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CERN Main Auditorium
QUANTUM TECHNOLOGY CONFERENCE
QT4HEP 20-24 January 2025

High critical temperature superconducting particle detectors

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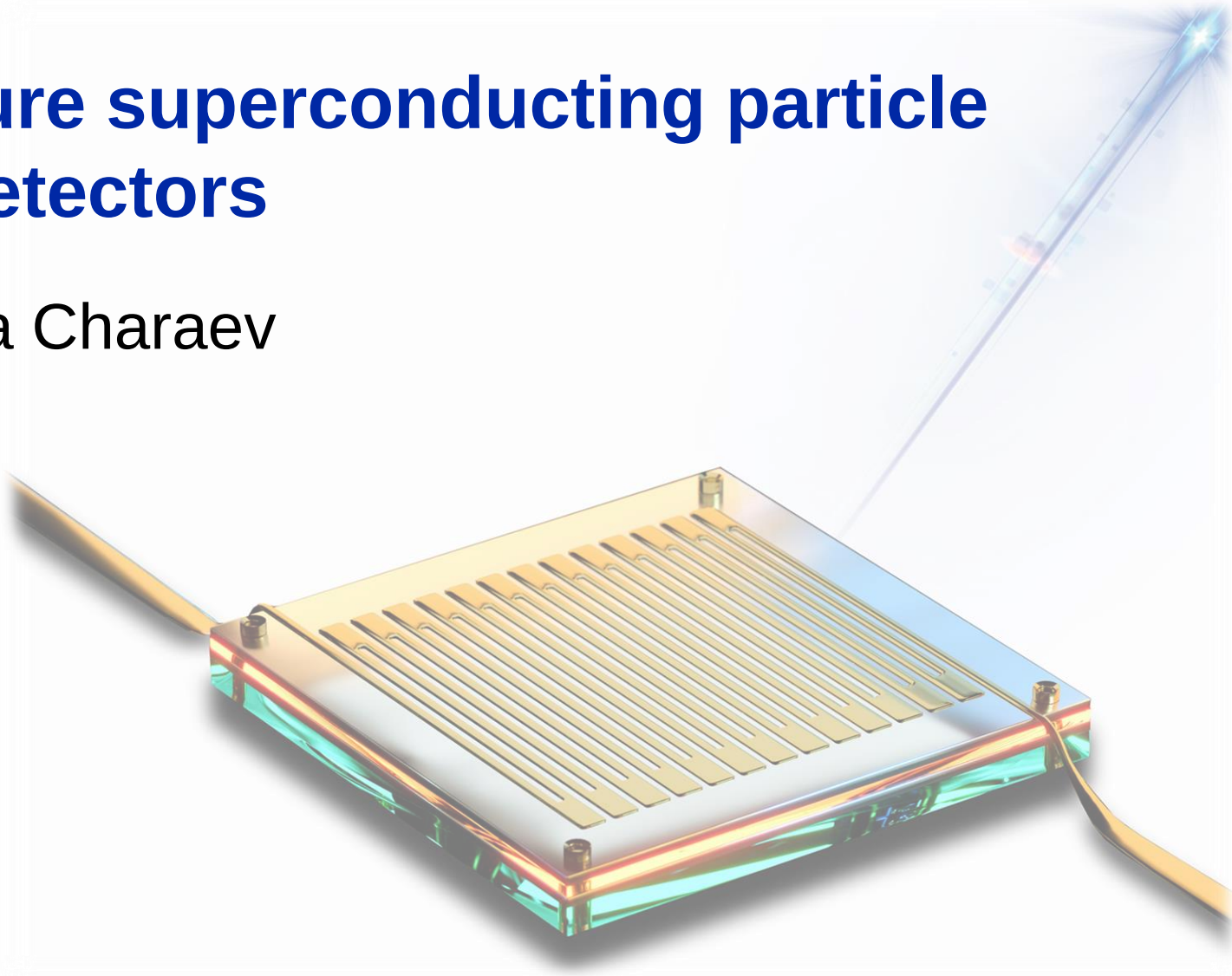

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First prototypes

SUPERCONDUCTING NUCLEAR PARTICLE DETECTOR

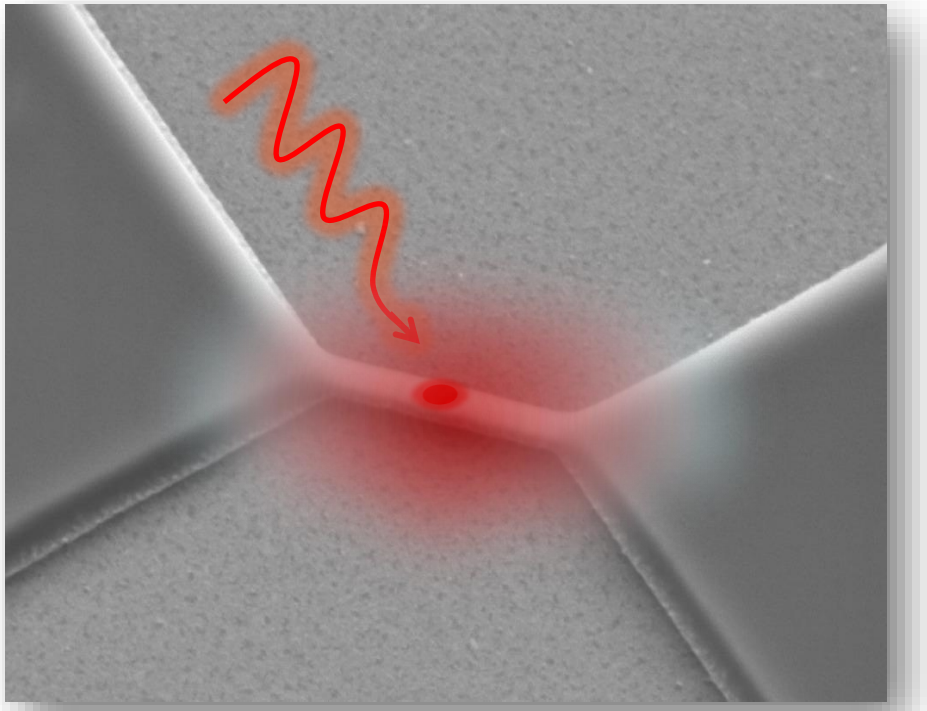
N. K. Sherman
Queen's University, Kingston, Ontario, Canada
(Received May 2, 1962)

Bolometric and nonbolometric infrared photoresponses in ultrathin superconducting NbN films

M. W. Johnson[a] and A. M. Herr
Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627
A. M. Kadin
Department of Electrical Engineering, University of Rochester, Rochester, New York 14627
(Received 16 August 1995; accepted for publication 22 January 1996)

Picosecond superconducting single-photon optical detector

G. N. Gol'tsman,[a] O. Okunev, G. Chulkova, A. Lipatov, A. Semenov, K. Smirnov, B. Voronov, and A. Dzardanov
Department of Physics, Moscow State Pedagogical University, Moscow 119435, Russia
C. Williams and Roman Sobolewski[b]
Department of Electrical and Computer Engineering and Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14627-0231
(Received 22 January 2001; accepted for publication 1 June 2001)



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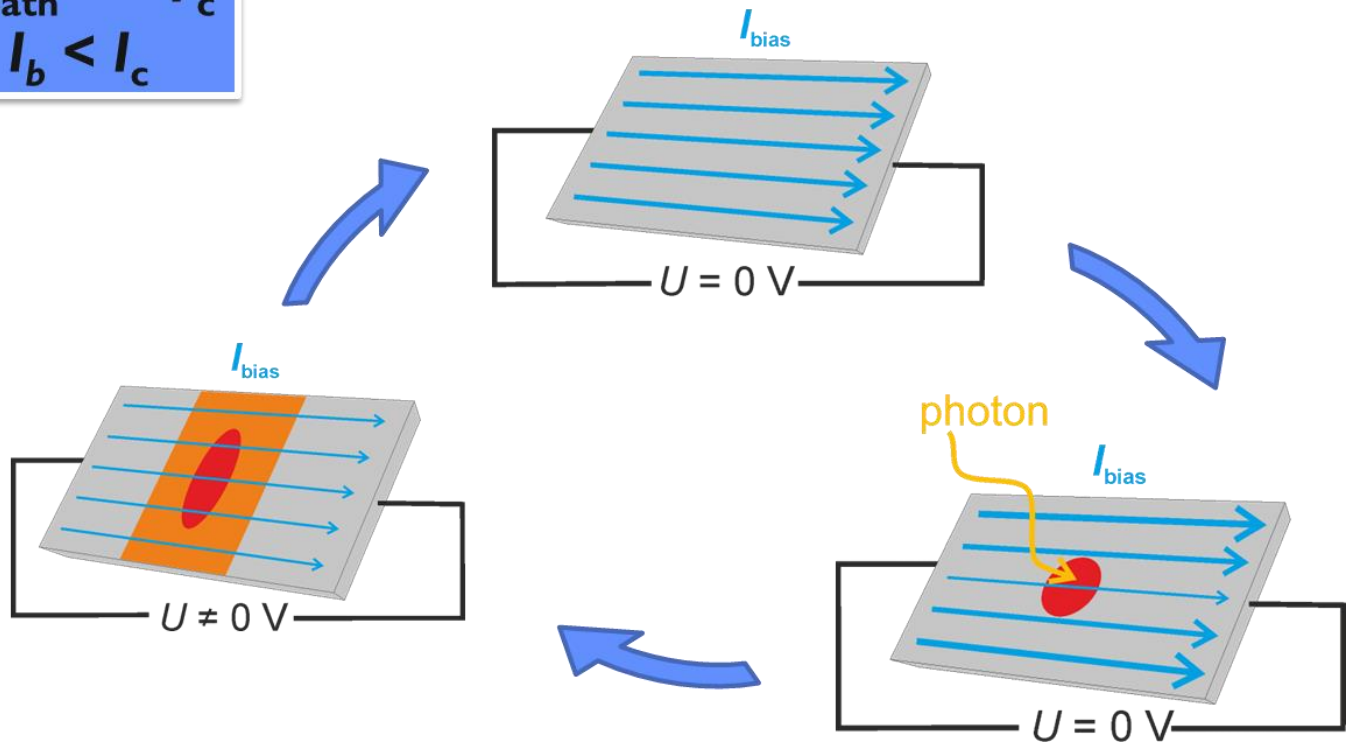
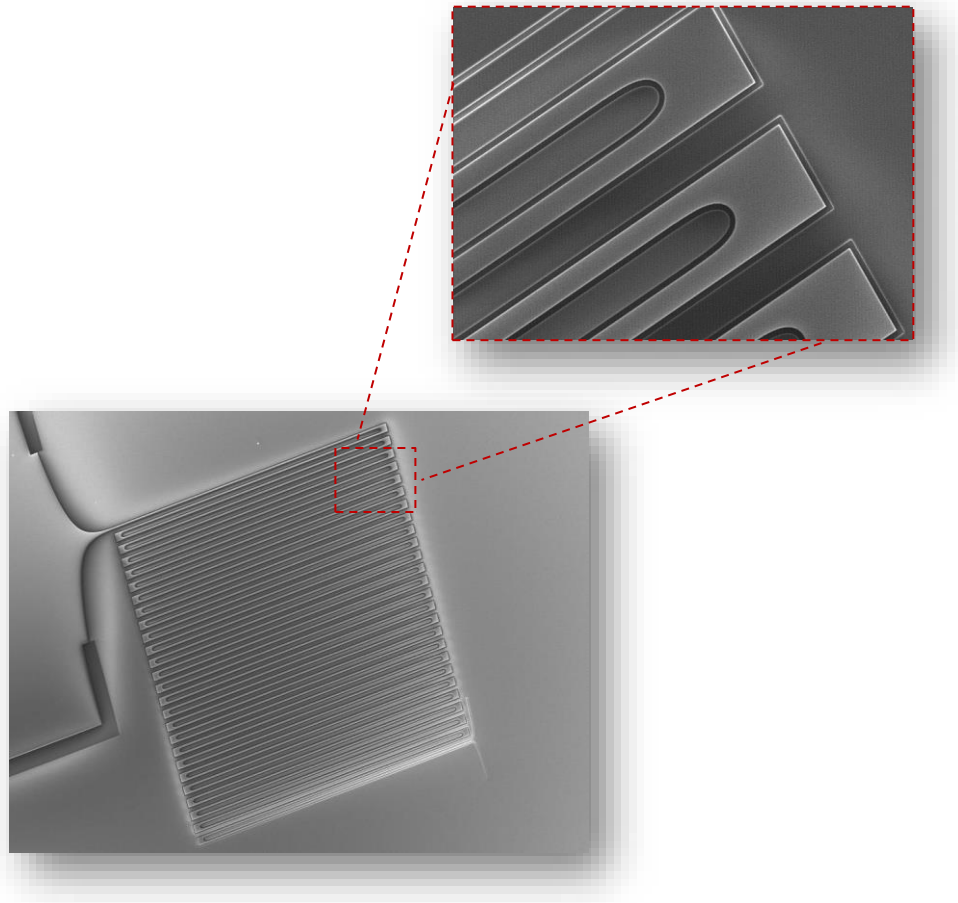
Superconducting Nanowire Single-Photon Detector (SNSPD)

$T_{bath} << T_c$

$I_b < I_c$





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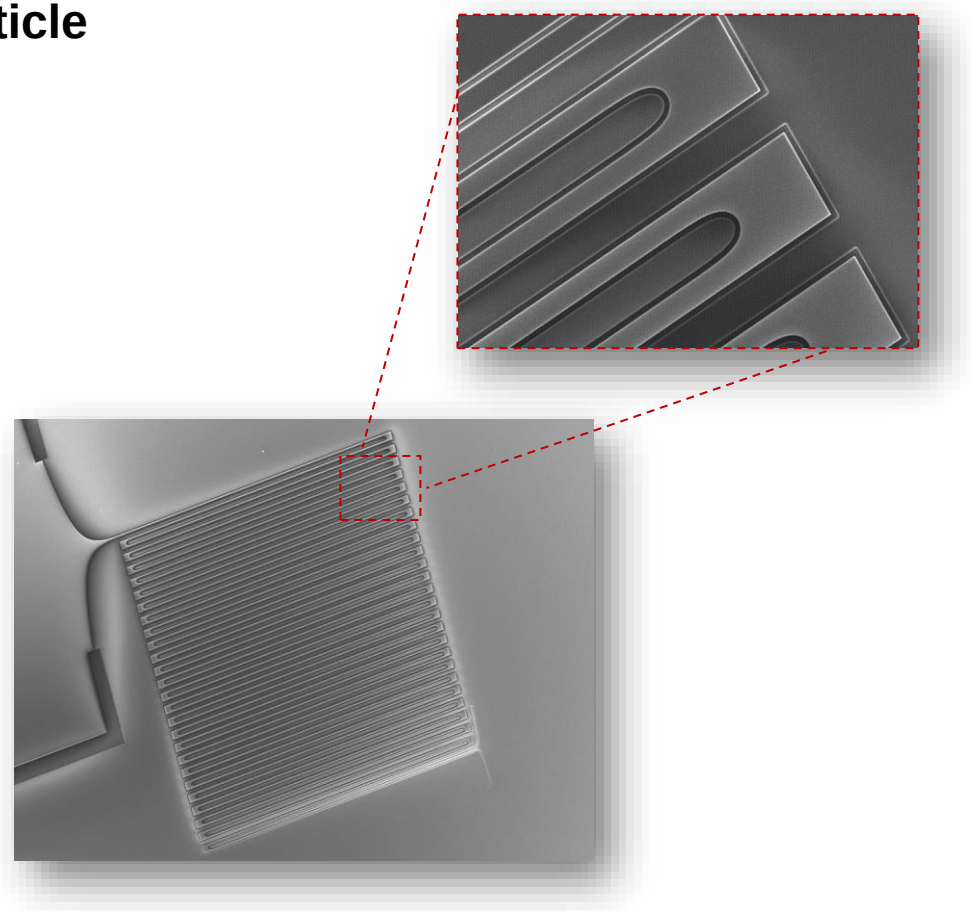
Superconducting Nanowire Single-Photon Detector (SNSPD)

Initially developed for photon counting, but can be used for **direct particle detection** or **coupled to scintillators**

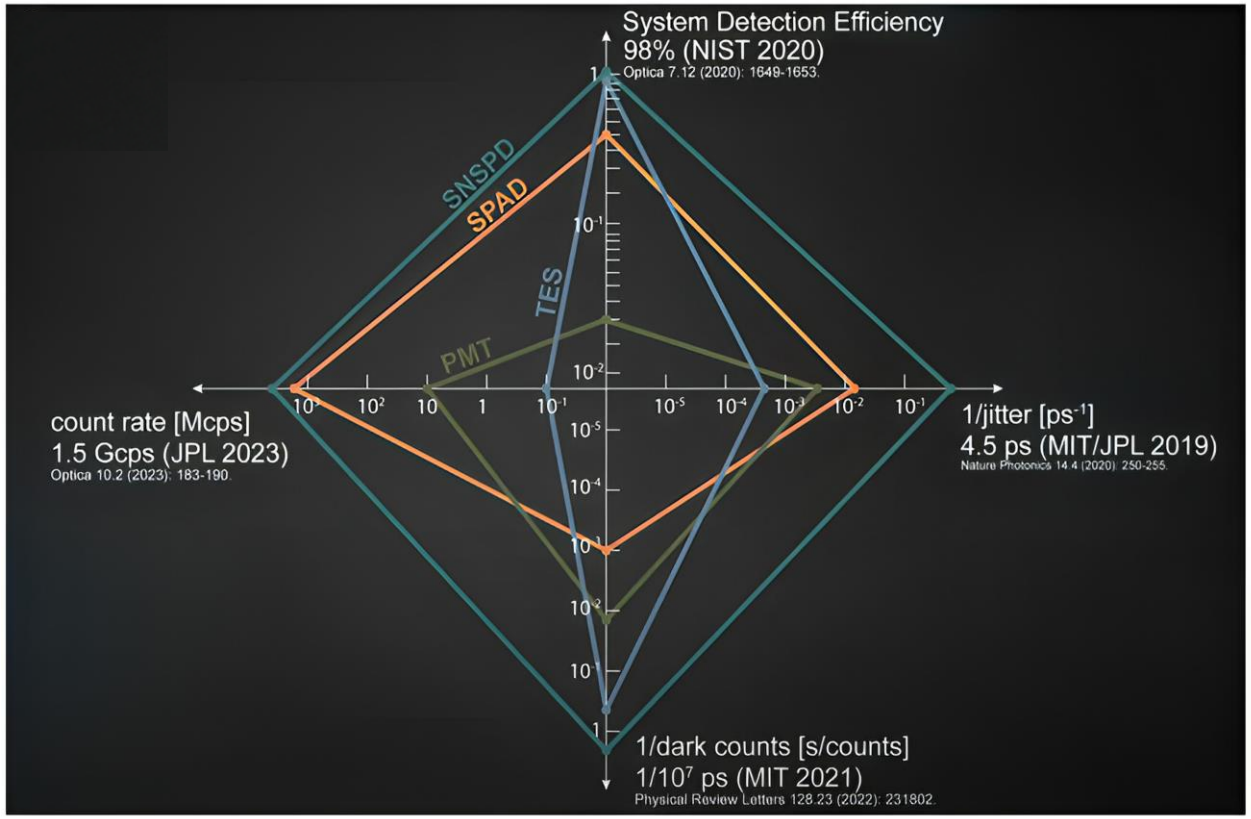


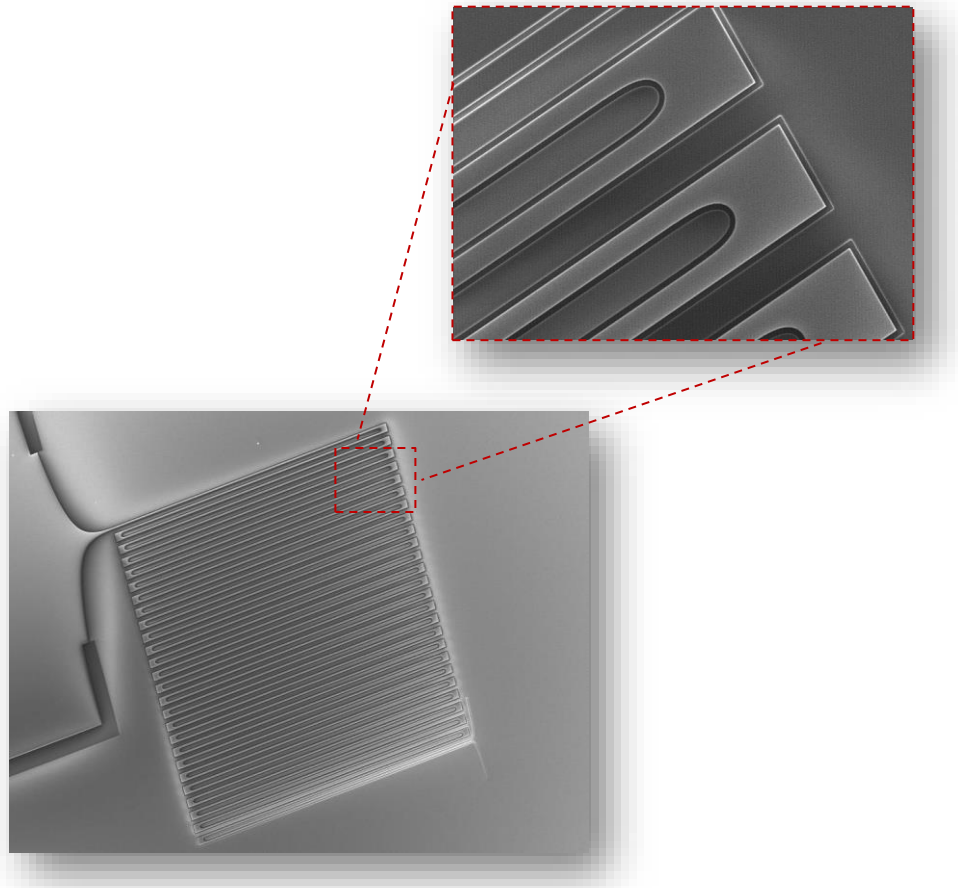
Characteristics:

- High detection efficiency : **98%**
- Broad response range: from **0.043 eV** to **120 GeV**[1]
- Ultra short timing jitter: **< 3 ps**[2]
- Low noise characteristic: **< 10^{-5} cps**
- Sub-ns reset time: **~100 ps**[3]
- Camera with **400,000-pixels**[4]
- **WSi, NbN, MgB_2**[5]**, BSCCO**[6]**, …**

[1] *2312.13405 [physics.ins-det] (2023)*
[2] *Nat. Photonics 14, 250–255 (2020)*
[3] *Supercond. Sci. Technol. 34, 044001 (2021)*
[4] *Nature 622 (7984), 730-734 (2023)*
[5] *Nat Commun 15, 3973 (2024)*
[6] *Nat. Nanotechnol. 18, 343–349 (2023)*

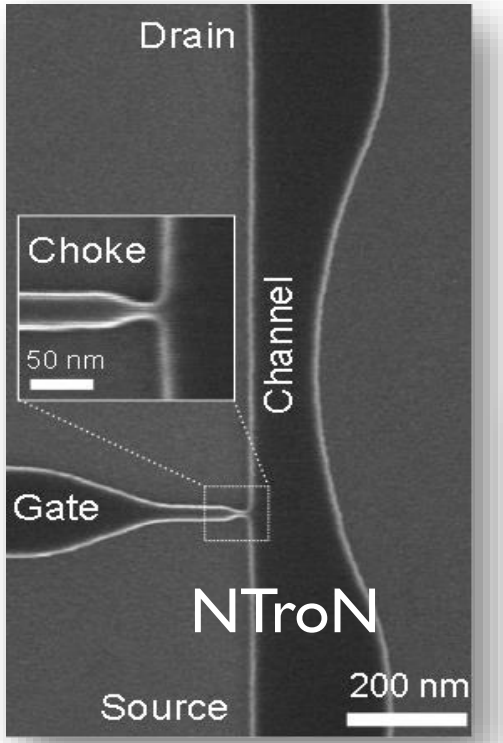
State-of-the-Art

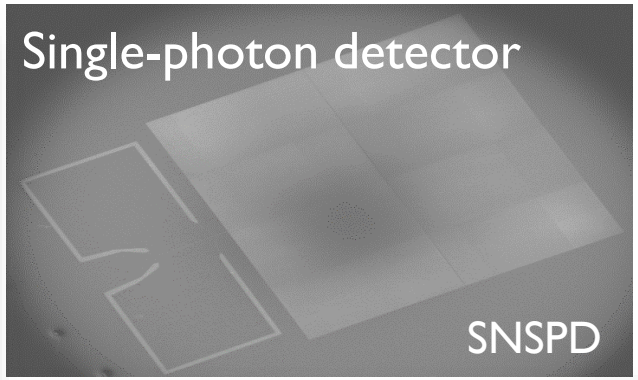


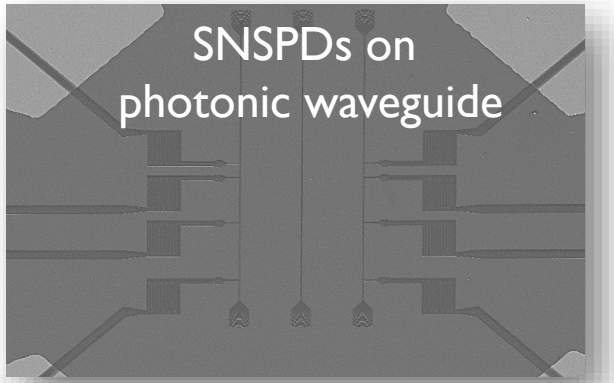


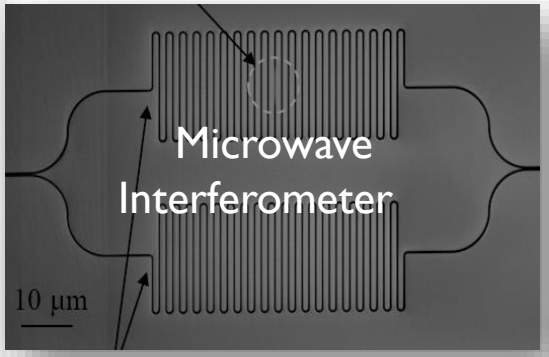
M. Colangelo, 'Superconducting Nanowire Technology for Microwave and Photonics Applications', *Ph.D. thesis, Massachusetts Institute of Technology, 2023*

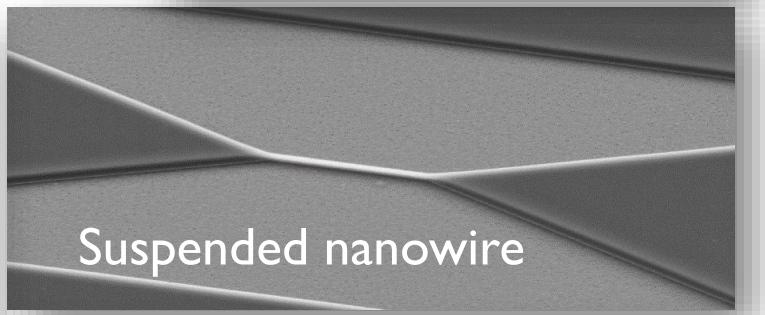
Superconducting nanowire architecture

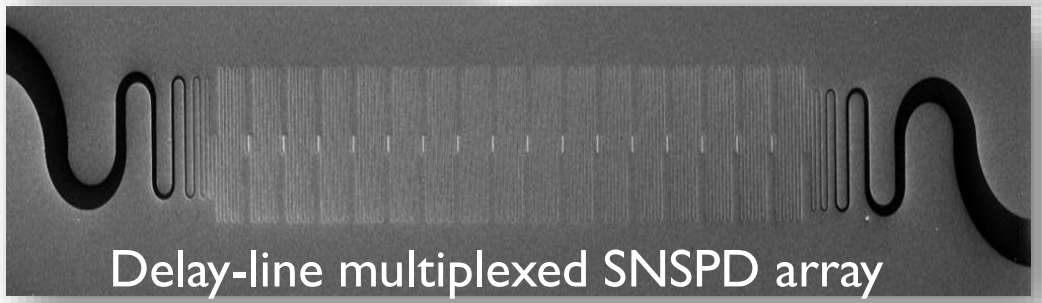


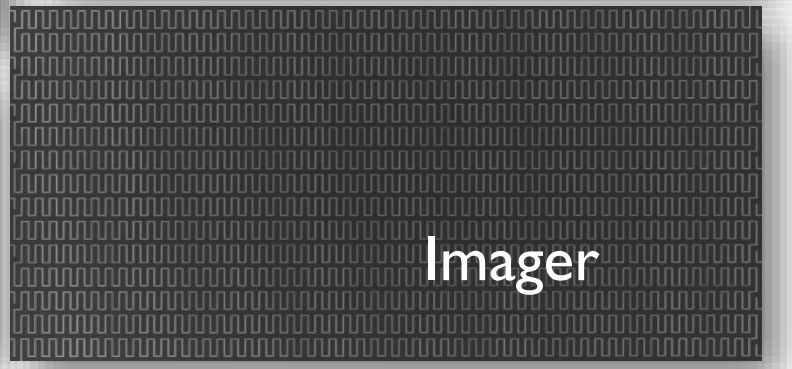












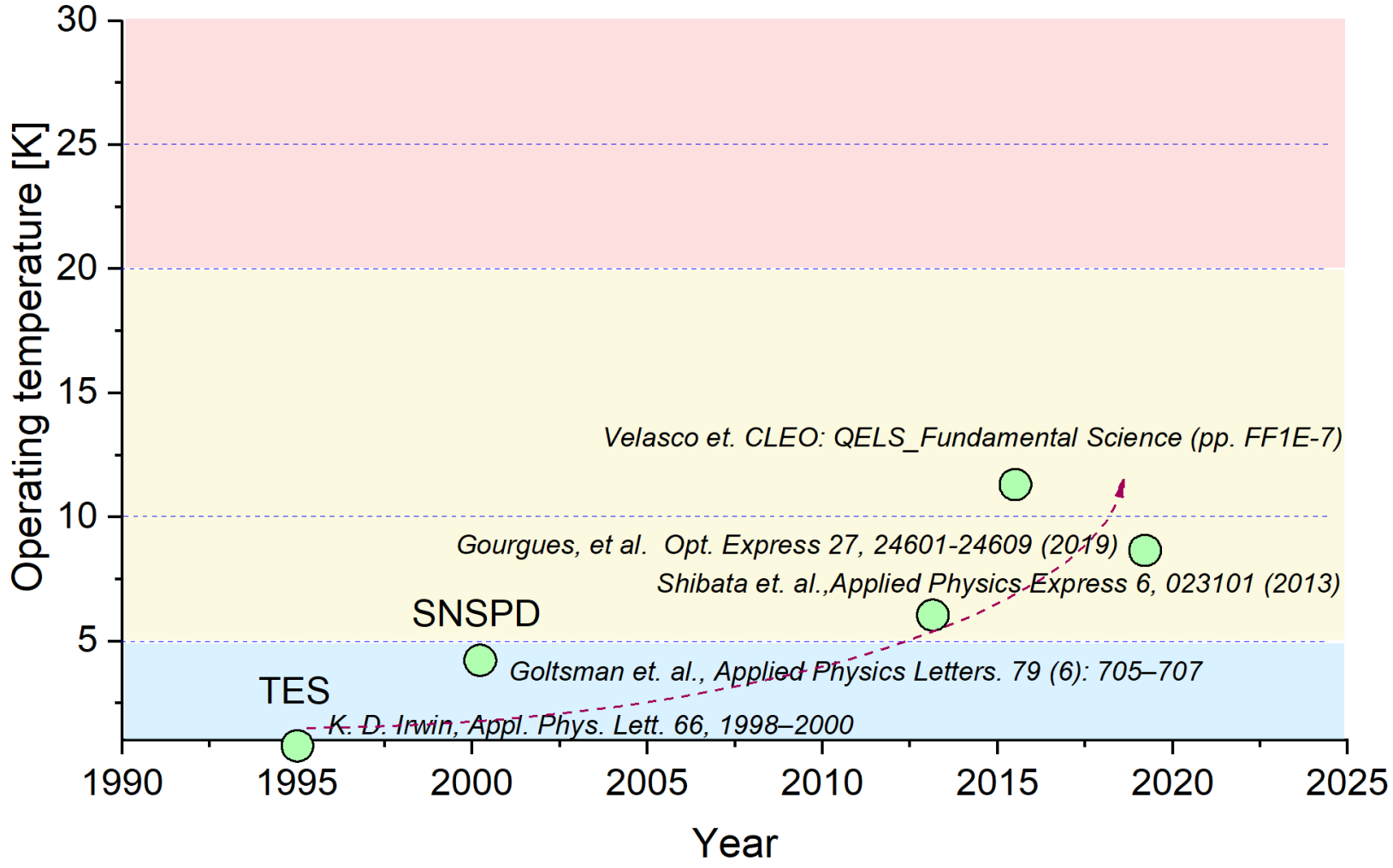
Superconducting Nanowire Single-Photon Detector (SNSPD)

Superconducting Nanowire Single-Photon Detector (SNSPD)

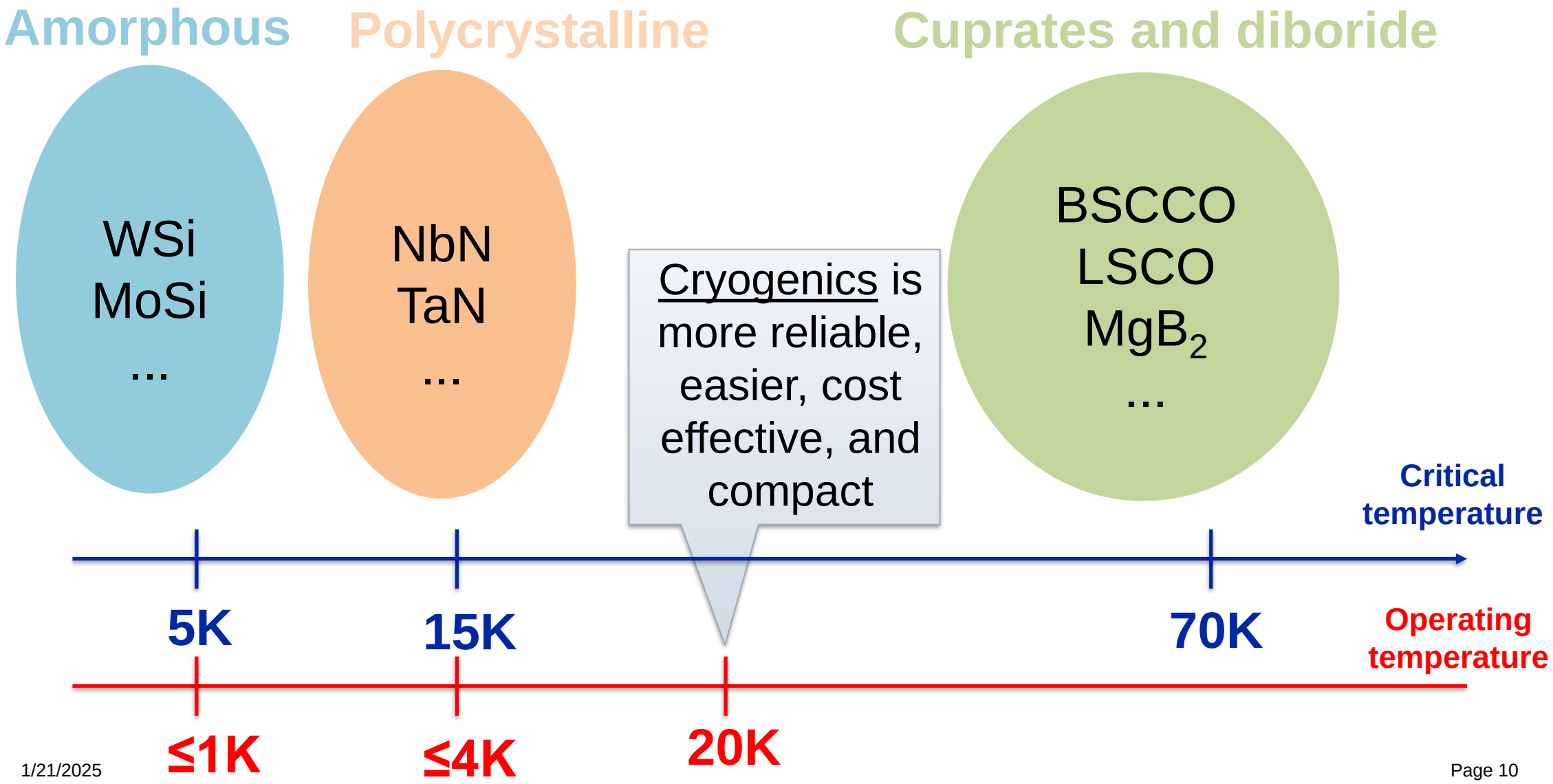
Problem: SNSPD are based on NbN orNbTiN thin films with low critical temperature and require operation below liquid helium *T*.

Last two decades: search for alternatives.

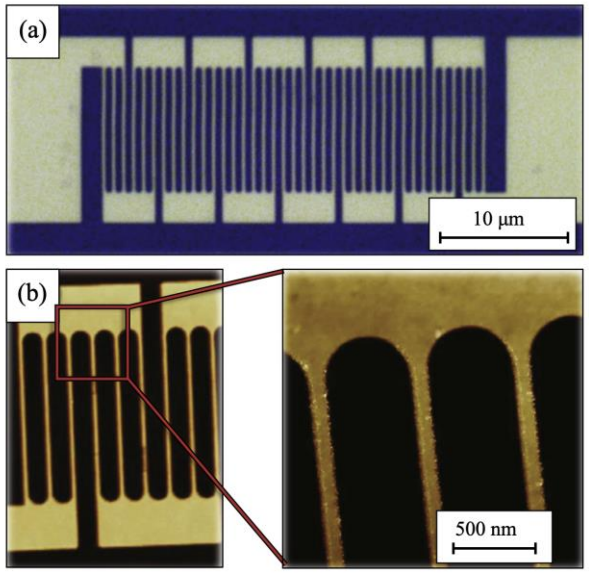
Operating temperature



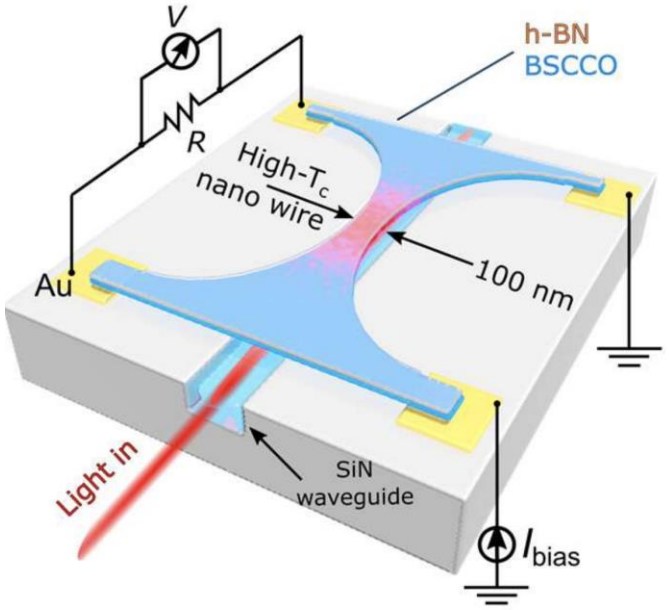
Materials for SNSPDs



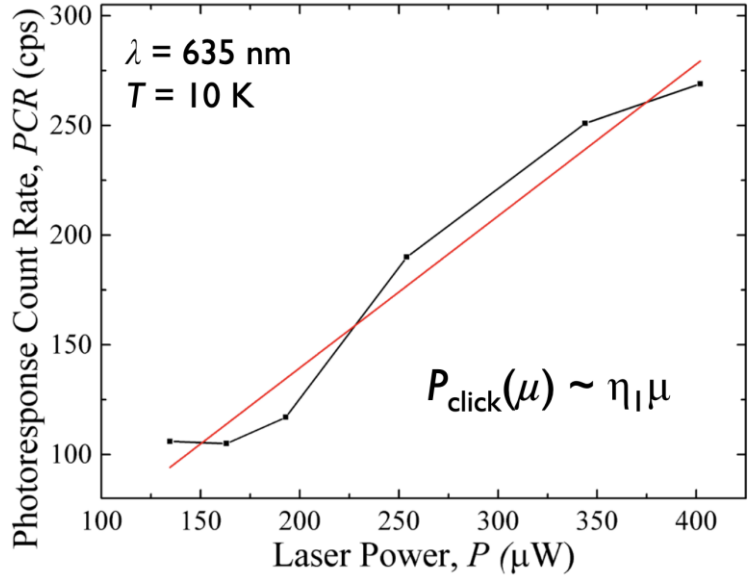
Natural solution: use high-*Tc* superconductors, but…



YBCO: Physica C 509 (2015)



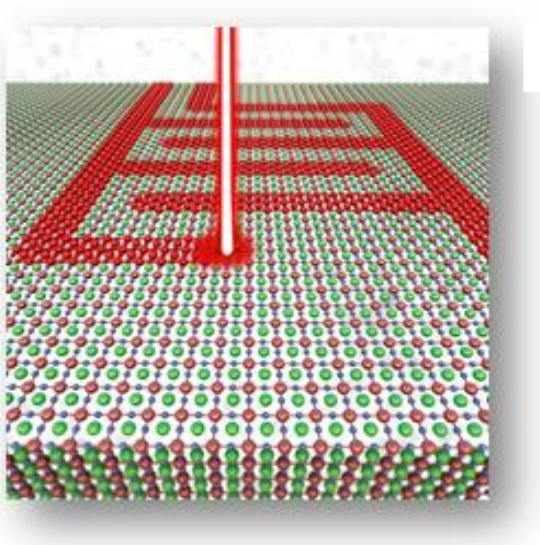
BSCCO: Seifert 2D Materials (2021)



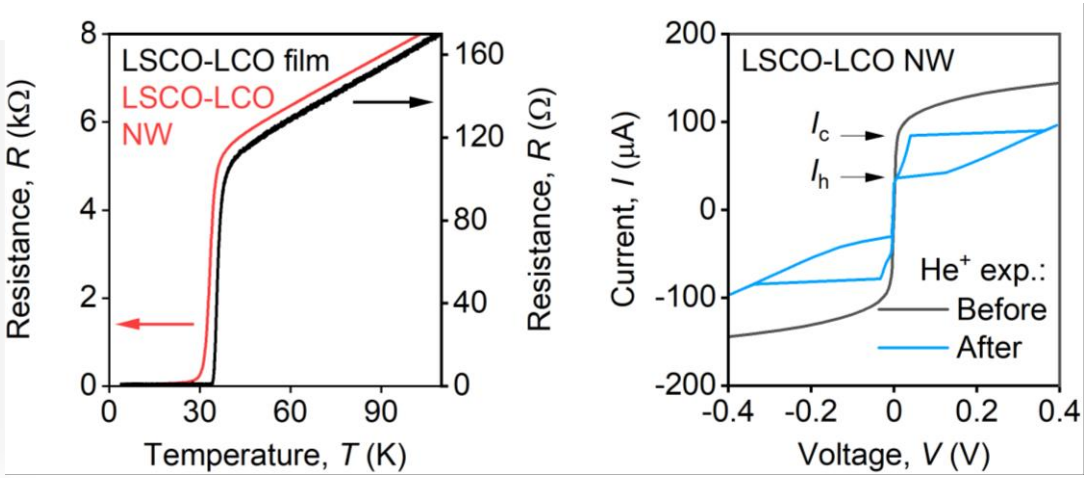
MgB_2: Velasco CLEO: QELS Fundamental Science (2016)

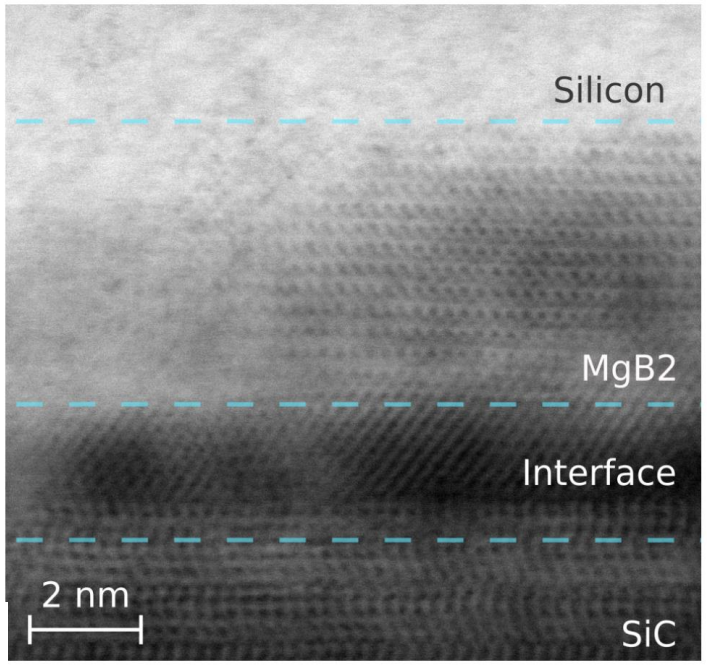
Challenge: how to fabricate nanowires out of high-T_c superconductors if they don't like nanofab?

Single-photon detection using high-*Tc* superconducting detectors

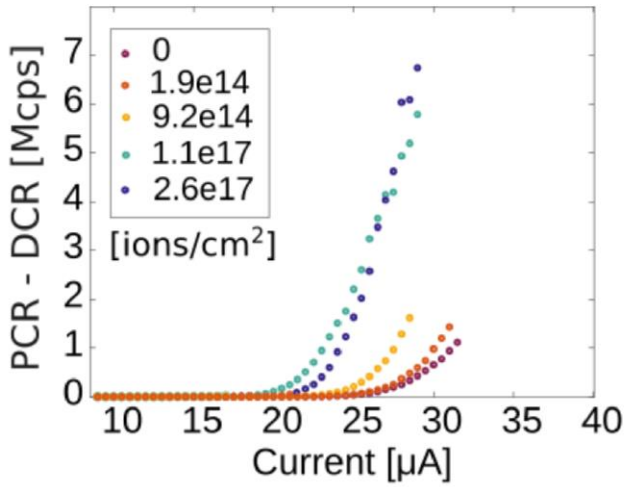


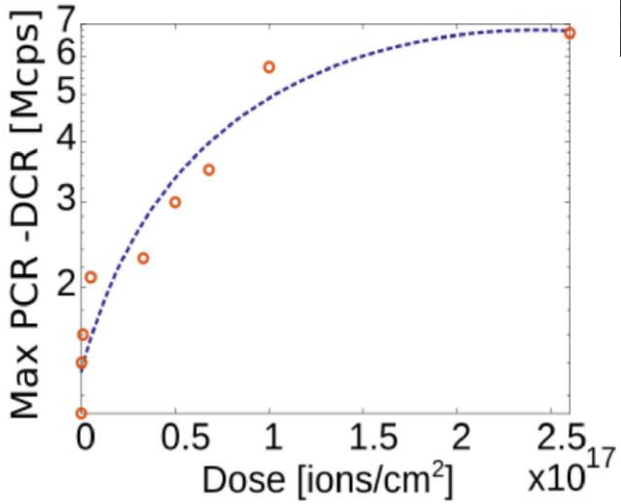
Local patterning without material etching





Post exposure with He ions



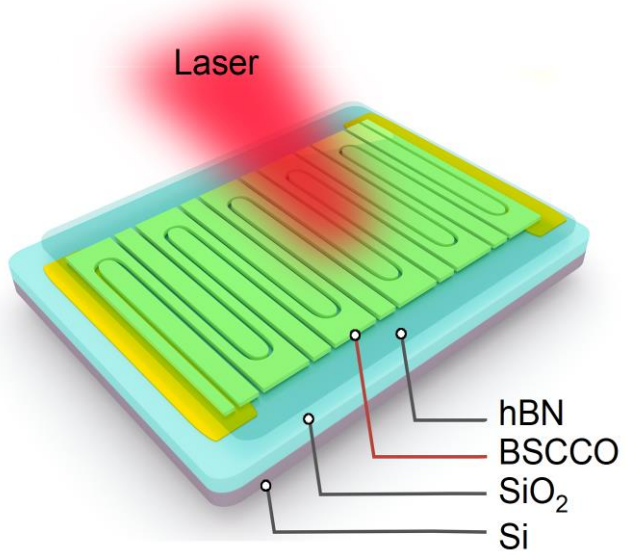


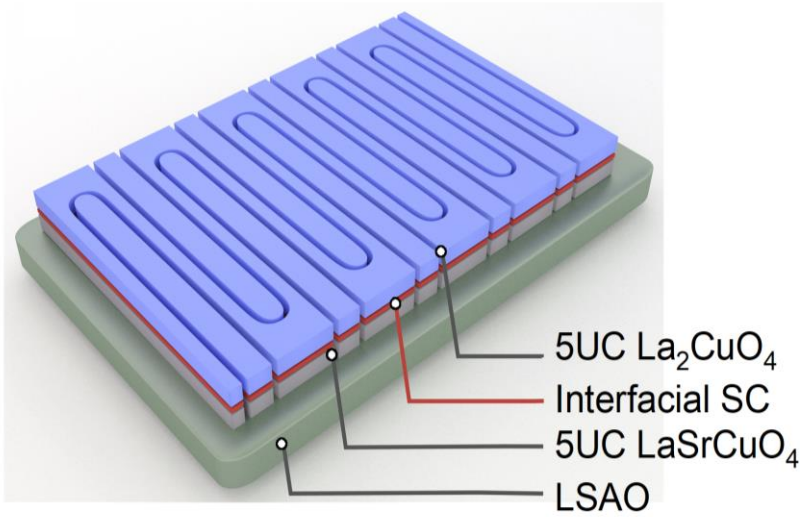
Single-photon detection using high-*Tc* superconducting detectors

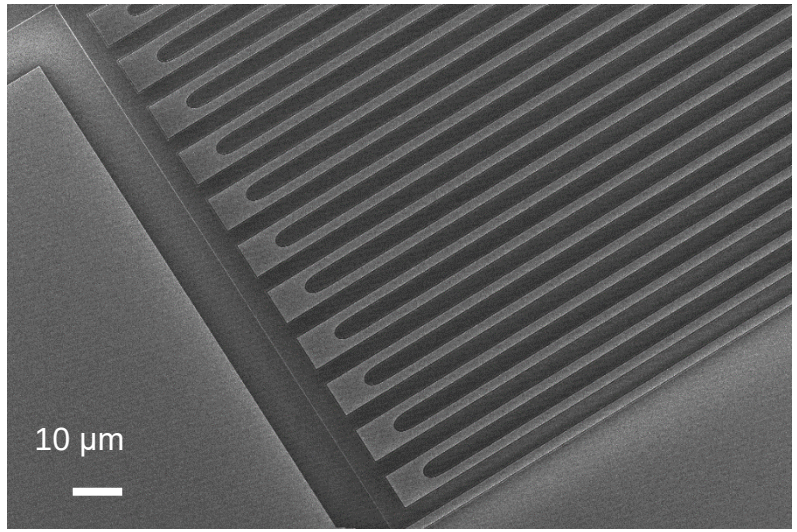
2D exfoliated $Bi_2Sr_2CaCu_2O_{8+\delta}$ flakes

Large-area MgB_2 microwire detectors

MBE grown $La_{1.55}Sr_{0.45}CuO_4$ /La_2CuO_4 sensors



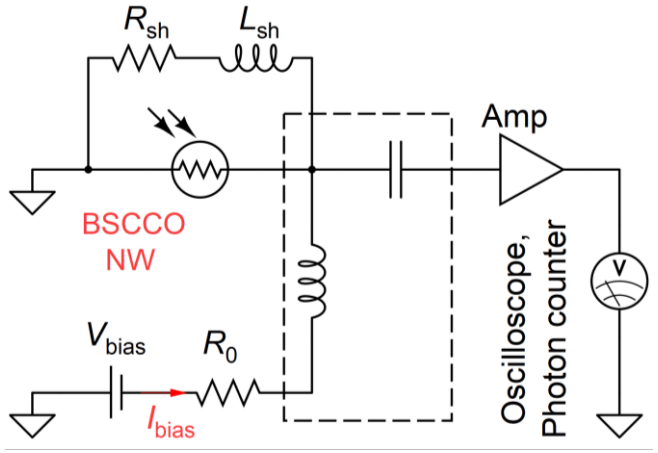


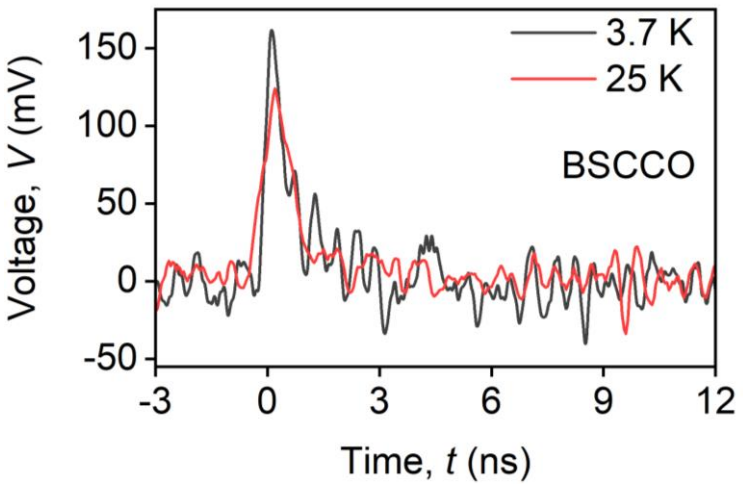


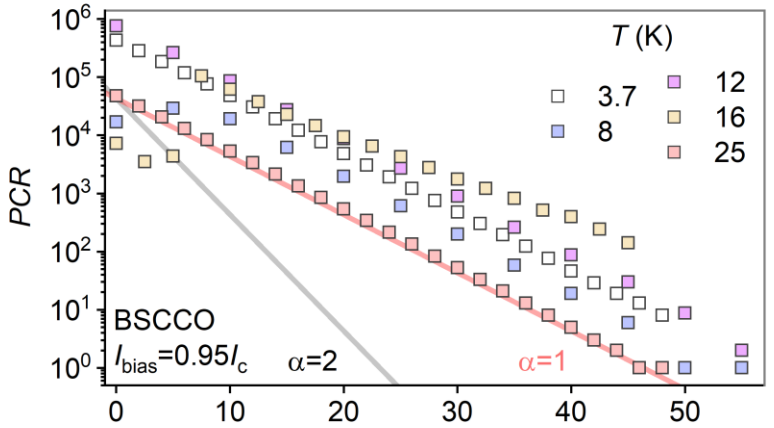
Charaev I, Bandurin DA, Bollinger AT, et al. *Nat Nanotechnol*. 2023;18(4)

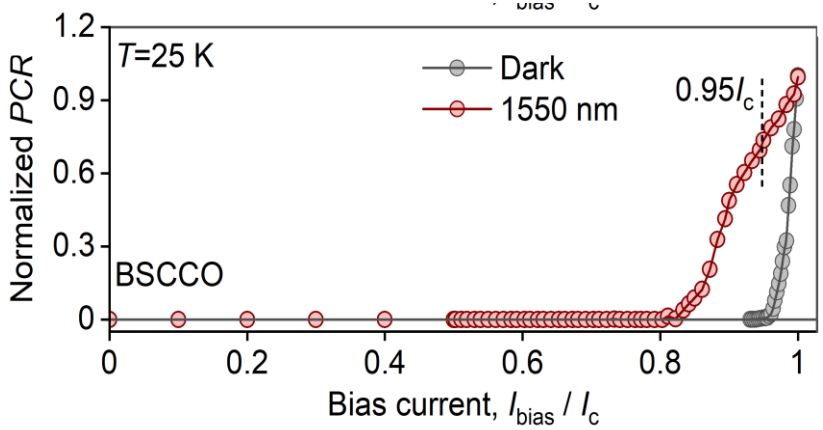
Charaev I, Batson EK, Cherednichenko S, et al. *Nat Commun*. 2024;15(1)

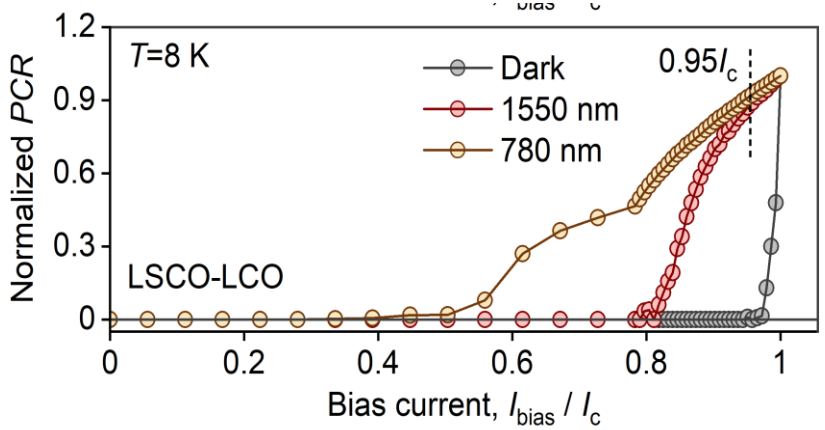
Experimental results

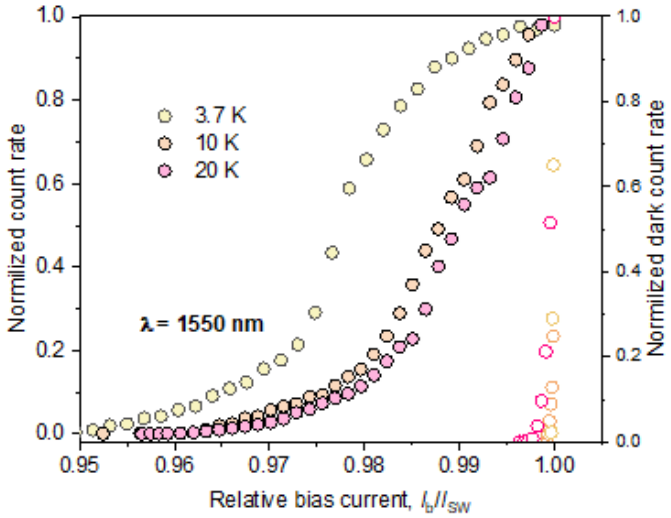












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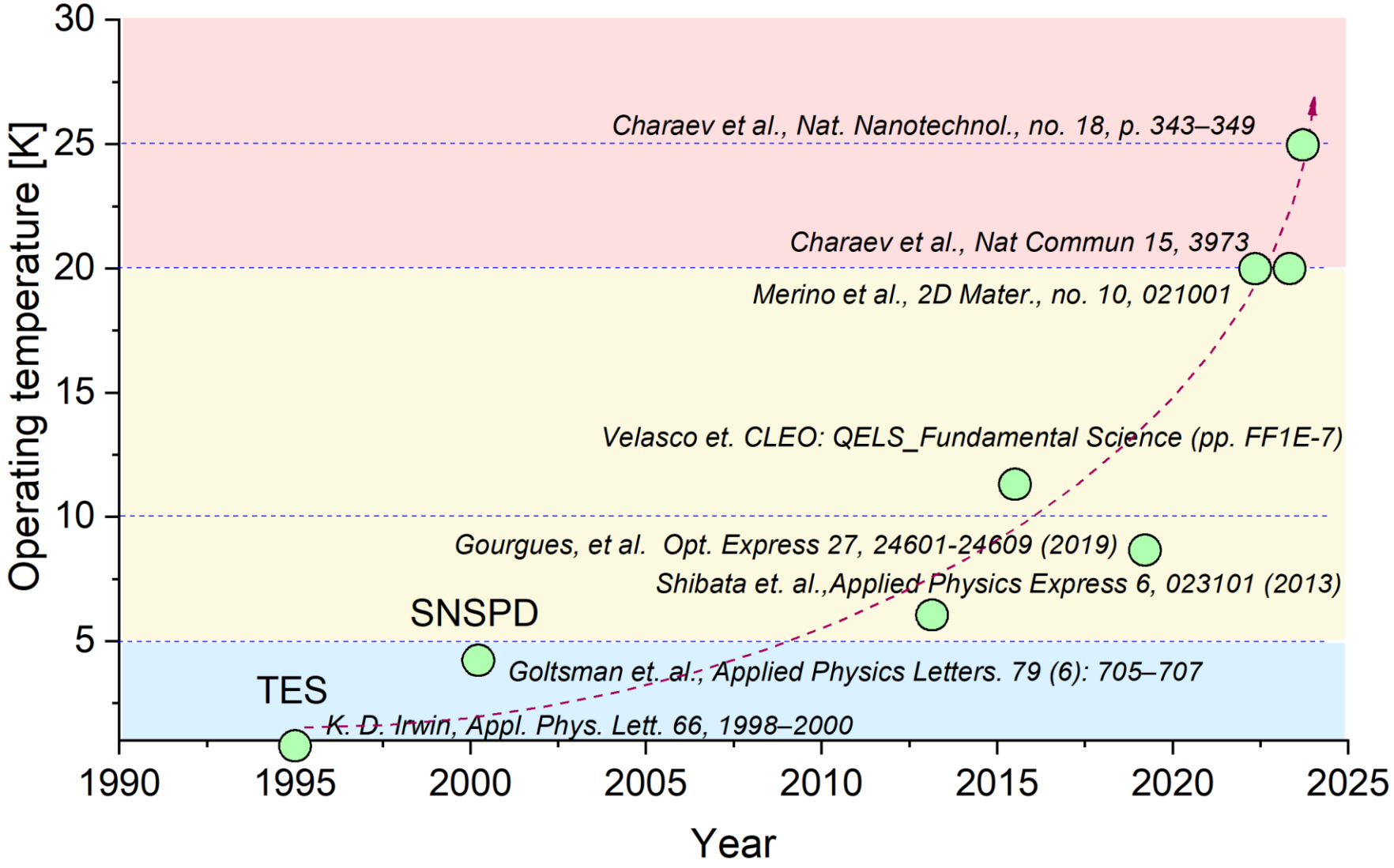
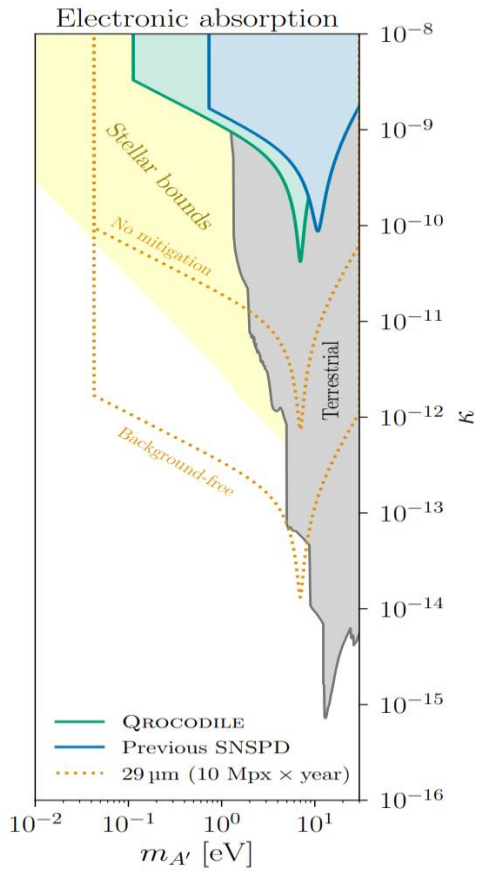
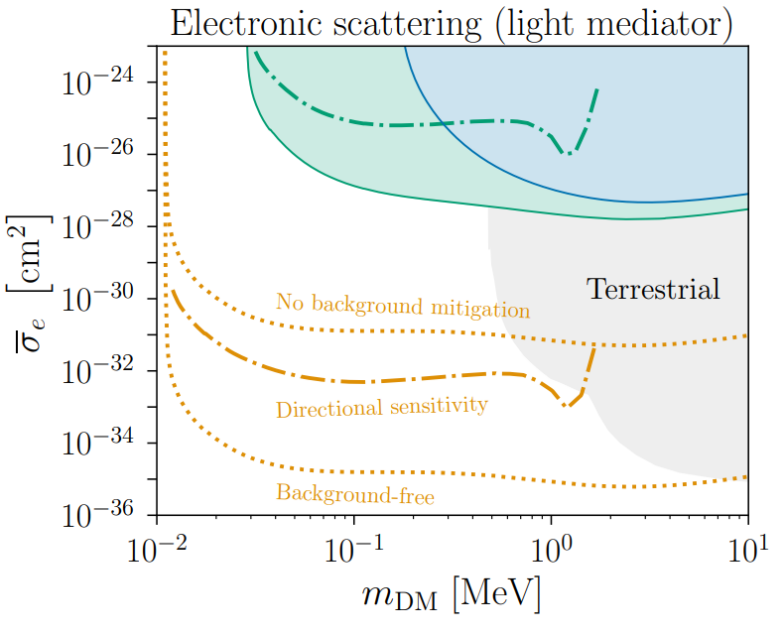
Operating temperature of SNSPDs



SNSPDs for high-energy and astro-particles applications

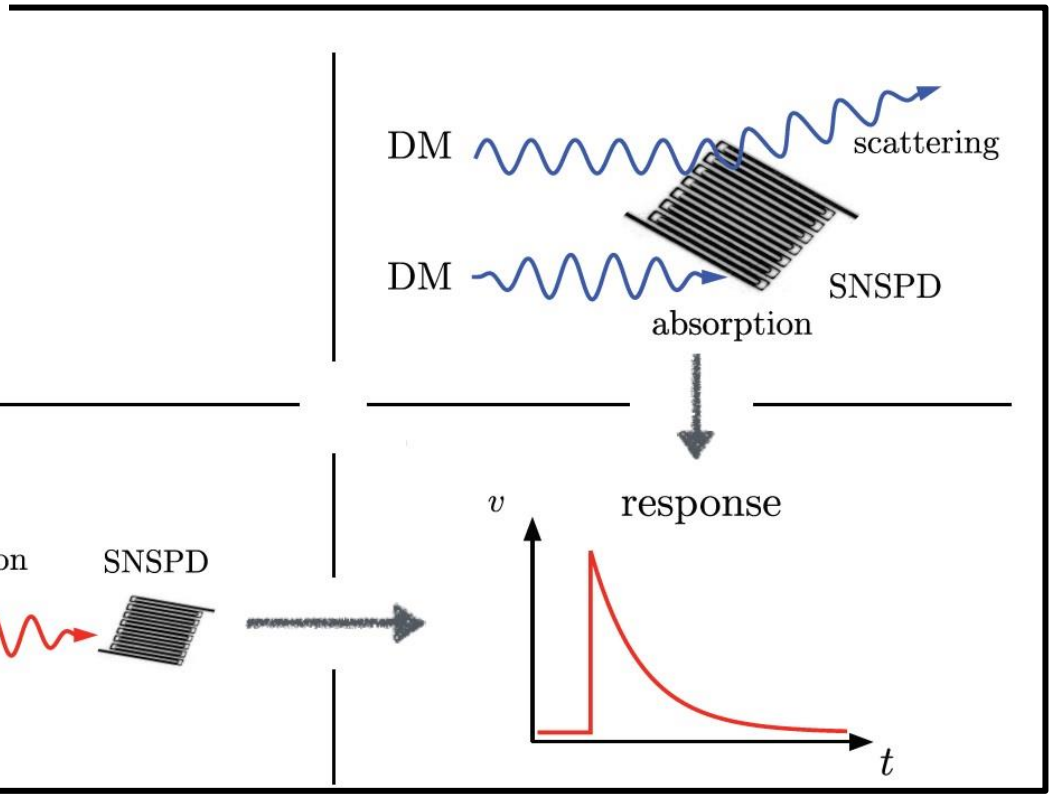
Dark matter searching via SNSPDs





Mass ranging 0.1 meV – 10 eV

Y. Hochberg, I. Charaev, S. W. Nam, V. Verma, M. Colangelo and K. K. Berggren, "Detecting Dark Matter with Superconducting Nanowires," , ***Phys. Rev. Lett. 123, 151802, 2019***



J. Chiles, I. Charaev*, R. Lasenby, M. Baryakhtar, J. Huang, A. Roshko, G. Burton, M. Colangelo, K. Van Tilburg, A. Arvanitaki, S.- W. Nam, and K. K. Berggren,* ***Phys. Rev. Lett. 128, 231802, 2022***

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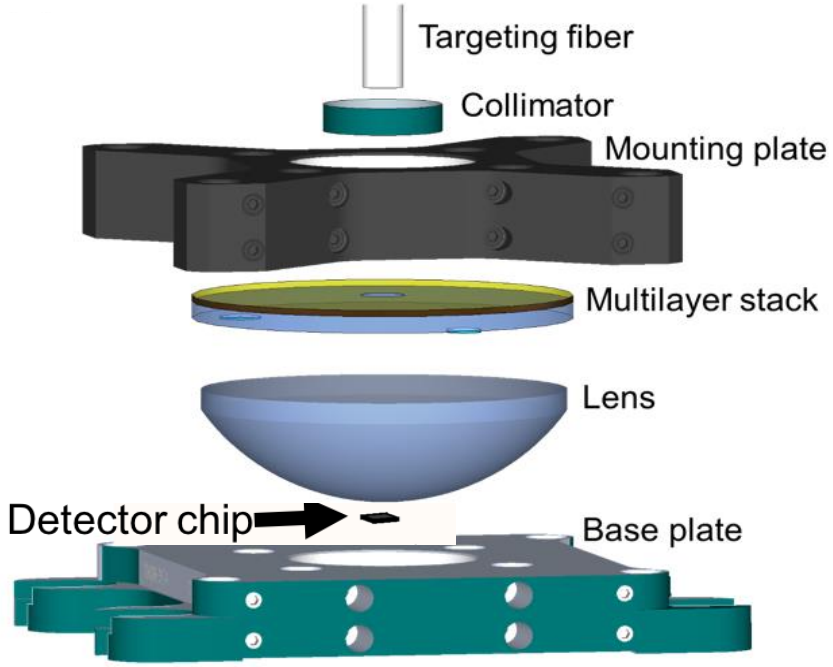
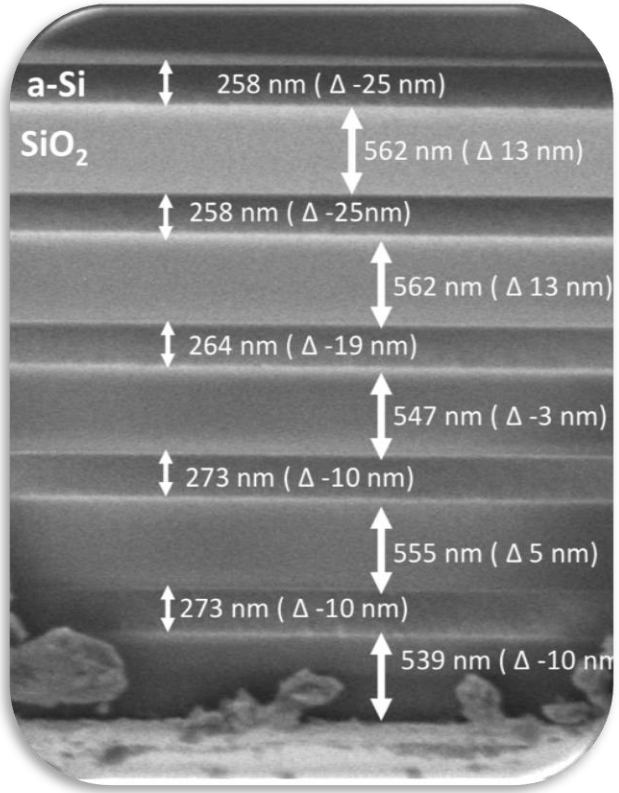
Target and SNSPDs



Exploded

Assembled



- 5 pairs of amorphous silicon / silicon dioxide (n = 2.74/1.45)

J. Chiles, I. Charaev*, R. Lasenby, M. Baryakhtar, J. Huang, A. Roshko, G. Burton, M. Colangelo, K. Van Tilburg, A. Arvanitaki, S.- W. Nam, and K. K. Berggren,* ***Phys. Rev. Lett. 128, 231802, 2022***

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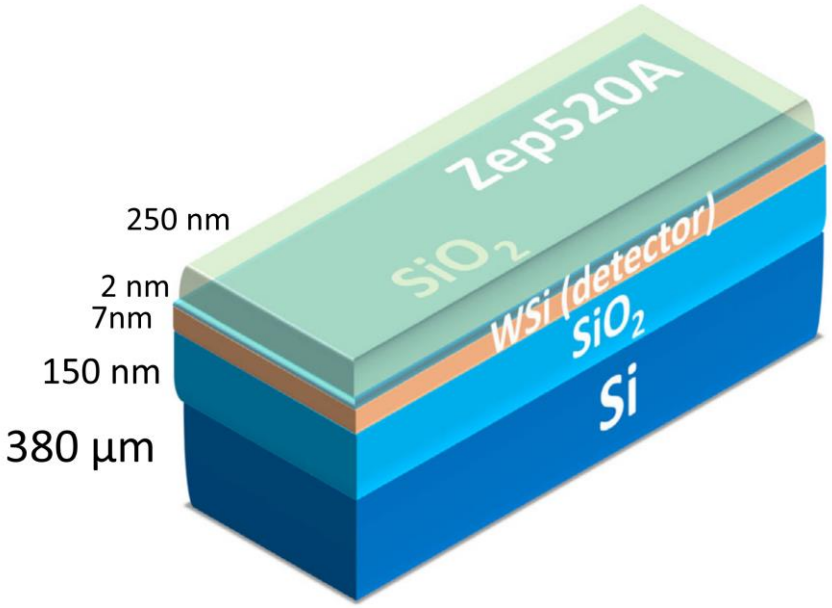
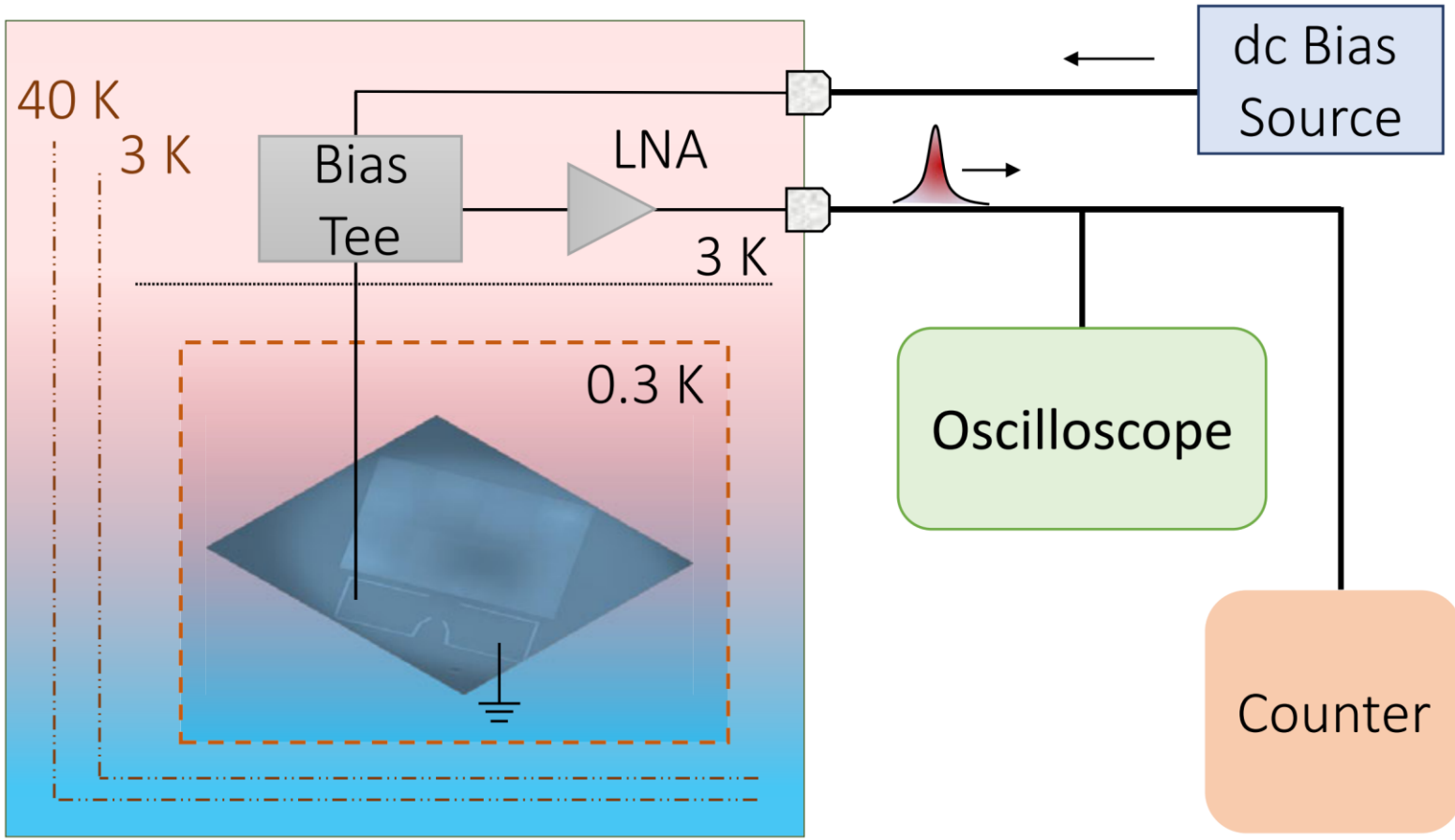
SNSPDs as both target and sensor





Y. Hochberg, I. Charaev, S. W. Nam, V. Verma, M. Colangelo and K. K. Berggren, "Detecting Dark Matter with Superconducting Nanowires," ,
Phys. Rev. Lett. 123, 151802, 2019

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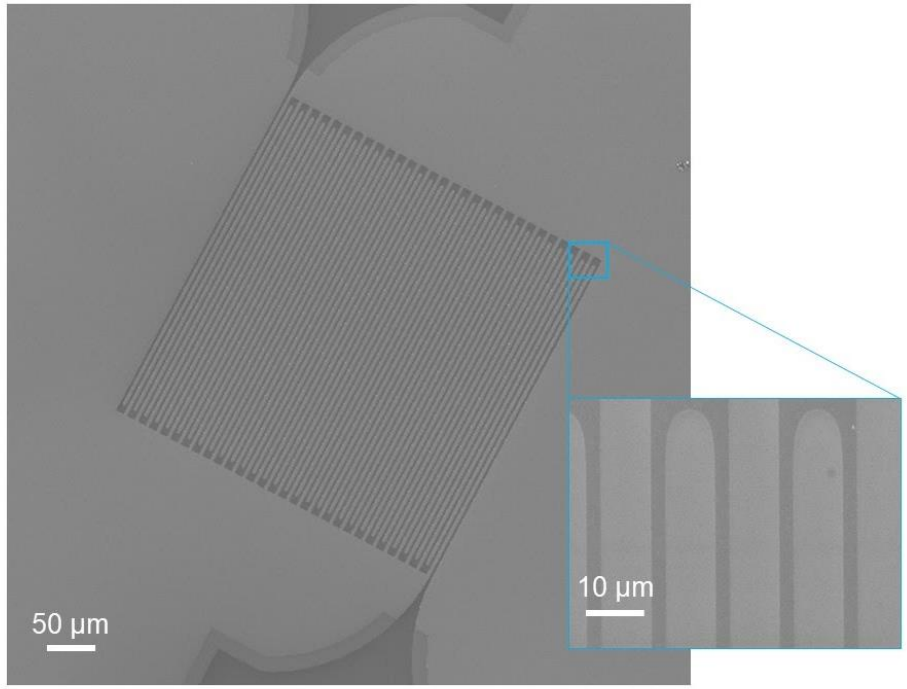
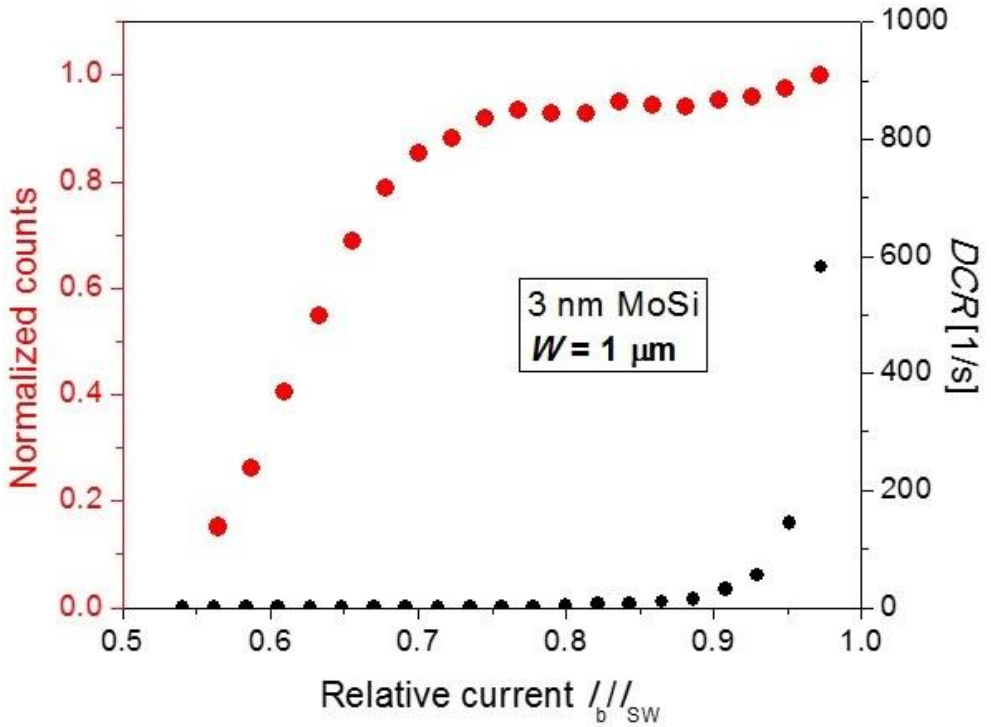
Towards mm scale SNSPDs





I. Charaev and et al, Appl. Phys. Lett. 116, 242603 (2020)

Similar results on WSi:

J. Chiles and et al, Appl. Phys. Lett. 116, 242602 (2020)

University of Zurich[UZH]

Dark matter searching via SNSPDs

A New Bite Into Dark Matter with the SNSPD-Based QROCODILE Experiment

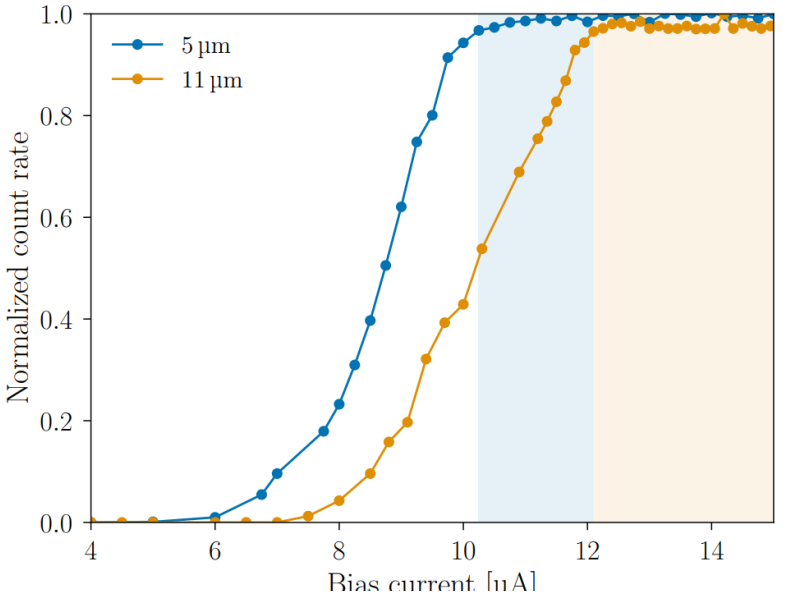
Laura Baudis,[1] Alexander Bismark,[1] Noah Brugger,[1] Chiara Capelli,[1] Ilya Charaev,[1] Jose Cuenca García,[1] Guy Daniel Hadas,[2] Yonit Hochberg,[2,3] Judith K. Hohmann,[4] Alexander Kavner,[1] Christian Koos,[4] Artem Kuzmin,[4] Benjamin V. Lehmann,[5] Severin Nägeli,[1] Titus Neupert,[1] Bjoern Penning,[1] Diego Ramírez García,[1] and Andreas Schilling[1]

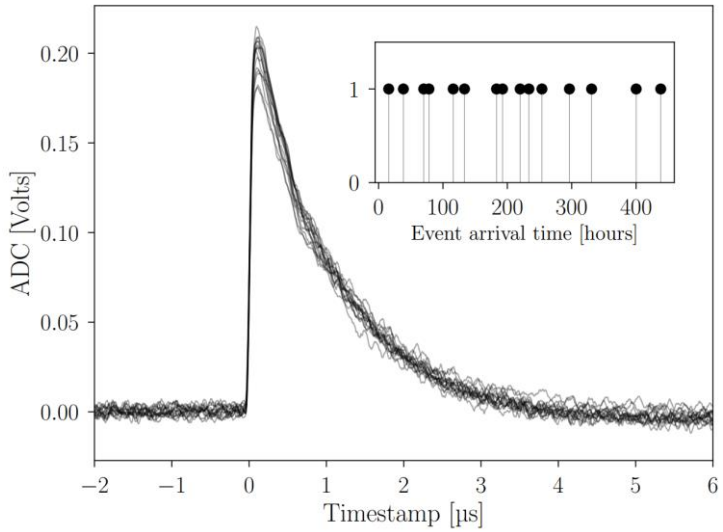
[1] *Department of Physics, University of Zürich, Winterthurerstrasse 190, CH-8057 Zürich, Switzerland*
[2] *Racah Institute of Physics, Hebrew University of Jerusalem, Jerusalem 91904, Israel*
[3] *Laboratory for Elementary Particle Physics, Cornell University, Ithaca, NY 14853, USA*
[4] *Karlsruhe Institute of Technology, Engesserstrasse 5, 76131 Karlsruhe, Germany*
[5] *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*

(Dated: December 24, 2024)

We present the first results from the *Quantum Resolution-Optimized Cryogenic Observatory for Dark matter Incident at Low Energy* (QROCODILE). The QROCODILE experiment uses a microwire-based superconducting nanowire single-photon detector (SNSPD) as a target and sensor for dark matter scattering and absorption, and is sensitive to energy deposits as low as 0.11 eV. We introduce the experimental configuration and report new world-leading constraints on the interactions of sub-MeV dark matter particles with masses as low as 30 keV. The thin-layer geometry of the system provides anisotropy in the interaction rate, enabling directional sensitivity. In addition, we leverage the coupling between phonons and quasiparticles in the detector to simultaneously constrain interactions with both electrons and nucleons. We discuss the potential for improvements to both the energy threshold and effective volume of the experiment in the coming years.

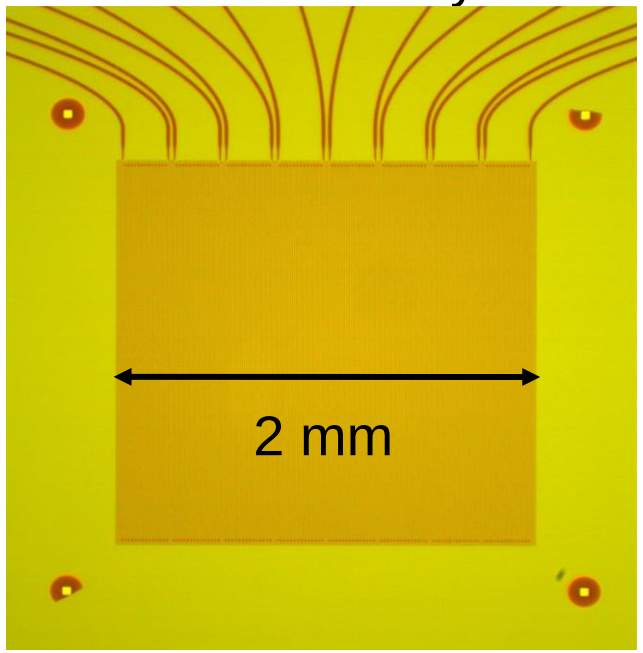
arXiv:2412.16279v1 [hep-ph] 20 Dec 2024



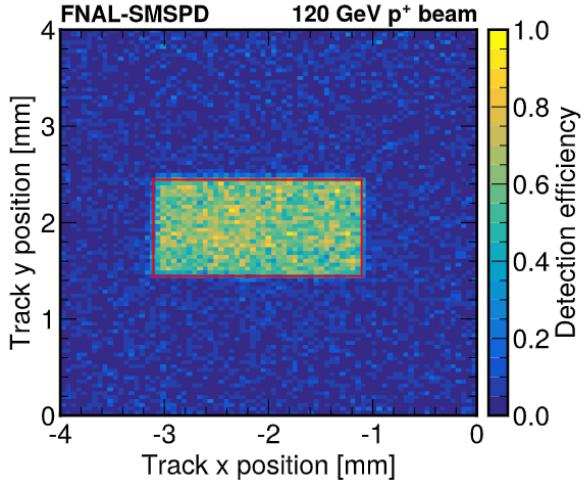


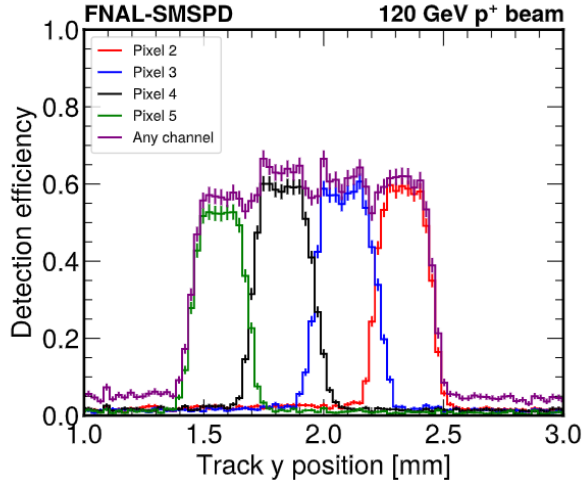
Particle detection with SNSPDs

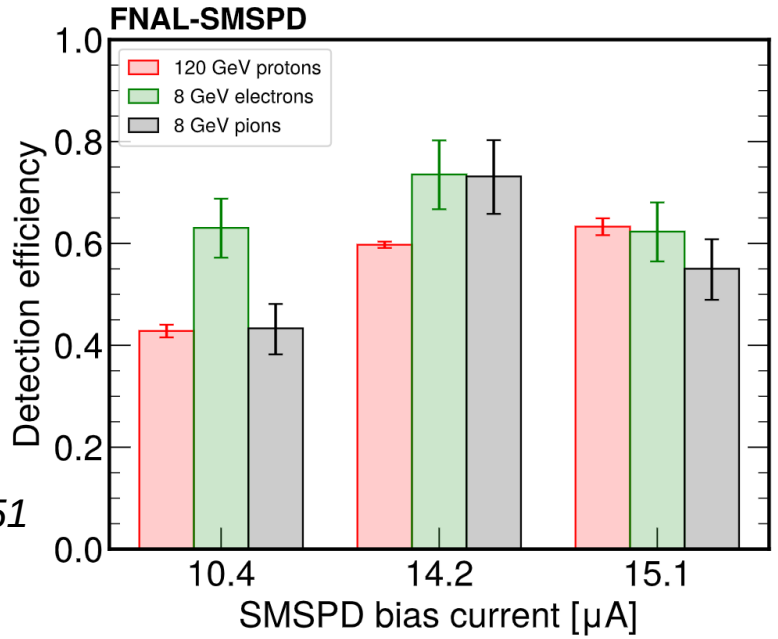
First proof-of-concept detection of relativistic particles achieved this year.



Superconducting analog of silicon-photomultiplier
… goal to reach x100 active area





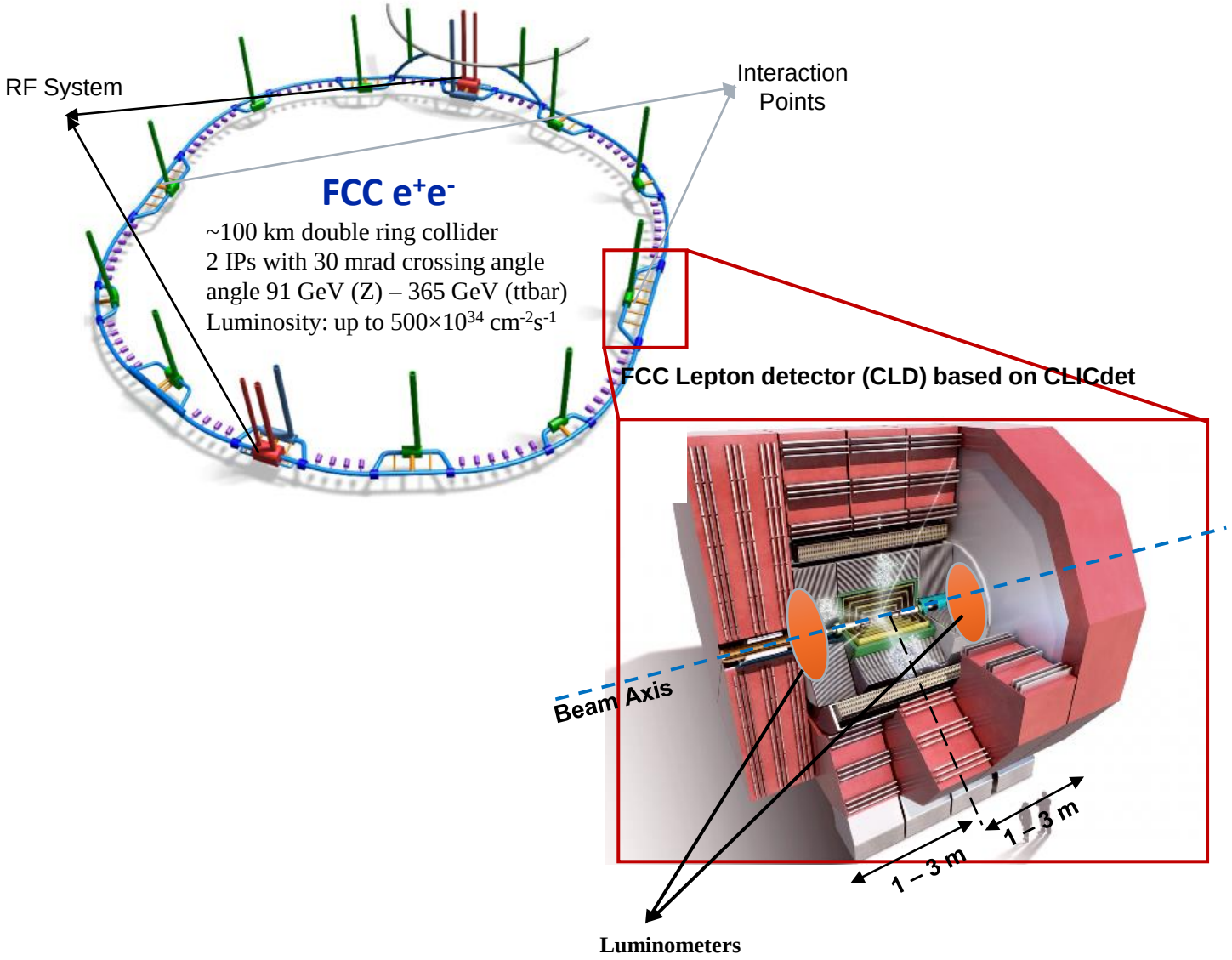


- >60% efficiencies have been demonstrated for proof-of-concept devices initially designed for photons
- Geometry optimization will improve this

Peña, Wang, Xi...Korzh...Shaw et al, arXiv:2410.00251

Luskin, Schmidt, Korzh, Beyer...Charaev...Pena…Shaw, Appl. Phys. Lett. 122, 243506 (2023)

Potential use case in FCC



- Luminometer concept:
  - Detector design fitting in available space
  - Simulation of detector design with Bhabha scattering, incoherent pairs / beam backgrounds
  - Understanding MDI constraints for detector concept & providing cryogenics
- Feedback between luminometer concept and SNSPD development
- Understanding of other applications of SNSPDs for dedicated detectors for ALPs, weakly interacting particles, etc.

- **Other use cases:**
  - Couple to Scintillating Fibers
    - Improve readout (faster response time)
    - Calorimetry?
    - Tracking?
  - Dedicated Axion-like particle detectors

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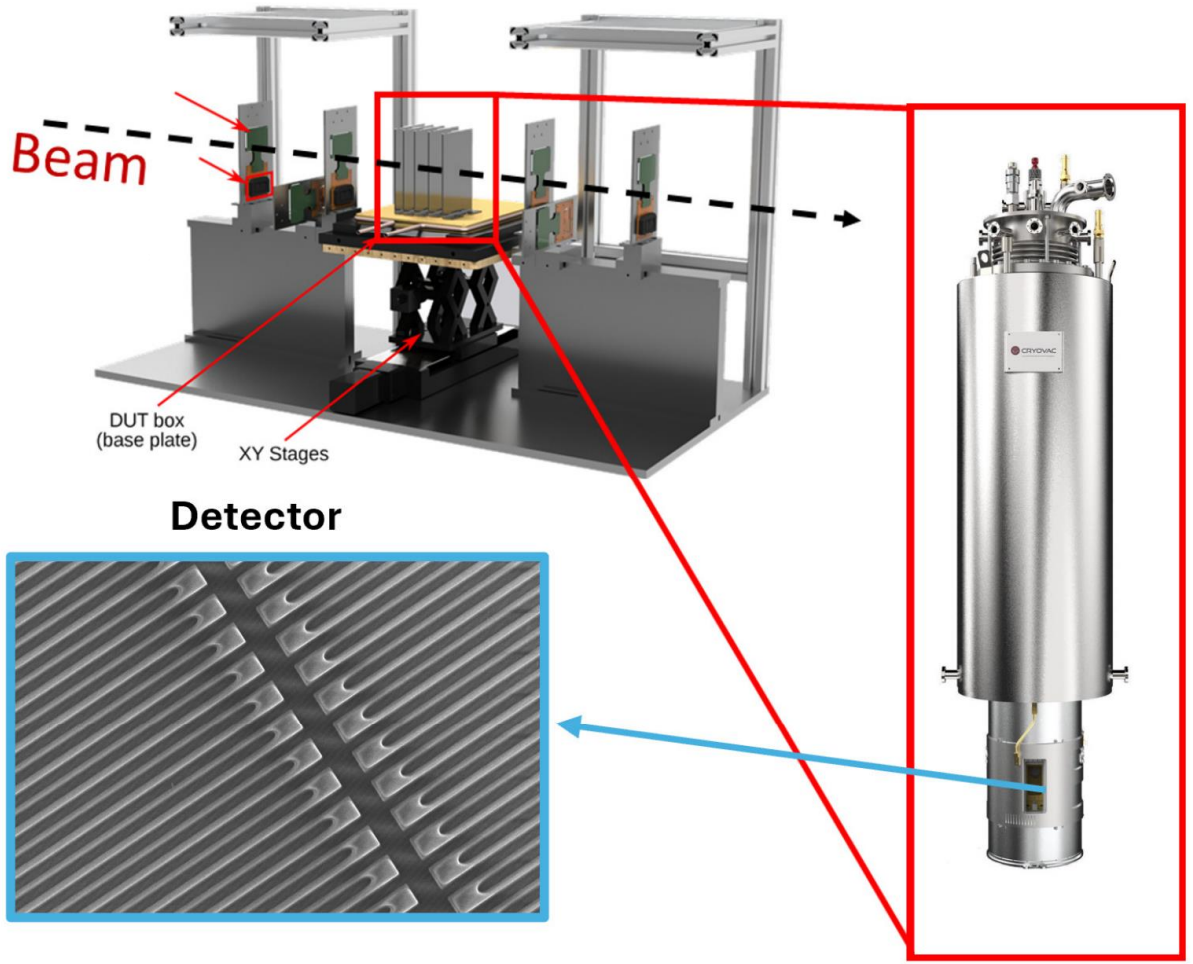
Potential use case in FCC

- Particle proof-of-concept: **protons, electrons, pions** [1]
- High efficiency: **98%** (photons) [2]
- Record energy threshold: **43 meV** [3]
- Timing resolution: **<3 ps** [4]
- Large cameras: **400,000 pixels** [5]

- SNSPD development
  - Scaling of SNSPD arrays up to >cm^2 scale
  - High-temperature (~20 K) SNSPD development
  - Scalable readout chain and signal processing
  - Geometry optimization
  - Characterization of particle response

Test beam setup at CERN



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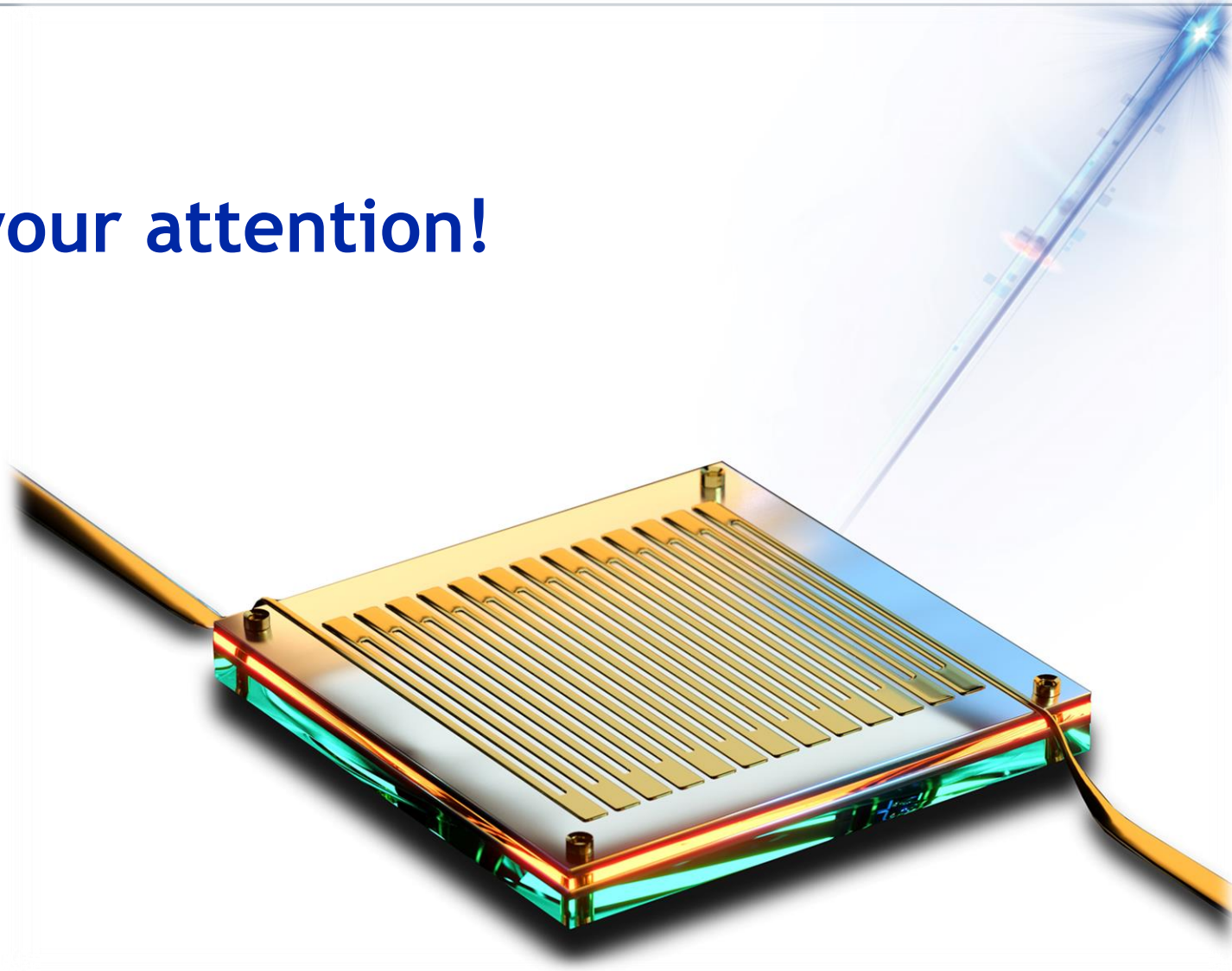
Thank you for your attention!



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