A workshop on the Frontier of Particle Physics: Exploring Muons, Quantum Science and the Cosmos at Kyoto

Progress of DarQ experiments

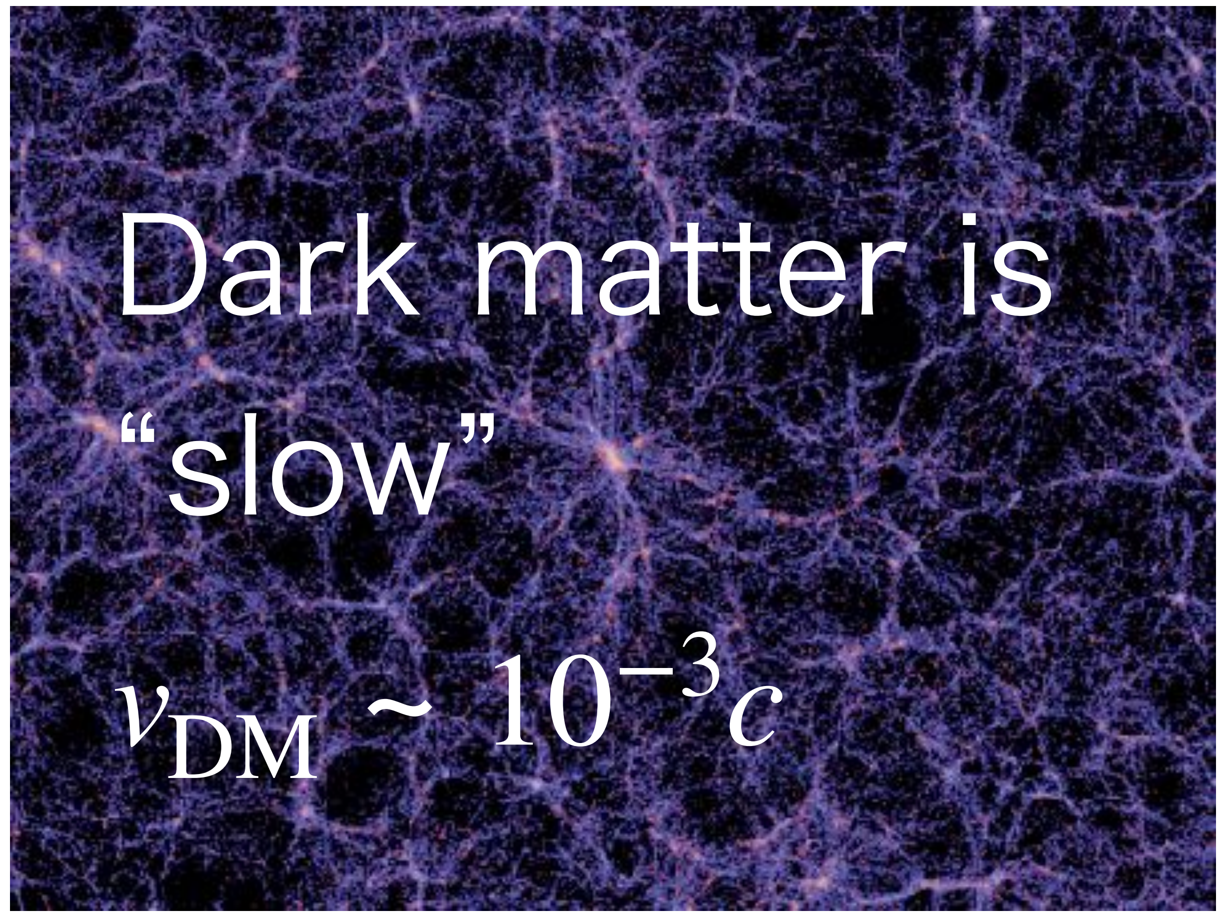
June 16, 2025

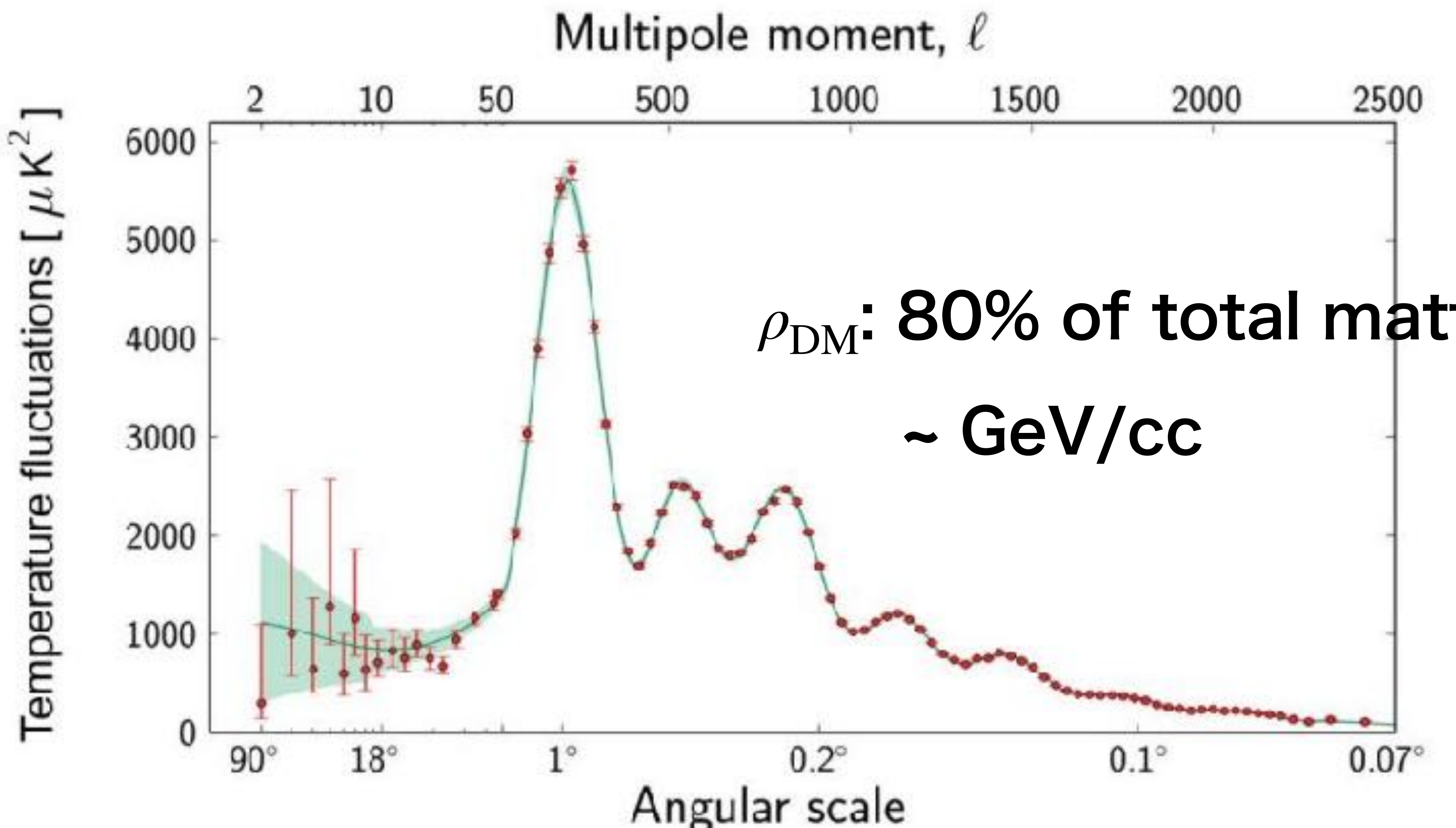
KEK, QUP
Tatsumi Nitta

Wavelike Dark Matter (DM)

Most of physicists believe

Dark Matter Exists!



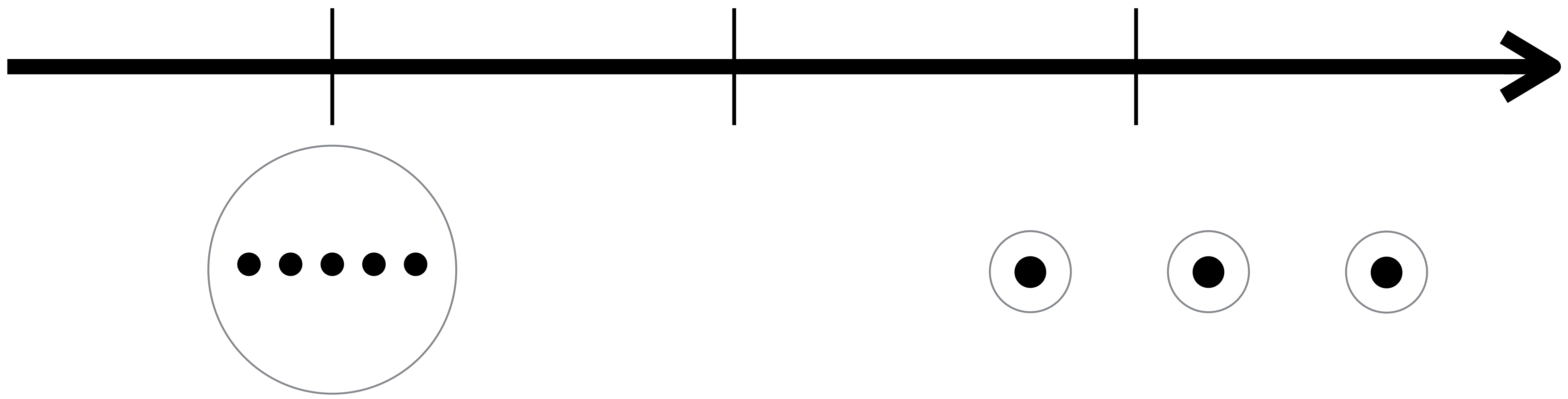


ρ_{DM}: 80% of total matter

~ GeV/cc

But… mass of DM is totally unknown

10^{-6}eV (μeV) 1 10^{12}eV(TeV) m



$d_{\text{nearest neighbor}} \ll \lambda_{\text{de Broglie}} \sim 100$ m

$d_{\text{nearest neighbor}} \gg \lambda_{\text{de Broglie}} \sim 0.1$ nm

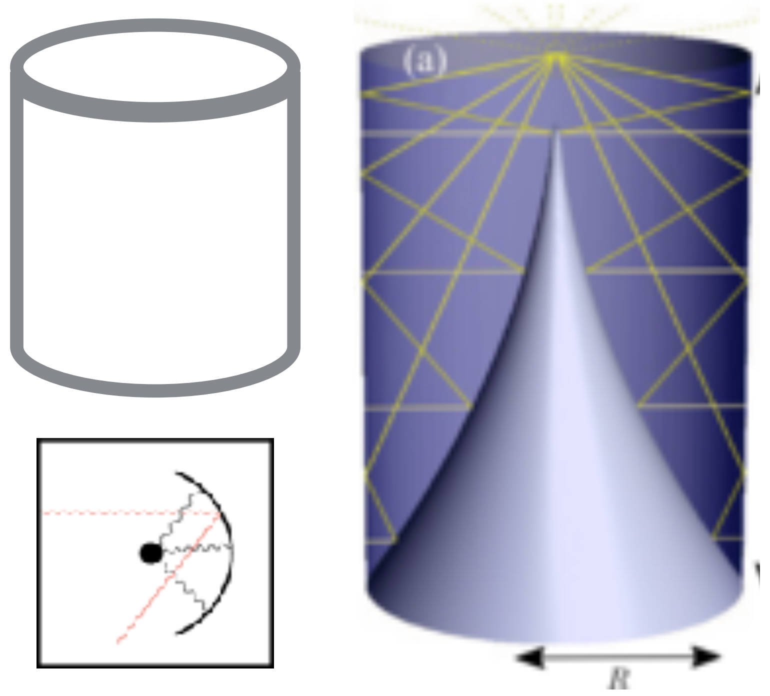
Wavelike DM

- Axion
- Dark Photon etc

Particle-like DM

- WIMP etc

Standard Detection Method

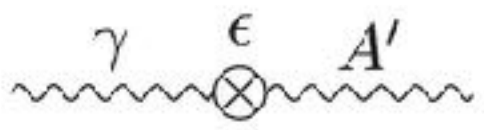


1. put a converter on the Earth

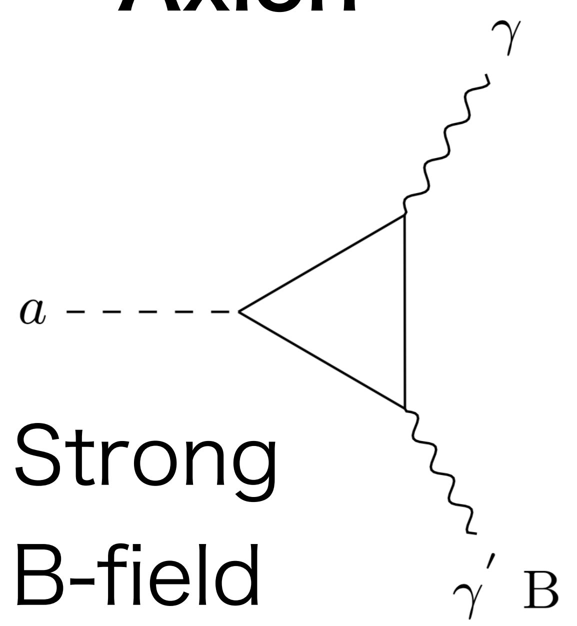
Metal surface
- Cavity
- Dish antenna

2. DM -> photon conversion

Dark Photon



Axion



Strong B-field is needed

This process happens continuously

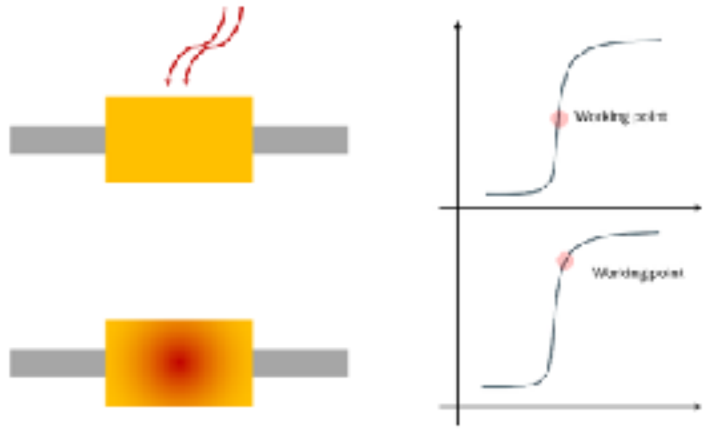
3. photon detection

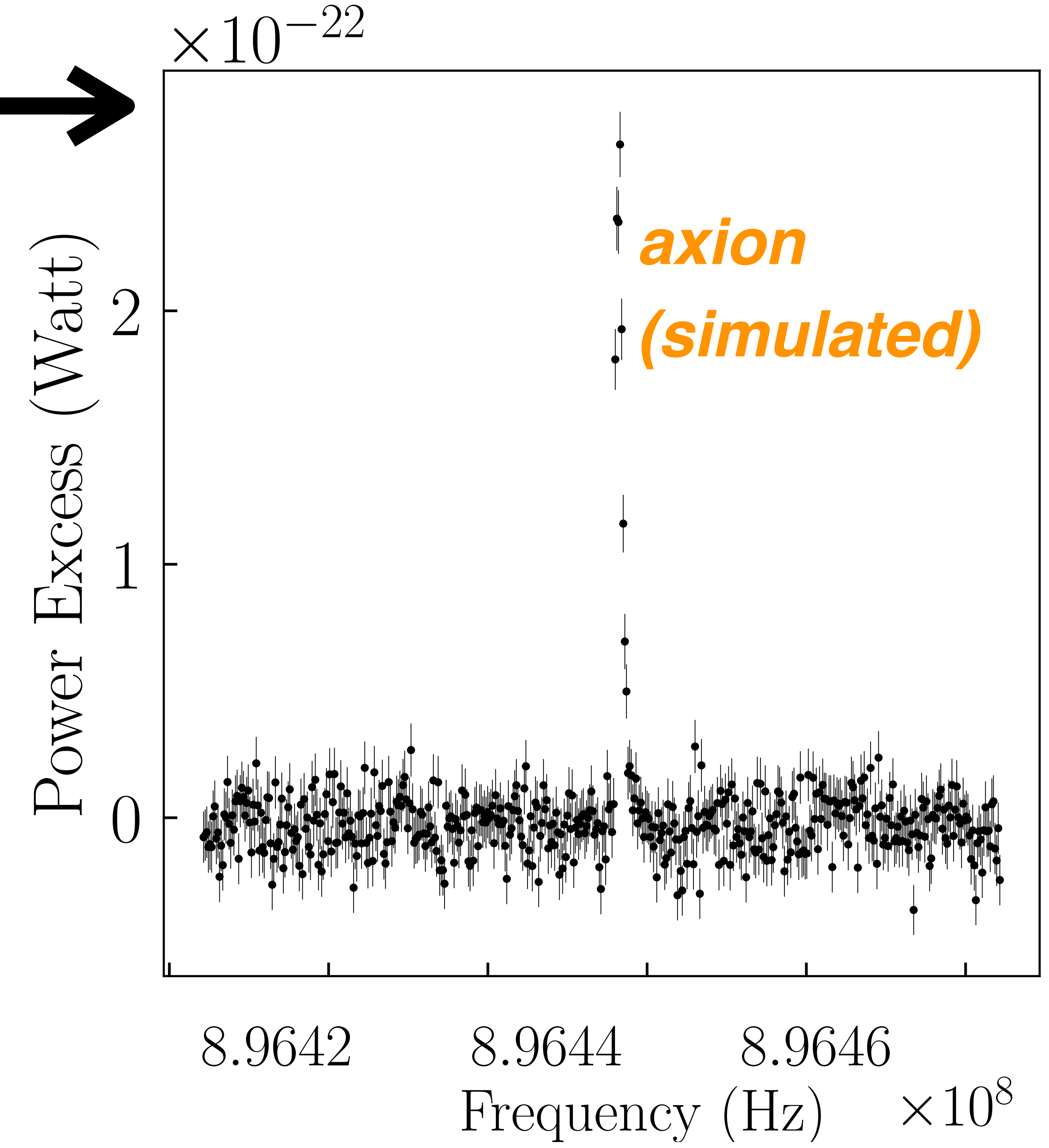
Detector → Amplifier →

Antenna

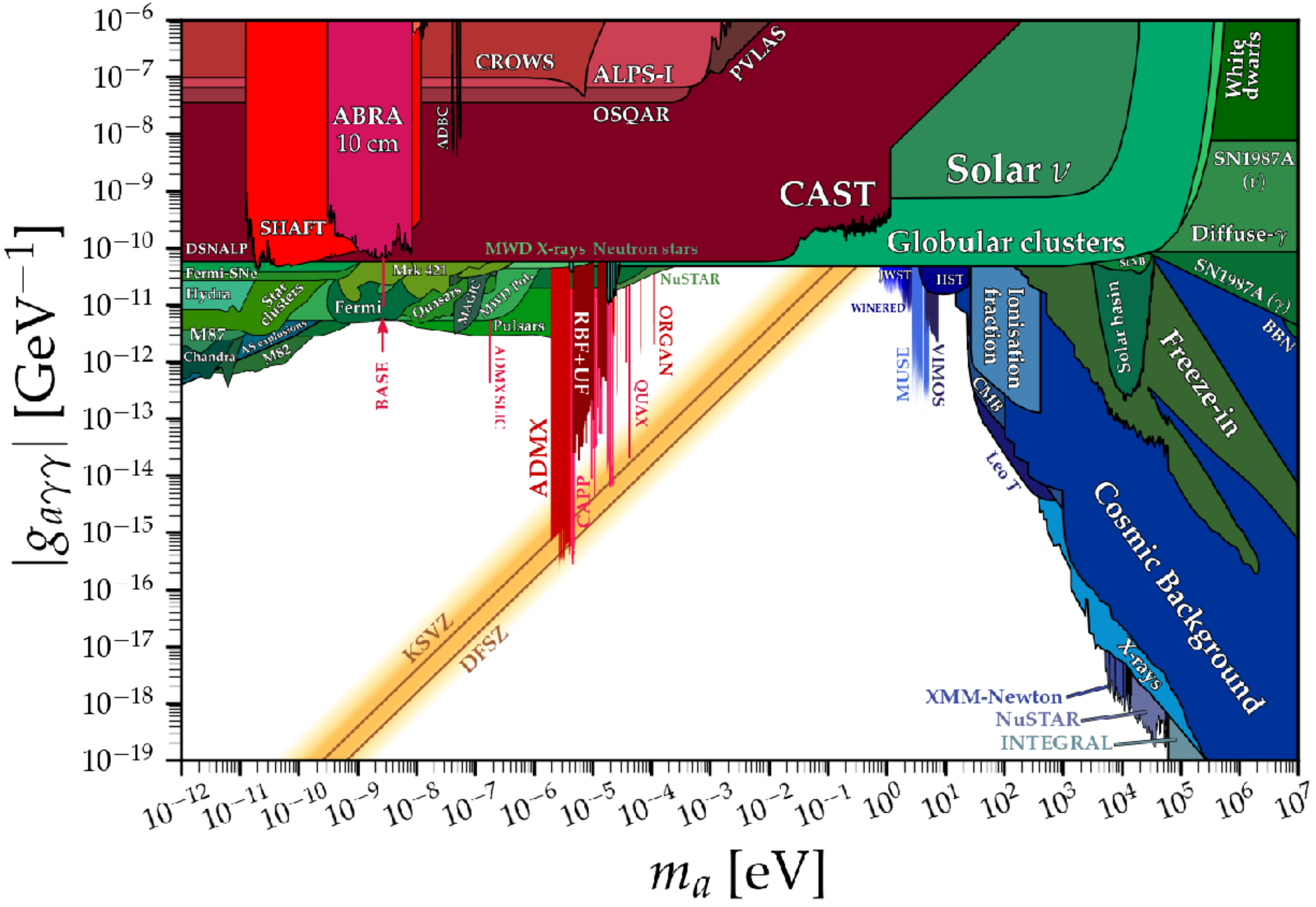
Quantum Amplifier

HEMT





Axion Hunting So Far



DFSZ sensitivity
- ADMX
- CAPP

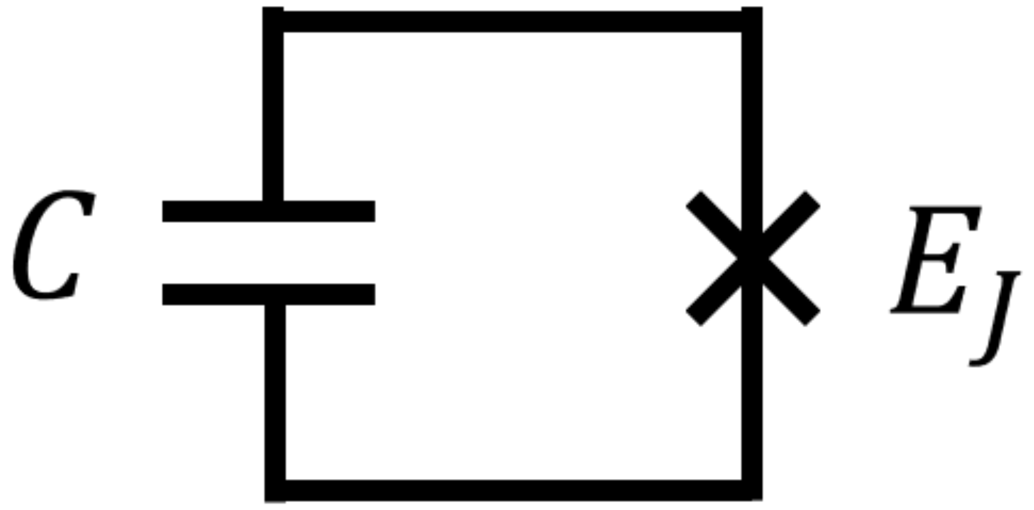
→ Probability of discovery is too low, so far

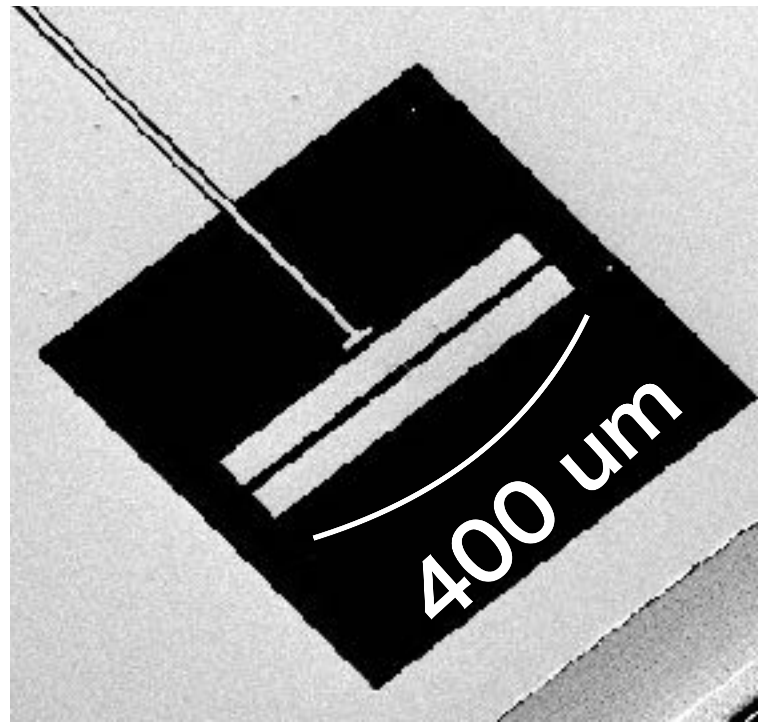
Big money (huge magnet etc) “partially” solves problems

New ideas and technologies are necessary for discovery

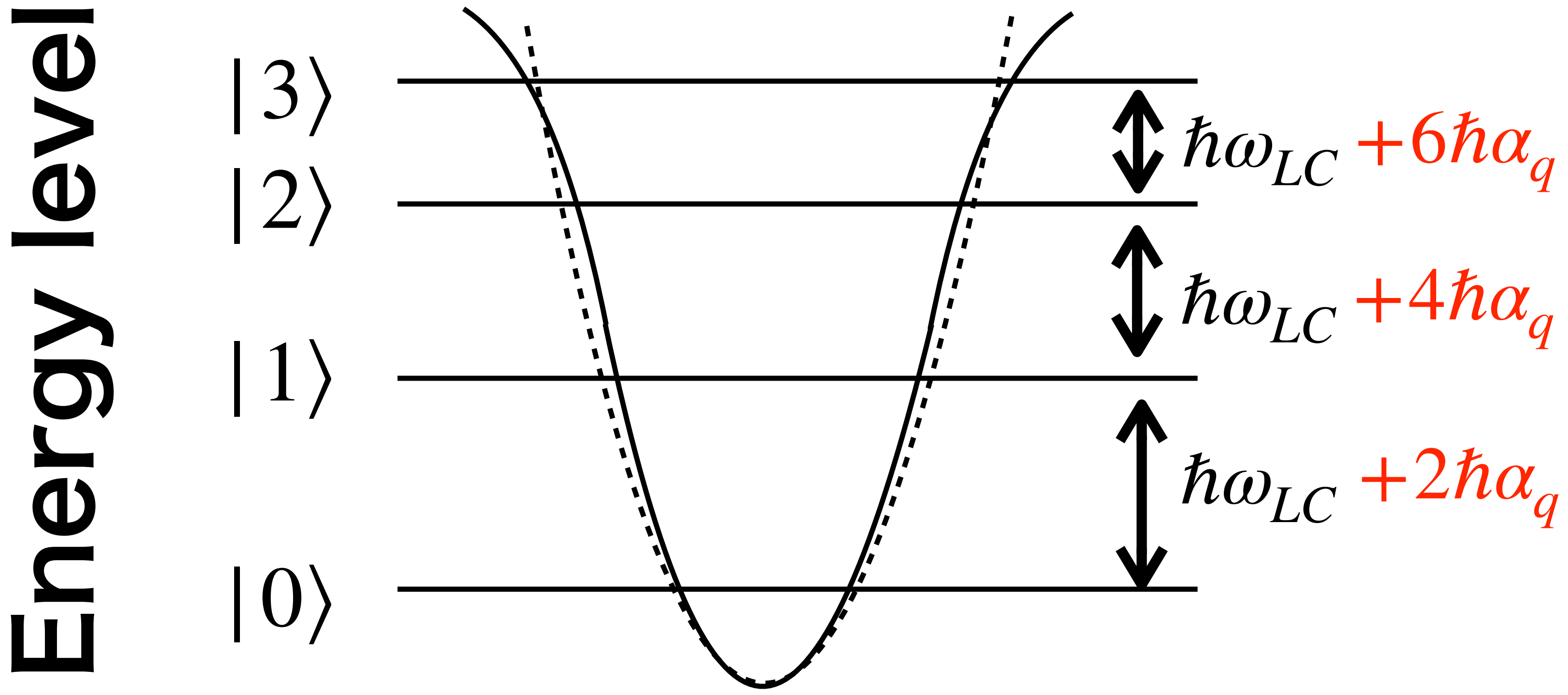
We are investigating possibilities of **superconducting qubits**

Superconducting Qubits





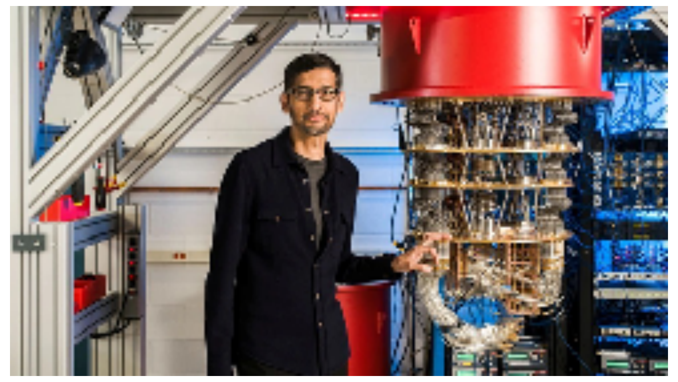
<u>Good points as DM sensor</u>



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

manipulatable

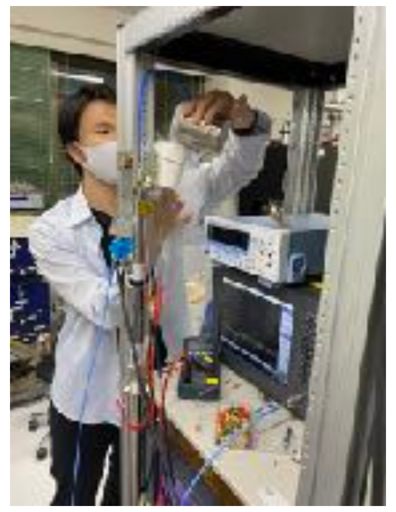
→ quantum computer



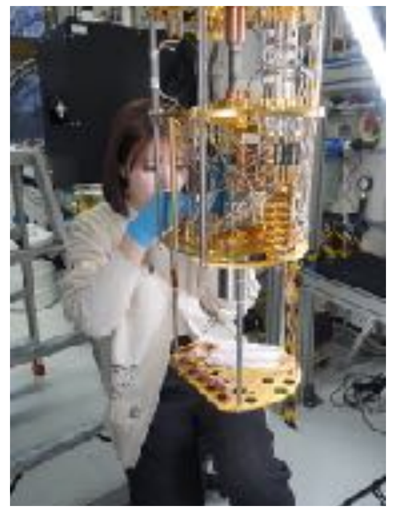
- **Large Electric Dipole Moment ~** $10^6 \times$ **single atom**
  → Very sensitive to ambient electric field
- $|0\rangle \rightarrow |1\rangle$ **energy ~ GHz ~ μeV**
  → Hot spot of wavelike DM
- **Working at mK temperature**
  → Low fake signals
- **Designable circuit**
  → Any desired sensors can be made
  in principle

DarQ: Dark matter search using Qubits

UTokyo ICEPP


Toshiaki Inada

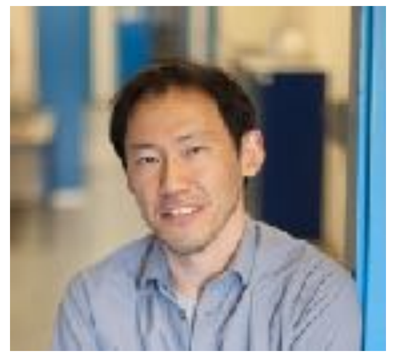

Yuya Mino


Karin Watanabe


Kan Nakazono


Chikara Kawai


Yutaro Iiyama

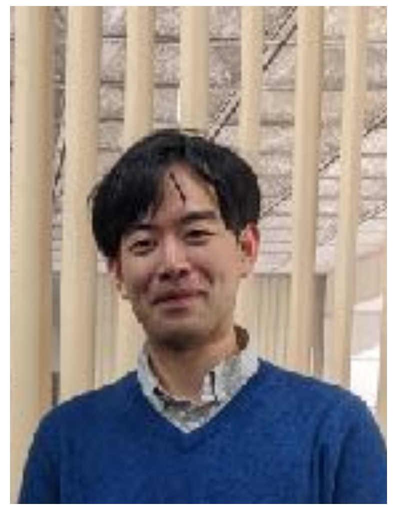

Koji Terashi


Ryu Sawada


Junichi Tanaka

UTokyo Moroi Lab

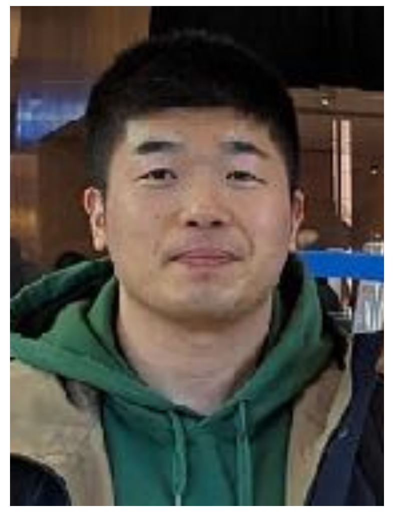

Takeo Moroi


Hajime Fukuda


Thanaporn Sichanugrist

UTokyo Noguchi Lab RIKEN RQC


Atsushi Noguchi


Shotaro Shirai

KyotoU HE Lab


Shion Chen


Tetsuro Nakagawa

KEK QUP

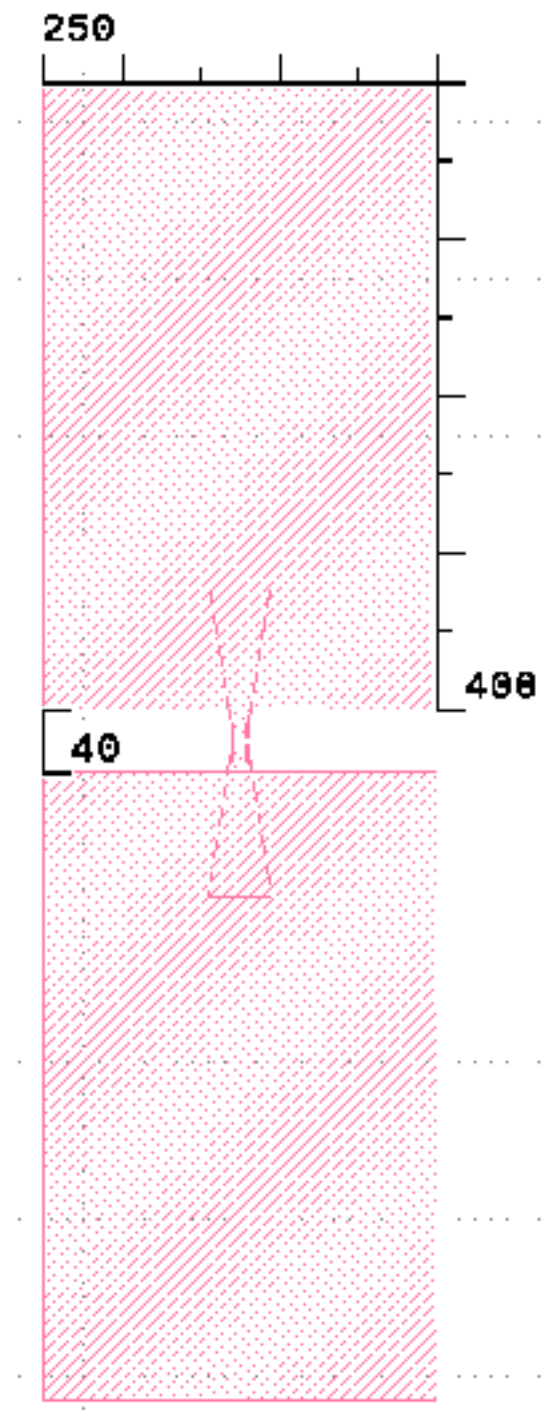
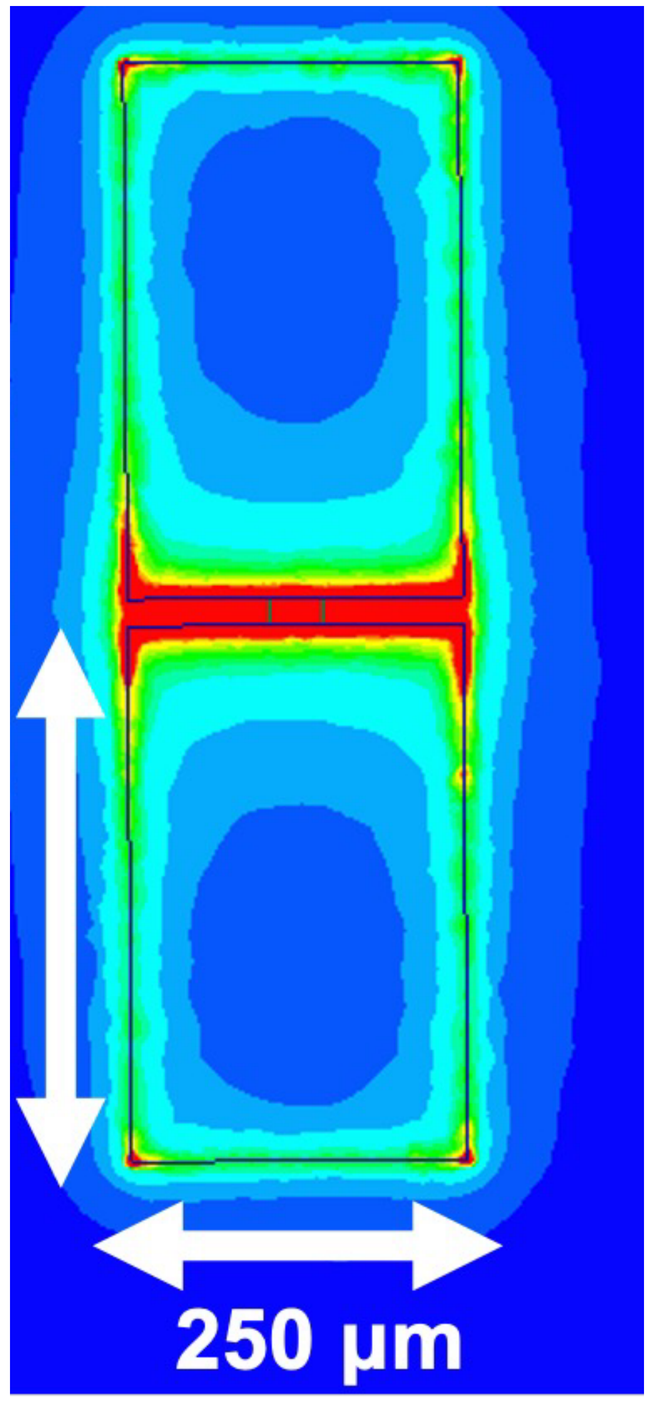
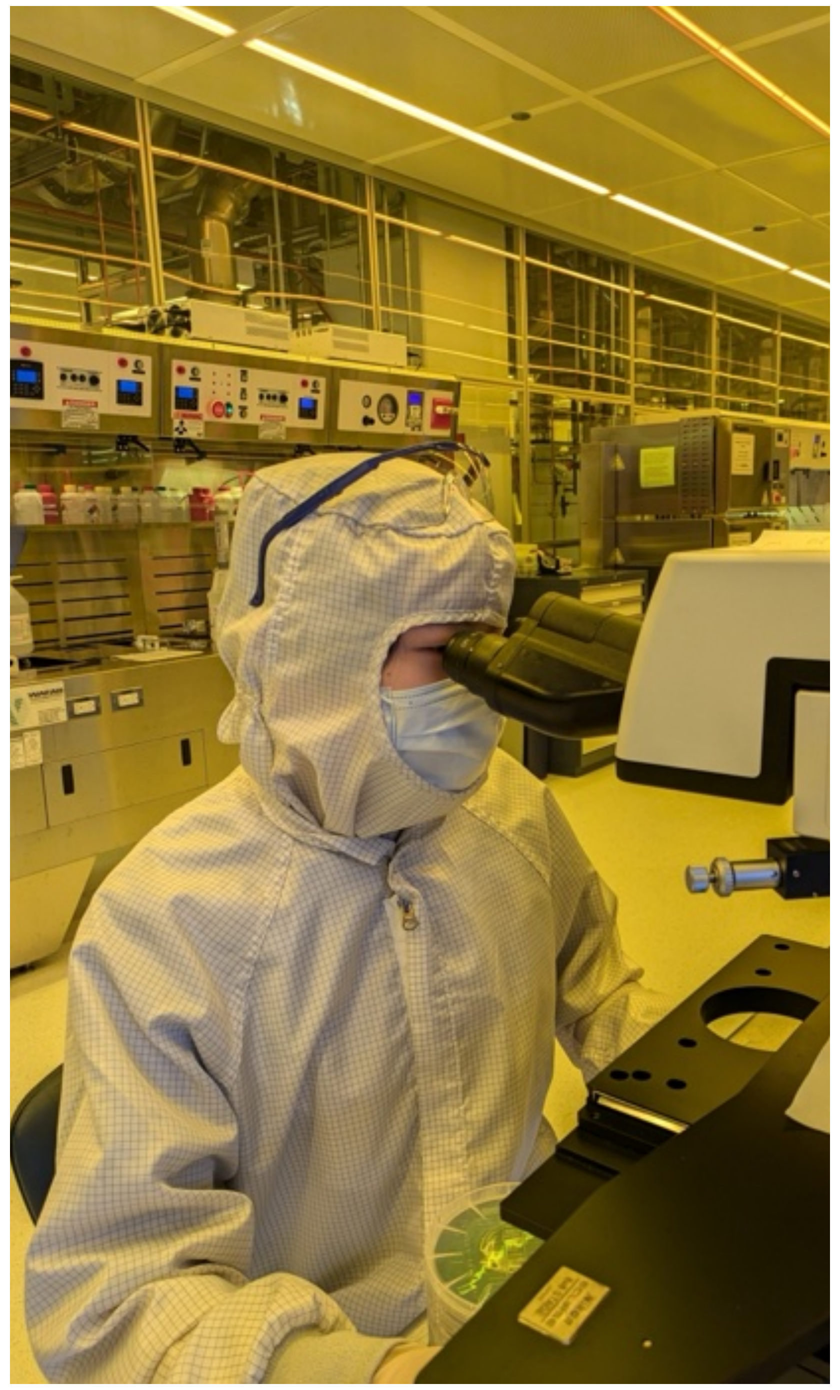
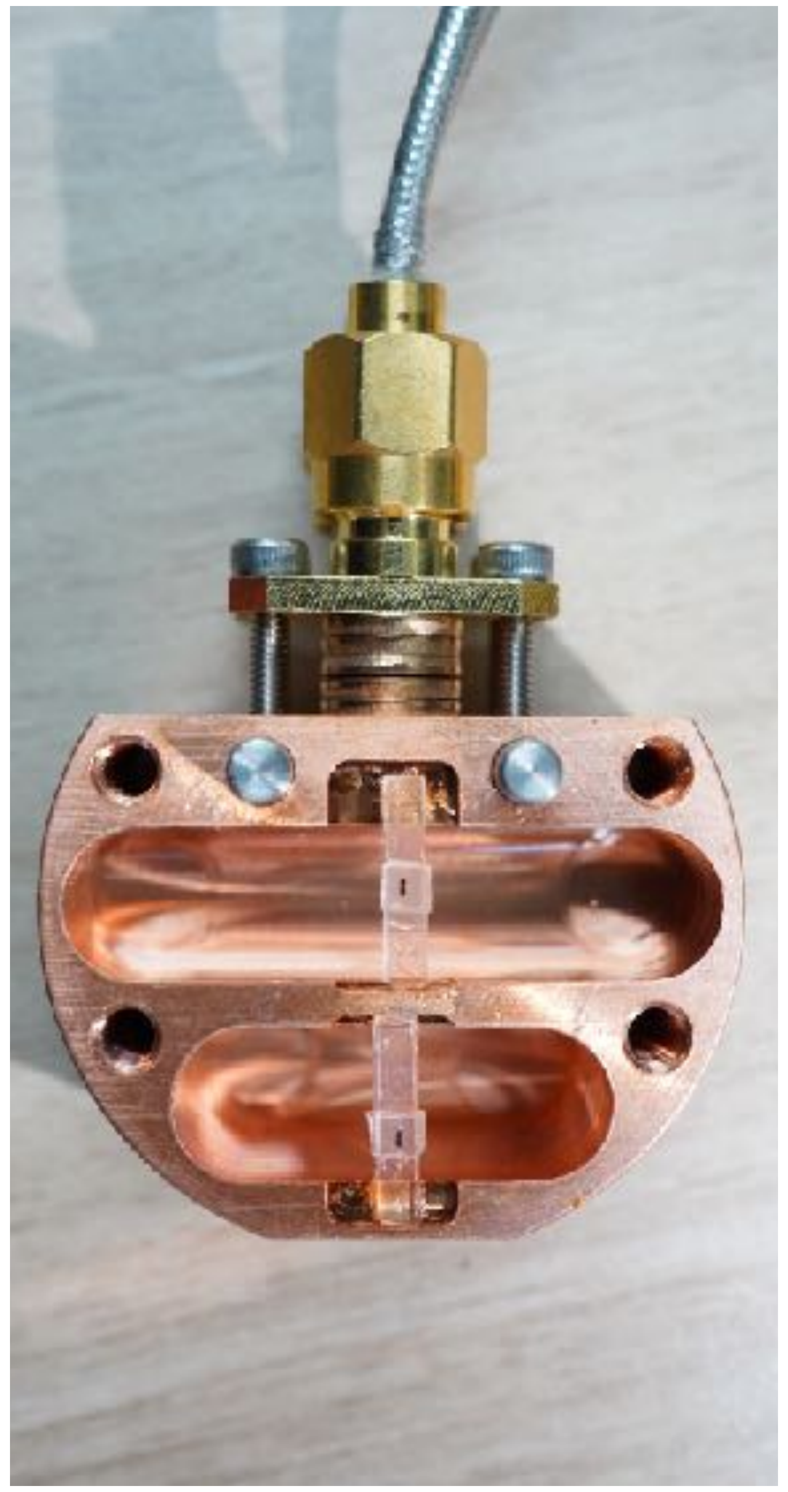
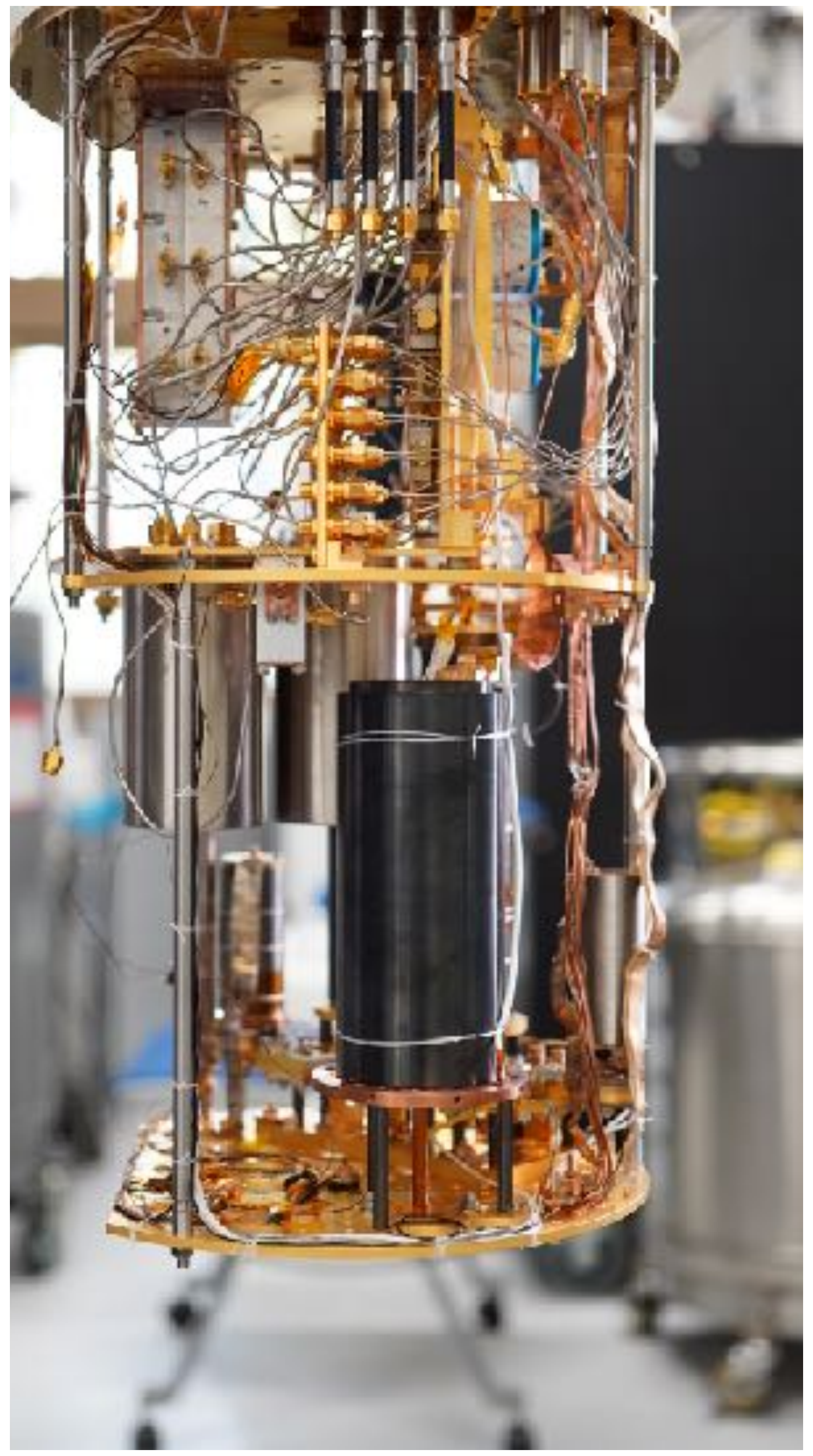

Tatsumi Nitta

UTokyo

Founded at U Tokyo → now expanding (decaying) to several institutes

DarQ homemade qubits

Qubits for **quantum computing** ≠ Qubits for **quantum sensing**

Design	Simulation	Fabrication	Packaging	Measurement
				

Acknowledge to cleanrooms at U Tokyo, Kyoto U, OIST, EPFL, and U Chicago

DarQ experimental site

Current site at U Tokyo

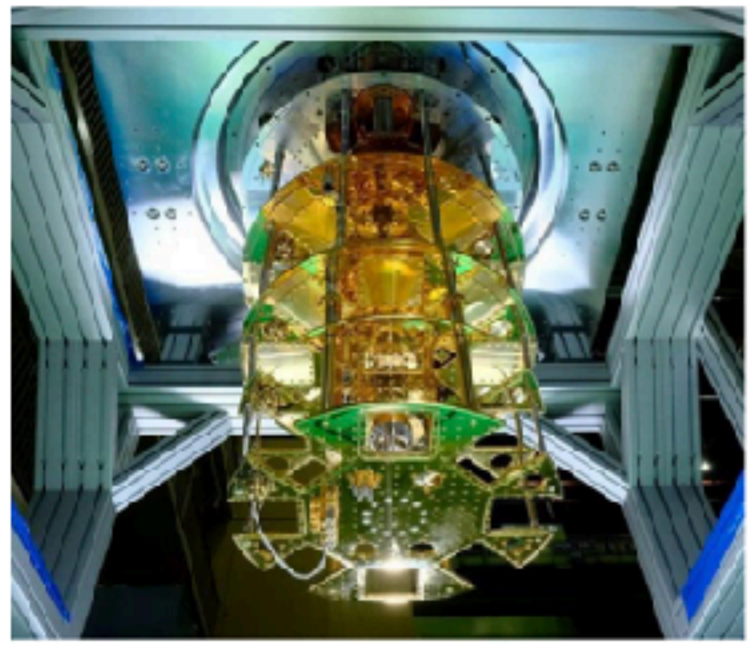
(shared facility)

Now building new experimental setup at QUP

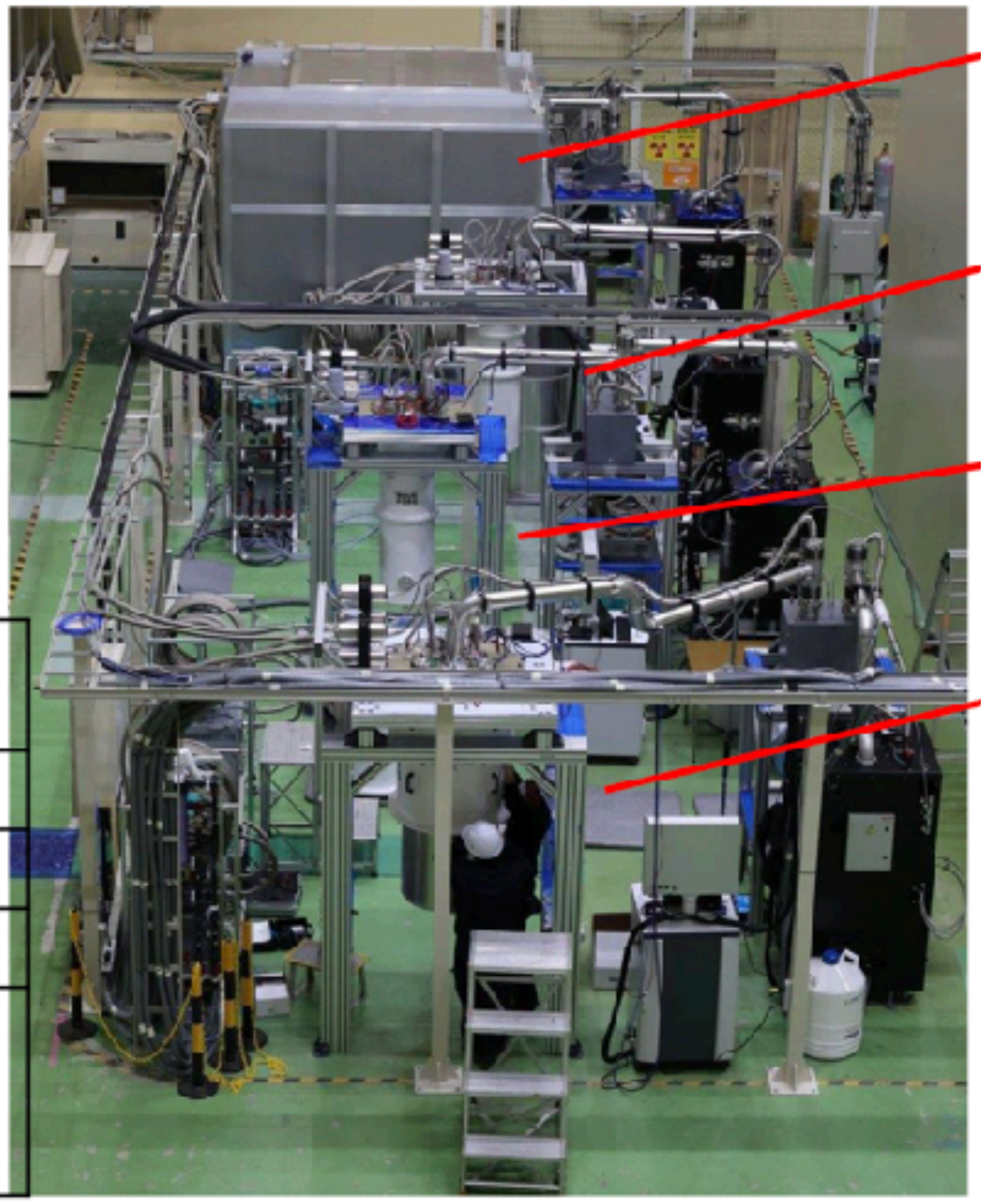
- 3 times larger fridge
- **DarQ is the primary user**
- Complete set of equipments will be delivered in December

  → We will conduct a O(month) period of data-taking

Cryo-Facility @Fuji Hall (B4)



^{3}He-^{4}He dilution cooler BlueFors XLD/LD400	
Base temp.	<10mK
Cooling power	500μW @0.1K
Cables	DC/RF
Available options	Anti vibration stage He. battery Optical window etc…



We are forming strong collaboration, elaborated fabrication recipe, and permanent experimental site

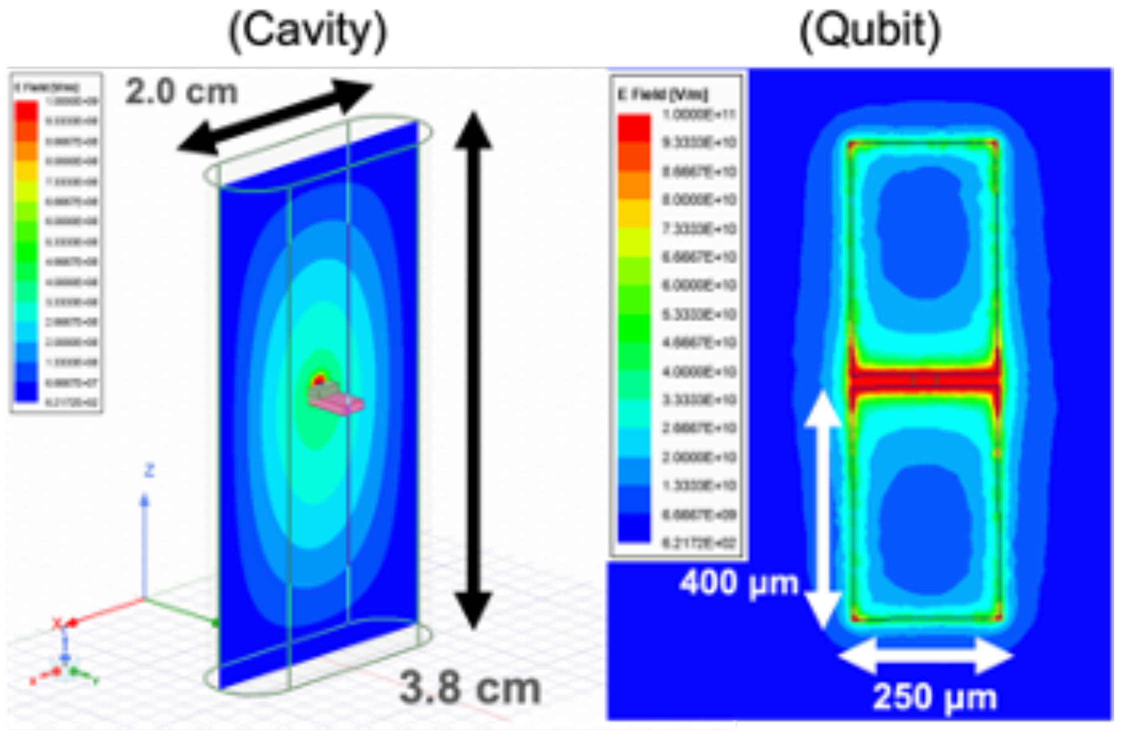
DarQ experiments

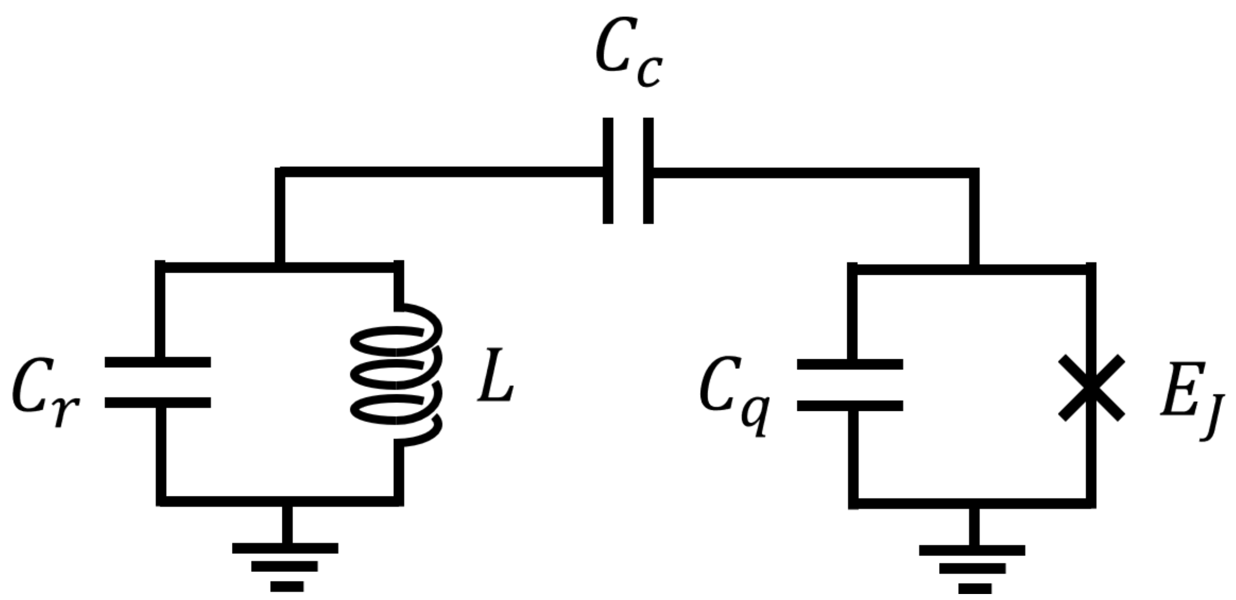
DarQ-Lamb

As cavity tuner

Zhao+ arXiv 2501.06882

Nakazono+ arXiv 2505.15619



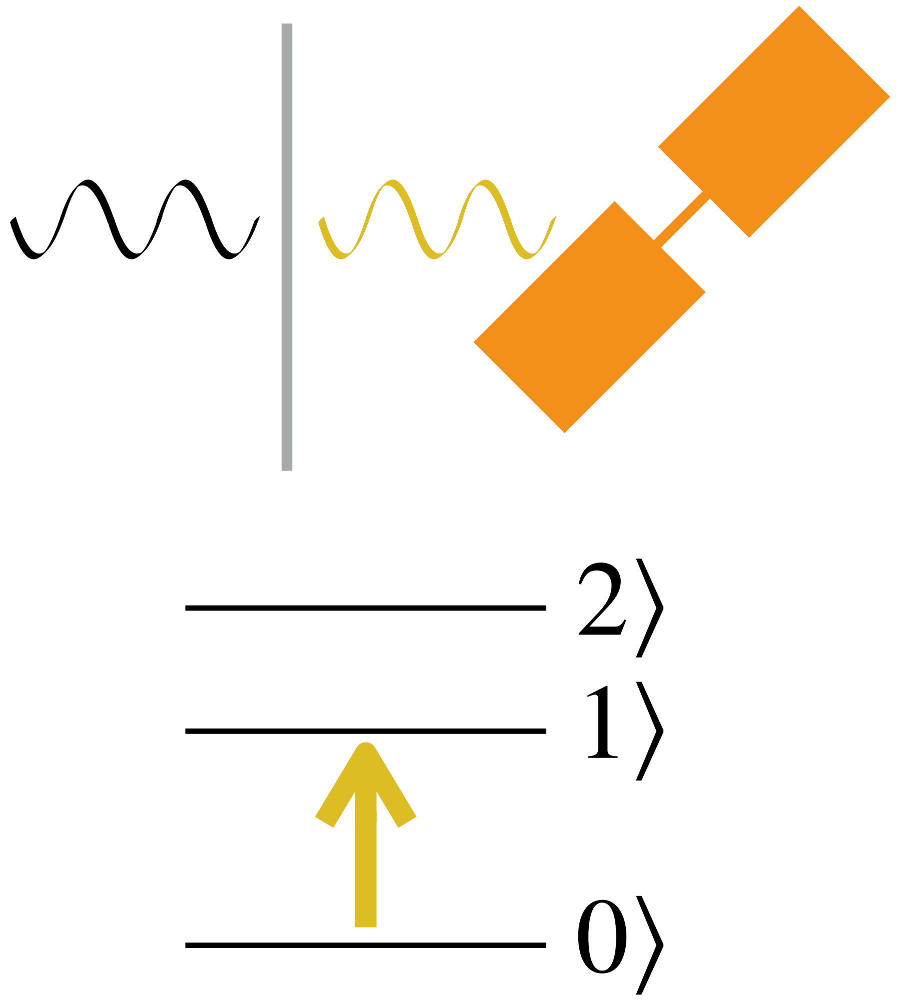


DarQ-Direct

As DM antenna

Moroi+ PRL **131**, 211001
Thanaporn+ PRL **133**, 021801
Thanaporn+ PRD **110**, 115021

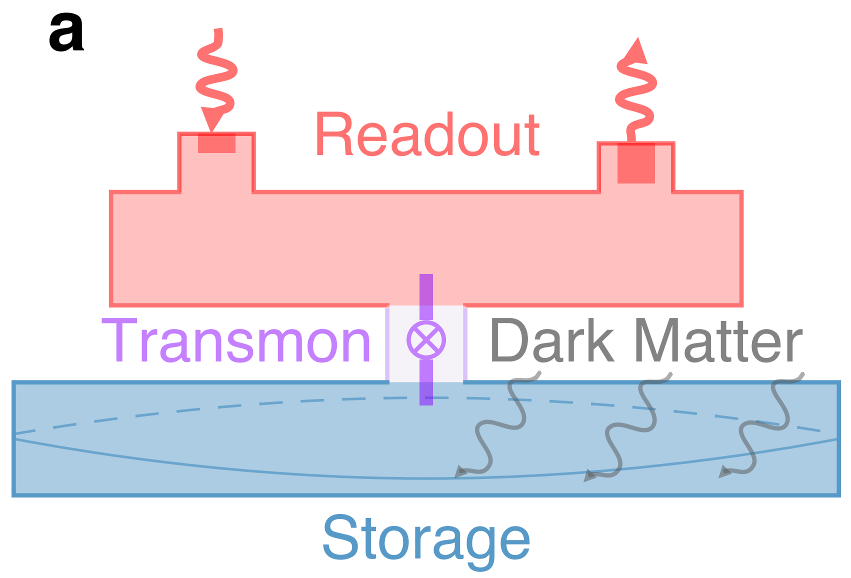
Watanabe+ Patras 2024
Kang+ arXiv 2503.18315

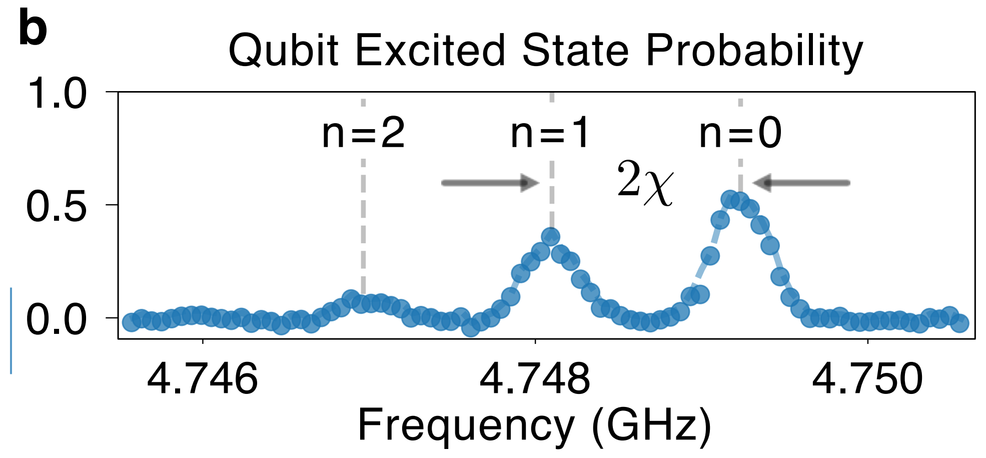


DarQ-SPC

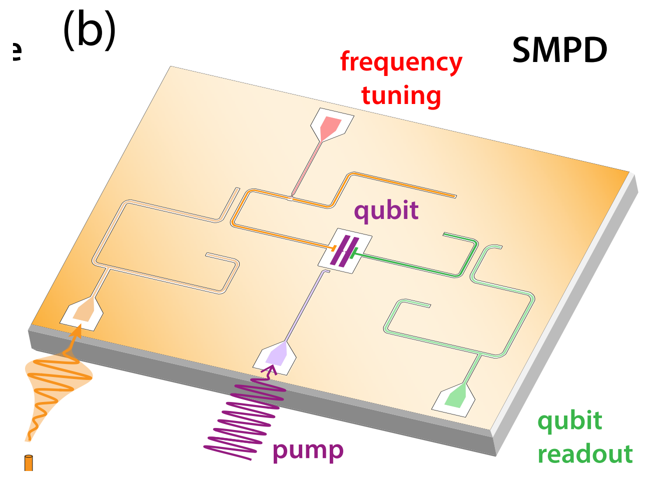
As microwave single photon counter

Dixit+ PRL **126** 141302
Agrawal+ PRL **132** 140801
Zhao+ arXiv 2501.06882

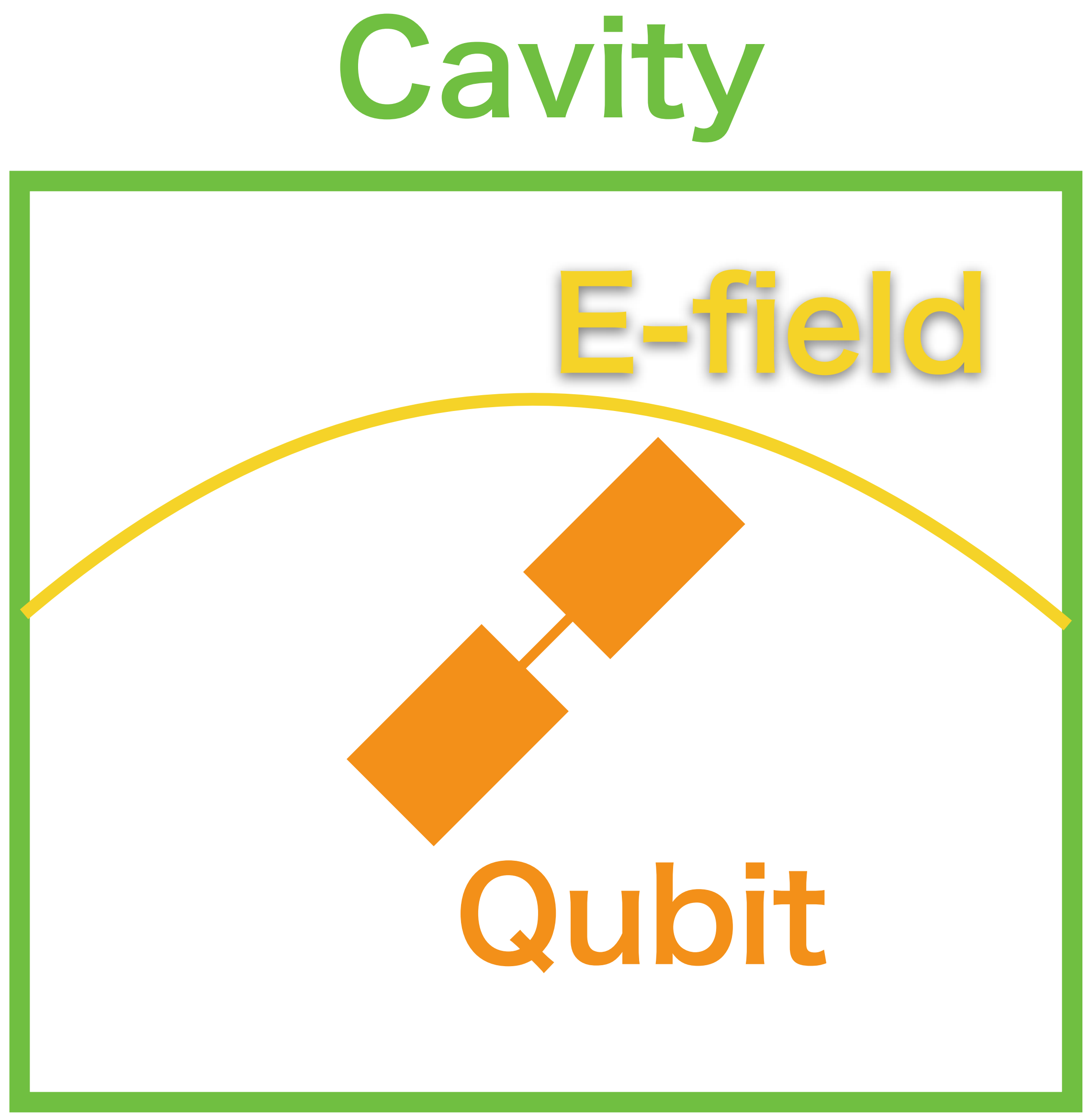




Braggio+ arXiv 2403.02321



DarQ-Lamb idea

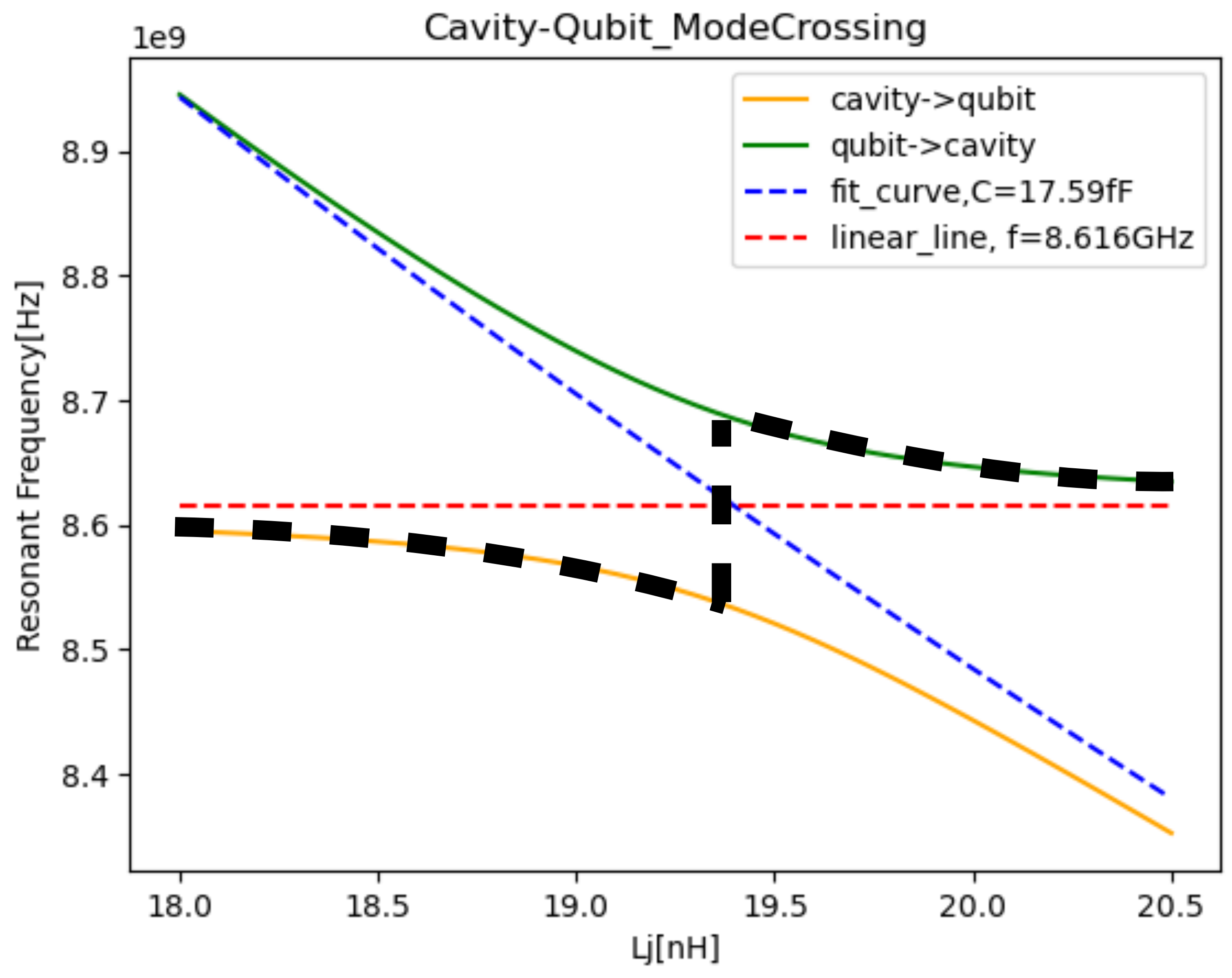


Qubit | Cavity | Interaction

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

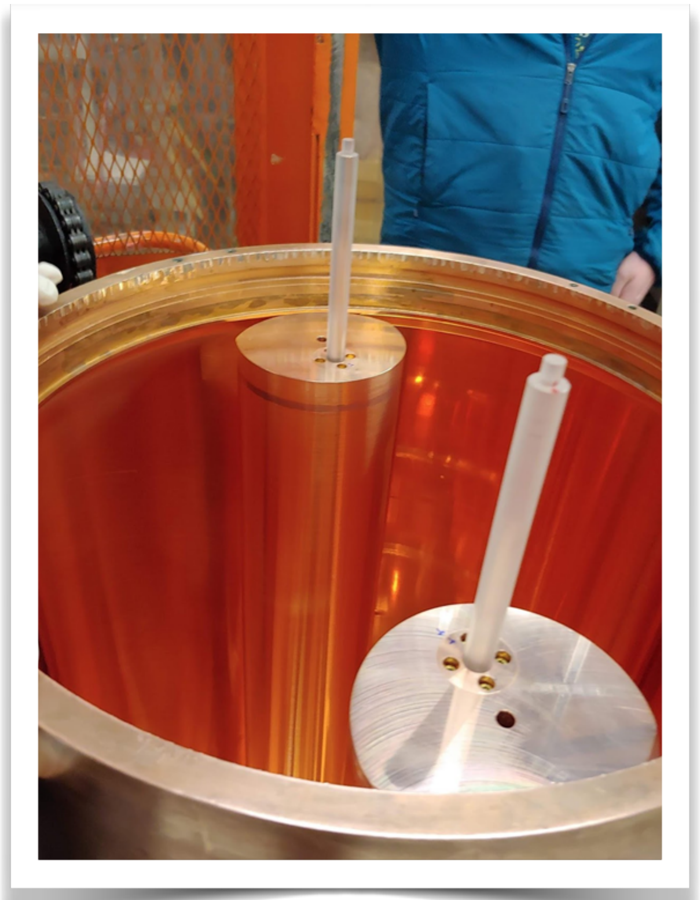
$$\mathscr{H}/\hbar = \left(\omega_c + g^2/\Delta\right)\sigma_z/2 + \left(\omega_q + g^2/\Delta\sigma_z\right)a^\dagger a$$

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



conventional tuning

- Friction heat
- Additional Mechanical parts
- Take care of EM leakage

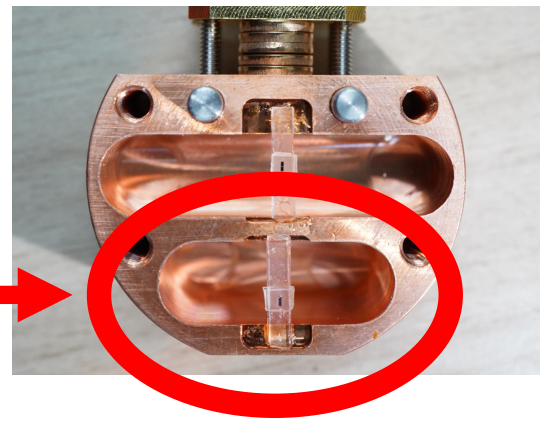


qubit tuning

- No heating
- Only qubit and coil
- No physical connection to outside

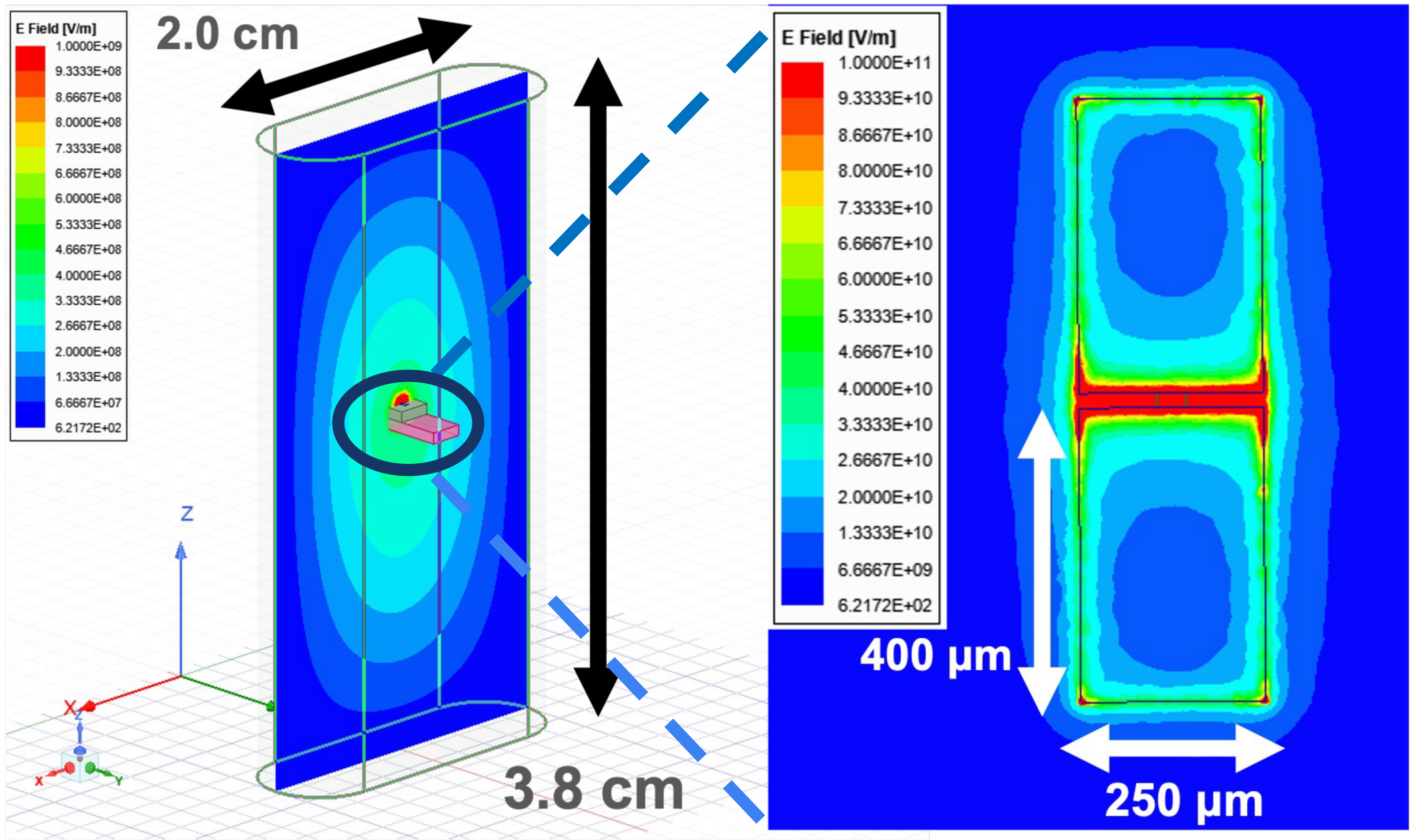
Simulation of the tuning

<u>The same design and material of the actual cavity and qubit</u>



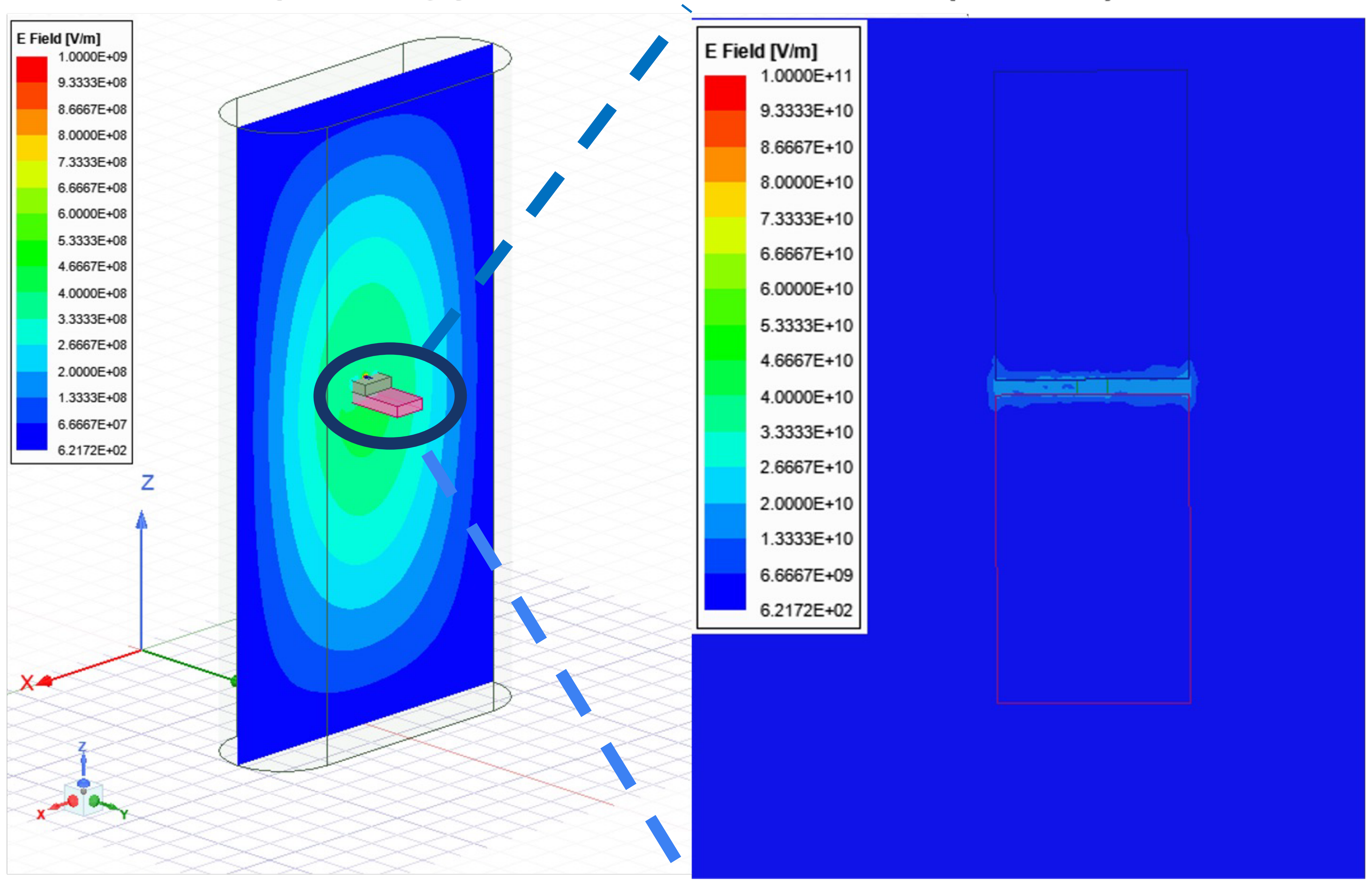
here!

(Cavity) (Qubit)



Interaction Maximum

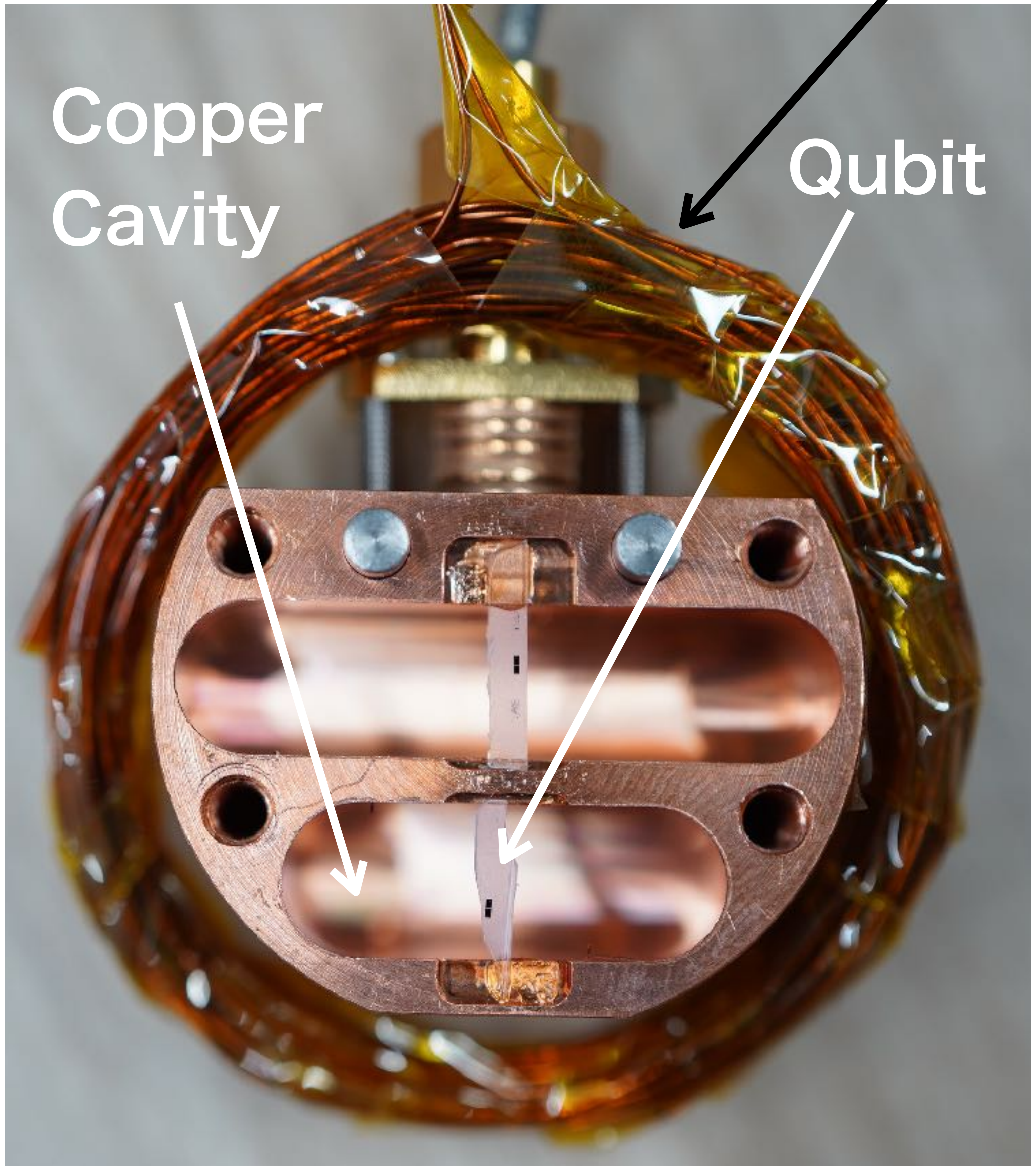
(Cavity) (Qubit)

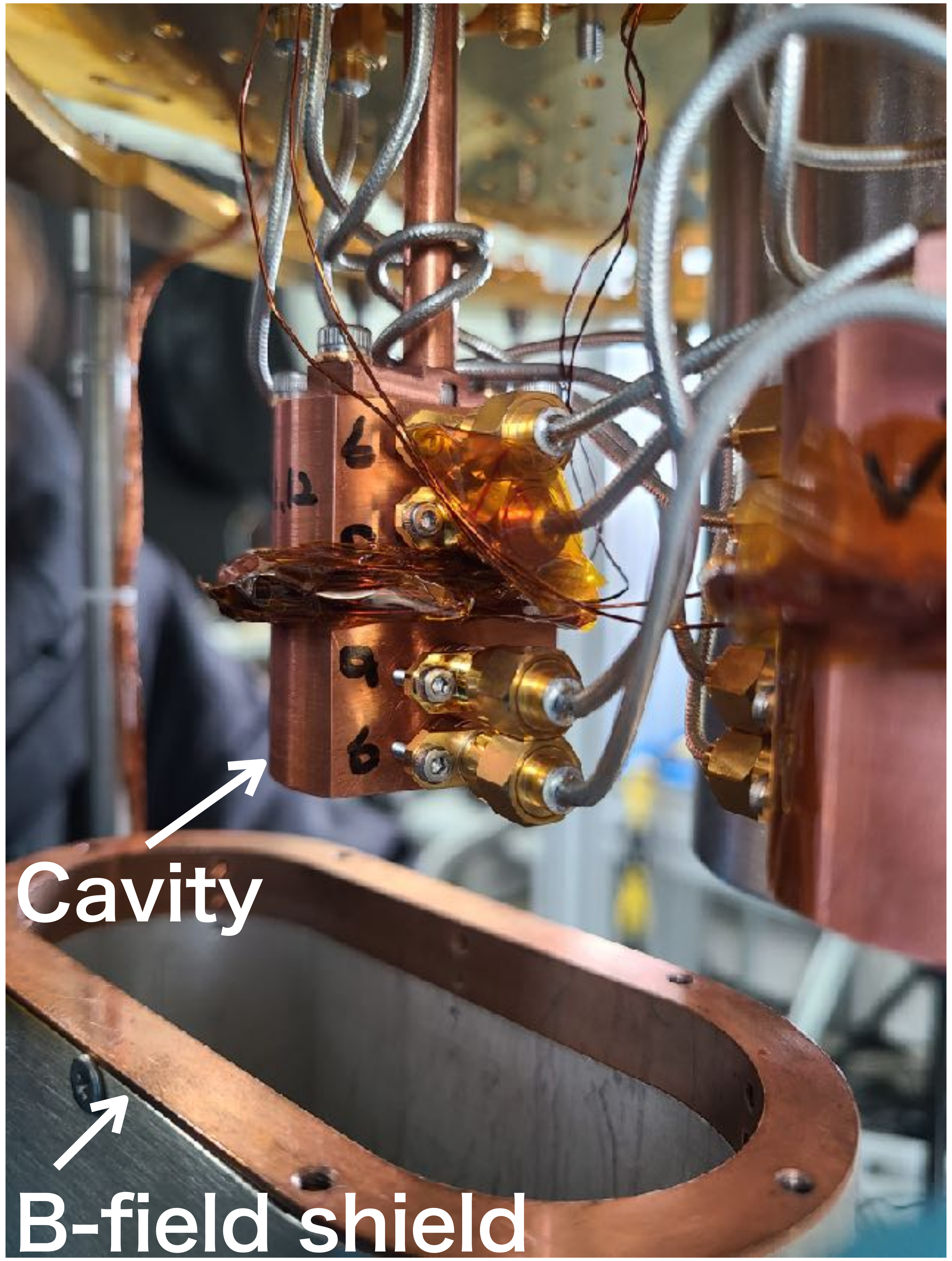


Interaction Minimum

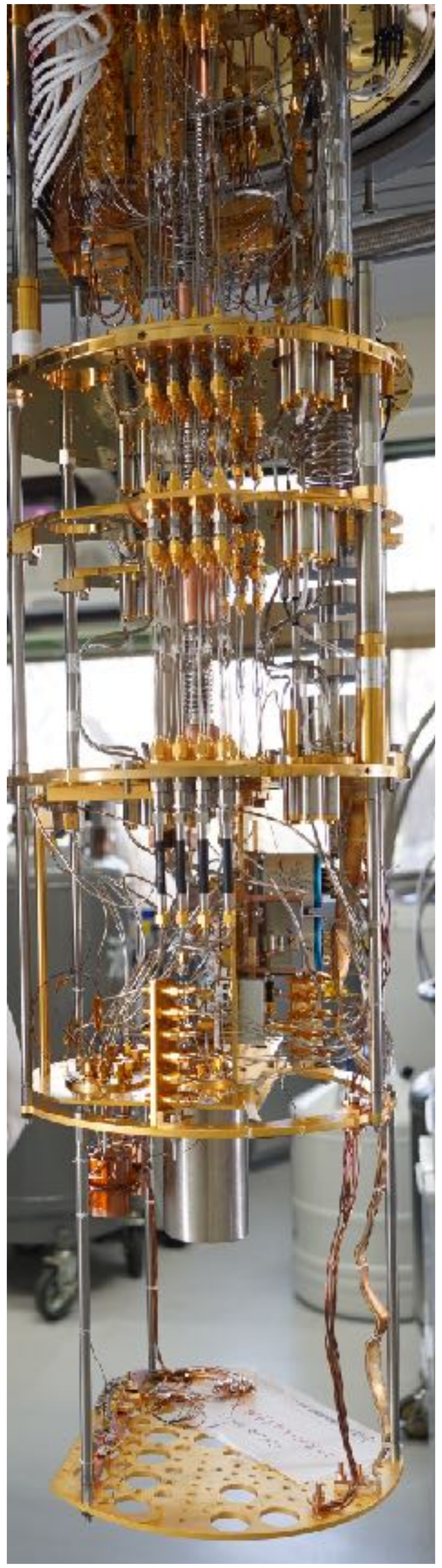
Courtesy of Kan Nakazono

Setup



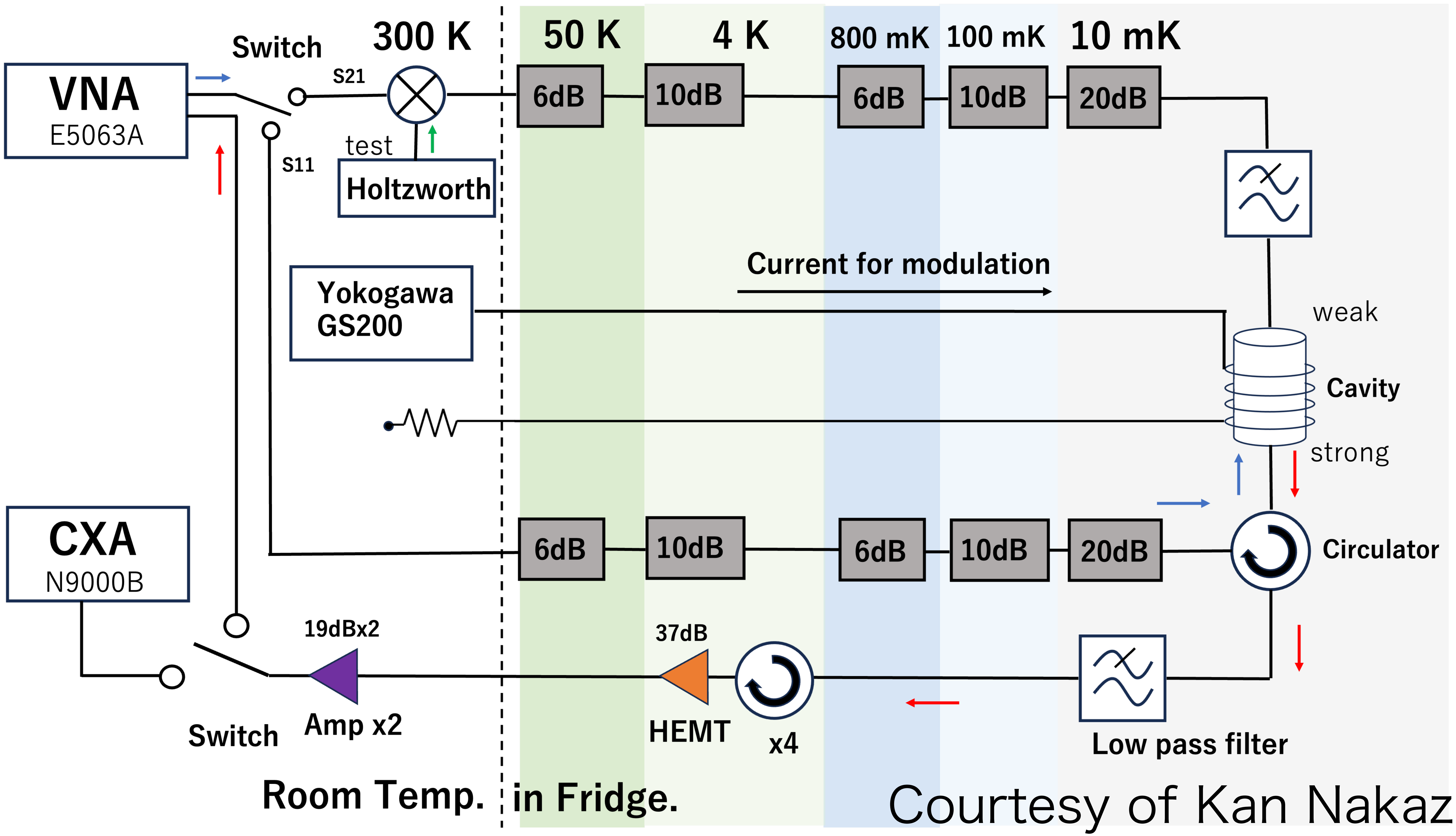


fridge



Setup

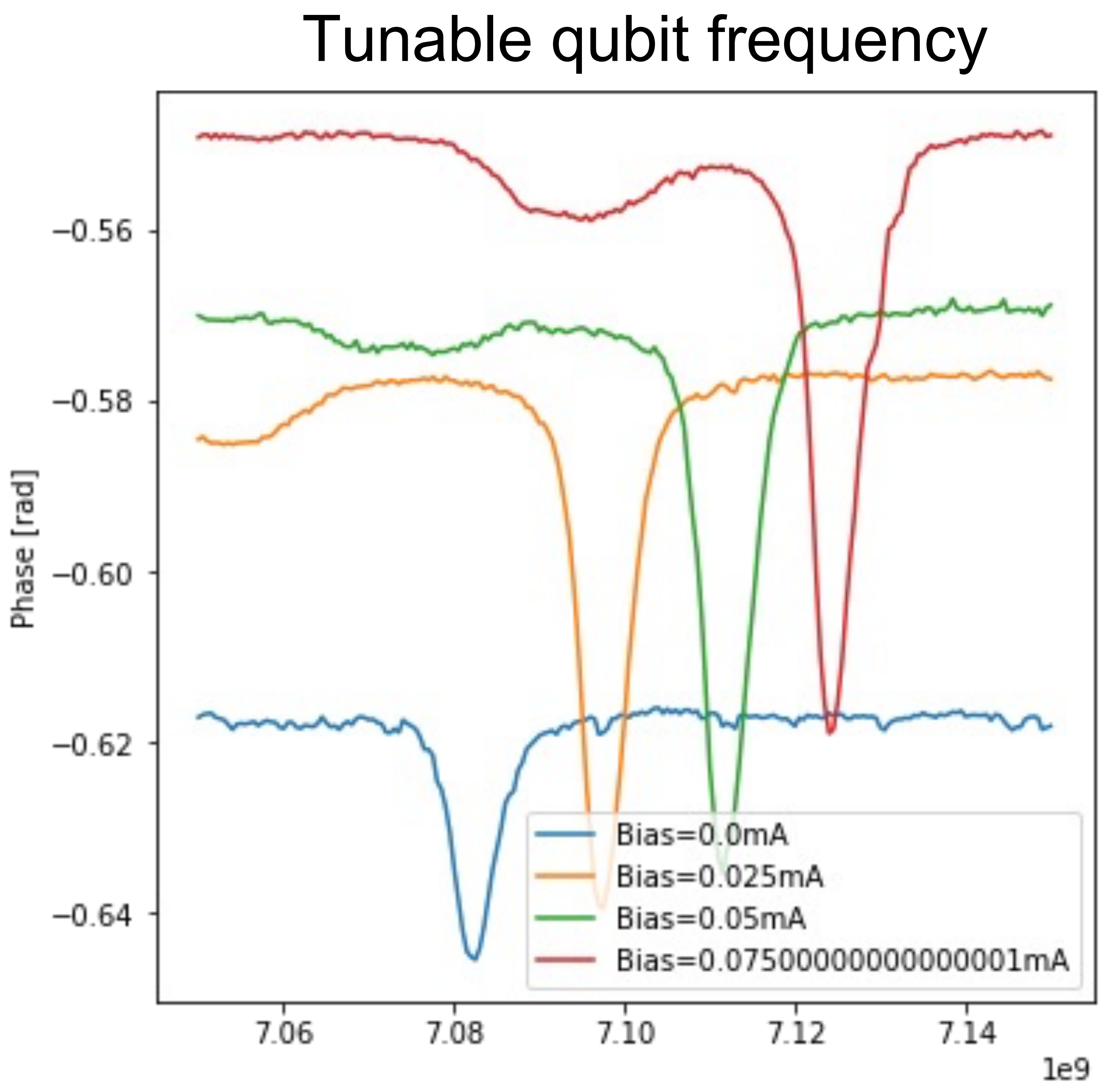
Similar to quantum computer setup



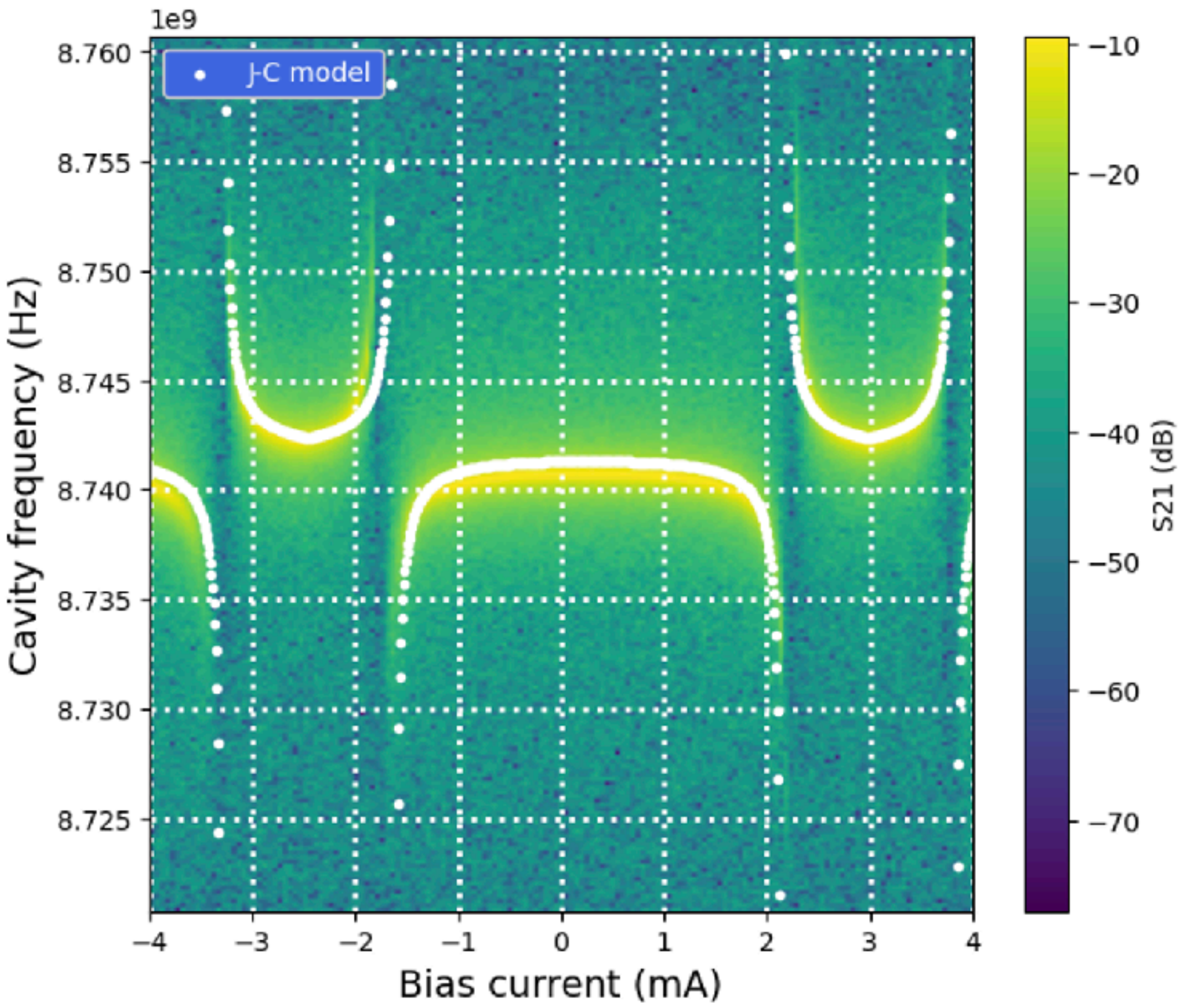
Courtesy of Kan Nakazono

Sanity Checks

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



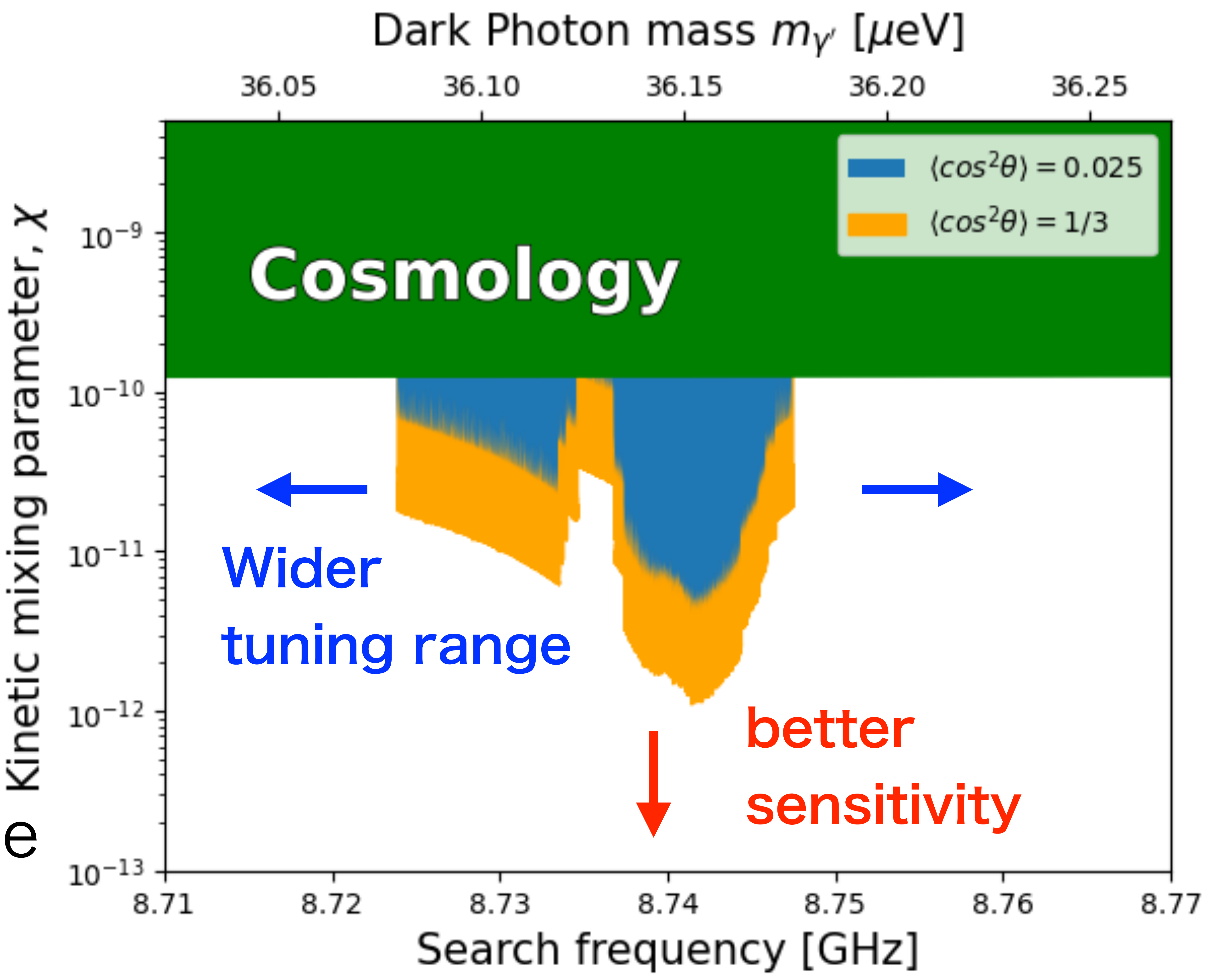
Qubit Frequency



Courtesy of Kan Nakazono

DarQ-Lamb Result

Variable	explanation	value	others
$m_{\gamma'}$	frequency	$\sim 8.74\,\mathrm{GHz}$	each measurement
ρ	DM density	$0.45\,\mathrm{GeV/cm^3}$	from (Asztalos et al., 2001)
β	coupling constant	~ 0.3	each measurement
T_{sys}	system noise	$7.9\,\mathrm{K}$	Y-factor measurement
V_{eff}	effective volume	$3.14\,\mathrm{cm^3}$	$V \times formfactor$
Q_L	(Loaded) Quality factor	~ 5000	each measurement
η	attenuation factor	1.02	SG filtering
N	number of data	100	per measurement
b	bandwidth	200 Hz	bandwidth of spectrum analyzer



We didn't find DM but
searched unexplored parameter space

Please check preprint: arXiv: 2505.15619

Courtesy of Kan Nakazono

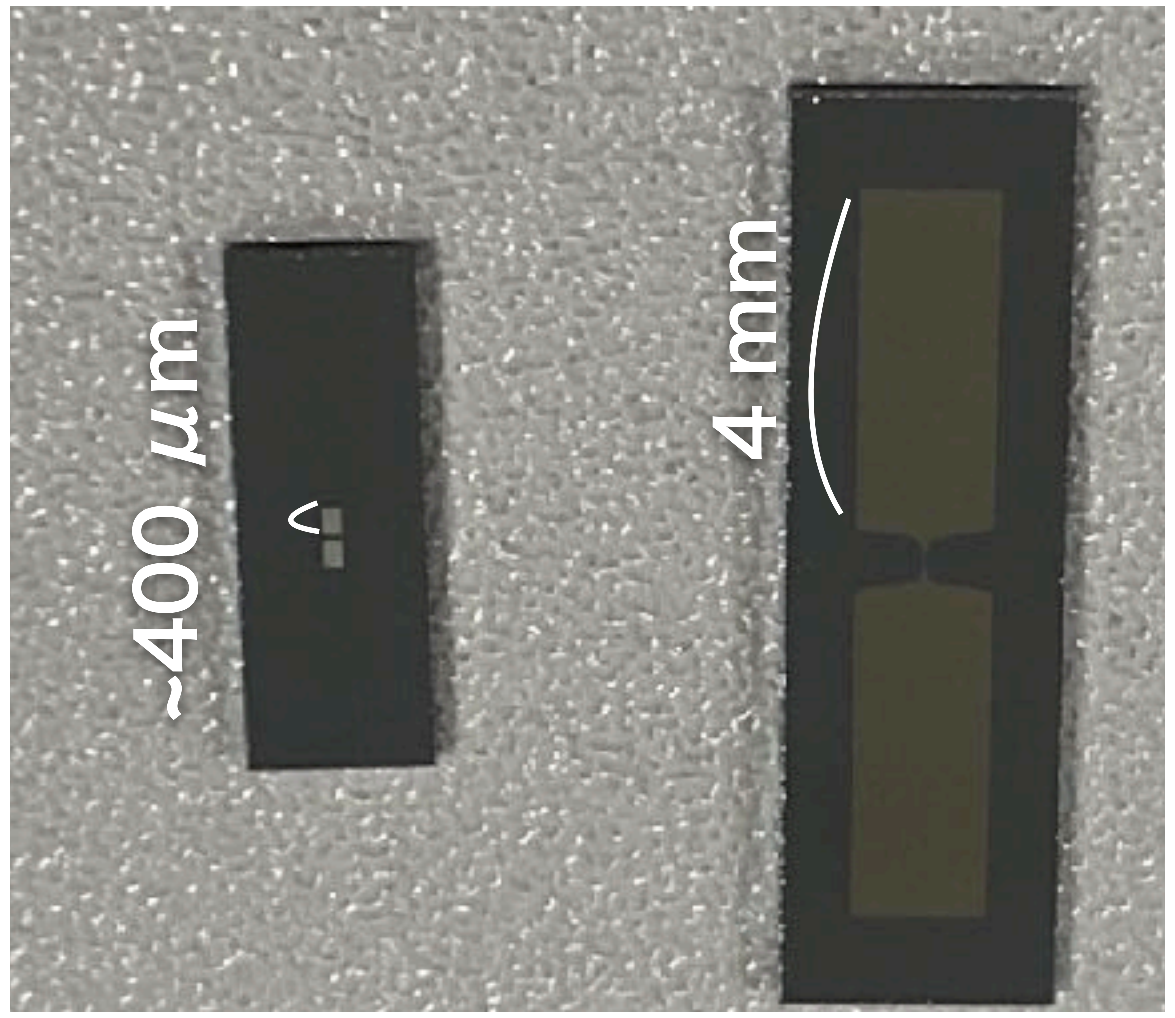
R&D for DarQ-Lamb

Towards wider tuning range

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

Larger pads

$\rightarrow$ O(100 MHz) tuning

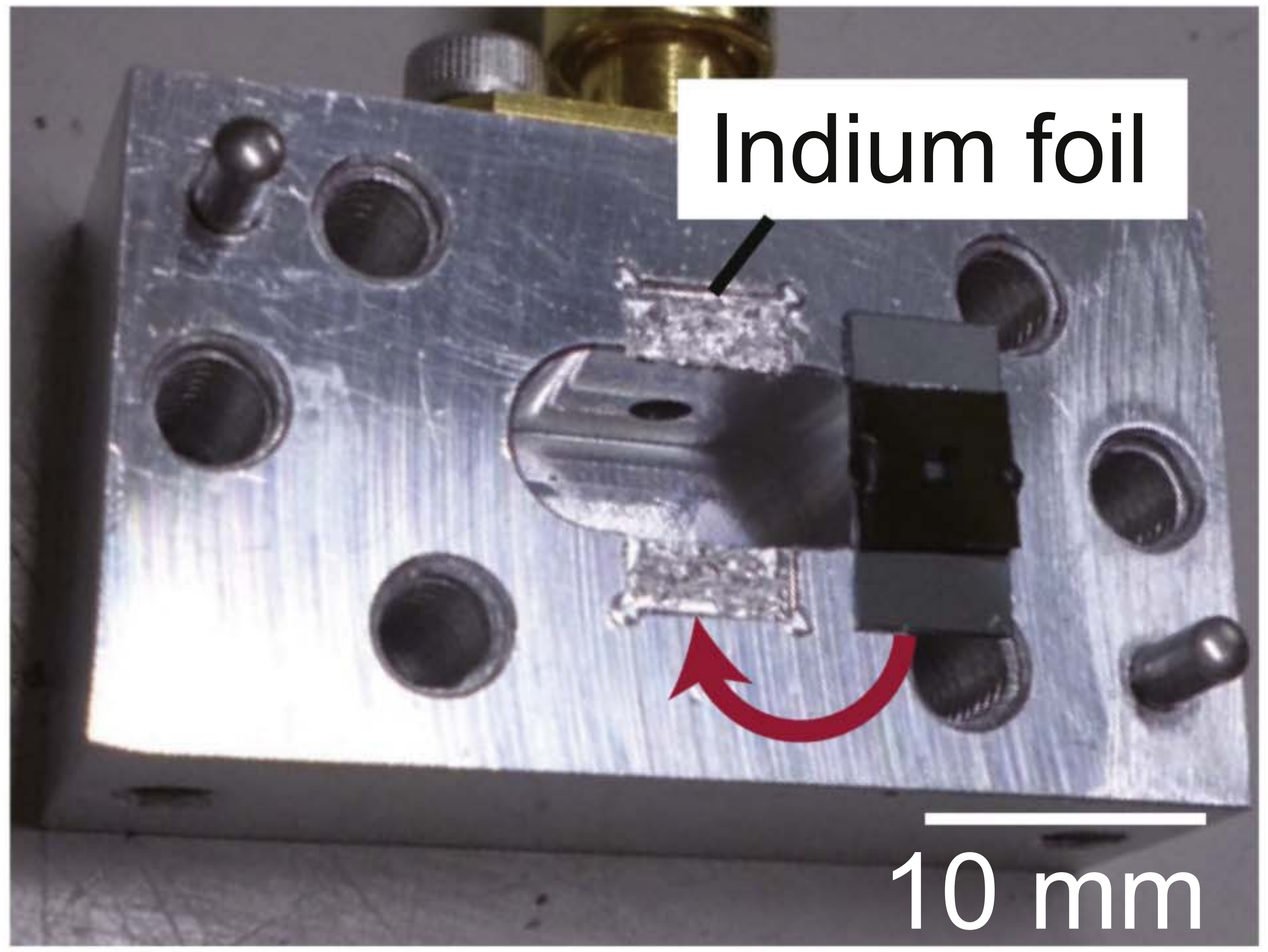


standard qubit

Large g qubit

Galvanic contacts

$\rightarrow$ O(1 GHz) tuning

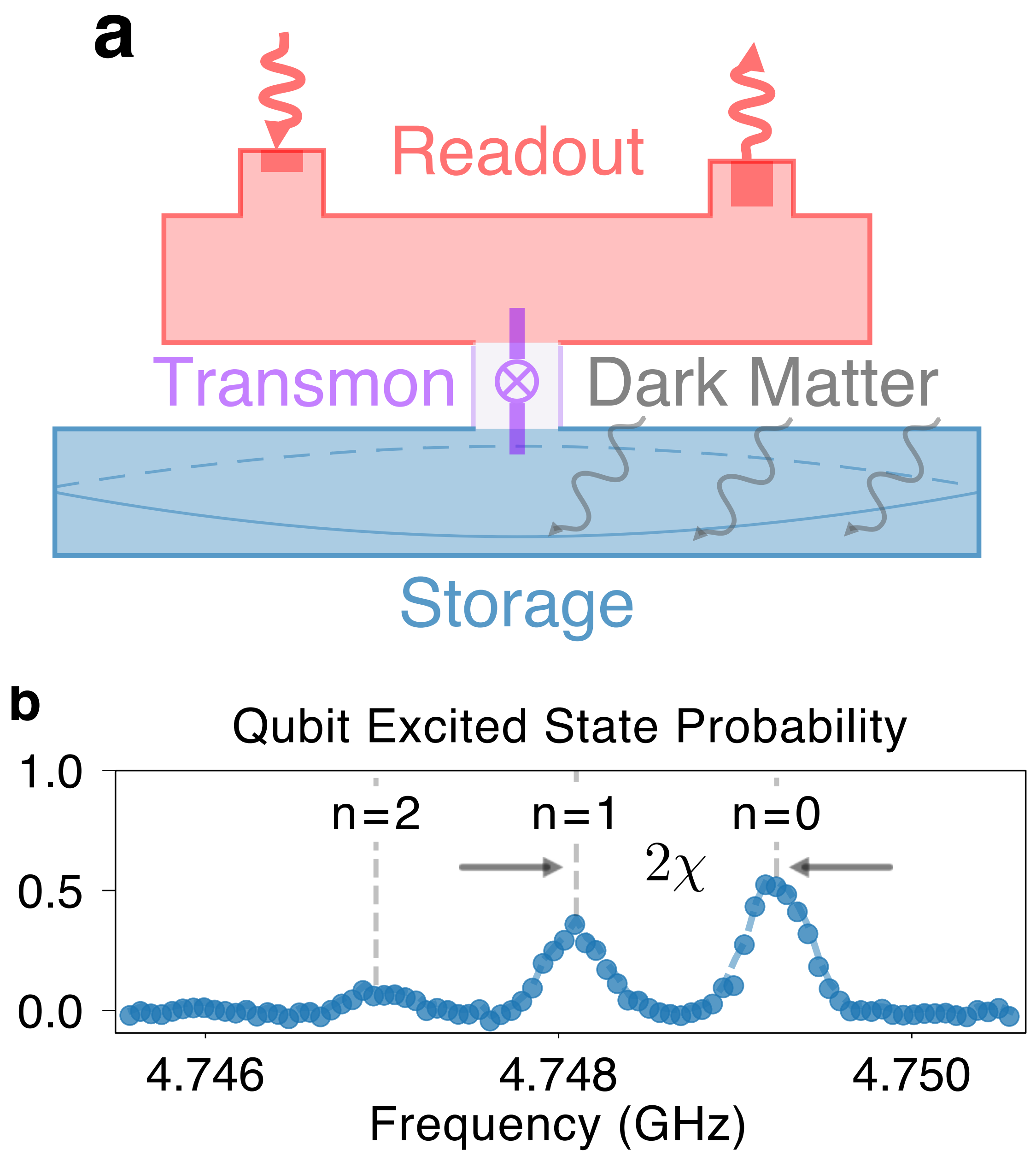


Noguchi+ 2016

Towards higher sensitivity

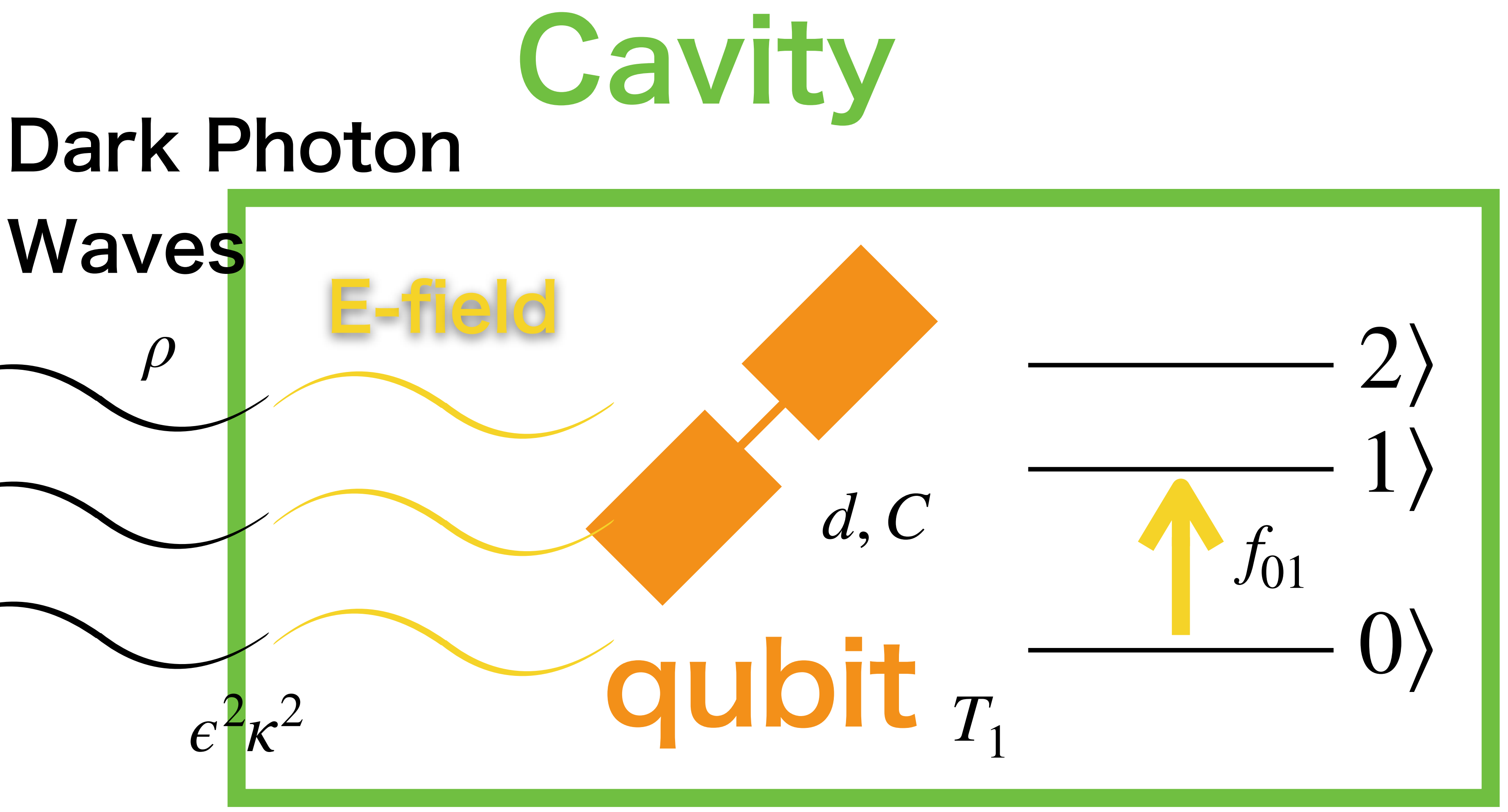
Aaron et.al.

PRL 126 141302 (2021)

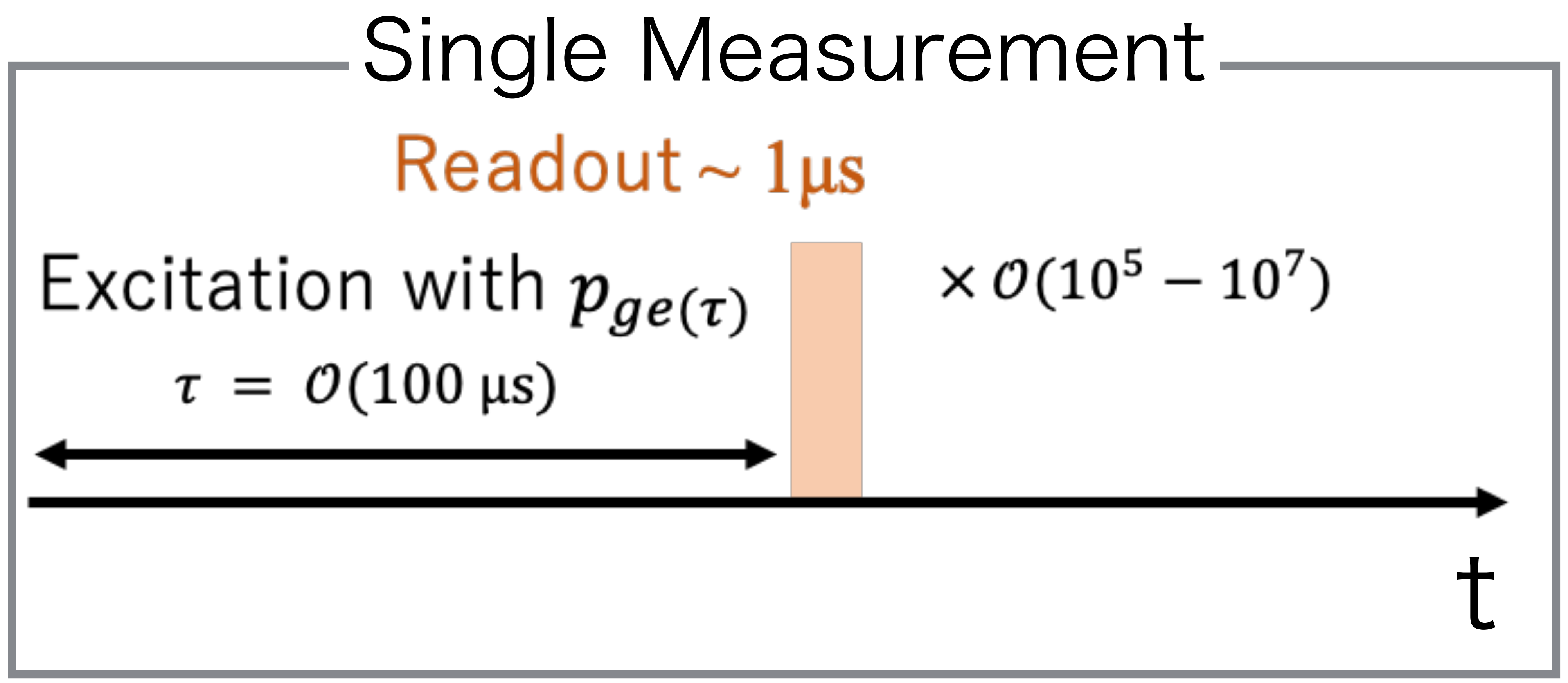


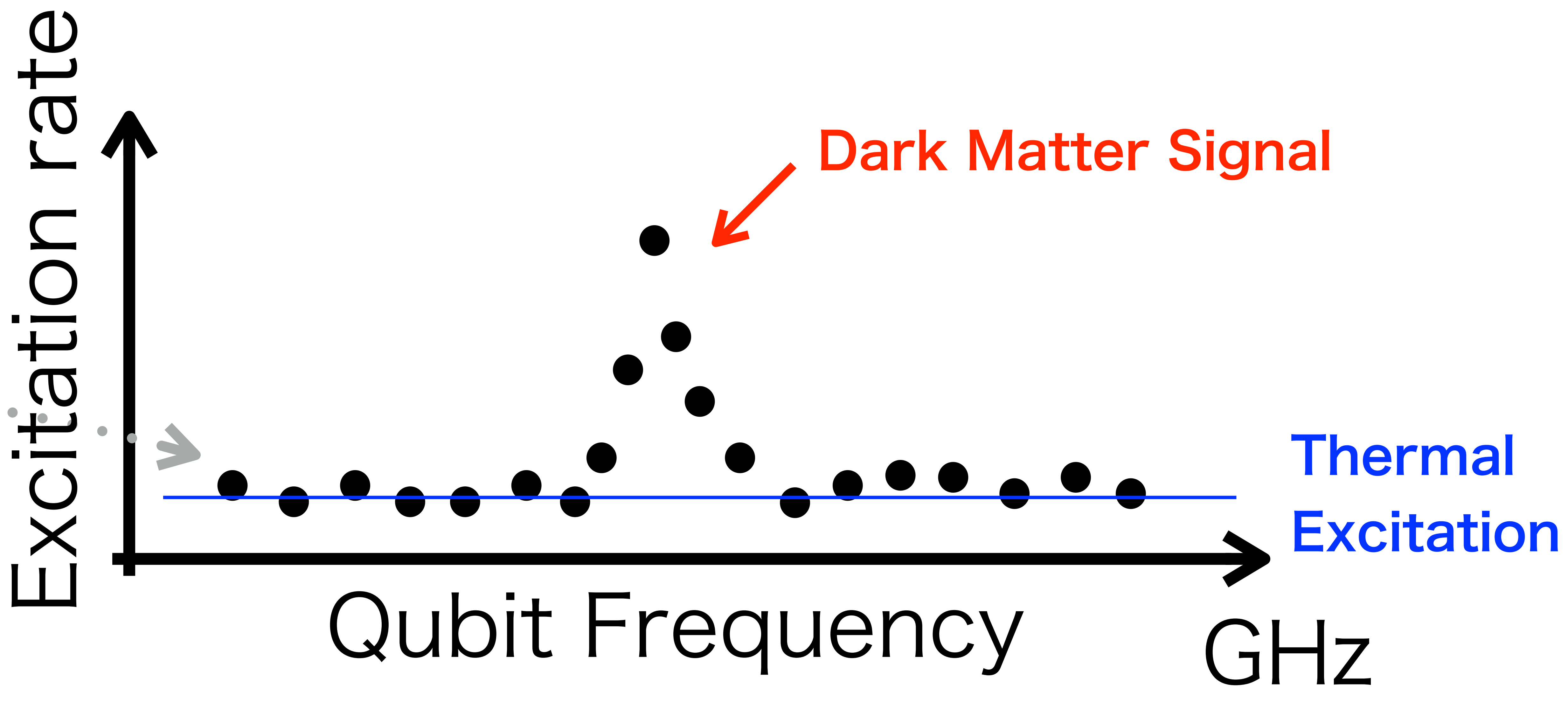
Much better sensitivity would be realized by combining with single photon counting

DarQ-Direct



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

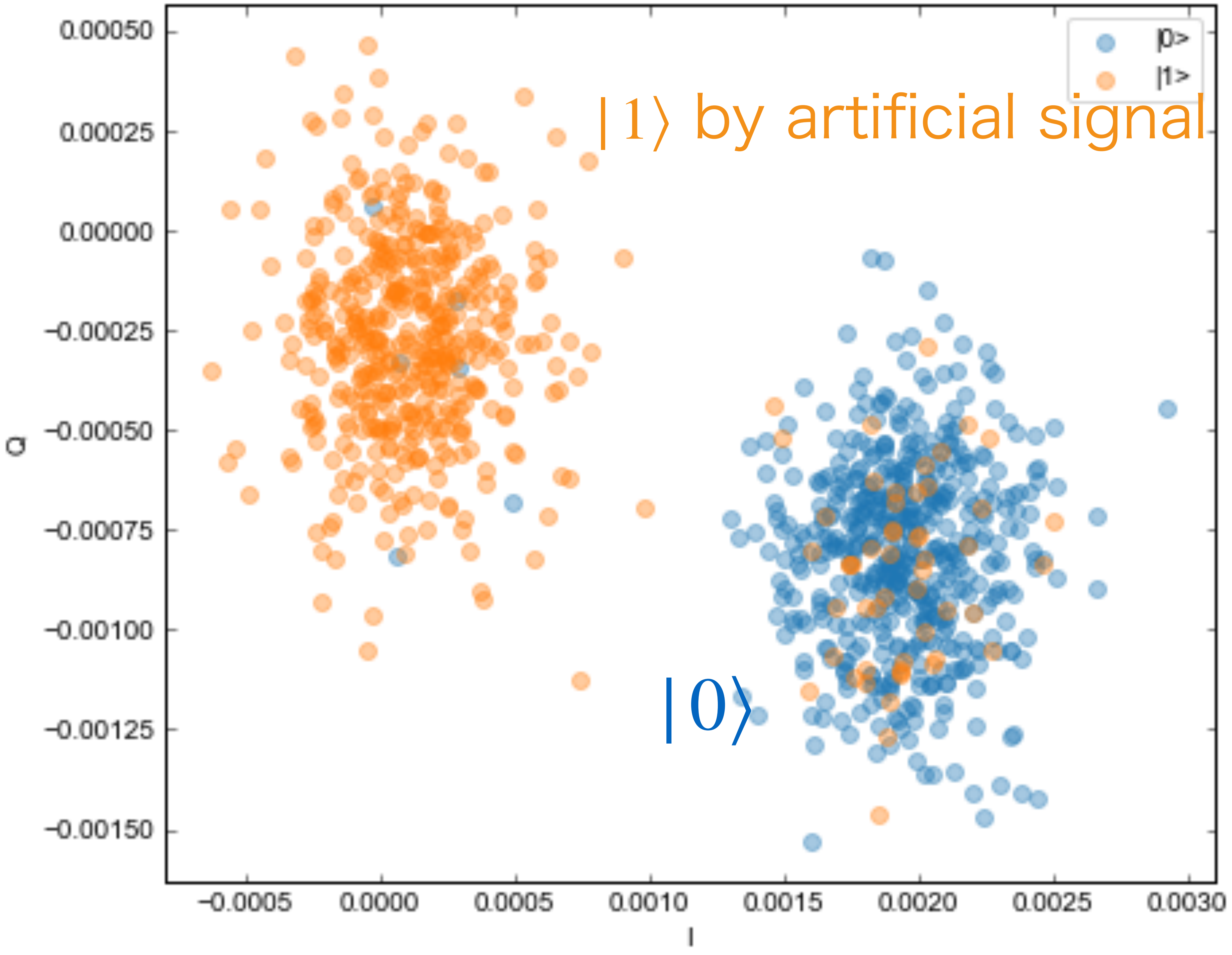




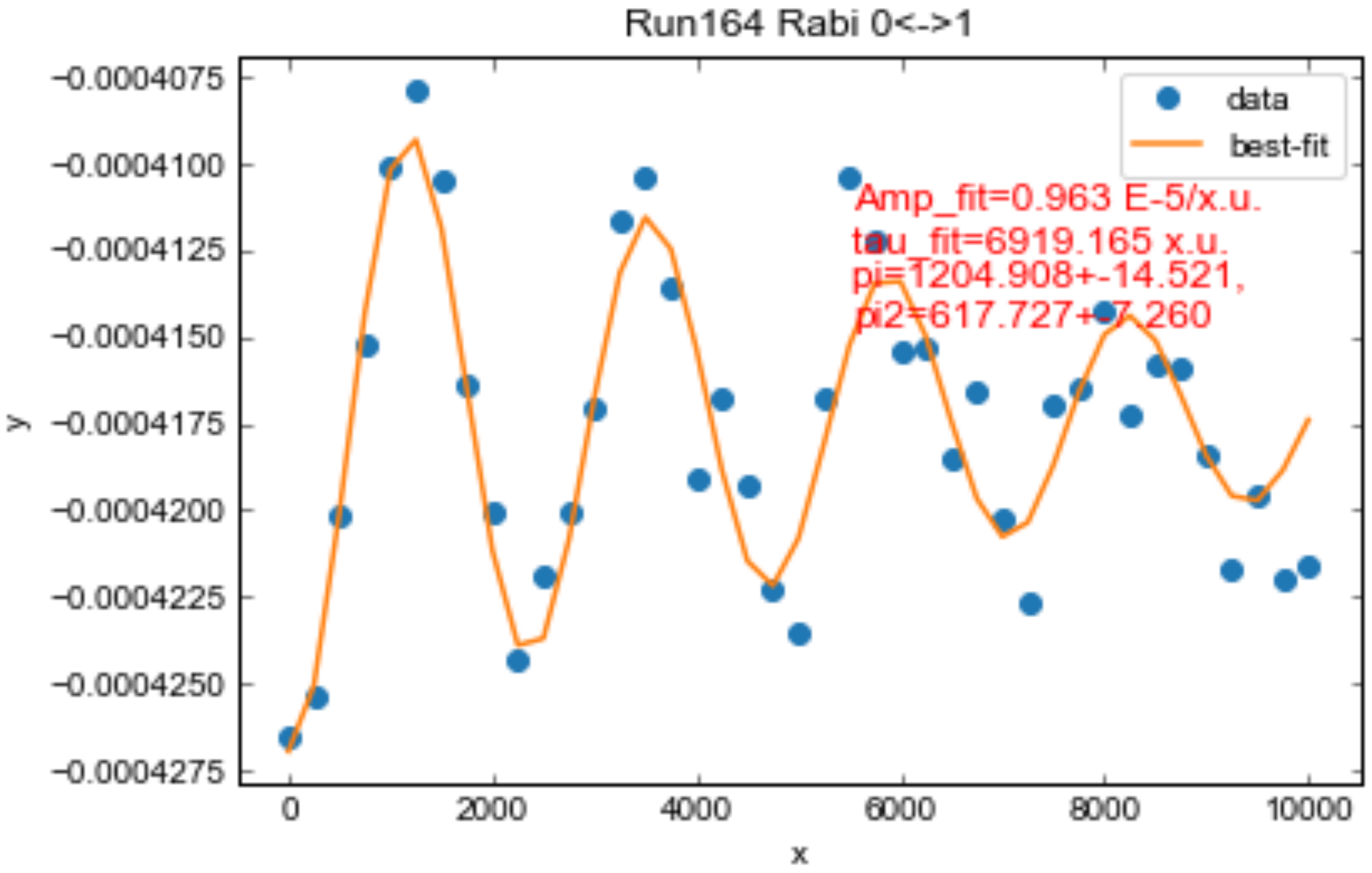
Sanity Check

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

discrimination

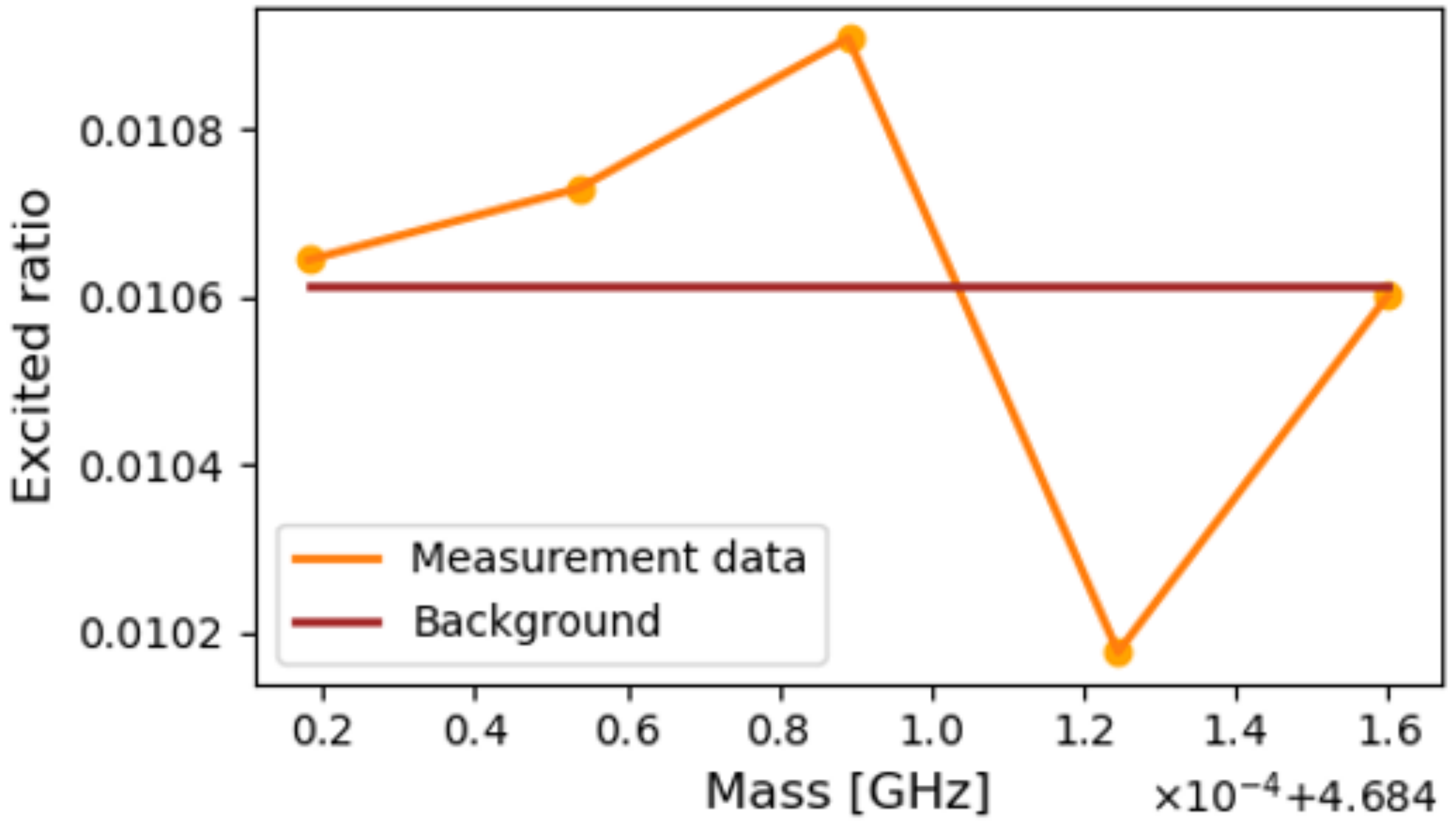


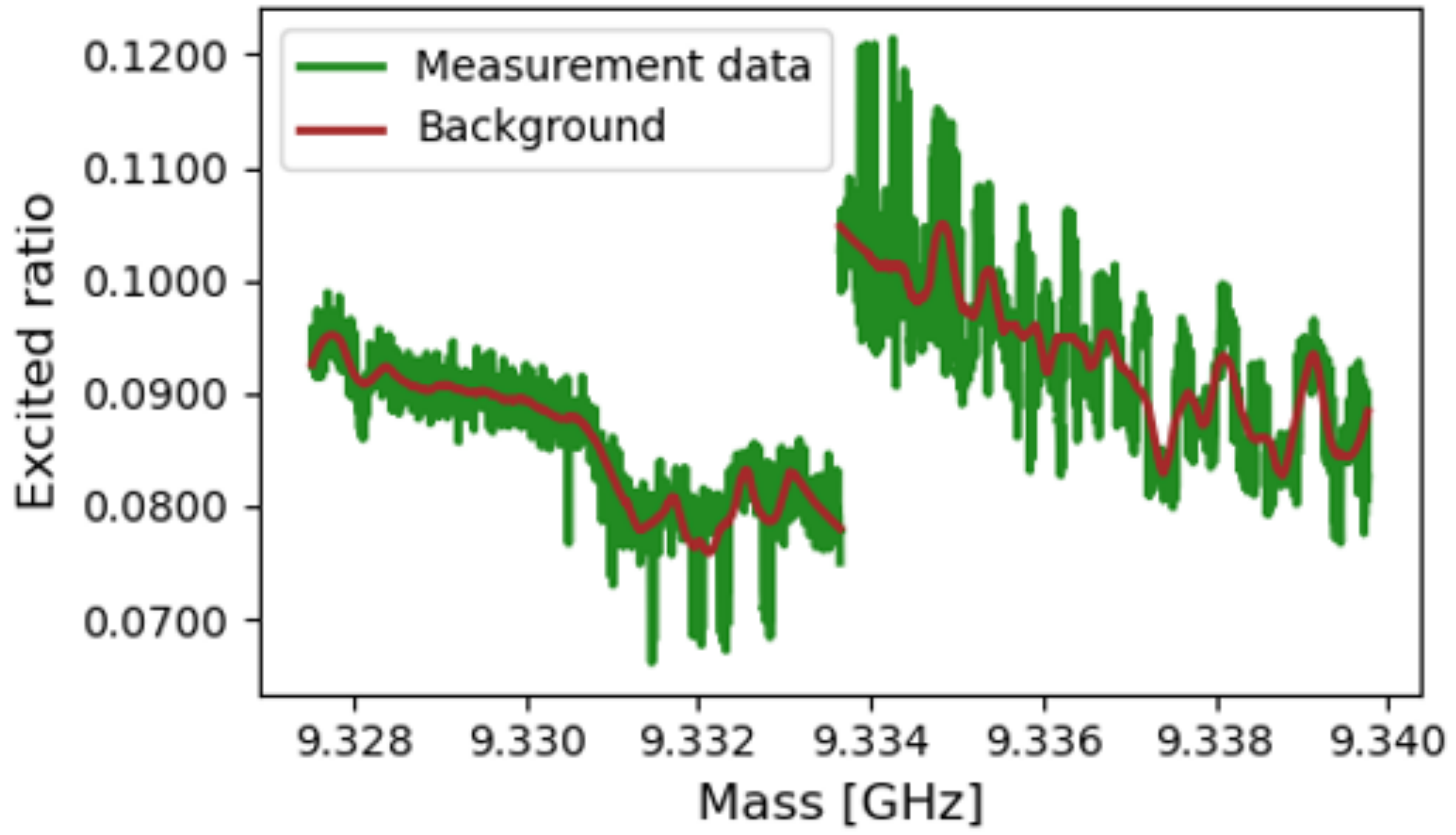
Artificial signal

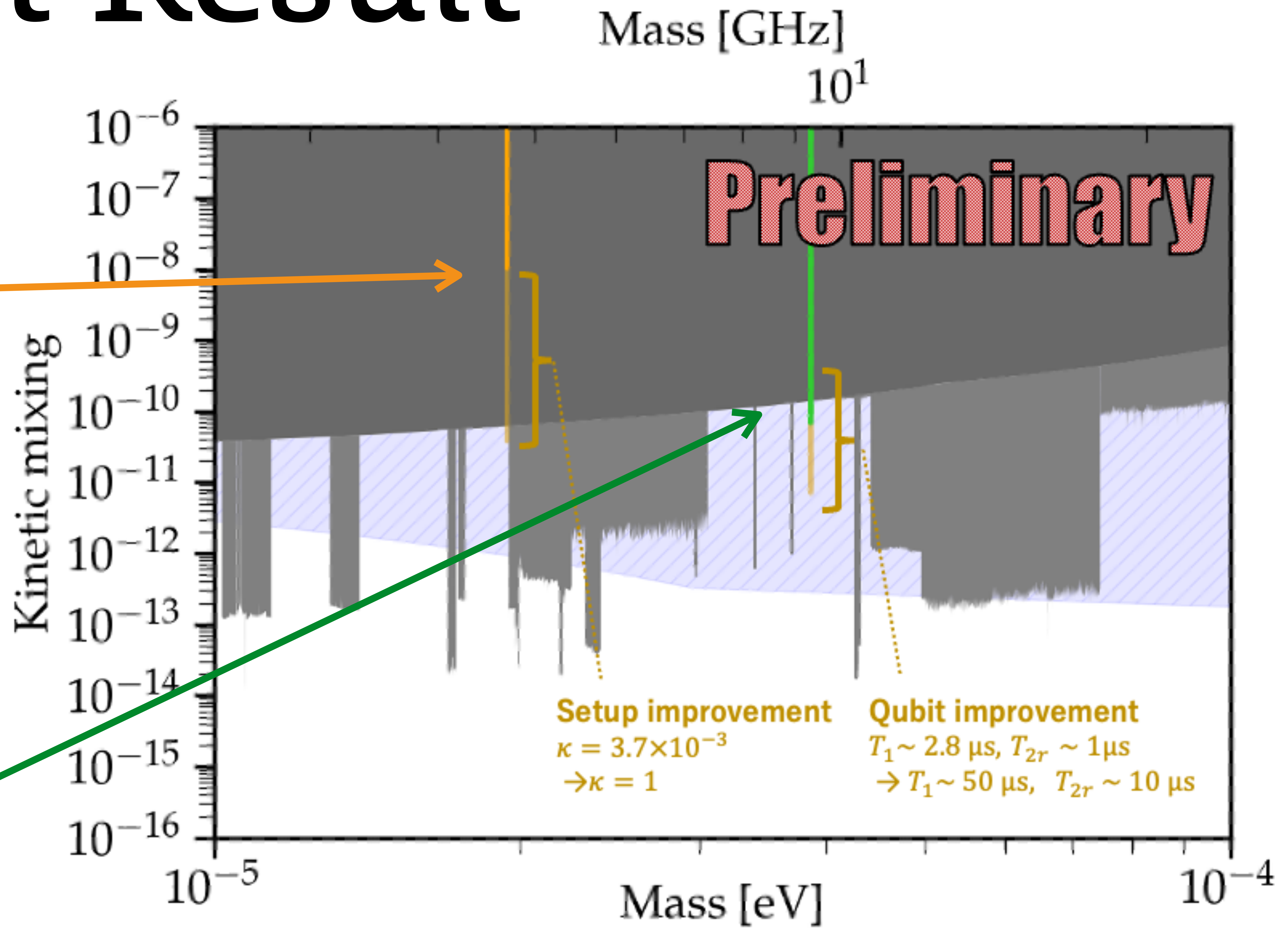


Courtesy of Karin Watanabe

DarQ-Direct Result







Courtesy of Karin Watanabe

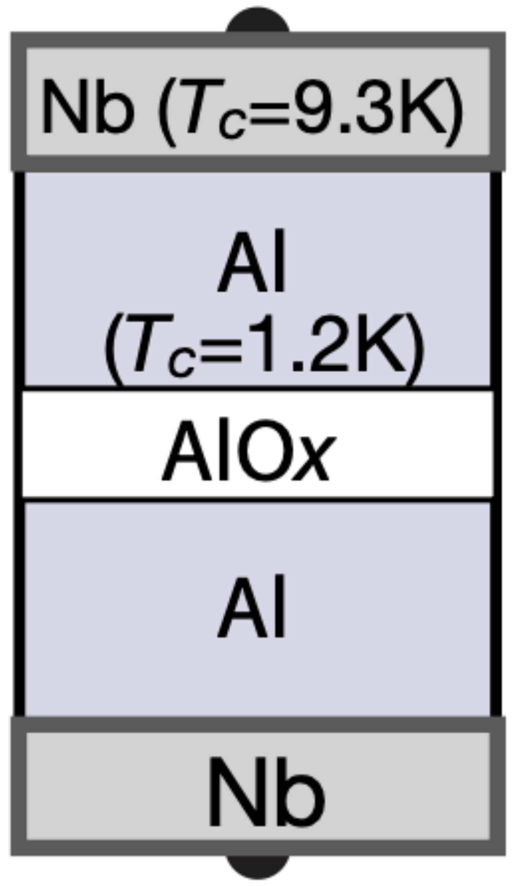
R&D for DarQ-Direct

Higher Freq. Qubits

led by Kyoto Group

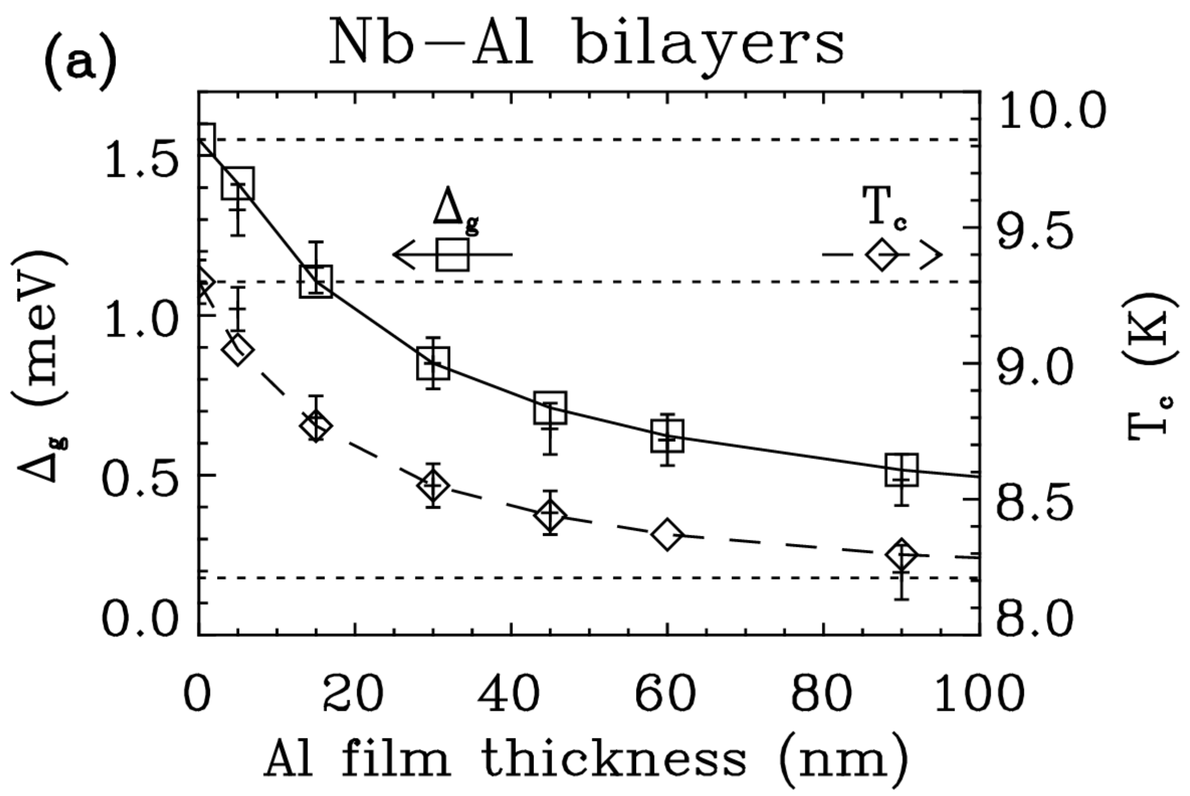
Shion Chen Tetsuro Nakagawa

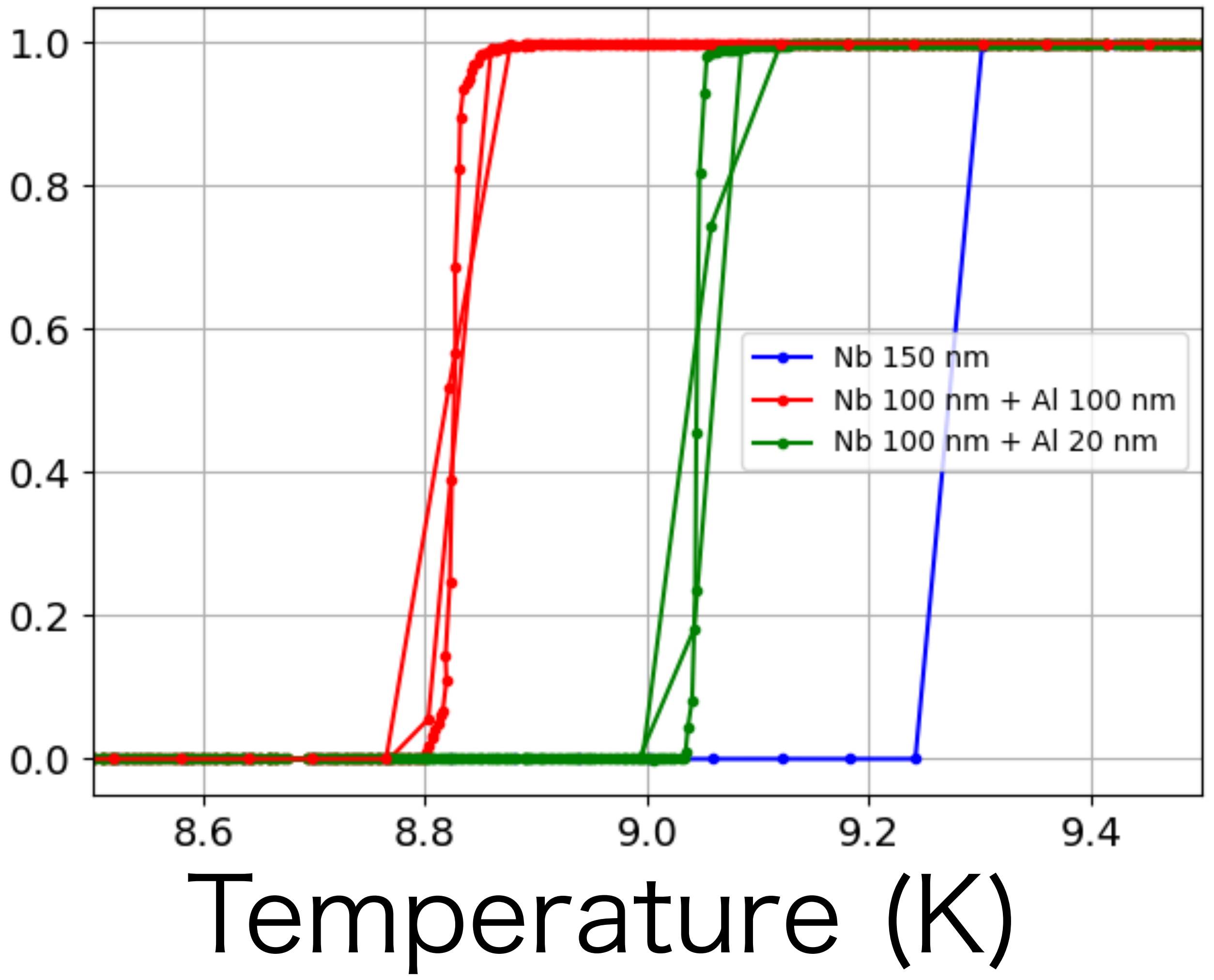
Yuya Mino



$$E_1 - E_0 \sim \sqrt{8E_C E_J}$$

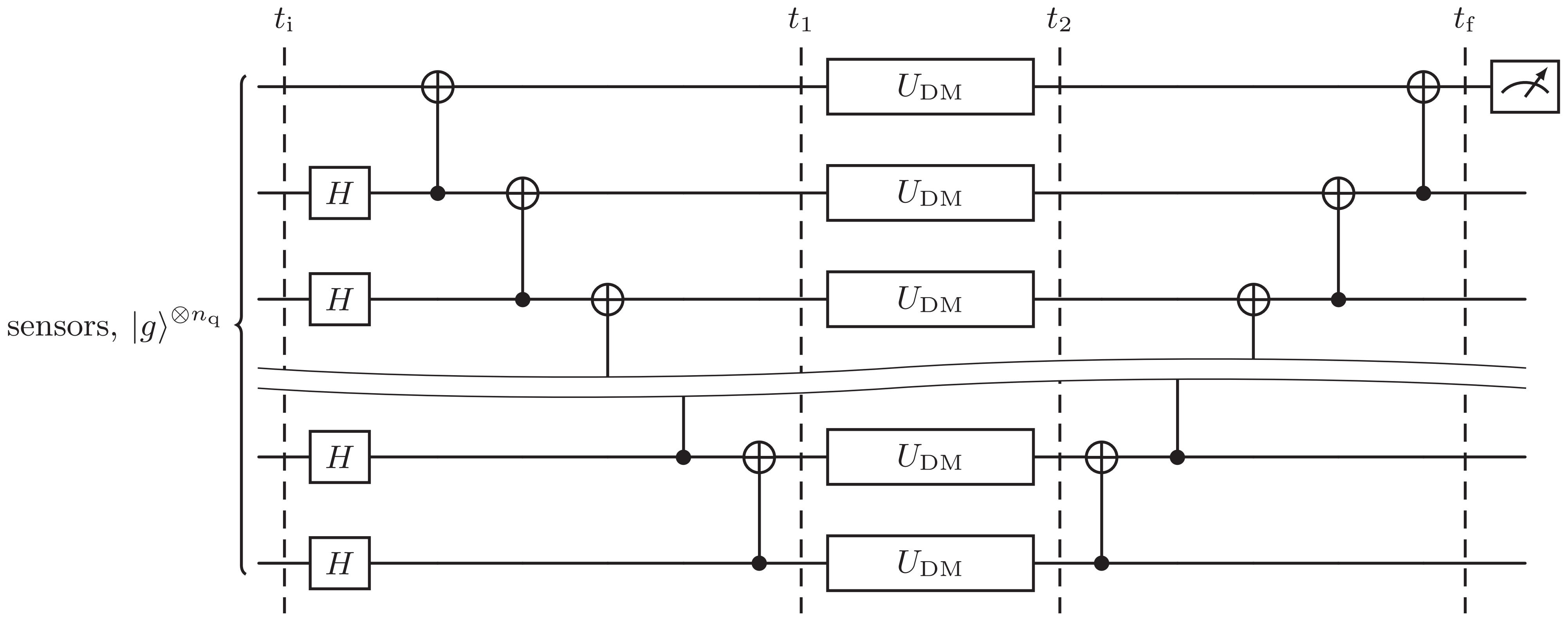
$$E_J = \frac{\pi}{2}\frac{\Delta}{R}$$





Utilize more quantum operations

Thanaporn+, PRL **133**, 021801

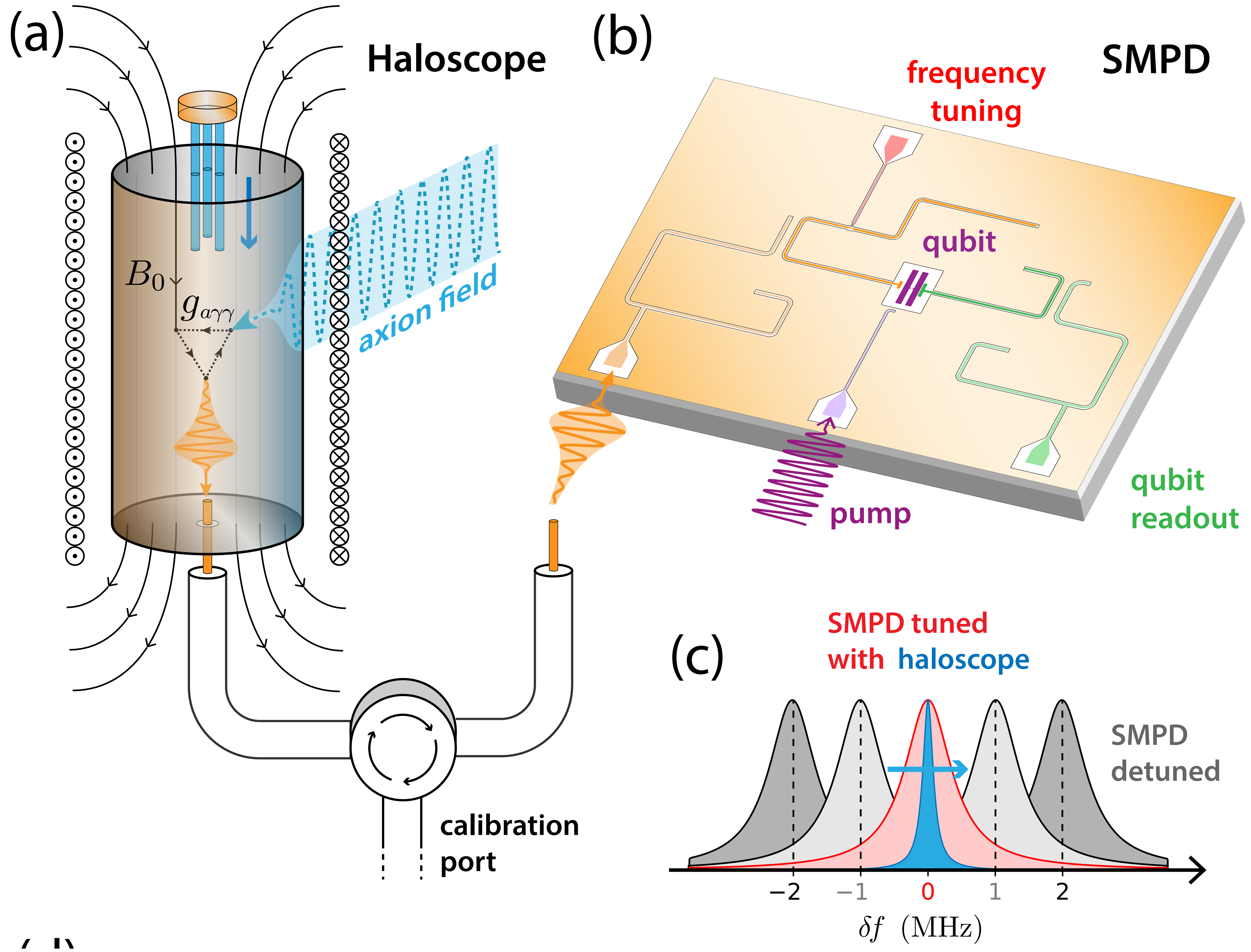


Entangling N qubits with CNOT gates leads sensitivity increase by N^2

Towards Axion Search

Photon transfer

Pros: Easer, Cons: Potentially lossy

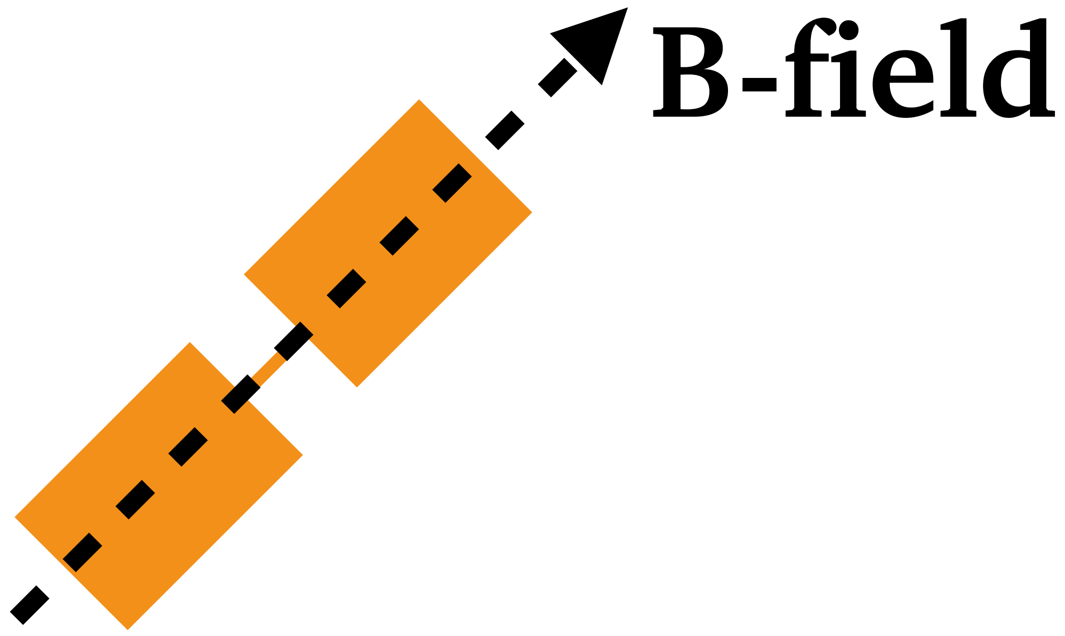


arXiv:2403.02321

B-field tolerant qubits

Pros: No loss

Cons: More difficult

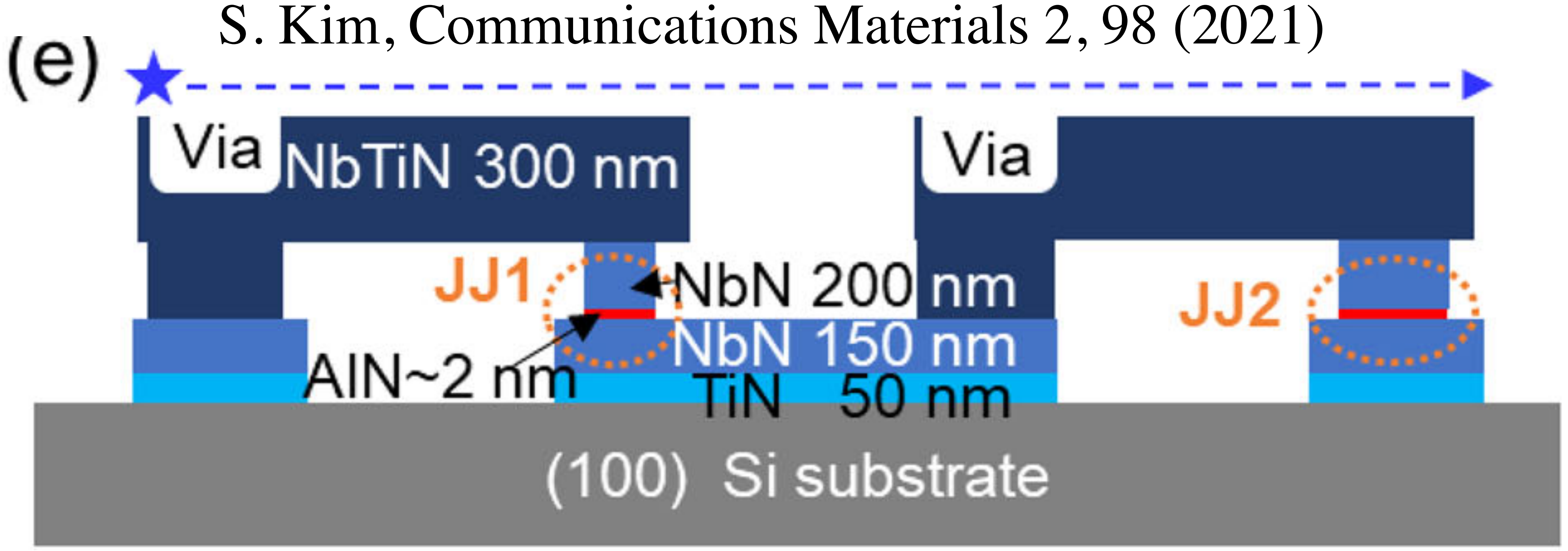


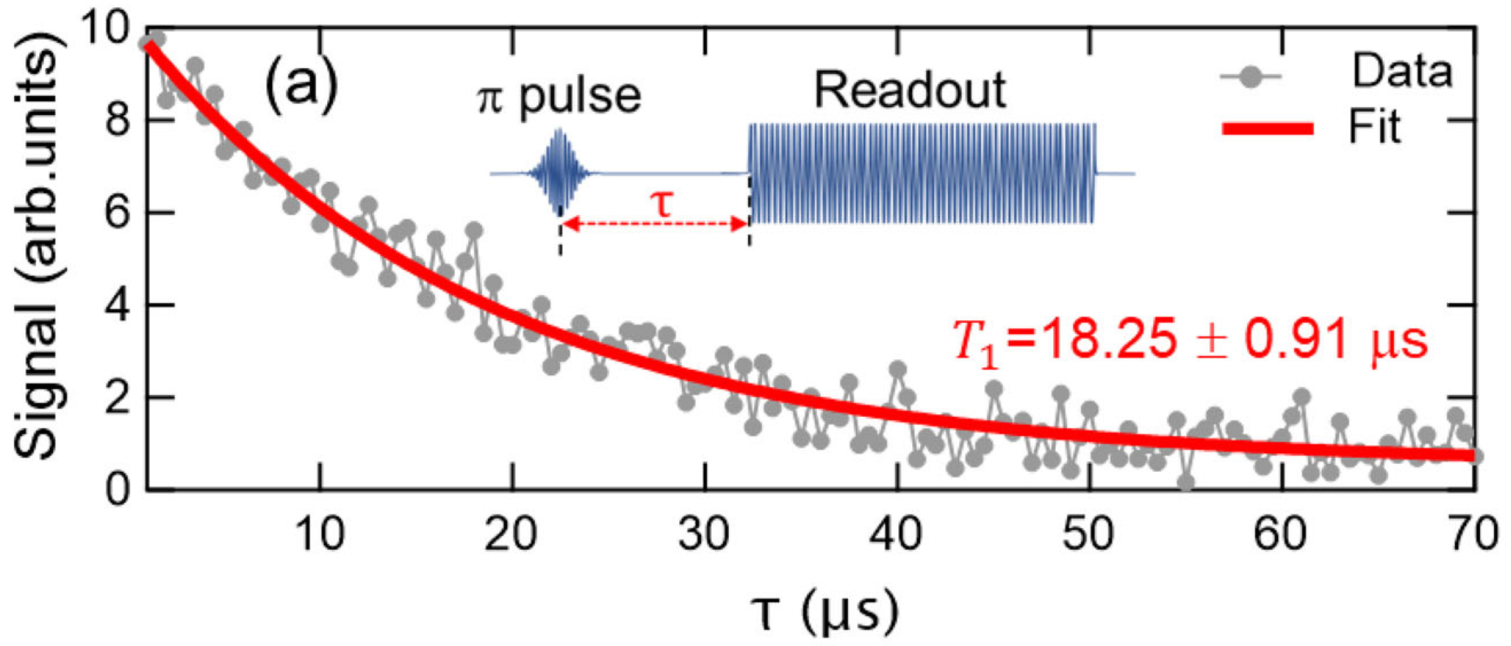
Qubits worked at least 1T

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

All-nitride qubits

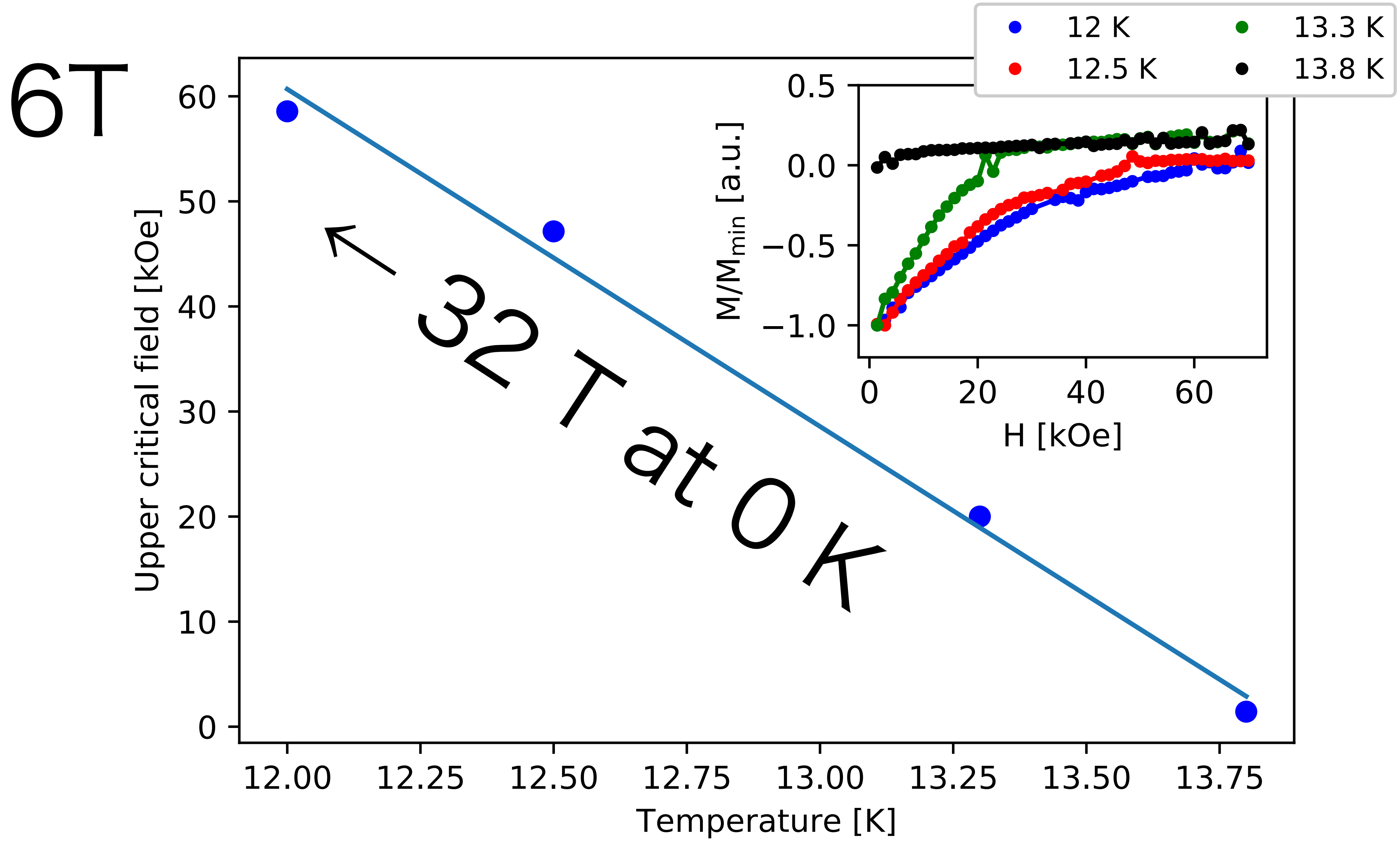
S. Kim, Communications Materials 2, 98 (2021)



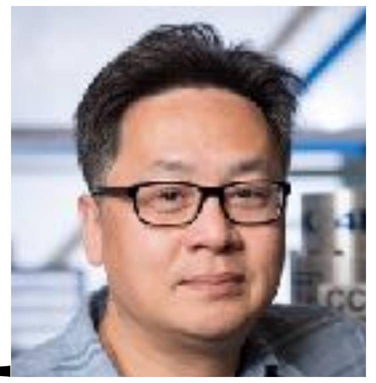


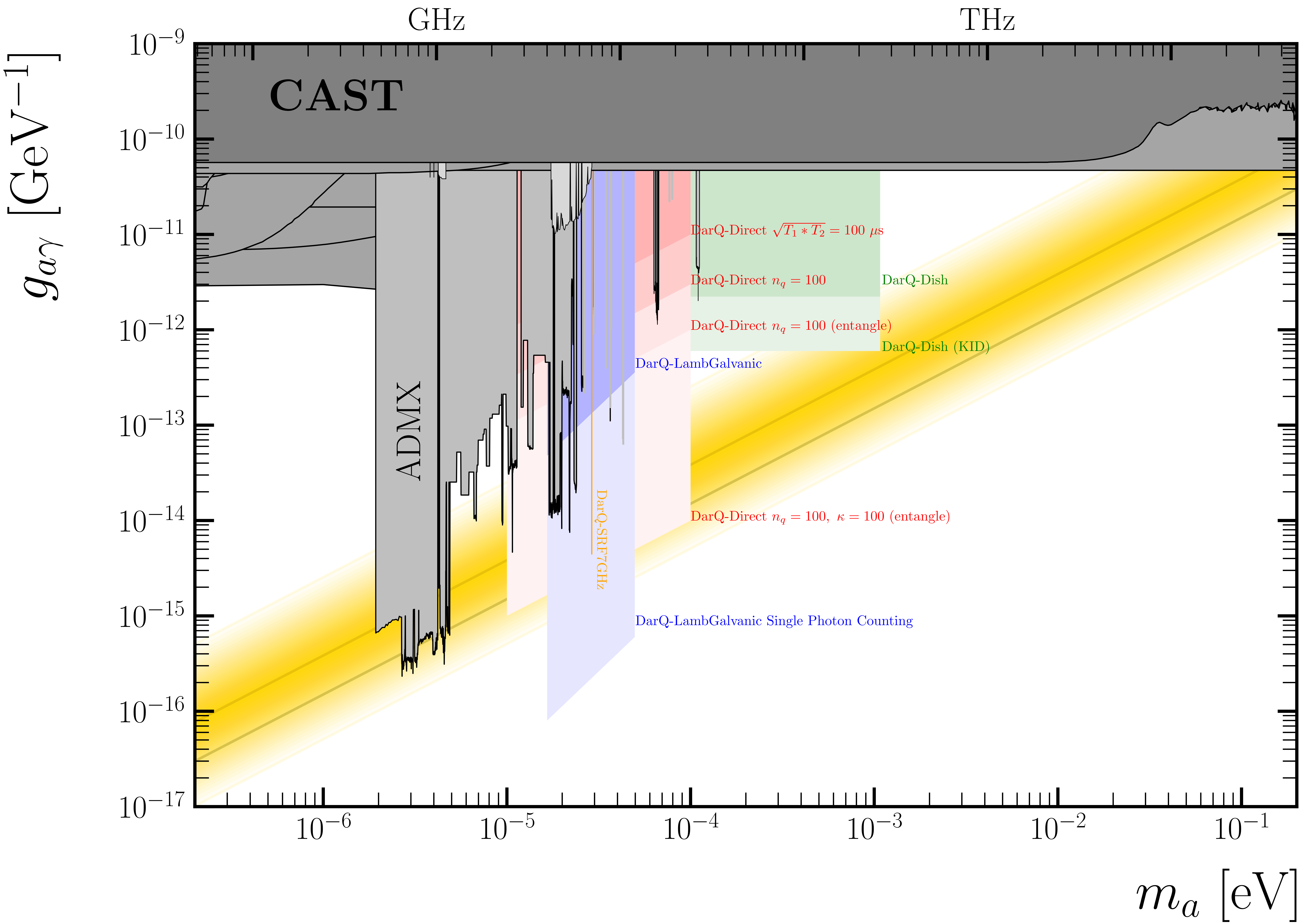
T. Polakovic, APL Materials 6 (2018) 076107

NbN 240 nm film



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

We are collaborating with NICT  / FNAL  people


GHz
THz
CAST
ADMX
DarQ-SRF7GHz
DarQ-Direct $\sqrt{T_1 * T_2} = 100\ \mu s$
DarQ-Direct $n_q = 100$
DarQ-Dish
DarQ-Direct $n_q = 100$ (entangle)
DarQ-Dish (KID)
DarQ-LambGalvanic
DarQ-Direct $n_q = 100,\ \kappa = 100$ (entangle)
DarQ-LambGalvanic Single Photon Counting
$g_{a\gamma}$ [GeV^{-1}]
m_a [eV]
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}

High Q / B-field Resilient Cavity

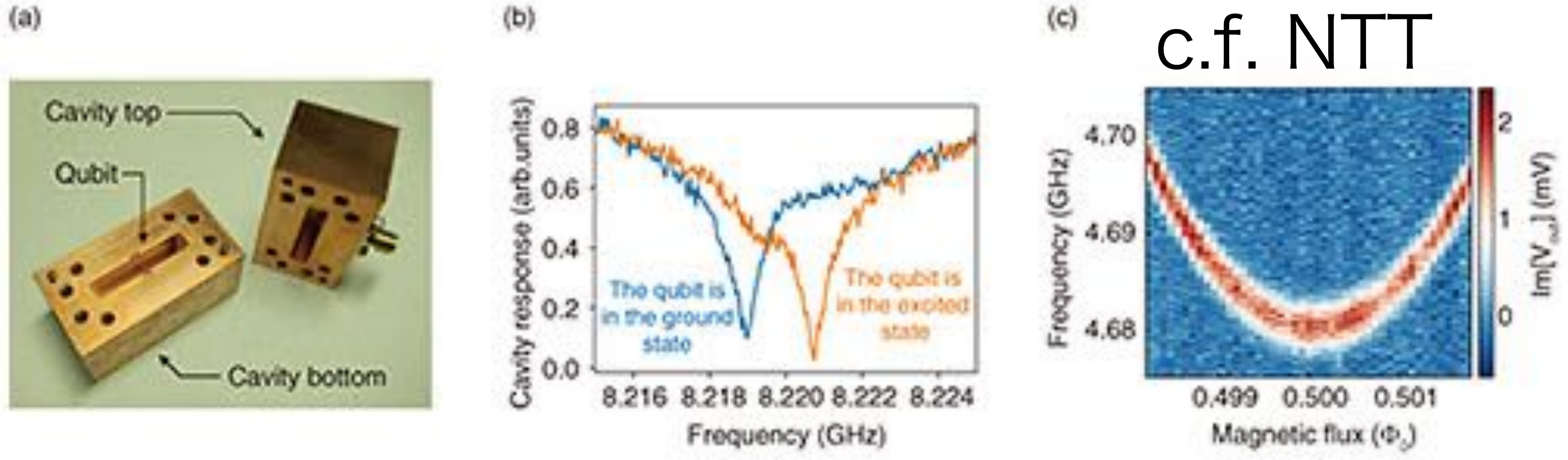
Needs:

1. DM searches

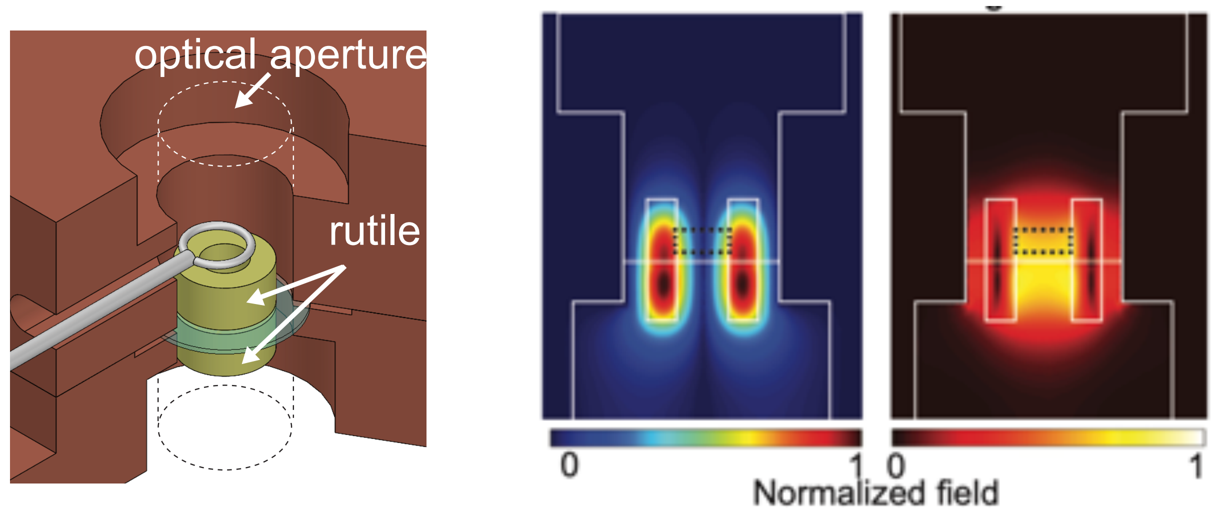
Everyone needs
high Q cavity in B-field

2. bosonic quantum computing

c.f. NTT

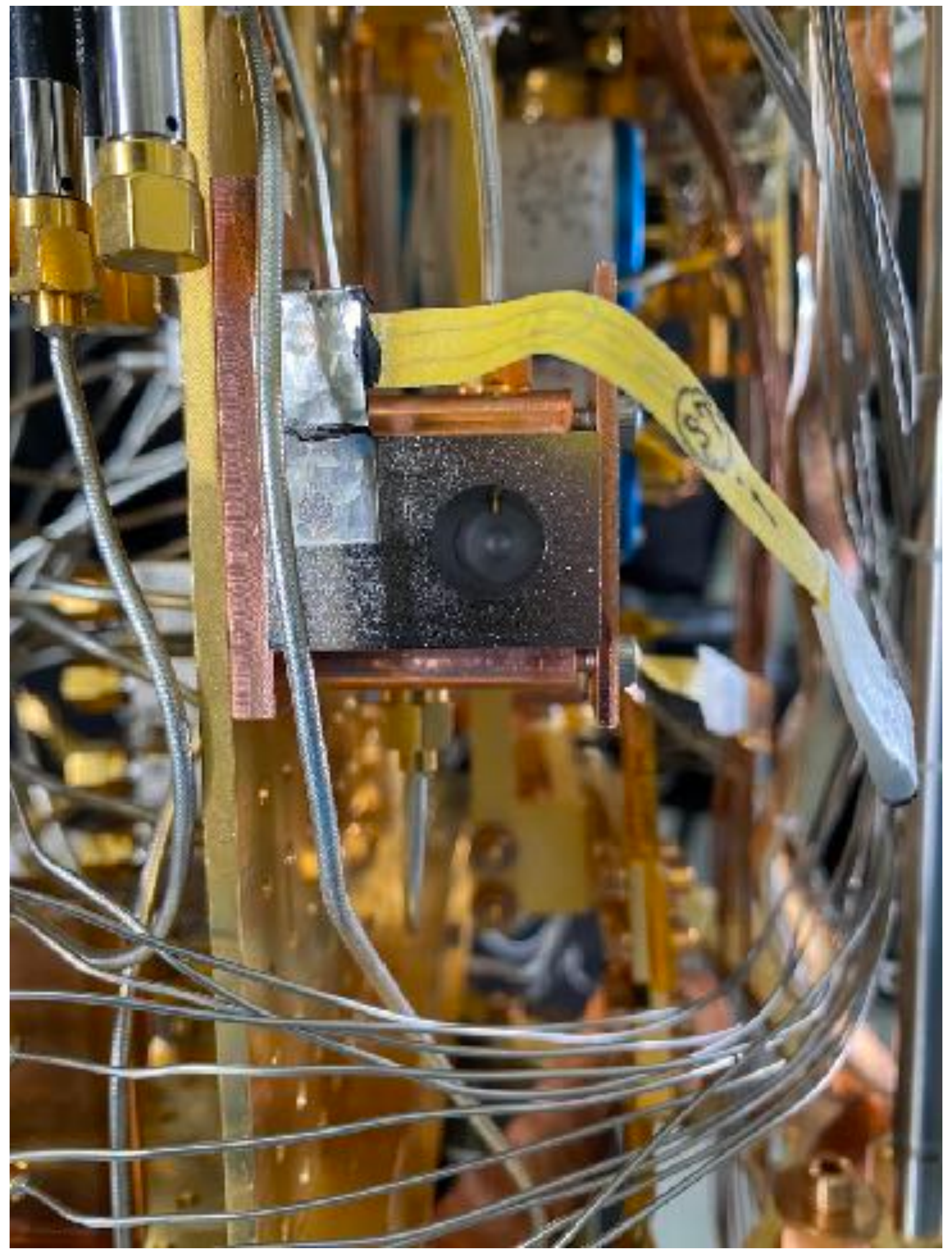


3. Electron Spin based Quantum Device



Kubo+, arXiv:2403.08458

Low power superconducting cavity
at **10 mK** isn't explored so much



- Nb cavity machined/treated at KEK
  (we achieved Q>10^7@7GHz already)
- Higher Q cavity with different material
- Nb3Sn for B-field Resilient

Takayuki Kubo
(KEK)

cavity
theory
expert

Hayato Ito
(KEK)

Nb3Sn
cavity
expert

Yuimaru Kubo
(OIST)

Quantum
Technology
expert

Summary & Prospect

DarQ
Experiment

Dark matter search using Qubits

We are forming
- Strong collaboration (Tokyo, Kyoto, Riken, KEK)
- Elaborated fabrication recipe
- Permanent experimental site at QUP

Superconducting qubit is a promising technology for DM search

- Ongoing experiments
  - DarQ-Lamb DM search with cavity tuning by qubits
    → First result on arXiv
  - DarQ-Direct DM search with direct excitation of qubits
    → Aiming to publish the first result in this year
- Future R&D for Large coupling/High frequency/B-field resilient qubits
  → Aiming to search axion/dark photon parameter spaces around GHz comprehensively