Desktop superconducting photon detectors and … computers?

Quantum Opus, LLC

Aaron J. Miller, PhD

Founder, President

Quantum Opus

Outline

- Superconducting photon detection
  - Ideal photon detectors
  - Superconducting Transition-Edge Sensors
  - Superconducting Nanowire Detectors
- Quantum Opus commercial nanowire detectors
  - Laboratory system
  - Desktop system
- New applications of a cool technology
  - Optical Communication
  - Cryogenic Computing
  - Quantum Sensing

Motivation for Single-Photon Detection

- Fundamental quantum information science
- Quantum key distribution
- Random number generation
- LiDAR – from 10 cm to 1 cm, range from 1 km to 10s km
- Single-molecule fluorescence
- Oxygen singlet detection for drug delivery studies
- Non-invasive “x-rays”
- Ultra-low-power telecommunication (Mars-link, battlefield)

The ideal detector

Eisaman, Fan, Migdall, Polyakov (2011)*:

We consider an ideal single-photon detector to be one for which: the **detection efficiency** (the probability that a photon incident upon the detector is successfully detected) is **100%**, the **dark-count rate** (rate of detector output pulses in the absence of any incident photons) is **zero**, the **dead time** (time after a photon-detection event during which the detector is incapable of detecting a photon) is **zero**, and the timing **jitter** (variation from event to event in the delay between the input of the optical signal and the output of the electrical signal) is **zero**.

Ideal Specs.

DE = 100%

DCR = 0 cts/s

Dead-time = 0 s

Jitter = 0 s

* REVIEW OF SCIENTIFIC INSTRUMENTS 82, 071101 (2011)

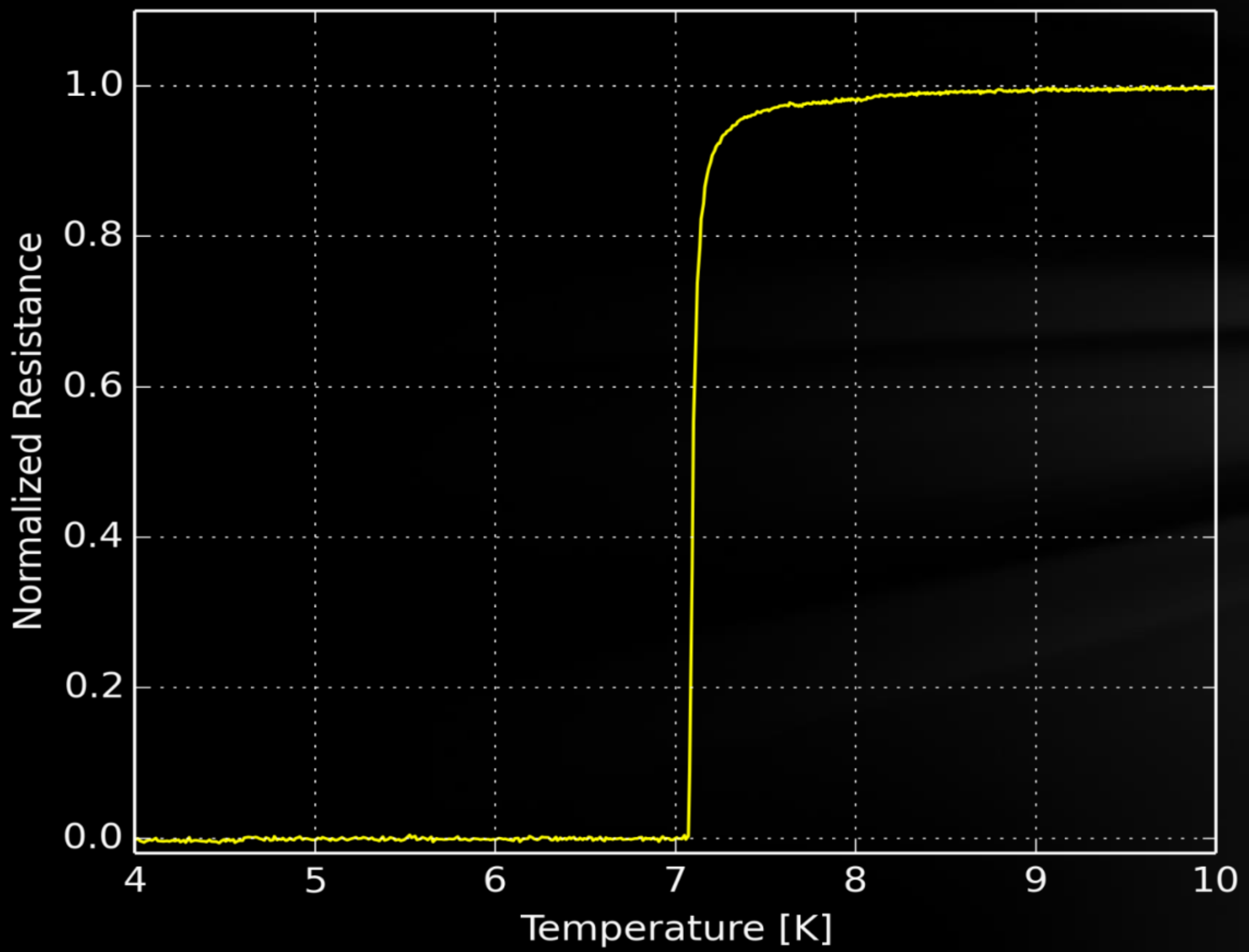
Motivation for superconducting detectors

- Fundamental excitation energy meV instead of eV
- Simple device design—usually cleaner response
- Low operating temperature helps thermal noise limits
- Performance benefits outweigh cryogenic costs
- Relatively new technology—innovations are frequent

Two main “winning” photon counting technologies:

TES, SNSPD

Superconductivity

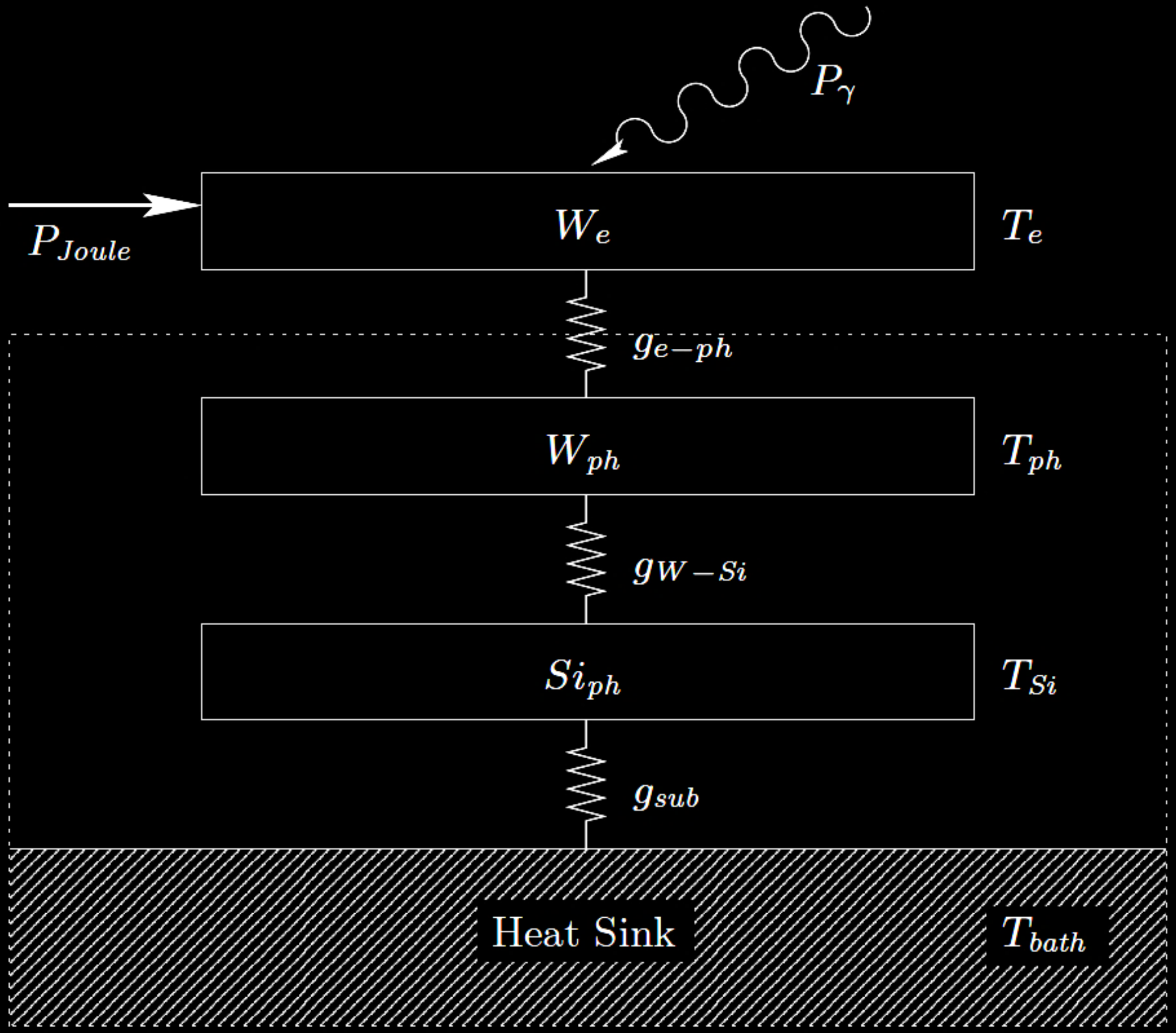


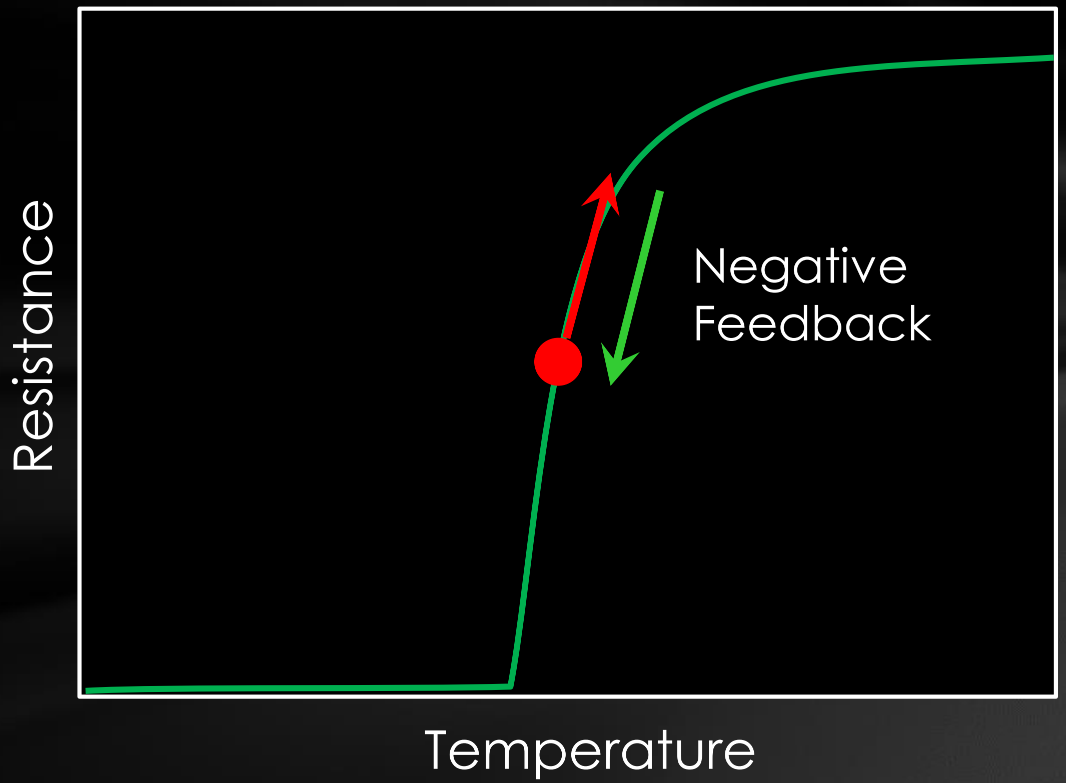
Useful features of superconductors

- True zero dc resistance
- Sharp transition via *I*, *H*, *T*
- Large resistance change
- (Relatively) simple electro-thermal system with rapid thermalization
- Extremely low noise

TES vs Nanowire…

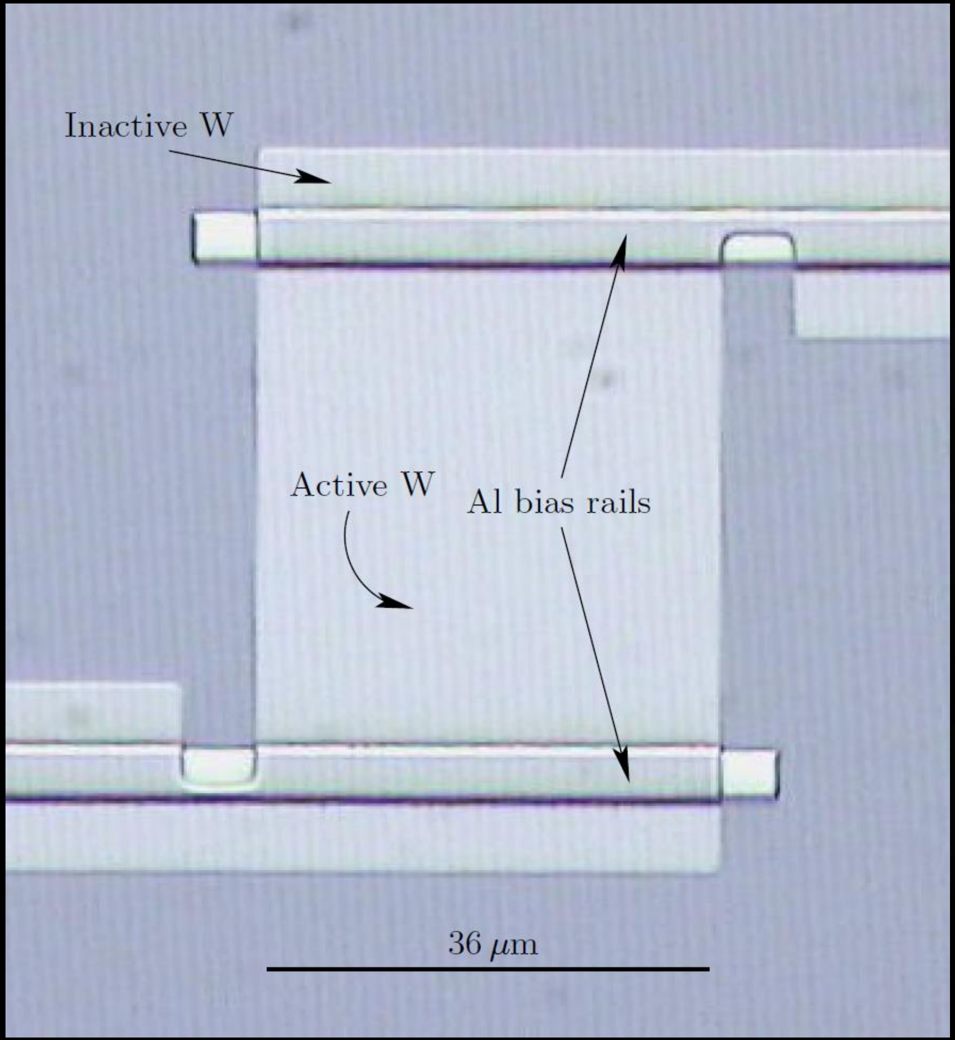
Transition-edge sensor (TES) electrothermal system

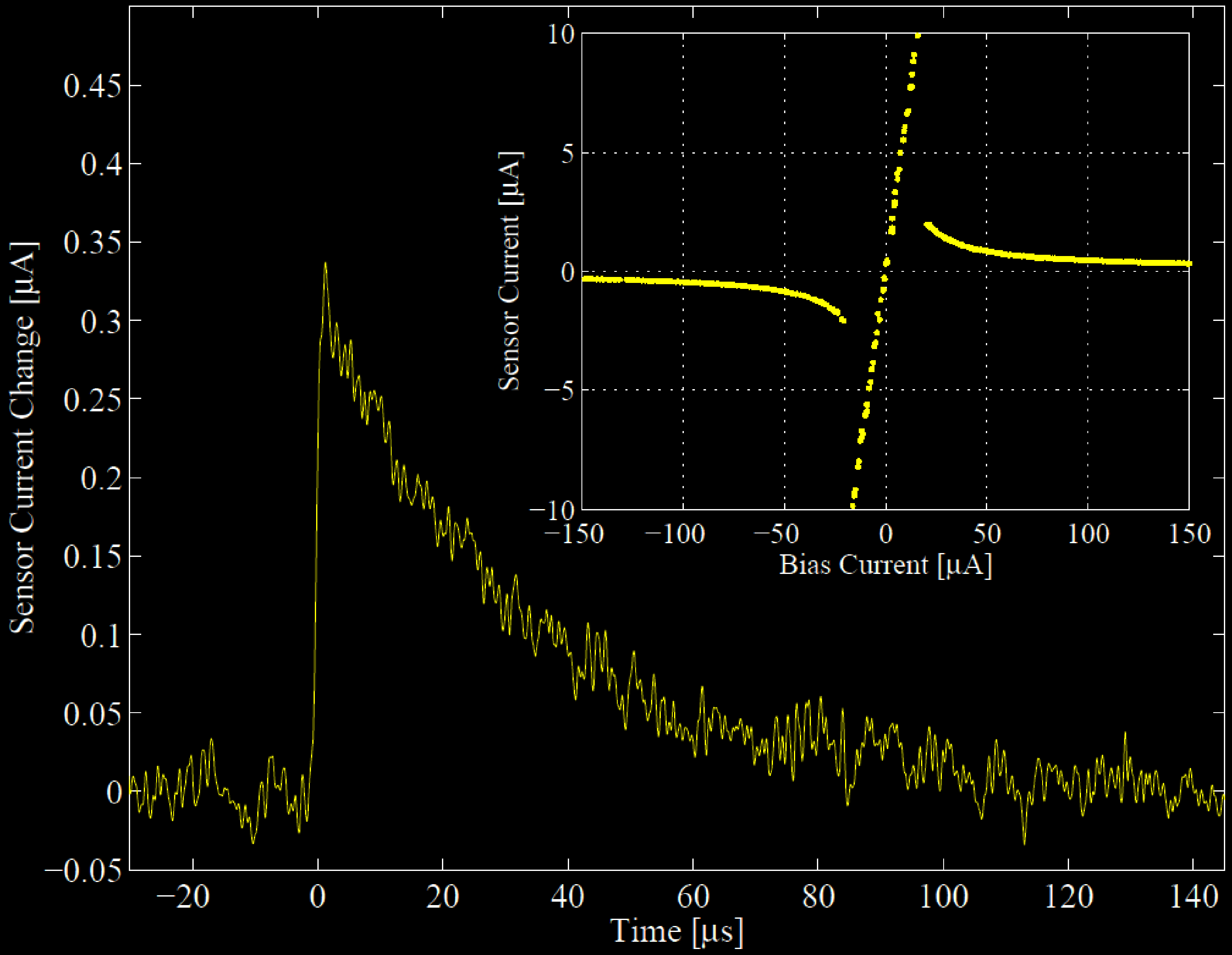




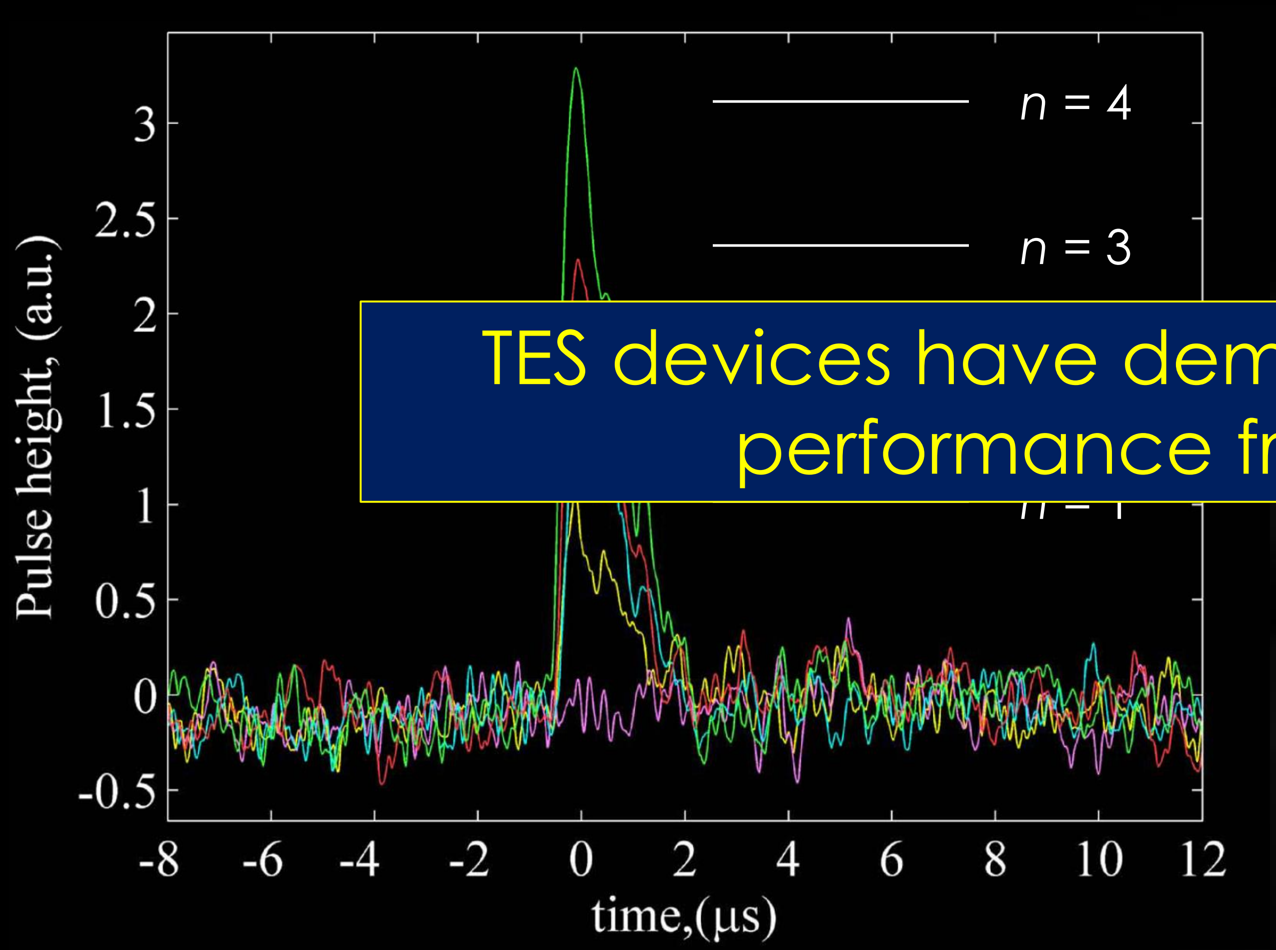
Voltage biased—
as T increases, V^2/R heating decreases…
→ Negative Electro-Thermal Feedback

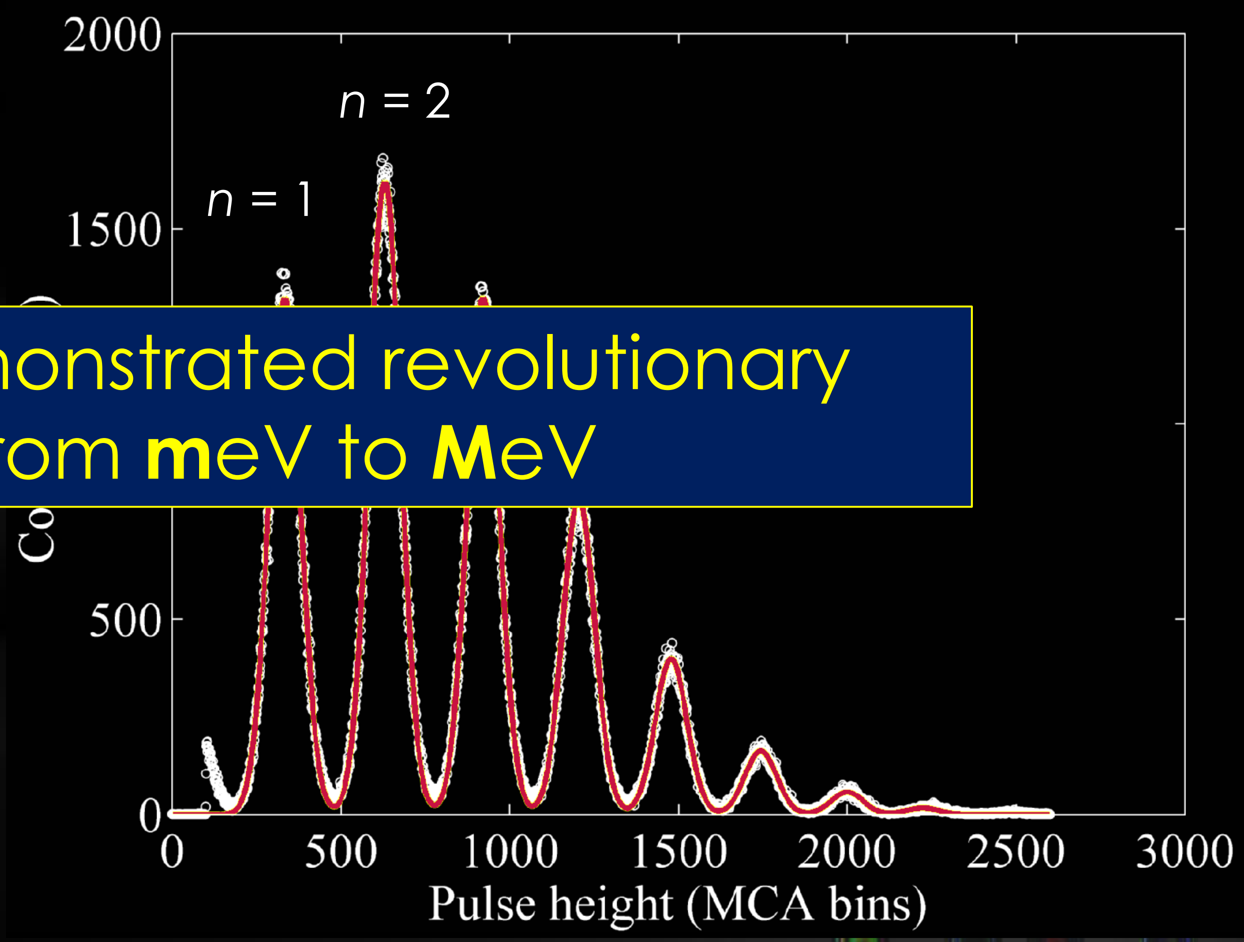
Detecting photons with a W-TES





Photon number resolution of TES devices

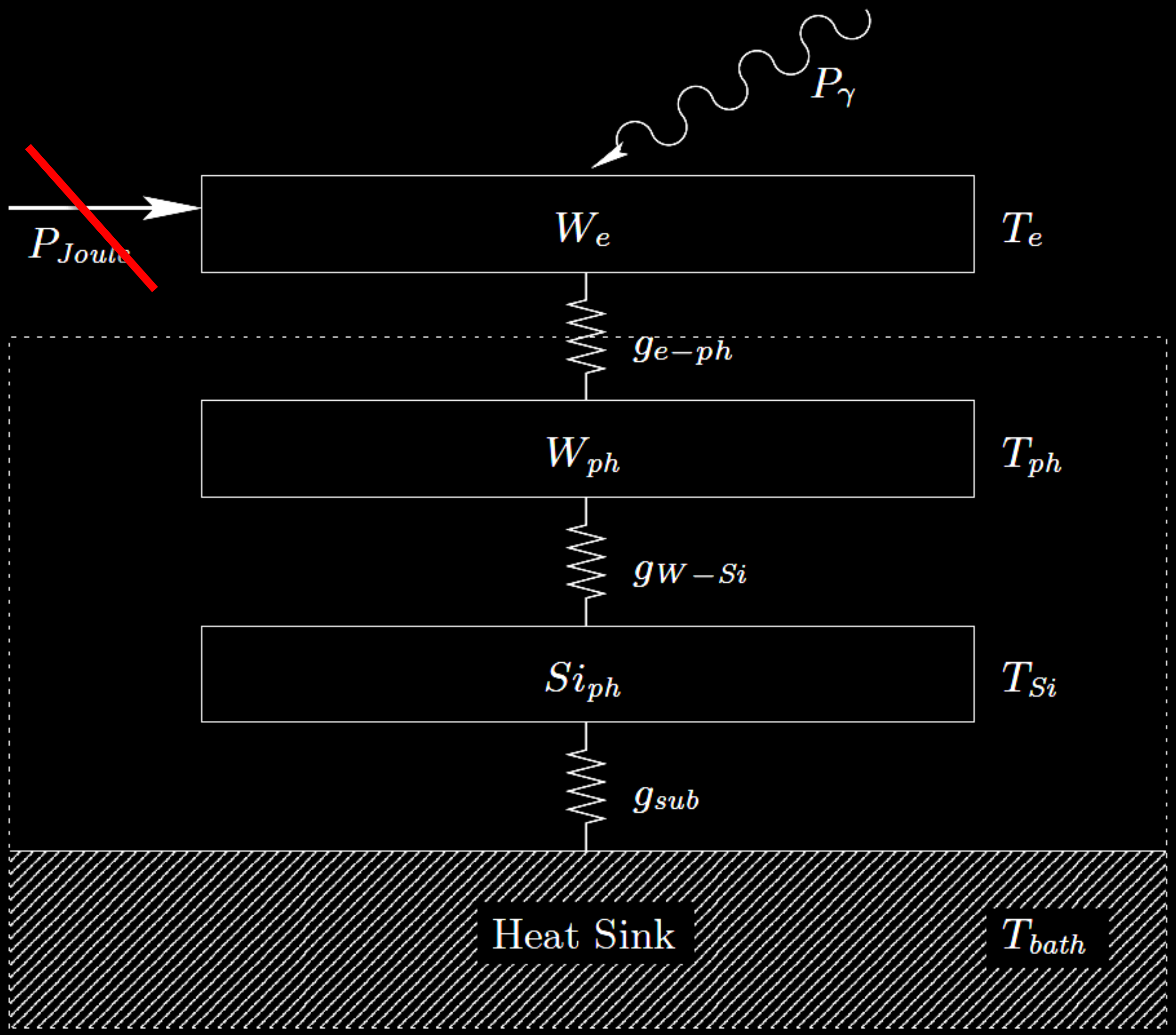


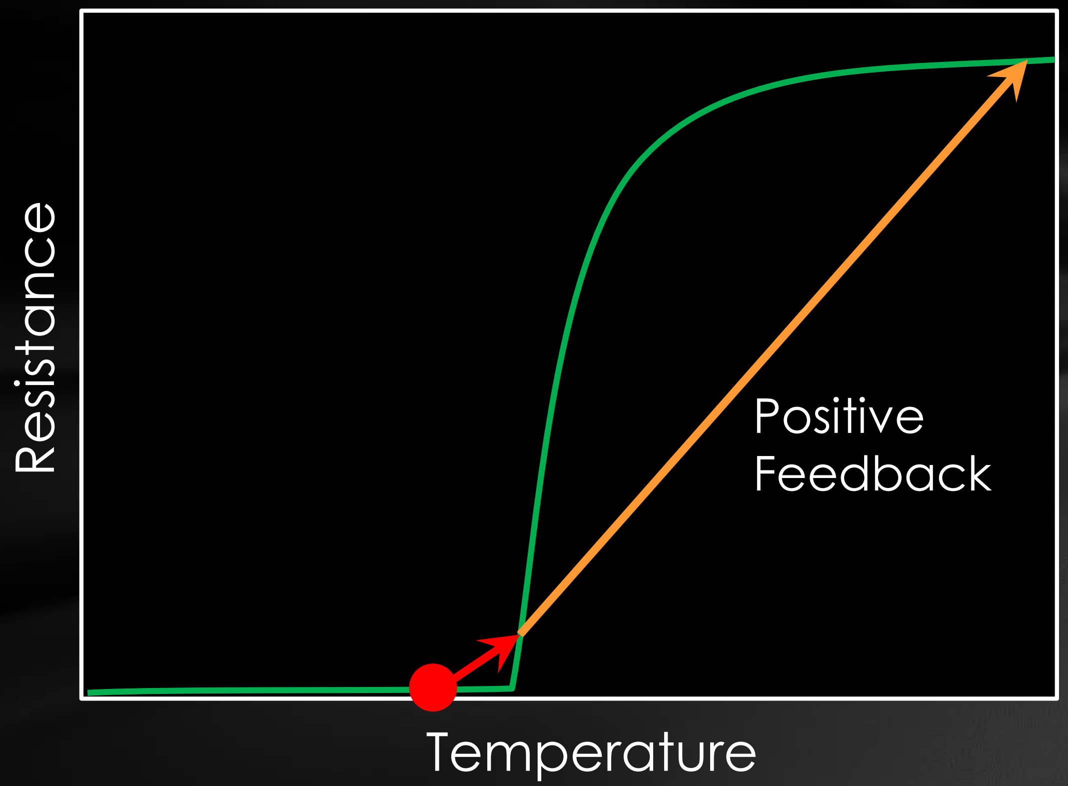


TES devices have demonstrated revolutionary performance from **m**eV to **M**eV

Lita, Miller, Nam, OPTICS EXPRESS, 3 March 2008 v16(5) 3032

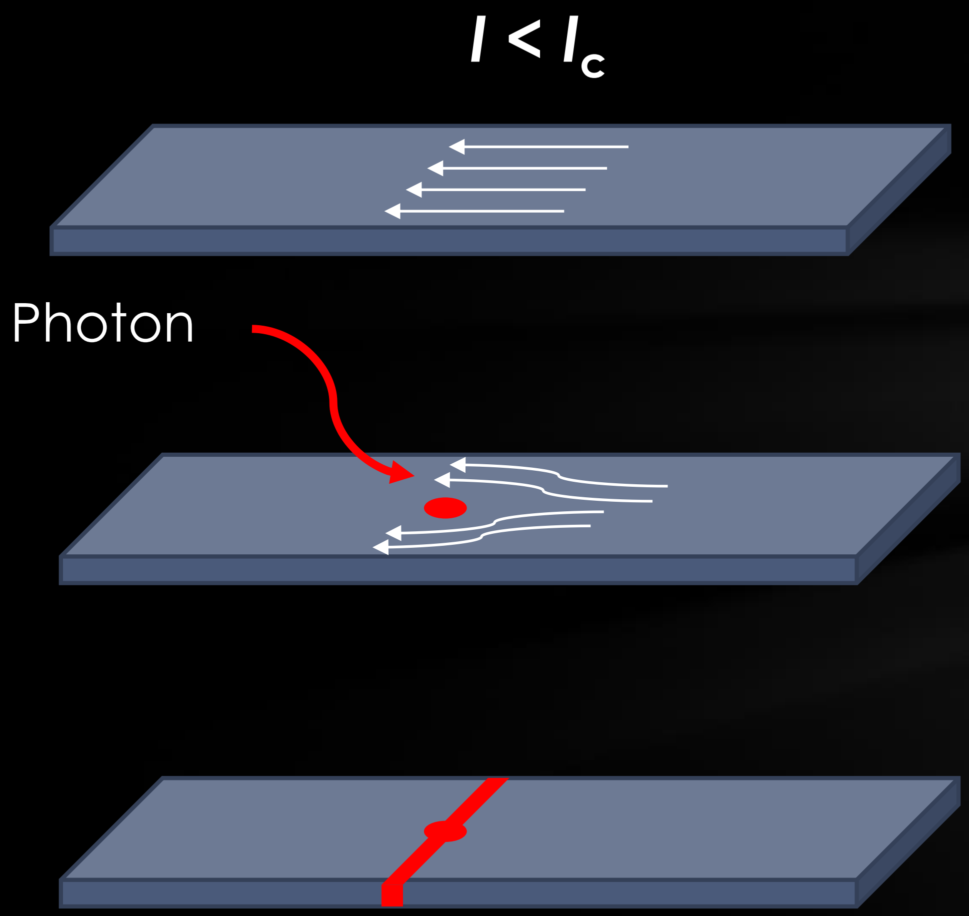
Nanowire (SNSPD) electrothermal system





Current biased—
if T increases, I^2R heating increases…
→ Positive Electro-Thermal Feedback

Convenient Conceptual Principle of Operation



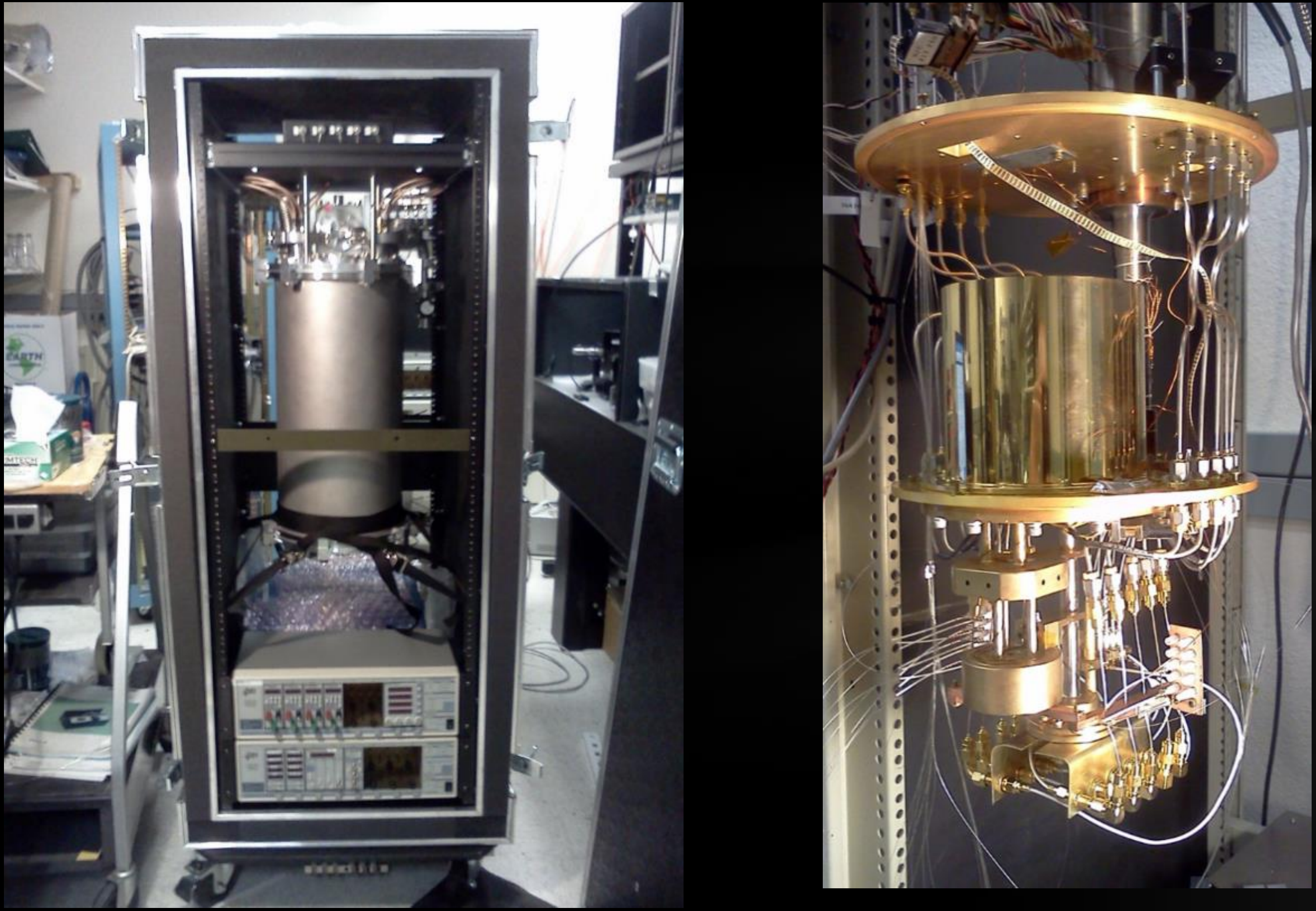
R = small, $V = 0$

R = small, $V = 0$

R = big, $V > 0$

Demonstrated Performance

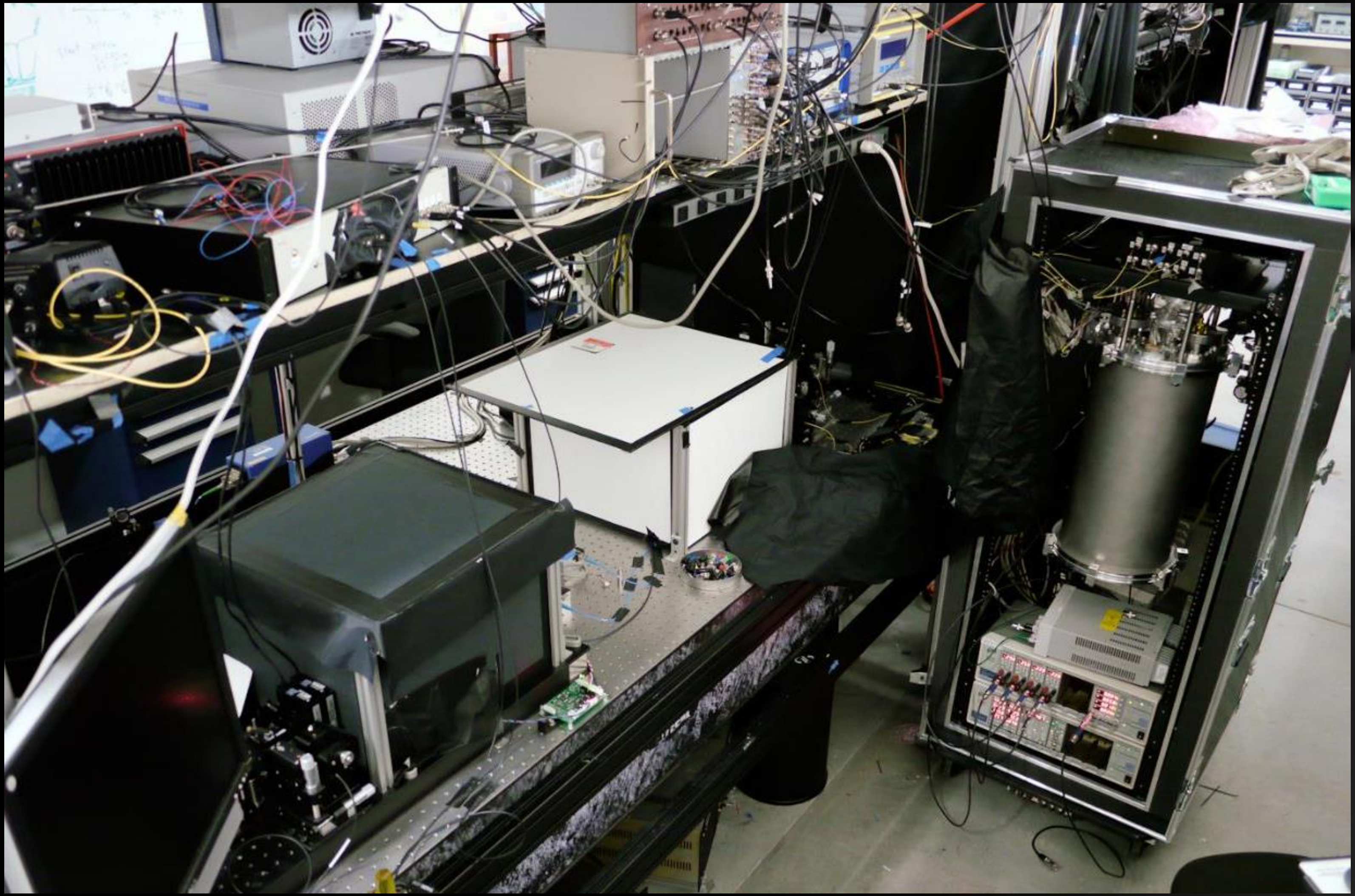
QO founder assisted in the construction and demonstration of NIST 8-channel high-efficiency nanowire system – first in the world.



First 8-channel >1520nm system with SDE >80% on all channels

Demonstrated Performance

NIST 8-channel system demonstrated on-site at the Institute for Quantum Computing (U. Waterloo)



Revolutionary Performance

Without nanowire devices

- Goal of cascaded spontaneous parametric down conversion to generate entangled "triplets" of photons.
- Waterloo group previously demonstrated a generation rate of 7 triplets per hour using InGaAs/InP SPDs (10-25% DE, DCR 10^2-10^4 cts/sec)[1]

With nanowire devices

- Detection efficiencies between 80% and 90% on all channels
- Triplet rate increased to ~600 triplets per hour an 87x increase
- Measurement performed in one week that would have taken almost two years.
- Published 2014 in Nature Photonics[2]

[1] L. K. Shalm, et al., Three-photon energy-time entanglement. *Nature Physics* **9**, 19-22 (2013).

[2] D. R. Hamel, et al., Direct generation of three-photon polarization entanglement, *Nature Photonics* **8**, 801–807 (2014)

Challenges with the NIST system

- Bulky
- Expensive
- Fragile
- Sorption-cooled ^{3}He/^{4}He unit required 2 hrs. of downtime every recharge (8 hrs.)
- Not commercially available

Commercial goals for SNSPDs

- Broadband – Visible, NIR (esp. telecom bands)
- High detection efficiency (> 80% @ 1550 nm)
- Low dark-count rate (intrinsic < 100 cts/sec, ungated)
- Low dead time (< 25 ns)
- Low jitter (< 50 ps)
- Ungated operation
- No damage from light overload
- Control and read-out with conventional electronics
- “Invisible” cryogenics

Quantum Opus

Founded in March 2013—three founding members and private equity.

Aaron J. Miller, PhD

- B.A. in Physics/Mathematics, Albion College,1995
- Ph.D. in Physics, Stanford University, 2001
- Postdoc/Staff Scientist NIST 2001-2005
- Asst./Assoc. Professor, Albion College 2005-2015

Holly B. Miller, MBA

- B.A. in Economics and French, Albion College, 1996
- CPA with Coopers and Lybrand, PwC
- Internal and external audit, ethics
- MBA, Finance Concentration, MSU 2015

Josh A. Cassada, PhD

- B.A. in Physics, Albion College,1995
- Ph.D. in Physics, U. Rochester, 2000
- 13 years Navy pilot and instructor
- Worked for ~6 mo. on process dev.
- Selected for Astronaut program June 2013

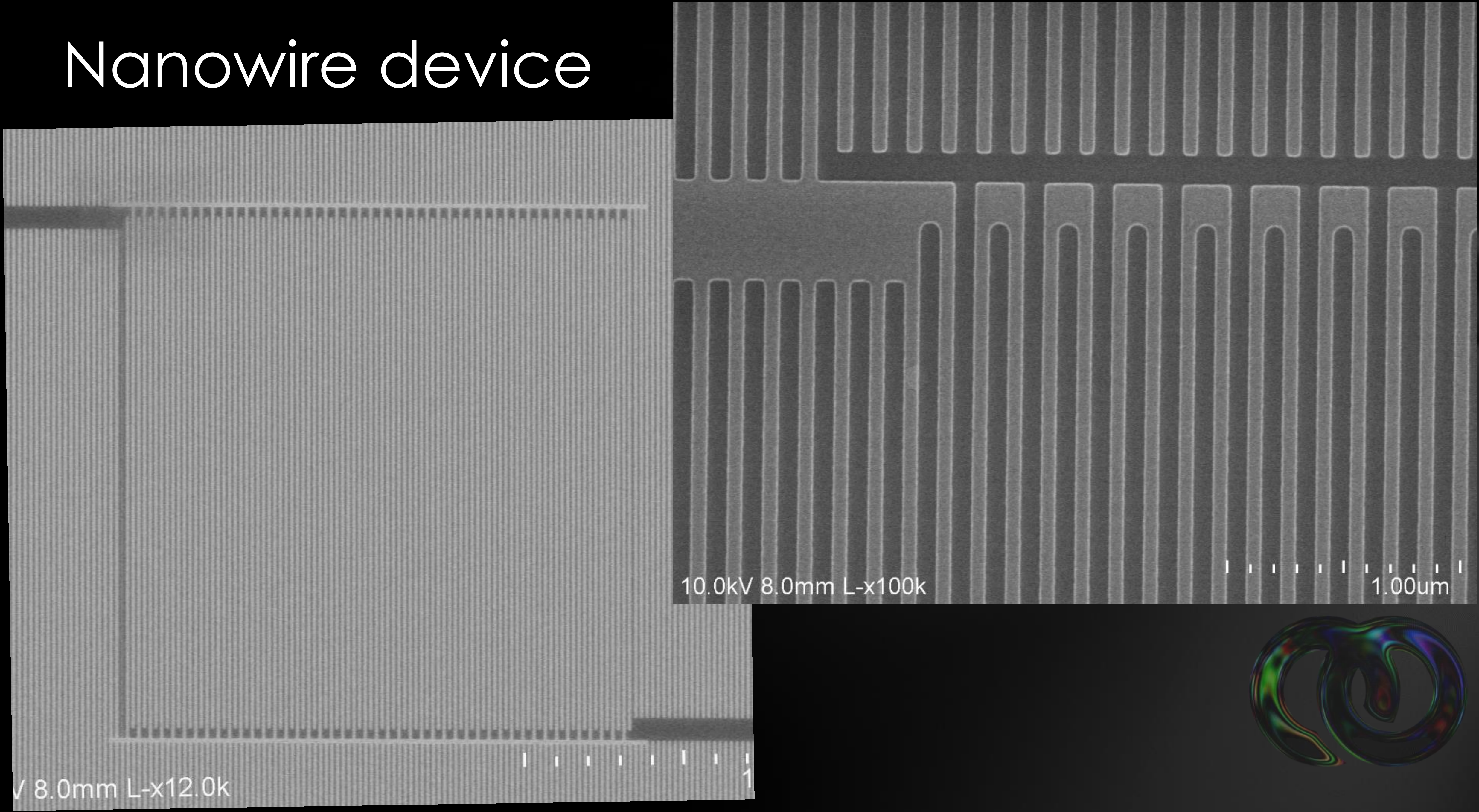
Amy Conover, MS

- Assembly and Measurement Technician
- QA and process control

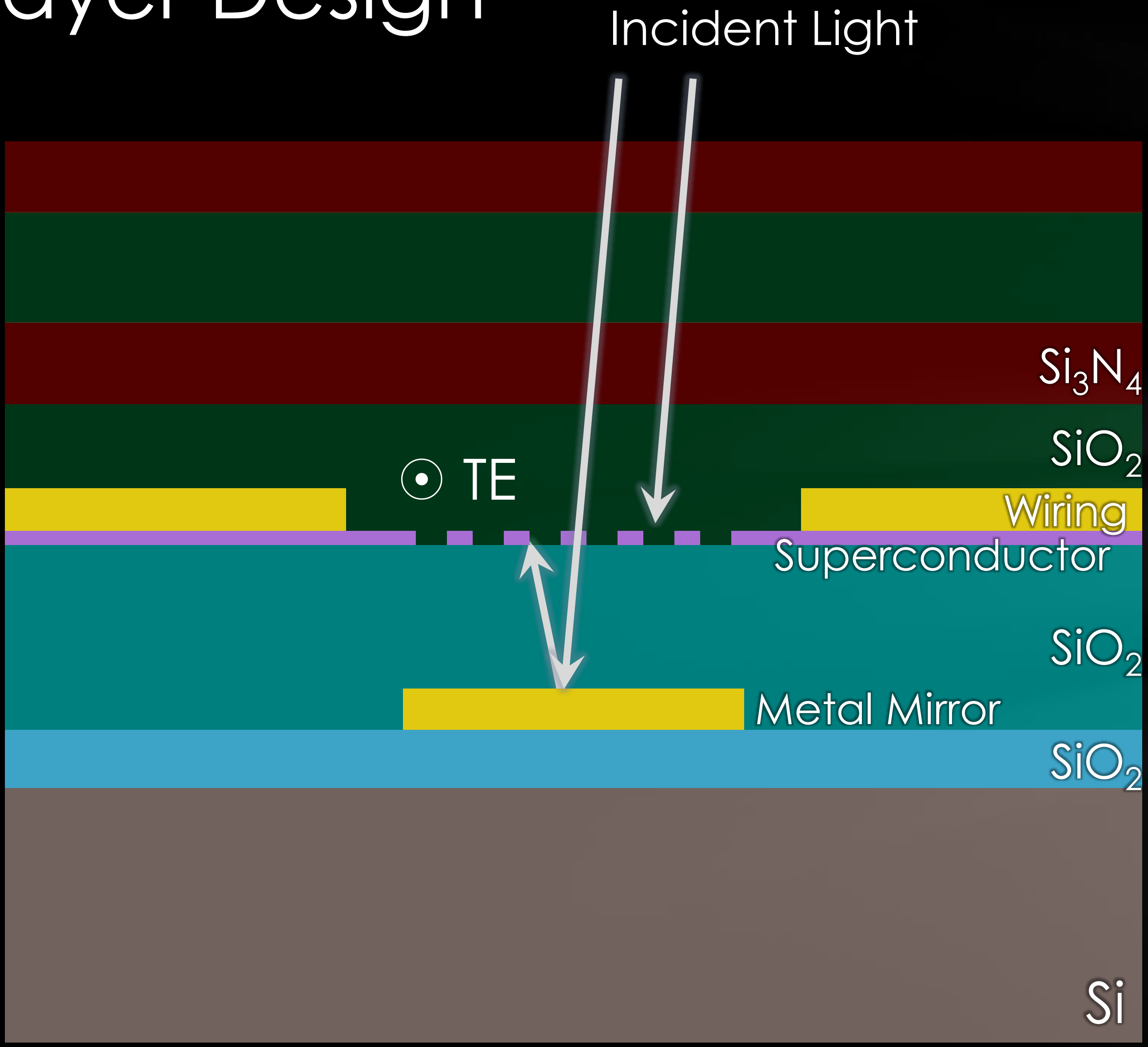
Tim Rambo, PhD

- B.A. in Physics, Comp. Sci, Albion College, 2009
- Ph.D. EECS, Northwestern, 2016

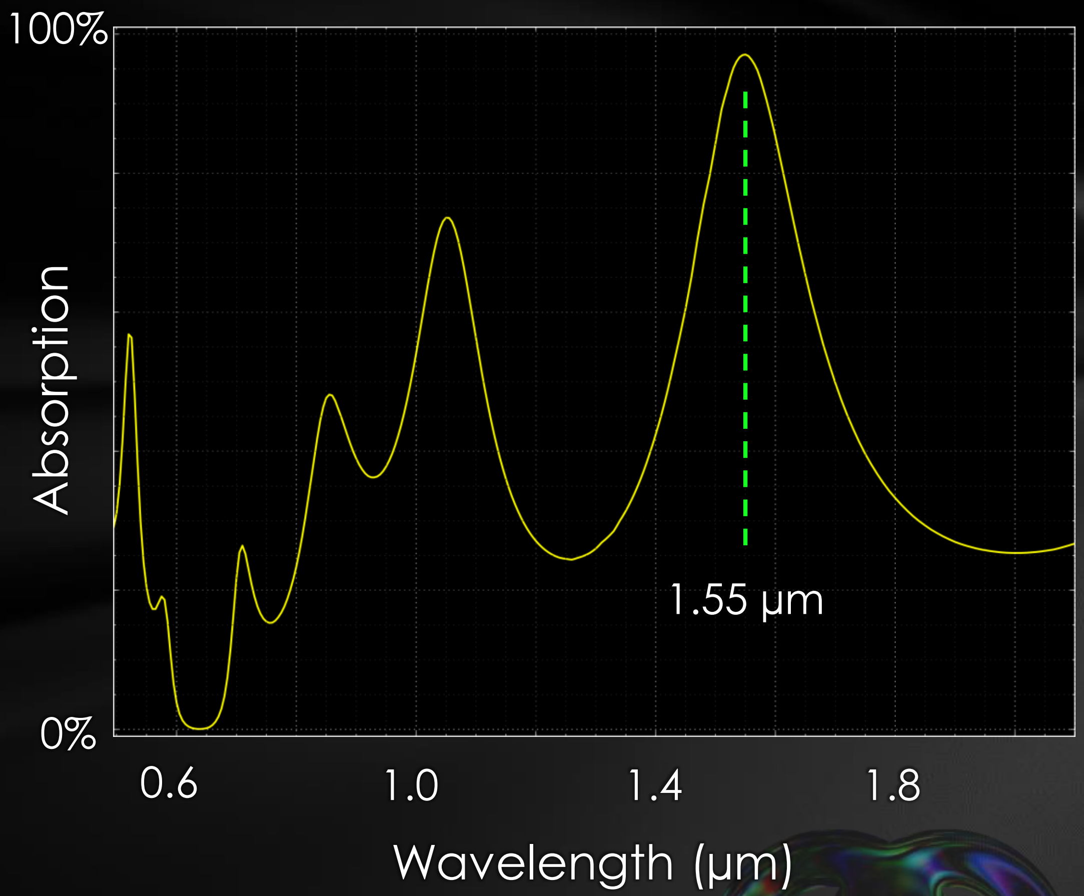
Nanowire device



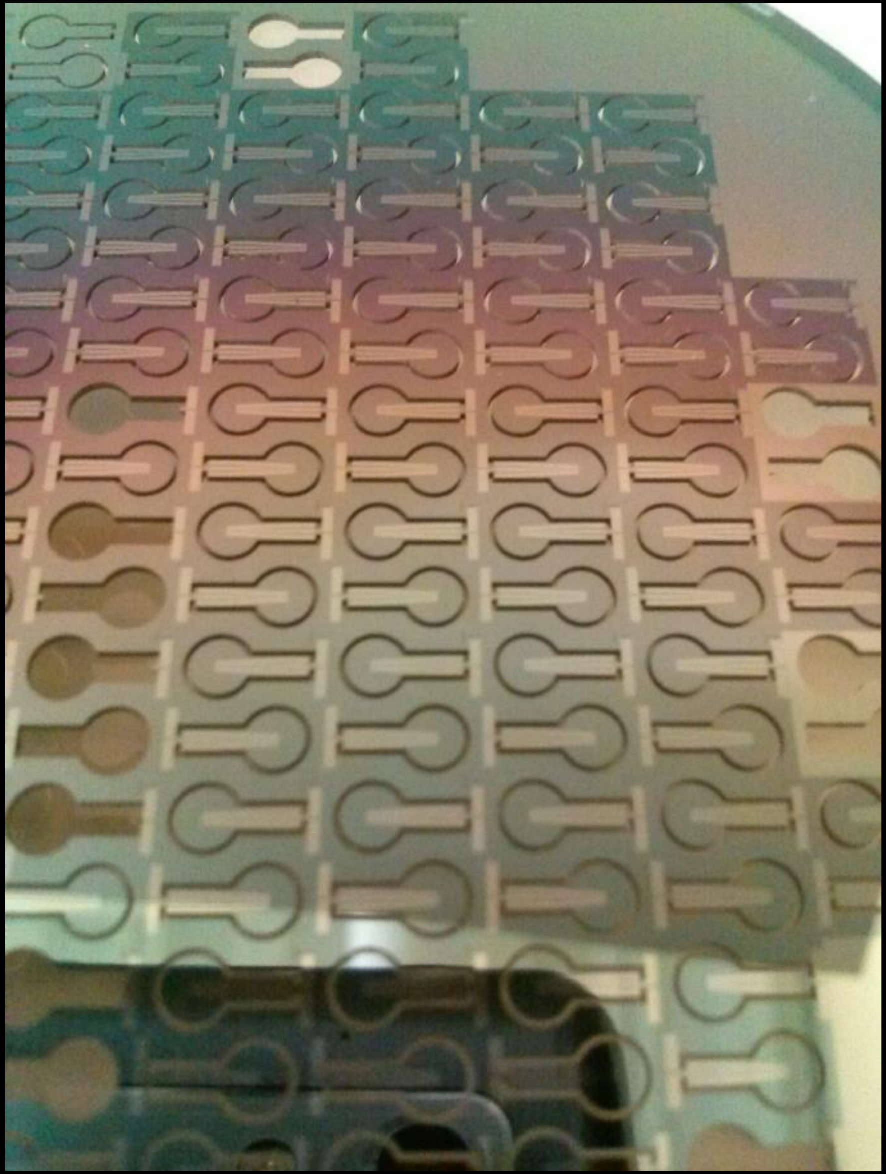
Layer Design

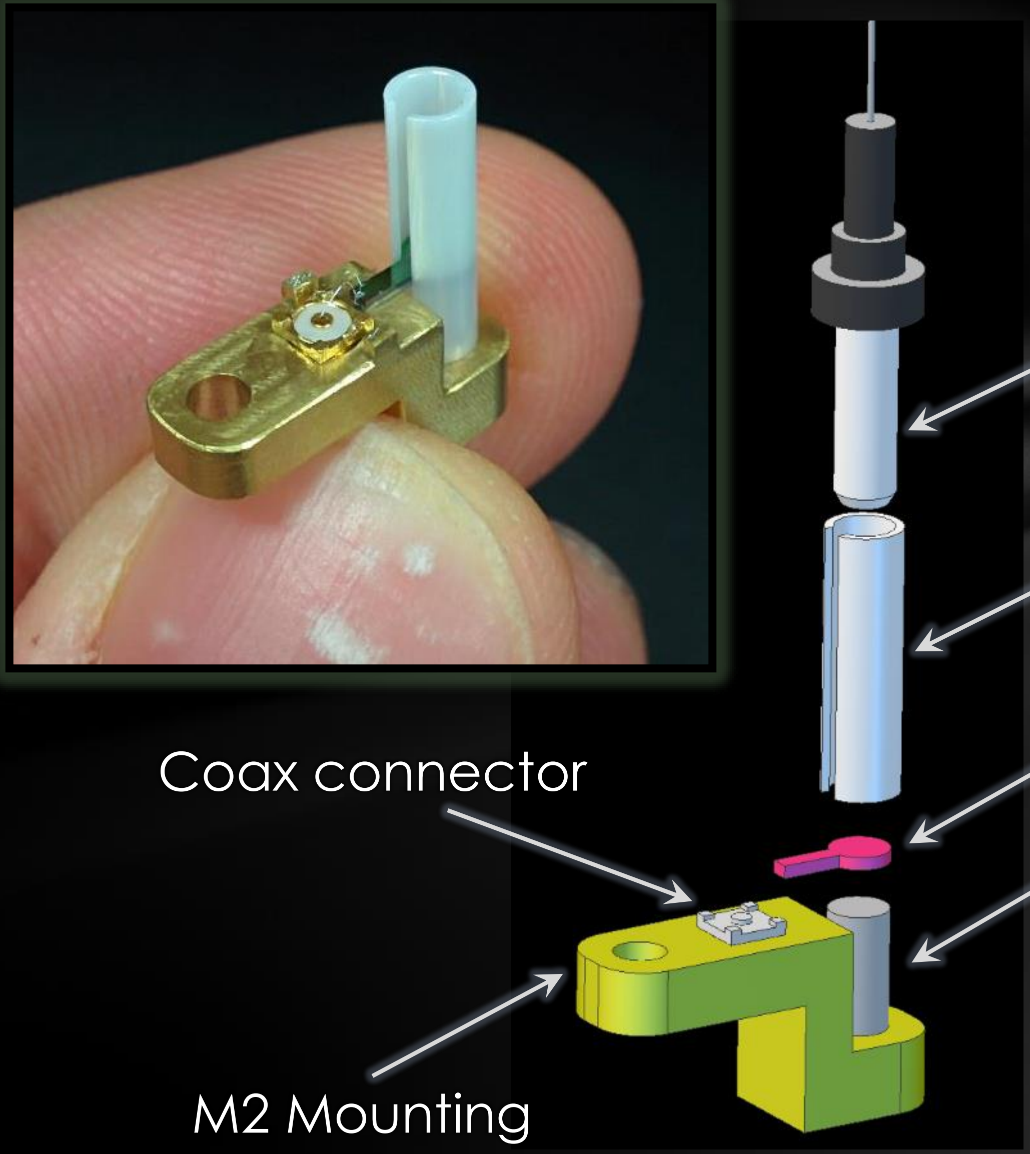


> 90% absorption (TE) at target wavelengths in NIR



Device Assembly and Optical Alignment





Zirconia fiber ferrule

Zirconia sleeve

SNSPD Chip

Sapphire rod

Coax connector

M2 Mounting hole

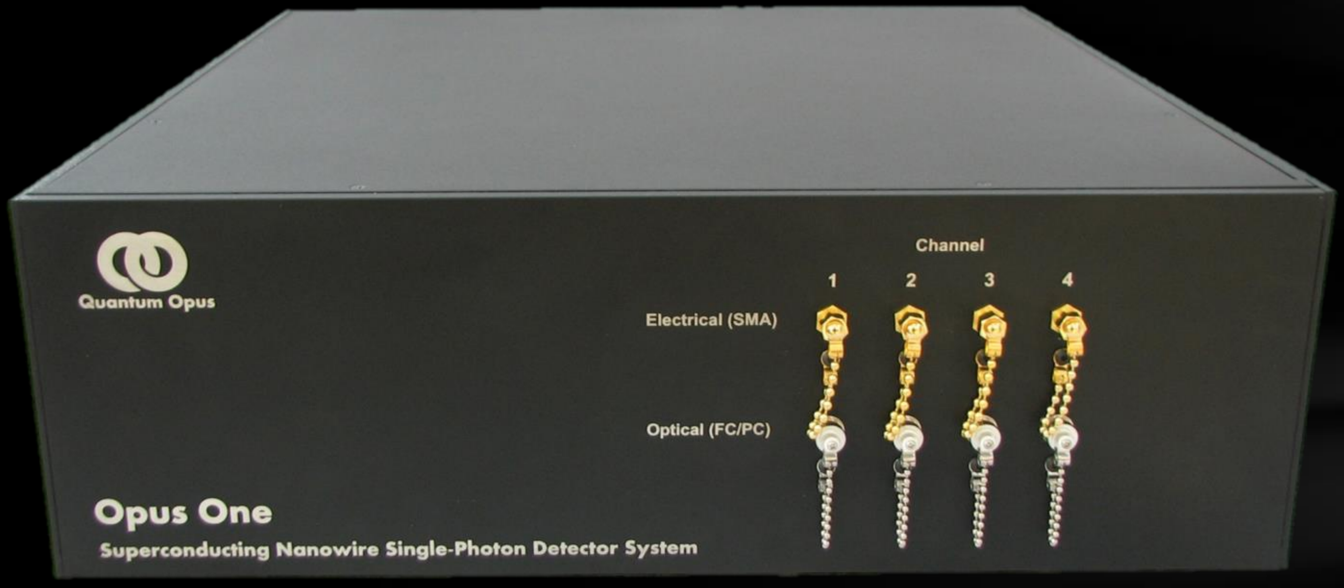
SHI Cryogenics Components: a typical configuration for commercial systems.

Cold Head

Compressor

One of our commercial goals: design a more compact system

Opus One



Physical

- 3U 19” Rack Mount
- Modular construction
- Upgradable to 32 ch
- Convenient electronics

Optical/Electrical

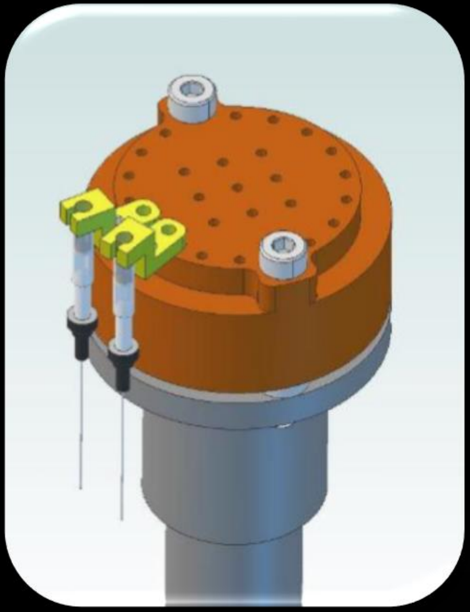
- NIR DE = 80 % (1550 nm)
- Dead time < 25 ns
- Jitter < 60 ps
- DCR < 100 cts/sec

www.QuantumOpus.com

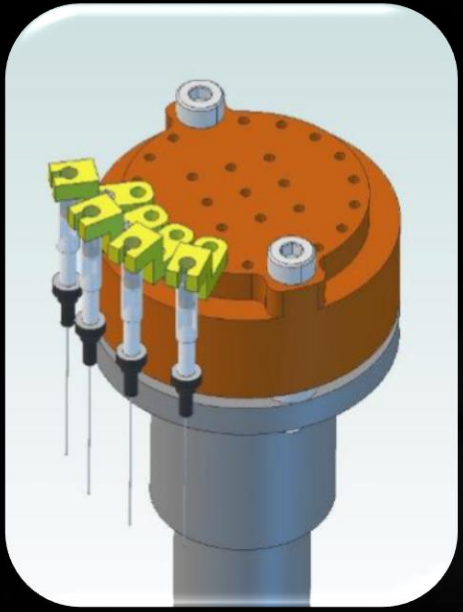
Modular Electronics

Low-noise, high-speed amplifier and bias module integrates with SIM rack for computer control and monitoring

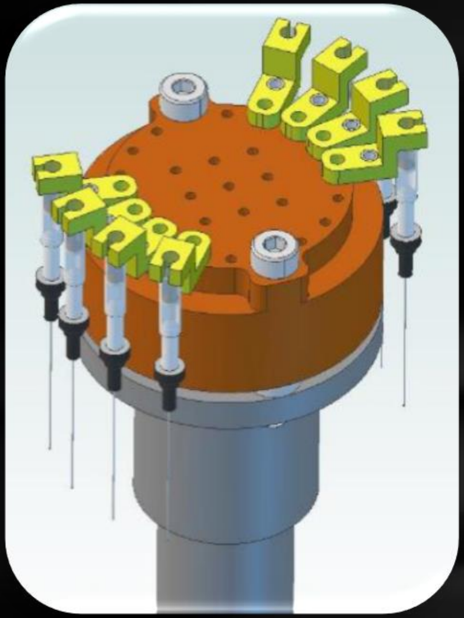
Expandable to 16 detectors



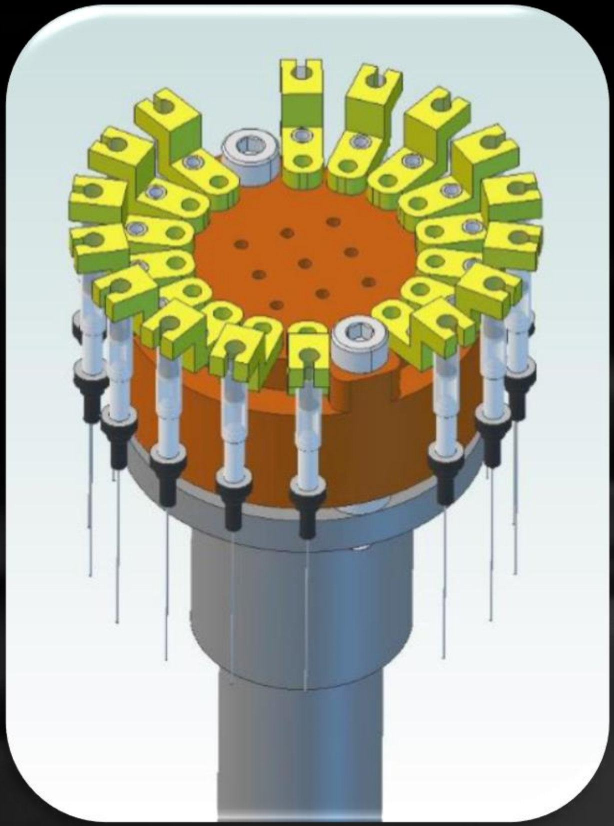
2 Devices



4 Devices



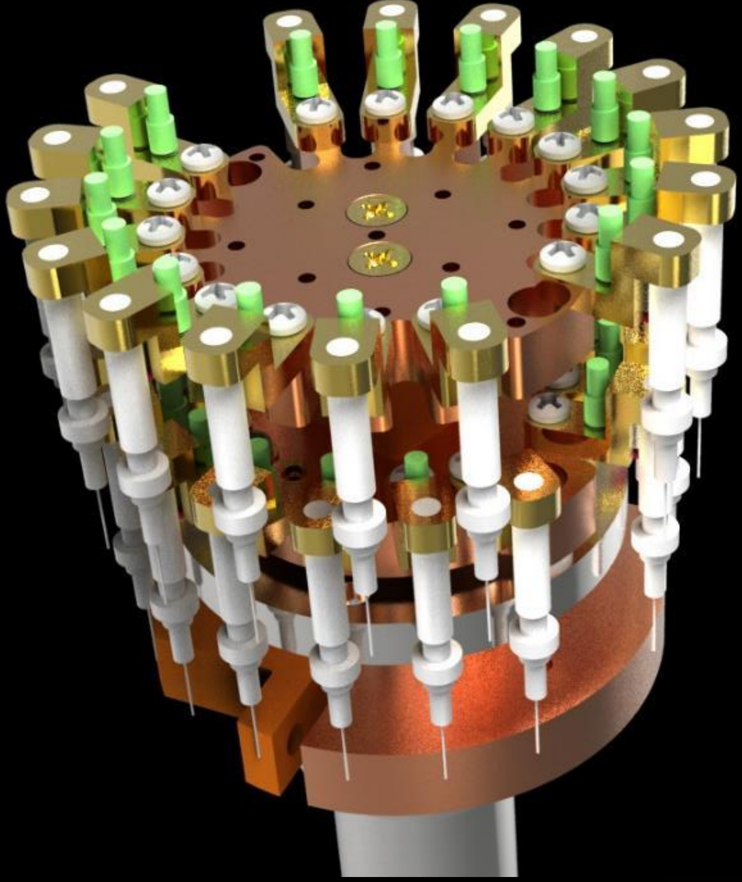
8 Devices



16 Devices

Two high-efficiency superconducting nanowire detectors coupled to SMF28e fibers and coaxial readout cables.

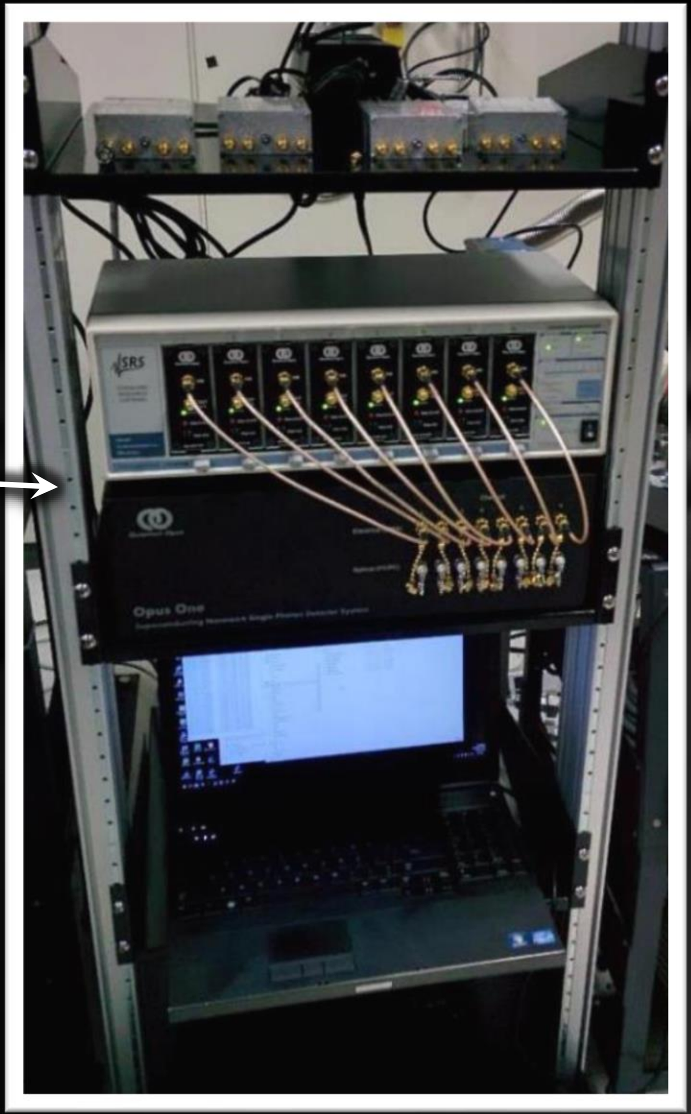
Custom 32-channel System



Customer installation examples

Shelf above optical table

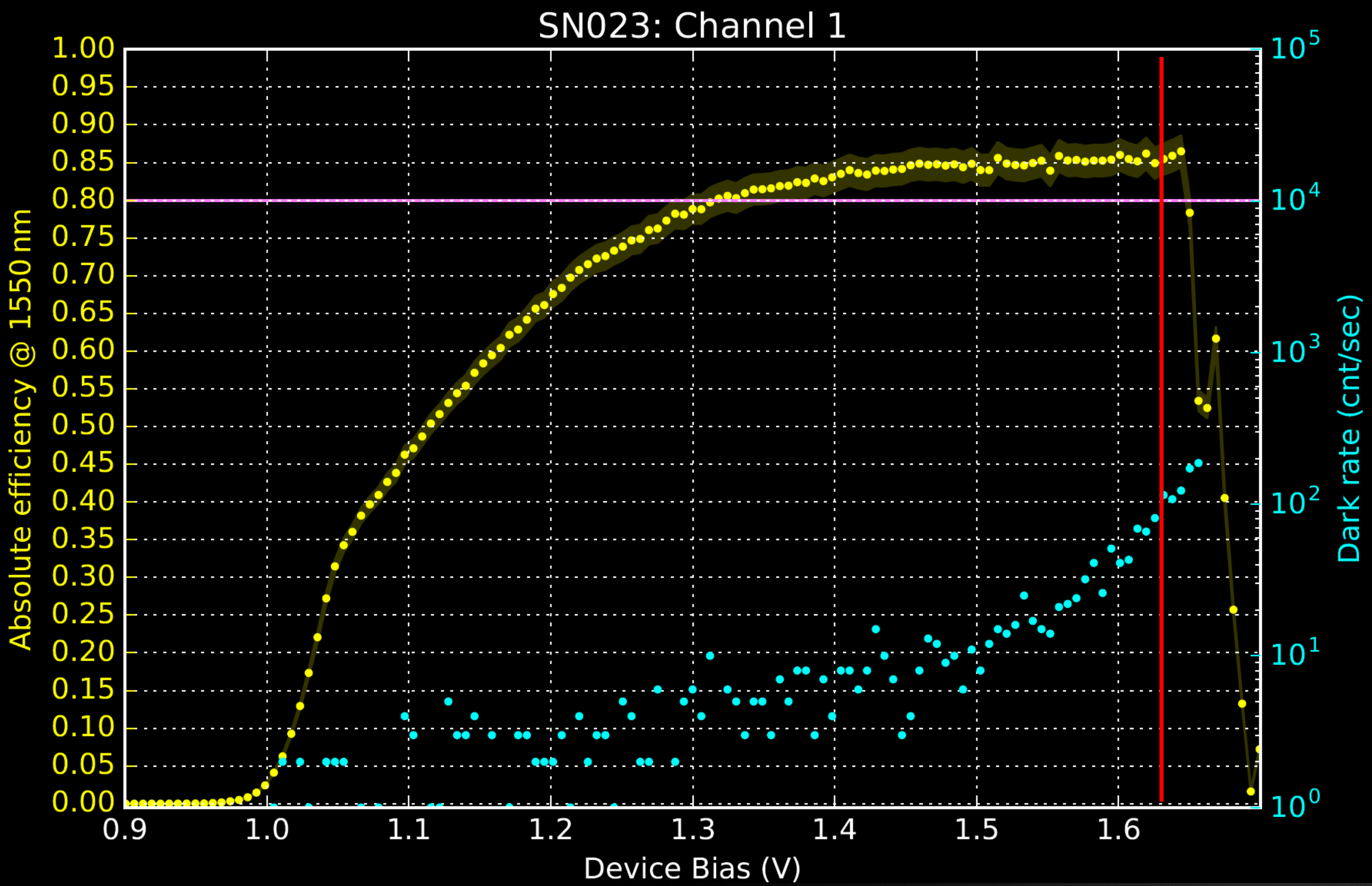
Standard 19-inch rack



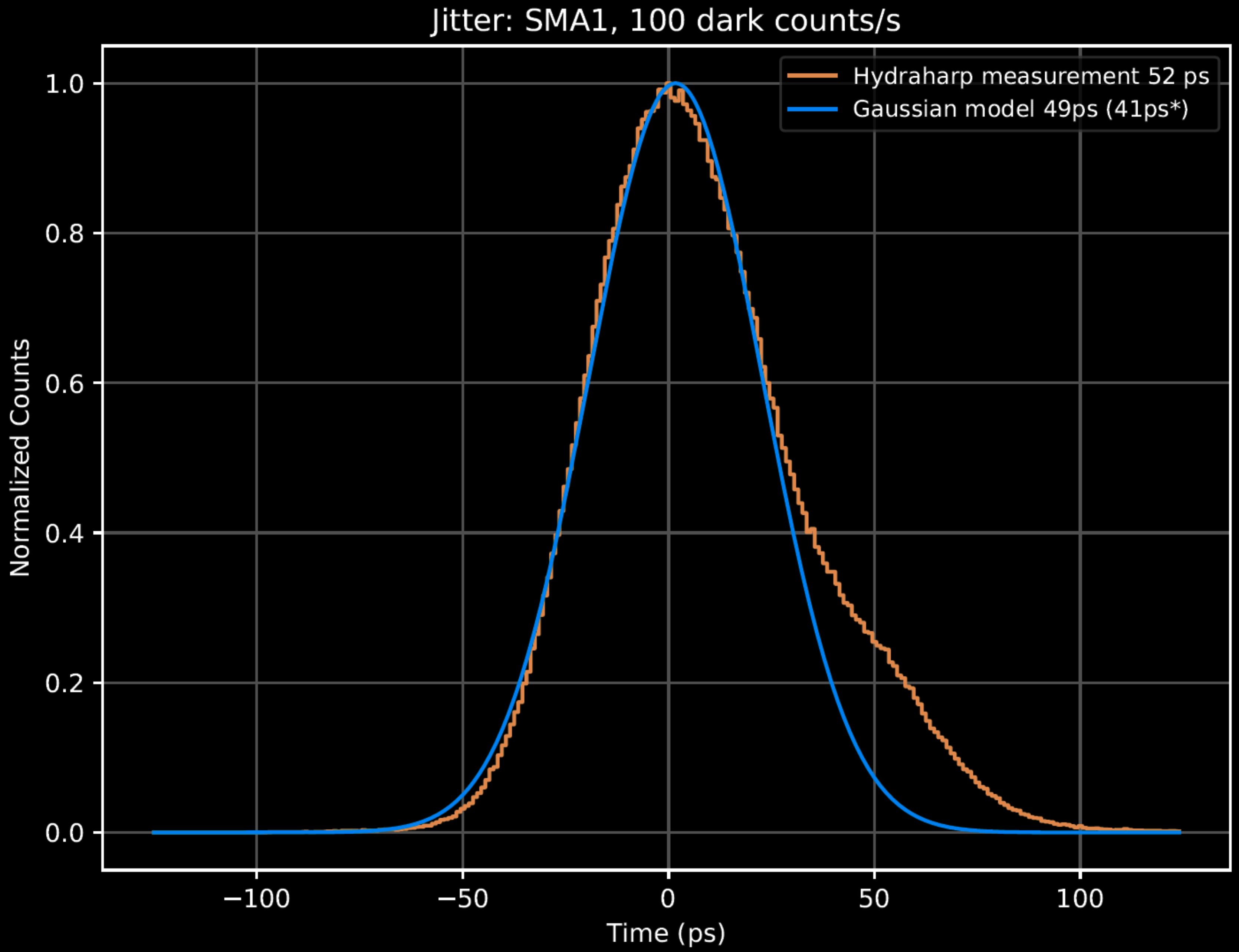
Opus One cryostat and electronics

Water-cooled Compressor

Recent system performance: Efficiency



Recent system performance: Jitter

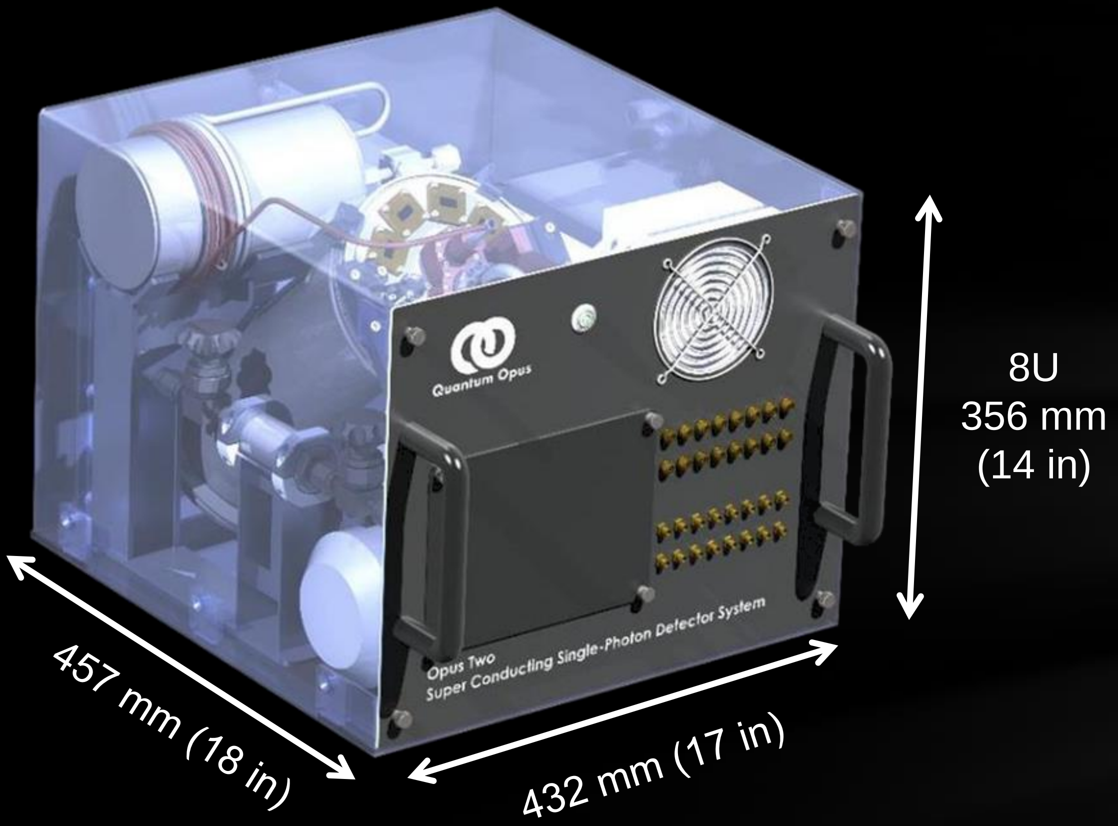


*Inferred via RMS subtraction of 20-ps laser jitter, 8-ps laser pulse width, and 12ps time-tagger jitter.

Current Research and Development

- Decreased polarization dependence (goal: <5%)
- Increased collection area (goal: 30+ µm MM fiber)
- Increased count rate, PNR (goal: G-cnt/sec)
- Multimode fiber coupling
- Compact multi-channel instrumentation (goal: 100s)
- Increased efficiency (goal: 90% at 1550nm)
- **Compact cryogenics**

The **Opus Two** — The world’s first desktop <2 K Cryosystem



- Continuous system operation; expected service interval 20,000 hours.
- Ultra-compact cryocooler and electronics draw **<300 Watts**
- Fully air-cooled
- Base temperature: 1.8K (<**1 K option**)
- 32+ detectors per system
- Available **Summer 2018**

DARPA

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

NASA

SBIR-funded revolutionary performance

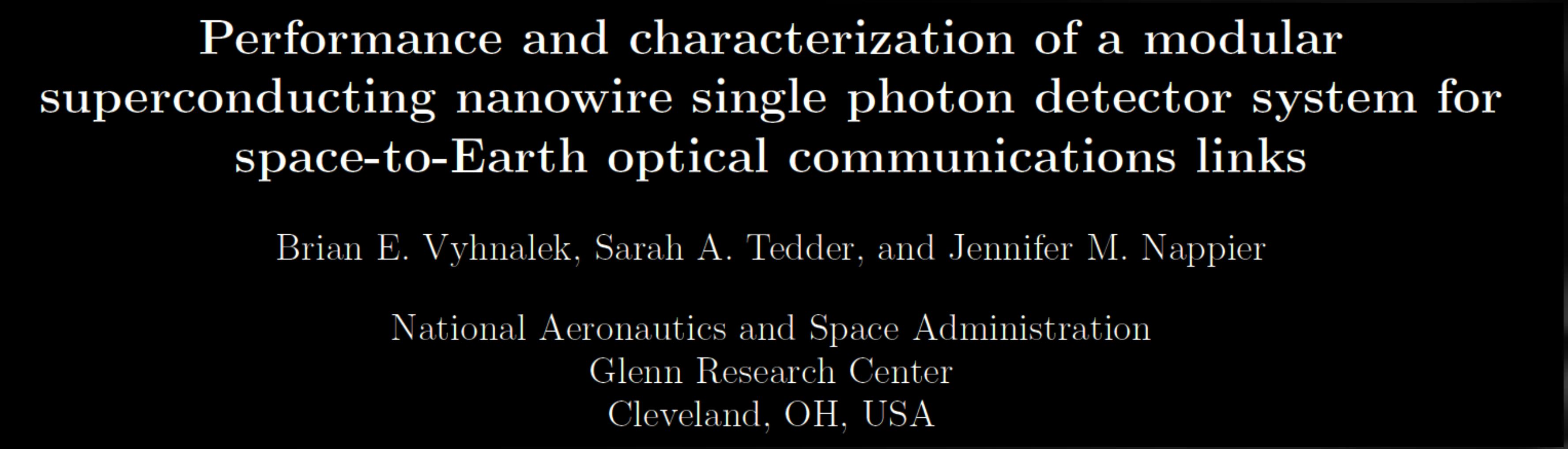
MADE IN
MICHIGAN
MADE IN

Opus One

Opus Two

System Style	*6U Rack-Mount Laboratory*	*Ultra-Compact Low-Power*
System Wall Power Draw	2.5 kW	0.3 kW
Operating Temperature	2.5 K	1.8 K (<1 K option)
Enclosure Cooling	Water or Air	Air
System Volume	0.16 m^3(10000 in^3)	0.07 m^3 (4300 in^3)
System Weight	160 kg (350 lbs)	30 kg (70 lbs)

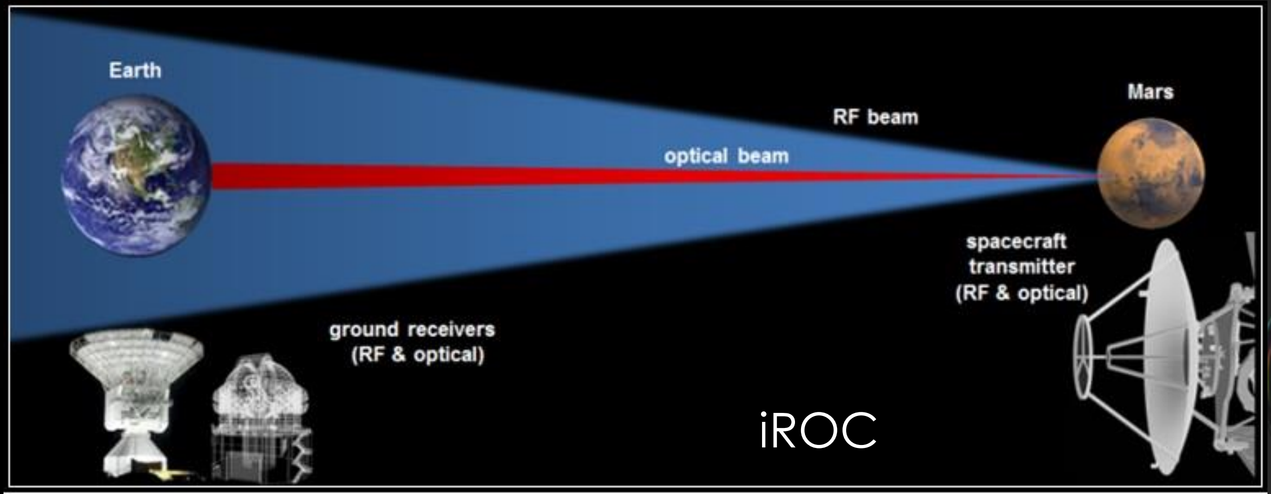
Optical Space Communication



Performance and characterization of a modular superconducting nanowire single photon detector system for space-to-Earth optical communications links

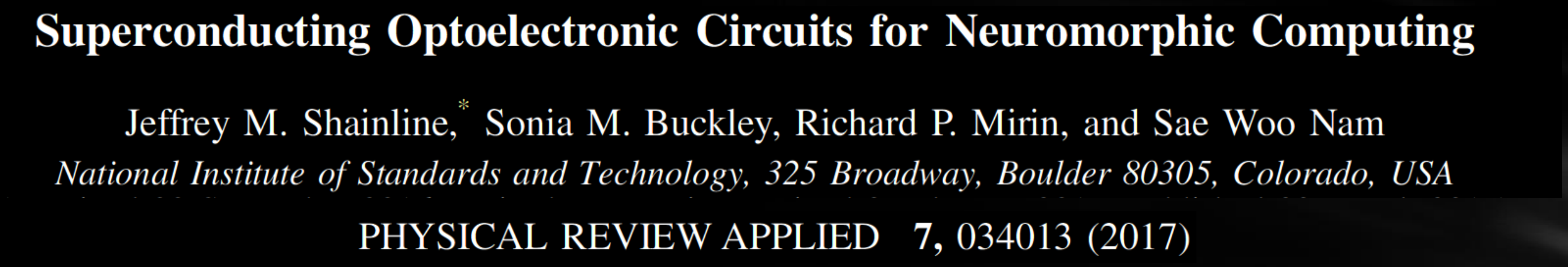
Brian E. Vyhnalek, Sarah A. Tedder, and Jennifer M. Nappier

National Aeronautics and Space Administration
Glenn Research Center
Cleveland, OH, USA



iROC

Not quantum… but also not von Neumann

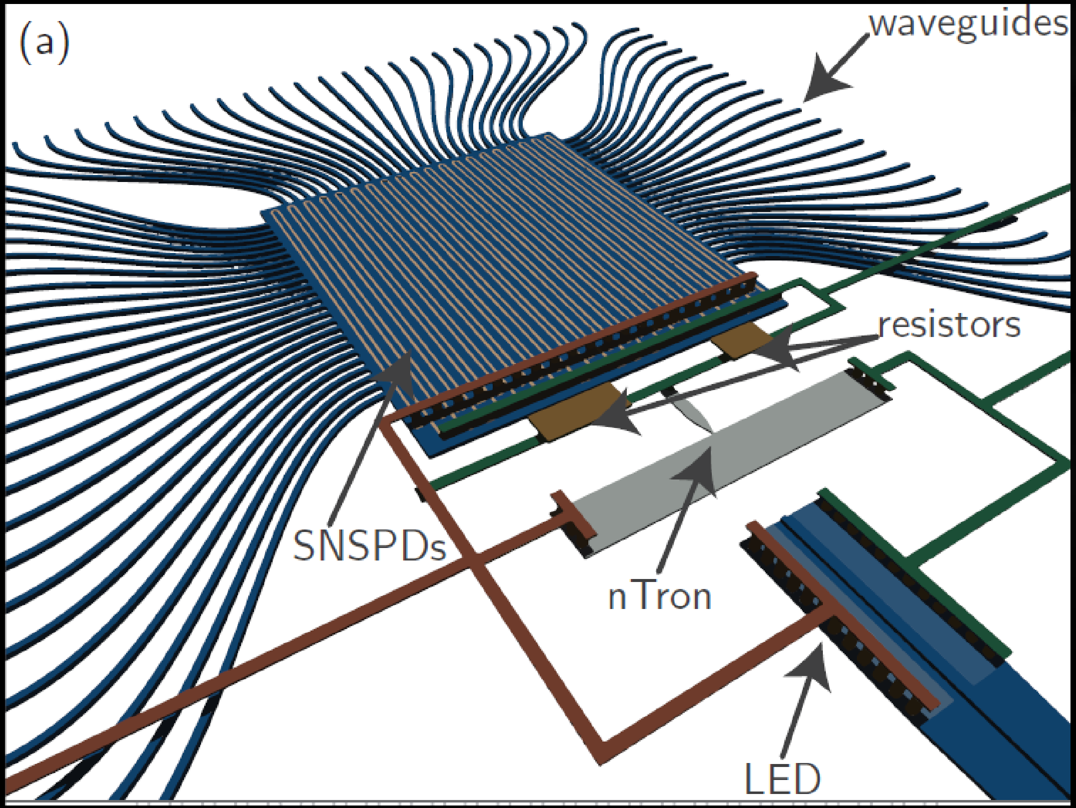


Superconducting Optoelectronic Circuits for Neuromorphic Computing

Jeffrey M. Shainline,* Sonia M. Buckley, Richard P. Mirin, and Sae Woo Nam

National Institute of Standards and Technology, 325 Broadway, Boulder 80305, Colorado, USA

PHYSICAL REVIEW APPLIED **7,** 034013 (2017)



SNSPD: 20 aJ/synapse event

BIO: 1 pJ/synapse event

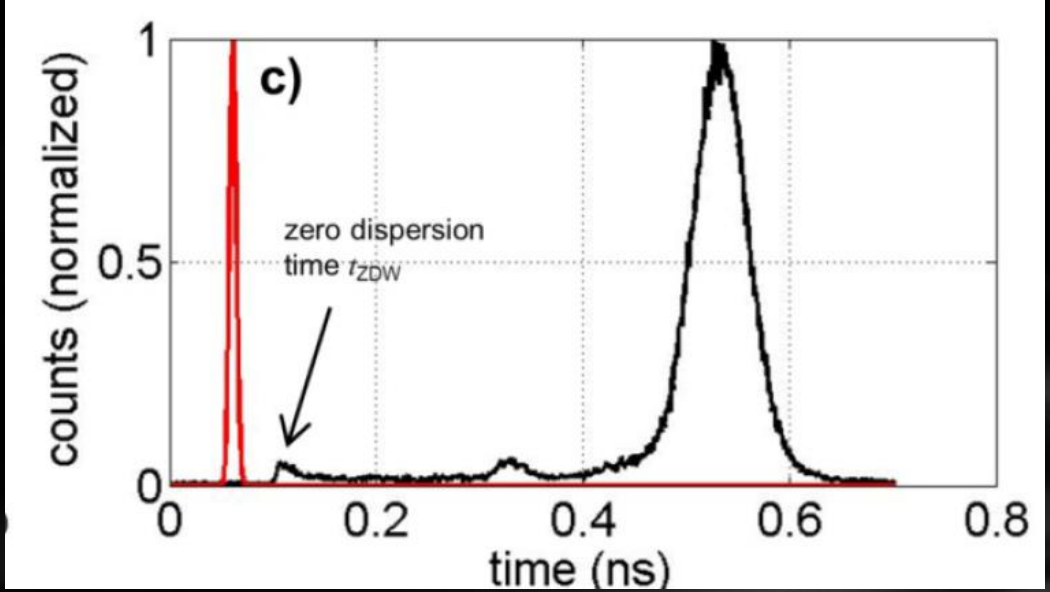
CMOS: 20 pJ/synapse event

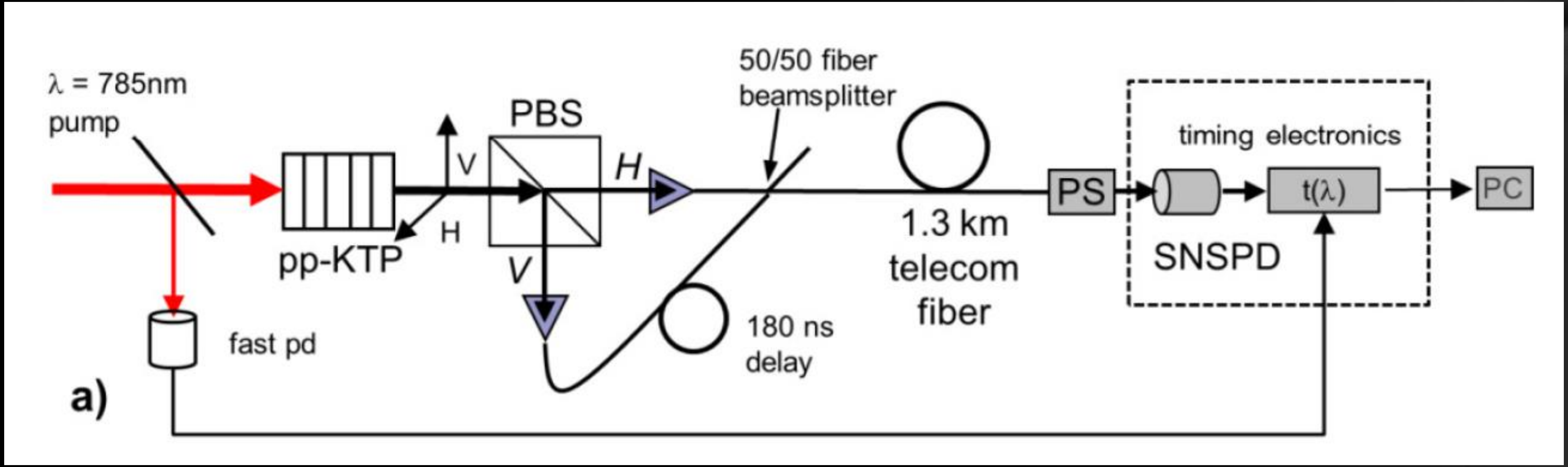
Brain: ~10^{14} synapse events/sec

Achieve this rate at 2 mW of cooling @ 2K, 200 W wall draw

Generation of degenerate, factorizable, pulsed squeezed light at telecom wavelengths

Thomas Gerrits[1], Martin J. Stevens[1], Burm Baek[1], Brice Calkins[1], Adriana Lita[1], Scott Glancy[1], Emanuel Knill[1], Sae Woo Nam[1], Richard P. Mirin[1], Robert H. Hadfield[2], Ryan S. Bennink[3], Warren P. Grice[3], Sander Dorenbos[4], Tony Zijlstra[4], Teun Klapwijk[4], and Val Zwiller[4]





Plans and Possibilities

- Custom superconducting device fabrication
  - Novel device architectures
  - Integrated optics and detectors
- Multi-element devices, photon number resolution
- Fiber quantum repeaters in telecom closet
- Cryogenic logic development
- Mid-infrared and ultraviolet photon counting
- Thermal imaging at NIR
- $\alpha, \beta, \gamma, e^-$ particle detection
- Terahertz sensing and imaging
- Low wall-draw cooling for microwave LNAs
- Desktop Dilution Refrigerator? 500nW cooling at 50 mK

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Multi-photon detection using a conventional superconducting nanowire single-photon detector

CLINTON CAHALL,[1,*] KATHRYN L. NICOLICH,[2] NURUL T. ISLAM,[3] GREGORY P. LAFYATIS,[2] AARON J. MILLER,[4] DANIEL J. GAUTHIER,[2] AND JUNGSANG KIM[1,5]