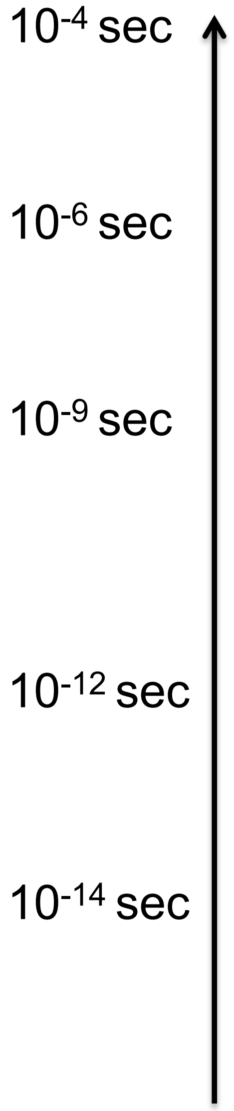
Imaging and time-stamping single photons with nanosecond resolution for QIS applications

Andrei Nomerotski (BNL)

Fermilab

23 October 2020

Types of fast Imaging



10^{-4} sec

10^{-6} sec

10^{-9} sec

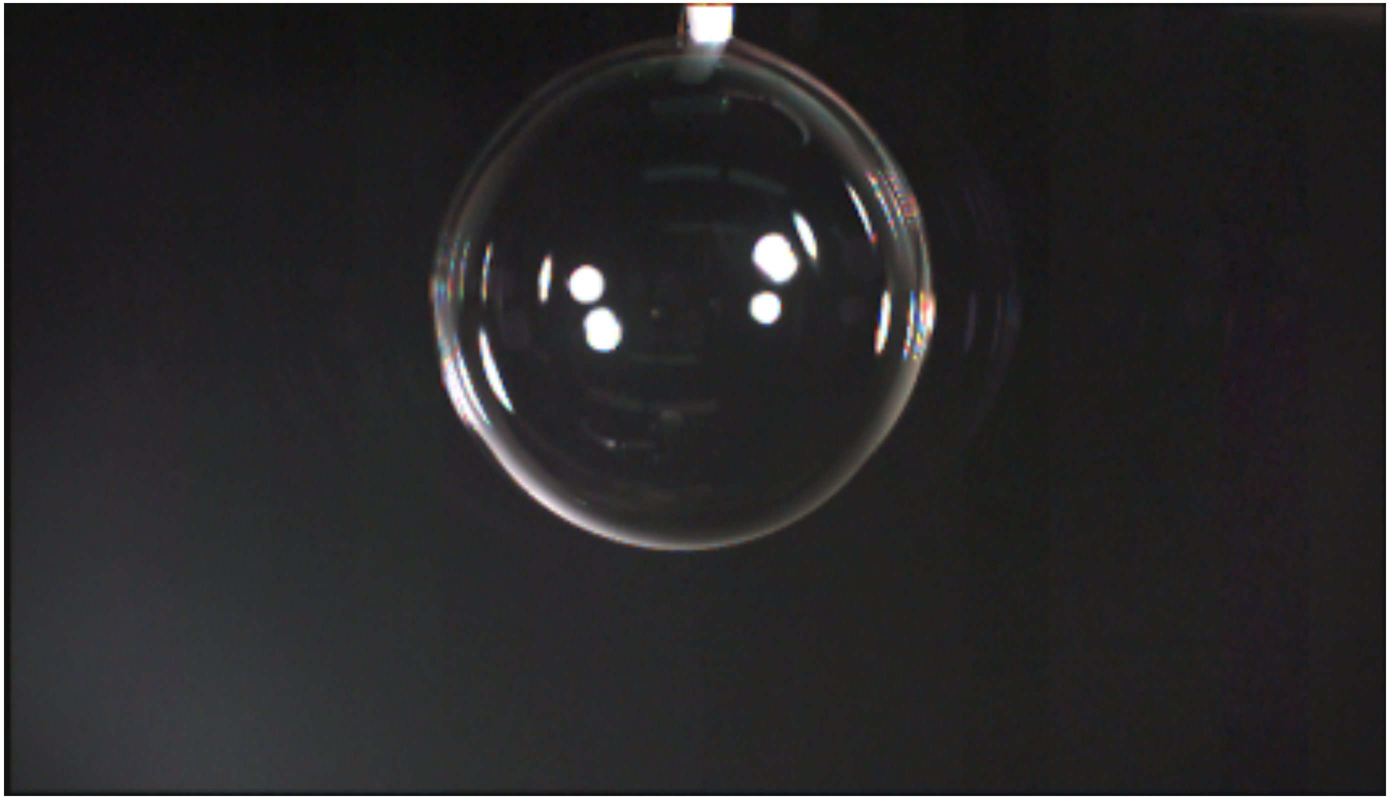
10^{-12} sec

10^{-14} sec

- “normal” cameras: 0.1 ms → 10 μs
- Burst mode cameras: 1 μs → 10 ns
- Data-driven cameras: 10 → 0.01 nsec
- Streak cameras: 1 psec
- Repetitive “pump/probe cameras” : fsec

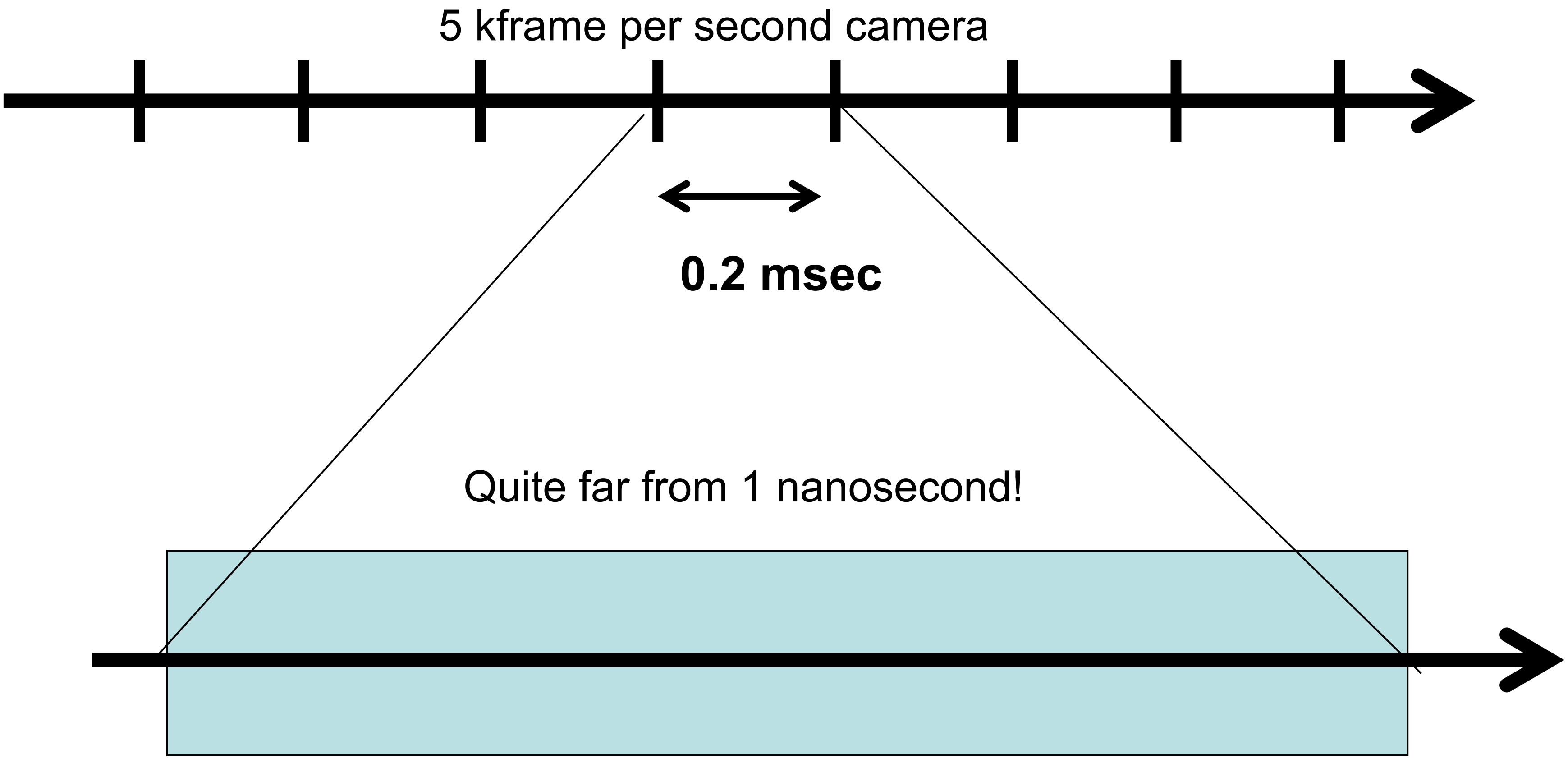
‘Normal’ fast CMOS camera: 5 kfps = 0.2 ms/frame

- Soap bubble



G.Etoh

Normally signal is integrated in a slice of time

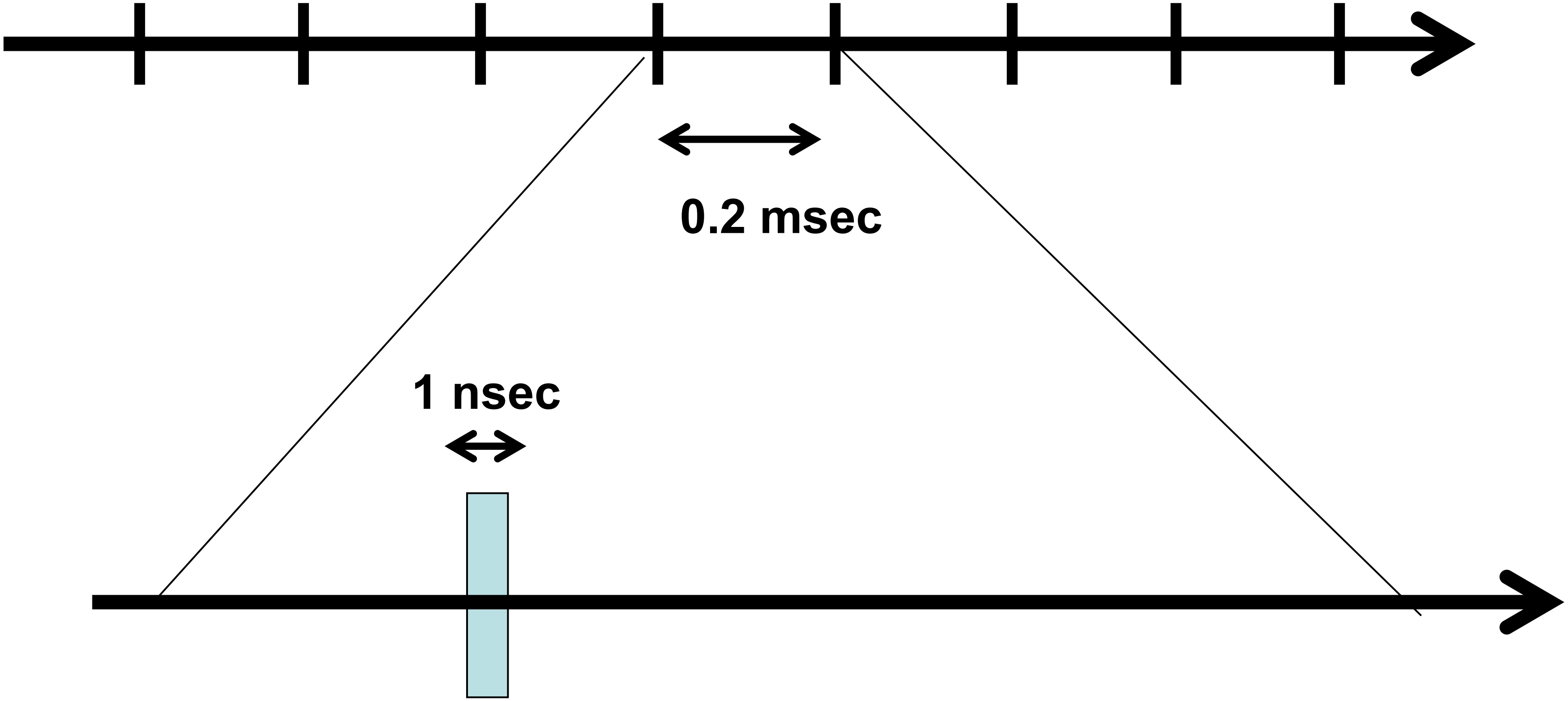


5 kframe per second camera

0.2 msec

Quite far from 1 nanosecond!

Can achieve faster imaging by gating (of intensifier)

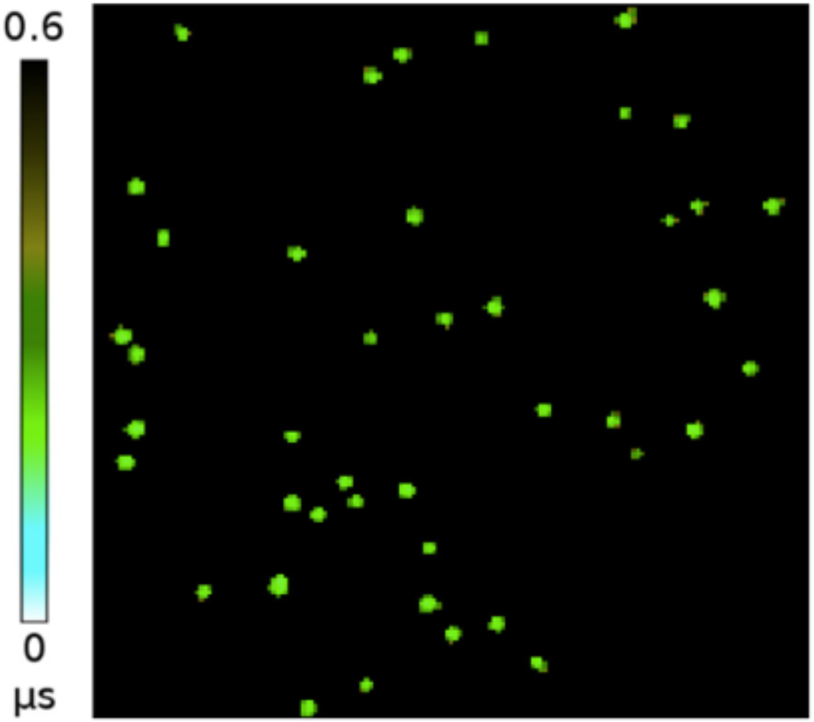


- Smaller time window = Less signal = Lower occupancy
- Ultimately resolve single photons

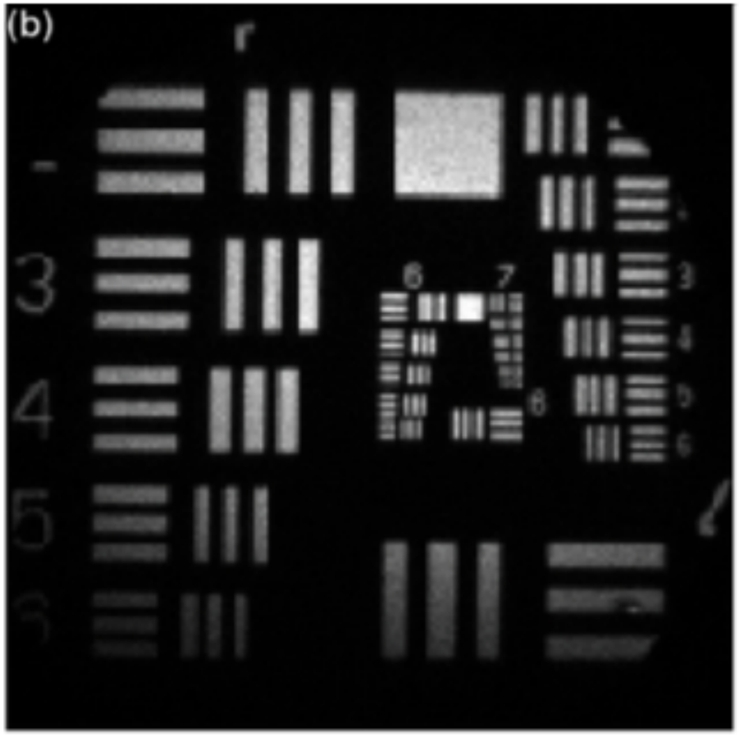
Imaging with photon counting

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

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

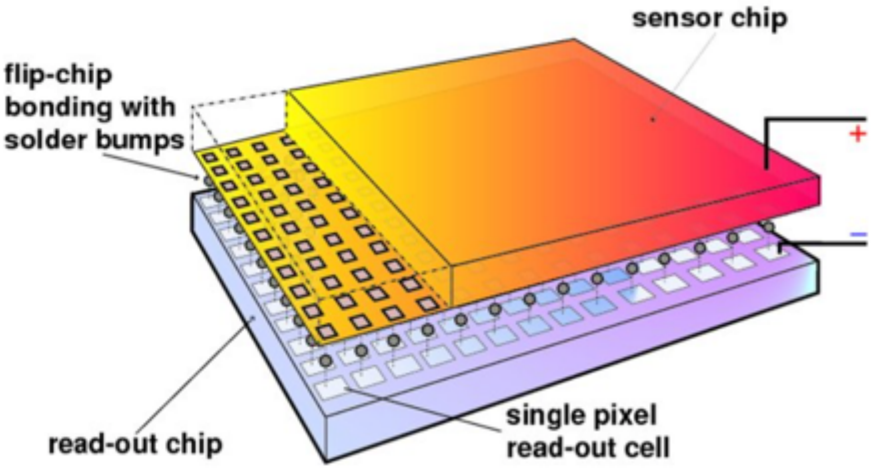
Tpx3Cam: time-stamp 10 MHz flux of photons with 1 ns precision

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

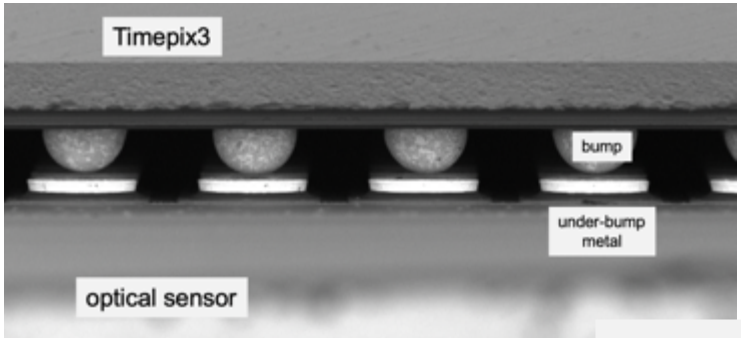
Timepix Optical Cameras

Hybrid pixel detectors

Have roots in R&D for LEP/LHC vertex 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)



credit: IZM

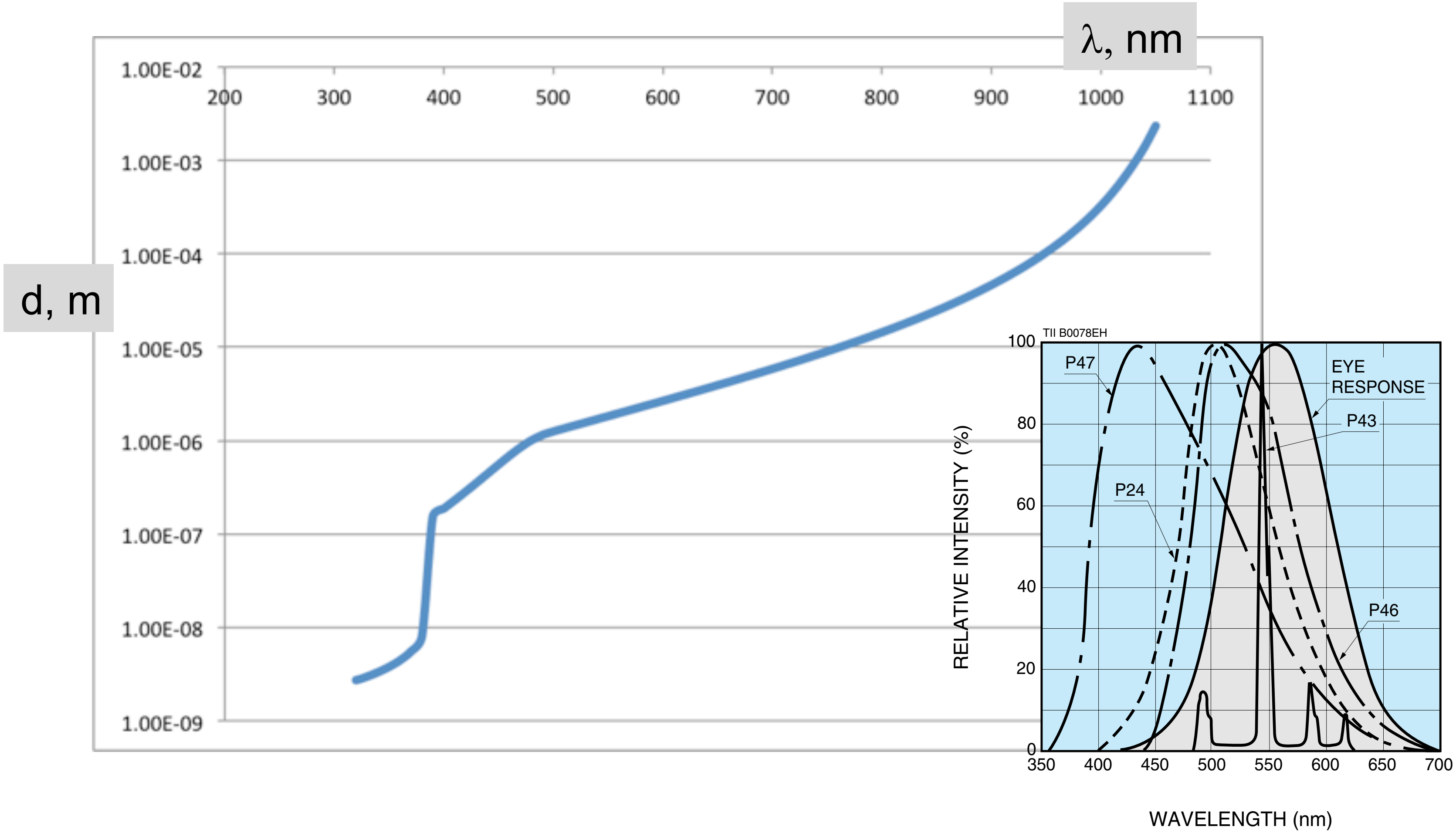
- Decouple readout chip and sensor
- Optimize technologies for chip and sensor separately

Use different sensors with same readout, versatile approach for x-rays (Si, CZT)

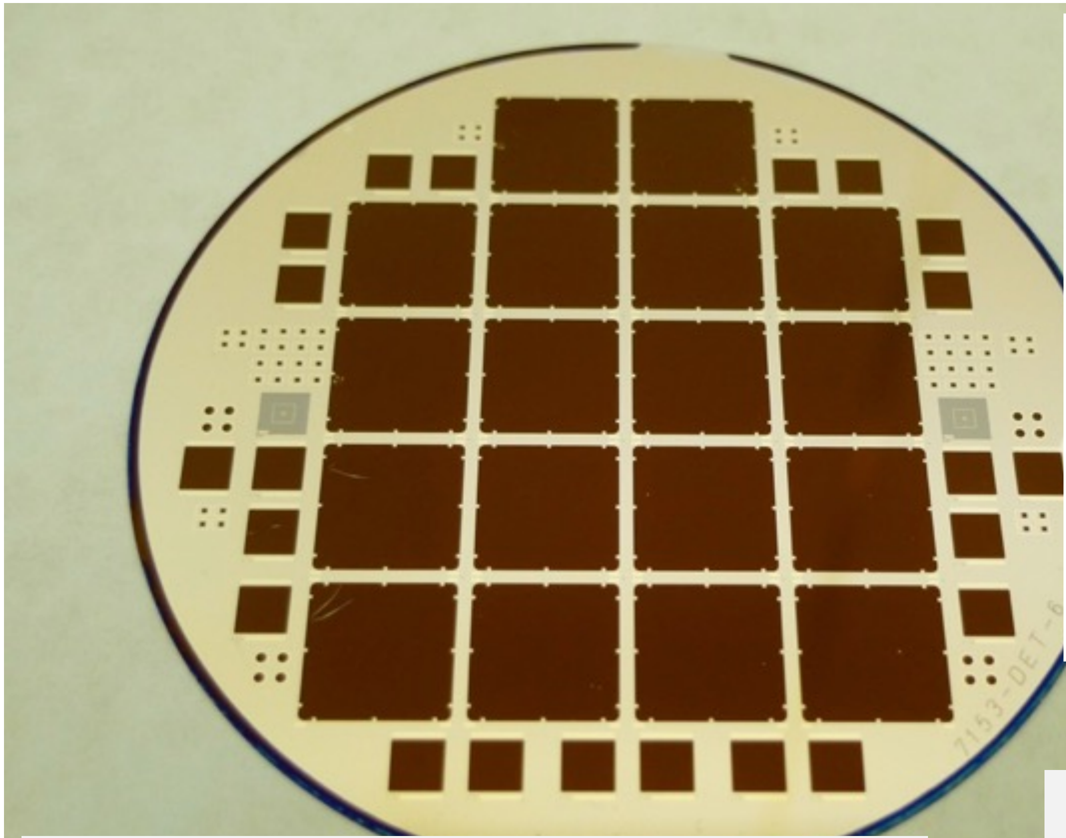
→ we will use OPTICAL sensors

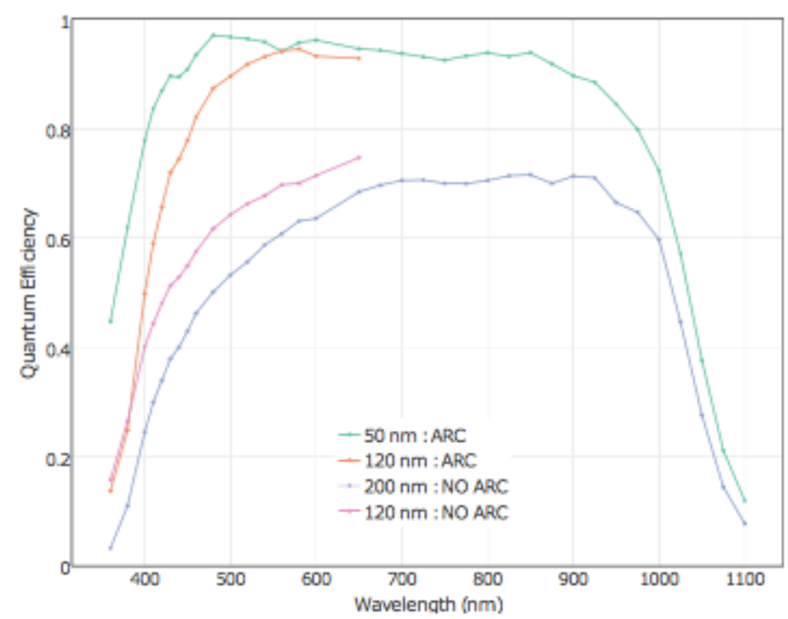
Photon absorption in silicon

- Blue photons are absorbed near the surface (~0.25 um for 430 nm, P47 max emission)
- ~1 um for 500 nm, ~10 um for 800 nm



Thin window optical sensors





High QE

Backside illuminated optical sensors
Anti-reflective coating, thickness 300 um

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, first produced at CNM (Barcelona, Spain) in 2015
Surface preparation is very important, inspired by astronomical CCDs (LSST)

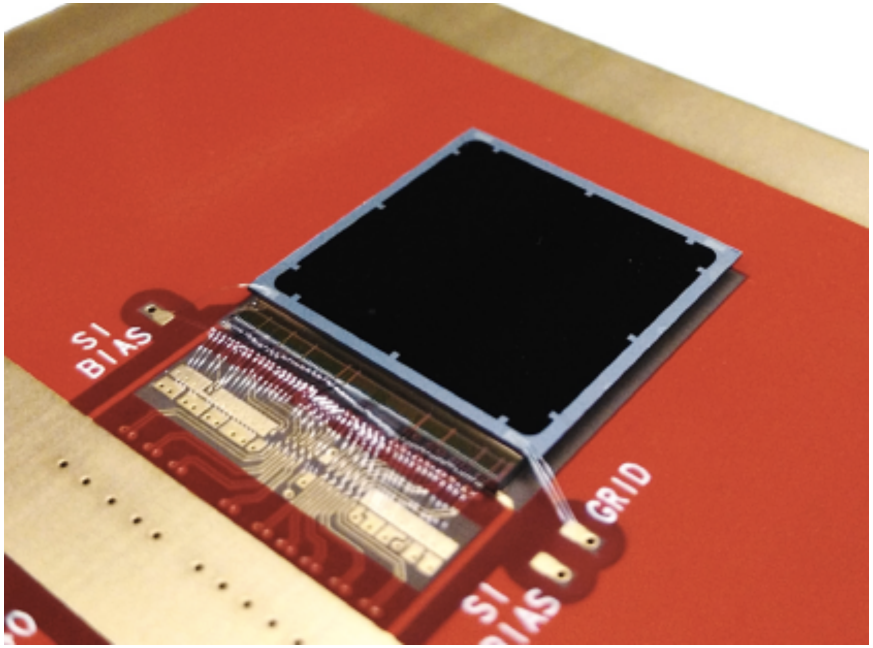
Timepix3 Camera → Tpx3Cam

Camera = sensor + ASIC + readout

Timepix3 ASIC:

- 256 x 256 array, 55 x 55 micron pixel
  - 14 mm x 14 mm active area
- 1.56 ns timing resolution
- Data-driven readout, 600 e min threshold, 80 Mpix/sec, no deadtime
- each pixel measures time and flux, ~1μs pixel deadtime when hit

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.



Sensor is bump-bonded to chip

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

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)

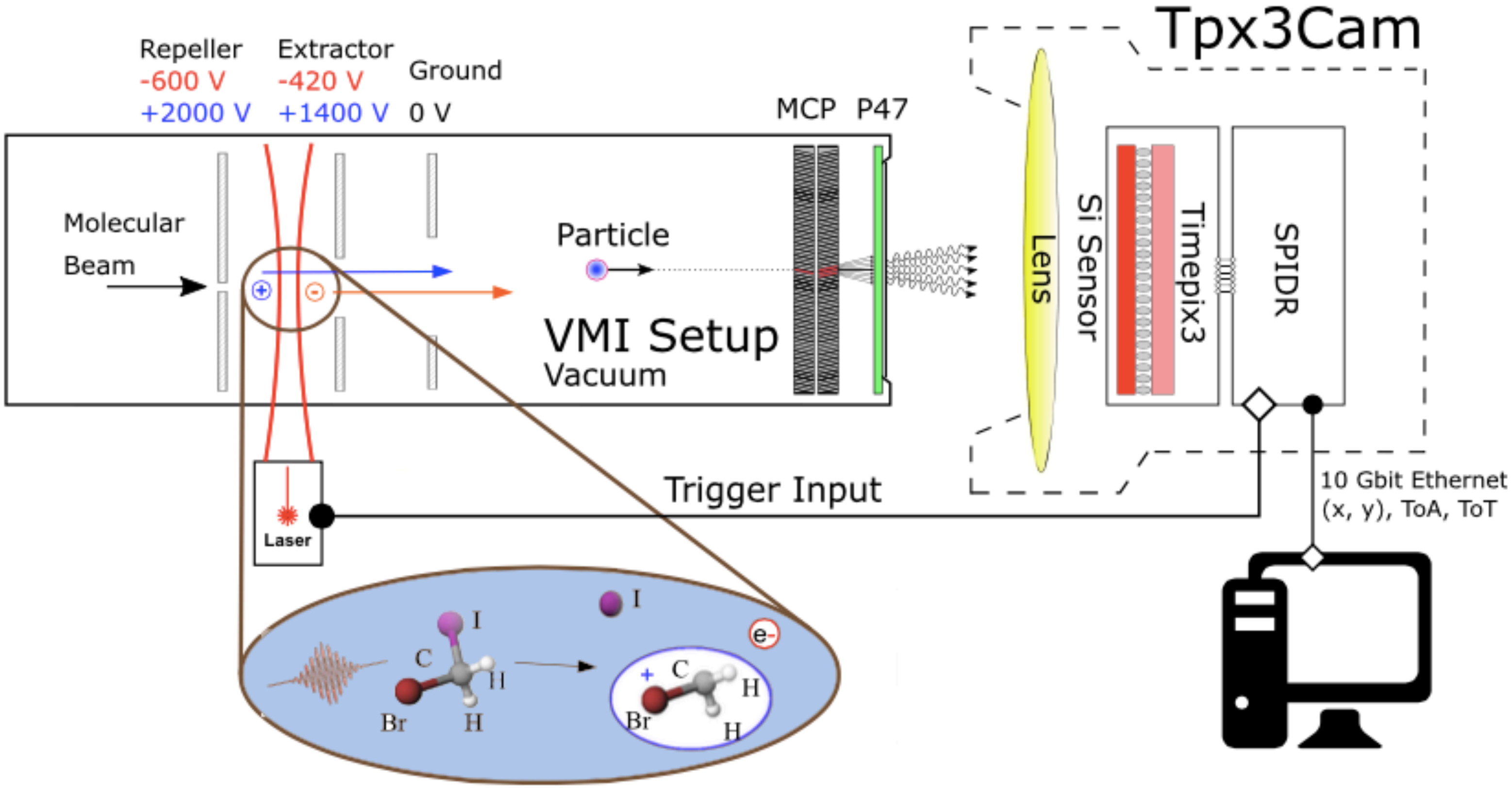
J. Visser et al, SPIDR: a readout system for Medipix3 and Timepix3, Journal of Instrumentation 10 (12) (2015) C12028.

eX readout for Timepix2 (Imatek)

Applications & Results

- Ion imaging - briefly
- Quantum imaging – in more detail
- HEP applications – briefly
- Lifetime imaging – next time

Ion Imaging



5. A. Zhao, M. van Beuzekom, B. Bouwens, D. Byelov, I. Chakaberia, Ch. Cheng, E. Maddox, A. Nomerotski, P. Svihra, J. Visser, V. Vrba and T. Weinacht: '*Coincidence velocity map imaging using Tpx3Cam, a time stamping optical camera with 1.5 ns timing resolution*'. Rev Sci Instrum. 88(11), 10.1063/1.4996888 (2017)

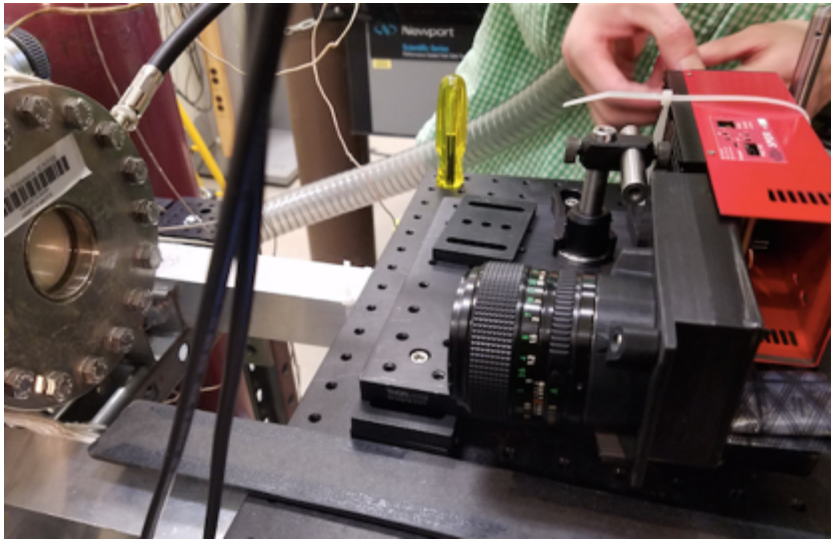
Advantages of optical approach

Outside of vacuum

- Decoupled from setup
- No cooling in vacuum
- No HV close to electronics

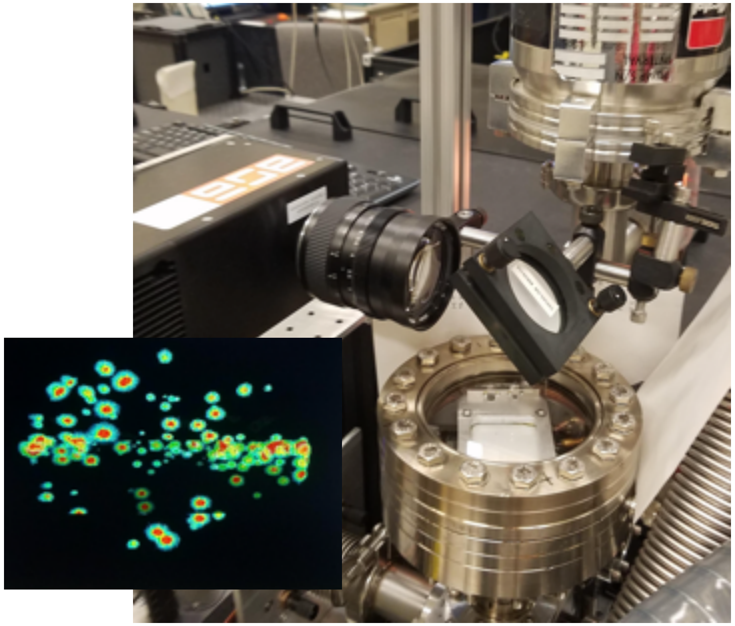
Power of optics

- lens & mirrors
- magnification/ demagnification, flexible mapping between scintillator screen and sensor

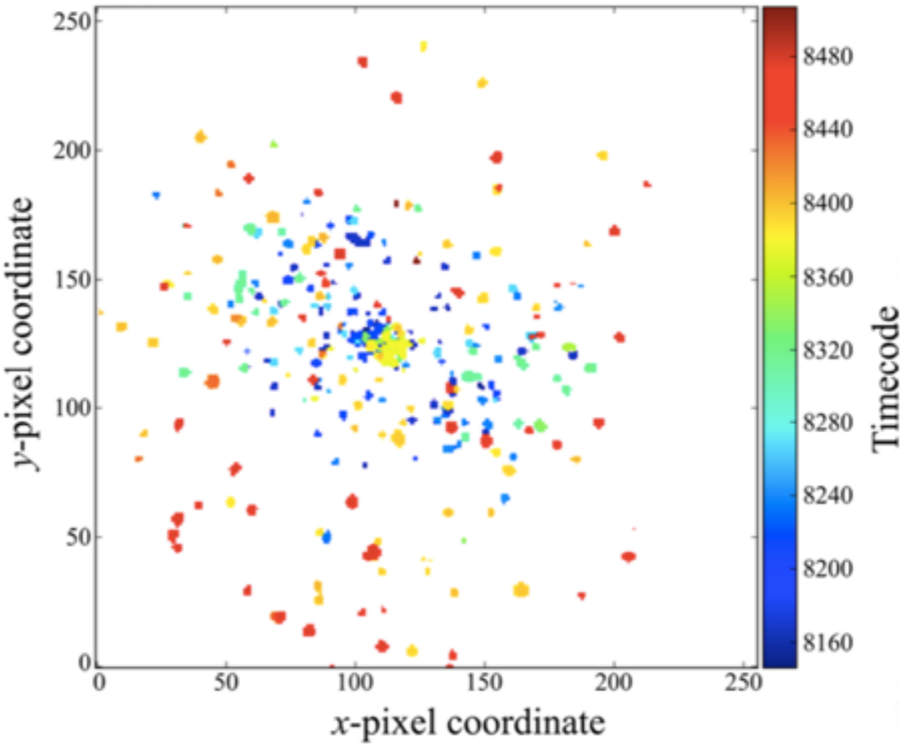


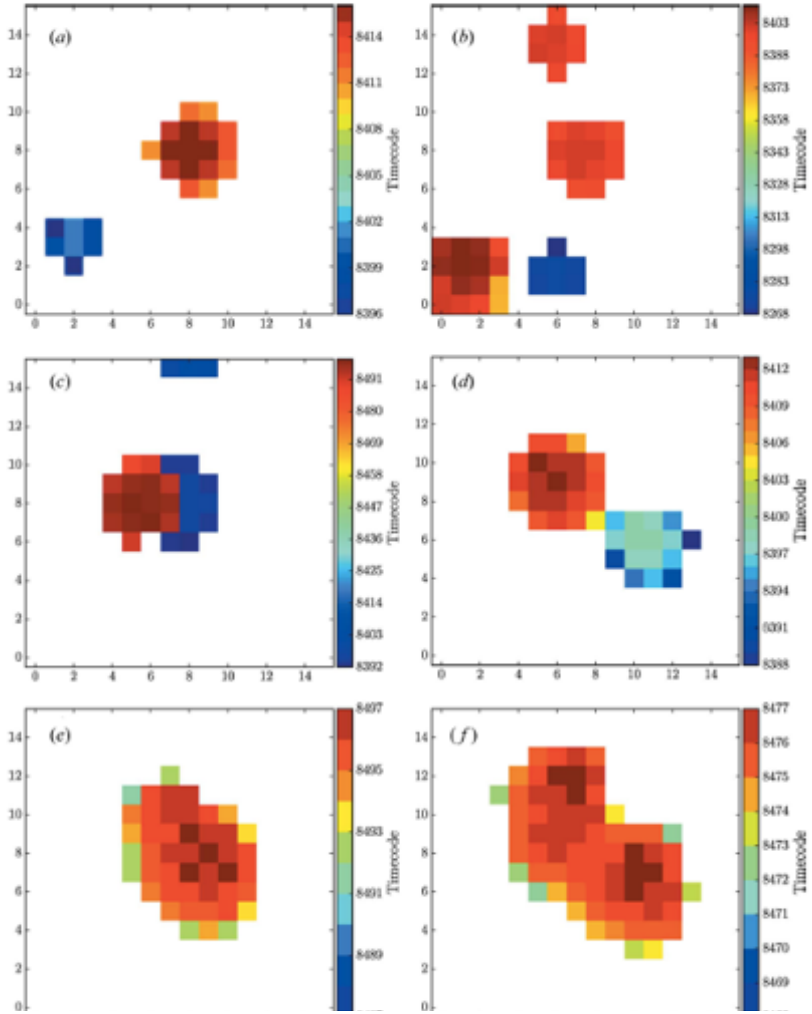
“Hybrid” approach

- Use same camera for different applications
- Easily upgradable: different cameras with same setup
- Use different photocathodes/ intensifiers with same camera

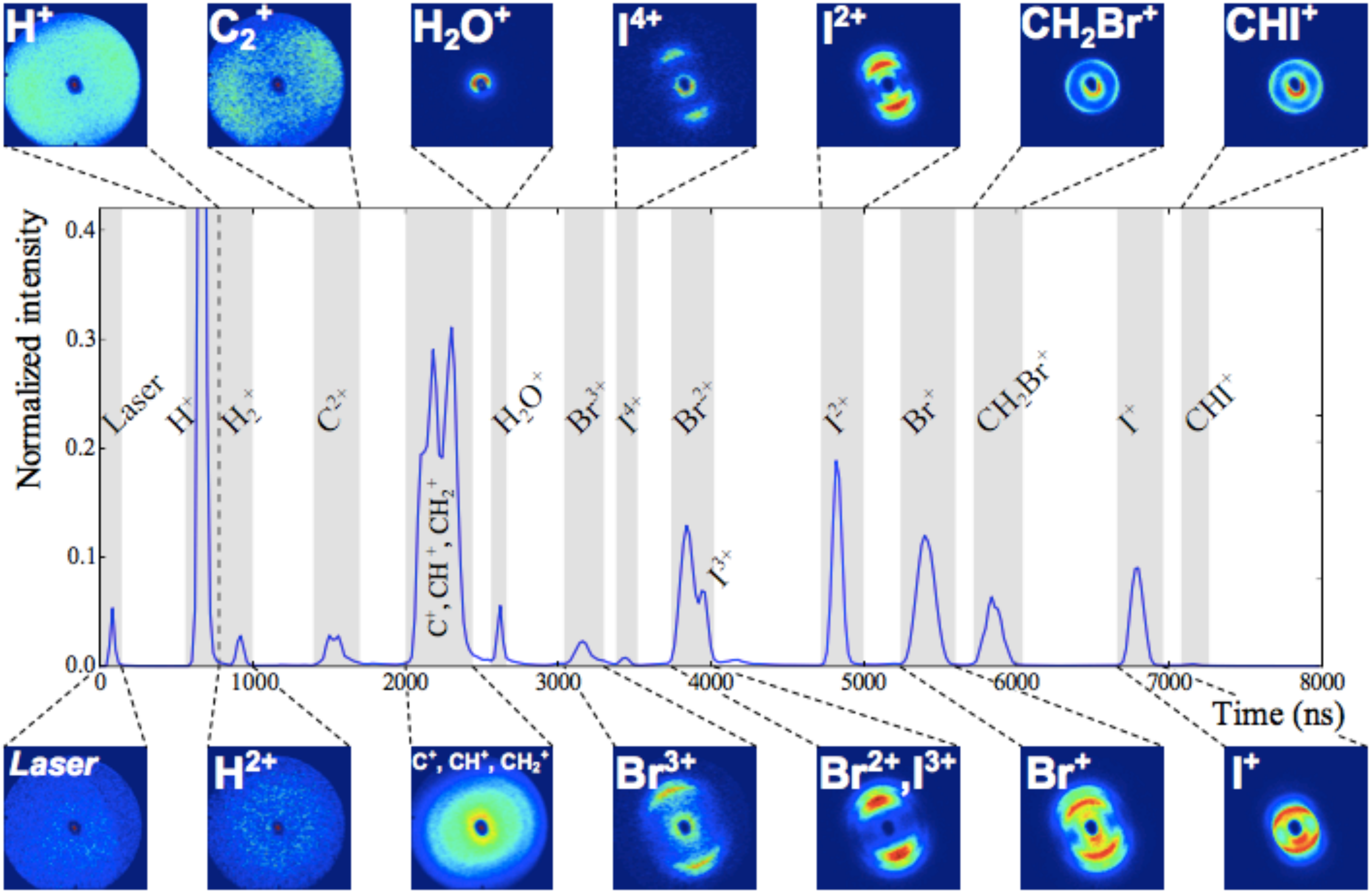


Ions in TimepixCam





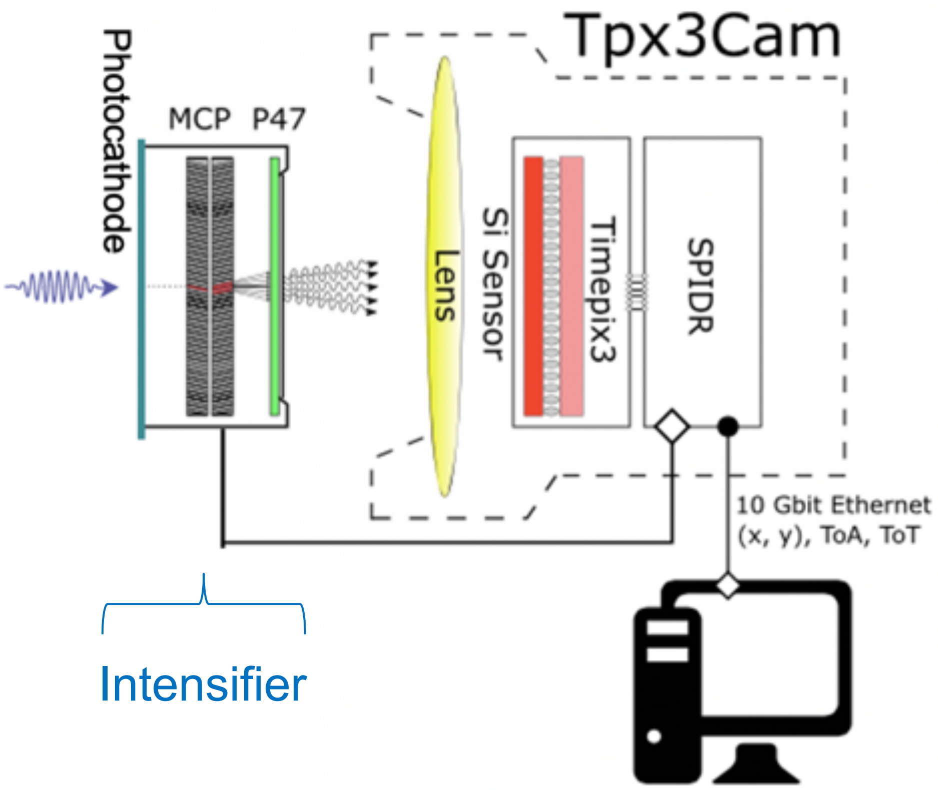
6. M. Fisher-Levine, R. Boll, F. Ziaee, C. Bomme, B. Erk, D. Rompotis, T. Marchenko, A. Nomerotski and D. Rolles: '*Time-Resolved Ion Imaging at Free-Electron Lasers Using TimepixCam*'. Journal of Synchrotron Radiation.(2018) 25 https://doi.org/10.1107/S16005775170



6. M. Fisher-Levine, R. Boll, F. Ziaee, C. Bomme, B. Erk, D. Rompotis, T. Marchenko, A. Nomerotski and D. Rolles: '*Time-Resolved Ion Imaging at Free-Electron Lasers Using TimepixCam*'. Journal of Synchrotron Radiation.(2018) 25 https://doi.org/10.1107/S16005775170

Single (optical) photons

Intensified camera: use off-the-shelf image intensifier



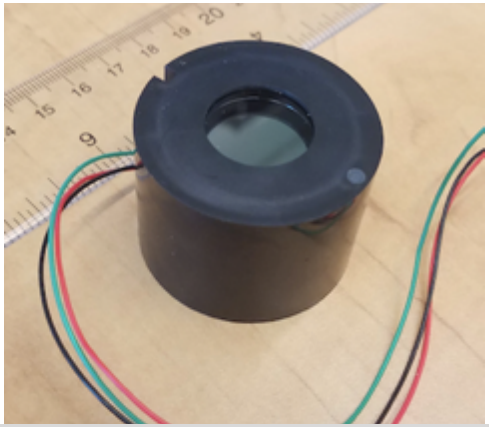
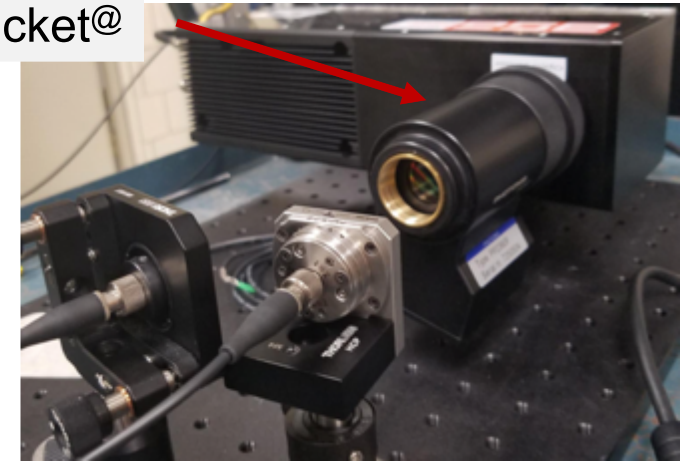


Image intensifier (Photonis PP0360EG)

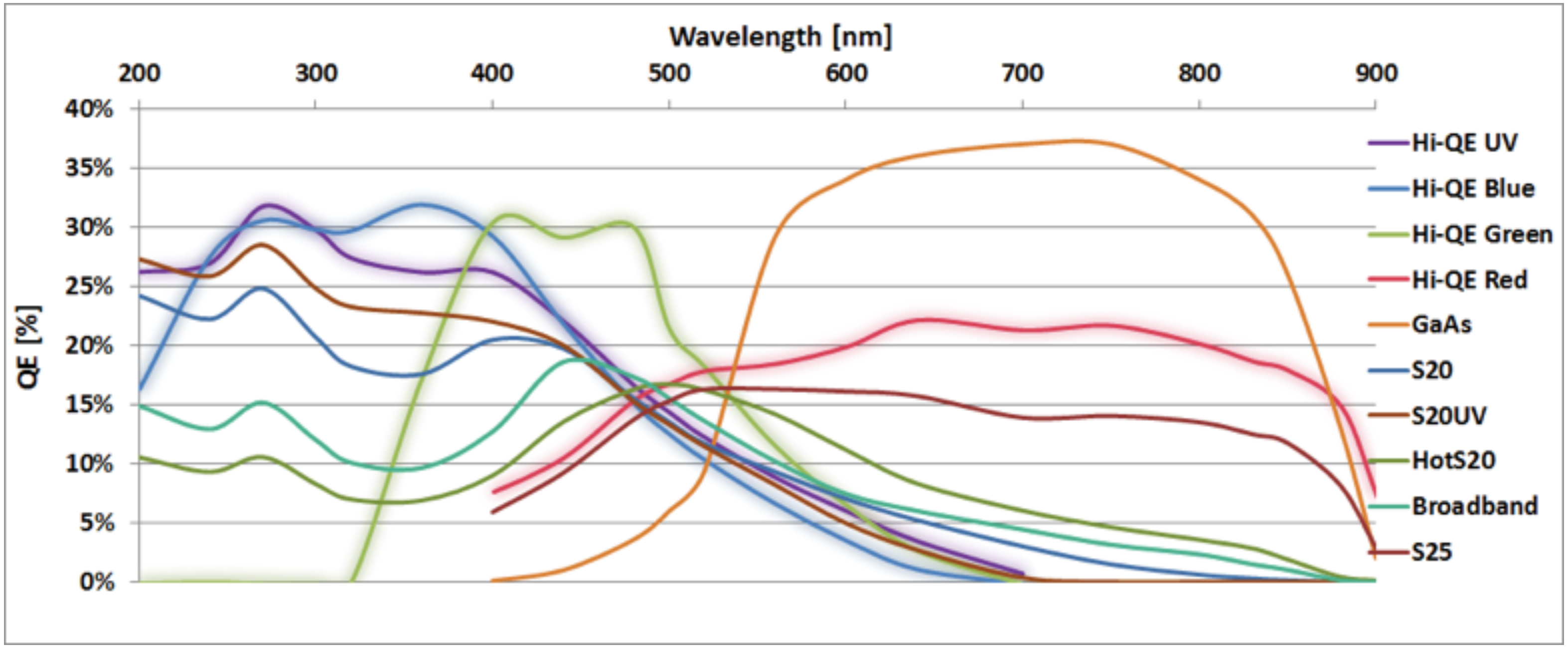
Cricket@



Intensified cameras are common:

- iCCD
- iCMOS cameras

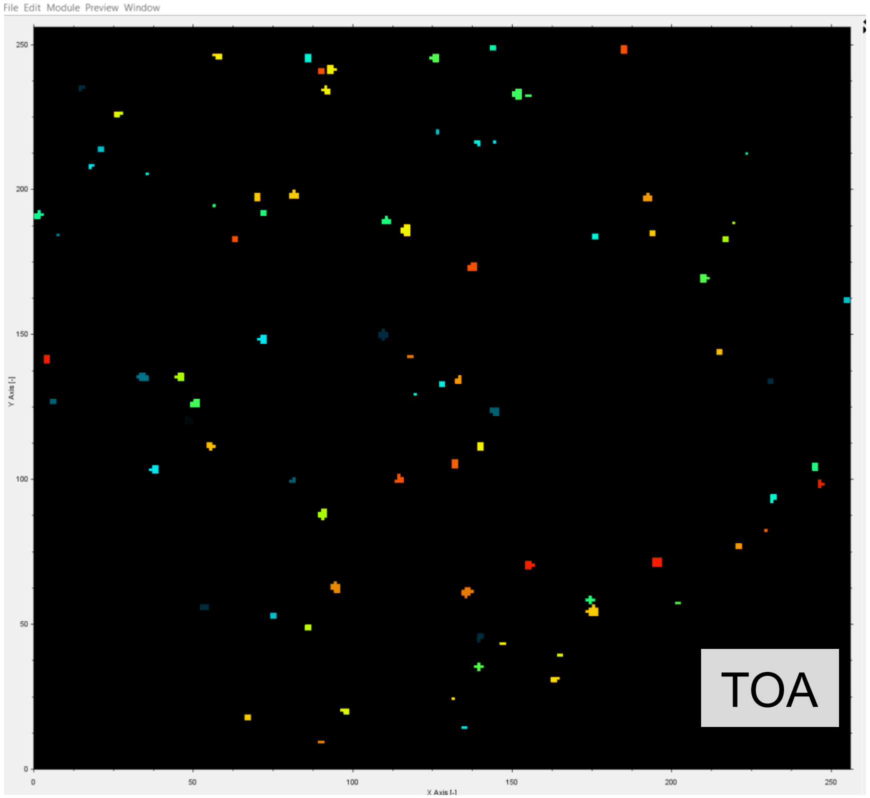
Choice of photocathodes

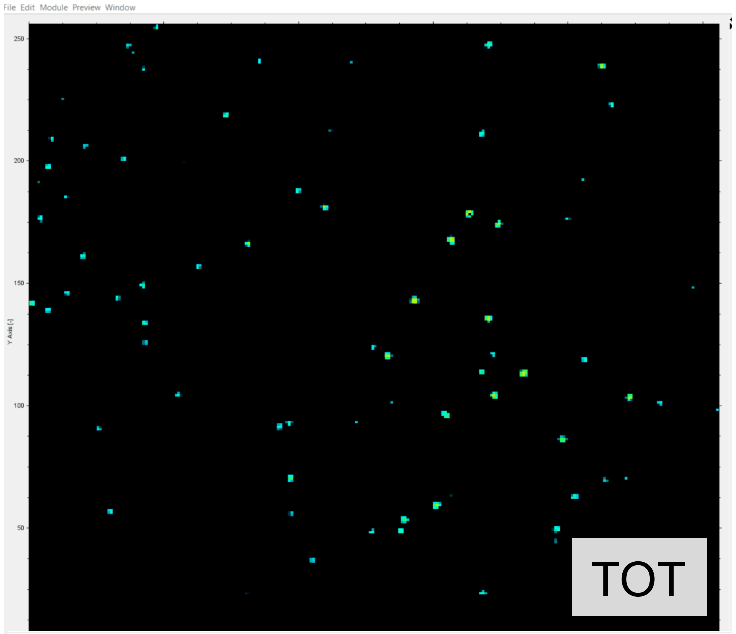


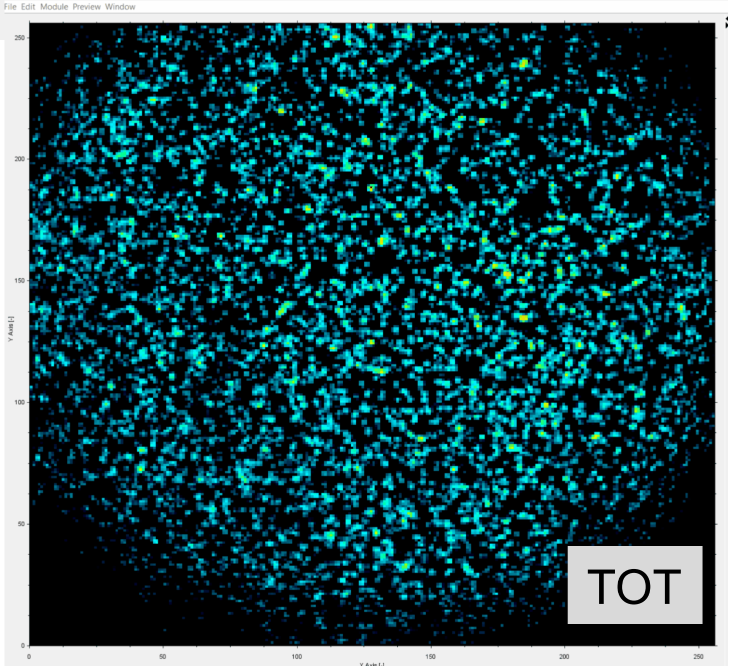
Photonis photocathodes

Single Photons in Tpx3Cam

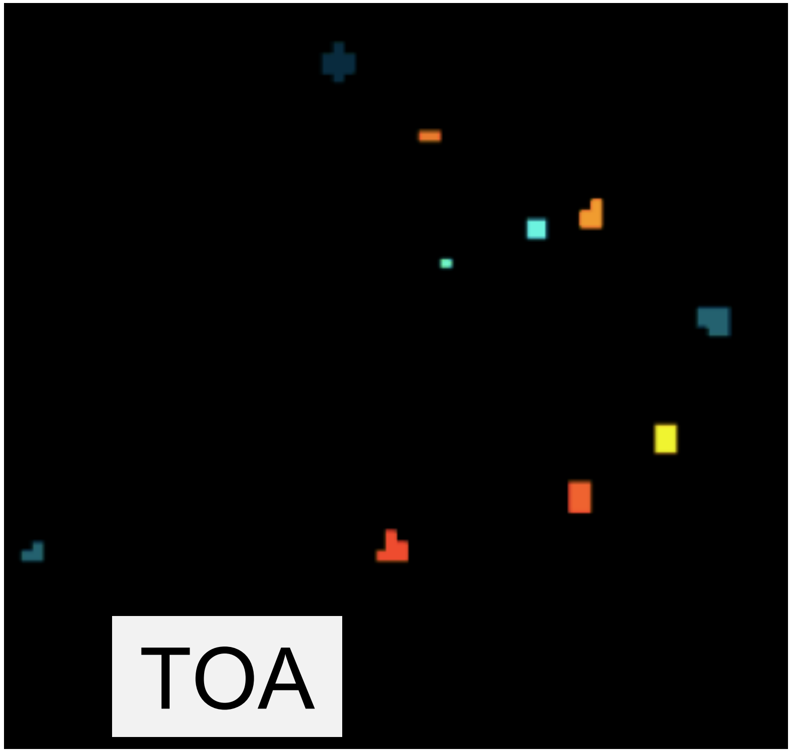
1 ms slice of data
1.5ns time-stamping

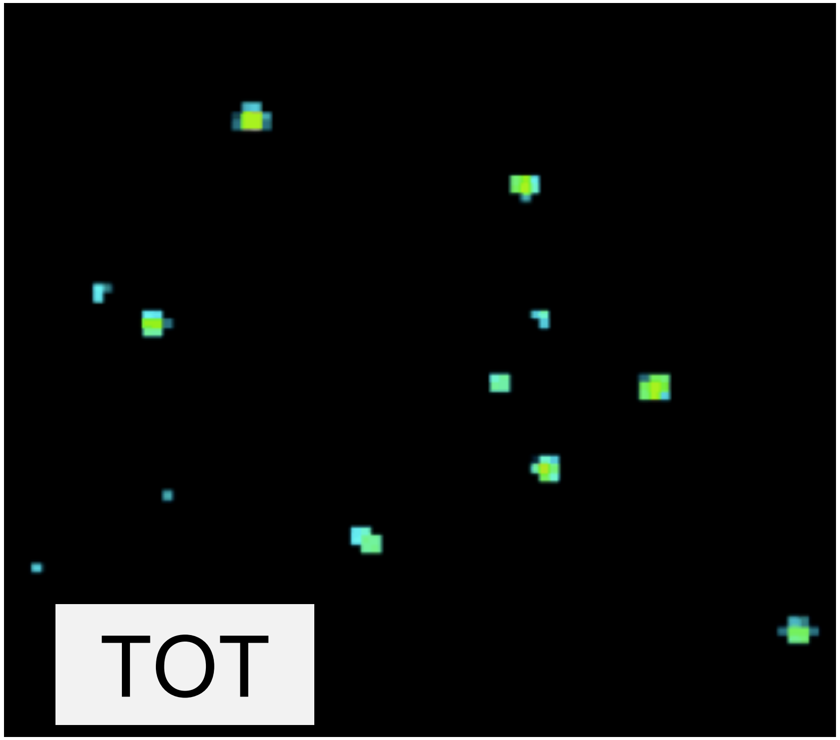






Tpx3Cam + intensifier by Photonis
data taken by J. Long (ASI)





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

Spatial resolution: 0.1 pixel / photon

Time resolution: < 1 ns / photon

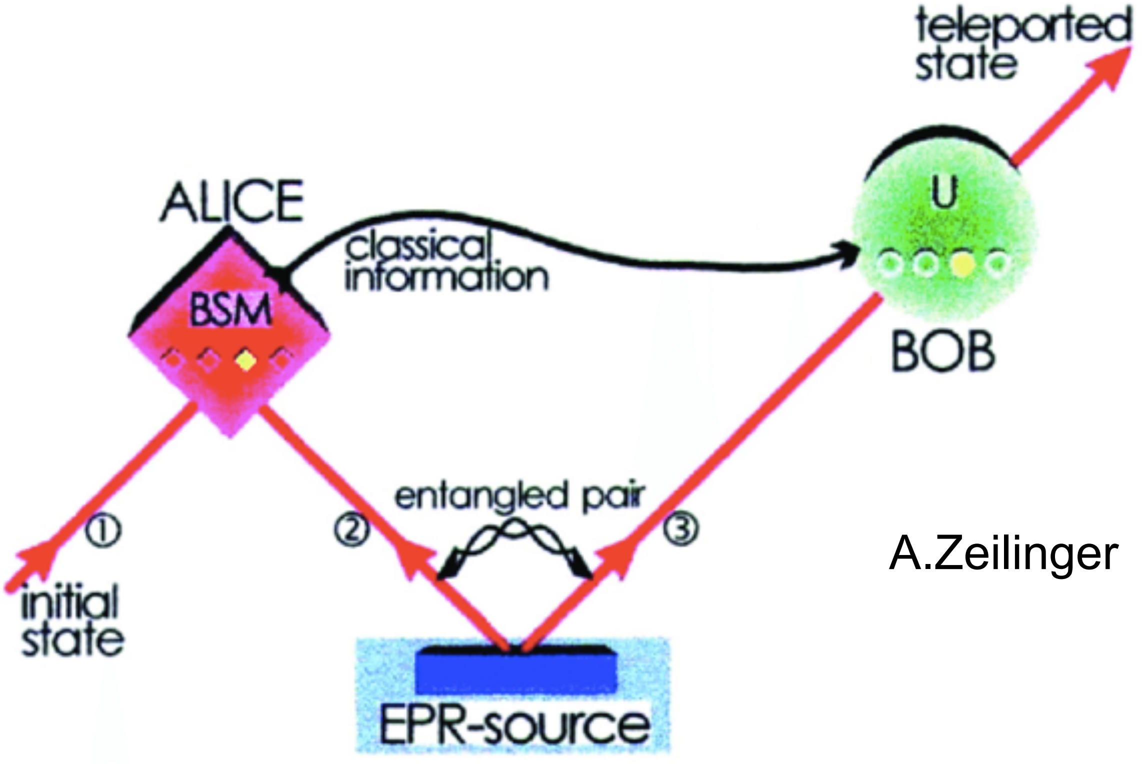
Quantum Information Science, Quantum-Assisted Imaging for telescopes and others

Will mention other applications only briefly

Quantum Network

- Attenuation in fibers → need quantum repeater to reproduce qubits
  - Simple amplification will not conserve the quantum state

- Qubit teleportation: produce entangled photons and send them to two locations
- Bell State Measurement (BSM) on one photon will collapse the wave function of the other one (or swap entanglement)



A.Zeilinger

Quantum Communications

Collaboration with Stony Brook U (Figueroa group)

Long-term goals :

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

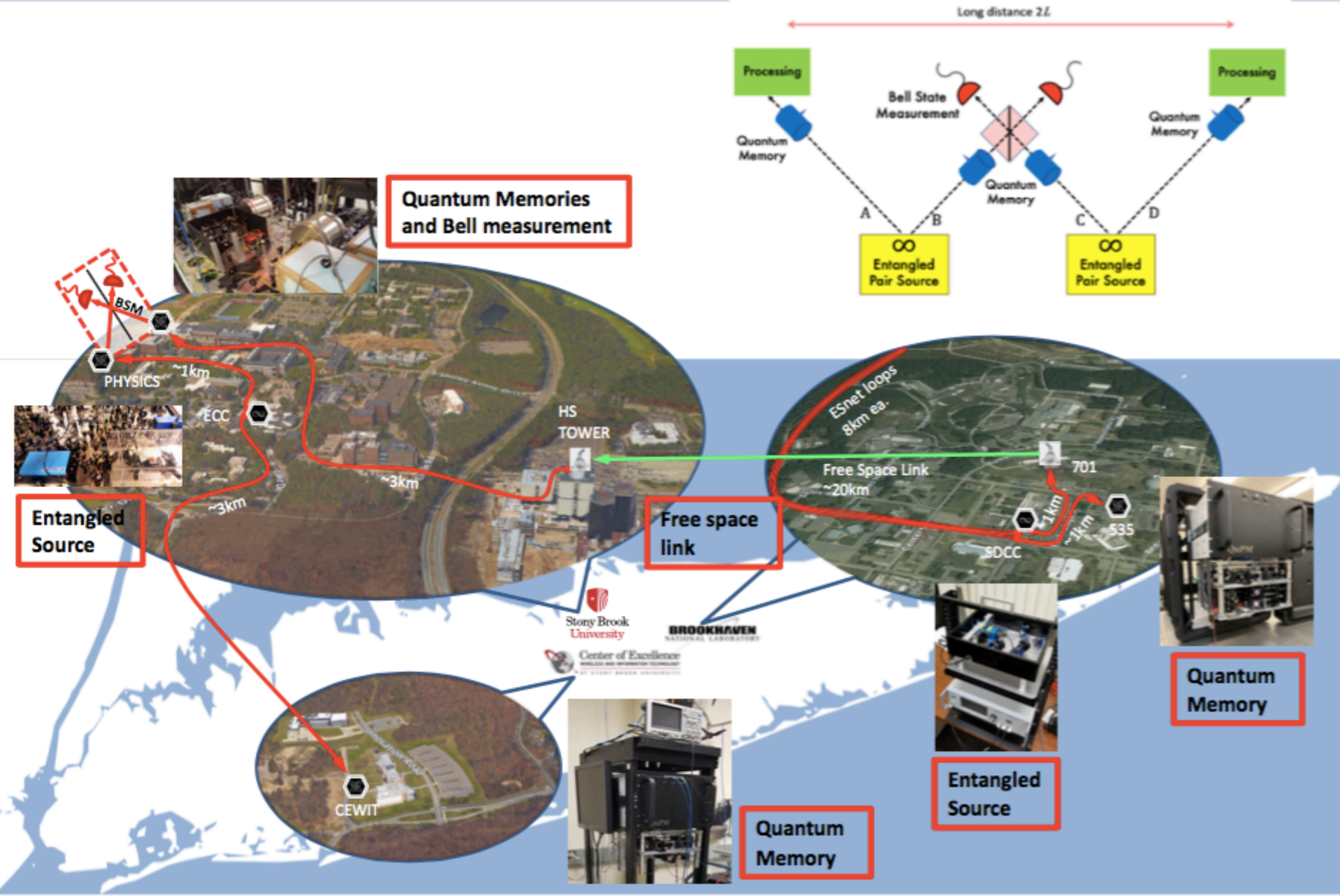
- room temperature Rb quantum memories;
- entangled photon sources compatible with memories;
- characterization devices for single photons

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

Demonstration of scalability: connect multiple & diverse quantum devices

Path to quantum internet

SBU BNL Quantum repeater test bed



Quantum Memories and Bell measurement

Entangled Source

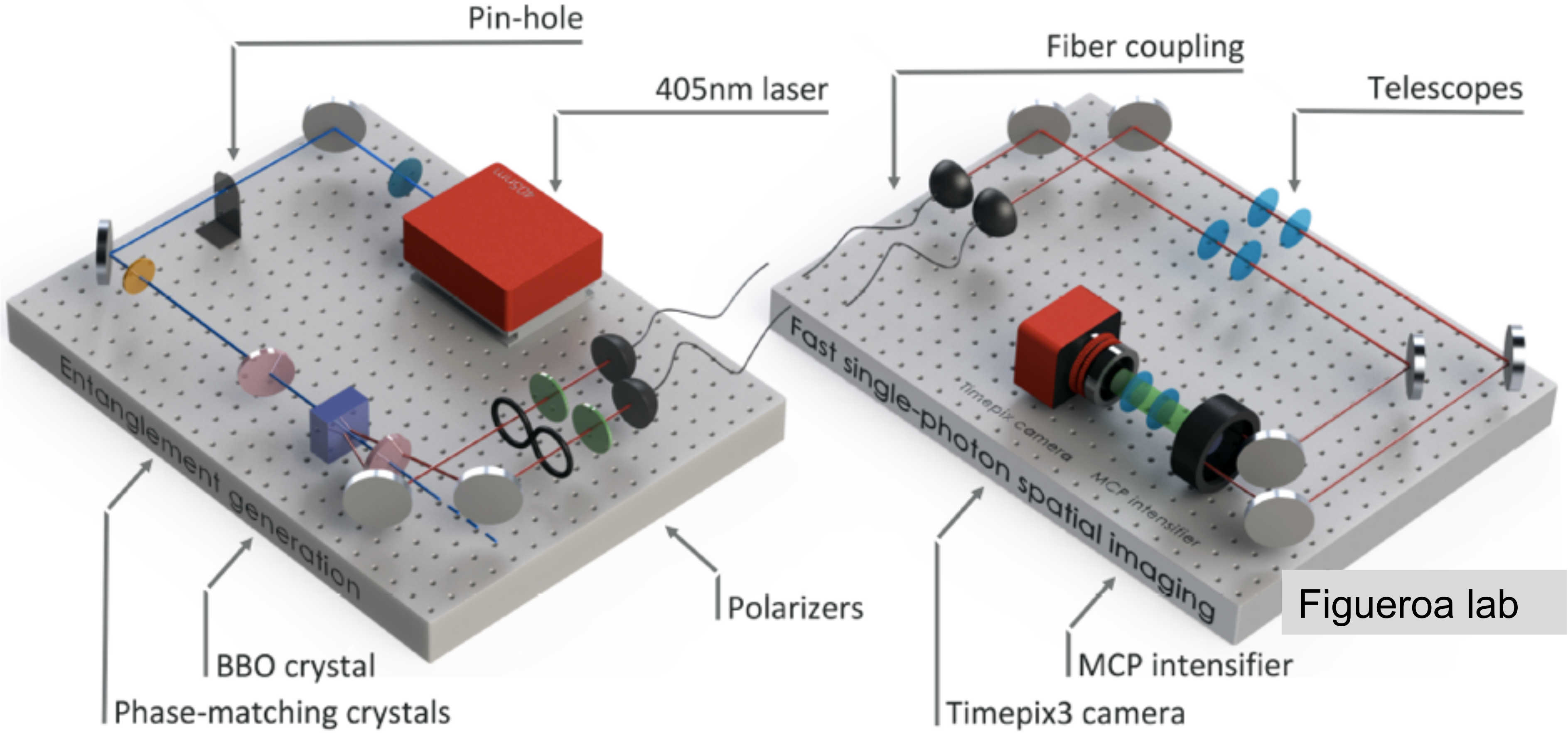
Free space link

Quantum Memory

Entangled Source

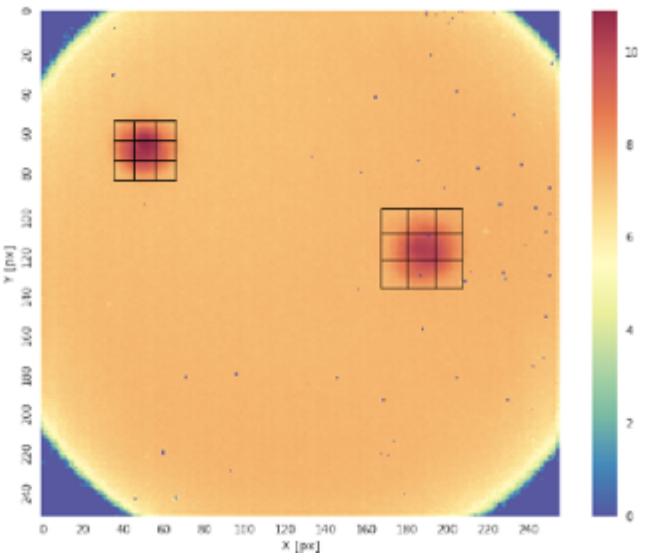
Quantum Memory

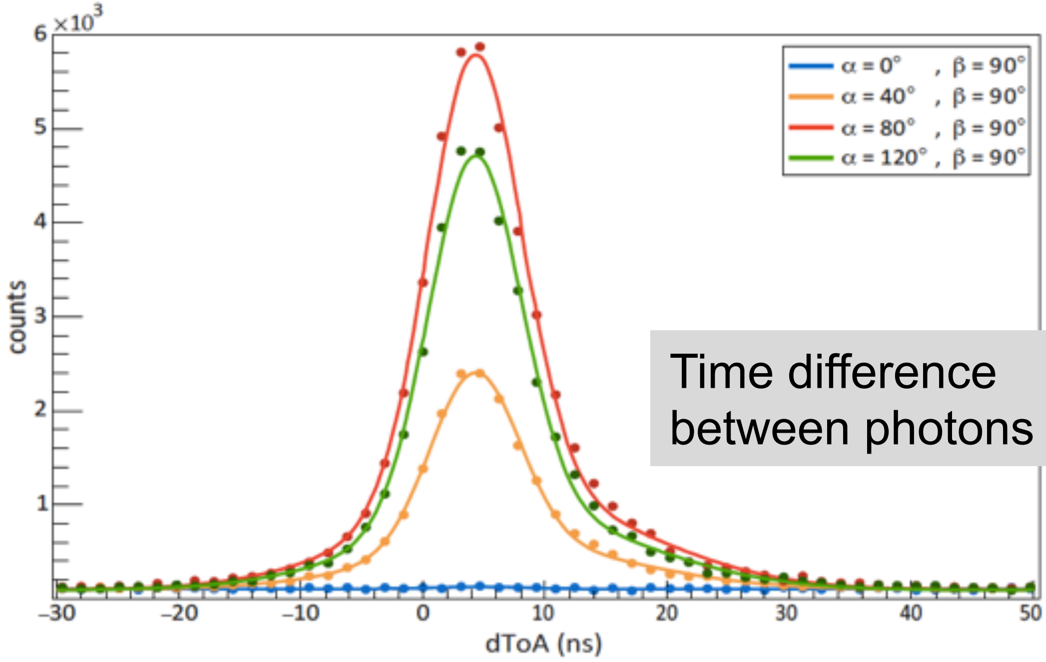
Characterization of Single Photon Down-Conversion Source



Figueroa lab

qubit: use H, V photon polarization states $|\phi^{\pm}\rangle = \frac{(|HH\rangle \pm |VV\rangle)}{\sqrt{2}}$





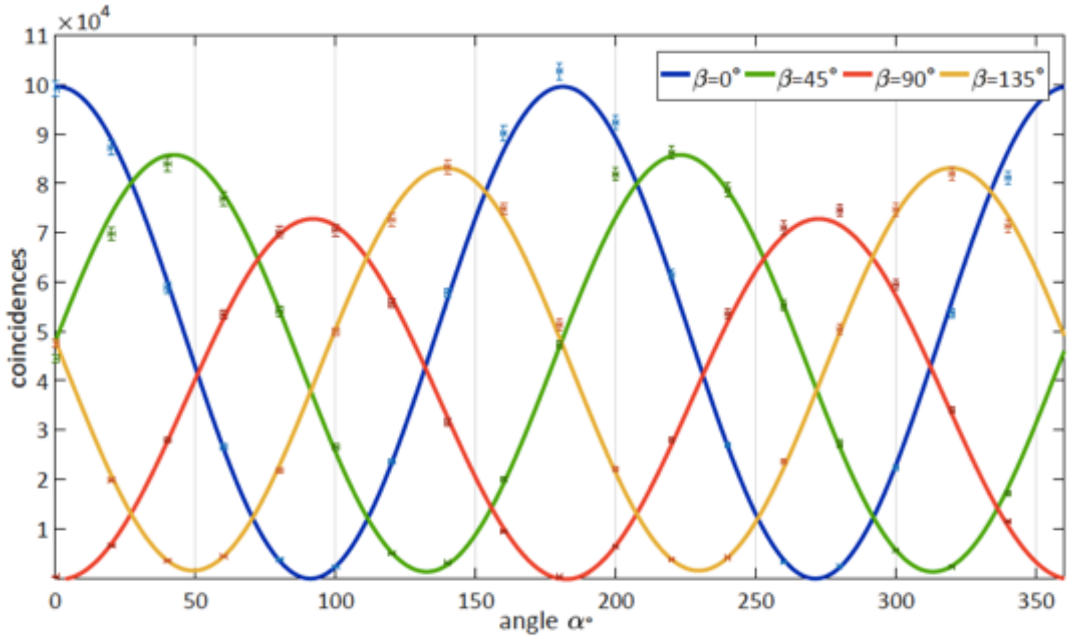
Time difference between photons

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

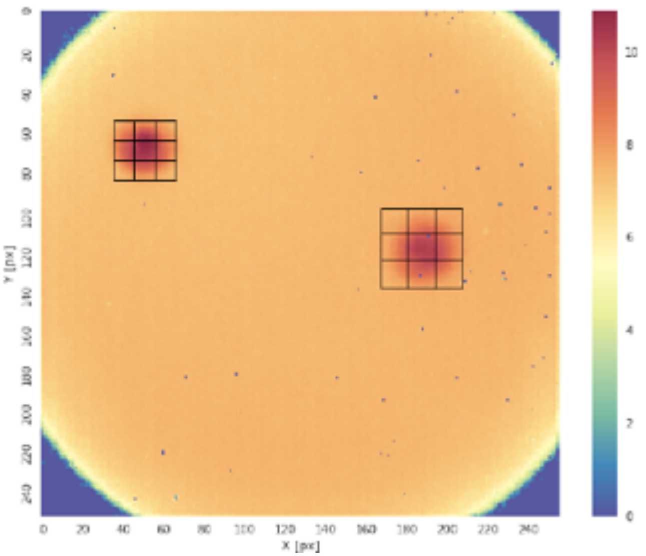
- Measurement:

S-value = 2.72±0.02

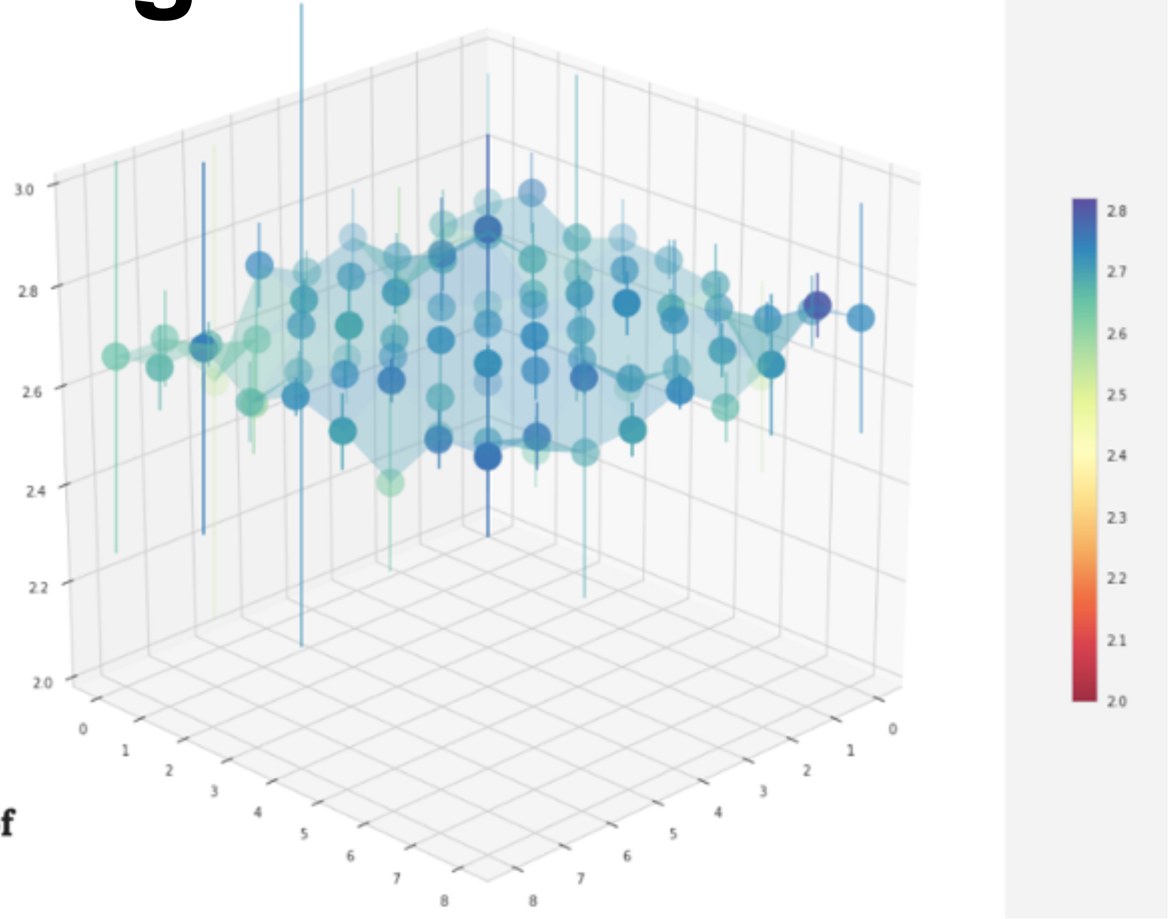
Time resolution: 2ns



Spatial characterization of tanglement



Measure S-value
for 81 combinations of subareas



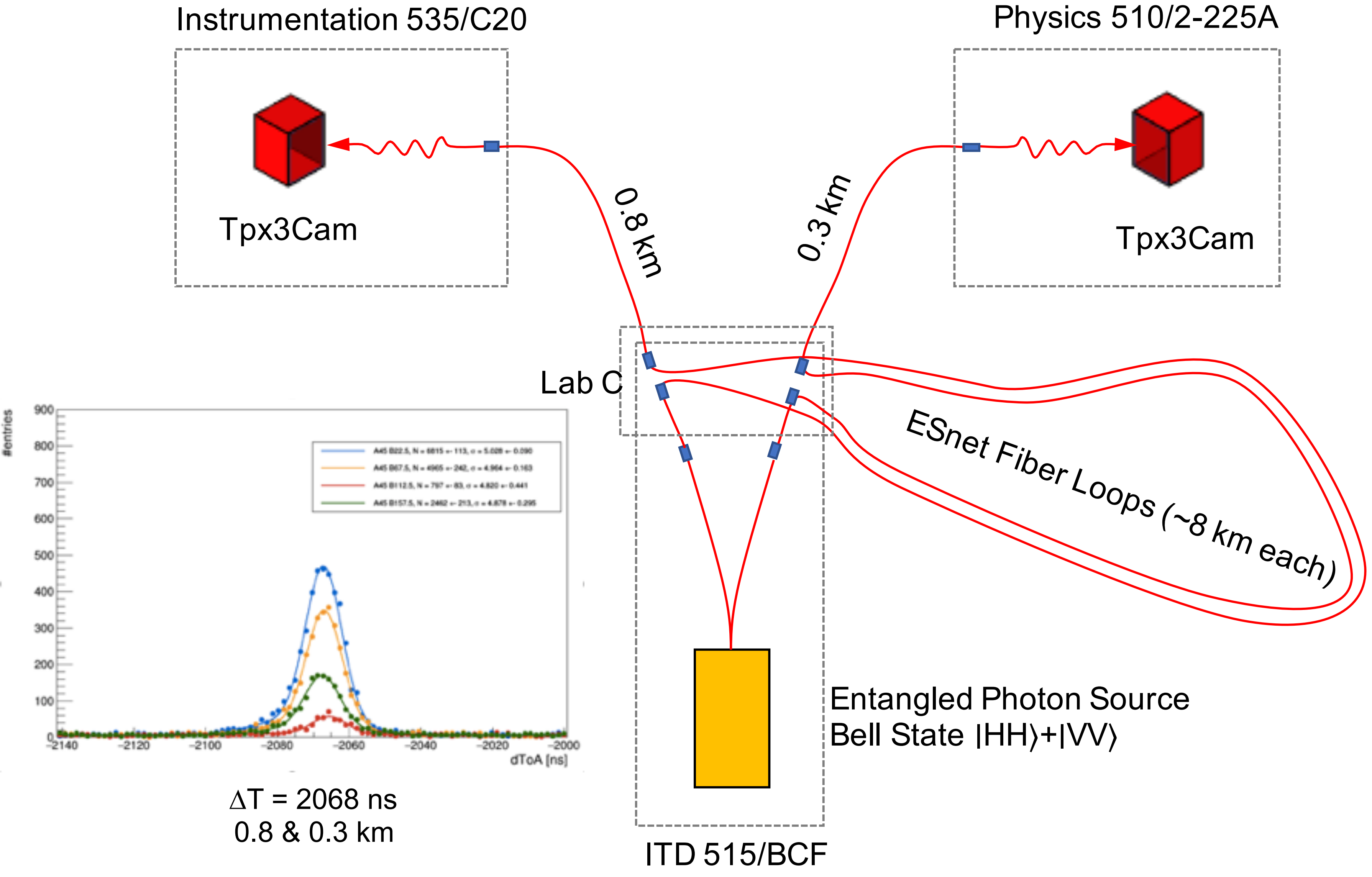
Fast camera spatial characterization of photonic polarization entanglement

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

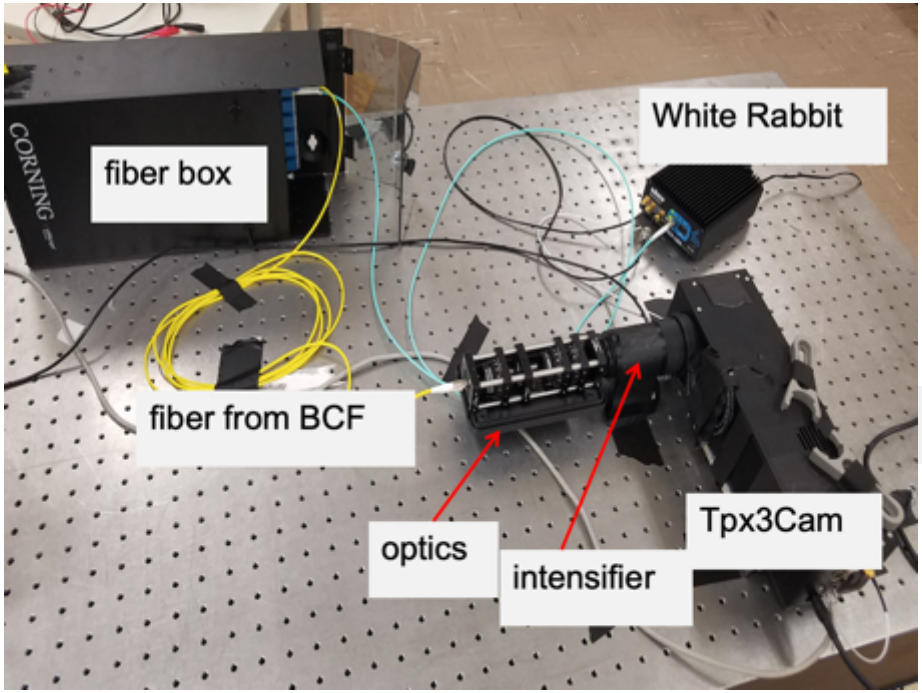
Scientific Reports **10**, Article number: 6181 (2020) | Cite this article

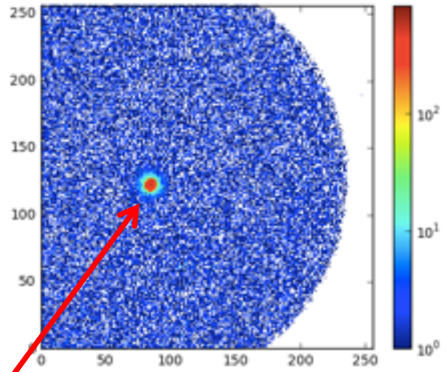
Uniform within errors as expected

Characterization of entanglement for long-distance network



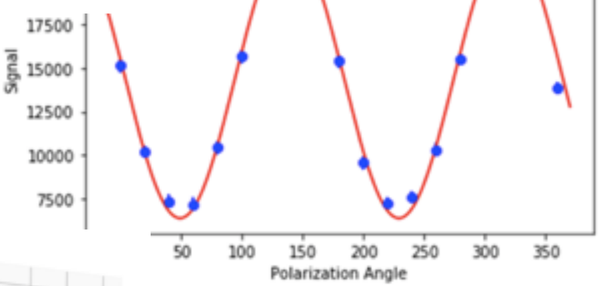
ΔT = 2068 ns
0.8 & 0.3 km

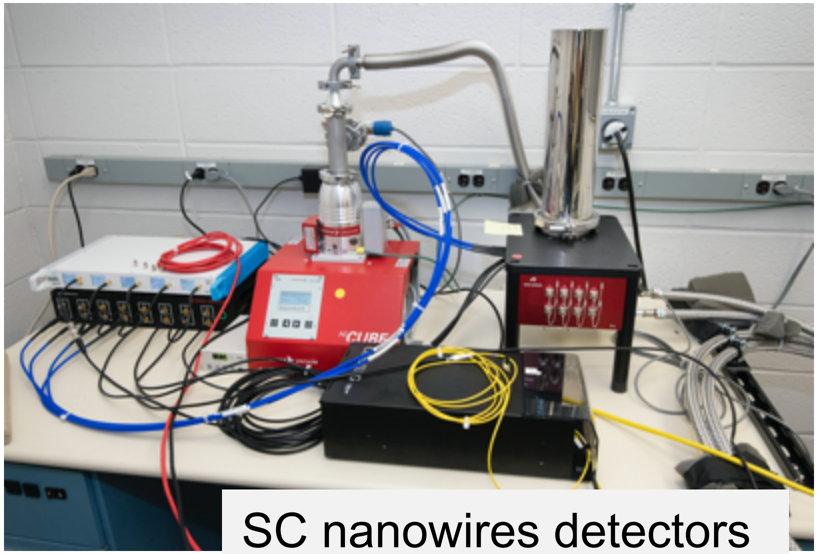




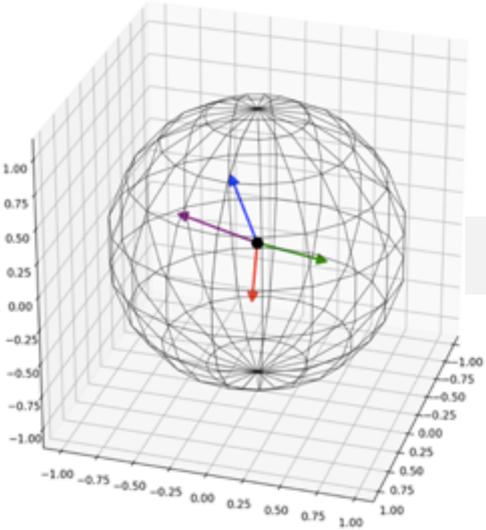
Signal from fiber

Polarization Angle VS Signal





SC nanowires detectors
O.Saira, P.Stankus



Stokes parameters

Long-distance qubit transfer experiments between BNL and SBU are in progress

Quantum entanglement distribution between BNL and SBU

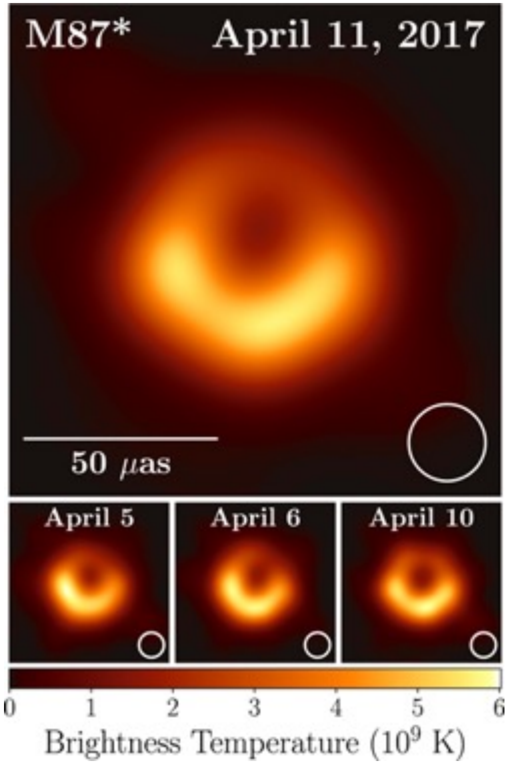
Quantum Astrometry

- BNL QuantISED project, started in Sept 2019
  - DOE QIS-HEP program

- Idea: employ quantum entanglement to improve precision of optical interferometers

Two-photon amplitude interferometry for precision astrometry
Paul Stankus, Andrei Nomerotski, Anže Slosar, Stephen Vintskevich
https://arxiv.org/abs/2010.09100

Astronomy picture of the decade

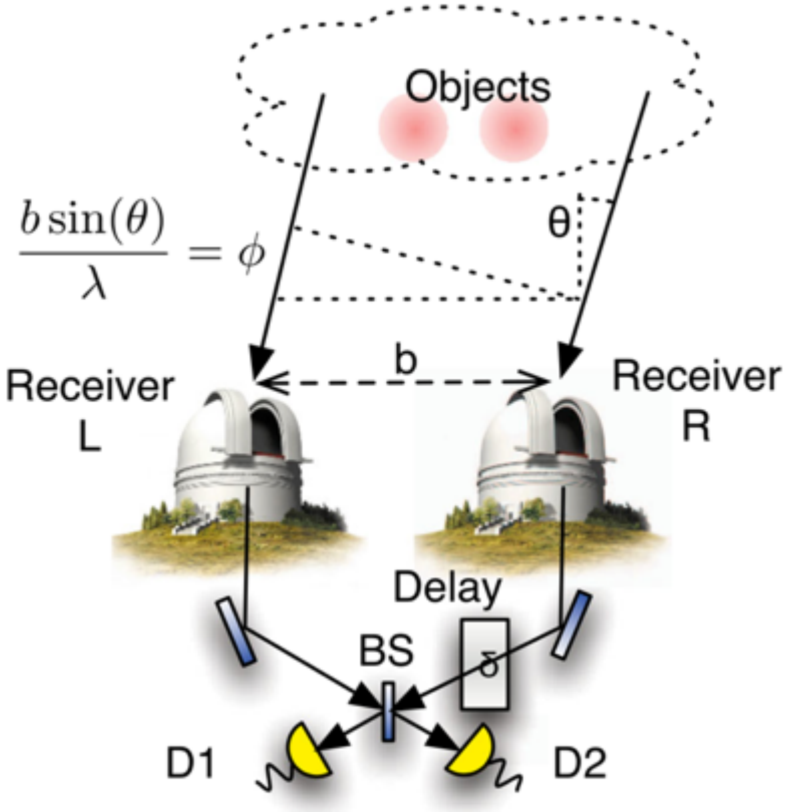


2019 ApJL 875

Black hole in the center of M87 imaged at 1.3mm

Achieved by radio interferometry with ~10000 km baselines

Classical optical interferometer

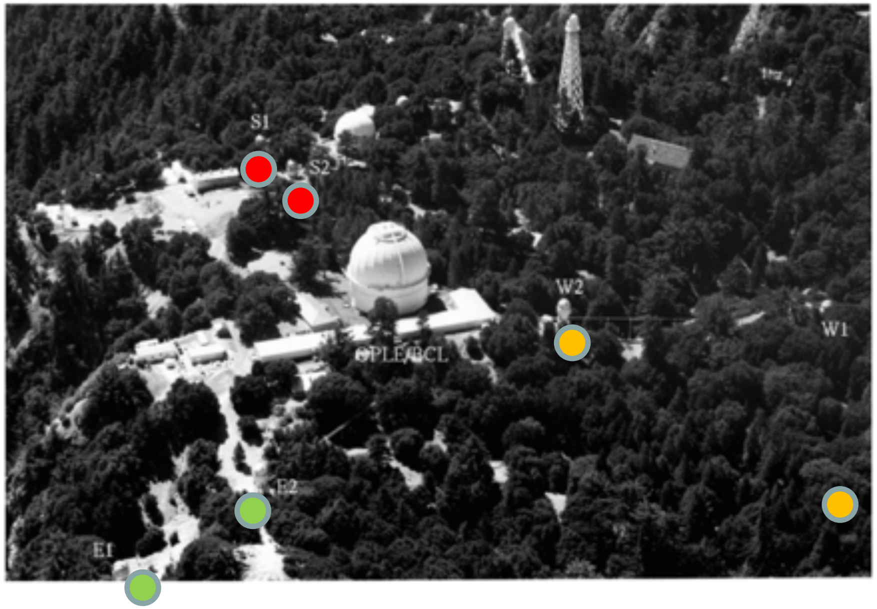


sensitive to features on angular scale

$$\Delta\theta \sim \frac{\lambda}{b}$$

- Need to bring light to the same location
- Baselines limited to 100 m

Optical Interferometers



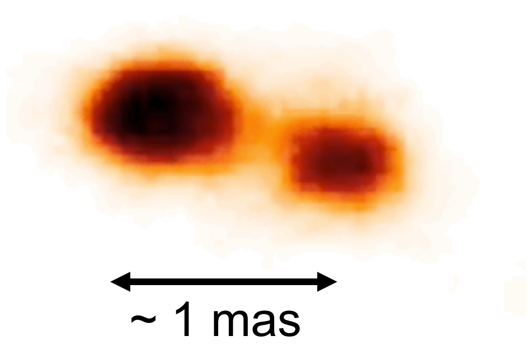
CHARA (Center for High Angular Resolution Astronomy) Observatory at Mt.Wilson in CA

The Astrophysical Journal, 628:453–465

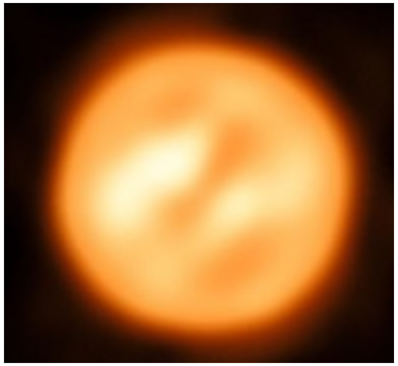
Beam line path length control at CHARA

Path lengths must be balanced so arrival times on two legs match to within $\Delta t \sim 1/\nu$ i.e. $1/$photon bandwidth

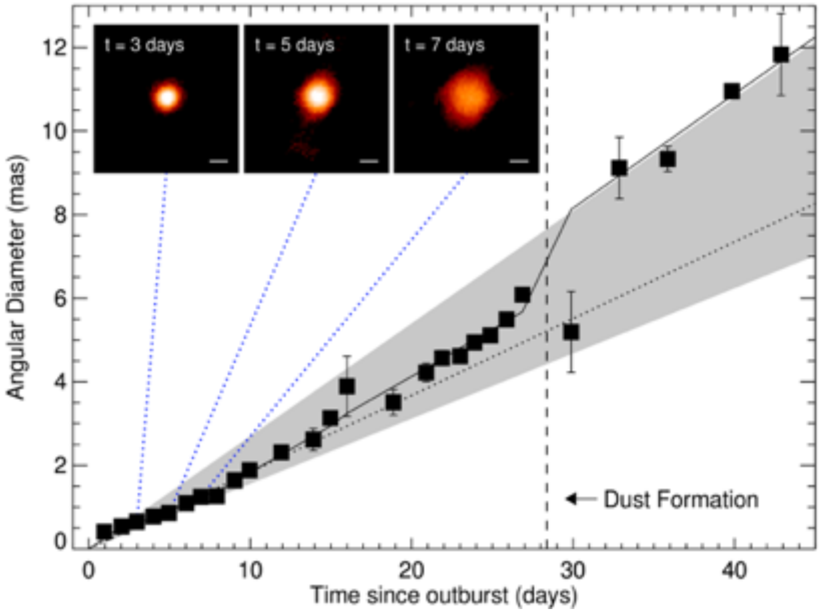
Optical interferometry examples



CHARA Collaboration, “First Resolved Images of the Eclipsing and Interacting Binary β Lyrae”; arXiv:0808.0932, The Astrophysical Journal, 684: L95–L98.



Dynamic convection on Antares
(VLTI, ESO)

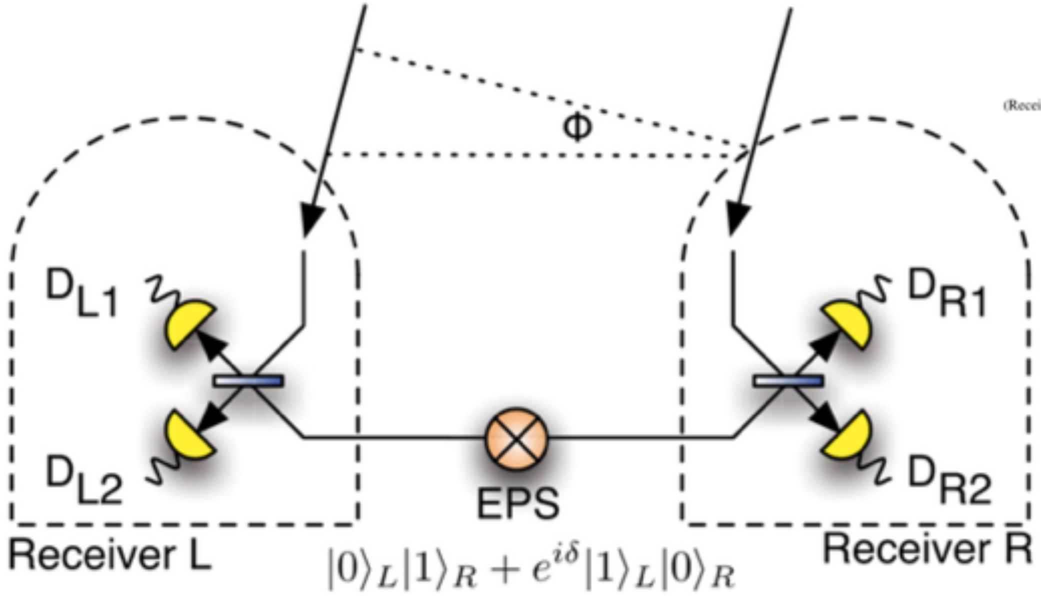


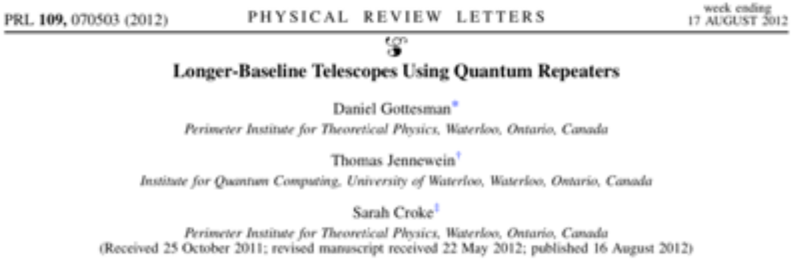
Nova in progress (CHARA)

Two-photon techniques (quantum mechanical)

Original idea in 2012

Quantum (two-photon) interferometer





PRL **109,** 070503 (2012) PHYSICAL REVIEW LETTERS week ending 17 AUGUST 2012

Longer-Baseline Telescopes Using Quantum Repeaters

Daniel Gottesman*
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Sarah Croke‡
Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada
(Received 25 October 2011; revised manuscript received 22 May 2012; published 16 August 2012)

$$\Delta\theta \sim \frac{\lambda}{b}$$

- Measure photon wave function phase difference performing Bell State Measurement at one station so teleporting the sky photon to the other station
- Enables long baselines and could improve astrometric precision by orders of magnitude

Possible impact on astrophysics and cosmology

it is a blue-sky research

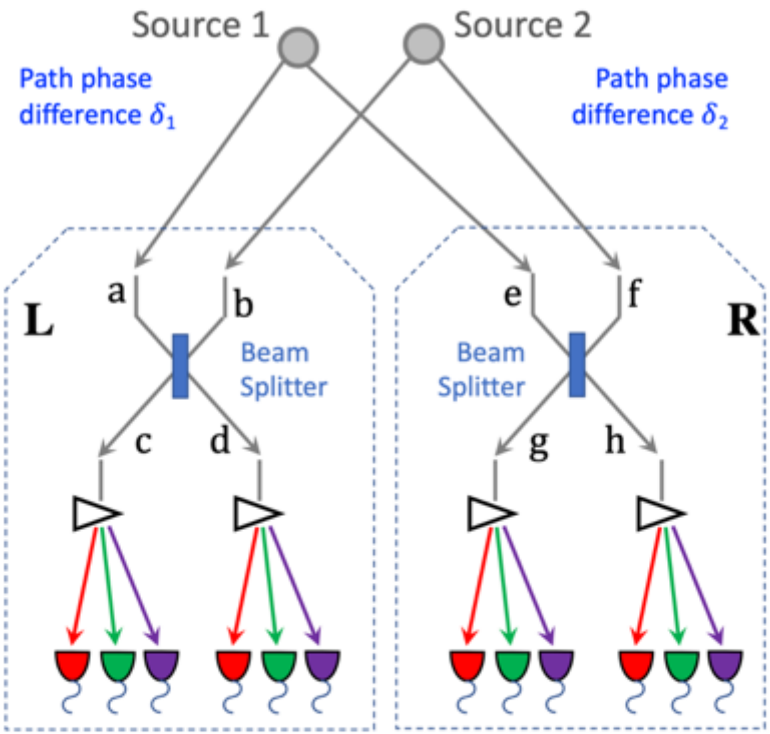
BUT if successful : orders of magnitude better astrometry

- Imaging of black holes → general relativity checks
- Parallax: improved distance ladder → SN science → DE
- Proper motions: local DM patterns
- Microlensing, see motions and shape changes, DM hunting

- Gravitational waves, coherent motions of stars
- Exoplanets
- etc

Quantum Astrometry

Proof of principle experiments: demonstrate two-photon interference using two sky sources



https://arxiv.org/abs/2010.09100

$$
\begin{aligned}
P(c^2) = P(d^2) = P(g^2) = P(h^2) &= 1/8 \\
P(cg) = P(dh) &= (1/8)(1+\cos(\delta_1-\delta_2)) \\
P(ch) = P(dg) &= (1/8)(1-\cos(\delta_1-\delta_2))
\end{aligned}
$$

$$
\begin{aligned}
&N_c(xy) = \eta_1\eta_2 A^2 \int_0^{T_r} P_{L,R,\tau}^{\text{two photons}} d\tau = \\
&A^2\eta_1\eta_2 T_r \Bigg[(I_1+I_2)^2 + I_1^2 \frac{\tau_c g_{11}}{T_r} + I_2^2 \frac{\tau_c g_{22}}{T_r} \pm \\
&2 I_1 I_2 \frac{\tau_c g_{12}}{T_r} \cos\left(\frac{\omega_0 B(\sin\theta_1 - \sin\theta_2)}{c} + \frac{\omega_0 \Delta L}{c} \right) \Bigg] (30)
\end{aligned}
$$

- Relative path phase difference $\delta_1 - \delta_2$ can be extracted from the coincidence rates of four single photon counters: c, d, g and f
- Different from Hanbury Brown Twiss intensity interferometry, can produce both negative and positive rate oscillations → amplitude interferometry
- Requirements to detectors: photons must be similar enough to interfere → excellent (<ns) time resolution and spectral resolution → 1 ns & 0.001 nm (can be traded)

Observables

https://arxiv.org/abs/2010.09100

Earth rotation fringe rate

- Path differences gradually modulated by Earth's rotation

$$\langle N_{xy}\rangle(t) = \bar{N}_{xy}\left[1 \pm V\cos\left(\omega_f t + \Phi\right)\right]$$

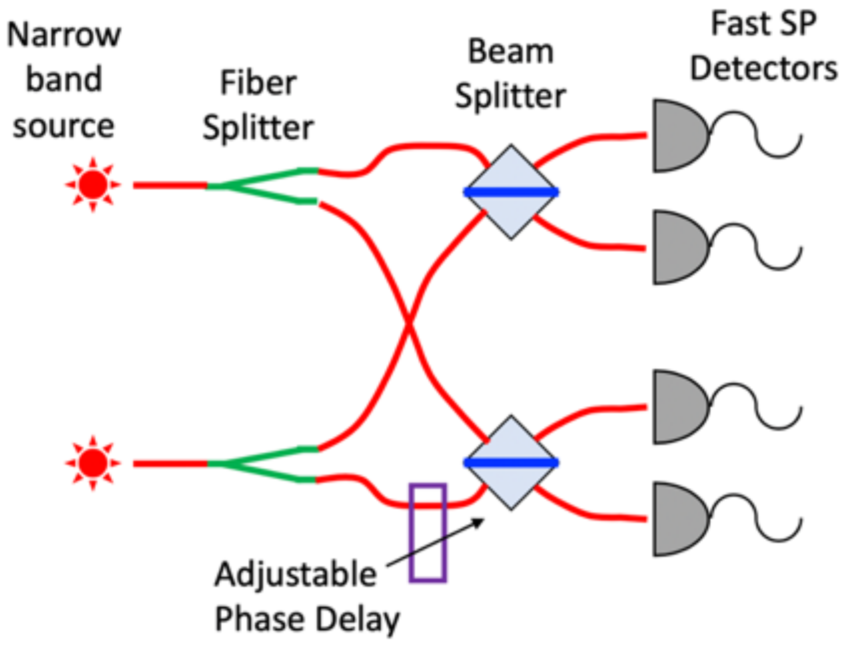
$$\omega_f = \frac{2\pi B\Omega_\oplus \sin\theta_0}{\lambda}\Delta\theta$$

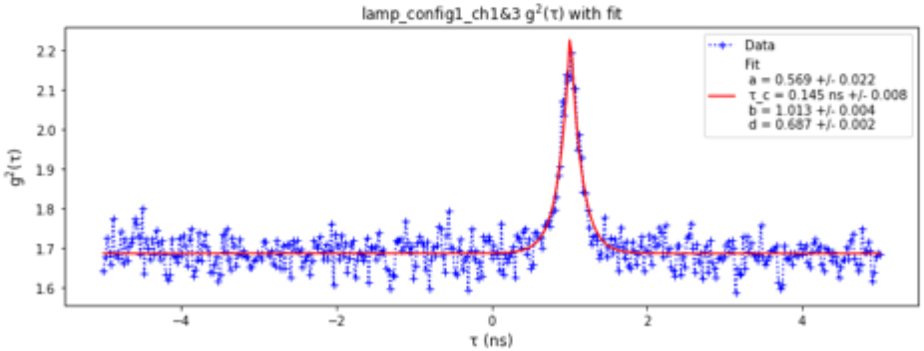
For magnitude 2 stars (bright!)

- 0.1 Hz coincidence rate in 0.15 ns bin & 1 GHz bandwidth
- Assuming $4*10^4$ 1 GHz bins and one night (10^4 sec) get 10 µas resolution
  - for 500 – 1000 nm range → $3*10^5$ 1 GHz bins

First experiments

Lab demonstration of two-photon interference (Hong-Ou-Mandel effect) and spectroscopic binning using various single photon sources: coherent, down-conversion and thermal



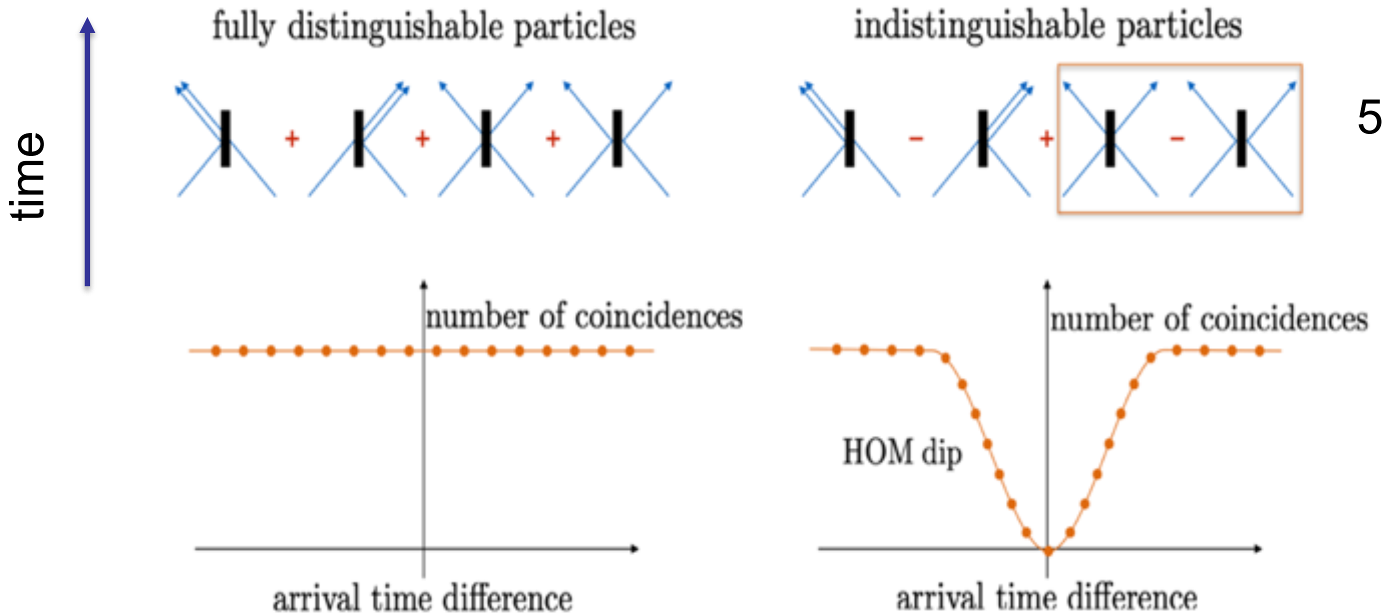


Time correlation of two channels
SC nanowires
100 ps time resolution
narrow Ar thermal line 795 nm

Demonstrates HBT effect → photon coherence time

Work in progress, not published yet

Hong-Ou-Mandel effect

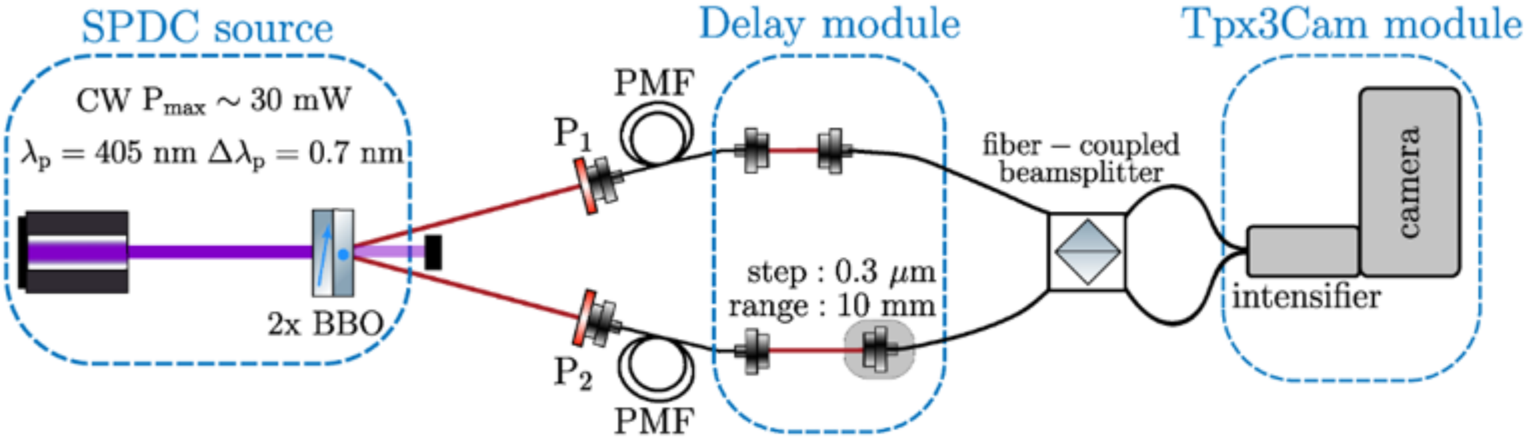


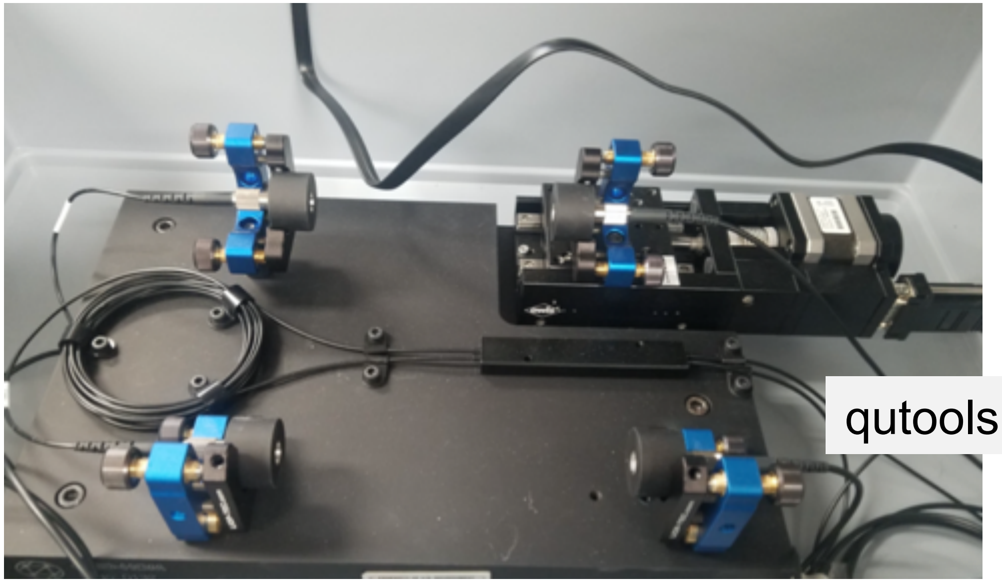
50/50 beam splitter

credit: Wikipedia HOM article

1) HOM dip for coincidences of two fibers
2) Bunched photons in single fibers

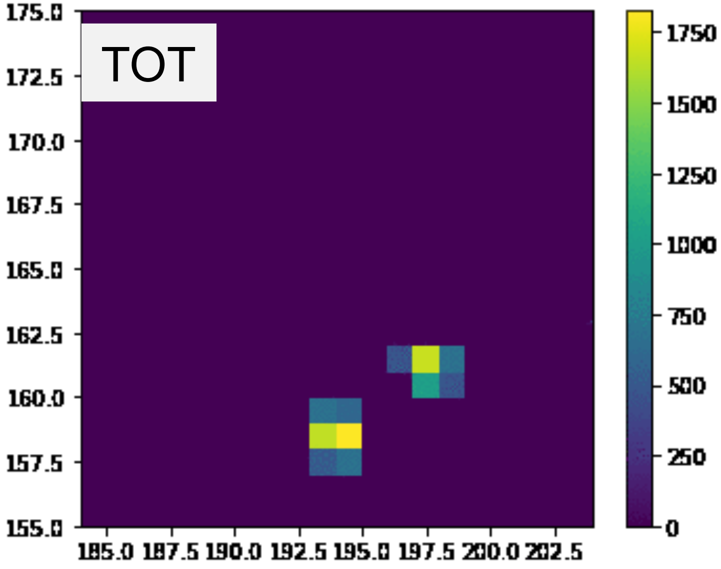
HOM Setup

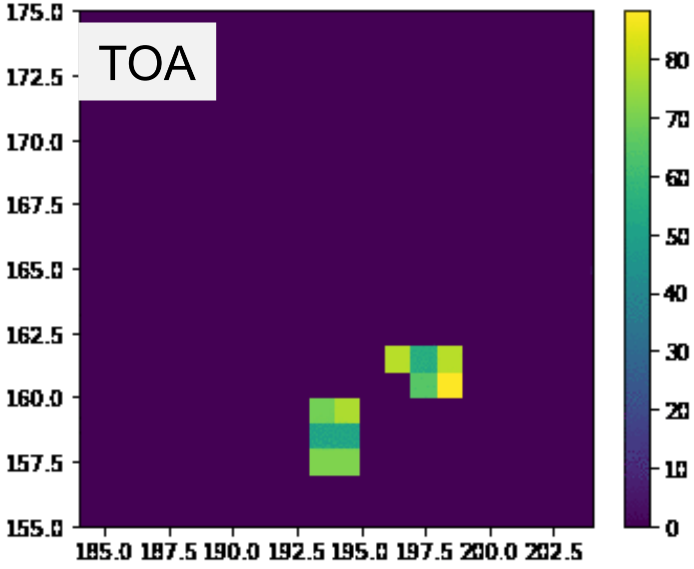


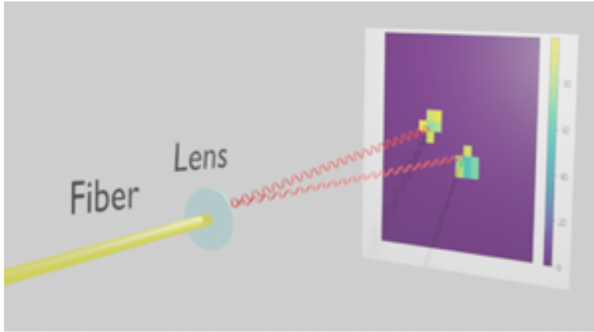


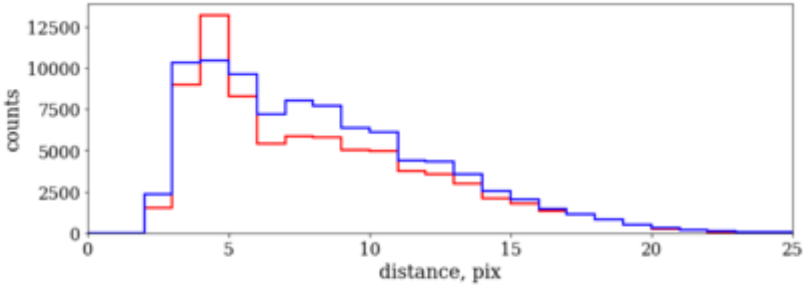
qutools.com

Examples of bunched HOM photons





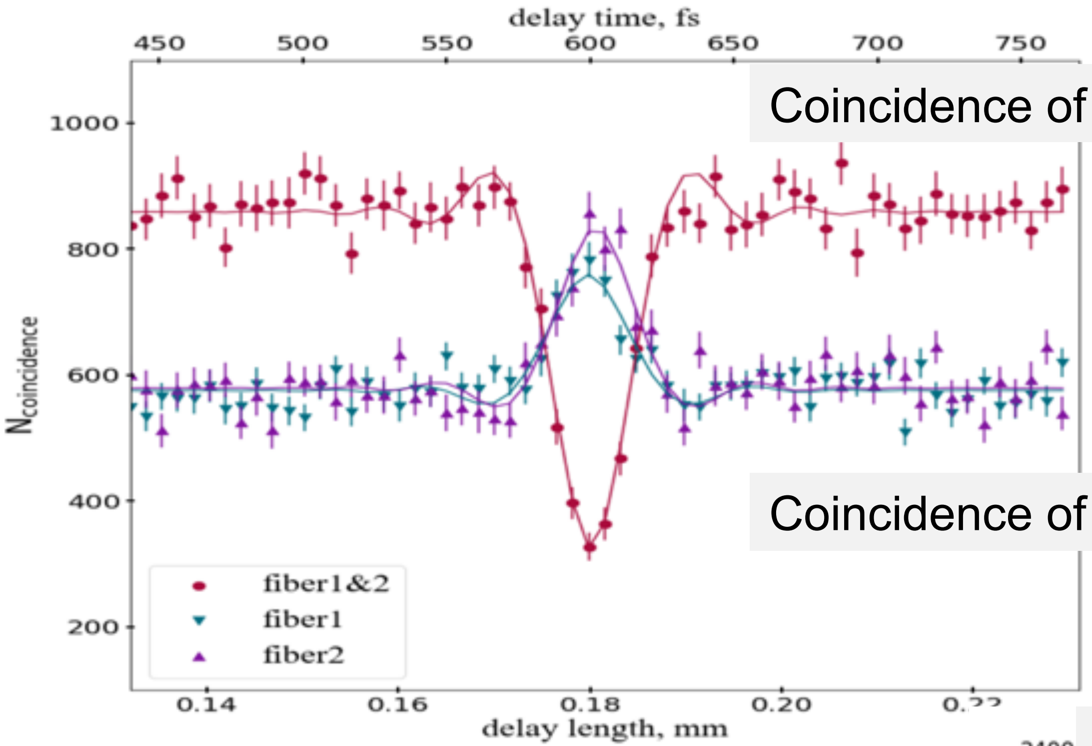




Distance between two photons, pix

Hong-Ou-Mandel effect

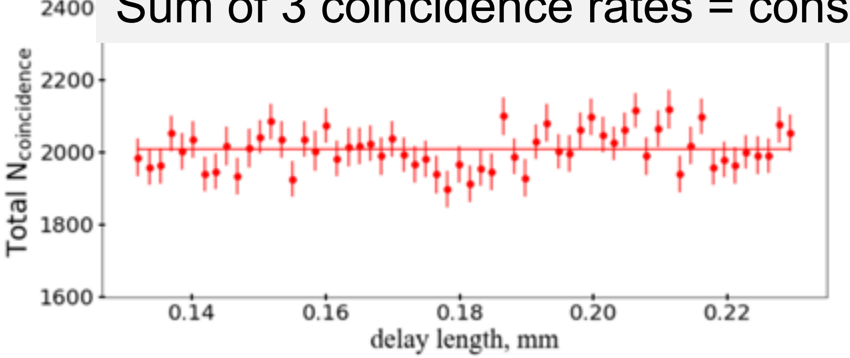
$$f(d-d_0) = \frac{3}{4\sqrt{\pi}} \int dy \, [\mathrm{sinc}\left(y^2\right)]^2 \, e^{-iy\frac{\sqrt{4\log 2}(d-d0)}{\mathrm{FWHM}}}.$$



Coincidence of photons in two fibers

Coincidence of photons in single fibers

Sum of 3 coincidence rates = const

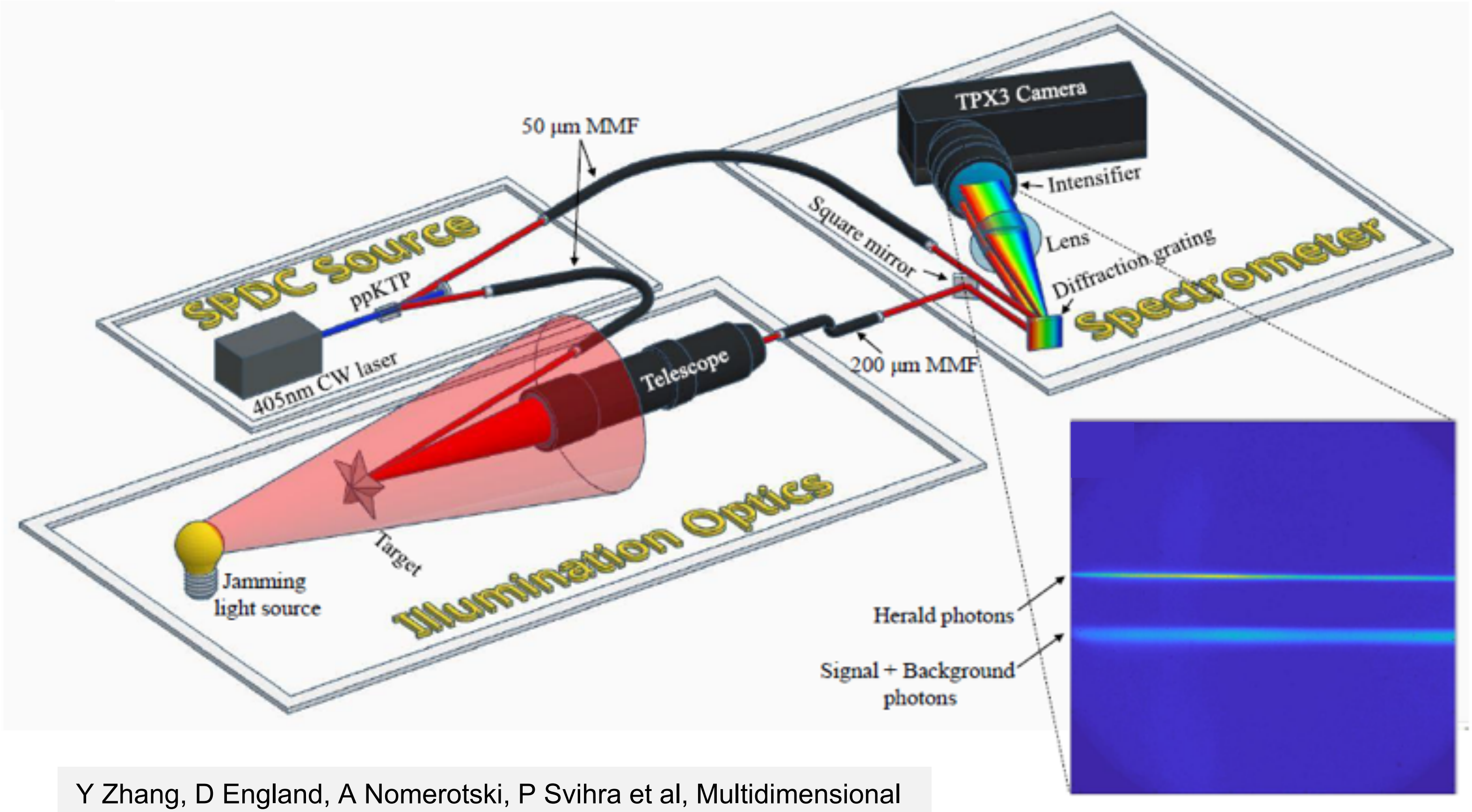


A. Nomerotski, M. Keach, P. Stankus, P. Svihra, and S. Vintskevich, "Counting of hong-ou-mandel bunched optical photons using a fast pixel camera," arXiv:2005.07982 (2020).

Proves that photon counting is real

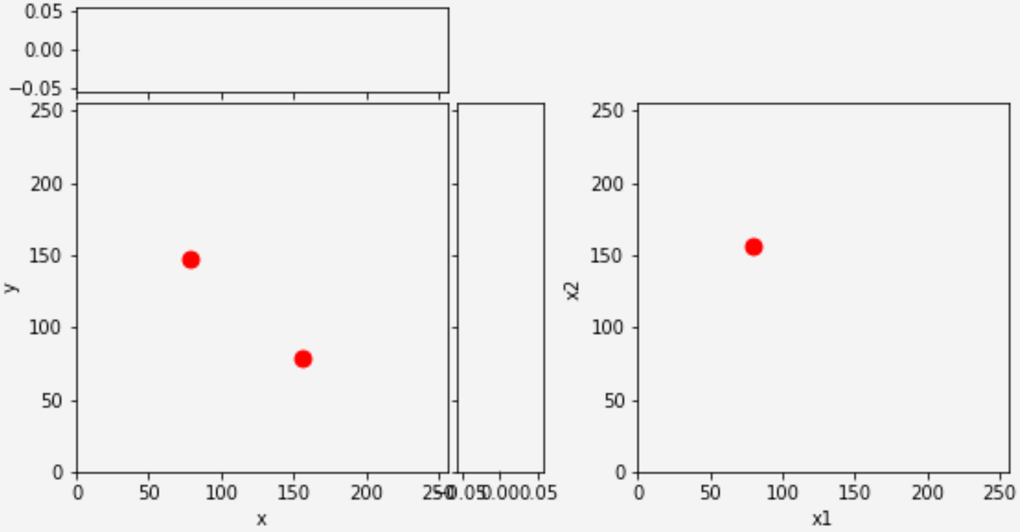
Spectroscopic binning for Quantum-Enhanced Target Detection

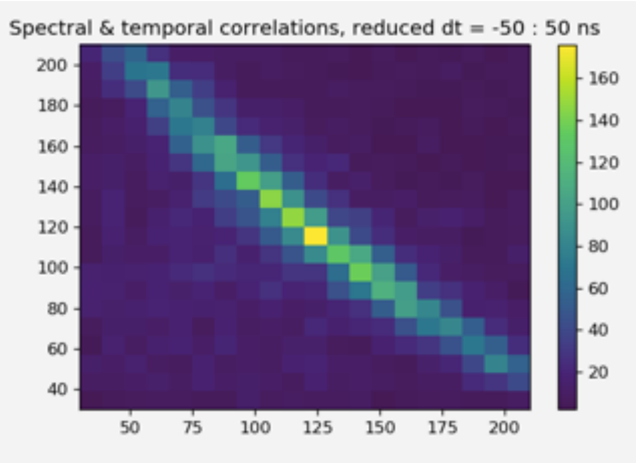
In collaboration with NRC (Ottawa CA) D.England et al
Primary interest: quantum LIDAR and quantum illumination

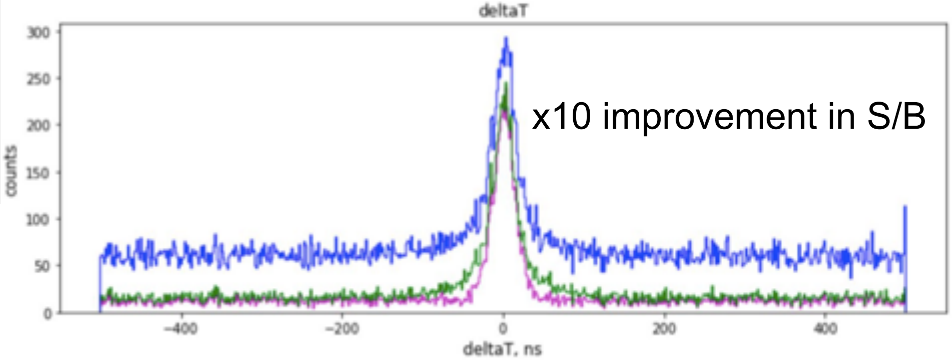


Y Zhang, D England, A Nomerotski, P Svihra et al, Multidimensional quantum-enhanced target detection via spectrotemporal-correlation measurements, Physical Review A 101 (5), 053808

Spectral and temporal correlations





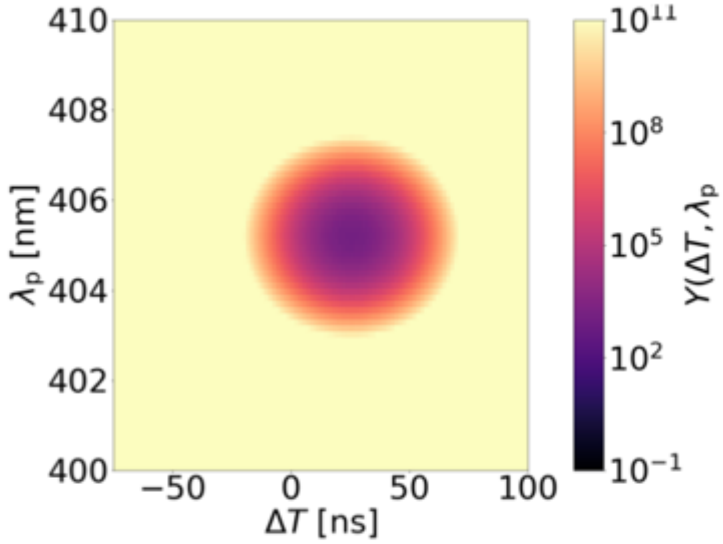


x10 improvement in S/B

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)

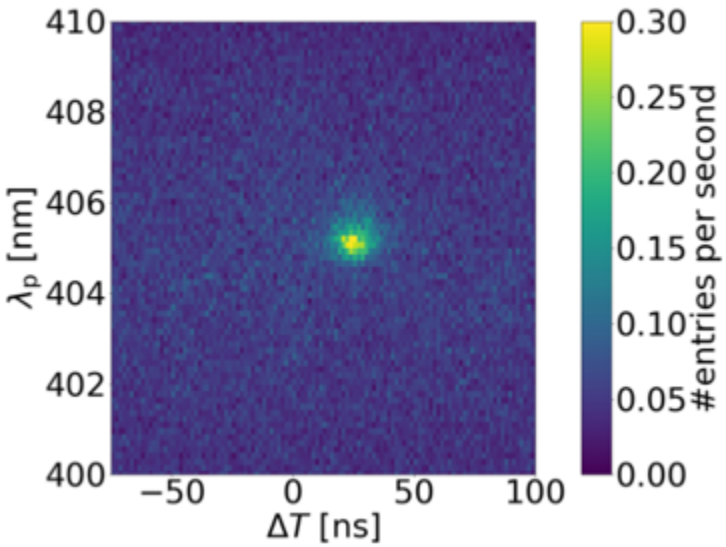
Optimal multivariate discrimination

Since both temporal and spectral information is available on pair by pair basis we can do multivariate analysis, simplest one using likelihood ratios



$$Y = \frac{f^B(x_1,\ldots,x_n)}{f^S(x_1,\ldots,x_n)} = \prod_{i=1}^{n} \frac{f^B(x_i)}{f^S(x_i)} = \prod_{i=1}^{n} Y_i$$

Likelihood ratios



Pump photon wavelength vs delta T

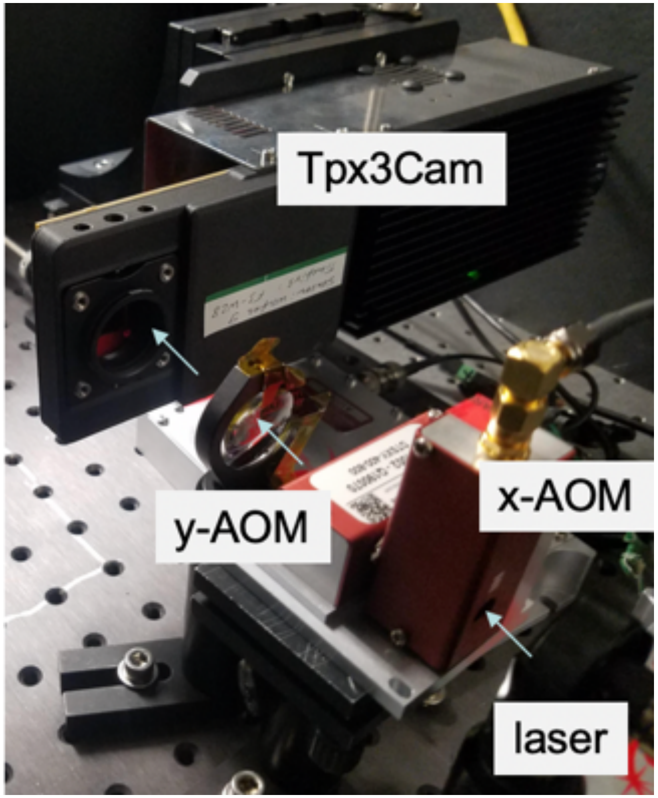
P Svihra, Y Zhang et al, Multivariate Discrimination in Quantum Target Detection, arXiv preprint arXiv:2005.00612
Appl. Phys. Lett. **117**, 044001 (2020)

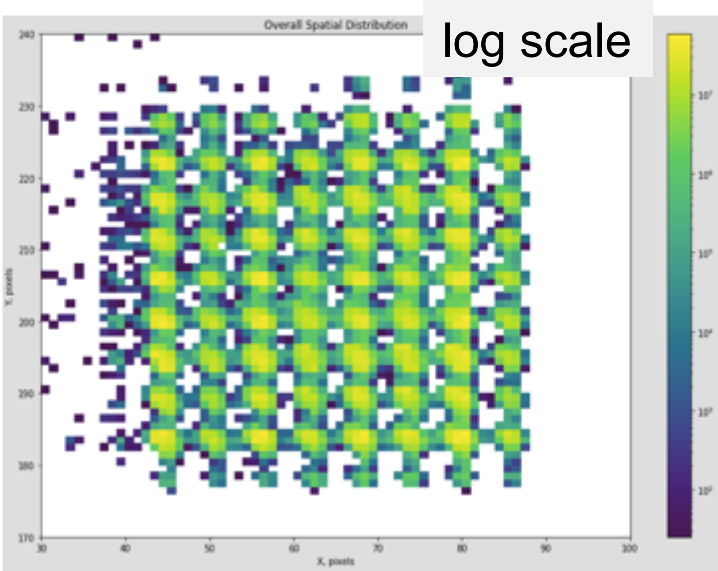
Scalability

Tpx3Cam supports 10MHz single photon rate :
= 10 x 10 x 100kHz beams

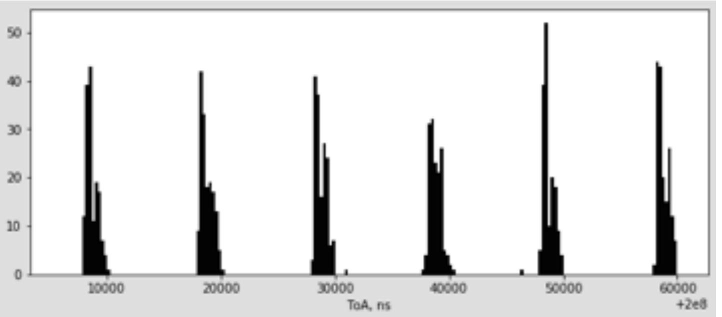
Photon router:

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





70 x 70 pixel area with 64 beams
total area 256 x 256 pixels

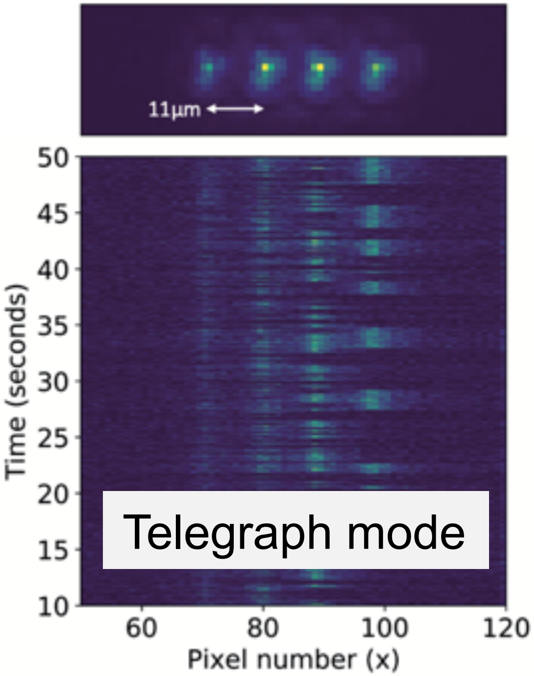


Time, ns

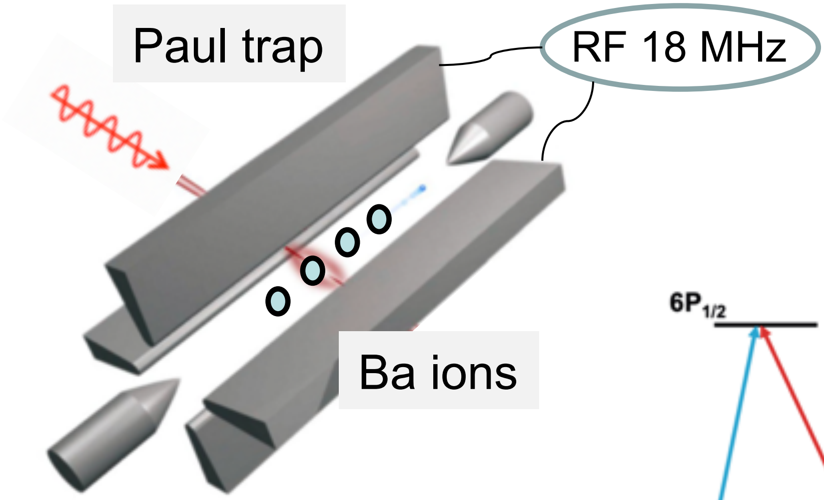
More quantum imaging

Imaging of trapped ions

Time resolved qubit manipulation (Blinov group, UWash)



Telegraph mode

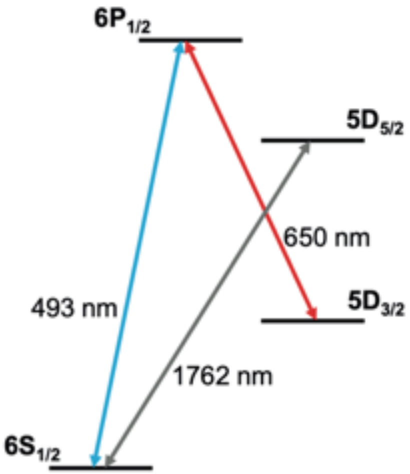


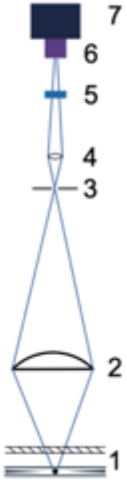
Paul trap

RF 18 MHz

Ba ions

Boris Blinov
Mila Zhukas



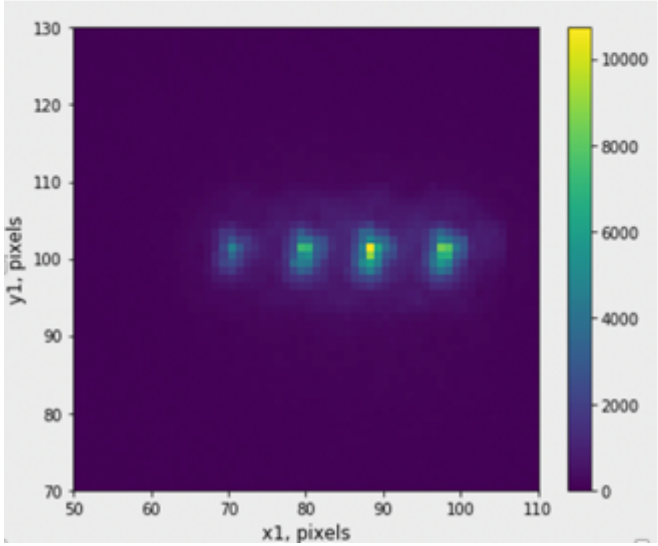


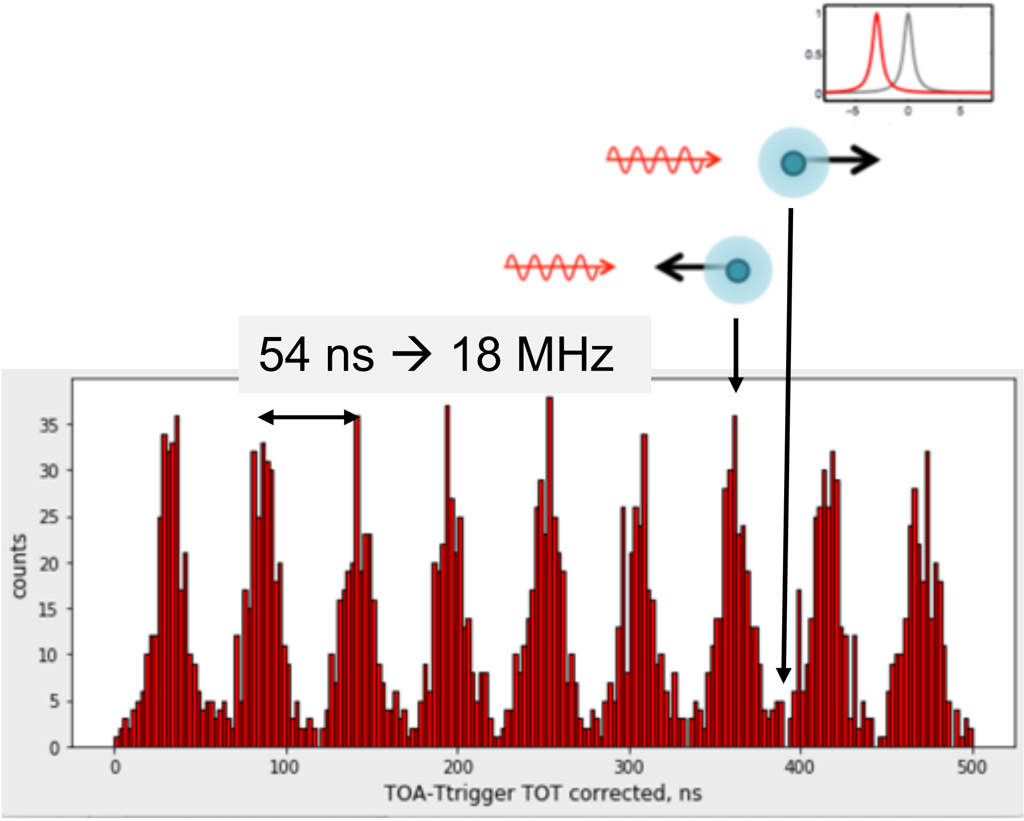
Register 493 nm photons to probe dark/bright state of ion = state of qubit register

Fast Simultaneous Detection of Trapped Ion Qubit Register with Low Crosstalk, M.Zhukas, P.Svihra, A.Nomerotski, B.Blinov, arxiv.org/abs/2006.12801

single qubit detection fidelity 0.99995

Time resolved ion oscillations




54 ns → 18 MHz

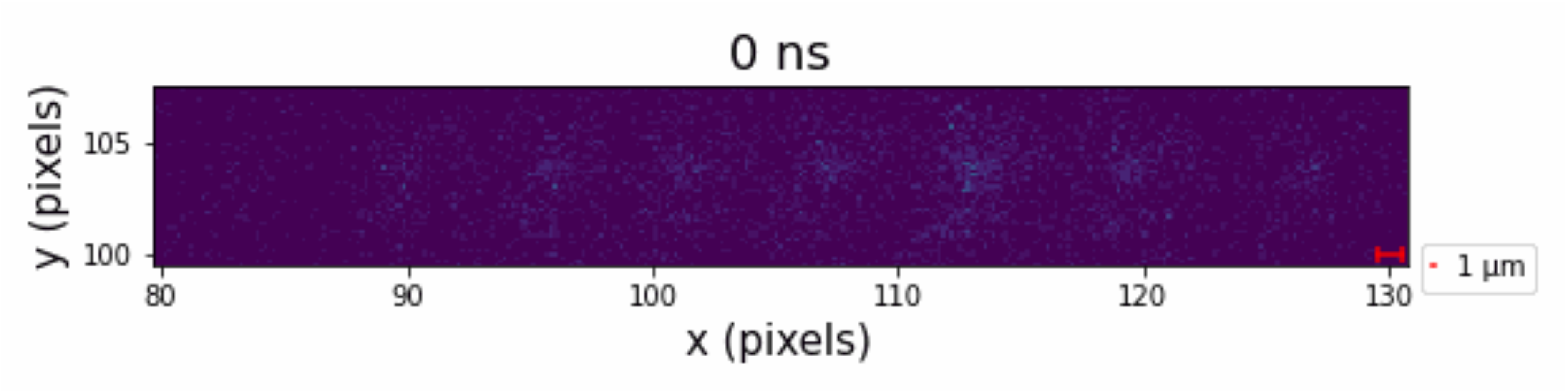
- Emission rate oscillations due to Doppler shift of laser light wrt moving ion
- Simultaneous time & position information allows to monitor ion micro-motions
- Powerful technique to characterize traps

Paper in preparation: Direct observation of micromotions in Paul trap

Ion micromotions

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

- Period 54 ns
- Amplitude 0.4 micron



Direct Observation of Ion Micromotion in a Linear Paul Trap
Liudmila A. Zhukas, Maverick J. Millican, Peter Svihra, Andrei Nomerotski, Boris B. Blinov, arxiv: 2010.00159

Imaging with 30 ps timing

take precise timing from MCP

Electron spectroscopy at Wayne State U

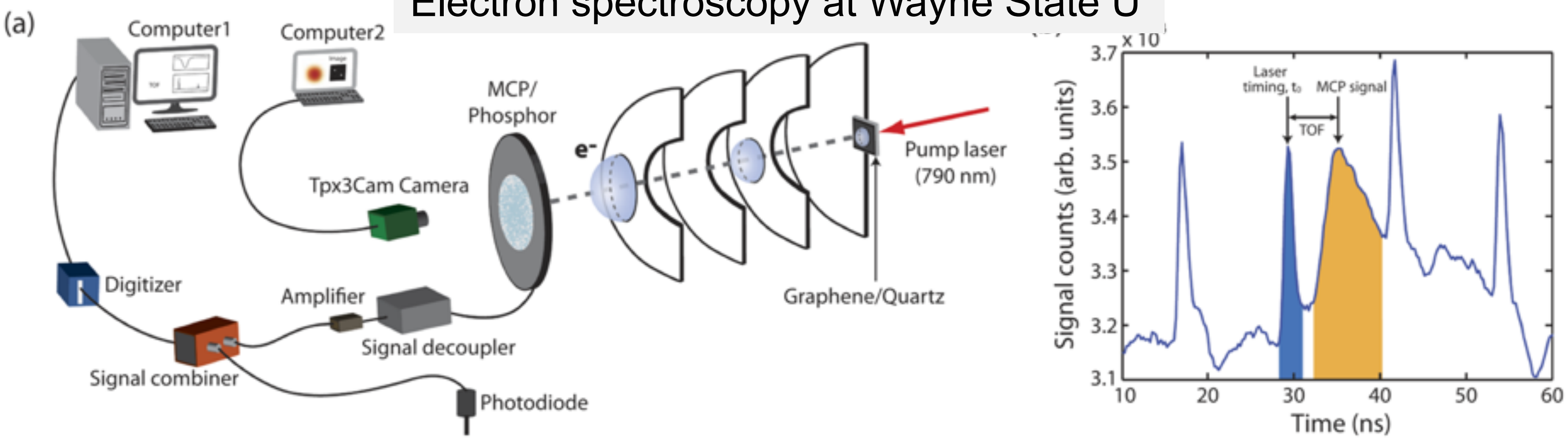


FIG. 1. (a) Schematic of the experimental setup and (b) a typical TOF trace measured from the digitizer.

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

HEP applications

TPX3Cam on ARIADNE 1-ton dual phase Liquid argon TPC

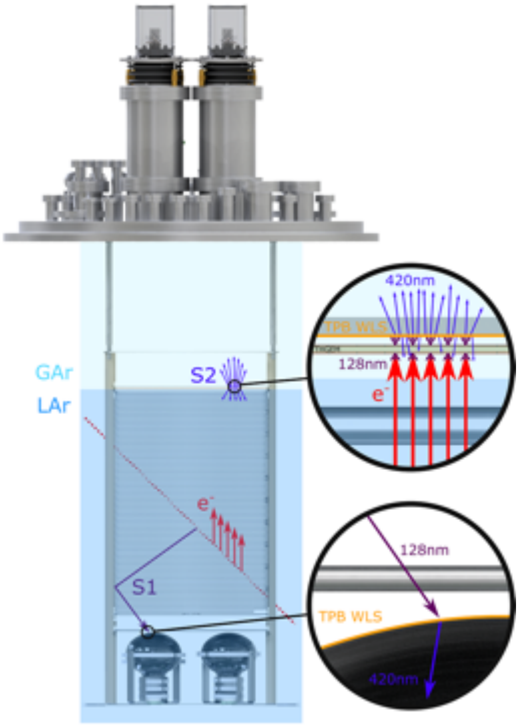
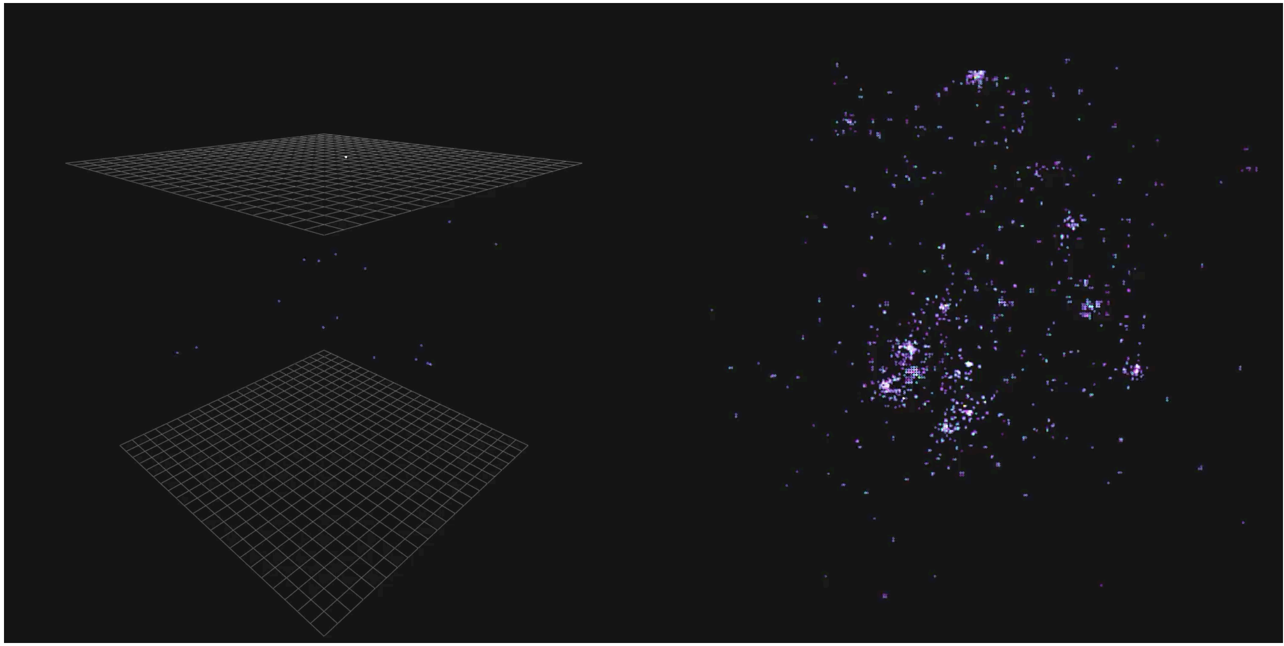


Image light from avalanches in gas phase in THGEM

LAr Cosmic Muons (10msec slice)

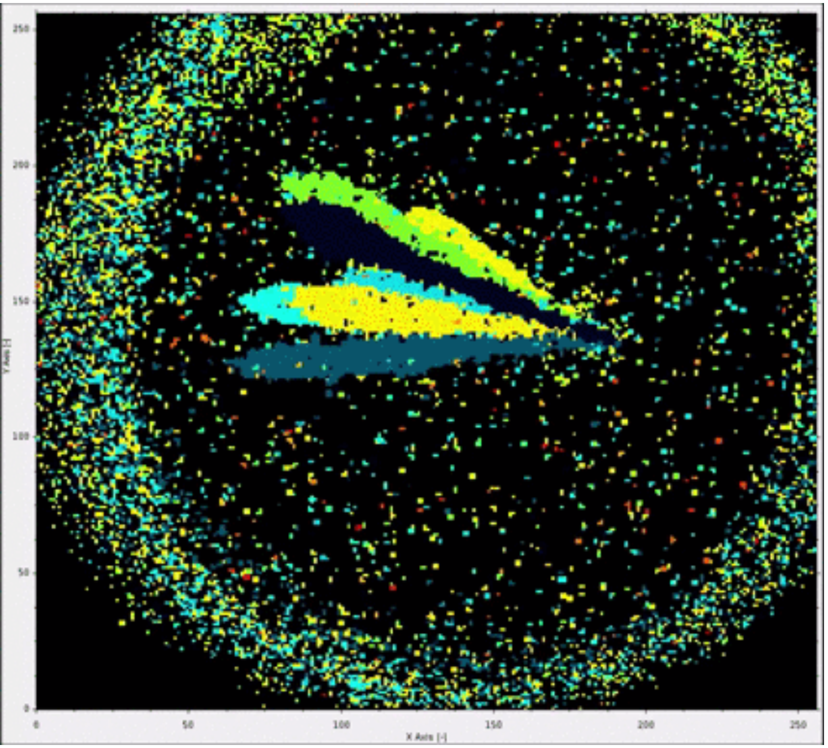


hep.ph.liv.ac.uk/ariadne/index.html
Kostas Mavrokoridis et al

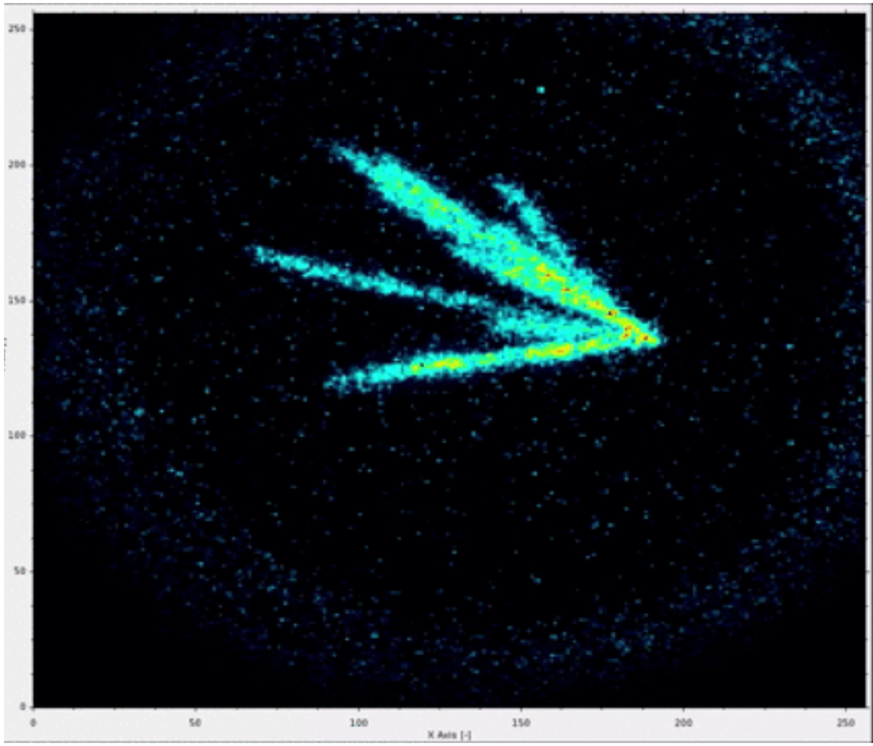
D. Hollywood et al, 2020 ARIADNE—A novel optical LArTPC: technical design report and initial characterisation using a secondary beam from the CERN PS and cosmic muons *JINST* **15** P03003

A. Roberts et al., 2019 First demonstration of 3D optical readout of a TPC using a single photon sensitive Timepix3 based camera *JINST* **14** P06001

5.5 MeV alphas in CF_4 gas in Tpx3Cam



Color = TOA

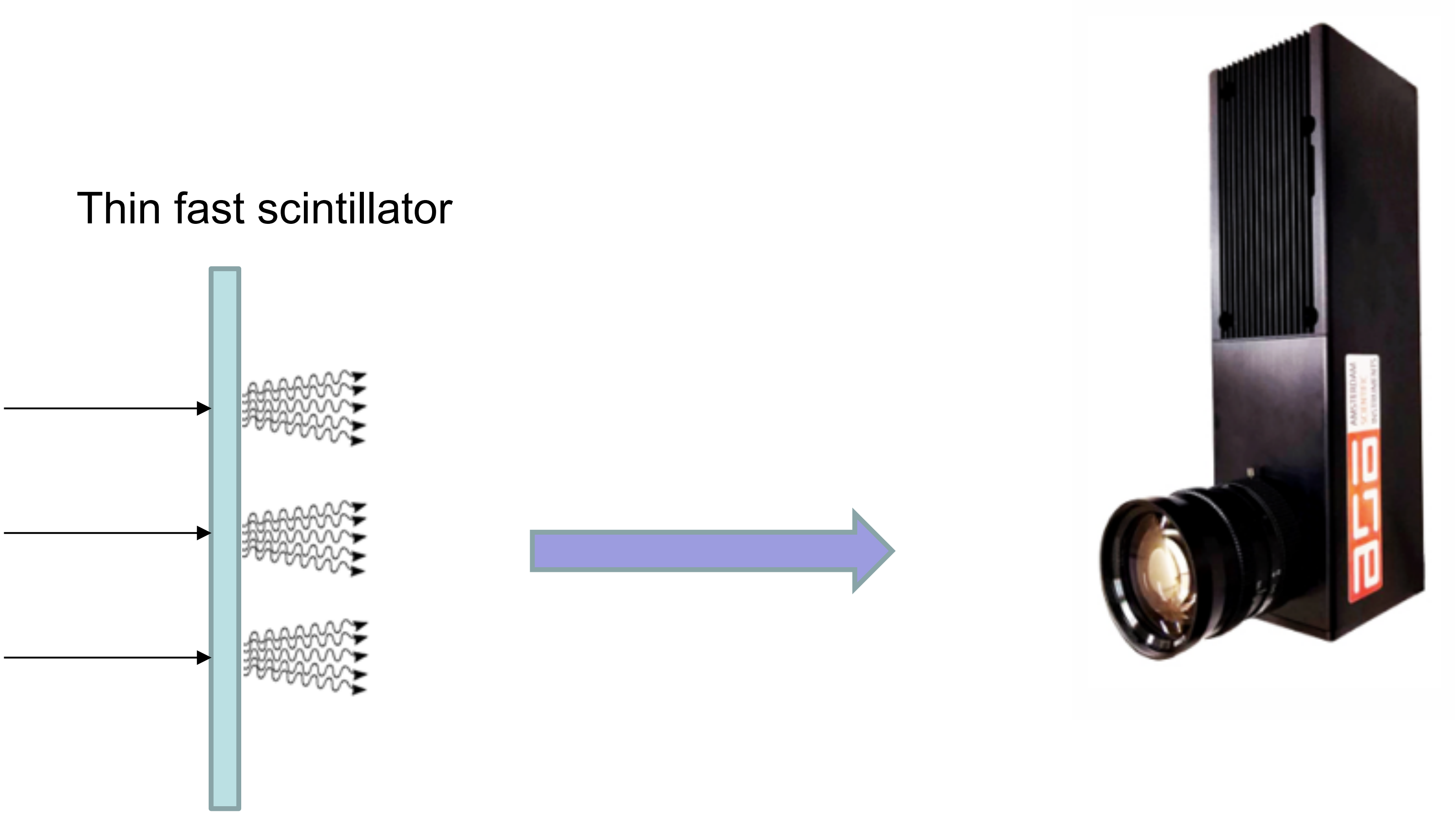


Color = TOT

First demonstration of 3D optical readout of a TPC using a single photon sensitive Timepix3 based camera, A Roberts, P Svihra, A Al-Refaie, H Graafsma, J Küpper, K Majumdar, ... K. Mavrokoridis, A.Nomerotski … Journal of Instrumentation 14 (06), P06001 (2019)

More ideas

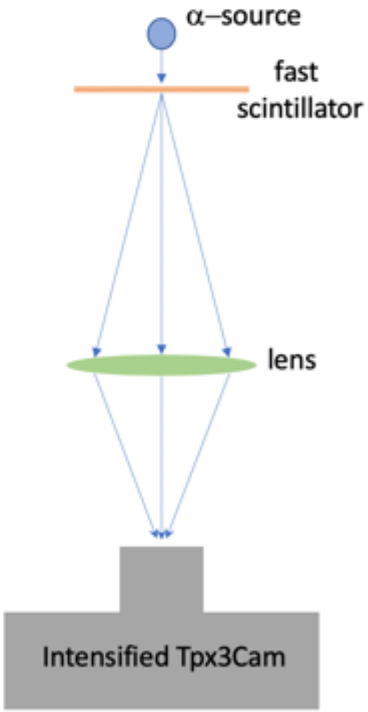
- Scintillator flashes are imaged by intensified Tpx3Cam
- Alphas, hard x–rays, neutrons, …

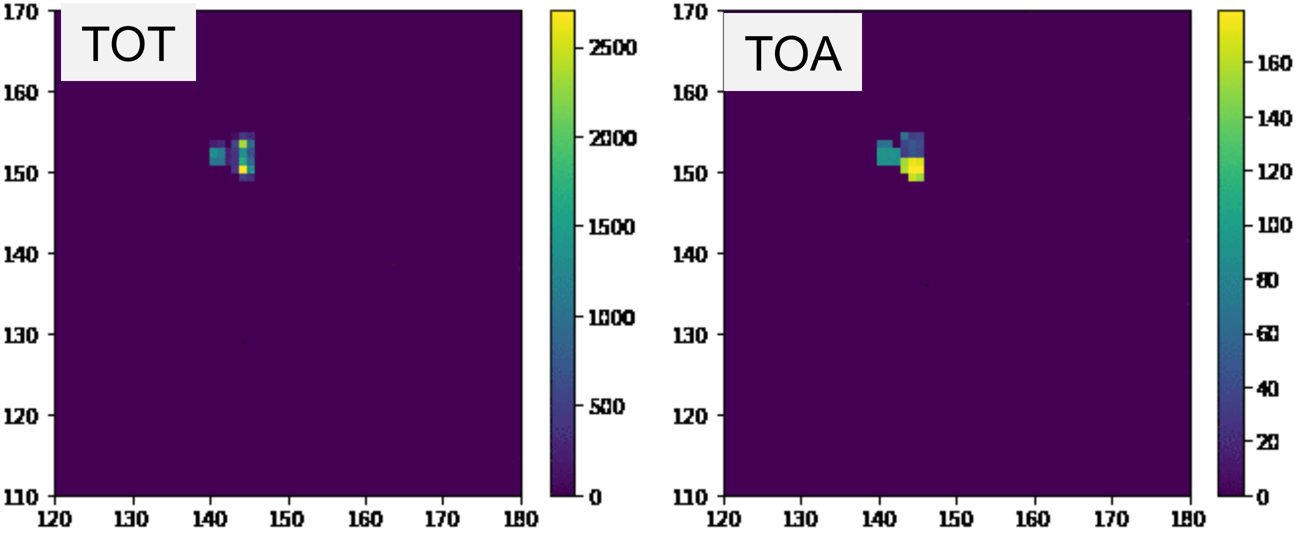

Thin fast scintillator

Difficulty: light collection efficiency (but it’s single photon sensitive)
Advantage: outside of the beam, around the corner (with mirrors)

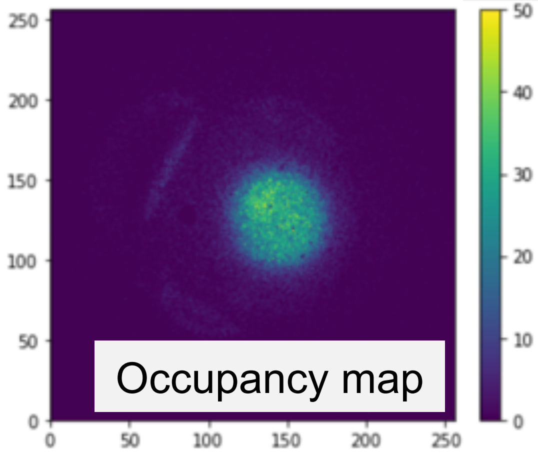
Alphas in LYSO in Tpx3Cam

Am241 5.5 MeV alphas
LYSO 0.5 mm thickness

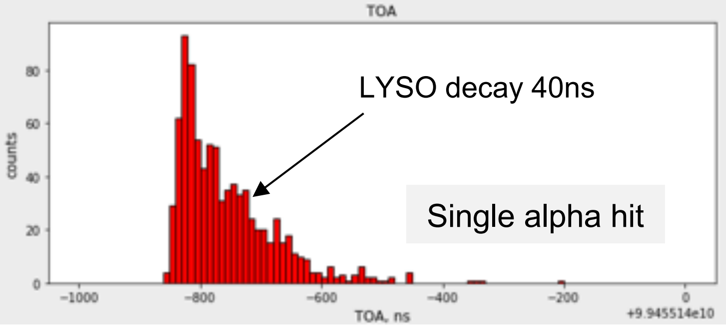




Alpha hits in Tpx3Cam



Occupancy map



LYSO decay 40ns

Single alpha hit

TOA, ns

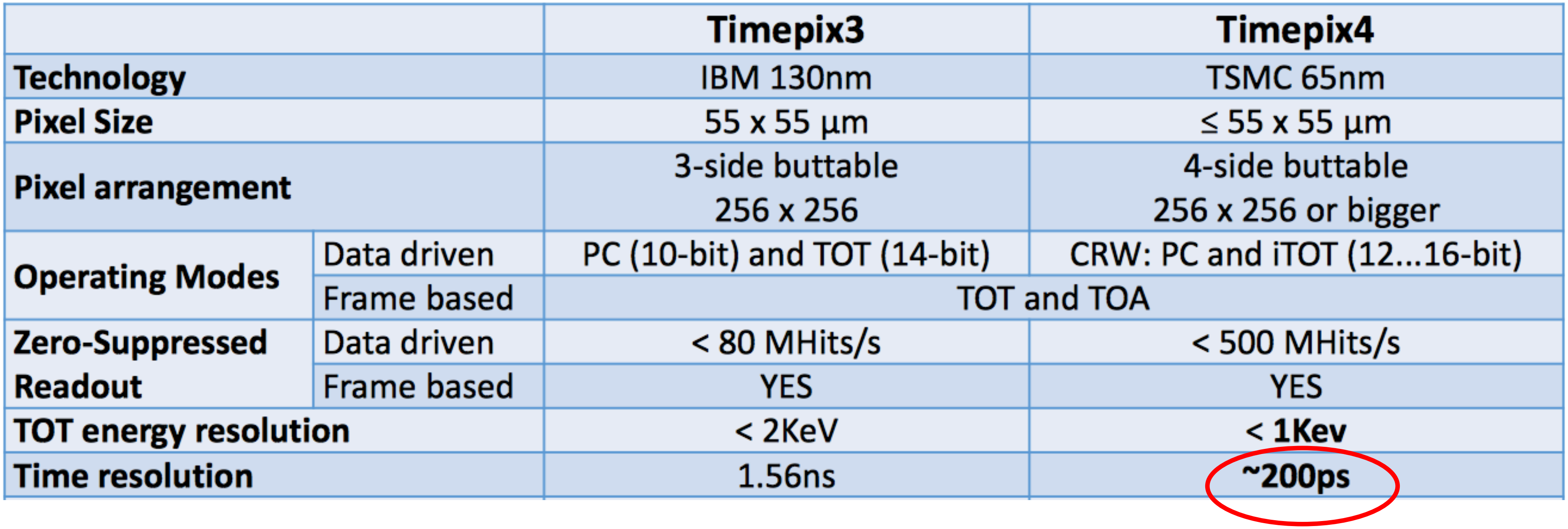
Paper in preparation: **Novel imaging technique for α-particles using a fast optical camera** G. D'Amen,[a] M. Keach,[a] A. Nomerotski,[a] P. Svihra,[b,c] A. Tricoli[a]

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**

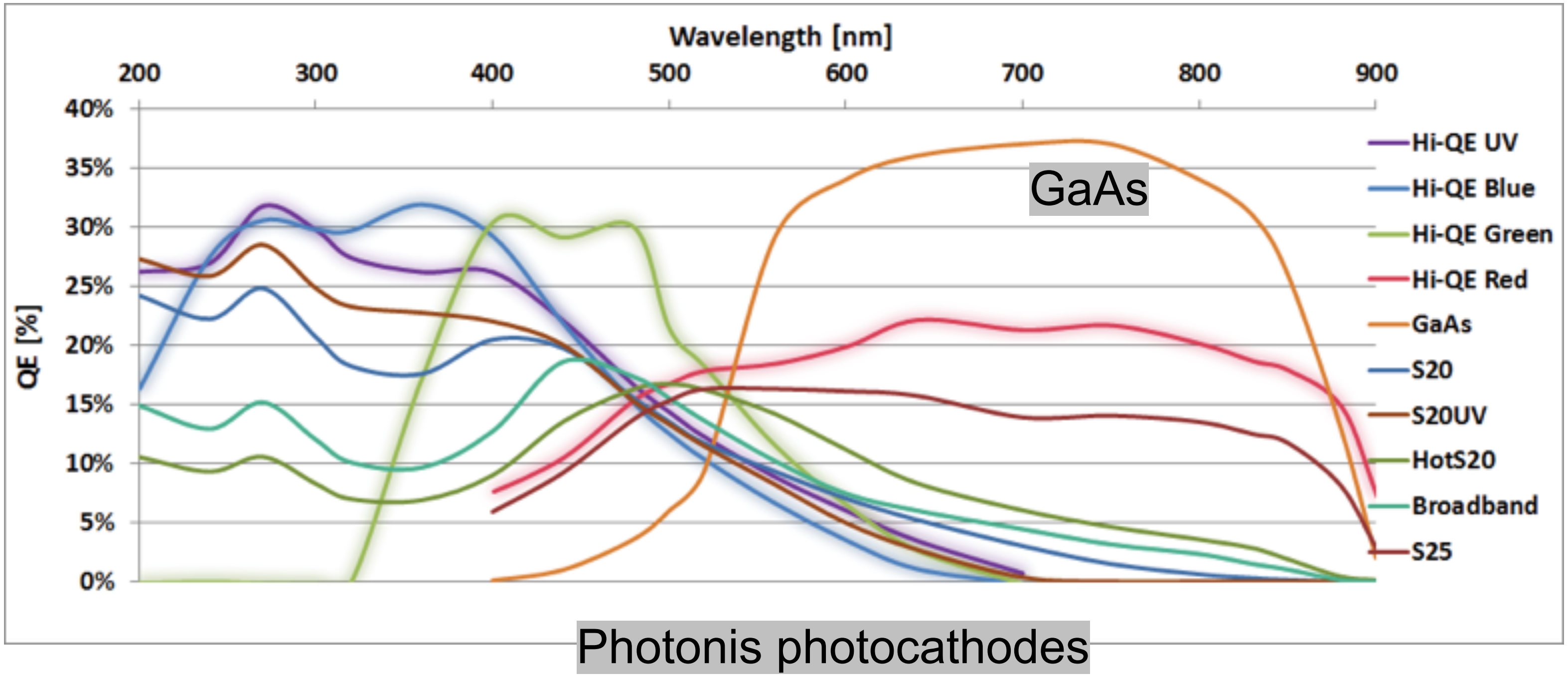
WISH LIST:

ASIC with optimized timing for clusters and triggering capabilities, synchronization hooks for outside devices and multiple chips

Readout with several 10 ps TDCs in synch with Tpx

Single Photon Sensitivity without intensifier?

- So far needed outside amplification (MCP) to have a detectable signal
- Limitation: QE ~ 35% (for 800nm)



Photonis photocathodes

Single Photon Sensitivity without intensifier?

- Can the amplification be integrated into the sensor? Silicon QE can be >90%

SPADs

- Currently PDE (photon detection eff) ~30-50% but there is no fundamental limit. High PDE is crucial for some QIS applications

100 ps 32x32 pixel SPAD Camera

NATURE COMMUNICATIONS | ARTICLE OPEN

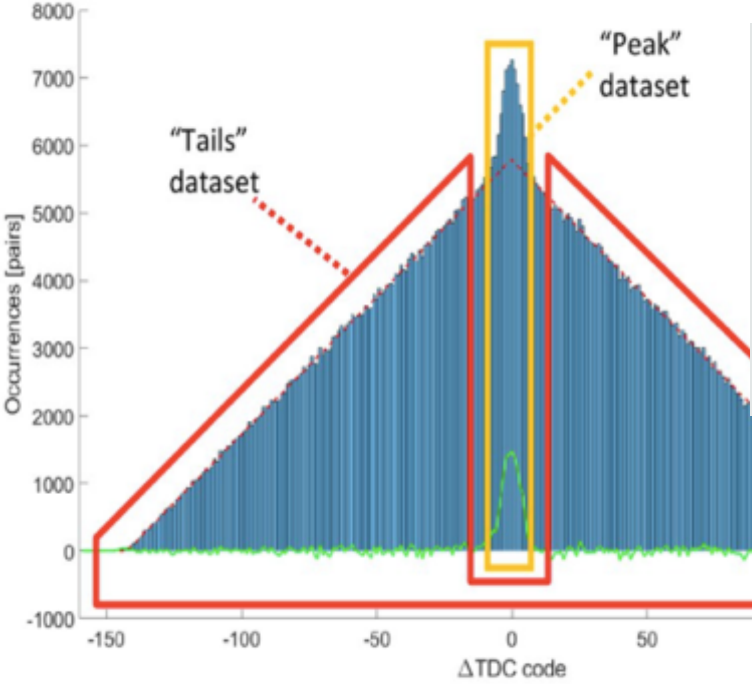
Single-photon sensitive light-in-fight imaging

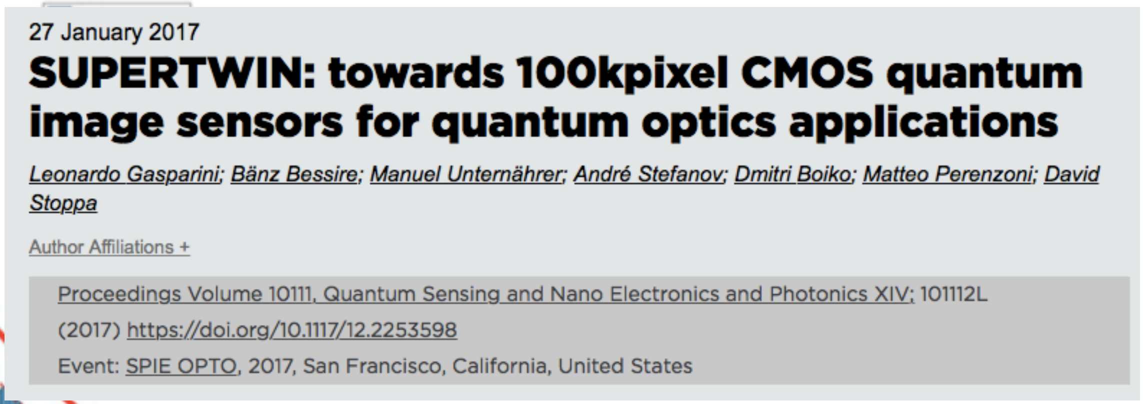
Genevieve Gariepy, Nikola Krstajić, Robert Henderson, Chunyong Li, Robert R. Thomson, Gerald S. Buller, Barmak Heshmat, Ramesh Raskar, Jonathan Leach & Daniele Faccio

Affiliations | Contributions | Corresponding authors

Nature Communications **6**, Article number: 6021 | doi:10.1038/ncomms7021
Received 18 August 2014 | Accepted 02 December 2014 | Published 27 January 2015

fully digital 8×16 pixel SPAD array





27 January 2017

SUPERTWIN: towards 100kpixel CMOS quantum image sensors for quantum optics applications

Leonardo Gasparini; Bänz Bessire; Manuel Unternährer; André Stefanov; Dmitri Boiko; Matteo Perenzoni; David Stoppa

Author Affiliations +

Proceedings Volume 10111, Quantum Sensing and Nano Electronics and Photonics XIV; 101112L (2017) https://doi.org/10.1117/12.2253598
Event: SPIE OPTO, 2017, San Francisco, California, United States

Superb time resolution
BUT high dark count rate,
difficulties in integration of complex designs in a monolithic sensor, try hybrid?

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 fast single photon detection → hot topic in QIS applications

Acknowledgements

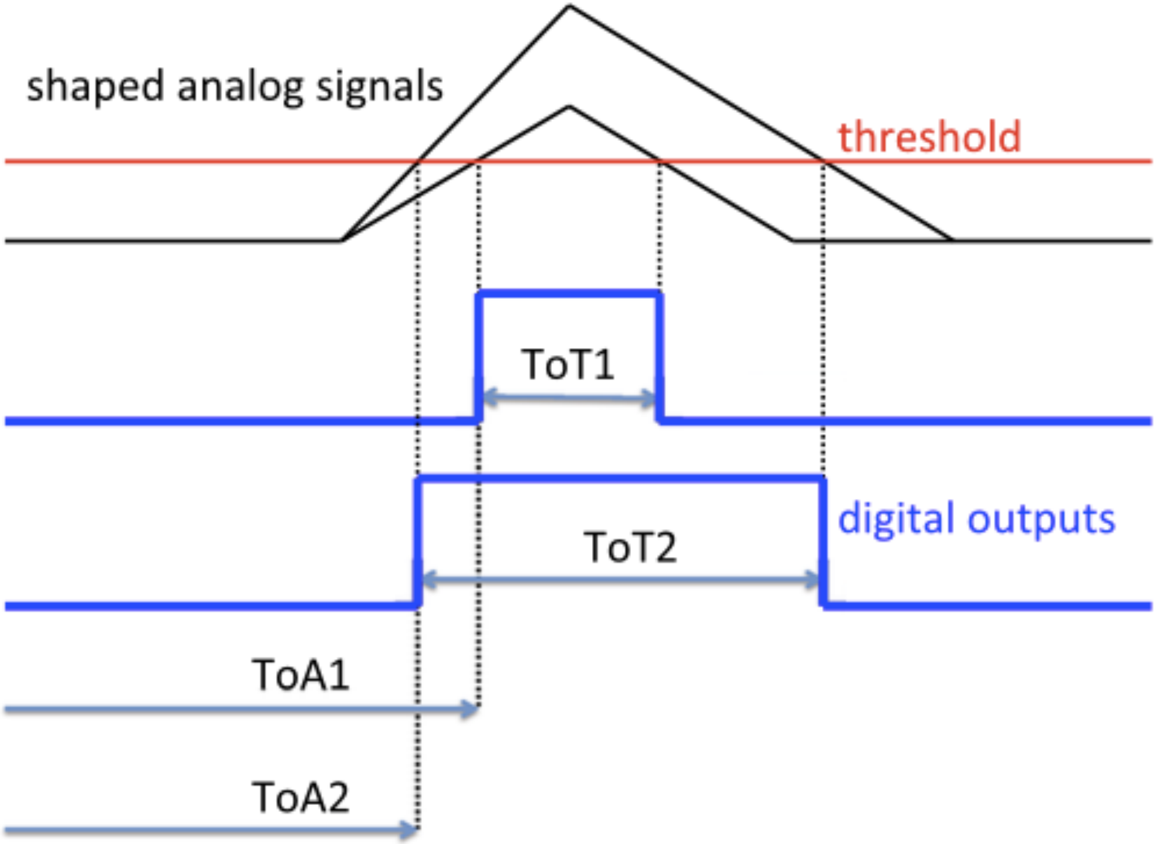
Eden Figueroa
Paul Stankus
Tom Tsang
Justine Haupt
Mael Flament
Guodong Cui
Sonali Gera
Youngshin Kim
Dimitros Katramatos
Michael O’Connor
Gabriella Carini
David Asner
Anand Kandasamy
Michael Keach
Steven Paci

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


BNL team

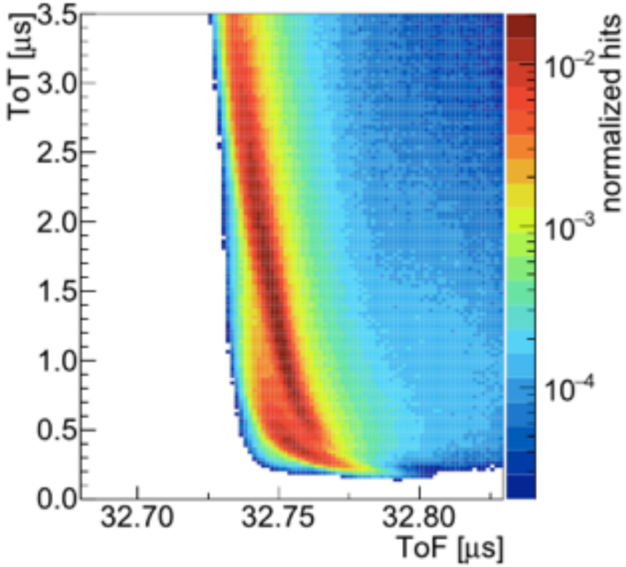

SBU team

ToT vs ToF: time walk

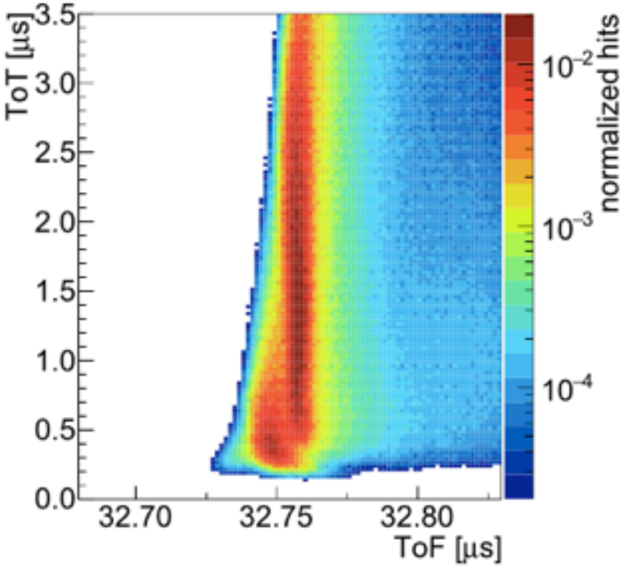


Time resolution: TOT correction and centroiding

before TOT correction



after TOT correction



- After TOT correction < 2 ns (rms)

- Each pixel measure TOA independently → time centroiding
  Time resolution: < 1 ns / photon

S. Tsigaridas, M.v. Beuzekom, H.v.d. Graaf, F. Hartjes, K. Heijhoff, N.P. Hessey, P.J. de Jong, V. Prodanovic, Timewalk correction for the Timepix3 chip obtained with real particle data, Nuclear Instruments and Methods A, 930, (2019) pp185-190

Coincidences in multiple cameras

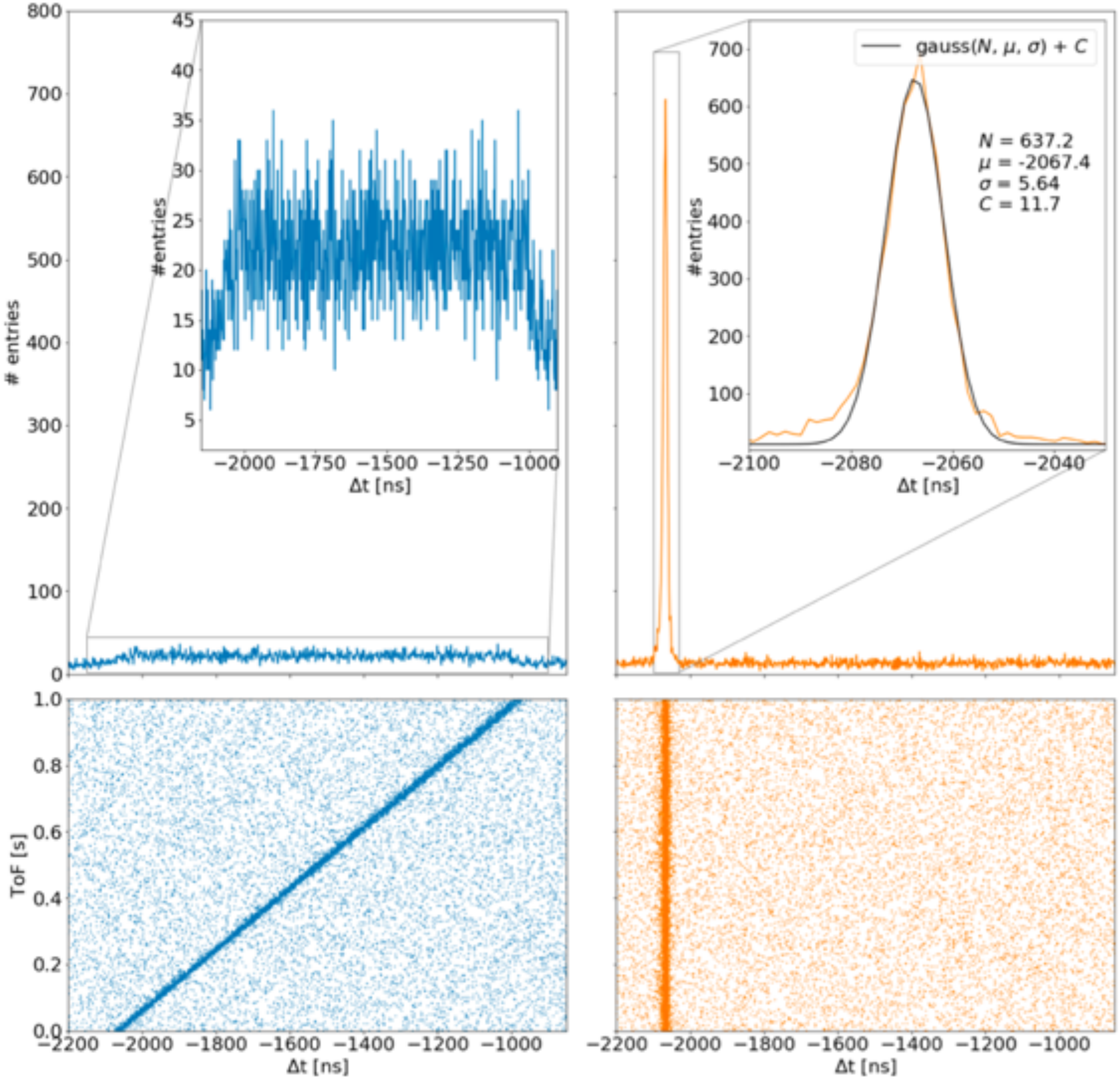
Camera clock is stable only to few ppm

> 1 ppm = 1 μsec per 1 sec
>
> we aim for nsec resolution so not acceptable

Need drift correction

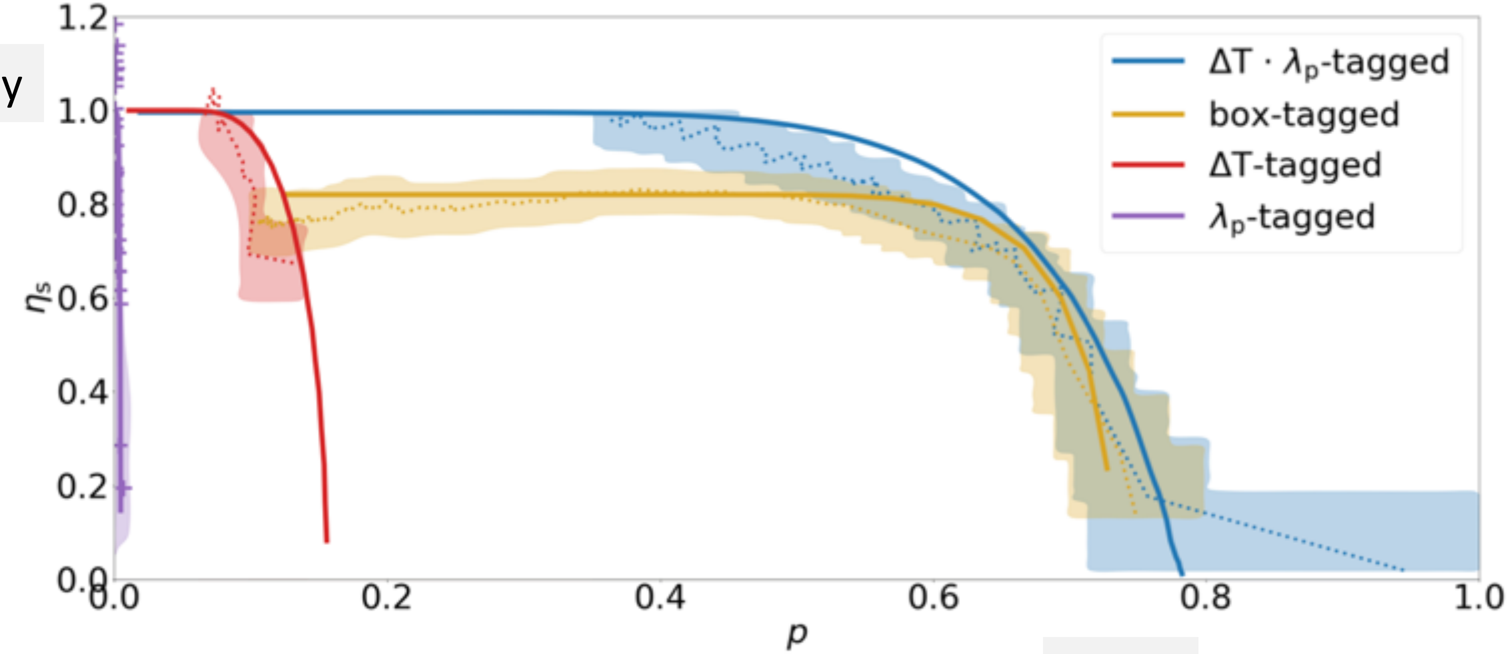
Need to synchronize two camera clocks = find T_0

Use White Rabbit system (CERN) to synchronize



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

Optimal multivariate discrimination



Efficiency

Purity

P Svihra, Y Zhang et al, Multivariate Discrimination in Quantum Target Detection, arXiv preprint arXiv:2005.00612 Appl. Phys. Lett. **117**, 044001 (2020)