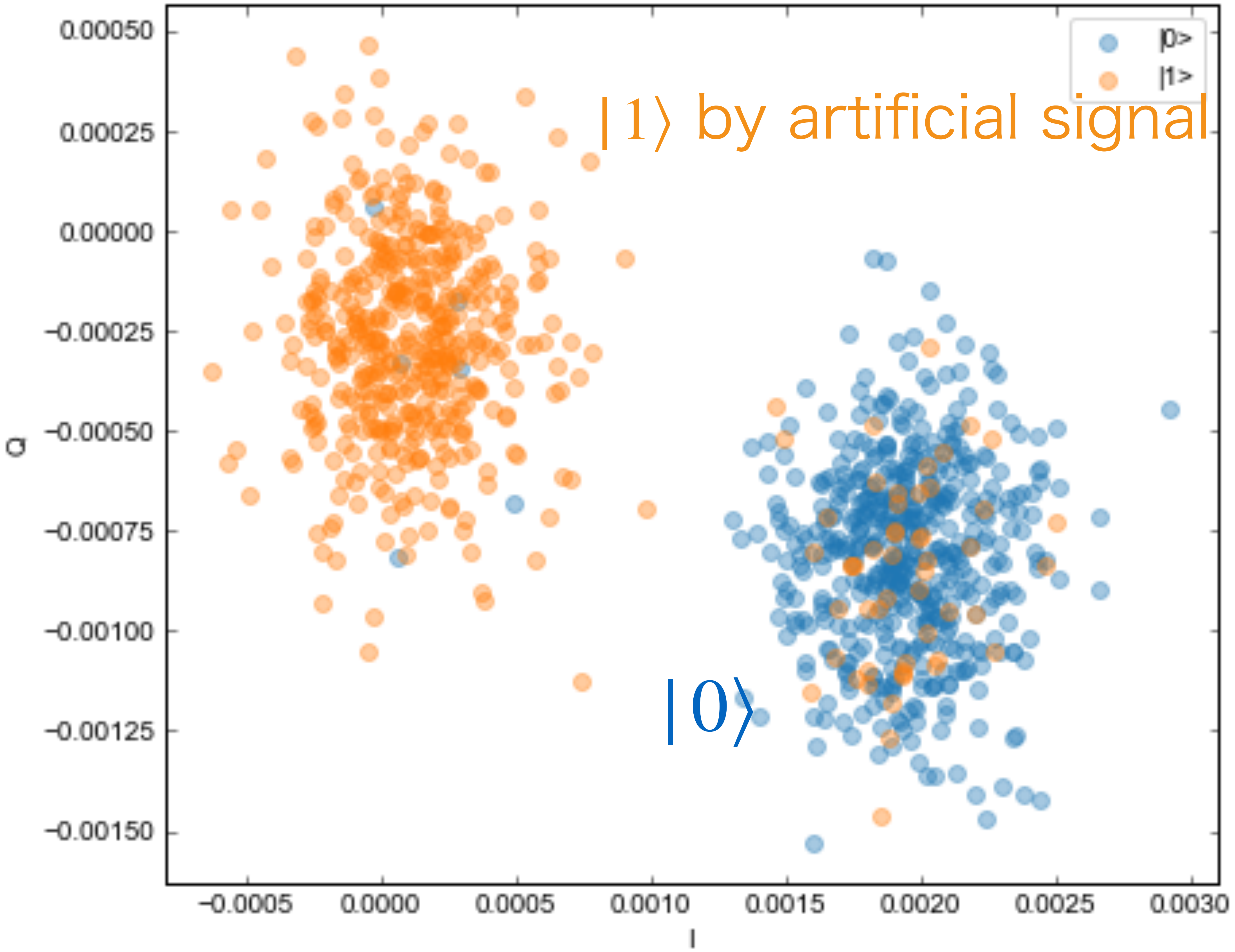


Much better sensitivity would be realized by combining with single photon counting

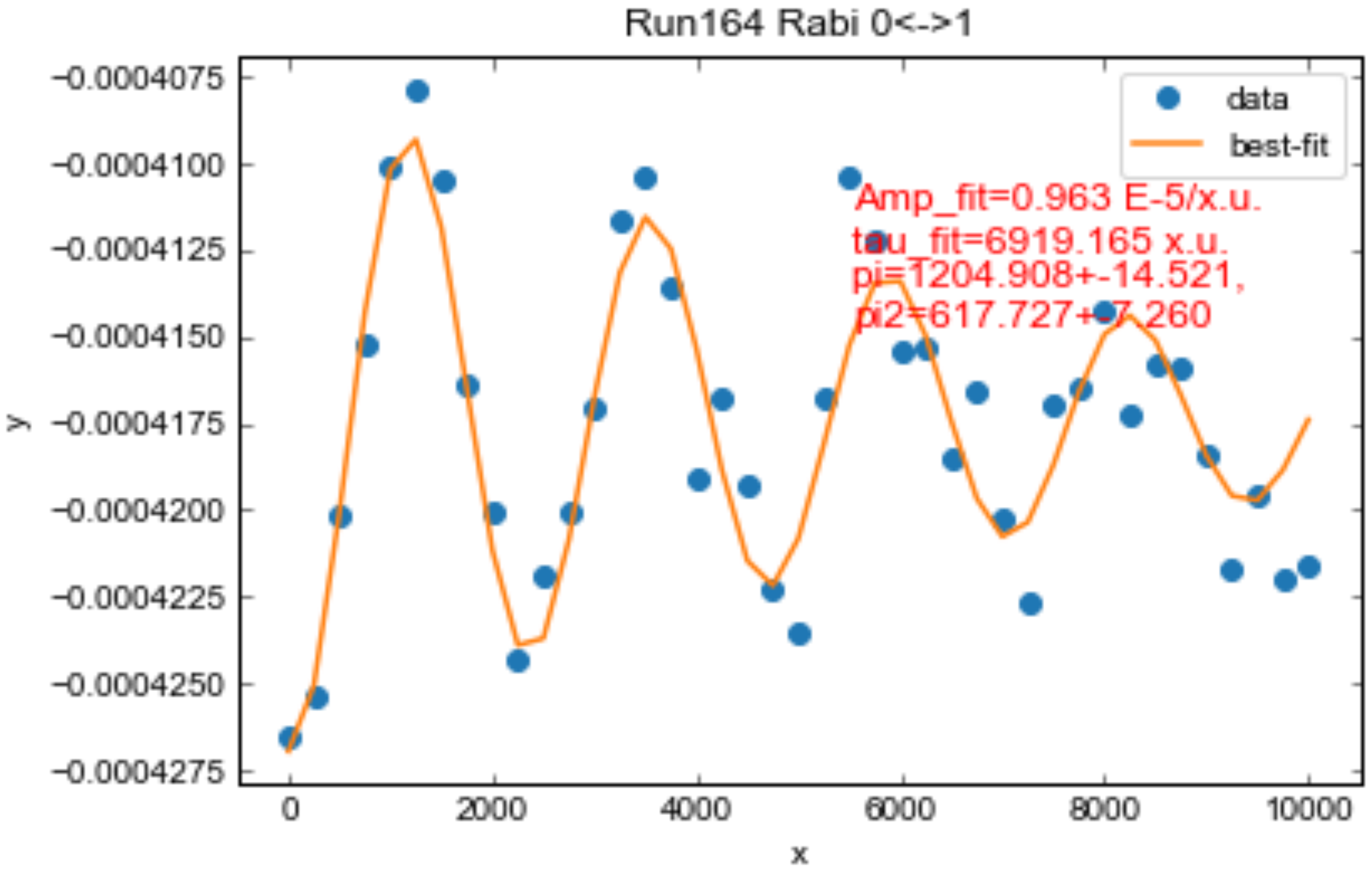
Direct Excitation Experiment

Basic checks for $|0\rangle$ $|1\rangle$

discrimination

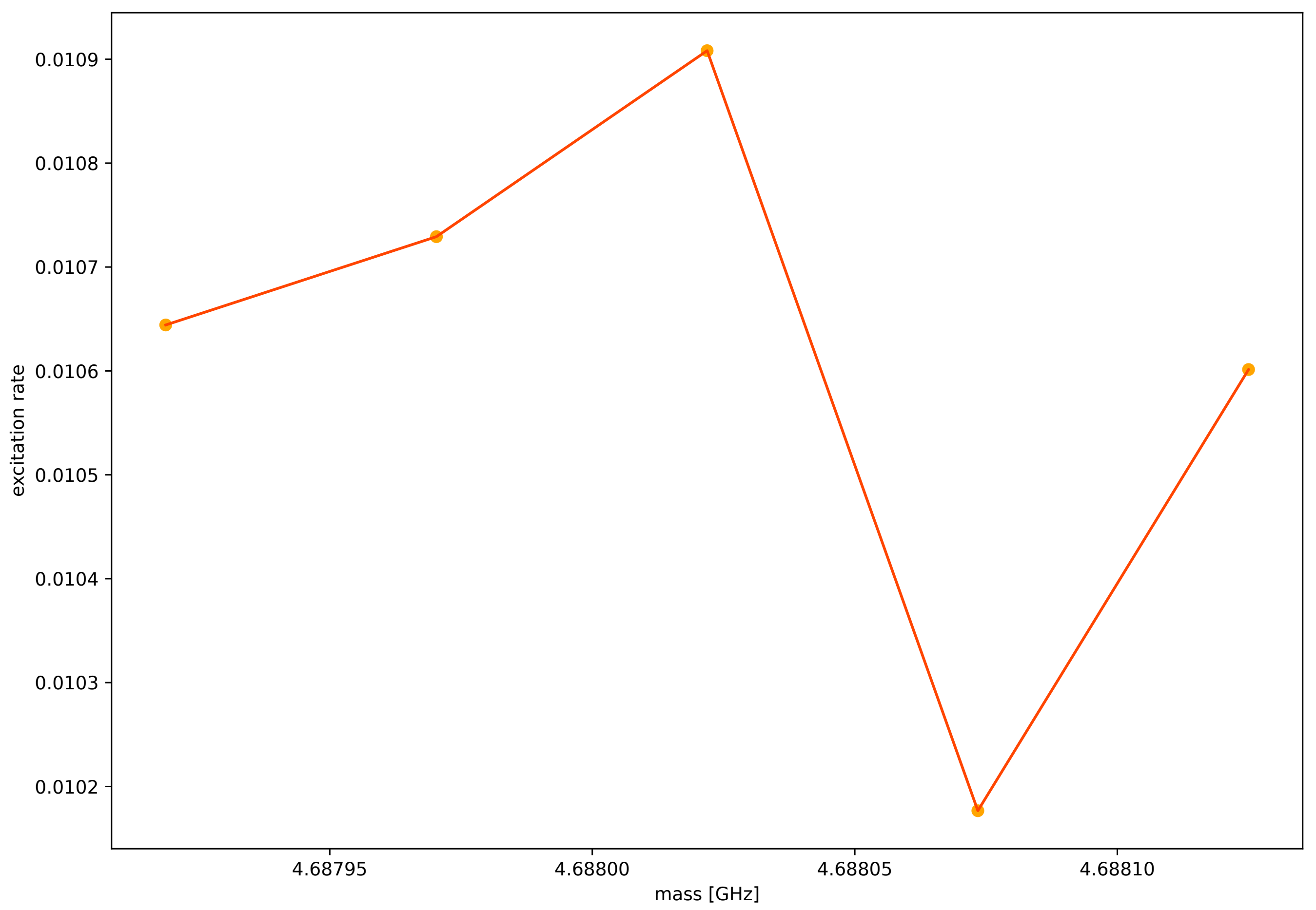


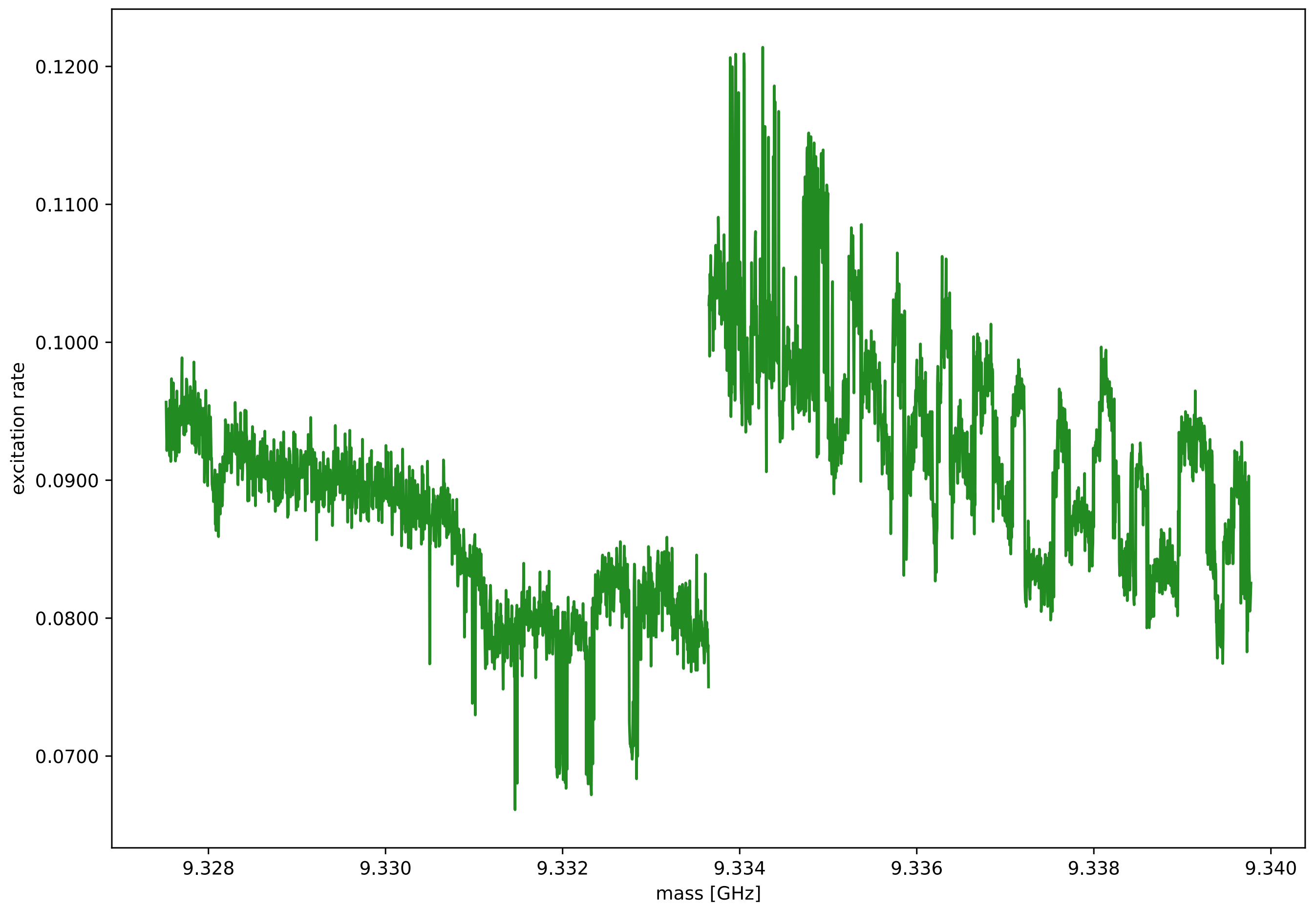
Artificial signal

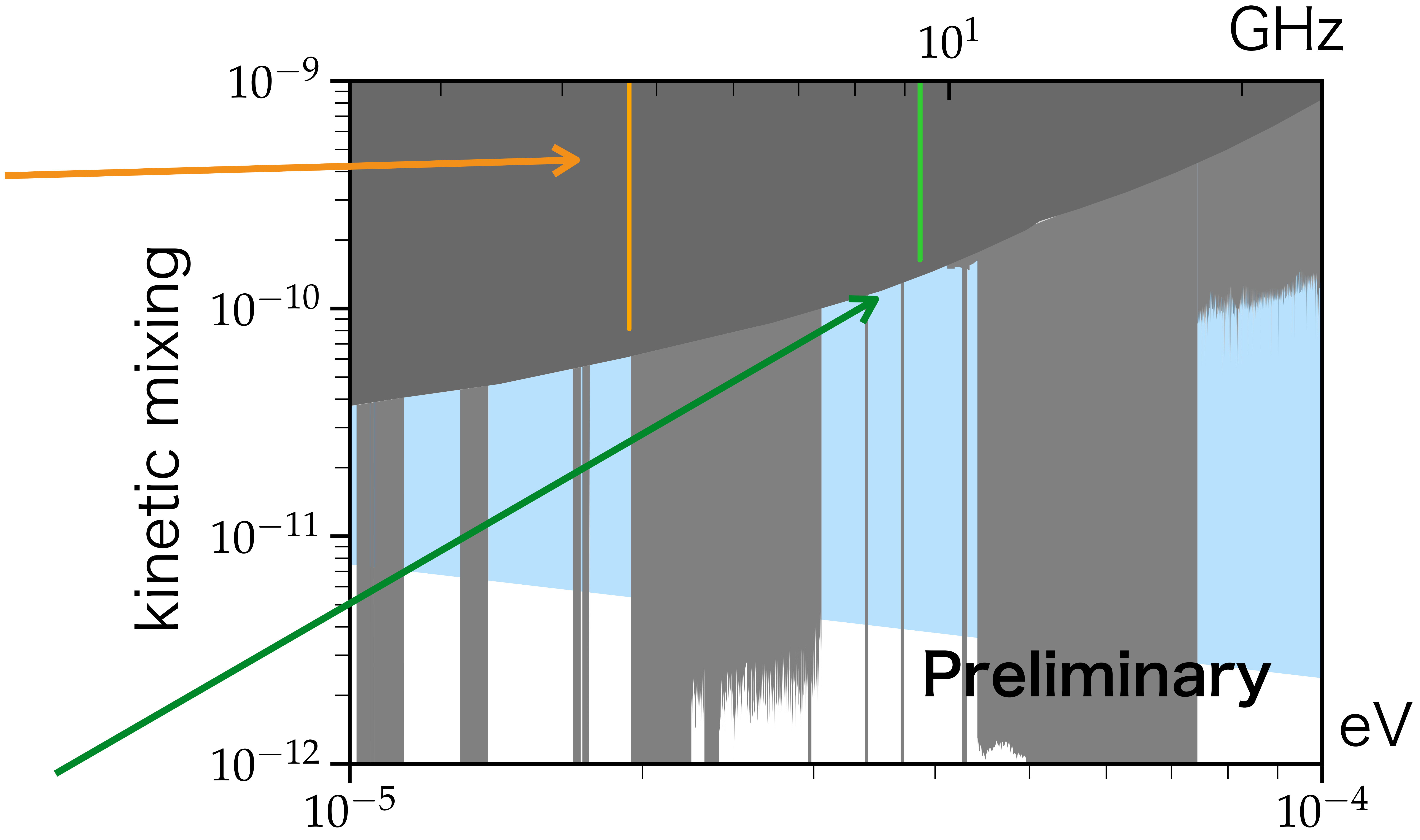


Courtesy of Karin Watanabe

Direct Excitation Experiment





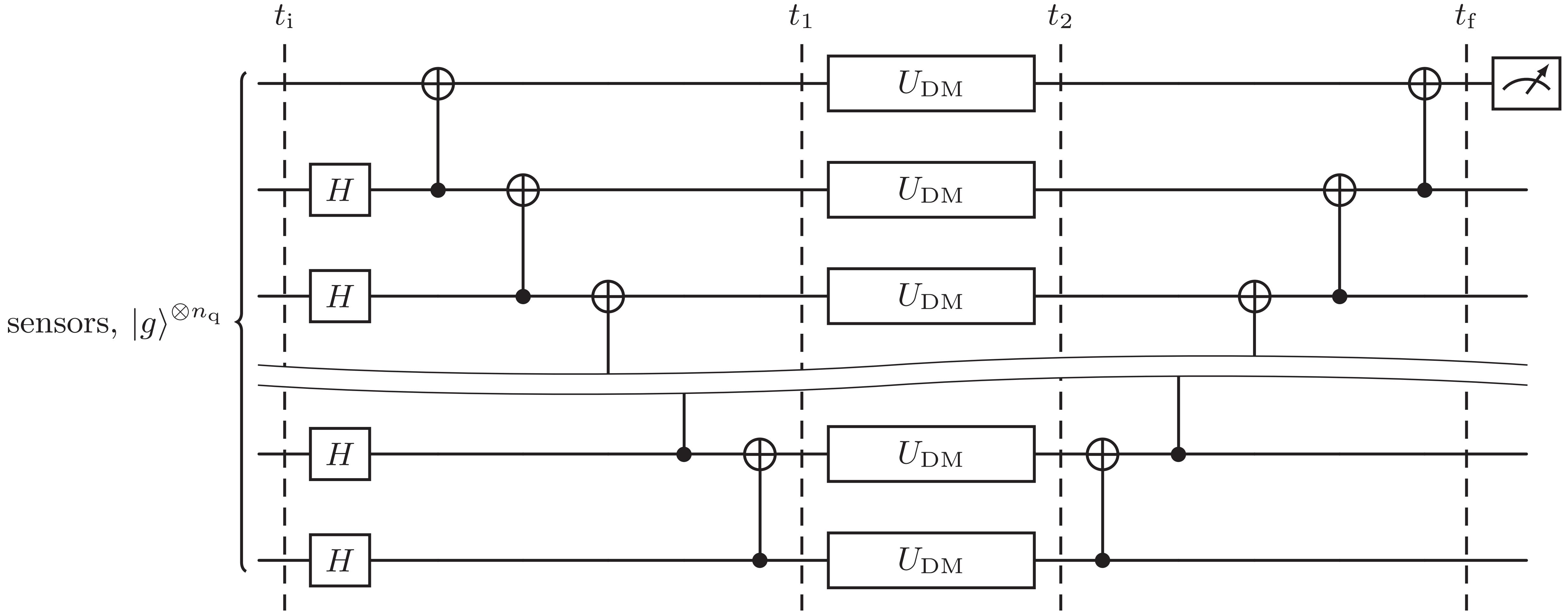


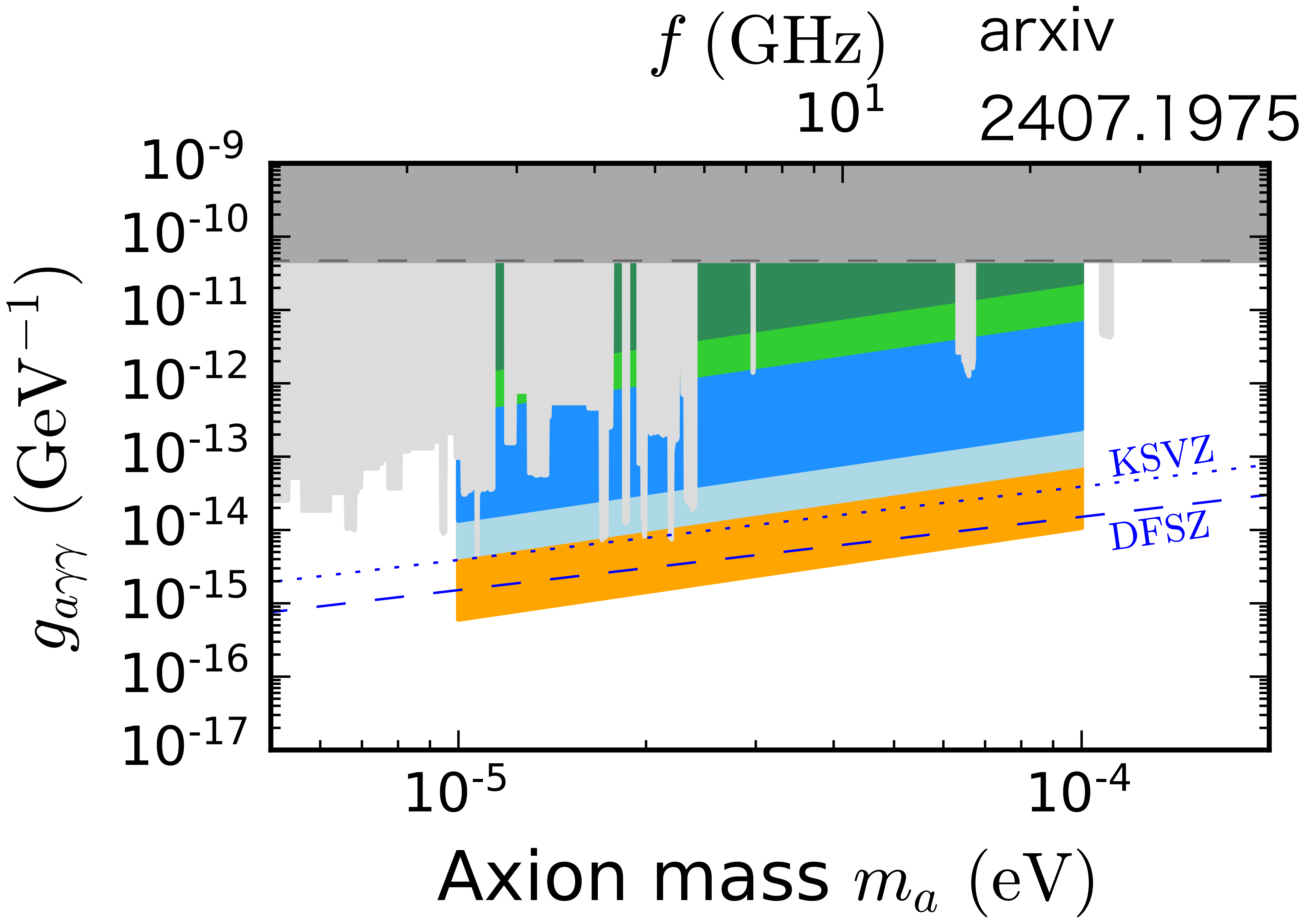
Courtesy of Karin Watanabe

Future plan for direct excitation

Sichanugrist+
arxiv
2407.19755

Moroi +, PRL 133, 021801





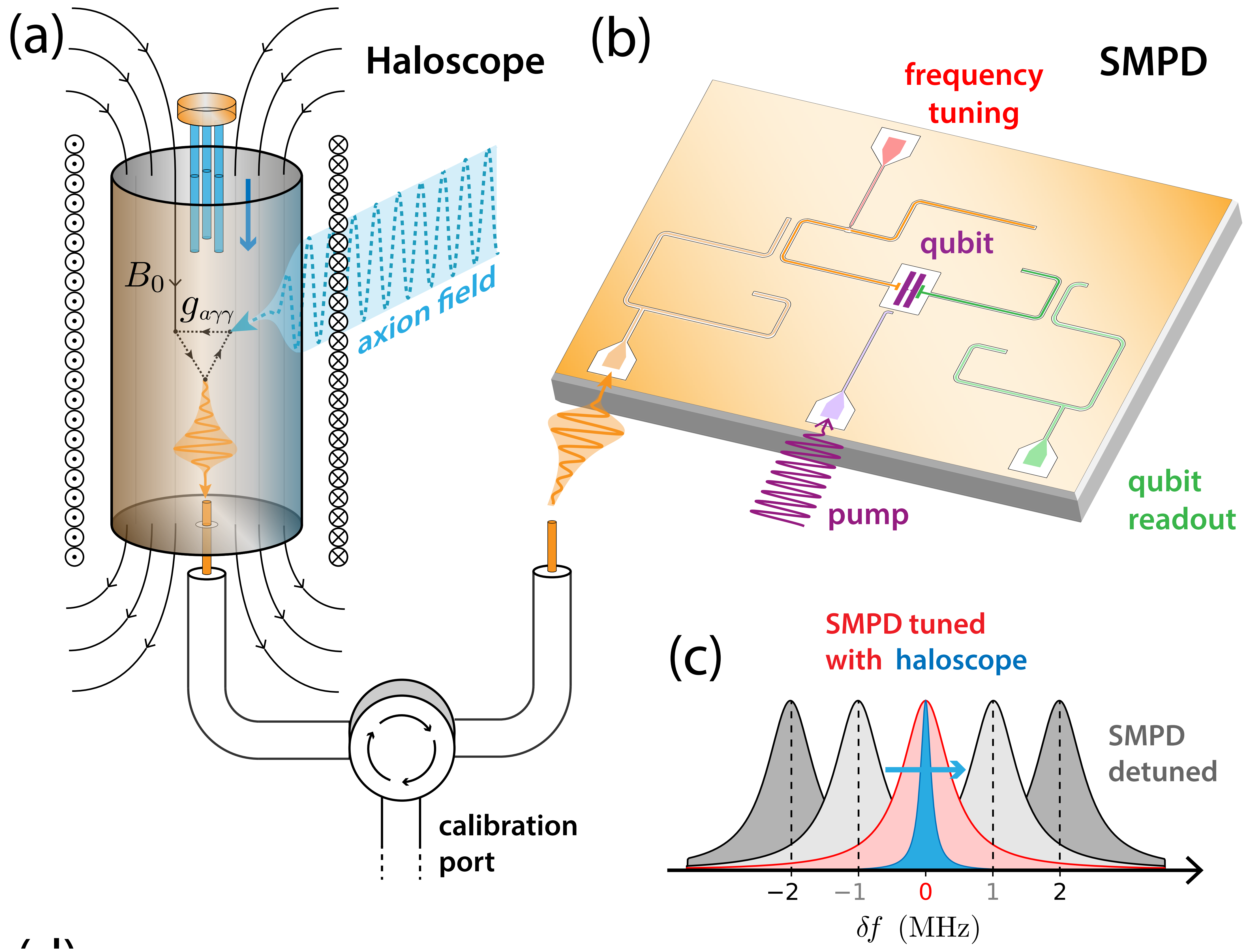
Entangling N qubits with CNOT gates leads sensitivity increase by N^2

Off course we want to search axion
→ Applying magnetic field in parallel to O(10) T

Towards Axion Search

Photon transfer

Pros: Easer, Cons: Potentially lossy

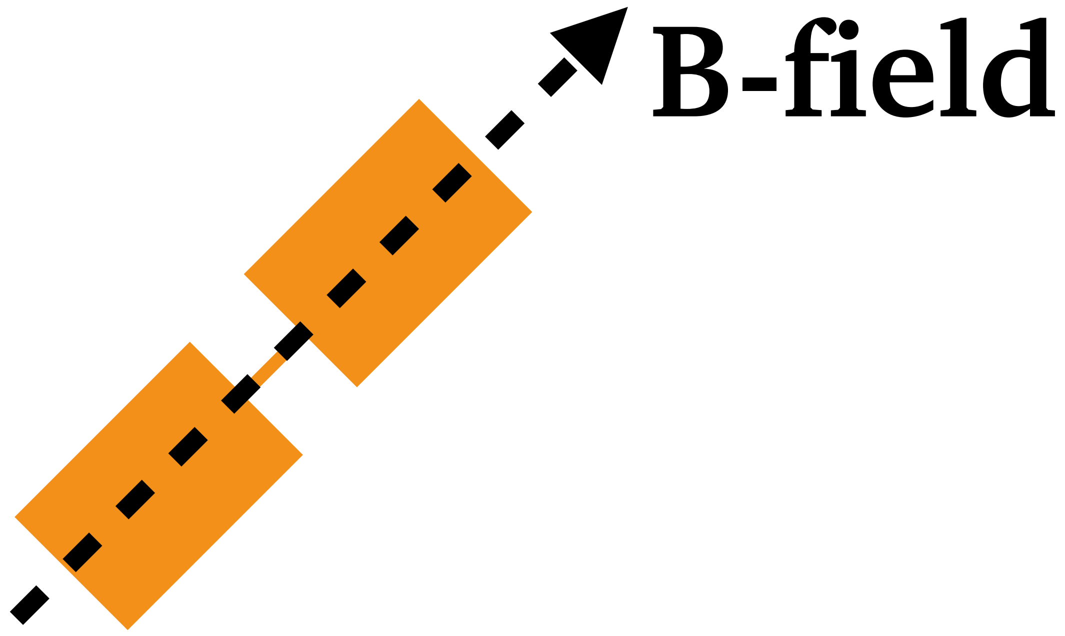


arXiv:2403.02321

B-field tolerant qubits

Pros: No loss

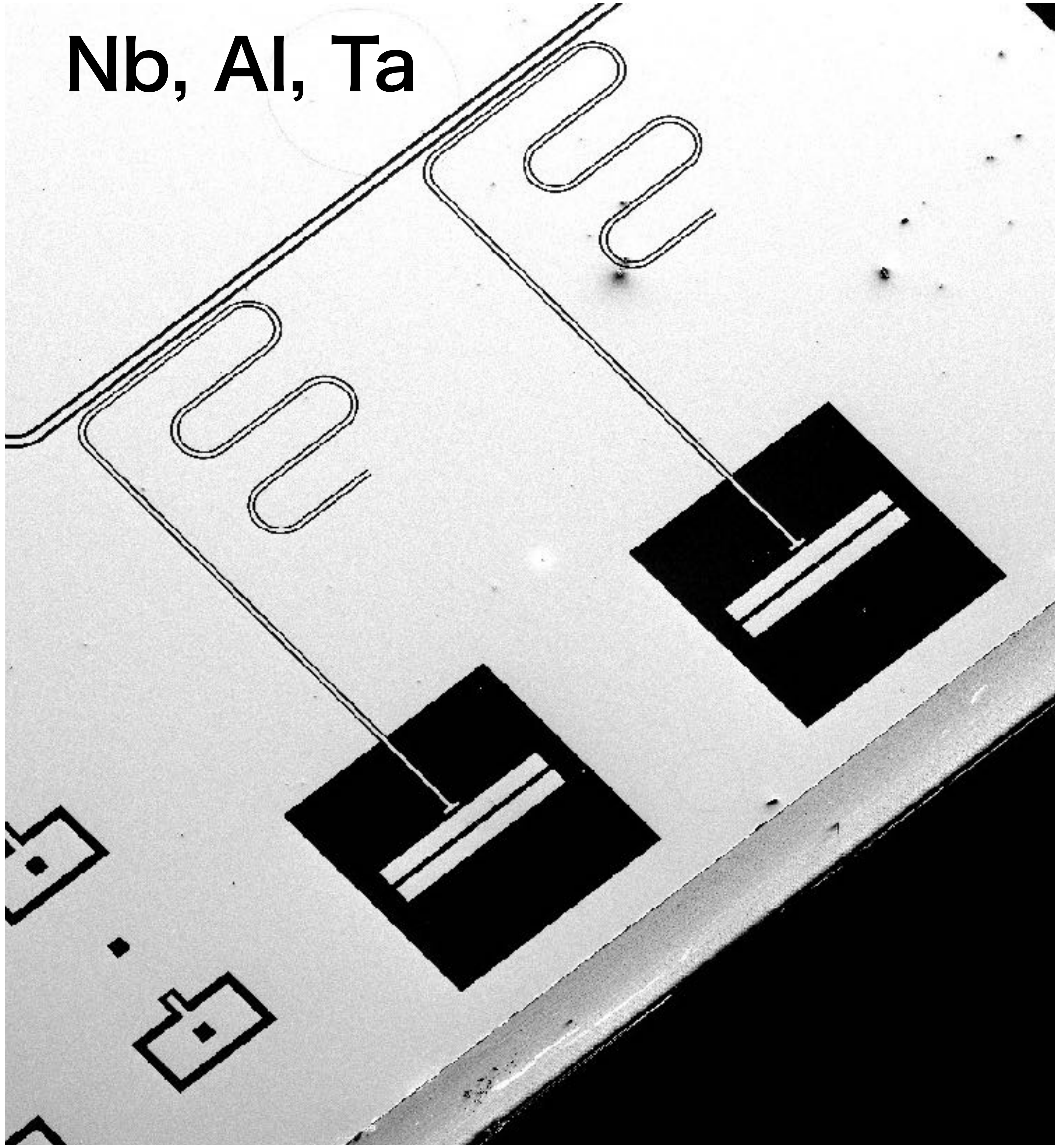
Cons: More difficult

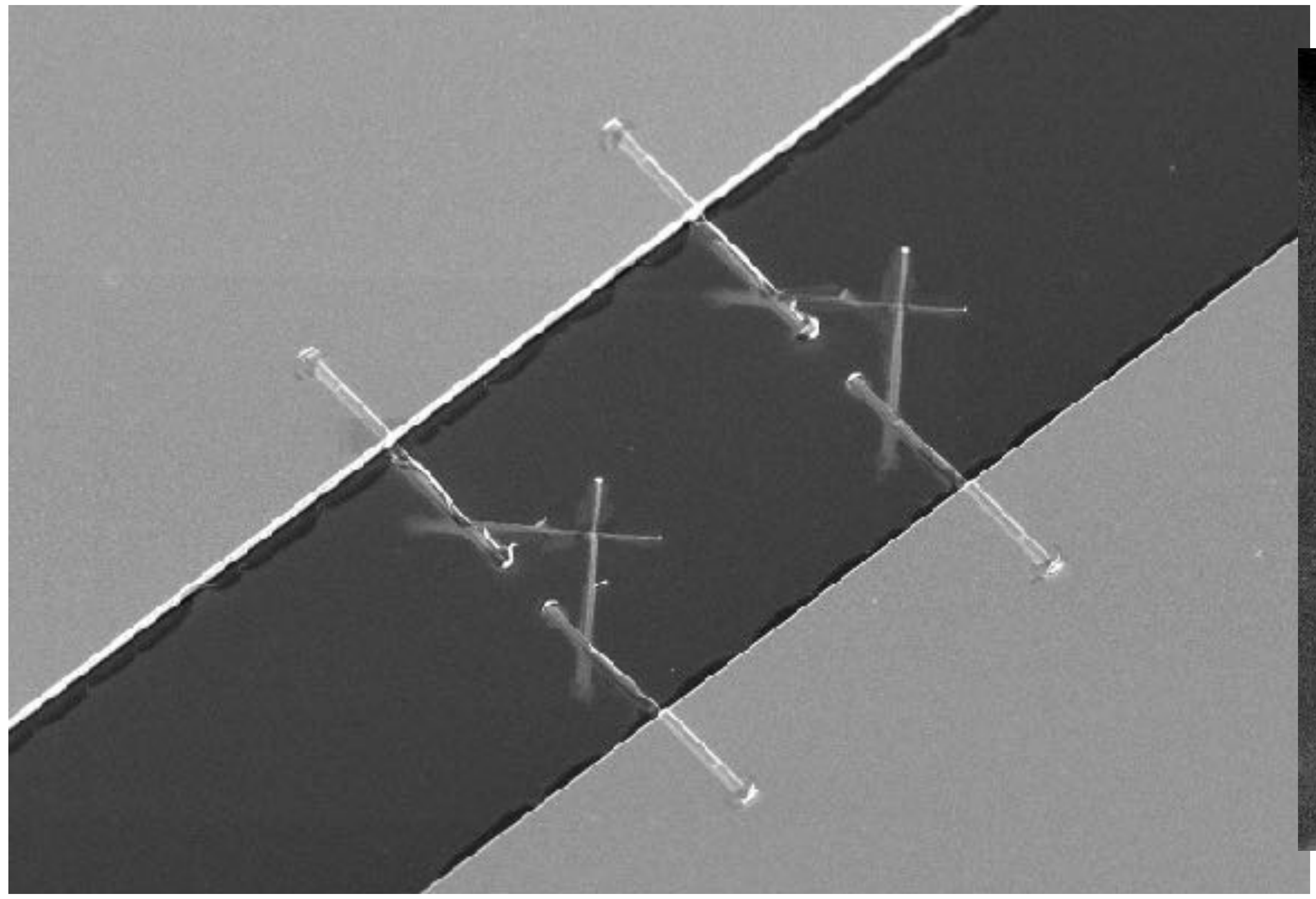


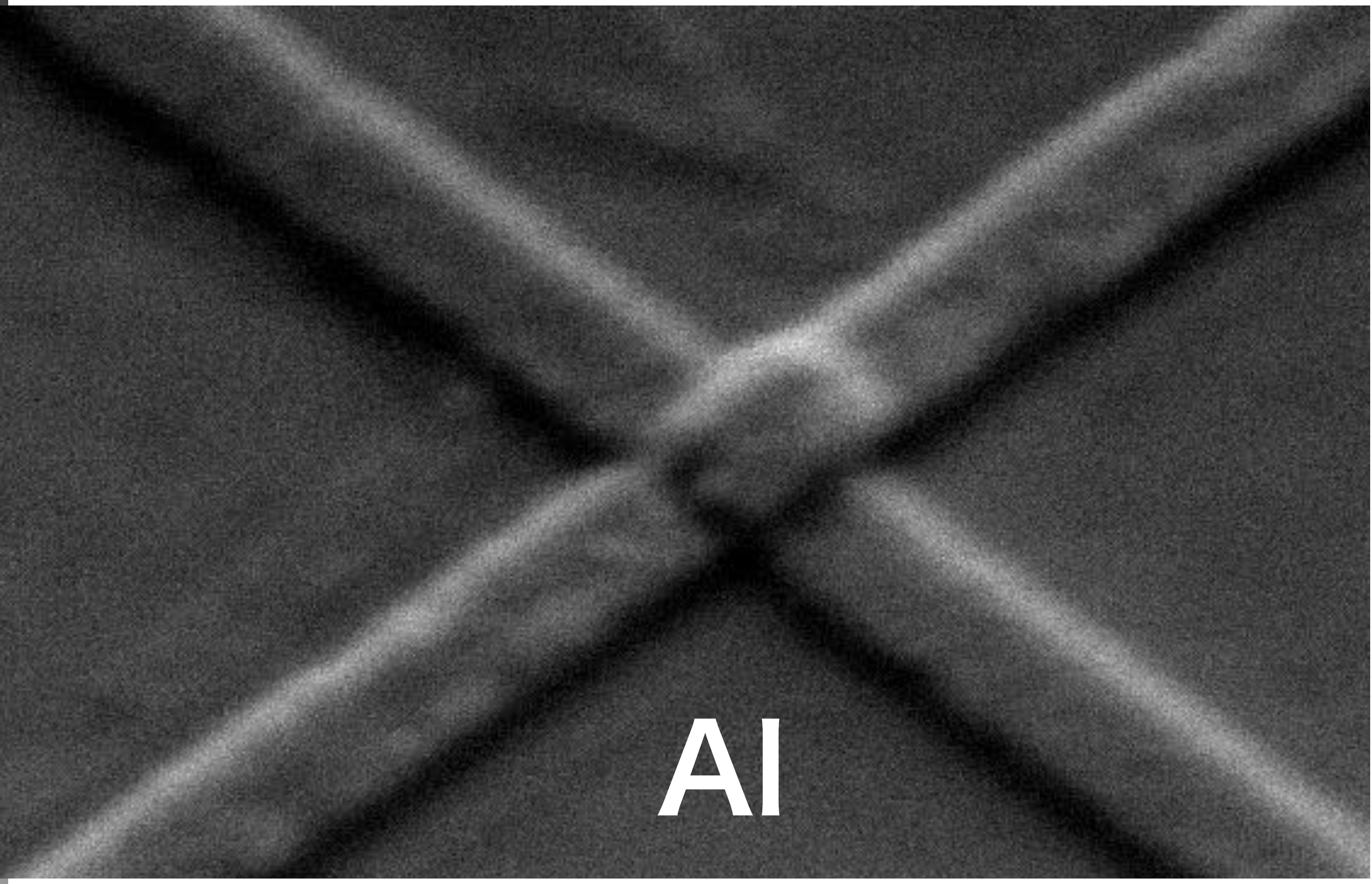
Qubits worked at least 1T

J. Krause et.al., Phys. Rev. Applied 17, 034032 (2022)

Difficulty



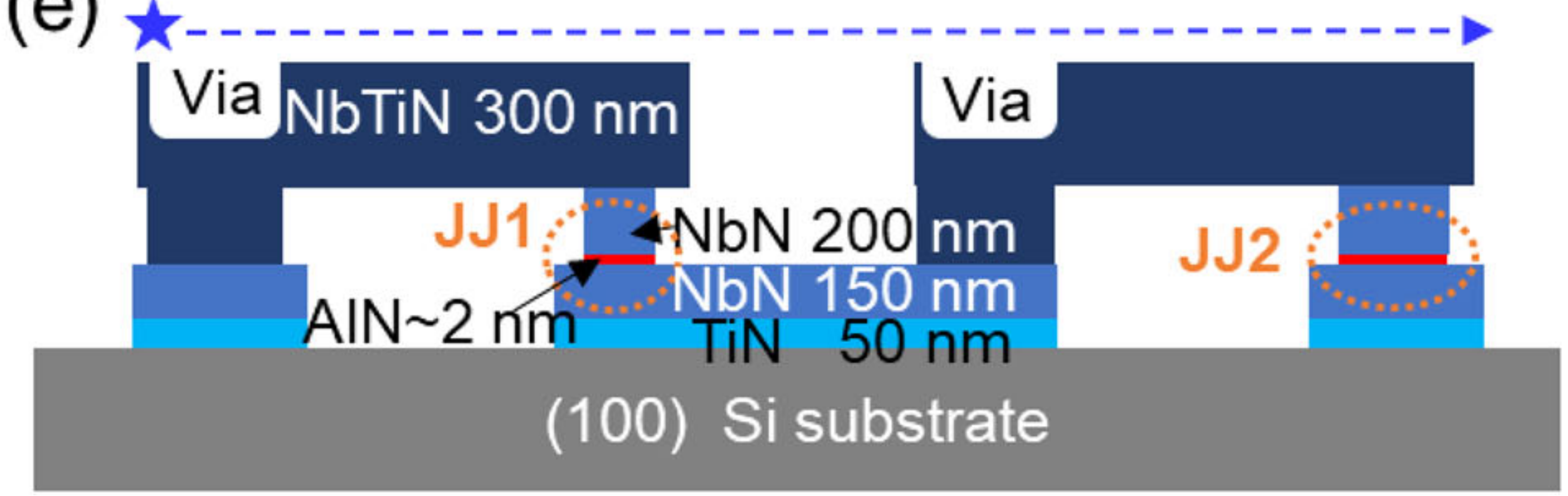


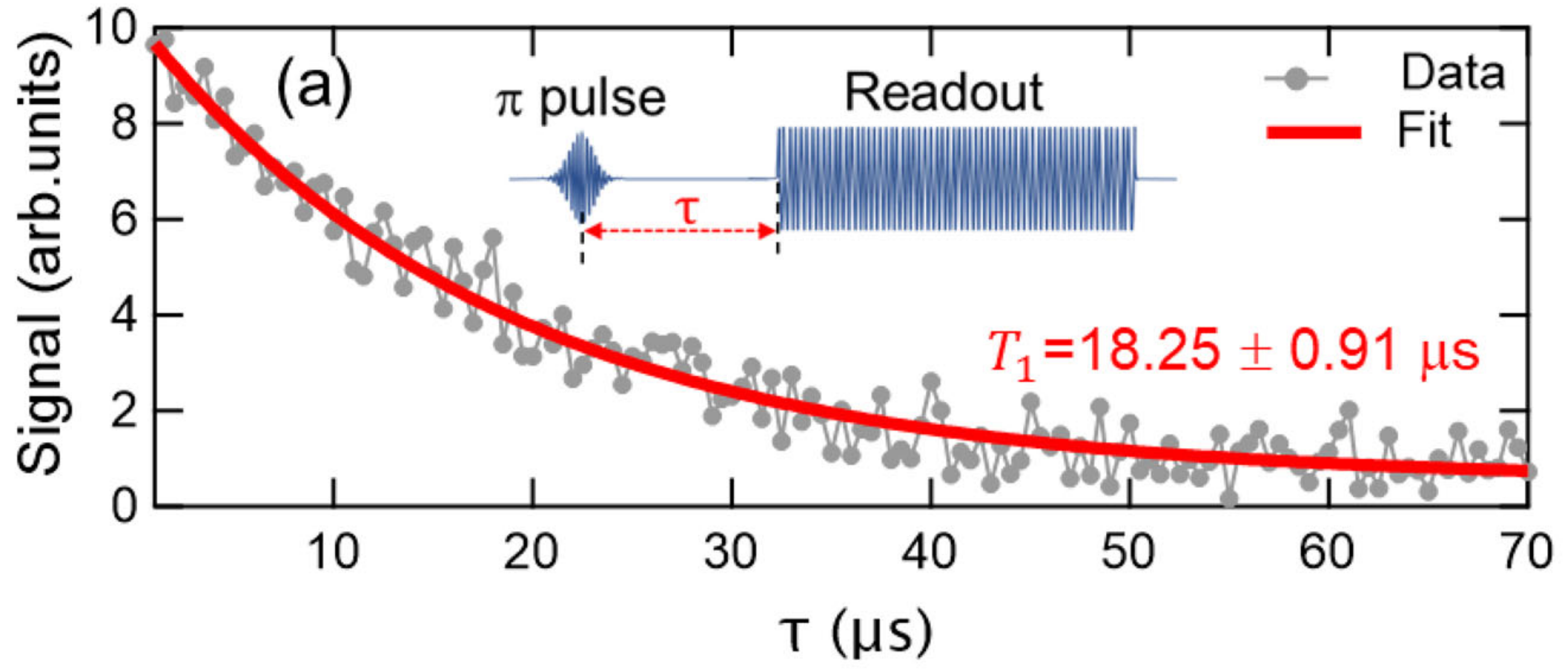


- Critical field
- Suppression of Josephson effect

Solution: All-nitride qubits

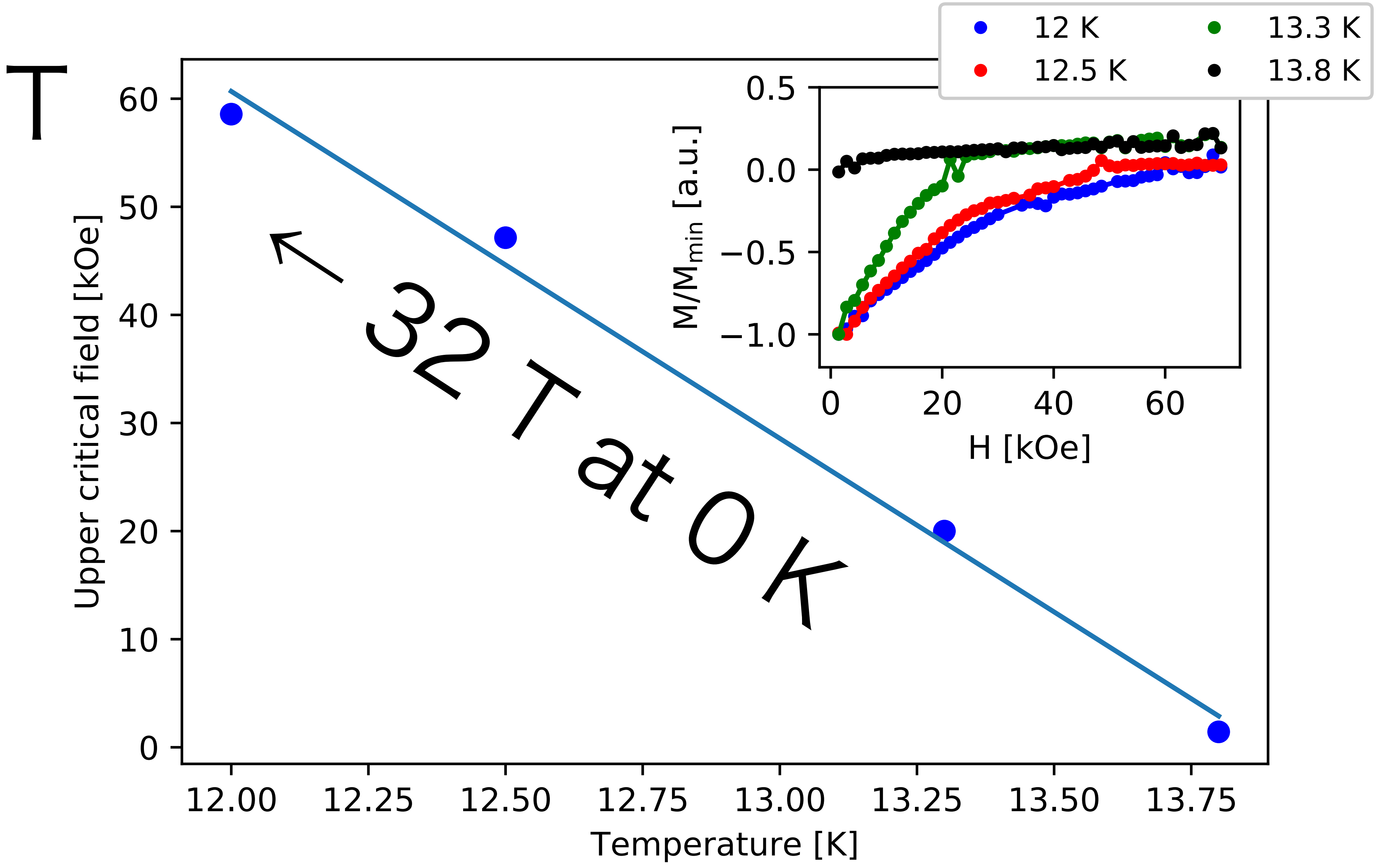
S. Kim, Communications Materials 2, 98 (2021)





T. Polakovic, APL Materials 6 (2018) 076107

NbN 240 nm film



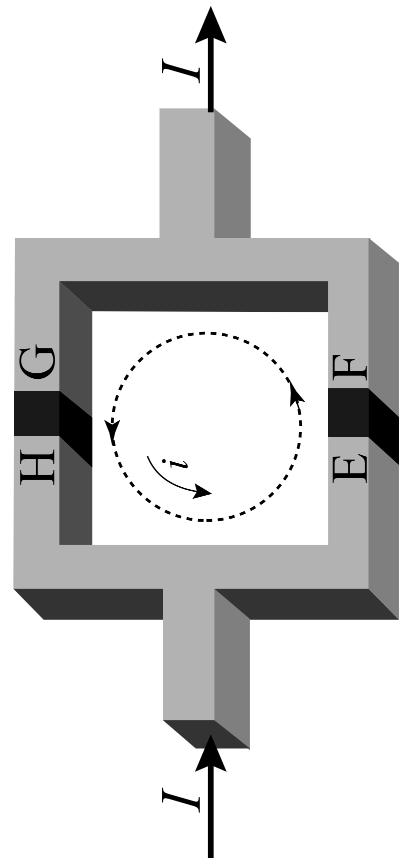
6T

← 32 T at 0 K

Nitride has high Tc2 → **We don’t have to care about critical field**

Suppression of Josephson Effect

SQUID



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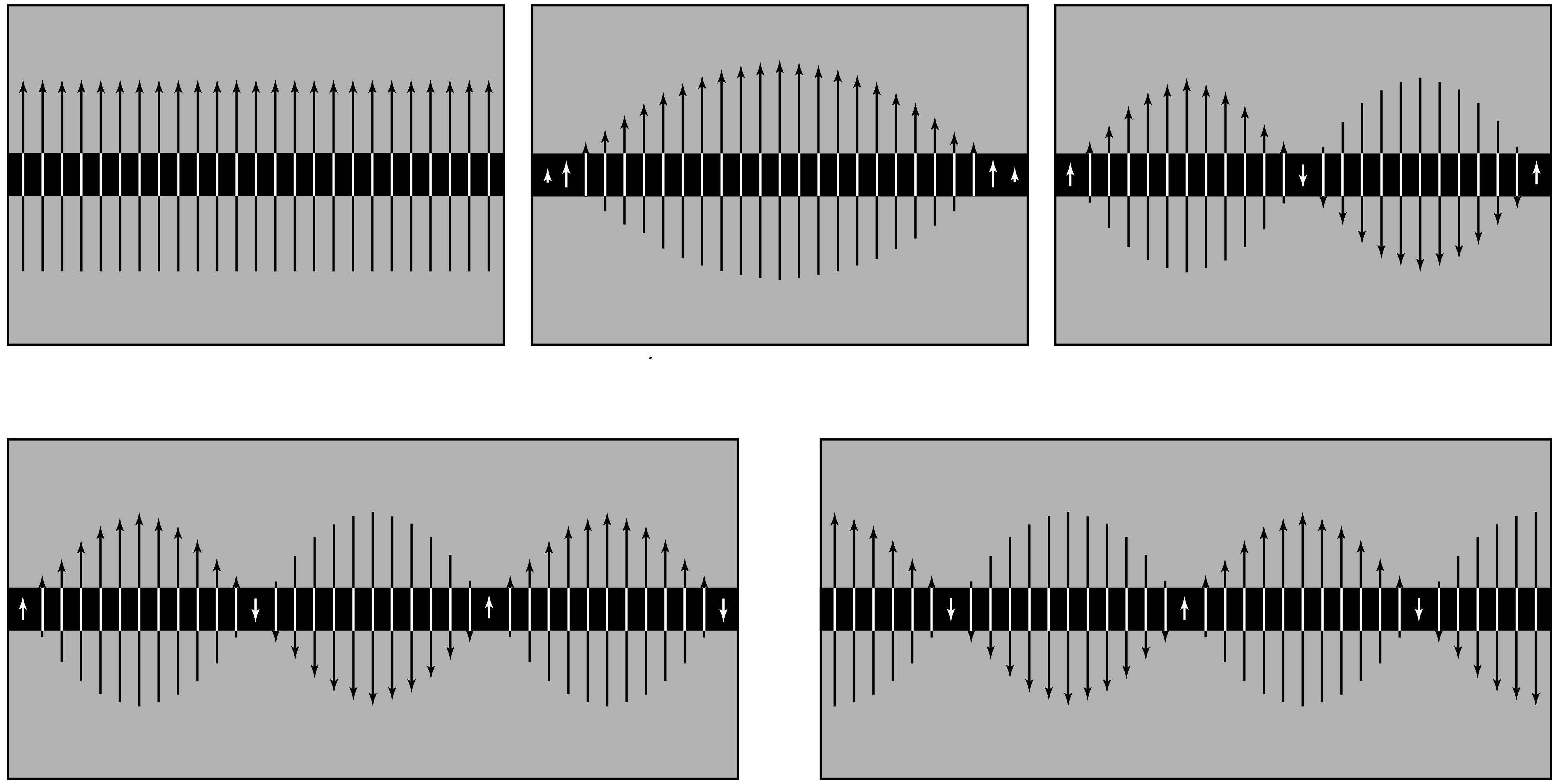
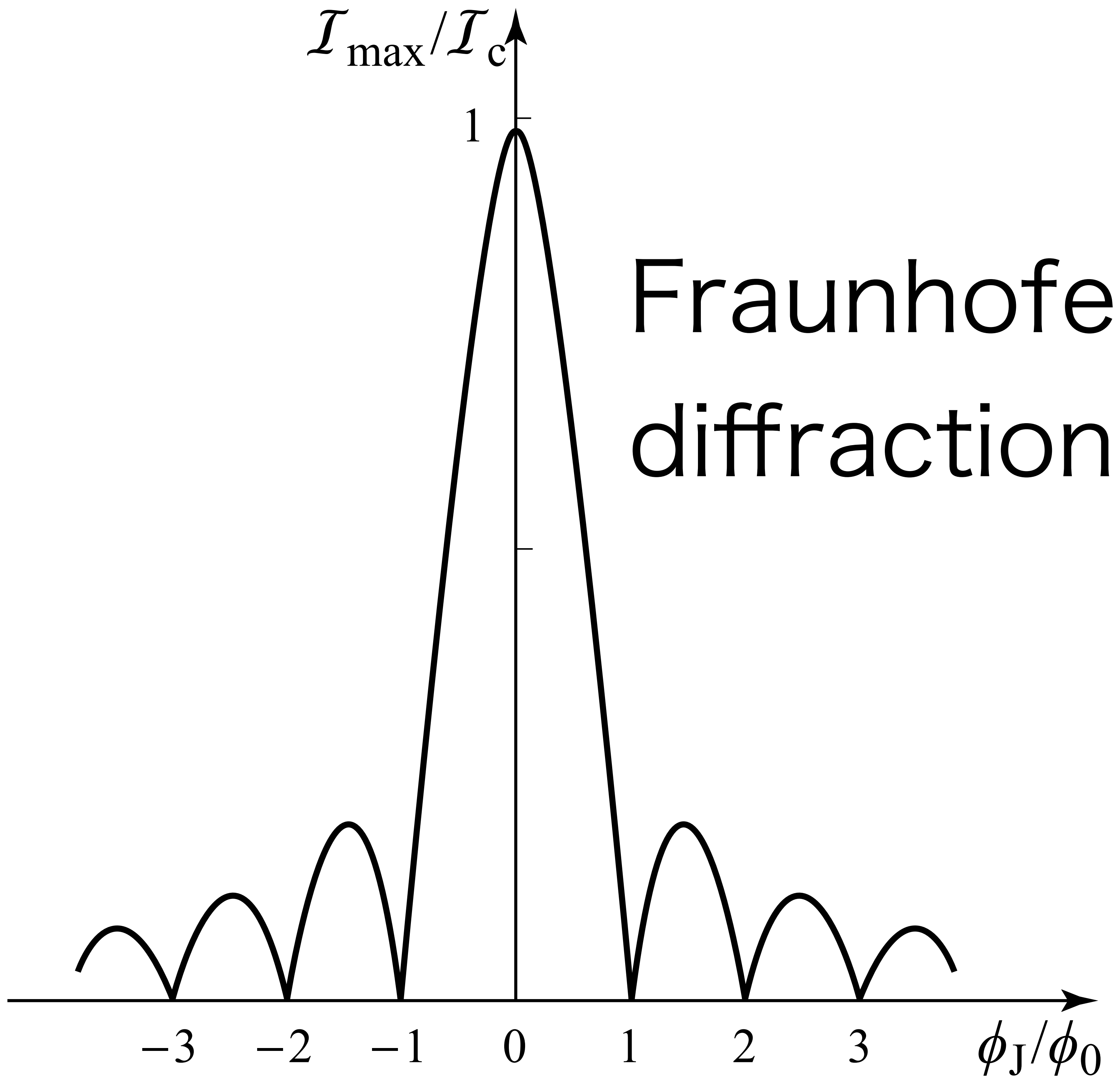
single JJ under high B-field



From “Superconductivity An introduction” Mangin - Kahn

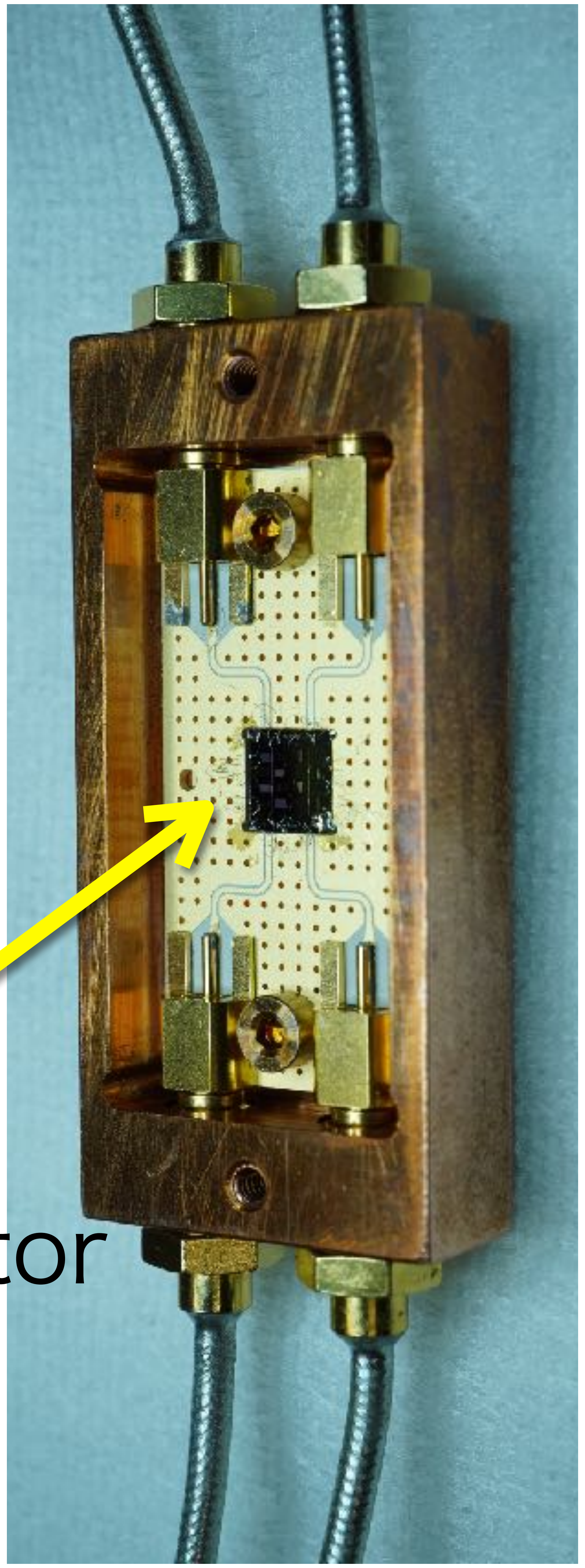


Fraunhofer diffraction

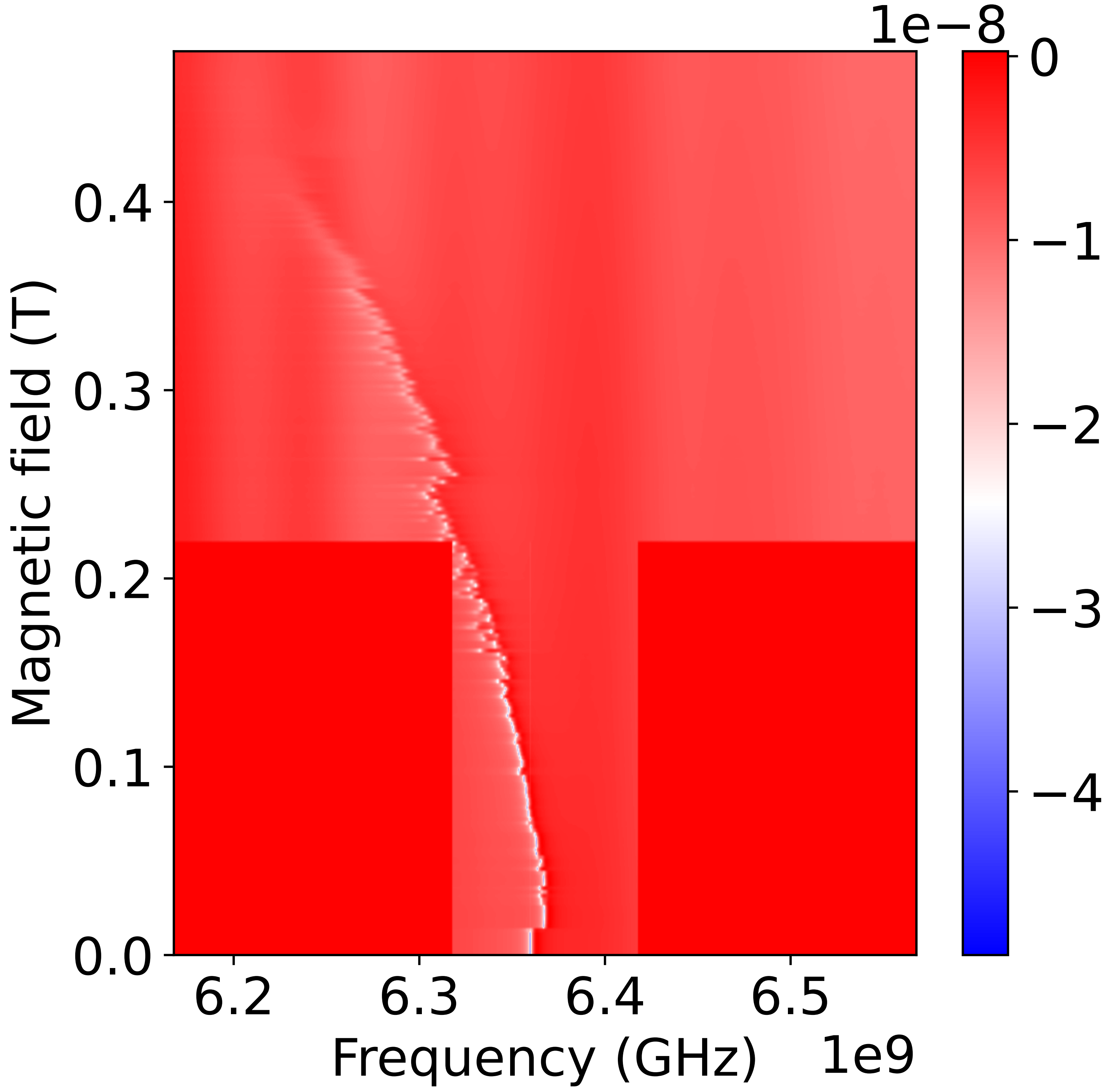
10 T = 1 flux quantum / (14 nm)^2

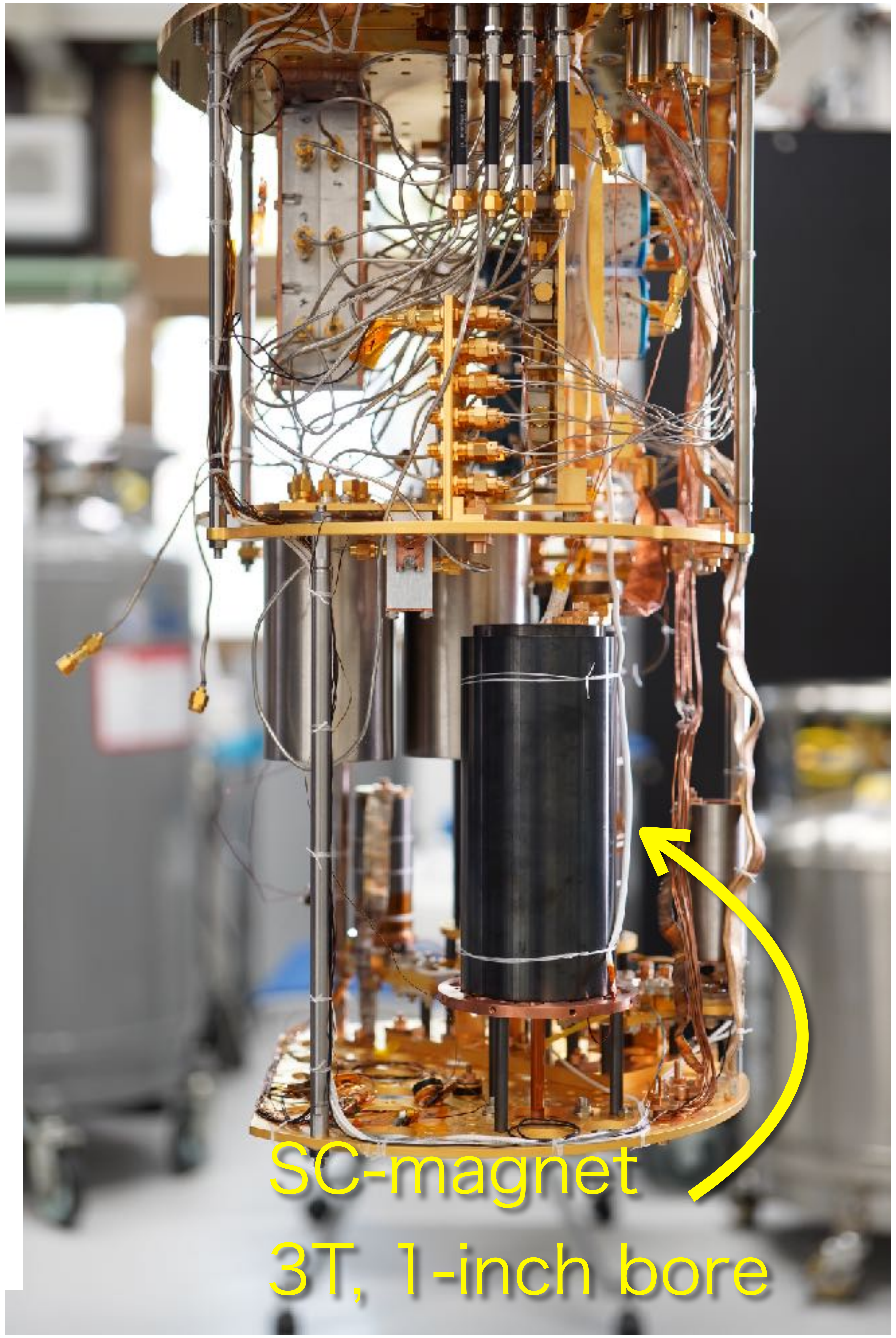
→ **Have to keep the cross-section to the magnetic field small**

Current Status



TiN 2D resonator





SC-magnet
3T, 1-inch bore

Summary

- Superconducting qubit is a promising platform for DM search

- We did two experiments
  - Direct excitation (Lead by Karin Watanabe)
  - Lamb shift tuning (Lead by Kan Nakazono)

- We are working on
  - Larger electric dipole coupling qubits for wider tuning range for Lamb shift & better sensitivity for direct exitation
  - Applying strong magnetic field in parallel to thin film for axion