Time-stamping and counting of single photons using fast camera

Andrei Nomerotski
Brookhaven National Laboratory, Upton NY, USA

26 May 2020

Types of fast Imaging

10^{-4} sec

- "normal" cameras: 0.1 ms → 10 μs

10^{-6} sec

- Burst mode cameras: 1 μs → 10 ns

10^{-9} sec

- Data-driven cameras: 10 → 0.01 nsec

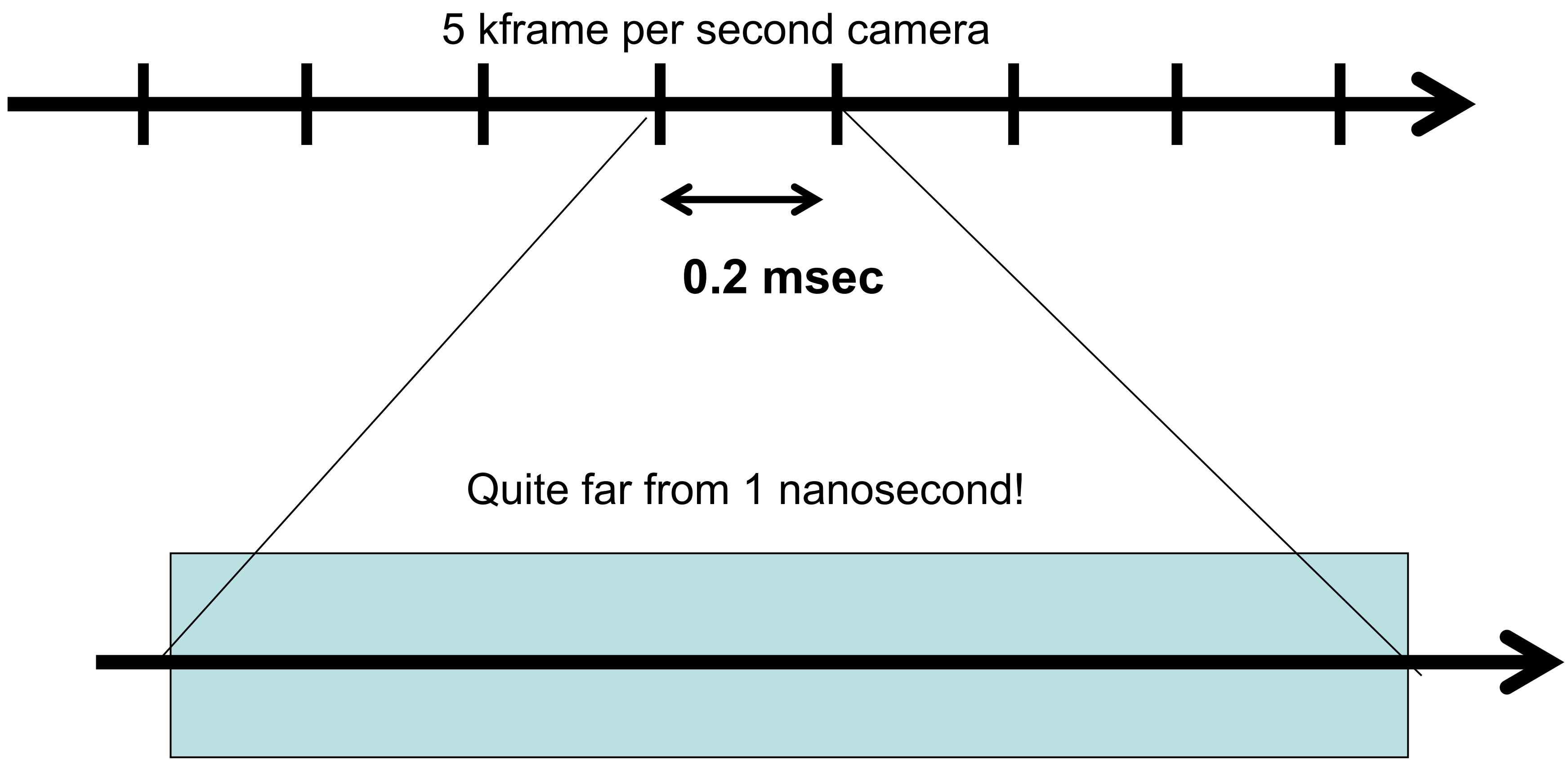
10^{-12} sec

- Streak cameras: 1 psec

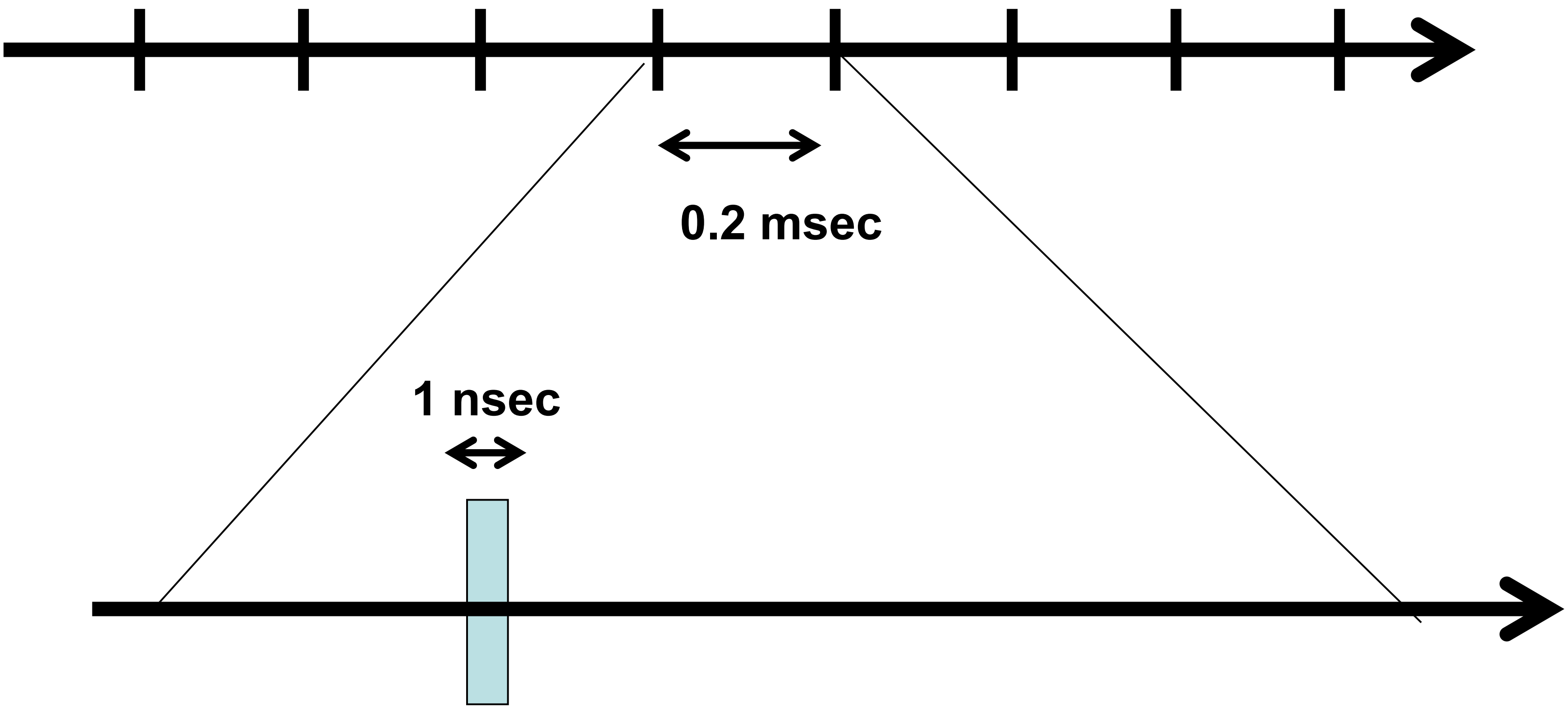
10^{-14} sec

- Repetitive "pump/probe cameras" : fsec

Normally signal is integrated in a slice of time



Can achieve faster imaging by gating (of intensifier)



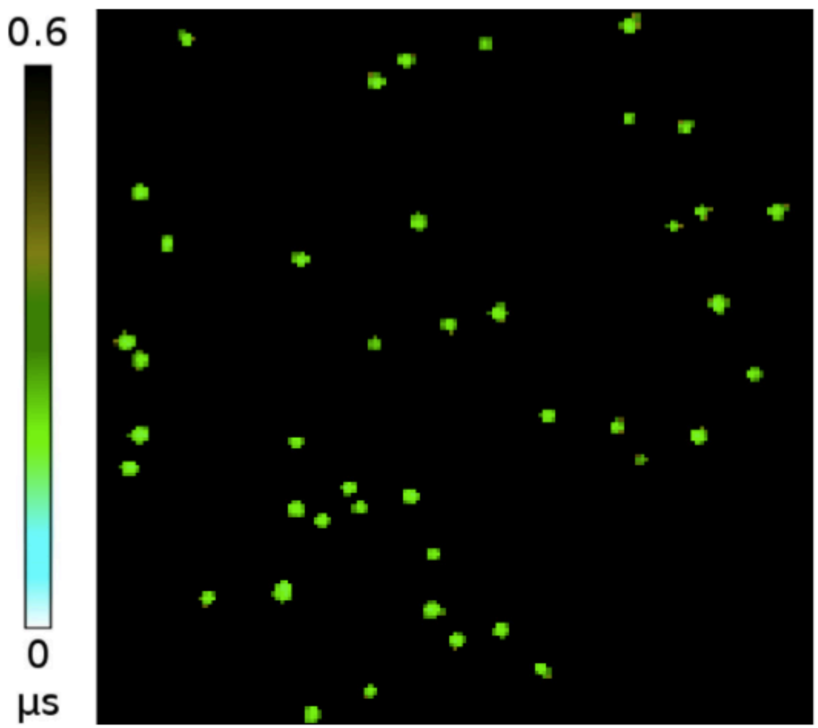
- Smaller time window = Less signal = Lower occupancy
- Ultimately resolve single photons

(at expense of small duty cycle)

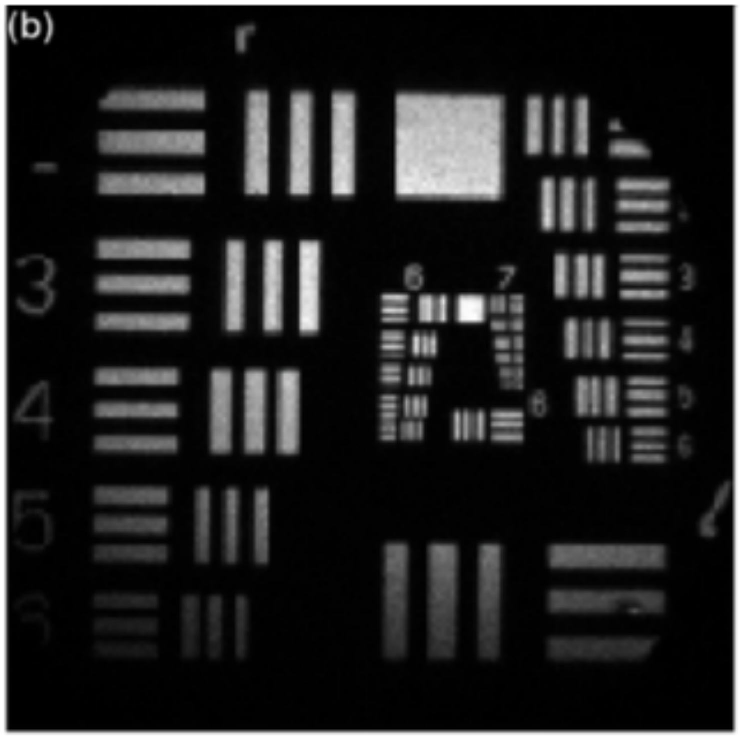
Imaging with photon counting

Photons appear as standalone objects ←→ data driven readout
Has parallels with x-ray imaging and particle detection

Low occupancy



Integrated image



L. M. Hirvonen, M. Fisher-Levine, K. Suhling, and A. Nomerotski: *'Photon counting phosphorescence lifetime imaging with TimepixCam'*. Rev. Sci. Instrum. 88, 013104 (2017).

Alternative Approach to Optical Imaging

- Detect and time stamp photons, one by one, using **intelligent pixels with data-driven readout**
- Accumulate statistics for images, also for more complex analysis (coincidences, correlations etc)

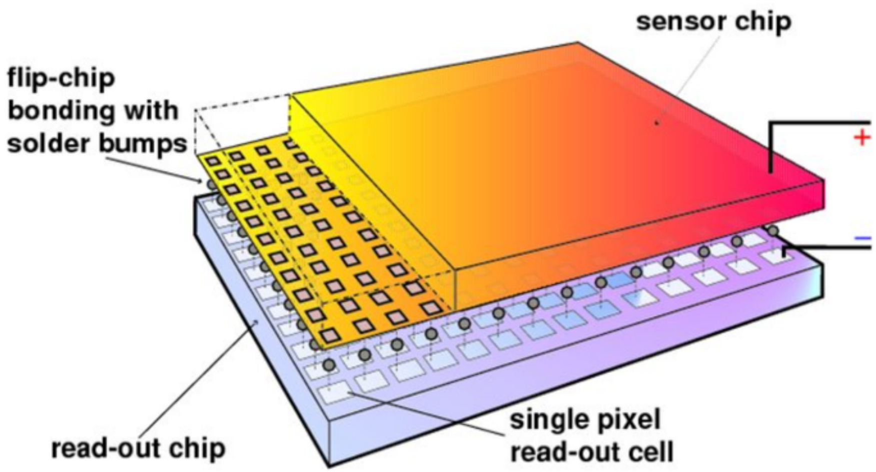
Frame-by-frame imaging →
continuous stream of time stamped single photons

Tpx3Cam: time-stamp 10 MHz flux of photons with 1 ns precision

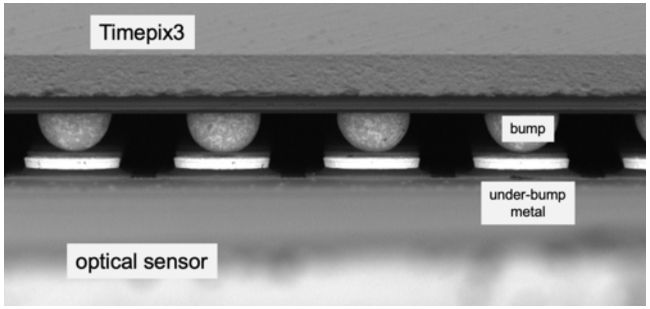
A.Nomerotski, Imaging and time stamping of photons with nanosecond resolution in Timepix based optical cameras, Nuclear Instruments and Methods Sec A, Volume 937 (2019) pp 26-30

Timepix Optical Cameras

Hybrid pixel detectors

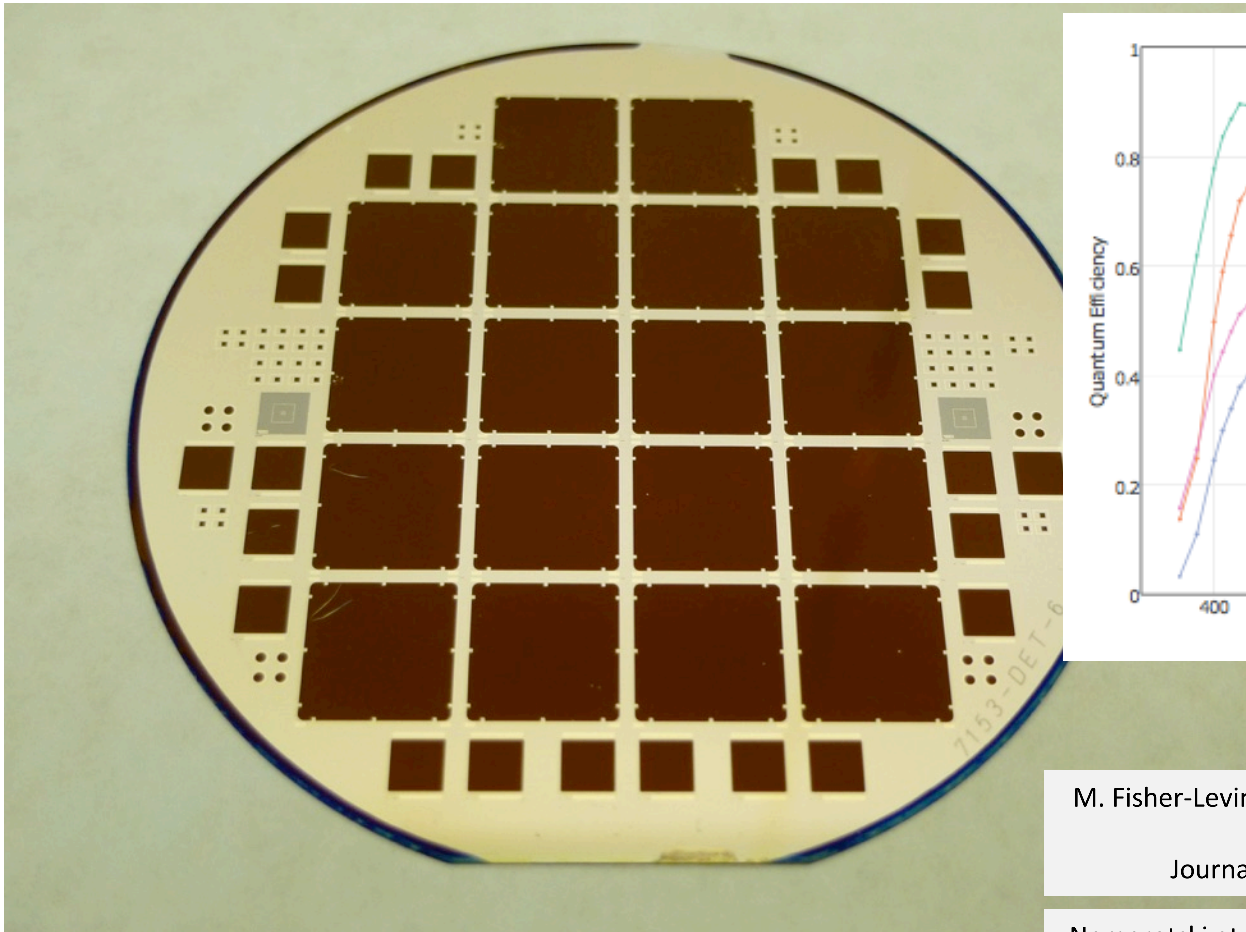


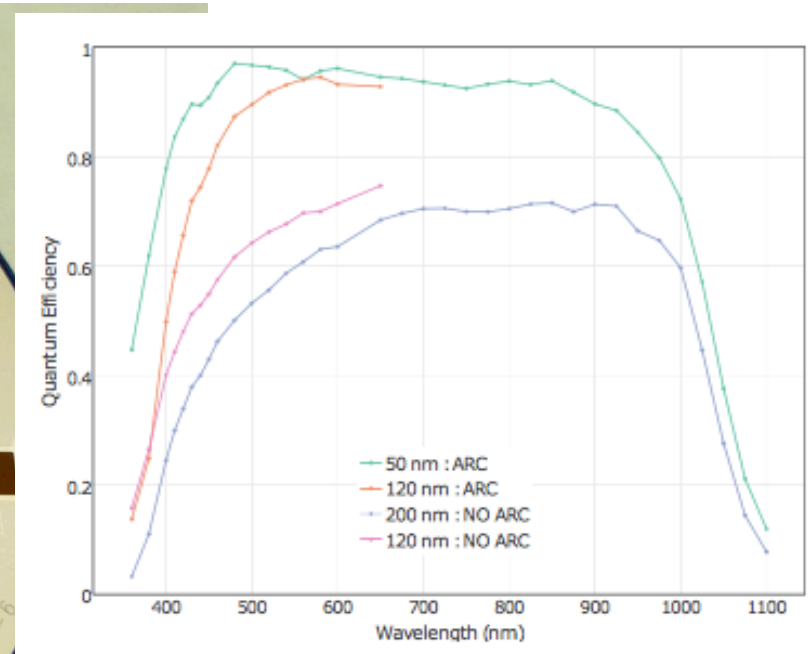
Lukas Tlustos and Erik H. M. Heijne, Performance and limitations of high granularity single photon processing X-ray imaging detectors, in CERN proceedings (2005)



- Decouple design and production of readout chip and sensor
  - Optimize technologies for chip and sensor separately
- Use different sensors with same readouts

Thin window optical sensors





High QE

M. Fisher-Levine, A. Nomerotski, Timepixcam: a fast optical imager with time-stamping, Journal of Instrumentation 11 (03) (2016) C03016.

Nomerotski et al, Characterization of TimepixCam, a fast imager for the time- stamping of optical photons, Journal of Instrumentation 12 (01) (2017) C01017.

Developed at BNL, produced at CNM (Barcelona, Spain)
Surface preparation is very important, inspired by astronomical CCDs (LSST)

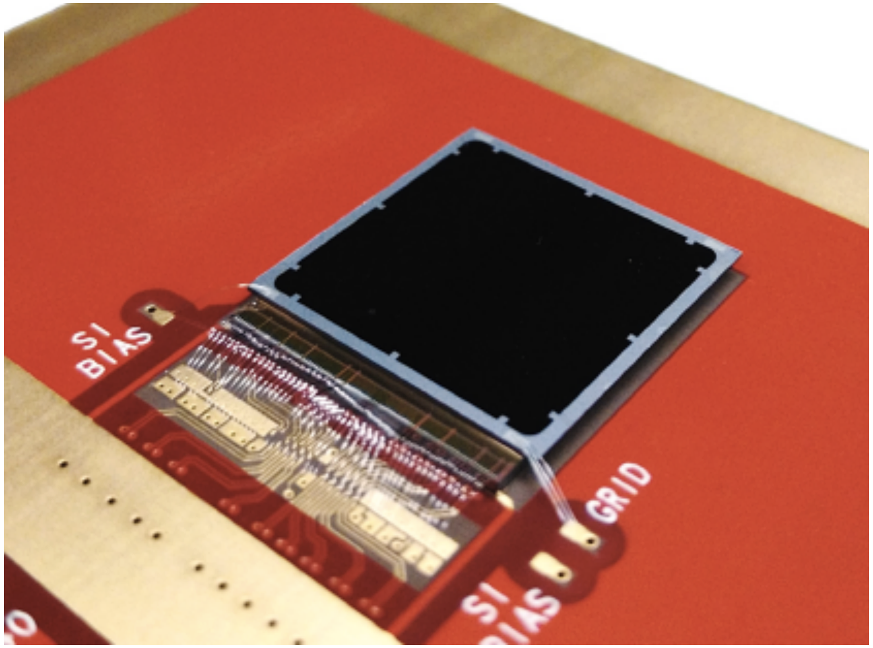
Timepix3 Camera → Tpx3Cam

- Camera = sensor + ASIC + readout
- Timepix3 ASIC: spin-out of R&D for LHC at CERN

- 256 x 256 array, 55 x 55 micron pixel
  - 14 mm x 14 mm active area

- 1.5 ns timing resolution
- Data-driven readout, 500 e threshold 80 Mpix/sec, no deadtime

- each pixel measures time and flux, ~1us pixel deadtime when hit



Sensor is bump-bonded to chip

Use existing x-ray readouts:
SPIDR (Nikhef, ASI)
www.amscins.com

T. Poikela et al, Timepix3: a 65k channel hybrid pixel readout chip with simultaneous ToA/ToT and sparse readout, Journal of Instrumentation 9 (05) (2014) C05013.

Zhao et al, Coincidence velocity map imaging using Tpx3Cam, a time stamping optical camera with 1.5 ns timing resolution, Review of Scientific Instruments 88 (11) (2017) 113104.

Use existing readouts of x-ray detectors:

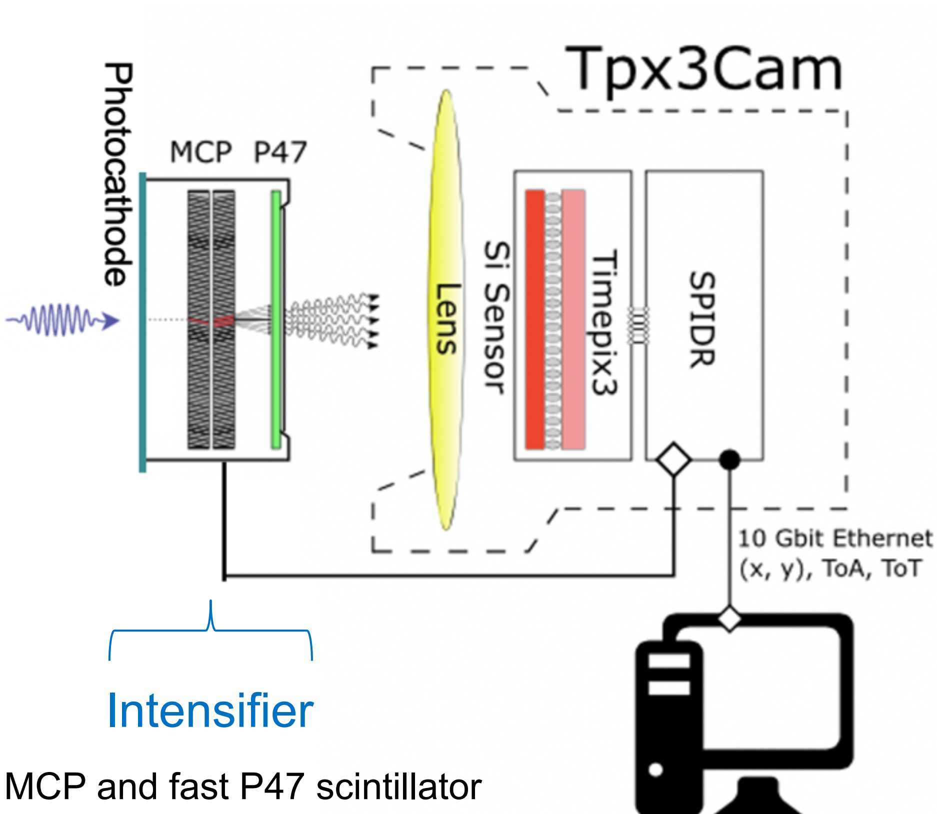
TPX3Cam @ ASI

SPIDR readout for Timepix3 (Nikhef, ASI)

J. Visser et al, SPIDR: a readout system for Medipix3 and Timepix3, Journal of Instrumentation 10 (12) (2015) C12028.

eX readout for Timepix (Imatek)

Single (optical) photons → intensified camera



Intensifier

MCP and fast P47 scintillator support ns time resolution

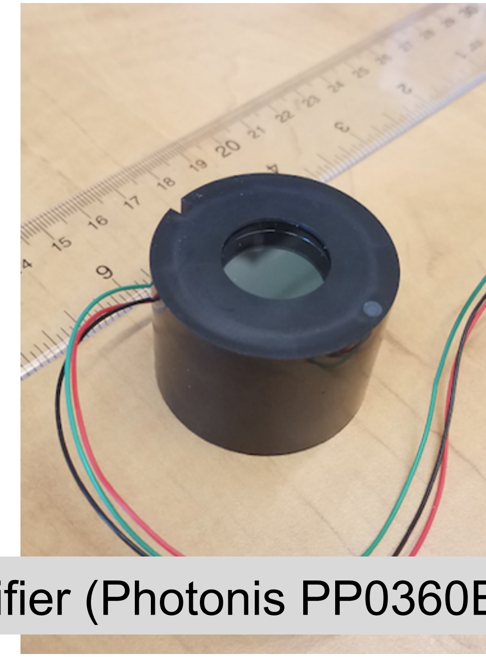
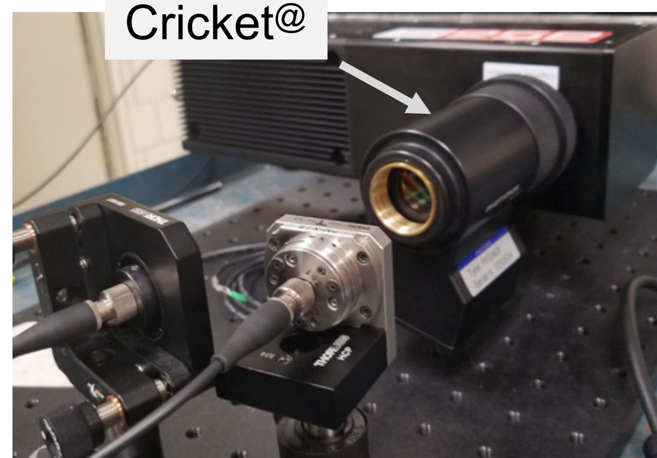


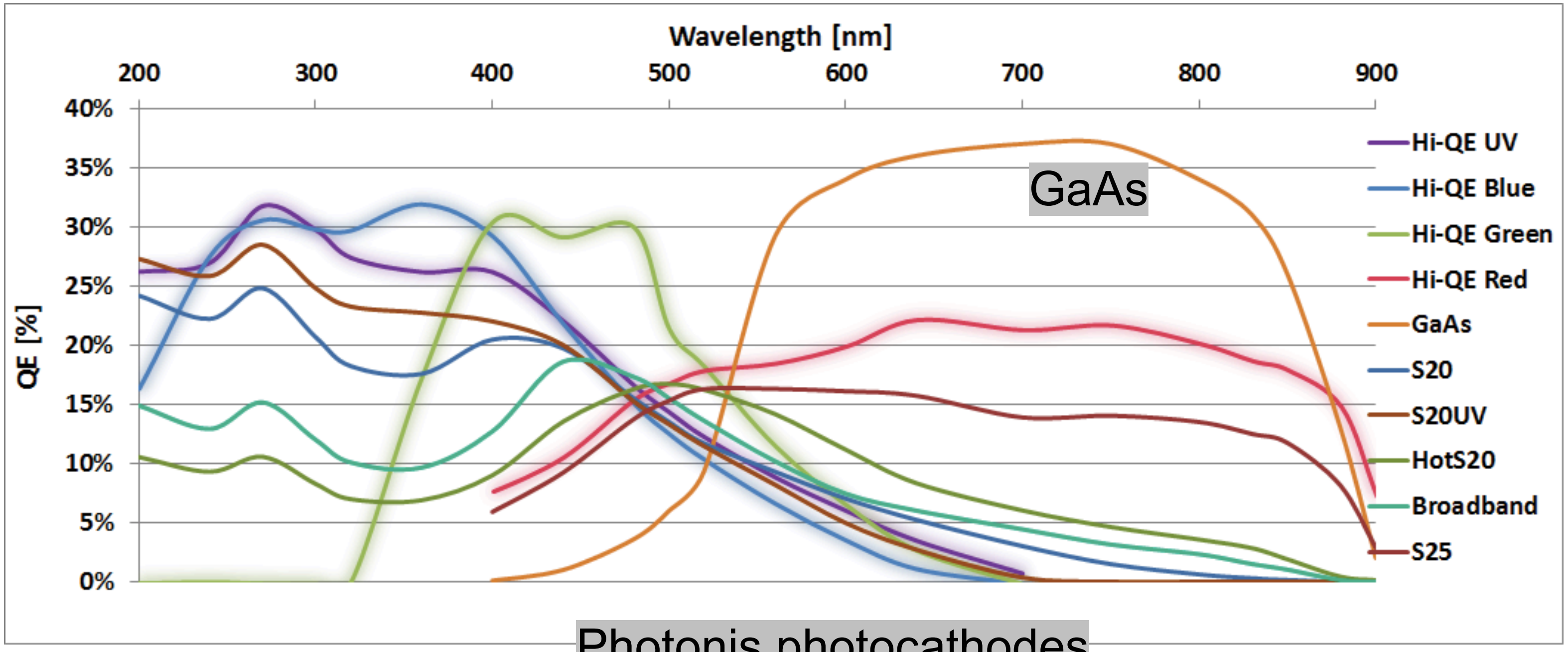
Image intensifier (Photonis PP0360EG)

Cricket@



Photocathodes

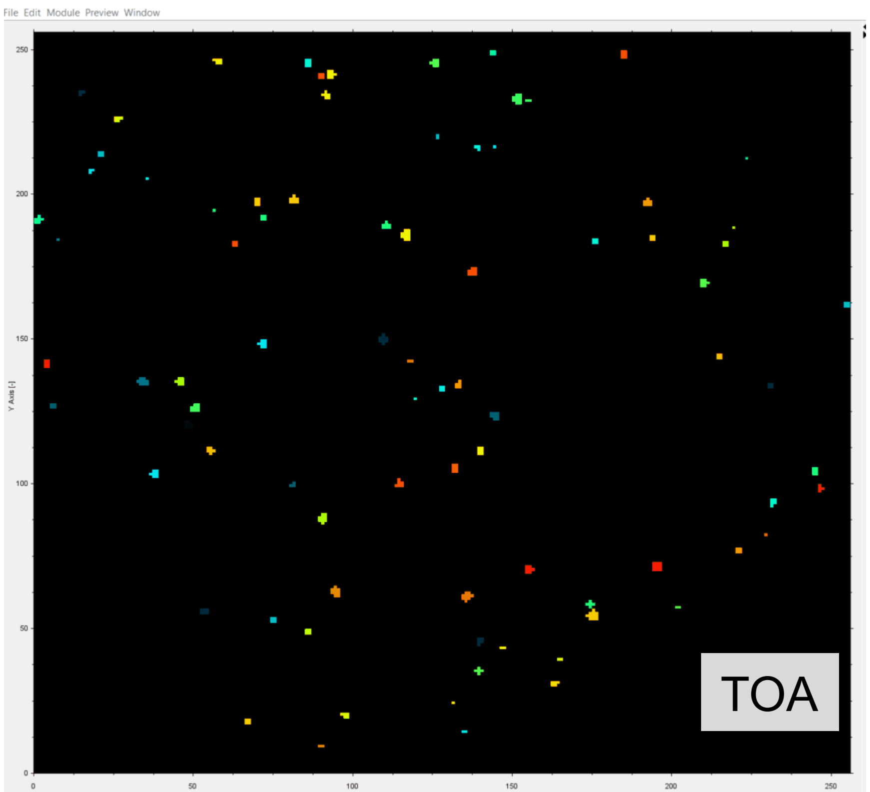
Can choose any wavelength!

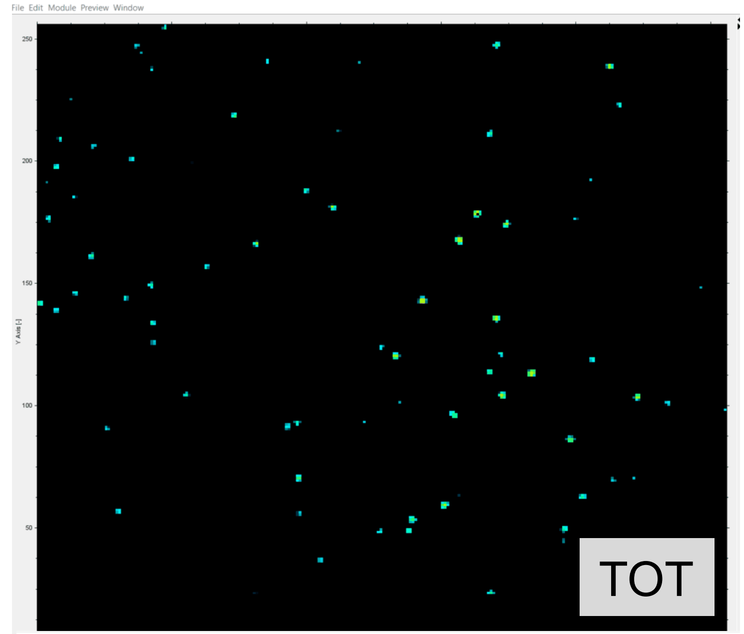


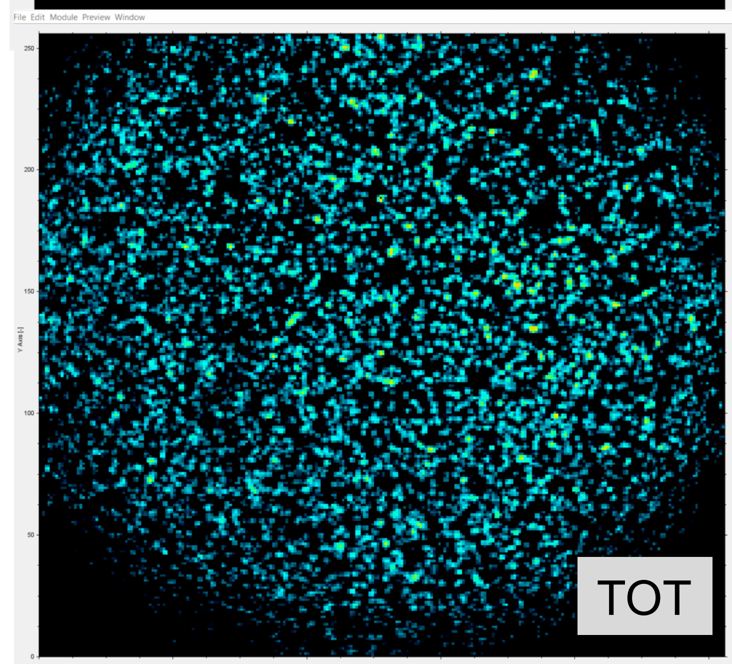
Photonis photocathodes

Single Photons in Tpx3Cam

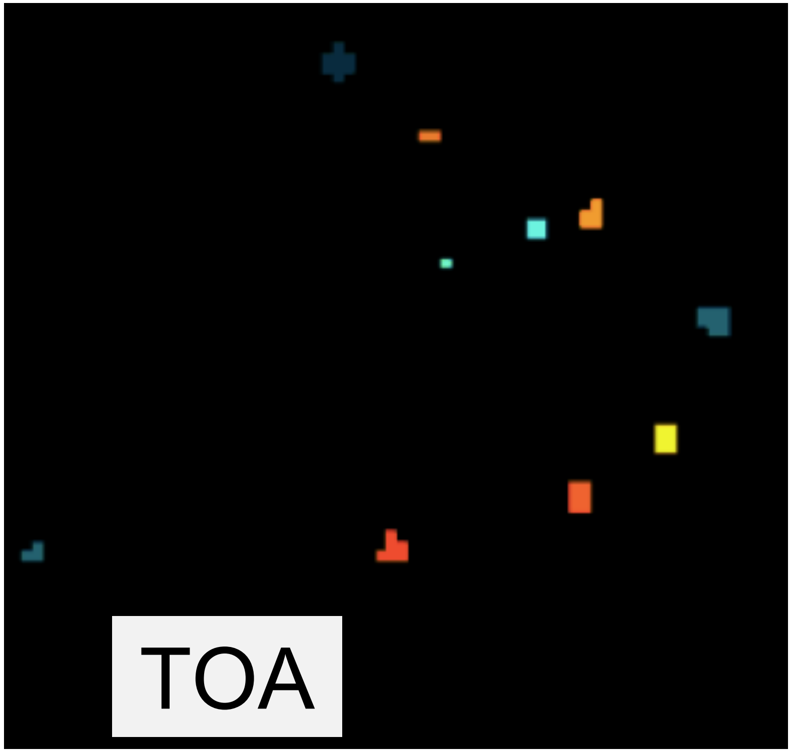
1 ms slice of data
1.5ns time-stamping

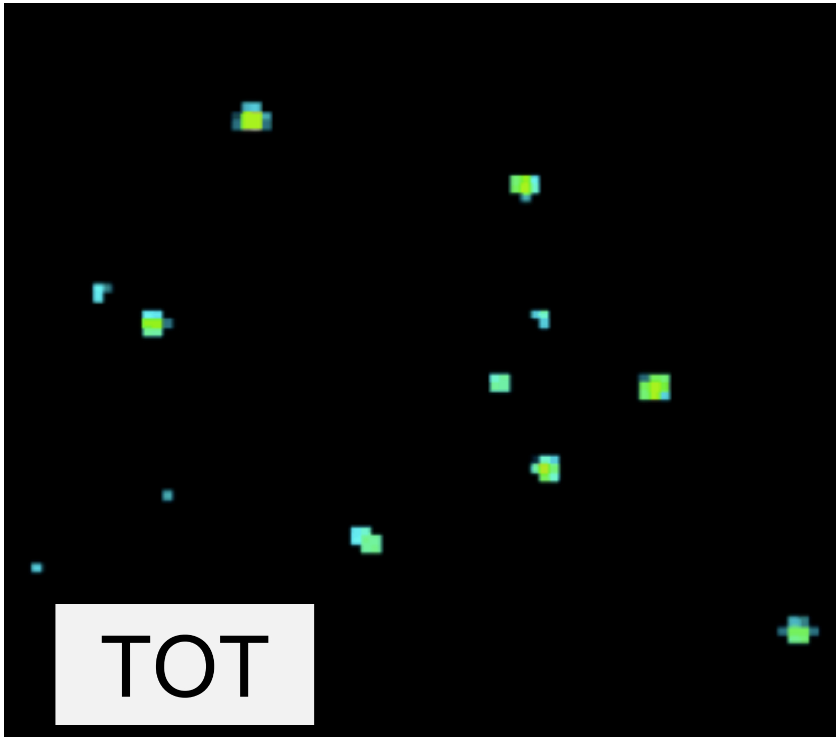






Tpx3Cam + intensifier by Photonis
data taken by J. Long (ASI)





Each photon is a cluster of pixels
→ 3D (x,y,t) centoiding

Spatial resolution: 0.1 pixel / photon

Time resolution: < 1 ns / photon

Applications & Results

Quantum Communications

Collaboration with Stony Brook U (Eden Figueroa group)

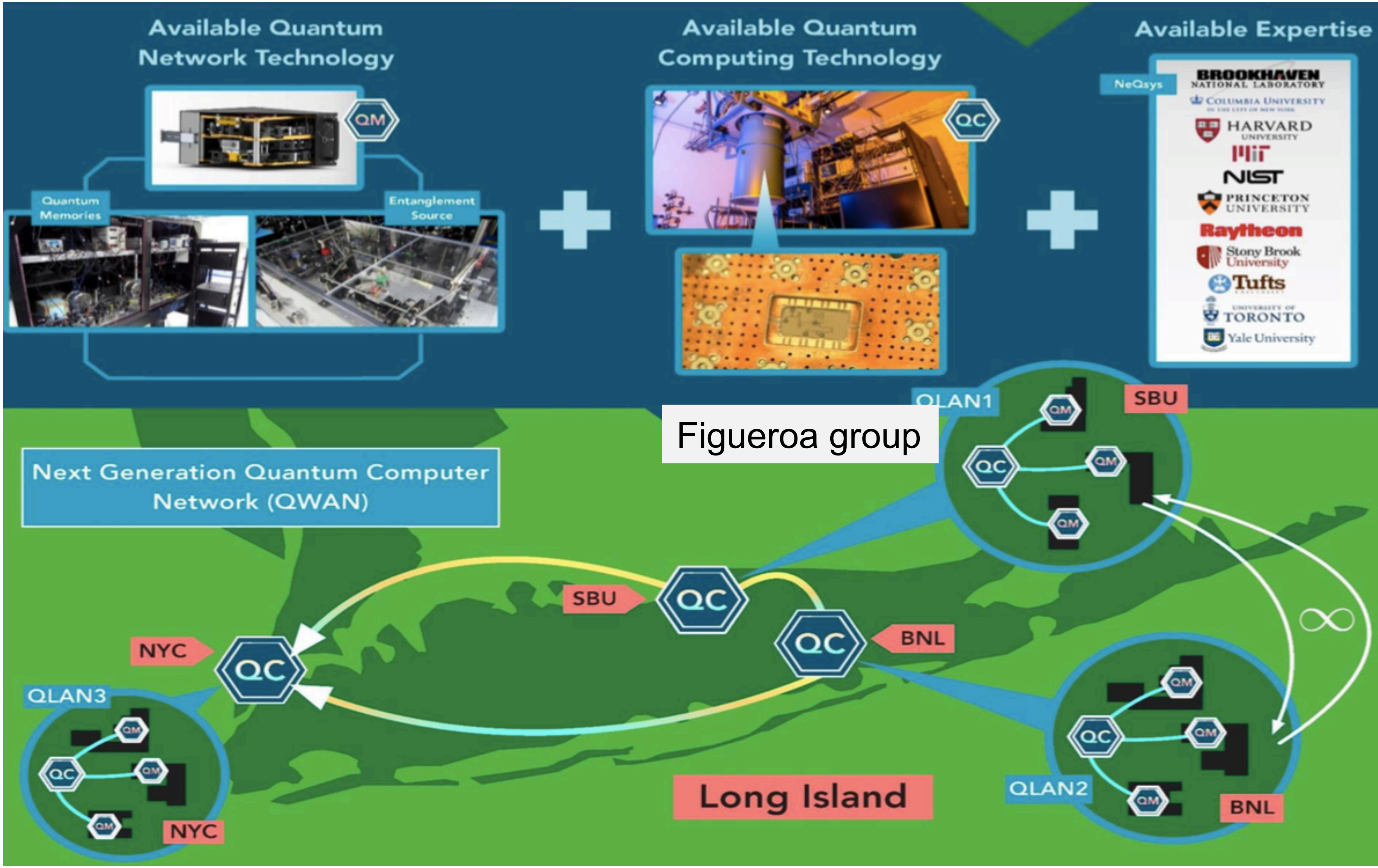
Long-term goals :

Long-distance **quantum network with quantum repeater** using a modular approach based on

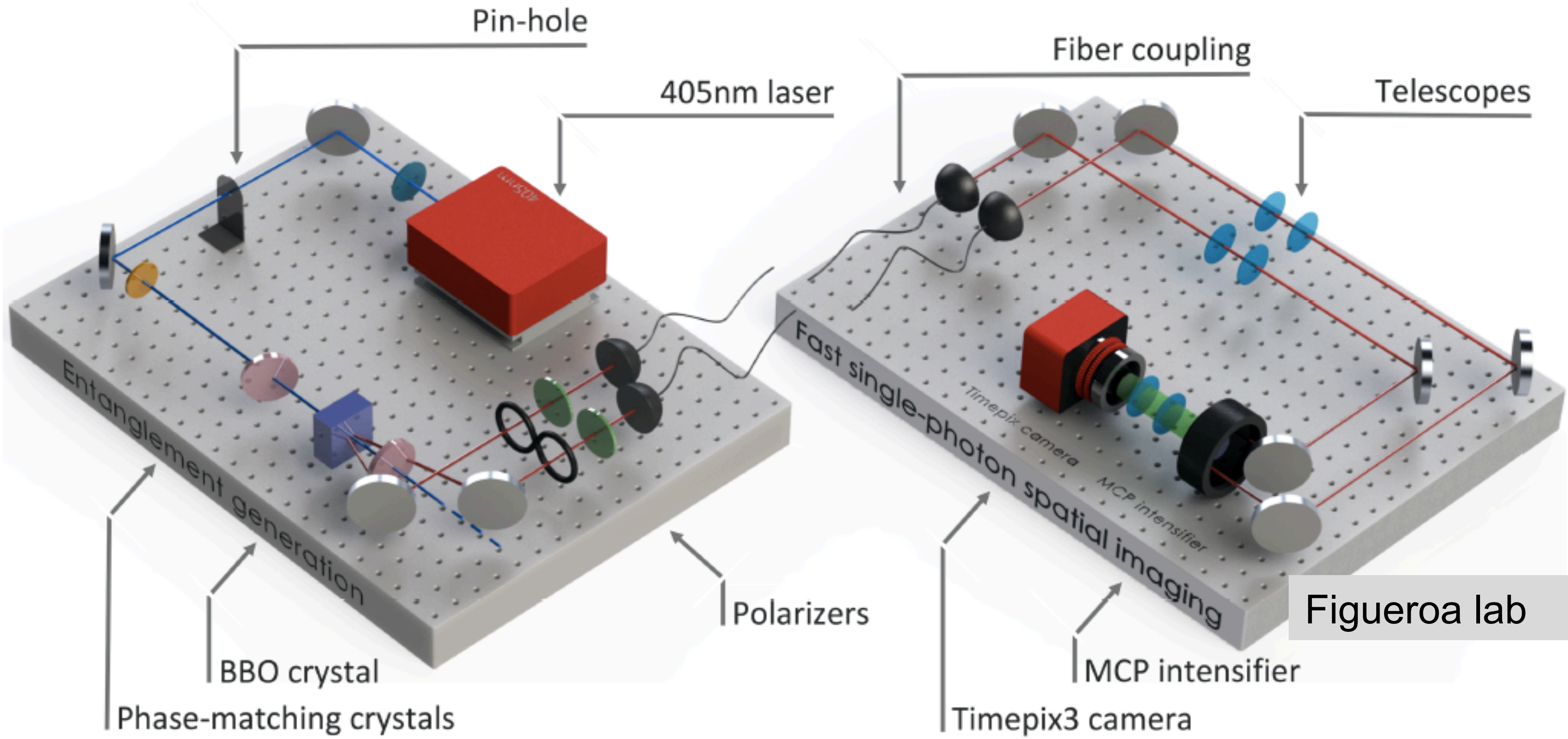
- room temperature Rb quantum memories;
- entangled photon sources compatible with memories;
- characterization devices for single photons

Quantum sensing: investigate how photonic quantum systems entangled at long distances can be applied to sensing

Demonstration of scalability: connect multiple & diverse quantum devices

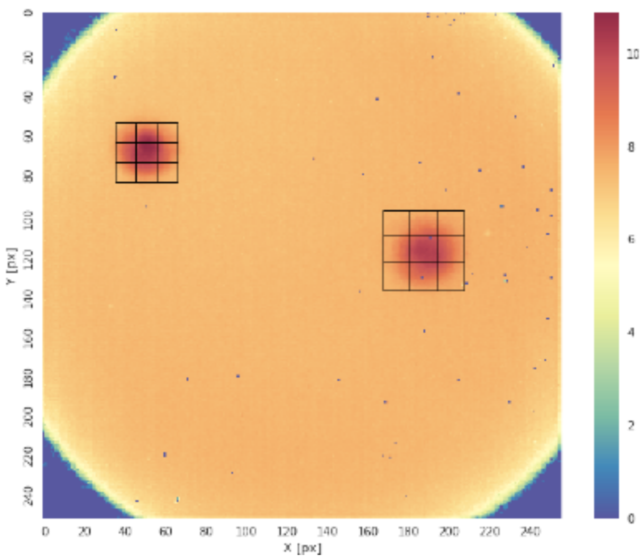

Available Quantum Network Technology
QM
Quantum Memories
Entanglement Source
Available Quantum Computing Technology
QC
Available Expertise
NeQsys
BROOKHAVEN NATIONAL LABORATORY
COLUMBIA UNIVERSITY
HARVARD UNIVERSITY
MIT
NIST
PRINCETON UNIVERSITY
Raytheon
Stony Brook University
Tufts
UNIVERSITY OF TORONTO
Yale University
Figueroa group
QLAN1
SBU
Next Generation Quantum Computer Network (QWAN)
SBU
BNL
NYC
QLAN3
NYC
Long Island
QLAN2
BNL

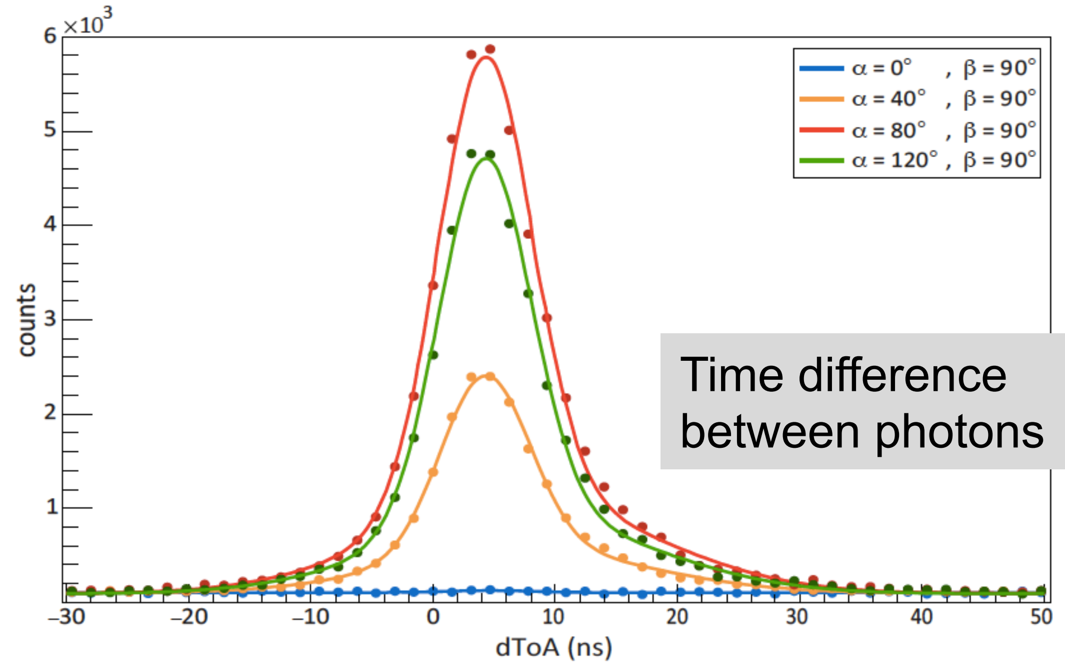
Characterization of Single Photon Down-Conversion Source



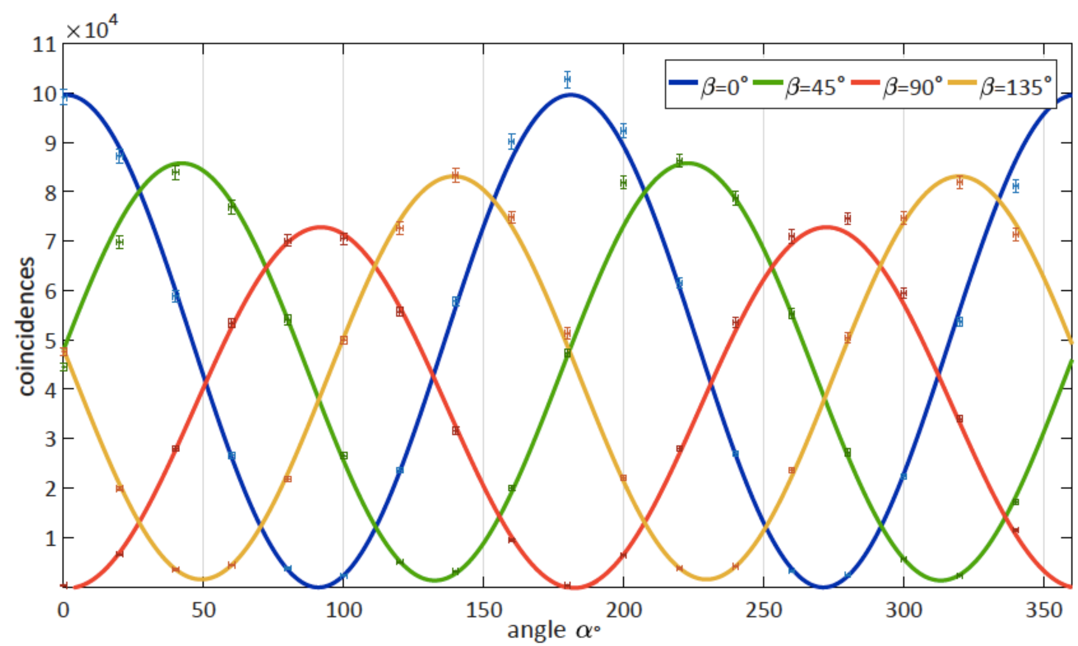
qubit: use H, V photon polarization states

$$|\phi^{\pm}\rangle = \frac{(|HH\rangle \pm |VV\rangle)}{\sqrt{2}}$$





- Find coincidences, plot as function of two polarizations
- Figure of merit: S-value
  - If > 2: photons are entangled
  - max value: $2\sqrt{2} = 2.82$

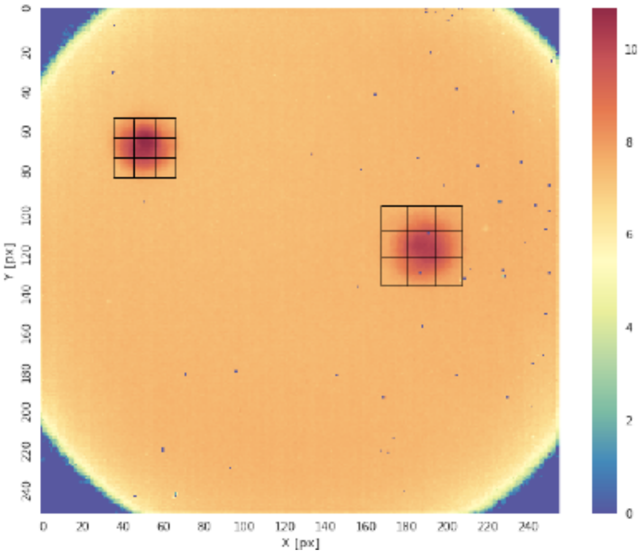


- Measurement:

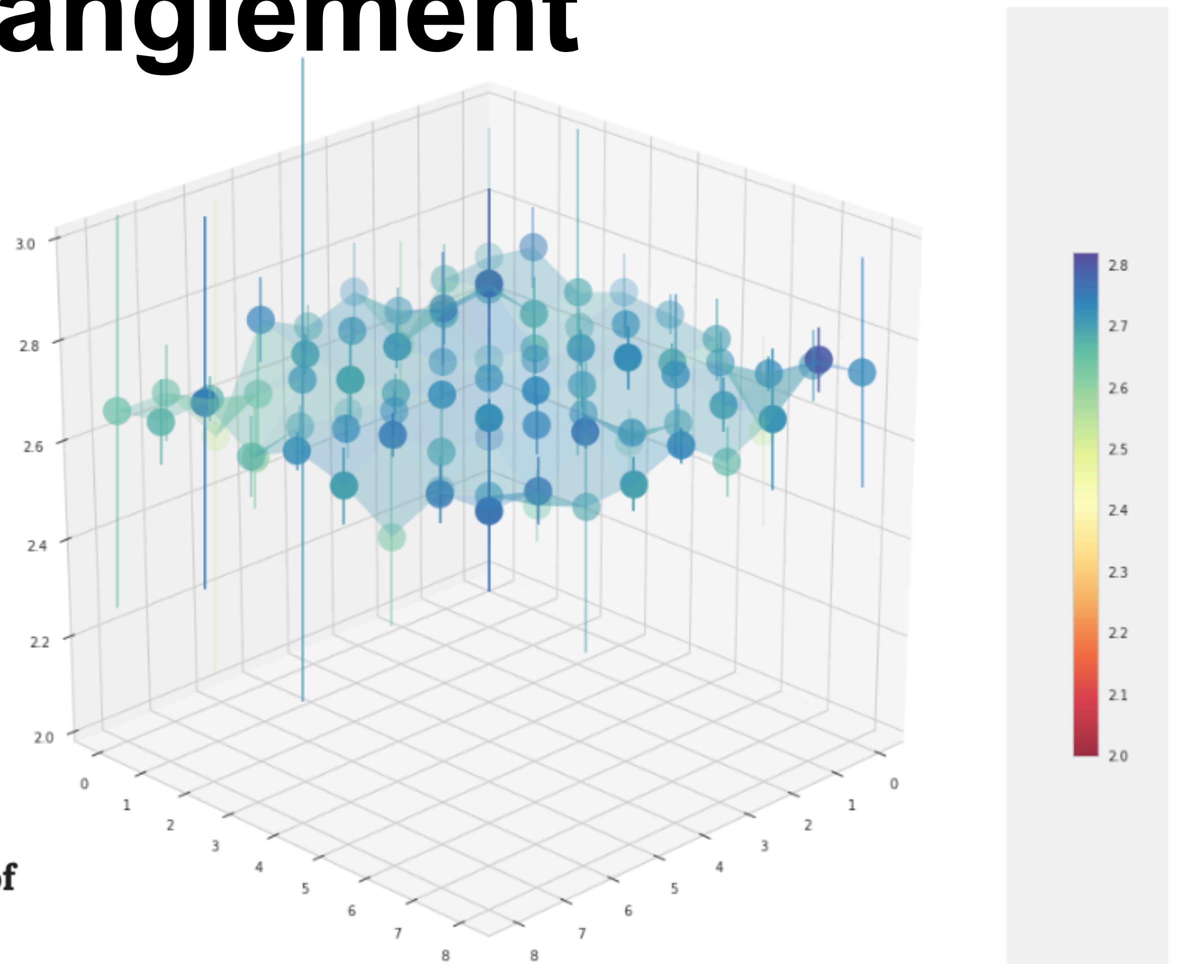
S-value = 2.72±0.02

Time resolution: 2ns

Spatial characterization of tanglement



Measure S-value
for 81 combinations of subareas



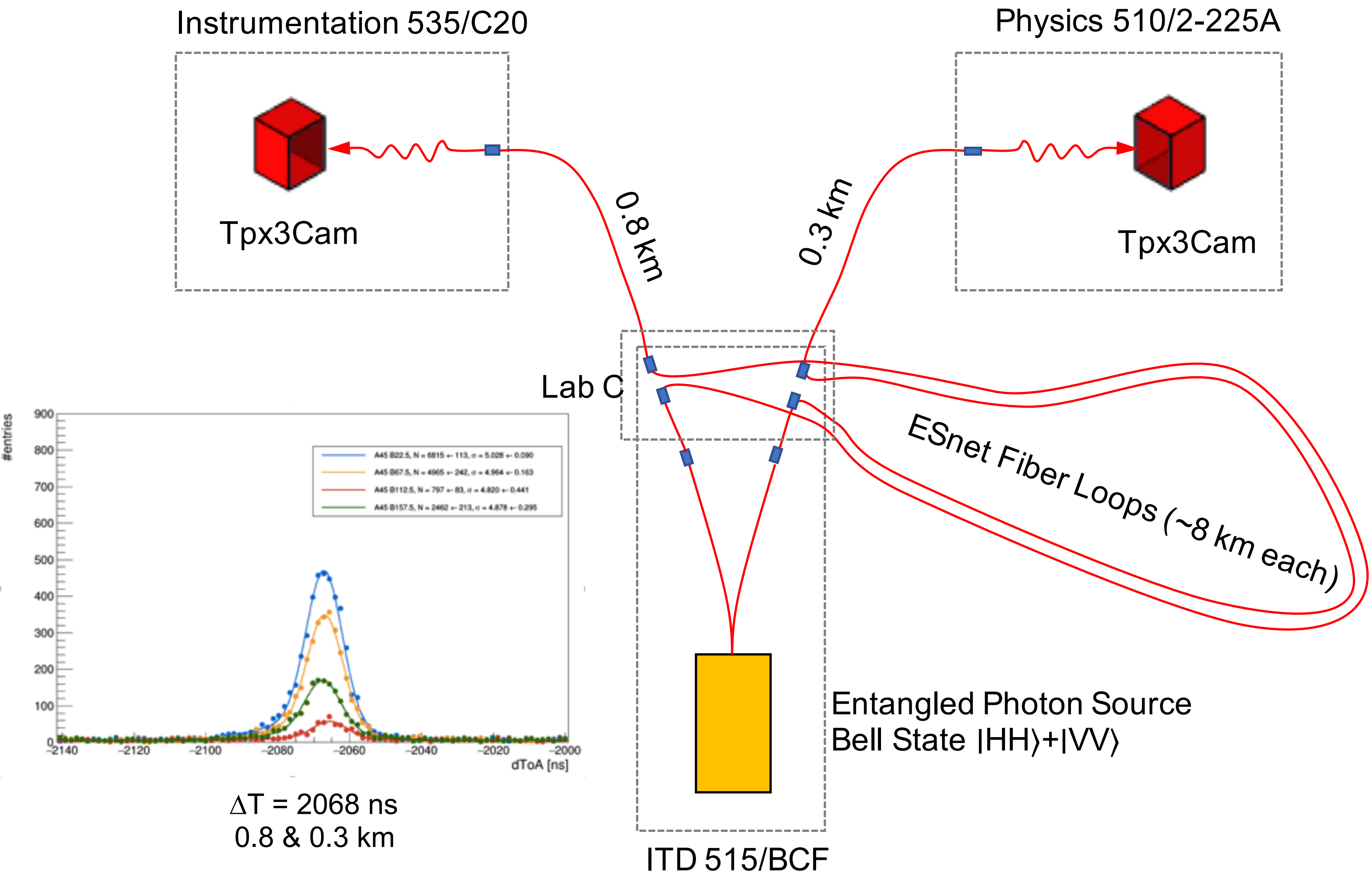
Fast camera spatial characterization of photonic polarization entanglement

Christopher Ianzano, Peter Svihra, Mael Flament, Andrew Hardy, Guodong Cui, Andrei Nomerotski & Eden Figueroa

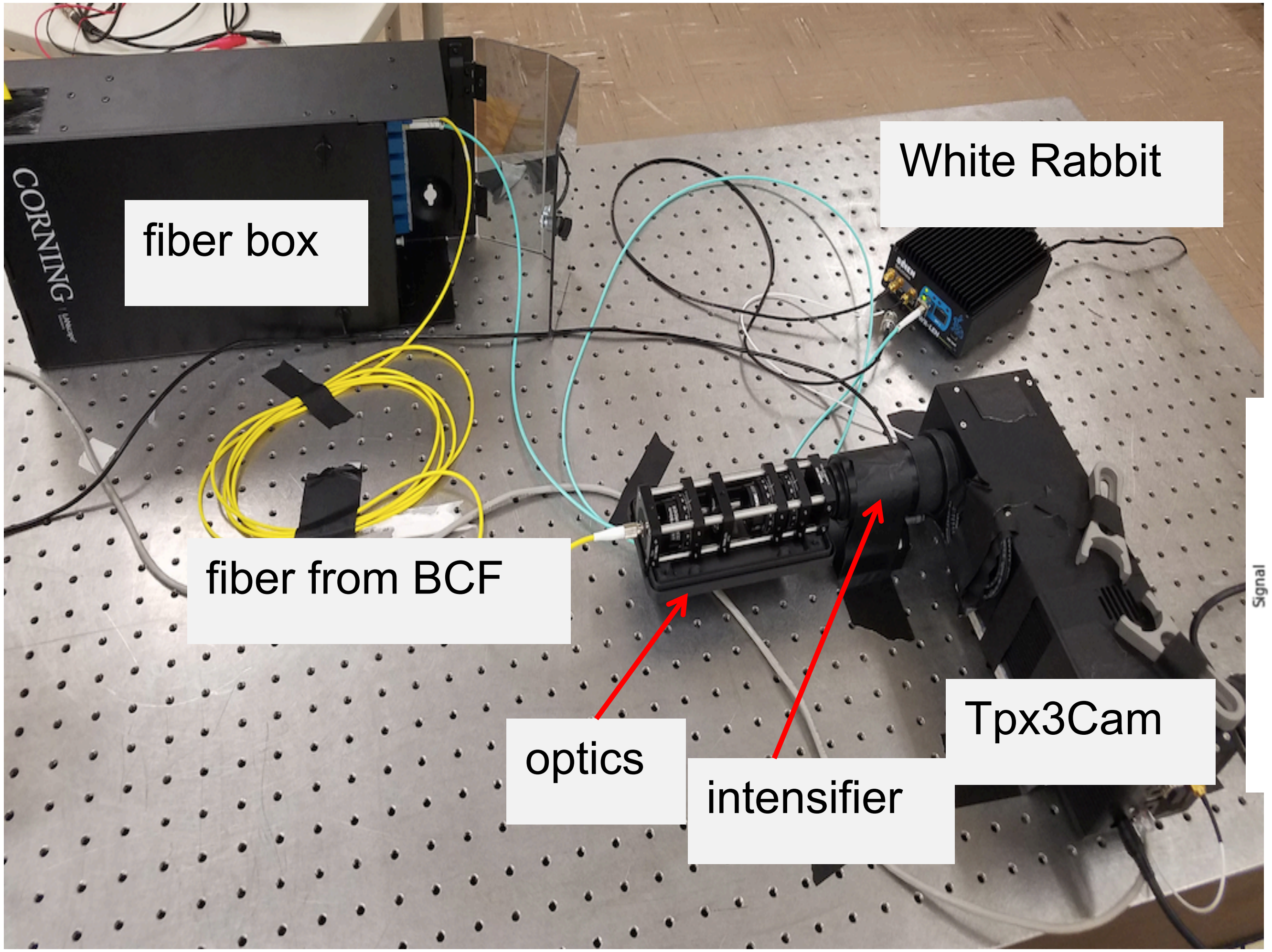
Scientific Reports **10**, Article number: 6181 (2020) | Cite this article

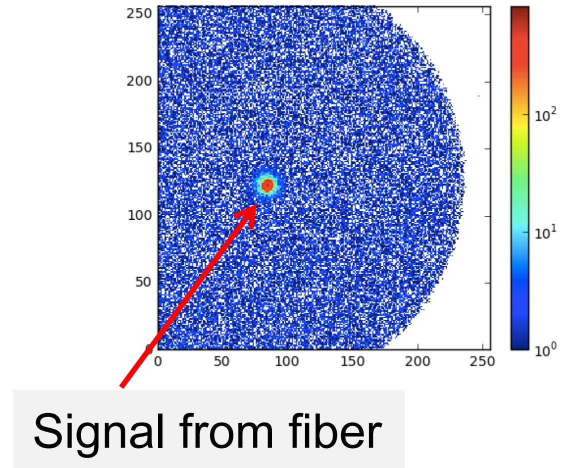
Uniform within errors as expected

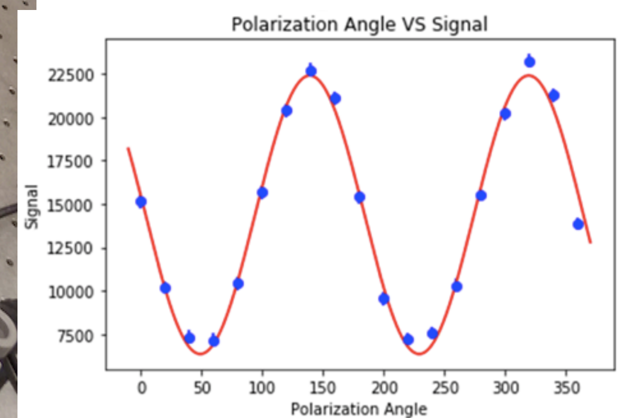
Characterization of entanglement for long-distance network

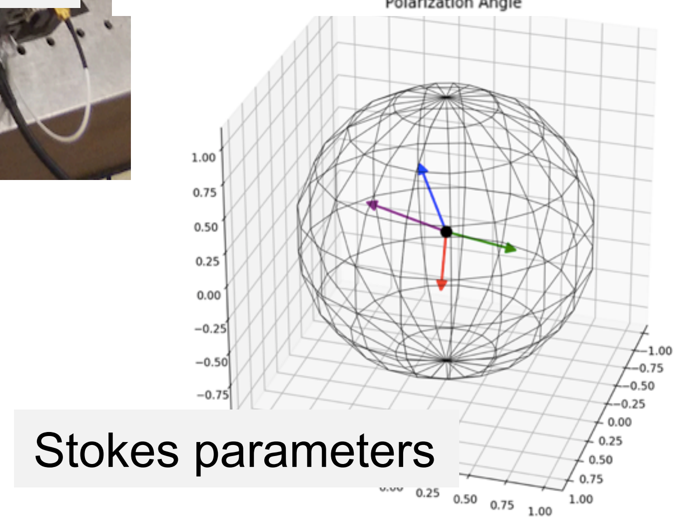


ΔT = 2068 ns
0.8 & 0.3 km









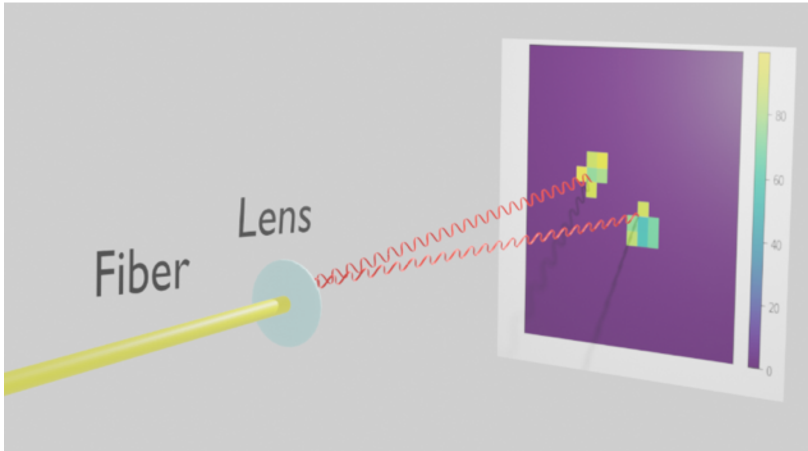
Spatial and temporal characterization of polarization entanglement,
A Nomerotski, D Katramatos, P Stankus, P Svihra, G Cui, S Gera,
..., International Journal of Quantum Information, 1941027

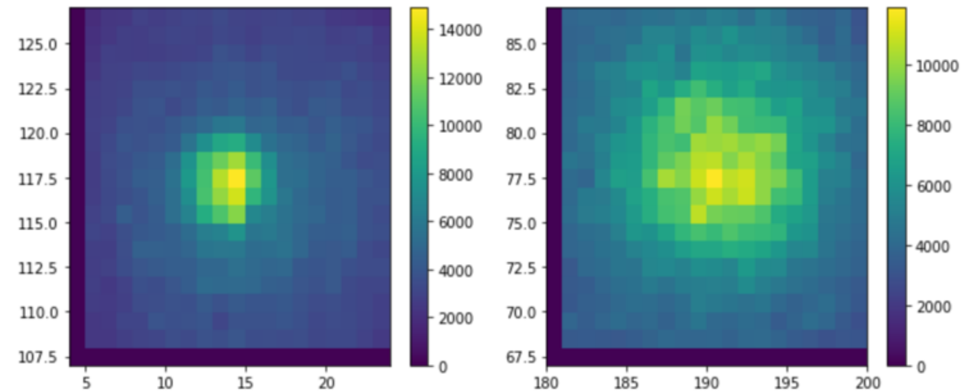
Quantum imaging

- Characterization of single photon sources

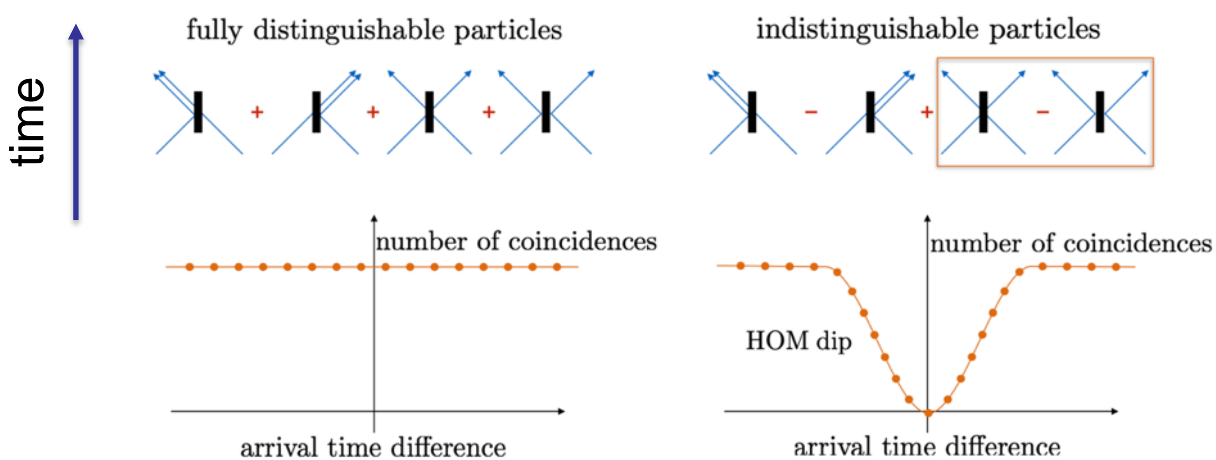
- Quantum target detection
- Ion traps: crystalline structures in 1D and 2D
- Single photon counting

Photon counting in Tpx3Cam



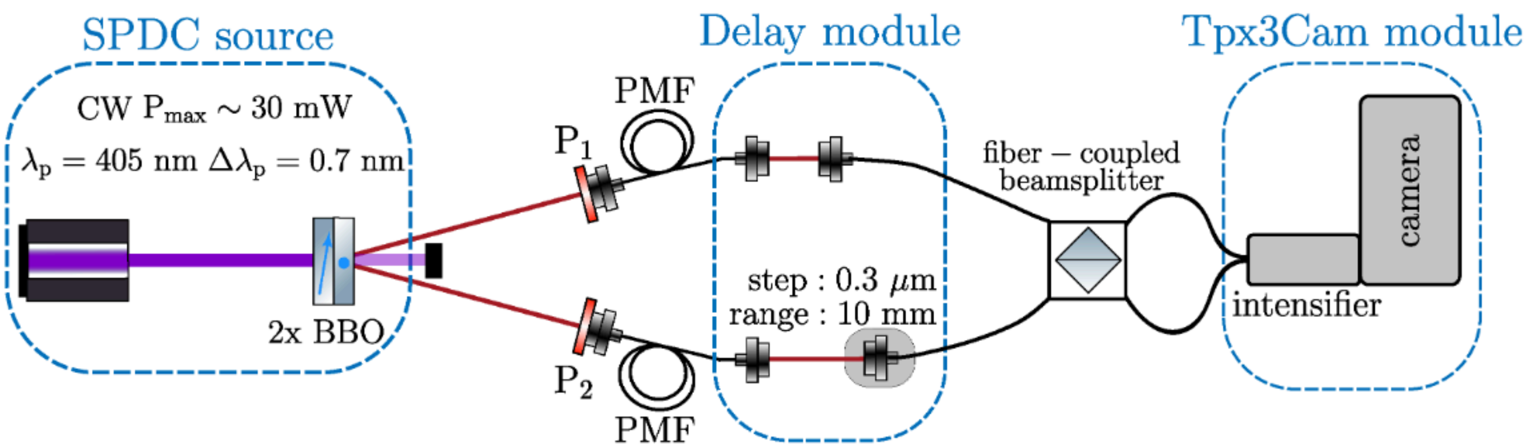


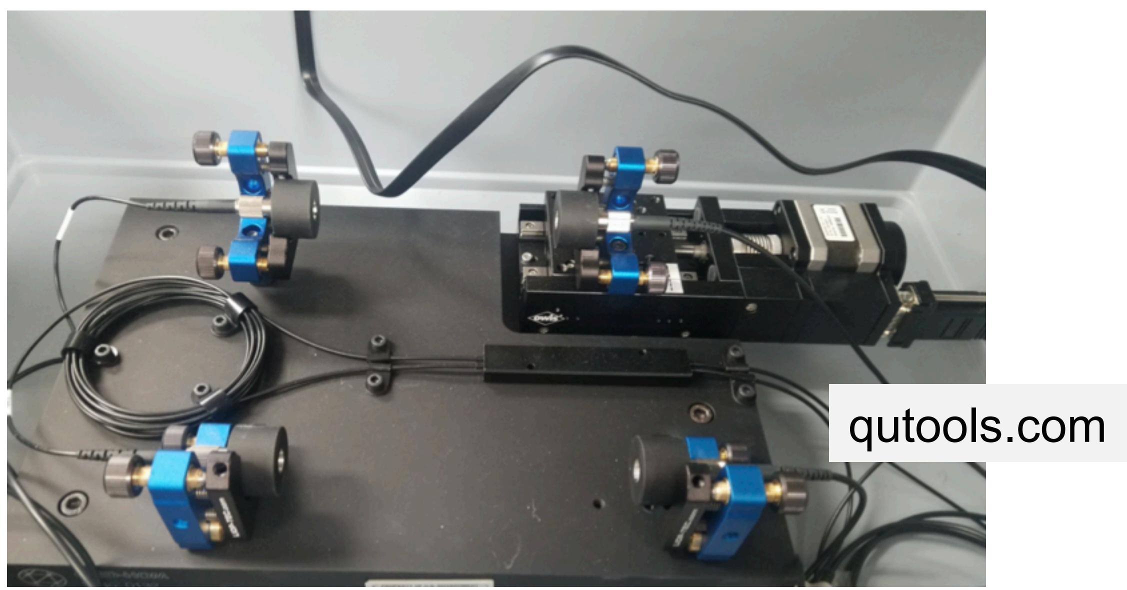
Used Hong-Ou-Mandel effect to characterize photon counting in Tpx3Cam



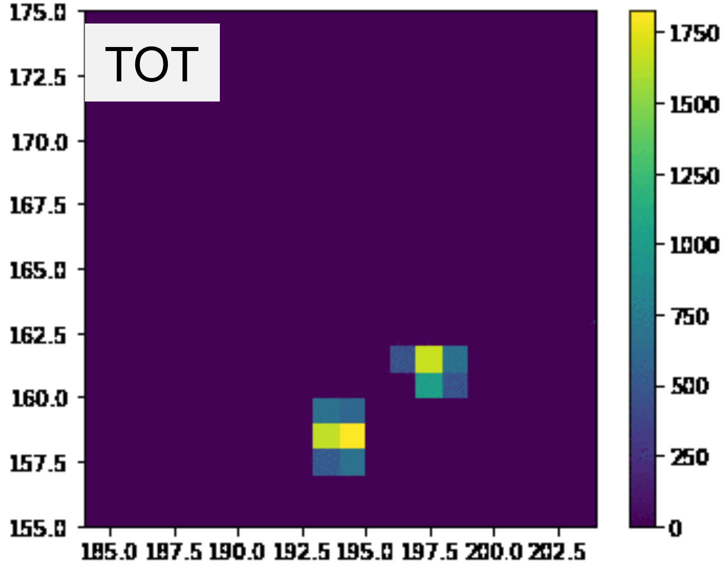
credit: Wikipedia HOM article

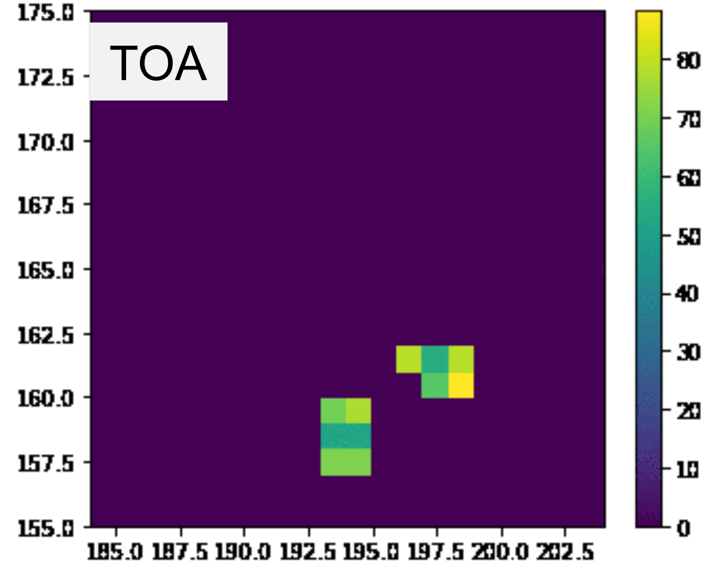
HOM Setup

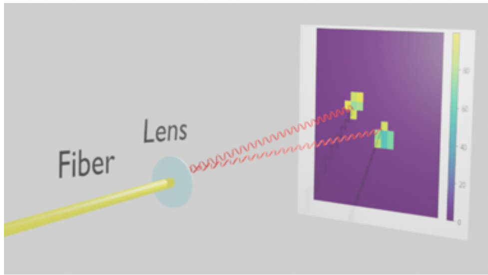

SPDC source
Delay module
Tpx3Cam module
CW $P_{max} \sim 30$ mW
$\lambda_p = 405$ nm $\Delta\lambda_p = 0.7$ nm
2x BBO
P_1
P_2
PMF
PMF
step : 0.3 μm
range : 10 mm
fiber – coupled
beamsplitter
camera
intensifier


qutools.com

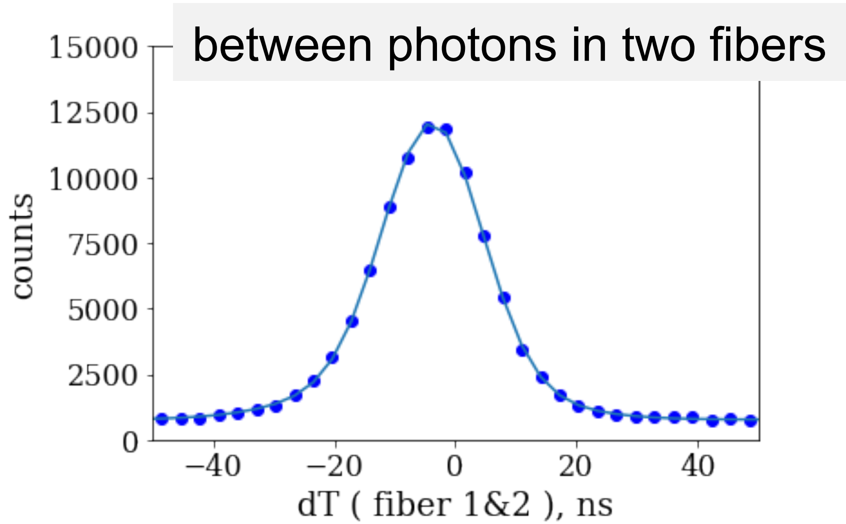
Examples of bunched HOM photons

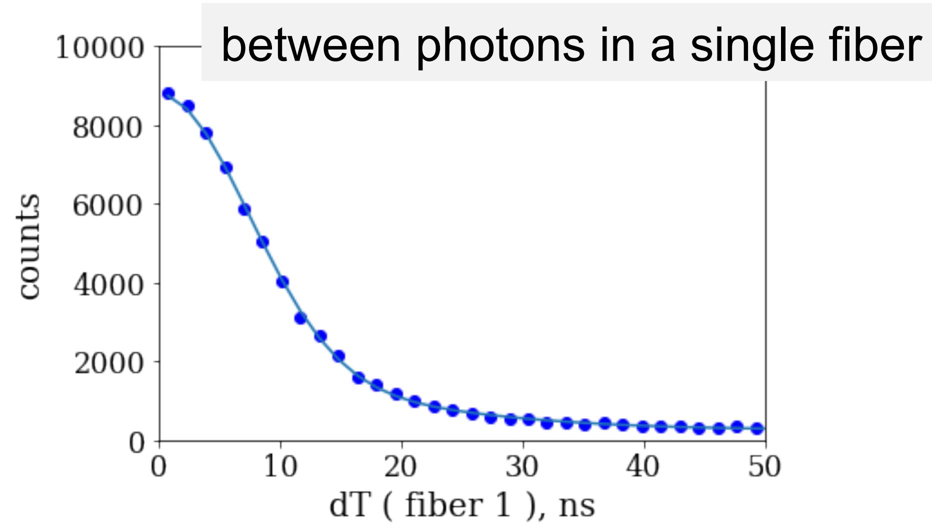






Coincidences



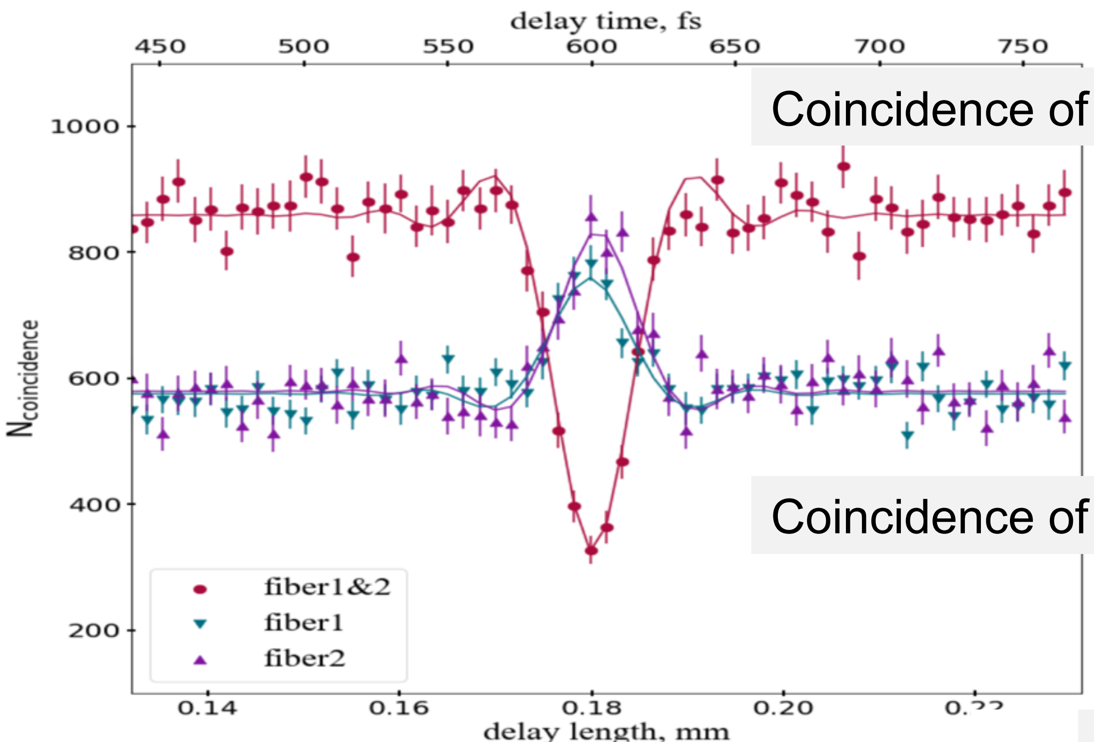


Time difference between two photons – full statistics

Binned as function of delay → HOM dip

Hong-Ou-Mandel effect

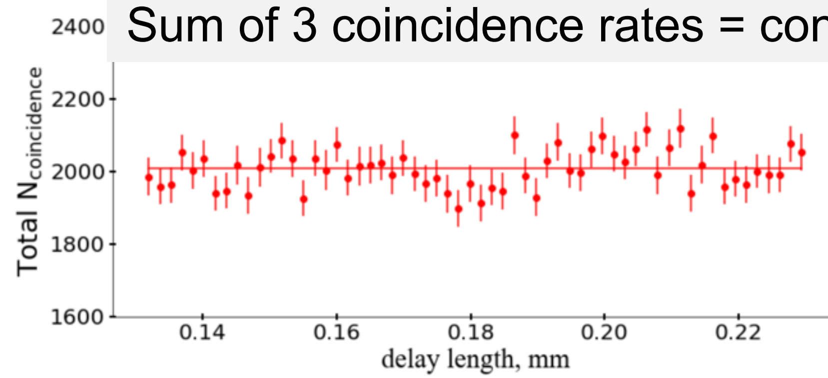
$$f(d-d_0) = \frac{3}{4\sqrt{\pi}} \int dy\, [\mathrm{sinc}\left(y^2\right)]^2\, e^{-iy\frac{\sqrt{4\log 2}(d-d0)}{\mathrm{FWHM}}},$$



Coincidence of photons in two fibers

Coincidence of photons in single fibers

Sum of 3 coincidence rates = const



A. Nomerotski, M. Keach, P. Stankus, P. Svihra, and S. Vintskevich, “Counting of hong-ou-mandel bunched optical photons using a fast pixel camera,” arXiv:2005.07982 (2020).

Proves that photon counting is real

Scalability

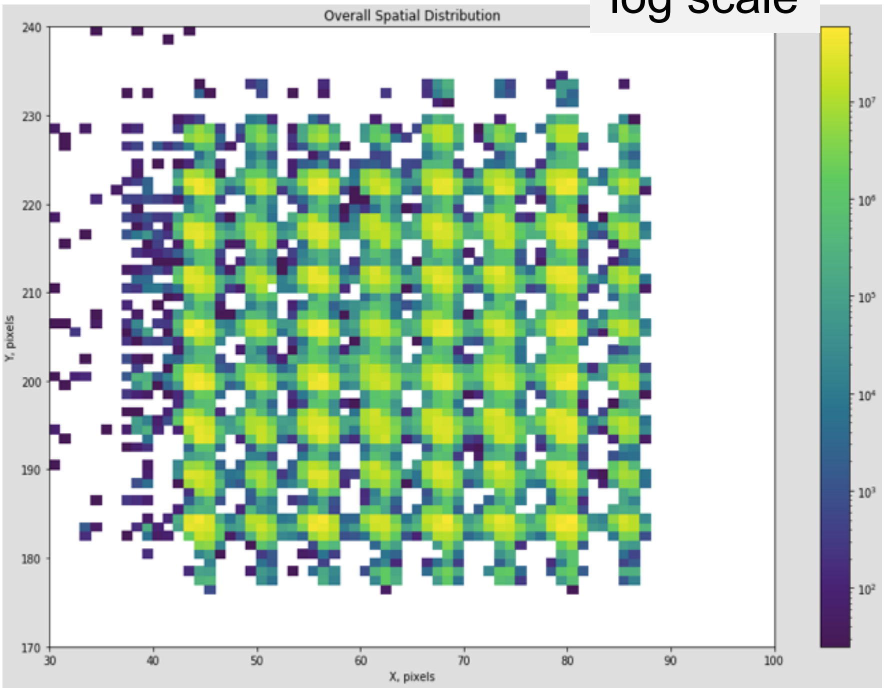
Tpx3Cam supports 10MHz single photon rate :

= 10 x 10 x 100kHz beams

First tries :

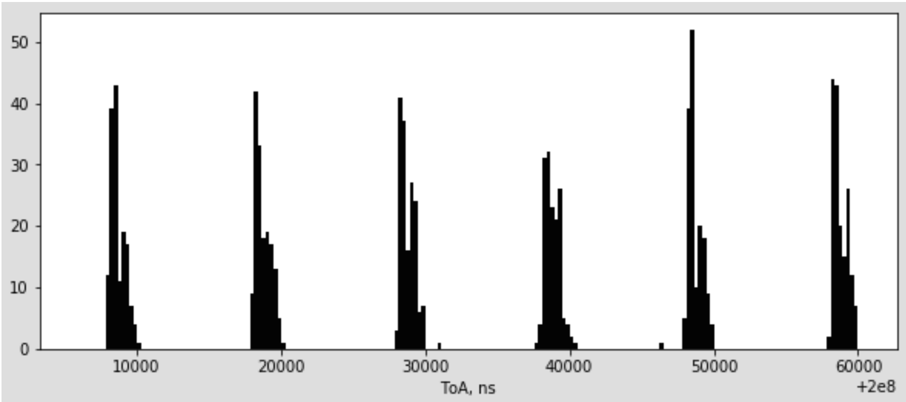
- Used acousto-optical modulator to create 8x8 grid
- Arbitrary routing between spots
- 10 ns time resolution, 1 µs switching

log scale



70 x 70 pixel area with 64 beams

total area 256 x 256 pixels

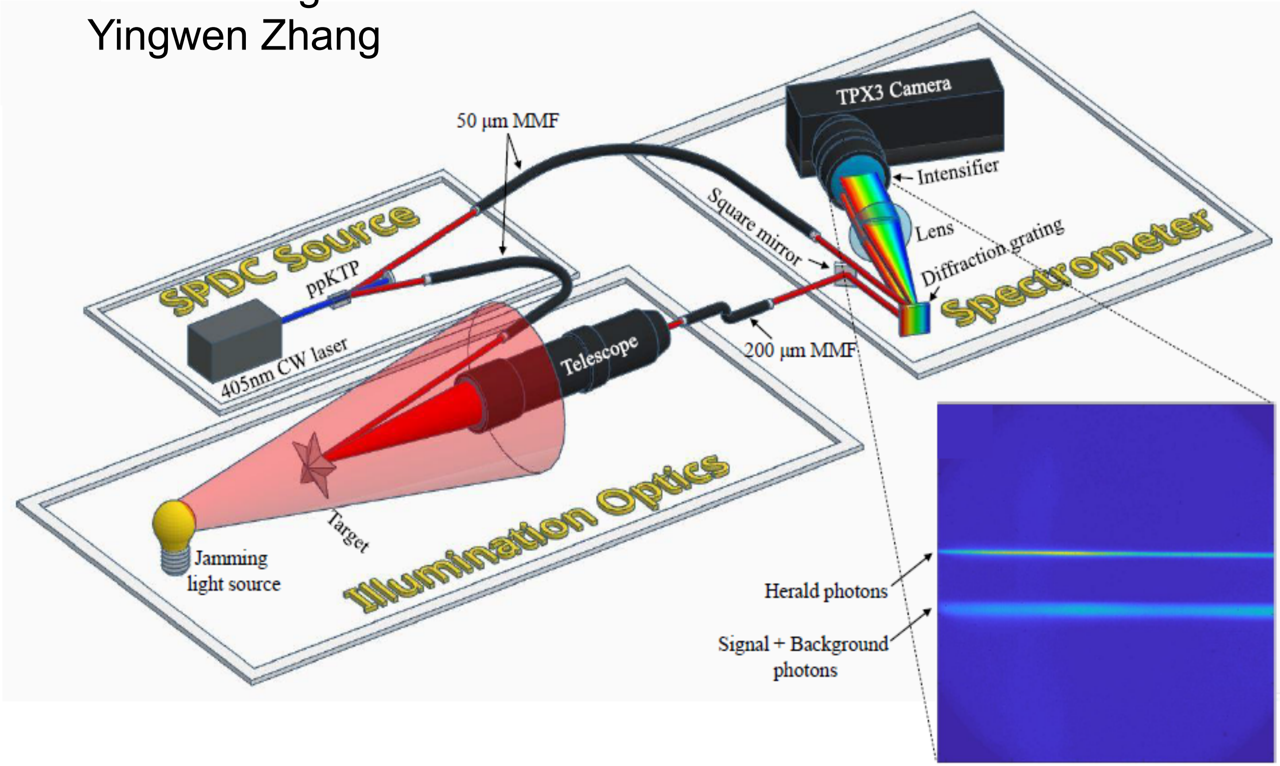


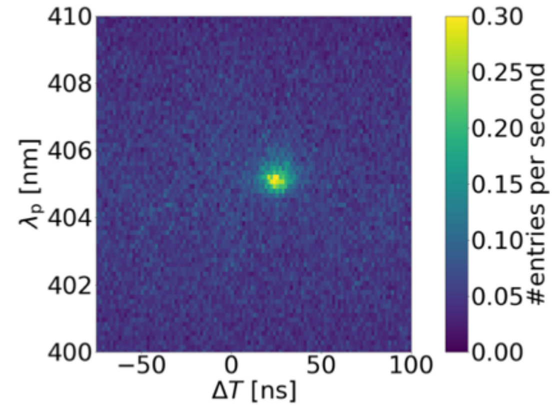
Time, ns

Quantum-Enhanced Target Detection

In collaboration with NRC (Ottawa)

Duncan England
Yingwen Zhang



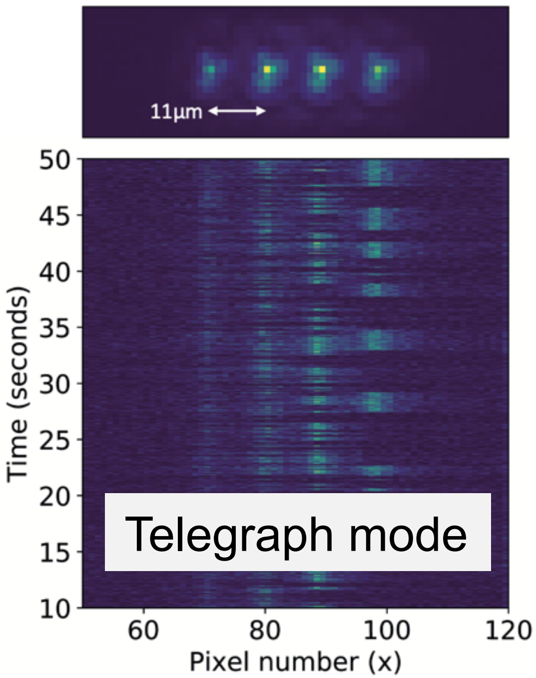


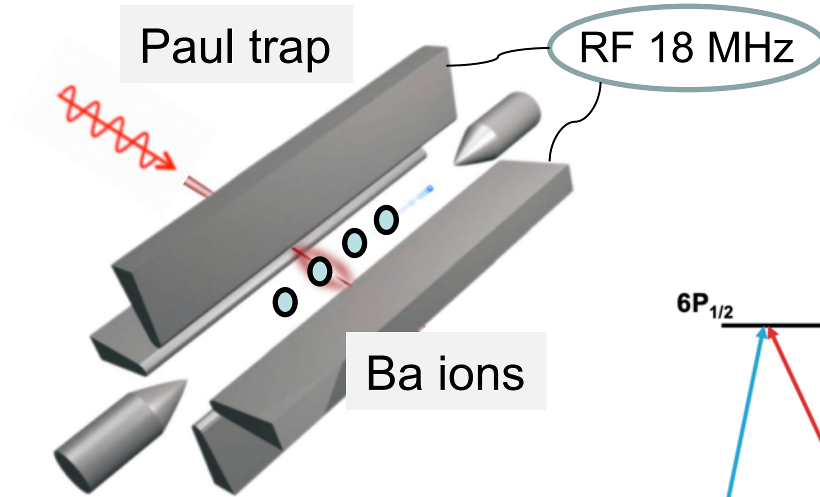
P Svihra, Y Zhang et al, Multivariate Discrimination in Quantum Target Detection, arXiv preprint arXiv:2005.00612

Y Zhang, D England, A Nomerotski, P Svihra, S Ferrante, P Hockett, B Sussman, Multidimensional quantum-enhanced target detection via spectrotemporal-correlation measurements, Physical Review A 101 (5), 053808 (2020)

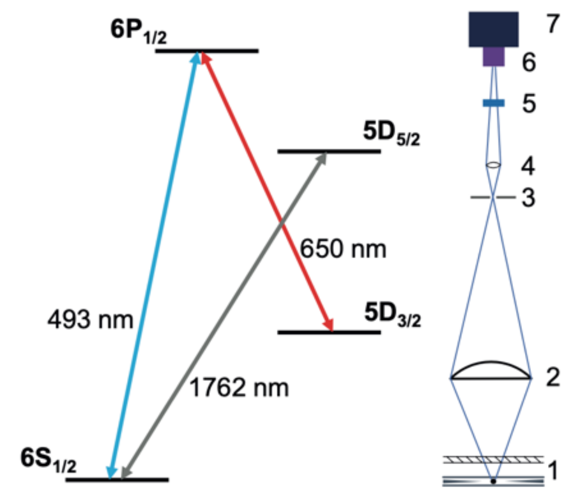
Imaging of trapped ions

Time resolved qubit manipulation (Blinov group, UWash)





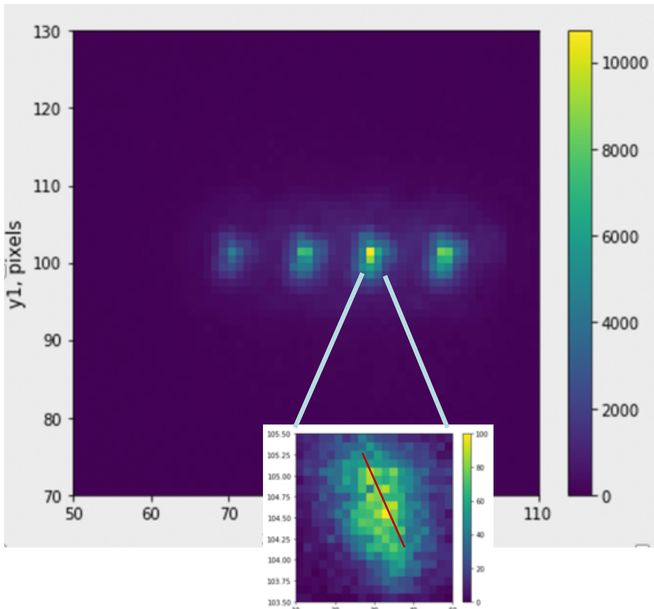
Boris Blinov
Mila Zhukas

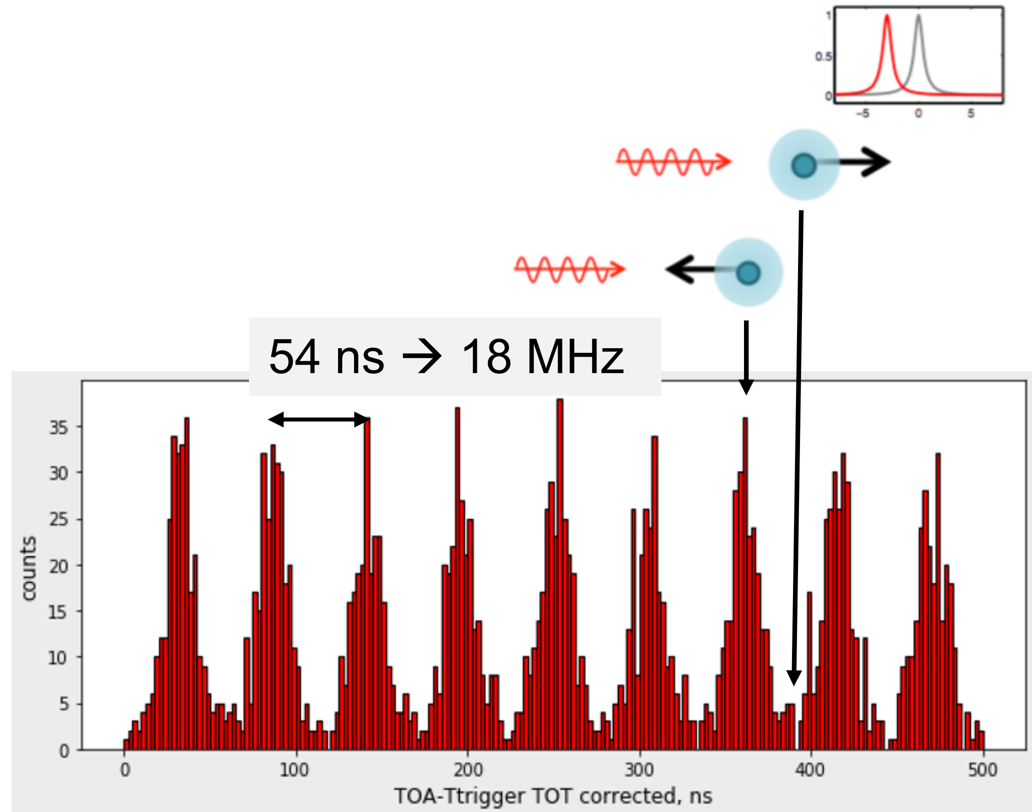


Register 493 nm photons to probe dark/bright state of ion = state of qubit register

Paper in preparation: *Fast Simultaneous Detection of Trapped Ion Qubit Register with Low Crosstalk, M.Zhukas, P.Svihra, A.Nomerotski, B.Blinov*

Time resolved ion oscillations





- Emission rate oscillations due to Doppler shift of laser light wrt moving ion
- Simultaneous time & position information allows to monitor ion micro-motions
- Powerful technique to characterize traps

Paper in preparation

Imaging capable of 1 Mhits/s and 30ps timing

Electron spectroscopy at WSU

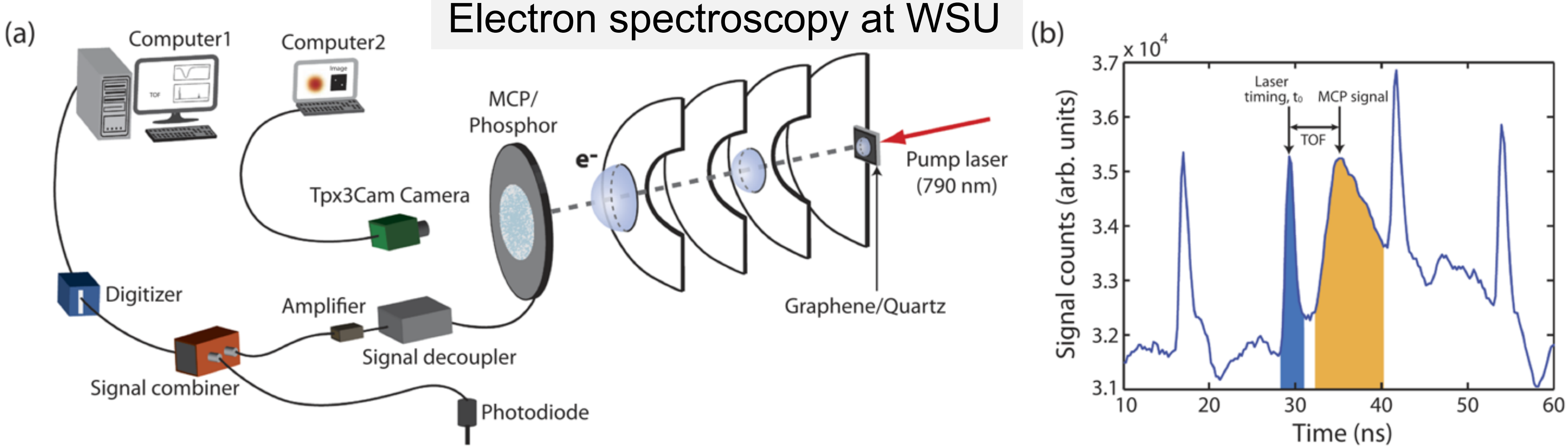


FIG. 1. (a) Schematic of the experimental setup and (b) a typical TOF trace measured from the digitizer.

D.Debrah , G.Stewart, G.Basnayake, A.Nomerotski , P.Svihra , S.K.Lee, and Wen Li
Developing a camera-based 3D momentum imaging system capable of 1 Mhits/s
Rev. Sci. Instrum. 91, 023316 (2020)

- 32 ps timing resolution from MCP+digitizer
  - 0.7 ns deadtime
- Imaging of electrons with 1Mhit/sec rate: Tpx3Cam
  - Improved from few kHz rate

Future directions

Timepix3 → Timepix4

by Medipix4 collaboration

X. Llopart

		Timepix3	Timepix4
Technology		IBM 130nm	TSMC 65nm
Pixel Size		55 x 55 µm	≤ 55 x 55 µm
Pixel arrangement		3-side buttable 256 x 256	4-side buttable 256 x 256 or bigger
Operating Modes	Data driven	PC (10-bit) and TOT (14-bit)	CRW: PC and iTOT (12...16-bit)
	Frame based	TOT and TOA	
Zero-Suppressed Readout	Data driven	< 80 MHits/s	< 500 MHits/s
	Frame based	YES	YES
TOT energy resolution		< 2KeV	**< 1Kev**
Time resolution		1.56ns	**~200ps**

Summary

- Time stamping of optical photons with data-driven readout is attractive alternative to frame readout

  Works well for sparse data

  Needs intelligent pixels with complex functionality

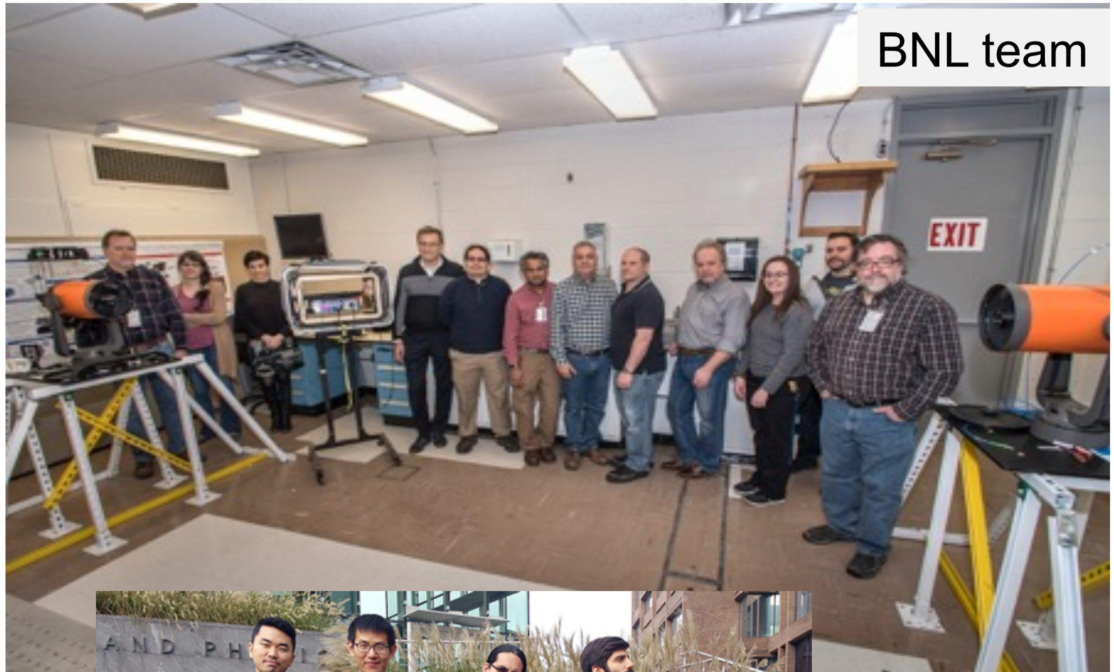
- Timing resolution: 10 nsec → 0.1 nsec
- Photon sensitivity: 1000 photons → single photon

- New technologies for single photon detection is a hot topic in QIS applications

Acknowledgements

Eden Figueroa
Paul Stankus
Tom Tsang
Justine Haupt
Mael Flament
Guodong Cui
Sonali Gera
Youngshin Kim
Peter Svihra
Dimitros Katramatos
Michael O'Connor
Gabriella Carini
David Asner
Anand Kandasamy
Michael Keach
Steven Paci

Jingming Long
Martin van Beuzekom
Bram Bouwens
Erik Maddox
Jord Prangsma
Duncan England
Yingwen Zhang
Boris Blinov
Mila Zhukas



BNL team


SBU team