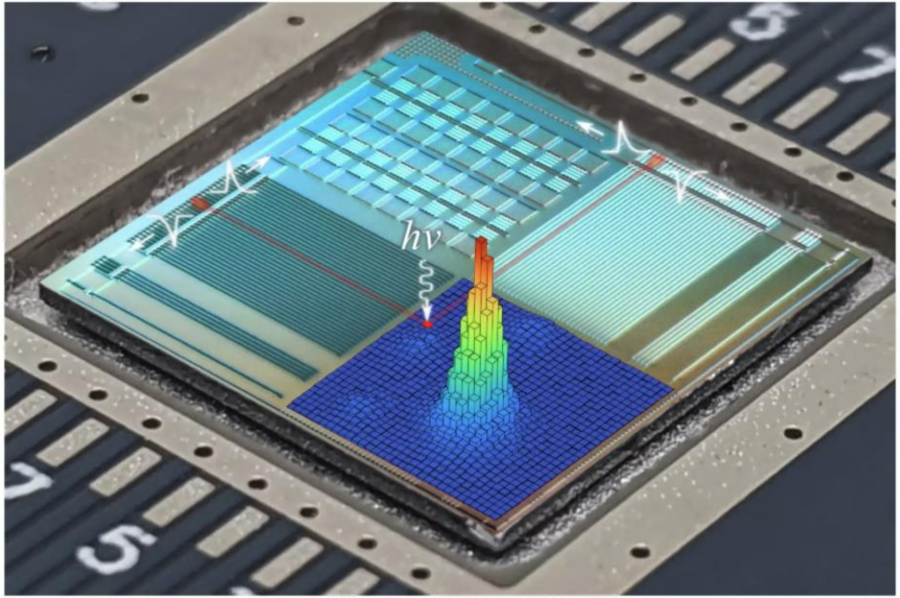

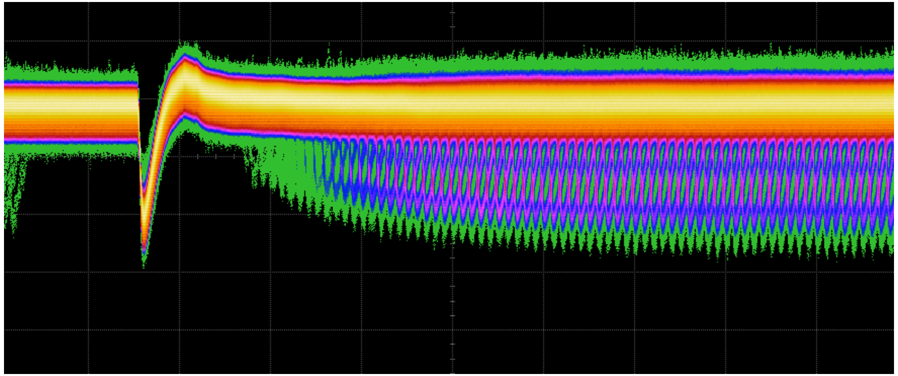

24th Oct 2025

# Superconducting nanowire detectors: from quantum science to high energy physics

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*University of Geneva, Switzerland*

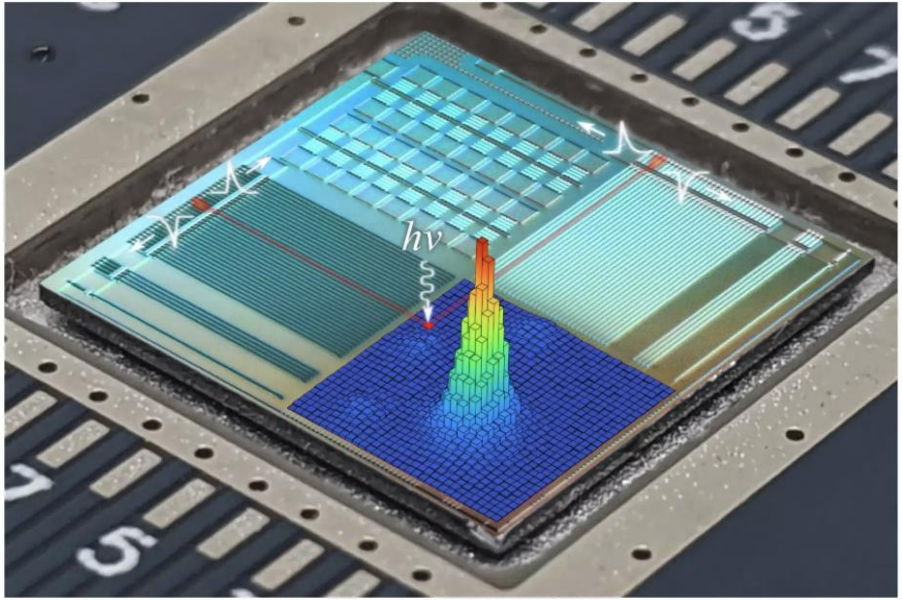
UNIVERSITÉ DE GENÈVE

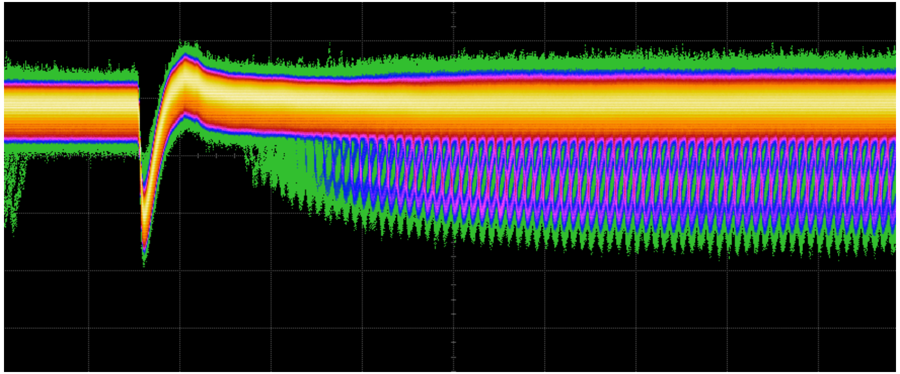
Jet Propulsion Laboratory
California Institute of Technology

*boris.korzh@unige.ch*

# Outline

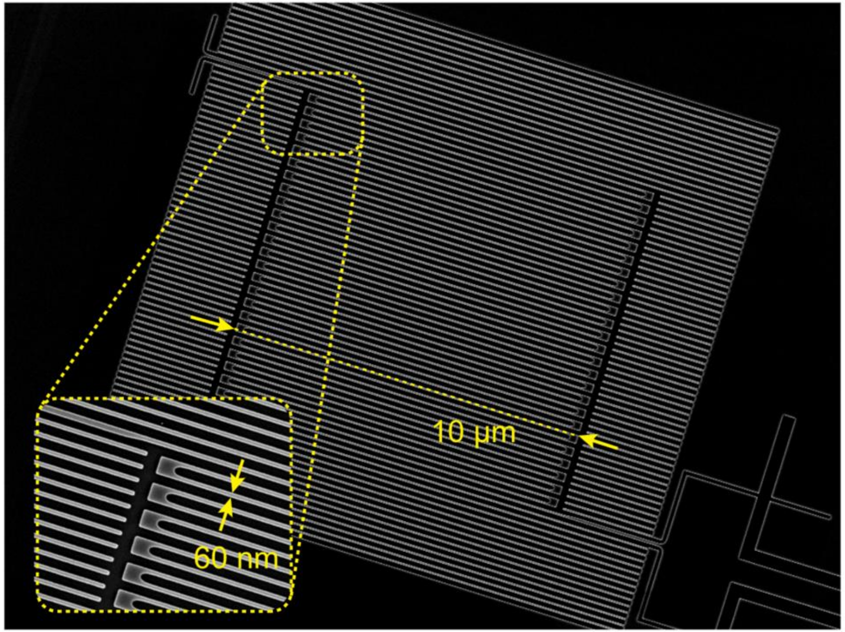
1. Superconducting nanowire basics
2. Established applications:
   - Quantum science
   - Deep space optical communication
3. Detection mechanism
4. High-energy particle detection
5. Emerging imaging arrays
6. Towards dark matter searches



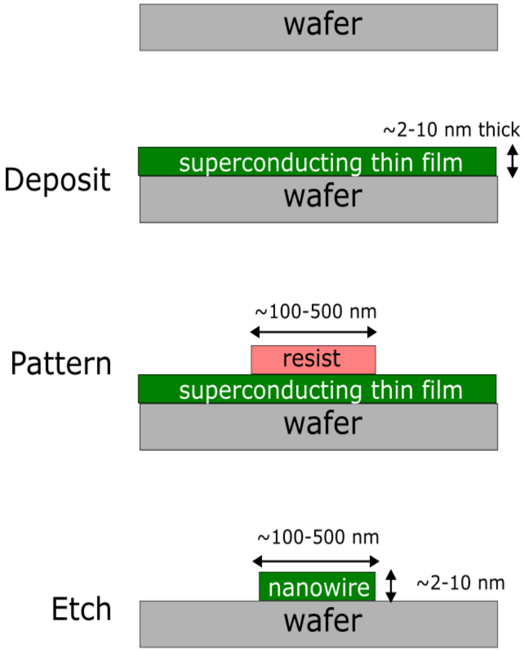
# Superconducting nanowire detector

**(typically "single-photon" → SNSPD)**



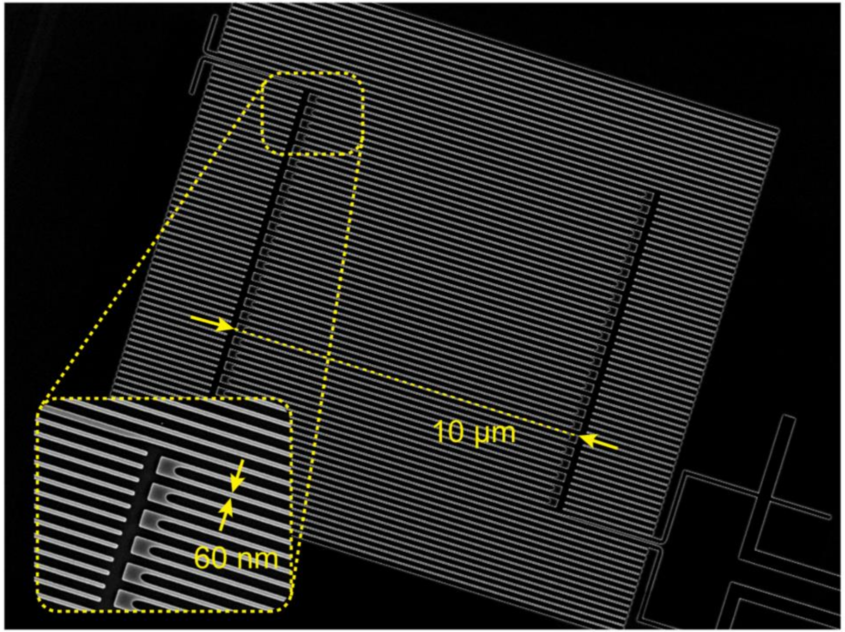

Single-pixel detector

Nanofabrication

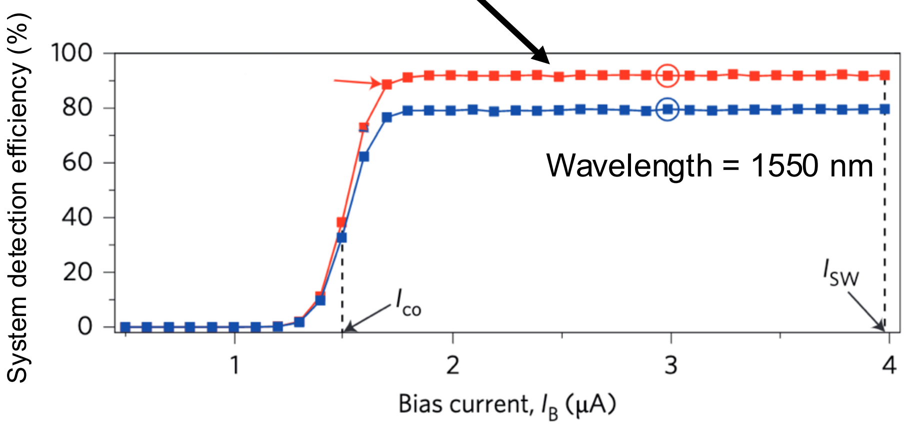



Goltsman, *et al*, ***APL* 79**, 705 (2001)

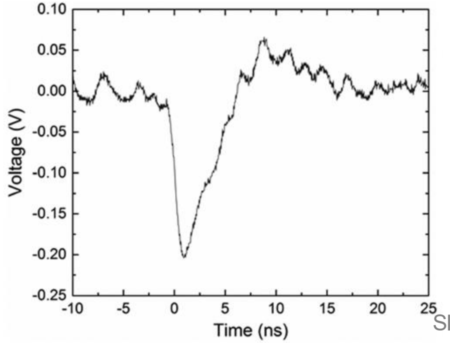
# System efficiency




Unity Quantum Efficiency




Photon "click"

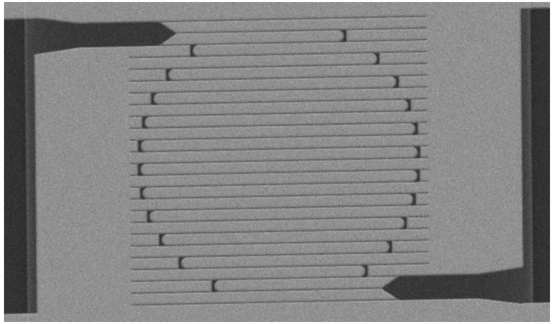



*Fully digital*

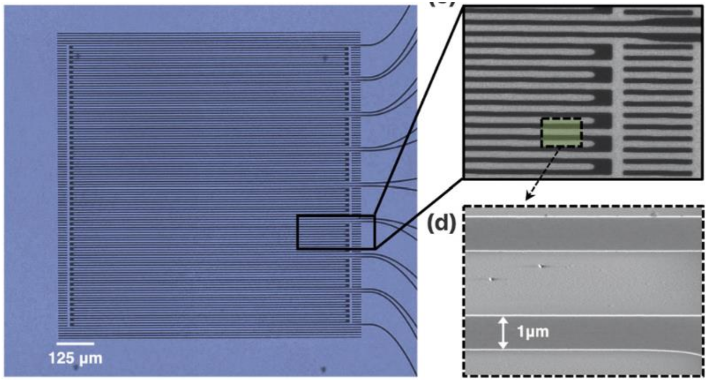
Marsili, Verma, Stern *et al*, ***Nature Photonics*** **7**, 210-214 (2013)

# Different formats

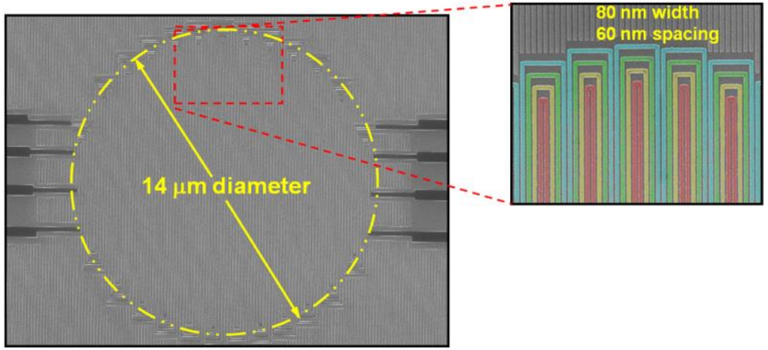
## Single-pixel
*Quantum science*



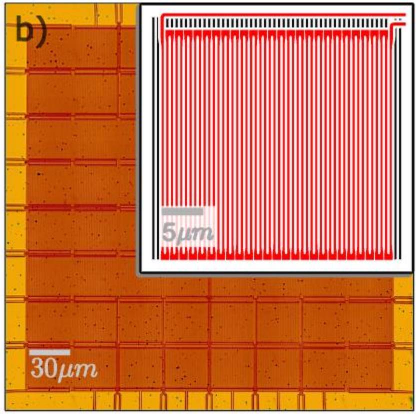
## Linear arrays
*Large collection area / spectroscopy*



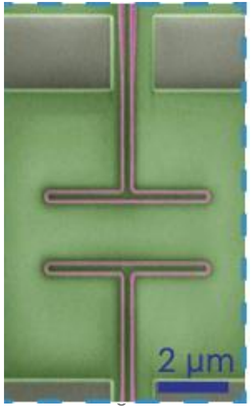

## Interleaved pixel
*Fast count rates*




## Pixel array
*Imaging*

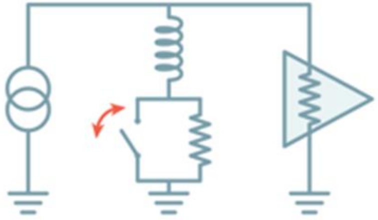


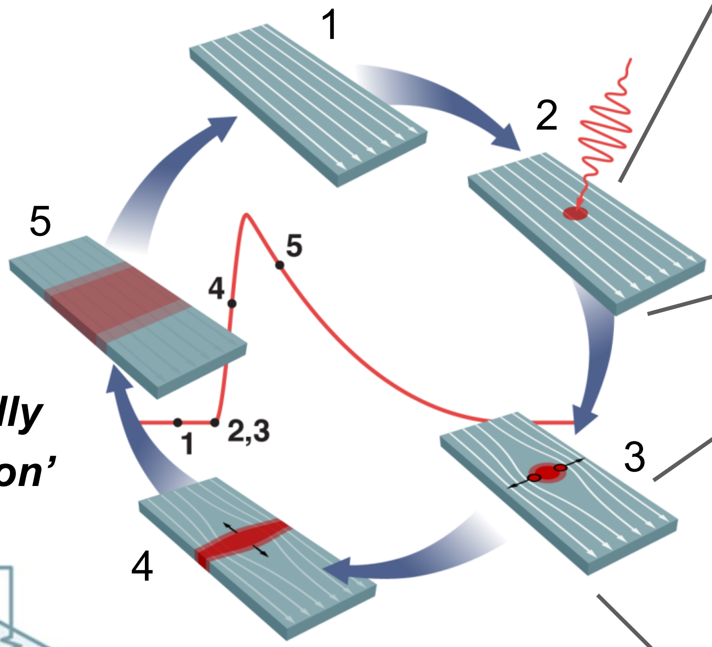

## Waveguide



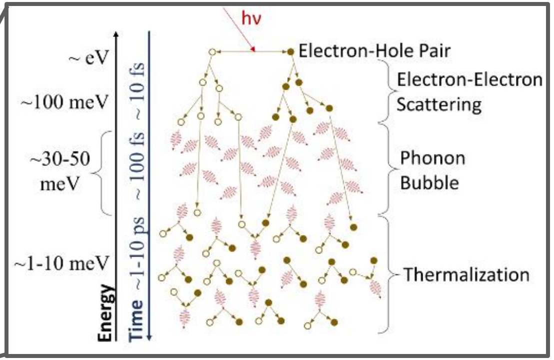
# SNSPD detection mechanism

1. Current-biased superconducting nanowire
2. Photon absorption & Hotspot formation
3. Suppression of superconductivity
4. Normal domain growth – ***Fully digital → no 'energy resolution'***
5. Recovery

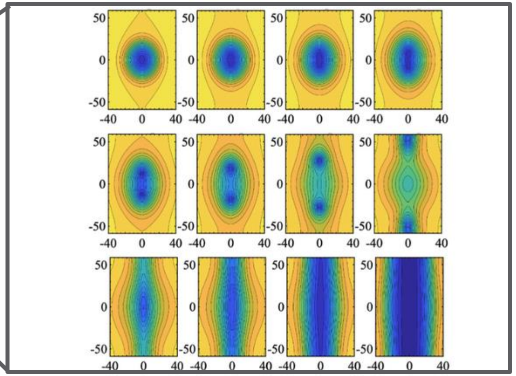





*Typically operating at 0.3-5 kelvin*




***thousands of carriers per photon***

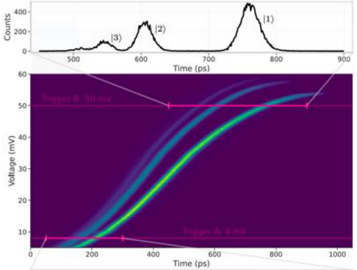


Allmaras, Kozorezov, Korzh, Berggren and Shaw, ***PRApplied* 11** 034062 (2019)
Allmaras, *Modeling and Development of Superconducting Nanowire Single-Photon Detectors*, **Ph.D. Dissertation**, Caltech (2020)

# Established SNSPD Applications

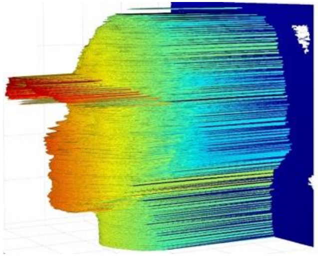
## Quantum Information Science

- ***Quantum comm***
- *Quantum optics*
- ***Trapped ion and neutral atom quantum Computing***
- ***Linear optical quantum computing***
- *Space-to-ground quantum comm*



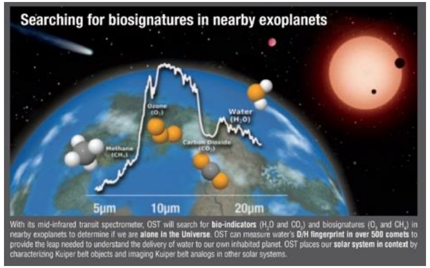

## Laser Comm, Ranging, Remote sensing

- ***Deep Space Optical Comm (NASA Psyche)***
- ***LIDAR***
- *Remote gas sensing*
- *Fiber sensing (temperature, transmission, strain)*



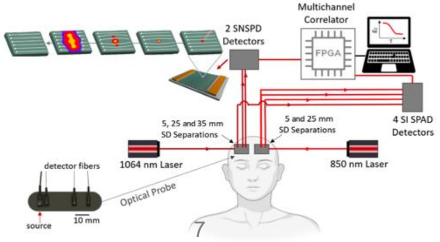
## Physics, Astronomy

- *Stellar Intensity Interf.*
- ***Dark matter searches***
- *Exoplanet searches*
- *Far-UV/Far-IR astrophysics*
- *Searches for quantum gravity*
- ***Particle detection***

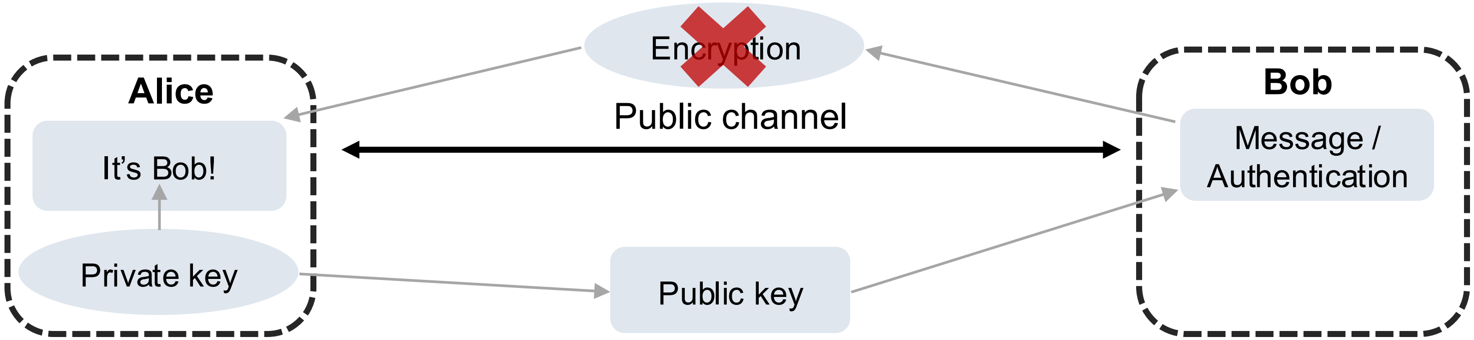



## Biomedicine, Physical chemistry

- *Ultrafast transients*
- *Fluorescence microscopy*
- *Dosimetry in cancer therapy*
- *Blood-flow monitoring*
- *Deep tissue imaging*
- *MIR spectroscopy*



# Cryptography and quantum computing

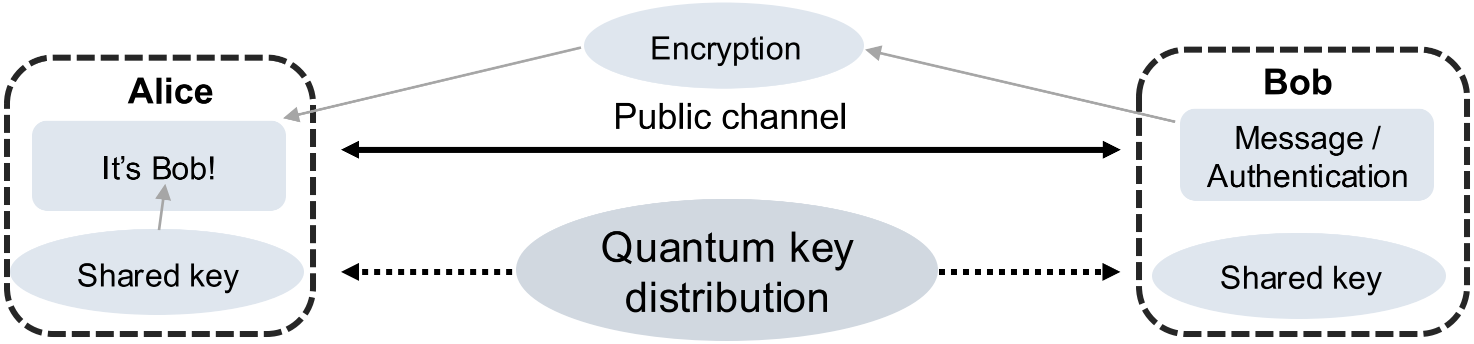



Based on computational complexity -- not perfectly secure

Quantum computing drastically reduces the complexity for some problems

Quantum
Computing and
Simulation

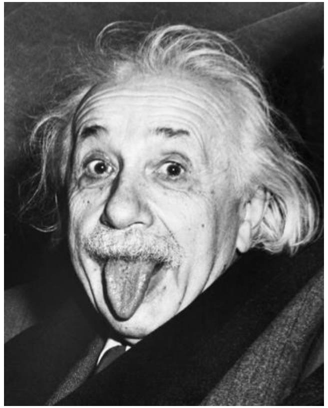
# Cryptography and quantum computing



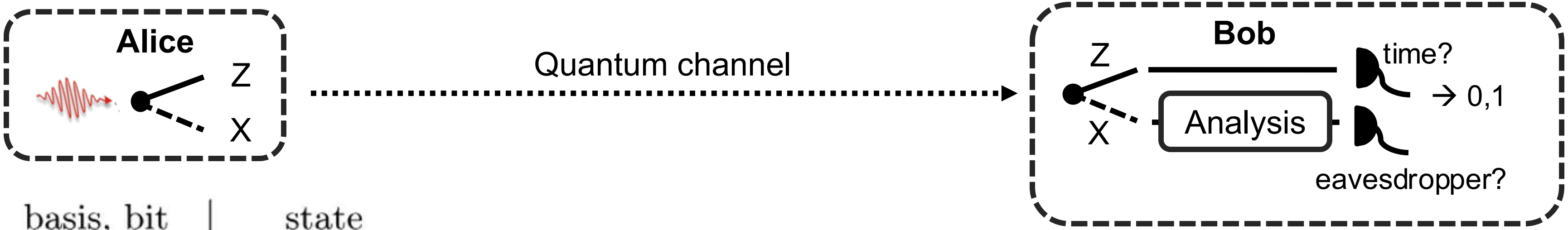

Provably secure!

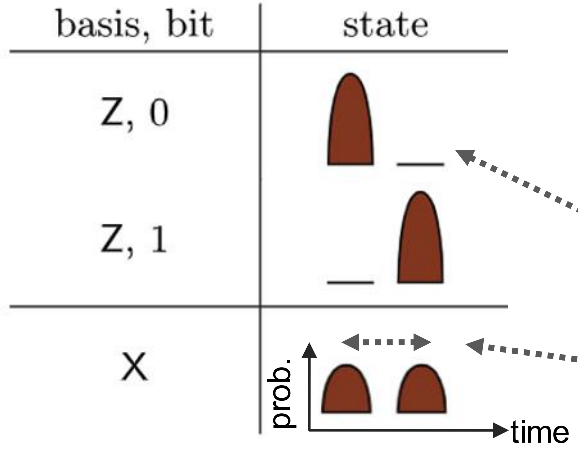
But need to distribute the key

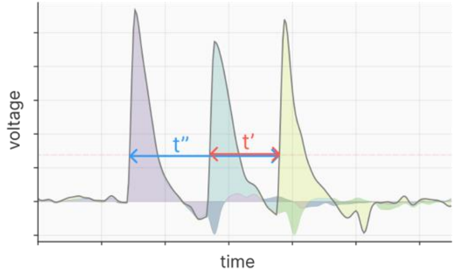
Security guaranteed by Laws of Physics!



# Quantum communication with photons




Detector **inefficiency** → slower rate of key generation

Detector **dark counts** → quantum bit errors

Speed limited by detector **timing accuracy**

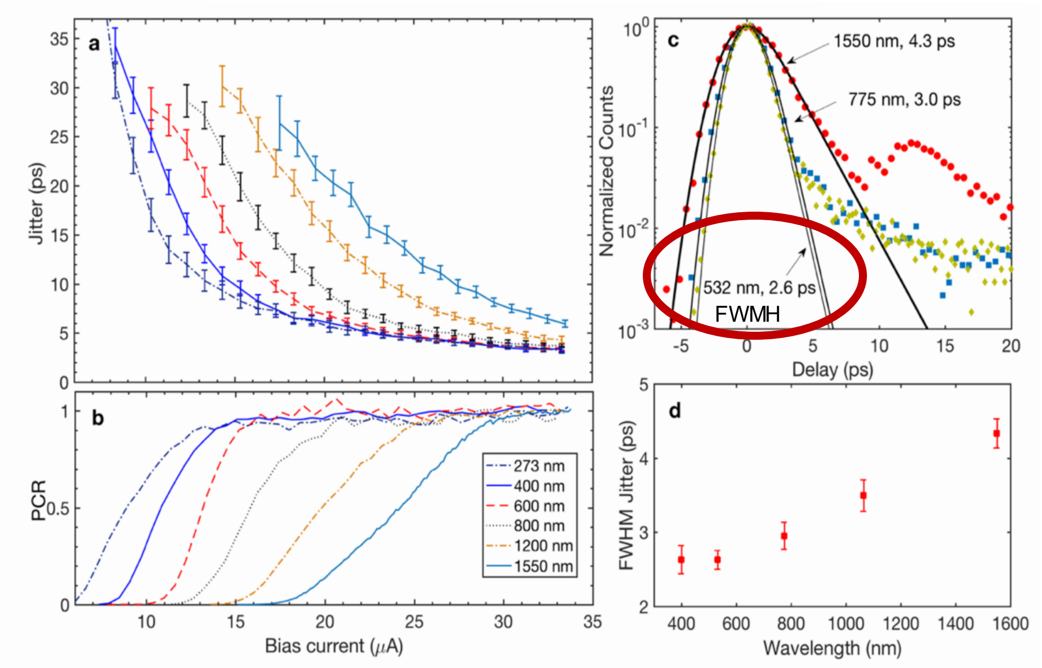
Photon rate limited by detector **recovery time**

# Advances in superconducting nanowire detectors

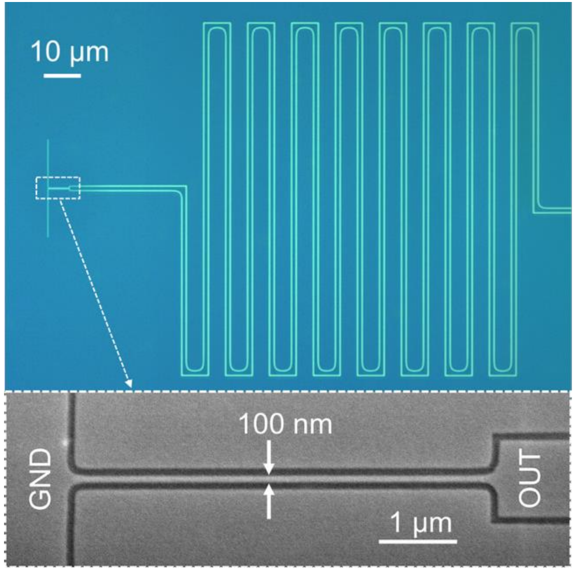
| | Timing jitter | Intrinsic photon number resolution | Efficiency | Array size | Maximum count rate | Dark count rate | Active area | Cut-off wavelength |
|---|---|---|---|---|---|---|---|---|
| Records in 2016 | 18 ps | None | 93% | 64 | 1 Gcps | 4 /s/mm$^2$ | 0.001 cm$^2$ | 5 µm |
| **Current records for isolated devices** | **2.6 ps** [1] | **3-5 photons** | **98%** [2] | **4x10$^5$** [3] | **1.5 Gcps** [4,5] | **4x10$^{-5}$ /s/mm$^2$** [6] | **0.1 cm$^2$** [3] | **29 µm** [7] |
| Expected performance by 2030 | **1 ps** | **10** | **99 %** | **10$^7$** | **10 Gcps** | **1x10$^{-6}$ /s/mm$^2$** | **1 cm$^2$** | **100 µm** |

[1] Korzh, Zhao et al, ***Nature Photonics*** *14*, 250 (2020)
[2] Reddy et al, ***Optica*** 7, 1649 (2020)
[3] Oripov, Rampini, Allmaras, Shaw, Nam, Korzh, and McCaughan, ***Nature*** 622, 730 (2023)
[4] Craiciu, Korzh et al, ***Optica*** 10, 183 (2023)
[5] Resta et al, ***Nano Letters*** (2023)
[6] Chiles, ***PRL*** 128, 231802 (2022)
[7] Taylor, Walter, Korzh et al, ***Optica***, (2023)

# Record timing accuracy

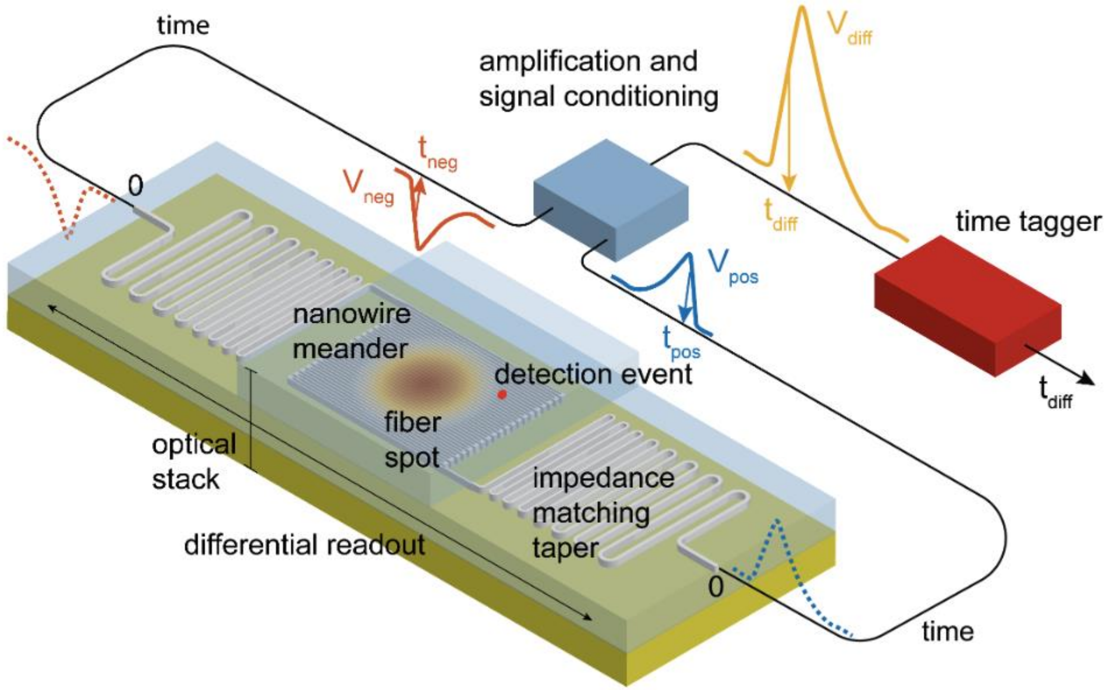


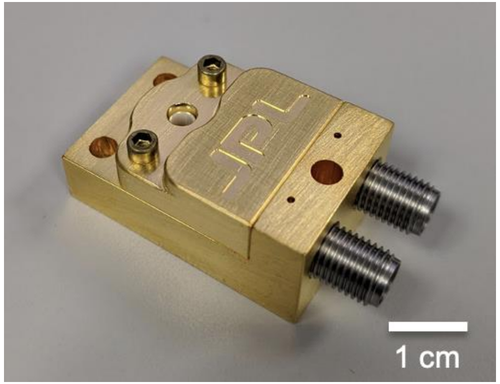

Probing the intrinsic timescales




Korzh, Zhao, Allmaras, Frasca *et al* ***Nature Photonics* 14,** 250-255 (2020)

# Practical single-pixel detectors

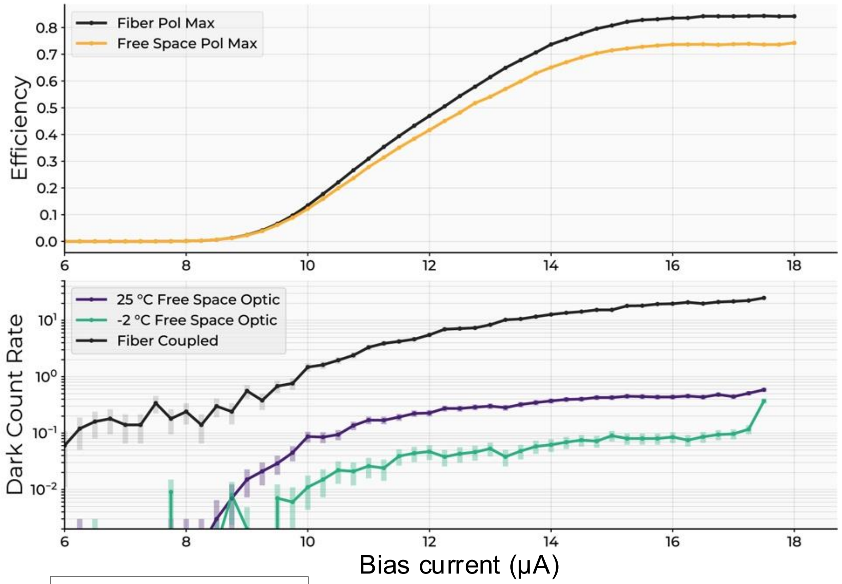



Colangelo, Korzh, Allmaras, Beyer *et al*, ***PRApplied* 19**, 044093 (2023)

# Detector requirements for Quantum Communication

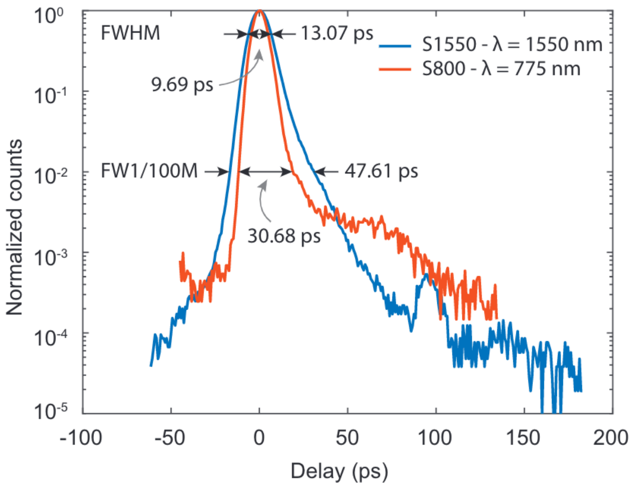
High efficiency




Low noise

Intrinsic dark counts can be <$10^{-5}$ cps

Low timing jitter




Mueller, Korzh, Runyan *et al*, ***Optica* 8,** 1586 (2021)

# Quantum key distribution

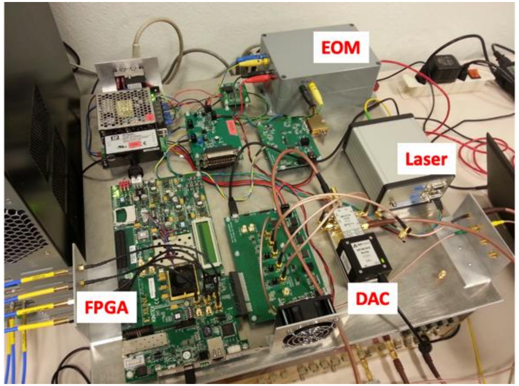
**Rates**

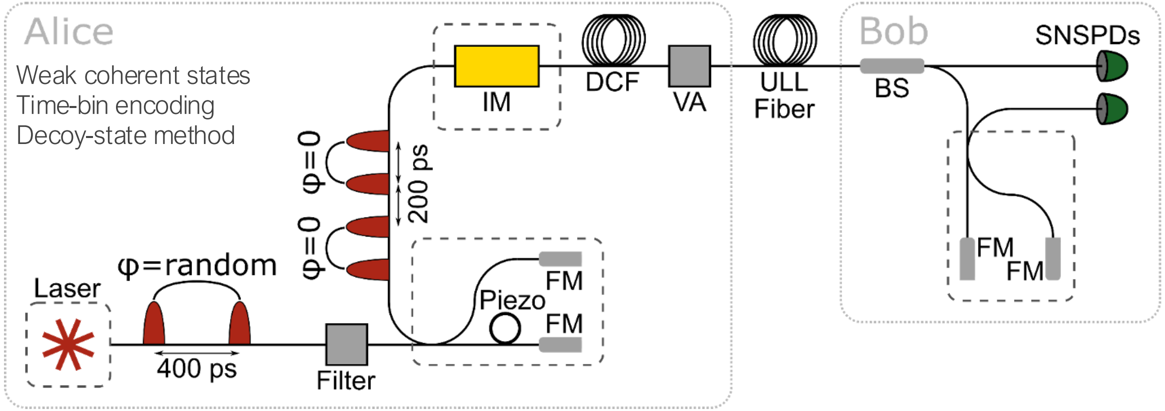
64 Mbps @ 10km

3Mbps @ 100km

**Distances**

421km



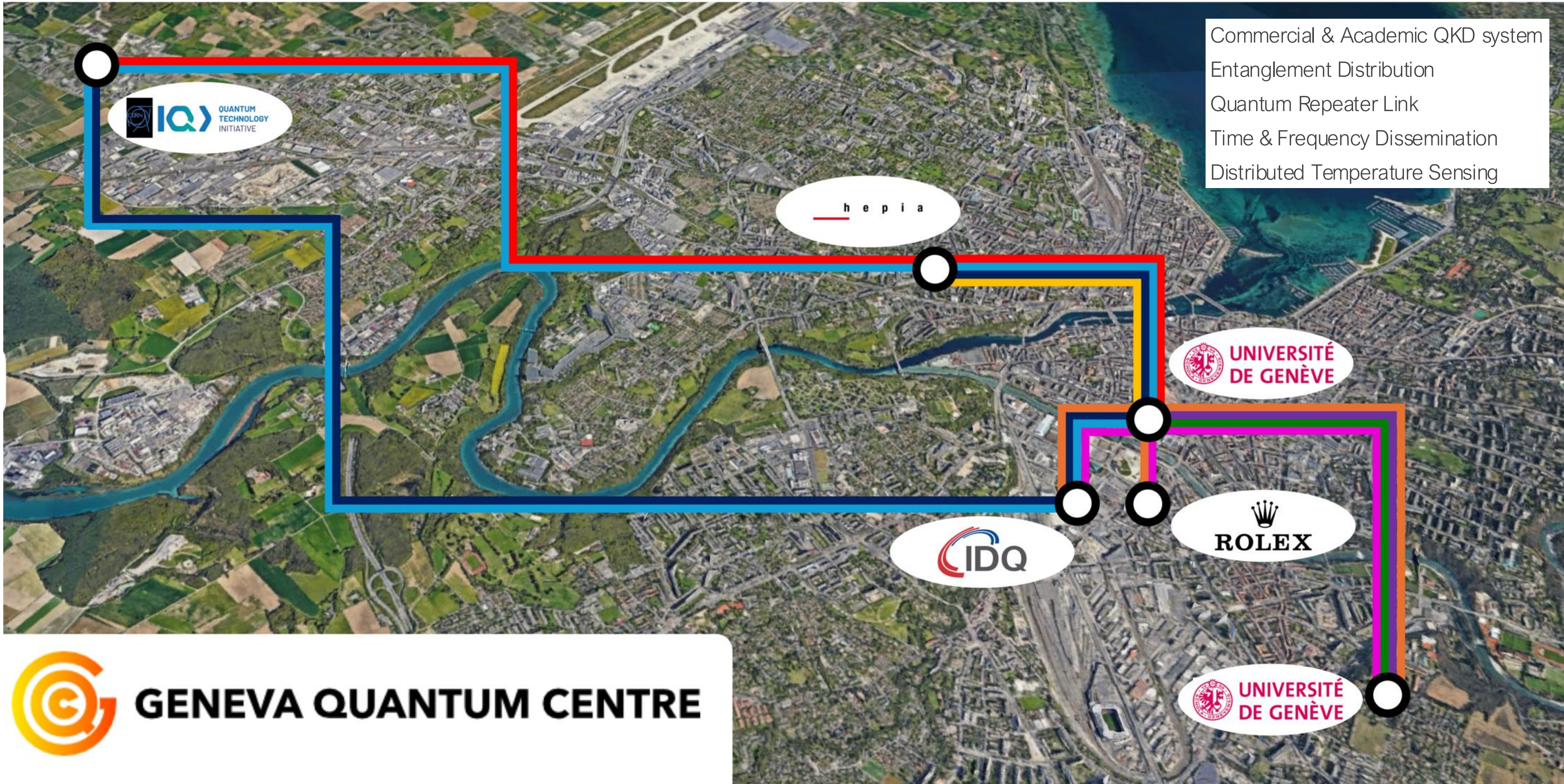




F. Grünenfelder *et al.*, Nature phot, 17, 422 (2023)

A. Boaron et al., Phys. Rev. Lett. **121**, 190502 (2018)

# Geneva Quantum Network

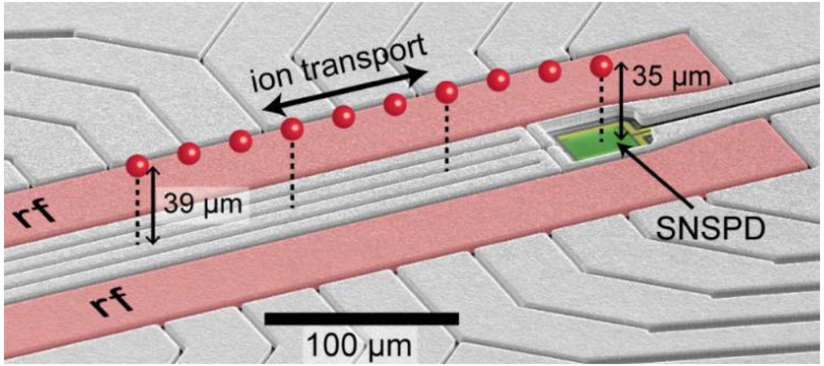
GENEVA QUANTUM CENTRE UNIVERSITÉ DE GENÈVE




GENEVA QUANTUM CENTRE

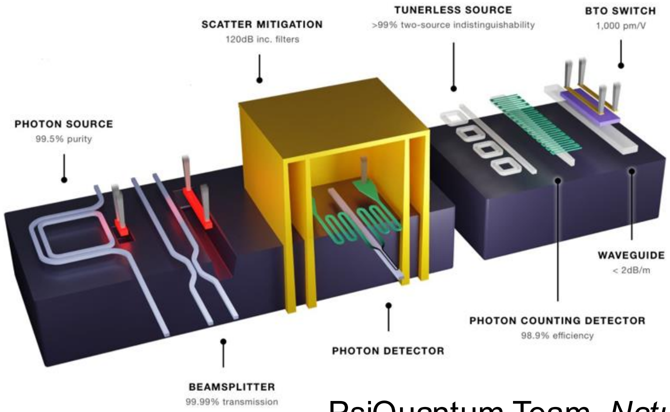
# Quantum computing enabled by SNSPDs

## *Atomic state readout*

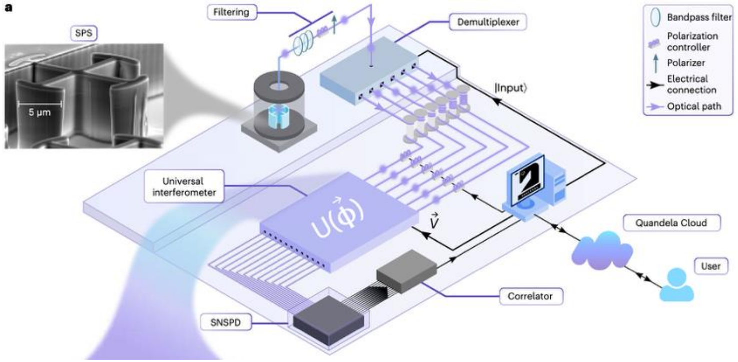



NIST, 2021

## *Photon qubits*




PsiQuantum Team, *Nature* (2025)

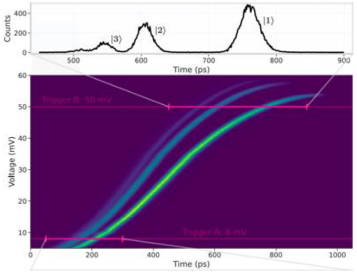



Quandela Team, *Nature Photonics* (2024)

# Established SNSPD Applications

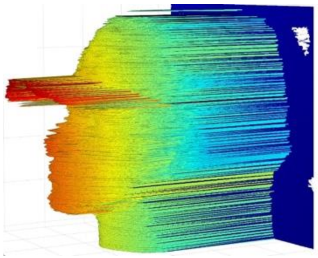
## Quantum Information Science

- ***Quantum comm***
- *Quantum optics*
- ***Trapped ion and neutral atom quantum Computing***
- ***Linear optical quantum computing***
- *Space-to-ground quantum comm*



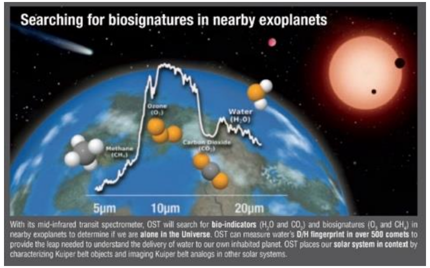

## Laser Comm, Ranging, Remote sensing

- *Lunar Laser Comm Demo*
- ***Deep Space Optical Comm (NASA Psyche)***
- ***LIDAR***
- *Remote gas sensing*
- *Fiber sensing (temperature, transmission, strain)*



## Physics, Astronomy

- ***Dark matter searches***
- *Exoplanet searches*
- *Far-UV astrophysics*
- *Far infrared astrophysics*
- *Searches for quantum gravity*
- ***Particle detection***




## Biomedicine, Physical chemistry

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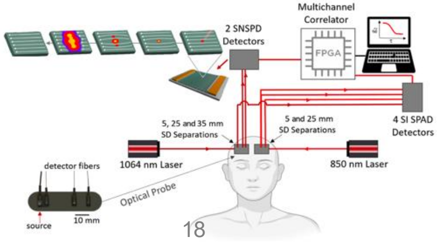
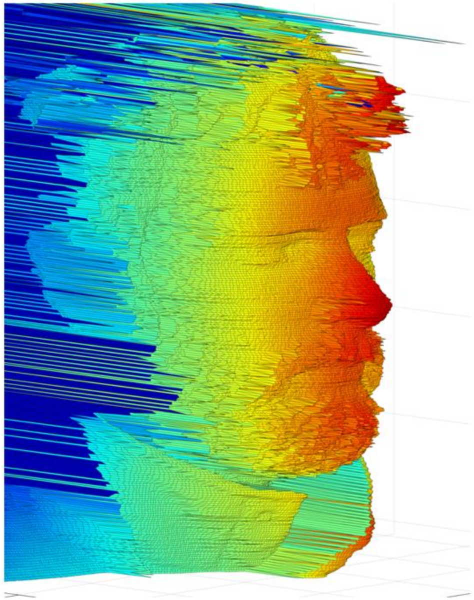
- *Dosimetry in cancer therapy*
- *blood-flow monitoring*
- *Deep tissue imaging*
- *MIR spectroscopy*



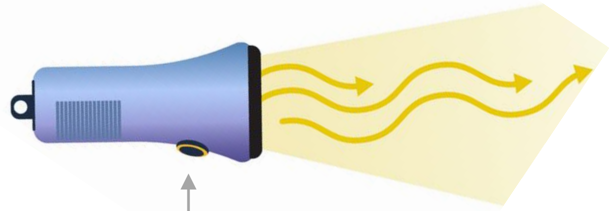
# Remote sensing



*Laser ranging, but with single photons!*

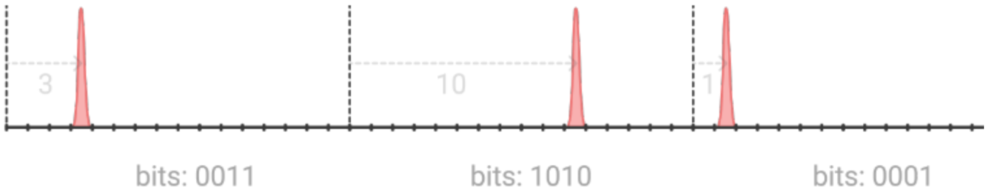
McCarthy, A. et al *Optica*. 12, 168-177 (2025)

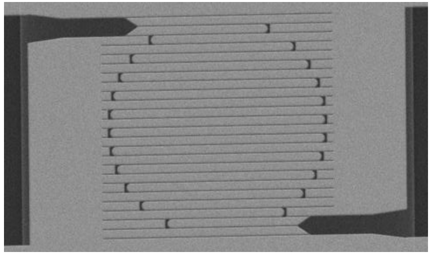
# Classical optical communication

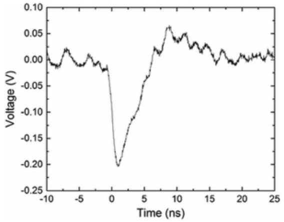


Message

**Alice**



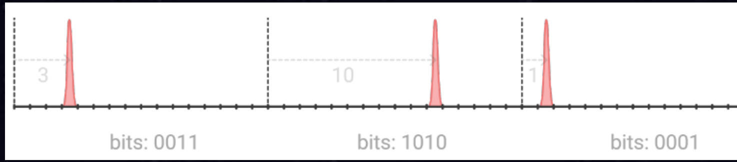


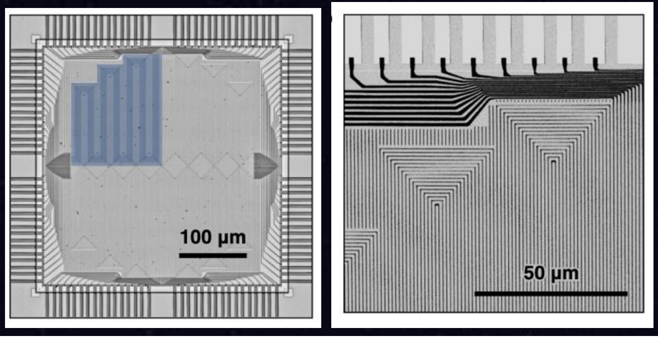

**Bob**

# NASA Deep Space Optical Communication


~10 exa-photons / sec ($10^{19}$)

~1 mega-photons / sec ($10^{6}$)




Wollman, Allmaras, Beyer, Korzh, Runyan, Narváez, Farr, et al. 2024. “An SNSPD-Based Detector System for NASA’s Deep Space Optical Communications Project.”

# Space-to-ground tests

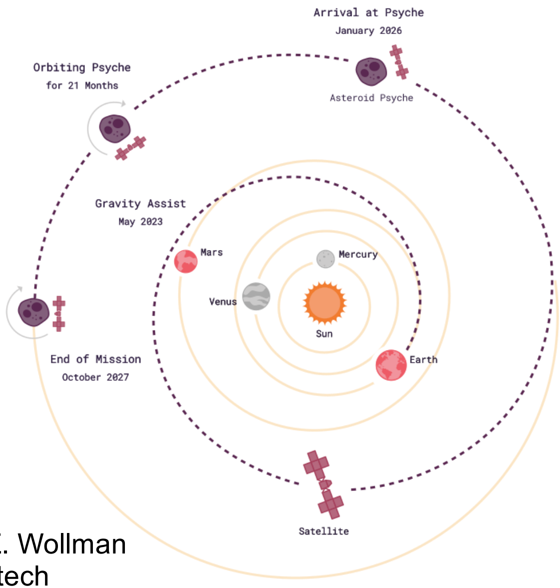
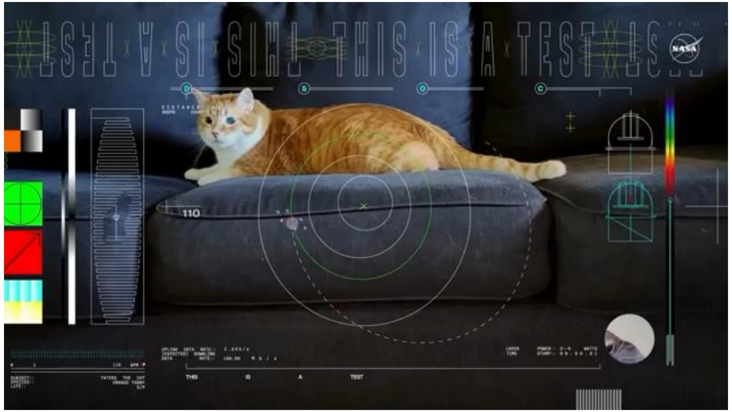



Image: E. Wollman
JPL, Caltech

Launched in Oct 2023

**Received from 30 Million kilometers!**




Operations started Nov 2023:

- **267 Mbps** up to 0.37 AU (equivalent to the minimum Earth-Mars distance)
- **25 Mbps** up to 1.5 AU (equivalent to the average Earth-Mars distance)
- **8.33 Mbps** 2.68 AU (equivalent to Mars farthest range)

Wollman, Allmaras, Beyer, Korzh, Runyan, Narváez, Farr, et al. 2024. “An SNSPD-Based Detector System for NASA’s Deep Space Optical Communications Project.”

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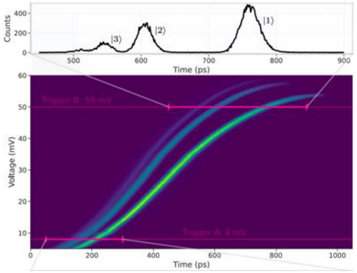


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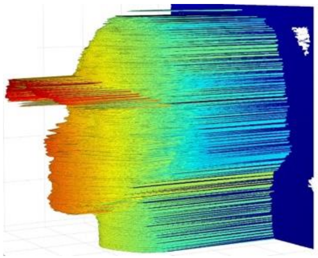

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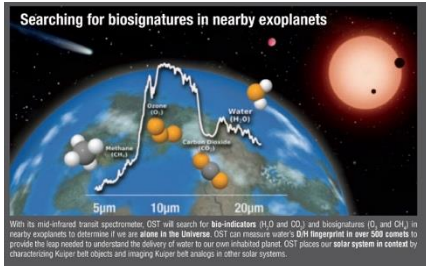
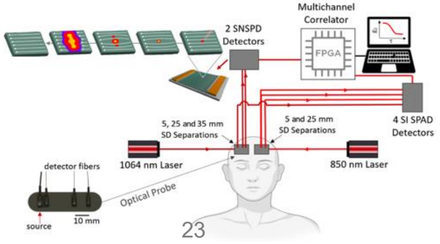
- *Searches for quantum gravity*
- ***Particle detection***




## Biomedicine, Physical chemistry

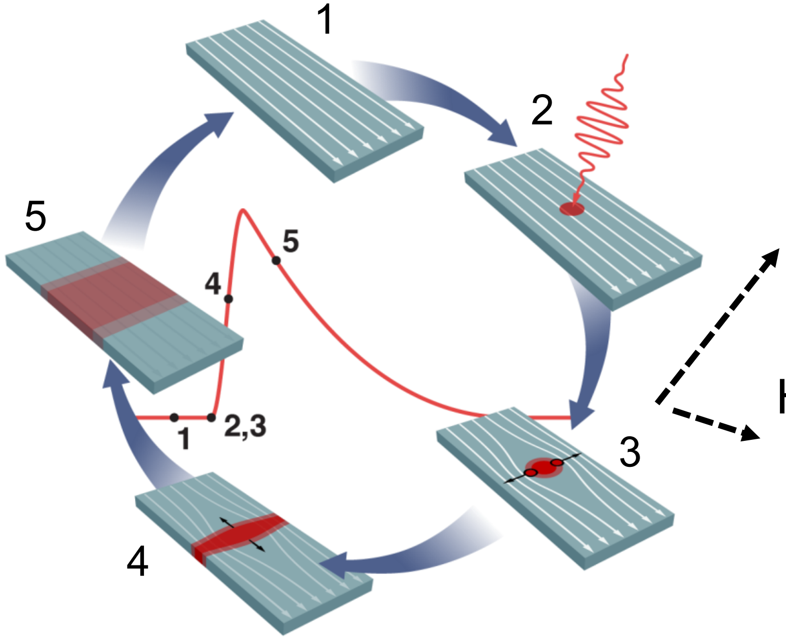
- *Ultrafast transients*
- *Fluorescence microscopy*
- *Dosimetry in cancer therapy*
- *blood-flow monitoring*
- *Deep tissue imaging*
- *MIR spectroscopy*



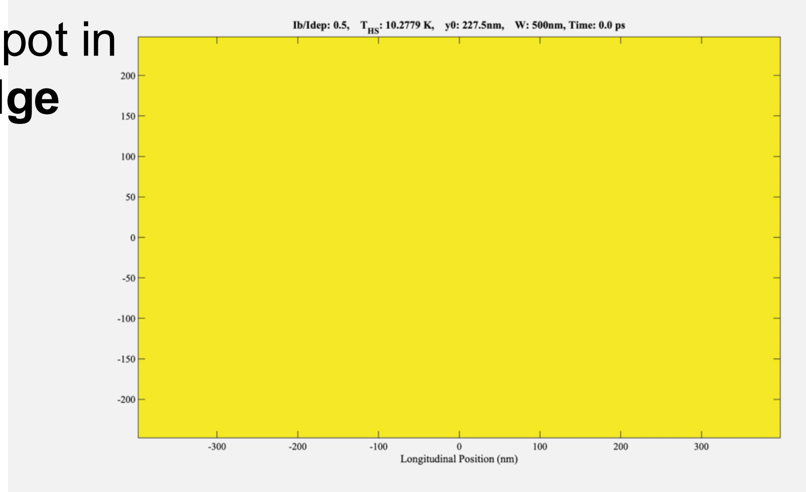
**First let's understand a bit better how they work….**

**….and what we can detect with them**

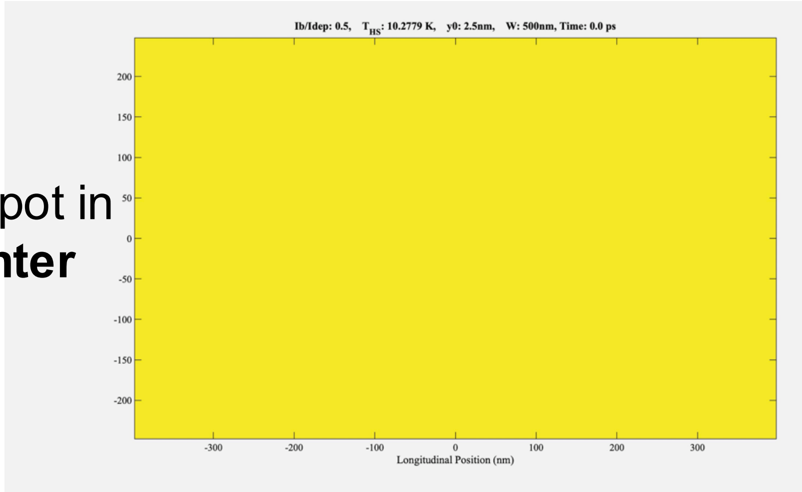
# Suppression of superconductivity across wire




Hot-spot in
**Edge**

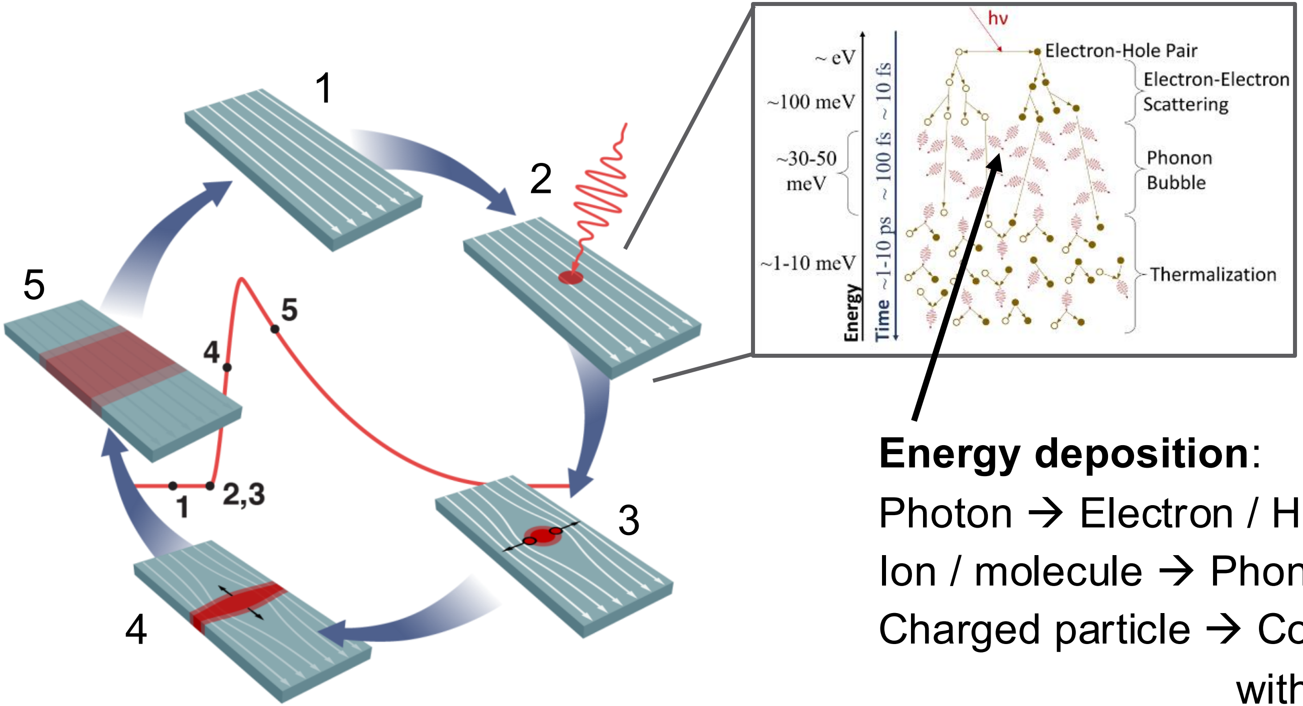



Hot-spot in
**Center**




Allmaras, *Modeling and Development of Superconducting Nanowire Single-Photon Detectors*, **Ph.D. Dissertation**, Caltech (2020)

# Energy threshold – to initiate vortices




**Energy deposition**:

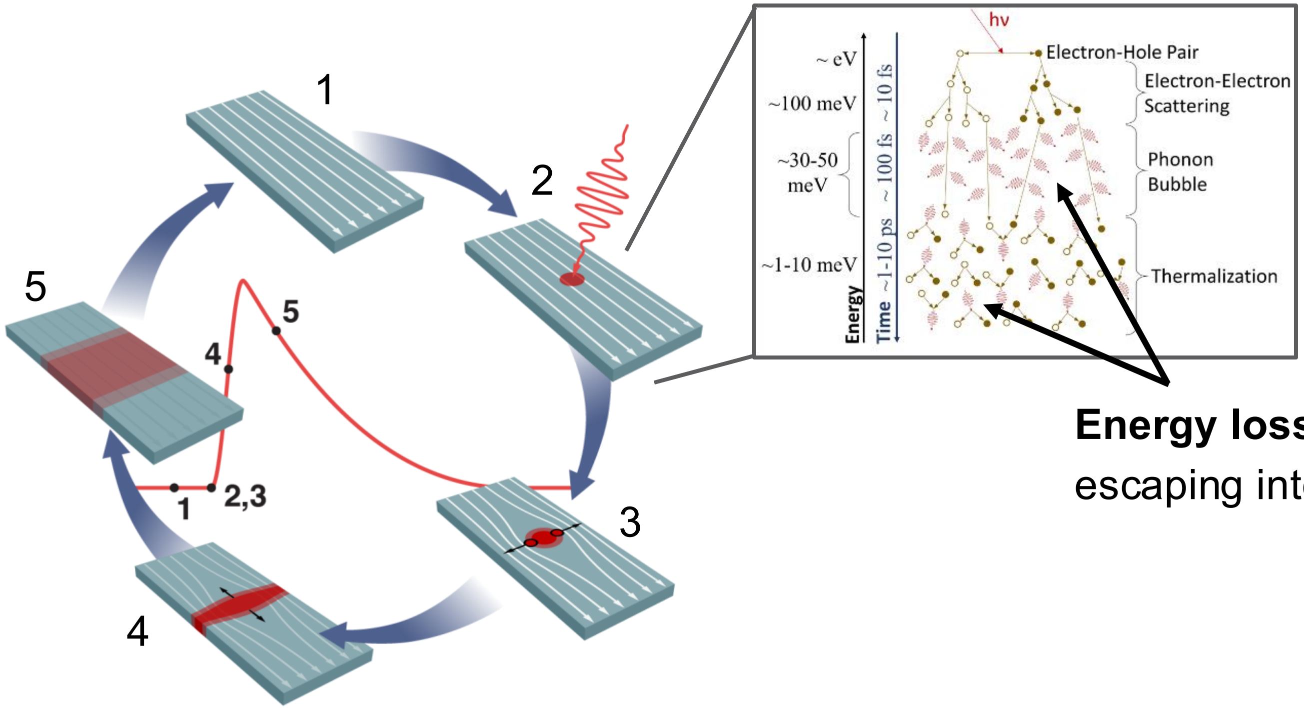
Photon → Electron / Hole

Ion / molecule → Phonons at surface

Charged particle → Coulomb interaction with electrons

Allmaras, *Modeling and Development of Superconducting Nanowire Single-Photon Detectors*, **Ph.D. Dissertation**, Caltech (2020)

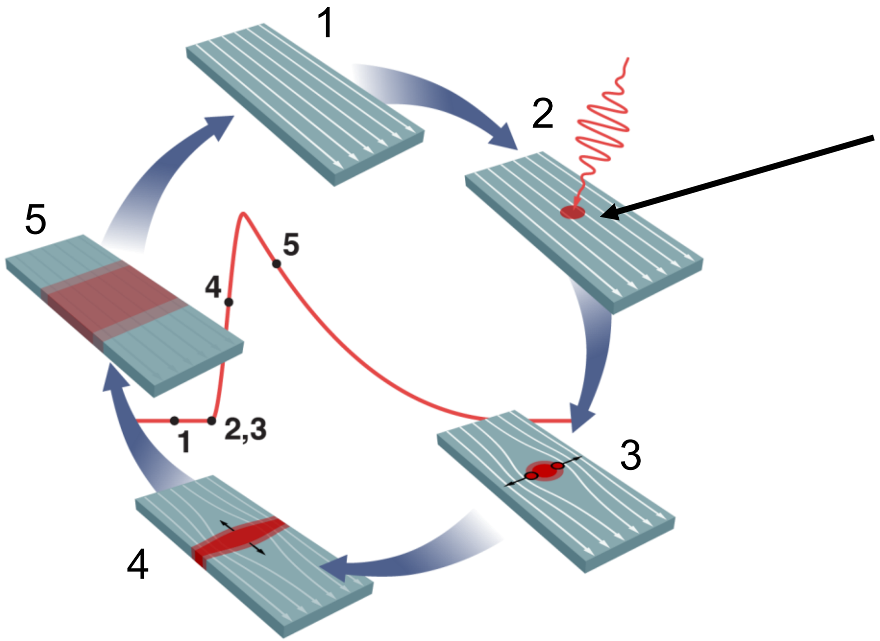
# Energy threshold




**Energy loss** by phonons escaping into substrate

Allmaras, *Modeling and Development of Superconducting Nanowire Single-Photon Detectors*, **Ph.D. Dissertation**, Caltech (2020)

# Energy threshold




What is **minimum amount of energy** that we needs to be left in **electron system** to initiate vortices?

Allmaras, *Modeling and Development of Superconducting Nanowire Single-Photon Detectors,* **Ph.D. Dissertation**, Caltech (2020)

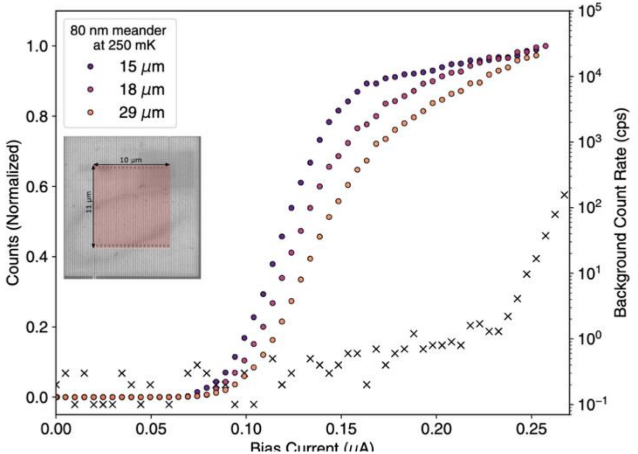
# Energy threshold – first order approximation

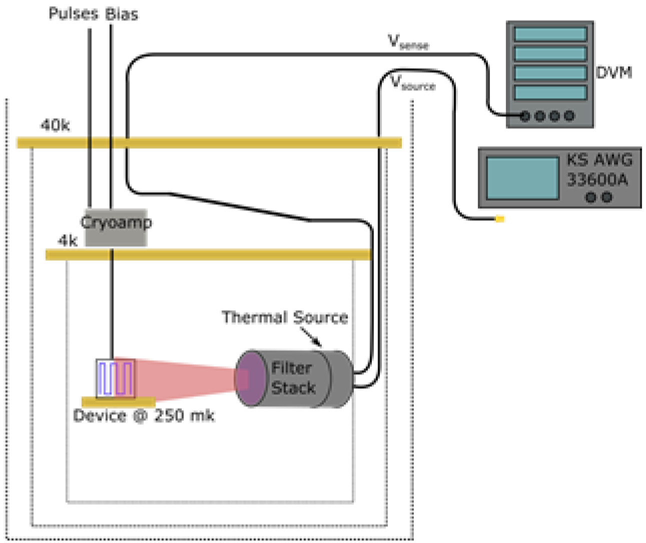
| | |
|---|---|
| $E_0 = 4N(0)(k_B T_C)^2 V_0$ | Characteristic energy |
| $N(0)$ | Density of states per spin at the Fermi level in the normal state |
| $T_C$ | Critical temperature |
| $4N(0)(k_B T_C)^2$ | Energy density relating the difference between the superconducting and normal states |
| $V_0$ | Characteristic volume where superconductivity is suppressed ***after down-conversion***. Depends on the **diffusion coefficient** and **thickness** |

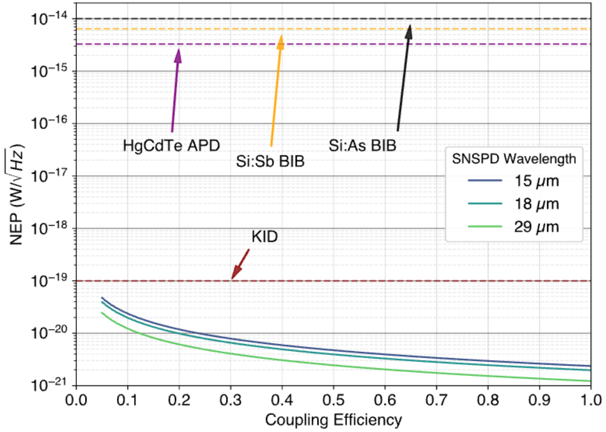
Colangelo, et al. 2022, *Nano Letters* 22 (14): 5667–73.

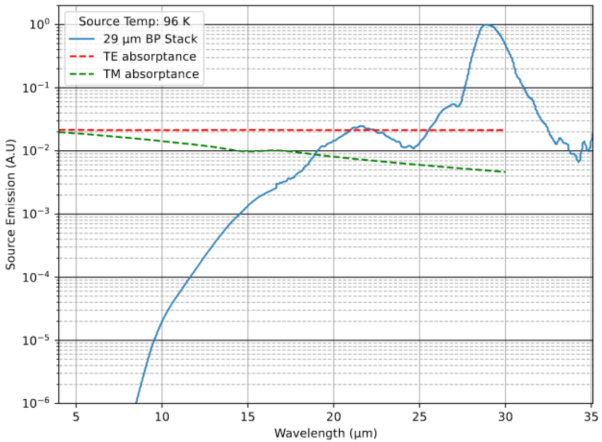
# Let’s do an energy sweep

# Photons – 43 meV (29 μm)



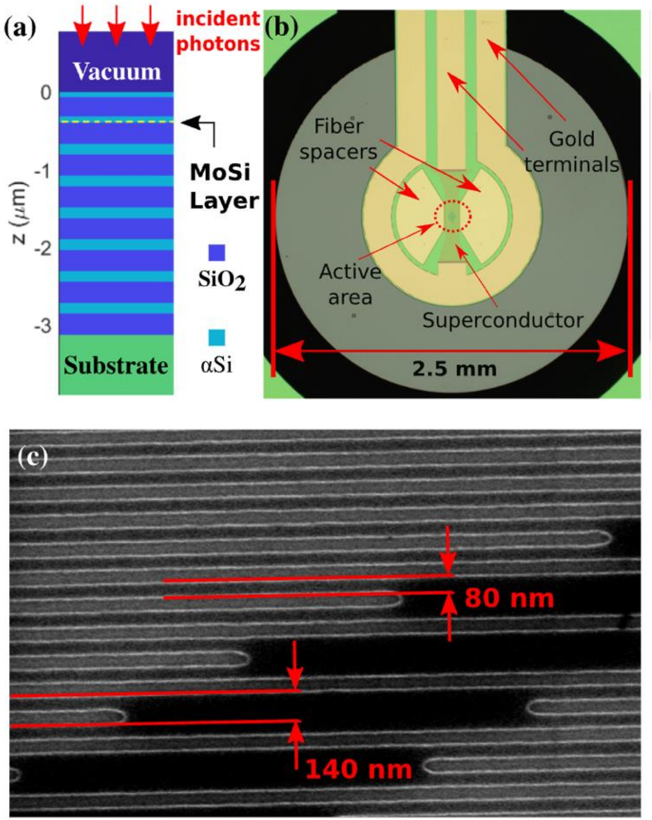



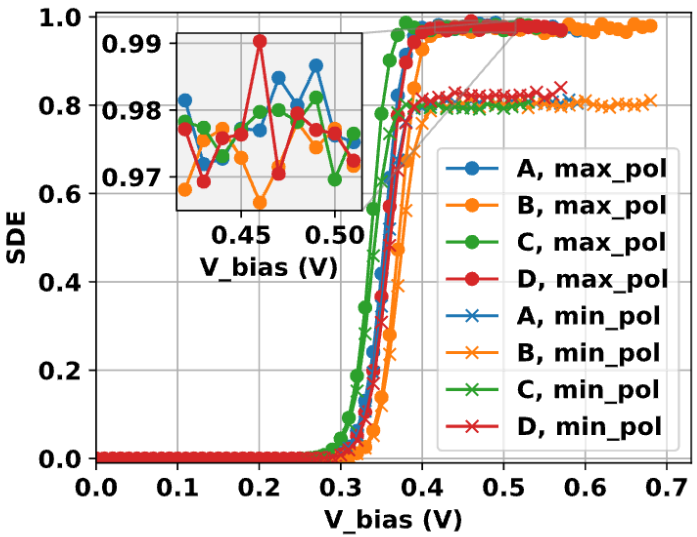




Taylor et al. 2023. "Low-Noise Single-Photon Counting Superconducting Nanowire Detectors at Infrared Wavelengths up to 29 Mm." *Optica* 10: 1672.

# Photons – 0.8 eV (1.55 μm)




## Record *system efficiency* of 98%

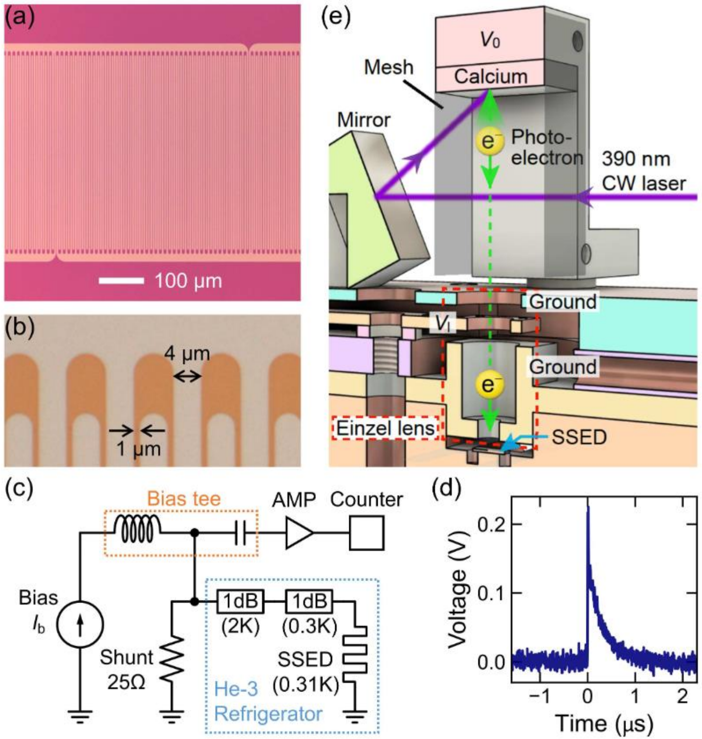


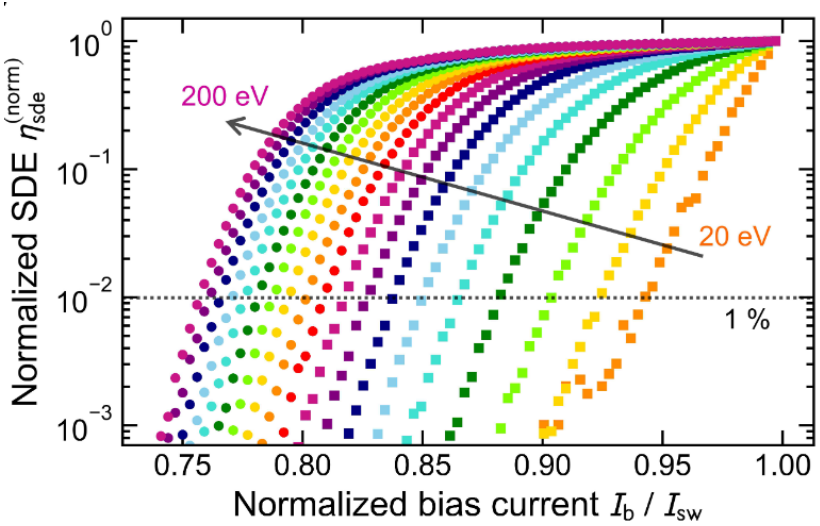

Reddy et al. 2020 "Superconducting Nanowire Single-Photon Detectors with 98% System Detection Efficiency at 1550 nm." *Optica* 7 (12): 1649

# Electrons – 10 eV

efficiency 37 % for 200 eV electron

≈ 6 nm-thick NbTiN film

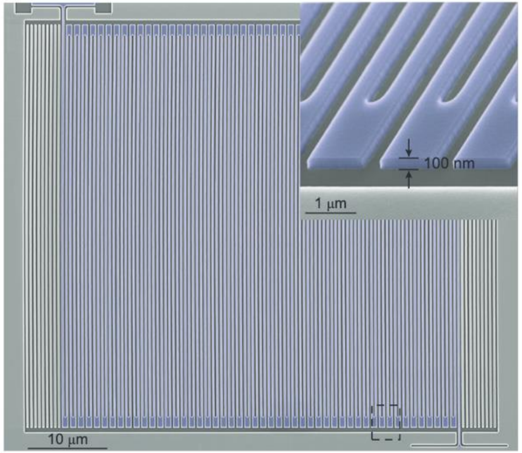


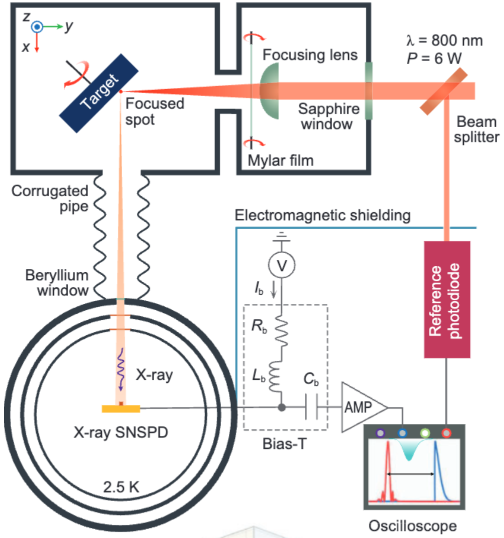



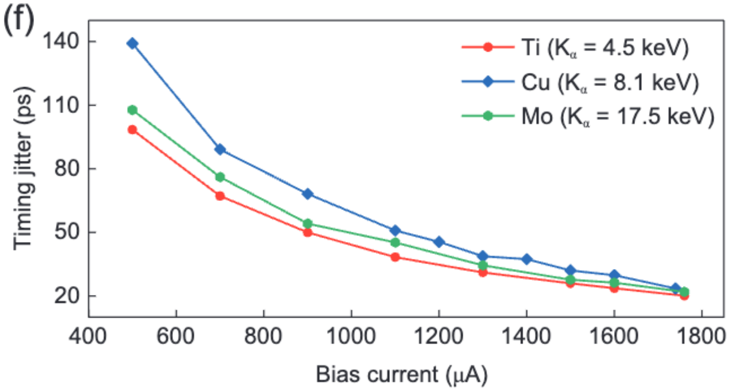

“minimum detectable energy of electrons is about 10 eV ….much lower than those of ions, which implies that the **electron-electron interaction** plays a significant role.”

Shigefuji et al 2023. “Efficient Low-Energy Single-Electron Detection Using a Large-Area Superconducting Microstrip.” http://arxiv.org/abs/2301.11212.

# Photons – 5-20 keV



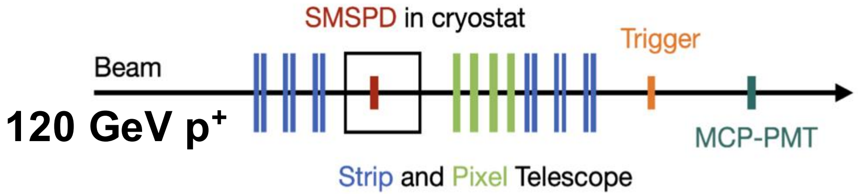



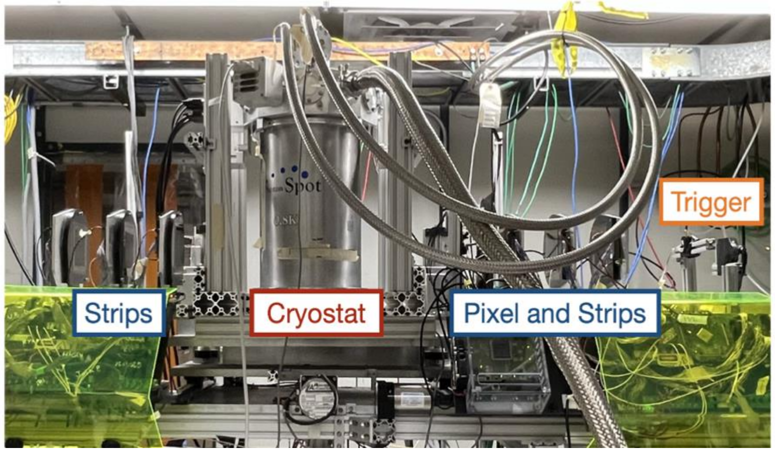




Films are made thicker to efficiently absorb the X-Ray photons

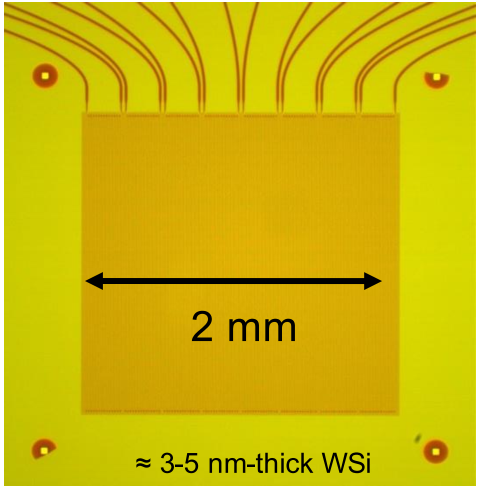
Guo et al. 2024. "High-Timing-Precision Detection of Single X-Ray Photons by Superconducting Nanowires." *National Science Review* 11 (1): nwad102.

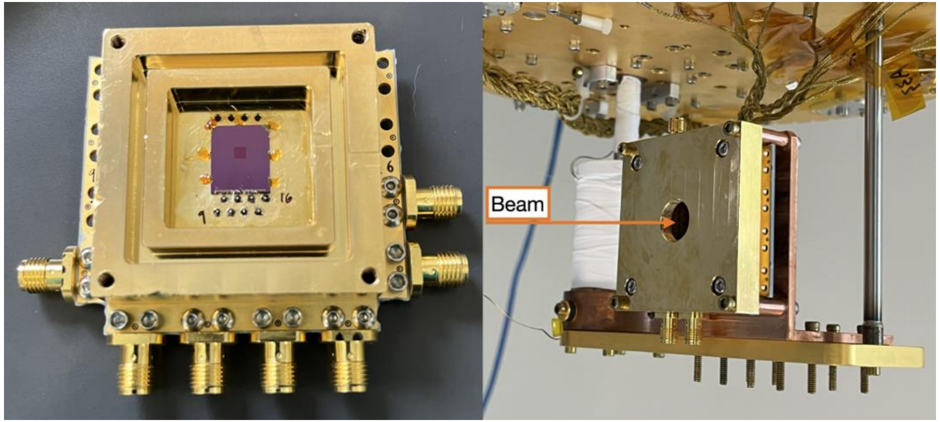
# Relativistic charged particles – 8-120 GeV



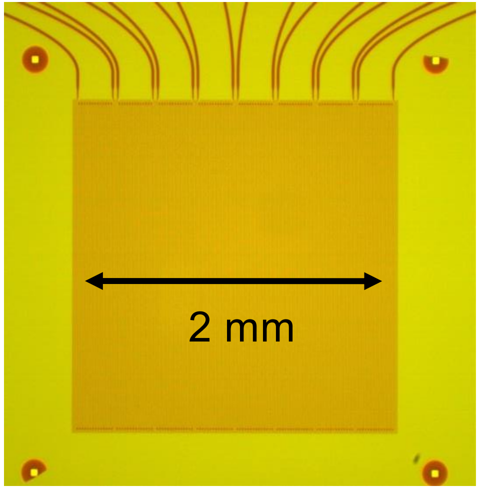

Fermilab Test Beam

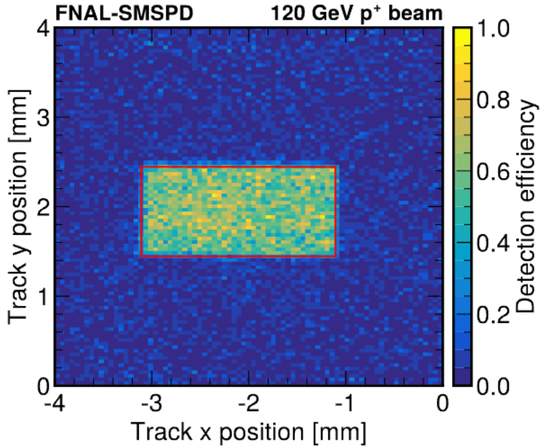


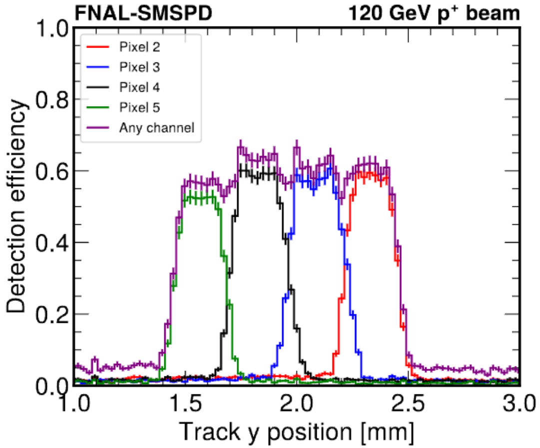




C. Peña et al, High energy particle detection with large area superconducting microwire array. *Journal of Instrumentation 20*(03), P03001 (2025).

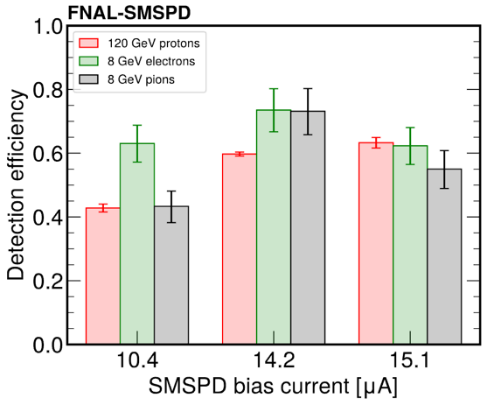
# First detection of relativistic particles with SNSPDs



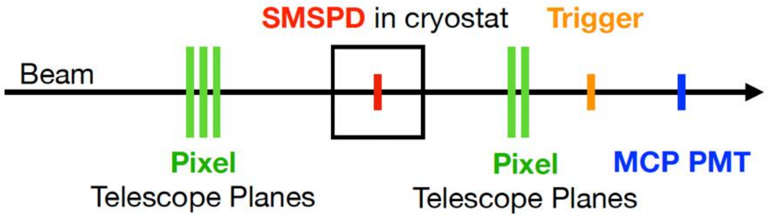

***First trial*** with detectors initially designed for photons (1 eV)

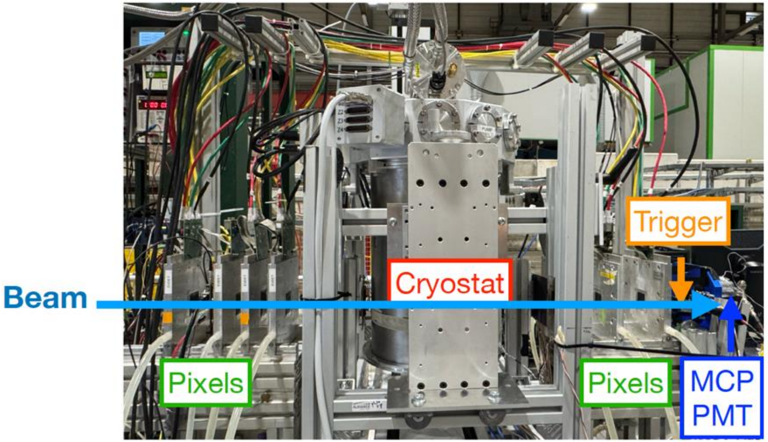


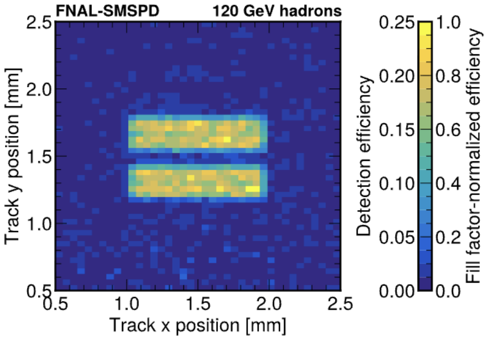

C. Peña et al, High energy particle detection with large area superconducting microwire array. *Journal of Instrumentation 20*(03), P03001 (2025).

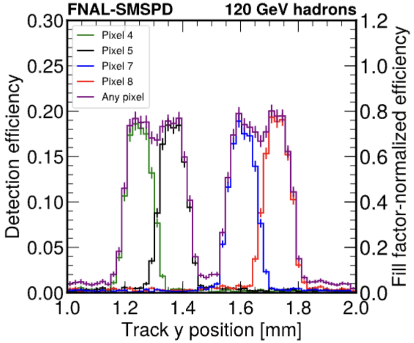
# Superconducting Nanowire Single ~~Photon~~ Particle Detector (SNSPD)

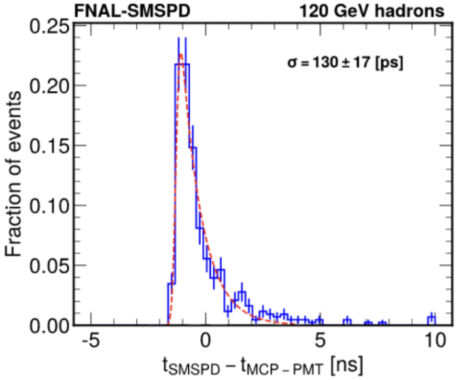
## Follow up at CERN



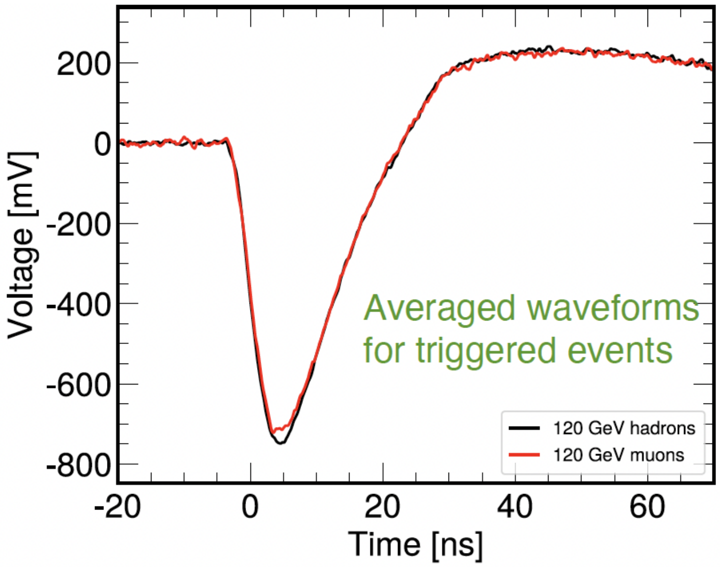




C. Wang et al, Towards High-Efficiency Particle Detection Using Superconducting Microwire Arrays arXiv 2510.11725 (2025)

# First 120 GeV muon detection with SNSPDs




Similar pulse shape, amplitude, and detection efficiency observed between hadron and muons

C. Wang et al, Towards High-Efficiency Particle Detection Using Superconducting Microwire Arrays arXiv 2510.11725 (2025)

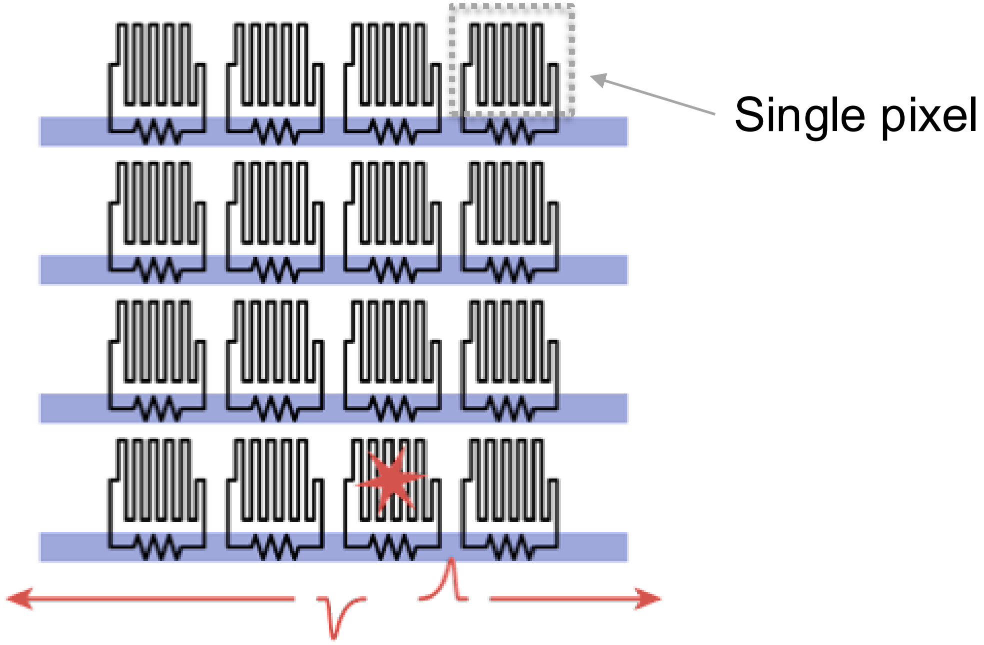
# Advances in superconducting nanowire detectors

| | Timing jitter | Intrinsic photon number resolution | Efficiency | Array size | Maximum count rate | Dark count rate | Active area | Cut-off wavelength |
|---|---|---|---|---|---|---|---|---|
| Records in 2016 | 18 ps | None | 93% | 64 | 1 Gcps | 4 /s/mm$^2$ | 0.001 cm$^2$ | 5 µm |
| **Current records for isolated devices** | **2.6 ps** [1] | **3-5 photons** | **98%** [2] | **4x10$^5$** [3] | **1.5 Gcps** [4,5] | **4x10$^{-5}$ /s/mm$^2$** [6] | **0.1 cm$^2$** [3] | **29 µm** [7] |
| Expected performance by 2030 | **1 ps** | **10** | **99 %** | **10$^7$** | **10 Gcps** | **1x10$^{-6}$ /s/mm$^2$** | **1 cm$^2$** | **100 µm** |

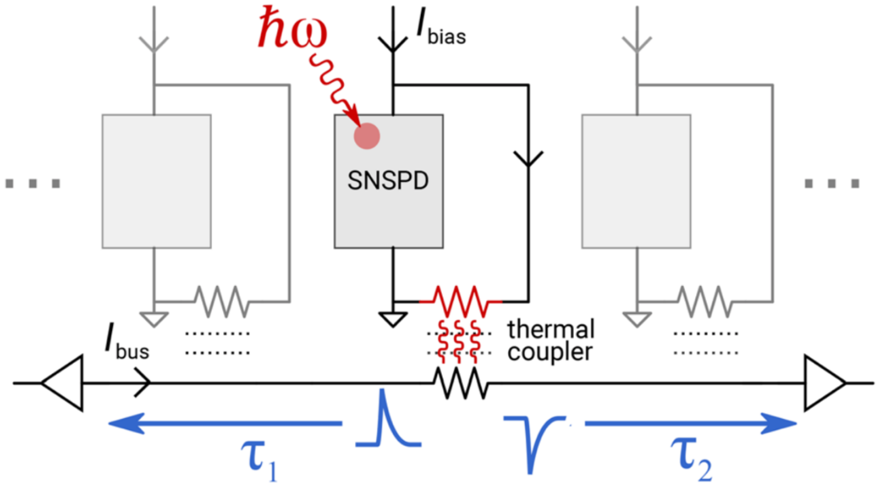

[1] Korzh, Zhao et al, ***Nature Photonics*** 14, 250 (2020)
[2] Reddy et al, ***Optica*** 7, 1649 (2020)
[3] Oripov, Rampini, Allmaras, Shaw, Nam, Korzh, and McCaughan, ***Nature*** 622, 730 (2023)
[4] Craiciu, Korzh et al, ***Optica*** 10, 183 (2023)
[5] Resta et al, ***Nano Letters*** (2023)
[6] Chiles, ***PRL*** 128, 231802 (2022)
[7] Taylor, Walter, Korzh et al, ***Optica***, (2023)

# How do we make a larger camera?

So far, most experiments only had access to single/few pixels/nanowires…



# Time-domain multiplexing




Time-of-flight difference in a superconducting bus

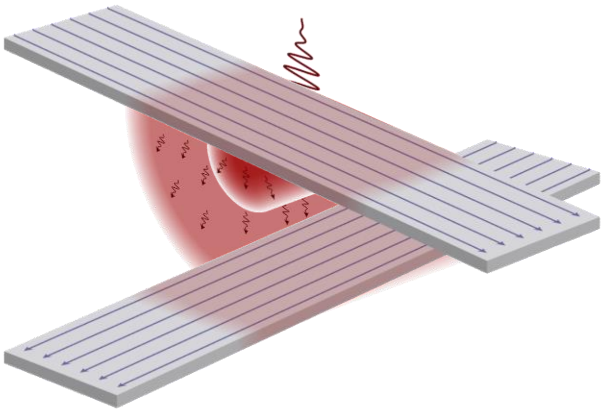
**$v_{ph}$ ≈ 0.01c (3 μm/ps) velocity**

**→ 10 ps timing resolution enables 15 μm pixels to be resolved**

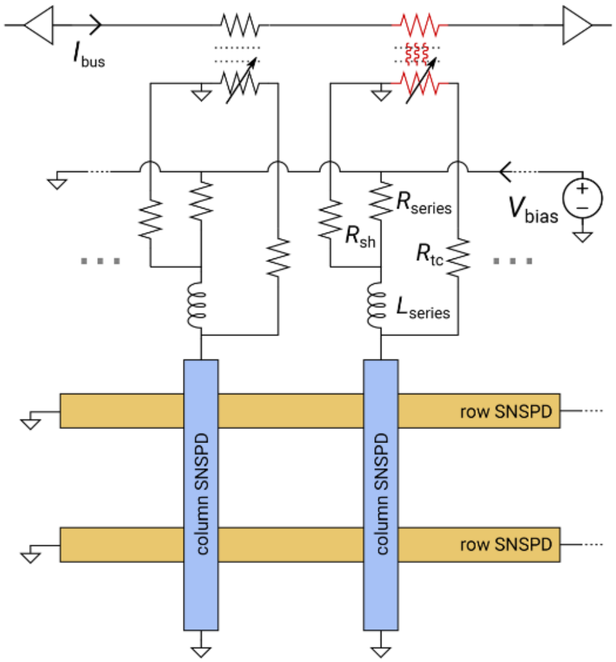
McCaughan, Zhai, Korzh *et al*, ***APL* 121**, 102602 (2022)

# Thermal coupling between layers

- Row-column thermal coupling
  - Layer 1: SNSPDs = columns
  - Layer 2: SNSPDs = rows



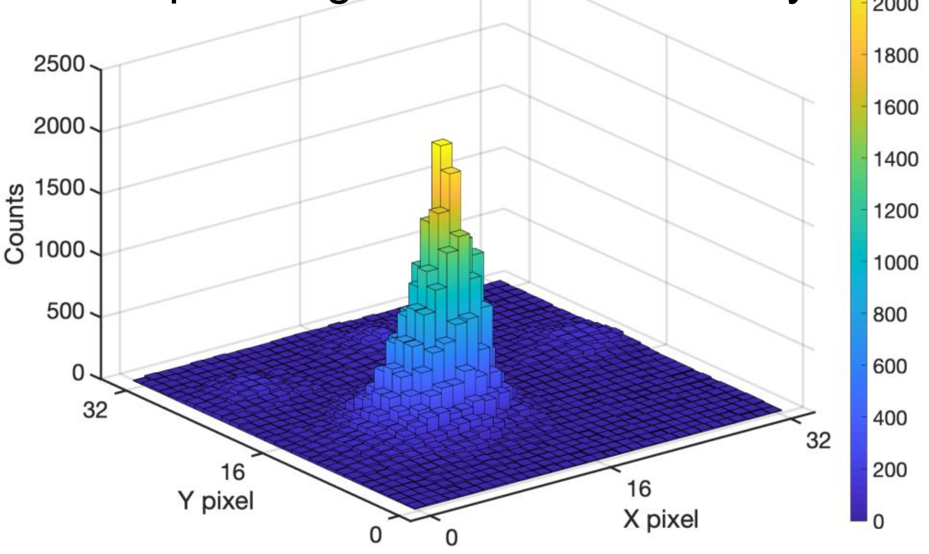
Combination with time-multiplexing

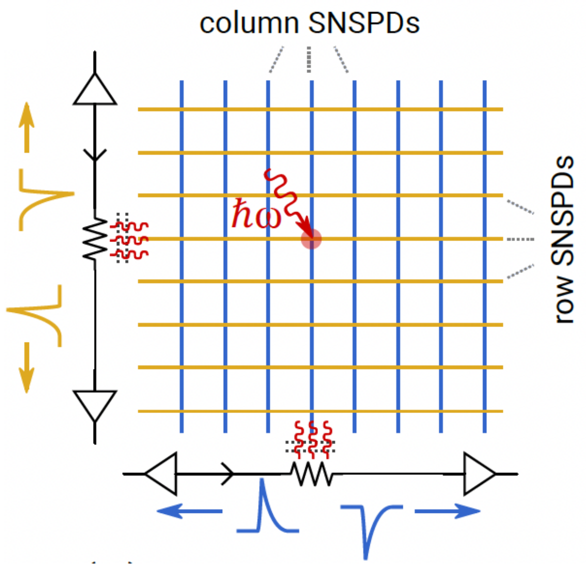



Allmaras, Wollman *et al*, ***Nano Letters* 20,** 2163–2168 (2020)

# Thermally-coupled imager

UV spot imaged with a 32x32 array

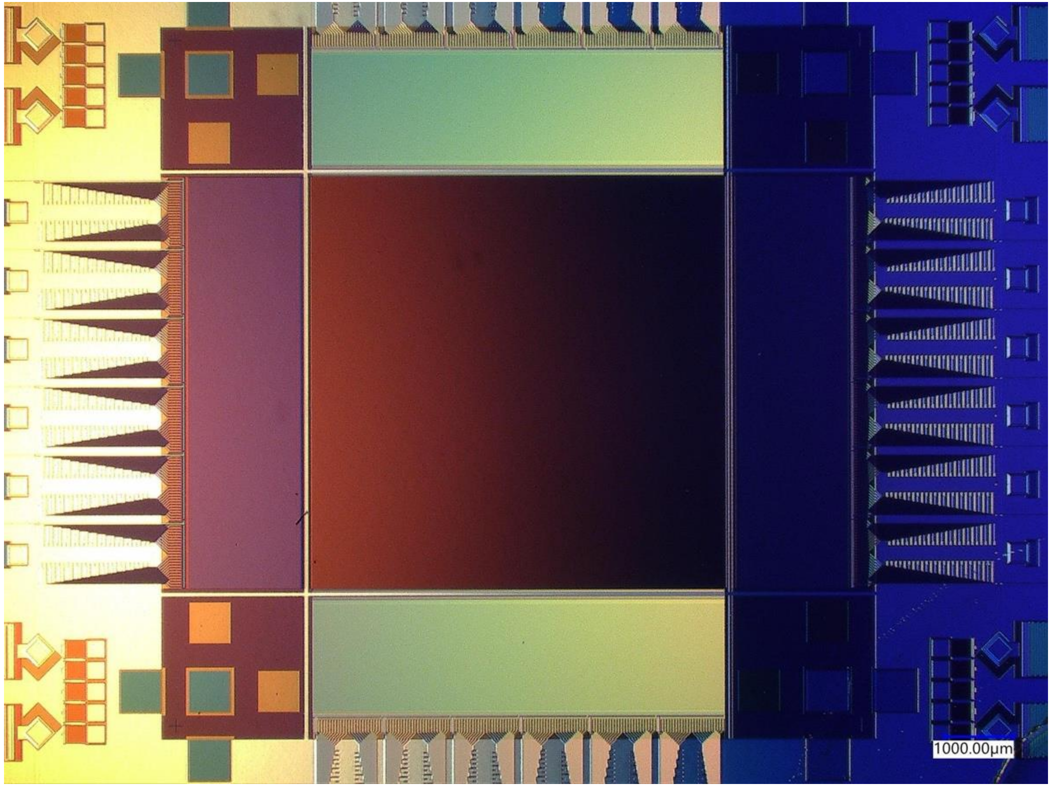


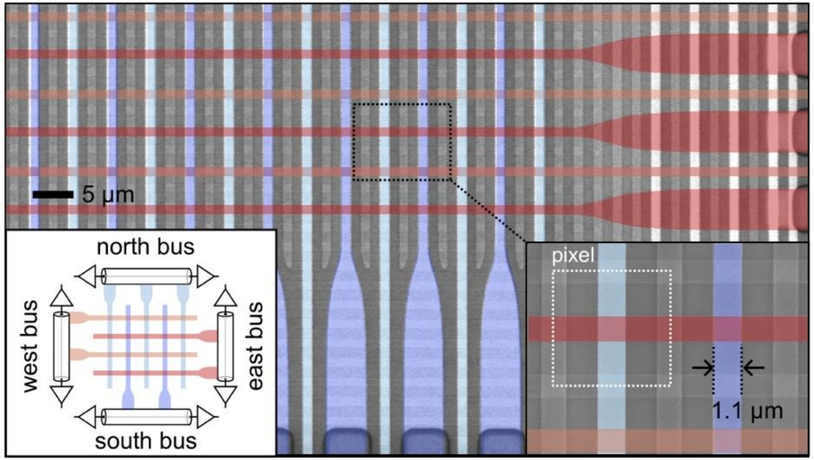




☺ **Only 4 coaxes needed**

McCaughan, Zhai, Korzh, Allmaras *et al*, ***APL*** **121**, 102602 (2022)

# 400,000 pixel camera



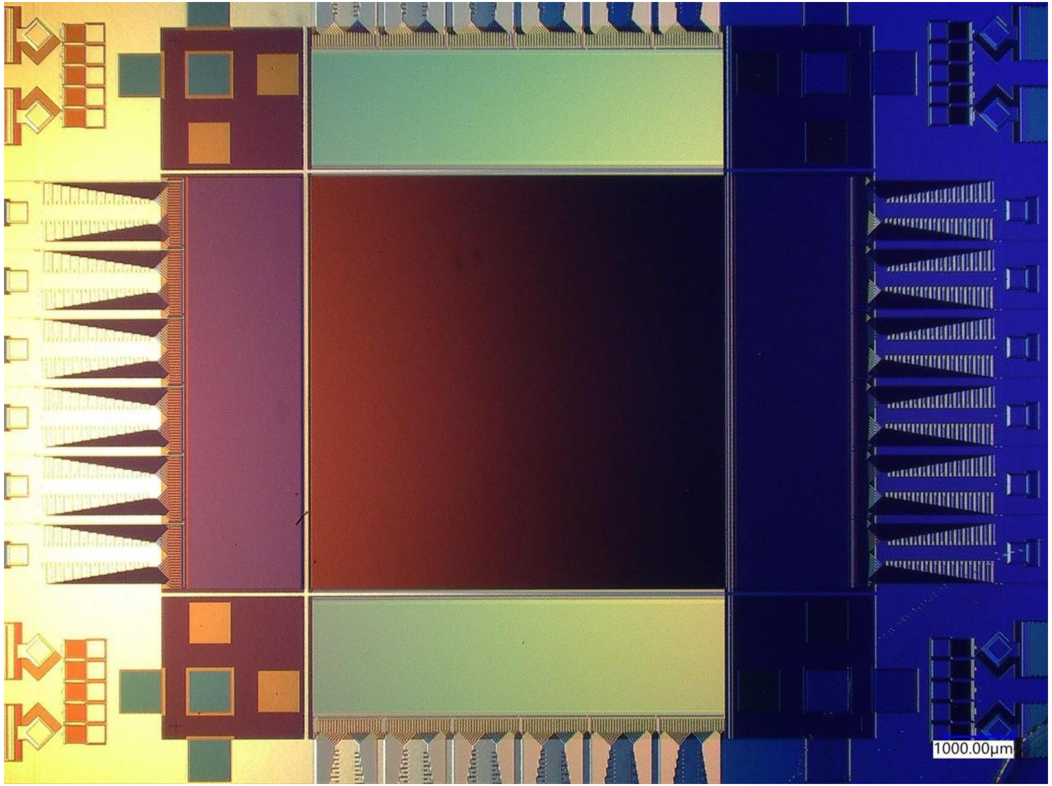



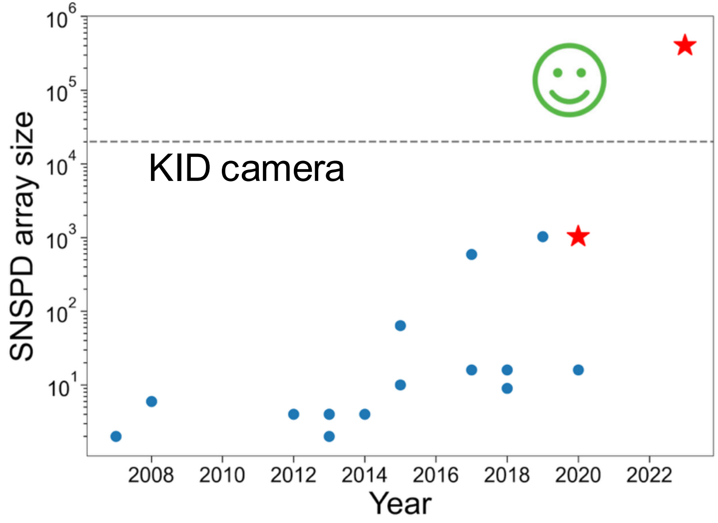

- 5 um spatial resolution

Oripov, Rampini, Allmaras, Shaw, Nam, Korzh, and McCaughan, ***Nature*** **622**, 730 (2023)

# 400,000 pixel camera

Largest superconducting camera by x20




- 300 kHz readout rate
  - **Count rate increases quadratically** with number of readout lines
  - To be implemented in next generation

Initially ***developed for photon starved*** applications:

- Extreme/deep-UV Astrophysics, **Earth-like exo-planet** imaging

Oripov, Rampini, Allmaras, Shaw, Nam, Korzh, and McCaughan, ***Nature* 622**, 730 (2023)

# Other photon-counting superconducting cameras

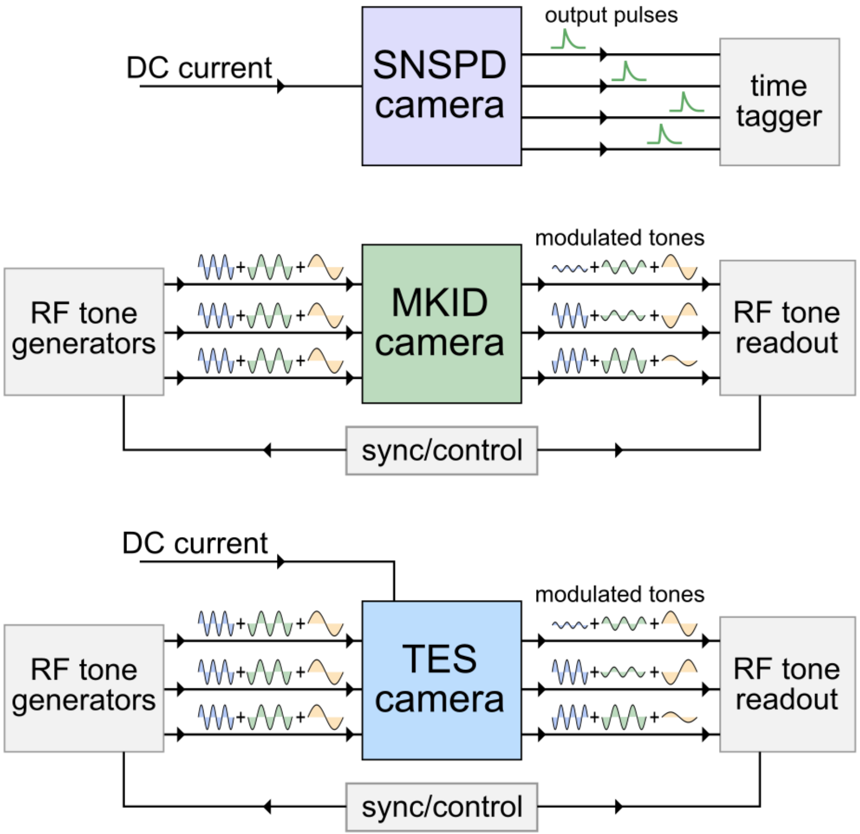



Image credit: **Adam McCaughan (NIST)**

- Detection-driven power dissipation – doesn't limit number of pixels
- No energy resolution

- Continuos power dissipation – pixel number limitation
- Energy resolution

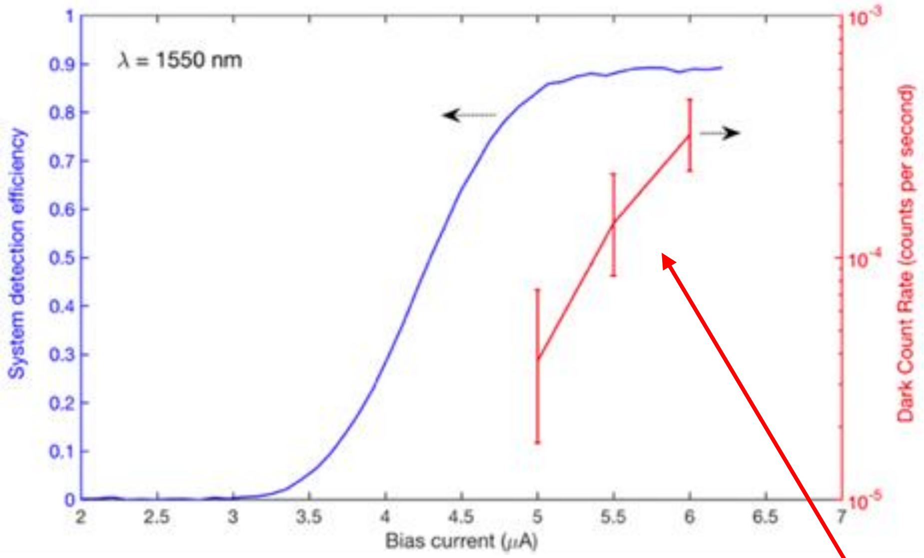
- Continuos power dissipation – pixel number limitation
- Energy resolution

# Advances in superconducting nanowire detectors

| Timing jitter | Intrinsic photon number resolution | Efficiency | Array size | Maximum count rate | Dark count rate | Active area | Cut-off wavelength | |
|---|---|---|---|---|---|---|---|---|
| 18 ps | None | 93% | 64 | 1 Gcps | 4 /s/mm$^2$ | 0.001 cm$^2$ | 5 µm | Records in 2016 |
| **2.6 ps** [1] | **3-5 photons** | **98%** [2] | **4x10$^5$** [3] | **1.5 Gcps** [4,5] | **4x10$^{-5}$ /s/mm$^2$** [6] | **0.1 cm$^2$** [3] | **29 µm** [7] | **Current records for isolated devices** |
| **1 ps** | **10** | **99 %** | **10$^7$** | **10 Gcps** | **1x10$^{-6}$ /s/mm$^2$** | **1 cm$^2$** | **100 µm** | Expected performance by 2030 |

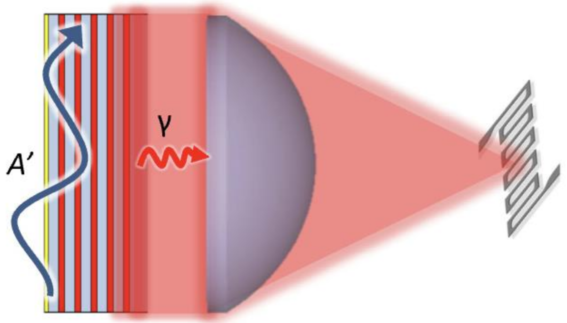

[1] Korzh, Zhao et al, ***Nature Photonics*** 14, 250 (2020)
[2] Reddy et al, ***Optica*** 7, 1649 (2020)
[3] Oripov, Rampini, Allmaras, Shaw, Nam, Korzh, and McCaughan, ***Nature*** 622, 730 (2023)
[4] Craiciu, Korzh et al, ***Optica*** 10, 183 (2023)
[5] Resta et al, ***Nano Letters*** (2023)
[6] Chiles, ***PRL*** 128, 231802 (2022)
[7] Taylor, Walter, Korzh et al, ***Optica***, (2023)

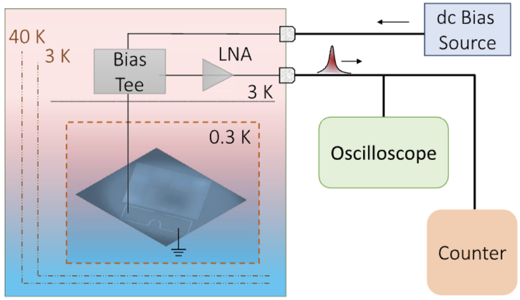
# Dark counts




Exponential dependence on **bias current** and **temperature**

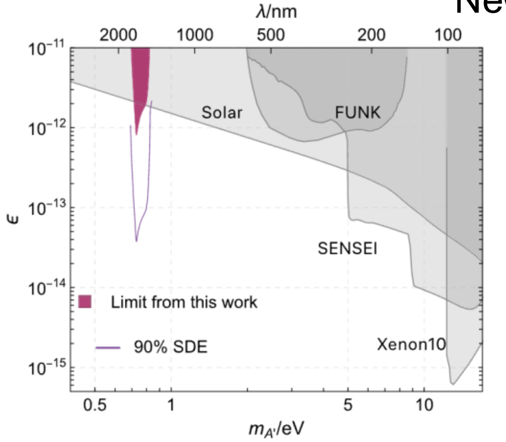
# Dark matter searches



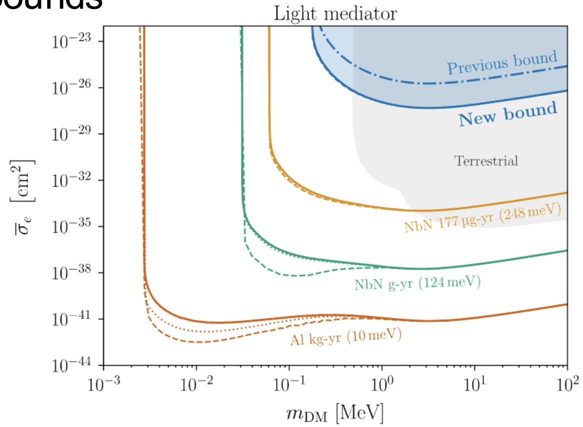




1 dark count per day!

New bounds




Dark photon
*with haloscope*

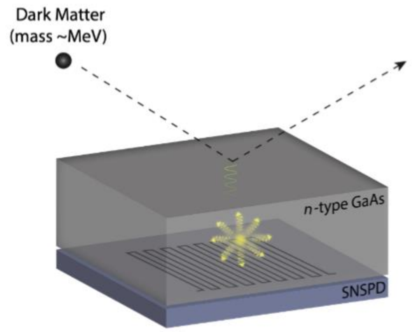


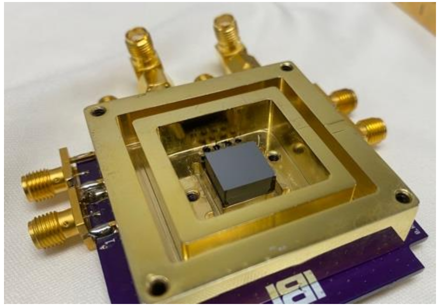

Electron scattering, dark photon
*directly in nanowire*

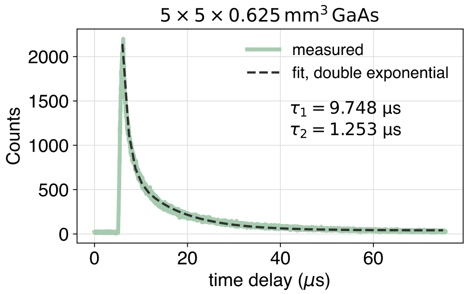
Chiles, et al. 2022. “New Constraints on Dark Photon Dark Matter with Superconducting Nanowire Detectors in an Optical Haloscope.” *Physical Review Letters* 128 (23): 231802.

Hochberg, et al. 2022. “New Constraints on Dark Matter from Superconducting Nanowires.” *Physical Review D* 106 (11): 112005.

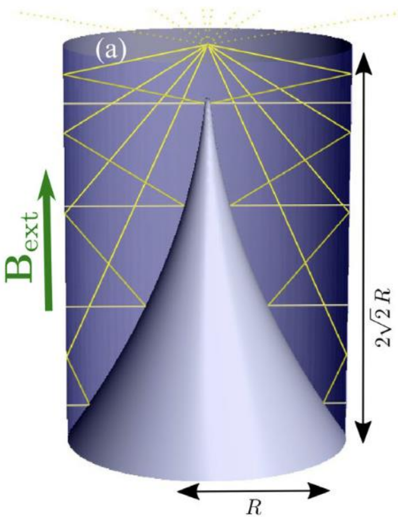
# Dark matter search proposals

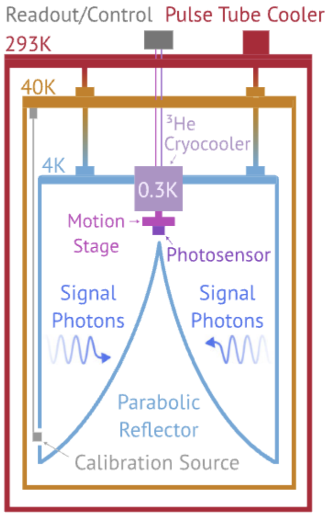





Credit: **Jamie Luskin (JPL)**




**Axion-like dark matter**

**Electron scattering in scintillators**

Luskin, et al 2023. “Large Active-Area Superconducting Microwire Detector Array with Single-Photon Sensitivity in the near-Infrared.” *Journal of Physics D: Applied Physics*. https://doi.org/10.1063/5.0150282.

Liu, et al. 2022. “Broadband Solenoidal Haloscope for Terahertz Axion Detection.” *Physical Review Letters* 128 (13).

# Advances in superconducting nanowire detectors

| | Timing jitter | Intrinsic photon number resolution | Efficiency | Array size | Maximum count rate | Dark count rate | Active area | Cut-off wavelength |
|---|---|---|---|---|---|---|---|---|
| Records in 2016 | 18 ps | None | 93% | 64 | 1 Gcps | 4 /s/mm$^2$ | 0.001 cm$^2$ | 5 μm |
| **Current records for isolated devices** | **2.6 ps** [1] | **3-5 photons** | **98%** [2] | **4x10$^5$** [3] | **1.5 Gcps** [4,5] | **4x10$^{-5}$ /s/mm$^2$** [6] | **0.1 cm$^2$** [3] | **29 μm** [7] |
| Expected performance by 2030 | **1 ps** | **10** | **99 %** | **10$^7$** | **10 Gcps** | **1x10$^{-6}$ /s/mm$^2$** | **1 cm$^2$** | **100 μm** |


[1] Korzh, Zhao et al, ***Nature Photonics*** *14*, 250 (2020)
[2] Reddy et al, ***Optica*** 7, 1649 (2020)
[3] Oripov, Rampini, Allmaras, Shaw, Nam, Korzh, and McCaughan, ***Nature*** 622, 730 (2023)
[4] Craiciu, Korzh et al, ***Optica*** 10, 183 (2023)
[5] Resta et al, ***Nano Letters*** (2023)
[6] Chiles, ***PRL*** 128, 231802 (2022)
[7] Taylor, Walter, Korzh et al, ***Optica***, (2023)

# Summary

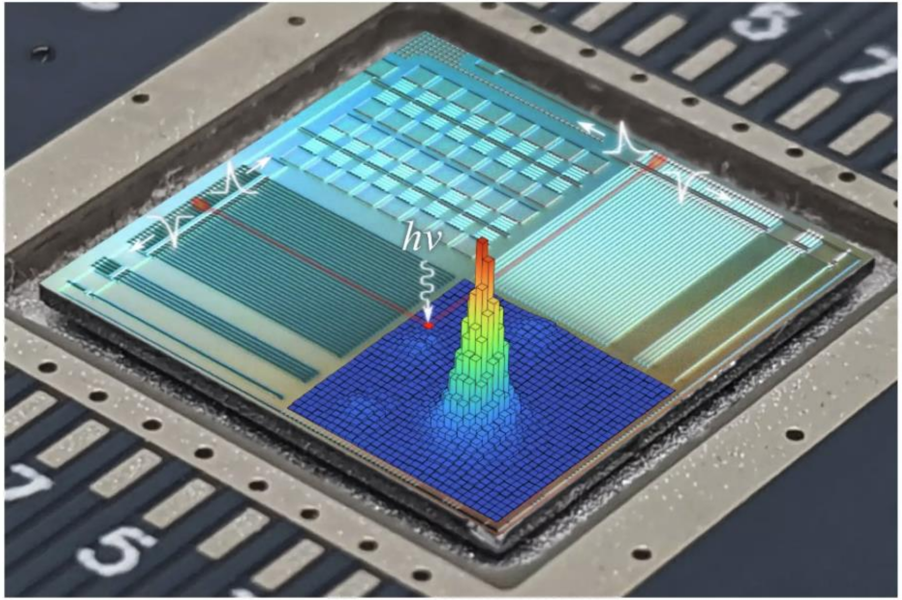
- SNSPD are **fully digital**, enabling:
  - **Fast timing**
  - **Large-scale** time-domain multiplexing
  - Threshold detection (energy resolution is lost)
    - **Insensitive to low energy phonons** in substrate → low dark counts
  - **Ultra-low energy threshold**

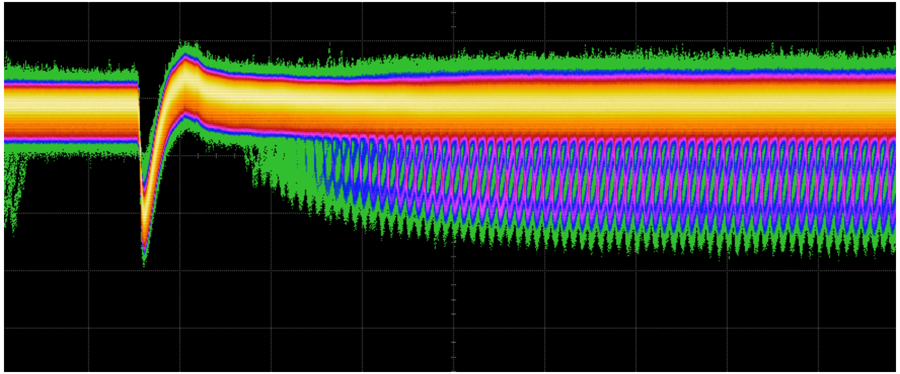
- Can adapted for
  - Photons
  - Charged particles
  - Ions
  - Molecules
  - Maybe optical *phonons* in future?

- Becoming deployed in **quantum networks**
- Essential for many **quantum computers**

- Highest TLR application is **deep-space optical comm**

- **HEP experiment proposals** are expanding





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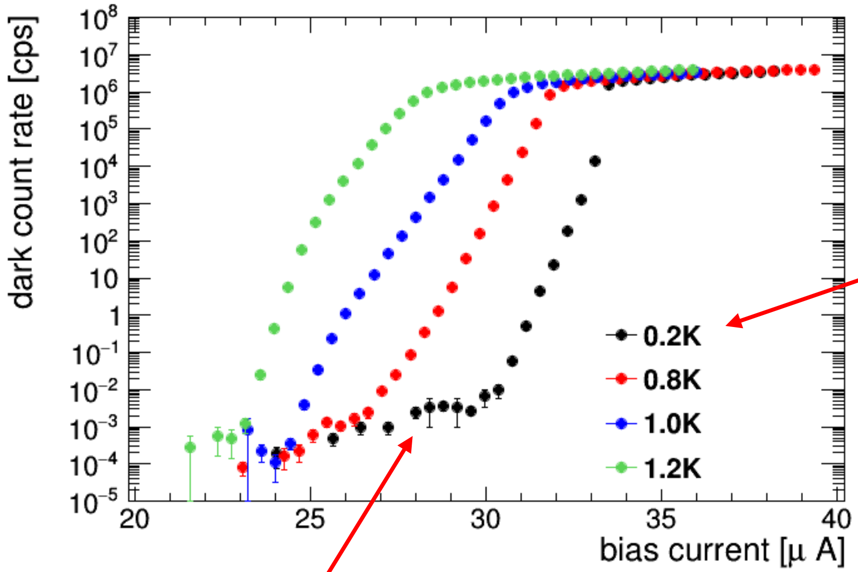
# Dark counts – temperature dependence

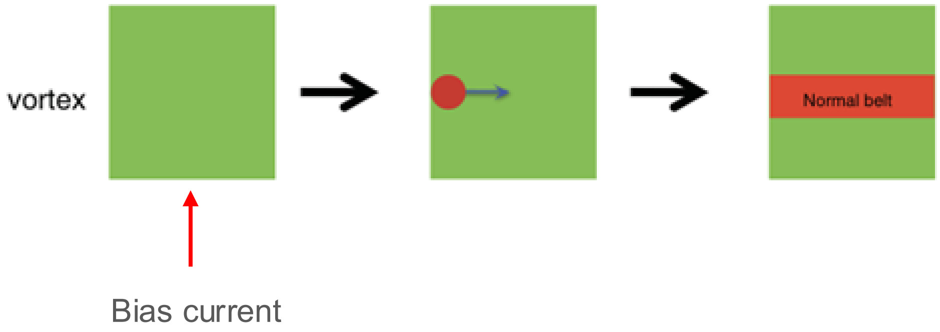



Handy to operate at <300 mK …same temp as the 43 meV detector

Credit: **Christina Wang (Fermilab)**

Preliminary results suggest this floor is from cosmic rays….
**Looks like they can be vetoed by coincidences in pixels thanks to high timing resolution!**

# Intrinsic dark counts in SNSPDs



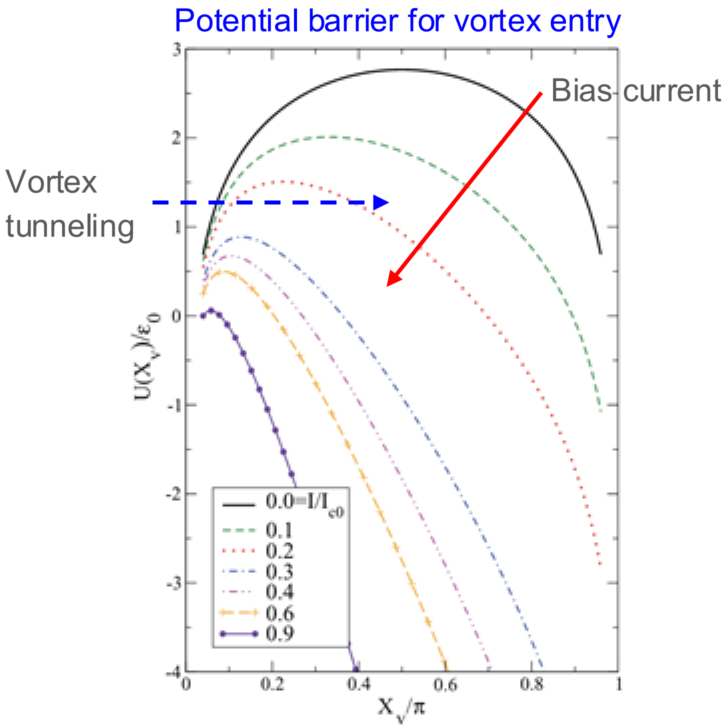




FIG. 2. (Color online) Position dependence, $X_v = \pi x_v/w$, of the potential energy for vortex entry in zero magnetic field for several bias currents. The potential is cut off for distances less than one coherence length $\xi$ from the left and right edges of strip, because of the finite vortex core.

Bulaevskii *et al*, **PRB 85**, 014505 (2012)

- Primary dark counts arise due to **vortex entry from the edge of nanowire**
- Vortex tunnels across potential barrier
  - **~ Exponential tunneling rate dependence on bias current**
  - Thermal fluctuations further reduce barrier

# Energy threshold – tuning the material

Colangelo, et al. 2022, *Nano Letters*

**Table 1. Comparison of the Physical Properties and Parameters of WSi Thin-Films Used for Fabrication of SNSPDs[a]**

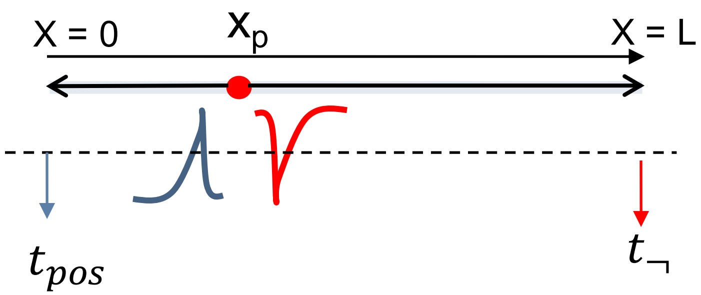
| ref | Si fraction | thickness | $D$ | sheet resistance | RRR | $T_C$ | $N(0)$ | $4N(0)(k_BT_C)^2$ |
|---|---|---|---|---|---|---|---|---|
| Chiles et al.[22] | 36% | 2.1 nm | 0.68 $cm^2/s$ | 967 Ω per square | 0.96 | 3.2 K | 23.6 $eV^{-1}$ $nm^{-3}$ | 7.16 μeV $nm^{-3}$ |
| Chiles et al.[22] | 48% | 2.1 nm | 0.71 $cm^2/s$ | 1.05 kΩ per square | 0.94 | 2.9 K | 21.2 $eV^{-1}$ $nm^{-3}$ | 5.30 μeV $nm^{-3}$ |
| Frasca et al.[23] | 12% | 7 nm | 0.74 $cm^2/s$ | 260 Ω per square | | 3.5 K | 28.8 $eV^{-1}$ $nm^{-3}$[b] | 9.38 μeV $nm^{-3}$ |
| Verma et al.[10] | 48% | 2.6 nm | | | | 2.8 K | 17.2 $eV^{-1}$ $nm^{-3}$[c] | 3.99 μeV $nm^{-3}$ |
| this work | 58% | 7.1 nm | 0.53 $cm^2/s$ | 450 Ω per square | 0.93 | 2 K | 19.8 $eV^{-1}$ $nm^{-3}$ | 2.35 μeV $nm^{-3}$ |

Taylor, et al. 2023 *Optica*

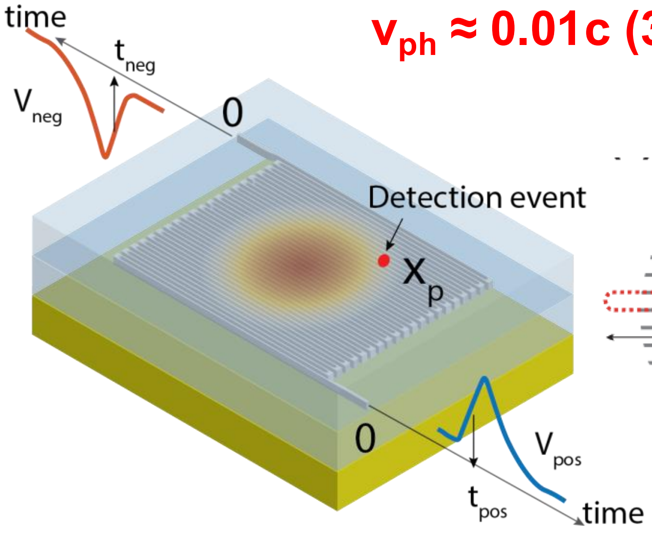
**Table 1. Summary of Material Parameters in This Work Compared to Previous Demonstrations of Mid-Infrared Photon Detection with SNSPDs**

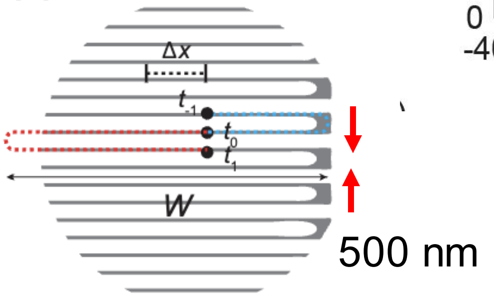
| Work | $T_c$ (K) | Film Thickness (nm) | $N(0)$ ($eV^{-1}$ $nm^{-3}$) | $4N(0)(k_bT_c)^2$ (μeV $nm^{-3}$) |
|---|---|---|---|---|
| Verma *et al.* [11] | 2.8 | 2.6 | 17.2 | 3.99 |
| Colangelo *et al.* [45] | 2 | 7.1 | 19.8 | 2.35 |
| This work | 1.3 | 3 | 17.3 | 0.8 |

# High spatial resolution

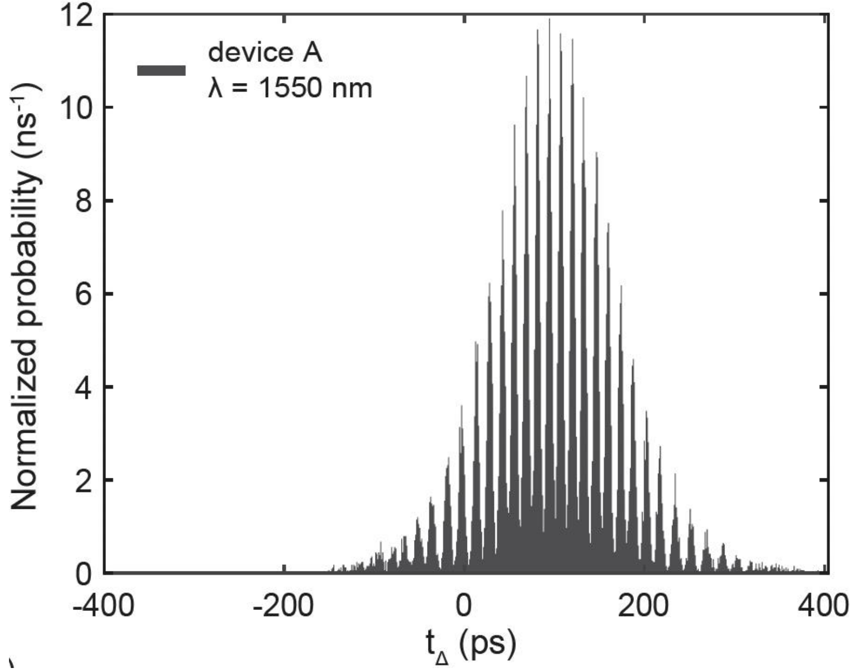



$v_{ph} \approx 0.01c$ (3 μm/ps)



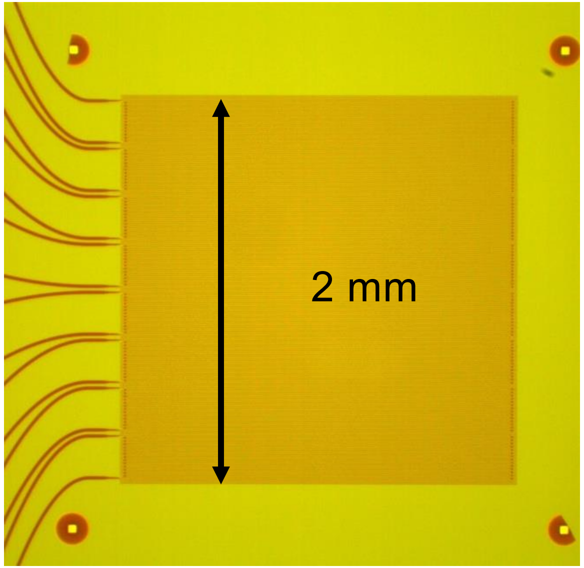



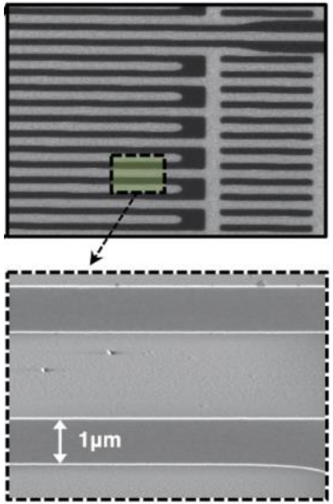

Experimental demo: 500 nm resolution




Colangelo, Korzh, Allmaras, Beyer *et al*, ***PRApplied*** **19**, 044093 (2023)

# Next: Improve device uniformity over large areas

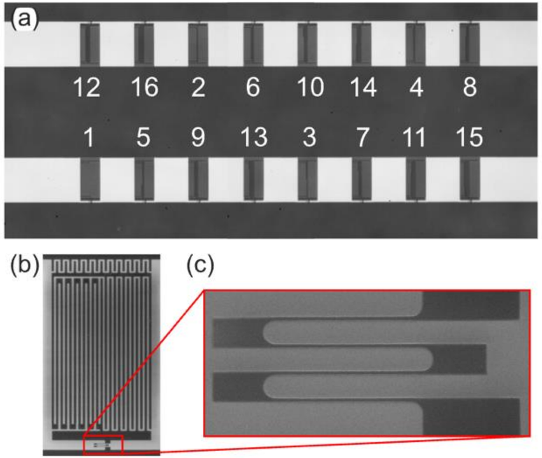


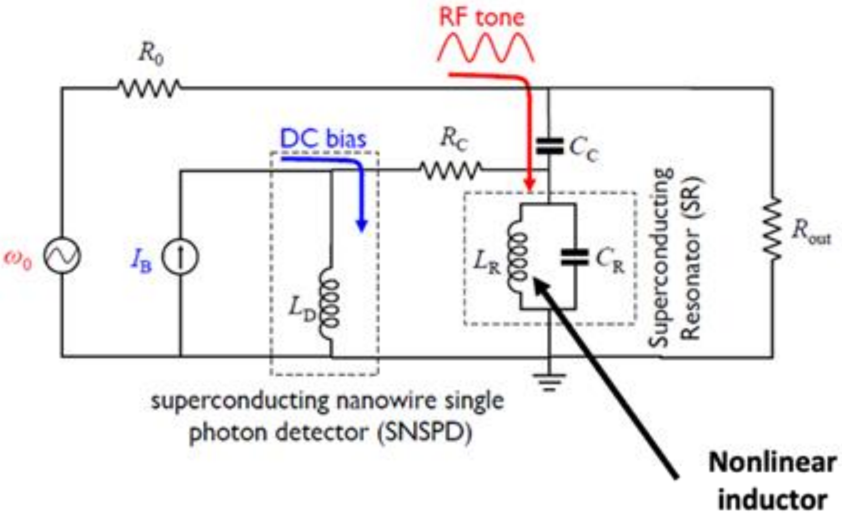

- Improved **film properties** to scale to >1 um-wide wires
- Switched to **photolithography** for better scalability


D. Y. Vodolazov, Phys. Rev. Appl. 7, 034014 **(2017)** – Theory prediction
Y. Korneeva et al, Phys. Rev. Appl. 9, 064037 **(2018)** – Experiment in short wire, NbN
I. Charaev et al, *Applied Physics Letters*, *116*(24), 242603. **(2020)** – pixels, MoSi
J. Chiles et al, *Applied Physics Letters*, *116*(24), 242602 **(2020) – pixels, WSi**
J. Luskin et al, *Appl. Phys. Lett.* 122, 243506 **(2023)** – **First millimeter scale arrays, Wsi**
C. Peña, et al *Journal of Instrumentation 20*(03), P03001 **(2025)** – **2x2 mm arrays, WSi**

# Frequency-domain multiplexing




Doerner, et al “Frequency-Multiplexed Bias and Readout of a 16-Pixel Superconducting Nanowire Single-Photon Detector Array.” *Applied Physics Letters* 111 (3): 032603 (2017)

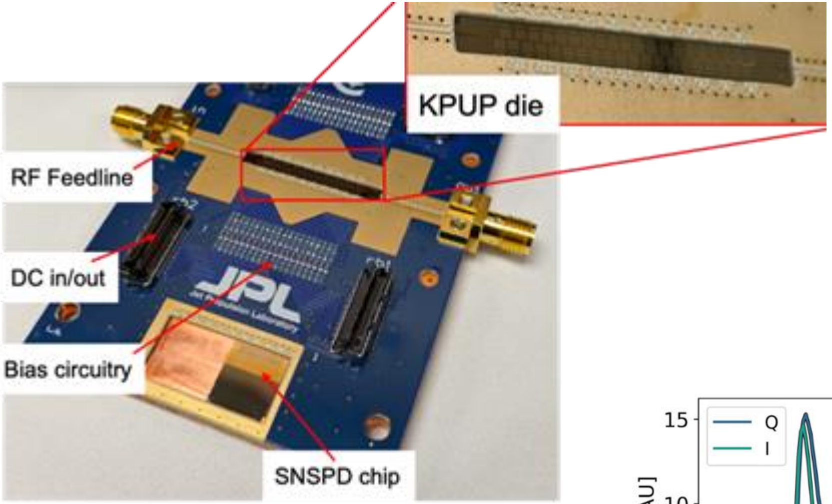



Sypkens et al “Frequency-Domain Multiplexing of SNSPDs with Tunable Superconducting Resonators.” *Applied Physics Letters* 124 (26): 262602 (2024)

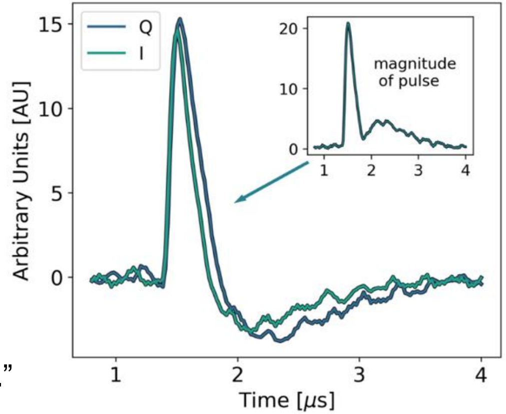
Great for low-energy threshold SNSPDs, due to low currents

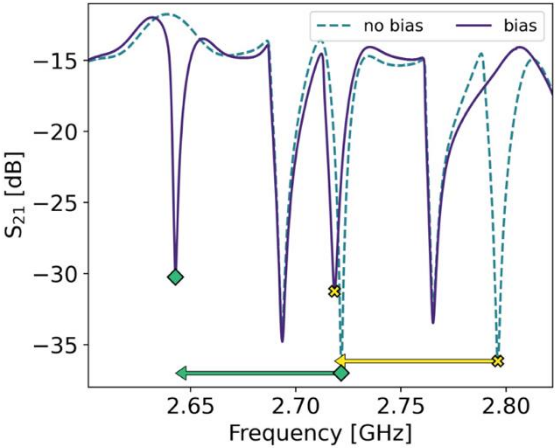
High power dissipation of readout electronics

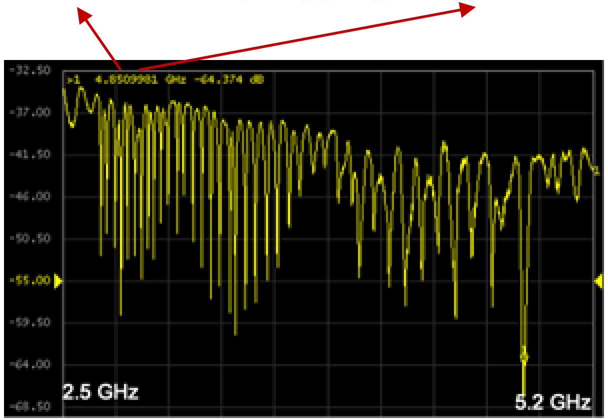
# Frequency-domain multiplexing




SNSPD array interfaced to resonator chip



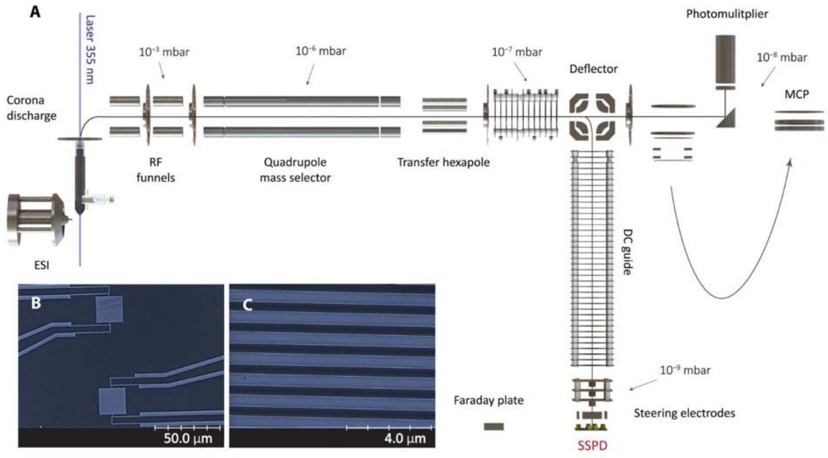



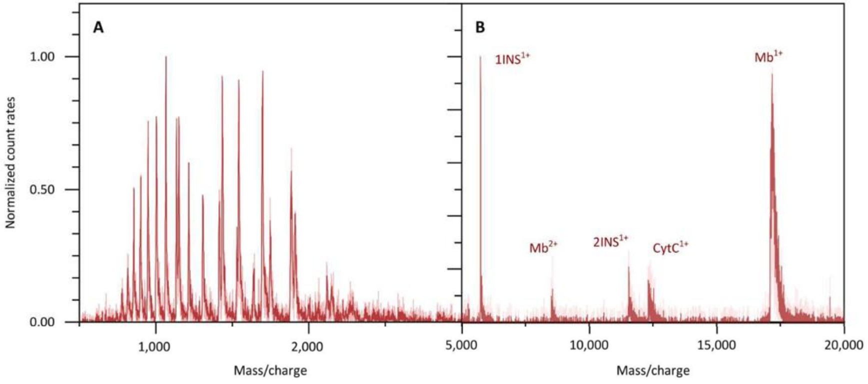



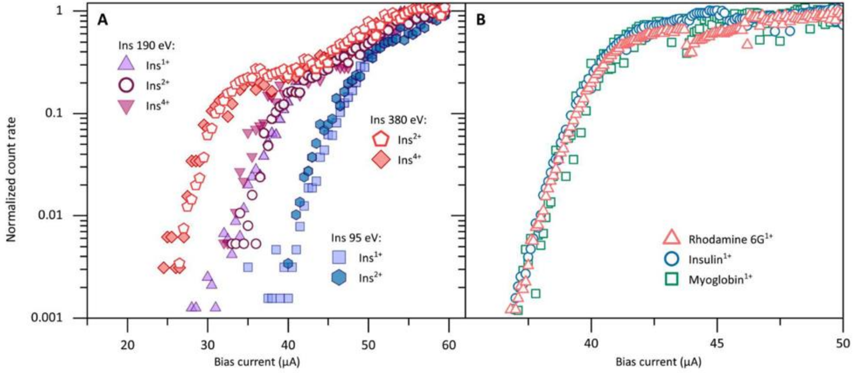

40 microwave resonators on one feedline

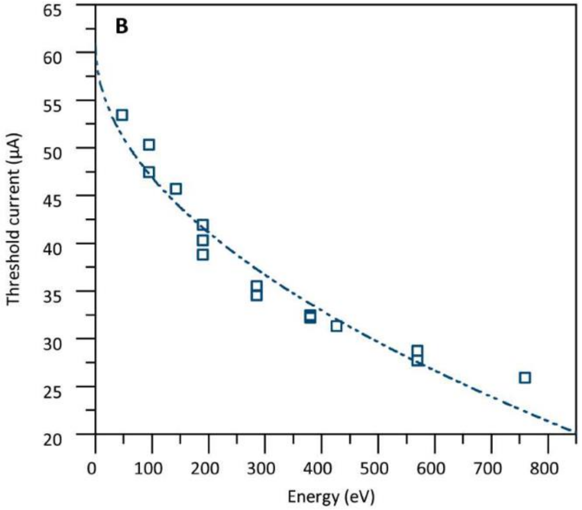
Sypkens et al "Frequency-Domain Multiplexing of SNSPDs with Tunable Superconducting Resonators." *Applied Physics Letters* 124 (26): 262602 (2024)

# Molecules – 100 eV



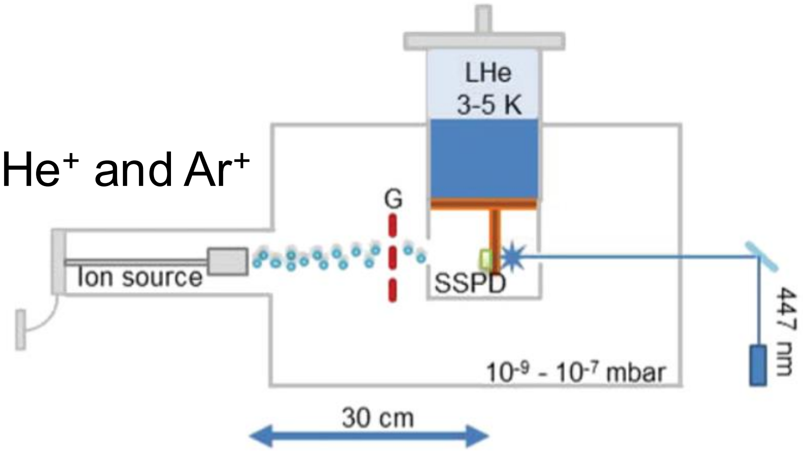



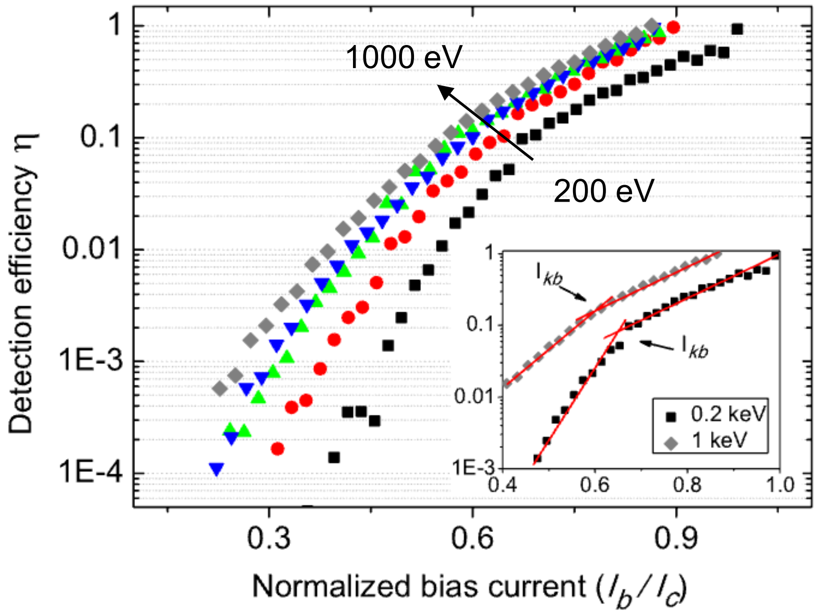




Strauß, et al. 2023. "Highly Sensitive Single-Molecule Detection of Macromolecule Ion Beams." *Science Advances* 9 (48): eadj2801.

# Ions – 1 keV

He⁺ and Ar⁺



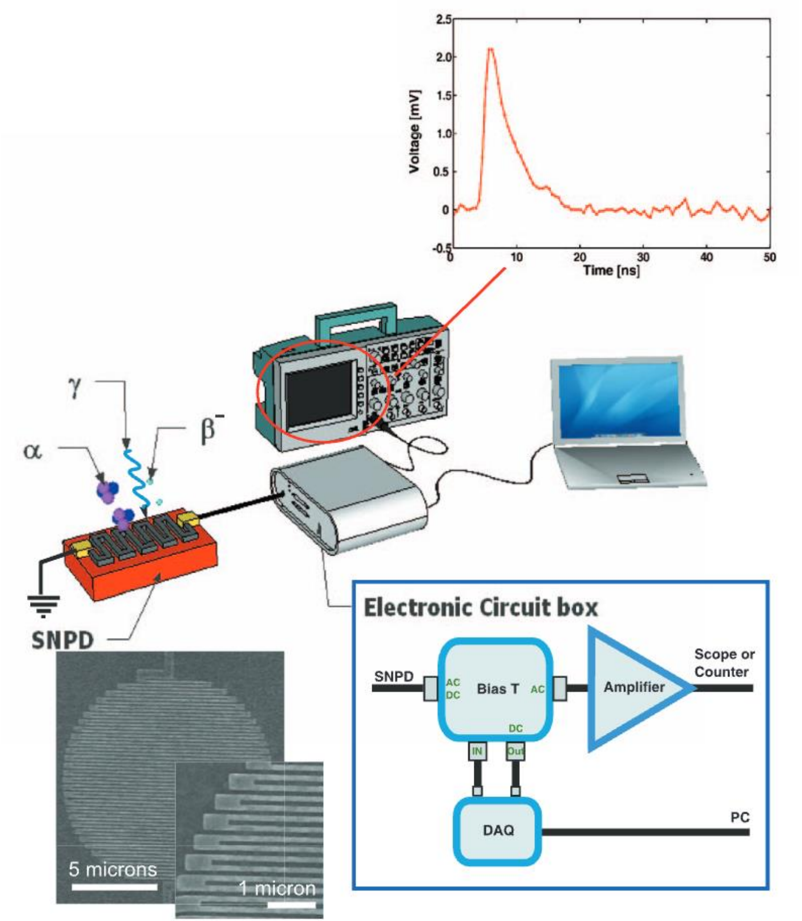




…implies that over 99 % of the kinetic energy of incident helium ions is **not transferred** to the electron subsystem…

Sclafani, et al. 2012. "Sensitivity of a Superconducting Nanowire Detector for Single Ions at Low Energy." *Nanotechnology* 23 (6): 065501.

# α- and β-particles – 1-5 MeV

| Source | Type | Initial Activity | Average Energy | Published Half-life ($t_{\frac{1}{2}}$) | Detection Efficiency ($DE$) |
|---|---|---|---|---|---|
| $^{210}Po$ | $\alpha$ | 41.2 kBq | 5.30 MeV | 138.38 days | $0.78 \pm 0.18$ |
| $^{42}K$ | $\beta^-$ | 40 MBq | 3.52 MeV | 12.36 hours | $0.95 \pm 0.14$ |
| $^{31}Si$ | $\beta^-$ | 26 MBq | 1.49 MeV | 2.62 hours | $1.06 \pm 0.12$ |
| $^{241}Am$ | $\gamma, X$ | – | ~5.95 keV | – | $0 \pm 0.10$ |




Azzouz et al 2012. “Efficient Single Particle Detection with a Superconducting Nanowire.” *AIP Advances* 2 (3): 032124.