Optical Transition-Edge Sensors: From Quantum Computing to Light Dark Matter Search

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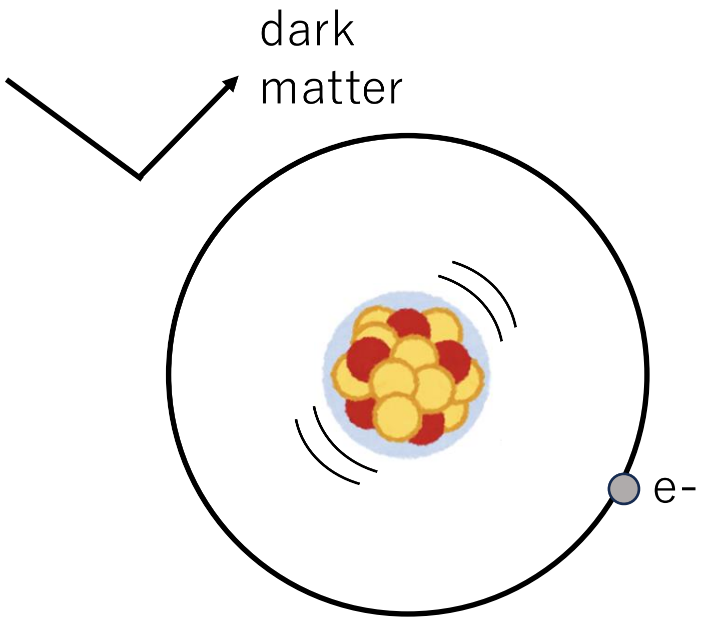
[1]KEK, QUP [2]LBNL [3]Tohoku University [4]RIKEN [5]University of Tokyo
[6]Kyoto University, [7]Rikkyo University

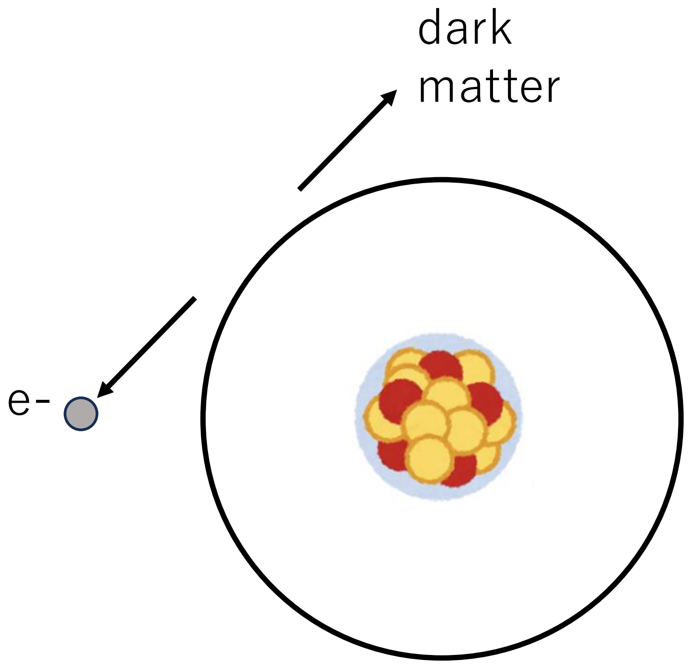
MeV dark matter direct detection



DM-nuclear scattering

$$E_R \sim 50 \text{ keV} \left(\frac{m_\chi}{100 \text{ GeV}}\right)^2 \left(\frac{100 \text{ GeV}}{m_N}\right)$$

$$E_R \sim 10^{-5} \text{eV}$$



DM-electron scattering

$$E_R \sim 0.5 \text{ eV} \left(\frac{m_\chi}{1 \text{ MeV}}\right)$$

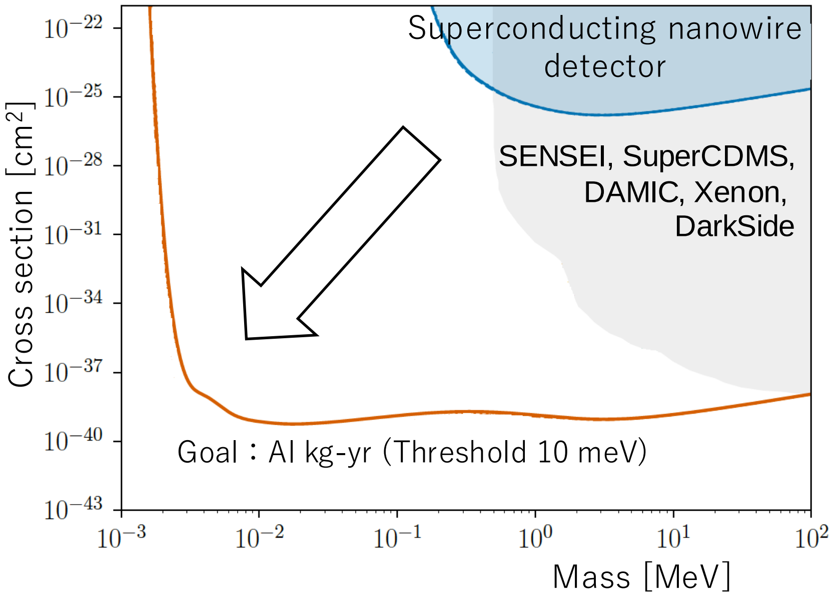
$$E_R \sim 0.5 \text{ eV}$$

Superconducting detectors
sensitive to sub-eV signals

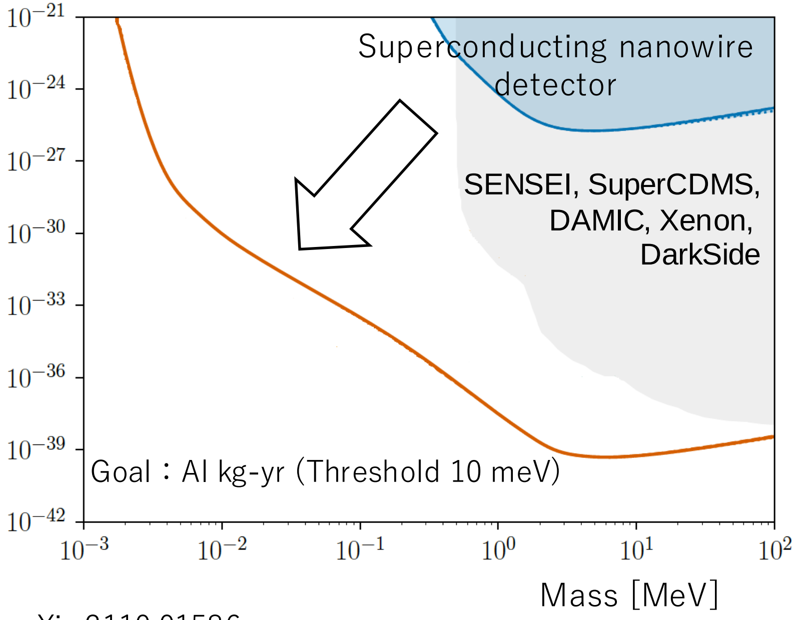
$$m_\chi = 1 \text{ MeV}$$
$$m_N = 25 \text{ GeV}$$

MeV dark matter search

DM-electron scattering：light mediator



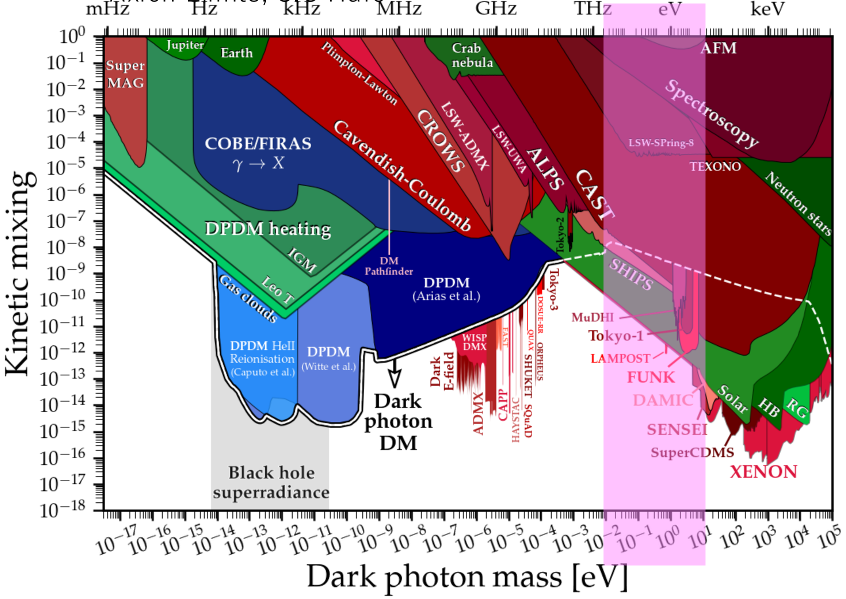
Heavy mediator



Y. Hochberg et al., arXiv:2110.01586

Absorption：dark photon

Axion Limits, C.O'Hare



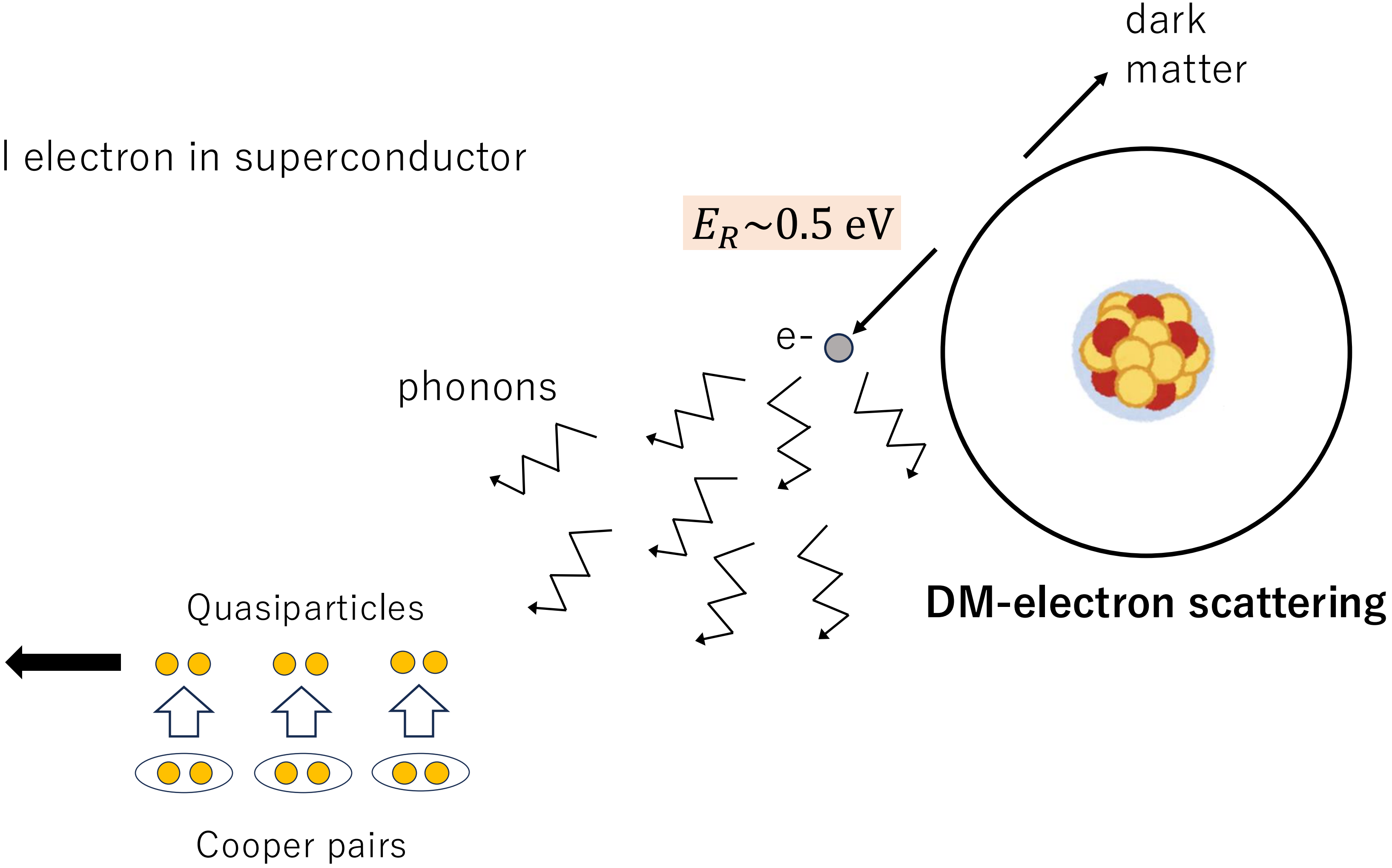
Explore 0.01 – 10 eV

Explore MeV region with detectors sensitive to sub-eV signals.
Low energy threshold (100 meV) is crucial to search sub-MeV dark matter.

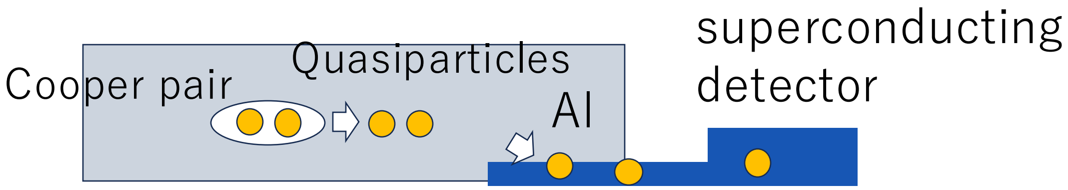
MeV dark matter direct detection

Recoil electron in superconductor

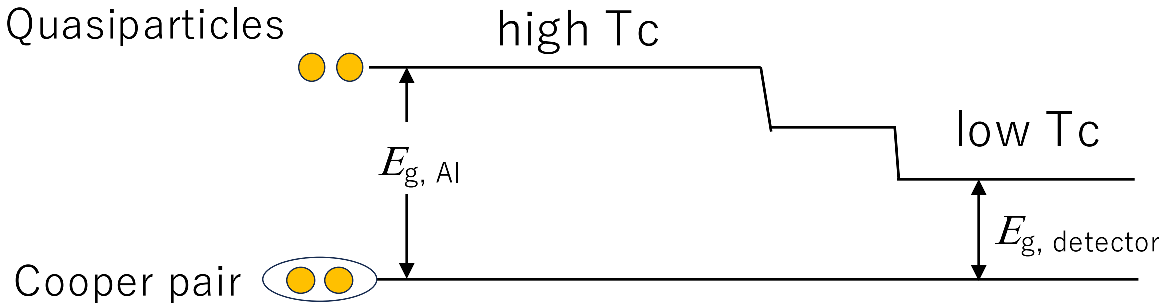
Detected by superconducting detectors sensitive to sub-eV signals



Quasiparticle detectors



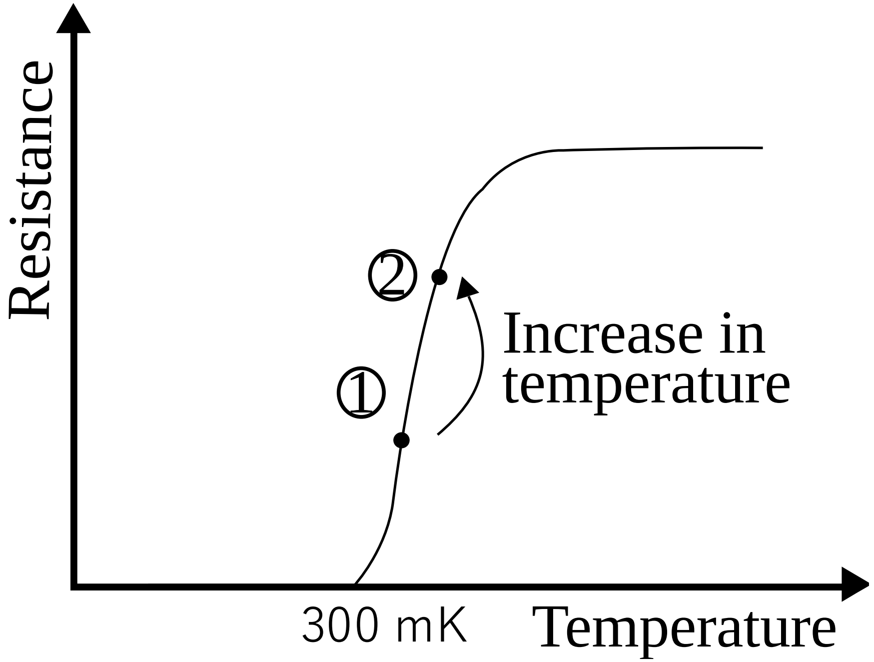
Tc: critical temperature below
which resistance drops to zero

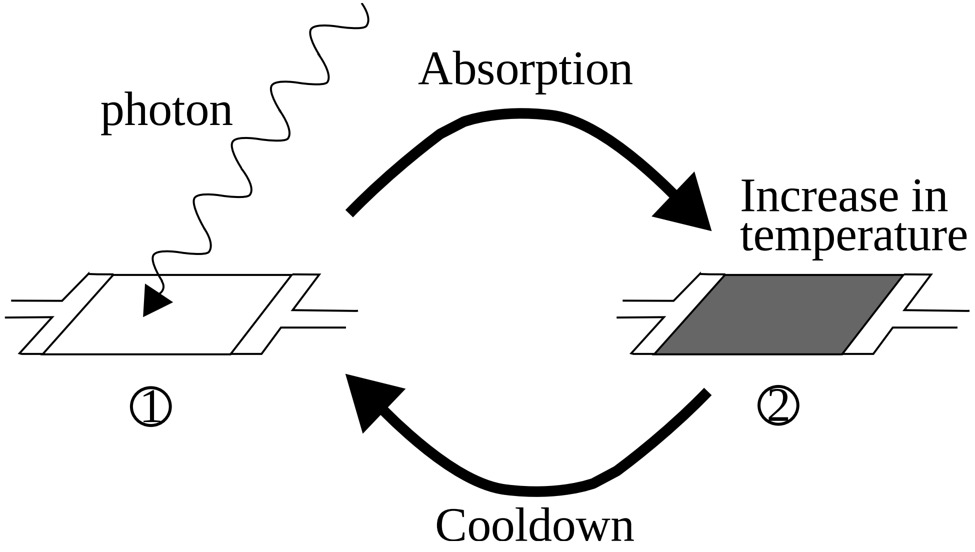


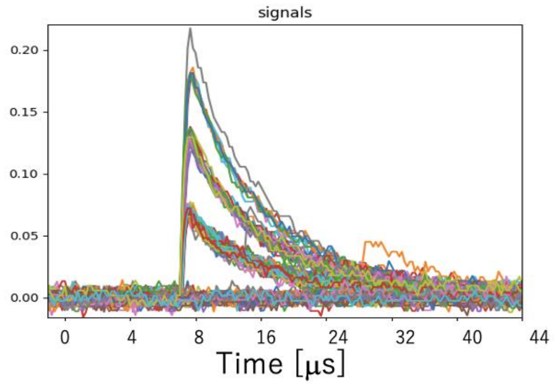
Quasiparticles trapped in superconducting detector
Warm up electrons in detector → thermometer

Transition-edge sensor (TES)

very sensitive thermometer





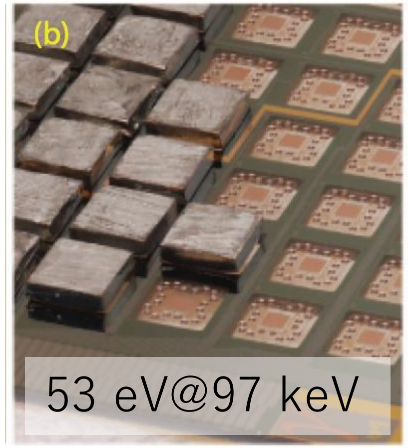


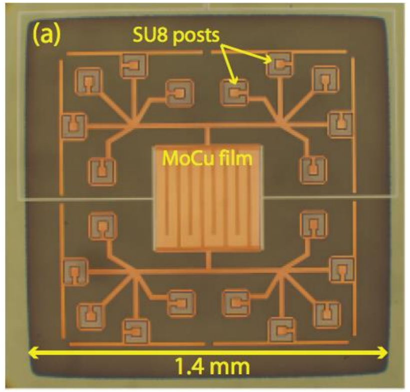
1. Bias the detector in transition
2. Energy is deposited in a detector and is converted to heat.
3. Increase in temperature results in increase in resistance

TES calorimeters

gamma-ray

D. A. Bennett et al., Rev. Sci. Instrum. 83, 093113 (2012)

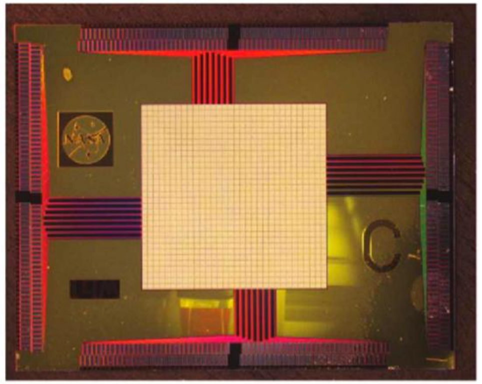




absorber：1 mm×1 mm ×sub-mm
TES： sub-mm × sub-mm × sub-μm

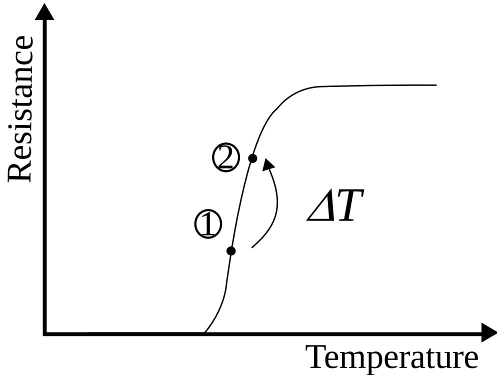
X-ray

J. N. Ullom et al. Supercond. Sci. Technol. 28 (2015) 084003



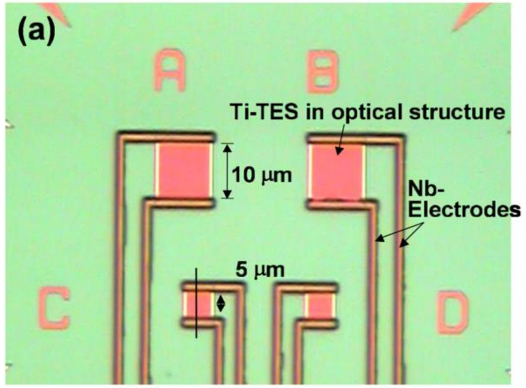
absorber：200μm、thickness a few μm
TES：100-200μm、thickness 100nm

$$\Delta T = E_{photon}/C$$



Optical
Near infra-red

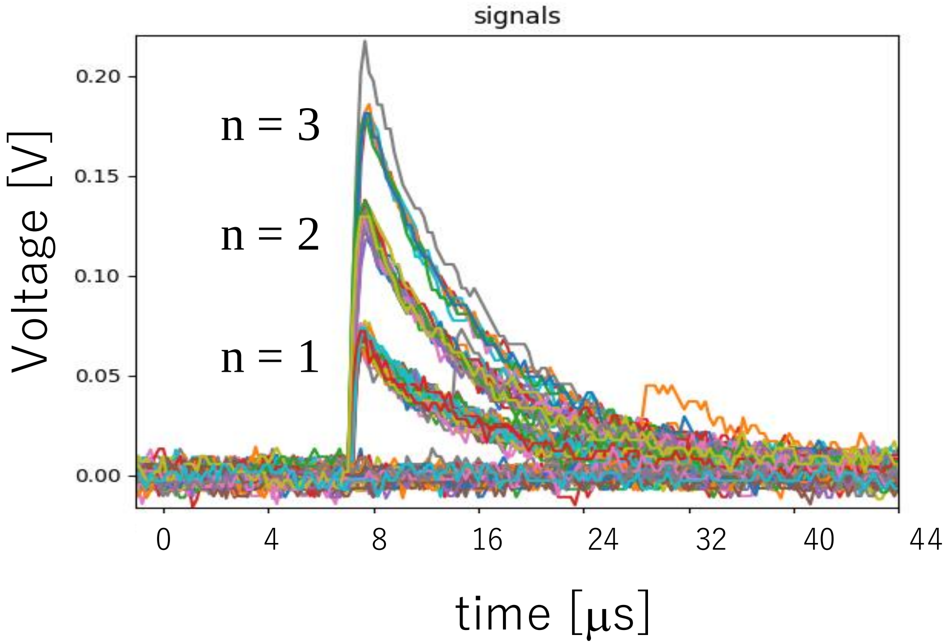
67m eV@0.8 eV



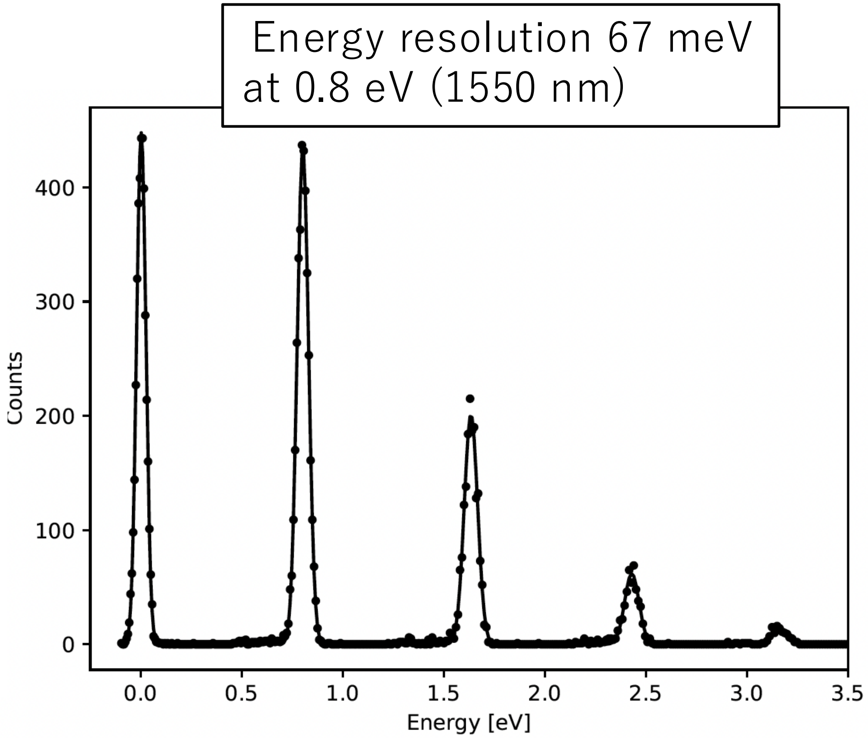
D. Fukuda et al., Metrologia, 46 (2009) S288–S292

TES：5-10μm, thickness 20nm
No absorber or membrane

TESs sensitive to sub-eV signals

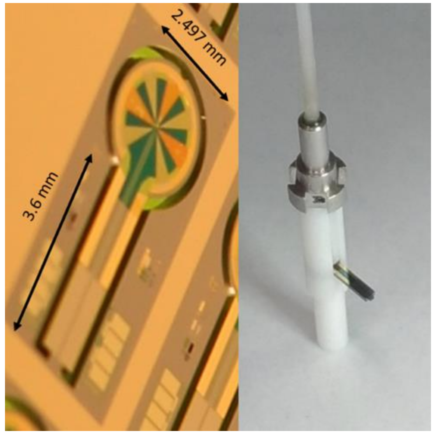


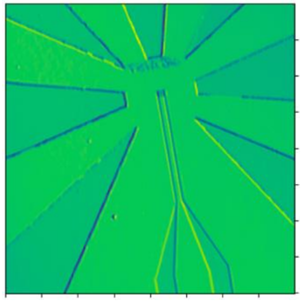
Ti/Au (20/10 nm) bilayer
8×8 μm



K. Hattori et al., Supercond. Sci. Technol. 35 (2022) 095002

coupled with a fiber





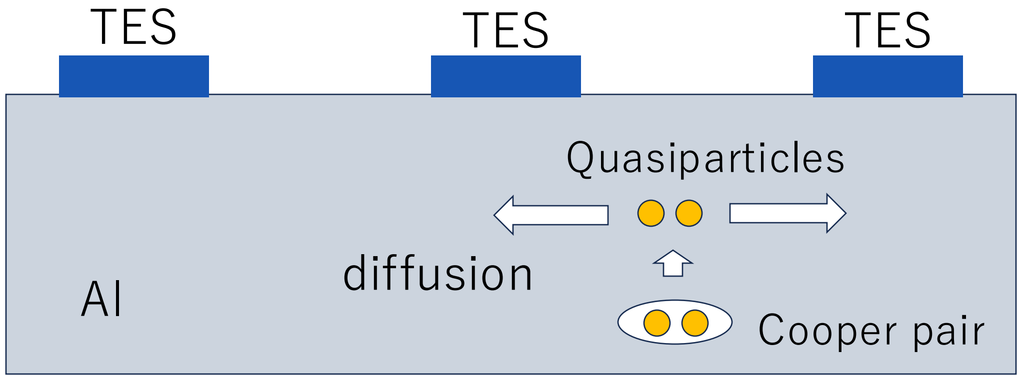
Optical TES can also detect quasiparticles.

TES coupled with aluminum target

Low energy threshold (100 meV) is crucial to search sub-MeV dark matter.

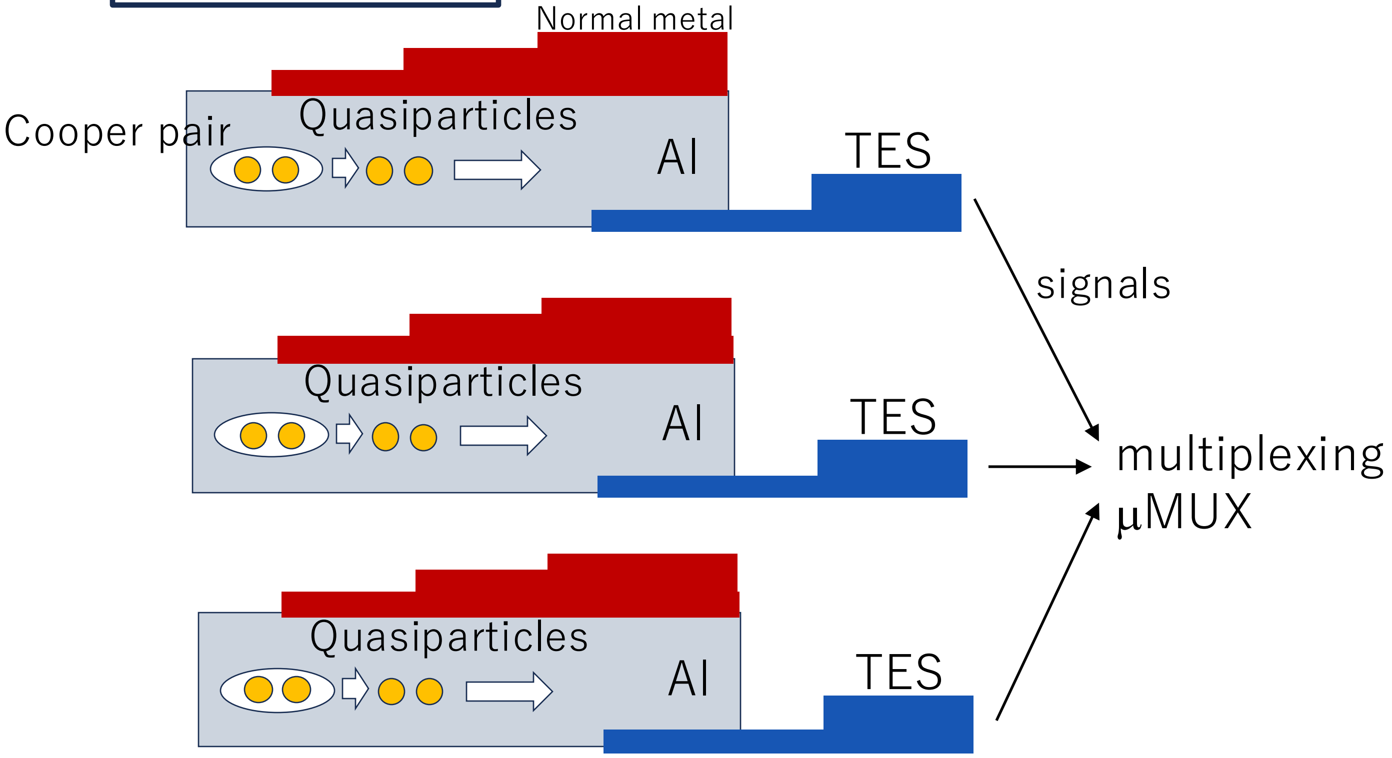
Initial design

Low collection efficiency of quasiparticles



New design

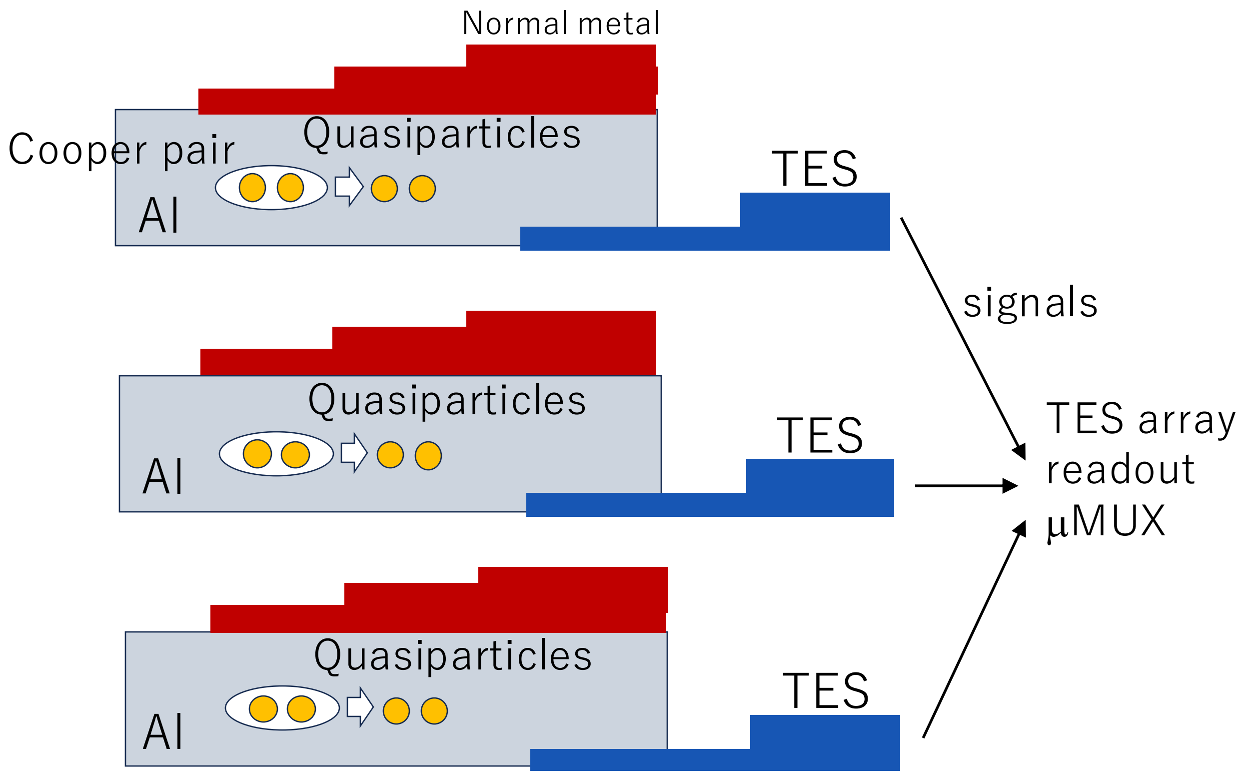
80% collection efficiency (target)



Normal metal is deposited above Al to control flow of quasiparticles.
Could improve collection efficiency of qps and lower threshold.

TES coupled with aluminum target

Low energy threshold is crucial to search sub-MeV dark matter.



quasiparticle-trap-assisted TES (QET)
K. Irwin et al., Rev. Sci. Instrum. 66, 5322 (1995).

Candidate for TES material

Ti/Au bilayer film

- High energy resolution (67 meV FWHM)
- Thin Ti film is required to couple Al and TES

AlMn film

- AlMn TES bolometers have been used for CMB experiments
- Easy to couple with Al target

Schedule

Step a
QUP TESx 40

Step b
TES+Al x 80

Step b
TES+Al x 2,000

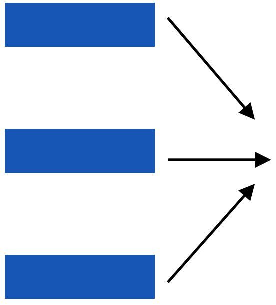
2026 2027 2028 2029

Three candidates
- Ti/Au TESs, AIST
- Ti/Au TESs, JAXA/NAOJ
- AlMn TESs, Seeqc

⇩ Choose one of them

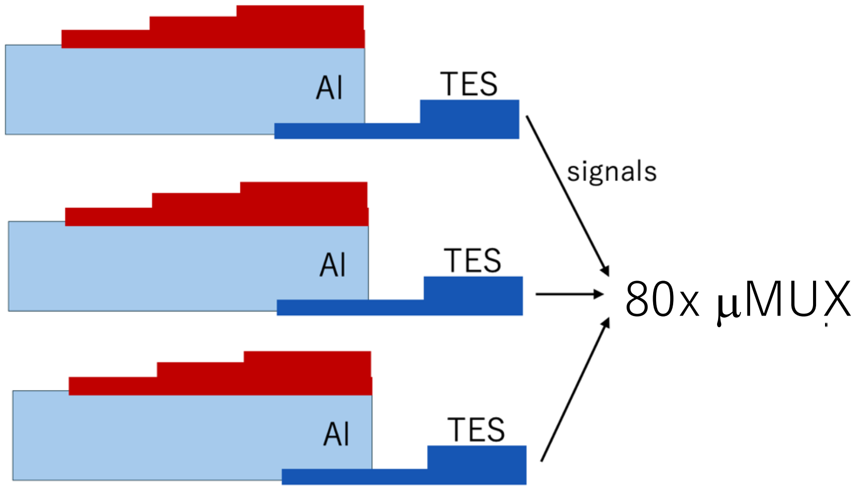
Step a Straightforward to achieve low threshold.

40 TESs

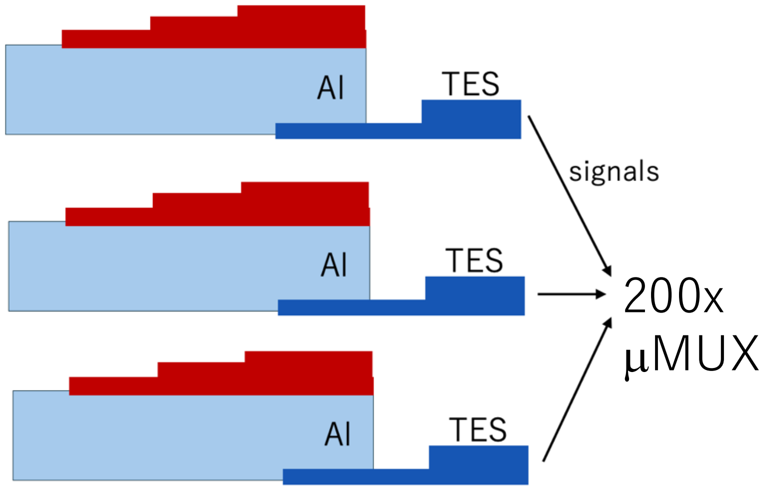


multiplexing
40x μMUX

Step b 80 channels



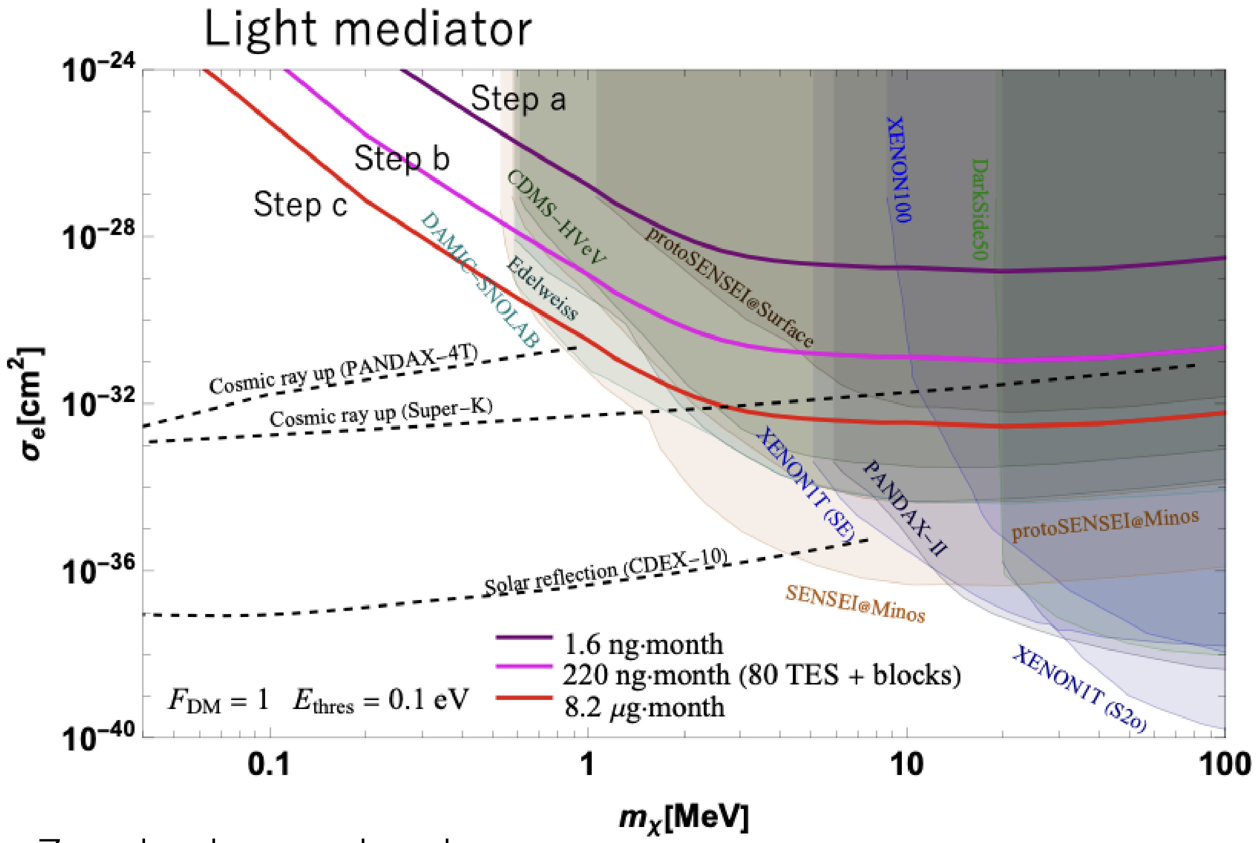
Step c Ultimate goal
2,000 channels

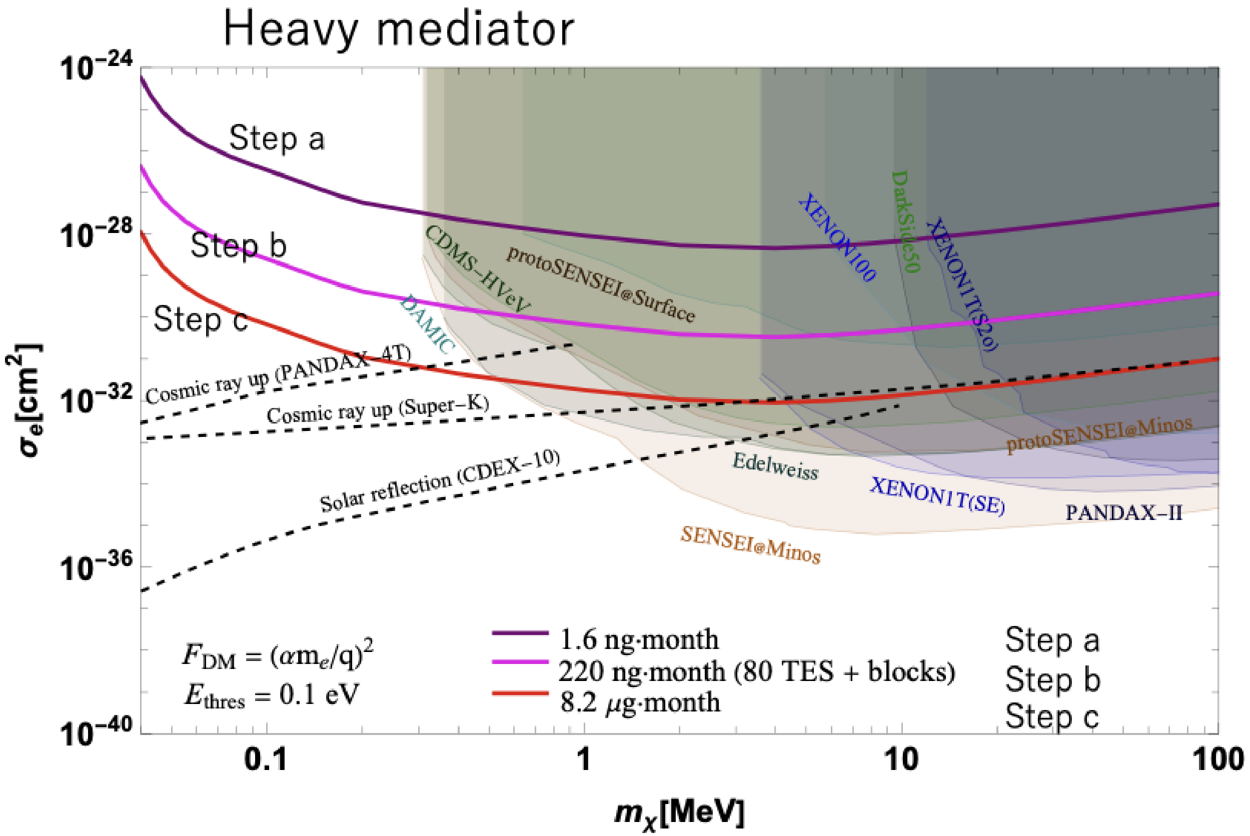


Estimated Sensitivity - Scattering

With low energy threshold, search with small mass can be competitive.

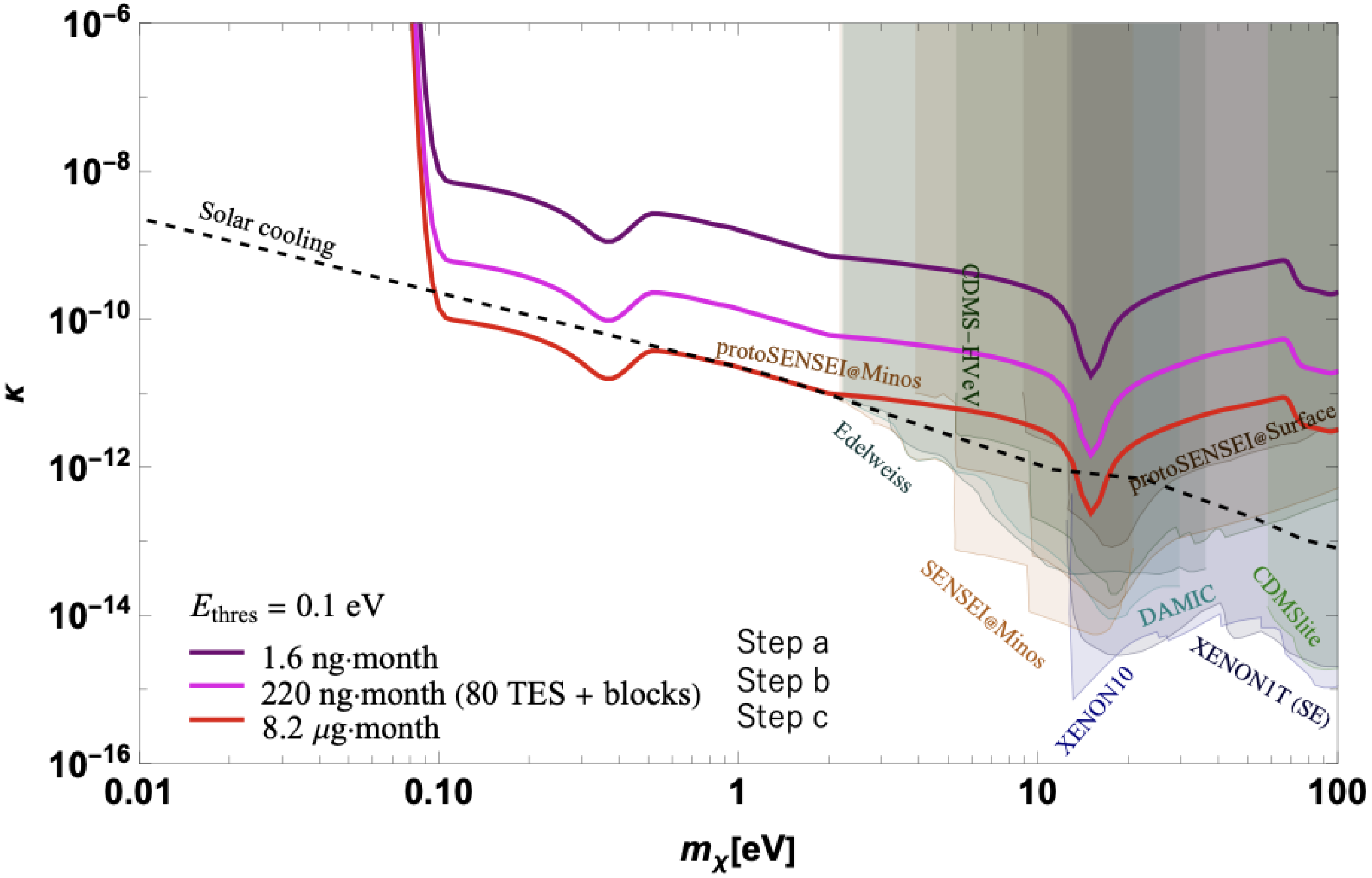
M. Chen, K. Hattori, K. Nakayama, V. Takhistov





– Zero background and
100% collection efficiency of quasiparticles are assumed.

Estimated Sensitivity - Absorption



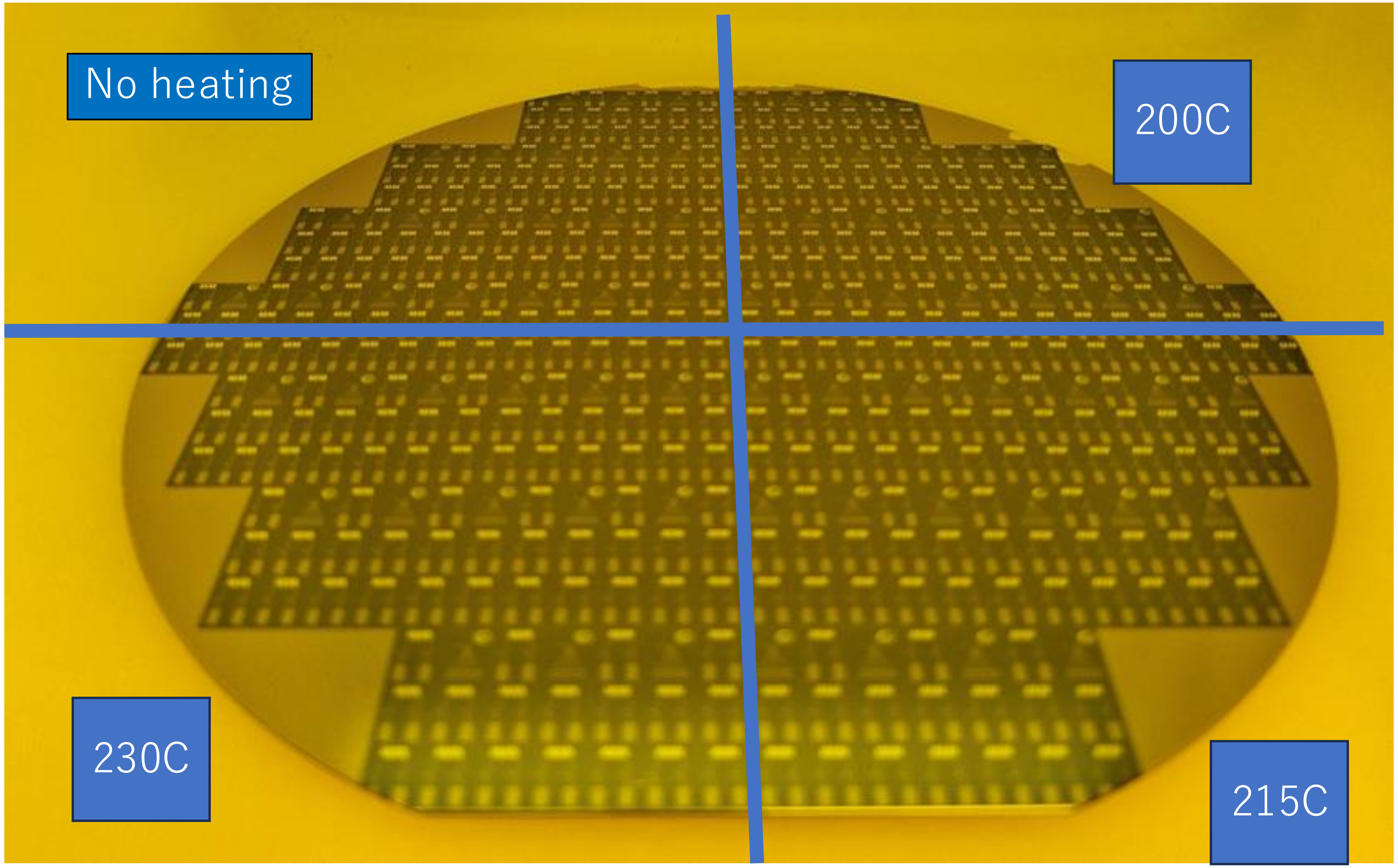
Zero background and
100% collection efficiency of quasiparticles are assumed.

Calculation considering detector noise is ongoing.

AlMn TESs

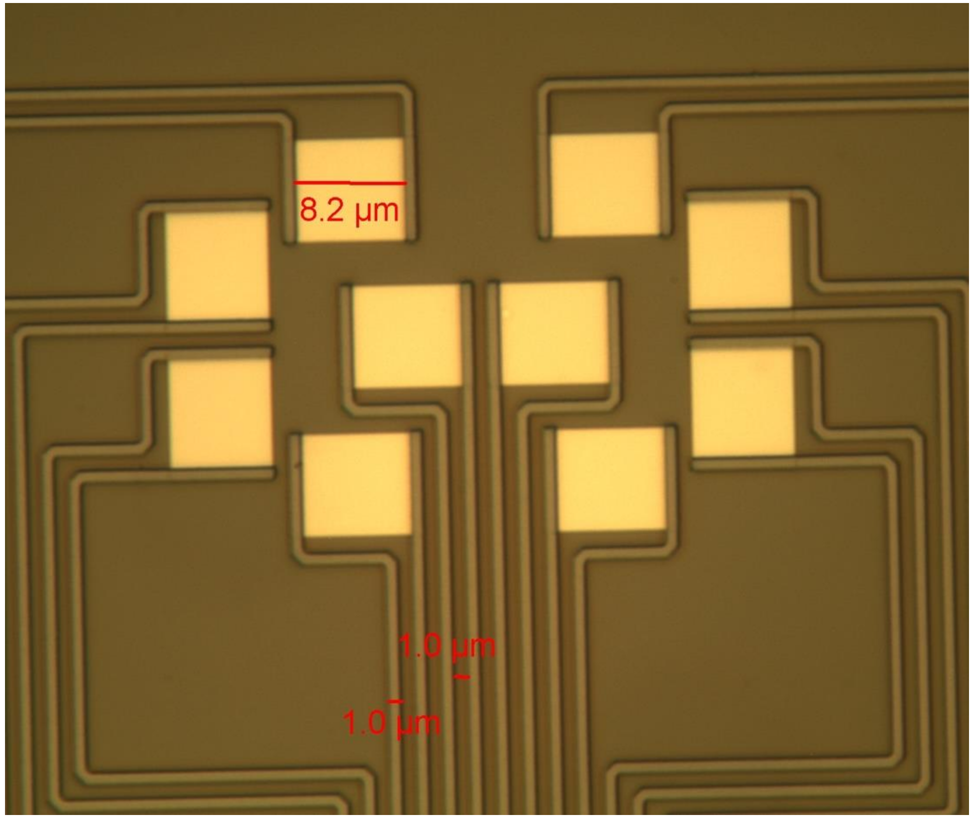
M. Garcia-Sciveres, K. Hattori, A. Suzuki, Y. Zhou
Fabricated by Seeqc (US).

6 inch wafer.
T_c can be controlled
by heating temperature.

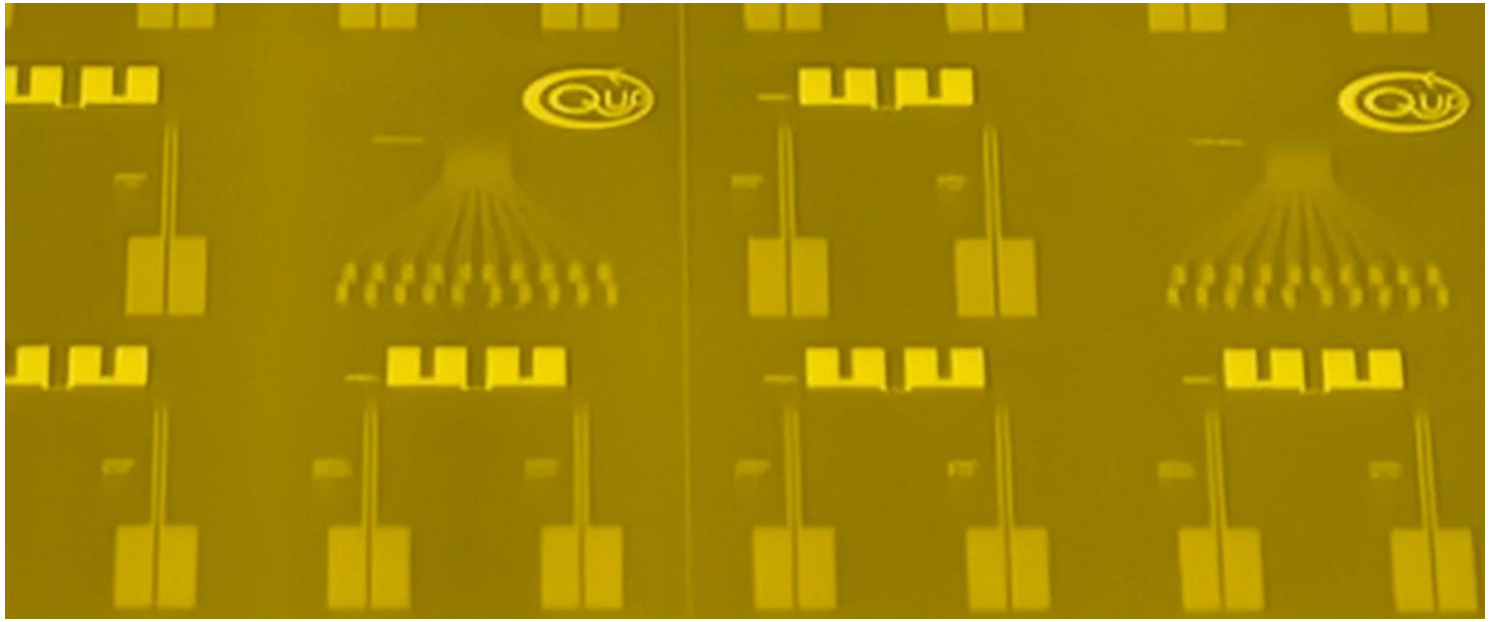


AlMn TESs

TES array



Design：T. Hayashi (立教大)



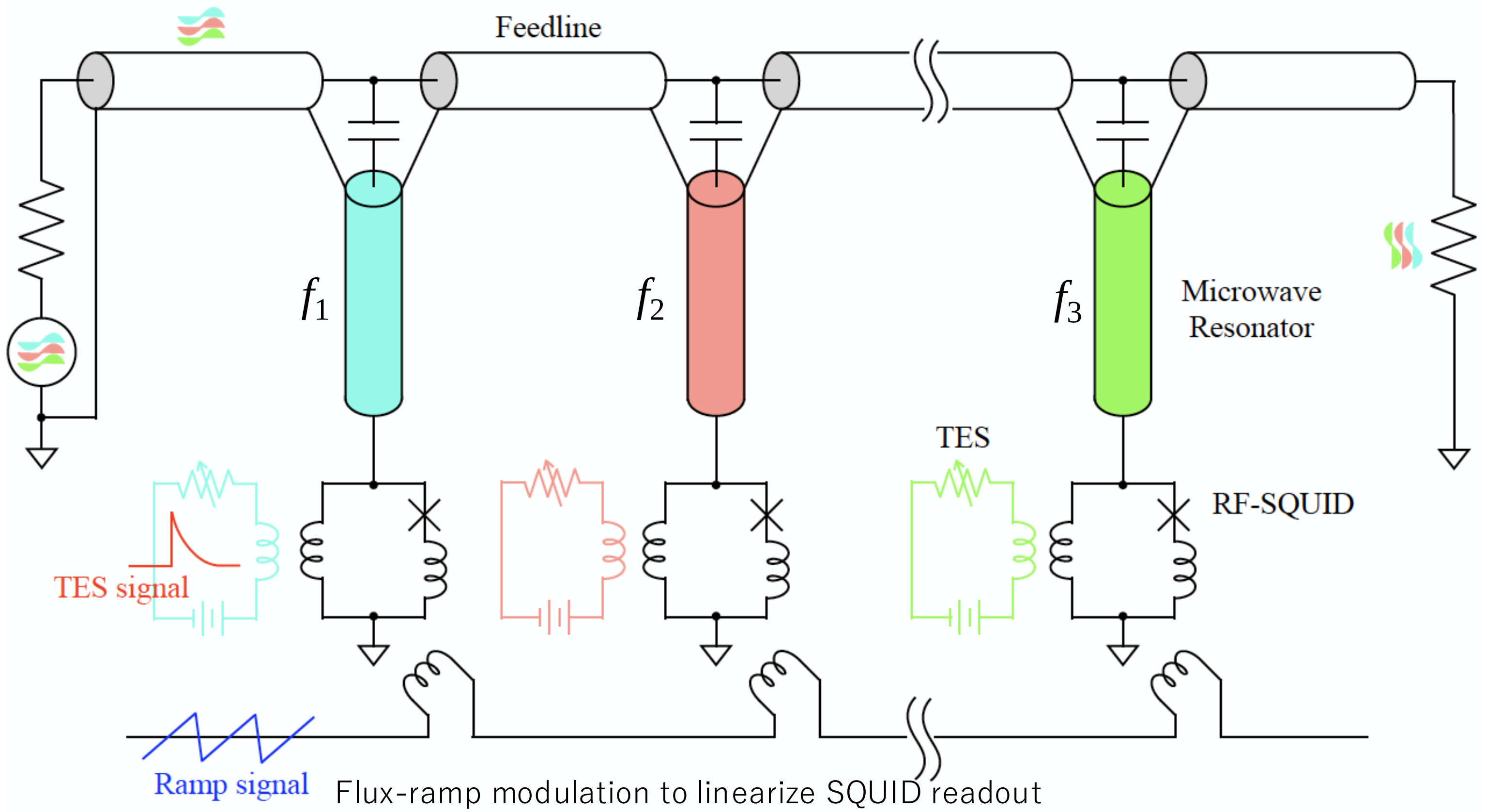
Will measure Tc and detector response on near-infrared photons.

Backup plans
Ti/Au TES array (40 channels) fabricated by JAXA – this year
Ti/Au TES array (9 channels) fabricated by AIST – ongoing

TES array readout

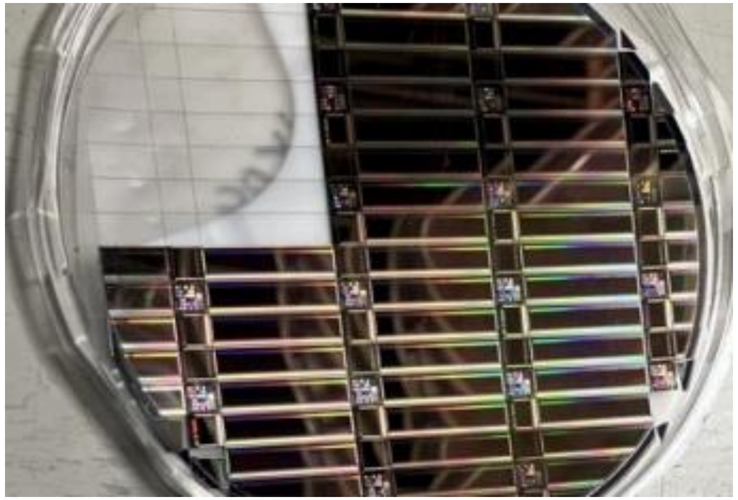
Microwave SQUID multiplexers

R. Hayakawa



Flux-ramp modulation to linearize SQUID readout

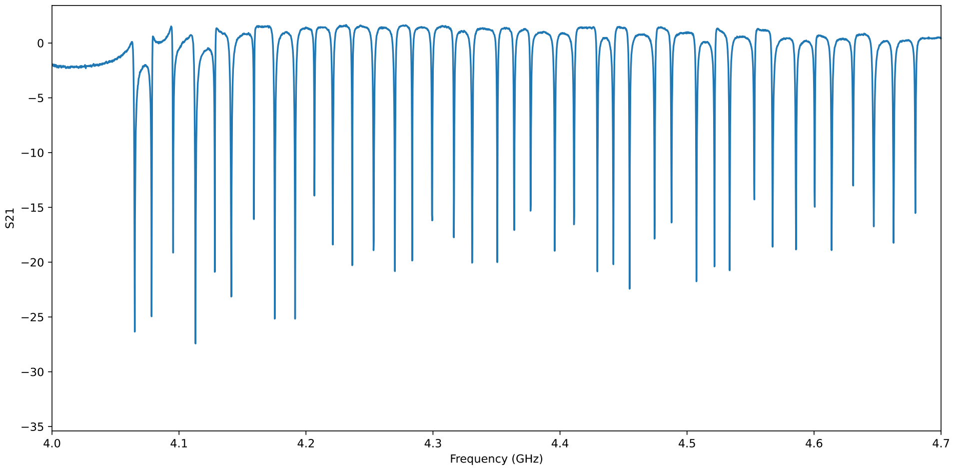
40 channels



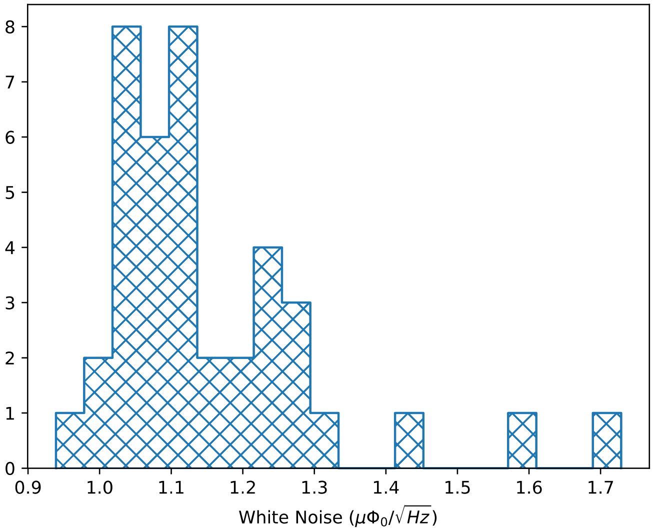
Fabricated by AIST in 2024.
Designed for X-ray TESs.

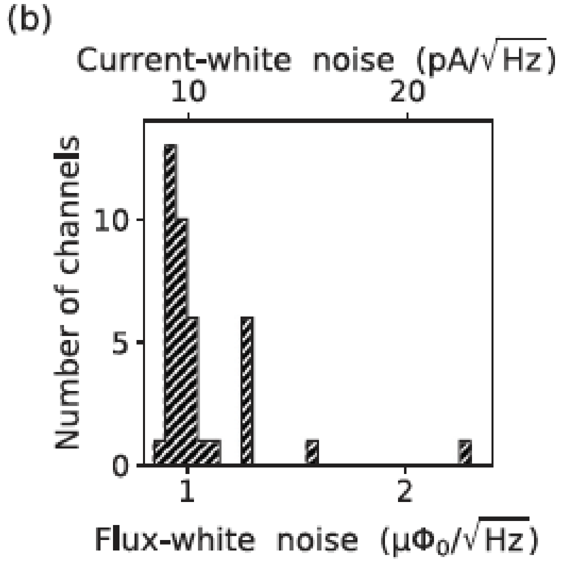
TES array readout

40-channel resonance peaks



Noise level is at the same level as previous study.





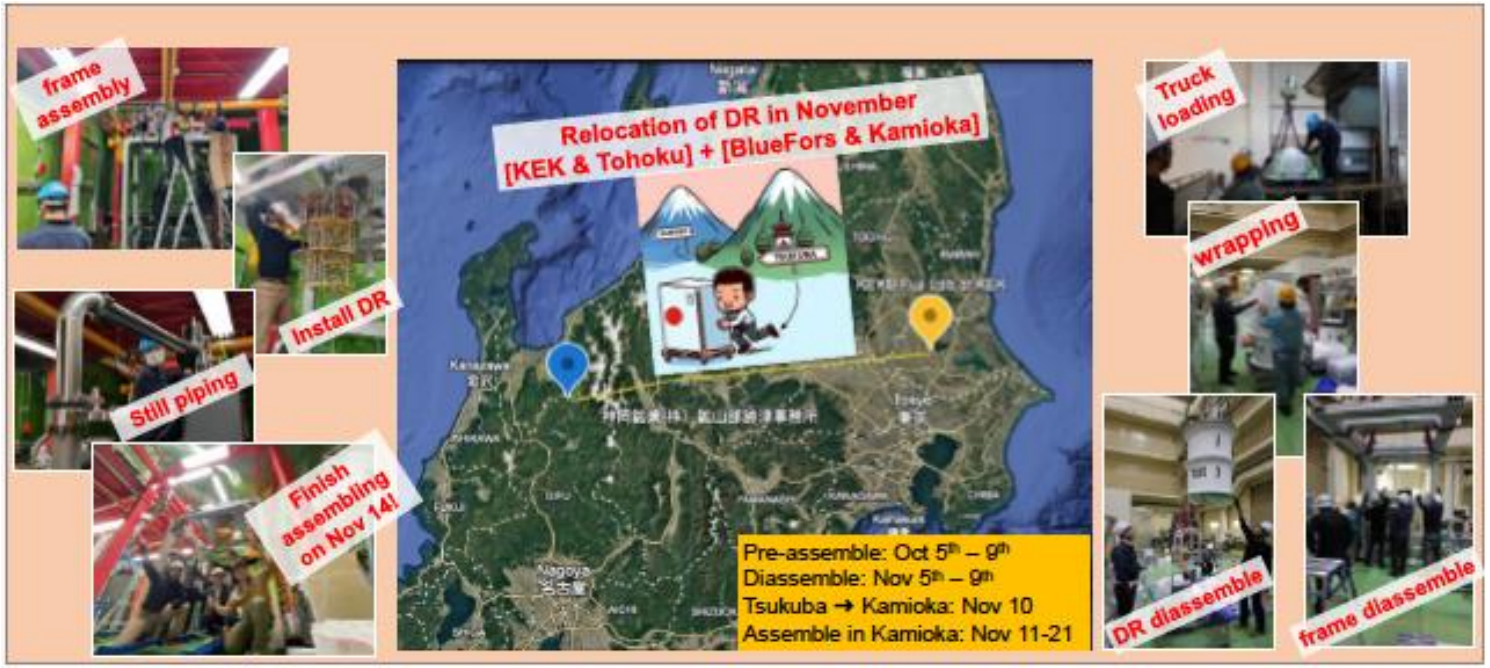
Y. Nakashima, Appl. Phys. Lett. 117, 122601 (2020).

R. Hayakawa, T. Hayashi

We are testing the readout with TES array for X-ray photons.
We will test it with new TES array sensitive to sub-eV signals soon.

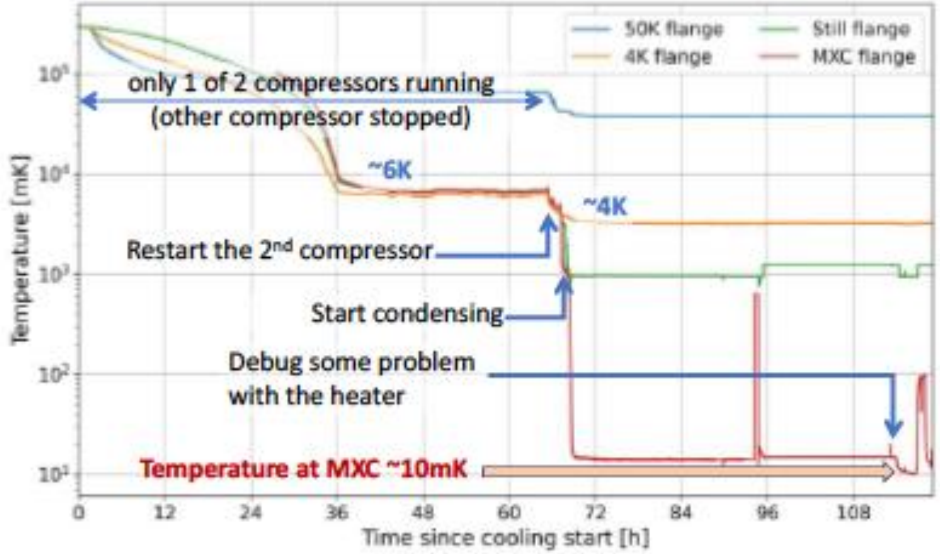
Kamioka DM project

M. Garcia-Sciveres, K. Hattori, R. Hayakawa, Y. Zhou, Bui Tuan Khai, S. Burkhant, M. Hasegawa, K. Ichimura, K. Ishidoshiro, Y. Kamei, A. Kusaka, K. Kiuchi, X. Li, A. Suzuki, J. Suzuki, V. Takhistov, O. Tajima, S. Yoshida



Slide from Bui Tuan Khai

Placed in KamLAND area.



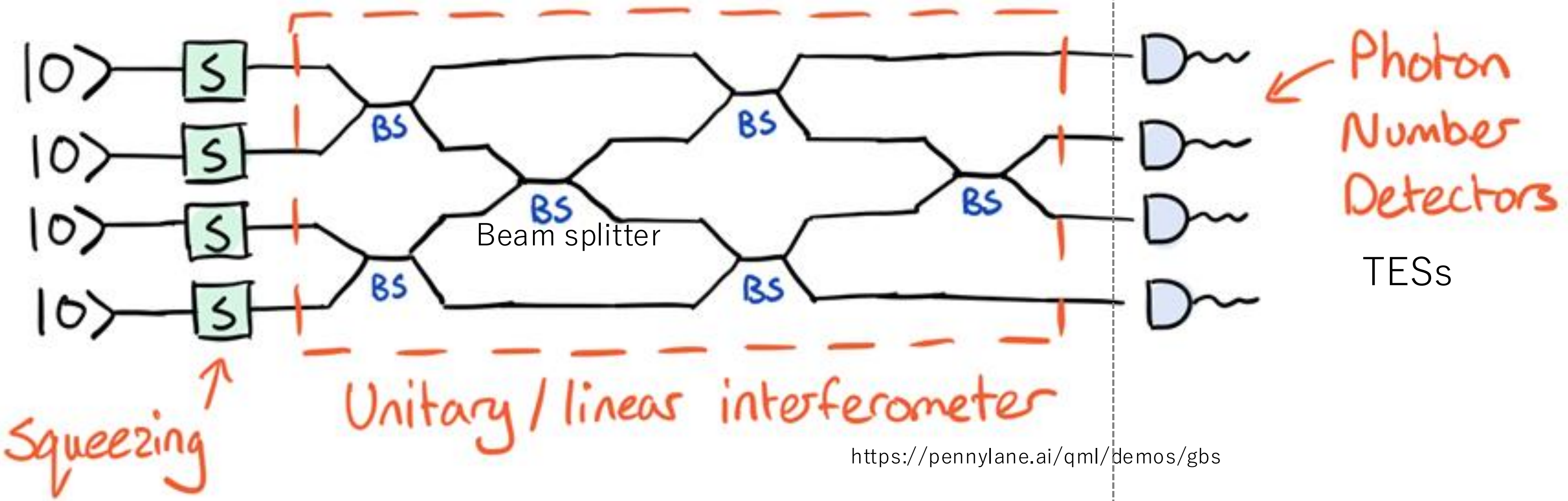
Relocated a dilution fridge to Kamioka.
First payload will be HeRALD
(Helium Roton Apparatus for Light Dark matter).
Second payload will be TESs coupled with Al targets.

Application of optical TESs to quantum computing

Photonic quantum computing

Optical circuits are at room temperature.
TESs at cryotemperature serve as photon counters.
Pulsed lasers are used: Several photons / pulse
→Calorimeters can measure the total energy and thus the total photon number.

Gaussian Boson Sampling (GBS)



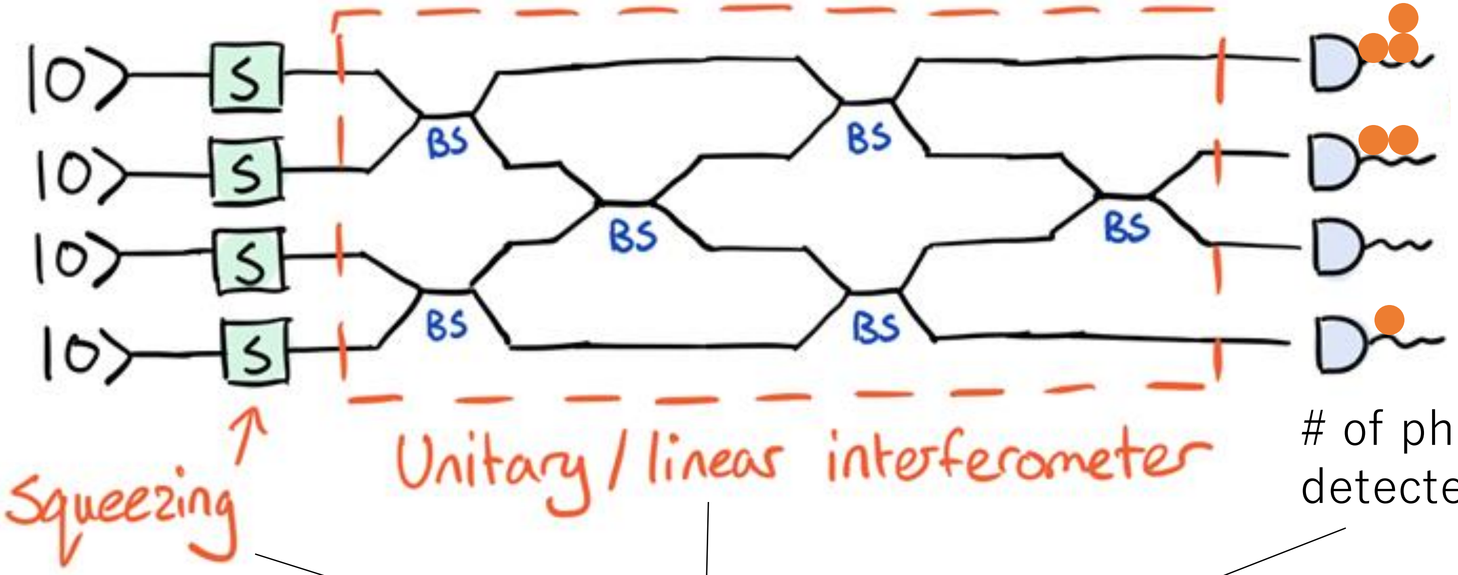
Beam splitter

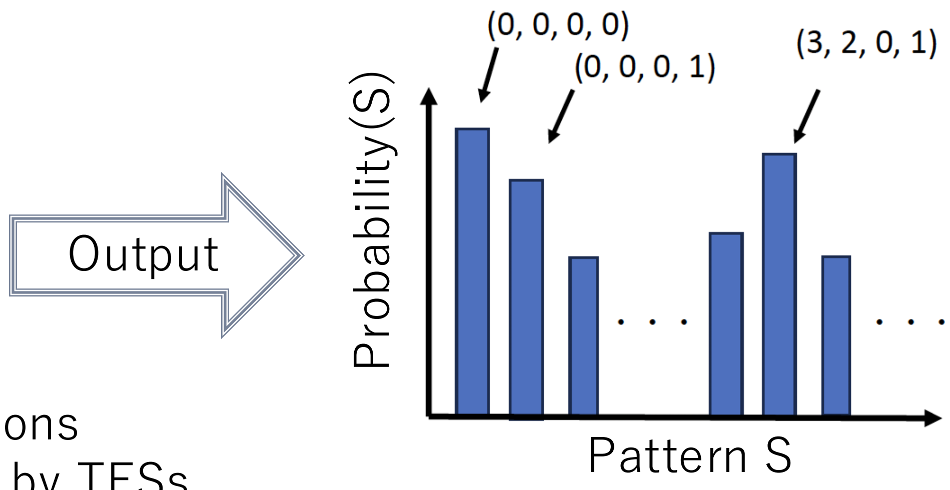
TESs

https://pennylane.ai/qml/demos/gbs

room temperature

Gaussian Boson Sampling (GBS)





# of photons
detected by TESs

$$\mathrm{P}(S) \propto |\mathrm{Permanent}[C(U, \boldsymbol{r}, S)]|^2$$

Polynomial in entire of a square matrix
Similar to determinant

⇓

Graph optimization
Quantum chemistry
Quantum machine learning

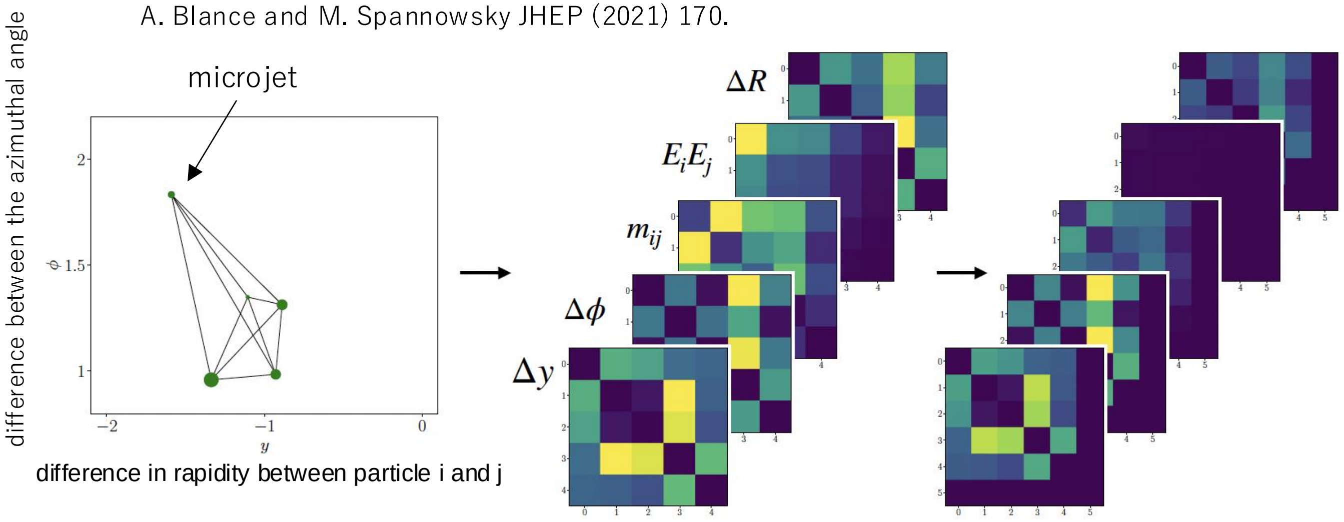
Classical computing:
Computational task (Ryser's formula) $\propto O(N2^n)$.
N : # of detectors
n : # of photons detected by TESs

⇓

Exponentially hard to simulate
using classical computation.

Application of GBS to high-energy physics

A. Blance and M. Spannowsky JHEP (2021) 170.



Construct graph

Converted to matrices

→ Gaussian Boson Sampling

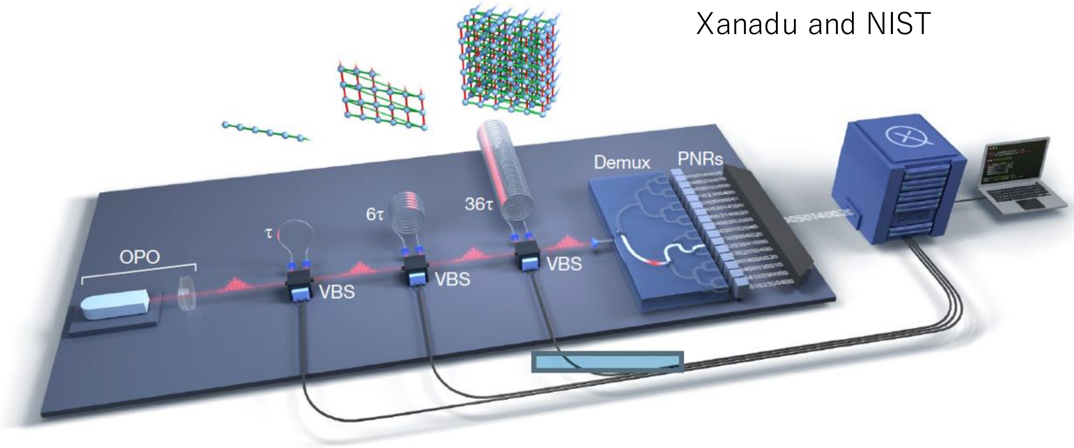
Graphs have proven to be a powerful representation for collider data.
Combined with an anomaly detection method could be useful.

Gaussian Boson Sampling (GBS)

Quantum computational advantage

H. Zhong et al., Science 370, 1460-1463 (2020).

Xanadu and NIST



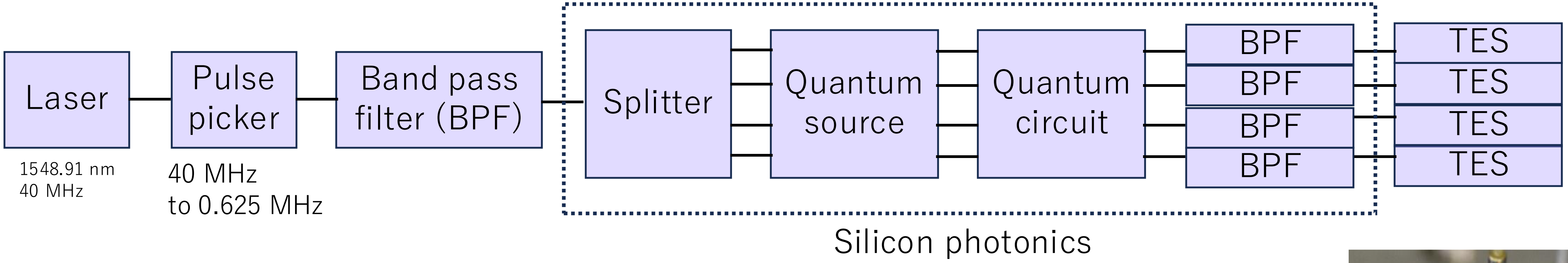
L. S. Madsen et al.,Nature, **606** 75 (2022).

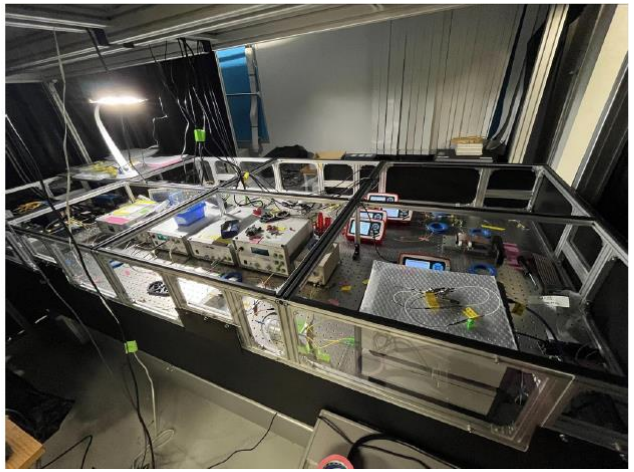
Computational time reduced from 30×10^{6} yr to 200 s.
100 single-photon nanowire detectors (SNSPDs)

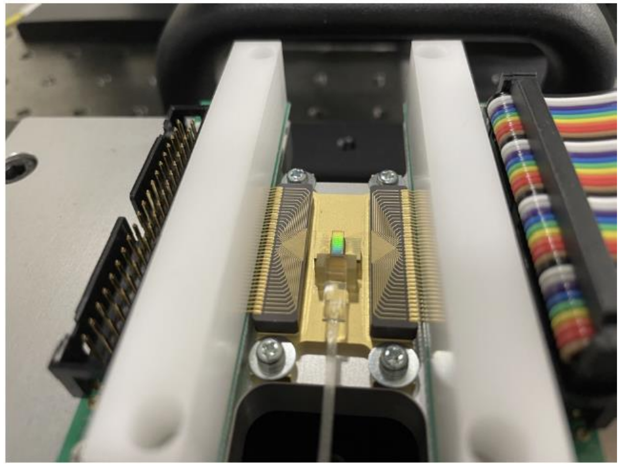
Computational time reduced from 9×10^{3} yr to 36 μs.
16 TESs

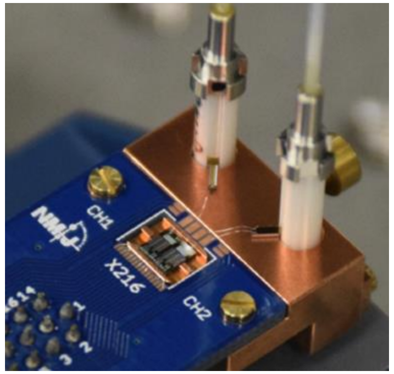
Gaussian Boson Sampling

AIST : M. Okano
Tohoku Univ. : T. Motohashi, T. Odaga
S. Ogawara, N. Matsuda



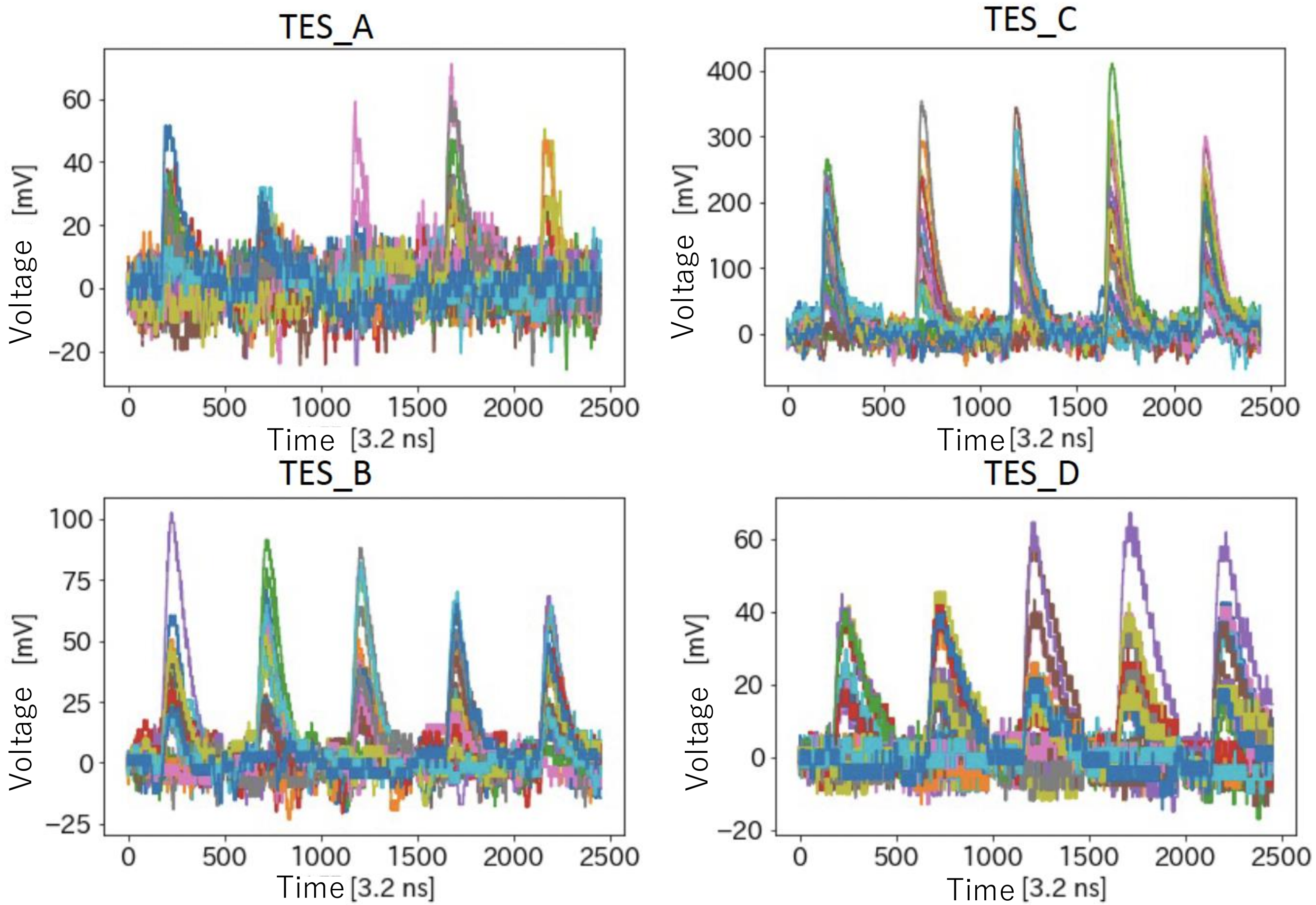




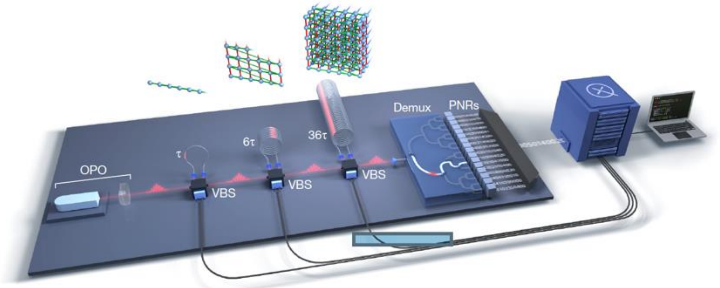


TESs read out
by DC SQUIDs.
Not multiplexed.

TESs detected photons from a 0.625 MHz pulsed laser



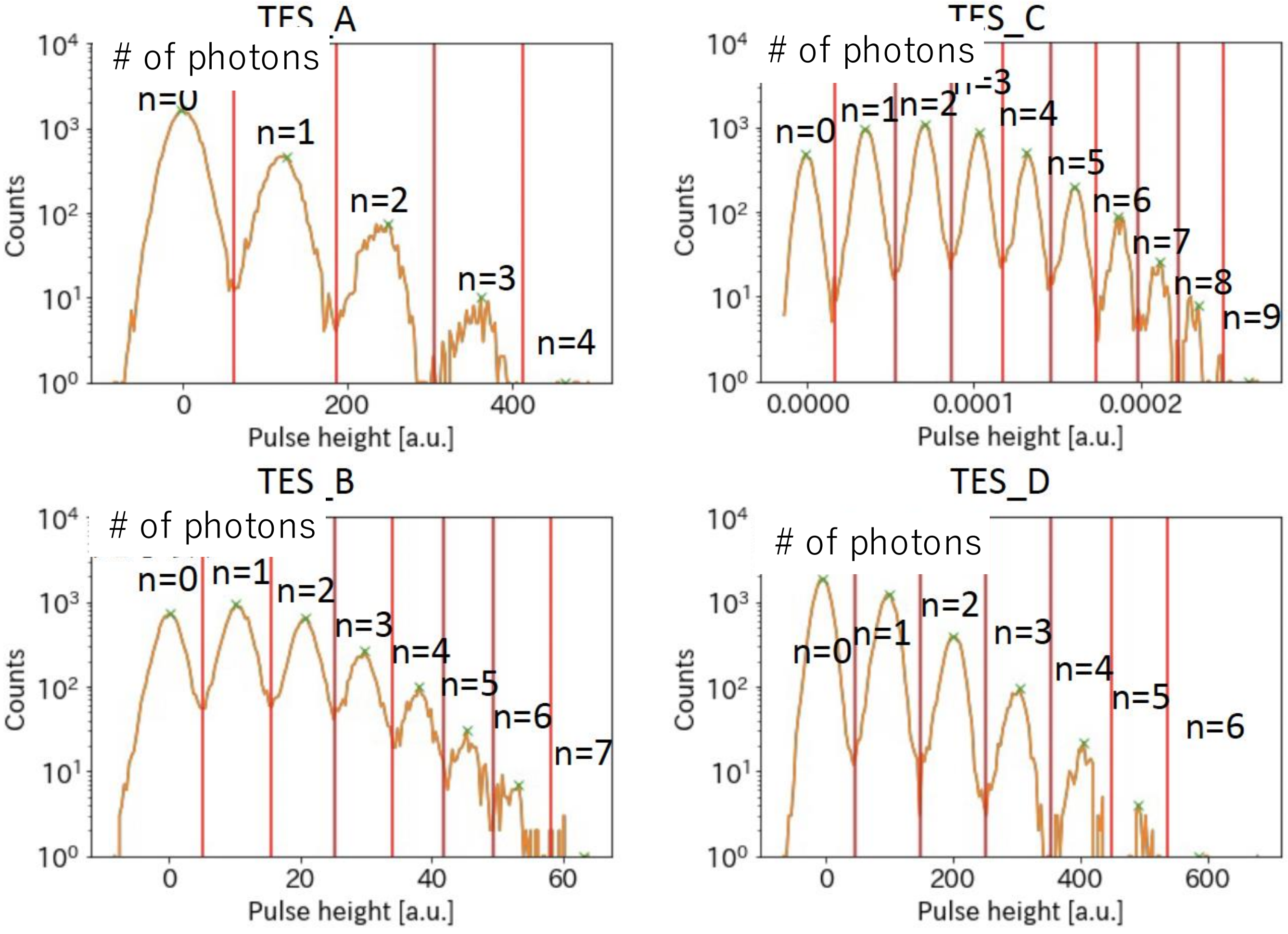
Xanadu and NIST



L. S. Madsen et al.,Nature, **606** 75 (2022).

6 MHz / 16 = 0.375 MHz
for each TES

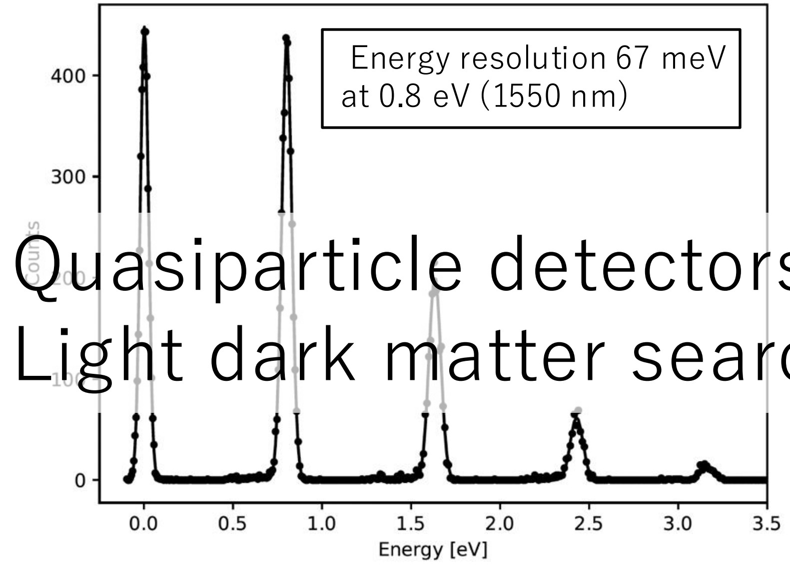
Spectra



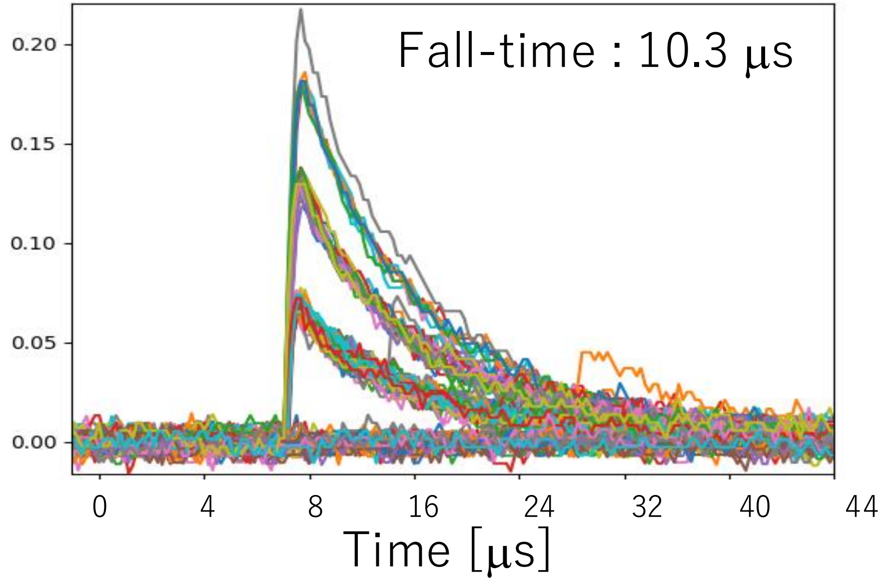
Successfully counted the number of photons at 0.625 MHz

Summary

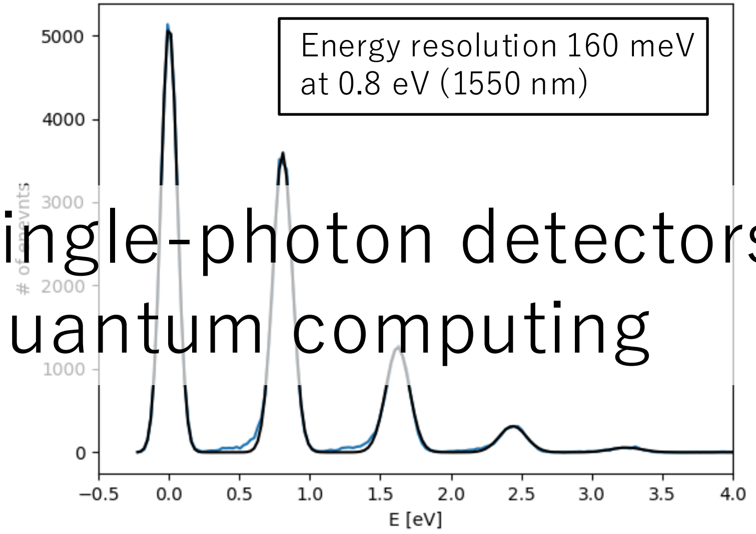
TES with high energy resolution ($T_c \sim 100$ mK)



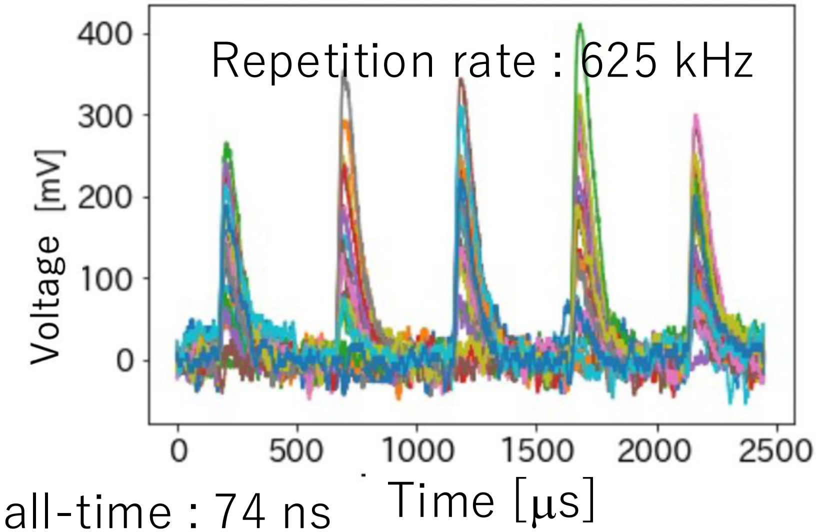
Quasiparticle detectors for
Light dark matter search



Fast TES ($T_c = 300$ mK)



Single-photon detectors for
Quantum computing



Fall-time : 74 ns

R. Kobayashi et al., IEEE Trans. Appl. Super. 29 210115 (2019).