Quantum Measurements with Superconducting Nanowire Single Photon Detectors

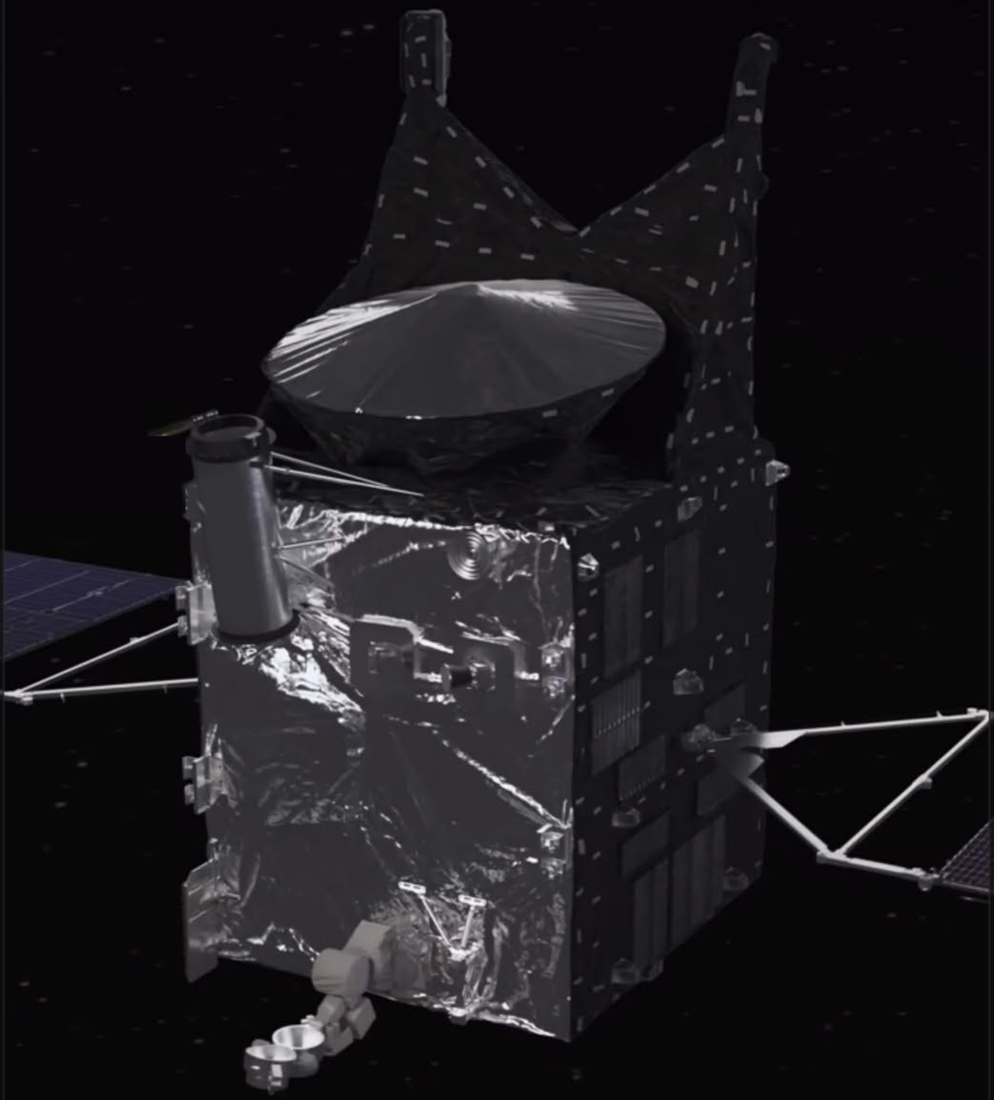
Andrew Mueller

December 11th

Psyche

Radio Communication

Via the **Deep Space Network**



Laser Communication

Now

Deep Space Optical Communication (DSOC)

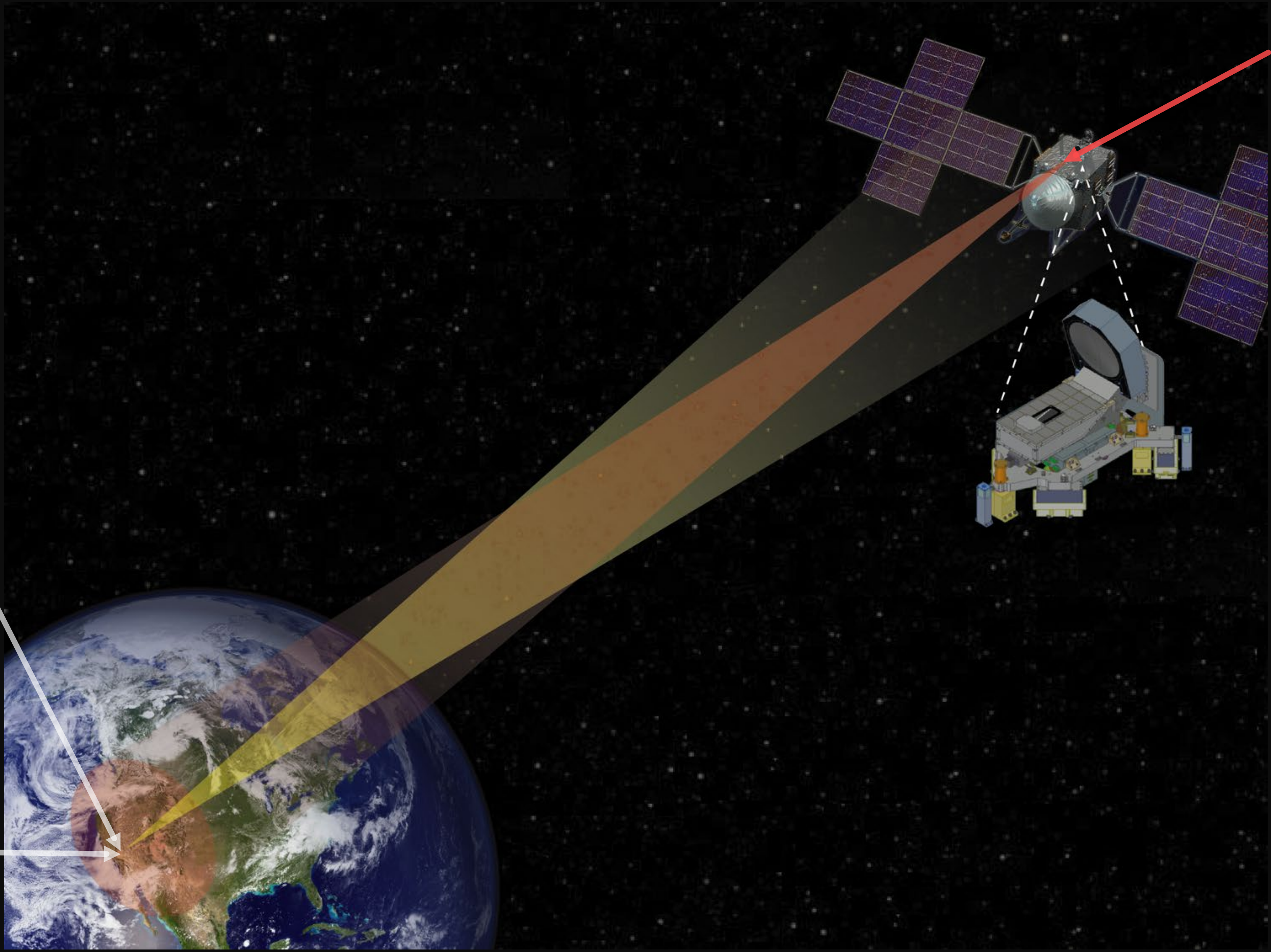
- 0.2 Mbit/s to over 200 Mbit/s [1]
- 2 GHz clock rate

Future

10 – 100x faster

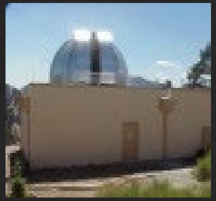
For future deep space laser links [1]

Deep Space Optical Communication (DSOC)



4 W laser
1550 nm

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

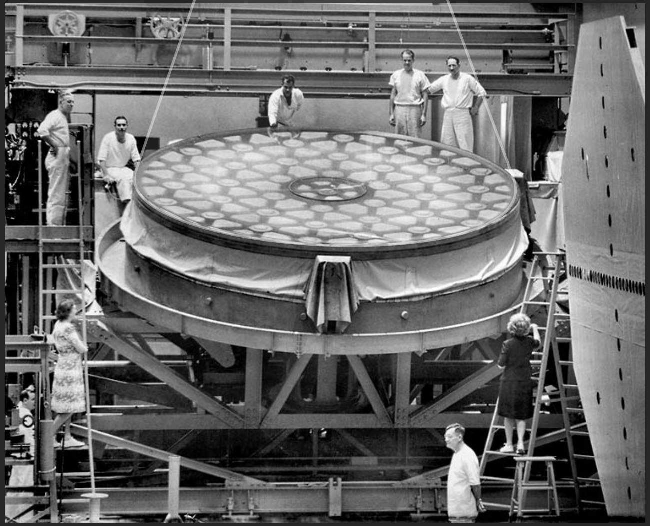


Ground Laser Receiver
Palomar Mtn, CA
5 m Hale telescope

NASA/JPL-Caltech/ASU

Deep Space Optical Communication (DSOC)

Hale Telescope, Palomar Observatory
San Diego County



Corning Museum of Glass, Caltech Archives

4 W laser power

0.000000000002%
captured

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

Deep Space Optical Communication (DSOC)

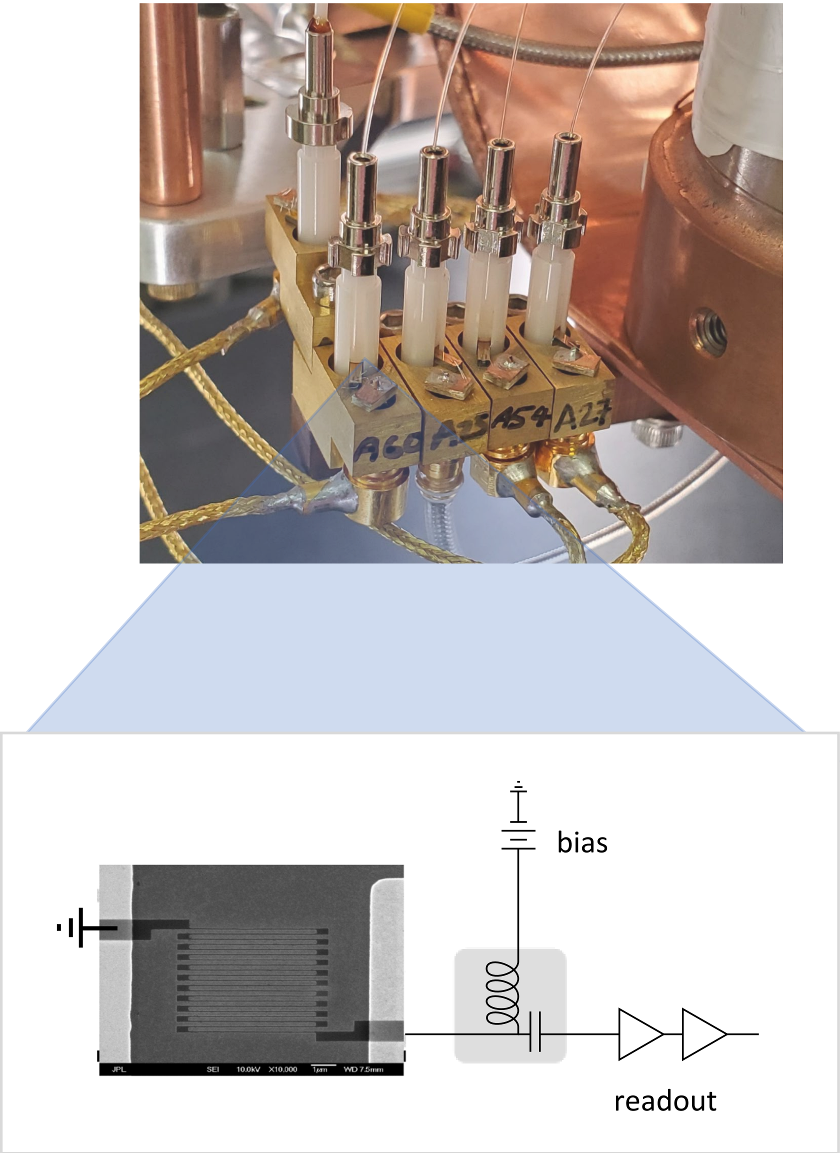
TECHNOLOGY

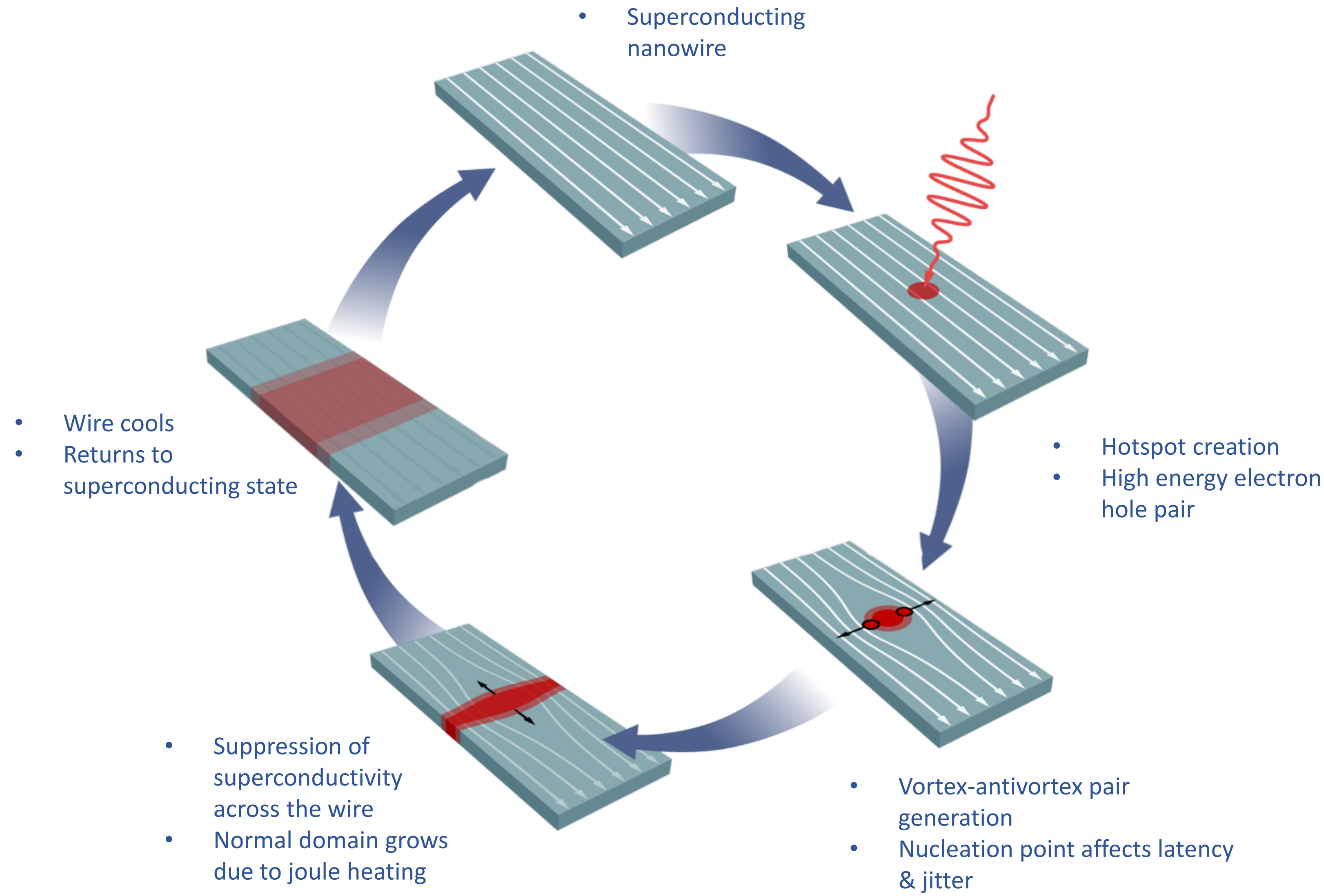
NASA's Deep Space Optical Comm Demo Sends, Receives First Data

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

Operation

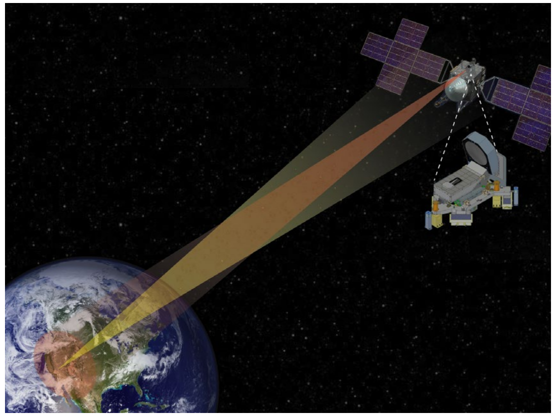

bias
readout

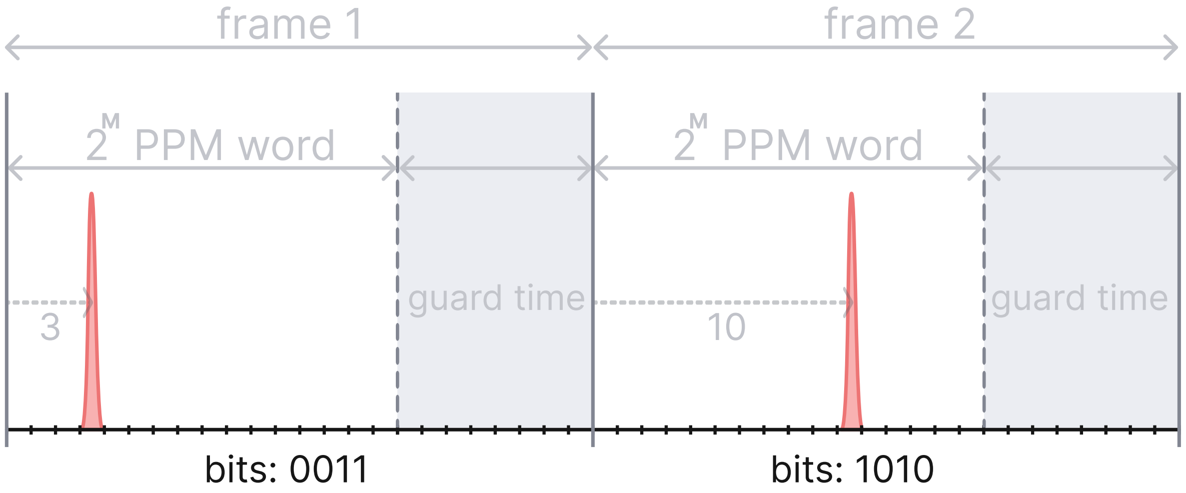

• Superconducting nanowire
• Hotspot creation
• High energy electron hole pair
• Vortex-antivortex pair generation
• Nucleation point affects latency & jitter
• Suppression of superconductivity across the wire
• Normal domain grows due to joule heating
• Wire cools
• Returns to superconducting state

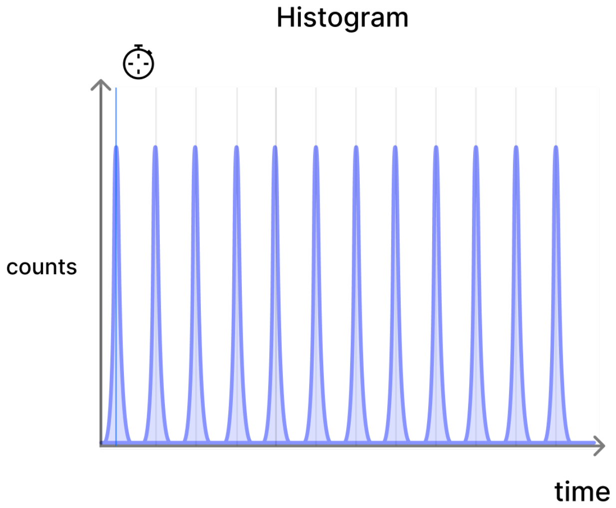
Metric 1: Timing Resolution

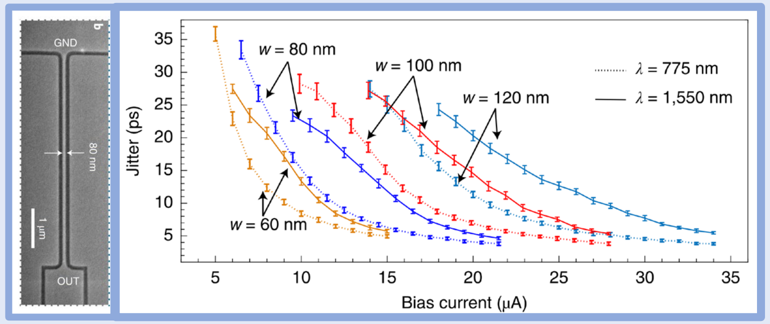
High **timing resolution** (low ***jitter***) enables higher system repetition rates and data rates

① timing resolution





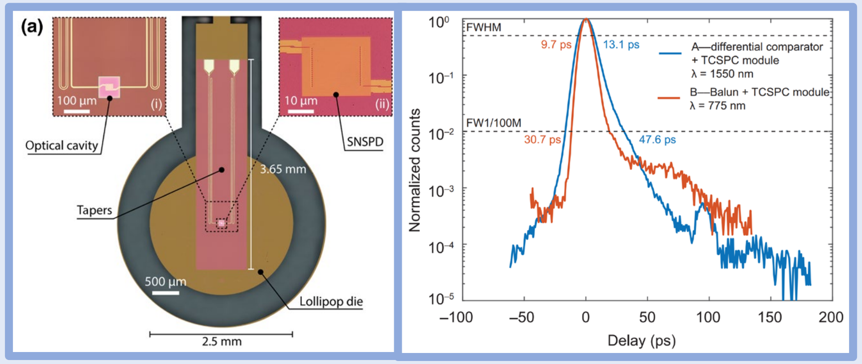




Example: State-of-the-art for short wires

- 2.6 ps visible wavelengths
- 4.3 ps at 1550 nm

[1] Korzh et al. 2020



Example: State-of-the-art for efficient fiber coupling

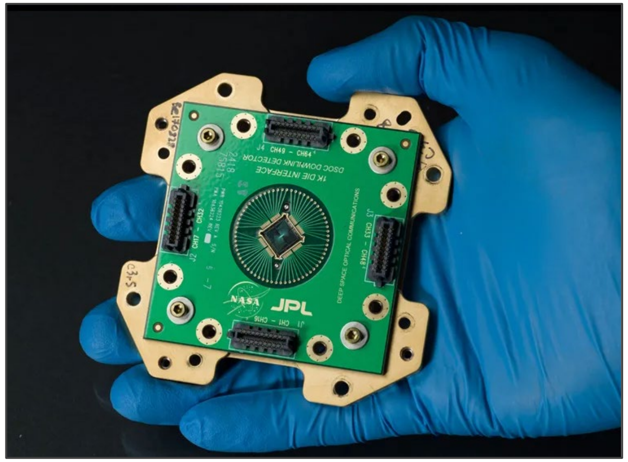
- 9.7 ps FWHM at 775 nm
- 13.1 ps FWHM at 1550 nm

[2] Colangelo et al. 2023

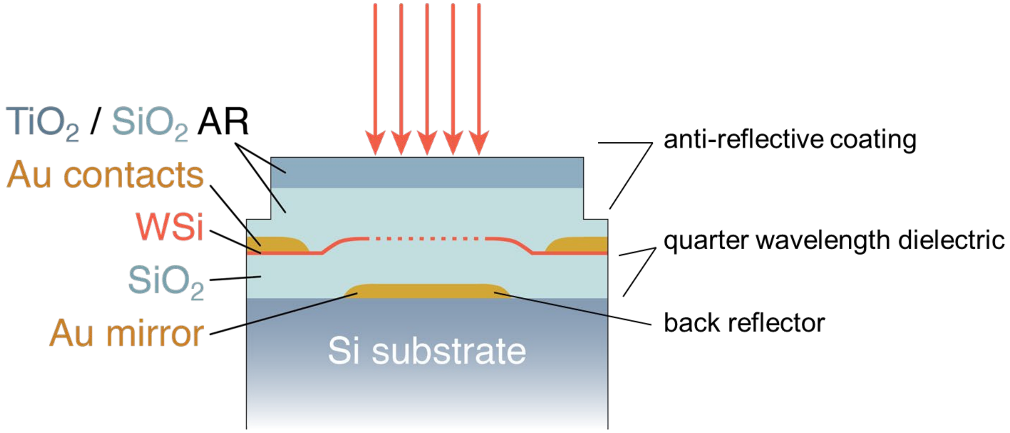
Metric 2: Efficiency

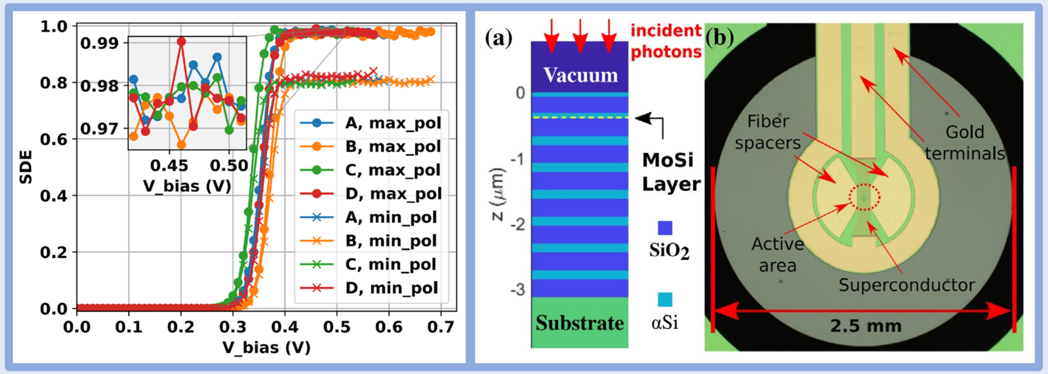
High **system detection efficiency** enables efficient use of other resources, higher chance of collecting sent data

② system detection efficiency



NASA/JPL-Caltech





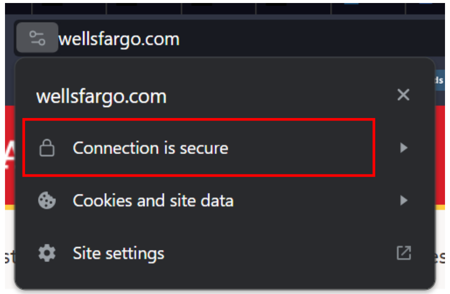
Example: Up to 98% system detection efficiency demonstrated
- 1550 nm
- fiber coupled
- DBR based optical stack

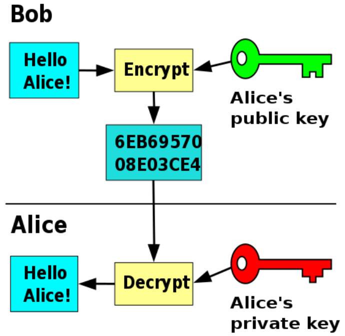
[1] Dileep Reddy et al. 2020

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

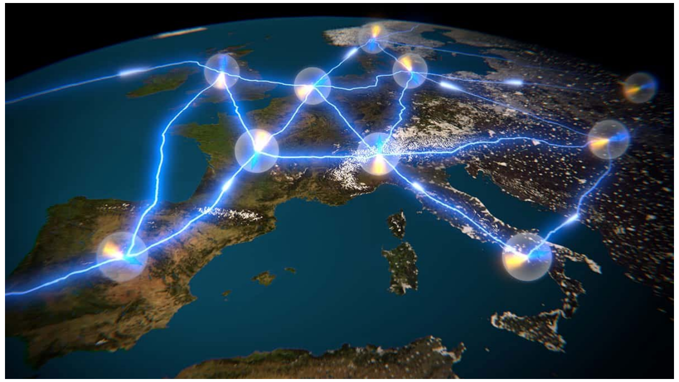




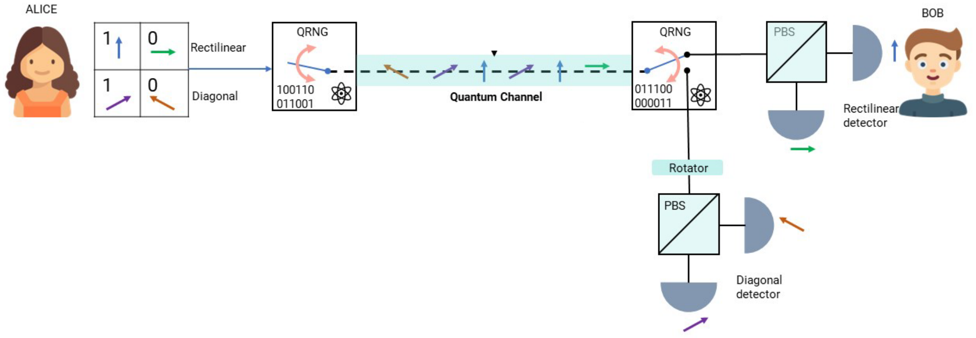
Wikipedia.org

Other quantum network applications

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

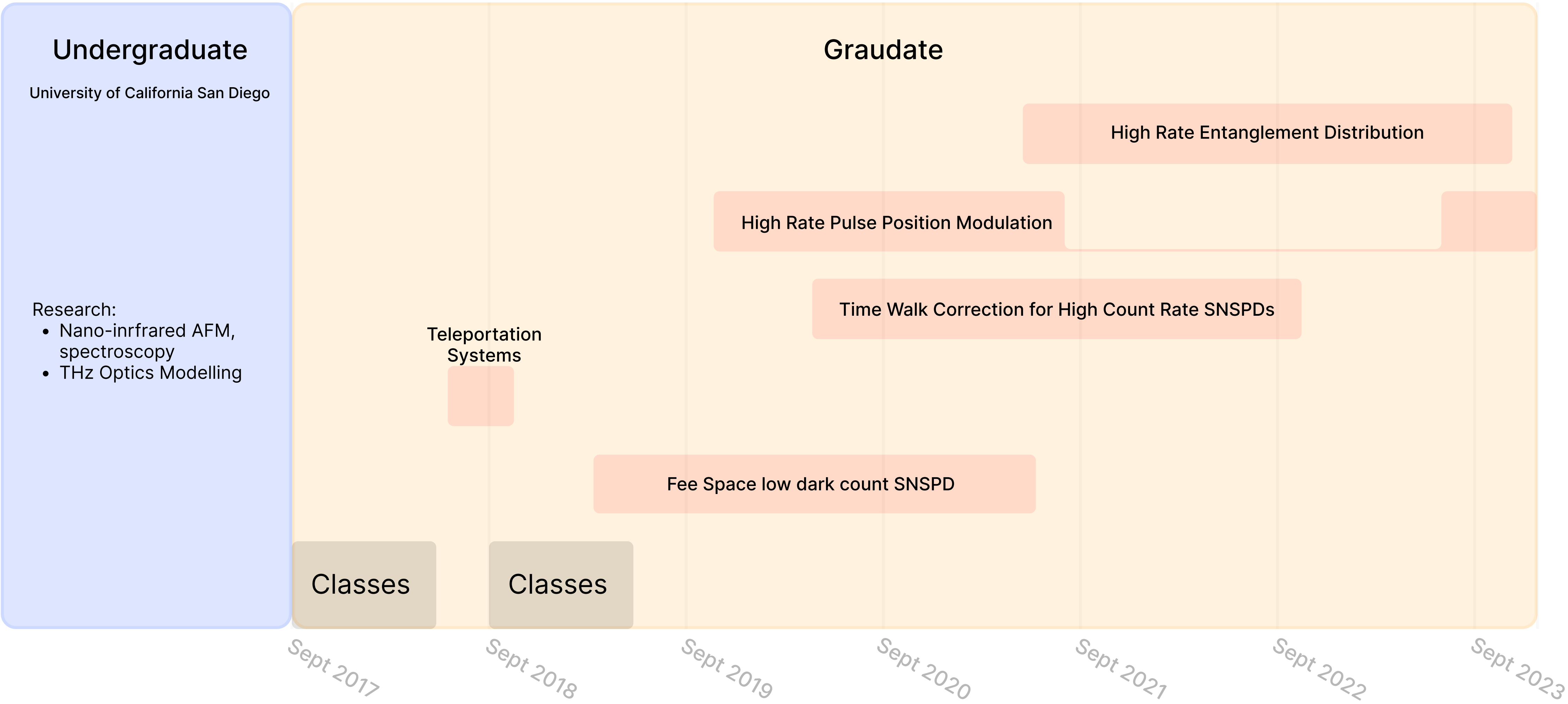


Physics World



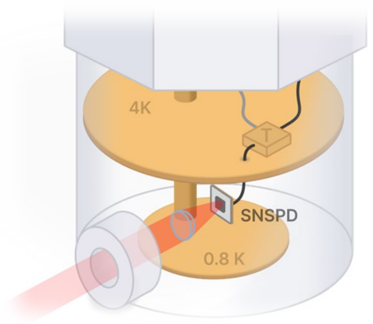
Quside

Timeline

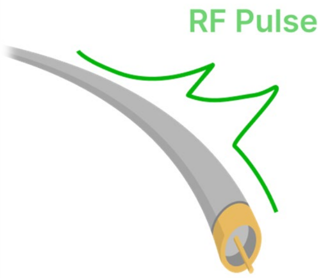

Undergraduate
University of California San Diego
Research:
• Nano-inrfrared AFM, spectroscopy
• THz Optics Modelling
Graudate
High Rate Entanglement Distribution
High Rate Pulse Position Modulation
Time Walk Correction for High Count Rate SNSPDs
Teleportation Systems
Fee Space low dark count SNSPD
Classes
Classes
Sept 2017
Sept 2018
Sept 2019
Sept 2020
Sept 2021
Sept 2022
Sept 2023

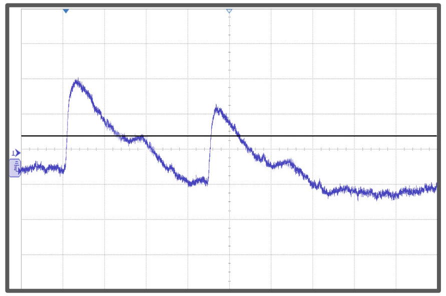
Outline

1. Low Dark Count Rate Free Space Coupled SNSPD

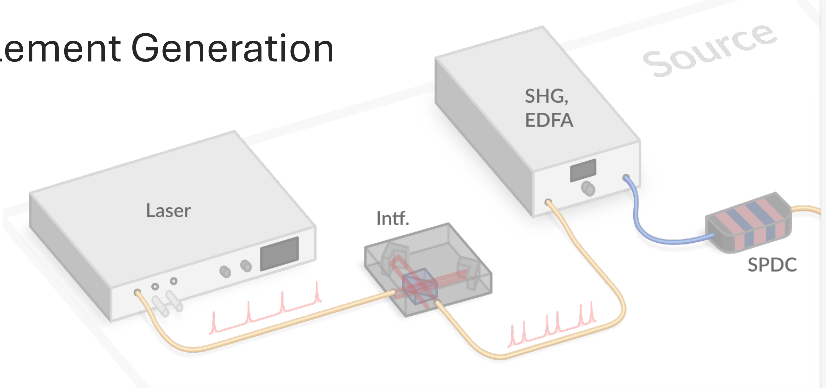


2. Time Walk Correction



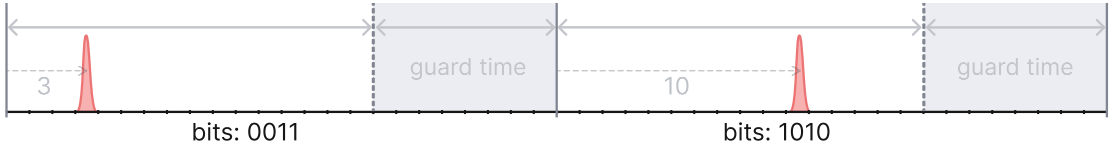


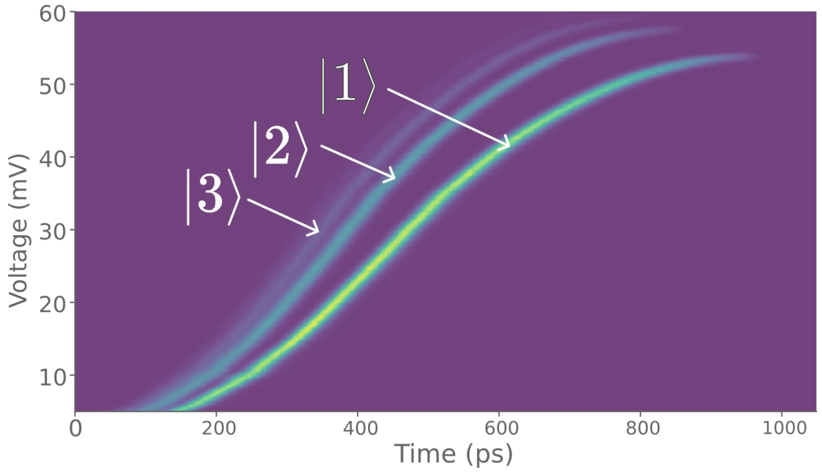
3. High-Rate Entanglement Generation



Aside: Phase Locked Loops

4. Pulse Position Modulation & Photon Number Resolution





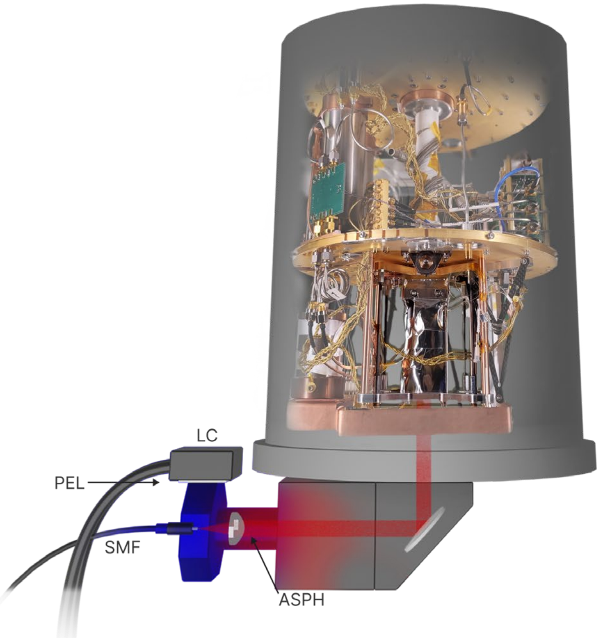
Conclusion & Outlook

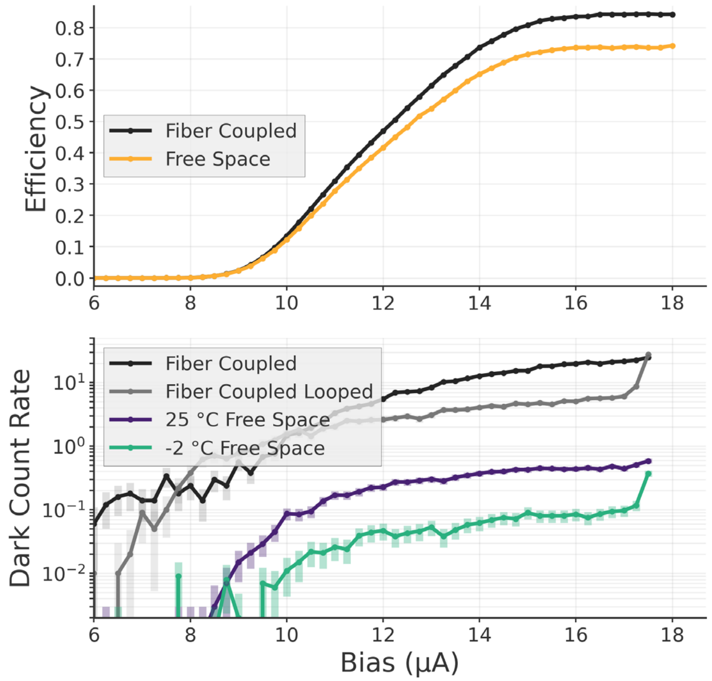
Achievement

- **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
  - Much more **practical** that other records





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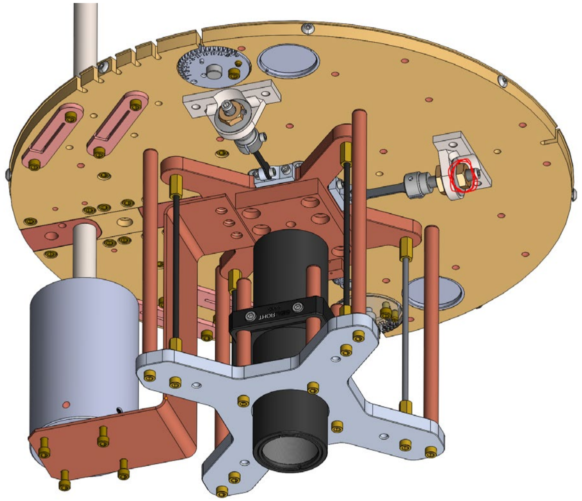
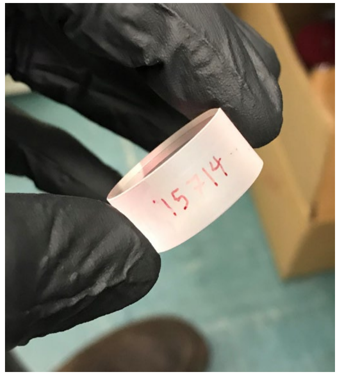
Free-space coupled superconducting nanowire single-photon detector with low dark counts

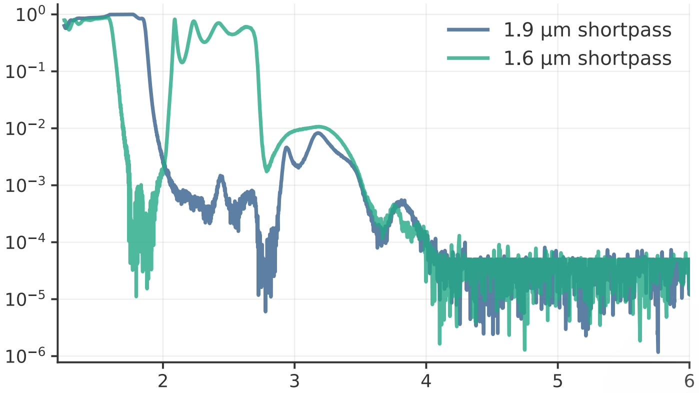
Andrew S. Mueller, Boris Korzh, Marcus Runyan, Emma E. Wollman, Andrew D. Beyer, Jason P. Allmaras, Angel E. Velasco, Ioana Craiciu, Bruce Bumble, Ryan M. Briggs, Lautaro Narvaez, Cristián Peña, Maria Spiropulu, and Matthew D. Shaw

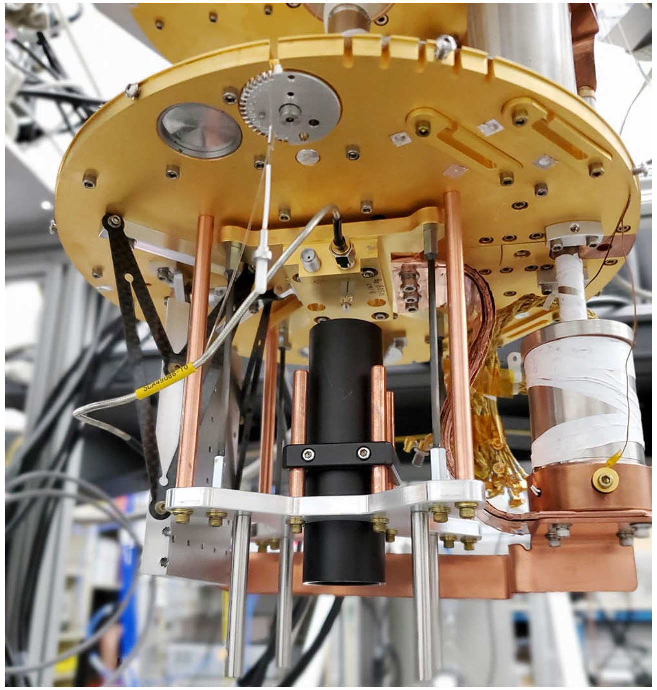
Filtering & Design

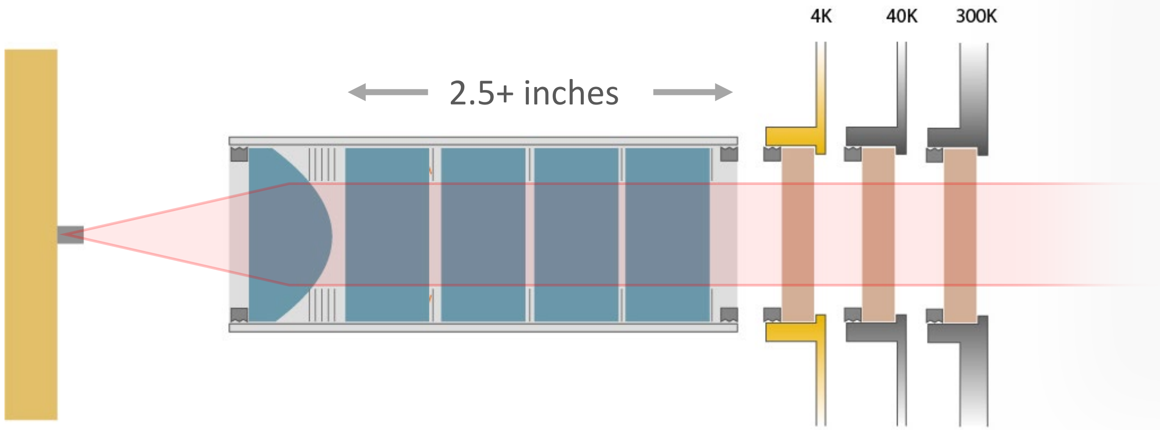
- custom short pass filters (andover corp.)
  - 1.6 & 1.9 μm cutoff
  - Attenuate mid-IR with thick BK7 substrate & coatings
  - 98.8 +/- 0.3 % transmission at 1550 nm
  - 12 mm thick





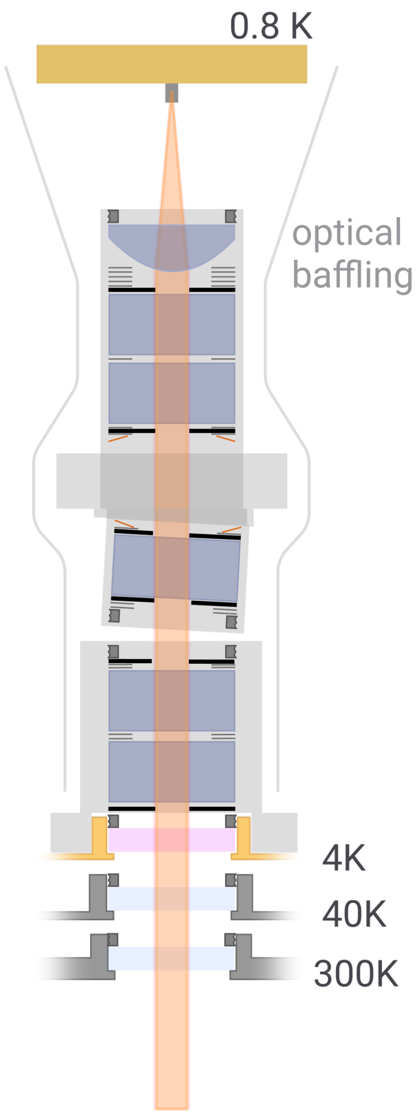




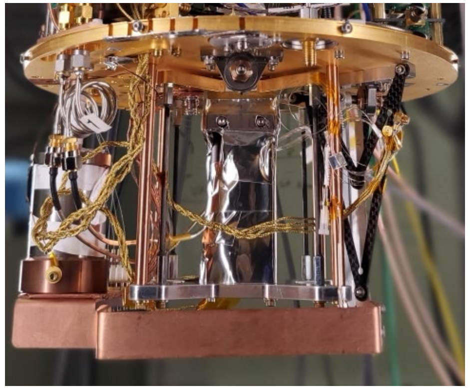


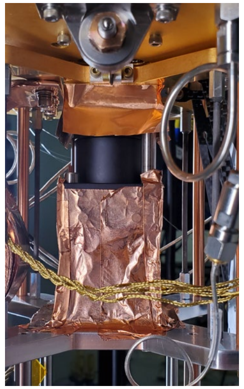
Cryo-lens enables:
- Small detector
- Low jitter

System Design



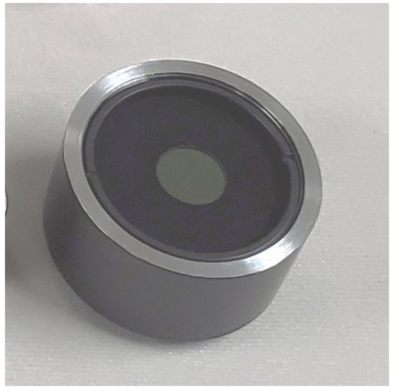
1. Optical baffling





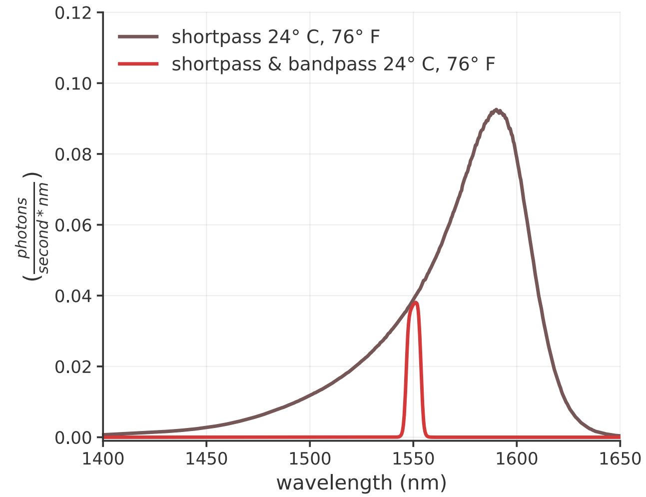
2. Apertures

Custom 8mm, Acktar spectral black material



3. 1550 nm bandpass filter

8 nm FWHM – ideal for fast wide-bandwidth pulses

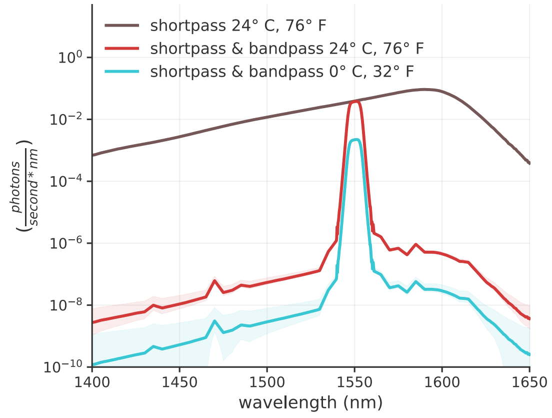


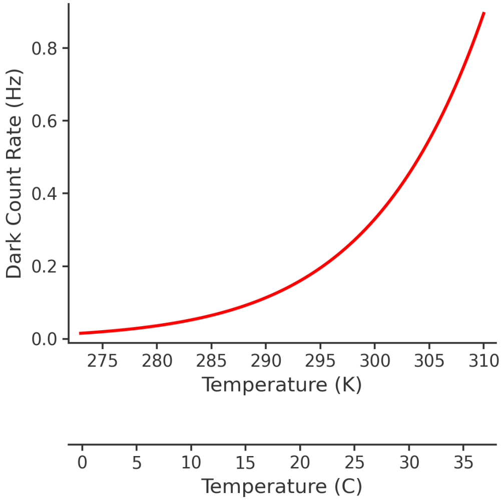
4. Painted radiation shield

Aeroglaze Z306 high mid-IR absorption

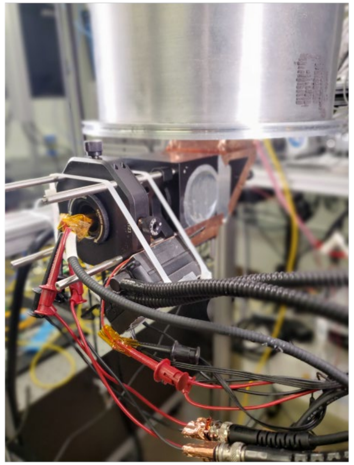
Results & Cooling

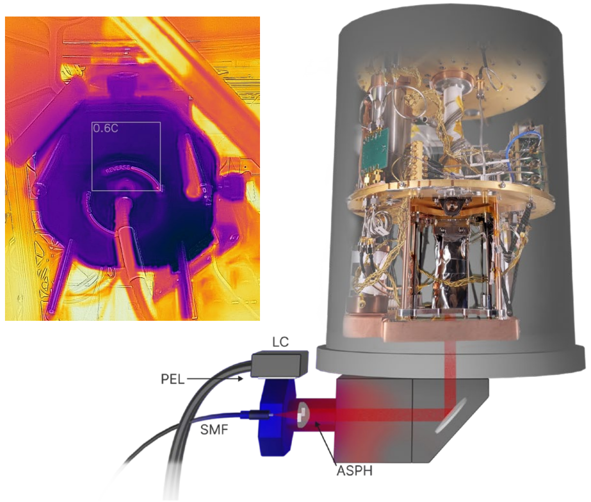
Strong dependence of **room temperature** on **dark count rate**

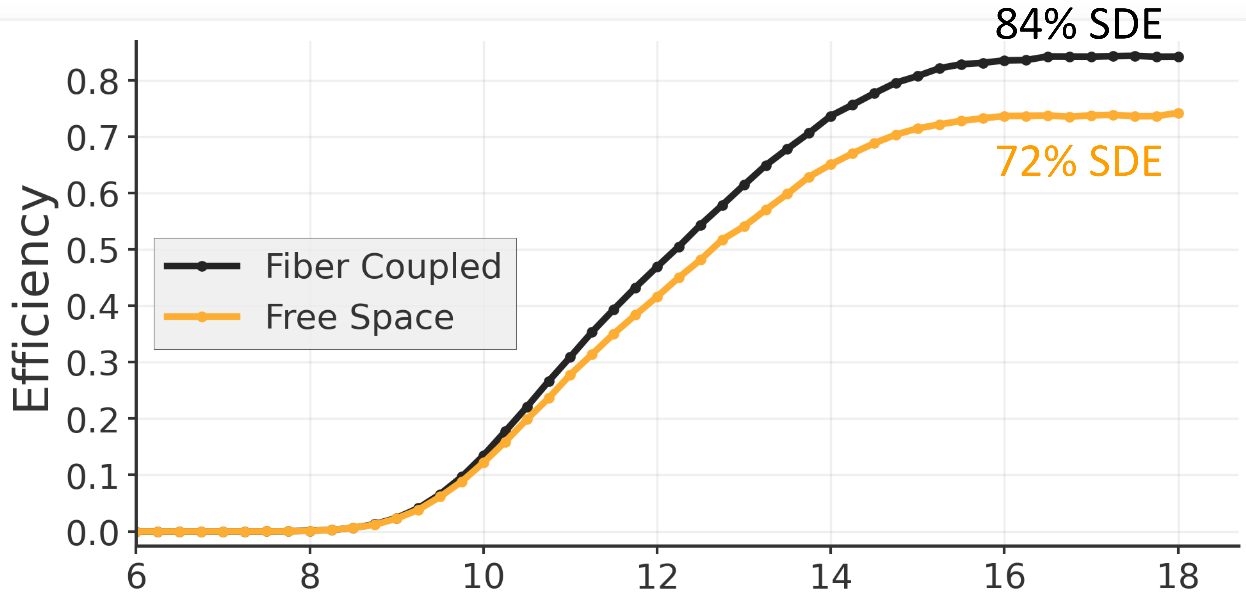


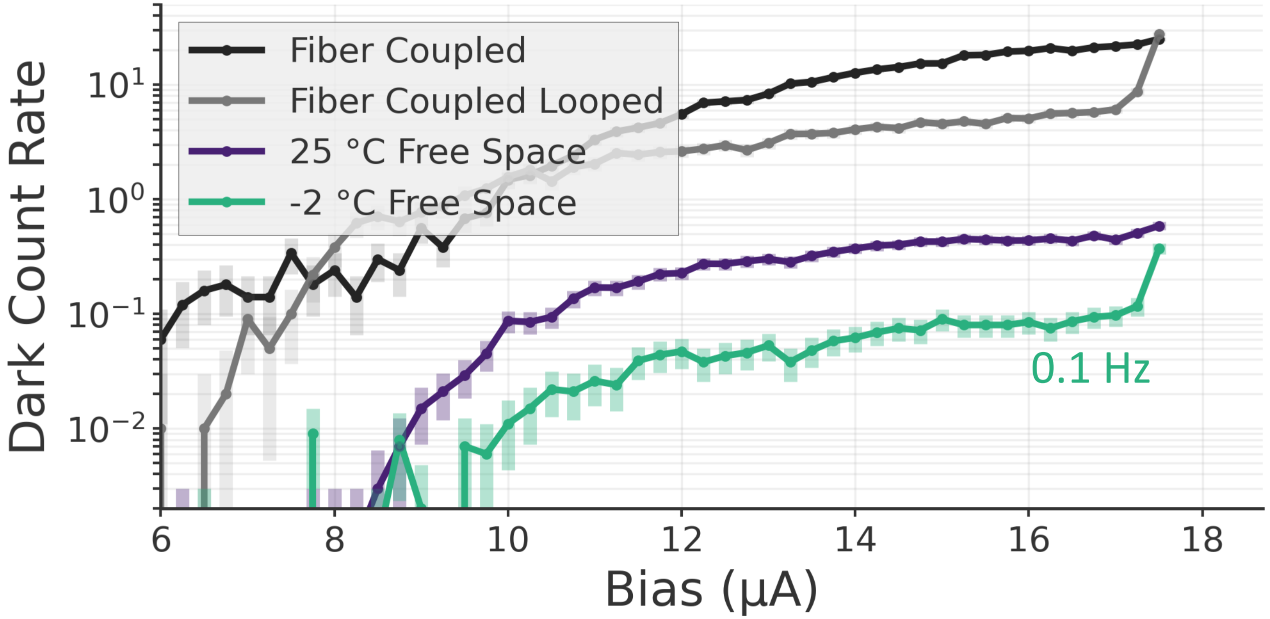


Apply mild cooling to surface imaged onto detector



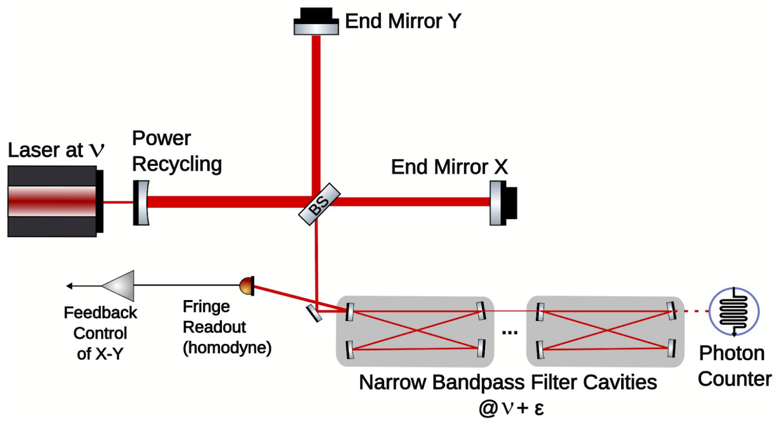






Outlook

Gravity from Quantum Entanglement of Space-Time (GQuEST)



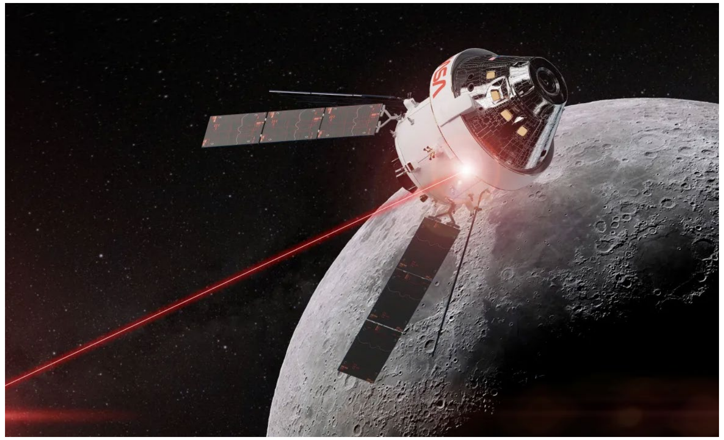
GQuEST

- 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

Lee McCuller

Fermilab Caltech

Optical to Orion (O2O) ground terminal



- Similar optical coupling & cryostat design

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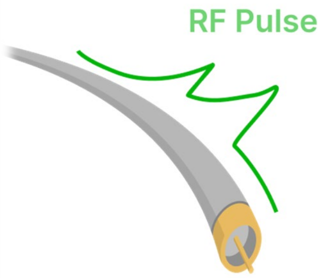
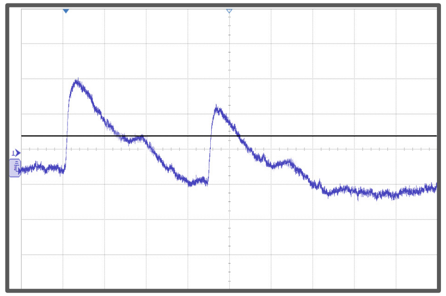
1. Low Dark Count Rate Free Space Coupled SNSPD

2. Time Walk Correction





3. High-Rate Entanglement Generation

Aside: Phase Locked Loops

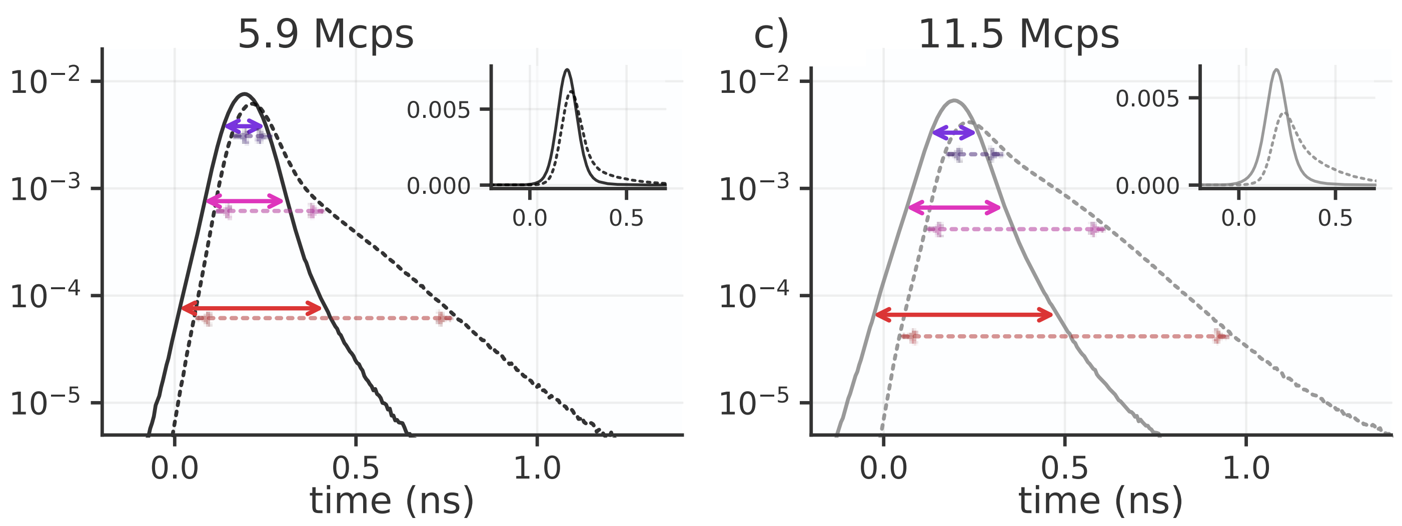
4. Pulse Position Modulation

Conclusion & Outlook

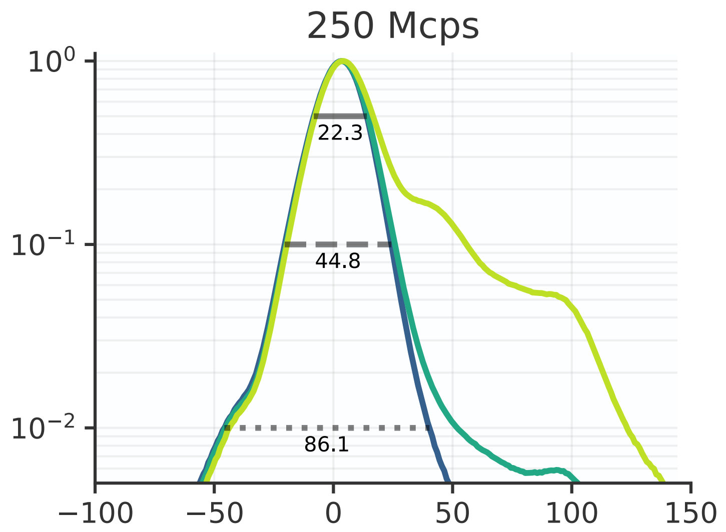
Achievement

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

Check for updates

+ Author & Article Information

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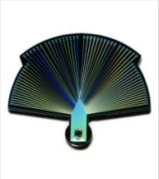
https://doi.org/10.1063/5.0129147 Article history

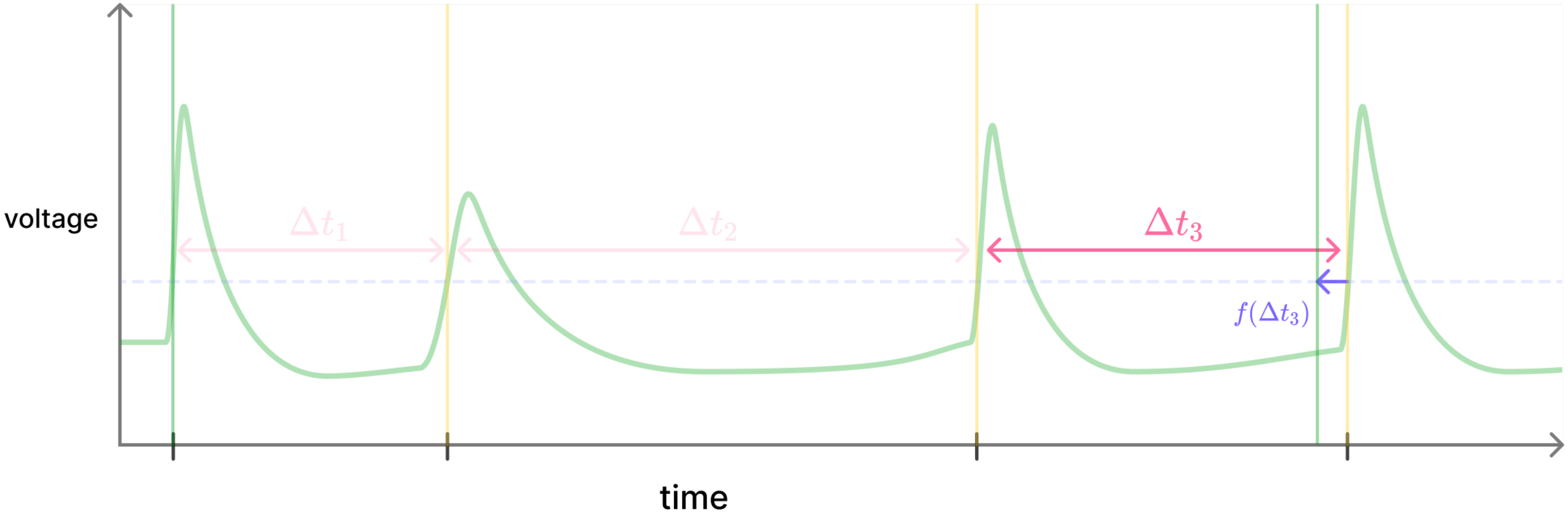
Optica Vol. 10, Issue 2, pp. 183-190 (2023) • https://doi.org/10.1364/OPTICA.478960



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

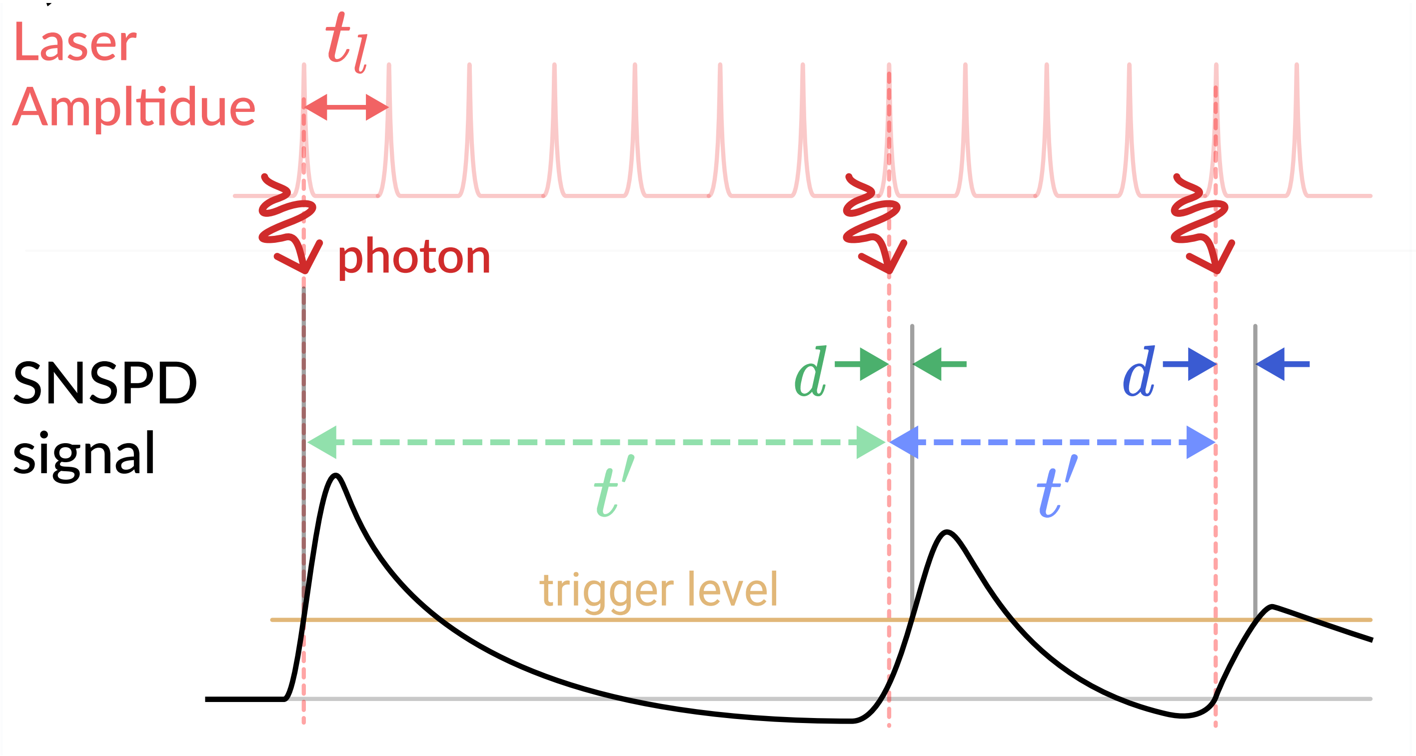
Ioana Craiciu, Boris Korzh, Andrew D. Beyer, Andrew Mueller, Jason P. Allmaras, Lautaro Narváez, Maria Spiropulu, Bruce Bumble, Thomas Lehner, Emma E. Wollman, and Matthew D. Shaw

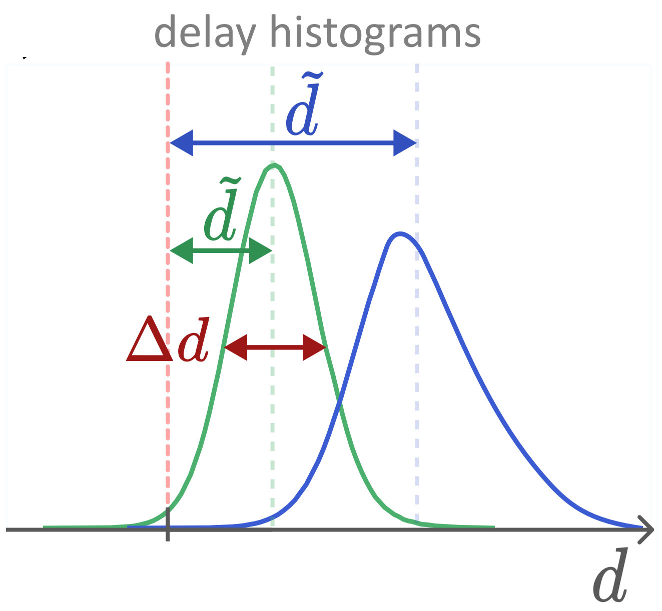
Photon Arrival time & Histograms

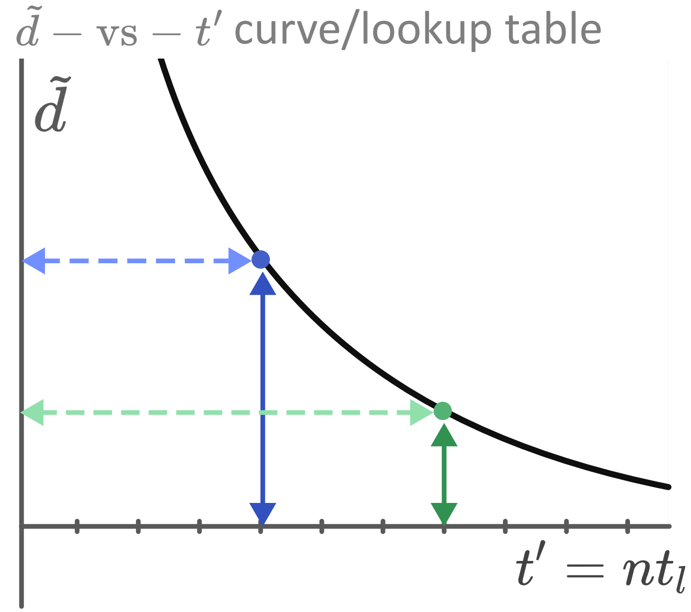


Calibration: Delays from Δt

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

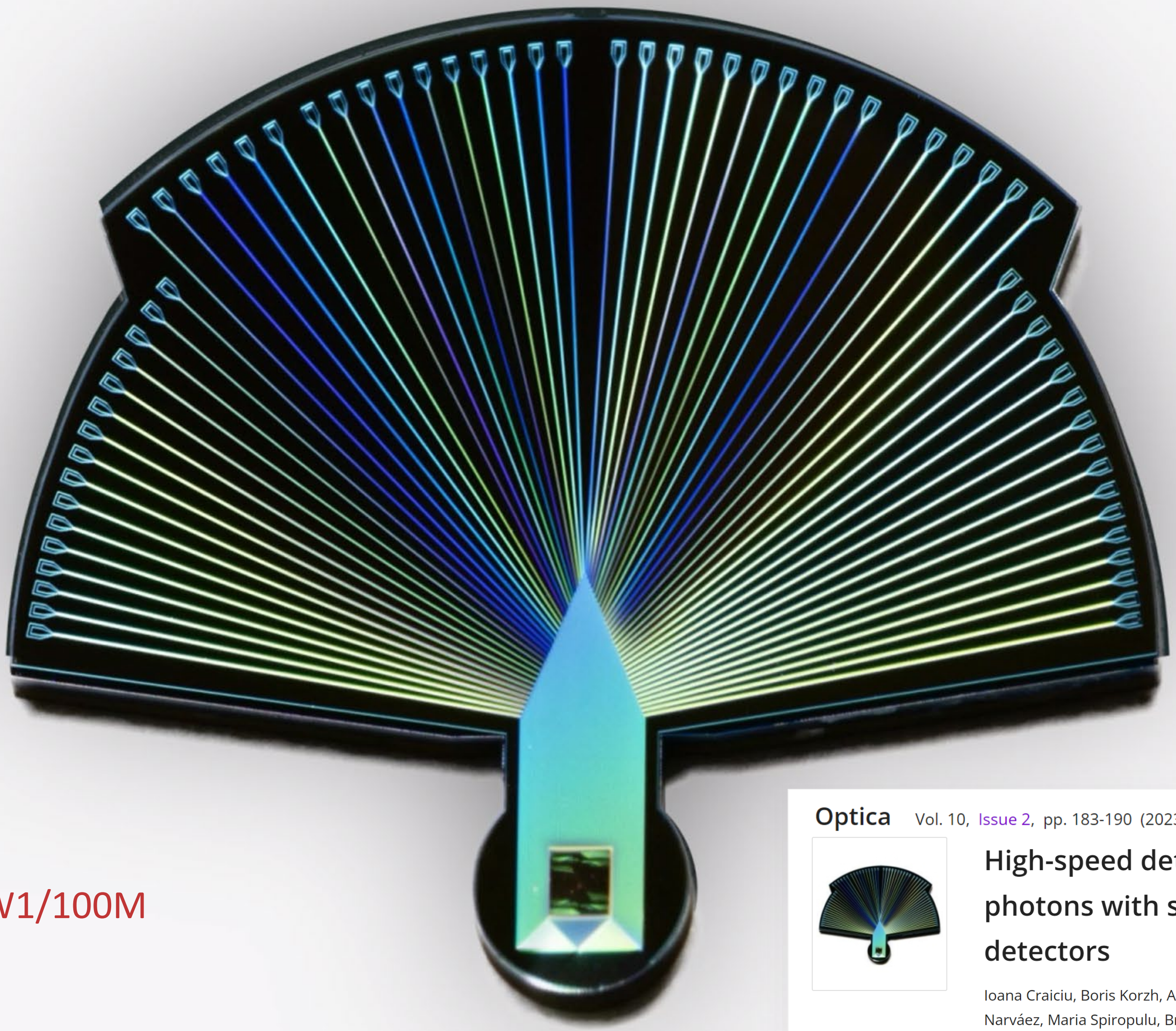






Performance **E**nhanced **A**rray for **C**ounting **O**ptical **Q**uanta (**PEACOQ**)

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



- 250 Mcps with 86 ps FW1/100M

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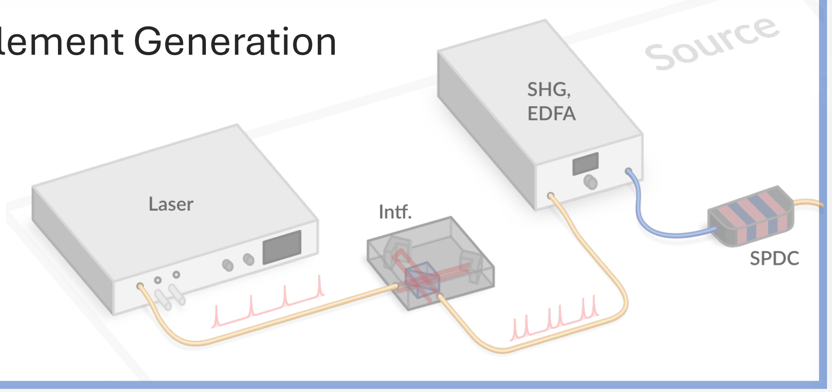
2. Time Walk Correction

3. High-Rate Entanglement Generation



Aside: Phase Locked Loops

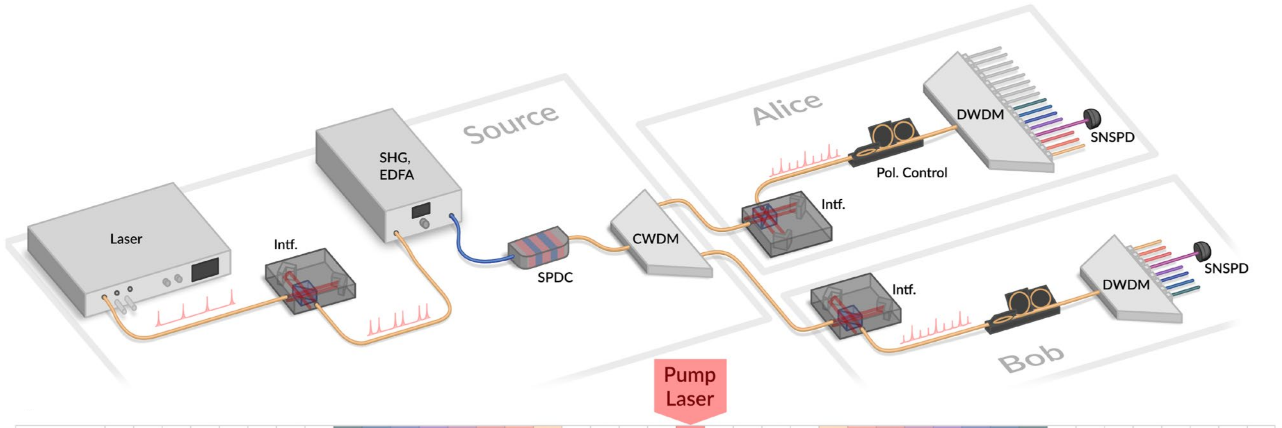
4. Pulse Position Modulation & Photon Number Resolution

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



ITU Channel	27	28	29	30	31	32	33	34	35	36	37	38	39	40
Wavelength (nm)	1555.75	1554.94	1554.13	1553.33	1552.52	1551.72	1550.92	1550.12	1549.32	1548.51	1547.72	1546.92	15546.12	15545.32

ITU Channel	41	42	43	44	45	46	47	48	49	50	51	52	53	54
Wavelength (nm)	1544.53	1543.73	1542.94	1542.14	1541.35	1540.56	1539.77	1538.98	1538.19	1537.40	1536.61	1535.82	1535.04	1534.25

ITU Channel	55	56	57	58	59	60	61	62	63	64	65	66	67
Wavelength (nm)	1533.47	1532.68	1531.90	1531.12	1530.33	1529.55	1528.77	1527.99	1527.22	1526.44	1525.66	1524.89	1524.11

16 ch. DWDM

8 ch. DWDM

Under review at **Optica Quantum**

arXiv > quant-ph > arXiv:2310.01804

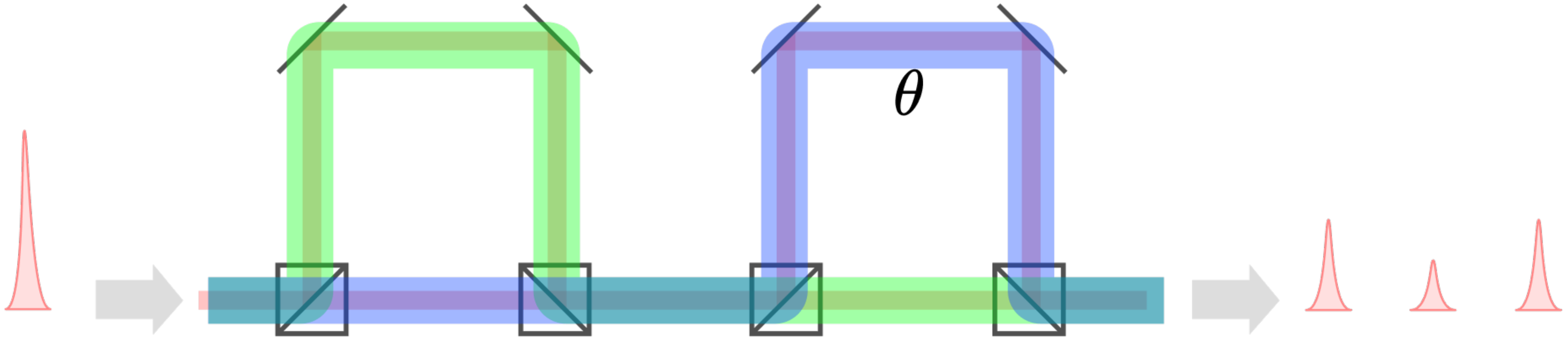
Quantum Physics

[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

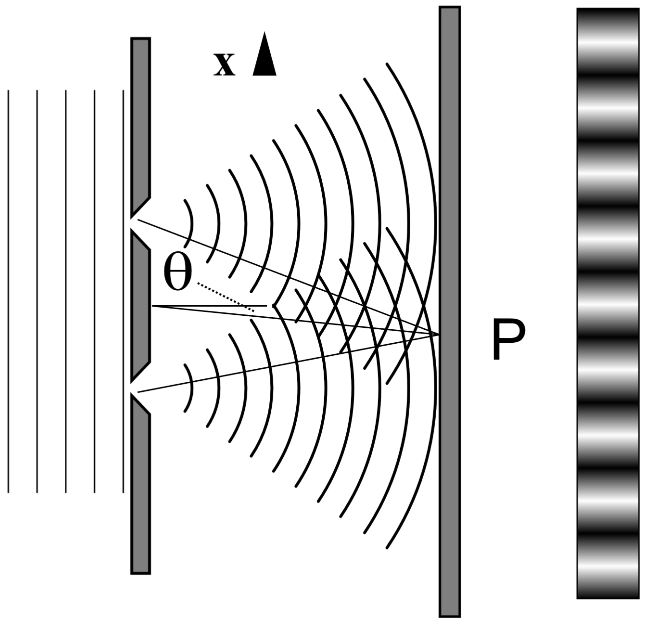
Superposition & Entanglement



Interference between the photon taking the green and blue path

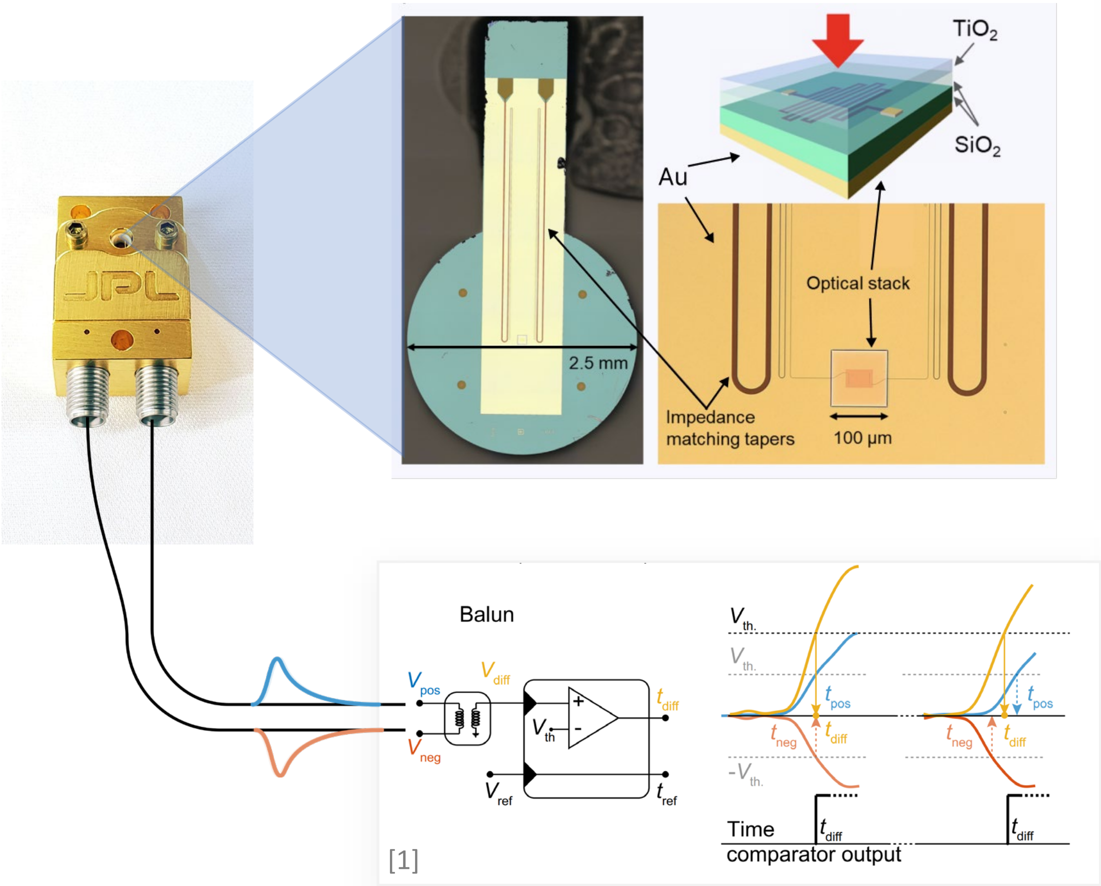
double slit experiment

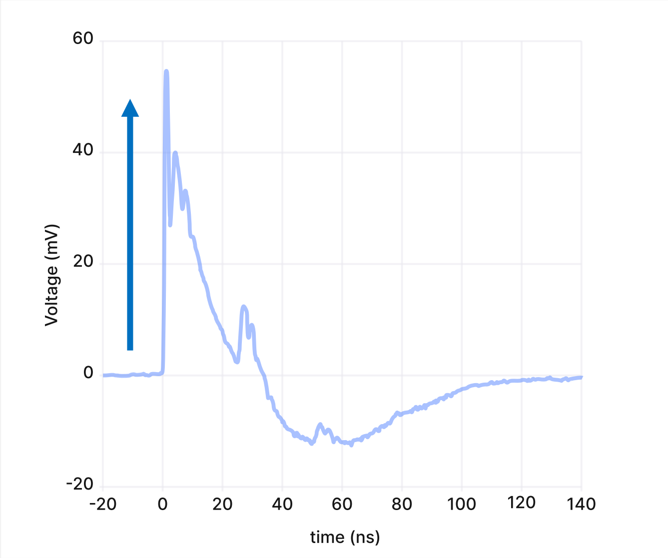
- **interference** between traversal of upper and lower slit

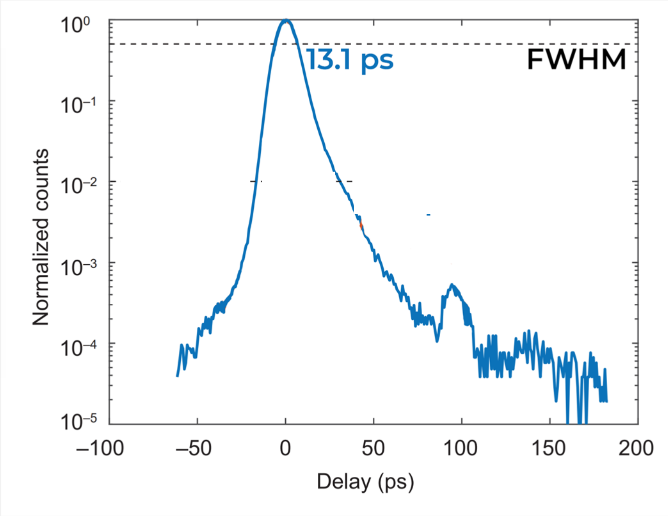


Differential Single Pixel

- Impedance matching tapers **increase pulse height and rise time**
- Differential readout & balun **cancels geometric jitter**

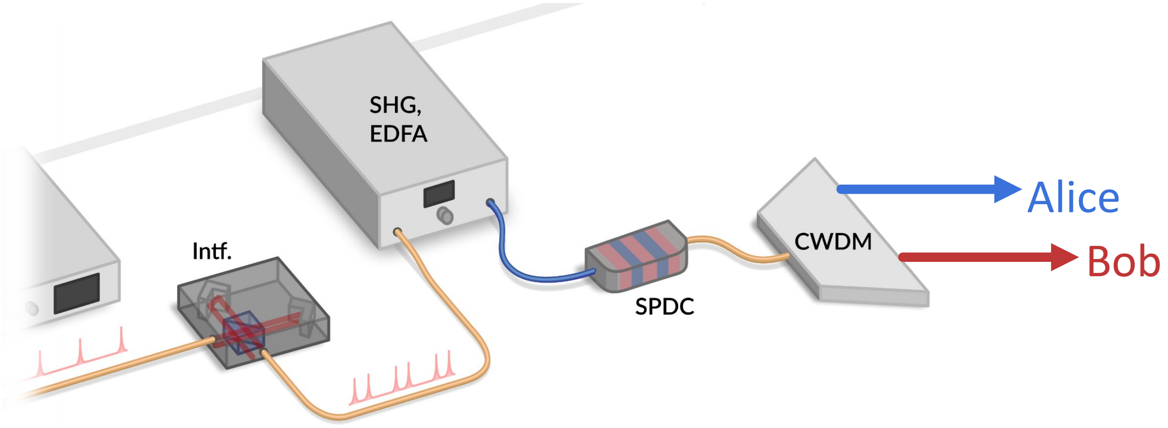






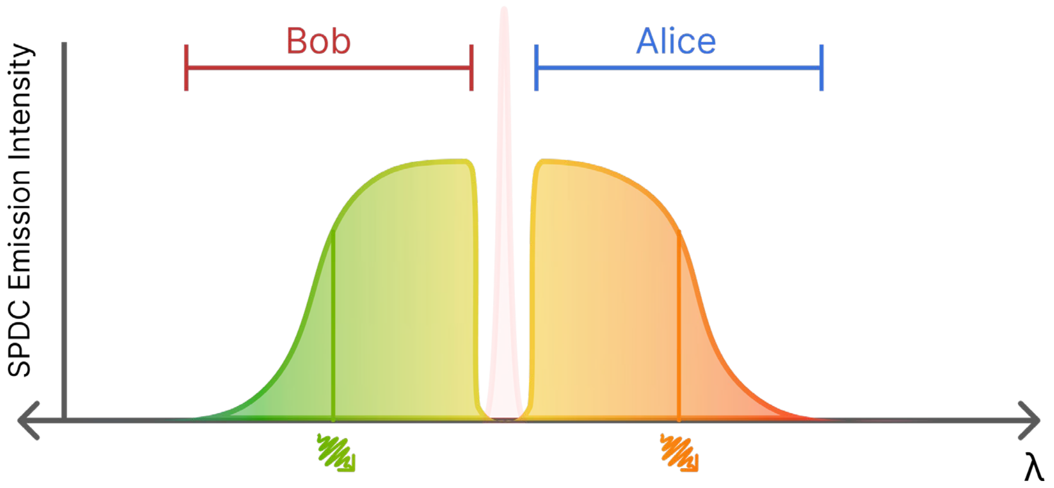
[1] Colangelo et al. 2023

Source



Entangled pairs obey **energy conservation**

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



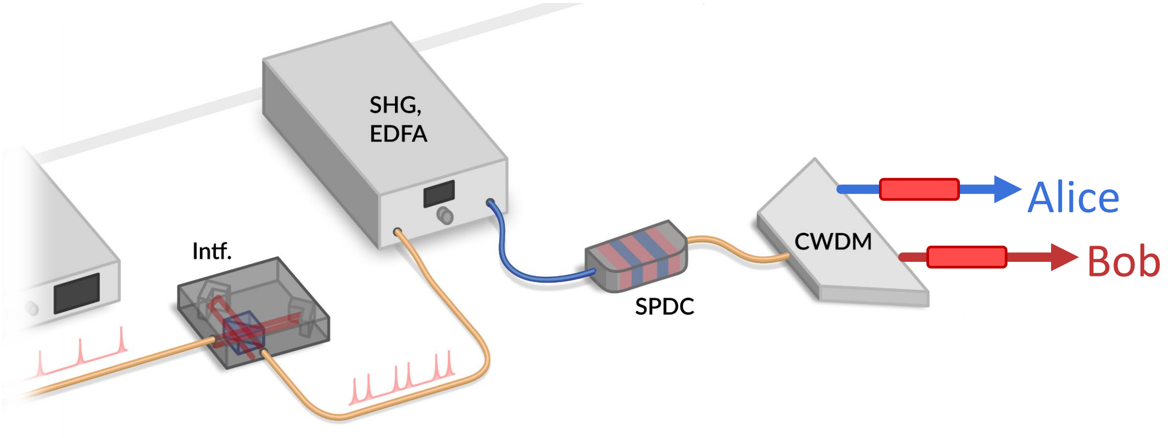
80 ps delay line interferometers

- 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**

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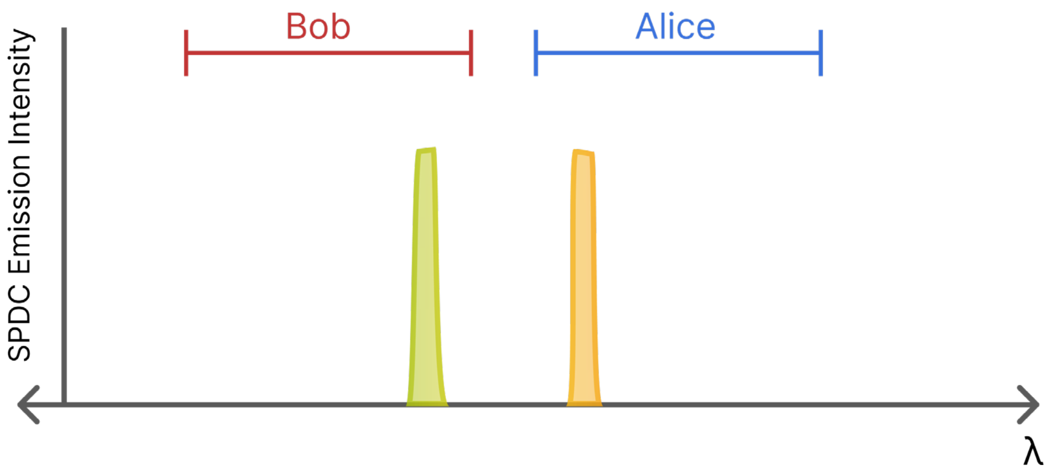
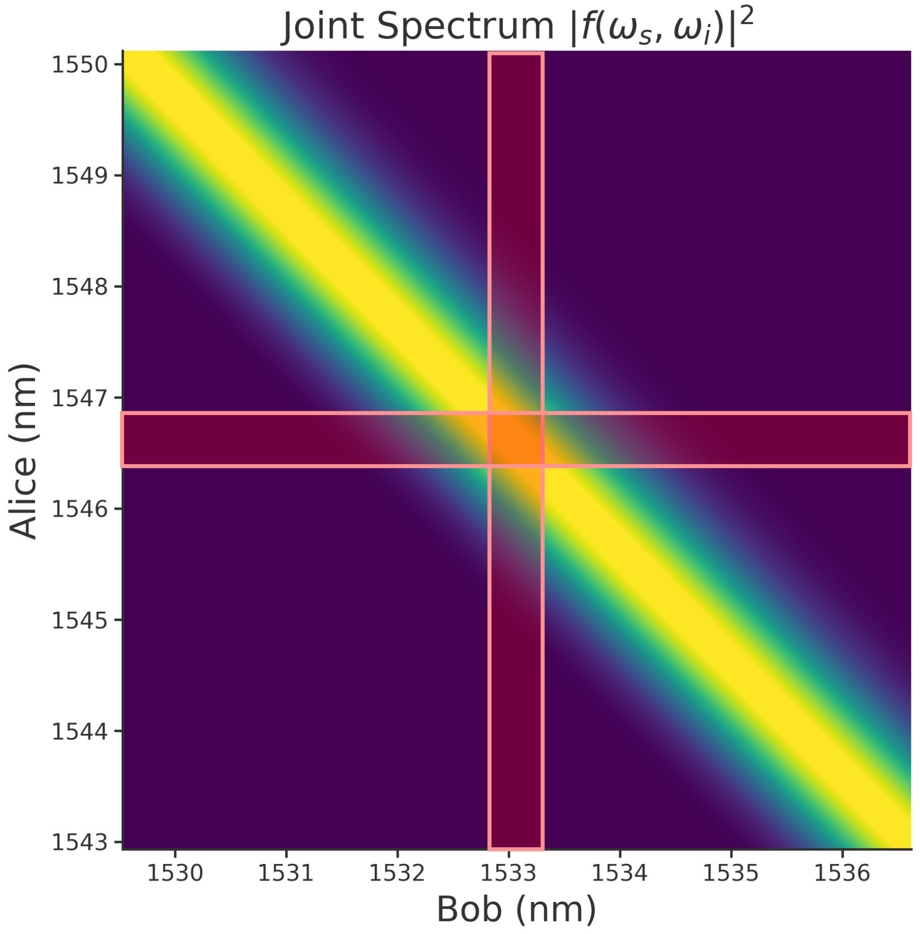


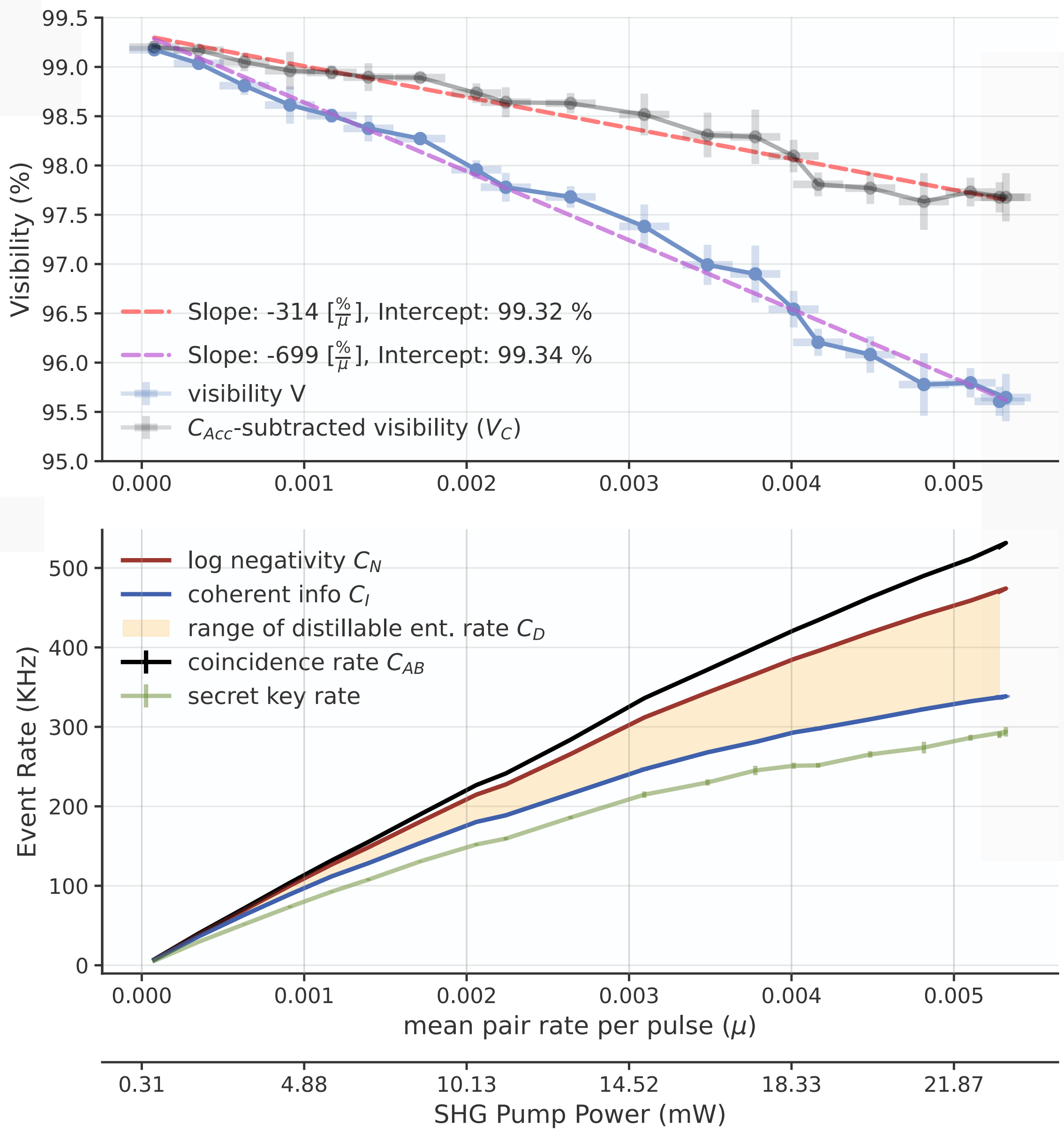


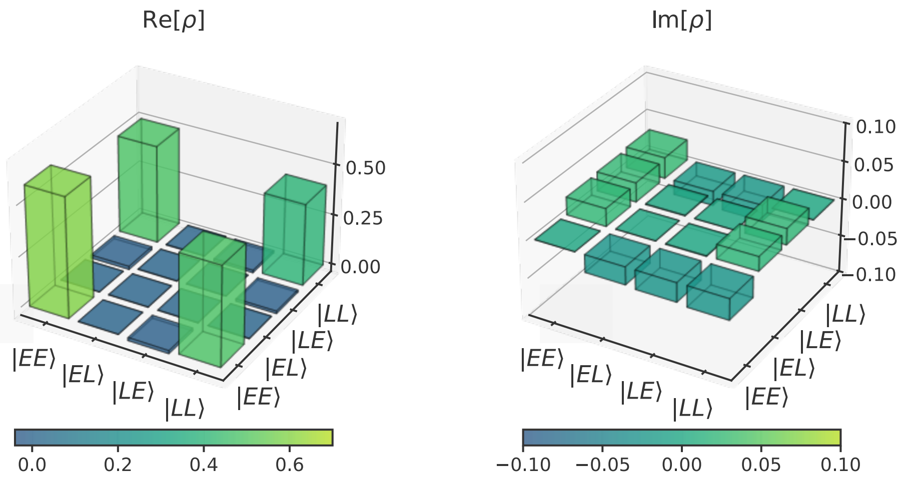
$$|f(\omega_s, \omega_i)|^2 = |\psi_{\mathrm{ph}}(\omega_s, \omega_i)|^2 * |\psi_p(\omega_s, \omega_i)|^2$$

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

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

Results



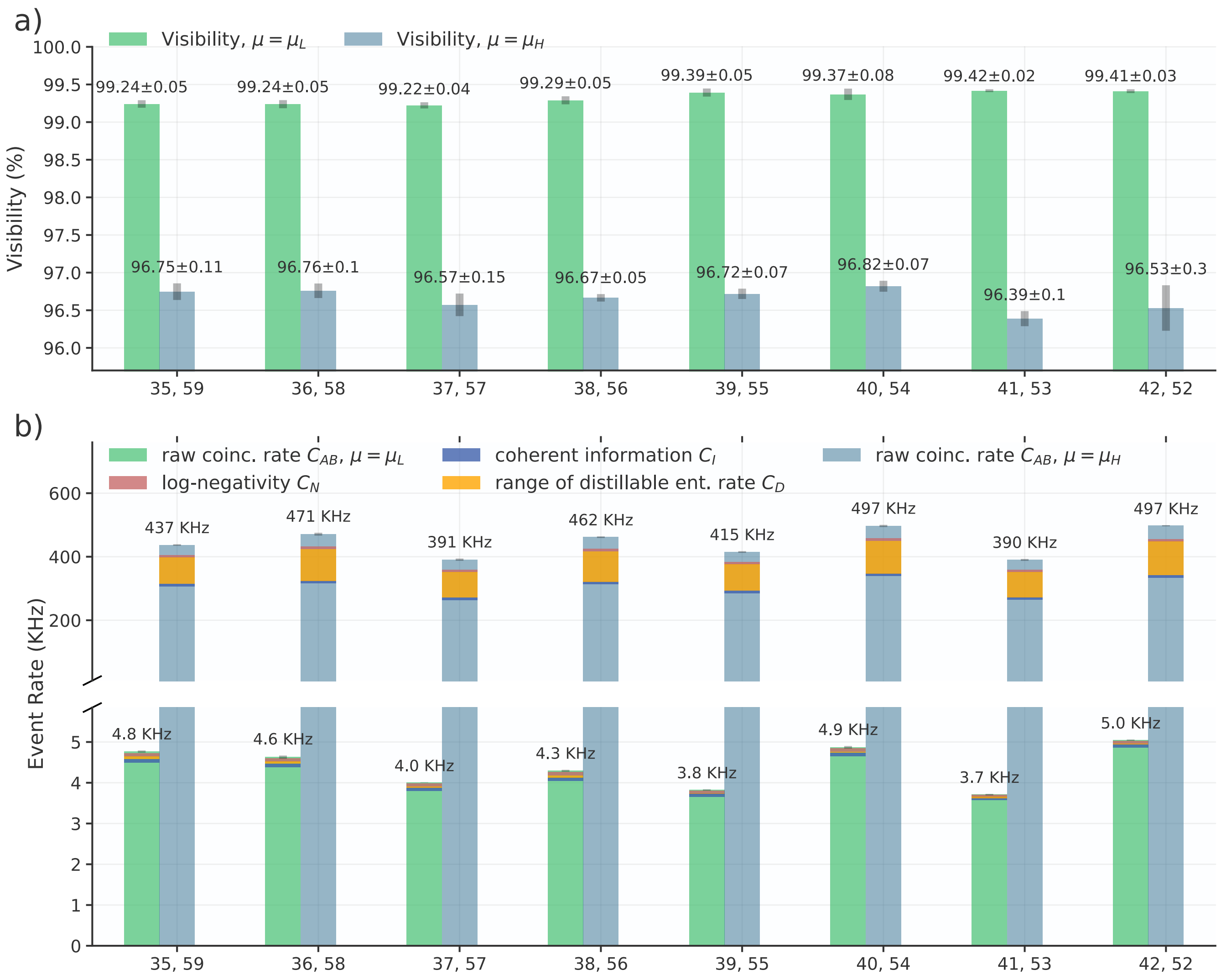


Distillable entanglement rate is bounded above by logarithmic negativity and below by coherent information

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

Coherent Information: $I_{A \to B} = H\left(\rho^{\mathrm{B}}\right) - H\left(\rho^{\mathrm{AB}}\right)$

Results



3.55e6 coincidences/s

Across 8 multiplexed pairs

Up to 99.3% entanglement visibility

At μ = 5.6e-5

2.46 – 3.25 Mebits/s

μ = 5.0e-3, V ≃ 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

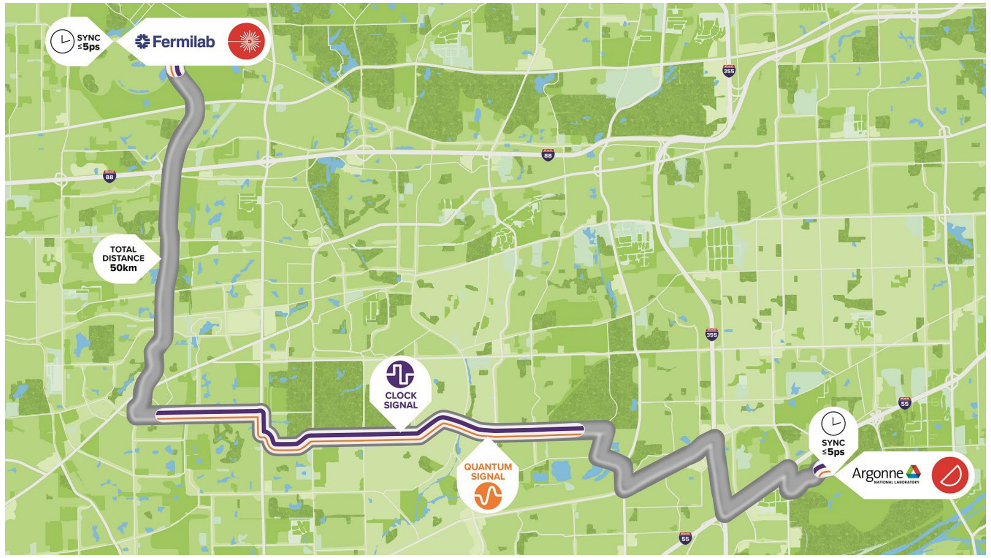
AUGUST 29, 2023

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

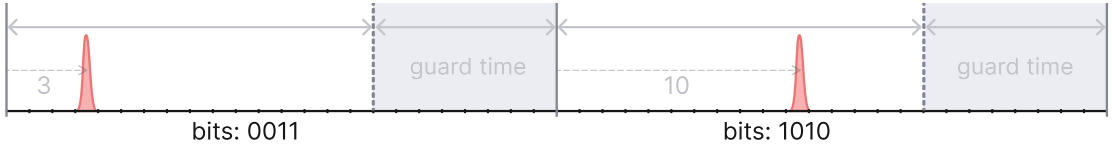
1. Low Dark Count Rate Free Space Coupled SNSPD

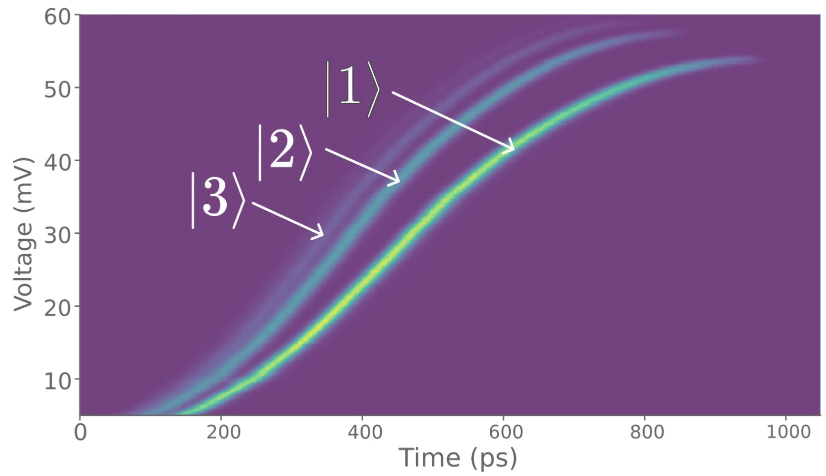
2. Time Walk Correction

3. High-Rate Entanglement Generation

Aside: Phase Locked Loops

4. Pulse Position Modulation & Photon Number Resolution



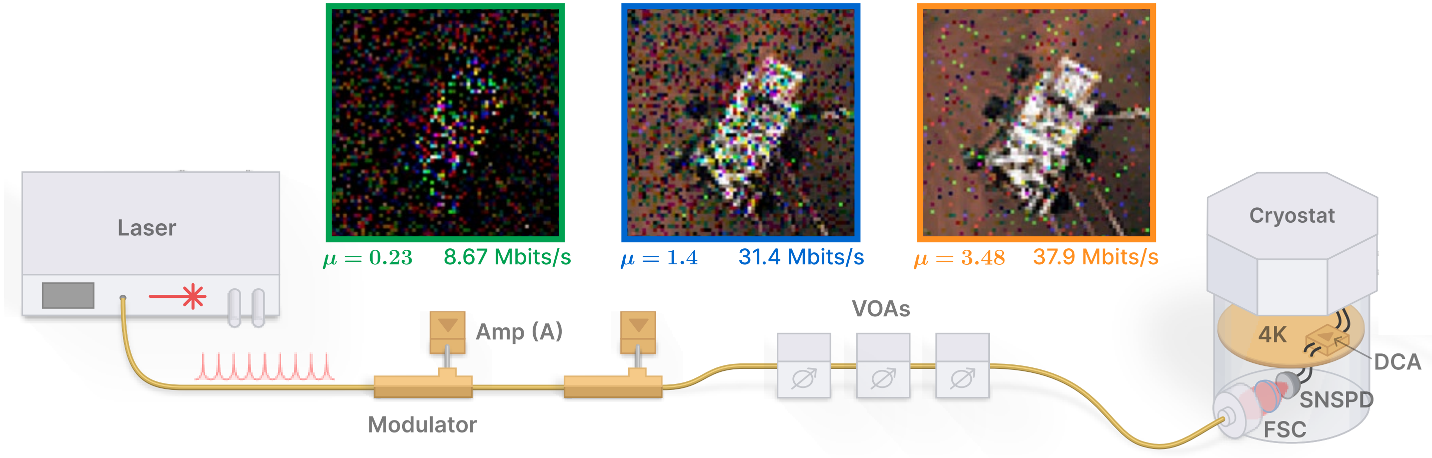


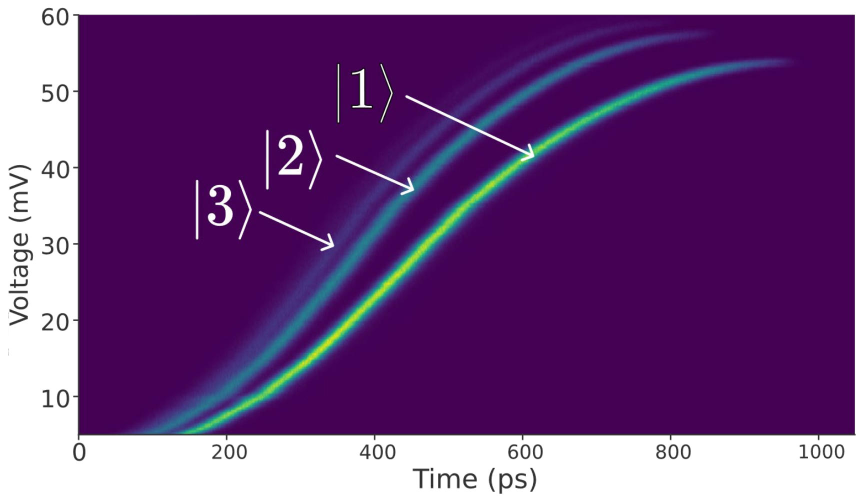
Conclusion & Outlook

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



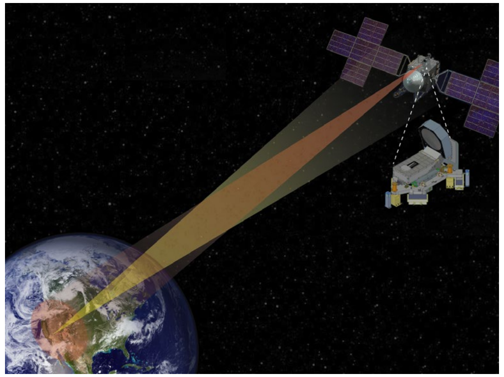


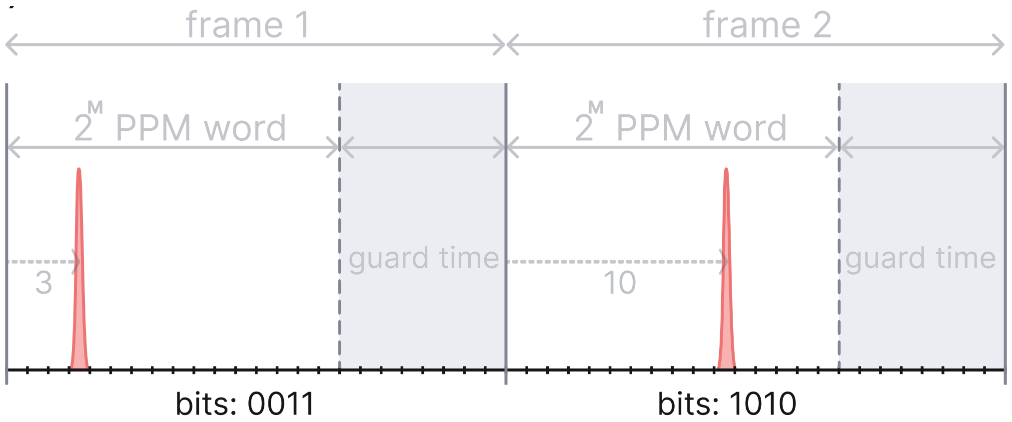
Manuscript in preparation for submission to Optics Express

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





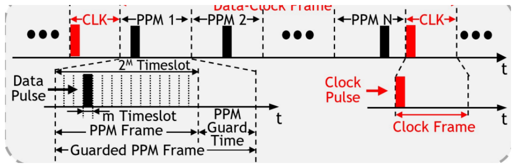
arXiv > quant-ph > arXiv:2310.02191

Quantum Physics

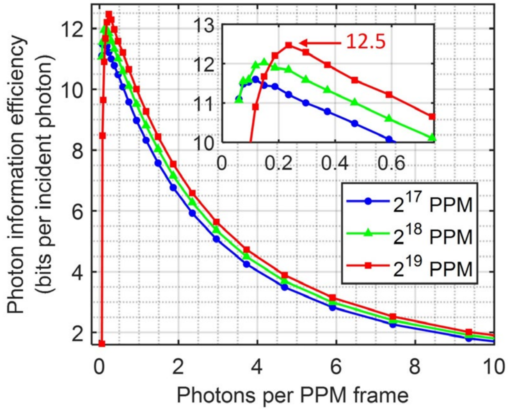
[Submitted on 3 Oct 2023]

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

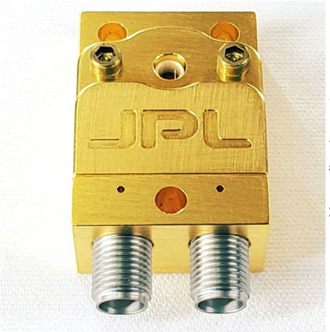


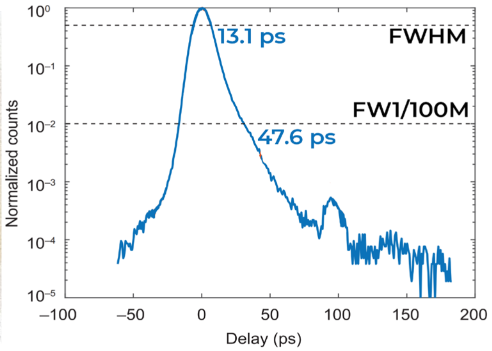
- M = 17, 18, **19**
- **> 500,000 time slots** to send 19 bits of data



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

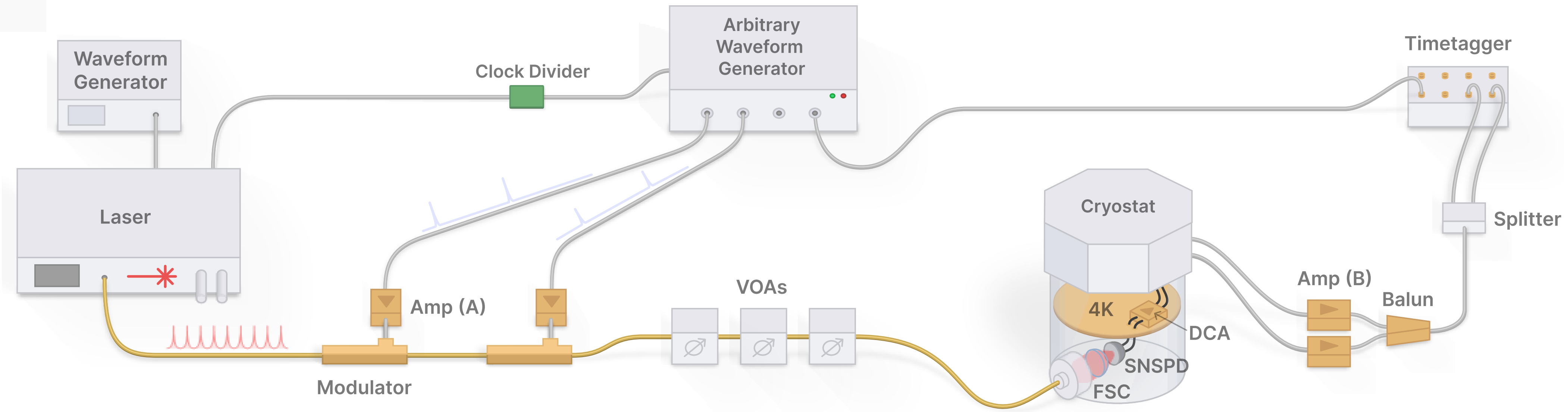
Low jitter enables higher rates





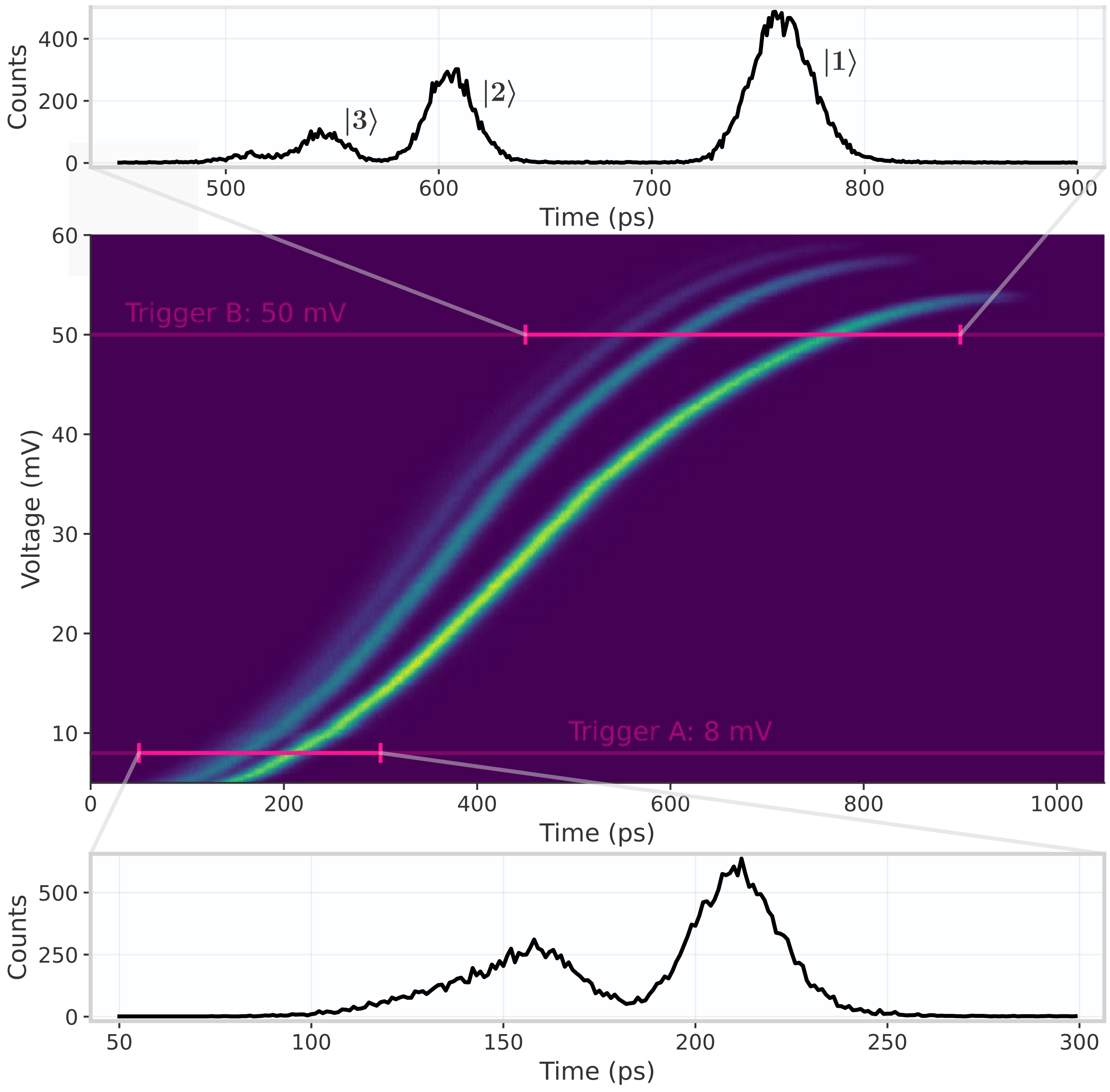
Plan
1. Demonstrate PPM at up to 20 GHz (50 ps bins)
2. Demonstrate large-M code words

PPM



Waveform Generator
Laser
Clock Divider
Arbitrary Waveform Generator
Timetagger
Amp (A)
Modulator
VOAs
Cryostat
4K
DCA
SNSPD
FSC
Splitter
Amp (B)
Balun

PPM



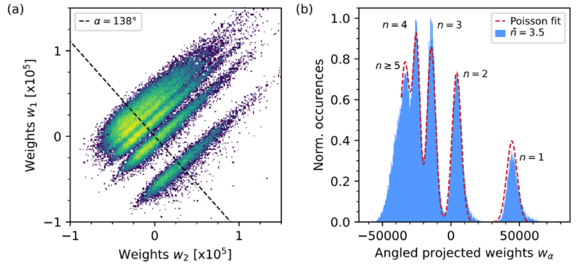
arXiv > quant-ph > arXiv:2310.12471

Quantum Physics

[Submitted on 19 Oct 2023 (v1), last revised 10 Nov 2023 (this version, v2)]

How well can superconducting nanowire single-photon detectors resolve photon number?

Timon Schapeler, Niklas Lamberty, Thomas Hummel, Fabian Schlue, Michael Stefszky, Benjamin Brecht, Christine Silberhorn, Tim J. Bartley



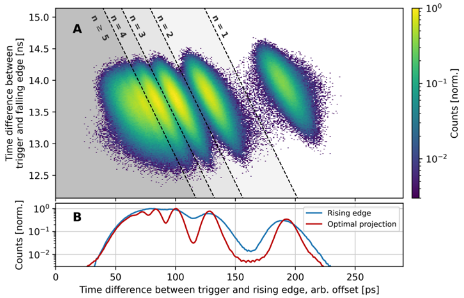
arXiv > quant-ph > arXiv:2310.12472

Quantum Physics

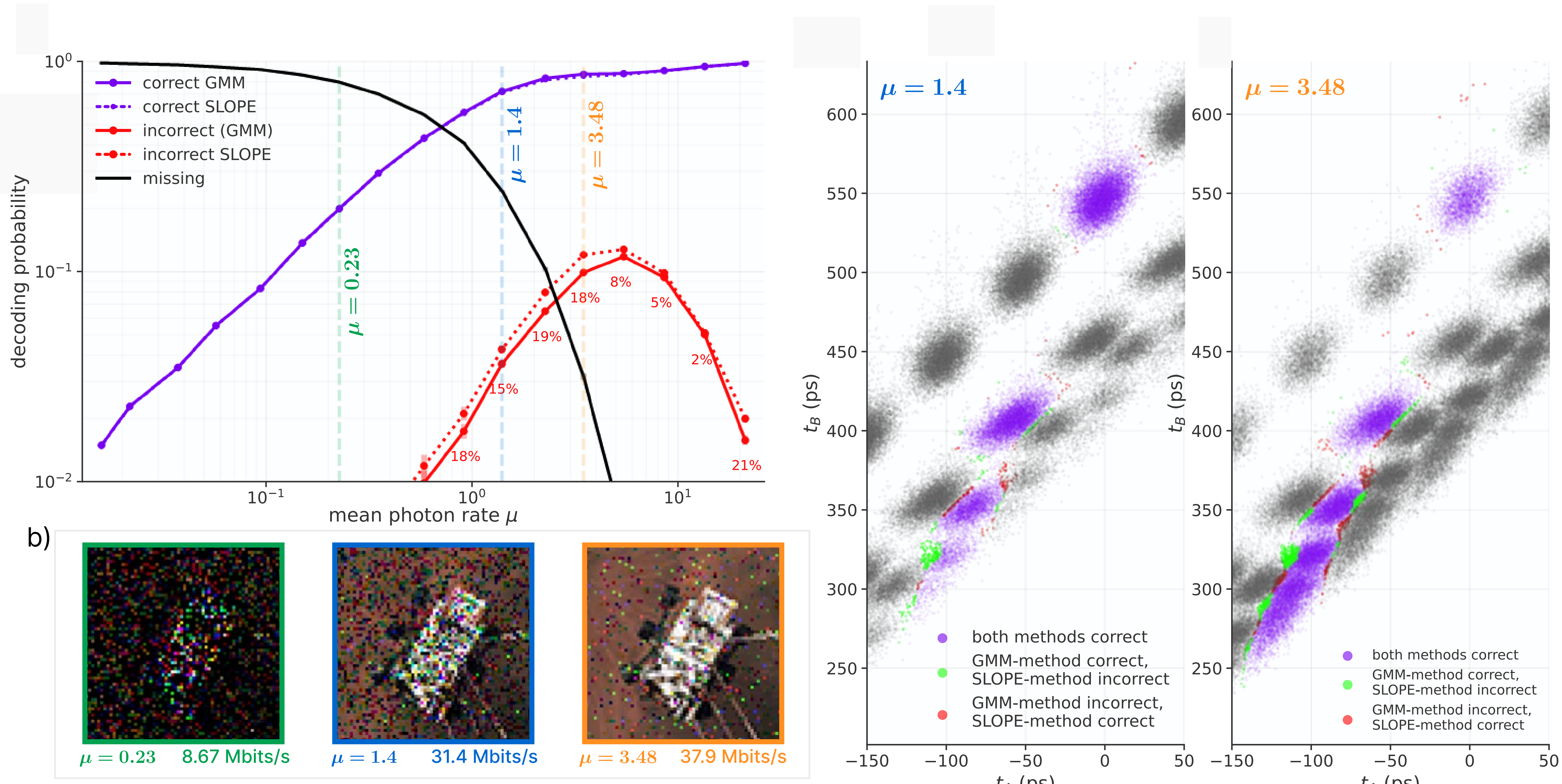
[Submitted on 19 Oct 2023]

Resolving Photon Numbers Using Ultra-High-Resolution Timing of a Single Low-Jitter Superconducting Nanowire Detector

Gregor Sauer, Mirco Kolarczik, Rodrigo Gomez, Johanna Conrad, Fabian Steinlechner



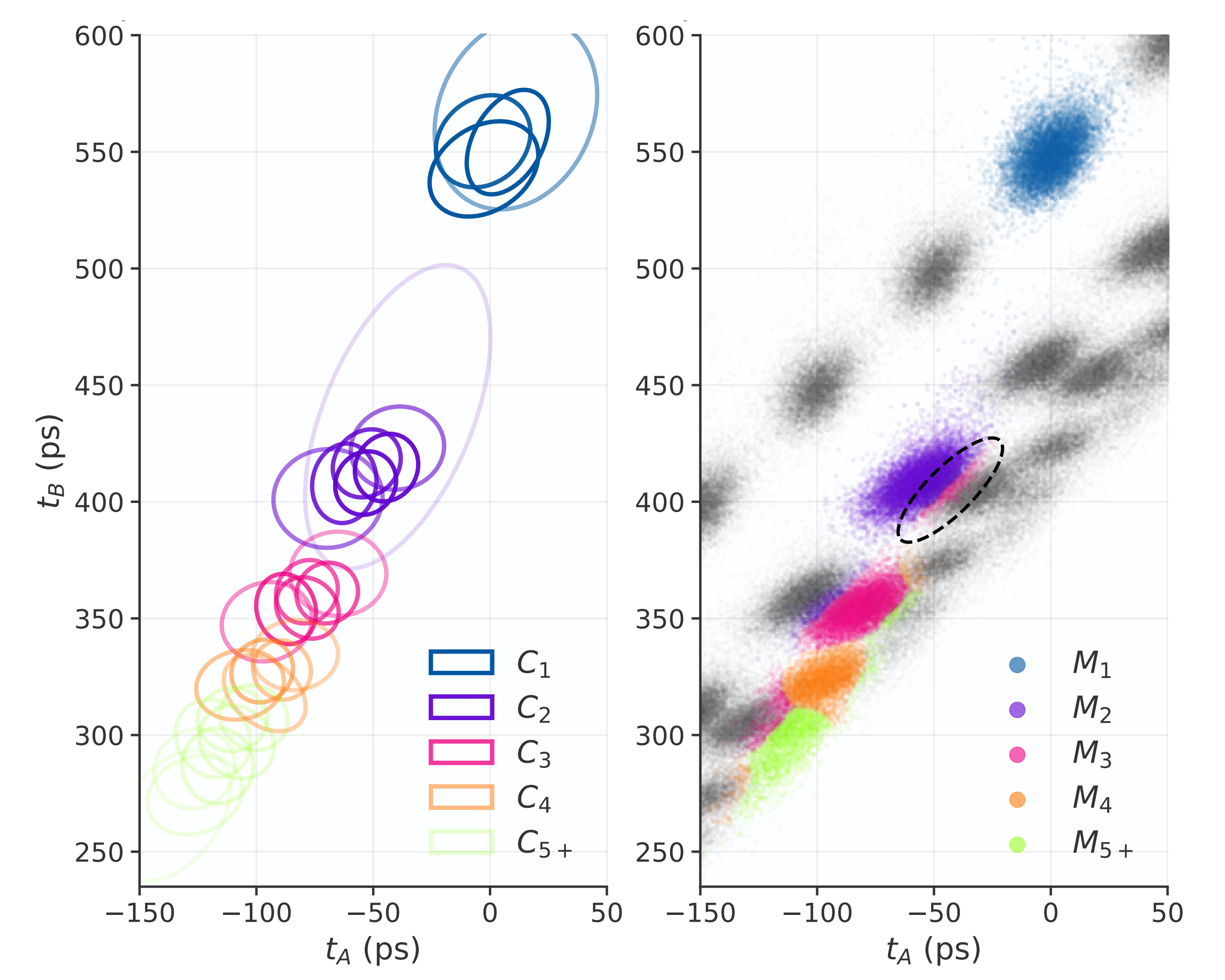
PPM

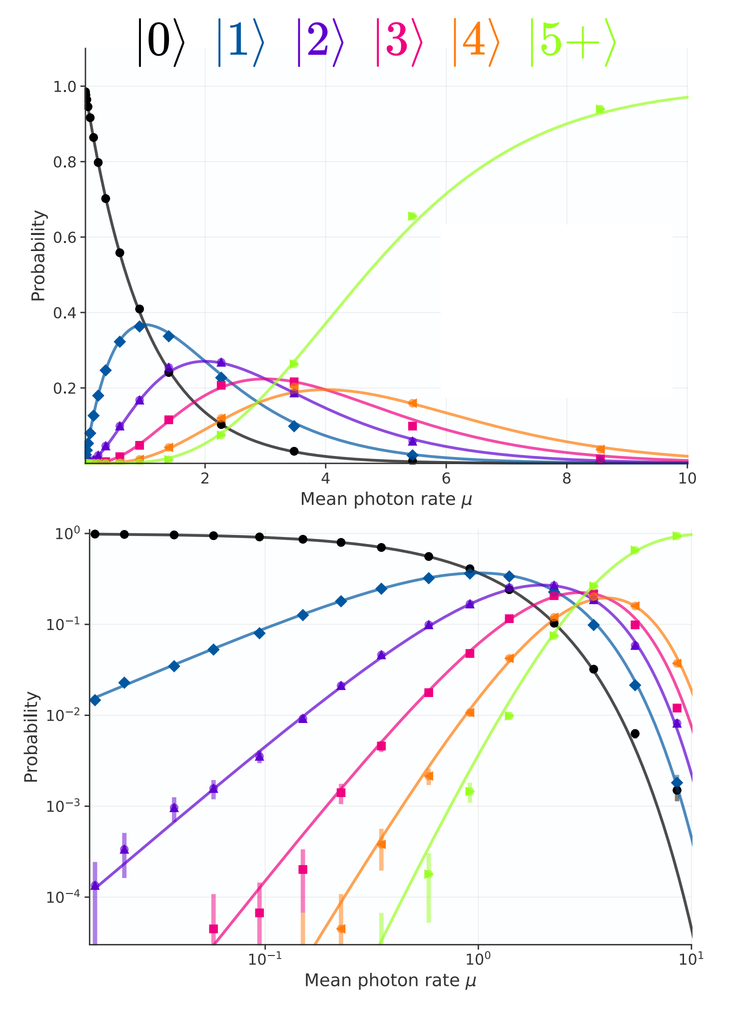


correct GMM
correct SLOPE
incorrect (GMM)
incorrect SLOPE
missing
decoding probability
mean photon rate μ
10^0
10^{-1}
10^{-2}
$\mu = 0.23$
$\mu = 1.4$
$\mu = 3.48$
18%
15%
19%
18%
8%
5%
2%
21%
b)
$\mu = 0.23$ 8.67 Mbits/s
$\mu = 1.4$ 31.4 Mbits/s
$\mu = 3.48$ 37.9 Mbits/s
t_B (ps)
t_A (ps)
both methods correct
GMM-method correct, SLOPE-method incorrect
GMM-method incorrect, SLOPE-method correct

Photon Number Attribution

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



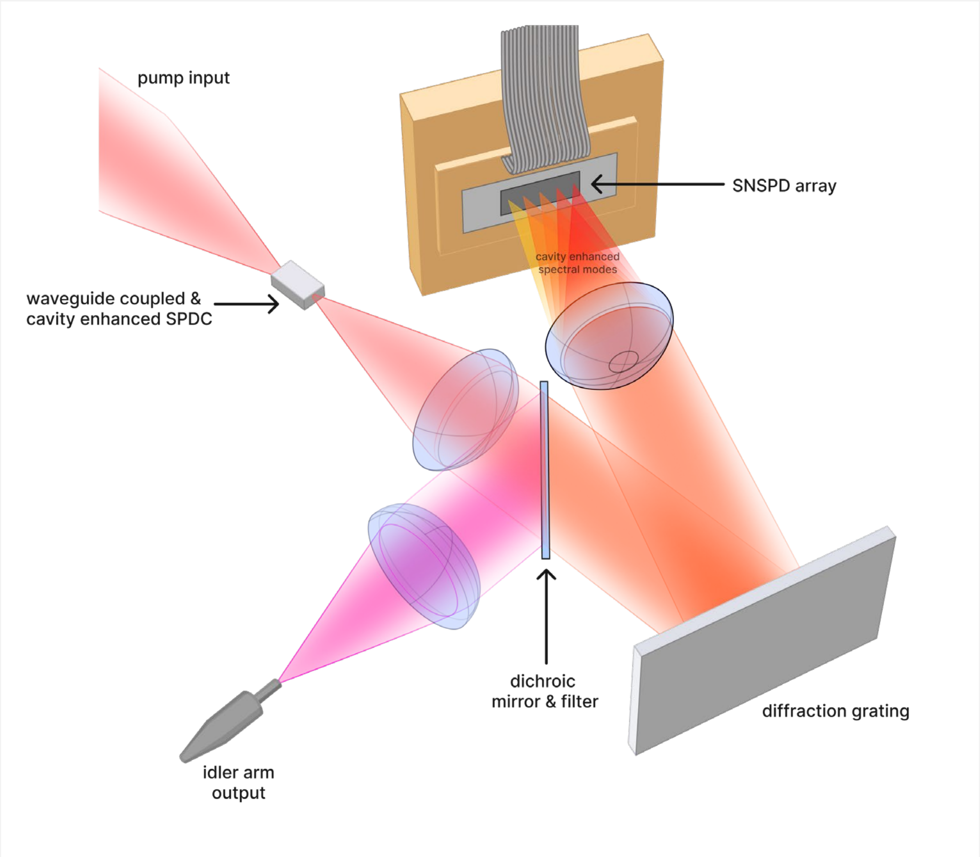


Conclusion

- 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



Acknowledgements

Special thanks to the committee:

Andrei Faraon, Oskar Painter, Maria Spiropulu, Matthew Shaw, and Nick Hutzler (Chair)

Mentors

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