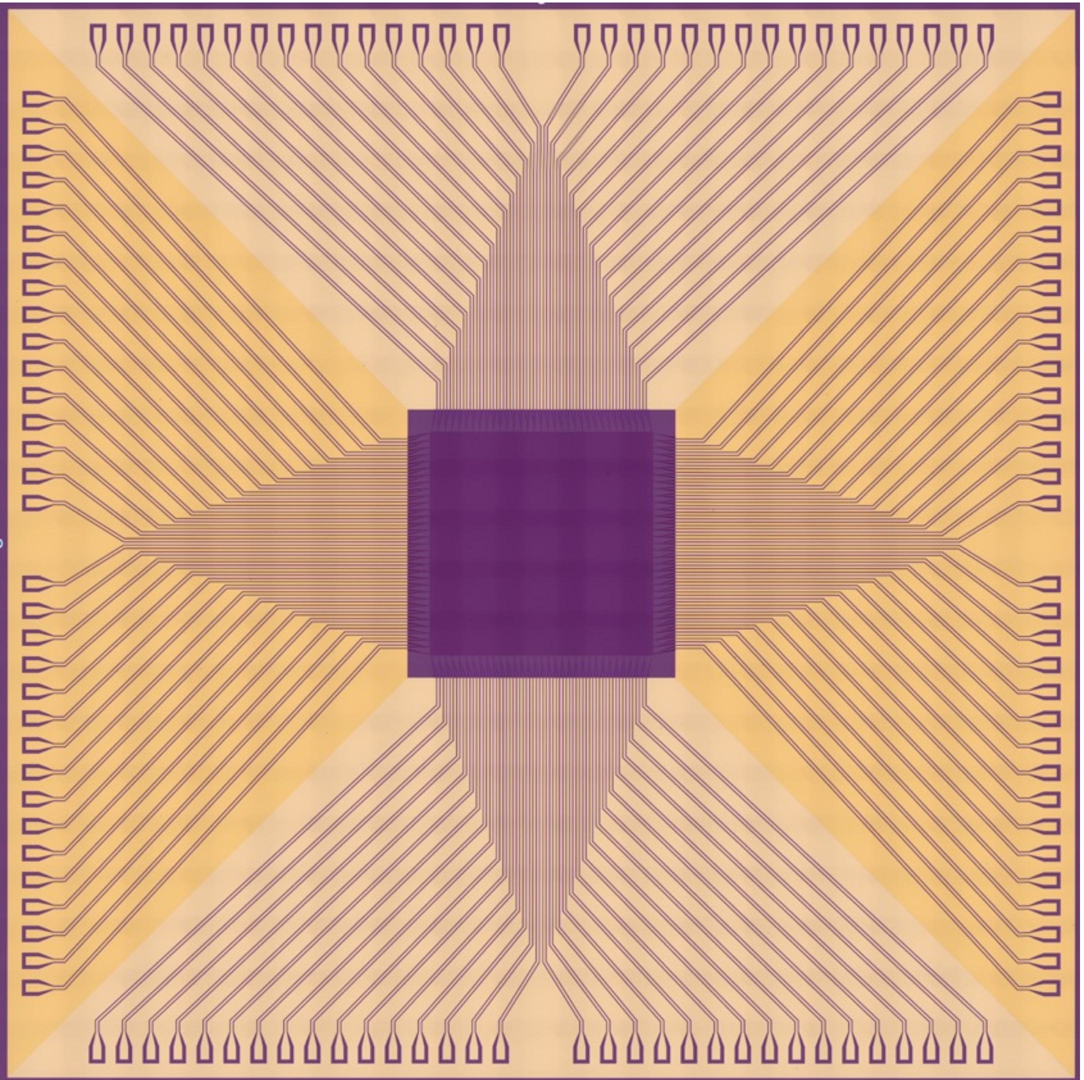


# Superconducting Nanowire Single Photon Detectors

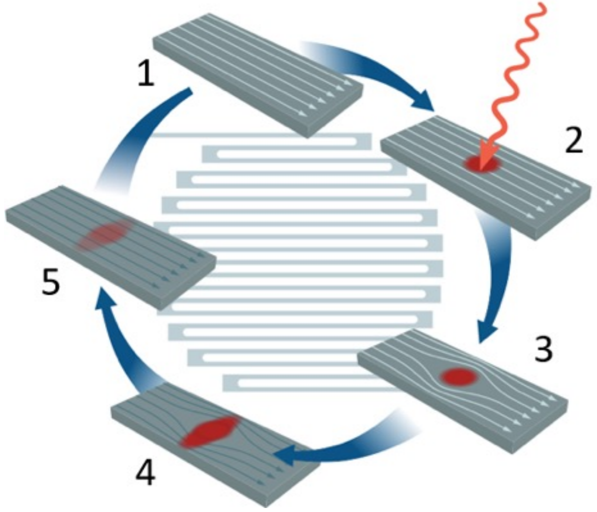
**CPAD, Stony Brook**

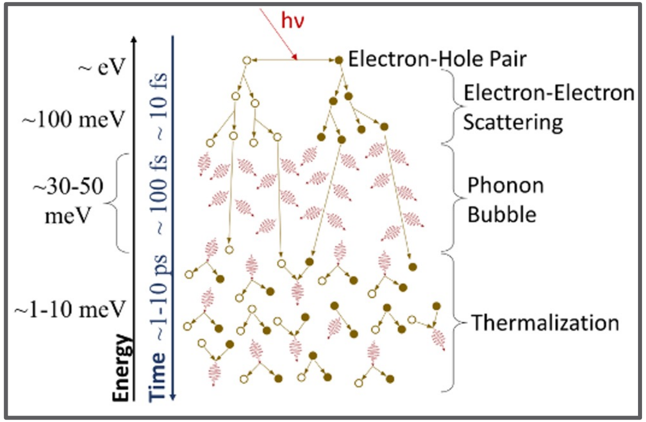
**29 November 2022**

Matt Shaw
Supervisor
Superconducting and Quantum Devices Group,
Jet Propulsion Laboratory

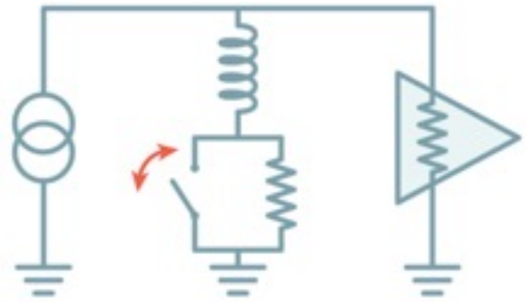
**Jet Propulsion Laboratory**
California Institute of Technology

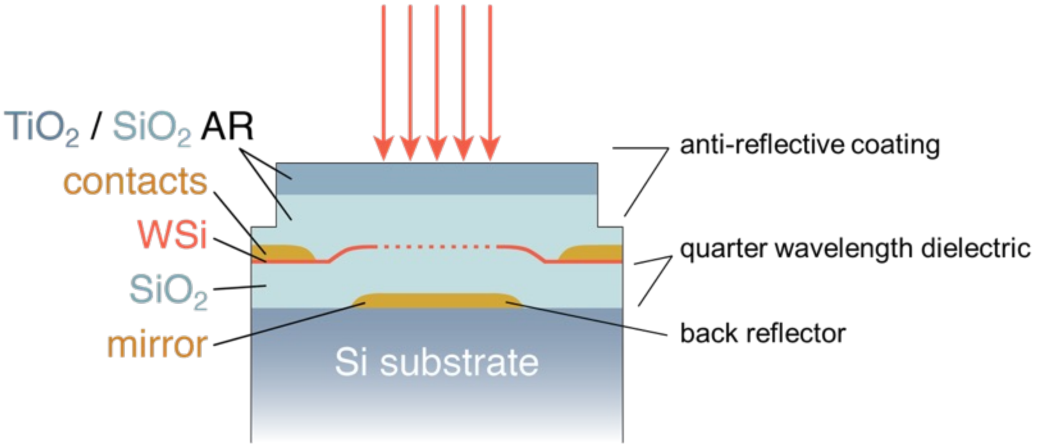
# Superconducting Nanowire Single Photon Detectors




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

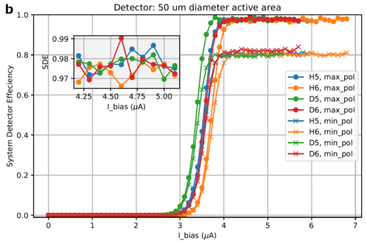




# Present State of The Art in SNSPDs

## High Efficiency

98% SDE @ 1550 nm (NIST)

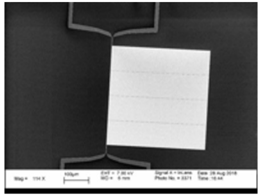


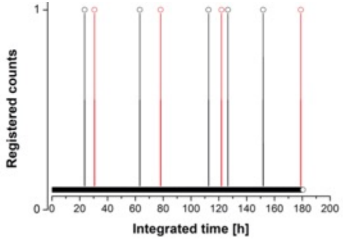

Reddy et al, *Optica* (2018)

## Low Dark Counts

6e-6 cps (MIT/NIST)

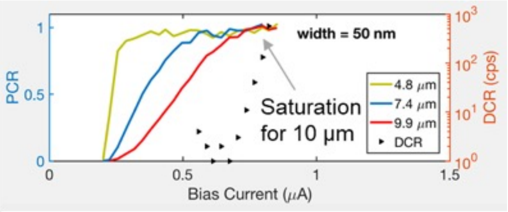
Chiles et al, *Phys. Rev. Lett.* (2022)

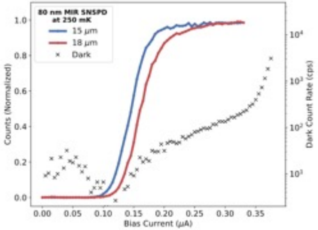





## UV – Mid-IR Operation

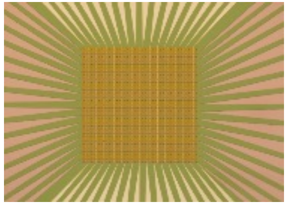
Photon counting to 18 μm (JPL/MIT/NIST)

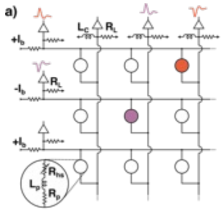



## Kilopixel Array Formats

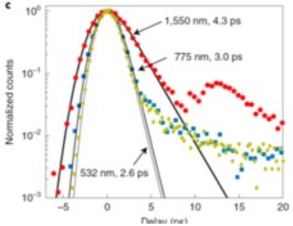
32x32 “row-column” array (NIST/JPL)

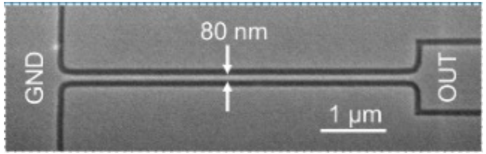





## High Time Resolution

2.6 ps FWHM (MIT/JPL/NIST)



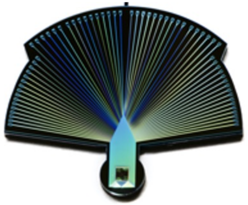




Korzh et al, *Nature Photonics* (2020)

## High Event Rate

Wollman et al, *Optics Express* (2019)

1.4 Gcps in 32-element array (JPL)



NIST MIT JPL

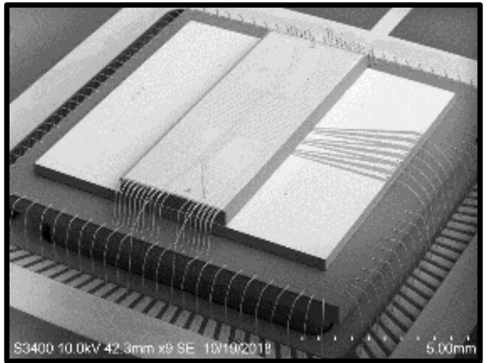
# SNSPD Applications

## Free-Space Optical Communication

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

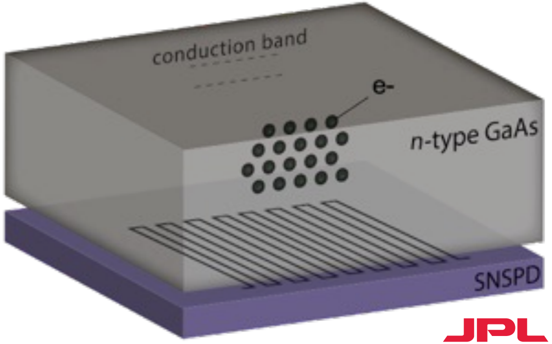
## Quantum Information Science

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




## Fundamental Physics

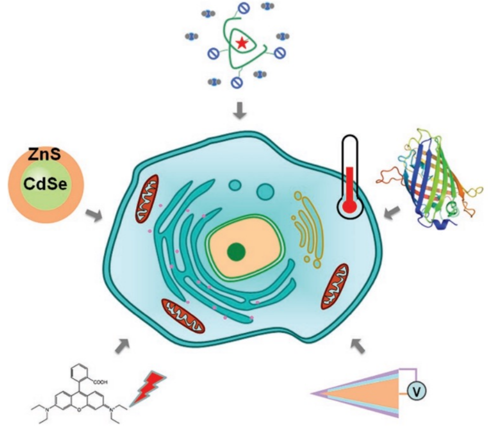
- *Dark Matter searches (scintillation from GaAs, dielectric haloscopes, BREAD)*
- *Tabletop tests of quantum gravity*



# SNSPD Applications

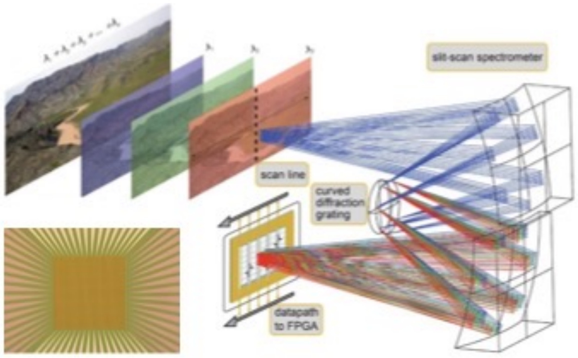
## Biomedical

- *Diffuse Correlation Spectroscopy*
- *Fluorescence Lifetime Imaging Spectroscopy*
- *Singlet Oxygen Detection*
- *Thermal microscopy*




## Remote Sensing

- *Passive Thermal Rangefinding*
- *Photon-counting Lidar*
- *Time-resolved Raman spectroscopy*
- *Entangled-photon spectroscopy*




## Astronomy and Heliophysics

- *Exoplanet transit spectroscopy (IR)*
- *Interferometry for exoplanets (IR)*
- *Direct exoplanet imaging (vis/IR)*
- *UV astronomy*
- *Optical counterparts of fast radio bursts (NIR)*
- *Metastable helium lidar (NIR)*

# SNSPD Advantages for Fundamental Physics

**Dark Matter Detection**

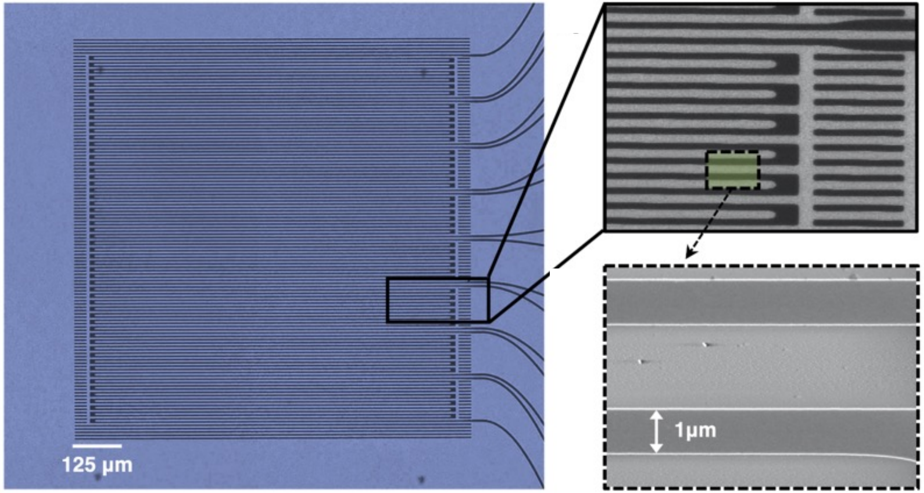
- Low dark counts ($10^{-5}$ cps)
- Low energy threshold (70 meV)
- Large active area ($mm^2 \rightarrow cm^2$)

**Nuclear Physics and Collider Physics**

- High time resolution (3 ps)
- Low dark counts ($10^{-5}$ cps)
- Radiation hardness

**Tests of Quantum Gravity**

- Low dark counts ($10^{-5}$ cps)
- High efficiency (98% @ 1.5 μm)
- Photon number resolution (1, 2, or many)



# Technology Development for Dark Matter

## Active Area

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

## 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

## Energy Threshold

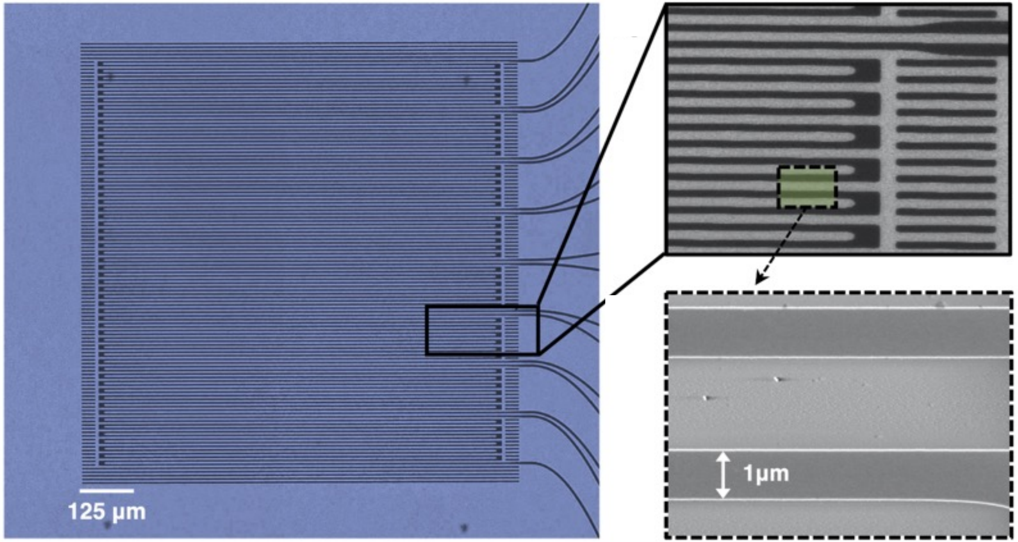
- Currently at 18 μm (70 meV)
- Likely possible to reach 30 μm (40 meV) and possibly lower
- Exploring strategies to efficiently couple (antennas, dielectric stacks, photonics)

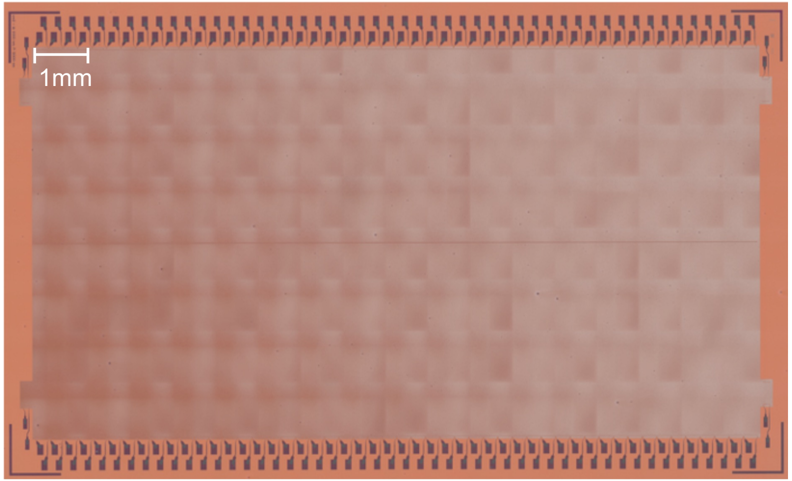
## UV Operation

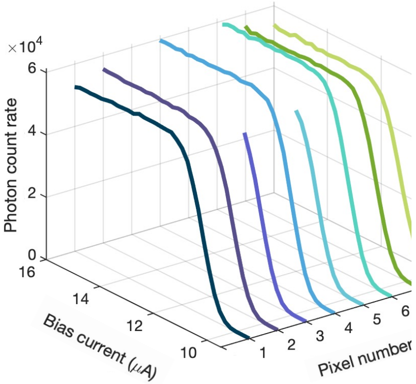
- Characterization and optimization of SNSPDs at VUV energies
- Currently preparing cryostat for SNSPD measurements at NIST SURF synchrotron (3 – 300 eV photons, ~1 ns pulses)

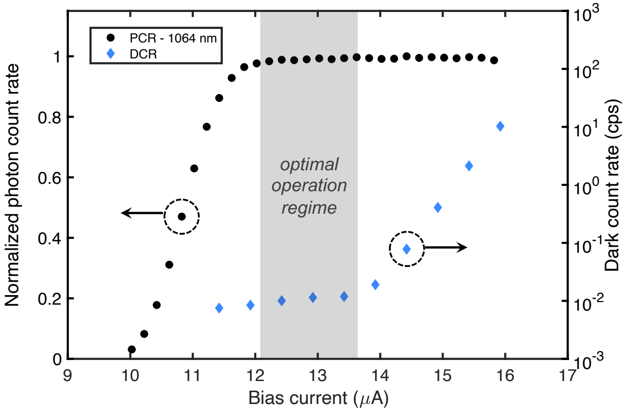
# Scaling to Larger Areas

- 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



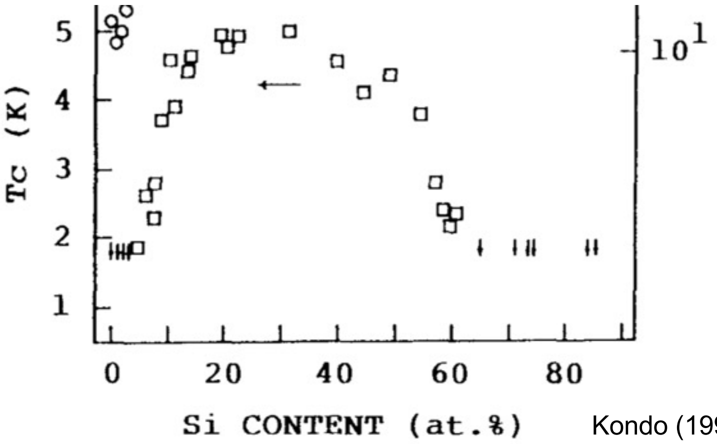



# Strategies for Lower Energy Thresholds

## Reduced Superconducting Gap Energy

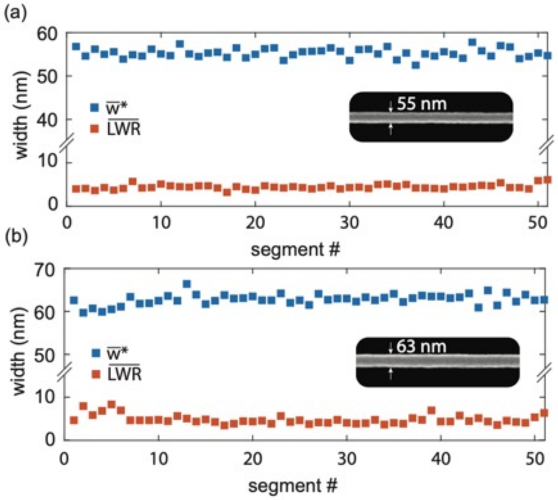
- Now using Si-rich WSi to reduce Tc to 1.3-2.1 K (depending on thickness)
- “Conventional” WSi for NIR devices has Tc = 3.1 – 3.6 K




Kondo (1991)

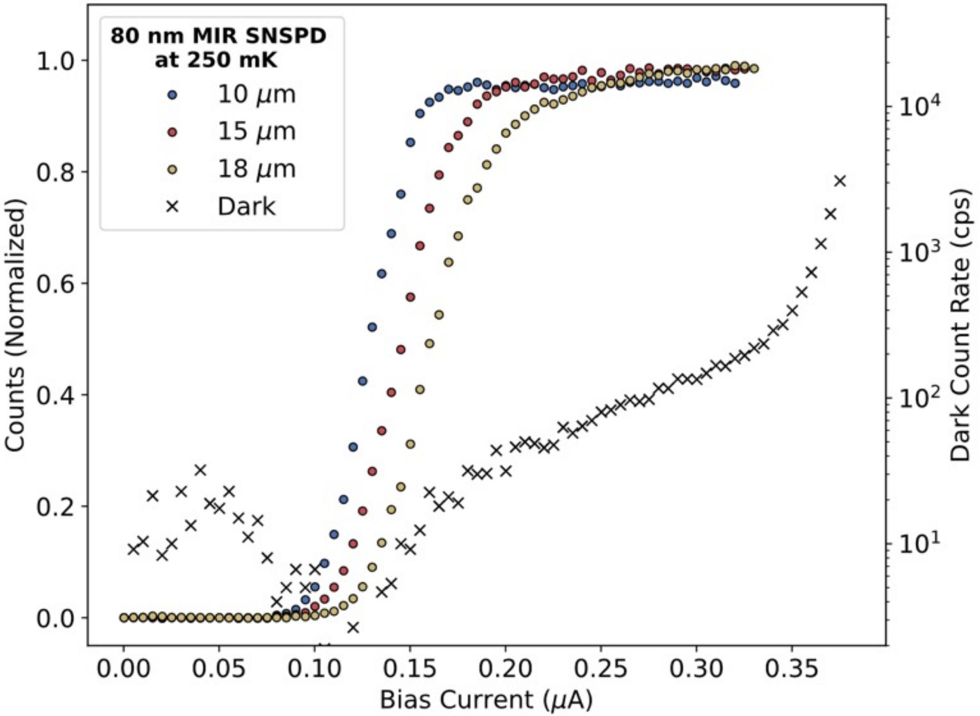
## Narrow Nanowires

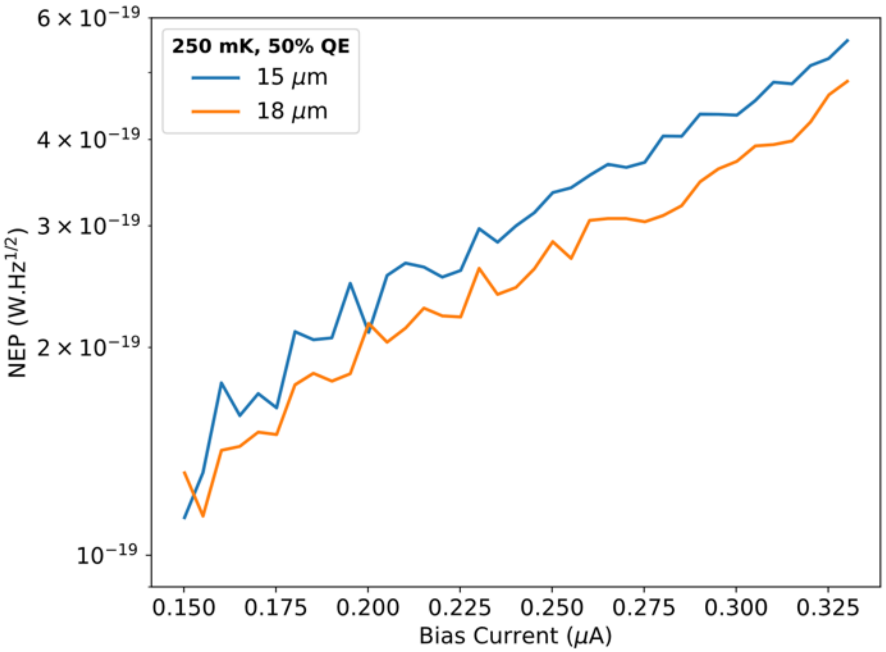
- Narrower nanowires enhance IR sensitivity by constraining hotspot growth
- Reliably fabricating SNSPDs with 50-60 nm wires using electron-beam lithography




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

# Saturated Internal Efficiency from 10 - 18 μm

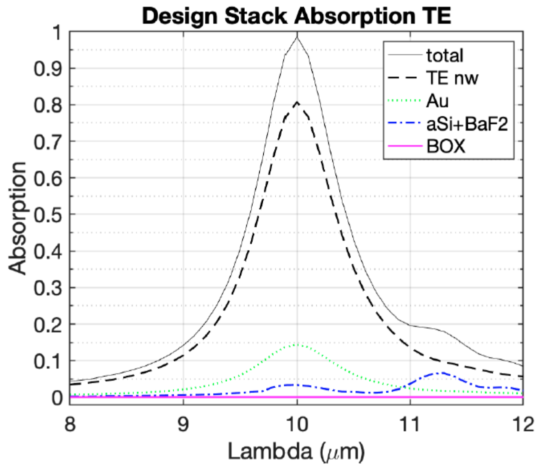


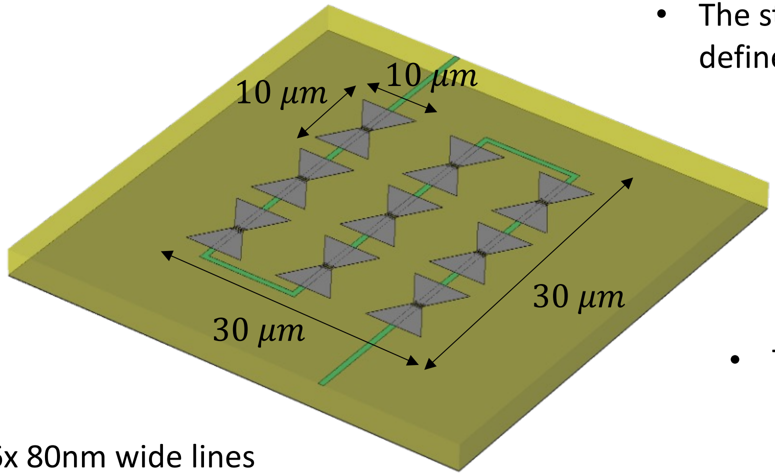

**WSi SNSPD nanobridge with 3 nm thickness: Tc = 1.3 K**

# 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

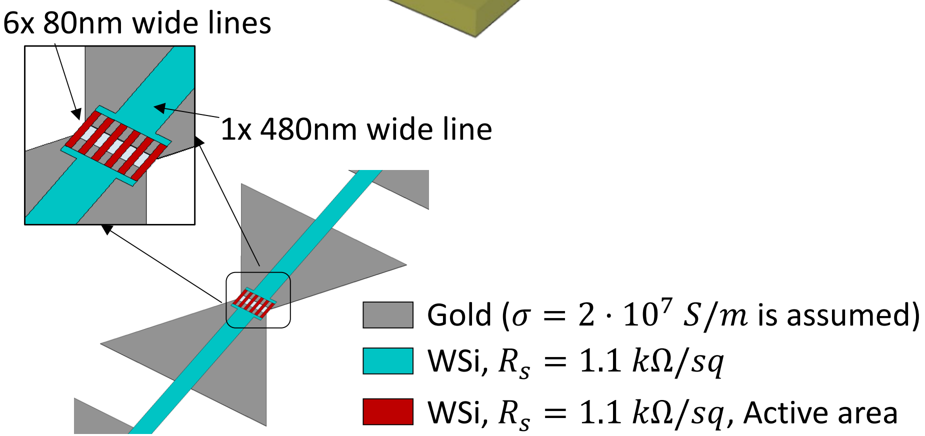
# Approach to Efficient Coupling: Dipole Antennas

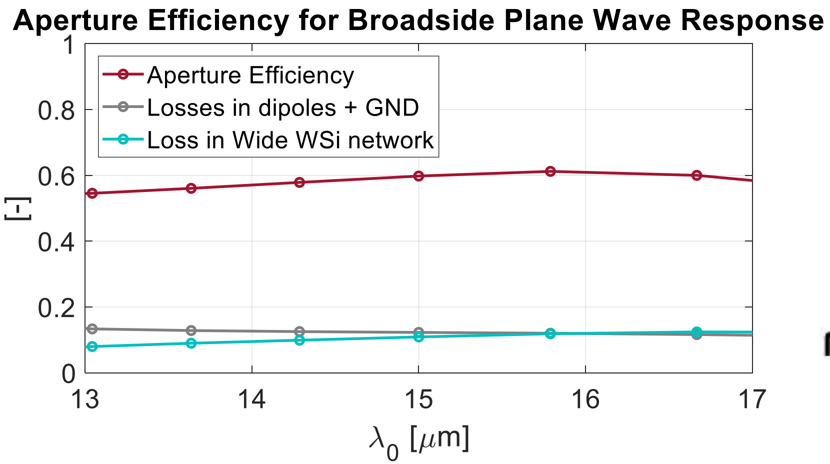



- The structure is illuminated by a plane-wave at broadside incidence. It is defined with unitary amplitude $|E_x| = 1\ V/m$
  - The power incident on the 3x3 active area ($30\ \mu m \times 30\ \mu m$) is:

$$P_{inc}^{PW} = \frac{1}{2\zeta_0}|E_x|^2 A_{active}$$

  - The aperture efficiency is defined as: $\eta_{ape} = \frac{P_{inc}^{PW}}{P_{abs}^{WSi,Active}}$
- The loss is the power dissipated in the antennae or the wide WSi network.



# Conclusions

- *SNSPDs are the highest performing detectors available for time-resolved single photon counting, from the UV to the Infrared*
- *SNSPDs are rapidly advancing with significant room for further gains*
- *SNSPDs can be a powerful new tool for fundamental physics*