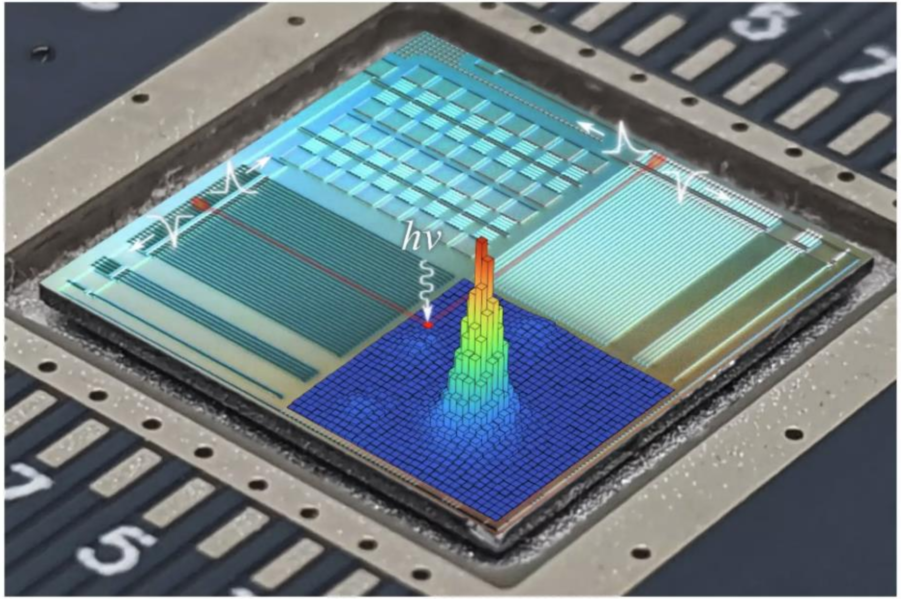
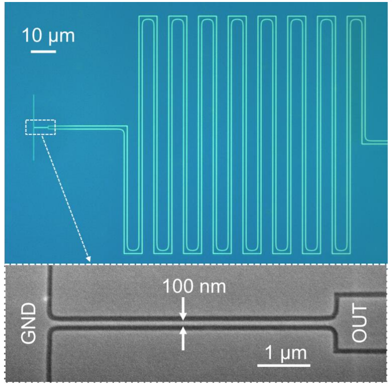
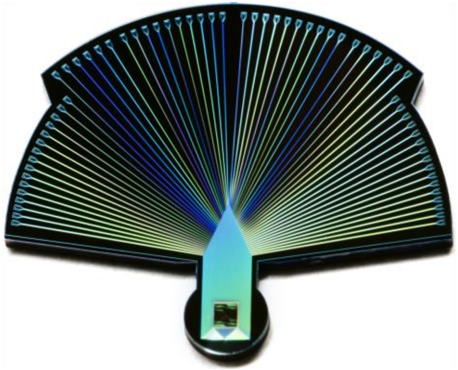






20th January 2025

High-speed SNSPDs for clock-rate scaling in quantum networks

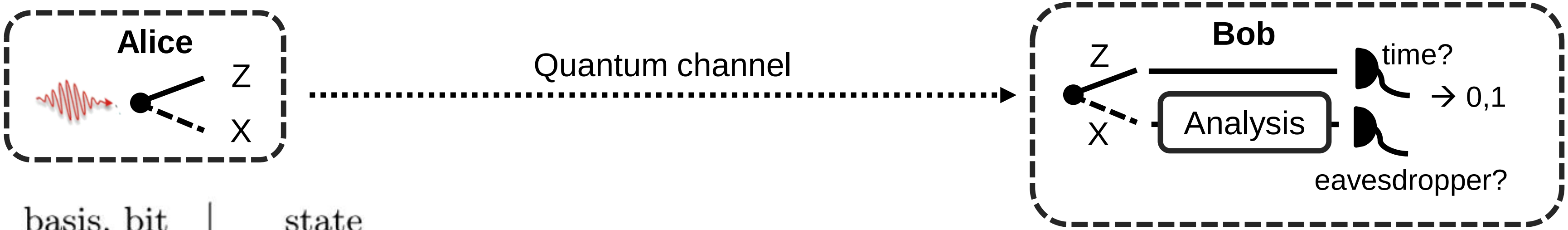
Boris Korzh

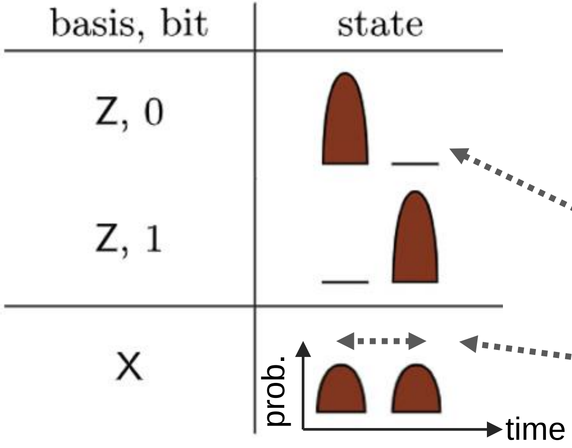
University of Geneva, Switzerland

UNIVERSITÉ DE GENÈVE

Jet Propulsion Laboratory
California Institute of Technology

Quantum communication with photons

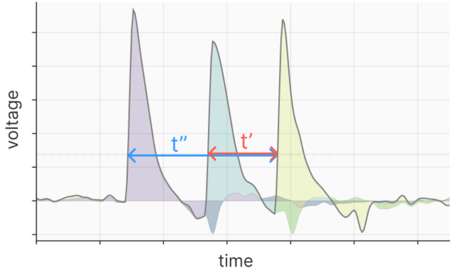




Detector **inefficiency** → slower rate of key generation

Detector **dark counts** → quantum bit errors

Speed limited by detector **timing accuracy**

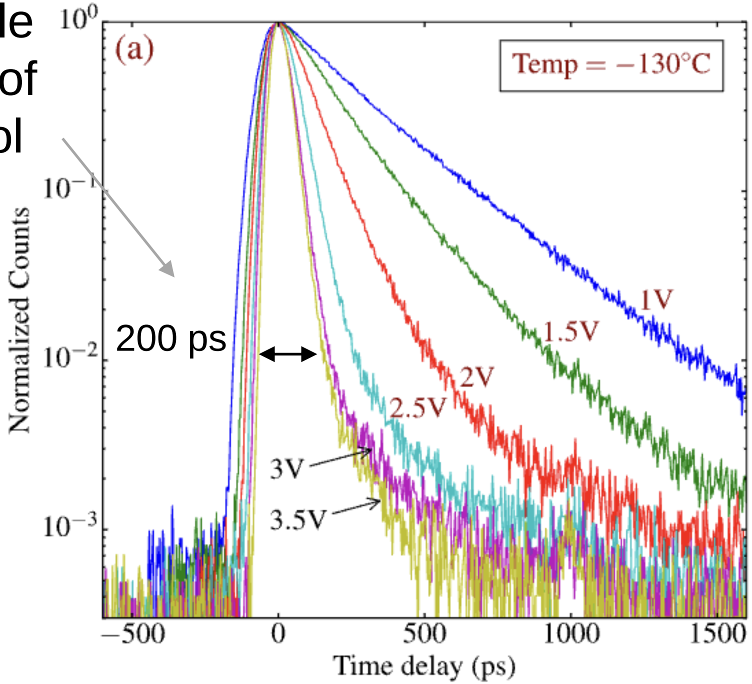


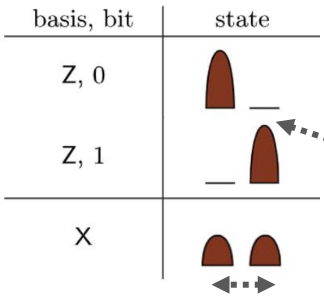
Photon rate limited by detector **recovery time**

Free-running single-photon avalanche diodes

Possible speed of protocol

5 GHz





Detector **dark counts** → bit errors

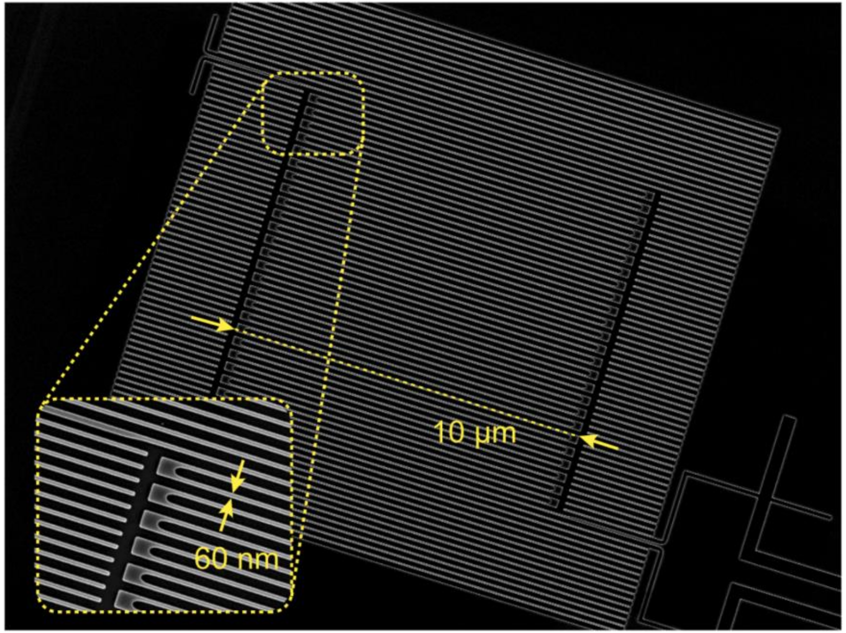
Repetition rate limited by detector **timing accuracy** → 5 GHz here

	Quantum channel		Detector	
	Distance (km)	Attenuation (dB)	Type	Temperature (K)
This work	307	51.9	InGaAs‡	153
Wang 2012[24]	260	52.9	SNSPD	1.7
Stucki 2009[25]	250	42.9	SNSPD	2.5
Takesue 2007[26]	200	42.1	SNSPD	3
Liu 2010[27]	200	–	SNSPD	2.4
Rosenberg 2009[28]	135	27.8	SNSPD	3
Namekata 2011[29]	160	33.6	InGaAs§	193
Yuan 2009[30]	100	20	InGaAs§	243
Shimizu 2014[23]	90*	30	SNSPD	2.5
Lucamarini 2013[19]	80†	16	InGaAs§	243
Walenta 2014[18]	25†	5.3	InGaAs§	293

Amri, Boso, Korzh, and Zbinden ***Optics Letters*** 41 (24): 5728 (2016)

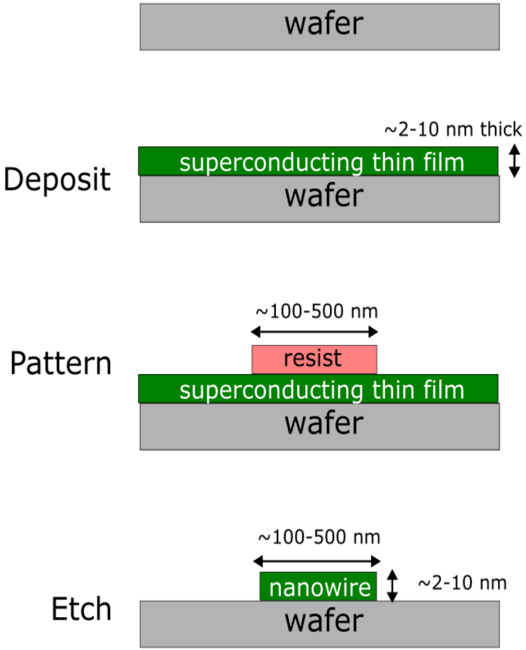
Korzh, Lim et al ***Nature Photonics* 9** 163 (2015)

Superconducting nanowire single-photon detector (SNSPD)



Single-pixel detector

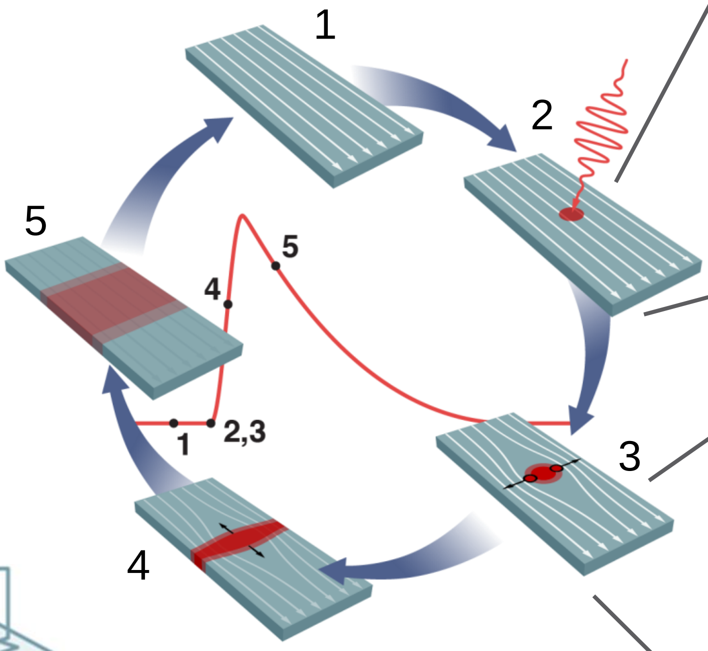
Nanofabrication

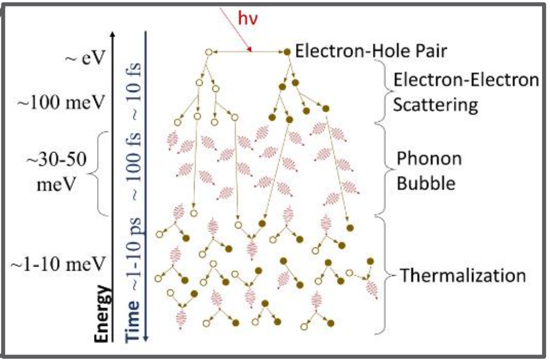


Goltsman, *et al*, ***APL* 79**, 705 (2001)

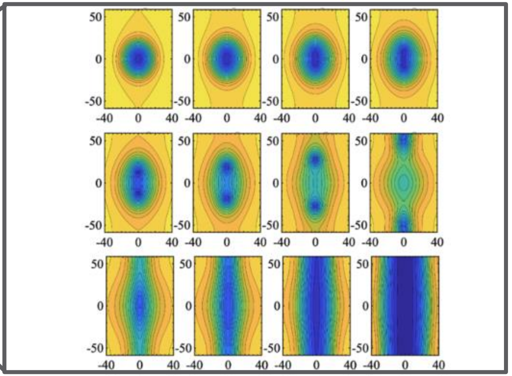
SNSPD detection mechanism

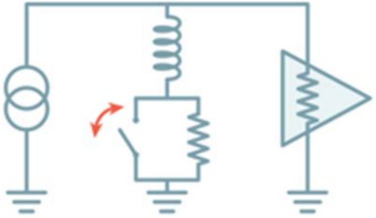
1. Current-biased superconducting nanowire
2. Photon absorption & Hotspot formation
3. Suppression of superconductivity
4. Normal domain growth - ***internal gain***
5. Recovery





thousands of carriers per photon





Typically operating at 1-4 kelvin

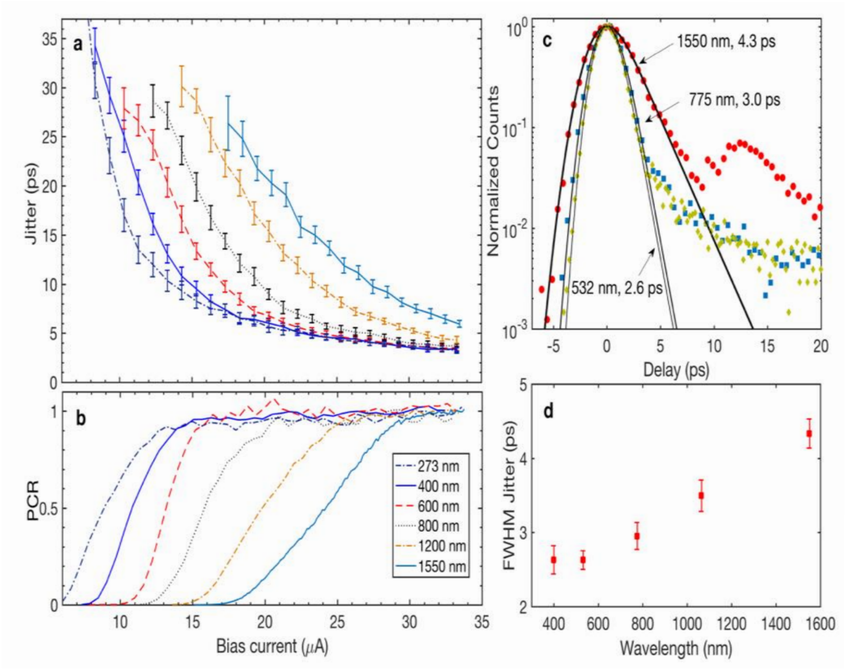
Allmaras, Kozorezov, Korzh, Berggren and Shaw, ***PRApplied* 11** 034062 (2019)
Allmaras, *Modeling and Development of Superconducting Nanowire Single-Photon Detectors,* **Ph.D. Dissertation**, Caltech (2020)

Advances in superconducting nanowire detectors

	Timing jitter	Intrinsic photon number resolution	Efficiency	Array size	Maximum count rate	Dark count rate	Active area	Cut-off wavelength
Records in 2016	18 ps	None	93%	64	1 Gcps	4 /s/mm^2	0.001 cm^2	5 µm
Current records for isolated devices	**2.6 ps** [1]	**3-5 photons**	**98%** [2]	**4x10^5** [3]	**1.5 Gcps** [4,5]	**4x10^{-5} /s/mm^2** [6]	**0.1 cm^2** [3]	**29 µm** [7]
Expected performance by 2030	**1 ps**	**10**	**99 %**	**10^7**	**10 Gcps**	**1x10^{-6} /s/mm^2**	**1 cm^2**	**100 µm**

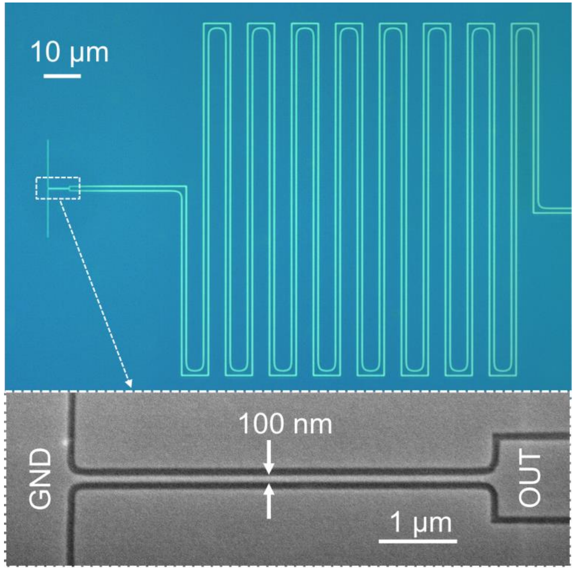
[1] Korzh, Zhao et al, ***Nature Photonics*** *14*, 250 (2020)
[2] Reddy et al, ***Optica*** 7, 1649 (2020)
[3] Oripov, Rampini, Allmaras, Shaw, Nam, Korzh, and McCaughan, ***Nature*** 622, 730 (2023)
[4] Craiciu, Korzh et al, ***Optica*** 10, 183 (2023)
[5] Resta et al, ***Nano Letters*** (2023)
[6] Chiles, ***PRL*** 128, 231802 (2022)
[7] Taylor, Walter, Korzh et al, ***Optica**,* (2023)

Record timing accuracy



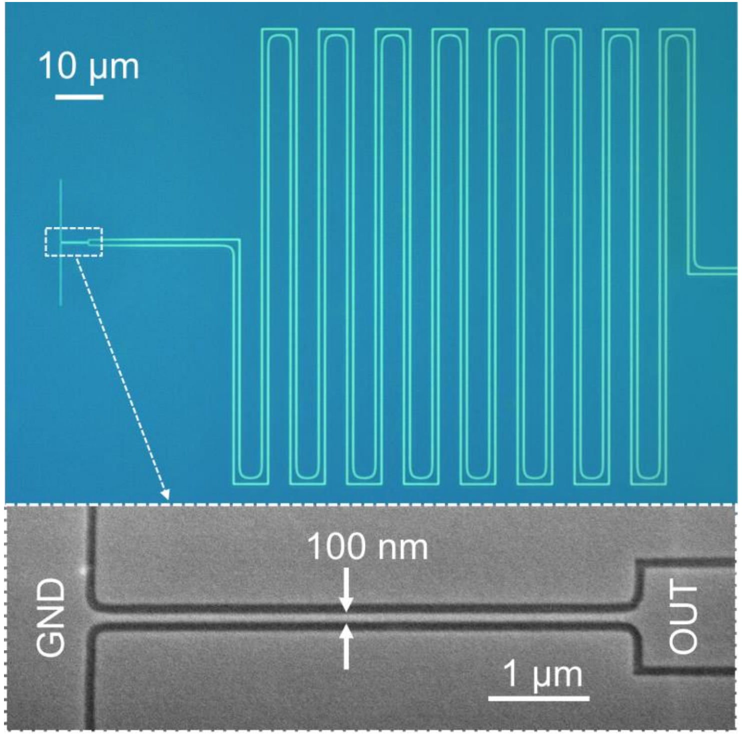
Probing the intrinsic timescales of the **detection process for first time**

Future material investigations will lead to <1 ps timing accuracy

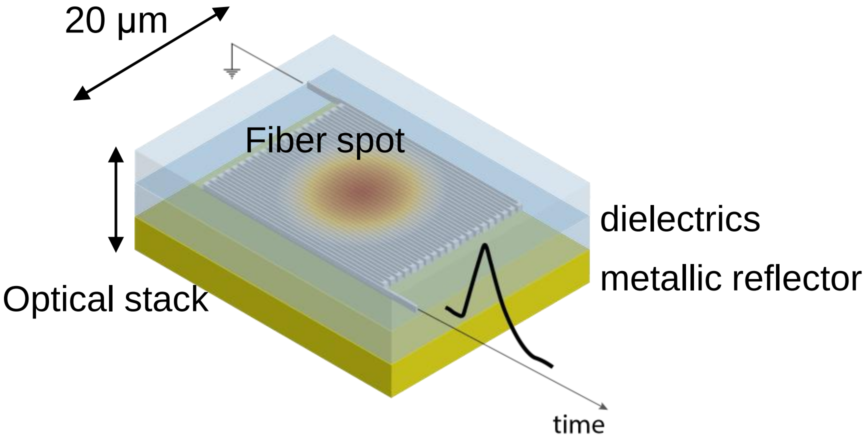


Korzh, Zhao, Allmaras, Frasca *et al* ***Nature Photonics* 14,** 250-255 (2020)

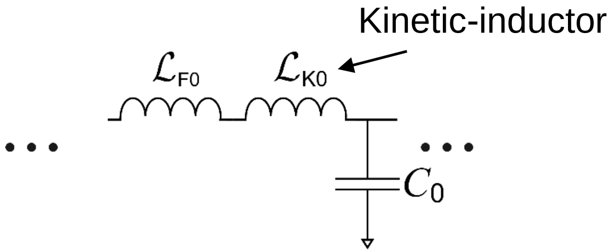
Need to increase the active area…



Low-velocity superconducting transmission lines



Full nanowire ~1000 µm long
→ 300 ps jitter, potentially



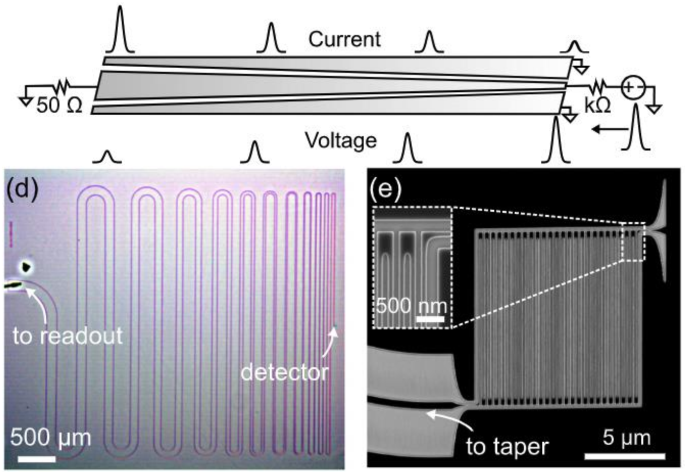
For a ≈ 5 nm thick ≈ 100 nm wide strip

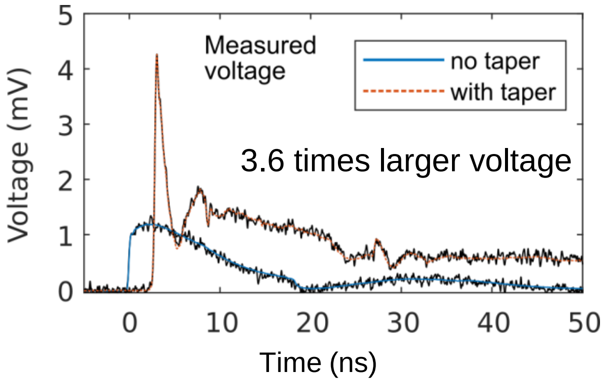
$$\mathcal{L}_{K0} \approx 100\,\mu_0 \quad \mathcal{L}_{F0} \approx 0.1\,\mu_0 \quad \mathcal{C}_0 \approx 10\,\epsilon_0$$

$Z_0 \approx k\Omega$

$v_{ph} \approx 0.01c$
3 µm/ps

Improved signal readout with impedance matching



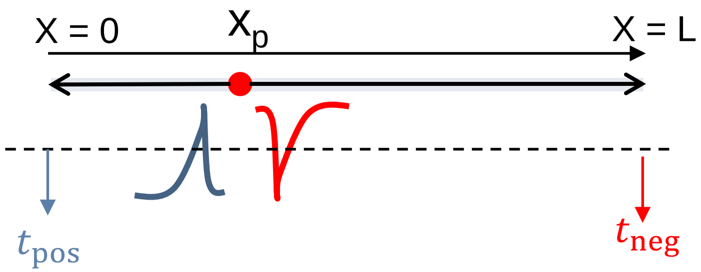


Compact impedance matching tapers

Zhu, Colangelo, Korzh *et al*, ***APL*** **114**, 042601 (2019)

Differential readout

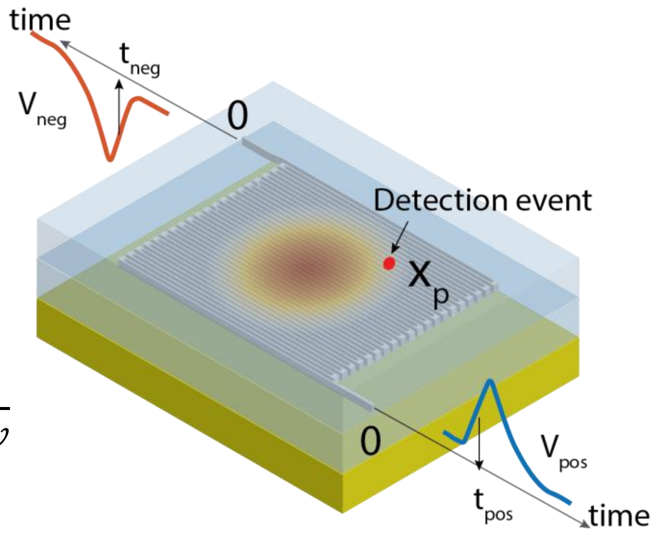
Geometric Effects (Slow speed → $v_{ph} \approx 0.01c$)



$$t_{pos} = \frac{x_p}{v}$$

$$t_{neg} = \frac{L - x_p}{v}$$

$$t_\Sigma = \frac{t_{pos} + t_{neg}}{2} = \frac{L}{2v}$$

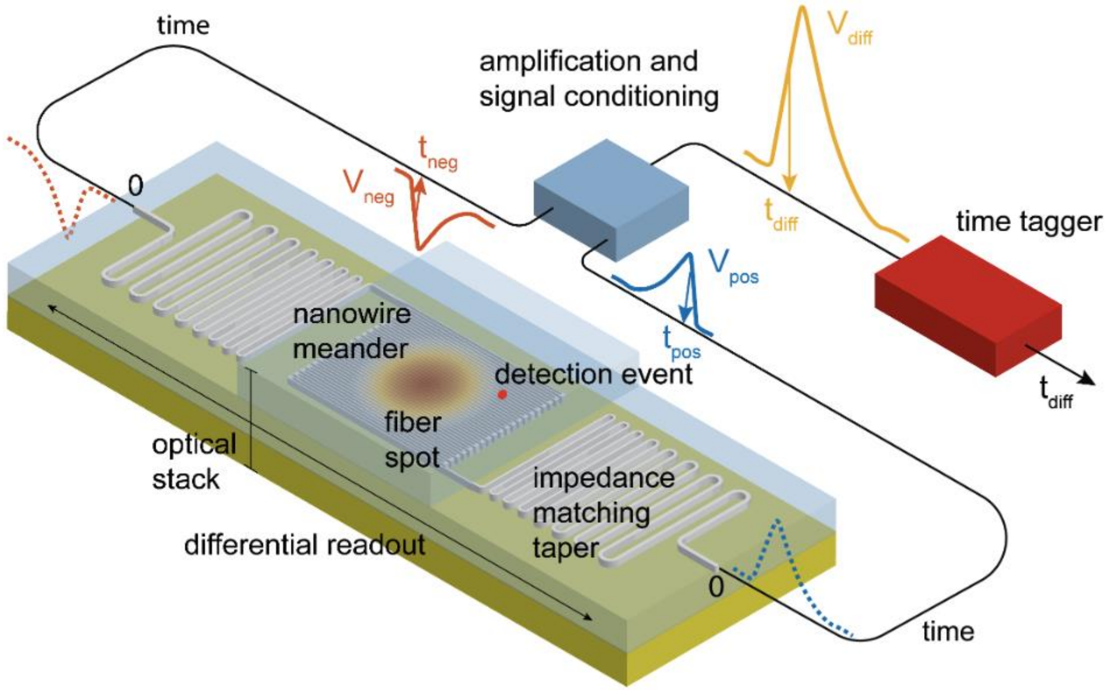


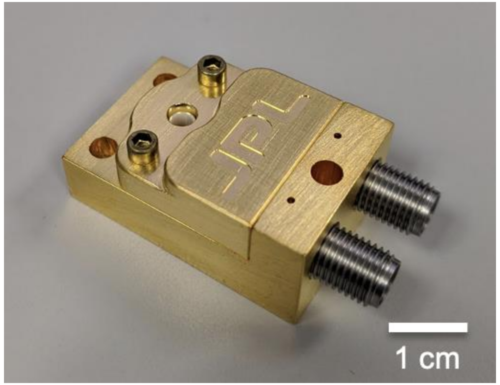
The detector jitter $\boldsymbol{j_\Sigma}$ is independent from x_{p}

Geometric contributions are cancelled out!

Colangelo, Korzh, Allmaras, Beyer *et al*, ***PRApplied* 19**, 044093 (2023)

Practical single-pixel detectors



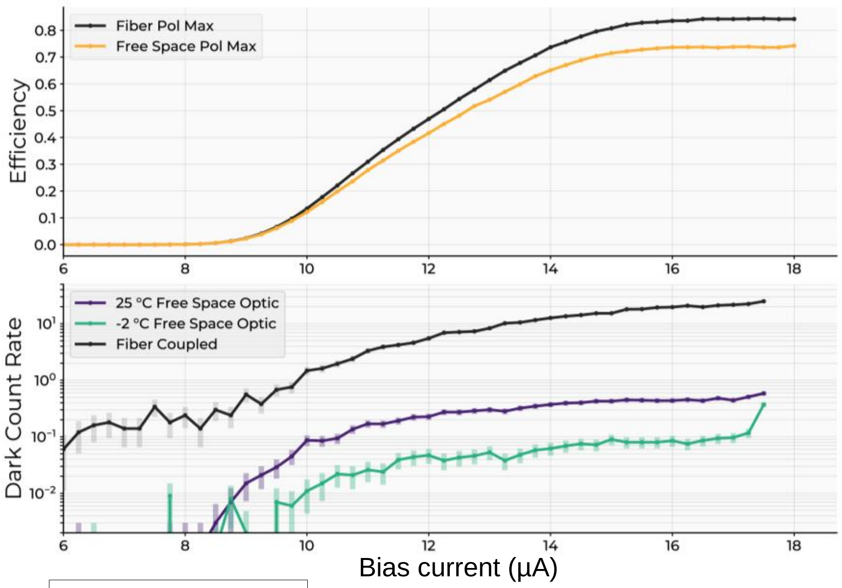


Colangelo, Korzh, Allmaras, Beyer *et al*, ***PRApplied*** **19**, 044093 (2023)

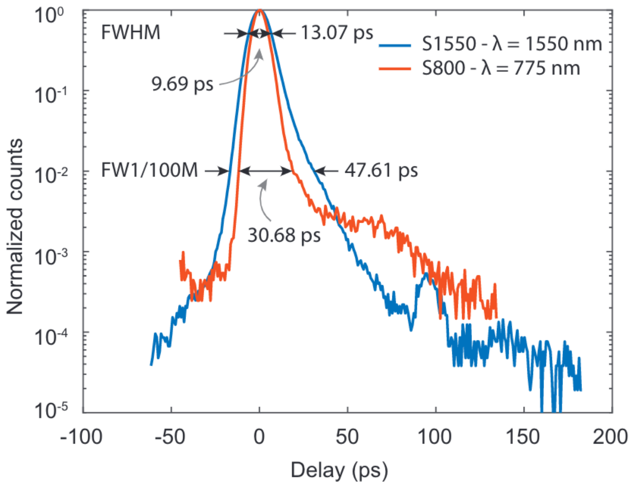
Detector requirements for Quantum Communication

High efficiency

Low timing jitter



Intrinsic dark counts can be $<10^{-5}$ cps



Low noise

Useful figure of merit [1]:

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

- Here H~**5x10⁹**
- Previous record H~1.25x10⁹
  - 421 km, 1-way QKD [2]
  - With SNSPDs

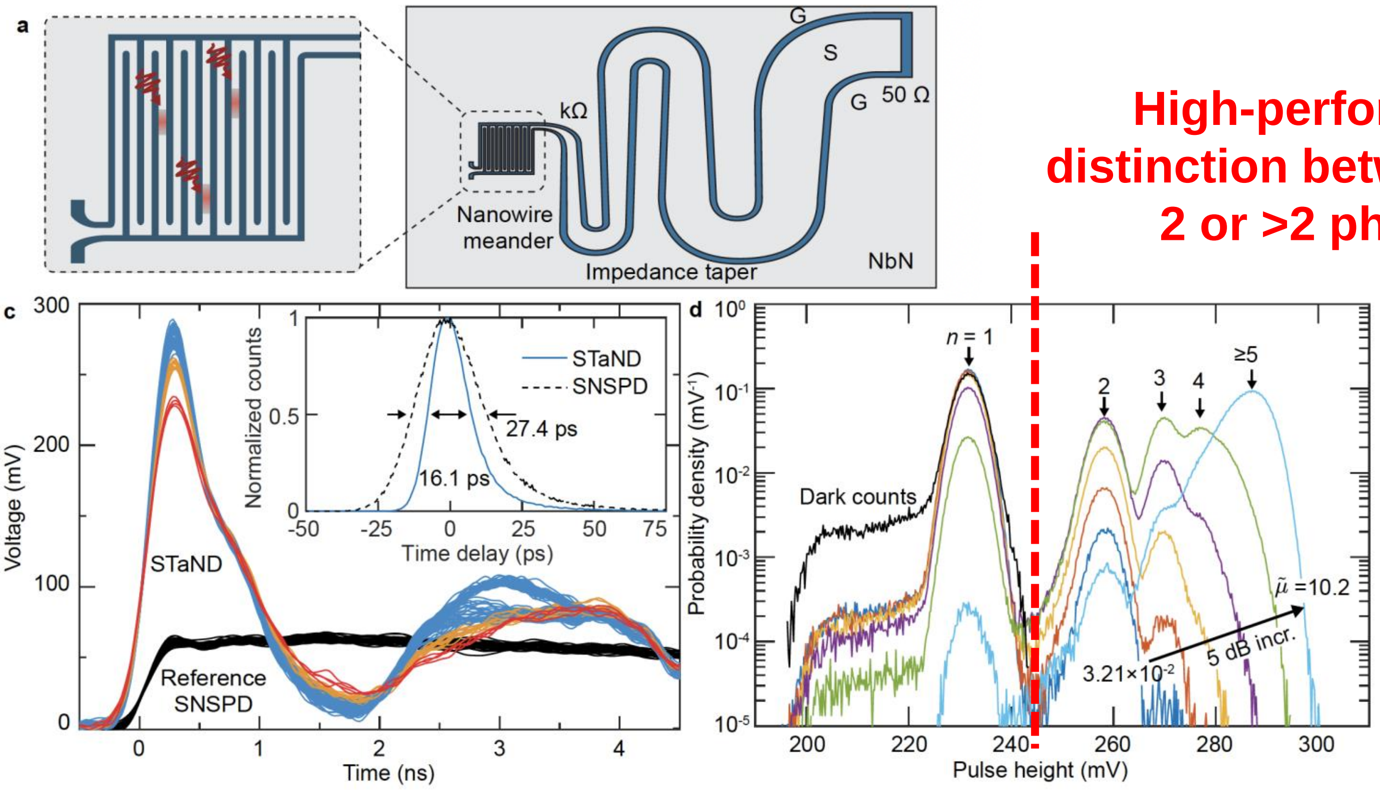
Now have pathway to 10-20 GHz clock rates in Quantum Communication

Mueller, Korzh, Runyan *et al*, ***Optica* 8,** 1586 (2021)

[1] R. Hadfield, *Nat. Photonics* **3**, 696 (2009)
[2] UniGe: A. Boaron, et al., *PRL* 121, 190502 (2018)

Other useful features….

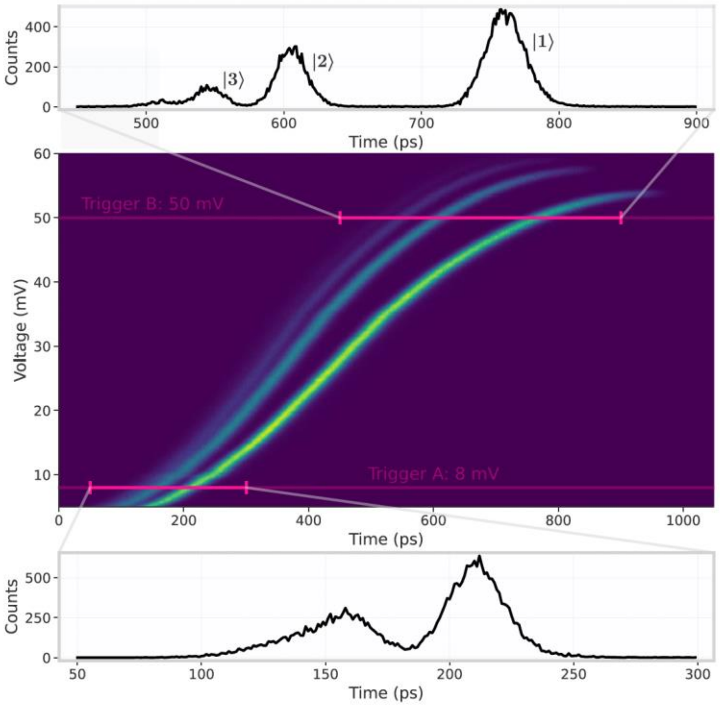
Photon number resolution

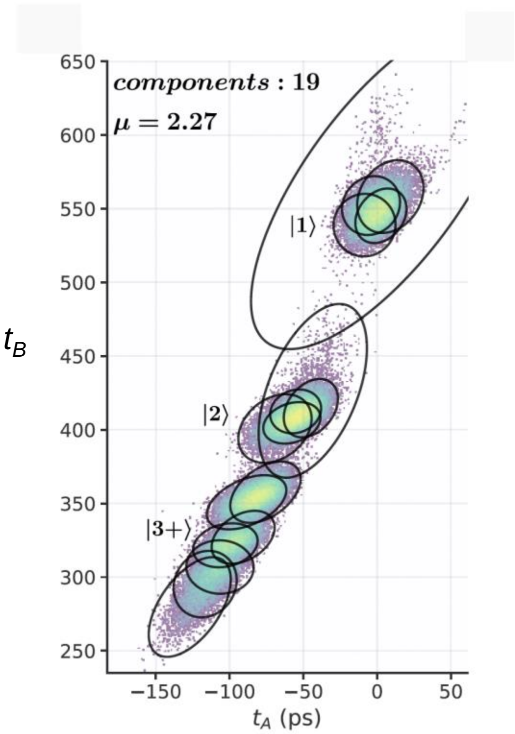


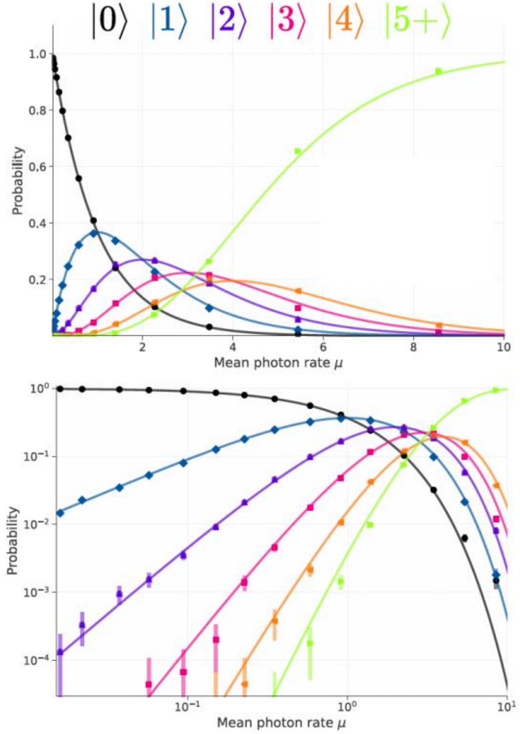
High-performance distinction between 1 and 2 or >2 photons

Zhu, Colangelo *et al*, ***Nano Letters* 20** 3858-3863 (2020)

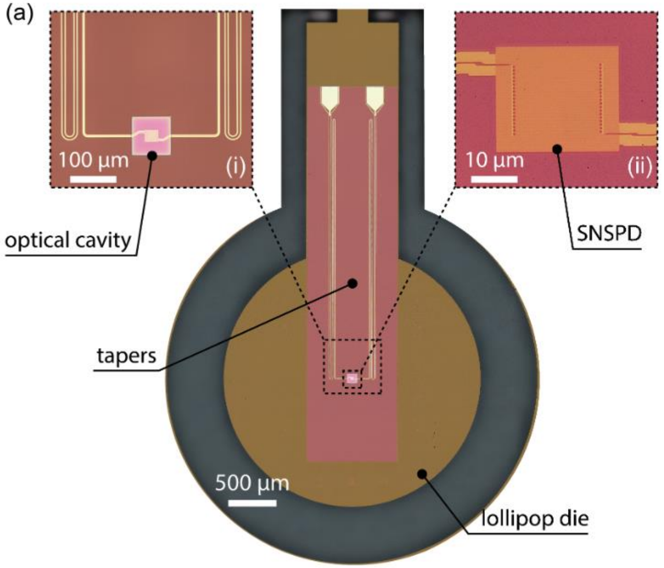
Photon number resolution with differential detector





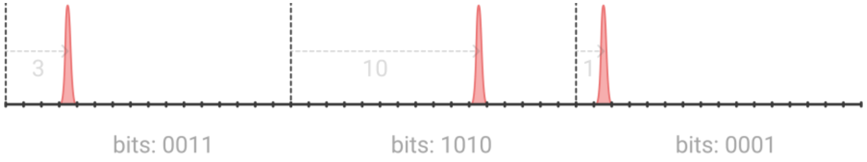


Some use cases….

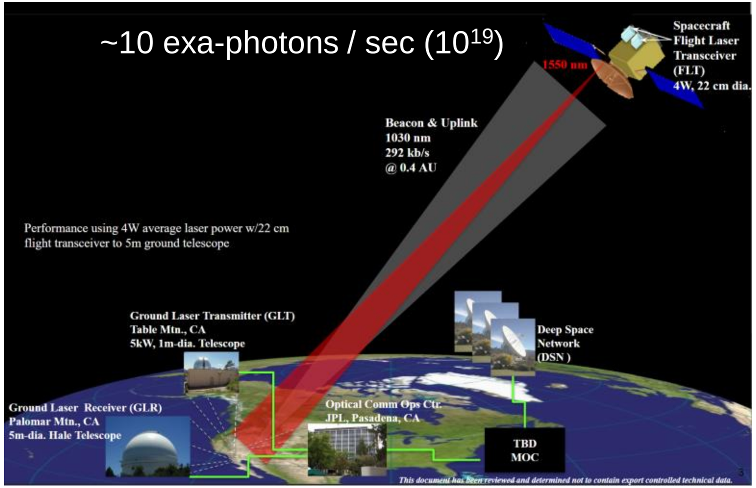


Pulse position modulation for classical communication

- Large-M PPM sends more bits per photon to minimize power at transmitter

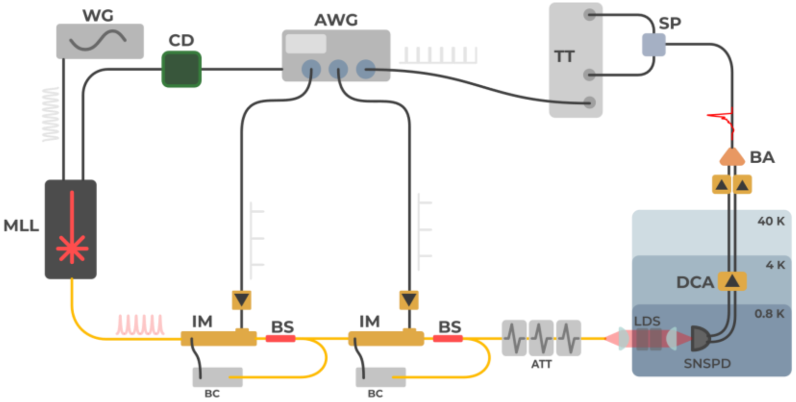


Deep-space optical communication



Current DSOC implementation **500 ps slot** width --> can we go to 50 ps in future?

Fiber *classical* communication

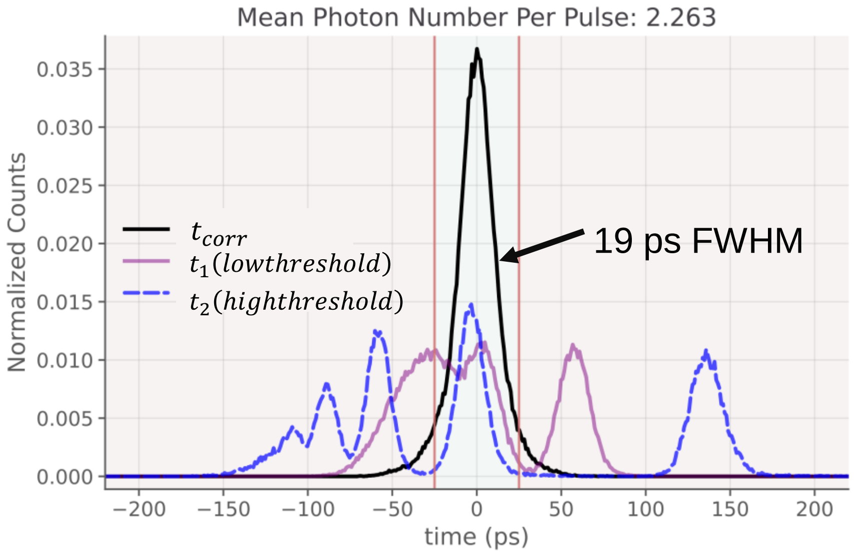


Lower Raman noise for classical communications in Quantum Networks

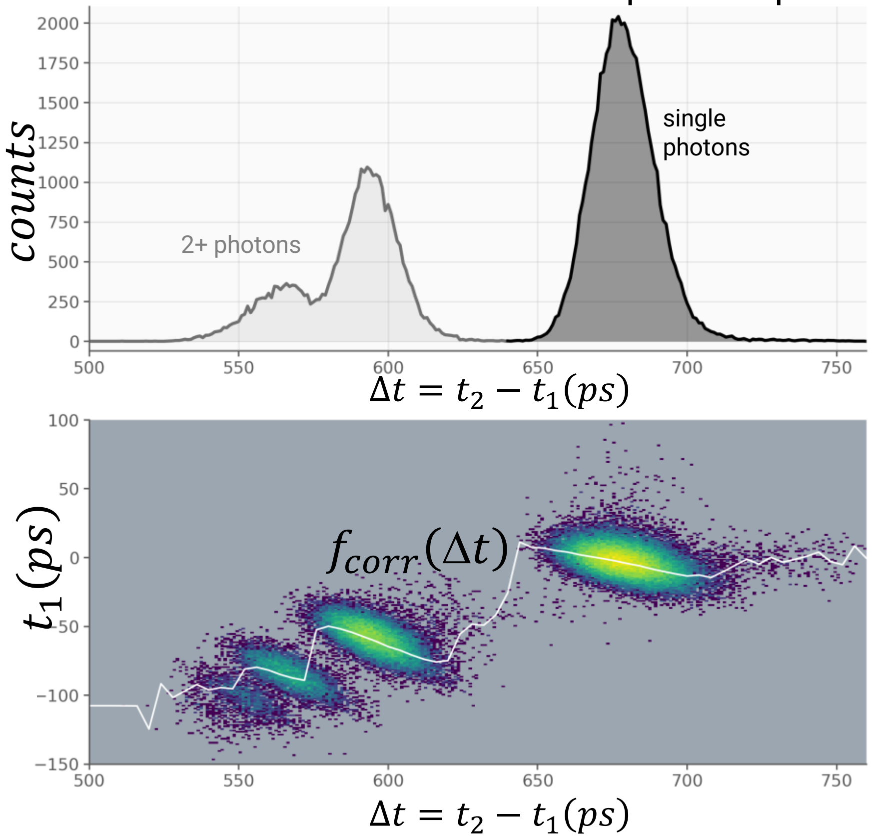
- Classical channel in QKD or teleportation
- Clock synchronization

Wollman et al ***Optics Express*** 32 (27): 48185 (2024)

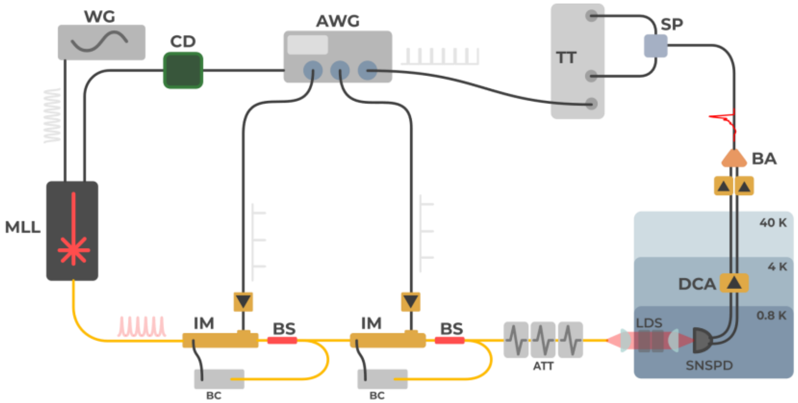
Photon-number resolution for timing correction

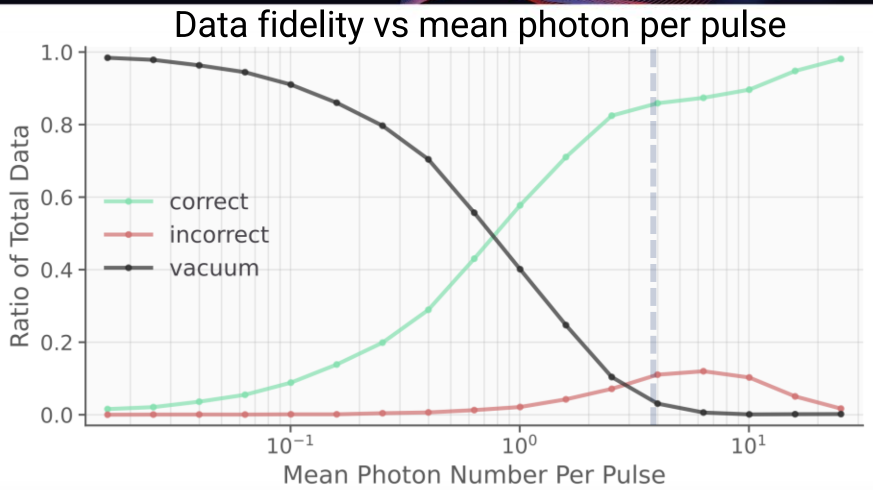


$$t_{corr} = t_1 - f_{corr}(\Delta t)$$



20 GHz PPM demonstration





Sent Image

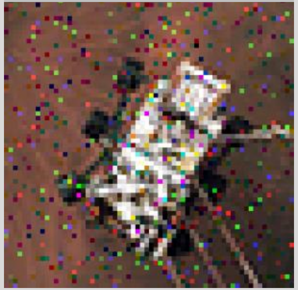
98 kBit image sent as 8955 laser pulses

11 bits of data per pulse

No data error correction

(Hamming code, parity bits)

Received image



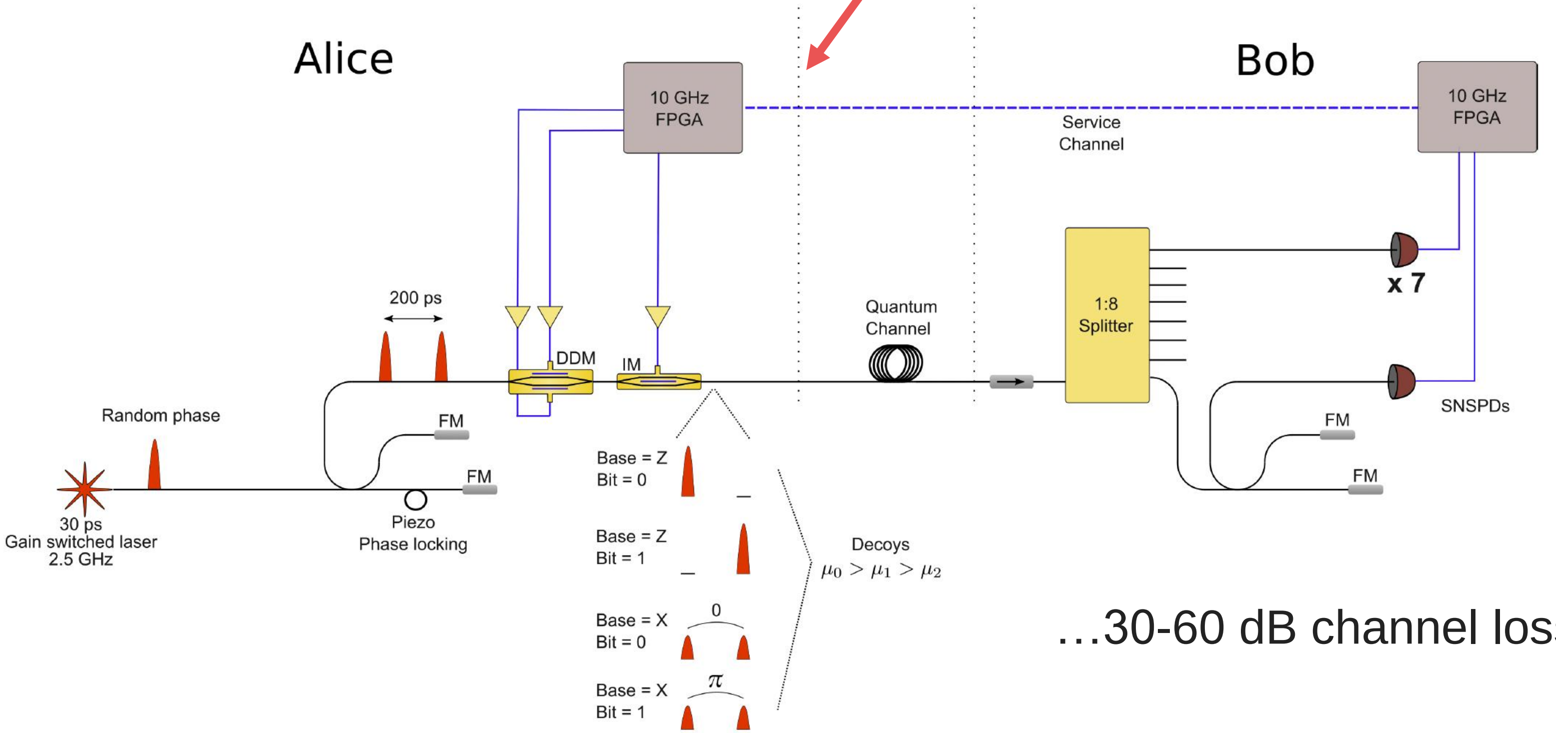
35,800 photons received

Quantum communication

Similar to optical comm but…

Single photons at this point!

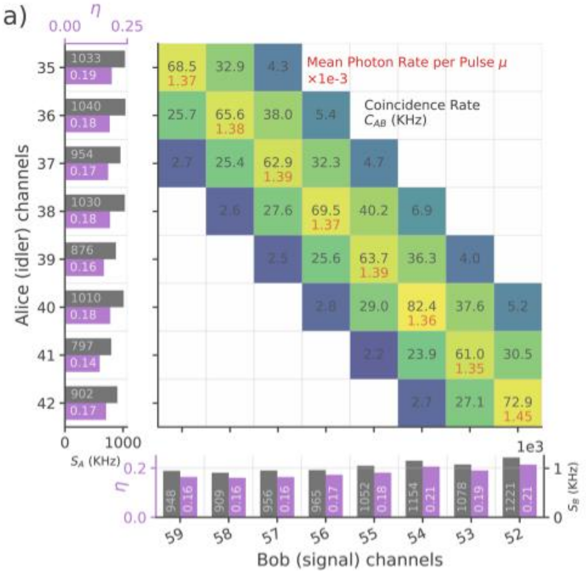
~10^9 photons / sec

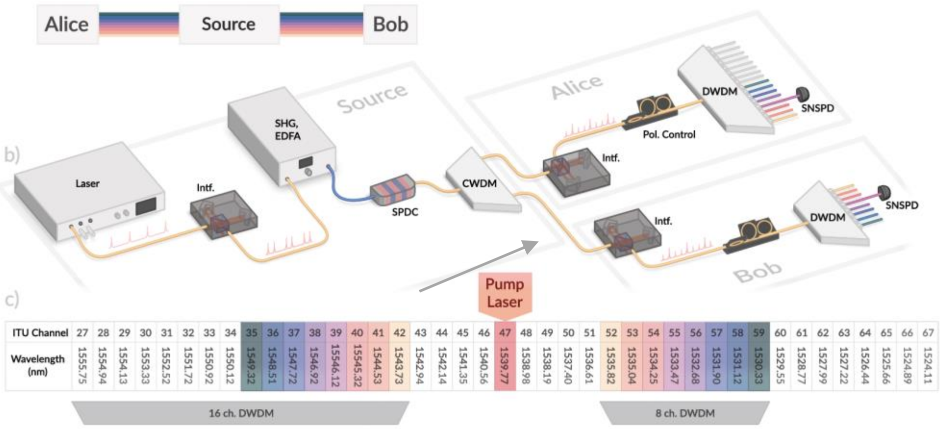


…30-60 dB channel loss is realistic

High speed entanglement distribution

Resource for quantum cryptography and communication

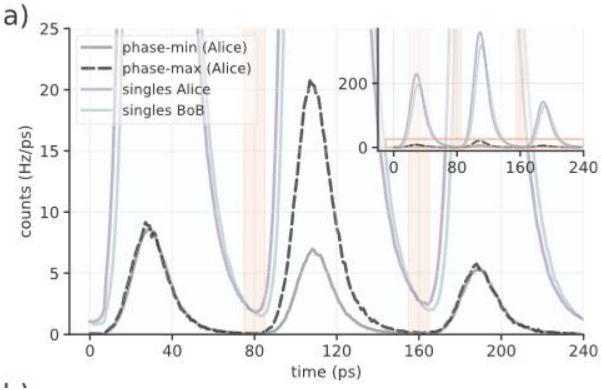




ITU Channel	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47
Wavelength (nm)	1555.75	1554.94	1554.13	1553.33	1552.52	1551.72	1550.92	1550.12	1549.32	1548.51	1547.72	1546.92	15546.12	15545.32	1544.53	1543.73	1542.94	1542.14	1541.35	1540.56	1539.77

ITU Channel	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67
Wavelength (nm)	1538.98	1538.19	1537.40	1536.61	1535.82	1535.04	1534.25	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

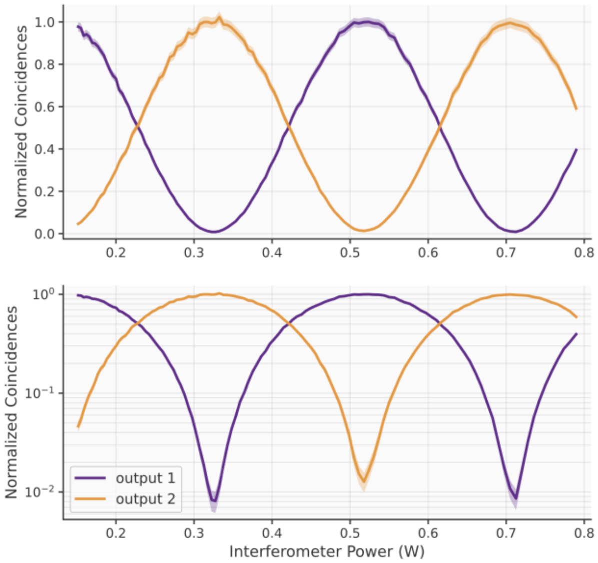
12.5 GHz clock rate

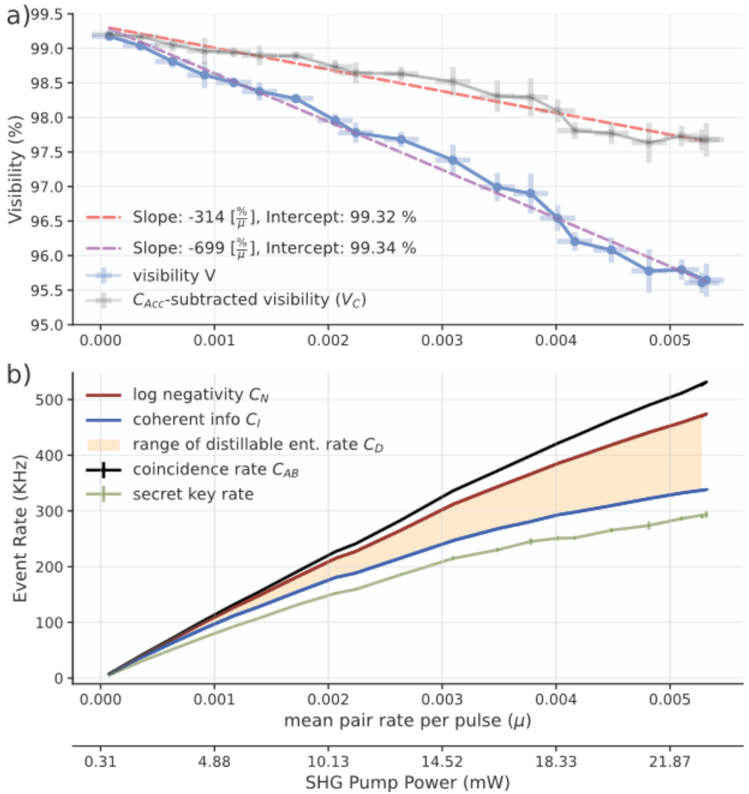


Mueller, Davis, Korzh, Valivarthi et al, ***Optica Quantum*** 2, 65 (2024)

High clock-rate entanglement-based quantum comm

>99% interference visibility



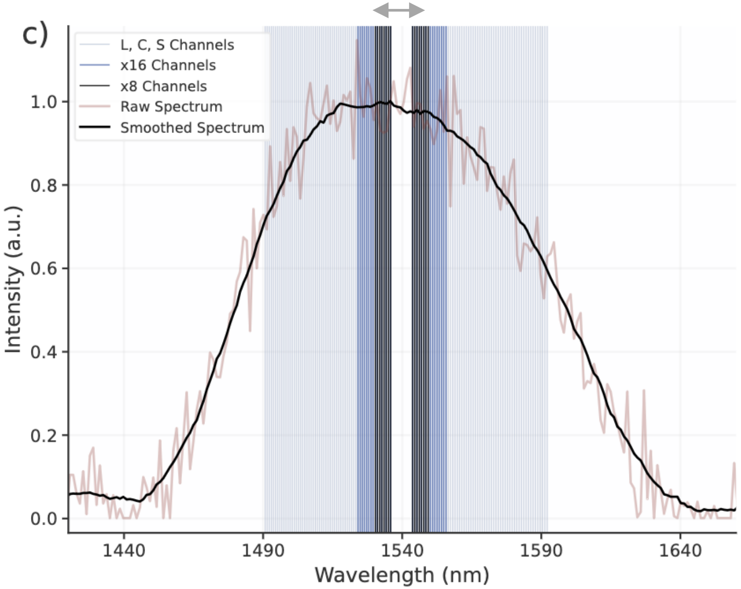


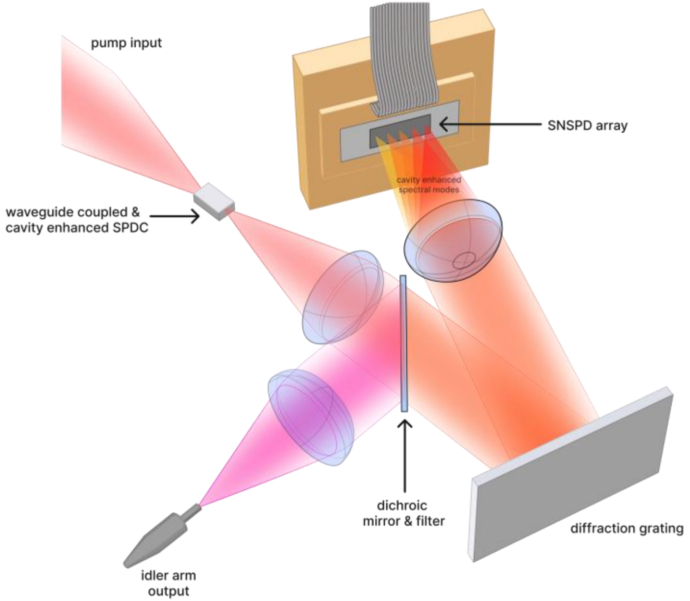
Mueller, Davis, Korzh, Valivarthi et al, ***Optica Quantum*** 2, 65 (2024)

Wavelength multiplexing

Future detector architecture

Only using small fraction of available photons





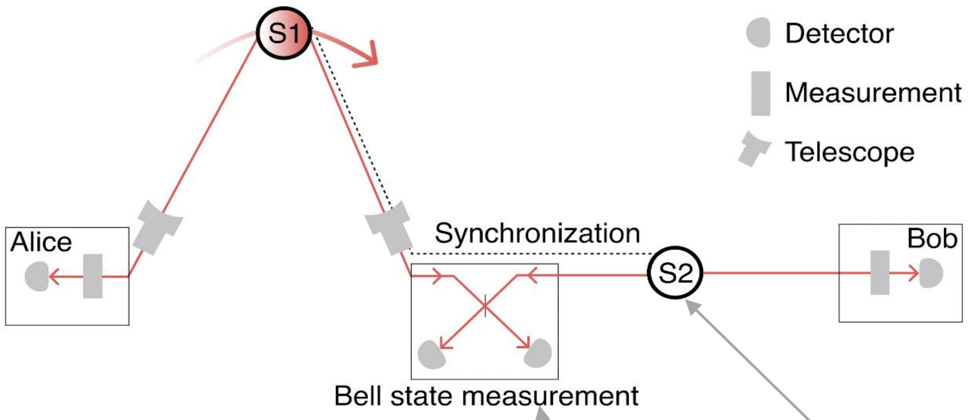
Towards multiplexed quantum memories

Table 2. Extrapolated Rates (MHz)[a]

Rate Metric (μ at max)	1 Channel	8 Channels	16 Channels	60 Channels
Coincidence Rate, C_{AB} (0.014)	0.755	5.41	11.6	34.9
Log Negativity, C_N (0.010)	0.600	4.30	9.19	27.7
Coherent Info., C_I (0.006)	0.345	2.47	5.28	15.9
Secret Key Rate, SKR (0.007)	0.309	2.21	4.73	14.3

Mueller, Davis, Korzh, Valivarthi et al, ***Optica Quantum*** 2, 65 (2024)

Can we supplement $H = \frac{\eta}{(\Delta t D)}$, with high count rate?

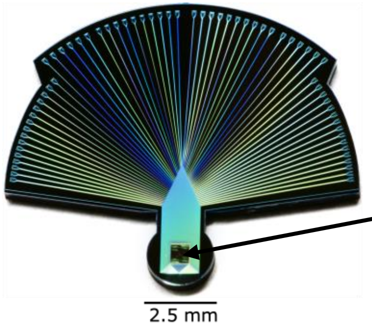


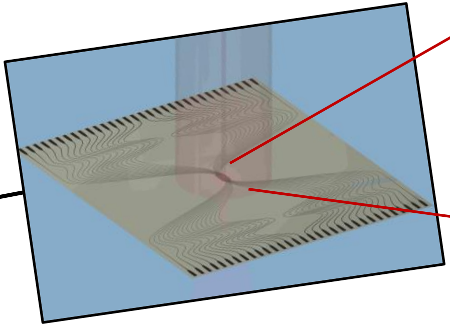
>10 GHz clock rate

Need >1 Gcps !

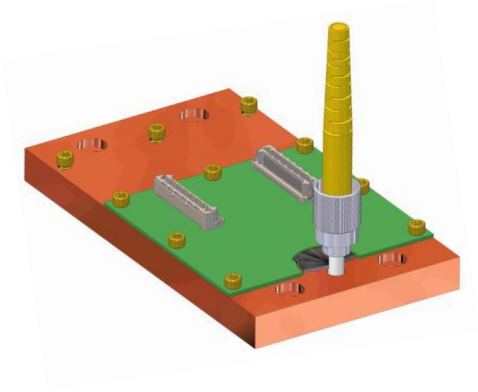
PEACOQ

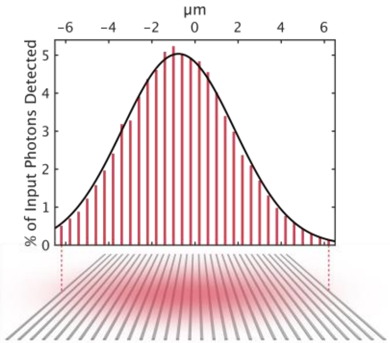
Performance Enhanced Array for Counting Optical Quanta





Only straight lines!
Avoids bends and
wider sections





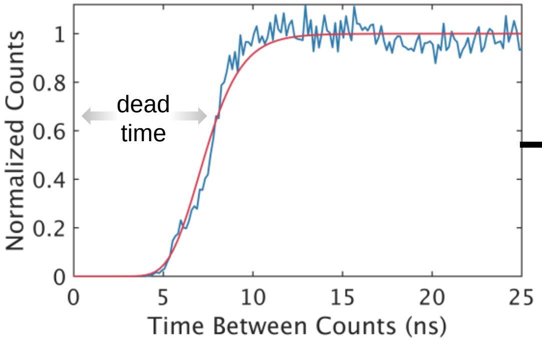
Metrics:

- λ = 1550 nm ± 75 nm
- 78% ± 4% system detection efficiency
- 160 dark counts per second
- sub-100 ps timing jitter
- 1.5 Gcps count rate (3 dB compression)

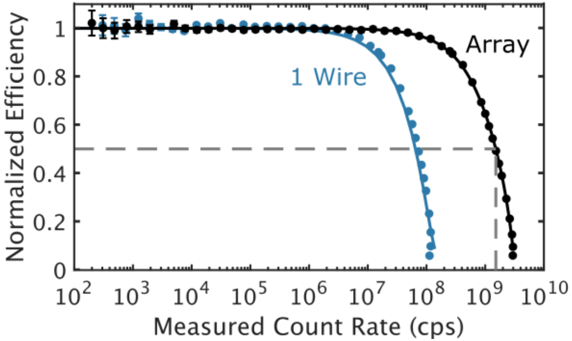
I. Craiciu, B. Korzh et al., **Optica** (2023)

PEACOQ Maximum Count Rate (MCR)

Detection efficiency vs. time since last detection



Normalized efficiency versus count rate



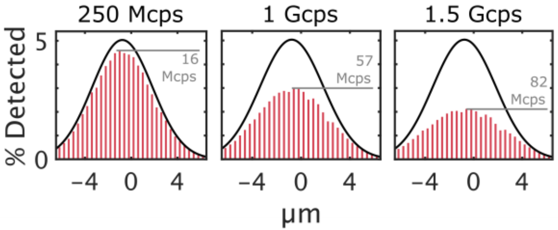
Maximum count rates (3 dB):

1 nanowire: 48 – 73 Mcps

32-wire array: 1.5 Gcps

Highest count rate measured: 3 Gcps

Saturation at different array count rates



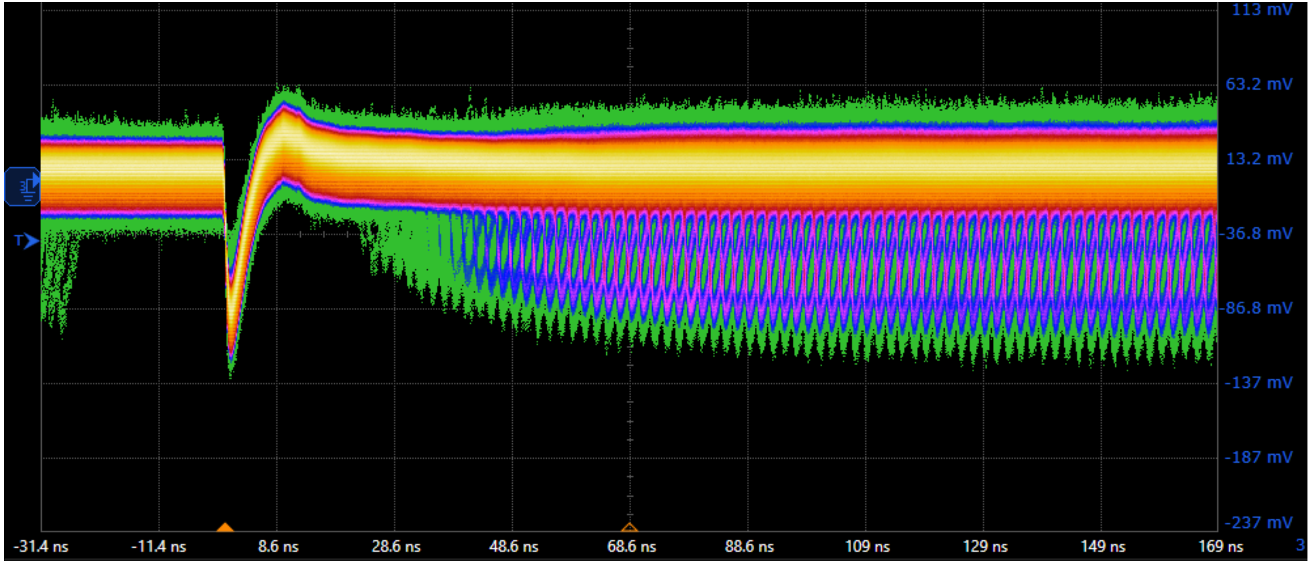
Future work:

- How fast can we push the ***single wire*** count rate?
  - 1.5 GHz has been achieved with 14 wires [2]
  - Enabled 100 Mb/s QKD [3]
- Scalable multiplexing that **preserves the fast pulse** shape

I. Craiciu, B. Korzh et al., **Optica** (2023)

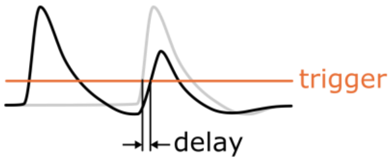
[2] Resta et al, ***Nano Letters*** 23 (13): 6018 (2023)
[3] Grünenfelder et al, ***Nature Photonics*** 17 (5): 422 (2023)

Considerations at high count rates….

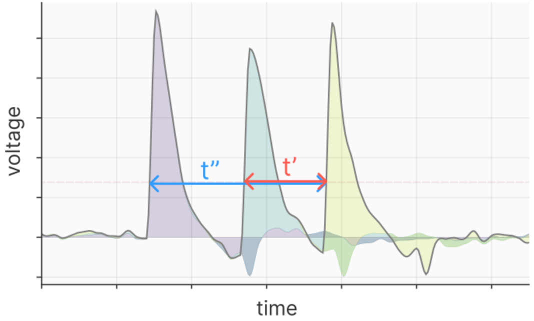


PEACOQ Timing Jitter at High Count Rates – 1 Wire

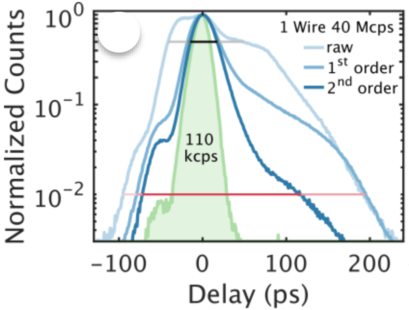
Timing jitter is affected by
time-walk effect and amplifier distortions

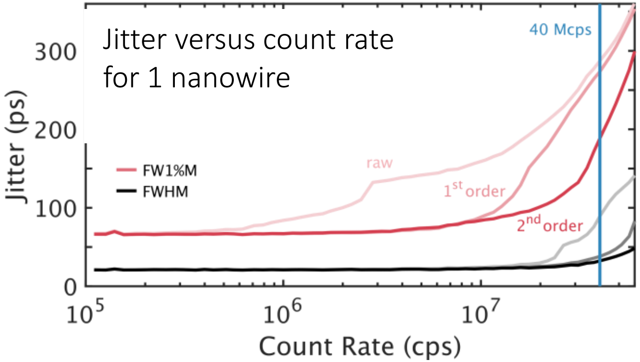


Three closely-spaced SNSPD pulses



Jitter histogram
with and without time-walk correction

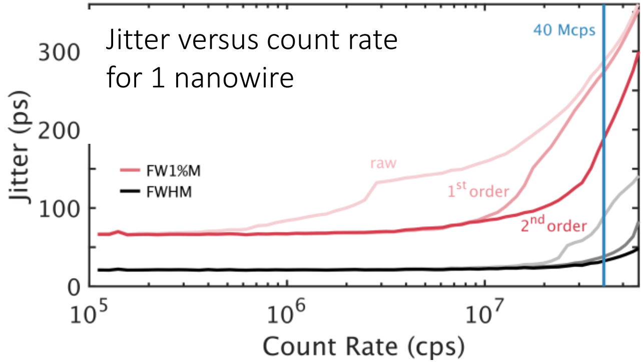




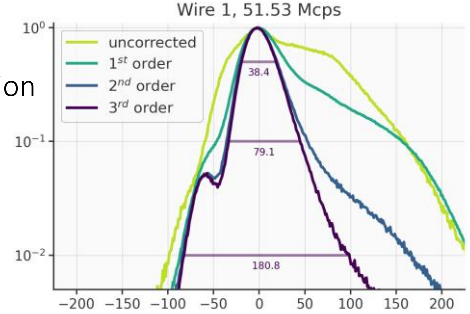
Mueller et al., ***Appl. Phys. Lett.*** **122**, 044001 (2023)

PEACOQ Timing Jitter at High Count Rates – Array

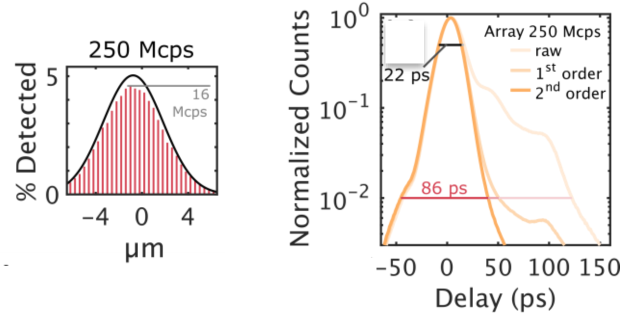
Jitter versus count rate for 1 nanowire



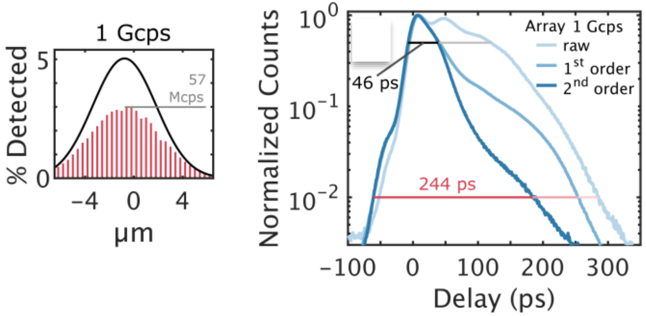
Preliminary results with 3rd order time-walk correction



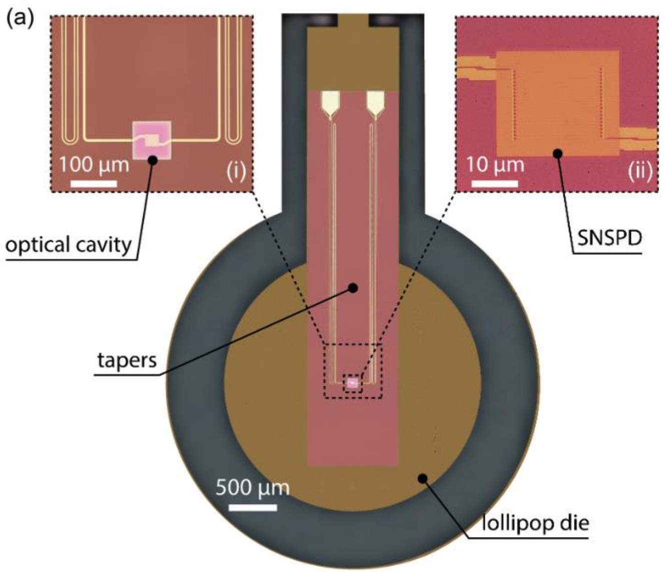
Estimated Array Jitter



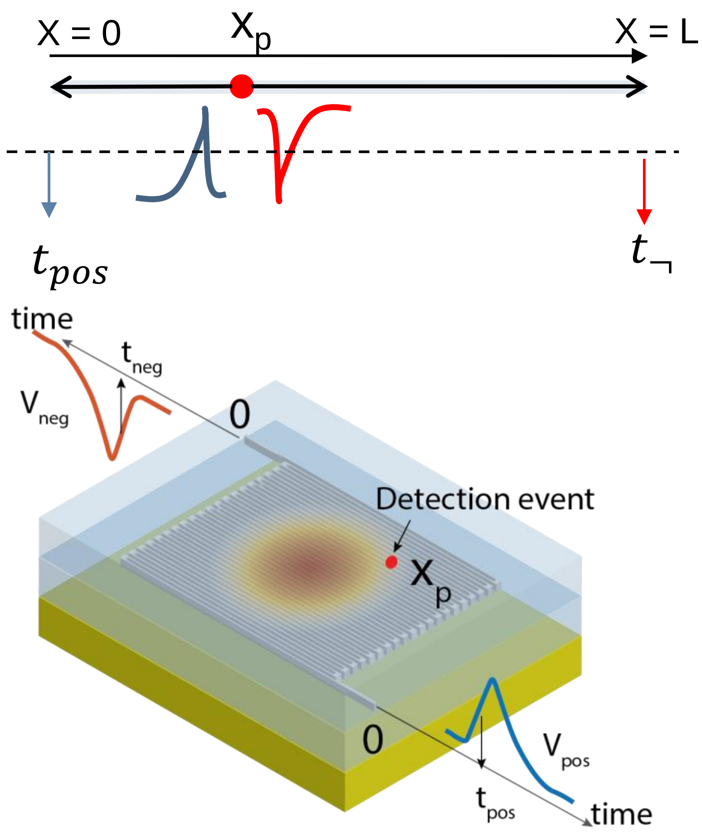
Estimated Array Jitter



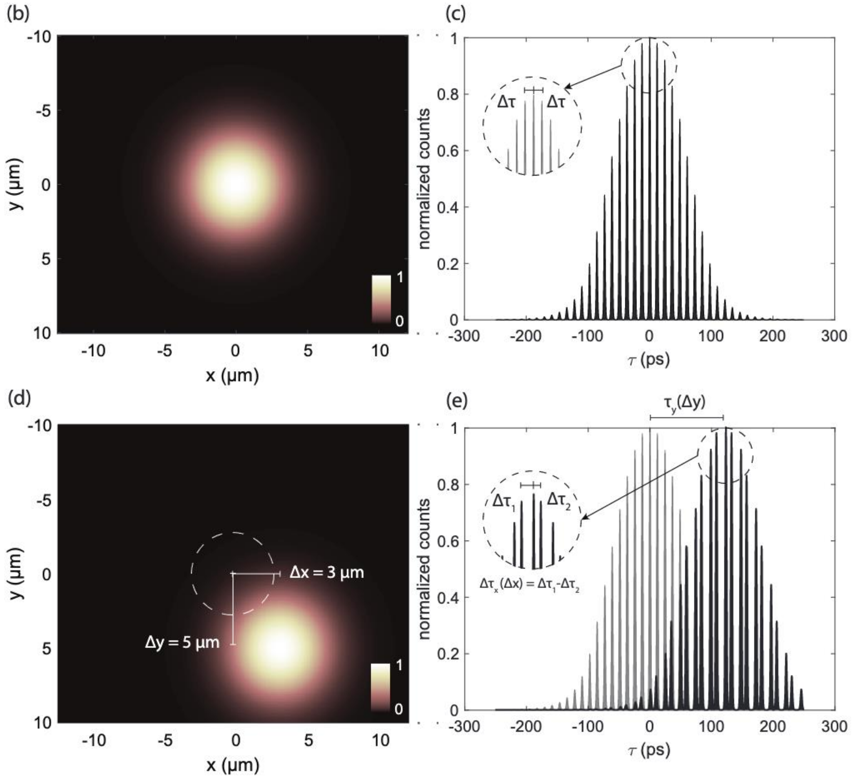
Other useful features….



Intrinsic imaging



Simulation



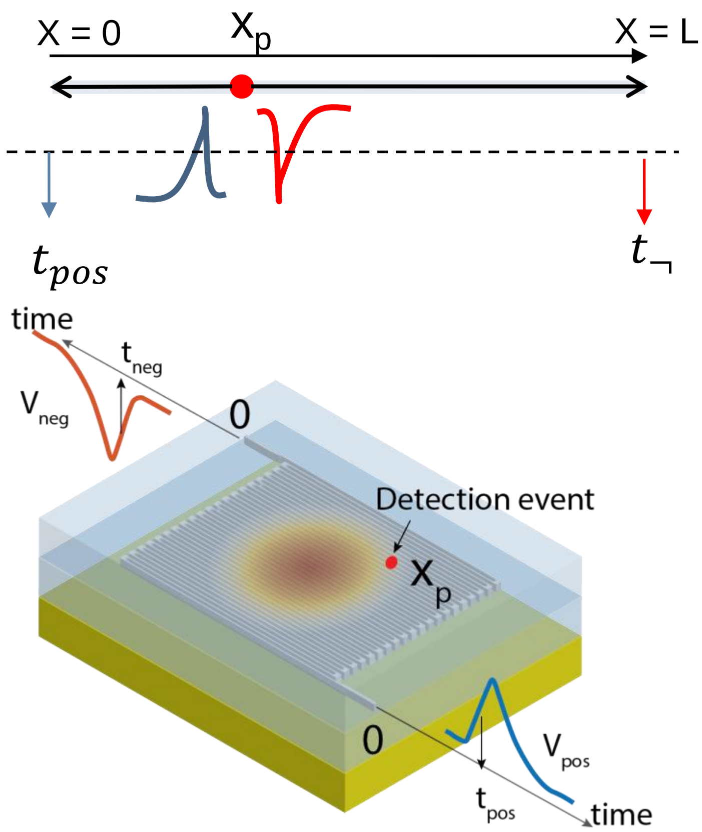
Useful for:

- Spatial correlation studies
- Optical fiber alignment studies

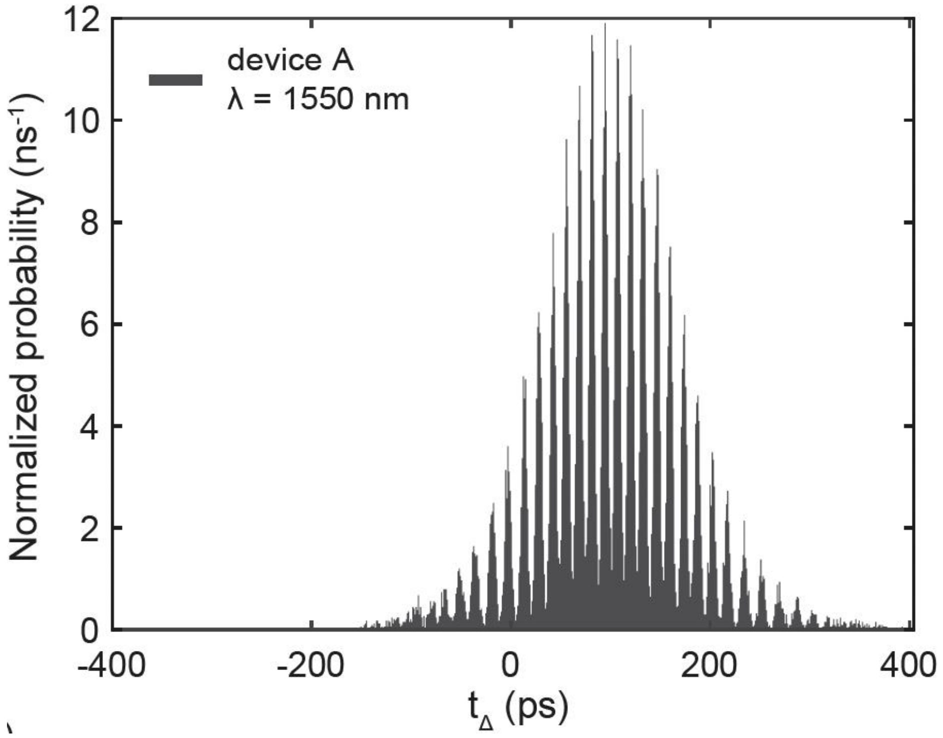
First demo:
Zhao et al, *Nat. Photonics* **11**, 247 (2017)

Colangelo, Korzh, Allmaras, Beyer *et al*, ***PRApplied*** **19**, 044093 (2023)

Intrinsic imaging



Experimental demo



Colangelo, Korzh, Allmaras, Beyer *et al*, ***PRApplied* 19**, 044093 (2023)

Advances in superconducting nanowire detectors

	Timing jitter	Intrinsic photon number resolution	Efficiency	Array size	Maximum count rate	Dark count rate	Active area	Cut-off wavelength
Records in 2016	18 ps	None	93%	64	1 Gcps	4 /s/mm^2	0.001 cm^2	5 µm
Current records for isolated devices	**2.6 ps** [1]	**3-5 photons**	**98%** [2]	**4x10^5** [3]	**1.5 Gcps** [4,5]	**4x10^{-5} /s/mm^2** [6]	**0.1 cm^2** [3]	**29 µm** [7]
Expected performance by 2030	**1 ps**	**10**	**99 %**	**10^7**	**10 Gcps**	**1x10^{-6} /s/mm^2**	**1 cm^2**	**100 µm**

[1] Korzh, Zhao et al, ***Nature Photonics*** *14*, 250 (2020)
[2] Reddy et al, ***Optica*** 7, 1649 (2020)
[3] Oripov, Rampini, Allmaras, Shaw, Nam, Korzh, and McCaughan, ***Nature*** 622, 730 (2023)
[4] Craiciu, Korzh et al, ***Optica*** 10, 183 (2023)
[5] Resta et al, ***Nano Letters*** (2023)
[6] Chiles, ***PRL*** 128, 231802 (2022)
[7] Taylor, Walter, Korzh et al, ***Optica***, (2023)

Summary

- High efficiency, low jitter (10-15 ps) detectors are **enabling increased clock rates in quantum communication** (>10 GHz)
- **>1 GHz detection rates** and processing are available
- **Intrinsic photon number resolution** is an additional tool becoming available
- **Large scale arrays** are on the horizon
  - Multiplexing in quantum networks
  - Optical readout in quantum computing
- Ideal for **space-to-group quantum comm**