High Energy Particle Detection with SMSPD

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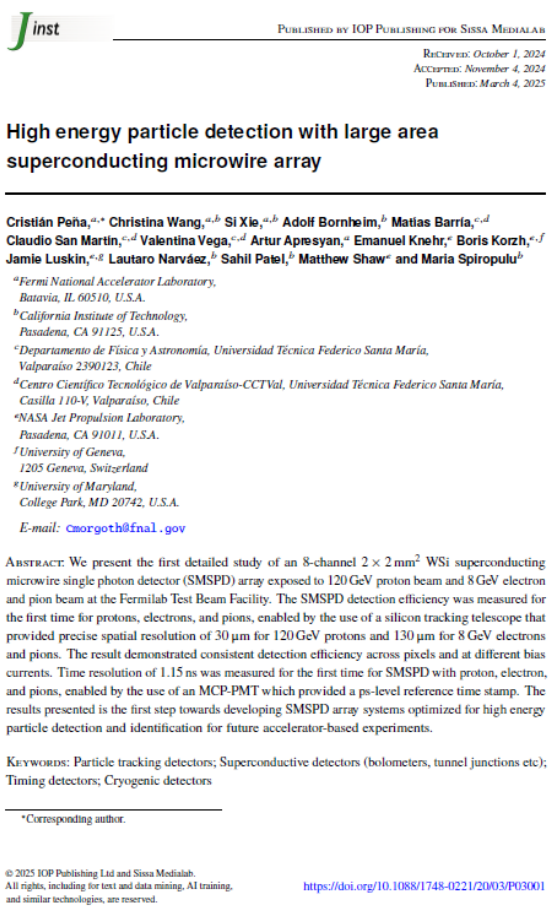
30.10.2025

Outline & Context

- This talk gives a brief overview on high energy particle detection with SMSPD in test beams.
- SMSPDs have a number of features (low noise, high sensitivity, good time resolution, size) that make them interesting for particle detection.
  - Additional features (radiation resilience, magnetic field tolerance) may turn out to be favorable as well.
- These tests are one facet of a much wider program on quantum technology and quantum networking (INQNET, AQNET) research :
  - See presentation by Cristian Pena yesterday.
- More details on SNSPD and test beam infrastucture at CERN discussed yesterday.

- Test beam experiments (Adi) :
  - Based on experience from two test beams, 2024 in FNAL M-Test and 2025 in CERN NA.
  - 2024 results are published, 2025 results are available as preprint.
- Underlying SMSPD technology (Boris) :
  - SMSPD detection mechanism
  - Fabrication and operation



Jinst

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High energy particle detection with large area superconducting microwire array

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Abstract: We present the first detailed study of an 8-channel $2 \times 2\,mm^2$ WSi superconducting microwire single photon detector (SMSPD) array exposed to 120 GeV proton beam and 8 GeV electron and pion beam at the Fermilab Test Beam Facility. The SMSPD detection efficiency was measured for the first time for protons, electrons, and pions, enabled by the use of a silicon tracking telescope that provided precise spatial resolution of 30 μm for 120 GeV protons and 130 μm for 8 GeV electrons and pions. The result demonstrated consistent detection efficiency across pixels and at different bias currents. Time resolution of 1.15 ns was measured for the first time for SMSPD with proton, electron, and pions, enabled by the use of an MCP-PMT which provided a ps-level reference time stamp. The results presented is the first step towards developing SMSPD array systems optimized for high energy particle detection and identification for future accelerator-based experiments.

Keywords: Particle tracking detectors; Superconductive detectors (bolometers, tunnel junctions etc); Timing detectors; Cryogenic detectors

*Corresponding author.

https://doi.org/10.1088/1748-0221/20/03/P03001

Prepared for submission to JINST

Towards High-Efficiency Particle Detection Using Superconducting Microwire Arrays

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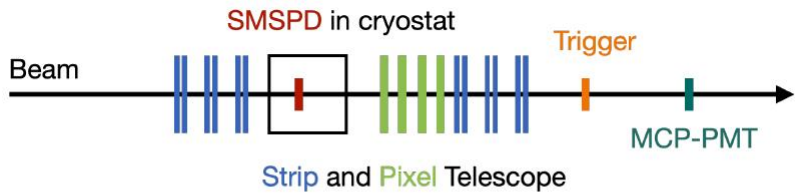
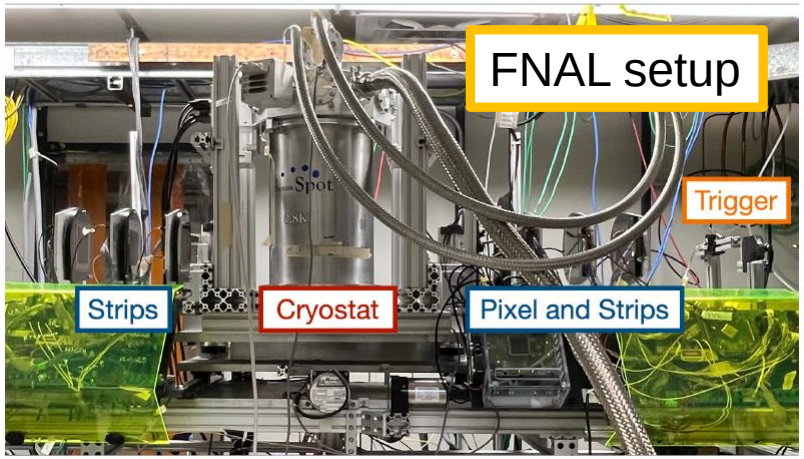
Abstract: We present a detailed study of an 8-channel $1 \times 1\,mm^2$ WSi superconducting microwire single photon detector (SMSPD) array exposed to 120 GeV hadron beam and 120 GeV muon beam at the CERN Super Proton Synchrotron H6 beamline. Following up on our first detailed characterization of the efficiency and response of an SMSPD fabricated on a 3 nm WSi film, we report measurements of enhanced particle detection efficiency using a sensor fabricated from a thicker 4.7 nm-thick WSi film. We also report the first SMSPD detection efficiency measurement made for muons. Measurements are enabled by a silicon tracking telescope providing 10 μm in-situ spatial resolution. The results show a fill factor-normalized detection efficiency of 75% and a time resolution of about 130 ps across pixels. These findings represent a significant advancement toward developing high-efficiency SMSPD charged particle tracking systems with simultaneous precision timing, with potential applications in future accelerator-based experiments such as the FCC-ee and Muon Collider.

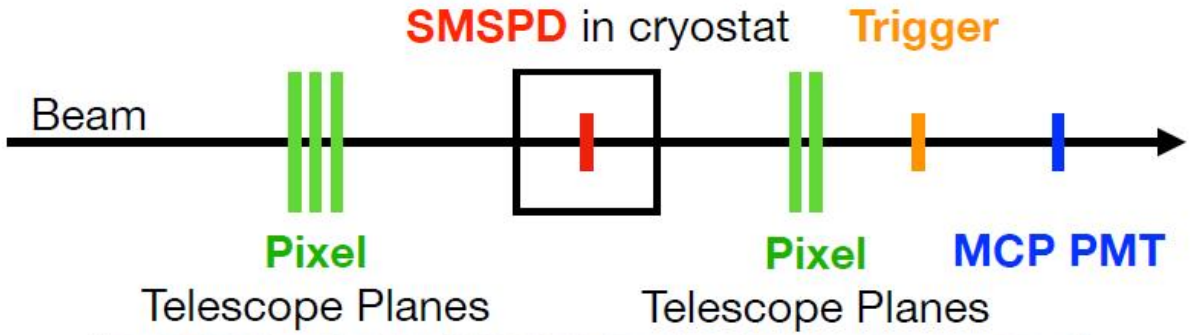
Keywords: Particle detectors, Superconductive detection materials, Cryogenic detectors

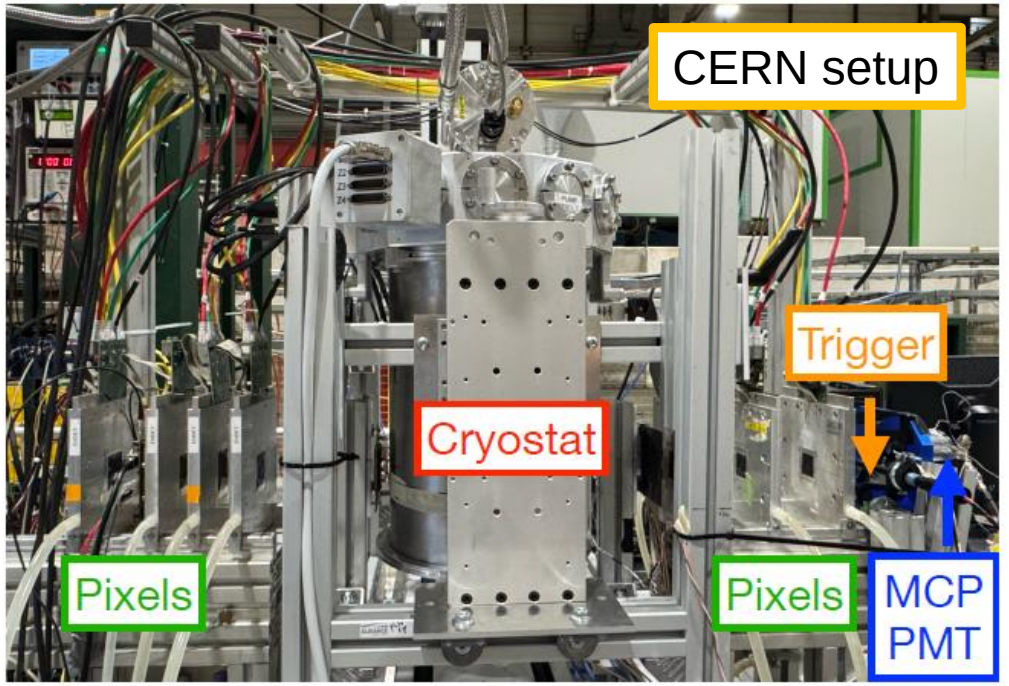
Test beam setup

- Test beam setup similar for FNAL and CERN, focus here on CERN setup.
- Principal components :
  - A particle beam.
  - Cryostate with SMSPD infrastructure
  - Tracking system to measure the impact point of the particle on the SMSPD
  - Trigger system with acceptance slightly larger than and aligned with the SMSPD.
  - Precision timing reference counter to measure time resolution of the SMSPD.



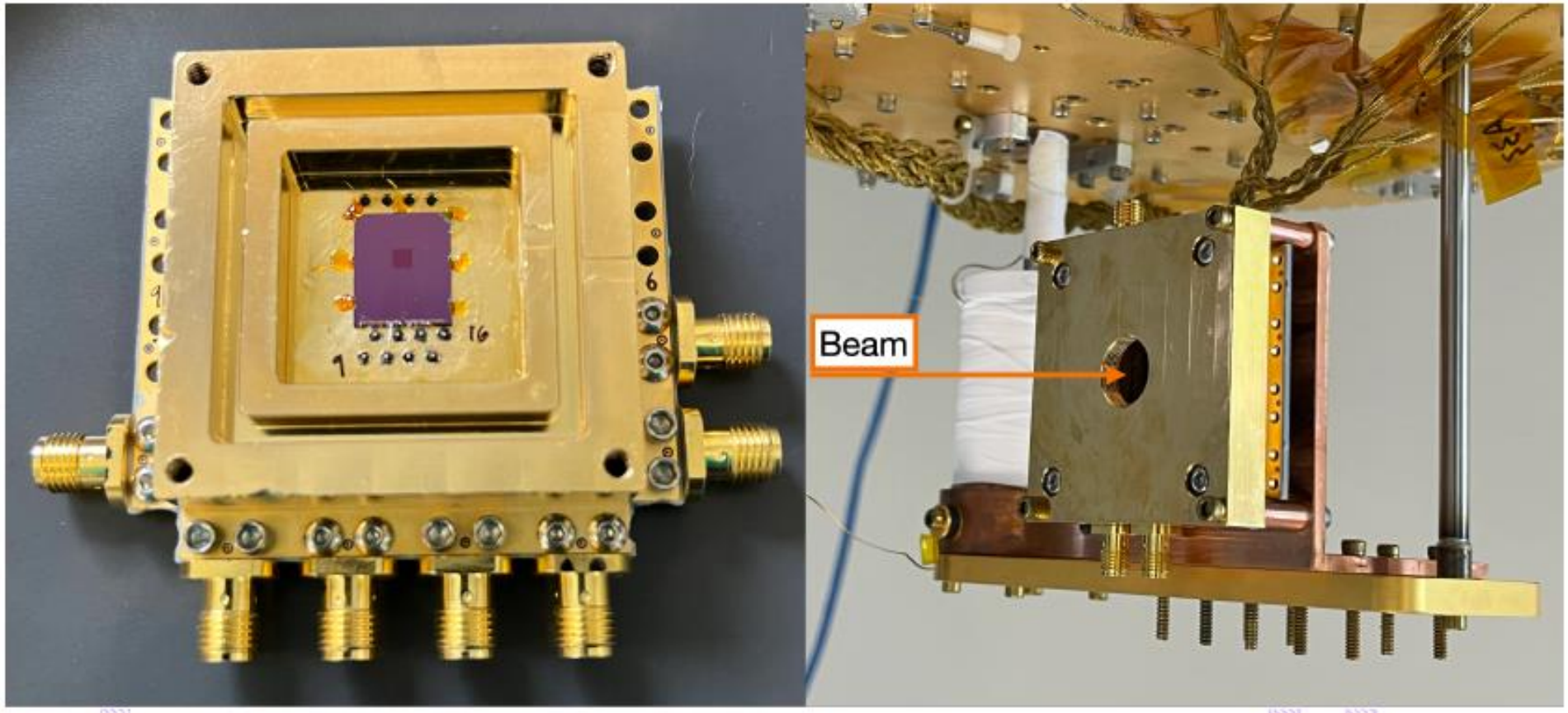






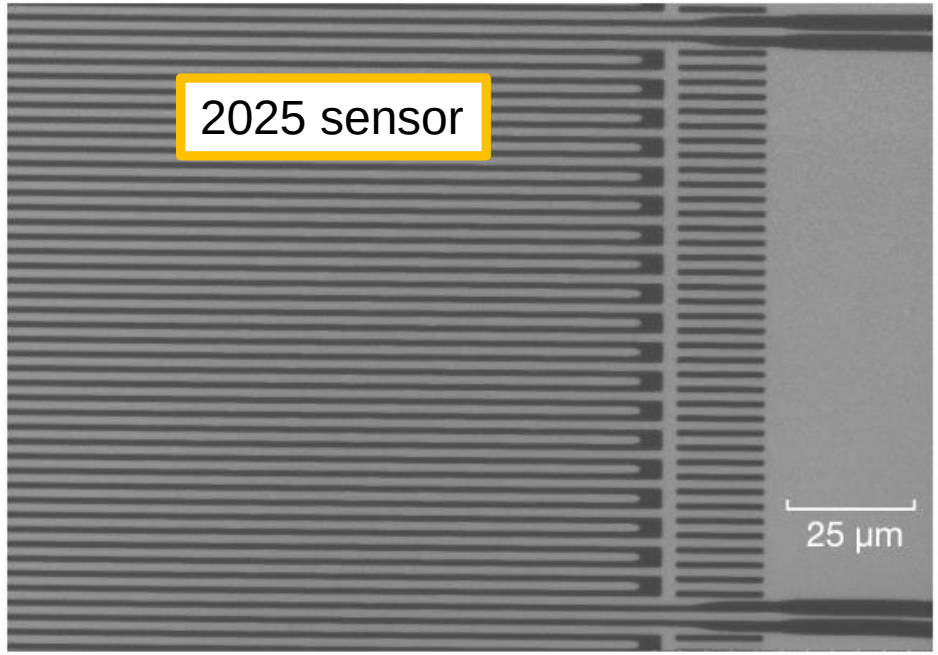
SMSPD

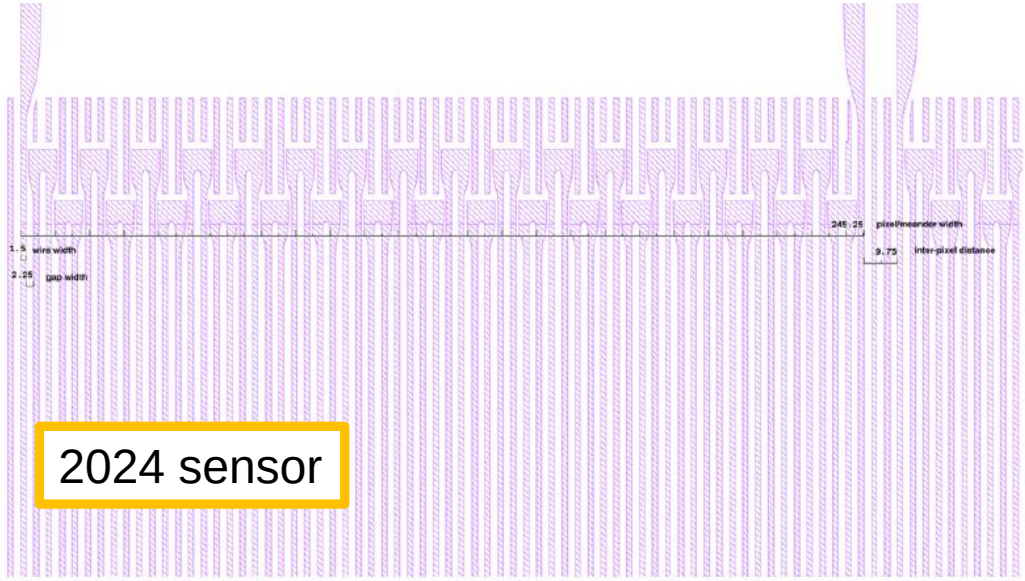
- We use a WSi SMSPD manufactured at JPL.
- SMSPD holder is one used for SMSPD research, not particularly customized for beam tests.
- 1 K cold stage has sensor, sensor holder and cable connections.
- Sensor holder dominates the material budget around the sensor.



Detailed sensor studies

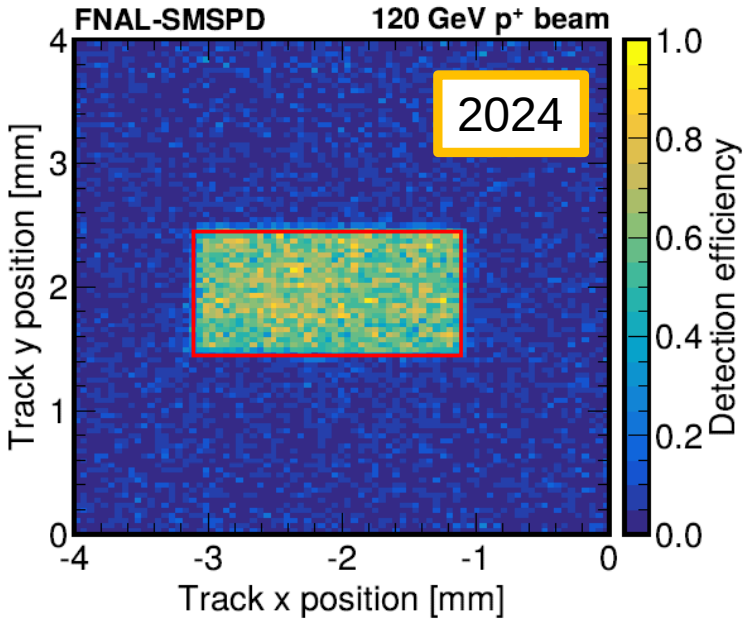
- We find high efficiency detection upon impact of the particle on the sensor area - within the resolution of the tracking device.
- The feature size of the SMSPD used at CERN is 1 mμ wire width and 3 mμ wire distance, 4.75 nm thickness (1.5/2.25/3 at FNAL).
- We used a pixel tracking device (AIDA telescope) to determine the impact point of the particle on the SMSPD.
- Using the edge of a thin trigger counter we meaured the «edge detection» resolution of the tracker to be around 10 mμ.
  - Close, but not quite good enough to resolve features of the SMSPD.
  - Close, but not exactly the resolution expected from the tracking device.

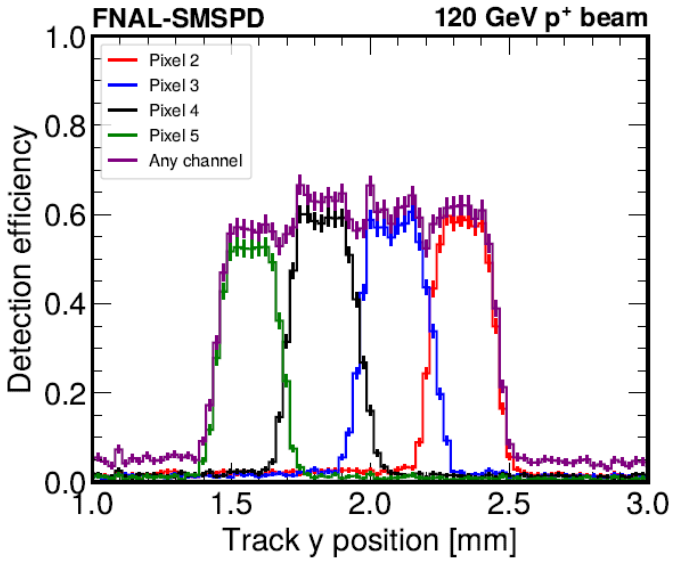


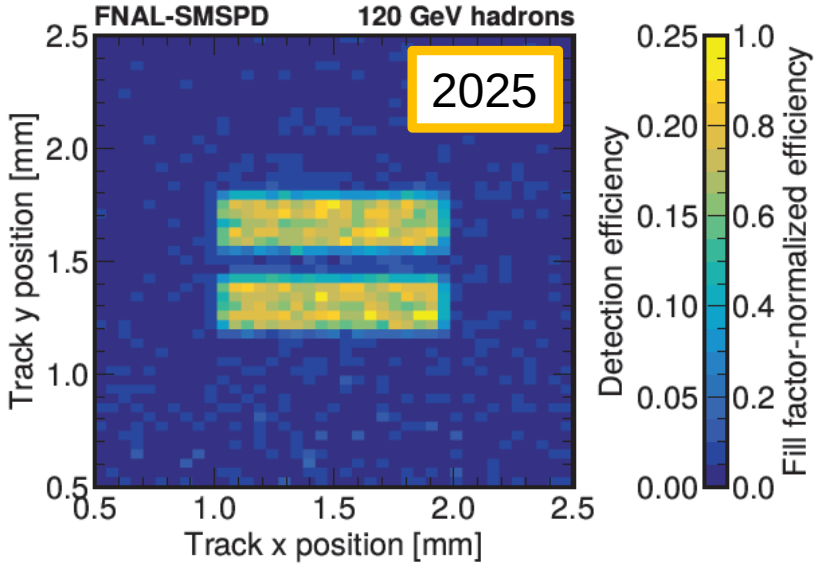


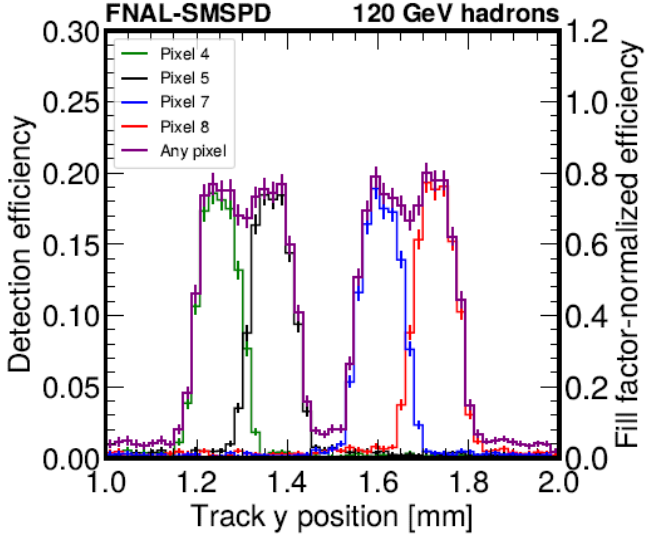
Test beam scope and results

- Tests have been performed with 120 GeV hadron beams and 8 GeV electrons (FNAL) and 120 GeV hadrons and 120 muons at CERN.
- The scope of the 2024 test beam was to explore if SMSPDs can detect high energy particles.
  - Success of this test allready allowed study of the detection performance.
- The scope of the second test was to study the detection performance (spatial, temporal resolution and efficiency) and start exploring the detection mechanism.
  - Conduct tests similar to typical HEP sensor R&D approach.



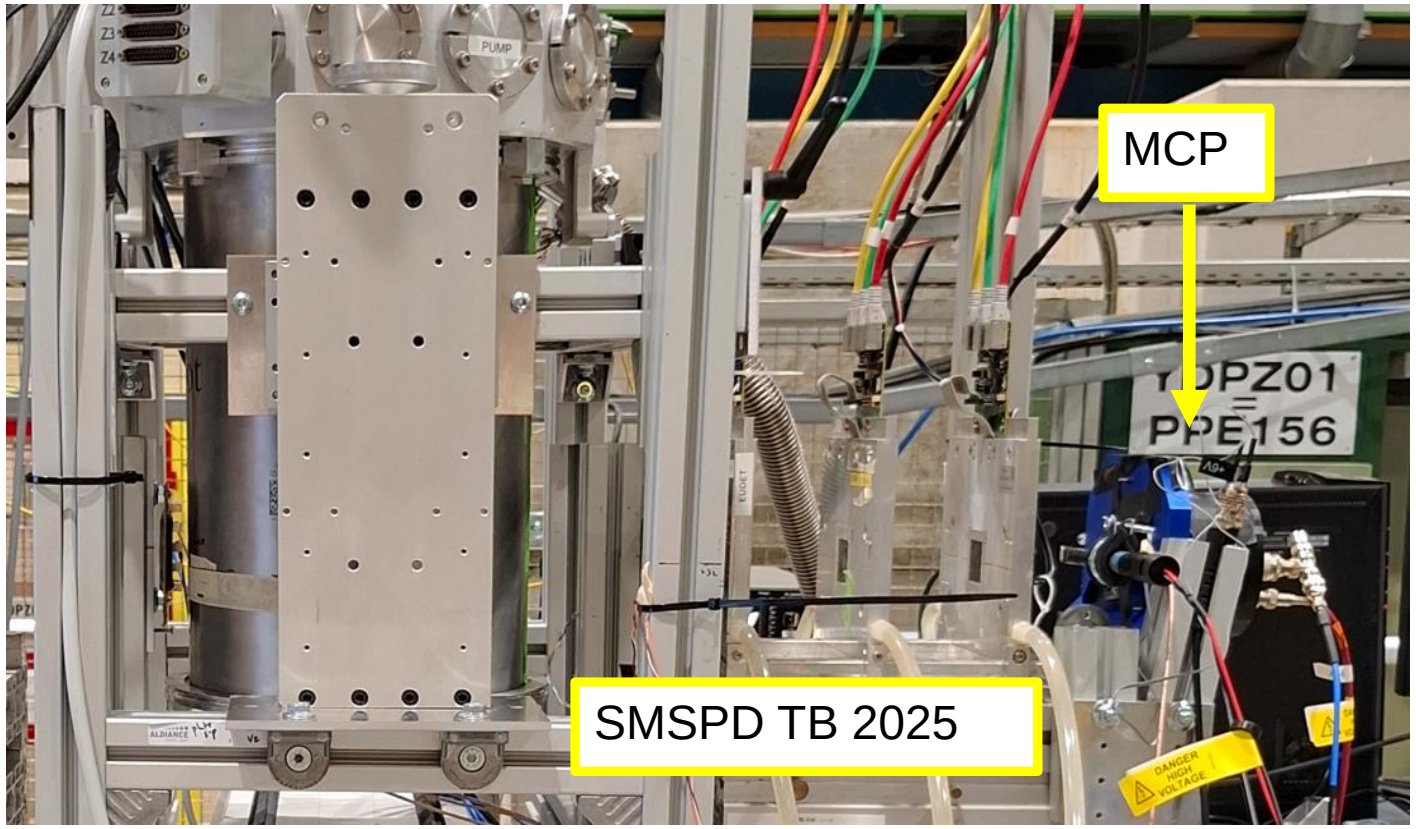


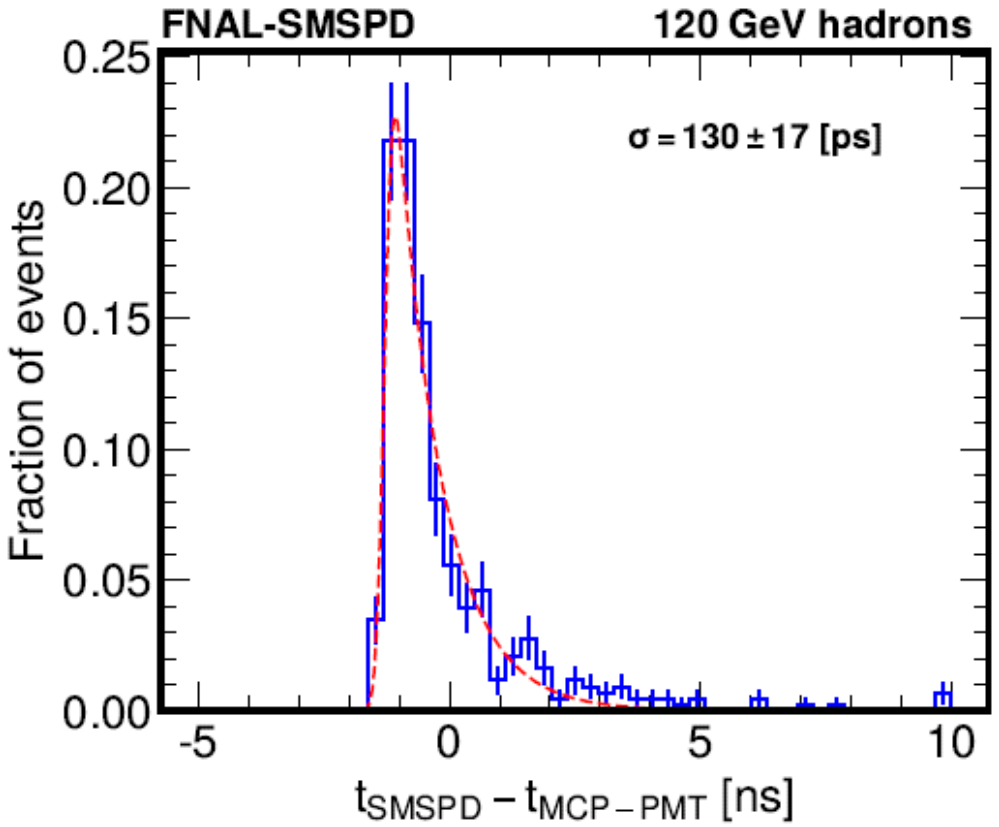




Time reference

- Ultimate goal : Fully exploit know good timing performance of SMSPD down to a few ps.
- Benchmarking against a reference with a resolution of ~10 ps.
- CERN sensor and electronics achieved 130 ps.
  - Some geometric jitter observed.
  - Ultimate performance will require very good time reference and patial resolution.





The team !

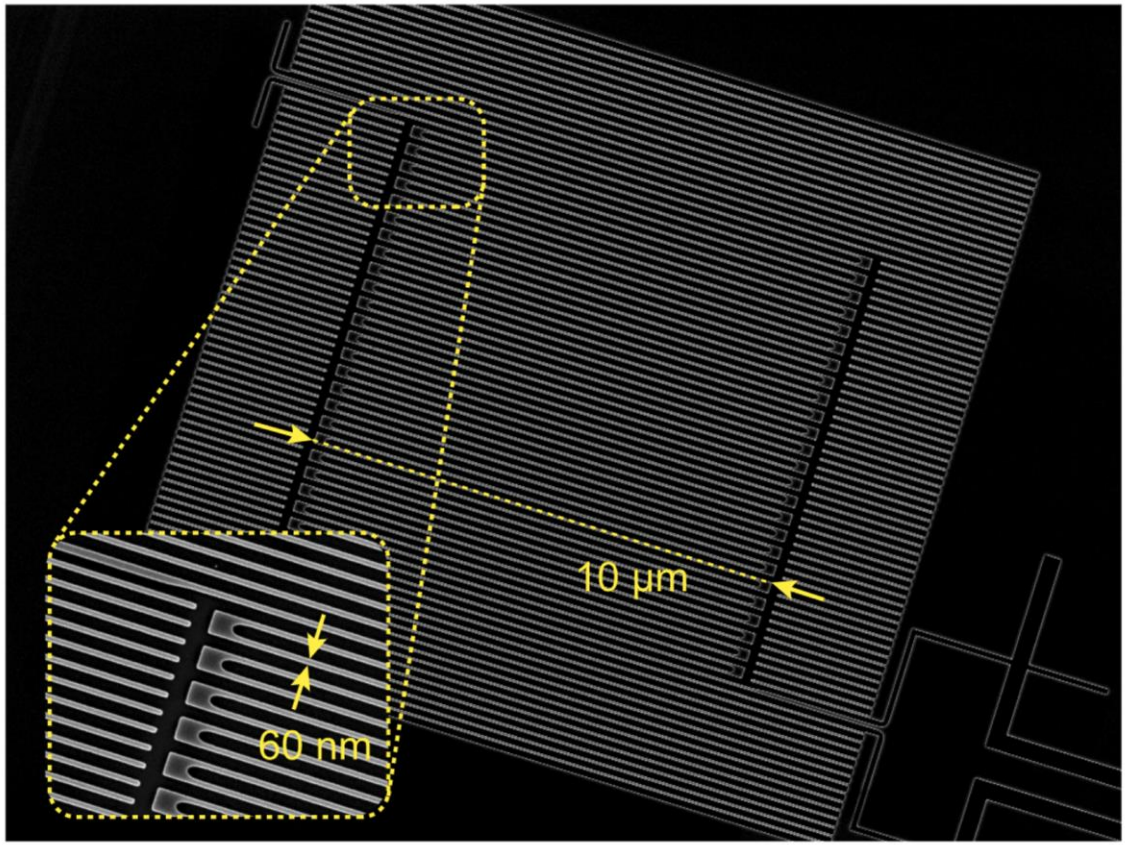
- The test beam at CERN relied heavily on the previous experience at FNAL.
  - Dedicated prep time for the CERN test was several weeks excluding actual SMSPD R&D.
  - Prep time for the initial FNAL test was rather months with repeated beam time slots.
- Curiosity driven team enjoying the process !

Summary

- We demonstrated efficient detection of high energy particles with SMSPD.
- Results from two test beam campaigns already allow to explore performance as a function of sensor features.
- Goal is to start optimizing SMSPD for particle detection.

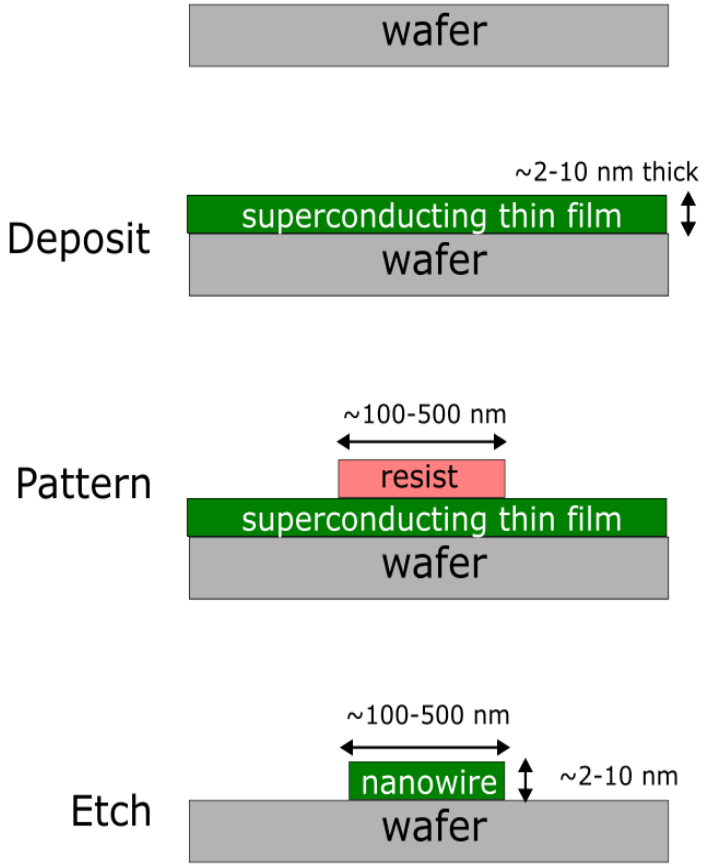
Superconducting nanowire detector

(typically "single-photon" → SNSPD)



Single-pixel detector

Nanofabrication

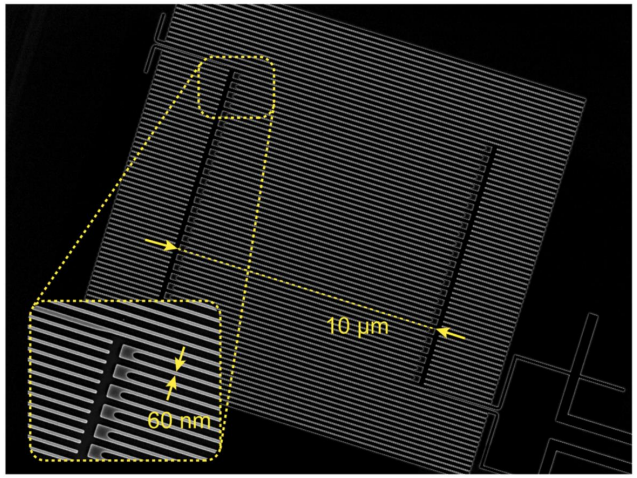


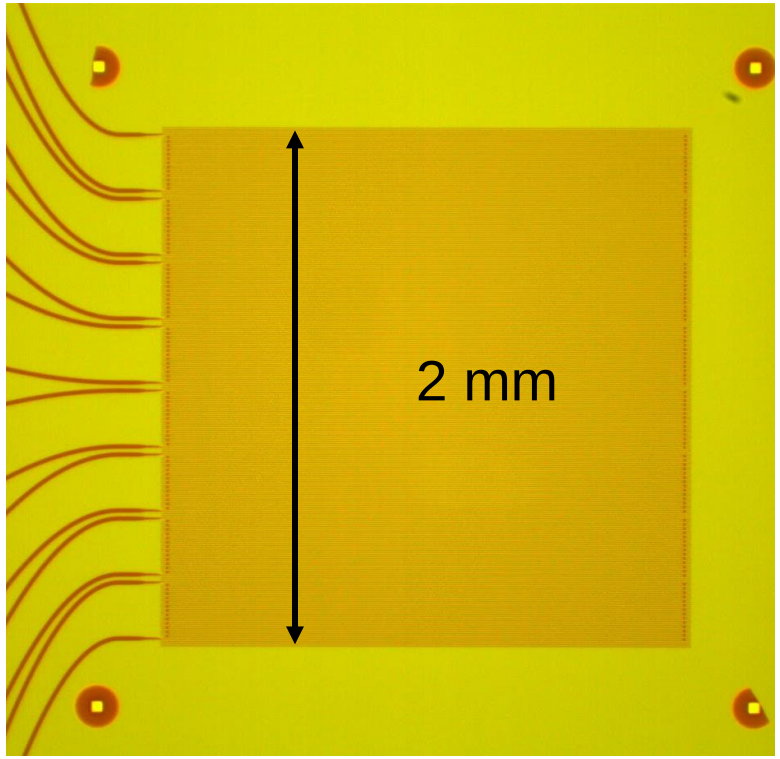
Goltsman, *et al*, ***APL* 79**, 705 (2001)

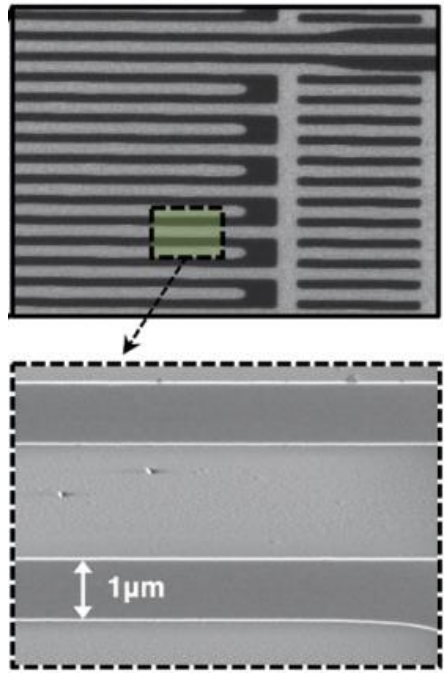
Development of micron-wide detectors

WSi

T_c = 1.85 K



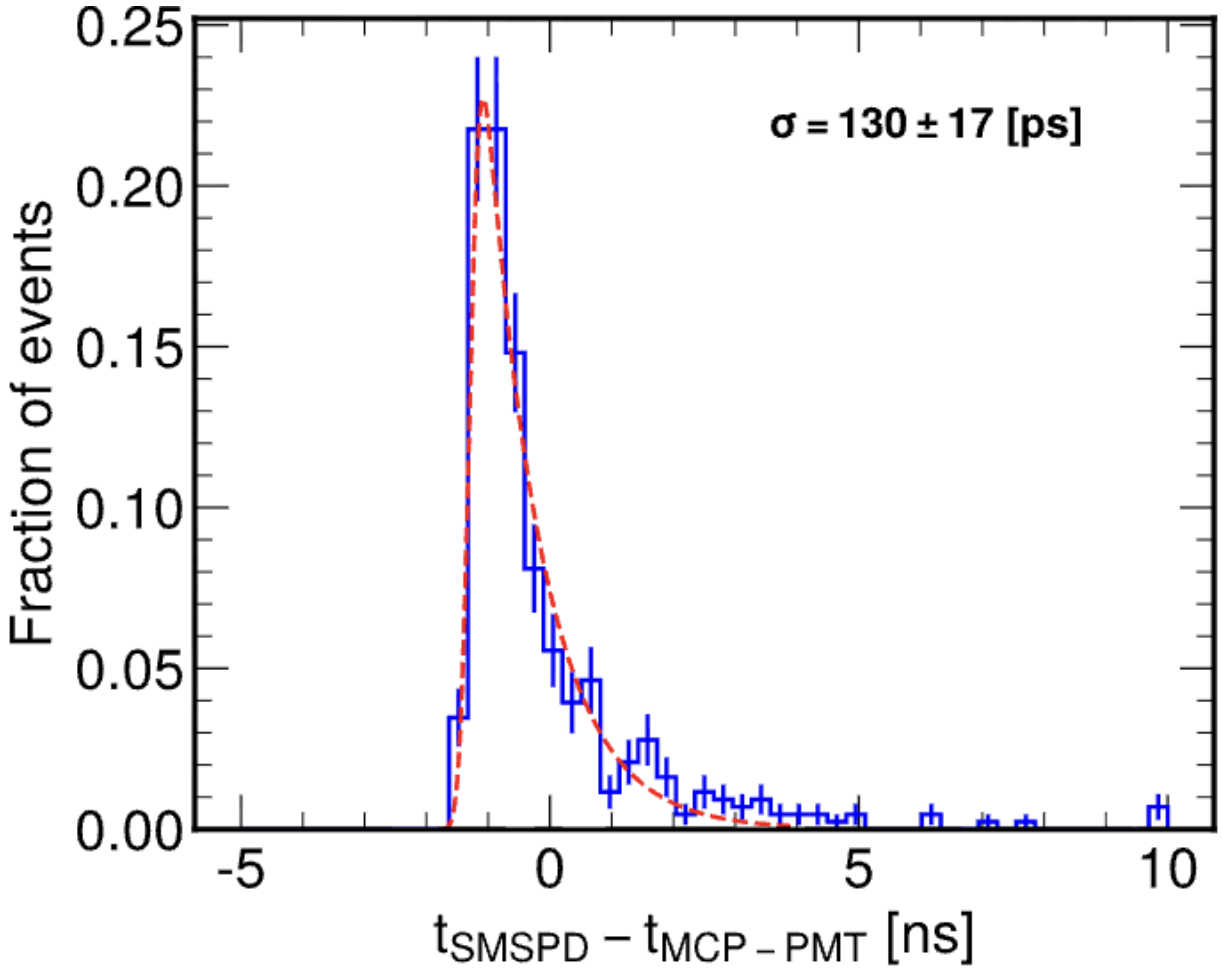




- Improved **film properties** to scale to >1 um-wide wires
- Switched to **photolithography** for better scalability

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**

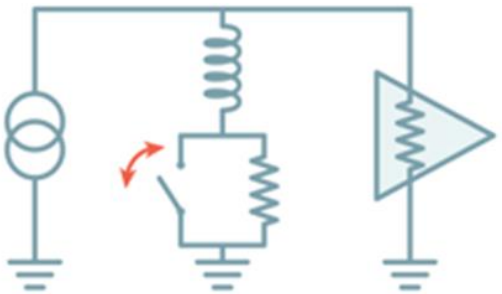
Can we start studying detection mechanism for particles?

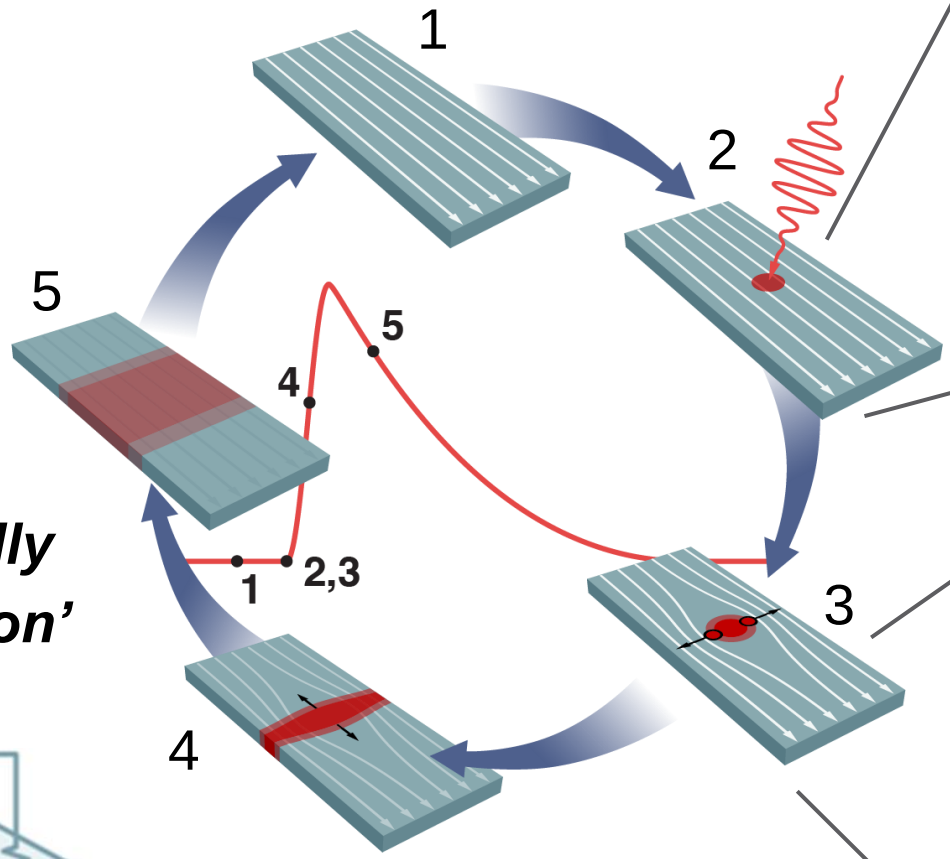


C. Peña et al, High energy particle detection with large area superconducting microwire array. *Journal of Instrumentation 20*(03), P03001 (2025).
C. Wang et al, Towards High-Efficiency Particle Detection Using Superconducting Microwire Arrays arXiv 2510.11725 (2025)

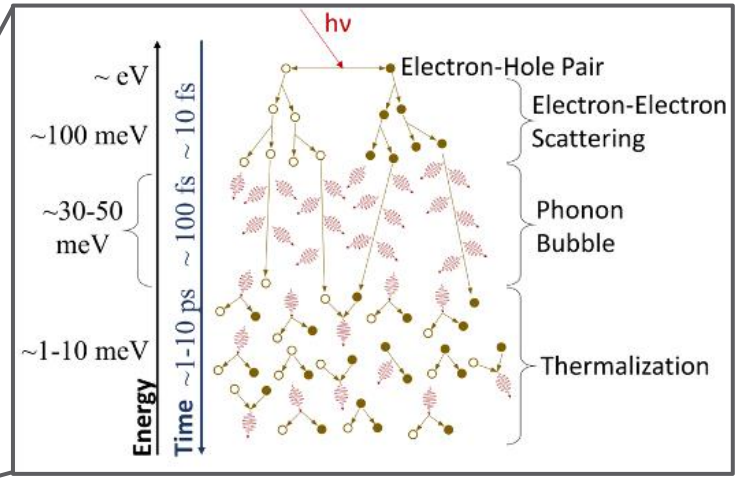
SNSPD detection mechanism

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

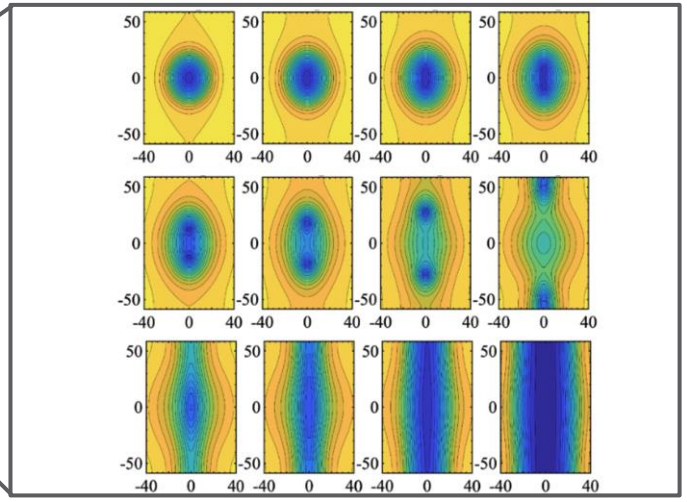




Typically operating at 0.3-5 kelvin



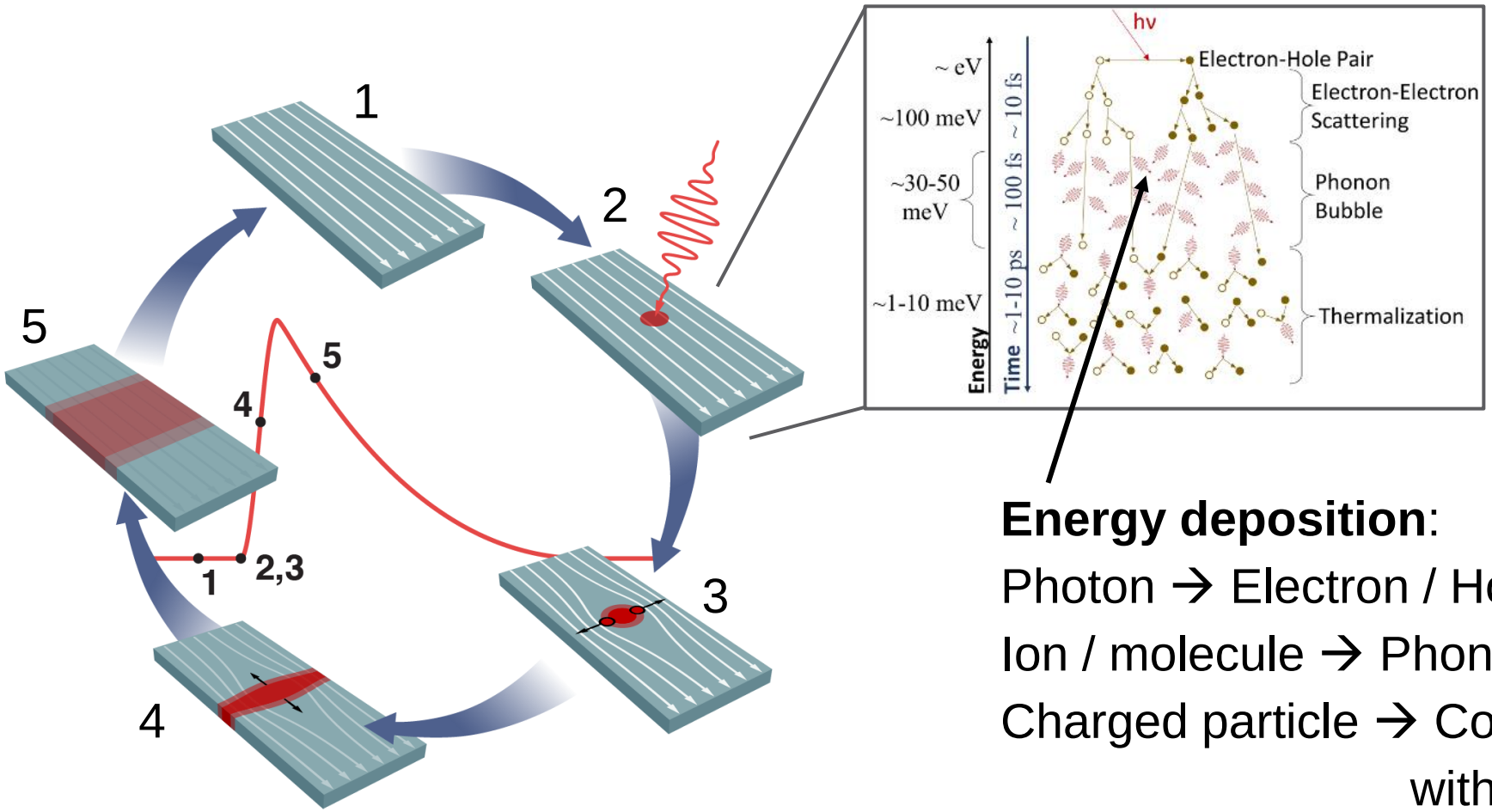
thousands of carriers per photon



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)

Suppression of superconductivity across wire



Energy deposition:

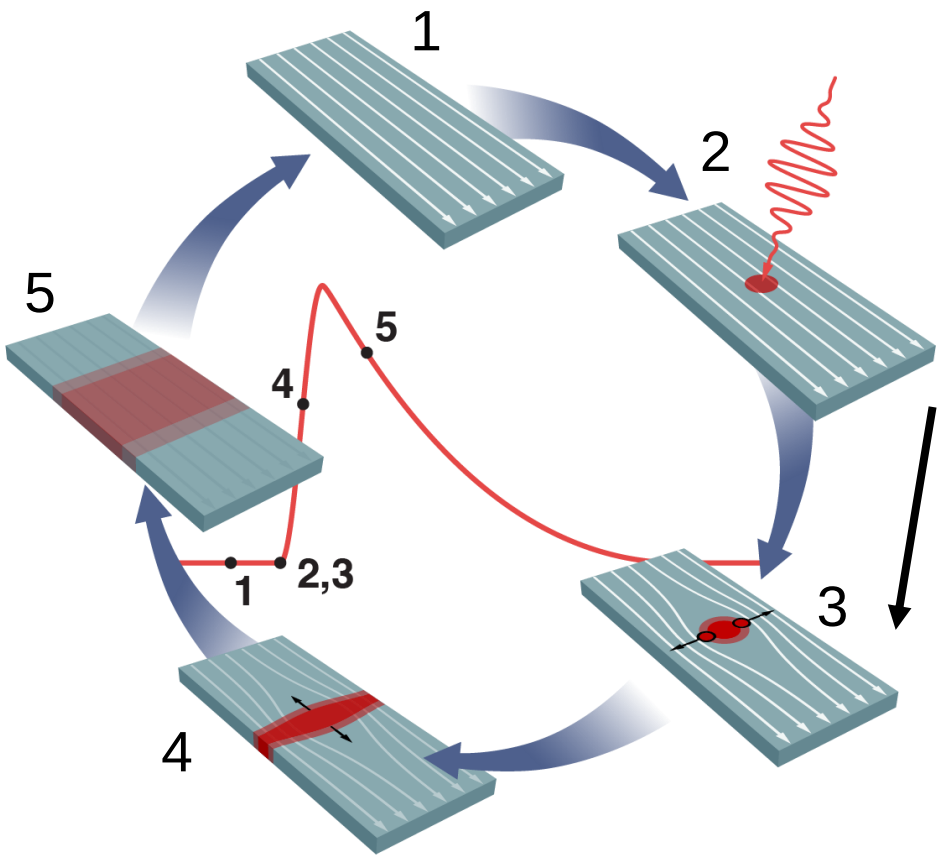
Photon → Electron / Hole

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)

Vortex entry into nanowire



Tunneling event

Potential barrier for vortex entry

Vortex tunneling

Bias current

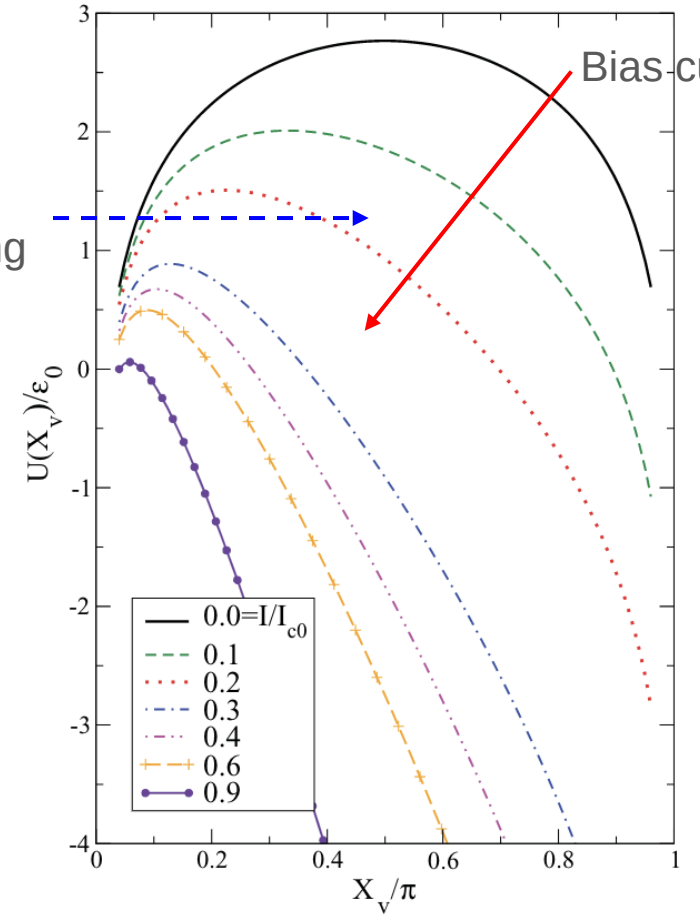
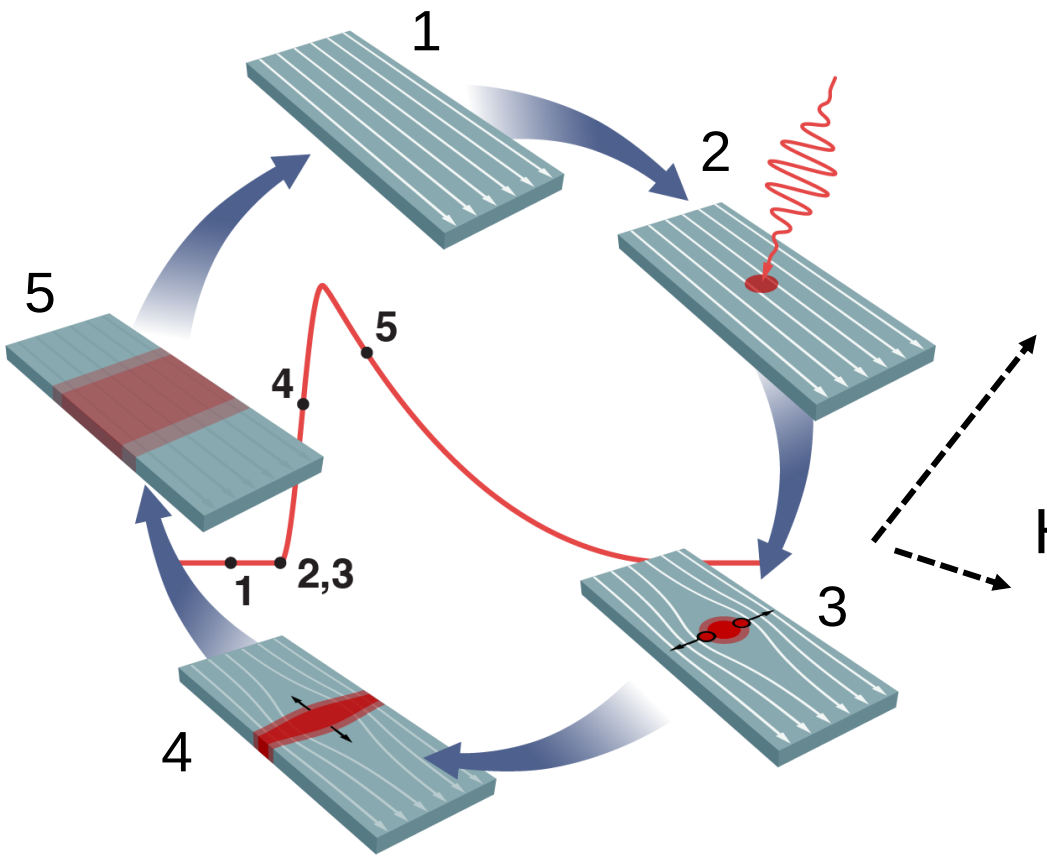


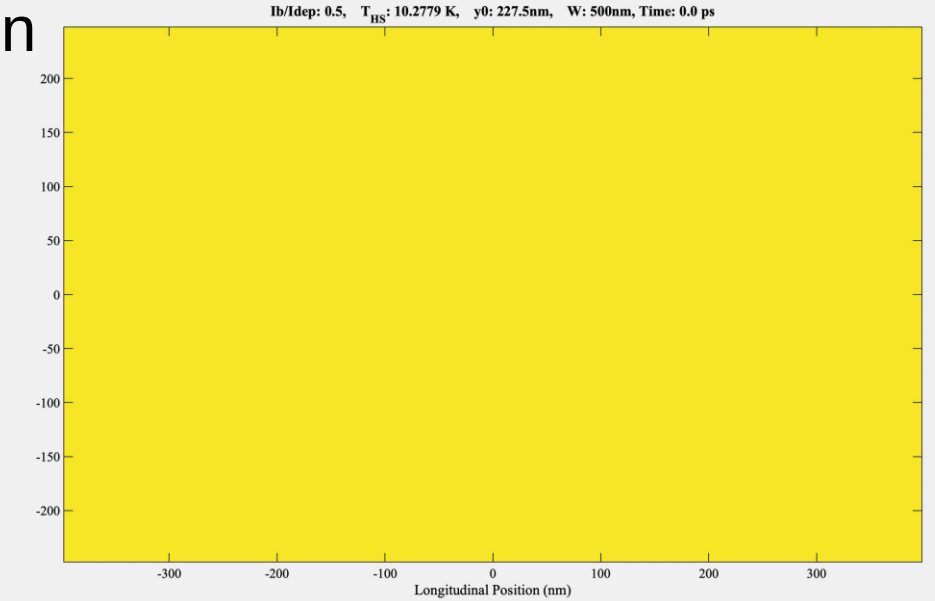
FIG. 2. (Color online) Position dependence, $X_v = \pi x_v/w$, of the potential energy for vortex entry in zero magnetic field for several bias currents. The potential is cut off for distances less than one coherence length ξ from the left and right edges of strip, because of the finite vortex core.

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

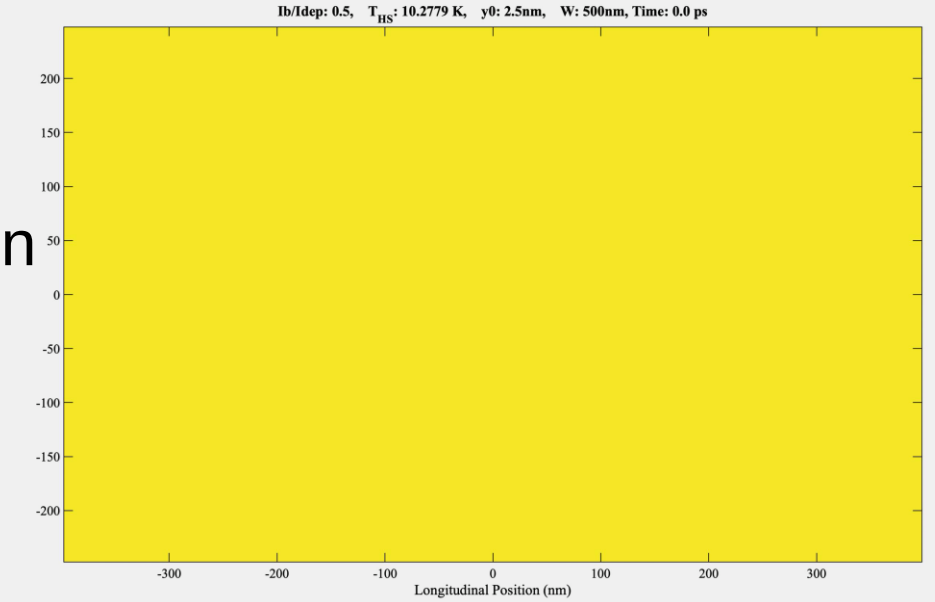
Suppression of superconductivity across wire



Hot-spot in **Edge**

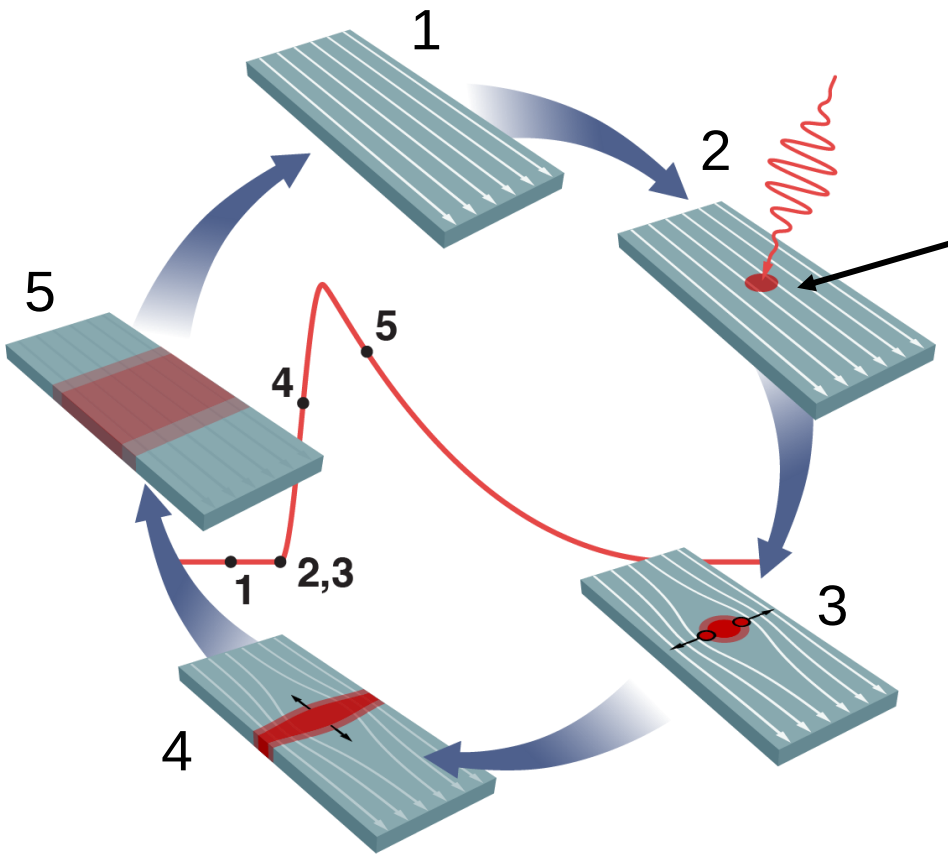


Hot-spot in **Center**



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

Energy threshold



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

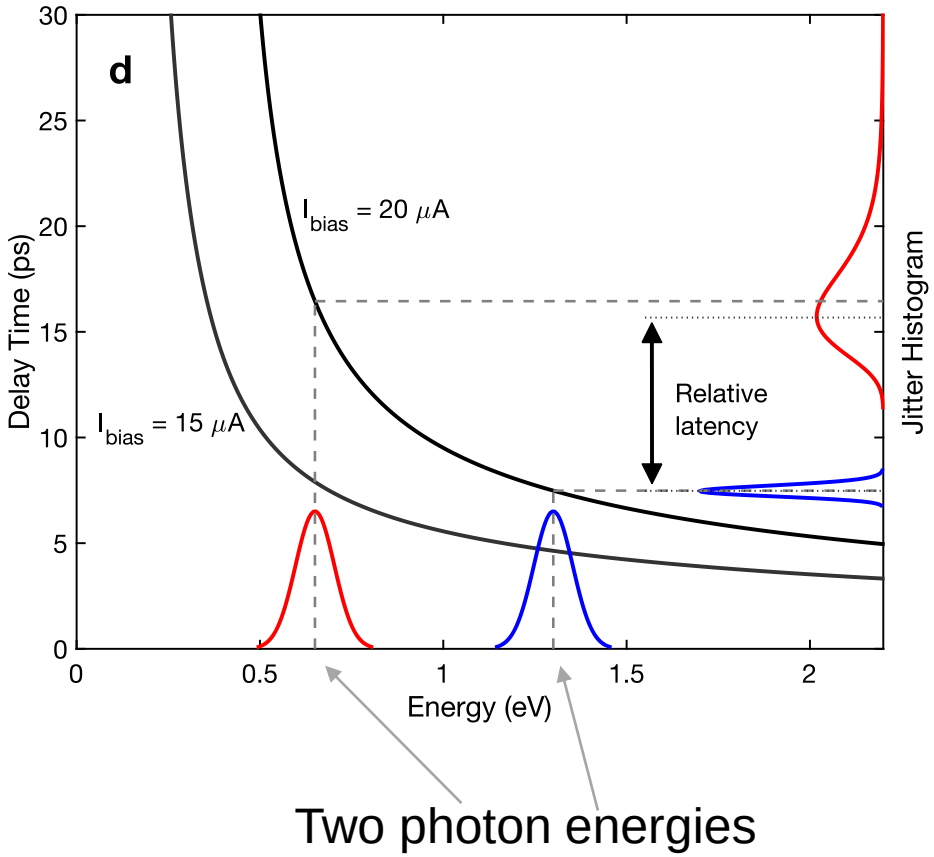
T_C Critical temperature

$4N(0)(k_B T_C)^2$ Energy density relating the difference between the superconducting and normal states

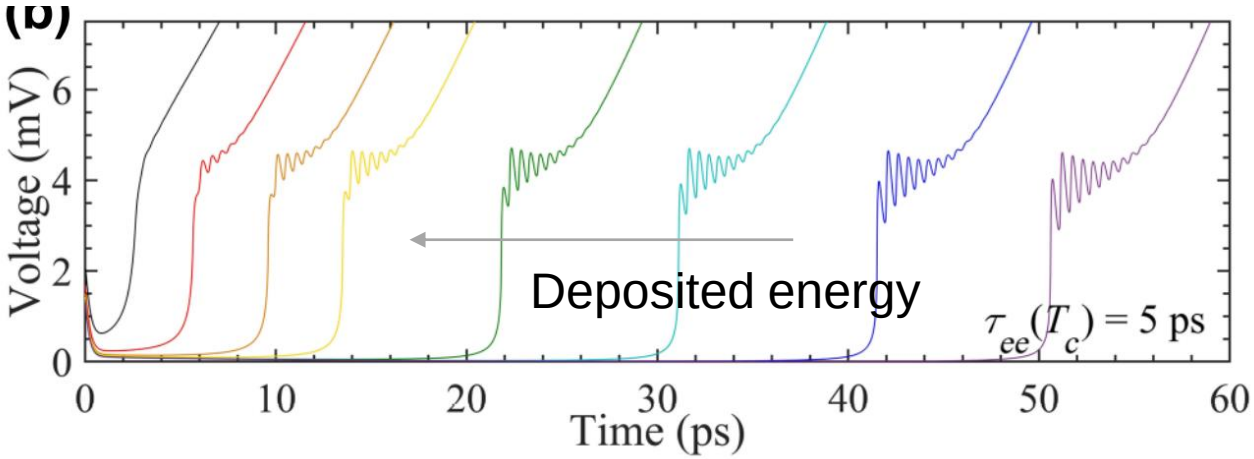
V_0 Characteristic volume where superconductivity is suppressed ***after down-conversion***. Depends on the **diffusion coefficient** and **thickness**

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

Relative latency of detection

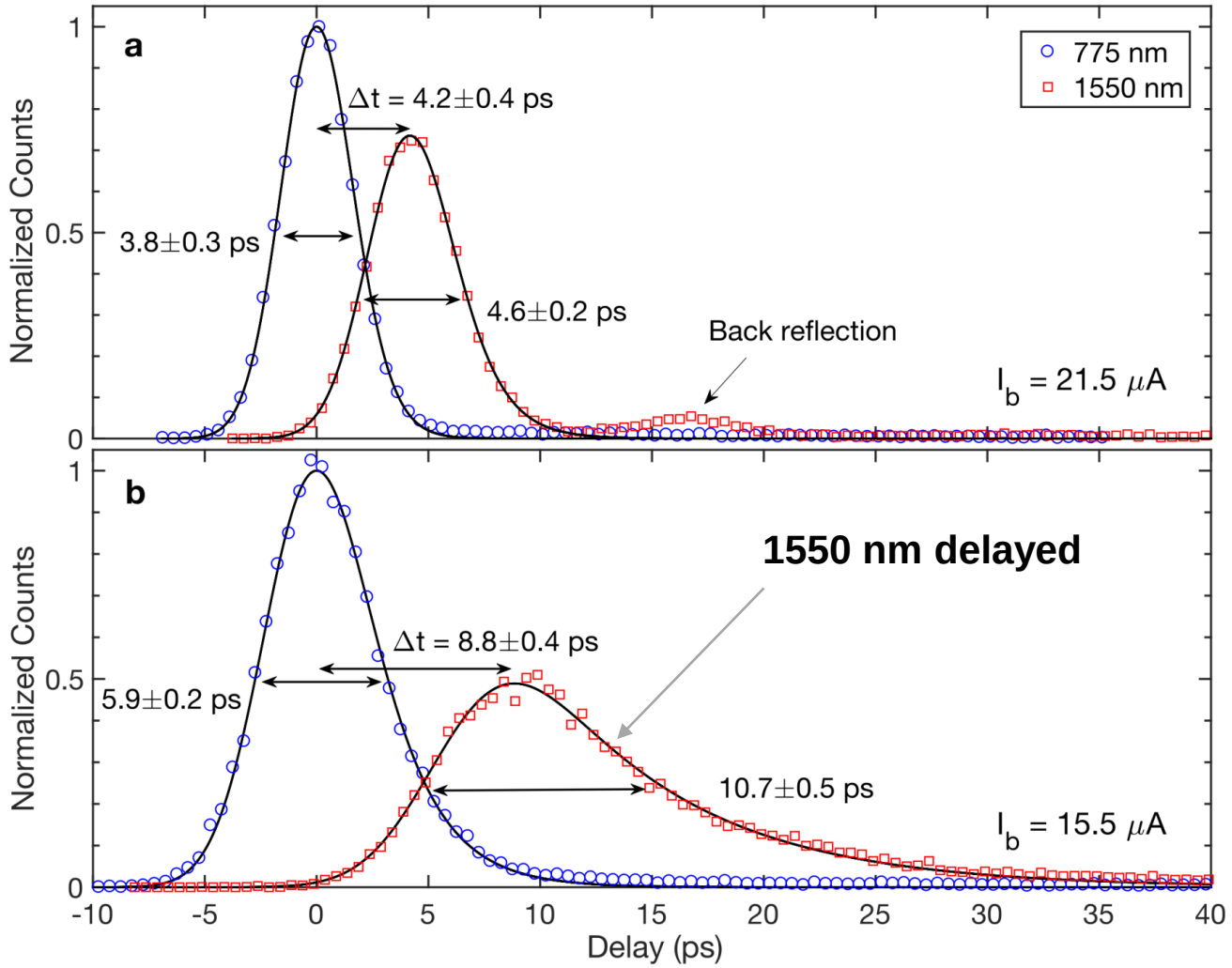


1D model



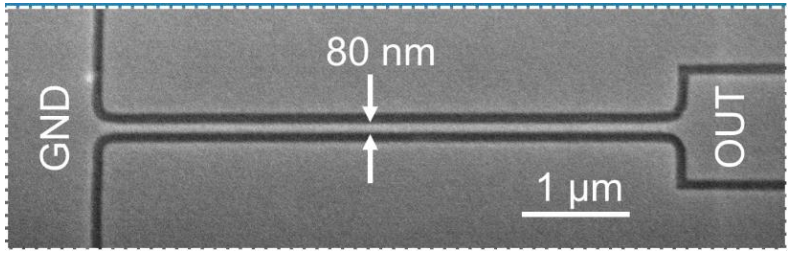
Allmaras, Kozorezov, Korzh, Berggren and Shaw
***PRApplied* 11** 034062 (2019)

Temporal jitter and latency



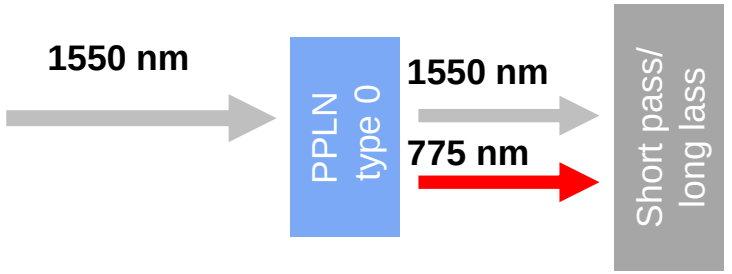
NbN

T_c = 8.6 K



Lower energy photons result in **larger detection latency**

First measurement of SNSPD detection time-scales



Korzh, Zhao, Allmaras, Frasca, Autry, Bersin, Beyer, Briggs, Bumble, Colangelo *et al*
***Nature Photonics* 14,** 250-255 (2020)

Temporal jitter and latency

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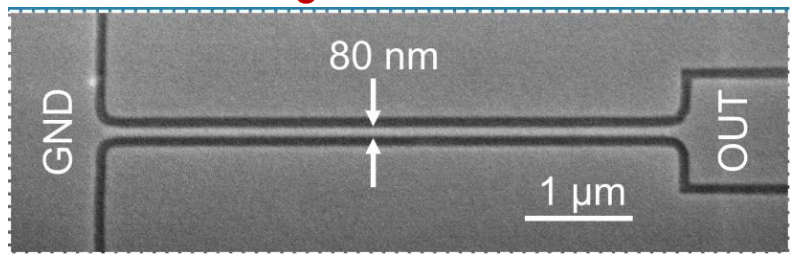
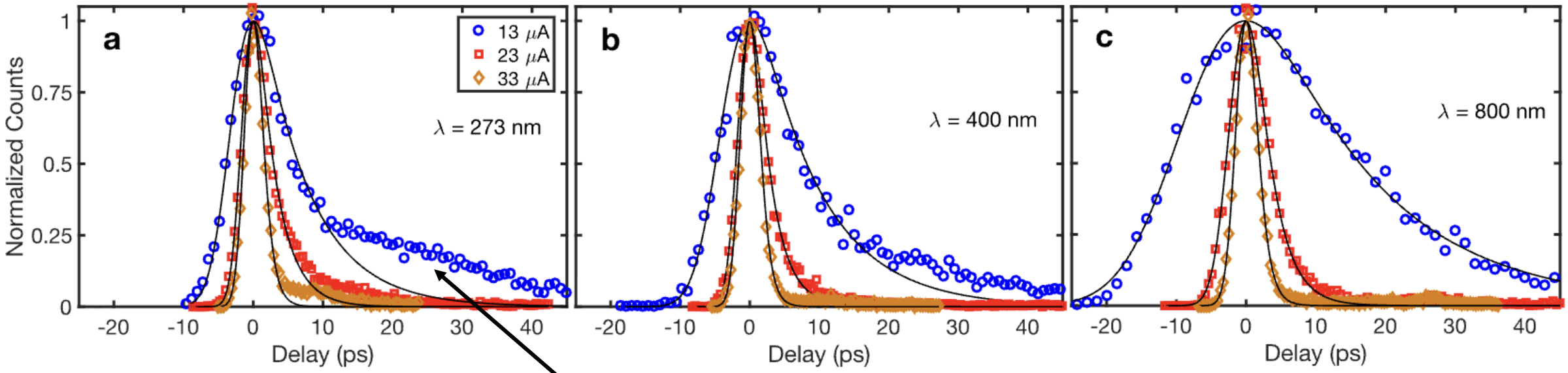


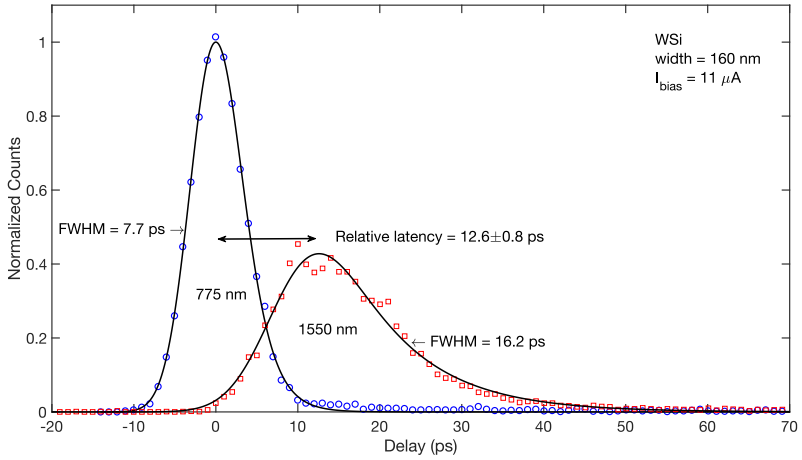


Signatures of 2D effects

Korzh, Zhao, Allmaras, Frasca, Autry, Bersin, Beyer, Briggs, Bumble, Colangelo *et al*
***Nature Photonics* 14,** 250-255 (2020)

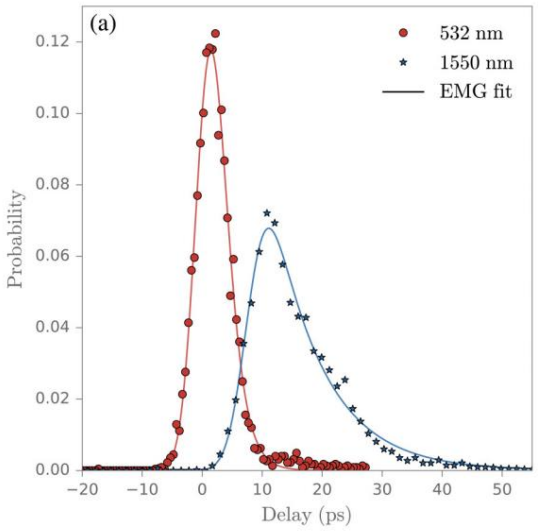
Latency measurements for material comparison

WSi has larger latency (x3-4), **T_c~ 3-4 Kelvin**
→ larger intrinsic jitter



~13 ps relative latency

16.2 ps jitter @ 1550 nm



MoSi

T_c ~ 5 Kelvin

10.6 ps jitter @ 1550 nm

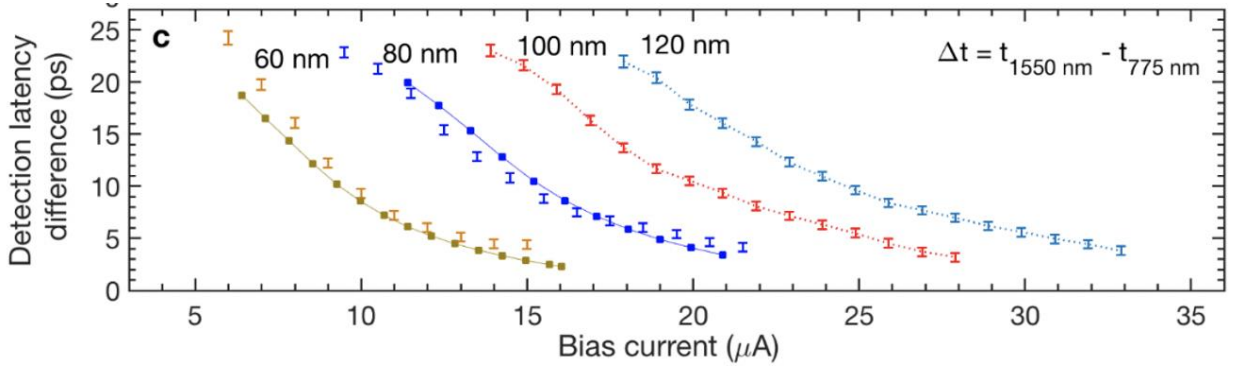
Caloz, Korzh *et al* ***JAP*** **126**, 164501 (2019)

NbN

T_c ~ 7-8 Kelvin

4.3 ps jitter @ 1550 nm

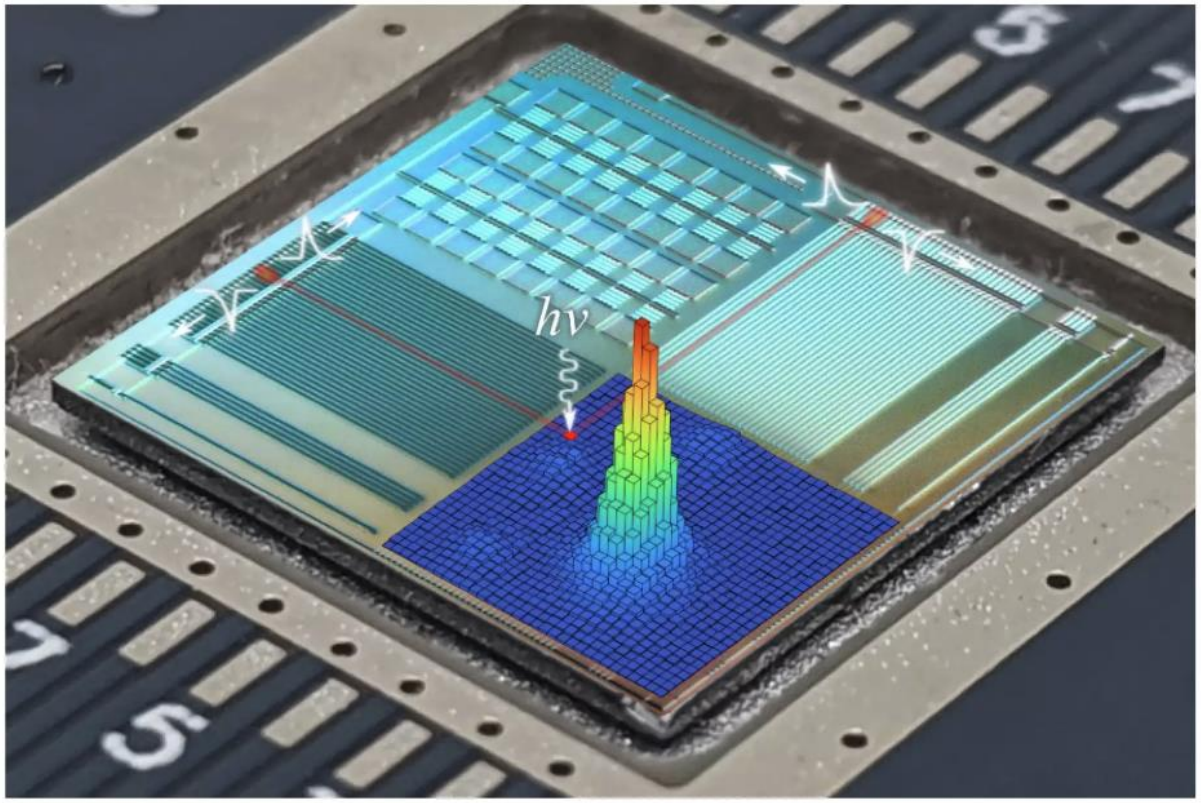
~4 ps relative latency

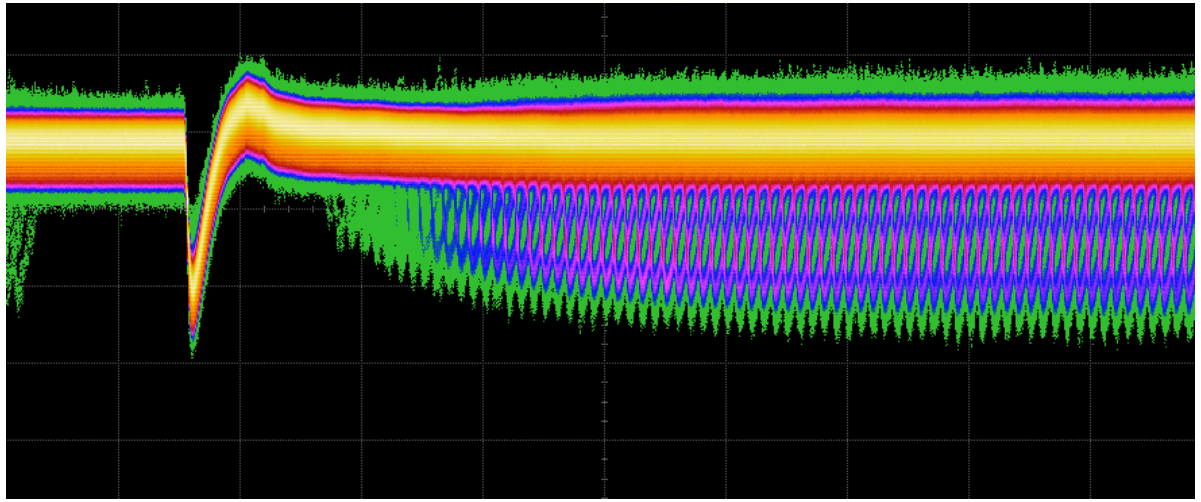


Higher-Tc materials seem to be pathway to lower jitter

Summary

- Starting to **probe the detection mechanism** of SNSPD for particle detection
- Future test beams:
  - Improve **instrument response function** of system:
    - **Geometric jitter** needs to be cancelled
      - Differential readout
    - Next-gen **cryogenic amplifiers**
  - Study **effect of material types/parameters**
  - Boost the **system detection efficiency** to near unity
  - Temperature dependence
- SNSPDs Can adapted for:
  - Photons
  - Charged particles
  - Ions
  - Molecules
  - Maybe optical *phonons* in future?





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
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]
1 ps	10	99 %	10^7	10 Gcps	1x10^{-6} /s/mm^2	1 cm^2	100 µm

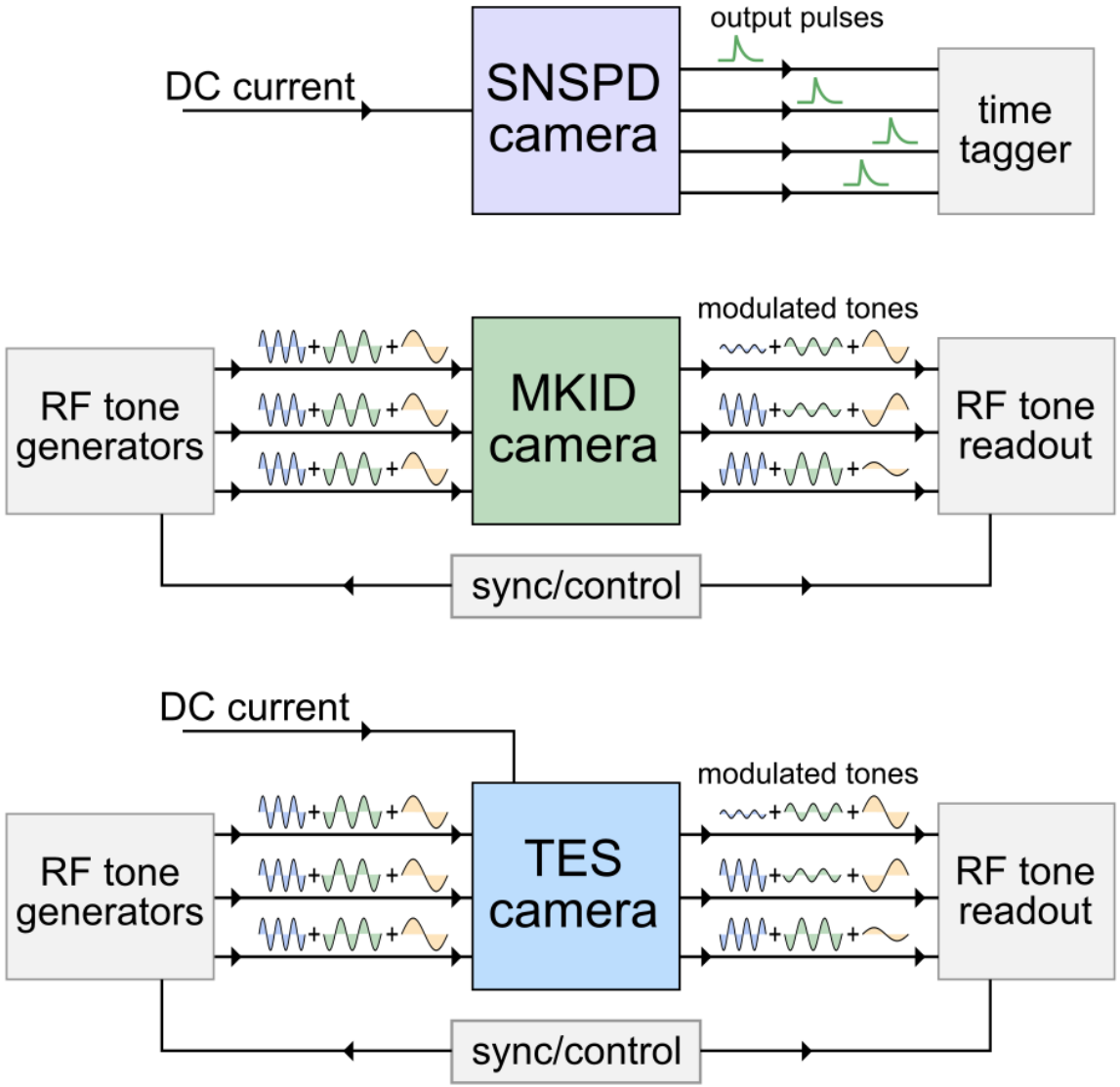
Records in 2016

Current records for isolated devices

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)

Other photon-counting superconducting cameras



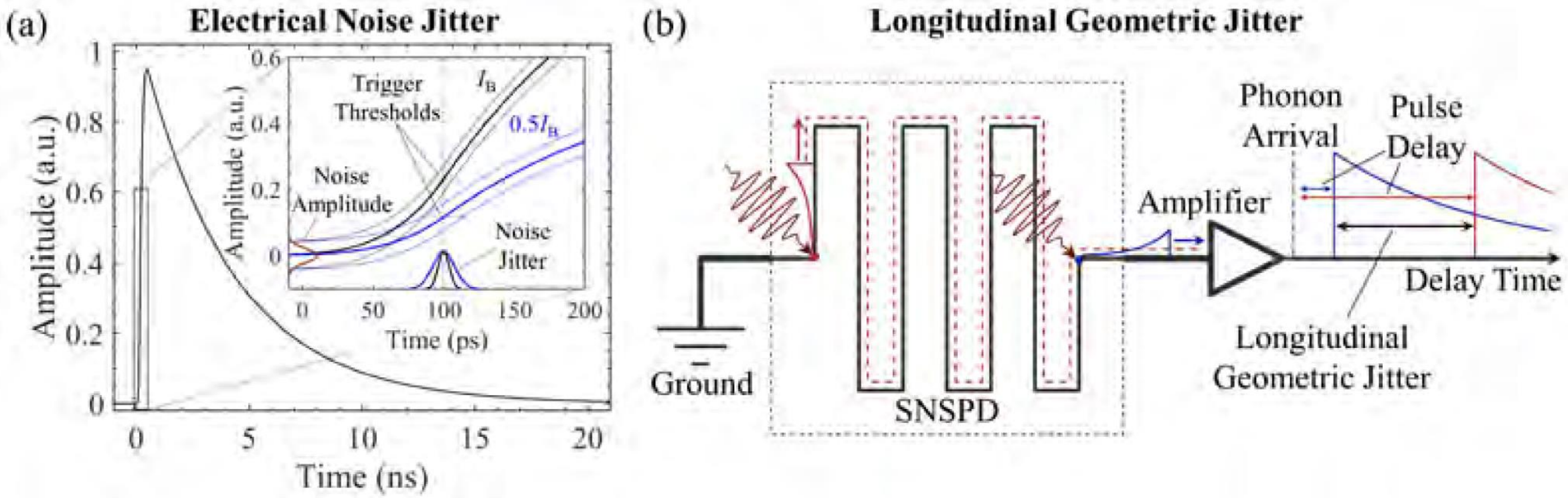
- Detection-driven power dissipation – doesn't limit number of pixels
- No energy resolution

- Continuos power dissipation – pixel number limitation
- Energy resolution

- Continuos power dissipation – pixel number limitation
- Energy resolution

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

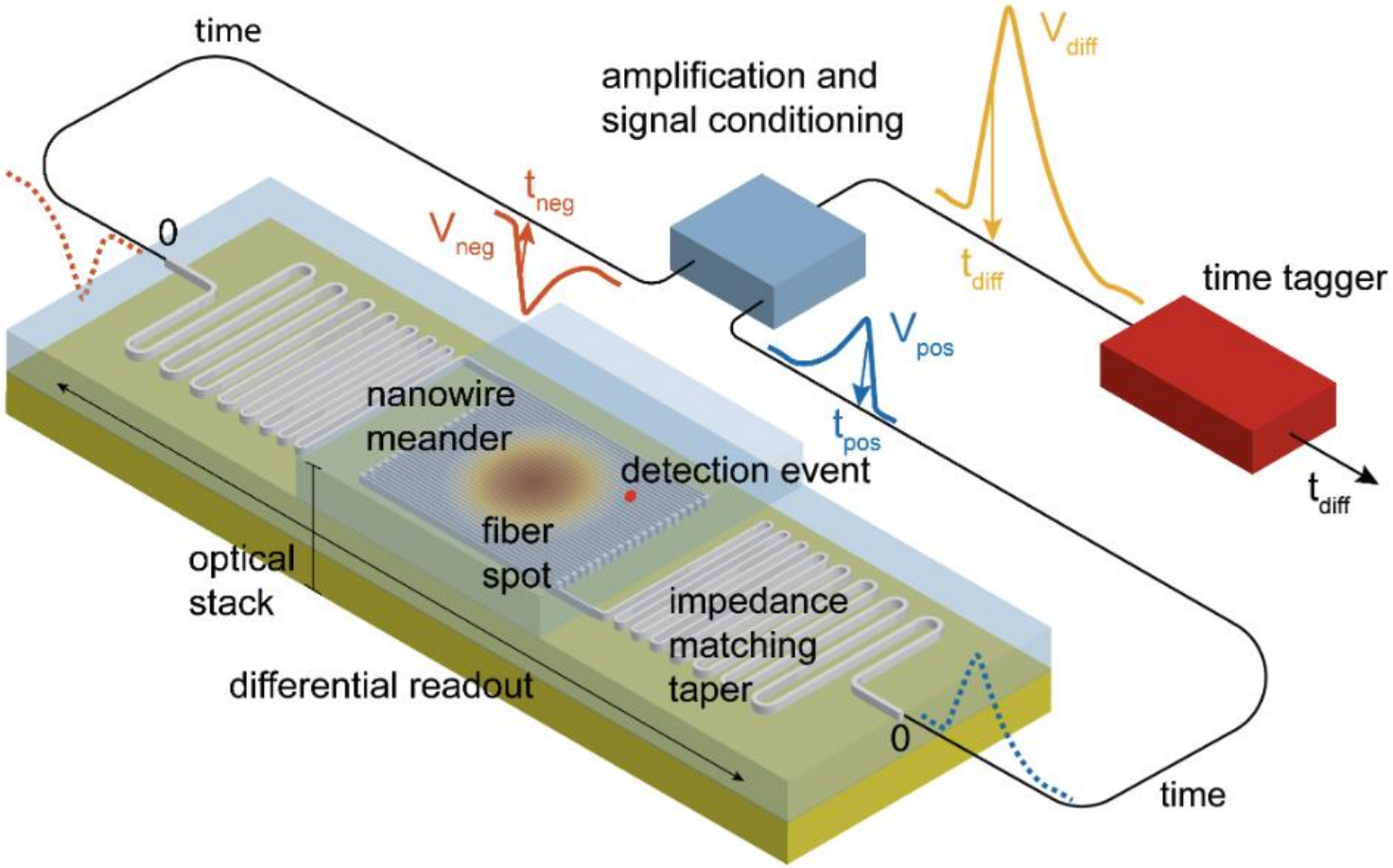
Instrument contribution to timing jitter

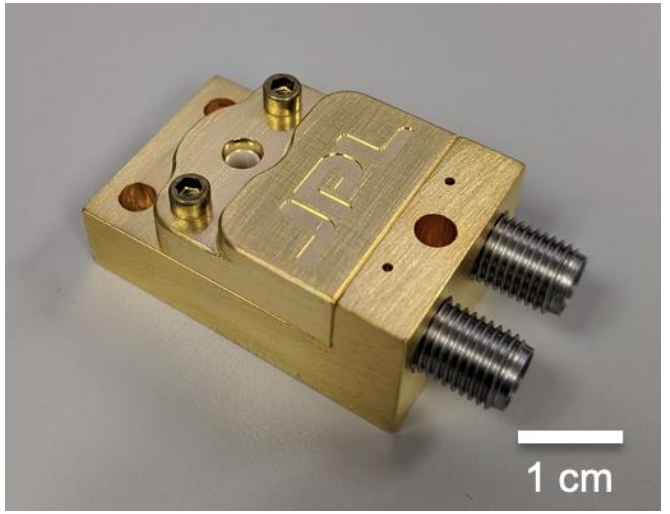


Allmaras, Kozorezov, Korzh, Berggren and Shaw, ***PRApplied* 11** 034062 (2019)

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

Practical single-pixel detectors

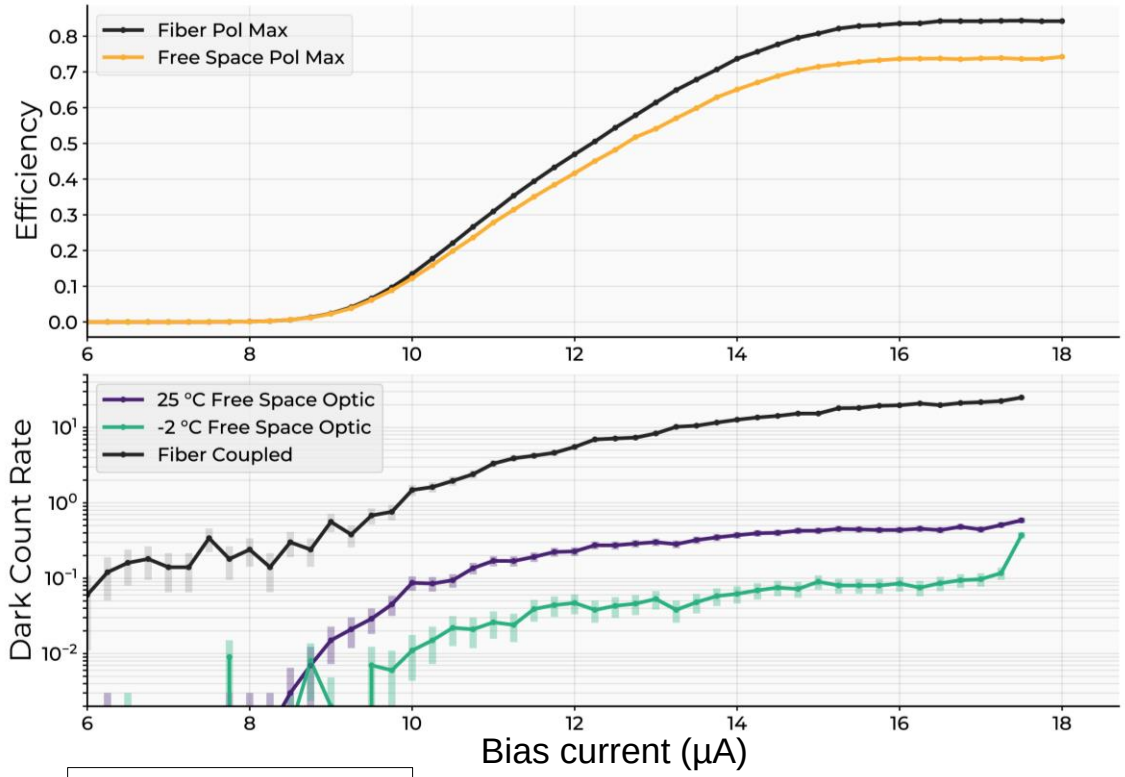




Colangelo, Korzh, Allmaras, Beyer *et al*, ***PRApplied* 19**, 044093 (2023)

Detector requirements for Quantum Communication

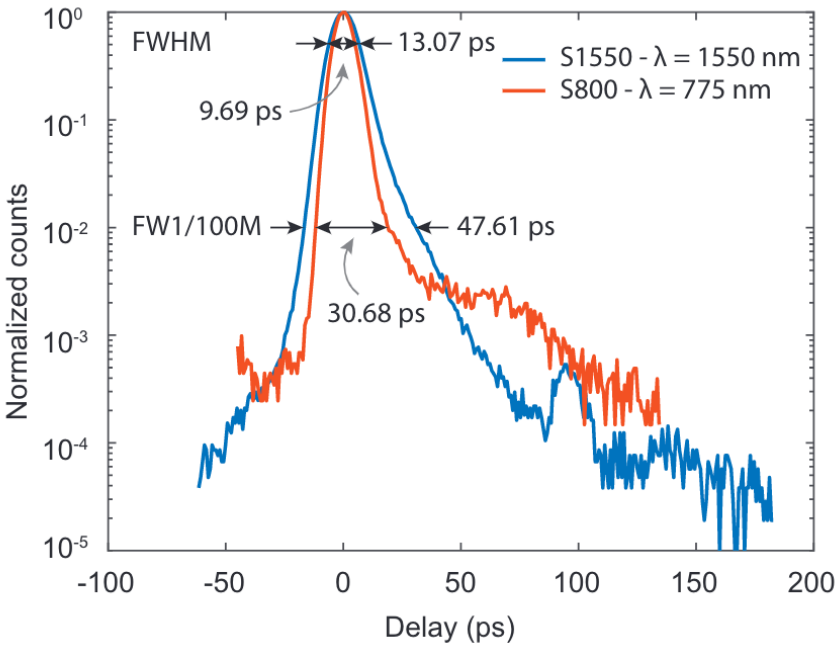
High efficiency



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

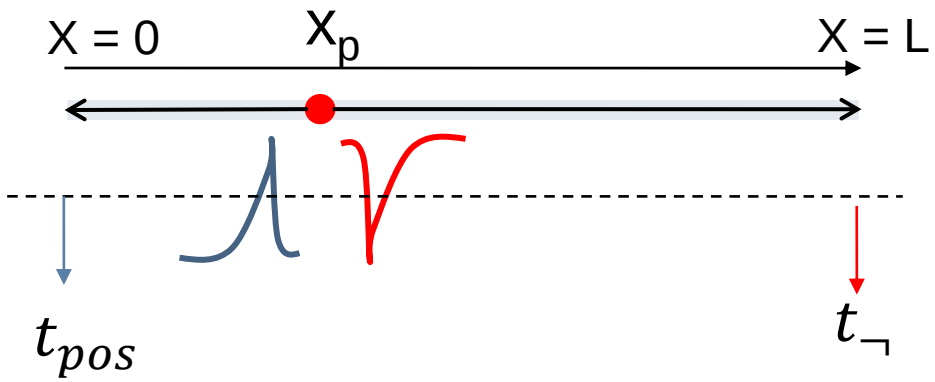
Low noise

Low timing jitter

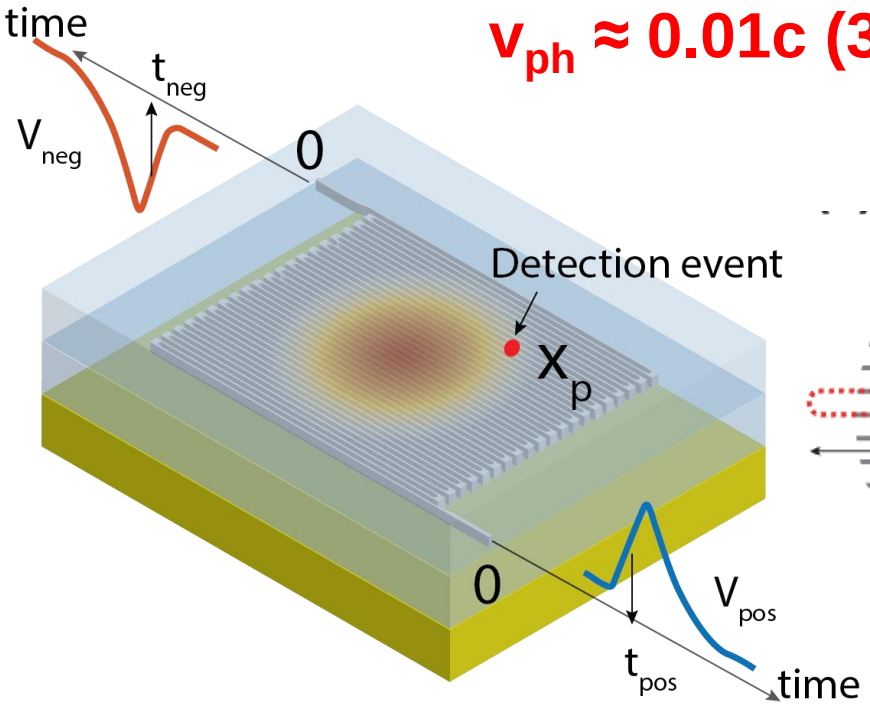


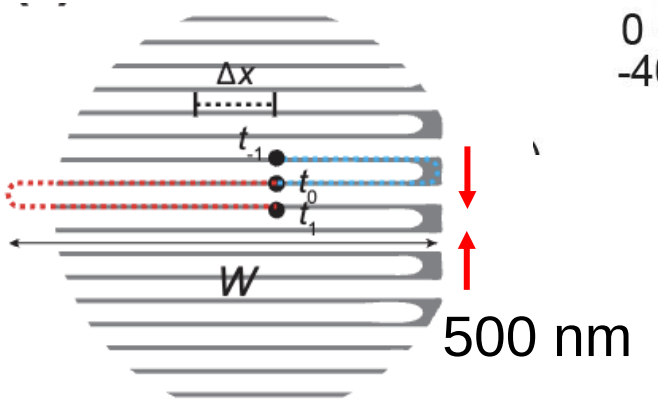
Mueller, Korzh, Runyan *et al,* ***Optica* 8,** 1586 (2021)

High spatial resolution



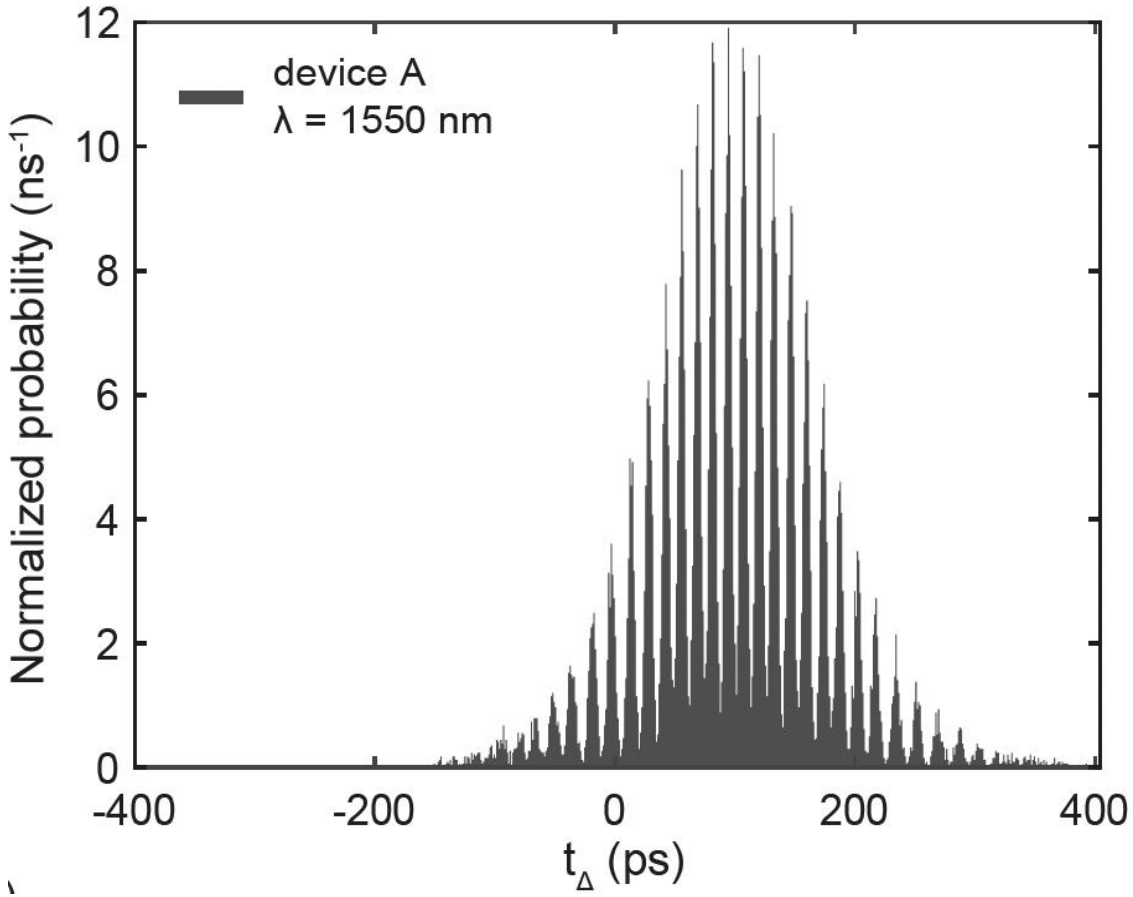
$v_{ph} \approx 0.01c$ (3 µm/ps)





500 nm

Experimental demo: 500 nm resolution



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

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