Superconducting Nanowire-Based Single-Photon Detectors

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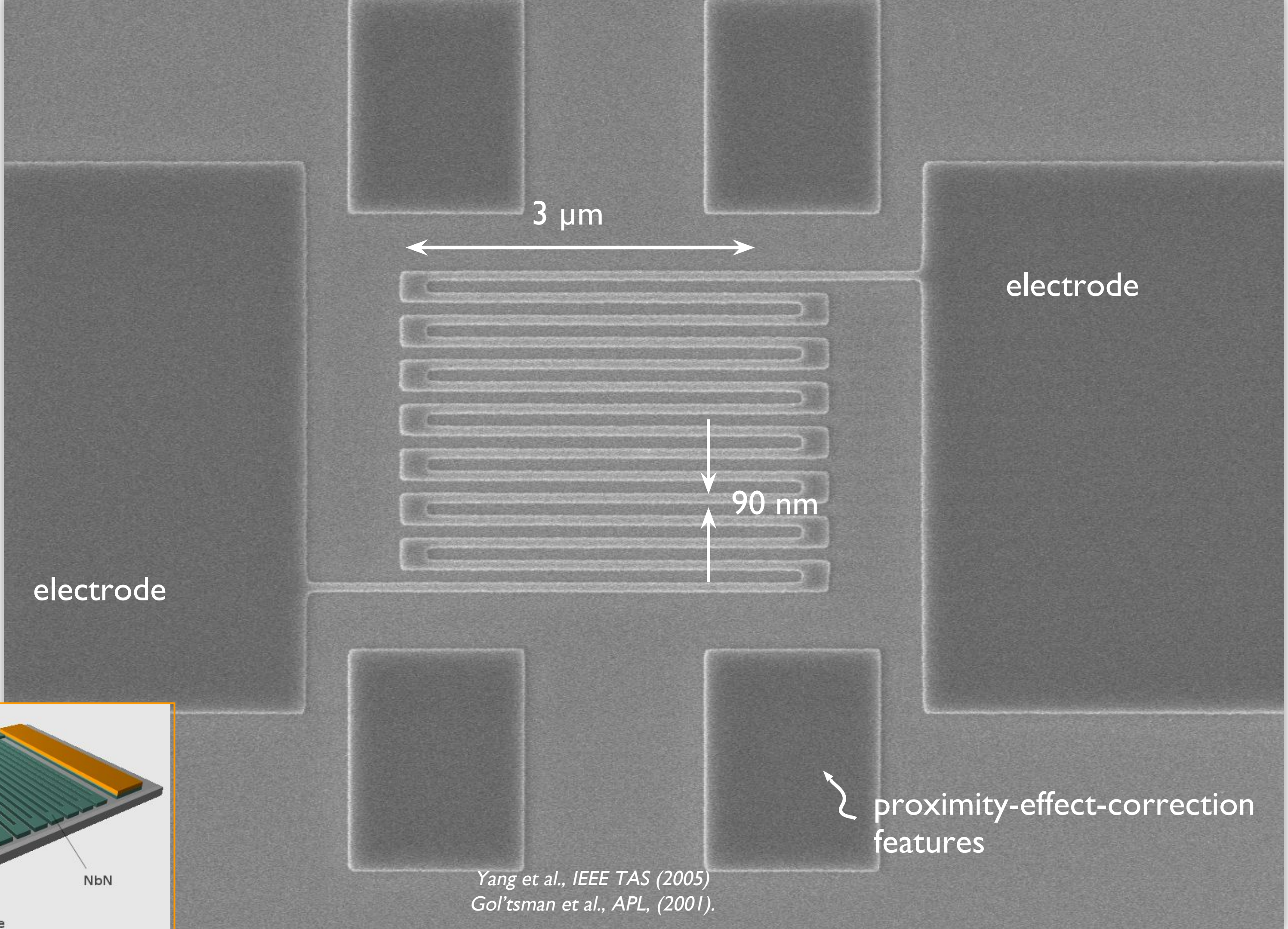
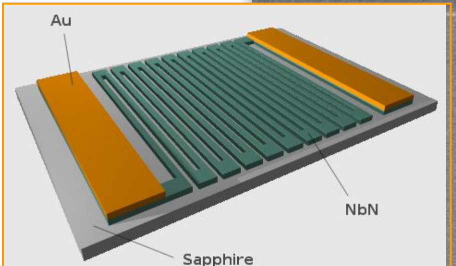
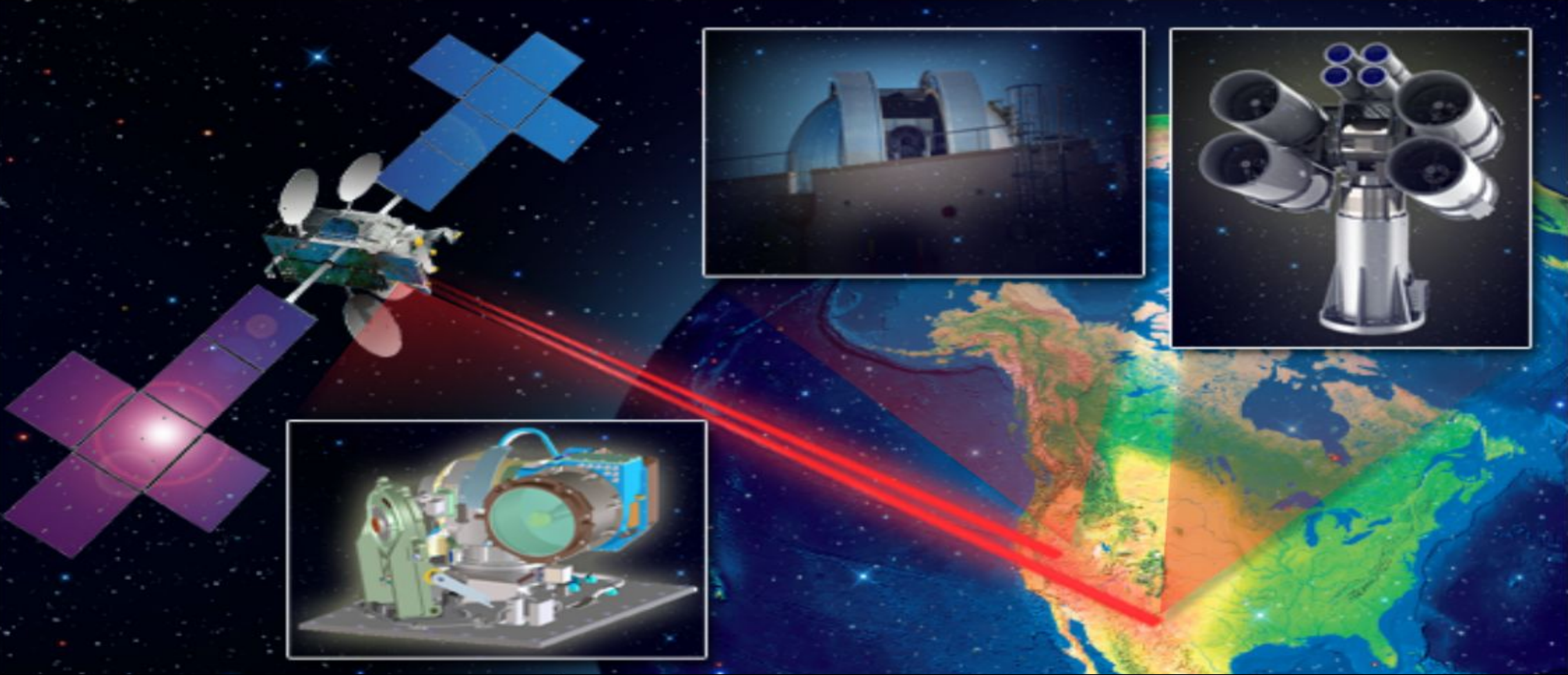
Massachusetts Institute of Technology





Yang et al., IEEE TAS (2005)
Gol'tsman et al., APL, (2001).



“LLCD will be 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 in collaboration with MIT campus.

VLSI Circuit Evaluation

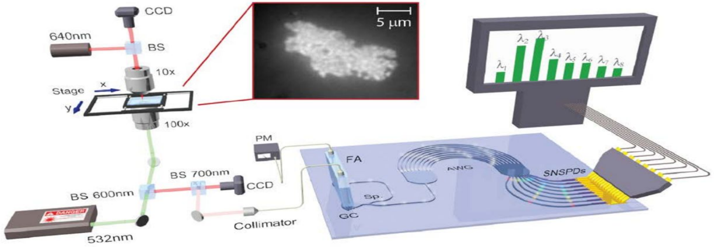
- VLSI circuit imaging and debugging
- SNSPD enables performance advances

Image courtesy of DCG Systems

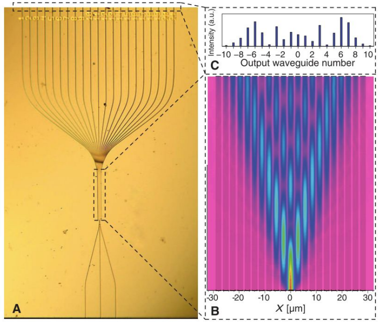
Collaboration between BU, DCG Systems, IBM, Photonspot, funded by IARPA

Applications

Single-photon spectrometer

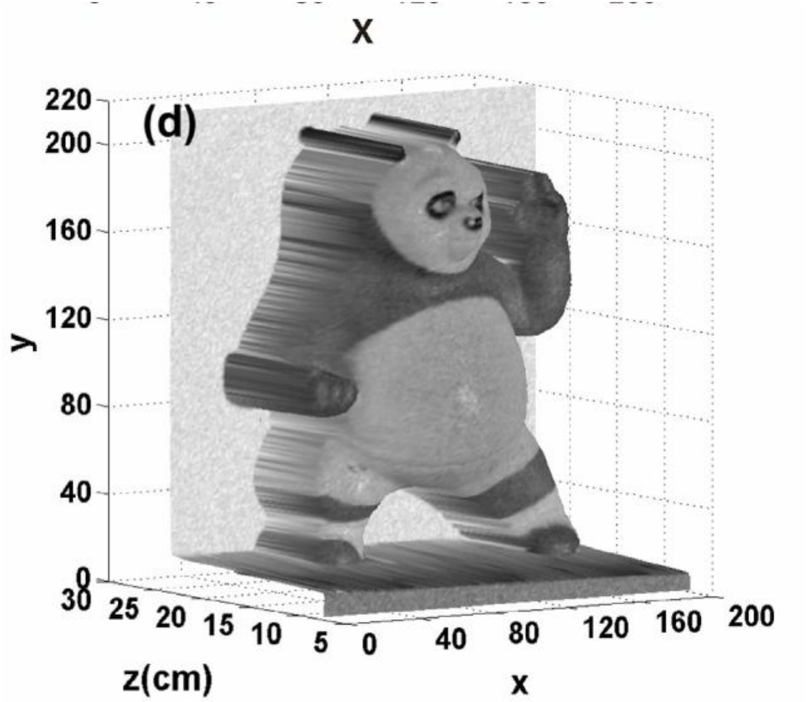


Kahl, et al., arXiv:1609.07857 (2016)



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

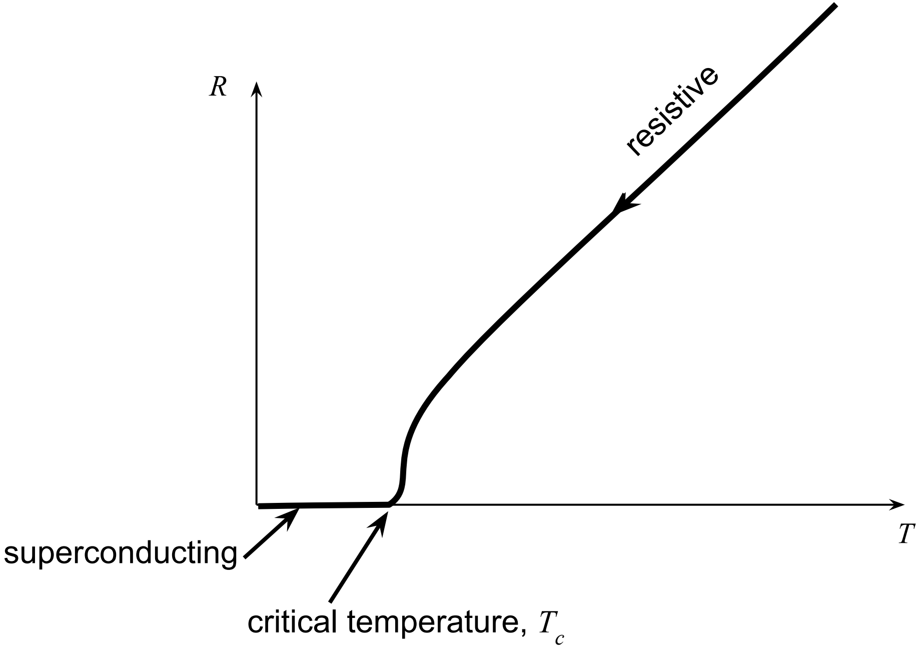
LIDAR



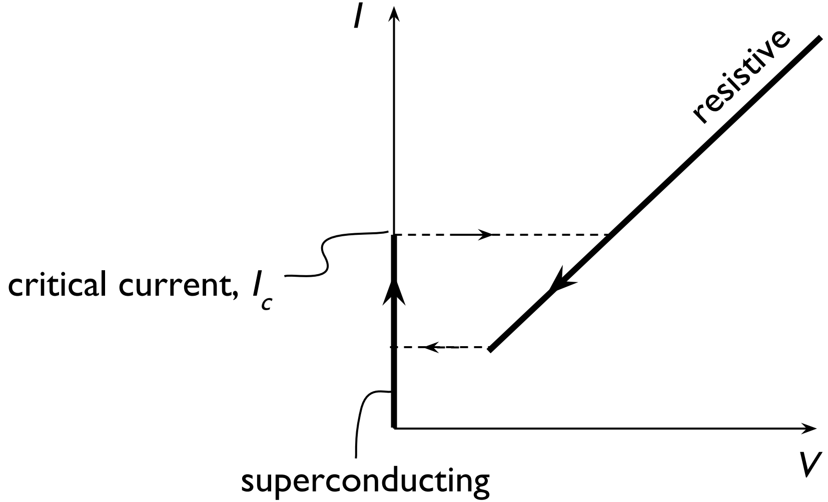
Hadfield, Glasgow

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

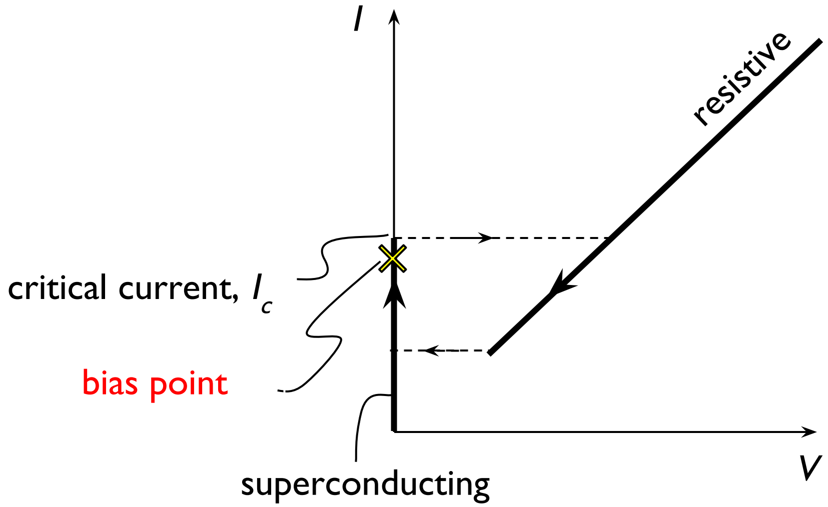
Analog Amplifiers (e.g. Transition-Edge Sensors)



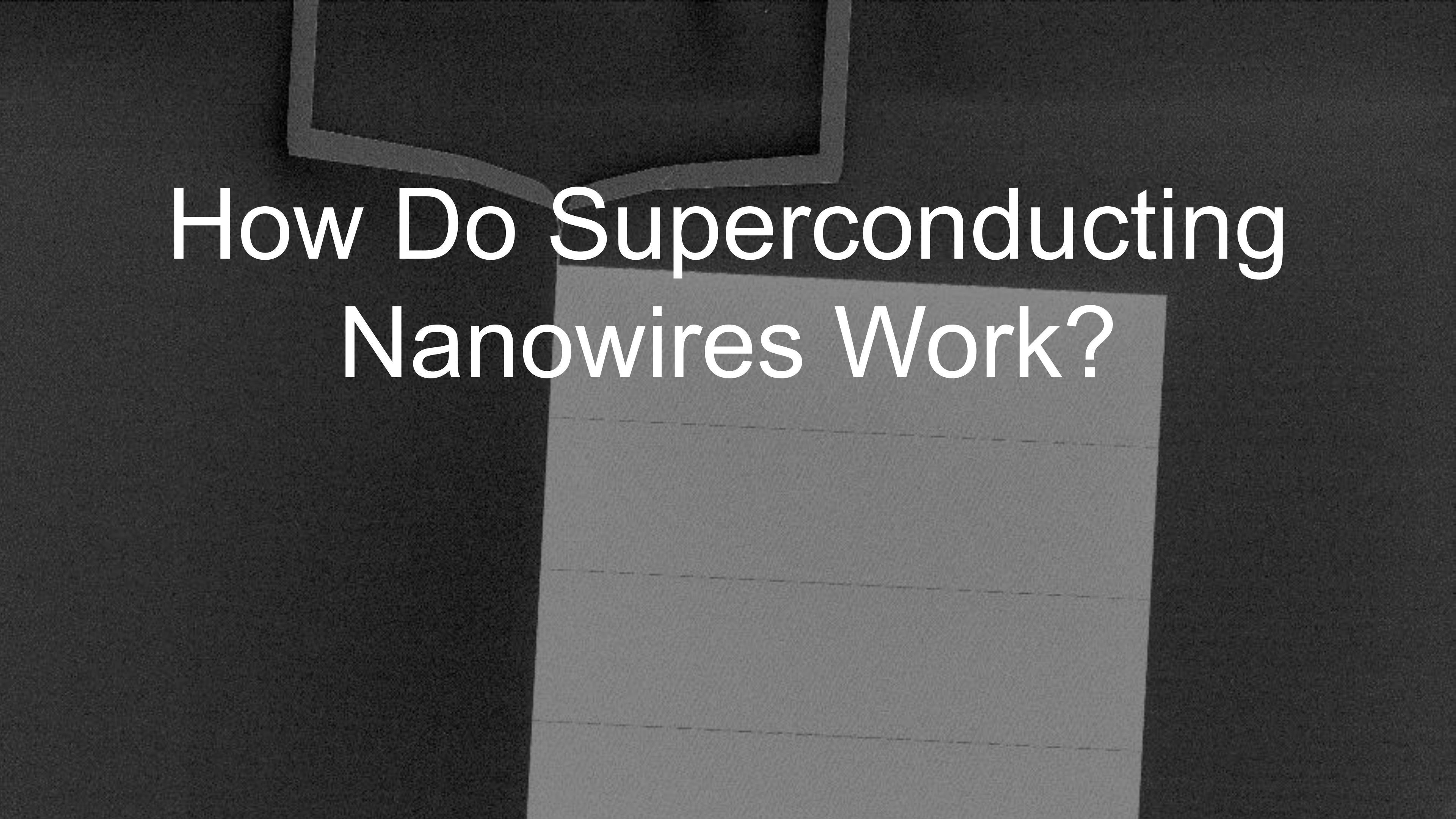
Comparison-Based Device



Comparison-Based Device



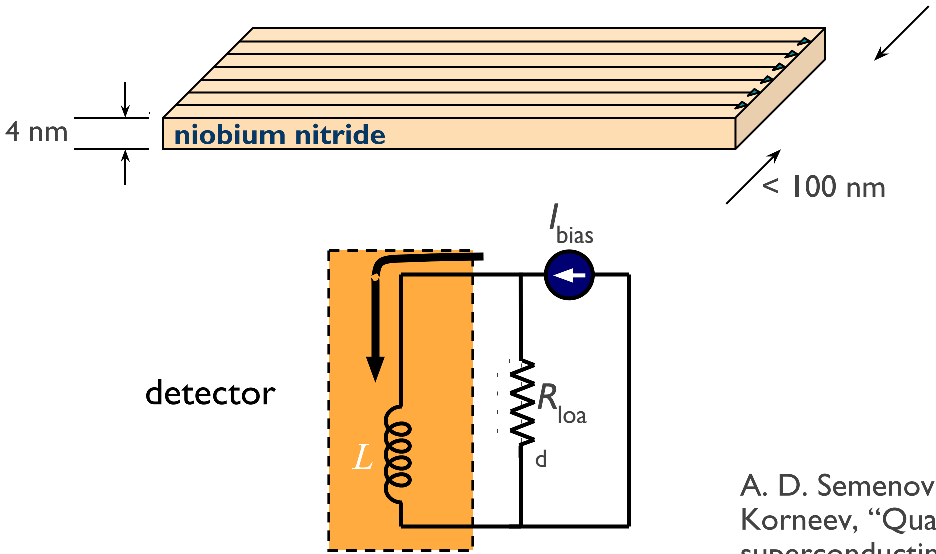
How Do Superconducting Nanowires Work?



Current Bias

Critical Temperature ~ 11 K

superconductor is biased near its transition

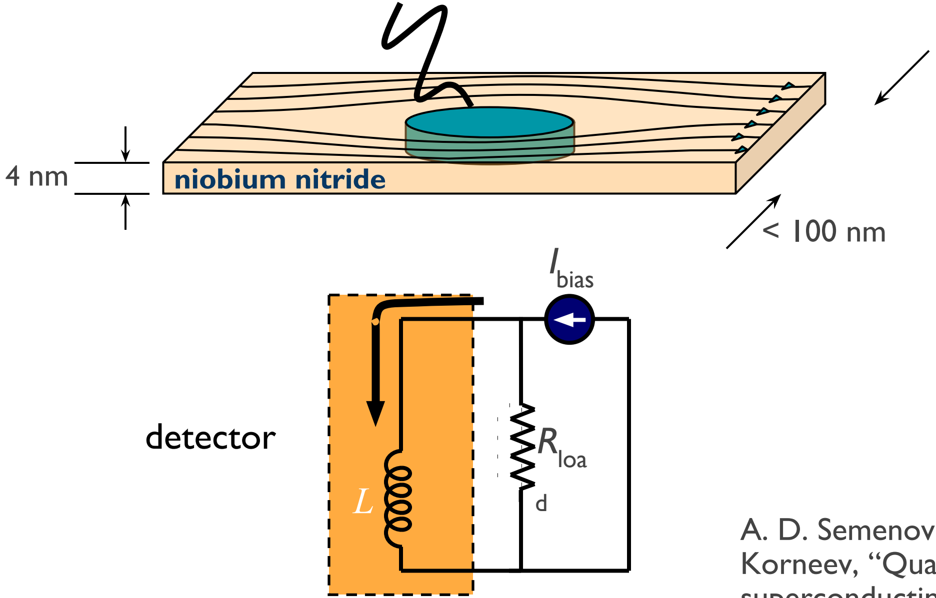


A. D. Semenov, G. N. Gol'tsman, and A. A. Korneev, "Quantum detection by current carrying superconducting film," *Physica*

Absorption

Critical Temperature ~ 11 K

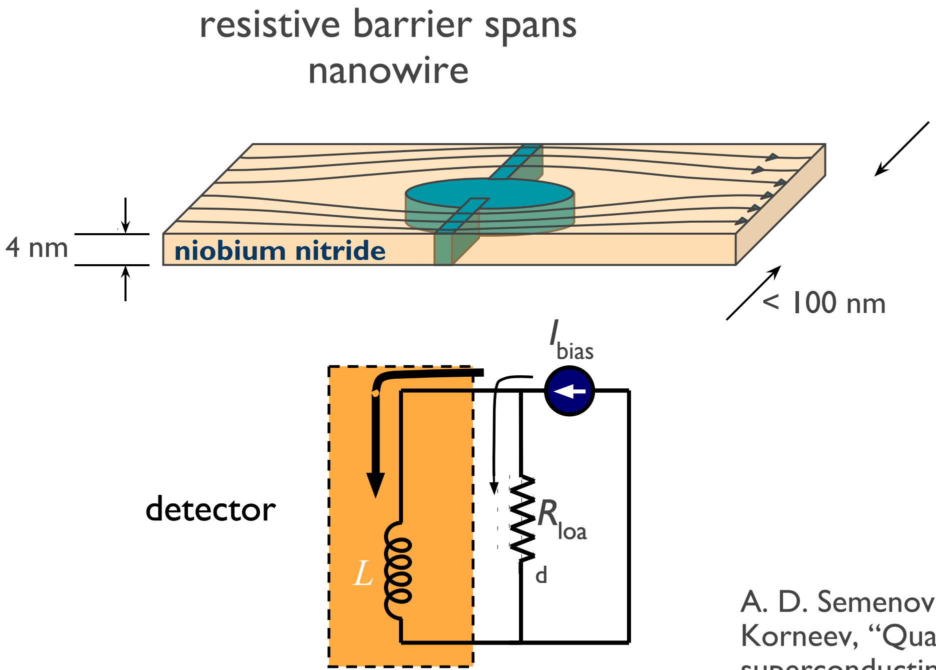
photon-induced hotspot forces bias current above critical density



A. D. Semenov, G. N. Gol'tsman, and A. A. Korneev, "Quantum detection by current carrying superconducting film," *Physica*

Breakdown

Critical Temperature ~ 11 K

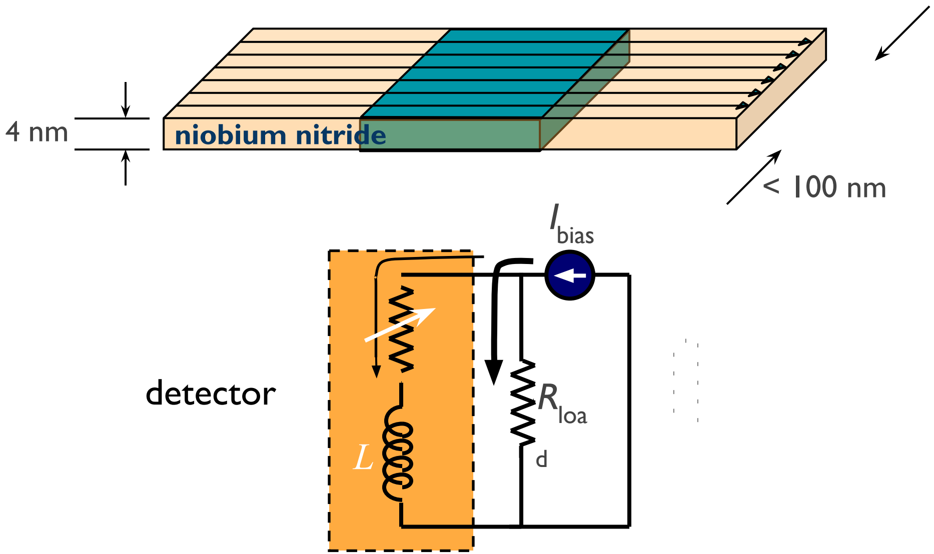


A. D. Semenov, G. N. Gol'tsman, and A. A. Korneev, "Quantum detection by current carrying superconducting film," *Physica*

Acceleration/Heating

Critical Temperature ~ 11 K

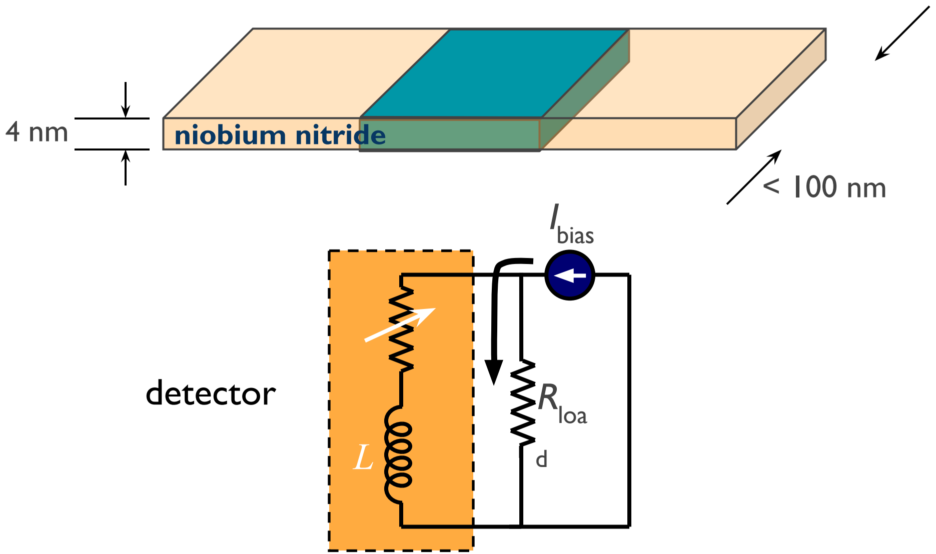
resistance grows from heating



Diversion of Current

Critical Temperature ~ 11 K

current is diverted

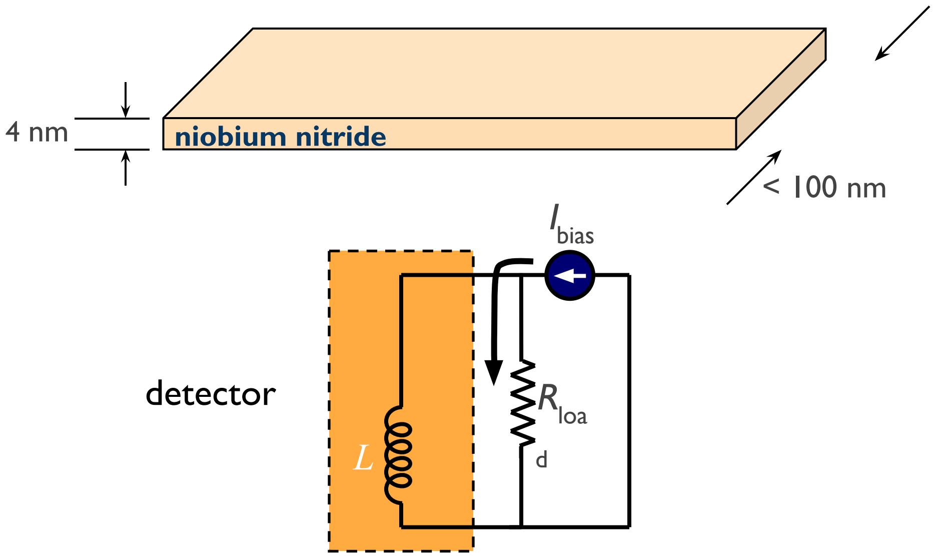


Cooling

current is diverted

Critical Temperature ~ 11 K

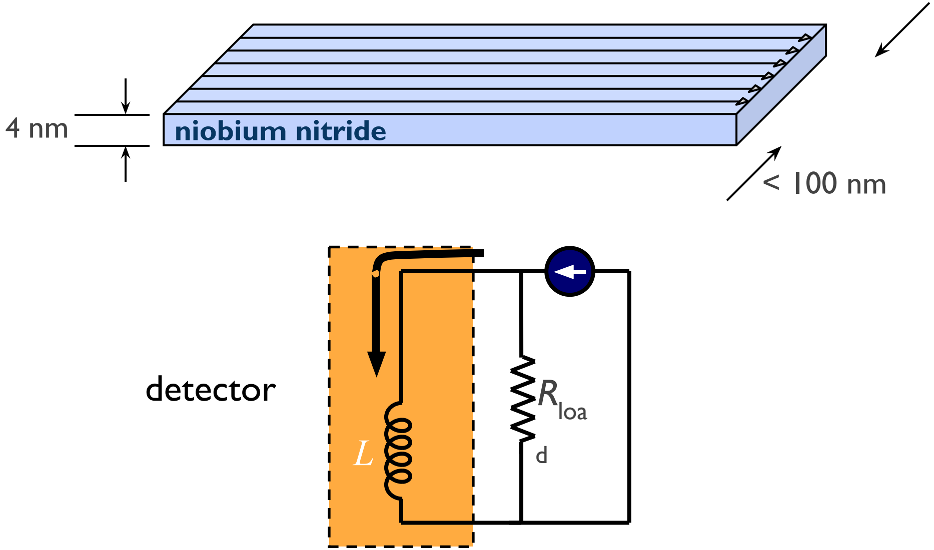
superconductivity is restored

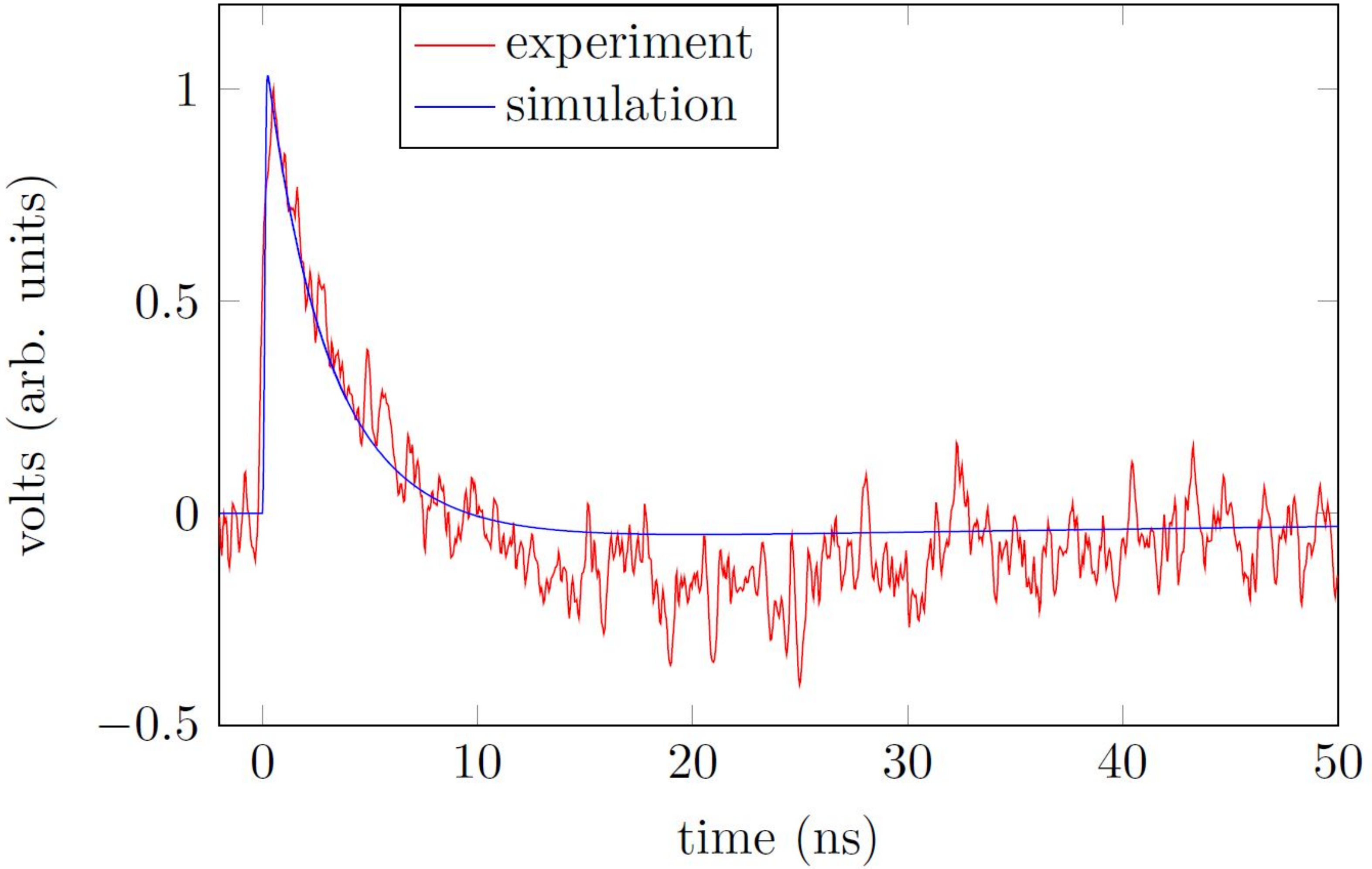


Reset

Critical Temperature ~ 11 K

bias current is restored

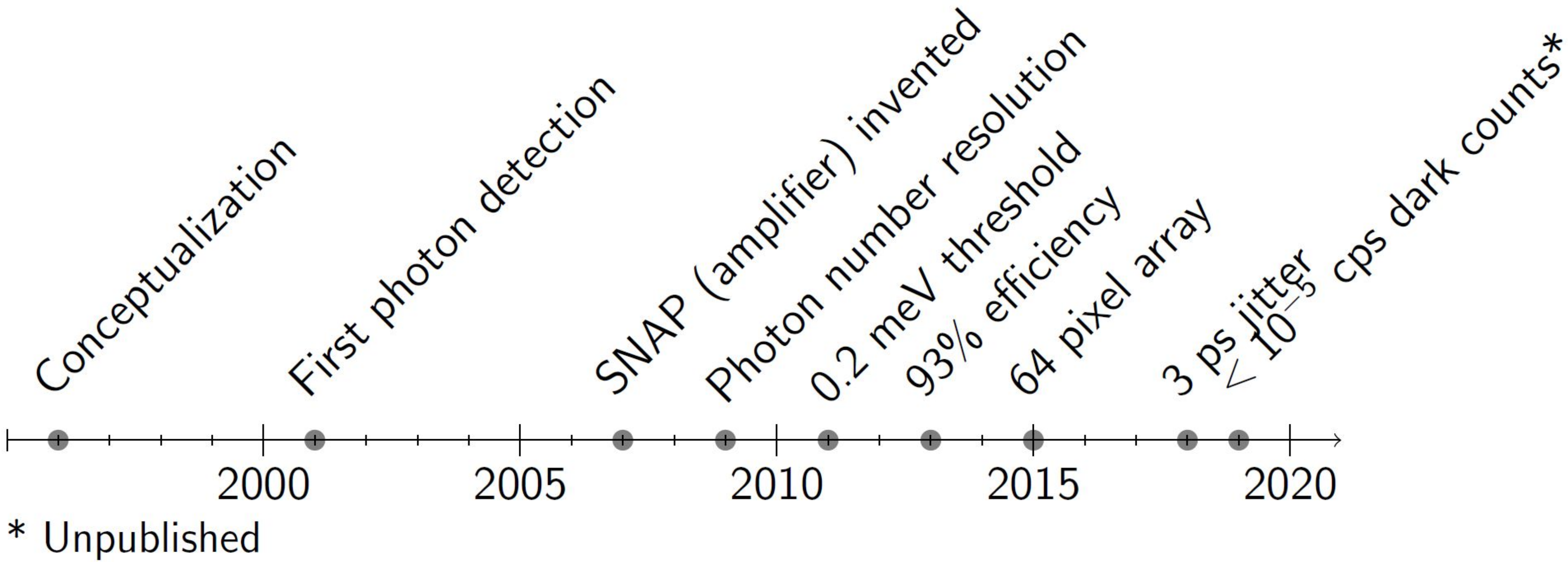



experiment
simulation
volts (arb. units)
time (ns)
1
0.5
0
−0.5
0
10
20
30
40
50

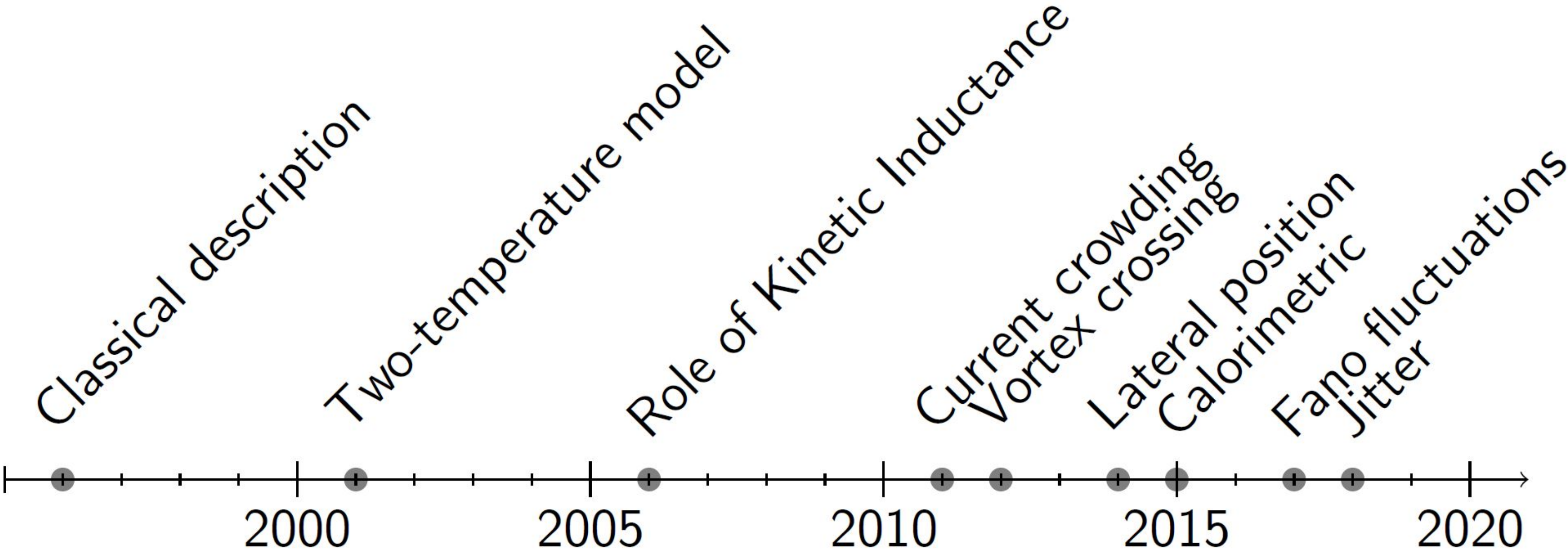
about SNSPDs

- Operation temperatures 1-4 K
- Relatively unshielded environments
- 100 MHz to 2 GHz off the shelf amplifiers
  - (often operating at room temperature)
- Blackbody radiation major source of background
- Typical current, 10 uA
- Typical voltage after amplifier 200 mV

SNSPD Experimental Timeline



SNSPD Theory Timeline

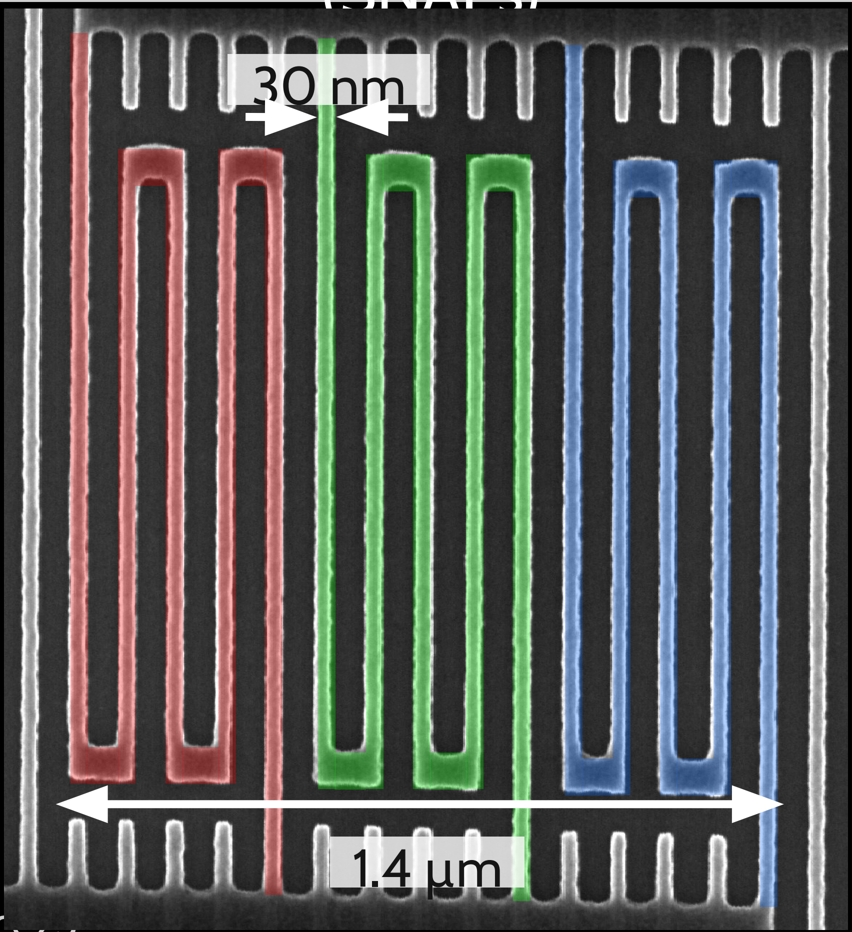


“A Cascade Switching Superconducting Single Photon Detector,”

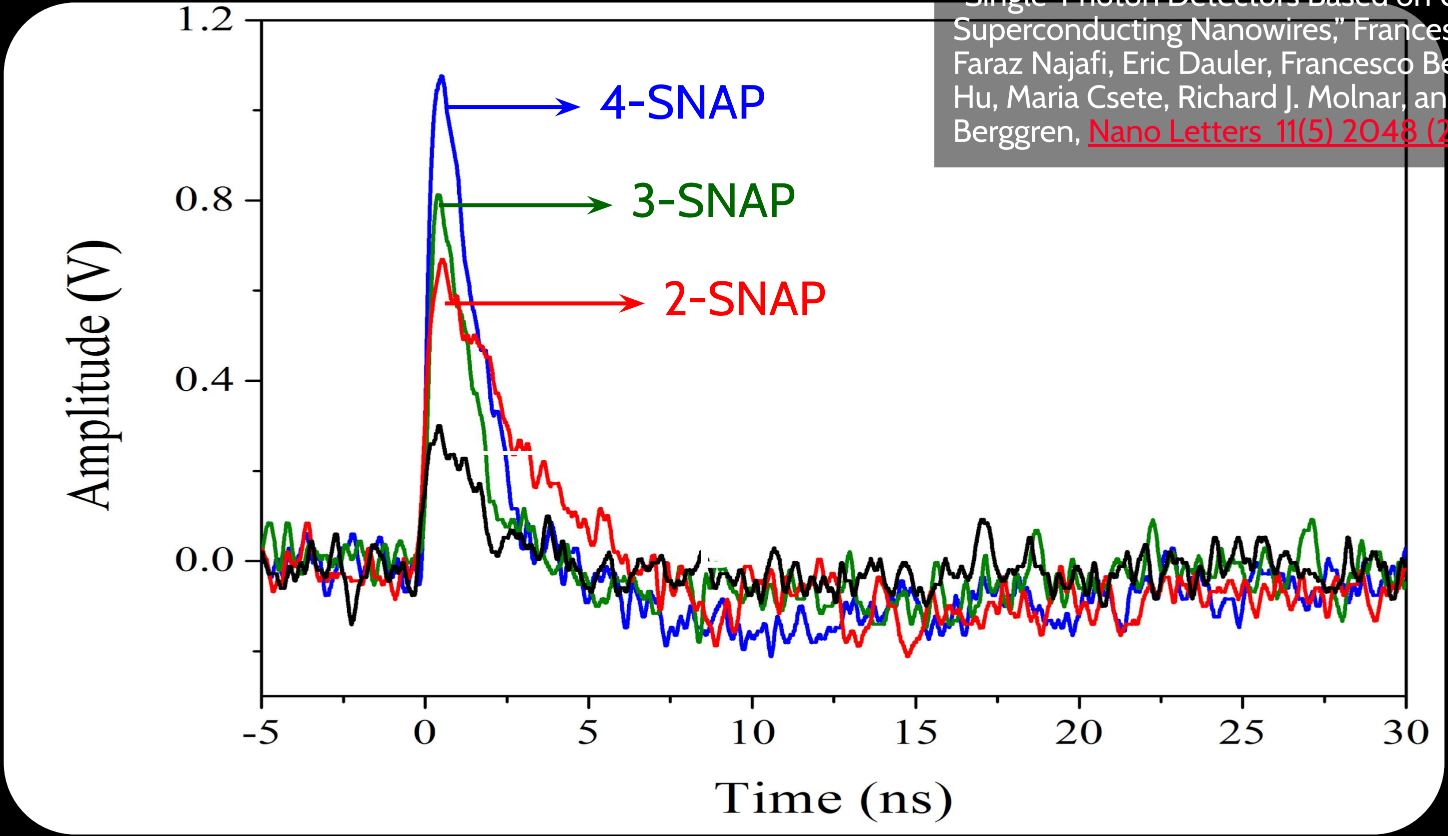
M. Ejrnaes, R. Cristiano, O. Quaranta, S. Pagano, A. Gaggero, F. Mattioli, R. Leoni, B. Voronov, and G. Gol'tsman,

Appl. Phys. Lett. 91, 262509 (2007)

Superconducting Nanowire Avalanche Photodetectors (SNAPs)



Improved SNR for 20-nm Wire



"Single-Photon Detectors Based on Ultranarrow Superconducting Nanowires," Francesco Marsili, Faraz Najafi, Eric Dauler, Francesco Bellei, Xiaolong Hu, Maria Csete, Richard J. Molnar, and Karl K. Berggren, Nano Letters 11(5) 2048 (2011).

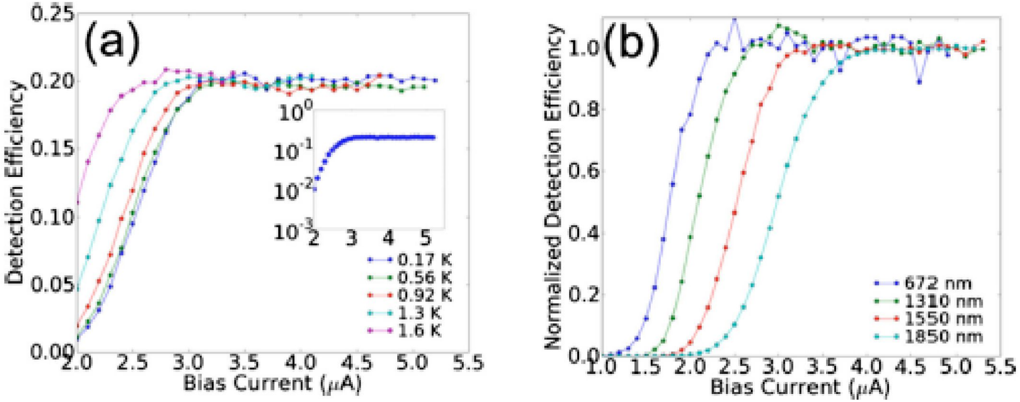
APPLIED PHYSICS LETTERS **98**, 251105 (2011)

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

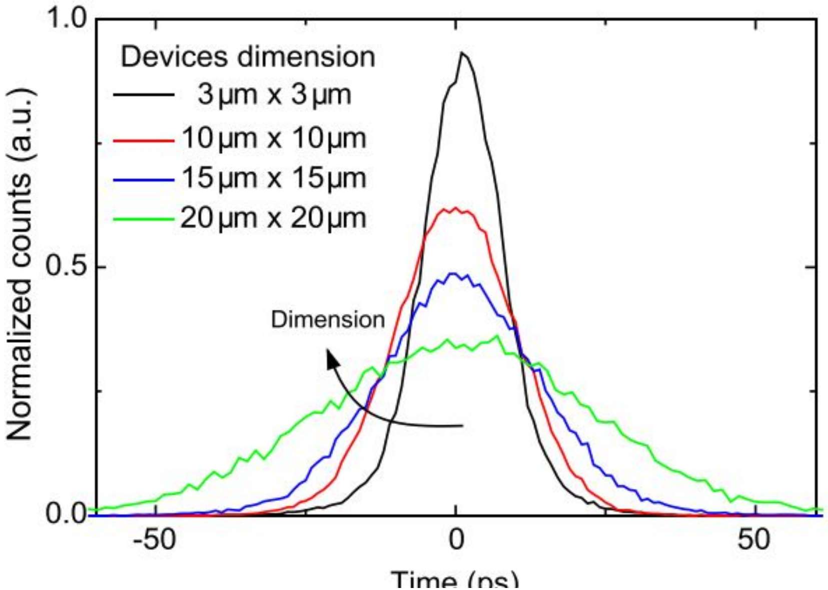
Burm Baek,[a)] Adriana E. Lita, Varun Verma, and Sae Woo Nam
National Institute of Standards and Technology, 325 Broadway, Boulder, Colorado 80305, USA

(Received 6 May 2011; accepted 27 May 2011; published online 21 June 2011)

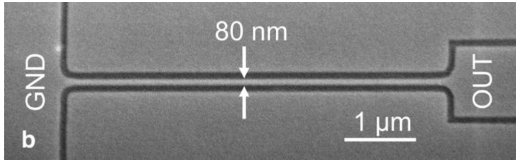
We have developed a single-photon detector based on superconducting amorphous tungsten–silicon alloy (a-W_xSi_{1-x}) nanowire. Our device made from a uniform a-W_xSi_{1-x} nanowire covers a practical detection area ($16\ \mu m \times 16\ \mu m$) and shows high sensitivity featuring a plateau of the internal quantum efficiencies, i.e., efficiencies of generating an electrical pulse per absorbed photon, over a broad wavelength and bias range. This material system for superconducting nanowire detector technology could overcome the limitations of the prevalent nanowire devices based on NbN and lead to more practical, ideal single-photon detectors having high efficiency, low noise, and high count rates. © *2011 American Institute of Physics*. [doi:10.1063/1.3600793]

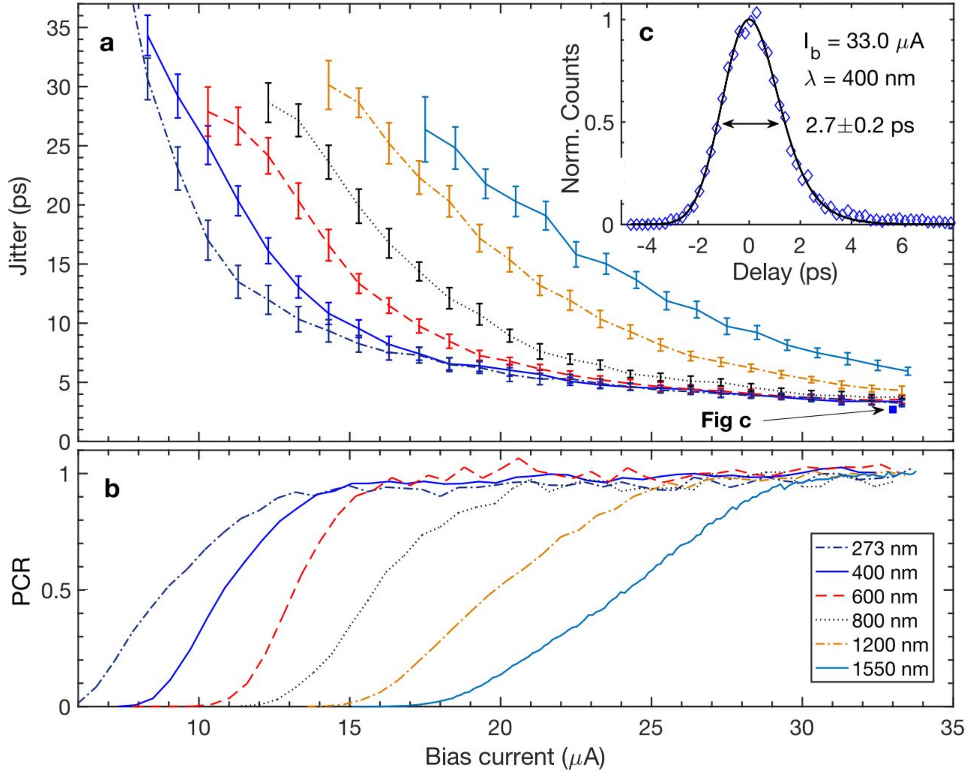


Timing jitter limited by detector geometry



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

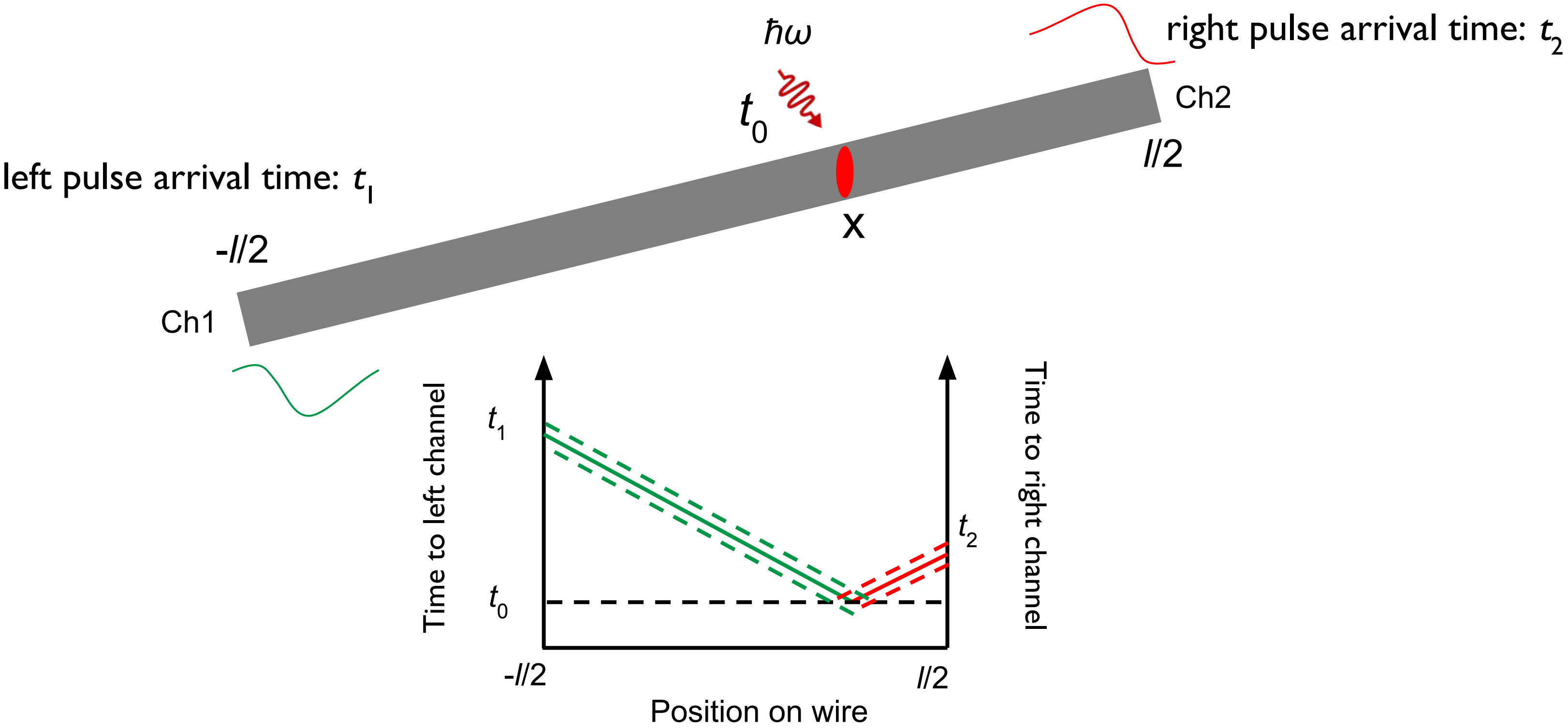




Korzh et al., 1804.06839

With JPL and NIST

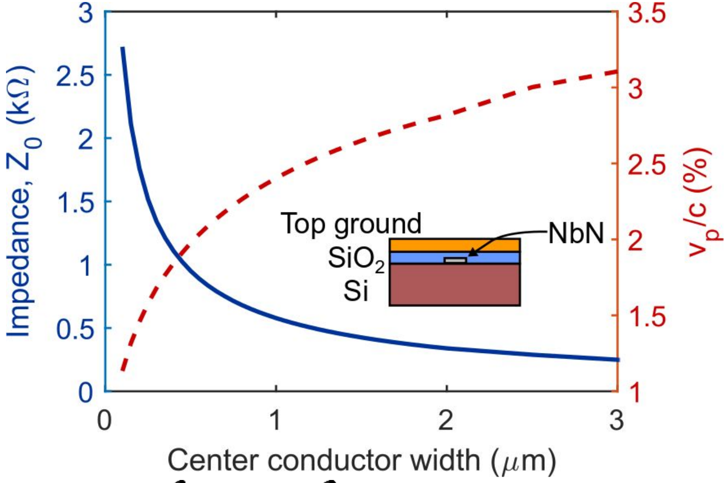
Spatial and temporal resolution in a wire

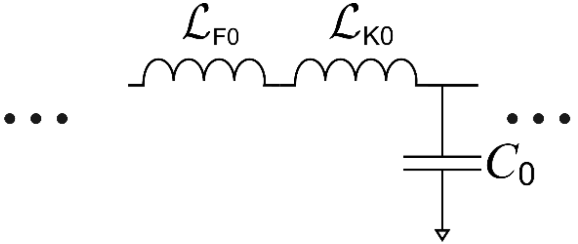


spatial resolution = timing jitter × speed of light

Slow-wave transmission line

A typical nanowire transmission line

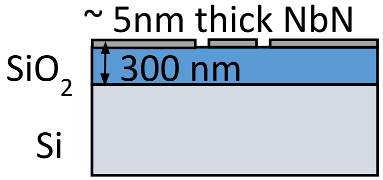




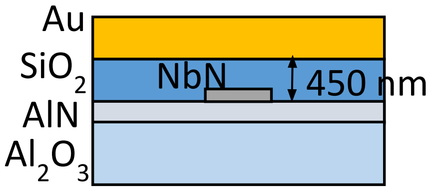
For a ~ 5 nm thick 300 nm wide NbN microstrip,

$\mathcal{L}_{K0} \approx 212\mu_0$ $\mathcal{L}_{F0} \approx 0.3\mu_0$ $C_0 \approx 21\epsilon_0$

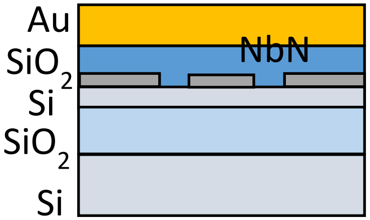
Measured group velocities to date



CPW, 300 nm center conductor width, 3μm gap, SiO2 on Si substrate
Signal speed ~2%*c*
Zhao et al. Nat. Photonics 11, 247 (2017)



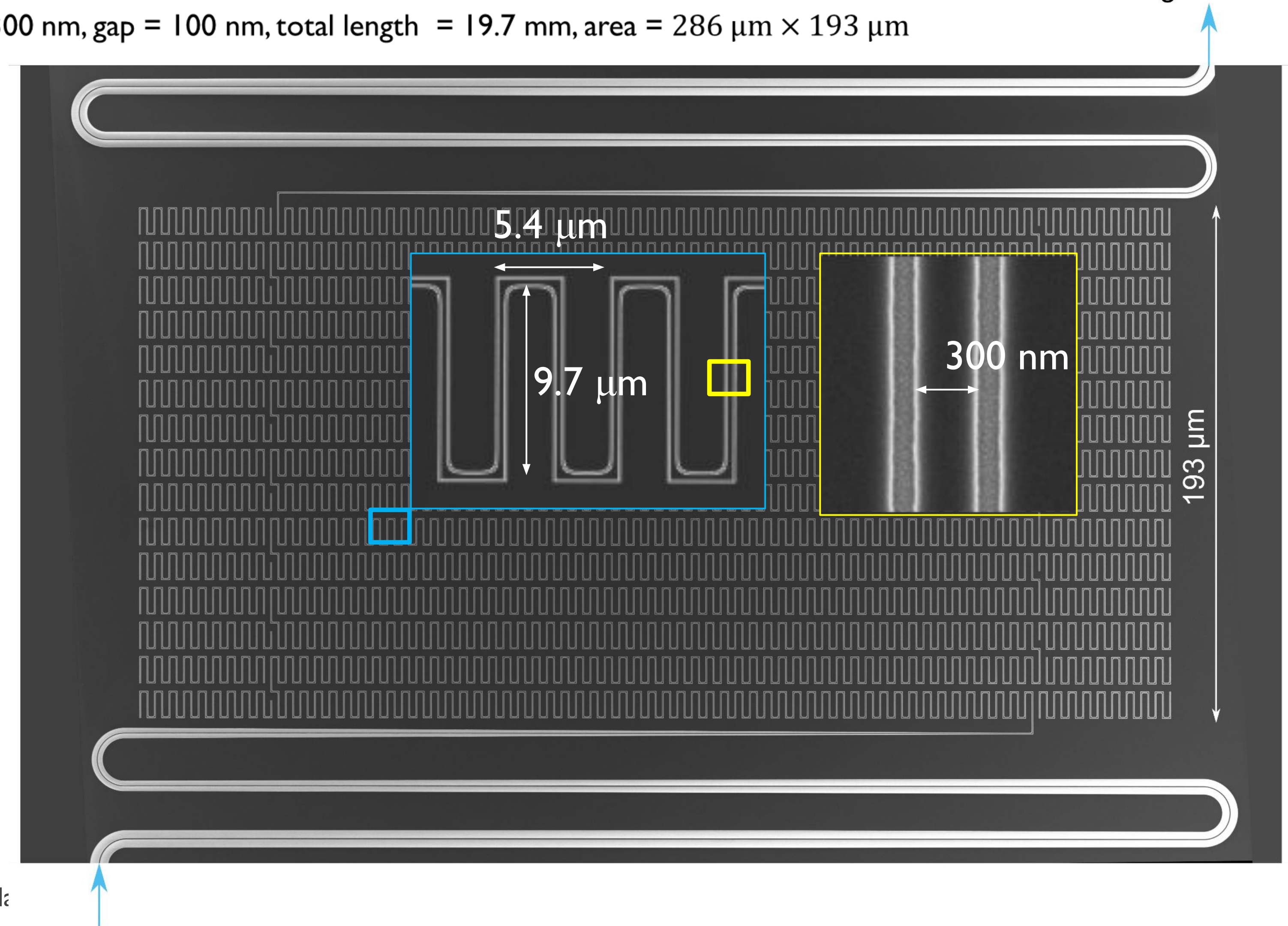
Microstrip, 300 nm width
AlN on Al_2O_3 substrate
Signal speed 1.6%*c*
Zhu et al. Nat. Nanotech. 13, 596 (2018)



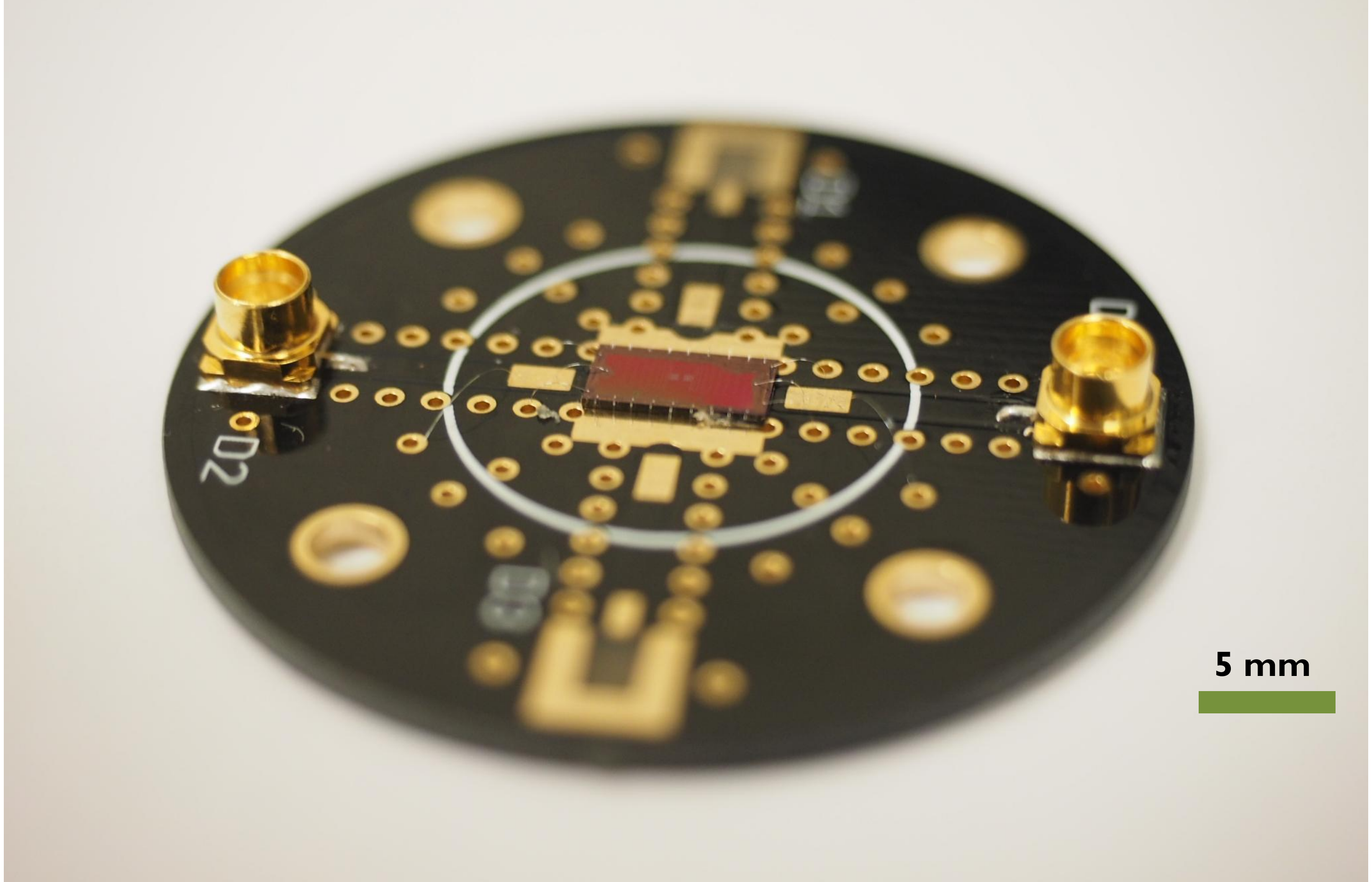
CPW with top ground, 200 nm width, 1μm gap, 450 nm spacer, SOI substrate Signal speed 0.87%*c*
Zhu et al. (2018), unpublished

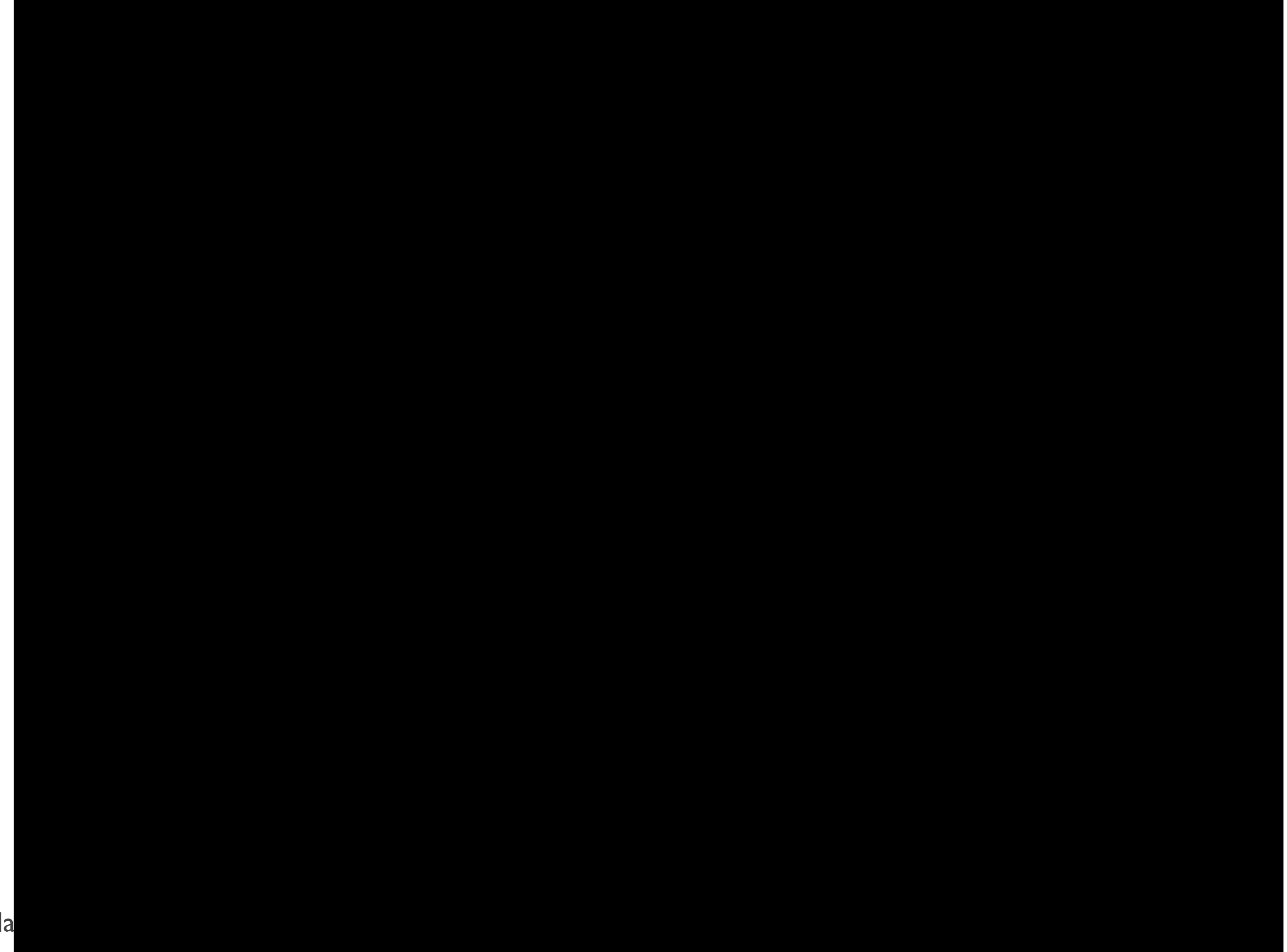
The group velocity can be further reduced by using high-index dielectric materials

*In collaboration with **Daniel Santavicca (UNF)*** width = 300 nm, gap = 100 nm, total length = 19.7 mm, area = 286 μm × 193 μm



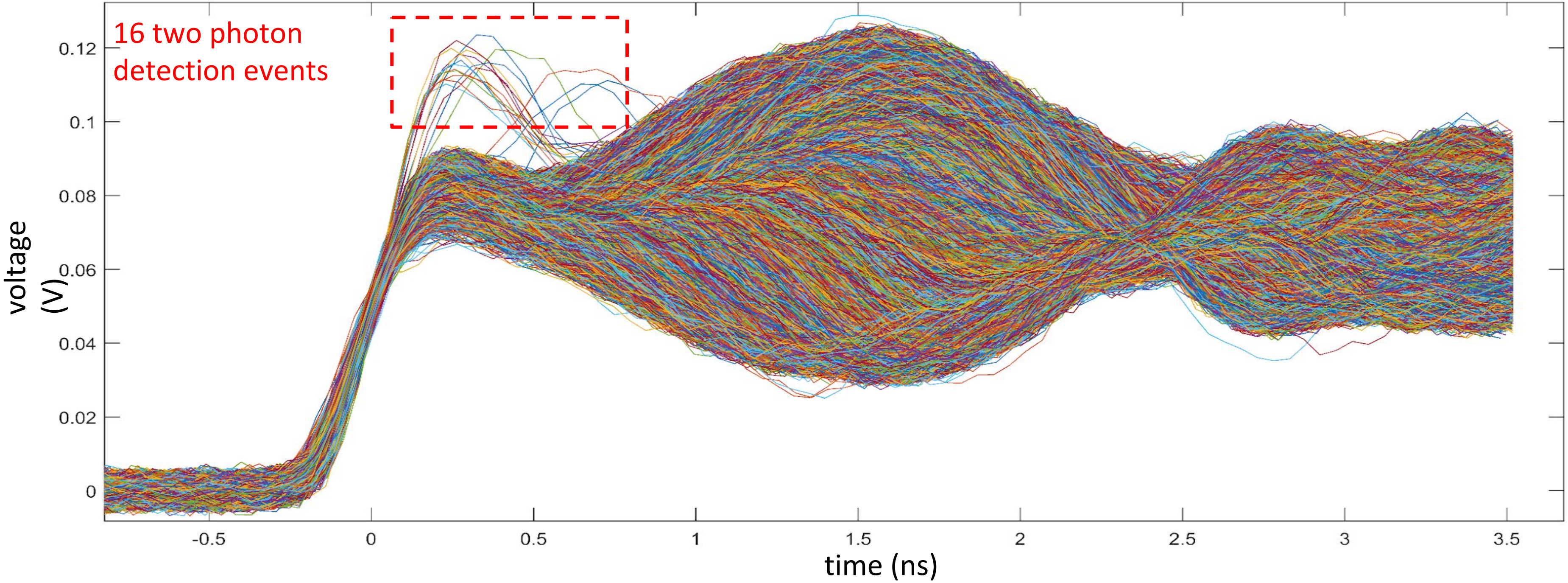
Two connectors for one imager (>500 pixels)





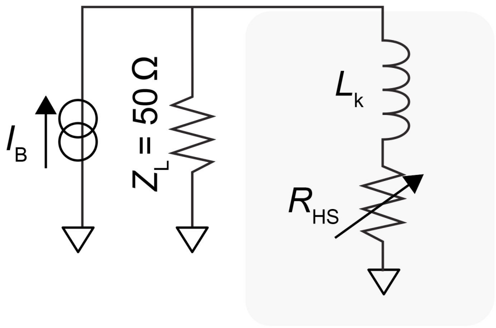
Detecting two-photon-firing events

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

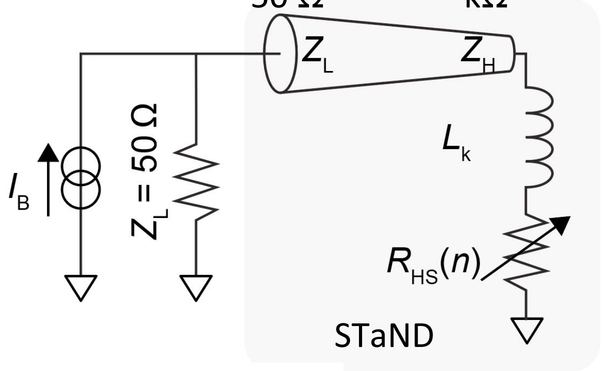


Superconducting Tapered Nanowire Detector (STaND)

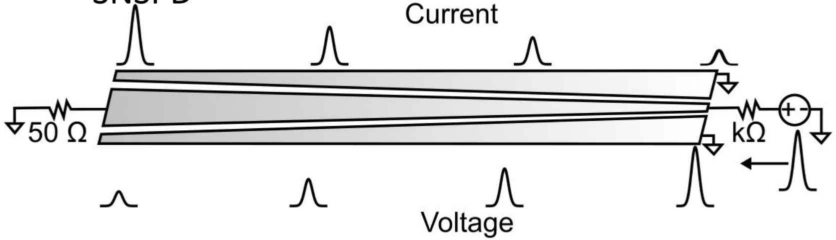
- Photon absorption induces kΩ hotspot in the nanowire
- Using 50 Ω load to read out kΩ device is inefficient
- Large impedance mismatch in conventional SNSPD makes the output insensitive to photon-number-dependent hotspot resistance



Conventional SNSPD

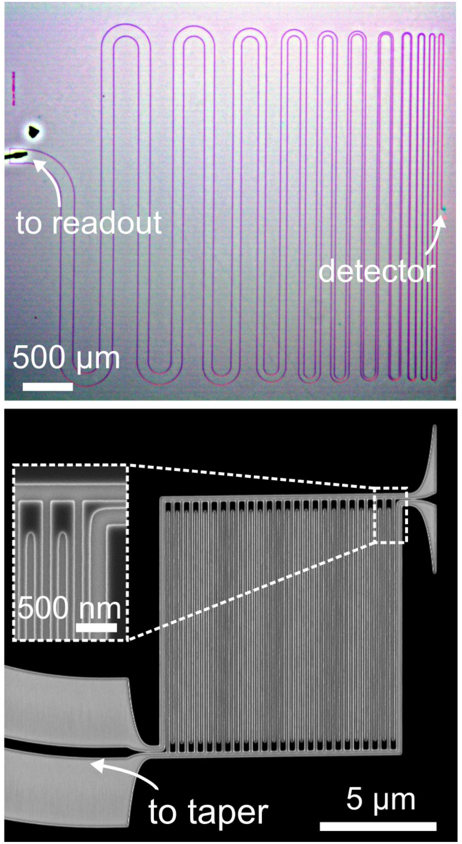


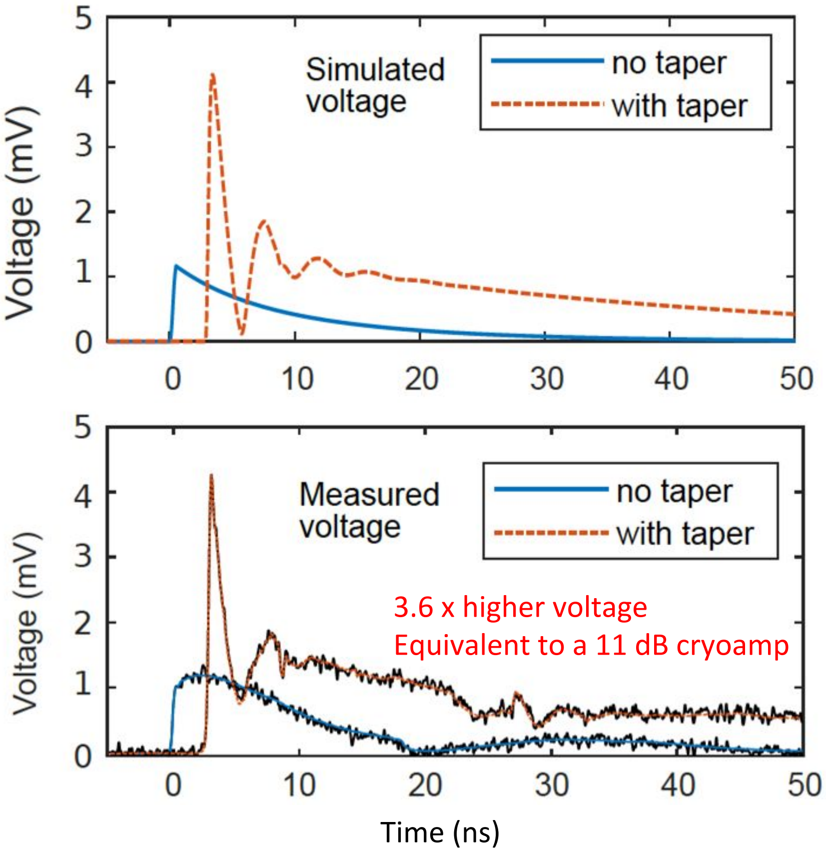
STaND



In collaboration with JPL

Increasing output voltage



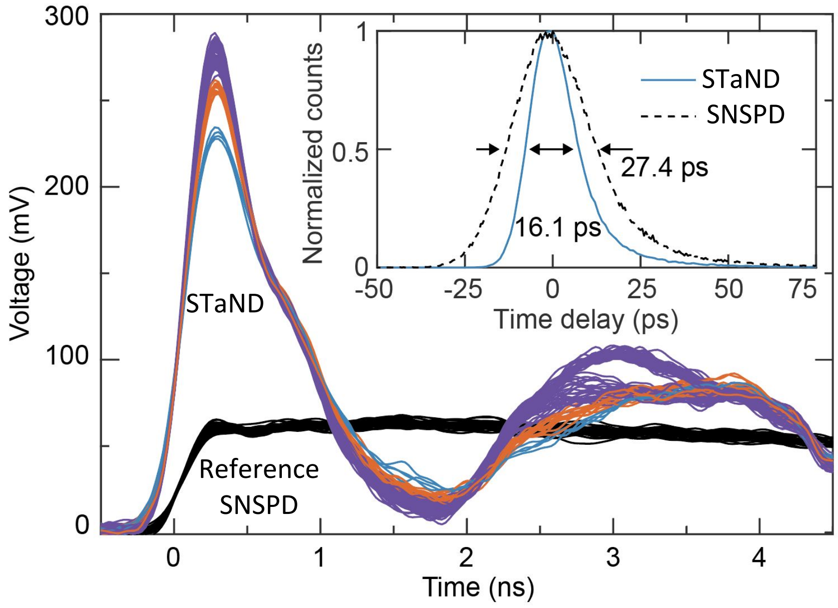


3.6 x higher voltage
Equivalent to a 11 dB cryoamp

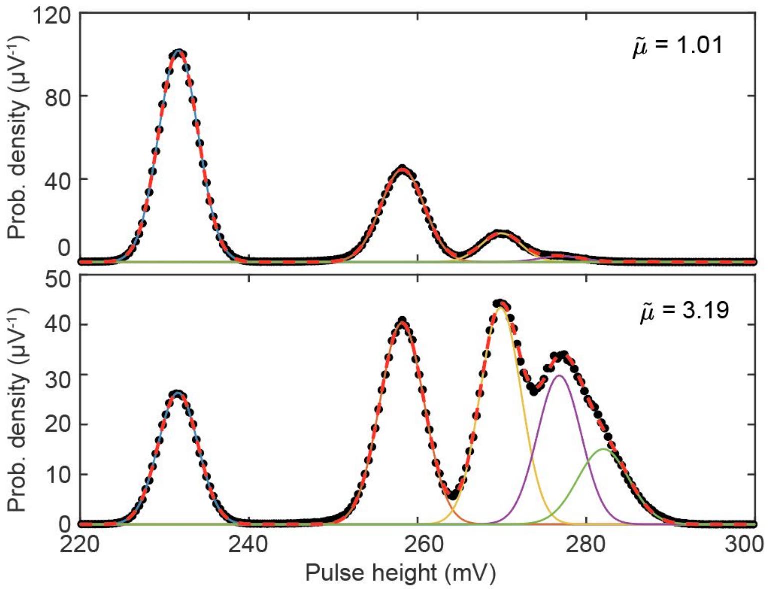
Zhu, D., Colangelo, M., Korzh, B.A., Zhao, Q.Y., Frasca, S., Dane, A.E., Velasco, A.E., Beyer, A.D., Allmaras, J.P., Ramirez, E., Strickland, W.J., Santavicca, D., Shaw, M.D. and Berggren, K.K. - *Appl. Phys. Lett.* 114(4), 042601 (2019)

Reducing timing jitter and enabling photon number resolution

Jitter reduction



Photon number resolution



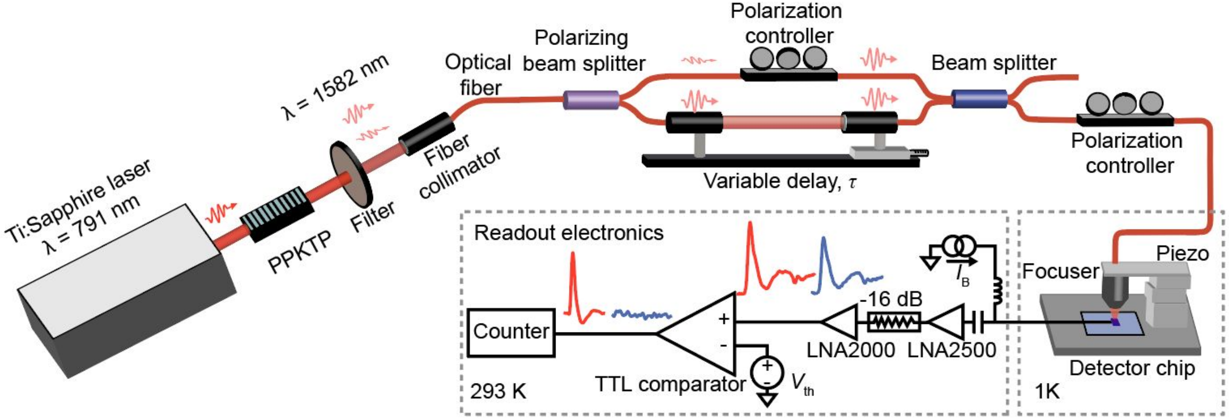
*Unpublished data

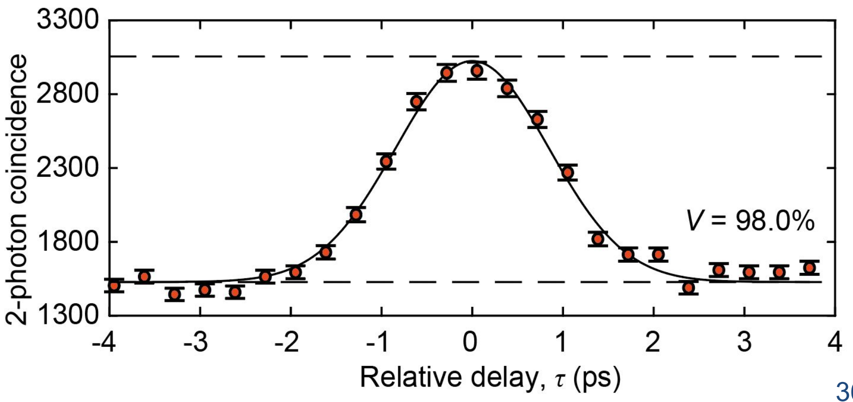
Tapered readout has also enabled:

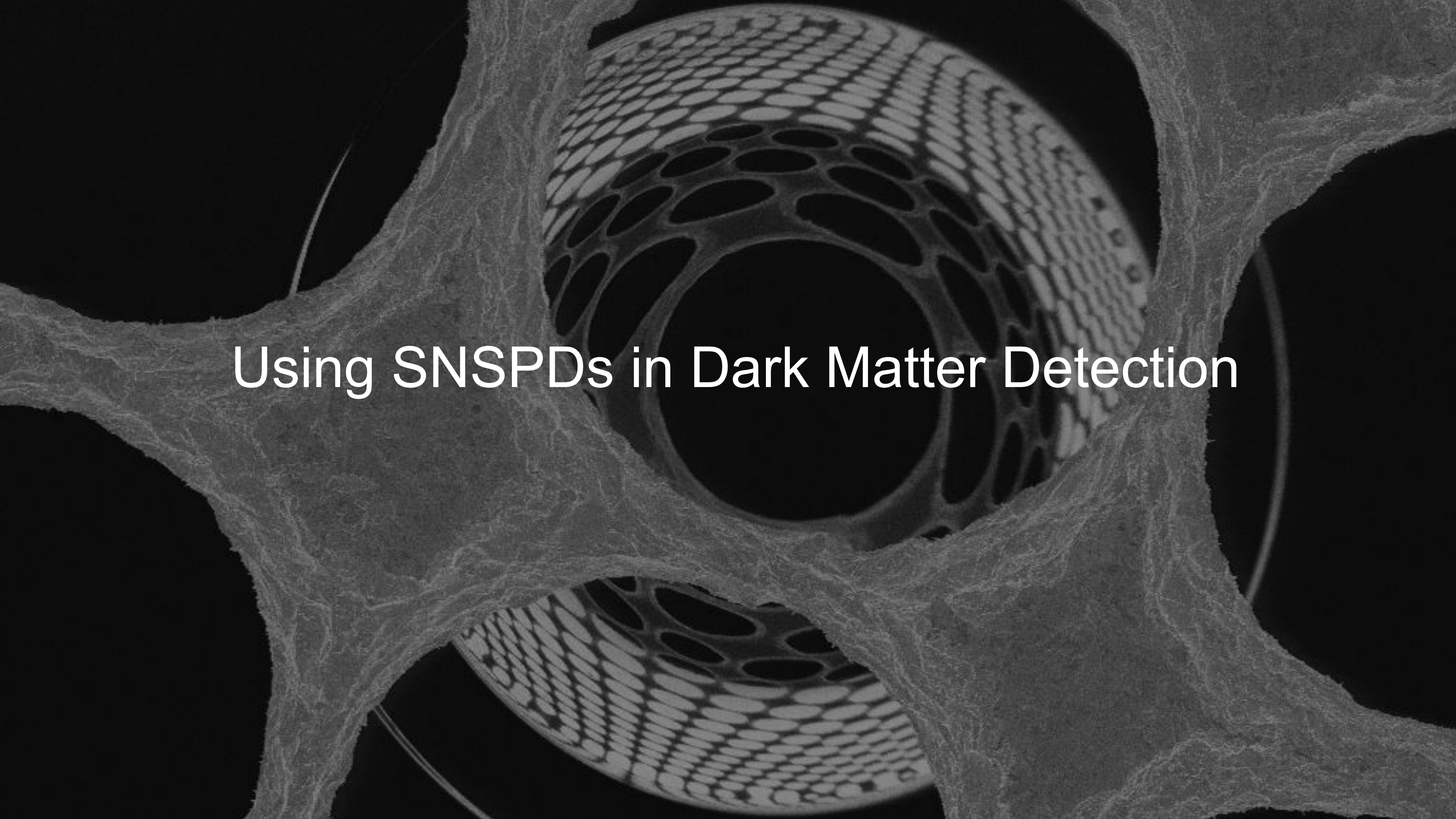
1. 25 ps jitter in NbN SNSPD without amplifier (measured at JPL)
2. sub-5 ps jitter in WSi using cryogenic amplifiers (Korzh et al. CLEO 2018, paper FW3F.3)

Direct measurement of photon bunching in HOM interference

- Frequency degenerated entangled photon pairs generated through spontaneous parametric down conversion (SPDC)
- Comparator readout switches the STaND between single-photon-detector and coincidence-counter modes
- Measured HOM interference visibility of 98%







Using SNSPDs in Dark Matter Detection

Nanowire Detection of Photons from the Dark Side

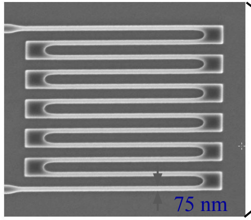
Karl K. Berggren (co-PI, MIT), Sae Woo Nam (co-PI, NIST), Asimina Arvanitaki (Perimeter), Ilya Charaev (MIT), Jeffrey Chiles (NIST), Andrew E. Dane (MIT), Ken Van Tilburg (NYU/IAS), Masha Baryakhtar (Perimeter), Robert Lasenby (Stanford University), Junwu Huang (Perimeter)

Collaboration of fundamental physics theorists, device designers, and system integrators and engineers:

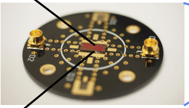
(1) Use quantum interference of dark matter to build up population in a single-photon state;

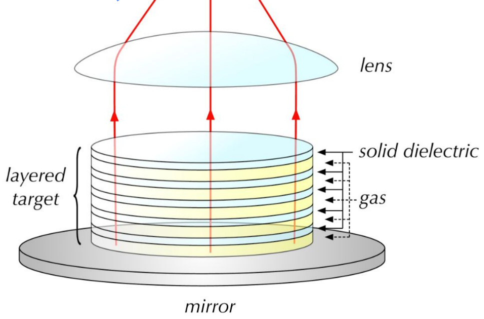
(2) Use detector technology perfected for quantum-optics to sense photon.

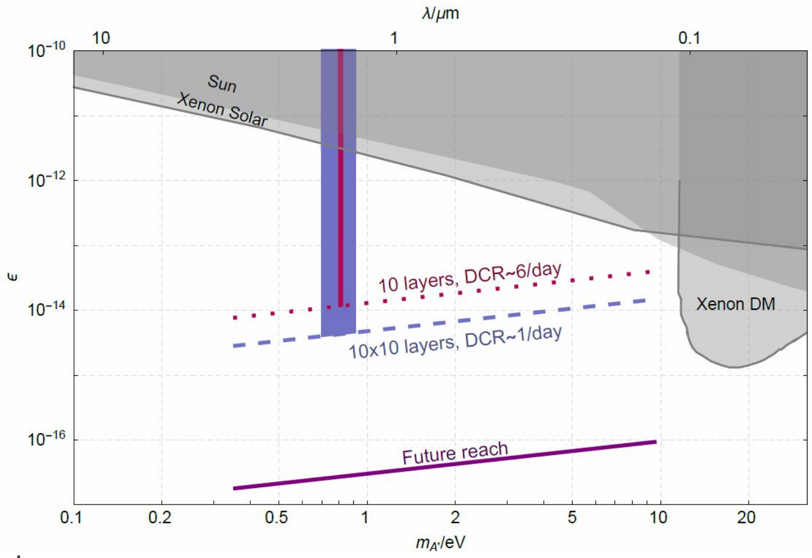
superconducting



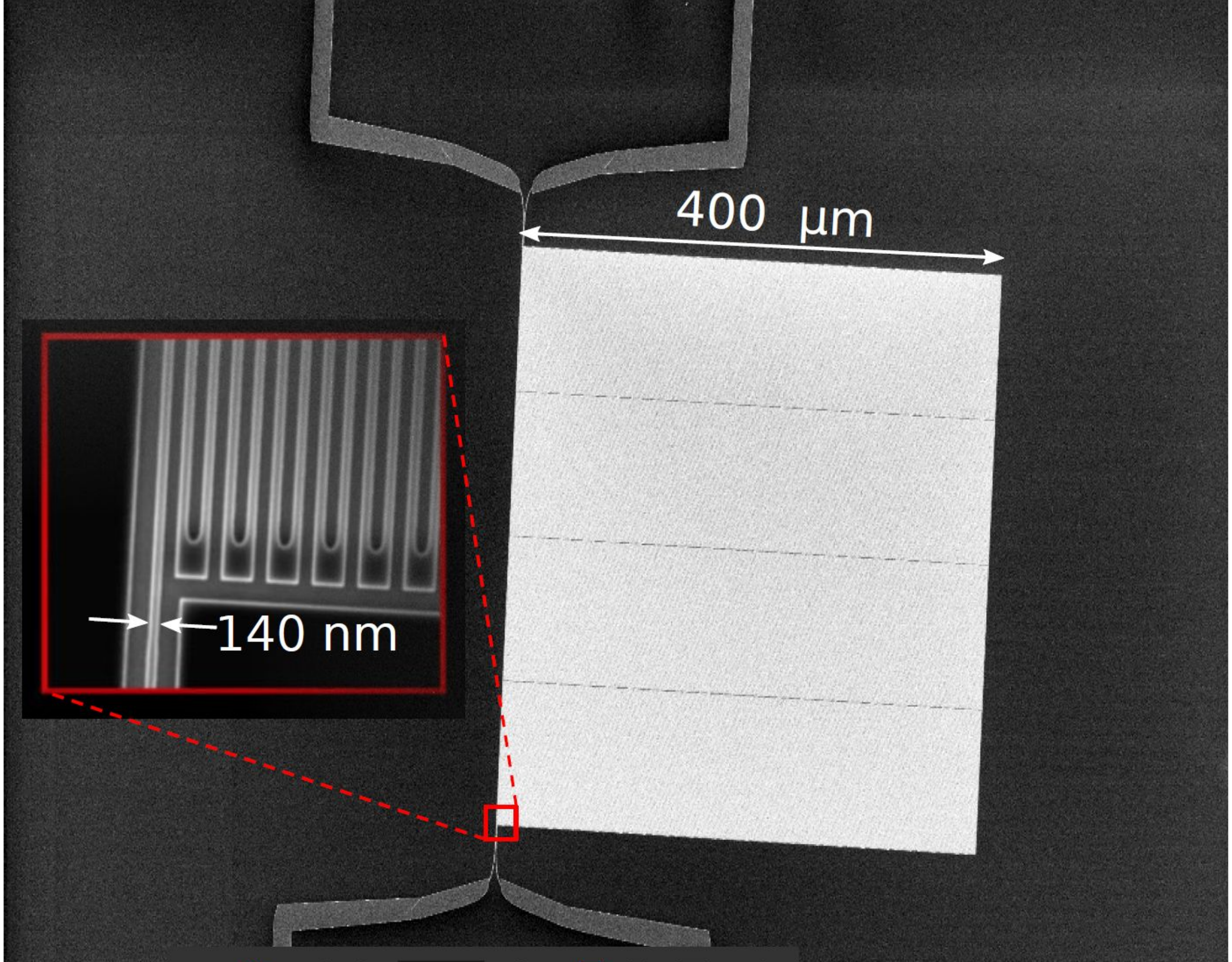
Dark-Matter Detector Concept







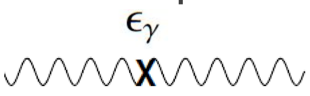
Key advantage of these detectors is low Dark Count Rate (DCR) and low-energy threshold. Depending on number of layers in target, and achievable DCR, reach of experiment could extend well beyond what is possible today

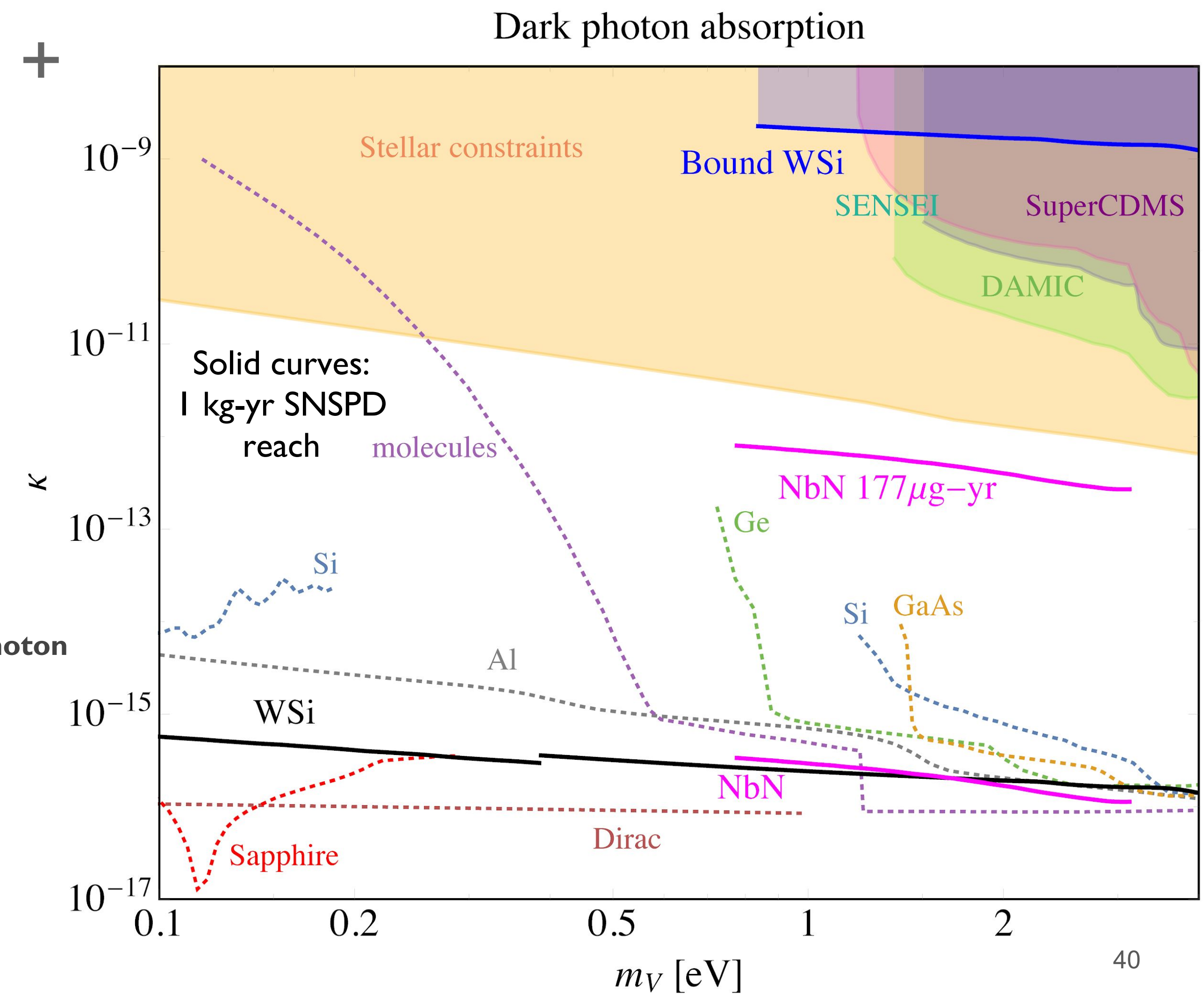

400 μm
140 nm

SNSPDs as target + sensor

[Hochberg, Charaev, Nam, Verma, Colangolo, KKB, 1903.05101]

Absorption of kinetically mixed dark photon



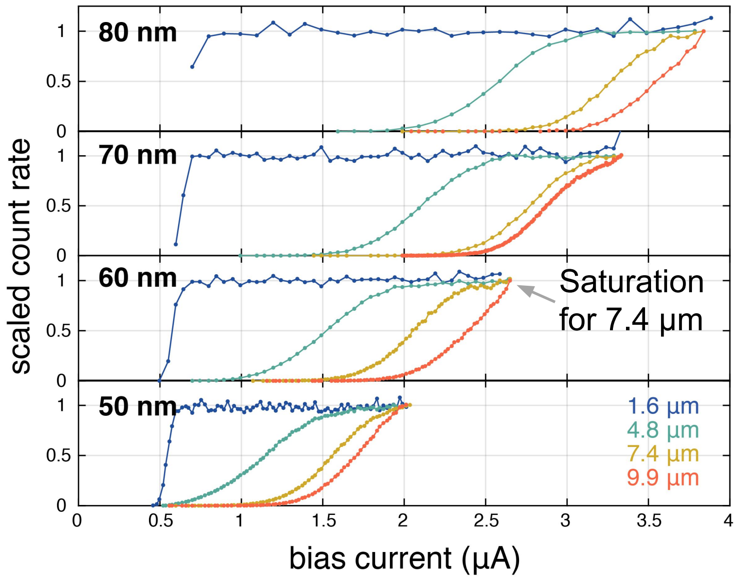


Mid-IR single-photon sensitivity

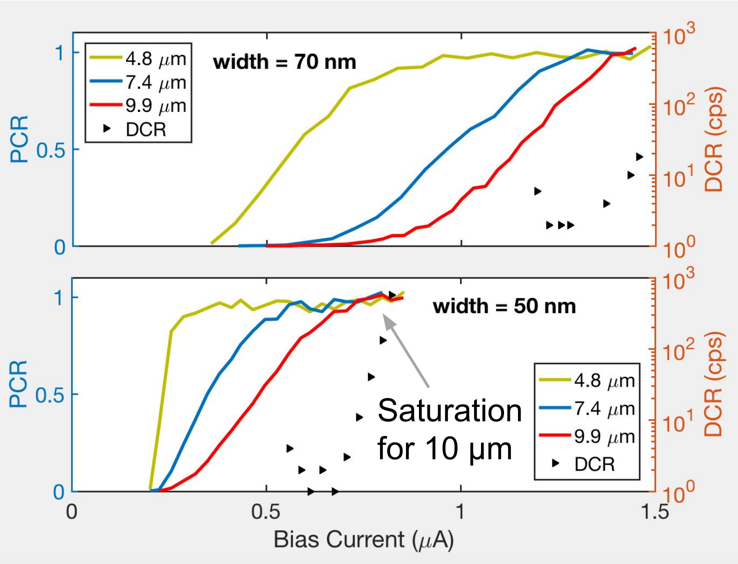
Current status

- 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



NIST
JPL

What Are We Excited About?

1. Microwave dynamics will enable improved performance/architectures
2. Commercial systems are coming online rapidly
3. Integration with nanowire-based logic family

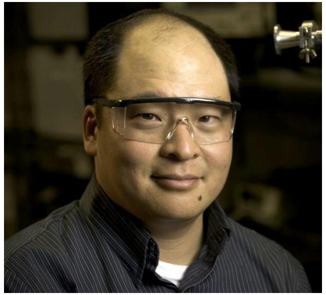
What Are We Worried About?

1. Understanding of device physics still lacking in some key areas

FINANCIAL SUPPORT

- Dept. of Energy
- 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

Dark-Matter Collaborators



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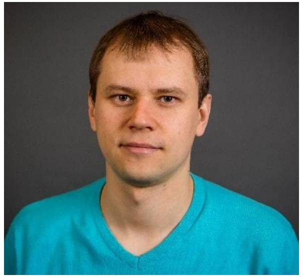

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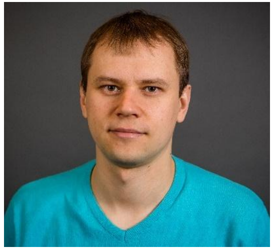
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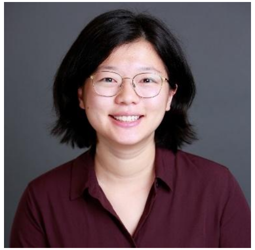
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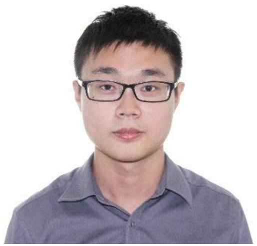
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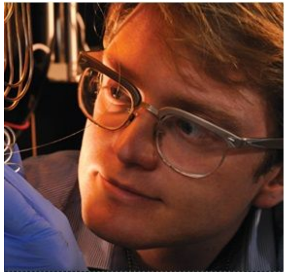

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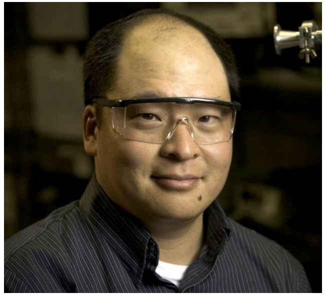

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