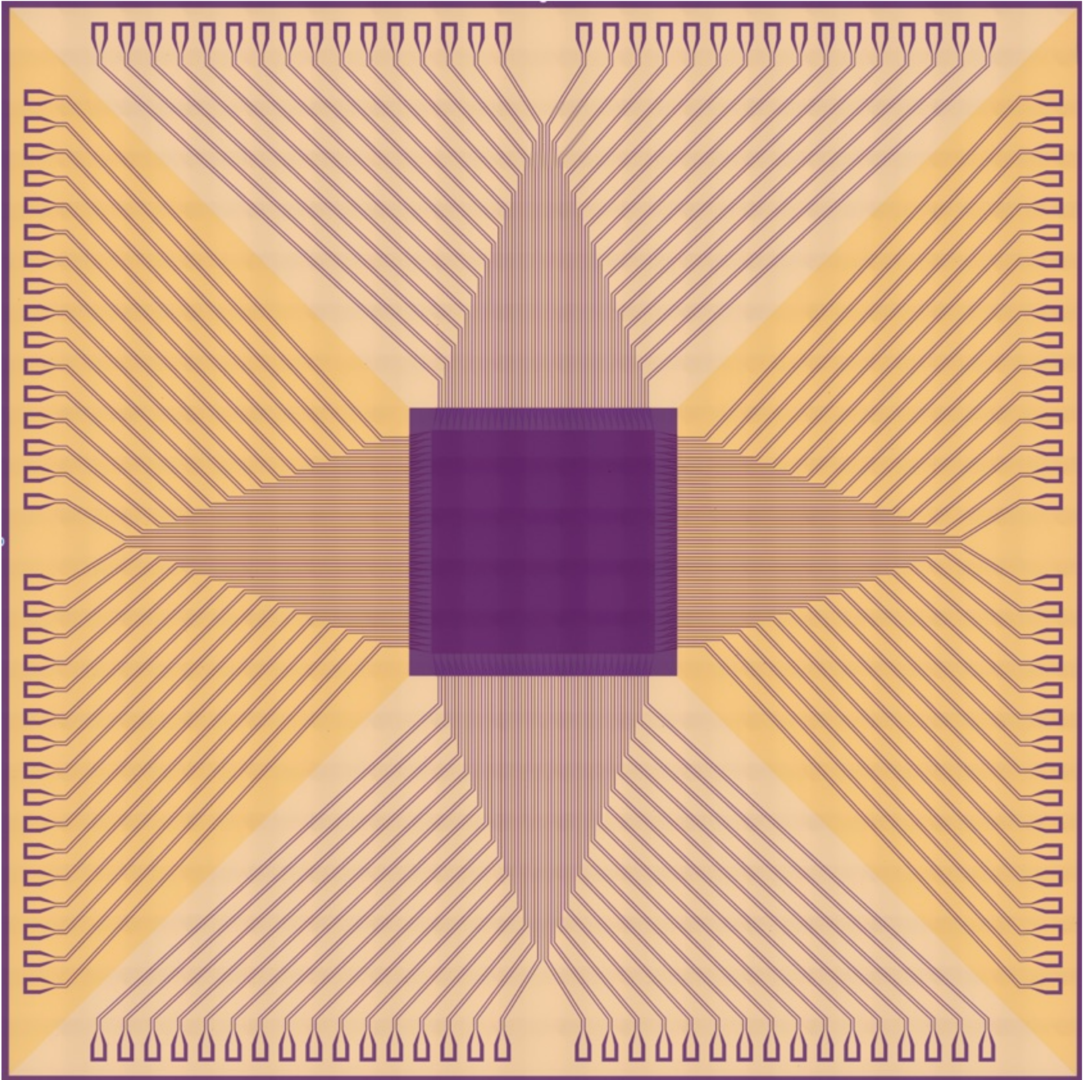


Superconducting Nanowire Single Photon Detectors with Low Energy Thresholds

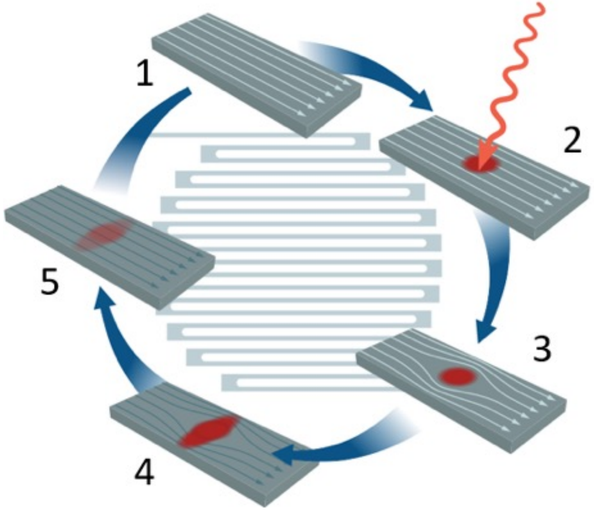
Matt Shaw

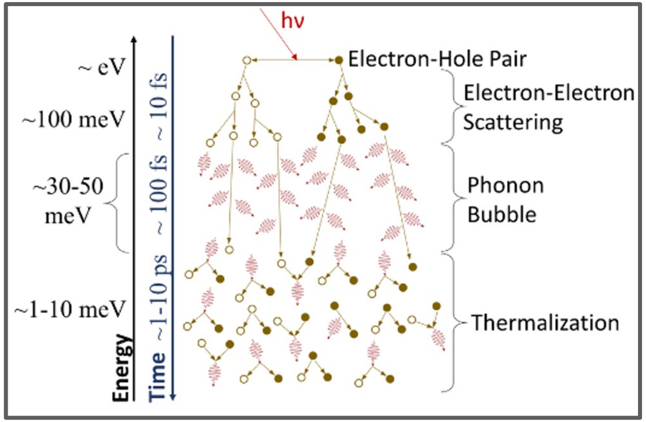
Jet Propulsion Laboratory

12 January 2023

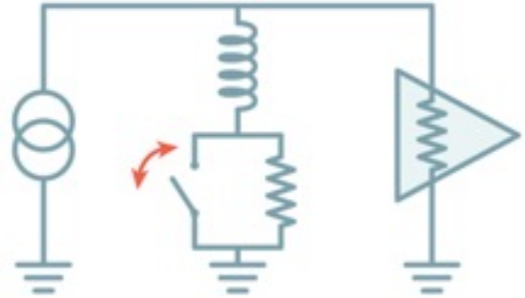
Jet Propulsion Laboratory
California Institute of Technology

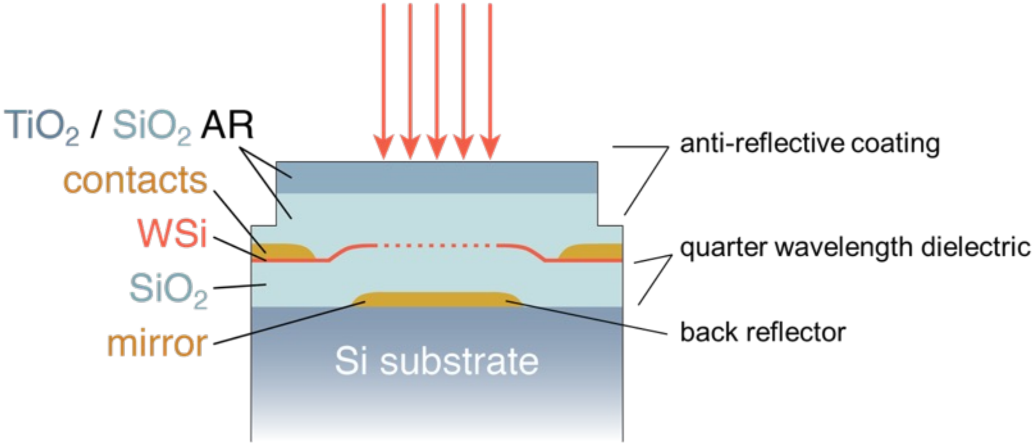
Superconducting Nanowire Single Photon Detectors





- Time-resolved single photon counting from UV to mid-IR
- World-leading detector performance
- Operating temperature 1-4 K in most cases

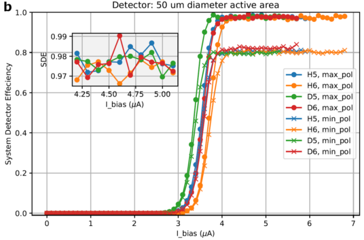




Present State of The Art in SNSPDs

High Efficiency

98% SDE @ 1550 nm (NIST)

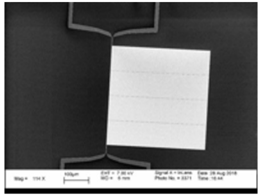


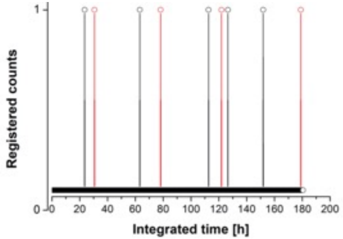
Reddy et al,
Optica (2018)

Low Dark Counts

6e-6 cps (MIT/NIST)

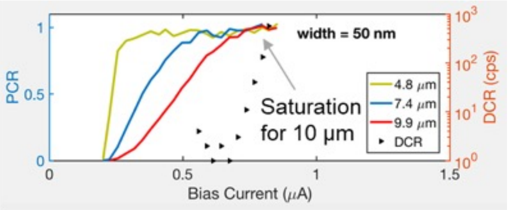
Chiles et al, *Phys. Rev. Lett.* (2022)

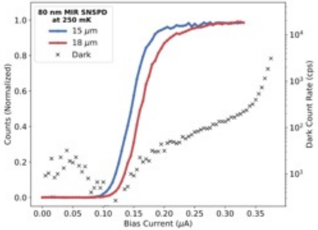




UV – Mid-IR Operation

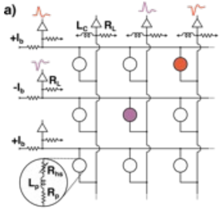
Photon counting from 0.1 - 18 μm (JPL/MIT/NIST)

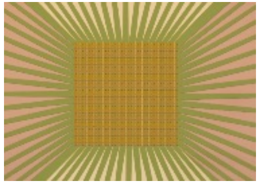


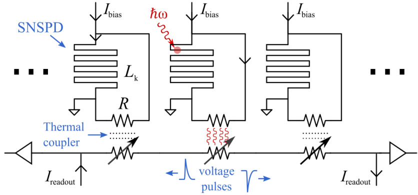


Kilopixel Array Formats

32x32 "row-column" / thermally coupled imager (NIST/JPL)



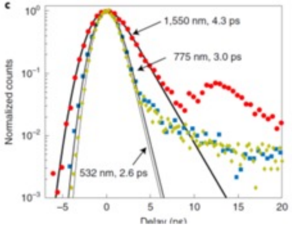


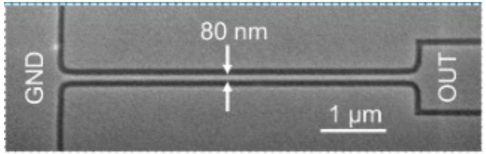


Wollman et al, *Optics Express* (2019)
MacCaughan et al, *APL* (2022)

High Time Resolution

2.6 ps FWHM (MIT/JPL/NIST)

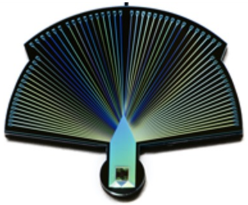




Korzh et al, *Nature Photonics* (2020)

High Event Rate

1.4 Gcps in 32-element array (JPL)



Craiciu et al, *Optica* (2023)

NIST
MIT
JPL

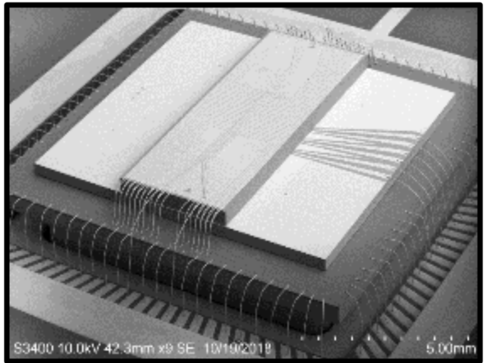
SNSPD Applications

Free-Space Optical Communication

- *Deep Space Optical Communication (Psyche)*
- *Optical-to-Orion*
- *Lunar Laser Comm Demo*
- *Space-to-Ground Quantum Communication*

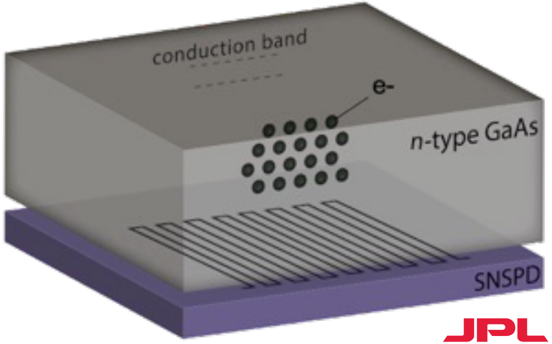
Quantum Information Science

- *Quantum Communication*
- *Trapped Ion Quantum Computing*
- *Linear Optical Quantum Computing*



Fundamental Physics and Astronomy

- *Dark Matter searches*
- *Tabletop tests of quantum gravity*
- *Exoplanet science*
- *Ultrafast optical transients*



Motivation for Lower Energy Thresholds

Astronomy

- General need for sensitive, low-noise detectors in 15-30 um band for space astronomy
- Exoplanet transit spectroscopy (*Origins:* 3 – 25 μm)
- Nulling interferometry for exoplanet detection (*LIFE: 4* - 18 μm)

Dark Matter Detection

- Low energy threshold for direct detection of infrared axions or hidden sector photons
- Measurement of scintillation from low-bandgap crystal targets, molecular scattering

Remote Sensing

- Photon counting lidar
- Passive thermal rangefinding

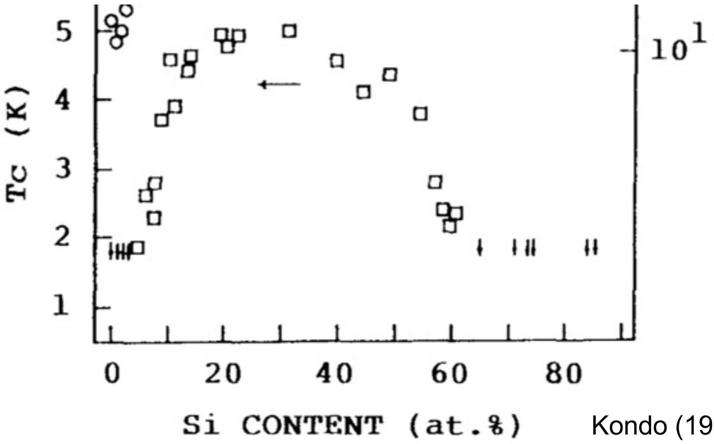
Quantum Information Science

- Characterization of exotic quantum emitters
- Quantum imaging and sensing

Strategies for Lower Energy Thresholds

Reduced Superconducting Gap Energy

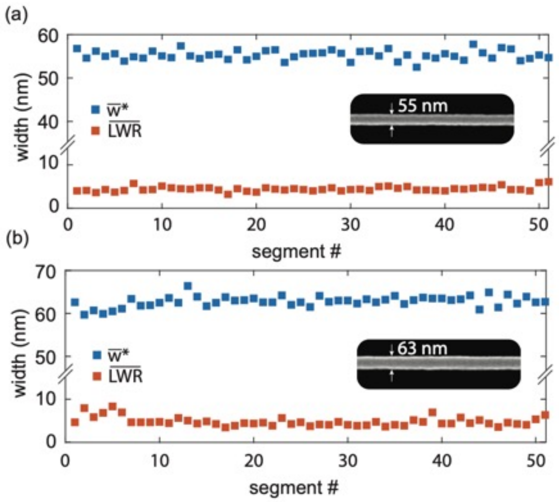
- Now using Si-rich WSi to reduce Tc to 1.3-2.1 K (depending on thickness)
- “Conventional” WSi for NIR devices has Tc = 3.1 – 3.6 K



Kondo (1991)

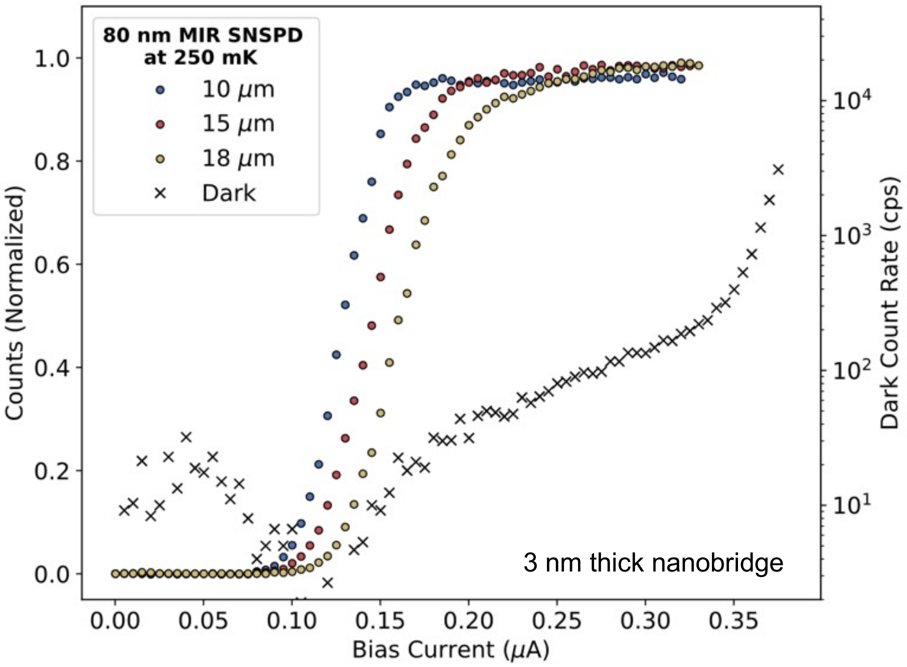
Narrow Nanowires

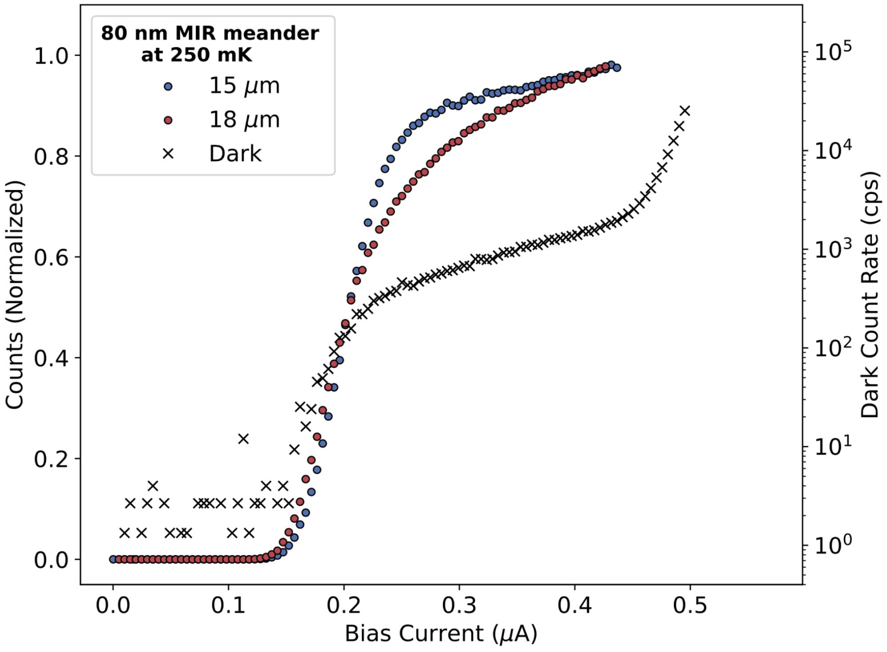
- Narrower nanowires enhance IR sensitivity by constraining hotspot growth
- Reliably fabricating SNSPDs with 50-60 nm wires using electron-beam lithography



Tradeoffs: Lower operating temperature (< 1 K) and smaller readout currents (< 2 uA)

Saturated Internal Efficiency up to 18 µm (70 meV)



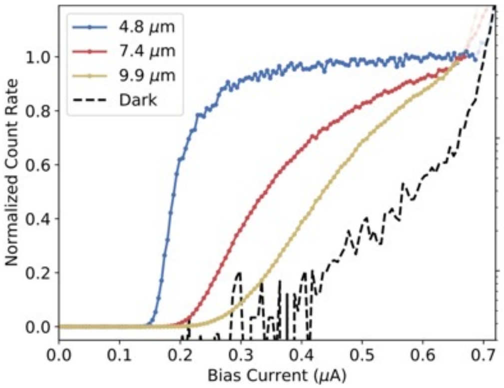


Devices have 100% *internal* efficiency, but need to be optimized for efficient coupling at these wavelengths

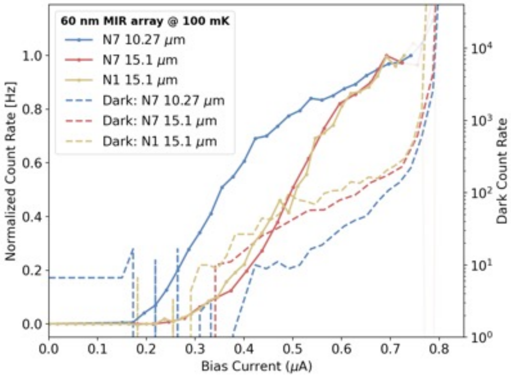
NIST
MIT
JPL

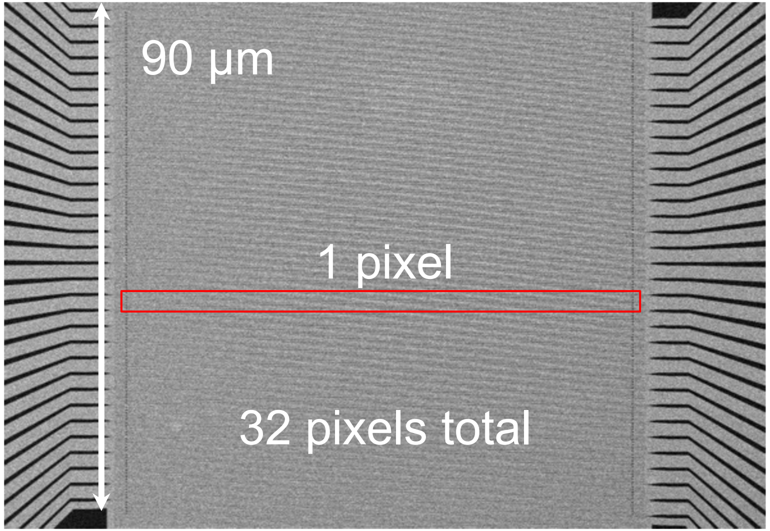
Scaling to 32-element Arrays in Mid-IR

T = 850 mK

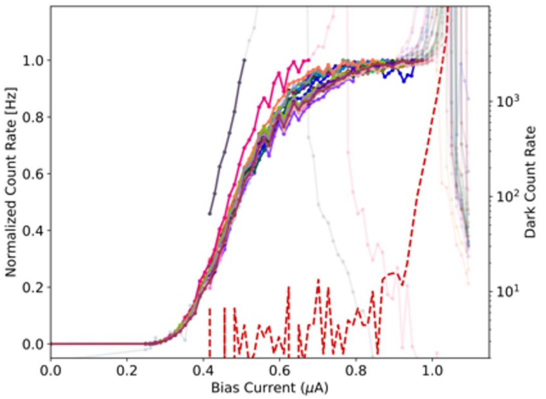


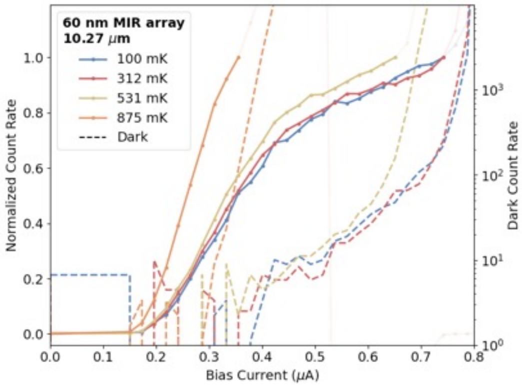
T = 100 mK





6.1 um, T = 880 mK

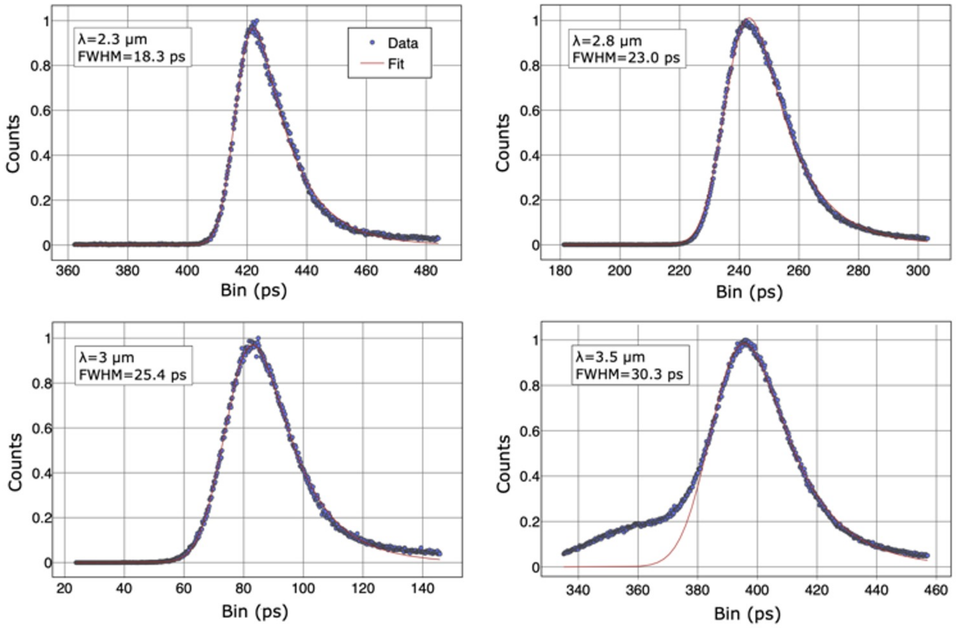




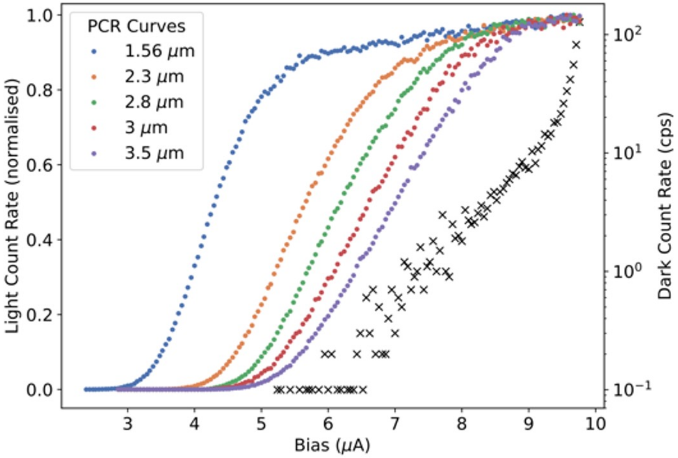
- Active area of pixel: 90x3 µm
- 4.7 nm thick WSi, 60-100 nm wide
- 30/32 channels working at 6.1 um
- 15 um photon counting in array

First Demonstration of Low Jitter in MWIR

- Measured **<30 ps FWHM** jitter from 1.56 μm to 3.5 μm in an NbTiN SNSPD
- **First demonstration of fast timing** in an MWIR SNSPD
- Demonstrates feasiblity of time-domain multiplexing using MWIR SNSPDs
- Also demonstrates practicality for lidar and optical communication in MWIR



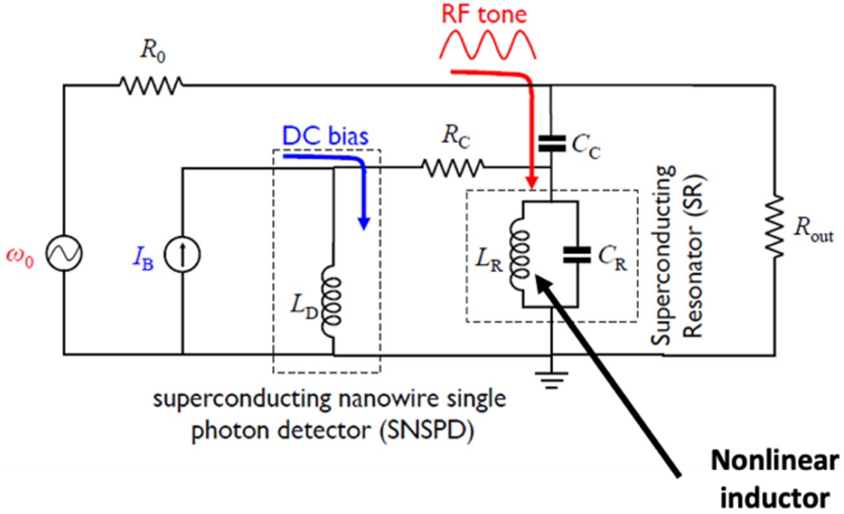
Jitter histograms from 2.3 μm to 3.5 μm. Note the distortion in the 3.5 μm histogram is due to optical reflections within the source.



Work performed in collaboration with U. Glasgow

Frequency Domain Multiplexing of SNSPDs

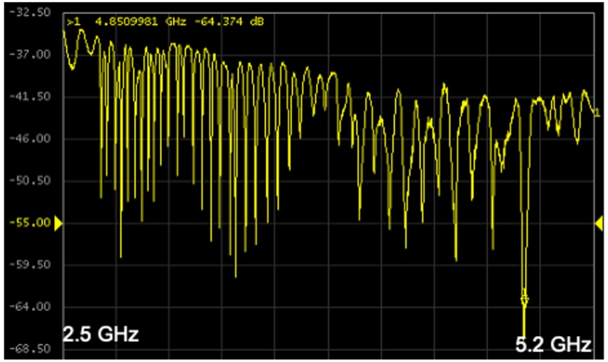
- Current from SNSPD is shunted to a superconducting microwave resonator instead of an amplifier
- Thousands of resonators can be read out on one RF feedline
- Most bandwidth-efficient way to make use of the readout lines in the cryostat
- Exceptional (<< 1 uA) current sensitivity compared to conventional amplifiers, critical for mid-IR devices
- DC bias provides a degree of reconfigurability
- Leverages decades of development from microwave kinetic inductance detectors and superconducting qubit readouts



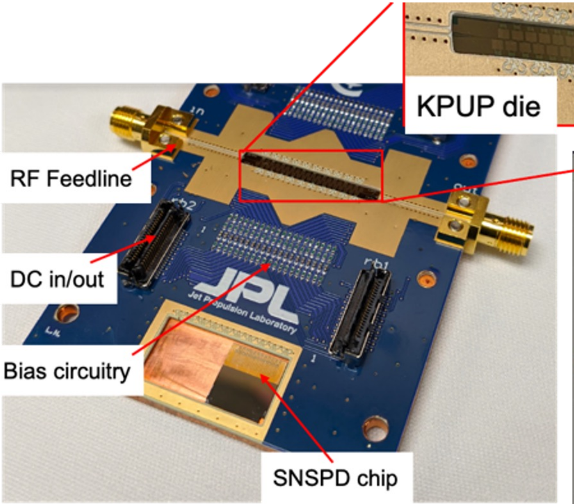
Nonlinear inductor

Preliminary results with frequency multiplexing

- Interfaced SNSPD array with KPUP chip containing 40 resonators on one feedline
- Successfully read out SNSPD pulse and demonstrated DC frequency shifting necessary for reconfigurable readout

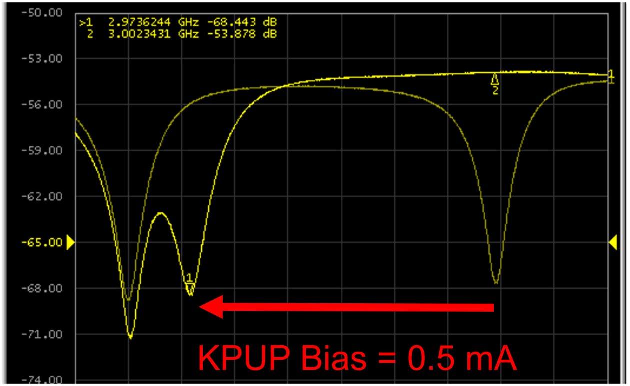


40 microwave resonators on one feedline



SNSPD array interfaced to resonator chip

Frequency domain SNSPD readout



Demonstration of resonator shift with DC bias

Next Steps for Longwave SNSPD Development

- Move to co-sputtered films with higher Si content to further reduce Tc
- Expect Tc ~ 0.5 – 0.7 K is possible with WSi, for 100 – 200 mK operating temperature
- Demonstrate saturated efficiency at 30 µm wavelengths
- Work on optimized coupling efficiency at long wavelengths using optical stacks and antennas
- Develop calibrated efficiency measurements at long wavelengths
- Scale up frequency-domain readout to large number of pixels

Applications for QICK for Superconducting Detectors

- Longwave Infrared SNSPDs
- Photon-Counting KIDs
- Far-infrared KIDs
- Quantum Capacitance Detectors
- Frequency Domain TES Readout