Applied Superconductivity Conference 2020

SNSPDs for Space Applications

Ekkehart Schmidt, Jason Allmaras, Emma Wollman, Boris Korzh, Andrew Beyer, Bruce Bumble, Alexander Walter, Andrew Mueller, Edward Ramirez, Ryan Briggs, Matthew Shaw

Jet Propulsion Laboratory, California Institute of Technology

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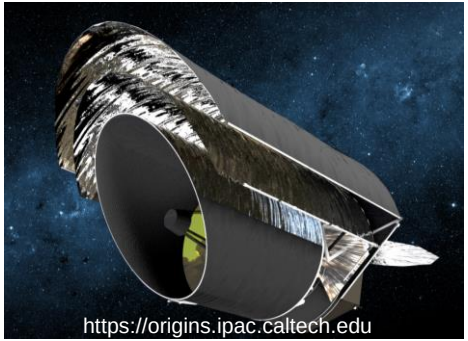
Established SNSPD Applications

Free-Space Laser Communication

- *Lunar Laser Comm Demo*
- *Deep Space Optical Comm Demo (Psyche)*

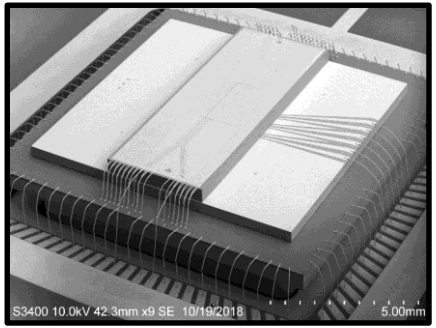
Physics & Astronomy

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



Quantum Information Science

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



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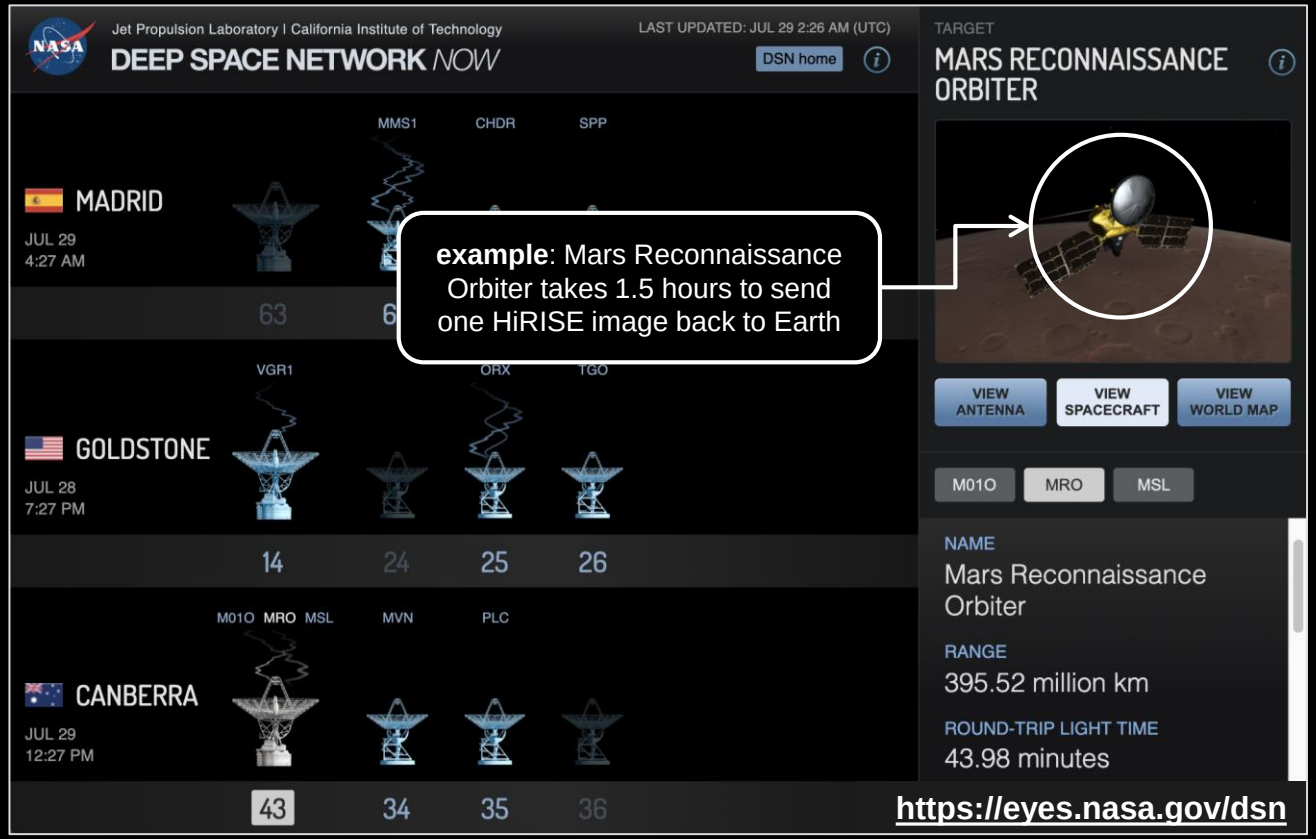
Why deep space optical communication?



example: Mars Reconnaissance Orbiter takes 1.5 hours to send one HiRISE image back to Earth

- All of NASA's interplanetary spacecraft currently communicate with Earth through the RF dishes of the Deep Space Network (DSN).
- <u>The volume of data passing through the DSN is expected to increase in the coming decades</u> due to both an increase in the number of spacecraft and more advanced instruments.
- NASA's Space Communications and Navigation office seeks solutions to enhance and complement existing RF communication.

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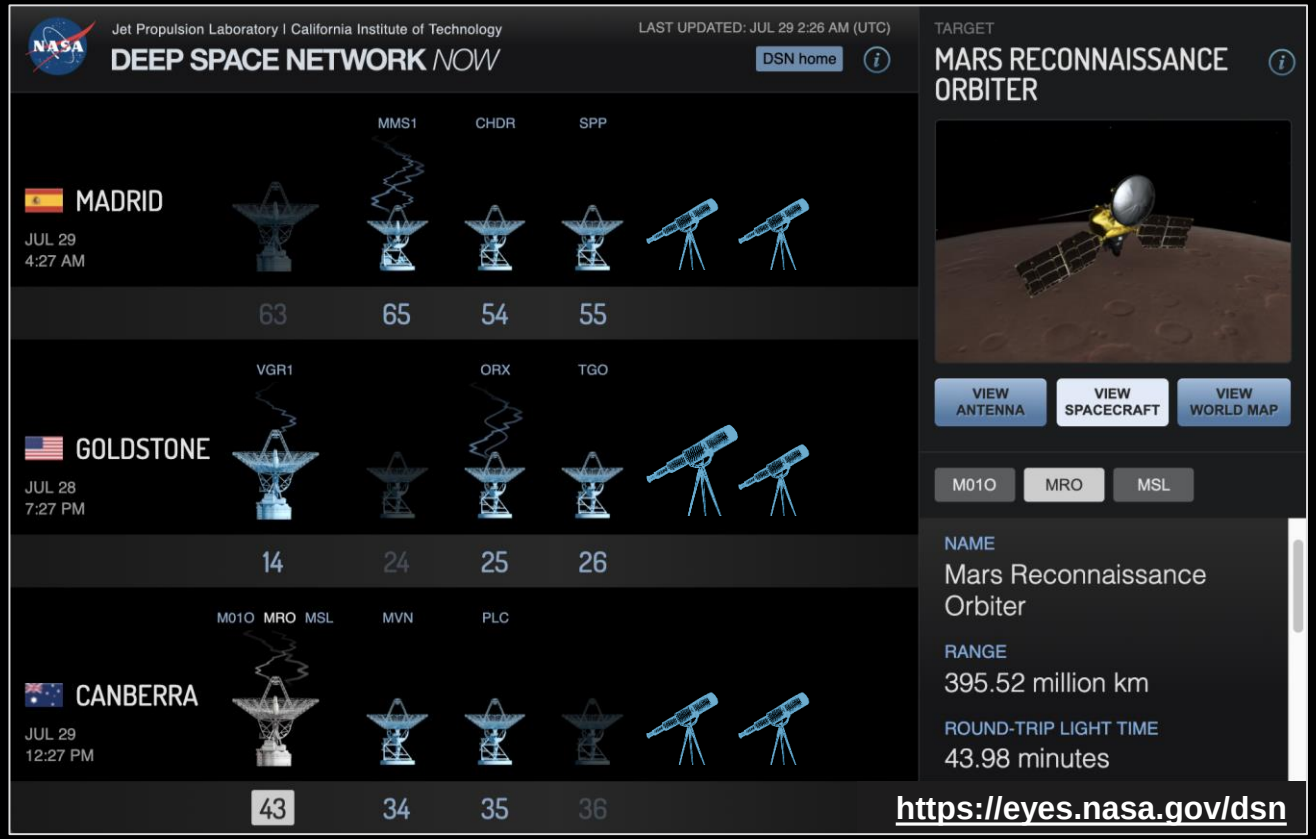
Why deep space optical communication?



https://eyes.nasa.gov/dsn

- Optical communication promises 10-100x more data than Ka-band RF links for equivalent mass and power on the spacecraft
- Will require a network of large (~10m) telescopes
- Currently, deep space optical communication missions are limited to technology demonstration missions with more moderate data rate increases

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Lunar Laser Communication Demo (2013-2014)

- First demonstration of laser communication beyond earth orbit
- Bidirectional laser communication demo from LADEE Spacecraft in lunar orbit (400,000 km) at 1550 nm
- Uplink rates 10-20 Mbps, Downlink rates 39-622 Mbps
- Managed by GSFC. Primary ground terminal at White Sands, NM implemented by MIT-LL
- Secondary ground terminal at Table Mountain, CA implemented by JPL
- Both ground terminals used SNSPD arrays

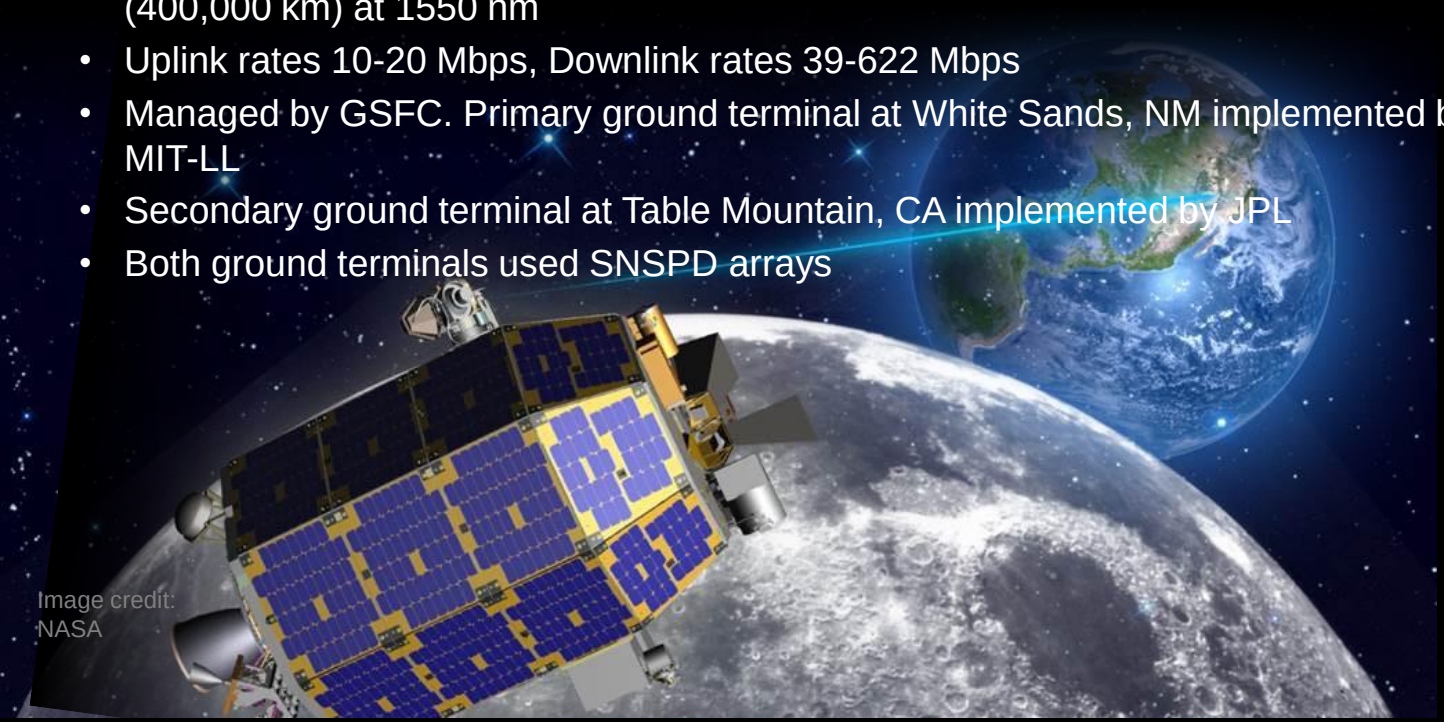
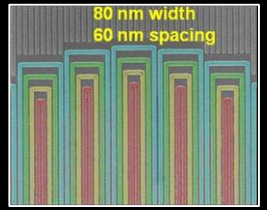
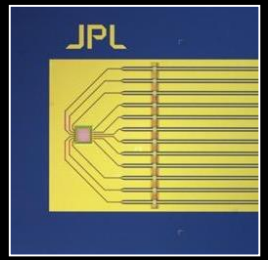


Image credit: NASA



4-channel MIT-LL NbN SNSPD array



16-channel JPL WSi SNSPD array

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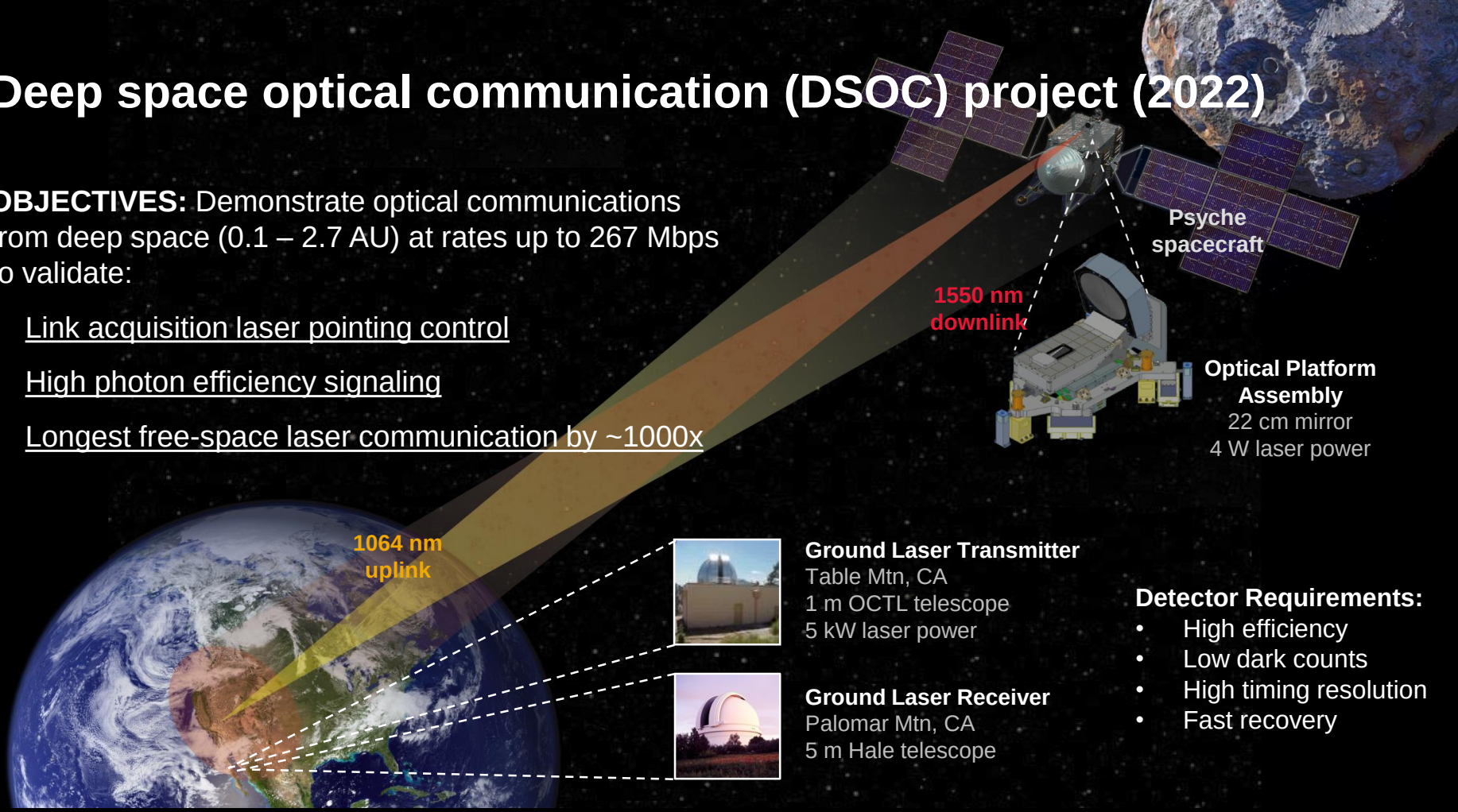
Deep space optical communication (DSOC) project (2022)

OBJECTIVES: Demonstrate 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
- Longest free-space laser communication by ~1000x



Detector Requirements:

- High efficiency
- Low dark counts
- High timing resolution
- Fast recovery

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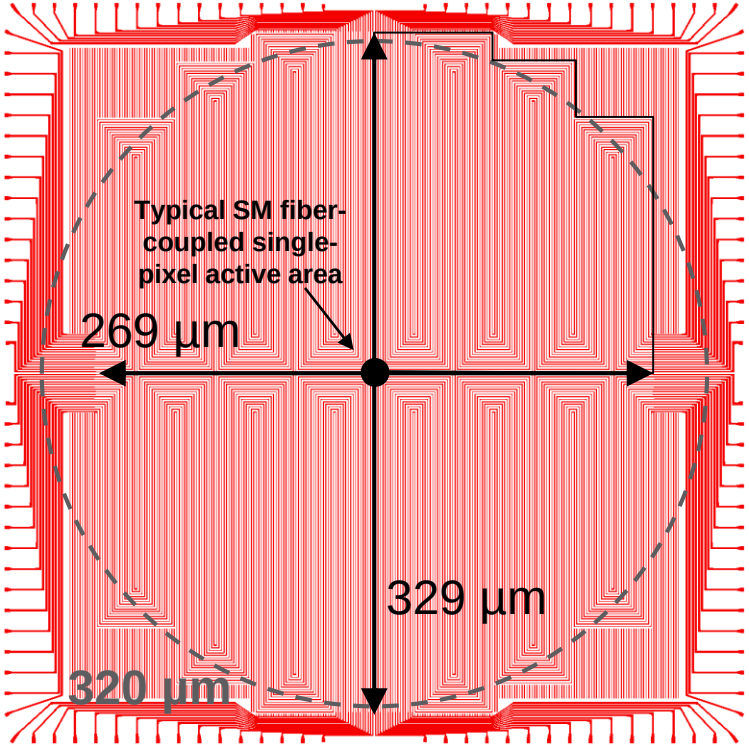
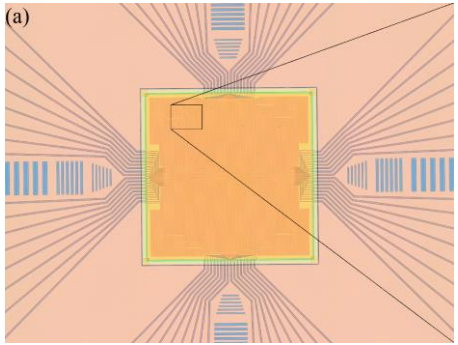
64-channel SNSPD array design

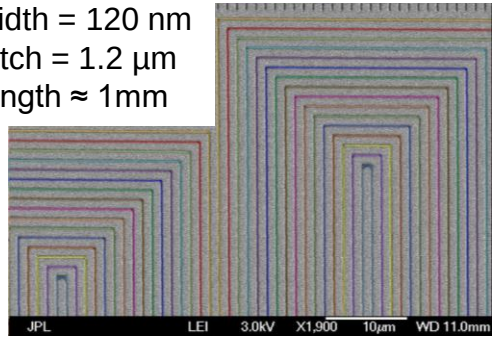


CAD Design of SNSPD focal plane array

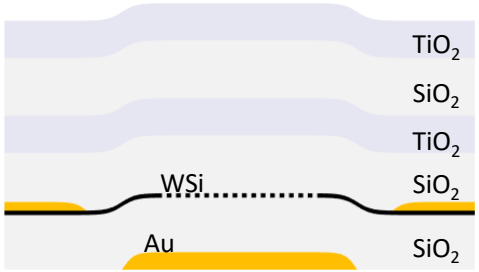


Optical image of detector

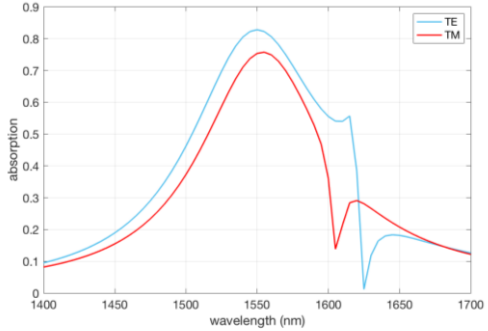
width = 120 nm
pitch = 1.2 µm
length ≈ 1mm



SEM of co-wound wires



Cross-section of optical stack



Modeled absorption vs. wavelength

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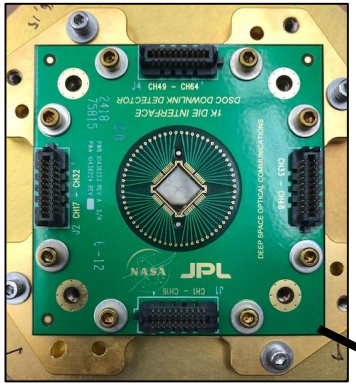
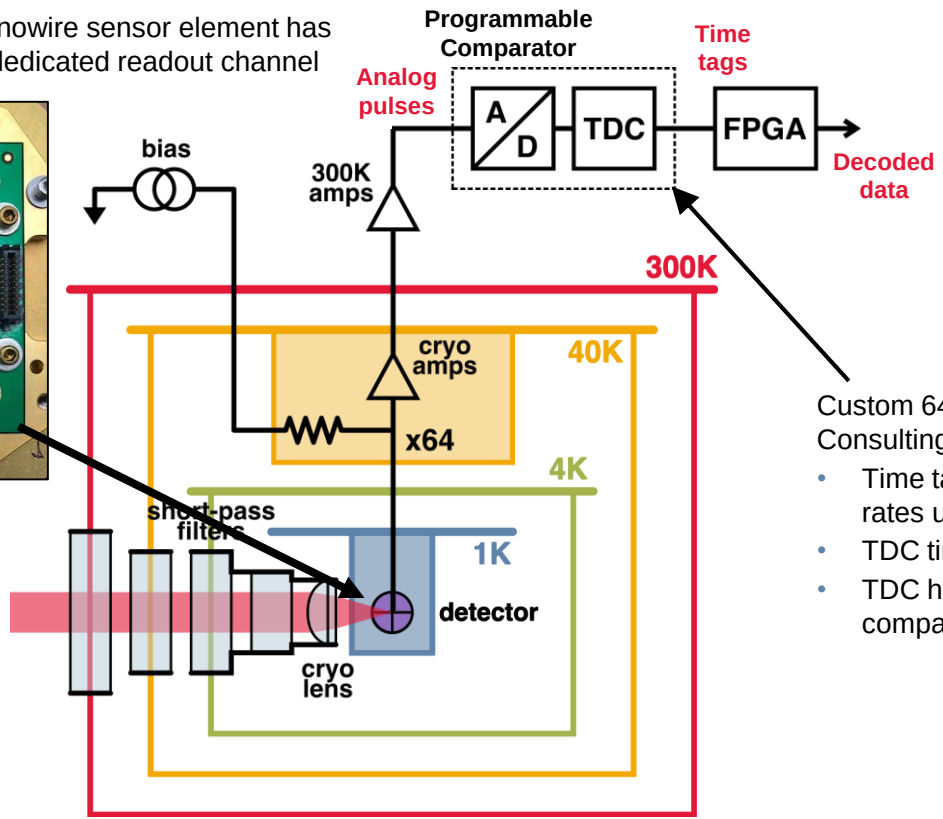
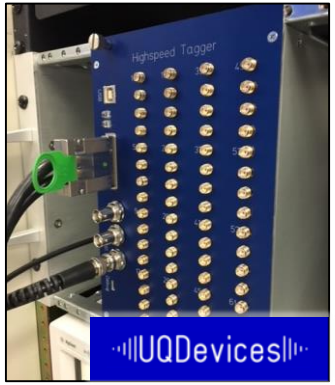
Ground detector / receiver system

Each nanowire sensor element has its own dedicated readout channel







Custom 64-channel TDC from DotFast Consulting / UQDevices

- Time tags are streamed over PCIe at rates up to 900 MTags/s
- TDC timing resolution ~50ps (FWHM)
- TDC has a 64-channel programmable comparator front-end

Light entering the cryostat passes through cryogenic filters and is focused on the array with a cryogenic lens

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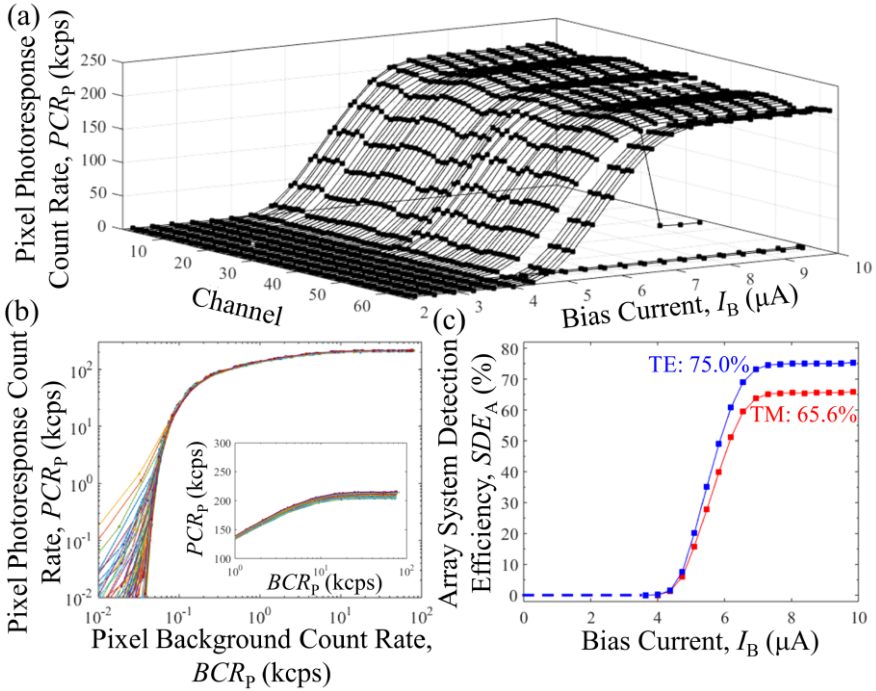
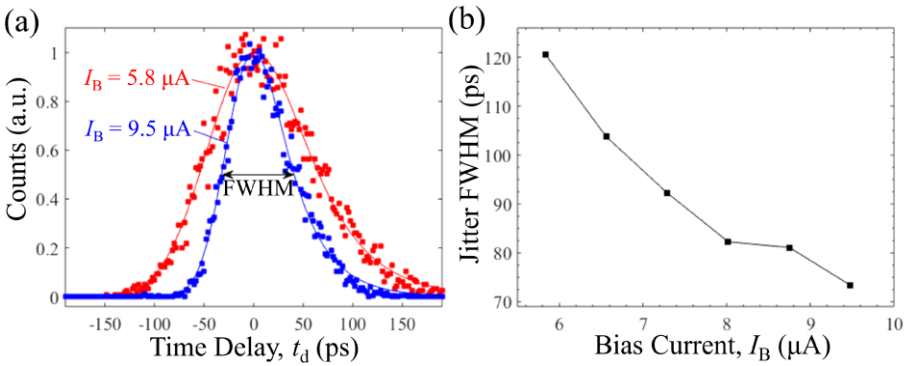
64-Pixel SNSPD Array performance





- 75% system detection efficiency at 1550 nm
- Saturation for 64 pixel
- < 80 ps FWHM timing jitter

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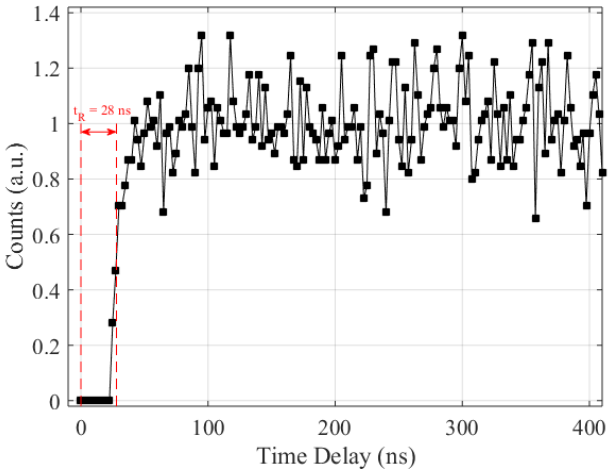
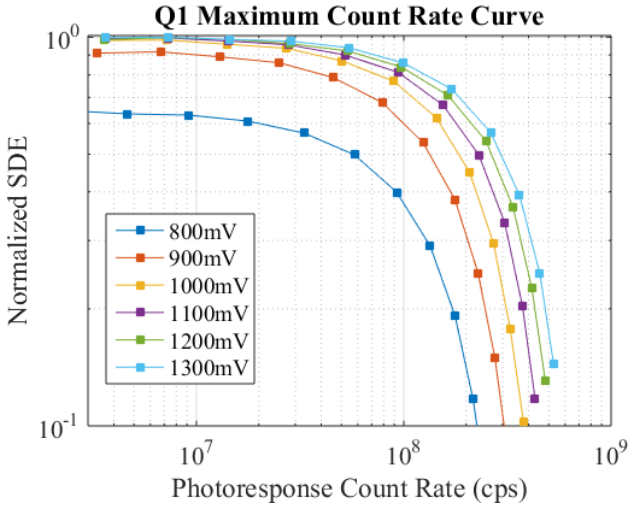
64-channel array performance: Maximum count rate



Interarrival time histogram showing 28 ns dead time, no afterpulsing



Maximum count rate measured for one 16-channel quadrant

- 120 – 300 Mcps per quadrant (3dB point)
- Scales to 465 – 1160 Mcps across 62 pixels (prototype array)
- Present total counting rate is limited to 900 Mcps by time tagging electronics

Detector meets requirements for DSOC

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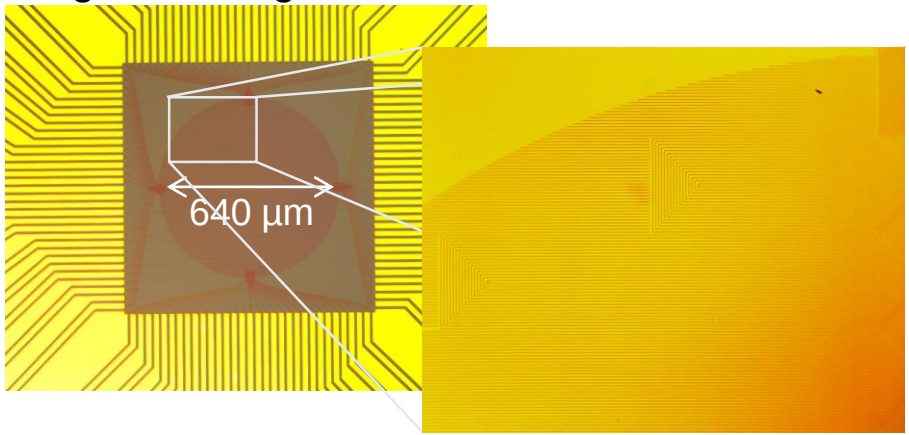
Future of development

- Beyond DSOC, future receivers will require 10x larger active areas, 6x higher count rates
- Example: RF-optical hybrid with mirror panels on existing radio dishes to achieve larger apertures

Progress to larger devices



Goldstone's DSS-23 Antenna (Artist's Concept)

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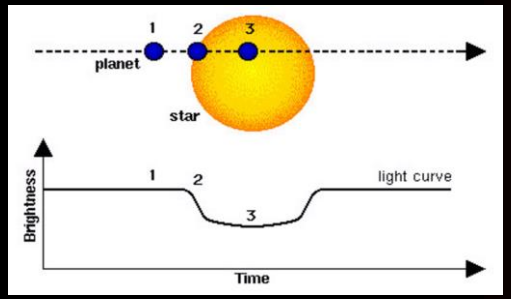
SNSPDs for astronomy



Planet transit measurement

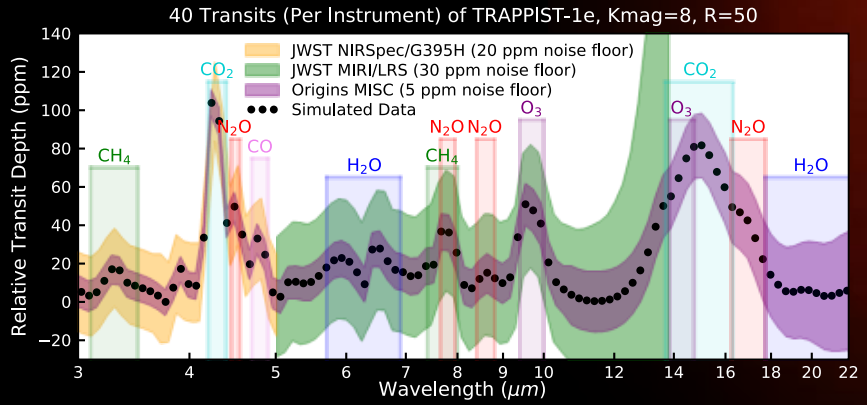
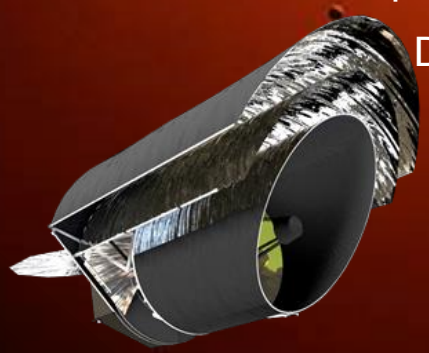


Image credit: spitzer.caltech.edu
TRAPPIST-1 Illustration

- **O**rigins **S**pace **T**elescope:
  - mission concept for future space-based observatory
  - 6 m telescope at 4.5 K
  - mid-infrared imager to perform exoplanet transit spectroscopy
  - ultra-stable photometry to resolve 5-10 ppm spectral features from 6-20 µm



Detector requirements:

- $>10^3$ pixel/array
- High efficiency in MIR
- High stability (5 ppm)

origins.ipac.caltech.edu

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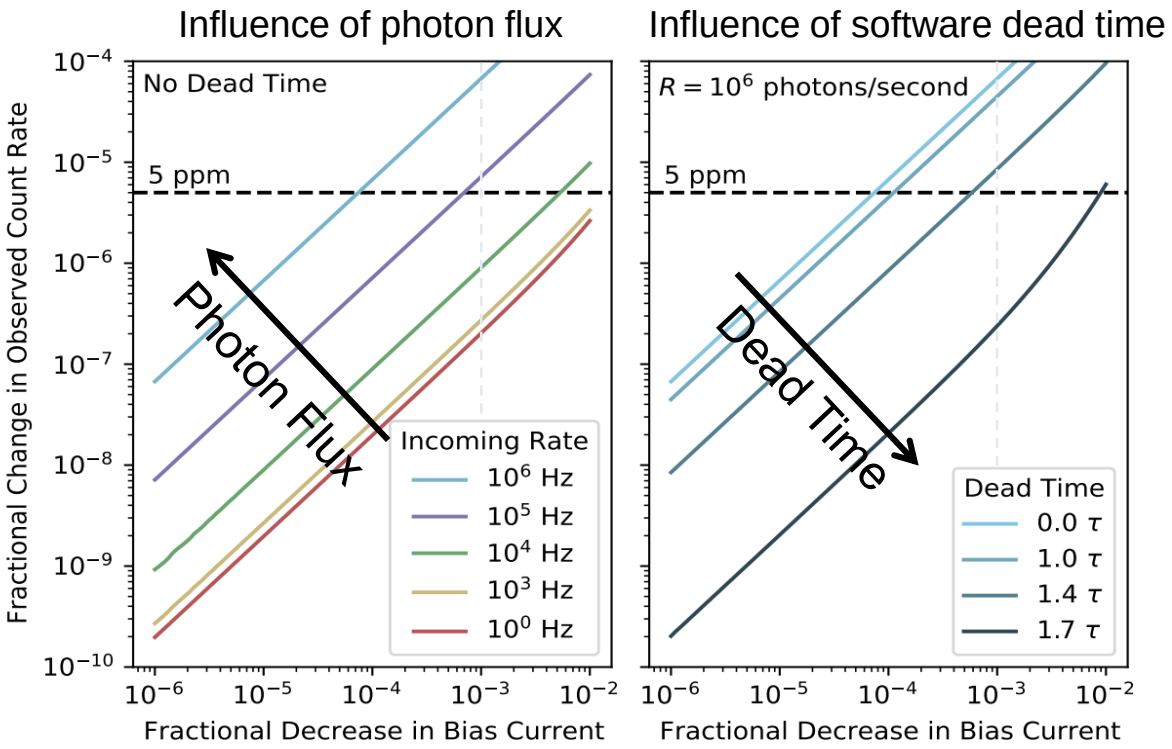
SNSPD stability – saturated efficiency



- SNSPDs can archive 5 ppm stability with reasonable bias drifts of .1%

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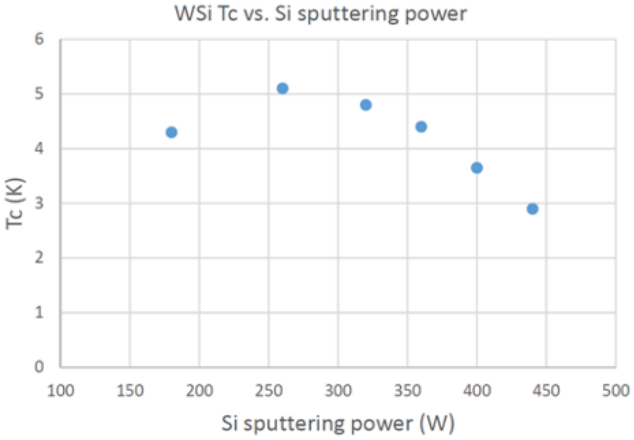
Photon detection in MIR

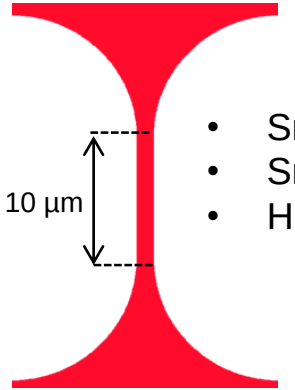
Detection of low energy photons:

$$E_{min} = \varsigma^{-1} N_o \Delta^2 \sqrt{\pi D \tau_{th}} \cdot wd\left(1 - \frac{I_B}{I_{dep}}\right) [1]$$

Material depended



Geometry dependend



- Small width (< 100 nm)
- Small thickness (< 3nm)
- High homogeneity:
  - Short length
  - Amorphous superconductor

[1] Semenov et al, *Eur. Phys. J. B* **47,** 495–501 (2005)

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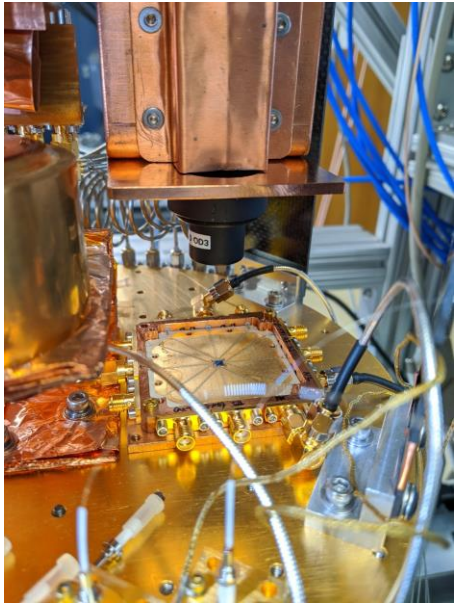
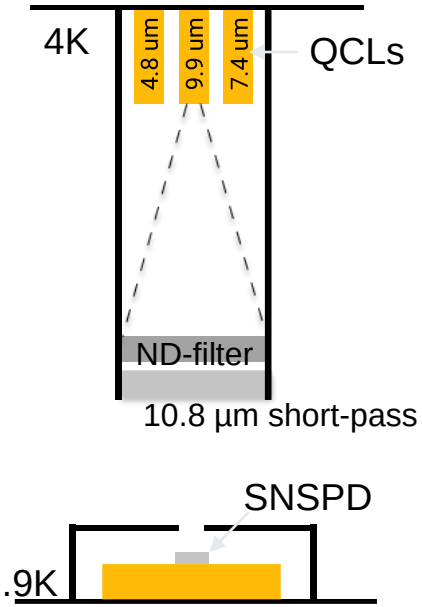
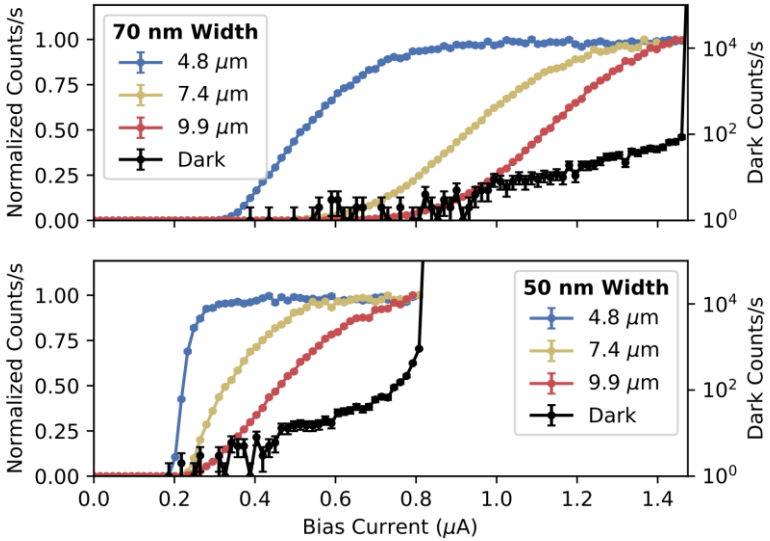
Photon detection in MIR

Optical setup





PCR and DCR



Deterministic single-photon detection down to λ = 9.9 µm

FABRICATED AT NIST
TESTED AT JPL

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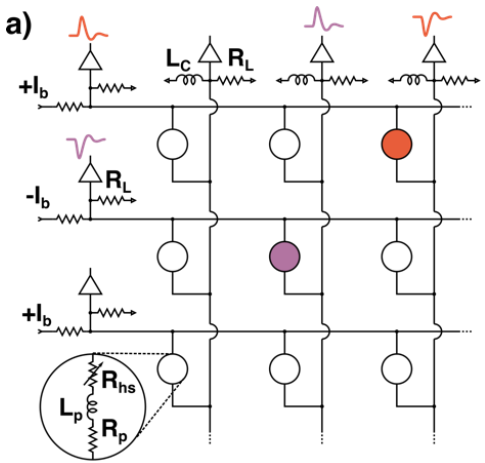
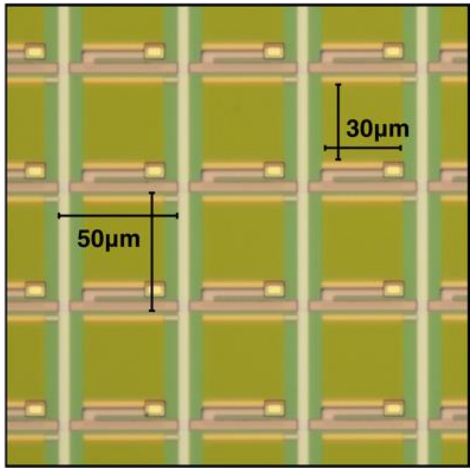
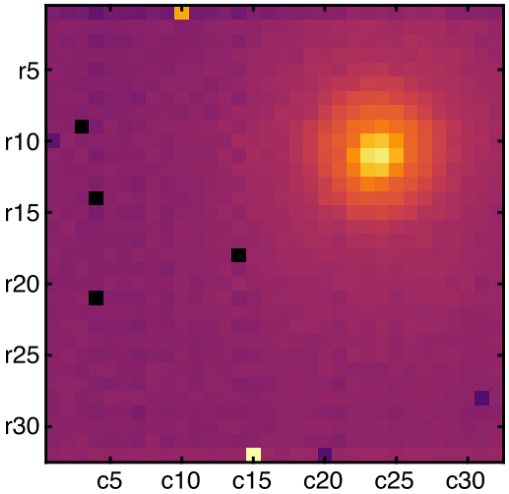
SNSPD kilopixel arrays – Row Column architecture







- 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

Talk by Varun Verma on Thursday: Wk1EOr3C-01

E. Wollman, Varun Verma et al., *Optics Express,* Vol. 27, Issue 24. pp. 35279-35289 (2019)

NIST

FABRICATED AT NIST
TESTED AT JPL

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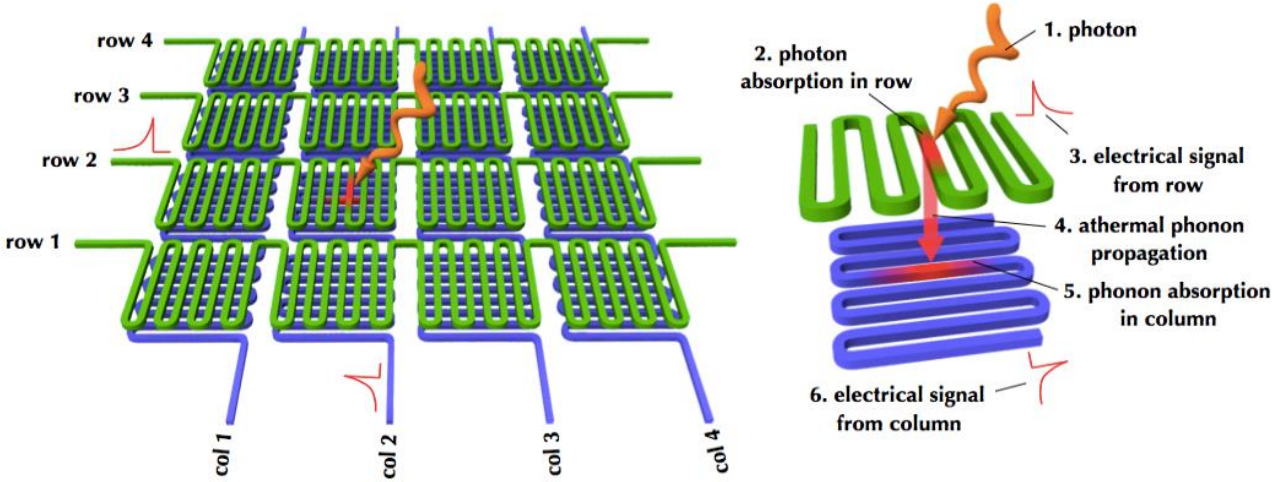
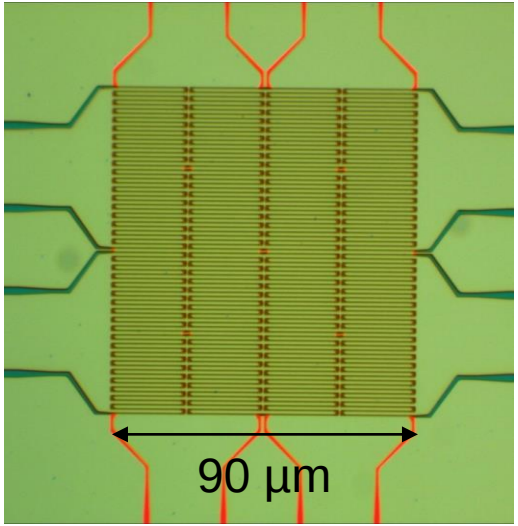
Scaling to kilopixel arrays – Thermal Row Column





- Demonstration of a 4x4-pixel imaging array
- Successful demonstration of new type of row-column architecture

Poster by Jason Allmaras in the upcoming poster session: Wk1EPo1A-03

J. Allmaras al., *Nano Lett.* 2020, 20, 3, 2163–216 (2020)

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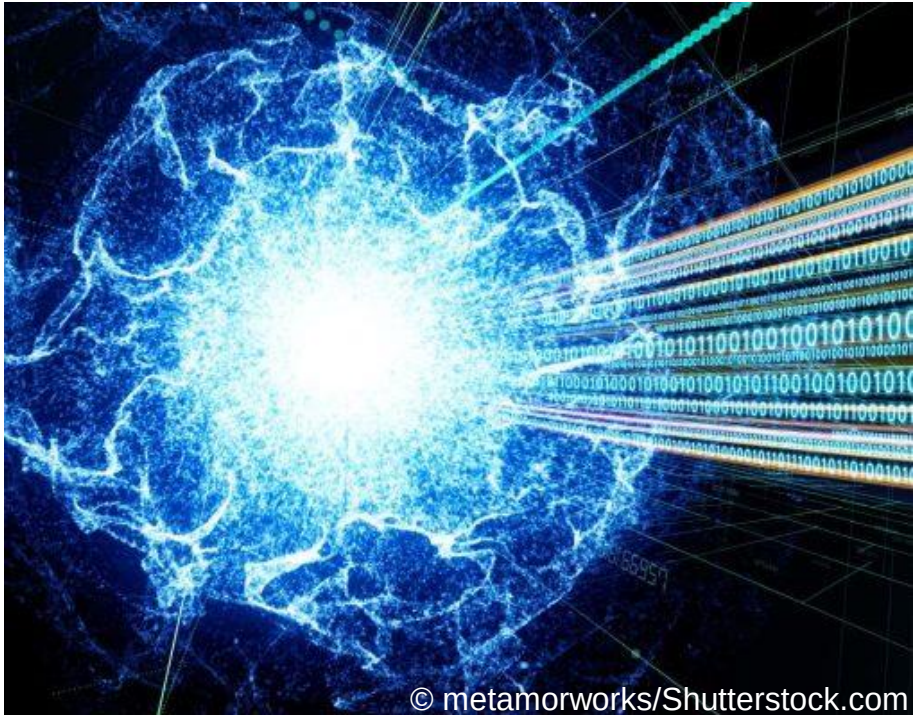
SNSPDs for quantum information science

- Key figure-of-merit H for quantum communication:

$$H = \frac{\eta}{\Delta t D}$$

- Derived detector requirements:
  - Telecom operation
  - low-jitter (Δt)
  - high-efficiency (η)
  - low-noise (D)



[1] R. Hadfield, *Nat. Photonics* **3**, 696 (2009)

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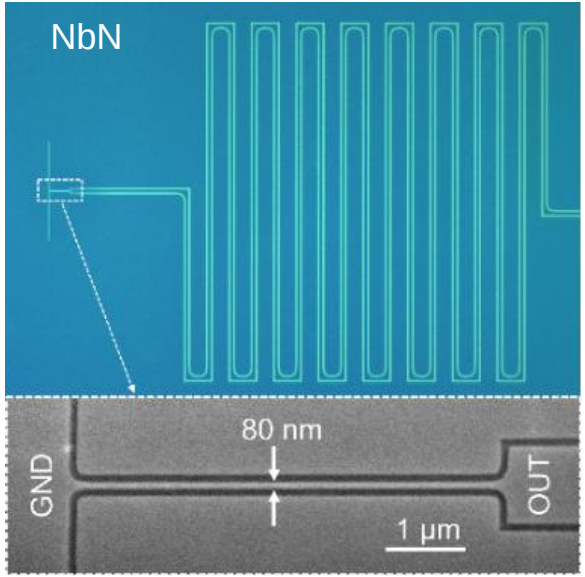
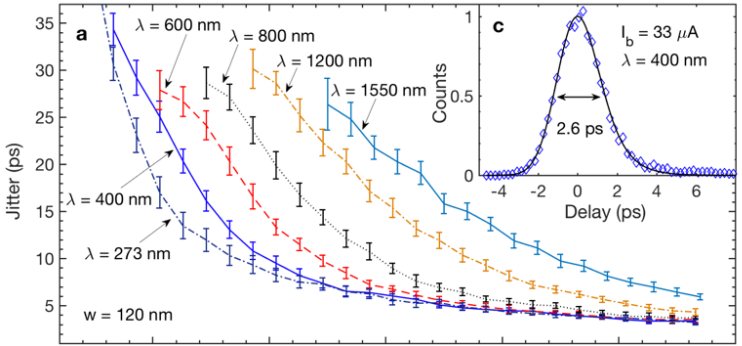
Improving timing resolution: Ultra high time resolution



- Short nano-bridge to limit the geometric jitter.
- Tapered readout for impedance matching
- Devices fabricated at MIT, measured with low-noise readouts at JPL and NIST



- **Record time resolution for free-running single photon detector: 2.6 ps FWHM**
- Photon energy dependence indicates presence of intrinsic effects due to detection mechanism.

Low jitter is achievable, but short nanobridges have negligible efficiency

Boris Korzh et al., *Nature Photonics* **volume 14**, pages 250–255(2020)

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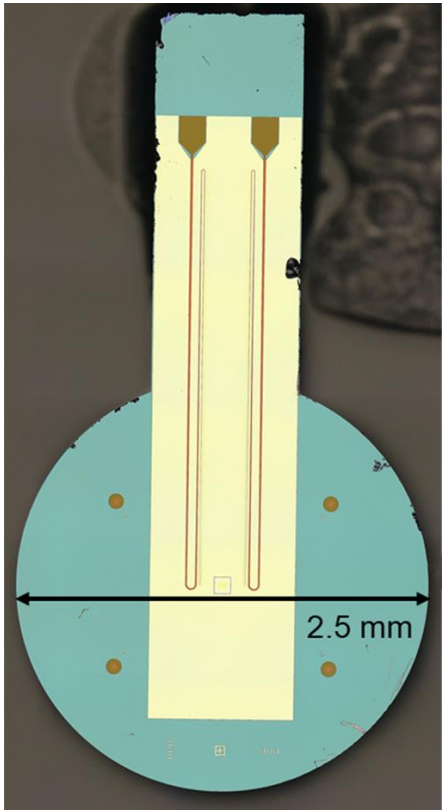
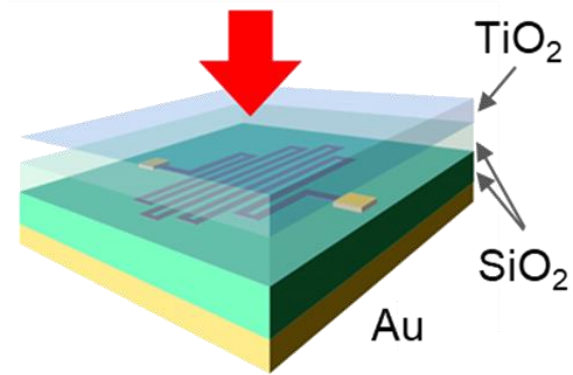
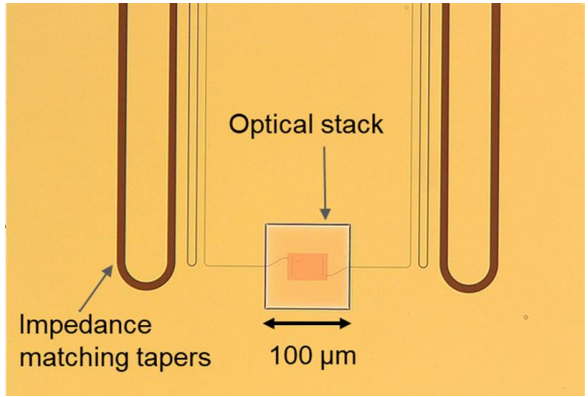
Differential SNSPD with cavity







- Differential readout cancels geometric jitter
- Optical cavity for high efficiency
- NbN for fast response
- Photon number resolution [1]

[1] Di Zhu et al., *Nano Lett.* 2020, 20, 5, 3858–3863

Fabrication lead:
JPL Andrew Beyer
MIT Marco Colangelo

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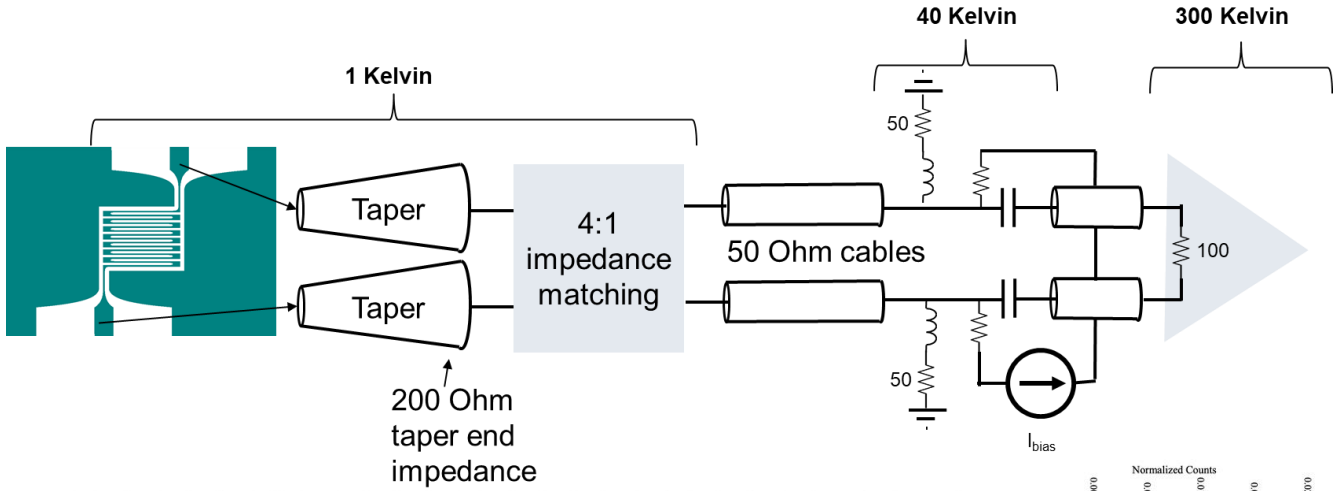
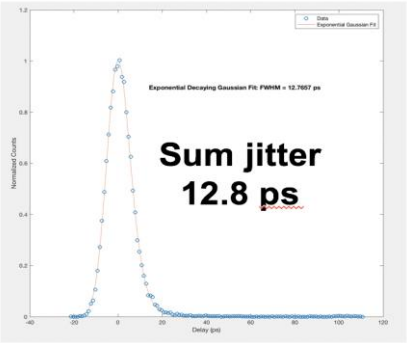
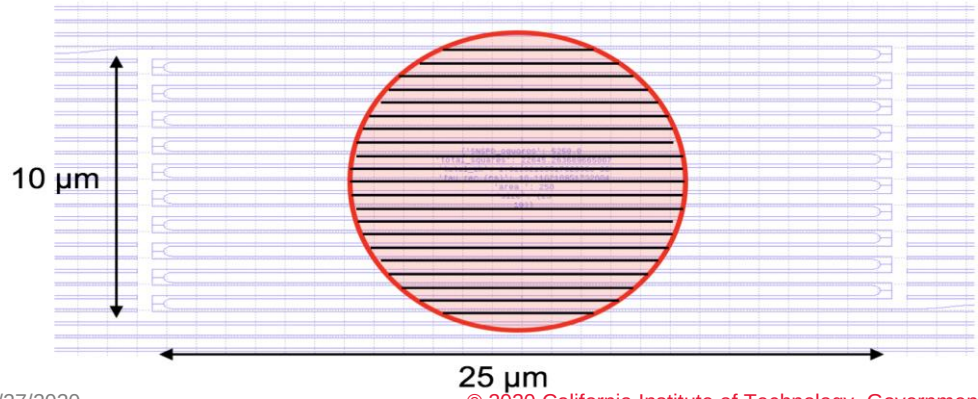
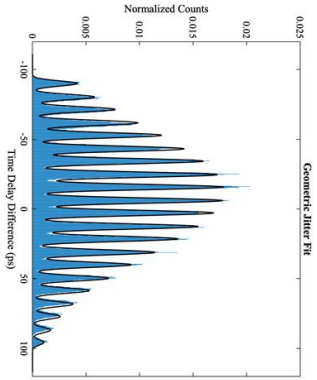
Matched differential readout









Difference jitter

21 peaks corresponding to 21 meander lines

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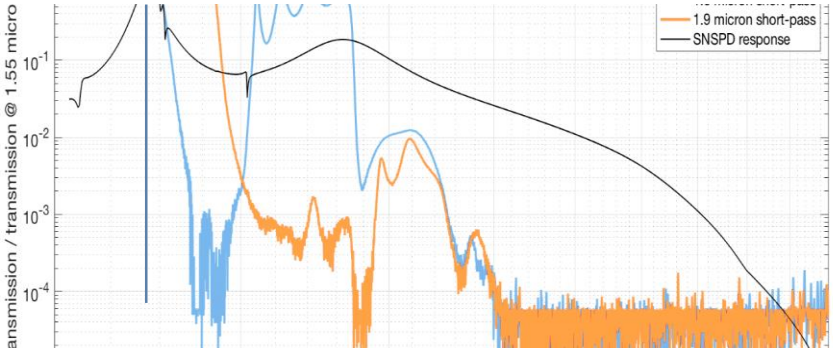
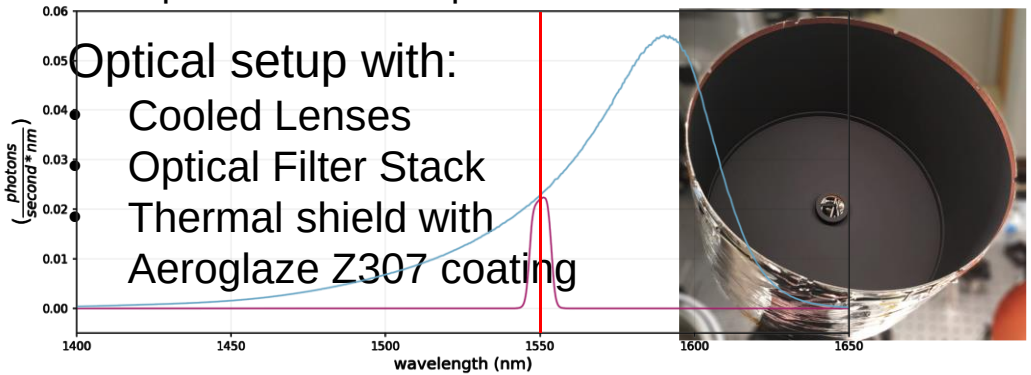
Efficient suppression of thermal dark counts

Spectral Transmission and SNSPD response



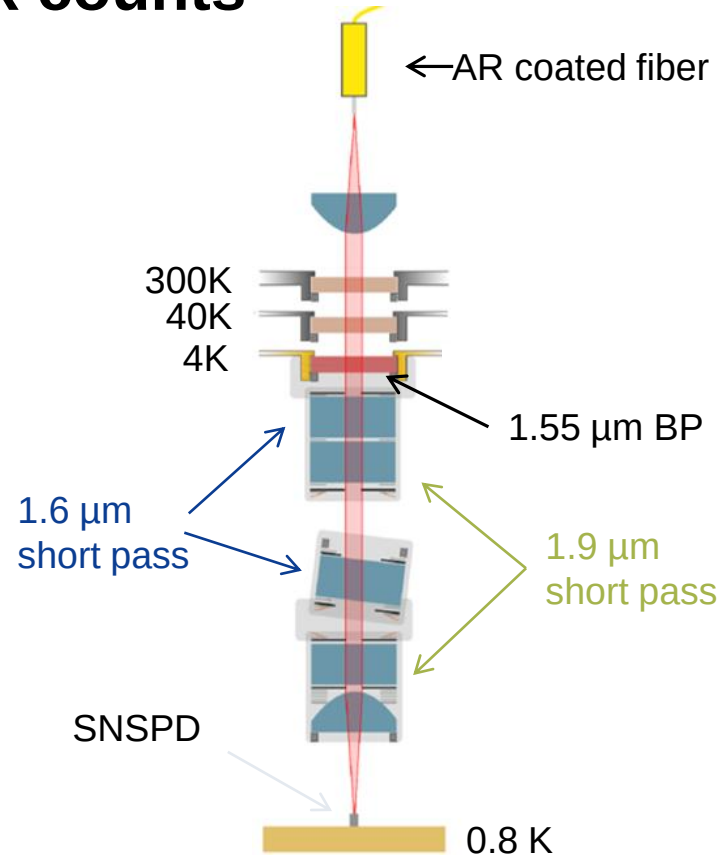
Bandpass influence of photon transmission

Thermal shield



Optical setup with:

- Cooled Lenses
- Optical Filter Stack
- Thermal shield with Aeroglaze Z307 coating



Main investigator: Andrew Mueller

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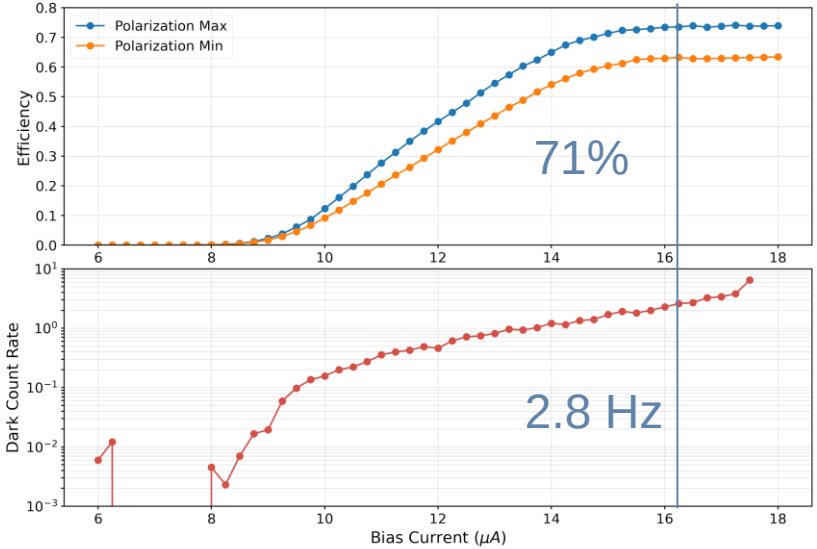
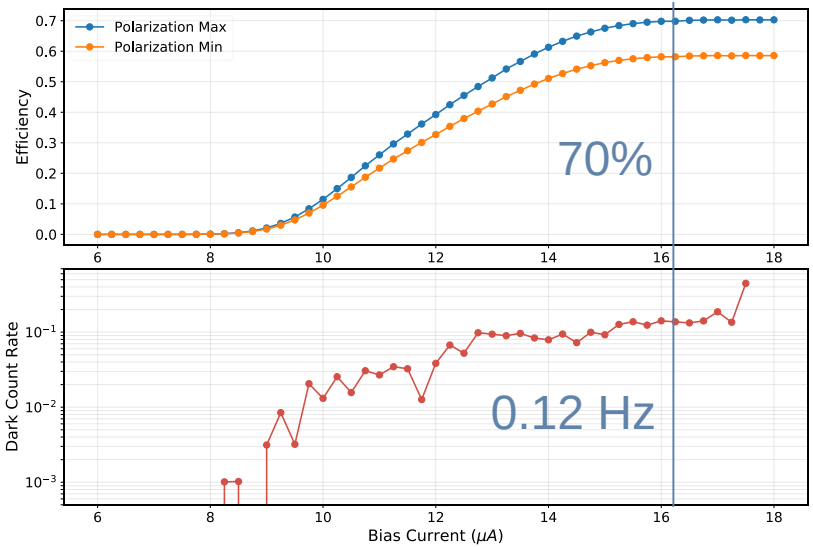
Efficient suppression of thermal dark counts

Fiber coupled SNSPD



Free space coupled SNSPD



Successful combination of high efficiency free space coupling with a low dark count rate and high timing resolution

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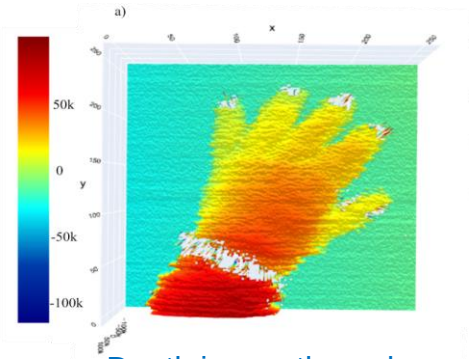
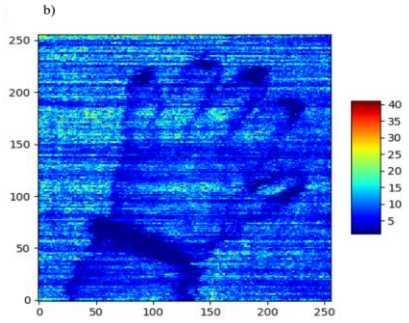
Application example: Field trial LIDAR

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

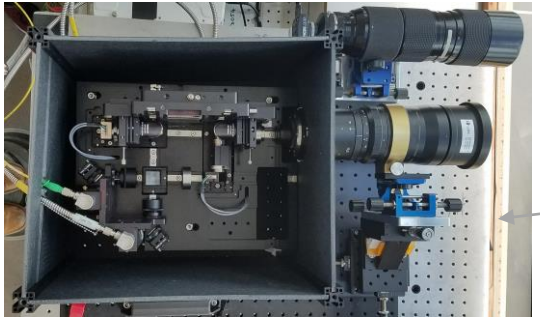


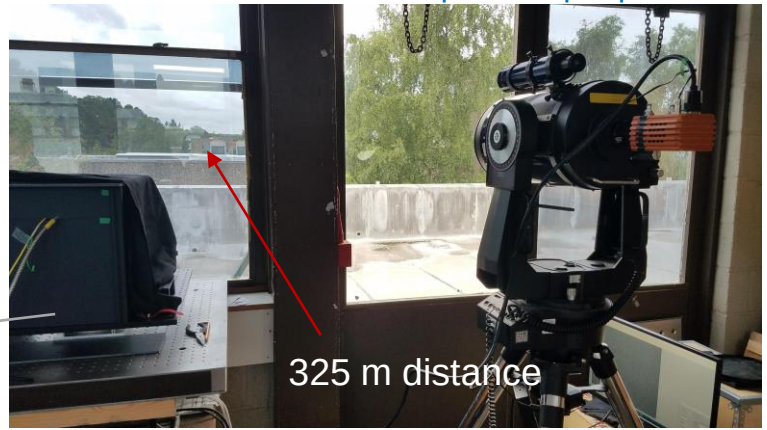
Depth image through 325 m turbulent air



Acquired photon number 10-15 photons per pixel

Laser scanner





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SNSPDs are a powerful detectors for

- Deep Space Laser Communication:
  - 10-100x higher data rates for equivalent mass and power on the spacecraft
  - Projected first demonstration of optical comm from beyond lunar orbit
  - 64-pixel SNSPD arrays are a key technology for ground receivers
- SNSPDs for astronomy:
  - Kilopixel SNSPD arrays available
  - Deterministic single-photon detection down to $\lambda = 9.9\ \mu m$
  - 5 ppm stability with a bias drifts of >.1% achievable
- Quantum information science:
  - unique combination of:
    - High efficiency > 70% (@1550 nm)
    - Timing resolution < 13 ps
    - Low Noise < 0.2 Hz DCR

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Direction for further SNSPD development

- 10x larger detectors at 6x higher count rates
- Maintaining low jitter and high count rates for larger areas
- IR sensitivity toward 20 µm and beyond
- Development of large Area MIR SNSPDs
- Advanced readout for larger pixel numbers

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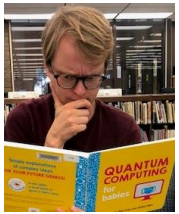
JPL SNSPD Development Team

JPL Staff



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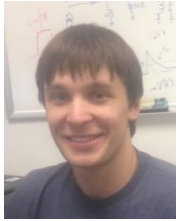
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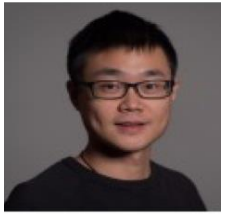

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