Superconducting Nanowire Single-Photon Detectors: From Photon-Number Resolution to Dark-Matter Detection

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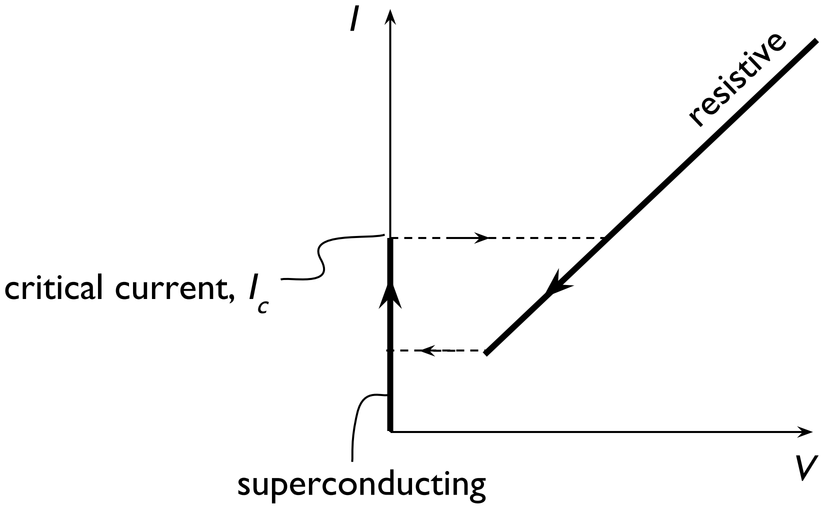
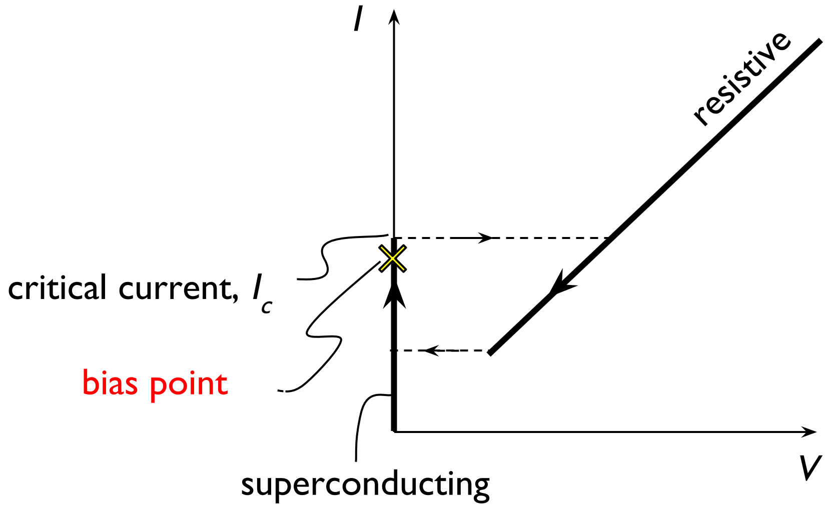
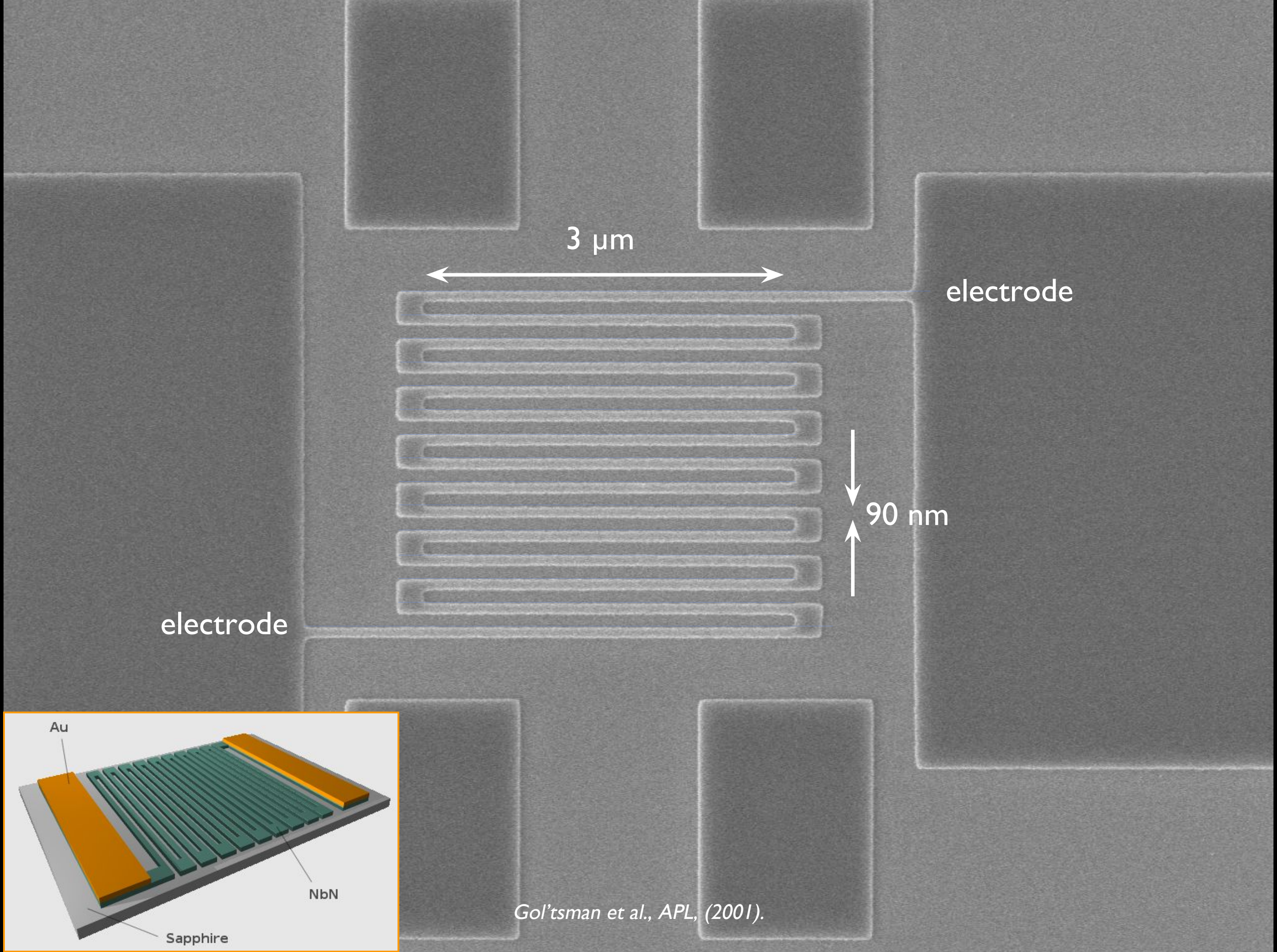
rit photonics for Quantum.2

Threshold-Based (Digital) Sensor



Threshold-Based (Digital) Sensor

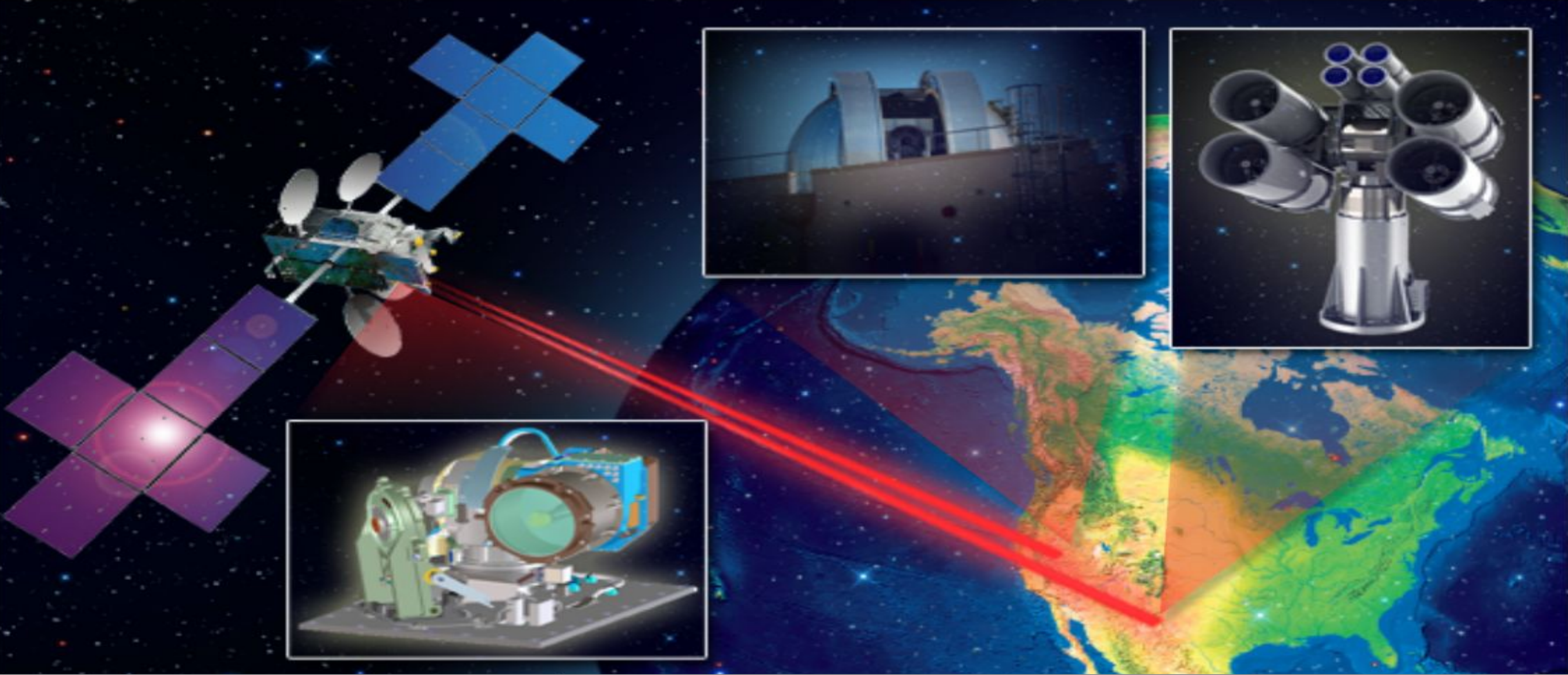




Gol'tsman et al., APL, (2001).

Why are SNSPDs Special?

- Infrared efficiency for single photons up to 10 μm: single photon sensitivity
- Jitter < 3 ps: nothing else can match it for single photons (Korzh+, Nature Photonics 14 '20)
- Efficiency: Competes with transition-edge sensors (98%, Reddy+ CLEO/QELS '19)
- Count rate (~ 1-10 ns)
- Dark-count rate (~ 1 per day)
- Convenient fabrication, shielding, amplification, temperature



"... 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 MIT Lincoln Laboratory and JPL.

VLSI Circuit Evaluation

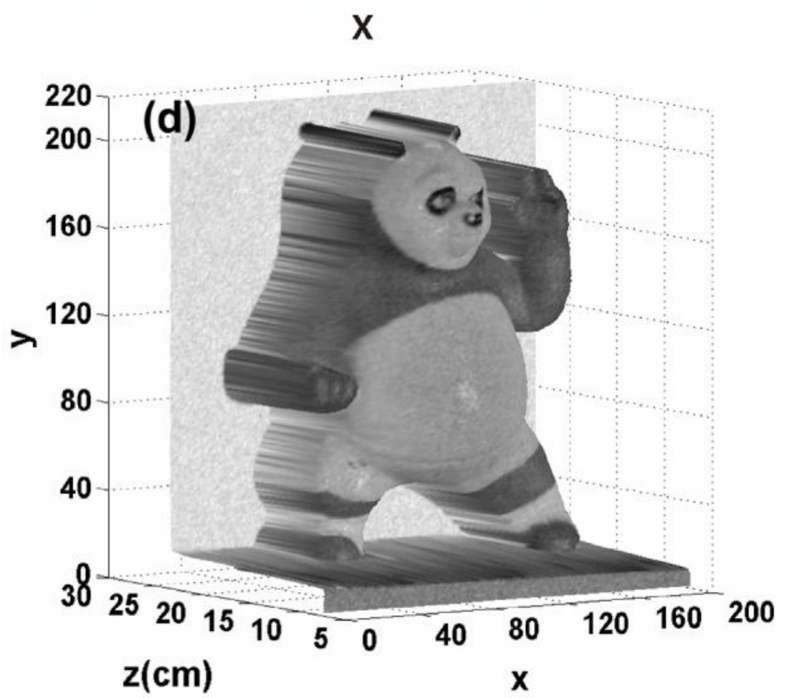
VLSI circuit imaging and debugging

SNSPD enabled performance advances

Image courtesy of DCG Systems

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

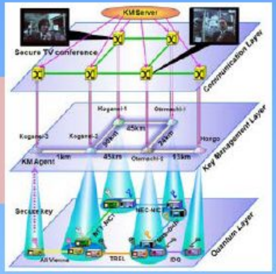
LIDAR



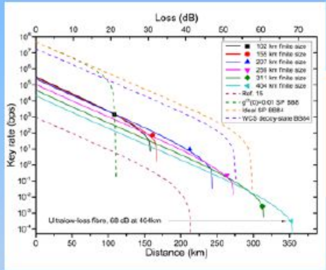
Zhou et al., Opt. Expr. 23, 14603 (2015)
SIMIT

University of Glasgow

Quantum Communications Milestones with SNSPDs

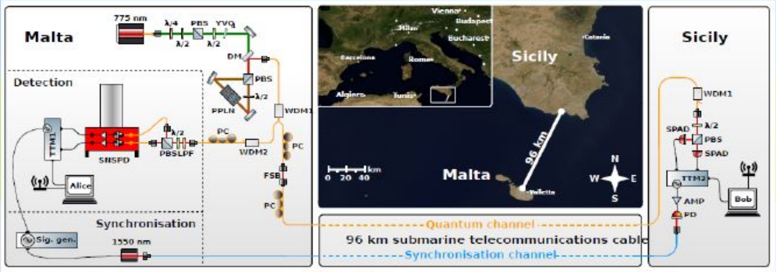


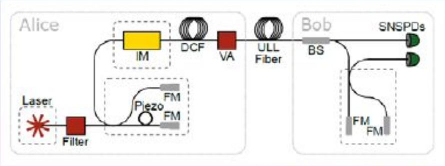
Tokyo QKD Network
Sasaki *et al.* Optics Express 19 10387 (2011)



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



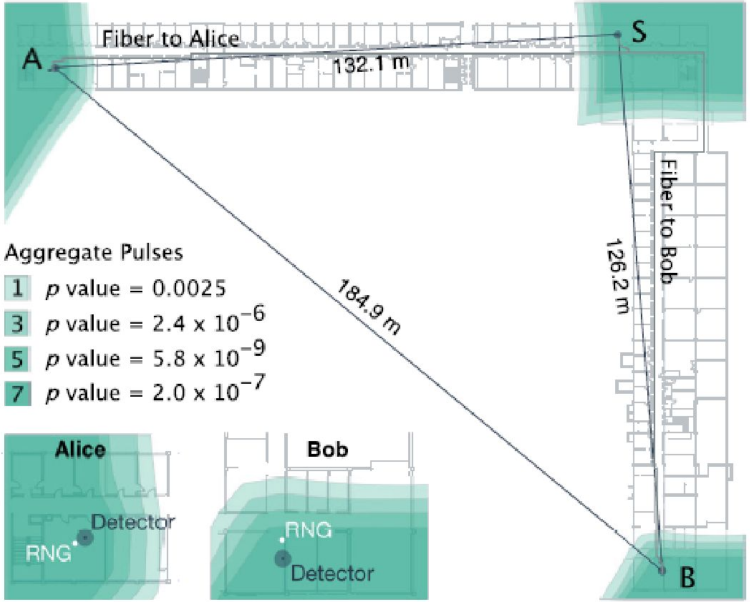


QKD over 421 km optical fibre
Boaron *et al.* Phys. Rev. Lett. 121 190502 (2018)

Slide courtesy of Robert Hadfield

"Loophole-free" Bell test (2015)

NIST



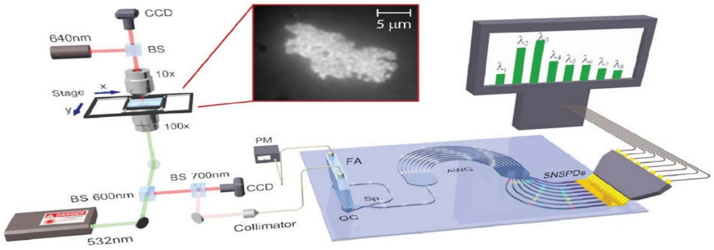
L. K. Shalm et. al, PRL ***115****, 250402 (2015)*

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

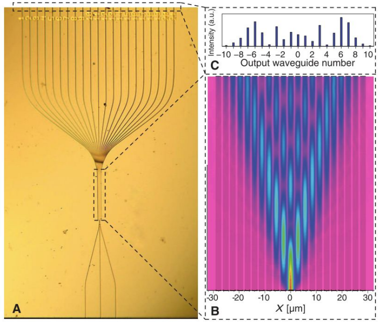
Slide courtesy of Sae-Woo Nam

Quantum Science Applications

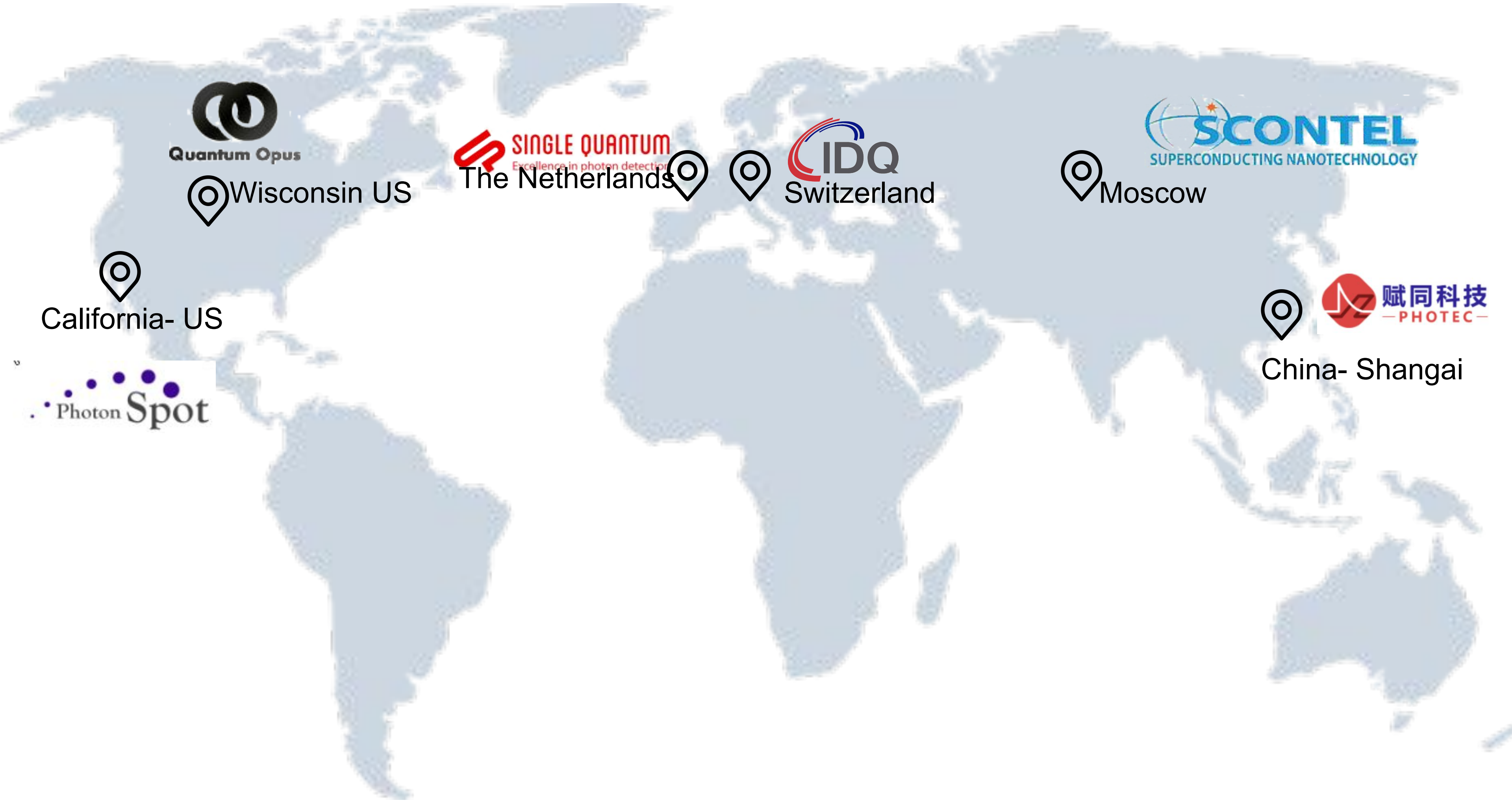
Single-photon spectrometer

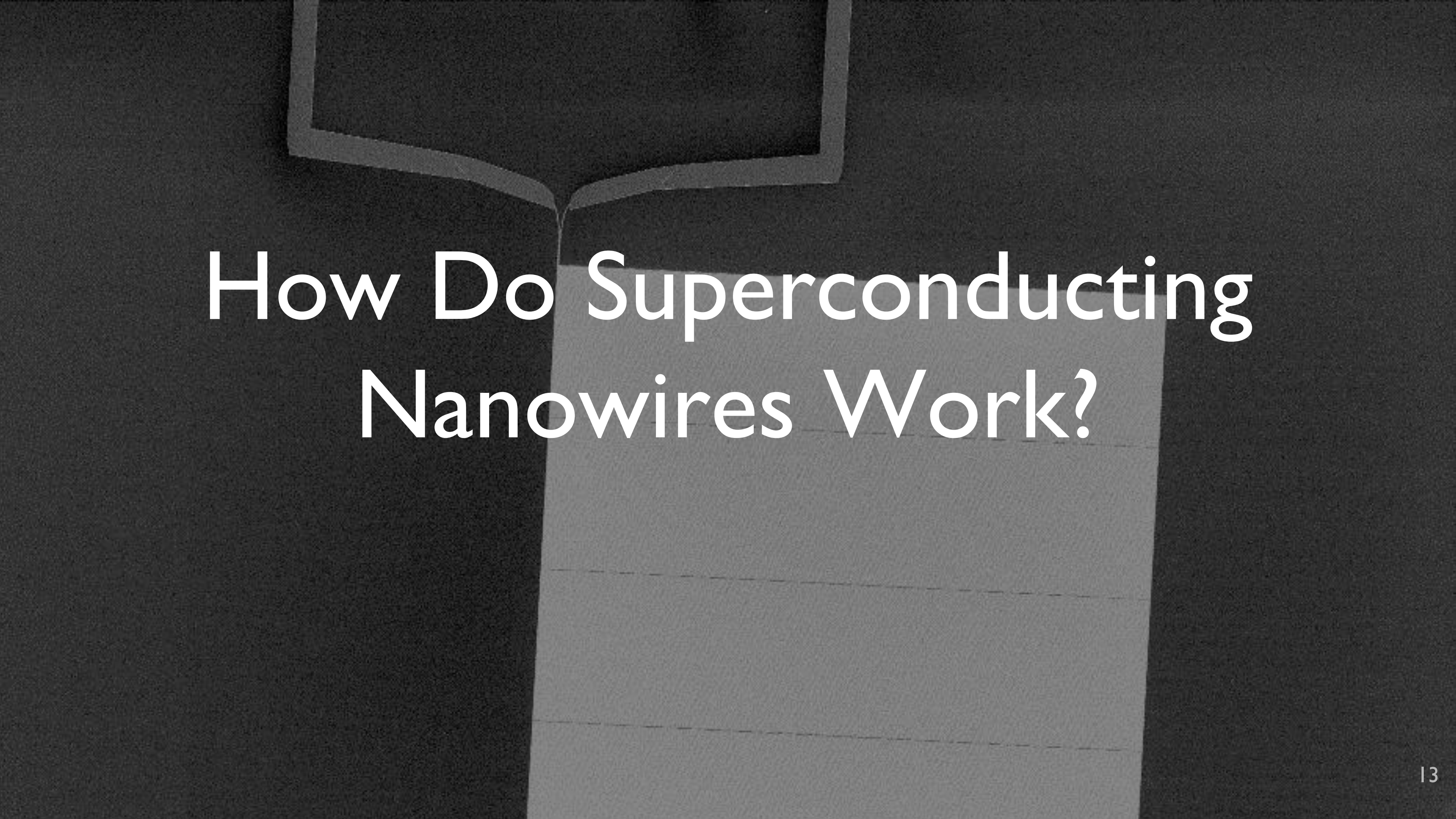


Kahl, et al., arXiv:1609.07857 (2016)



Peruzzo, et al., Science 329 (5998), 1500-1503 (2010)


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

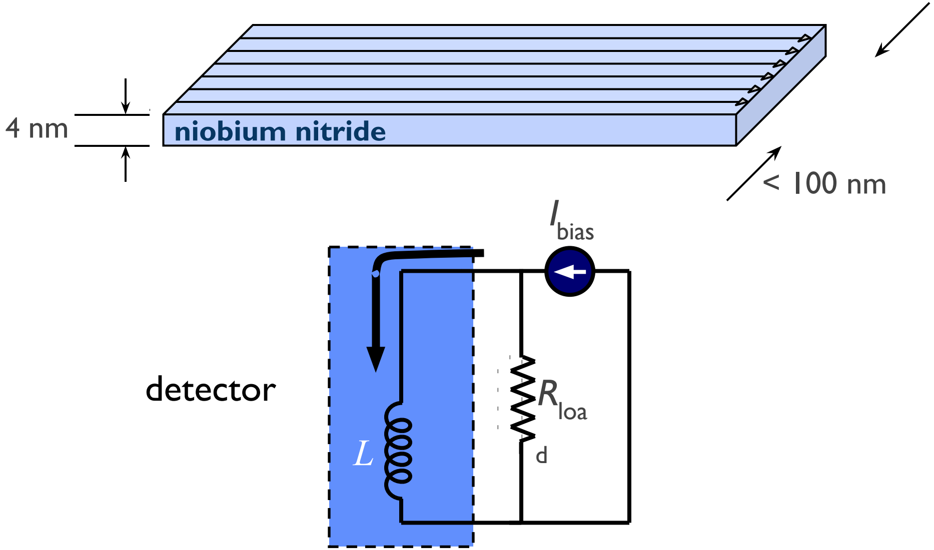


How Do Superconducting Nanowires Work?

Current Bias

Critical Temperature ~ 11 K

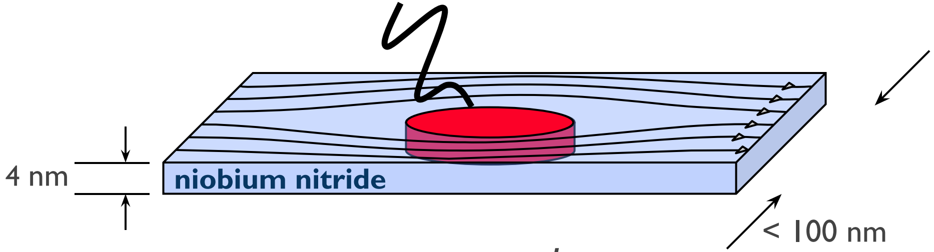
superconductor is biased near its transition

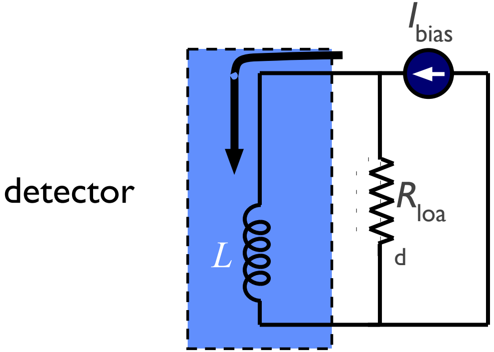


Absorption

Critical Temperature ~ 11 K

photon-induced hotspot forces bias current above critical density

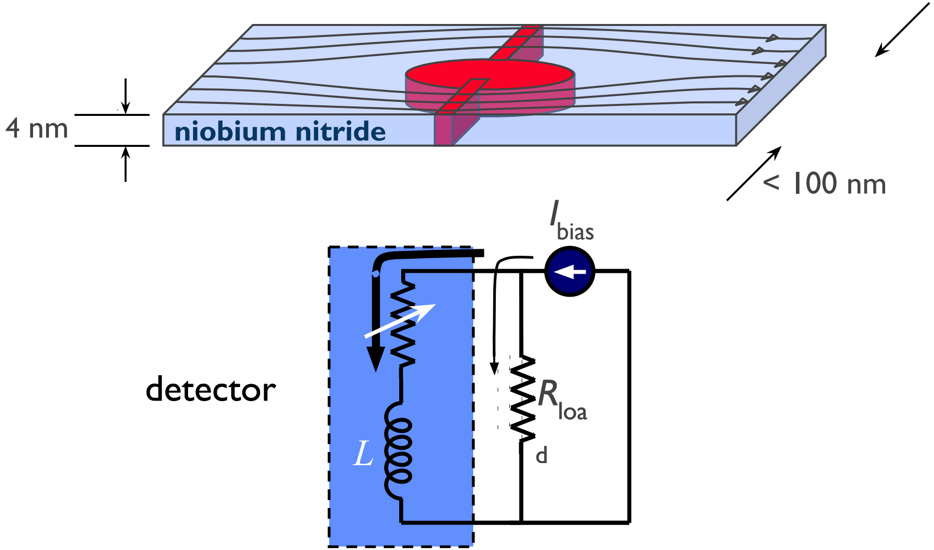




Breakdown

Critical Temperature ~ 11 K

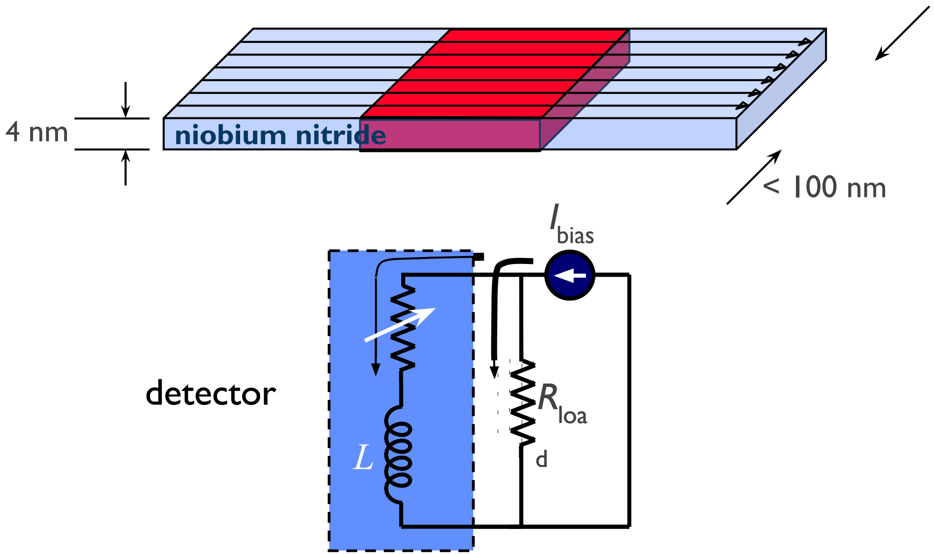
resistive barrier spans
nanowire



Acceleration/Heating

Critical Temperature ~ 11 K

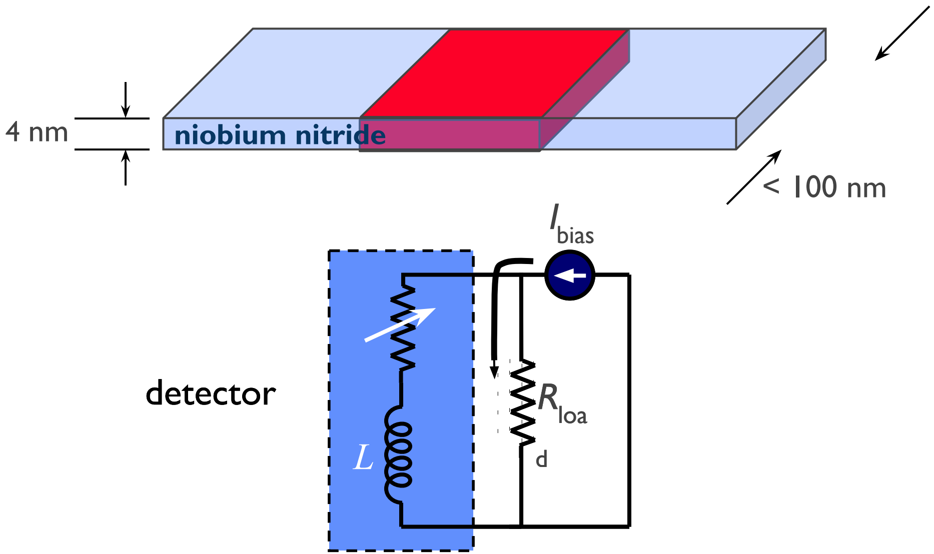
resistance grows from heating



Diversion of Current

Critical Temperature ~ 11 K

current is diverted

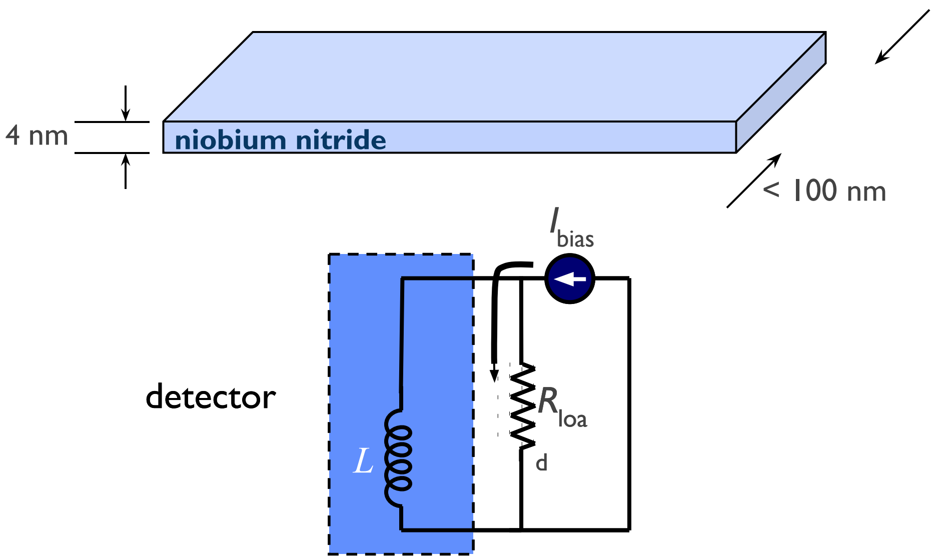


Cooling

current is diverted

Critical Temperature ~ 11 K

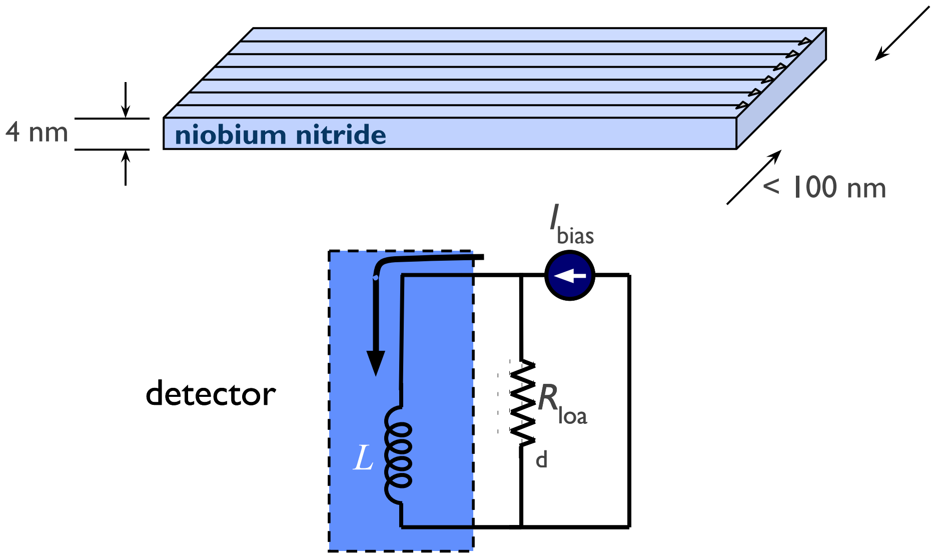
superconductivity is restored

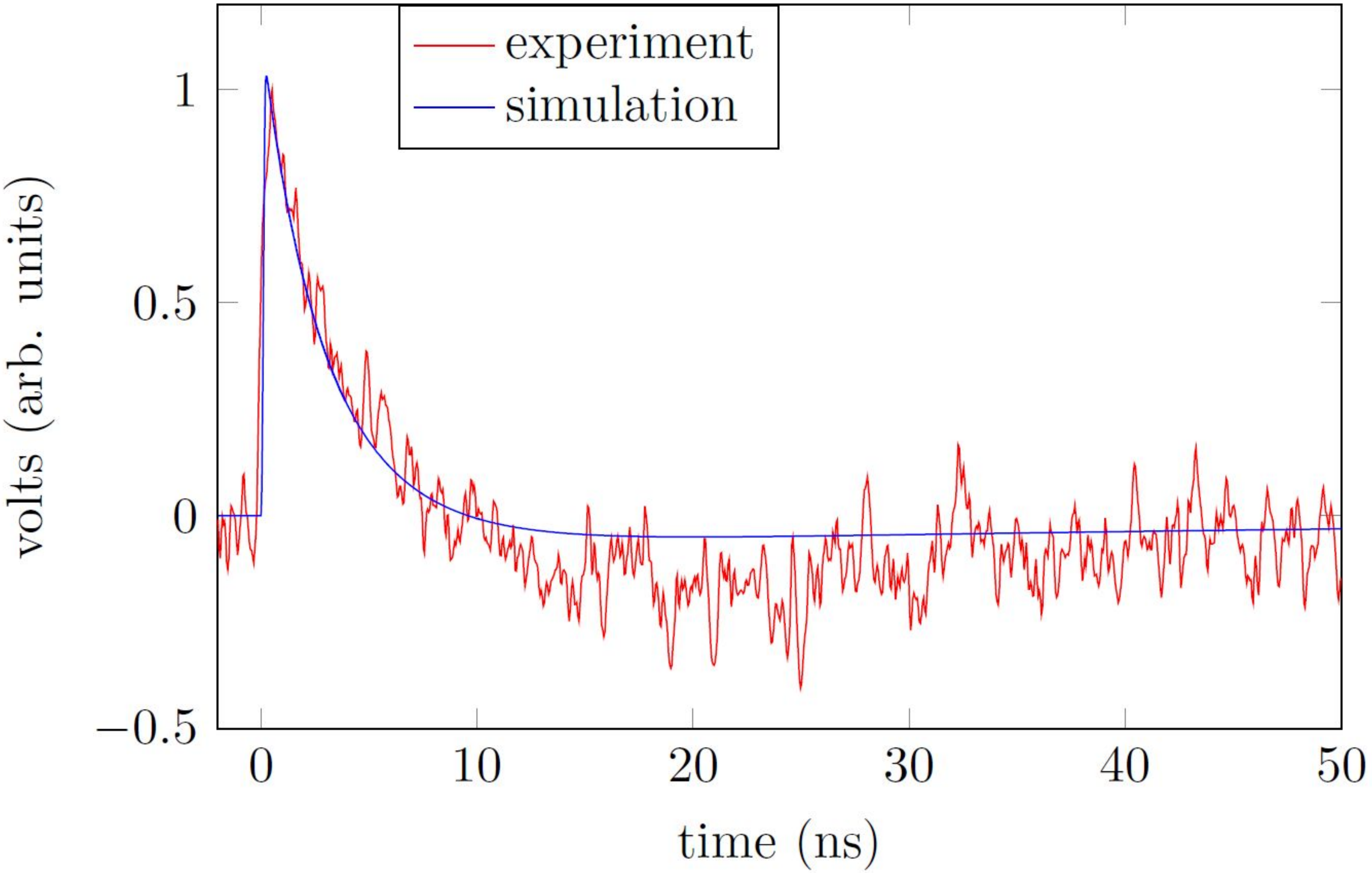


Reset

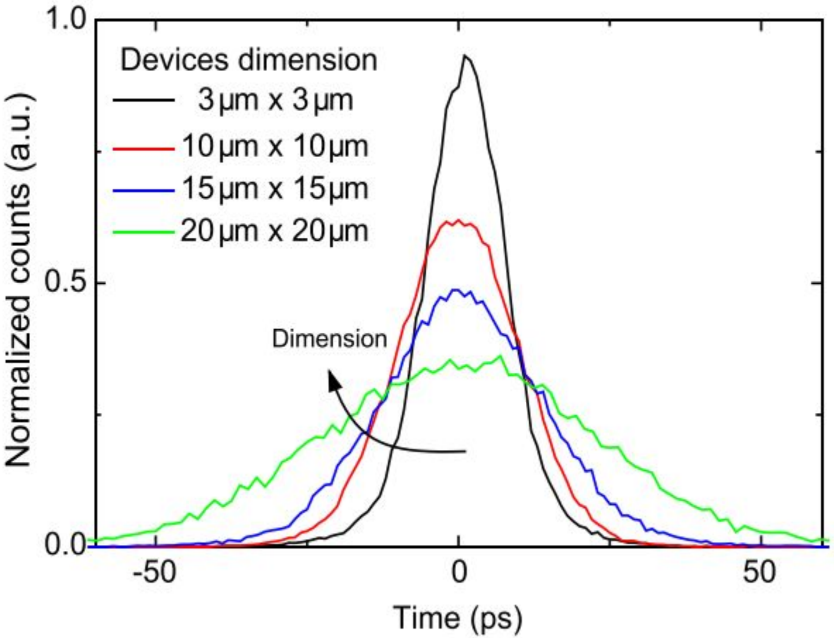
Critical Temperature ~ 11 K

bias current is restored

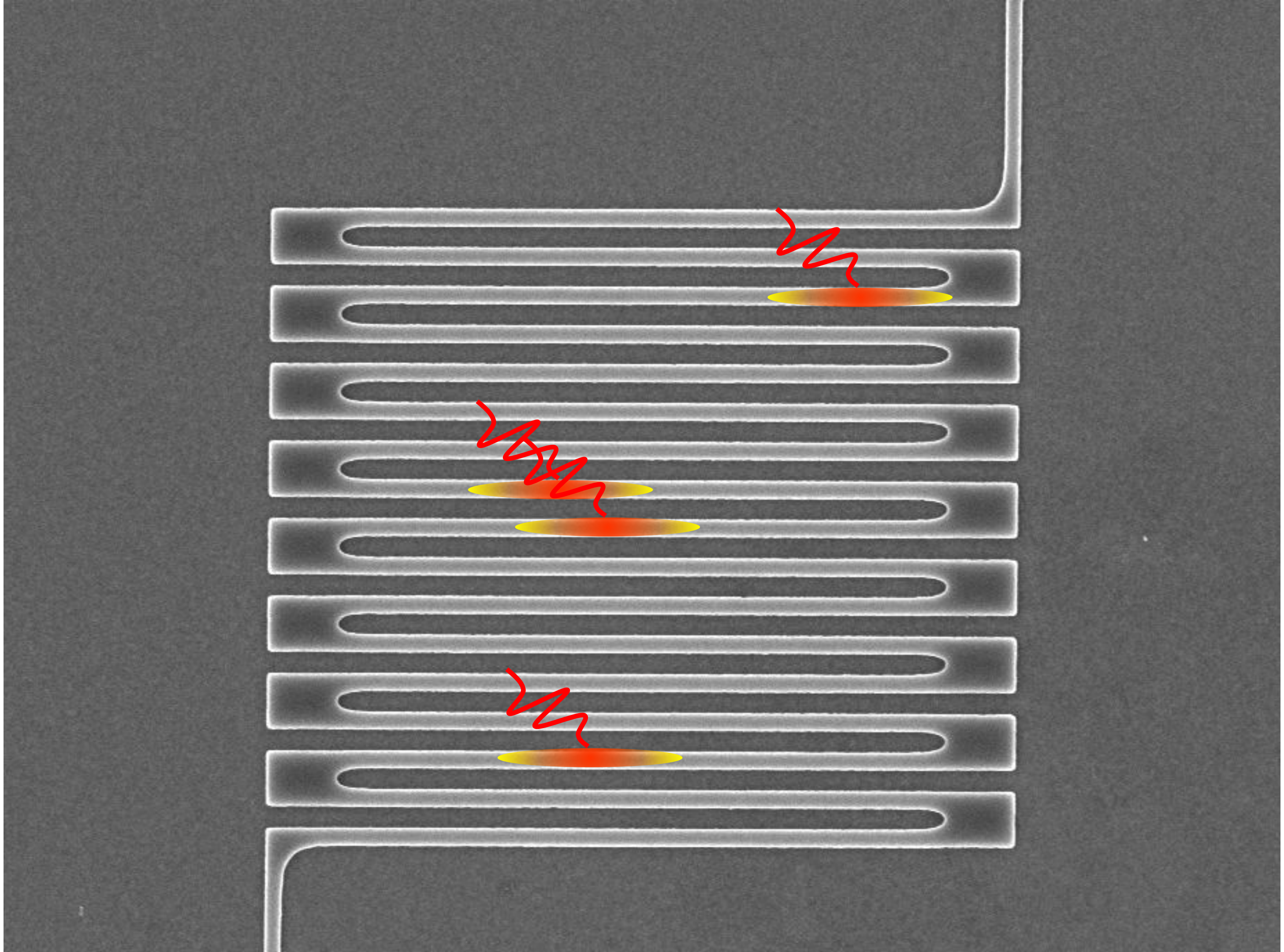



experiment
simulation
volts (arb. units)
1
0.5
0
−0.5
0
10
20
30
40
50
time (ns)

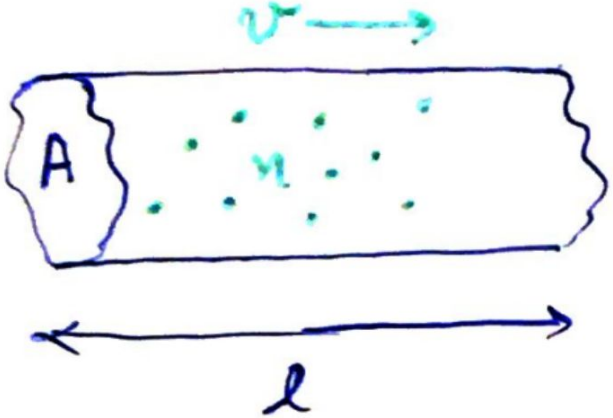
Timing jitter limited by detector geometry



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



Kinetic Inductors



$v \equiv$ drift vel.

$n \equiv$ carrier dens.

Inductive energy $\equiv$ kinetic energy

$$\Rightarrow \frac{1}{2} L_k i^2 \equiv \frac{1}{2} M v^2 \qquad (1)$$

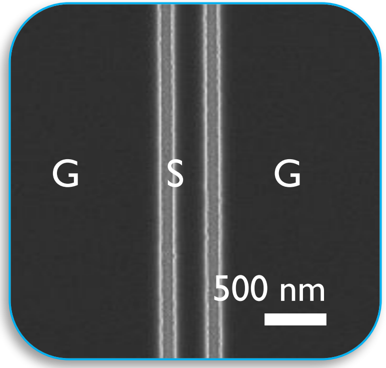
$$i = A \cdot n \cdot e \cdot v \qquad M = l \cdot A \cdot m_e n \Rightarrow \boxed{\Lambda = m/ne^2}$$

inductivity

https://youtu.be/MAHkYROmriY

Kinetic Inductance: Superconductivity's Ugly Secret

Top view



Side view

$$\begin{aligned}\text{Specific Inductance} &\equiv L_S \\ &= \mu_\circ \frac{\lambda^2}{\text{Area}} \\ &\approx 400\,\text{pH}\,\mu\text{m}^{-1}\end{aligned}$$

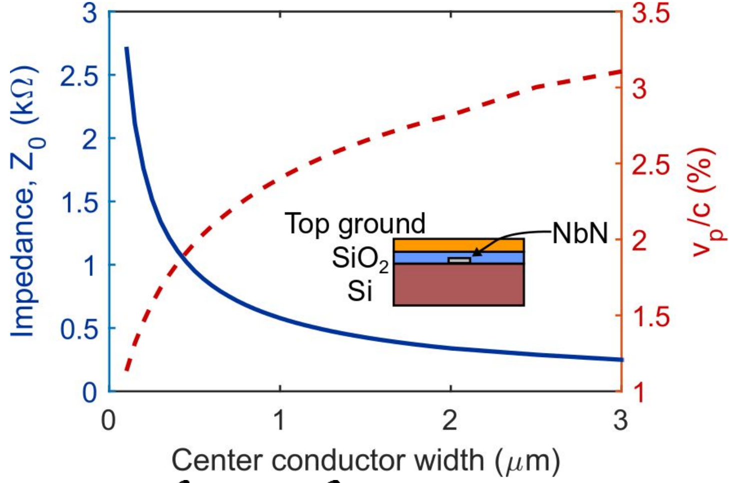
$$\begin{aligned}\text{Specific Capacitance} &\equiv C_S \\ &\approx 3.3\epsilon_\circ \\ &\approx 30\,\text{aF}\,\mu\text{m}^{-1}\end{aligned}$$

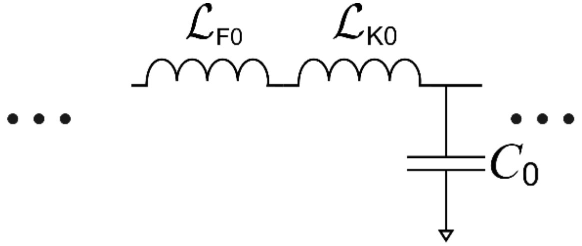
$$\begin{aligned}\text{Signal Speed} &= c_{\text{eff}} \\ &= \frac{1}{\sqrt{C_S L_S}} \sim \frac{c}{30} \\ &= 3\%\,c\end{aligned}$$

$n_{\text{eff}} \sim 30$

Slow-wave transmission line

A typical nanowire transmission line

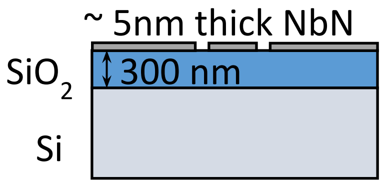




For a ~ 5 nm thick 300 nm wide NbN microstrip,

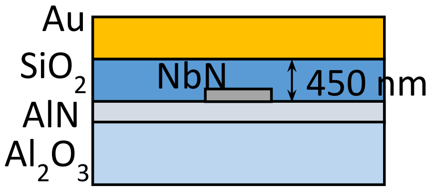
$$\mathcal{L}_{K0} \approx 212\mu_0 \quad \mathcal{L}_{F0} \approx 0.3\mu_0 \quad \mathcal{C}_0 \approx 21\epsilon_0$$

Measured group velocities to date



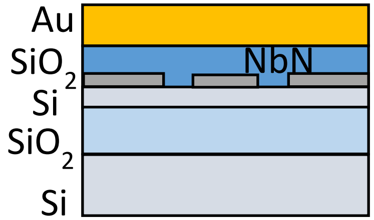
Signal speed ~2%*c* = 6 μm / ps

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)

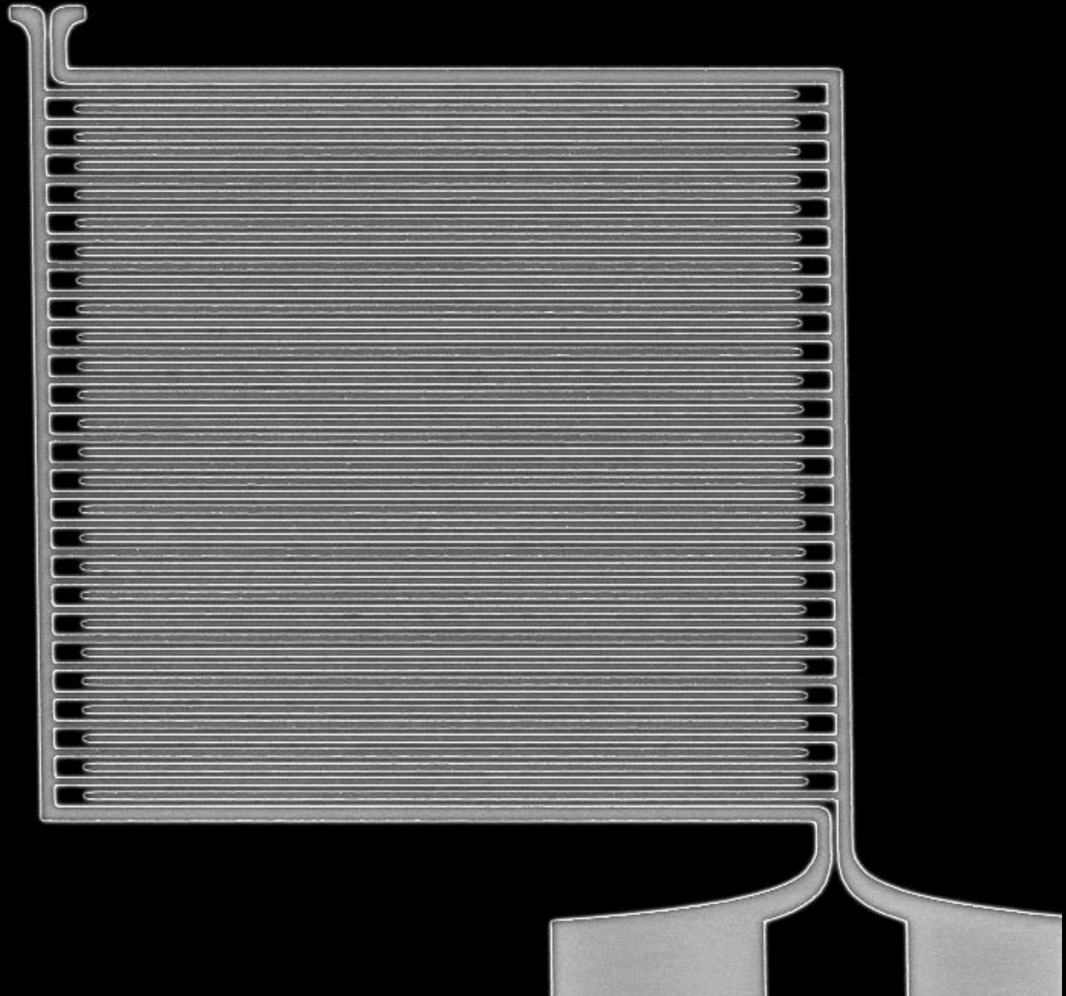


Signal speed = 2.7 μm/ps

Zhu et al. (2018), unpublished

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

Using high impedance

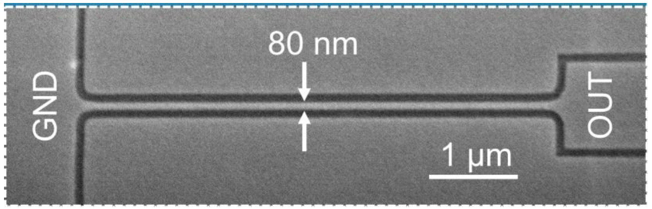


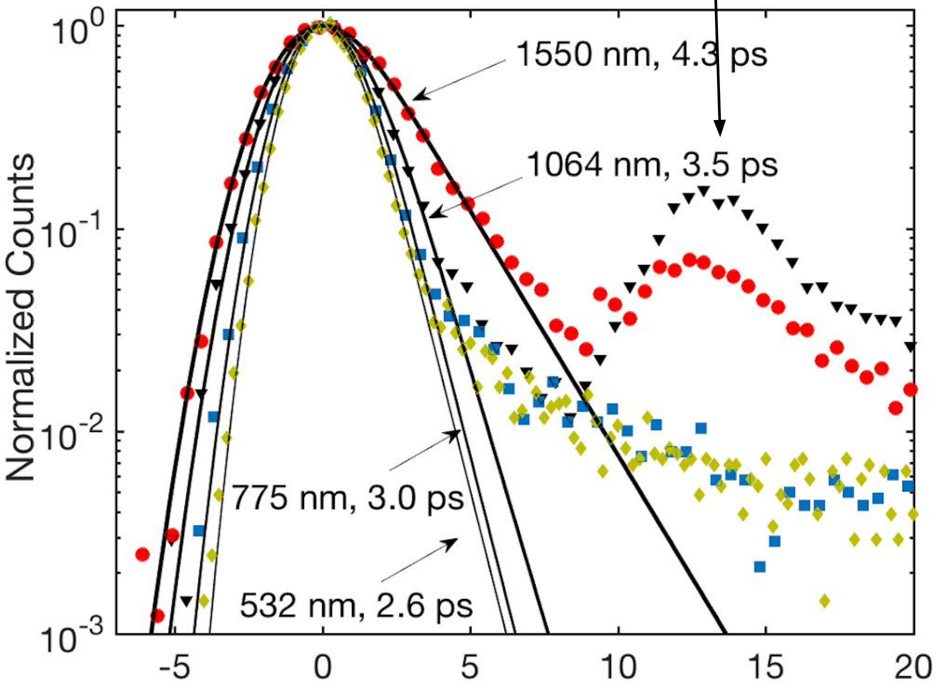
Collaboration with JPL, NIST, U. of Lancaster

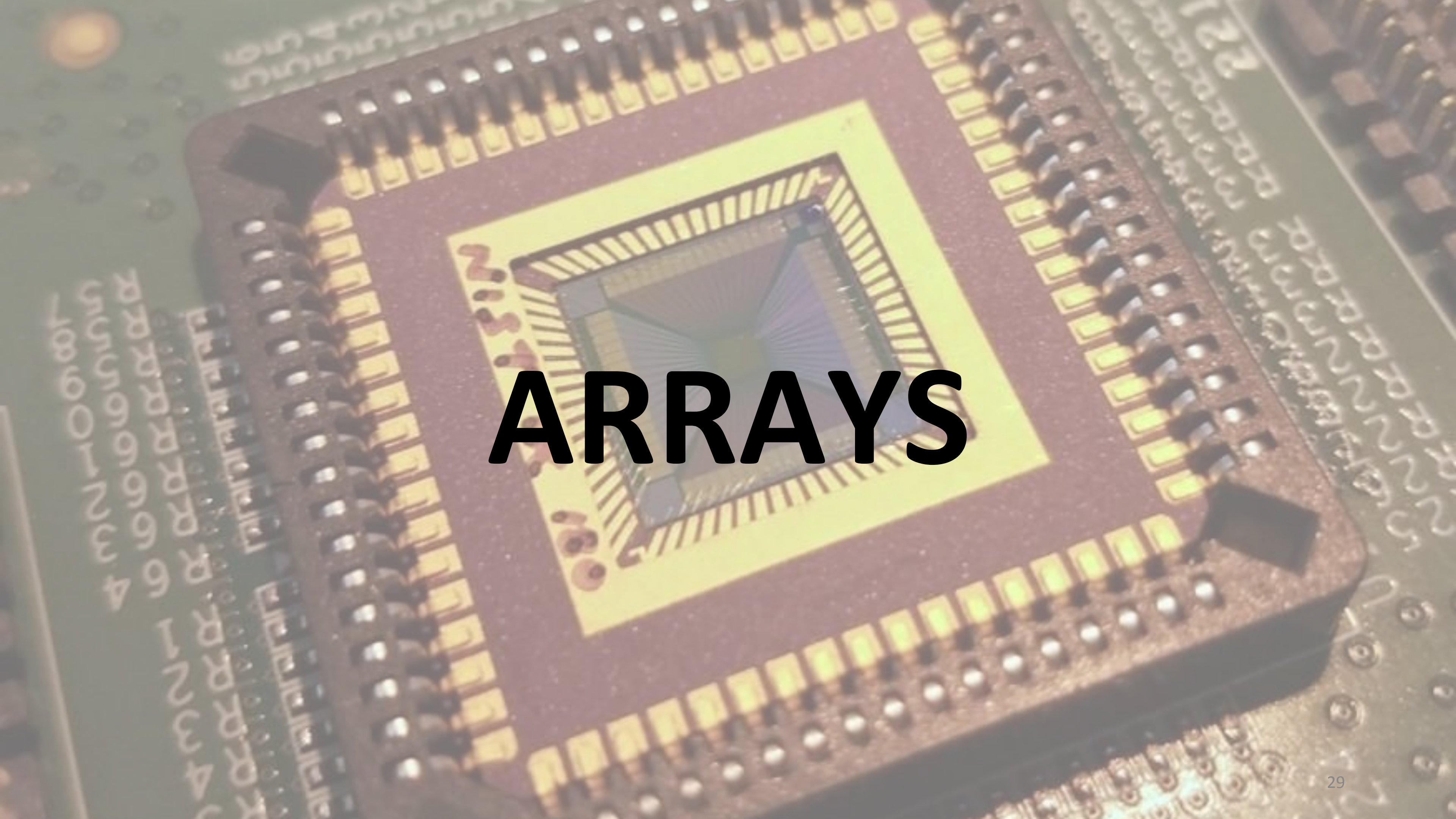
Timing jitter

Timing jitter of 2.6 ps achieved with a **short single-ended device**

Bump due to reflection from back of wafer





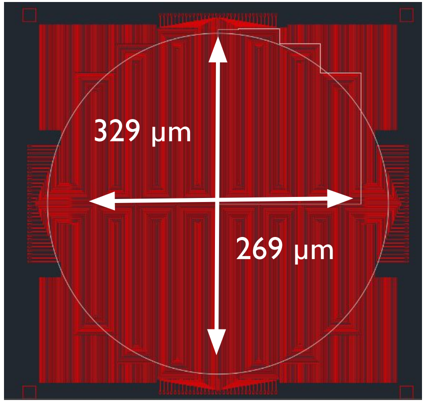


ARRAYS

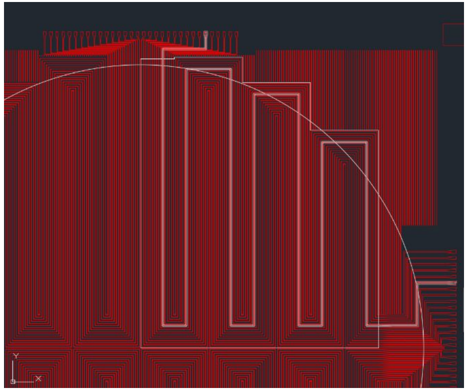
64-Element SNSPD for Ground Receiver, JPL

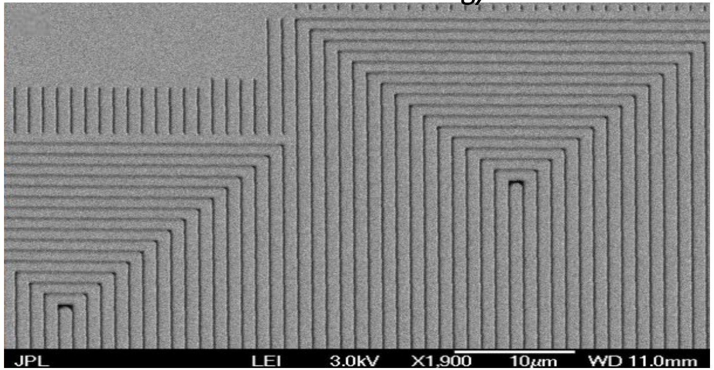
- SNSPD planned for DSOC Ground Laser Receiver at 200 inch Palomar telescope (5.1 m)
- 64-element WSi SNSPD array (equivalent to 318.5 μm diameter)
- Free-space coupling to 1 Kelvin cryostat
- 78% system detection efficiency at 1550 nm, < 80 ps jitter
- ~1.2 Gcps maximum count rate

Ref. Jet Propulsion Laboratory - NASA
California Institute of Technology



CAD Design of SNSPD focal plane array


CAD Design showing one of 16 individual sensor elements per quadrant

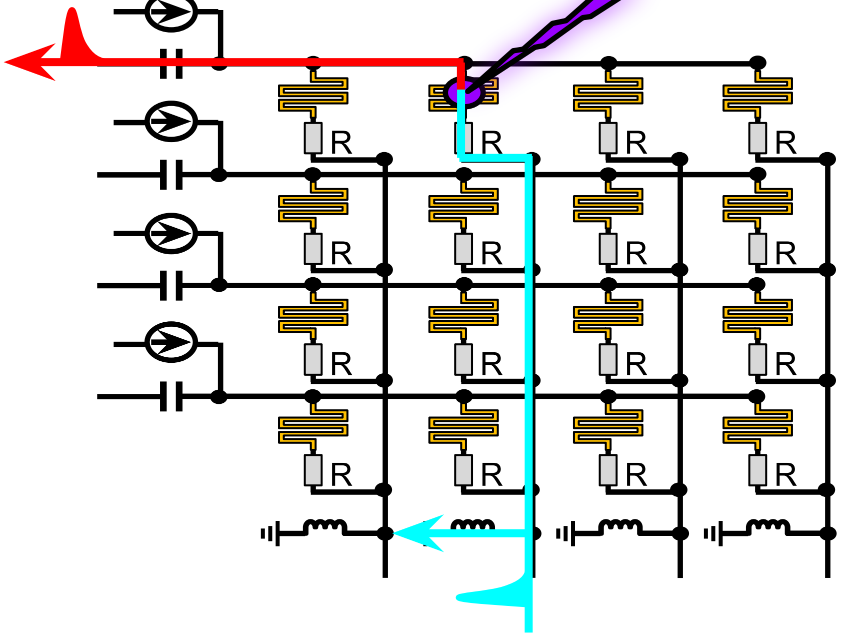


Electron Microscope Image of Nanowire Structure

Row-Column readout architecture

A pair of output signals from Row and Column direction, which has positive and negative polarity respectively

Read out cables for N×N arrays
→ 2×N

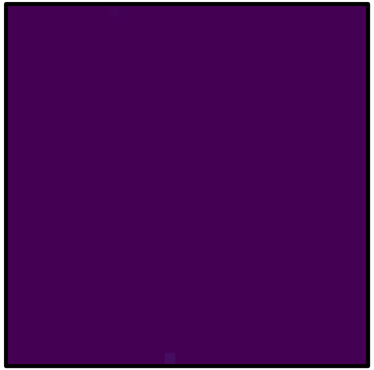


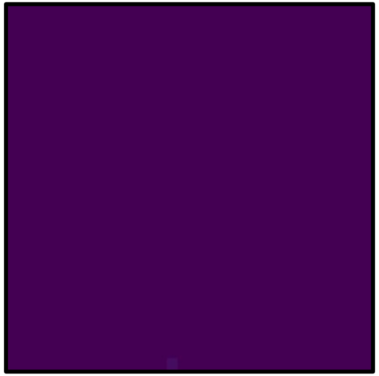
[1] V.B.Verma et al., APL, 104, 051115 (2014).
[2] M.S.Allman et al., APL, 106, 192601 (2015).

Scaling to Kilopixel Arrays

- 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

FABRICATED AT NIST
TESTED AT JPL





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]

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[2]*Graduate School of Engineering Faculty of Engineering, Kobe University, 1-1 Rokko-dai cho, Nada-ku, Kobe 657-0013, Japan*
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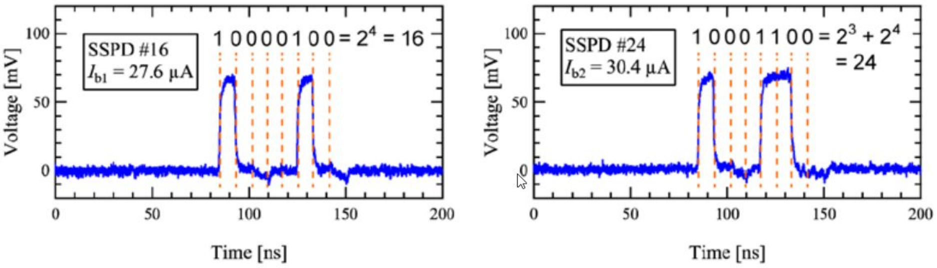
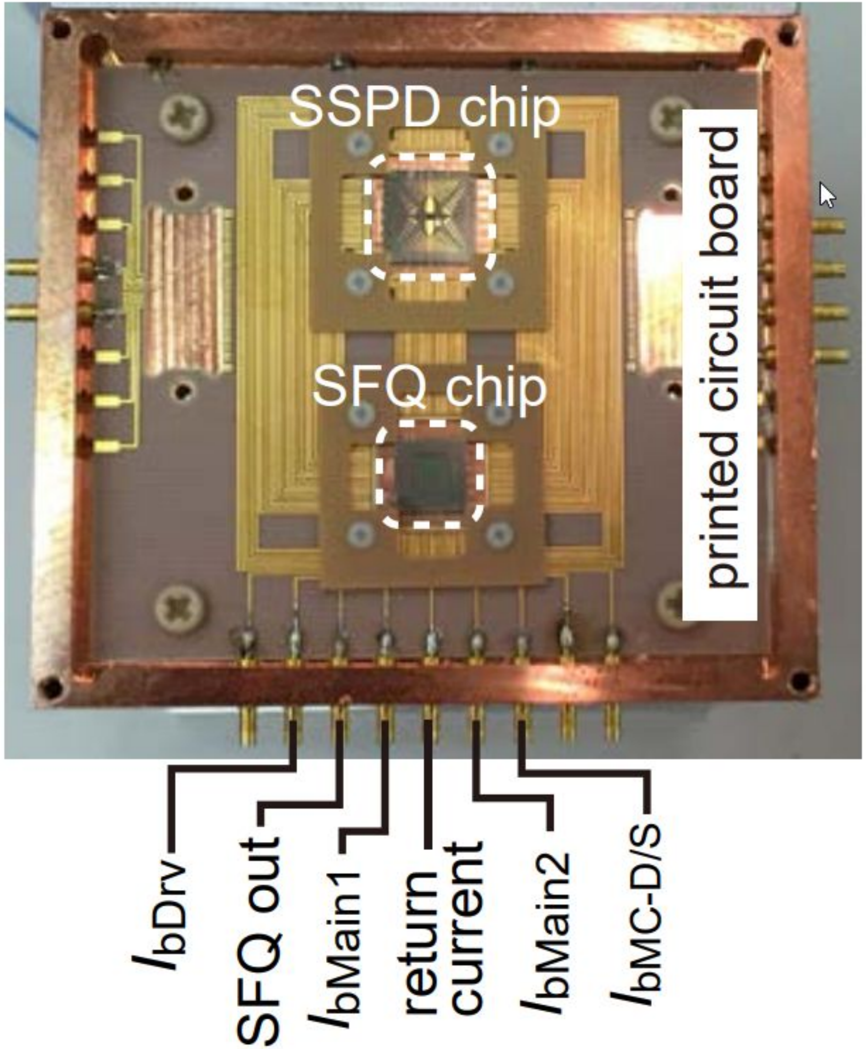
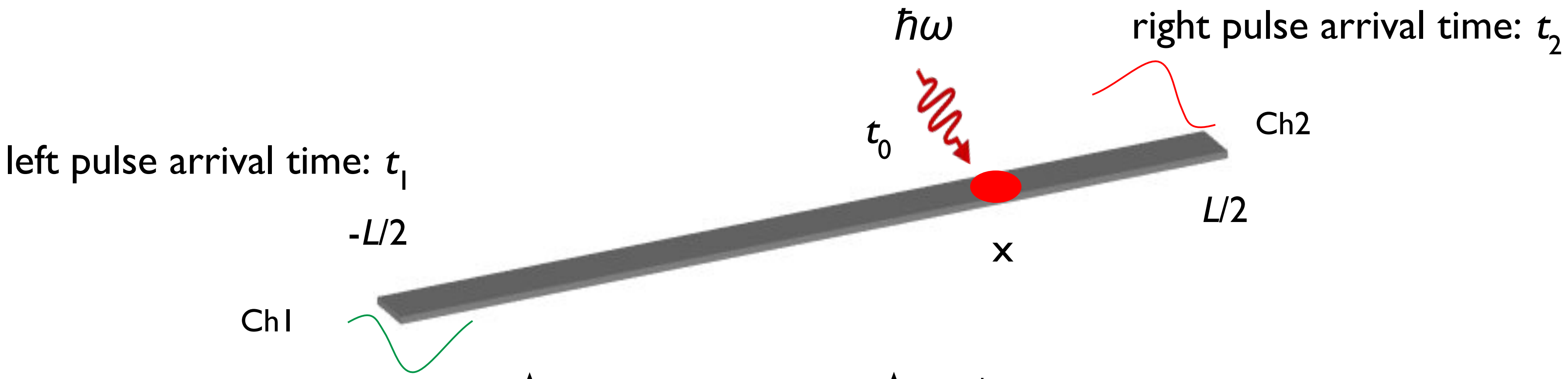
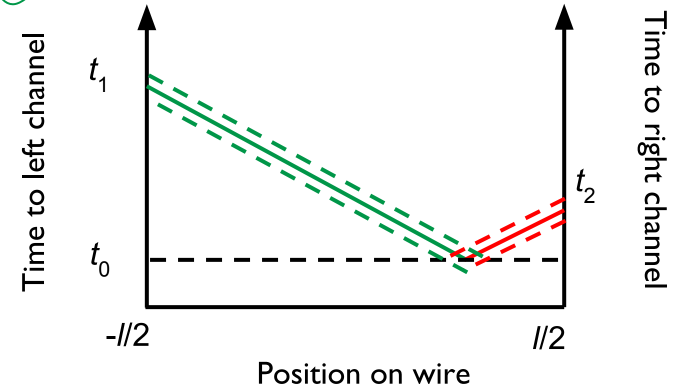
[4]*PRESTO, Japan Science and Technology Agency, 4-1-8 Honcho, Kawaguchi, Saitama 332-0012, Japan*
*miyajima@nict.go.jp





Spatial and temporal resolution in a wire

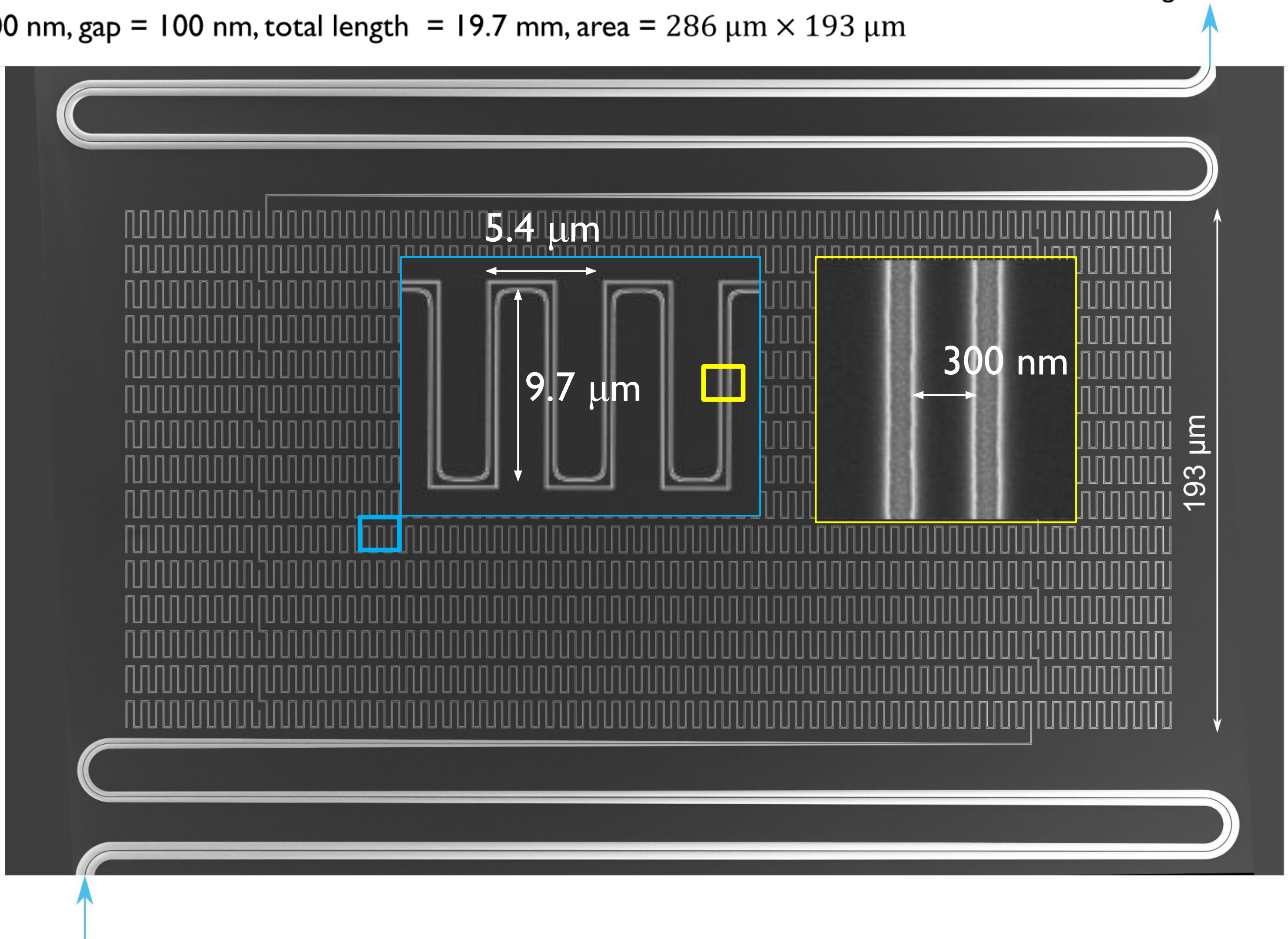




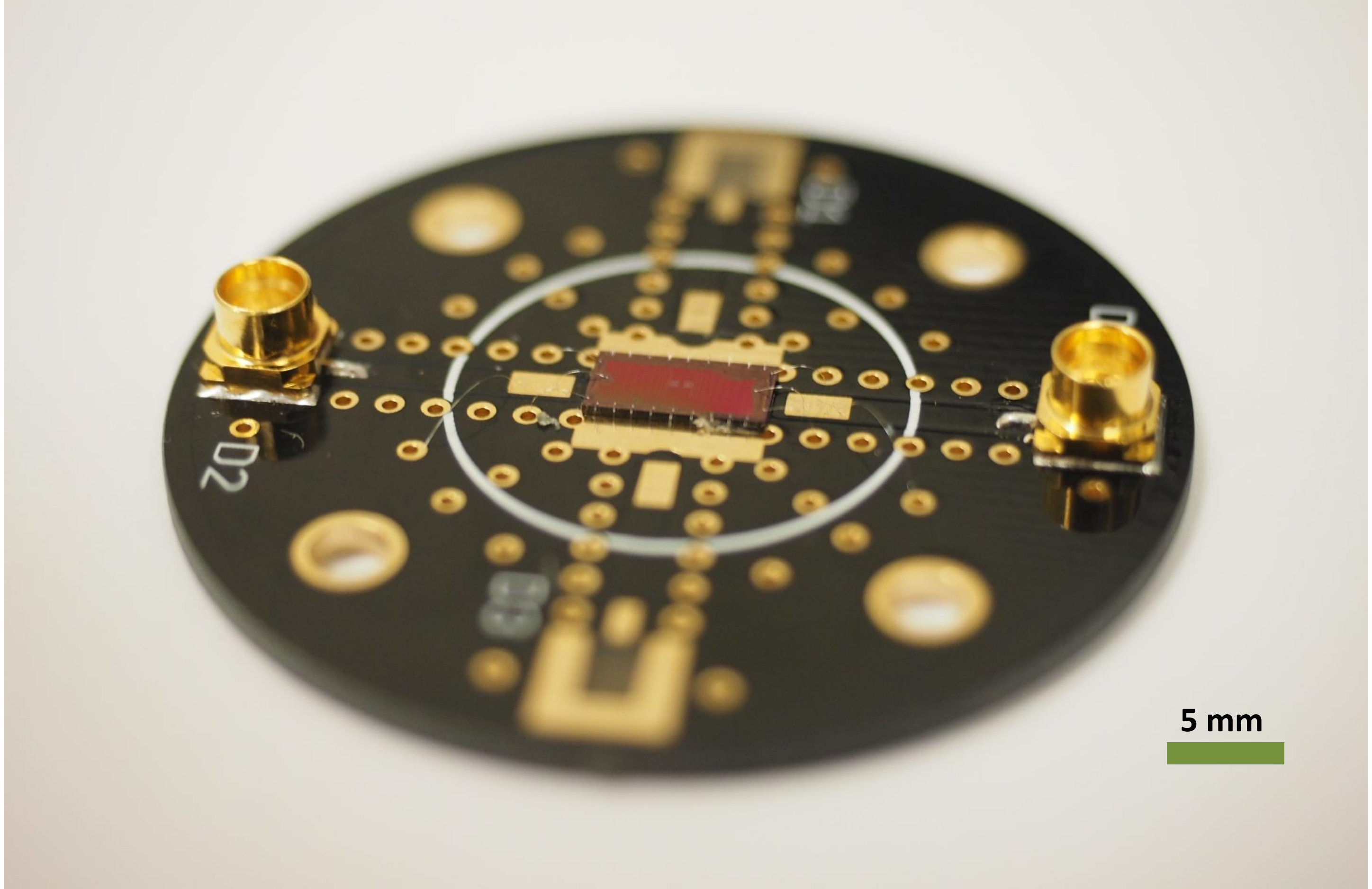
Q.-Y. Zhao, *et.al.*, *Nature Photonics* 11 (4), 247-251

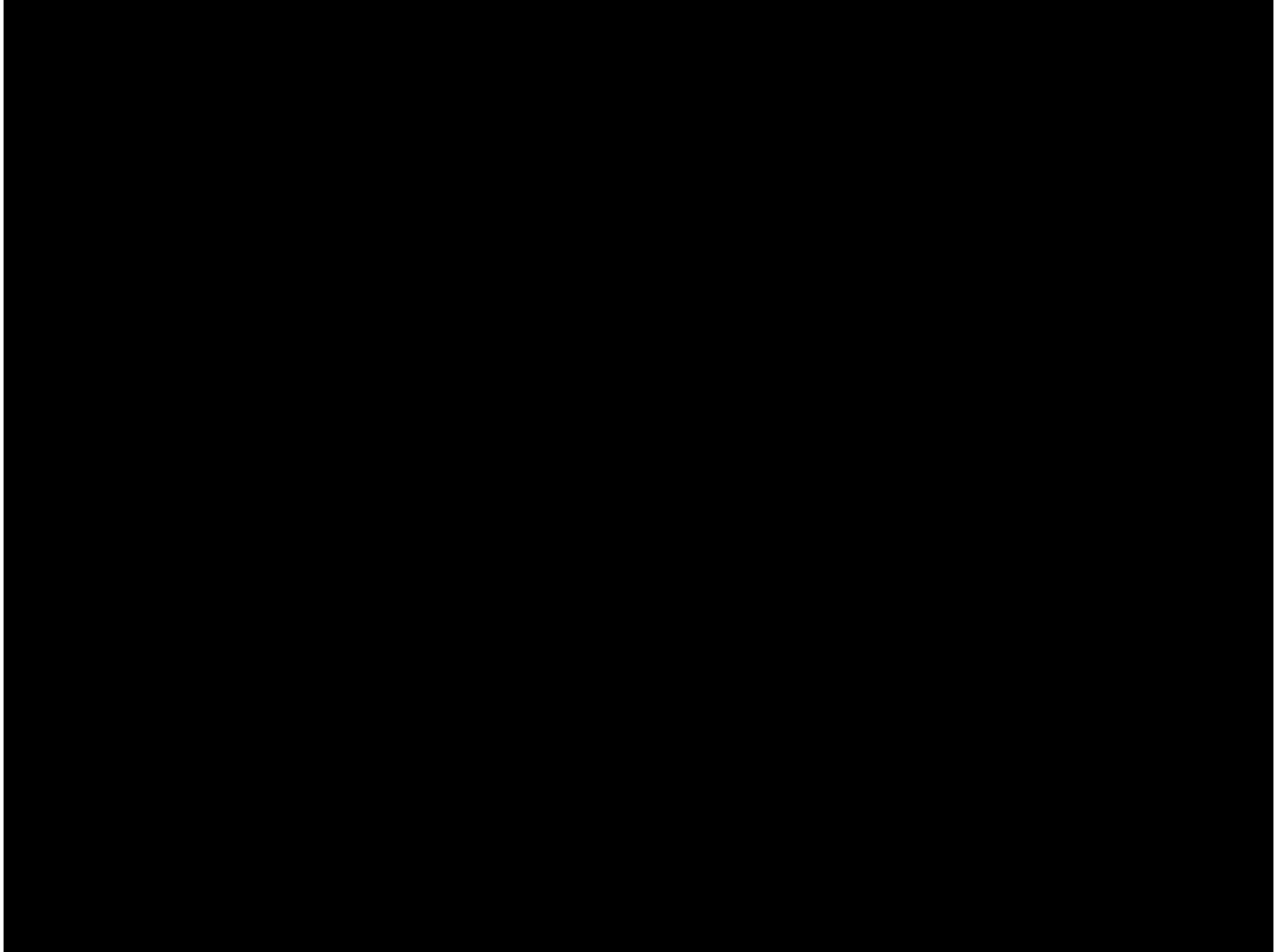
Qingyuan Zhao

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



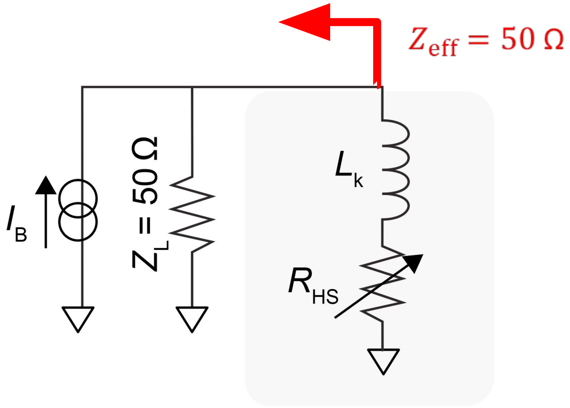
Two connectors for one imager (>500 pixels)



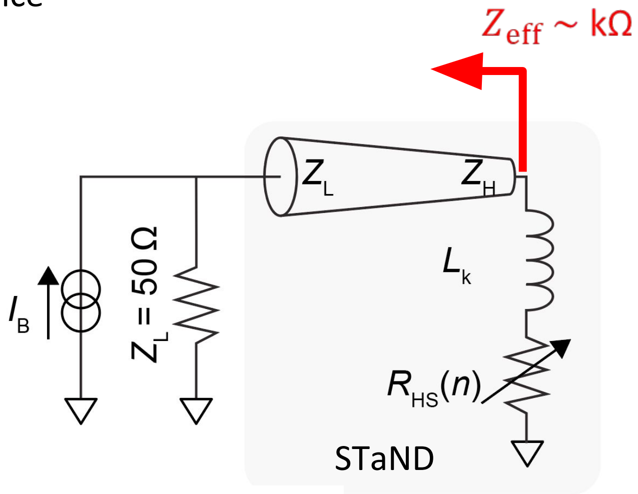


Superconducting Tapered Nanowire Detector (STaND)

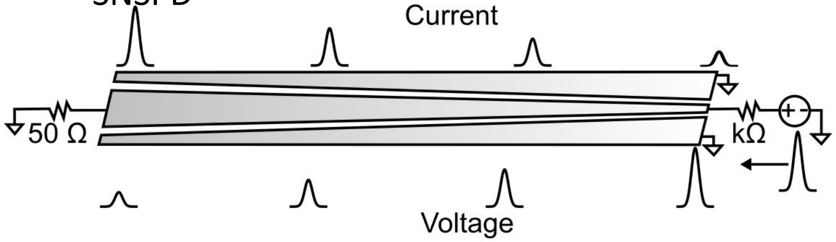
- Photon absorption induces kΩ hotspot in the nanowire
- Using 50 Ω load to read out kΩ device is inefficient
- Large impedance mismatch in conventional SNSPD makes the output insensitive to photon-number-dependent hotspot resistance



Conventional SNSPD

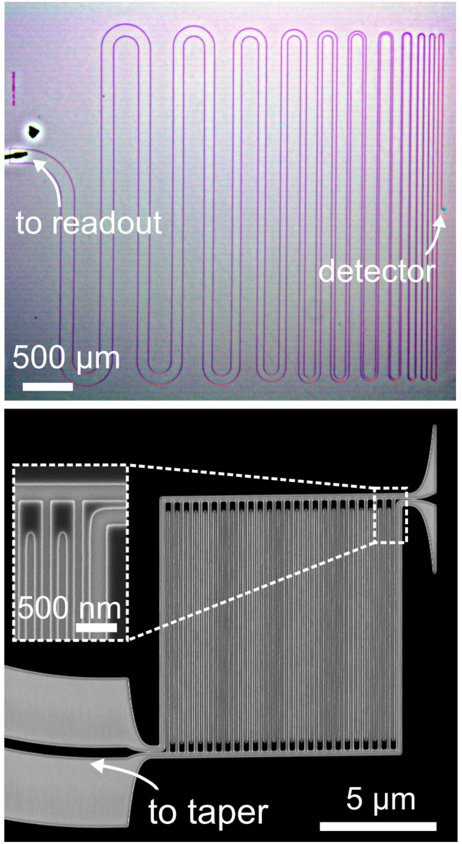


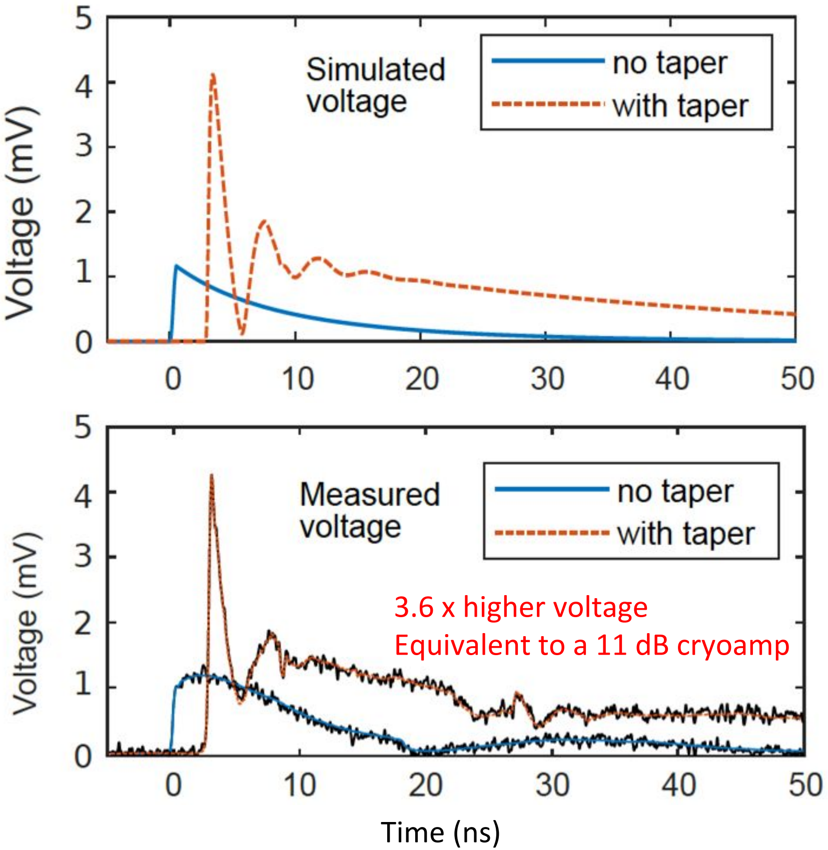
STaND



In collaboration with JPL

Increasing output voltage

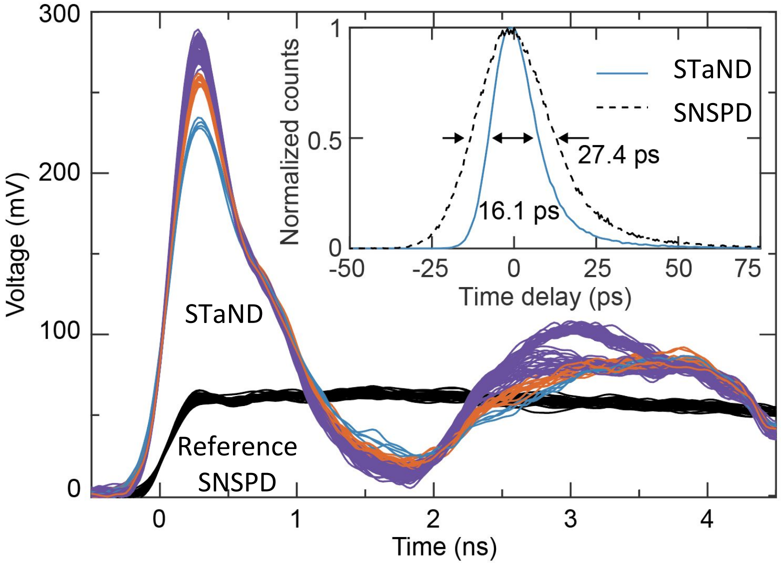




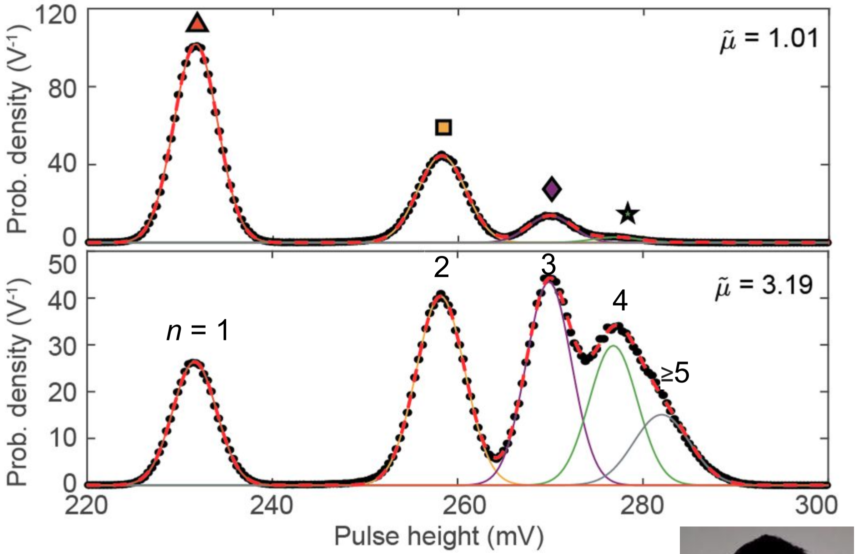
Zhu, D., Colangelo, M., Korzh, B.A., Zhao, Q.Y., Frasca, S., Dane, A.E., Velasco, A.E., Beyer, A.D., Allmaras, J.P., Ramirez, E., Strickland, W.J., Santavicca, D., Shaw, M.D. and Berggren, K.K. - *Appl. Phys. Lett.* 114(4), 042601 (2019)

Reducing timing jitter and enabling photon number resolution

Jitter reduction

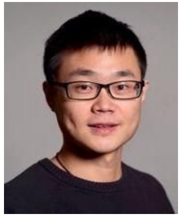


Photon number resolution



Tapered readout has also enabled:

1. 25 ps jitter in NbN SNSPD without amplifier
2. sub-5 ps jitter in WSi using cryogenic amplifiers



Di Zhu

D. Zhu M. Colangelo, C. Chen, B.A. Korzh, F. N. C. Wong, M.D. Shaw, and K.K. Berggren, "Resolving Photon Numbers Using a Superconducting Nanowire with Impedance-Matching Taper," *Nano Lett.*, 2020.

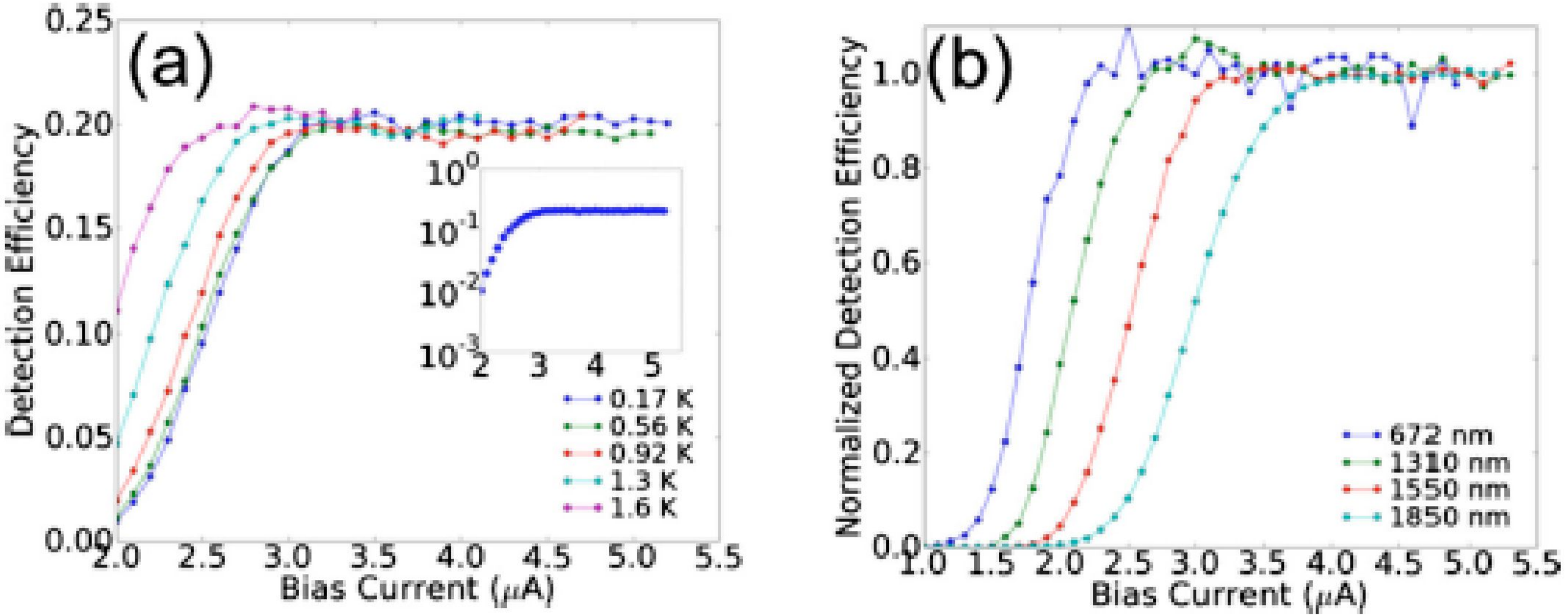
B. Korzh, Q.-Y. Zhao, "Demonstration of sub-3 ps temporal resolution with a superconducting nanowire single-photon detector," *Nat. Photonics*, 14, 250–255 2020.

Materials

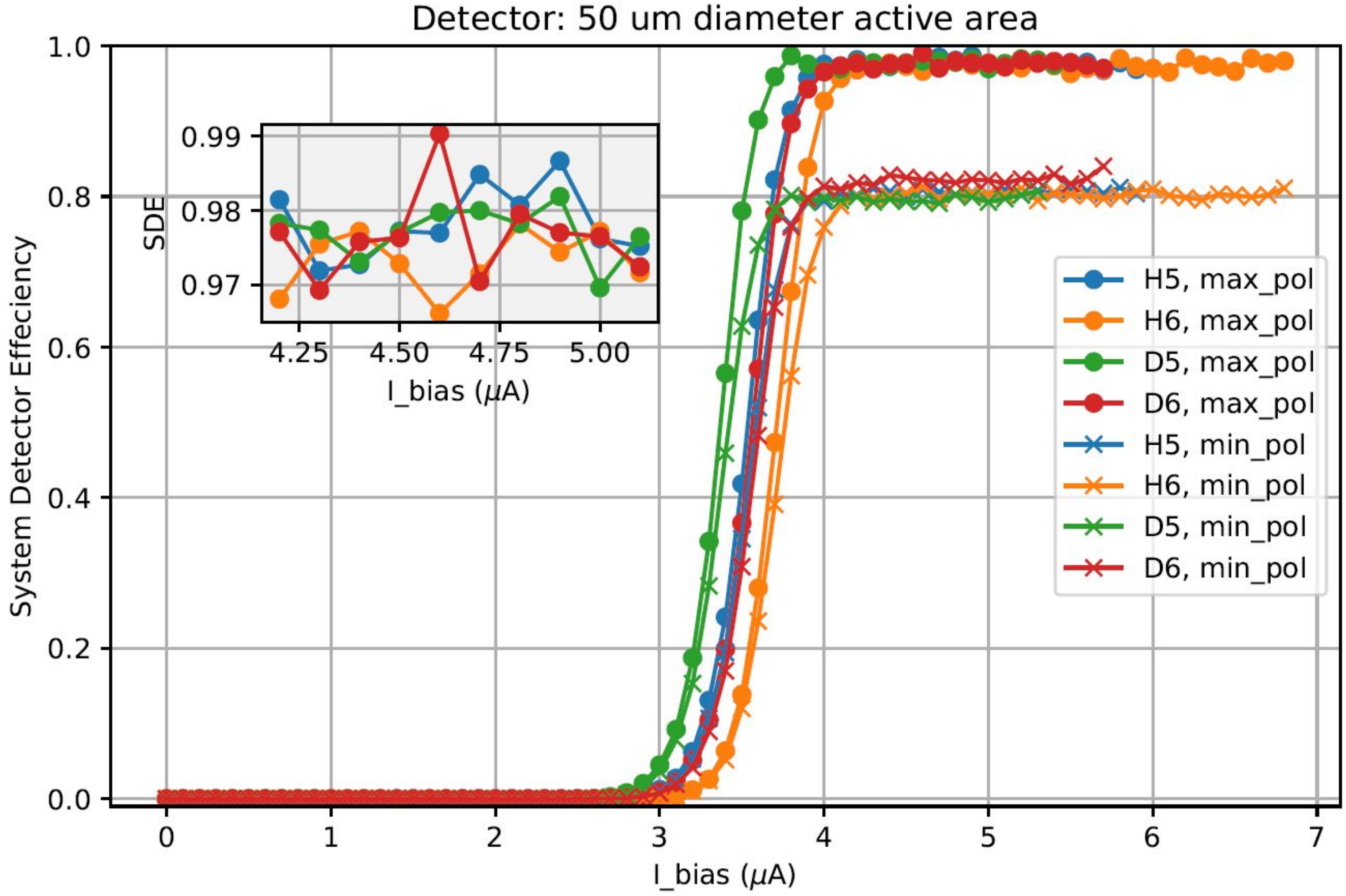
APPLIED PHYSICS LETTERS 98, 251105 (2011)

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



MoSi

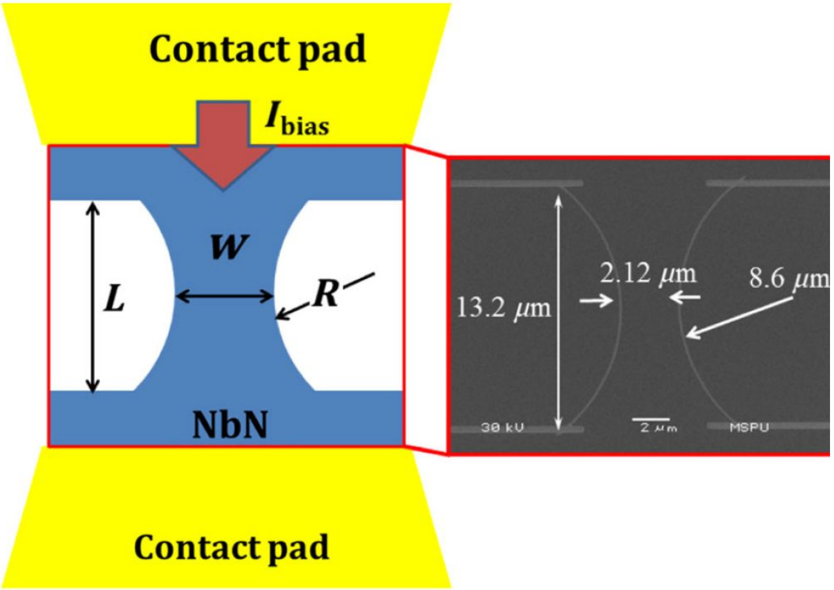


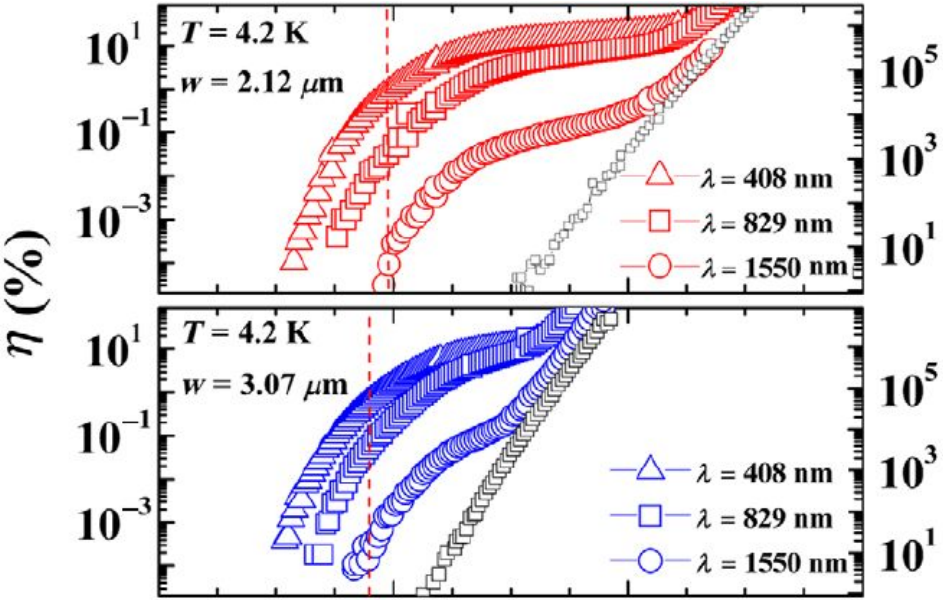
NIST, Reddy et al., CLEO/QELS 2019 https://doi.org/10.1364/CLEO_QELS.2019.FF1A.3

Single-photon detection in short micro-scale NbN wires

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

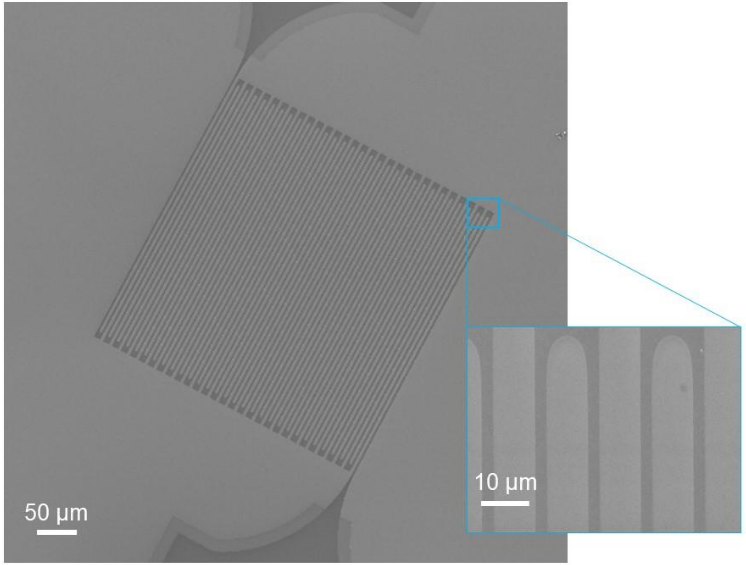
Goltsman's group at MSPU

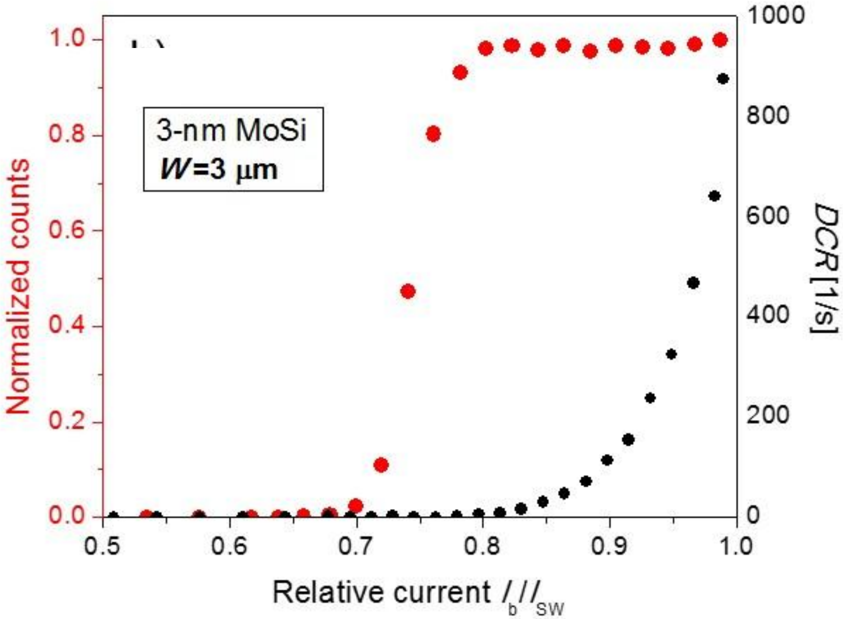




Yu. P. Korneeva and et. al.,Phys. Rev. Applied 9, 064037, 2018

Large-area microwire MoSi single-photon detectors

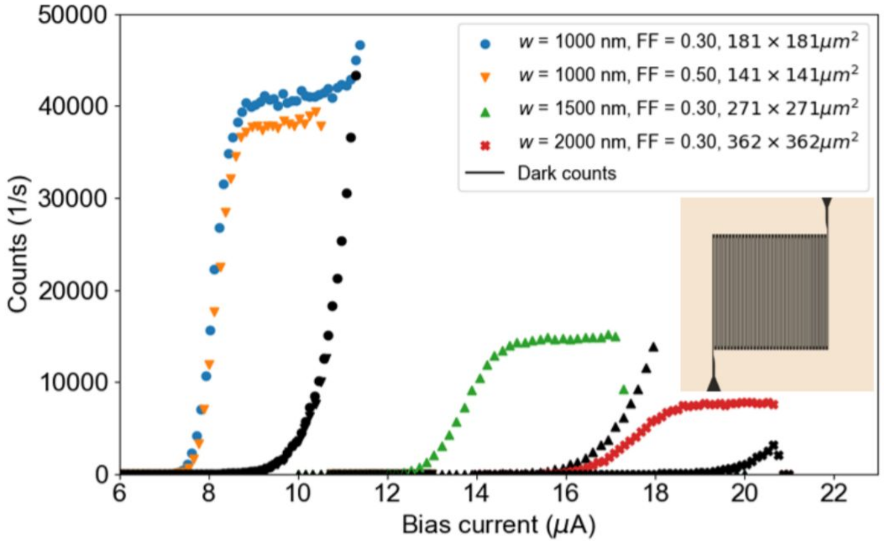


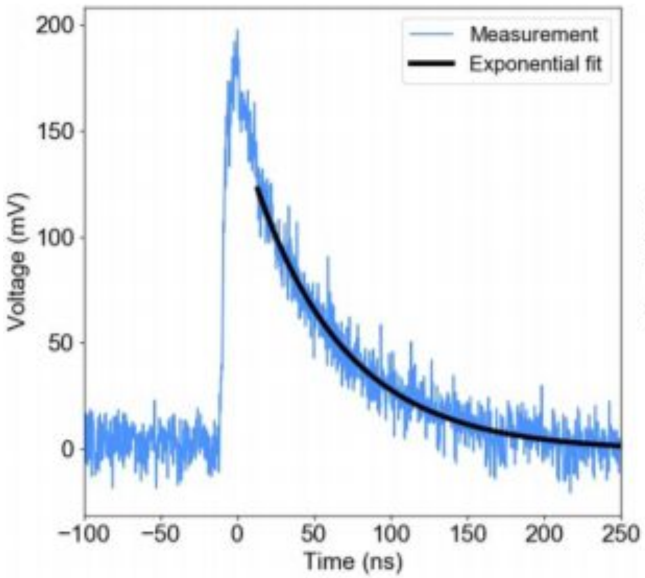


Thin 3-nm MoSi film, up to 3 µm-wide, operating T = 0.3 K, λ = 1550 nm

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

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

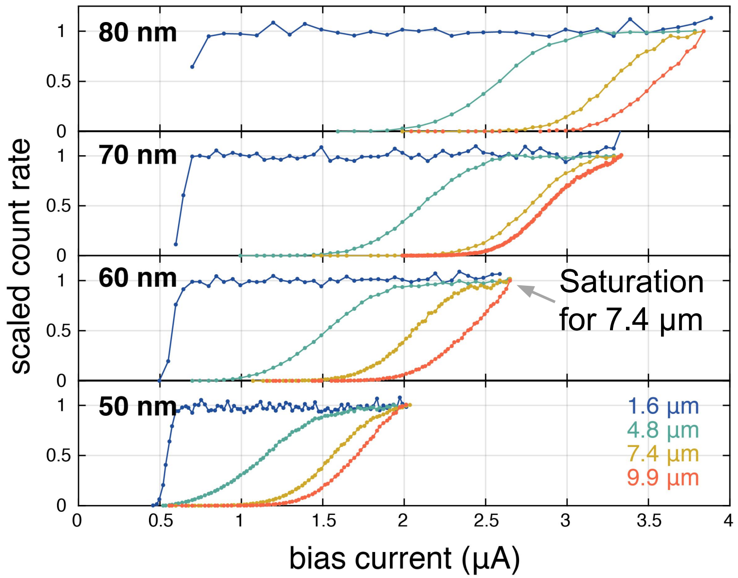
J. Chiles and et al, Appl. Phys. Lett. 116, 242602 (2020)

Mid-IR single-photon sensitivity

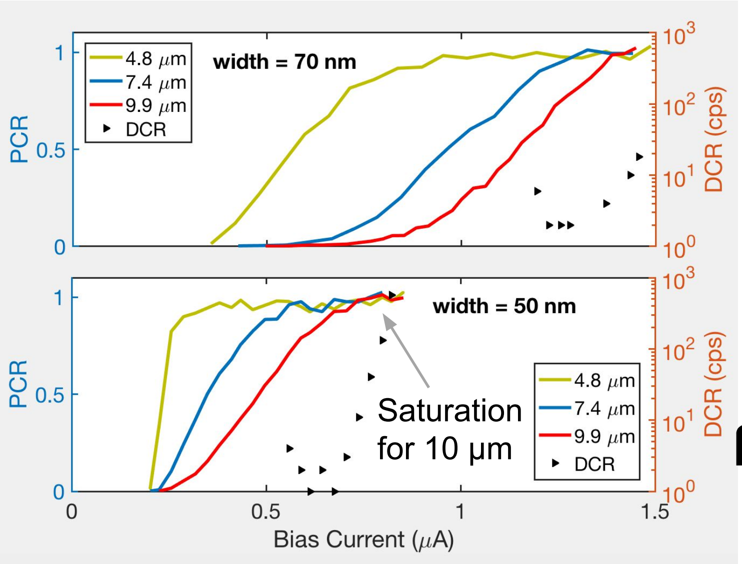
Current status

- Single photon sensitivity and internal saturated efficiency demonstrated out to 10 µm with low coupling efficiency.
- Currently pursuing lower-Tc materials for sensitivity to longer wavelengths

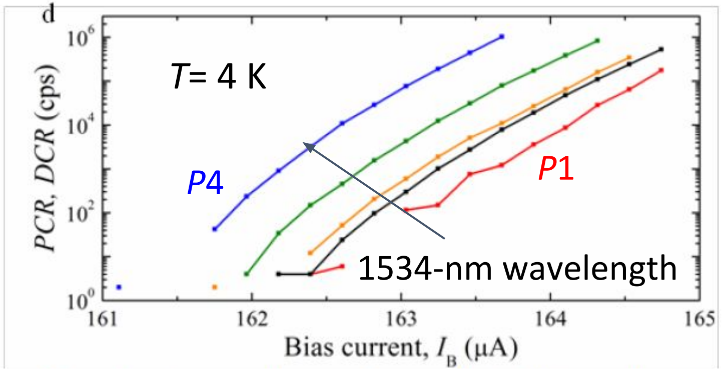
Tc = 3.1 K



Tc = 2.8 K

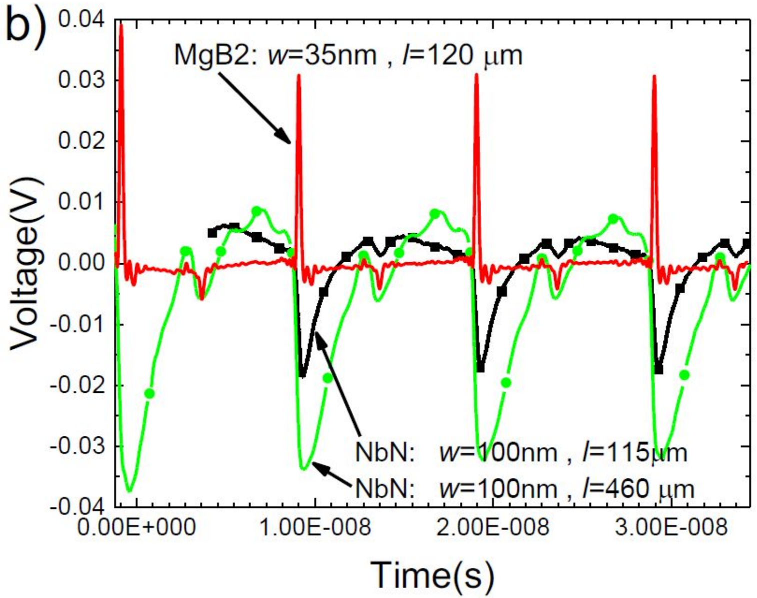


MgB_2 films



	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

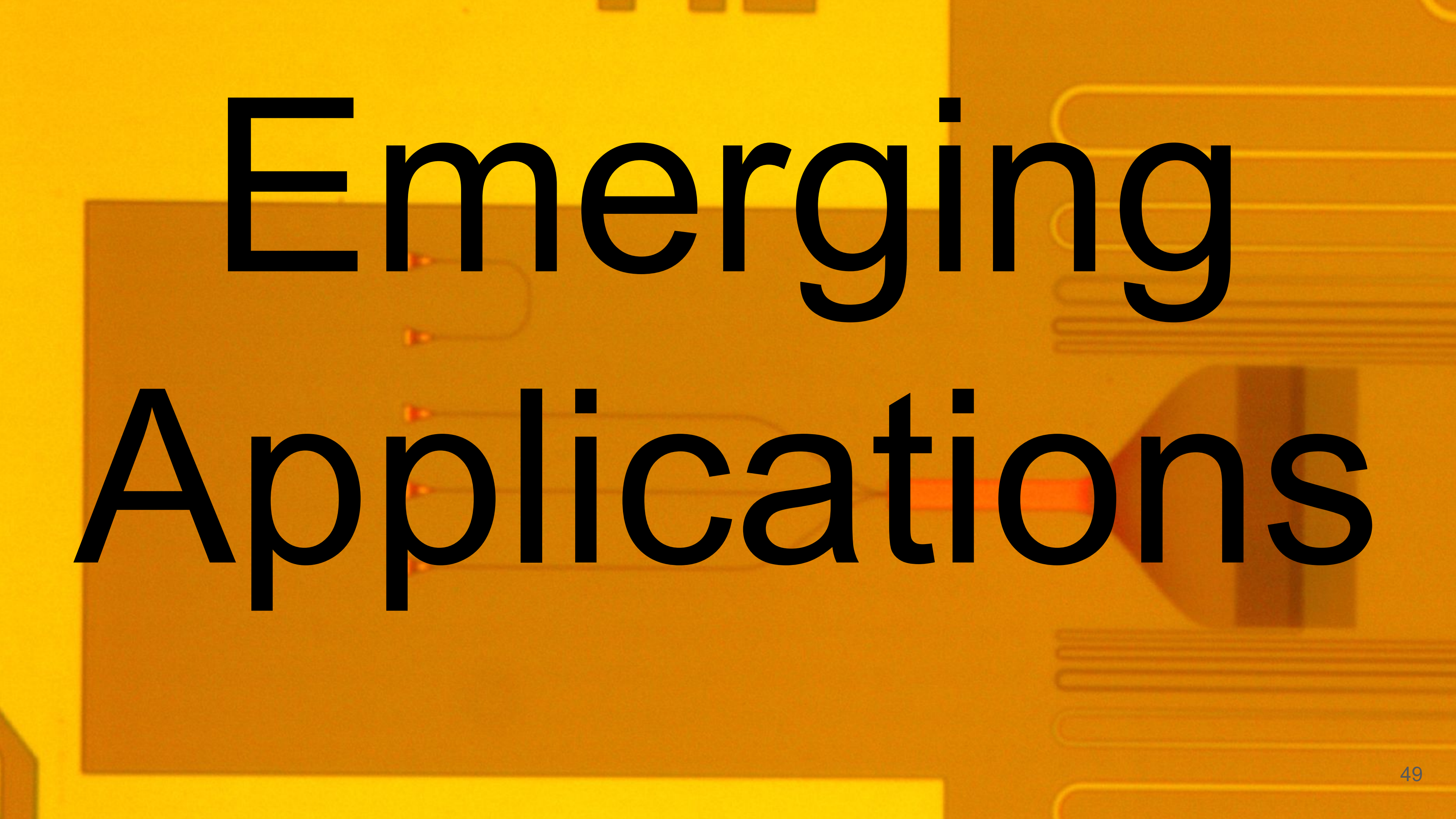
F. Marsili, CLEO 2015, conference slides



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

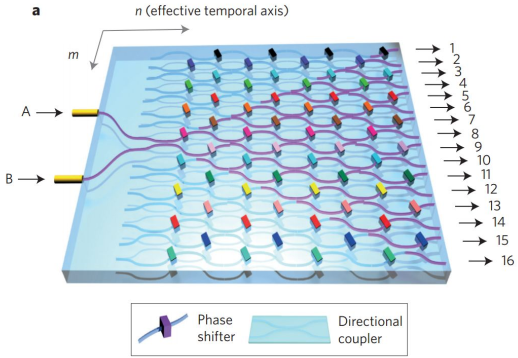
- Sub-ns reset time
- T_C~40 K

Single-photon detection at 20 K never demonstrated

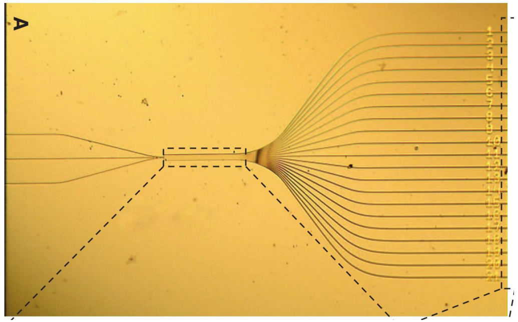


Emerging Applications

Potential application: on-chip quantum simulation



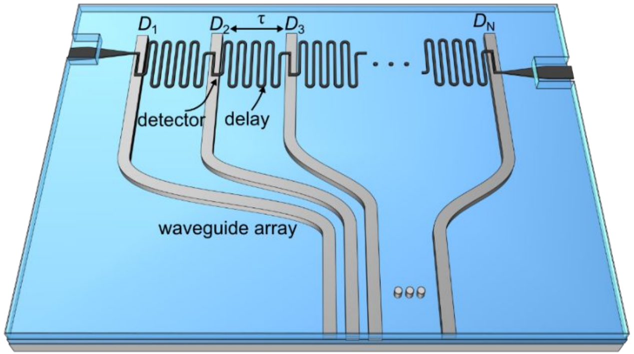
Crespi, et al., Nat. Photon. 7, 322 (2013)



Peruzzo, et al., Science 329, 1500 (2010)

Other potential applications, such as on-chip spectrometer, O. Kahl, et al., " Optica, 4(5) 557, 2017.

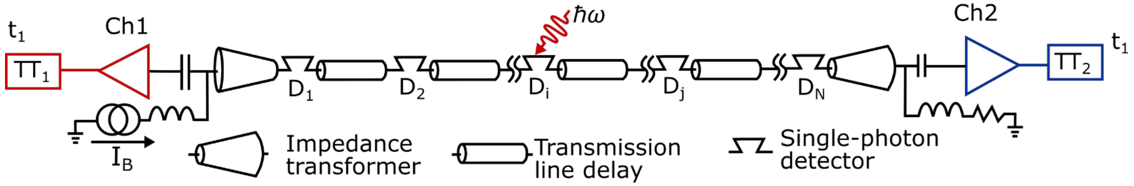
On-chip detection

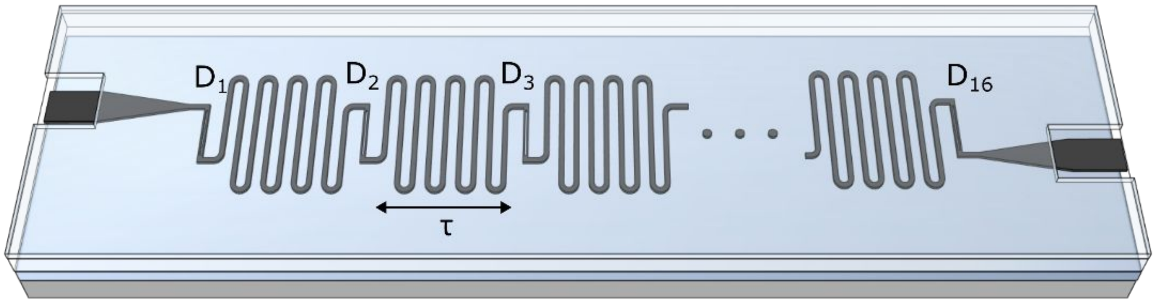


Can We Observe Two-Photon Coincidences?

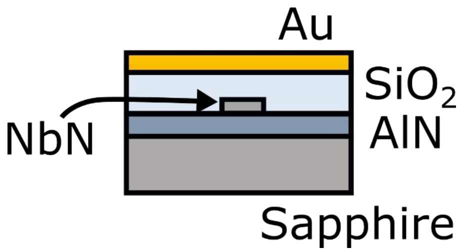
- Assume a pulsed source of photons (not continuous wave sources)
- Assume light will be coupled in via waveguides (not free space)

Delay-line Multiplexing

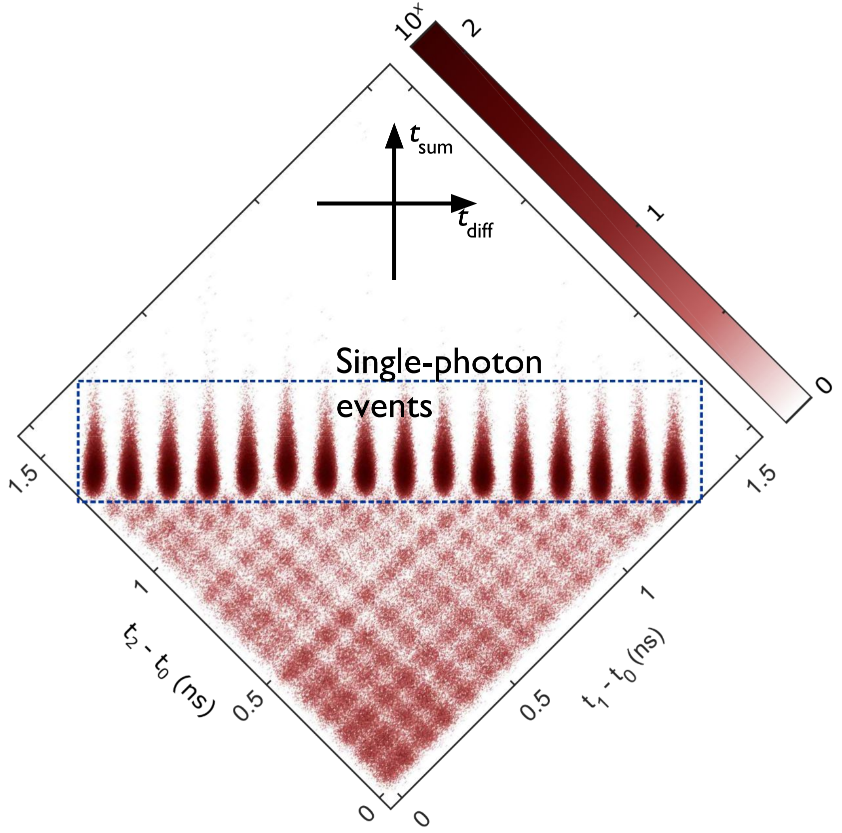




Nanowire microstrip transmission line

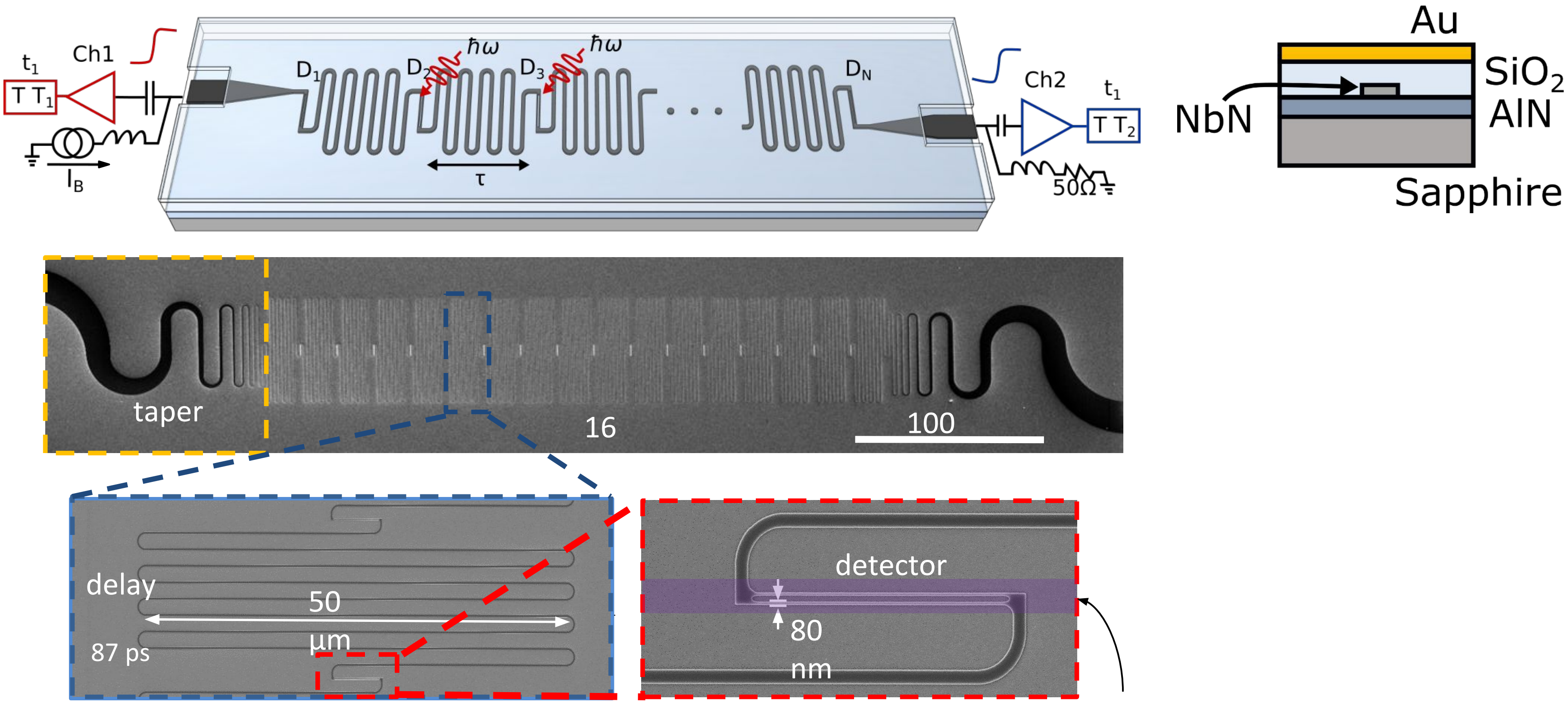


16-Element-detector chain



D Zhu, *et. al, Nat. Nanotech. 13, 596–601(2018)*

Delay-line multiplexed SNSPD array

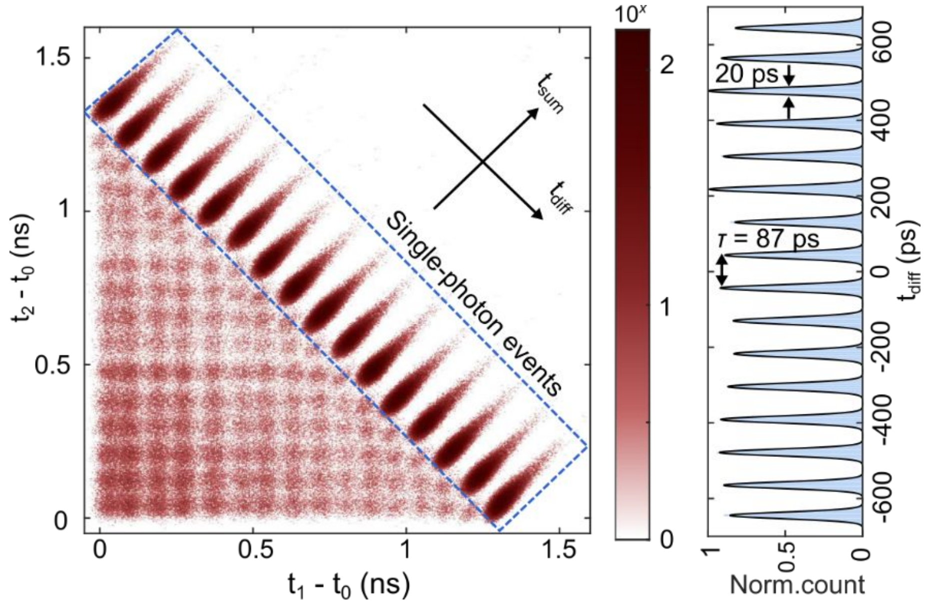


Potential waveguide integration

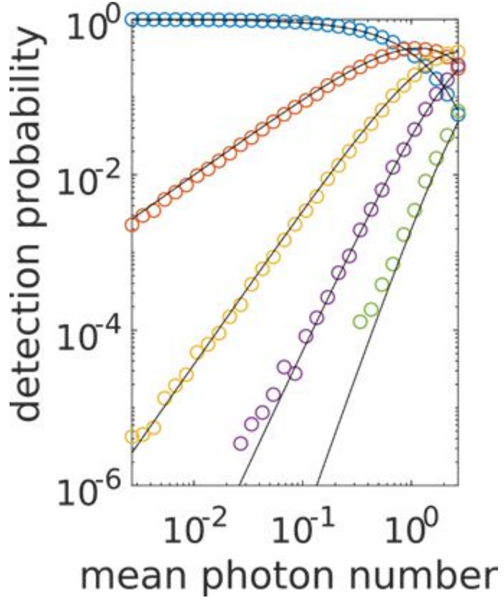
D. Zhu et al., Nat. Nanotech. 13, 596–601 (2018)

Optimized delay-line based linear arrays

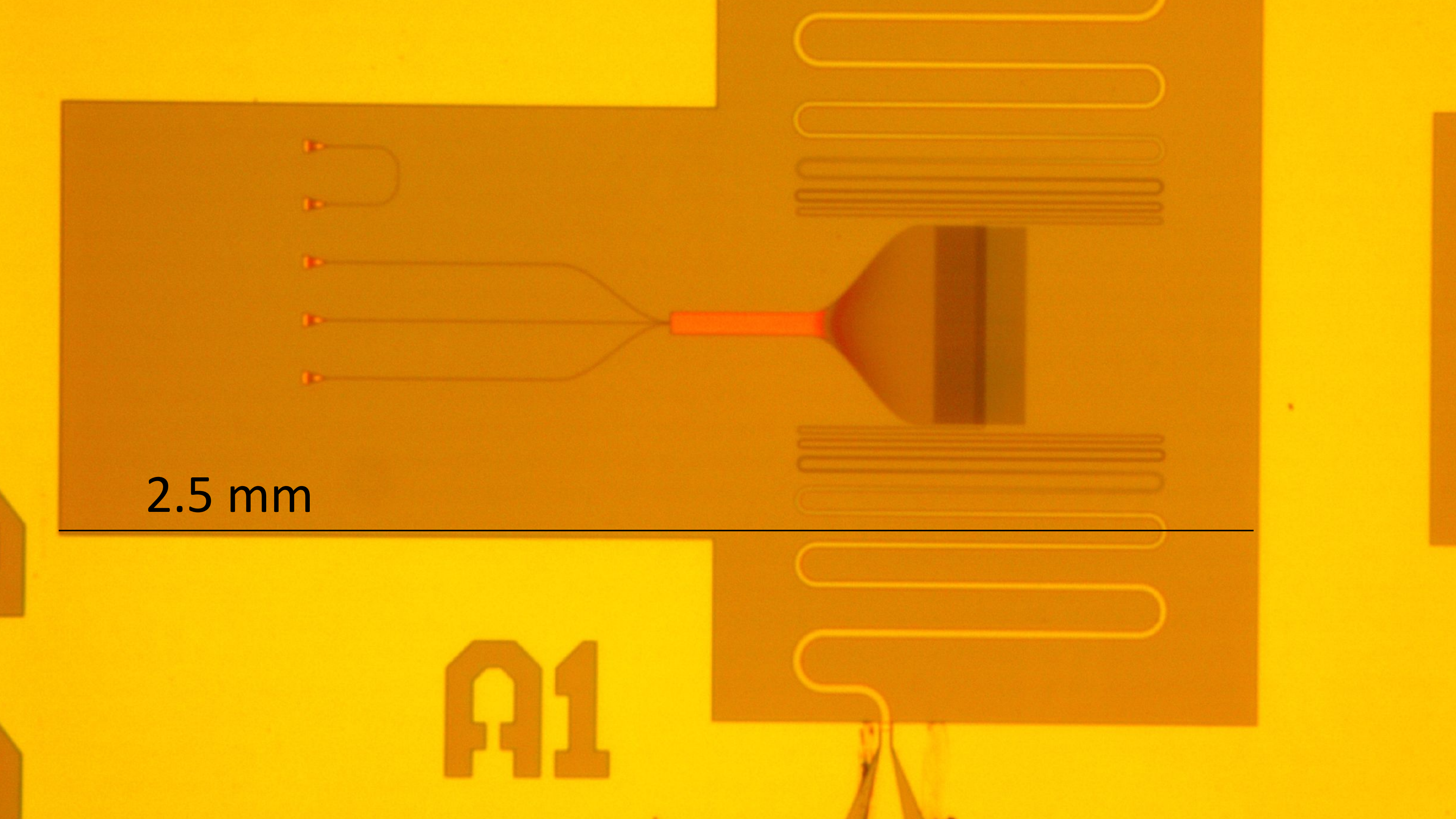
Two-photon coincidence counting



Pseudo-photon number resolving (from pulse shape recognition)



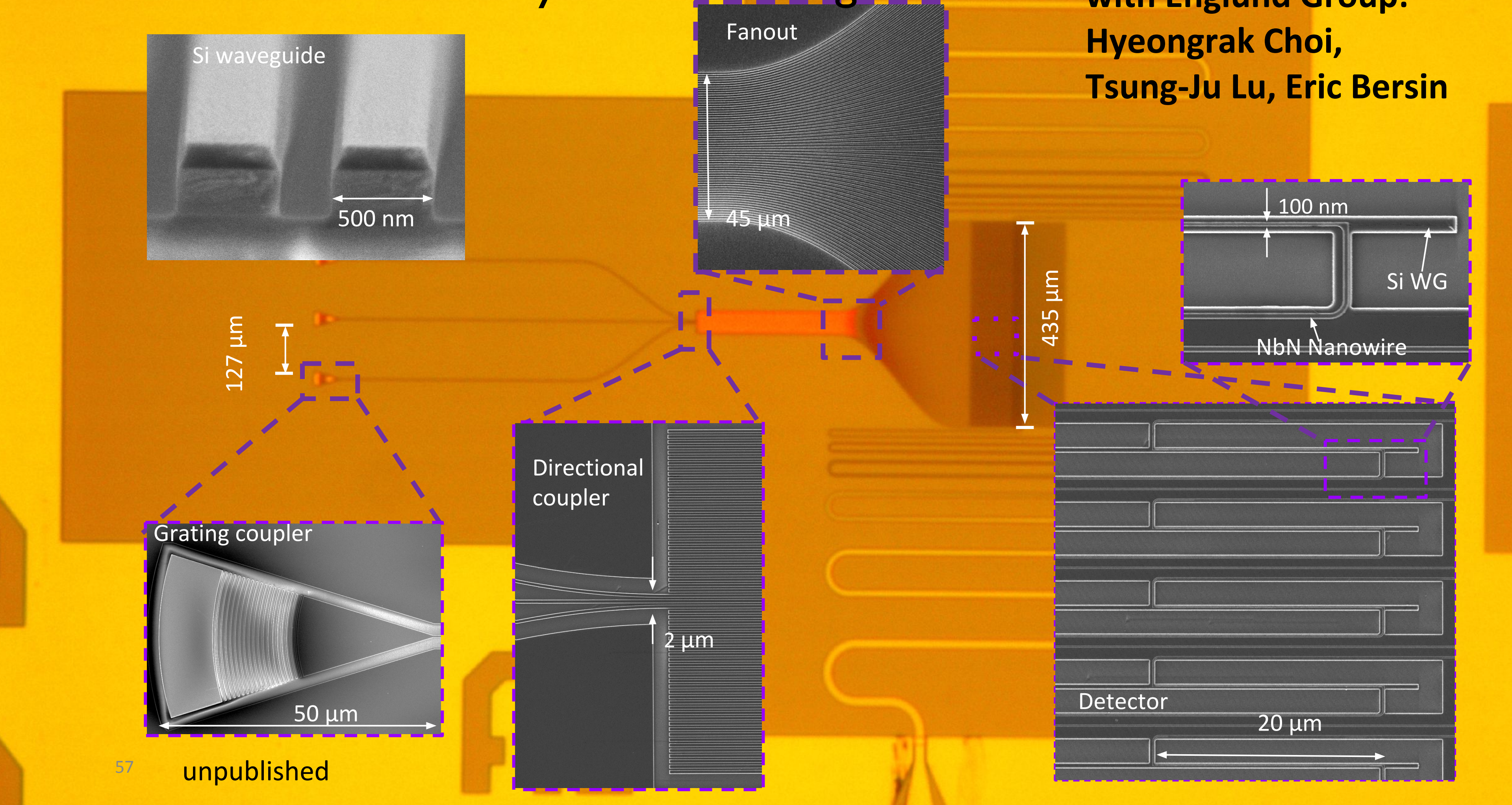
D. Zhu et al., Nat. Nanotech. 13, 596–601 (2018)



2.5 mm
A1

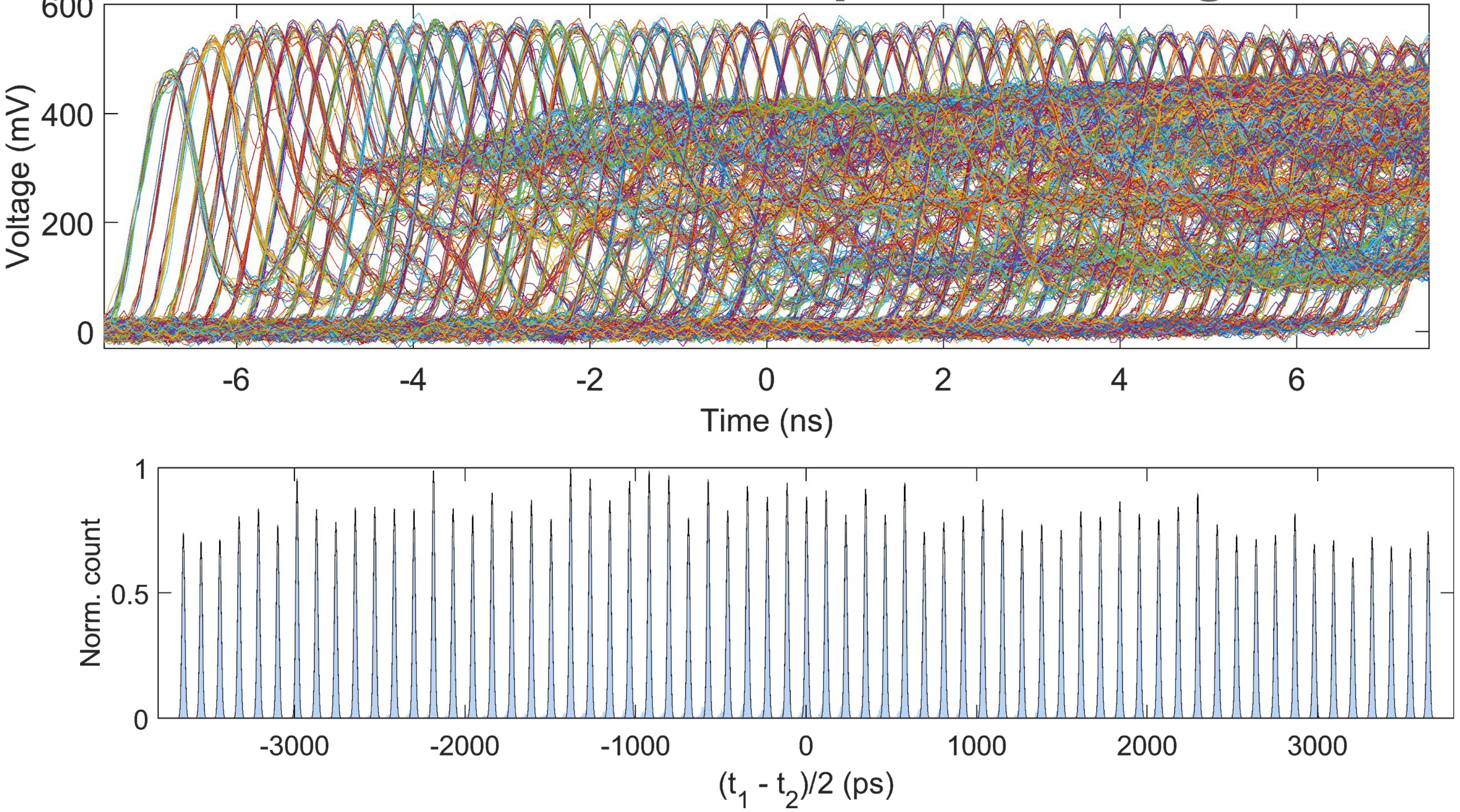
65-element SNSPD array on SOI waveguides

with Englund Group:
Hyeongrak Choi,
Tsung-Ju Lu, Eric Bersin



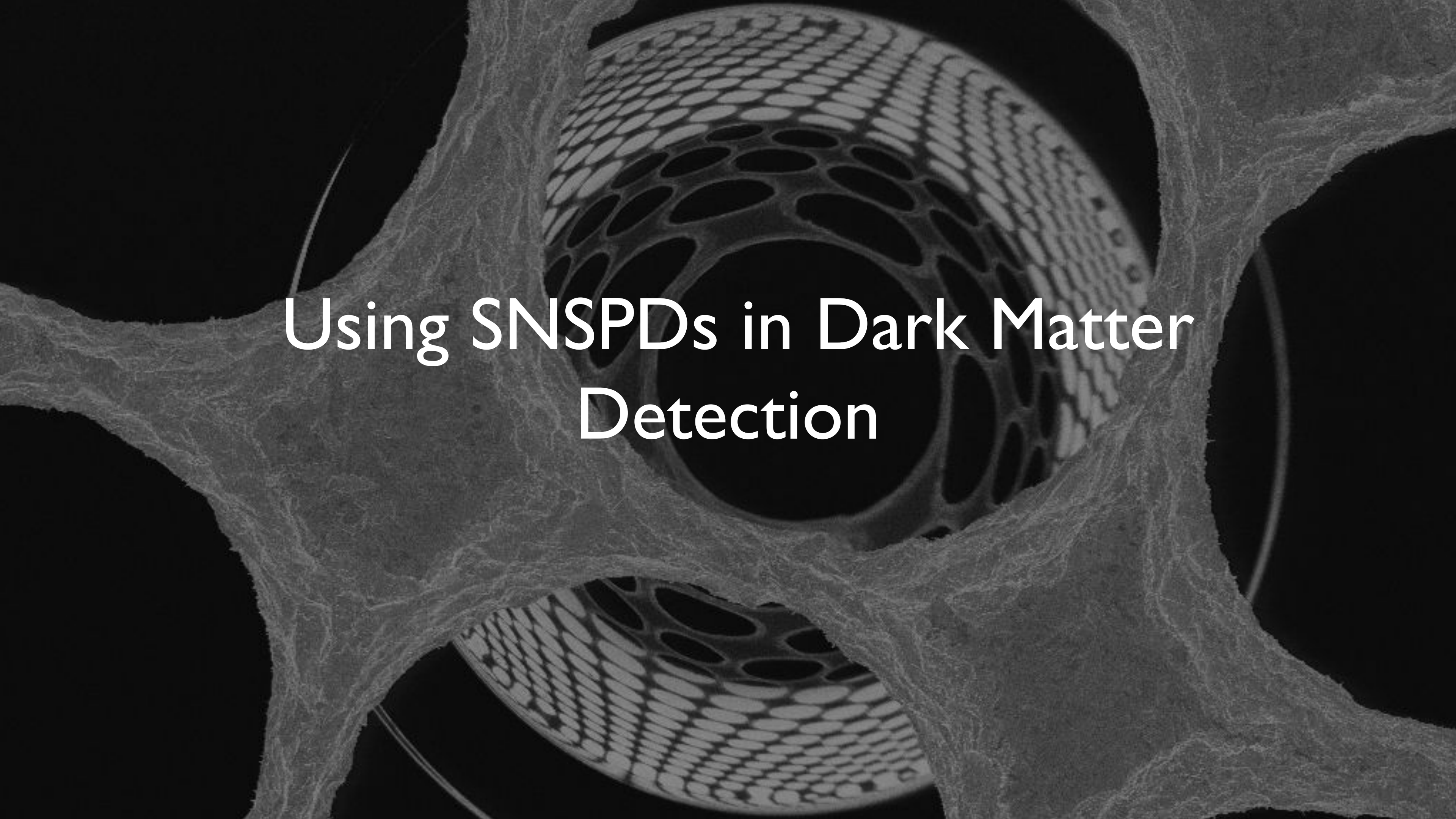
unpublished

A 65-element SNSPD array on SOI waveguides

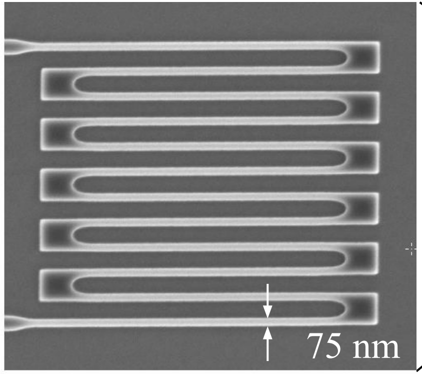


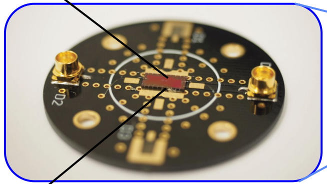
* Data from flood illumination at 1550 nm (single photon regime); unpublished

Using SNSPDs in Dark Matter Detection

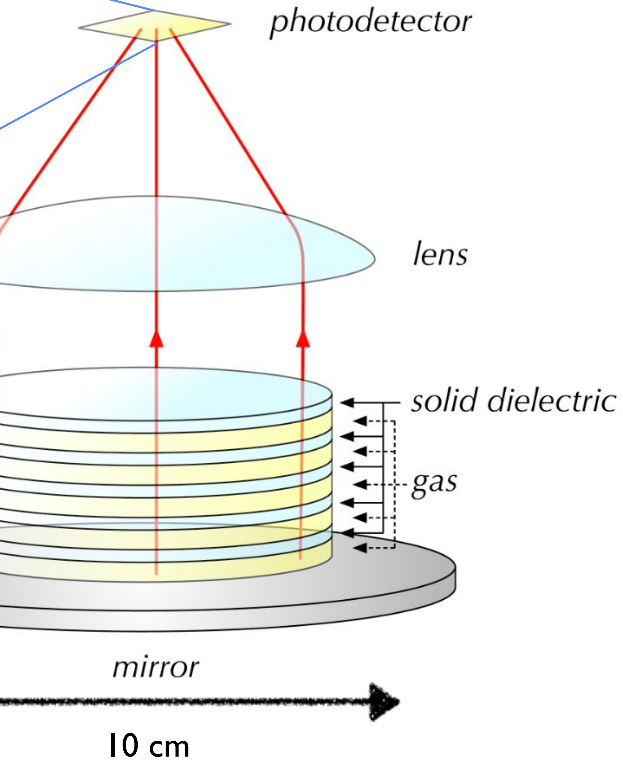


Nanowire Detection of Photons from the Dark Side





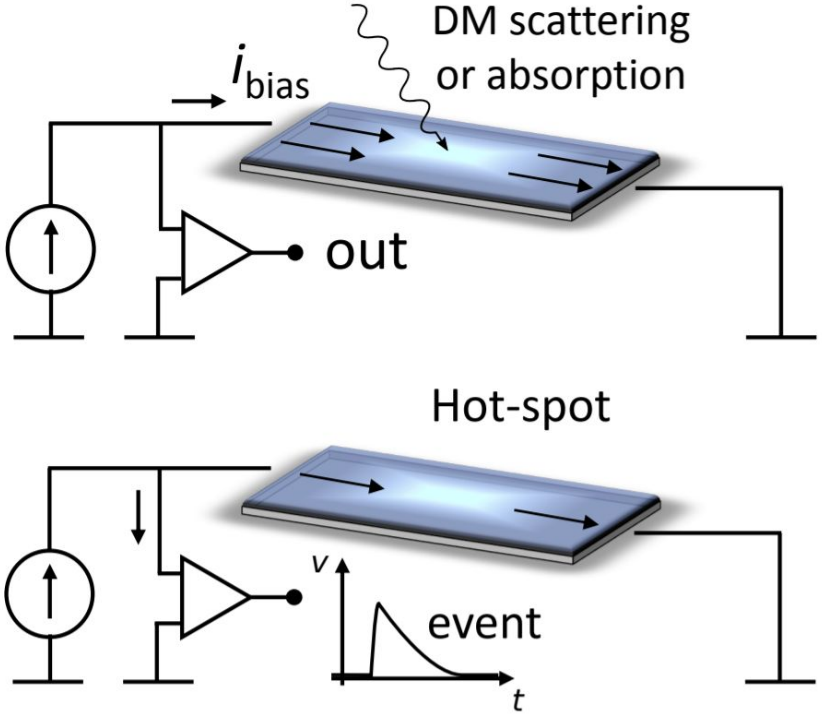
Dark-Matter Detector Concept



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)

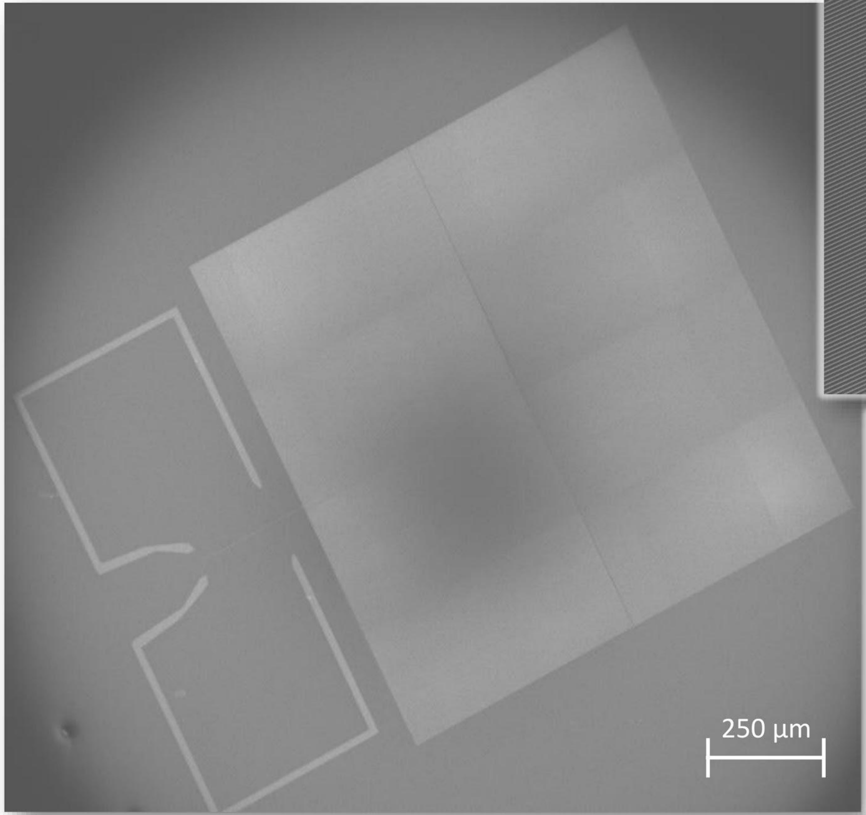
Detecting Dark Matter with Superconducting Nanowires

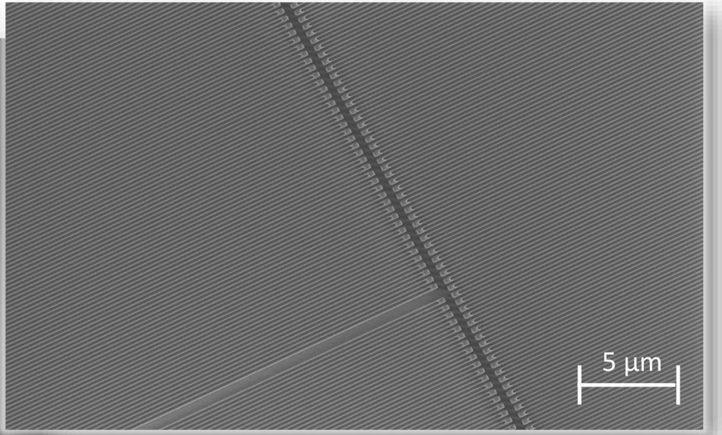
Yonit Hochberg[1],* Ilya Charaev[2],† Sae-Woo Nam[3],‡ Varun Verma[3],§ Marco Colangelo[2],¶ and Karl K. Berggren[2]**
[1] Racah Institute of Physics, Hebrew University of Jerusalem, Jerusalem 91904, Israel
[2] Massachusetts Institute of Technology, Department of Electrical Engineering and Computer Science,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

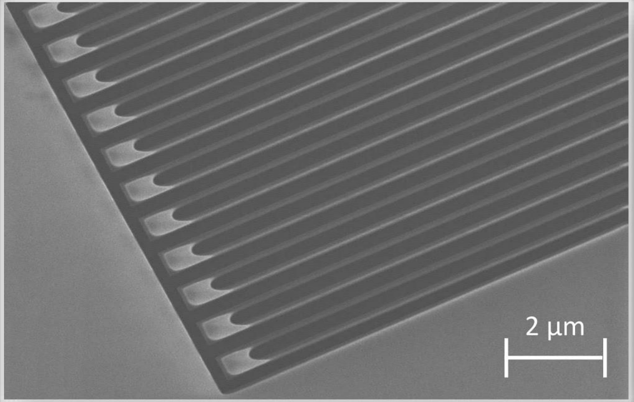


Phys. Rev. Lett. 123, 151802 (2019)

Large-area WSi SNSPD



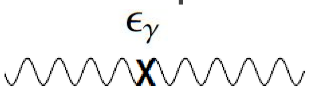


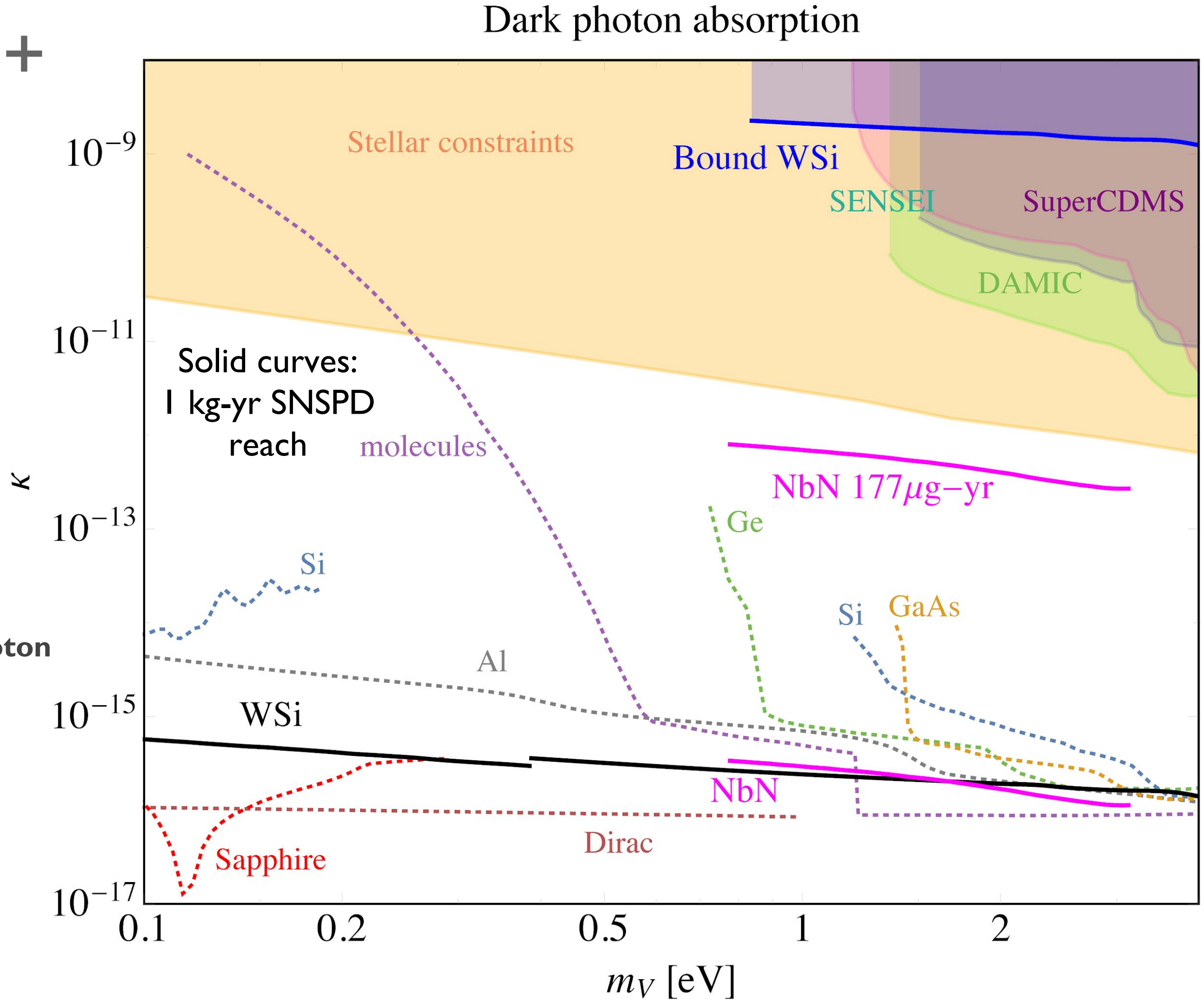


SNSPDs as target + sensor

[Hochberg, Charaev, Nam, Verma, Colangolo, KKB, Phys. Rev. Lett. 123, 151802 (2019)]

Absorption of kinetically mixed dark photon





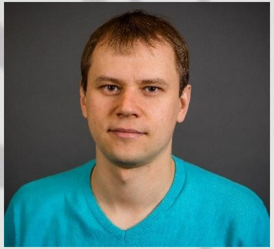
Takeaways:

1. SNSPDs provide position and time sensitivity for low-energy thresholded detection
2. Emerging capabilities for wide wires suggest easier fabrication, larger areas, alternative architectures
3. May be compatible with superconducting electronics based on nanowires or other

What Is Coming Soon?

1. Wide wires
2. Sensitivity further into infrared
3. Larger arrays
4. Higher temperature operation

Superconductivity Team in QNN Group



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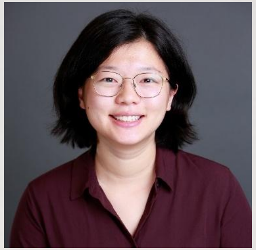

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(Masters Student, BU)

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Lucy Archer
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Andrew Dane
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Adam McCaughan
Faraz Najafi
Murat Onen
Kristen Sunter
Hao-Zhu Wang
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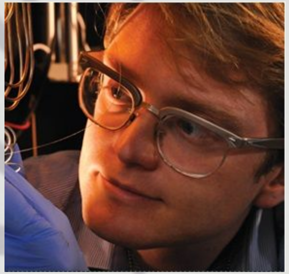
Di Zhu
Emily Toomey

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

Collaborators

Boris Korzh
(JPL)



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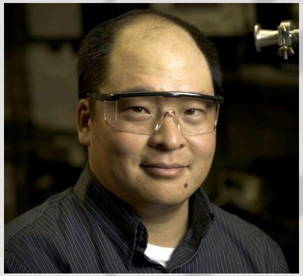
- Angle Velasco (JPL)
- Andrew Beyer (JPL)
- Jason Allmaras (JPL)
- Edward Ramirez (JPL)
- Alex Kozorezov (U. of Lancaster)

Daniel
Santavicca
(UNF)

- Brian Noble (UNF)
- William Strickland (UNF)



Sae Woo Nam

NIST
National Institute of
Standards and Technology
U.S. Department of Commerce

Joshua
Bienfang
(NIST)

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

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- U.S. Air force Office of Scientific Research
- U.S. Office of Naval Research
- DARPA DETECT program
- IARPA
- NASA
- NSF
- Skoltech
- Many U.S. and international fellowships

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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END OF PRESENTATION

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