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

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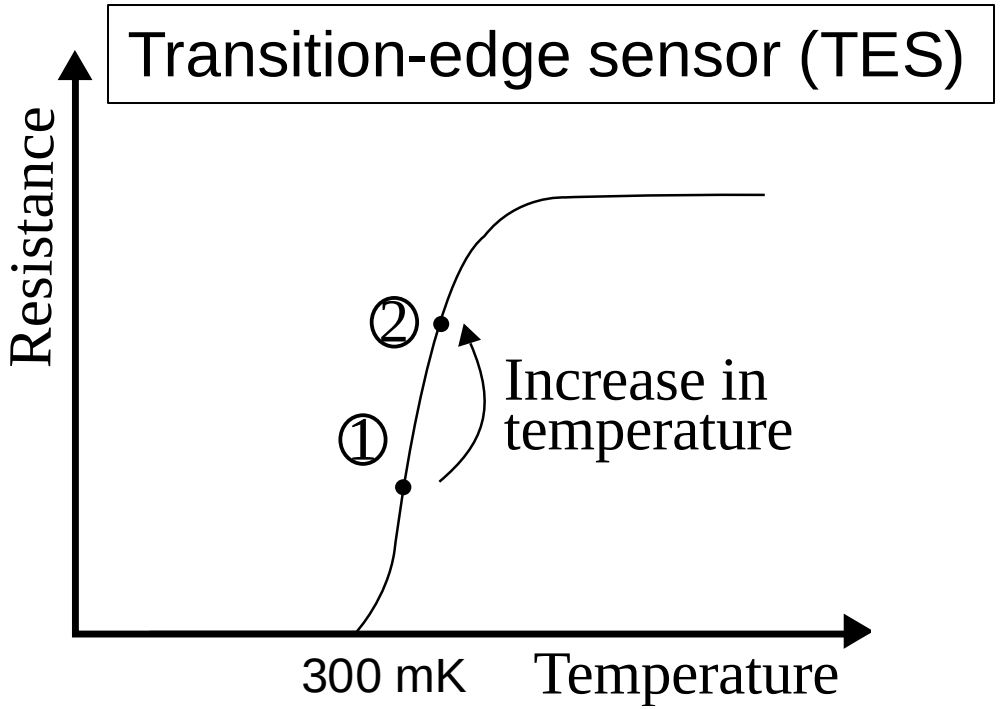
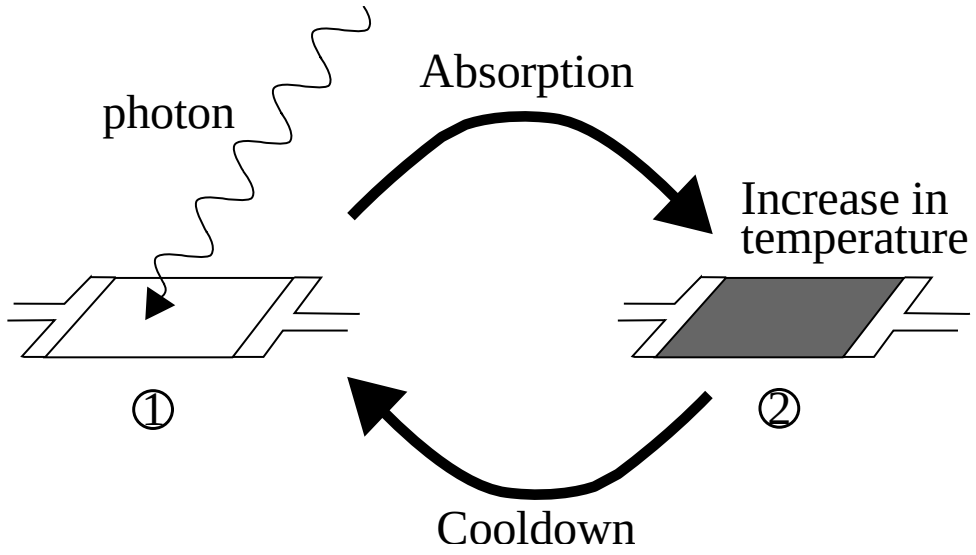
National Institute of Advanced Industrial Science and Technology (AIST)[1]

QUP KEK[2]

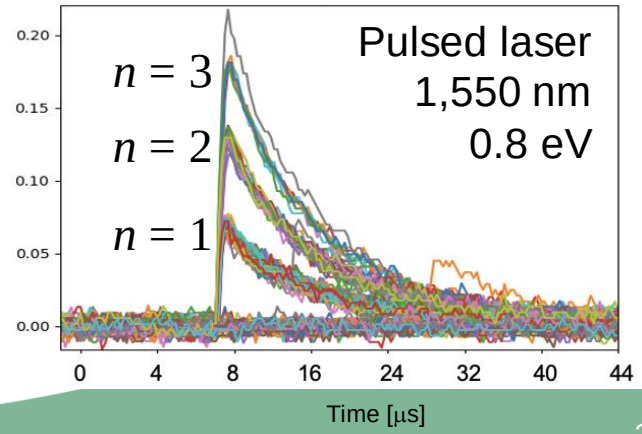
Optical transition-edge sensor



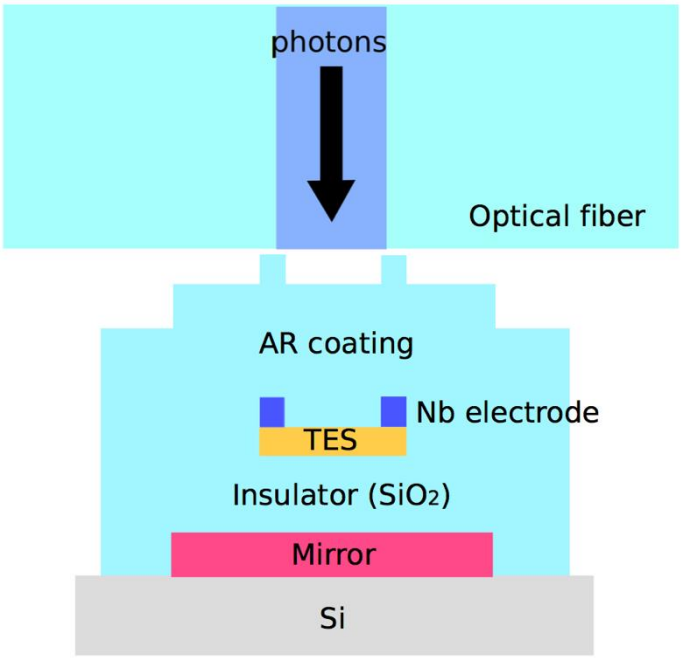


Ti (20 nm)/ Au (10 nm) bilayer film
Size : 8 μm×8 μm

1. Bias the detector in transition
2. A photon is absorbed in a detector and is converted to heat.
3. Increase in temperature results in increase in resistance
4. Measure change in resistance
5. Can measure energy of a photon / Can count number of photons

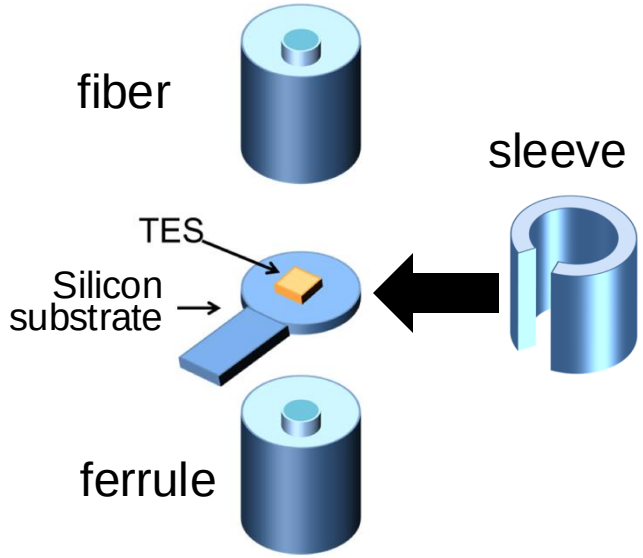


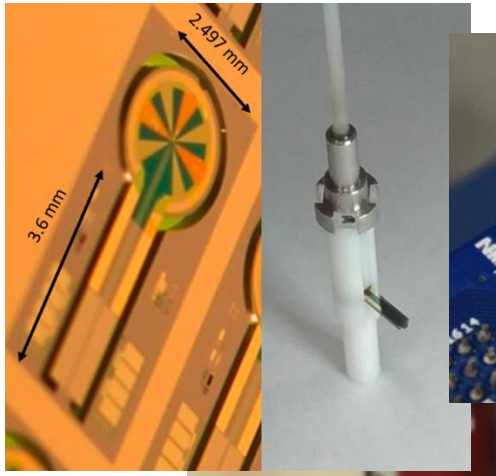
Fiber-coupled TES

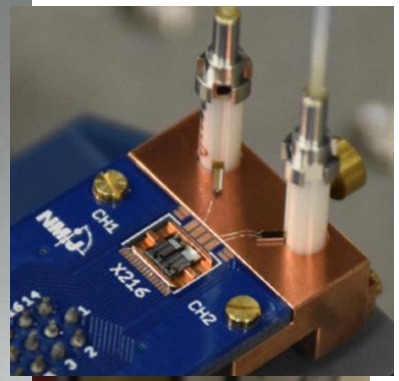


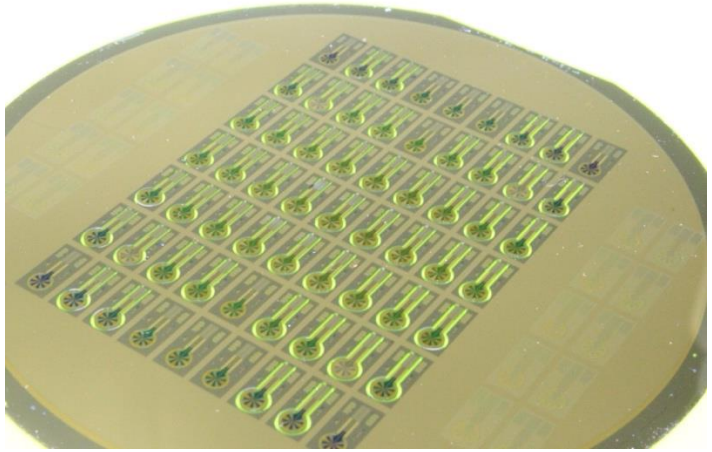
self-aligning fiber-to-detector coupling

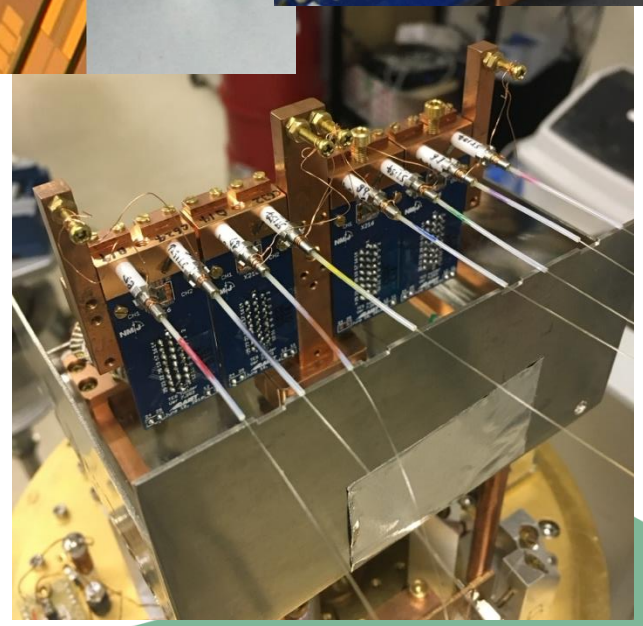
A. Miller et al., Opt. Exp. 19 (2010) 9102.









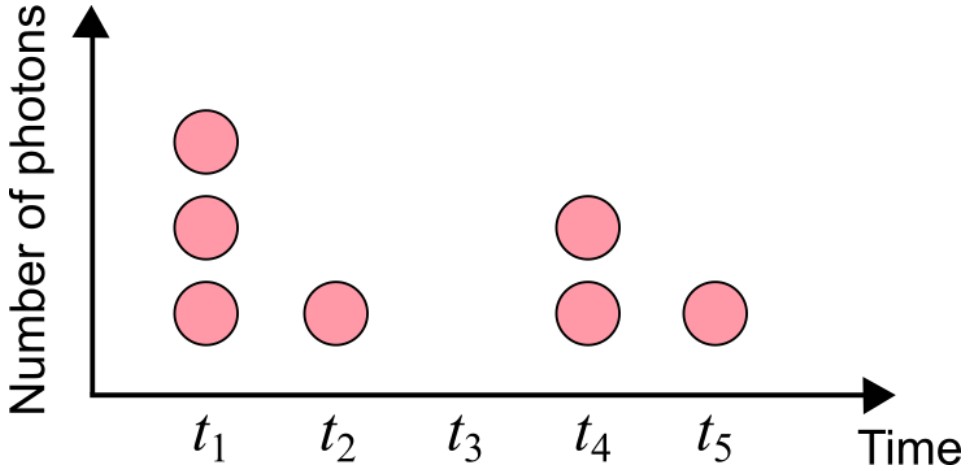


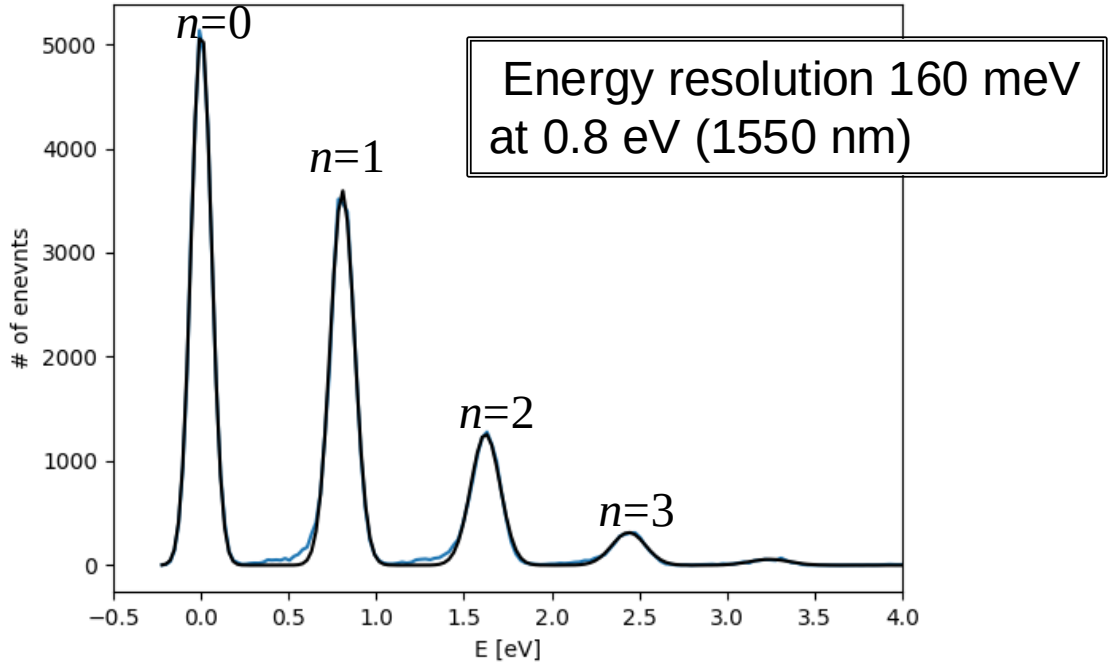
Embedded in optical cavity
Enhance detection efficiency
at desired wavelength

System detection efficiency
98% at 850 nm D. Fukuda et al., Opt. Exp., 19, 870 (2011).
95% at 1550 nm A. E. Lita et al., Opt. Exp., 16, 3032 (2008).

TES as photon-number resolving detector

Calorimeters can measure the total energy and thus the total photon number.
→Photon number resolving detectors

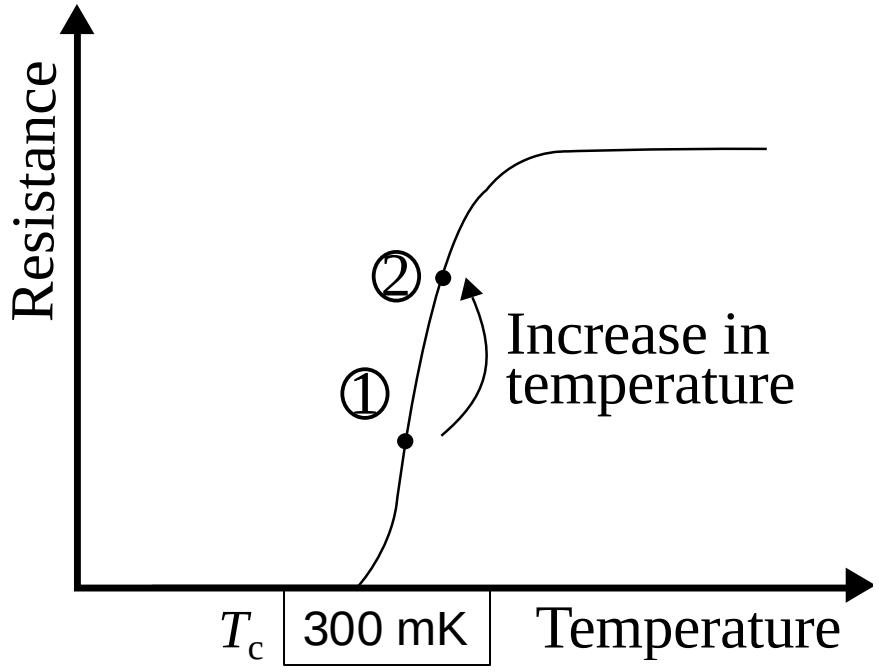


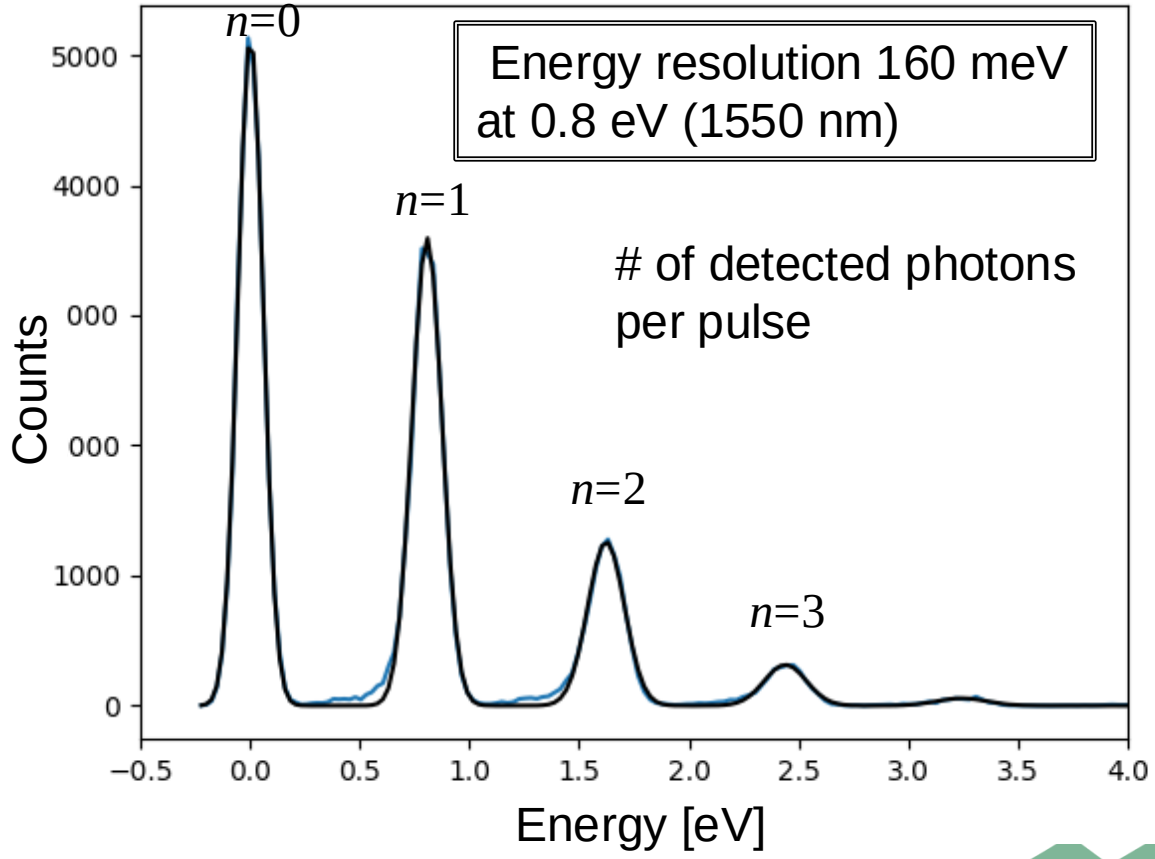


Detector irradiated with pulsed laser.
Wavelength of incident photons is known.
Count photons per pulse.
The number fluctuates and follows Poisson distribution.

Energy resolution

Energy resolution $\Delta E \propto T_c^{1.5}$





Energy resolution

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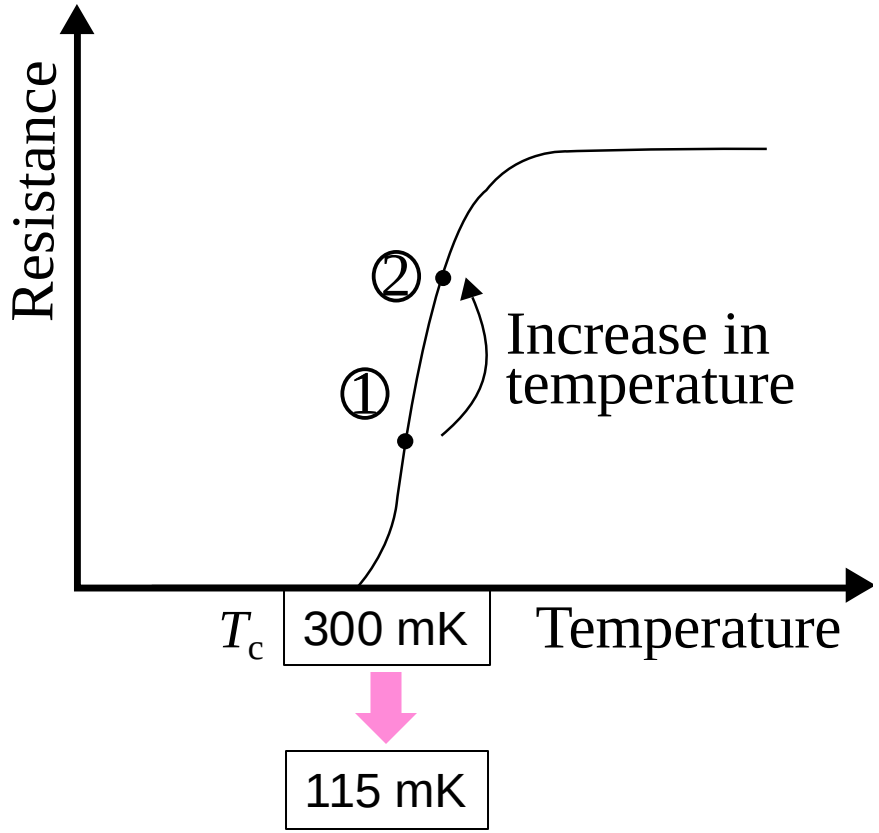
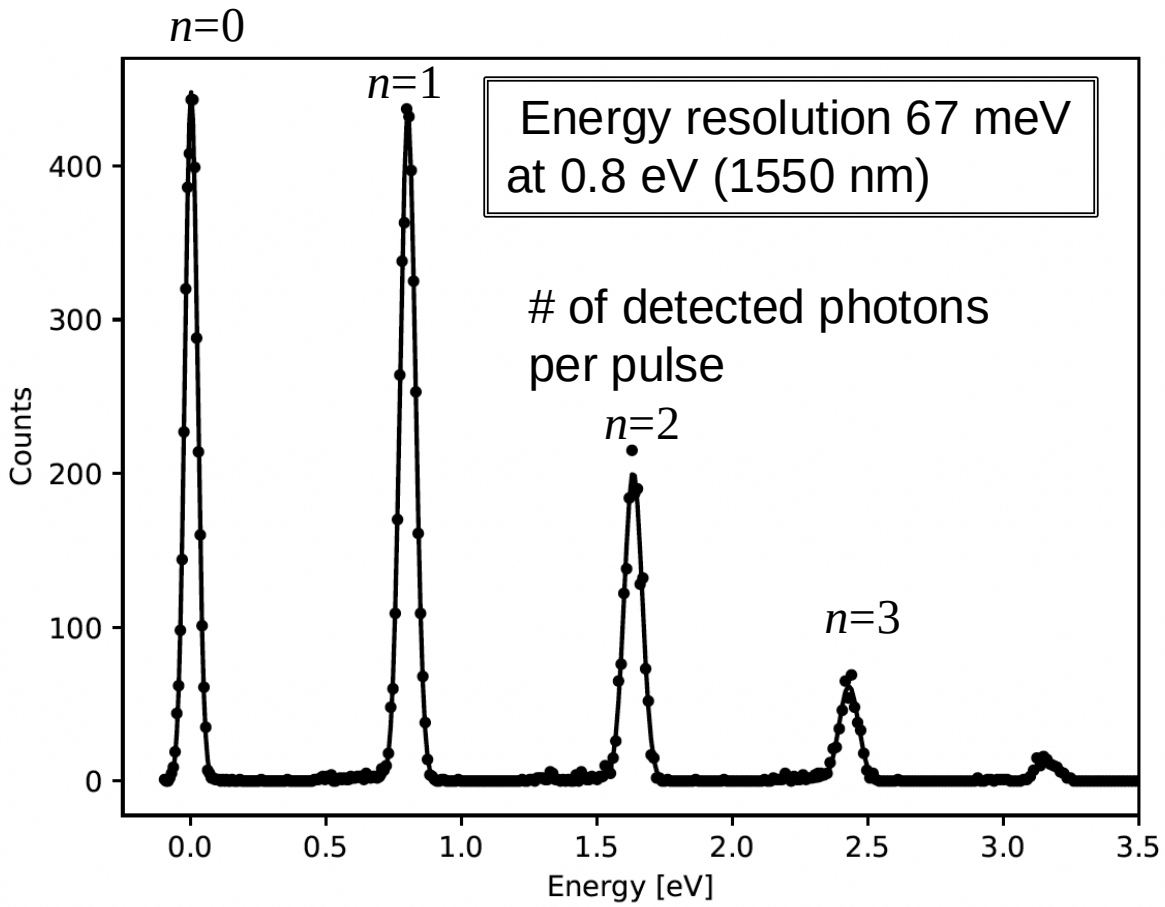


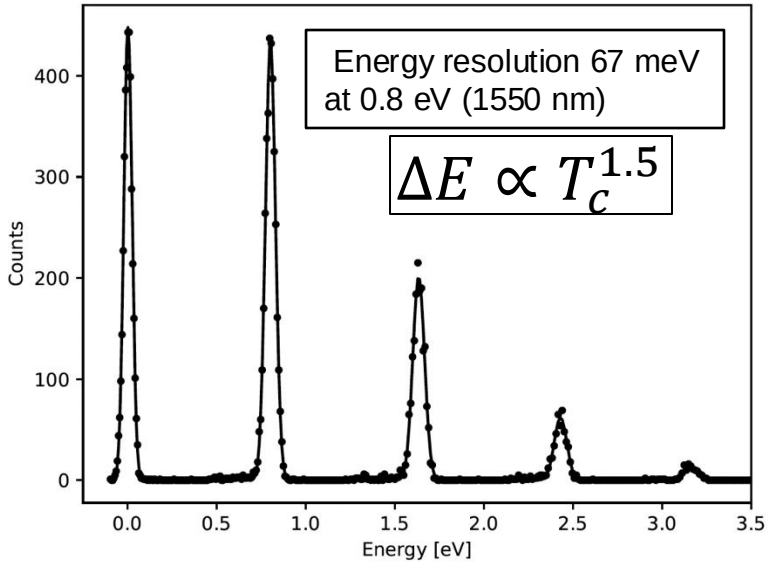


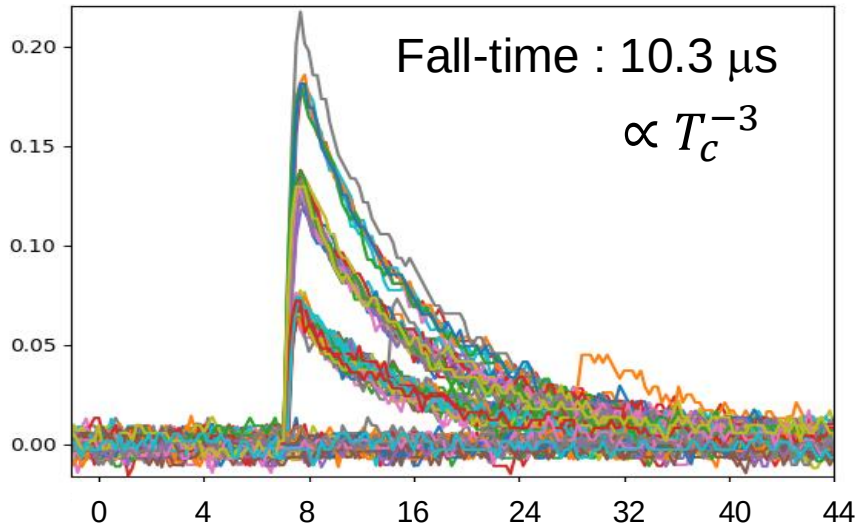
K. Hattori et al., Supercond. Sci. Technol. 35 (2022) 095002

Energy resolution was expected to be higher than 40 meV.

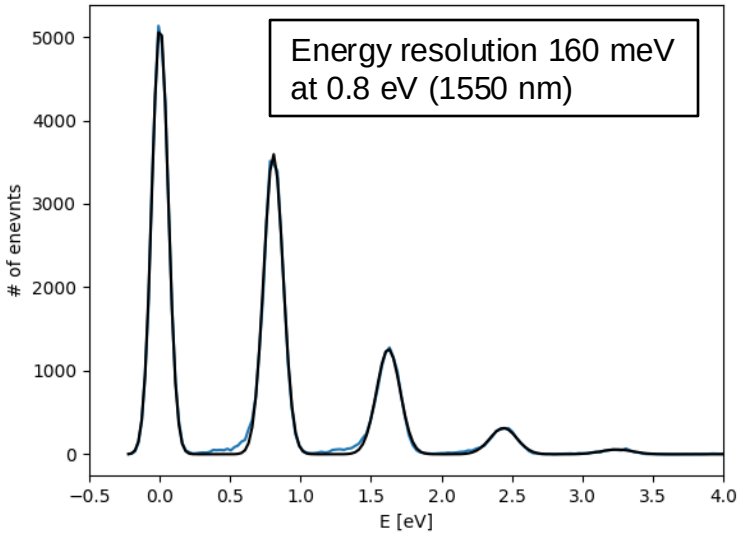
Tradeoff between ΔE and time constant

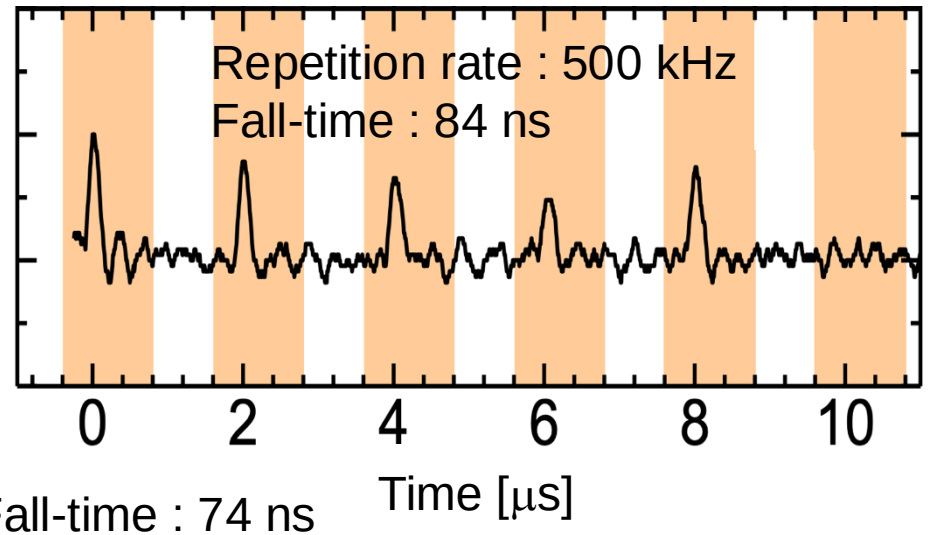
Slow TES (T_c = 115 mK)





Fast TES (T_c = 300 mK)





Fall-time : 74 ns

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

Tradeoff between ΔE and time constant

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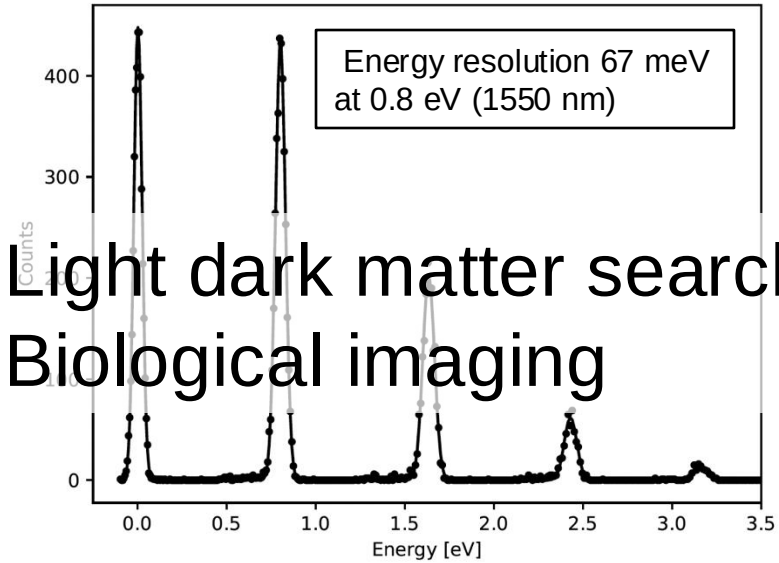
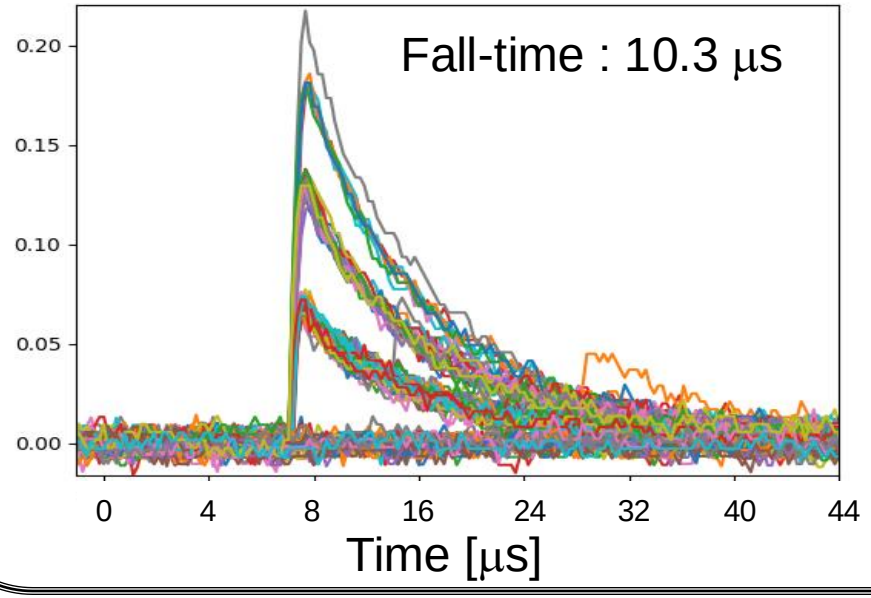
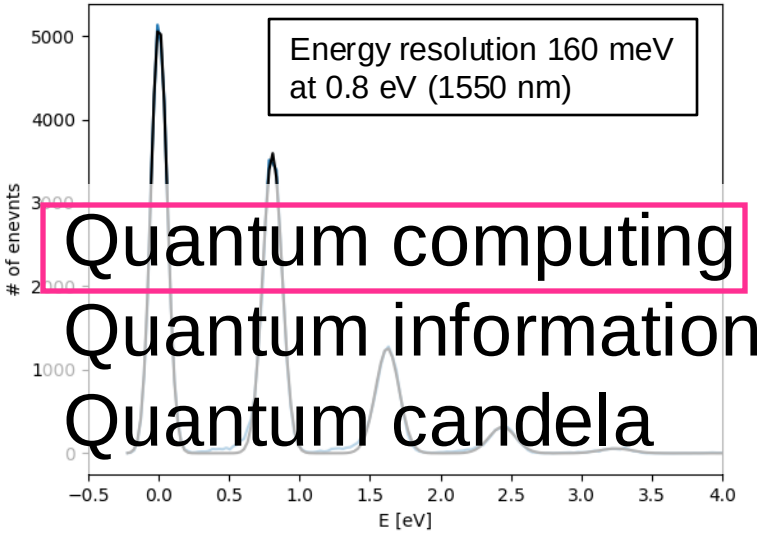


Light dark matter search

Biological imaging



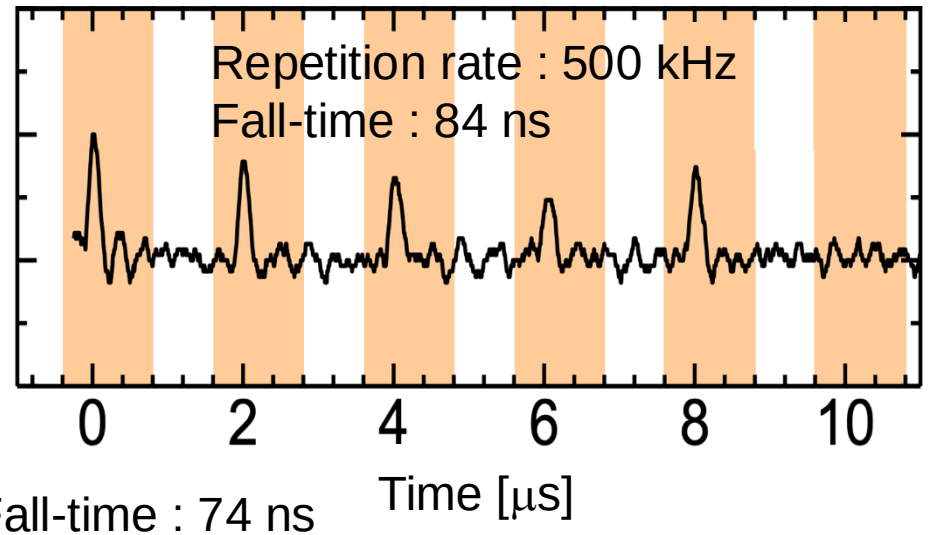
Fast TES (T_c = 300 mK)



Quantum computing

Quantum information

Quantum candela



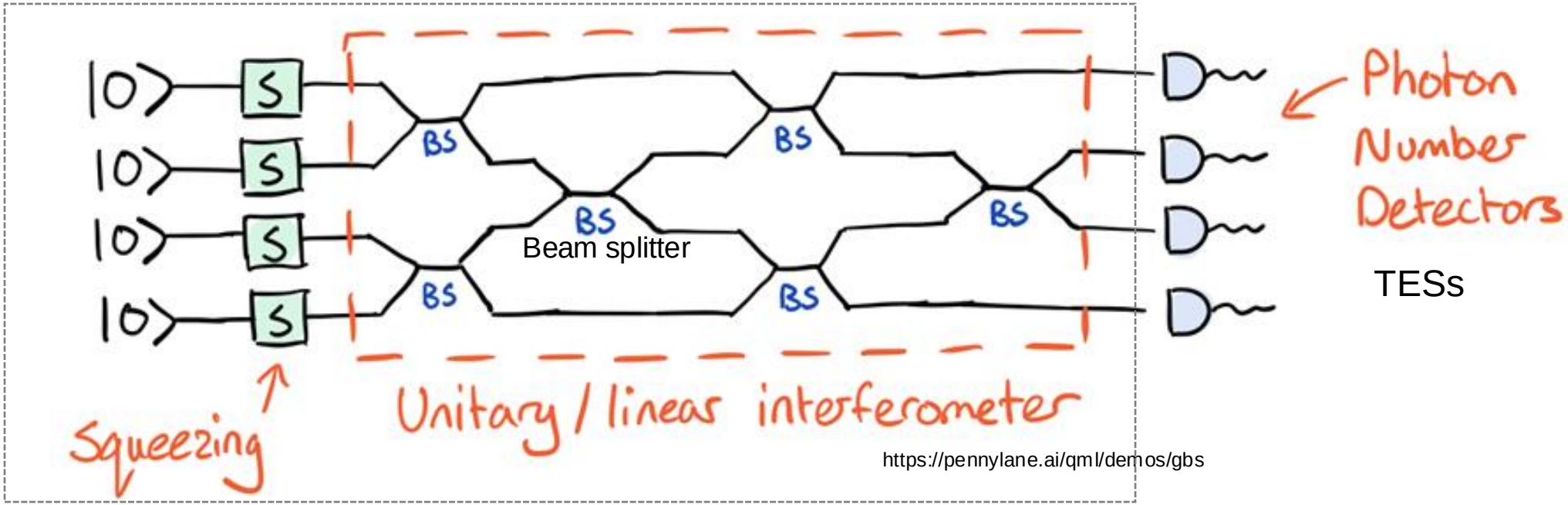
Fall-time : 74 ns

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

Photonic quantum computing

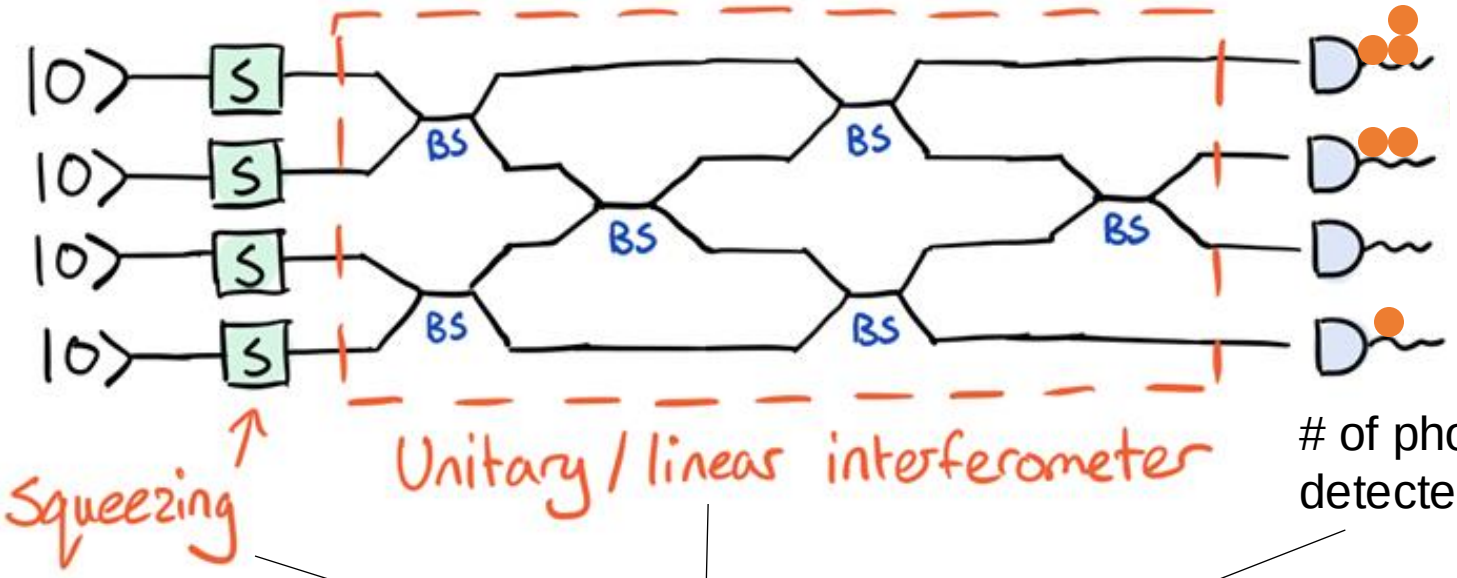
Optical circuits are at room temperature.
TESs at cryotemperature serves as photon counters.
Pulsed lasers are used: Several photons / pulse
→Calorimeters can measure the total energy and thus the total photon number.

Gaussian Boson Sampling (GBS)

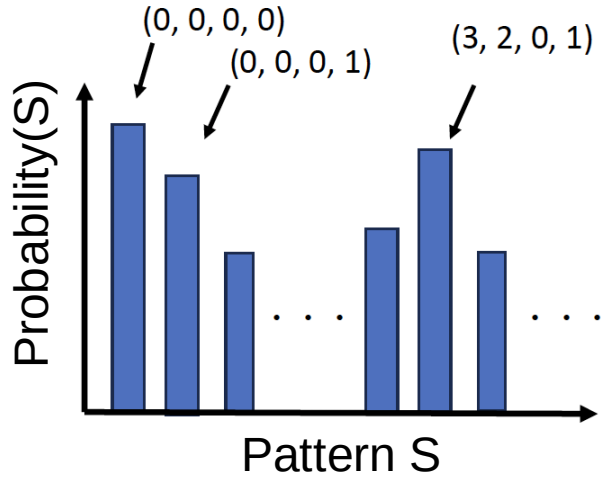


room temperature

Gaussian Boson Sampling (GBS)



Output



# 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

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Graph optimization
Quantum chemistry
Quantum machine learning

Classical computing:
Computational task (Ryser's formula) $\propto \mathrm{O}(N2^n)$.

N : # of detectors
n : # of photons detected by TESs

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Exponentially hard to simulate using classical computation.

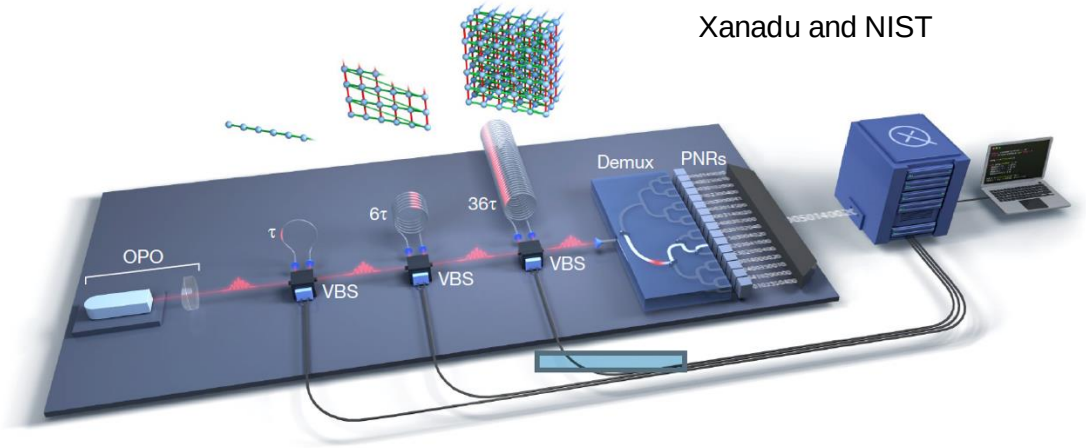
Gaussian Boson Sampling (GBS)

Quantum computational advantage

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

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

Xanadu and NIST

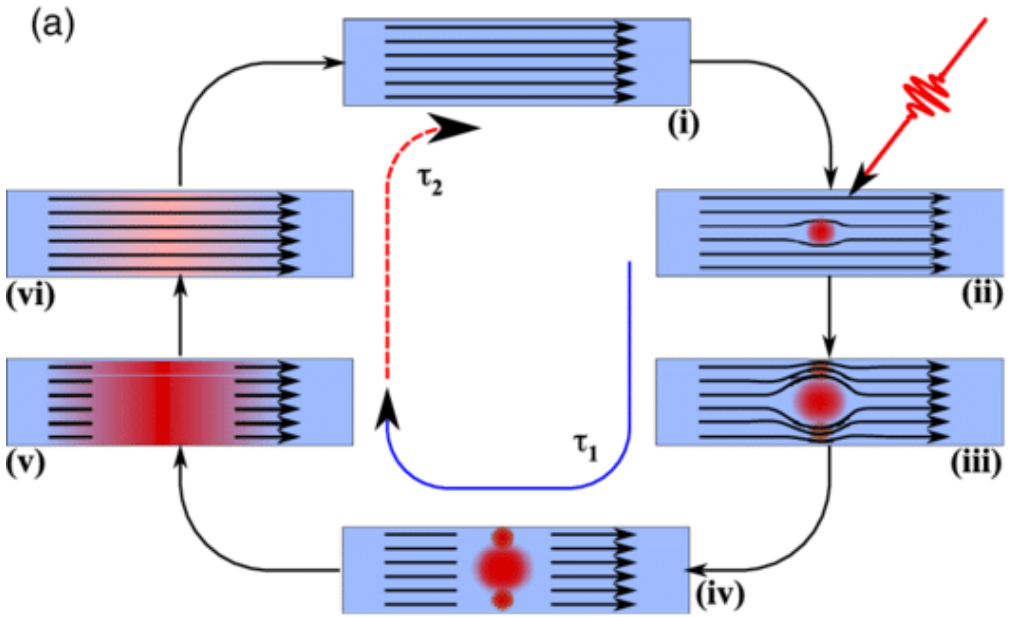


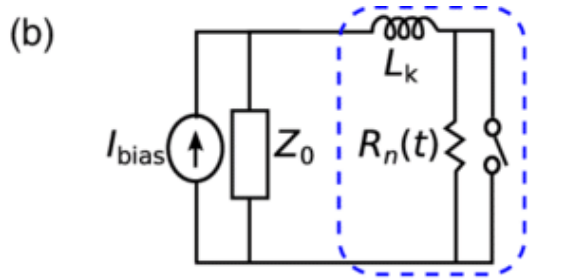
L. S. Madsen et al.,Nature, **606** 75 (2022).

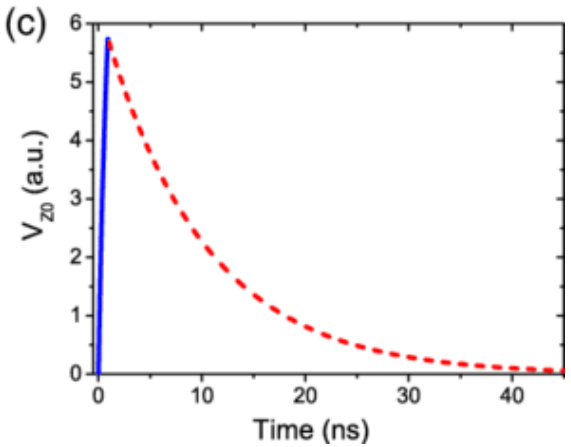
Computational time reduced from 9×10^3 yr to 36 μs.
16 TESs

Single photon detectors

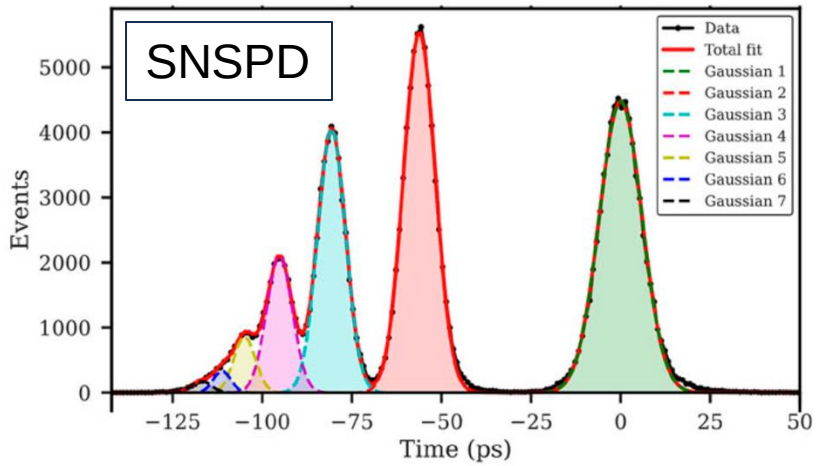
Single-photon nanowire detectors (SNSPDs)



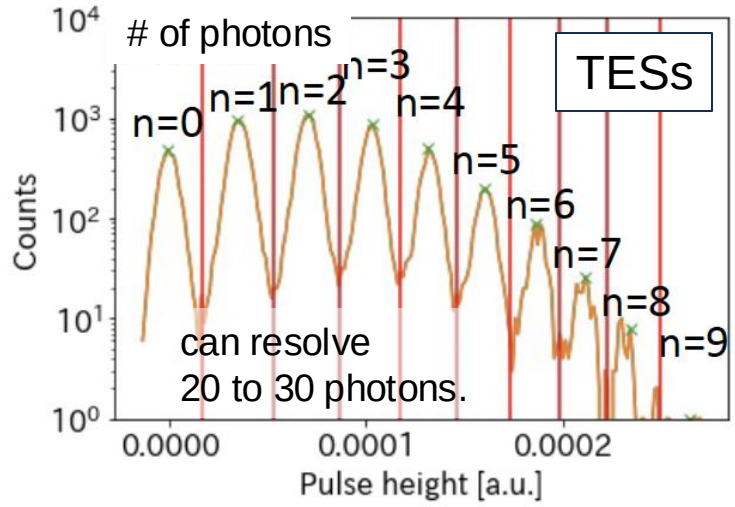




PNR experiments



J. W. Niels Los et al., APL Photonics 9, 066101 (2024).



Fast detector response.

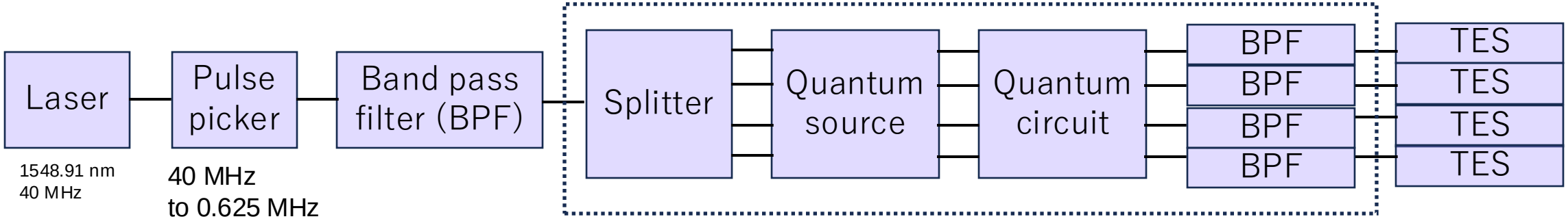
Low timing jitter < 3 ps B. Korzh et al. Nat. Photonics **14**, 250–255 (2020).

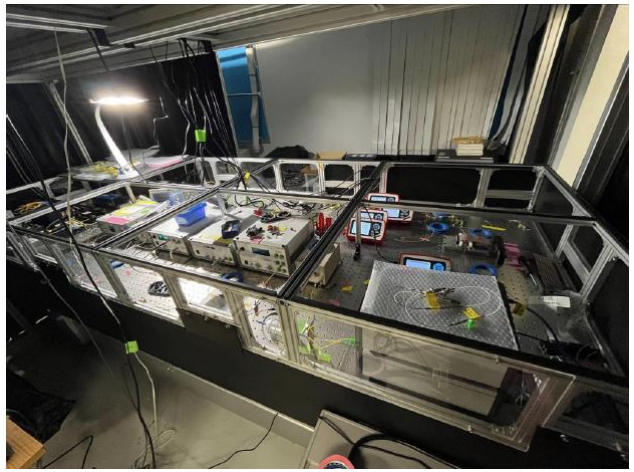
Photon number resolution up to several photons.

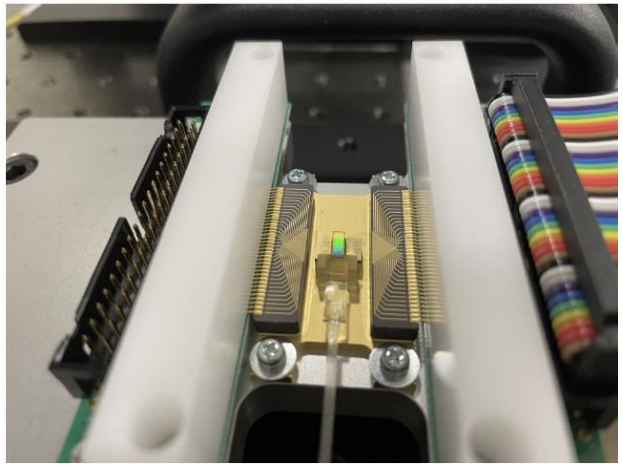
Resolving the number of photons in high-photon states is crucial for Gaussian Boson Sampling.

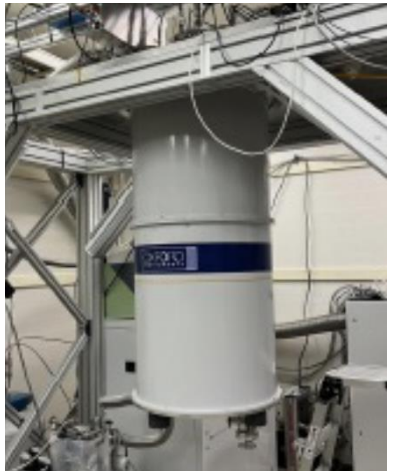
Gaussian Boson Sampling

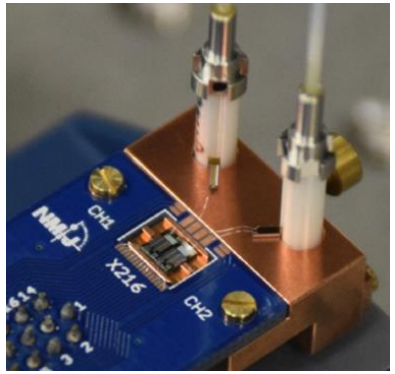
AIST : M. Okano
Tohoku Univ. : T. Motohashi, T. Odagawa
S. Ogawara, N. Matsuda





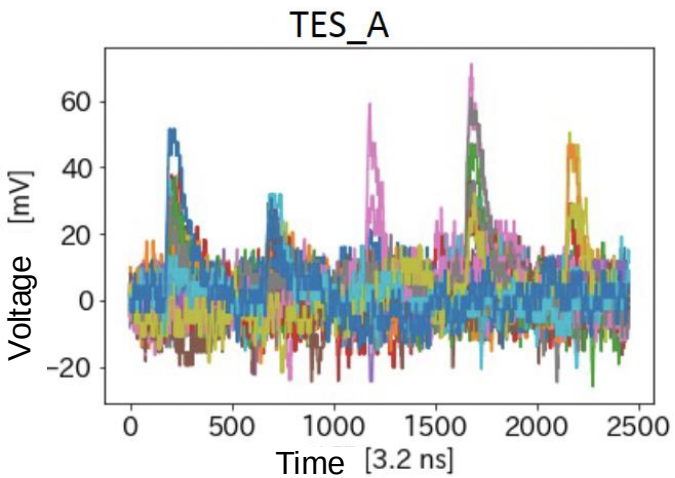


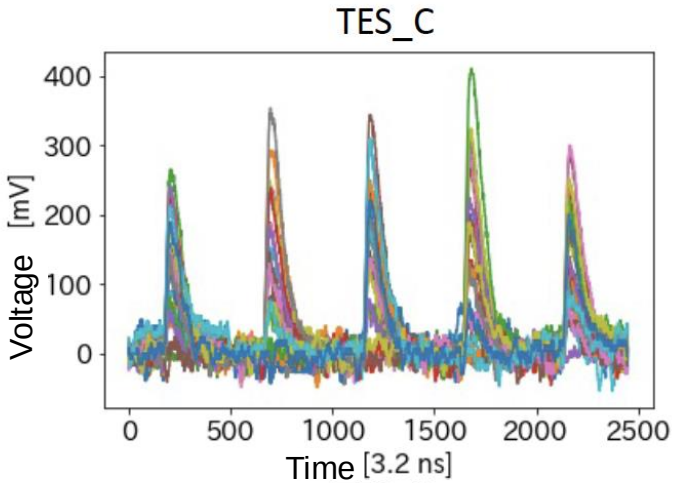


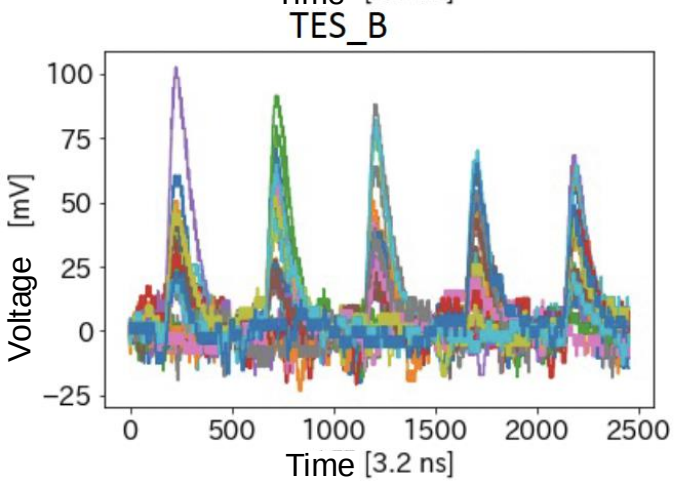


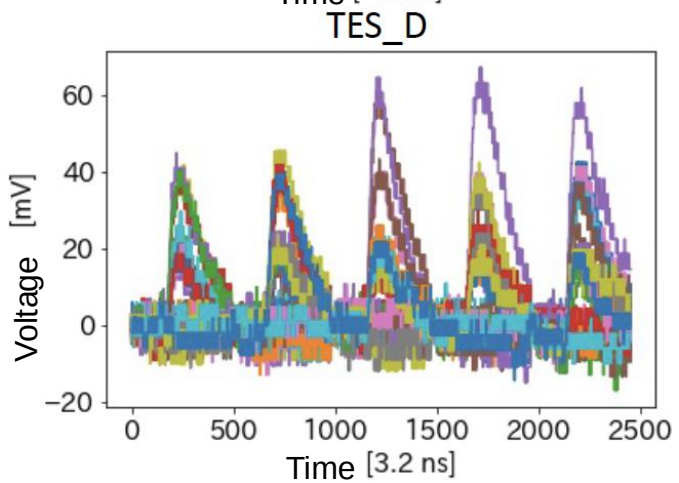
TESs read out
by DC SQUIDs.
Not multiplexed.

TESs detected photons from a 0.625 MHz pulsed laser

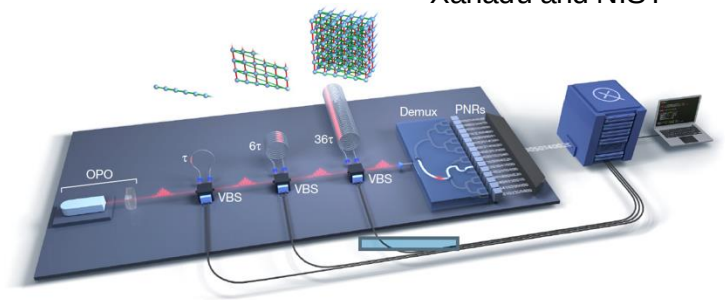








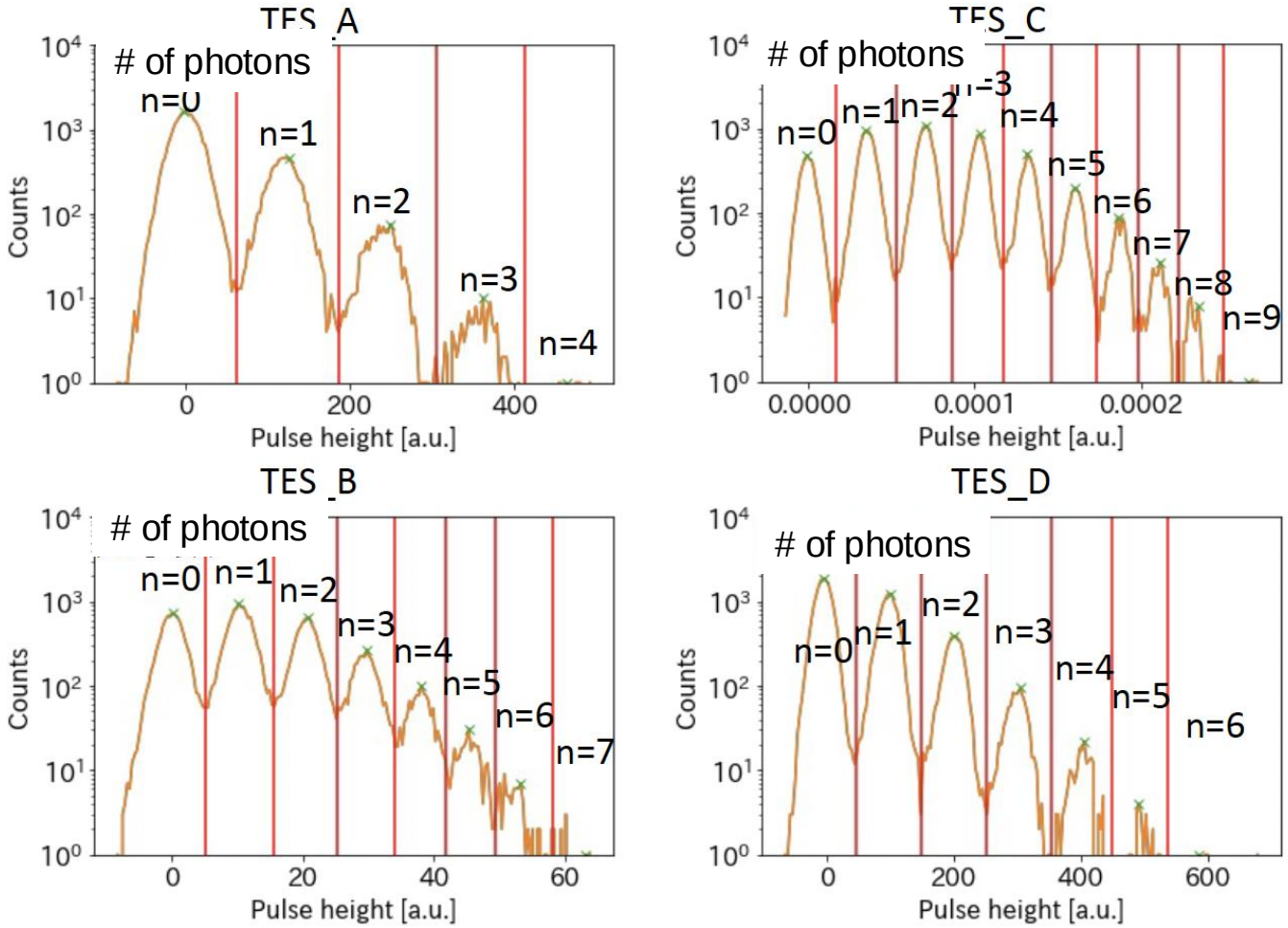
Xanadu and NIST



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

6 MHz / 16 = 0.375 kHz
for each TES

Spectra



Successfully counted the number of photons at 0.625 MHz

Can we accurately count photons?

Figure of merit:

Second-order coherence

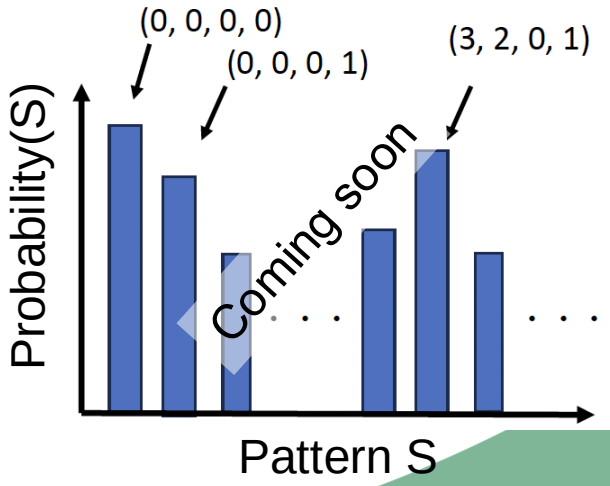
$$g^{(2)}(\tau) = 1 + \frac{\sigma(n)^2 - \langle \hat{n} \rangle}{\langle \hat{n} \rangle^2}$$

for monochromatic light source

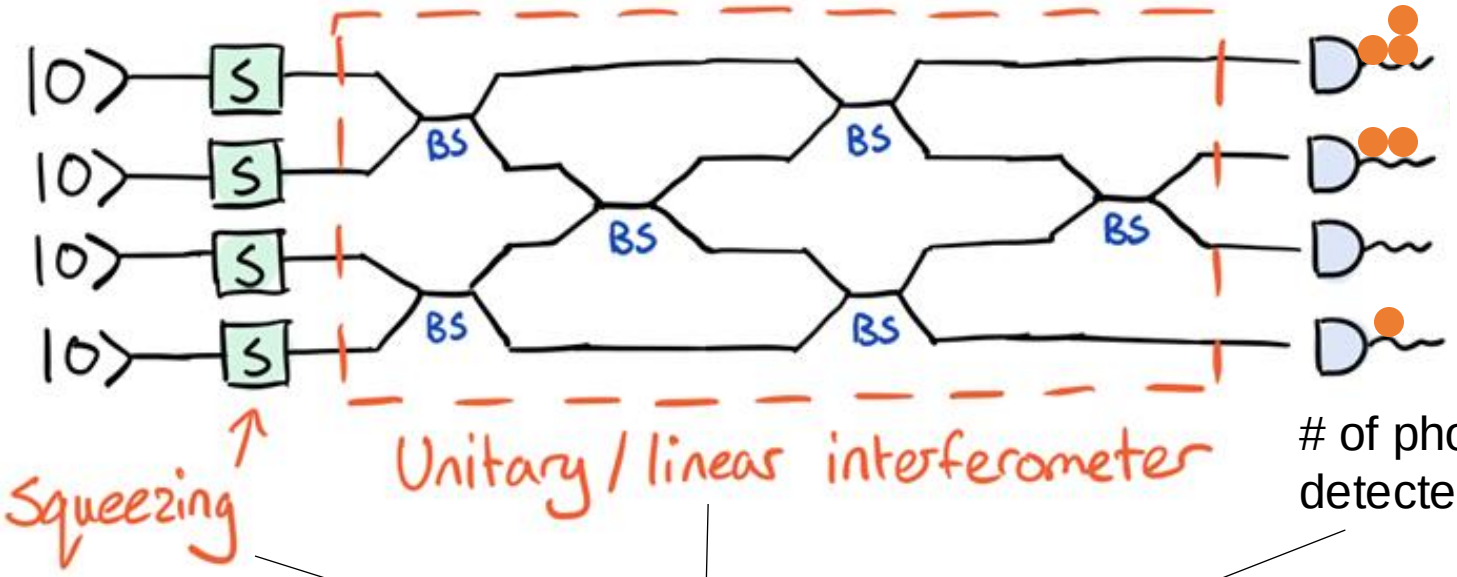
$g^{(2)} = 1$ for coherent light source

	$g^{(2)}$ at 0.625 MHz	$g^{(2)}$ at 20 kHz
TES_A	1.01	0.99
TES_B	1.01	0.98
TES_C	1.01	1.00
TES_D	1.01	1.00

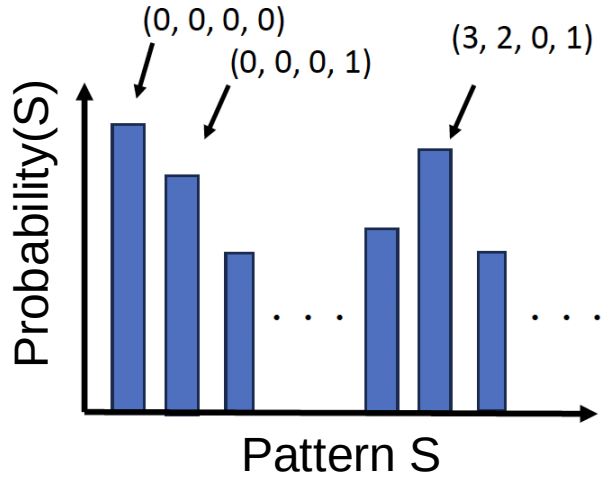
We are analyzing data obtained from silicon photonic device.



Gaussian Boson Sampling (GBS)



Output



# 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

Classical computing:
Computational task (Ryser's formula) $\propto \mathrm{O}(N2^n)$.

N : # of detectors
n : # of photons detected by TESs

⇩

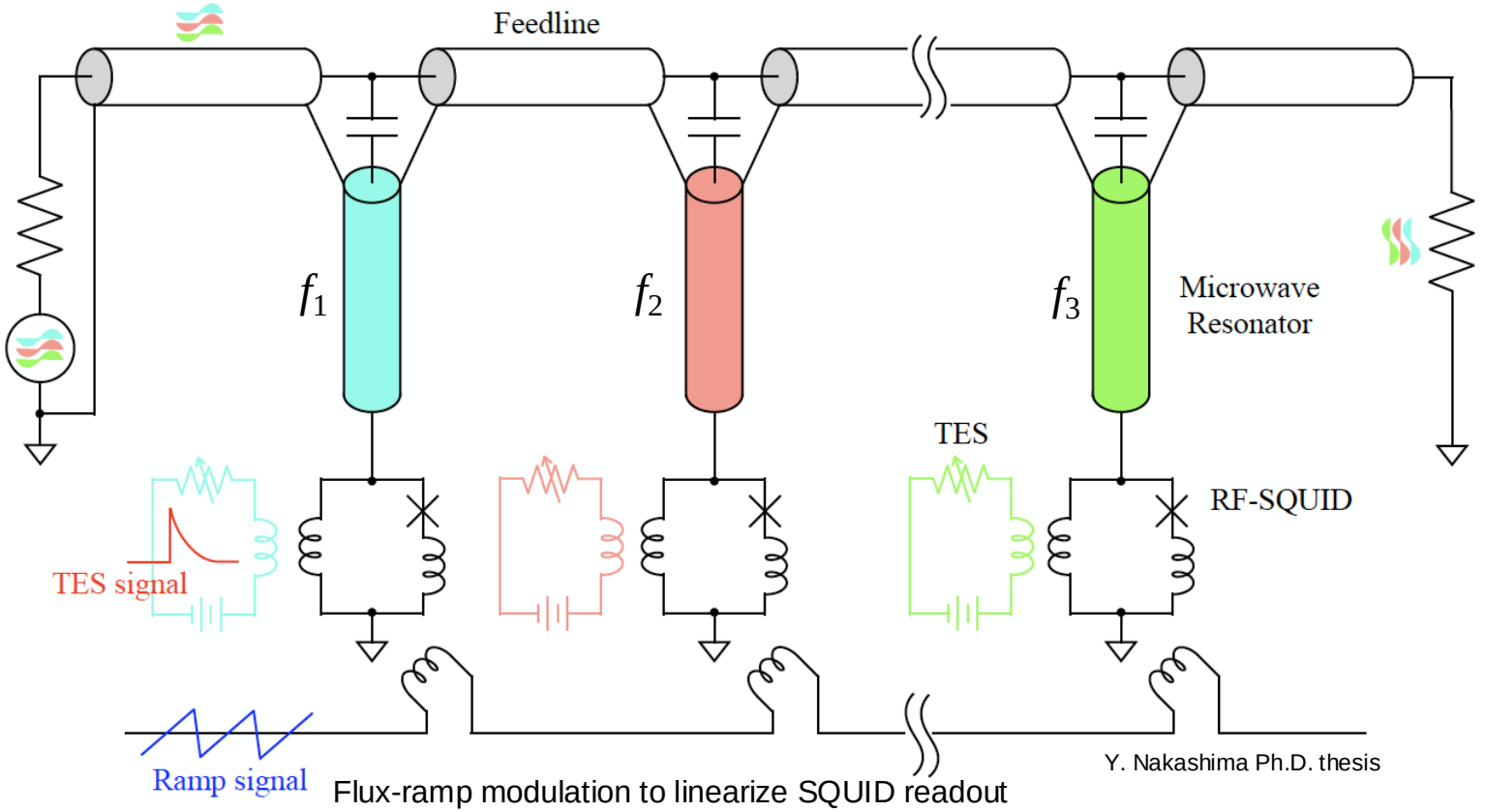
Increase # of TESs.
TES array readout is necessary.

TES array readout

Microwave SQUID multiplexers (μMUX)

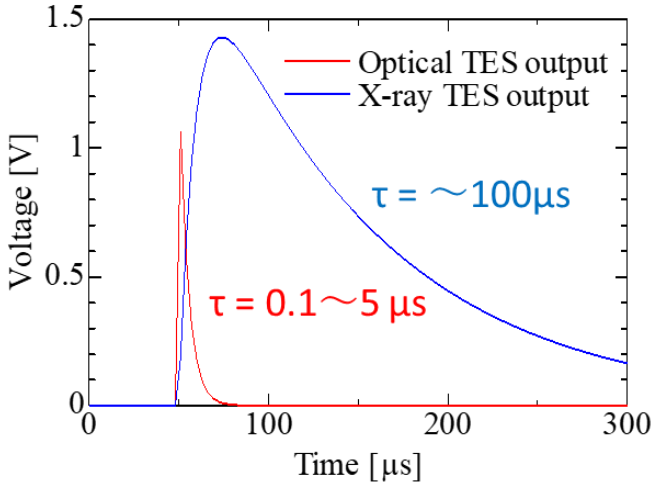
Ryota Hayakawa
poster at Quposium

Light dark matter search requires large format of TES arrays.

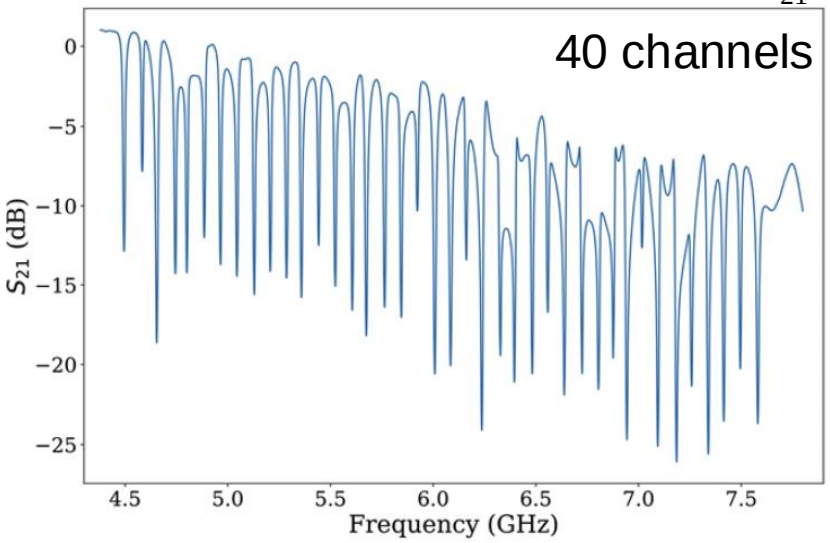


Y. Nakashima Ph.D. thesis

Flux-ramp modulation to linearize SQUID readout



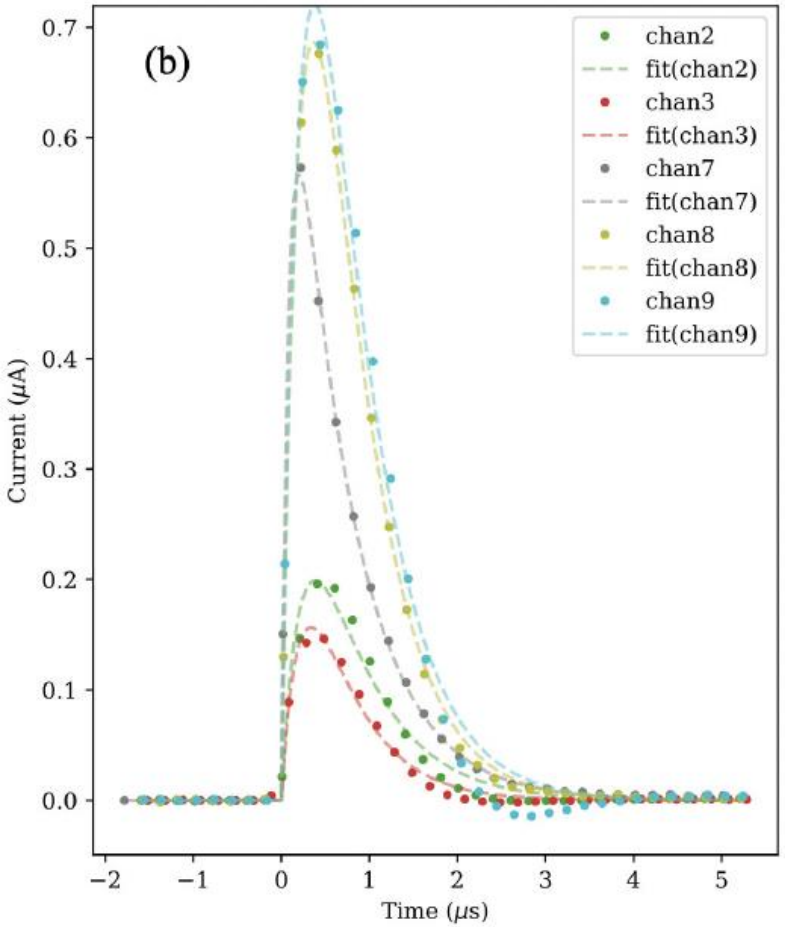
Microwave transmission coefficient S_{21}



R. Hayakawa et al., J Low Temp. Phys. 215 170 (2024).

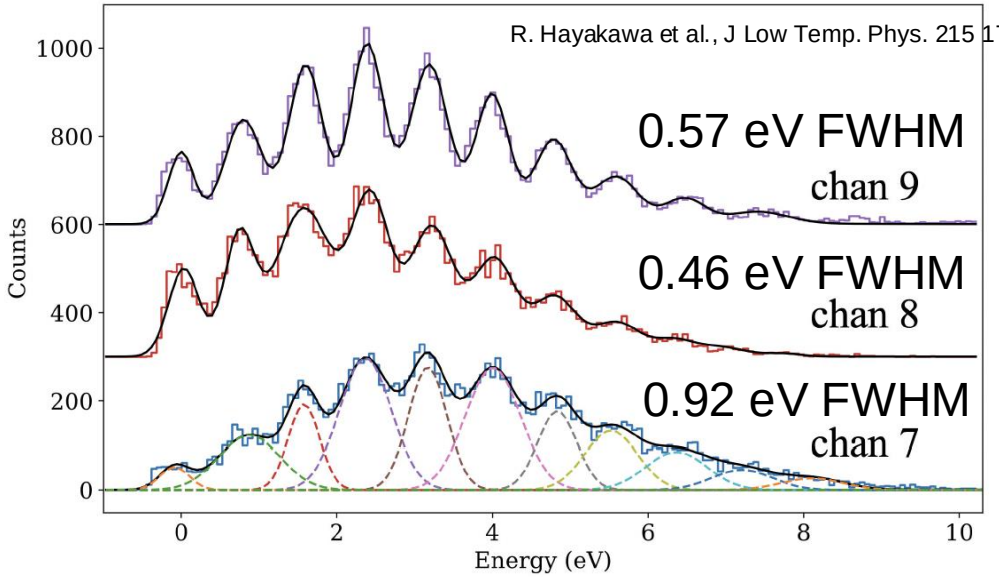
Sampling frequency increased from 0.5 MHz to 5 MHz.
Microwave SQUIDs redesigned to increase readout bandwidth.
Fastest TES array readout.

TES array readout

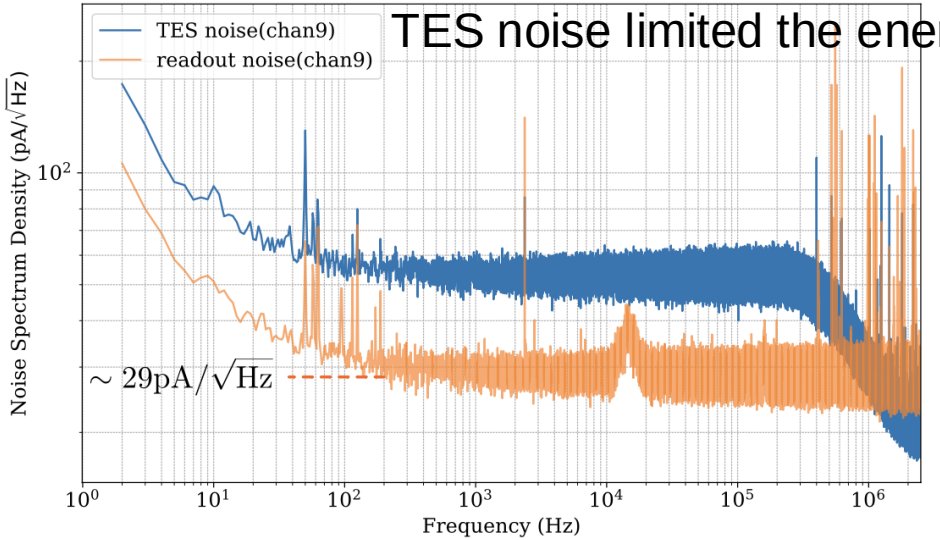


Signals sampled at 5 MHz.

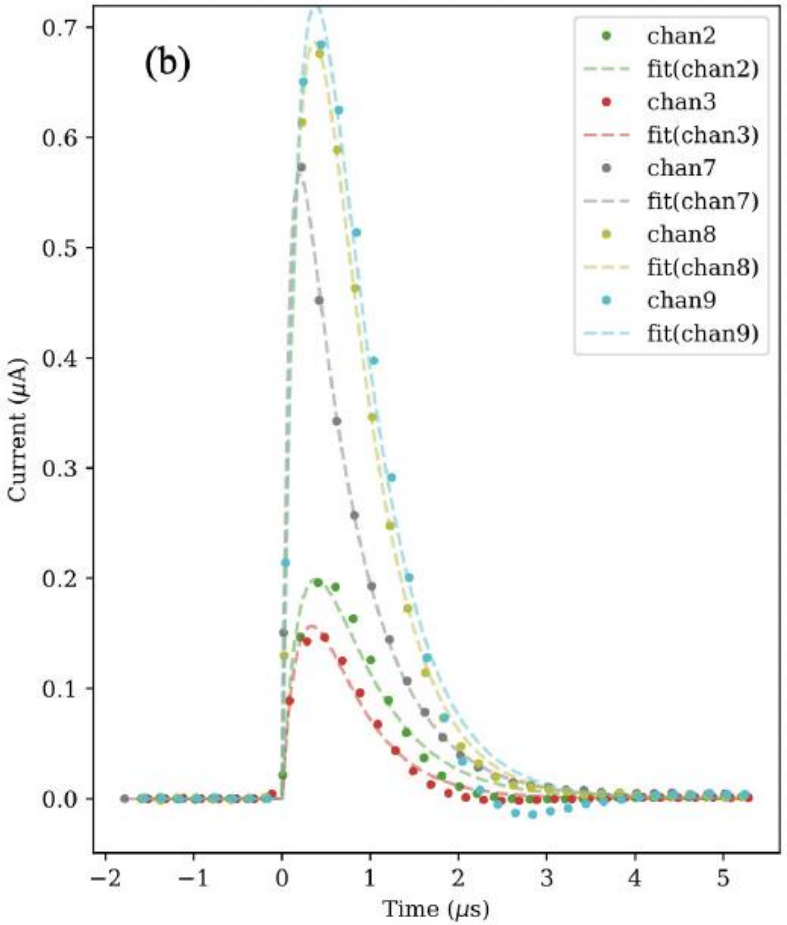
Read out multiple channels simultaneously.



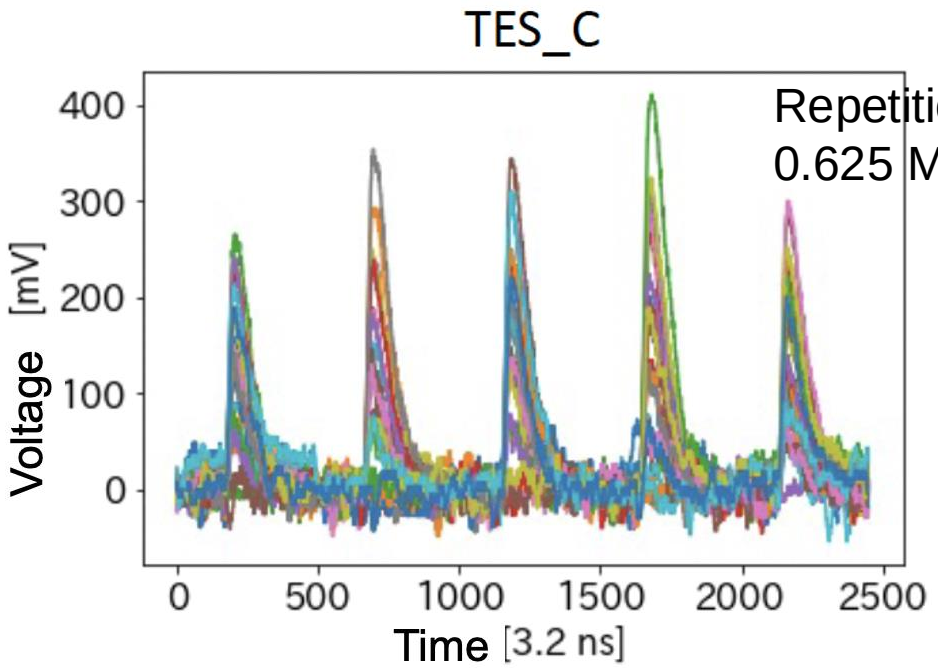
TES noise limited the energy resolution.



Toward multiplexing TESs for quantum computing



μMUX
Signals sampled at 5 MHz.



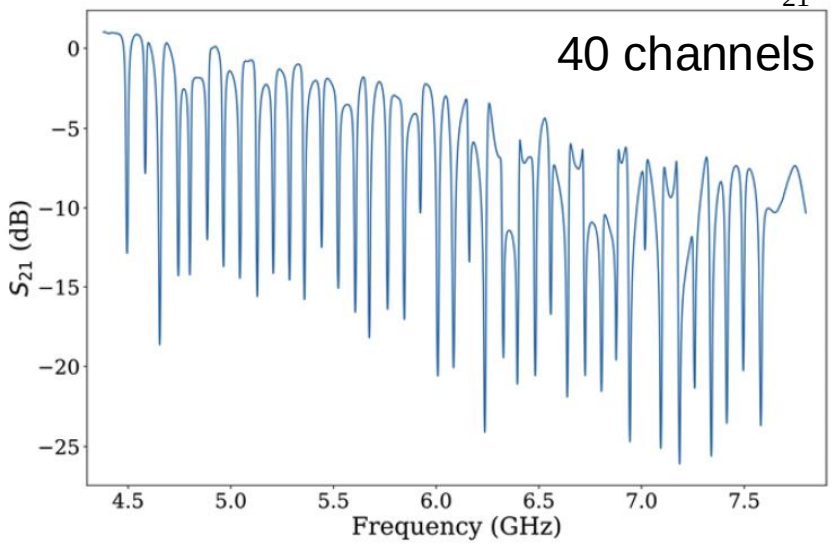
Repetition rate of
0.625 MHz

DC SQUID
Not multiplexed.
Signals sampled at 312.5 MHz using an oscilloscope.

Should TES array readout faster?

Toward multiplexing TESs for quantum computing

Microwave transmission coefficient S_{21}



To make μMUX faster,

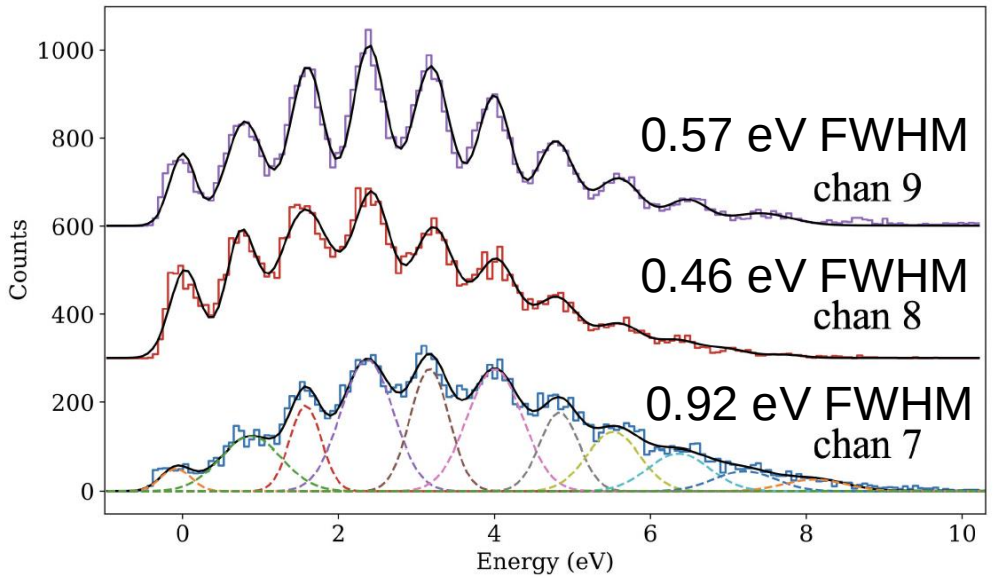
Increase the bandwidth of a resonator.

Results in wider spacing between carrier frequencies.

Reduce multiplexing factor.

# of TESs can exponentially increase calculation speed.

Repetition rate of a pulsed laser linearly increase calculation.



Next step will be

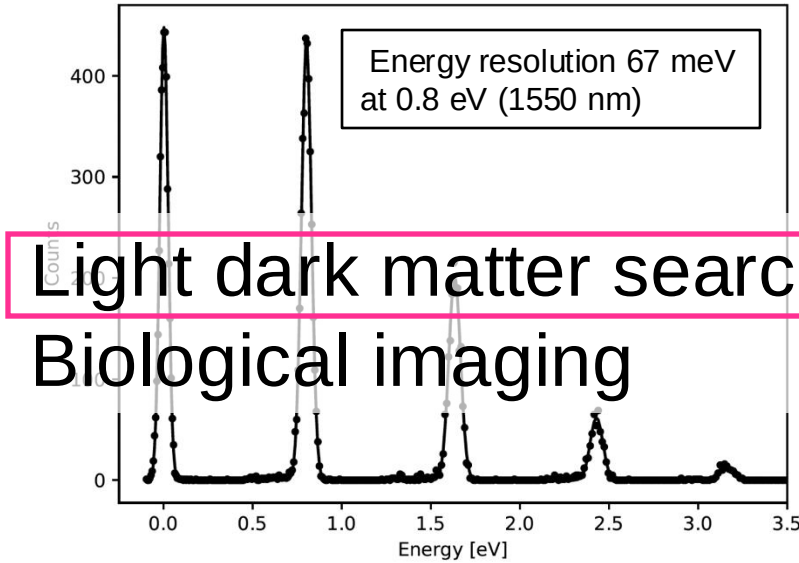
Keep the speed of μMUX as it is.

Reduce the speed of TESs.

Improve the energy resolution to resolve # of photons.

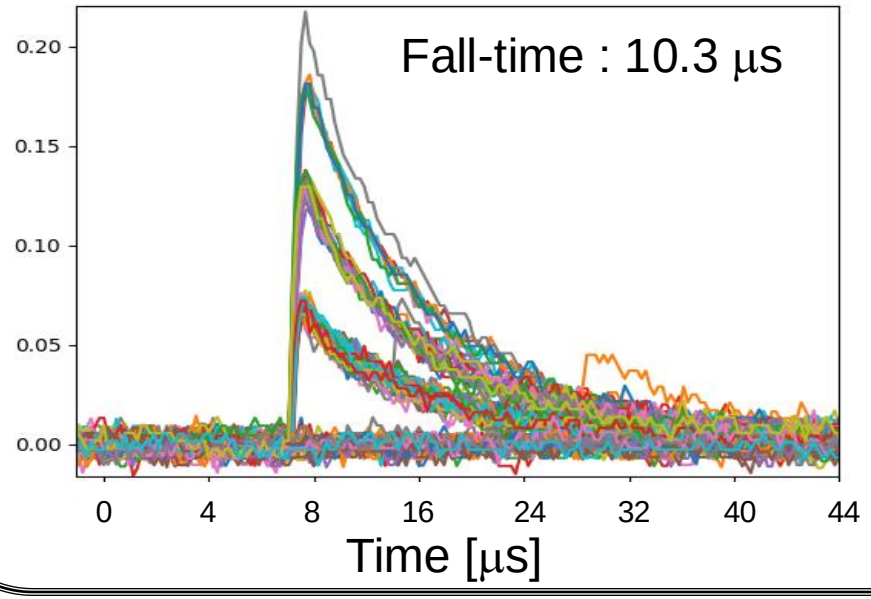
Tradeoff between ΔE and time constant

Slow TES (T_c = 115 mK)



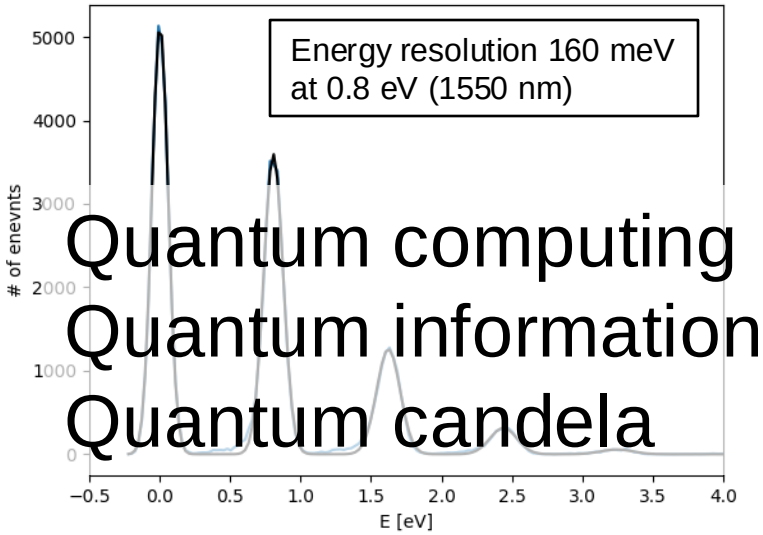
Light dark matter search

Biological imaging



μMUX with reduced speed

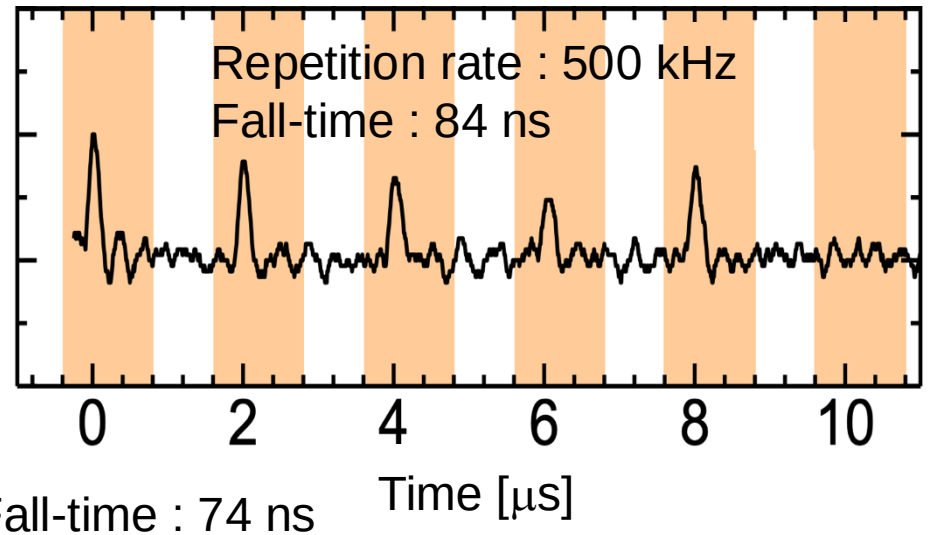
Fast TES (T_c = 300 mK)



Quantum computing

Quantum information

Quantum candela



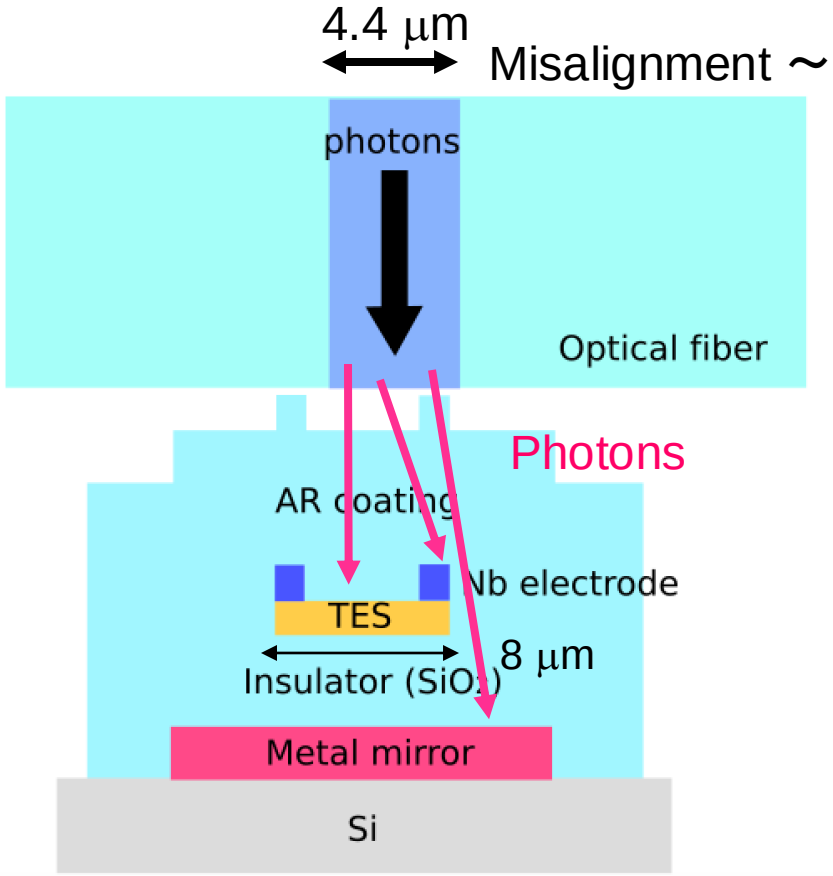
Fall-time : 74 ns

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

Energy resolution

Measured ΔE	67 meV
ΔE calculated from current noise / η	46 meV
Unknown sources	50 meV

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

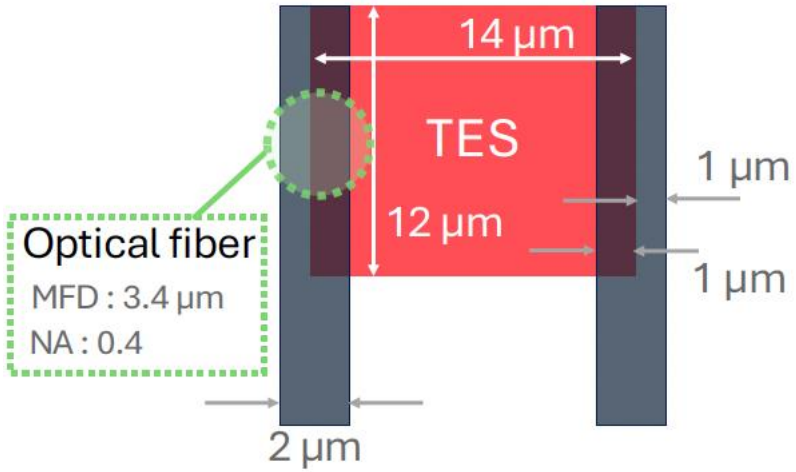


Unknown sources could include fluctuations in detector responses caused by misalignment.

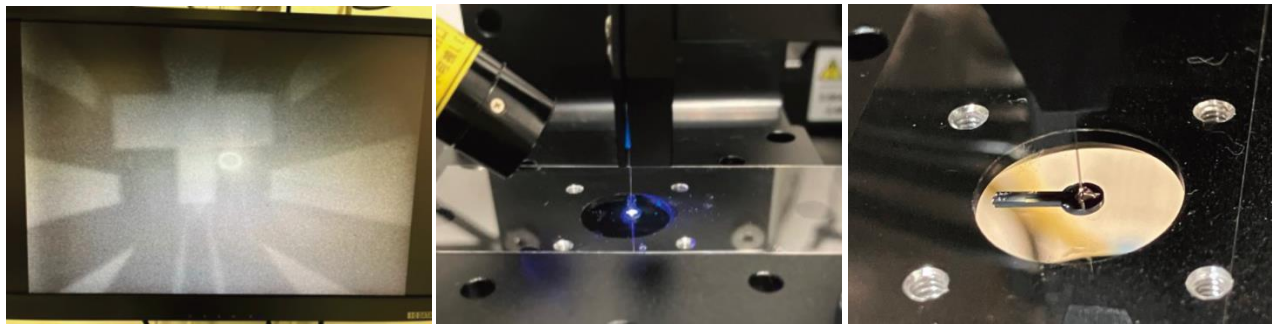
Position dependence of detector responses

N. Kominato and K. Shirota

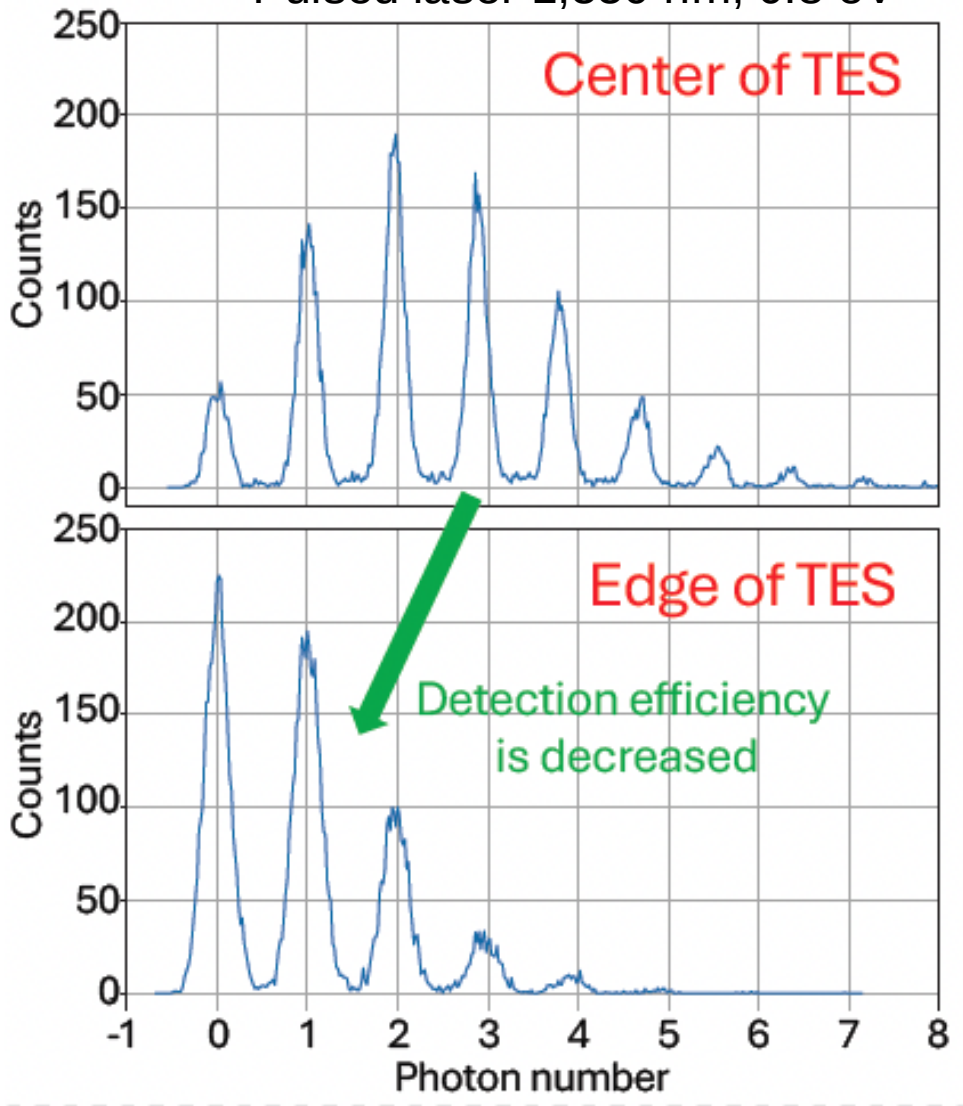
Investigate response at edge of a TES.



Fiber manually aligned with TES.



Pulsed laser 1,550 nm, 0.8 eV



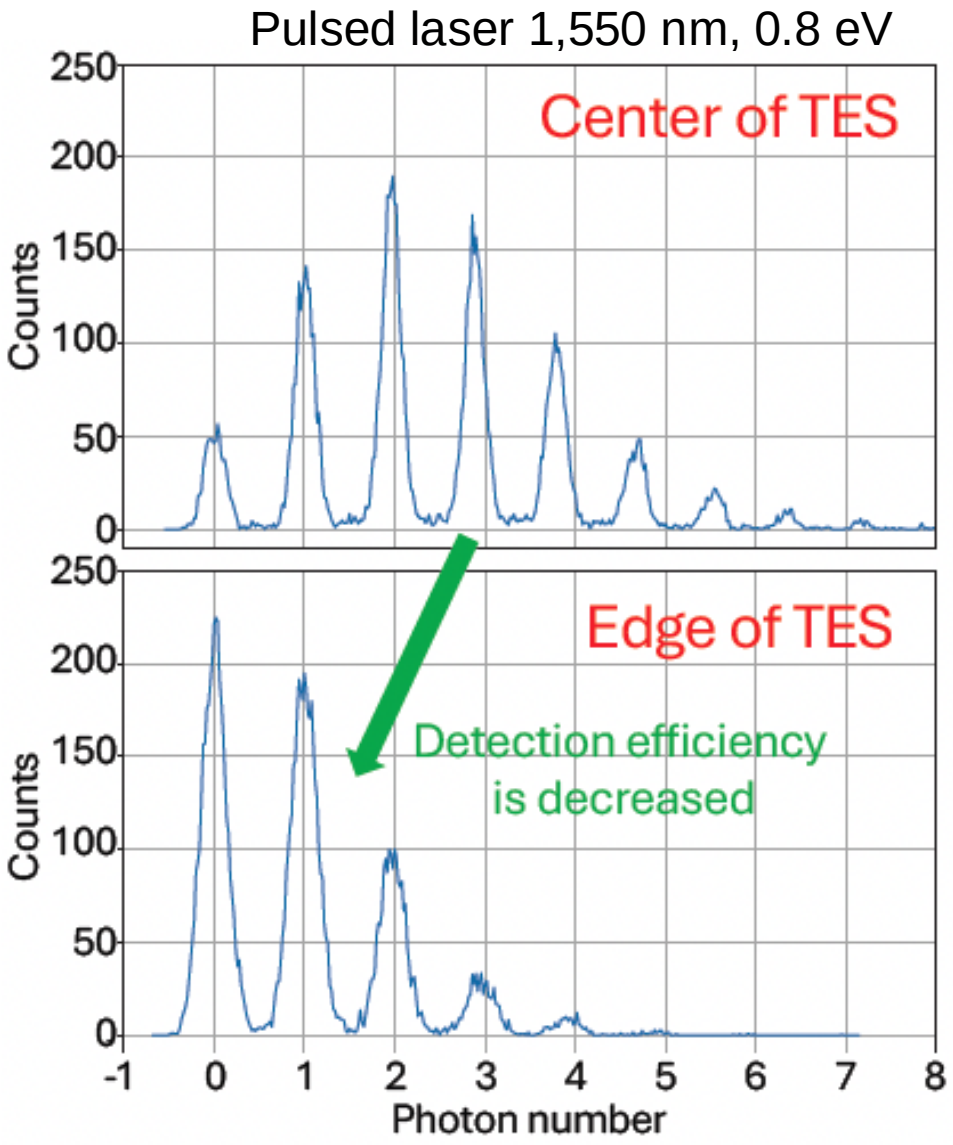
Is edge of TES sensitive to photons?

Position	ΔE (FWHM) (eV)	System detection efficiency (%)
Center	0.208	89.6
Edge	0.258	29.3

Both energy resolution and system detection efficiency deteriorated at the edge.

If photons absorbed in Nb electrode does not generate signals, expected efficiency would be 4%.
→The electrode is sensitive to photons.

Will further investigate the position dependence.

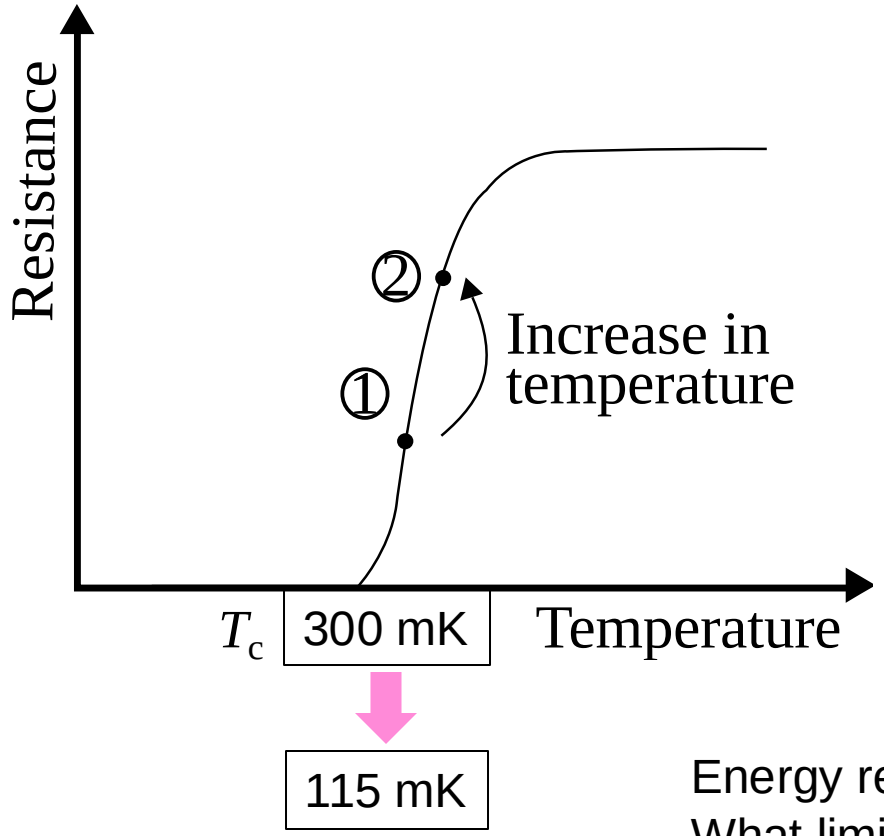


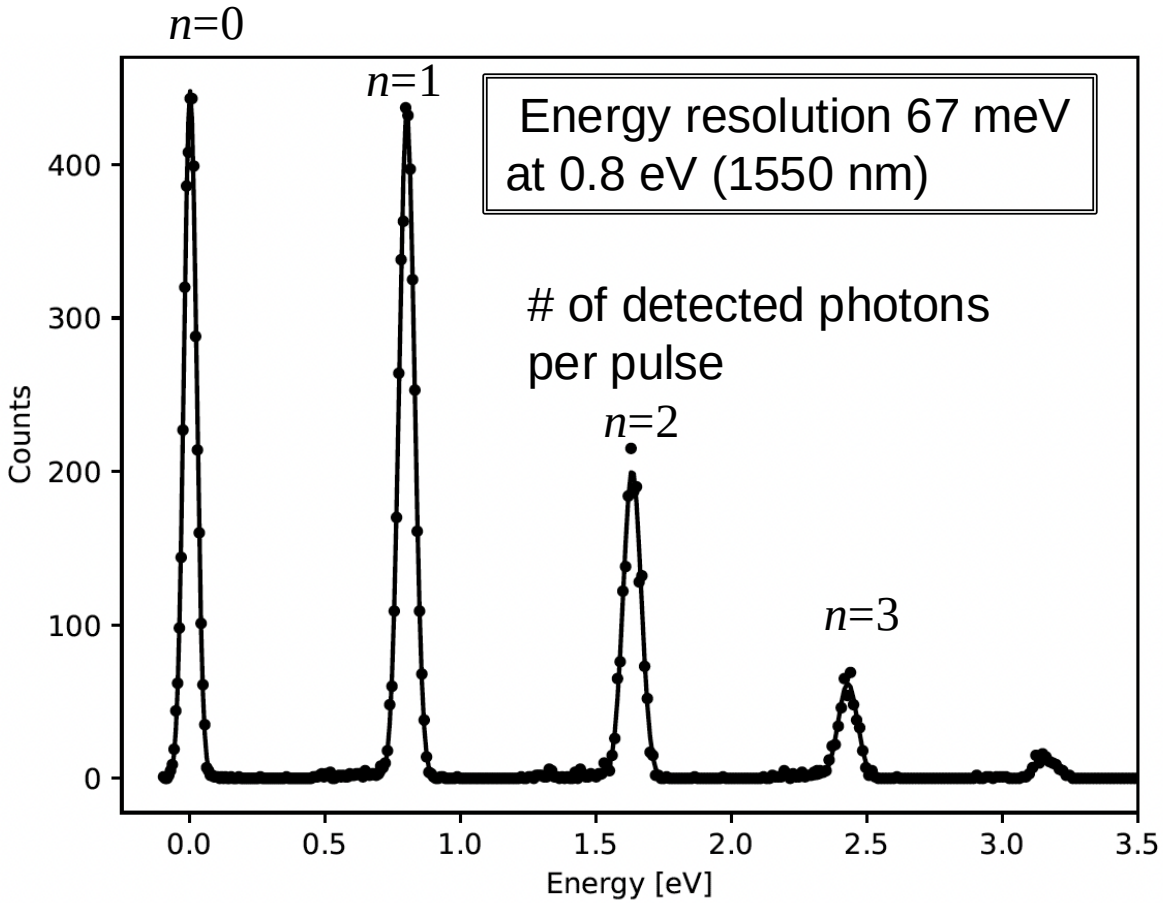
Summary

- ✓ Optical transition-edge sensor
  Can measure energy of each photon
  Can count the number of photons
- ✓ Trade-off between energy resolution and detector response
  TES with high Tc exhibit moderate energy resolution (0.1 to 0.2 eV) and fast detector response.
  →Suitable for quantum computing.
- ✓ Fall time of < 100 ns has achieved.
- ✓ Developed Microwave SQUID multiplexers and read out multiple channels at 5 MHz sampling.

Energy resolution

Energy resolution $\Delta E \propto T_c^{1.5}$





Energy resolution should be higher than 40 meV.
What limits the energy resolution?

Characterization of TES

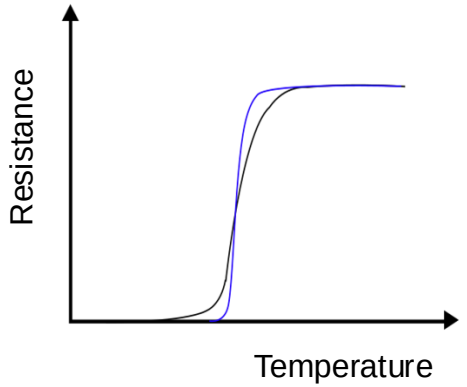
Energy resolution

$$\Delta E_{\mathrm{FWHM}} = 2\sqrt{(2\ln 2)}\left[\int_0^{\infty} \frac{4}{|I_\omega|^2}\left|\frac{dI}{dP}(\omega)\right|^2 df\right]^{-1/2}$$

Current noise

Responsivity

Parameters



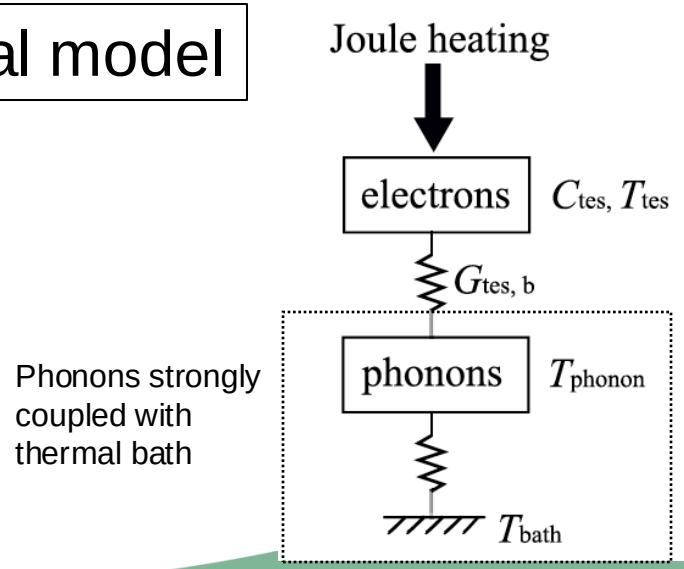
Temperature sensitivity

$$\alpha = \frac{T}{R}\frac{\partial R}{\partial T}\bigg|_I$$

Current sensitivity

$$\beta = \frac{I}{R}\frac{\partial R}{\partial I}\bigg|_T$$

Thermal model



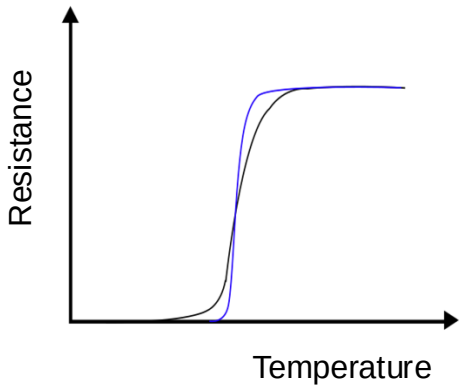
Phonons strongly coupled with thermal bath

- Measure current noise and estimate responsivity.
- Calculate ΔE_{FWHM}.

→Does calculated ΔE_{FWHM} differ from measured ΔE_{FWHM}?

Characterization of TES

Parameters



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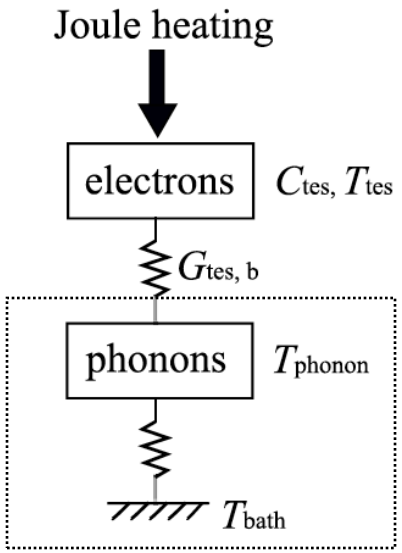
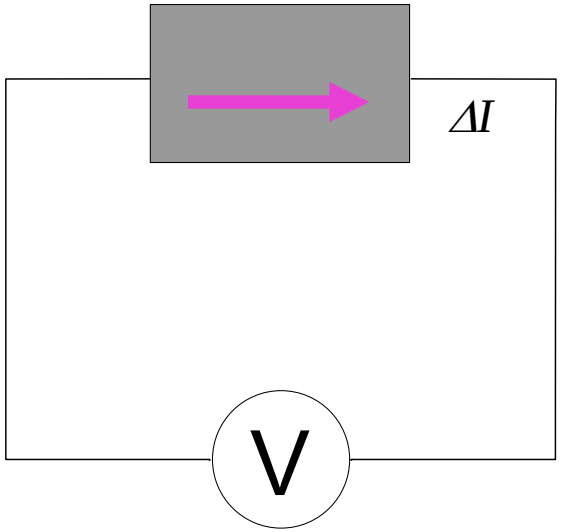


Phonons strongly coupled with thermal bath

Responses to small signals



Add small modulation to voltage bias

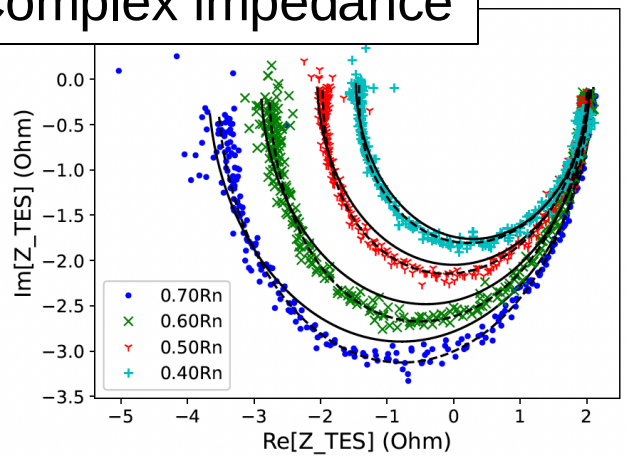
$$V + \Delta V sin\omega t$$

The parameters and a thermal model can be extracted from

Complex impedance $Z(\omega) = \frac{\Delta V}{\Delta I}$

Complex impedance and current noise

Complex impedance

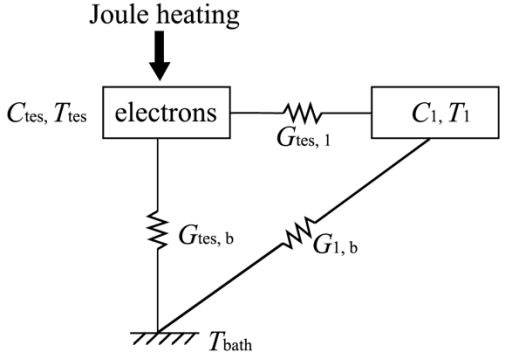


$$Z(\omega) = \frac{\Delta V}{\Delta I}$$

$$= R(1+\beta_I) + \frac{R\mathcal{L}_{\mathrm{eff}}(2+\beta_I)}{1-\mathcal{L}_{\mathrm{eff}}} \Big/ \left[1 + i\omega\tau_I - \frac{g_{\text{two-body}}}{(1-\mathcal{L}_{\mathrm{eff}})(1+i\omega\tau_1)}\right]$$

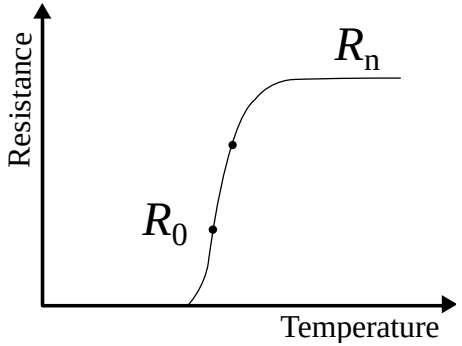
Thermal model

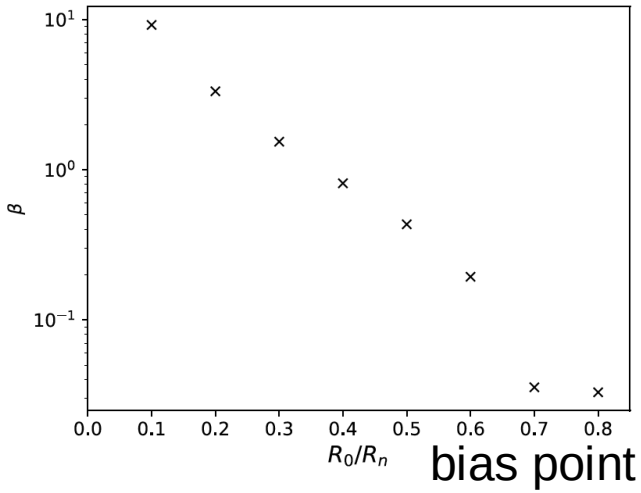
Two-block model



Current sensitivity

$$\beta = \frac{I}{R}\frac{\partial R}{\partial I}\bigg|_T$$

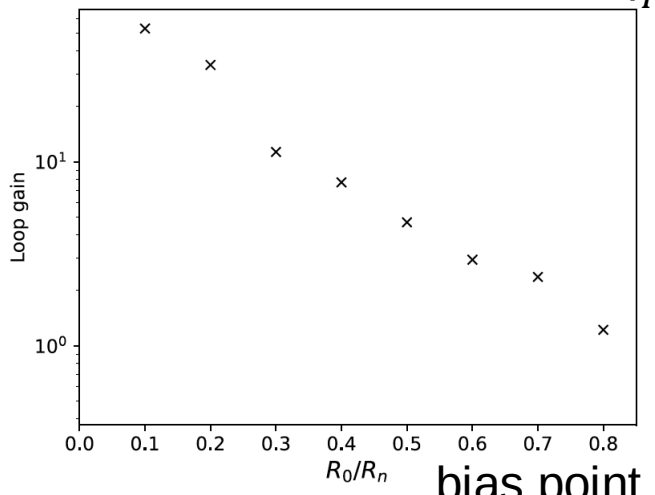




bias point

Loop gain

$$\propto \alpha = \frac{T}{R}\frac{\partial R}{\partial T}\bigg|_I$$



bias point

Characterization of TES

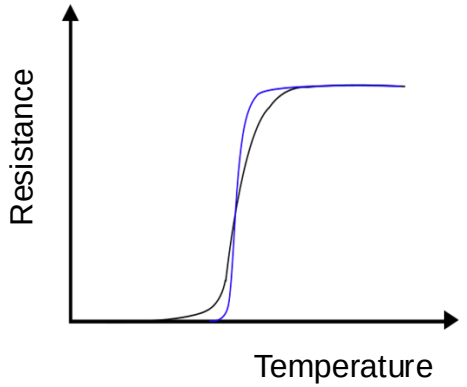
Energy resolution

$$\Delta E_{\mathrm{FWHM}} = 2\sqrt{(2\ln 2)}\left[\int_0^{\infty} \frac{4}{|I_\omega|^2}\left|\frac{dI}{dP}(\omega)\right|^2 df\right]^{-1/2}$$

Current noise

Responsivity

Parameters



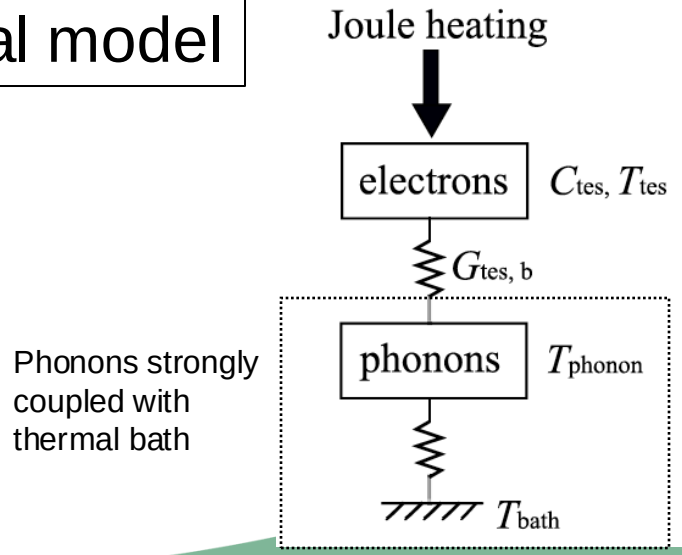
Temperature sensitivity

$$\alpha = \frac{T}{R}\frac{\partial R}{\partial T}\bigg|_I$$

Current sensitivity

$$\beta = \frac{I}{R}\frac{\partial R}{\partial I}\bigg|_T$$

Thermal model



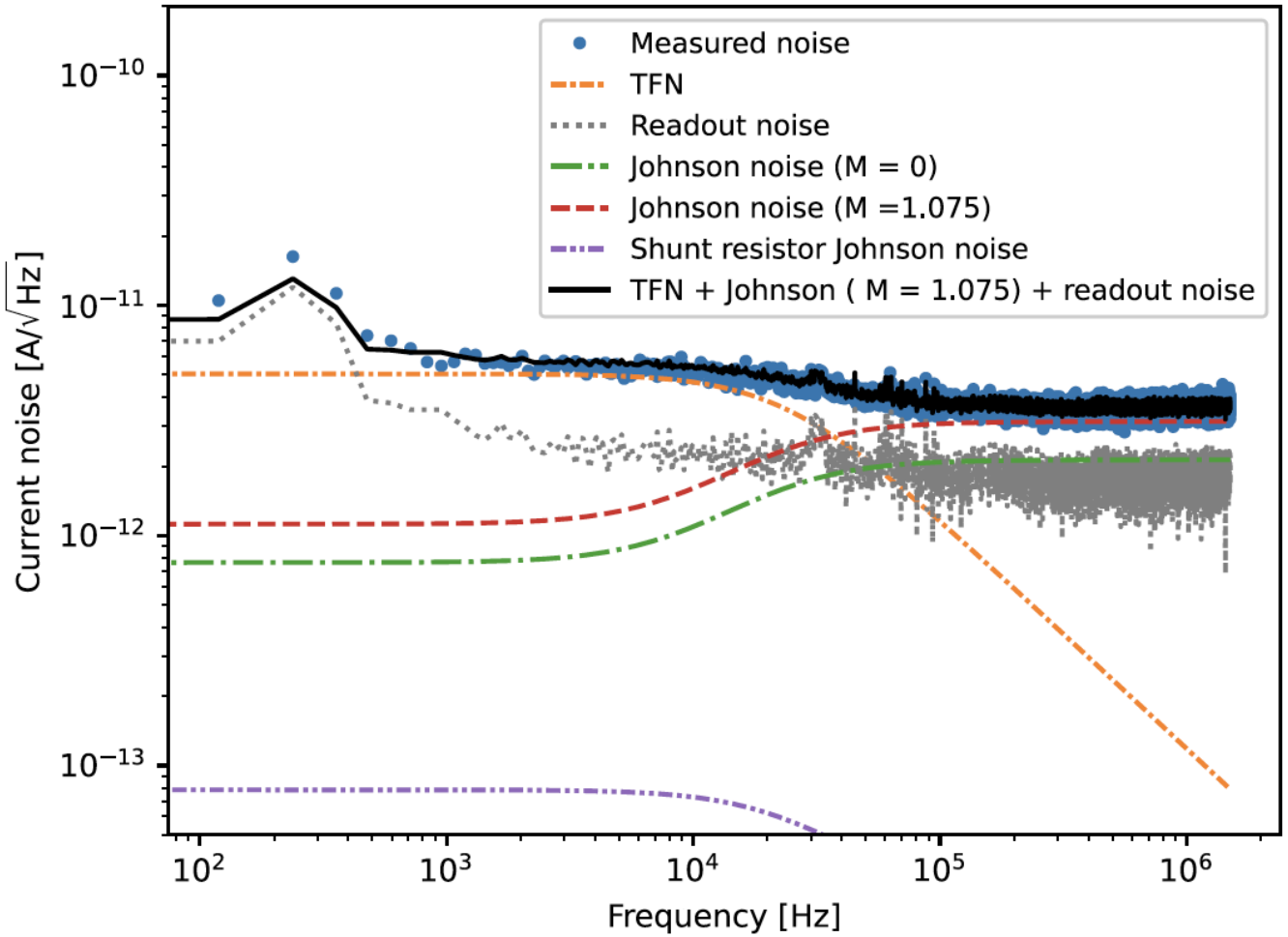
Phonons strongly coupled with thermal bath

- Measure current noise and estimate responsivity.
- Calculate ΔE_{FWHM}.

→Does calculated ΔE_{FWHM} differ from measured ΔE_{FWHM}?

Excess noise

Current noise (Bias point : $0.2R_n$)



The measured current noise agrees well with the theoretical model.

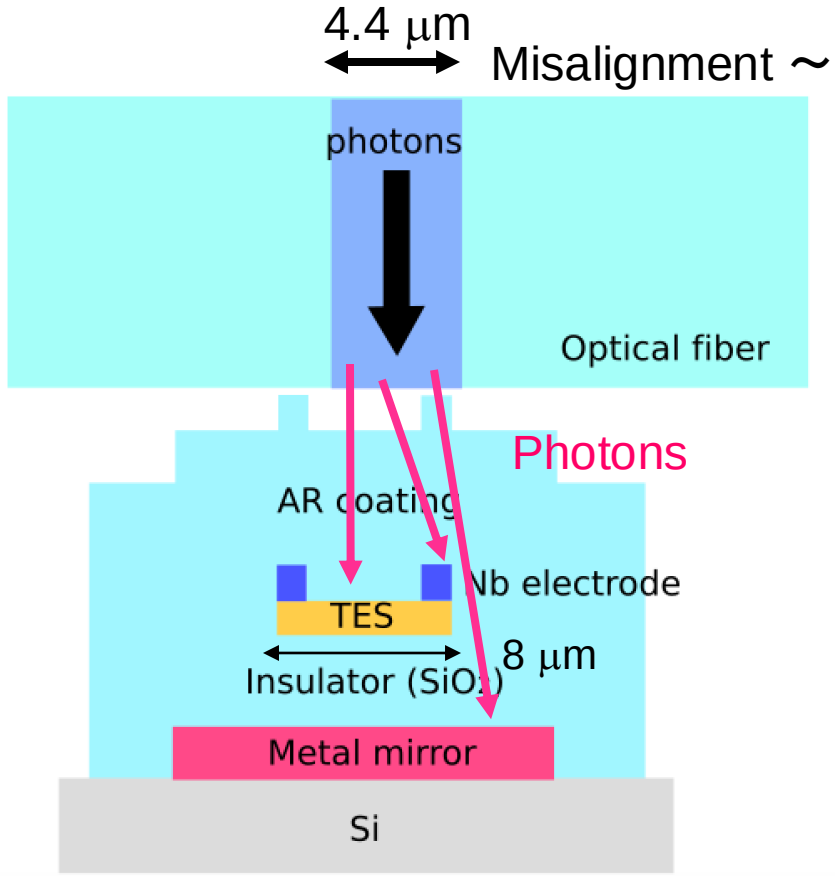
Comparison between theory and measurement

Measured ΔE	67 meV
ΔE calculated from current noise	40 meV
Energy collection efficiency η	88 %
ΔE calculated from current noise / η	46 meV
Unknown sources	50 meV

To obtain the energy resolution higher than 50 meV, unknown sources should be eliminated.

Comparison between theory and measurement

Measured ΔE	67 meV
ΔE calculated from current noise	40 meV
Energy collection efficiency η	88 %
ΔE calculated from current noise / η	46 meV
Unknown sources	50 meV



Unknown sources could include fluctuations in detector responses caused by misalignment.