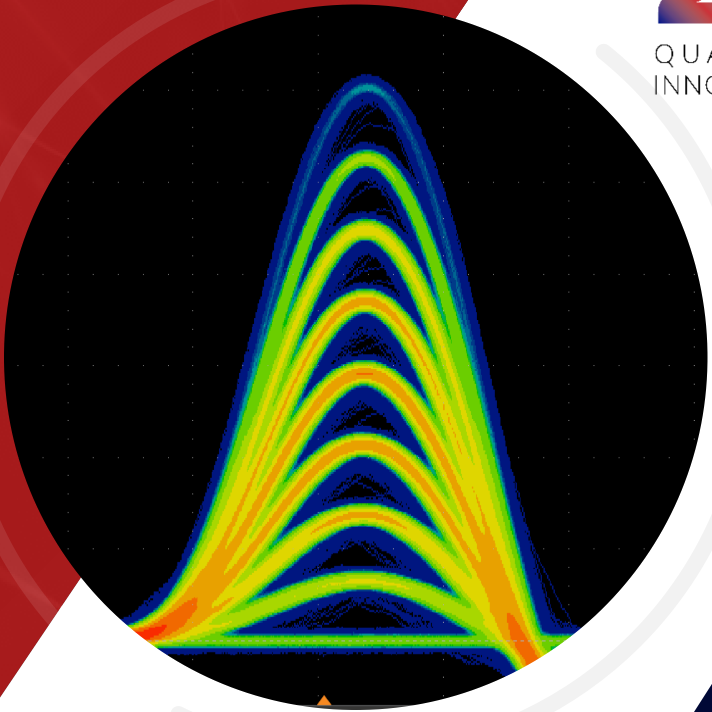
Opportunities and challenges for photon-number resolution with SNSPDs



Lorenzo Stasi

ID Quantique

Quantum Technologies Group, University of Geneva

Edinburgh, 18-22 November 2024

UNIVERSITÉ DE GENÈVE

20 YEARS QUANTUM INNOVATION

MARIE CURIE ACTIONS

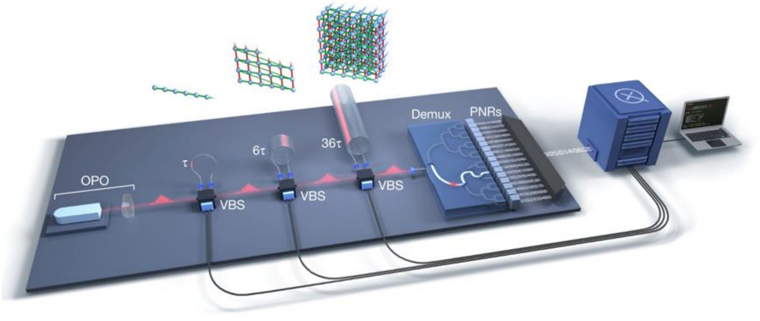
Photon-number resolving detector

Enable photonic quantum technologies

Gaussian Boson Sampling

Article

Quantum computational advantage with a programmable photonic processor



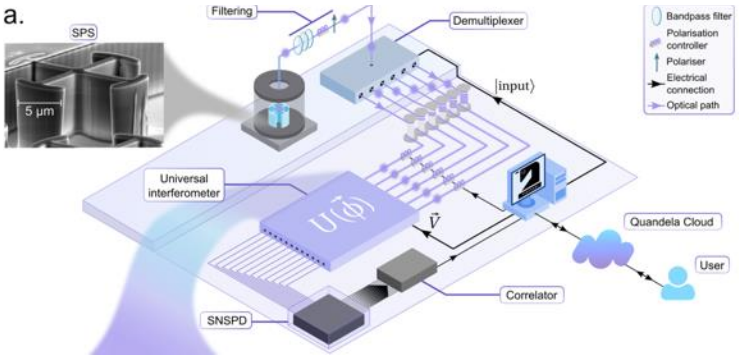
Madsen, L. S. et al., Quantum computational advantage with a programmable photonic processor, Nature 606, 75-81, (2022)

Photonic Quantum Computing

Article

https://doi.org/10.1038/s41566-024-01403-4

A versatile single-photon-based quantum computing platform



Maring, N. *et al.* A versatile single-photon-based quantum computing platform. Nat. Photon. pp 1-7 (2024)

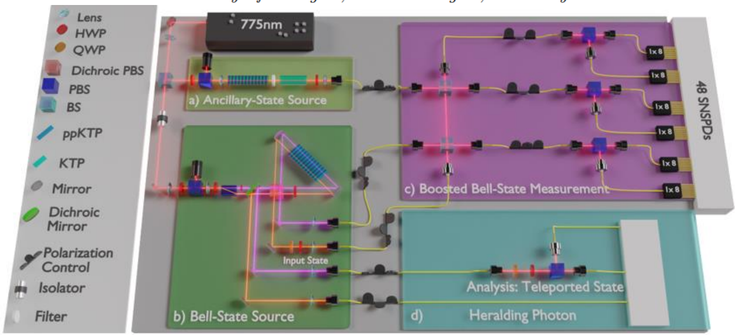
Photon-number resolving detector

Enable photonic quantum technologies

Quantum Networks

Boosted quantum teleportation

Simone E. D'Aurelio,[1,2,*] Matthias J. Bayerbach,[1,2,*] and Stefanie Barz[1,2]
[1] *Institute for Functional Matter and Quantum Technologies, University of Stuttgart, 70569 Stuttgart, Germany*
[2] *Center for Integrated Quantum Science and Technology (IQST), University of Stuttgart, 70569 Stuttgart, Germany.*

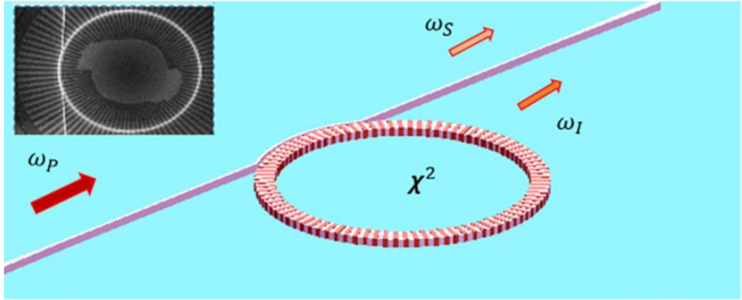


Bayerbach, M. J. et al., Sci. Adv. 9, eadf4080 (2023)
D'Aurelio, S. E. *et al.* Boosted quantum teleportation, arXiv2406.05182

Integrated Quantum Photonics

PHYSICAL REVIEW APPLIED **20,** 044033 (2023)

Highly efficient and pure few-photon source on chip



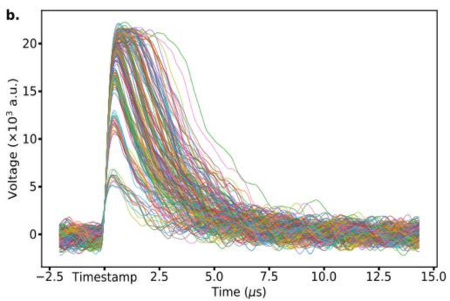
Zhaohui, M. et al., Phys. Rev. Applied 20, 044033 (2023)

Photon-number resolving detector

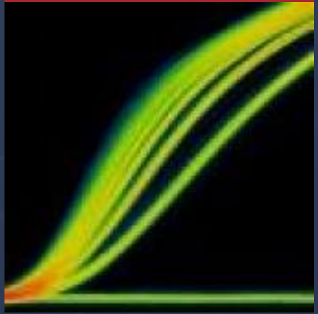
Several approaches

Superconducting Nanowire Single-Photon Detectors

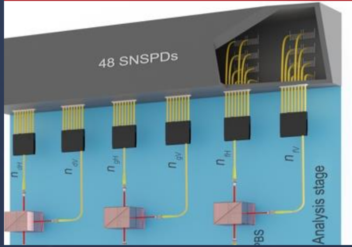
Transition edge sensor



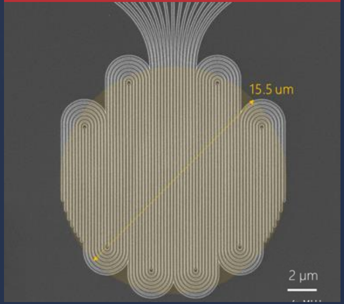
Rising edge SNSPD



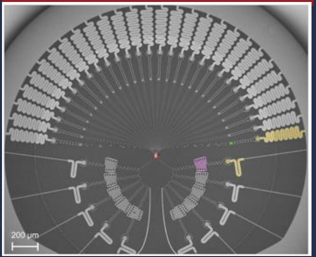
Many SNSPD with beam splitter



Independent multi-pixel array



Parallel SNSPD

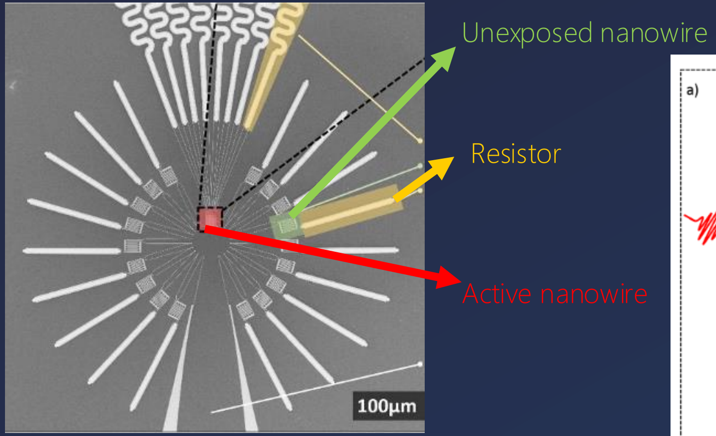


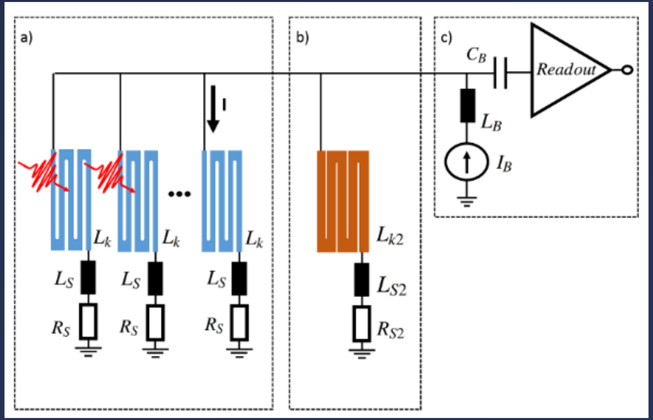
Morais, L. A. et al., *Quantum* 8, 1355 (2024)
Endo, M. et al. Opt. Exp. 29, 11728-11738 (2021)

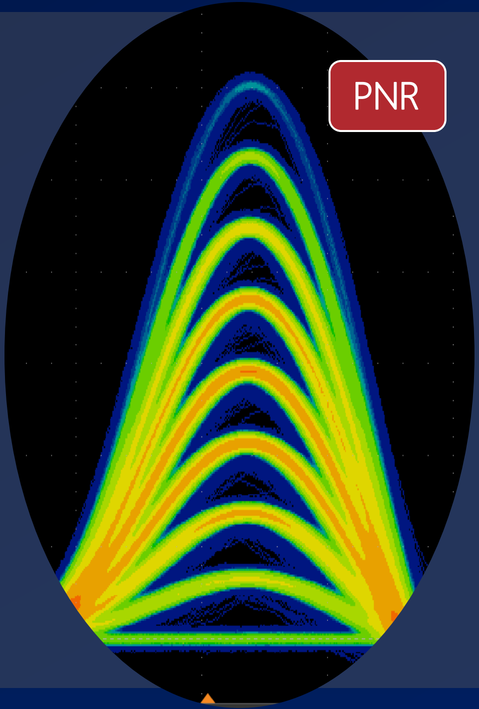
Bayerbach, M. J. et al., *Sci. Adv.* 9, eadf4080 (2023)
Resta, G. V. et al., *Nano Letters* 23, 6018–6026 (2023)
Stasi, L. et al, arXiv:2406.15312 (2024)

Parallel SNSPDs (P-SNSPDs)

Unique patented architecture







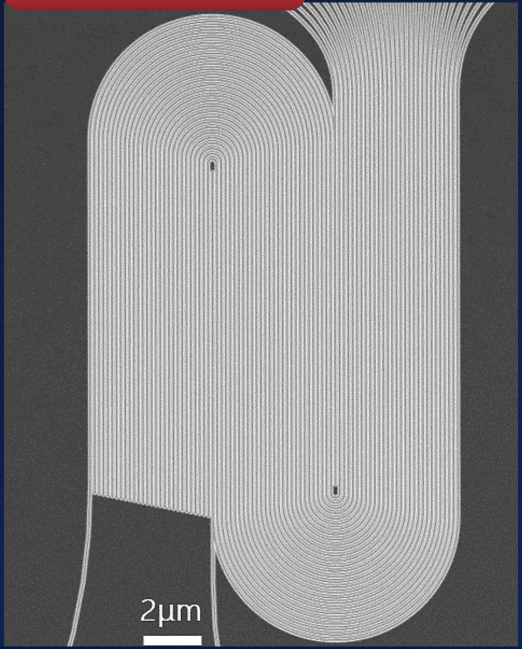
Additional unexposed nanowire in parallel to minimize current redistribution effect

Perrenoud, M., et al. *Superconductor Science and Technology* 34.2 (2021): 024002

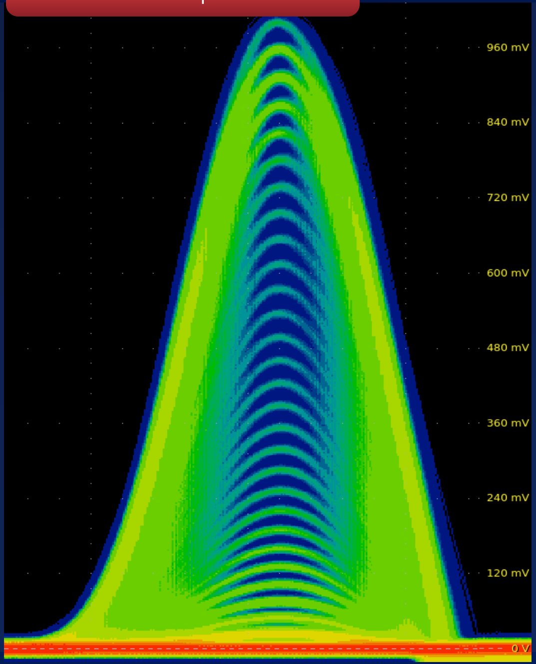
Parallel SNSPDs : a new generation

28 interleaved active pixels

SEM image



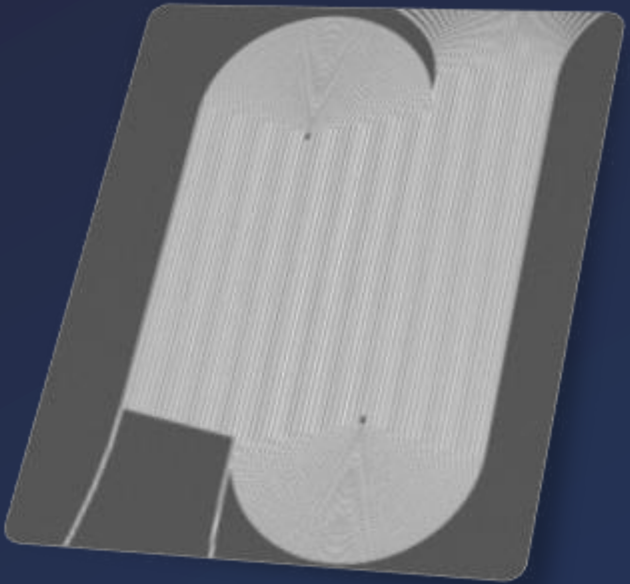
Oscilloscope trace



Parallel SNSPDs : a new generation

28 interleaved active pixels

More pixels is better !



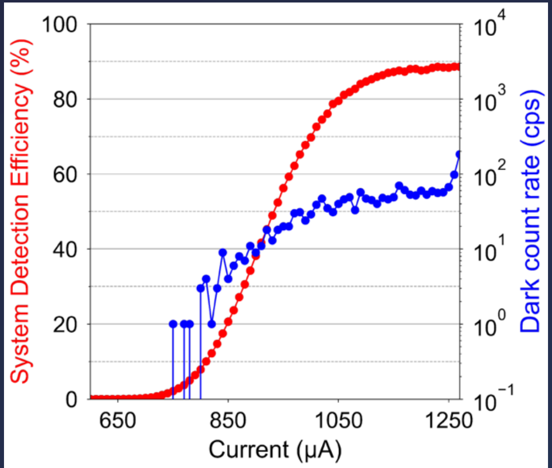
Poster 147
Towsif Taher

- Faster detectors ✓
- Performances stable at higher count rates ✓
- Improved n-photon efficiencies ✓
- Only 1 coaxial line needed ✓

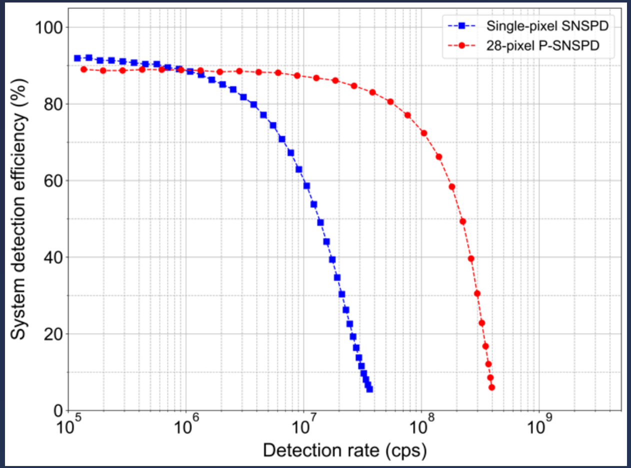
Stasi, L. et al, arXiv:2406.15312 (2024)

28-pixel P-SNSPD

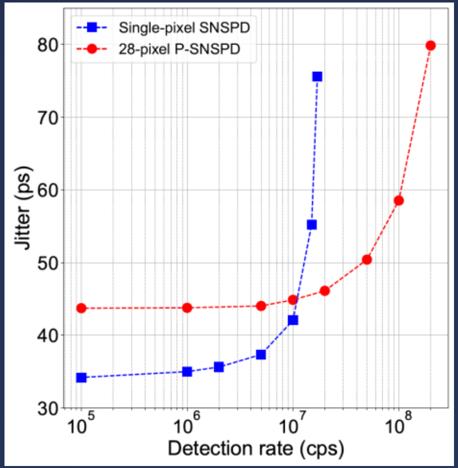
Performances



88% SDE, 1550nm



>200 Mcps @ 50% SDE



Jitter <60 ps @ 100 Mcps

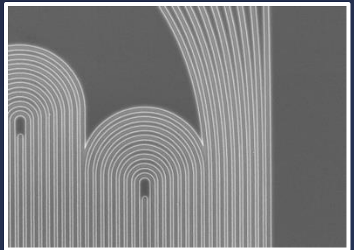
Stasi *et al.*, arXiv:2406.15312 (2024)

Photon-number resolution and high-speed with SNSPDs

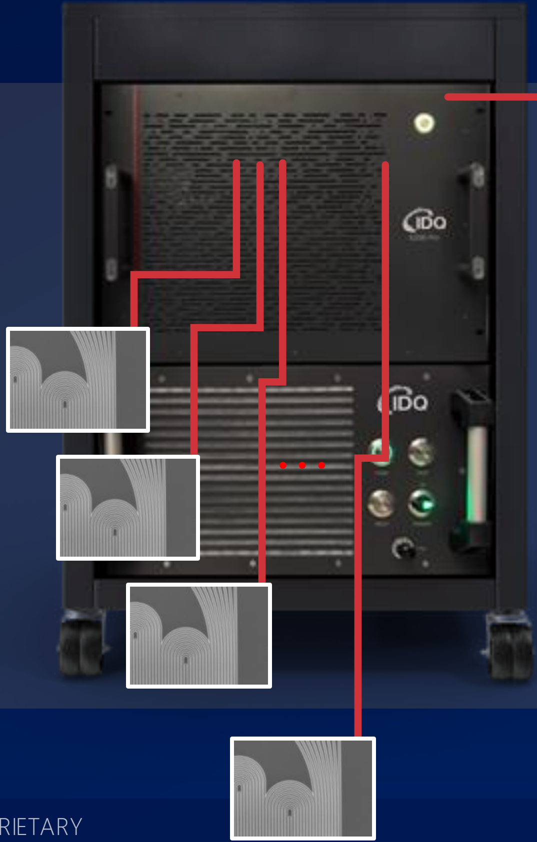
Divide detection area into multiple smaller SNSPDs (pixels)

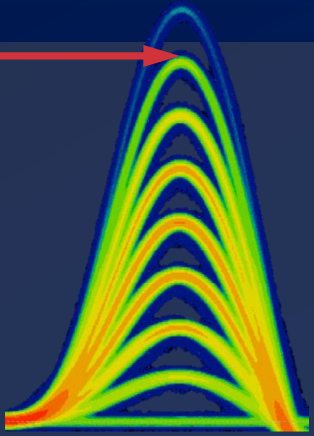
Parallel SNSPDs (P-SNSPDs)

- *N* pixels connected with 1 readout line (up to 16 devices in a 16-channel cryostat)
- High-fidelity PNR via amplitude of output pulse
- Low recovery time and high detection rate



INNOVATION AWARD
LASER World of PHOTONICS
EUROPA SCIENCE





Amplitude of output pulse encodes photon number

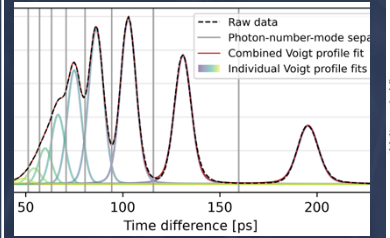
Perrenoud, M. et al. *Superconductor Science and Technology*, *34*(2), p.024002 (2021)
Stasi, L. et al. *Physical Review Applied*, *19*(6), p.064041 (2023)
Stasi, L. et al. *Quantum Sci. Technol.* 8 045006 (2023)

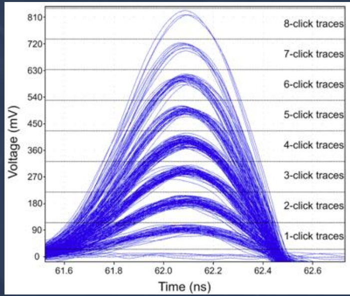
Ideal PNR detectors

Suggested requirements

Properties

- n-photon efficiencies depend only on η, thus $P_{nn} = \eta^n$
- 100% assignment probability at any n-click event



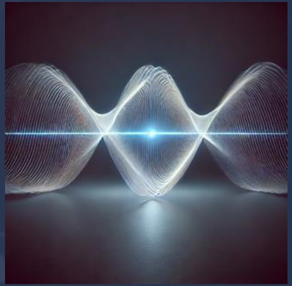


Features

a. Ability to work with any light pulse duration

b. Ability to work at high count rates

c. Scalability and operational simplicity



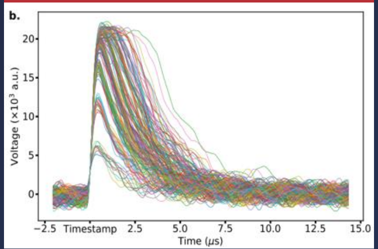
Stasi, L. et al, arXiv:2406.15312 (2024)
Sauer, G. et al arXiv:2310.12472v1 (2023)

1) n-photon efficiencies

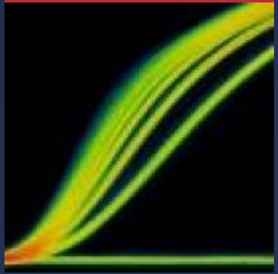
Intrinsic capability

$$P_{nn} = \eta^n$$

Transition edge sensor



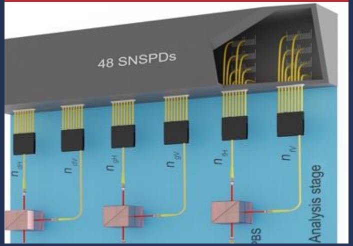
Rising edge SNSPD



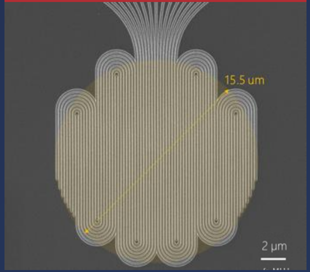
Multipixel scheme with SNSPD

$$P_{nn} = \frac{N!}{(N-n)!}\left(\frac{\eta}{N}\right)^n$$

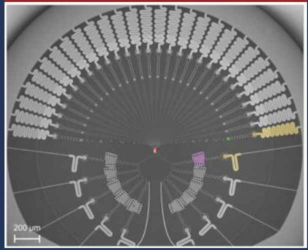
Many SNSPD with beam splitter



Independent multi-pixel array



Parallel SNSPD



Morais, L. A. et al., *Quantum* 8, 1355 (2024)
Endo, M. et al. Opt. Exp. 29, 11728-11738 (2021)

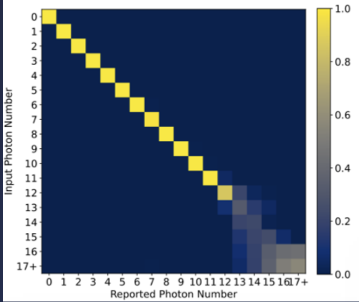
Bayerbach, M. J. et al., *Sci. Adv.* 9, eadf4080 (2023)
Resta, G. V. et al., *Nano Letters* 23, 6018–6026 (2023)
Stasi, L. et al, arXiv:2406.15312 (2024)

2) 100% assignment probability at any n-click event

Probability to assign each different output signal to the corresponding n-click event

Intrinsic capability

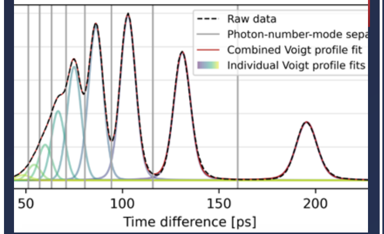
Transition edge sensor



Up to 10 photons

Signal digitalization and postprocessing

Rising edge SNSPD

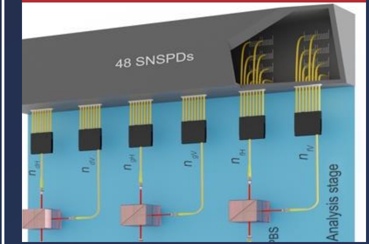


Up to 4 photons

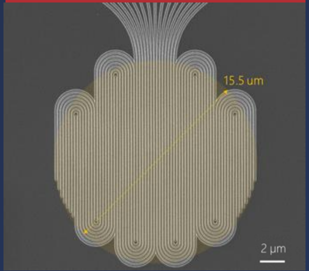
Low jitter electronics and low jitter detector/slow rise time

Multipixel scheme with SNSPD

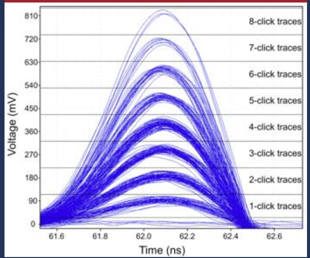
Many SNSPD with beam splitter



Independent multi-pixel array



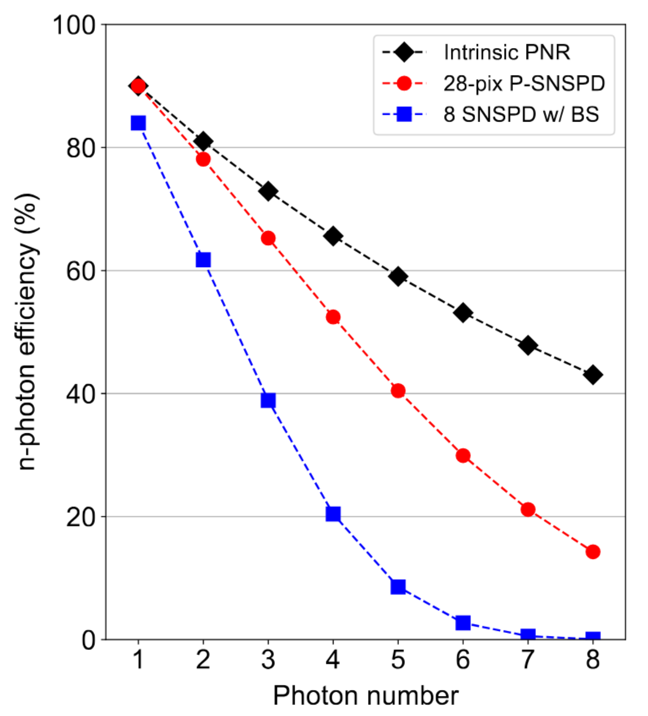
Parallel SNSPD



ALWAYS VERIFIED

n-photon efficiency

Comparison between different PNR approaches



Detector	n-photon efficiency							
	1-ph	2-ph	3-ph	4-ph	5-ph	6-ph	7-ph	8-ph
8 SNSPD w/ BS	84*	61.7	38.9	20.41	8.6	2.7	0.57	0.1
28-pixel P-SNSPD	90	78.1	65.3	52.4	40.5	29.9	21.1	14.3
Intrinsic PNR**	90	81	72.9	65.6	59.1	53.1	47.8	43.1

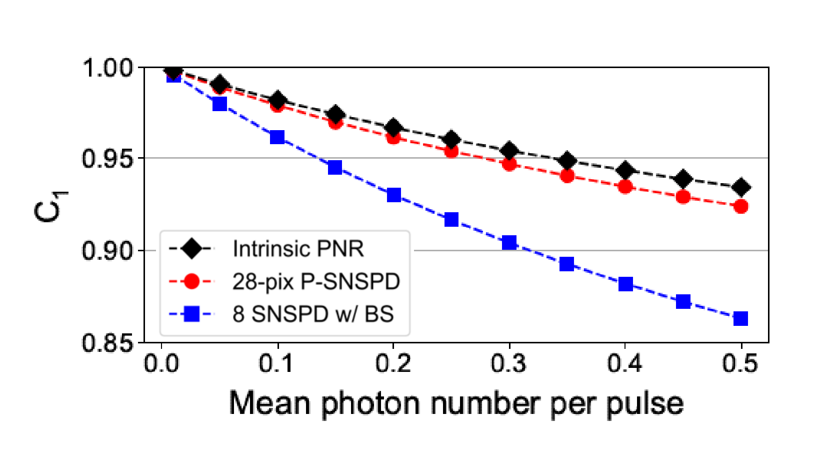
* 0.3dB added to simulate optical beam splitter loss
** Assuming 100% assignment probability

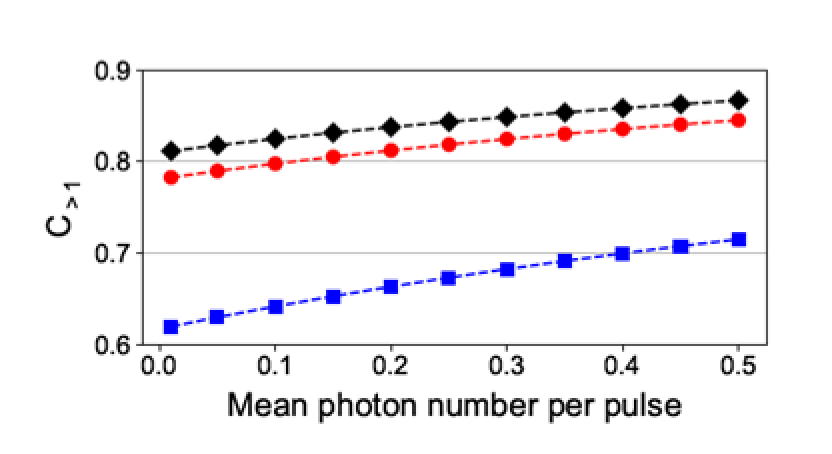
Stasi, L. et al, arXiv:2406.15312 (2024)

Confidence of PNR detectors with thermal light (TMSVS)

What is the probability that given a 1-click event there were 1-photons in the input state?

What is the probability that given an input state with >1 photon, there will be a >1-click event registered?





Ideal PNR detectors

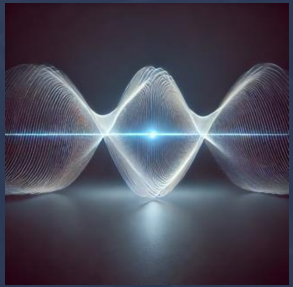
Suggested requirements

Features

a. Ability to work with any light pulse duration

b. Ability to work at high count rates

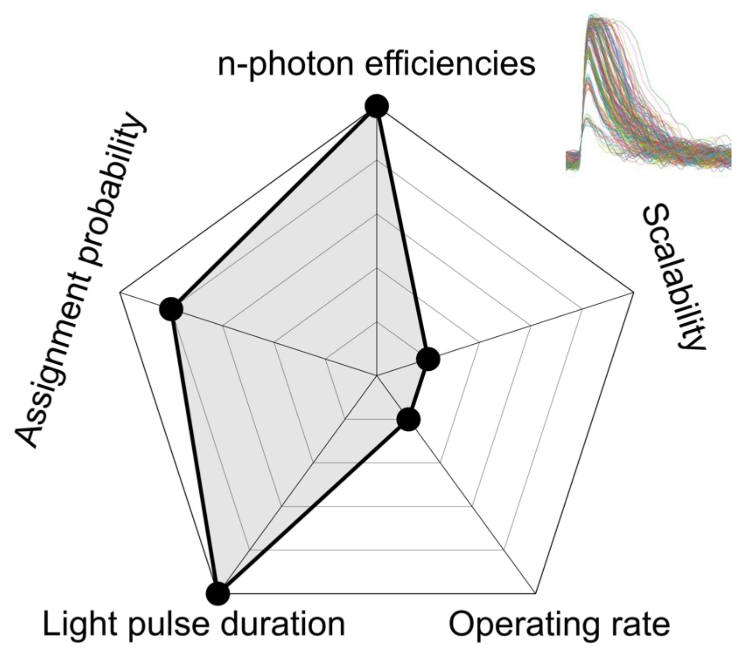
c. Scalability and operational simplicity



Nat. Mater. 20, 273 (2021)

Features - TES

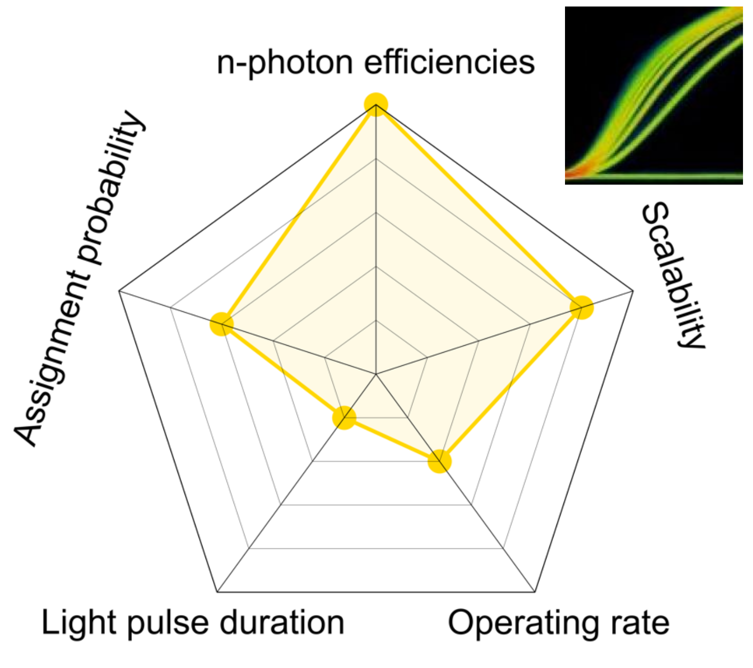
Transition edge sensor



- Demonstrated up to 10s ns light pulses
- Slow recovery time limiting to 100s kHz operation
- Dilution fridge and SQUID readout
- Trace digitalization and postprocessing

Features – Rising edge SNSPD

Rising edge SNSPD



- Limited to few 10s ps light pulses
- Recovery time limits to few MHz
- Time tagging with ps resolution
- Low jitter detector or slow rising edge

Features – SNSPDs with optical beam splitter

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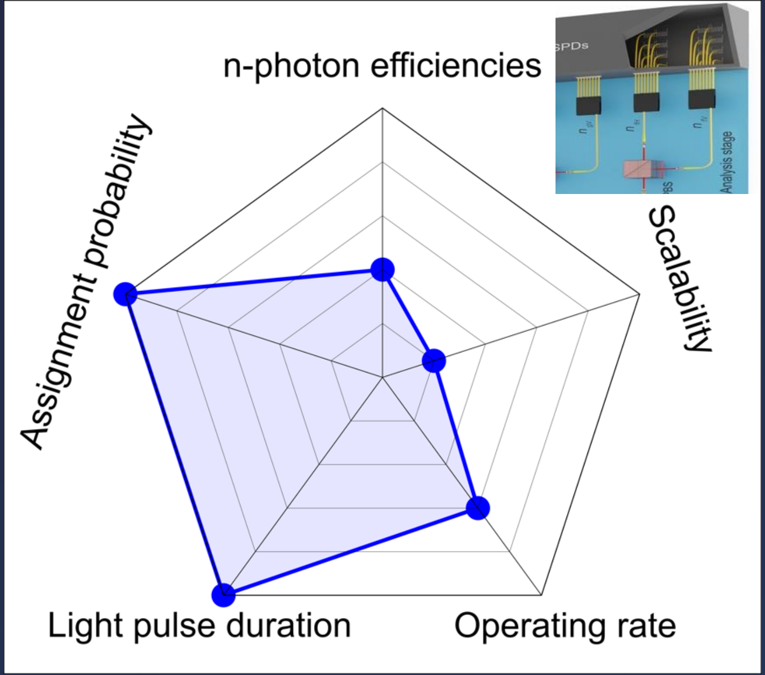
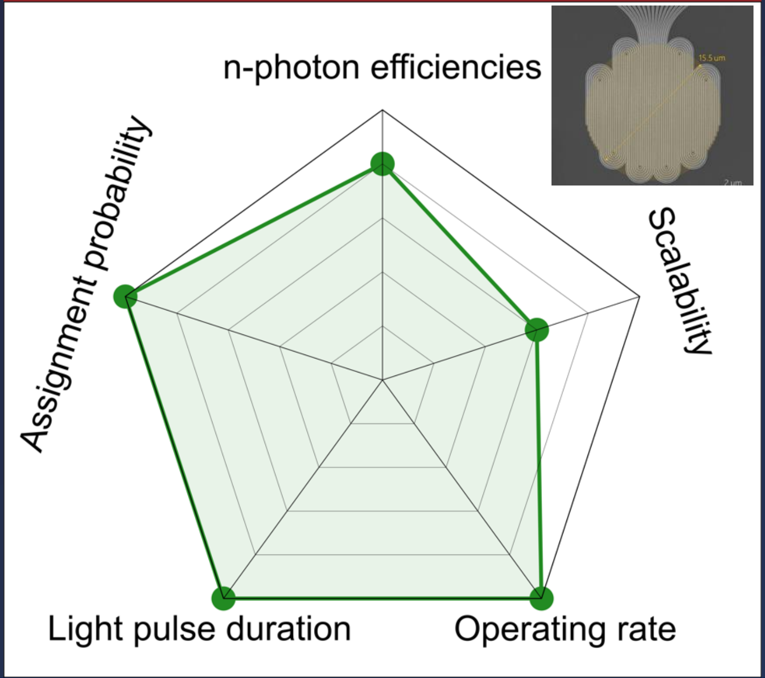
SNSPDs w/ optical BS



- No restriction on light pulse duration
- Recovery time limits to few MHz
- Losses of optical BS
- N cryogenic coaxes for N detector
- Coincidence analysis across all channels

Features – Independent multi-pixel array

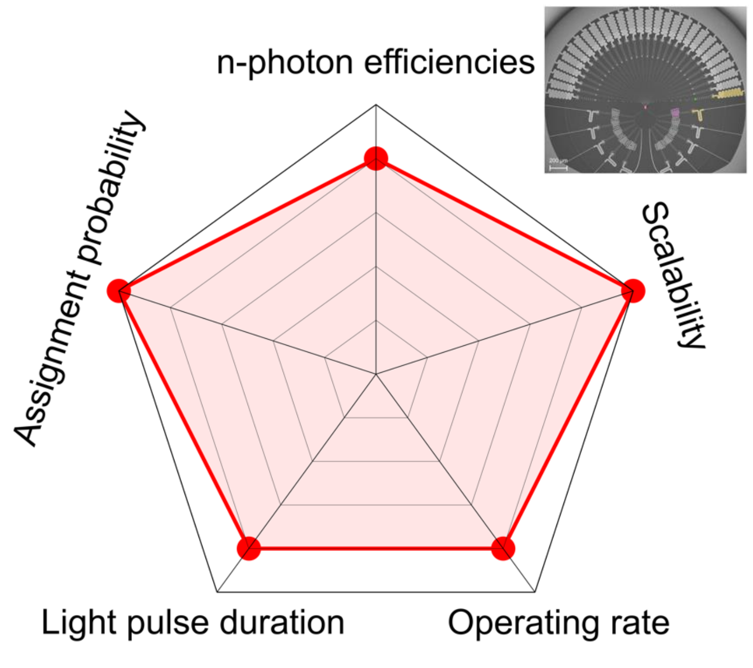
Independent multi-pixel array



- No restriction on light pulse duration
- 100 MHz thanks to fast recovery time
- No losses of optical BS
- N cryogenic coaxes for N pixels
- Coincidence analysis across all channels

Features – Parallel SNSPD

P-SNSPD



- Works with light pulses in the few hundreds of ps (~300ps)
- Demonstrated 40MHz PNR operation [1]
- 1 cryogenic coaxes for N pixels
- Amplitude discrimination with any time taggers

[1] Stasi, L. et al, arXiv:2406.15312 (2024)

Highlights

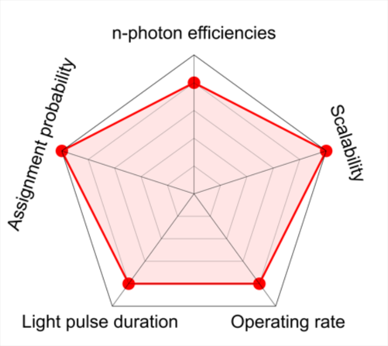
Solving detection challenges for quantum networks and computing

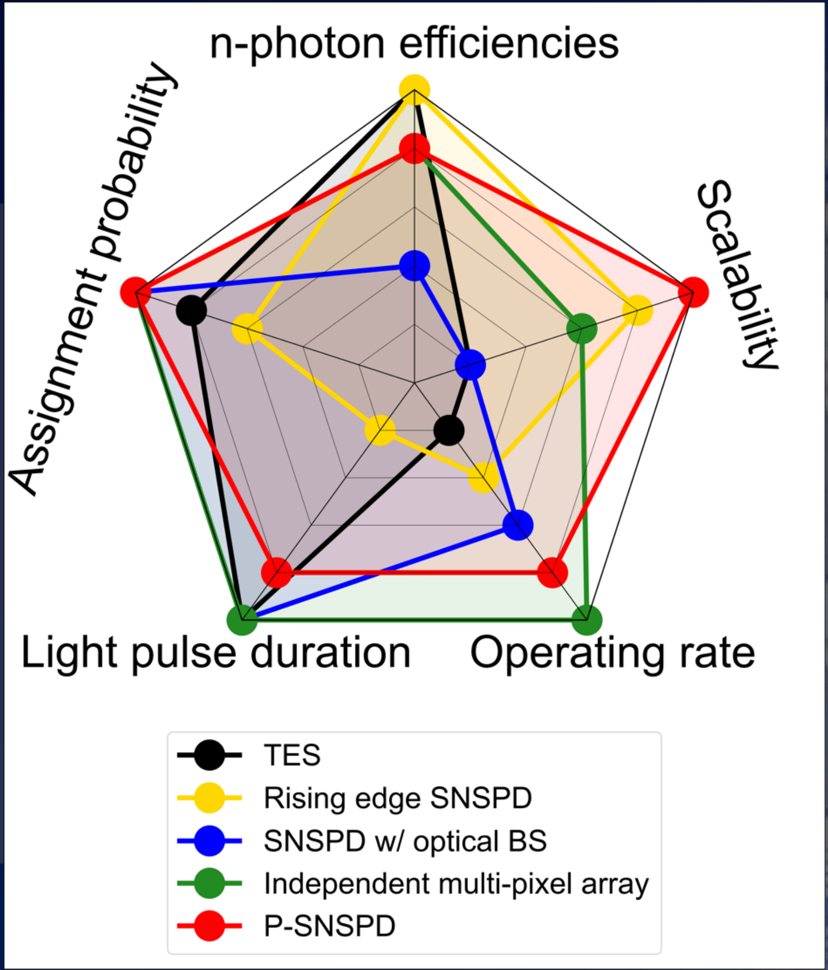
Parallel SNSPD: P-SNSPD

- *N* pixels connected with 1 readout line (up to 16 devices in a 16-channel cryostat)
- Amplitude of output pulse encodes photon number info
- State-of-the-art PNR + Fast detection

New generation 28 pixel

- >200 Mcps @ 50% SDE
- 60 ps jitter @ 100 Mcps
- High n-photon efficiencies




n-photon efficiencies
Scalability
Operating rate
Light pulse duration
Assignment probability
TES
Rising edge SNSPD
SNSPD w/ optical BS
Independent multi-pixel array
P-SNSPD

Team members

ID Quantique

Founded in 2001

Team of > 100 people

Geneva, Seoul, Boston, Austria

We develop products for

Quantum-safe security
Quantum technologies

Academic and companies
Startups and industry

IDQ

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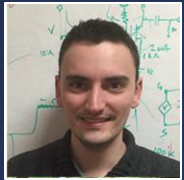
Félix Bussières

Giovanni V. Resta

Matthieu Perrenoud



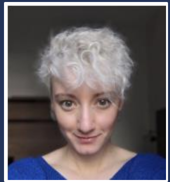
Gaëtan Gras

Hanan Jaffal

Rob Thew

Hugo Zbinden

Towsif Taher



Tiff Brydges

Patrik Caspar

Geneva Quantum Centre

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 956071