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IEEE 16th Workshop on Low Temperature Electronics
WOLTE16
Cagliari, Sardinia, Italy | June 3-6, 2024

Superconducting
Photonic
Quantum
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Photon Number Resolving Superconducting Nanowire Single-Photon Detectors

Marco Colangelo
Electrical and Computer Engineering
Nano System Innovation Institute
Northeastern University

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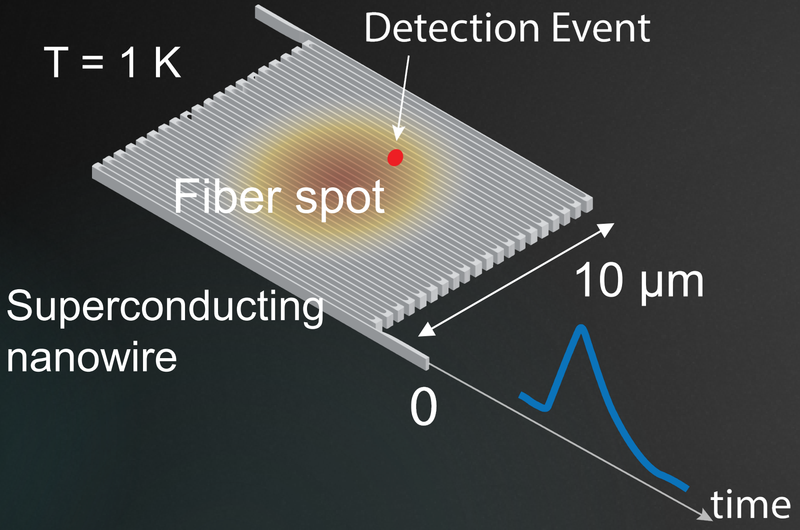
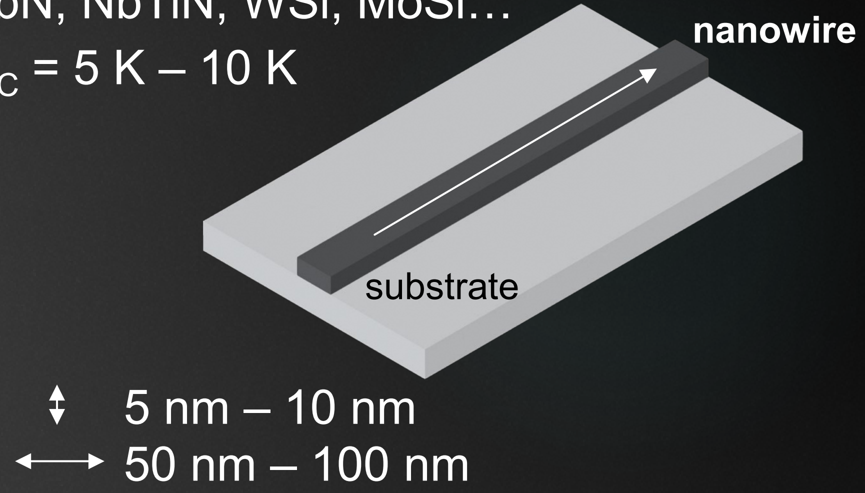
Superconducting nanowire single-photon detectors (SNSPD)



NbN, NbTiN, WSi, MoSi…

T_C = 5 K – 10 K



↕ 5 nm – 10 nm

↔ 50 nm – 100 nm

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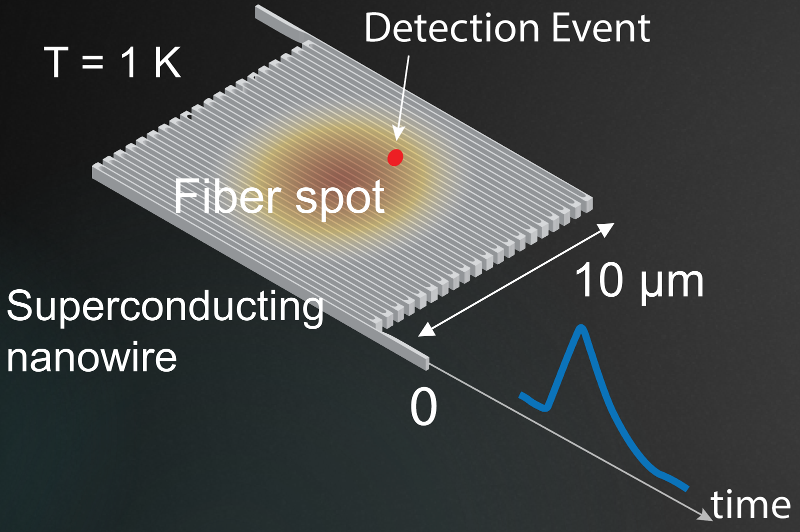

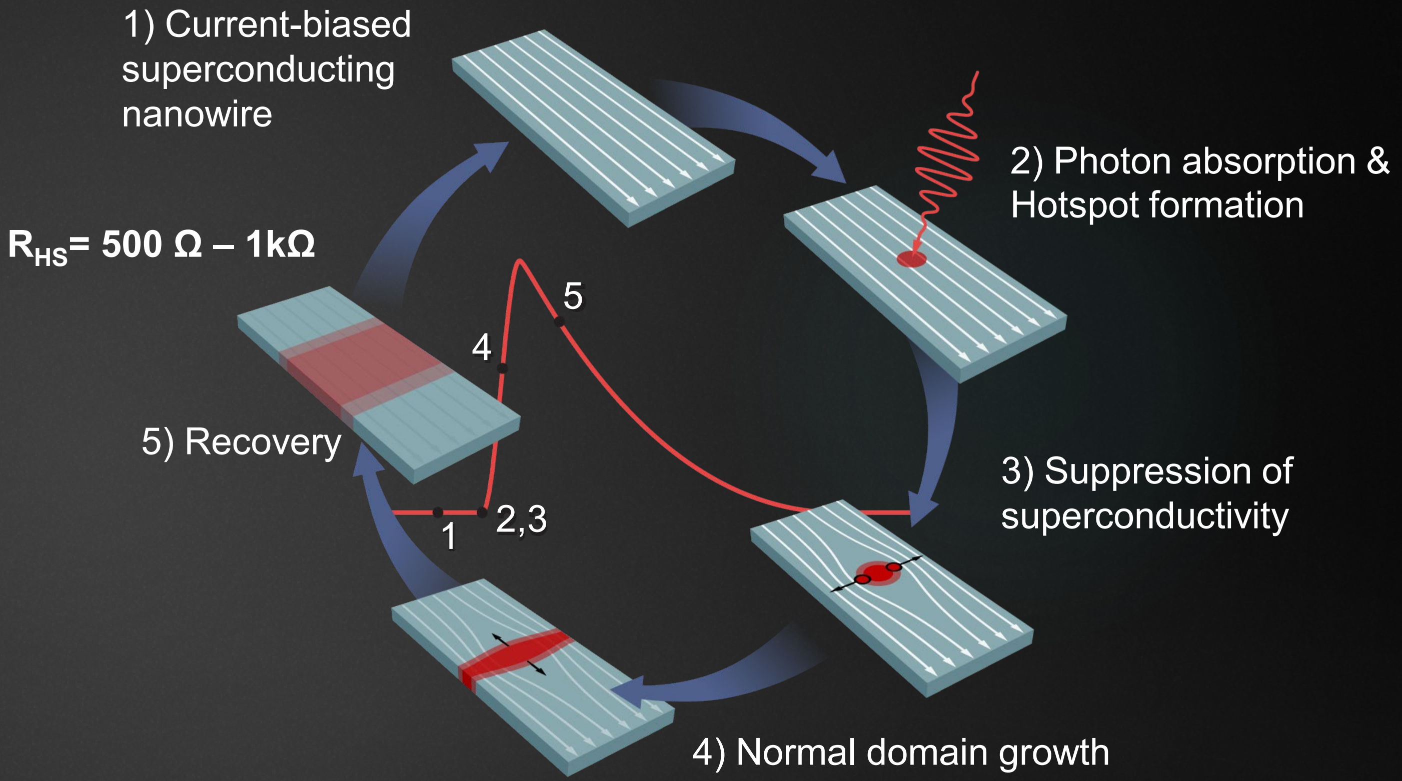

Allmaras et al., Physical Review Applied 11.3 (2019): 034062.
Allmaras et al. Diss. Caltech, 2020.

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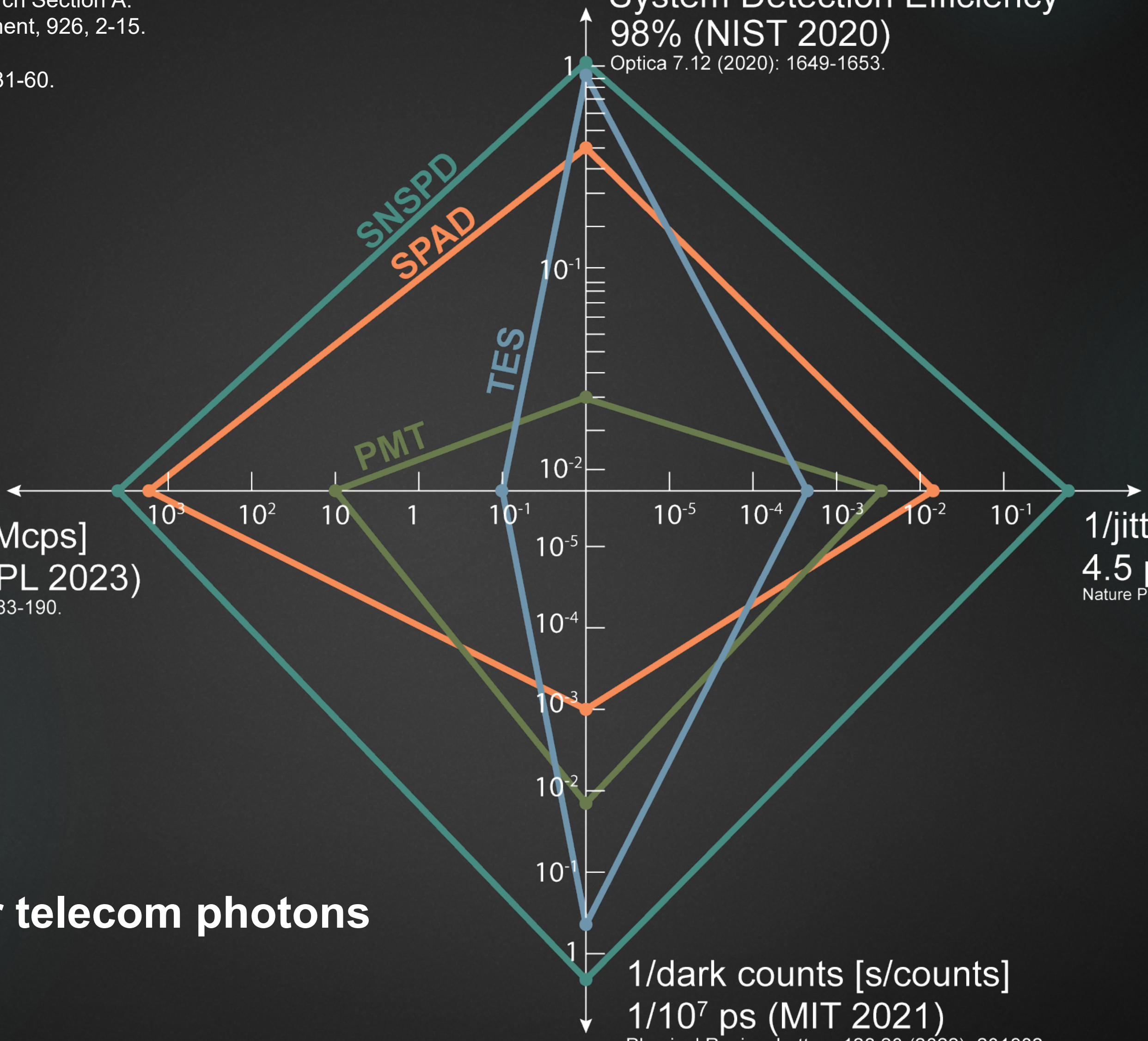
SNSPD performance metrics

PMT data: Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 926, 2-15.
SPAD data: Chip (2022): 100005.
TES data: Superconducting devices in quantum optics (2016): 31-60.
Other missing data: Nature photonics 3.12 (2009): 696-705.



System Detection Efficiency
98% (NIST 2020)
Optica 7.12 (2020): 1649-1653.

count rate [Mcps]
1.5 Gcps (JPL 2023)
Optica 10.2 (2023): 183-190.

1/jitter [ps^{-1}]
4.5 ps (MIT/JPL 2019)
Nature Photonics 14.4 (2020): 250-255.

1/dark counts [s/counts]
1/10^{7} ps (MIT 2021)
Physical Review Letters 128.23 (2022): 231802.

Best detection technology for telecom photons

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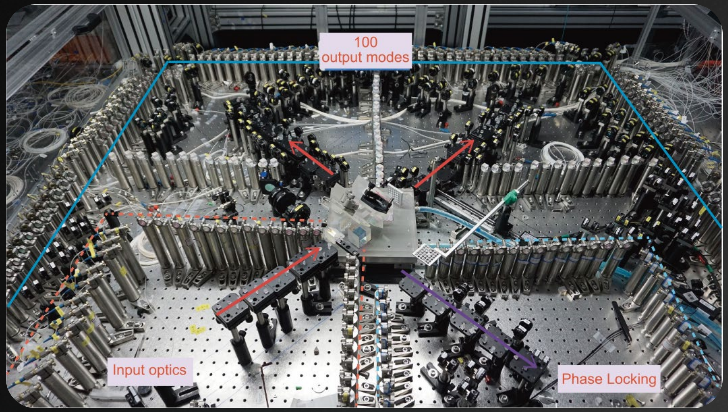
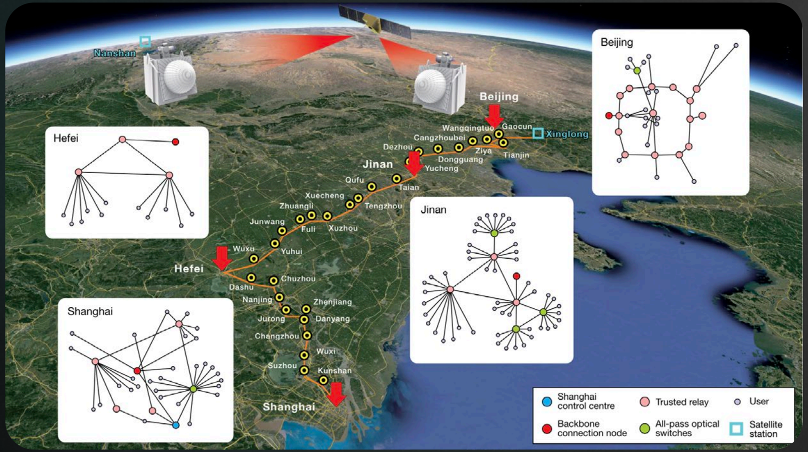
Application of SNSPDs

Photonic Quantum Computing



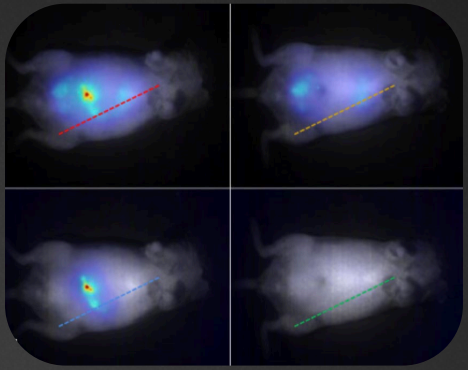
Science 370.6523 (2020): 1460-1463.

Quantum Networks and Repeaters



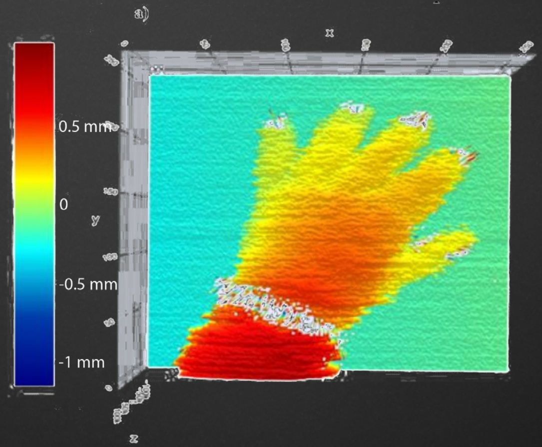
Nature 589.7841 (2021): 214-219.

Biomedical applications



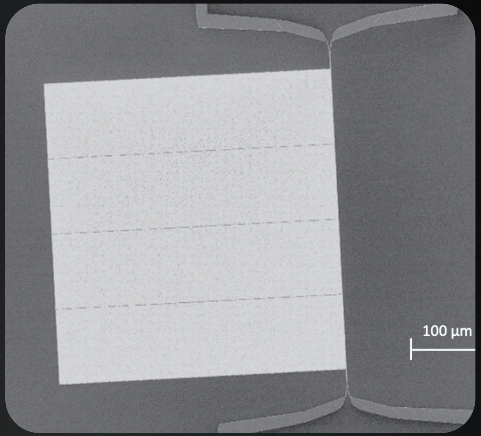
ACS nano, *16*(8), 12930-12940.

Single-photon LIDAR



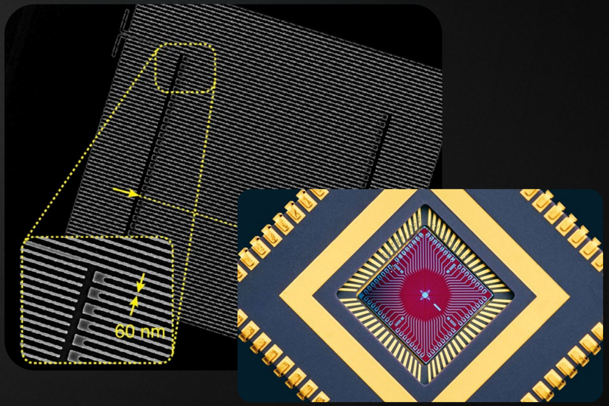
In CLEO 2020 - SM2M-6. Optica Publishing Group.

High-energy physics



Physical Review D 106.11 (2022): 112005.

Environmental sensing and space applications (DSOC)



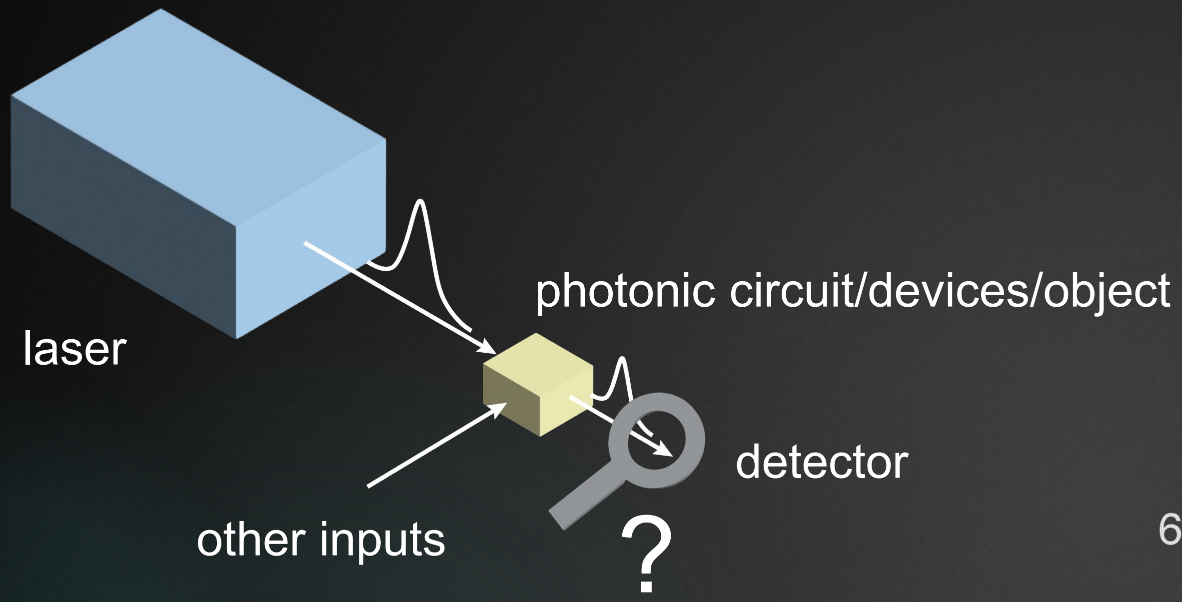
Nano Letters 22.14 (2022): 5667-5673

www.nasa.gov/mission/deep-space-optical-communications-dsoc/

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 56 Sept 2024. Presentation given at WOLTE-16 2024, June 2024, Cagliari, Italy.

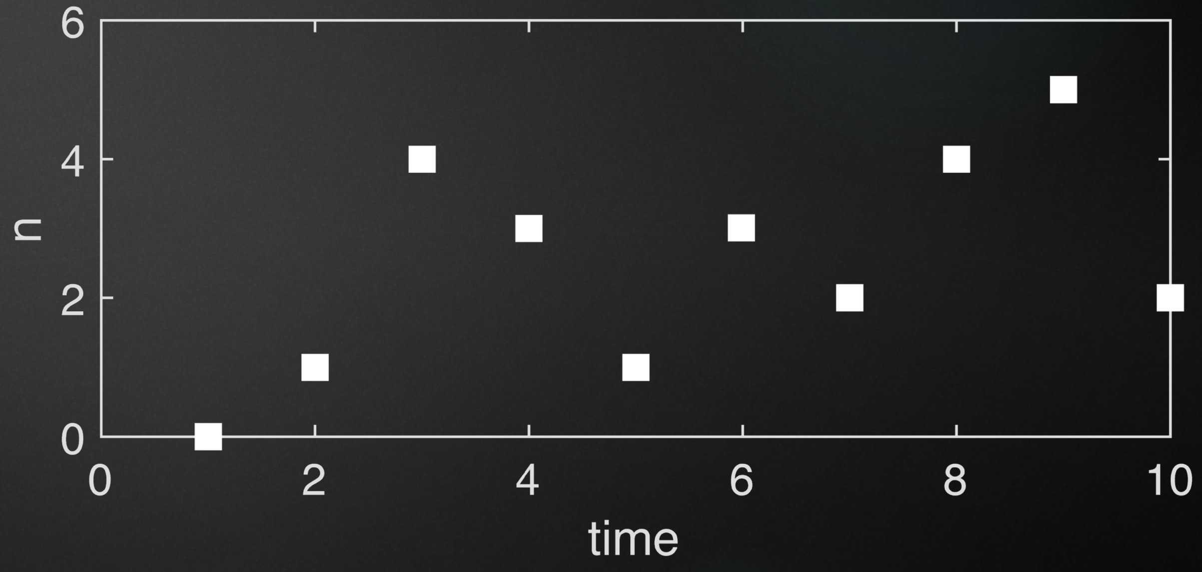
Photon Number Resolution

The ability to distinguish the number of photons in an optical packet



How many photons?
What light statistics?
How well?

Information out of a PNR detector →



1	0
2	1
3	4
4	3
5	1
6	3
7	2
8	4
9	5
10	2

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Why would we need to resolve the number of photons?

A non-exhaustive list

We need to know if it is exactly one or more

Quantum key distribution security (e.g., photon splitting attack against BB84 protocol)

Physical review letters 85.6 (2000): 1330.
Physical review letters 94.23 (2005): 230504
Physical Review A 73.3 (2006): 032305.

Linear Optical Quantum Computing (LOQC) protocols (KLM)

Nature 409.6816 (2001): 46-52.
Reviews of modern physics 79.1 (2007): 135

Generation and detection of non-classical states

Science advances 5.10 (2019): eaaw8586.
New Journal of Physics 8.1 (2006): 4.

Quantum repeaters

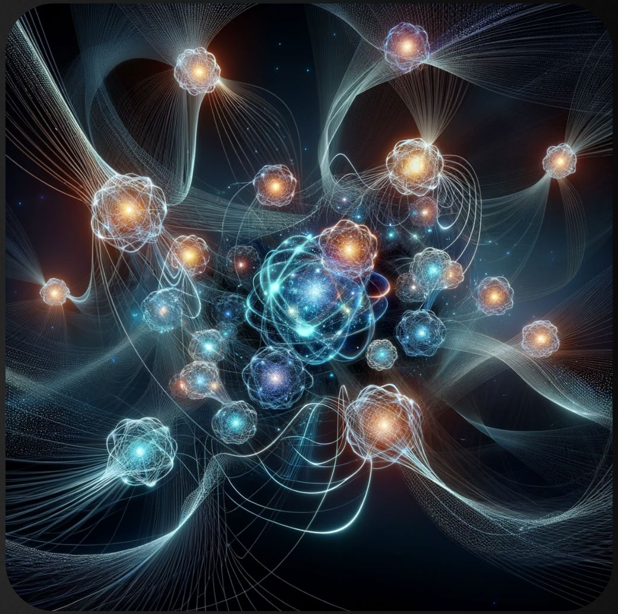
Physical Review A 92.2 (2015): 022357.
Applied Physics B 122 (2016): 1-8.

Standards definition

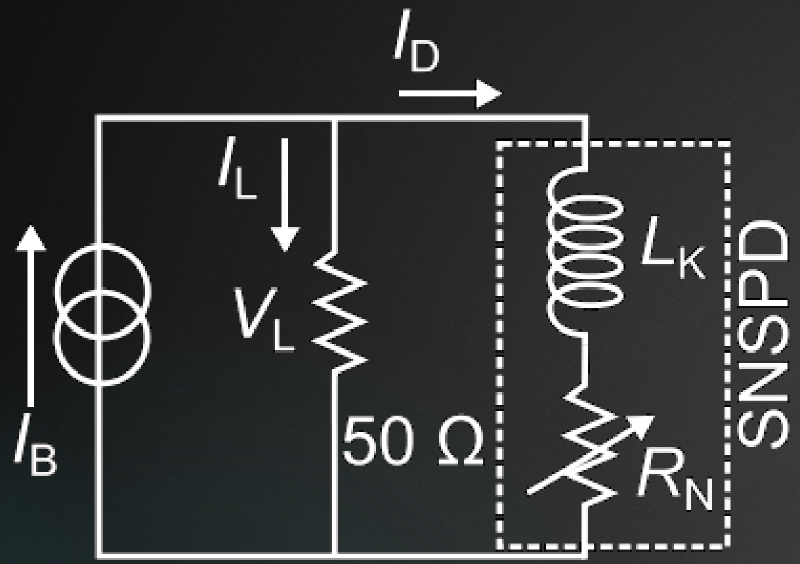
Metrologia 47.5 (2010): R15

Quantum-enhanced metrology (e.g., SNR improvement in LIDAR)

J. Opt., vol. 19, no. 9, 2017

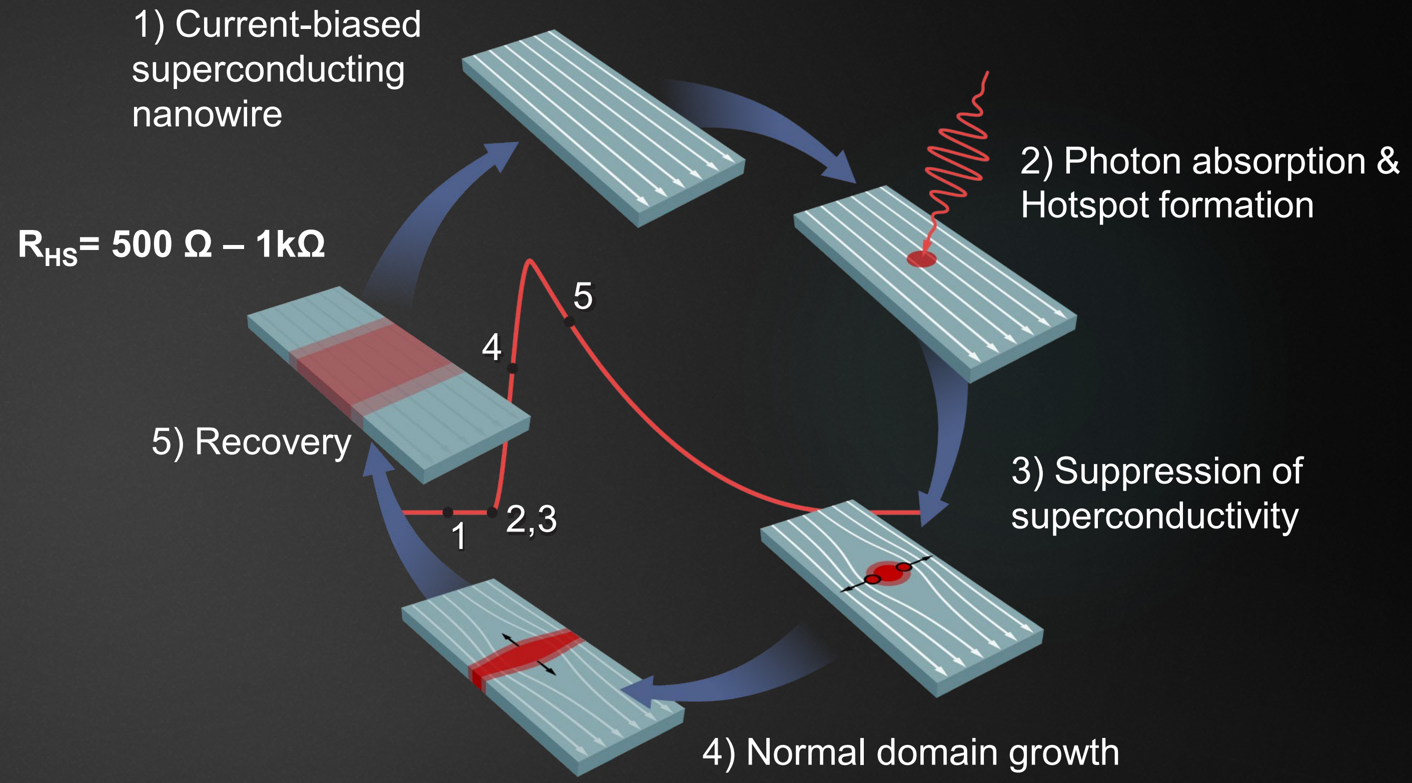


SNSPDs are not intrinsically PNR*



$$\max(V_L) \sim \frac{R_N(t,n)}{50\ \Omega + R_N(t,n)} \mathrm{I}_B$$

$$\times\ 50\ \Omega$$



1) Current-biased superconducting nanowire

2) Photon absorption & Hotspot formation

3) Suppression of superconductivity

4) Normal domain growth

5) Recovery

R_{HS}= 500 Ω – 1kΩ

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Allmaras et al. Diss. Caltech, 2020.

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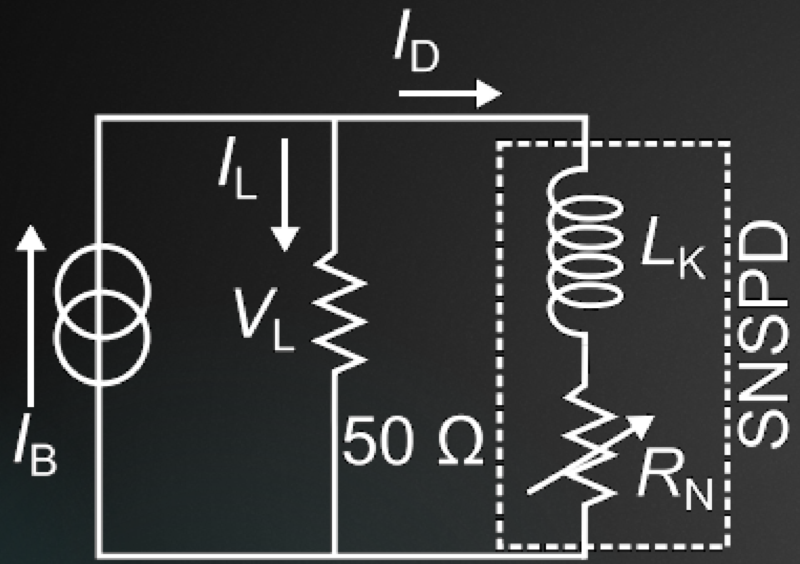
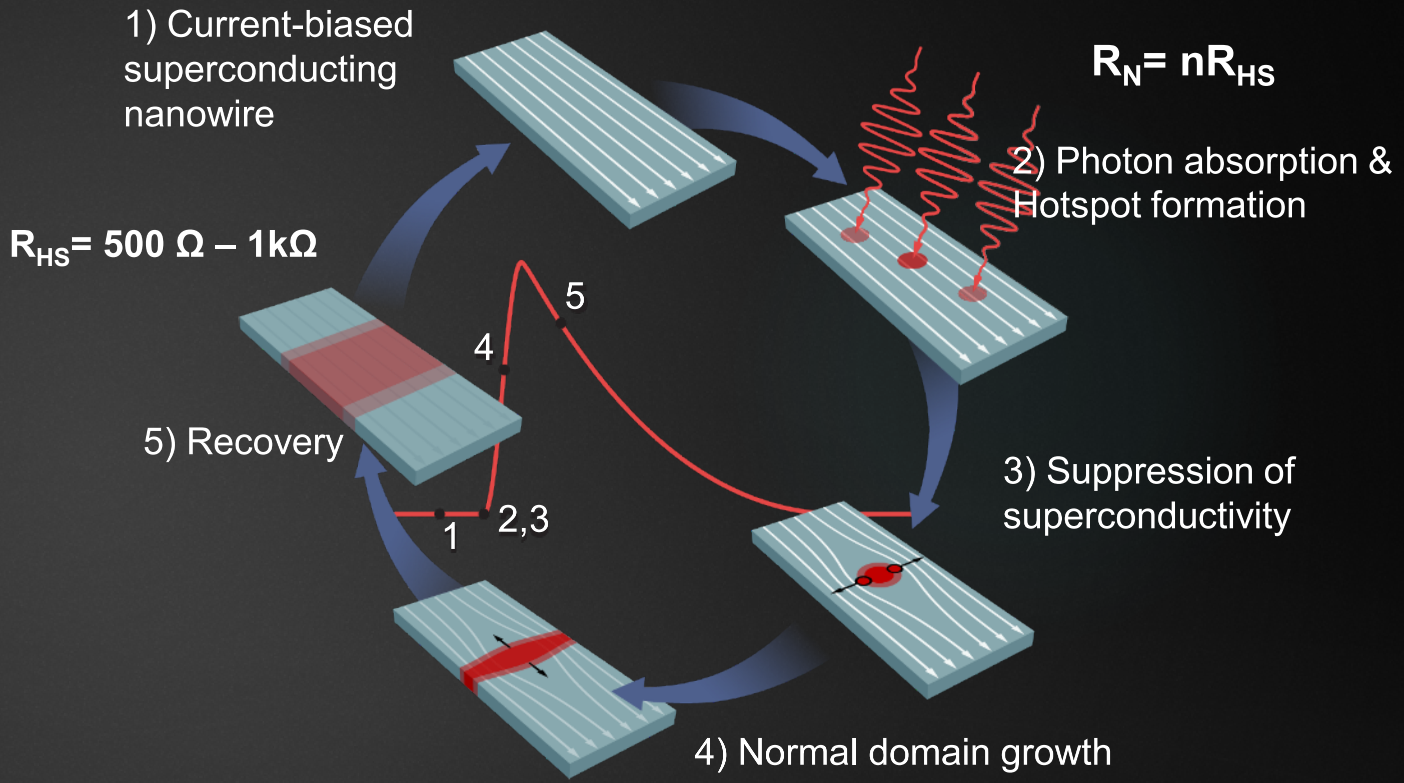


$$\max(V_L) \sim \underbrace{\frac{\cancel{R_N(t,n)}}{\cancel{50\,\Omega + R_N(t,n)}}}_{\approx 1} \mathrm{I}_B \times 50\,\Omega$$

The output voltage is not sensitive to the number of photons

Different photons generate different hotspots



Allmaras et al., Physical Review Applied 11.3 (2019): 034062.
Allmaras et al. Diss. Caltech, 2020.

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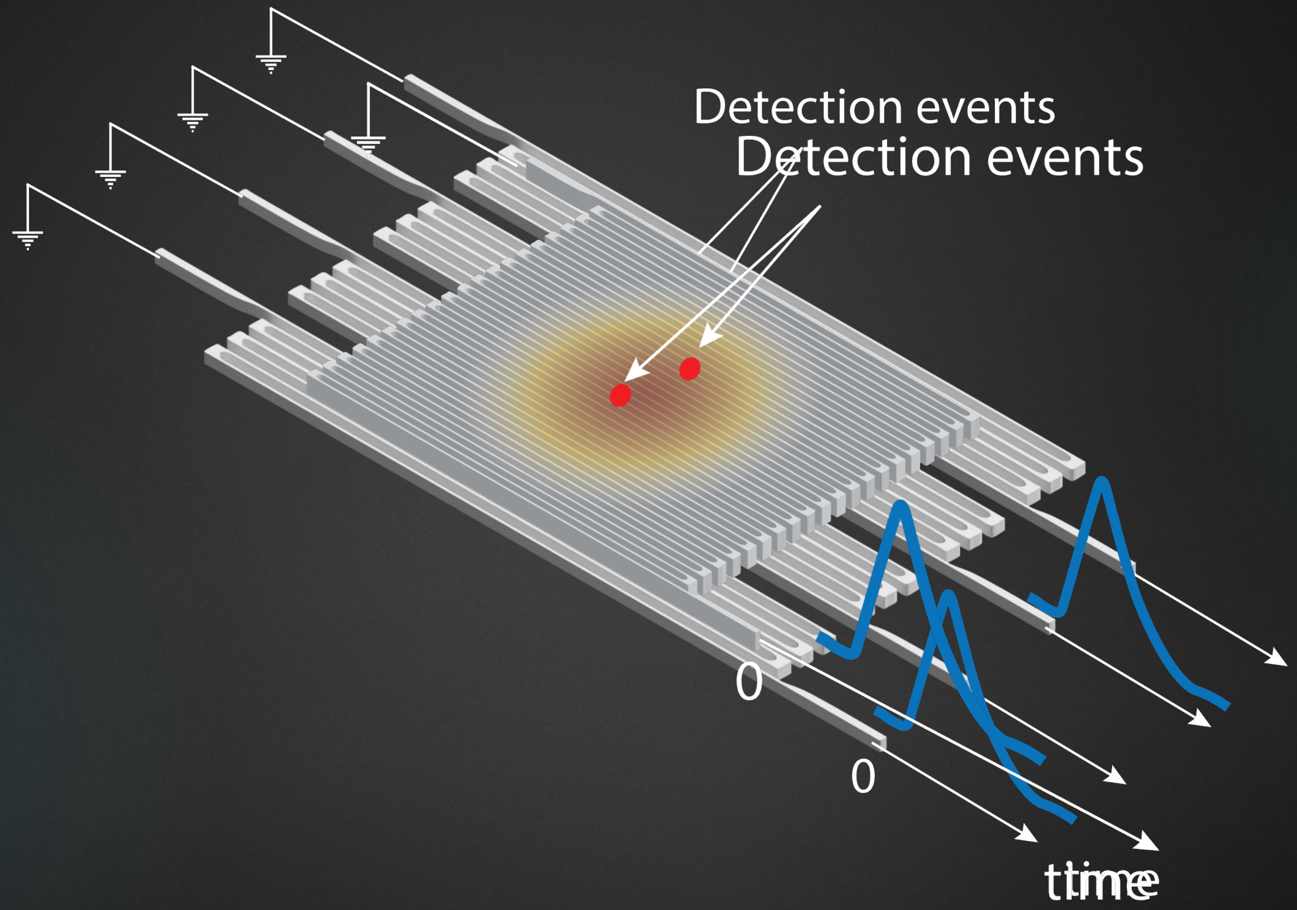
How do we get photon-number resolution in SNSPDs?

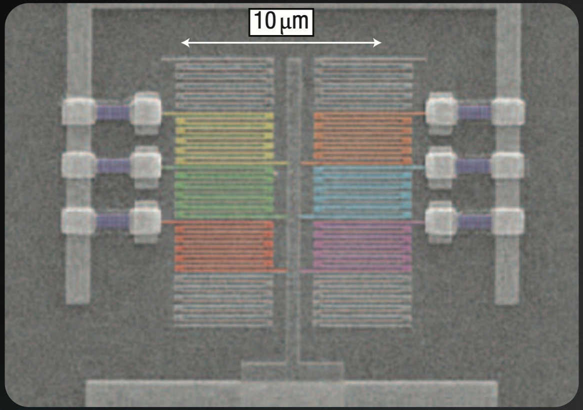
Multi-element approach

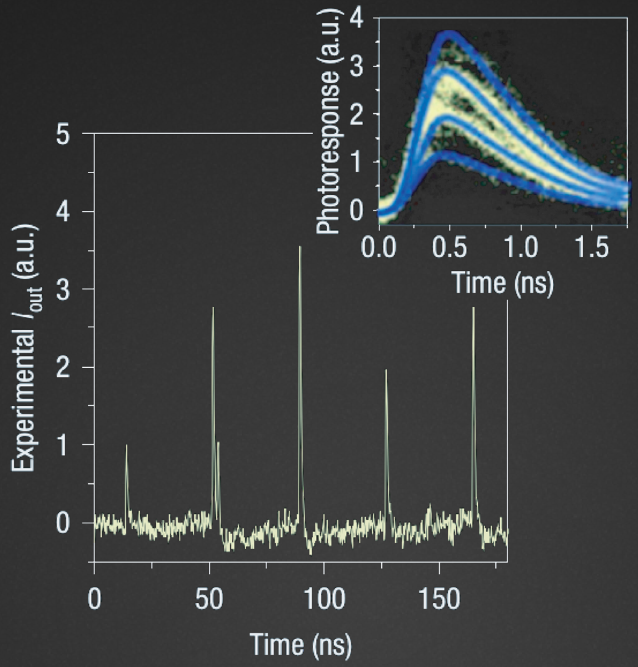


Multi-element approach – Amplitude and Spatial Multiplexing

Parallel Nanowire Detector (PND)

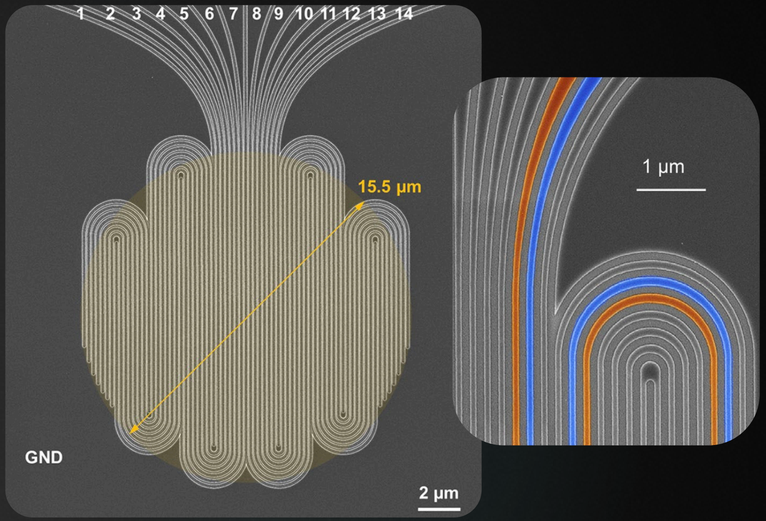
Nature Photonics 2.5 (2008): 302-306. (TU/e)





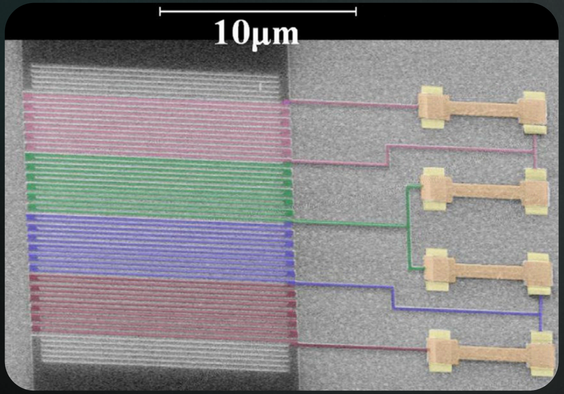
Multipixel array

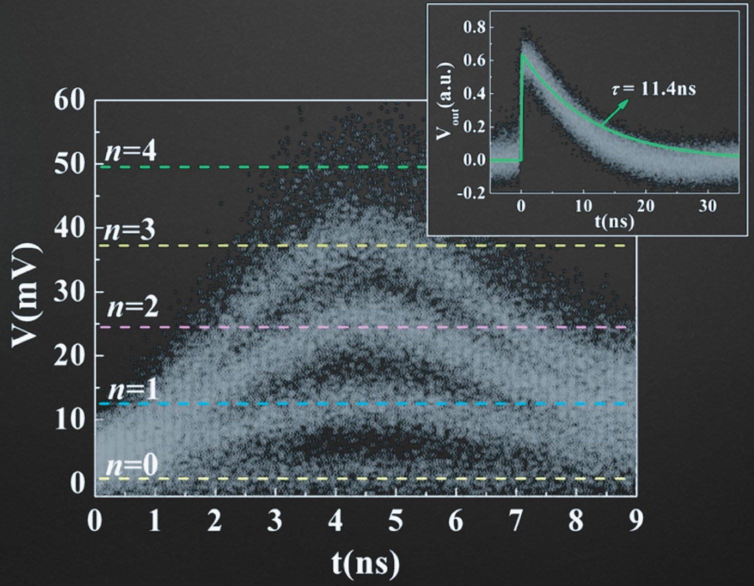
Nano Letters 23.13 (2023): 6018-6026. (UGeneva)



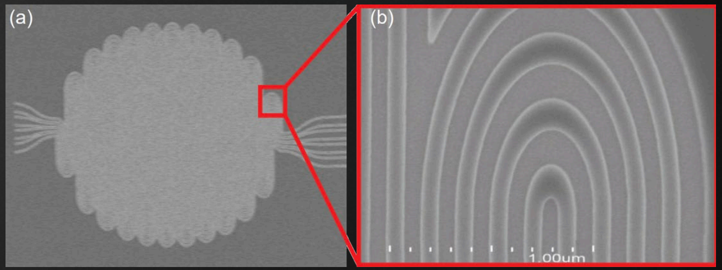
Series Nanowire Detector (SND)

Applied Physics Letters 101.7 (2012). (TU/e)





Quantum Computing, Communication, and Simulation IV. Vol. 12911. SPIE, 2024



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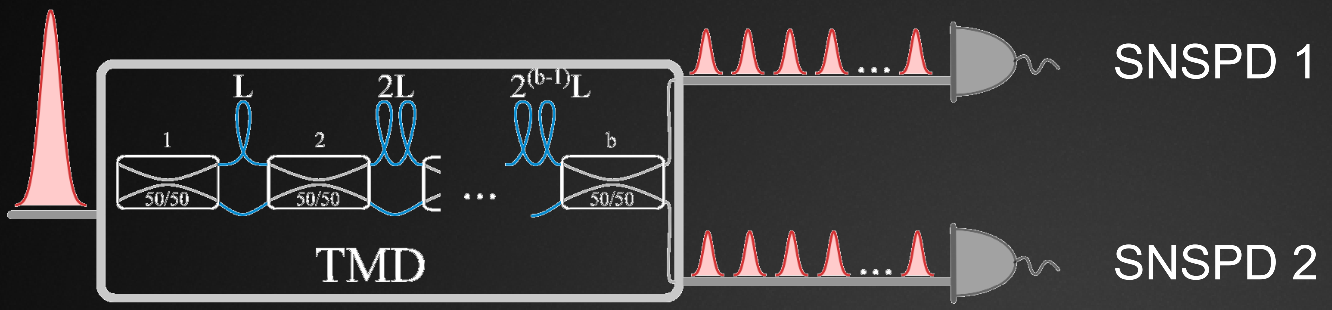
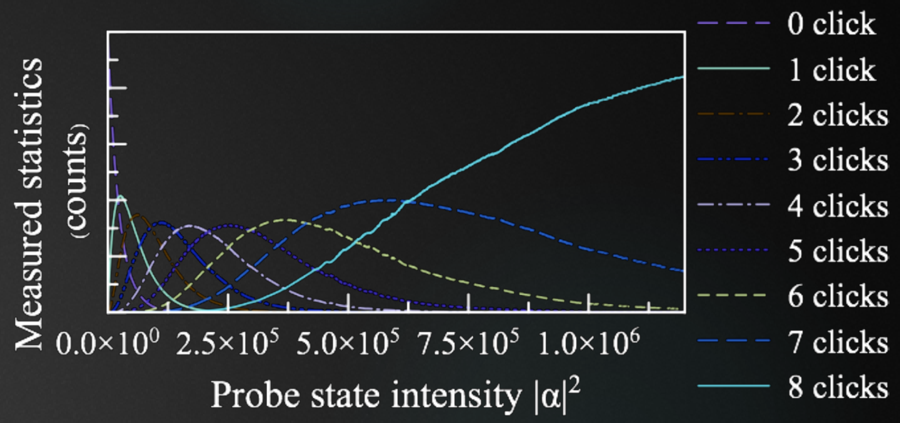
Multi-element approach – Temporal and delay-line multiplexing

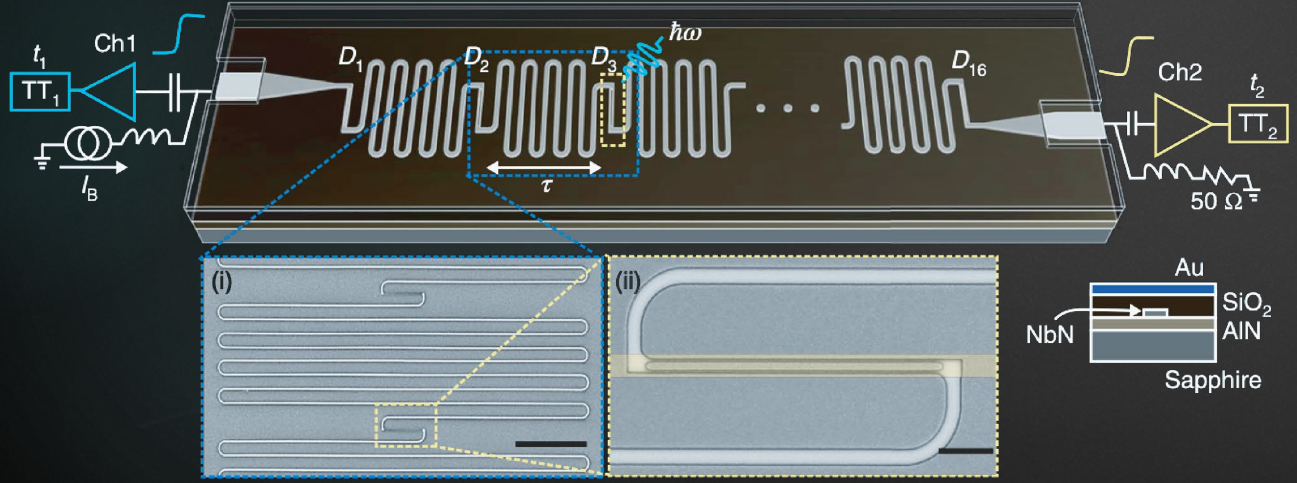
Temporal multiplexing

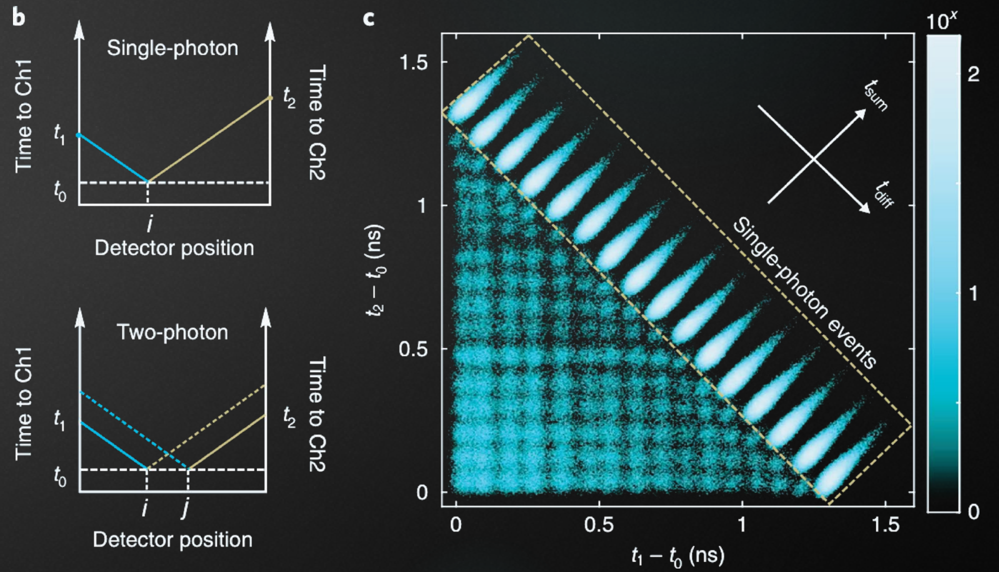




Physical Review A 95.2 (2017): 023815. (Paderborn University)
Optics express 21.1 (2013): 893-902 (Glasgow/TUDelft)

Delay-line multiplexing





Nature nanotechnology 13.7 (2018): 596-601 (MIT).

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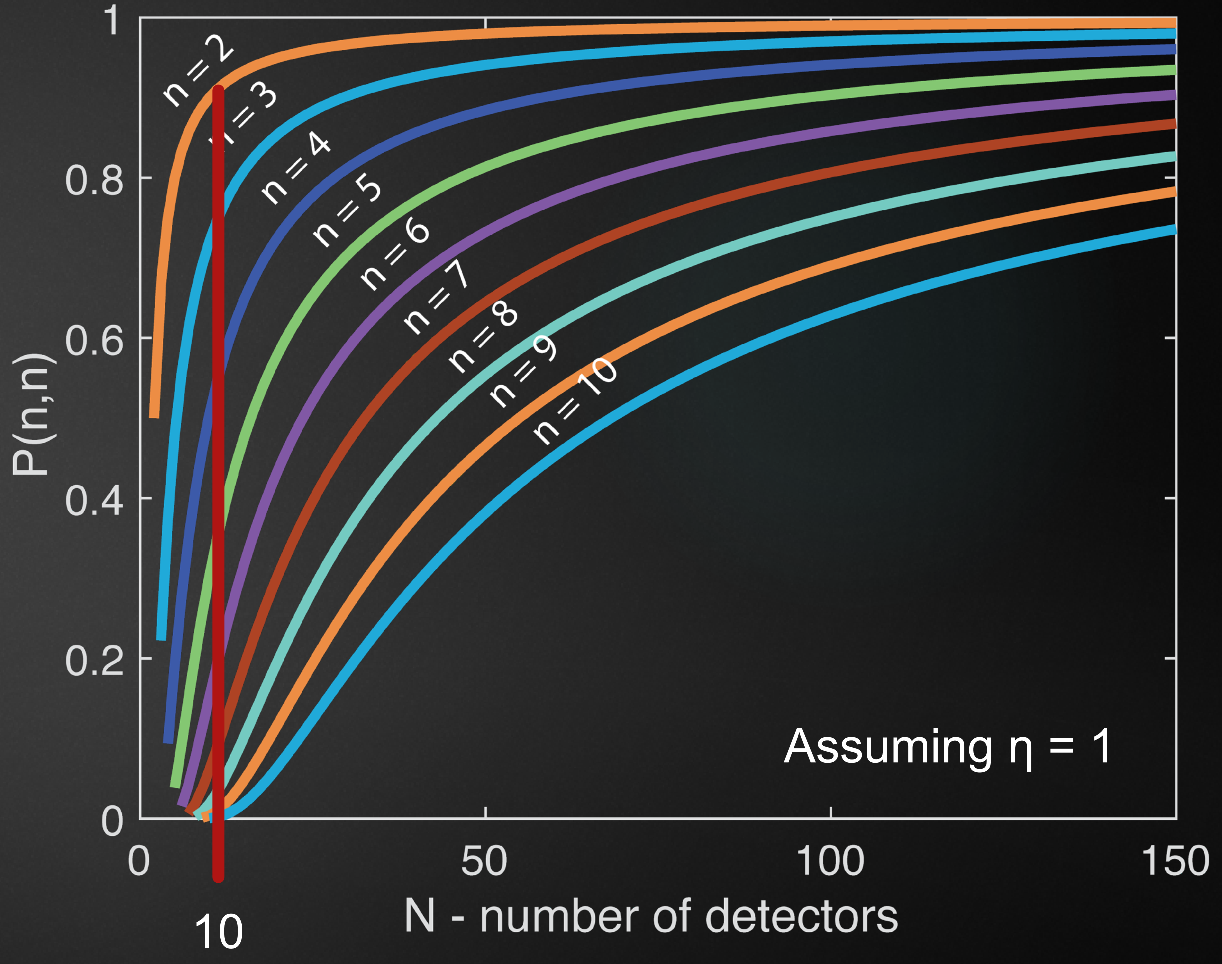
Multi-element approach – Fidelity

How well is a detector determining how many photons we have?

Assume we are illuminating a spatially multiplexed array with N elements with η using *n* photons

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

Need many elements (large array)



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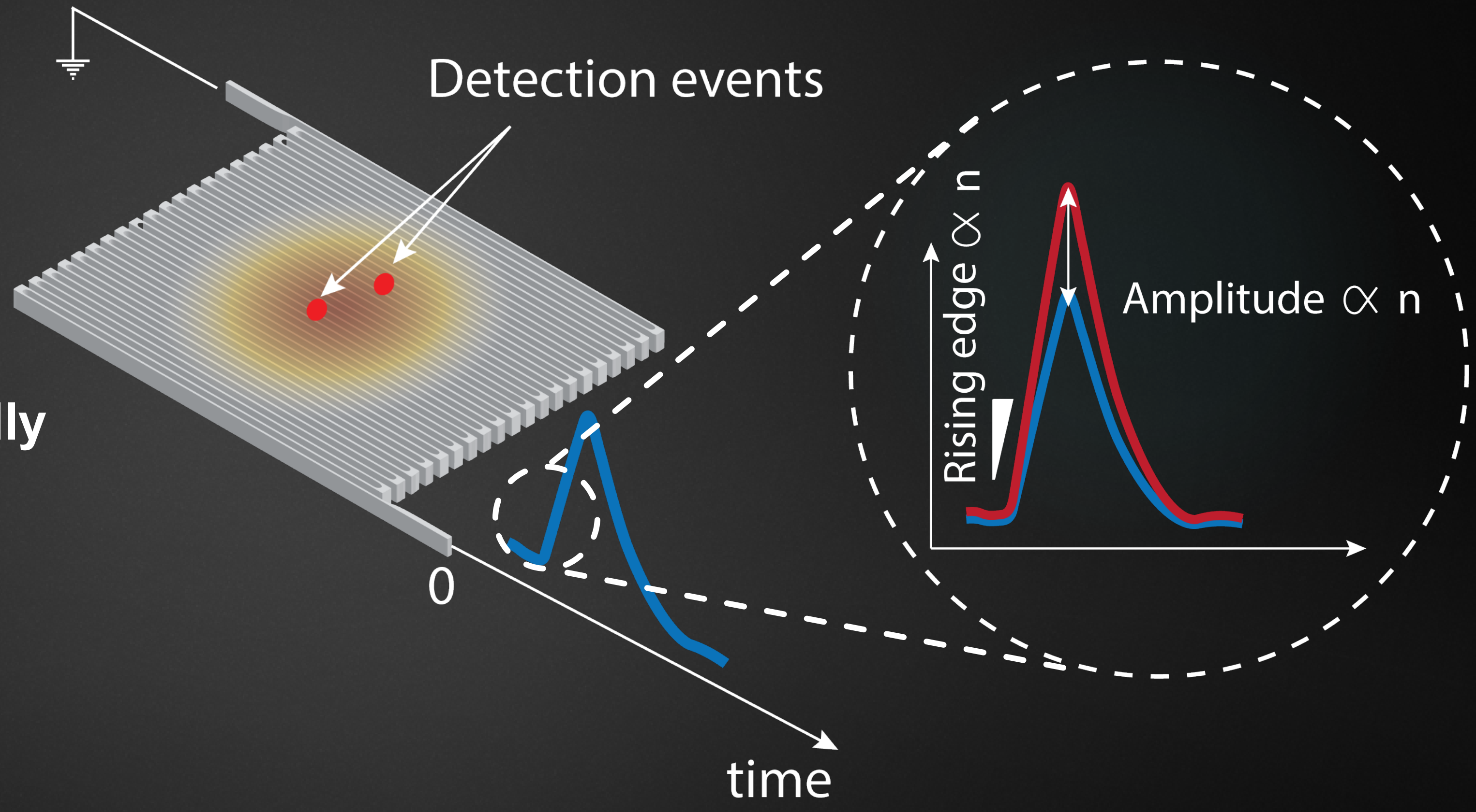
Single-element approach

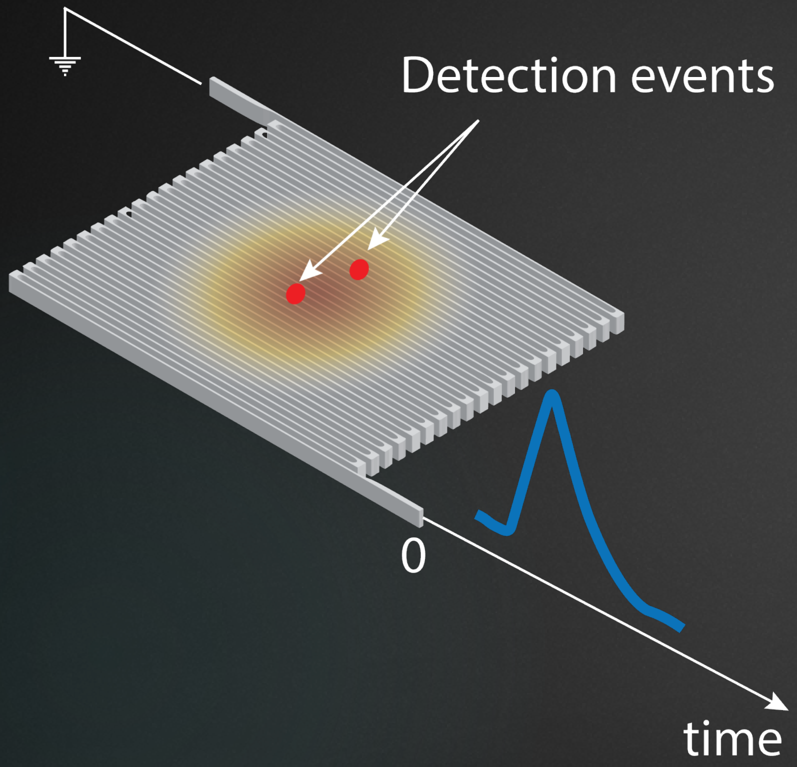


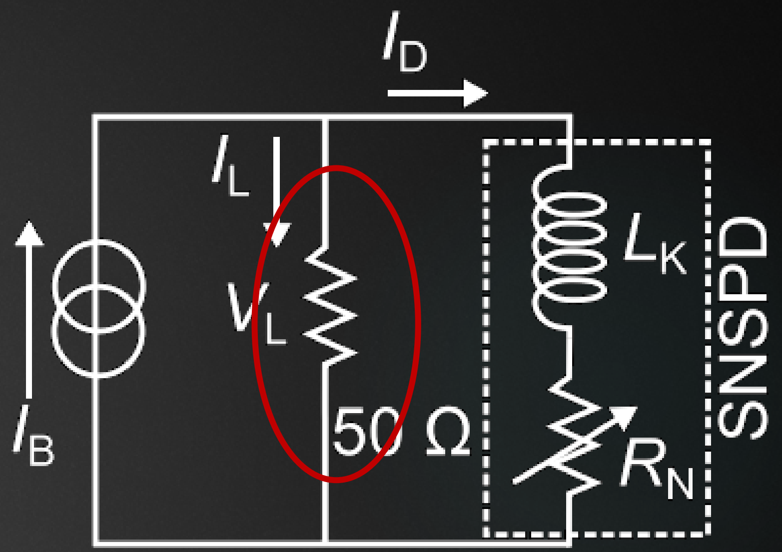
A meander behaves like a spatially multiplexed multi-pixel element

$R_N = nR_{HS}$

Nano Letters 20.5 (2020): 3858-3863.

Pulse amplitude PNR





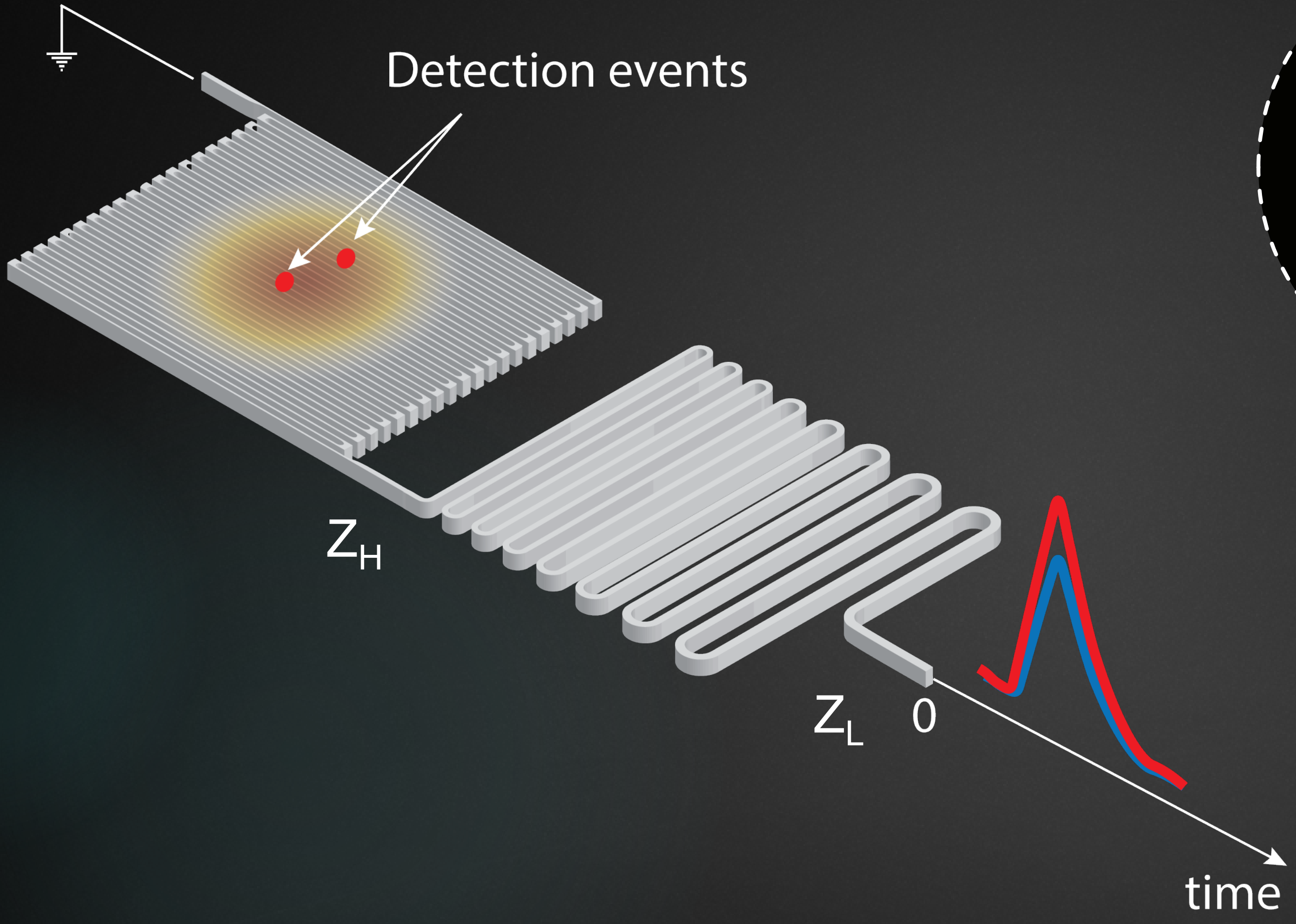
$$\max(V_L) \sim \frac{R_N(n,t)}{50\ \Omega + R_N(n,t)} \mathrm{I}_B \times 50\ \Omega$$

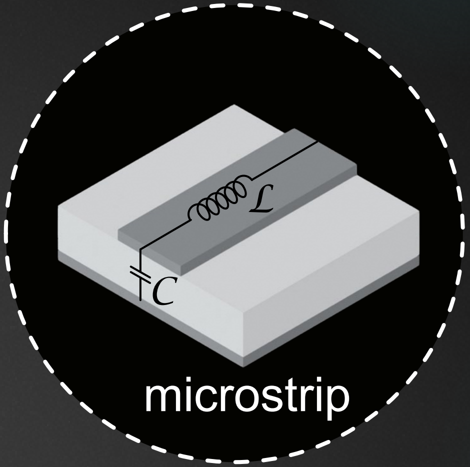
Independent from number of photons

We can’t simply swap the 50 Ω

Nano Letters 20.5 (2020): 3858-3863.

STaND: Superconducting Tapered Nanowire Detector



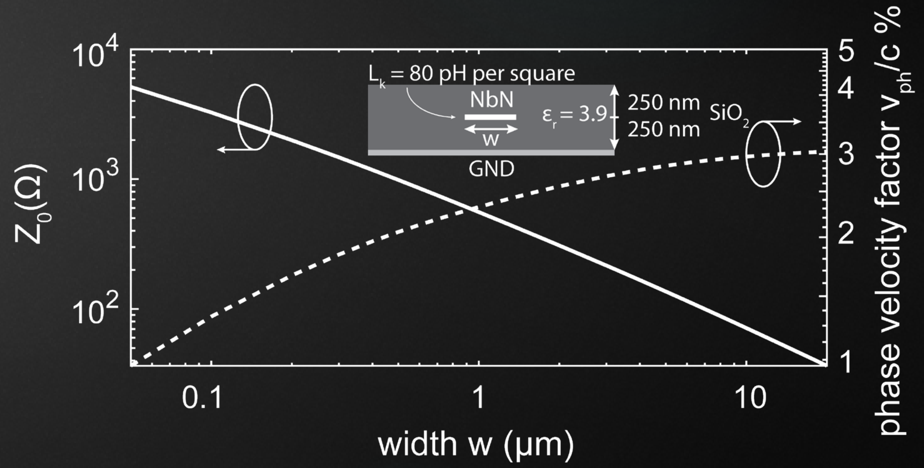


$$n_{eff} = c\sqrt{\mathcal{L}C}$$

$$Z_0 = \sqrt{\mathcal{L}/C}$$

$$\mathcal{L}_K \approx 1\ \mathrm{nH/\mu m}$$

About 1000 larger than the geometric inductance



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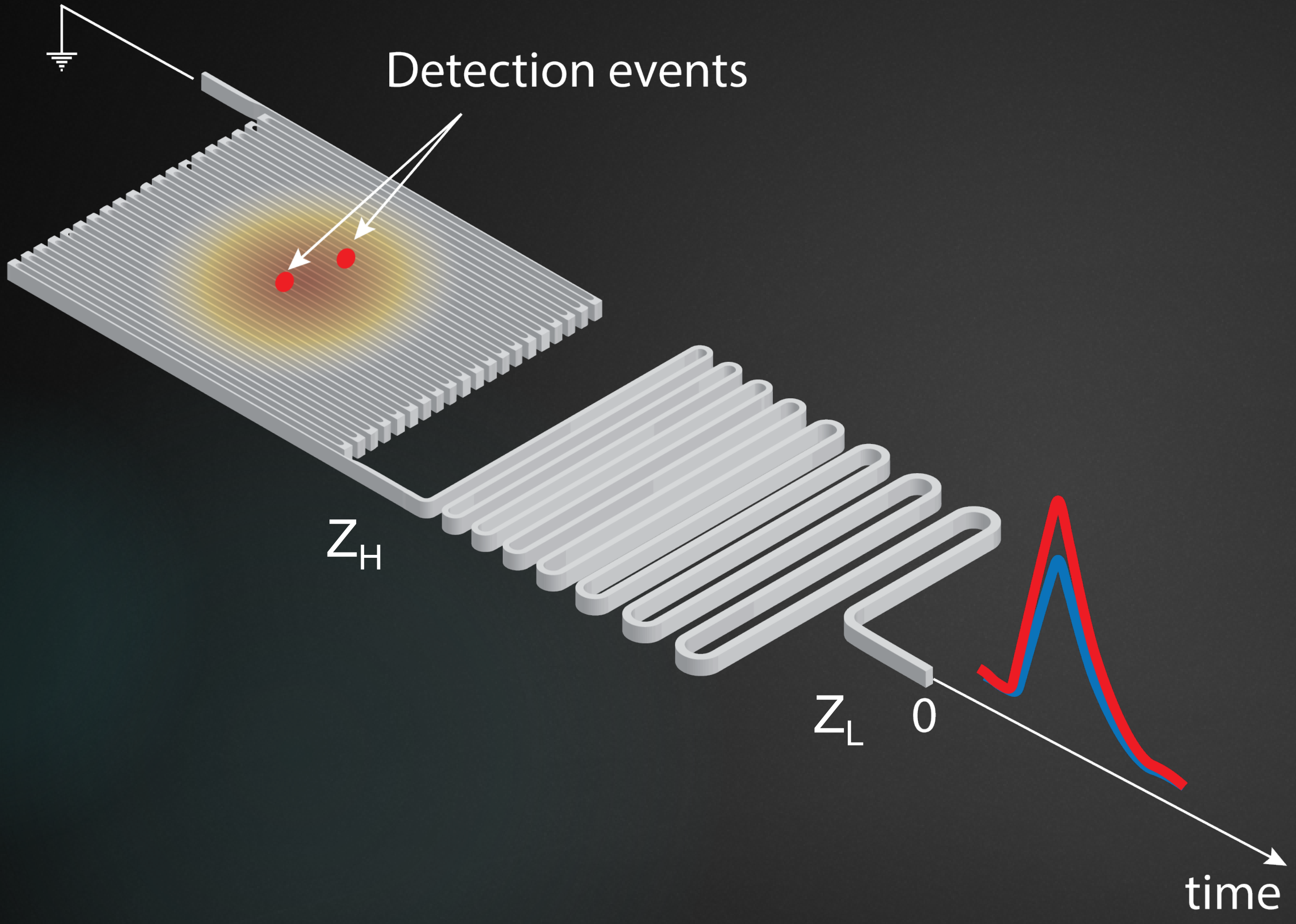

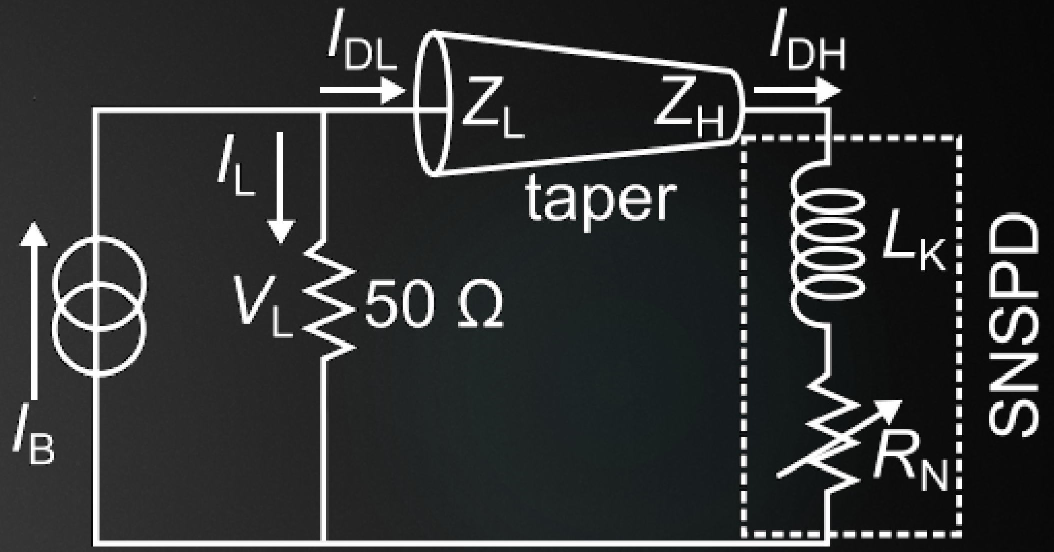

$$\max(V_L) \sim \frac{R_N(n,t)}{Z_H + R_N(n,t)} \sqrt{\frac{Z_H}{Z_L}}\ \mathrm{I}_B \times 50\ \Omega$$

$R_N = 500\ \Omega\ - 1\mathrm{k}\Omega$

$Z_H \sim 1\ \mathrm{k}\Omega$

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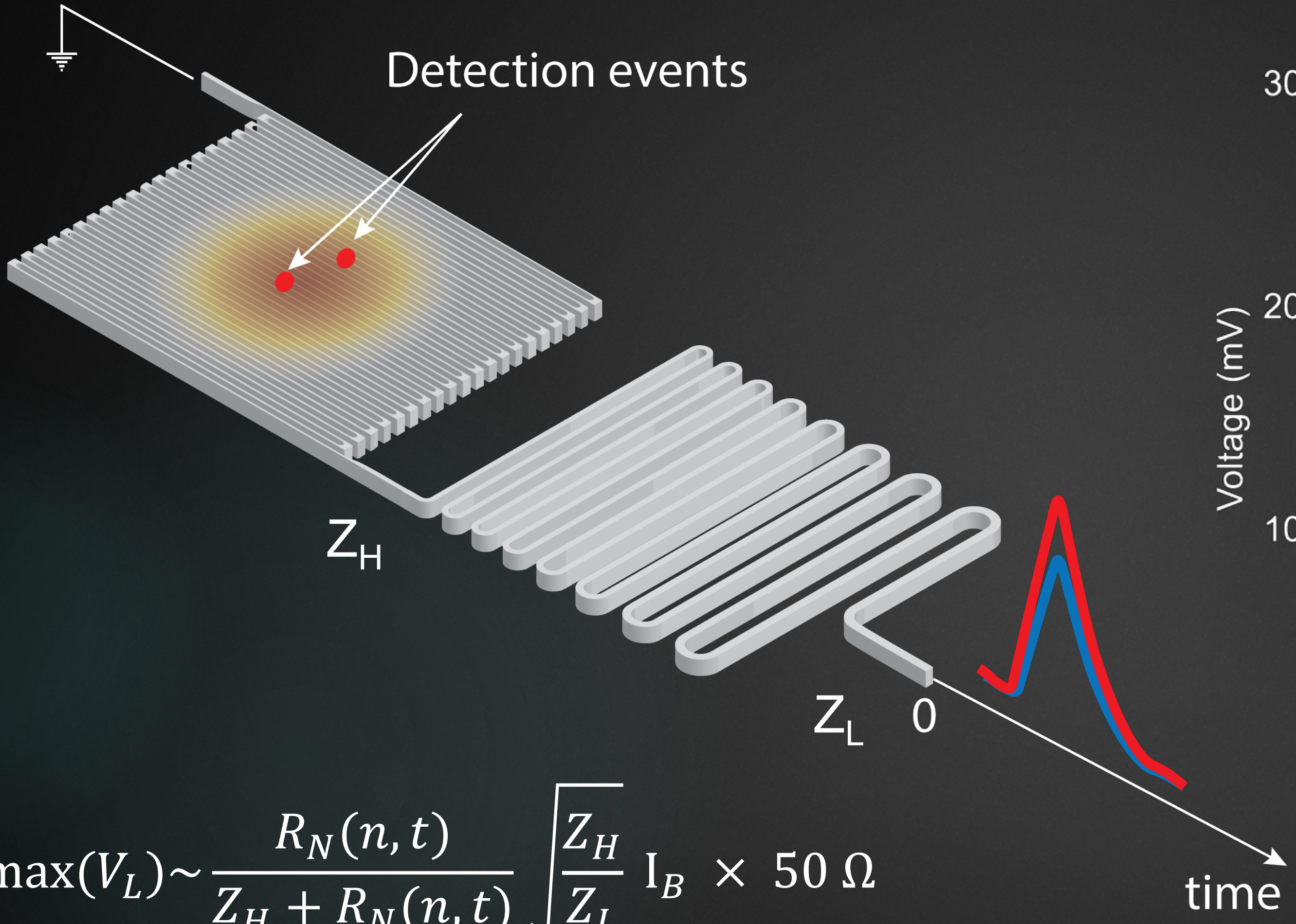

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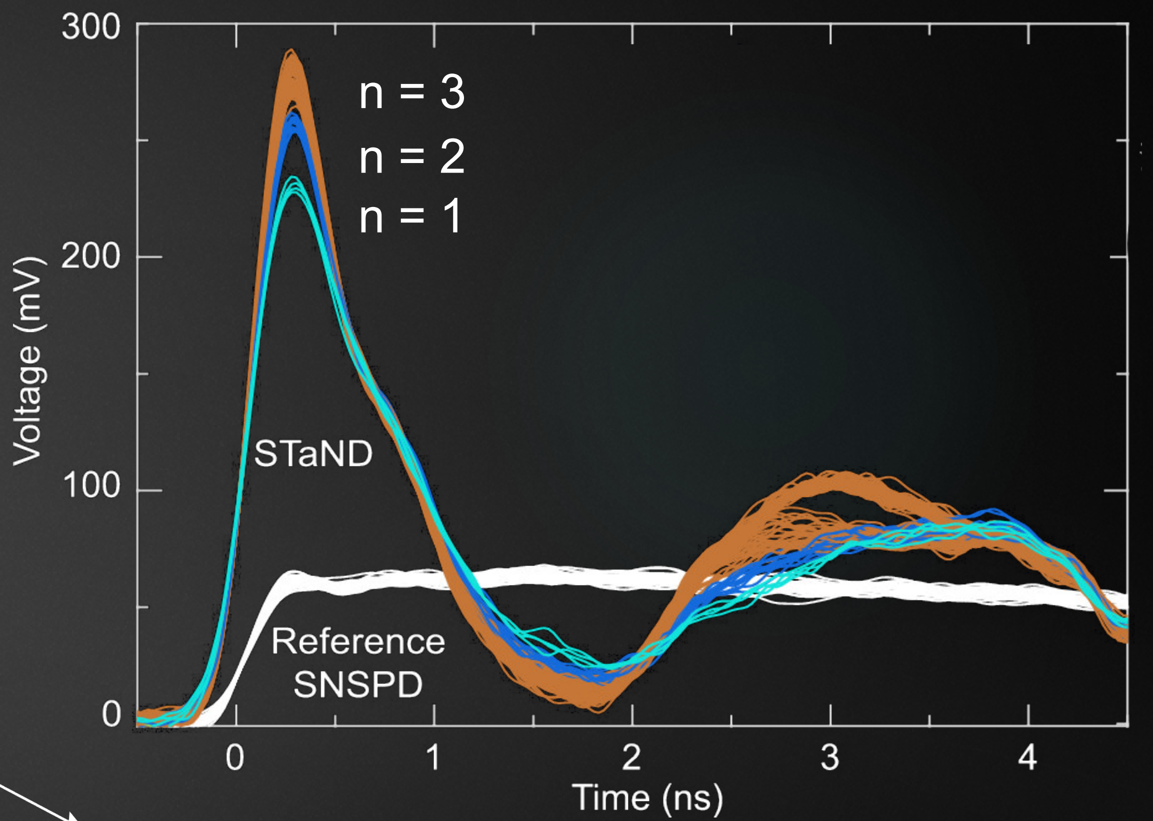


This detector is effectively like a spatially multiplexed multipixel detectors with many elements

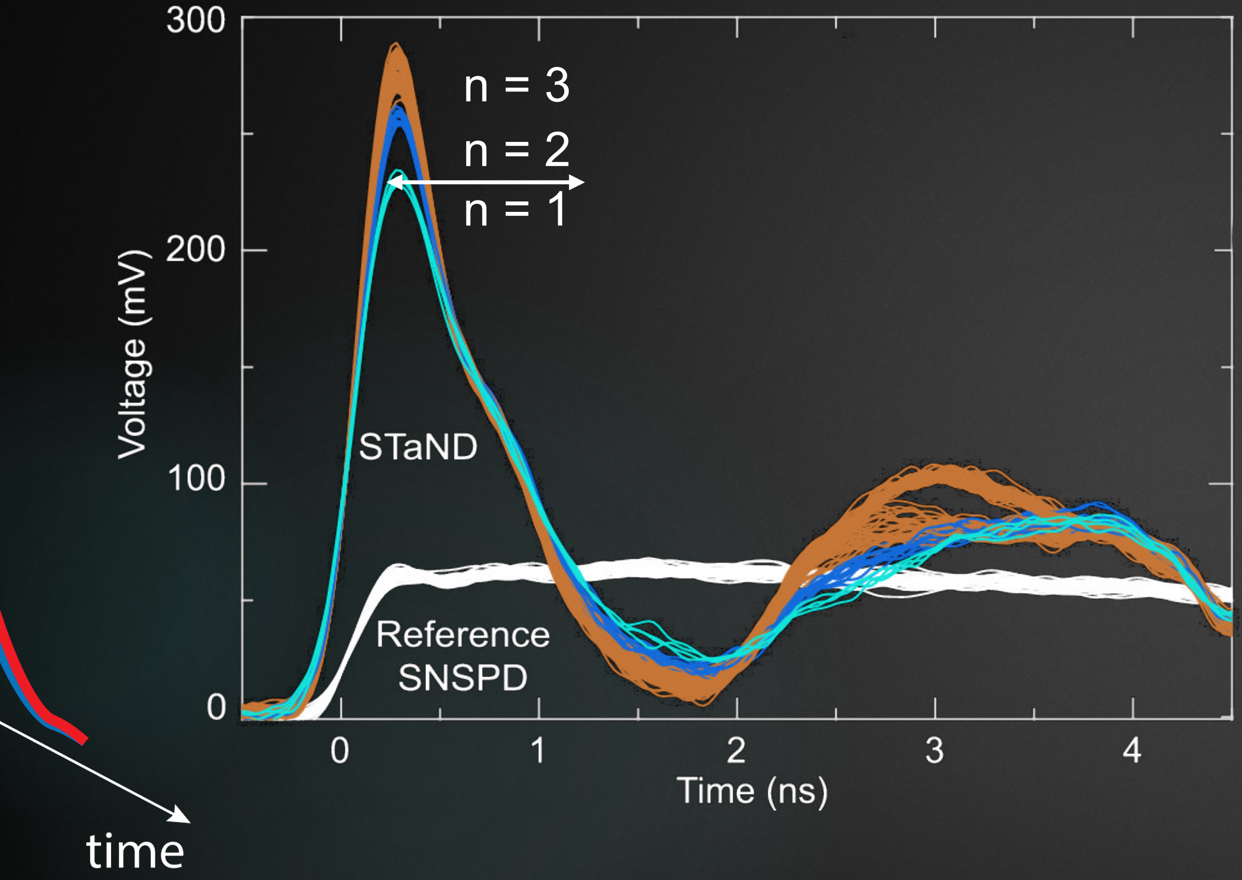
Nano Letters 20.5 (2020): 3858-3863.

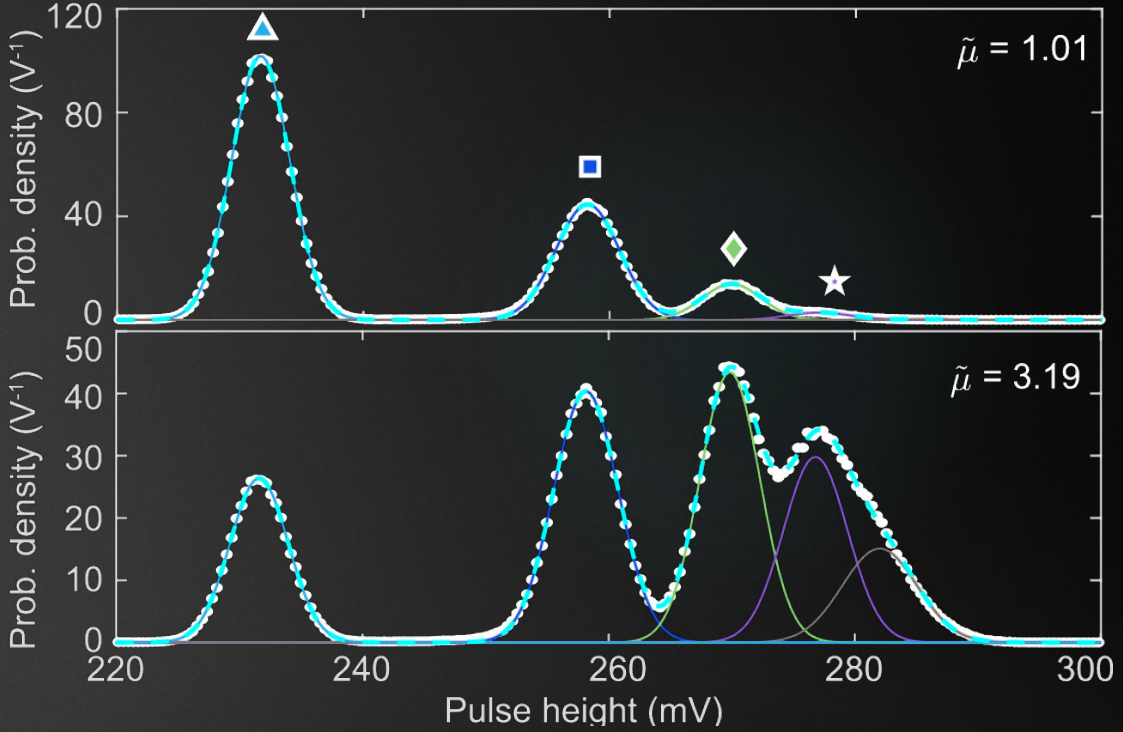
STaND: Superconducting Tapered Nanowire Detector

Poisson light

$$P(n) = \frac{< n >^n}{n!} e^{-<n>}$$

Perfect two-photon detector





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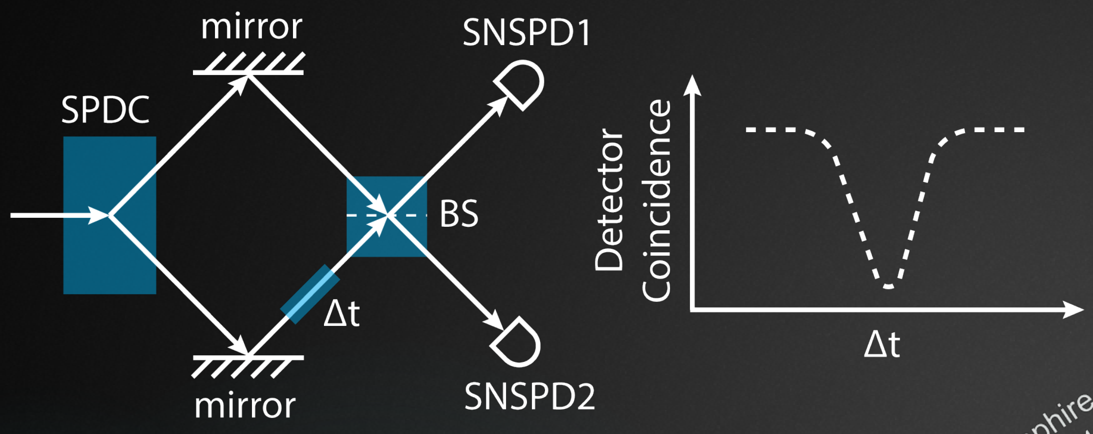
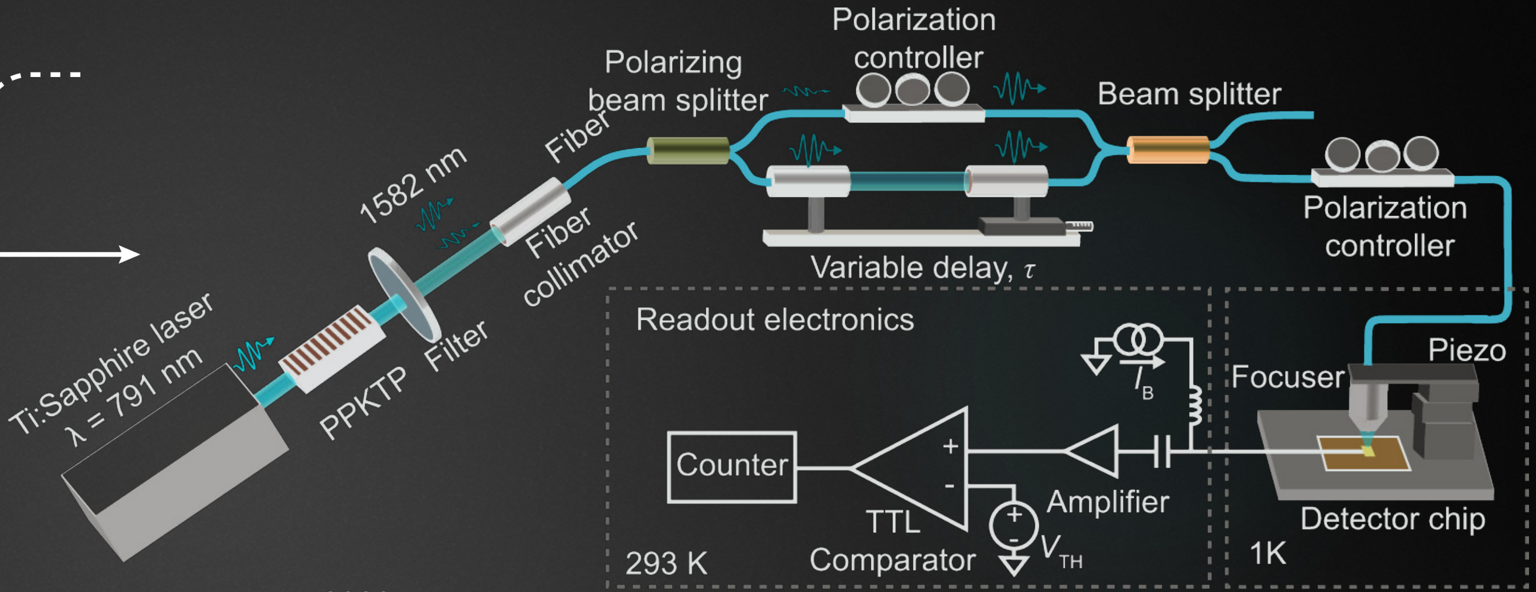
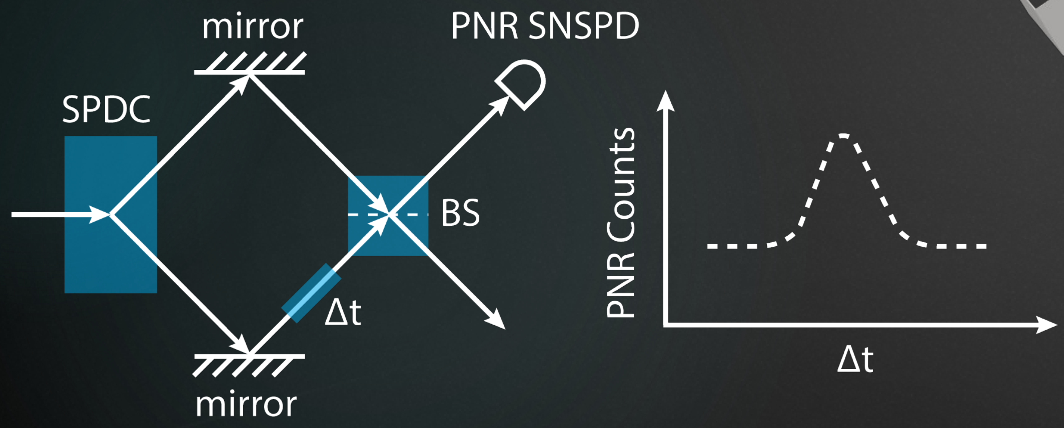
Hong-Ou-Mandel Interference

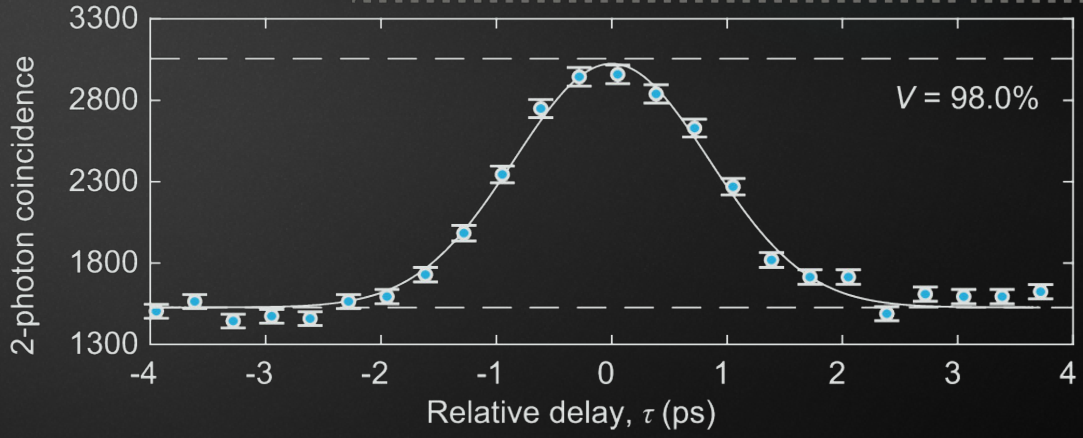
Standard HOM





PNR HOM





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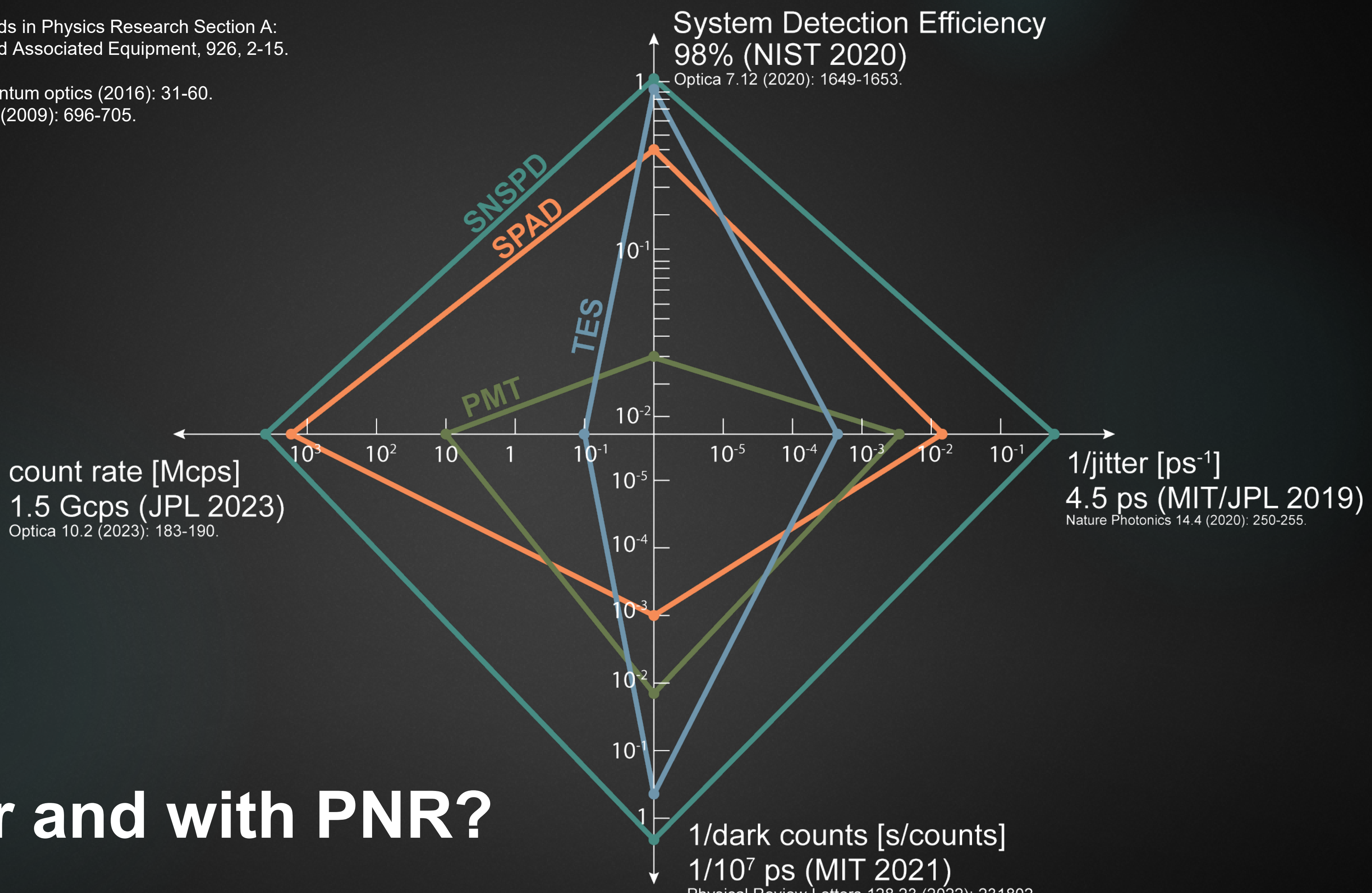


Optica 7.12 (2020): 1649-1653.

Optica 10.2 (2023): 183-190.

Nature Photonics 14.4 (2020): 250-255.

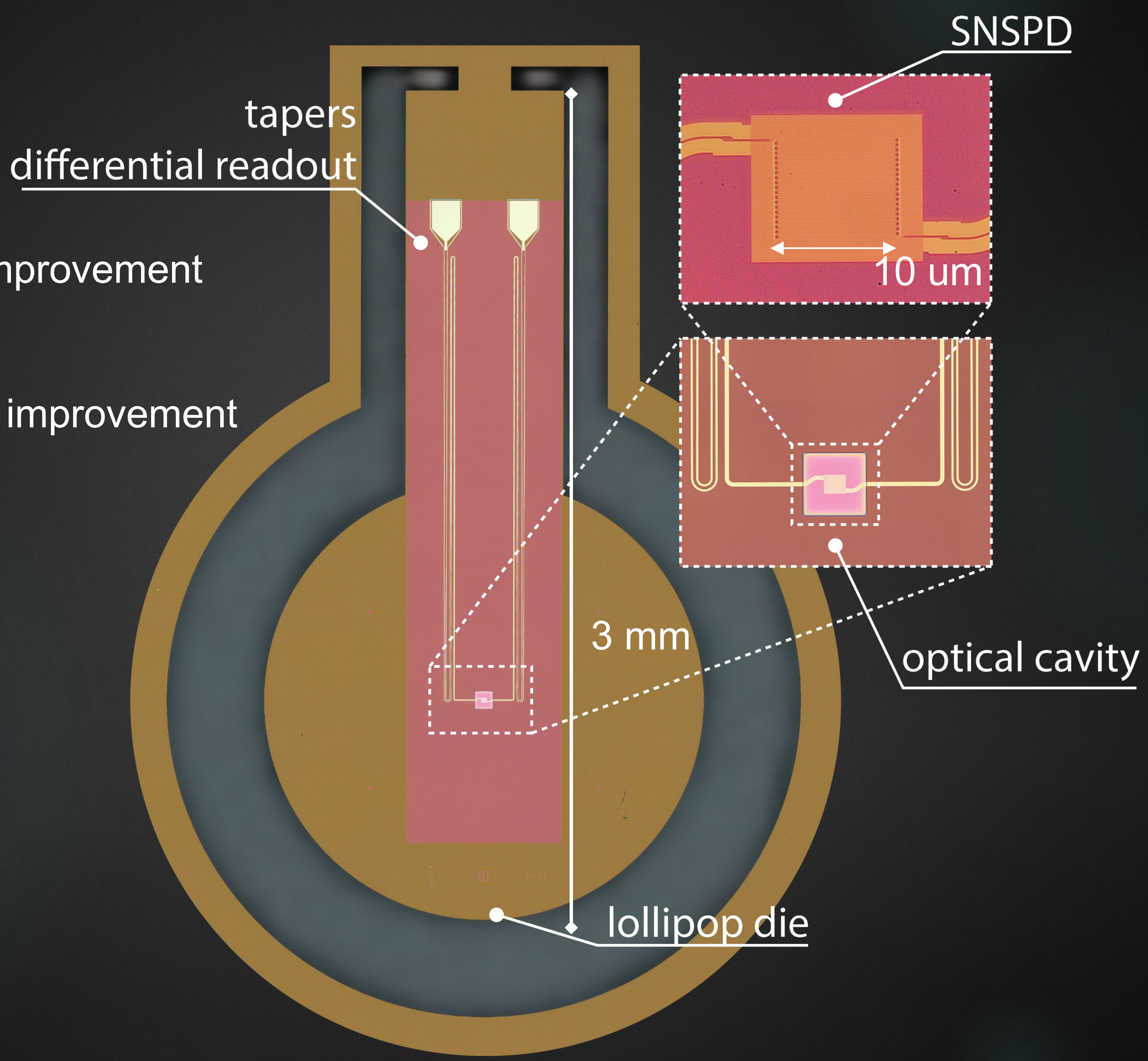
Physical Review Letters 128.23 (2022): 231802.

All together and with PNR?

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 56 Sept 2024. Presentation given at WOLTE-16 2024, June 2024, Cagliari, Italy.

Impedance-matched differential architecture

- Tapers for PNR and SNR improvement
- Cavity for efficiency
- Lollipop for coupling
- Differential readout for jitter improvement

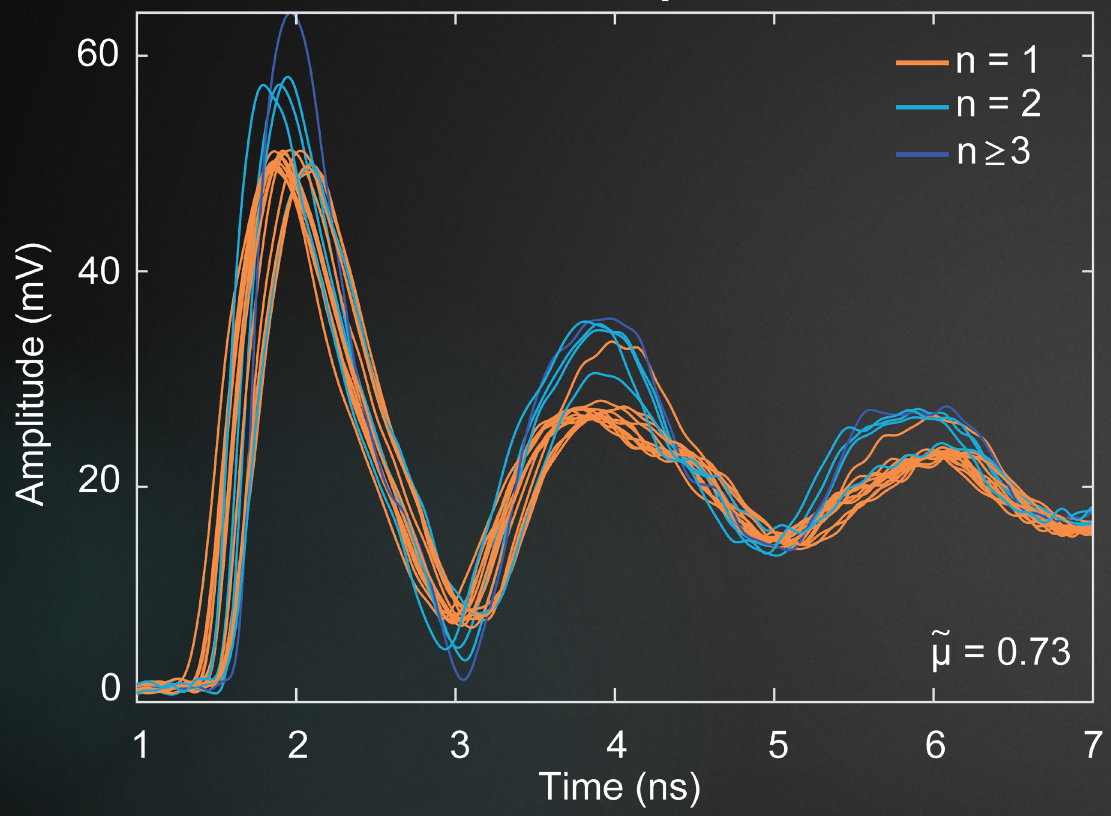


Colangelo et al. Phys. Rev. Applied 19, 044093 (2023)

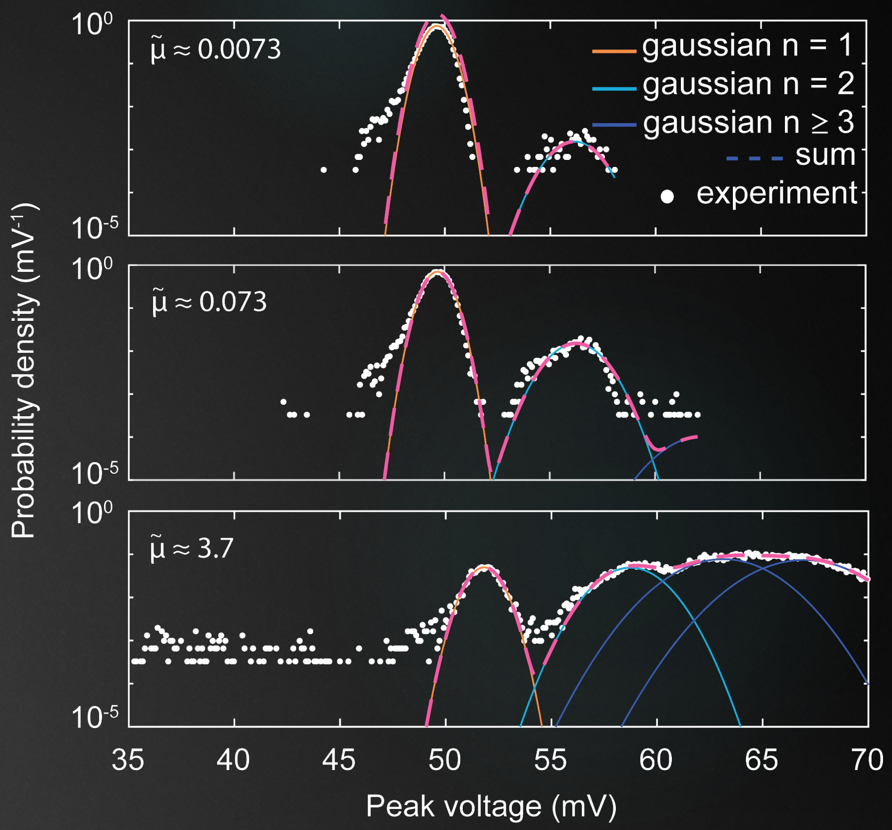
Impedance-matched differential architecture

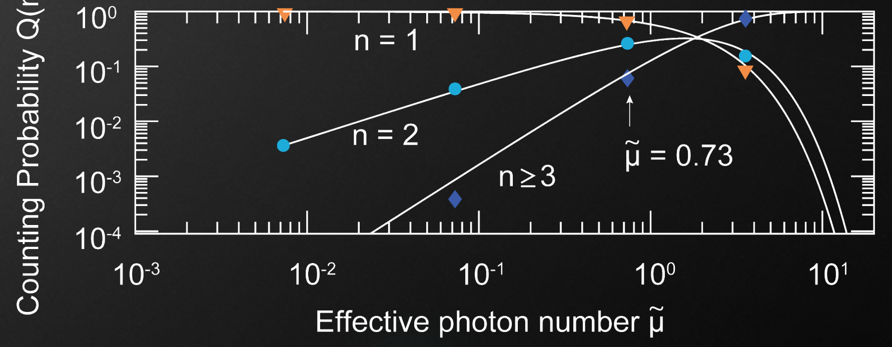
Tested at 0.85 K

Versatile solution for photon detection



With 85% efficiency and 12.1 ps jitter and imaging capabilities





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Superconducting
Photonic
Quantum
Nano Structures Laboratory

U.S. Patent No. 11,522,115. 6 Dec. 2022.

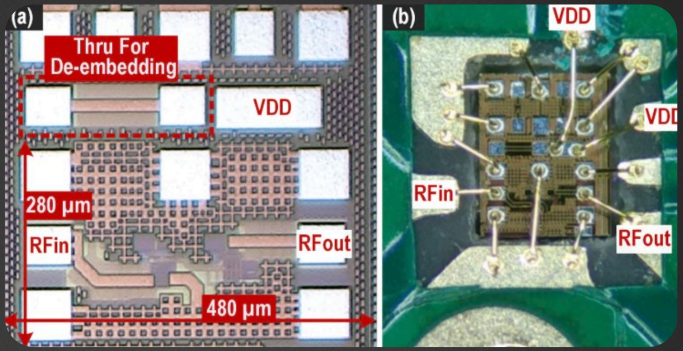
Colangelo et al. Phys. Rev. Applied 19, 044093 (2023)

Next opportunities for this technology

Development of specialized cryo-electronics for:

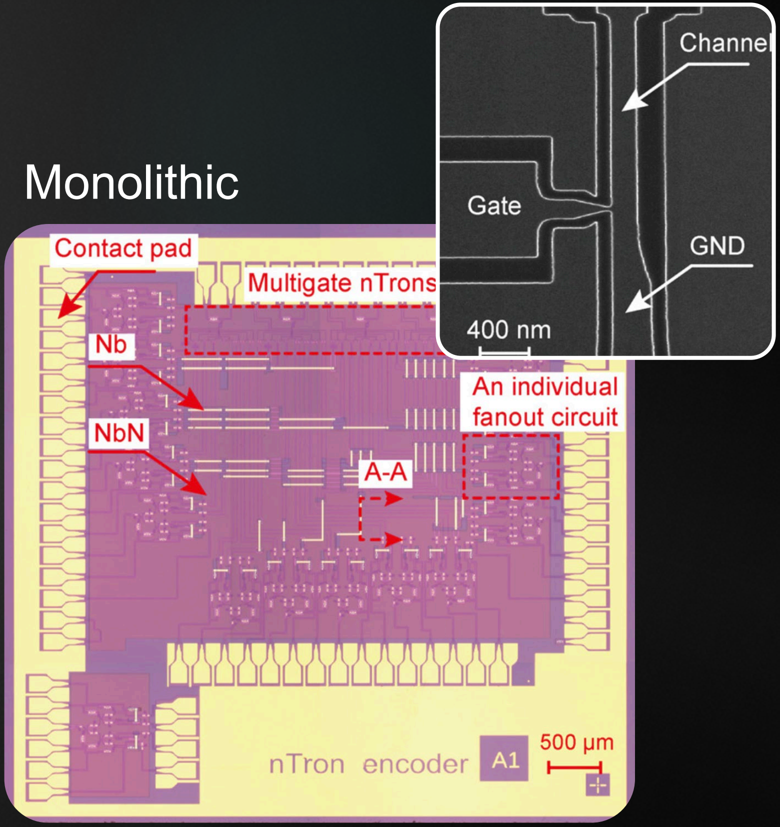
- Amplification
- Active Quenching
- Comparators
- Integrators
- Logic circuits
- Biasing circuits
- Array multiplexing support
- Differential technology support

Cryo-CMOS



IEEE Transactions on Microwave Theory and Techniques (2024).

Monolithic



Applied Physics Letters 124.19 (2024).

Superconducting
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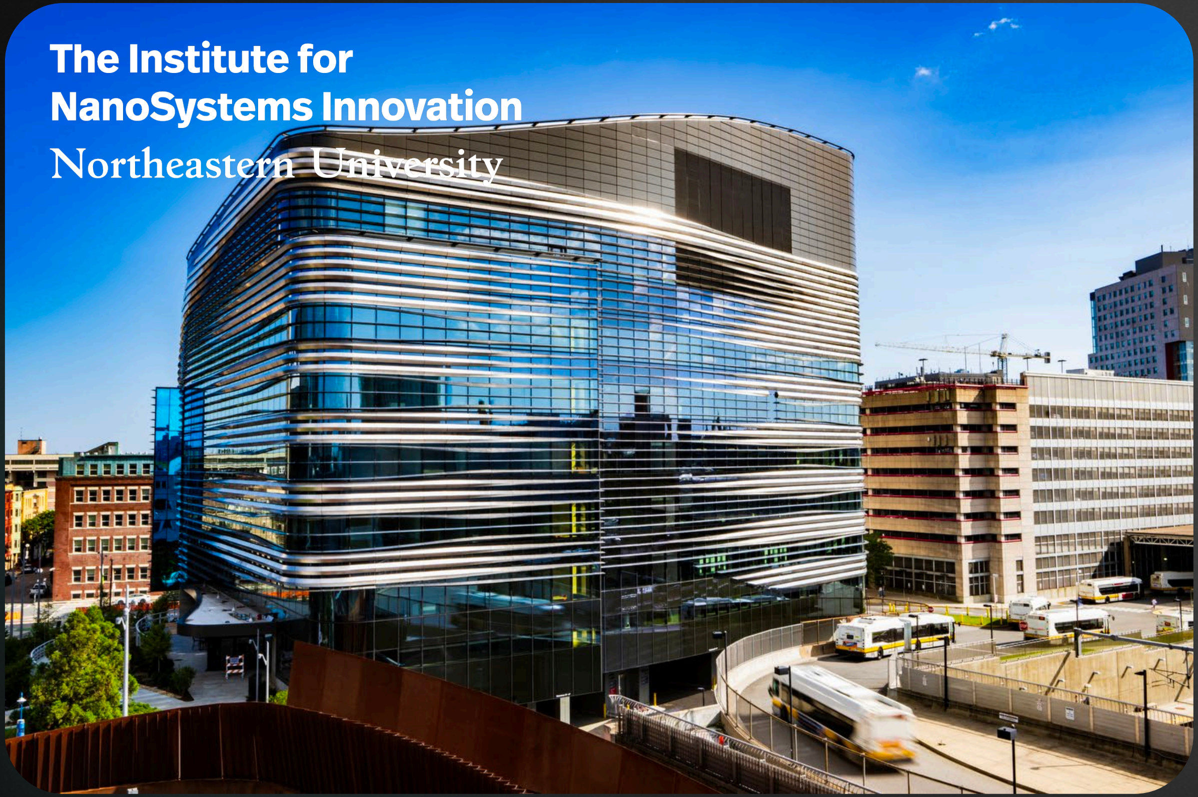
- 200 mm fabrication facility
- Equipped with state-of-the-art nanofabrication tools
- Equipped for superconducting device fabrication
- Equipped for cryogenic measurements

Northeastern EXP @ Boston Campus



- SNSPDs technology
  - Performance improvement
  - Heterogenous integration
  - New applications

- Nanowire microwave technology
  - High-kinetic inductance nanowire microwave devices

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EEC-1941585 (CQN)

DARPA
DETECT
Invisible Headlights

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 56 Sept 2024. Presentation given at WOLTE-16 2024, June 2024, Cagliari, Italy.

Thank you!

Questions?

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