OIST and UTokyo Symposium 2025
Quantum Nexus

Superconducting Qubits and Their Application to Dark Matter Searches

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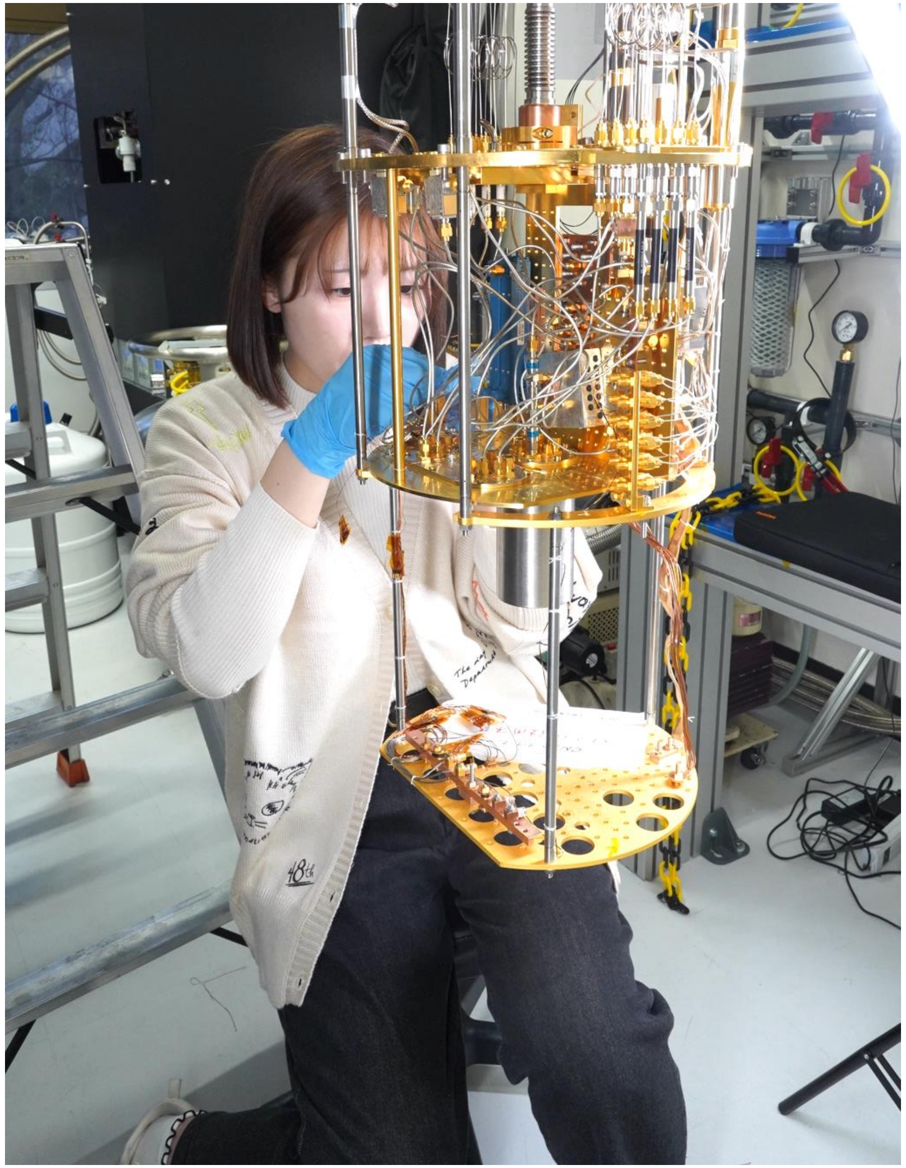
The University of Tokyo

Self-Introduction



Karin Watanabe

Ph.D. Student (1st Year)

Department of Physics, The University of Tokyo

Research field

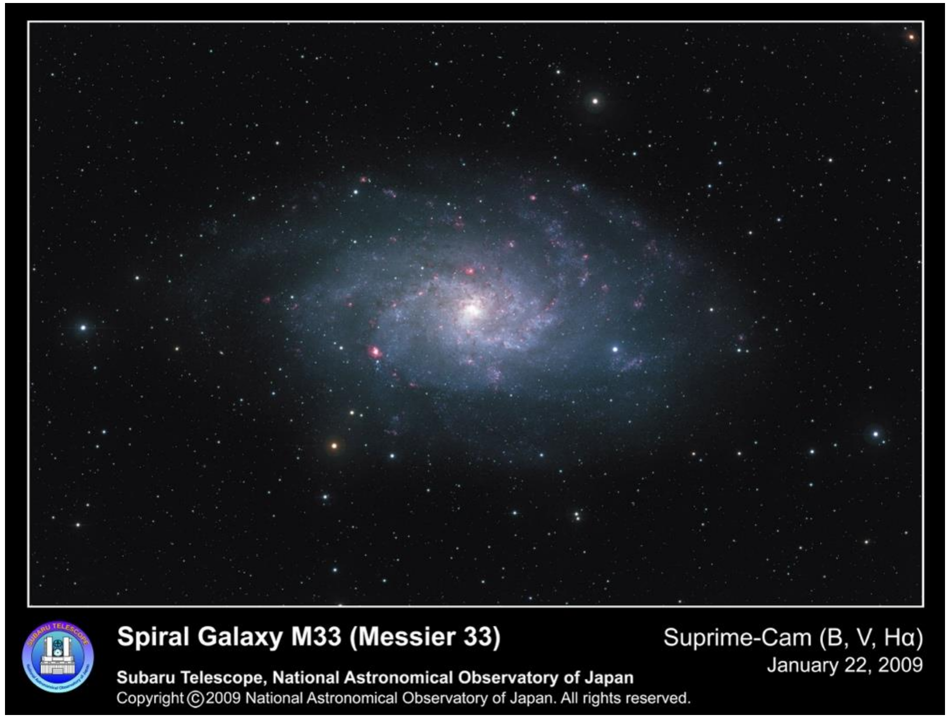
Elementary particle physics

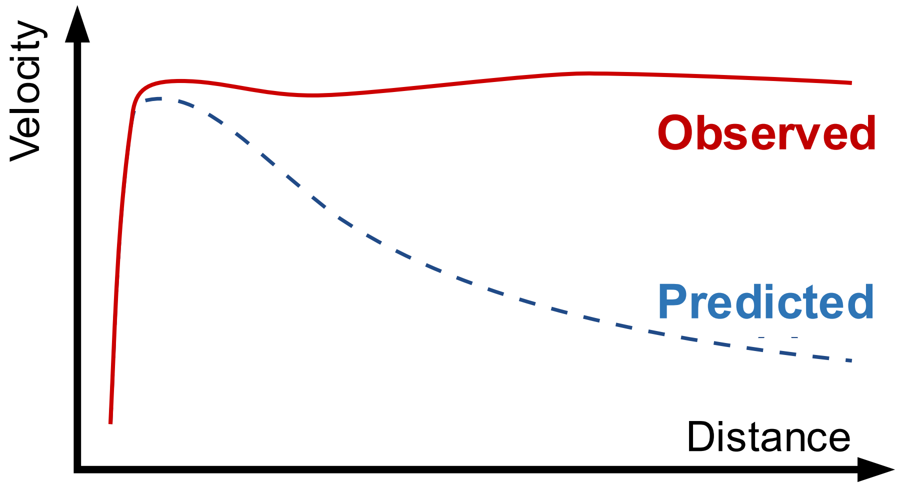
Current research

Searching for dark photons using superconducting qubits

Dark Matter

- Dark matter is something that has mass, but is not observable through light.
- Various cosmological observations provide indirect evidence.
- Numerous theoretical studies and direct searches have been conducted.
- But **dark matter remains undiscovered**.
- Determining the nature of dark matter is a crucial challenge for understanding both particle physics and cosmology.





Rotation Speed Discrepancy in Spiral Galaxies

Source: Phil Hibbs, *GalacticRotation2.svg* (Wikimedia Commons), CC BY-SA 3.0

Dark Matter

As candidate for dark matter:

Heavy: $m \gg$ eV

– e.g. Weakly Interacting Massive Particles (WIMPs)

– Direct searches via nuclear/electron recoil processes

Light: $m \ll$ eV

– e.g. Axion, Dark photon

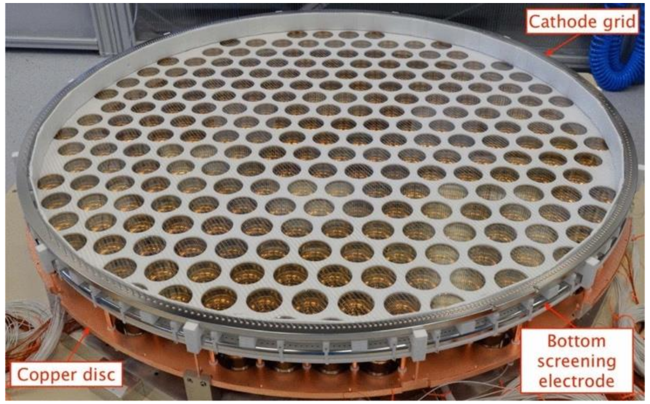
- Weakly coupled to ordinary photons
- Can be converted into **weak electromagnetic fields**

↑

What directly look for

E. Aprile et al., Eur. Phys. J. C 84, 784 (2024)

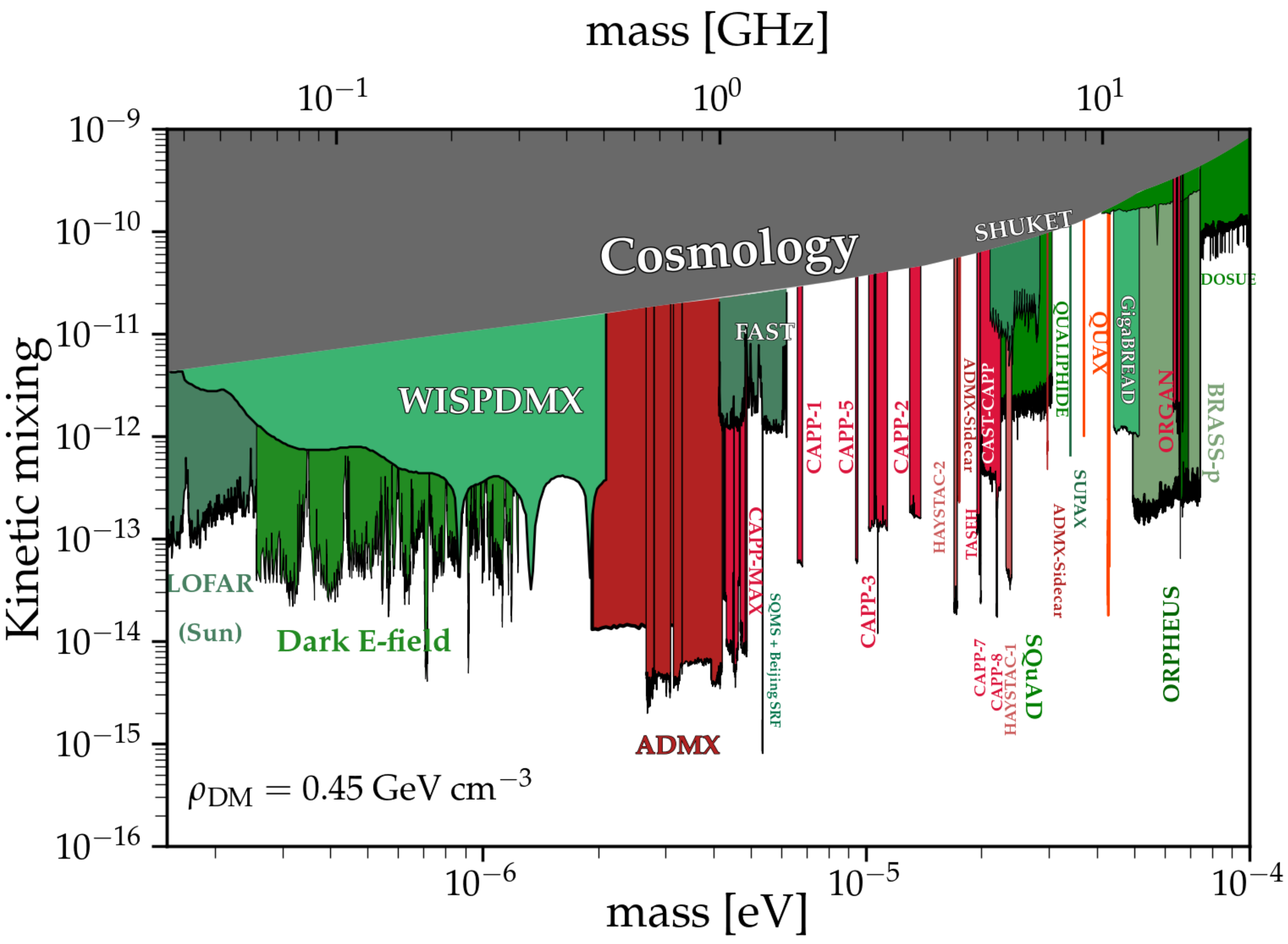
XENONNT (a WIMPs search experiment)



ADMX (an axion search experiment)

Credit: University of Washington (Public Domain)

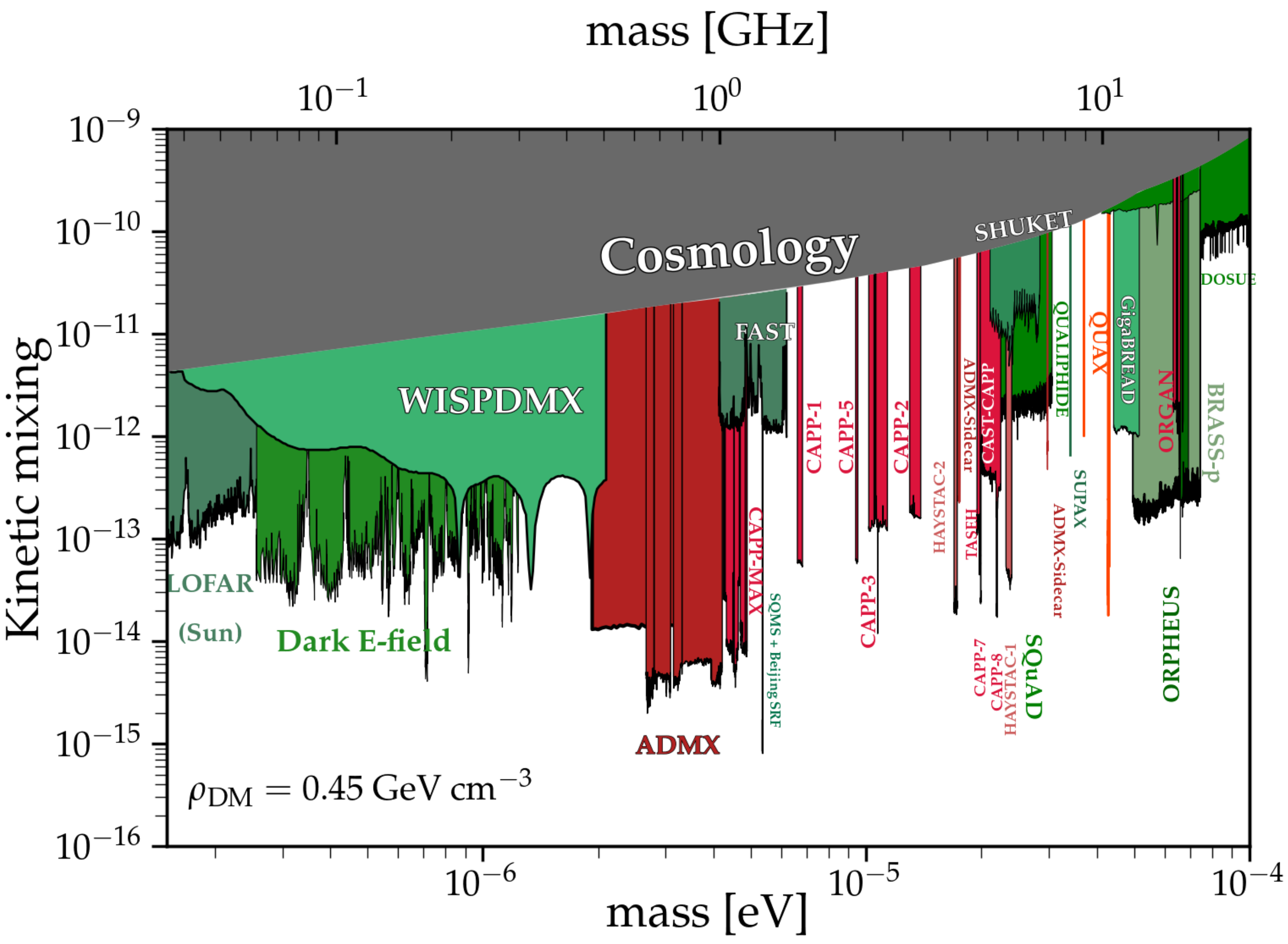
Dark Photon



- Existing approaches have geometry-limited mass reach.
- O(1–10) GHz detector implementations are technically challenging.

→ New method is needed

Dark Photon



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→ New method is needed

Using superconducting qubits

–Sensitive to electromagnetic signals

–Tunable across wide frequency ranges (> $\mathcal{O}$ (100) MHz)

Search for dark photons using superconducting qubits as sensors for dark-photon-induced electromagnetic signals.

Topic

1. **What a superconducting qubit is**

2. **How to search for dark photons using superconducting qubits**

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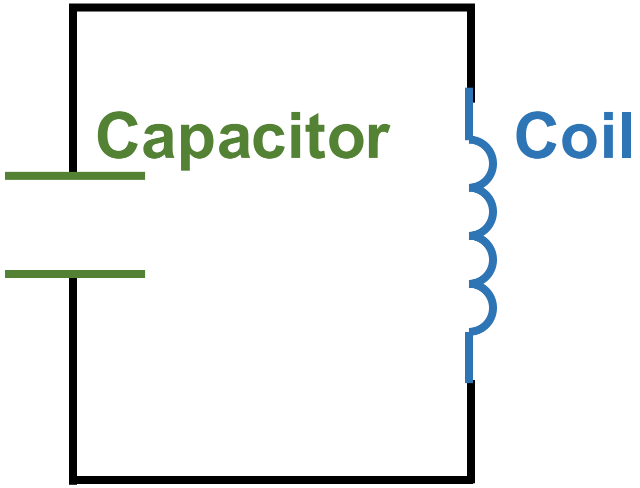
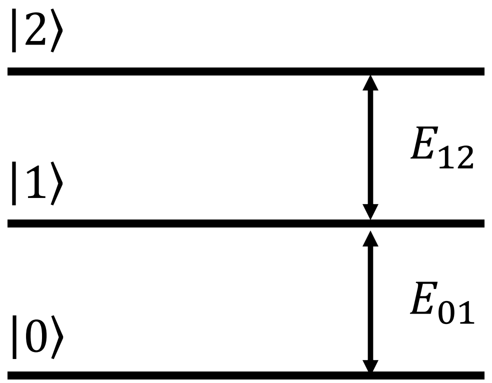
1. **What a superconducting qubit is**

2. How to search for dark photons using superconducting qubits

Superconducting Qubit

Linear LC circuit



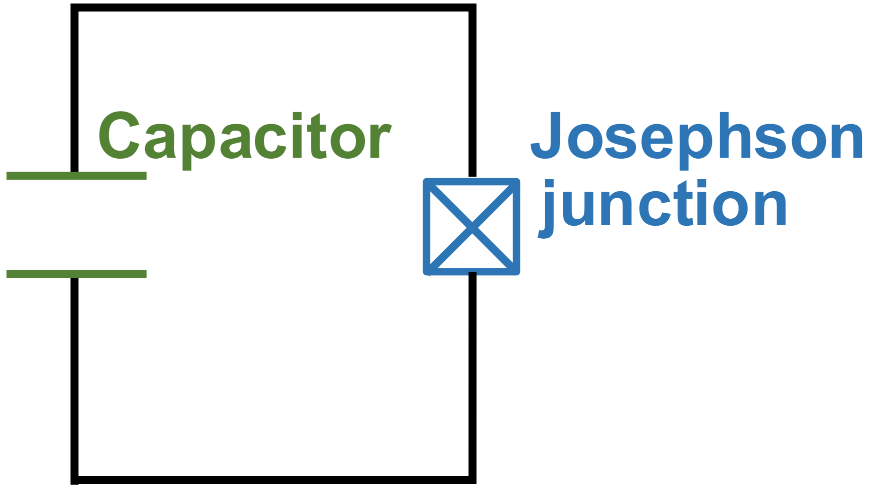


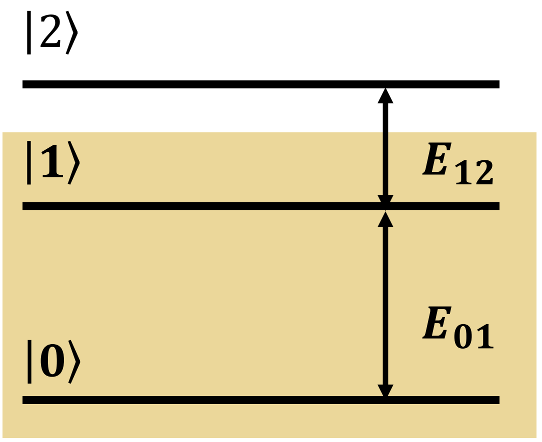
$$E_{01} = E_{12}$$

- A coil is a **linear** inductor.
- Energy levels are **equally** spaced.

Superconducting Qubit

Nonlinear LC circuit





Qubit

$E_{01} \neq E_{12}$

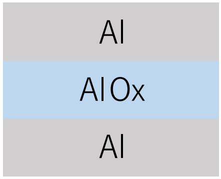
$\sim \mathcal{O}(\mathrm{GHz})$

- A Josephson junction is a **nonlinear** inductor.
- Energy levels are **unequally** spaced.

→ Prevents excitation to higher states.

→ Enables clean 2-level control.

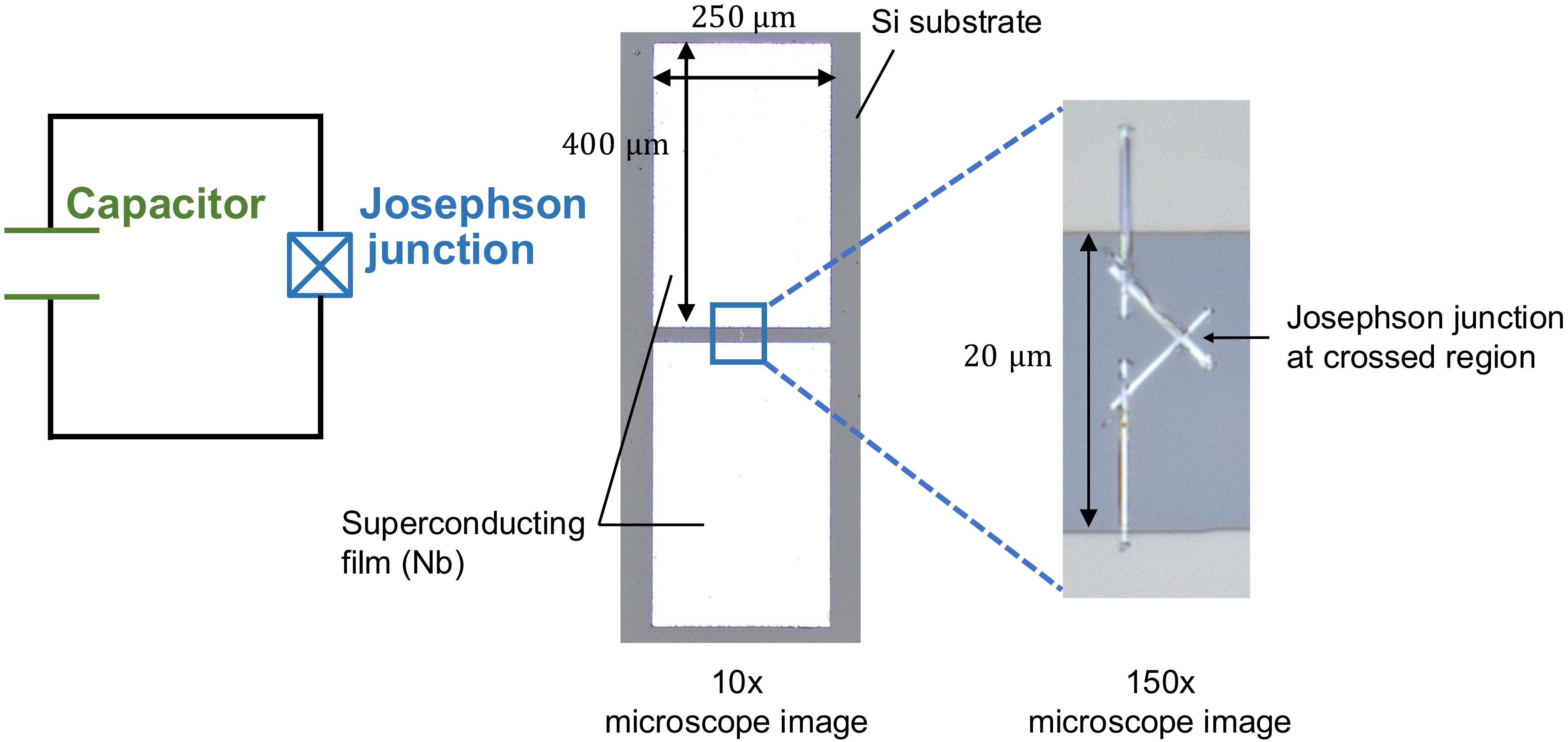
Josephson junction



T_c (Al) ~1.2 K

Superconductor-insulator-superconductor sandwich structure

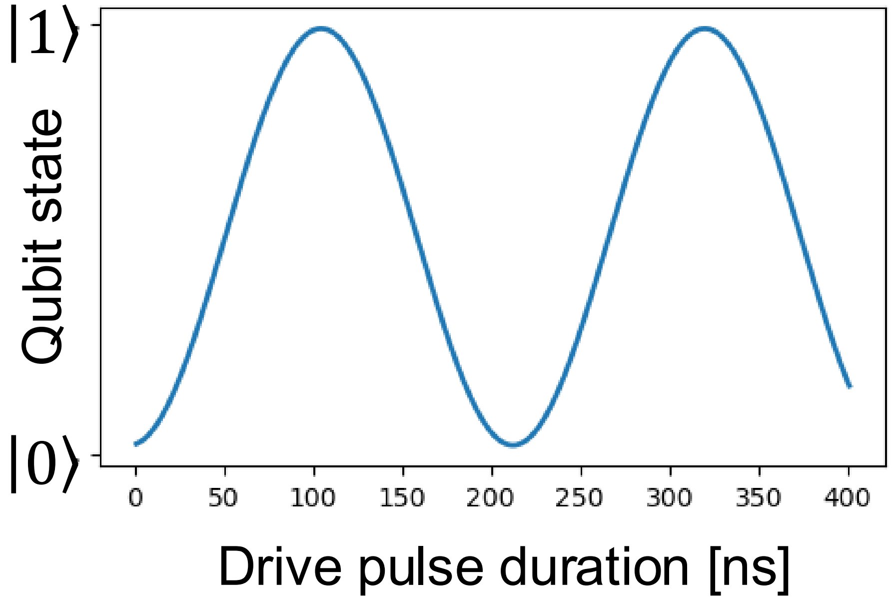
Superconducting Qubit



Superconducting Qubit – State Manipulation

$$f_{01} = \frac{E_{01}}{h}$$

- A drive pulse **at $\boldsymbol{f_{01}}$** makes the qubit oscillate between $|0\rangle$ and $|1\rangle$.



Superconducting Qubit – State Manipulation

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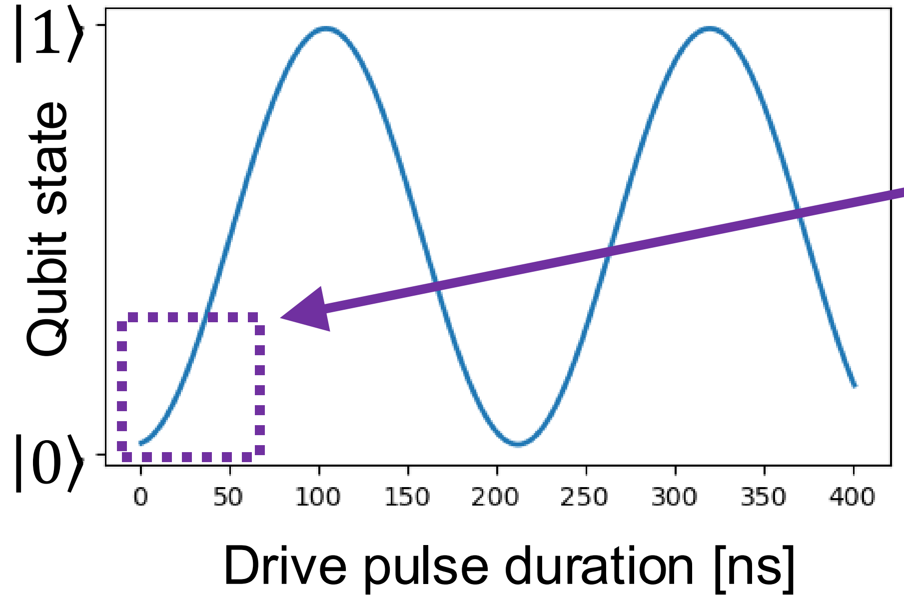

- A drive pulse **at $\boldsymbol{f_{01}}$** makes the qubit oscillate between $|0\rangle$ and $|1\rangle$.

- Even a very weak electromagnetic field can excite the qubit, leading to the initial part of the oscillation.

Superconducting Qubit – State Manipulation

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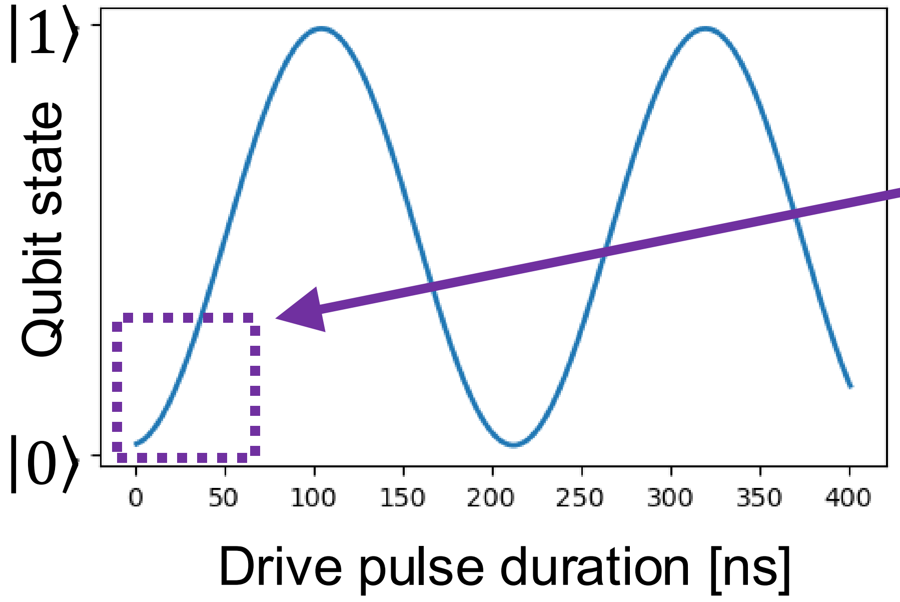
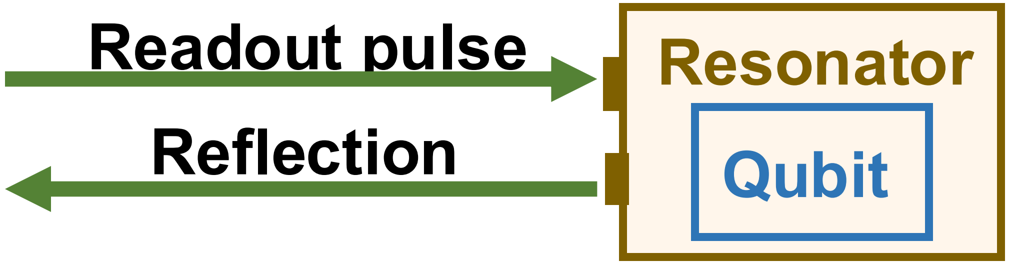


- A drive pulse **at f_{01}** makes the qubit oscillate between $|0\rangle$ and $|1\rangle$.

e.g. Dark photon signal

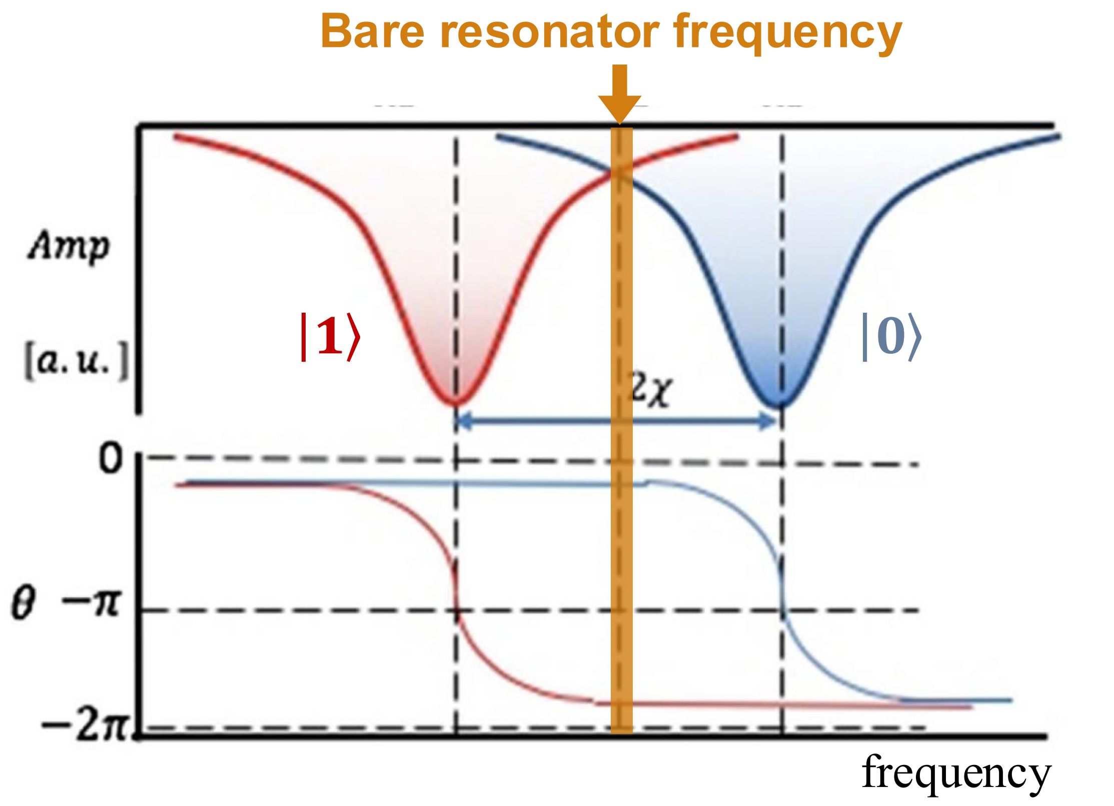
- Even a very weak electromagnetic field can excite the qubit, leading to the initial part of the oscillation.
- This enables the use of the qubit as an ultra-sensitive **electromagnetic field sensor by monitoring its excitation.**

Superconducting Qubit – State Readout



- The qubit and the resonator are weakly **coupled**
- The resonator frequency shifts depending on the qubit state.

→The amplitude and phase of the reflected signal change.



State-Dependent Reflection Phase and Amplitude

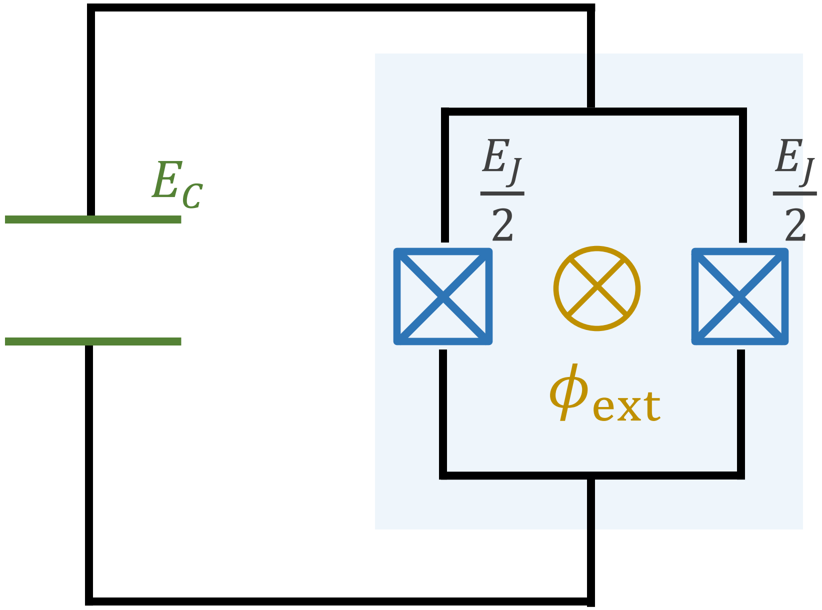
W. Chien et al., Journal of Electronic Materials 49, 6844–6858 (2020)

Superconducting Qubit – Tuning

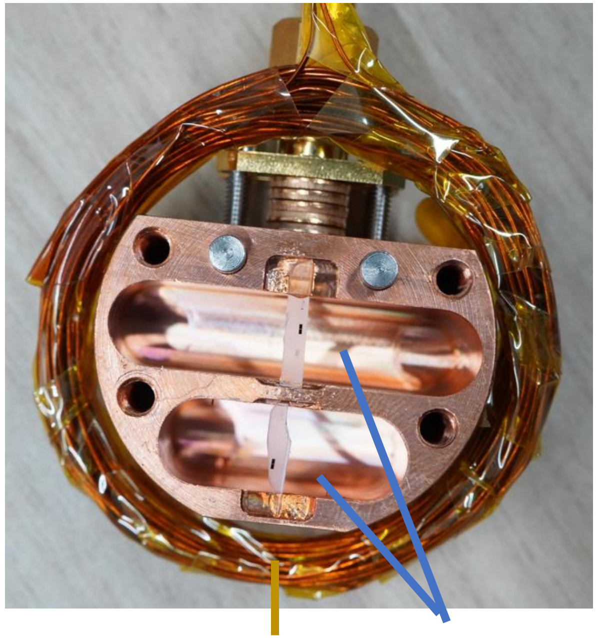
Tuning by applying a magnetic field to the **SQUID**

Controlled by the coil current

$$hf_{01} = \sqrt{8E_C E_J \cos\left(\frac{\varphi_{\text{ext}}}{2}\right)} - E_C$$

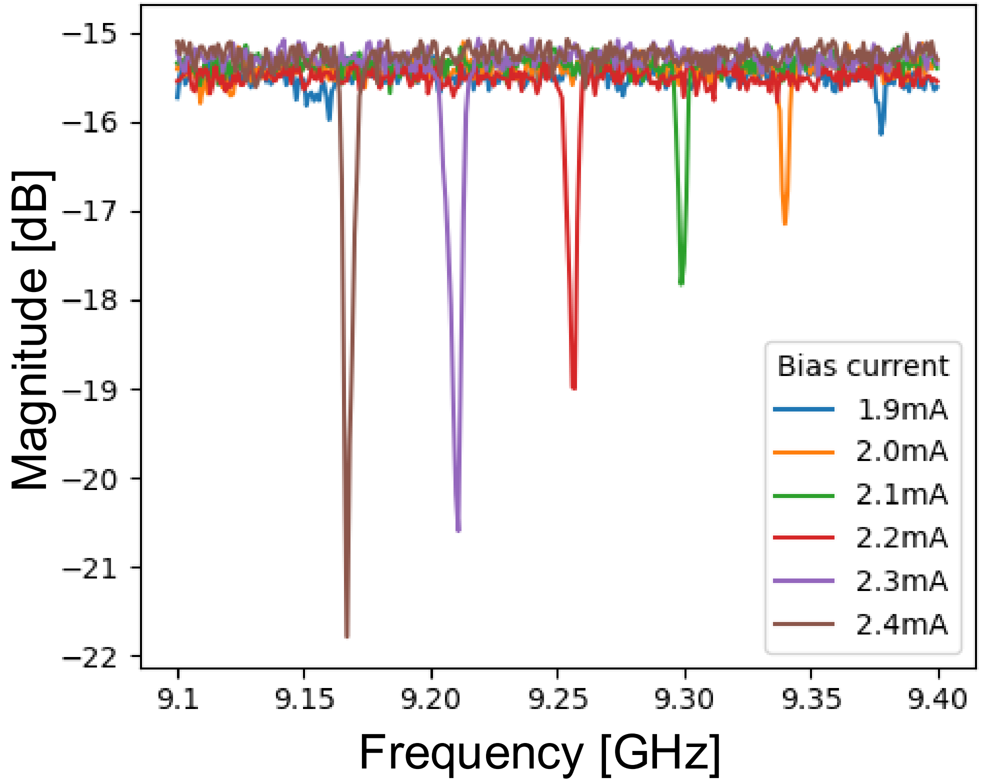


$\phi_{\text{ext}} = \varphi_{\text{ext}}\, \phi_o$



NbTi coil

Qubit

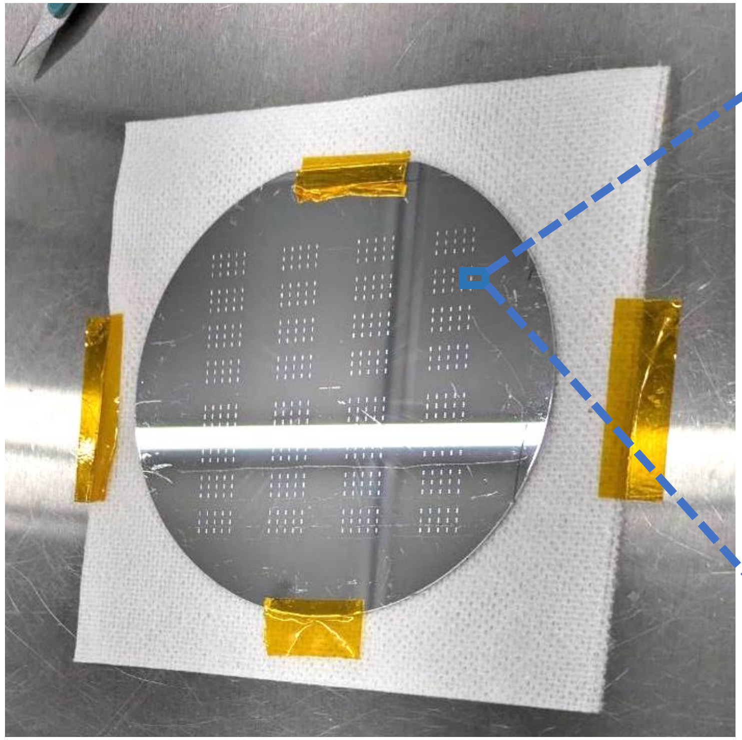


$f_{01} = 9.69$ GHz

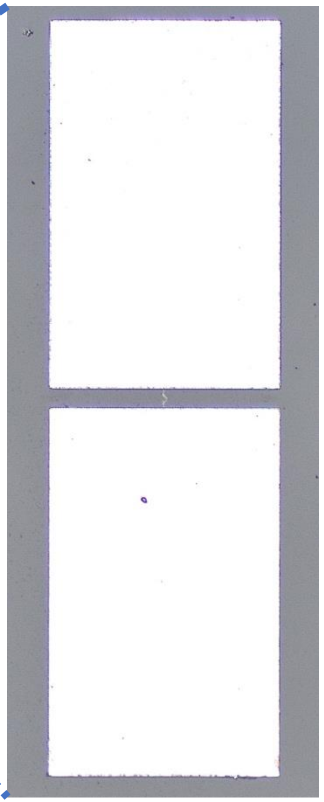
Topic

1. What a superconducting qubit is
   – **Fabrication**
2. How to search for dark photons using superconducting qubits

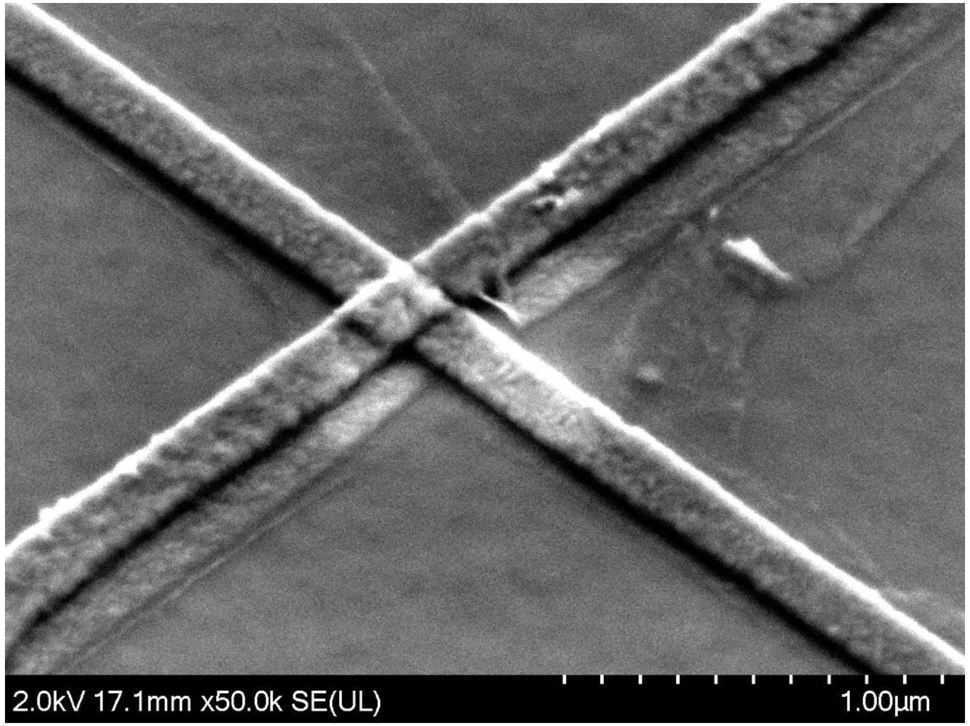
Superconducting Qubit – Fabrication



A fabricated 10cm wafer
with 480 qubits



10x microscope image
of the qubit

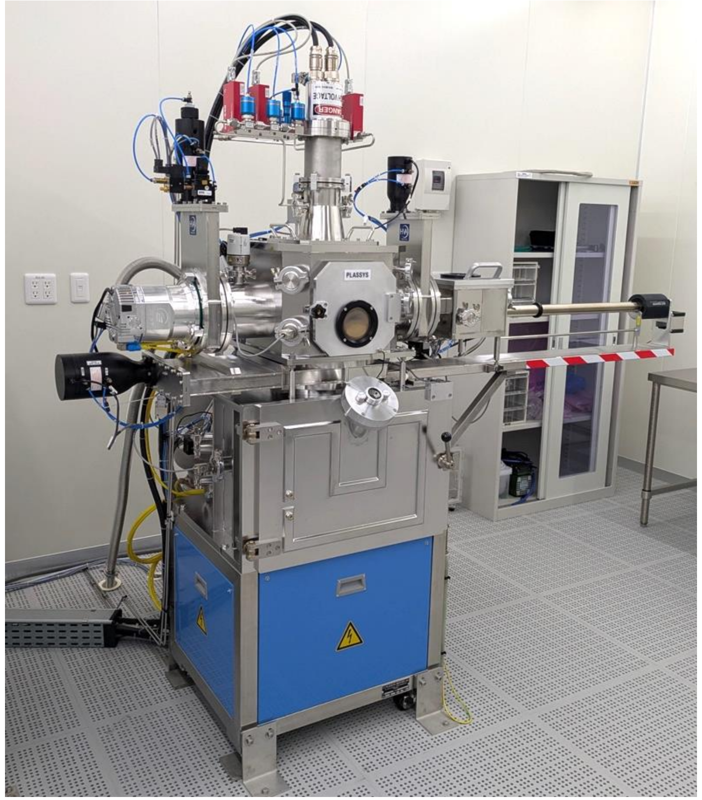


50kx SEM image
of the Josephson junction

Superconducting Qubit – Fabrication

Qubit Fabrication

- Capacitor pads: Made with standard microfabrication processes
- Josephson junction: Require **qubit-specific** processing



Plassys ＠OIST

Electron Beam Evaporator: Plassys

- Enables **angled** metal deposition essential for qubit Josephson junctions
- Available only at a few shared-use facilities

→ We are very grateful to have access at OIST.

Superconducting Qubit – Fabrication

Frequent visits to OIST

- 05/18-19
- 06/10-12
- 06/23-24
- 07/25-26
- 07/29-08/01
- 08/11-14

Superconducting Qubit – Fabrication

Working in the OIST Lab 5 Cleanroom — via the OIST Core Facilities External Use Program

Cleaning
before metal deposition

Installation
into the deposition tool (Plassys)

Operating the deposition tool

Topic

1. What a superconducting qubit is

2. **How to search for dark photons using superconducting qubits**

Dark Photon

- Candidate for dark matter
- Key properties

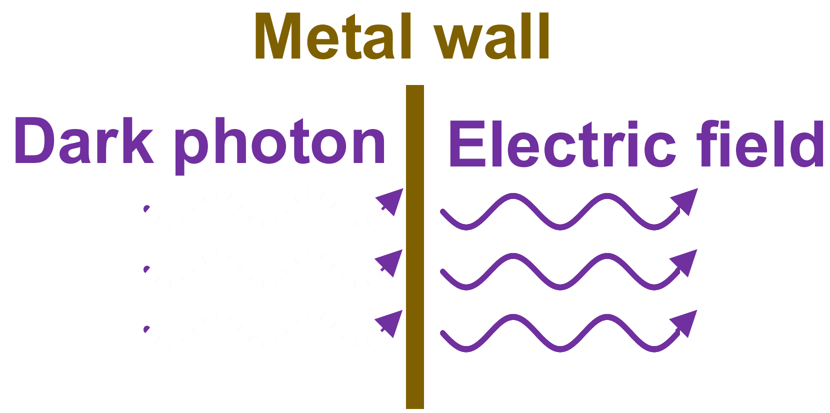
➢ Light mass $< \mathcal{O}(\mu\text{eV})$ → behave as a **coherent wave**

- Long de Broglie wavelength $> \mathcal{O}(100\ \text{m})$
- High number density $> \mathcal{O}(10^9\ \text{cm}^{-3})$

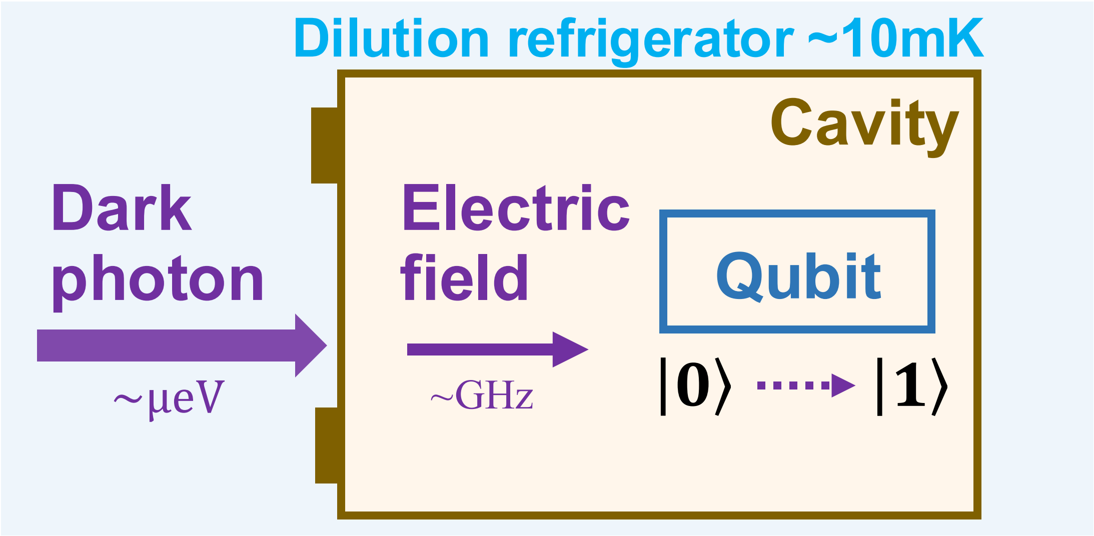
➢ **Interact with ordinary photons**

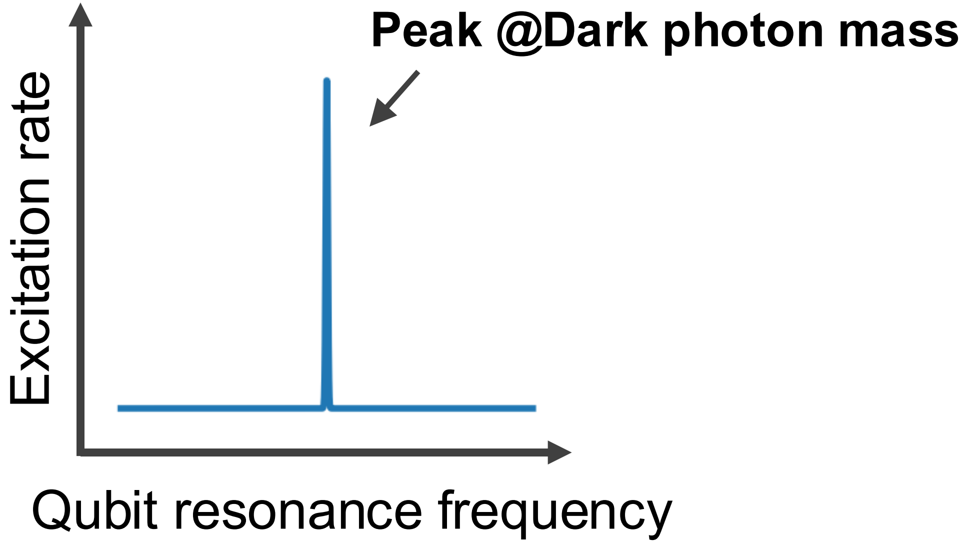
Can be converted into a **coherent, weak electromagnetic field** with a frequency corresponding to its mass

Be detected using a superconducting qubit



Dark Photon Search using Superconducting Qubit – Basic Idea





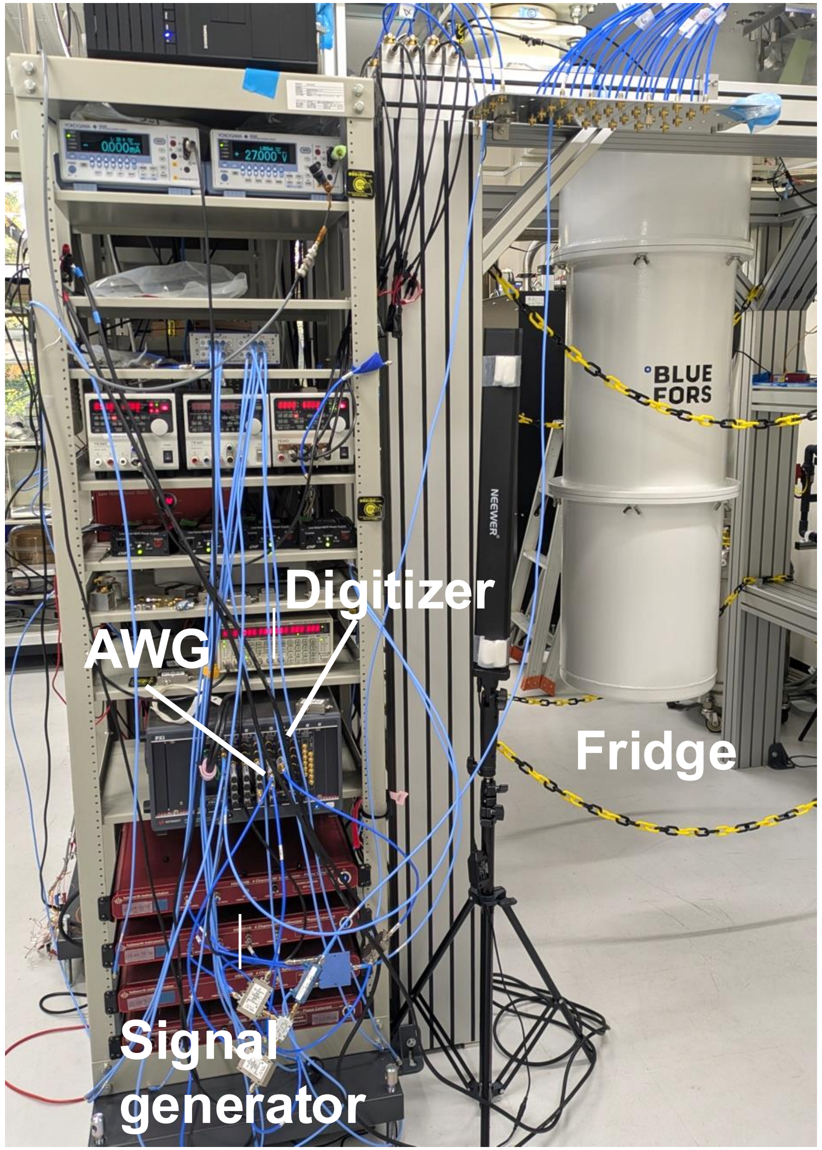
- When a dark photon passes through the metal wall, it is converted into an electric field at the frequency corresponding to its mass.

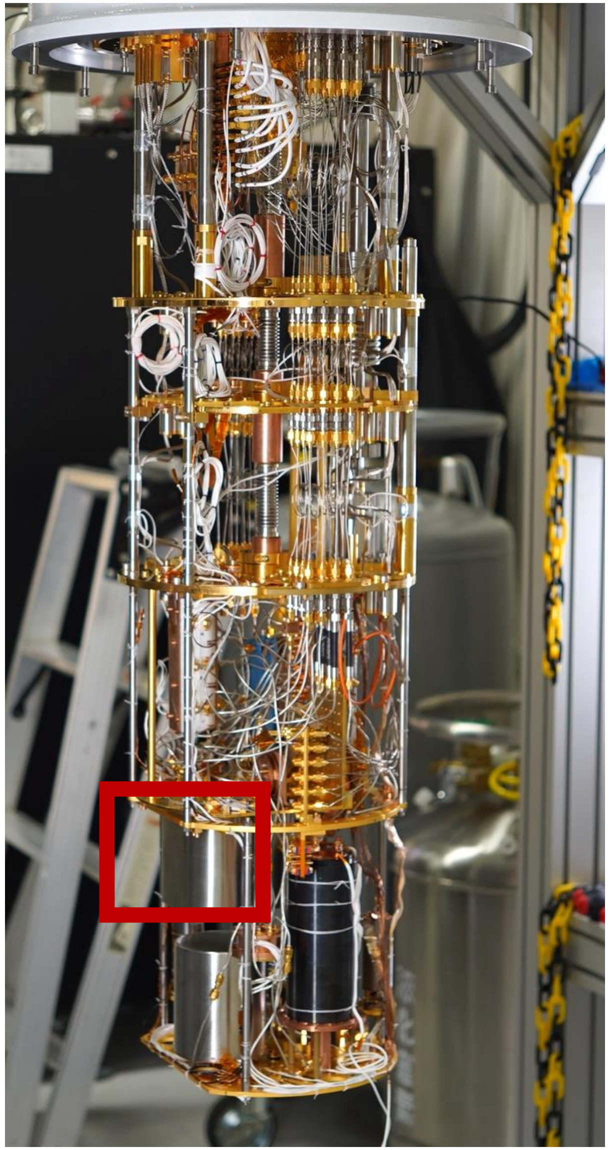
$$f \sim \frac{mc^2}{h}$$

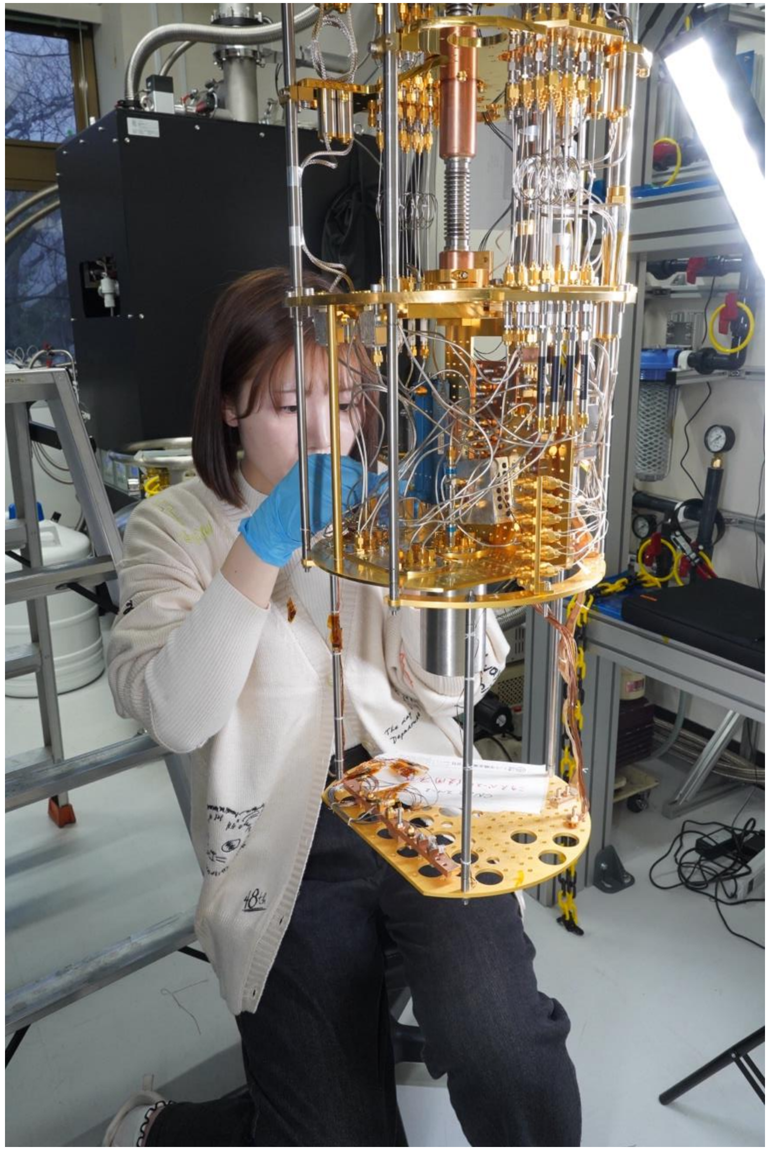
- The electric field frequency matches the qubit resonance frequency.
  → The qubit is excited.
- Sweep the qubit resonance frequency to find the peak of the excitation rate.

Moroi et al. PRL 131 (21), 211001 (2023)

Dark Photon Search using Superconducting Qubit –Experimental Setup

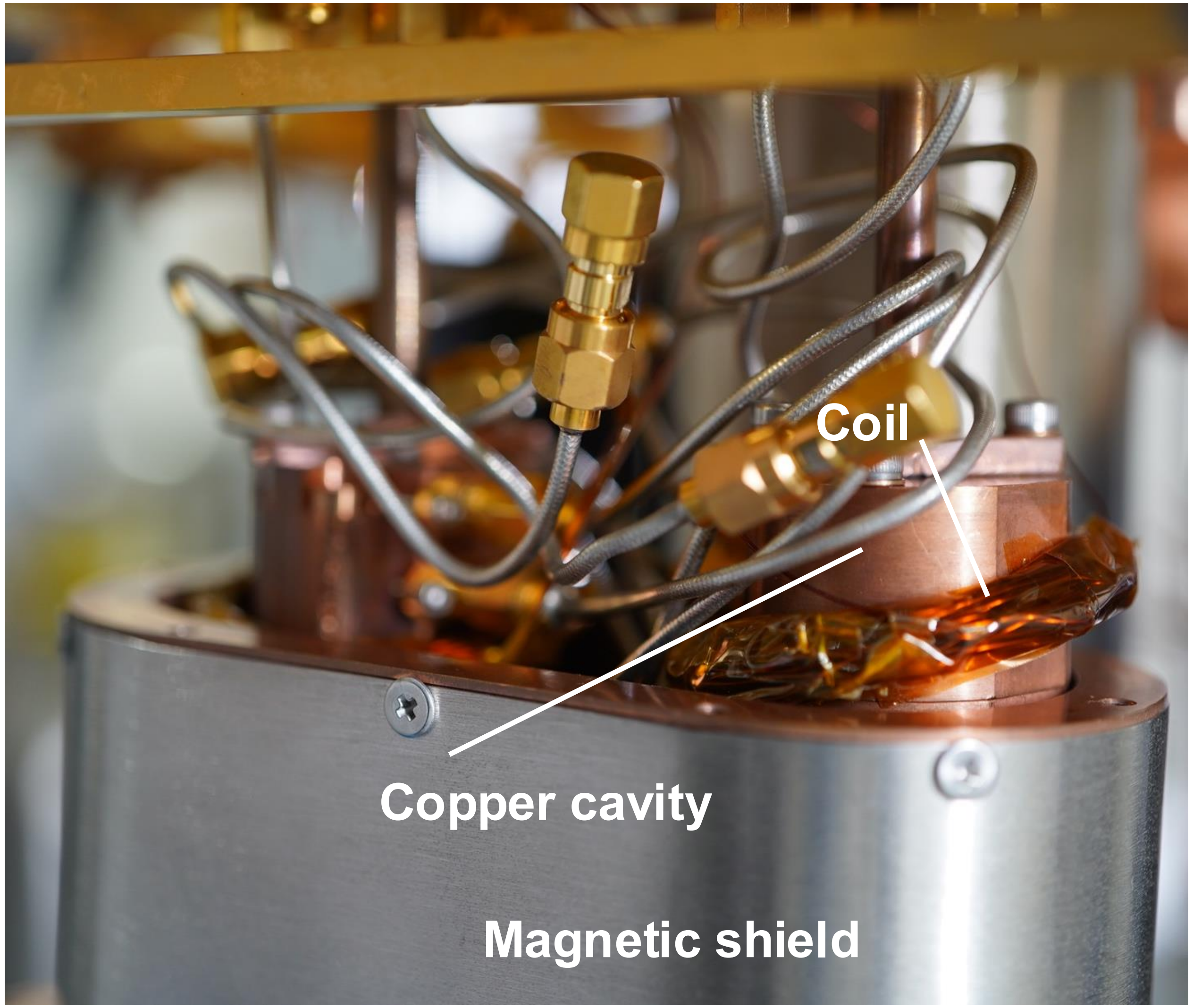


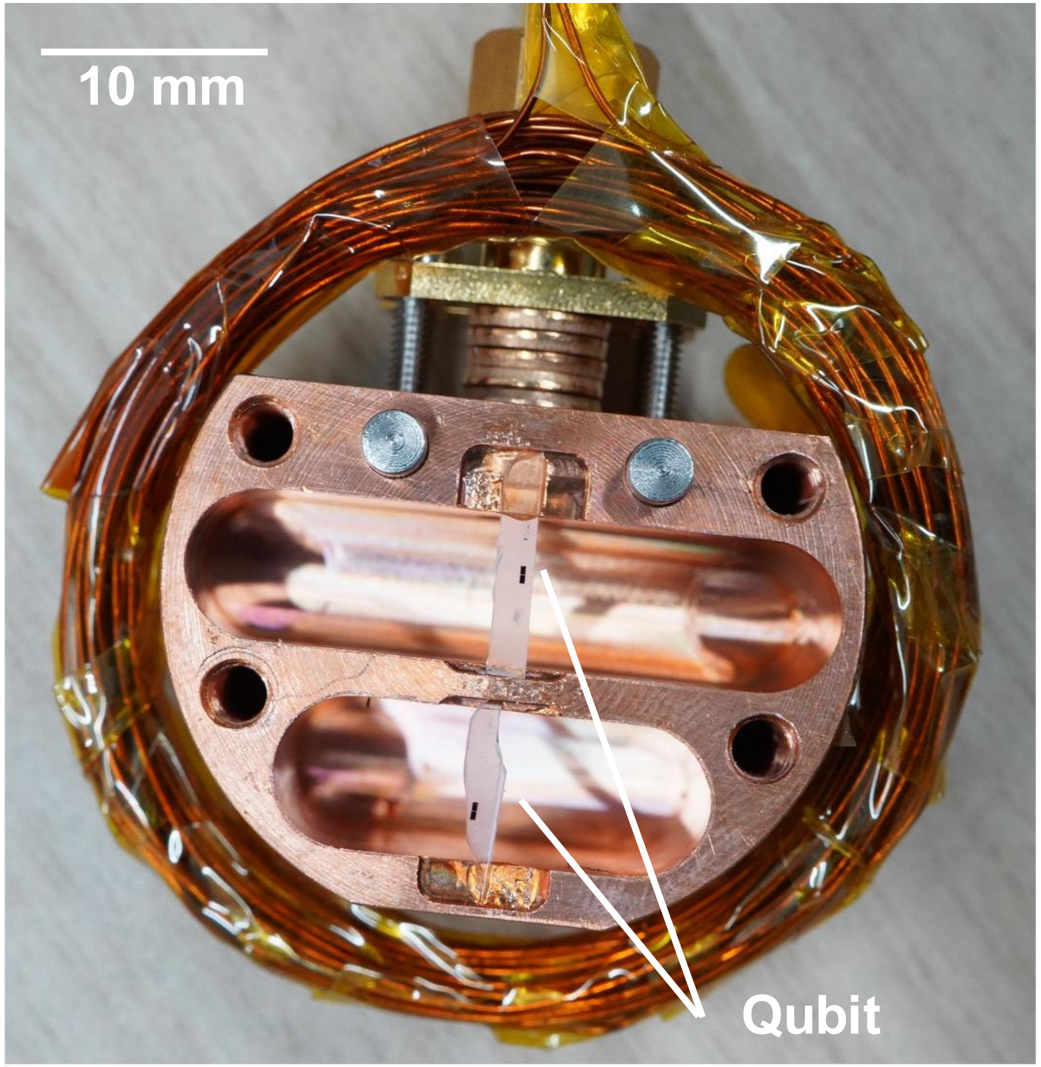




Experiments are performed using facilities of the Cryogenic Research Center, the University of Tokyo.

Dark Photon Search using Superconducting Qubit –Experimental Setup





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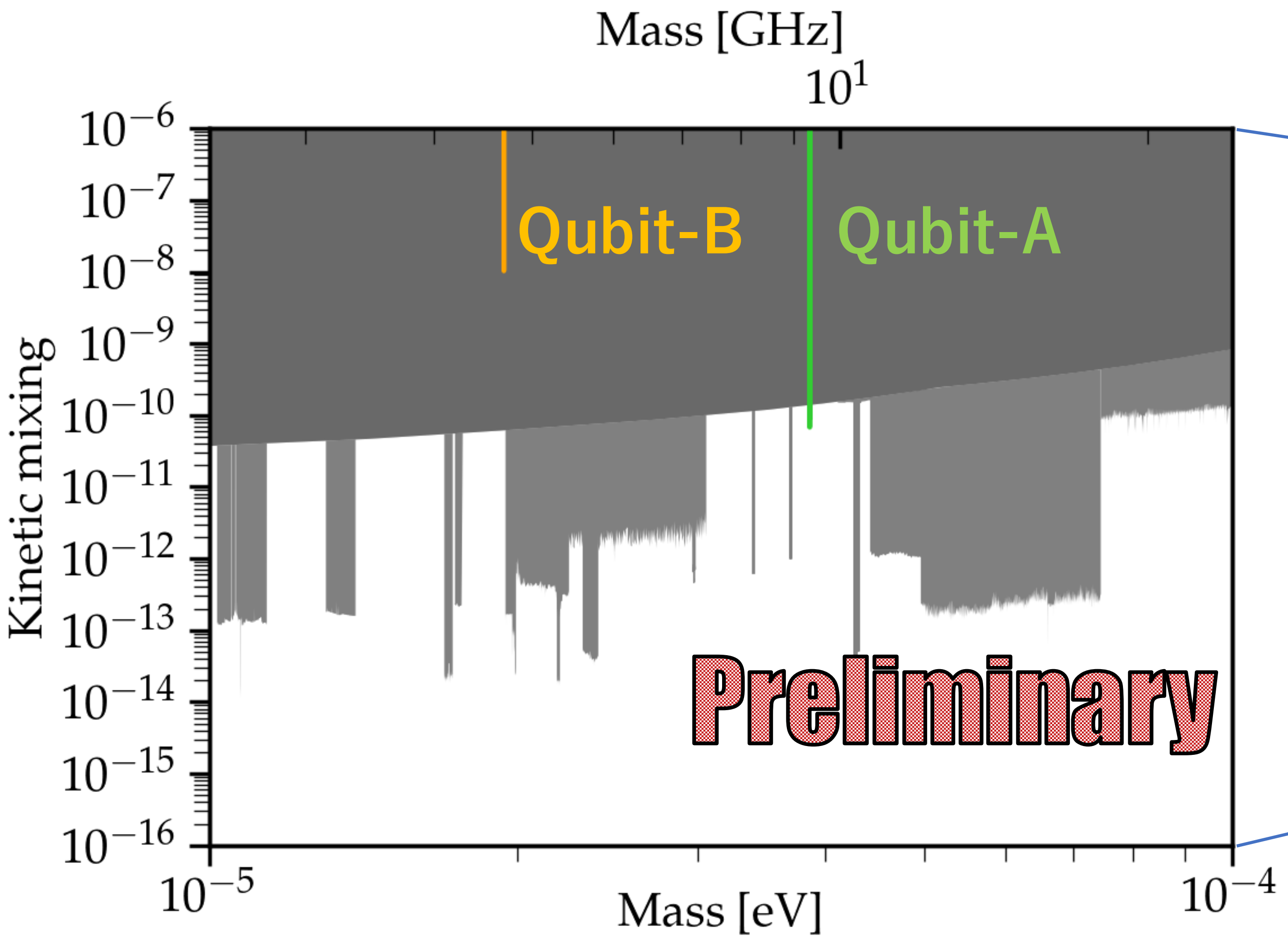
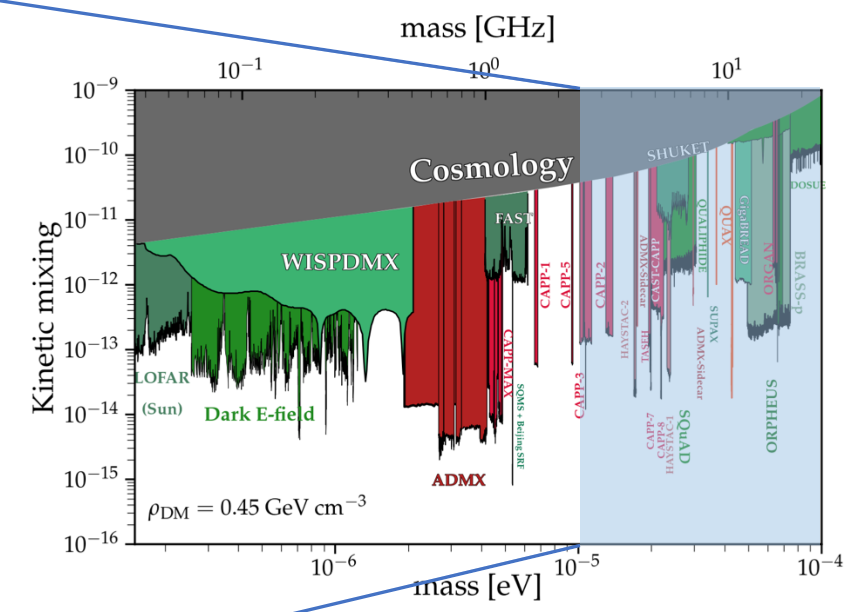
Dark Photon Search using Superconducting Qubit – Demonstration

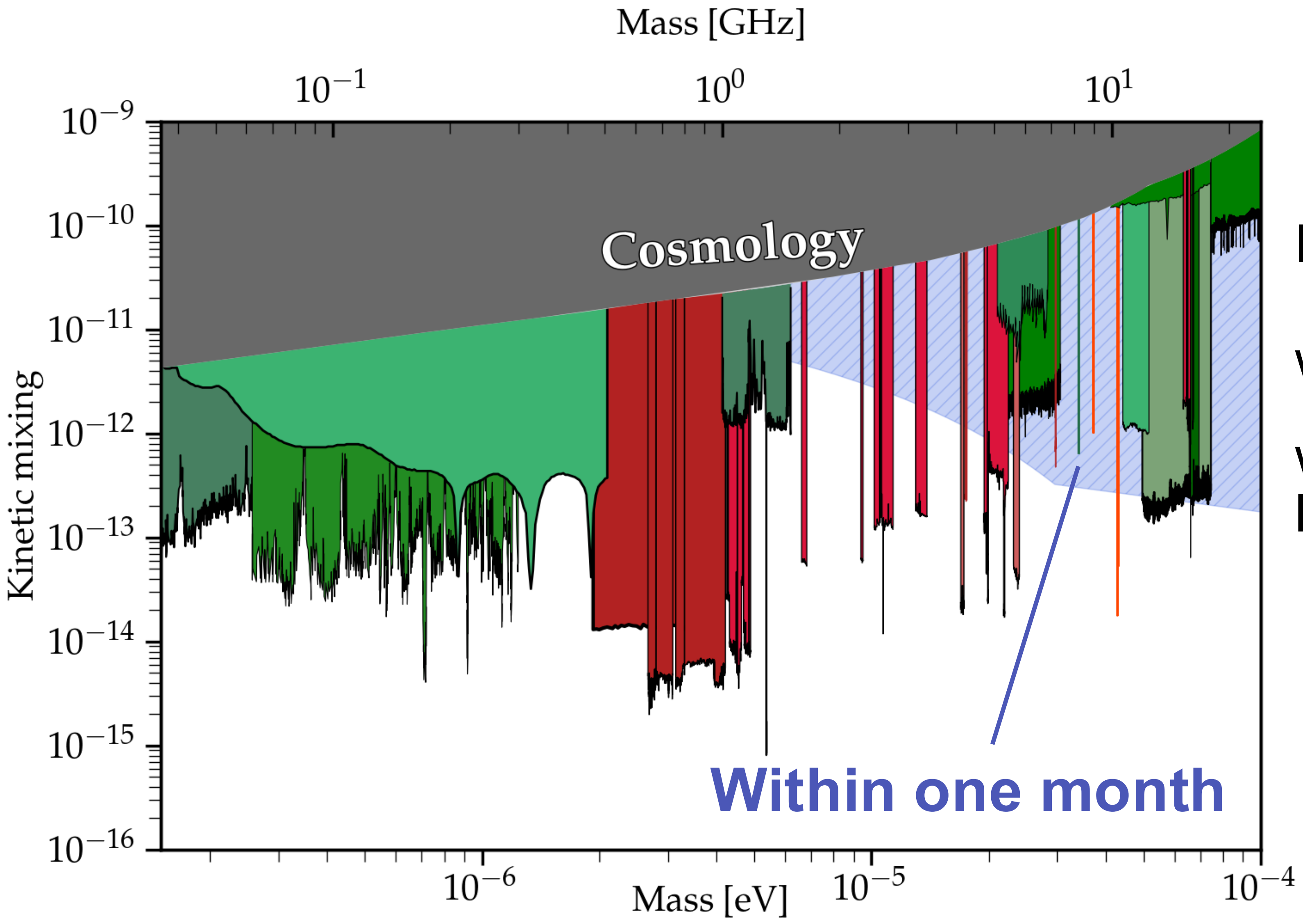
Two 2-night demonstration runs (Qubit-A & Qubit-B)





Exclusion Limit on Kinetic Mixing ϵ (90% C.L.)

Dark Photon Search using Superconducting Qubit – Future Search



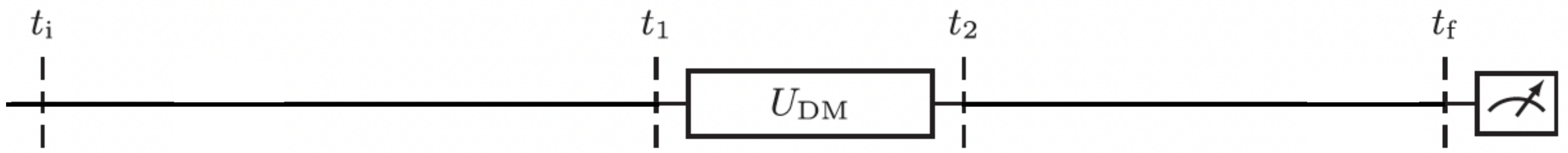
Enabling **wide-range** search

within a **practical time**

with sensitivity
beyond the cosmological limits

Dark Photon Search using Superconducting Qubit – Next Stage

Sensitivity enhancement via entanglement

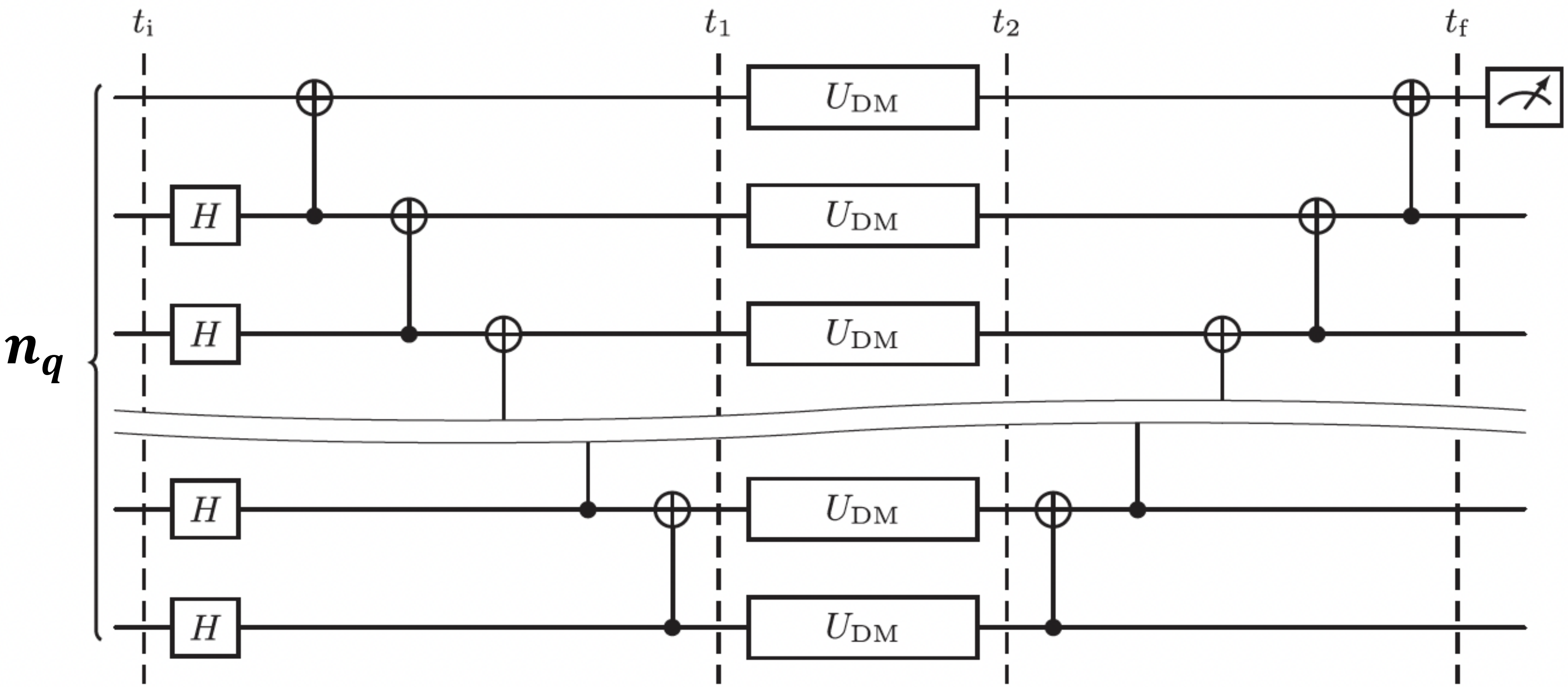


$\times\ \boldsymbol{n_q}$

Independent qubits: signal $\propto$ number of qubits (n_q)

Dark Photon Search using Superconducting Qubit – Next Stage

Sensitivity enhancement via entanglement



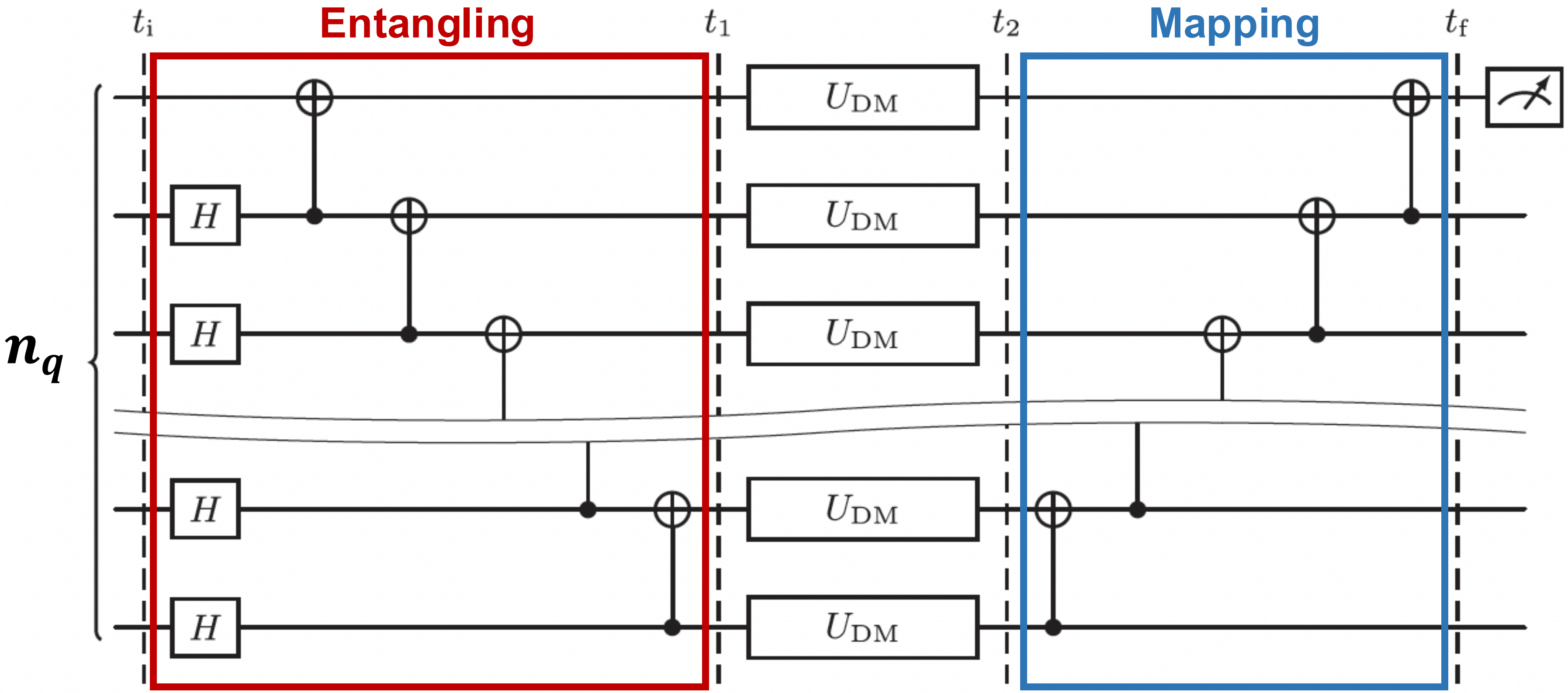
Independent qubits: signal ∝ number of qubits (n_q)

Entangled qubits: signal ∝ $\boldsymbol{n_q^2}$

S. Chen et al., PRL 133 (2), 021801 (2024).

Dark Photon Search using Superconducting Qubit – Next Stage

Sensitivity enhancement via entanglement



Independent qubits: signal ∝ number of qubits (n_q)

Entangled qubits: signal ∝ n_q^2

S. Chen et al., PRL 133 (2), 021801 (2024).

Conclusion

- Developed a new search method using superconducting qubits as ultra-sensitive electromagnetic field sensors, enabling wide-range dark photon searches with sensitivity beyond the cosmological limit.
  — impractical with conventional techniques.

- This work greatly benefited from our collaboration with OIST.

- Particle physics applications of quantum technology are still in their early stages.

- Continuing to explore how quantum technology can bring breakthroughs in other areas of physics will be exciting.

Acknowledgement

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- Members of the Cryogenic Quantum Platform, Cryogenic Science Center, University of Tokyo
  Hiroshi Fukuyama, Ryo Toda

  …Experiments using the dilution refrigerator were performed using facilities of the Cryogenic Research Center, the University of Tokyo.
- Prototype Laboratory, Department of Physics, Faculty of Science, University of Tokyo
  Shigemi Otsuka, Togo Shimozawa
- Members of the Superconducting Quantum Circuit Prototyping Facility, National Institute of Advanced Industrial Science and Technology
- École polytechnique fédérale de Lausanne
  Shingo Kono