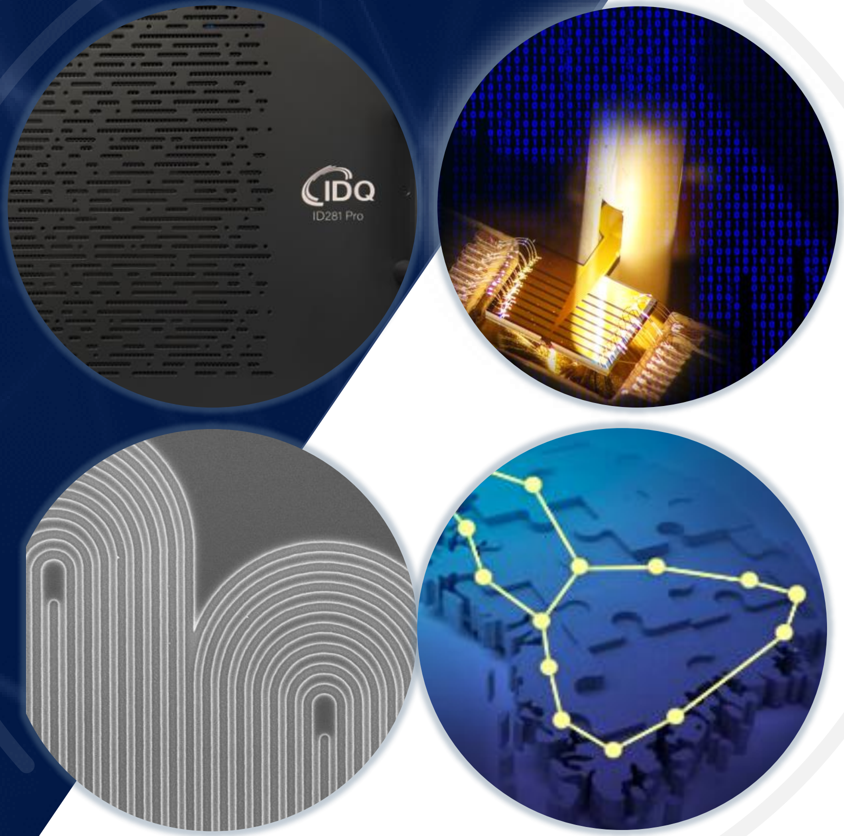
Photon-number resolving SNSPDs and their applications for quantum networks and quantum computing



Félix Bussières, *VP Quantum Detection*

ID Quantique

QT4HEP conference – CERN – January 2025

20 YEARS QUANTUM INNOVATION

Quantum networks : today and tomorrow

From QKD networks to quantum networks of quantum computers

Pionier-Q : Quantum communication infrastructure in Poland, QKD network, connecting to HPC

ID Quantique

Founded in 2001

Team of > 120

Geneva, Seoul, Boston, Austria

Two complementary BUs

Quantum-safe networks

Quantum detection systems

Quantum-safe networks

QKD and key management

QKD system for today's quantum-safe secure networks with KMS for end-to-end security

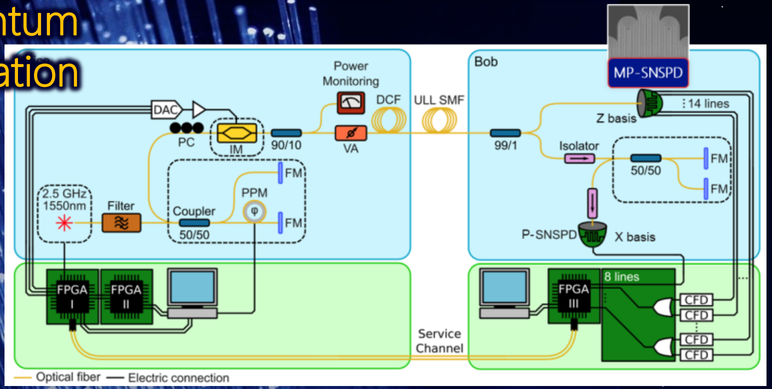
Markets

- Telecoms
- Government
- Bank and Finance
- Critical Infrastructure
- Healthcare
- Academia

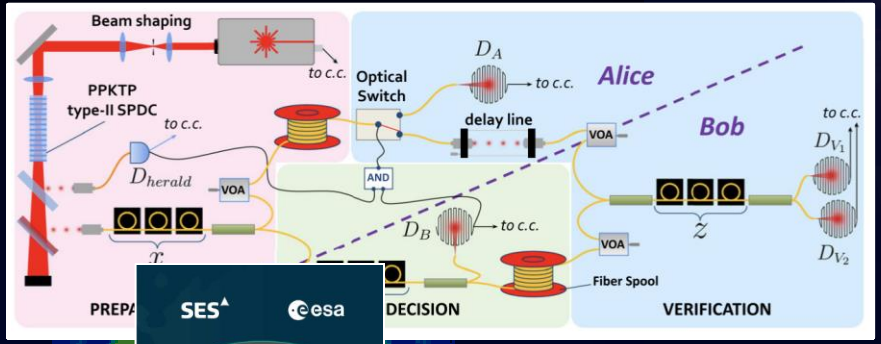
IDQ's Quantum detection systems :

Enabling the *Quantique* in networks, computers and science

Quantum communication

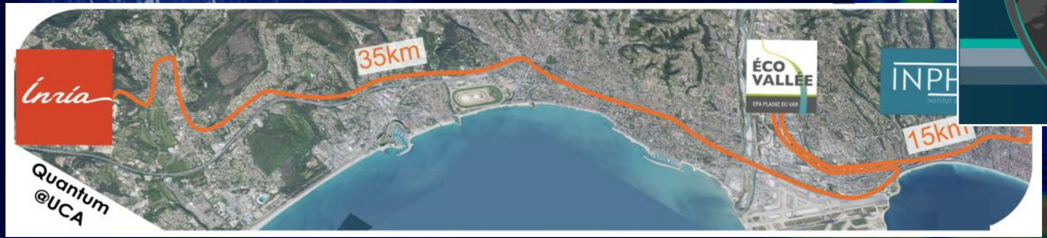


Grunfelder et al, Nat. Photon. 17, 422 (2023)



Neves et al, Nat. Comm. 14, 1855 (2023)

Quantum networks



Pelet et al., Phys. Rev. Applied 20, 044006 (2023)

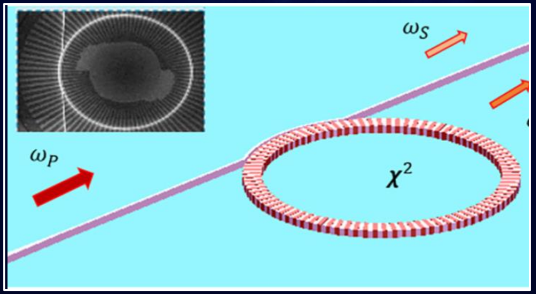
Rakonajac et al, Optica Quantum 1, 94 (2023)

Quantum computing

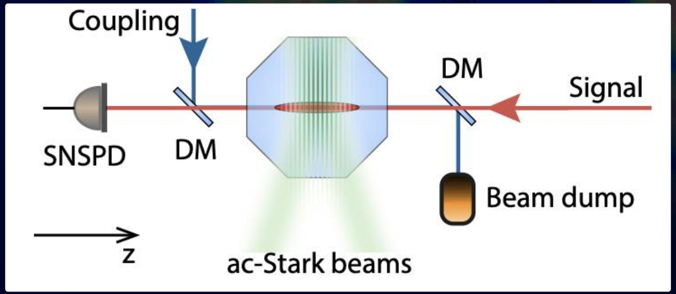
Quantum photonics

Quantum emitters

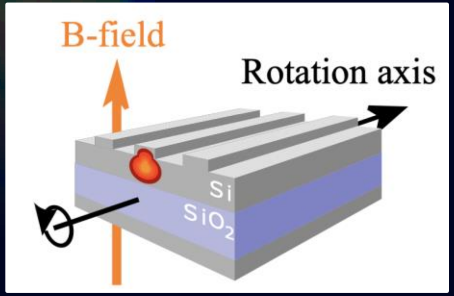
Material science



Zhaohui et al., PR Applied 20, 044033 (2023)

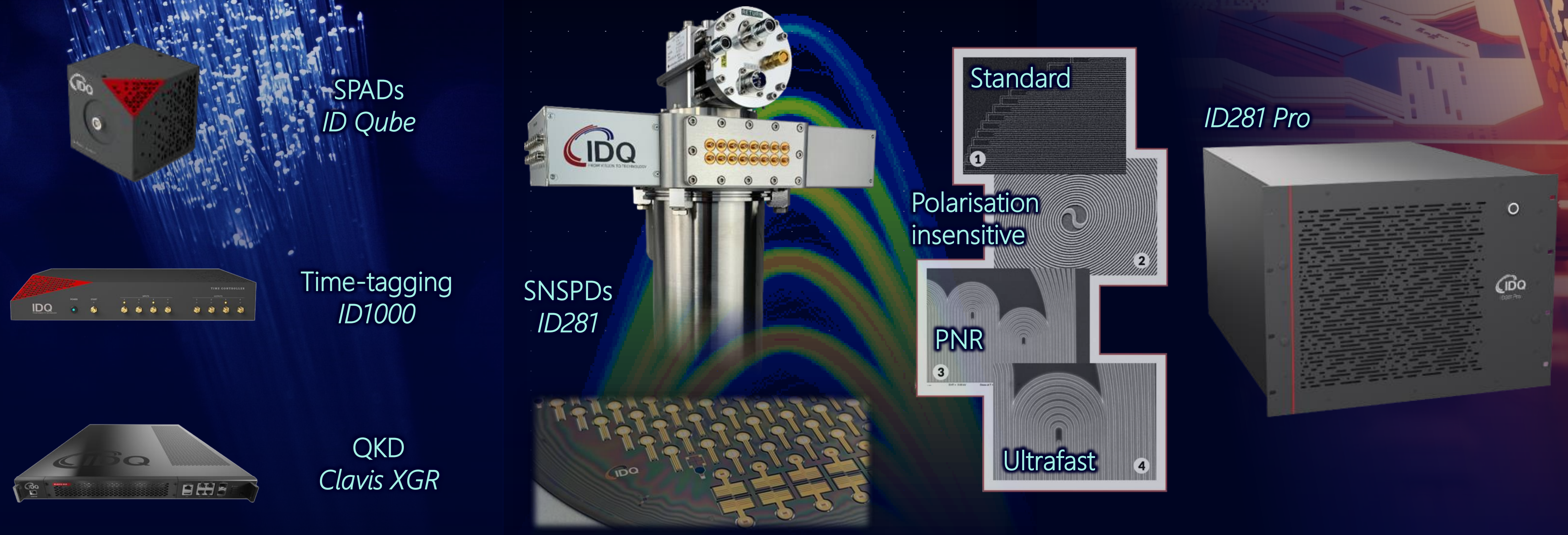


Kurzyna et al, arXiv:2402.06513 (2024)



Holzapfel et al, arXiv:2409.06571 (2024)

We develop and deliver state-of-the-art & industry-ready quantum detection systems to spark technological progress

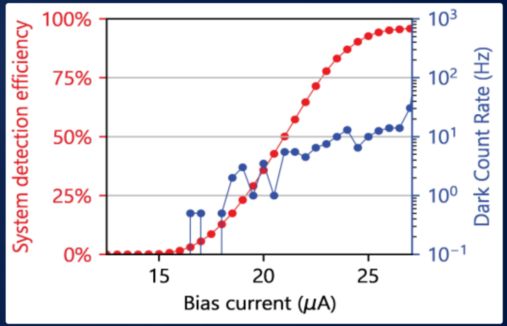


What makes a good single-photon detector ?

Key metrics

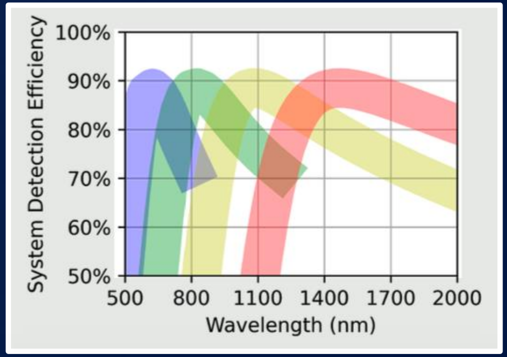
- High system detection efficiency (SDE)
- Low dark-count rate (DCR)
- Good timing precision (jitter)
- Fast detection rates
- Photon-number resolution (PNR)
- Form factor + compatibility + quality + …

Scalability with near-perfect detection efficiency



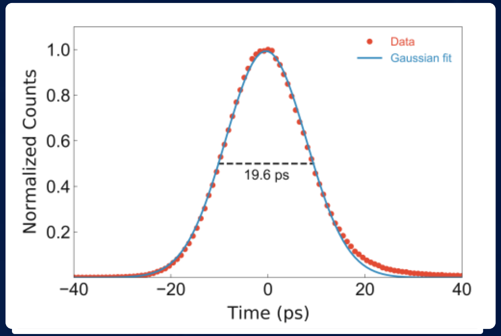
> 90% efficiency
< 1 cps DCR

Quantum science at any wavelength



From < 600 nm to > 2000 nm

Time precision for any occasion

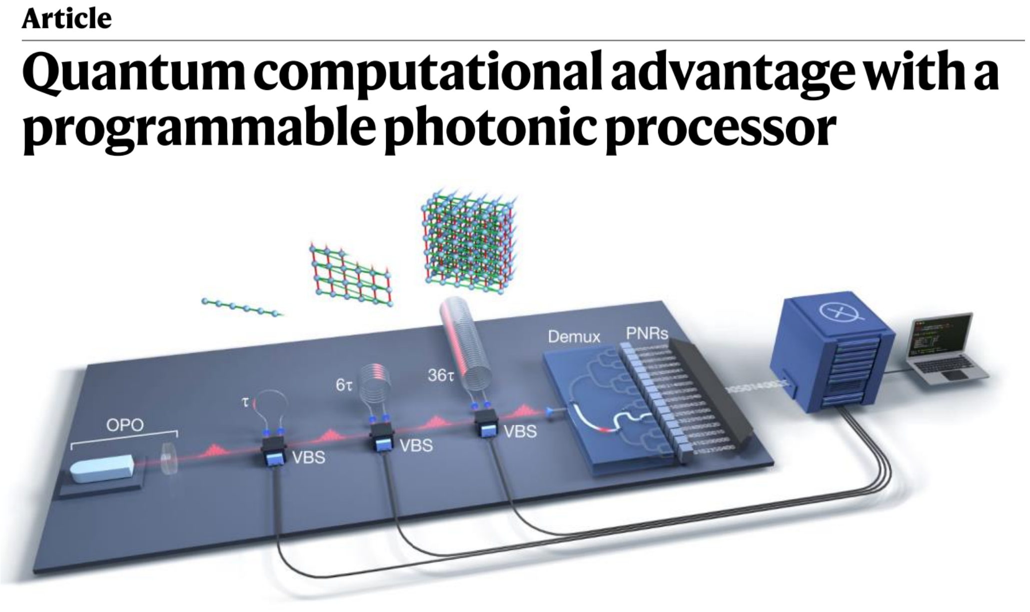


Jitter can be as low as < 20 ps

Photon-number resolving detector

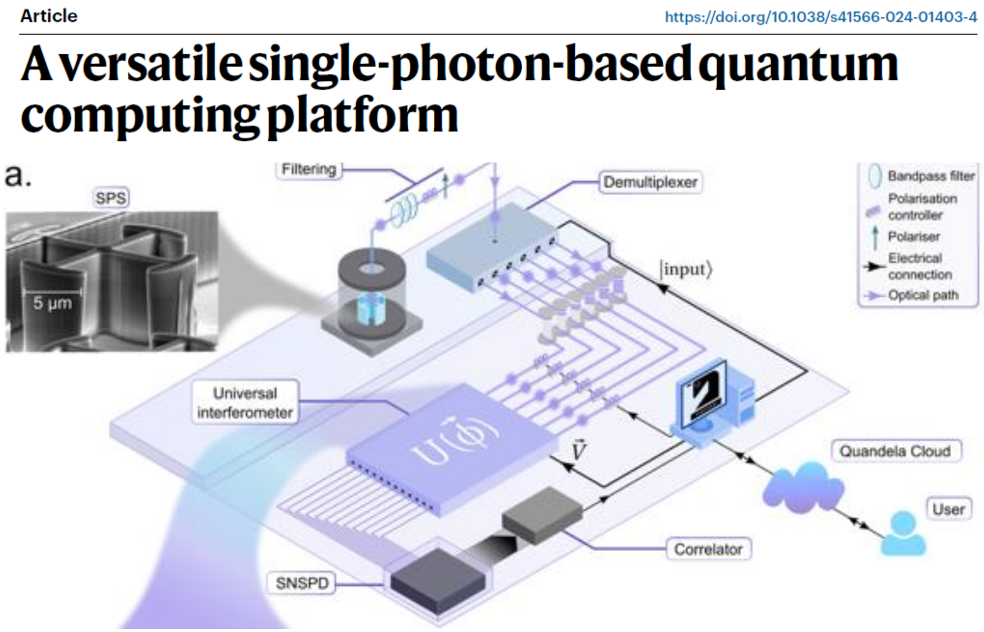
Enable photonic quantum technologies

Gaussian Boson Sampling



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

Photonic Quantum Computing



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

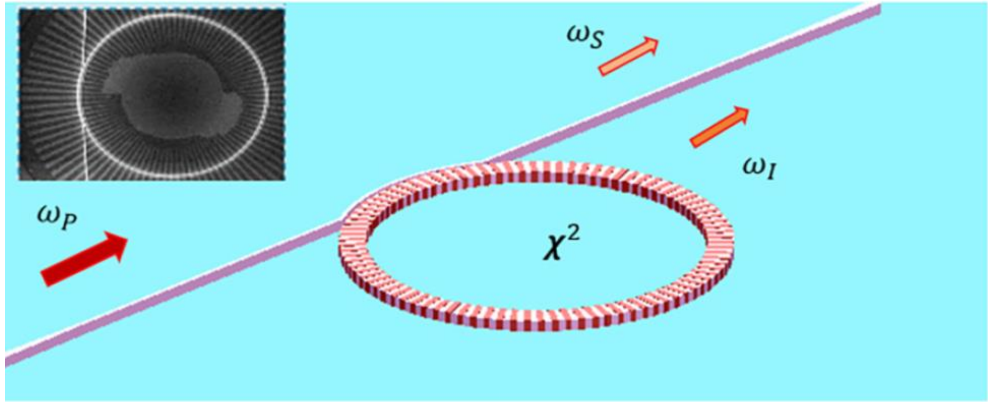
Photon-number resolving detector

Enable photonic quantum technologies

Integrated Quantum Photonics

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

Highly efficient and pure few-photon source on chip

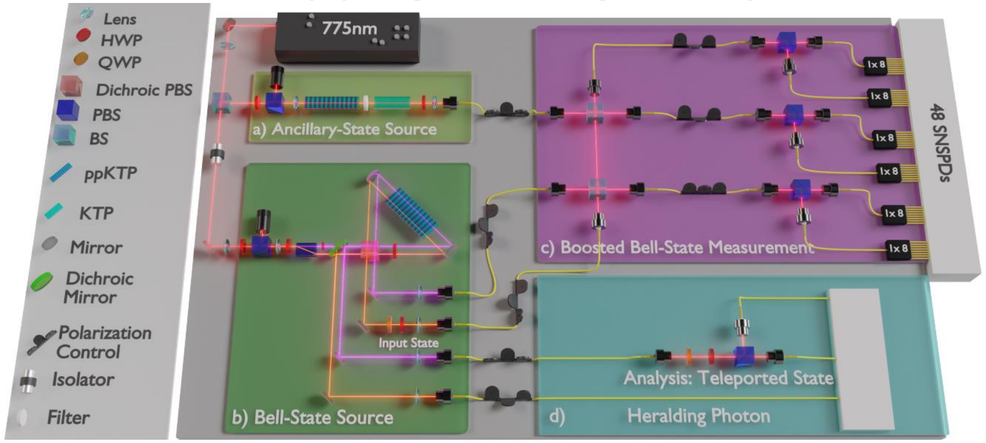


Zhaohui, M. et al., Phys. Rev. Applied 20, 044033 (2023)

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, arXiv:2406.05182

Photon-number resolving detector

Enable photonic quantum technologies

Quantum Networks

Boosted quantum teleportation

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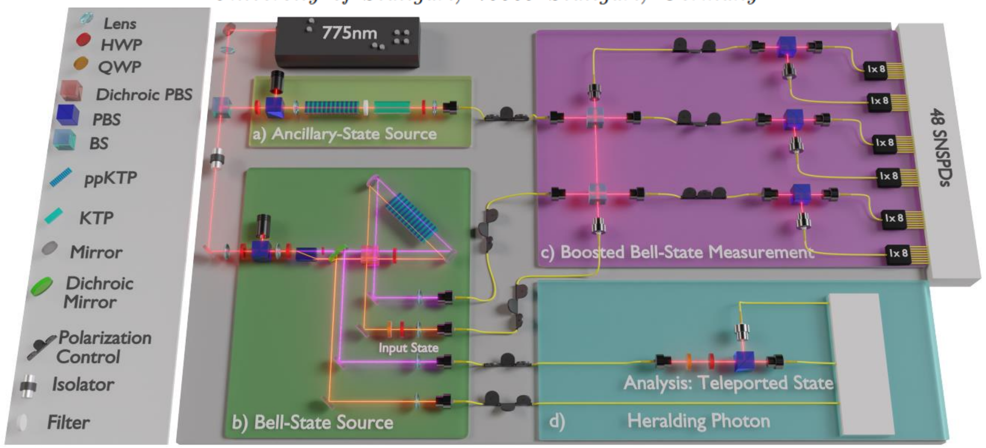

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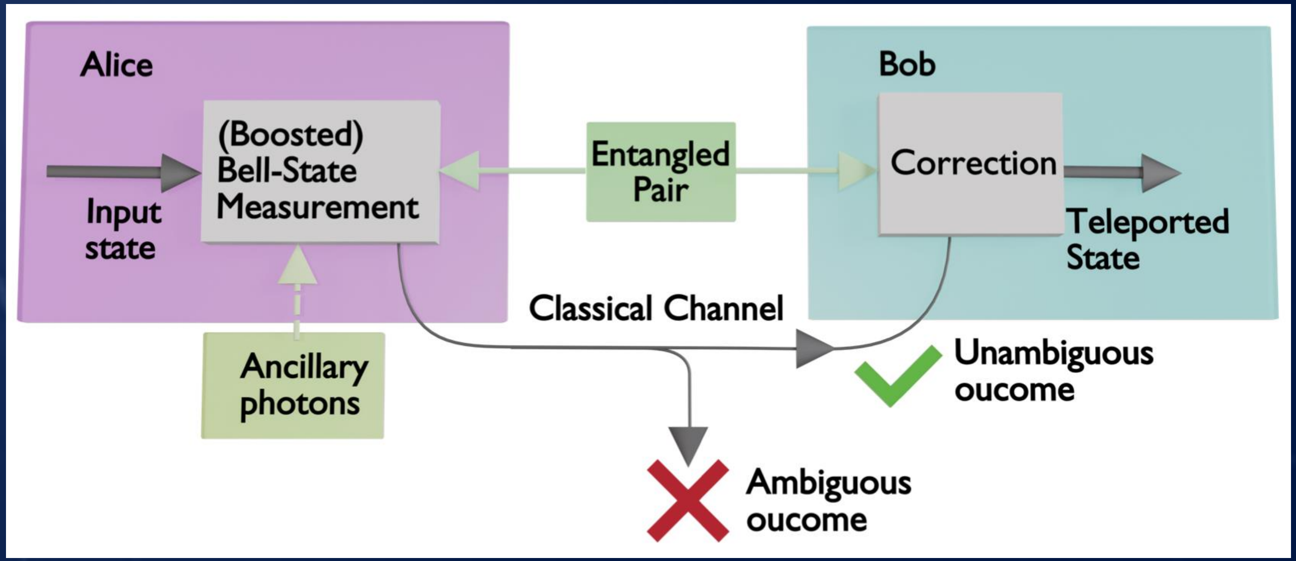


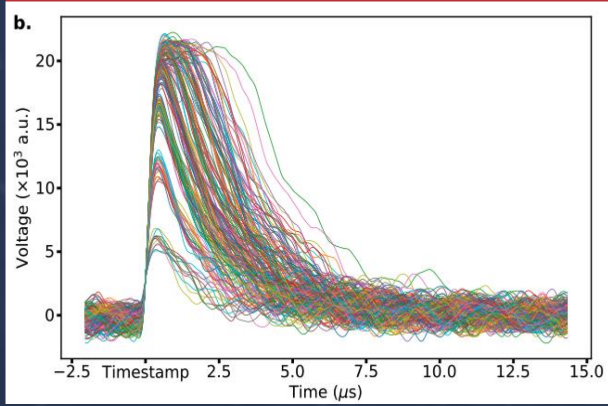
- Bell-state measurement with 69% success probability (compared to 50% theoretical limit) thanks to PNR detectors + ancillary photons

Photon-number resolving detector

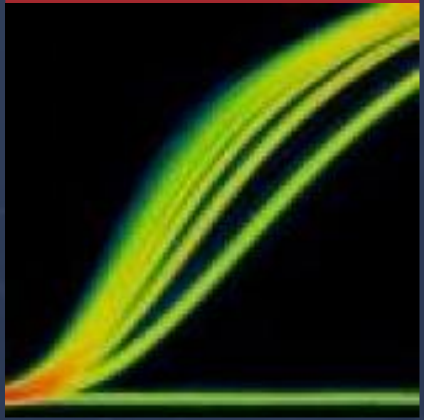
Several approaches

Superconducting Nanowire Single-Photon Detectors

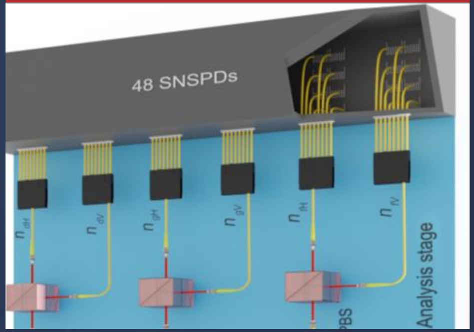
Transition edge sensor



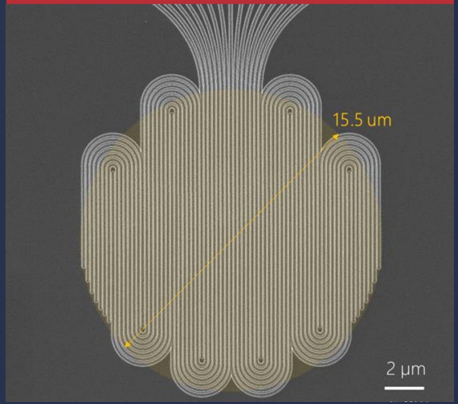
Rising edge SNSPD



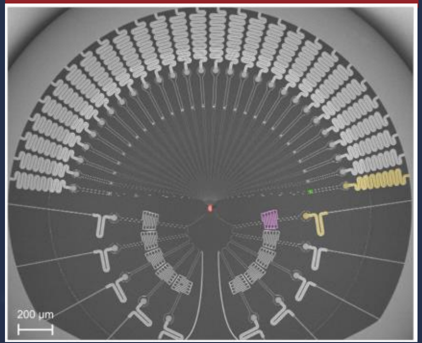
Many SNSPD with beam splitter



Independent multi-pixel array



Parallel SNSPD



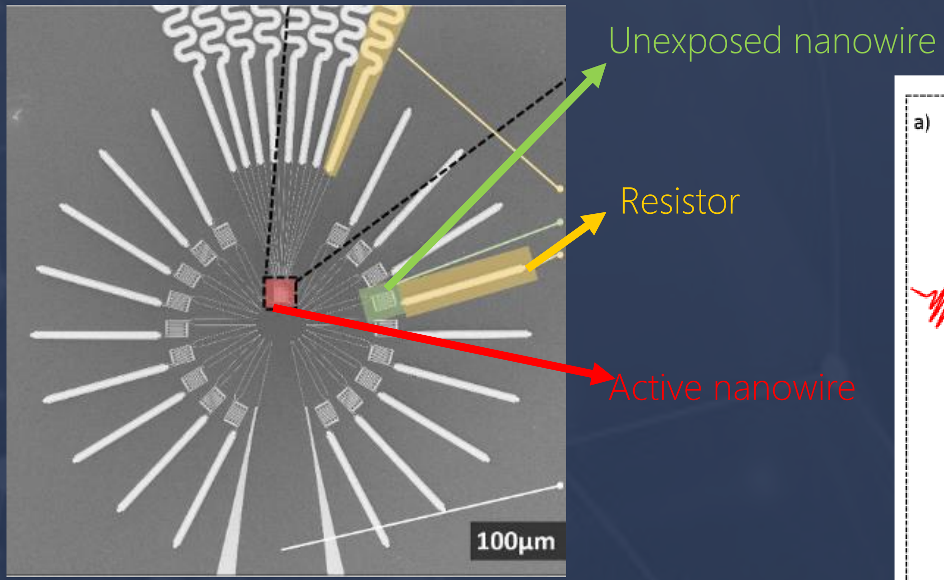
Morais, L. A. et al., *Quantum* 8, 1355 (2024)
Endo, M. et al. Opt. Exp. 29, 11728-11738 (2021)

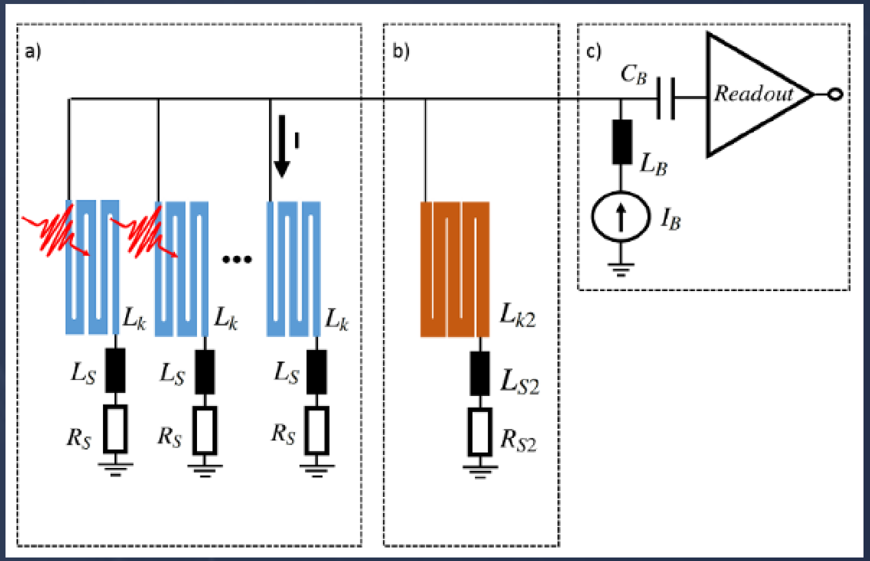
Bayerbach, M. J. et al., *Sci. Adv.* 9, eadf4080 (2023)
Resta, G. V. et al., *Nano Letters* 23, 6018–6026 (2023)
Stasi, L. et al, arXiv:2406.15312 (2024)

Parallel SNSPDs (P-SNSPDs)

Unique patented architecture

In collaboration with UNIVERSITÉ DE GENÈVE





Additional unexposed nanowire in parallel to minimize current redistribution effect

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

Parallel SNSPDs (P-SNSPDs)

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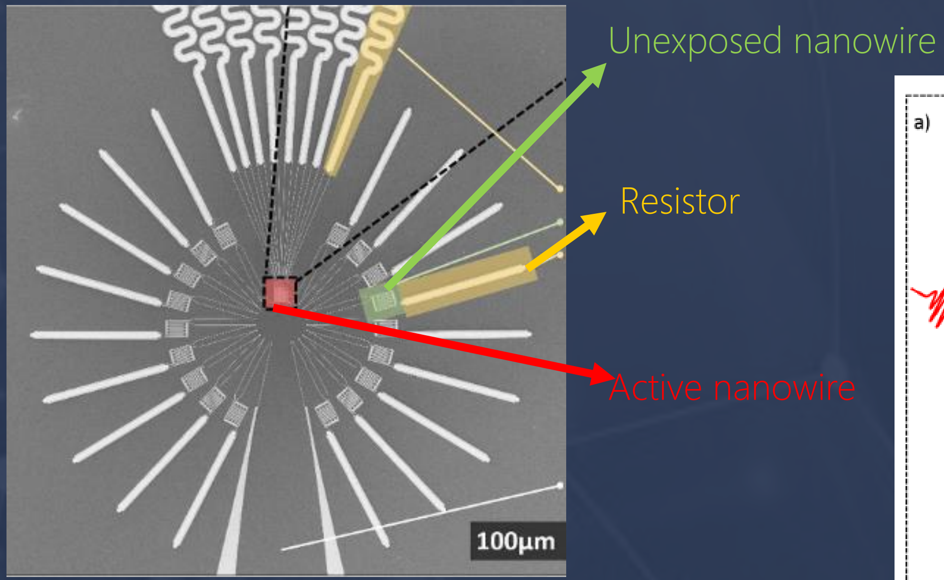

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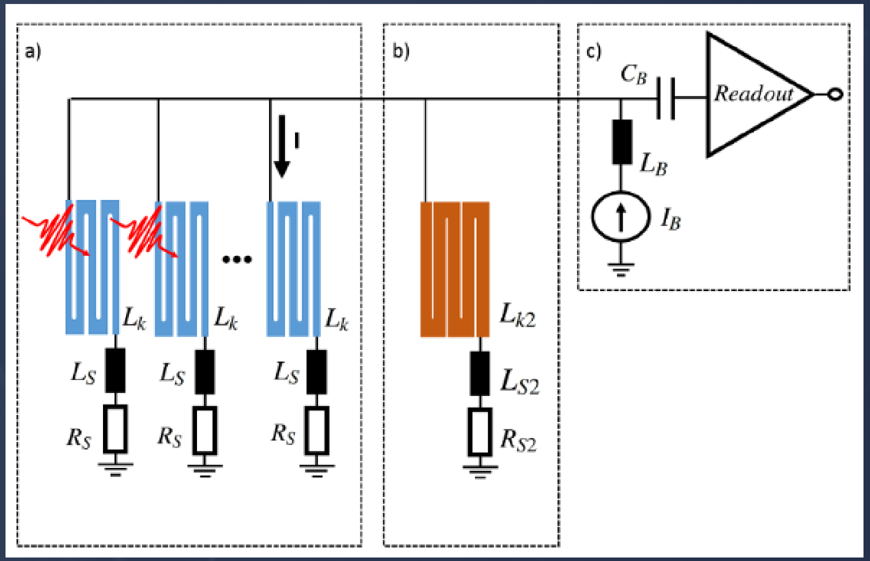
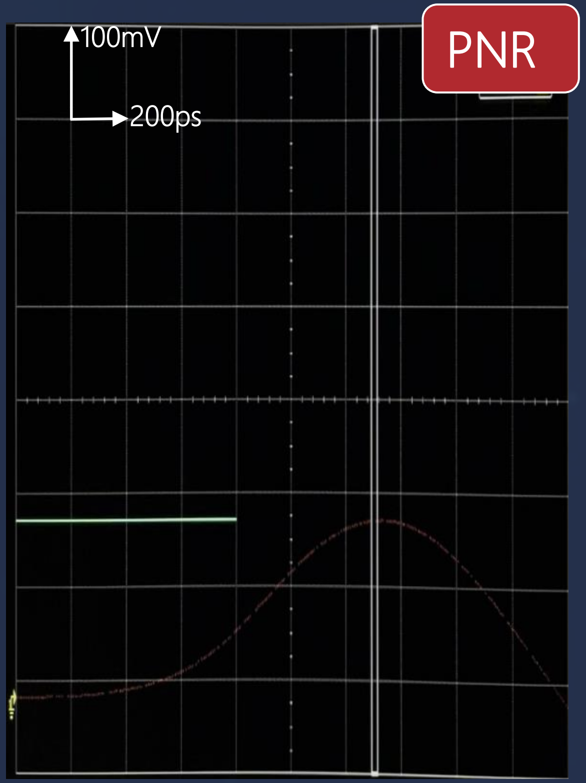




Perrenoud, M., et al. *Superconductor Science and Technology* 34.2 (2021): 024002

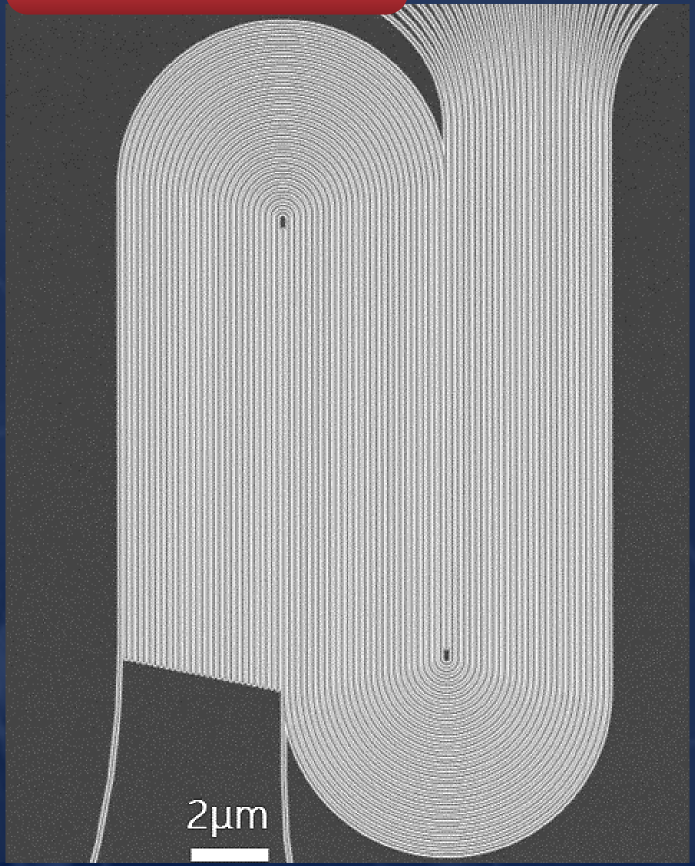
Parallel SNSPDs : a new generation

28 interleaved active pixels

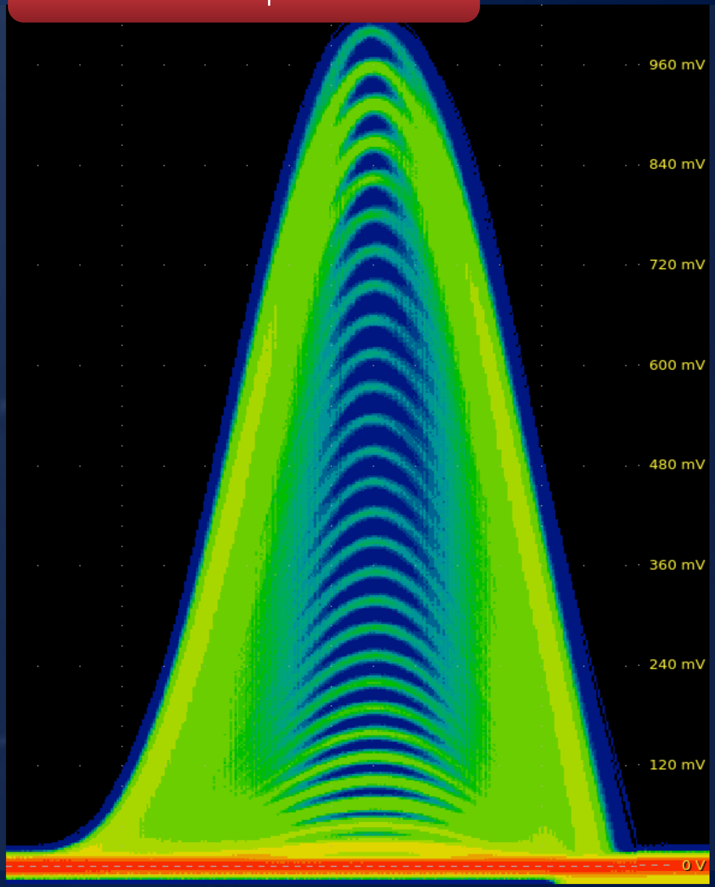
In collaboration with

UNIVERSITÉ DE GENÈVE

SEM image



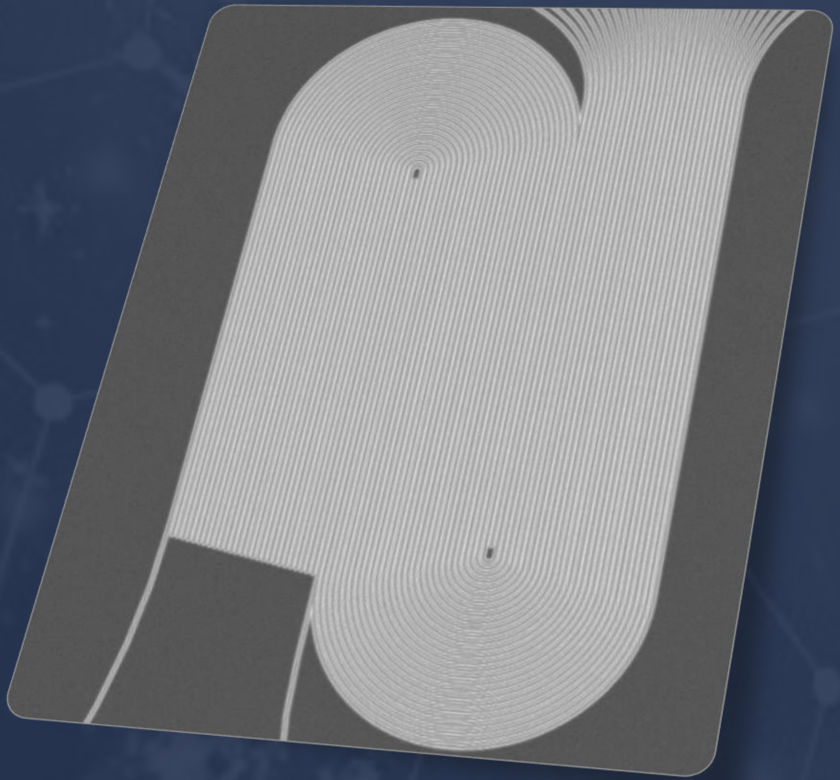
Oscilloscope trace



Parallel SNSPDs : a new generation

28 interleaved active pixels

More pixels is better !



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

In collaboration with UNIVERSITÉ DE GENÈVE

Stasi, L. et al, ACS Photonics 12, 320-329 (2025) - arXiv:2406.15312 (2024)

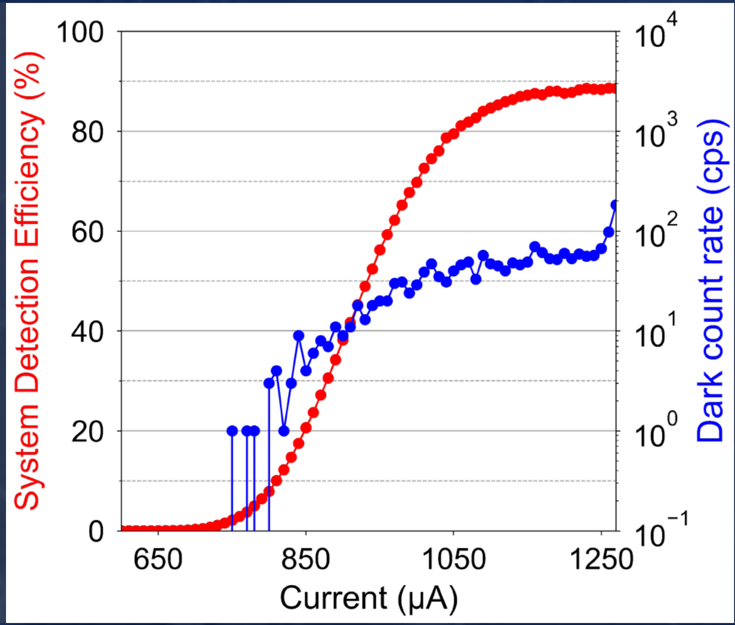
28-pixel P-SNSPD

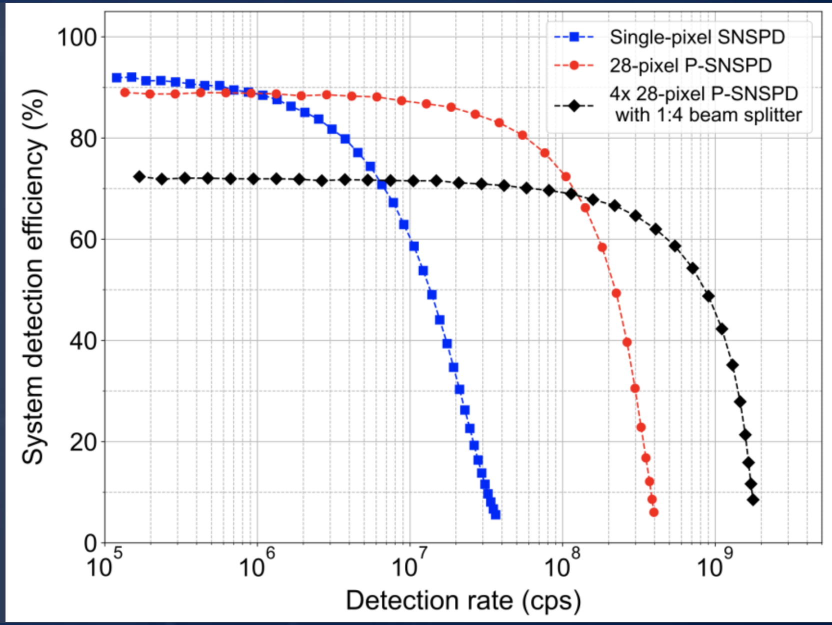
Performances

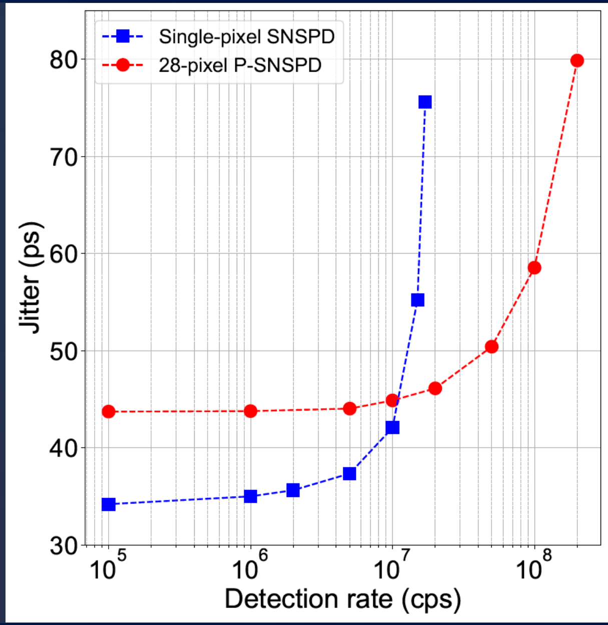
Speed-up the rate of entanglement distribution in quantum networks

Clock distribution

IDQ
In collaboration with
UNIVERSITÉ DE GENÈVE







88% SDE, 1550nm

>200 Mcps @ 50% SDE
> 1 Gcps with 4 devices

Jitter <60 ps @ 100 Mcps

Stasi, L. et al, ACS Photonics 12, 320-329 (2025) - arXiv:2406.15312 (2024)

IDQ's PNR SNSPDs empower ORCA's quantum processors

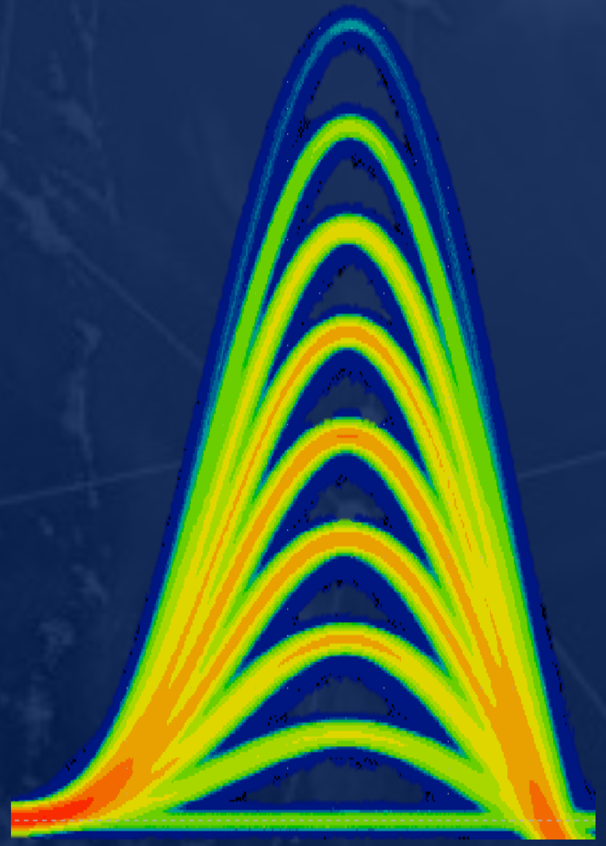
Quantum + AI with near-term usefulness

Near-ideal PNR detectors contribute to

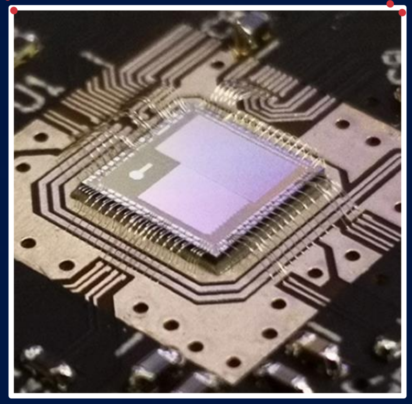
- Reaching/deepening quantum advantage
- Addressing a larger body of computational problems
- Making the processor scalable
- Enabling error-correction and fault-tolerance

Reading out the number of clicks in a single-shot

Two approaches

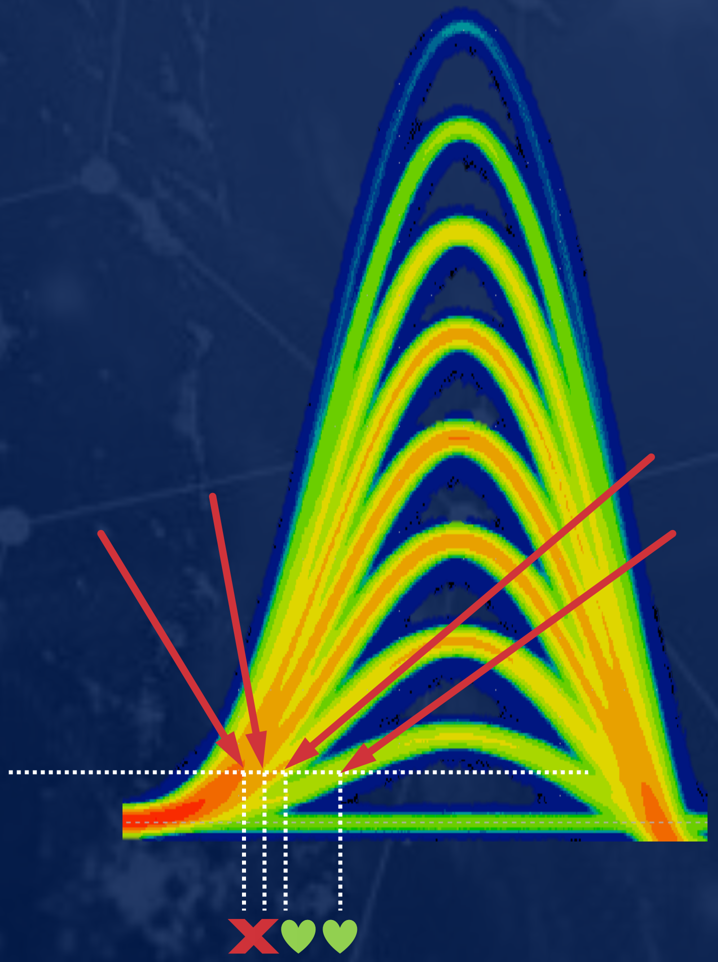


- IDQ's ID1000 time-tagger uses the picoTDC chipset developed by CERN
- 3 ps jitter (start-stop)
- Tool to enable clock recovery in quantum networks



Reading out the number of clicks in a single-shot

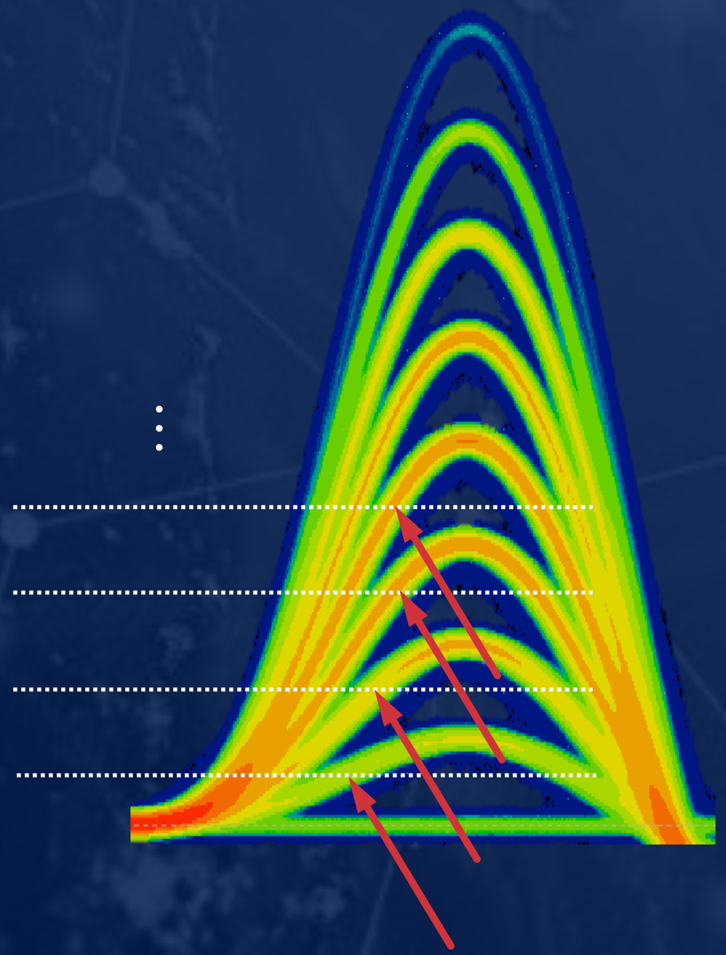
Two approaches

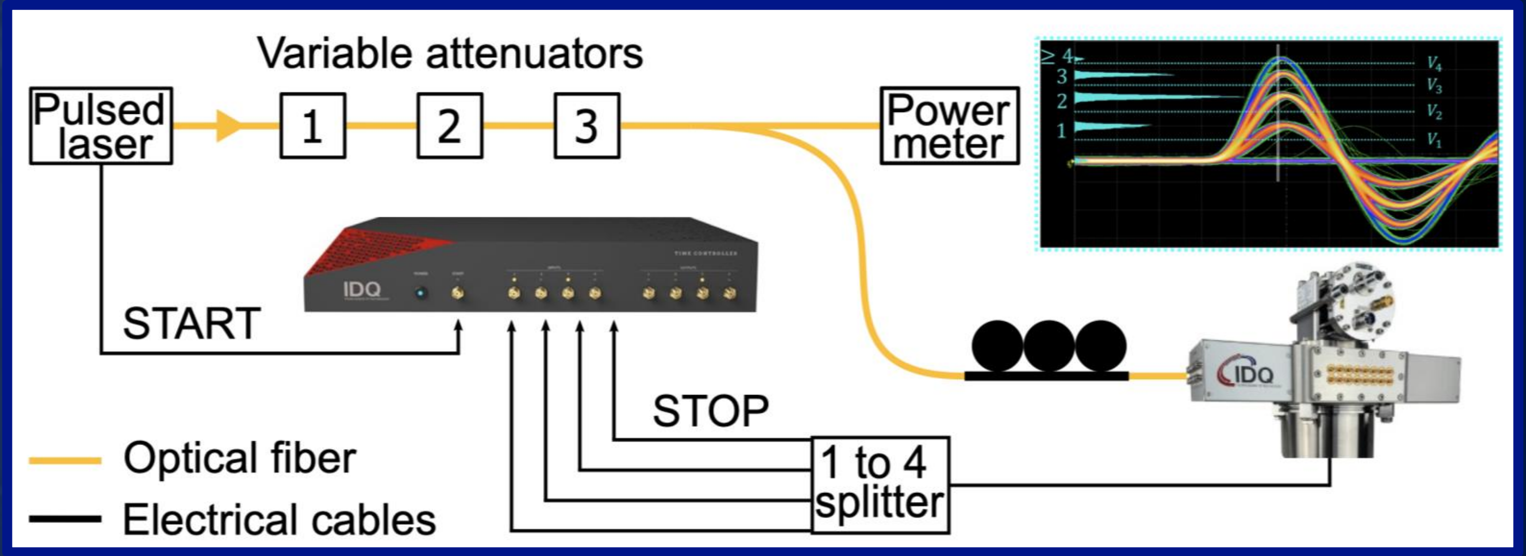


- With a single channel, the 1 and 2 click-levels can be registered well, but beyond the signals start to “meld” into each other

Reading out the number of clicks in a single-shot

Two approaches

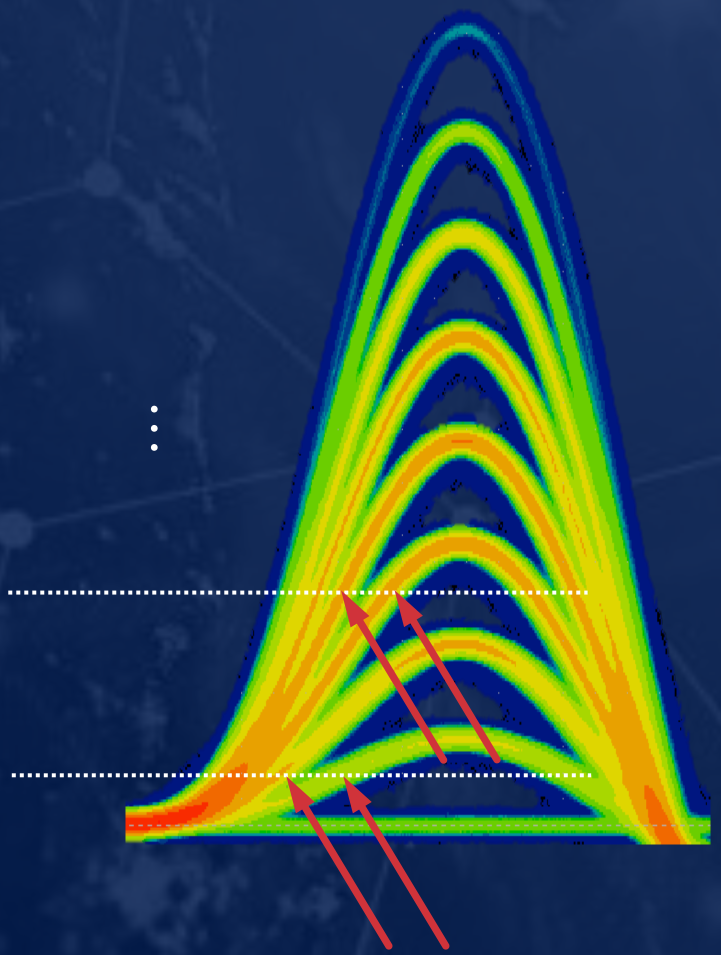


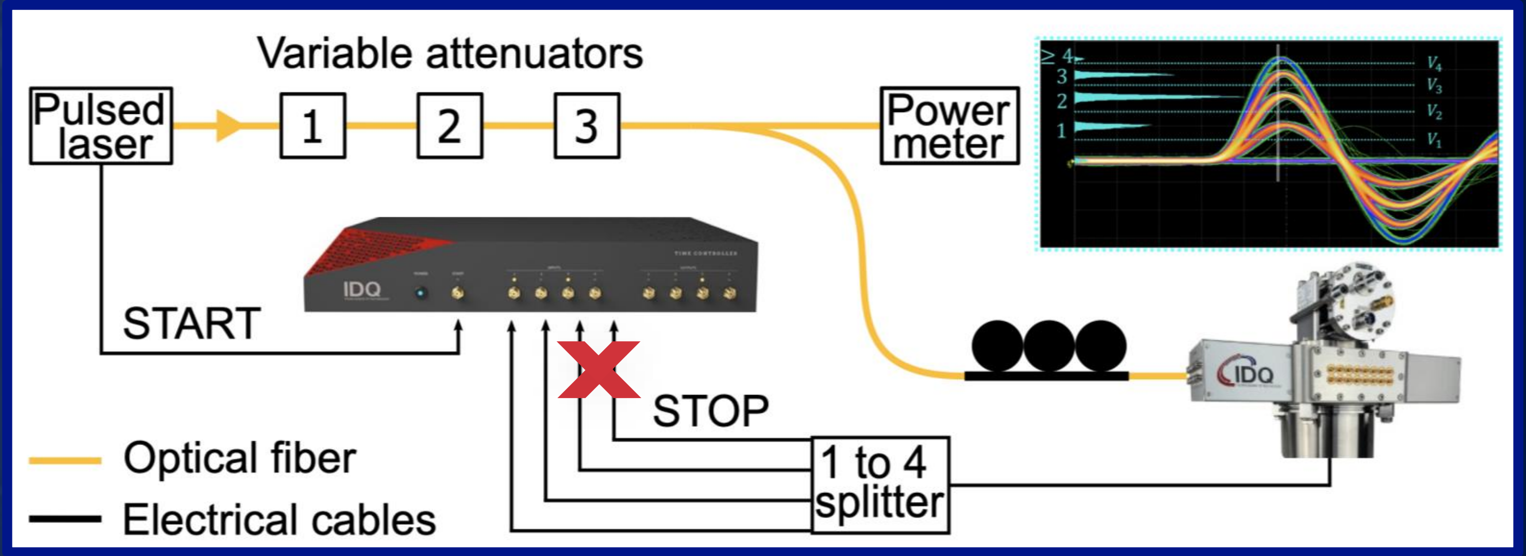


- Splitting the signal into 4 copies allows for a perfect assignment of the number of clicks
- Works perfectly for up to 8 clicks or more
- Great tool for guessing the right number of photons with great accuracy!

Reading out the number of clicks in a single-shot

Two approaches





- Splitting the signal in 2 copies + rise-time provides a near-perfect assignment of 1, 2, 3 and 4 clicks with only two time-tagging channels

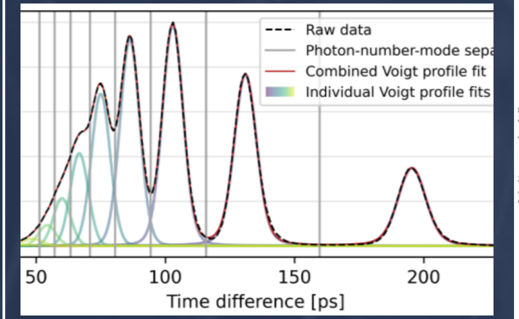
Ideal PNR detectors

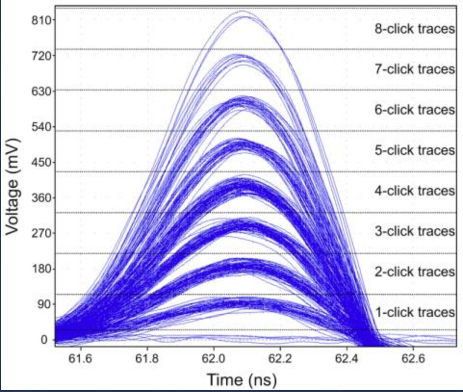
Suggested requirements

In collaboration with UNIVERSITÉ DE GENÈVE

Properties

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



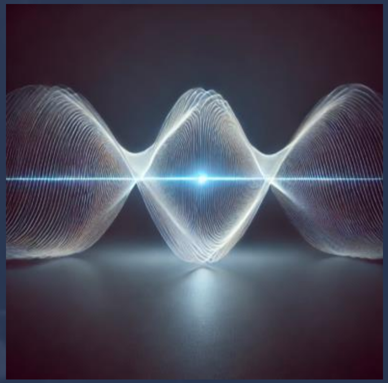


Features

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)

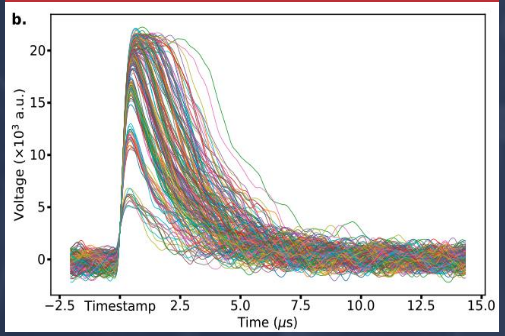
1) n-photon efficiencies

In collaboration with

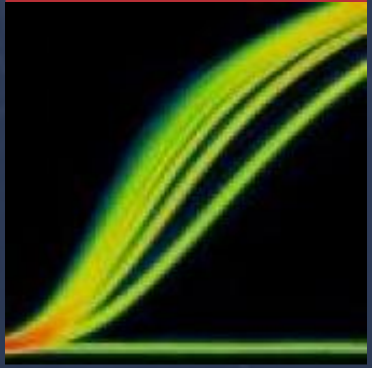
Intrinsic capability

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

Transition edge sensor



Rising edge SNSPD

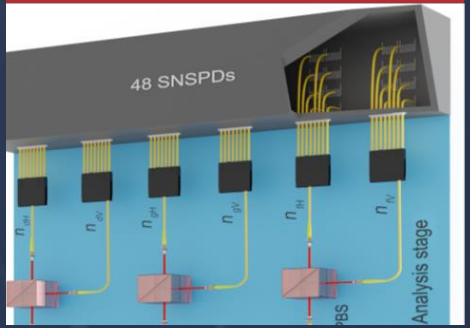


Morais, L. A. et al., *Quantum* 8, 1355 (2024)
Endo, M. et al. Opt. Exp. 29, 11728-11738 (2021)

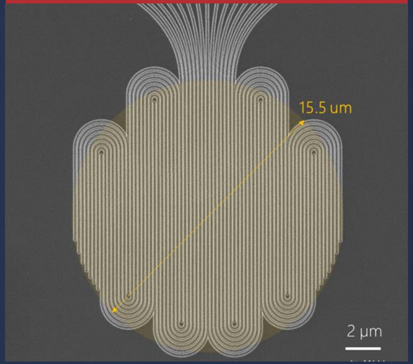
Multipixel scheme with SNSPD

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

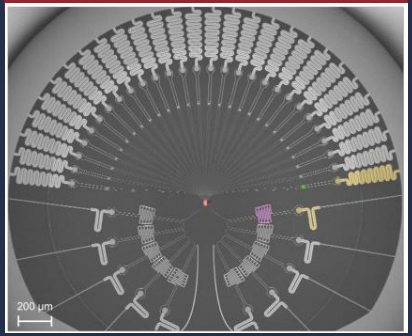
Many SNSPD with beam splitter



Independent multi-pixel array



Parallel SNSPD



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, ACS Photonics 12, 320-329 (2025) - arXiv:2406.15312 (2024)

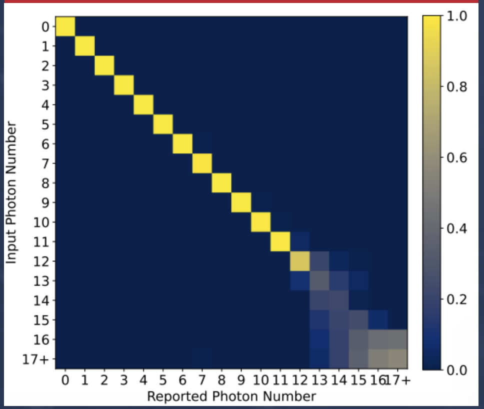
2) 100% assignment probability at any n-click event

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

In collaboration with

Intrinsic capability

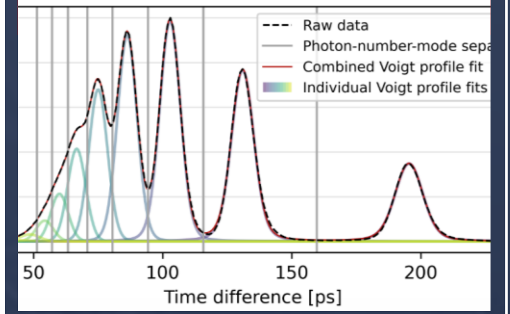
Transition edge sensor



Up to 10 photons

Signal digitalization and postprocessing

Rising edge SNSPD

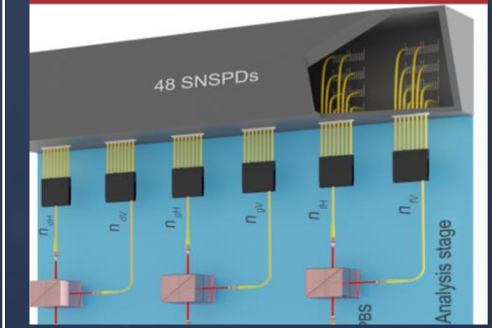


Up to 4 photons

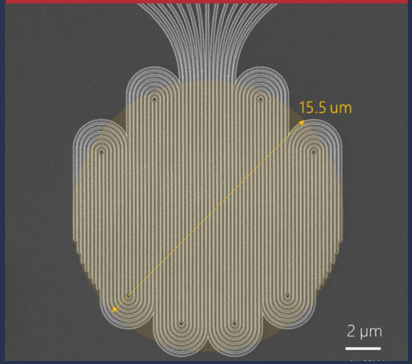
Low jitter electronics and low jitter detector/slow rise time

Multipixel scheme with SNSPD

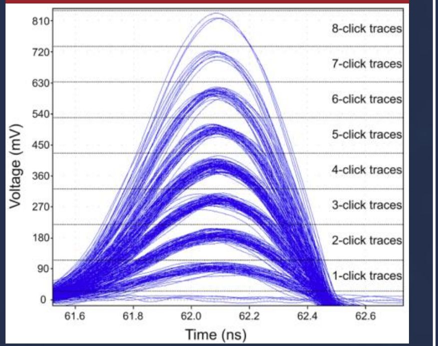
Many SNSPD with beam splitter



Independent multi-pixel array



Parallel SNSPD



ALWAYS VERIFIED

n-photon efficiency

Comparison between different PNR approaches

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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*							
28-pixel P-SNSPD	90							
Intrinsic PNR**	90							

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

n-photon efficiency

Comparison between different PNR approaches

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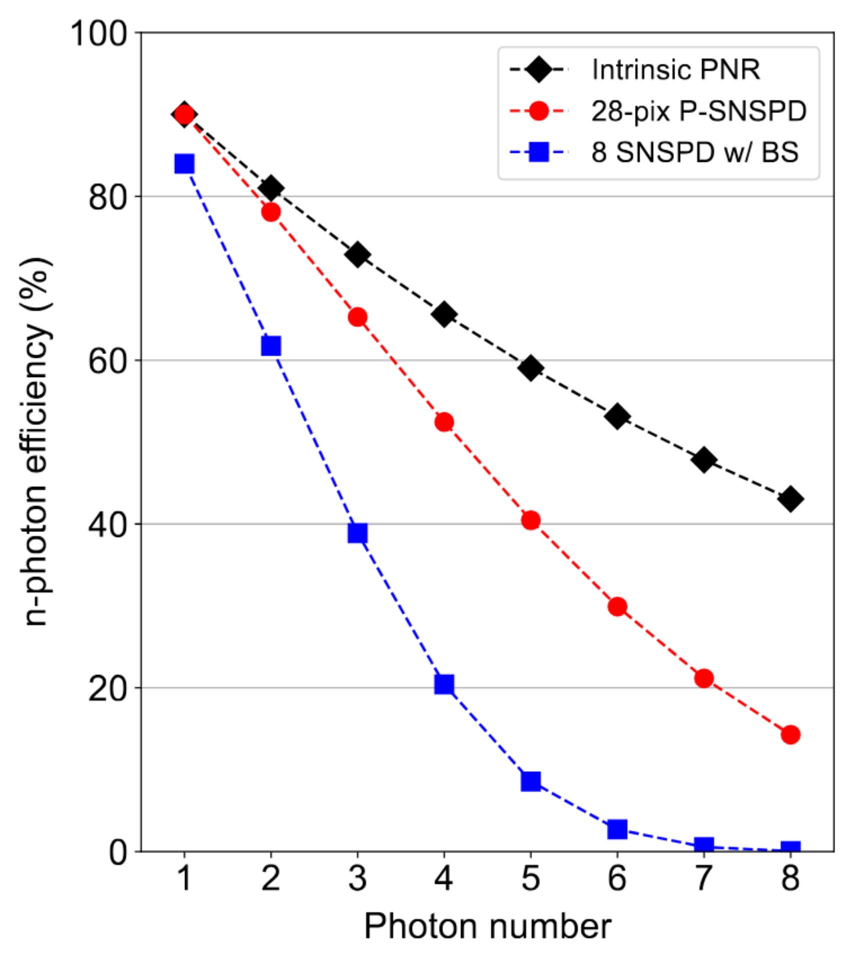

Detector	n-photon efficiency							
	1-ph	2-ph	3-ph	4-ph	5-ph	6-ph	7-ph	8-ph
8 SNSPD w/ BS	84*	61.7	38.9	20.41	8.6	2.7	0.57	0.1
28-pixel P-SNSPD	90	78.1	65.3	52.4	40.5	29.9	21.1	14.3
Intrinsic PNR**	90	81	72.9	65.6	59.1	53.1	47.8	43.1

* 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)

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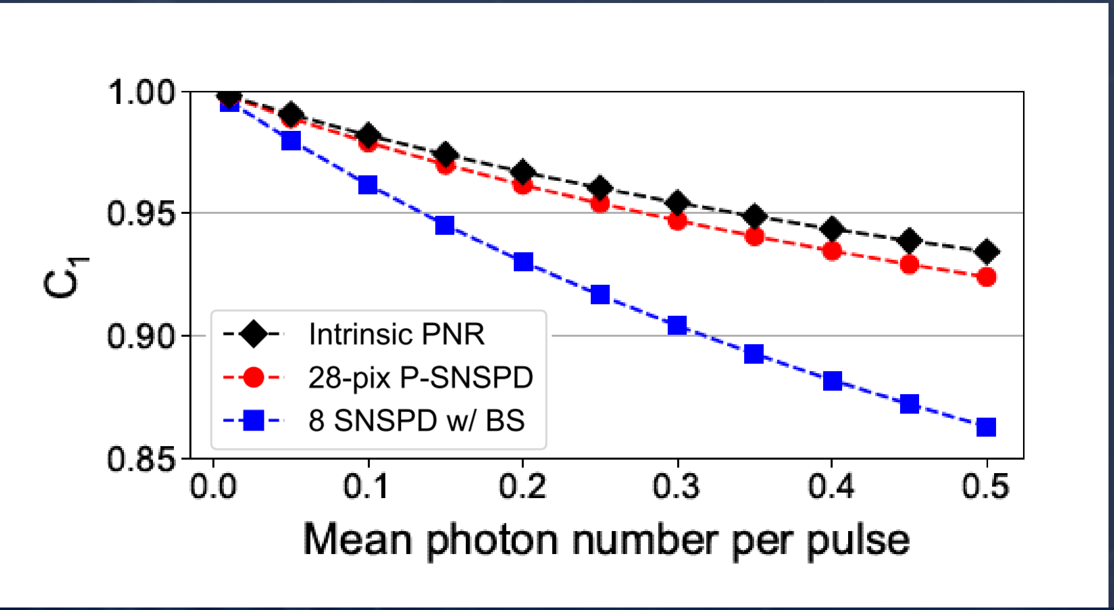
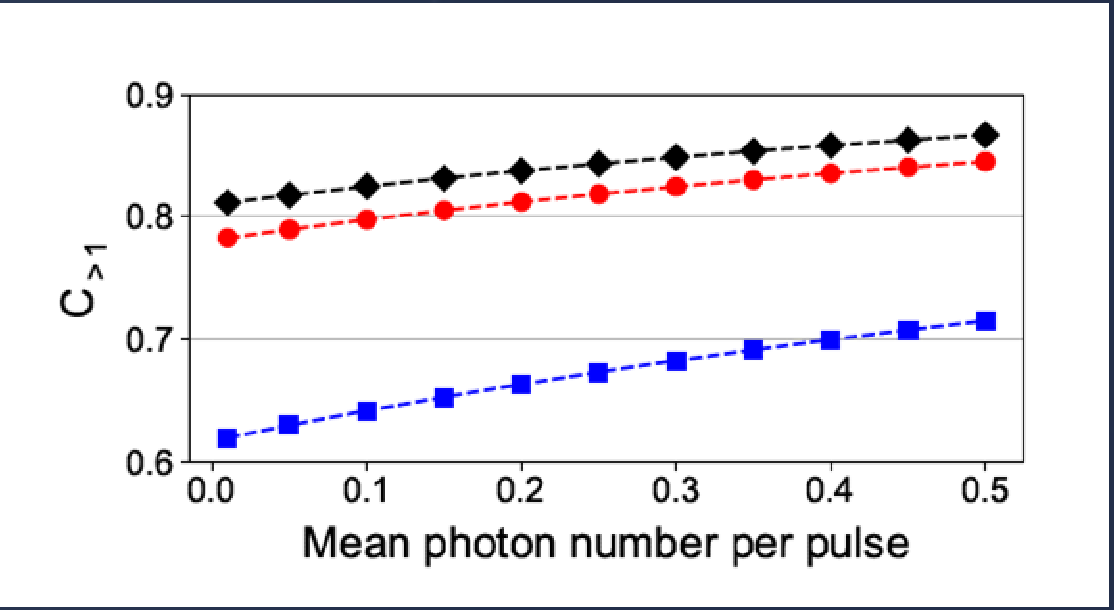
What is the probability that given a 1-click event there were 1-photons in the input state?

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

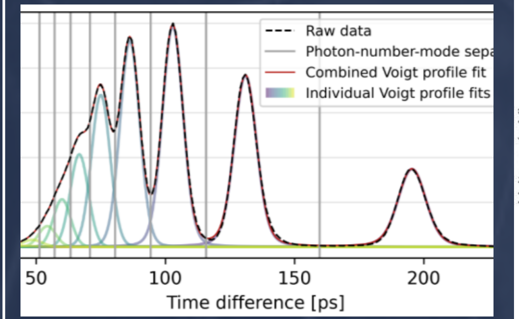


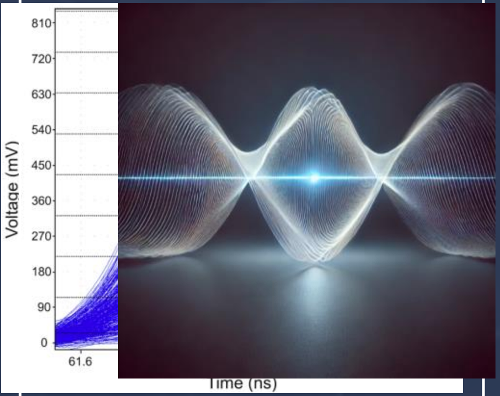


Ideal PNR detectors

Suggested requirements

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

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

Features - TES

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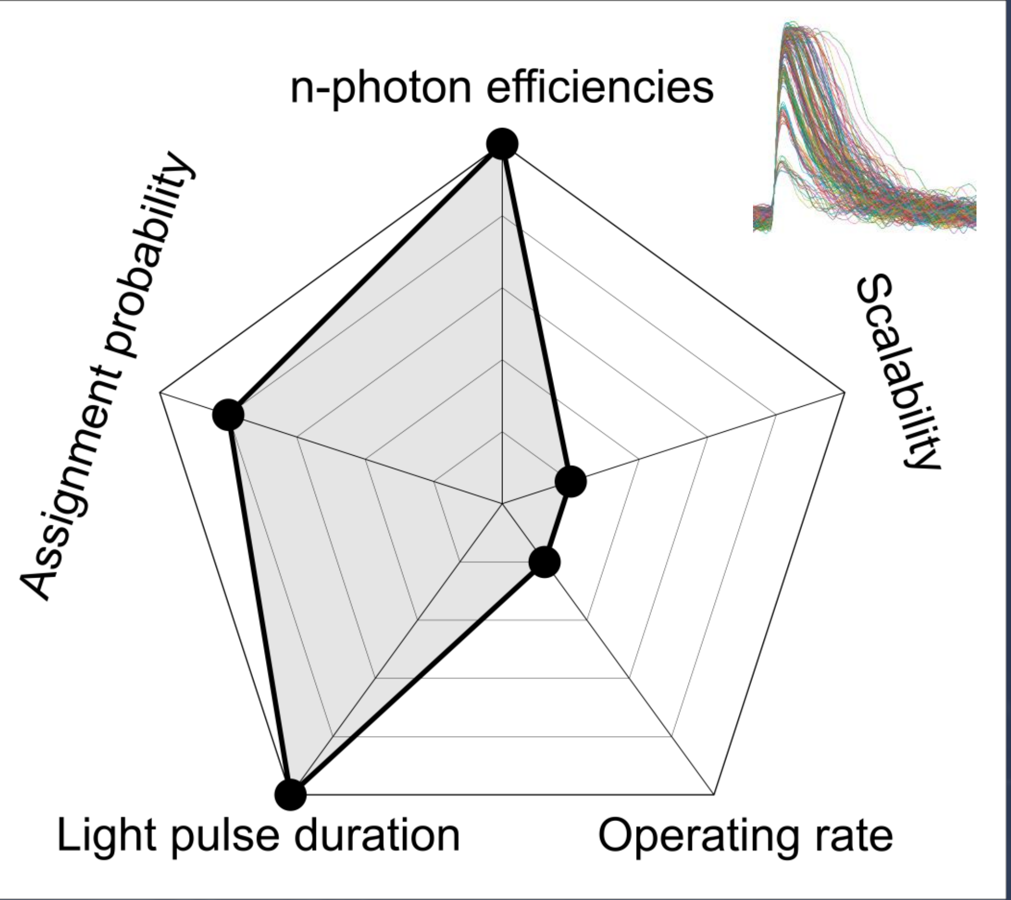
Transition edge sensor



- 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

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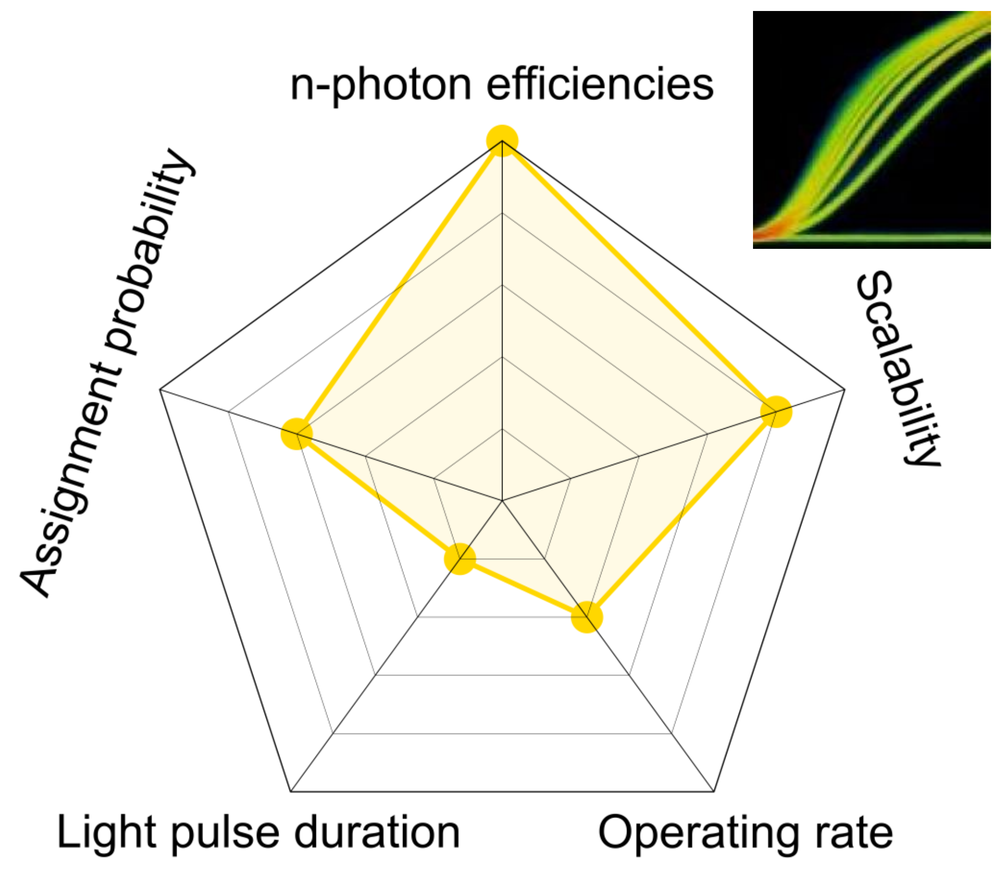
Rising edge SNSPD



- Limited to few 10s of 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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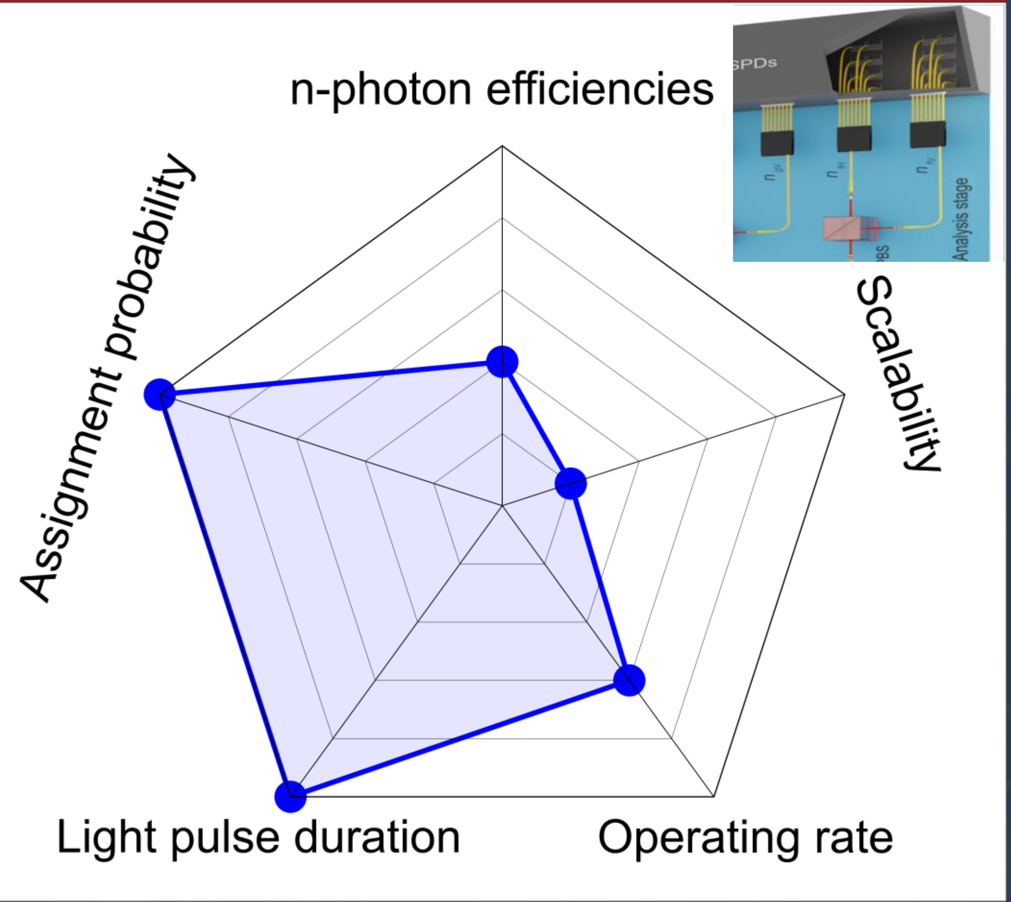
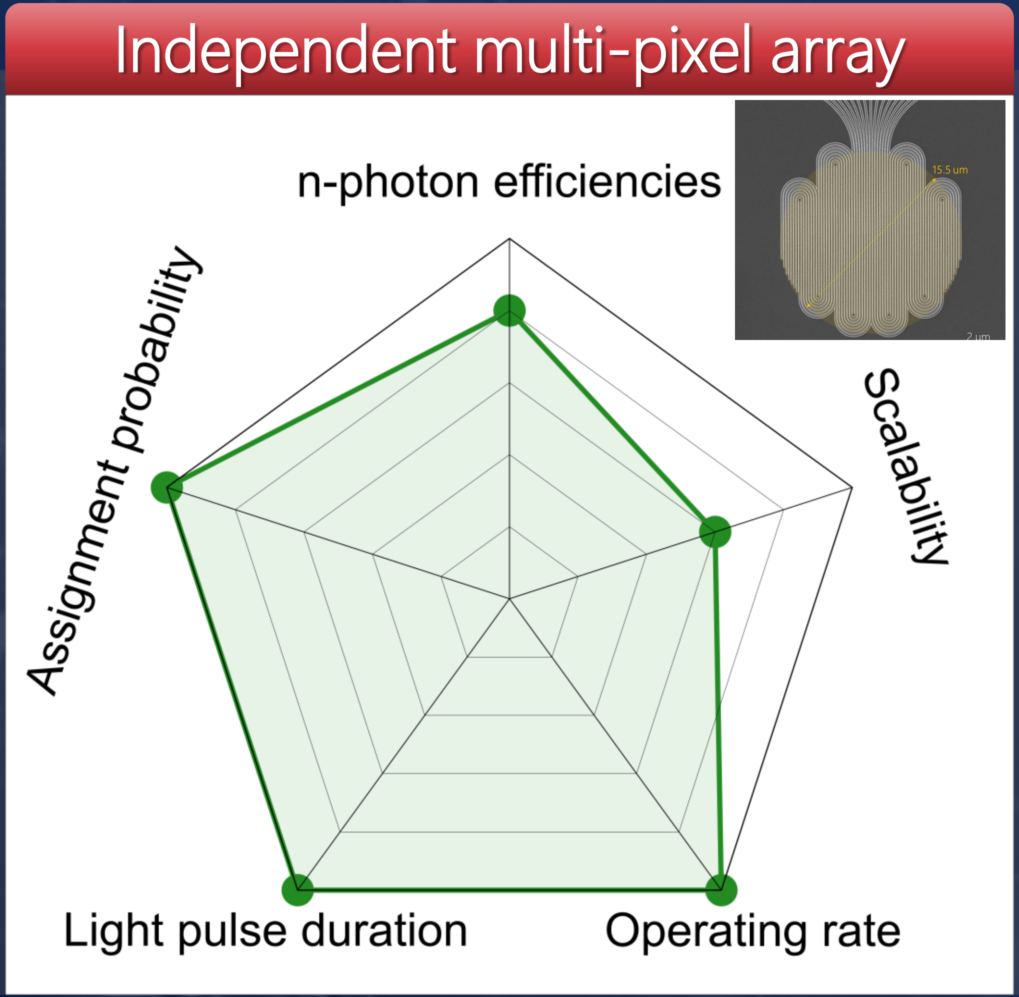
SNSPDs w/ optical BS



- 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



- 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

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Features – Parallel SNSPD

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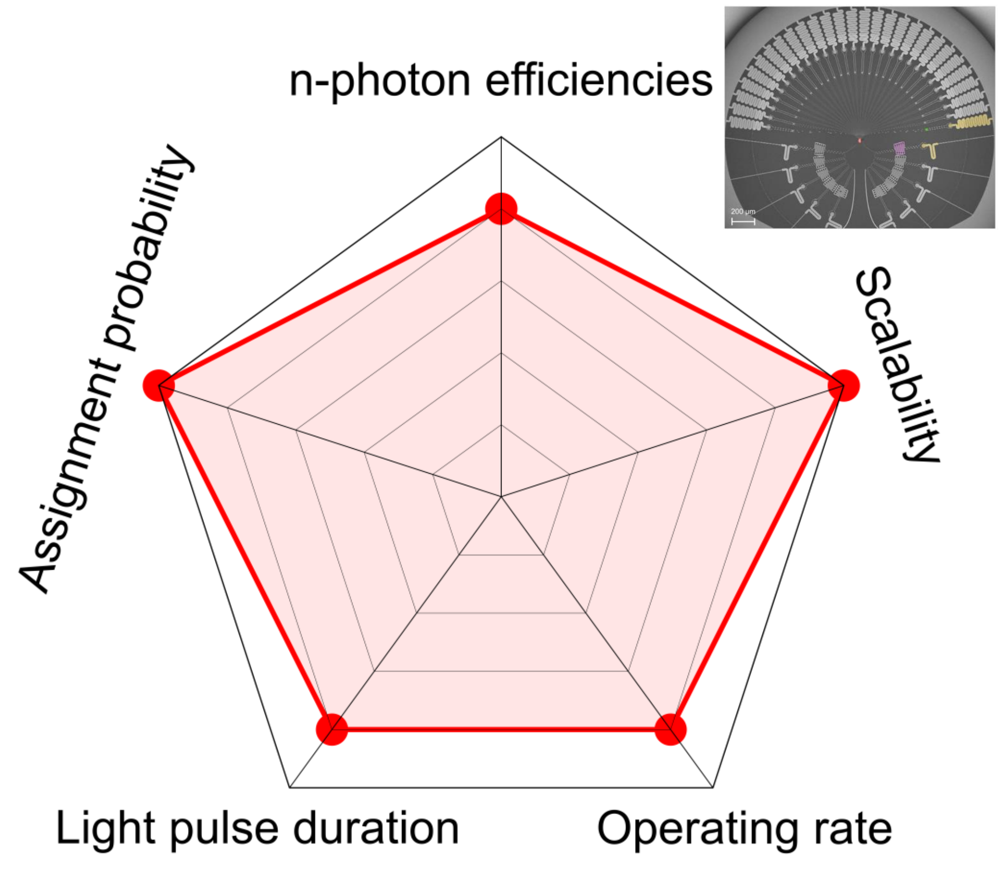
P-SNSPD



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

[1] Stasi, L. et al, ACS Photonics 12, 320-329 (2025) - arXiv:2406.15312 (2024)

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

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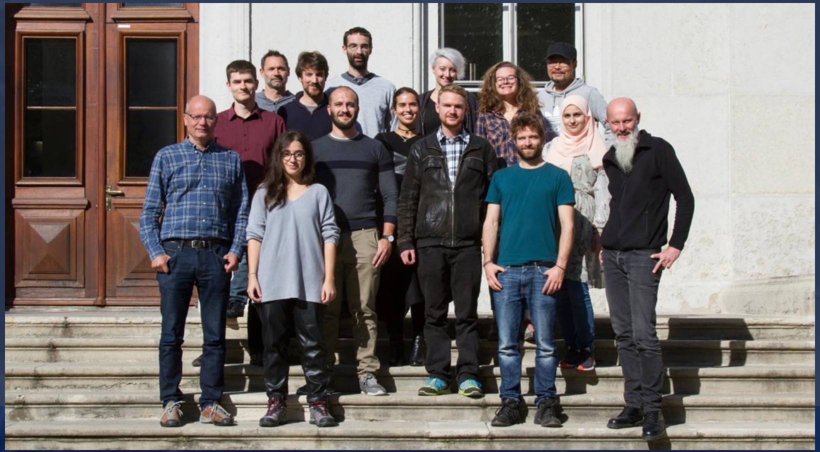

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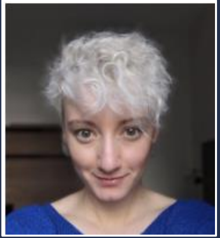
Tiff Brydges


Patrik Caspar

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

Thanks!

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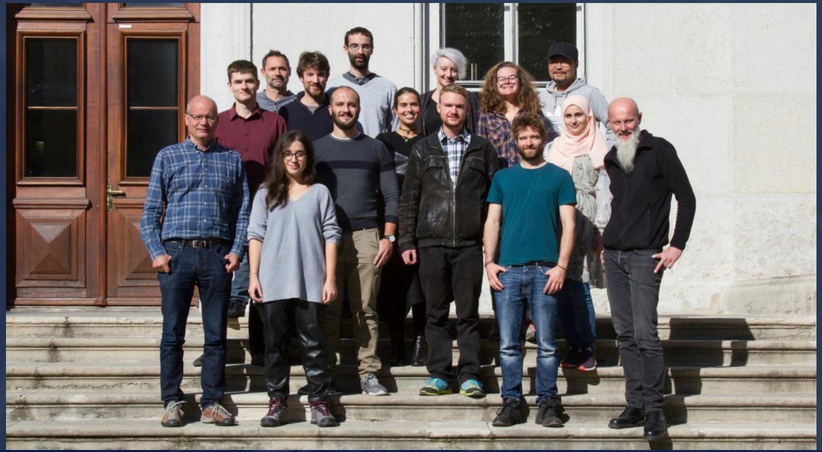

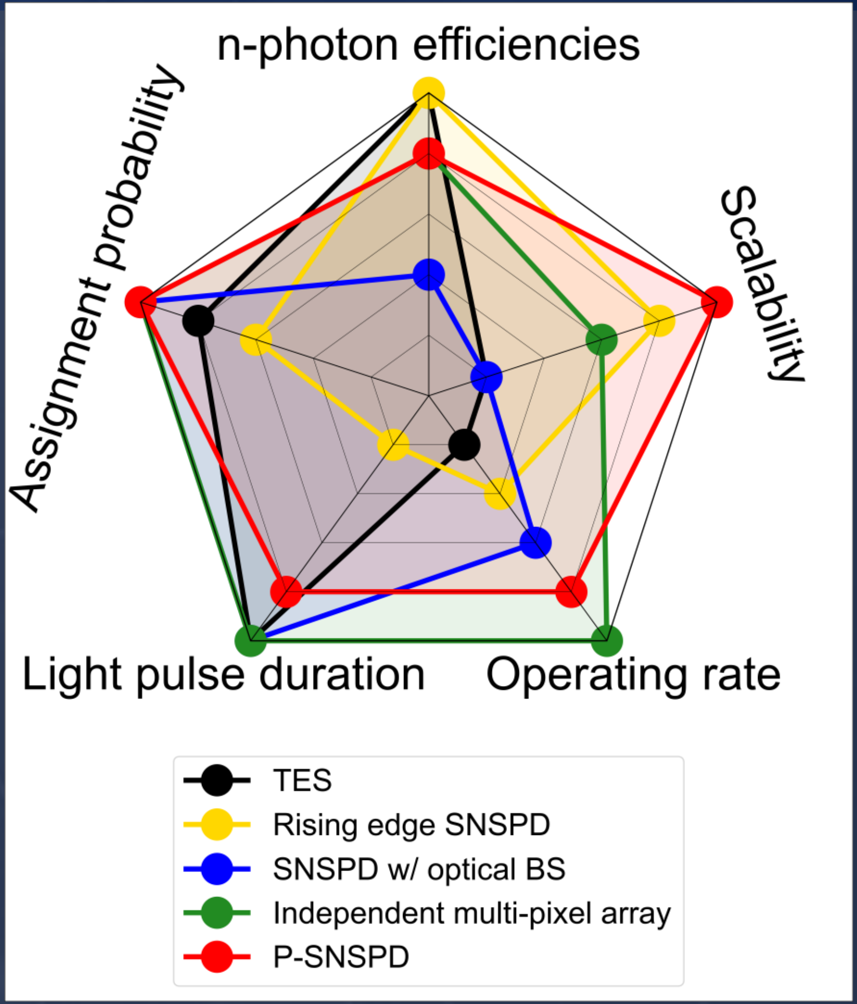

Advantages of P-SNSPDs for quantum networks

- Speeding up entanglement distribution
- "Boosted" BSM with PNR
- Clock distribution at high rates

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