ICEPP-QUP Quantum Workshop 2026

Superconducting qubits and cavities for DM sensors at QUP-KEK

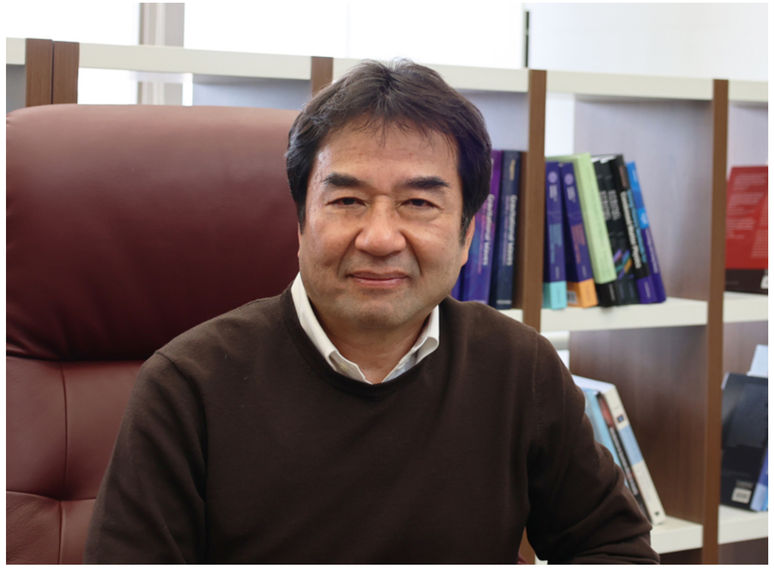
May 19, 2026

KEK, QUP
Tatsumi Nitta

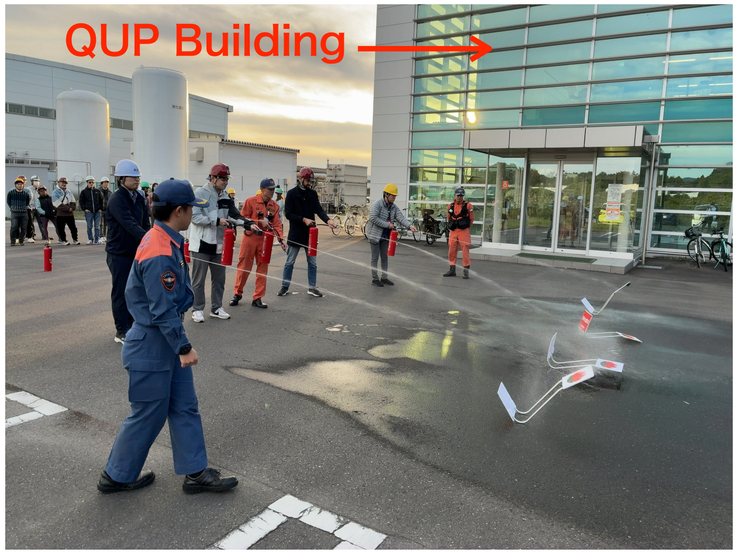
What is QUP?

QUP: International Center for **Q**uantum-field Measurement Systems for Studies of the **U**niverse and **P**articles

→ An institute under KEK dedicated to quantum sensor research



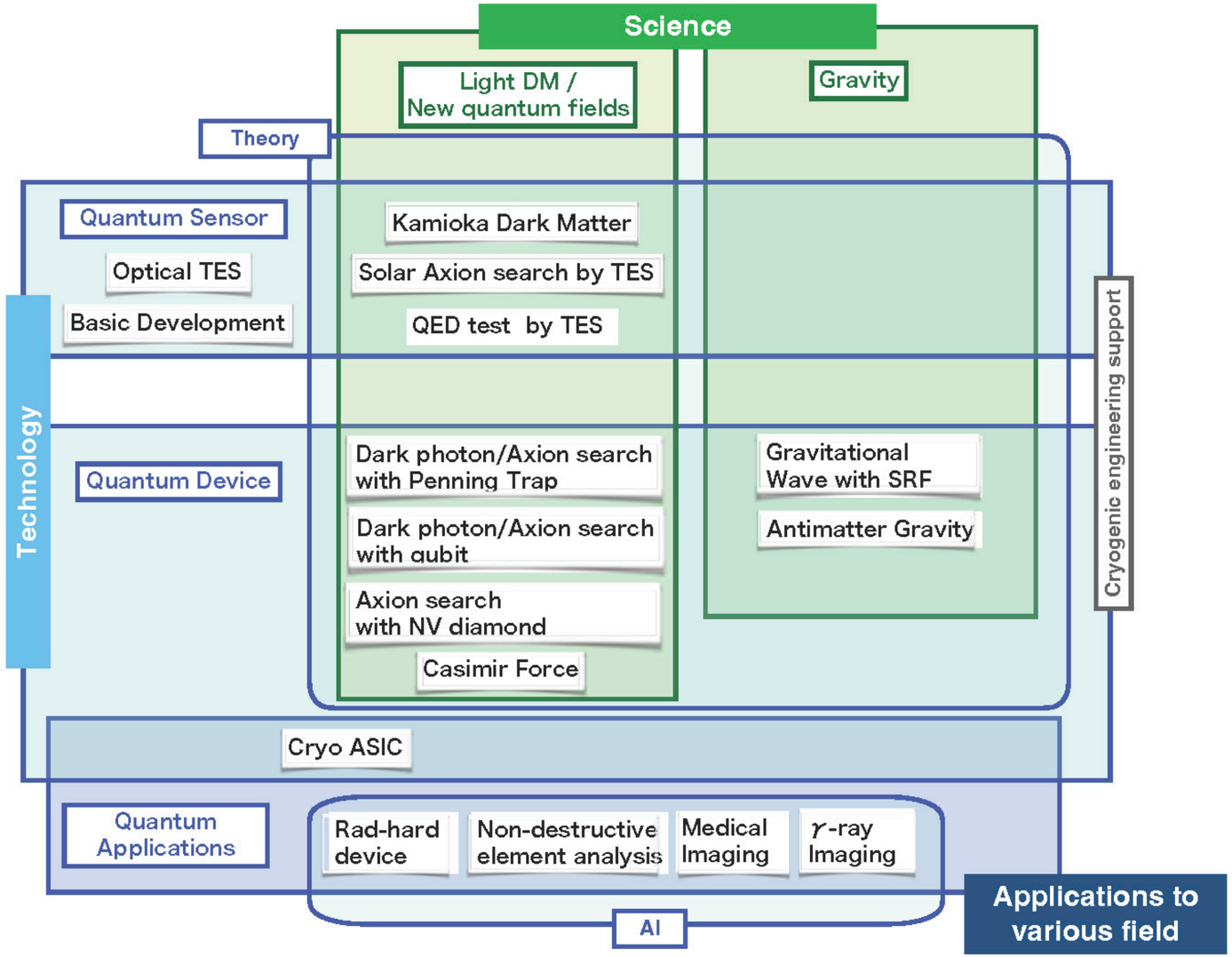
New director: Toshiyuki Azuma
as of Dec 2025.
Former PI at RIKEN and an expert in AMO physics





The new QUP building was completed in October 2025!

KEK - QUP overview



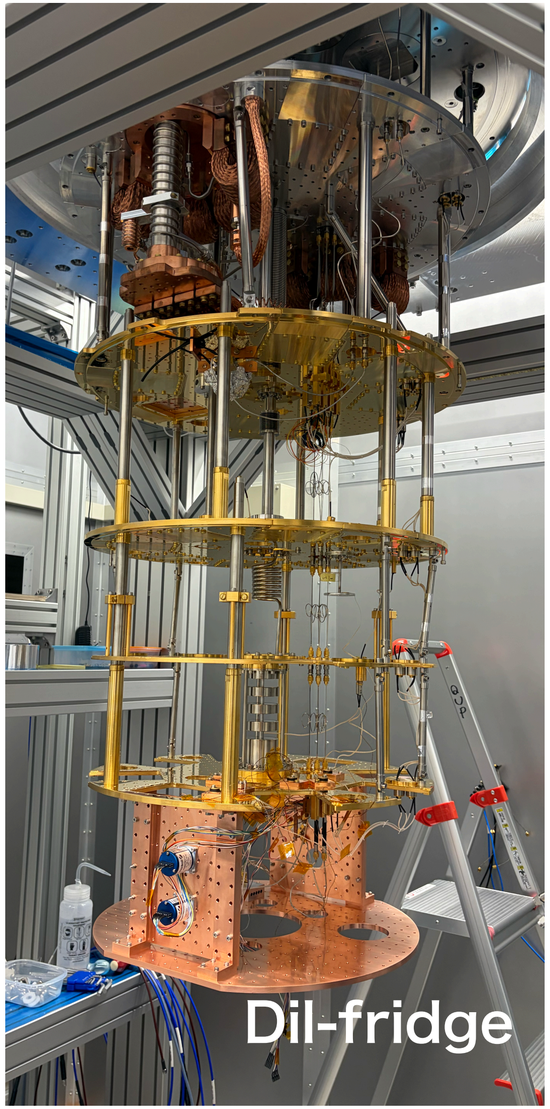
cryogenic facility

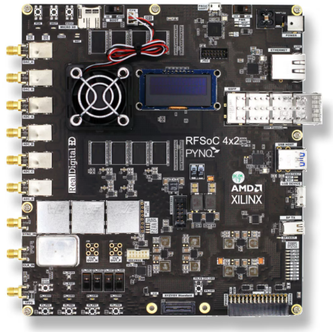
We have 5 dilution refrigerators
- 2 at old experimental hall
- 2 at new QUP building →
- 1 at Kamioka ↓



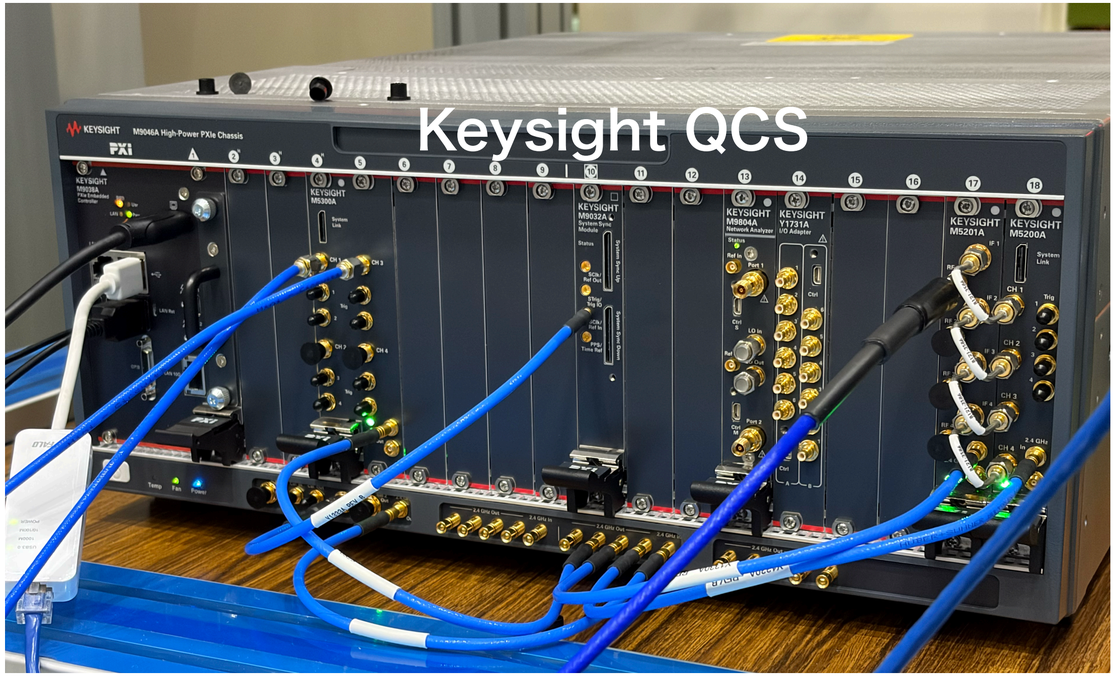


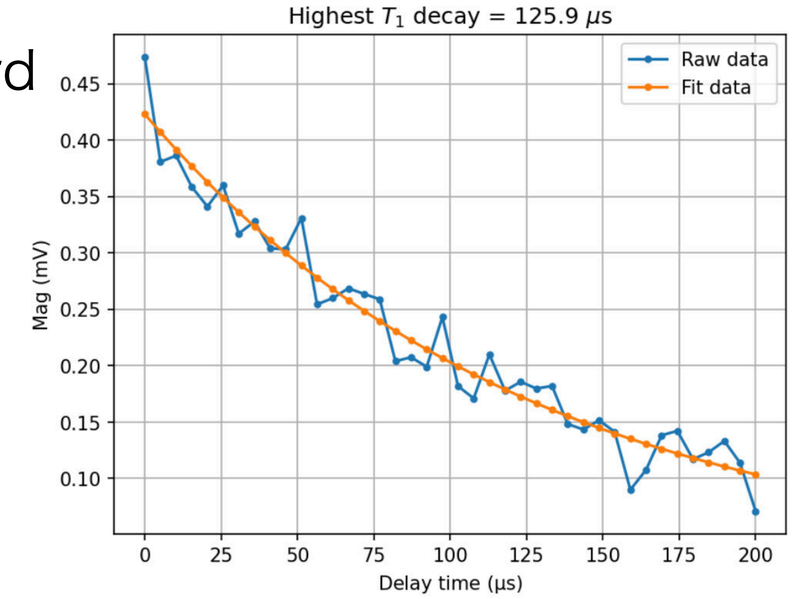
Qubit measurement facility





general purpose test board
to dedicated instrument

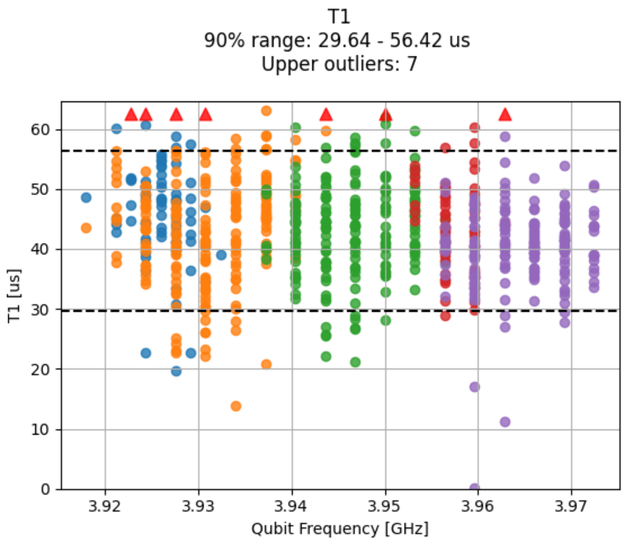


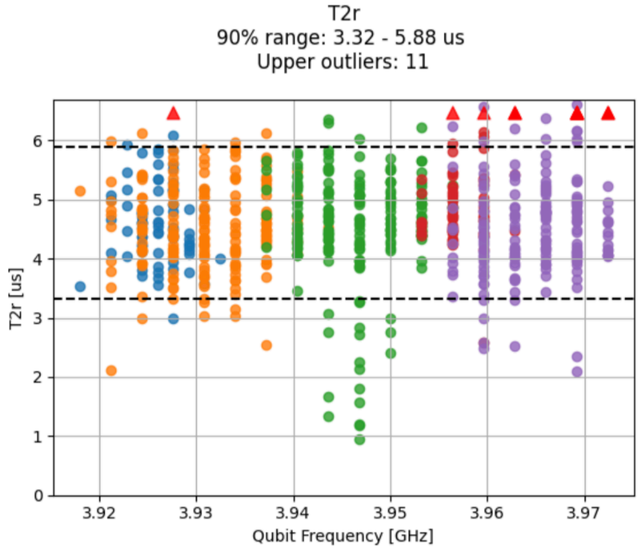


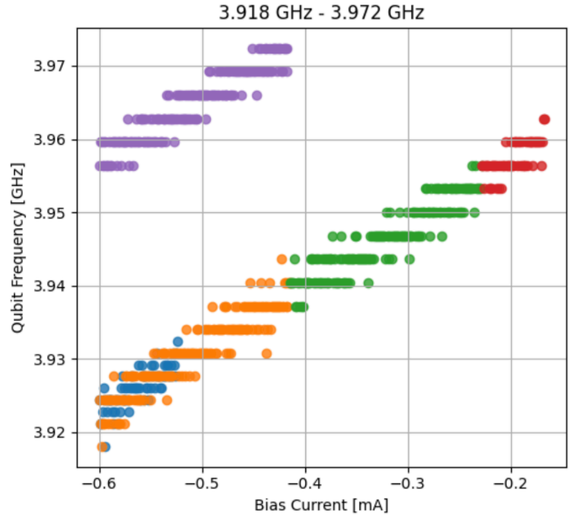
T1~125μs measured

Qubit measurement facility

DM data-taking has been already started at KEK QUP!







Plots from Karin Watanabe

More than 50 MHz scanned in a few days w/o quantum amplifier

Quantum amplifier arrived at KEK last week

-> 100 times faster measurements -> **Scan speed could be 1 GHz / day**

Other facilities

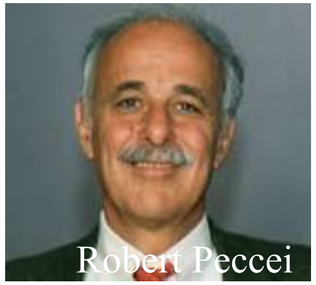
Clean Booth (Class 7)



Anechoic Chamber

DM search with superconducting qubits

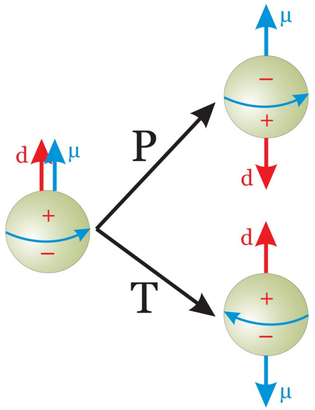
Motivation


Robert Peccei


Helen Quinn

Axion: New pseudoscalar elementary particle haven't been discovered yet

In quantum field theory

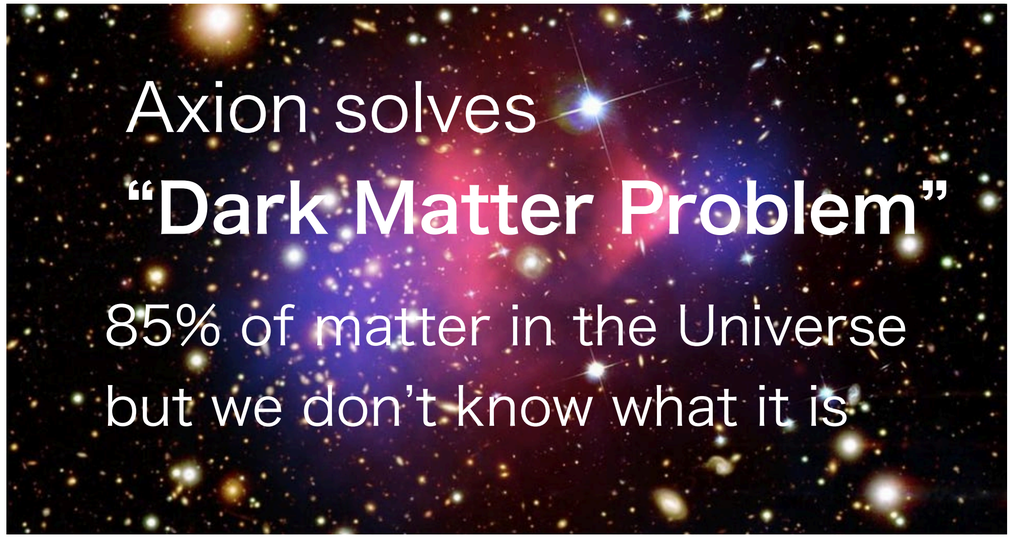


Axion solves

"Strong CP problem"

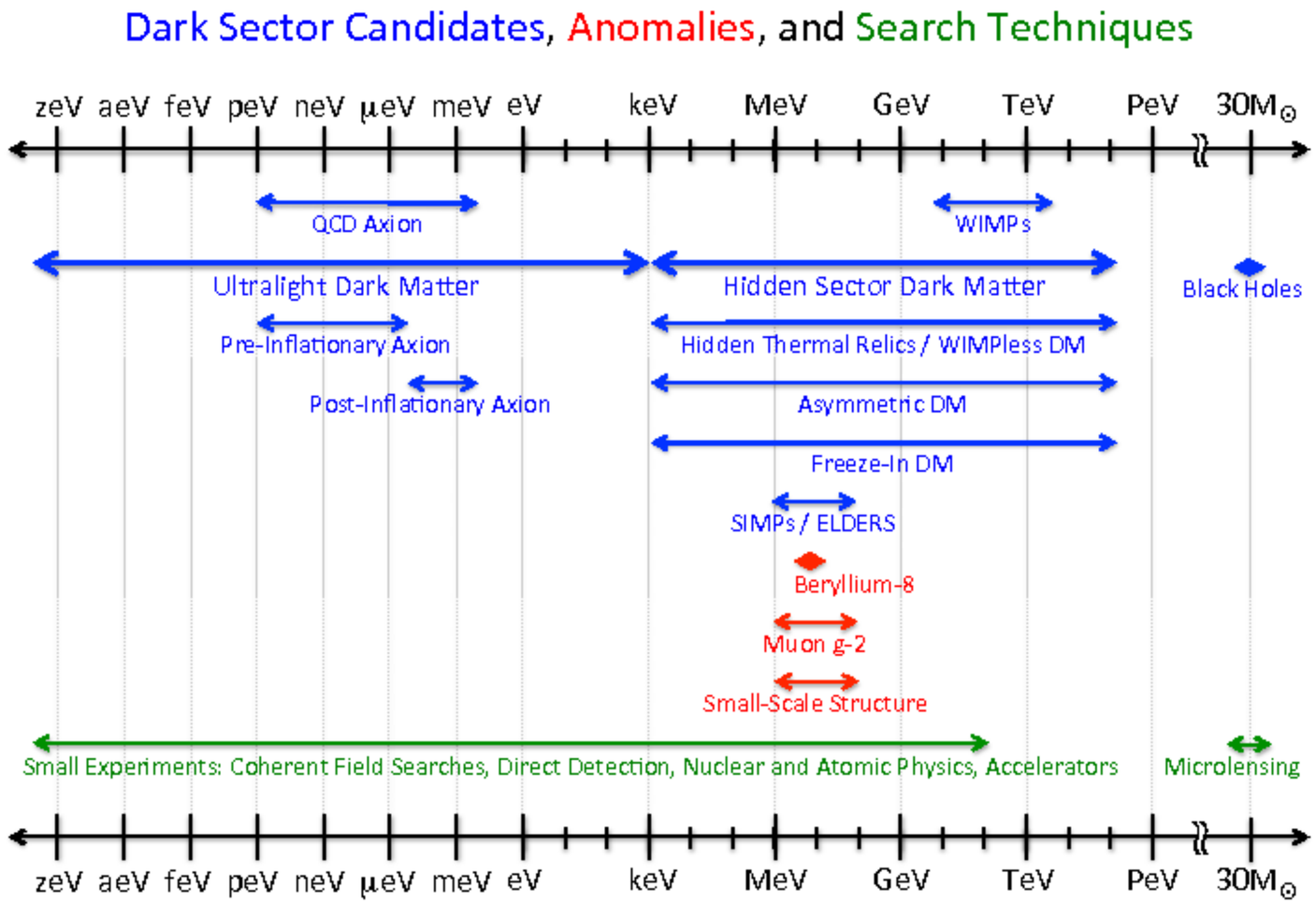
Observed neutron EDM is "unnaturally" small

In cosmology/astrophysics



Detecting "axion as dark matter" solves both

Axion is one of candidates, but…



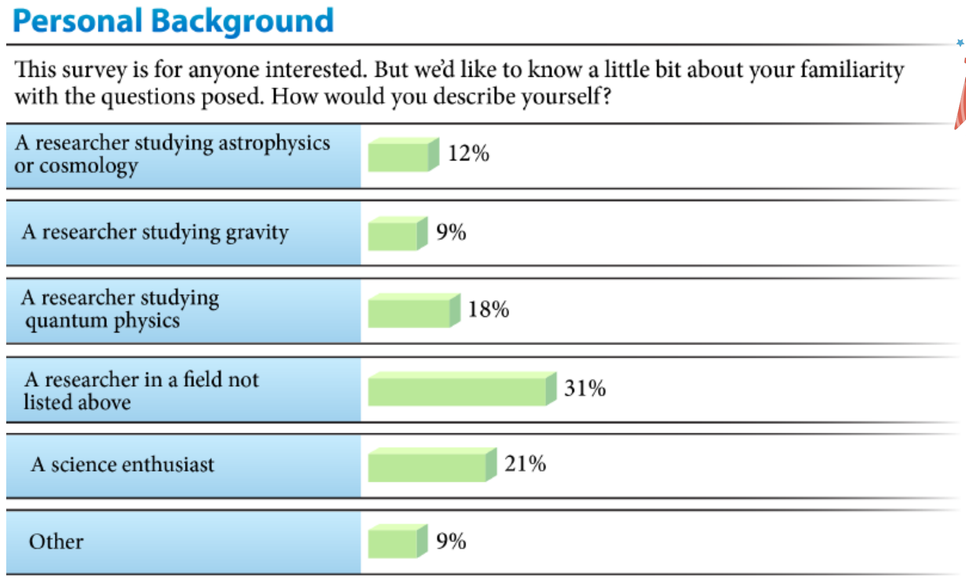
US Cosmic Visions: New Ideas in Dark Matter 2017: Community Report

Axion is the most promising!

Large scale survey (1675 participants)
of Big mysteries on Physics
by APS Physics Magazine

Appeared on arXiv last week

https://arxiv.org/pdf/2605.11058





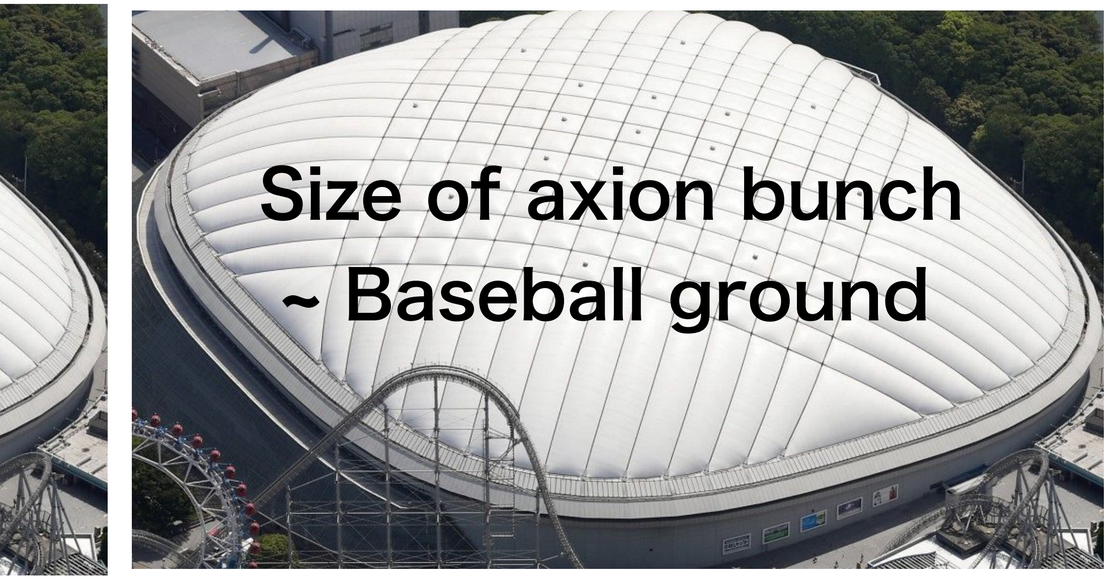
3. Question 3: Dark Matter or Modified Gravity

Question. The observed rotation rates of galaxies are faster than expected, given the gravitational pull of the light-emitting matter contained in the galaxies. These rotation rates and related observations (e.g., clusters of galaxies, baryonic acoustic oscillation, and cosmic microwave background anisotropies) have led to proposals for "new physics" either in the form of dark matter or of modifications to the laws of gravity. In your opinion what is the most likely candidate for explaining these gravitational anomalies?

Answer	Count ($\pm 1\sigma$)	Percent ($\pm 1\sigma$)
Low-mass dark matter particles (e.g., axions)	290 ± 17.0	17.4 ± 1.0
High-mass dark matter particles (e.g., WIMPs)	167 ± 12.9	10.0 ± 0.8
A modification to classical gravity on galaxy scales (e.g., MOND)	192 ± 13.9	11.5 ± 0.8
Primordial black holes	90 ± 9.5	5.4 ± 0.6
A hybrid of the above	344 ± 18.5	20.6 ± 1.1
Effects of quantum gravity	168 ± 13.0	10.1 ± 0.8
Other	164 ± 12.8	9.8 ± 0.8
No opinion	252 ± 15.9	15.1 ± 0.9

Axion as Dark Matter

$m_a = \mathcal{O}(1)\ \mu\mathrm{eV/c^2}$, $\rho_a \sim 0.45\ \mathrm{GeV/cc}$, $\lambda_{de\ Broglie} = \mathcal{O}(100)\ \mathrm{m} \gg \bar{d}_{\mathrm{DM}}$ **(mean DM distance)**



$O(100\ \mathrm{m})$

$v_a \sim 10^{-3}c$

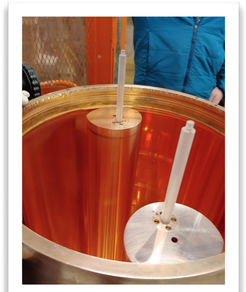
$t_c \sim 1\ \mathrm{ms}$



Axion DM is like a bunch of gigantic slow laser-like pulses

Nominal Axion Search and Difficulties

wavelike DM

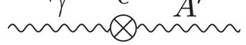


1. Put cavity on the Earth

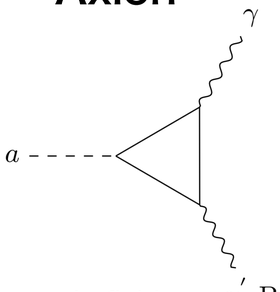
Tuning with metric rod

2. DM → Photon Converting

Dark Photon



Axion



Magnetic field is the most rich (virtual) photon source

3. Detecting tiny photon signal

Detector → Amplifier

antenna

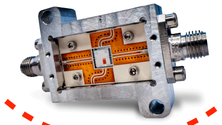


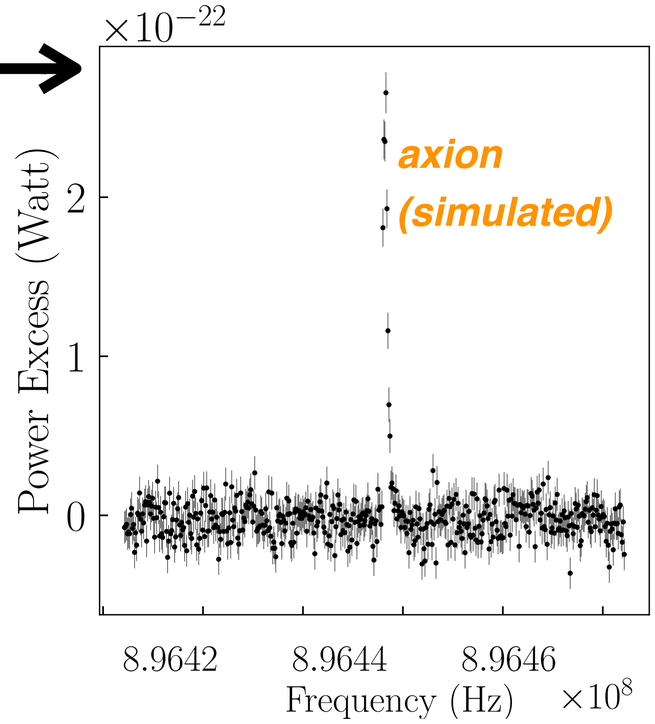


HEMT



Quantum amplifier

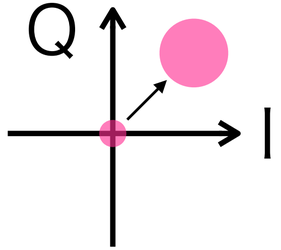




Easy tuning with qubit

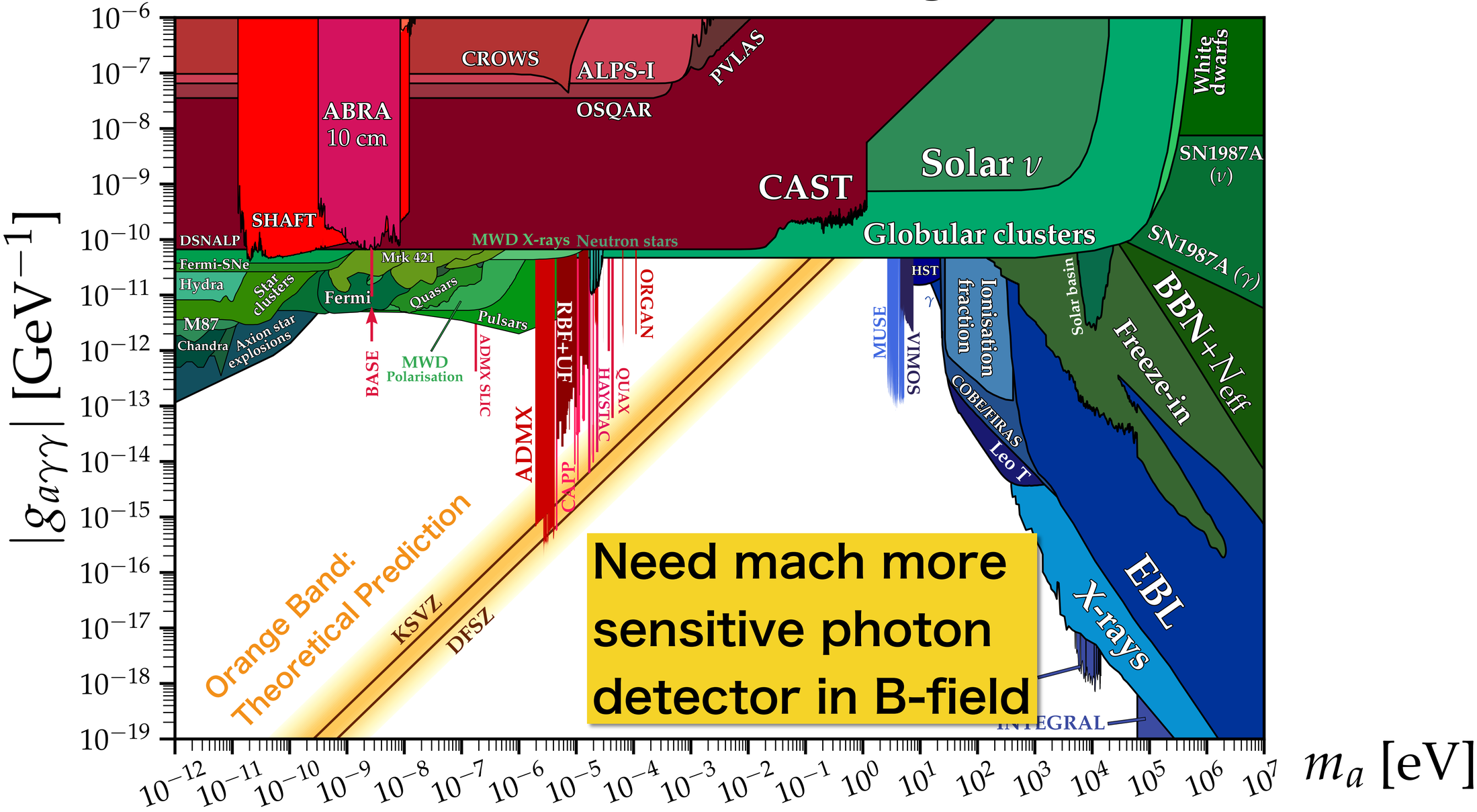
Cavity tuning is annoying
- heat problem
- mechanical problem
- EM leakage from cavity

Higher sensitivity with qubit



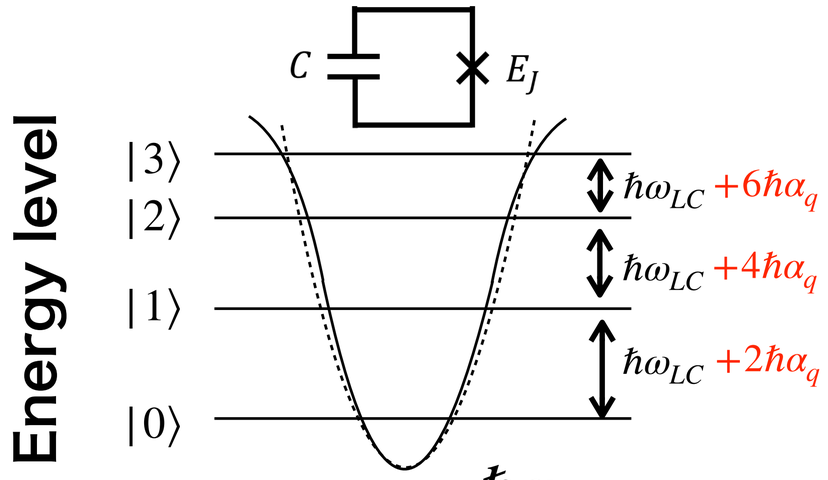
Amplifier (JPA, TWPA) limited by standard quantum limit:
uncertainty principle for measuring phase and amplitude at the same time

How close to discovery axion?



Main Idea

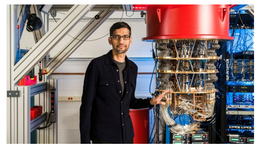
As a quantum computer



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

manipulatable

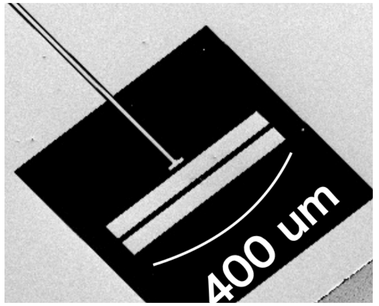
quantum computer

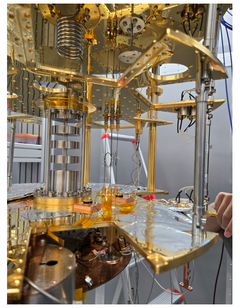


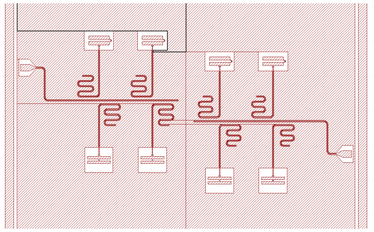
A lot of ideas invented at

QIS research area

As a quantum sensor







- **Large Electric Dipole Moment**
  → Very sensitive to ambient electric field
- **Working at mK temperature**
  → Low fake signals
- **Designable circuit**
  → Any desired sensors can be made

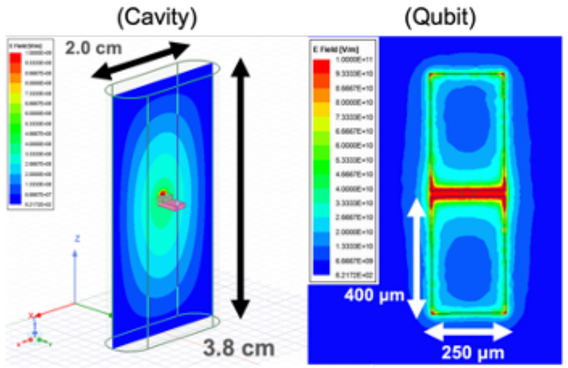
Adapt these advancements on

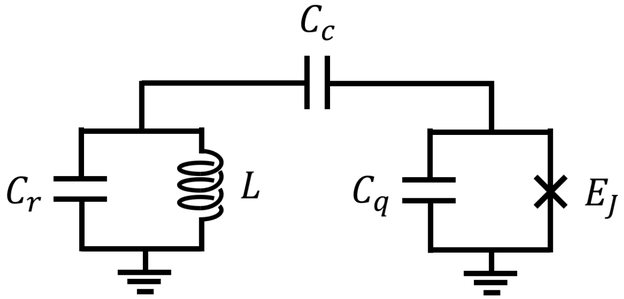
Particle, Astro research area

Qubit Application to DM search

As cavity tuner

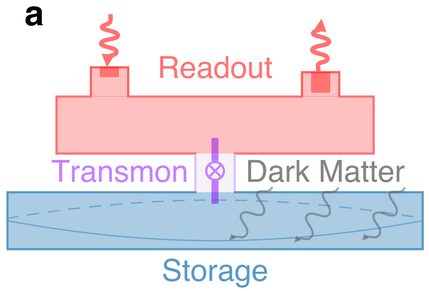
Zhao+ PRL **135,** 201002
Nakazono+ arXiv 2505.15619



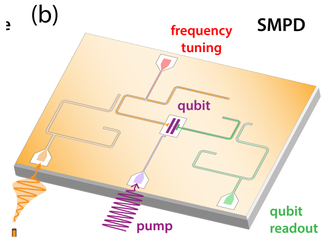


As single photon detector

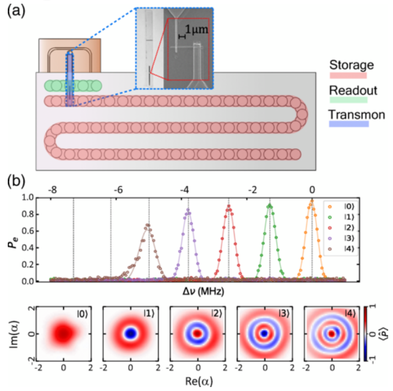
Dixit+ PRL **126,** 141302



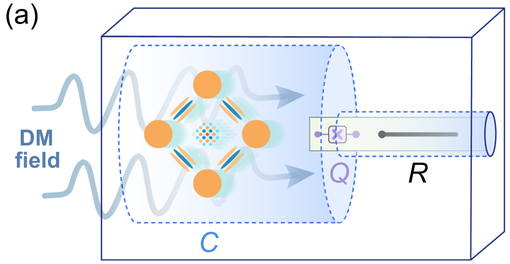
Braggio+ PRX **15,** 021031



Agrawal+ PRL **132,** 140801



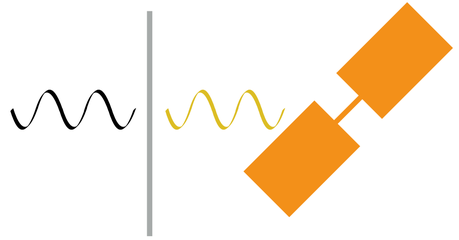
Zheng+ PRL **136**, 171002

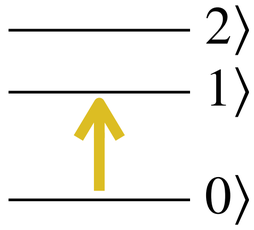


As DM antenna

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

Watanabe+ Patras 2024, 2025
Kang+ PRL **135**, 181004

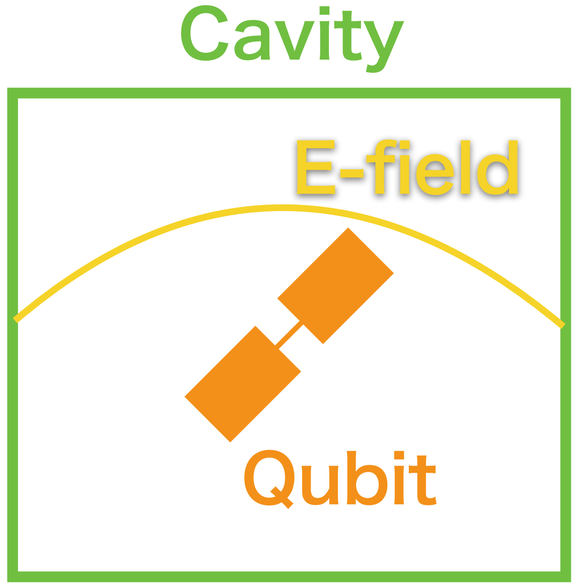




Shion Chen's talk

Qubit as cavity tuner: DarQ-Lamb

Qubit as cavity tuner

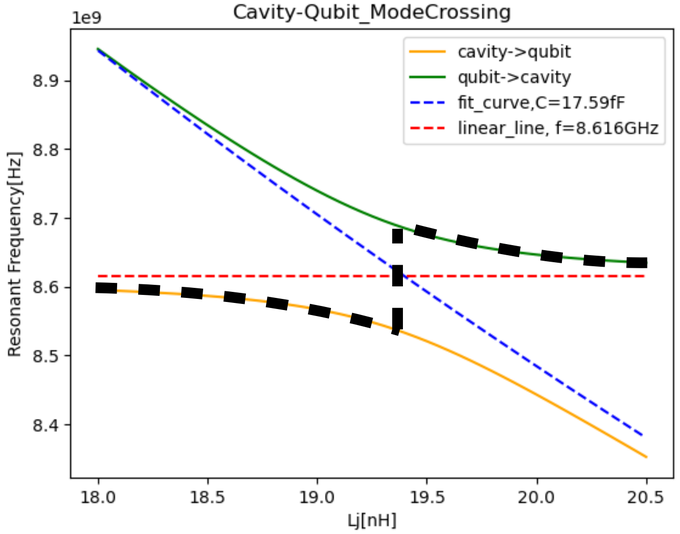


Qubit Cavity Interaction

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

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

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



Conventional tuning

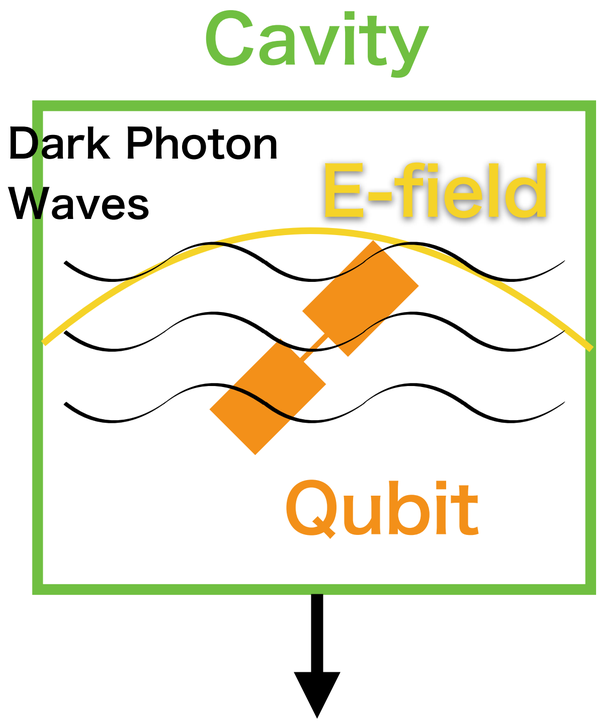
- friction heat
- mechanical difficulties
- EM leakage

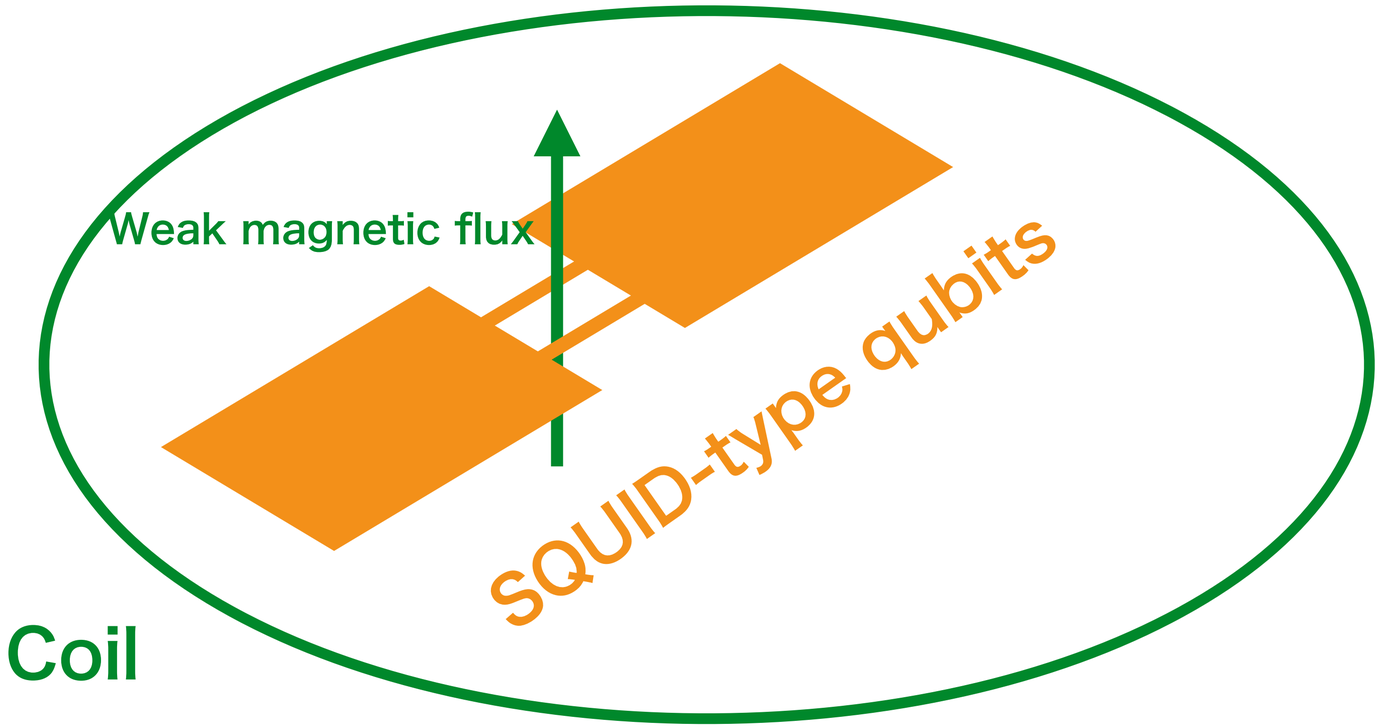


Qubit tuning

- No heat essentially
- No moving parts
- cavity can be perfect closed geometry

Qubit as cavity tuner

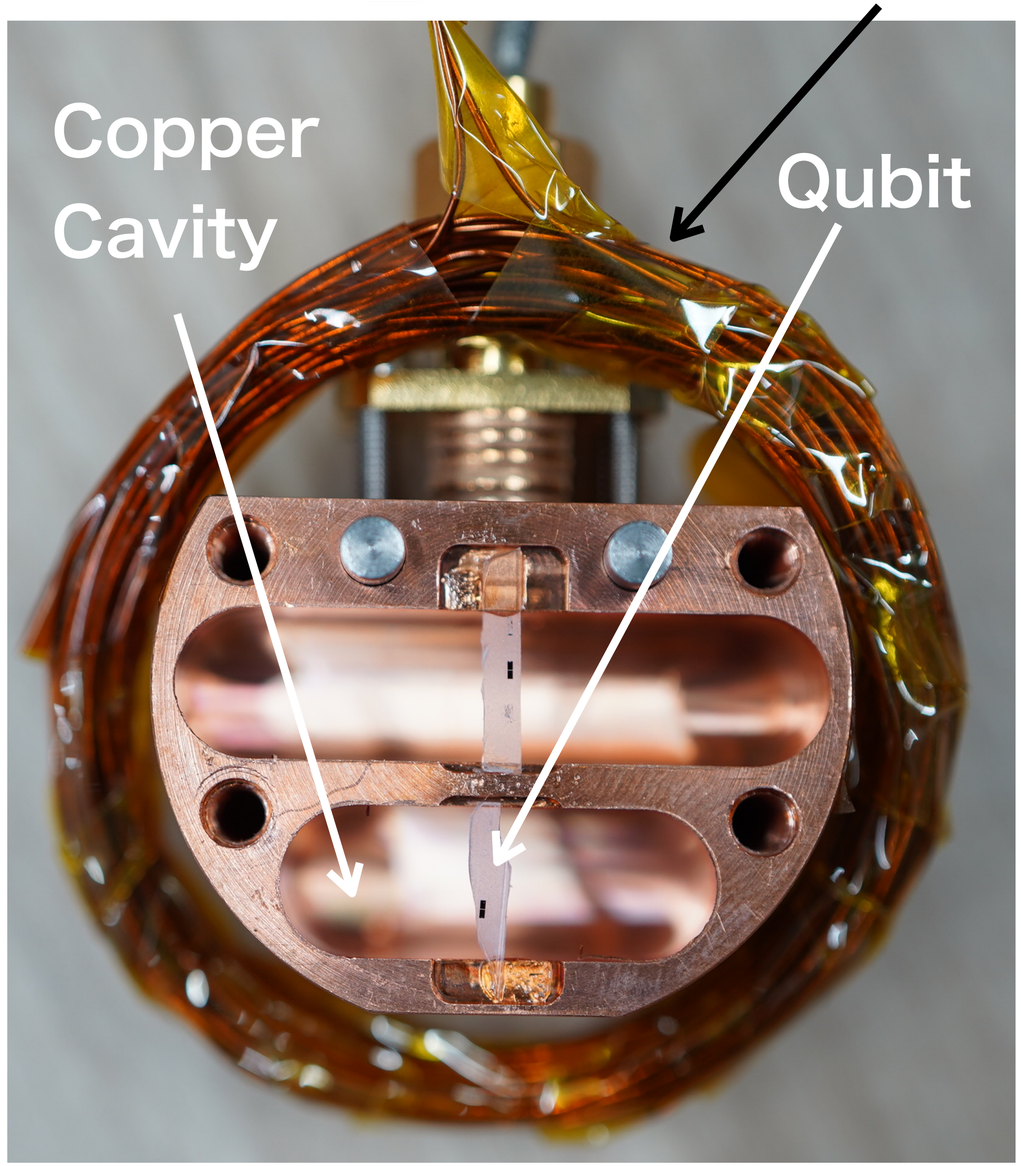


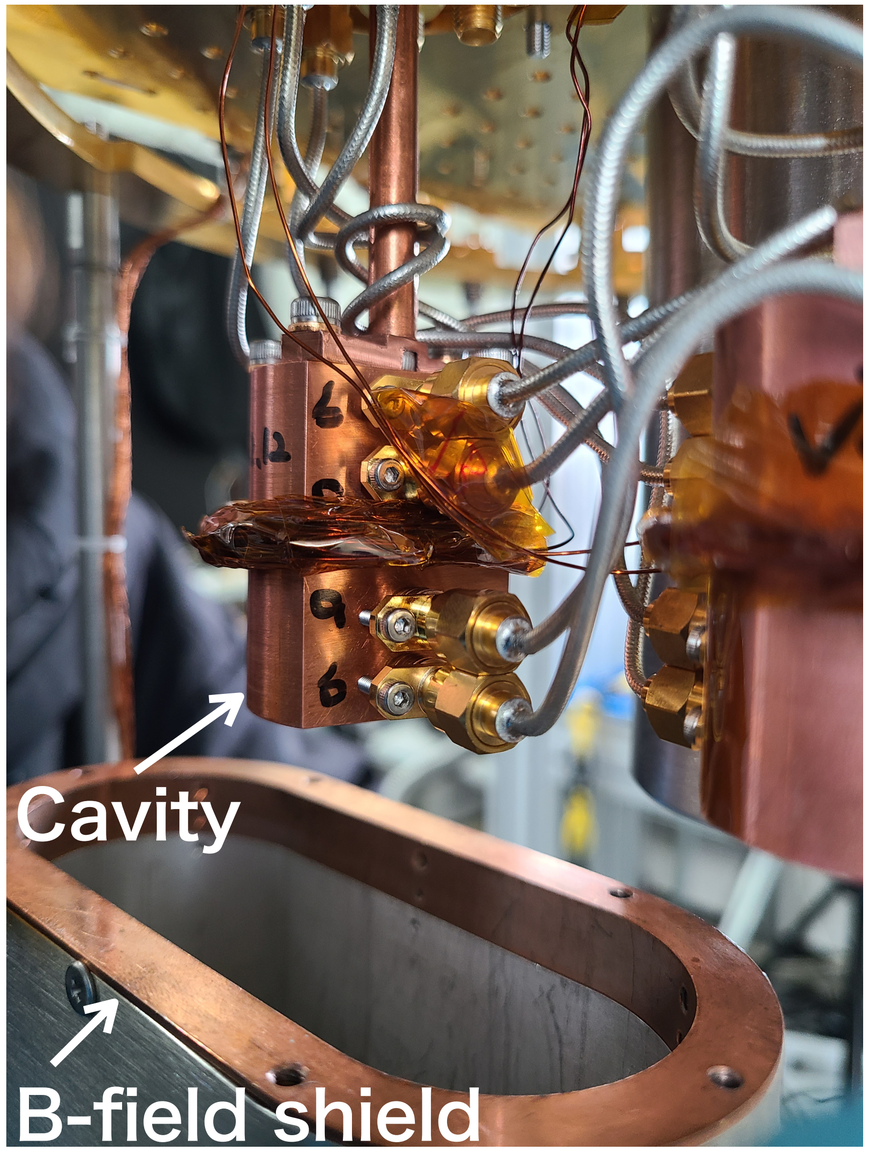


Readout by standard axion search like readout

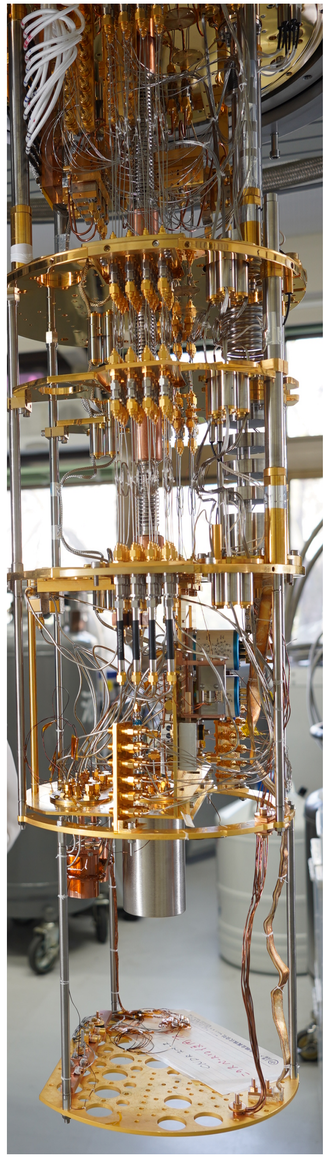
Tuning of qubit frequency is easy
Just applying external small magnetic field to the squid loop

Setup

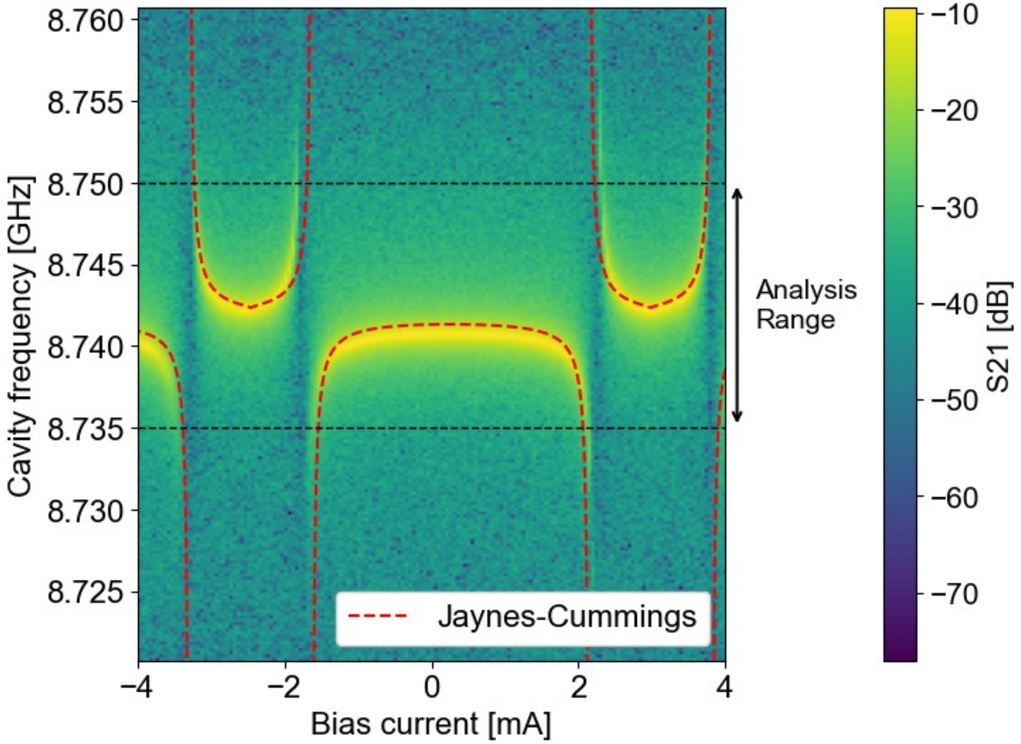


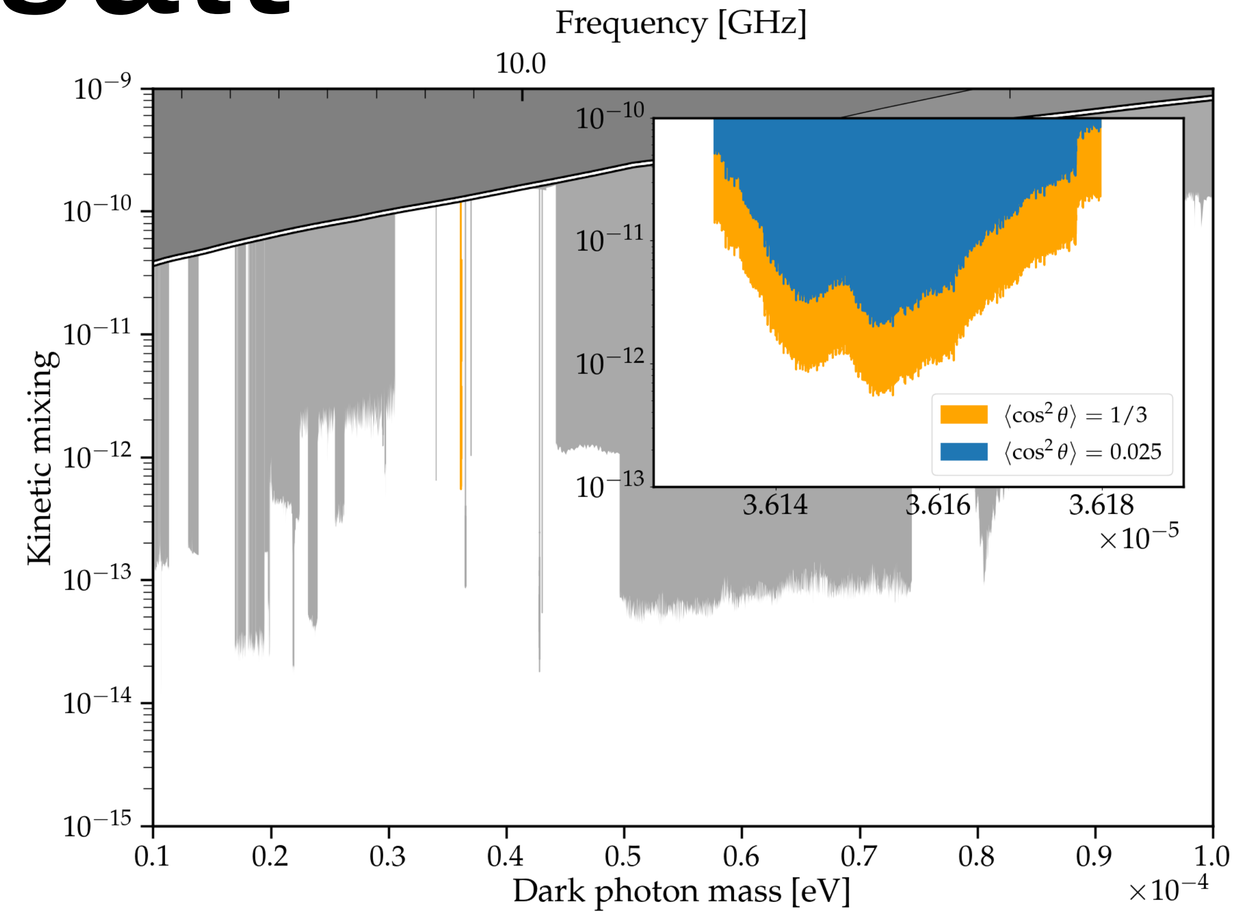


fridge



DarQ-Lamb Result





Proof of principle experiment arXiv:2505.15619

Tuning range is proportion to the coupling between qubit and cavity

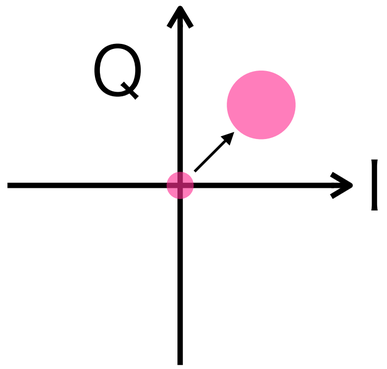
We are trying to enlarge coupling with optimized qubits

Qubit as single photon counter

Why Single Photon Counting?

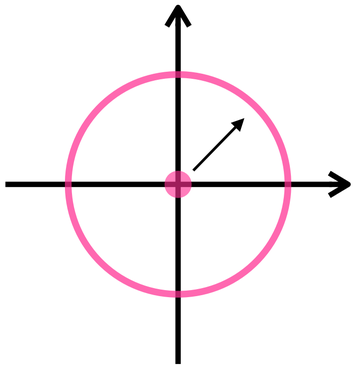
Sensitivity already hits the standard quantum limit

$\Delta n \Delta \phi \geq \frac{1}{2}$: ~30 mK@1GHz, ~300 mK@10GHz



Quantum limited amplifier
(JPA or TWPA)
amplify both
amplitude and phase

Single Photon Counter



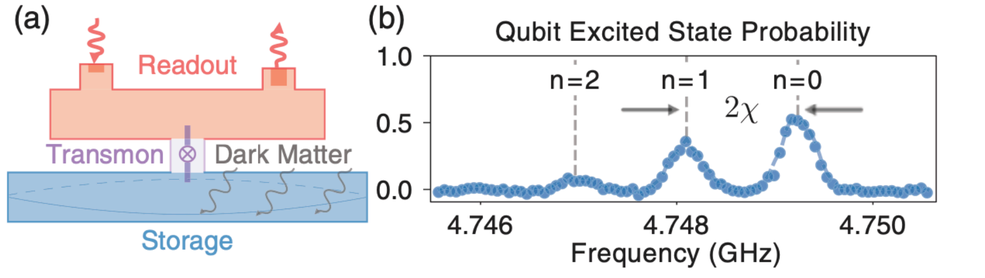
subverts the limit
(just ignore phase
information)

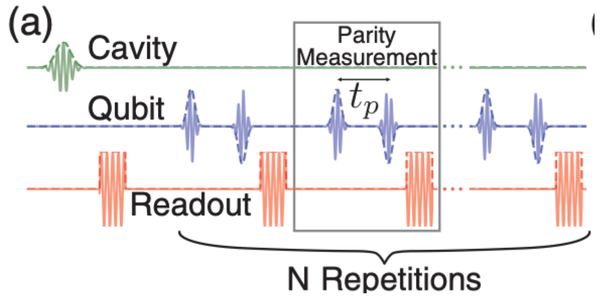
Single photon counting

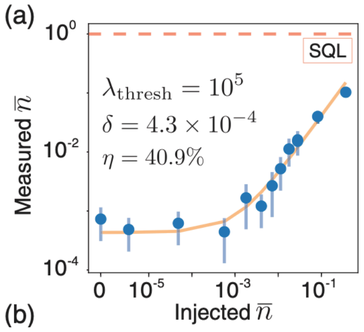
Pioneering work from FNAL/U Chicago

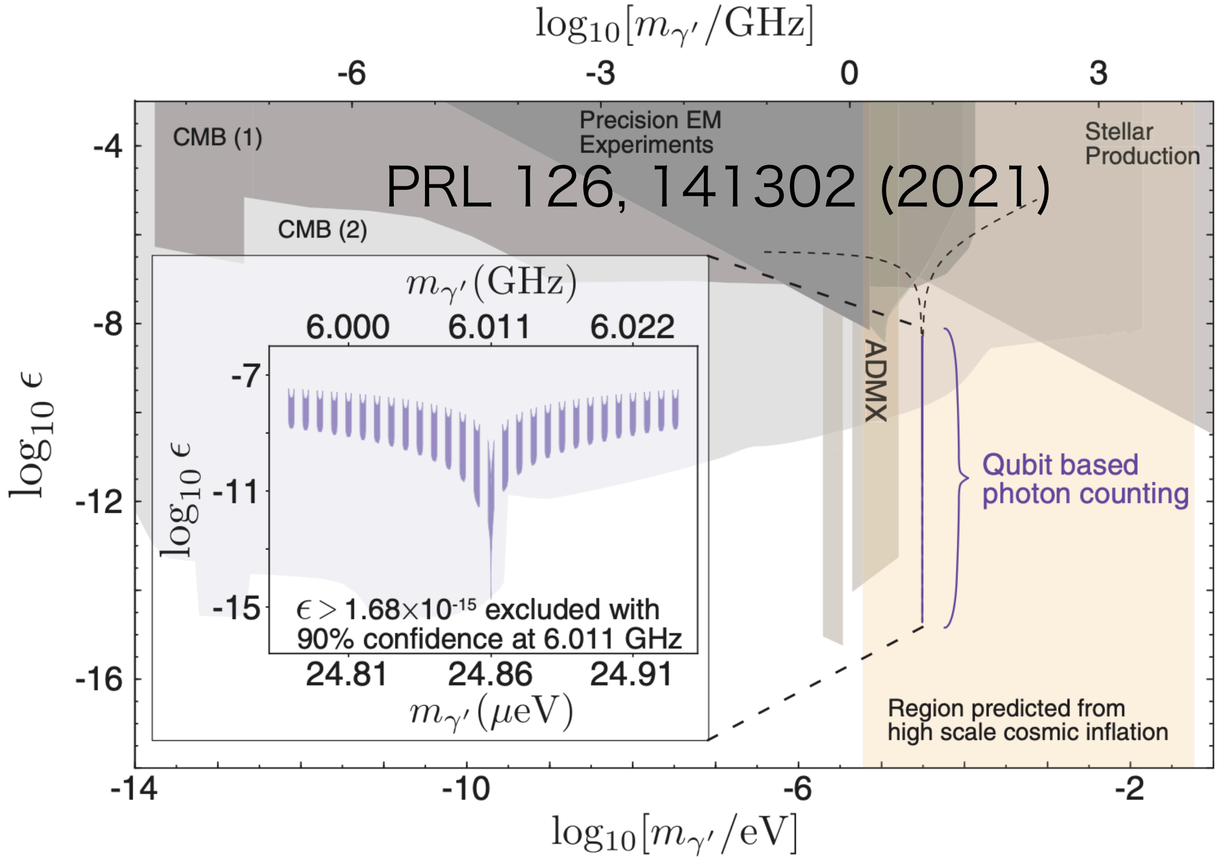
Dixit+ PRL **126,** 141302

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





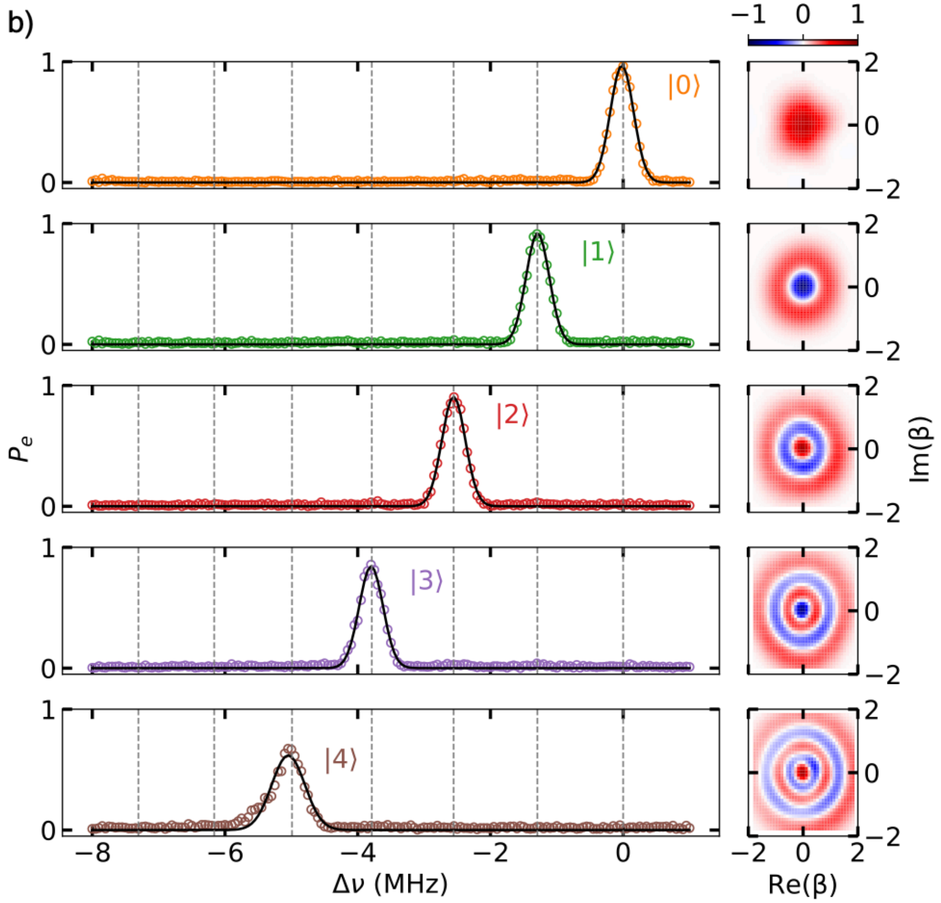


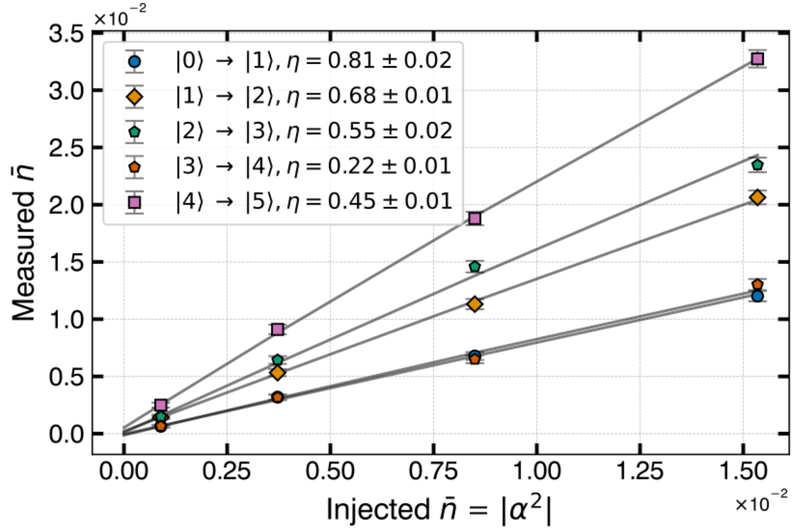


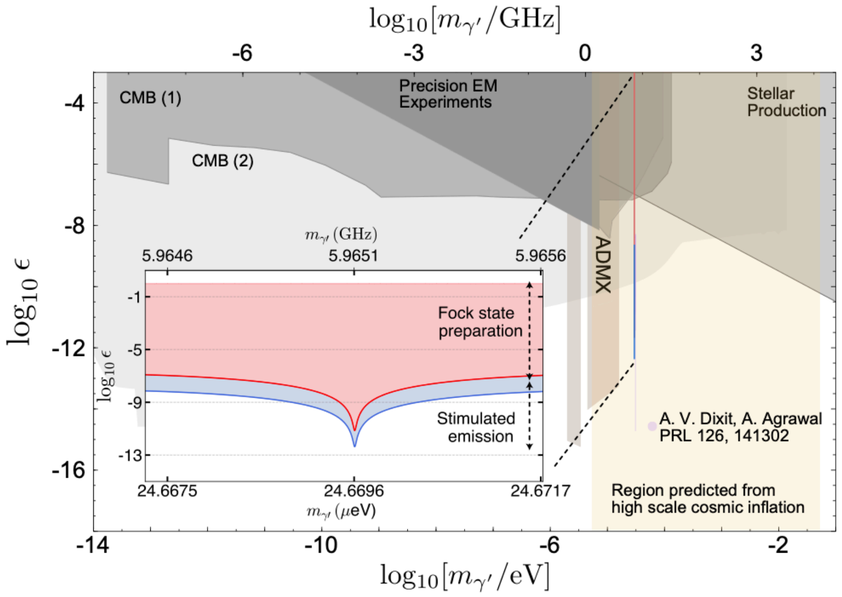
1/37 of SQL → ~1300x speed up

Bose enhancement

$$|\langle n+1|\hat{\mathcal{D}}(\alpha)|n\rangle|^2 = |\langle n+1|e^{(\alpha a^\dagger - \alpha^* a)}|n\rangle|^2$$
$$\sim |\langle n+1|\alpha a^\dagger|n\rangle|^2 = (n+1)\alpha^2$$







Up to $|n = 4\rangle$

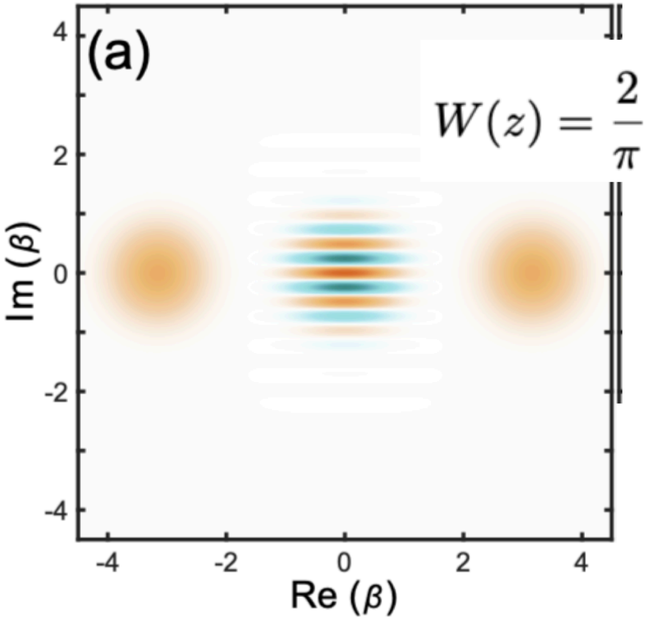
→ 2.78x signal

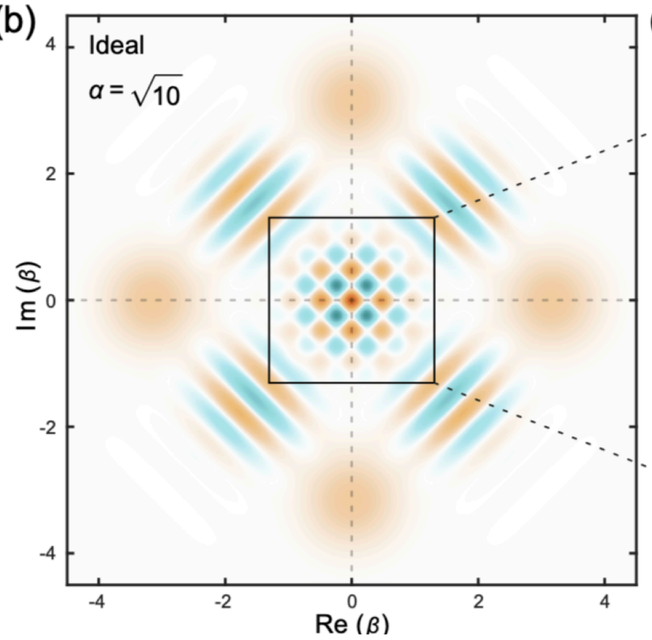
< 4+1

- State preparation
- Faster decay

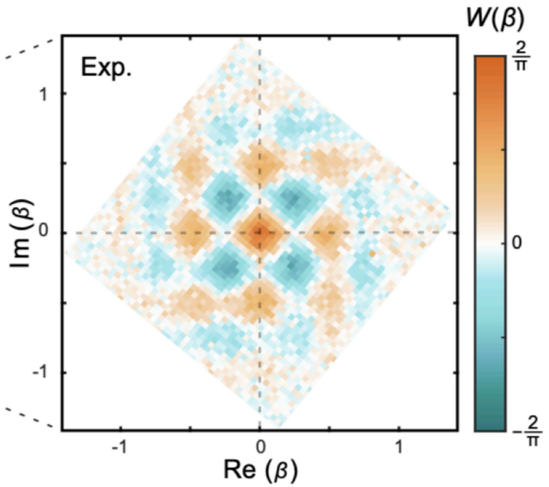
Sudden news from China: Cat

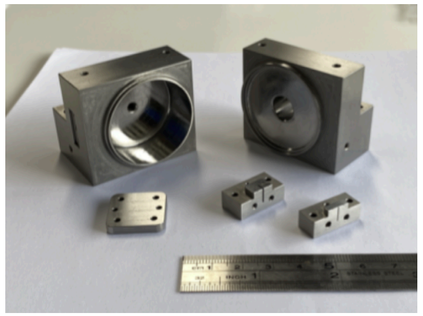
https://conference-indico.kek.jp/event/352/contributions/7337/attachments/4931/8075/KEK-QUP2025-30min.pdf

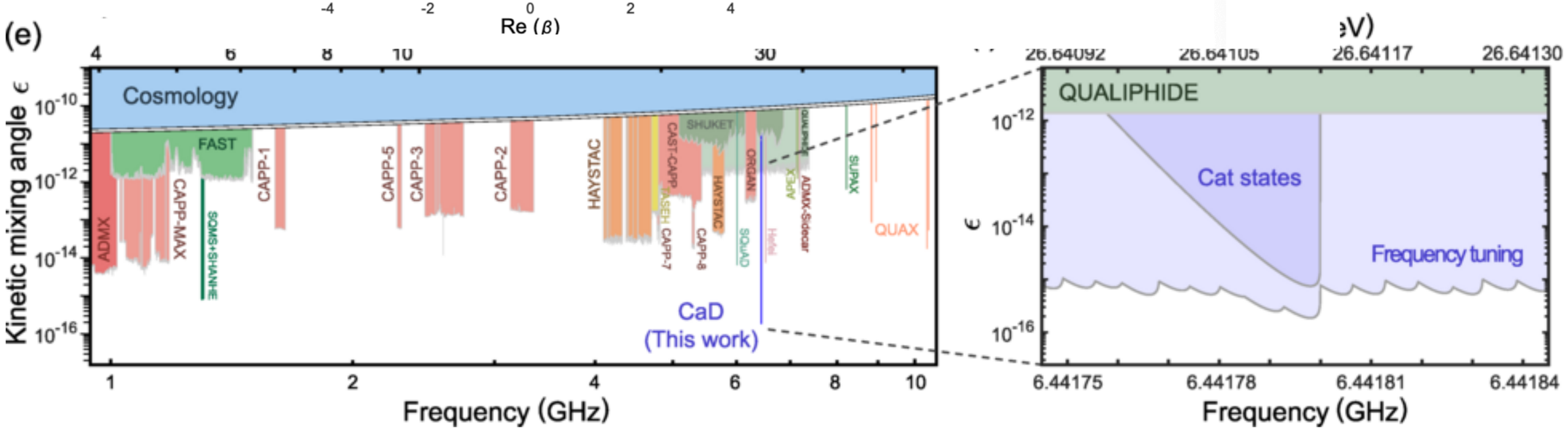




(c) DM, weak displacement

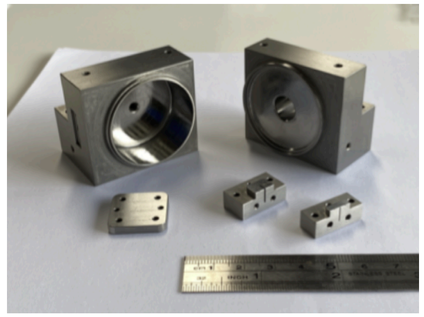




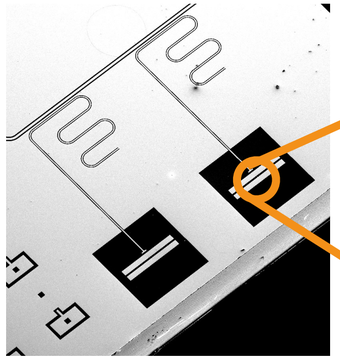


Axion needs B-field

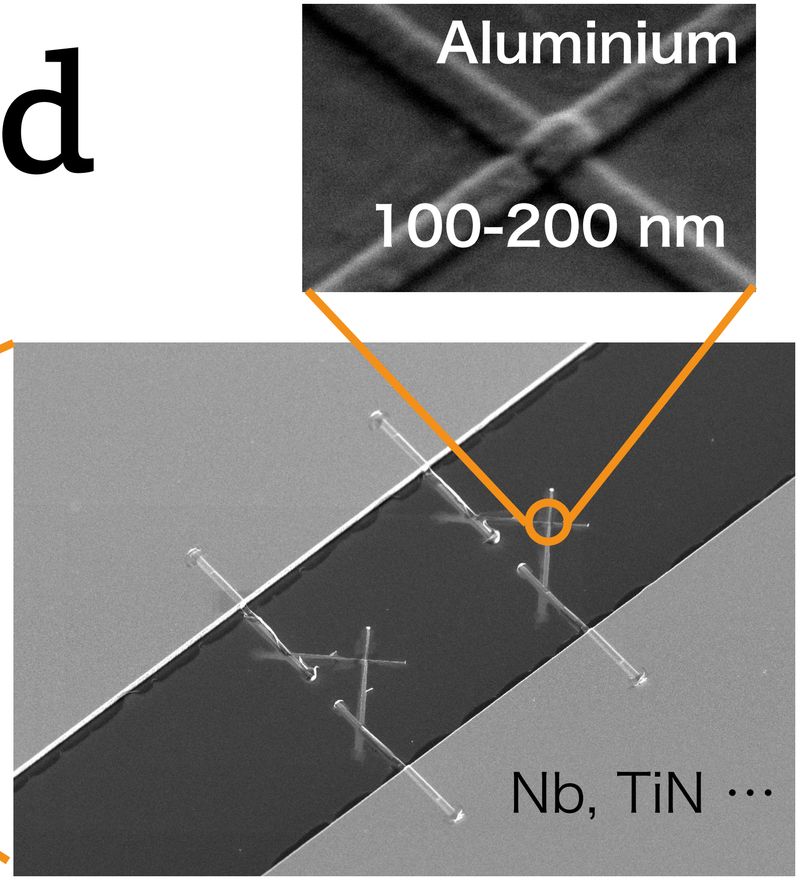
How can we survive?



Nb dies << 1Tesla



Qubit dies << 1 Tesla

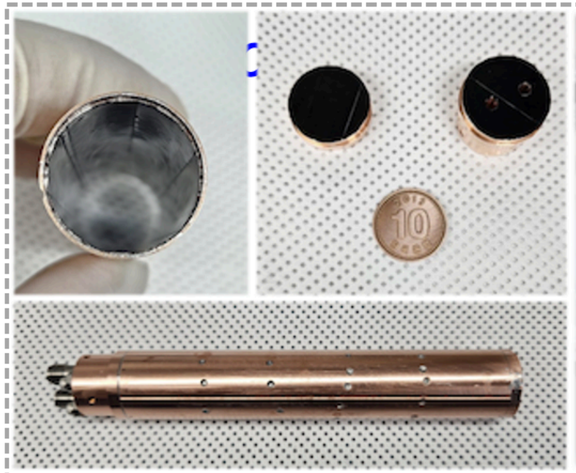


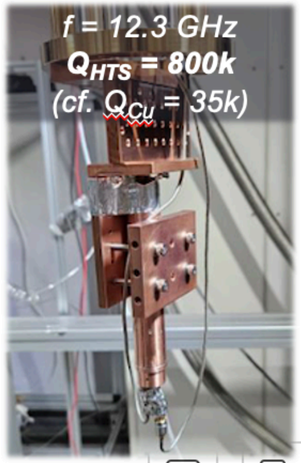
Most of superconductor for qubits are pure material

→ Explore other than pure material !

High Temp. Superconductors

https://indico-tdli.sjtu.edu.cn/event/4847/timetable/#20260428







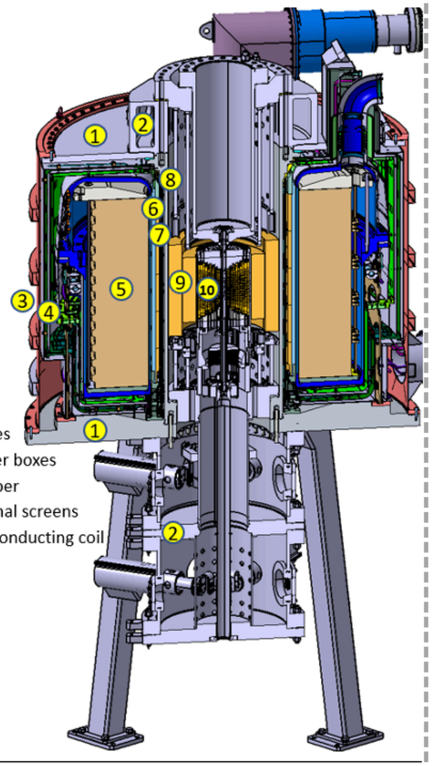
- *HTS performance test up to 42T*
- *Commissioning run for axion search*



B(T)	Q_0
0.0000	6.0000e+05
8.5000	5.2000e+05
0.0000	6.0500e+05
20.000	4.4700e+05
30.000	4.3000e+05
42.000	3.9000e+05

$Q_{HTS} > 10 \times Q_{Cu}$

Grenoble hybrid magnet

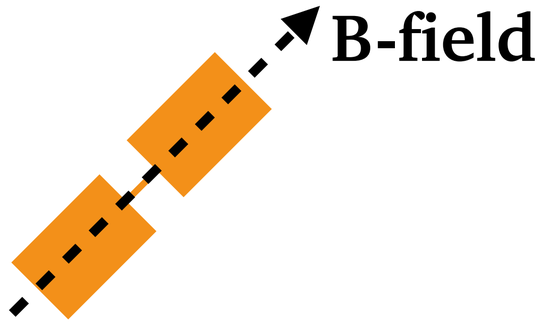


① Top and bottom plates
② Top and bottom water boxes
③ Outer vacuum chamber
④ 2 sets of active thermal screens
⑤ He vessel and superconducting coil
⑥ Eddy-current shield
⑦ Inner thermal screen
⑧ Inner bore tube
⑨ 2 Bitter magnets
⑩ 14 polyhelix insert

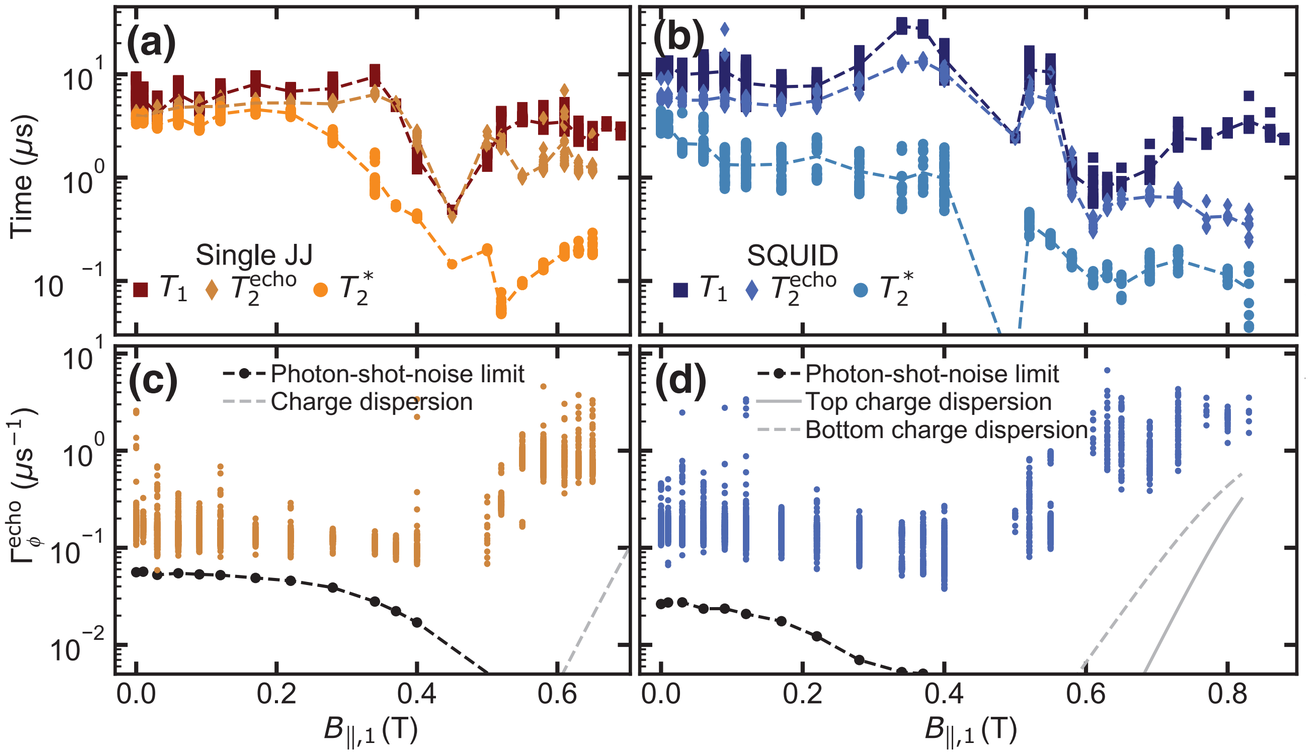
Field in T (nominal)	Warm dia. in mm	Grenoble hybrid magnet configurations	Electrical power in MW [2]
42 (43) [1]	34	14 helix + 2 Bitter + superc.	20.7 + 2.8 + 0.4
34 (35)	34	14 helix + superc.	10.6 + 1.1 + 0.4
17.3 (17.5)	375	2 Bitter + superc.	10.9 + 1.1 + 0.4
8.5 (9.5)	812	Superc. alone	0.4 [3]

Slides from SungWoo Youn
IBS-DMAG

Ways to introduce B-field



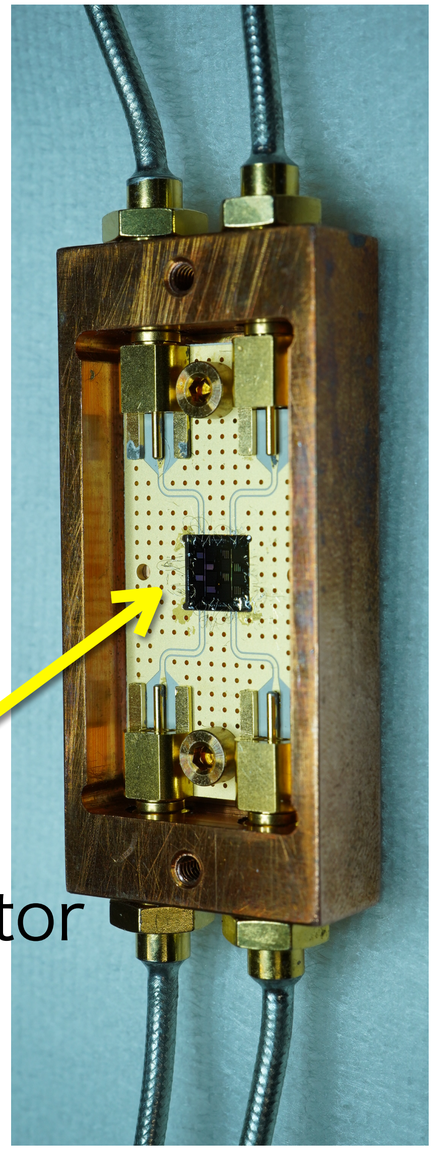
Parallel field doesn't penetrate superconductor
→ qubit can survive in B-field!



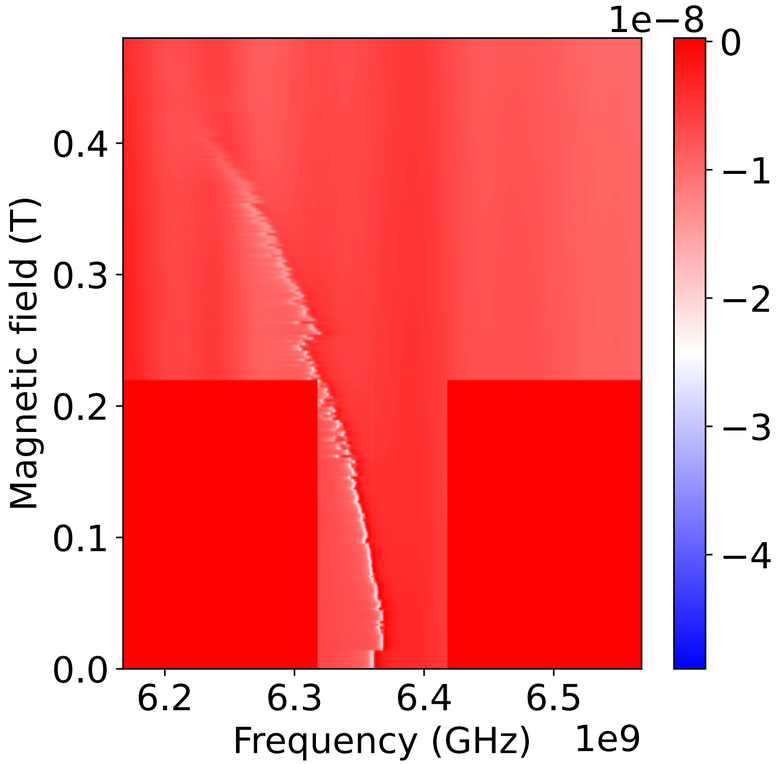
J. Krause et.al., Phys. Rev. Applied, 17, 034032 (2022)

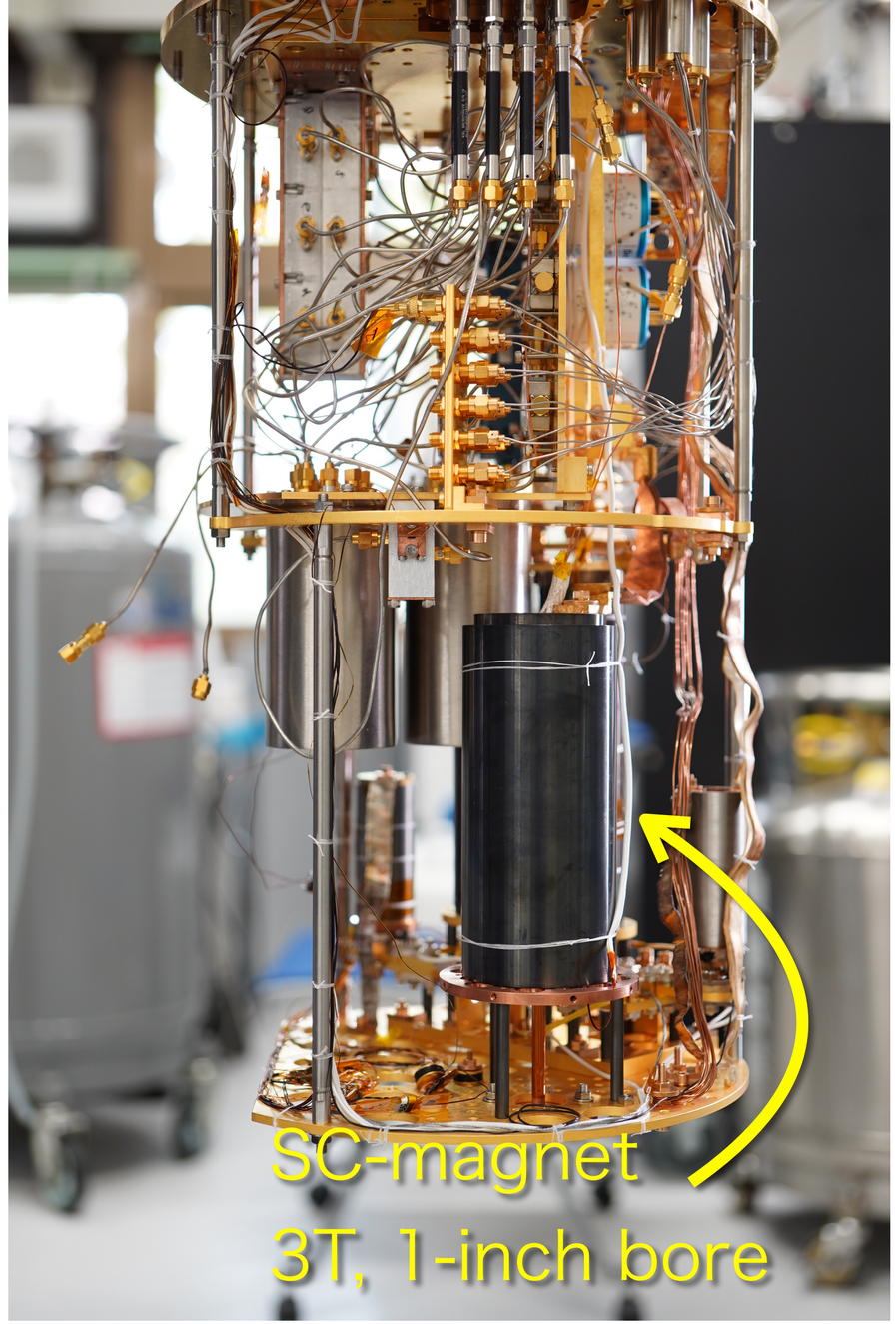
Usual qubits (Niobium film + Aluminium junctions) live at least 1Tesla
→ We aim to increase up to ~ 10 Tesla with some improvement (like high Hc superconductor)

Study ongoing



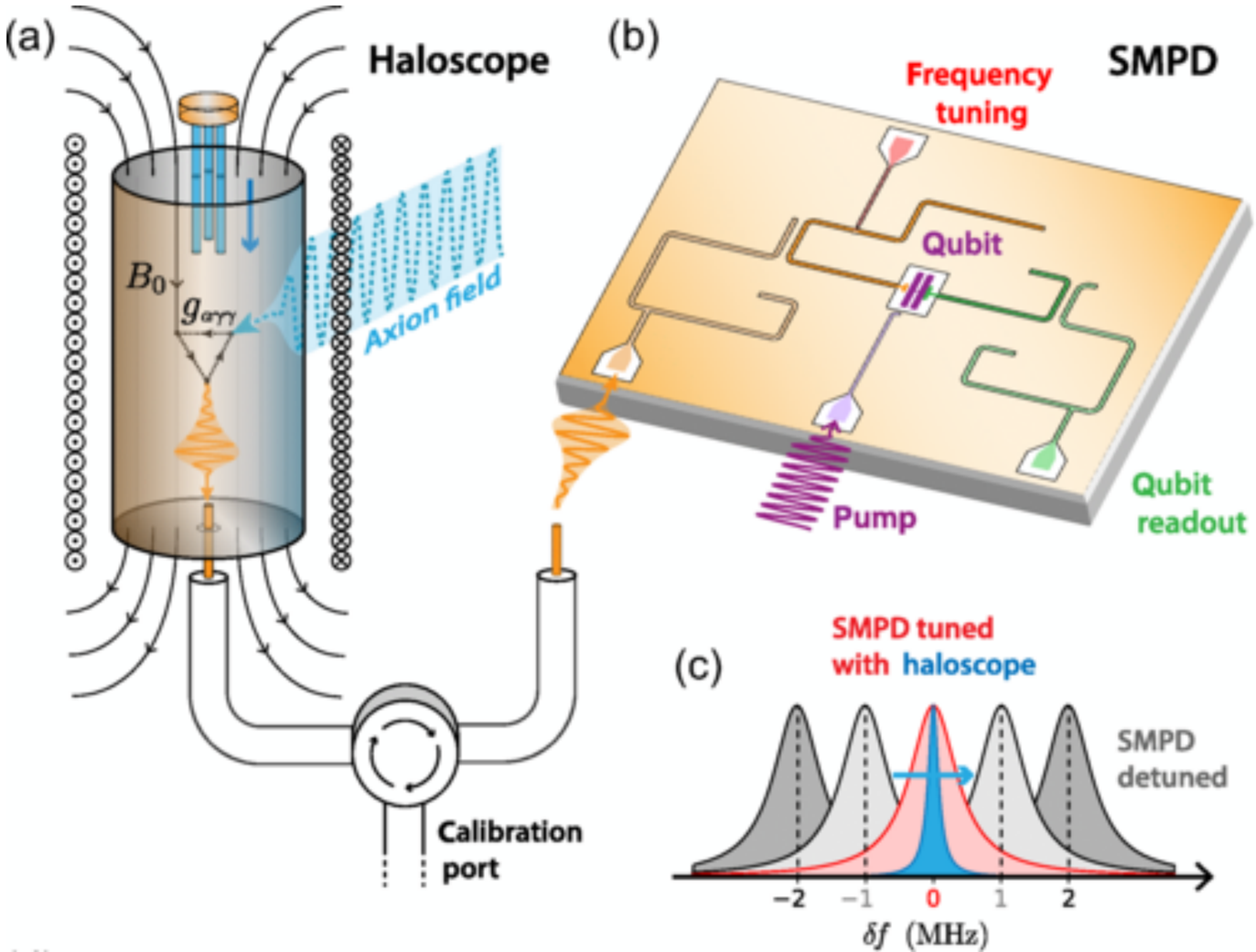
TiN 2D resonator

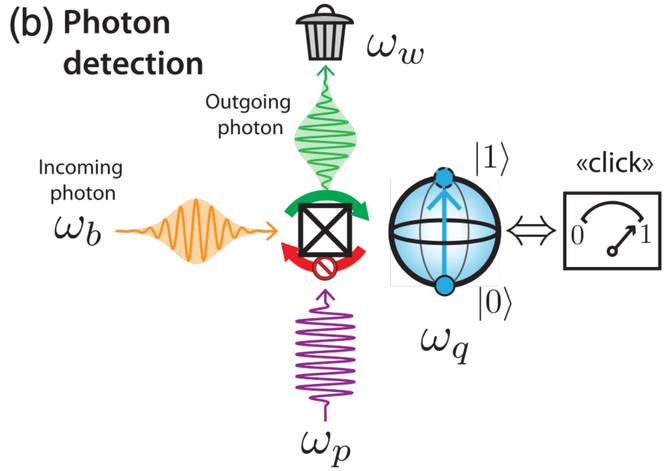




8 Tesla magnet will be delivered at QUP!

Sudden news from Italy: SMPD



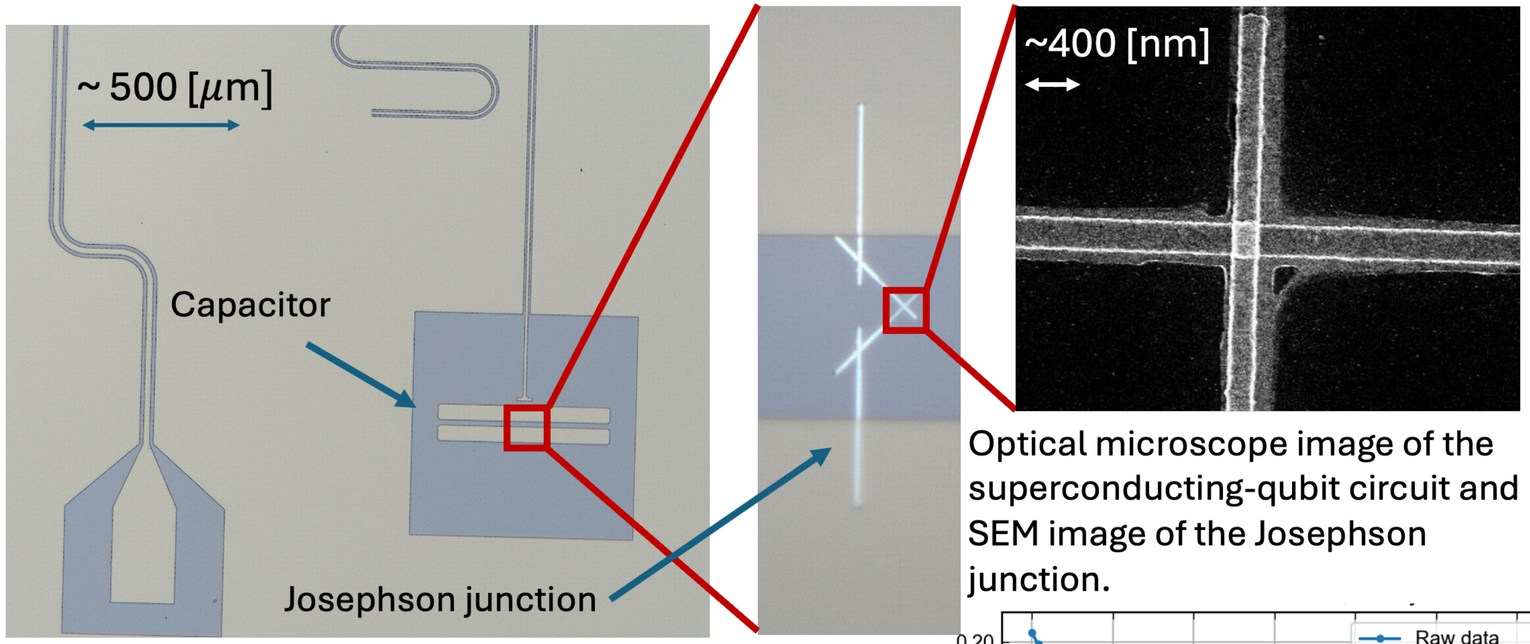


Lescanne *et al. Phys. Rev. X* **10**, 021038 (2020)

Similar noise level to Fock state

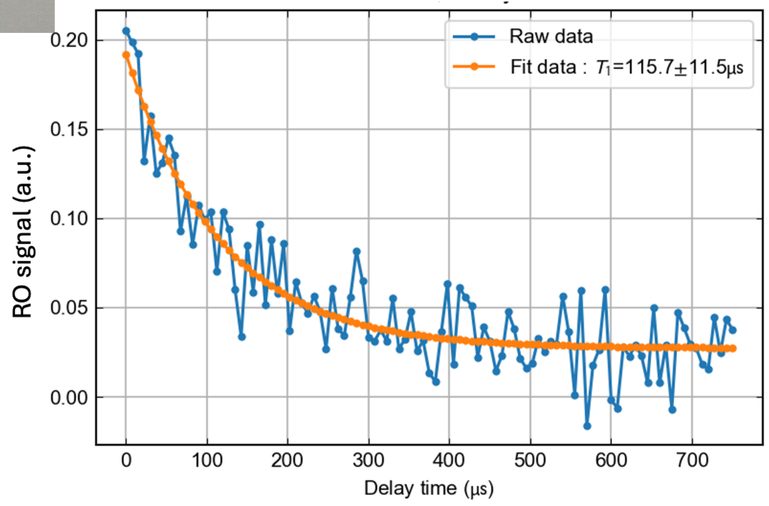
This can be operated OUTSIDE of magnet !!

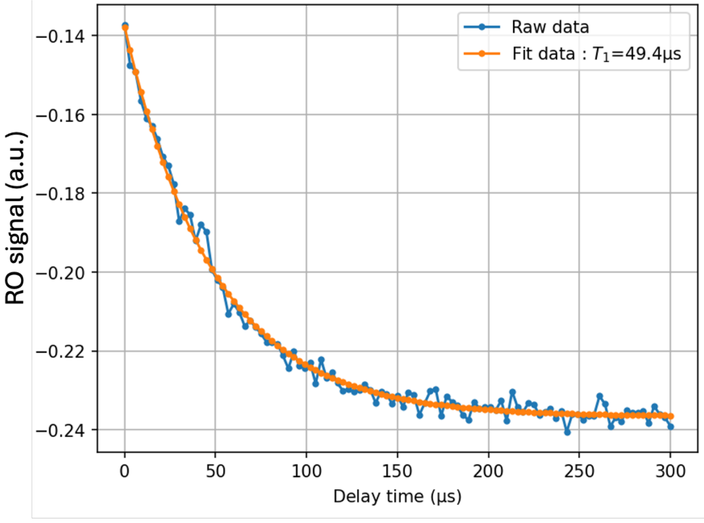
For preparing sudden news from Japan



Optical microscope image of the superconducting-qubit circuit and SEM image of the Josephson junction.

See Chikara Kawai's poster





Summary

- Recently founded QUP is working on quantum sensing

- Axion is the most promising dark matter candidate

- Qubit can be tuner of cavity
  → Initial results

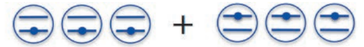
- Qubit can be variety of single photon counters
  Fock, Cat, SMPD…

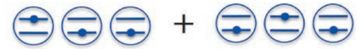
- We (as particle physicists) shouldn’t forgot about magnetic field
  Nb3Sn, ReBCo, Nitride qubits …

- We (as particle physicists) should think about the best way to
  utilize quantum technology for particle physics
  “novel quantum way” gives results but not always leads discovery of DM!!

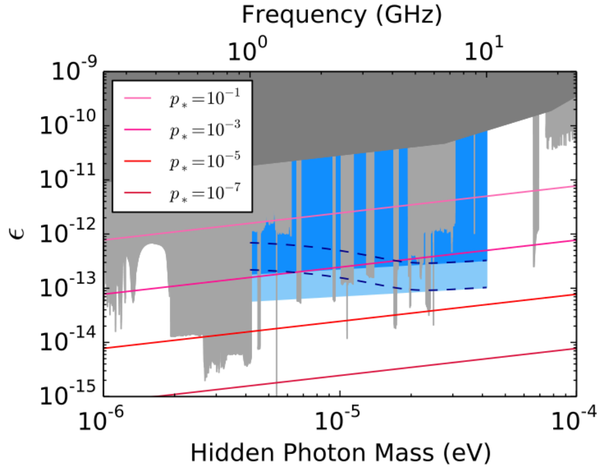
Backup

Game changer: Entanglement

$|\mathrm{GHZ}\rangle \equiv$  $+$

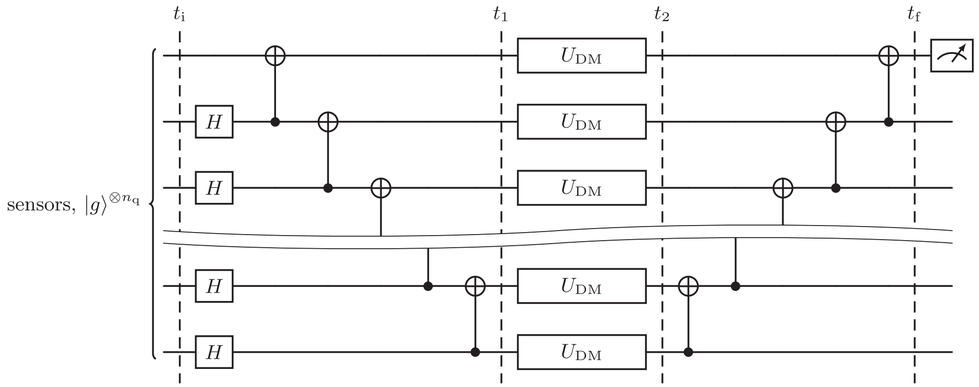
$|\mathrm{W}\rangle \equiv$  $+$ $+$ 

PRL .131.211001 (2023)



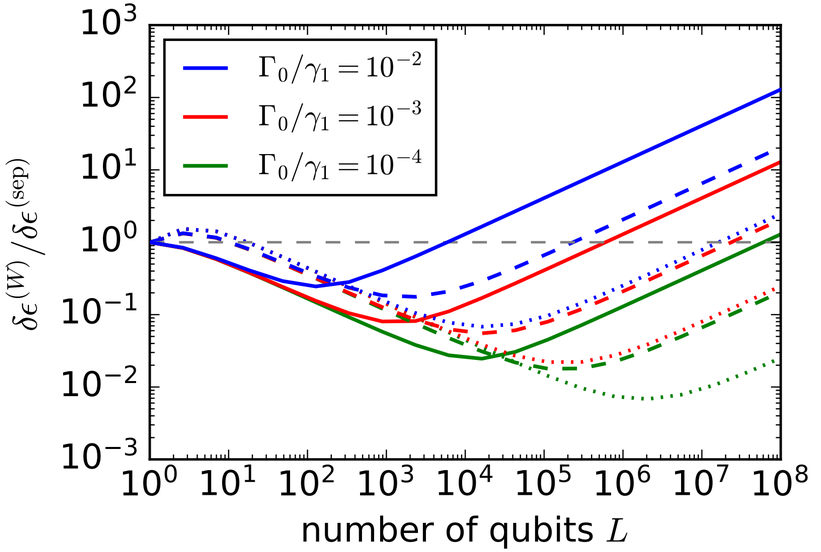
DM excites
a single qubit
→ signal $\propto n_{\mathrm{qubit}}$

PRL 133, 021801 (2024)



Prepare GHZ state of
n qubit array
→ signal $\propto n_{\mathrm{qubit}}^2$

arXiv:2510.01816



Projection to W states
→ signal $\propto n_{\mathrm{qubit}}^2$
at noisy environment

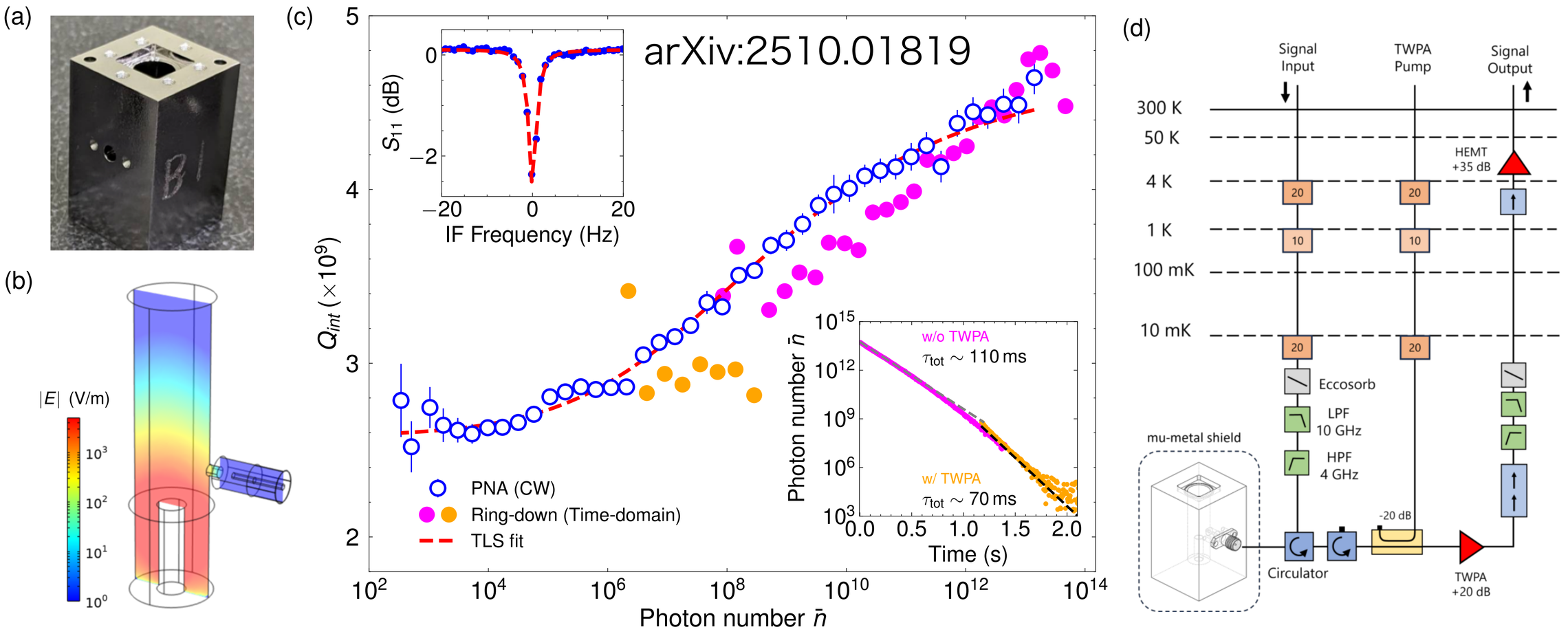
We did this already

These n_{qubit}^2 enhancement is truly game changer

→ Towards large scale experiment with many qubit array

SRF cavity for Quantum

Collaboration with NTT and iCASA at KEK. World best Q value at single photon level



Direct application to quantum computing (bosonic codes) might be another direction