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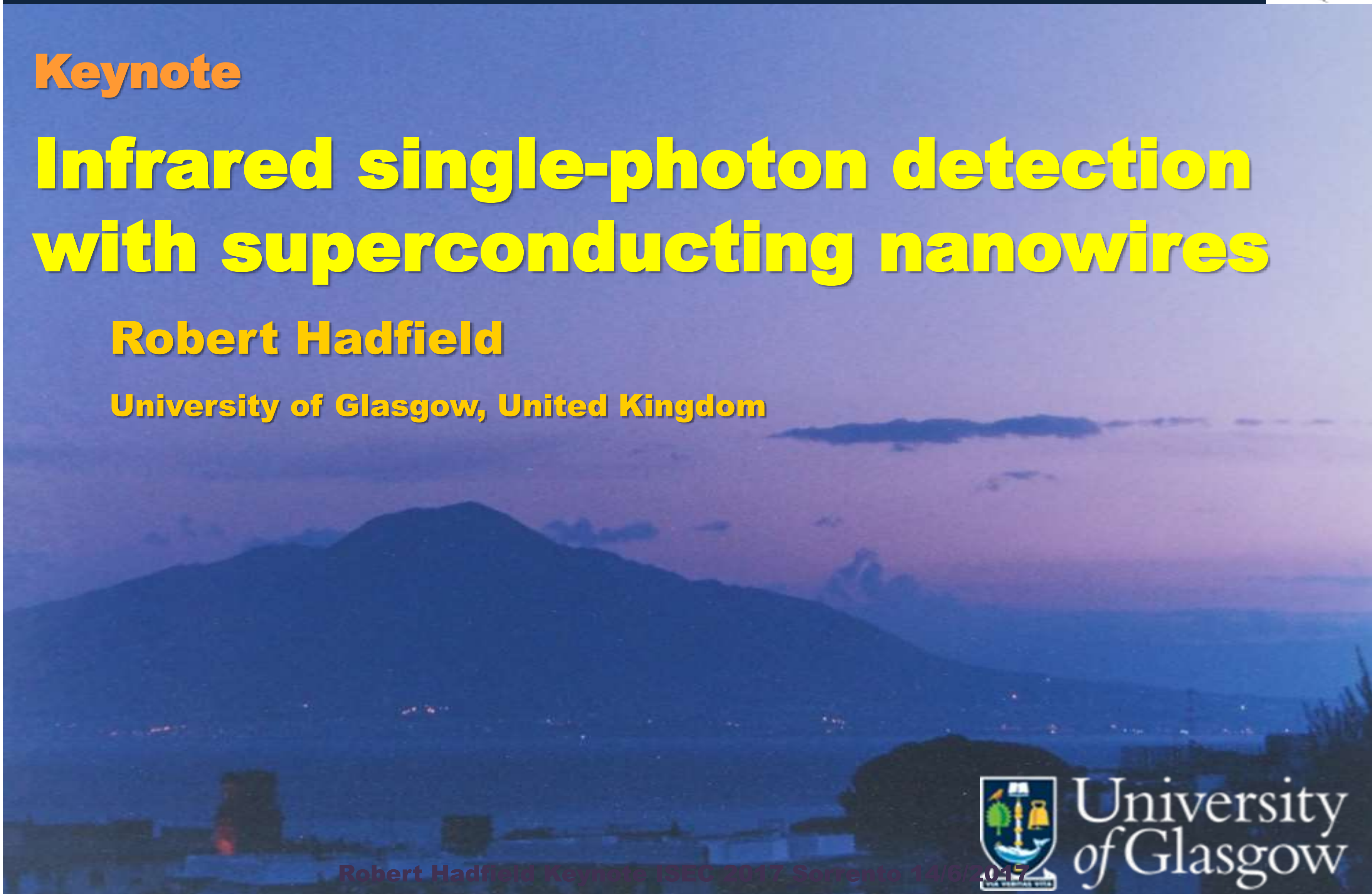
This keynote presentation We-KEY-01 was given at ISEC 2017.

16th International Superconductive Electronics Conference • Sorrento • Italy



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University of Glasgow

Quantum Sensors Group

School of Engineering

Professor

Robert Hadfield

Lecturer

Alessandro Casaburi

Postdoctoral Researchers

Rob Heath

Nathan Gemmell

Dmitry Morozov

PhD students

Luke Baker

Andrea Pizzone

Archan Banerjee

Gavin Orchin

Kleanthis Erotokritou

Umberto Nasti

Konstantinos Tsminvrakidis

Jon Collins

The University of Glasgow, UK

Past

Founded 1451:
World's 4th oldest English-speaking University

Famous alumni:
William Thompson (Lord Kelvin) and James Watt

Lord Kelvin

James Watt

Present

The **James Watt Nanofabrication Centre**
http://www.jwnc.gla.ac.uk

The **QUANTIC** Quantum Technology hub
http://www.quantic.ac.uk
(one of four national QT hubs created in December 2014)

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European Conference on Applied Superconductivity 2019

Glasgow, United Kingdom is the venue for **EUCAS 2019**

Host City
Glasgow, Scotland

Venue & Date
Scottish Event Campus (SEC) ,Glasgow

1^{st}-5^{th} September 2019

Chairs
Professor Robert Hadfield (Glasgow)

Dr John Durrell (Cambridge)

EUCAS 2019 GLASGOW

UNIVERSITY OF CAMBRIDGE

University of Glasgow

SEC Scottish Event Campus

University of Glasgow

16th International Superconductive Electronics Conference
ISEC 2017
JUNE 12/16 2017 - SORRENTO (NAPOLI) ITALY

Infrared single-photon detection with superconducting nanowires

- Single photon detection: a brief introduction
- Evolution of superconducting nanowire single photon detectors
- From single pixels to cameras
- New developments in refrigeration

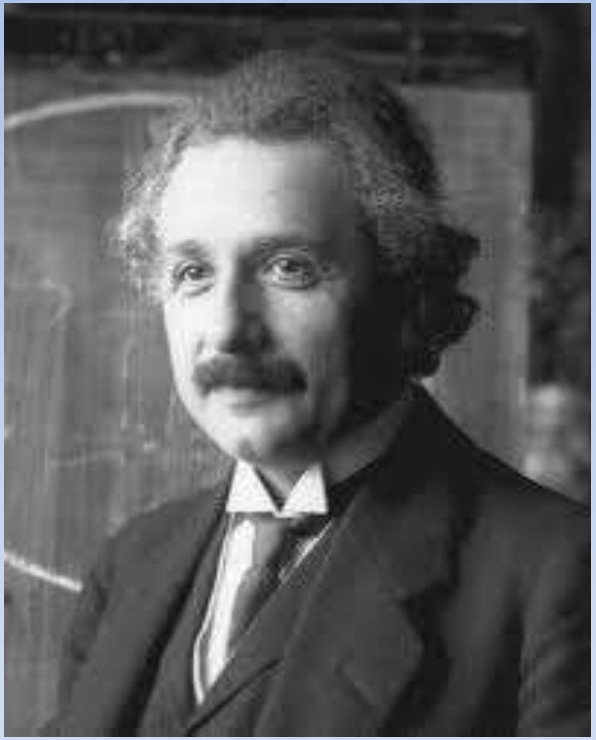
Robert Hadfield • Keynote ISEC 2017 Sorrento • 14th June 2017

University of Glasgow

What is a photon?

- Einstein: a Photon is packet of electromagnetic energy

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



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

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Photon-counting technology

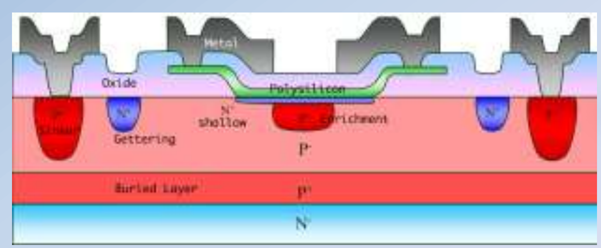
Wavelength

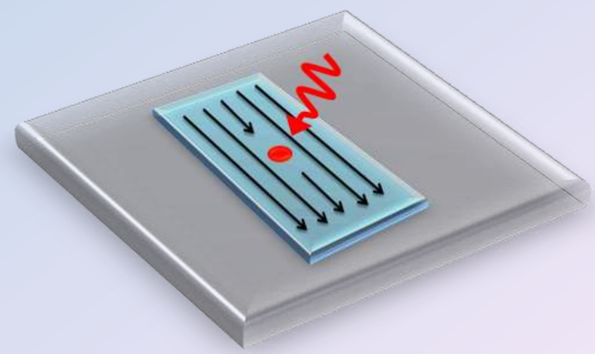
Detectors

Photomultipliers | IR PMTs

Si SPADs | InGaAs SPADs

Superconducting detectors





Topical Review: R. Hadfield Nat. Photon. **3** 696 (2009)

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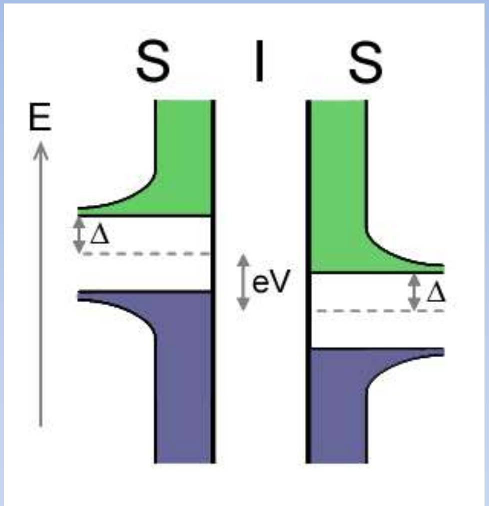
Infrared photon counting with superconducting detectors

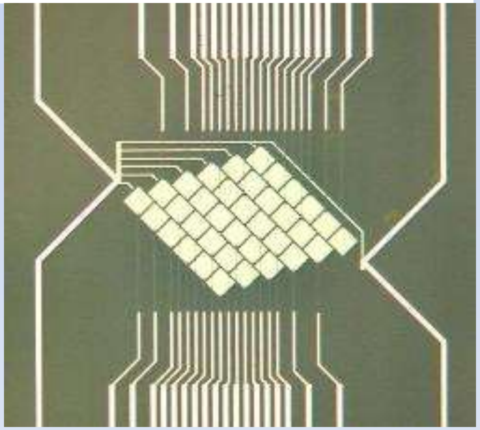
Superconducting Tunnel Junction (STJ)
Peacock Nature 381 135 (1996)

Transition Edge Sensor (TES)
Lita Optics Express (2009)

Kinetic Inductance Detector (KID)
Day Nature **425** 817(2002)
Gao APL **101** 142602 (2012)

Superconducting Nanowire Single-Photon Detectors (SSPDs/SNSPDs)
Gol'tsman APL **79** 705 (2001)
Natarajan SUST **25** 063001(2012)





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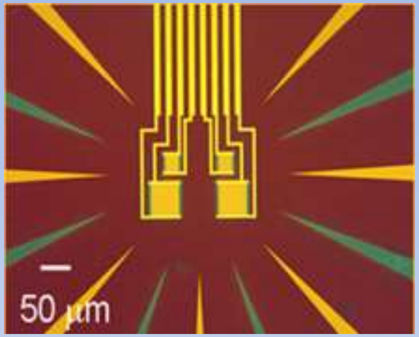

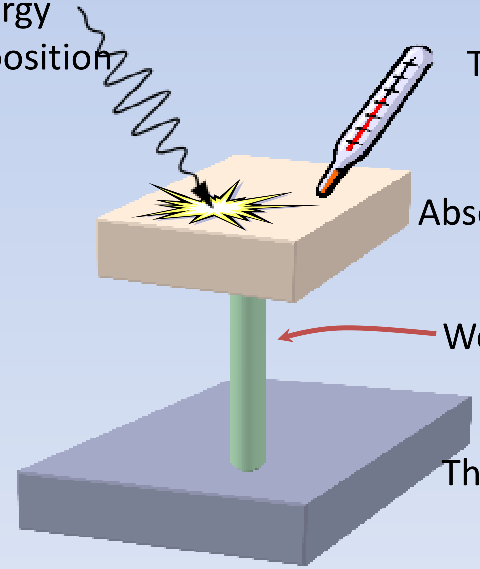

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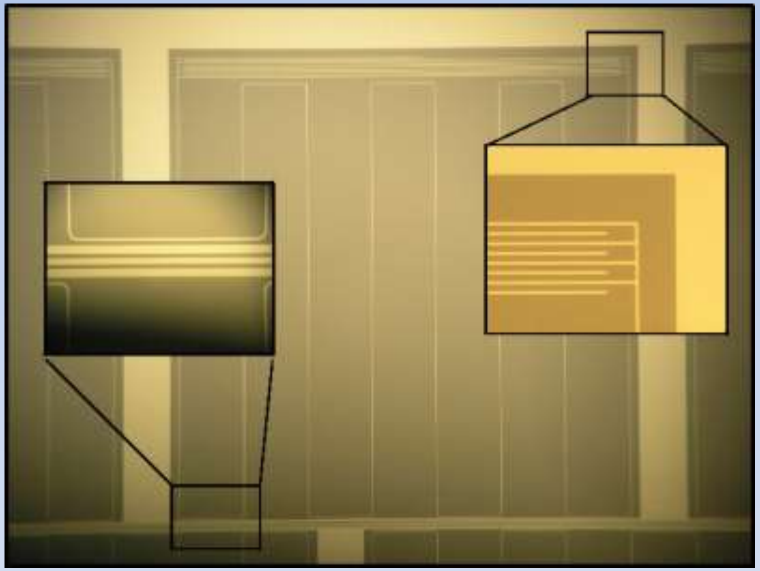

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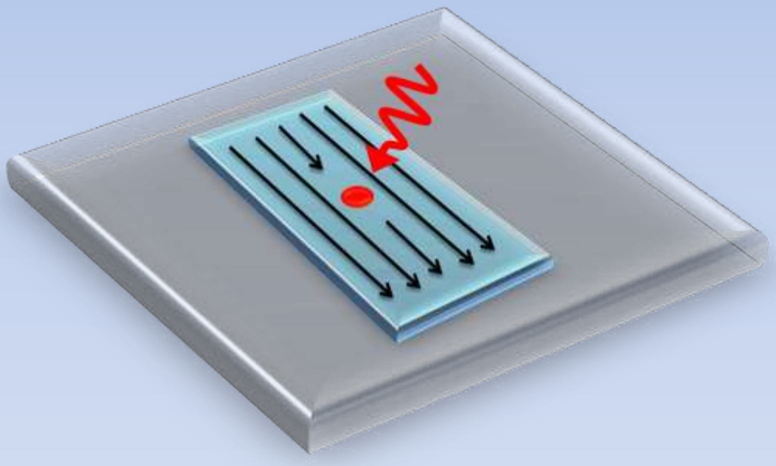

Superconducting Nanowire Single-photon Detectors (SSPDs/SNSPDs)

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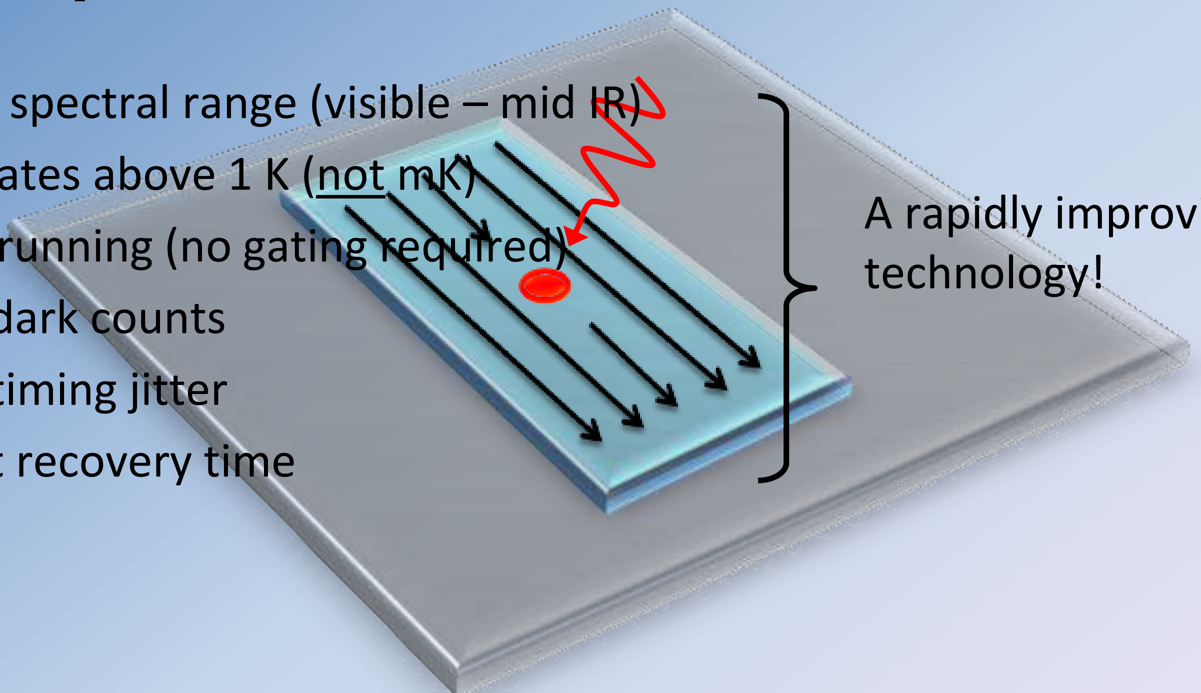
Superconducting nanowire single photon detector

Key Properties

- Wide spectral range (visible – mid IR)
- Operates above 1 K (not mK)
- Free running (no gating required)
- Low dark counts
- Low timing jitter
- Short recovery time

A rapidly improving technology!



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

Topical Review: Natarajan *et al* Superconductor Science & Technology **25** 063001 (2012) **Open Access**

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Applications of SNSPDs

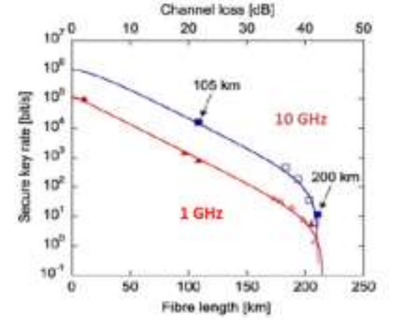
Quantum information

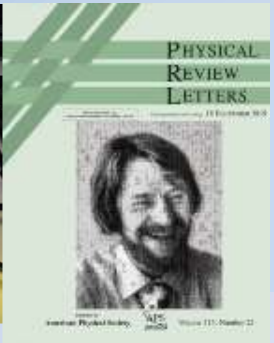
Stanford, NIST, Glasgow, Bristol

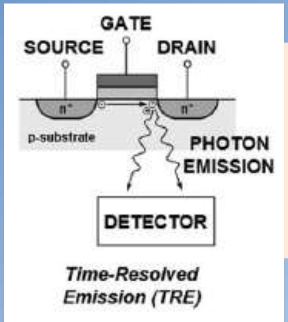
Takesue *et al.* Nature Photonics **1** 343 (2007)

Silverstone *et al.* Nat Photon **8** 104 (2014)

Shalm *et al.* Phys. Rev. Lett. **115** 250402 (2015)







Integrated circuit testing

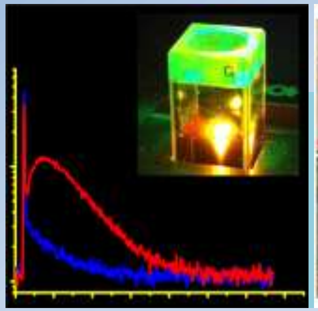
Rochester, IBM, MIT, DCG Systems, PhotonSpot

Zhang *et al*. Elec. Lett. 39 1086 (2003); Bhagat Shehata *et al*. Proc. ISTFA 2014 pp 406

Space-to-ground communications

NASA JPL, MIT Lincoln Labs

Robinson *et al*. Opt. Lett. **31** 444 (2006); Shaw *et al.* CLEO 2014 SM4J.2



Imaging and Sensing

Heriot-Watt, Glasgow

McCarthy *et al.* Optics Express **21** 8904 (2013)

Gemmell *et al.* Optics Express **21** 5005 (2013)

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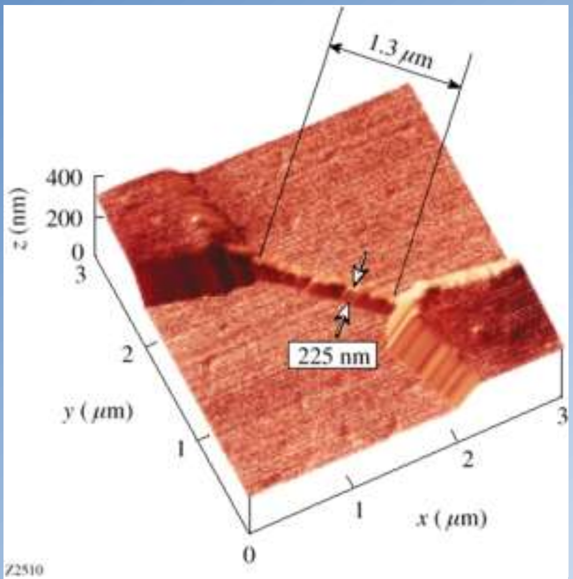
Commercialization of SNSPDs

Russia Scontel
USA PhotonSpot
USA Quantum Opus
NL Single Quantum
Switz. ID Quantique

University of Glasgow

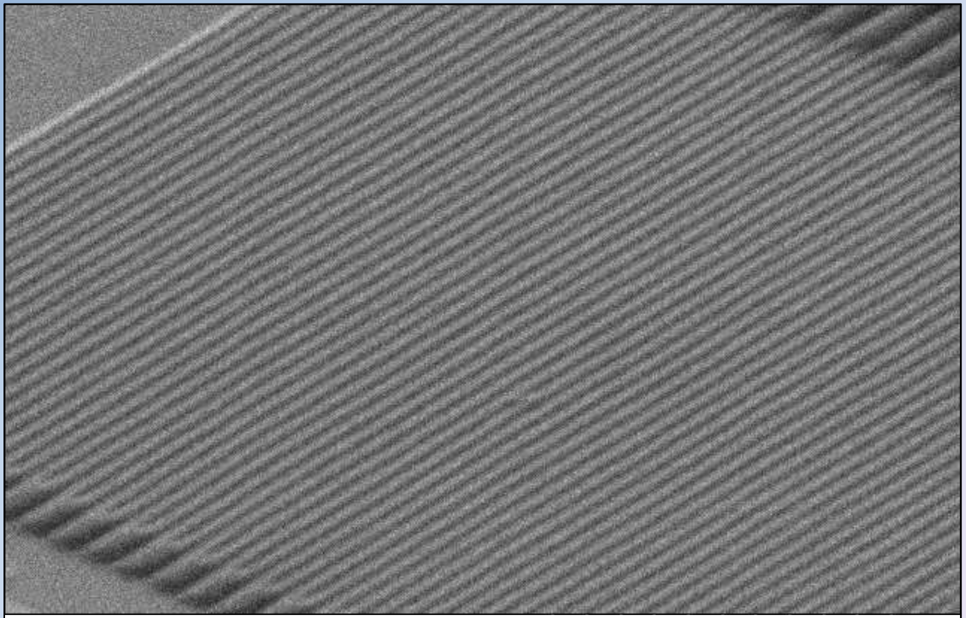
Superconducting nanowire single photon detector

Basic Device



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

Meander



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

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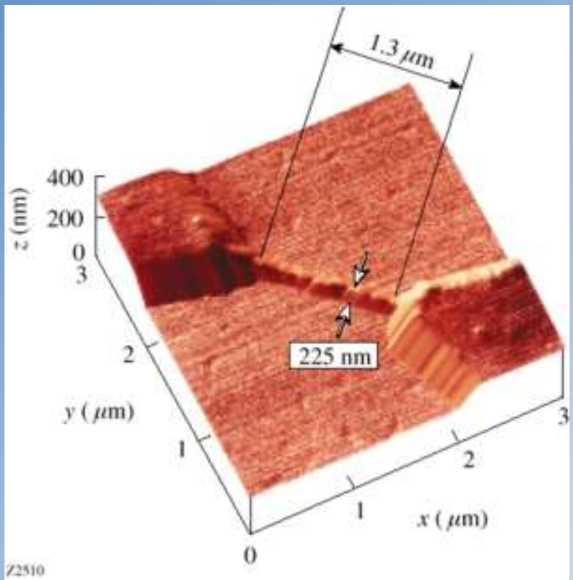
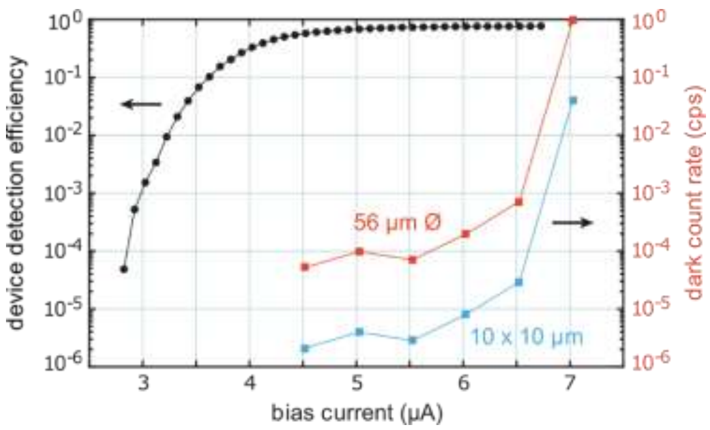
Superconducting nanowire single photon detector

Basic Device



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

Optical Cavity



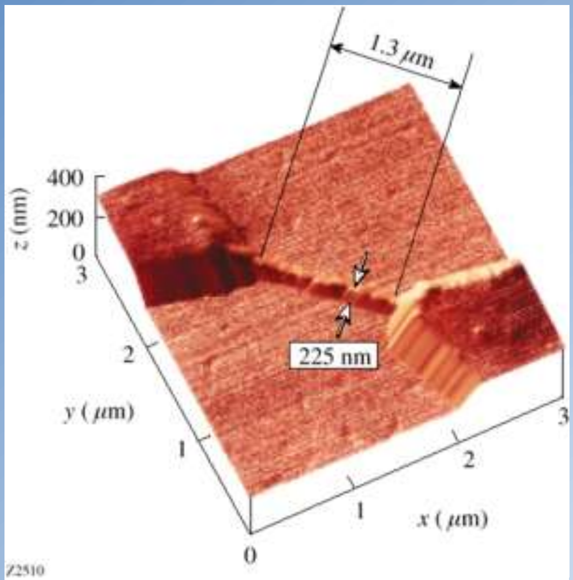
- JPL detectors made from MoSi
- 76% SDE @ 370 nm wavelength

E. Wollman JPL

University of Glasgow

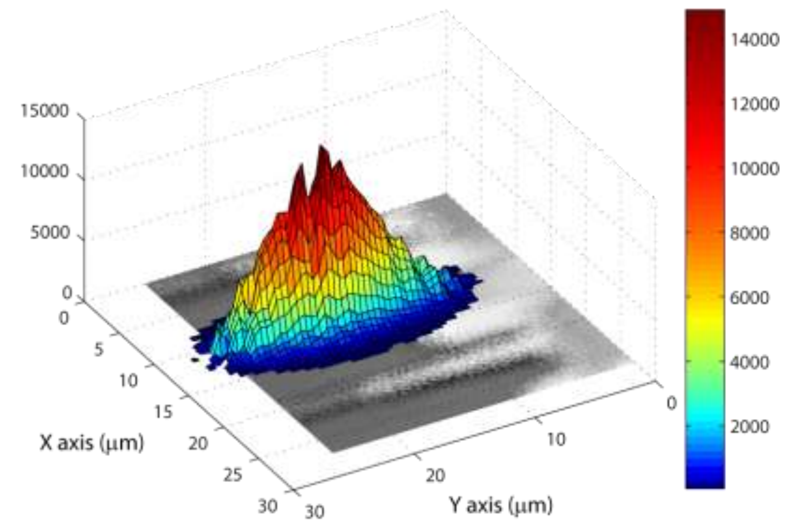
Superconducting nanowire single photon detector

Basic Device



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

Waveguide Integration

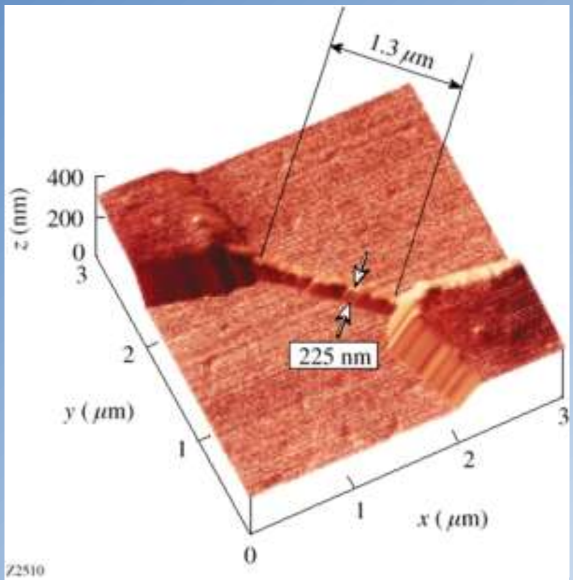


Li *et al.* Optics Express **24** 13931 (2016)
K. Erotokritou ISEC 2017 Poster Wed-SQD-12

University of Glasgow

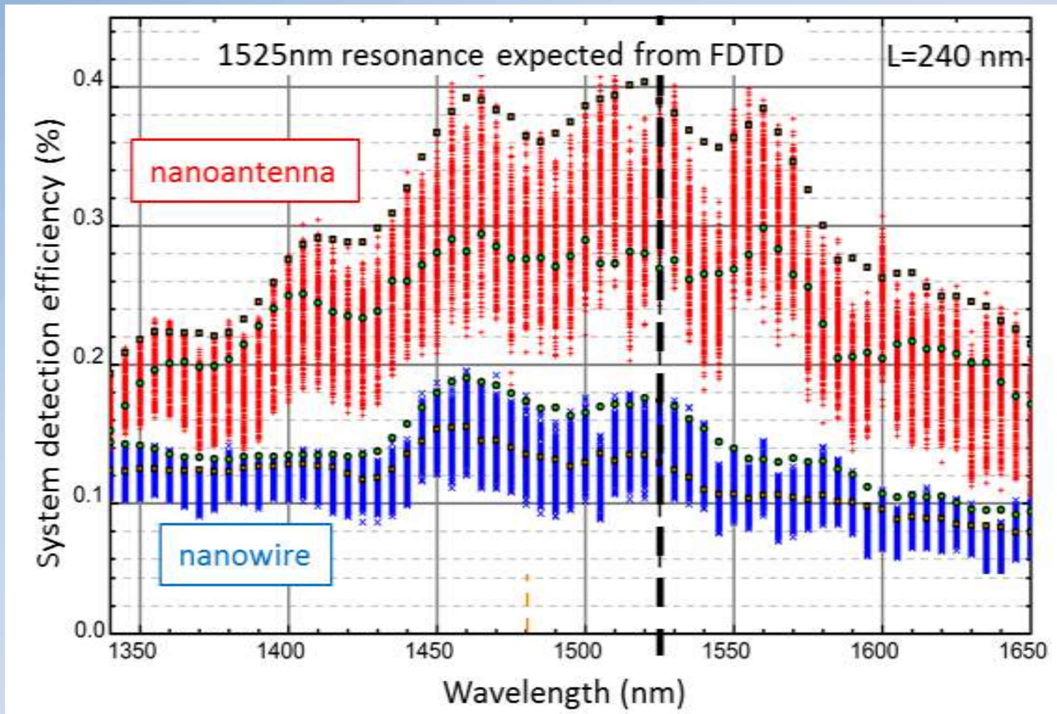
Superconducting nanowire single photon detector

Basic Device



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

Nanoantenna



Heath *et al*. **Nano Letters** 15 (2) 819 (2015)

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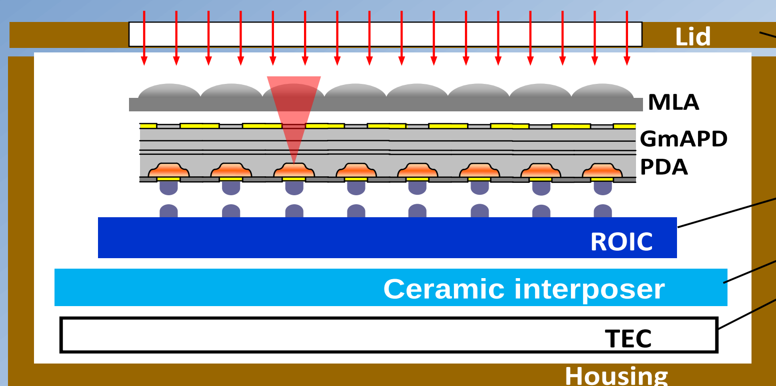
The competition: InGaAs photon counting camera

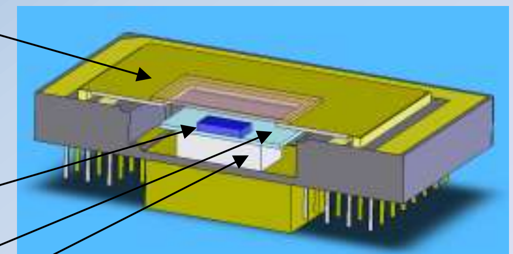
Mark Itzler, Princeton Lightwave

Princeton Lightwave

FPA format of 128 x 32 (4096 pixels)

λ=1550 nm DE ~ 30% DCR ~ 6 kHz per pixel





FPA solid body model

Growing market: IR photon-counting LIDAR for driverless cars

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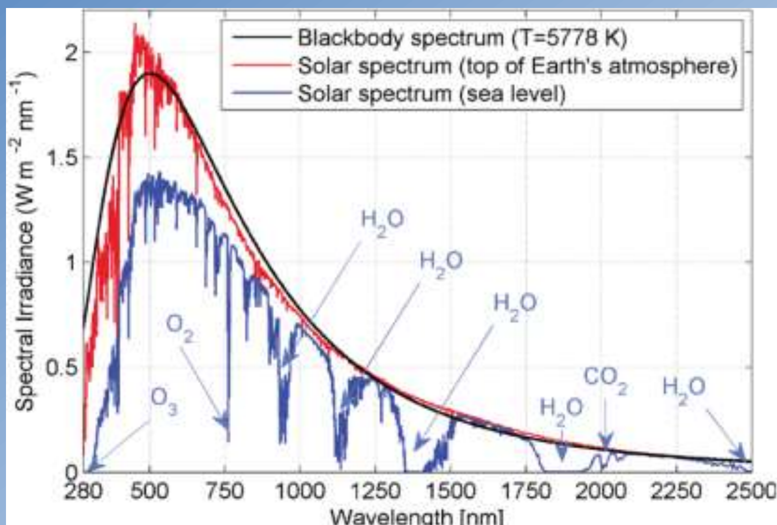
Imaging & remote sensing with SNSPDs

HERIOT WATT UNIVERSITY

QUANTIC

Key collaborator: Gerald Buller



SNSPDS have allowed us to move to 1550 nm wavelength, enabling eye real-time safe depth imaging over kilometre distances.

Possible extension to mid-IR for long range gas detection.

McCarthy *et al.* Optics Express **21** 8904 (2013)

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Photon Sparse Microscopy

Key Collaborator: Miles Padgett

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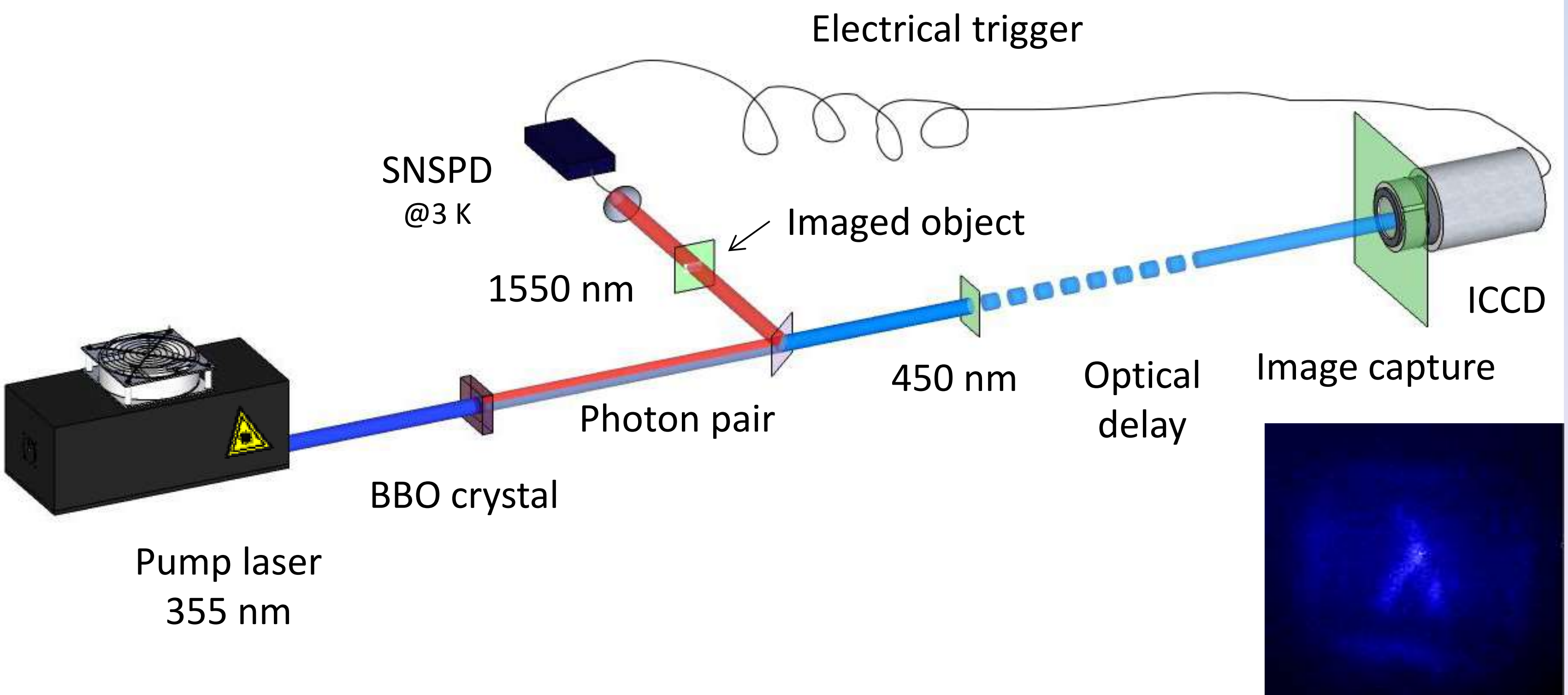

Extension of:
Aspden *et al* ***Photon sparse imaging: visible light imaging with infrared illumination*** **Optica 2** 1049 (2015)


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Science & Technology
Public Engagement
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QuantIC will link world-leading quantum technologists with global industry leaders to transform imaging in alignment with industry priorities.
Science & Technology
QuantIC will deliver new technology, bringing unprecedented advances in imaging in the industrial, scientific, security, healthcare and consumer sectors.
Public Engagement
QuantIC is currently working on creating a user engagement strategy which will shortly be published in this section.
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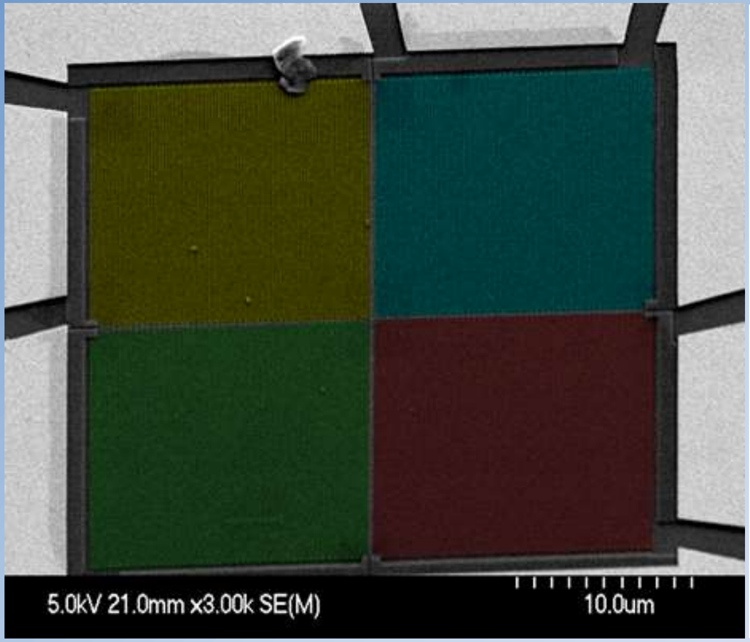
Supporters
Research supported by the EPSRC UK Quantum Technology Programme under grant EP/M01326X/1
UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

University of Glasgow

SNSPD Arrays

Casaburi *et al. Large area superconducting nanowire single photon detectors*

IEEE Conf. Proc. (2014) DOI: 10.1109/Fotonica.2014.6843851



Alessandro Casaburi
Andrea Pizzone
Robert Hadfield

MARIE CURIE ACTIONS

JWNC The James Watt Nanofabrication Centre

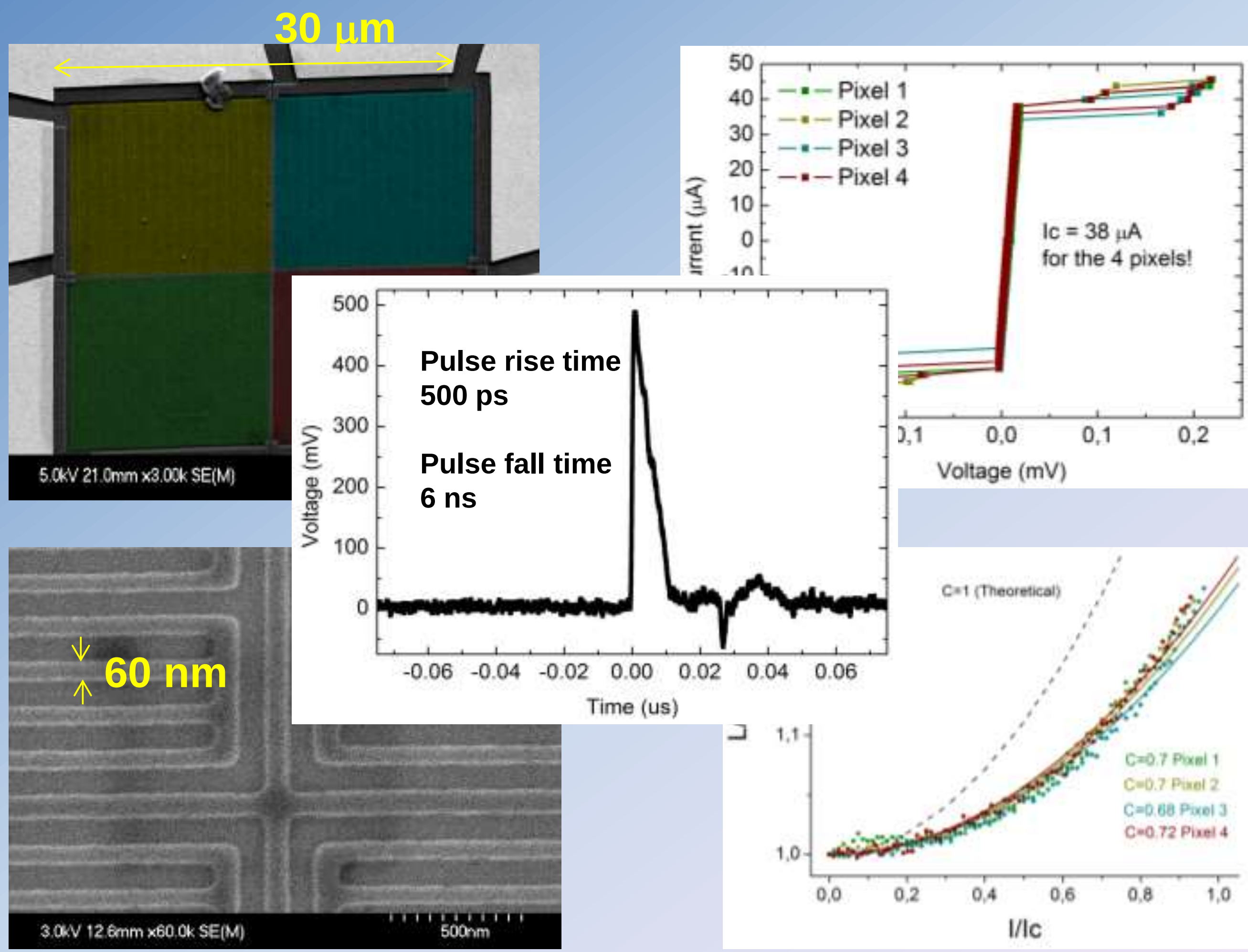
QUANTIC

erc

University of Glasgow

30 μm x 30 μm SNSPD Arrays

7nm thick NbTiN film on oxidised Si



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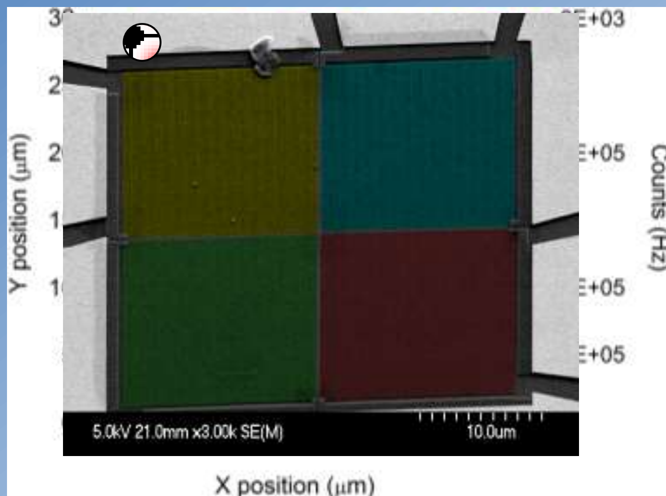
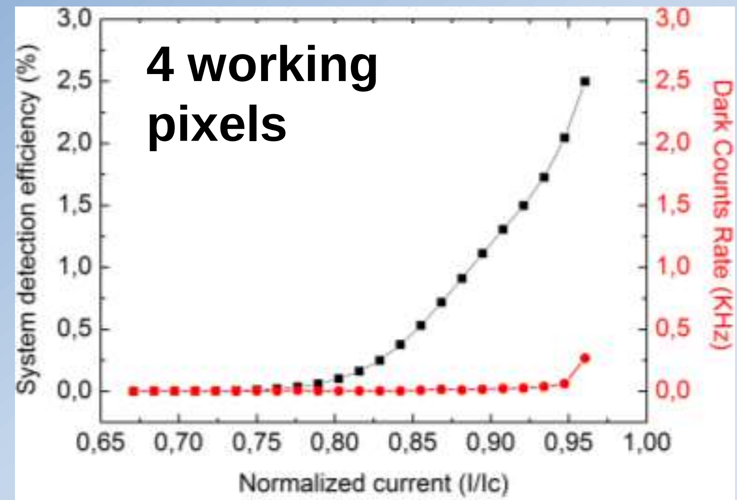
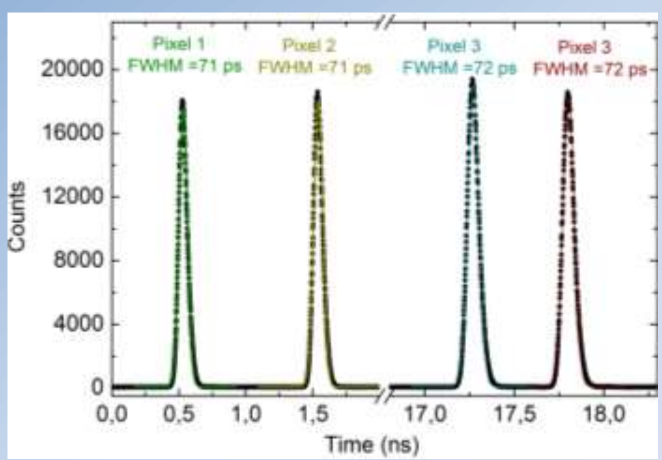
30 µm x 30 µm SNSPD Arrays

Photoresponse





Timing Jitter



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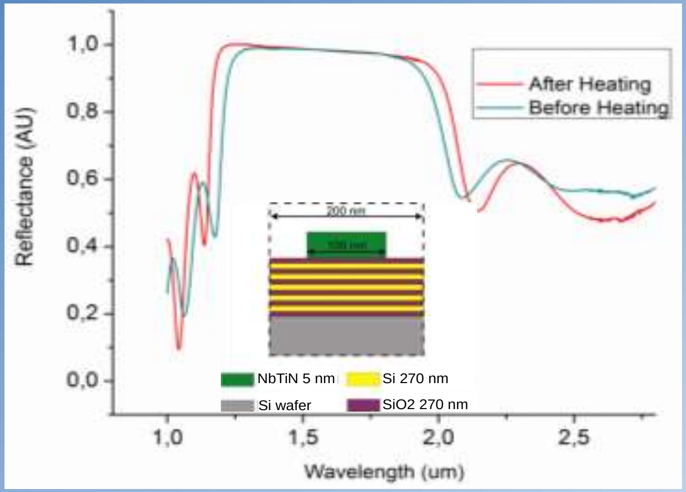
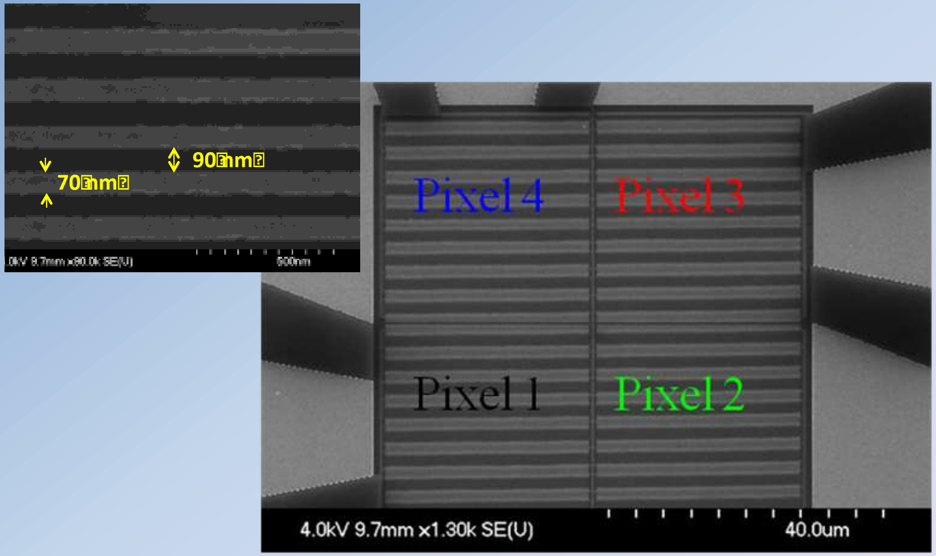
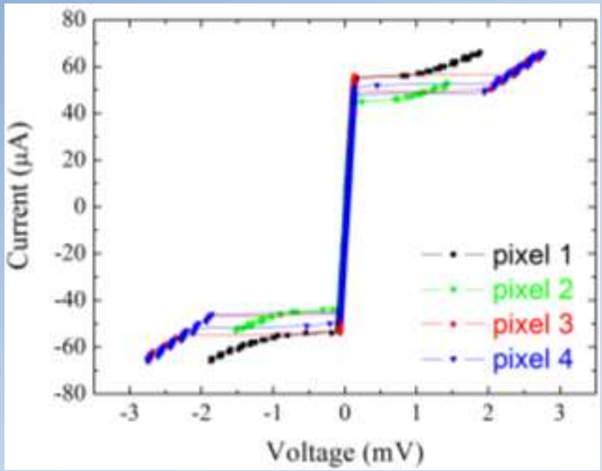
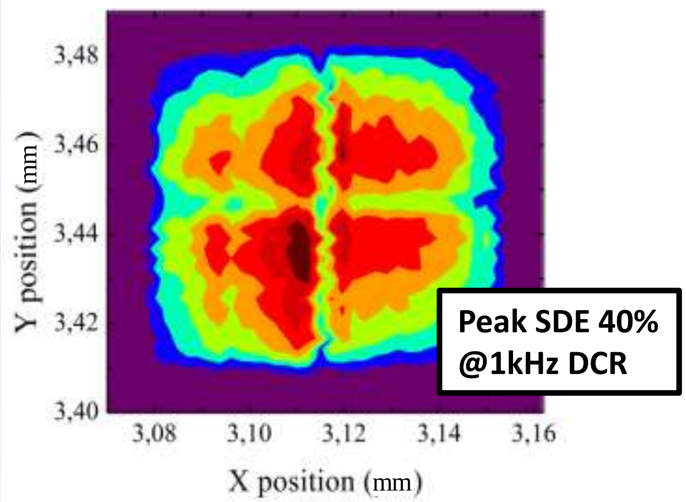
60 µm x 60 µm SNSPD Arrays









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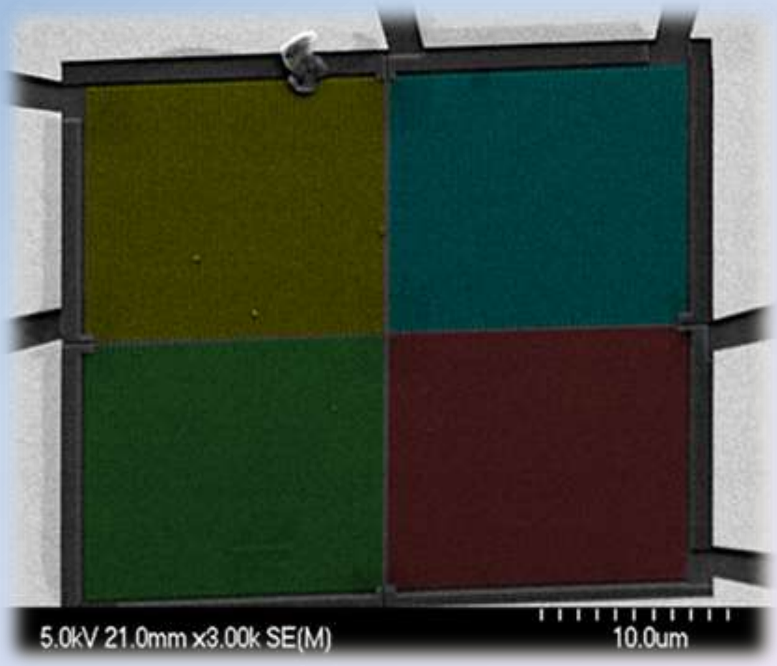
SNSPD Arrays

Key Challenges:

- Yield for large areas
- Heat load from bias & readout wires
- Cost of readout electronics



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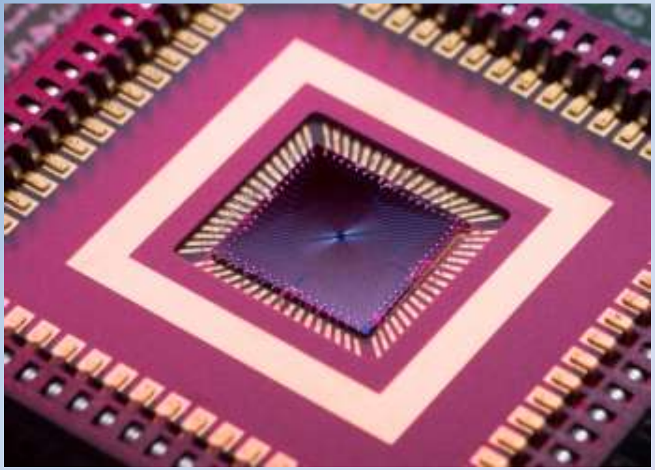
64 pixel SNSPD array for deep space comms

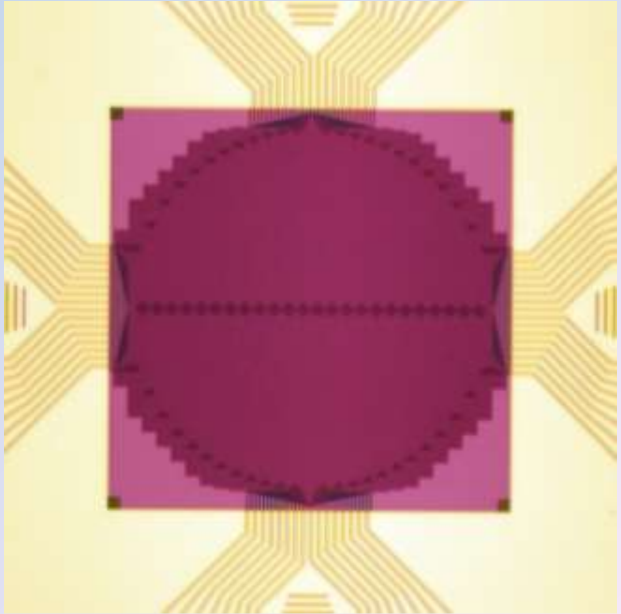
Matthew Shaw, JPL

- 64-pixel WSi SNSPD array is being used for the ground terminal in NASA's Deep Space Optical Communication (DSOC) demonstration
- 320-µm diameter active area suitable for coupling to 5-meter telescope
- 1.2 Gcps maximum count rate across all 64 pixels
- ~100 ps FWHM timing jitter at 1550 nm
- Free space coupled through windows into cryostat, ~50% system detection efficiency

NASA JPL Jet Propulsion Laboratory California Institute of Technology



Packaged SNSPD array mounted in chip carrier



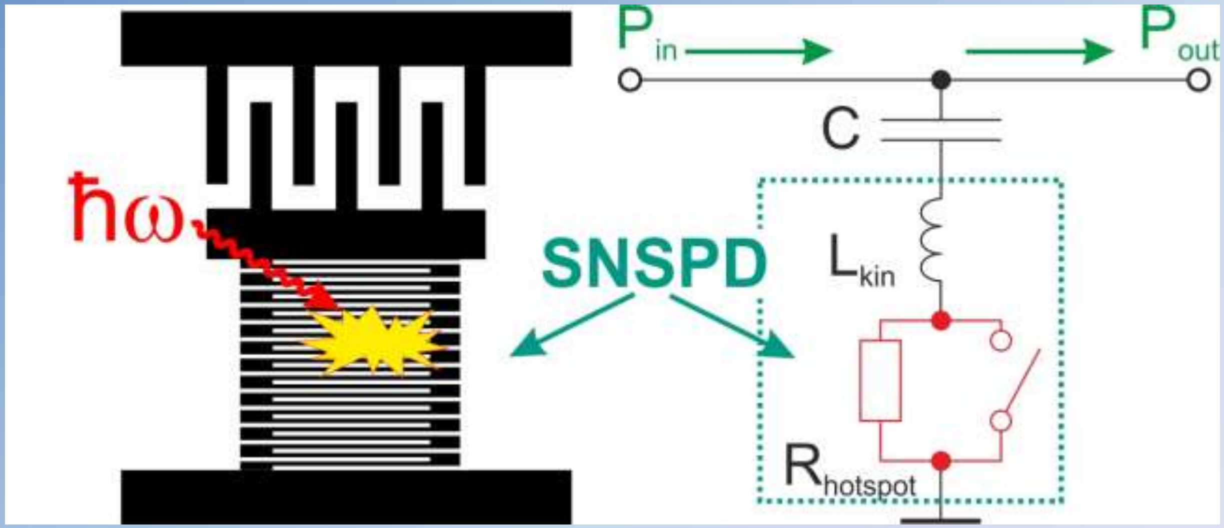
Optical microscope image of array

University of Glasgow

RF-SNSPD readout

Steffen Doerner, Michael Siegel, Karlsruhe

KIT Karlsruher Institut für Technologie



- Frequency multiplexed RF bias & readout
- All pixels coupled to common CPW
- Scalable: now tested up to 16 pixels

ISEC 2017 Friday-C-DET-04

Doerner et al.
arXiv:1705.05345 (2017)

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), No. 41, July 2017.
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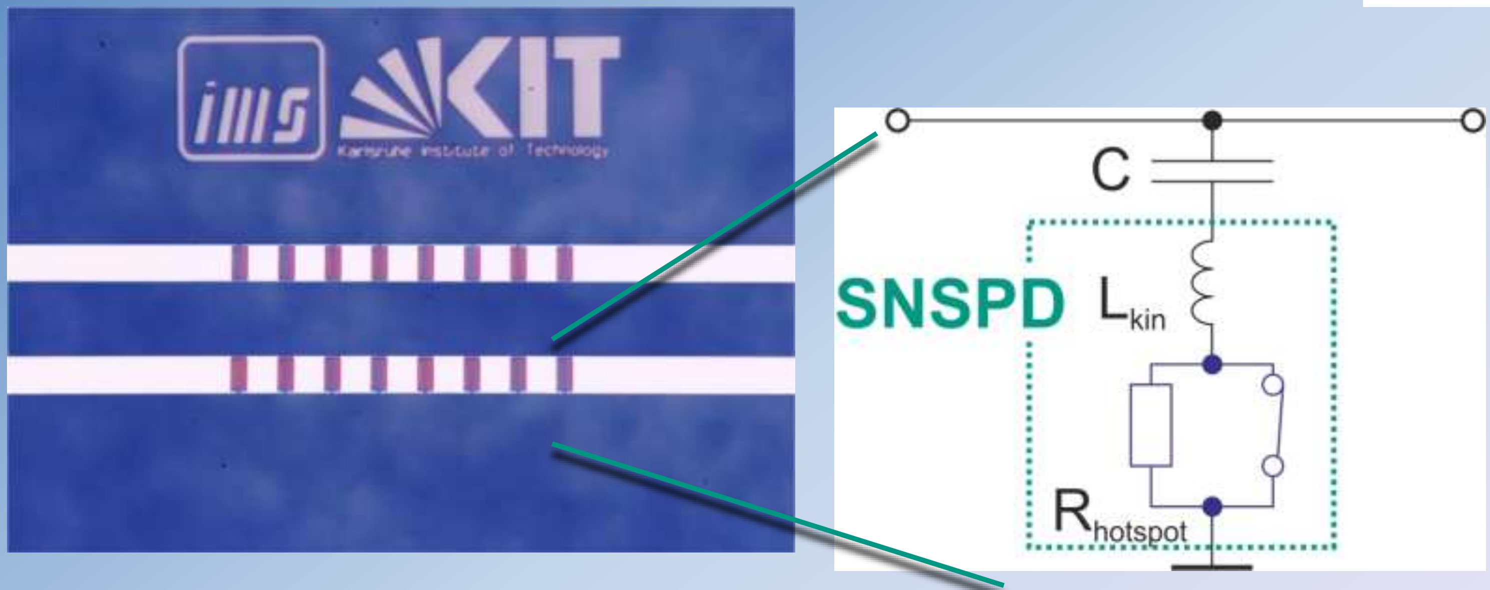
RF-SNSPD readout

Steffen Doerner, Michael Siegel, Karlsruhe



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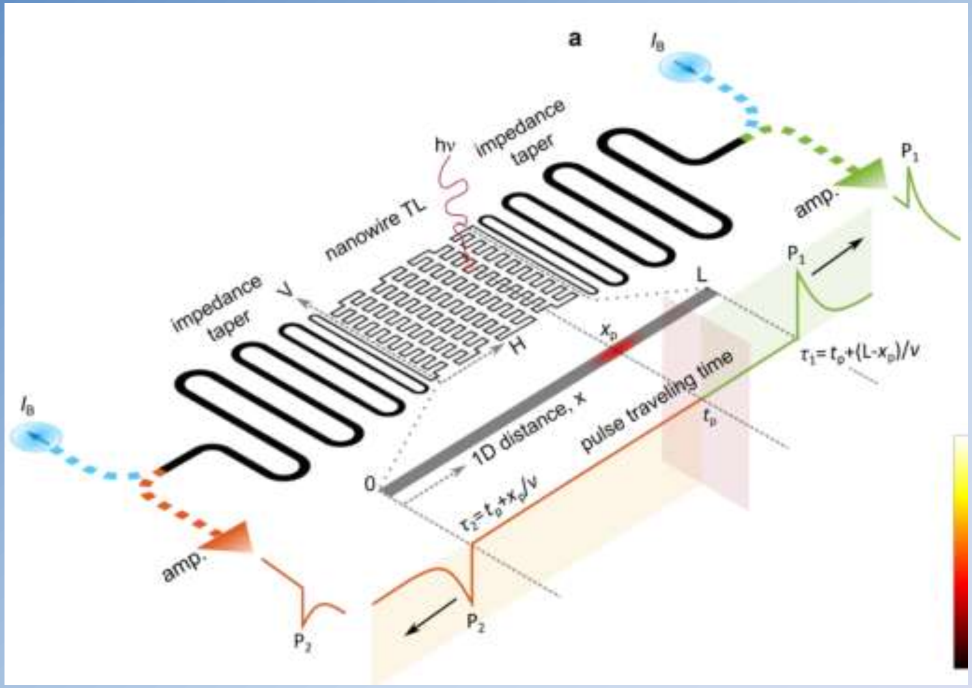
ISEC 2017 Friday-C-DET-04

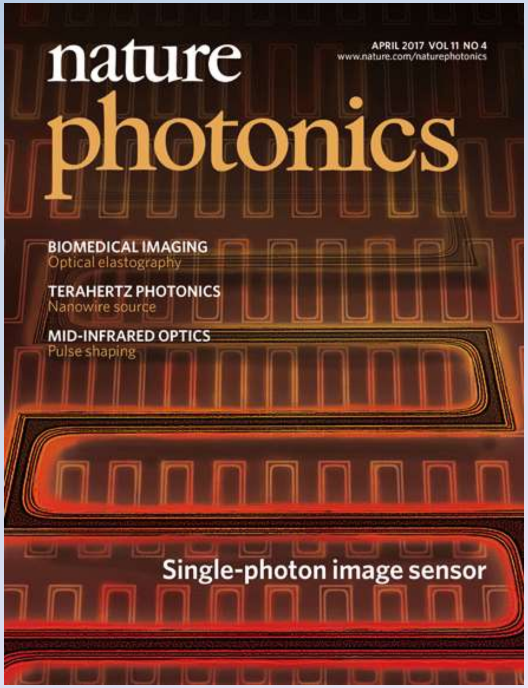
Doerner et al.
arXiv:1705.05345 (2017)

University of Glasgow

Single photon imager

Qingyuan Zhao, Karl Berggren, MIT





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

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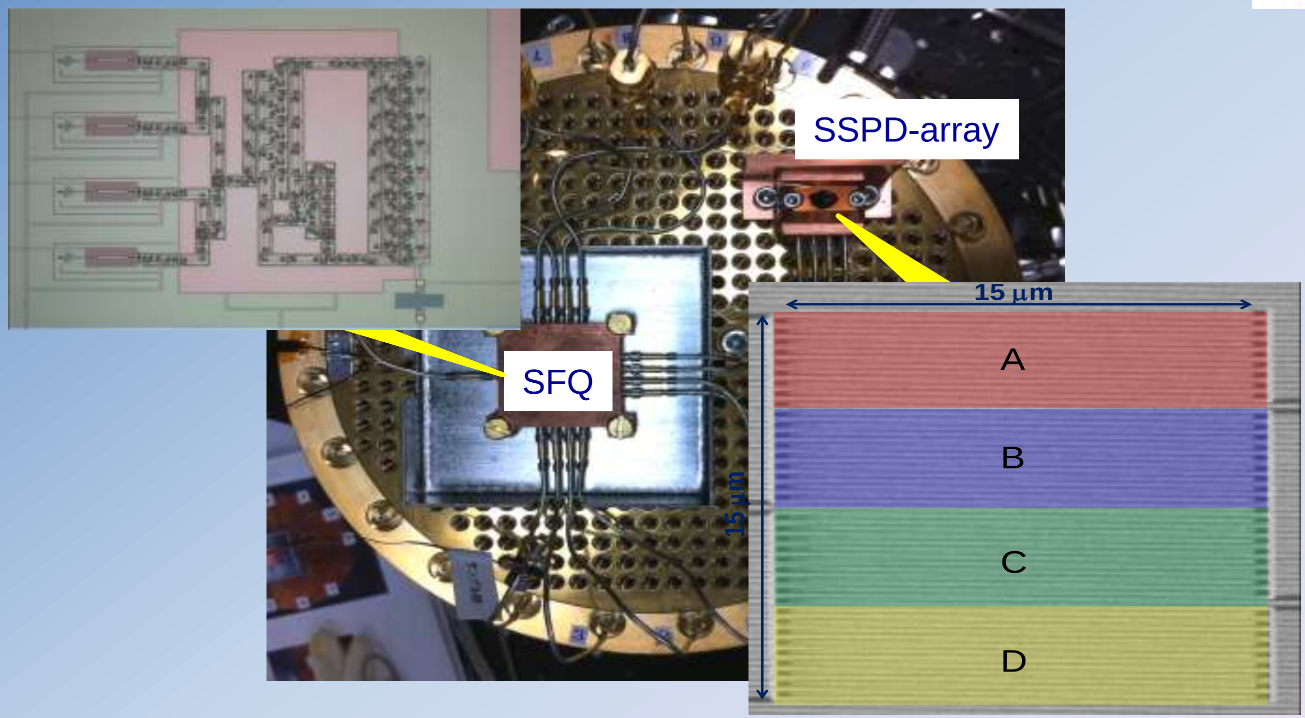
Single Flux Quantum Readout

S Miki, T Yamashita, H Terai NICT



4 pixel readout T. Yamashita, *et al.* Opt. Lett. **37** 2982 (2012)

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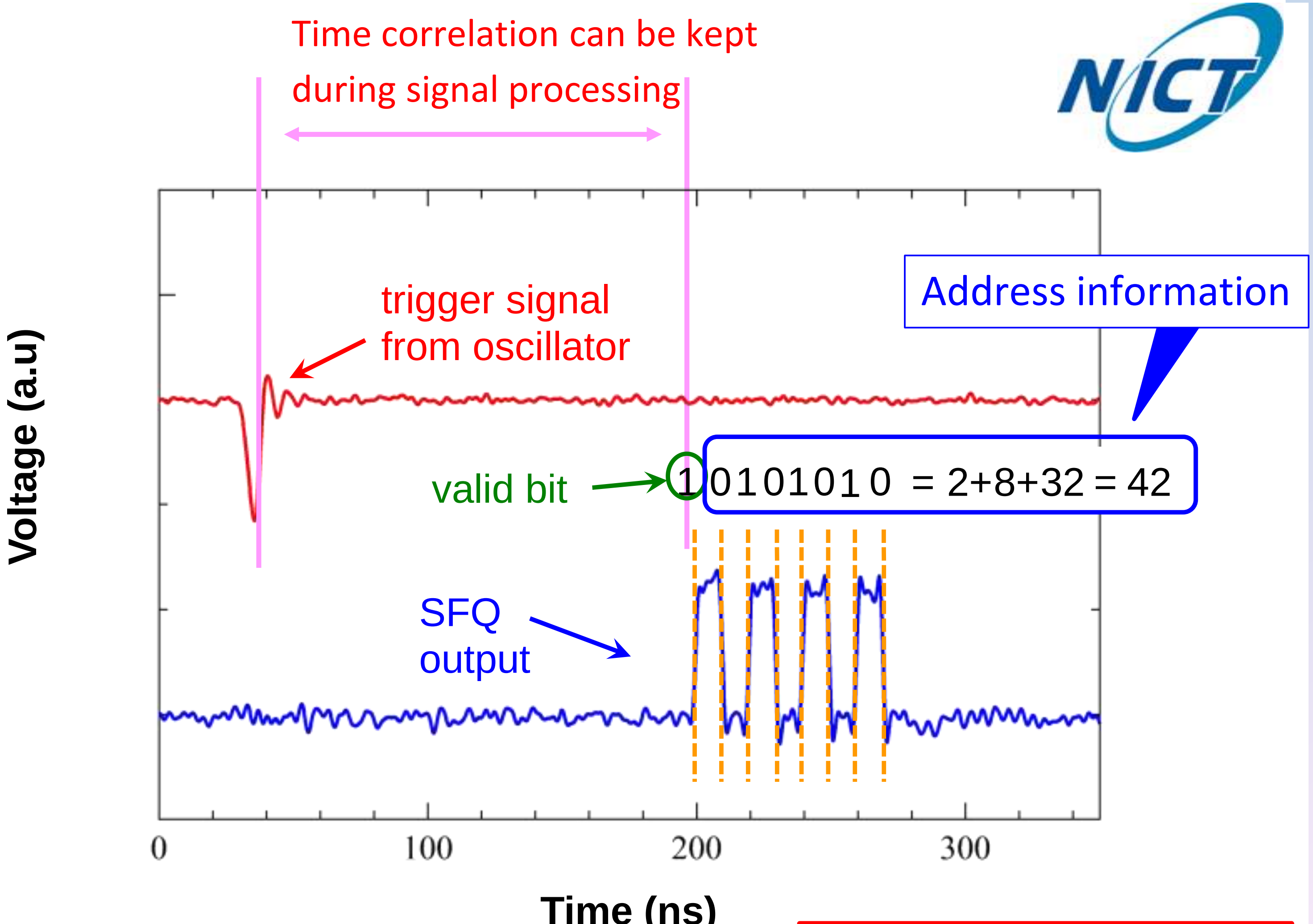
SFQ readout



Scaling to 64 pixel readout

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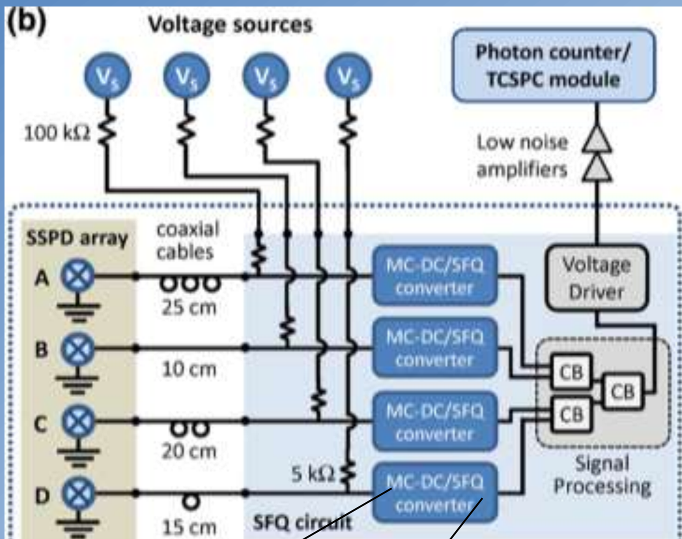
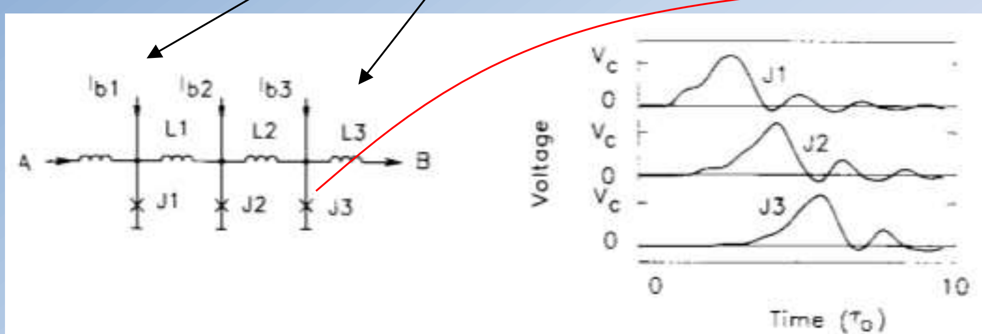
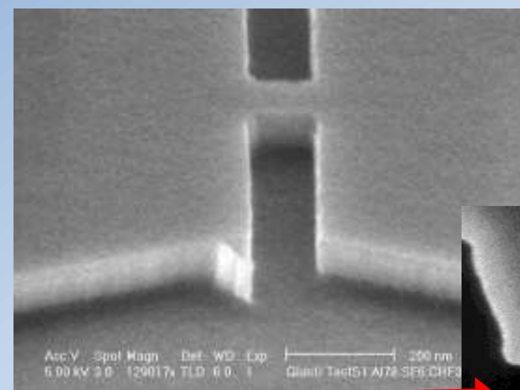
Nanobridge SFQ readout

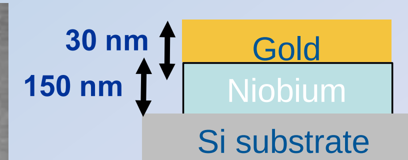
C Shelly ISEC 2017 Poster Th-SQD-04

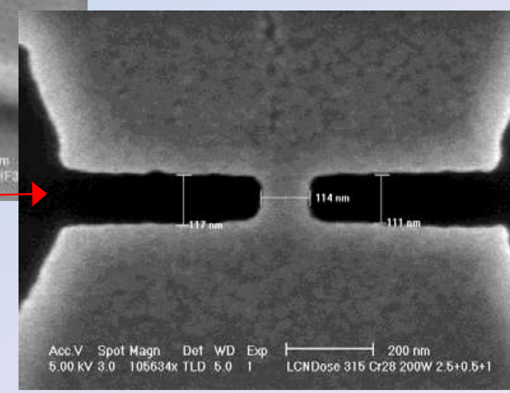




Single Nb/NbTiN layer technology for easy on chip integration with the SNSPDs







Pass, process and store binary information with small number of coax-cables from room to cryogenic temperature

NPL National Physical Laboratory

UCL

Innovate UK Technology Strategy Board

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16th International Superconductive Electronics Conference
ISEC 2017
JUNE 12/16 2017 - SORRENTO (NAPOLI) ITALY

Infrared single-photon detection with superconducting nanowires

- Single photon detection: a brief introduction
- Evolution of superconducting nanowire single photon detectors
- From single pixels to cameras
- New developments in refrigeration

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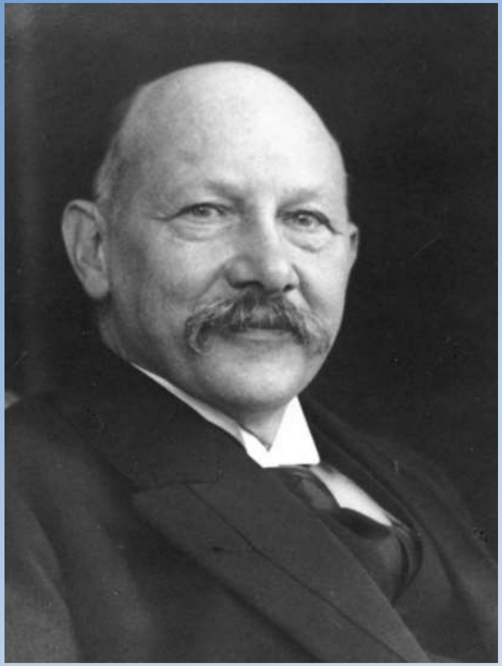
Historical Perspective

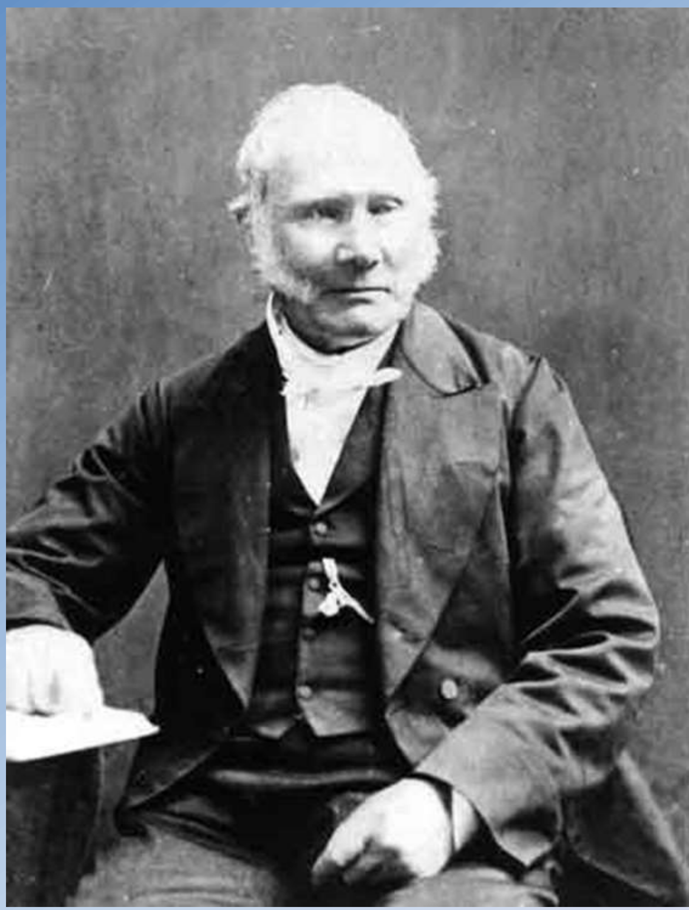
Discoverer of Superconductivity:

H. Kamerlingh Onnes, Leiden, the Netherlands, 1911



Closed cycle cooling (1816)

Reverend Robert Stirling
1790-1878



Hunterian Museum
Stirling Engine, 1827
University of Glasgow

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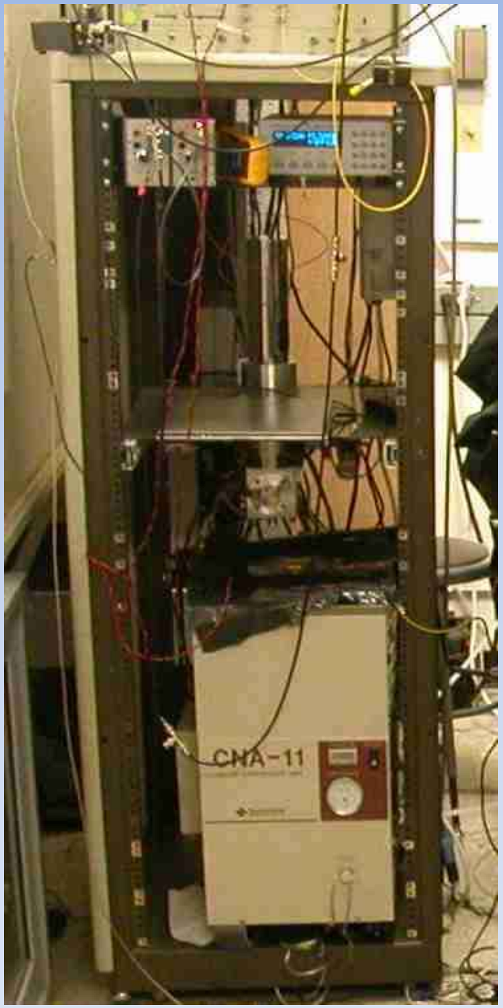
Cooling technology for SNSPDs (2005)

- Based on SHI RDK 101D cold head and CNA 11C compressor
- Weight of cold head/compressor 50kg
- Fits easily into standard 19” rack
- Air cooled
- 100 mW cooling power at 4.2 K
- 1 kW from 13 A plug
- Commercially available
  (20k Euro for cold head + compressor)



NIST

Sumitomo
(SHI) CRYOGENICS OF EUROPE LIMITED

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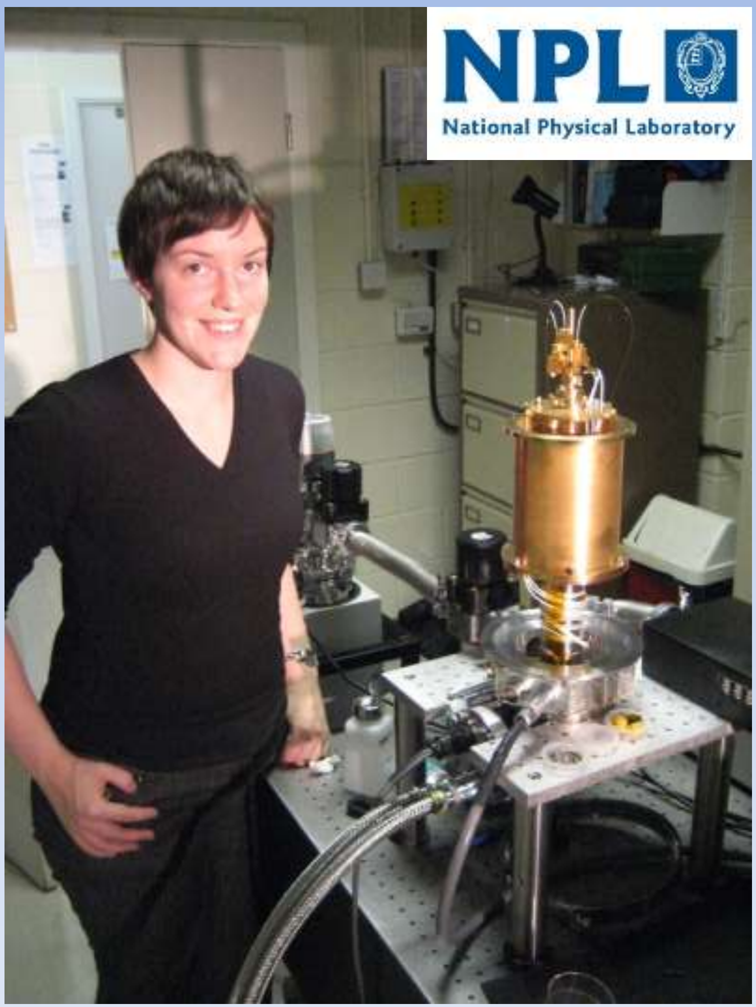
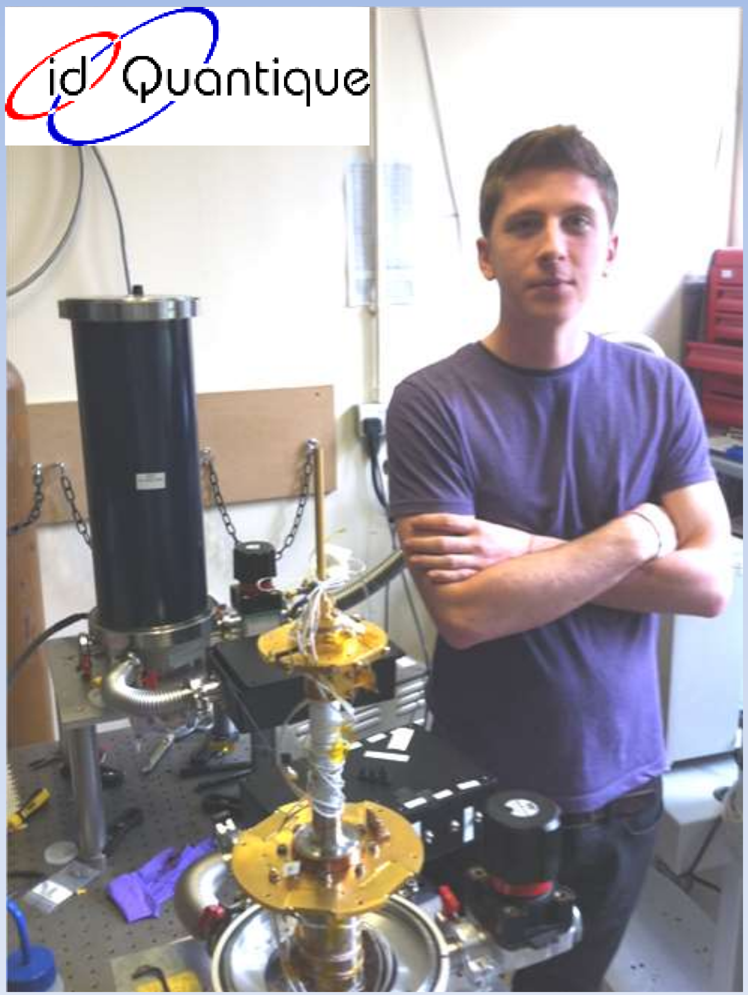
SNSPD systems for industry partners

2009



2011



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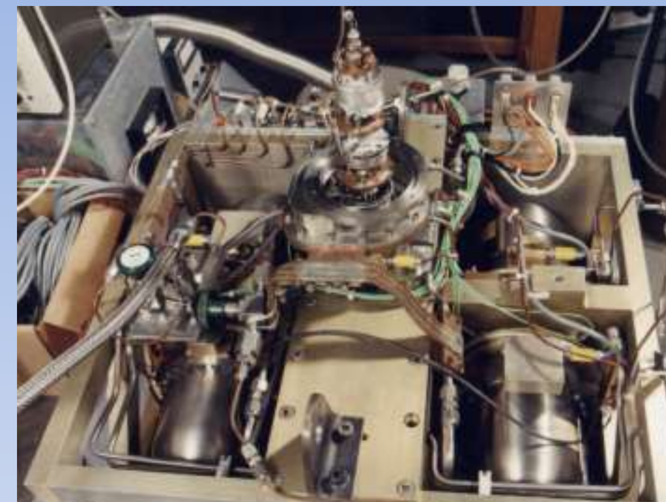
Cooling technology for SNSPDs 2016

- Cooling technology developed by Rutherford Appleton Laboratory UK for Planck Space Telescope (launched May 2009)
- Combined Stirling/Joule Thompson mechanism
- Weight of cold head/compressor 5kg
- 3 mW cooling power at 4.2 K
- 120 W from a battery
- Able to withstand 3000 g vibration at launch
- Bespoke item



Development Plan:

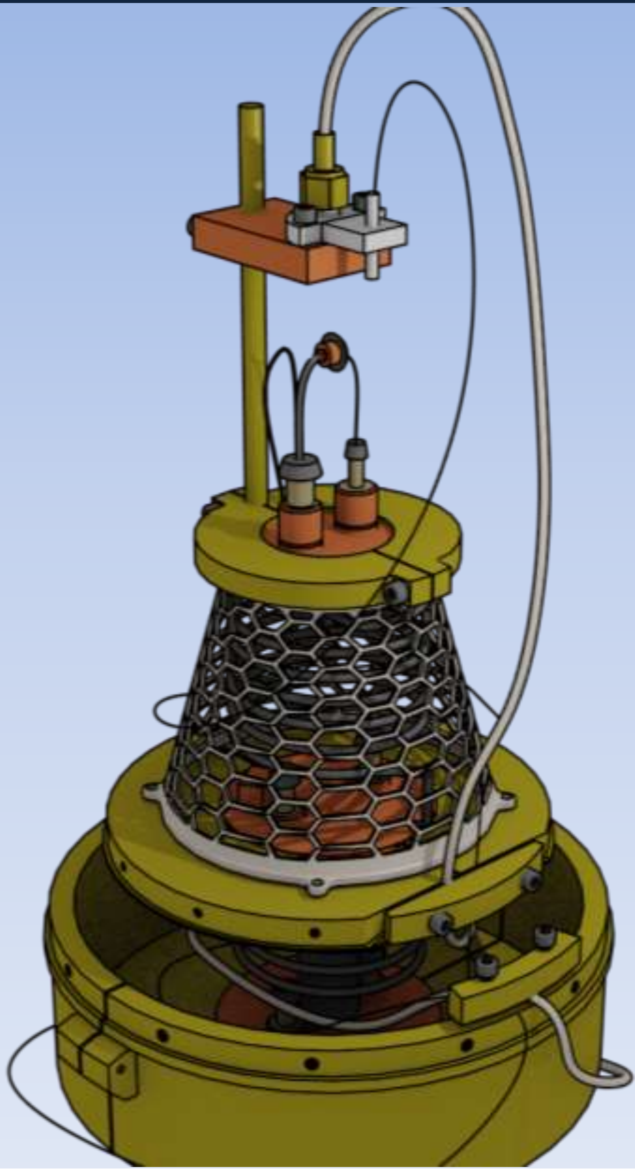
2016: single photon detector prototype demonstration (QUANTIC)

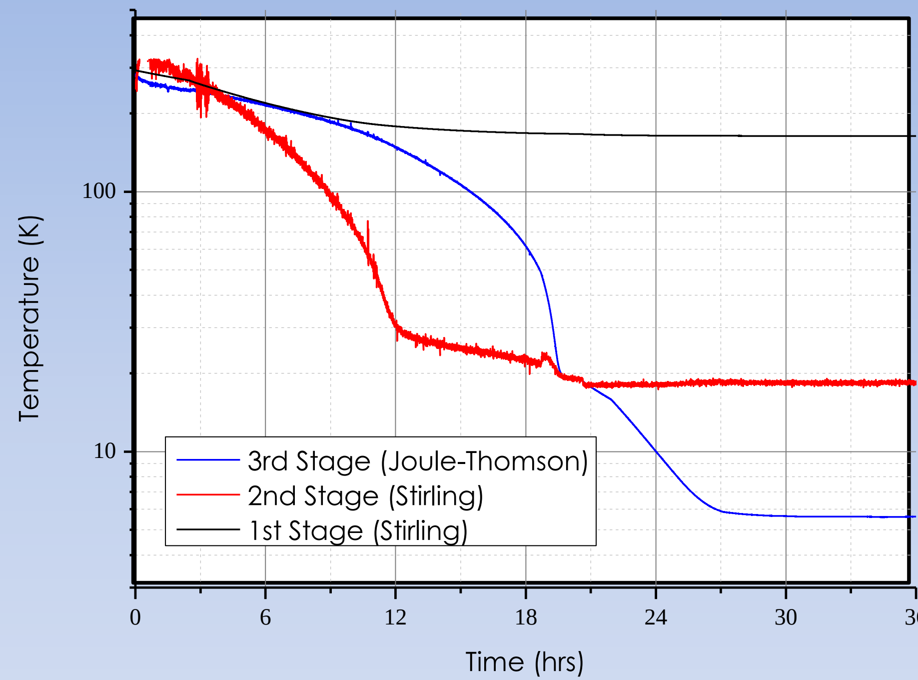
2018: redesign for simplified manufacture (ERC)

QUANTIC   erc   Science & Technology Facilities Council Rutherford Appleton Laboratory

University of Glasgow

Miniaturized 4 K cooling for SNSPDs





Heat load Testing:
Temperature kept below 5K and stable for 3mW heat load

QUANTIC

Science & Technology Facilities Council Rutherford Appleton Laboratory

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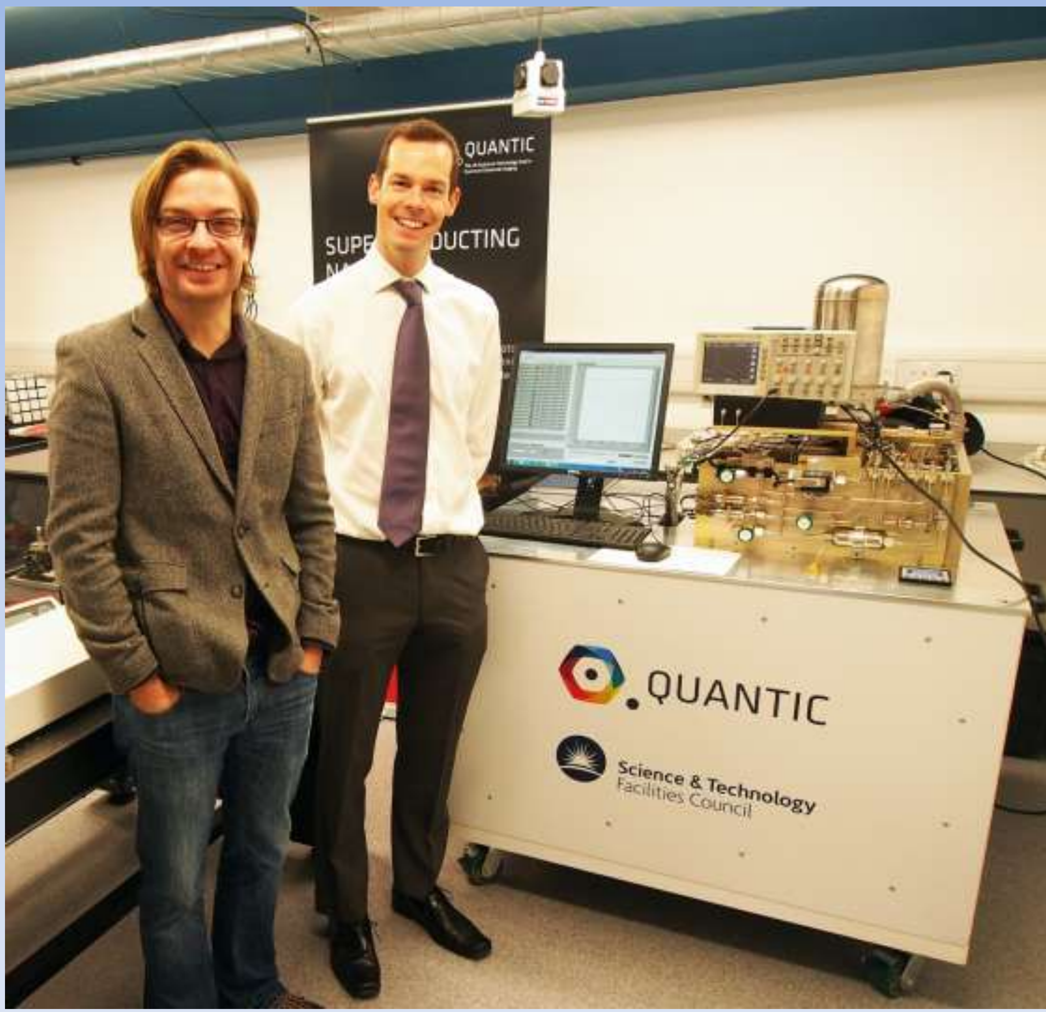
UK Quantum Showcase November 2016



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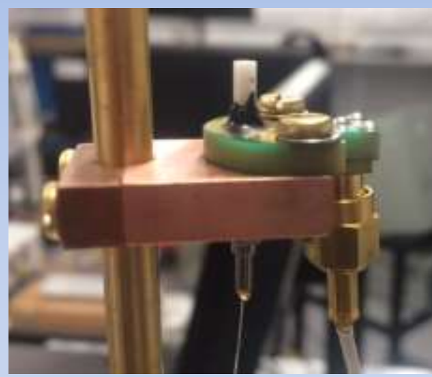
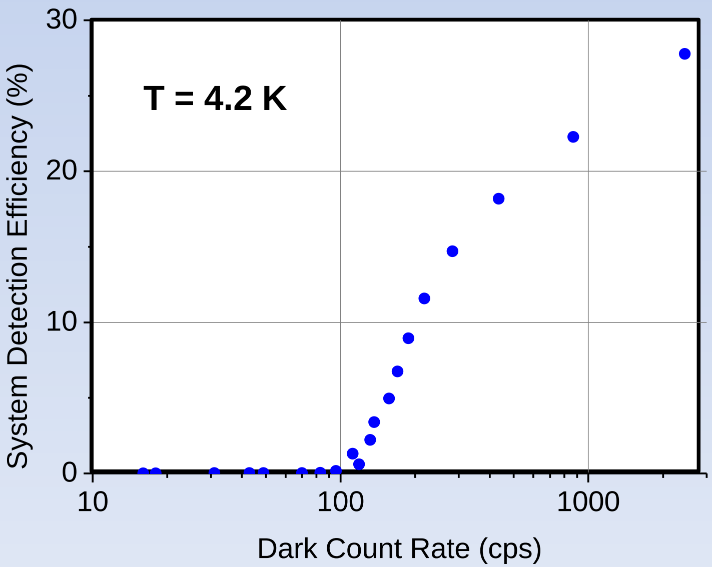
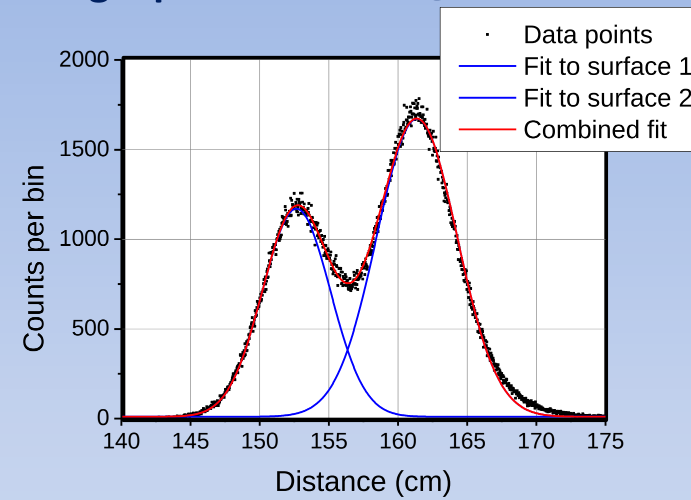
Photon counting demonstrations

SINGLE QUANTUM
Excellence in photon detection

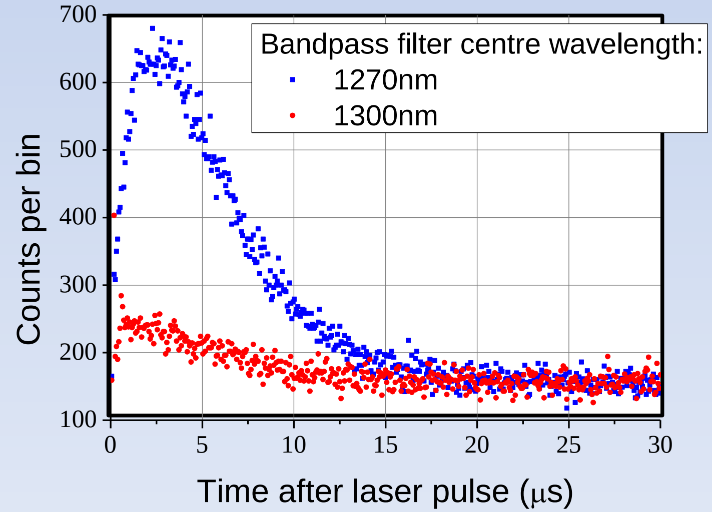




Single photon LIDAR @1550 nm



Singlet oxygen luminescence @1270 nm



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16th International Superconductive Electronics Conference
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Infrared single-photon detection with superconducting nanowires

- Superconducting nanowire single photon detectors (SNSPDs) are the world's leading infrared photon-counting technology
- SNSPDs are being widely adopted in a range of cutting edge applications
- There is a major push to scale up from single pixels to photon counting cameras
- Miniaturization of cooling platforms will widen the adoption of SNSPDs

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Infrared single-photon detection with superconducting nanowires

Robert Hadfield

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NIST

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UCL

UNIVERSITY OF CAMBRIDGE

Imperial College London

HERIOT WATT UNIVERSITY

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SINGLE QUANTUM Excellence in photon detection

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