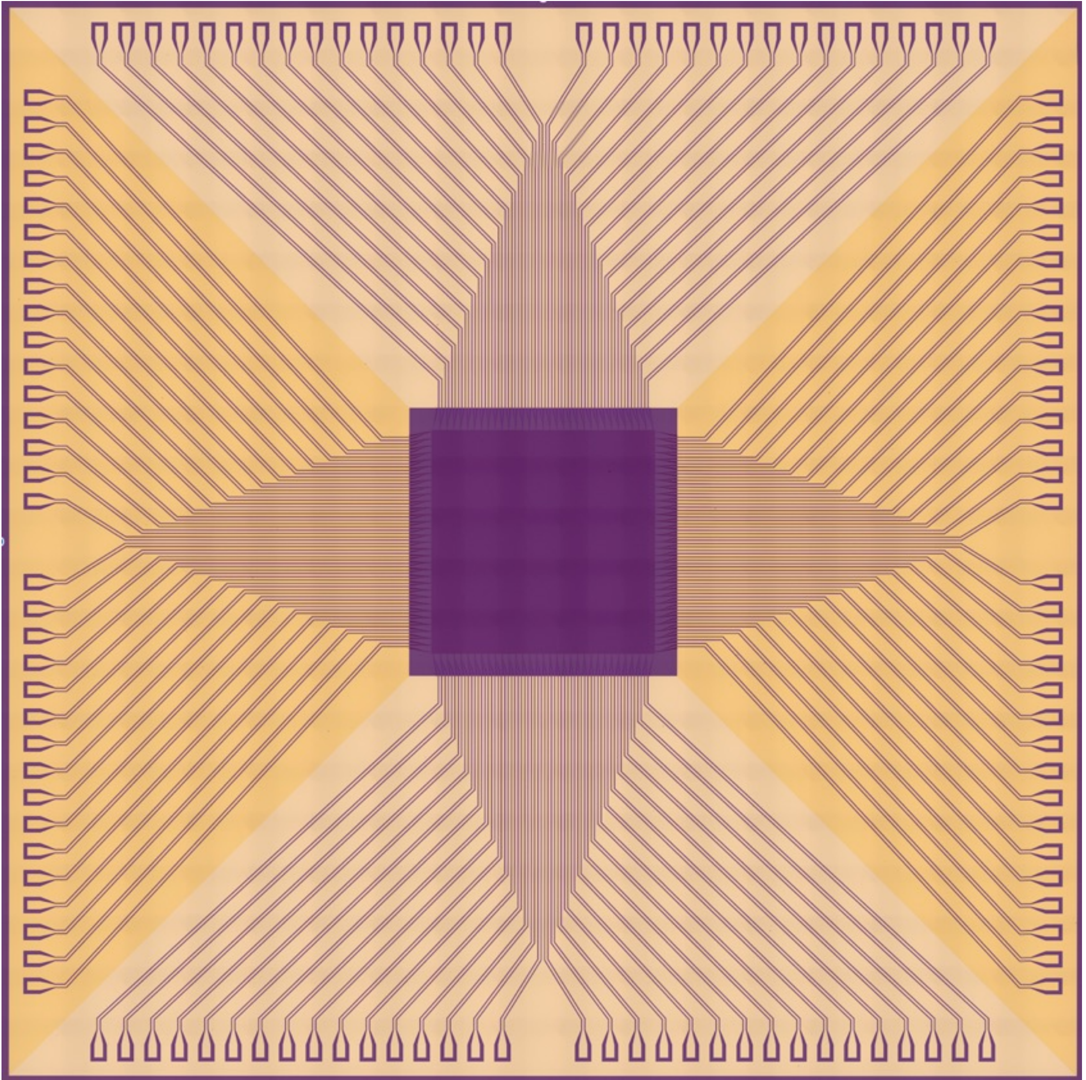

Superconducting Nanowire Single Photon Detectors

Matt Shaw

Jet Propulsion Laboratory

31 March 2023

UCLA Dark Matter Workshop

Jet Propulsion Laboratory

California Institute of Technology

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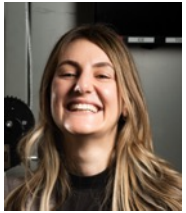
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Sahil Patel (Caltech MS)


Sasha Sypkens (Arizona State)

Key Collaborators

NIST

Fermilab

NASA Goddard Space Flight Center

Photon Spot

Berkeley Lab

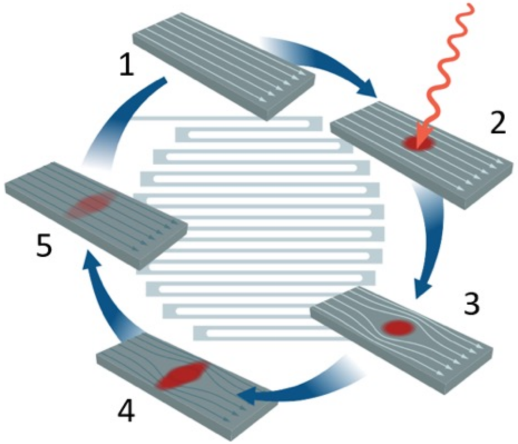
BU

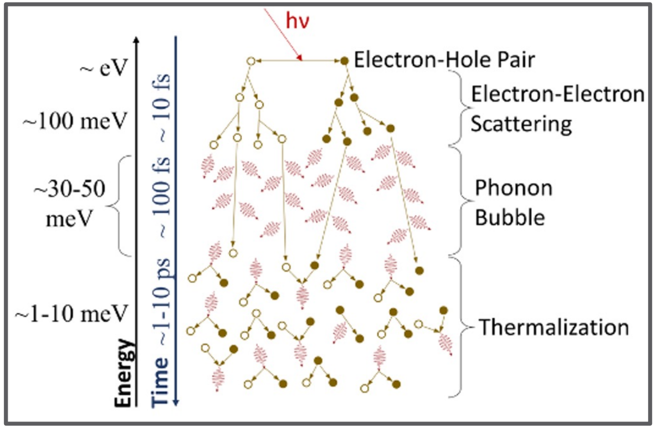
Heriot Watt University

University of Glasgow

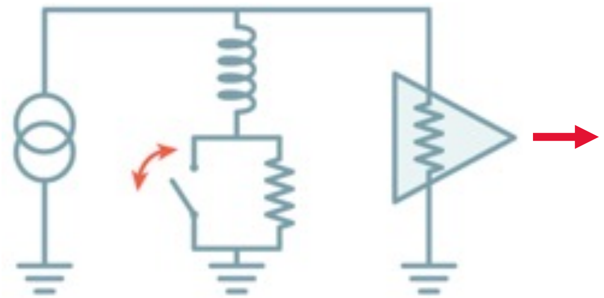
JPL

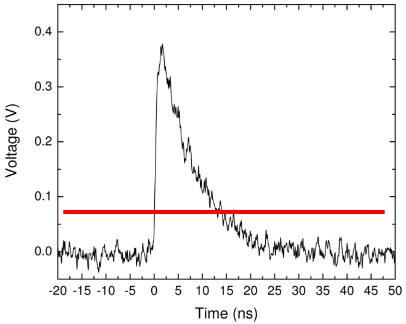
Superconducting Nanowire Single Photon Detectors

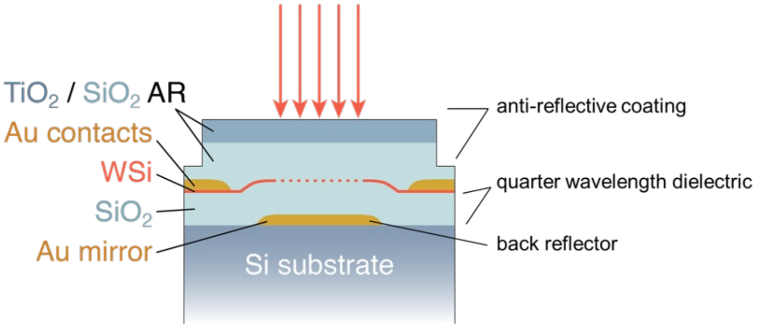




- Time-resolved single photon counting from UV to mid-IR
- Truly digital detection mechanism – reduced drift and zero read noise
- World-leading detector performance
- Operating temperature 1-4 K in most cases

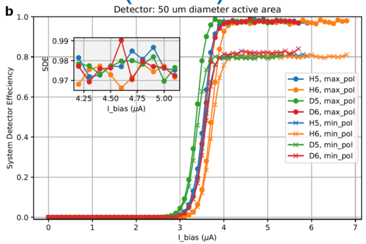






Present State of The Art in SNSPDs

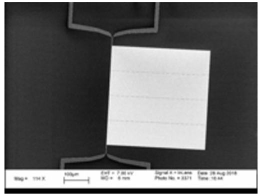
High Efficiency
98% SDE @ 1550 nm (NIST)

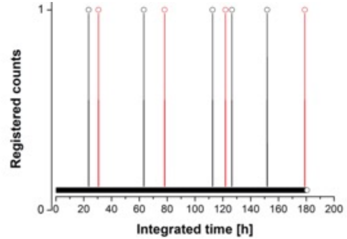


Reddy et al, *Optica* (2018)

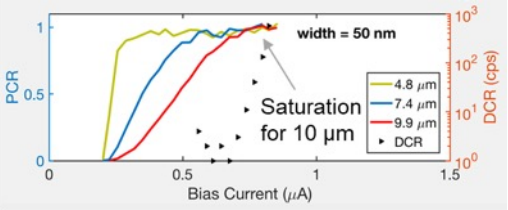
Low Dark Counts
6e-6 cps (MIT/NIST)

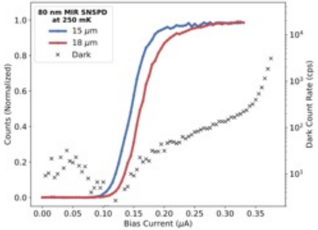
Chiles et al, *Phys. Rev. Lett.* (2022)



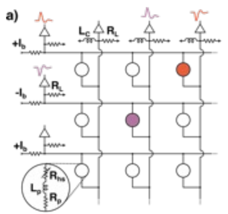


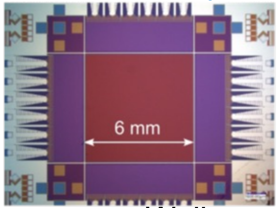
UV – Mid-IR Operation
Photon counting from 0.1 - 18 μm (JPL/MIT/NIST)

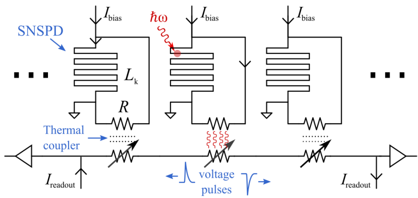




Kilopixel Array Formats
32x32 “row-column” / thermally coupled imager (NIST/JPL)



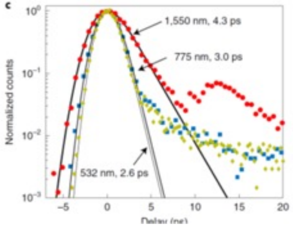


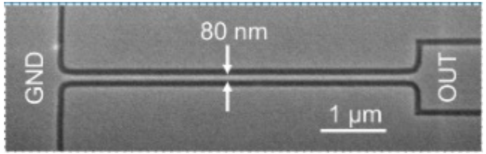


Wollman et al, *Optics Express* (2019)

MacCaughan et al, *APL* (2022)

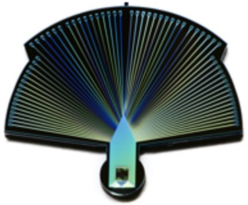
High Time Resolution
2.6 ps FWHM (MIT/JPL/NIST)

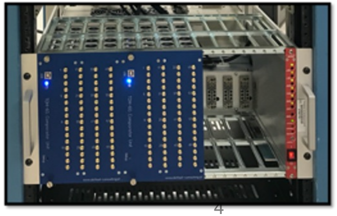




Korzh et al, *Nature Photonics* (2020)

High Event Rate
1.4 Gcps in 32-element array (JPL)





Craiciu et al, *Optica* (2023)

Technology Development Needs for Dark Matter

Active Area

- Currently ~mm^2 area
- Targeting cm^2 area and beyond
- Fab process development and readout

Energy Threshold

- Currently at 18 μm (70 meV)
- Likely possible to reach 30 μm (40 meV) and possibly lower
- Exploring strategies to efficiently couple (antennas, dielectric stacks, photonics)

Dark Counts

- Currently at <10^{-5} cps at 1550 nm
- Physical origin of dark counts is not well understood
- Limits are not well understood as energy threshold decreases

UV Operation

- Characterization and optimization of SNSPDs at VUV energies
- Currently preparing cryostat for SNSPD measurements at NIST SURF synchrotron (3 – 300 eV photons, ~1 ns pulses)

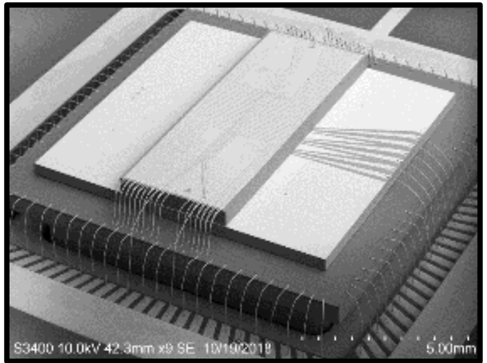
SNSPD Applications

Free-Space Optical Communication

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

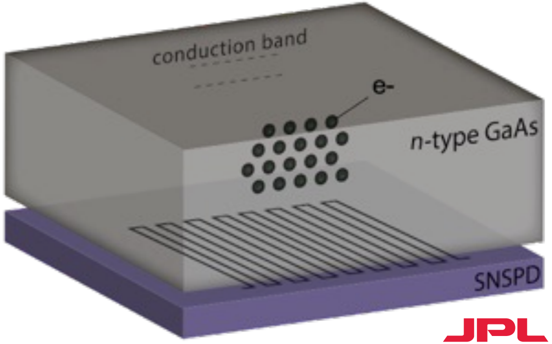
Quantum Information Science

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



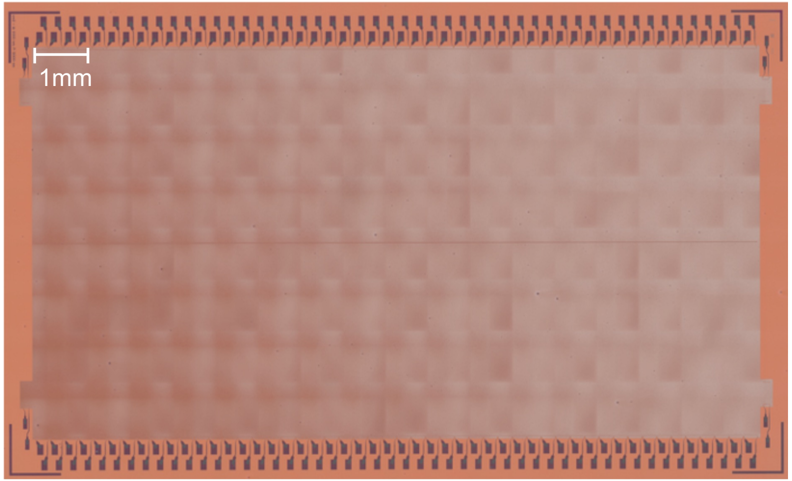
Fundamental Physics

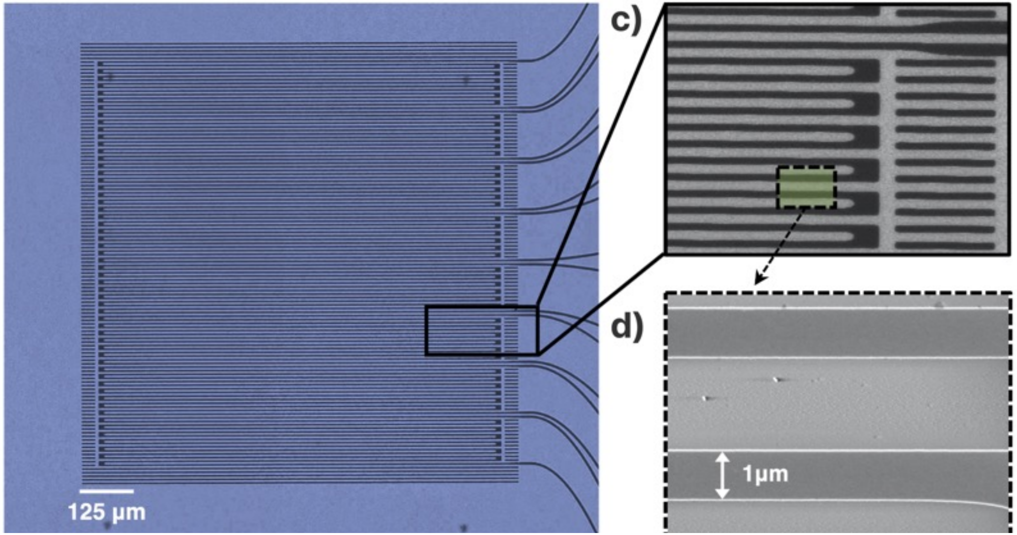
- *Dark Matter searches (Dielectric Haloscopes, scintillator readout)*
- *Tabletop tests of quantum gravity*
- *Infrared Astronomy*

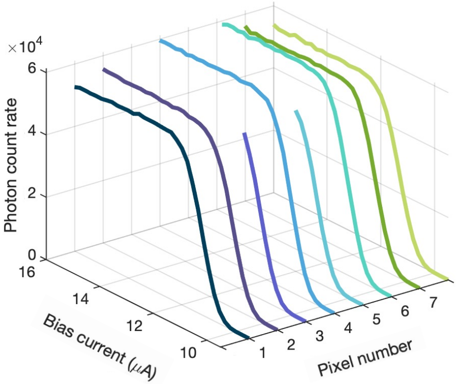


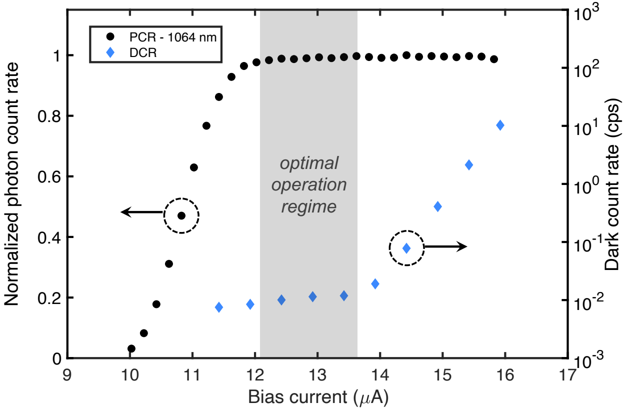
Large Area SNSPDs for Dark Matter

- Currently fabricating mm^2 and cm^2 SNSPD arrays
- Micron-wide wires enable larger area with photolithography
- Investigating multiple approaches to multiplexing many pixels
- Frequency-domain, thermal coupling, row-column readouts, SFQ





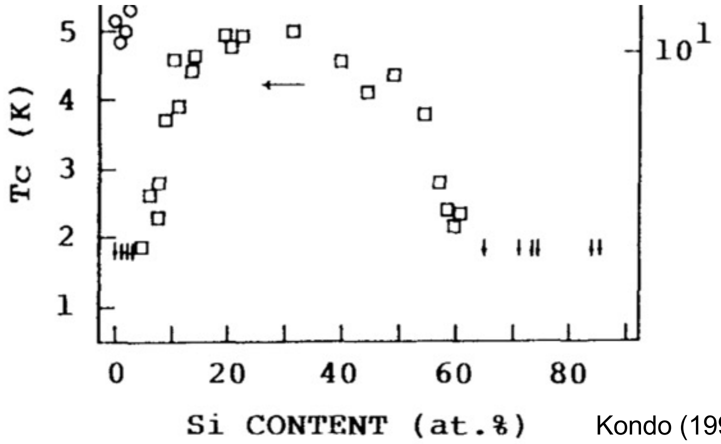




Strategies for Reduced Energy Threshold

Reduced Superconducting Gap Energy

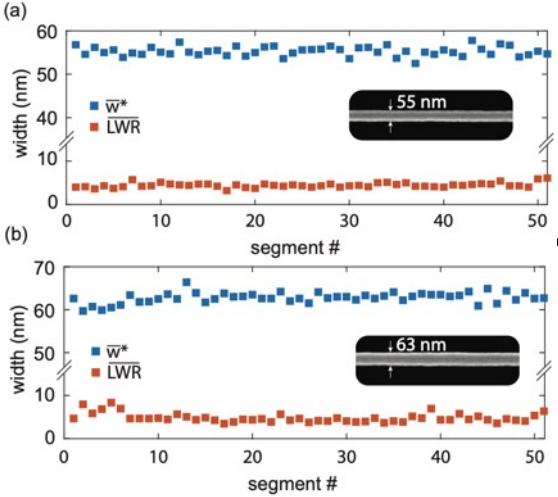
- Now using Si-rich WSi to reduce Tc to 1.3-2.1 K (depending on thickness)
- “Conventional” WSi for NIR devices has Tc = 3.1 – 3.6 K



Kondo (1991)

Narrow Nanowires

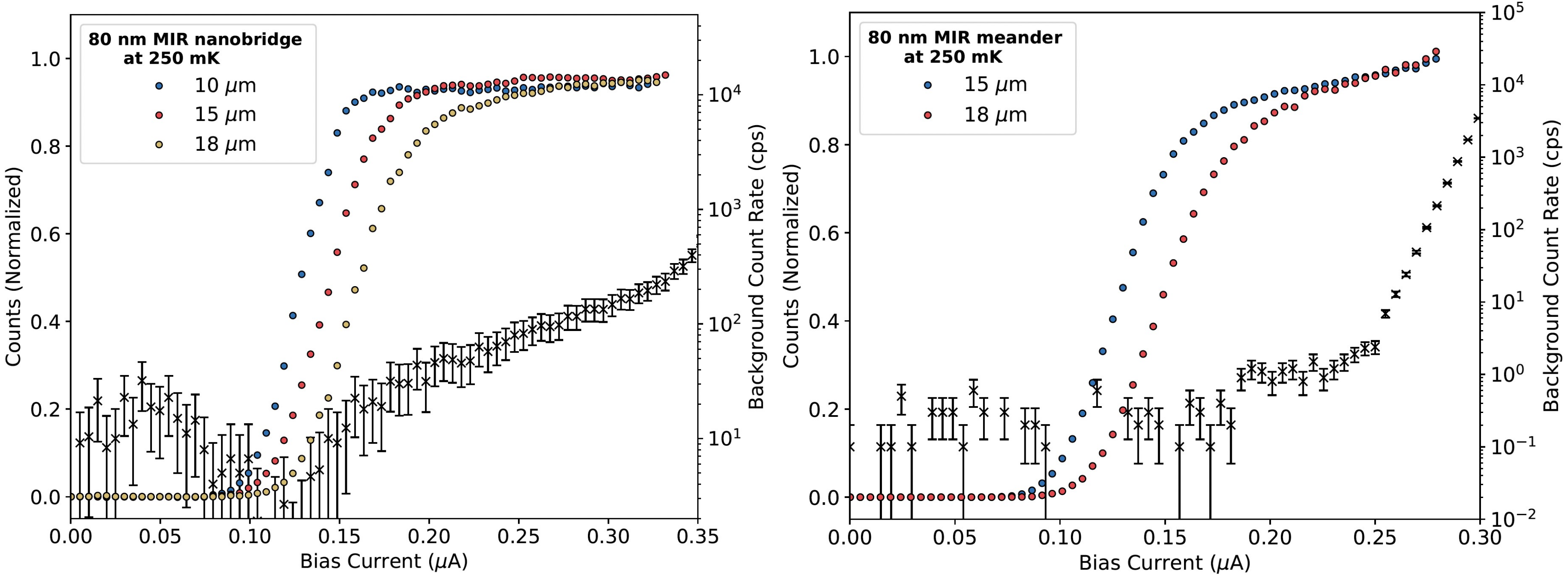
- Narrower nanowires enhance IR sensitivity by constraining hotspot growth
- Reliably fabricating SNSPDs with 50-60 nm wires using electron-beam lithography



Colangelo et al (APL 2022)

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

Saturated Internal Efficiency up to 18 μm (70 meV)

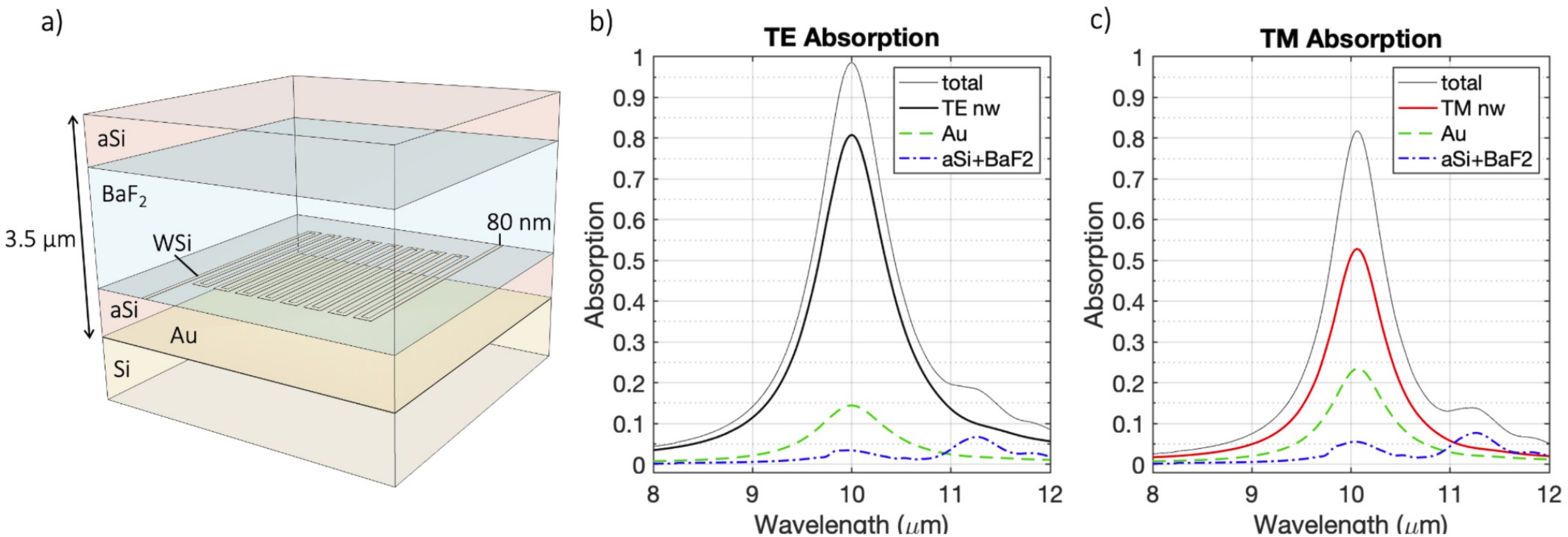


Devices have 100% *internal* efficiency, but need to be optimized for efficient coupling at these wavelengths

NIST
MIT
JPL

Approach to Efficient Coupling: Optical Stacks

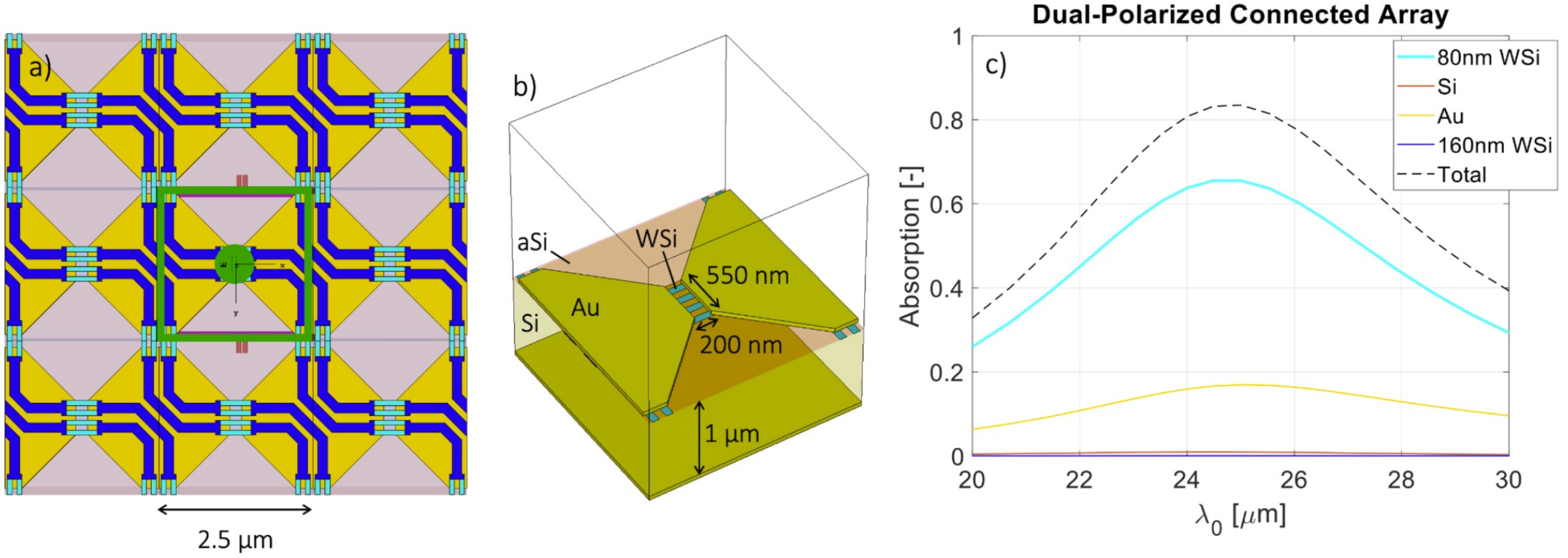
- Optical stack approach has proven very effective in the NIR (98% system detection efficiency observed at NIST)
- SNSPDs do not face the same restrictions on amorphous dielectrics as KIDs (TLS noise)
- Conventional materials will work to ~7 μm
- Adapting the approach for wavelengths as long as 18 μm requires careful selection of dielectric materials
- Investigating Ge, a-Si, c-Si, BaF_2, CdTe/PbSe as low-loss candidates at long wavelengths



NIST
MIT
JPL

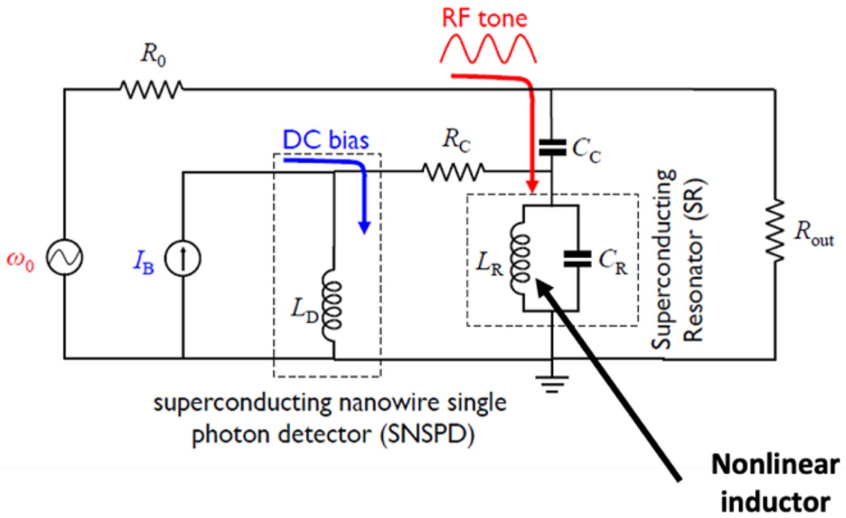
Approach to Efficient Coupling: Dipole Antennas

- For long wavelengths, resonant dipole antenna coupling is a good approach to reach high efficiencies
- Reduces active area of nanowire compared to direct absorption
- Currently investigating antenna designs in collaboration with MIT (Dip Joti Paul / Karl Berggren) and JPL (Sven van Berkel)
- Still requires good dielectrics in longwave infrared
- Dual-polarization designs are possible



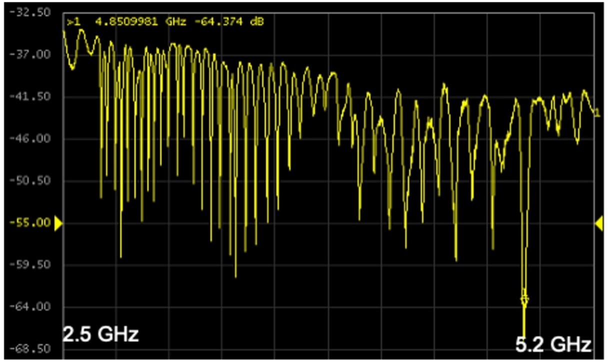
Frequency Domain Multiplexing of SNSPDs

- 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

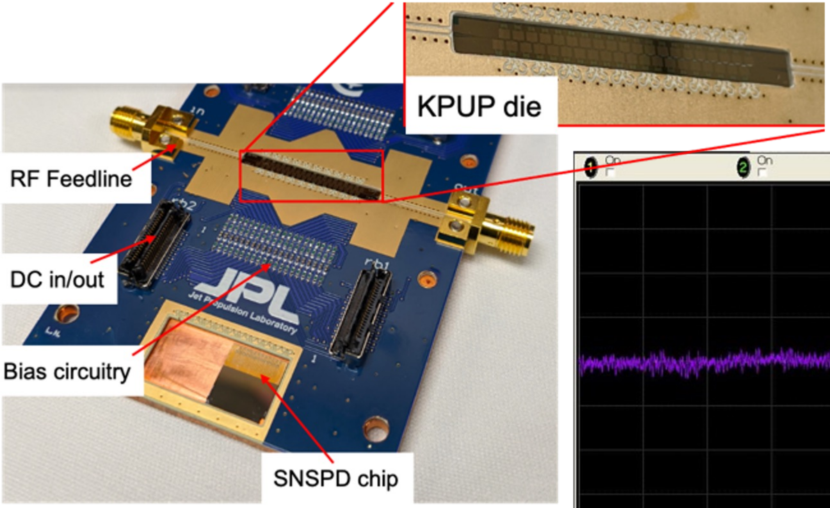


Preliminary results with frequency multiplexing

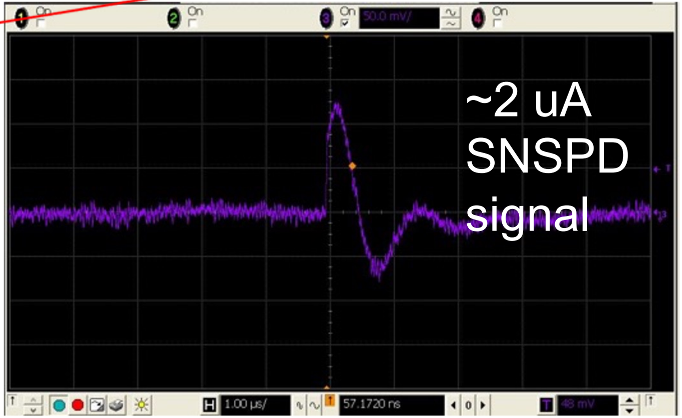
- Interfaced SNSPD array with KPUP chip containing 40 resonators on one feedline
- Successfully read out SNSPD pulse and demonstrated DC frequency shifting necessary for reconfigurable readout



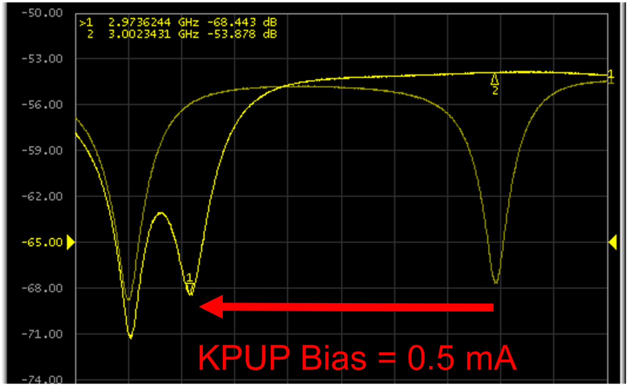
40 microwave resonators on one feedline



SNSPD array interfaced to resonator chip



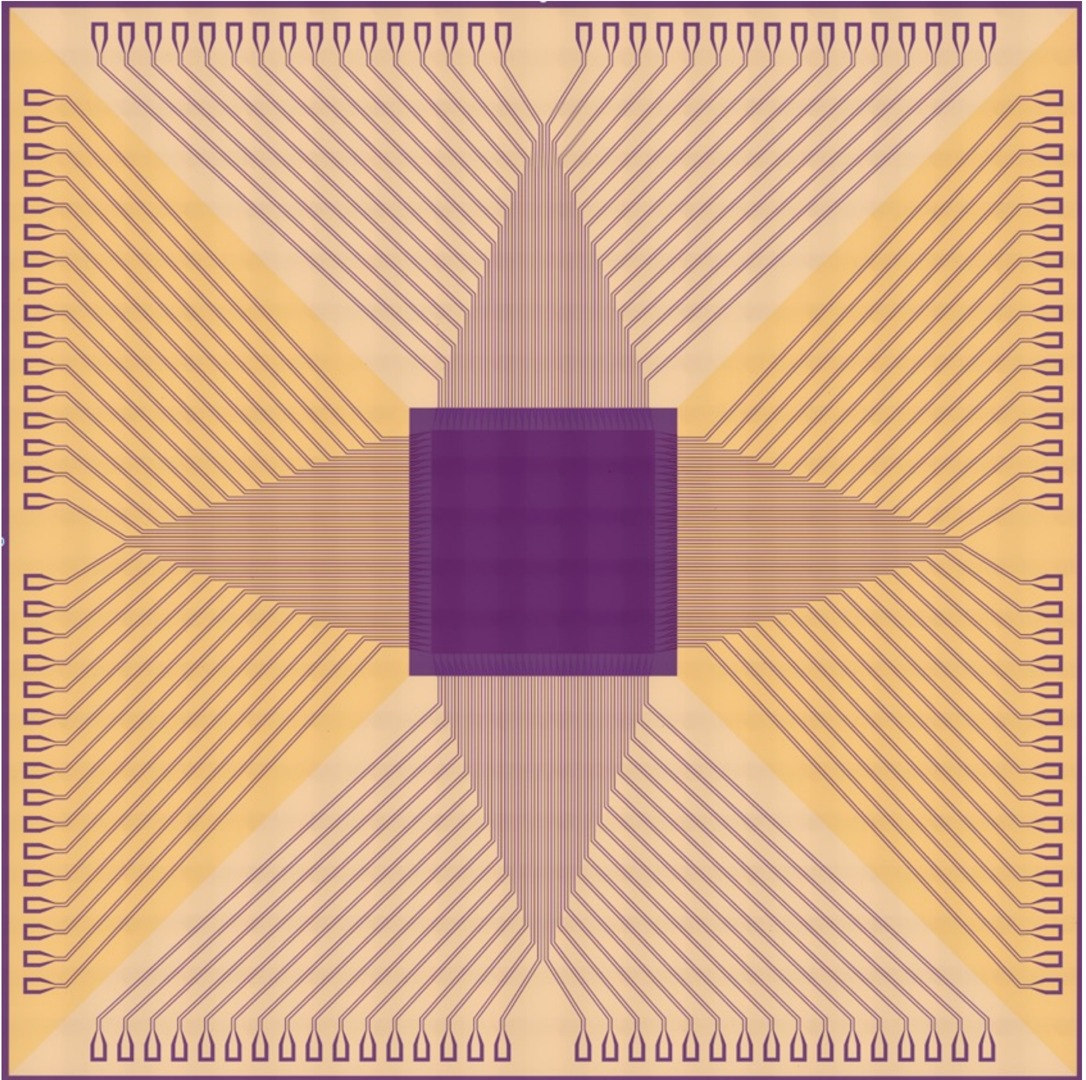
Frequency domain SNSPD readout



Demonstration of resonator shift with DC bias

Next Steps for SNSPD Development for Dark Matter

- Scaling active area to cm^2 and beyond
- Reducing energy threshold toward fundamental limits (20 meV?)
- Engineering high optical coupling efficiency for far-infrared photons
- Developing frequency-domain readout to scale to large arrays of low-threshold SNSPDs
- Understanding and mitigation of low-energy backgrounds



Thanks for your attention!

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Jet Propulsion Laboratory
California Institute of Technology