IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), July 2022.
This plenary presentation was given at the virtual EUCAS 2021, September 5-10, 2021.

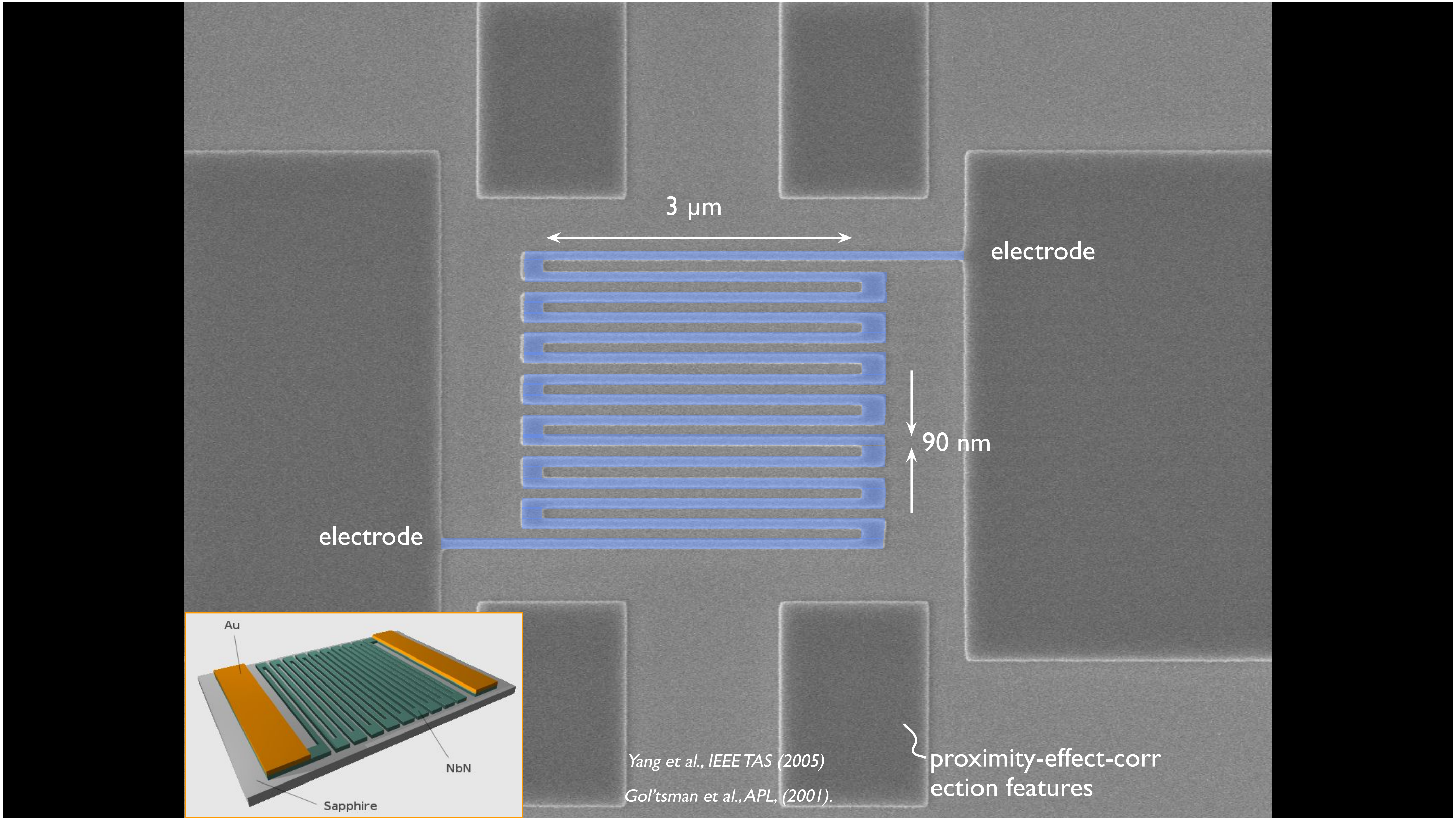
Looking Forward from Twenty Years of Superconducting Single-Photon Detectors

Karl K. Berggren

berggren@mit.edu

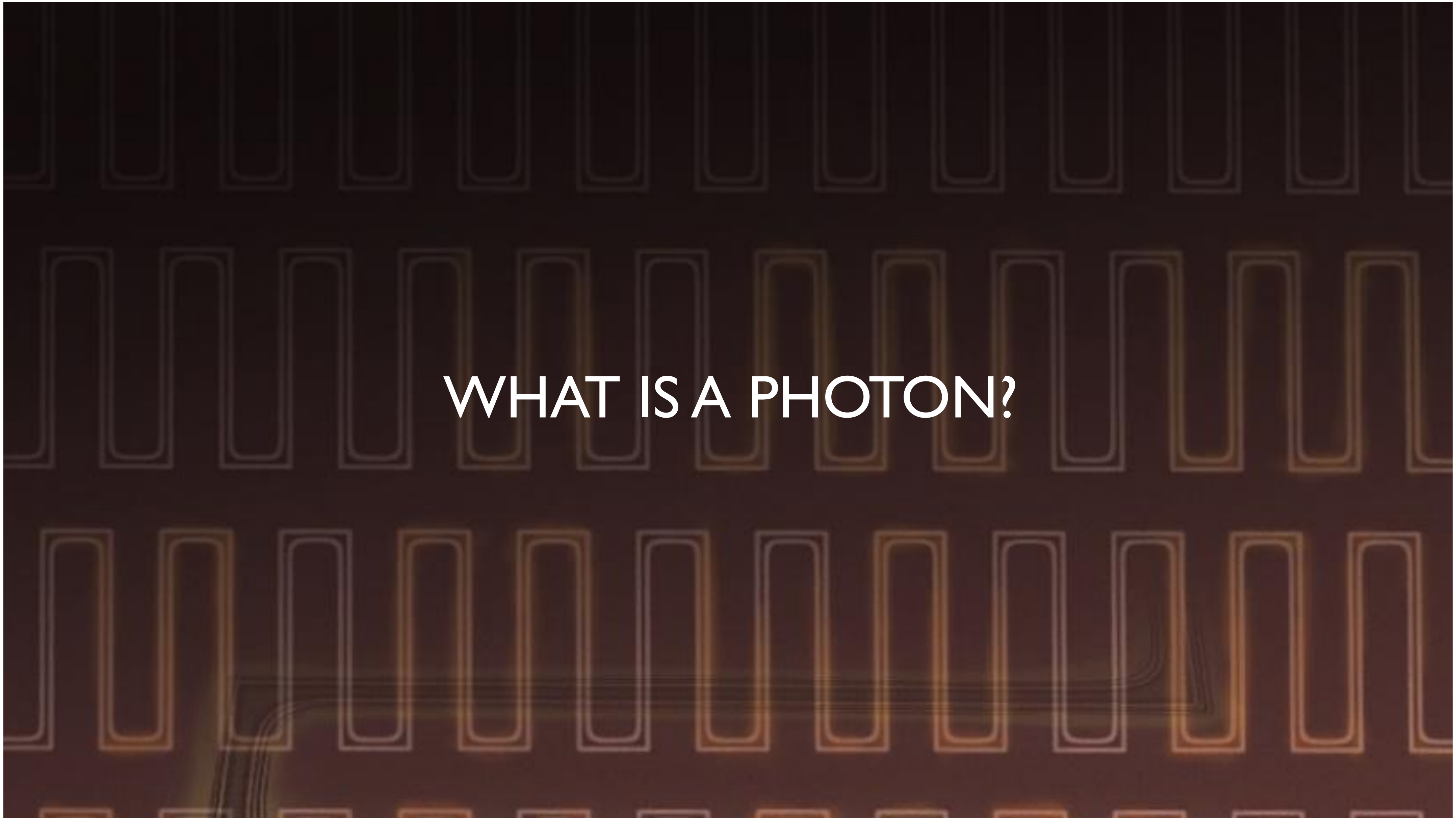
Massachusetts Institute of Technology

EUCAS, Sept 9th, 2021



Yang et al., IEEE TAS (2005)

Gol'tsman et al., APL, (2001).


WHAT IS A PHOTON?

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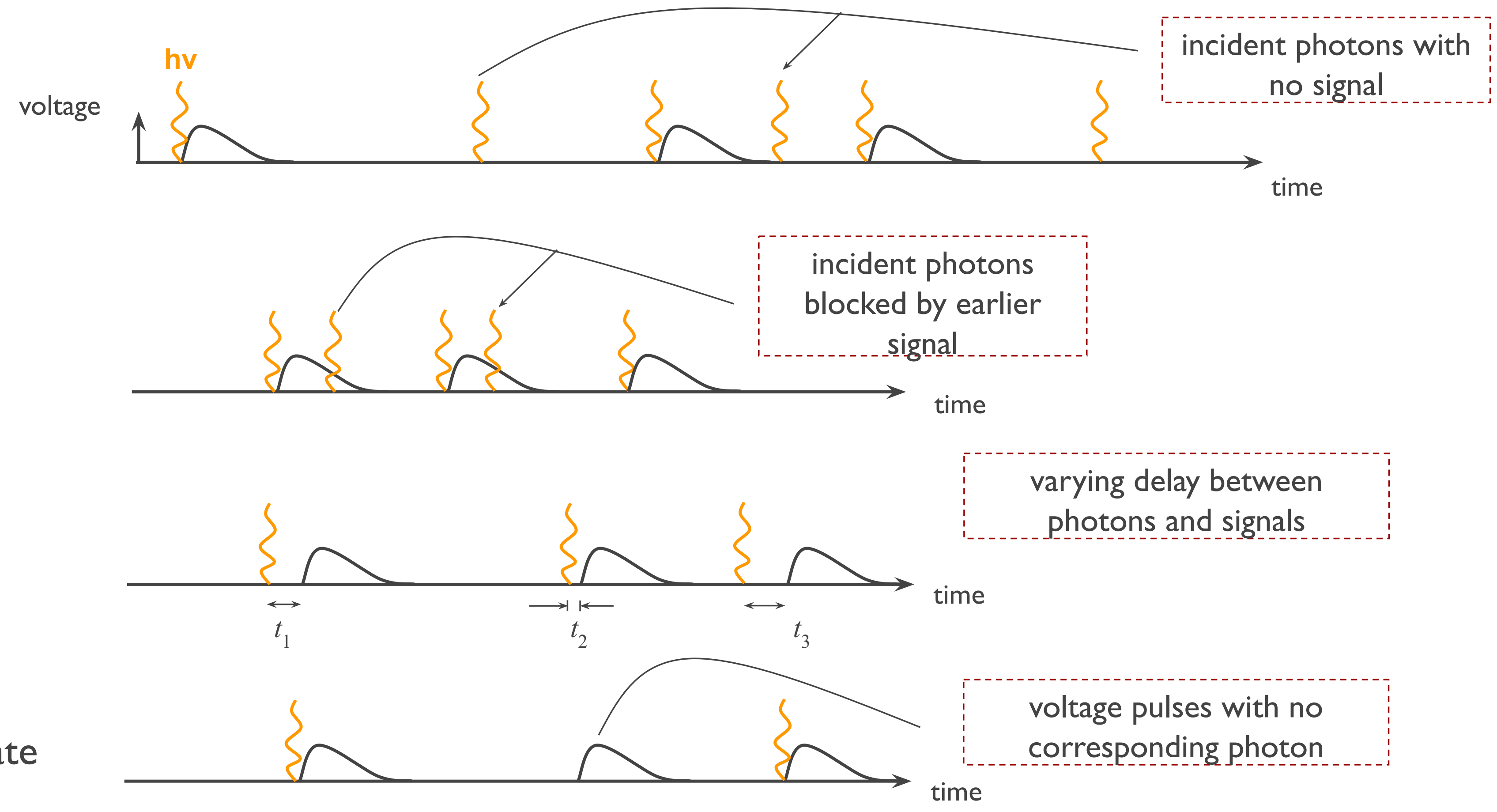
Characteristics of Photon Detectors

- Efficiency
- Reset time
- Jitter
- Dark count rate



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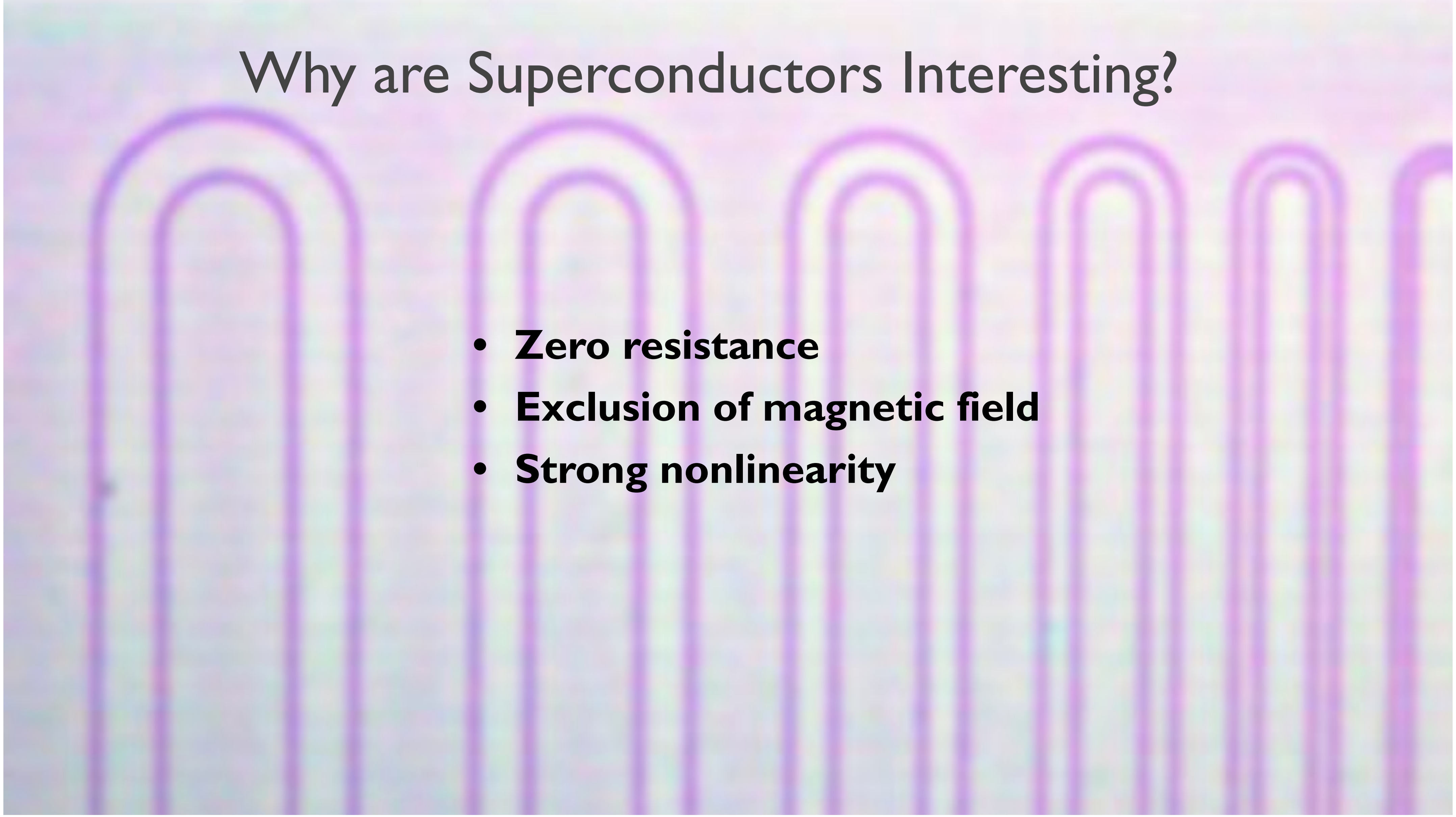
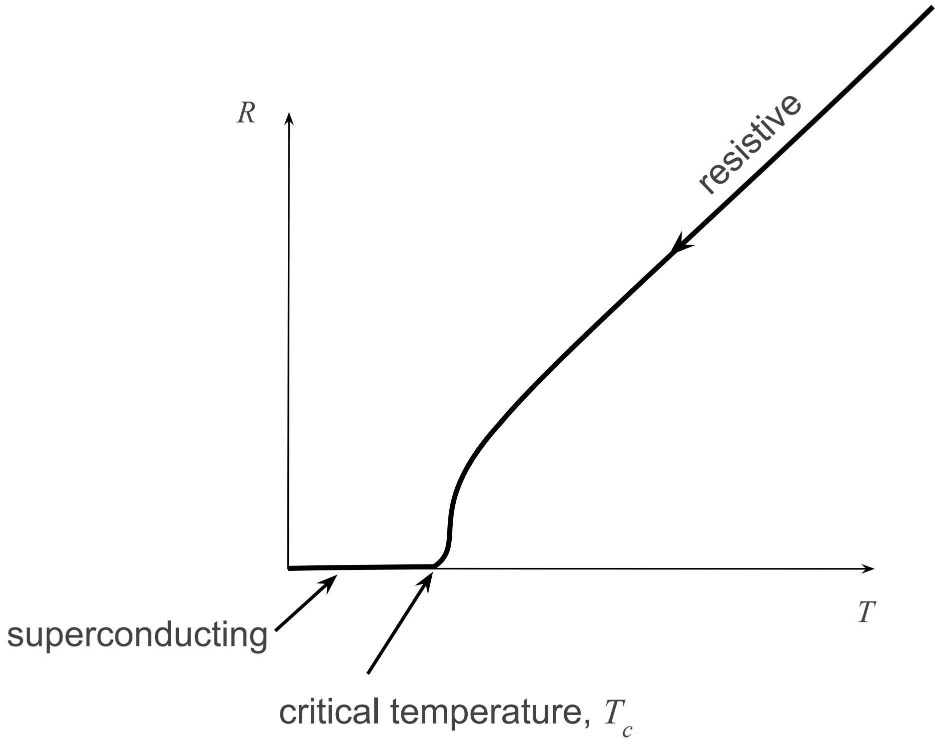


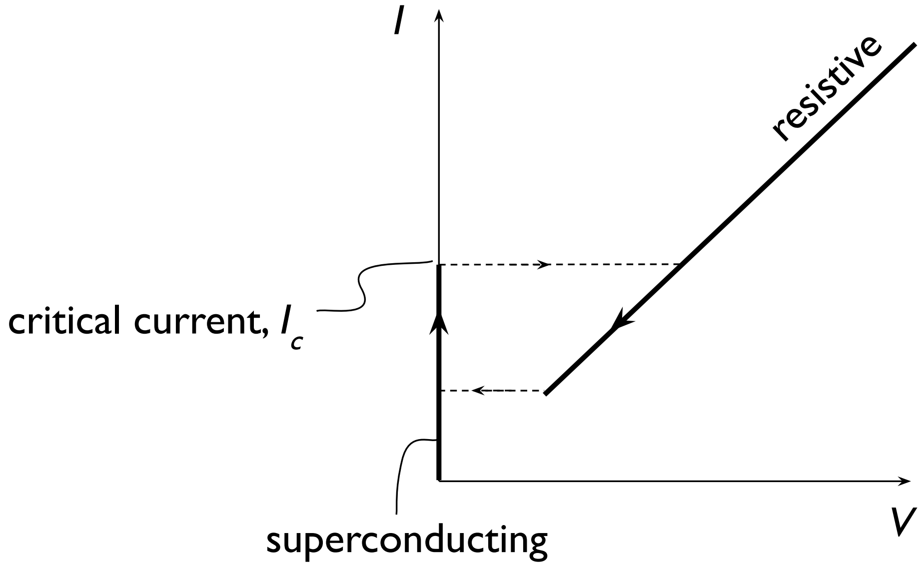
Why are Superconductors Interesting?

- **Zero resistance**
- **Exclusion of magnetic field**
- **Strong nonlinearity**

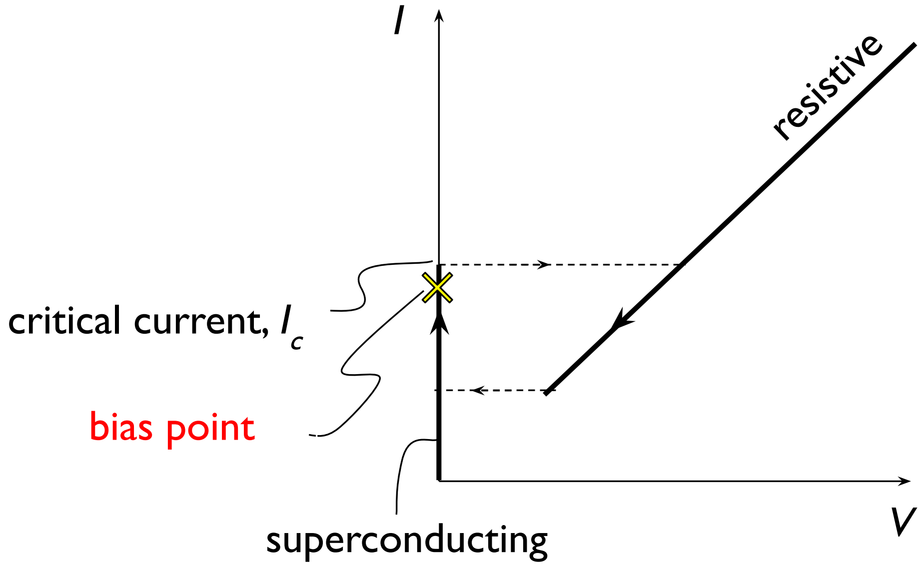
Analog Amplifiers

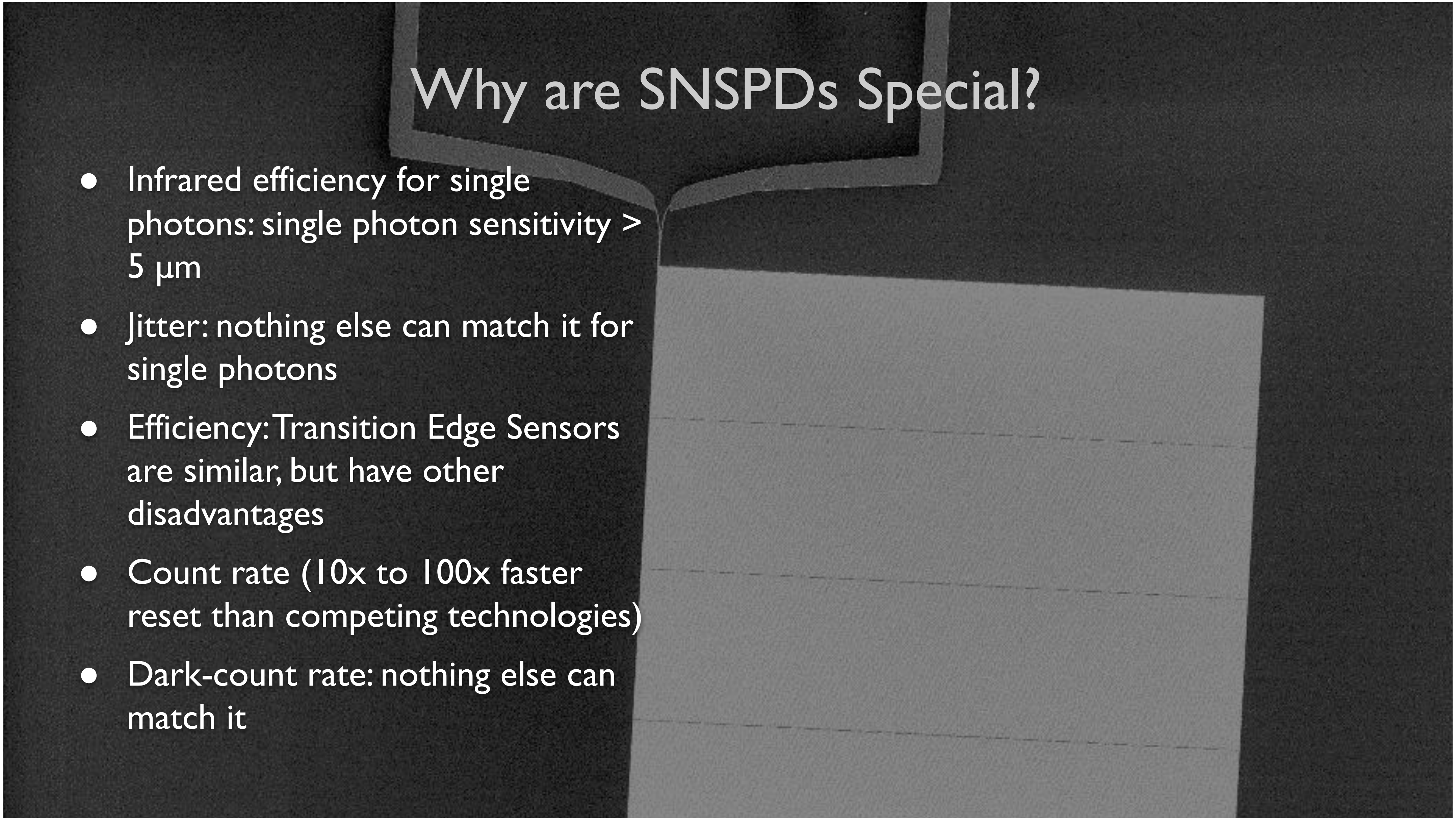


Comparison-Based Device



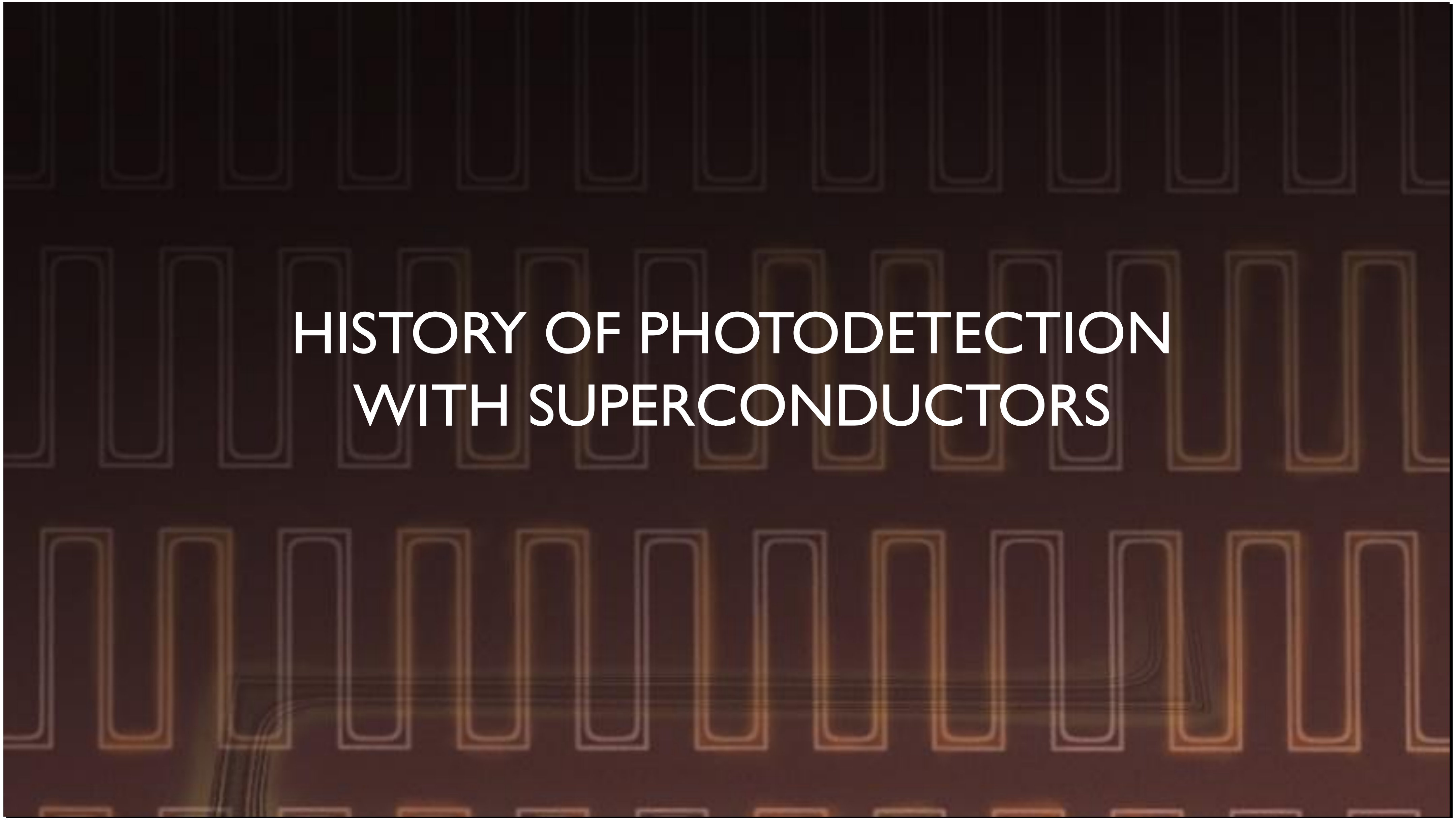
Comparison-Based Device





Why are SNSPDs Special?

- Infrared efficiency for single photons: single photon sensitivity > 5 μm
- Jitter: nothing else can match it for single photons
- Efficiency: Transition Edge Sensors are similar, but have other disadvantages
- Count rate (10x to 100x faster reset than competing technologies)
- Dark-count rate: nothing else can match it


HISTORY OF PHOTODETECTION
WITH SUPERCONDUCTORS

Phys. Rev. Lett. **8**, 438 – Published 1 June 1962

SUPERCONDUCTING NUCLEAR PARTICLE DETECTOR

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

Recently the cryotron was proposed as a detector of nuclear particles.[1] An even simpler detector should be possible, capable of discriminating between particles of different ionizing power. It would consist of a narrow, thin film of current-carrying superconductor cooled well below its transition temperature, in series with a small resistance. Should an ionizing particle pass through the film, the current will be reduced and a voltage pulse will appear across the resistor.

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)

The photoresponse of 10 nm thick superconducting NbN meander lines is measured using an amplitude modulated infrared semiconductor laser operating at a wavelength of 1300 nm. The response time of the film is found to be less than 1 ns with a measured responsivity of up to 1500 V/W of absorbed power at 100 kHz. Thermal properties of the film are extracted from current–voltage characteristics using a self-heating hot spot model. At temperatures well below the superconducting transition, the magnitude of the photoresponse is found to be an order of magnitude too large to be purely bolometric, even when electron heating and effects due to intergranular weak links are taken into account. The photoresponse is seen to be bolometric near T_c. Other contributions to photoresponse are discussed, including kinetic inductance and the photofluxonic effect. [S0021-8979(96)04209-2]

Journal of Applied Physics 79, 7069 (1996)

Picosecond superconducting single-photon optical detector

Appl. Phys. Lett., Vol. 79, No. 6, 6 August 2001

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)

We experimentally demonstrate a supercurrent-assisted, hotspot-formation mechanism for ultrafast detection and counting of visible and infrared photons. A photon-induced hotspot leads to a temporary formation of a resistive barrier across the superconducting sensor strip and results in an easily measurable voltage pulse. Subsequent hotspot healing in ~30 ps time frame, restores the superconductivity (zero-voltage state), and the detector is ready to register another photon. Our device consists of an ultrathin, very narrow NbN strip, maintained at 4.2 K and current-biased close to the critical current. It exhibits an experimentally measured quantum efficiency of ~20% for 0.81 μm wavelength photons and negligible dark counts.
[DOI: 10.1063/1.1388868]

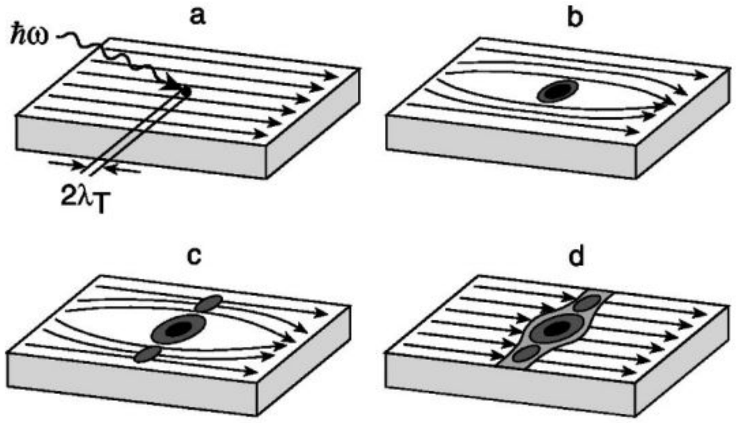


FIG. 1. Schematics of the supercurrent-assisted hotspot formation mechanism in an ultrathin and narrow superconducting strip, kept at temperature far below T_C are shown. The arrows indicate direction of the supercurrent flow.

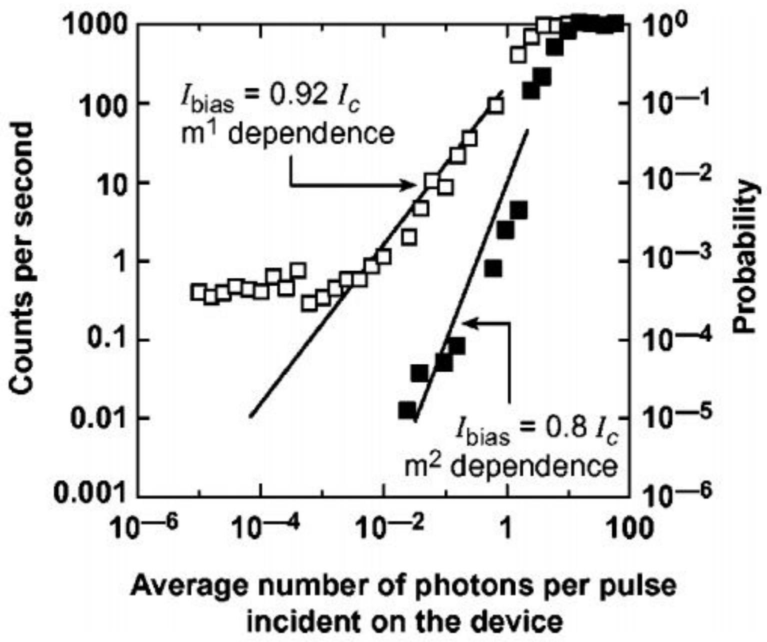


FIG. 3. Number of counts per second recorded by the NbN SPD versus the average number of photons per pulse incident upon the device, for two different bias current levels is shown. The solid lines correspond to the Eq. (4) theoretical predictions. The incident photon wavelength was 0.81 μm.

The IEEE Award for Continuing and Significant Contributions in the Field of Applied Superconductivity

Gregory Goltsman

Details

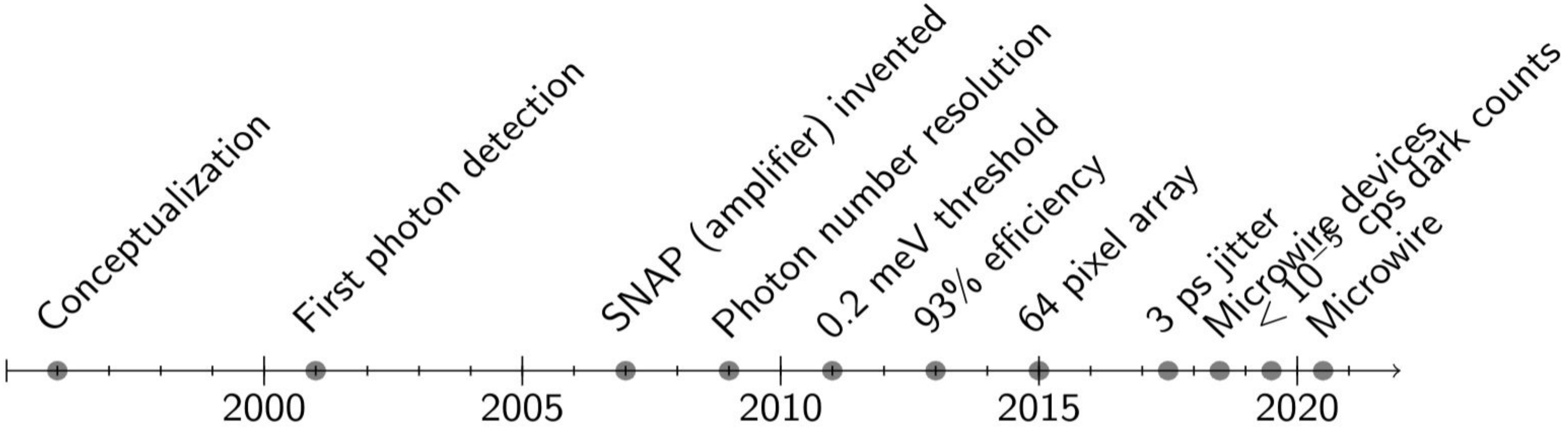
Affiliation: Moscow State Pedagogical University

AWARD RECIPIENT

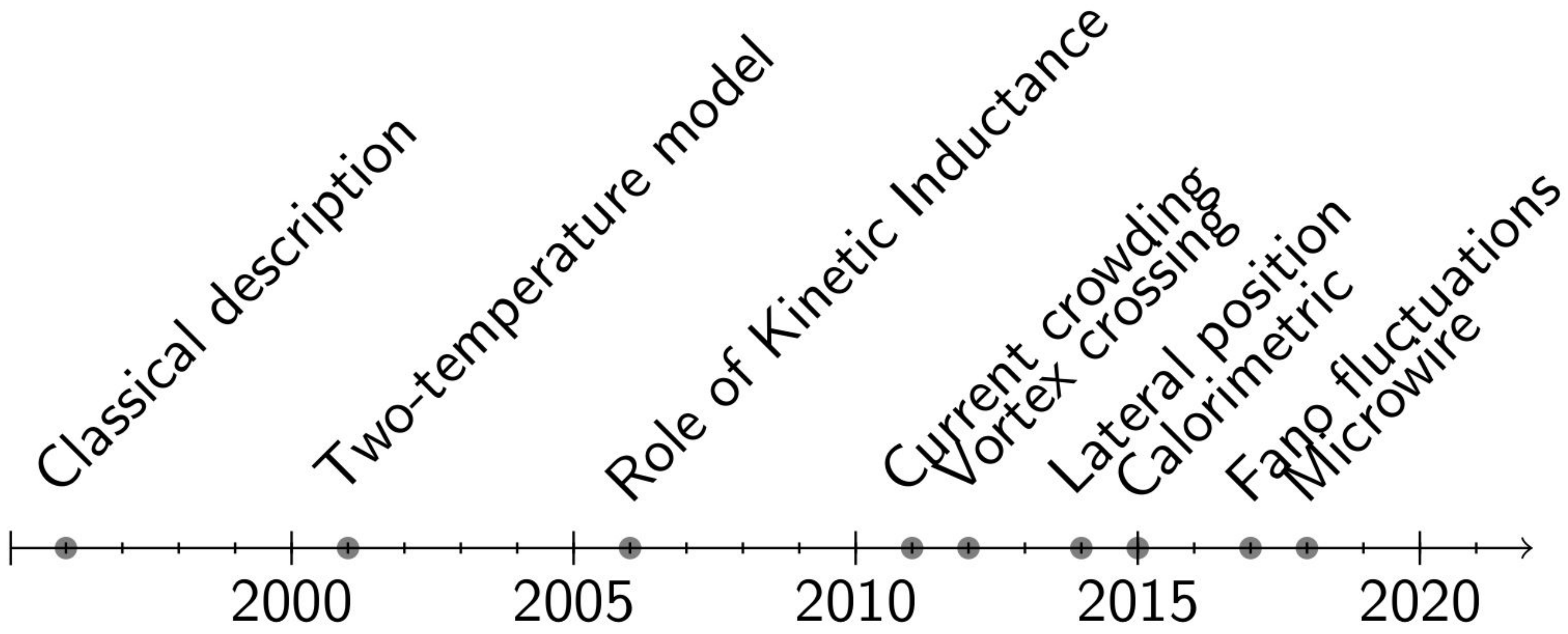
For continuing and significant contributions in the field of superconductive electronics, in particular:

- for invention and advancement of the superconducting hot-electron bolometric mixer, now one of the key astrophysics detectors,
- for invention and advancement of the superconducting single-photon detector, which has enabled new high-speed optical communication applications, and
- for contributions to the understanding of electron energy relaxation processes in impure superconducting films.

SNSPD Experimental Timeline



SNSPD Theory Timeline



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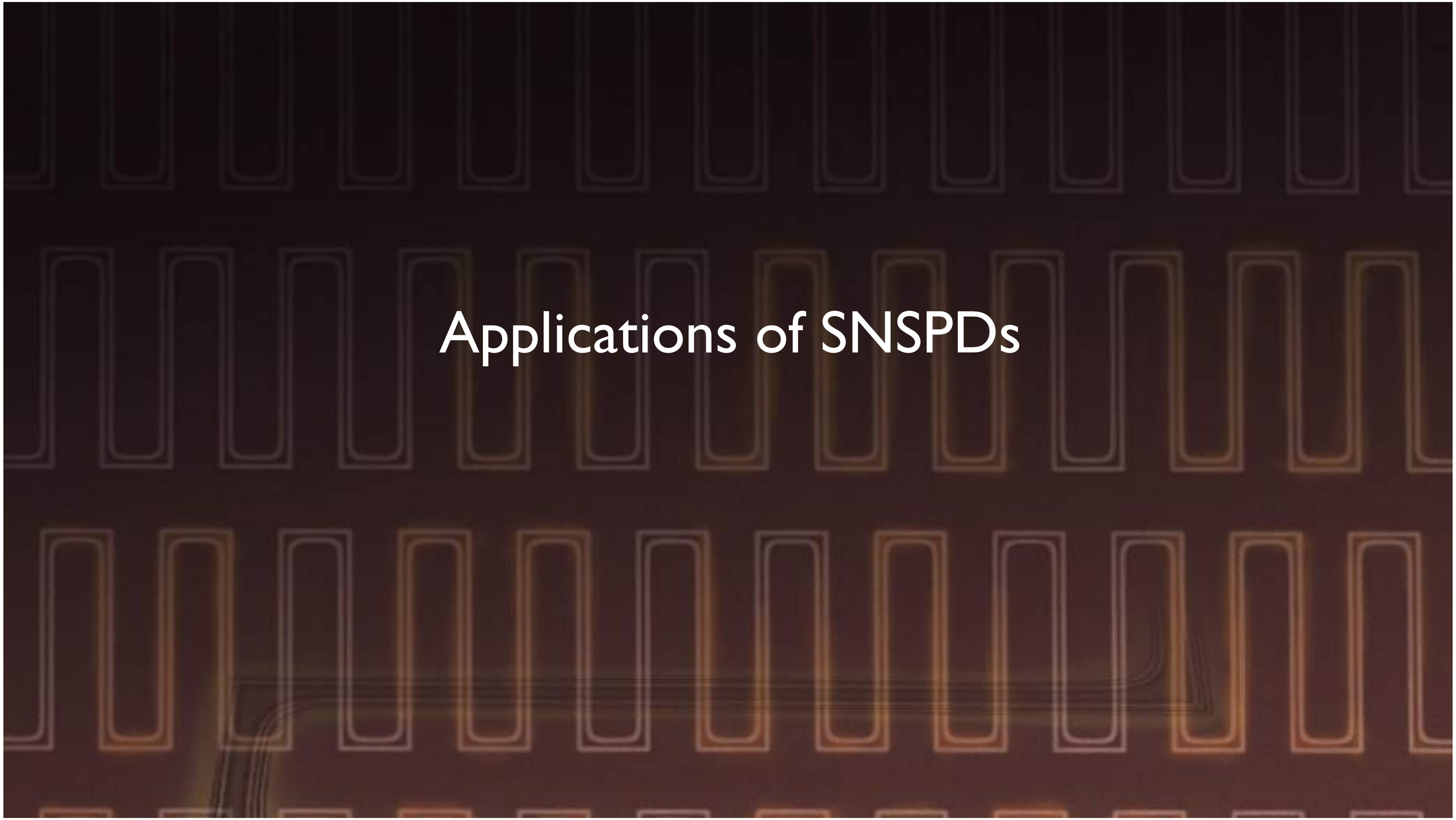


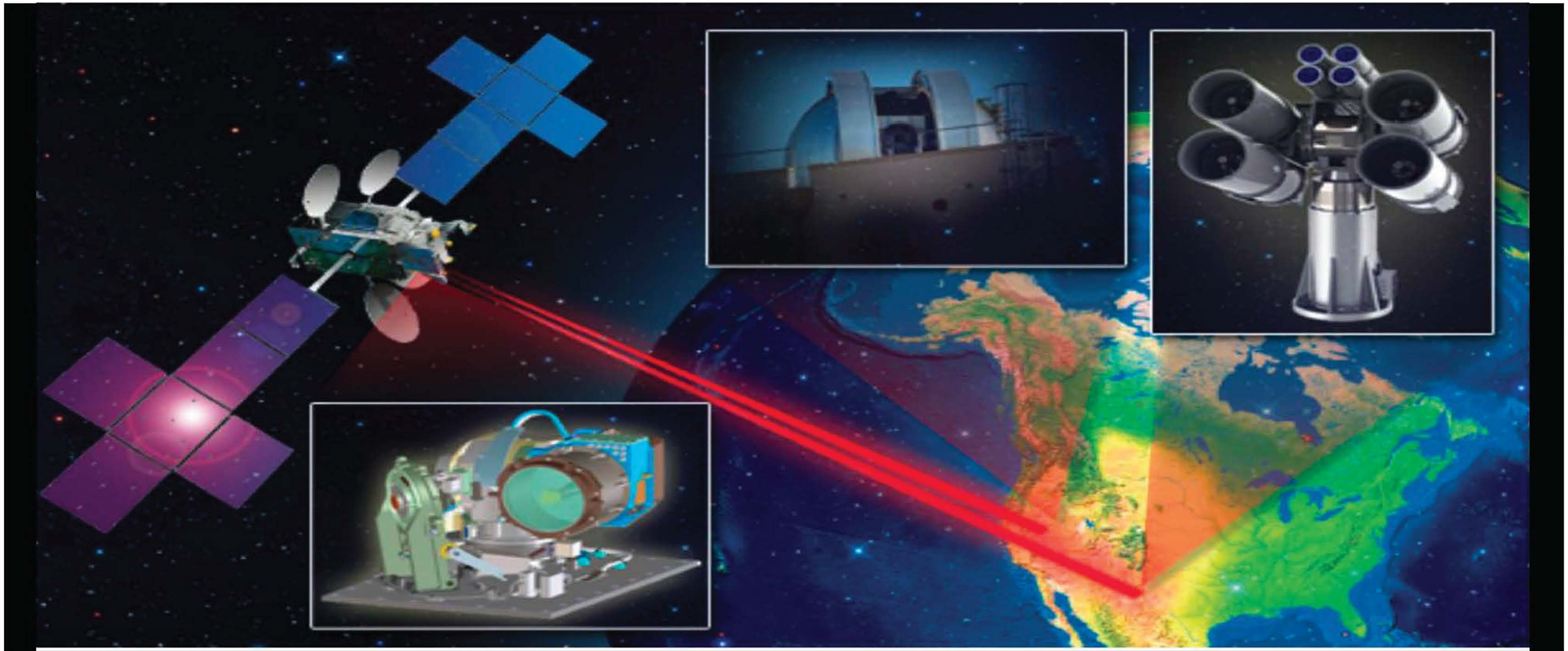
VLSI Circuit Evaluation

VLSI circuit imaging and debugging

SNSPD enabled performance advances

Image courtesy of DCG Systems

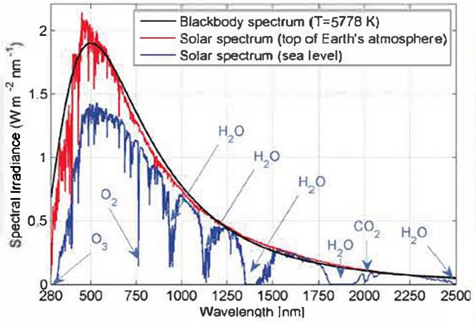
Collaboration between BU, DCG Systems*, IBM, Photonspot, funded by IARPA
* Now Thermofisher



"... the first high-rate space laser communications system that can be operated over a range ten times larger than the near-Earth ranges that have been demonstrated to date." from http://esc.gsfc.nasa.gov/267/271.html, enabled by nanowire detectors developed at Lincoln Laboratory and JPL in collaboration with MIT campus.

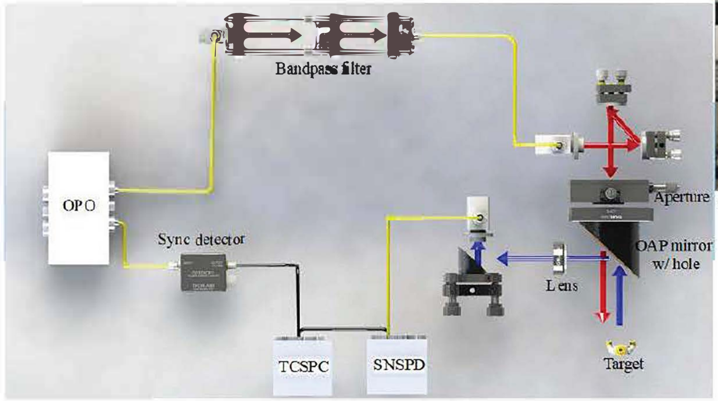
Infrared single-photon LIDAR with SNSPDs

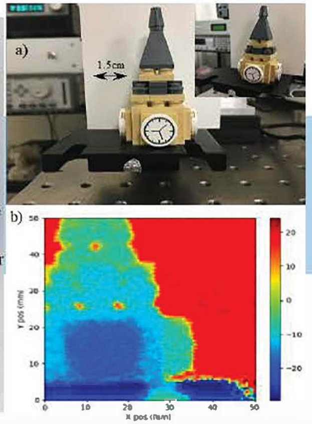
University of Glasgow, UK & partners



1 km range daylight depth imaging at 1550 nm wavelength

McCarthy *et al* Optics Express 21 8904 (2013) Glasgow/Heriot-Watt/Delft



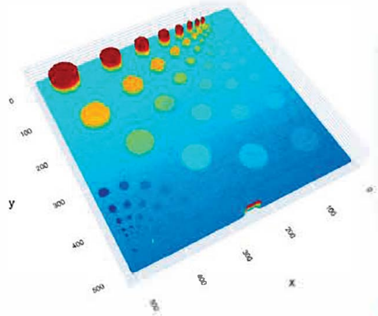


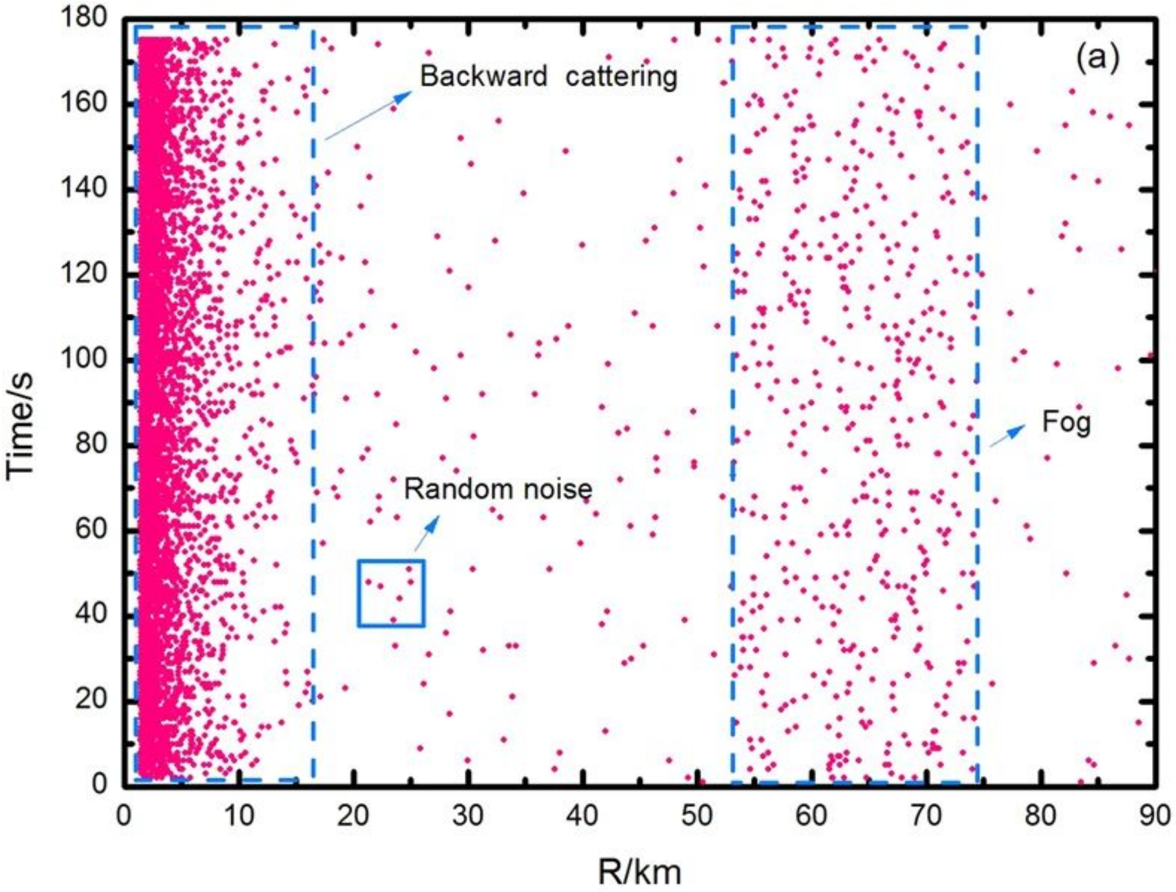
Benchtop depth imaging at 2.3 µm wavelength

Taylor *et al* Optics Express 27 8147 (2019) Glasgow/NICT

Low jitter SNSPD LIDAR field trials at 1550 nm wavelength

Taylor *et al* CLEO SM2M.6 (2020) Glasgow/Heriot-Watt/JPL

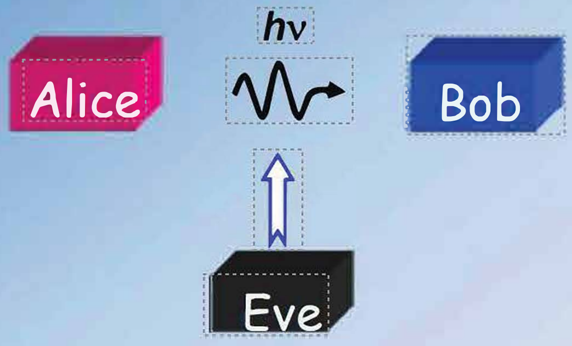




Zhu, J., Chen, Y., Zhang, L. *et al.*
Demonstration of measuring sea fog with an SNSPD-based Lidar system.
Sci Rep 7, 15113 (2017).

University of Glasgow

Quantum Key Distribution



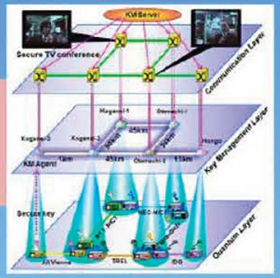
- Principle: a secret key is generated over a public channel with security guaranteed by laws of Quantum Mechanics
- Information encoded on the phase or polarization of individual photons
- Eavesdropping introduces errors

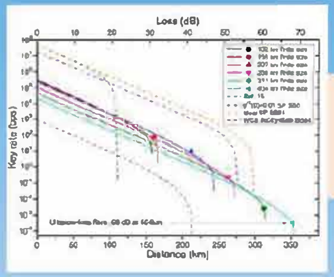
Robert Hadfield • Heraeus Seminar Bad Honnef • 15th November 2018

University of Glasgow

Quantum Communications Milestones with SNSPDs

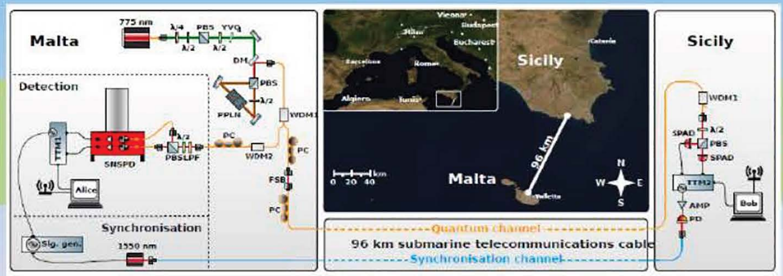
Tokyo QKD Network
Sasaki *et al.* Optics Express 19 10387 (2011)

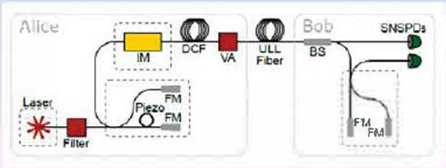




MDI-QKD over 404 km optical fibre
Yin *et al.* Phys. Rev. Lett. 117 190501 (2016)

Entanglement distribution over 91 km submarine fibre arXiv:1803.00583





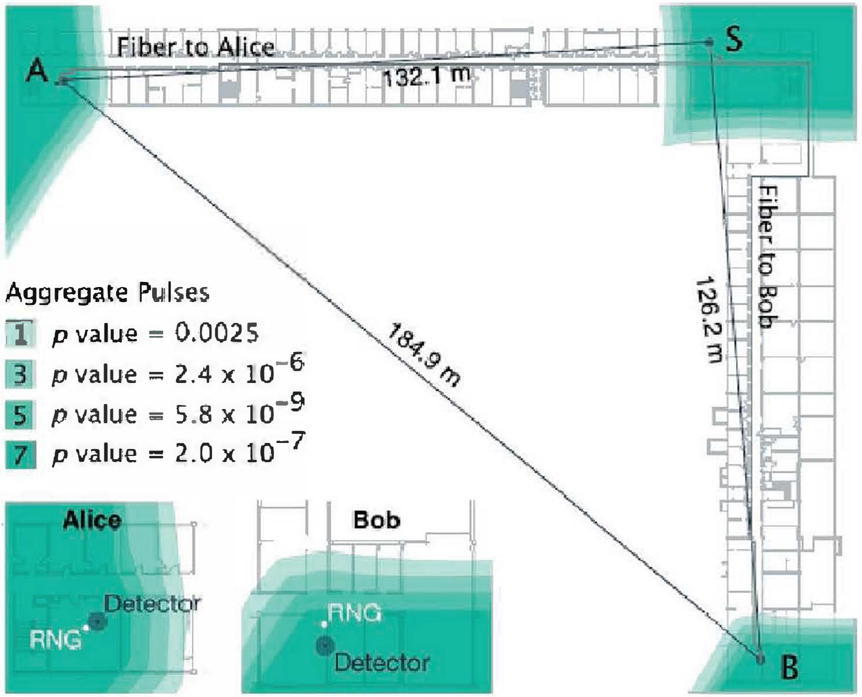
QKD over 421 km optical fibre
Boaron *et al.* Phys. Rev. Lett. 121 190502 (2018)

Robert Hadfield • Heraeus Seminar Bad Honnef • 14th November 2018

Slide courtesy of Robert Hadfield

"Loophole-free" Bell test (2015)

NIST



*L. K. Shalm et. al, PRL **115**, 250402 (2015)*

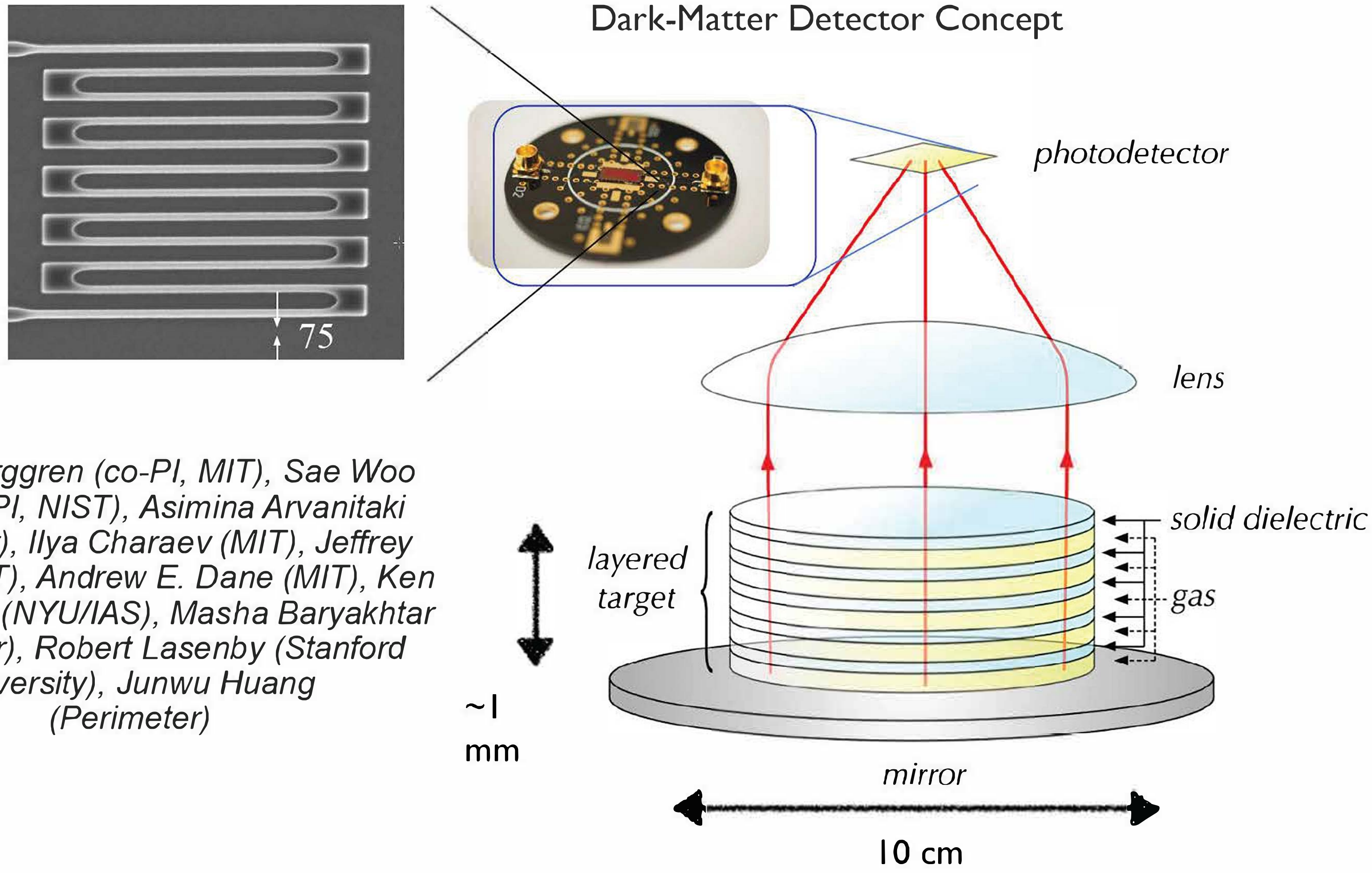
Two high-efficiency WSi SNSPDs used to close loopholes in prior Bell's inequality experiments

Slide courtesy of Sae-Woo Nam

Dark Matter Detection

- Not just matter that's hard to see!
- We know it's there because… gravity
  - Velocity vs. radius of galaxial matter
  - Explains observed gravitational lensing
  - Explains galaxial collisions
- Does it interact in any other way?
- What is it?

Nanowire Detection of Photons from the Dark Side



Karl K. Berggren (co-PI, MIT), Sae Woo Nam (co-PI, NIST), Asimina Arvanitaki (Perimeter), Ilya Charaev (MIT), Jeffrey Chiles (NIST), Andrew E. Dane (MIT), Ken Van Tilburg (NYU/IAS), Masha Baryakhtar (Perimeter), Robert Lasenby (Stanford University), Junwu Huang (Perimeter)

Nanowire Detection of Photons from the Dark Side

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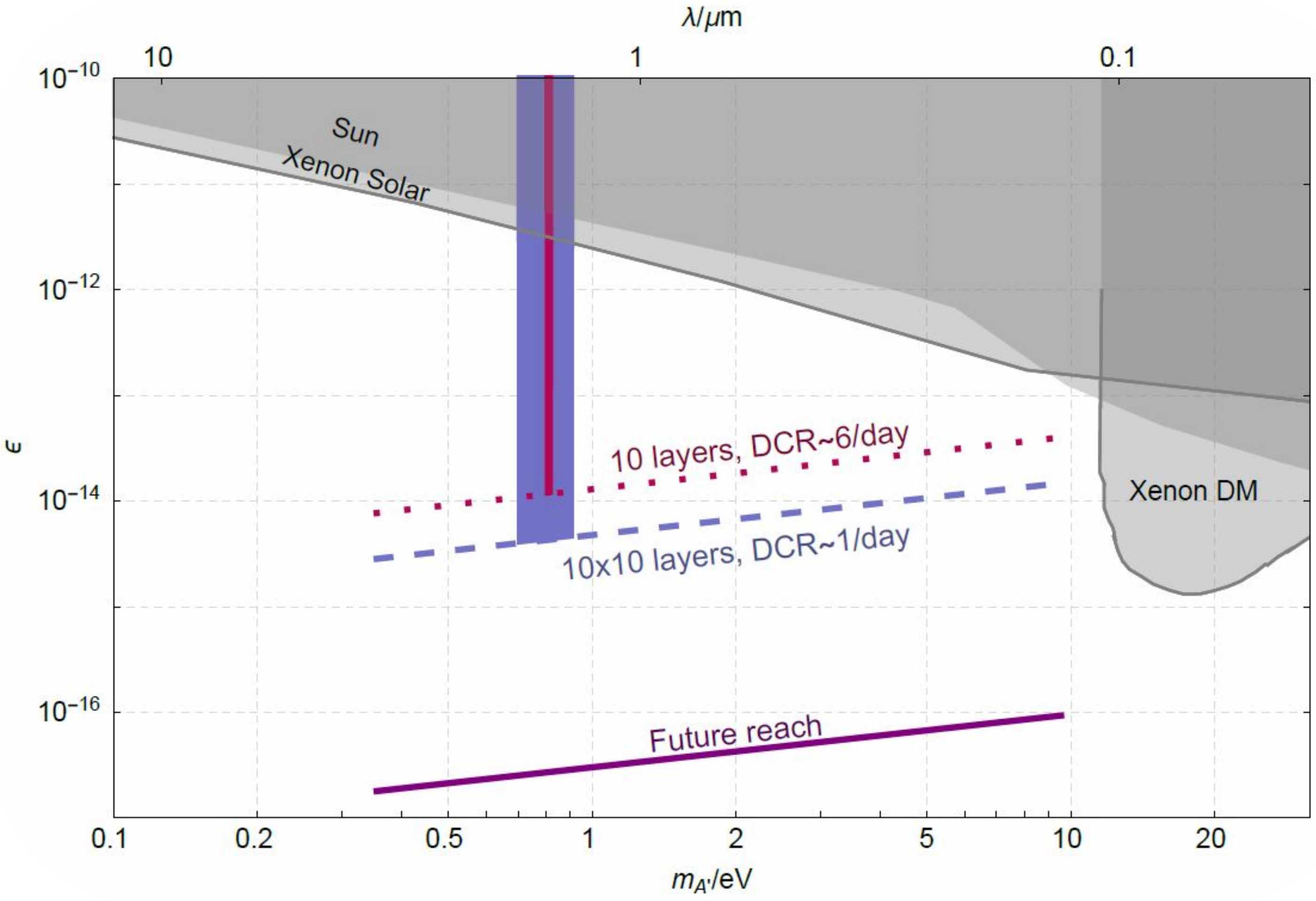
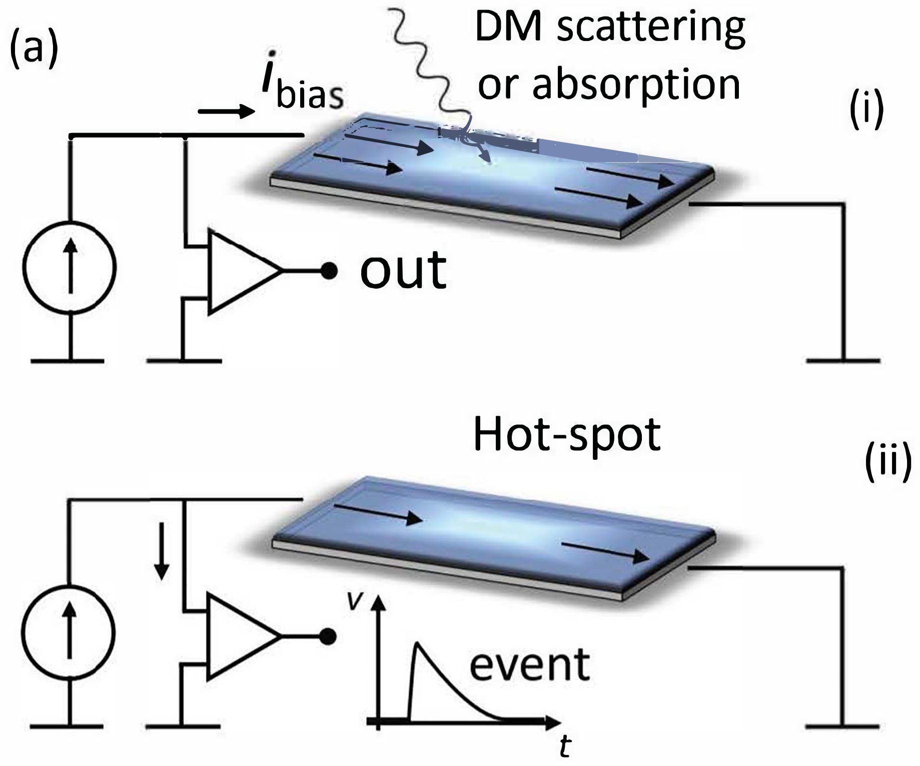
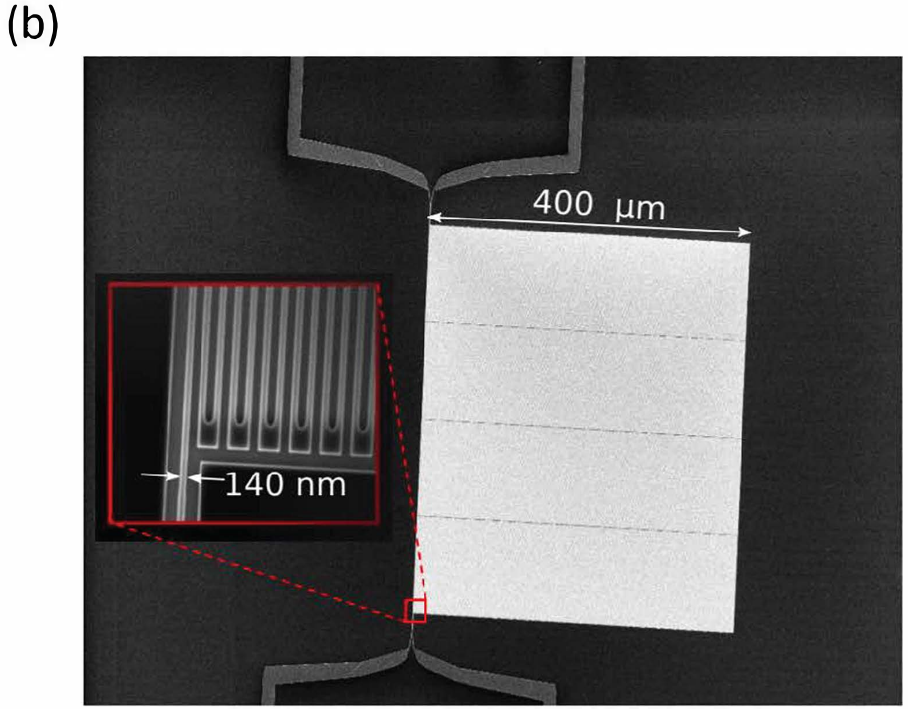


Detecting Dark Matter with Superconducting Nanowires

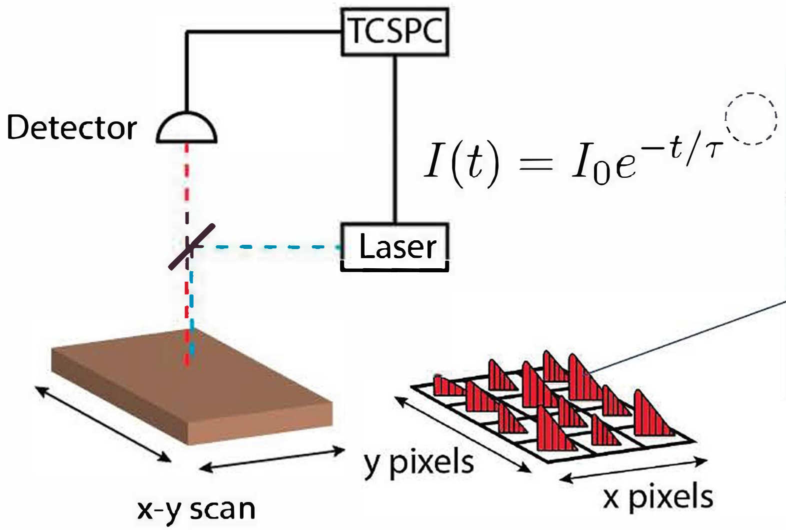
Yonit Hochberg[1],* Ilya Charaev[2],† Sae-Woo Nam[3],‡ Varun Verma[3],§ Marco Colangelo[2],¶ and Karl K. Berggren[2]**
[1]Racah Institute of Physics, Hebrew University of Jerusalem, Jerusalem 91904, Israel
[2]Massachusetts Institute of Technology, Department of Electrical Engineering and Computer Science, Cambridge, MA, USA and
[3]National Institute of Standards and Technology, Boulder, CO, USA

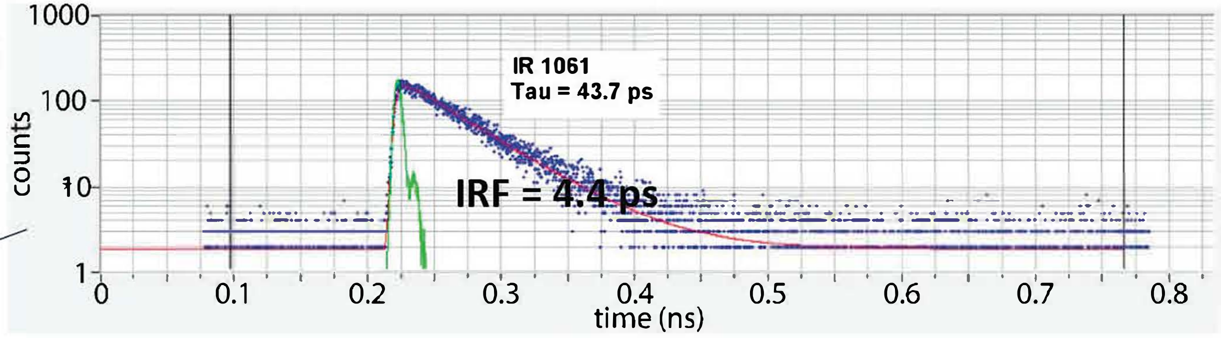




Phys. Rev. Lett. 123, 151802 (2019)

Bio applications: (towards) **Fluorescence-lifetime imaging microscopy (FLIM) with SNSPDs**

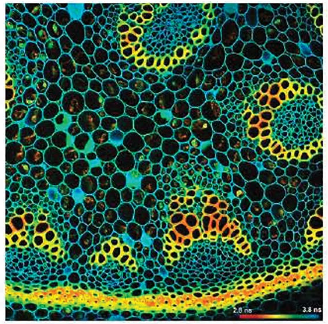




Becker, Wolfgang, et al. "4.4 ps IRF width of TCSPC with an NbN Superconducting Nanowire Single Photon Detector."

FLIM image of a convallaria (plant) not with SNSPDs

- Colors: different decay time
- Brigthness: signal



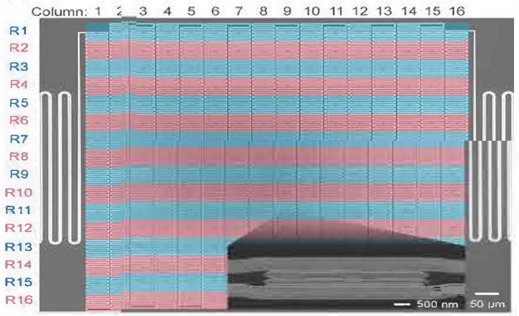
Advantages of SNSPD as a FLIM detector

- Fast instrument response function (IRF)
- Resolving fast decay fluorophores
- Enable use of new fluorophores

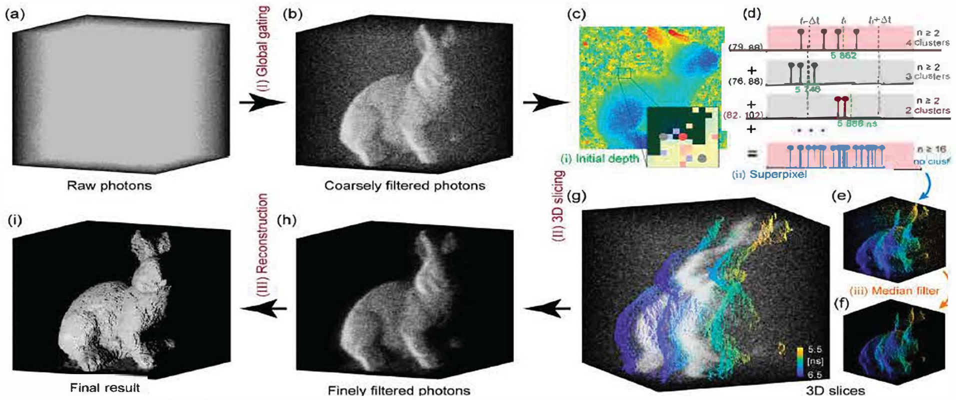
Computational Imaging & Spectroscopy using SNSPDs

Superconducting Quantum Electronics & Photon Information Lab

Qing-Yuan Zhao
Professor of School of Electronic Science and Engineering,
Nanjing University, China

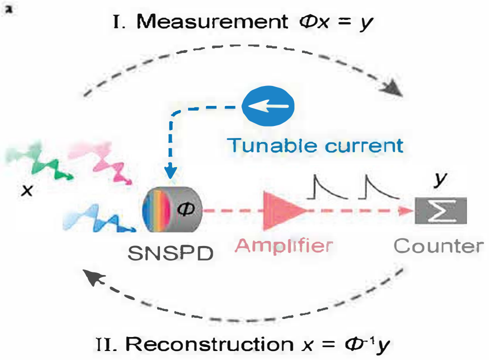


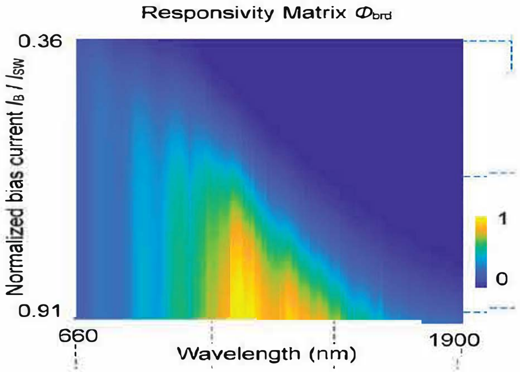
Noise-tolerant single-photon computational imaging



Opt. Lett. **45**(24), 6732 (2020).

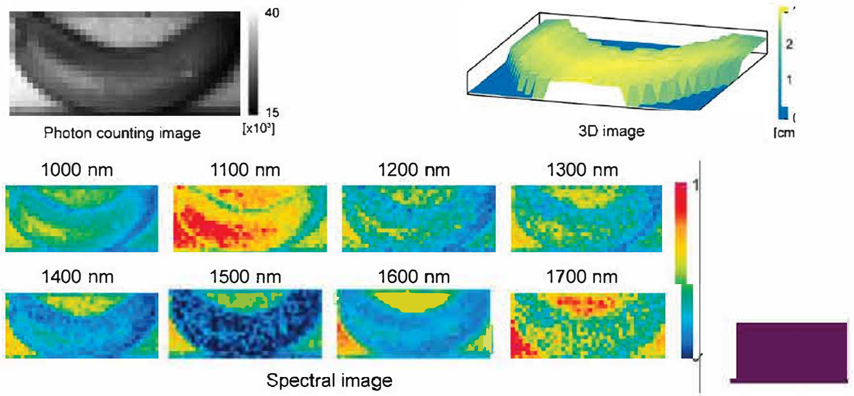
Computational Spectrometer using a modulated SNSPD





arxiv, 2011.02191

Spectral LiDAR




Photon Spot
California, US
Quantum Opus
Wisconsin, US
SINGLE QUANTUM
Excellence in photon detection
The Netherlands
Switzerland
IDQ
SCONTEL
SUPERCONDUCTING NANOTECHNOLOGY
Moscow, Russia
赋同科技
PHOTEC
Shangai, China

California Institute of Technology

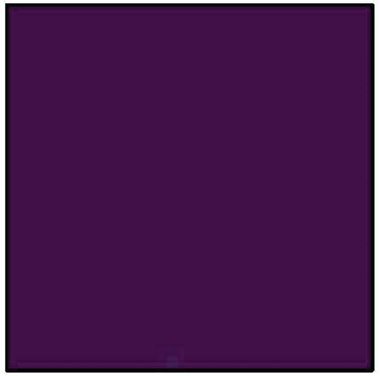
Scaling to Kilopixel Arrays

Jet Propulsion Laboratory

- Demonstration of **1024-pixel imaging array** with > 99% pixel yield
- 32 × 32 imager read out using only 64 readout lines
- 30 × 30 μm active area on 50 μm pitch – total area 0.92 mm^2

NIST

FABRICATED AT NIST
TESTED AT JPL



Emma E. Wollman, Varun B. Verma, Adriana E. Lita, William H. Farr, Matthew D. Shaw, Richard P. Mirin, and Sae Woo Nam, "Kilopixel array of superconducting nanowire single-photon detectors," Opt. Express 27, 35279-35289 (2019)

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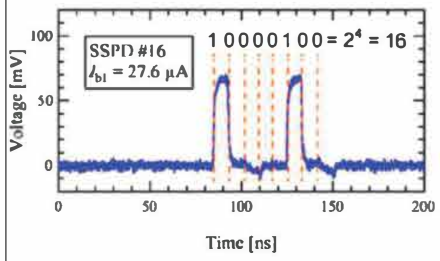
Research Article | Vol. 26, No. 22 | 29 Oct 2018 | OPTICS EXPRESS 29045

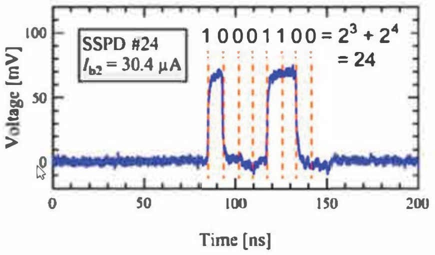
Optics EXPRESS

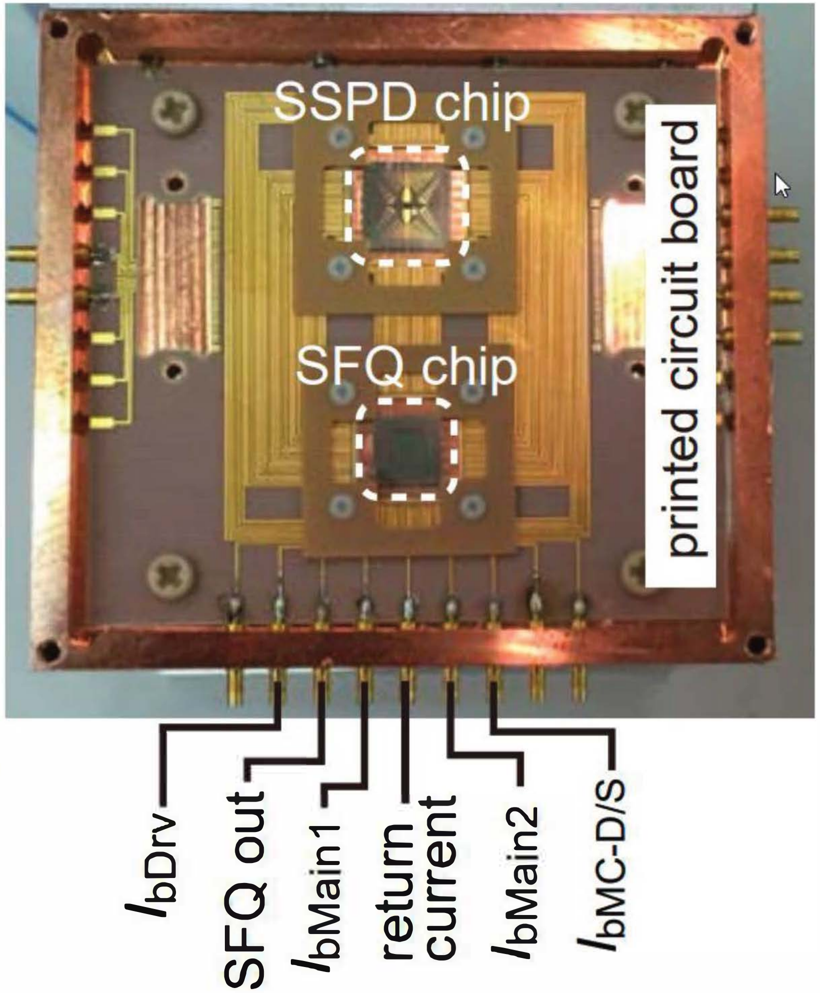
High-time-resolved 64-channel single-flux quantum-based address encoder integrated with a multi-pixel superconducting nanowire single-photon detector

SHIGEYUKI MIYAJIMA,[1,*] MASAHIRO YABUNO,[1] SHIGEHITO MIKI,[1,2] TARO YAMASHITA,[3,4] AND HIROTAKA TERAI[1]

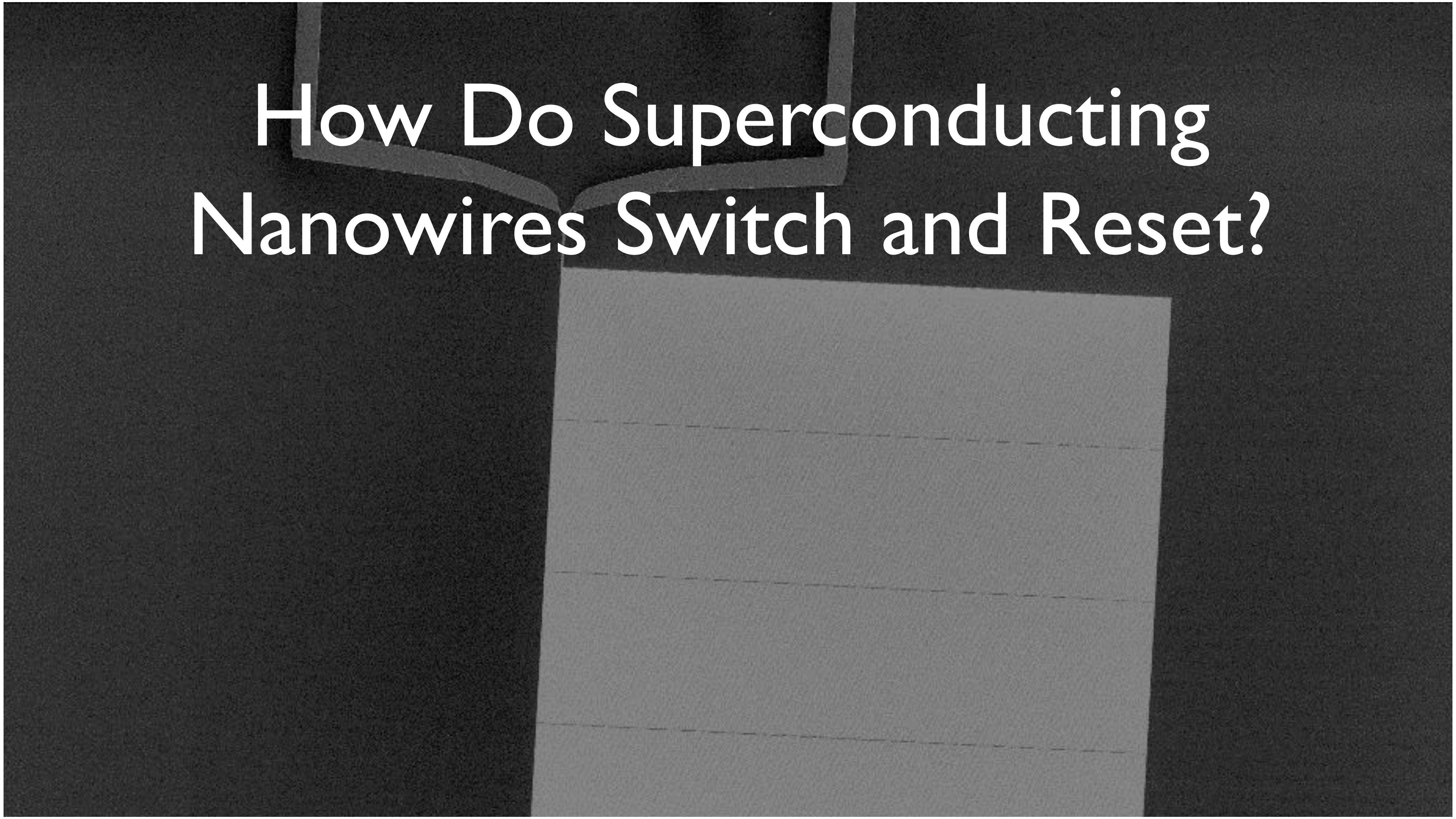
[1]*National Institute of Information and Communications Technology, 588-2 Iwaoka, Nishi-ku, Kobe 651-2492, Japan*
[2]*Graduate School of Engineering Faculty of Engineering, Kobe University, 1-1 Rokko-dai cho, Nada-ku, Kobe 657-0013, Japan*
[3]*Graduate school of Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan*
[4]*PRESTO, Japan Science and Technology Agency, 4-1-8 Honcho, Kawaguchi, Saitama 332-0012, Japan*
**miyajima@nict.go.jp*







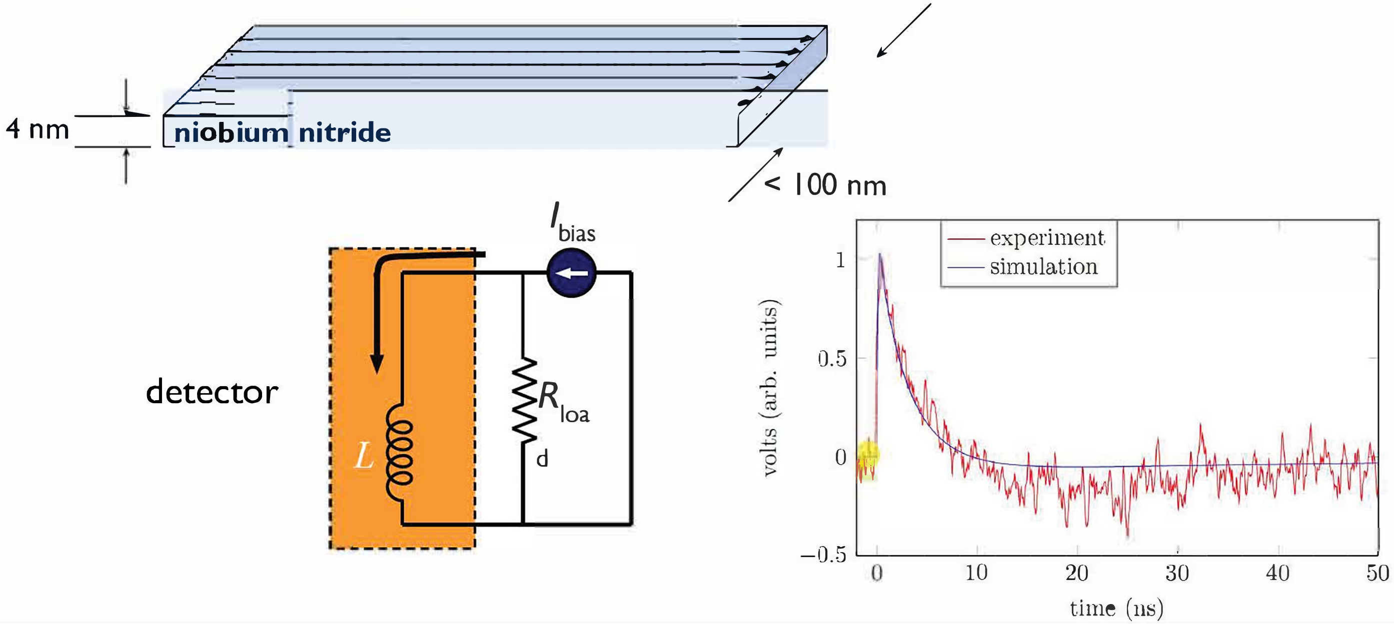
How Do Superconducting Nanowires Switch and Reset?



Current Bias

Critical Temperature ~ 11 K

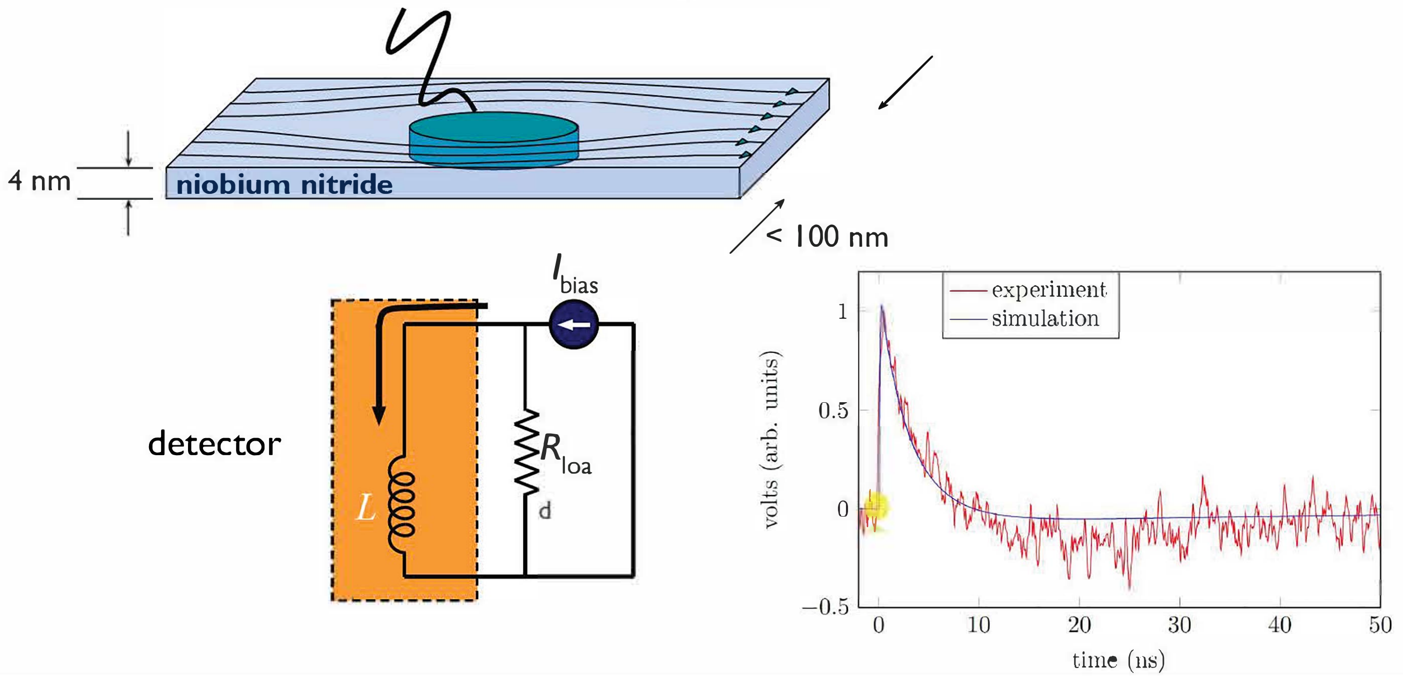
superconductor is biased near its transition



Absorption

Critical Temperature ~ 11 K

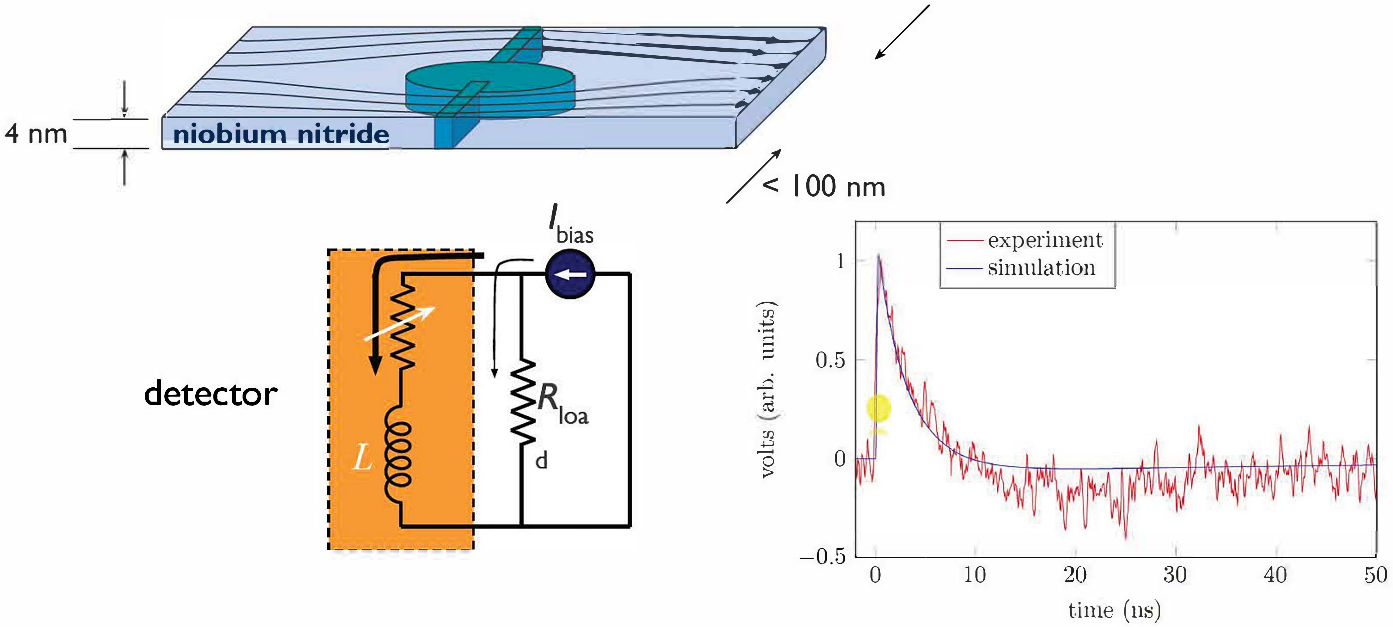
photon-induced hotspot forces bias current above critical density



Breakdown

Critical Temperature ~ 11 K

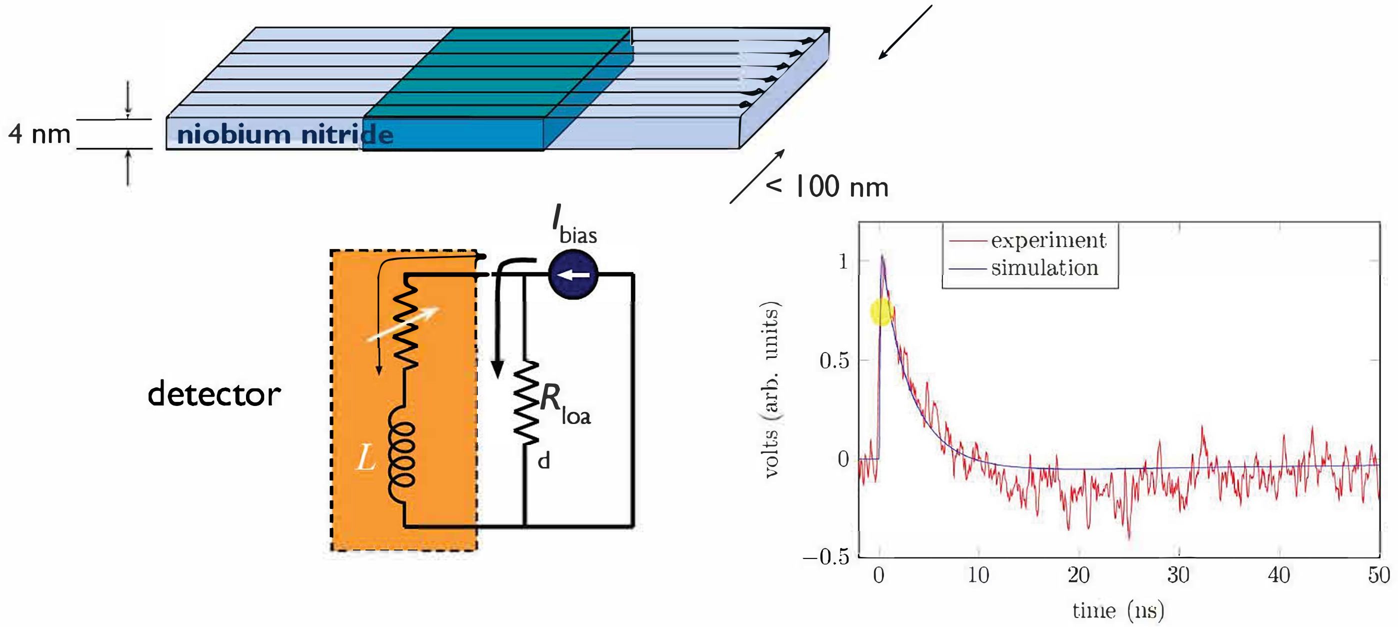
resistive barrier spans nanowire



Acceleration/Heating

Critical Temperature ~ 11 K

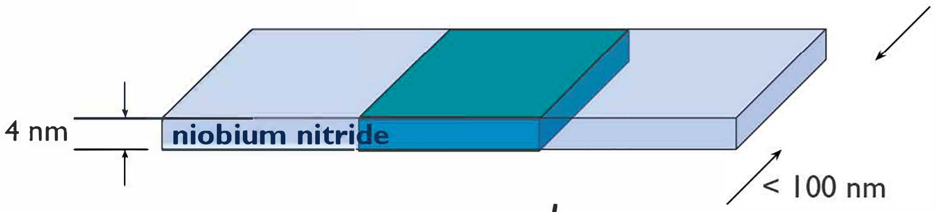
resistance grows from heating



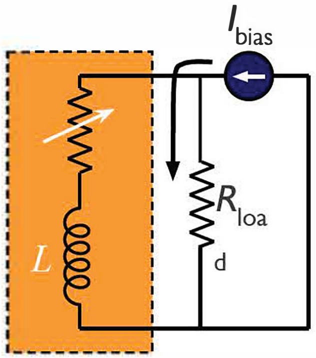
Diversion of Current

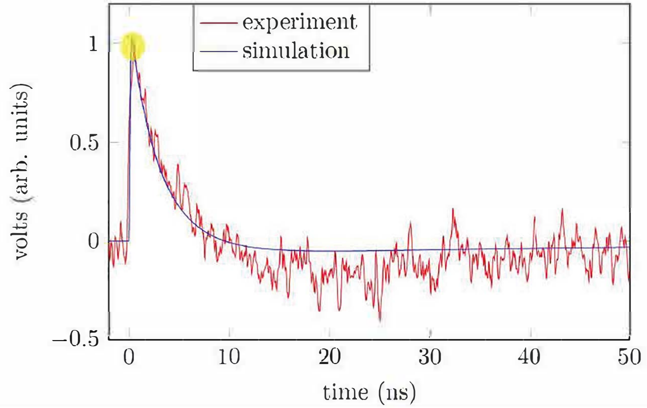
Critical Temperature ~ 11 K

current is diverted



detector



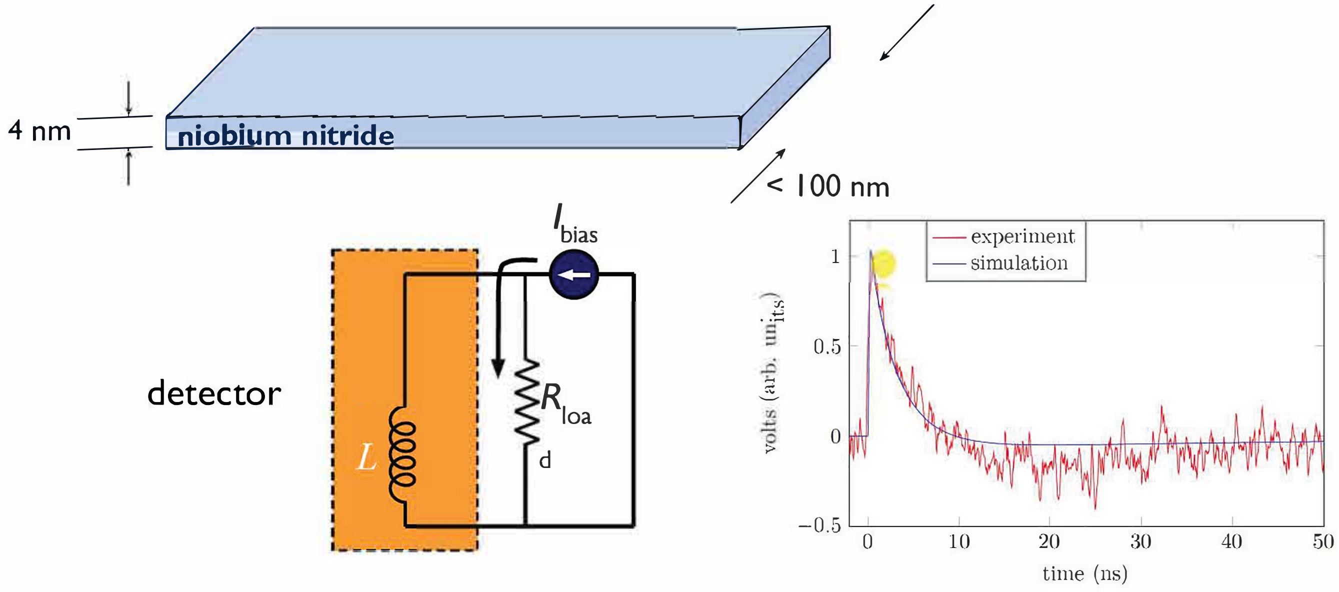


Cooling

current is diverted

Critical Temperature ~ 11 K

superconductivity is restored



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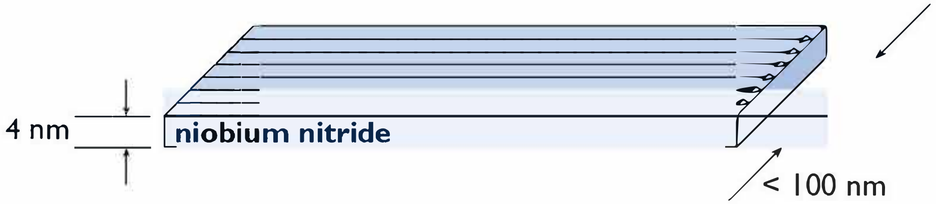
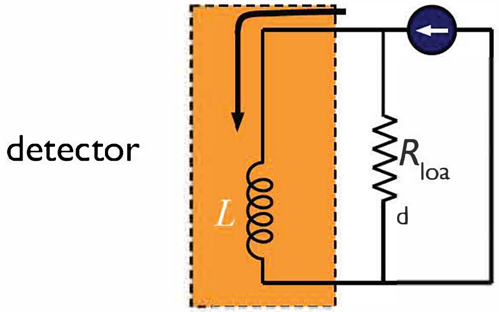
This plenary presentation was given at the virtual EUCAS 2021, September 5-10, 2021.

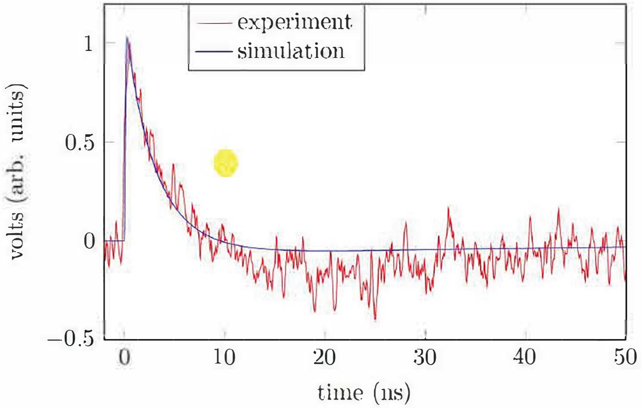
Reset

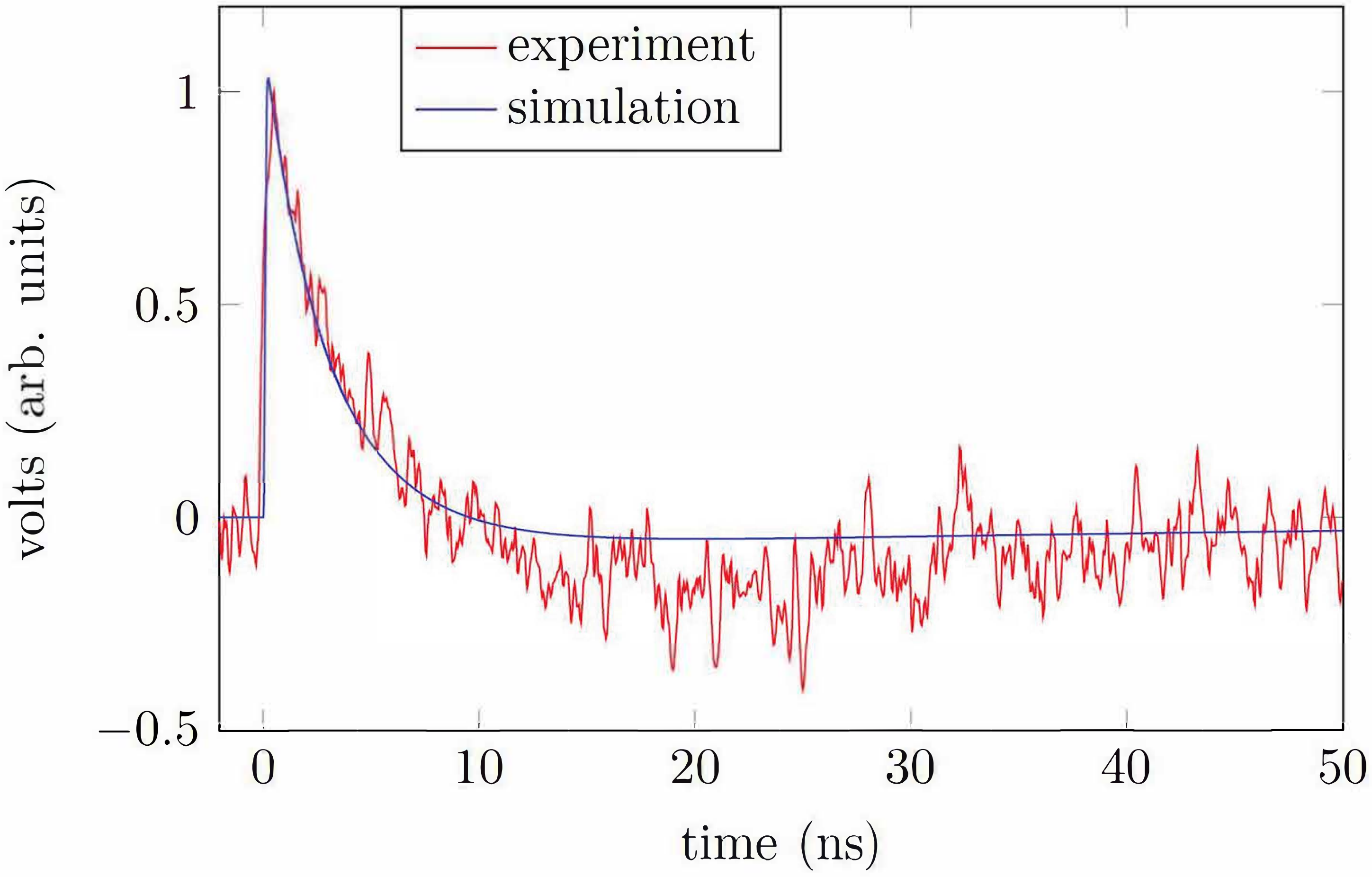
Critical Temperature ~ 11 K

bias current is restored

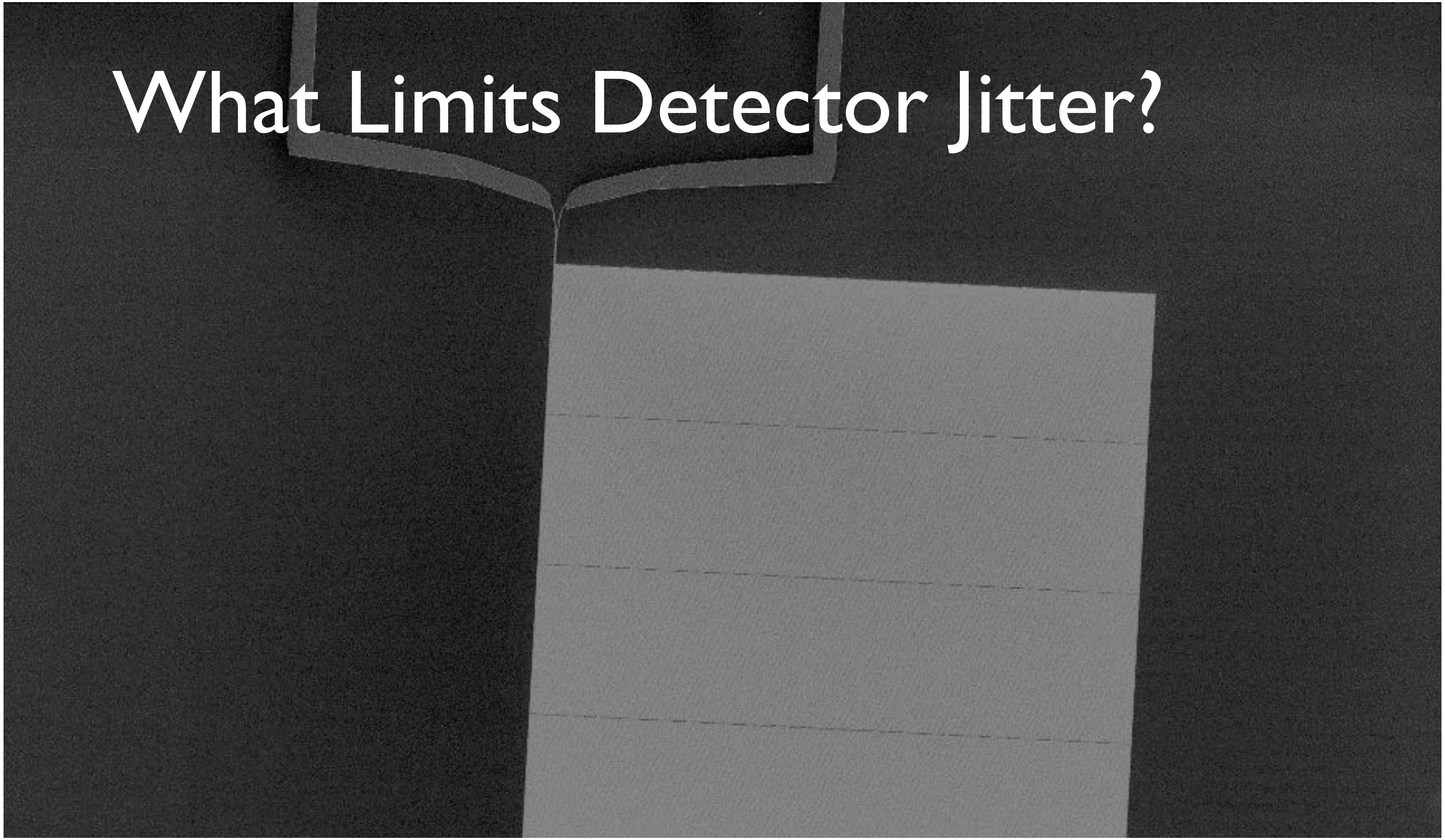







experiment
simulation
volts (arb. units)
1
0.5
0
−0.5
0
10
20
30
40
50
time (ns)

What Limits Detector Jitter?



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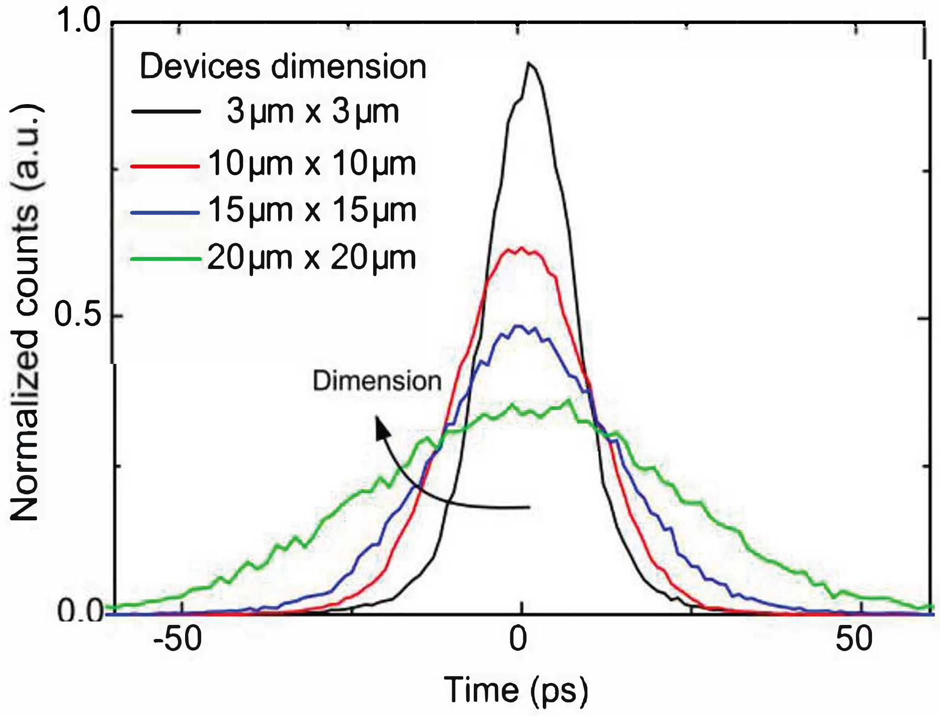
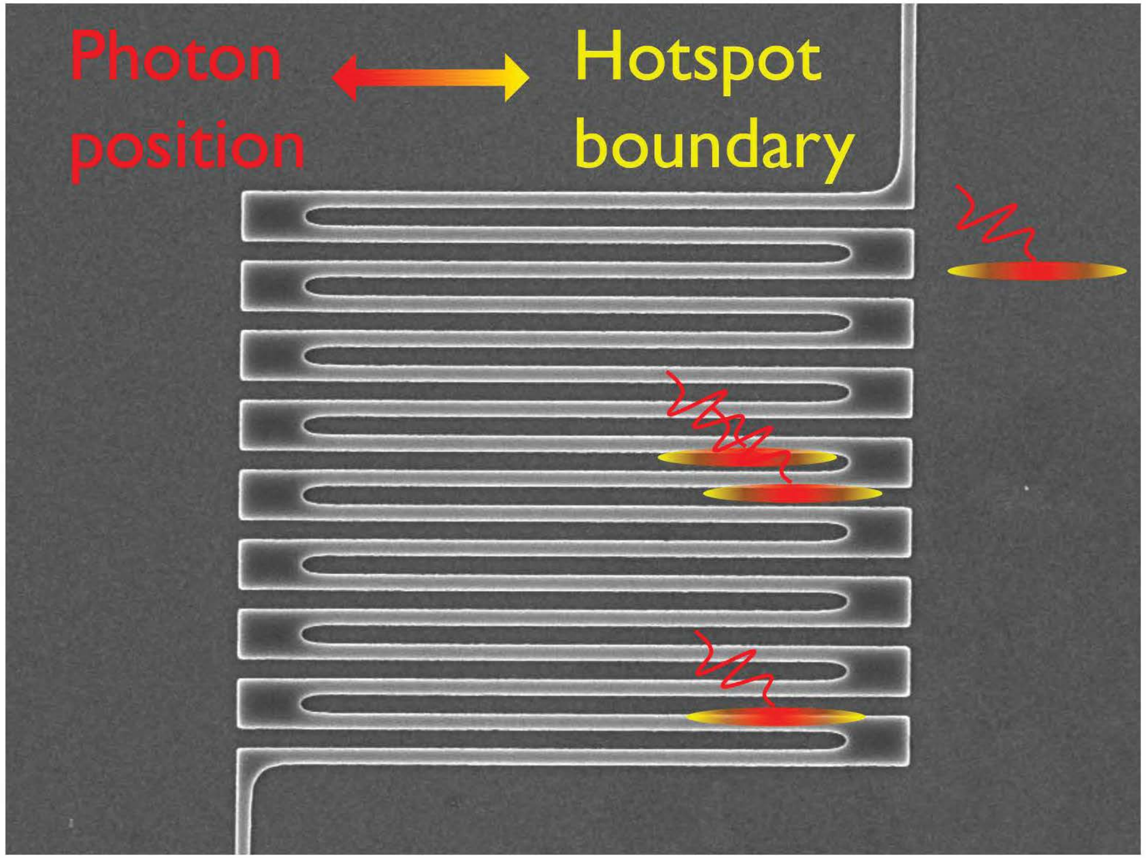
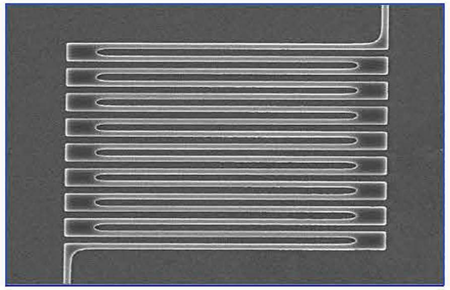
Timing jitter limited by detector geometry



Calandri et al., *Appl. Phys. Lett.*, 109 (15) 152601(2016).

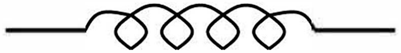

Photon position
Hotspot boundary

Q: what is the equivalent circuit model of an SNSPD?



Inductor

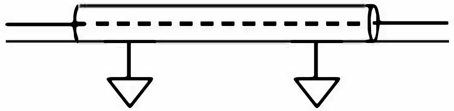
L_K



Lumped device
SNSPD

Transmission line

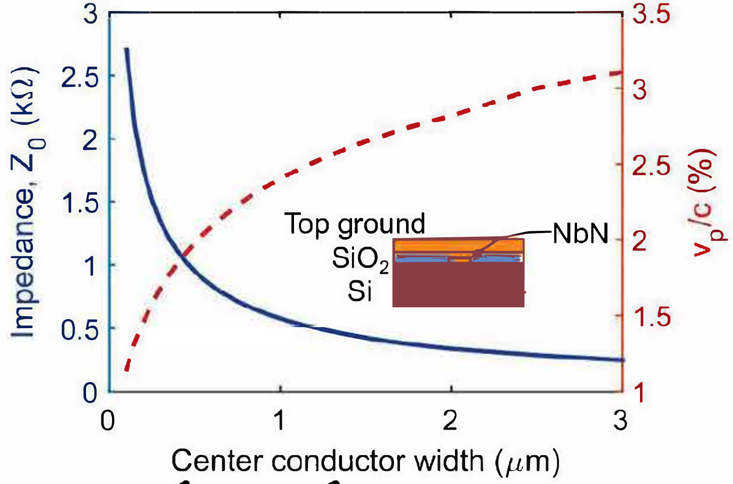
L, Z_n, V_n

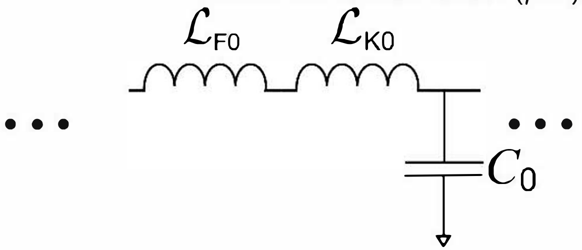


Distributed device
Imager

Slow-wave transmission line

A typical nanowire transmission line





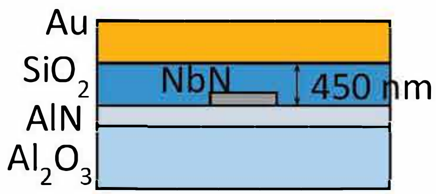
For a ~ 5 nm thick 300 nm wide NbN microstrip,

$\mathcal{L}_{K0} \approx 212\mu_0 \quad \mathcal{L}_{F0} \approx 0.3\mu_0 \quad \mathcal{C}_0 \approx 21\epsilon_0$

Measured group velocities to date

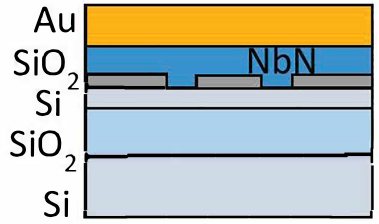
Signal speed ~2%*c* = 6 µm / ps

Zhao et al. Nat. Photonics 11, 247 (2017)



Signal speed 1.6%*c* = 4.8 µm / ps

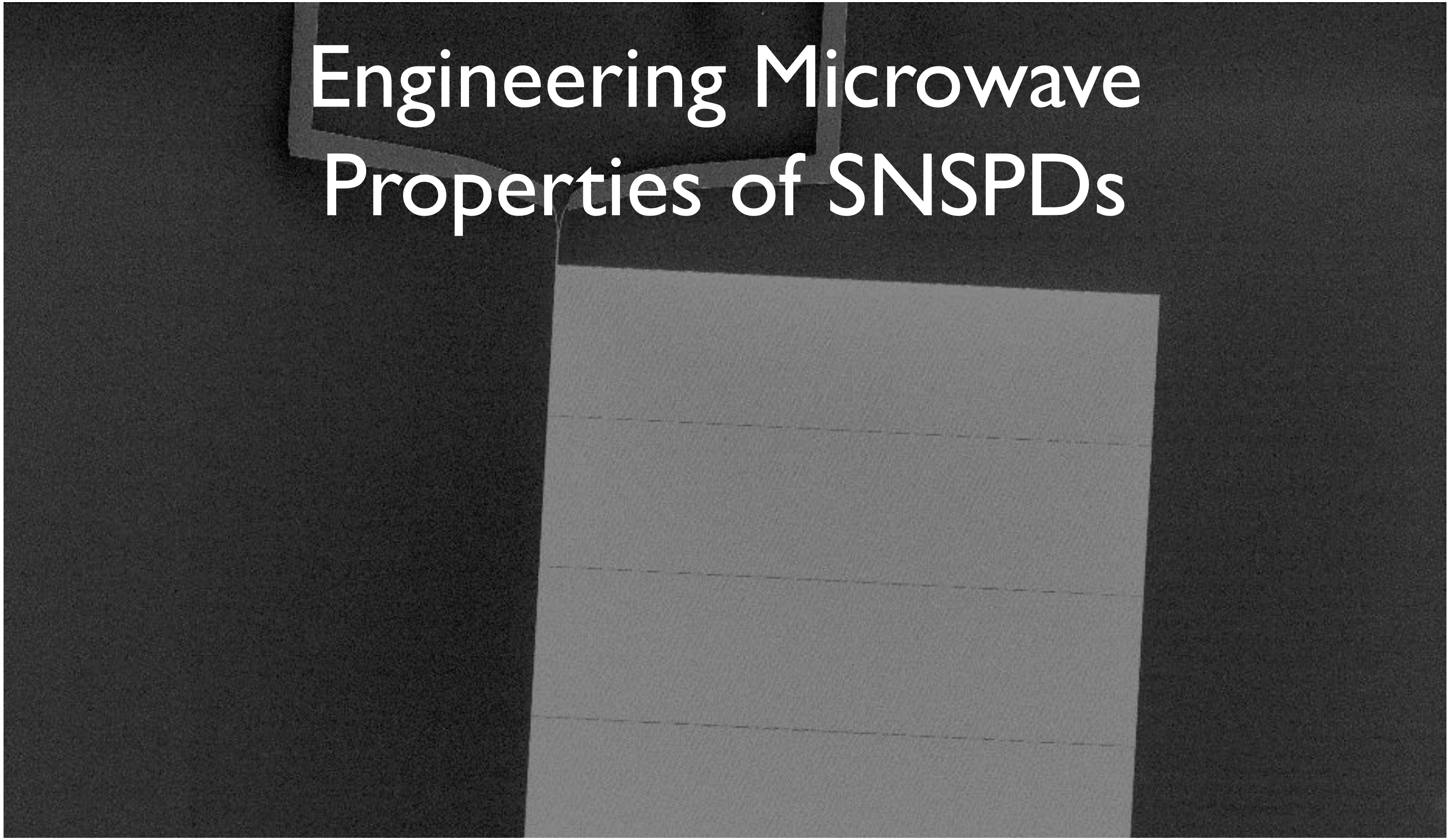
Zhu et al. Nat. Nanotech. 13, 596 (2018)



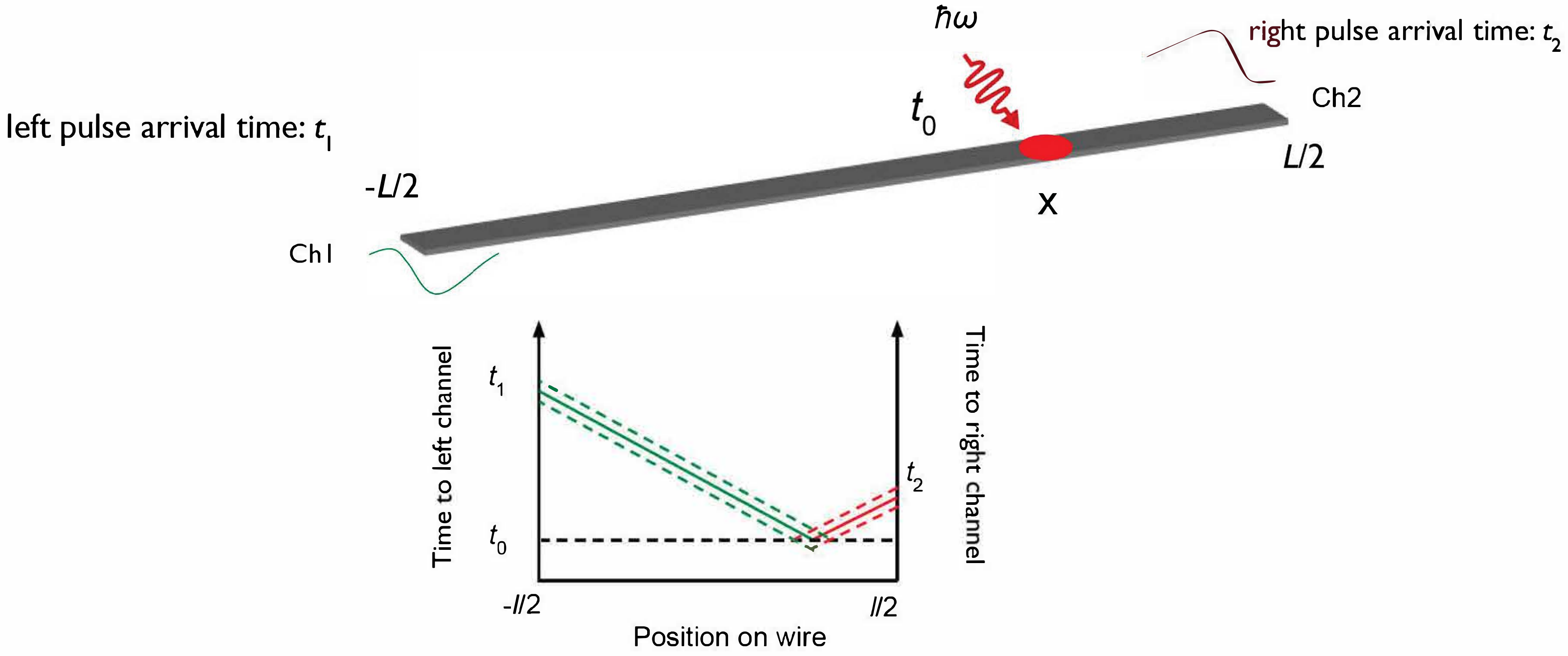
Signal speed = 2.7 µm/ps

Zhu et al. (2018), unpublished

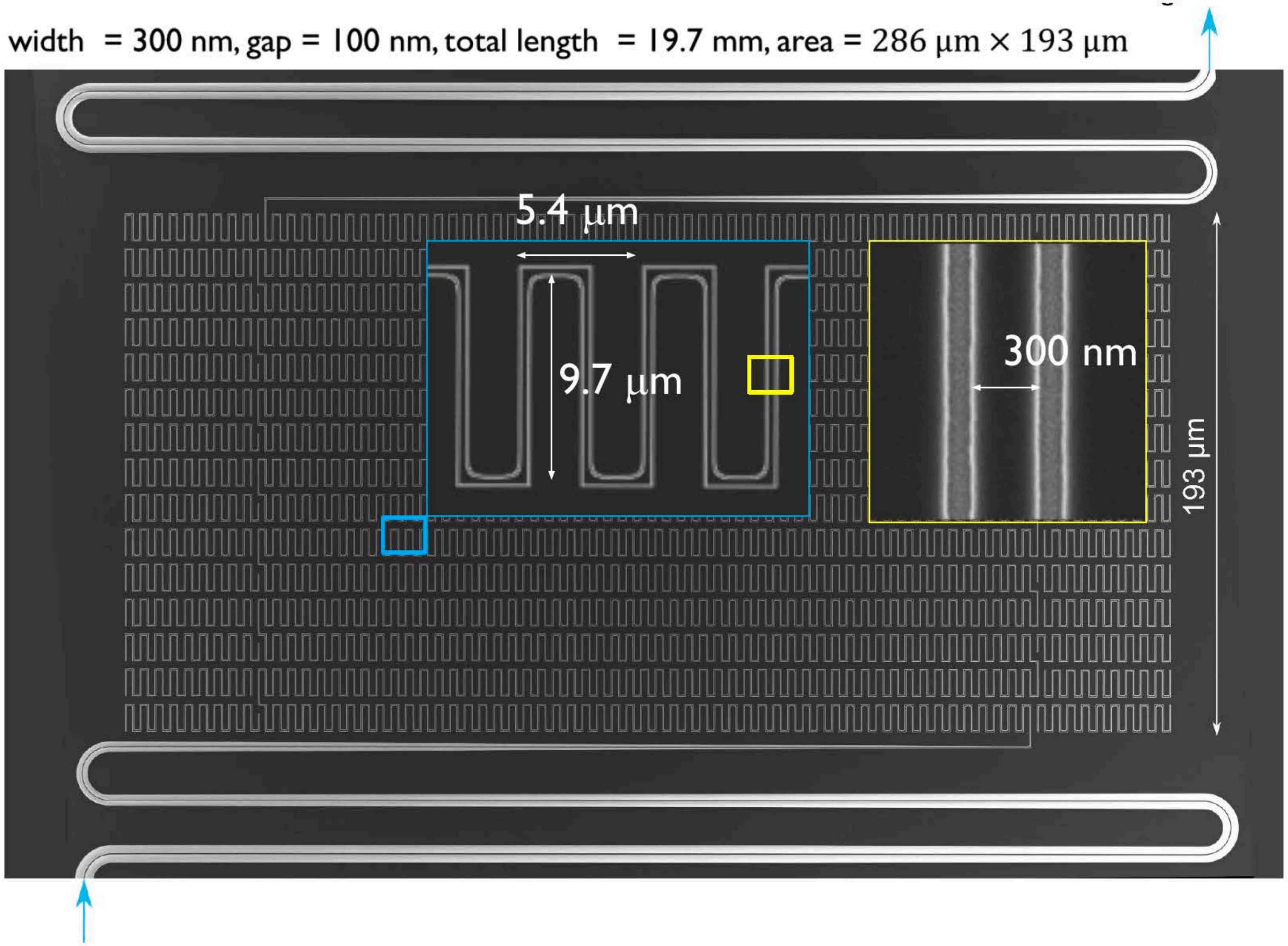
*In collaboration with **Daniel Santavicca (UNF)***


Engineering Microwave
Properties of SNSPDs

Spatial and temporal resolution in a wire



spatial resolution = timing jitter × speed of light width = 300 nm, gap = 100 nm, total length = 19.7 mm, area = 286 μm × 193 μm



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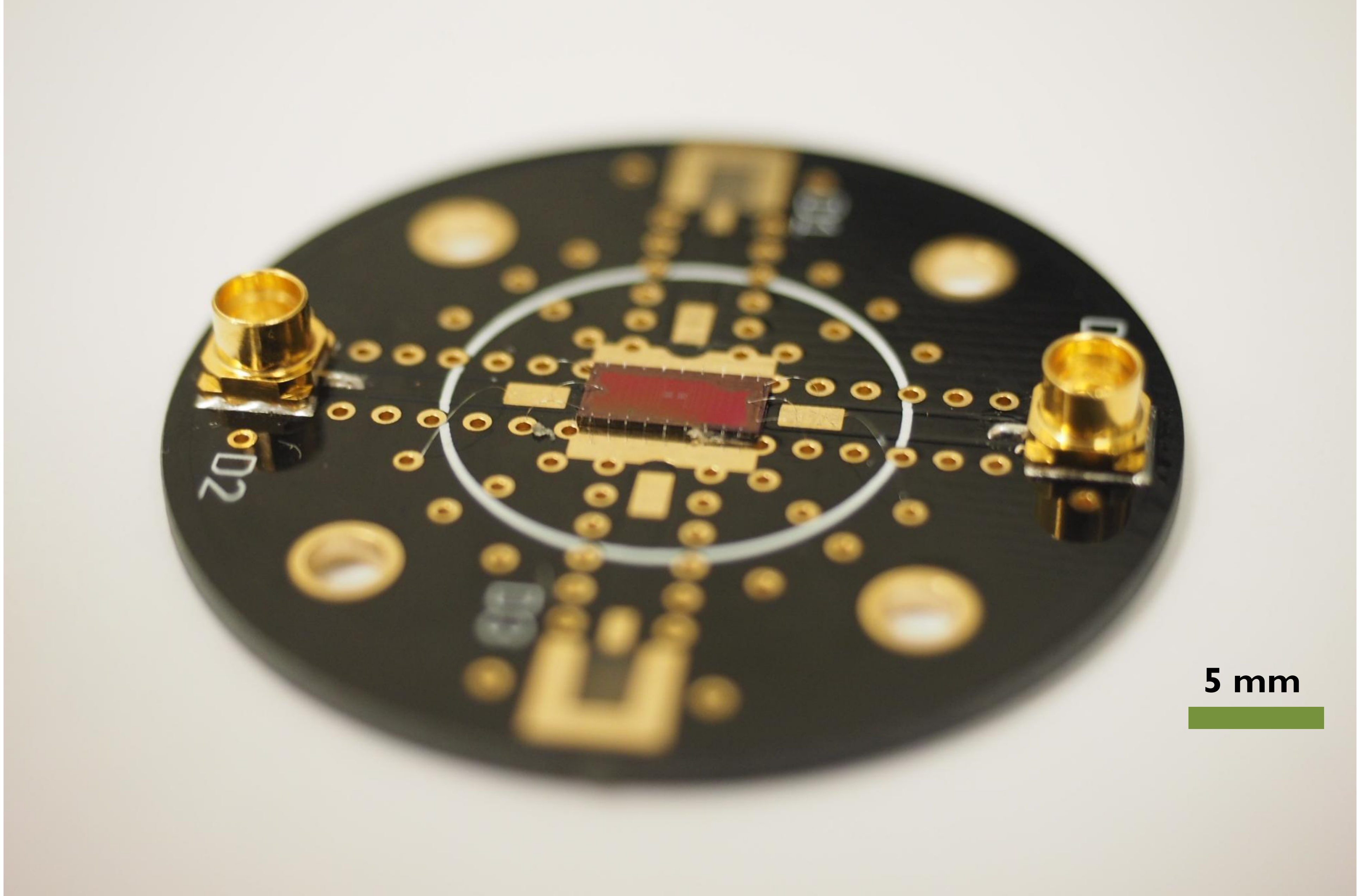
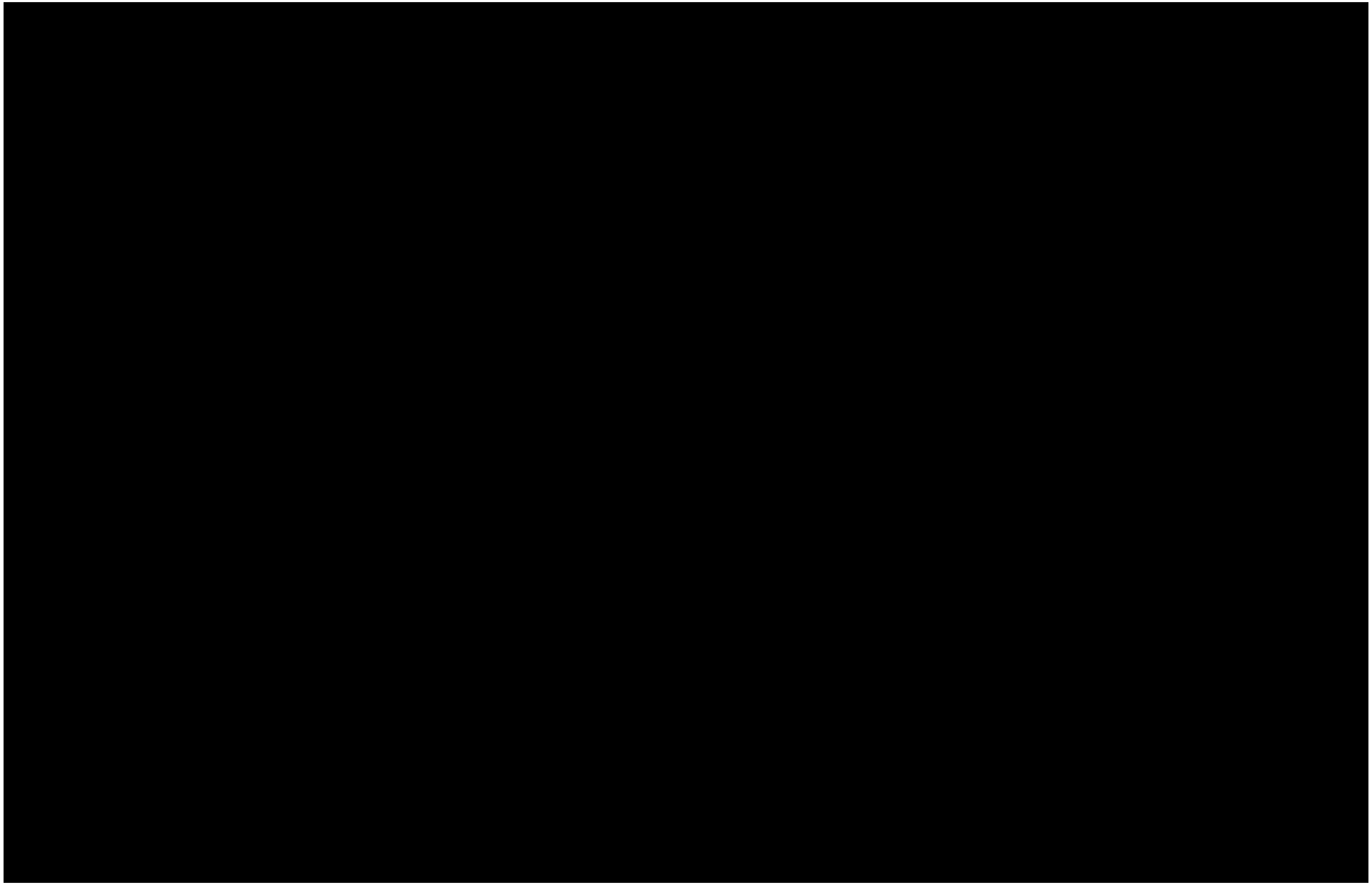
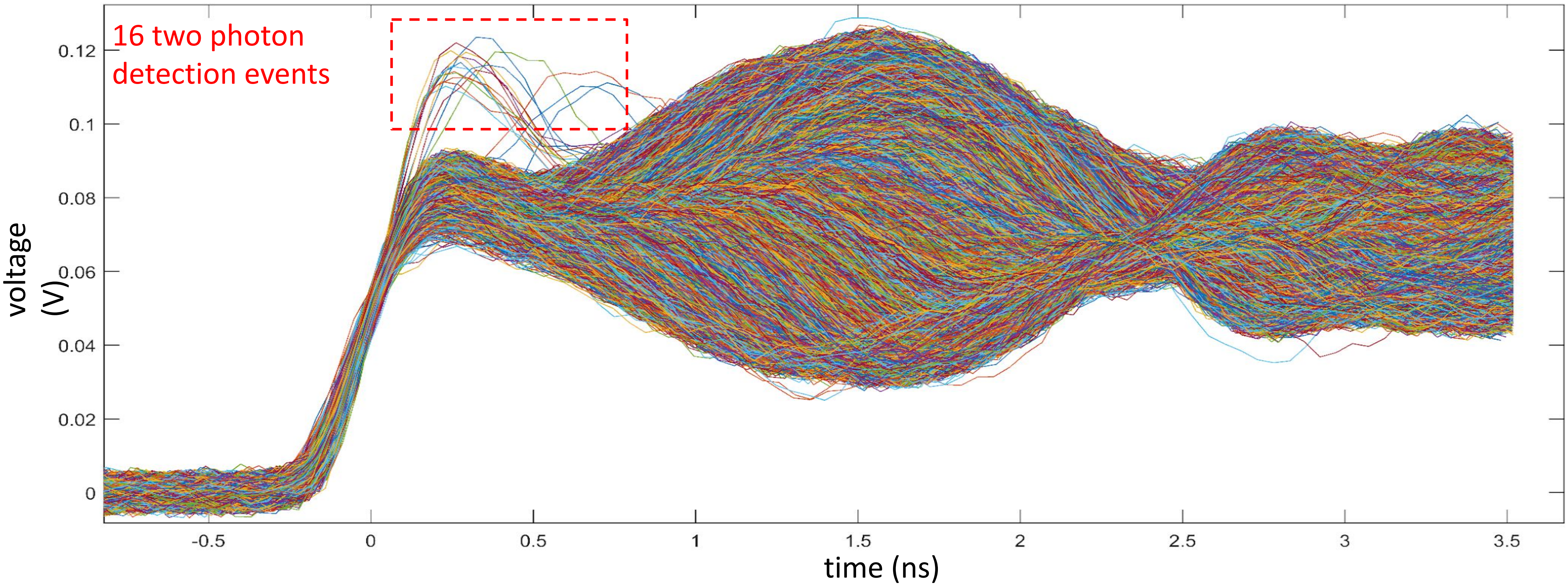
Two connectors for one imager (>500 pixels)





Detecting two-photon-firing events

16 two-photon firing events among 50,000 photon detection events
(flood illumination over the entire area)



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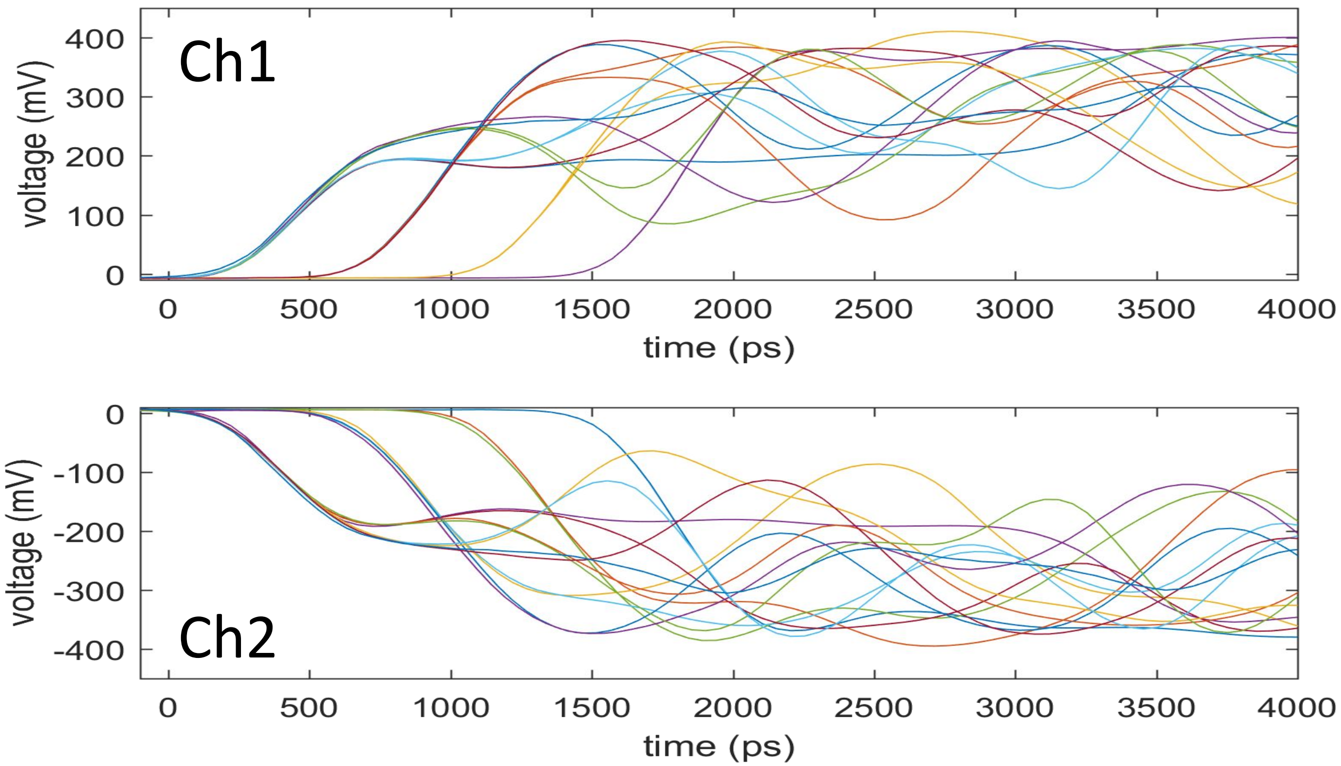
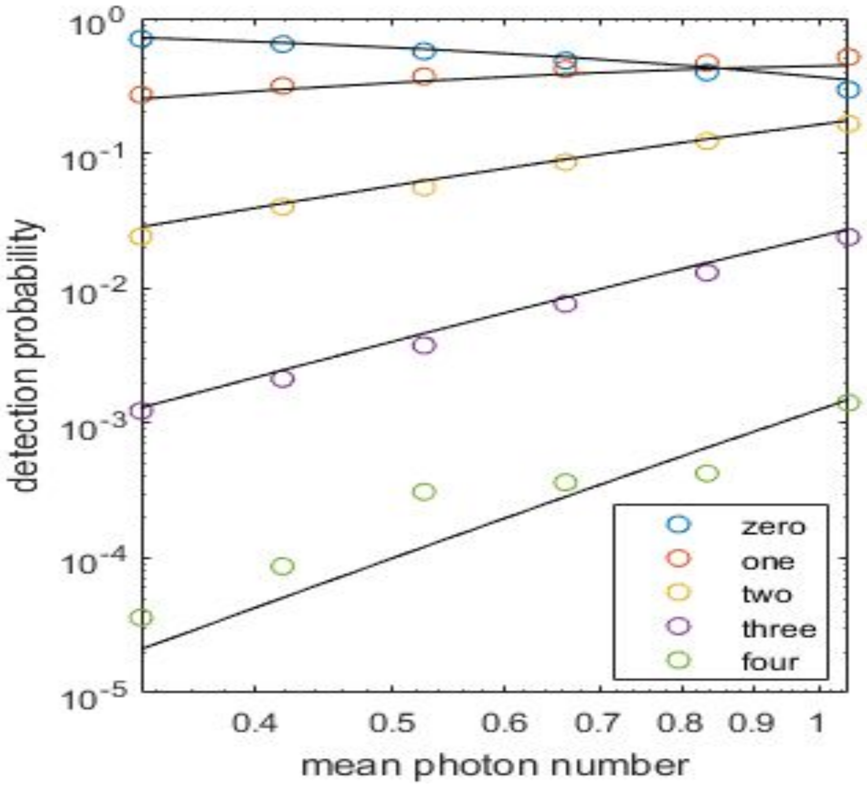
Multi-photon detection

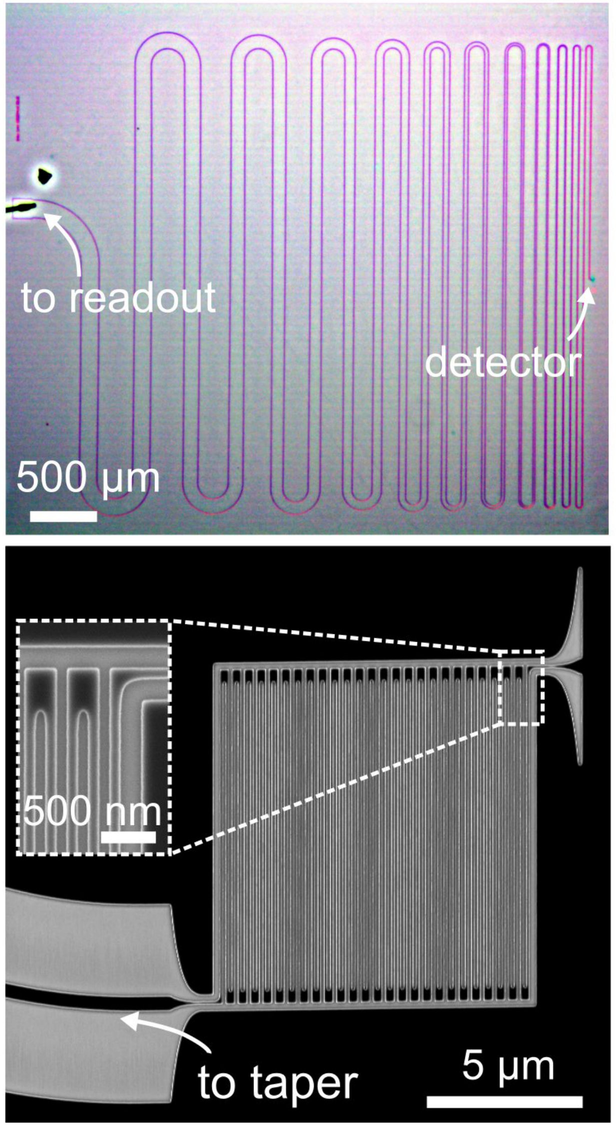
single photon (1), two photon (6), three photon (4), four count (1)

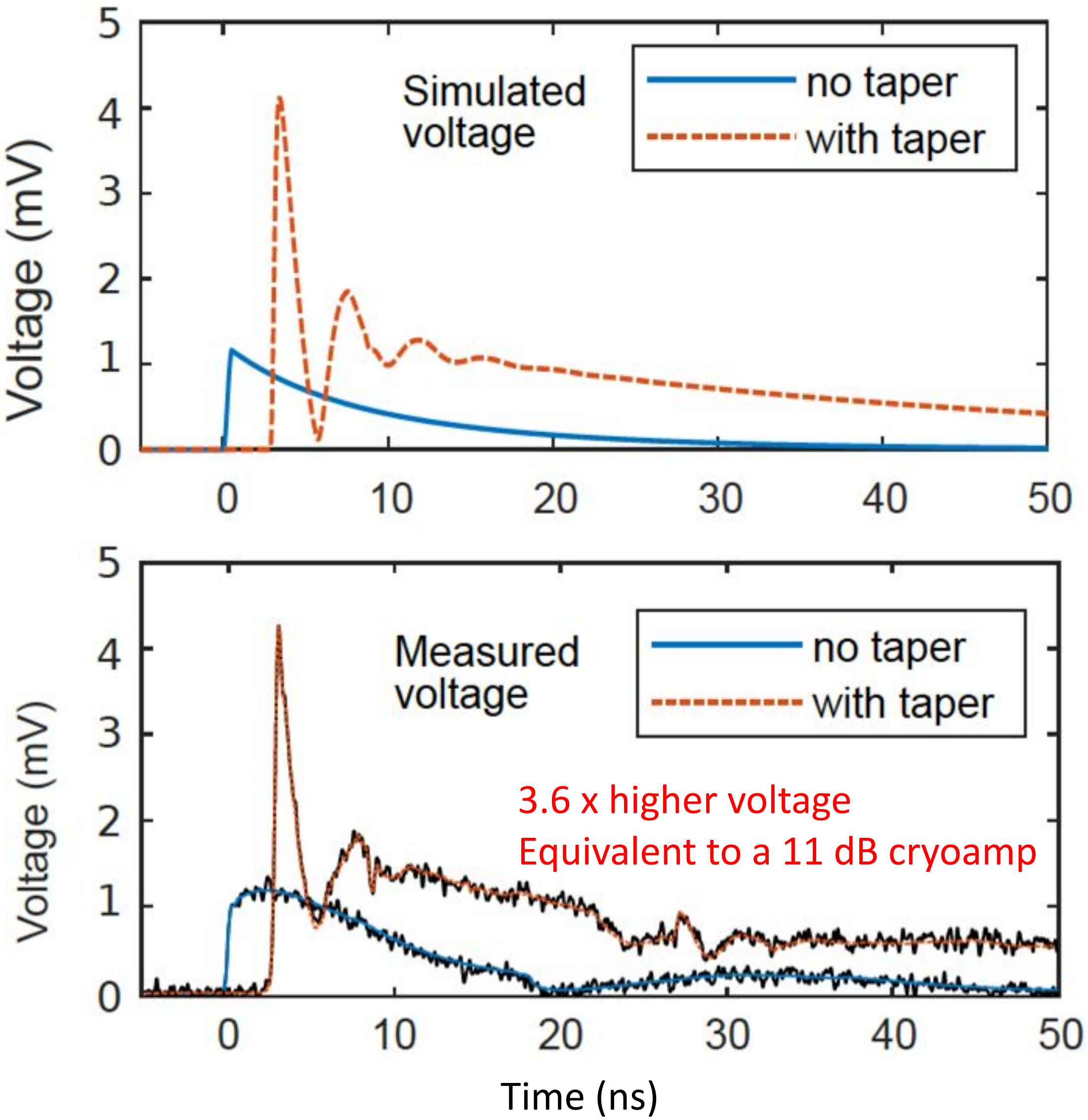
Photon number resolving!





Increasing output voltage



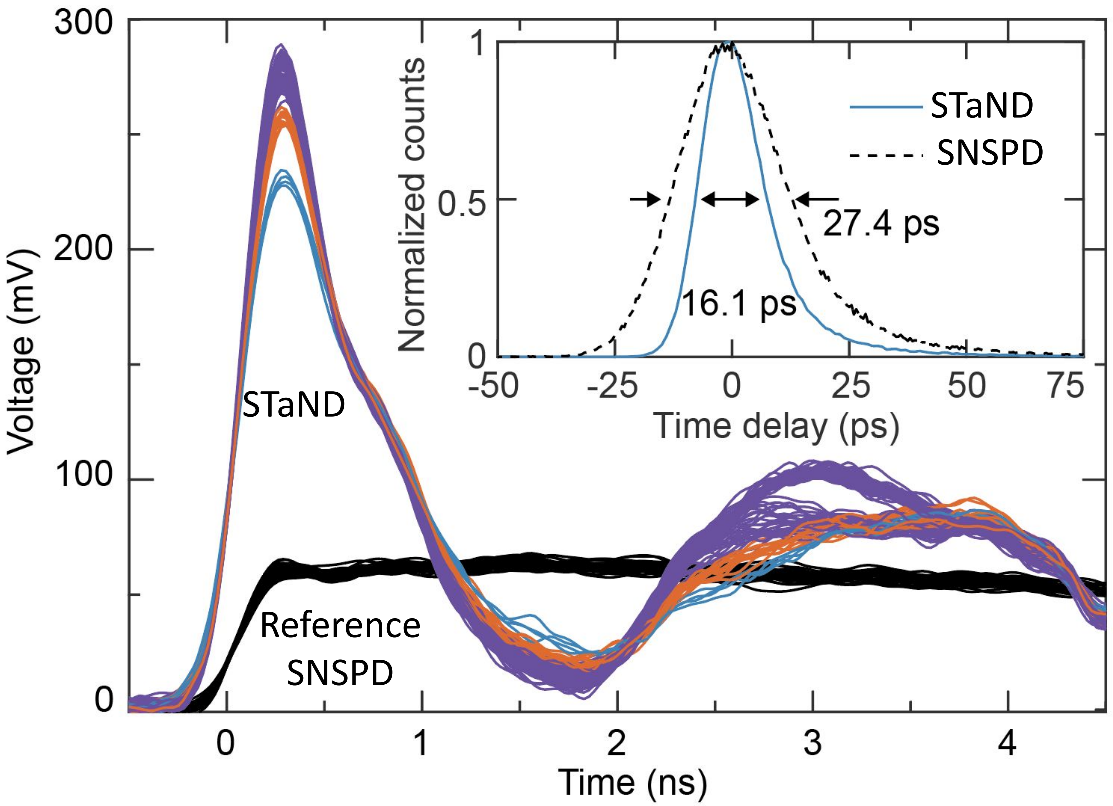


3.6 x higher voltage
Equivalent to a 11 dB cryoamp

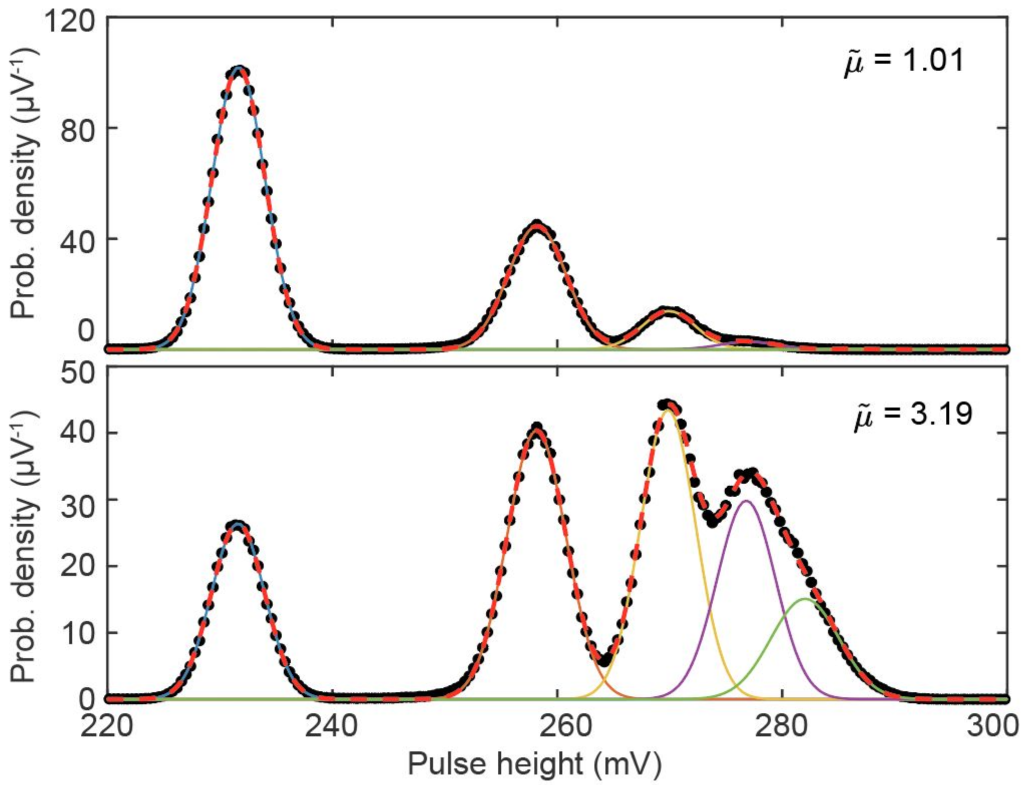
Zhu, D., Colangelo, M., Korzh, B.A., Zhao, Q.Y., Frasca, S., Dane, A.E., Velasco, A.E., Beyer, A.D., Allmaras, J.P., Ramirez, E., Strickland, W.J., Santavicca, D., Shaw, M.D. and Berggren, K.K. - *Appl. Phys. Lett.* 114(4), 042601 (2019)

Photon Number Resolution

Jitter reduction



Photon number resolution

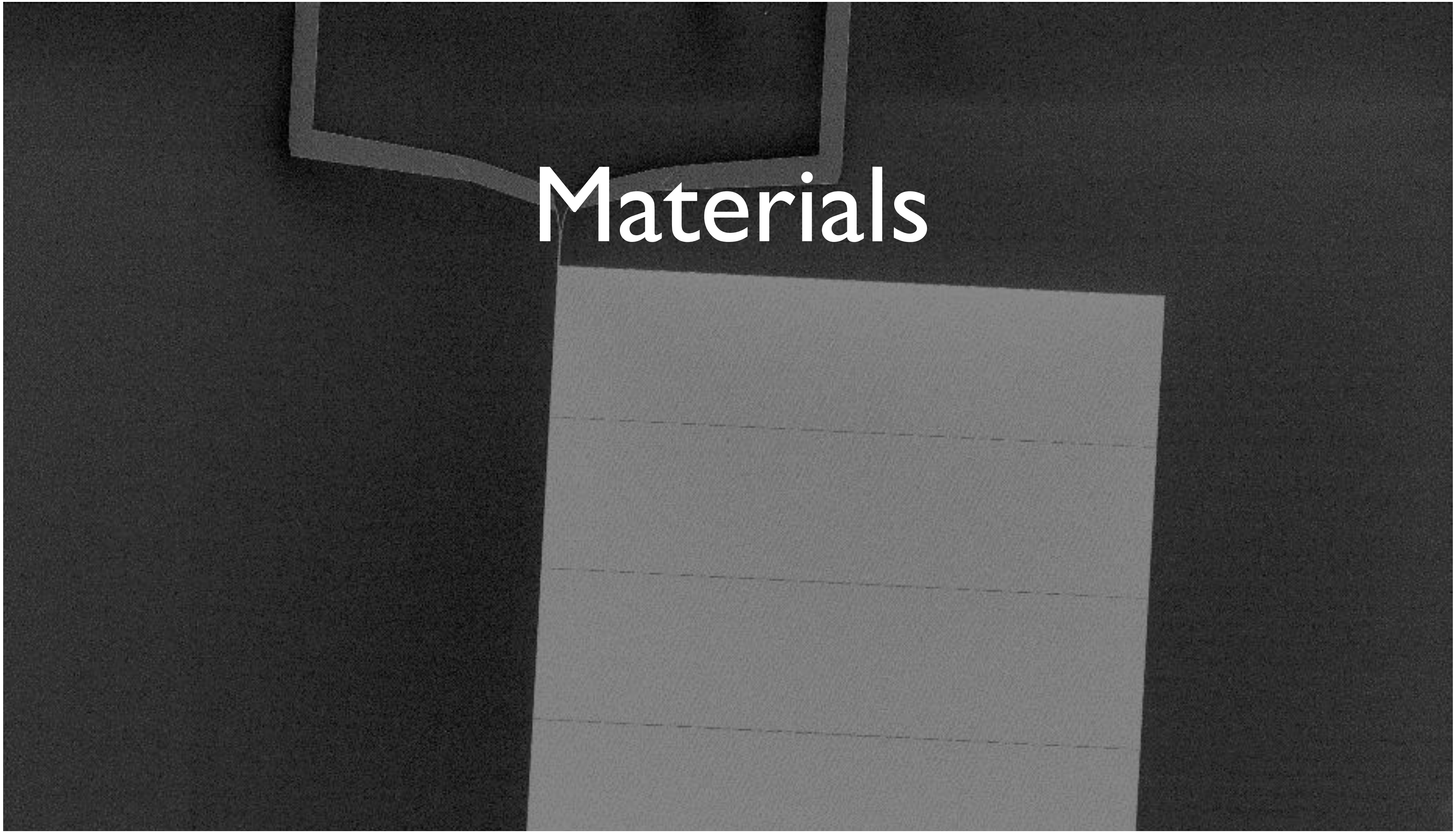


*Unpublished data

Tapered readout has also enabled:

1. 25 ps jitter in NbN SNSPD without amplifier (measured at JPL)
2. sub-5 ps jitter in WSi using cryogenic amplifiers (Korzh et al. CLEO 2018, paper FW3F.3)

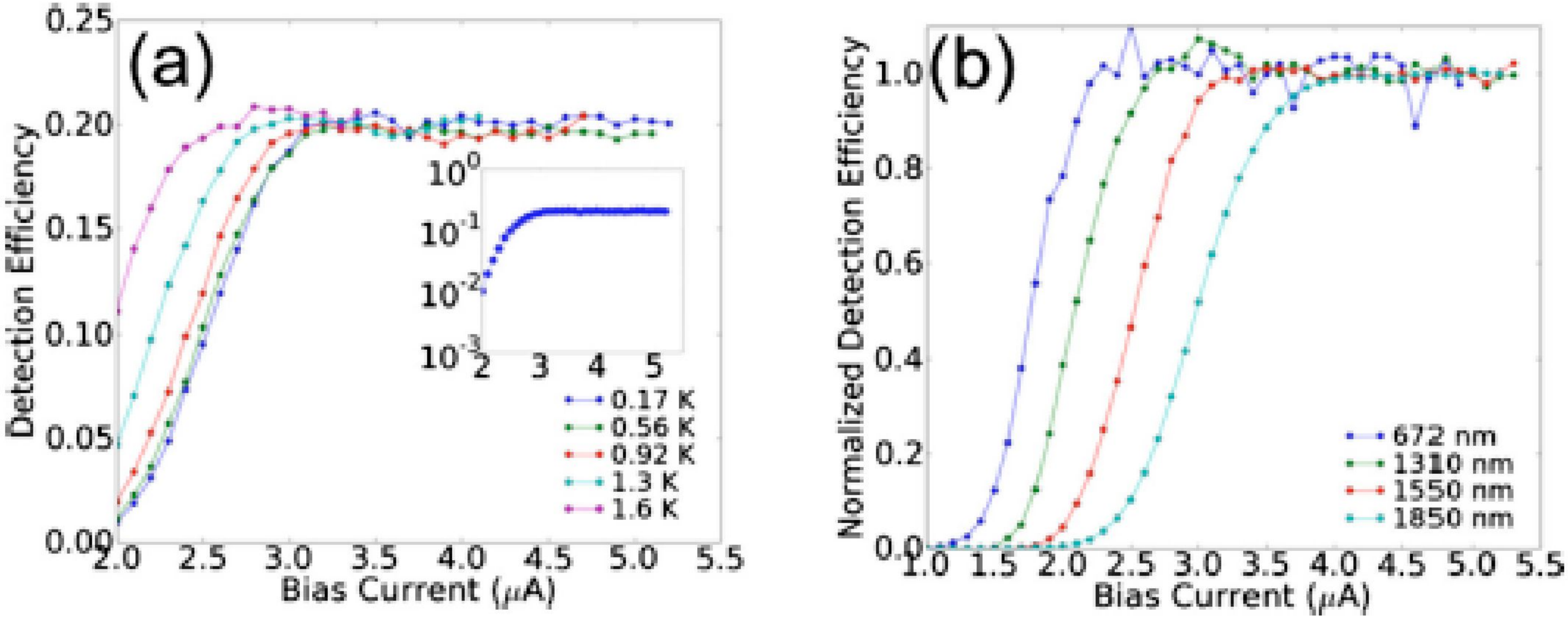
Materials



APPLIED PHYSICS LETTERS **98**, 251105 (2011)

Superconducting a-W_xSi_{1-x} nanowire single-photon detector with saturated internal quantum efficiency from visible to 1850 nm

Burm Baek,[a)] Adriana E. Lita, Varun Verma, and Sae Woo Nam
National Institute of Standards and Technology, 325 Broadway, Boulder, Colorado 80305, USA



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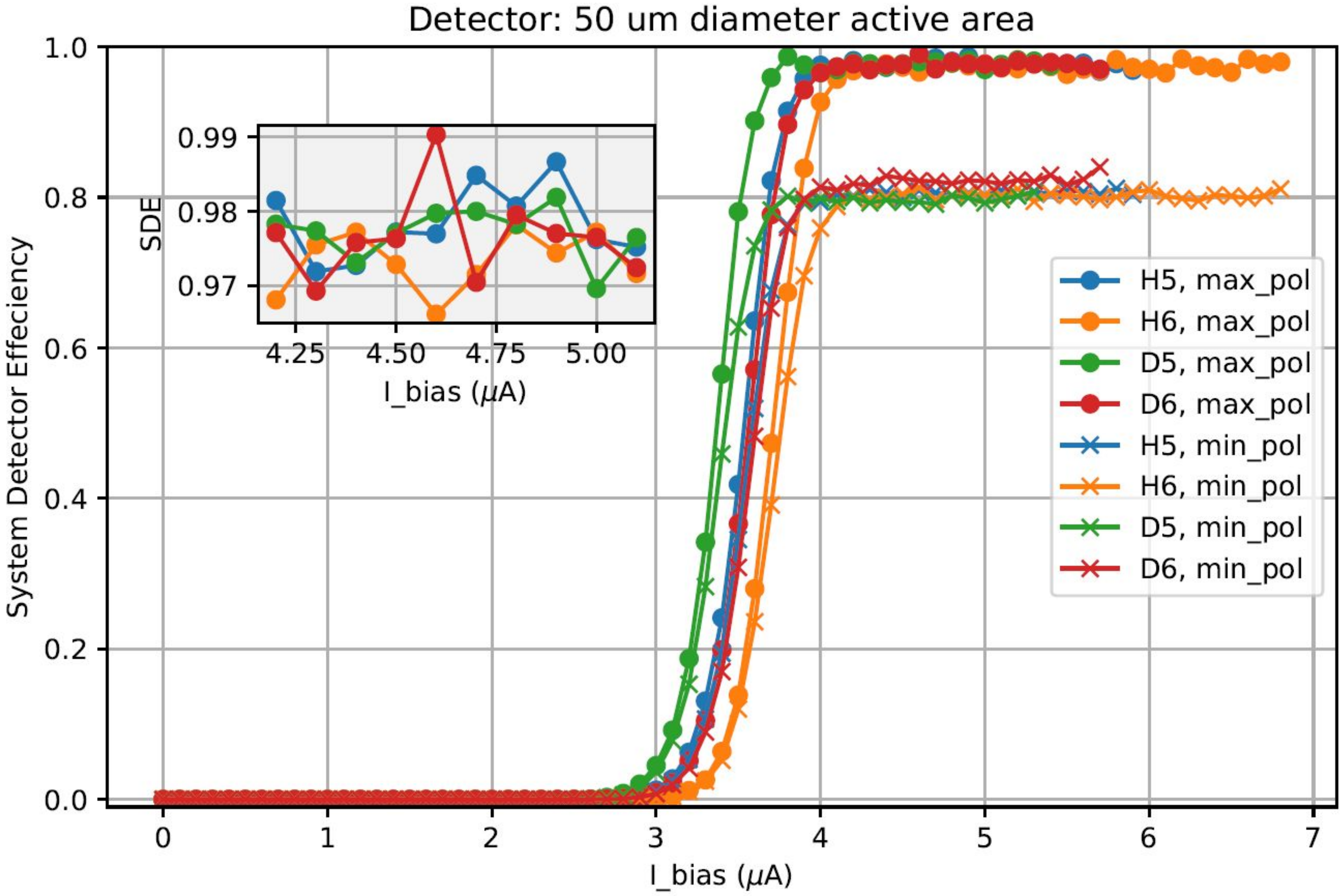
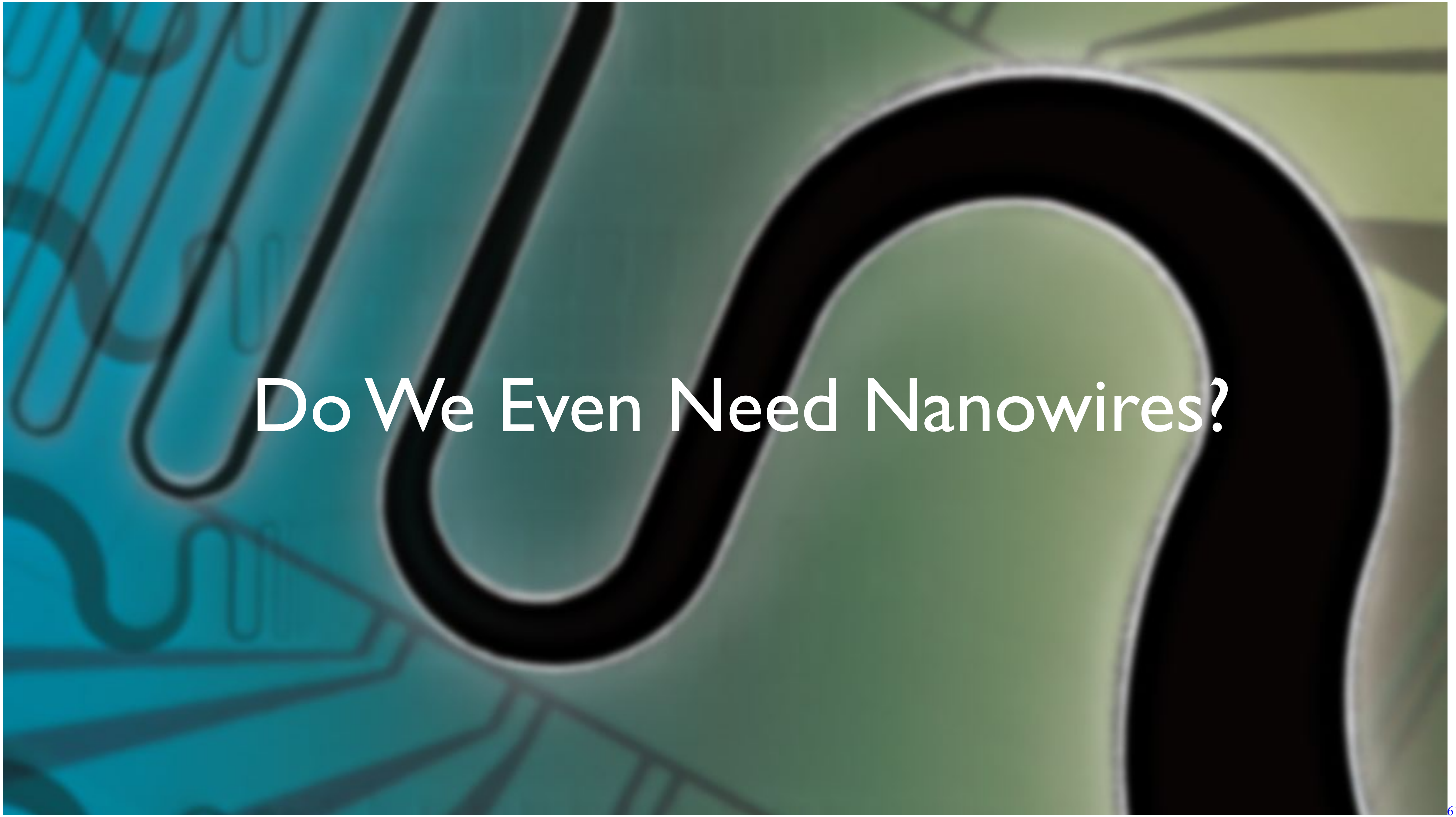
MoSi



NIST, Reddy et al., CLEO/QELS 2019 https://doi.org/10.1364/CLEO_QELS.2019.FF1A.3


Do We Even Need Nanowires?

Operating range of SNSPDs

PHYSICAL REVIEW APPLIED **7**, 034014 (2017)

Single-Photon Detection by a Dirty Current-Carrying Superconducting Strip Based on the Kinetic-Equation Approach

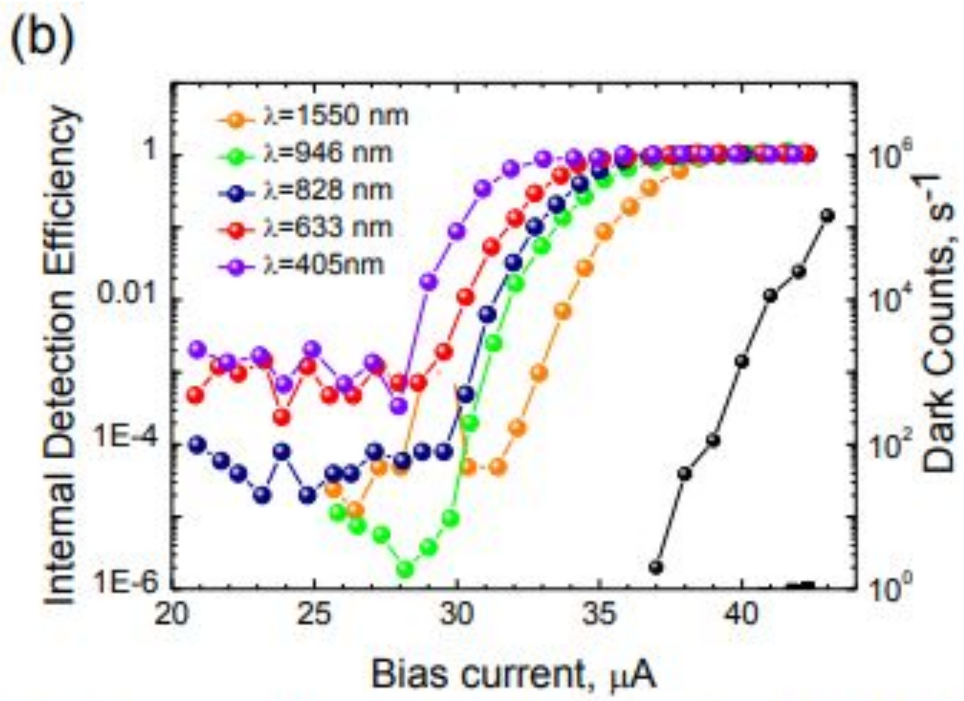
D. Yu. Vodolazov

Institute for Physics of Microstructures, Russian Academy of Sciences, 603950 Nizhny Novgorod, GSP-105, Russia

(Received 14 December 2016; revised manuscript received 30 January 2017; published 23 March 2017)

Using a kinetic-equation approach, we study the dynamics of electrons and phonons in current-carrying superconducting nanostrips after the absorption of a single photon of the near-infrared or optical range. We find that the larger the $C_e/C_{\rm ph}|_{T_c}$ ratio (where T_c is the critical temperature of a superconductor and C_e and $C_{\rm ph}$ are specific heat capacities of electrons and phonons, respectively), the larger the portion of the photon's energy goes to electrons. The electrons become more strongly heated and hence can thermalize faster during the initial stage of hot-spot formation. The thermalization time $\tau_{\rm th}$ can be less than 1 ps for superconductors with $C_e/C_{\rm ph}|_{T_c} \gg 1$ and a small diffusion coefficient of $D \simeq 0.5$ cm^2/s when thermalization occurs, mainly due to electron-phonon and phonon-electron scattering in a relatively small volume of approximately $\xi^2 d$ (ξ is a superconducting coherence length, while $d < \xi$ is a thickness of the strip). For longer time spans, due to diffusion of hot electrons' effective temperature inside the hot spot decreases, the size of the hot spot increases, the superconducting state becomes unstable, and the normal domain spreads in the strip at a current larger than the so-called detection current. We find the dependence of the detection current on the photon's energy, the location of its absorption in the strip, the width of the strip, and the magnetic field, and we compare this dependence with existing experiments. Our results demonstrate that materials with $C_e/C_{\rm ph}|_{T_c} \ll 1$ are bad candidates for single-photon detectors due to a small transfer of the photon's energy to electronic system and a large $\tau_{\rm th}$. We also predict that even a several-micron-wide dirty superconducting bridge is able to detect a single near-infrared or optical photon if its critical current exceeds 70% of the depairing current and $C_e/C_{\rm ph}|_{T_c} \gtrsim 1$.

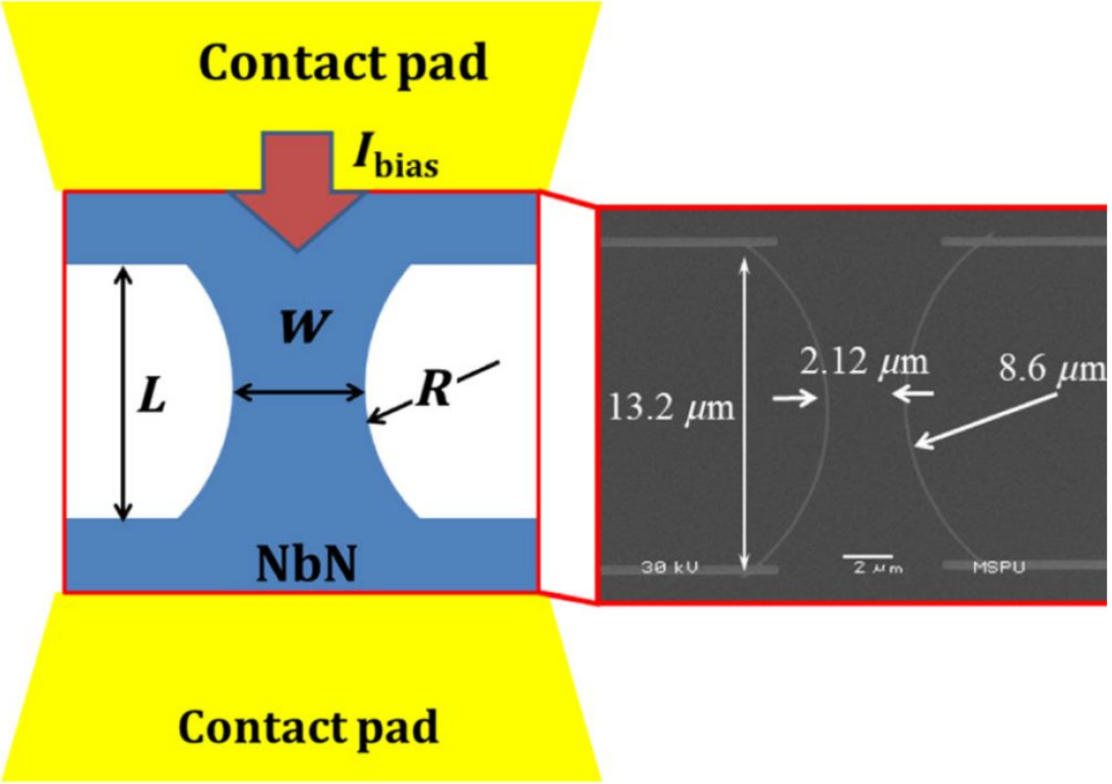
Korneeva, Y., Vodolazov, D., Florya, I., Manova, N., Smirnov, E., Korneev, A., Mikhailov, M., Goltsman, G., & Klapwijk, T. M. (2018). Single photon detection in micron scale NbN and α-MoSi superconducting strips. *EPJ Web of Conferences*, *190*, [04010]. https://doi.org/10.1051/epjconf/201819004010

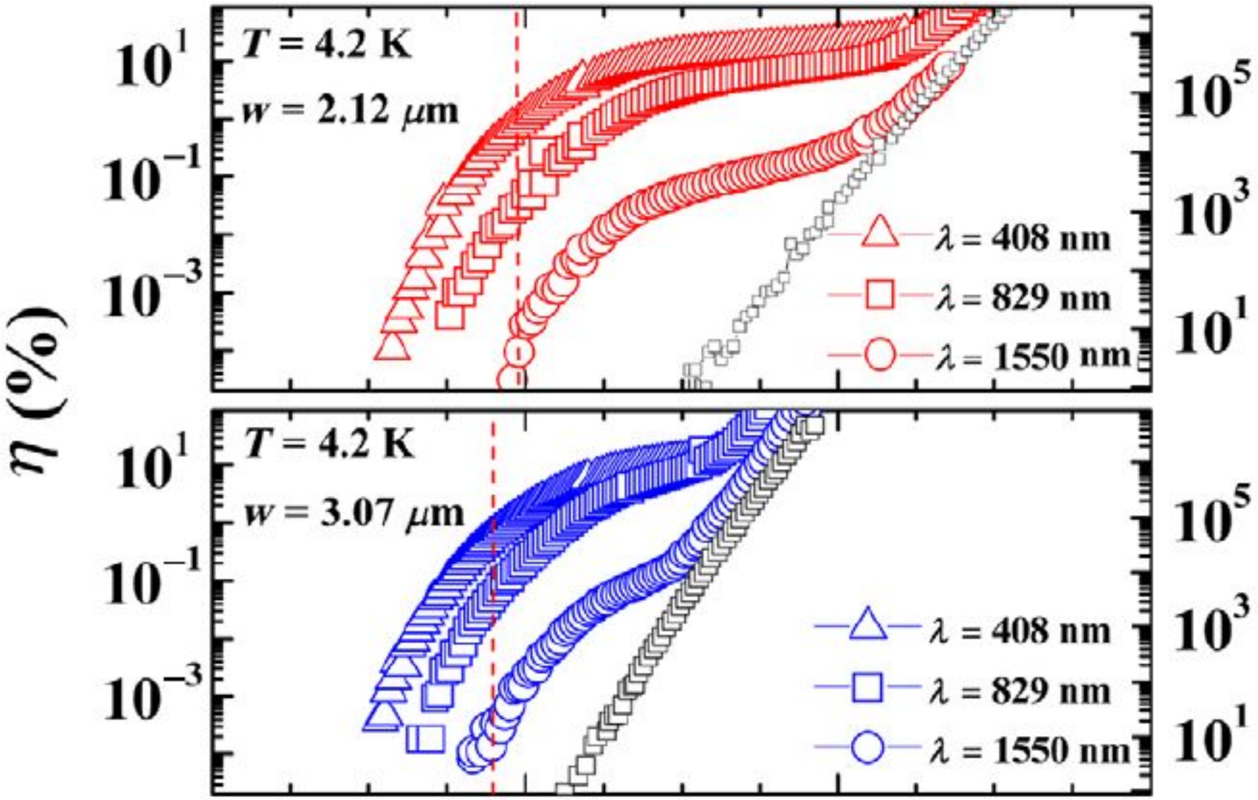


Single-photon detection in short micro-scale NbN wires

Suggested based on theory work by
D. Y. Vodolazov, Phys. Rev. Applied 7, 034014, 2017

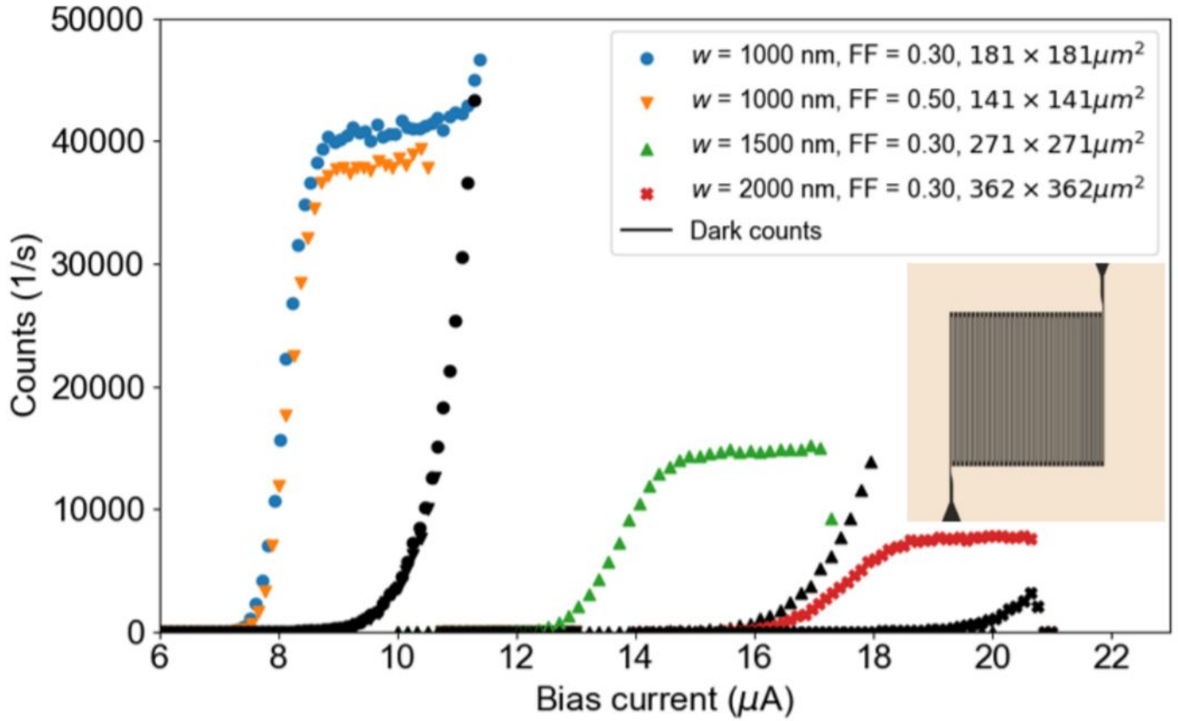
Goltsman's group at MSPU

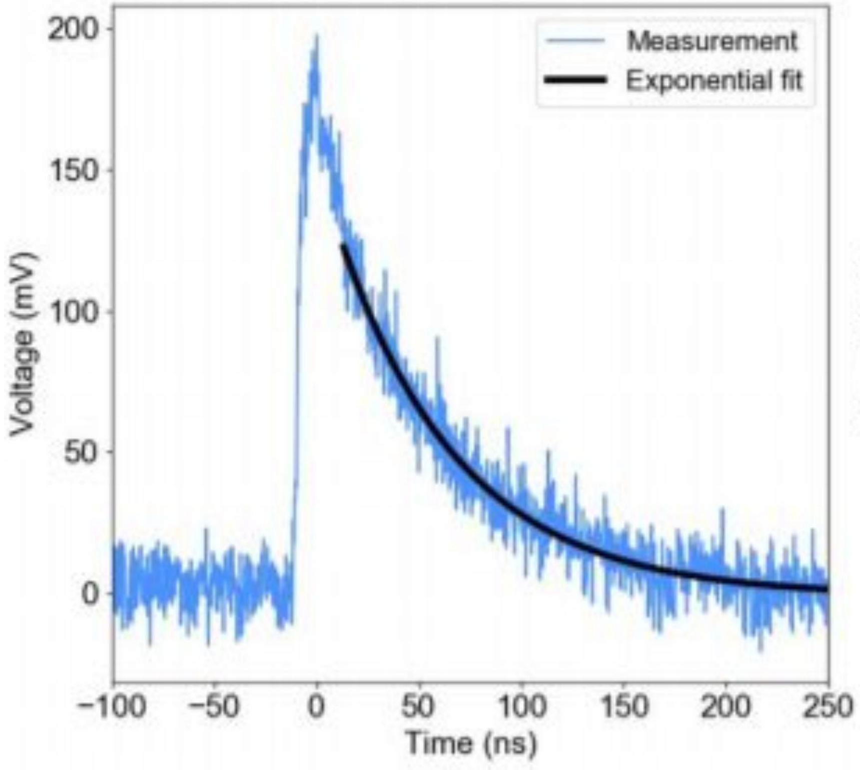




Yu. P. Korneeva and et. al.,Phys. Rev. Applied 9, 064037, 2018

Silicon-rich WSi microwires

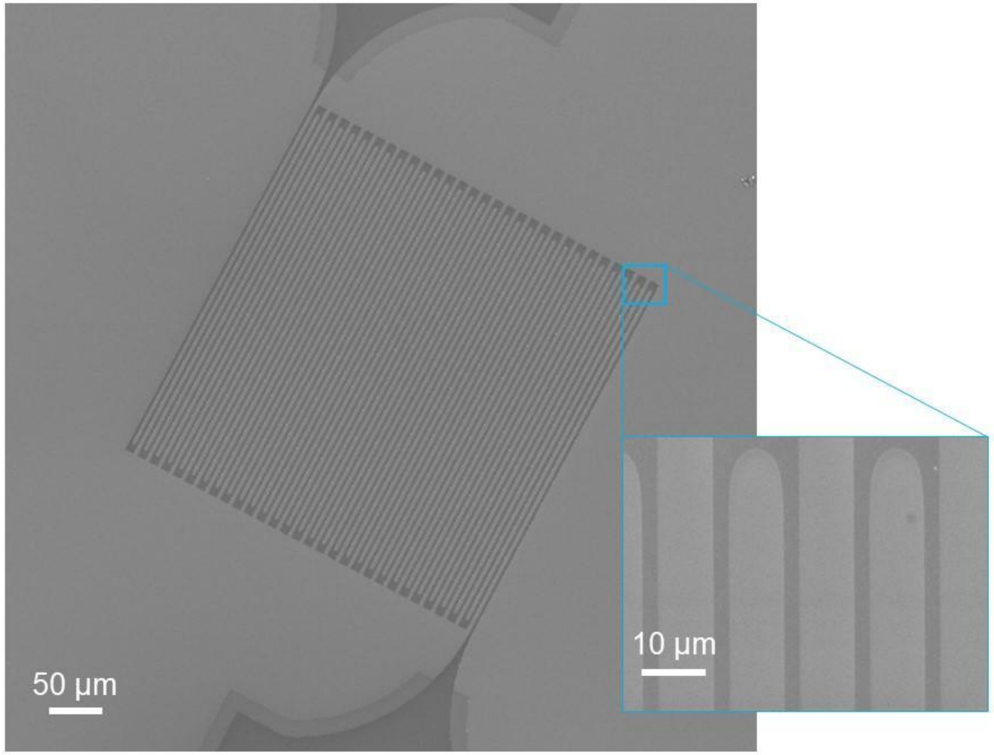


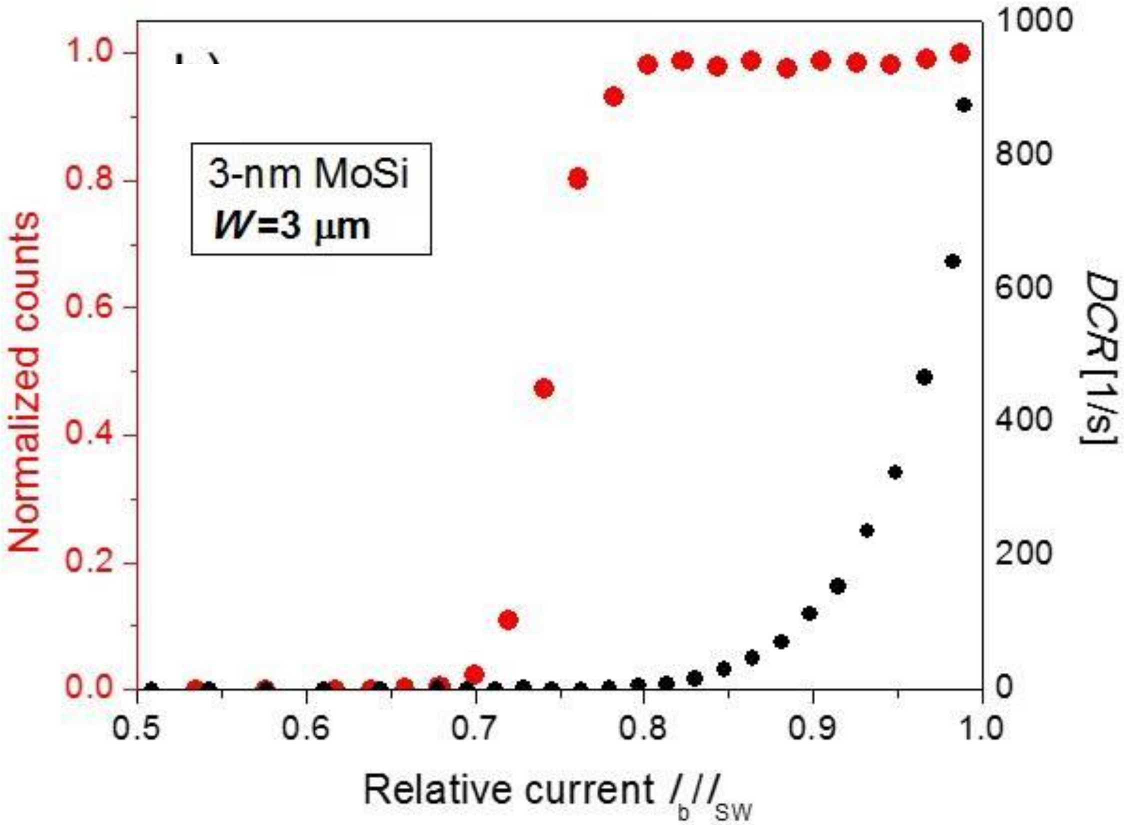


- 2-3 nm WSi microwires by e-beam and photolithography
- Width: 400 nm - 2 μm
- Wavelength: 1330 and 1550 nm
- Operating temperature: 0.8 K

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

Large-area microwire MoSi single-photon detectors





Thin 3-nm MoSi film, up to 3 μm-wide, operating T = 0.3 K, λ = 1550 nm

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

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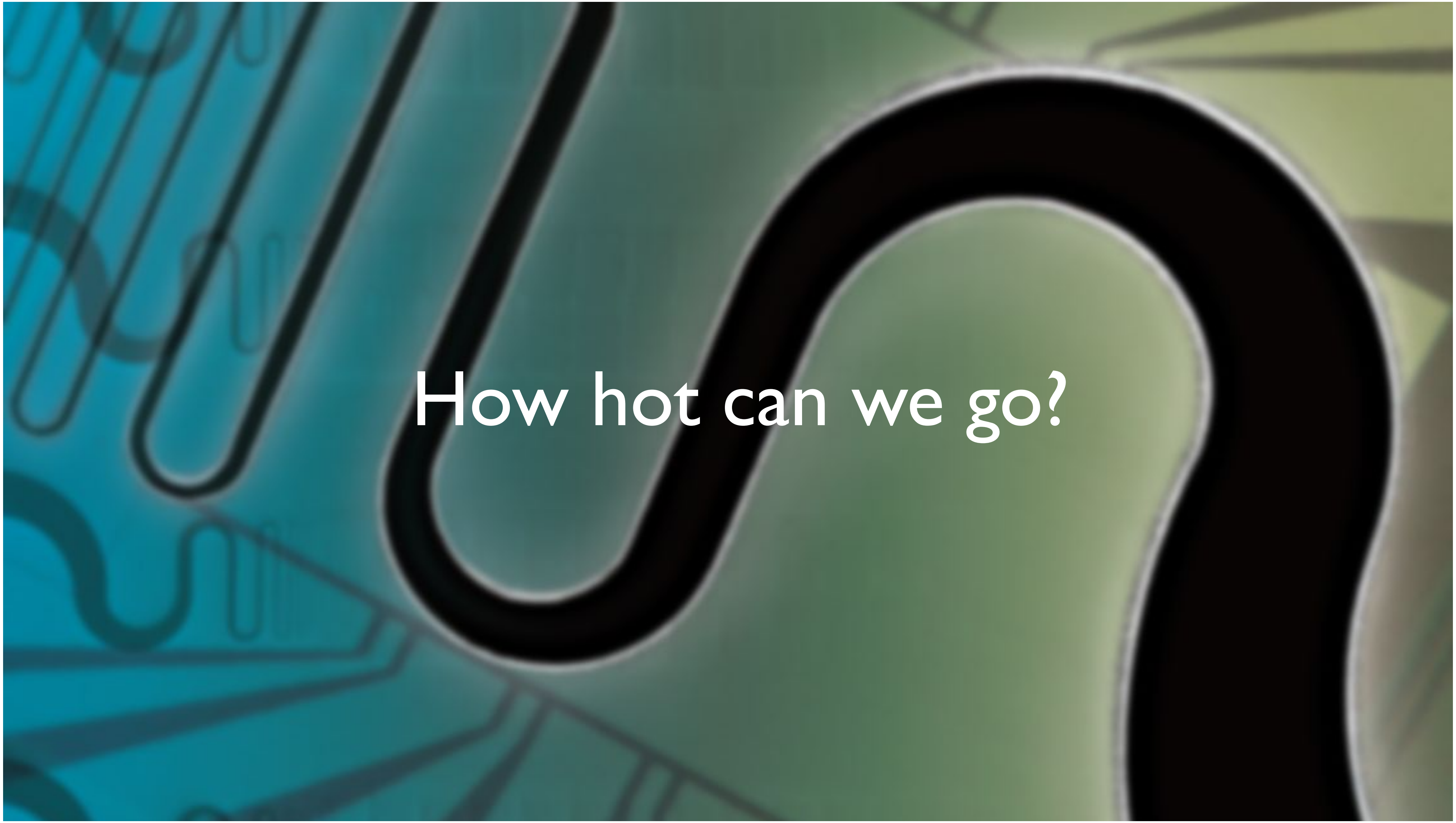
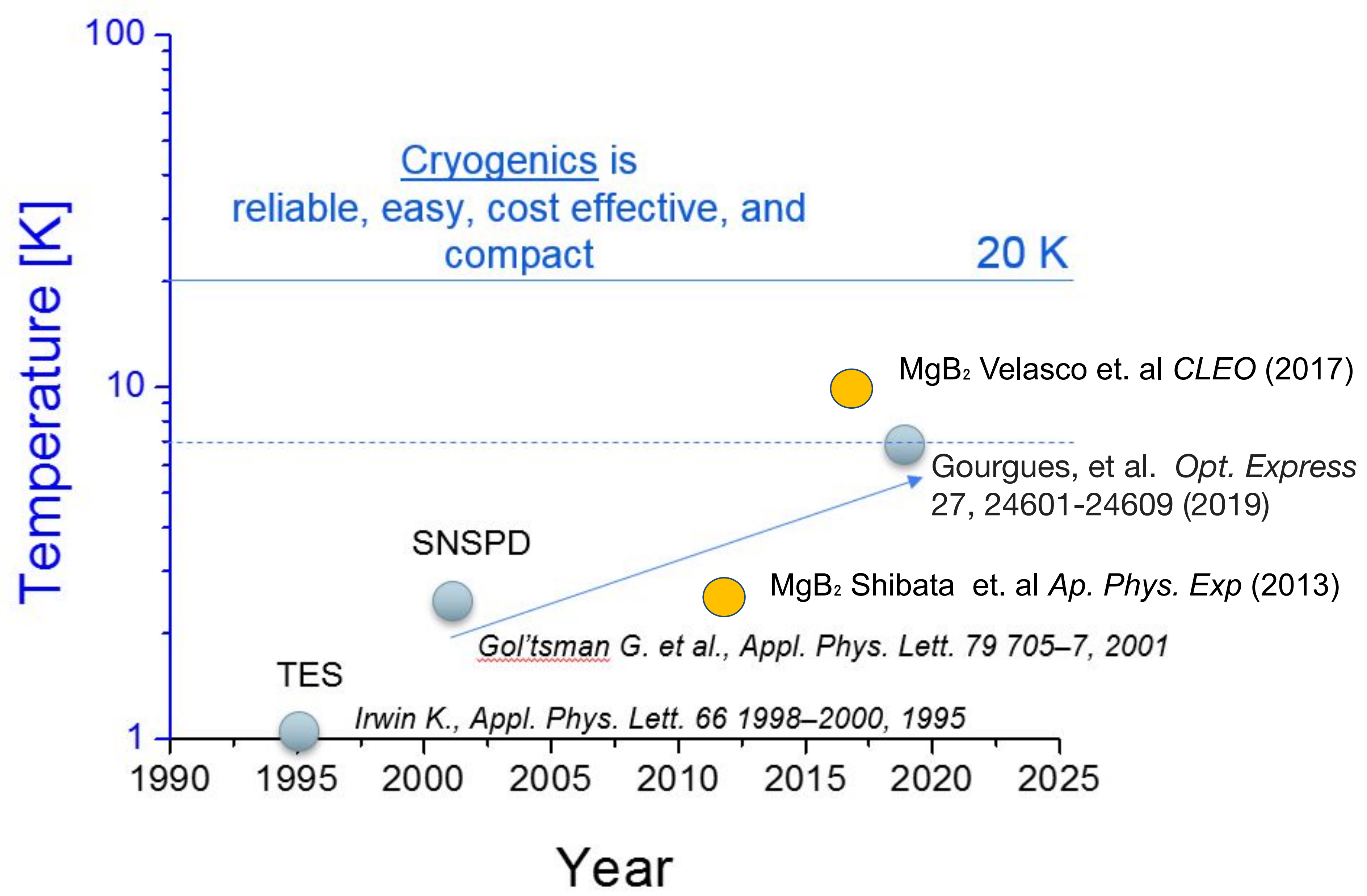


Operating Temperature of Superconducting Detectors



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Past Work on Single-Photon Detection with MgB_2

Hiroyuki Shibata et al
2013 Appl. Phys. Express
6 023101 (2012)

4.2K testing
~ 225 nm wires
1550 nm light
Tc ~ 20 K

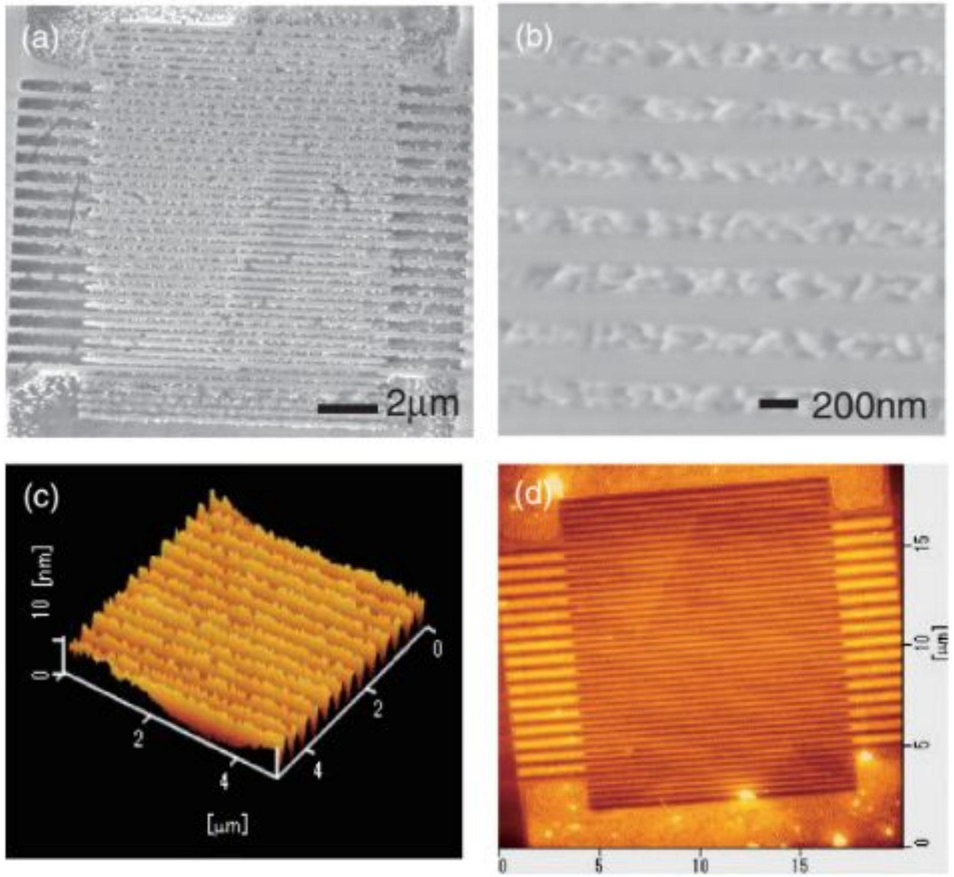
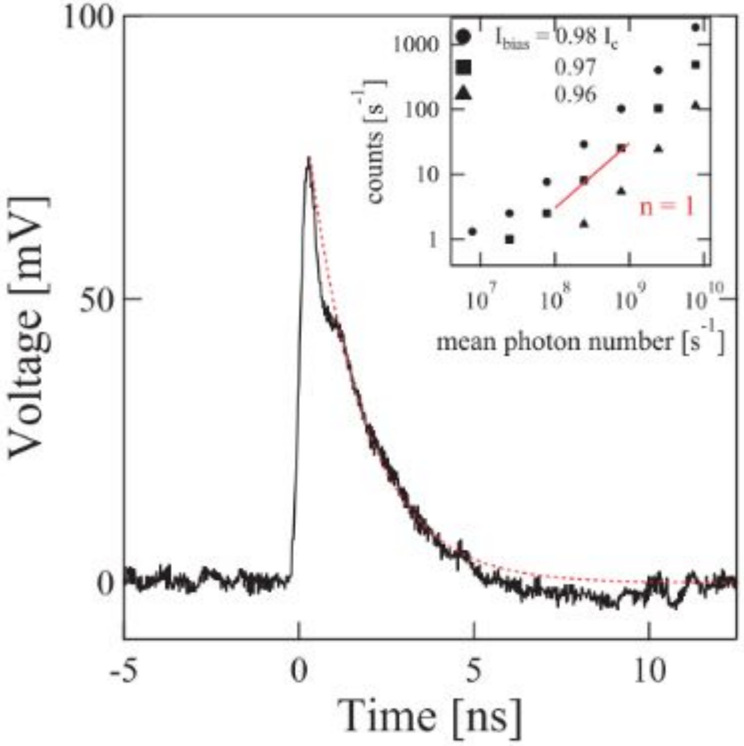
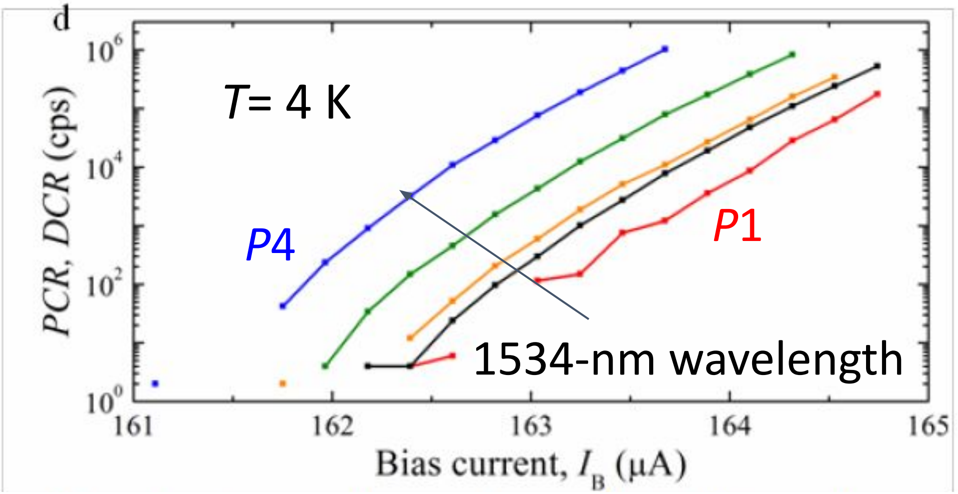


Fig. 2. (a) Scanning electron micrograph, (b) enlarged view, (c) atomic force microscopy 3D image, and (d) atomic force microscopy image of $10 \times 10\,\mu m^2$ MgB_2 meander pattern with the line width of 135 nm and the space width of 165 nm.

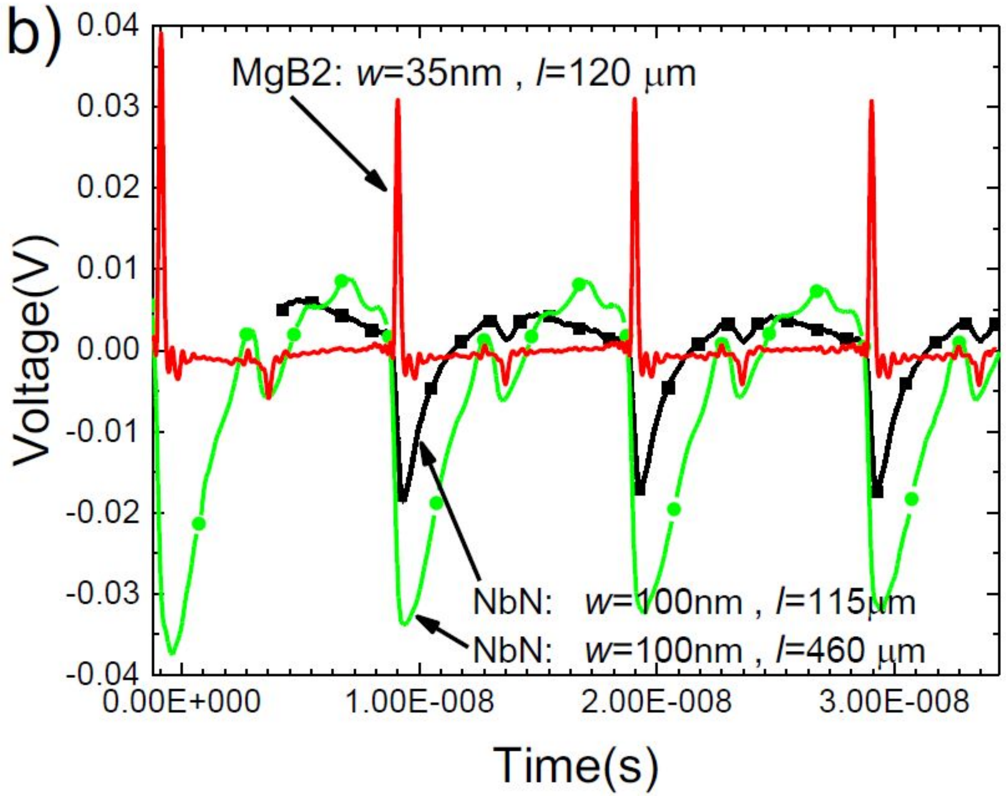


MgB_2 films



	Roughness (RMS)	T_C	Thickness
Ideal	< 1nm	40 K	5 nm
MBE	<0.35 nm	10 K	5 nm
HPCVD	2-4 nm	39 K	6 nm

F. Marsili, CLEO 2015, conference slides



S. Cherednichenko, and *et.al.,* arXiv:1911.01652

- Sub-ns reset time
- T_C~40 K

Single-photon detection at 20 K never demonstrated

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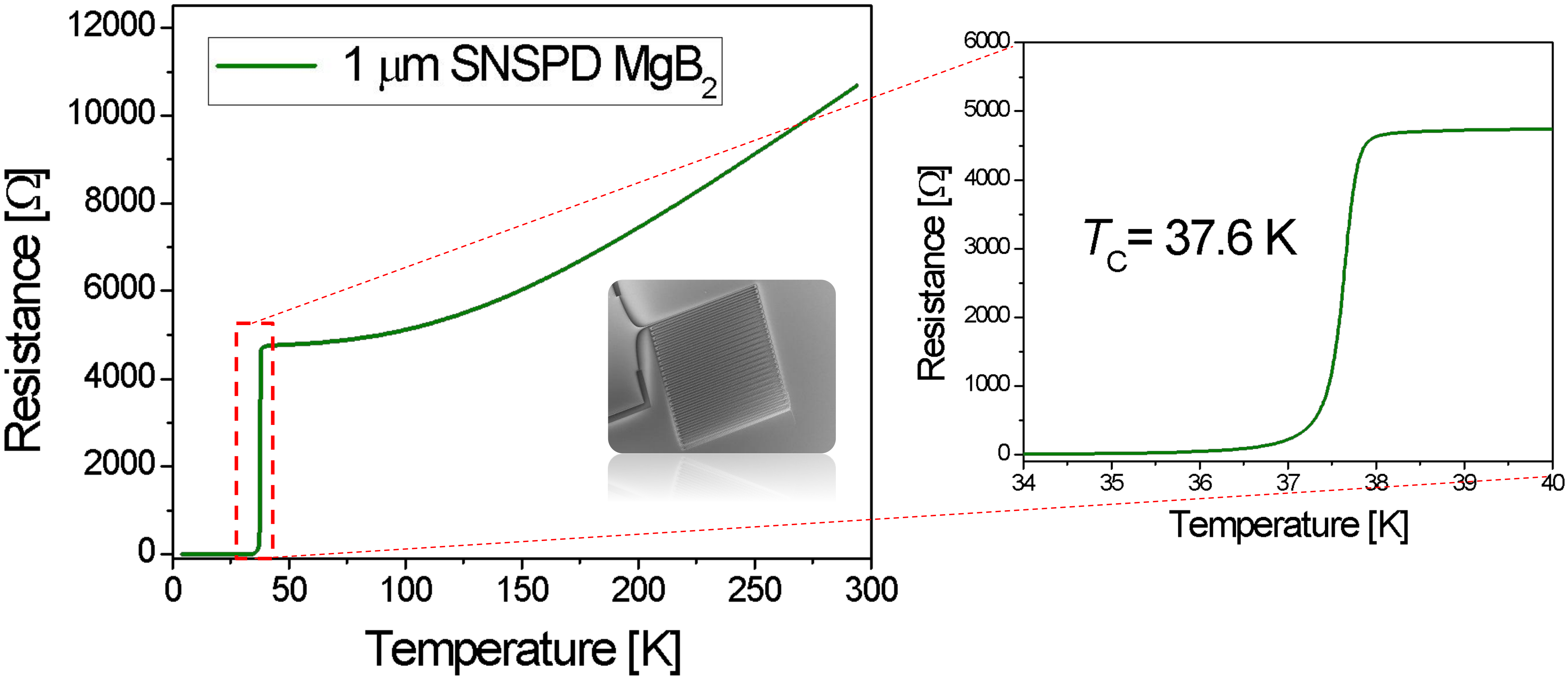
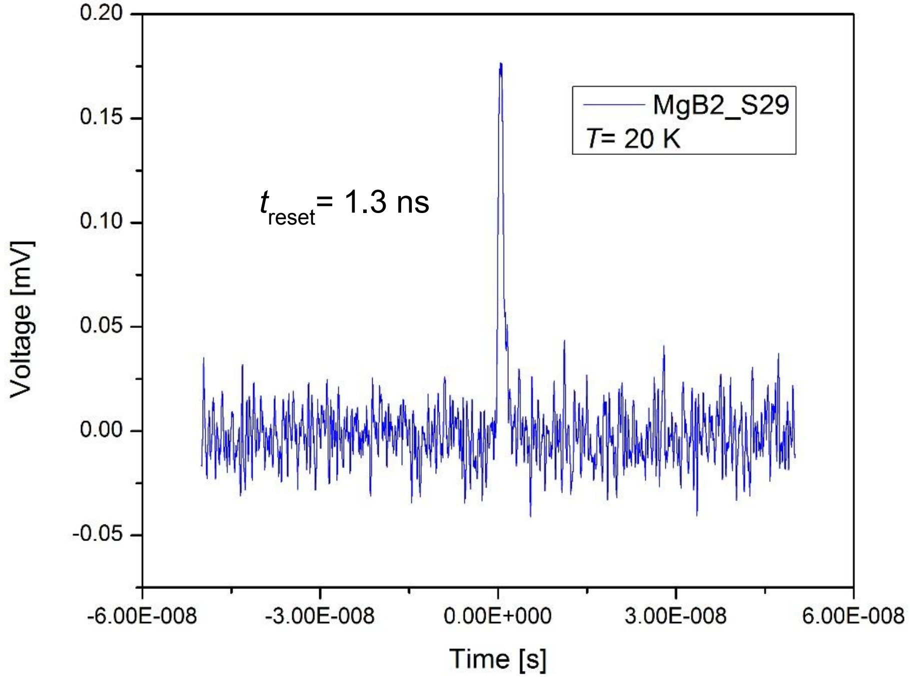
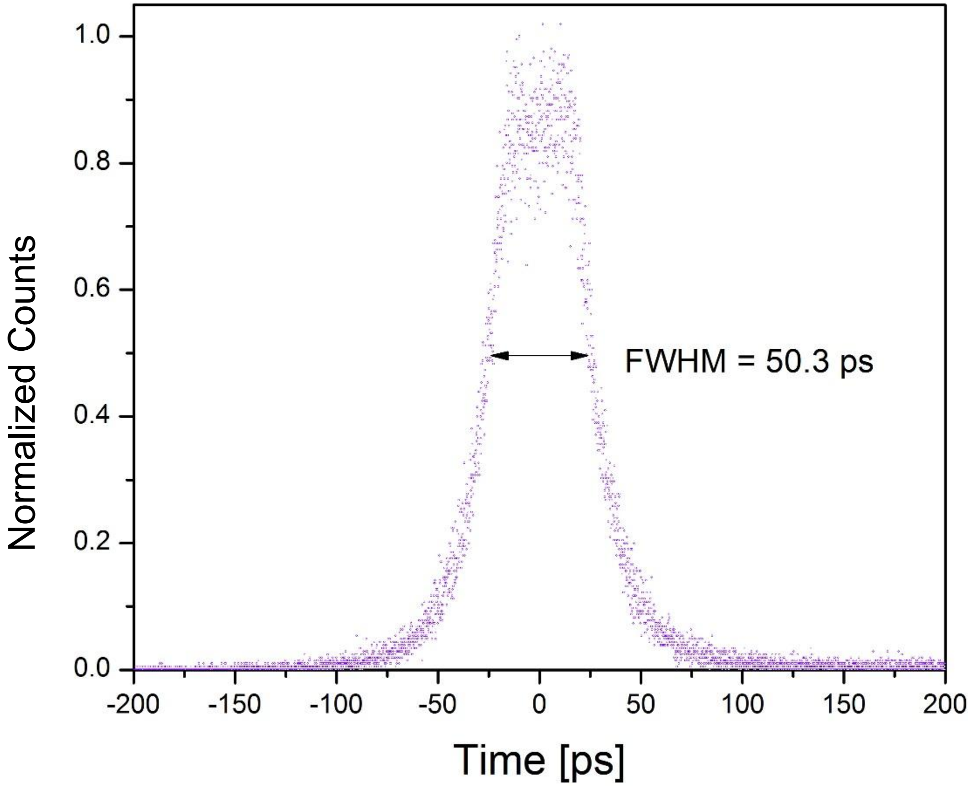
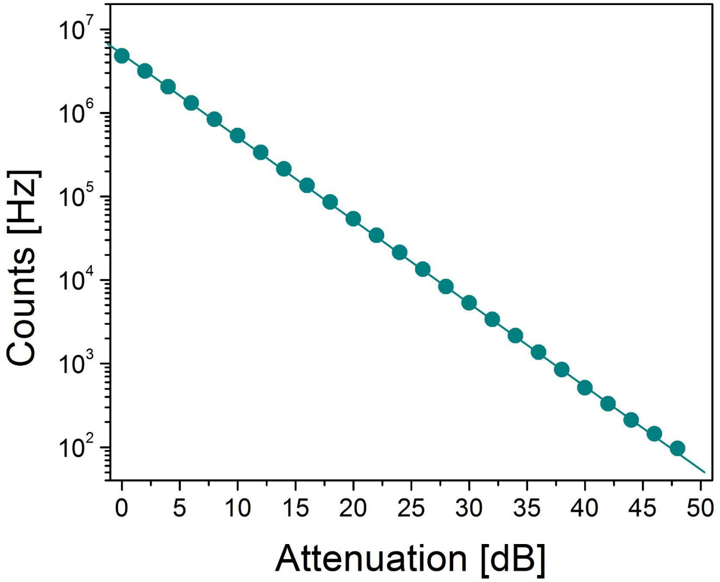
DC characterization



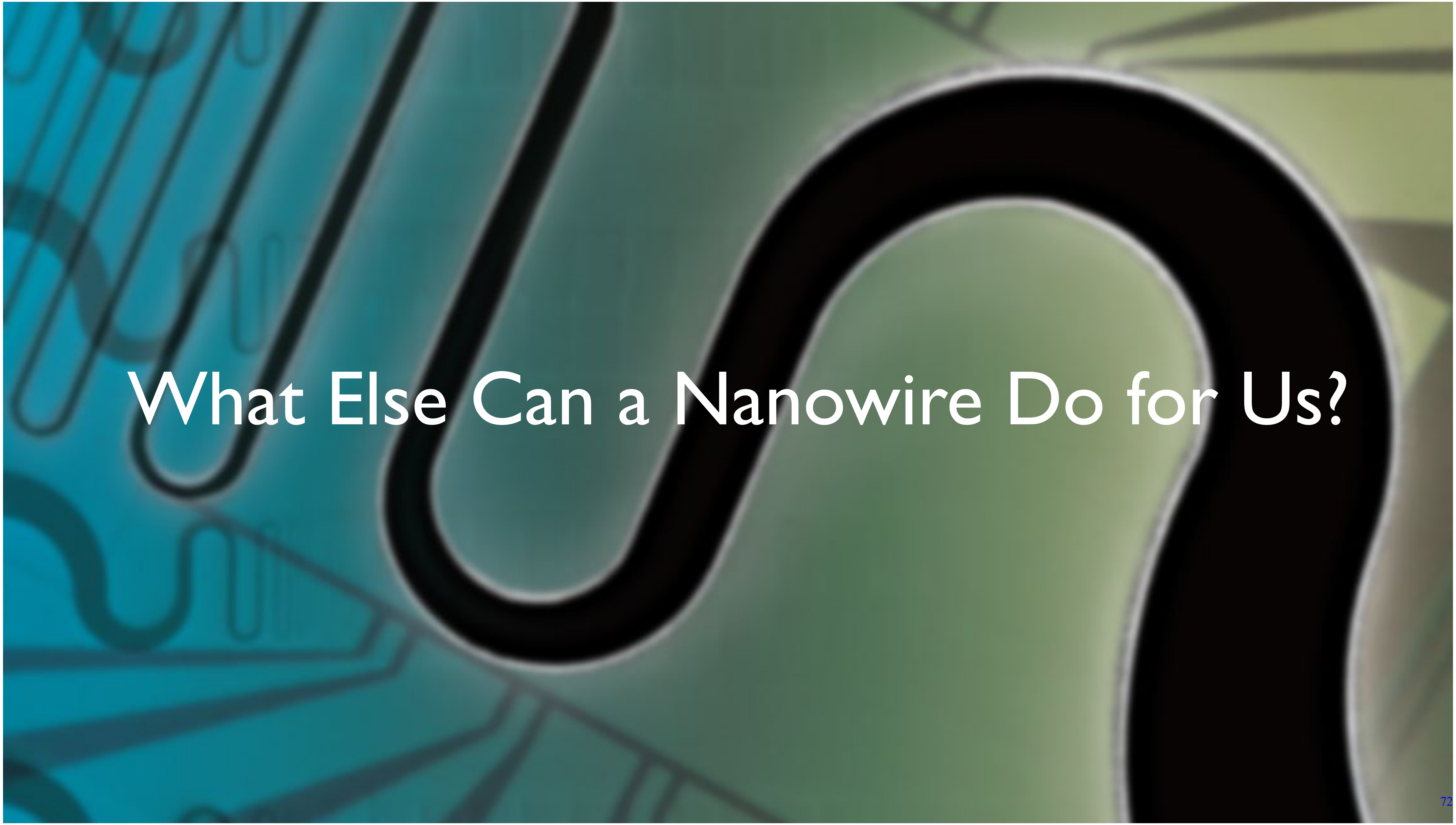
Pulse, linearity, timing jitter





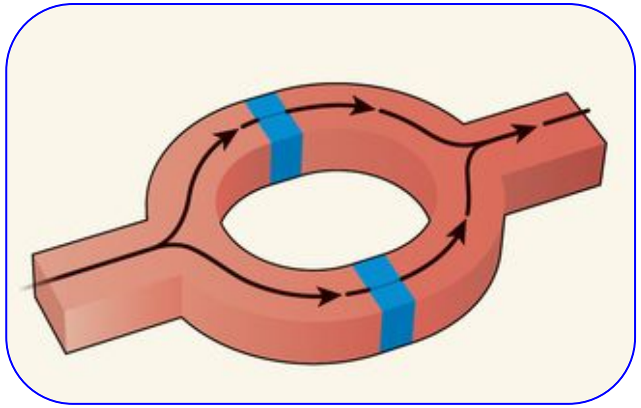


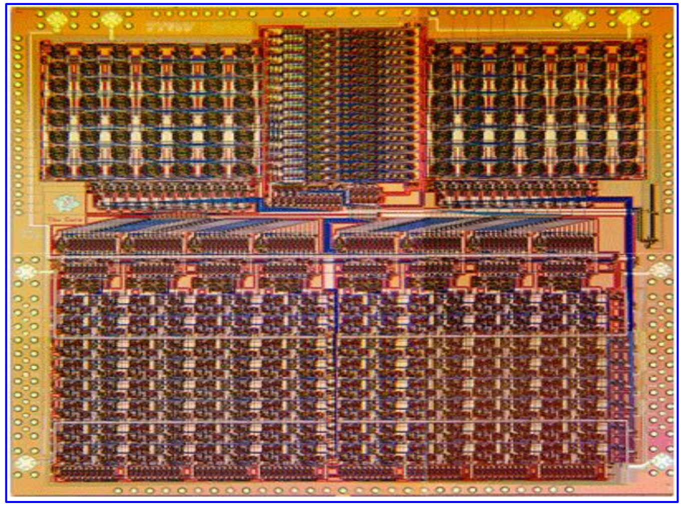
***T* = 20 K *W* = 1 μm λ = 1550 nm**


What Else Can a Nanowire Do for Us?

Josephson Junctions: Solving most problems

- SQUID
  - Magnetic sensors
  - Qubits
- SFQ[1][2]
  - Ultrafast computing
  - Ultralow power

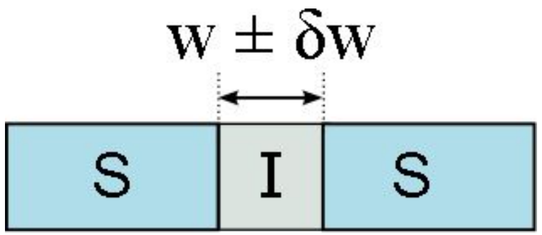




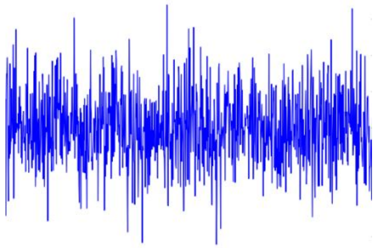
(NGST/SUNY-Stony Brook/JPL)

[1] Likharev, K. K. (2012). *Physica C: Superconductivity*, *482*, 6–18
[2] Volkmann, M. H., et. al. (2013) *Superconductor Science and Technology*, *26*(1), 015002.

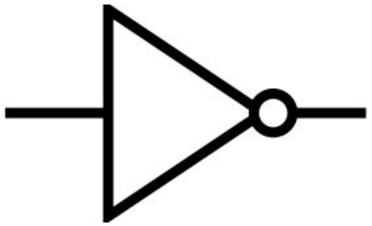
Some Challenges facing JJs



Tunnel barriers…



Magnetic noise

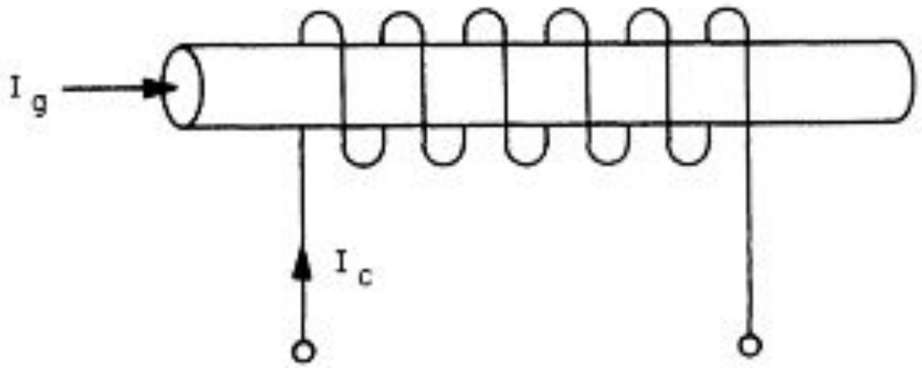


Selected applications (e.g. high-Z loads, fanout)

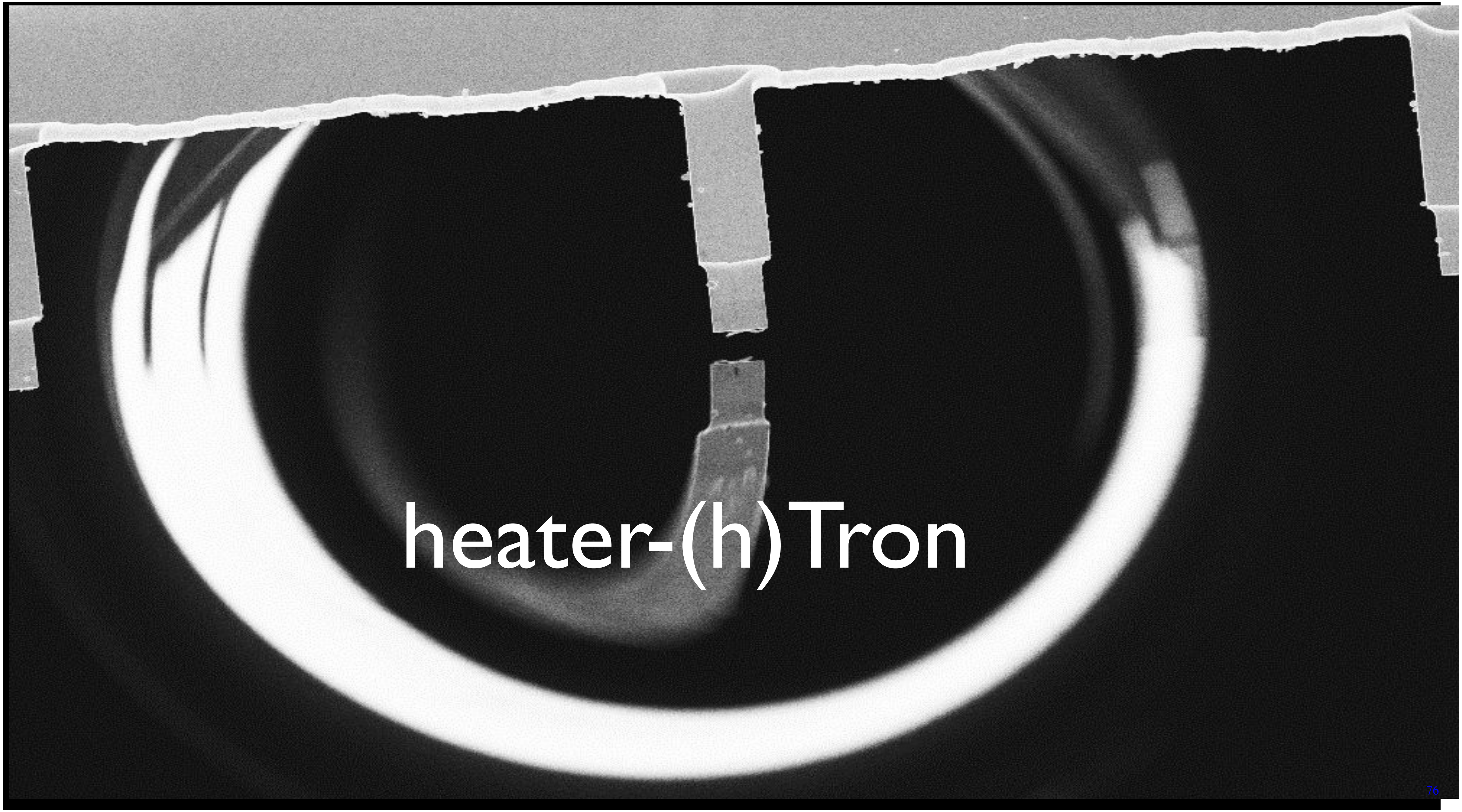
IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), July 2022.
This plenary presentation was given at the virtual EUCAS 2021, September 5-10, 2021.

The cryotron: magnetic suppression

- 1956, Dudley Buck at MIT
- Gate induces magnetic field
  - Suppresses channel I_c



Buck, D. (1956). The Cryotron - A Superconductive Computer Component. Proceedings of the IRE, 44(4), 482–493. doi:10.1109/JRPROC.1956.274


heater-(h)Tron

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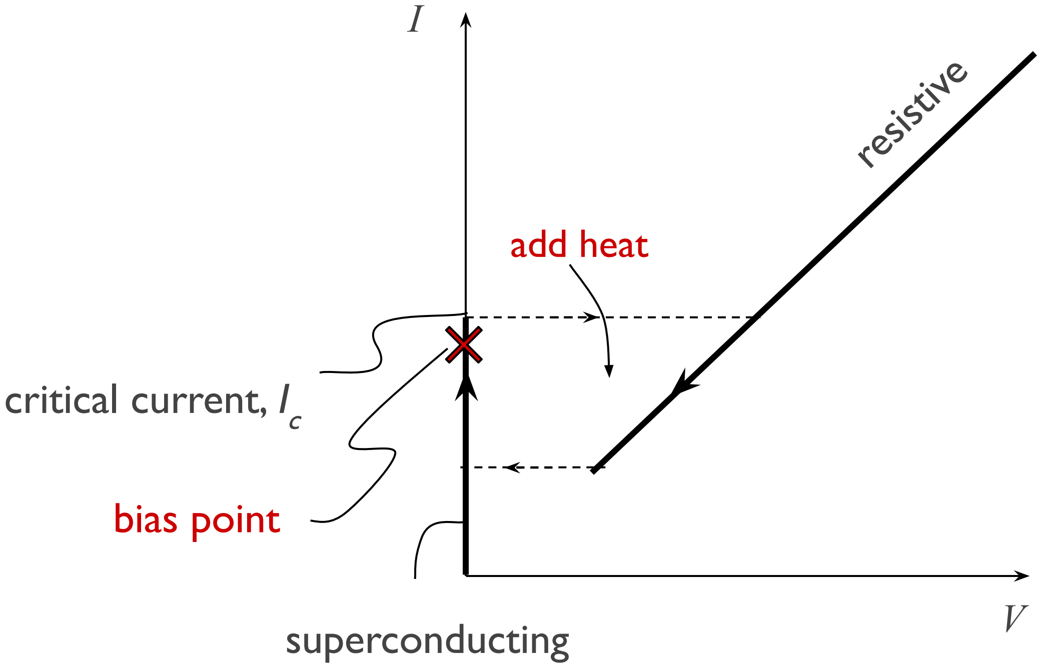
Thermo-Electric Switch



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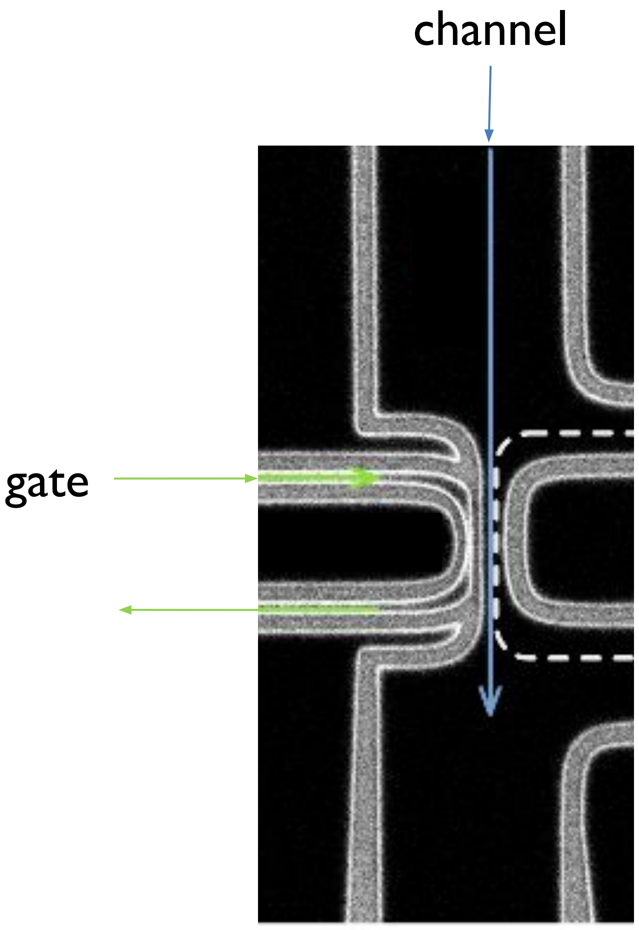
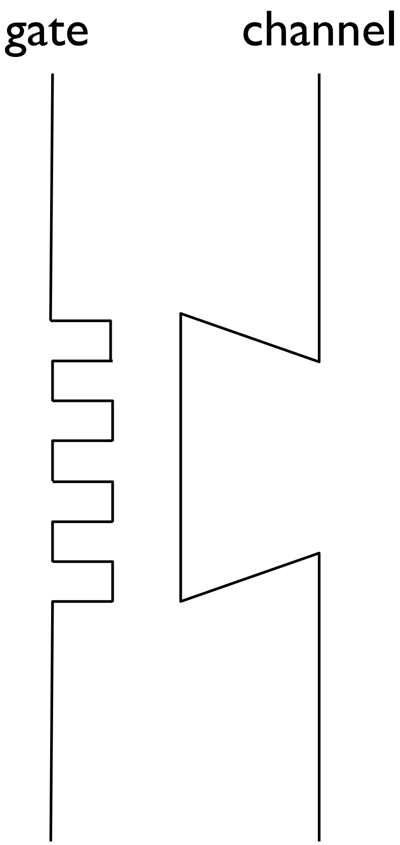
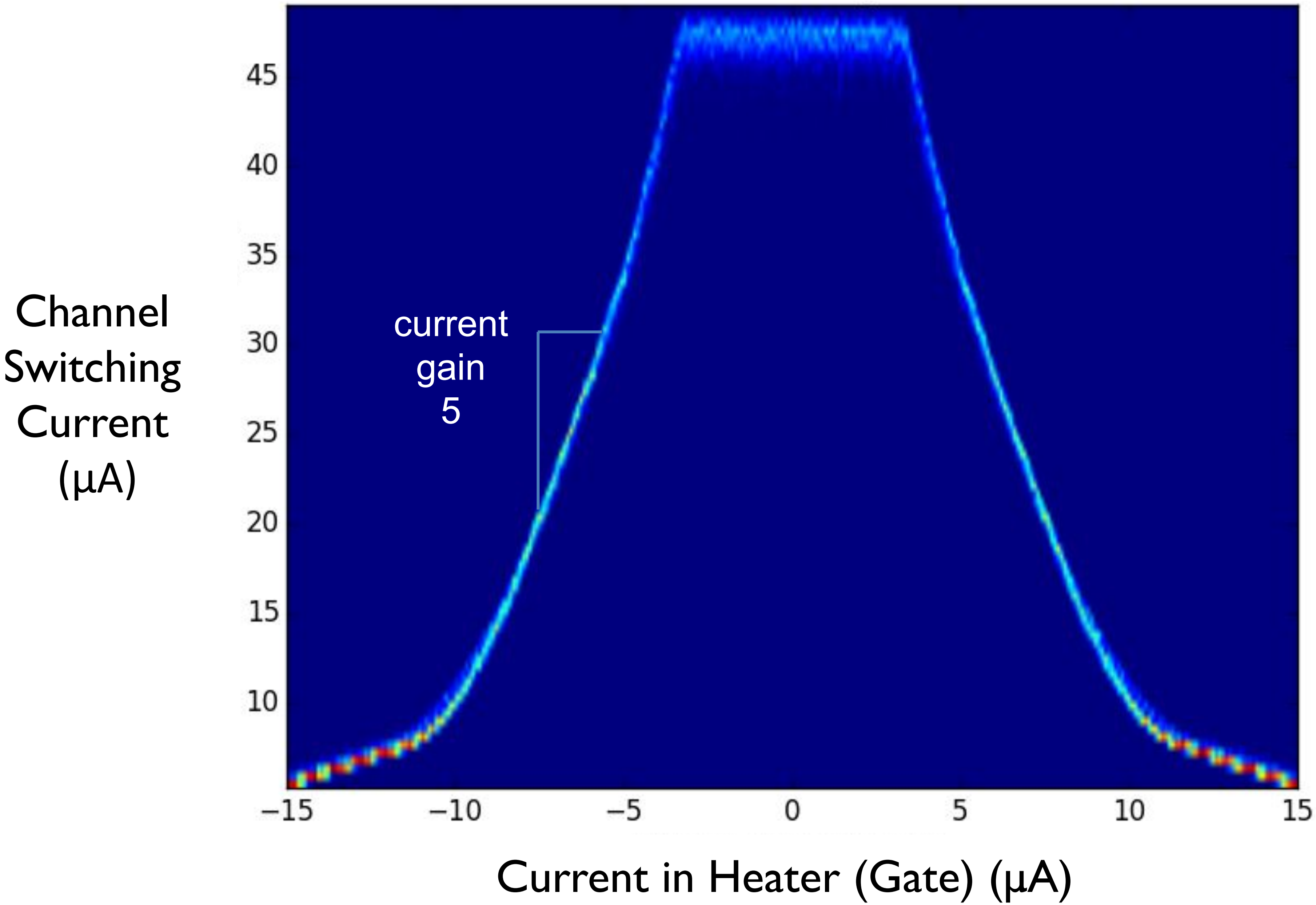
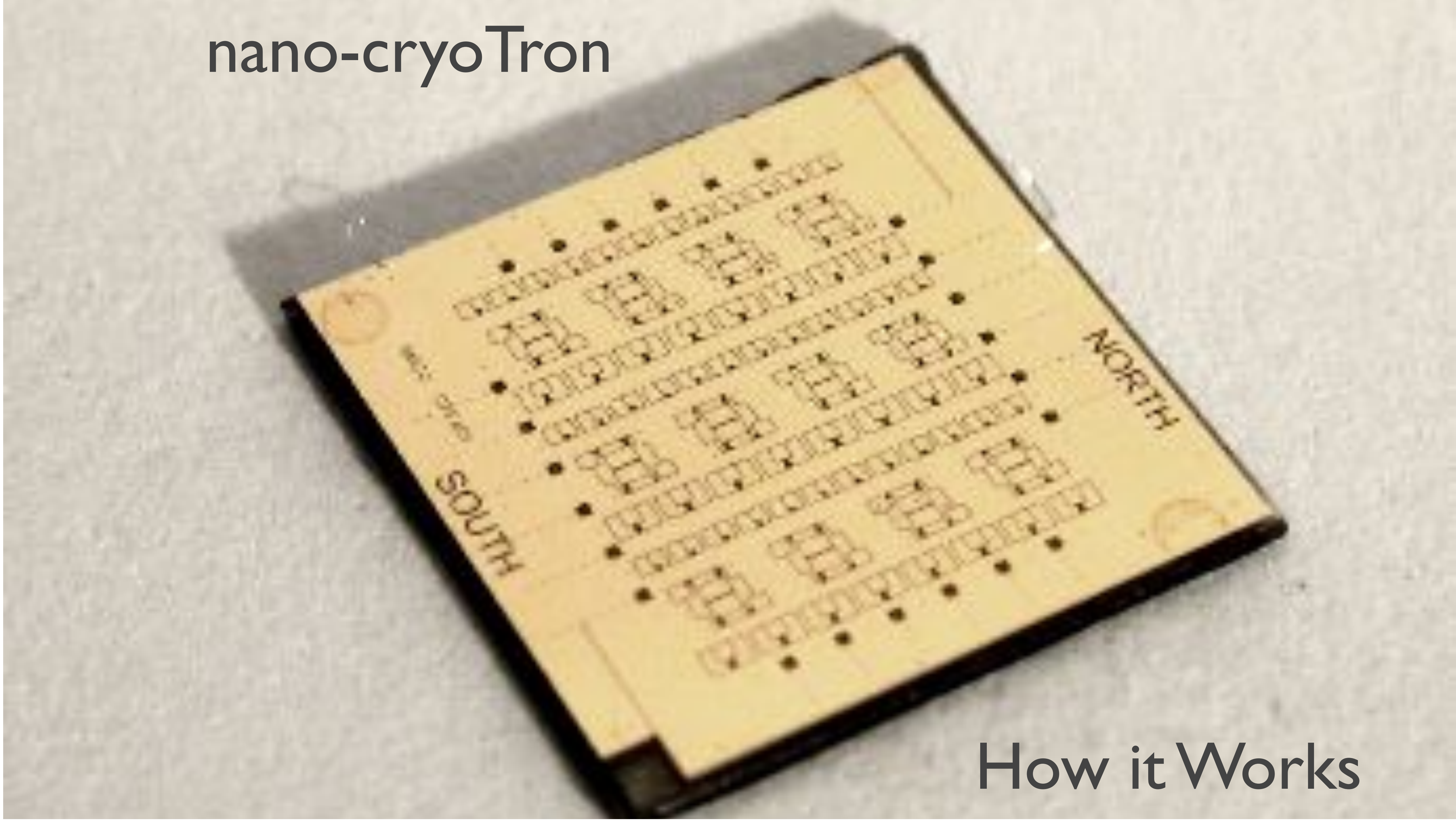
Thermal Cryotron: heater (h)Tron





hTron Switching Characteristics



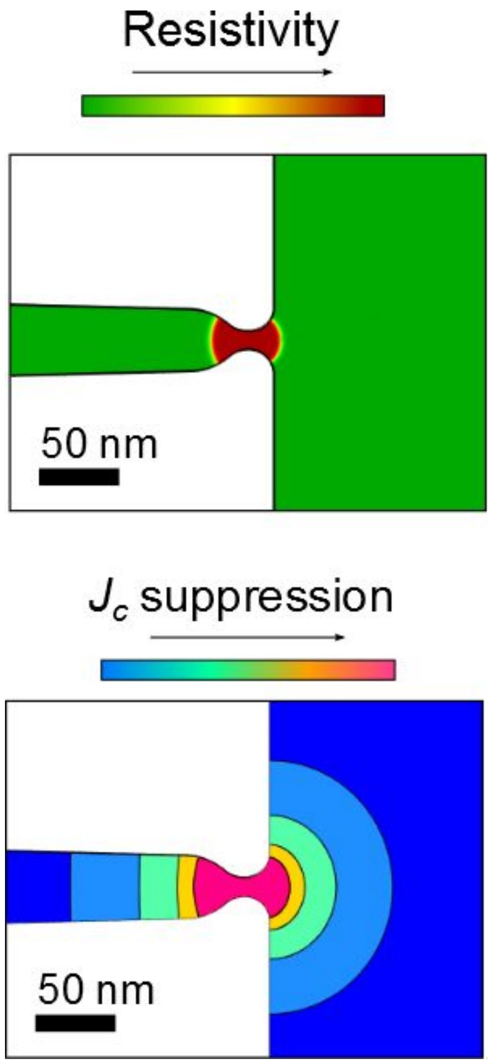

nano-cryoTron
NORTH
SOUTH
How it Works

The nTron: Electrothermal suppression

- Suppression mechanism
  - Cryotron: Magnetic
  - nTron: Electrothermal

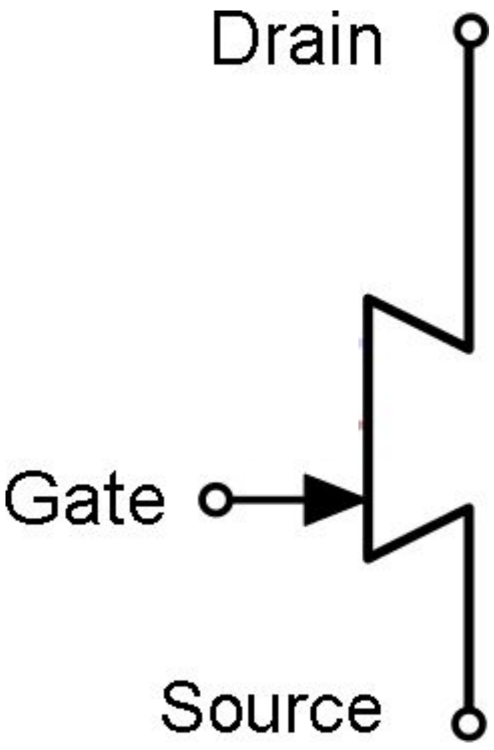
- Energy diffusion from hotspot
  - $L_D \approx$ 100 nm for NbN

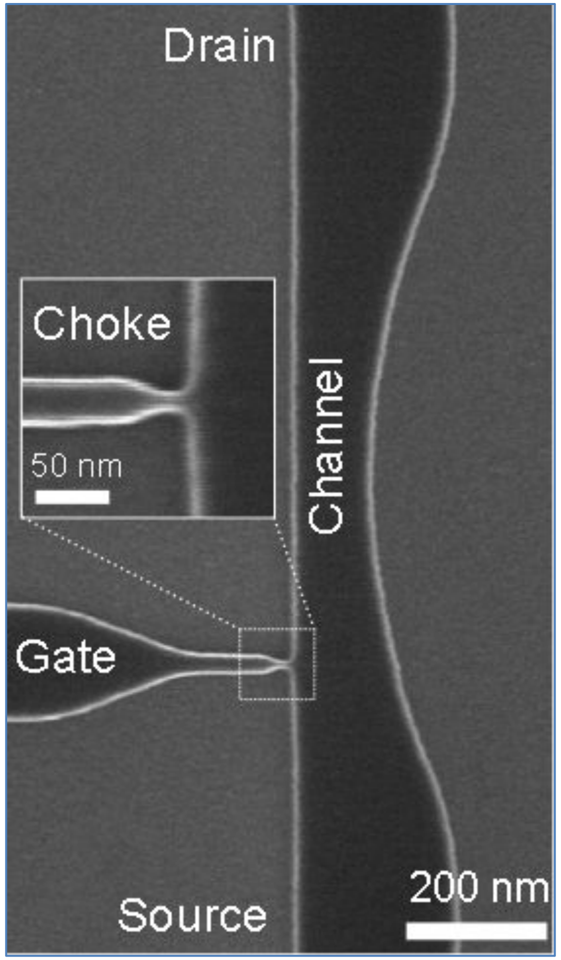
- Hotspot highly resistive, but speed limited by cooling



A. N. McCaughan and K. K. Berggren, Nano Letters **14**(10), 5748 (2014)

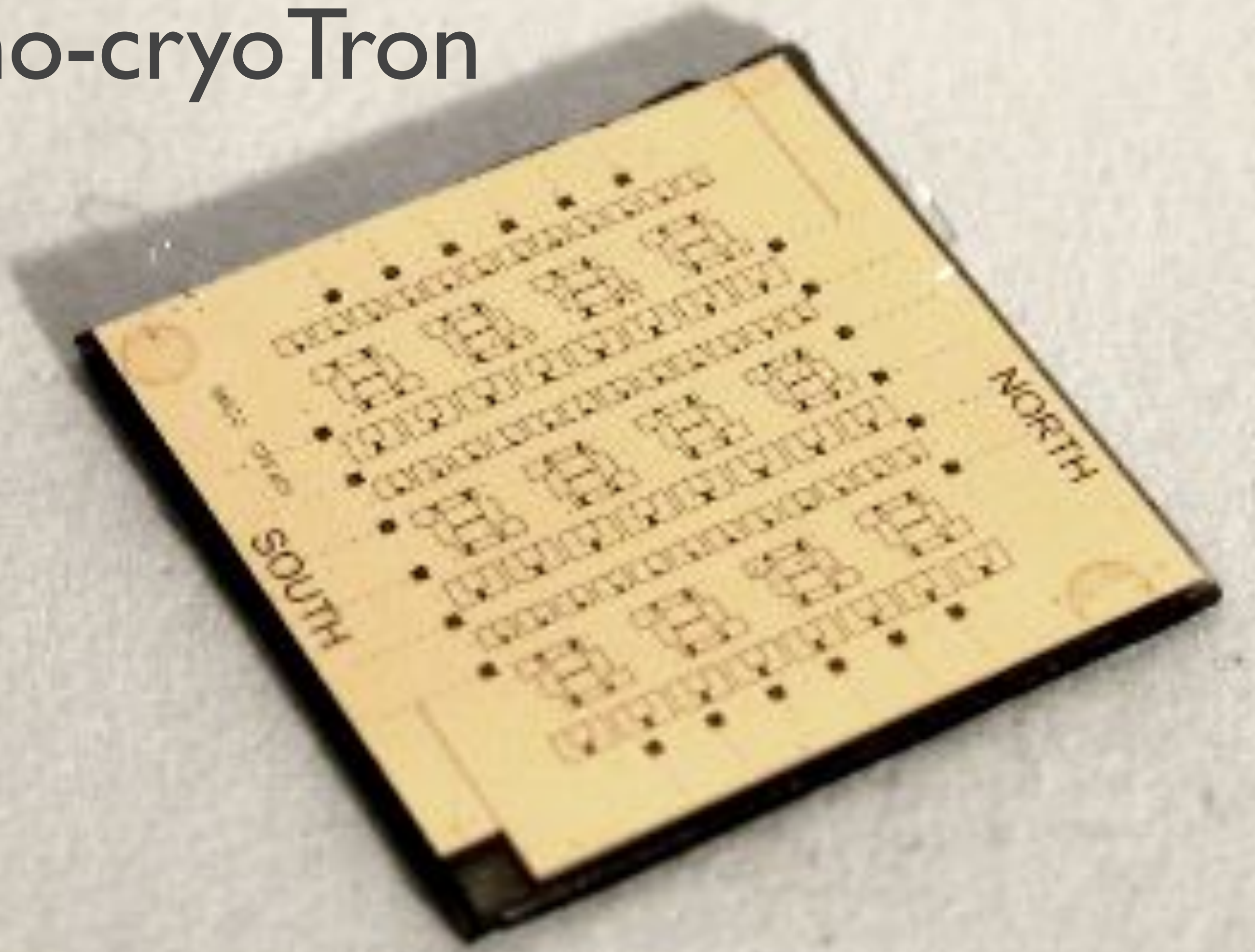
nTron geometry



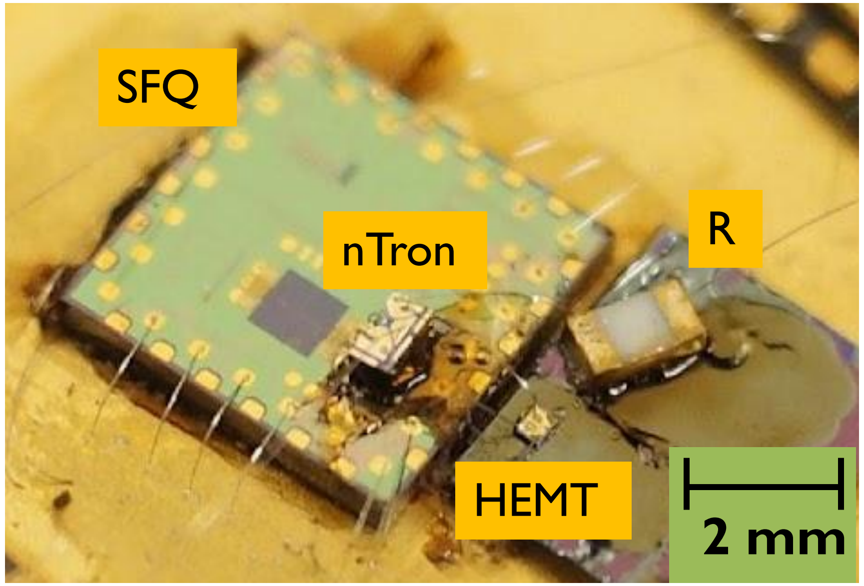


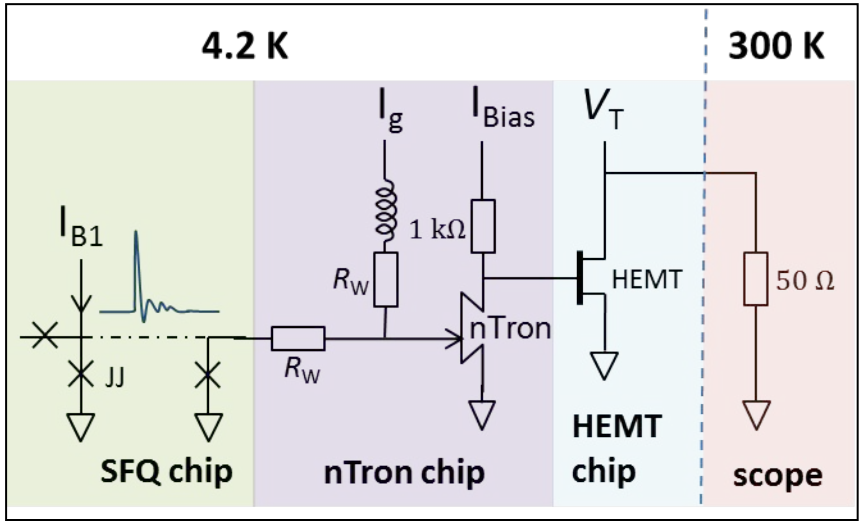
A. N. McCaughan and K. K. Berggren, [Nano Letters 14(10), 5748 (2014)]

Using the Nano-cryoTron



Interface between RSFQ and Semiconductors

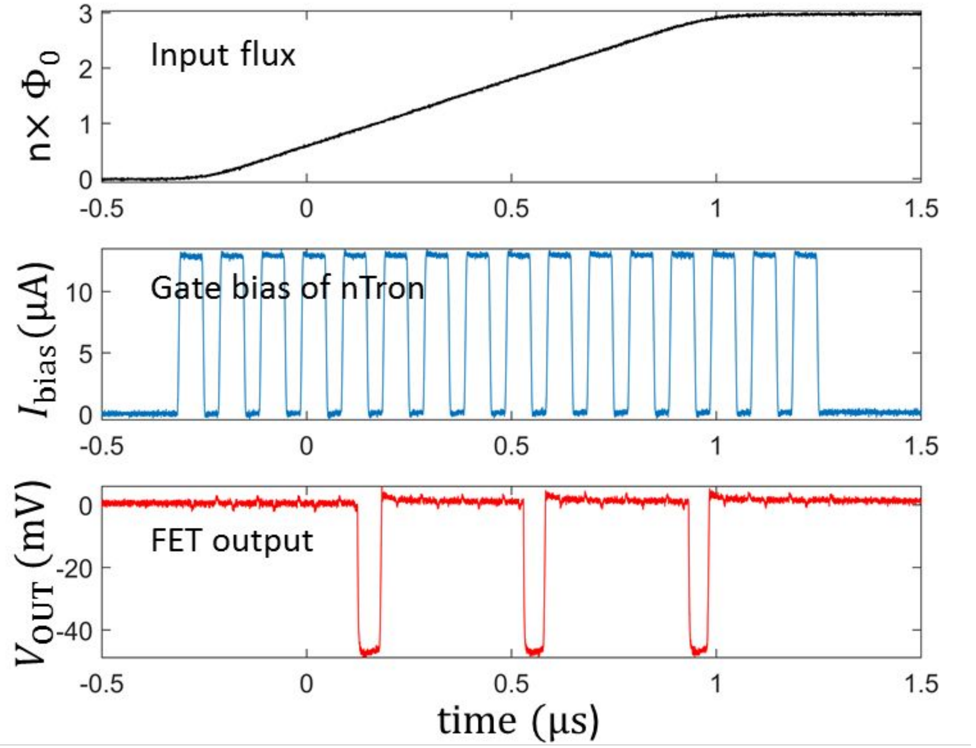




Experimental demonstration

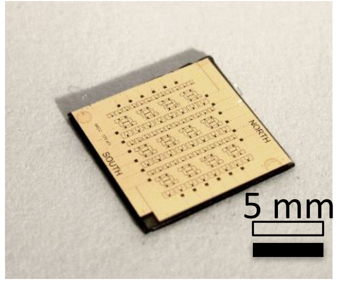
SFQ□nTron□HEMT

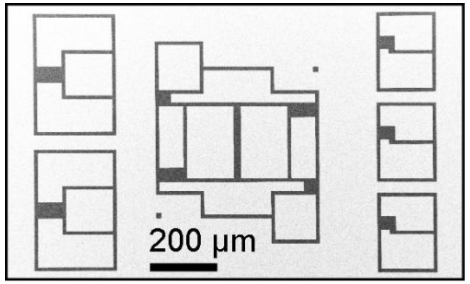
Josephson junction □ nanowire □ transistor

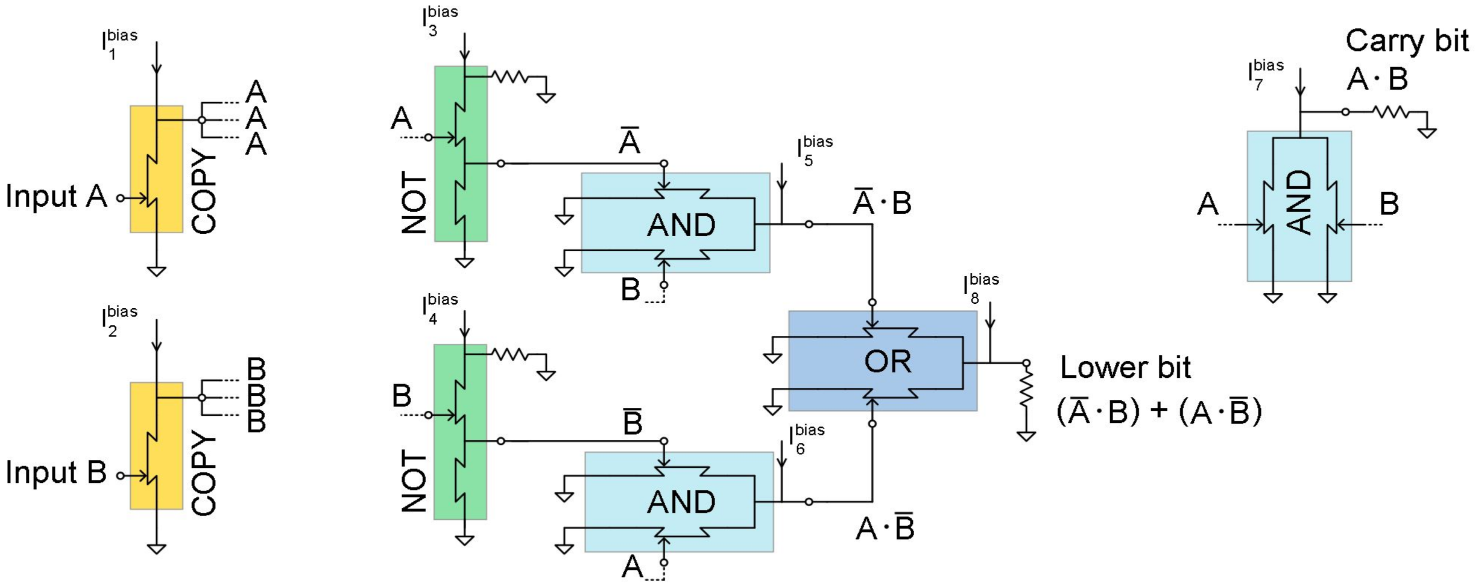


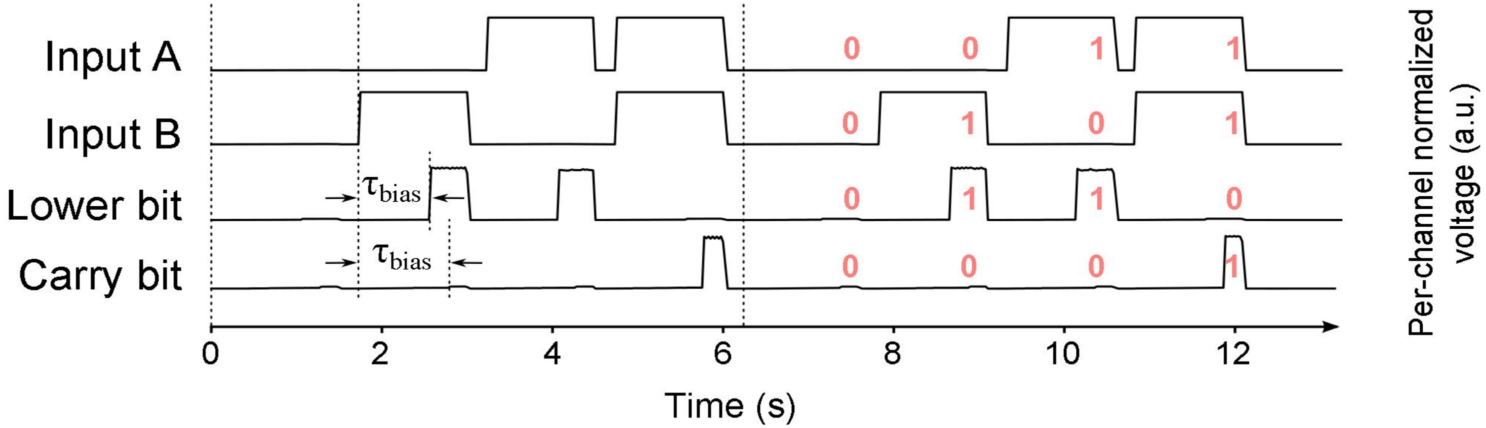
Collaborate with Thomas Ortlepp from CiS Research Institute for Microsensor Systems GmbH

Half-adder results

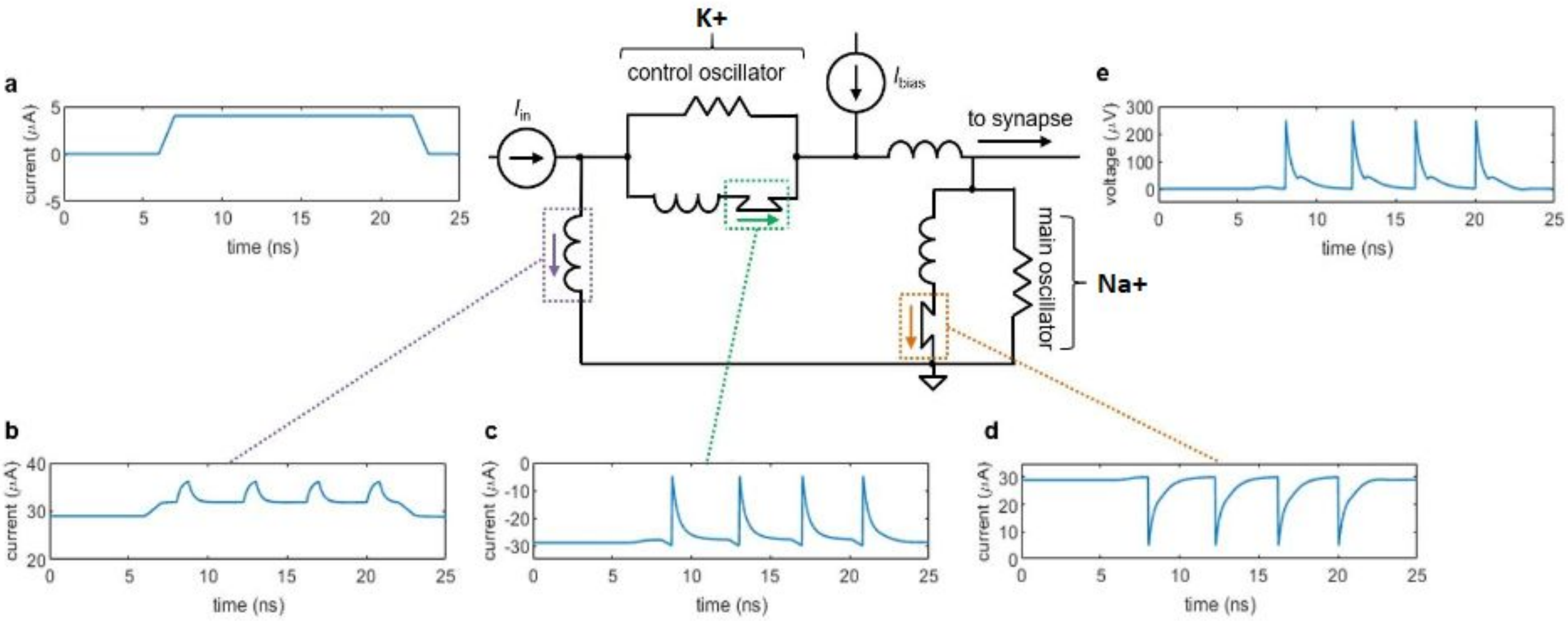






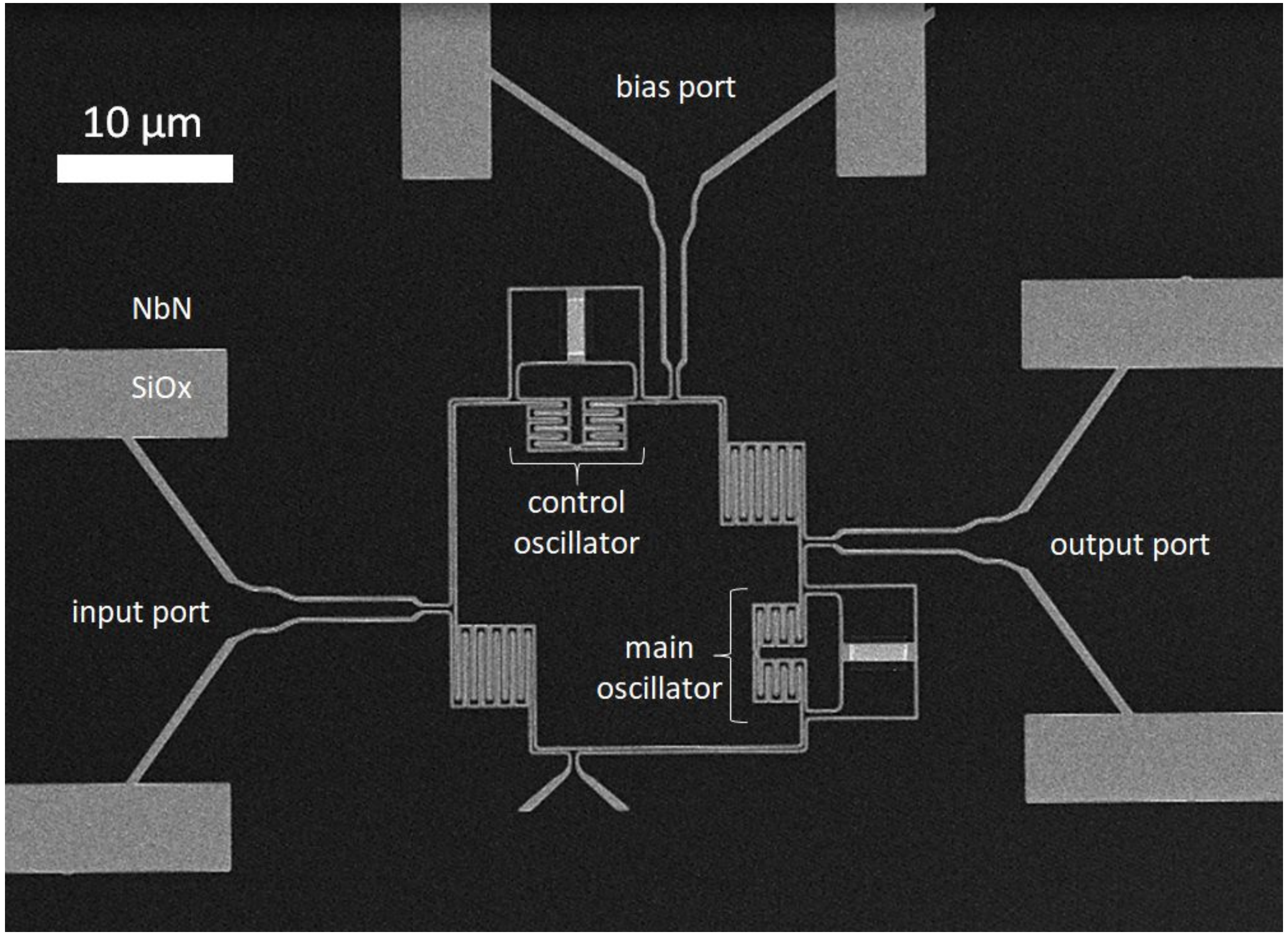


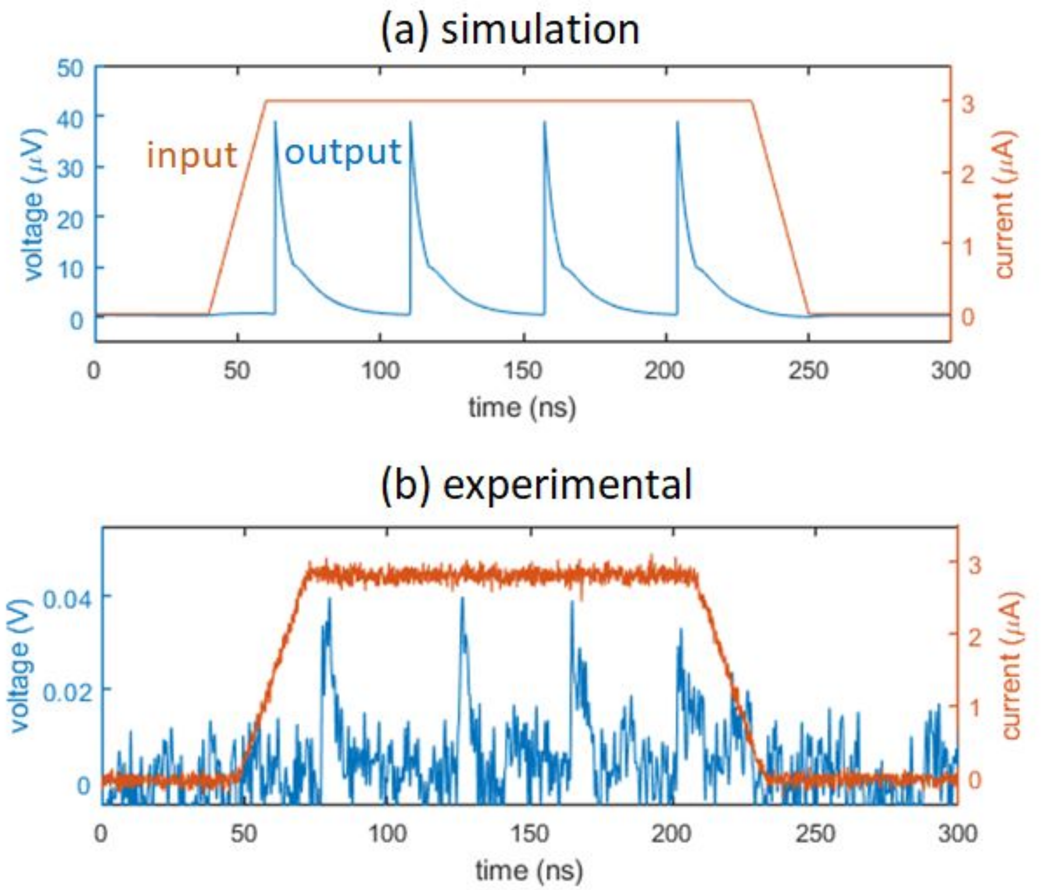
Nanowire neuron: circuit



- Two nanowire relaxation oscillators act analogously to the two ion channels of a biological neuron
- Able to replicate biorealistic characteristics (e.g. refractory period, threshold response)
- Can use nanowire slow-wave transmission line as an axon → preserve time-domain information

Superconducting Nanowire Neuron

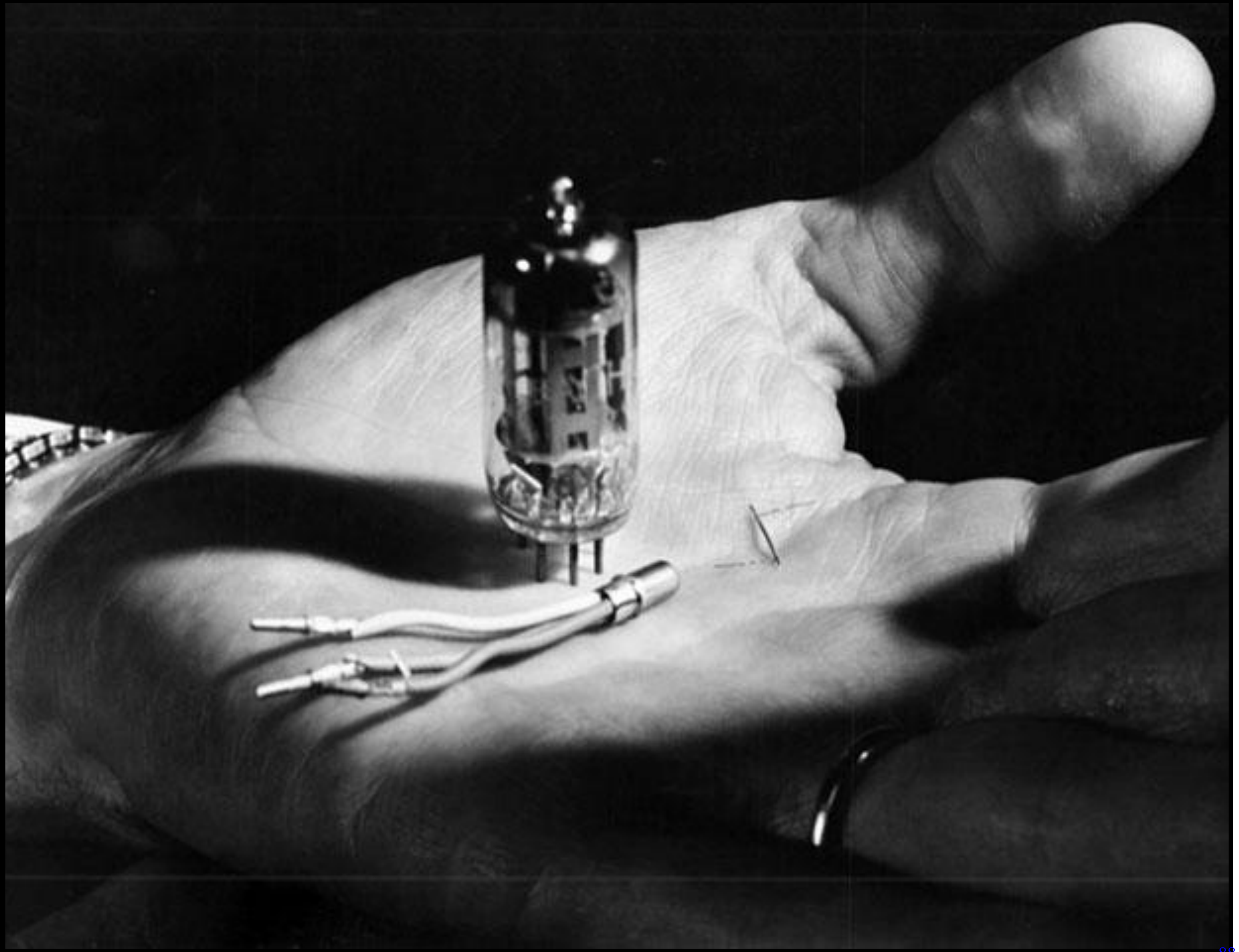




Emily Toomey, Ken Segall, Matteo Castellani, Marco Colangelo, Nancy Lynch, Karl K. Berggren
"Superconducting Nanowire Spiking Element for Neural Networks" Nano Letters 20.11 (2020)

"Pro"s and "Con"s of Nanowire-Based Electronics

- **"Pro"s**
  - Can drive high-impedance loads
  - Fast turn-on (~ 100 ps) and excellent jitter (~ 3 ps)
  - Low power consumption (tradeoff with output impedance)
  - Simple materials and process
- **"Con"s**
  - Reset is slow (~ ns)
  - Electron-beam lithography is beneficial (maybe not required?)



Thank You!

- To the hundreds (thousands?) of PIs, post-docs, students, technicians who have supported this field over decades, and the thousands of administrators/facilities workers/family members who have supported them.
- The major institutions that have been involved in this field include (in random order).
  - U. of Rochester, Moscow State Pedagogical University, Delft University of Technology, Karlsruhe Institute of Technology, National Institute of Standards and Technology, Yale University, University of Waterloo, University of British Columbia, Caltech Jet Propulsion Laboratory, EPFL Lausanne, MIT Lincoln Laboratory, Michigan State University, National Institute of Information and Communications Technology (NICT) in Kobe Japan, Nanjing University, Shanghai Institute of Microsystem and Information Technology (SIMIT), Heriot Watt University, Glasgow University, University of Roma TRE, Italian National Research Council (Rome, Naples)*, KTH Royal Institute of Technology, Los Alamos National Lab, Chalmers University, EPFL, Eindhoven University of Technology, The Technion, and others that have slipped my mind...

Apologies in advance to anyone I neglected to mention.

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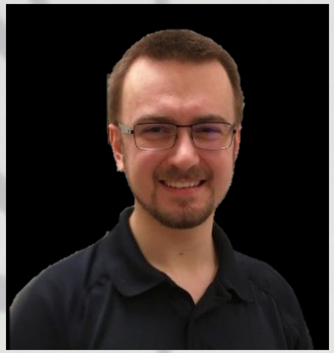

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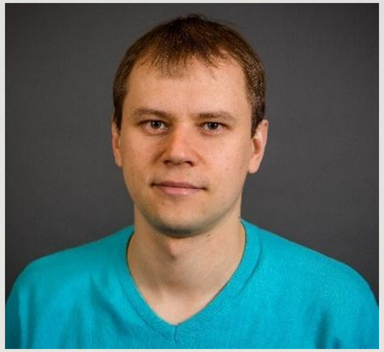

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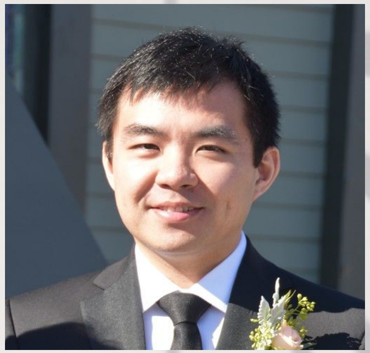

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Graduated/Former

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Thank you to Lara Ranieri and Rinske Wijtmans for assistance in preparing these slides for presentation

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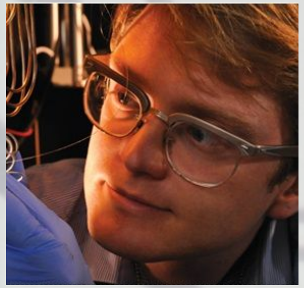

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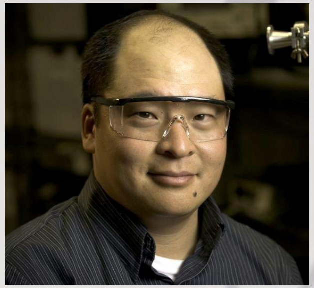

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- Edward Ramirez (JPL)

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- William Strickland (UNF)

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(Colgate)

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- Jeff Chiles (NIST)
- Adriana Lita (NIST)

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My Group

- https://www.rle.mit.edu/qnn
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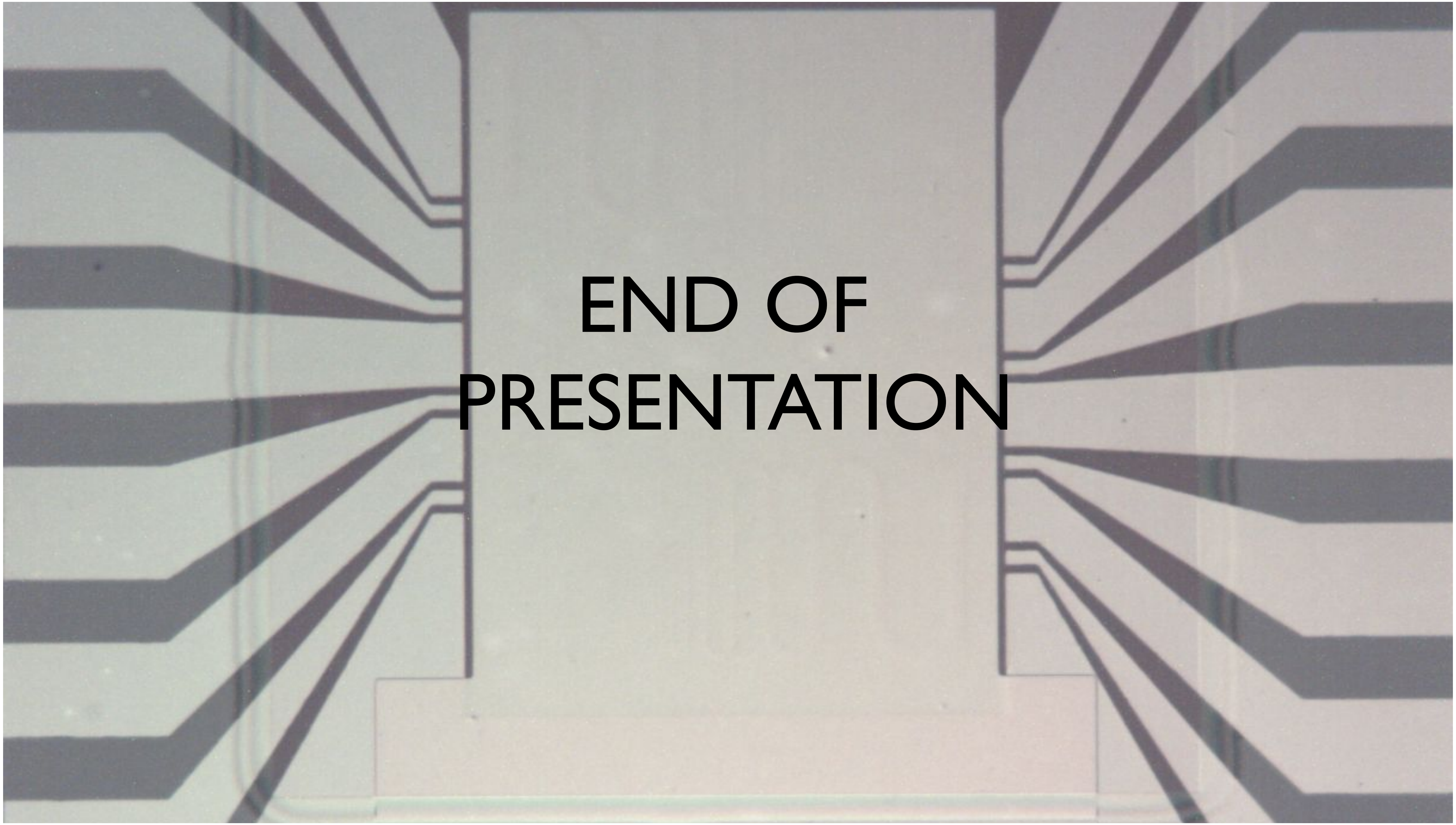
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