
Quantum Measurements with Superconducting Nanowire Single Photon Detectors

Andrew Mueller

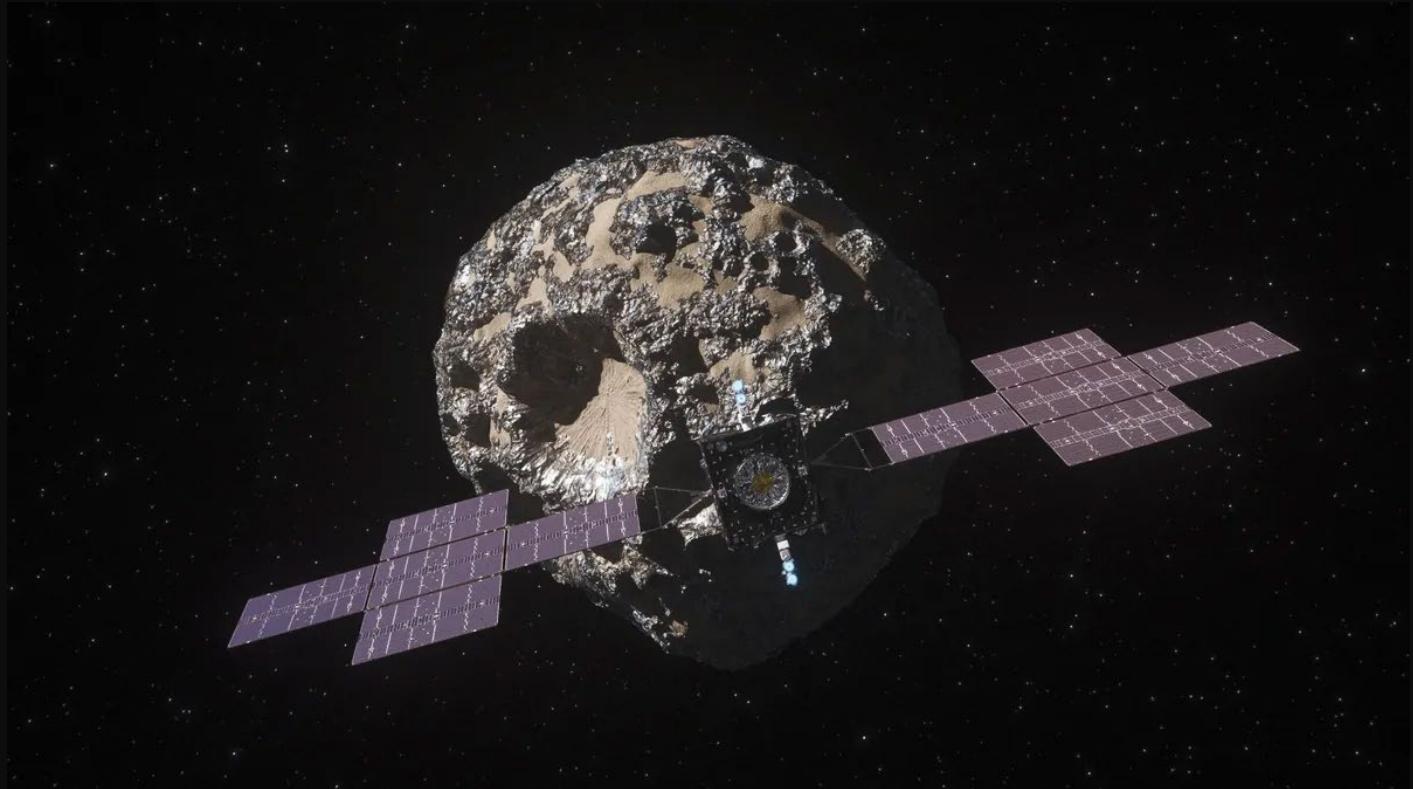
December 11th

Psyche

Oct. 13, 2023



Trevor Mahlmann, Ars Technica



NASA/JPL-Caltech/ASU

Radio Communication

Via the **Deep Space Network**

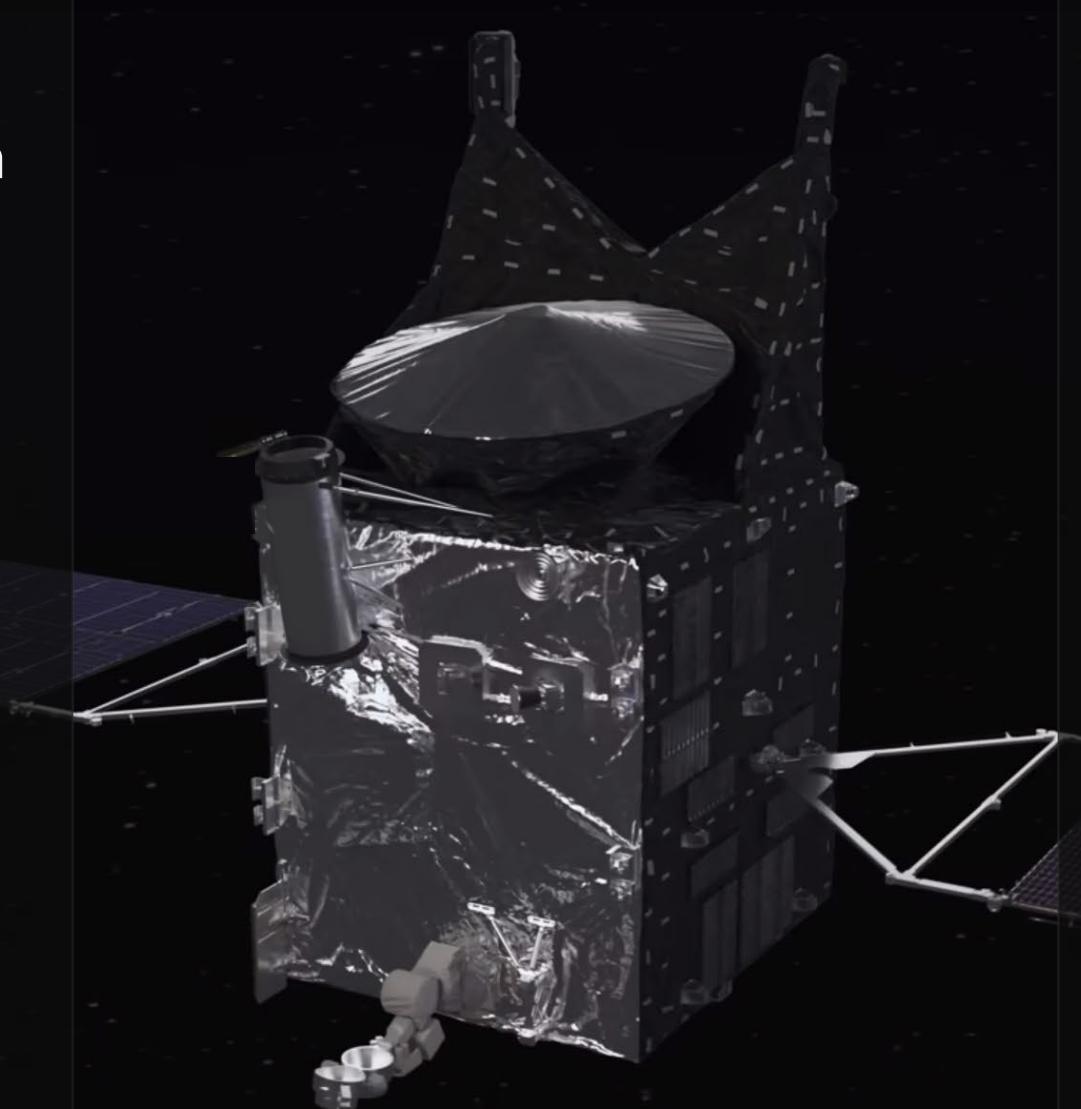


Laser Communication

Now

Deep Space Optical Communication (DSOC)
- 0.2 Mbit/s to over 200 Mbit/s [1]

- 2 GHz clock rate



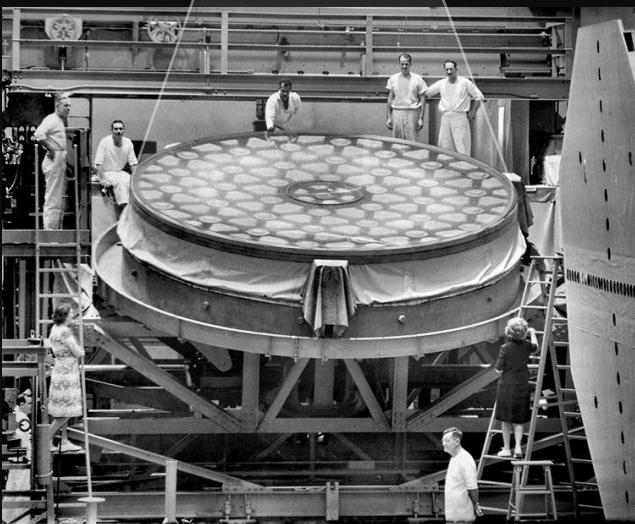
Future

10 – 100x faster

For future deep space laser links [1]

Deep Space Optical Communication (DSOC)

Hale Telescope, Palomar Observatory
San Diego County



Corning Museum of Glass, Caltech Archives



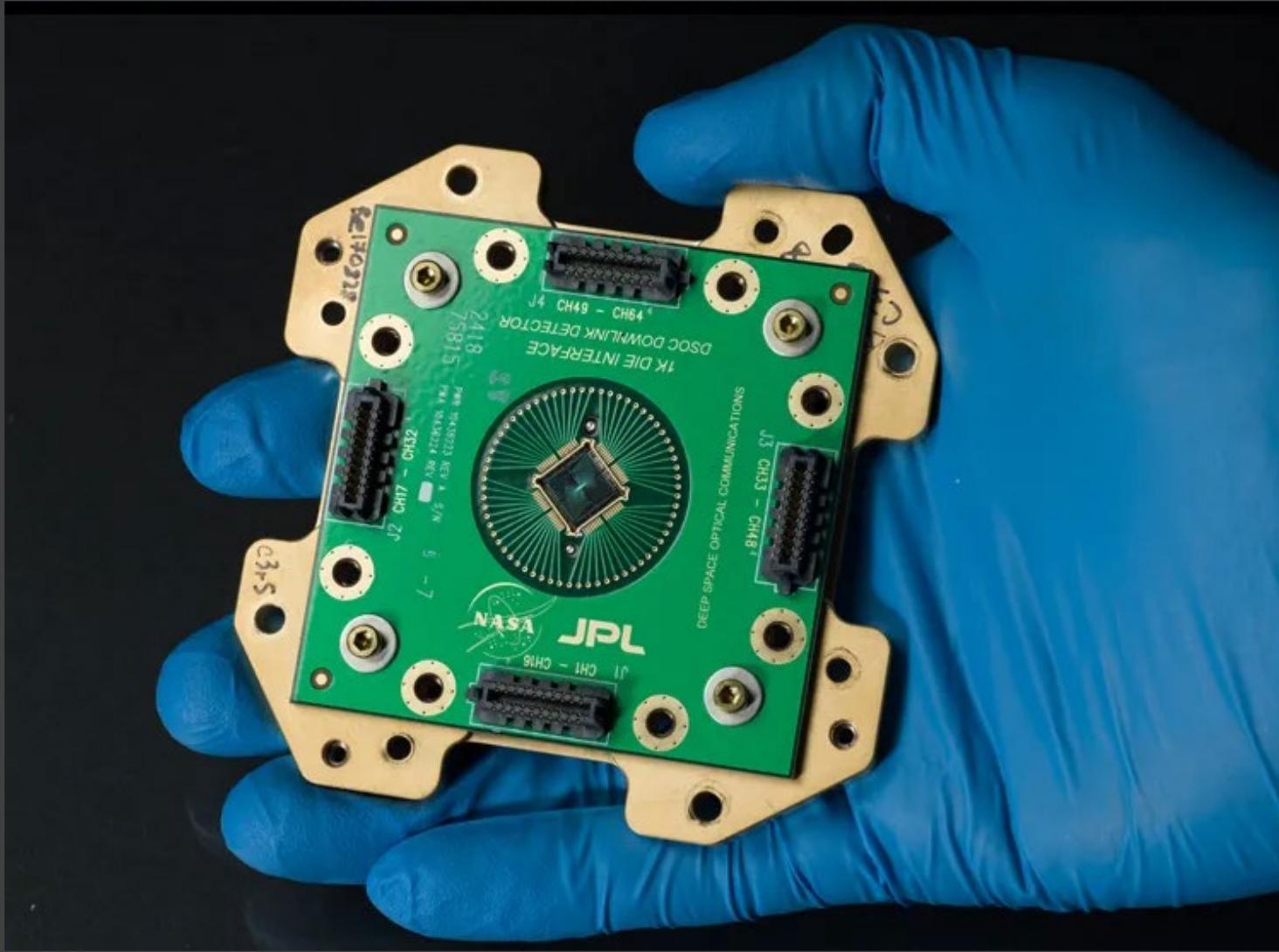
4 W laser power



0.00000000002%
captured

~ 100 femtowatts (10^{-15} W)

Superconducting Nanowire Single Photon Detector



NASA/JPL-Caltech

Deep Space Optical Communication (DSOC)

TECHNOLOGY

NASA's Deep Space Optical Comm Demo Sends, Receives First Data

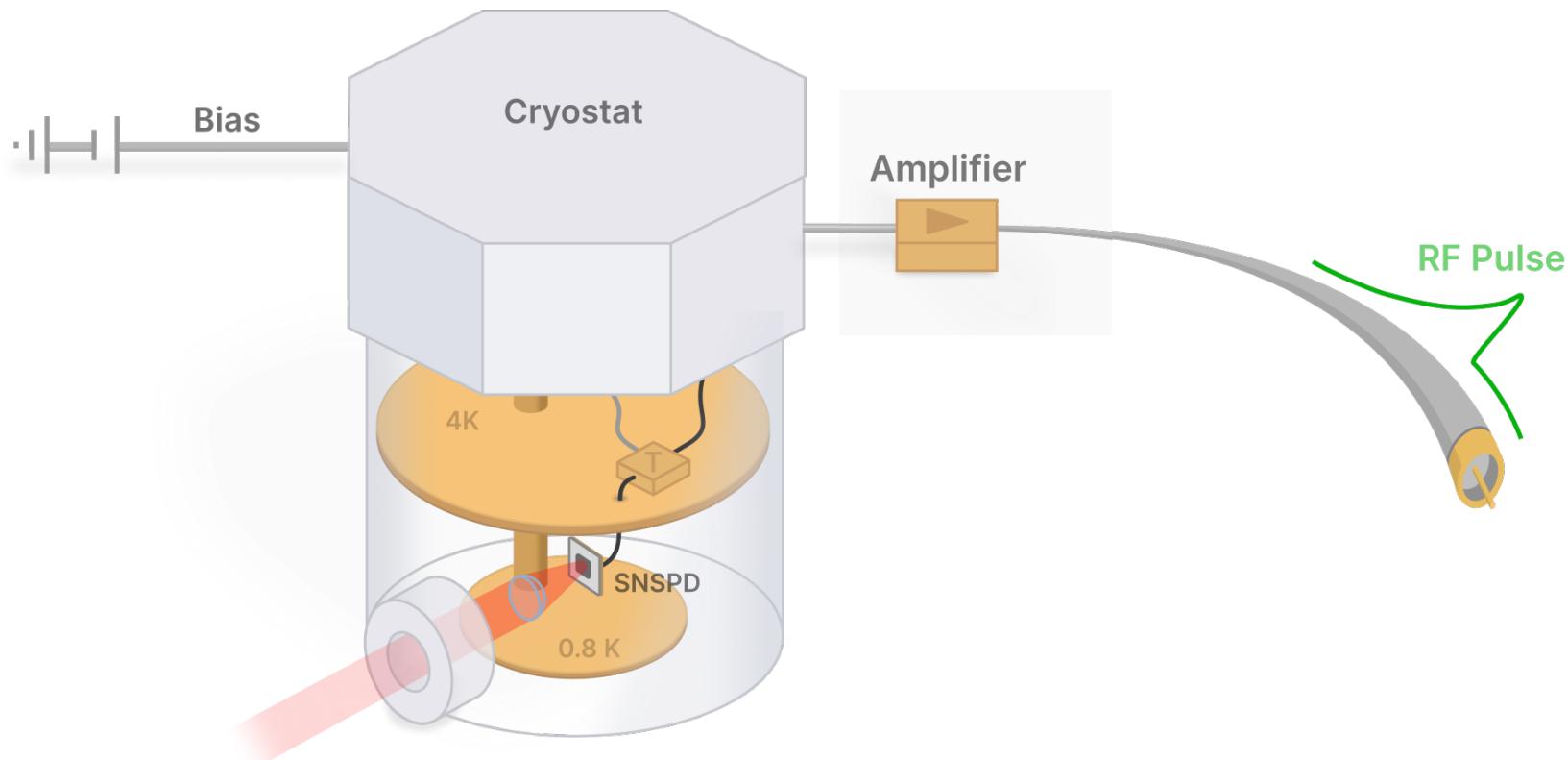
Nov. 16, 2023



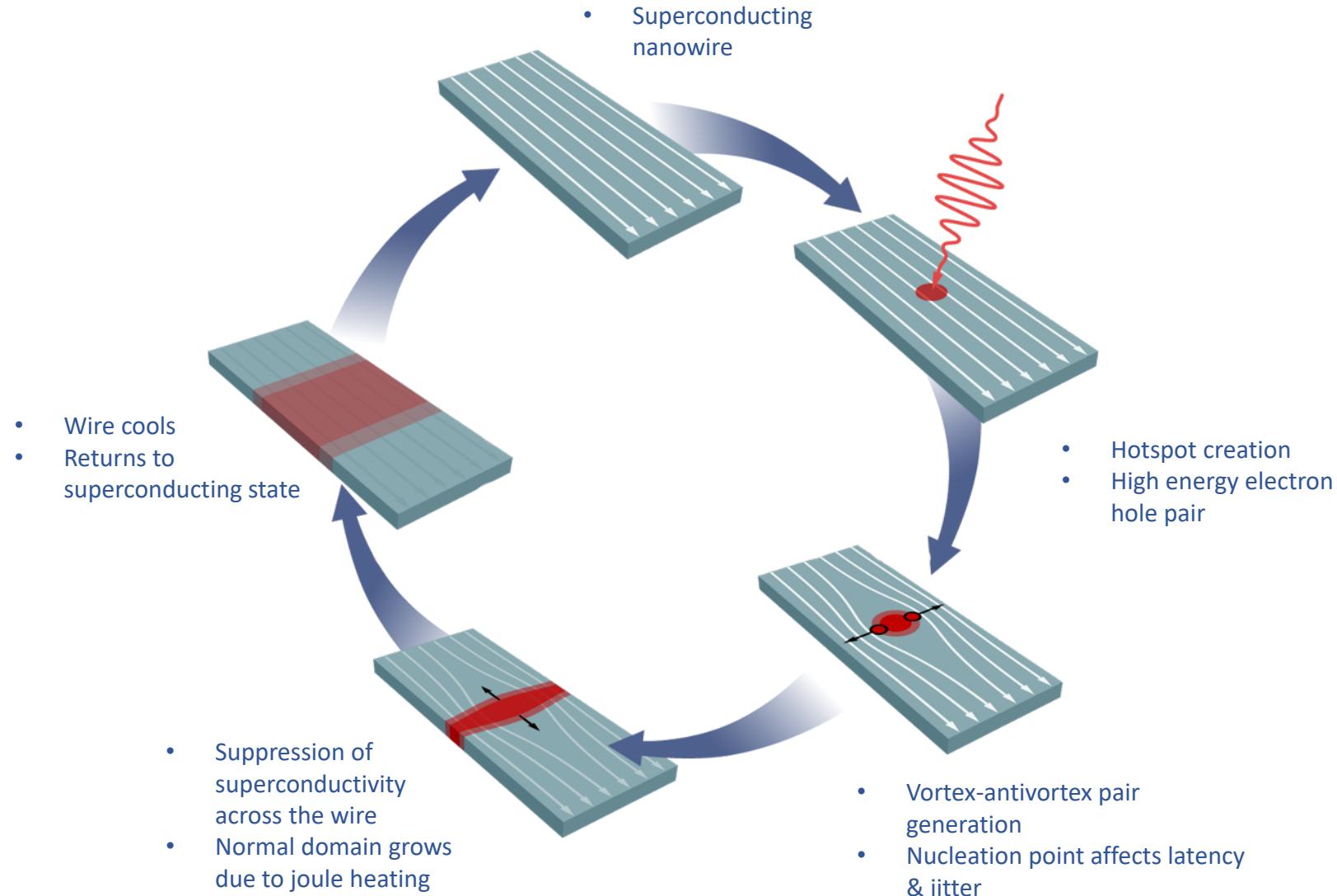
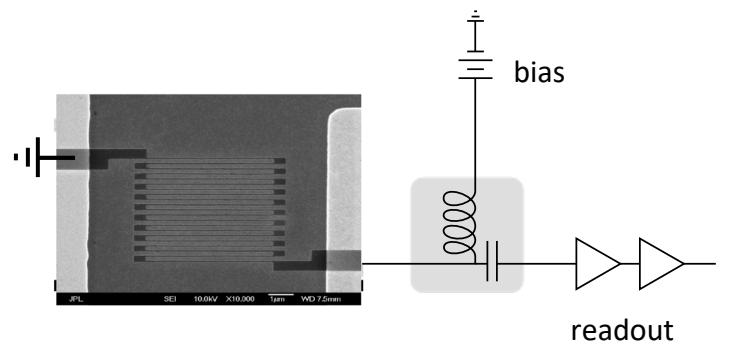
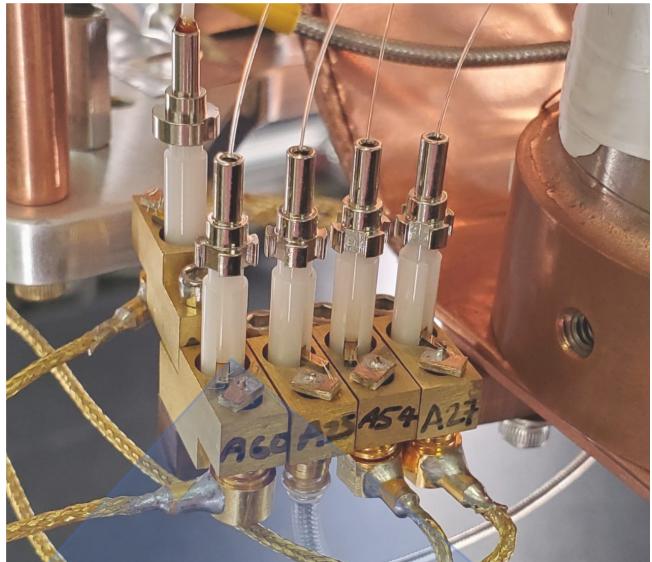
NASA's Psyche spacecraft is shown in a clean room at the Astrotech Space Operations facility near the agency's Kennedy Space Center in Florida on Dec. 8, 2022. DSOC's gold-capped flight laser transceiver can be seen, near center, attached to the spacecraft. Credit: NASA/Ben Smegelsky



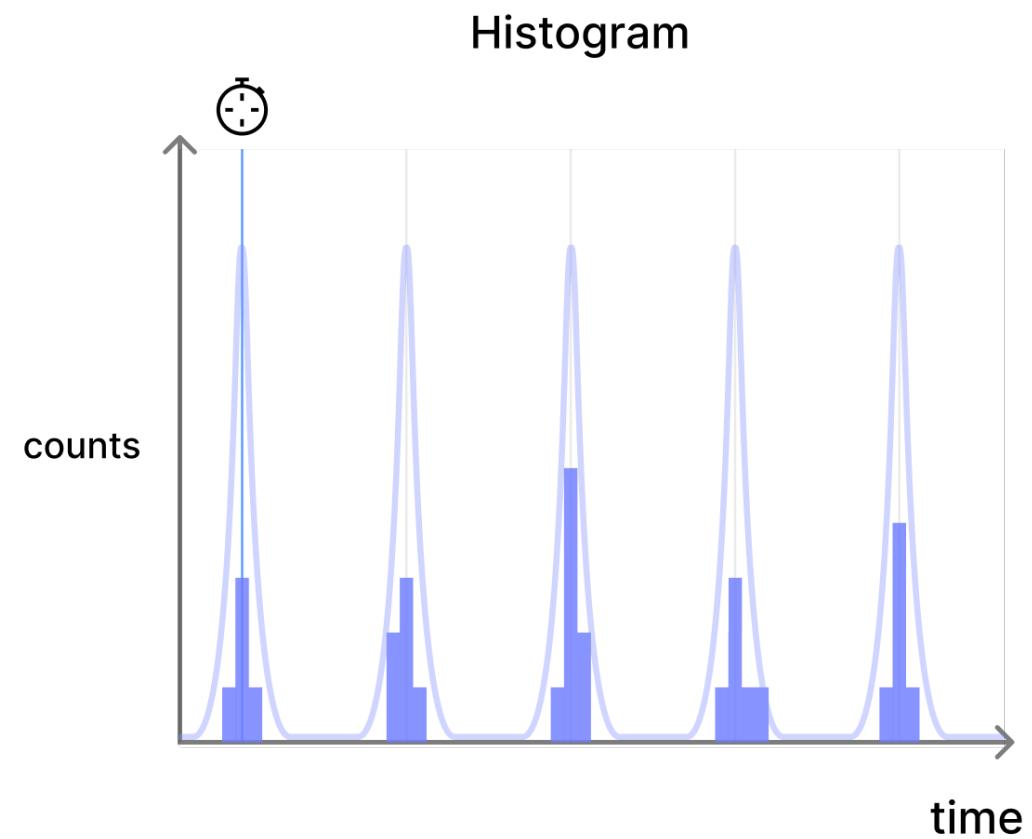
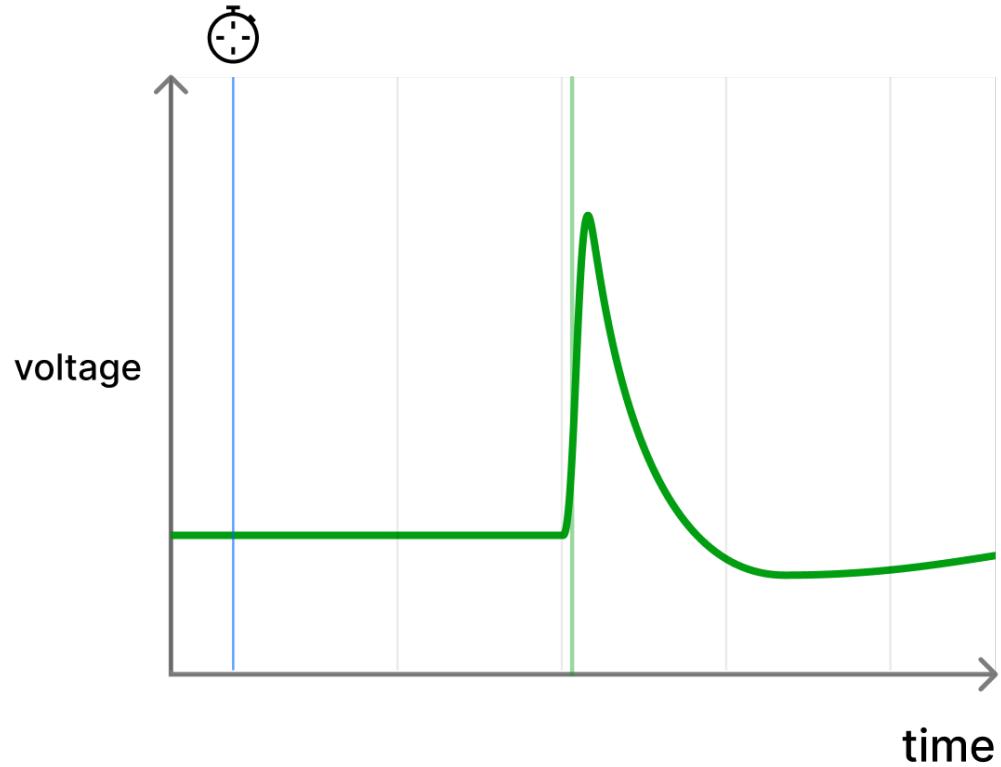
Context



Operation



Photon Arrival time & Histograms



Metrics

①

②

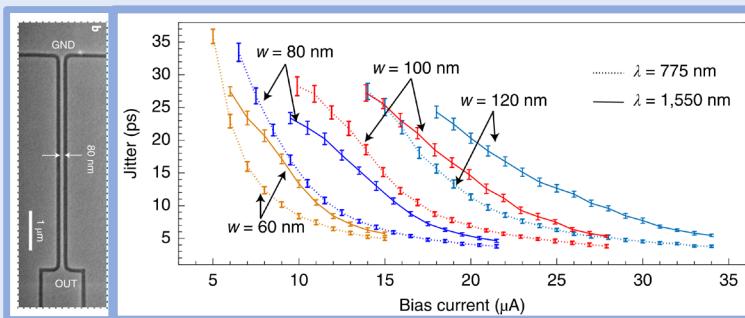
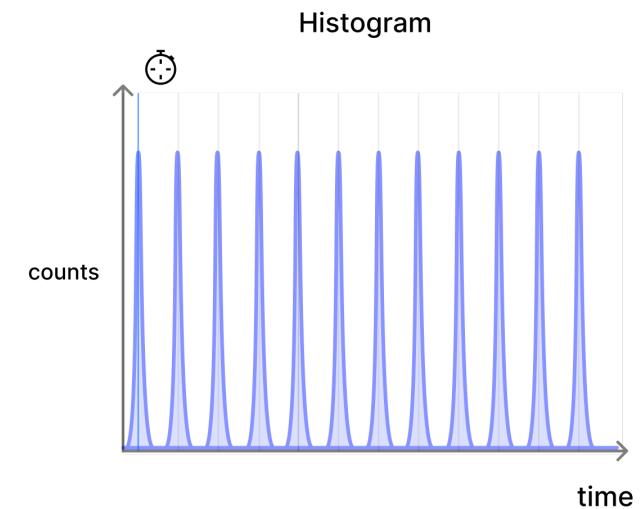
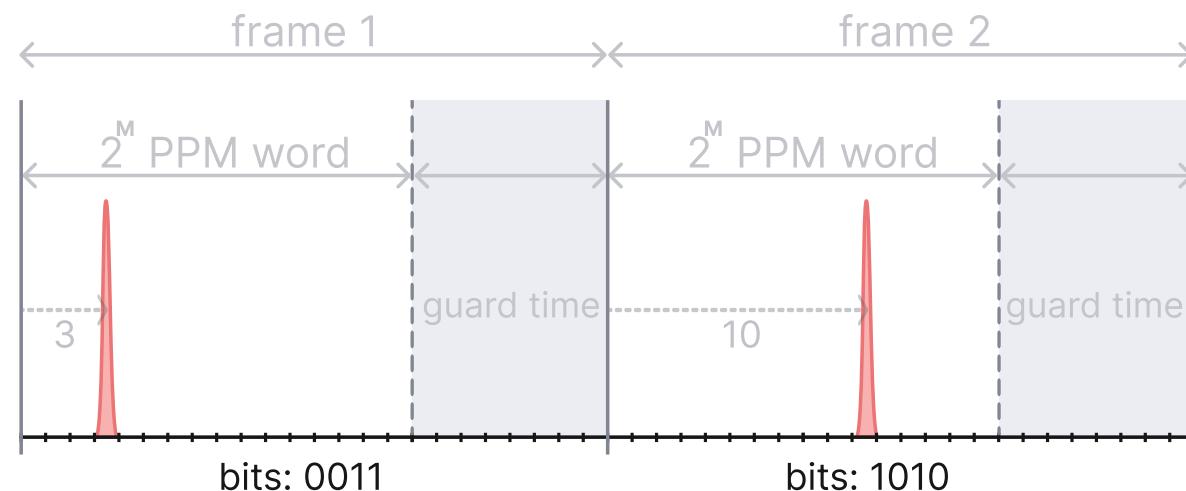
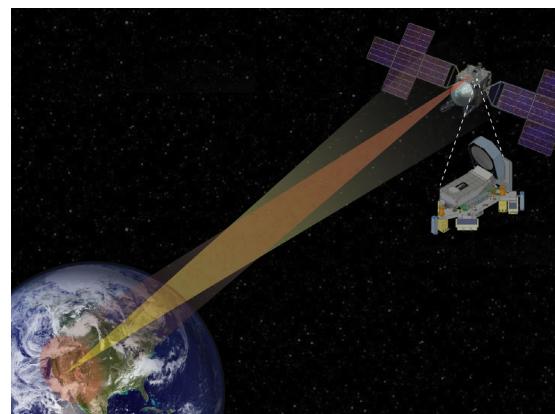
③

④

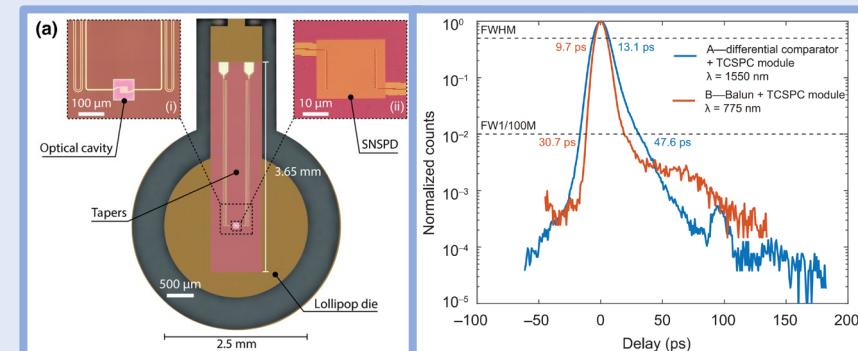
Metric 1: Timing Resolution

High timing resolution (low jitter) enables higher system repetition rates and data rates

① timing resolution



Example: State-of-the-art for short wires
- 2.6 ps visible wavelengths
- 4.3 ps at 1550 nm

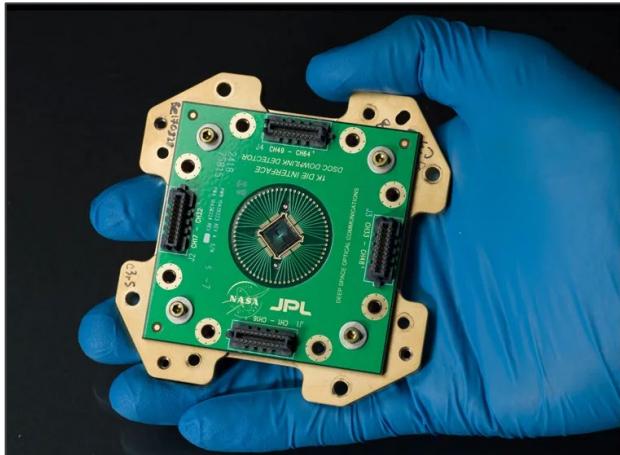


Example: State-of-the-art for efficient fiber coupling
- 9.7 ps FWHM at 775 nm
- 13.1 ps FWHM at 1550 nm

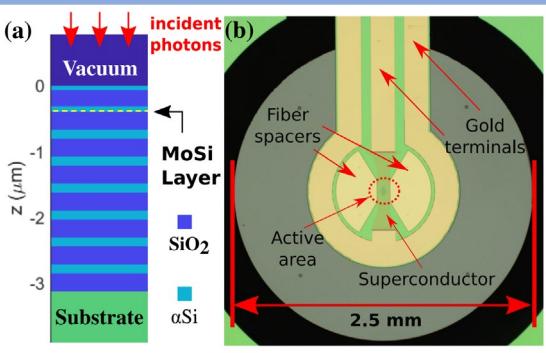
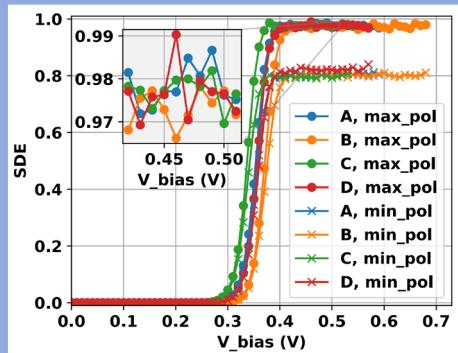
Metric 2: Efficiency

High system detection efficiency enables efficient use of other resources, higher chance of collecting sent data

② system detection efficiency

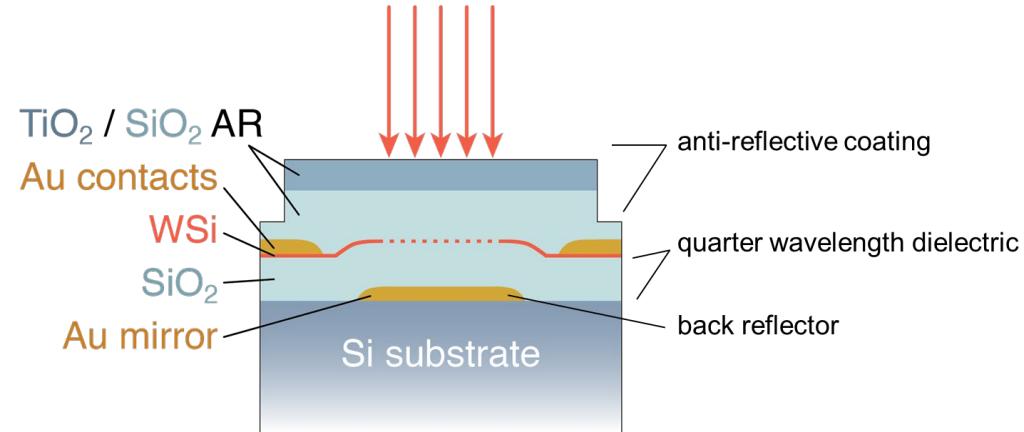


NASA/JPL-Caltech



Example: Up to 98% system detection efficiency demonstrated
- 1550 nm
- fiber coupled
- DBR based optical stack

[1] Dileep Reddy et al. 2020

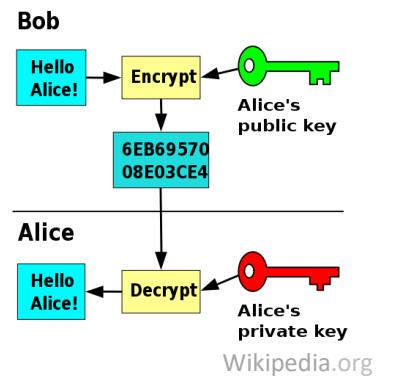
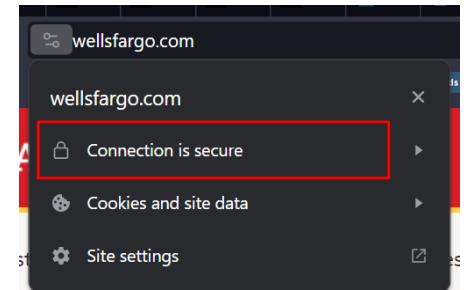


Quantum Computing, Quantum Networks

- Future **Quantum computers** will break existing encryption standards
- **Quantum networks** enable communication secured by the laws of quantum mechanics
 - **No-cloning theorem:** quantum states cannot be copied
- **Quantum key distribution (QKD)** provides verifiable security over single links (100 – 800 km)



AWS quantum

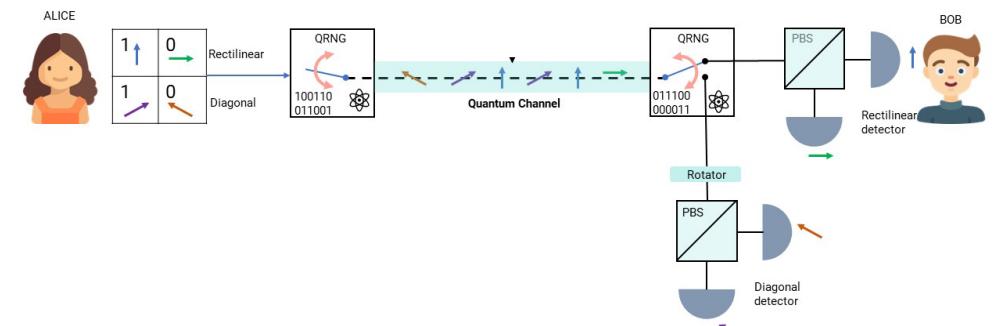


Other quantum network applications

- Quantum sensor networks
 - Magnetic field mapping
 - Distributed phase measurement, telescope arrays
- Blind quantum computing
- Network of atomic clocks



Physics World



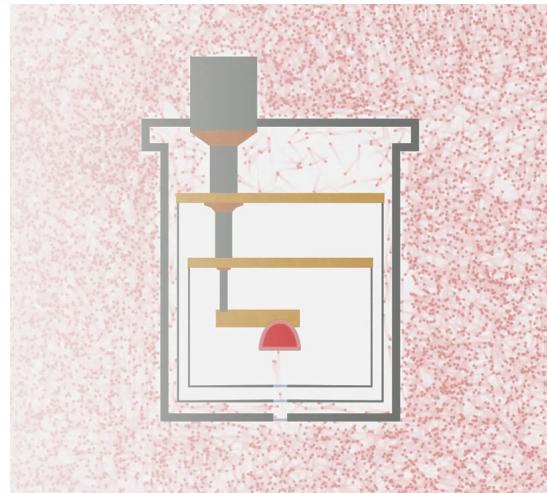
Quside

Metric 3: Dark count rate

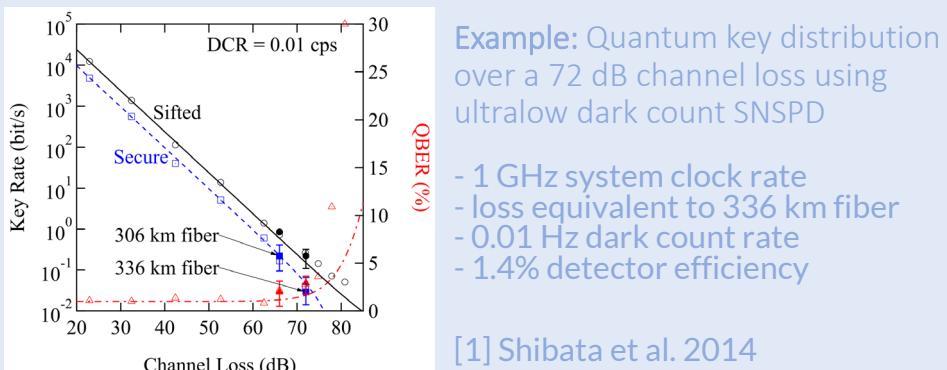
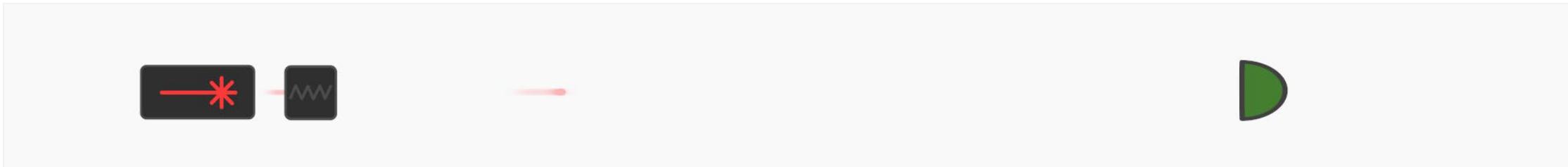
Long distance Quantum Key Distribution

- Involves low detector count rates
- **Dark counts** are a source of noise, introduce errors
 - **2 – 10 μm photons**, emitted by the ~ 300 K room temperature environment
 - Can couple to the detector through fiber or free space optics

Dark counts can couple to the detector through fiber or free space optics



③ dark count rate



Example: Quantum key distribution over a 72 dB channel loss using ultralow dark count SNSPD

- 1 GHz system clock rate
- loss equivalent to 336 km fiber
- 0.01 Hz dark count rate
- 1.4% detector efficiency

[1] Shibata et al. 2014

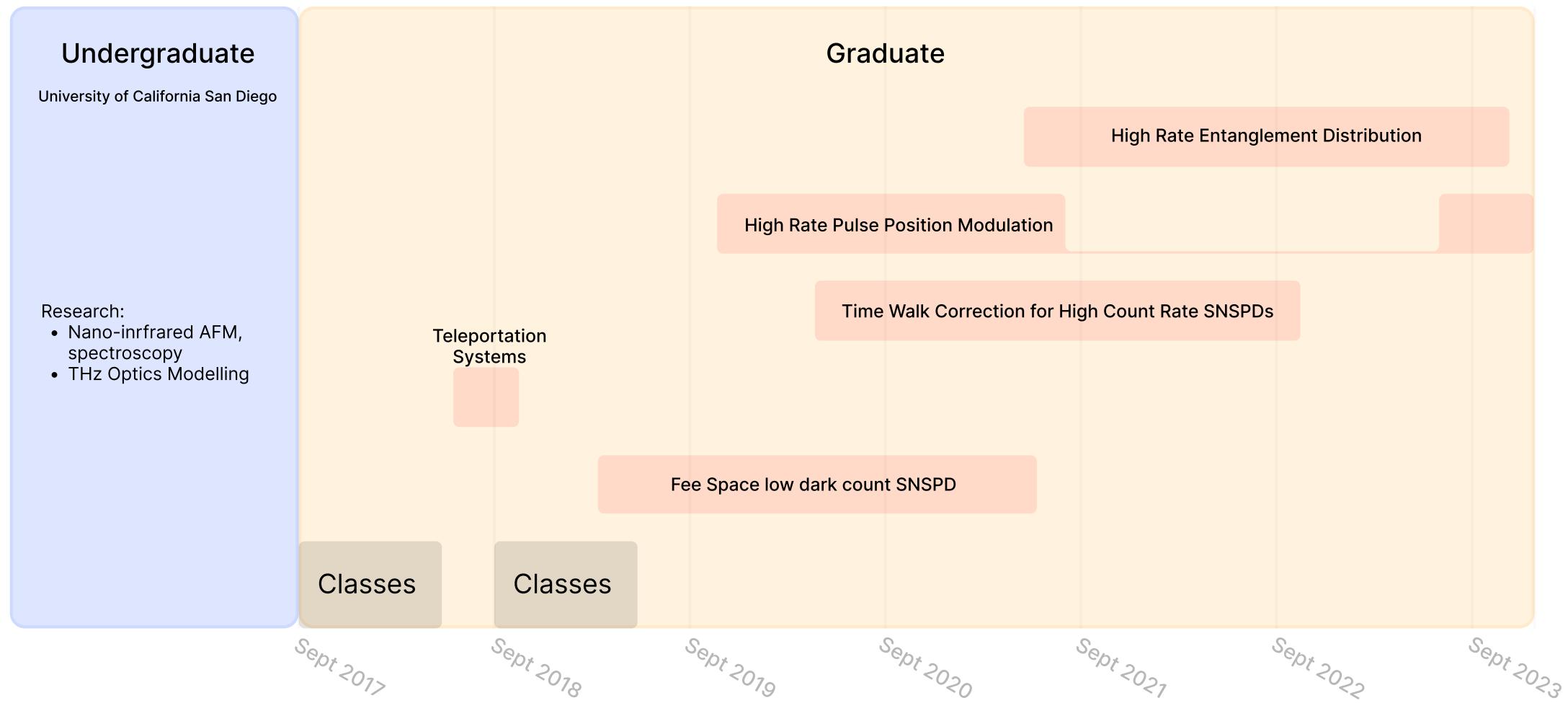
Metric 4: Maximum Count Rate

Some applications must process **large count rates**, to resolve a tiny fraction of ‘useful’ events

④ maximum count rate

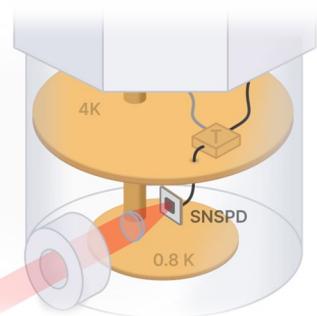
In progress

Timeline

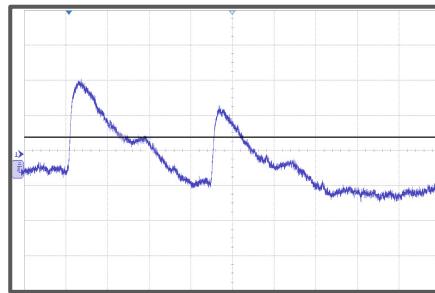
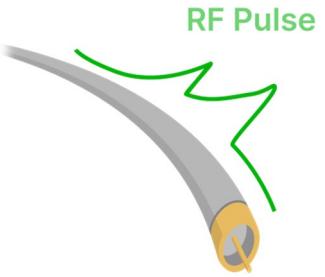


Outline

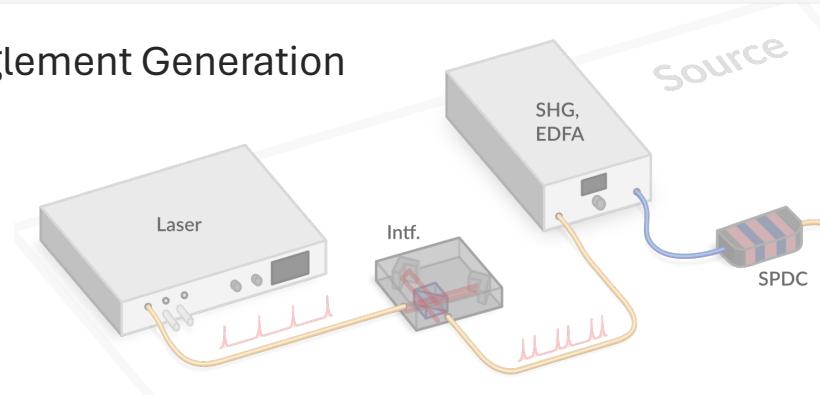
1. Low Dark Count Rate Free Space Coupled SNSPD



2. Time Walk Correction

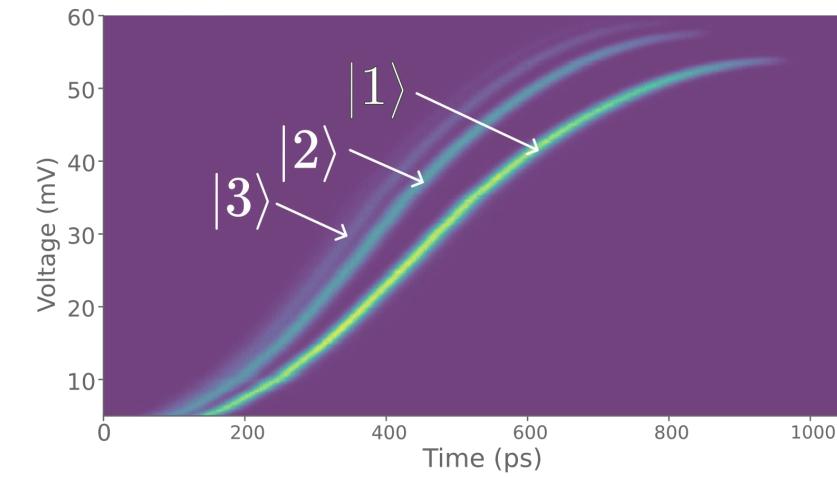
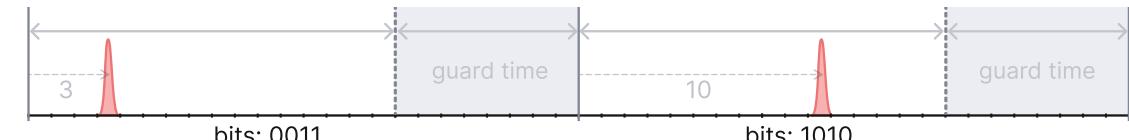


3. High-Rate Entanglement Generation



Aside: Phase Locked Loops

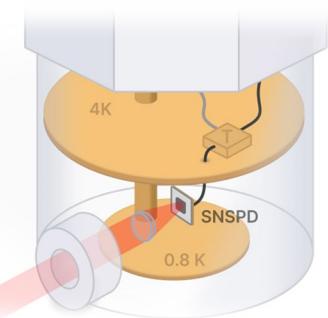
4. Pulse Position Modulation & Photon Number Resolution



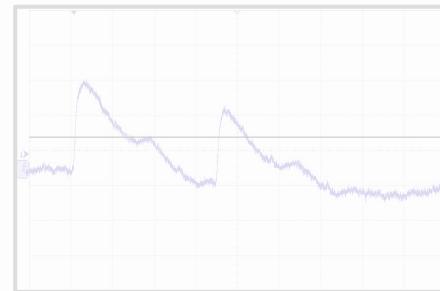
Conclusion & Outlook

Outline

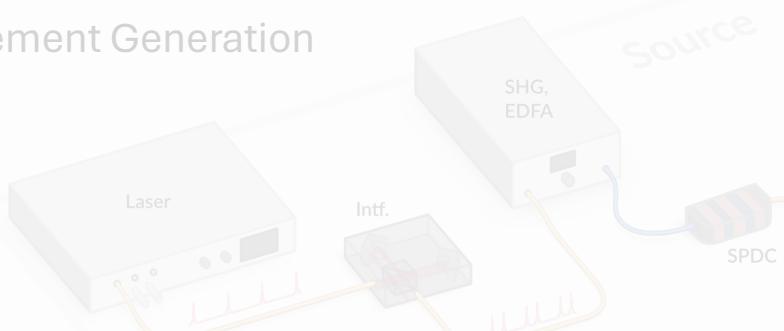
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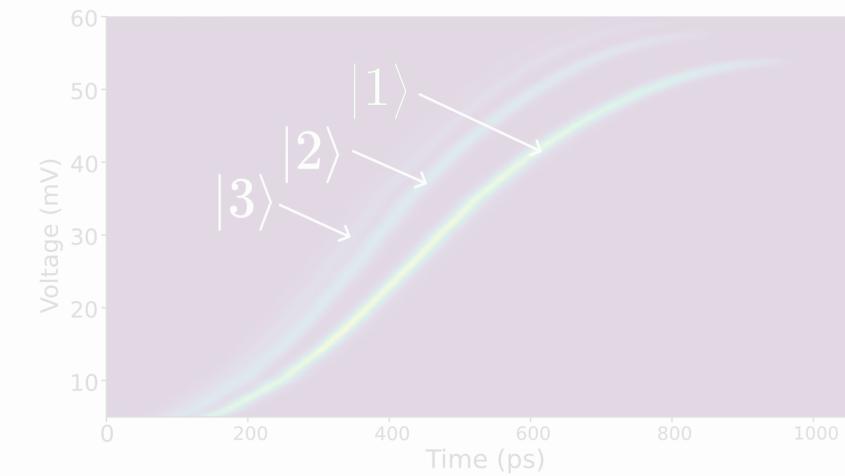


3. High-Rate Entanglement Generation



Aside: Phase Locked Loops

4. Pulse Position Modulation & Photon Number Resolution



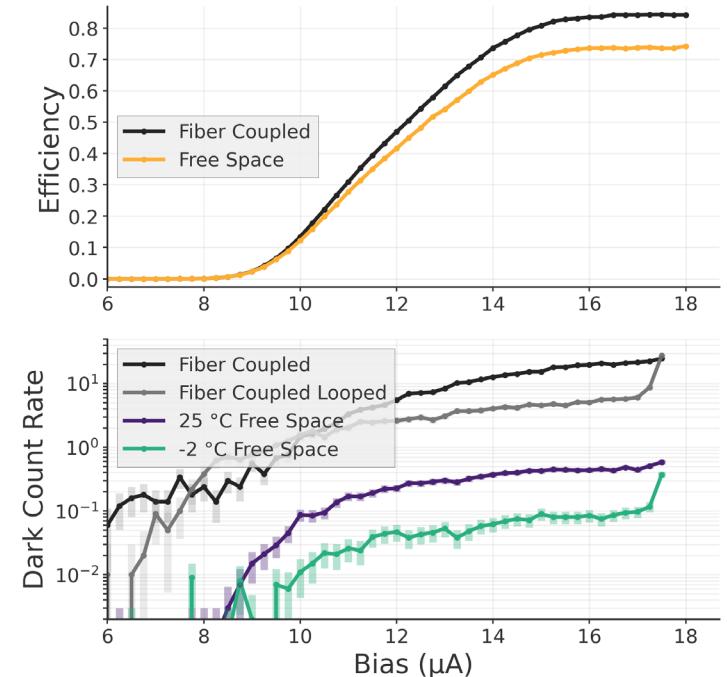
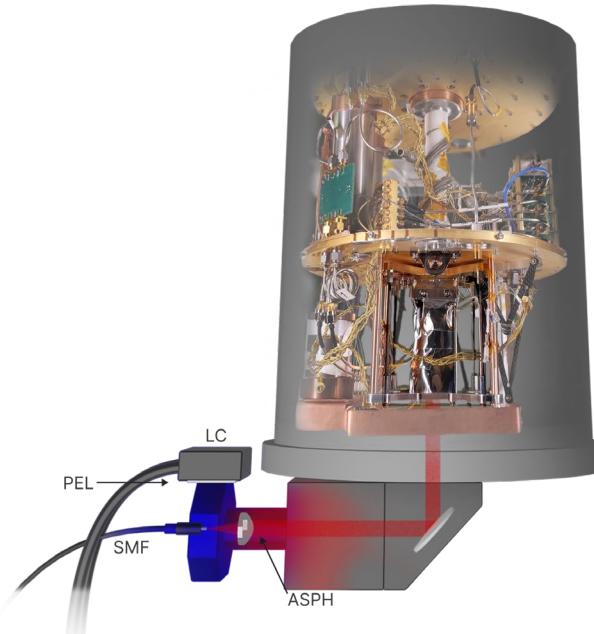
Conclusion & Outlook

Achievement

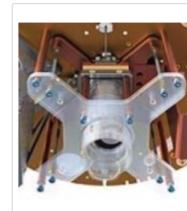
- 0.1 Hz dark count rate D
- 72% system detection efficiency η
- 14 ps timing jitter Δt

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

- $H = 5e11$
 - One of the highest H metrics for quantum communication detectors
 - More practical than other records



Optica Vol. 8, Issue 12, pp. 1586-1587 (2021) • <https://doi.org/10.1364/OPTICA.444108>

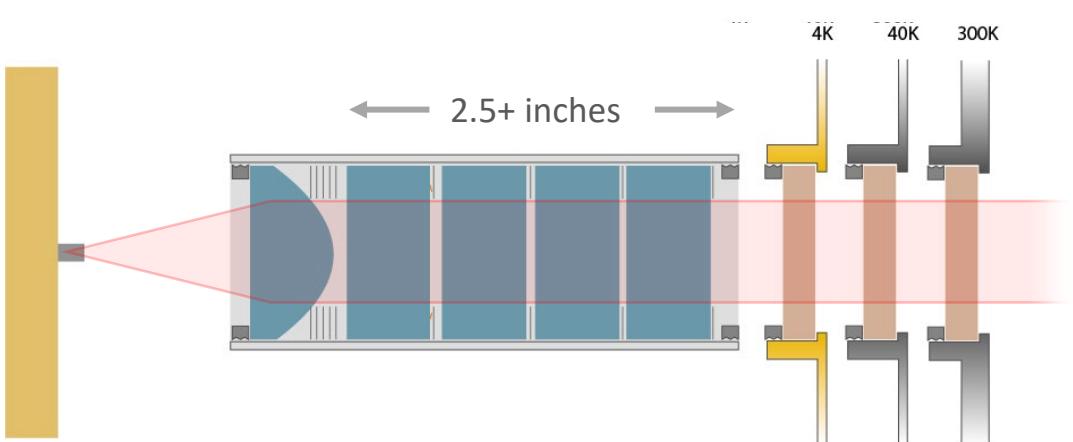
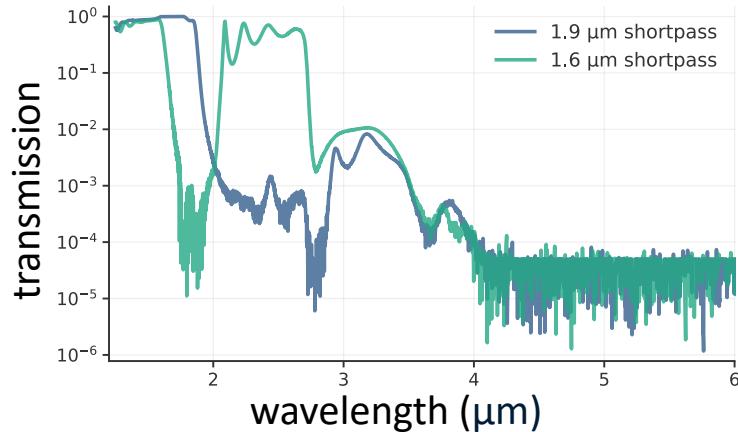
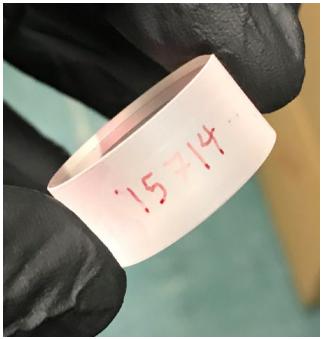


Free-space coupled superconducting nanowire single-photon detector with low dark counts

Andrew S. Mueller, Boris Korzh, Marcus Runyan, Emma E. Wollman, Andrew D. Beyer, Jason P. Allmaras, Angel E. Velasco, Ioana Craiciu, Bruce Bumble, Ryan M. Briggs, Lautaro Narvaez, Cristián Peña, Maria Spiropulu, and Matthew D. Shaw

Dark Count Filtering

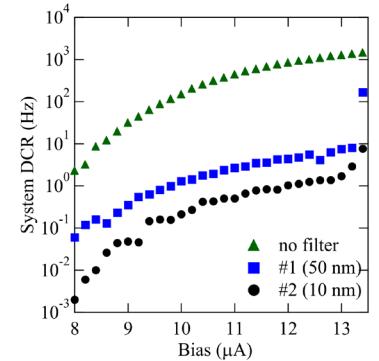
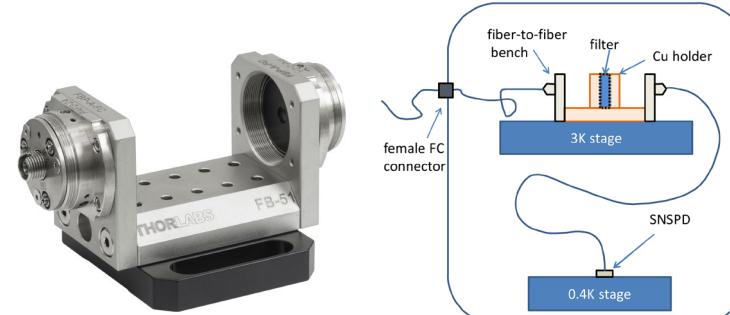
DSOC (~2018)



Detectors for long distance QKD



Filtering with cryogenic fiber looping



[1] Shibata et al. 2017

H. Shibata, et al., “Quantum key distribution over a 72 dB channel loss using ultralow dark count superconducting single-photon detectors,” Opt. Lett., vol. 39, 2014

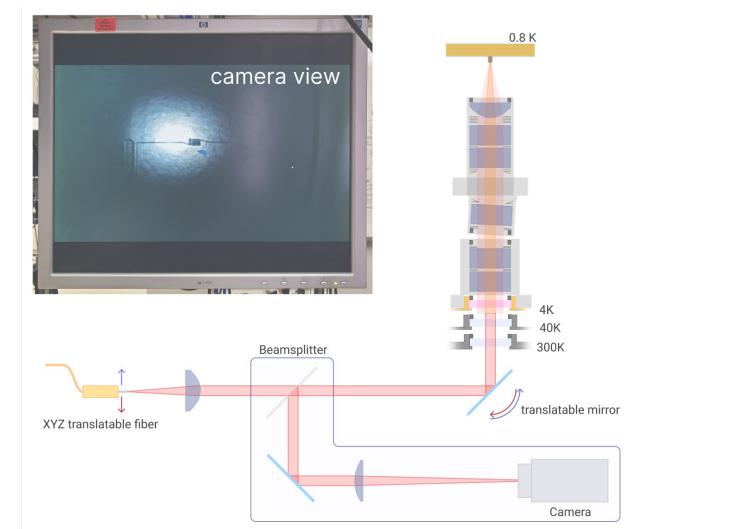
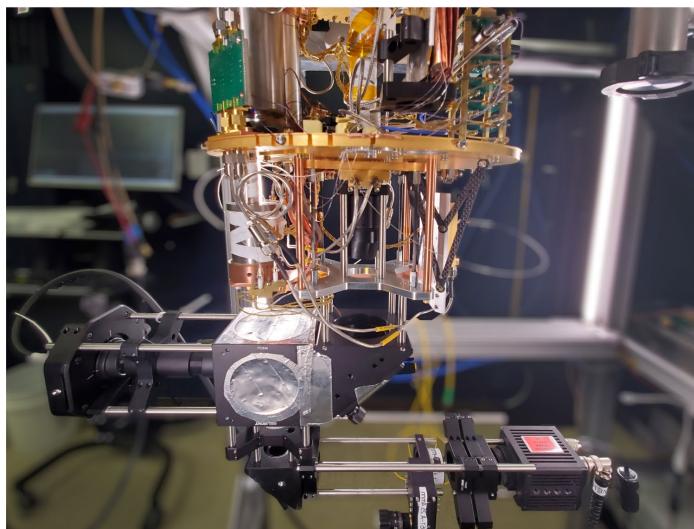
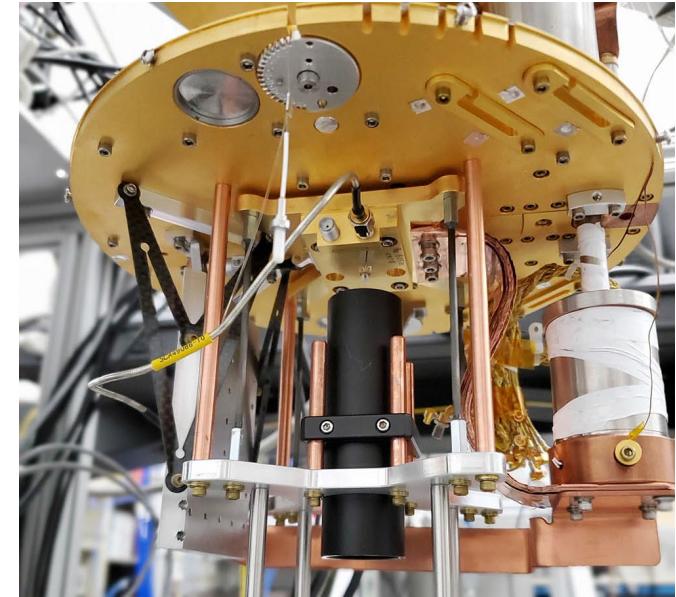
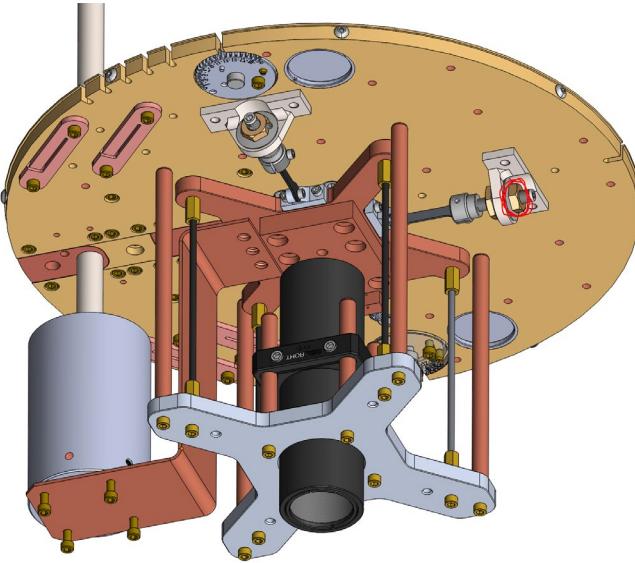
- deep space comm
- astronomy
- lidar, imaging
- other free space systems

Demonstrate a **low dark count rate, free space coupled** detector

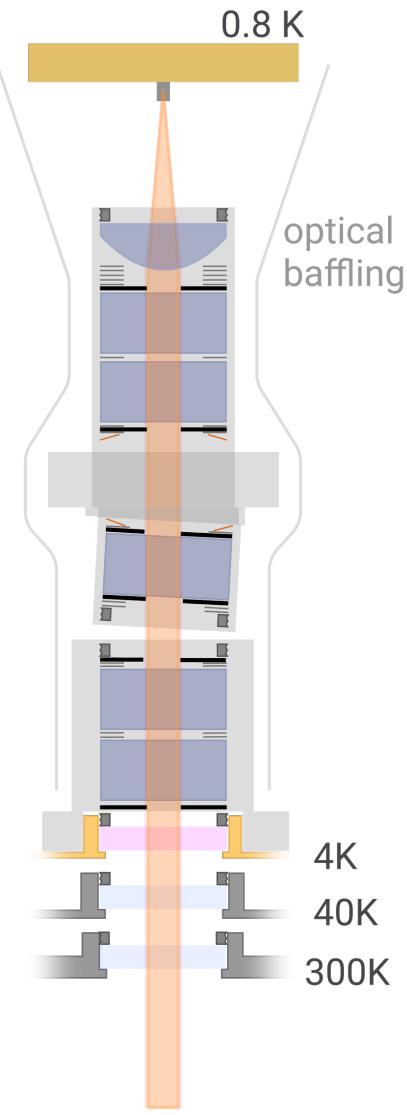
- quantum key distribution
- other (traditionally) fiber applications

System Design

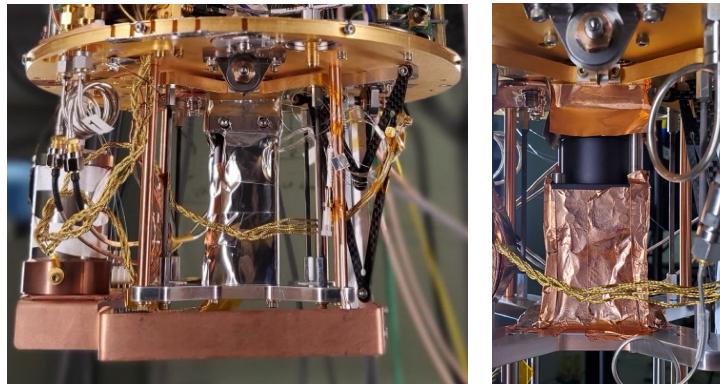
- Custom 0.8K stage design by Marc Runyan
 - XY translatable
 - Room for optics between bottom window and detector
- Detector supports both fiber and free space coupling
- Test alignment optics with cryostat open or closed



System Design



1. Optical baffling



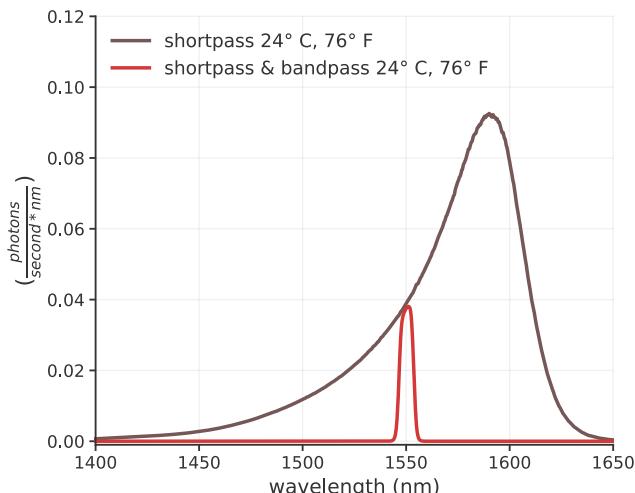
2. Apertures

Custom 8mm, Acktar spectral black material



3. 1550 nm bandpass filter

8 nm FWHM – ideal for fast wide-bandwidth pulses

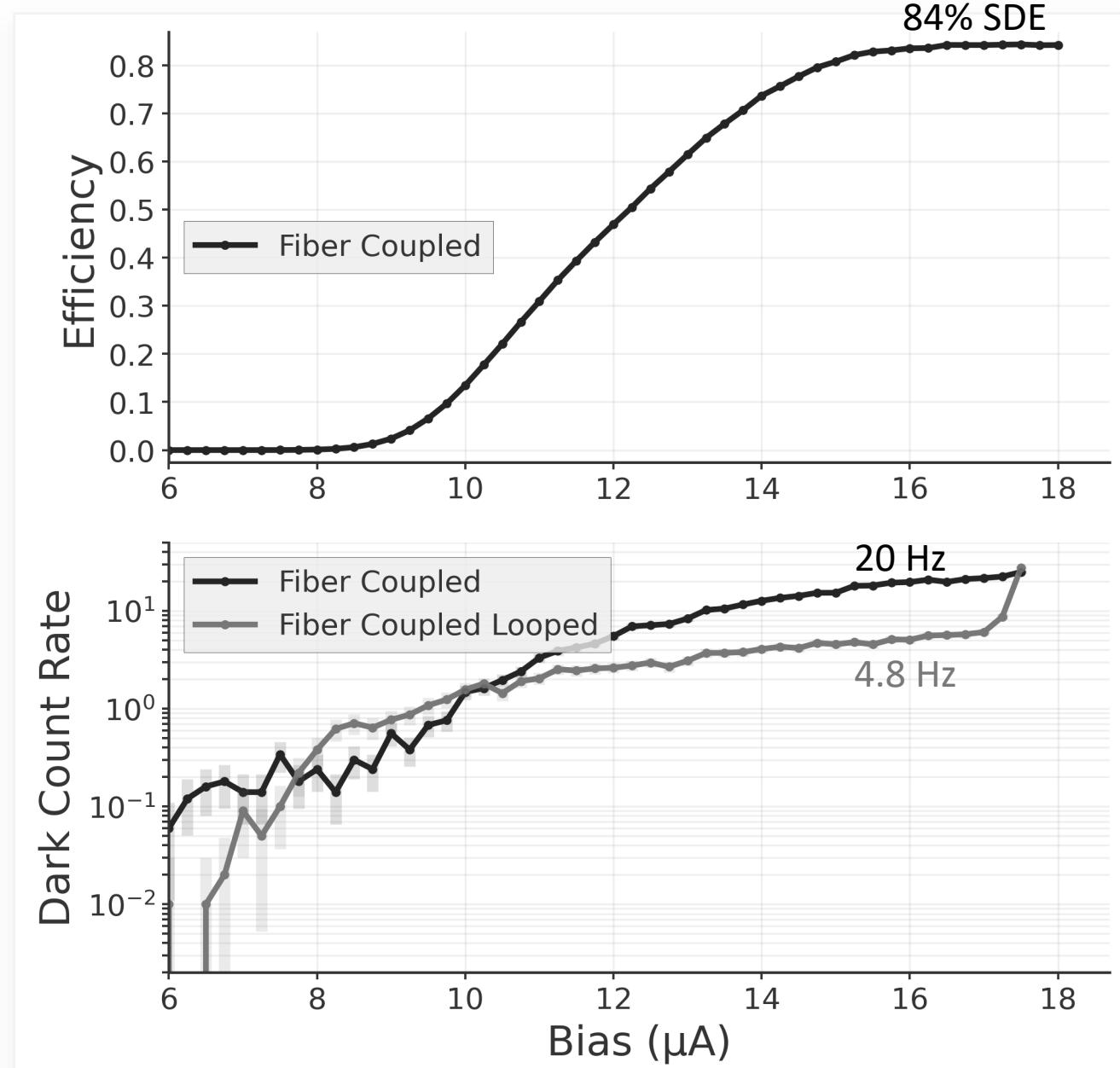
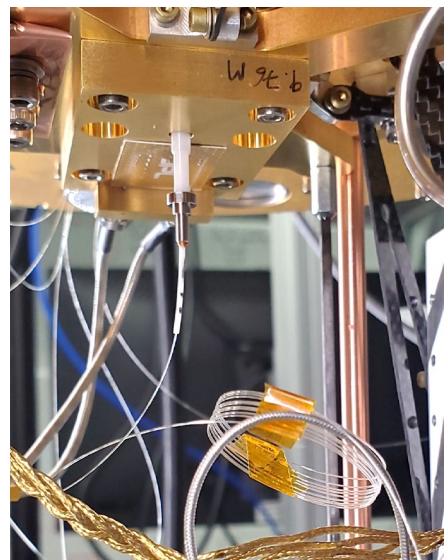


4. Painted radiation shield

Aeroglaze Z306 high mid-IR absorption

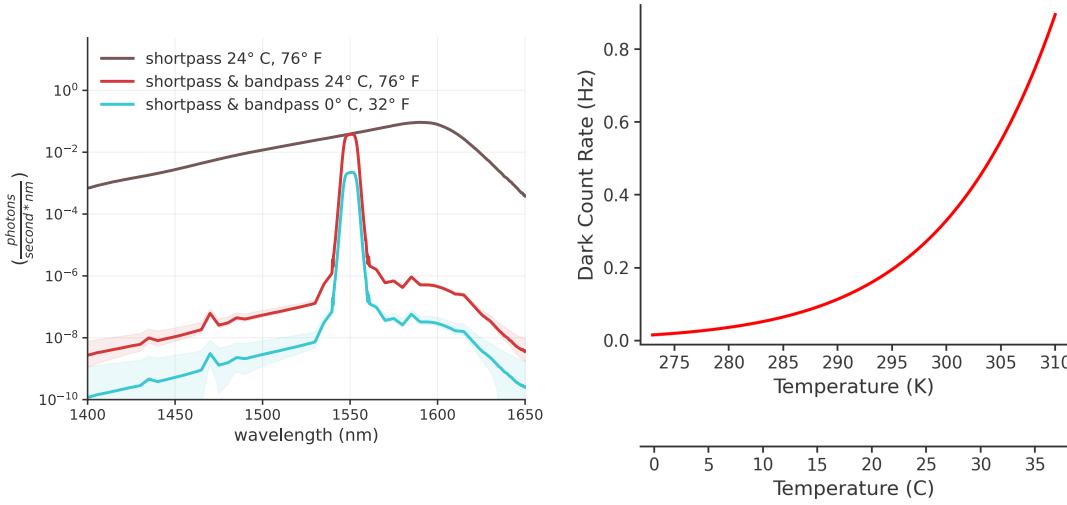


Results

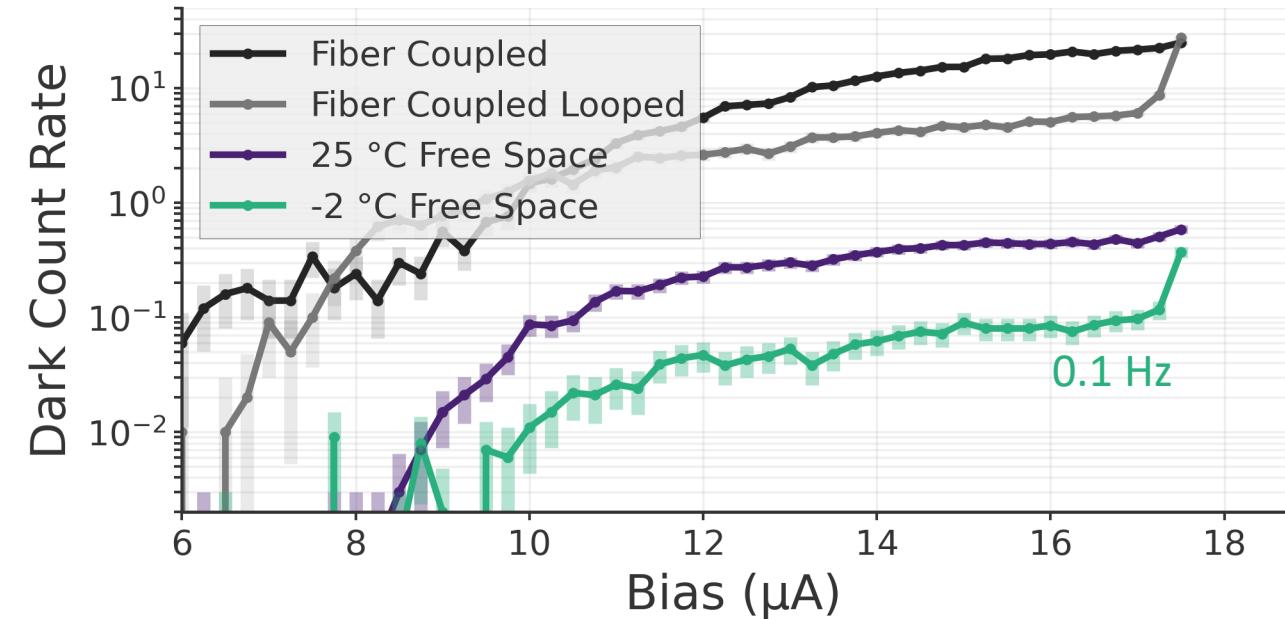
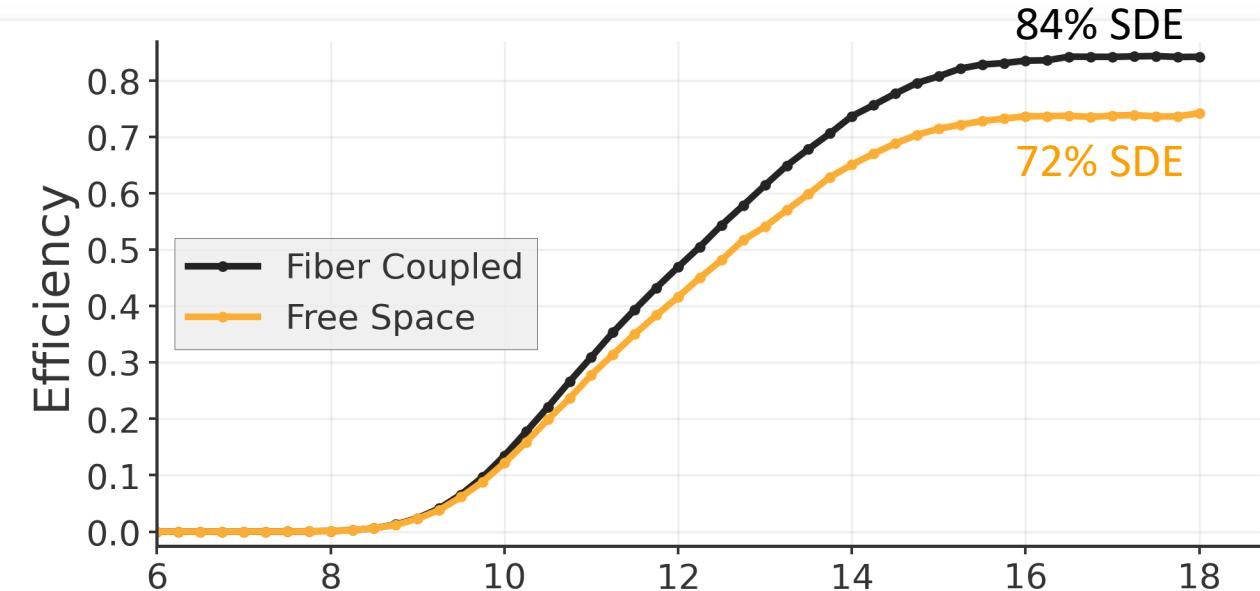
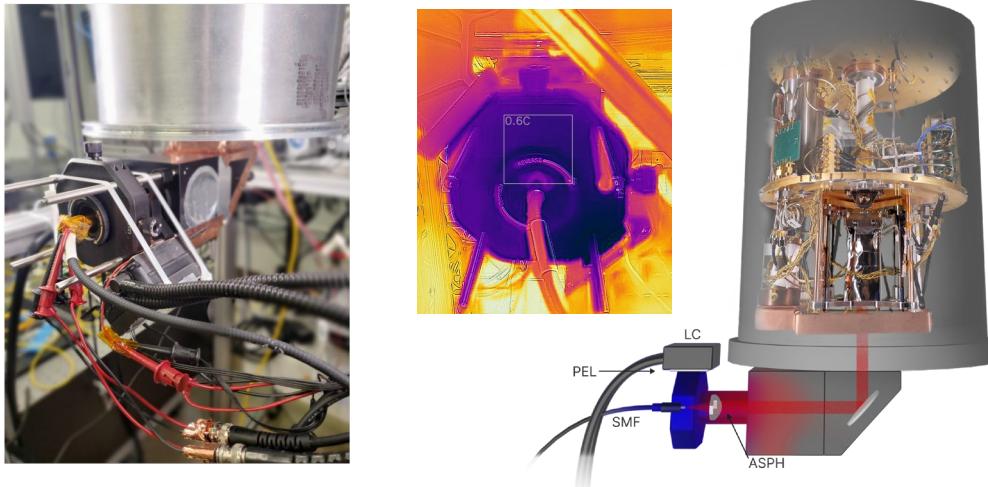


Results & Cooling

Strong dependence of room temperature on dark count rate

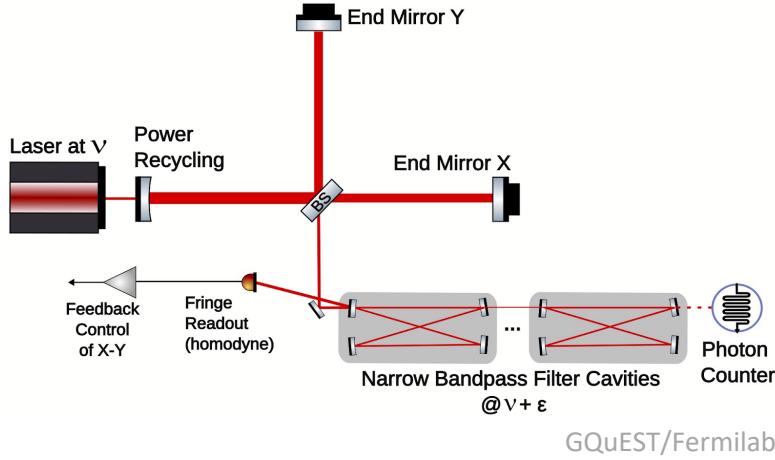


Apply mild cooling to surface imaged onto detector



Outlook

Gravity from Quantum Entanglement of Space-Time
(GQuEST)



GQuEST/Fermilab

- Use photon counting in LIGO-like interferometer experiment
- Study quantum gravity in the lab
- Filter 230 dB
- Image cryogenic fiber through free space optics onto SNSPD

Chris Stoughton, Fermilab; Lee McCuller; Caltech,
Kathryn Surek, Caltech

Optical to Orion (O2O) ground terminal



NASA/JPL

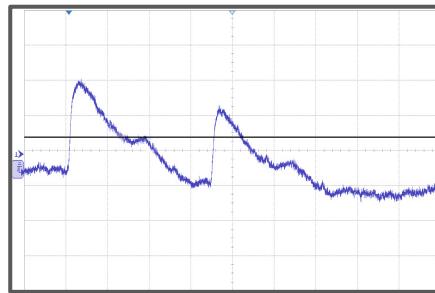
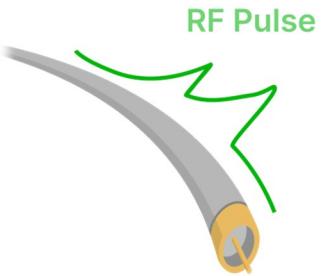
- Similar optical coupling & cryostat design

Outline

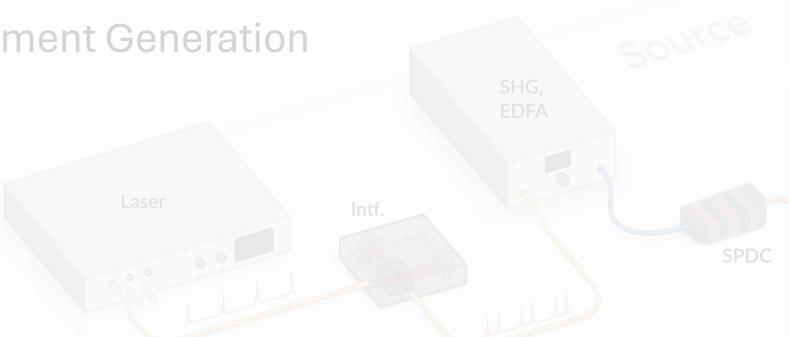
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2. Time Walk Correction

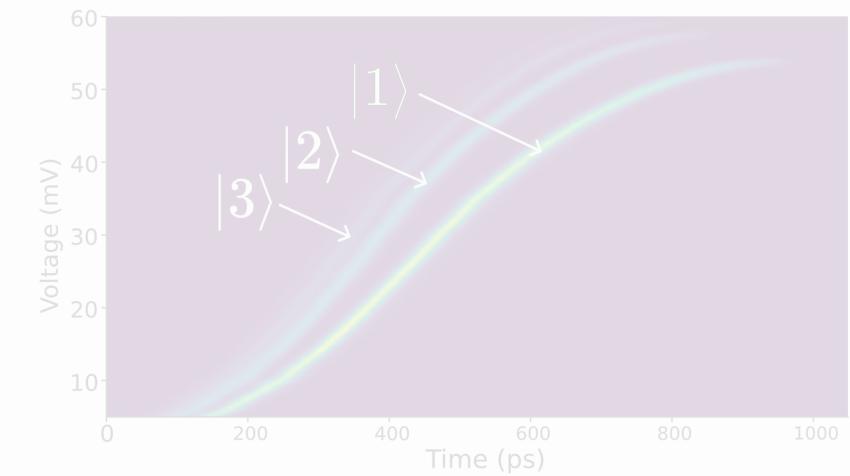


3. High-Rate Entanglement Generation



Aside: Phase Locked Loops

4. Pulse Position Modulation

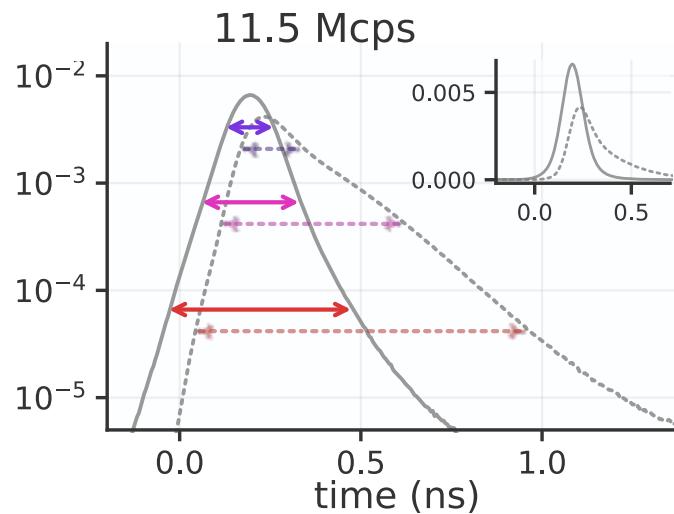
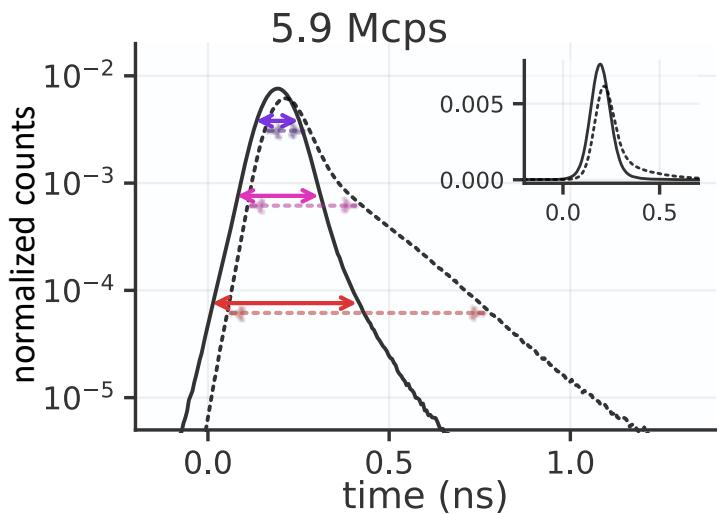


Conclusion & Outlook

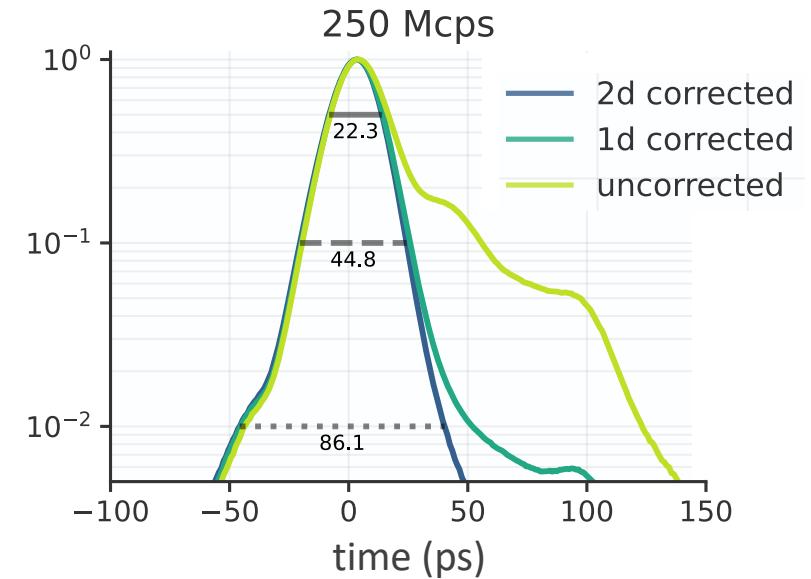
Achievement

Reduce jitter by up to 50% at high count rates

For conventional WSi SNSPDs



And emerging ultra-high-count rate SNSPDs



RESEARCH ARTICLE | JANUARY 27 2023

Time-walk and jitter correction in SNSPDs at high count rates



Andrew Mueller ; Emma E. Wollman ; Boris Korzh ; Andrew D. Beyer ; Lautaro Narvaez ;
Ryan Rogalin ; Maria Spiropulu; Matthew D. Shaw

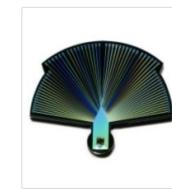


+ Author & Article Information

Appl. Phys. Lett. 122, 044001 (2023)

<https://doi.org/10.1063/5.0129147> Article history

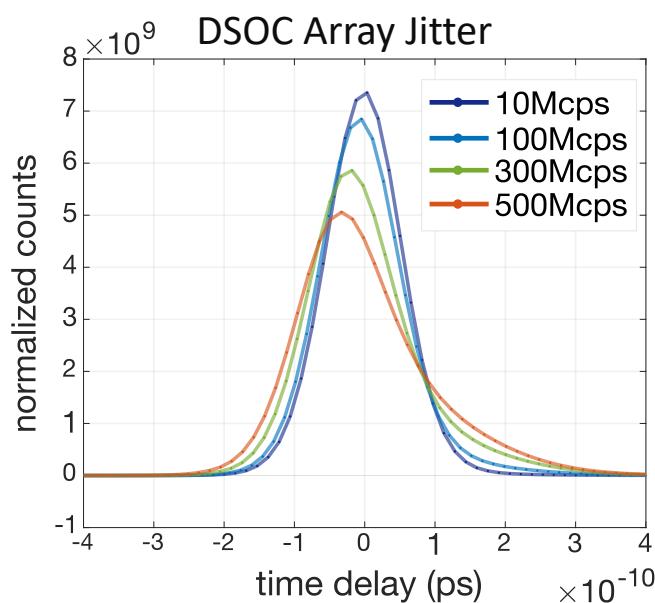
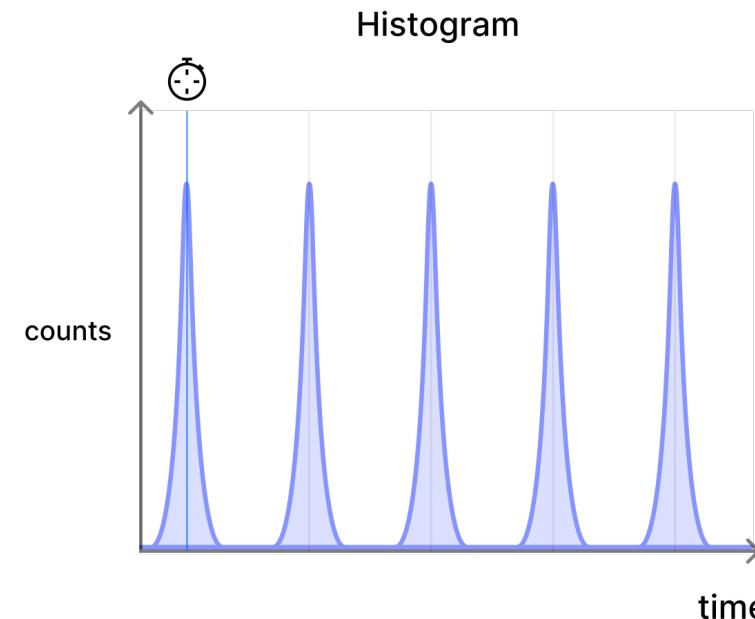
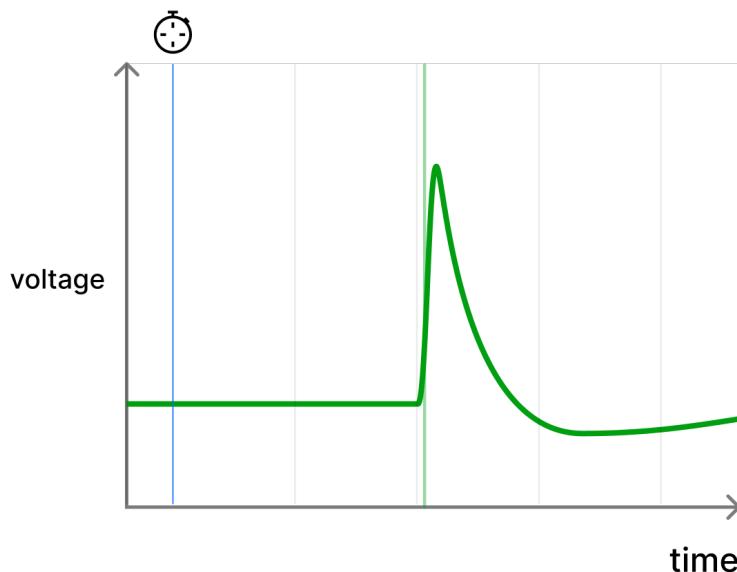
Optica Vol. 10, Issue 2, pp. 183-190 (2023) • <https://doi.org/10.1364/OPTICA.478960>



High-speed detection of 1550 nm single photons with superconducting nanowire detectors

Ioana Craiciu, Boris Korzh, Andrew D. Beyer, Andrew Mueller, Jason P. Allmaras, Lautaro Narváez, María Spiropulu, Bruce Bumble, Thomas Lehner, Emma E. Wollman, and Matthew D. Shaw

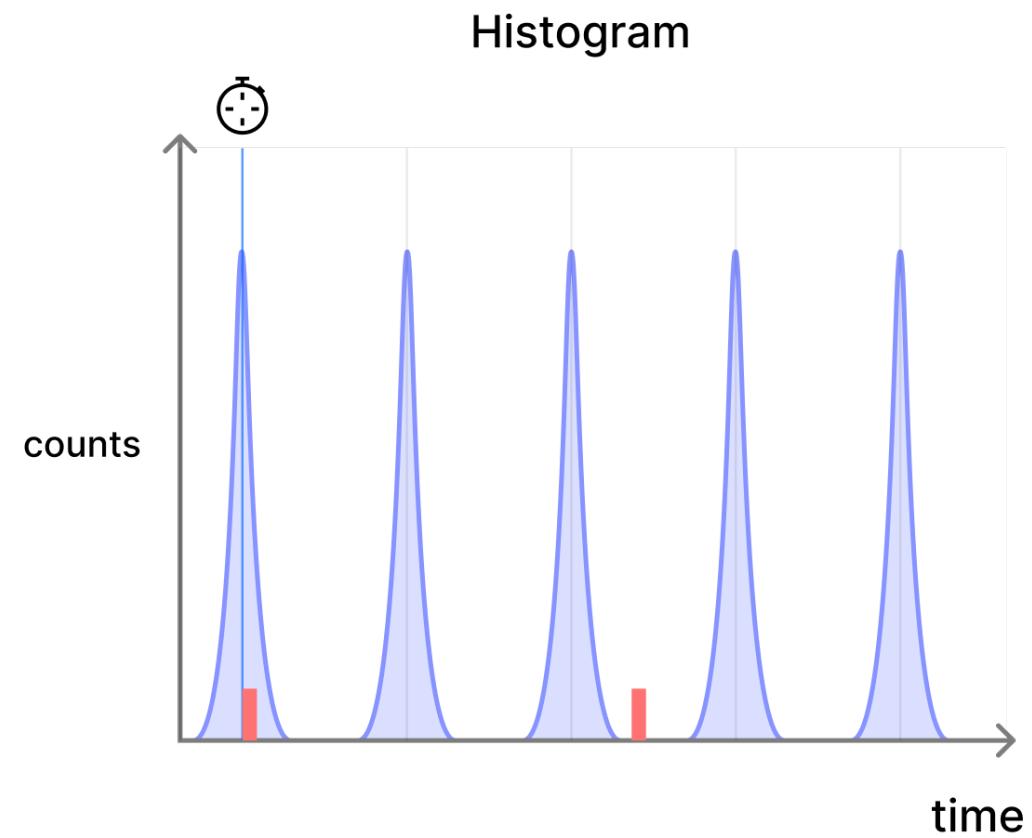
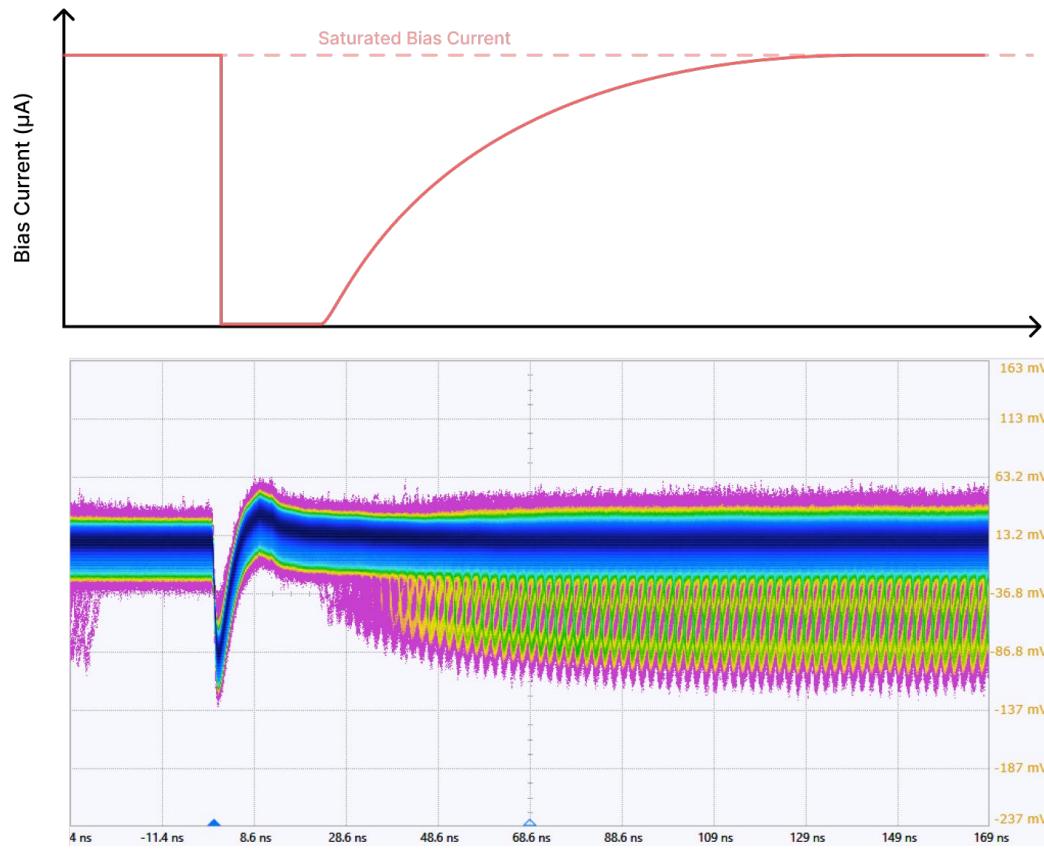
Issue



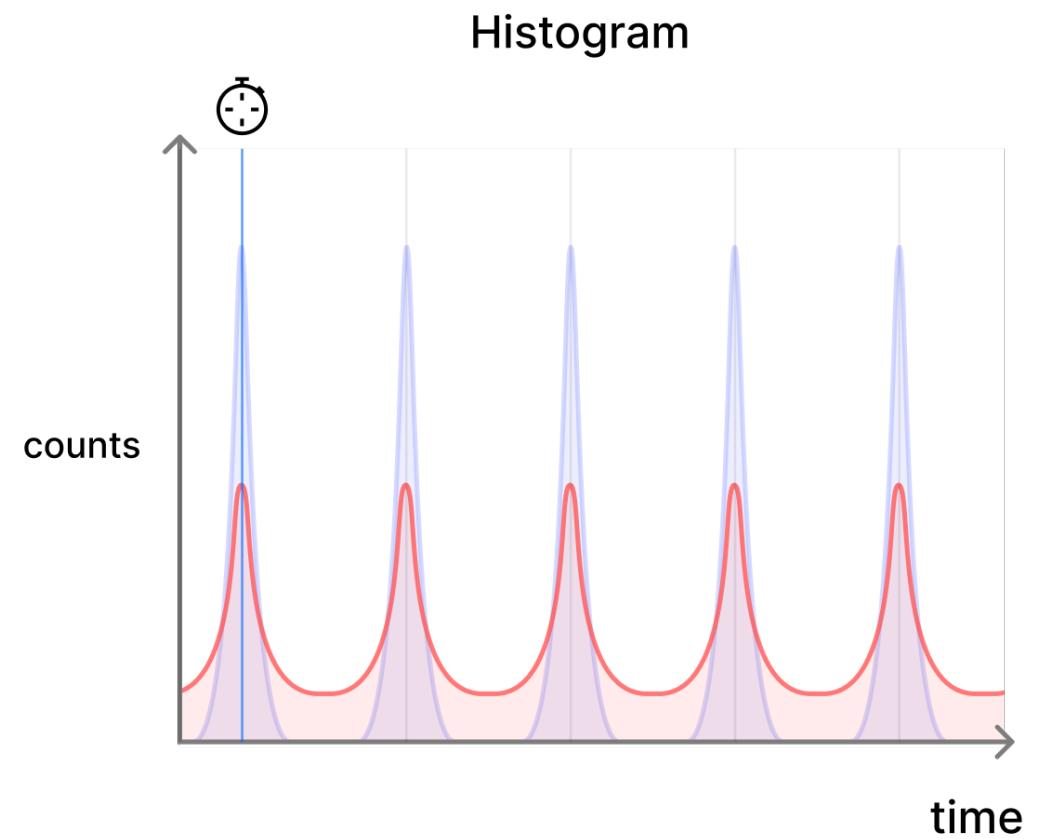
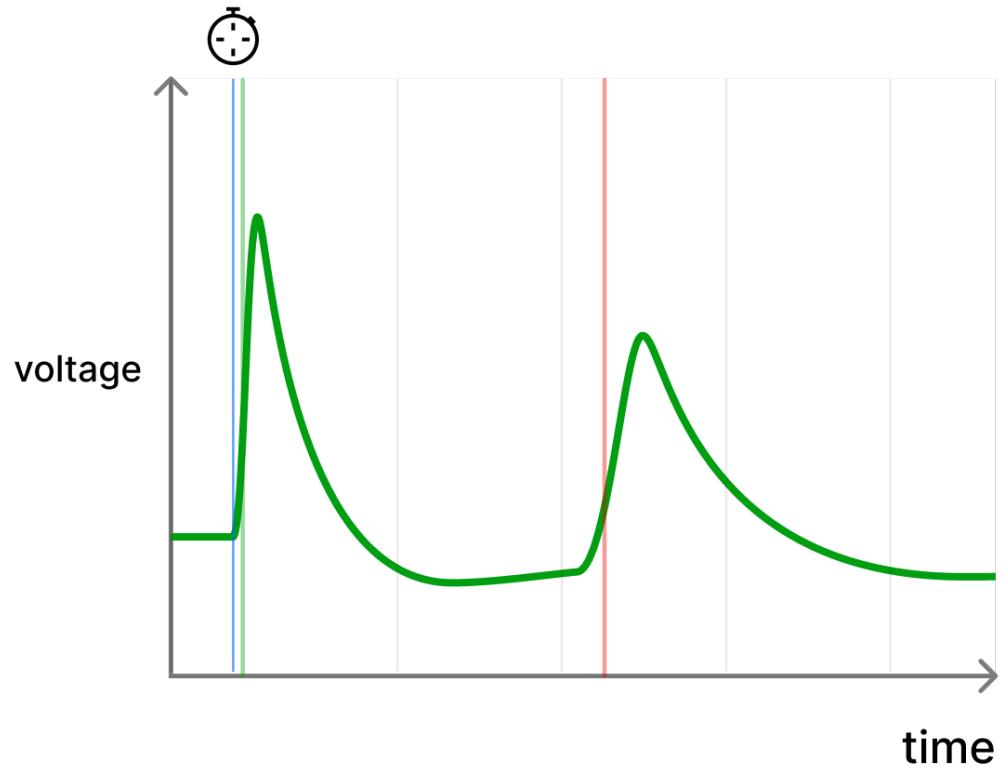
Increase in jitter with count rate

Designed for lower count rates, but atmosphere and pointing variations can cause **spikes to high count rate**

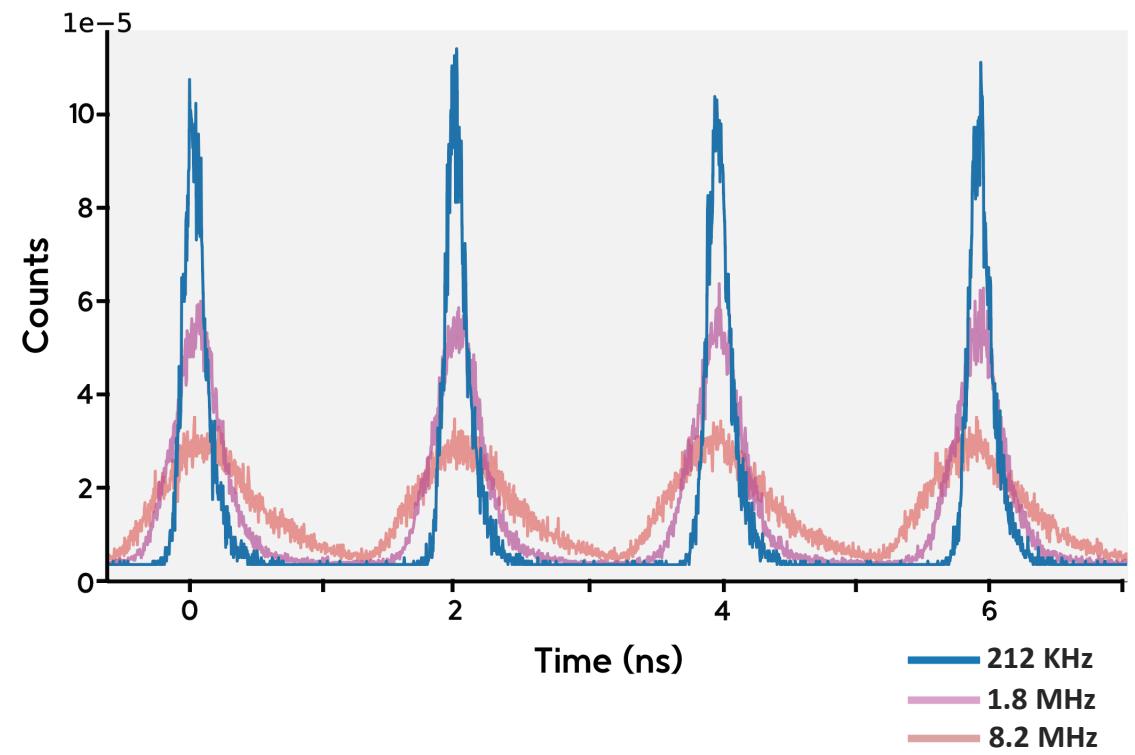
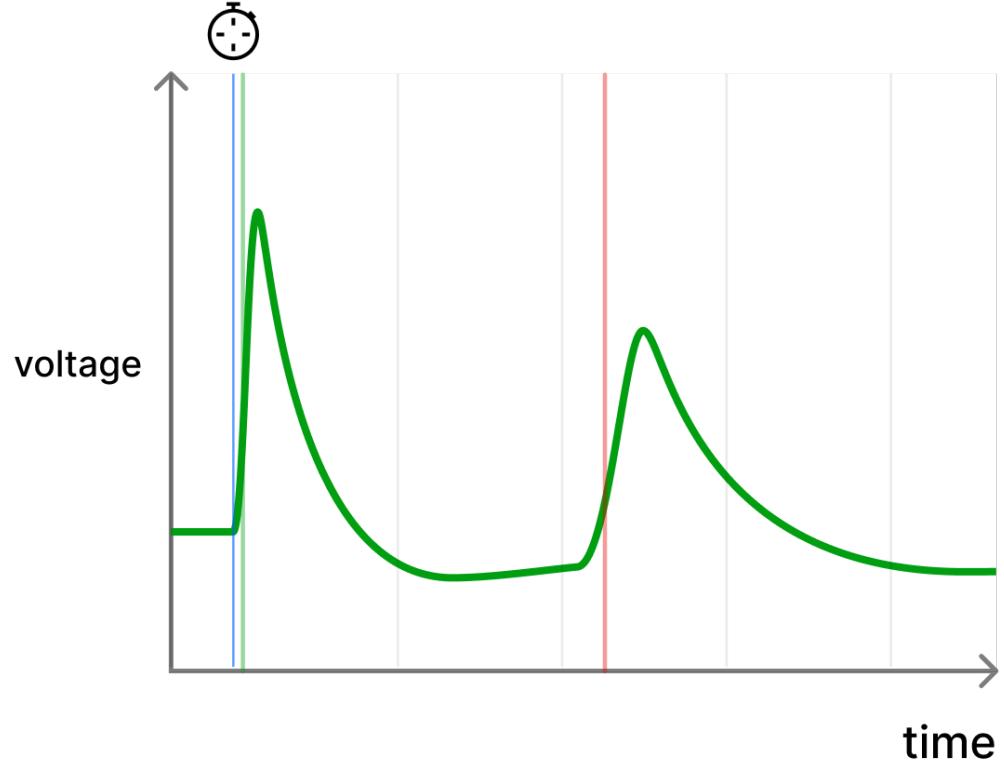
Photon Arrival time & Histograms



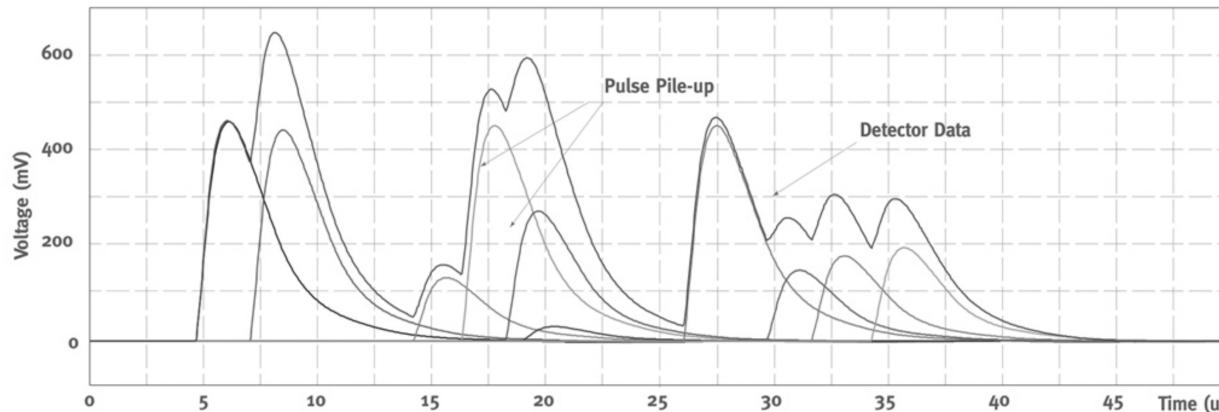
Photon Arrival time & Histograms



Photon Arrival time & Histograms

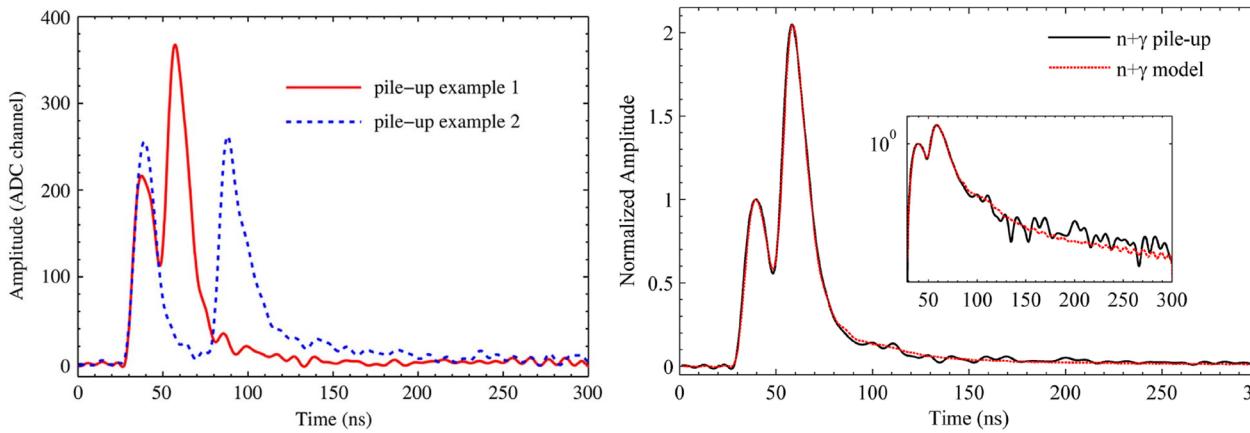


Previous Pileup Correction Methods



Real Time Pulse Pile-up Recovery in a High Throughput Digital Pulse Processor

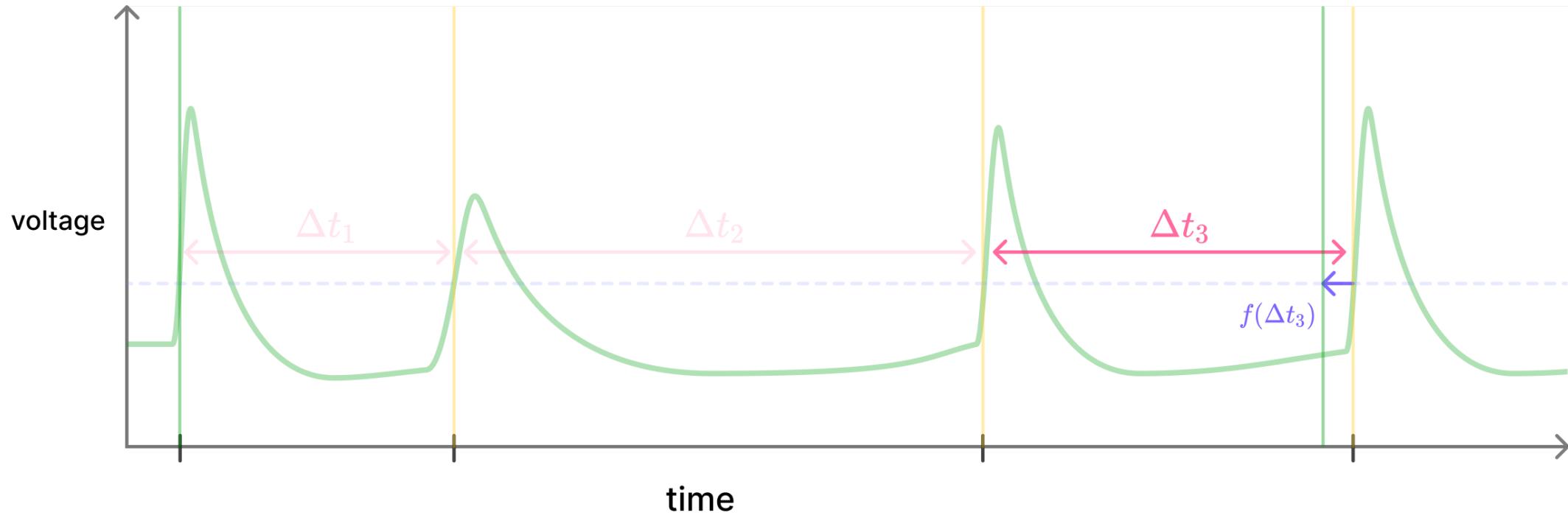
Paul A. B. Scoullar et al. 2011



Pulse pile-up identification and reconstruction for liquid scintillator based neutron detectors

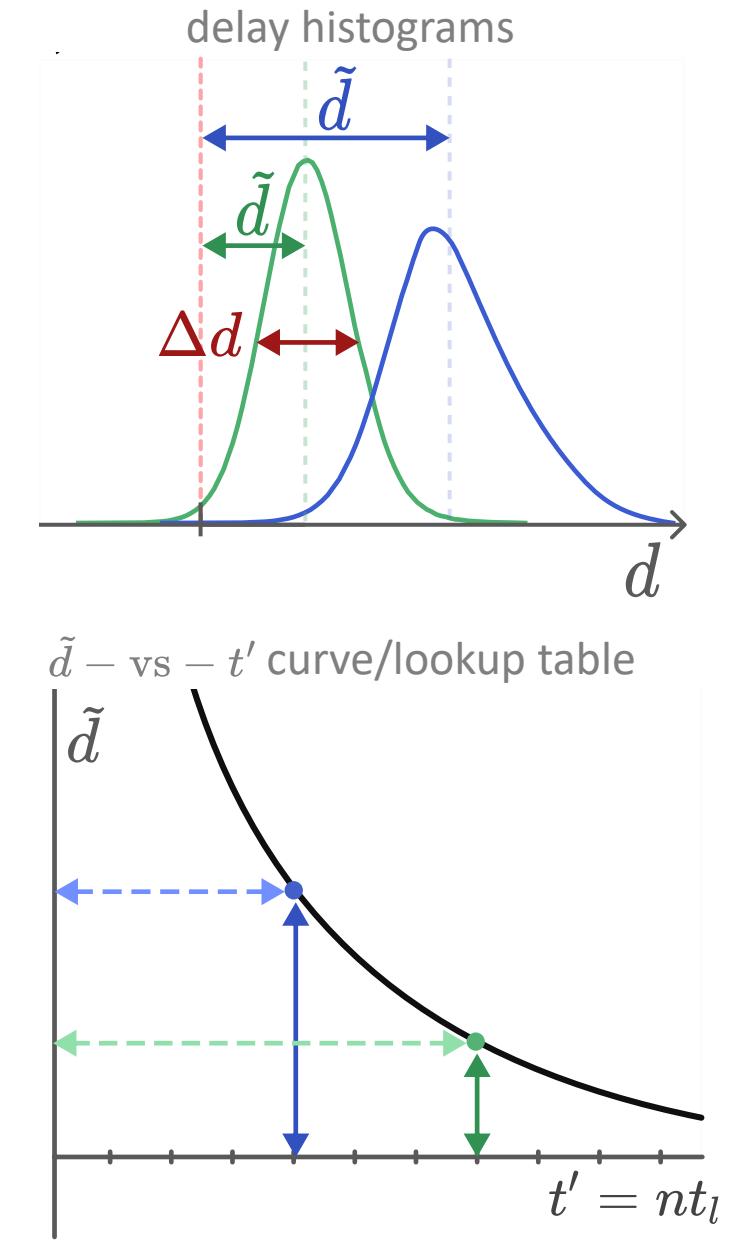
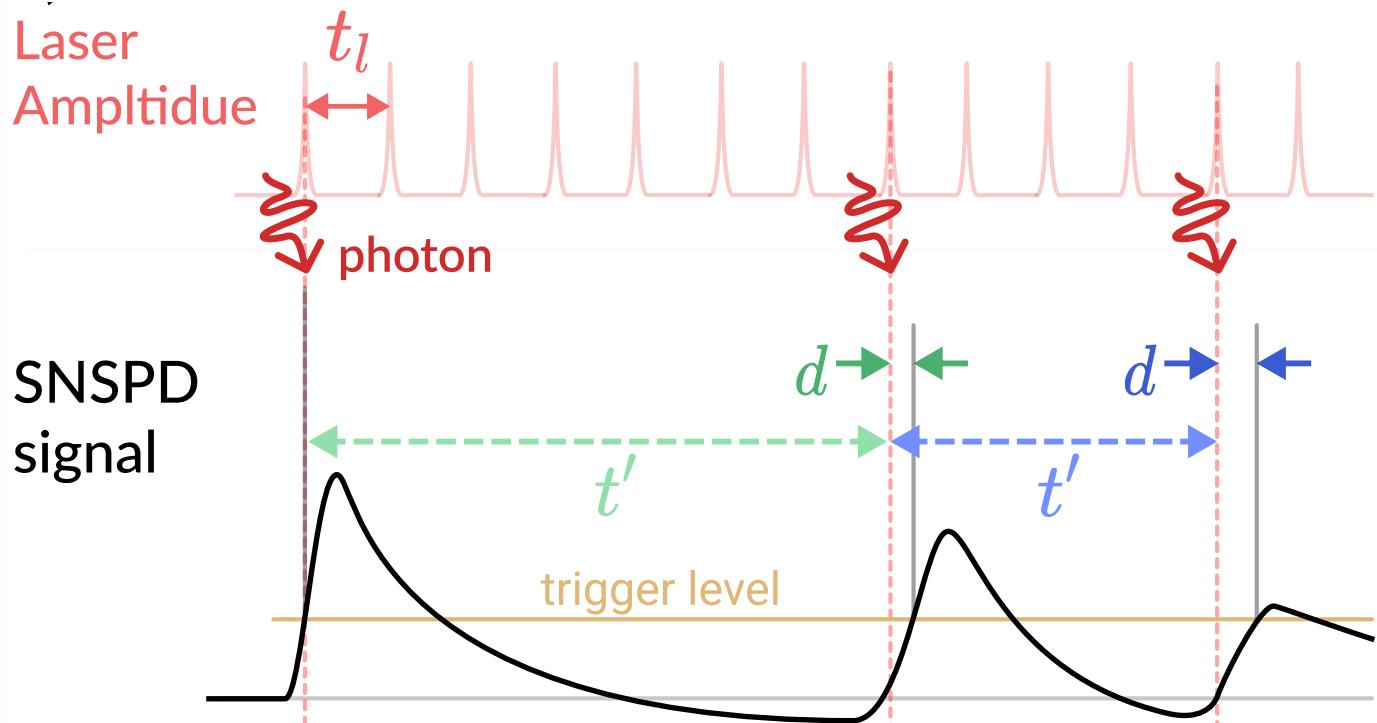
X.L. Luo et al. 2018

Photon Arrival time & Histograms



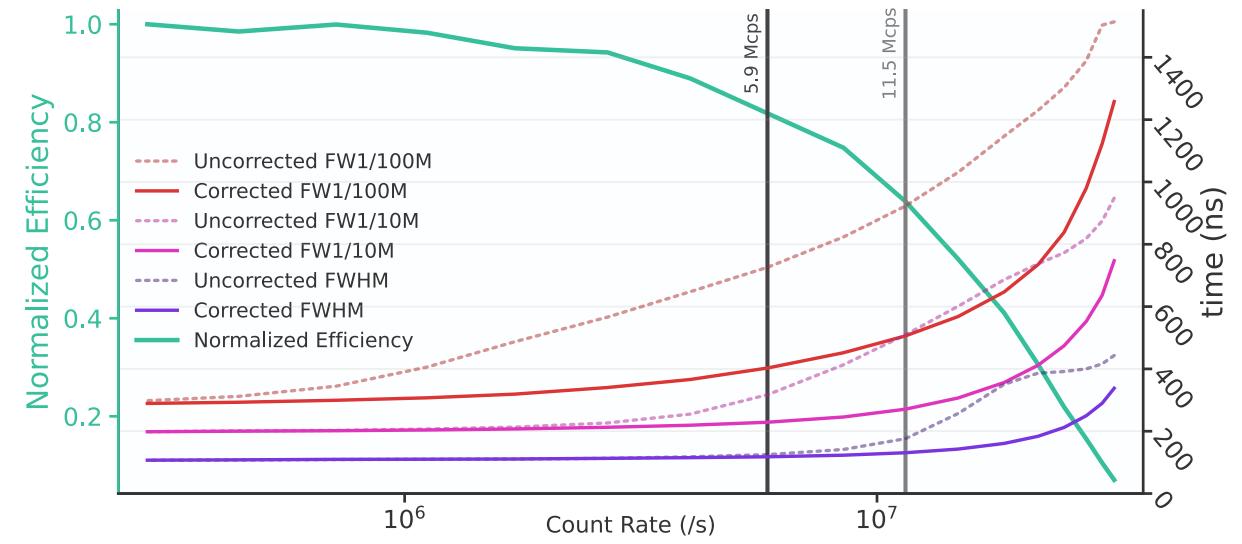
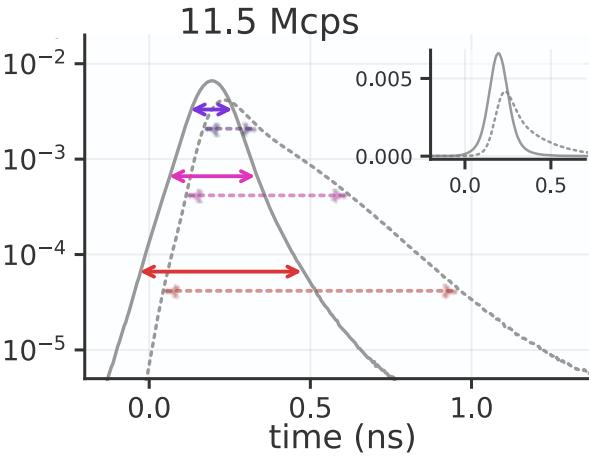
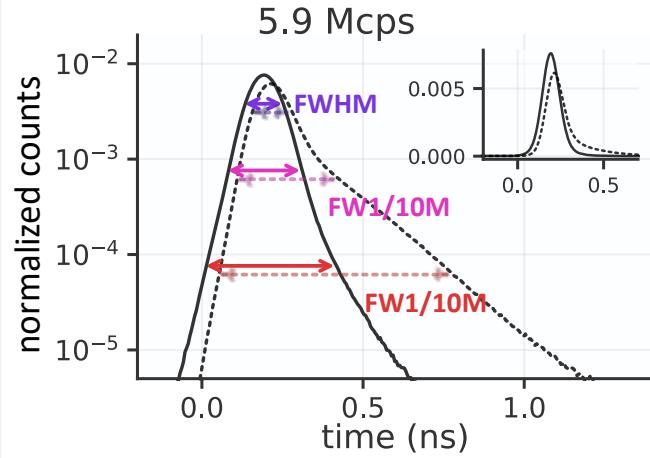
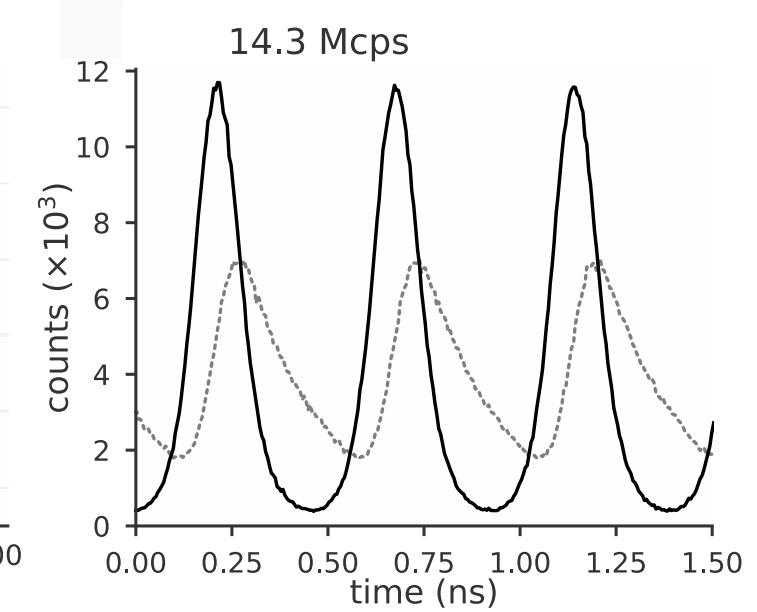
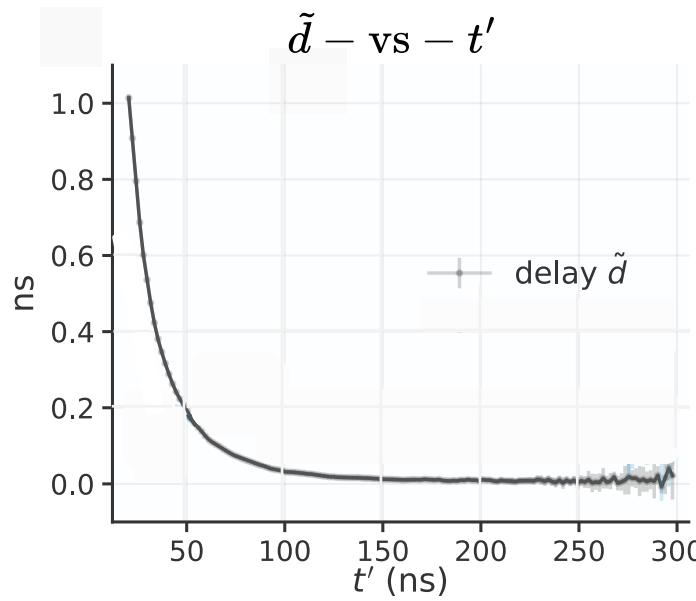
Calibration: Delays from Δt

- Measure delays referenced from regular laser pulses;
- Group them by interarrival time
- Extract median for each group to form delay vs interarrival time $\tilde{d} - \text{vs} - t'$ curve



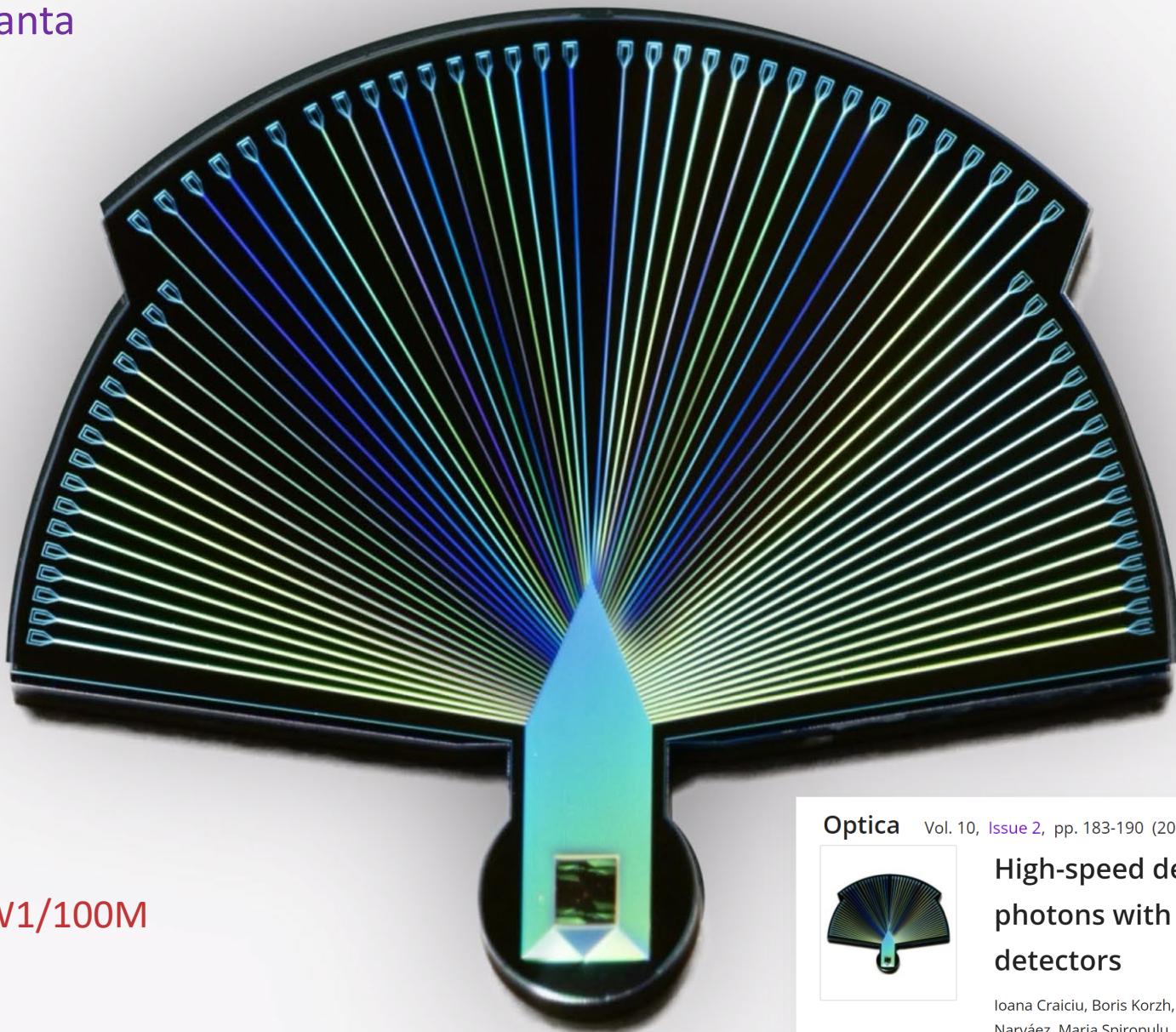
Calibration Curve

- Interpolate on the $\tilde{d} - \text{vs} - t'$ curve to determine correction from interarrival time
- No requirement that calibration rep-rate matches application rep-rate



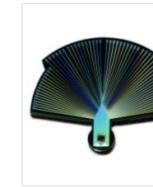
Performance Enhanced Array for Counting Optical Quanta (PEACOQ)

- 32 straight NbN wires
- Fiber coupled
- 1.5 Gcounts/s
 3 dB compression
- 78% system detection efficiency



- 250 Mcps with 86 ps FW1/100M

Optica Vol. 10, Issue 2, pp. 183-190 (2023) • <https://doi.org/10.1364/OPTICA.478960>

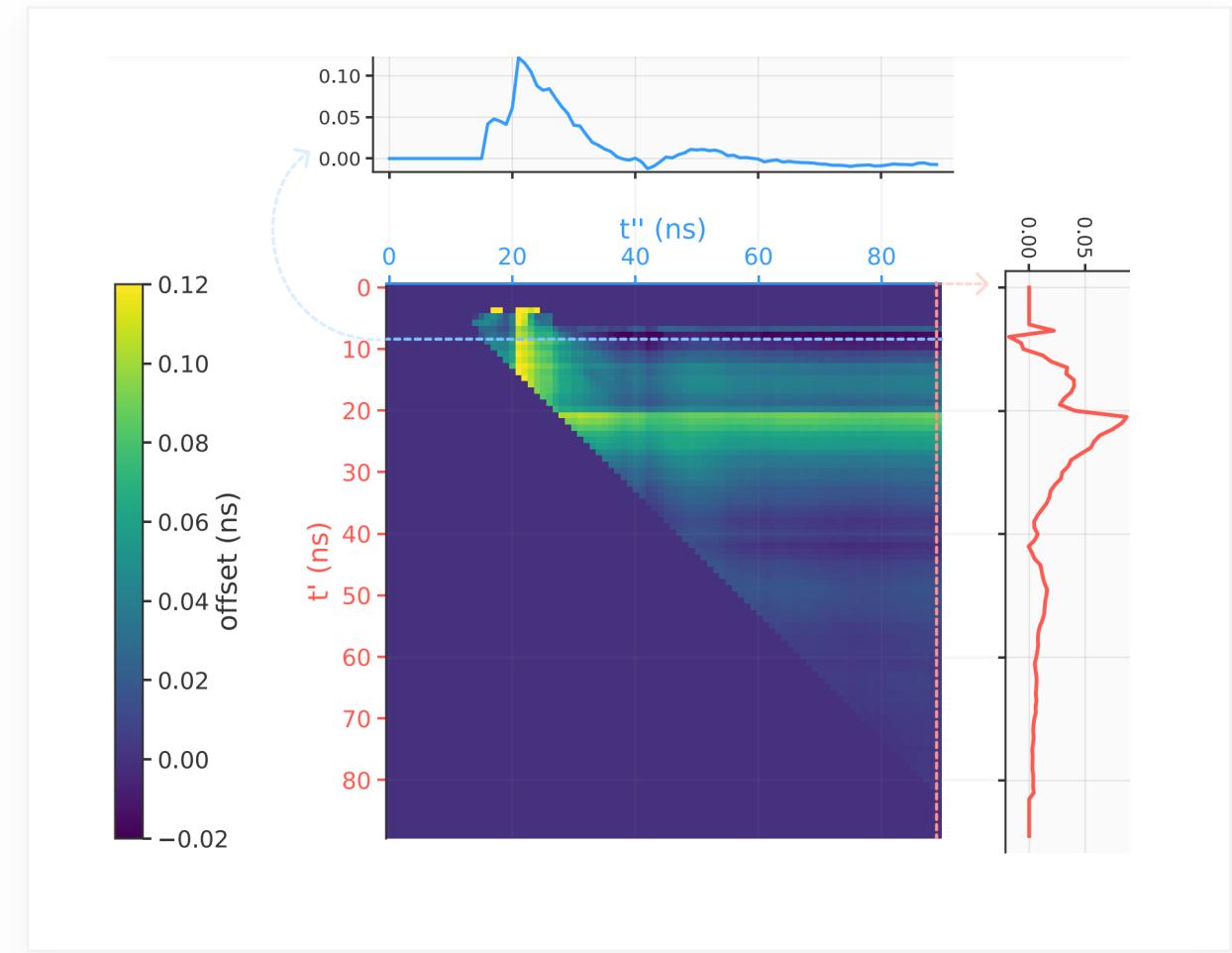
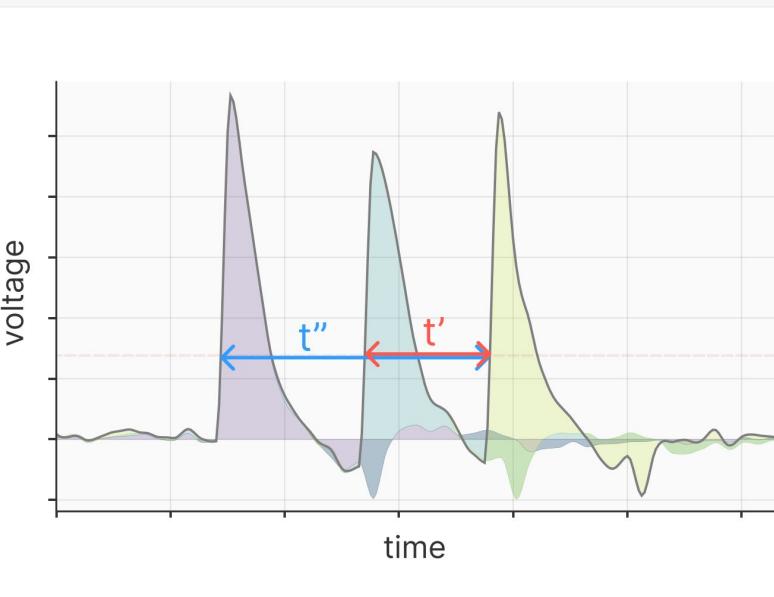
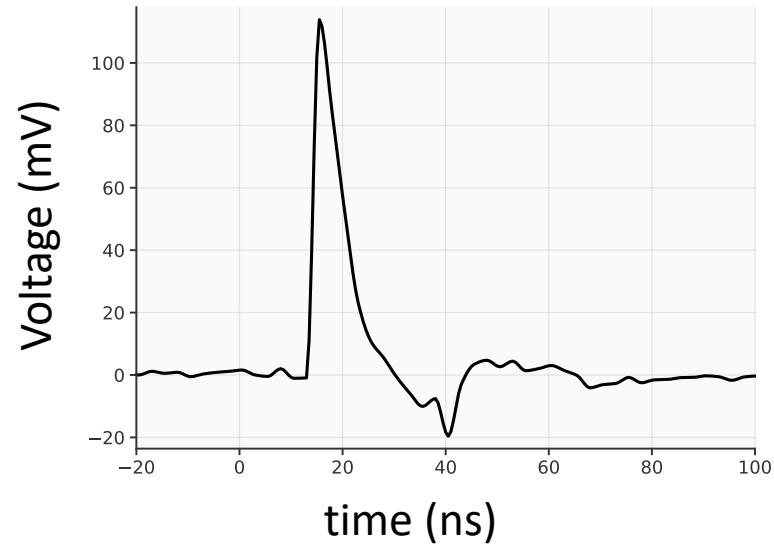


High-speed detection of 1550 nm single photons with superconducting nanowire detectors

Ioana Craiciu, Boris Korzh, Andrew D. Beyer, Andrew Mueller, Jason P. Allmaras, Lautaro Narváez, Maria Spiropulu, Bruce Bumble, Thomas Lehner, Emma E. Wollman, and Matthew D. Shaw

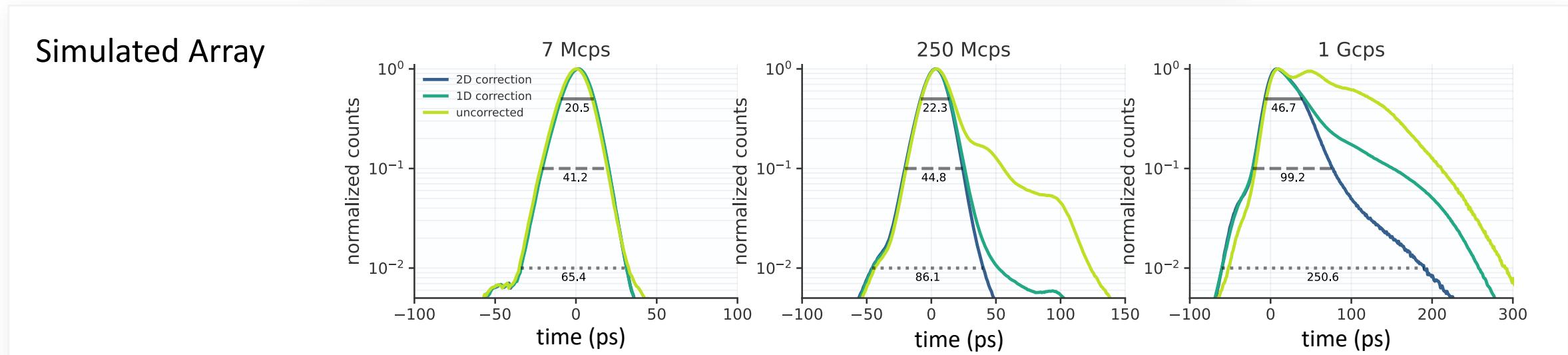
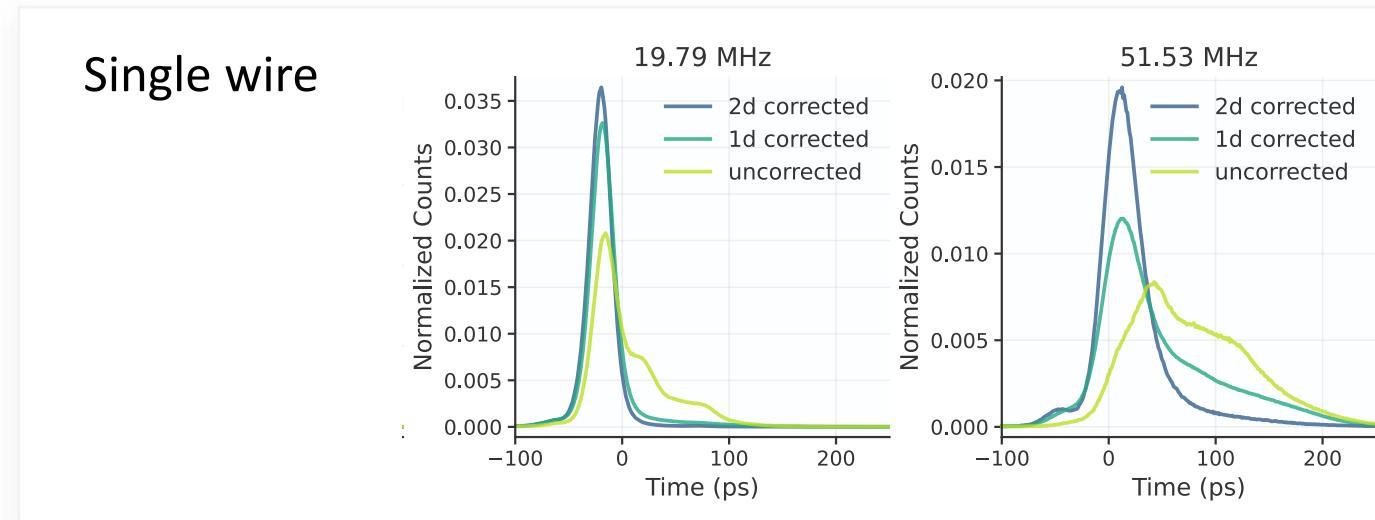


PEACOQ



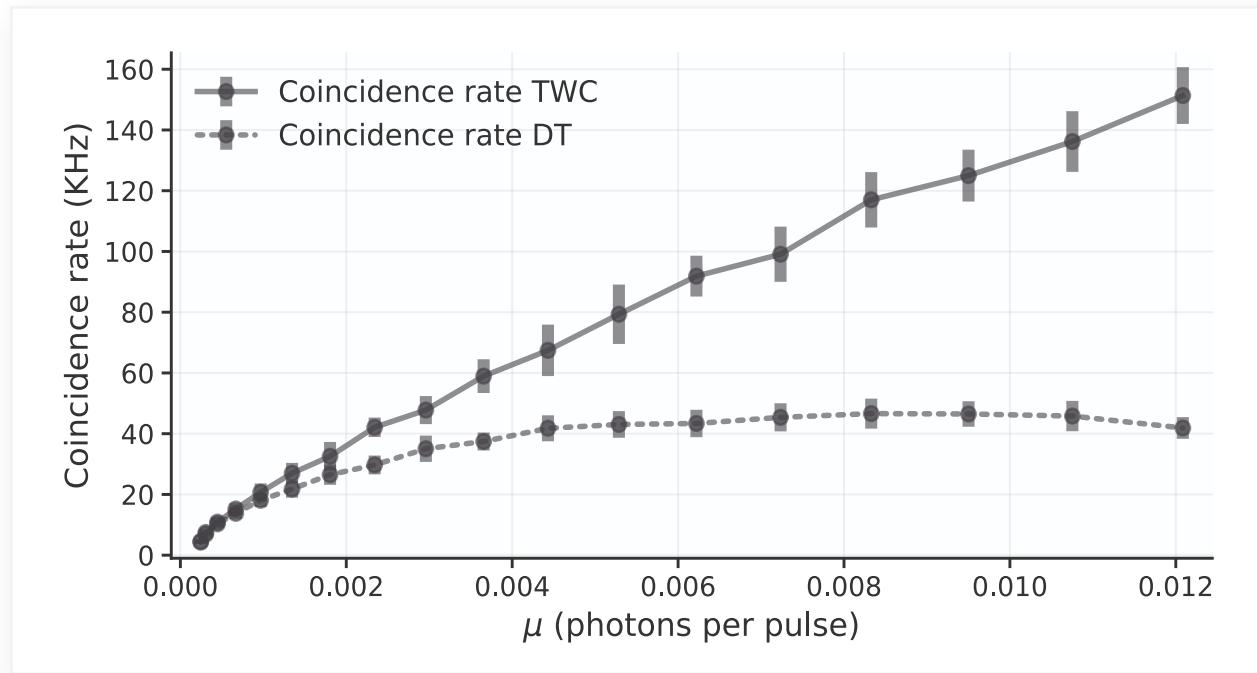
PEACOQ Results

- Applying correction **decrease single-wire jitter** at FW1/100M level by **40-50%** over a wide range of count rates
- **10x higher count rates** possible with a 100 ps limit on FW1/100M



Outlook

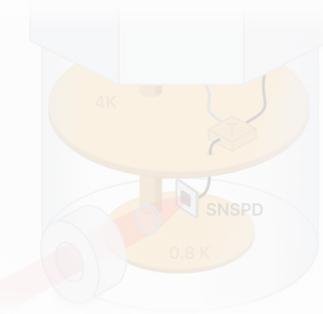
- **Time walk correction** can substantially increase usable count rate of SNSPDs.
- Especially with:
 - AC coupled amps [undershoot effects]
 - Tapered detectors [ringing, slower reset time]
 - Impedance mismatch in readout circuit [reflections]



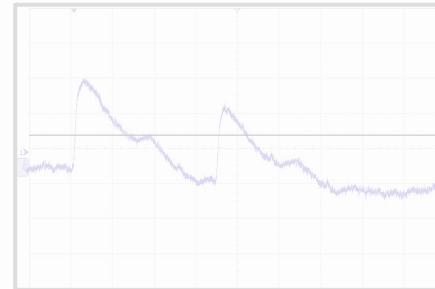
**3x increase in coincidence rate
with time walk correction**

Outline

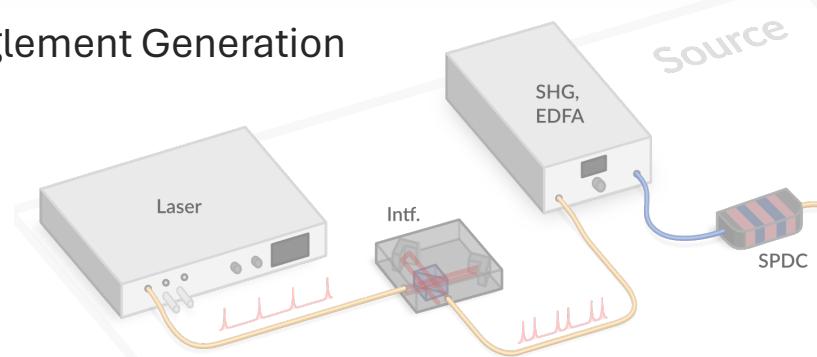
1. Low Dark Count Rate Free Space Coupled SNSPD



2. Time Walk Correction

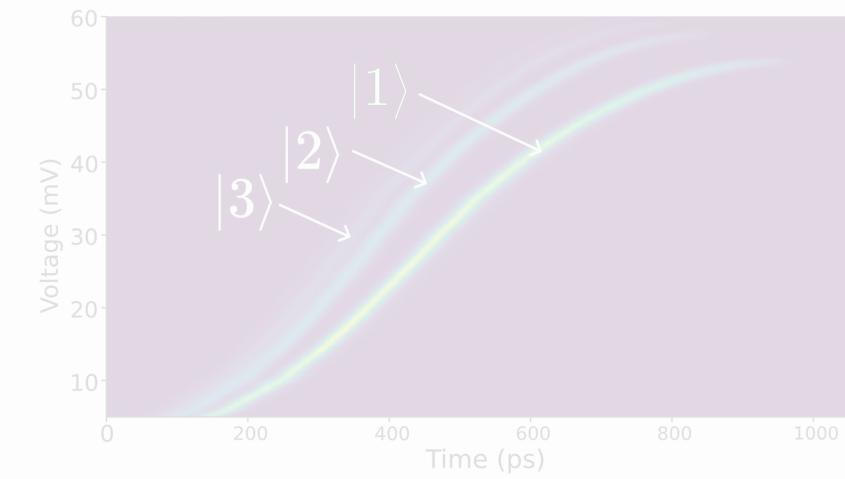


3. High-Rate Entanglement Generation



Aside: Phase Locked Loops

4. Pulse Position Modulation & Photon Number Resolution

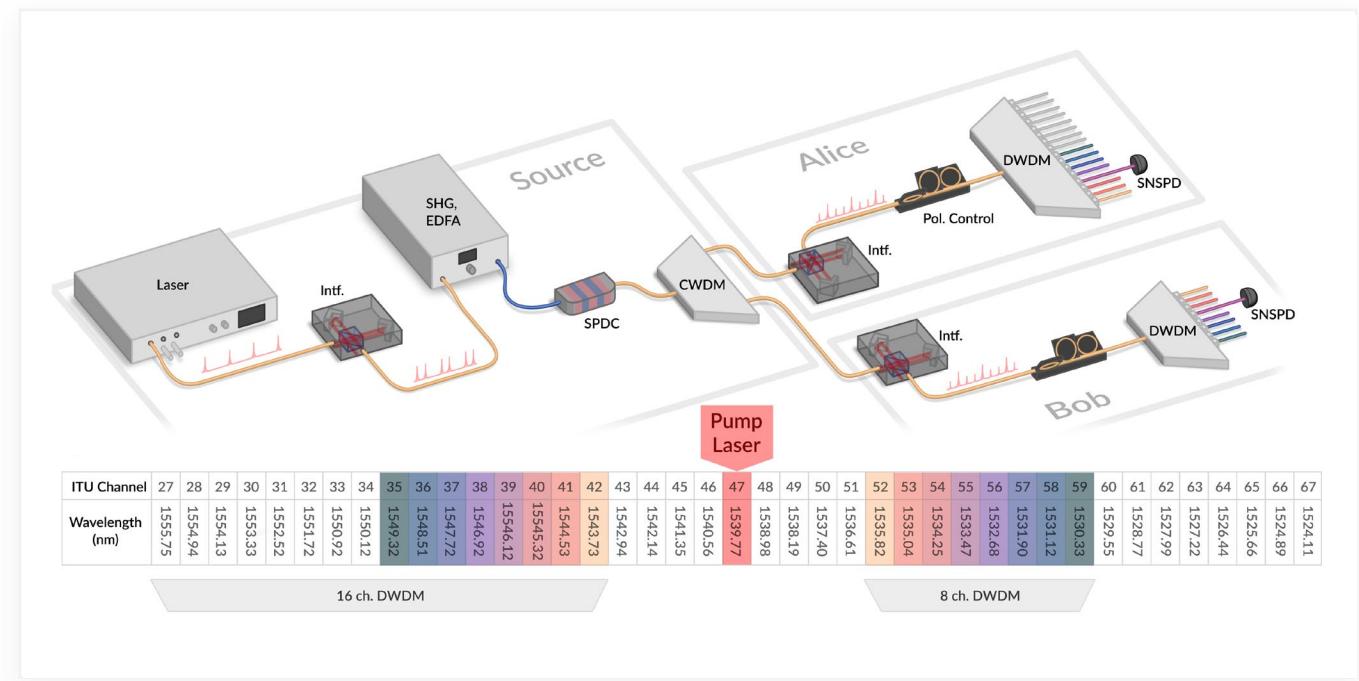


Conclusion & Outlook

Achievement

High rate multiplexed entanglement source with time-bin qubits for quantum networks

- **3.55e6 coincidences/s** across 8 spectrally multiplexed channels
- **95.7 – 99.3%** entanglement visibility
- Using low jitter SNSPDs & time-walk correction
- **Schmidt number** $1/K = 0.87$ (100 GHz) & $1/K = 0.96$ (50 GHz) for filtered channel pairs; suitable for HOM and bell state measurements



arXiv > quant-ph > arXiv:2310.01804

Quantum Physics

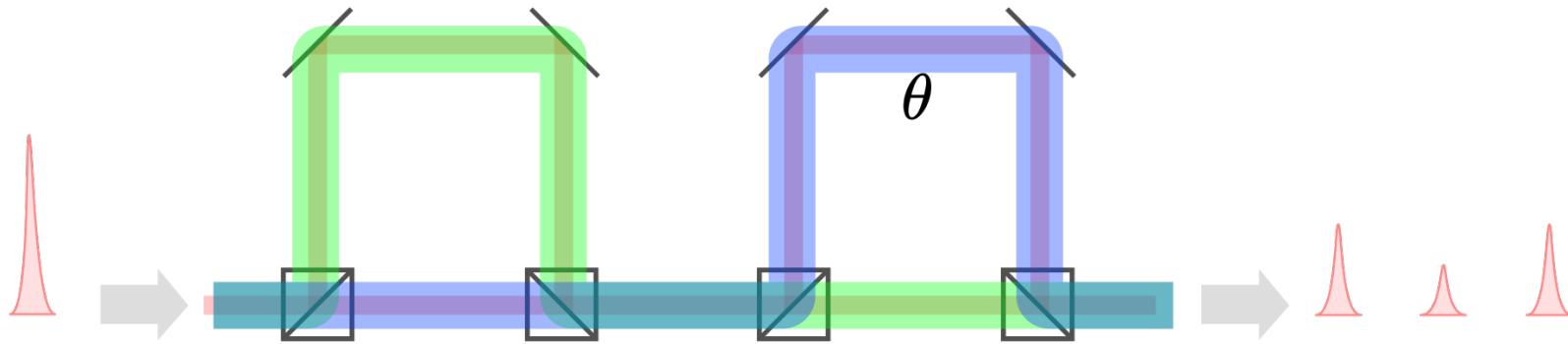
[Submitted on 3 Oct 2023 (v1), last revised 4 Oct 2023 (this version, v2)]

High-rate multiplexed entanglement source based on time-bin qubits for advanced quantum networks

Andrew Mueller, Samantha Davis, Boris Korzh, Raju Valivarthi, Andrew D. Beyer, Rahaf Youssef, Neil Sinclair, Matthew D. Shaw, Maria Spiropulu

Under review at [Optica Quantum](#)

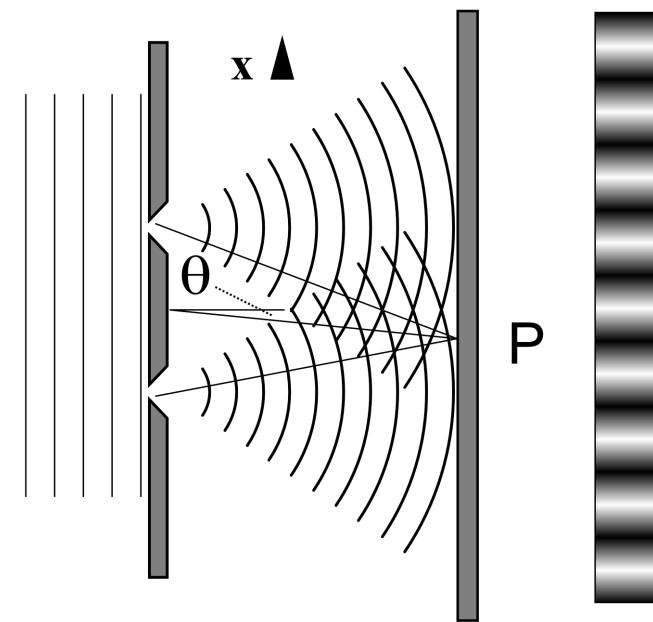
Superposition & Entanglement



Interference between the photon taking the **green** and **blue** path

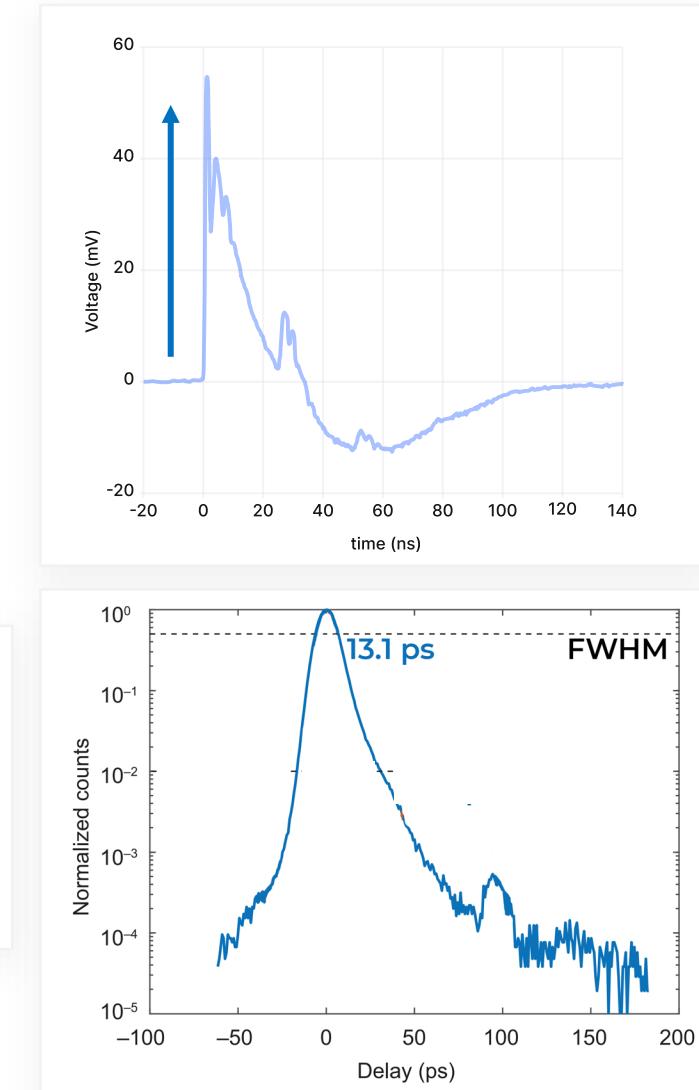
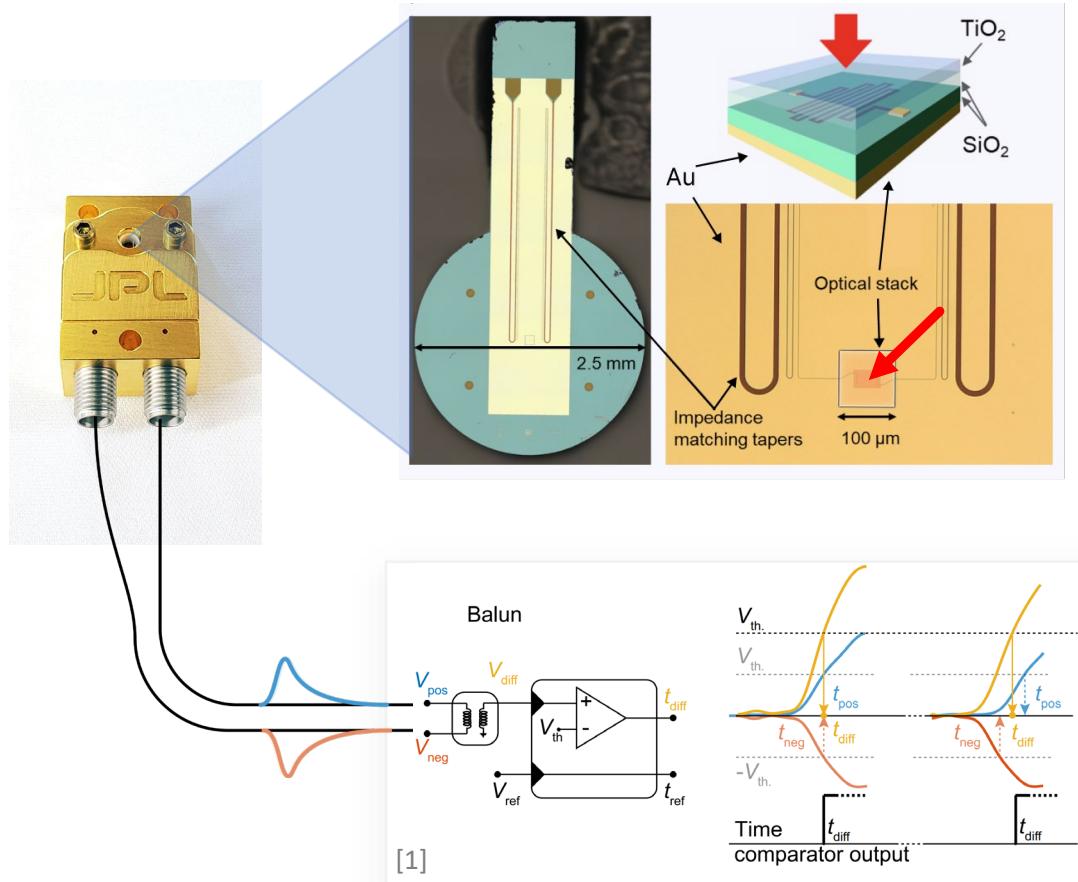
double slit experiment

- **interference** between traversal of **upper** and **lower** slit

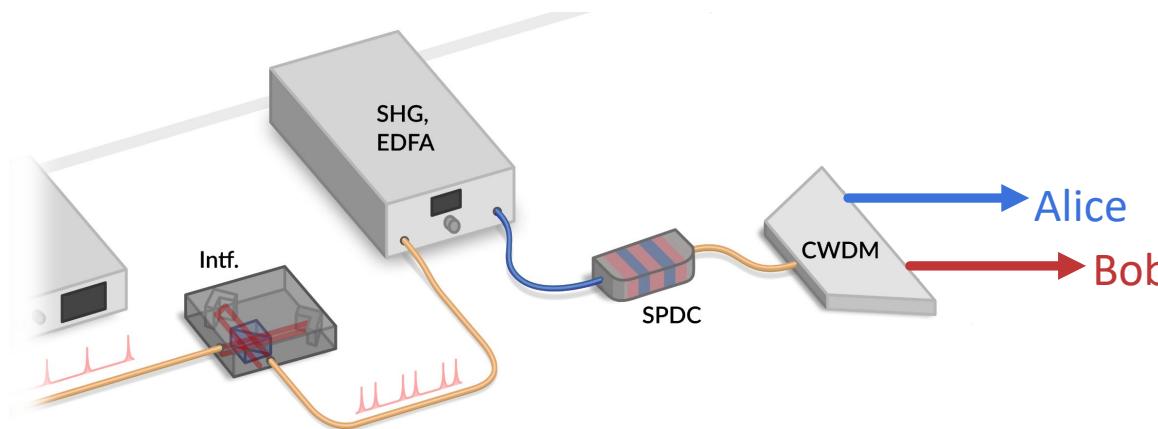


Differential Single Pixel

- Impedance matching tapers **increase pulse height and rise time**

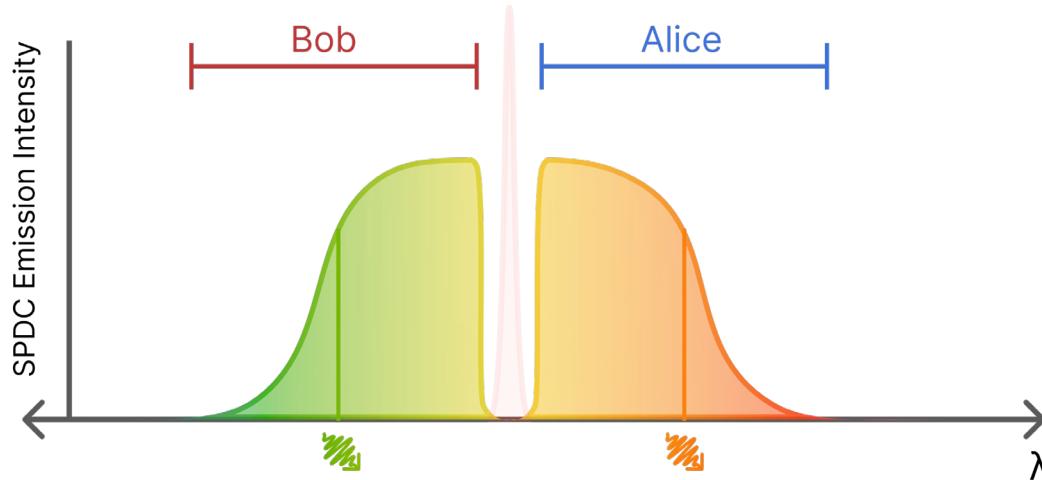


Source



Entangled pairs obey **energy conservation**

$$\omega_{pump} = \omega_{signal} + \omega_{idler}$$



80 ps delay line interferometers



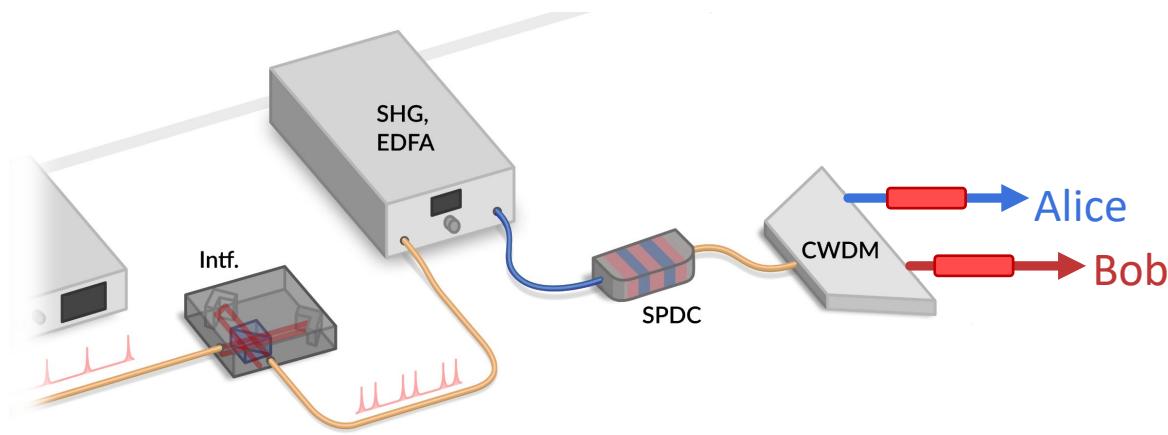
- Michelson
- Aspectral
- Athermal
- 100 Ghz free spectral range

Spontaneous Parametric Down Conversion (SPDC)

- MgO doped Periodically Poled Lithium Niobate (PPLN)
- $\chi^{(2)}$, signal & idler separated by wavelength
- 1 cm long, waveguide coupled

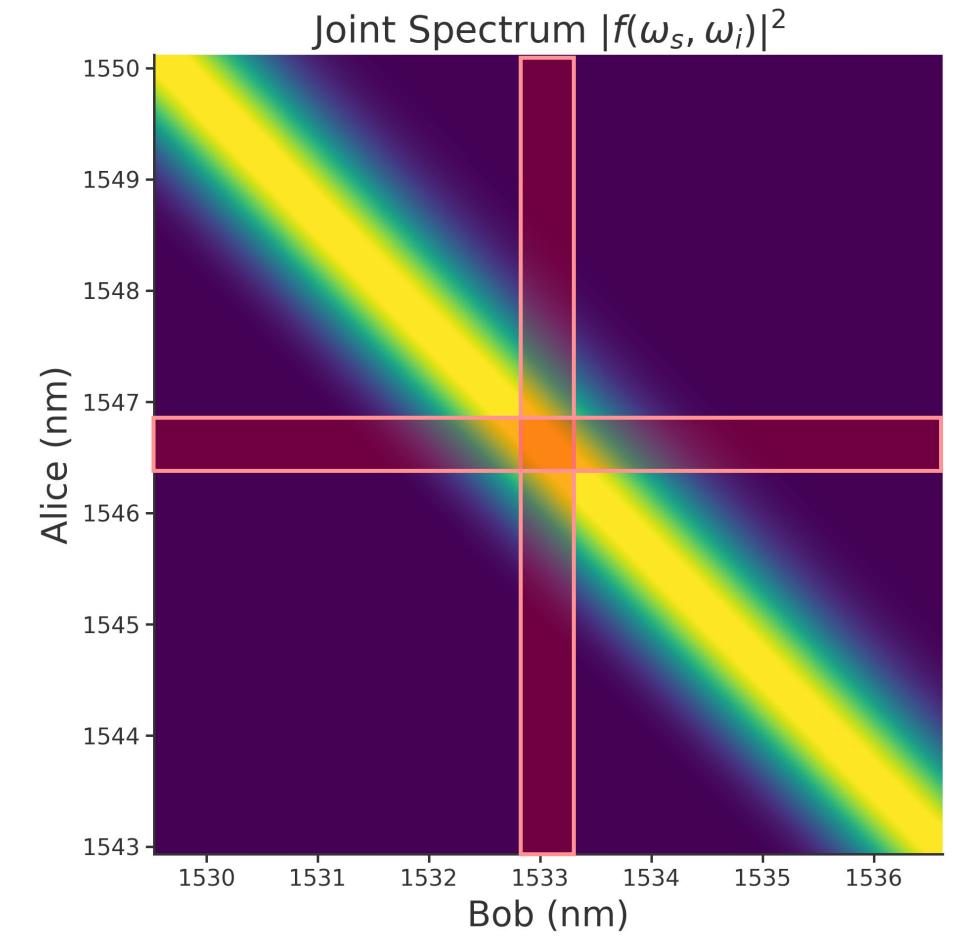
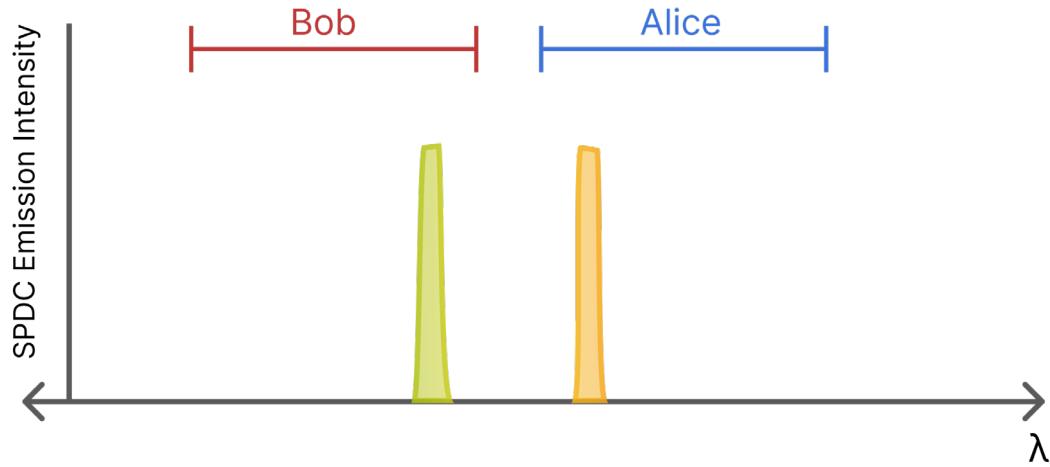


Source



Entangled pairs obey **energy conservation**

$$\omega_{\text{pump}} = \omega_{\text{signal}} + \omega_{\text{idler}}$$

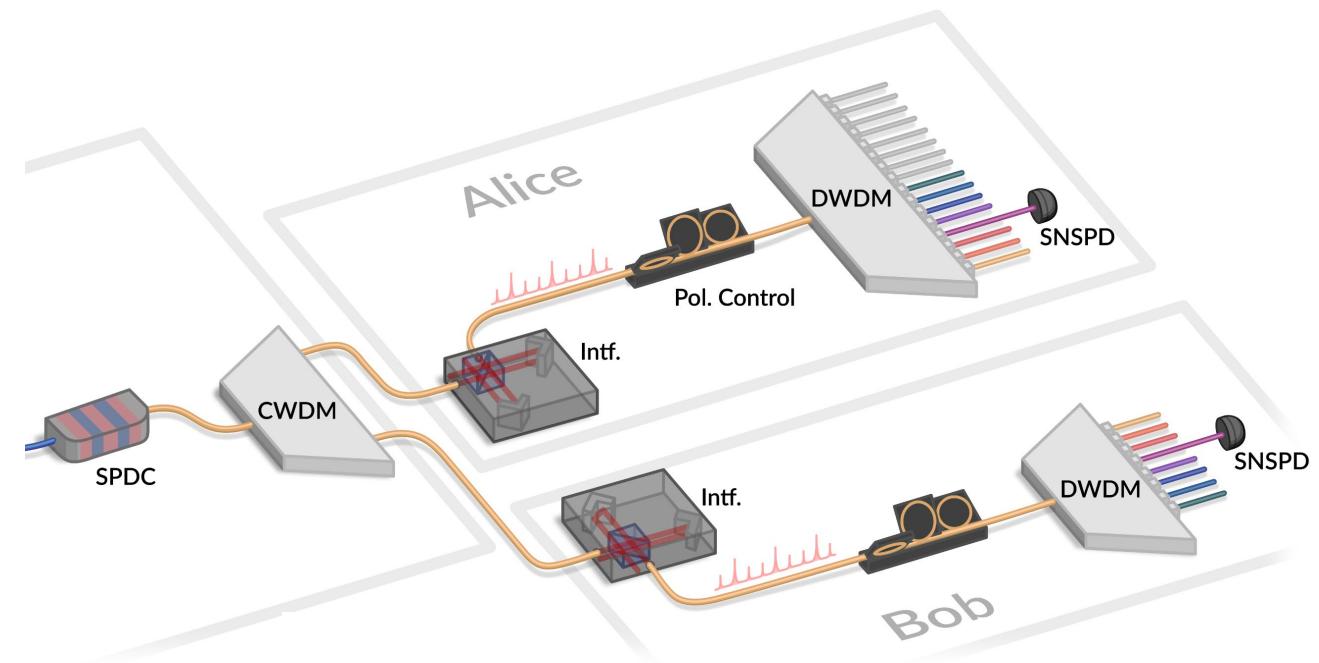
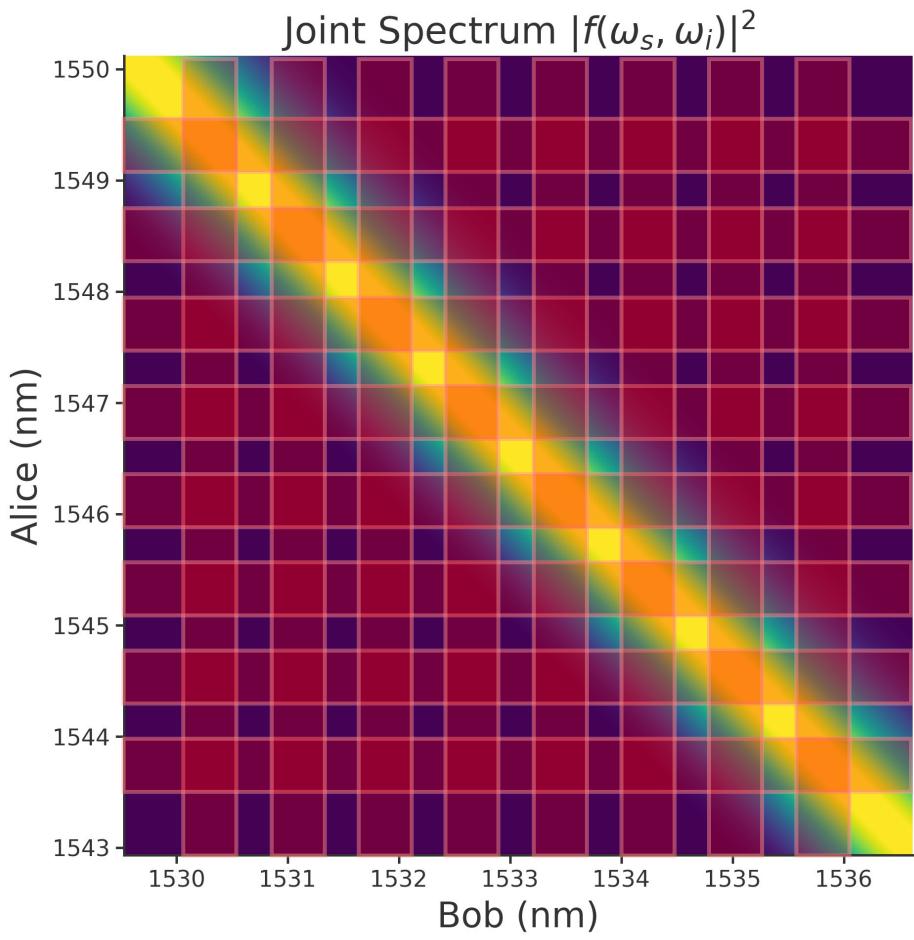


$$|f(\omega_s, \omega_i)|^2 = |\psi_{\text{ph}}(\omega_s, \omega_i)|^2 * |\psi_p(\omega_s, \omega_i)|^2$$

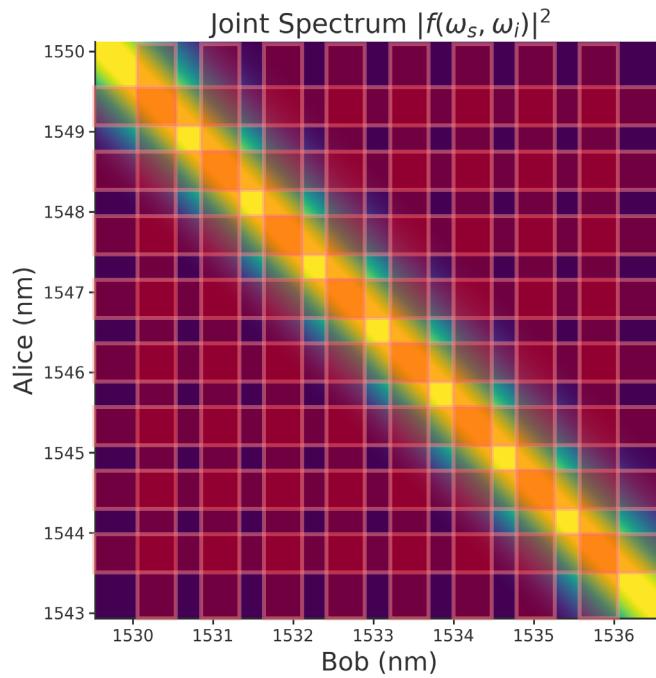
Emission joint spectrum is product of pump and phase-matching bandwidth

Phase matching likely limited by **group velocity walkoff** of fast pump pulse

Source

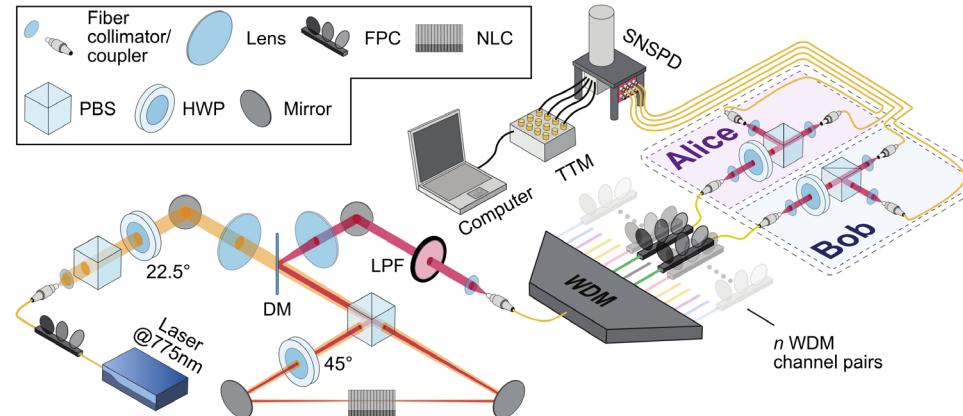


Prior Work



Experimental entanglement generation for quantum key distribution beyond 1 Gbit/s

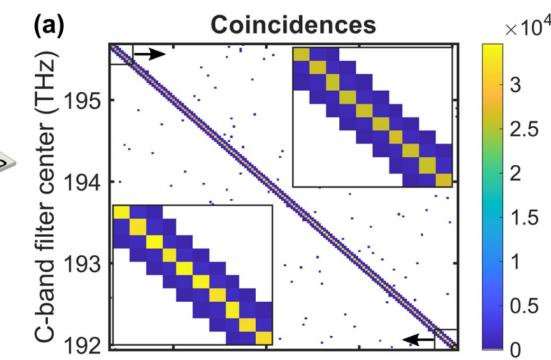
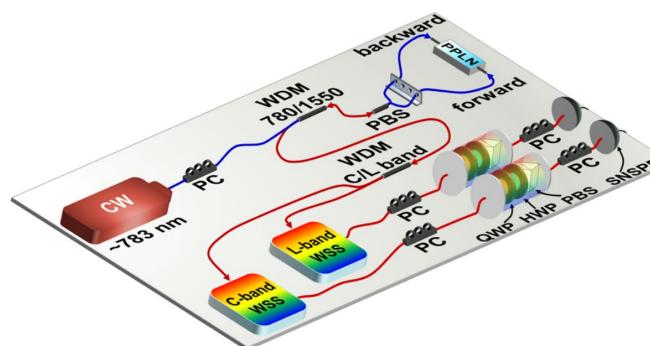
Sebastian Philipp Neumann^{1,2}, Mirela Selimovic^{1,2}, Martin Bohmann^{1,2}, and Rupert Ursin^{1,2}



- Claimed potential for very high rates (400 mW pump)
- Detectors limited real data to low rates
- (15 Kcoincidences/s, 50 μ W per channel)

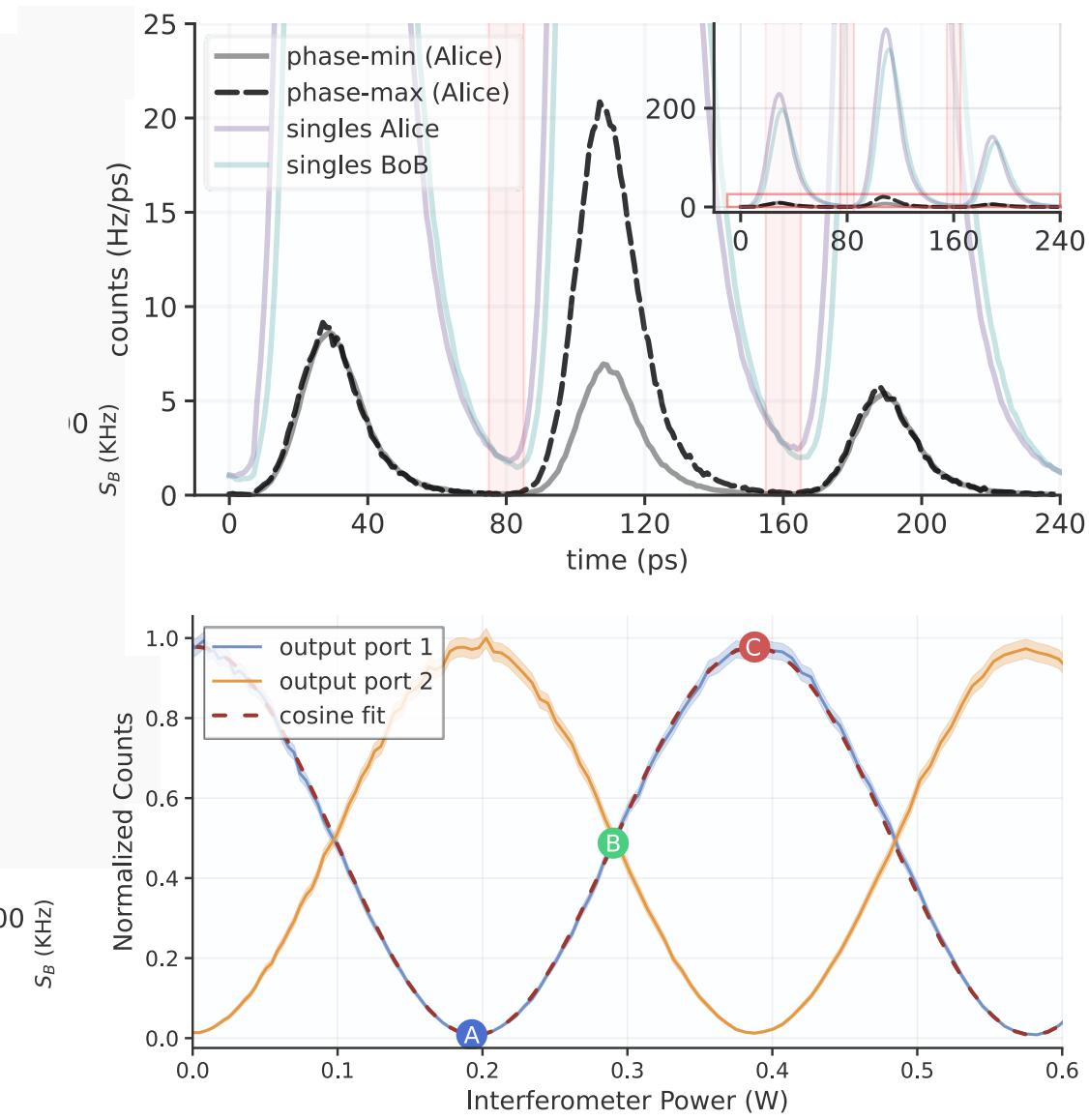
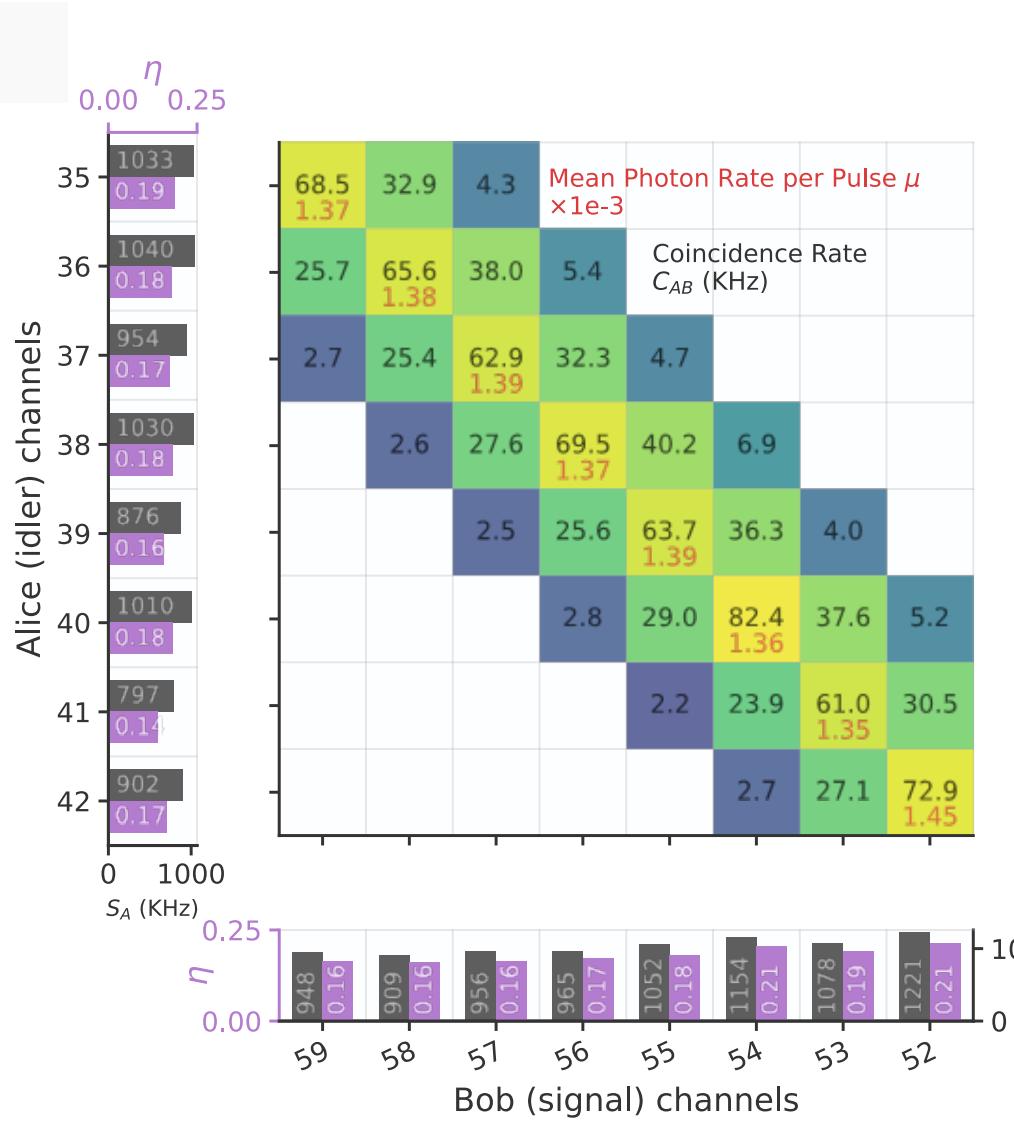
Broadband polarization-entangled source for C+L-band flex-grid quantum networks

MUNEER ALSHOWKAN,^{1,*} JOSEPH M. LUKENS,^{1,2} HSUAN-HAO LU,¹ BRIAN T. KIRBY,^{3,4} BRIAN P. WILLIAMS,¹ WARREN P. GRICE,¹ AND NICHOLAS A. PETERS¹

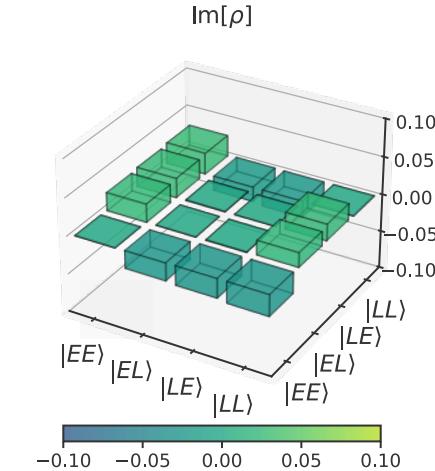
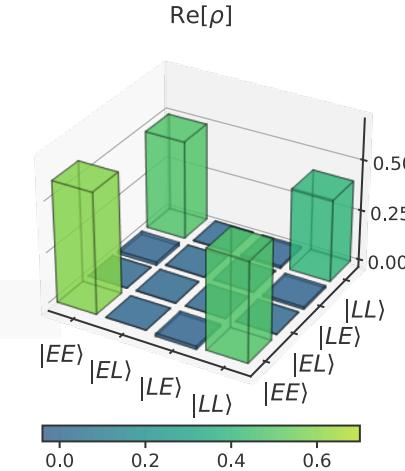
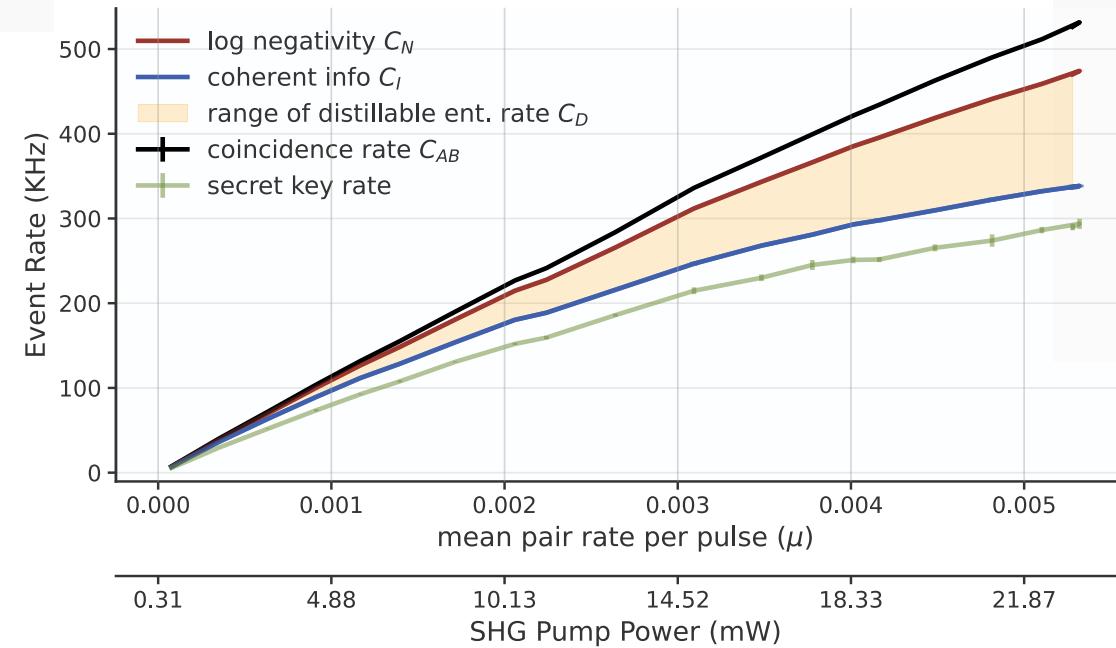
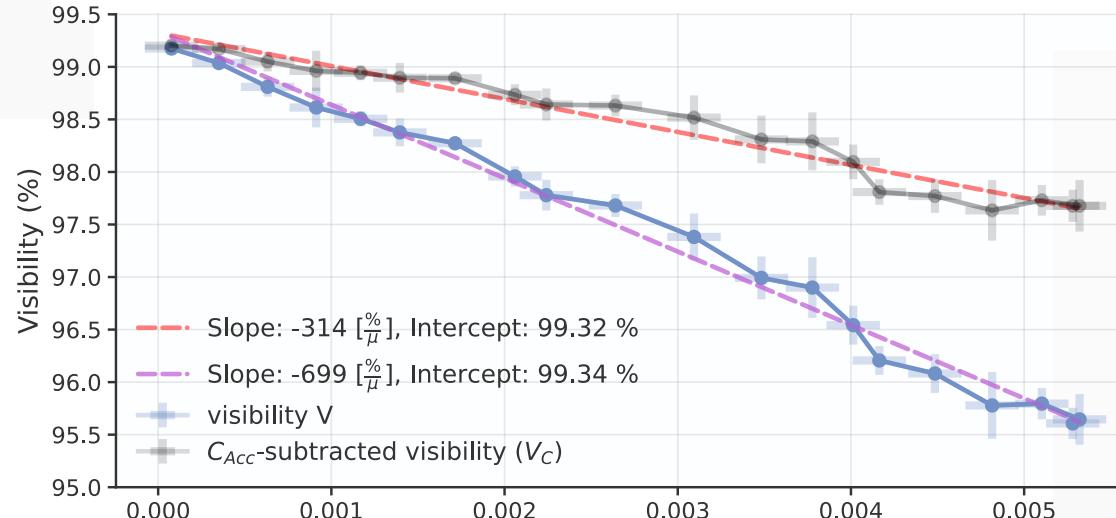


- >181 Kcoincidences/s over 150 channel pairs

Results



Results

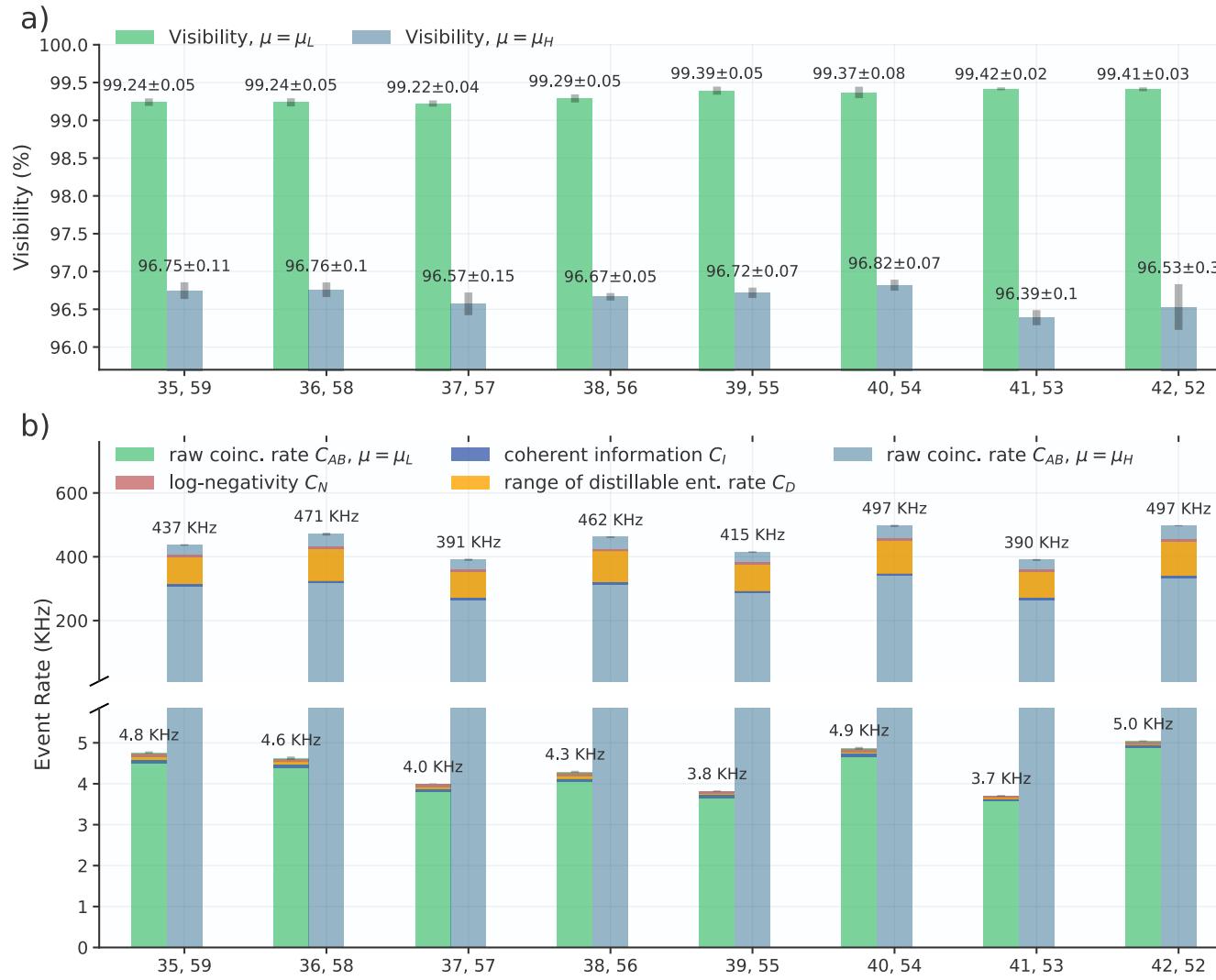


Distillable entanglement rate is bounded above by logarithmic negativity and below by coherent information

Logarithmic Negativity: $E_N = \log_2 \|\rho^A\|$

Coherent Information: $I_{A \rightarrow B} = H(\rho^B) - H(\rho^{AB})$

Results



3.55e6 coincidences/s
Across 8 multiplexed pairs

Up to 99.3% entanglement visibility
At $\mu = 5.6e-5$

2.46 – 3.25 Mebits/s
 $\mu = 5.0e-3, V \simeq 96.6\%$

Outlook

- Underlies of 1 of the 3 projects selected from the DOE's *Scientific Enablers of Scalable Quantum Communication* program
- For the upgrade and expansion of a quantum network between Fermilab and Argonne National Laboratories
- **Plans**
 - Future entanglement distribution across long distance deployed fiber
 - Study dispersion & drift effects
 - Future **high-rate teleportation & entanglement swapping** demonstrations

Office of Science

Department of Energy Announces \$24 Million for Research on Quantum Networks

AUGUST 29, 2023

Office of Science » Department of Energy Announces \$24 Million for Research on Quantum Networks

Projects Advance Scalable Quantum Network Communications

WASHINGTON, D.C. - Today, the U.S. Department of Energy (DOE) announced \$24 million in funding for three collaborative projects in quantum network research.

Department of Energy Office of Science

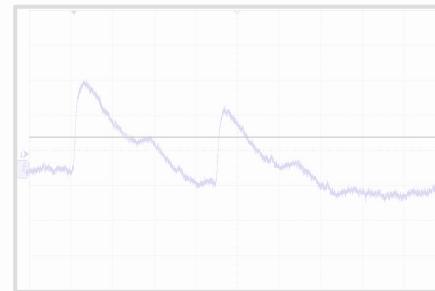
Fermilab

Outline

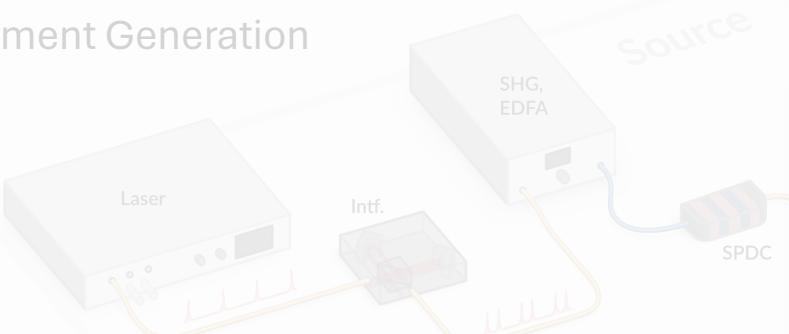
1. Low Dark Count Rate Free Space Coupled SNSPD



2. Time Walk Correction

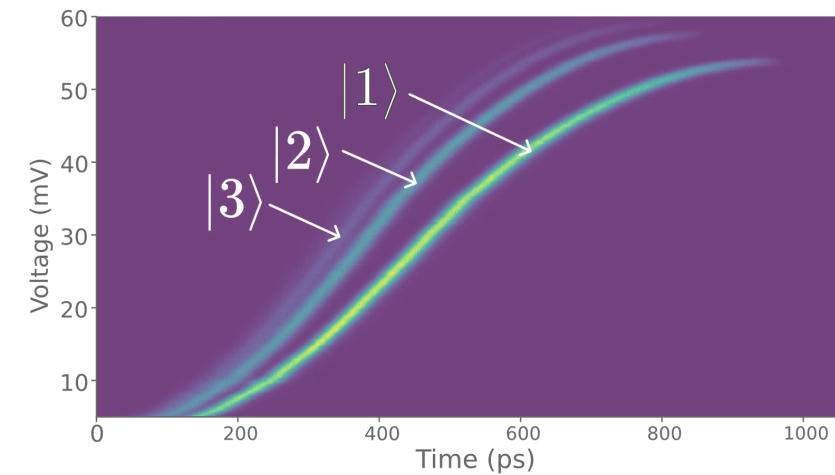


3. High-Rate Entanglement Generation



Aside: Phase Locked Loops

4. Pulse Position Modulation & Photon Number Resolution

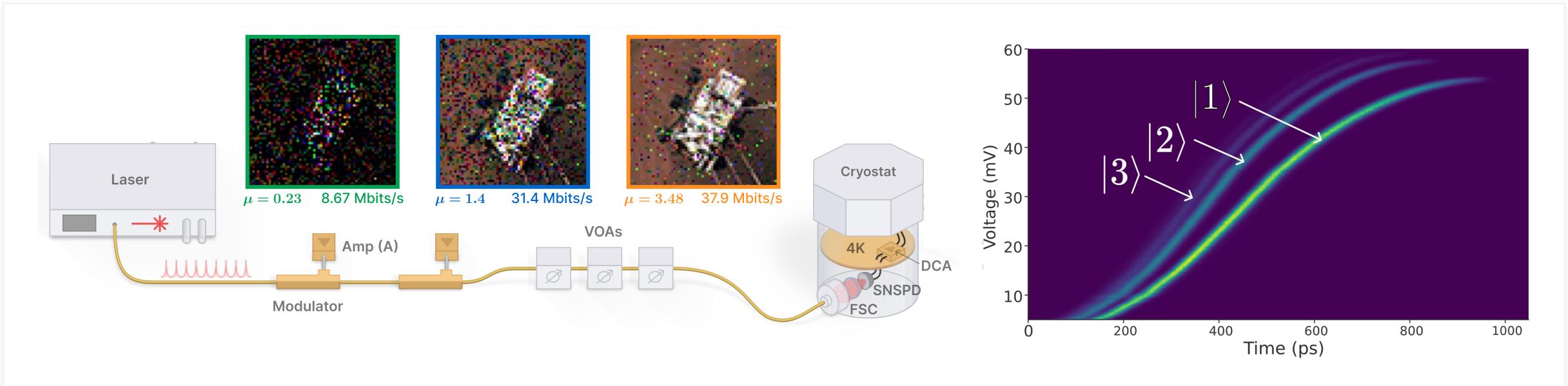


Conclusion & Outlook

Achievement

Pulse Position Modulation (PPM) communication on a 20 GHz & 10 GHz clock

- Resolve **arrival time** and **Photon Number Resolution (PNR)**
- Applicable to deterministic single photon sources, optical quantum computing, single-photon path entanglement

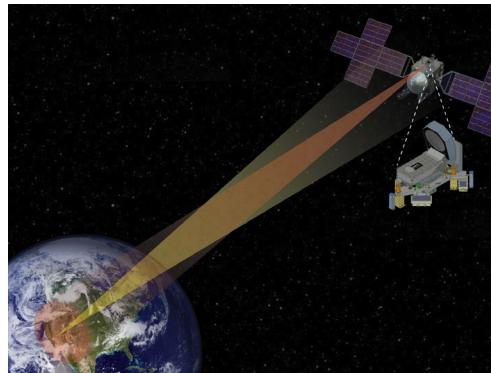


Manuscript in preparation for submission to Optics Express

Pulse Position Modulation

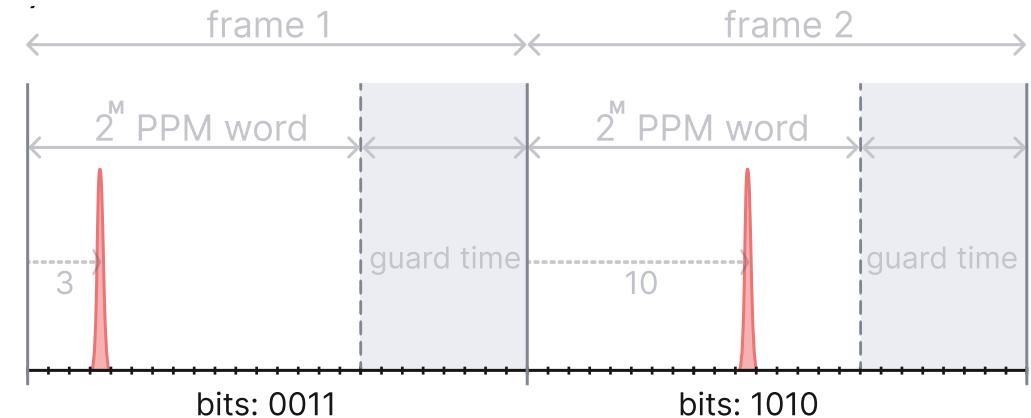
DSOC:

- 2 GHz repletion rate (500 ps bins)
- Up to 128 bins per laser pulse ($M = 7, 7$ bits per frame)



Beyond DSOC

- Higher clock rate
- Larger M , for higher photon information efficiency



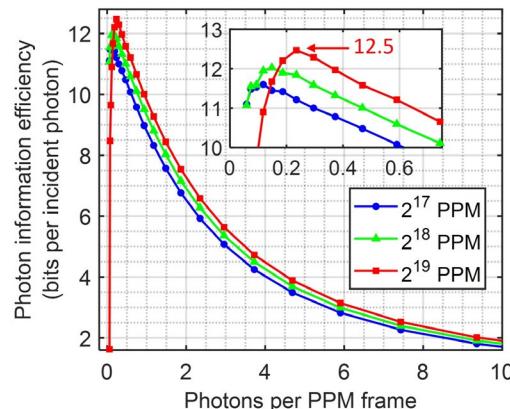
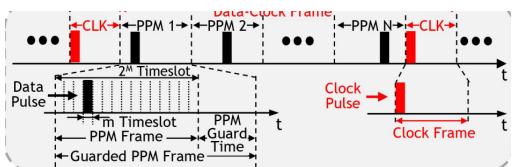
arXiv > quant-ph > arXiv:2310.02191

Quantum Physics

[Submitted on 3 Oct 2023]

Record Photon Information Efficiency with Optical Clock Transmission and Recovery of 12.5 bits/photon over an Optical Channel with 77 dB Loss

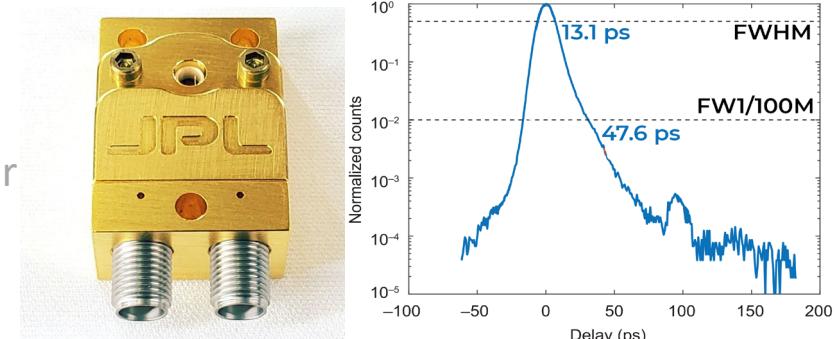
René-Jean Essiambre (1), Cheng Guo (1 and 2), Sai Kanth Dacha (1), Alexei Ashikhmin (1), Andrea Blanco-Redondo



- $M = 17, 18, 19$
- $> 500,000$ time slots to send 19 bits of data

- M-PPM beyond $M = 11$ is **exceedingly slow** and cumbersome
- Better to demonstrate moderately **much higher clock rate**, and moderate M values

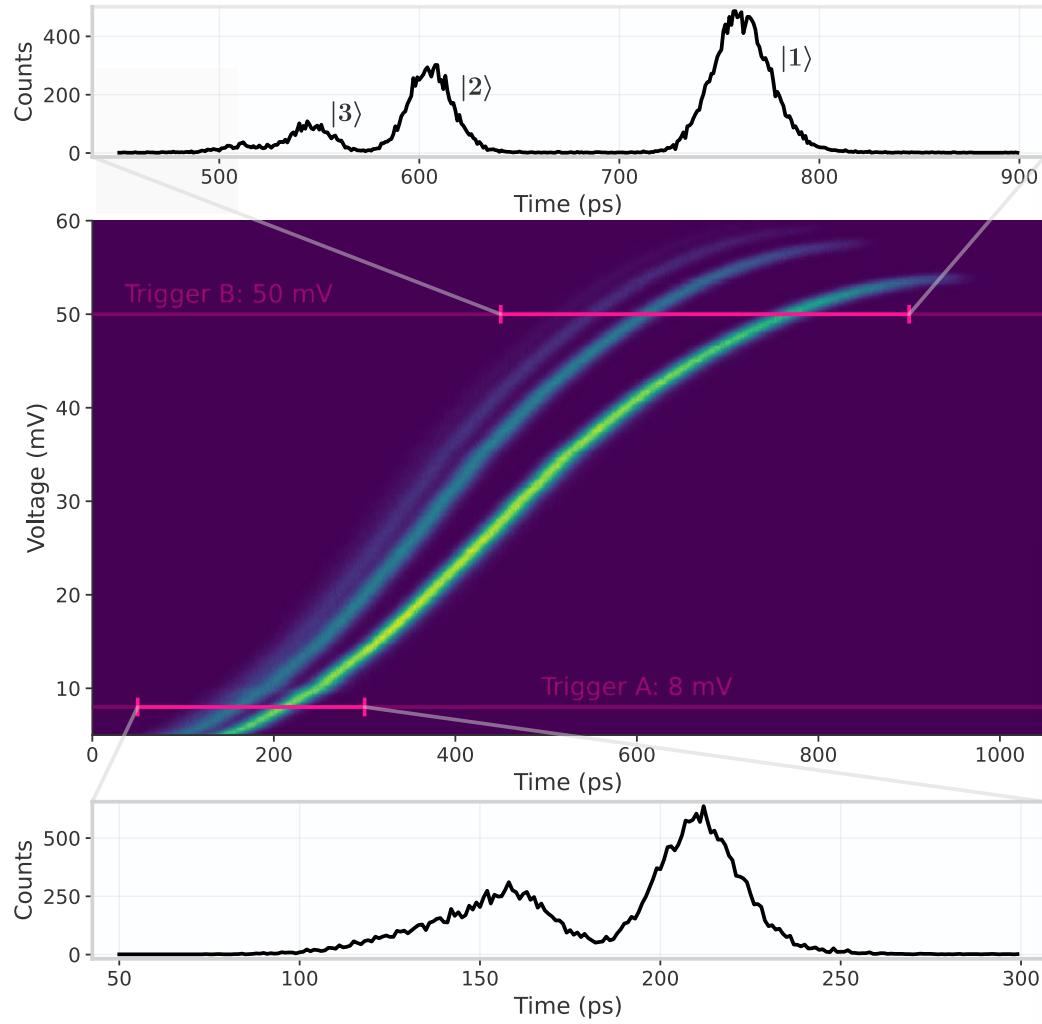
Low jitter
enables higher
rates



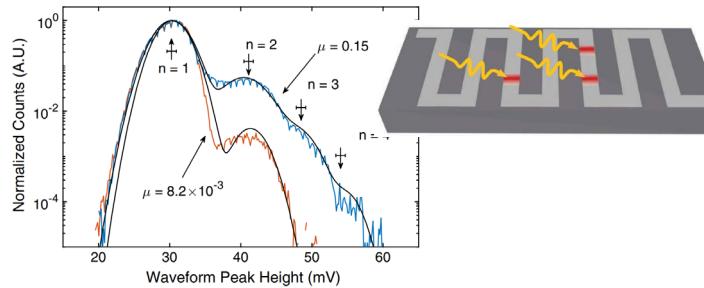
Plan

1. Demonstrate PPM at up to 20 GHz (50 ps bins)
2. Demonstrate large-M code words

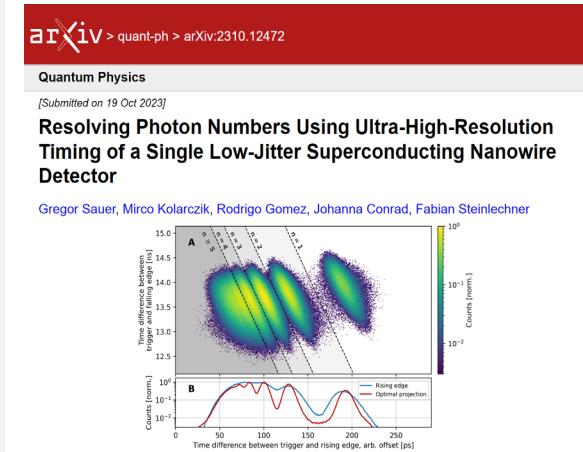
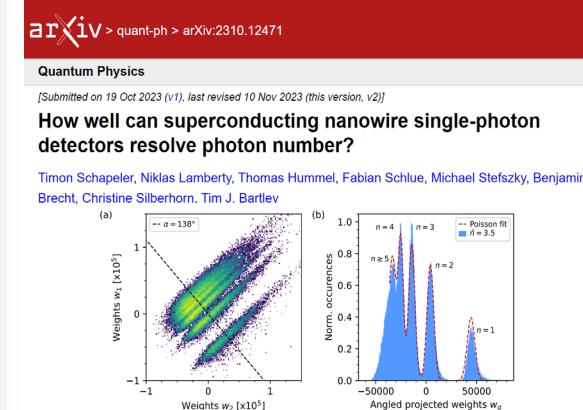
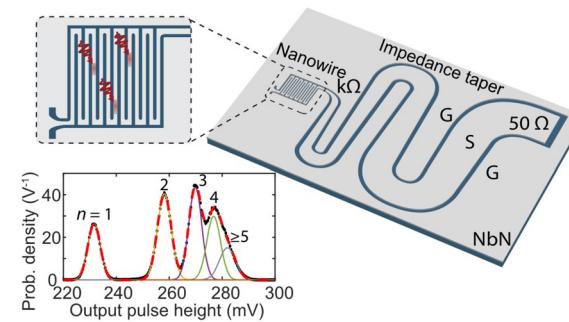
Photon Number Response



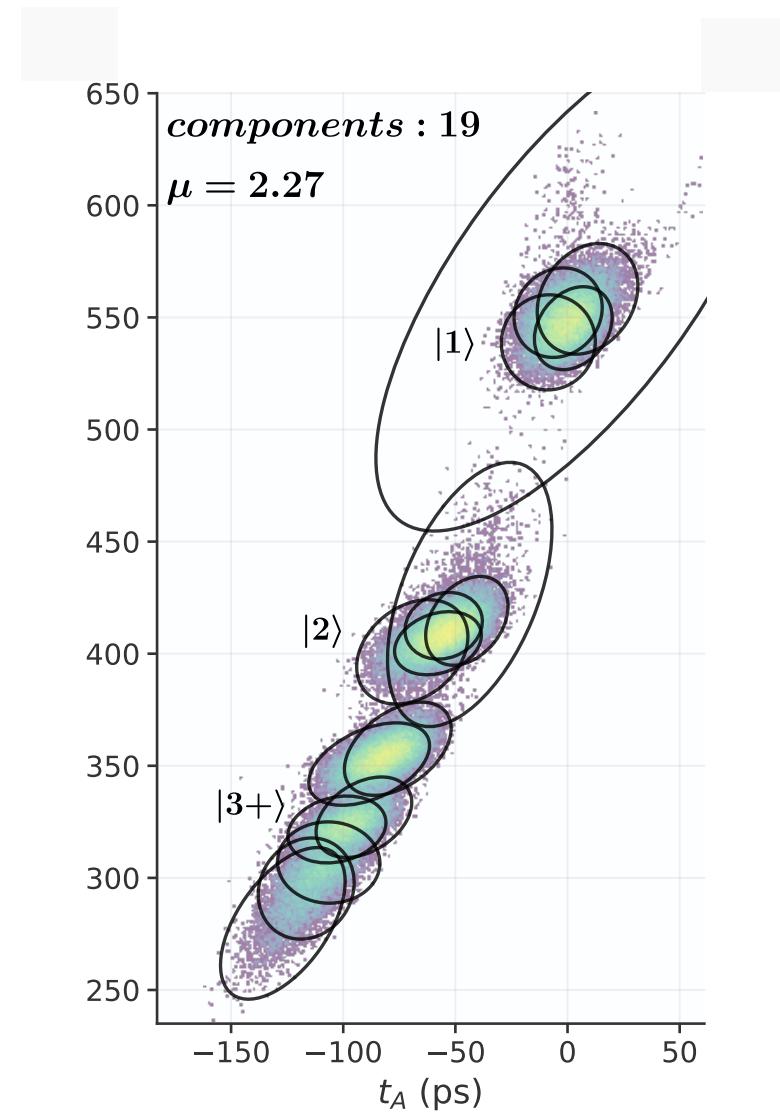
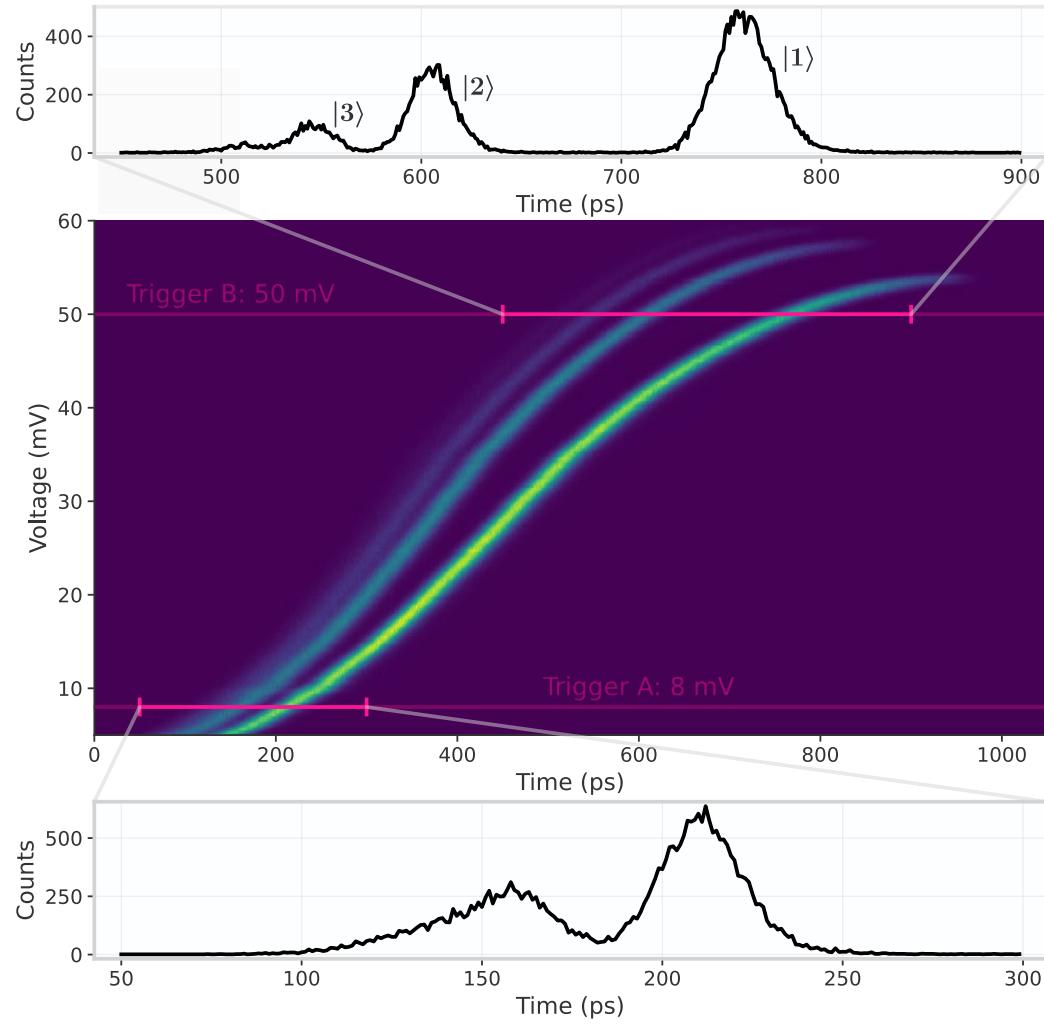
Multi-photon detection using a conventional superconducting nanowire single-photon detector
Cahall et al. 2017

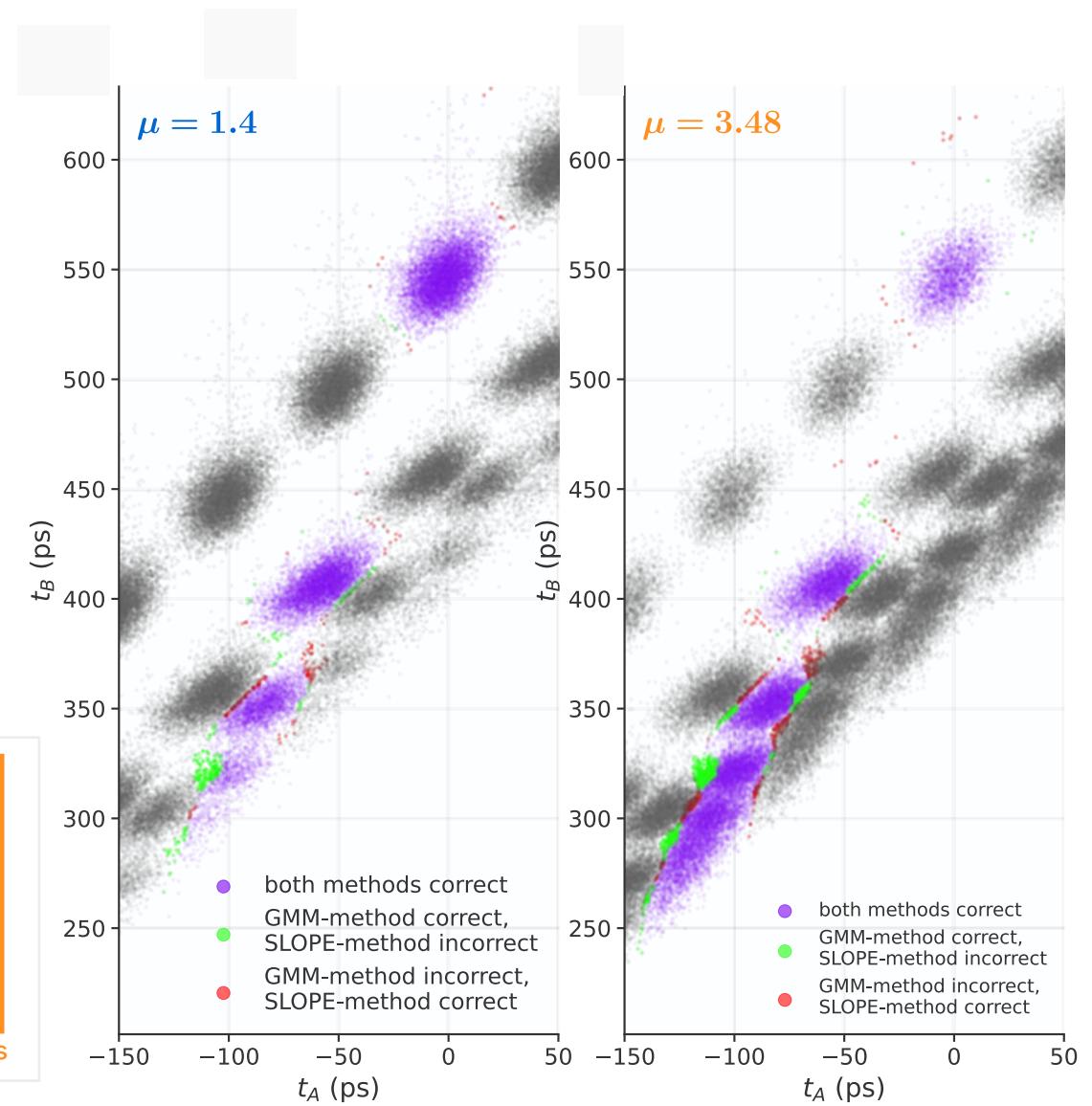
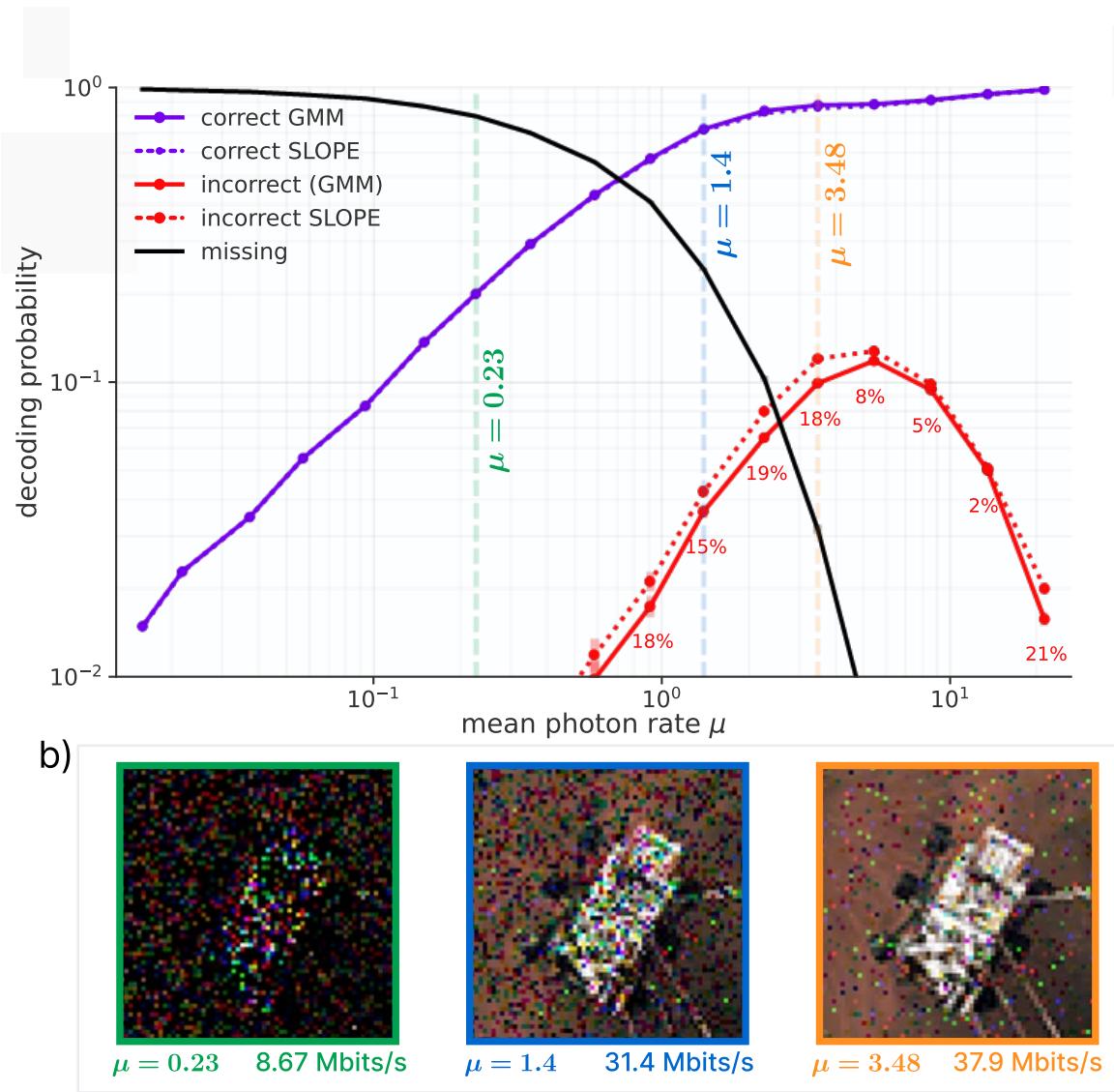


Resolving Photon Numbers Using a Superconducting Nanowire with Impedance-Matching Taper
Di Zhu et al. 2020



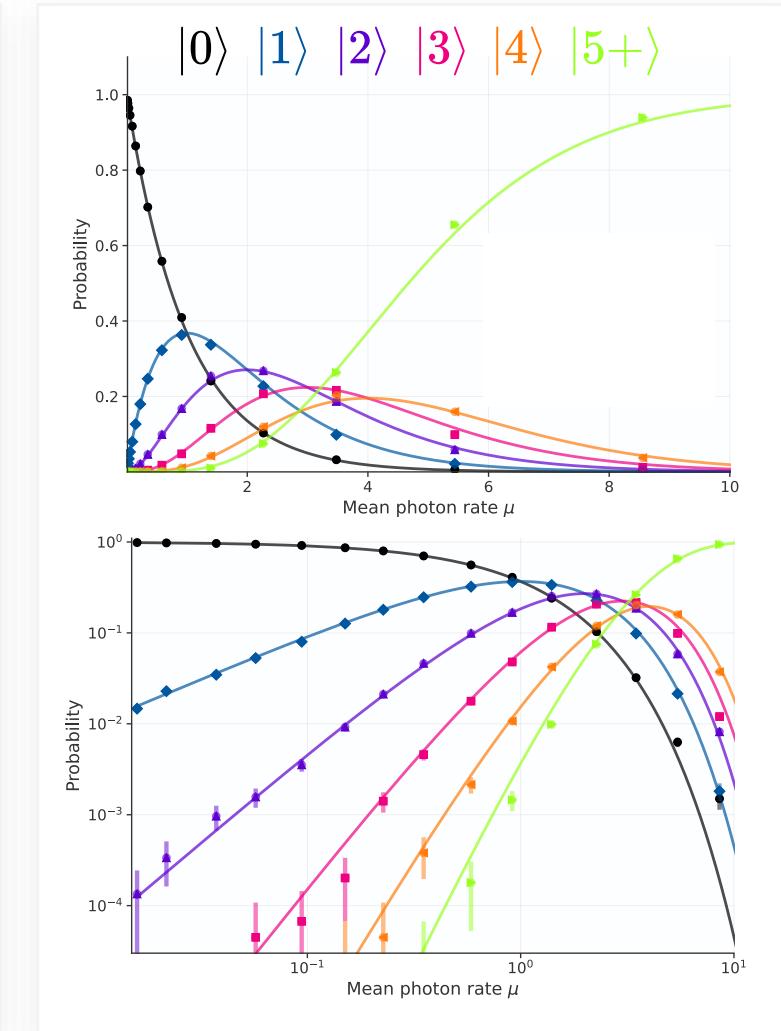
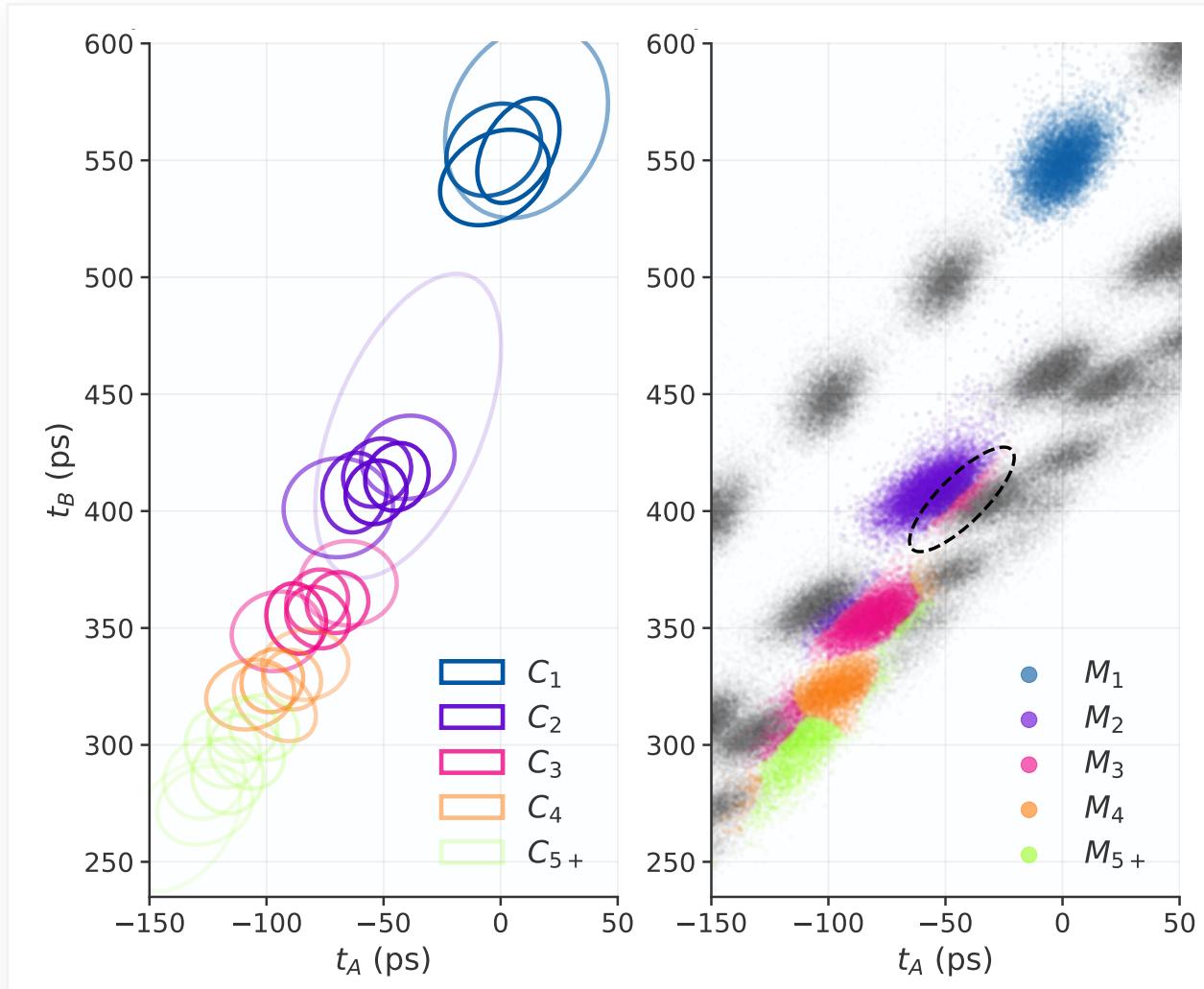
Photon Number Response





Photon Number Attribution

- Gaussian clusters model separate photon number responses
- Resolve **photon number** and **arrival time** of high-rate optical pulses **simultaneously**



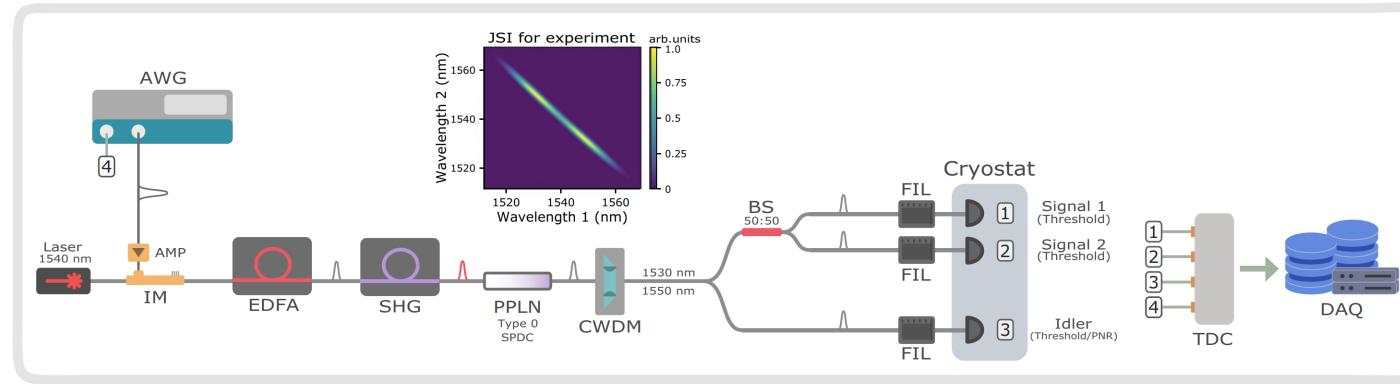
Outlook

1. Faster Deep Space Optical Communication

2. Advanced single photon sources

Improved Heralded Single-Photon Source with a Photon-Number-Resolving Superconducting Nanowire Detector

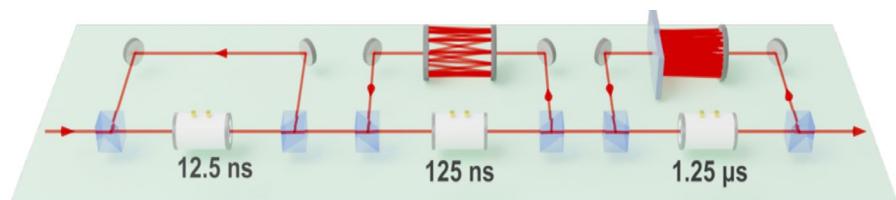
Samantha I. Davis, Andrew Mueller, Raju Valivarthi, Nikolai Lauk, Lautaro Narvaez, Boris Korzh, Andrew D. Beyer, Olmo Cerri, Marco Colangelo, Karl K. Berggren, Matthew D. Shaw, Si Xie, Neil Sinclair, and Maria Spiropulu
Phys. Rev. Applied **18**, 064007 – Published 2 December 2022



- ▼ Amplifier (AMP)
- Coarse Wave-Division Multiplexer (CWDM)
- Intensity Modulator (IM)
- Second-Harmonic Generation (SHG)
- Filter (FIL)
- Single-Photon Detector (SNSPD)
- Time-to-Digital Converter (TDC)
- Data Acquisition and Control (DAQ)
- Erbium-Doped Fiber Amplifier (EDFA)
- Periodically Poled Lithium Niobate (PPLN)
- Arbitrary Wave-Function Generator (AWG)
- Beam Splitter (BS)

Potential to make a **time-multiplexed single photon source**

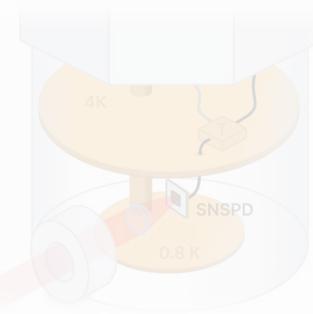
- With **heralded SPDC**
- Each clock cycle, pump SPDC tens or hundreds of times
- Herald idler single photon state with PNR SNSPD
- Delay signal photon in pocket cell memory



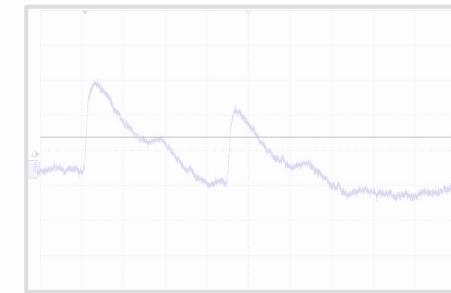
[1] Nathan Arnold et al. 2021

Outline

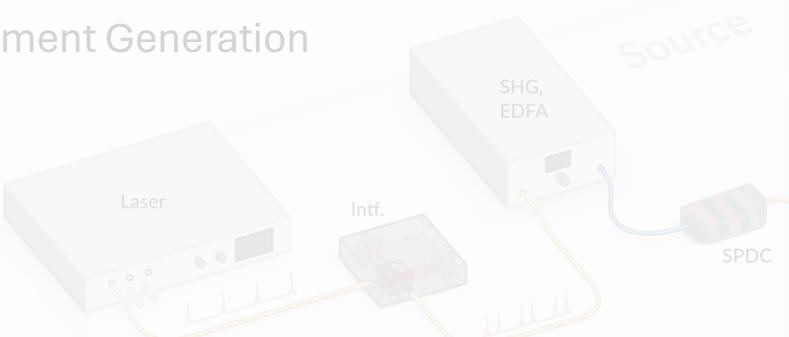
1. Low Dark Count Rate Free Space Coupled SNSPD



2. Time Walk Correction

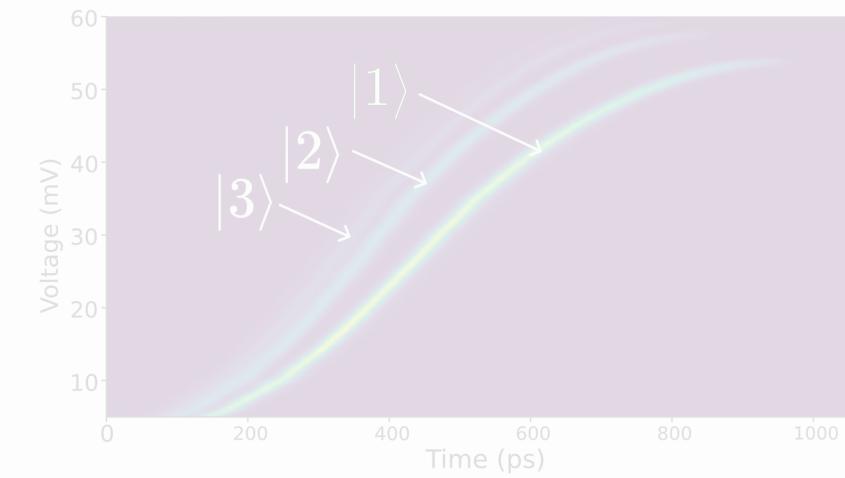


3. High-Rate Entanglement Generation



Aside: Phase Locked Loops

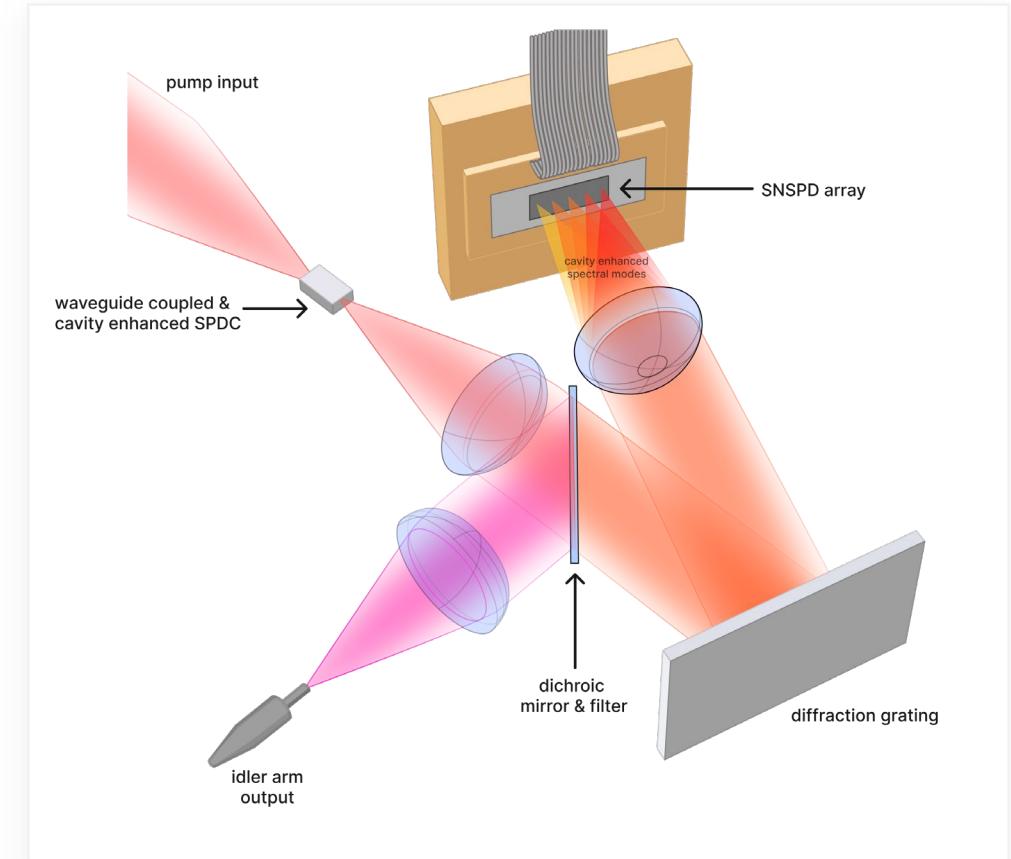
4. Pulse Position Modulation & Photon Number Resolution



Conclusion & Outlook

Conclusion

- Cryogenic free space optics are **manageable**, potentially **ideal for high efficiency & low dark count** applications
- Time walk correction
 - Enables **low jitter** is available at **much higher count rates**
 - Applicable *in situ* for quantum communication testbeds, with minimal setup
- Photon number & arrival time discrimination
 - Enables **high-rate heralding & multiplexing** for single photon sources
 - Single path entanglement, photon-number homodyne measurements



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