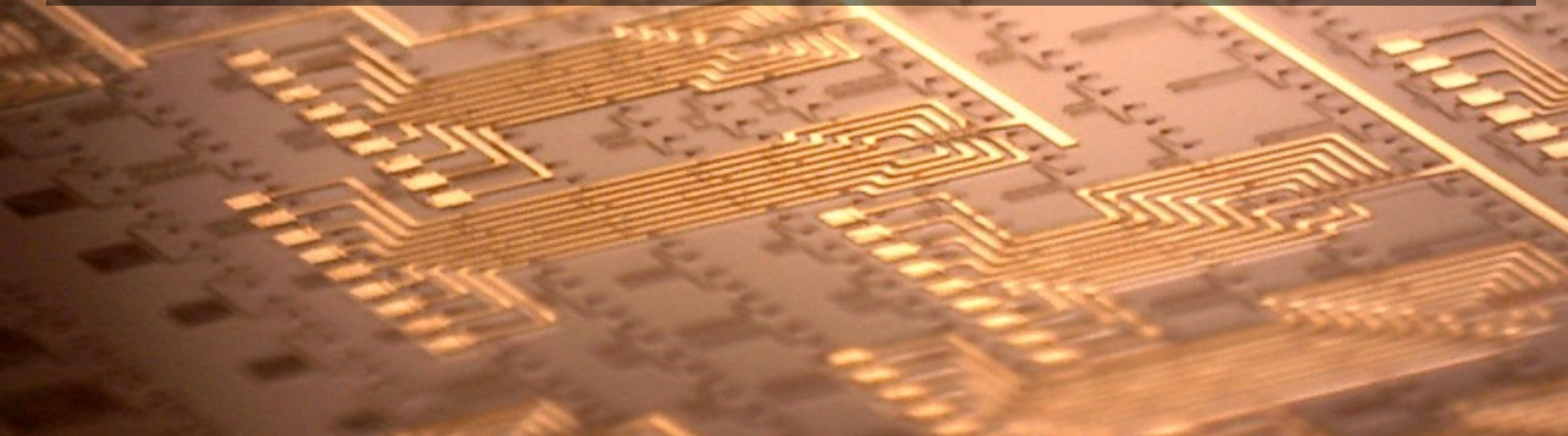
Superconducting Optoelectronics for Quantum and Neuromorphic Processing

Alex Tait



Faint Photonics Group — Sae Woo Nam
Quantum Nanophotonics Group — Rich Mirin

Photonics for Quantum Workshop – January 25, 2019
Rochester Institute of Technology

IS NATURE PREDICTABLE, IN THEORY?

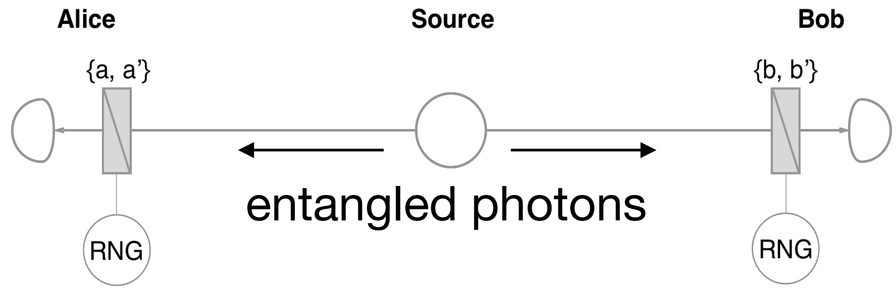
- Copenhagen interpretation
  - Probably not, and
  - in either case, the math is elegant
  - - Bohr, Heisenberg

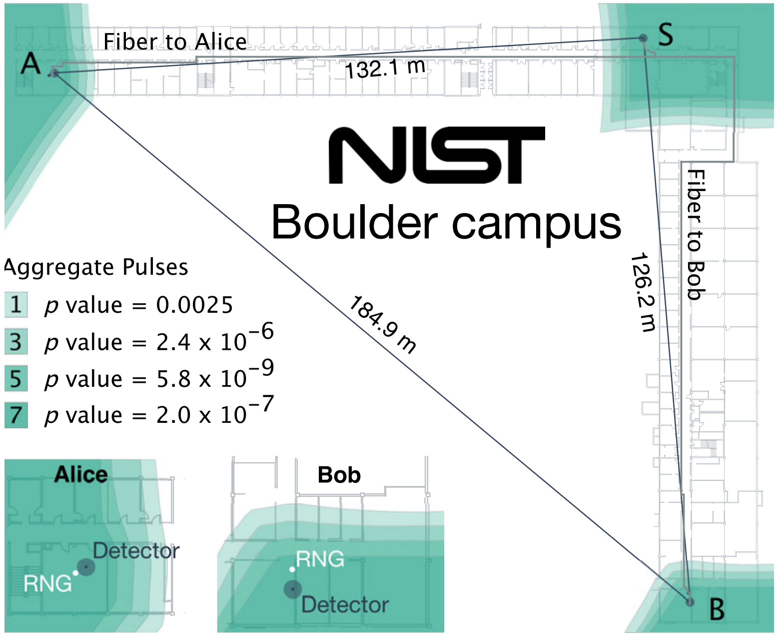
- Local realistic interpretation
  - Yes, there is a deterministic theory beneath quantum mechanics
  - - Einstein:

"God does not play dice"

DISPROVING LOCAL REALISM

- Local realism is testable
  - John Bell, 1975
- Local realism is false
  - Hensen et al., 2015
  - Giustina et al., 2015
  - Shalm et al., 2015 (NIST)
- Bell test can generate **provably** unpredictable random numbers
  - Bierhorst et al., 2018





B. Hensen et al., "Loophole-free Bell Inequality Violation Using Electron Spins Separated by 1.3 Kilometres," Nature 526, 682 (2015).
M. Giustina et al., "Significant-Loophole-Free Test of Bell's Theorem with Entangled Photons," Phys. Rev. Lett. 115, 250401 (2015).
L. K. Shalm et al., "Strong Loophole-Free Test of Local Realism," Phys. Rev. Lett. 115, 250402 (2015).
Bierhorst et al., "Experimentally generated randomness certified by the impossibility of superluminal signals," Nature 556, 7700 (2018).

God's Dice

- Random key generation is central to
  - Cybersecurity
  - E-commerce
  - Voting machines

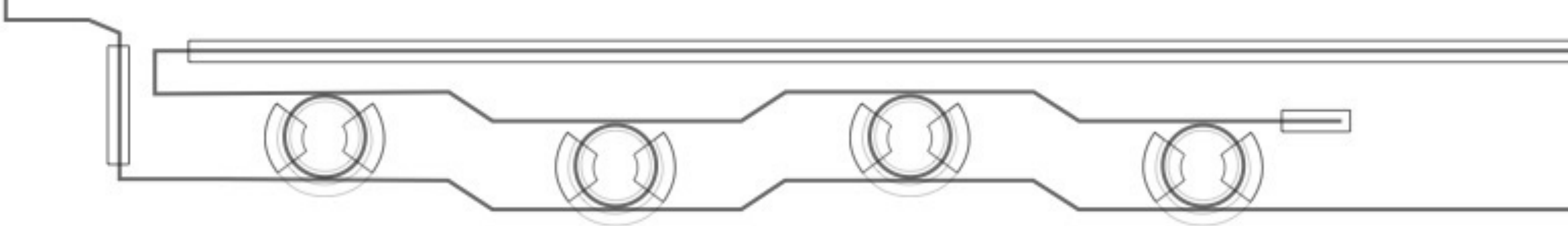
http://beacon.nist.gov

NEEDS FOR SINGLE PHOTON DETECTION

- Bell test
  - >67% detection efficiency
- Linear quantum computing
  - >99% detection efficiency
- Quantum communication
  - Photon loss -> redundancy -> vulnerability
- This is not comprehensive...

OUTLINE

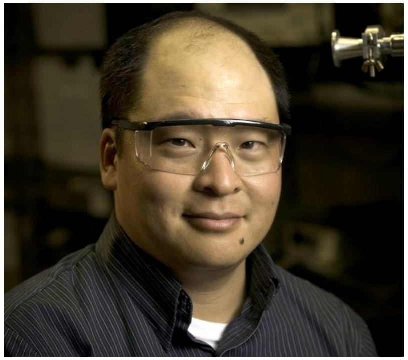
- Single photon detectors and quantum information
- Cryogenic silicon photonic integration
- Superconducting Optoelectronic Networks platform
- Neuromorphic photonics and quantum photonics



Single photon detectors

SINGLE PHOTON DETECTION AT NIST

- Advance science of measuring single photons
- Characterize single-photon sources
- Transfer detector technology to the public
- Investigate new applications
- Collaborate

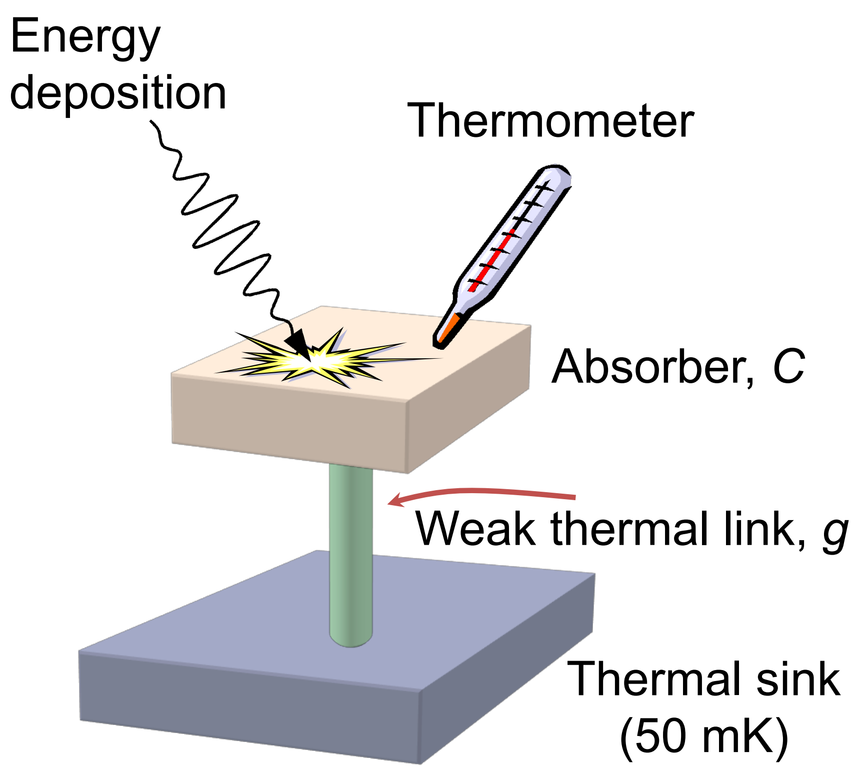


Sae Woo Nam

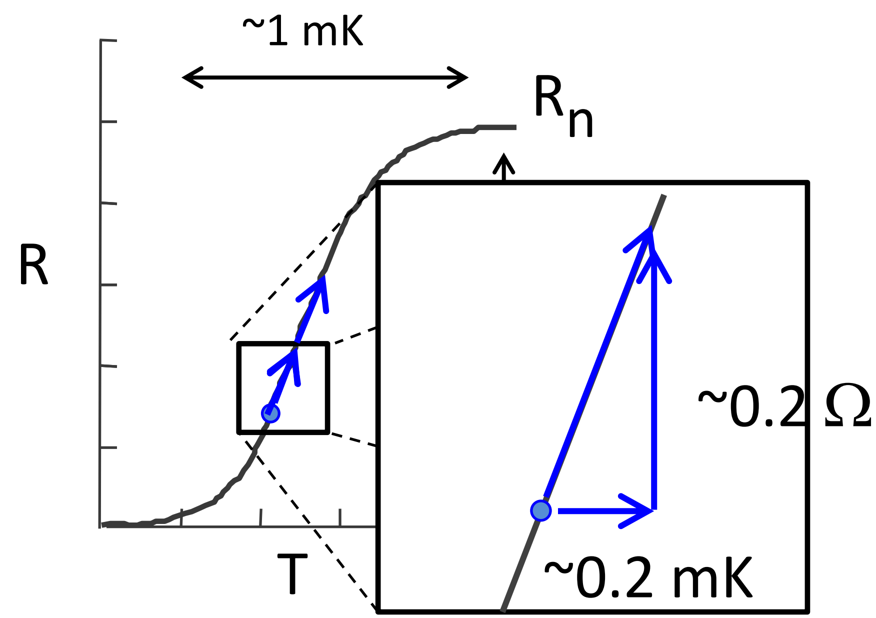
Contact
saewoo.nam@nist.gov
rich.mirin@nist.gov
jeffrey.shainline@nist.gov
alexander.tait@nist.gov

TRANSITION EDGE SENSOR (TES)

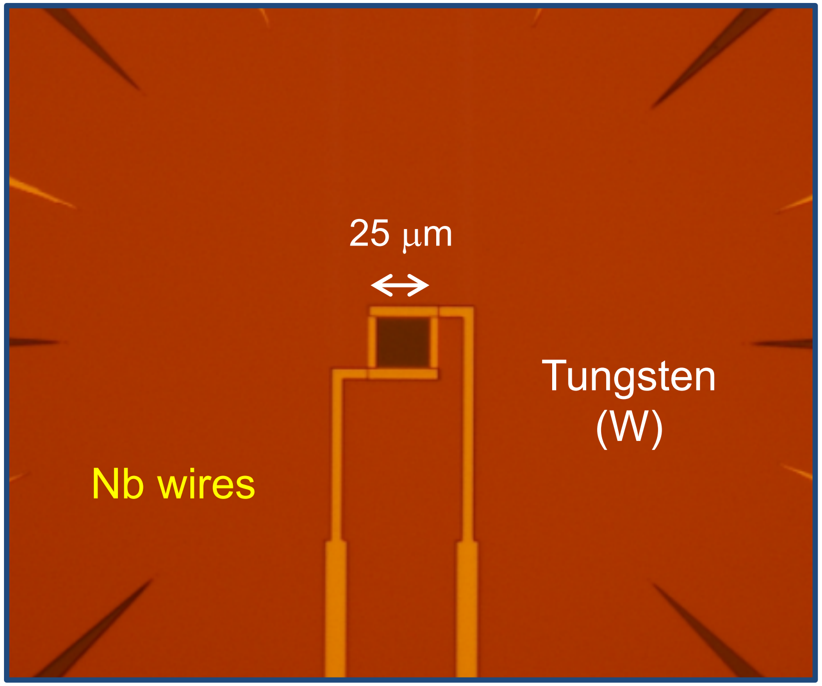
Calorimetric detection
UV/visible/IR photons

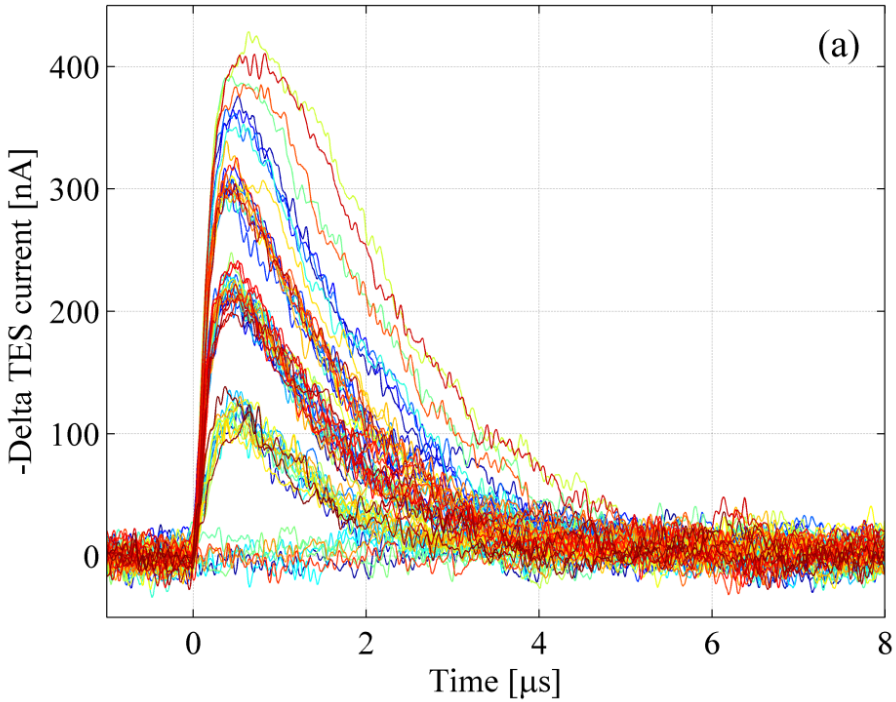


Superconducting
transition edge



TRANSITION EDGE SENSOR (TES)



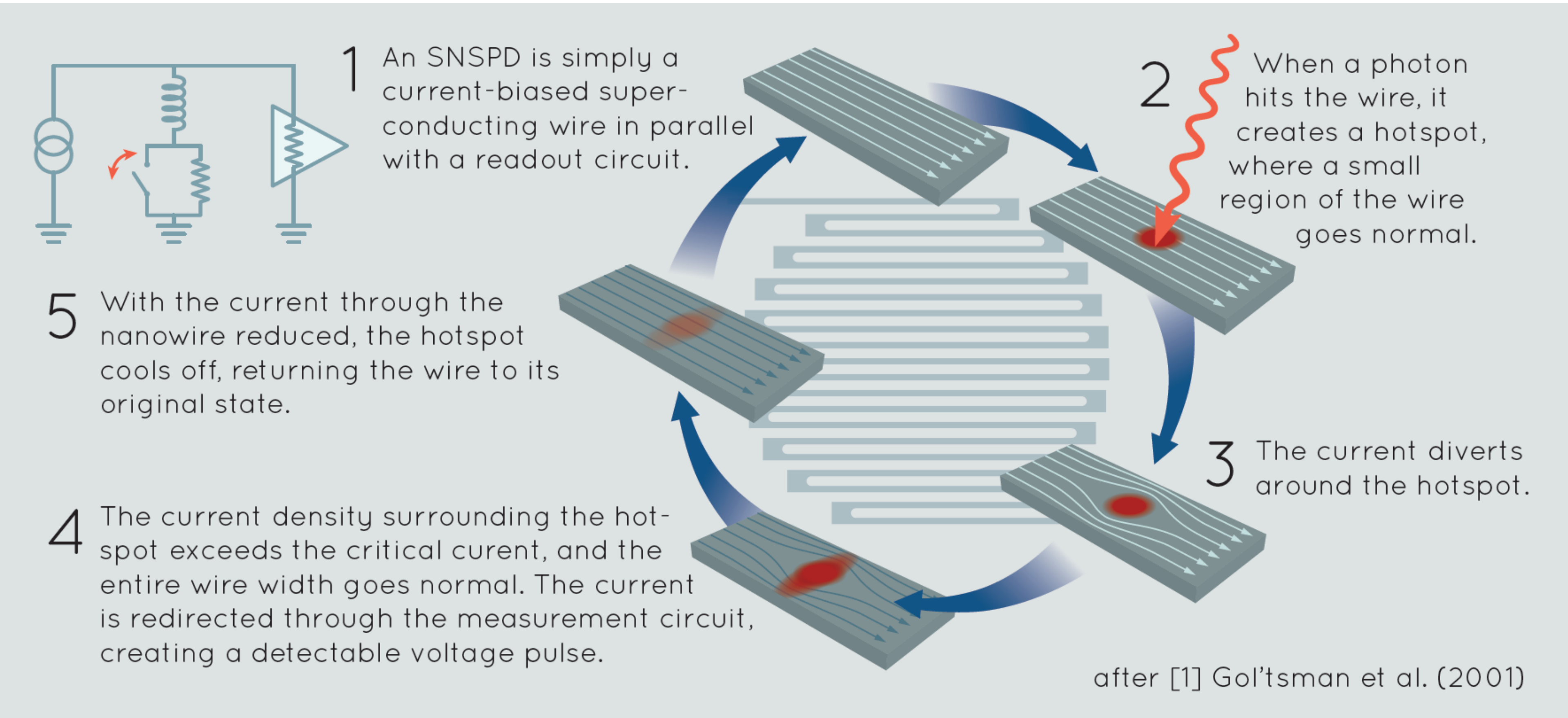


805 nm: $\eta_{System} = 97.7 \pm 1.5$ %

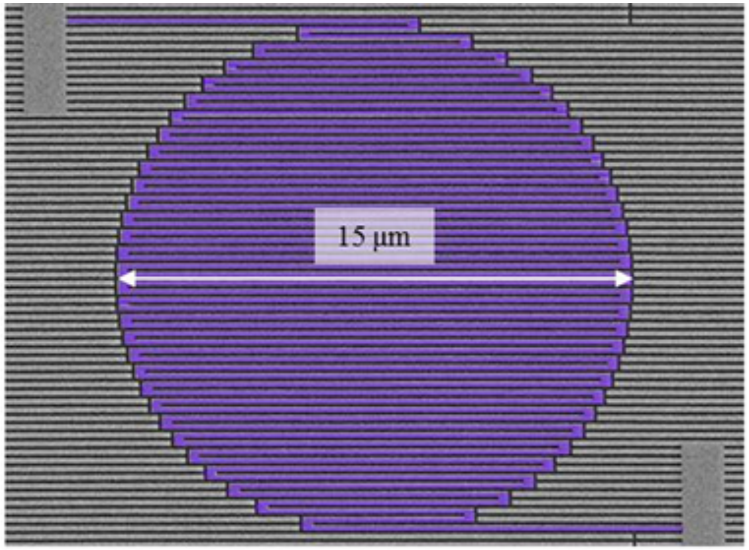
Goal 1: increase this number

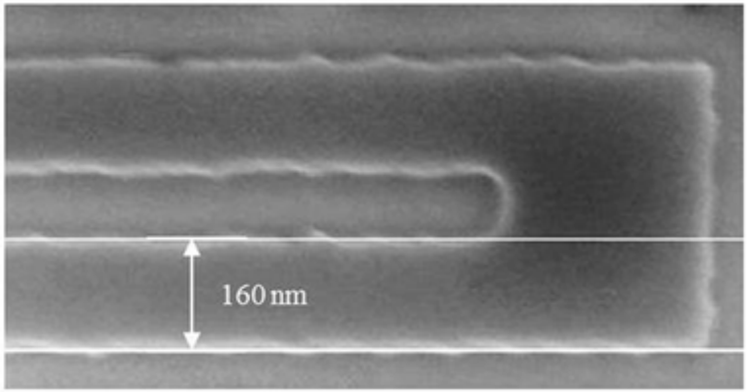
Goal 2: decrease this number

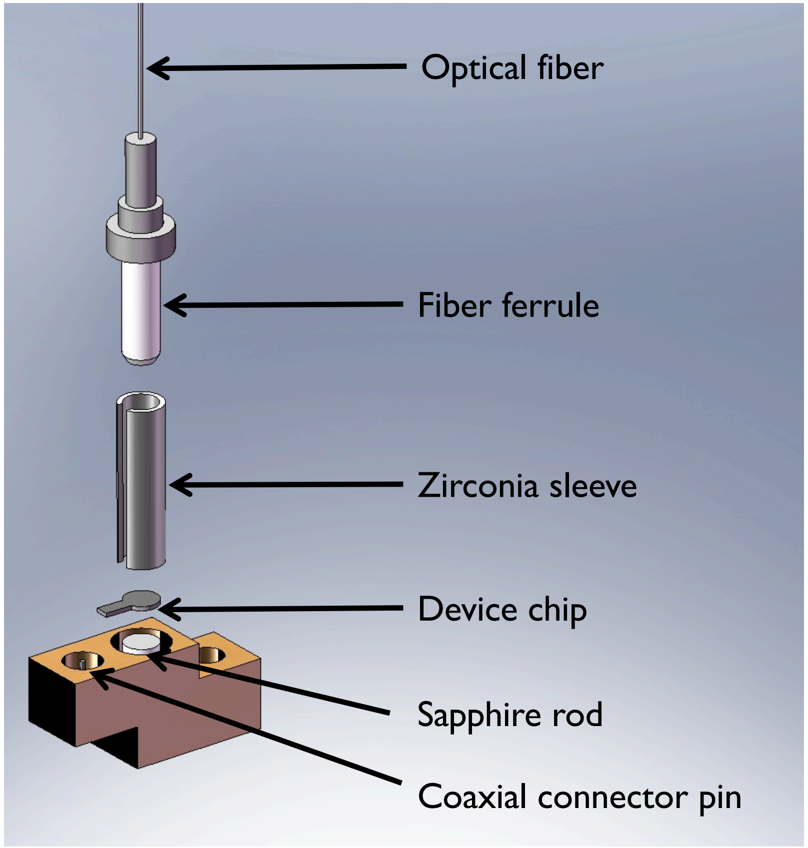
SUPERCONDUCTING NANOWIRE SINGLE-PHOTON DETECTOR (SNSPD)



SYSTEM DETECTION EFFICIENCY

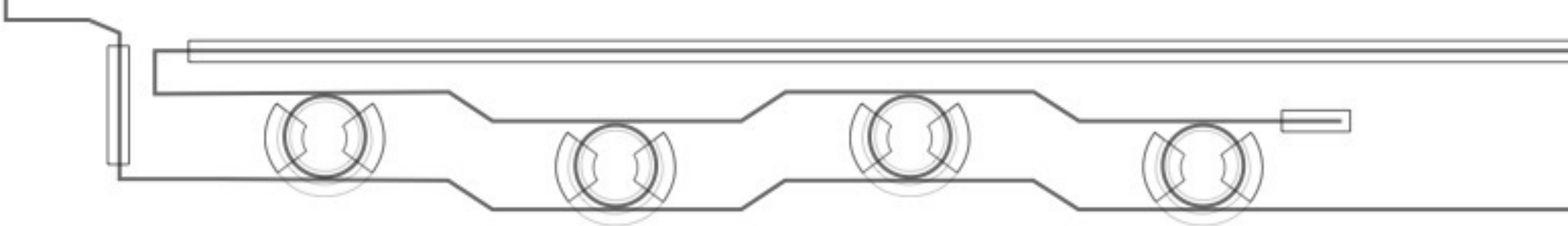






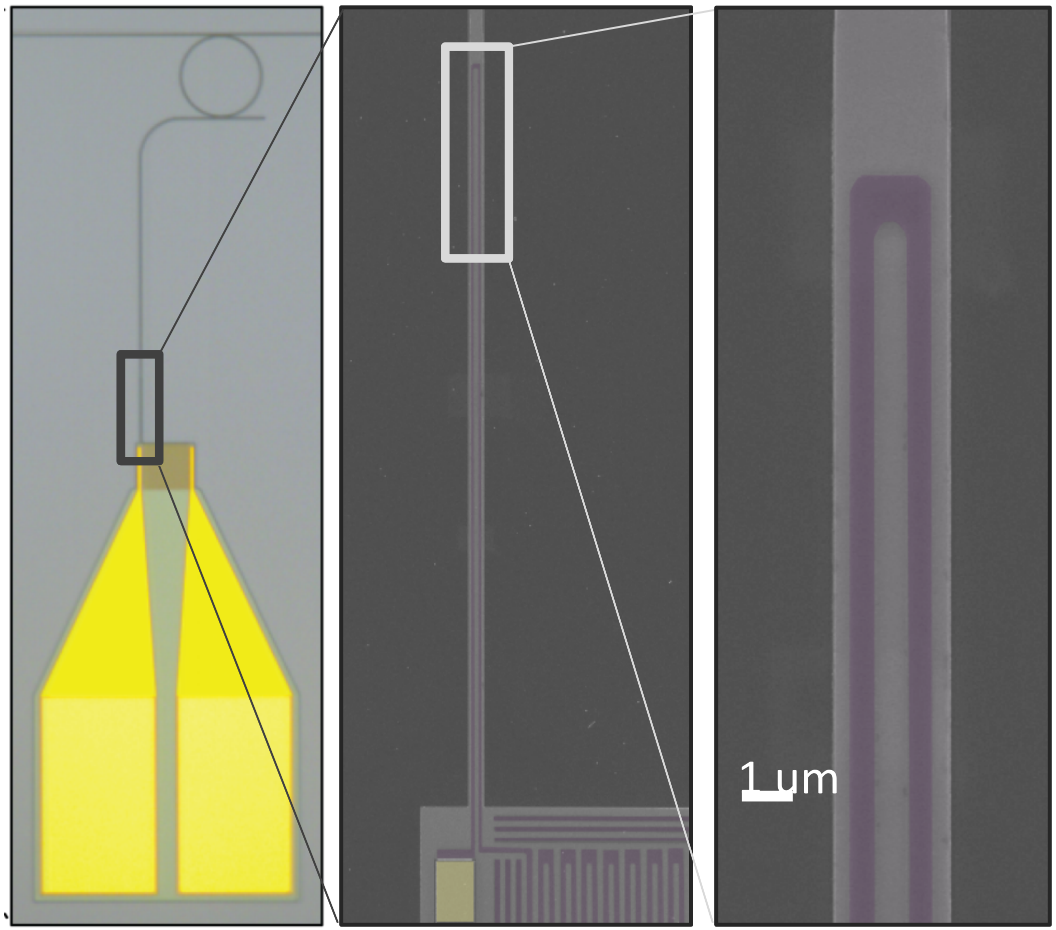
Miller et al., Opt. Express (2011)

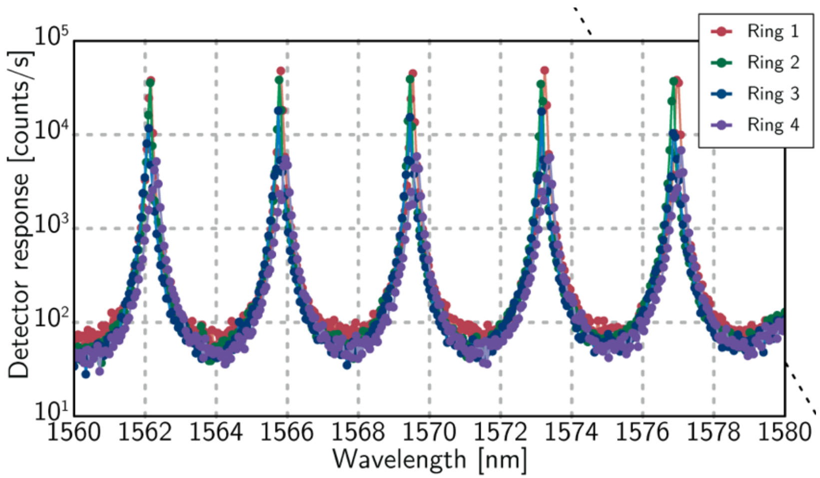
PhotonSpot Quantum Opus



Cryogenic silicon photonics

CO-INTEGRATION: WAVEGUIDES + SNSPDS

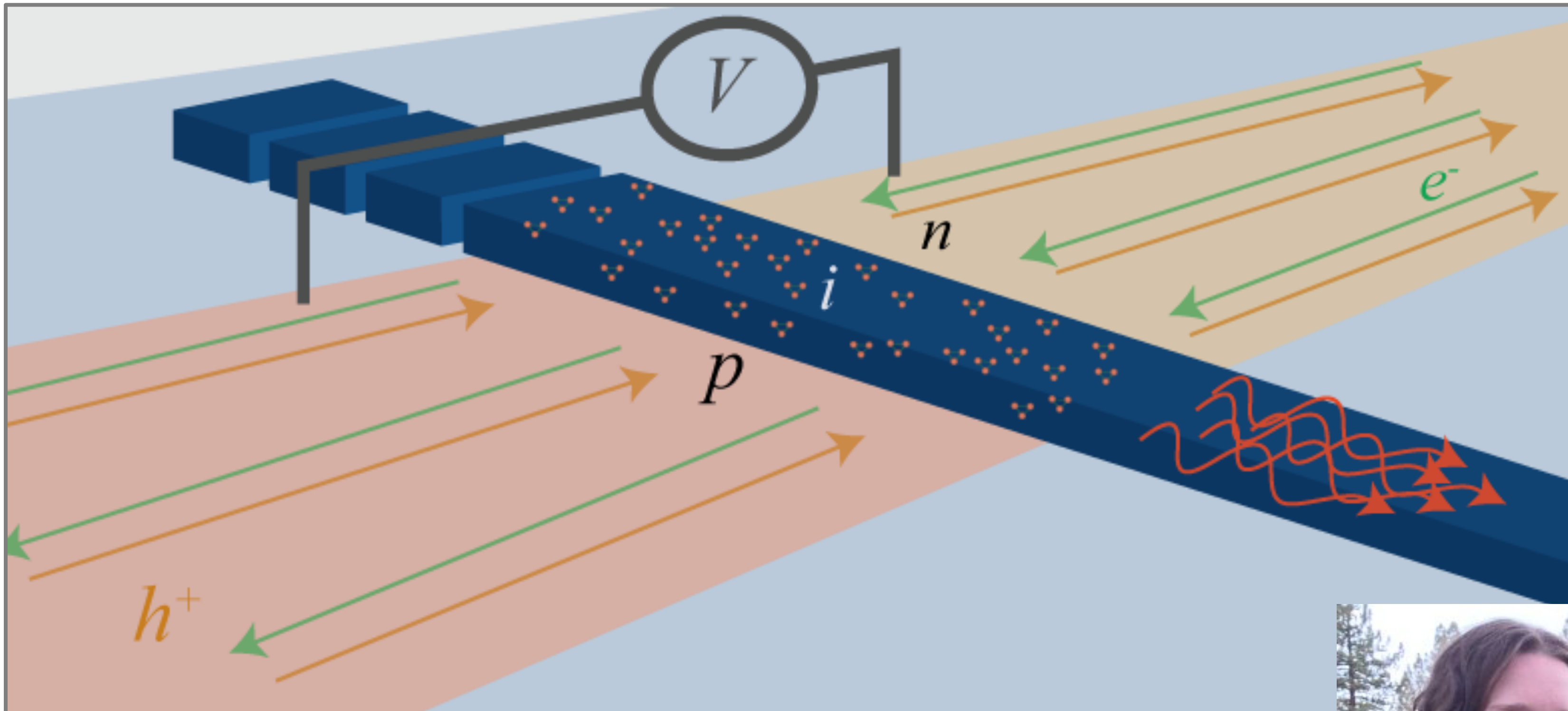




Jeff Shainline

Shainline et al. " Room-temperature-deposited dielectrics and superconductors for…" Op. Ex. **25** 10322 (2017).

ALL-SILICON LIGHT EMITTING DIODES



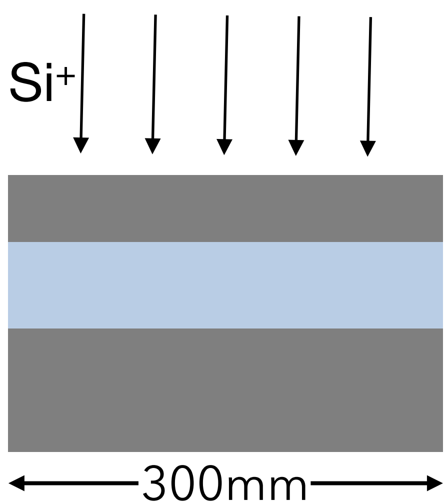
- Some Si defects have an optical transition
- Low temp. inhibits non-radiative decay
- Electrical pumping with PN junction

Sonia Buckley

S. M. Buckley et al. “All-silicon light-emitting diodes waveguide-integrated with superconducting single- photon detectors ” Applied Physics Letters, 111 (14). 2017.

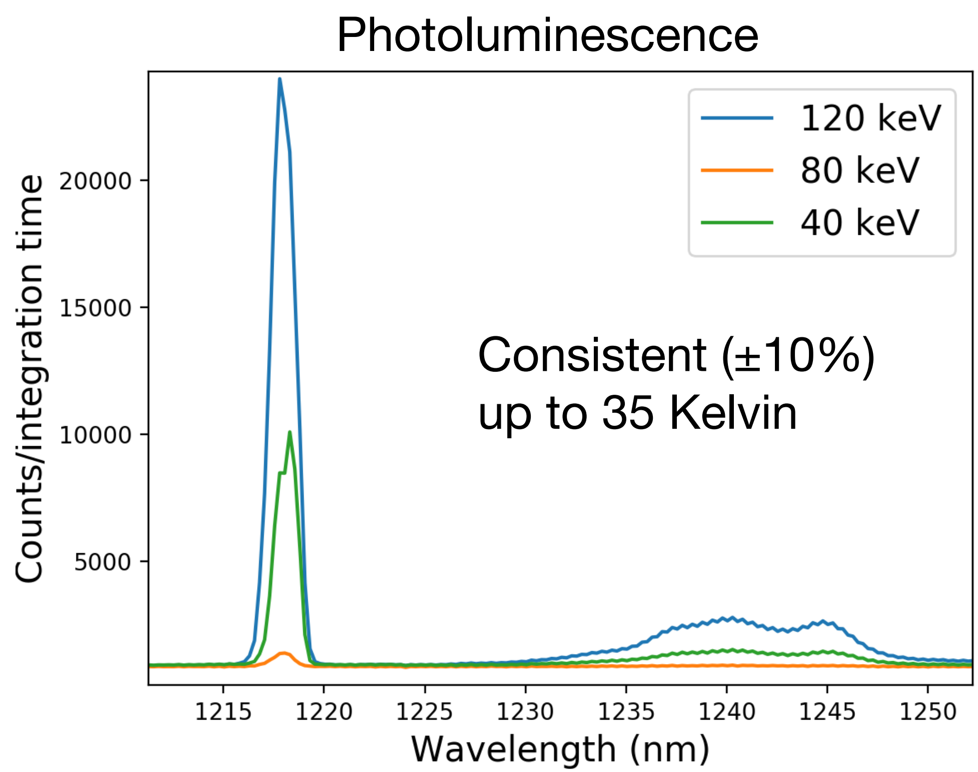
OPTIMIZING EMISSION ON 12 INCH WAFERS

- Implanted at SUNY Poly
- Measured at NIST



SUNY POLYTECHNIC INSTITUTE

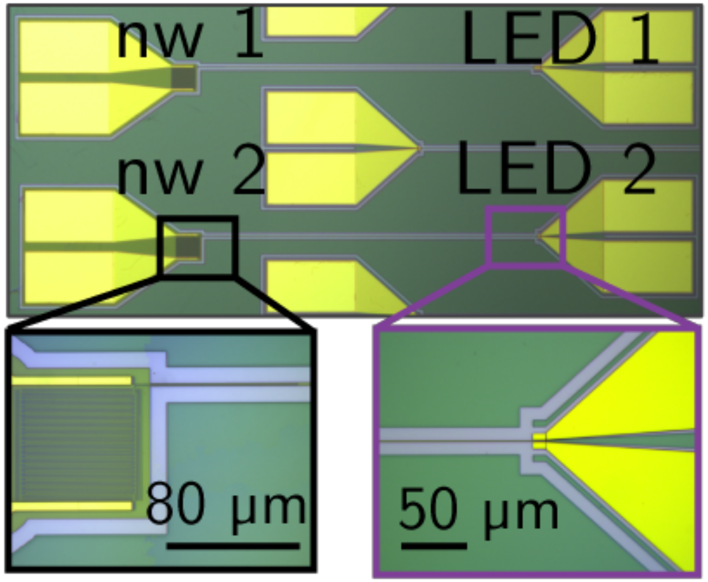
Pops

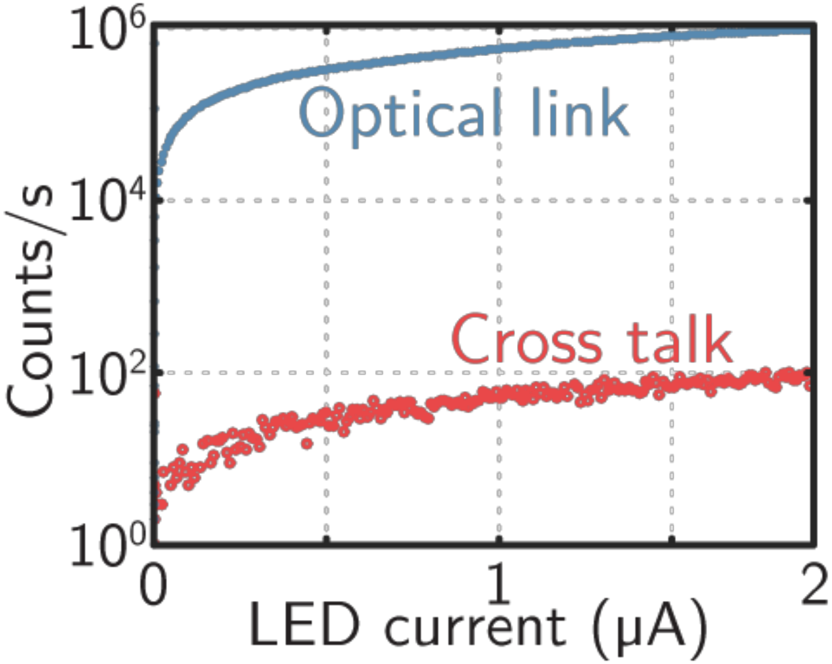


<u>Recent results</u>

- 50x enhancement from prior runs
- Evidence of localization in device layer, not handle layer

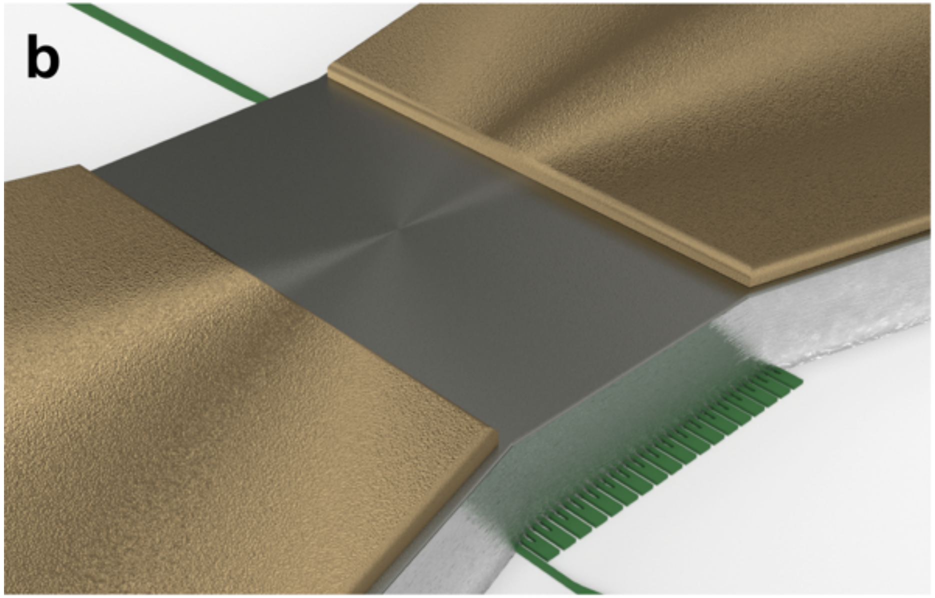
CO-INTEGRATION: SILICON LEDS + SNSPDS

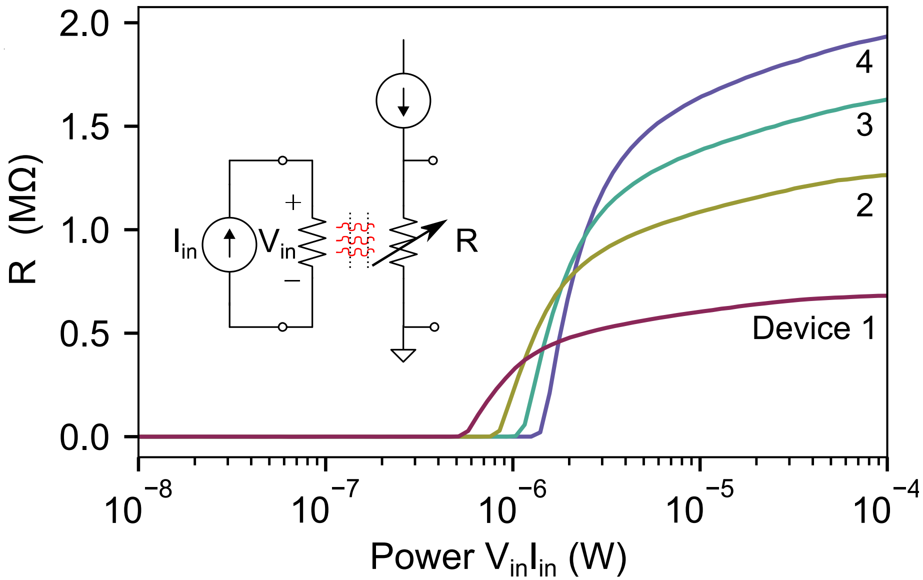




S. M. Buckley et al. "All-silicon light-emitting diodes waveguide-integrated with superconducting single-photon detectors" Applied Physics Letters, 111 (14). 2017.

SUPERCONDUCTING AMPLIFIERS

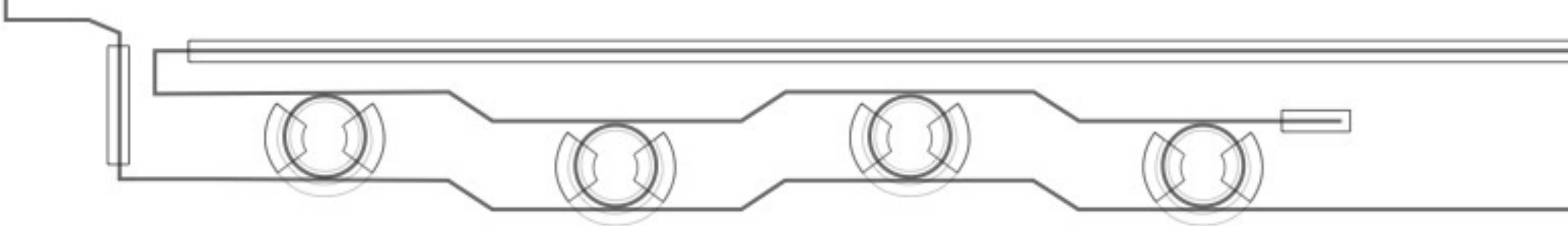




- Interface: superconductor signals to semiconductor readout
- millivolt input -> Volt output
- No Josephson Junctions

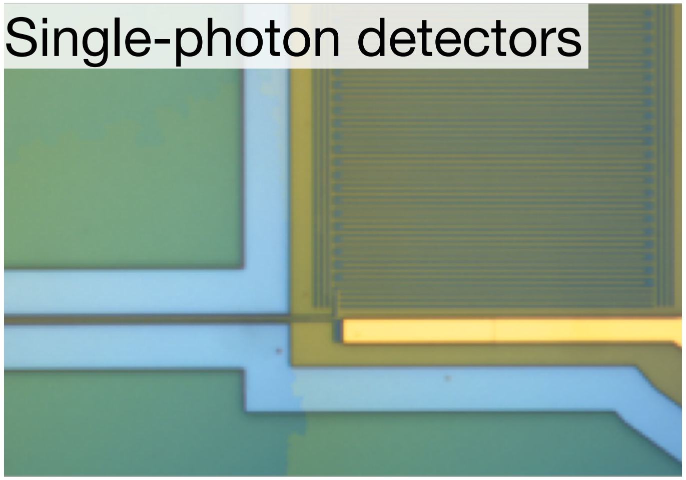
Adam McCaughan

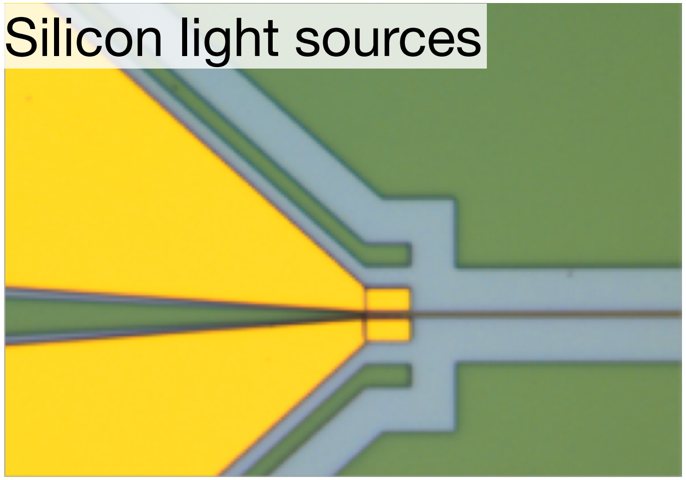
A. McCaughan et al. "A compact, ultrahigh impedance superconducting thermal switch for interfacing superconductors with semiconductors and optoelectronics," Submission pending government reopen. 2019

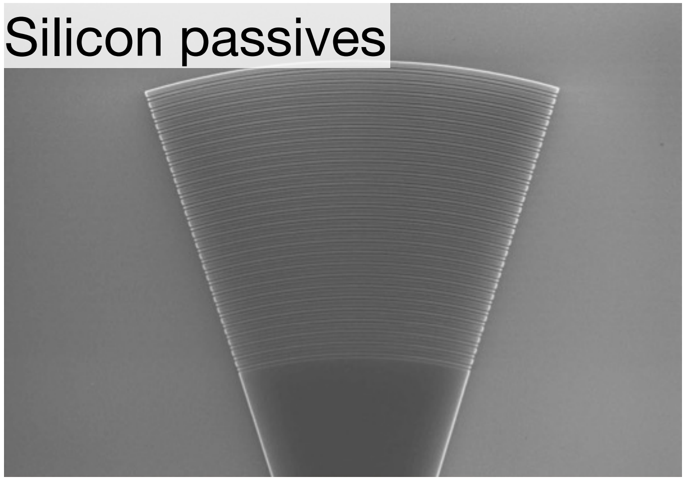


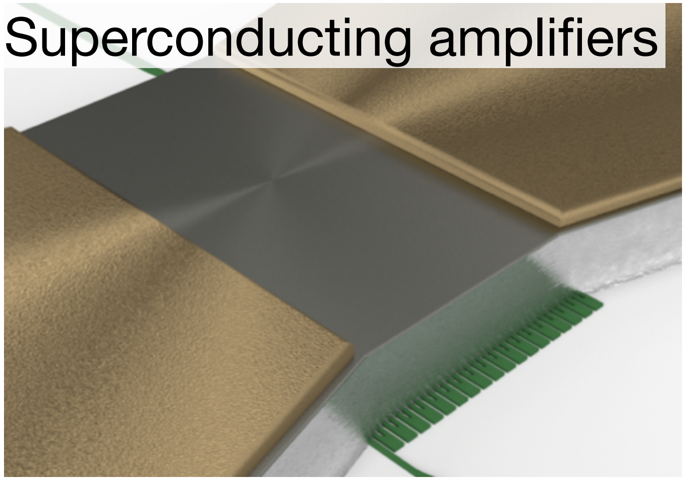
The SOEN platform

Superconducting OptoElectronic Networks





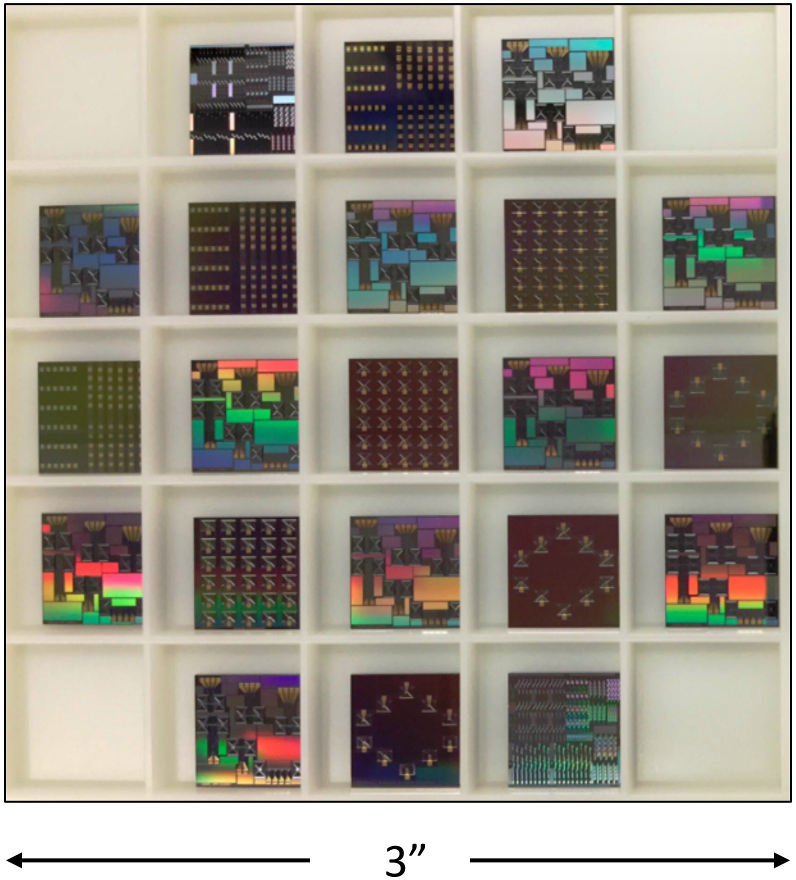




NIST is opening this process to the public

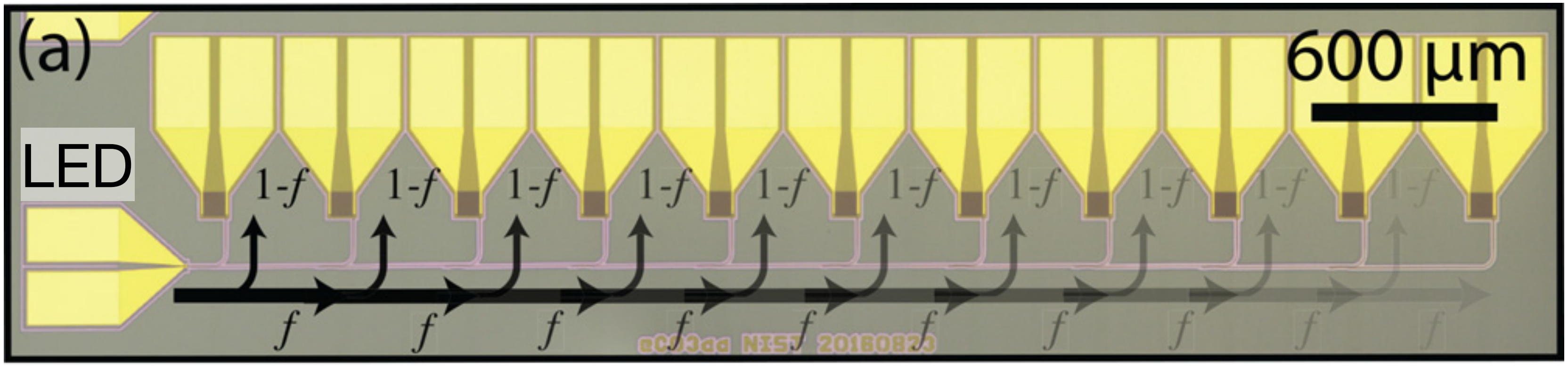
MULTI-PROJECT WAFER FORMAT

- Fabricated in NIST cleanroom
  - 3″ wafers, 1x1 cm die
  - 220nm SOI device layer
- Process design kit
  - Open-access, open-source
  - Online (pending govt. reopen)
- Preferred design tools
  - KLayout (free software)
  - phidl (open-source)

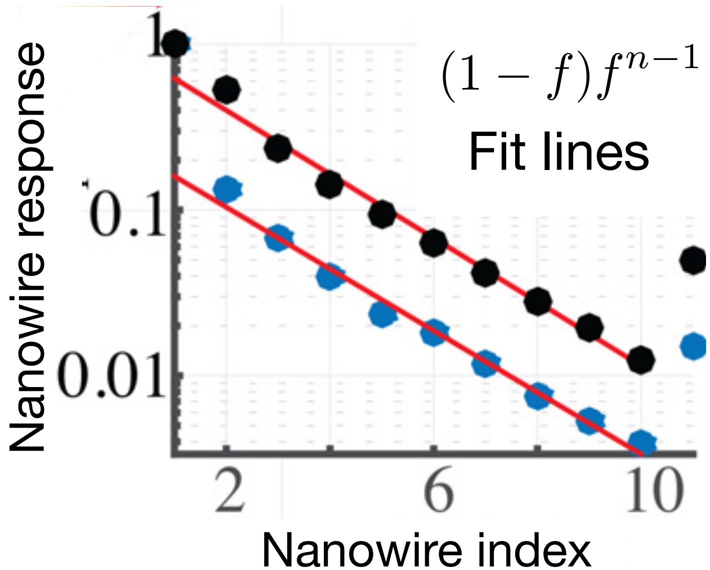


www.klayout.de
github.com/amccaugh/phidl

MORE COMPLEX SYSTEMS

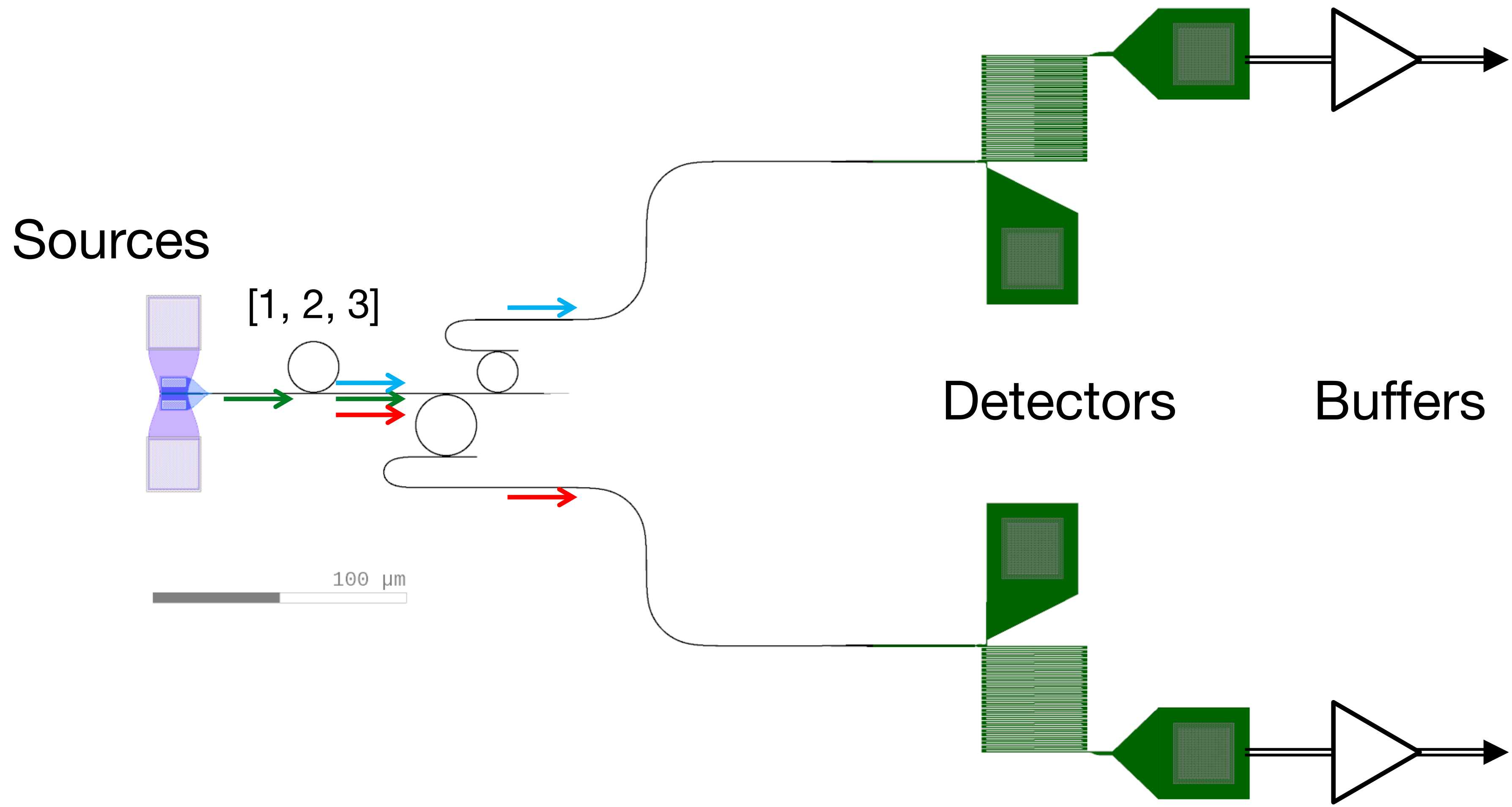


- Complex systems are enabled by
  - High yield
  - Electrical-in/Electrical-out
- High Dynamic Range Detector Array [1]
  - Consistent splitting and efficiency
  - No discrete optics or fibers



S. M. Buckley et al. "All-silicon light-emitting diodes waveguide-integrated with superconducting single- photon detectors " Applied Physics Letters, 111 (14). 2017.

EXAMPLE: PHOTON PAIR GENERATION

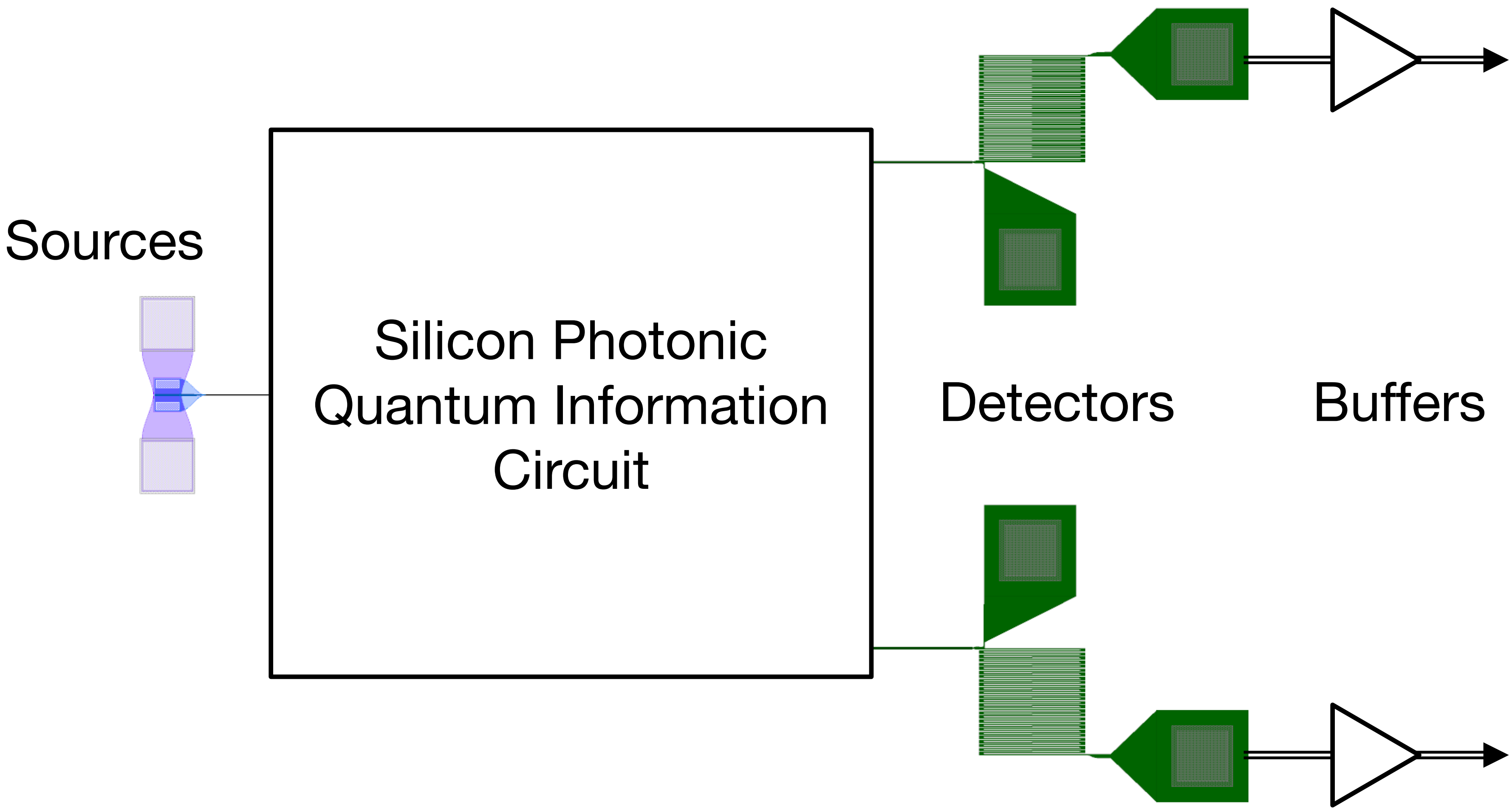


[1] Cale M. Gentry et al. "Quantum-correlated photon pairs generated in a commercial 45nm complementary metal-oxide semiconductor microelectronic chip," Optica, vol. 2, pp. 1065–1071, 2015.

[2] Marc Savanier, Ranjeet Kumar, and Shayan Mookherjea, "Photon pair generation from compact silicon microring resonators using microwatt-level pump powers," Op. Ex, vol. 24, pp. 3313–3328, 2016.

[3] Xiyuan Lu et al., "Chip-integrated visible-telecom photon pair sources for quantum communication," arXiv: 1805.04011, 2018.

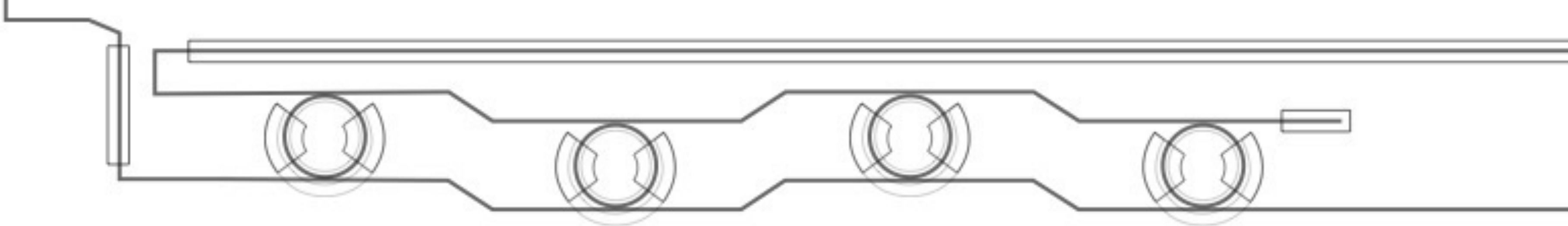
WHAT CAN YOU COME UP WITH?



WE ARE LOOKING FOR COLLABORATORS

- With expertise in integrated photonic device measurement
  - Cryogenic temperatures
  - High speed
- Have new ideas for applications in
  - Quantum information science
  - Measurement science
  - Neuromorphic Photonics
- Willing to design characterization structures and report findings
  - Detectors
  - Sources (esp. single photon)
  - Passives

Contact
jeffrey.shainline@nist.gov
alexander.tait@nist.gov
saewoo.nam@nist.gov
rich.mirin@nist.gov

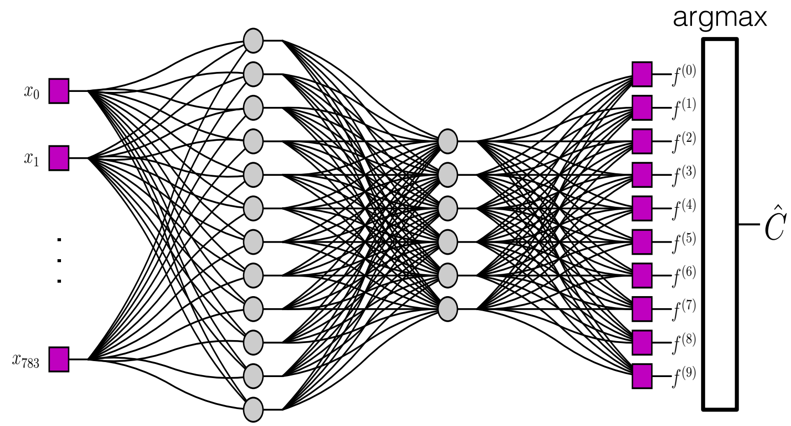


Neuromorphic Photonics

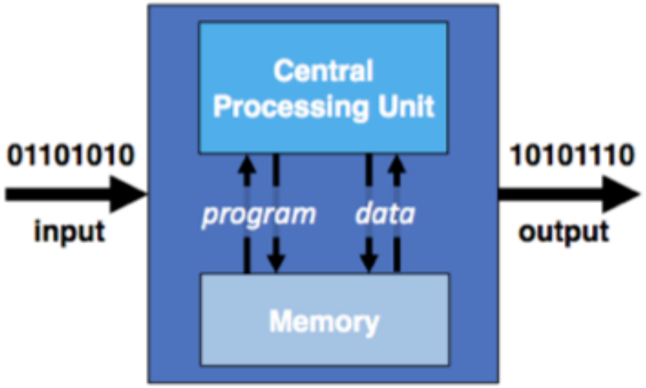
NEURAL NETWORKS IN COMPUTING

- Today, there is large demand to perform neural network operations
- Conventional computers are inefficient at doing these operations

Neural network: distributed

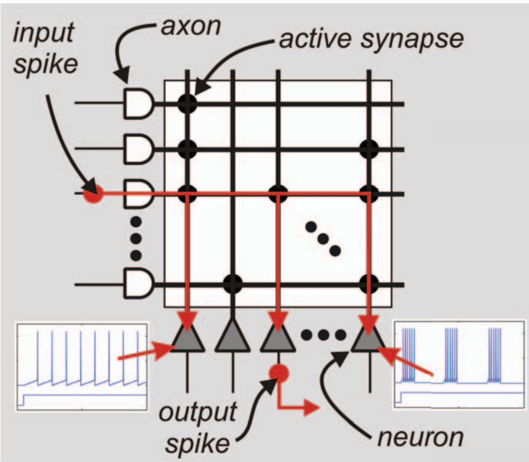


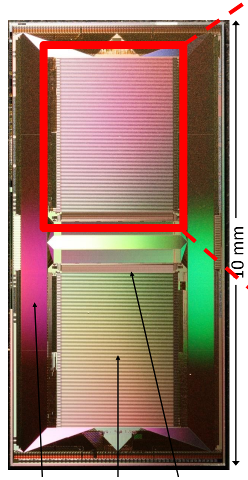
Conventional computer: centralized

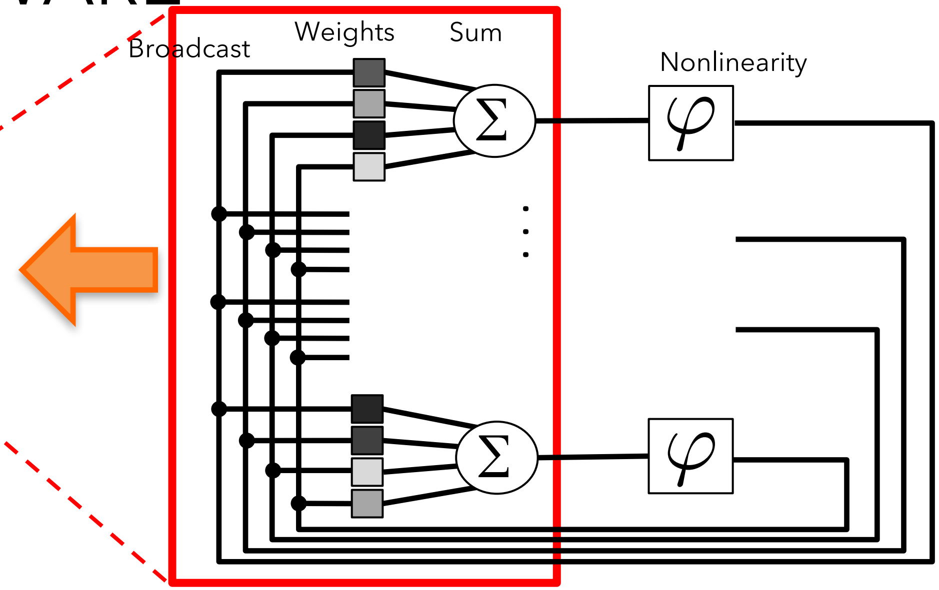


NEUROMORPHIC HARDWARE

Based on synaptic cross-bars





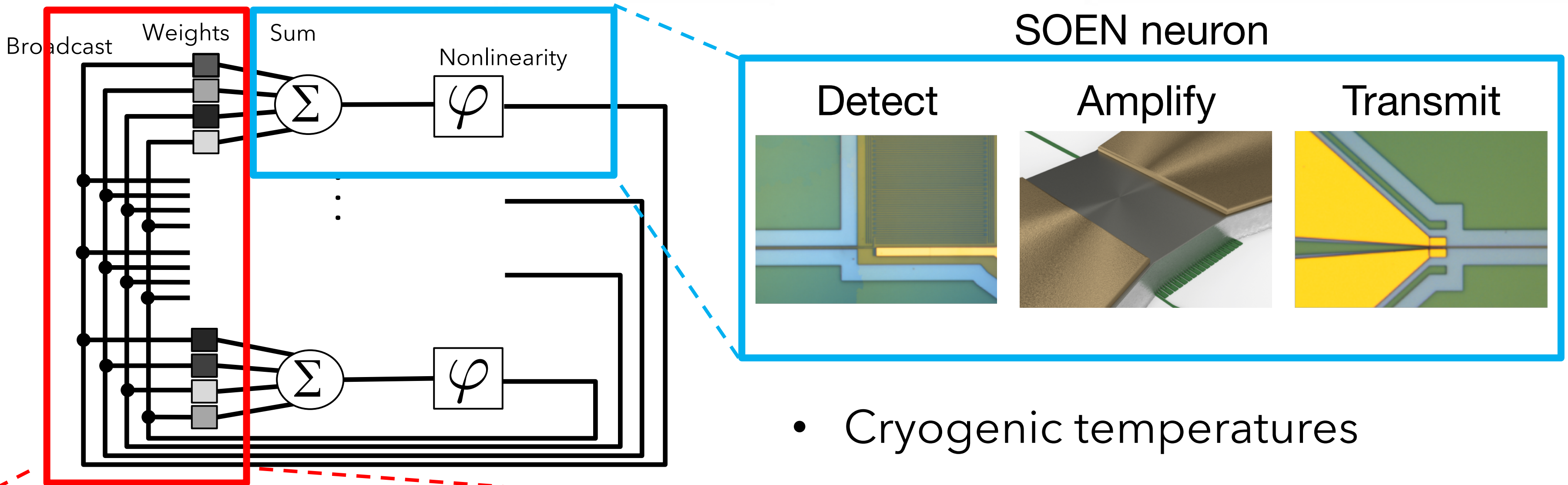


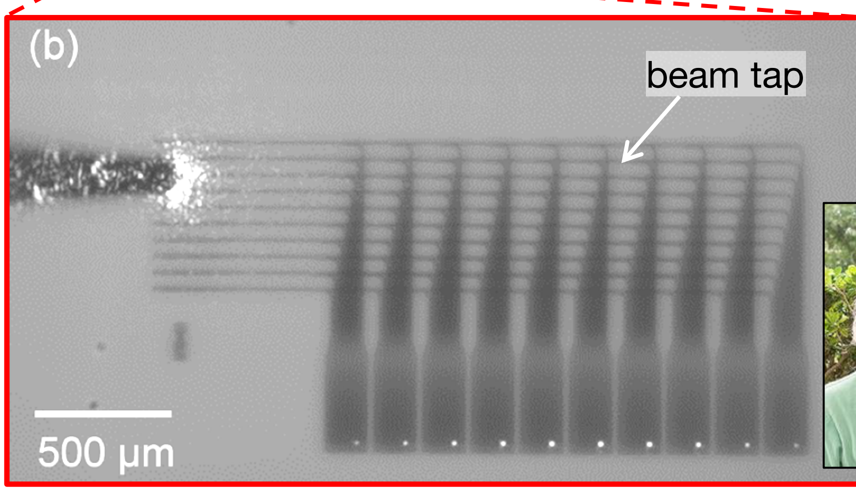
- Specialized distributed hardware
- Does neural network operations
- High communication cost
  - Energy
  - Time

Robotics, supercomputing

[1] F. Akopyan et al, "TrueNorth: Design and tool flow of a 65 mW 1 million neuron programmable neurosynaptic chip," 2015.
[2] S. B. Furber et al. "The SpiNNaker project," May 2014.

SUPERCONDUCTING OPTOELECTRONIC NETWORKS





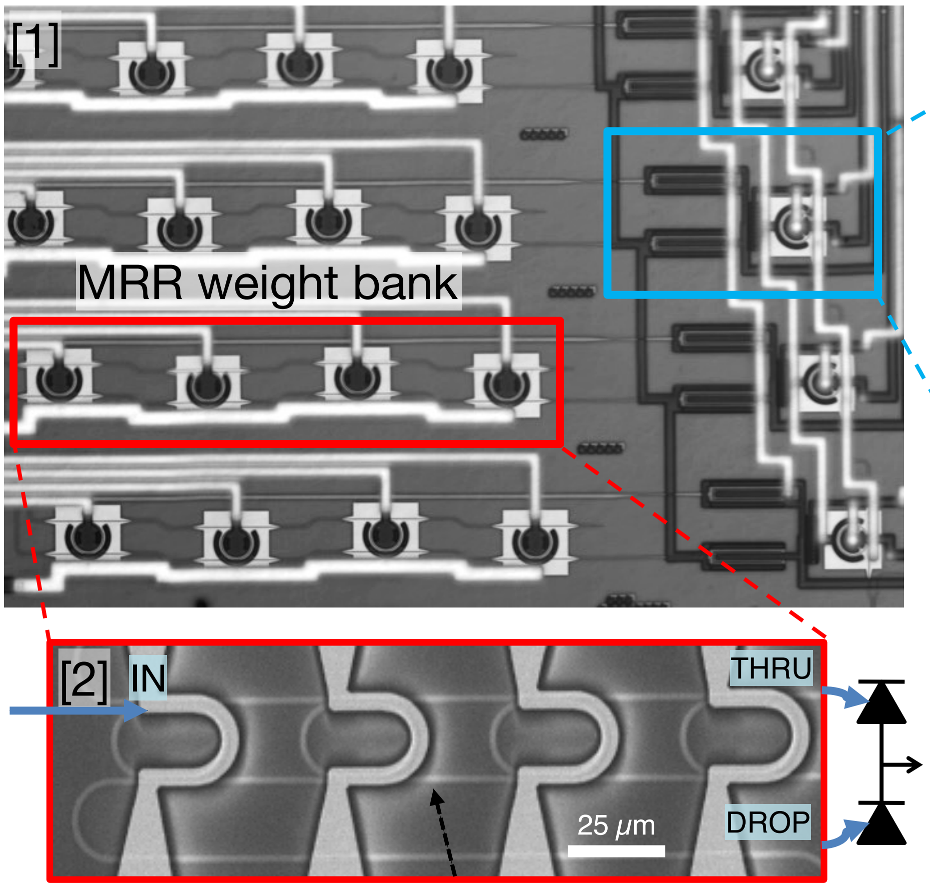
- Cryogenic temperatures
- Extremely low power dissipation
- Goal: Maximum scalability

Jeff Chiles

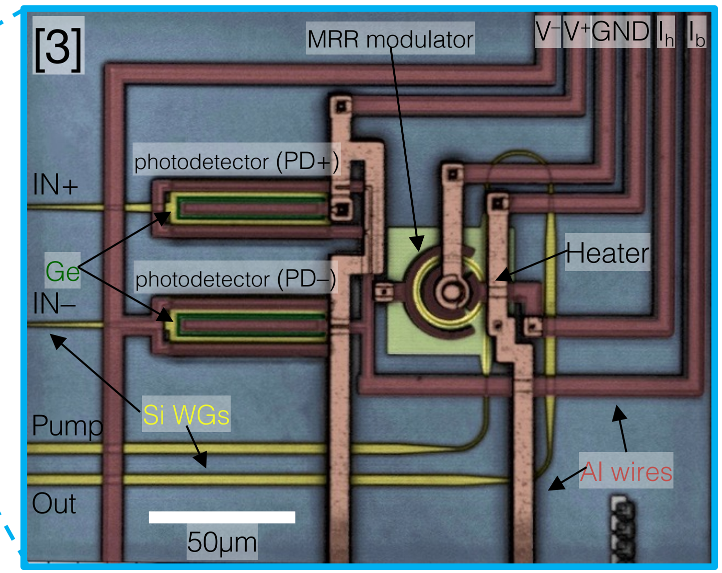
J. M. Shainline et al., “Superconducting optoelectronic circuits for neuromorphic computing,” Phys. Rev. Applied, vol. 7, p. 034013, Mar 2017.
J. Chiles et al., “Design, fabrication, and metrology of 10x100 multi-planar integrated photonic routing manifolds for neural networks,” APL Photonics, vol. 3, p. 106101, 2018/08/08 2018.

SILICON PHOTONIC NEURAL NETWORKS

weight matrix neurons



Silicon photonic neuron



- Electro-optic nonlinearity
- 10 – 40 GHz operation
- Foundry compatible

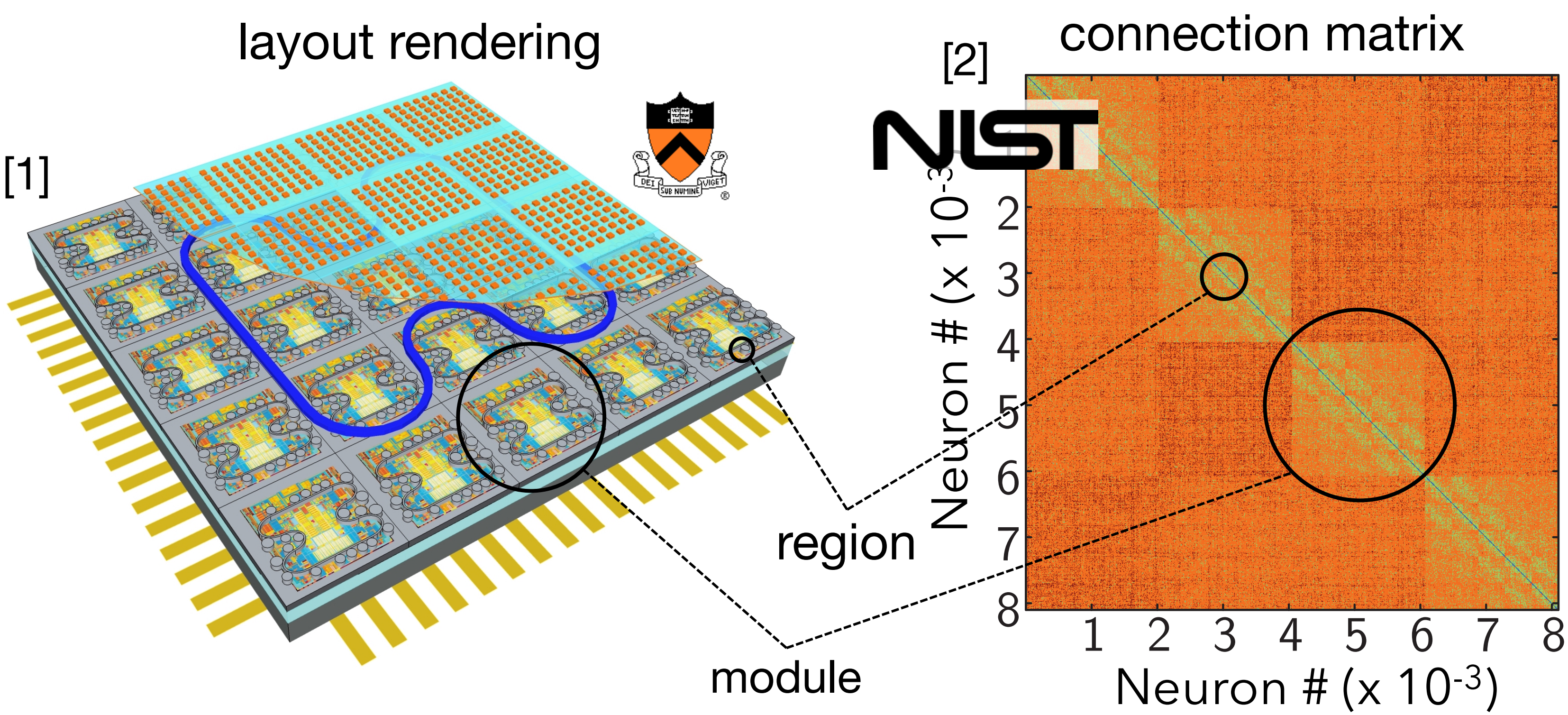
[1] A. Tait, M. A. Nahmias, B. J. Shastri, and P. R. Prucnal, "Broadcast and Weight: an Integrated Network for Scalable Photonic Spike Processing," J. Lightwave Technol., 32(21), 2014.

[2] A. Tait, T. Ferreira de Lima, E. Zhou, A. X. Wu, M. A. Nahmias, B. J. Shastri, and P. R. Prucnal, "Neuromorphic Photonic Networks Using Silicon Photonic Weight Banks." Scientific Reports, 7(1). 2017.

[3] A. Tait, T. Ferreira de Lima, M. A. Nahmias, H. B. Miller, H.-T. Peng, B. J. Shastri, and P. R. Prucnal "A silicon photonic modulator neuron." arXiv preprint:1812.11898. Dec. 2018.

NEXT STEPS: HIERARCHICAL NETWORKS

- Large neural networks are hierarchical
- Photonics does well with long-range communication
- How do we design chip-scale systems? wafer scale? datacenter scale?



[1] Paul Prucnal and Bhavin Shastri. **Neuromorphic Photonics**. CRC Press, 2017.
[2] J. M. Shainline et al. "Superconducting Optoelectronic Neurons V: Networks and Scaling," arXiv:1805:01942, 2018.

LARGE-SCALE SILICON PHOTONIC SYSTEMS

Challenges to quantum and neuromorphic computing are shared

- Basic component quality
- Large-volume manufacturability
- Small-volume research prototyping

LARGE-SCALE SILICON PHOTONIC SYSTEMS

Challenges to quantum and neuromorphic computing are shared

- Basic component quality
- Large-volume manufacturability
- Small-volume research prototyping

$\Bigg\}$ Externalized technological risk (thanks to Datacomm.)

[1] The Cattington Post

LARGE-SCALE SILICON PHOTONIC SYSTEMS

Challenges to quantum and neuromorphic computing are shared

- Basic component quality
- Large-volume manufacturability
- Small-volume research prototyping

Externalized technological risks (thanks to Datacomm.)

- I/O, packaging
- System-level design tools
- Process variation

Semi-externalized

- Control complexity
- Heat dissipation density

Specific to large-scale systems

SUMMARY

- Quantum and Neuromorphic share platform technologies
- Co-integrated passives, sources, amplifiers, SPDs
- This platform will become available to the public
- NIST trying to advance single photon devices, metrology, and applications

NIST TEAM

- Sae Woo Nam
- Rich Mirin
- Jeff Shainline
- Sonia Buckley
- Adam McCaughan
- Jeff Chiles
- Alex Tait
- Saeed Khan
- Krister Shalm
- Marty Stevens
- Adriana Lita
- Varun Verma
- Nima Nader
- Mike Mazurek
- Dileep Reddy
- Eric Stanton
- Galen Moody
- Kevin Silverman
- Thomas Gerrits

Postdoctoral opportunities

Contact
saewoo.nam@nist.gov
rich.mirin@nist.gov
jeffrey.shainline@nist.gov
alexander.tait@nist.gov

atait@ieee.org

Boulder Labs