Quantum Sensing

Introduction of QUP-KEK

International Center for Quantum-field Measurement Systems for Studies of the Universe and Particles



Toshiyuki Azuma
(Director of QUP)

November 5 2026

ICFA
A Standing Committee under IUPAP

My Science Vision

Fusion: Precision Frontier with Quantum Technology + Energy Frontier with Large Colliders

Ultimate Goal of understanding the fundamental physics

Physics at the GUT and Planck scales



Energy Frontier through Particle physics

J-PARC, SuperKEKB, LHC

My Science Vision **Fusion: Precision Frontier with Quantum Technology + Energy Frontier with Large Colliders**

Weak coupling

QUP pioneers a new frontier, bringing new ways to explore physics at high-energy scale

Precision Frontier through Quantum technology

Dark Matter, Axion, Gravity, …

Ultimate Goal of understanding the fundamental physics

Physics at the GUT and Planck scales

Fusion

KEK

Energy Frontier through Particle physics

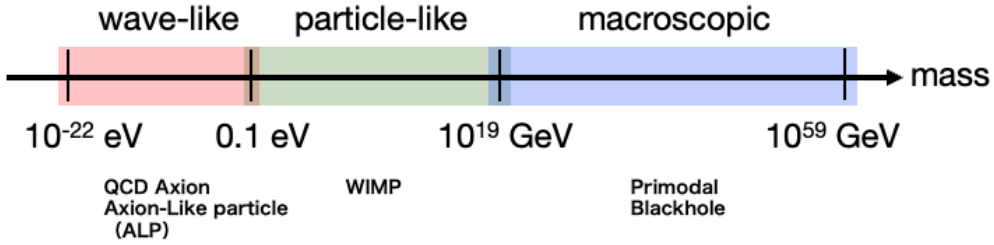
J-PARC, SuperKEKB, LHC

Ultimate goal of the research

reveal the invisible Universe with quantum eyes

■ Dark Matter (DM)

- ~85% of matter in the Universe is dark and remains unknown
- Compelling **Ultra-Light DM** candidates (≪1 eV), such as axions and dark photons, remain experimentally elusive



the projects outside QUP

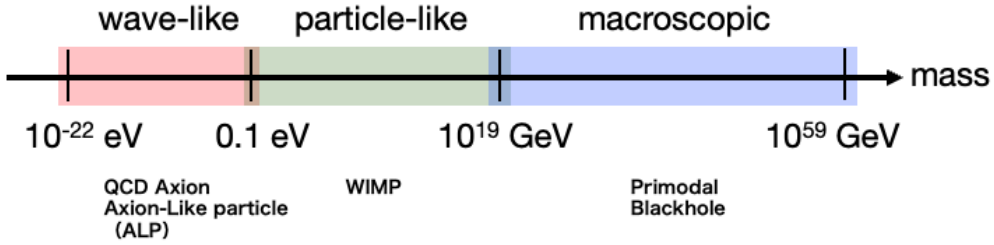


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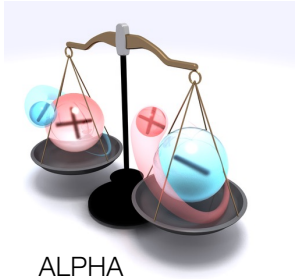


■ Gravity

- Weakest fundamental force with several insufficiently tested regimes
- Probing gravity at sub-micron scales and with antimatter
- LIGO/VIRGO/KAGRA established sub-kHz gravitational wave detection, higher frequencies remain uncharted territory

the projects outside QUP





ALPHA experiment



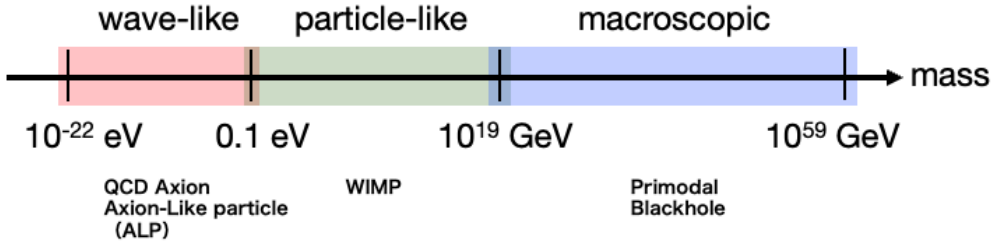
LIGO experiment

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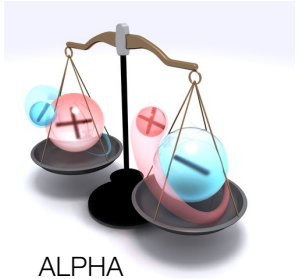


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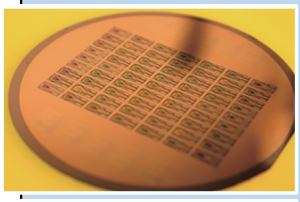
LIGO experiment

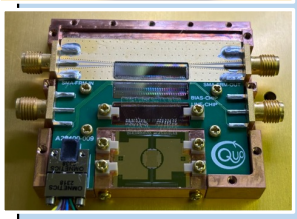
■ New Regimes of Other Fundamental Forces, Symmetries

Opening new research frontiers to drive discovery at the intersection of particle physics, astrophysics and quantum science

New framework

Theory Group PIs: Nakayama, Takhistov





Pillar 1
Fundamental Forces & Hidden Sectors

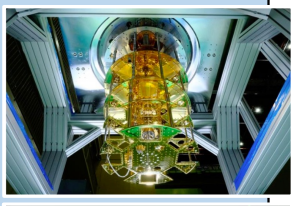
PI:
Azuma

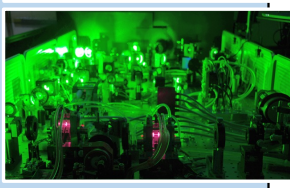
Pillar 2
Light Dark Matter

PI:
Nitta, Garcia-Sciveres
Hasegawa, Herbschleb

Pillar 3
Gravity

PI:
Nitta, Fujiwara





Technology Advancement

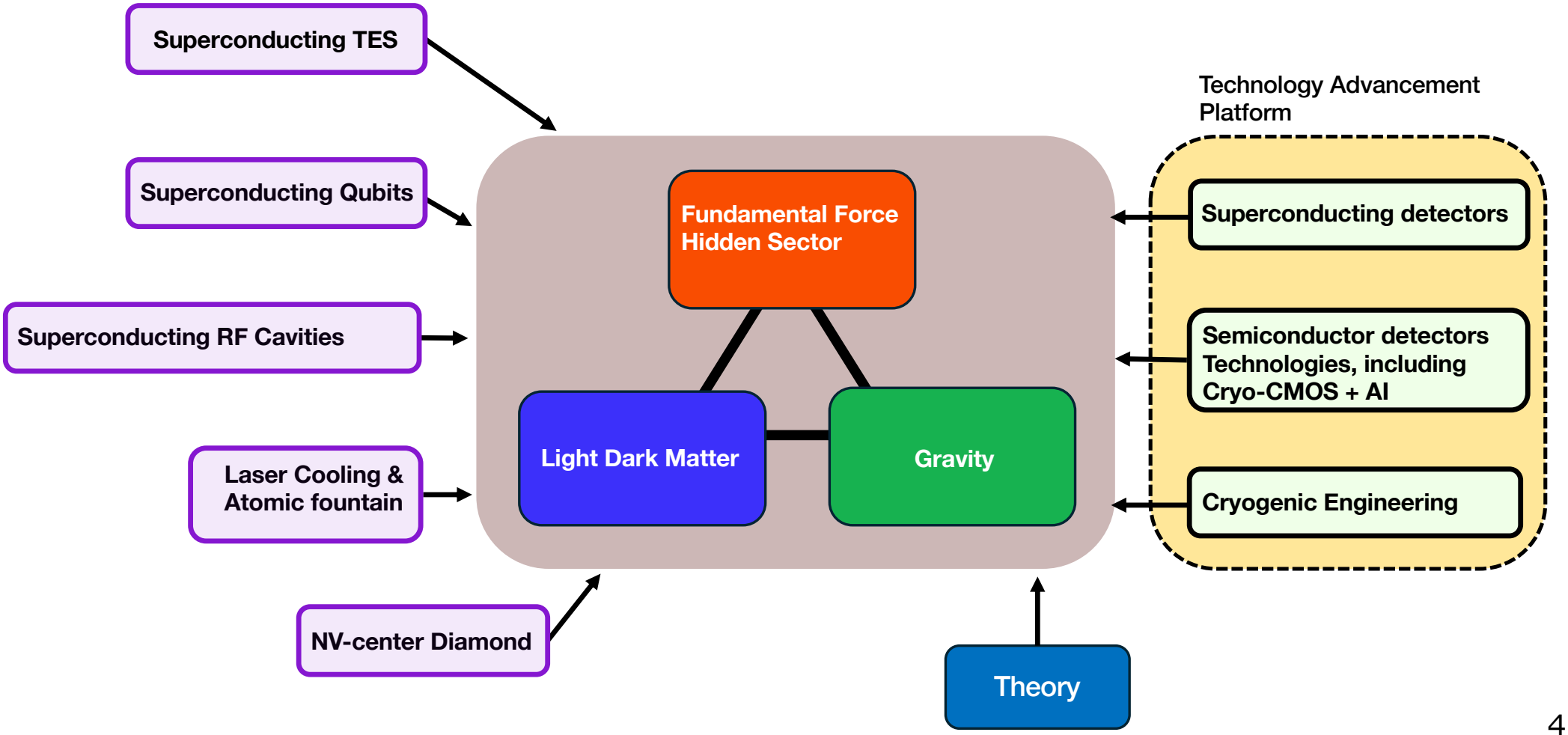
Superconducting Detectors
PIs:
Yamasaki, Lee

Semiconductor Detectors
PIs:
Bortoletto, Takahashi, Togawa, Miyahara, Nakahama

Cryogenic Engineering
PI: Okamura

Engineering support section led by Haba

New framework



QUP as a Core of KEK Quantum Research

TOYOTA CENTRAL R&D LABS

TOYOTA

Joint research with companies and national laboratories

AIST
NATIONAL INSTITUTE OF ADVANCED INDUSTRIAL SCIENCE AND TECHNOLOGY (AIST)

NIMS

and more

Different types of particle and photon beams allow us to probe the spin and other quantum states of atoms, electrons, and nuclei.

KEK

Alliance promotion department

Toward International Excellence in the Quantum Frontier

- Sensor for basic science
- Gravity
- Quantum connection
- Dark Matter detection

Material science

IMSS

Quantum material using multi-beam

Particle physics

IPNS

Cryo-CMOS Theory

QUP





Accelerator and Applied Research Laboratories

Cryo technology
SC cavity $Q>10^{11}$



World-wide research collaboration using KEK's network

Berkeley UNIVERSITY OF CALIFORNIA

UNIVERSITY OF OXFORD

CERN

NIST

Fermilab

THE UNIVERSITY OF CHICAGO

cea

TRIUMF

UTokyo

YNU Yokohama National University

and more

Growing Global Momentum

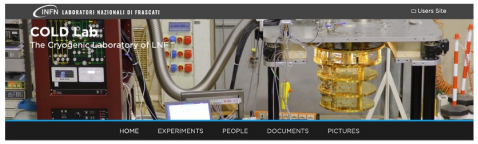
- Worldwide expansion of quantum-enabled searches for fundamental physics
- Similar initiatives emerging at major laboratories and universities

Strong communications with leading international partners: CERN, CEA, Fermilab, DESY, INFN

DESY

DESY. Center for Quantum Technology and Applications

INFN



FNL

SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

CERN

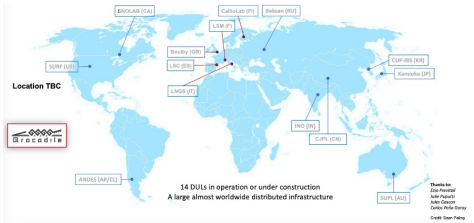
QUANTUM TECHNOLOGY INITIATIVE

DRD5

CEA

irfu iramis

Cryogenic Detectors for LDM
Figure from the talk by Belina von Krosigk



A Global Network to search for High Frequency Gravitational Waves

GravNet

UK

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

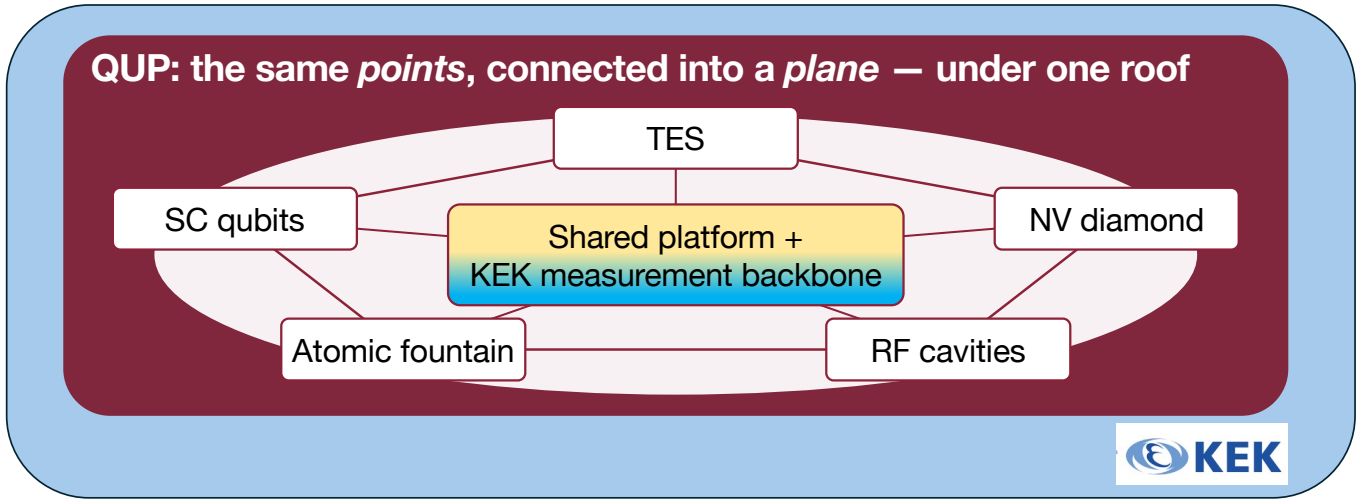
QUP Excellence: World Leadership

QUP's Position in the Global Research Landscape

What makes QUP so unique?

QUP integrates multiple quantum technologies and experimental approaches within a single organization for a single science goal of new physics

Many other groups focus on one detector or one experimental approach
No institute combines these searches as broadly as QUP.



plus: cross-disciplinary interactions based on shared technology platforms and
KEK's accelerator-based and detector-based knowledge accelerates innovation and discovery.

New Building for under one roof

The new QUP building in FY2025

- Office space
- Experimental space (~1,000 m²)
- Cryostats and other cryogenic equipment relocated to the new facility
- Semi-clean room

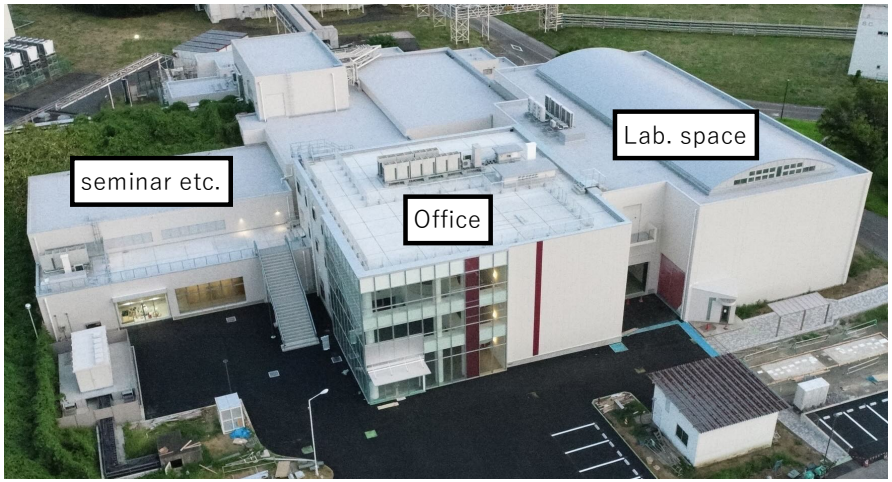
- Large anechoic chamber for microwave measurements

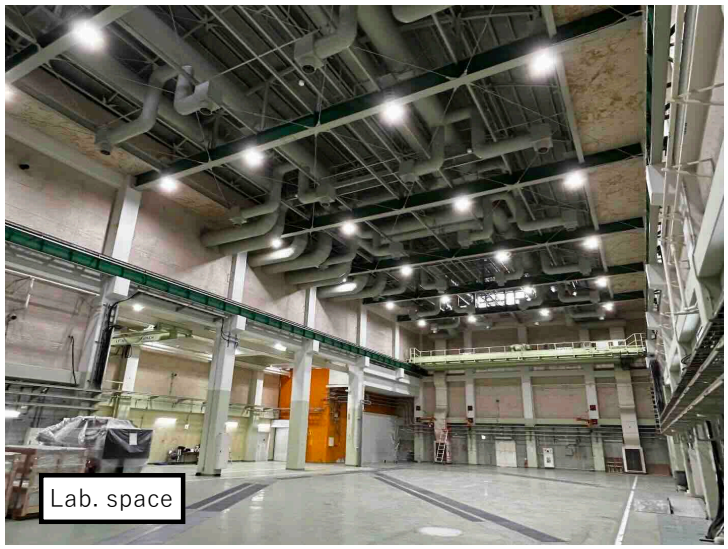
An international research hub for ultra-sensitive measurements in low-noise, low-background environments

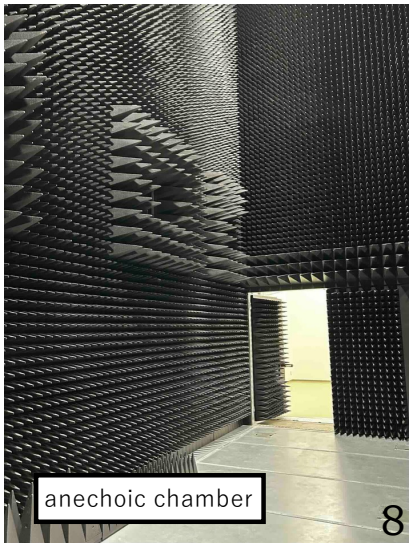
The Kamioka underground facility is one of the hub's core facilities.



54% reduction in energy consumption



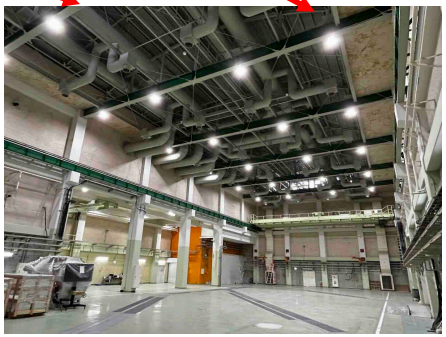


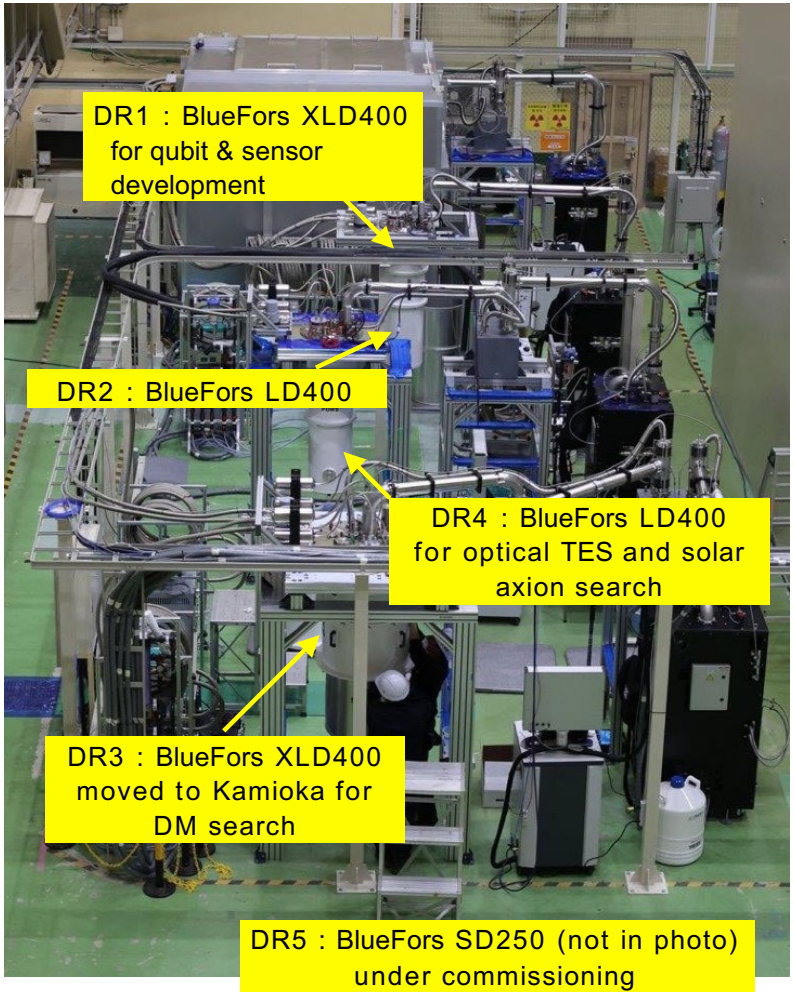


Five Cryogenics (Dilution Refrigerators)

DR1	DM search by qubit & sensor development
DR2	commissioning→DM/axion search by qubit
DR3	Kamioka DM search
DR4	Optical TES & Solar axion search
DR5	commissioning→wide applications

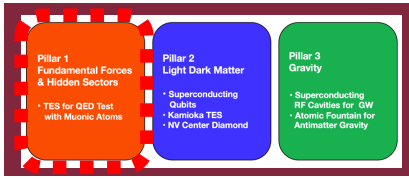






New QUP: output and perspective





Science Target I: Fundamental Forces, Hidden Sectors
QED Test with Muonic Atoms

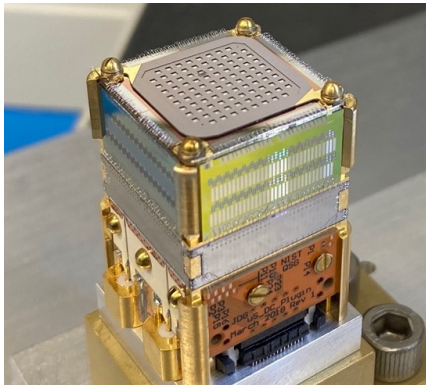


led by T. Azuma

Superconducting TES (Transition Edge-type Sensor)
for **x-ray detection covering the energy region from 1 keV to 150 keV**

Drastic improvement in the resolution (more than 50 times) compared with the traditional semiconductor device (ex. Silicon Drift Detector)

NIST

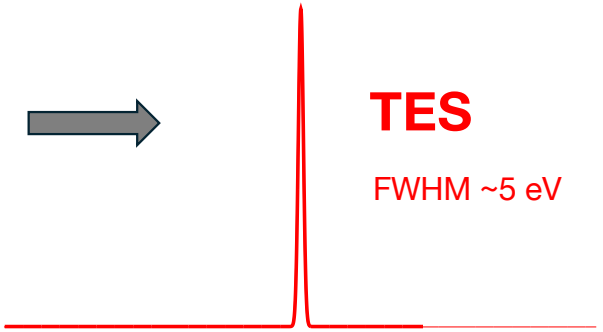


for 6 keV X-rays

SDD
FWHM ~150 eV

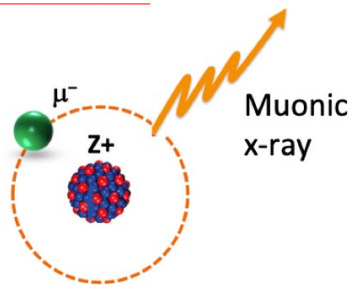


TES
FWHM ~5 eV

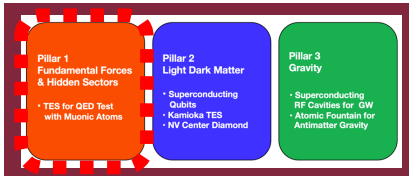




The world's highest-intensity slow-muon beam
supplied from **J-PARC/KEK**
enables the preparation of **muonic atoms** isolated in a vacuum

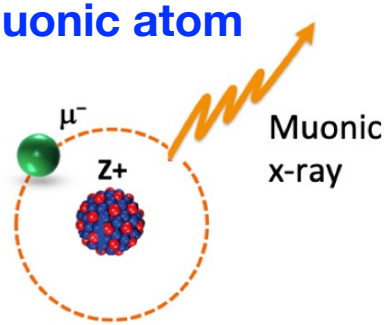


already excellent results based on our original idea:
[1] BSQED test: ***PRL***126,173001(2021) + ***PRL***130,173001(2023)
[2] Exotic highly-charged ions: ***PRL***134,193001(2025) + ***PRL***134,243001(2025) *Editors' Suggestion*
[3] fs dynamics of muon and electrons: ***PRL***127, 053001(2021) *Editors' Suggestion*



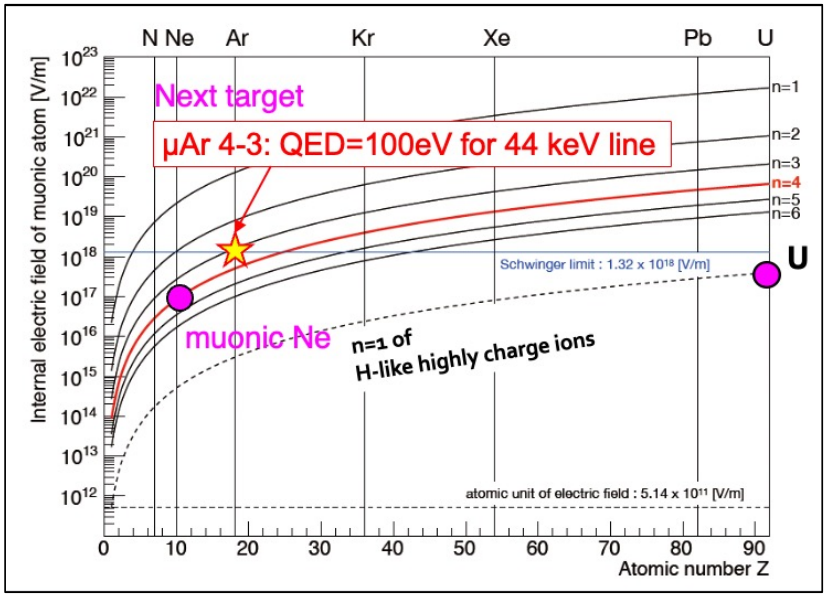
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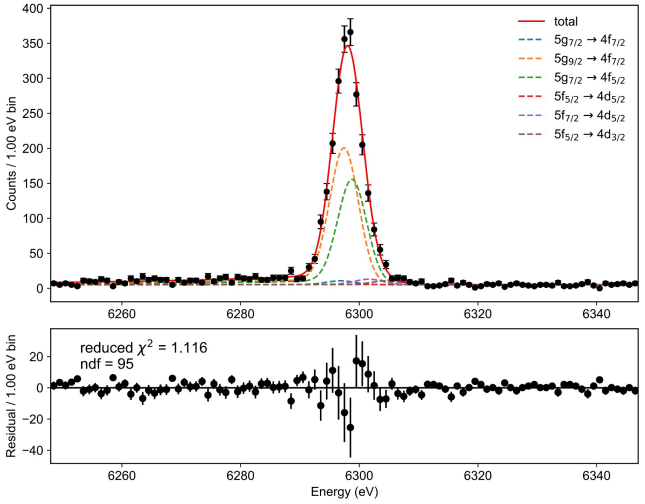
muonic atom



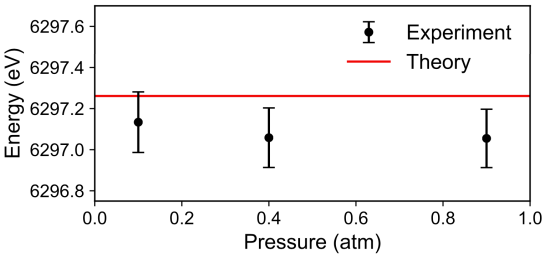
The orbit of a negative muon is located very close to, or even inside, the nucleus of a muonic atom.

Ideal probe to explore
QED (Quantum ElectroDynamics) test under the strongest fields



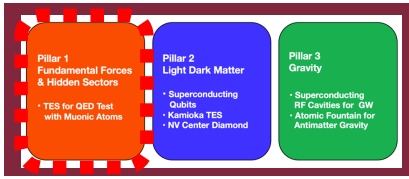


μNe μAr
accuracy of **5.8% → < 1%**



the $5g_{9/2}$- $4f_{7/2}$ transition energy of μNe :
our experiment:
6297.08 ± 0.04 (stat.) ± 0.13 (syst.) eV
most advanced theory:
6297.26 eV.

Phys. Rev. Lett. 126,173001(2021) + ***Phys. Rev. Lett.*** 130,173001(2023)



QED Test with Muonic Argon

X-ray region: 44 keV

Muonic Ar 4f-3d transition

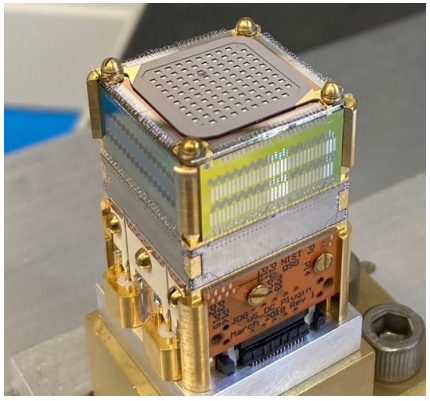
- **Ar gas** target 0.9 atm, 17 hours
- Fit with double Voigt + constant

- Estimated statistical error
  ~ 0.4 eV against **100 eV QED**

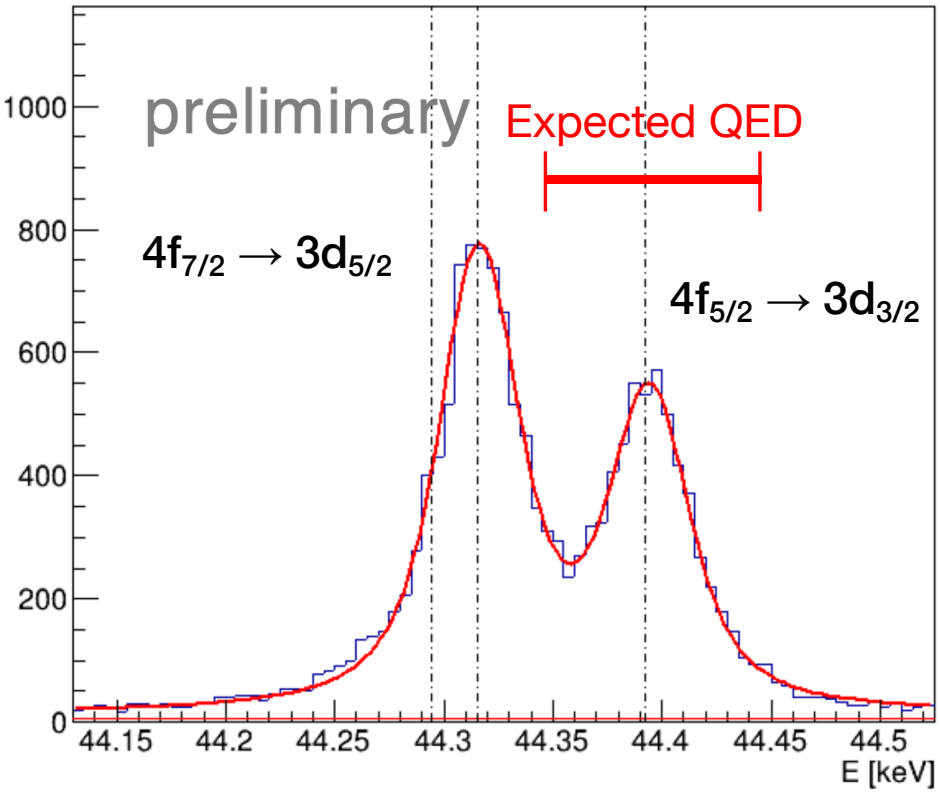


Unger,
QUP Postdoc

	50 keV TES
Saturation energy	70 keV
Readout system	microwave
Absorber thickness (material)	1.85 µm (Au) & 20 µm (Bi)
Absorber area	0.73 x 0.73 mm²
Absorber collimated area	0.67 x 0.67 mm²
Number of pixel	96
Total collection area	43.1 mm²
ΔE (FWHM)	20 eV @ 40 keV (8 eV @ 17 keV)



under analysis

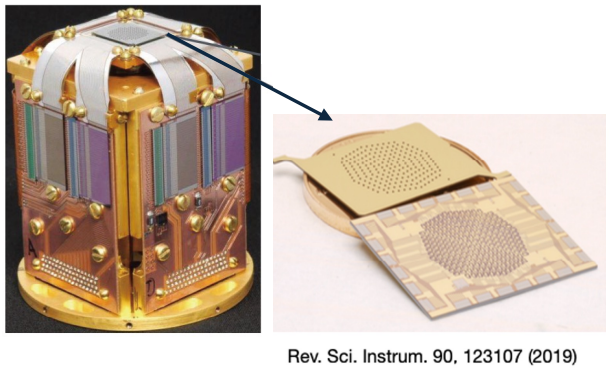


Muonic molecules

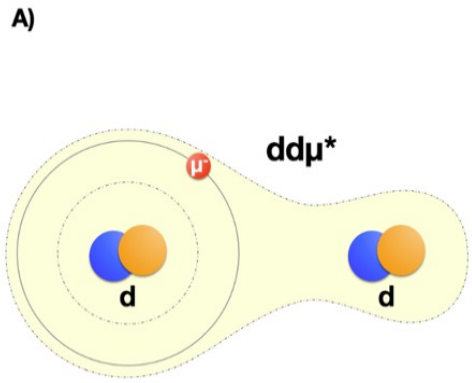
X-ray energy: 2 keV

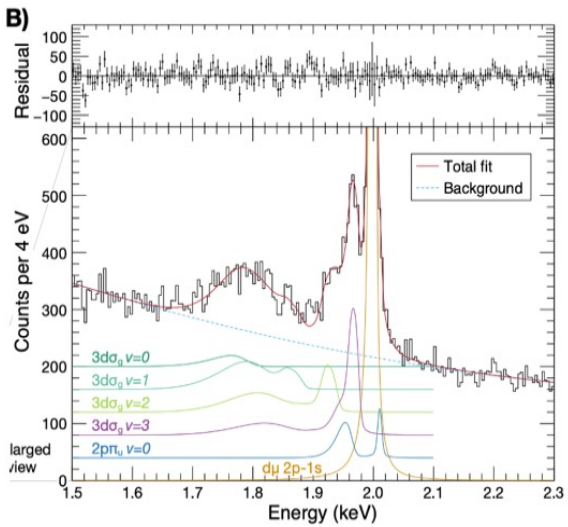
Science Advances 12 (2026) eaed3321

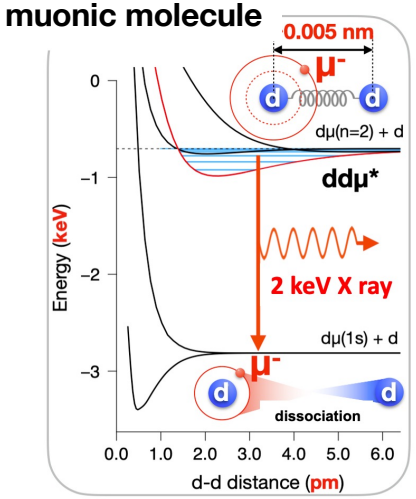
We are also pioneering precision studies of **muonic molecules** —an extension of muonic atom research—where the vibrational structure can only be described through rigorous few-body calculations. This represents the first high-precision experimental exploration of such systems.



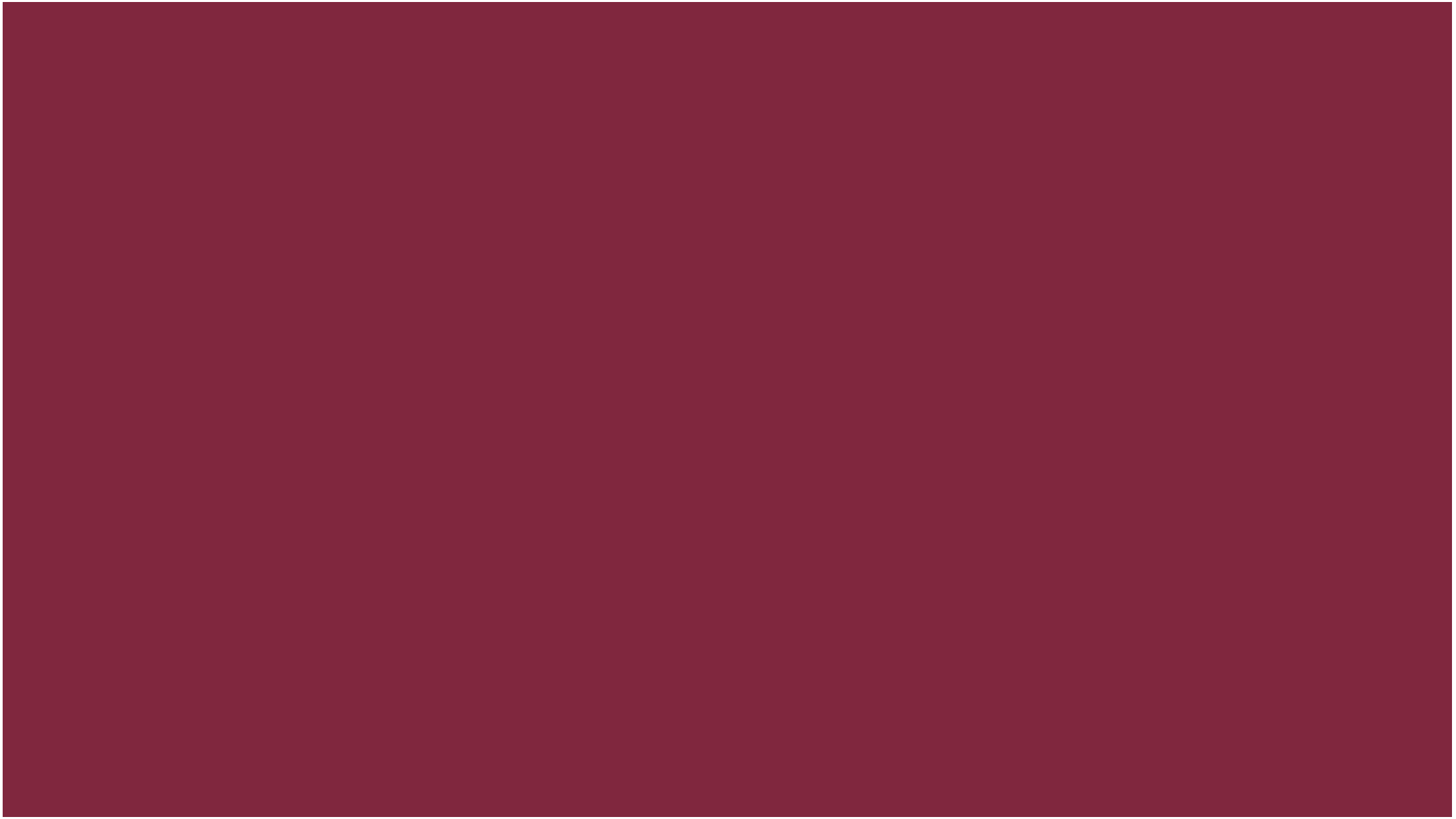
Rev. Sci. Instrum. 90, 123107 (2019)







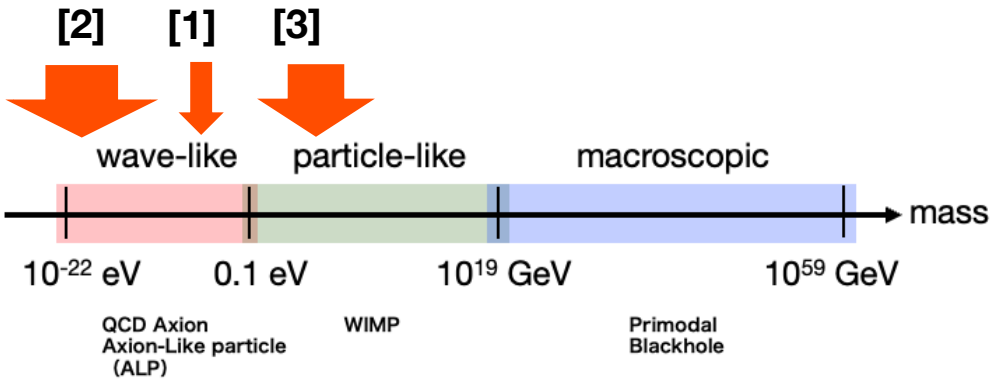
X-ray spectrum associated with the dissociation of resonance states in the muonic deuterium molecule. A) Schematic diagram of ddμ. B) Observed X-ray energy spectrum and the theoretical calculation.*



Light Dark Matter /Axion Search

Overview: A Coherent Strategy for the Low-Mass Frontier

	Approach	DM-type	Mass range (eV)	Interaction
[1]	**Superconducting Qubit**	**wave-like**	**10^{-5} – 10^{-2}**	**photon coupling**
[2]	**NV-diamond**	**wave-like**	**10^{-22} – 10^{-8}**	**fermion spin coupling**
[3]	**TES @ Kamioka**	**particle-like**	**10^{0} – 10^{9}**	**scattering**







Science Target II: Dark photon/Axion Search with a Qubit System in Superconducting Circuits

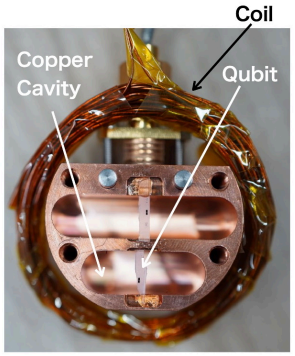
led by T. Nitta

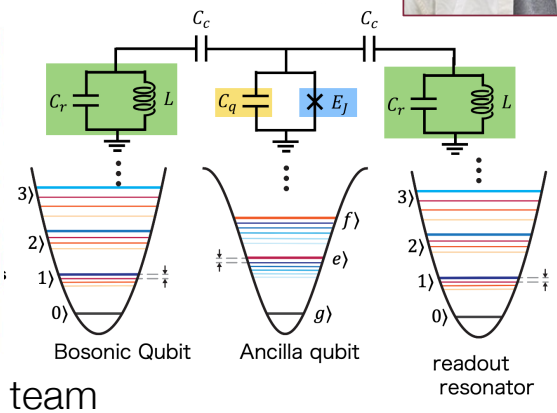


old exp. using a huge magnet at CERN
(**~ 10 m** size)



state-of-the-art quantum technologies: quantum qubit **(~ cm** size)



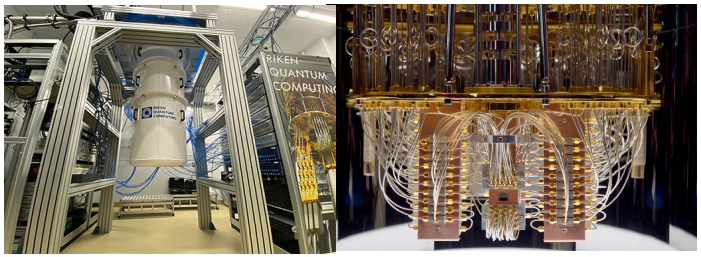


fabricated by our team

Why superconducting qubits?

Alternative Applications of Superconducting Quantum Computer Technology

- **Working at GHz**
  perfectly match the promising dark matter signal frequency range
- **Very sensitive**
- **Designable circuit**

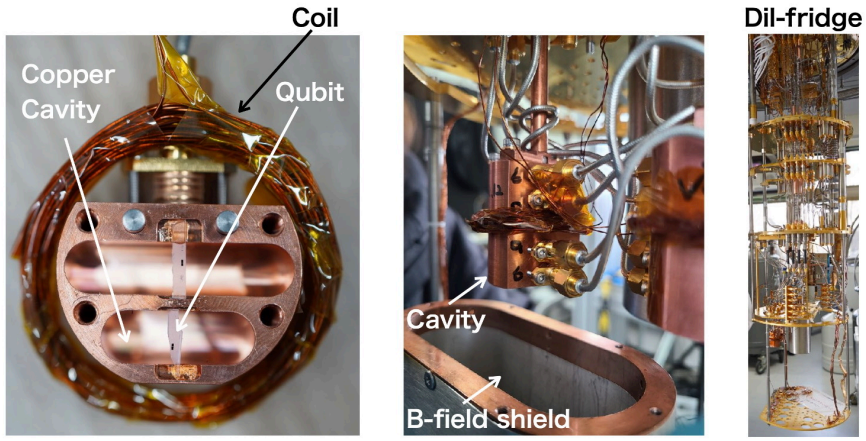


RIKEN U-Tokyo & IBM

Our original proposal: ***PRL***131,211001 (2023) + ***PRL***133,021801 (2024)

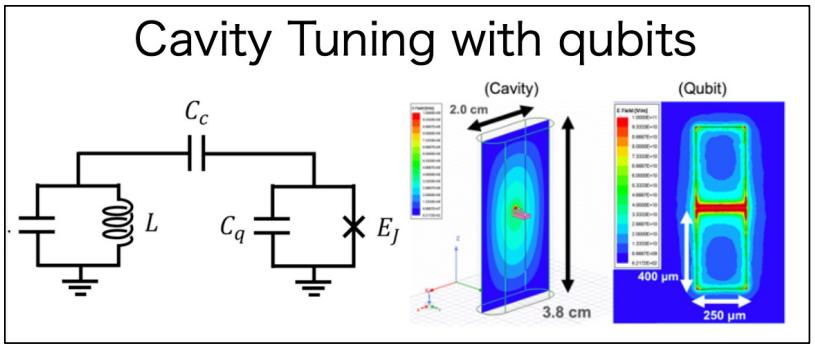


Qubit System in Superconducting Circuits

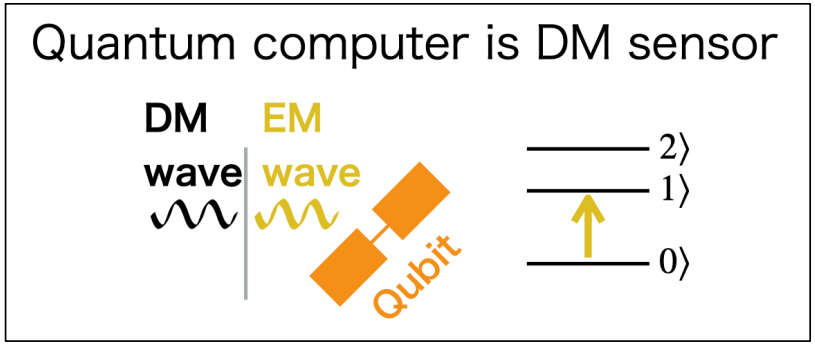


Developed cavity for qubit control under cryogenic environments

DarQ-Lamb



DarQ-Direct





Qubit System in Superconducting Circuits





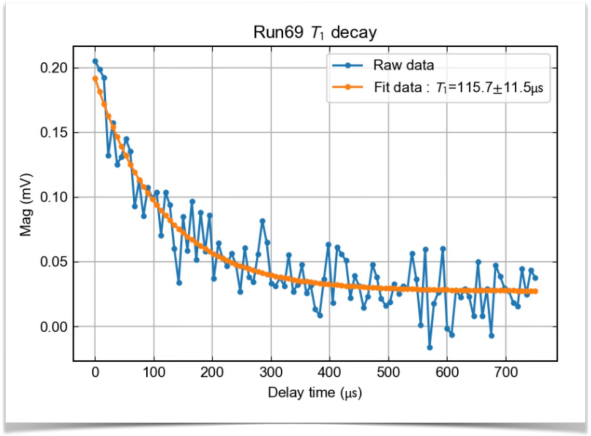
In-group fabricated qubits

- 2 of 5 QUP dilution refrigerators equip qubit RF lines
- Recently qubit control system was installed

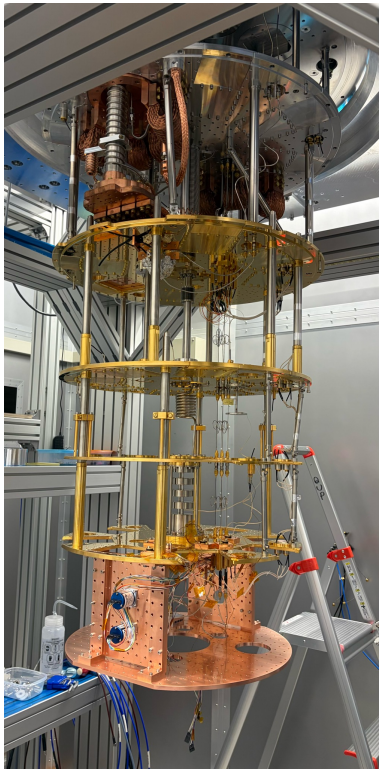
→ **Established qubit readout system**



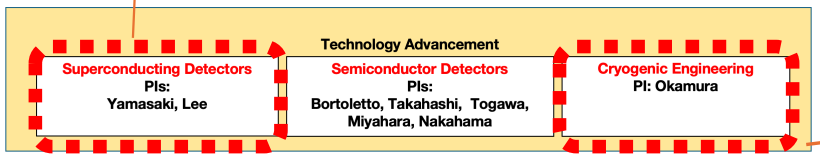
Qubit control system



In-group fabricated qubits have decent performance (**T1 and T2 > 100μs**)



QUP dilution refrigerator





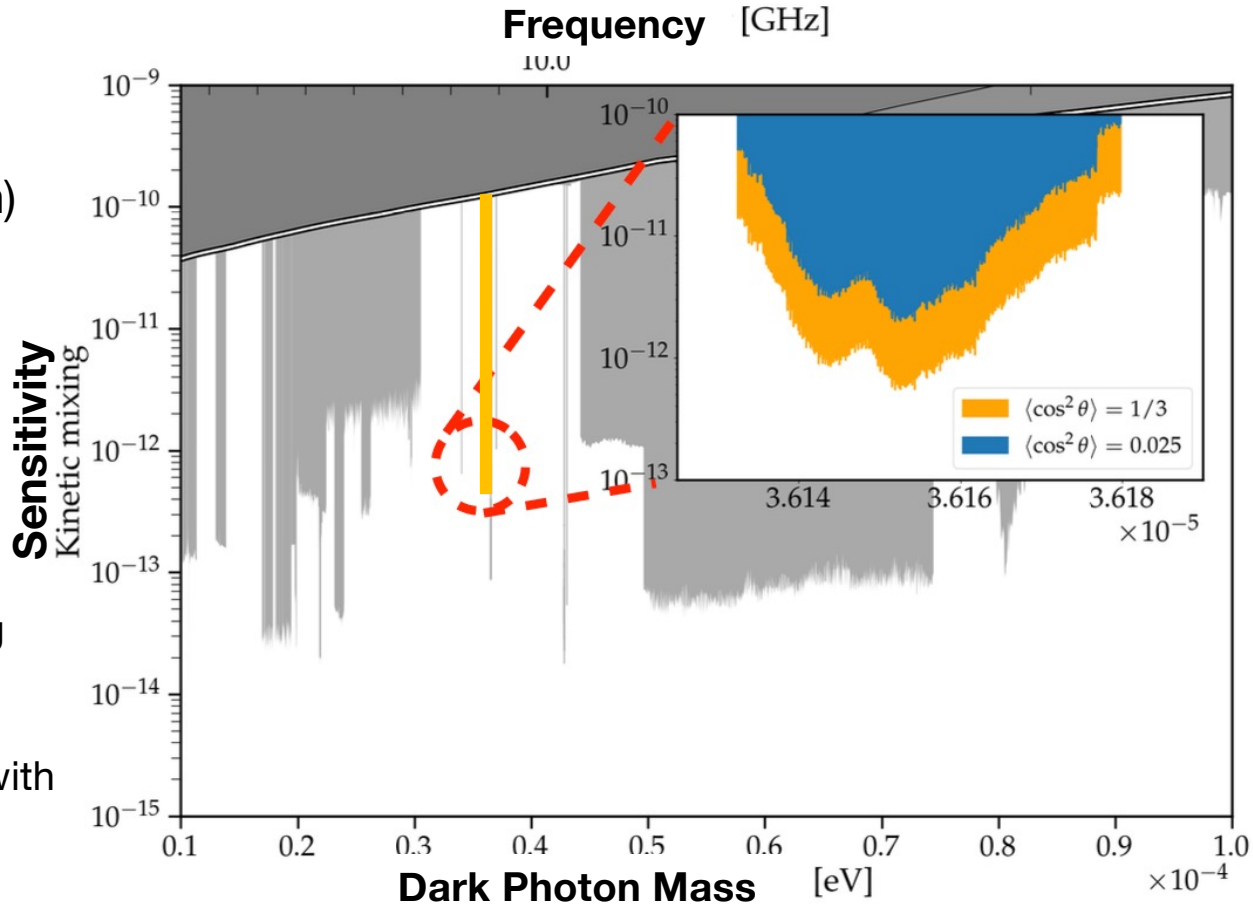
DarQ-Lamb Results

Proof of Principle experiment already submitted to arXiv:2505.15619 (DarQ Collaboration)

Next Step:
a wide frequency range
and
more sensitive measurement

Tuning range is proportional to the coupling between the qubit and the cavity

We are now trying to enlarge the coupling with optimized qubits.

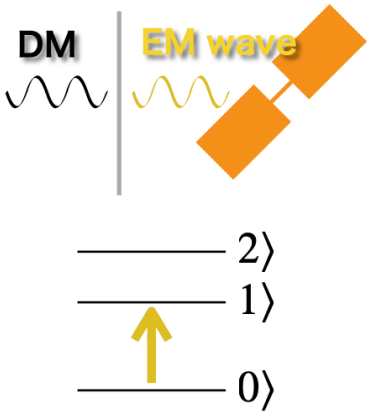




Future outlook

The Essence of Quantum: Quantum Entanglement

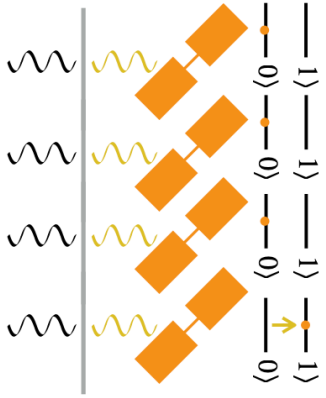
Single qubit



Sensitivity: 1

Already started

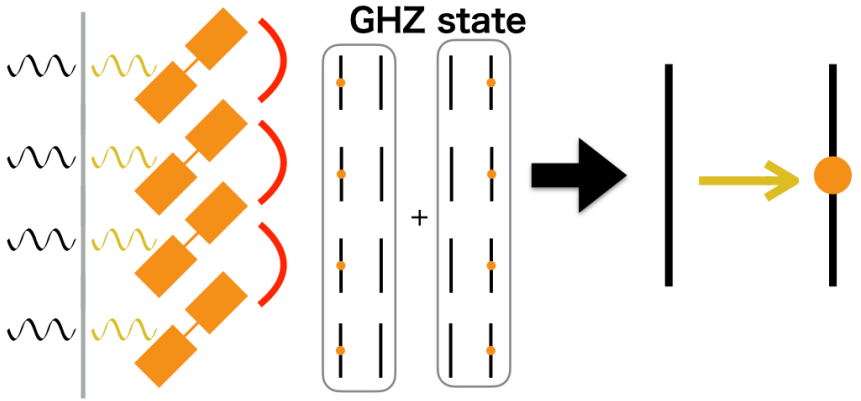
Independent 4 qubits



Sensitivity: 4

It is not bad because integration is possible

Entangled 4 qubits



Sensitivity: 4^2

N^2 **Enhancement (Heisenberg limit)**

→ **Huge scaling benefit**



Science Target III: Light Dark Matter Search Using NV center in diamond

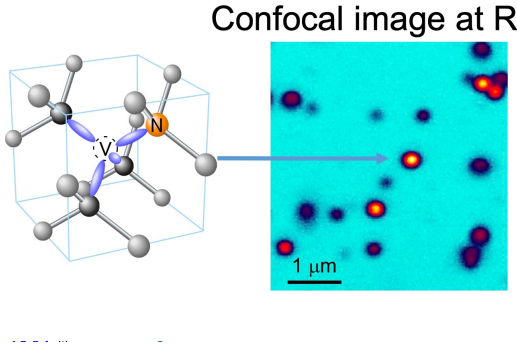
led by D. Herbschleb

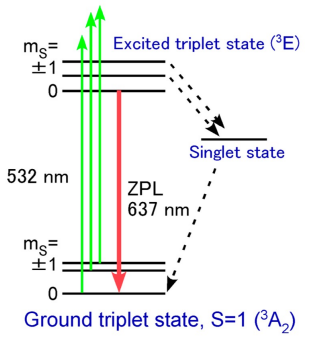


New ideas beyond qubits for DM search, including **qutrits**, are emerging from QUP theory
(QUP, **Kyoto-U**, **Tohoku-U**)

Goal:

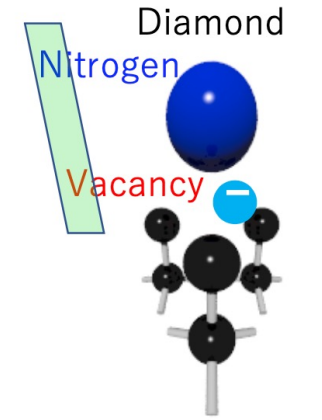
- Ensemble NV measurements under cryogenic (4K) conditions
- Searching for axion-like particles and dark-photon–type dark matter using a magnetic sensor based on NV-center **electron and nuclear spins**.
- Setting constraints on their couplings to electrons at least at one mass point in the range **$M=10^{-22} \sim 10^{-8}$ eV**





Approach:

- High-purity diamond synthesis by Mizuochi-Lab. for longer coherence time
- Lensing system and broader laser irradiation
- Antenna development for a cryogenic environment in collaboration with **TOYOTA Satellites**
- **Parallel setup at QUP and Kyoto** for simultaneous measurements





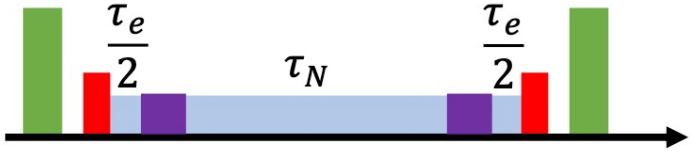
Science Target III: Light Dark Matter Search
Using NV center in diamond

New ideas: Original and Unconventional NV sensing for DM detection

one-to-one electron-nuclear spin

Hybrid-spin decoupling for noise-resilient DC quantum sensing

Sensor: nuclear spin
Method: novel

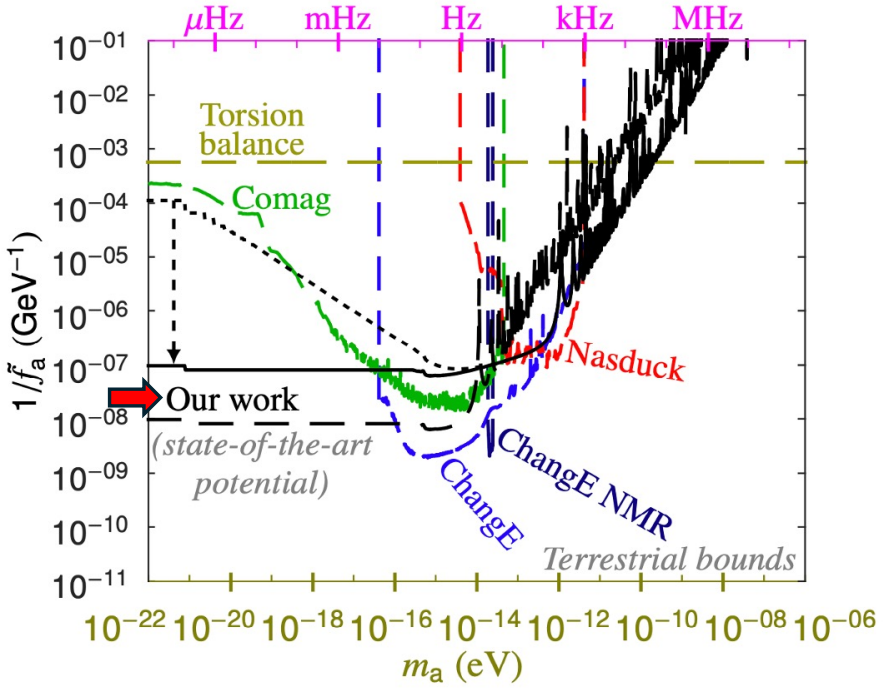


Magnetic field sensitivity: none
Frequency range: broad

Pseudo magnetic field

$$B_{ps} \approx 4 \times 10^4 \text{ aT} \times \left(\frac{g_{aNN}}{10^{-10}}\right)$$

Axion sensitivity: excellent



S. Chigusa, M. Hazumi, E. D. Herbschleb, Y. Matsuzaki, N. Mizuochi, K. Nakayama, arXiv:2511.16732 (**2025**).

extended coherence time at low-temperature



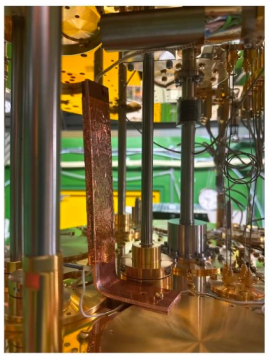
Science Target IV : Light Dark Matter Search at the underground of Kamioka Using Superconducting TES

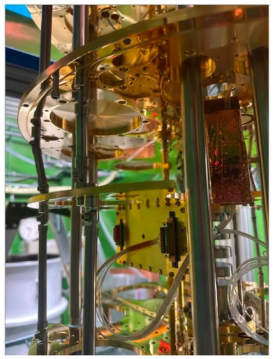
led by Garcia-Sciveres

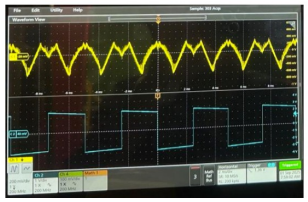


Cryogenic platform in a low-background underground environment
(collaboration of QUP, LBNL, Tohoku-U.)

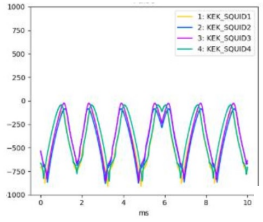
- Dilution Refrigerator successfully commissioned, and SQUID is ready
- The movable table for Lead Shielding was already installed in April, and full construction is scheduled to finish in September 2026.



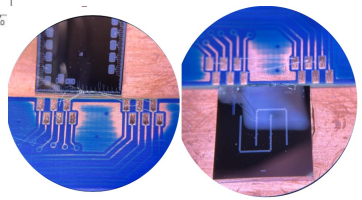




Voltage-flux from SQUID in Kamioka *(measured in Sep)*



Same SQUID measured in LBL



TES detector

Cryostat



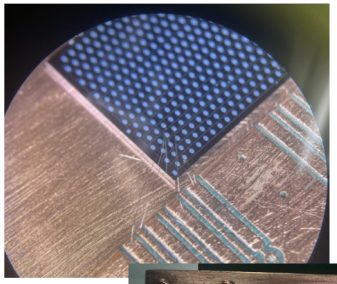
Rails for lead shield

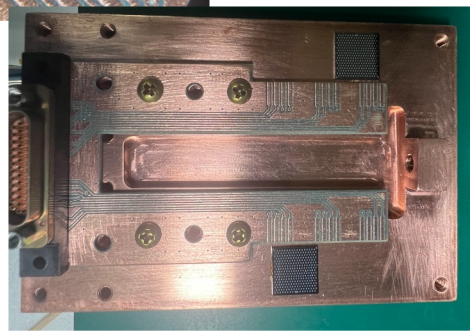


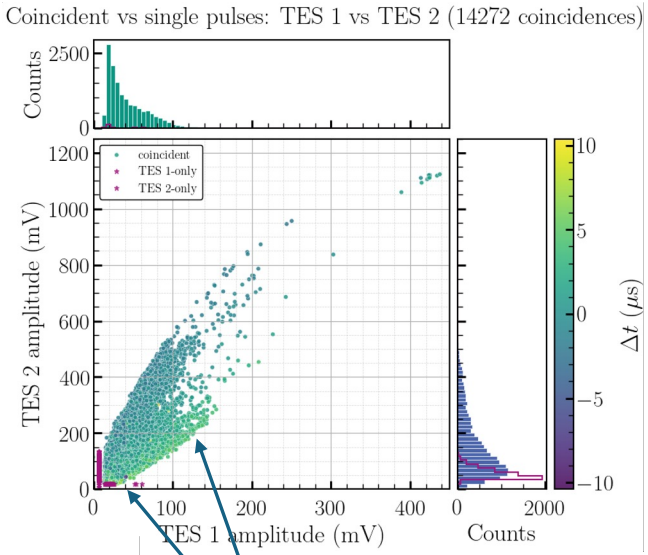
Detector operation results from Kamioka

Low-Energy Excess (origin of major background)

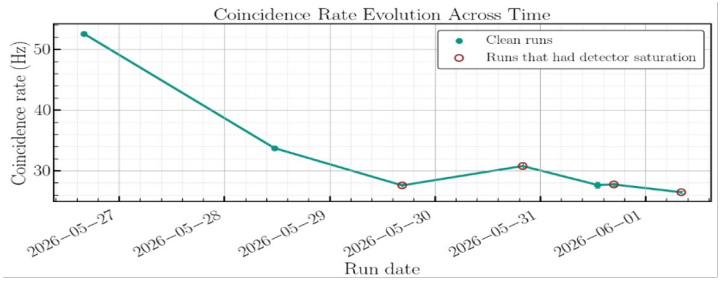
LEE Measurement on Silicon QET chips







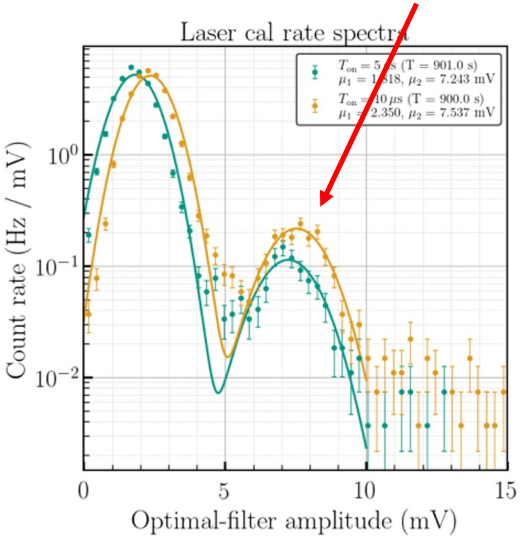
bulk LEE
metal film LEE



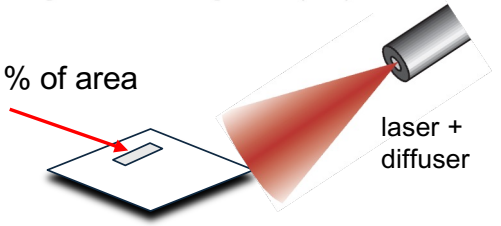
LEE decreases as time advances

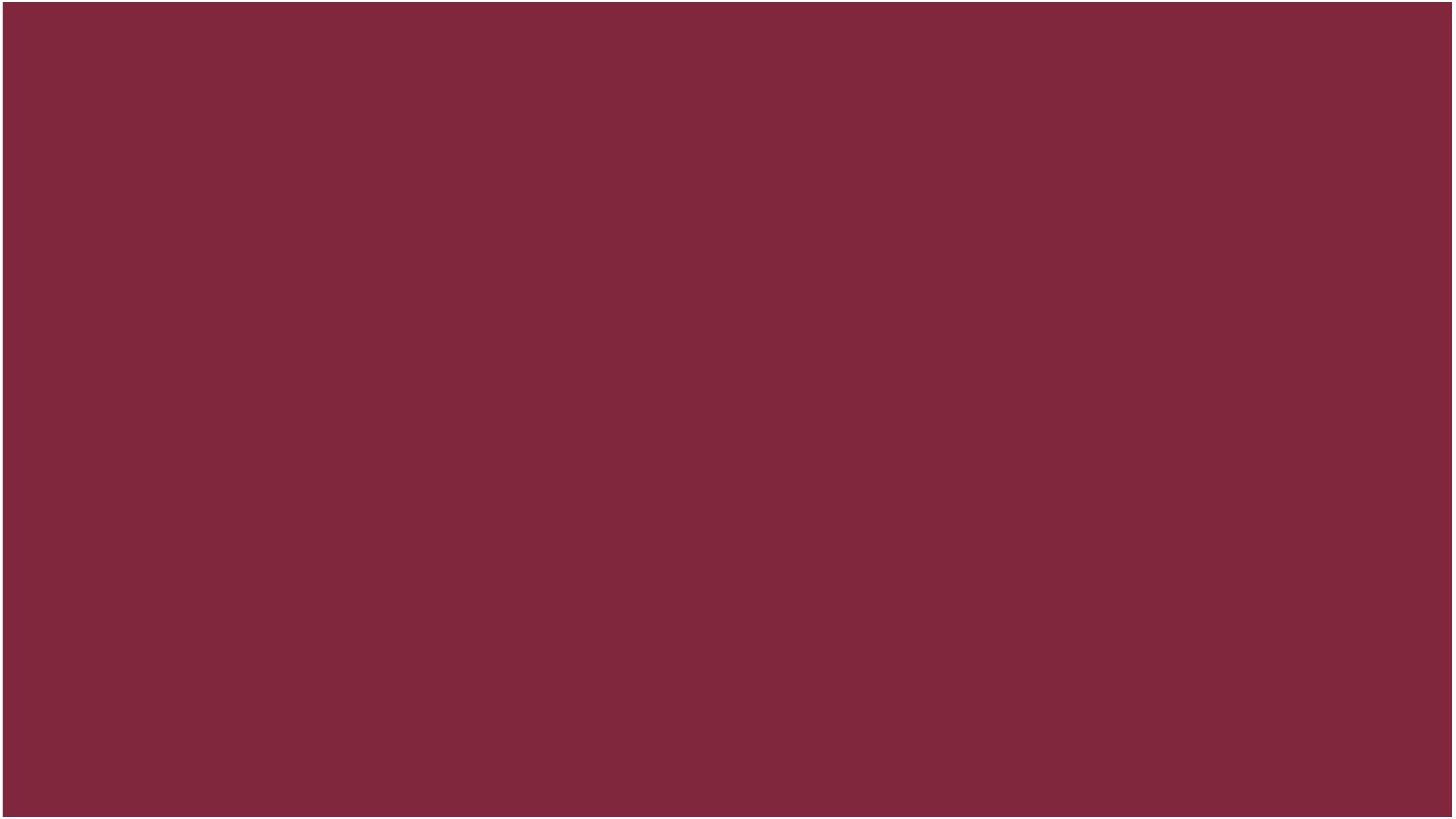
Laser calibration on single TES (on Si)

single photon signal



TES <1% of area







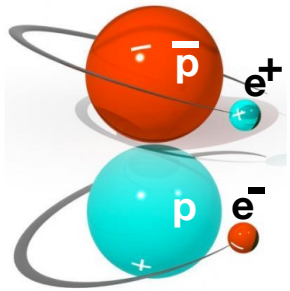
Science Target V : Antimatter Gravity
Using Atomic Fountain

led by M. Fujiwara



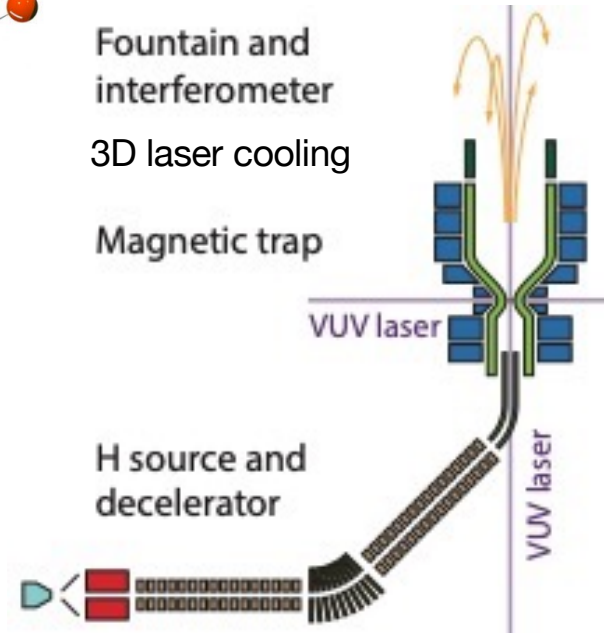
Test of **CPT** & **Weak Equivalence Principle**

Precision Antimatter Gravity Measurement with Quantum Techniques
– (Anti)Atomic Fountains, (Anti)Atom Interferometer



$\bar{H}$

H



starting with hydrogen
@ TRIUMF, Canada

Key technologies: high-intensity, short-wavelength lasers



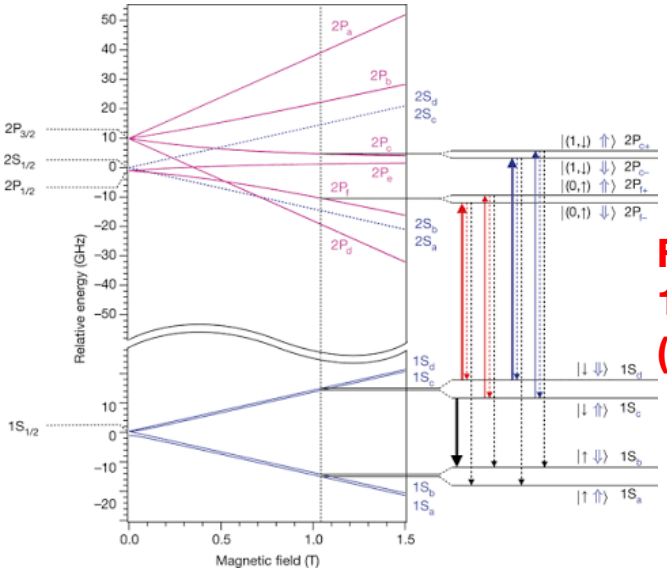
originally cultivated in
low-energy muon beam applications
@**J-PARC, KEK** plays a central role.

Joint Research and
Cross-disciplinary Collaboration with KEK



Why is quantum manipulation of (anti)H so hard?

Antihydrogen / Hydrogen



Fundamental Transitions
121 nm
(10.2 eV)

Vacuum-ultra violet light:

- **Does not transmit in air**
- **No solid-state laser medium**
- **Optics; e.g. windows only 50% efficiency**

QUP

Goal

10 μJ/pulse
100 MHz width
5 ns pulse length

World's Highest Power Narrow Line Pulse Laser at 121 nm

New VUV technologies (phase & time shape control of ns pulses)

Insight through Accelerators.
KEK



Science Target VI : Gravitational Wave Detection Using Superconducting RF (SRF) Cavities

led by T. Nitta with T. Kubo (KEK)



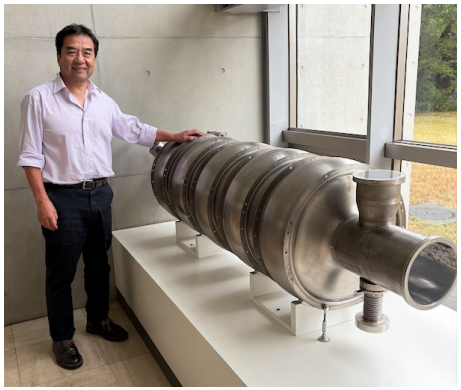
KEK's SRF technology (~ **m** size)

⟺

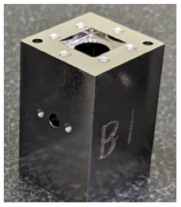
gravitational wave interferometers (~ **km** size)

Superconducting RF Cavities

Q-value: 10^{11} minimal energy loss



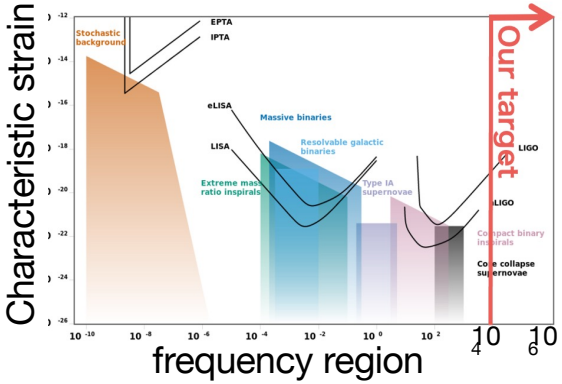
state-of-the-art quantum technologies: (~ **cm** size)



fabricated by our team



Joint Research and Cross-disciplinary Collaboration with KEK



Gravitation wave detection in the unexplored high-frequency region:

→ kHz - MHz GW can be detectable



Superconducting RF (SRF) Cavities

Phys. Rev. Applied 25, 034076 (2026)

Editors' suggestion

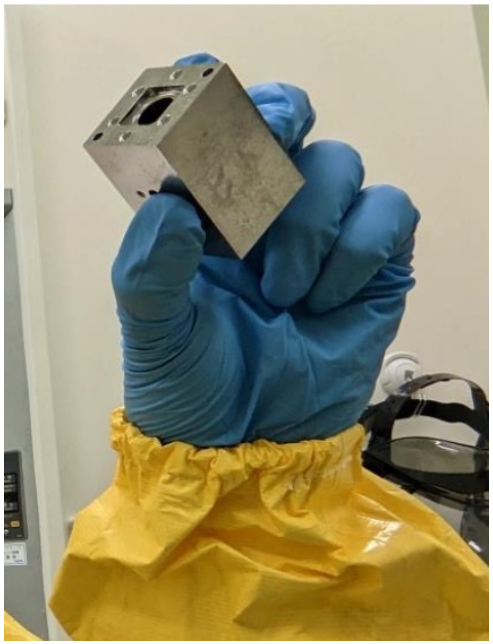
Achievement 2025

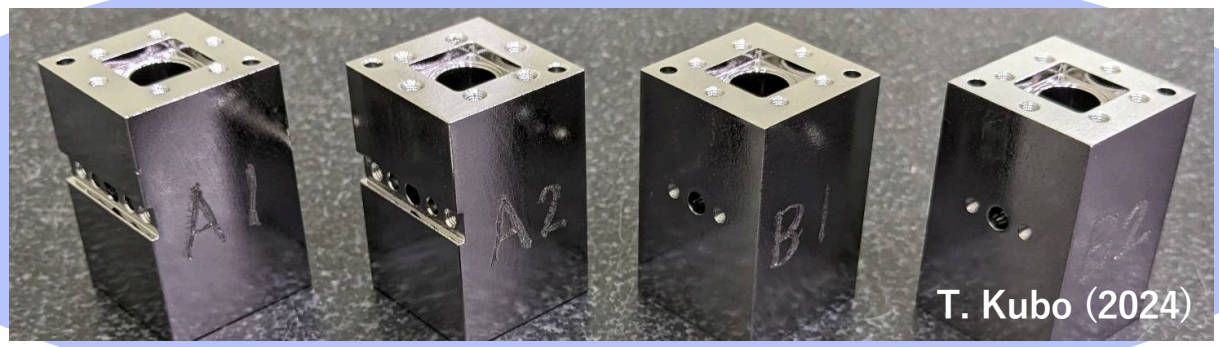
Three-dimensional niobium coaxial cavity

Q-value: 3 x 10^9 = T_1 ~0.1 sec
World record in coaxial cavities

Stable upon exposure to air

collaboration with NTT





Insight through Accelerators.
KEK



Superconducting RF (SRF) Cavities

Outlook

Gravitational Wave

A. **Cavity Q-factor at single photon regime**
Conservative: 4×10^9 with Nb coax cavity (almost achieved)

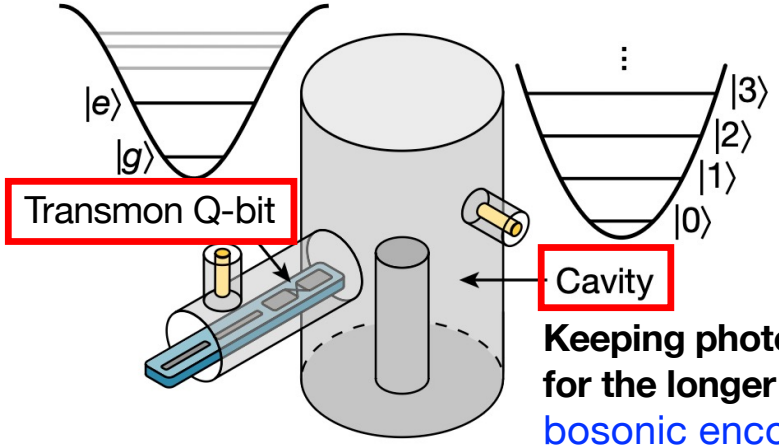
B. **Magnetic field introduced in the superconducting cavity**
(Nobody realized yet)
Conservative: 100 Gauss Nb cavity for cavity tuning with lower Q

Collaboration with **Akito KUSAKA** (Uni.of Tokyo)

C03 超伝導・量子技術によるマイクロ波重力波探索で挑む宇宙創生

Grant-in-Aid for Transformative Research Areas (A)

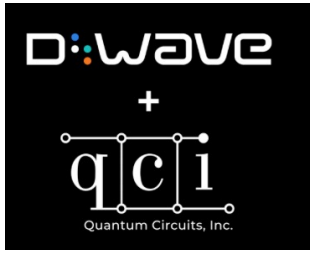
Quantum Memories → **Hybrid with Transmon Q-bit + Cavity**

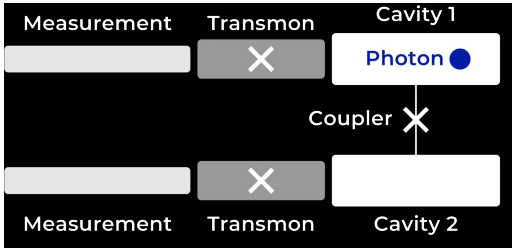


Keeping photons for the longer time
bosonic encoding

Yale group: Brock et al., Nature 2025

a different approach from integrated quantum bits on a chip





Company: Quantum Circuit

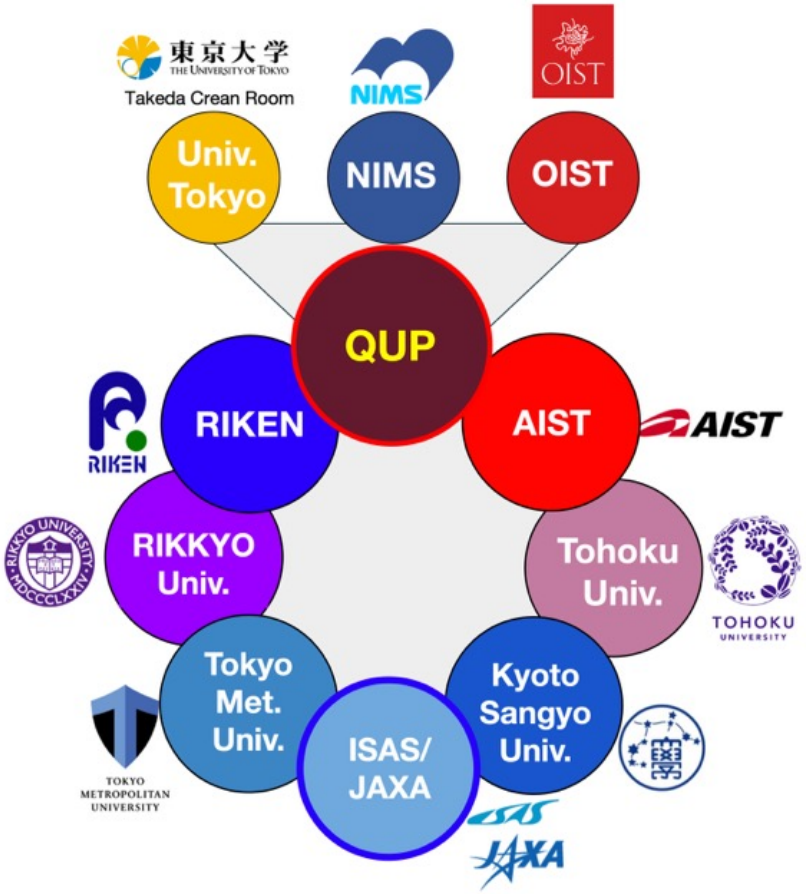
Technology Advancement Platform

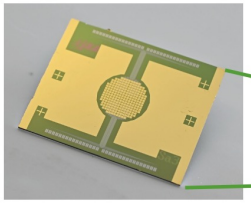
Technology Advancement

Superconducting Detectors	Semiconductor Detectors	Cryogenic Engineering
PIs: Yamasaki, Lee	PIs: Bortoletto, Takahashi, Togawa, Miyahara, Nakahama	PI: Okamura

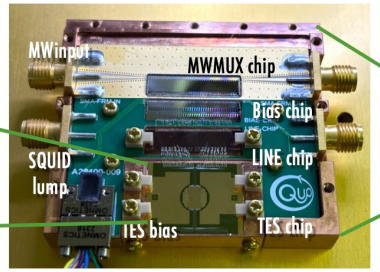
Superconducting Detector Platform closely connected with the JAXA satellite

led by N. Yamasaki





ISAS/JAXA

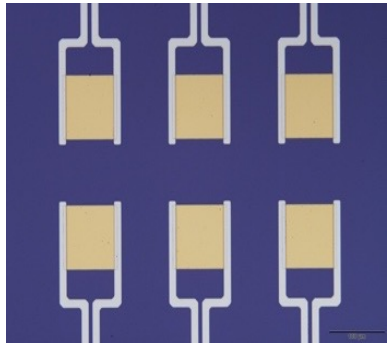


AIST

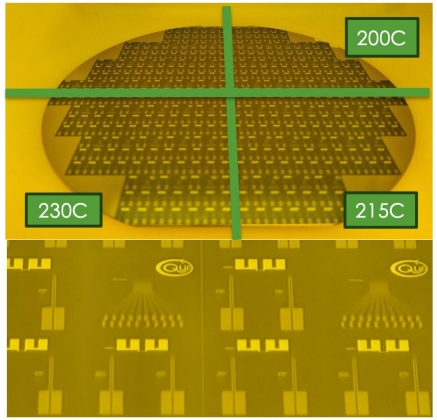


QUP

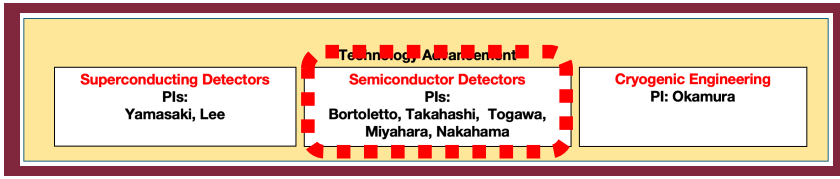




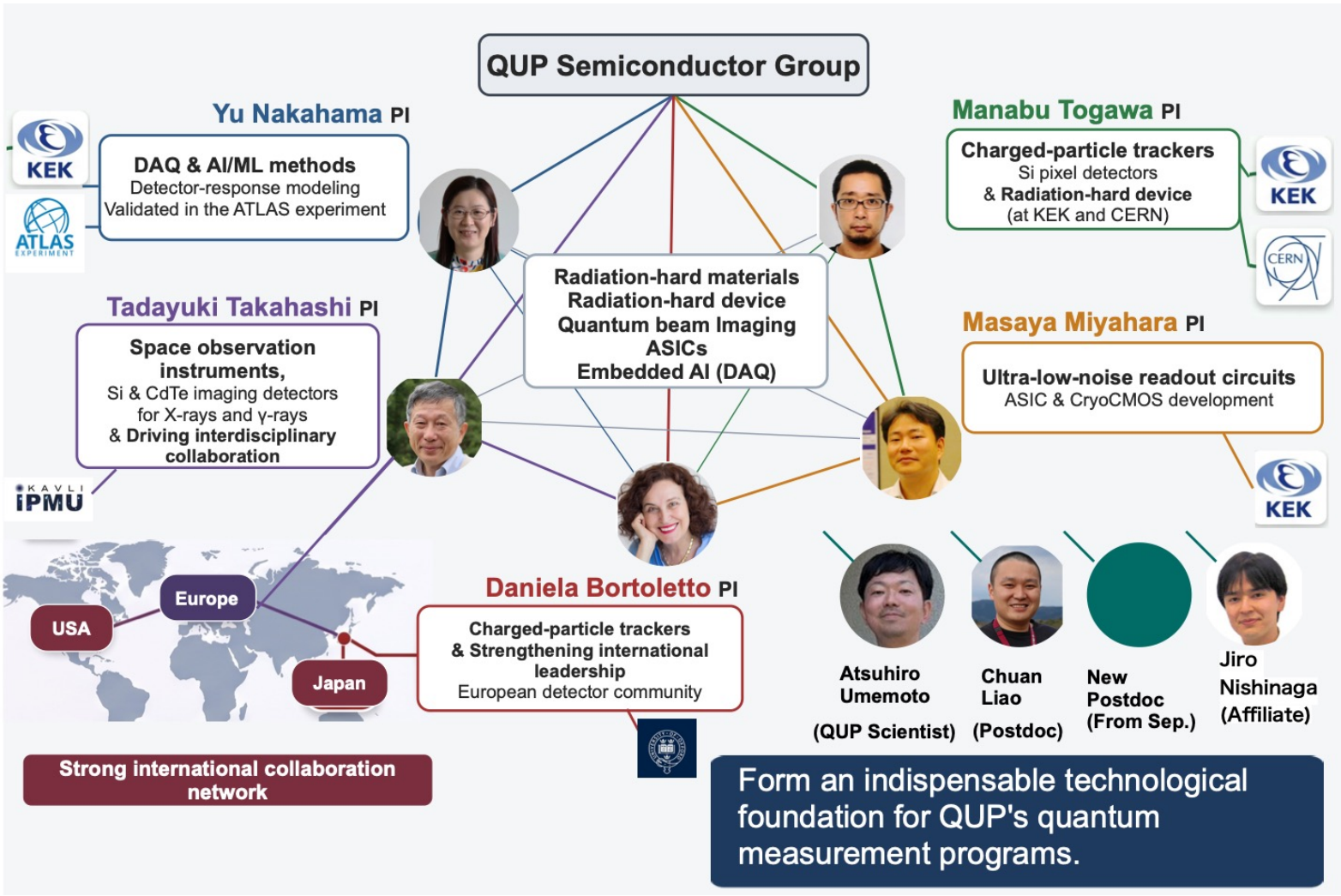
NIMS/QUP



Berkeley/QUP



Semiconductor platform



Technology Advancement

Superconducting Detectors
PIs:
Yamasaki, Lee

Semiconductor Detectors
PIs:
Bortoletto, Takahashi, Togawa, Miyahara, Nakahama

Cryogenic Engineering
PI: Okamura

CryoCMOS development: Cryo-CMOS ADC Verified at 4.2 K



led by M. Miyahara

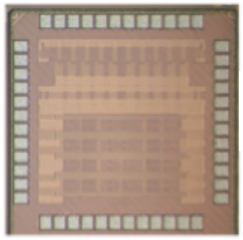
ここから、新・未来へ

MOONSHOT
RESEARCH & DEVELOPMENT PROGRAM

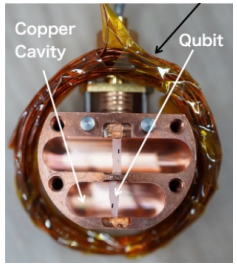
Cryo-CMOS ASIC for Quantum Qubit control / Quantum Computing

Essential technologies for high-density quantum computers

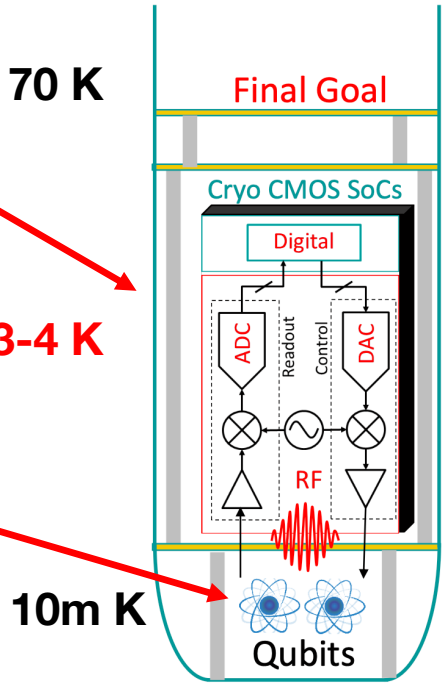
This technology is a key to QUP Superconducting Qubits (led by Nitta)

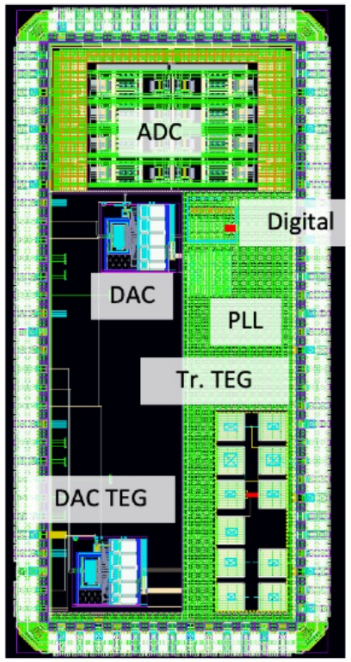


Cryo-CMOS ADC

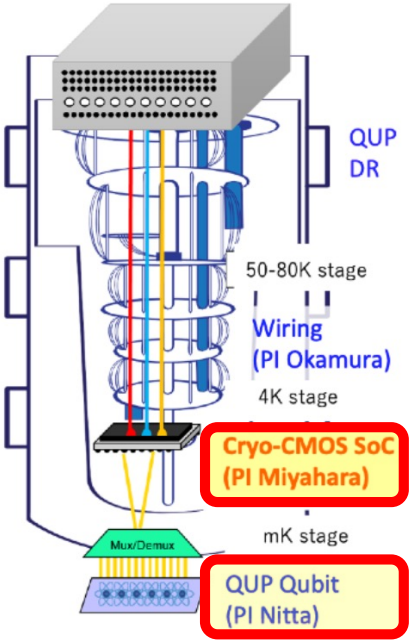


Supoerconducting Qubits

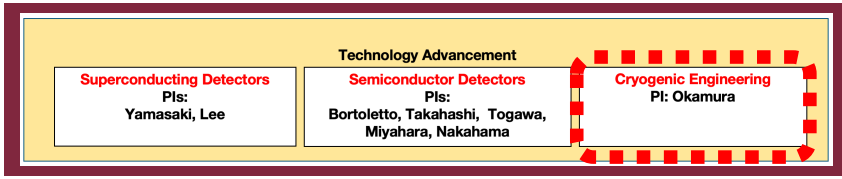




Cryo-CMOS SoC



SoC-based qubit control @KEK



Cryogenic Engineering platform led by T. Okamura

Newly established platform due to its strategic importance to QUP

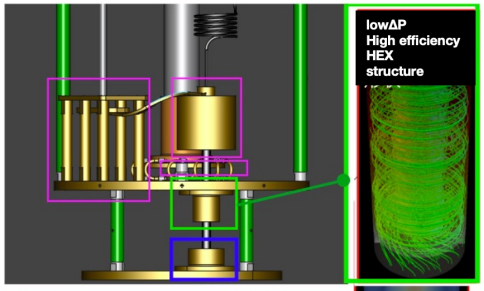
Research Field of PI Okamura (from **KEK**)

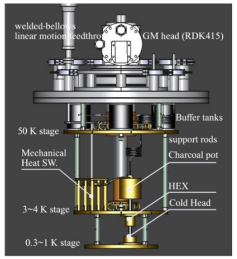
In collaboration with
Toyota Central R&D Labs

– Cryogenic system development for Cryo-CMOS

– Sub-Kelvin Cryogenic system development for Quantum Technologies.

Reduced He consumption and increased cooling capacity through optimized Kapitza thermal resistance, fluid control, and Adsorption.

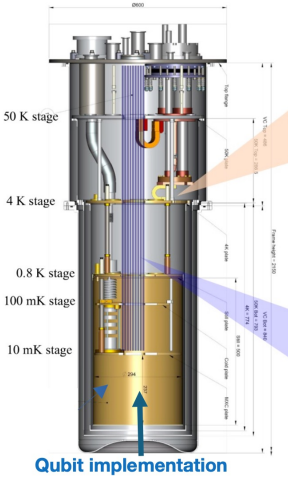


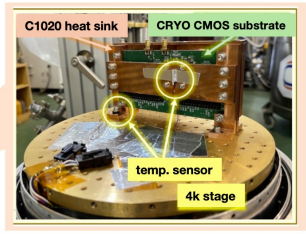


Reduced He consumption & enhanced colling power

Kapitza reduction + Efficient utilization of He heat-transfer

4He sorption
0.8K >1.5mW
3He sorption
0.3K > 100 uW











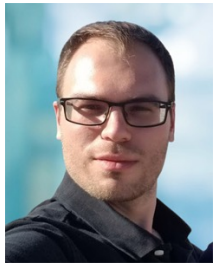
QUP member: Dr. **H. Fukuyama**
(Former Director of Cryogenic Research Center, The University of Tokyo)

Specialist in mK cryogenic system

Theory Group

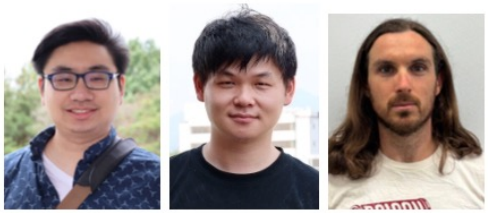
led by K. Nakayama, V. Takhistov

Foundational role in QUP's scientific program :
defining observables, developing search concepts, guiding sensitivity studies, and connecting QUP programs to fundamental physics discovery

- 22 small-team papers submitted or published since July 2025

- 9 WPI posters, multiple visiting international student/postdoc projects near publication





QUPIPs (internship students) were actively involved in research resulting in scientific publications" (ex: Arakawa, Takhistov, et al, JCAP 02 (2026) 026; de Giorgi, Takhistov, et al, JHEP accepted)

Advertisement: Quposium 2026 Dec 8-10, 2026@Tsukuba



Keynote talks

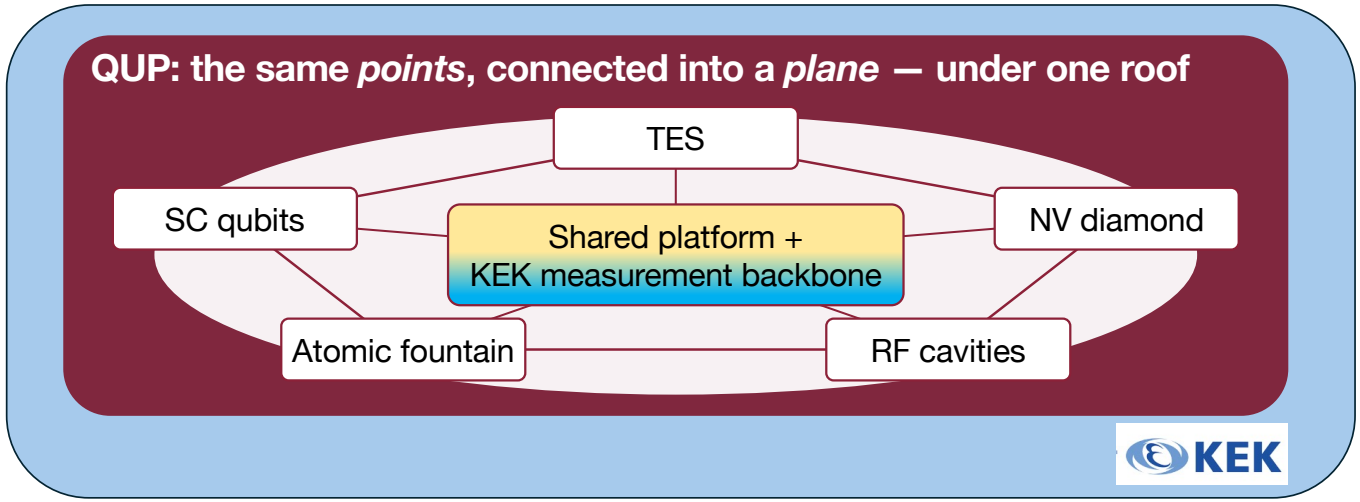
"New QUP: we have changed", **Toshiyuki Azuma** (QUP)
"Harnessing Molecular Complexity for Quantum Science", **John Doyle** (Harvard)
"New perspectives on CP violation and ultralight dark matter", **Gilad Perez** (Weizmann)
"Photonic Quantum Sensing Using Entangled Photons", **Shigeki Takeuchi** (Kyoto)

Confirmed invited speakers

Rana Adhikari (IQIM) | **Claudio Gatti** (INFN)
Maurice Garcia-Sciveres (QUP) | **David Herbschleb** (QUP) | **Hitoshi Ishiwata** (QST)
Kana Iwakuni (U.Electro-Comm) | **Akito Kusaka** (Tokyo) | **Tatsumi Nitta** (QUP)
Nancy Paul (LKB) | **Surjeet Rajendran** (Johns Hopkins) | **Boon Kok Tan** (Oxford)

Quantum Sensing for New Physics

Not one detector. Not one experiment.
One international center exploring nature through many quantum technologies.



Thank you