IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 55, January, 2024. Plenary presentation given at ISS 2023, 29 Nov. 2023, Wellington, New Zealand

Superconducting photon detectors: past, present & future

Plenary PL-4

Robert Hadfield

James Watt School of Engineering, University of Glasgow, UK

Robert.hadfield@glasgow.ac.uk @QuantumSensors

36th International Superconductivity Symposium, Takina, Wellington, New Zealand 29th November 2023

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 55, January, 2024. Plenary presentation given at ISS 2023, 29 Nov. 2023, Wellington, New Zealand

University of Glasgow

Mazumdar-Shaw Advanced Research Centre

36th International Superconductivity Symposium, Wellington, New Zealand 29th November 2023

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University of Glasgow

Superconducting detectors & circuits @UoGARC

SuperQuARC: Professors Martin Weides & Robert Hadfield

Superconducting Quantum Devices Workshop SQD23 July 2023
SQD23 Chair Dr Kaveh Delfanazari

36th International Superconductivity Symposium, Wellington, New Zealand 29th November 2023

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James Watt Nanofabrication Centre

ISS International Symposium on Superconductivity

Virtual Tour: https://www.gla.ac.uk/research/az/jwnc/

JWNC James Watt Nanofabrication Centre | University of Glasgow

36th International Superconductivity Symposium, Wellington, New Zealand 29th November 2023

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What is a Photon?

- Einstein: a Photon is packet of electromagnetic energy

$$E = h\nu = hc/\lambda$$

- Energy (E) inversely proportional to wavelength (λ)

Einstein receiving honorary doctorate from GU in 1933

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Photon-counting technology

Wavelength

Detectors

Photomultipliers	IR PMTs

Hadfield Nat. Photon. **3** 696 (2009) ; Hadfield *et al.* Optica **10** 1124 (2023)

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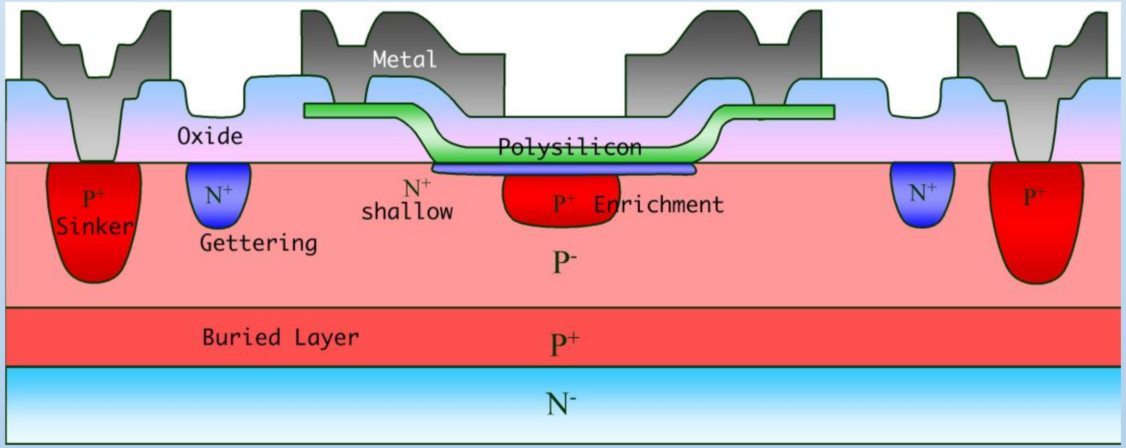
Photon-counting technology

Wavelength

Detectors

Photomultipliers | IR PMTs

Si SPADs | InGaAs SPADs



Hadfield Nat. Photon. **3** 696 (2009) ; Hadfield *et al.* Optica **10** 1124 (2023)

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Wavelength

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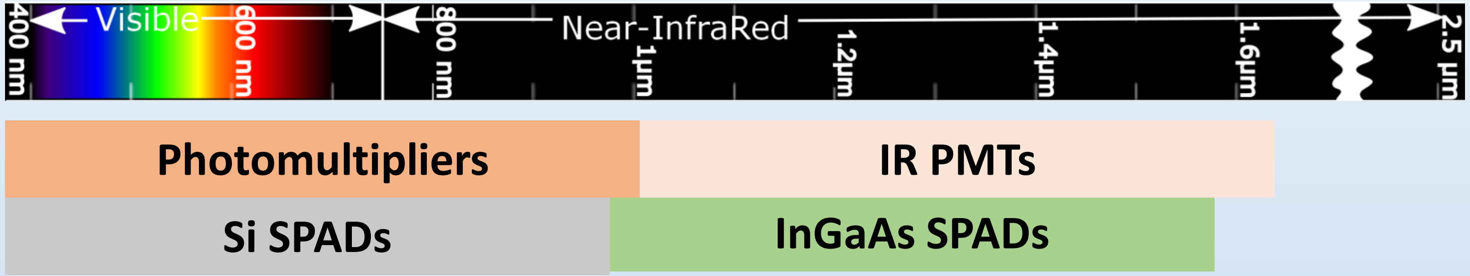

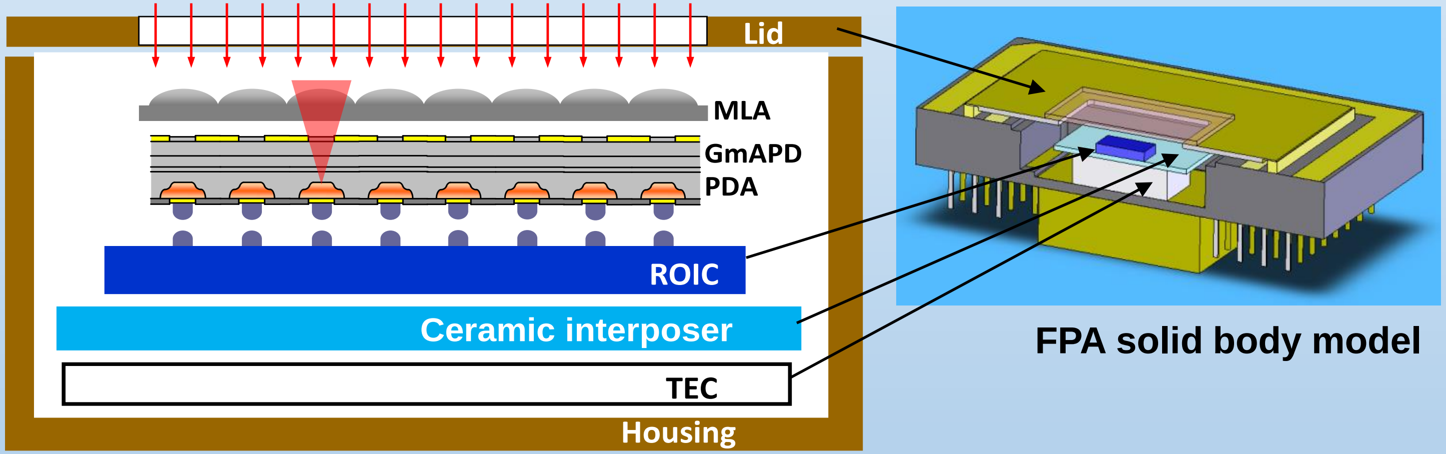

FPA solid body model

Hadfield Nat. Photon. **3** 696 (2009) ; Hadfield *et al.* Optica **10** 1124 (2023)

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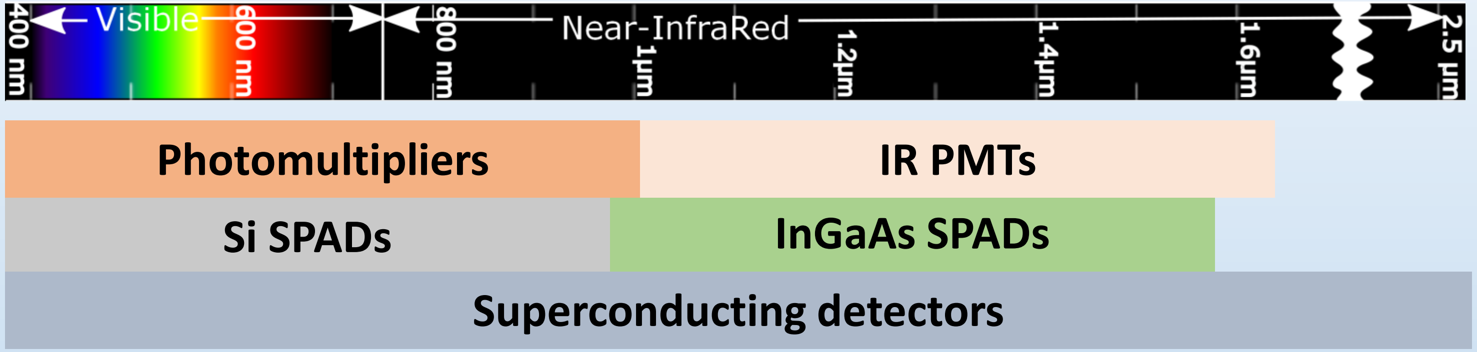
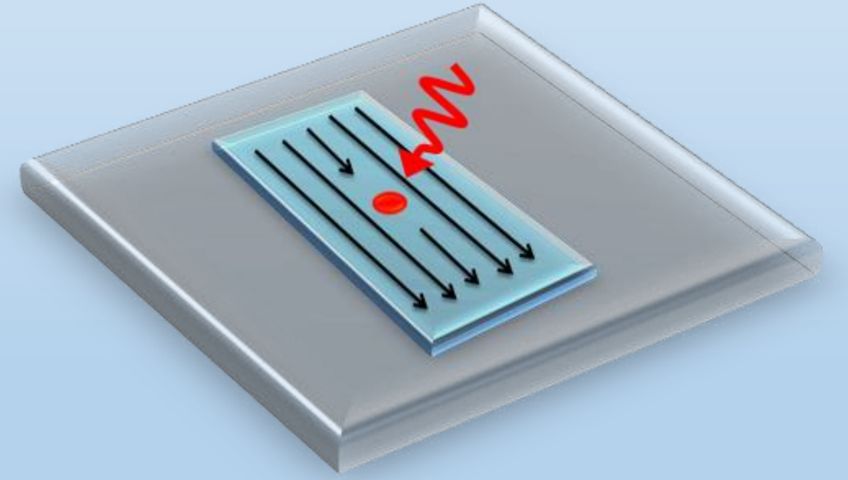
Photon-counting technology

Wavelength

Detectors





Hadfield Nat. Photon. **3** 696 (2009) ; Hadfield *et al.* Optica **10** 1124 (2023)

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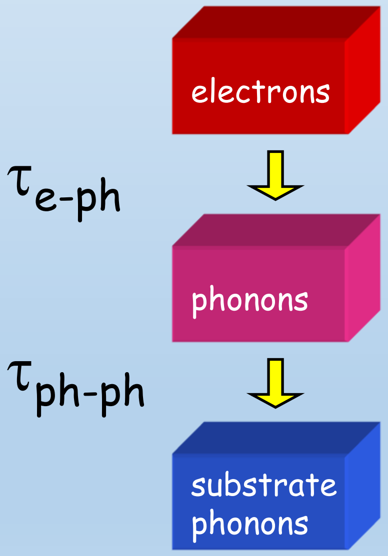
Photon detection in superconductors

Typically superconducting energy gap Δ ~meV.
=> Superconductors make extremely sensitive detectors from X-ray to Terahertz wavelengths.

One optical photon creates ~100–1000 excited electrons (superconducting gap ~2_meV for NbN). cf semiconductor – one optical photon creates one electron-hole pair, typical band gap 1-2 eV).



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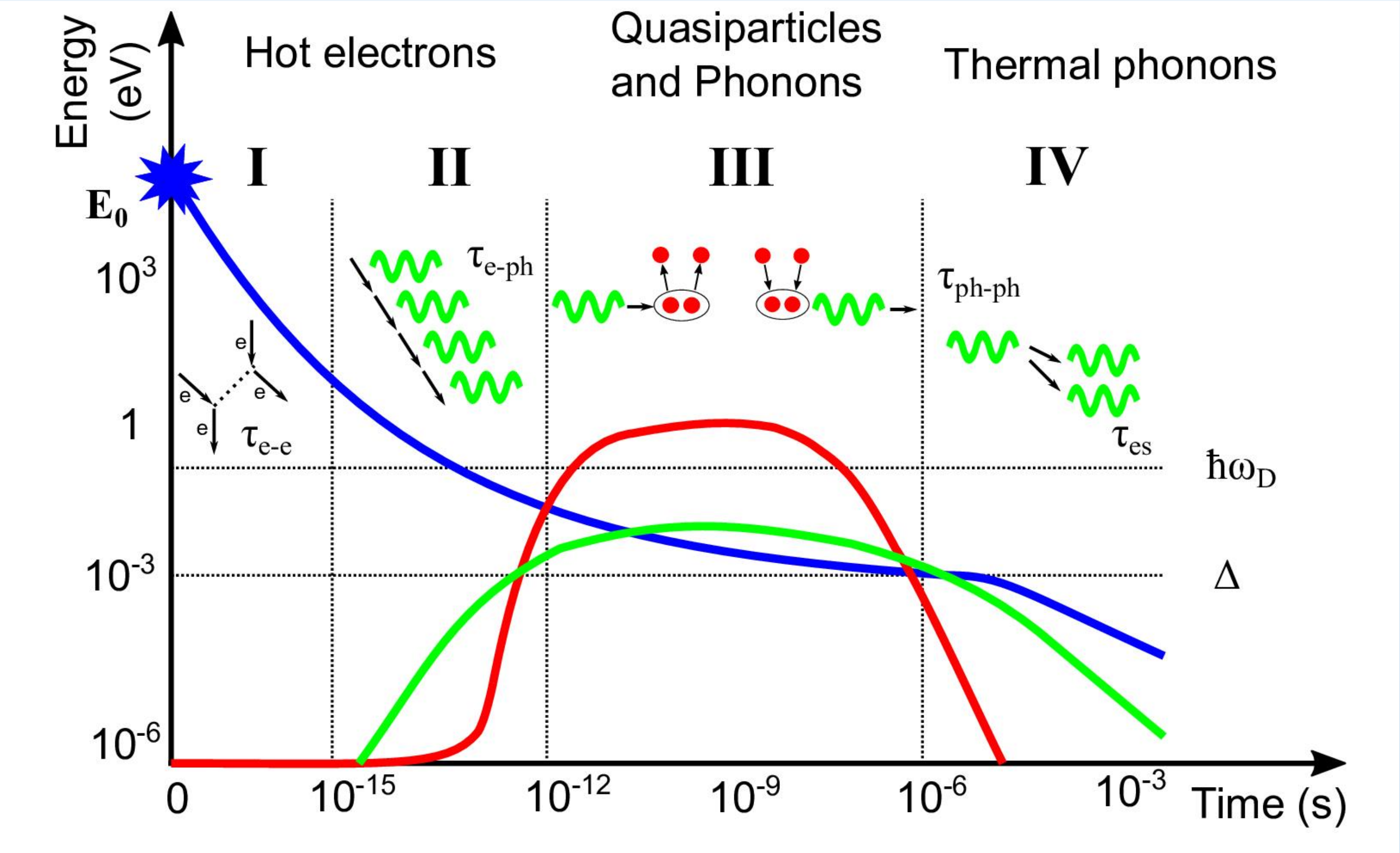

Review: *Superconducting Photon Detectors*
D Morozov, A Casaburi, RH Hadfield
Contemporary Physics 1-23 (2022)

36th International Superconductivity Symposium, Wellington, New Zealand 29th November 2023

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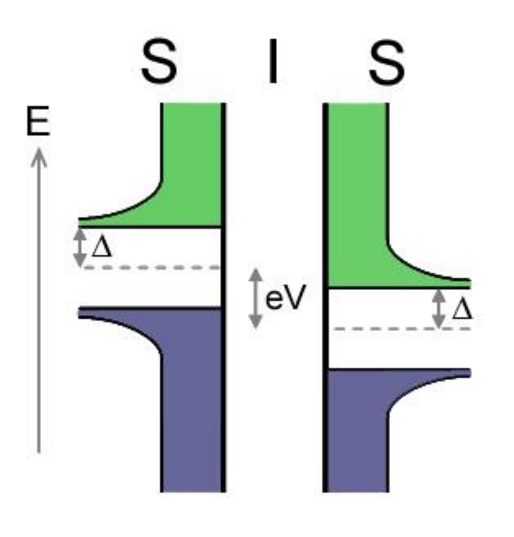
Superconducting photon detectors

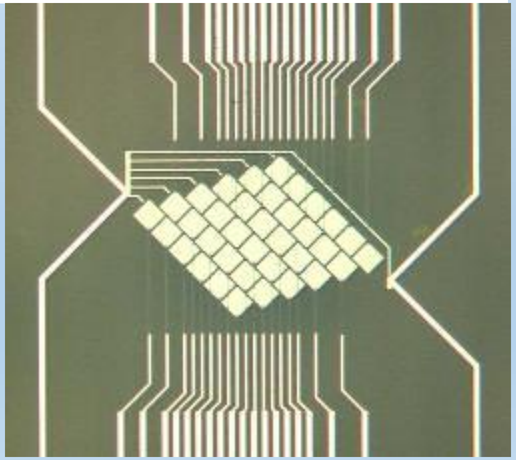
Superconducting Tunnel Junction (STJ)
Peacock Nature 381 135 (1996)

Transition Edge Sensor (TES)
Lita Optics Express **16** 3032 (2009)
Fukuda Optics Express **19** 870 (2011)

Kinetic Inductance Detector (KID)
Day Nature **425** 817(2002)
Zobrist APL **115** 213503 (2019)

Superconducting Nanowire Single-Photon Detectors (SSPDs/SNSPDs)
Gol'tsman APL **79** 705 (2001)
Oripov *et al. Nature* **622** 730 (2023)





See also session **ED-7** Detector Thursday 9am

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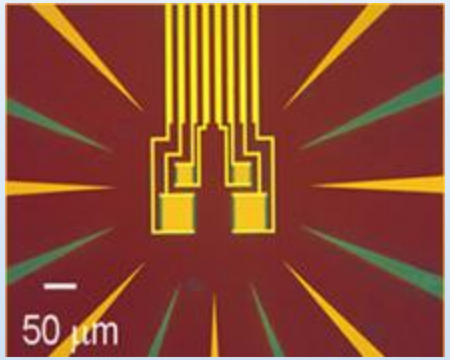

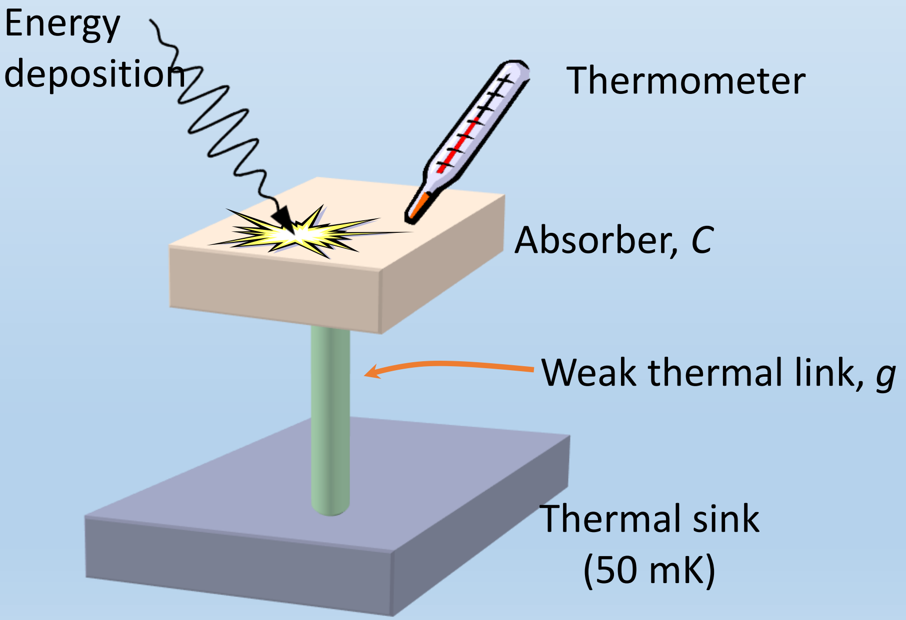

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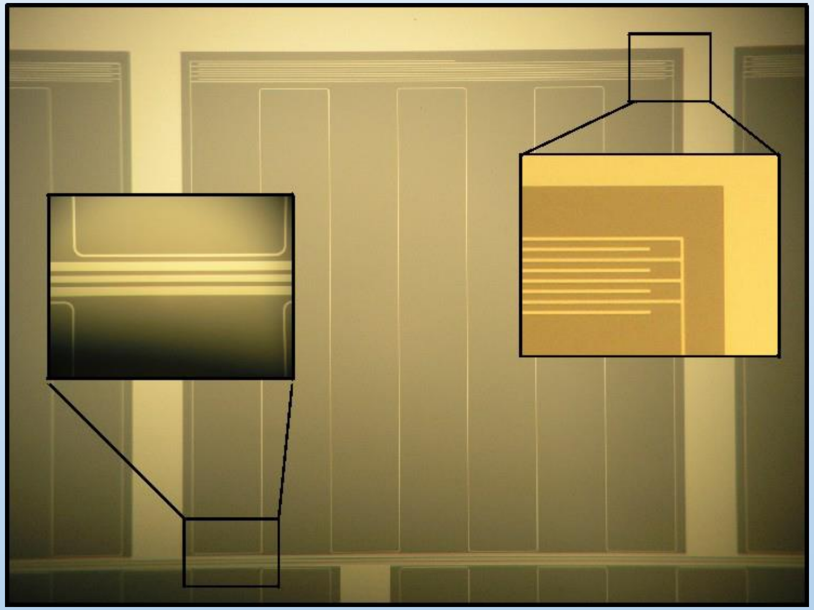

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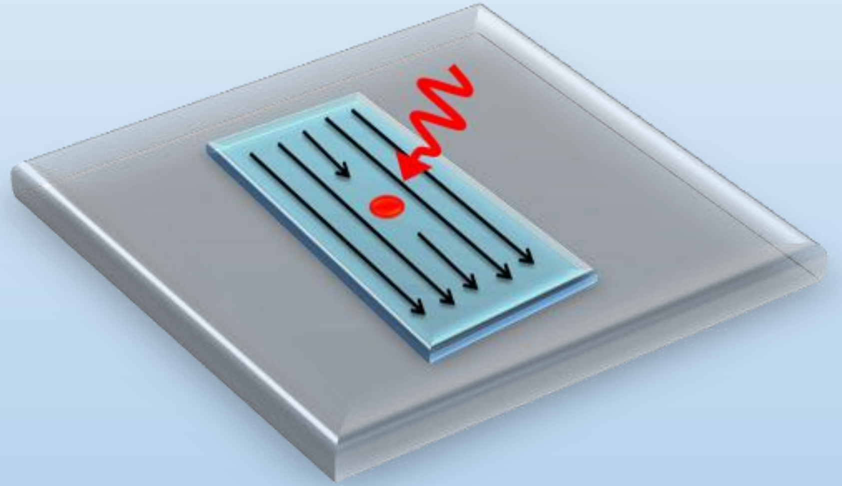
Gol'tsman APL 79 705 (2001)
Oripov et al. Nature 622 730 (2023)



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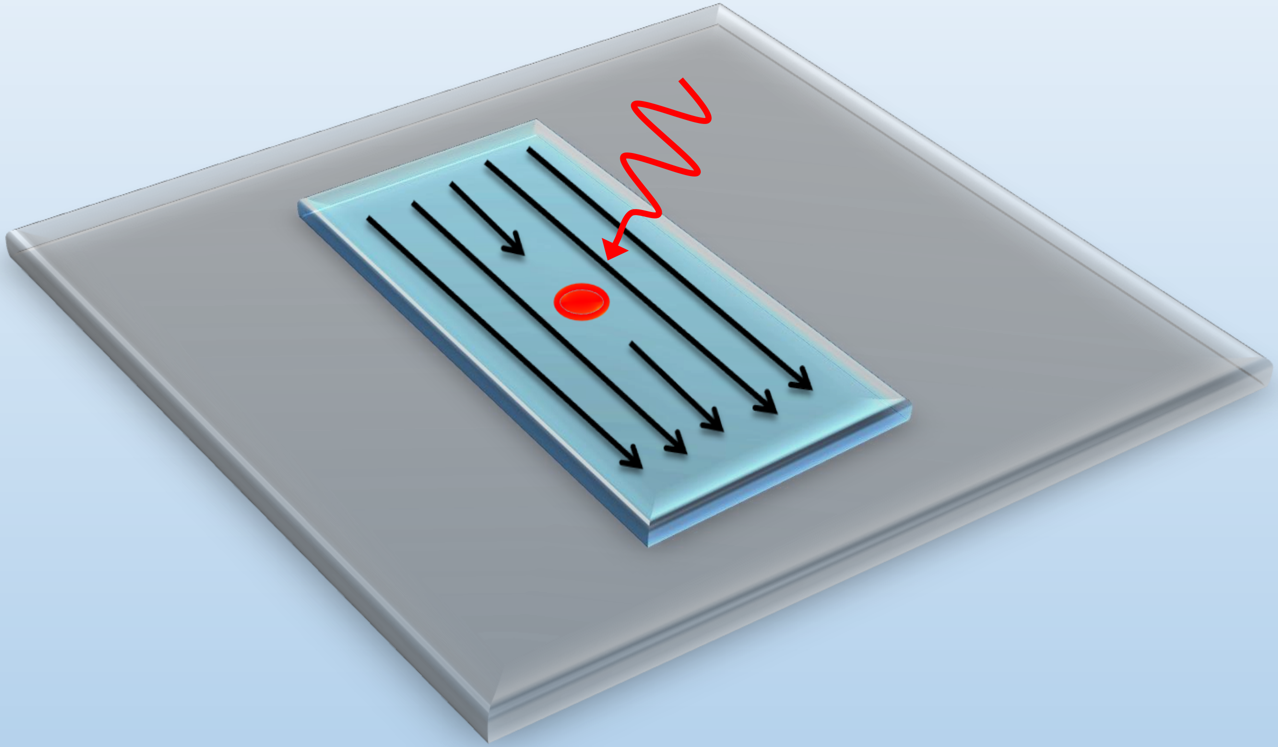
Superconducting Nanowire Single-Photon Detector (SNSPD)



Original Concept: Gol'tsman *et al* Applied Physics Letters **79** 705 (2001)

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Superconducting Nanowire Single-Photon Detector (SNSPD)

Key Properties

- Wide spectral range (UV – mid IR)
- Near unity detection efficiency possible
- Operates at 4 K (not mK)
- Free running (no gating required)
- Low dark counts
- Low timing jitter
- Short recovery time

A rapidly improving technology which is commercially available!

Topical Reviews: C M Natarajan *et al Superconducting nanowire single-photon detectors: physics & applications* Superconductor Science & Technology **25** 063001 (2012)
Morozov *et al Superconducting Photon Detectors* Contemporary Physics 1-23 (2022)

Original Concept: Gol'tsman *et al* Applied Physics Letters **79** 705 (2001)

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Worldwide SNSPD community: Bad Honnef, Germany, November 2018

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Commercialization of SNSPDs worldwide

DETECTORS

Russia Scontel
USA PhotonSpot
NL Single Quantum
USA Quantum Opus
Switz. ID Quantique
China Photon Technologies
Germany Pixel Photonics

CRYOGENICS

UK Chase Research Cryogenics
Japan Sumitomo Heavy Industries

Photon Spot — Cryogenics Detectors Solutions
Quantum Opus
Chase Research Cryogenics
SINGLE QUANTUM
id Quantique
Pixel Photonics
SCONTEL — SUPERCONDUCTING NANOTECHNOLOGY — Detect everything you want
赋同科技 —PHOTEC—
SHI Cryogenics Group

36th International Superconductivity Symposium, Wellington, New Zealand 29th November 2023

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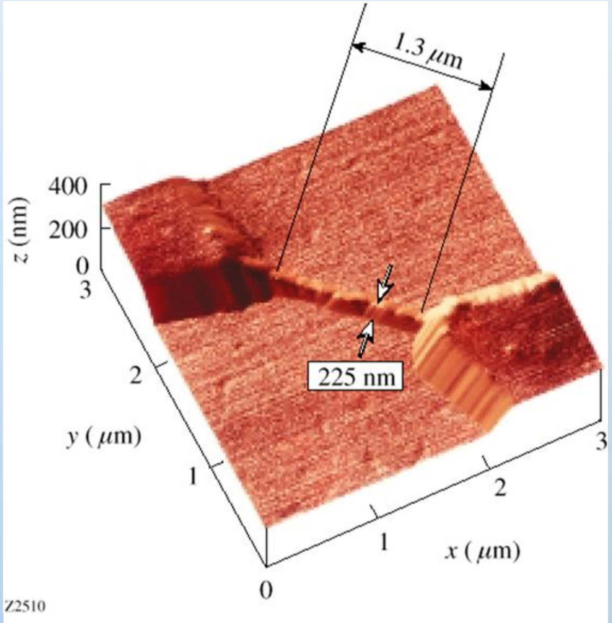
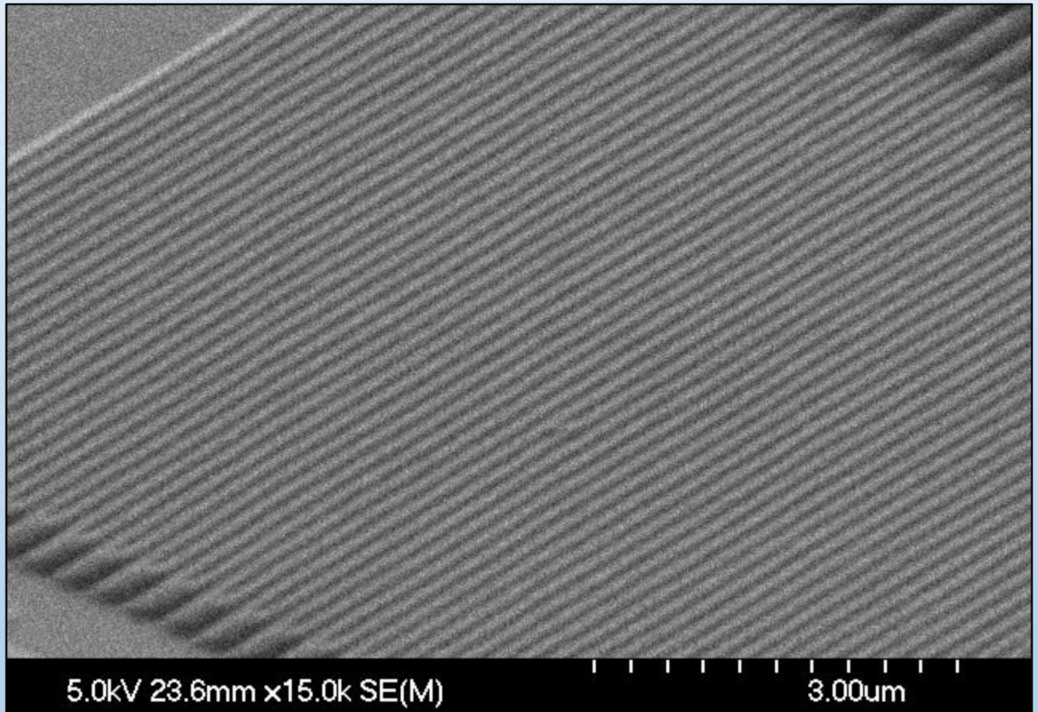
SNSPDs – increasing active area

Basic Device



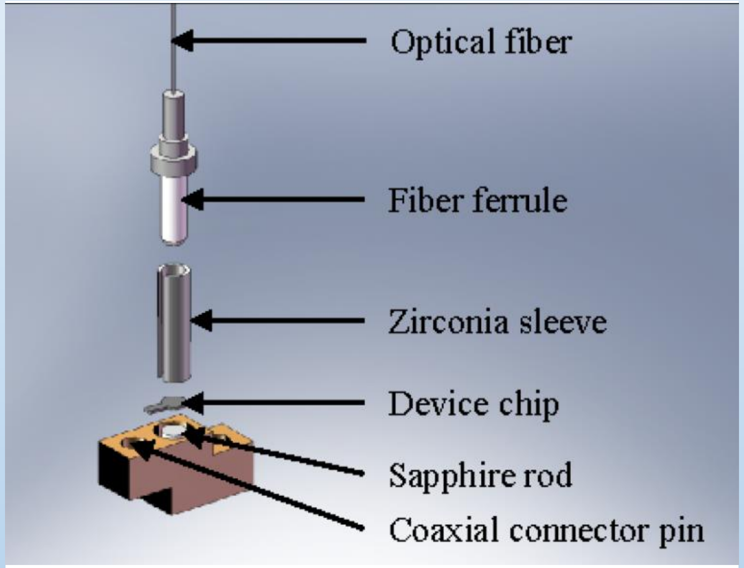
Gol'tsman *et al* Applied Physics Letters **79** 705 (2001)

Meander



Verevkin *et al* Applied Physics Letters 80 4687 (2002)

Fibre Coupling

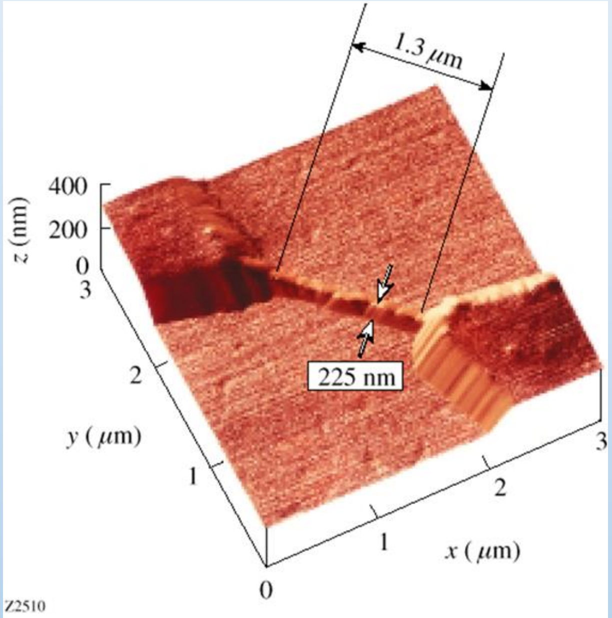


Dauler *et al* Optical Engineering (2014)

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 55, January, 2024. Plenary presentation given at ISS 2023, 29 Nov. 2023, Wellington, New Zealand

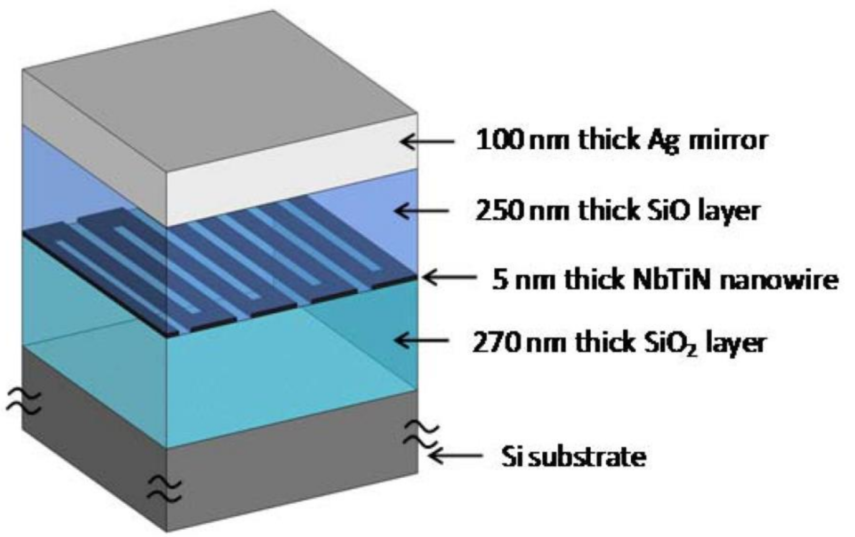
SNSPDs – maximising detection efficiency

Basic Device

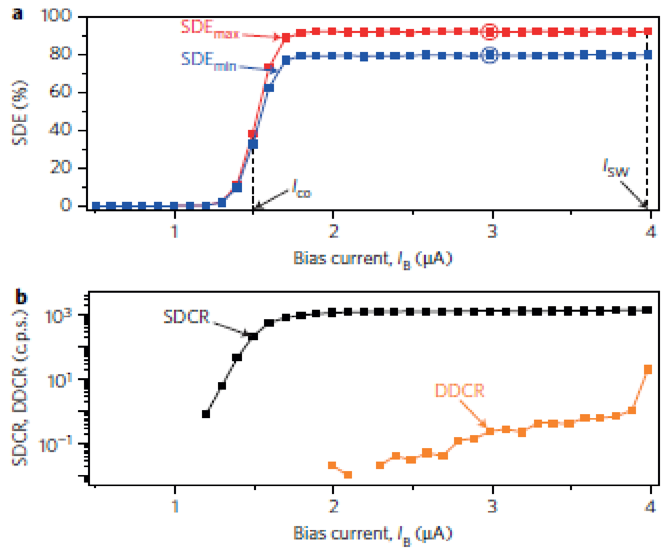


Gol'tsman *et al* Applied Physics Letters **79** 705 (2001)

Optical Cavity



Rosfjord *et al* Optics Express **14** 527 (2006)
Miki *et al* Optics Express **17** 23557 (2009)



93% Marsili *et al* Nat. Photon. **7** 210 (2013) λ=1550nm
98.5% Reddy *et al* Optica **7** 1649 (2020) λ=1550nm
99% Chang *et al* APL Photonics **6** 036114 (2021) λ=1310nm
90.5% Zhang et al IEEE JSTQE 28 3803708 (2022)) λ=1550nm
84% China et al Optics Express (2022) λ = 2μm

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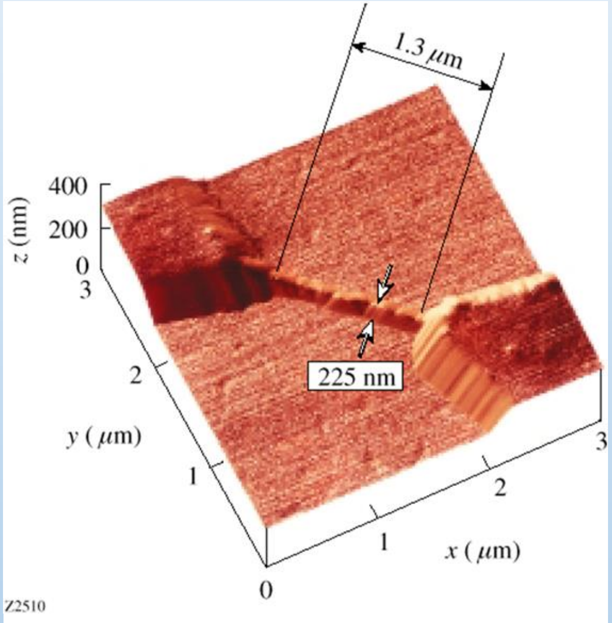
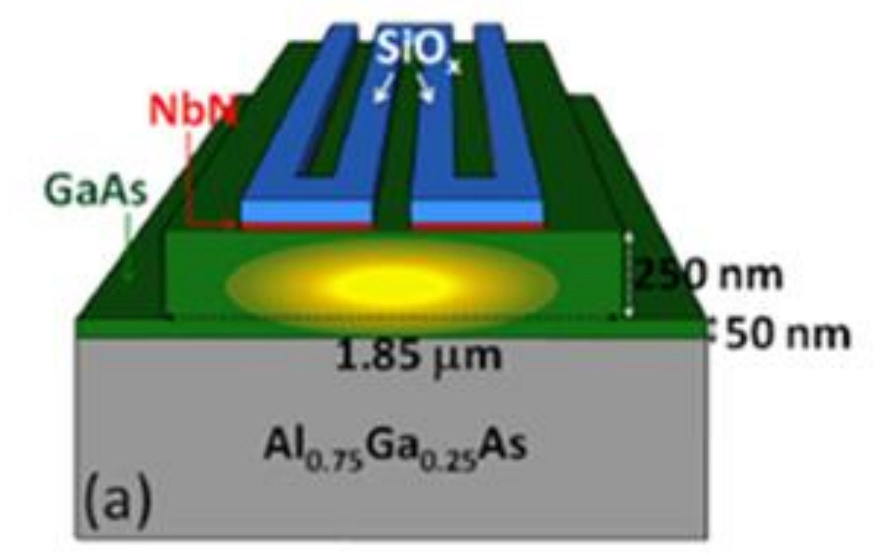
SNSPDs – waveguide integration

Basic Device



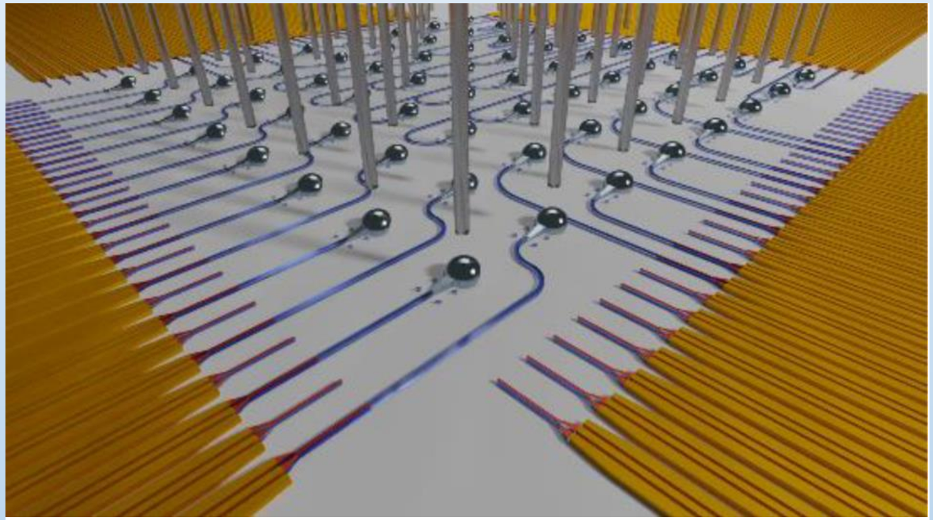
Gol'tsman *et al* Applied Physics Letters **79** 705 (2001)

Waveguide Integration



TU Eindhoven Sprengers APL **99** 18110 (2011)
Yale Pernice Nat. Comms **3** 1325(2012)

64-channel QKD receiver



Terhaar *et al.* Optics Express **31** 2675 (2023)
Pernice Munster/Heidelberg

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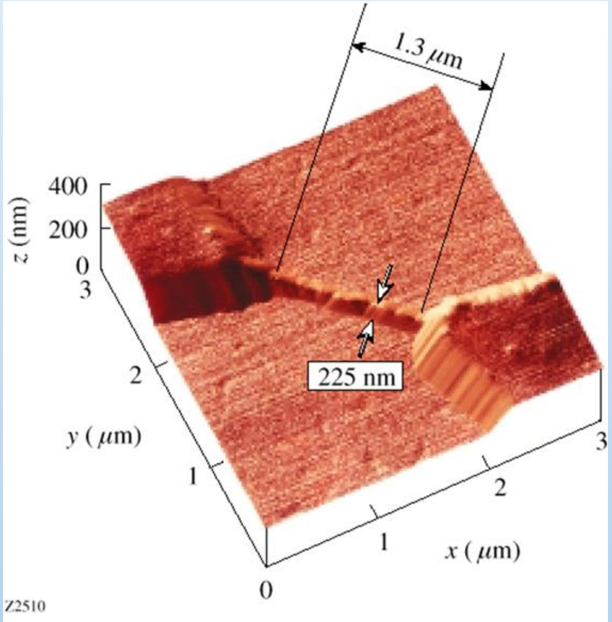
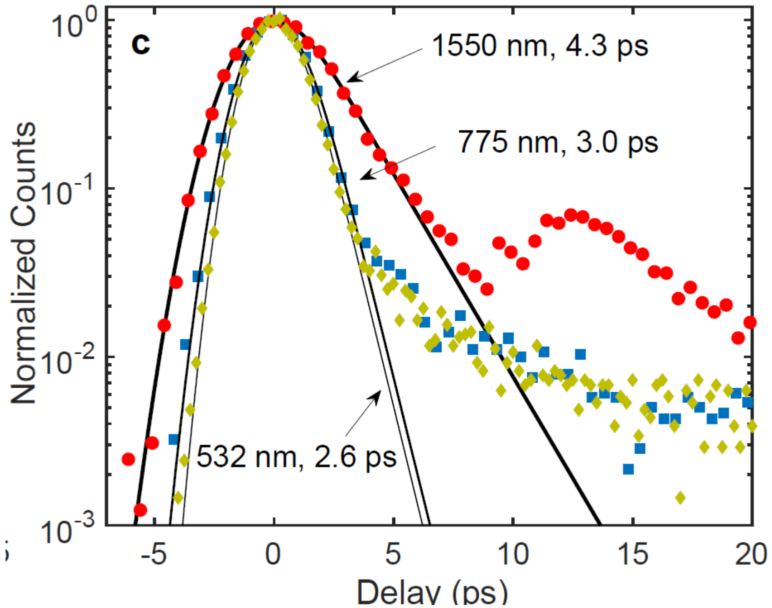
SNSPDs – low jitter

Basic Device



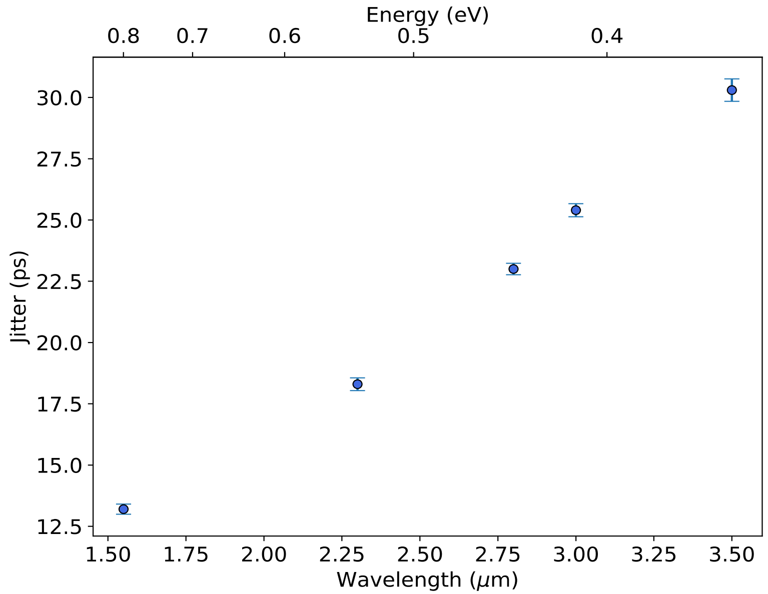
Gol'tsman *et al* Applied Physics Letters **79** 705 (2001)

3 ps timing jitter



Korzh *et al.* Nat. Photon. **14** 250 (2020)
News & Views Hadfield Nat. Photon. **14** 201 (2020)

NIR-MIR timing jitter



Taylor et al. Appl. Phys. Lett. 121 214001 (2022) Glasgow/NASA JPL

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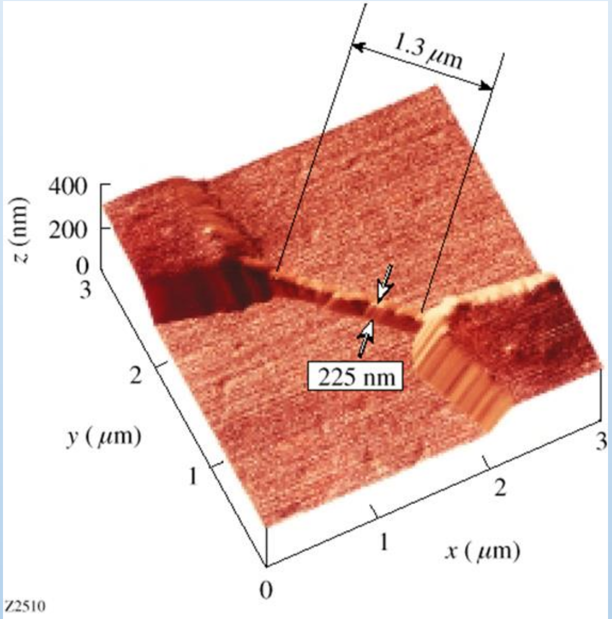
SNSPDs – low jitter

Basic Device



Gol'tsman *et al* Applied Physics Letters **79** 705 (2001)

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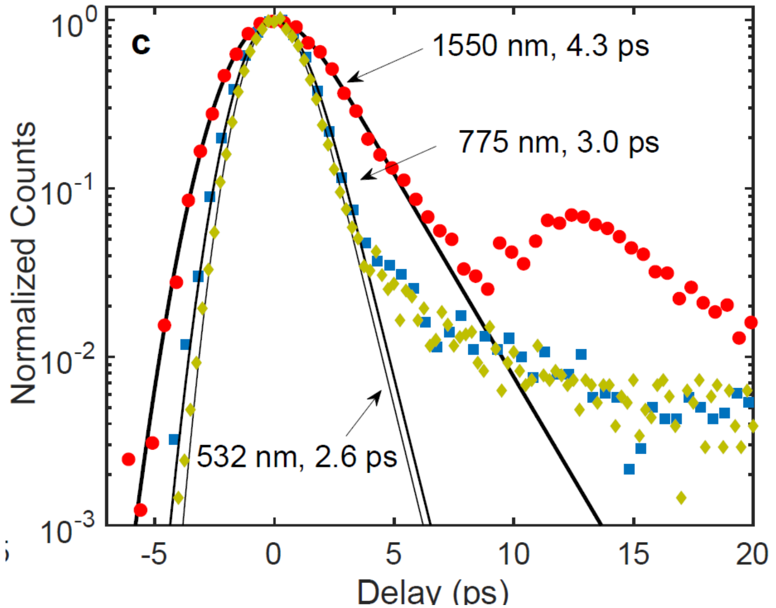
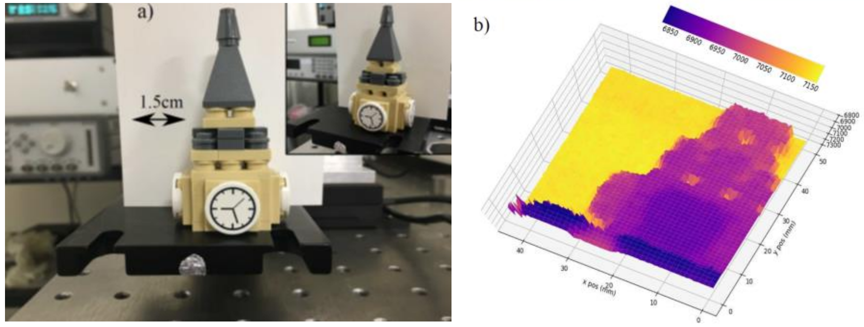


Korzh *et al.* Nat. Photon. **14** 250 (2020)

News & Views Hadfield Nat. Photon. **14** 201 (2020)

MIR single-photon LIDAR



SNSPD photon counting LIDAR at λ = 2.3 μm Glasgow/NICT

Taylor *et al* Optics Express **27** 8147 (2019)

Hadfield *et al* Optica **10** 1124 (2023)

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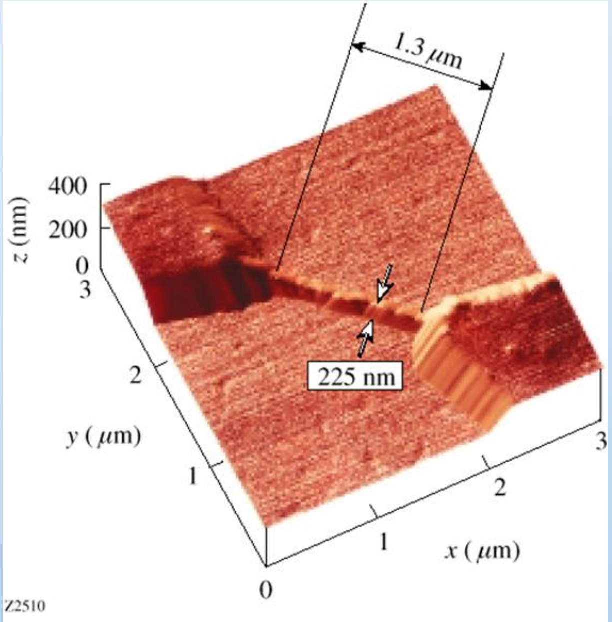
University of Glasgow

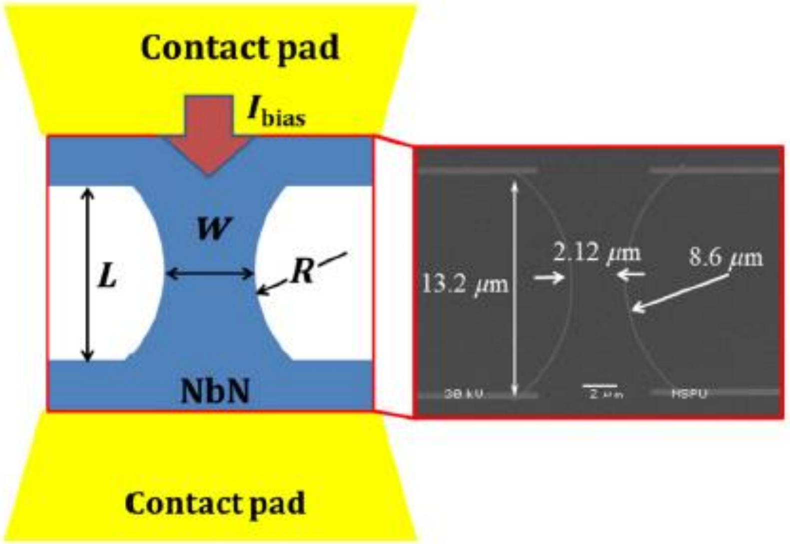
From nanowires to microstrips

Basic Device



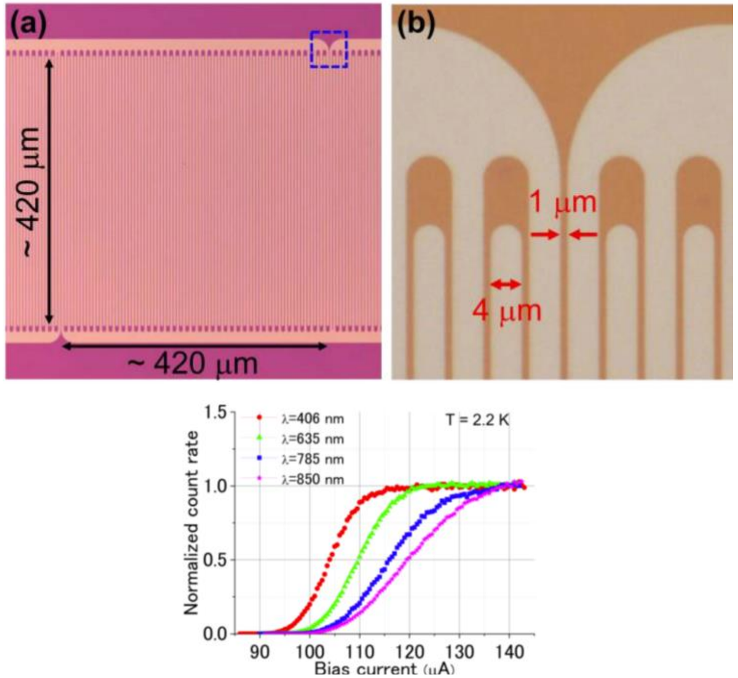
Gol'tsman *et al* Applied Physics Letters **79** 705 (2001)

Microstrip



Korneeva *et al* Phys Rev Applied 9 064037 (2018)

Microstrip with UV Stepper



Yabuno *et al* IEEE TAS 2200104 (2023)

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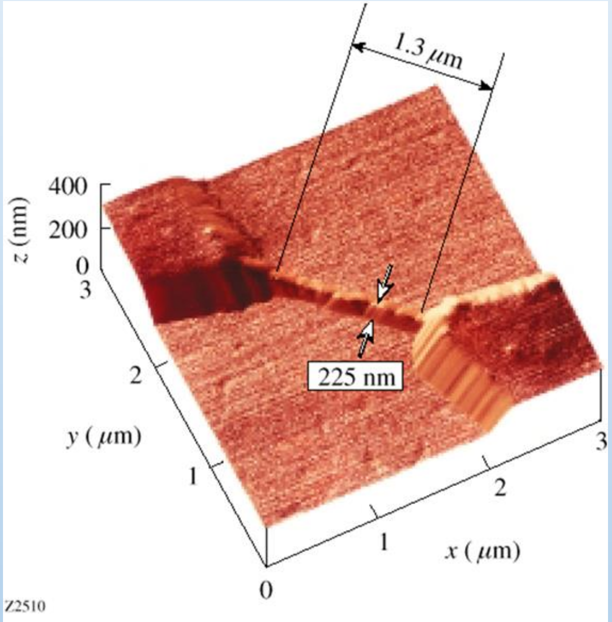
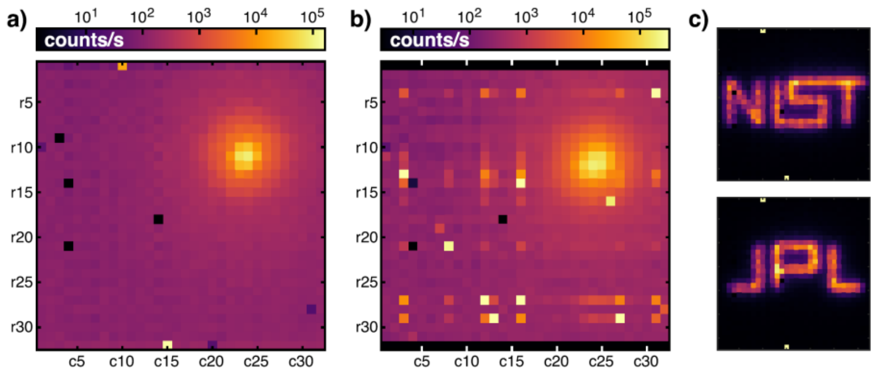
Scale up to large SNSPD arrays

Basic Device



Gol'tsman *et al* Applied Physics Letters **79** 705 (2001)

Row-Column readout



Low bias

High bias

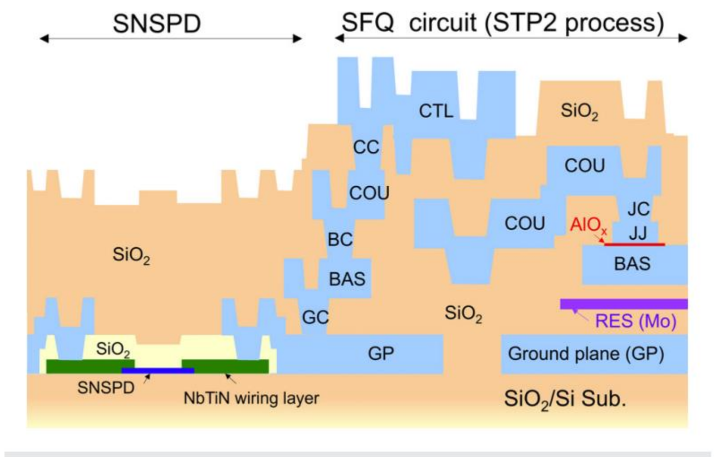
32 x 32 kilopixel array (JPL/NIST)

Wollman *et al.* Optics Express **11** 247 (2019)

SFQ integration

NICT/AIST

ISS 2023
ED-1-1-INV
S Miyajima



Yamashita, *et al.* Opt. Lett. **37** 2982 (2012)
Miyajima et al APL 122, 182602 (2023)

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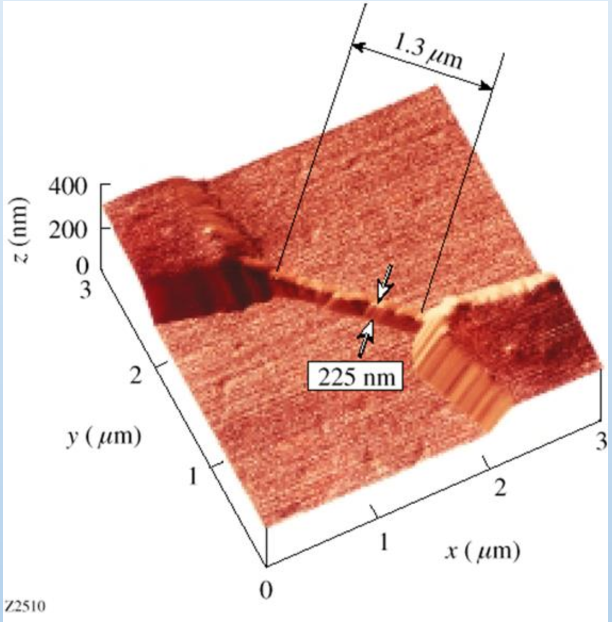
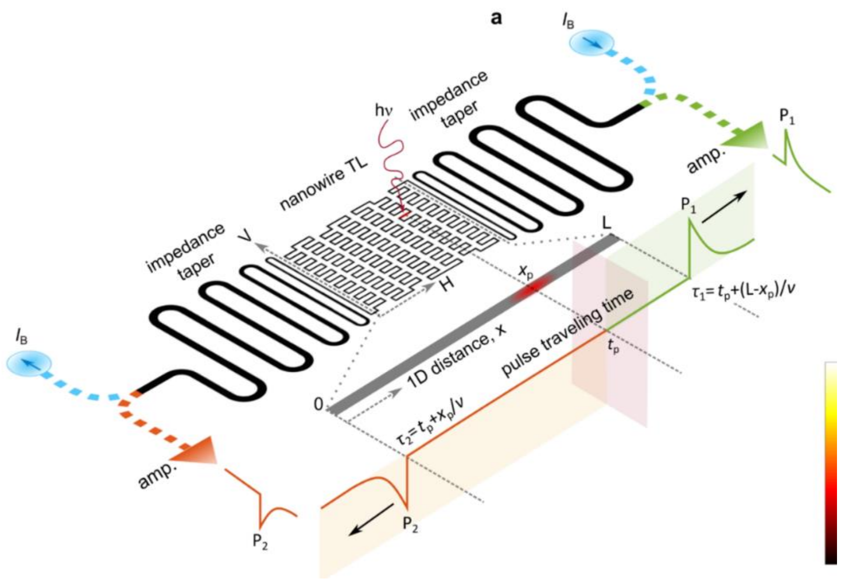


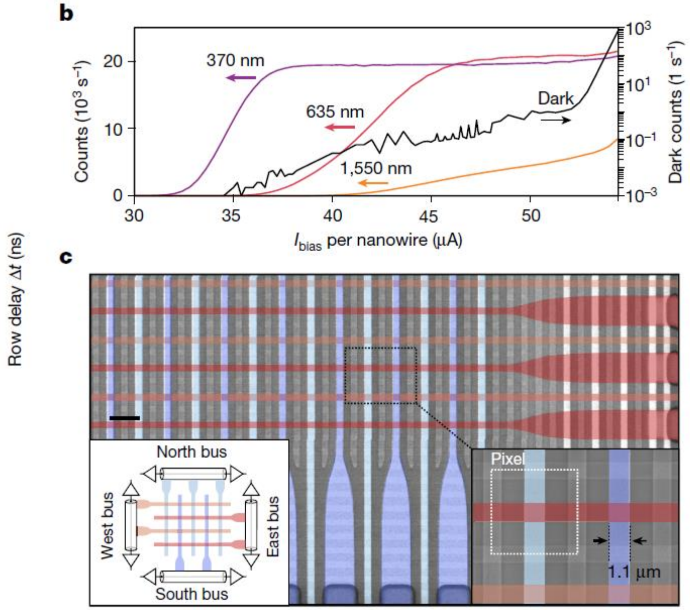
Gol’tsman *et al* Applied Physics Letters **79** 705 (2001)

Single photon imager



Zhao, Q.-Y. *et al. Nat. Photonics* **11,** 247–251 (2017)

400,000 pixel SNSPD array



A McCaughan *et al* APL **121** 102602 (2022)
B. Oripov *et al. Nature* **622** 730 (2023)

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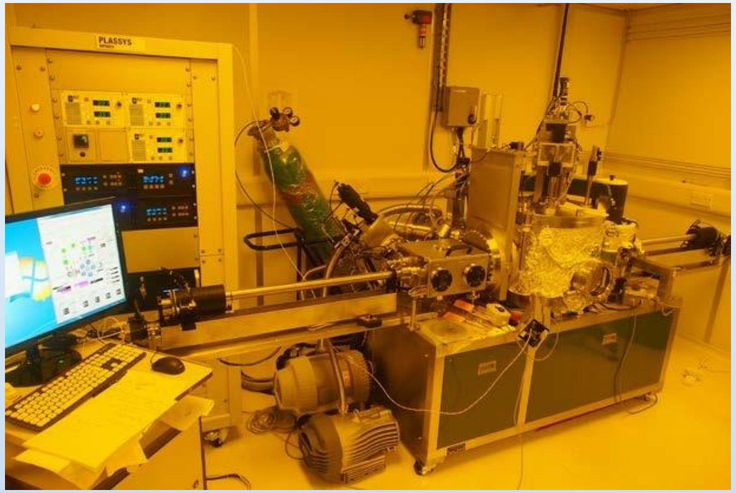
SNSPDs – materials development



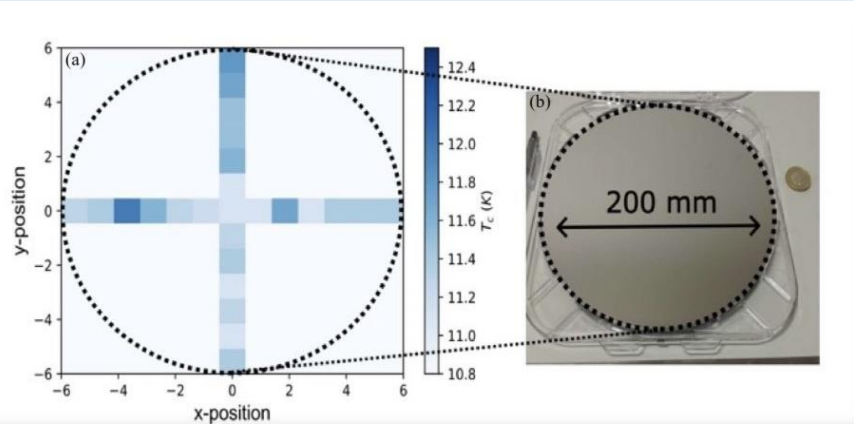
Sputtering

Reactive sputtering of NbN, TiN & NbTiN on room temperature or heated substrates

Sputtering of amorphous superconductors WSi, MoSi on room temp or cooled substrates

Plassys VI tool JWNC: deposition across 150 mm/6” wafers

A Banerjee *et al* Superconductor Science & Technology 30 084101 (2016)
A Banerjee *et al* Optics Materials Express 8 2072 (2018)



Atomic Layer Deposition

Layer by layer growth of NbN and TiN

Enhanced superconducting properties through substrate bias (OIPT Yatton)

Atomic layer etch (ALE) processes under development (TU Eindhoven)

Conformal growth across 200 mm/8” wafers

M Dineen, H Knoops, T Hemakumara
Atomic Layer Deposition for Quantum Devices OIPT White Paper (2019)
G Taylor *et al* Appl. Phys. Lett. 118 191106 (2021)
C Lennon *et al* Materials for Quantum Technology 3 045401 (2023)

JWNC James Watt Nanofabrication Centre | University of Glasgow | OXFORD INSTRUMENTS PLASMA TECHNOLOGY | TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY

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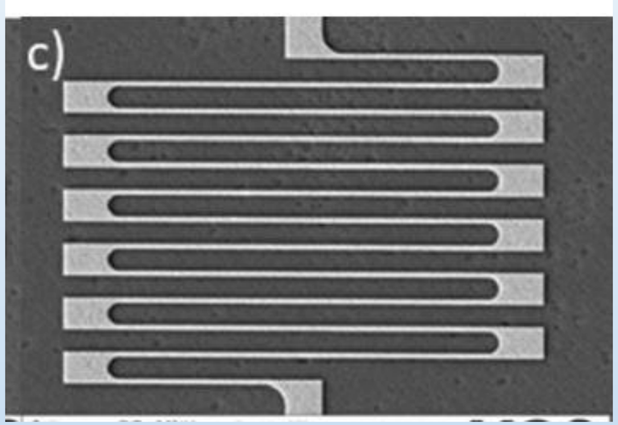
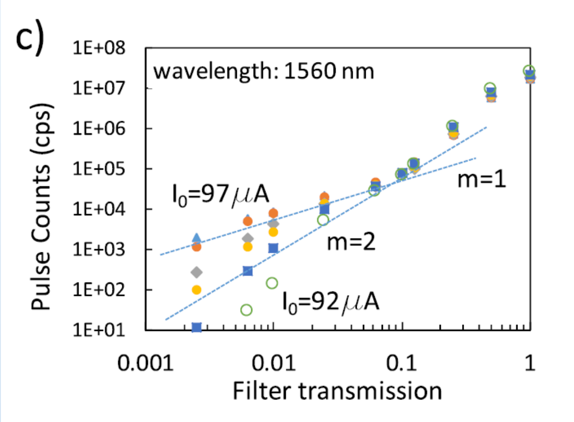
New materials for SNSPDs

Magnesium Diboride (MgB_2) SNSPDs

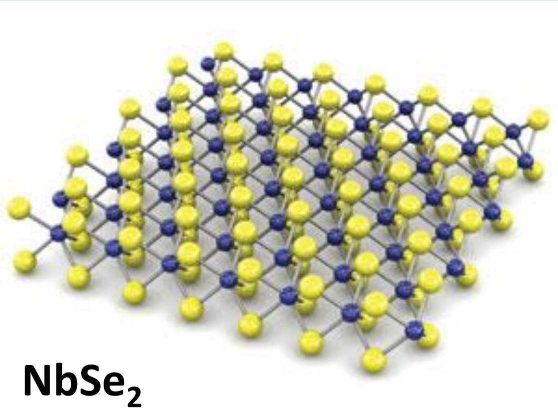
Shibata *et al.* APL 97 212504 (2010)
Shibata *et al.* Appl. Phys. Express 6 023101 (2013)
Cherednichenko *et al.* SUST 34 044001 (2021)

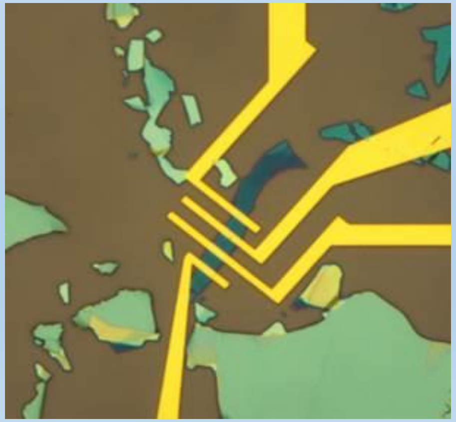


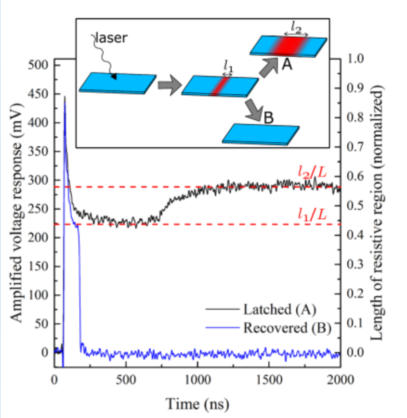


Niobium diselenide ($NbSe_2$) photodetector

Orchin *et al.* APL 114 251103 (2019)
Glasgow/Cambridge/Manchester







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High temperature superconductor SNSPDs

nature nanotechnology

Article https://doi.org/10.1038/s41565-023-01325-2

Single-photon detection using high-temperature superconductors

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Published online: 20 March 2023

Check for updates

I. Charaev[1,2,8], D. A. Bandurin[3,8], A. T. Bollinger[4], I. Y. Phinney[1], I. Drozdov[4], M. Colangelo[1], B. A. Butters[1], T. Taniguchi[5], K. Watanabe[6], X. He[4,7], O. Medeiros[1], I. Božović[4,7], P. Jarillo-Herrero[1] & K. K. Berggren[1]

News & views

2D materials https://doi.org/10.1038/s41565-023-01334-1

Superconducting single-photon detectors get hot

Jin Chang & Iman Esmaeil Zadeh

Check for updates

High-T_c superconducting nanowire detectors can detect single photons of telecom wavelengths at a temperature of 25 K and may enable applications in quantum sensing and quantum information processing.

and space exploration; b) several experiments have enhanced our understanding of the physical mechanisms behind the single-photon detection[4]. As for the latter, despite significant progress in the field, the exact detection mechanism still remains elusive. Importantly, while SNSPDs have excelled in many performance metrics, pushing their limits even further, e.g., improving the sensitivity to low energy photons, or increasing the operating temperature, may require deeper insights into the detection mechanism. Elevating the working tempera-

IOP Publishing 2D Mater. 10 (2023) 021001 https://doi.org/10.1088/2053-1583/acb4a8

2D Materials

LETTER

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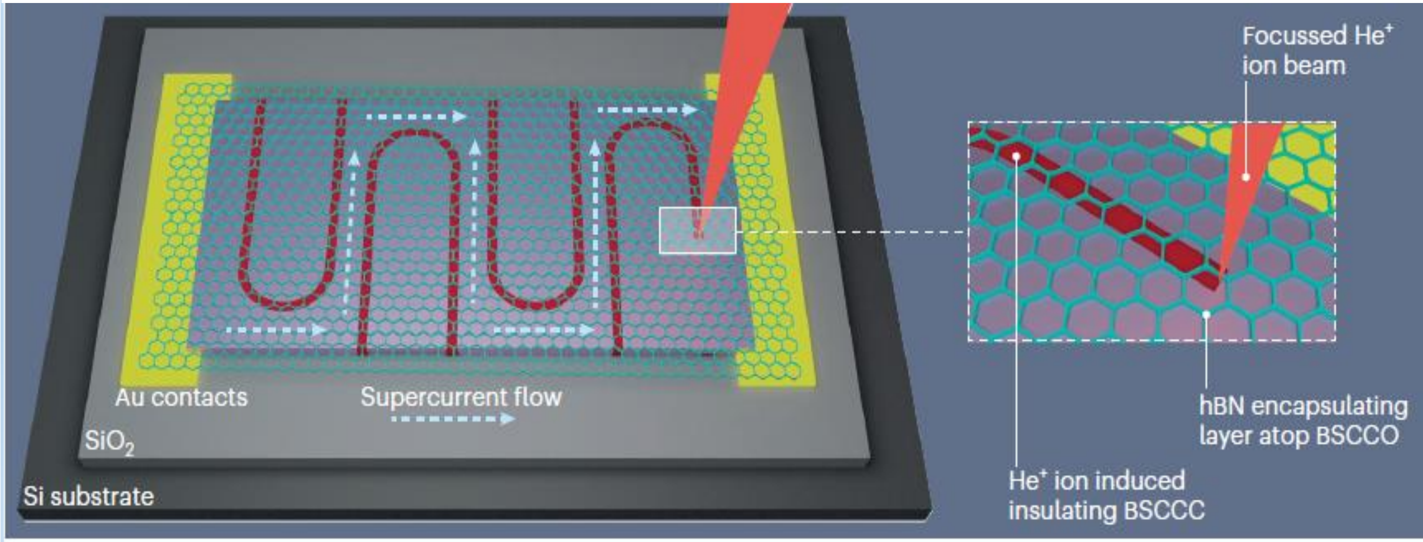
Two-dimensional cuprate nanodetector with single telecom photon sensitivity at $T = 20$ K

Rafael Luque Merino[1,8,9,*], Paul Seifert[1,2], José Durán Retamal[1,3], Roop K Mech[1,8,9], Takashi Taniguchi[4], Kenji Watanabe[5], Kazuo Kadowaki[6], Robert H Hadfield[7] and Dmitri K Efetov[1,8,9,*]

1 ICFO—Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, Castelldefels, Barcelona 08860, Spain
2 Institute of Physics, Faculty of Electrical Engineering and Information Technology (EIT 2), Universität der Bundeswehr München,



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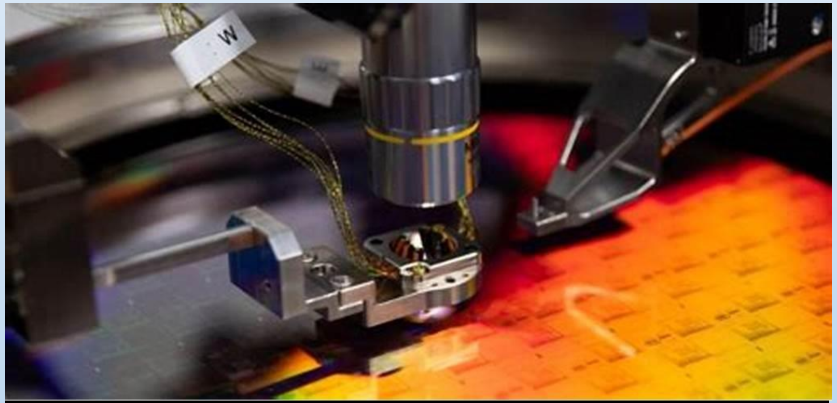
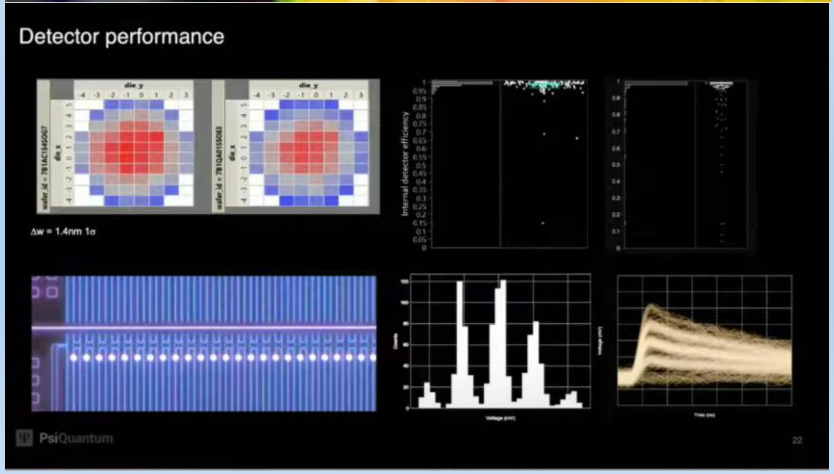
Frontier applications of superconducting photon detectors

Quantum Computing (See session **ED-5 & 9** for superconducting qubits)

Photonic quantum computer platform with integrated SNSPDs (PsiQuantum/Global Foundries)

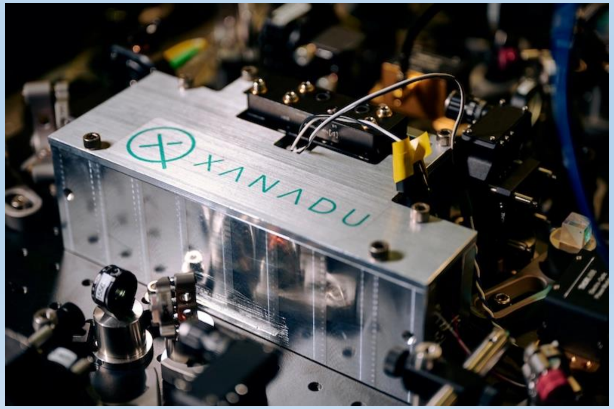




J L O'Brien *et al*. Quantum Australia (2023)

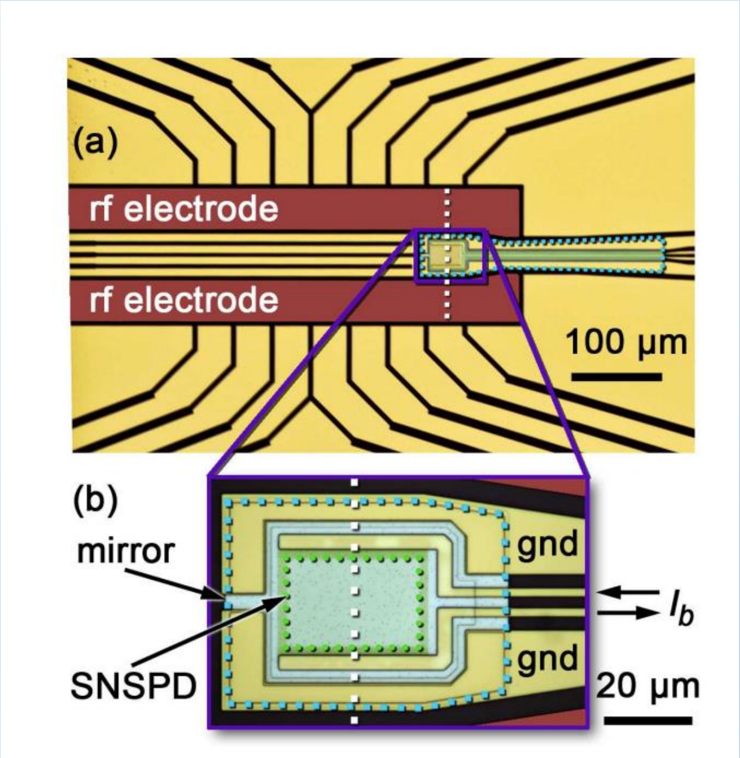
Quantum advantage via boson sampling SNSPDs (USTC China) TES (Xanadu/NIST)

Zhong *et al*. Science **370** 1460 (2020)



Madsen *et al*. Nature **606** 75 (2022)

Ion trap qubit with integrated SNSPD (NIST USA)



Hampel *et al*. APL **122** 174001 (2023)

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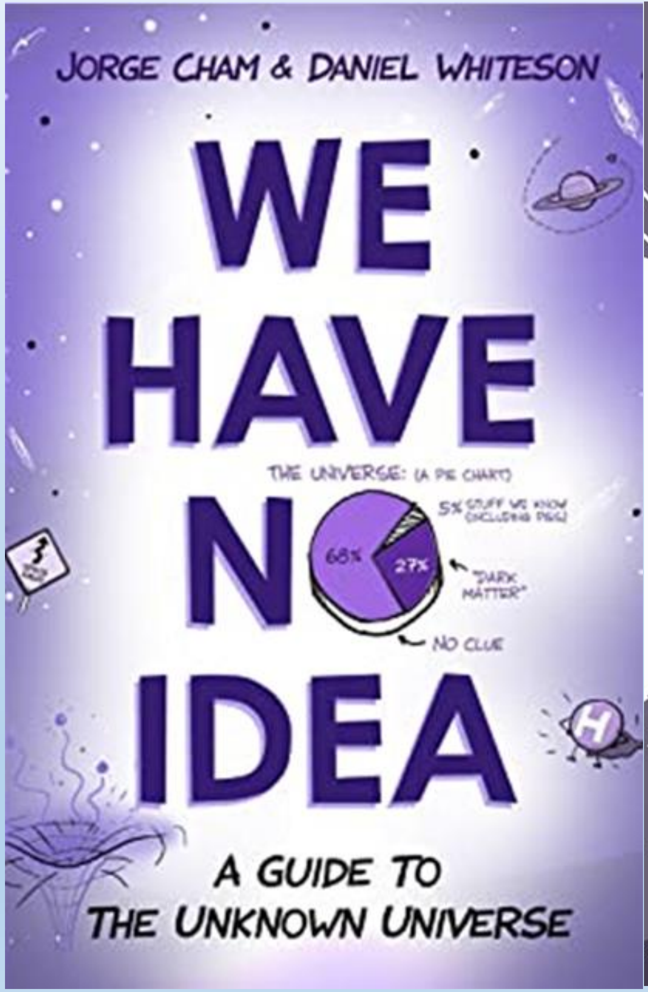
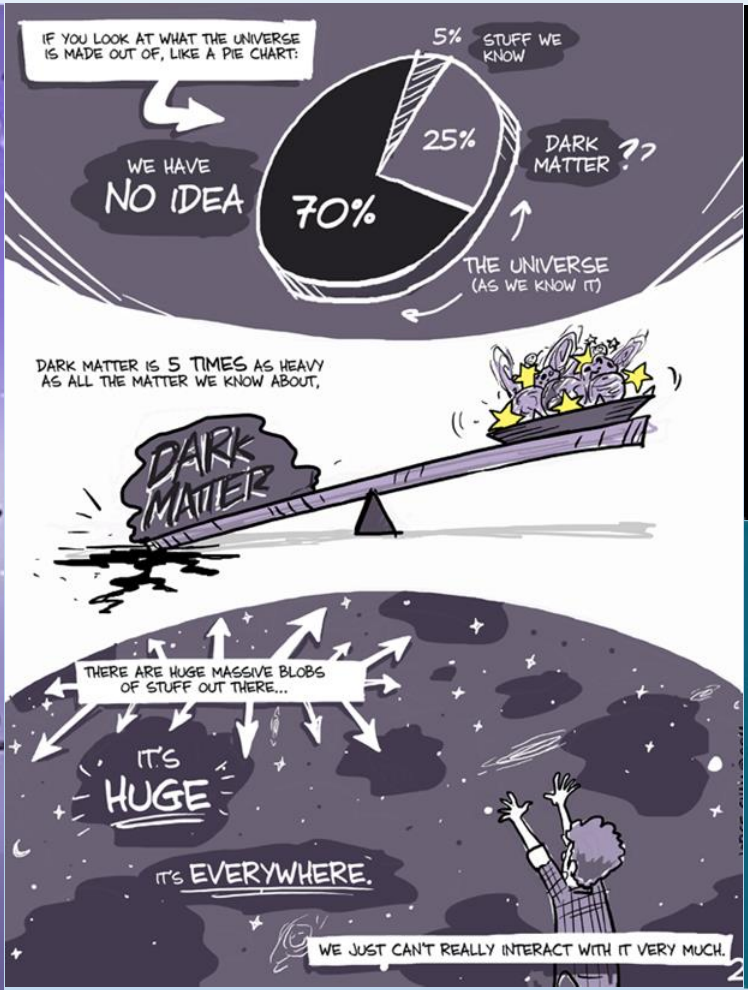
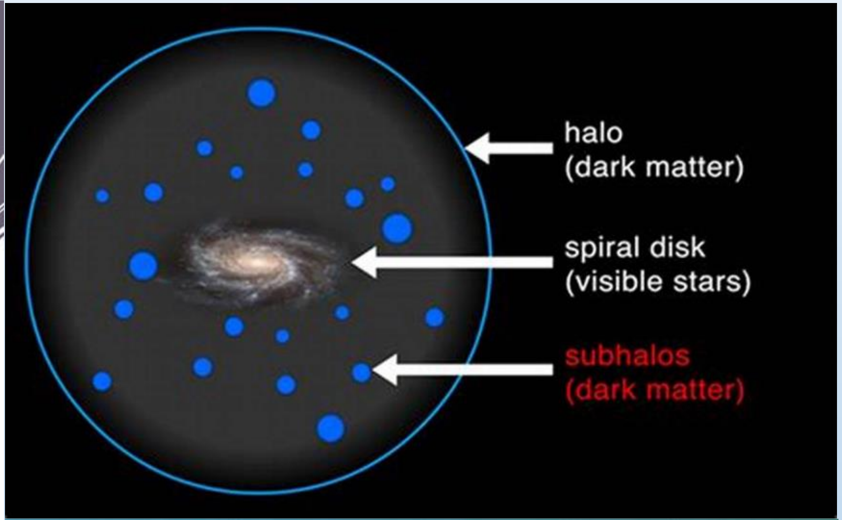
Frontier applications of superconducting photon detectors

Dark Matter Searches







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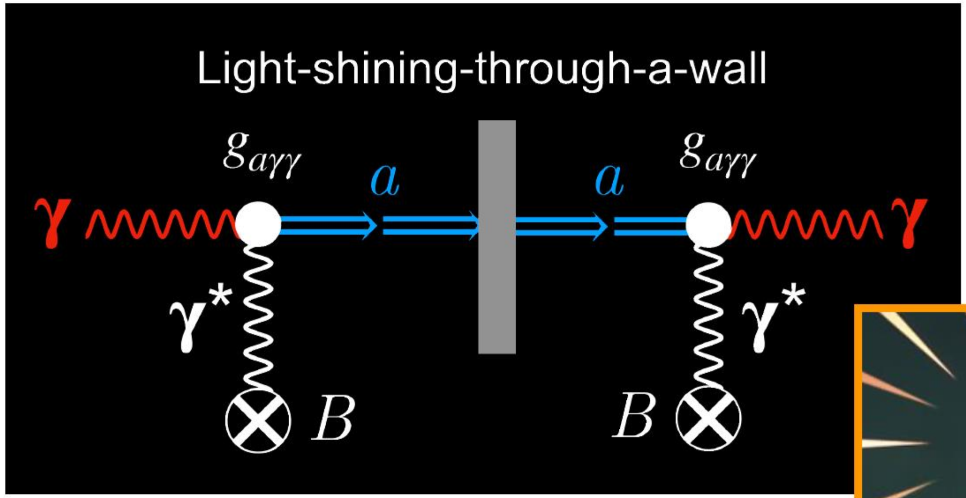
Frontier applications of superconducting photon detectors

Dark Matter Searches

TES for ALPS II Dark Matter Experiment



DESY

QI
Quantum-enhanced Interferometry for New Physics

Cryogenic particle detector from NIST
Tungsten 25 µm x 25 µm

SNSPDs for Dark Matter Searches

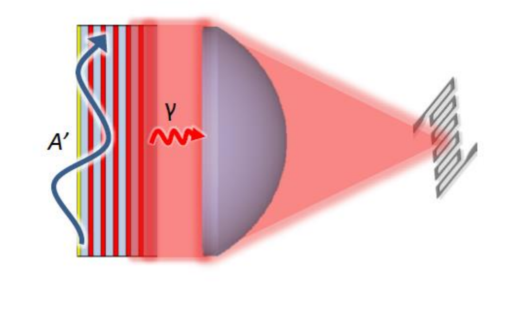


Figure 1. Sketch of the LAMPOST concept. The dark photon dark matter field A' converts to photons in a layered dielectric target. These photons are focused by a lens onto a small, low-noise SNSPD detector.

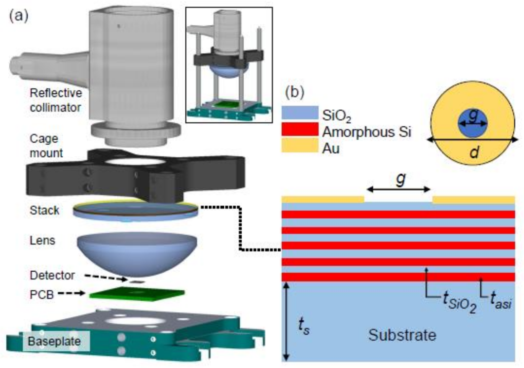


Figure 2. The LAMPOST prototype haloscope apparatus. (a) Exploded view with element details. Inset:

J. Chiles *et al* Physical Review Letters 128 (23), 231802 (2022)

Sensitivity improves with larger mass (larger active area) SNSPD
=> challenge to scale from 100 µm devices to full wafers

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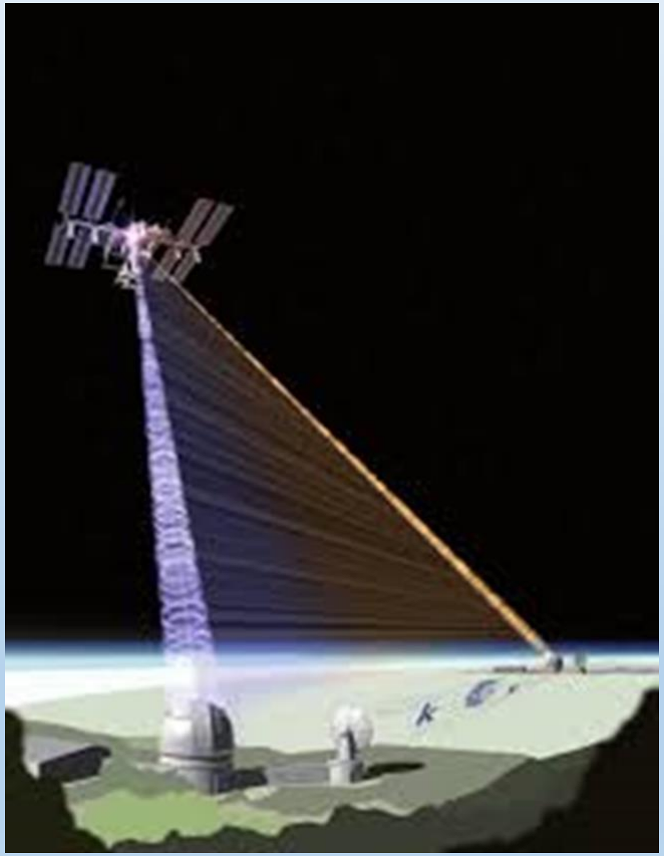
Frontier applications of superconducting photon detectors

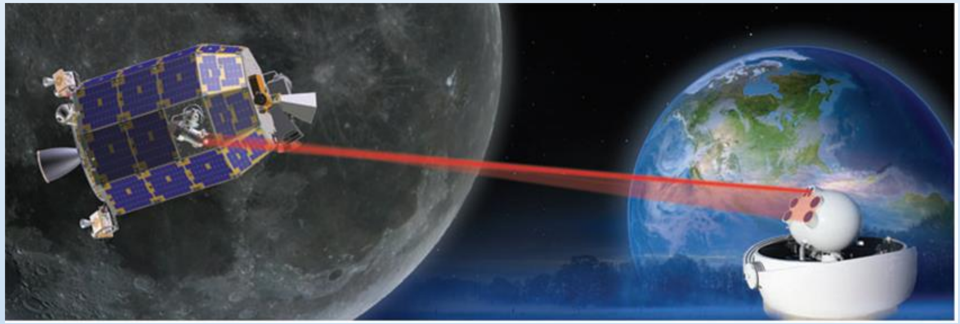
Deep space optical communications

Space to ground quantum comms



Ursin *et al.* Europhy. News 40 26 (2009)
Yin *et al.* Science 356 1140 (2017)

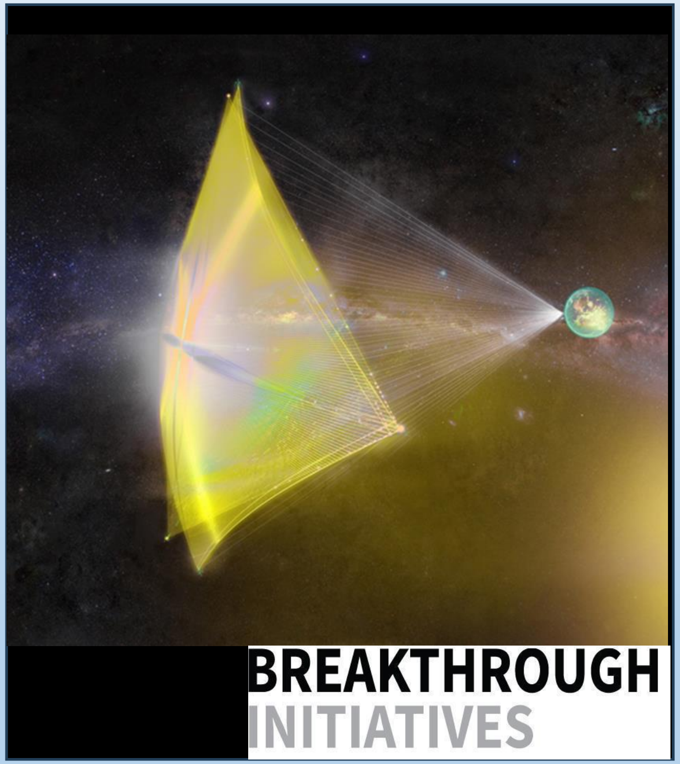
Single photon optical comms for space



NASA LADEE lunar orbiter 2014

NASA DSOC on board Psyche mission launched October 2023

Interstellar optical comms: Breakthrough Starshot



Phase 1 projects started 2021 – planned for launch 2050 & data 2075

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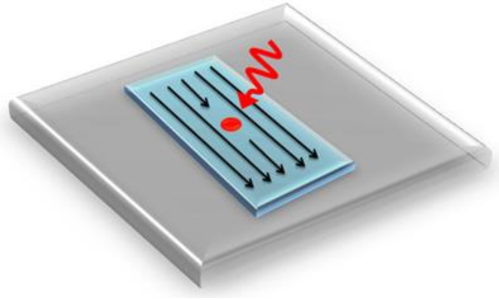
Superconducting photon detectors: past, present & future

Conclusions

- **Superconducting detectors** are an important **quantum technology** for **infrared photon counting**.
- **Superconducting Nanowire Single-Photon Detectors** (SNSPDs) have undergone rapid development and commercial translation.
- Important avenues for ongoing **SNSPD** development include **new materials**, **photonic integration** enhancing **mid-infrared** performance and **large scale arrays**.
- **New photon-counting applications for superconducting detectors** include photonic **quantum computing**, **dark matter** searches and **deep space optical communications**.



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OXFORD INSTRUMENTS PLASMA TECHNOLOGY

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BREAKTHROUGH INITIATIVES

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