Superconducting Nanowire Single Photon Detectors Opportunities for HEP

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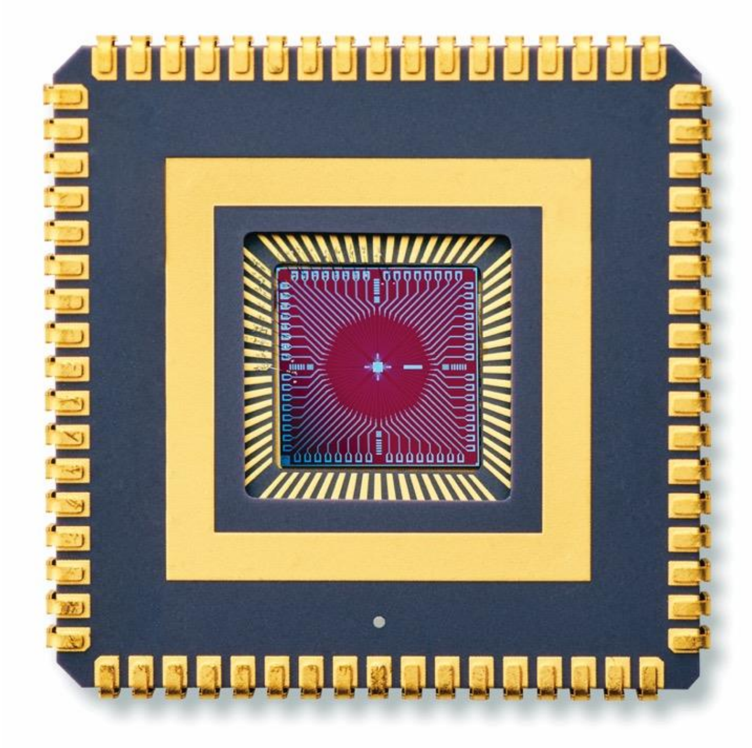
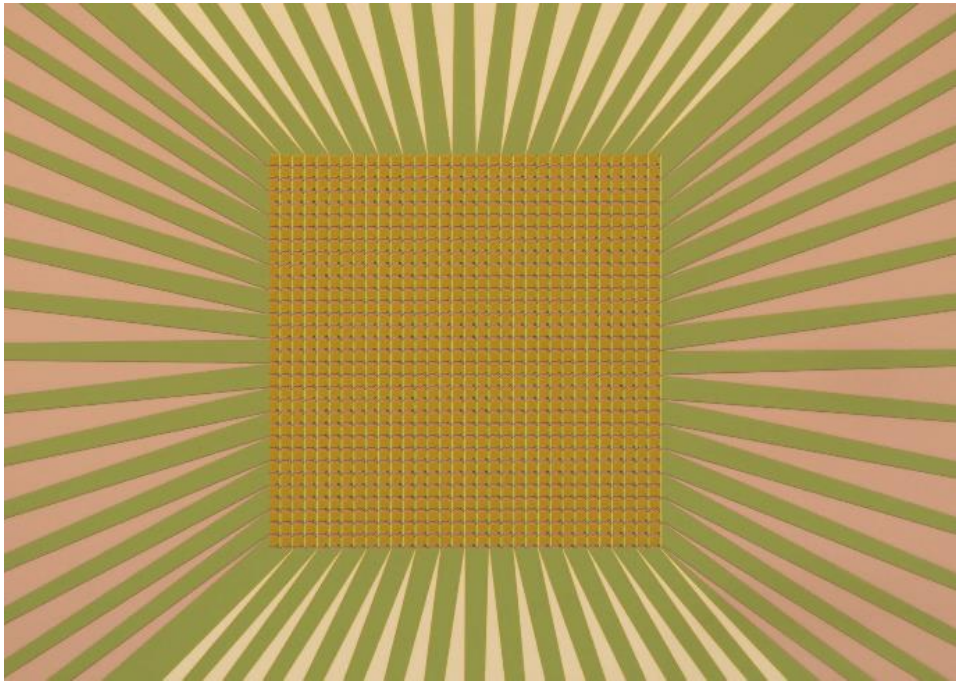
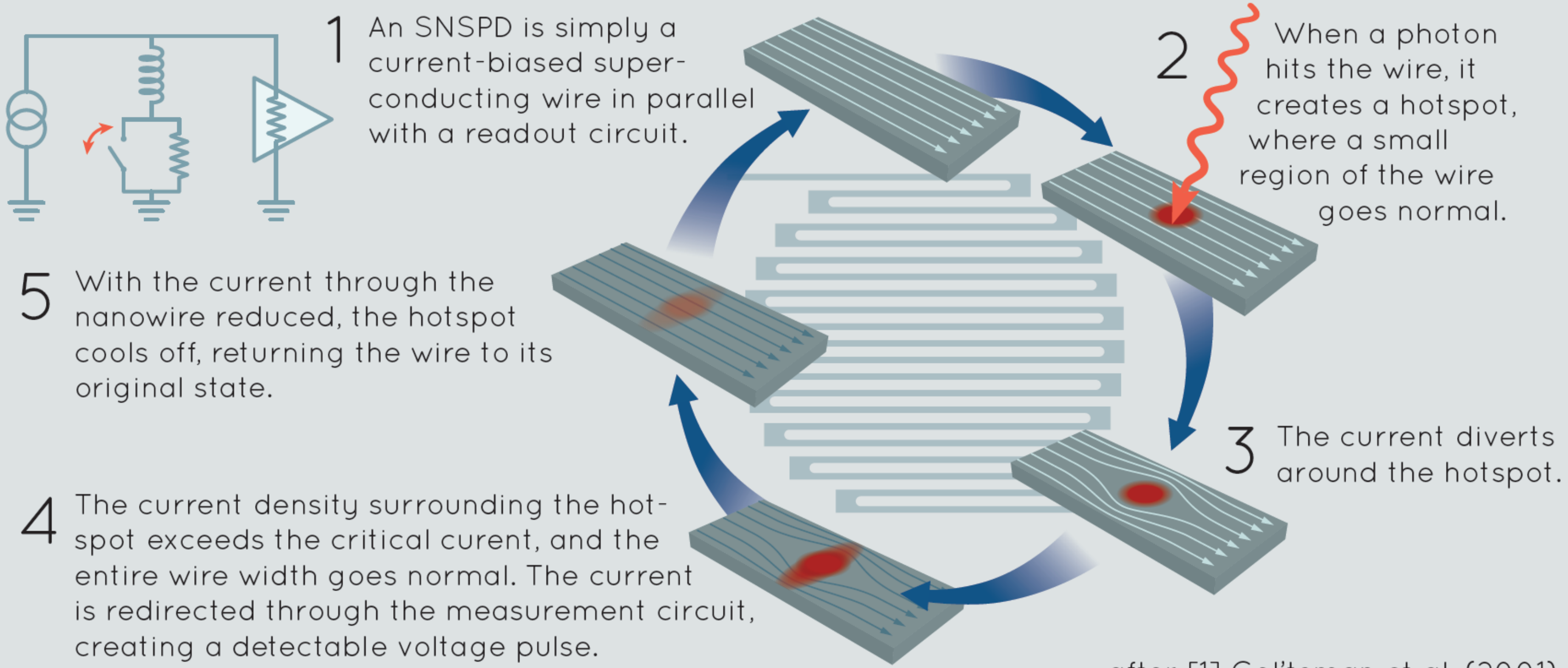
CPAD Workshop, 8 December 2019





SNSPD Device Concept

- Heat from a single photon triggers detector out of superconducting state
- Resistance jumps to few kΩ in picoseconds, shunting detector current into readout
- Highest performance single-photon detector available, from UV to mid-infrared
- 1 – 4 Kelvin operating temperature



1 An SNSPD is simply a current-biased superconducting wire in parallel with a readout circuit.

2 When a photon hits the wire, it creates a hotspot, where a small region of the wire goes normal.

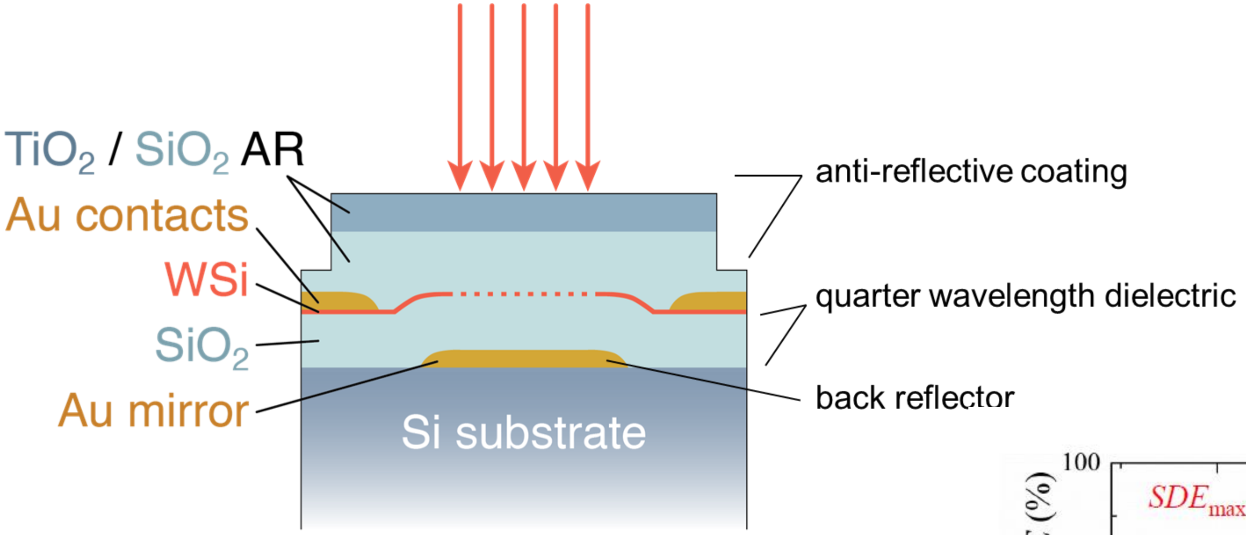
3 The current diverts around the hotspot.

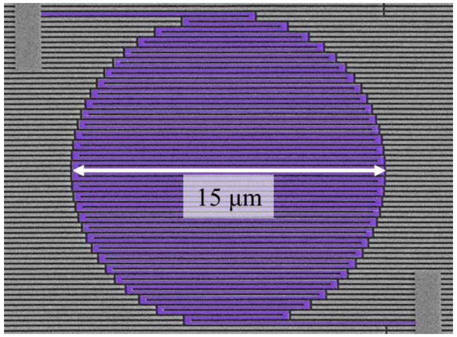
4 The current density surrounding the hotspot exceeds the critical curent, and the entire wire width goes normal. The current is redirected through the measurement circuit, creating a detectable voltage pulse.

5 With the current through the nanowire reduced, the hotspot cools off, returning the wire to its original state.

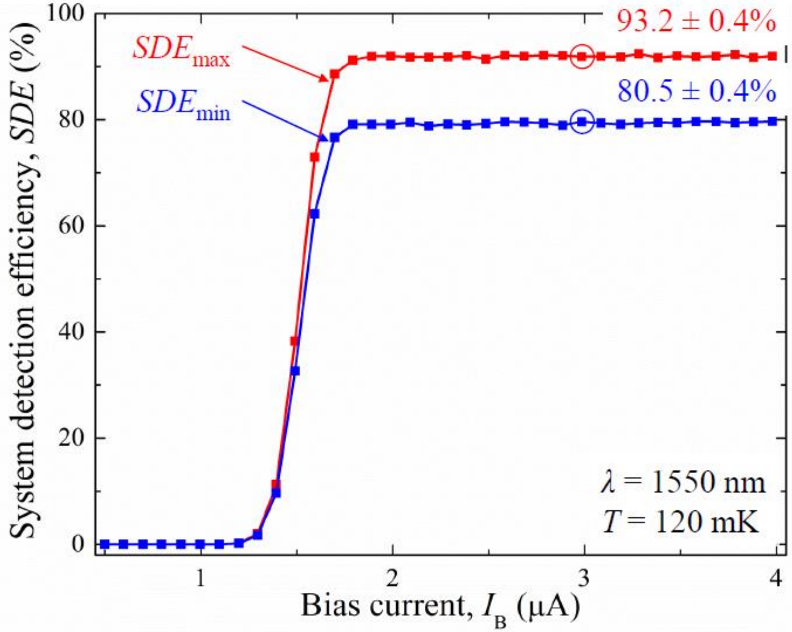
after [1] Gol’tsman et al. (2001)

WSi SNSPD Architecture





- WSi SNSPDs developed in 2012 by JPL and NIST
- Now fully commercialized
- System detection efficiency up to 93% @ 1550 nm
- Sub-Hertz intrinsic dark counts
- Maximum count rates of 20 Mcps (3 dB saturation)
- 80 ps FWHM timing jitter



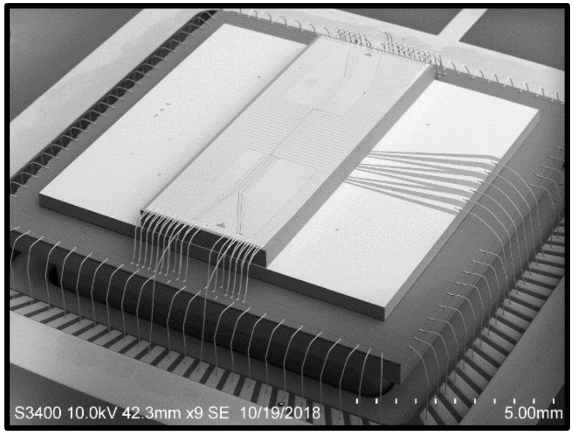
System detection efficiency for single pixel device

Marsili et al, *Nature Photonics* **7**, 210 (2013)

Established SNSPD Applications

Quantum Information Science

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

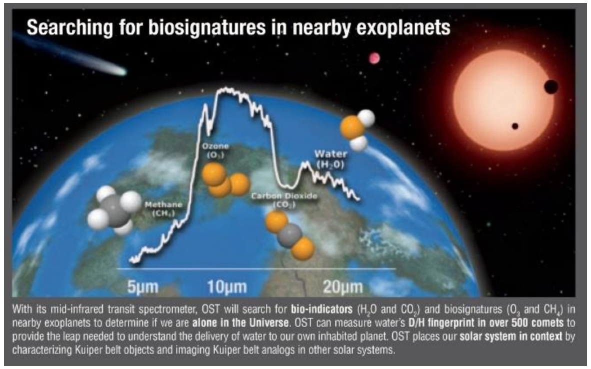


Free-Space Laser Communication

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

Physics & Astronomy

- *Dark Matter searches*
- *Exoplanet Transit Spectroscopy*
- *Ultrafast transients*



With its mid-infrared transit spectrometer, OST will search for **bio-indicators** (H_2O and CO_2) and biosignatures (O_3 and CH_4) in nearby exoplanets to determine if we are **alone in the Universe**. OST can measure water's **D/H fingerprint in over 500 comets** to provide the leap needed to understand the delivery of water to our own inhabited planet. OST places our **solar system in context** by characterizing Kuiper belt objects and imaging Kuiper belt analogs in other solar systems.

Summary of SNSPD Performance

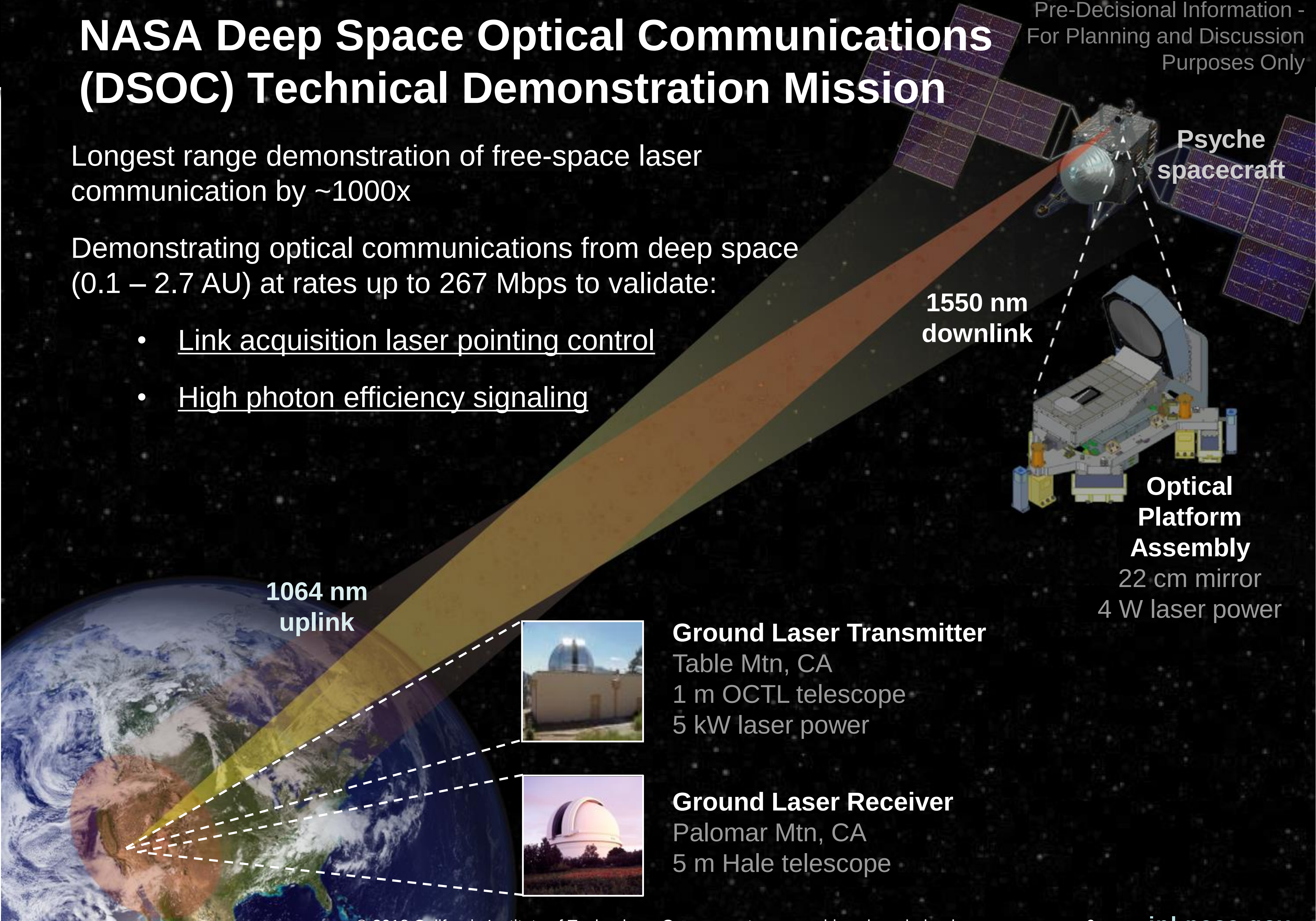
Parameter	SOA 2019	SOA 2016	Group
Efficiency	98% @ 1550 nm	93% @ 1550 nm	NIST
Dark Counts	< 1e-5 cps	< 0.1 cps	MIT / NIST
Energy Threshold	0.125 eV	0.250 eV	NIST / JPL / MIT
Timing Jitter	2.7 ps	16 ps	MIT / JPL / NIST
Active Area	0.92 mm^2	0.058 mm^2	NIST / JPL
Max Count Rate	1.2 Gcps	0.3 Gcps	JPL
Pixel Count	1024 (32x32)	64 (8x8)	NIST / JPL
Photon Number Resolution	1 from 2 or more w/ 95% confidence	None	MIT / JPL
Operating Temp	4.3 K @ 1550 nm	2.5 K @ 1550nm	Single Quantum

NASA Deep Space Optical Communications (DSOC) Technical Demonstration Mission

Longest range demonstration of free-space laser communication by ~1000x

Demonstrating optical communications from deep space (0.1 – 2.7 AU) at rates up to 267 Mbps to validate:

- Link acquisition laser pointing control
- High photon efficiency signaling



Psyche spacecraft

1550 nm downlink

Optical Platform Assembly
22 cm mirror
4 W laser power

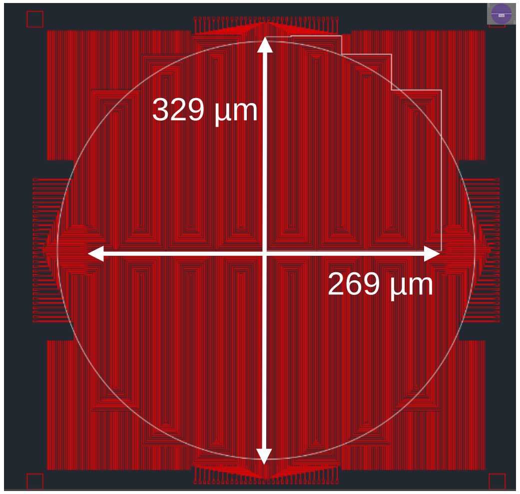
1064 nm uplink

Ground Laser Transmitter
Table Mtn, CA
1 m OCTL telescope
5 kW laser power

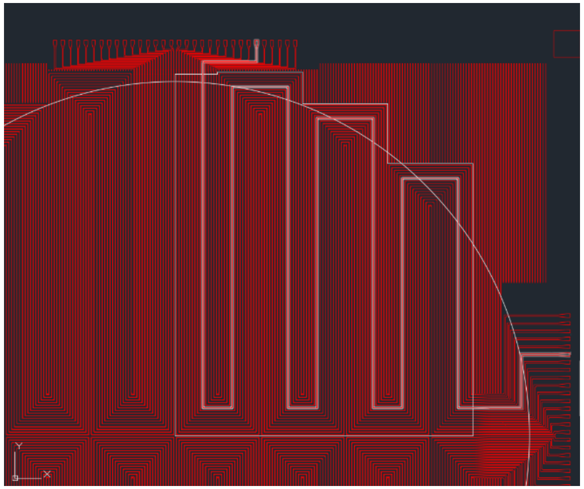
Ground Laser Receiver
Palomar Mtn, CA
5 m Hale telescope

64-Pixel SNSPD Array for DSOC

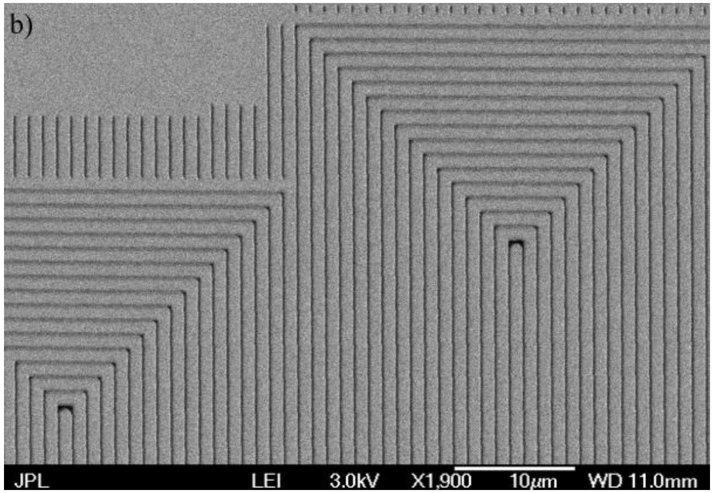
- SNSPD planned for DSOC Ground Laser Receiver at 200 inch Palomar telescope (5.1 m)
- 64-element WSi SNSPD array with >79,000 µm^2 area (equiv. to 318.5 µm diameter)
- Divided into four spatial quadrants for fast beam centroiding
- 160 nm WSi nanowires on 1200 nm pitch – each wire ~1 mm in length (~7000 squares)
- Free-space coupling to 1 Kelvin cryostat, with cryogenic filters and lens
- 78% system detection efficiency at 1550 nm
- < 80 ps FWHM timing jitter
- ~1.2 Gcps maximum count rate



CAD Design of SNSPD focal plane array



CAD Design showing one of 16 individual sensor elements per quadrant

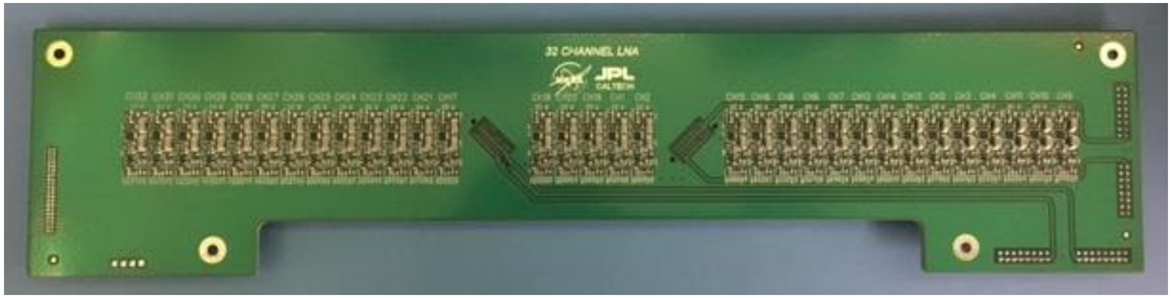


Electron Microscope Image of Nanowire Structure

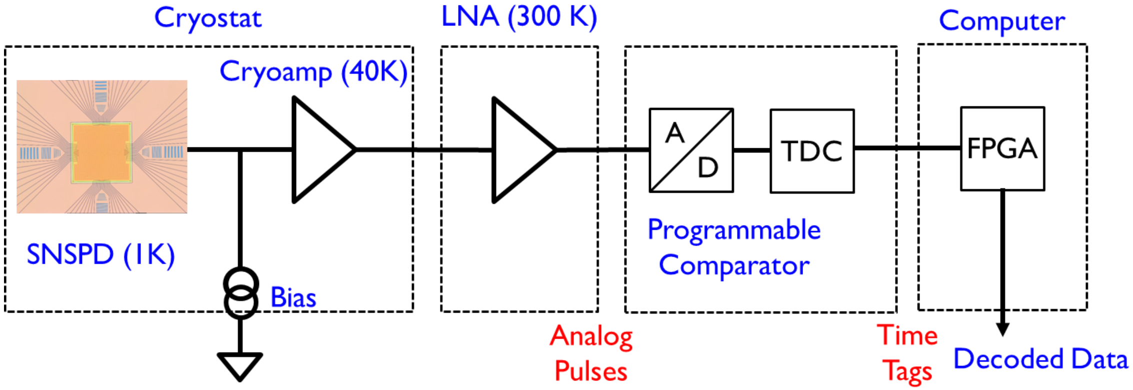
DSOC Readout Electronics

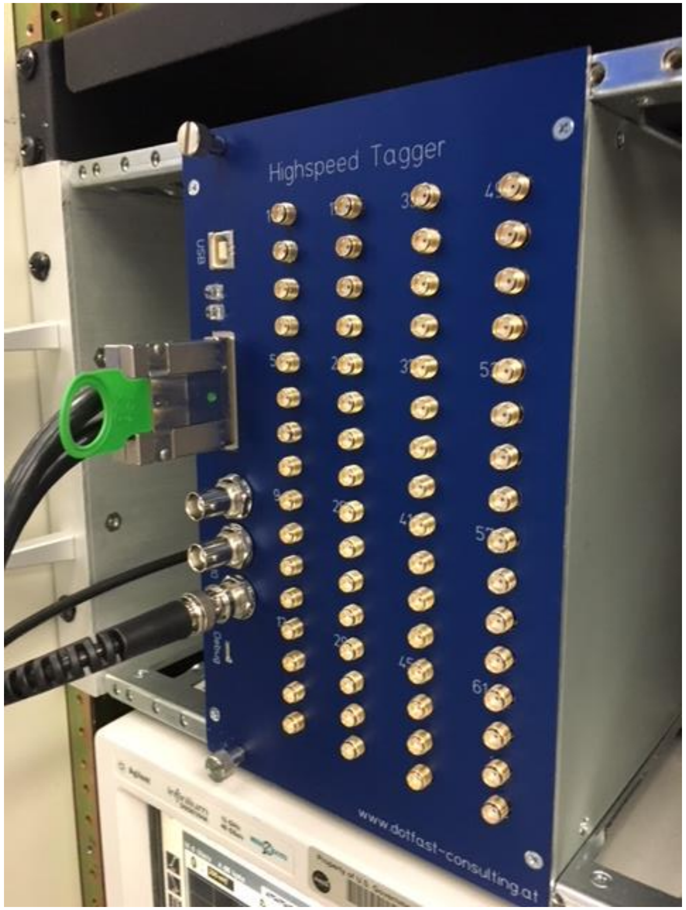
- Worked with industry on 64-channel TDC capable of streaming 900 Mtags / sec over PCIe
- Each nanowire sensor element has its own dedicated readout channel
- DC-coupled cryogenic amplifiers used at 40 K stage of cryostat

UQDevices



40 Kelvin Cryogenic Amplifier Board

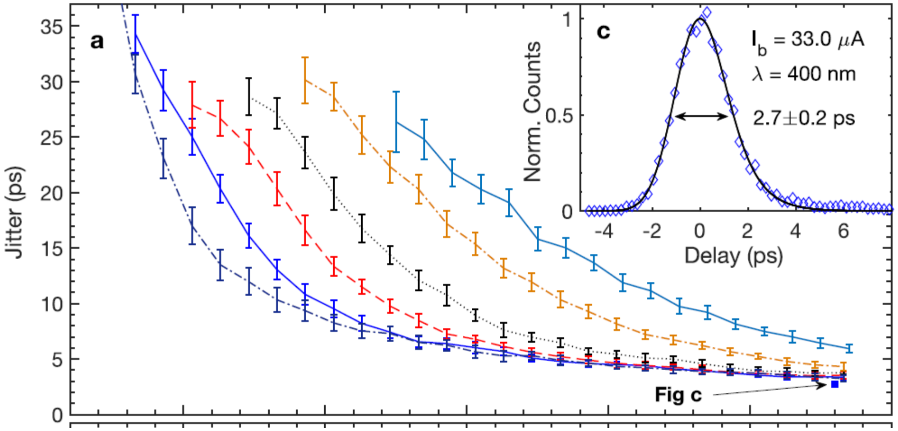




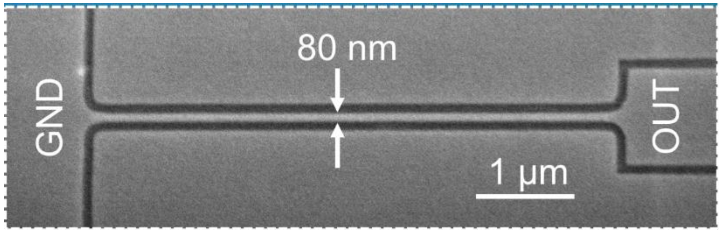
Streaming 64-channel time-to-digital converter

Ultra-high time resolution in SNSPDs

- Reduced timing jitter in SNSPDs from ~15 ps (2016 record) to 2.7 ps FWHM
- Advances in superconducting materials and low-noise readout technology
- Devices fabricated at MIT, measured with low-noise readouts at JPL and NIST
- Short nanobridges were used to avoid geometric jitter
- Proves that low jitter is achievable, but short nanobridges have negligible efficiency

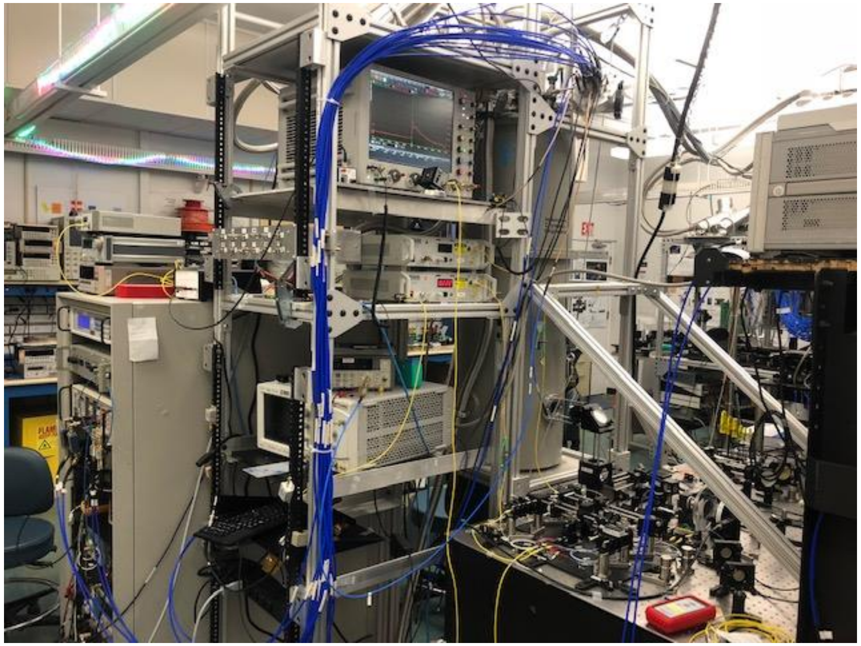


Dependence of timing jitter on photon energy



Specialized low-jitter NbN SNSPD

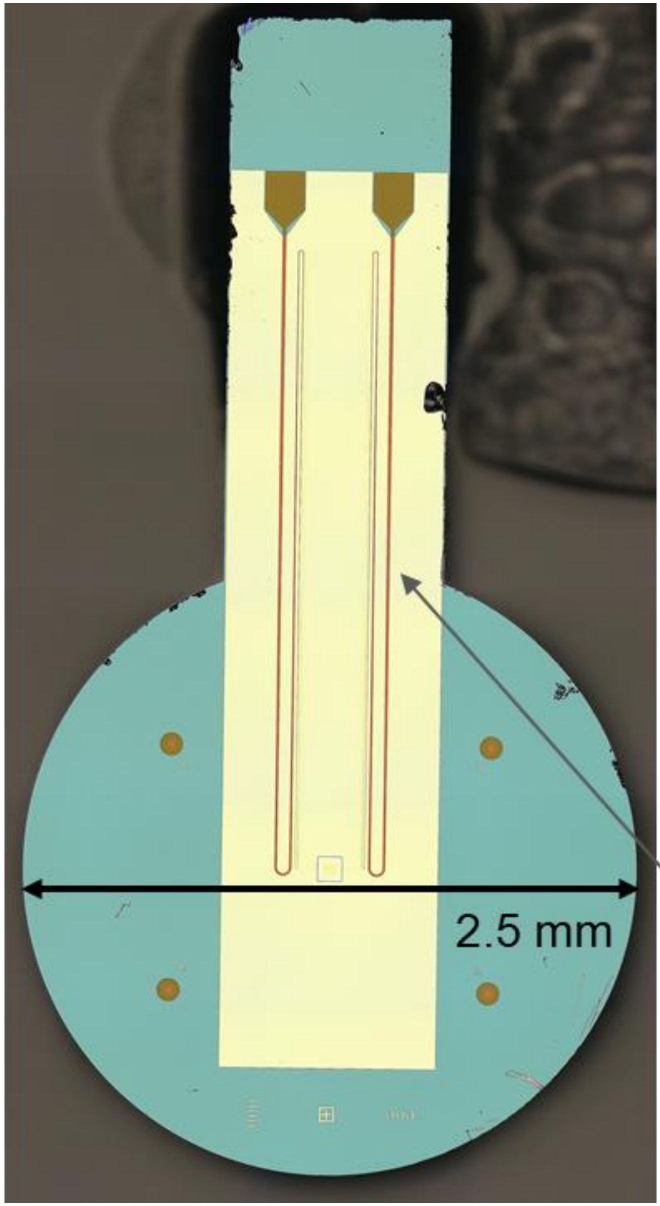
Korzh et al, arXiv 1804.06839 (2018)

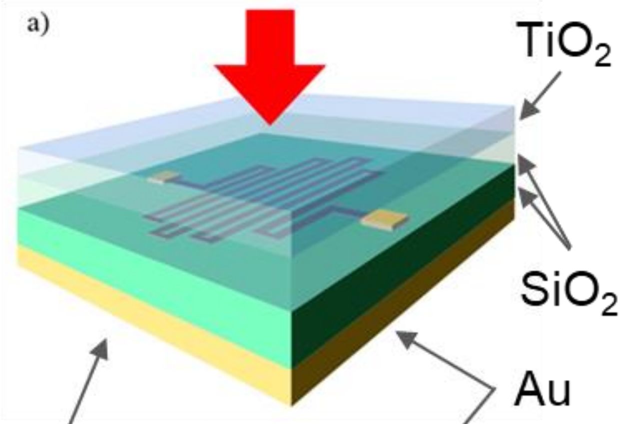


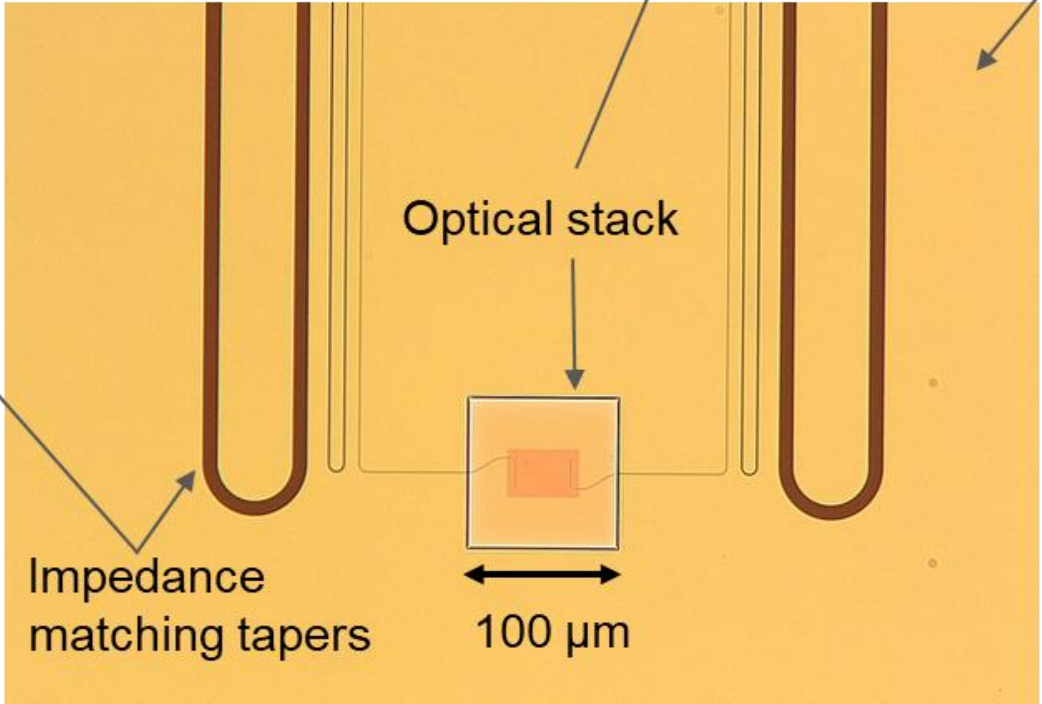
Ultra-low jitter measurement setup at JPL

Differential SNSPDs with Cavity

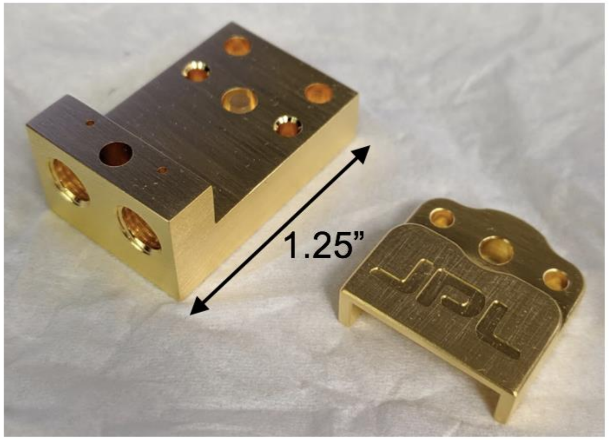
- Differential readout cancels geometric jitter
- 61% SDE @ 1550 nm
- 12 ps jitter (300K LNA)
- Photon number resolution



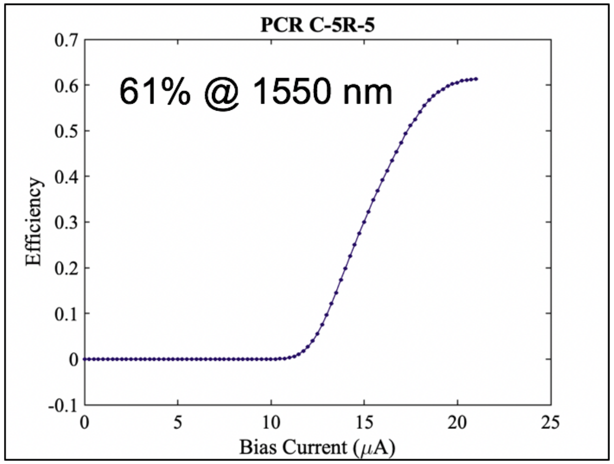




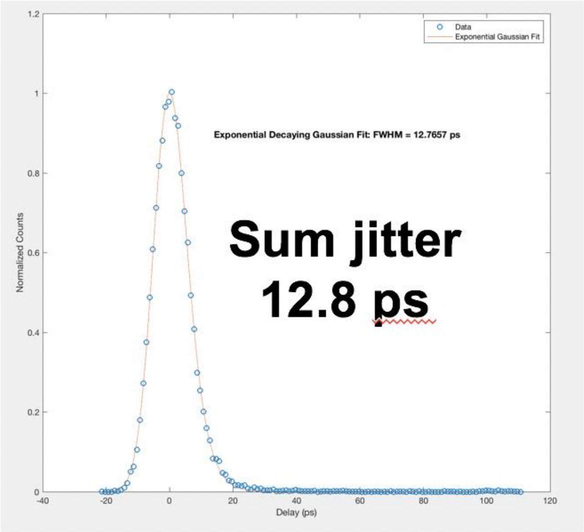
Differential SNSPDs with Cavity



Differential Device Package



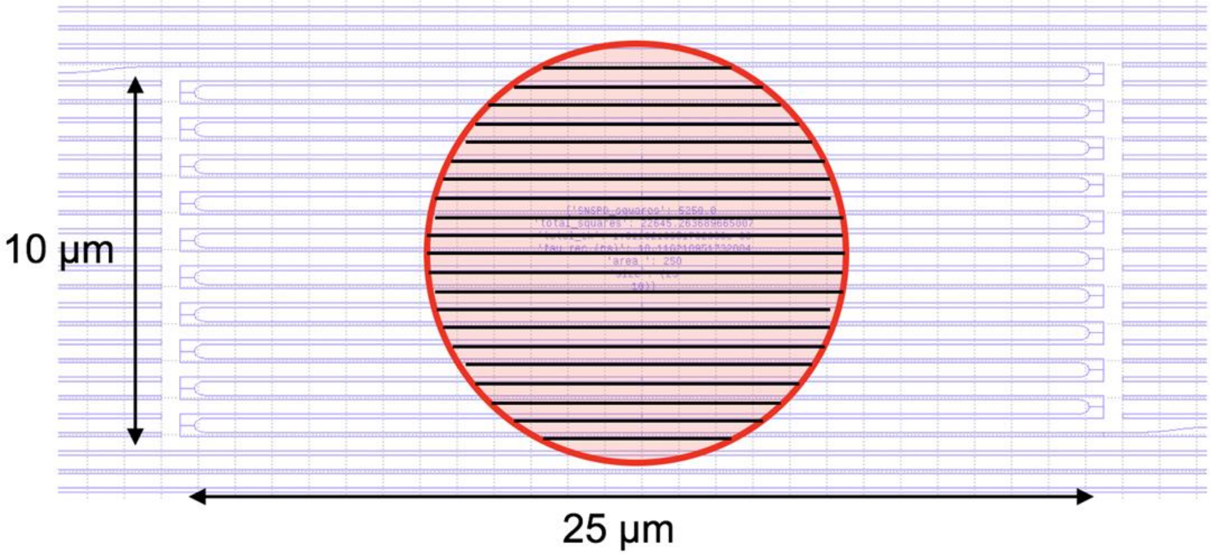
Efficiency

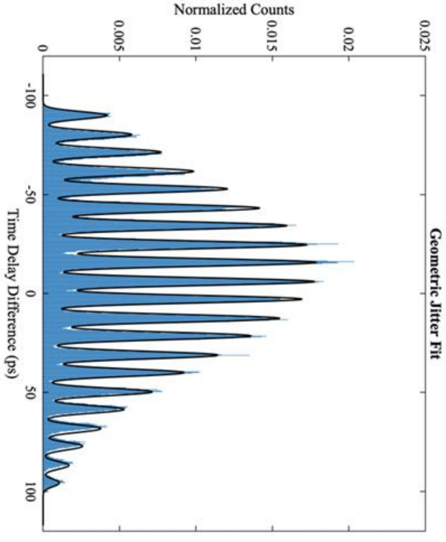


Sum jitter 12.8 ps

21 peaks correspond to the 21 meander lines of the pixel

Expect >75% efficiency with 2-layer AR coating

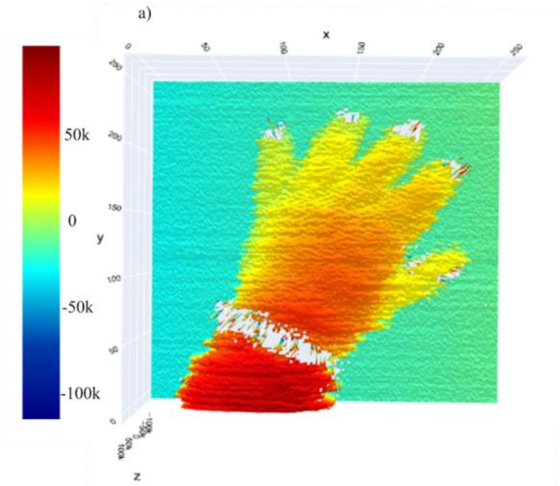




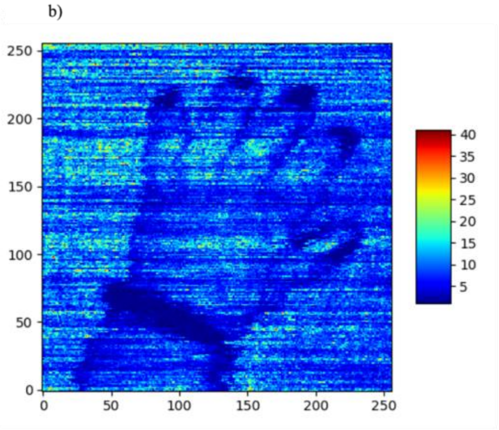
Difference jitter

Photon Counting Lidar With SNSPDs

- Differential SNSPDs infused into photon counting lidar field trials in Edinburgh, UK
- 12 ps FWHM timing jitter enables sub-cm depth resolution for every received photon



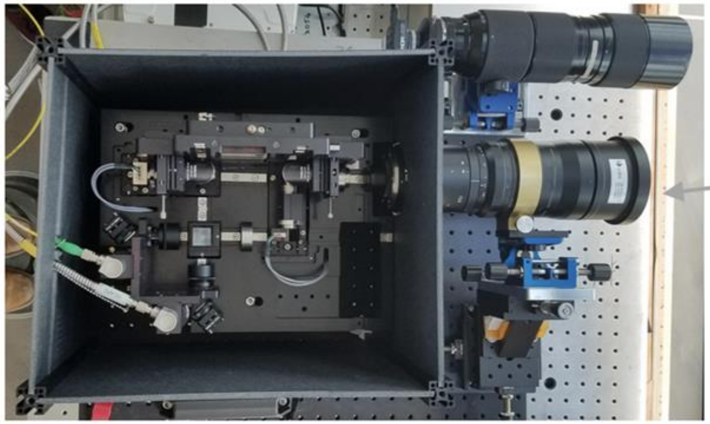
Depth image through 325 m turbulent air



Acquired photon number
10-15 photons per pixel

Heriot-Watt

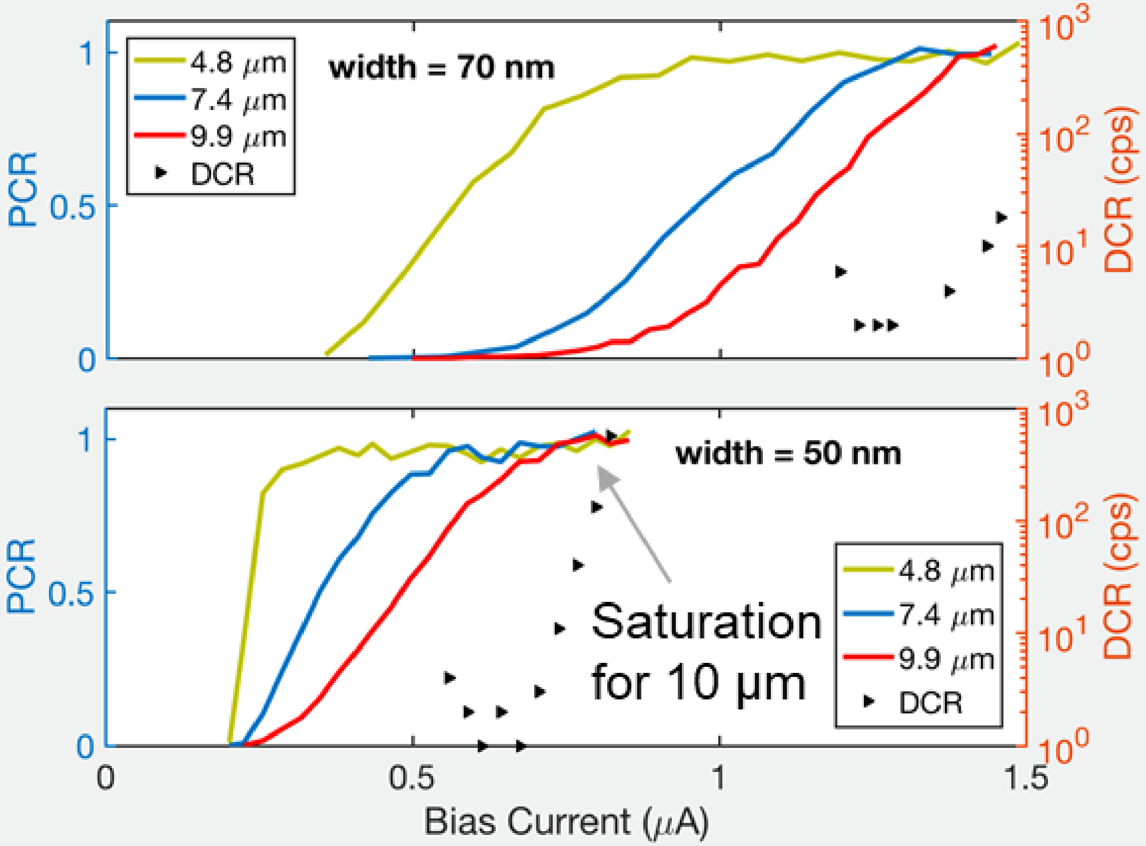
Scanner



325 m distance

Mid-Infrared Operation

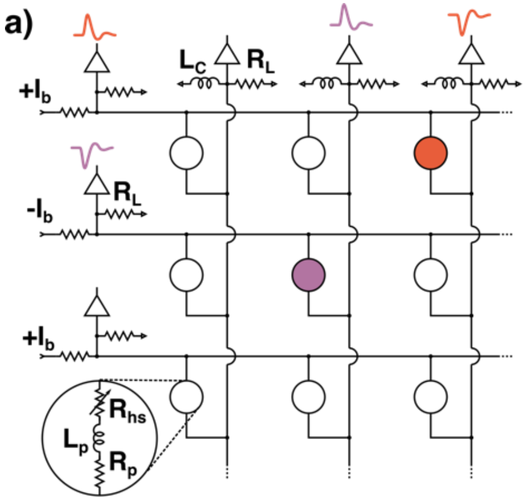
- SNSPDs are near-ideal detectors at 1550 nm – but can be modified to work well in mid-infrared
- NIST/JPL/MIT team recently demonstrated single photon sensitivity out to 9.92 µm (0.125 eV)
- Capability exists to develop **time-resolved single photon mid-IR focal plane arrays** with >60% efficiency and kilopixel form factors
- Advance enabled by WSi with reduced superconducting gap energy

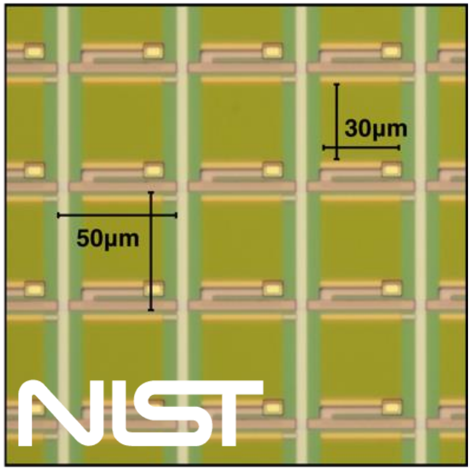


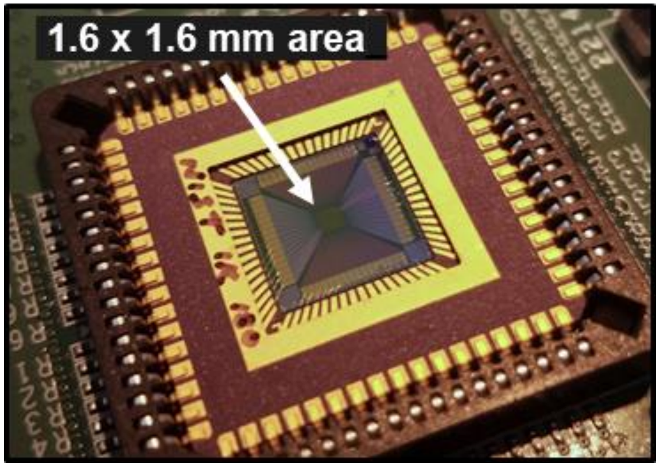
Scaling to Kilopixel Arrays

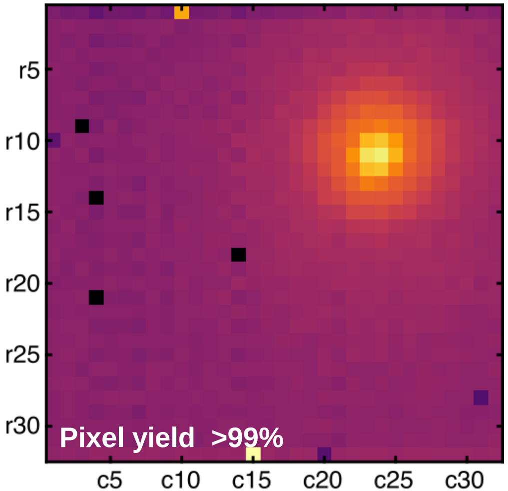
- Demonstration of 1024-pixel imaging array with >99% pixel yield
- First ever demonstration of SNSPD array larger than 64 pixels
- 32x32 imager read out using only 64 readout lines
- 30x30 µm active area on 50 µm pitch – total area 0.92 mm^2

FABRICATED AT NIST
TESTED AT JPL



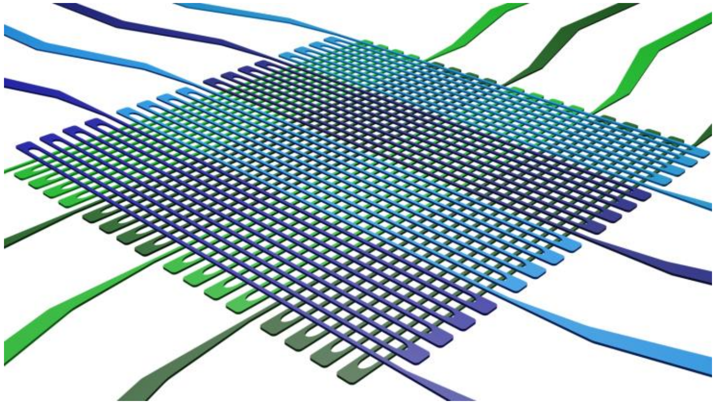




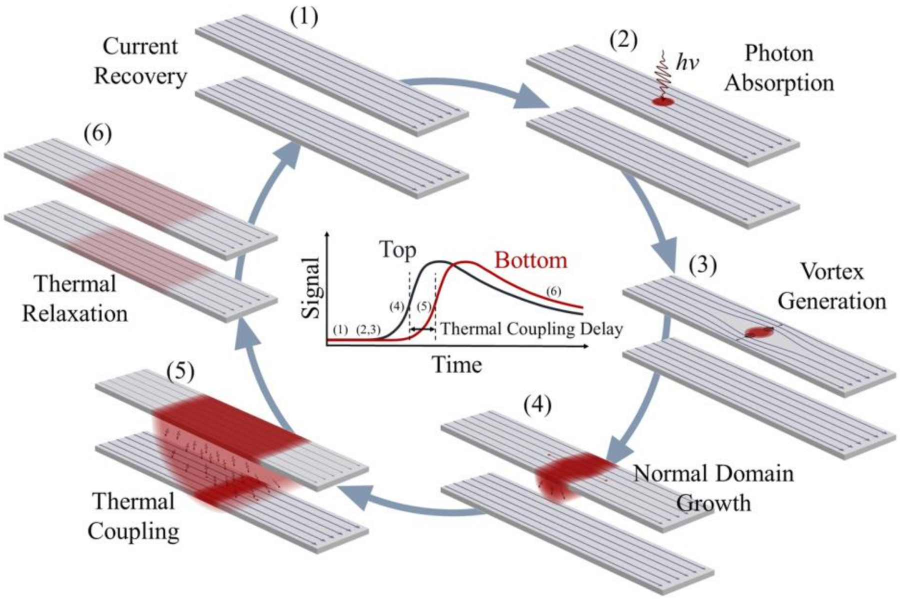


Thermal Row-Column Arrays

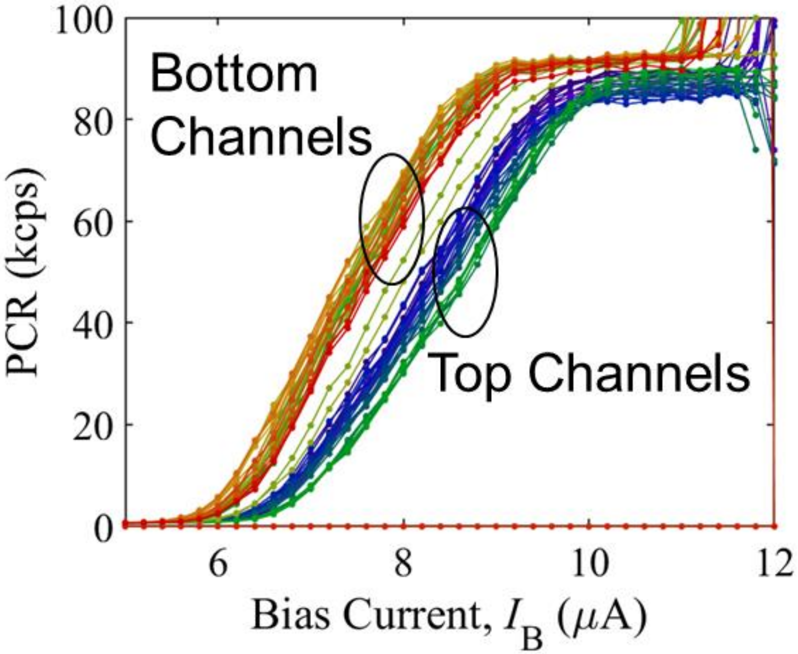
- Enables arrays with near-unity fill factor
- More scalable than conventional row-column
- Technique can be used at mid-IR wavelengths
- Working toward commercialization with NSF STTR
- 32x32 TRC array has 59 out of 64 channels working and 67% system detection efficiency at 1550 nm



Cross-polarized device design



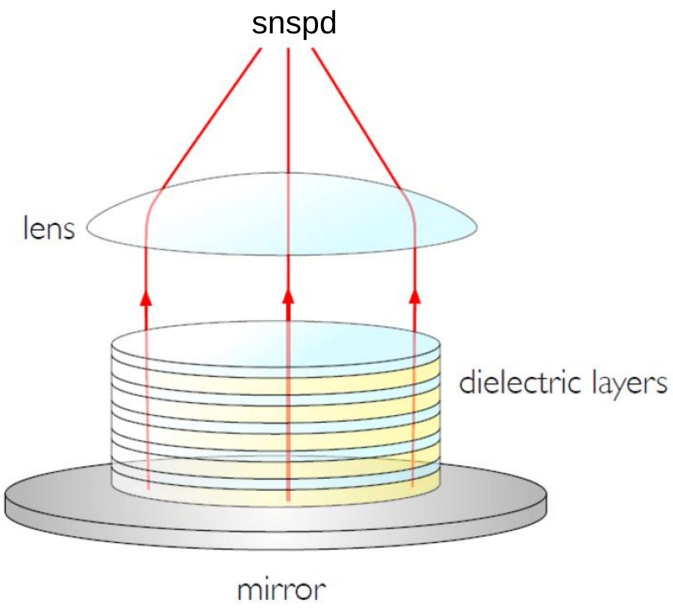
Device operation concept



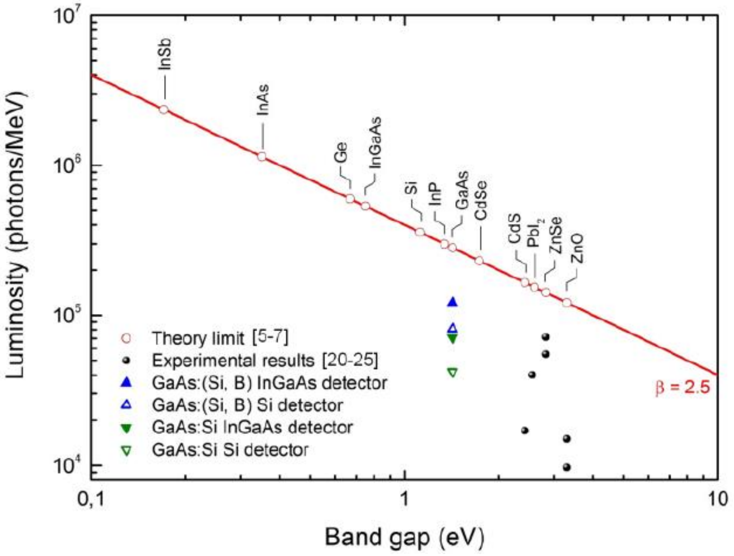
Preliminary Results on 32x32 TRC array

Dark Matter Detection with SNSPDs

- SNSPDs are ultra-low noise detectors with 1 - 0.1 eV energy thresholds
- Multiple proposed applications in searches for low-mass dark matter
    - Dark photon “haloscope”
    - Electron recoil in cryogenic semiconductors
    - Resonant absorption/scattering in molecular gases
    - Electron recoil in superconducting nanowire
- Technical challenges in scaling active area and pixel count to increase experimental reach



DM Haloscope Concept (Chiles et al 2018)



Cryogenic Scintillator Comparison
(Derenzo et al 2019)

Summary

- SNSPDs are a powerful technology for time-resolved single photon counting
- Progress in performance enhancement has been extremely rapid
- SNSPDs have much to offer for dark matter detection experiments
- For more information, contact **mattshaw@jpl.nasa.gov**