Title: Superconducting Nanowire Single Photon Detectors for Intensity Interferometry

Speakers: Ioana Craiciu

Collection/Series: Future Prospects of Intensity Interferometry

Subject: Cosmology

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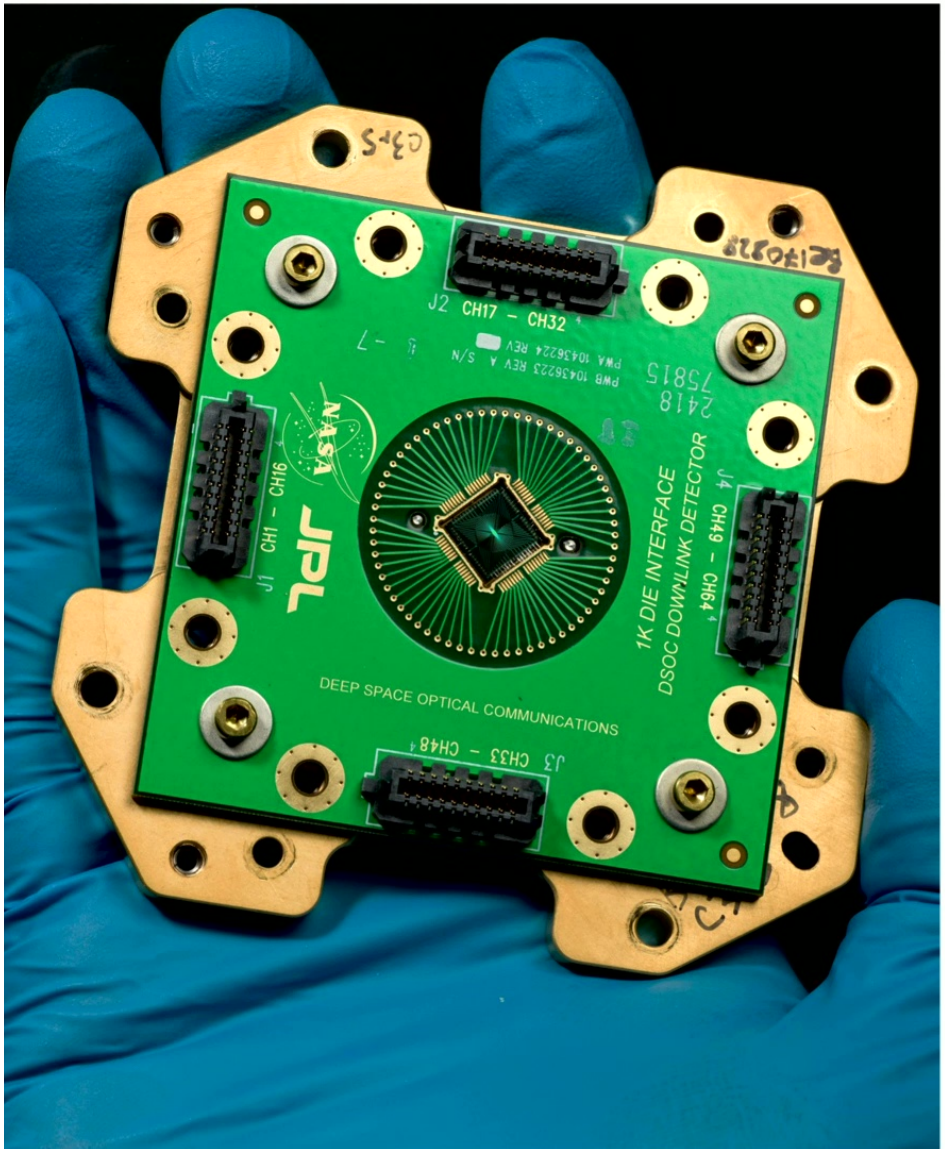
Abstract:

Superconducting nanowire single photon detectors (SNSPDs) are of interest for intensity interferometry measurements because they have picosecond timing resolution. In addition, they work from the UV to mid-IR, with excellent eOiciency at visible and near-IR wavelengths, and are being fabricated into ever-larger detector arrays. On behalf of my colleagues in the JPL SNSPD group, I will present on the Deep Space Optical Communication (DSOC) demonstration, in which an SNSPD array was coupled to the 5 mHale telescope at Palomar, and received data at 267 Mbps from the Psyche spacecraft, the first optical communication between Earth and interplanetary space. The DSOC infrastructure at Palomar is suitable for intensity interferometry, as demonstrated by g(2) correlation (photon bunching) measurements of the stars Rigel and Procyon. I will also describe our current work on SNSPD array readout schemes, extending detector sensitivity into the mid-IR, and improving the system timing jitter of SNSPD arrays.



Superconducting Nanowire Single Photon Detectors for Intensity Interferometry (and Deep Space Optical Comm)

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California Institute of Technology

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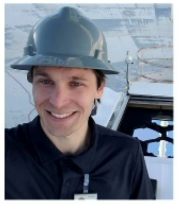
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Superconducting nanowire single photon detectors (SNSPDs)

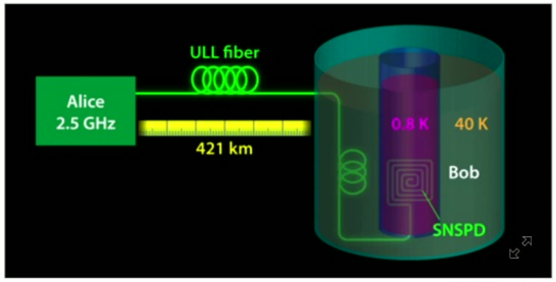
The ideal single photon detector	Best SNSPD performance (not all in the same detector)	
Works at wavelength of interest	250 nm to 29 µm	(Wollman 2017; Taylor 2022)
100% efficiency	98%	(Reddy 2020, Chang 2021)
Low dark count rate	6×10^{-6} counts/s	(Chiles 2022)
High timing resolution (low timing jitter)	3 ps FWHM	(Korzh 2020)
High count rate (low dead time)	1.7 giga-counts/s	(Hao 2024)
Multi-mode (arrays, photon number resolving wires)	400 kilopixel array, ~3 photons/wire	(Oripov 2023; Zhu 2020)

*SNSPDs require cryogenic operation < 4 K, usually < 1 K

Applications of SNSPDs

Optical Communication (Classical and Quantum)

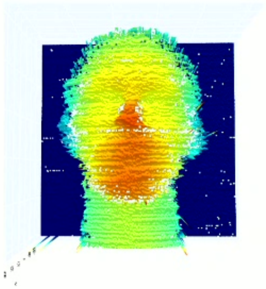
Optical Communication to Interplanetary Space, Wollman et al. 2024



APS/Alan Stonebraker

QKD over 421 km, Boaron et al. 2018

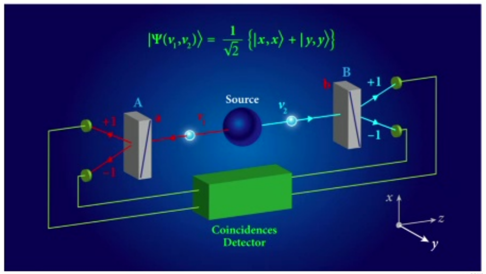
LIDAR



Photon counting LIDAR, Taylor et al. 2019

Quantum Information (Computing and Foundations)

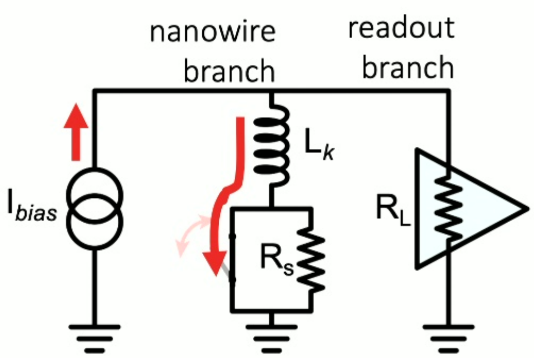
Boson sampling, Zhong et al. 2020

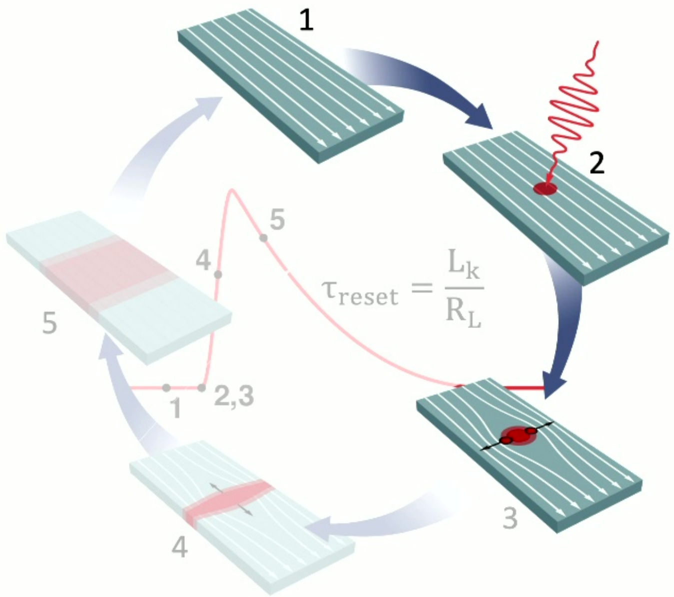


Local realism test, Shalm et al. 2015

- dark matter searches
- biomedical imaging
- intensity interferometry?

SNSPD Operation: Photon is absorbed and creates a hotspot

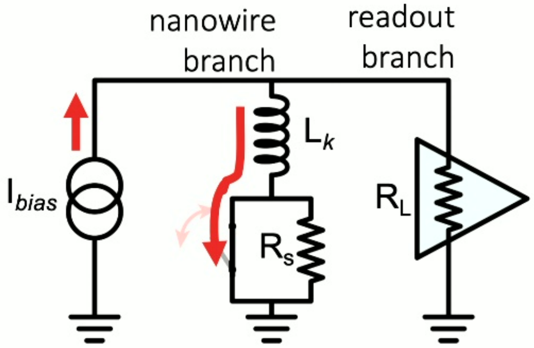

SNSPD Circuit


SNSPD Operation

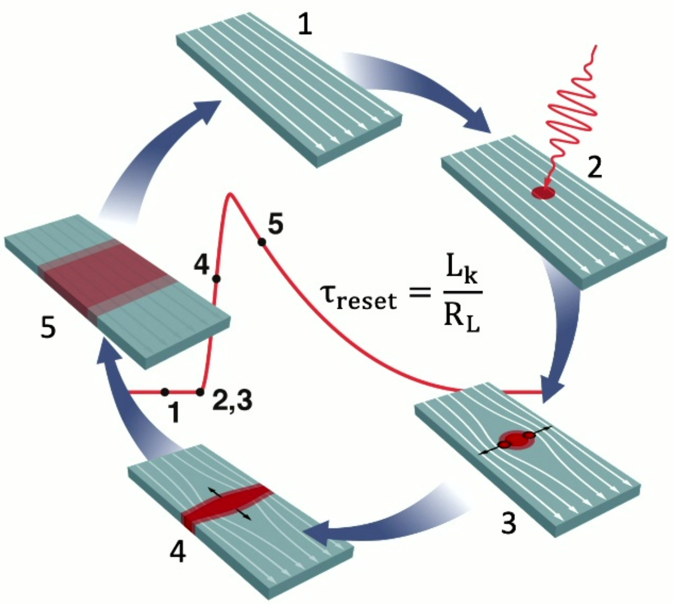
SNSPD Operation figure by Emma Wollman

SNSPD Operation: Nanowire cools, hotspot shrinks, cycle resets

SNSPD Circuit

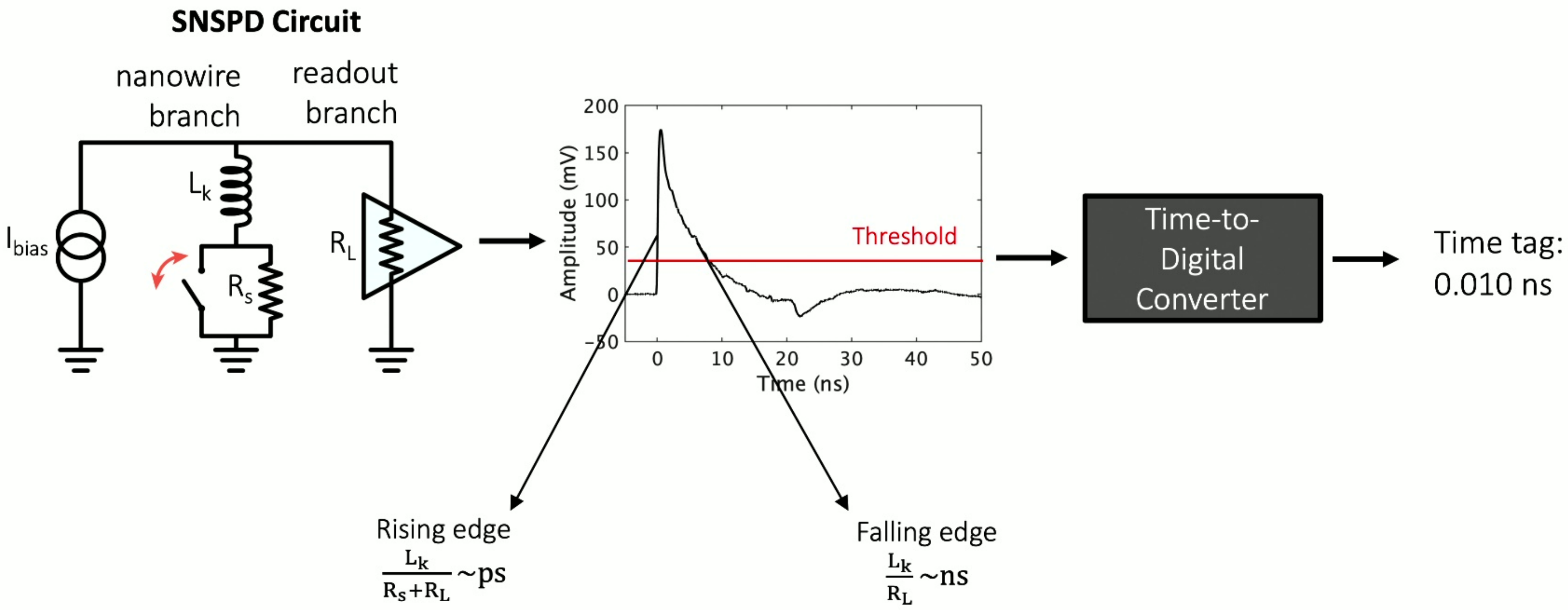


SNSPD Operation



SNSPD Operation figure by Emma Wollman

SNSPD Operation: Pulses to Time Tags

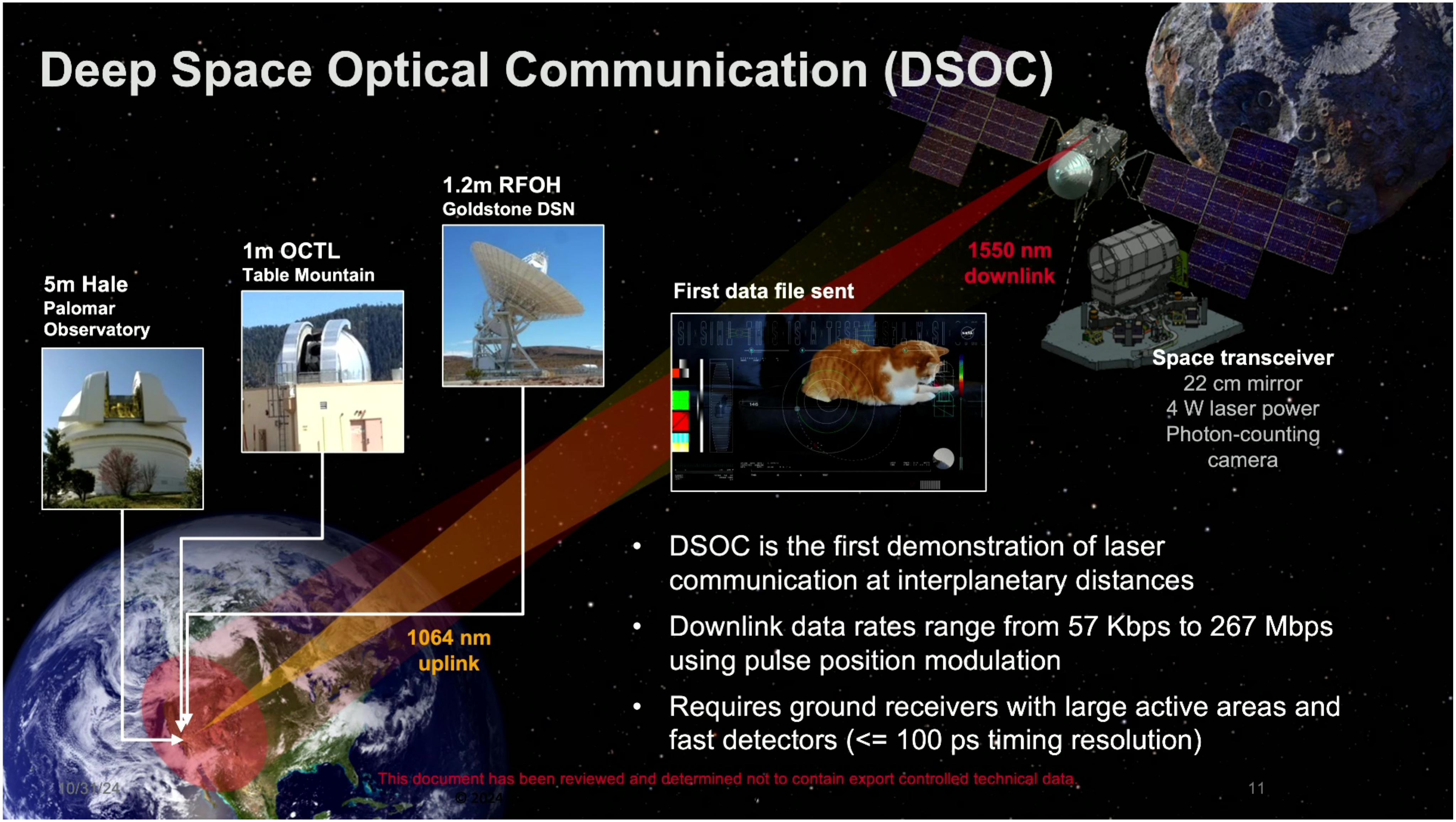


Time tag: 0.010 ns

Rising edge $\frac{L_k}{R_s+R_L} \sim \text{ps}$

Falling edge $\frac{L_k}{R_L} \sim \text{ns}$

Deep Space Optical Communication (DSOC)



5m Hale
Palomar
Observatory

1m OCTL
Table Mountain

1.2m RFOH
Goldstone DSN

First data file sent

1550 nm
downlink

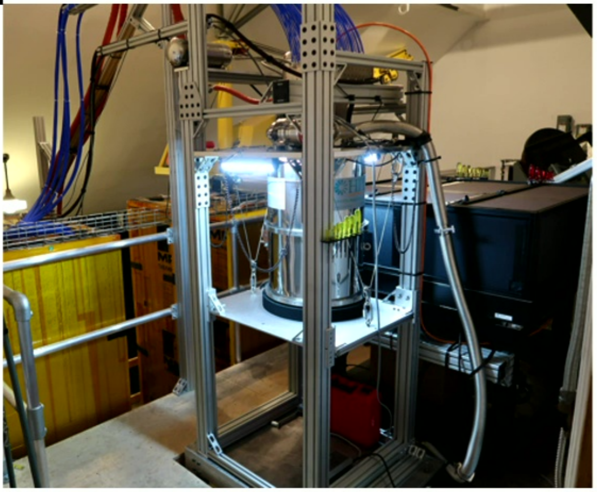
1064 nm
uplink

Space transceiver
22 cm mirror
4 W laser power
Photon-counting
camera

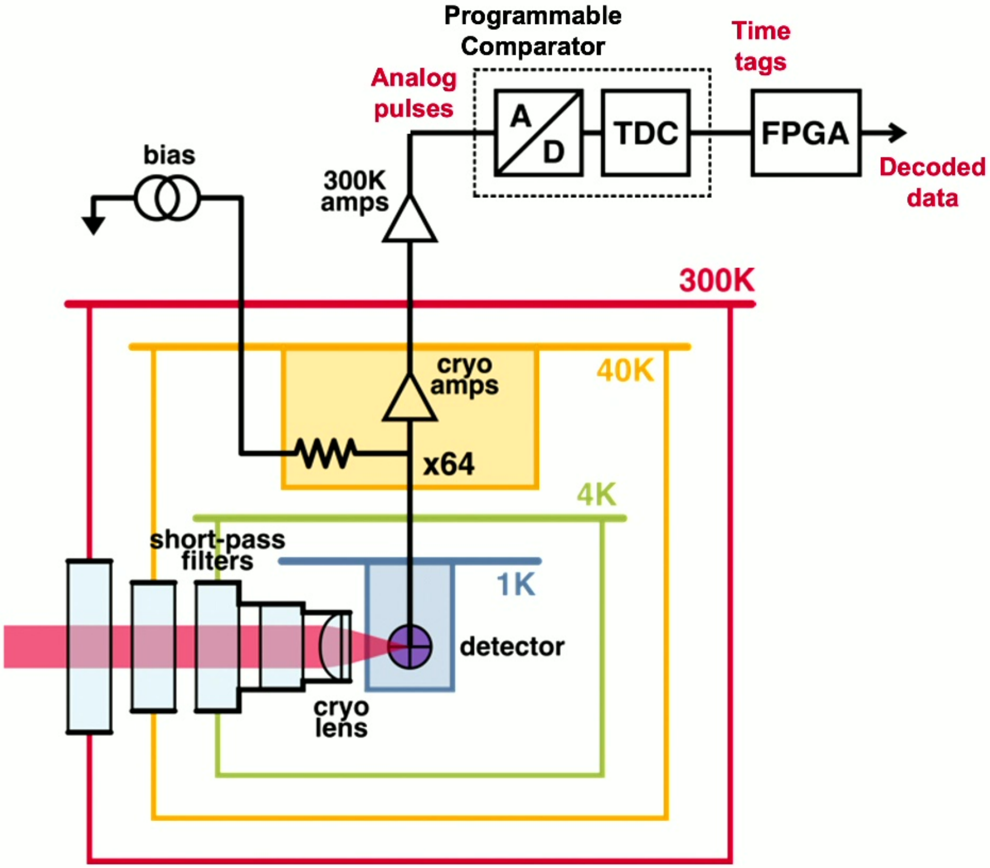
- DSOC is the first demonstration of laser communication at interplanetary distances
- Downlink data rates range from 57 Kbps to 267 Mbps using pulse position modulation
- Requires ground receivers with large active areas and fast detectors (<= 100 ps timing resolution)

SNSPDs for Deep Space Optical Communication

5 m Hale Telescope
at Palomar



Cryostat and
readout electronics
at the Coudé point
(fixed focus)



JPL SNSPD systems coupled to telescopes

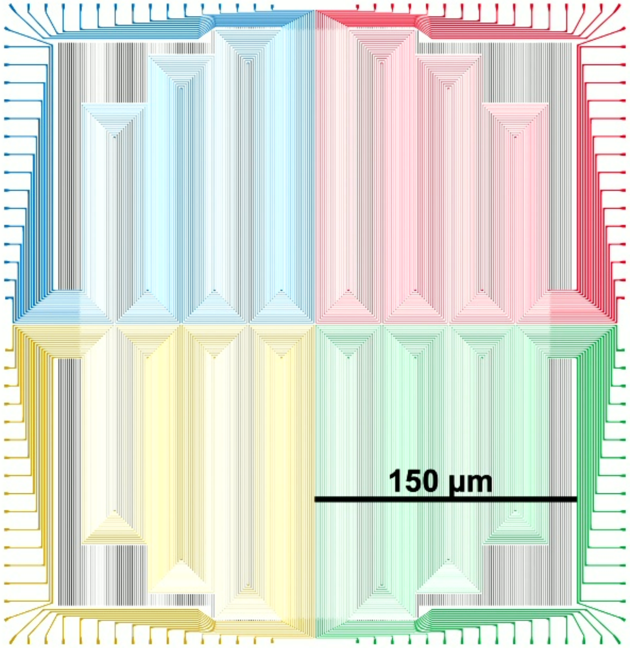
5m Hale
Telescope Coudé focus

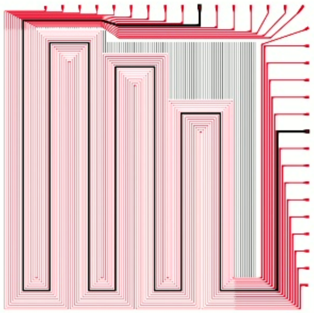
1m OCTL Telescope
Coudé focus

DSN 1.2m telescope
Fiber-coupled

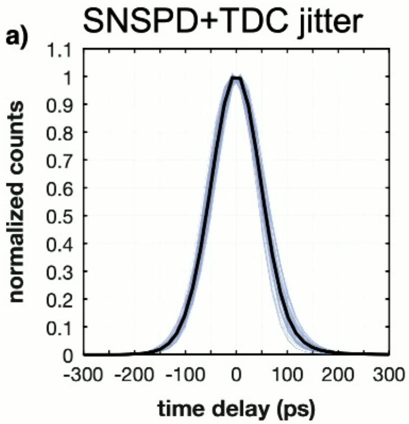
SNSPDs for Deep Space Optical Communication

64 nanowire array in 4 quadrants





Individual sensor element



Detection Efficiency:
70% / 65% for TE / TM-polarized at 1550 nm

Detector Area:
320 μm diameter active area for efficient coupling to 5 m telescope

Background:
3 – 30 kcps background count rate, depending on room temperature

Timing Jitter:
120 ps FWHM (51 ps RMS)

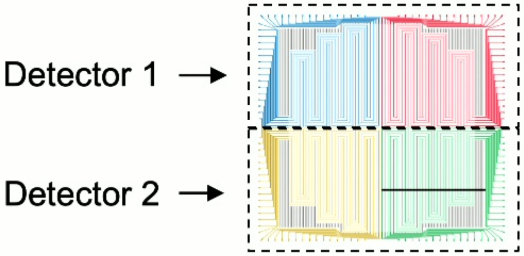
Maximum count rate:
1 Gcps (3 dB saturation)

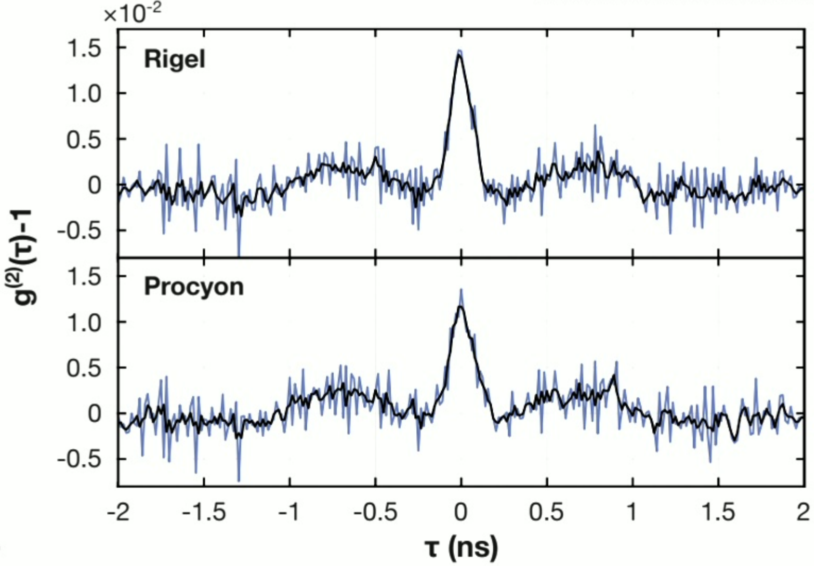
Wollman et al., arxiv.org/abs/2409.02356 (2024)

Photon Bunching Measurements with DSOC Receiver

Zero baseline intensity interferometry:

- Measured $g^{(2)}(\tau) = \int I(t)I(t+\tau)\,\mathrm{d}t$ for two bright stars
  - Analyzed timing correlations between time tags from two halves of the array in an HBT-type measurement.
- DSOC receiver at Palomar
  - 5 m telescope, FOV 25 – 50 μRad (5-10”)
  - 51 ps jitter RMS (118 ps FWHM)
  - Band: 1550 nm ± 0.9 nm
  - Polarizing beamsplitter in path
- Acquisition time:
  - Rigel: 123 s (44 Mcps, m=0.18)
  - Procyon: 40 s (81 Mcps, m=0.34)
  - Saved time tags to disk in 1-2 GB files for easier processing. Multiple acquisitions were taken for each target.





Wollman et al., arxiv.org/abs/2409.02356 (2024)

Optical communication ground station baselines

Palomar

5 m Hale

Table Mountain

1 m OCTL

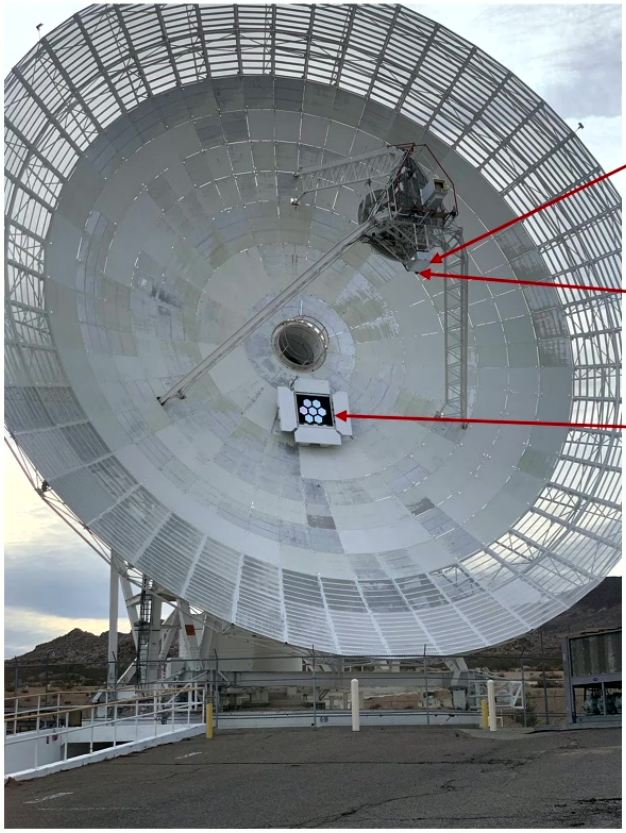
Goldstone

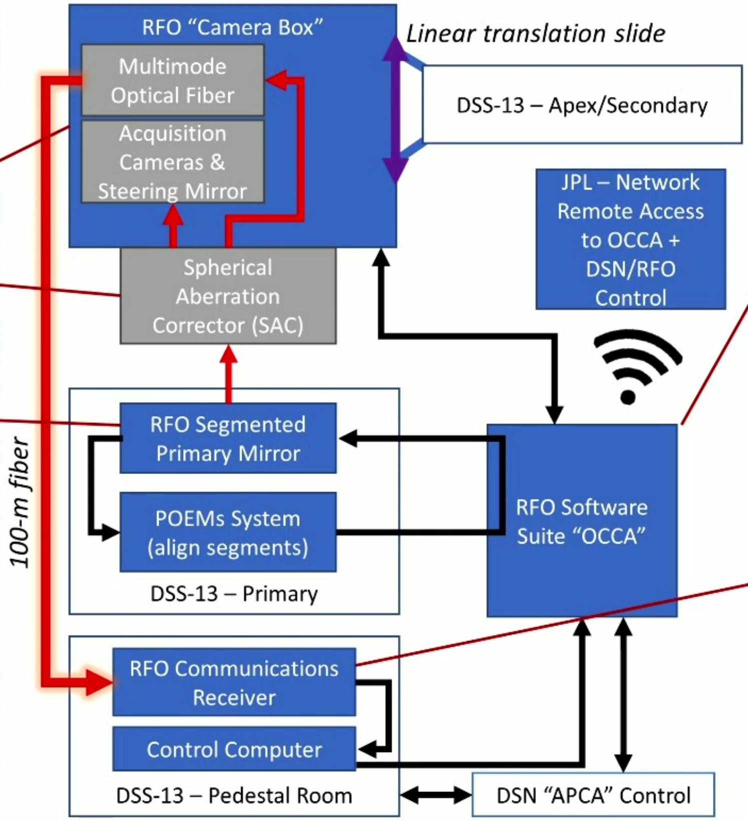
1.2 m DSN hybrid

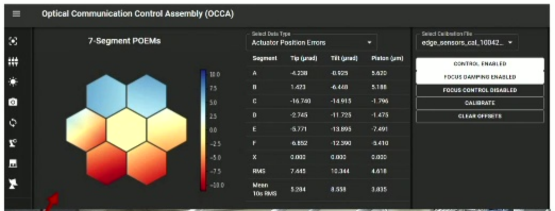
Station	**Diameter**	**Detector Jitter (FWHM)**
Palomar/ Hale	5 m	118 ps
Table Mountain/ OCTL	1 m	130 ps
Goldstone/ RFOH	1.2 m	190 ps

All at λ=1550 nm

RFO: an optical telescope built on an RF antenna





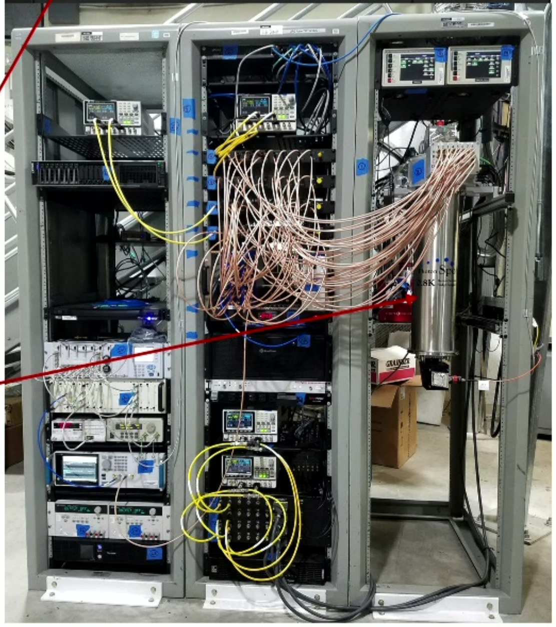

Optical Communication Control Assembly (OCCA)

7-Segment POEMs

Select Data Type: Actuator Position Errors

Select Calibration File: edge_sensors_cal_10042...

Segment	Tip (µrad)	Tilt (µrad)	Piston (µm)
A	-4.238	-0.925	5.620
B	1.423	-6.448	5.188
C	-16.740	-14.915	-1.796
D	-2.745	-11.725	-1.475
E	-5.771	-13.895	-7.491
F	-6.852	-12.390	-5.410
X	0.000	0.000	0.000
RMS	7.445	10.344	4.618
Mean 10s RMS	5.284	8.558	3.835



Relevant SNSPD Metrics: state of the art and our work

Intensity interferometry signal to noise ratio:

$$SNR \propto V(\nu_0, B)^2 \frac{\Gamma}{\Delta\nu} \sqrt{\frac{T_{\text{obs}}}{\sigma_t}}$$

Parameter:

Relevant SNSPD metric:

Visibility, a function of frequency and baseline, $V(\nu_0, \boldsymbol{B})$ → SNSPD sensitivity to wavelengths from **UV to mid-IR**

Detected photon count rate in band $\Delta\nu$, Γ → SNSPD **efficiency**

→ Efficient SNSPD coupling to telescope → **array readout**

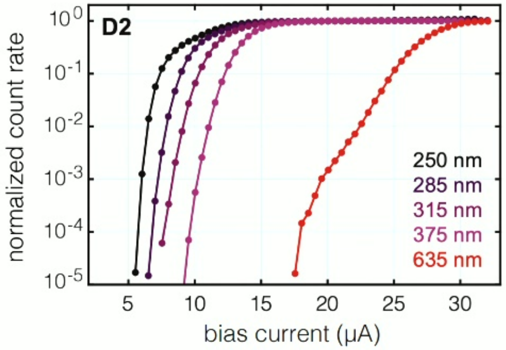
Timing jitter, σ_t → SNSPD **timing jitter** and system timing jitter

Observation time, T_{obs}

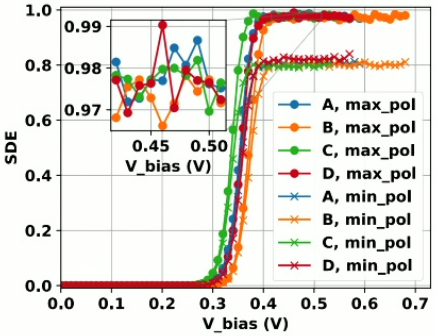
SNSPD sensitivity from the UV to the mid-IR

- SNSPDs can detect a photon when it creates an electron-hole pair in the nanowire with an energy >> superconductor bandgap
- As photon energy gets smaller → superconductor bandgap must be smaller → new materials with lower critical temperature → colder operation

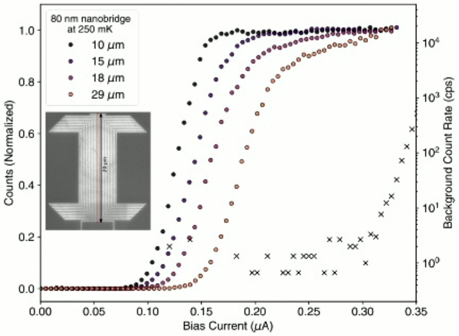
SNSPDs work in the UV … they work really well in the near-IR … they keep working into the mid-IR … and beyond?



λ = 250 nm
(Wollman et al., Optica, 2020)



λ = 1550 nm
(Reddy et al., Optica, 2020)

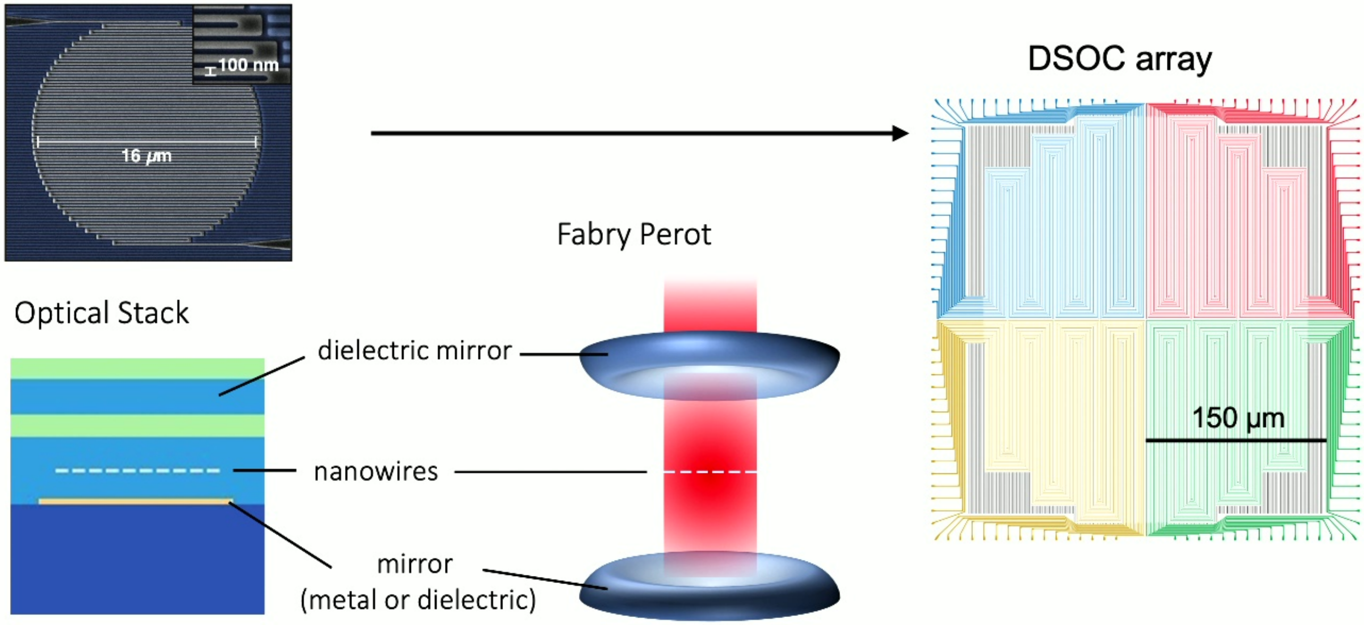


λ = 29 μm
(Taylor et al., Optica, 2023)

?

SNSPD efficiency

- To create an electron-hole pair, photon needs to absorbed in the ~ 5 nm thick, ~ 100 nm wide nanowire
  - Meander nanowires until they are the size of the optical mode
  - Create a dielectric stack such that light bounces around in the SNSPD chip until it is absorbed



From 5 m telescope, conservation of etendue requires detector ~ 300 μm across

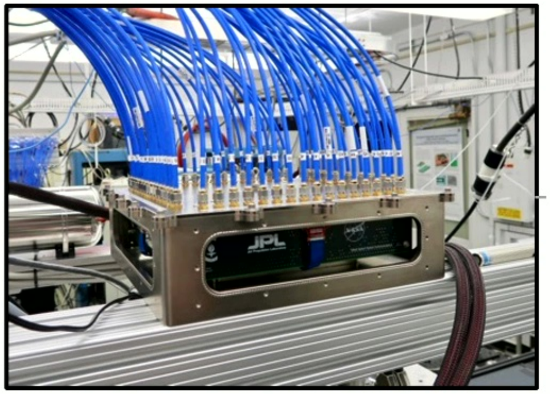
One nanowire meandered over (300 μm)^2 is too slow, so we use an array of 64 nanowires

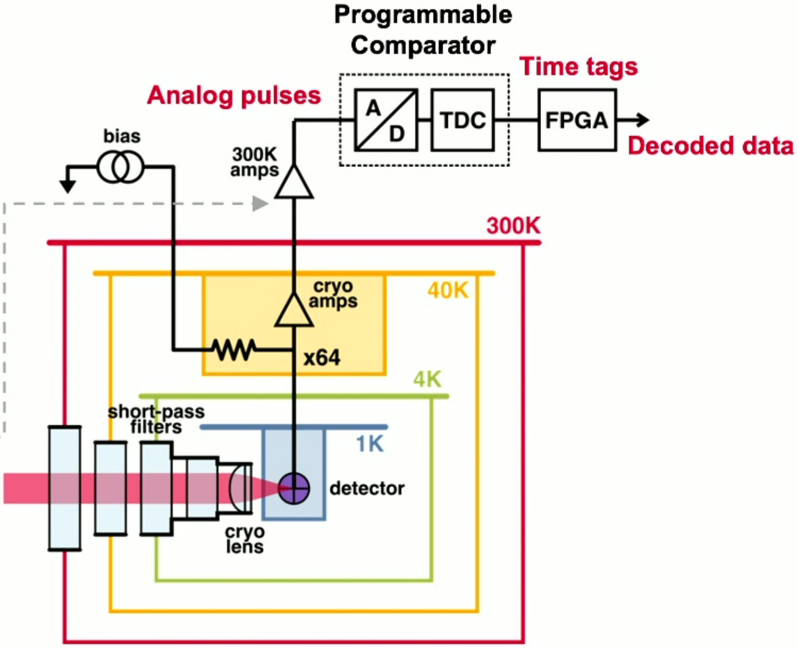
Wollman et al., J. Astron. Telesc. Instrum. Syst. 7 011004 (2021)

SNSPD array readout

DSOC uses direct readout, where each of 64 SNSPDs is biased and read out individually

- Simple in principle: copy 1 channel 64 times
- Higher heat load in cryostat: cables and cryoamplifiers
- Highest count rate as there is no multiplexing

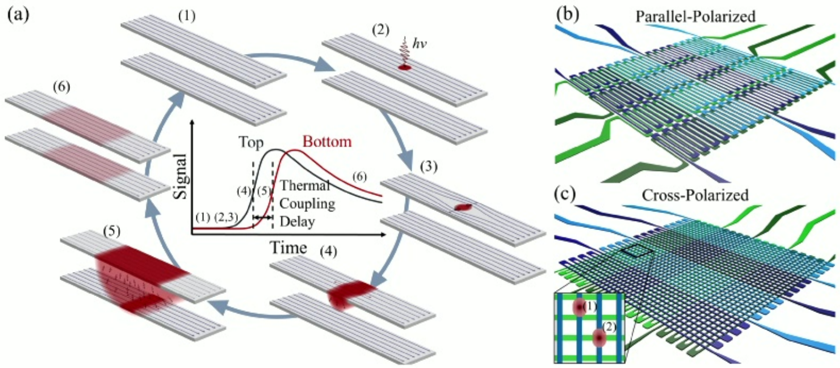




SNSPD array readout

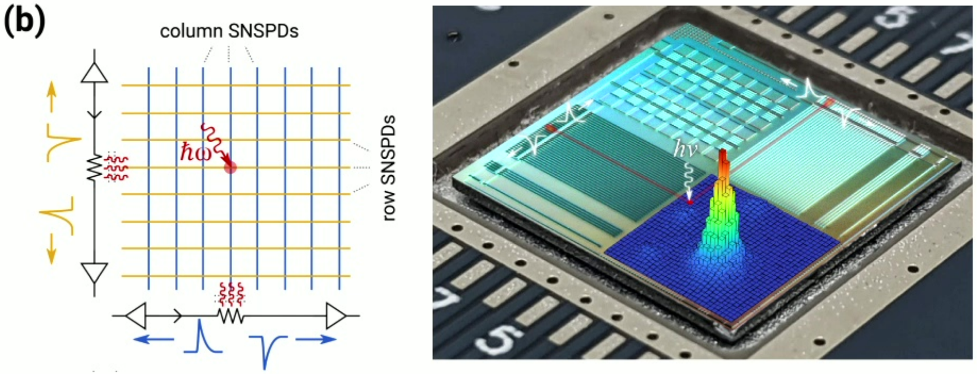
New readout schemes allow for SNSPD cameras with many more pixels

- Row-column multiplexing
- Thermal coupling

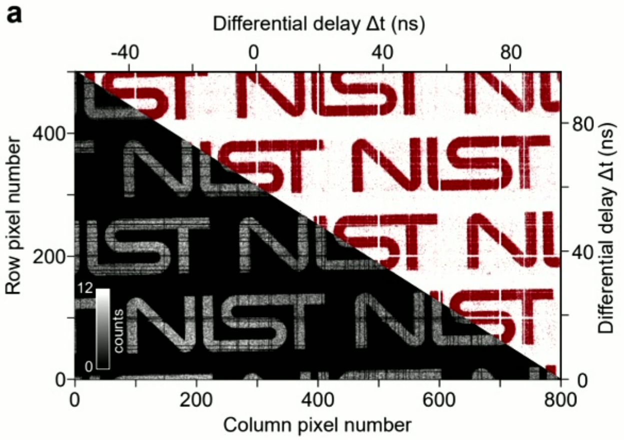


Thermally coupled row-column, Allmaras et al., 2020

- Frequency multiplexing
- Cryogenic logic



Thermally coupled imager, McCaughan et al., 2022

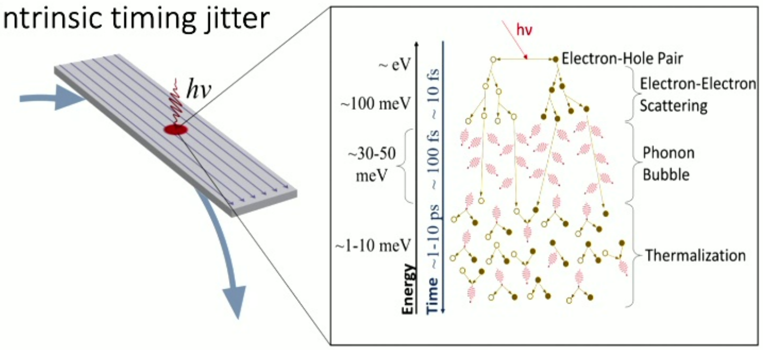


400 kilopixel thermally coupled imager, Oripov et al., 2023

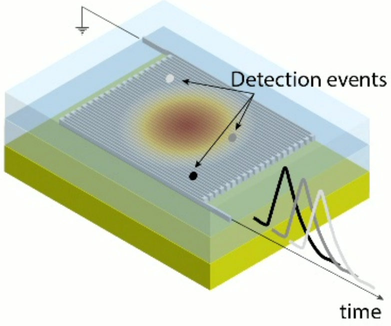
SNSPD Timing Jitter – Sources of jitter

Source	Description
intrinsic	variation in hotspot formation time
geometric	variation in location of hotspot formation
high count rate	variation in pulse size due to previous pulses
setup	source pulse width, timing jitter in TDC
noise	amplifier noise and other electronic noise

intrinsic timing jitter



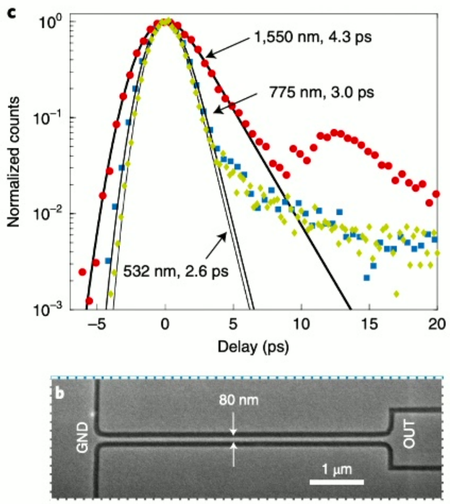
geometric timing jitter



Caloz et al., J. Appl. Phys. 126, 164501 (2019)
Allmaras, Thesis, Caltech (2020)
Colangelo et al., arXiv:2109.07962 (2021)

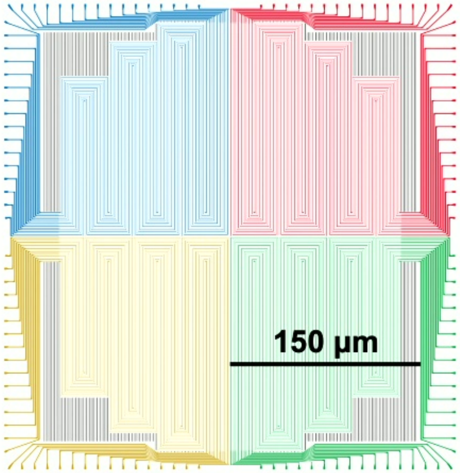
SNSPD Timing Jitter – Some numbers

sub-3 ps FWHM



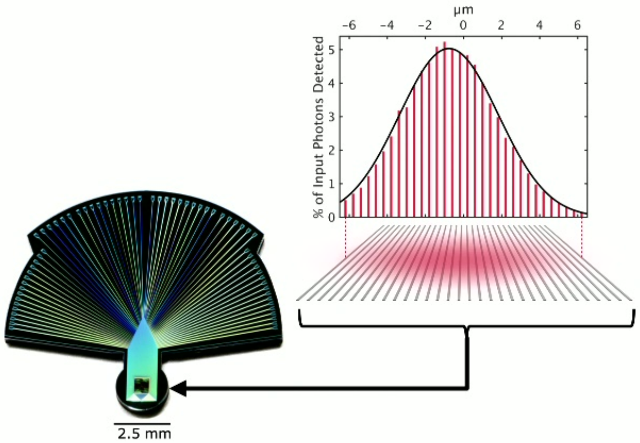
Intrinsic jitter of SNSPDs

118 ps FWHM



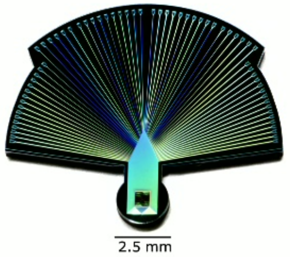
Practical jitter of 320 µm array

45 ps FWHM

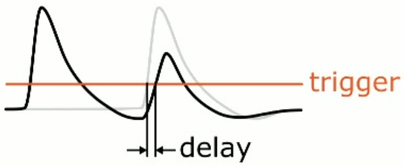


Optimizing jitter of 13 µm array
Intrinsic jitter is 16 ps FWHM
Work in progress

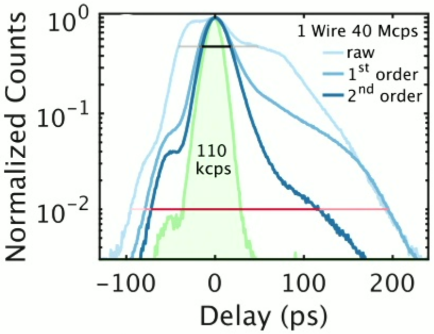
Timing Jitter of Peacoq detector



Peacoq is designed to maintain low timing jitter at high count rates
Use software correction to reduce jitter due to predictable time-walk effect



Jitter histogram
with and without time-walk correction



Count Rate (Mcps)	Efficiency (%)	Estimated Timing Jitter (ps FWHM)/(ps FW1%M)
7	78	21 / 66
250	70	22 / 86
1000	50	46 / 244

Jitter reduction steps:

- Material choice – NbN is a “faster” material in terms of hotspot formation: low intrinsic jitter
- Short nanowires: low geometric jitter
- Reducing system jitter with better time-to-digital electronics

To do:

- Reducing noise jitter using 4K cryoamplifiers (current results with same 40K amplifiers used for DSOC)
- Implementing differential readout, which allows for larger area arrays without geometric jitter

Thank you for listening!

Contact: ioana.craiciu@jpl.nasa.gov