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

Andrei Nomerotski, Brookhaven National Laboratory

AQUA lab Users Meeting

21 March 2022

Will talk about

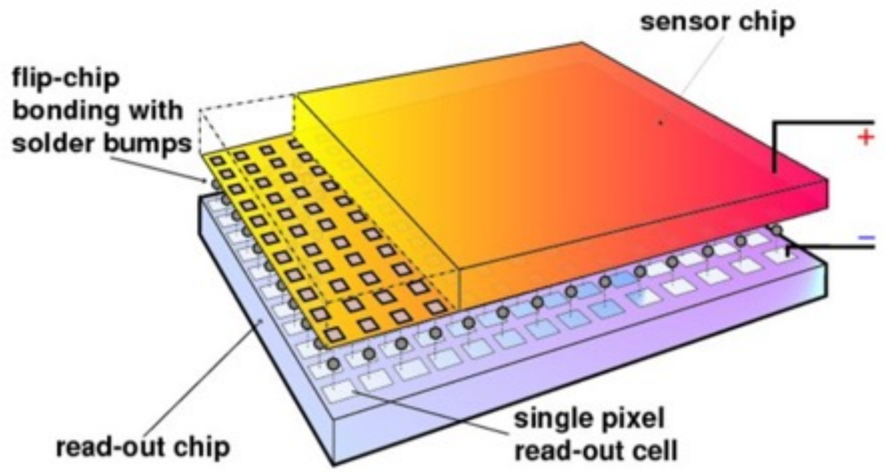
- Fast, data driven approach to optical imaging

- Quantum applications
- Quantum assisted telescopes

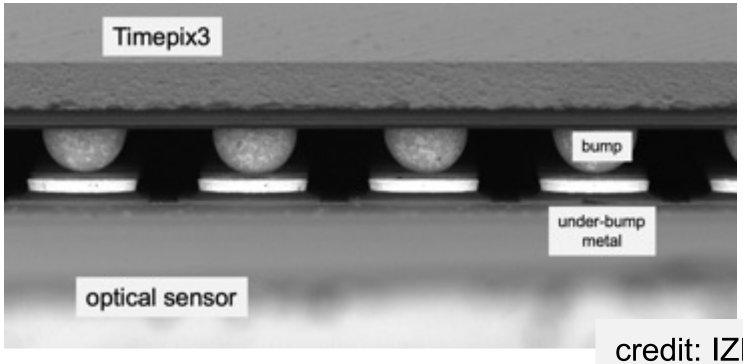
Timepix Optical Cameras

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)



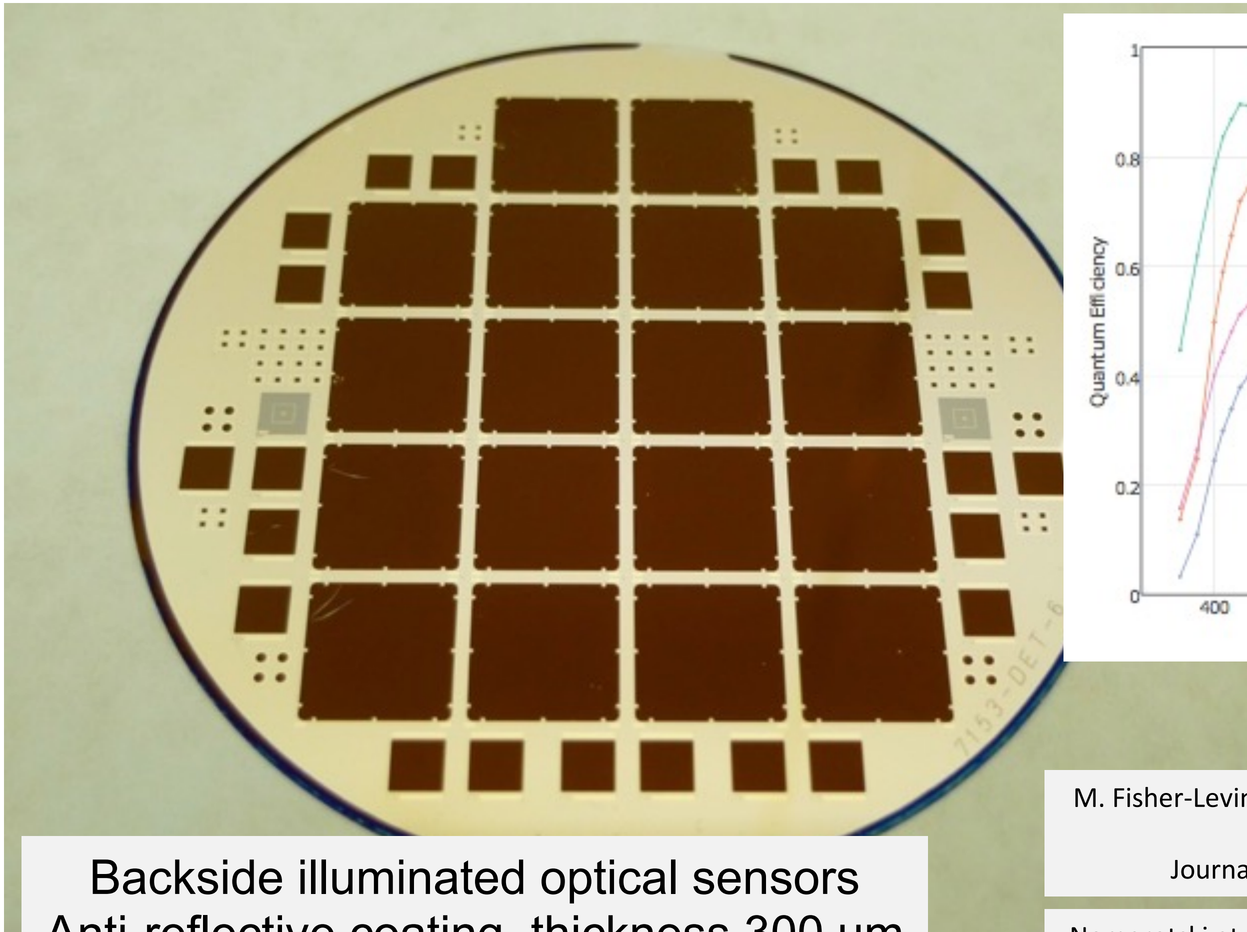
credit: IZM

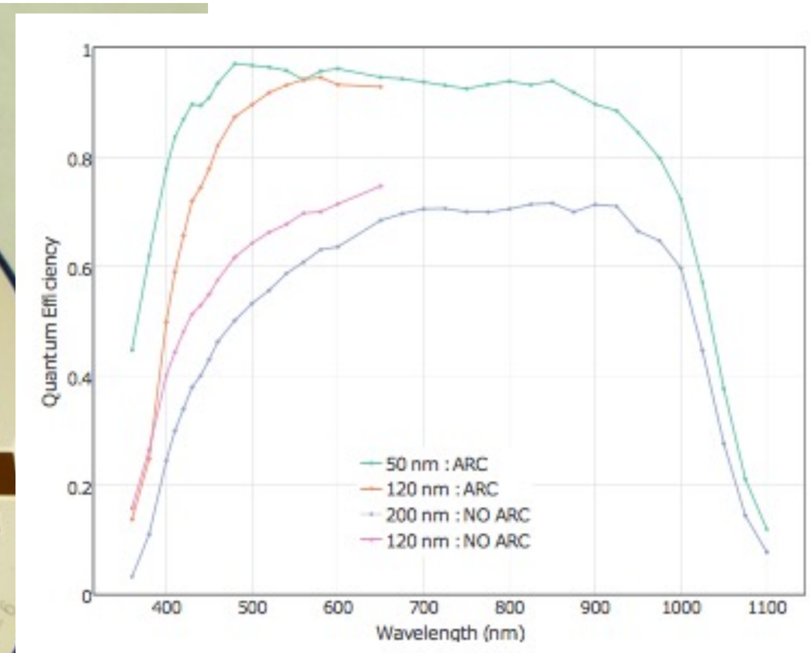
- Decouple readout chip and sensor
- Optimize technologies for chip and sensor separately

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

→ we will use OPTICAL sensors

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)

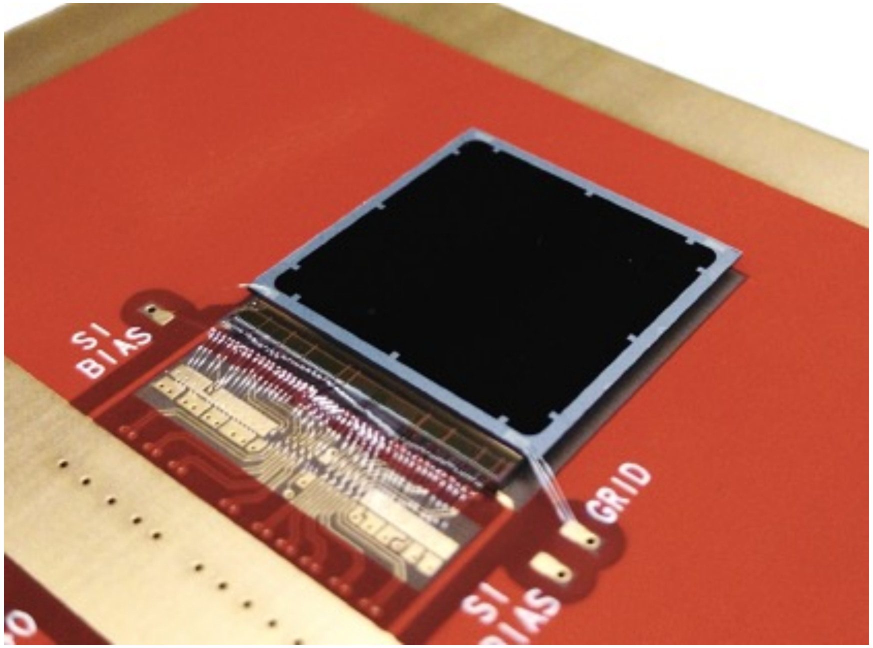
Timepix3 Camera → Tpx3Cam

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)

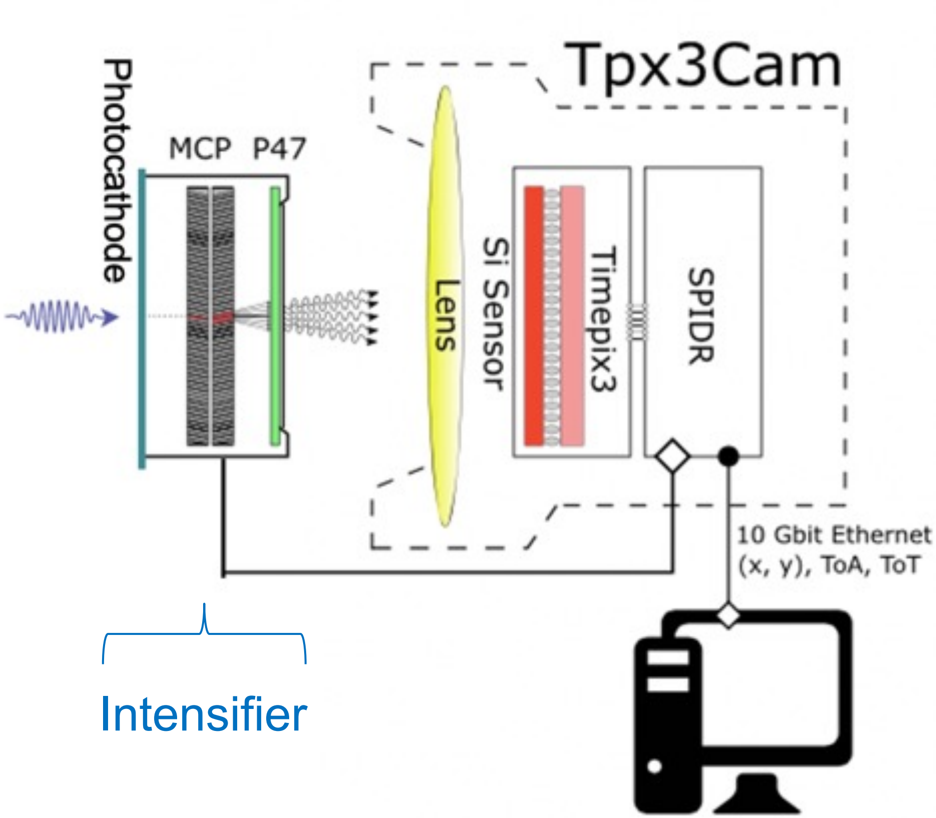
Applications & Results

- Quantum imaging

- High Energy Physics applications
- Neutron imaging
- Lifetime imaging

Single (optical) photons

Intensified camera: use off-the-shelf image intensifier



Intensifier

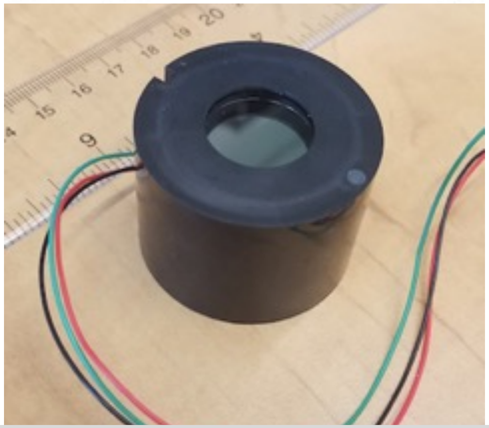
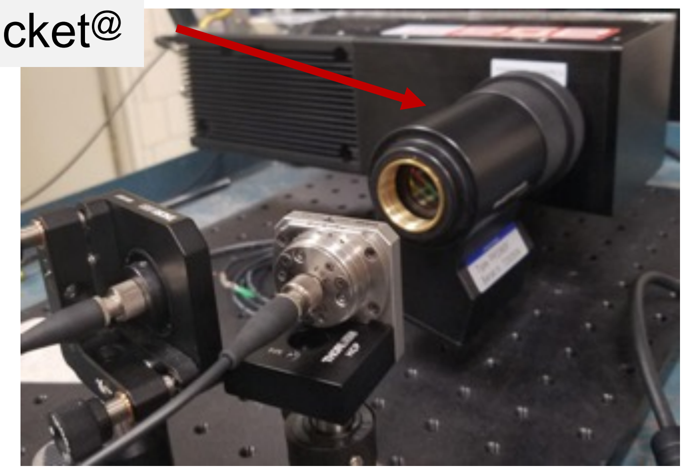


Image intensifier (Photonis PP0360EG)

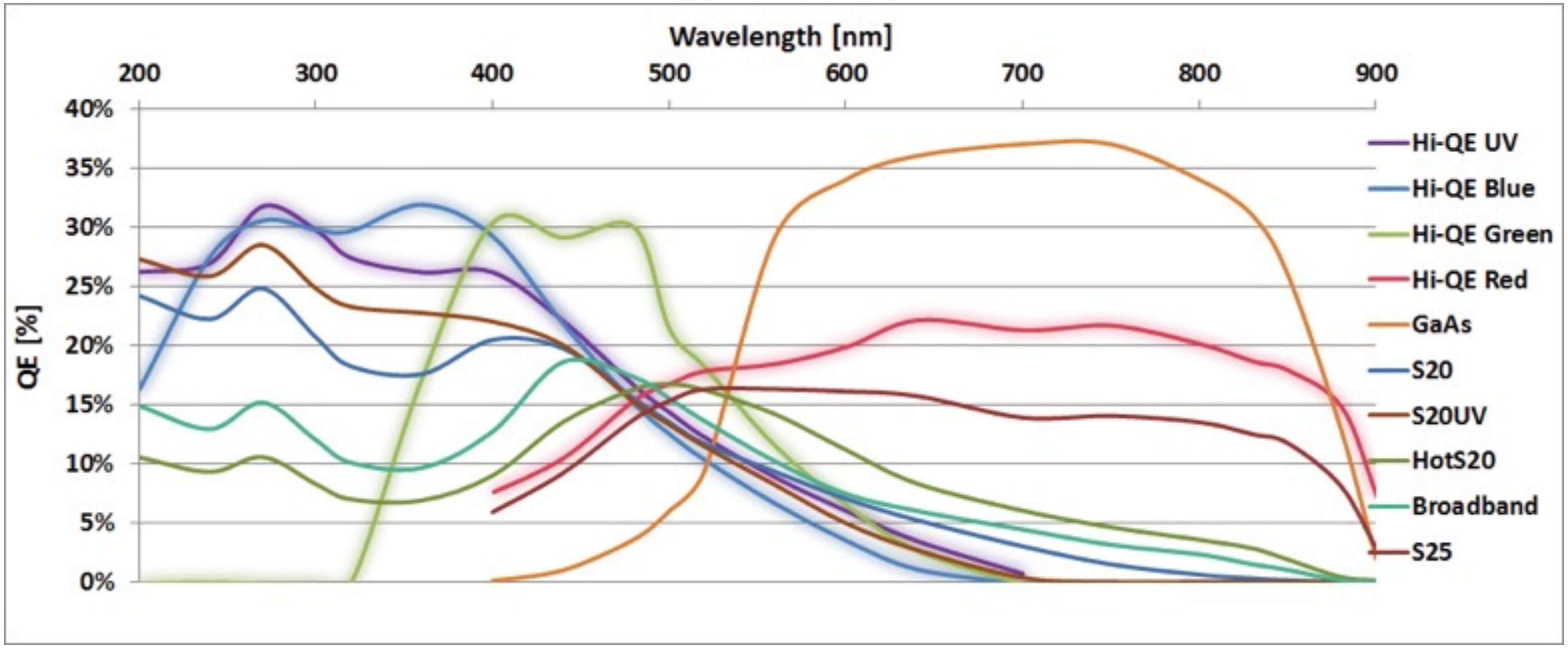
Cricket@



Intensified cameras are common:

- iCCD
- iCMOS cameras

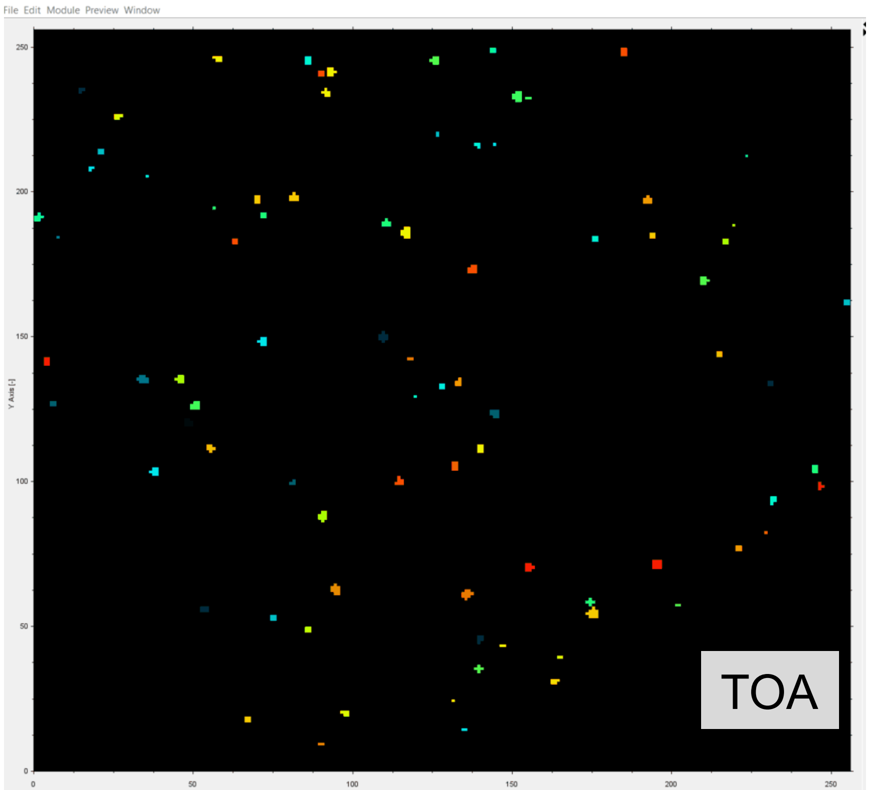
Choice of photocathodes

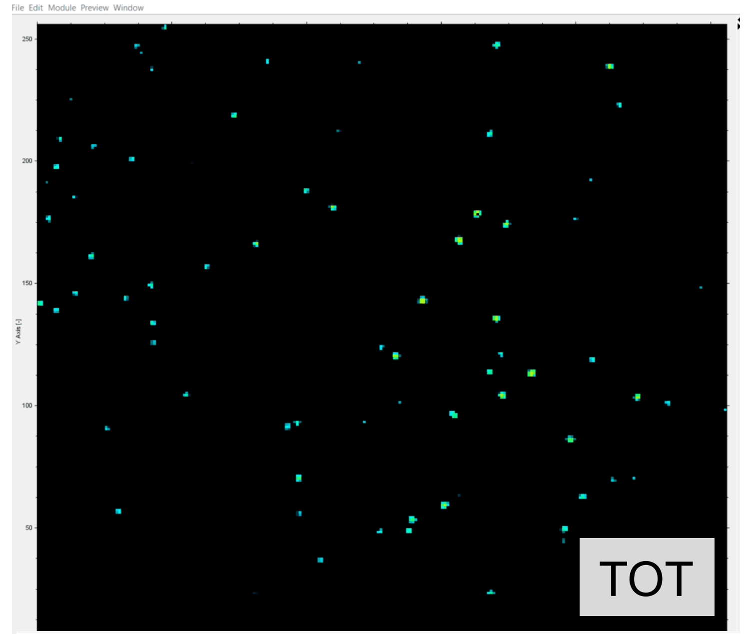


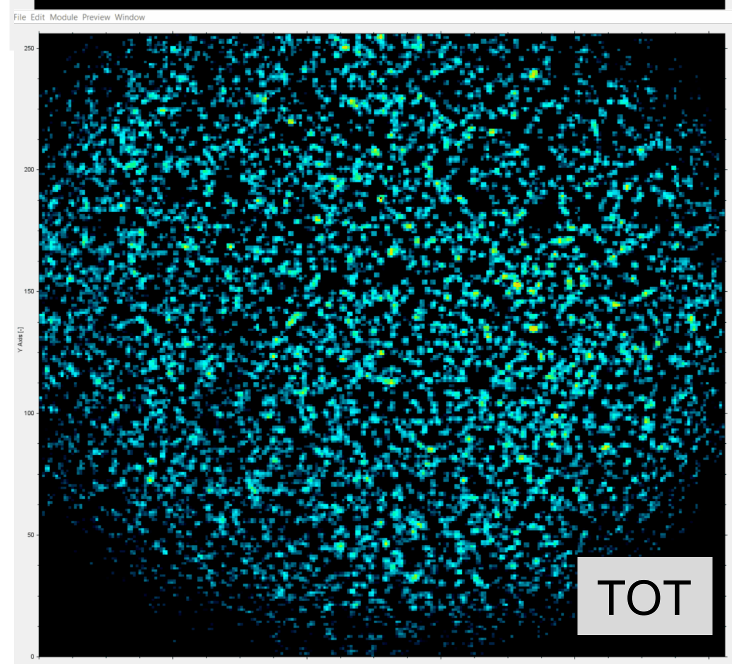
Photonis photocathodes

Single Photons in Tpx3Cam

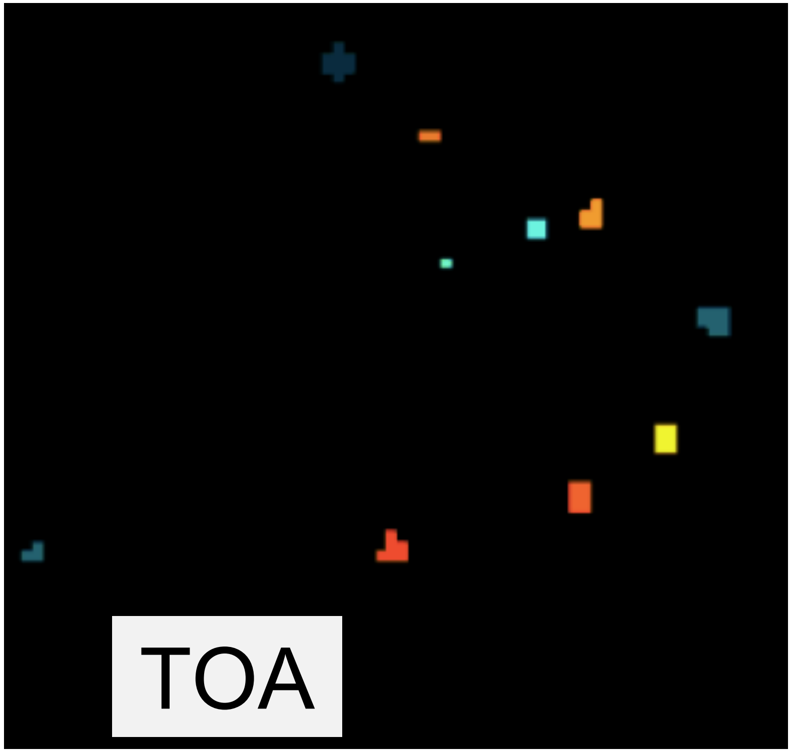
1 ms slice of data
1.5 ns time-stamping

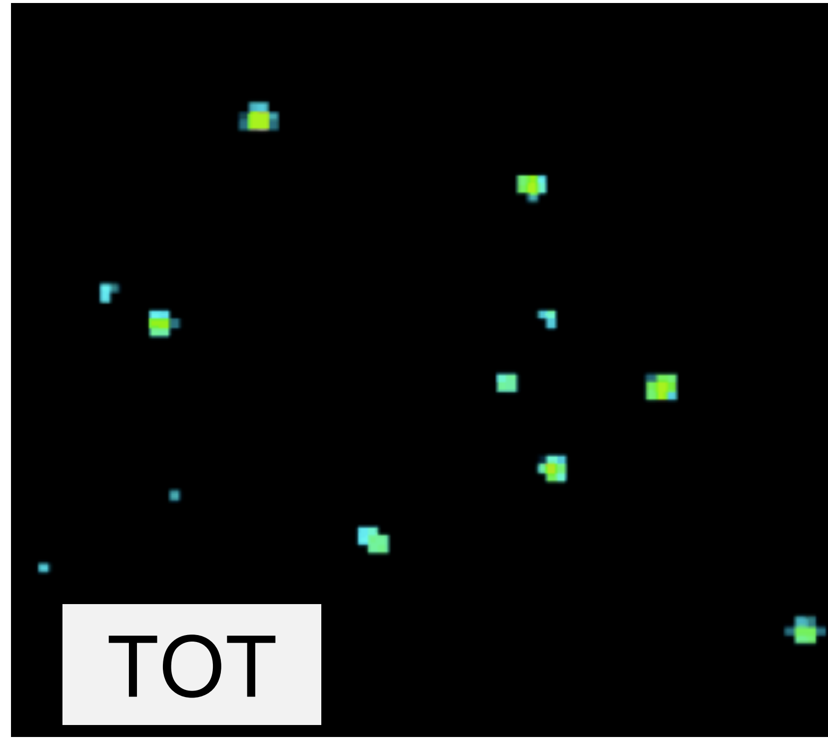






Tpx3Cam + intensifier by Photonis
data taken by J. Long (ASI)





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

Spatial resolution: 0.1 pixel / photon

Time resolution: < 1 ns / photon

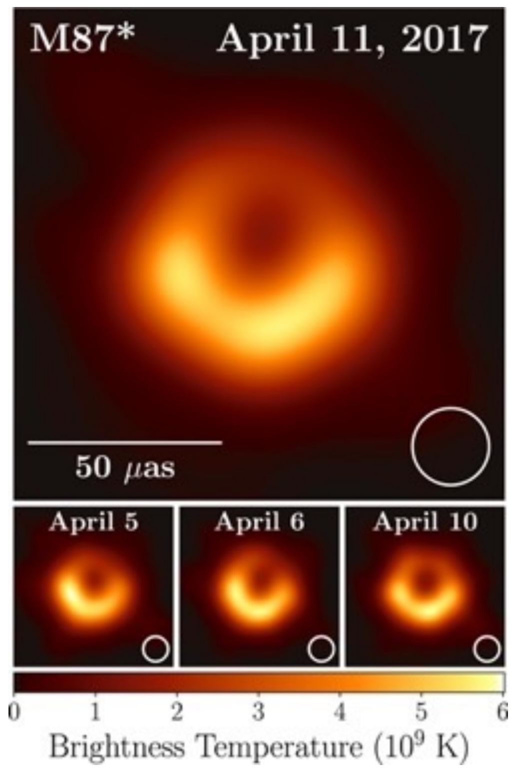
Quantum Information Science, Quantum-Assisted Imaging for telescopes and others

Quantum Astrometry

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

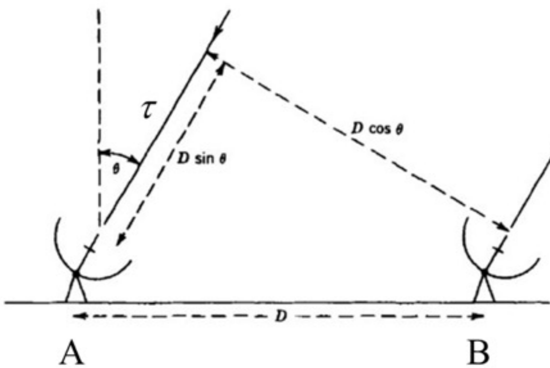
sensitive to features
on angular scale

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

Black hole in the center of M87 imaged at 1.3mm

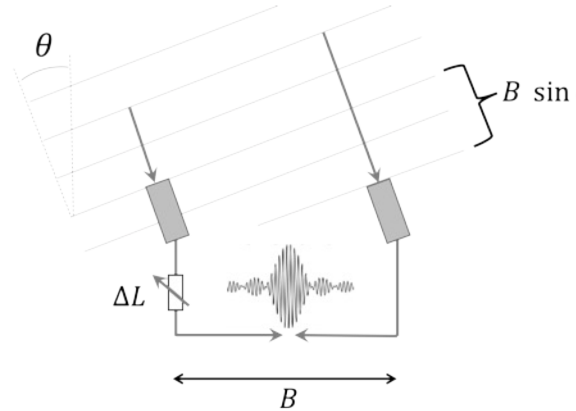
Achieved by radio interferometry with ~10000 km baselines

Radio $\bar{n} \gg 1$



Can literally record entire waveform, over some band, separately at each receiver station and interfere later offline

$\bar{n} \ll 1$ Optical



One photon at a time! Need to bring paths to common point in real time

Need path length *compensated* to better than *c*/bandwidth

Need path length *stabilized* to better than λ

Accuracy ~ 1 mas

Max baselines to ~ 100 m

Two-photon techniques

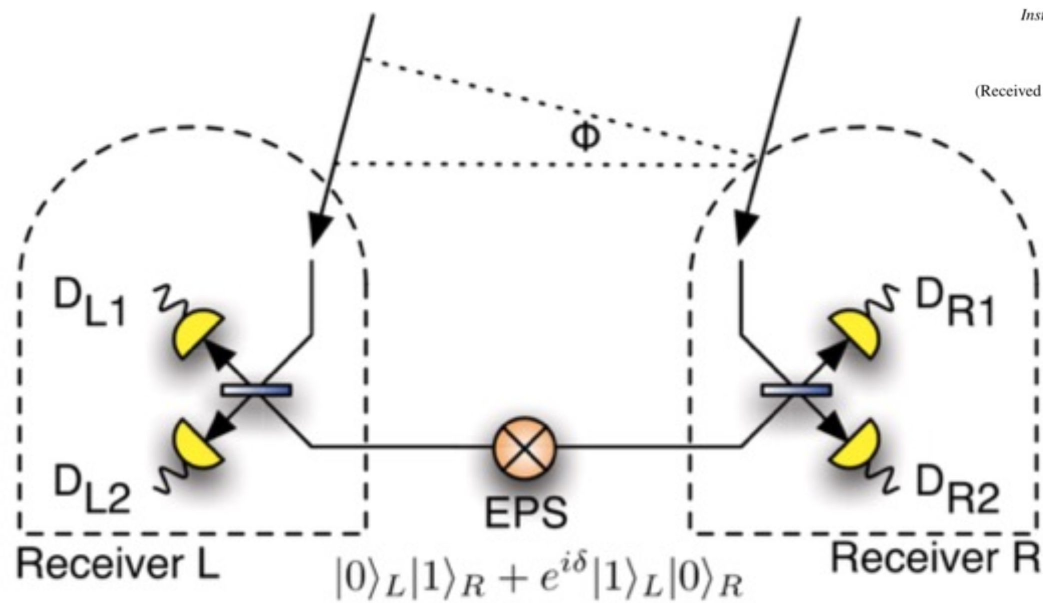
Second photon for quantum assist

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

Longer-Baseline Telescopes Using Quantum Repeaters

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

Quantum (two-photon) interferometer



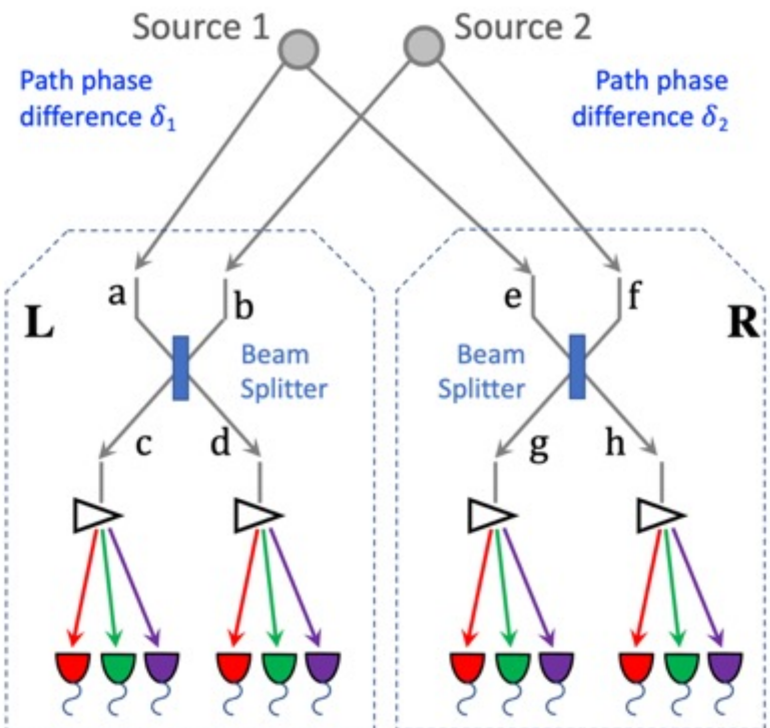
$$\Delta\theta \sim \frac{\lambda}{b}$$

- 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
- Major impact on astrophysics and cosmology

Quantum Astrometry

Idea: use another star as source of entangled states for the interference

https://arxiv.org/abs/2010.09100



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

Full QFT calculation

$$
N_c(xy) = \eta_1 \eta_2 A^2 \int_0^{T_r} P_{L,R,\tau}^{\text{two photons}} d\tau =
$$

Rates HBT

$$
A^2 \eta_1 \eta_2 T_r \left[(I_1 + I_2)^2 + I_1^2 \frac{\tau_c g_{11}}{T_r} + I_2^2 \frac{\tau_c g_{22}}{T_r} \pm \right.
$$

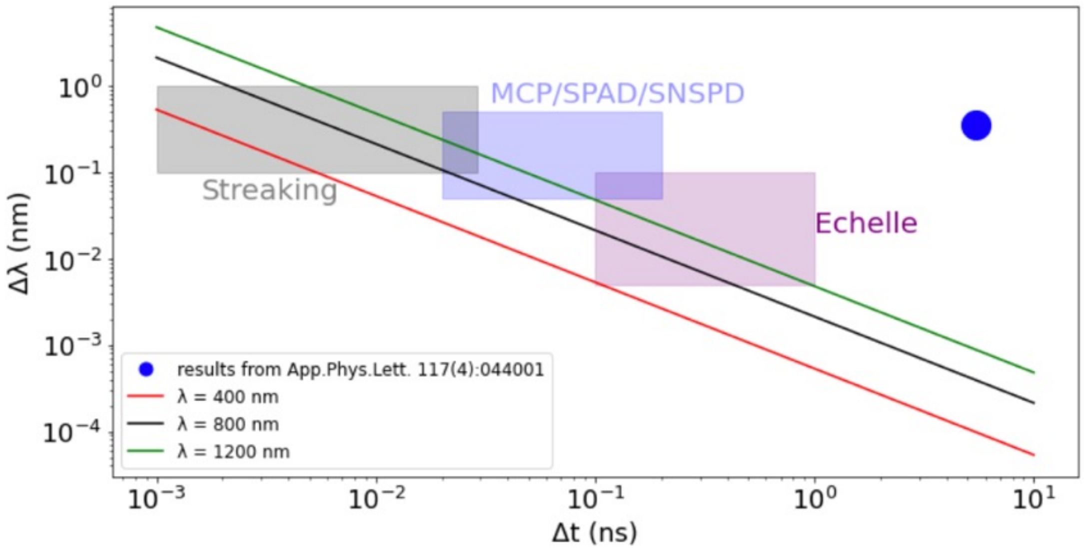
$$
\left. 2 I_1 I_2 \frac{\tau_c g_{12}}{T_r} \cos\left(\frac{\omega_0 B (\sin\theta_1 - \sin\theta_2)}{c} + \frac{\omega_0 \Delta L}{c} \right) \right] \quad (30)
$$

New oscillatory term!

- 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

- Can provide 10 microarcsec resolution for bright stars
- Perfect to start exploring this approach

Requirements for detectors



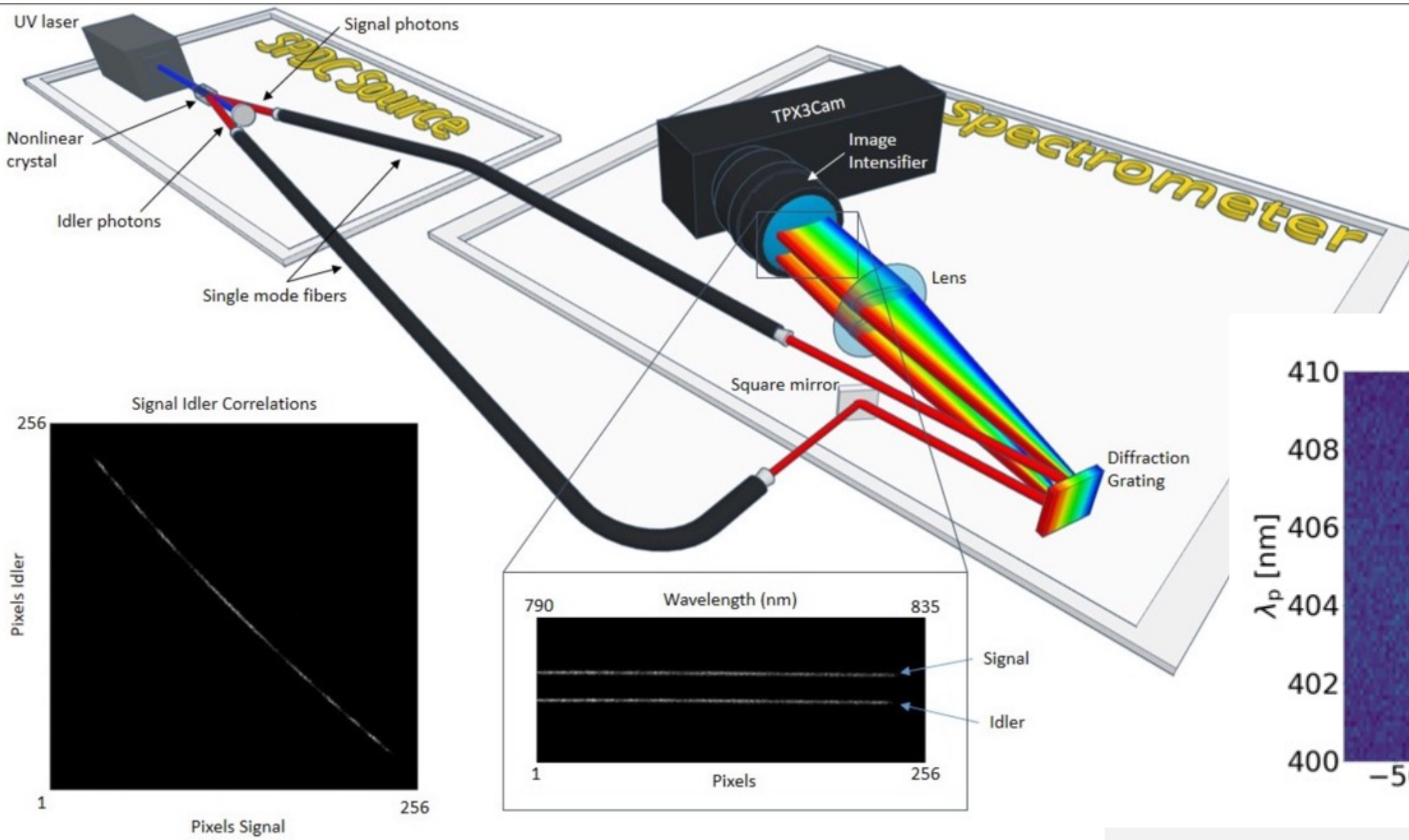
- Photons must be close enough in frequency and time to interfere → temporal & spectral binning: need ~ 0.01 ns * 0.2 nm for 800 nm

- Fast imaging techniques are the key
  - Several promising technologies: CMOS pixels+MCP, SPADs, SNSPDs, streaking
  - Target 1-100 ps resolution
- Spectral binning: diffraction gratings, Echelle spectrometers

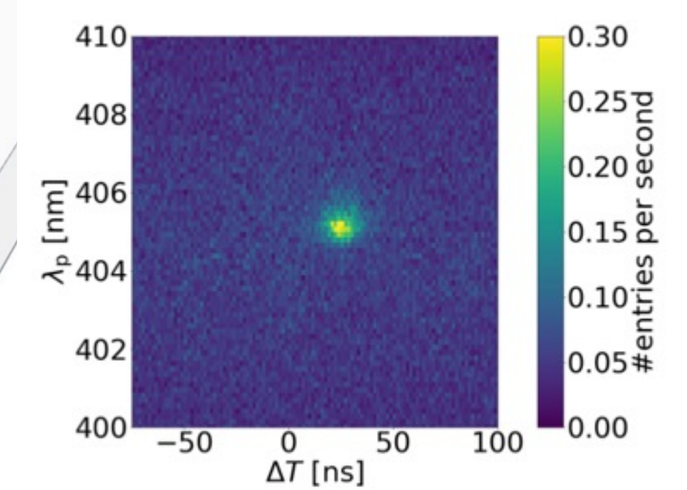
- Photon detection efficiency: high

Spectroscopic binning

In collaboration with NRC (Ottawa) D.England, Y.Zhang et al



$\delta\lambda * \delta t$ ~ 5 ns * 0.5 nm

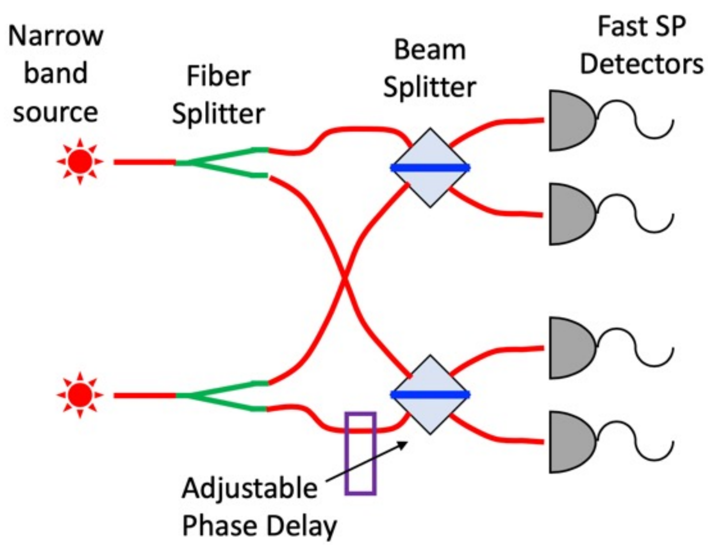


Pump photon wavelength vs time difference

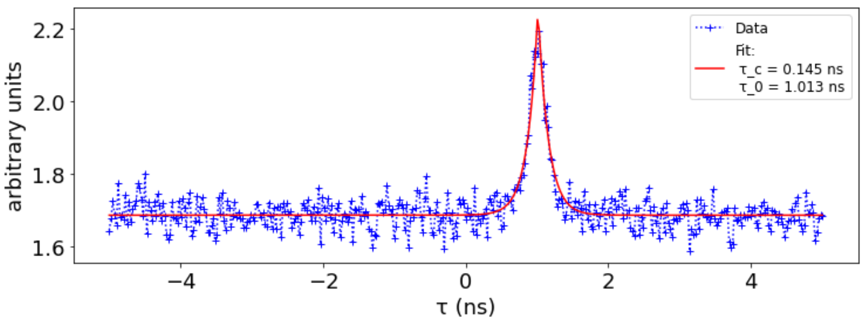
Y Zhang, D England, A Nomerotski, P Svihra et al, Multidimensional quantum-enhanced target detection via spectrotemporal-correlation measurements, Physical Review A 101 (5), 053808

P Svihra et al, Multivariate Discrimination in Quantum Target Detection, Appl. Phys. Lett. **117**, 044001 (2020)

Experiments in progress



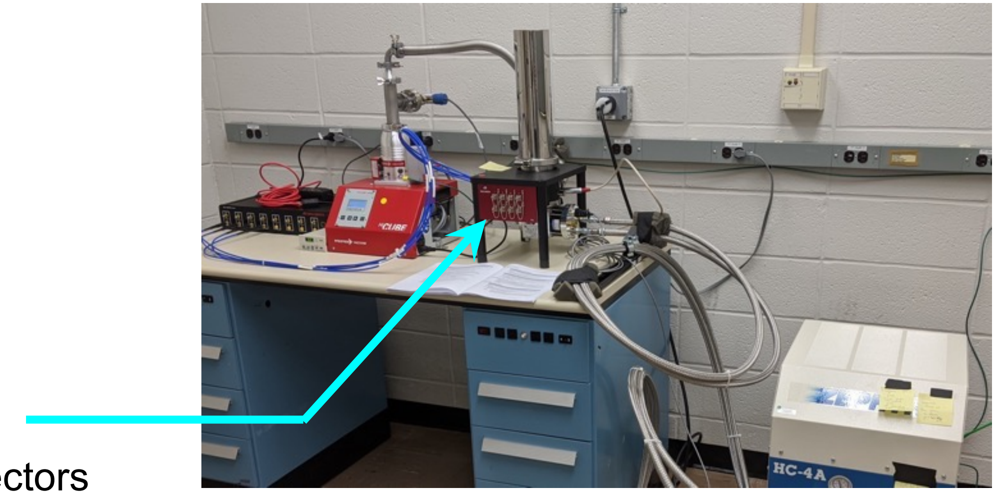
Strong HBT peak with single lamp



Bench-top model of two-photon interferometry

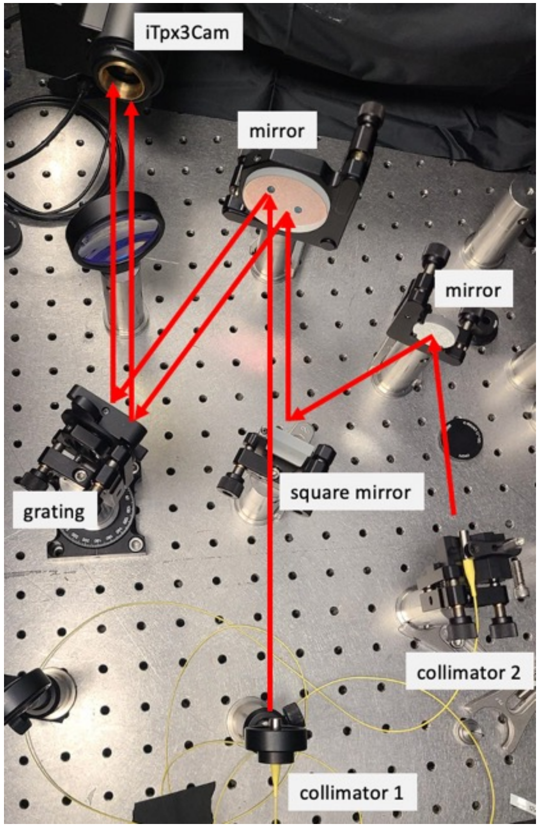
Ar vapor lamps with ultra-narrow band filters

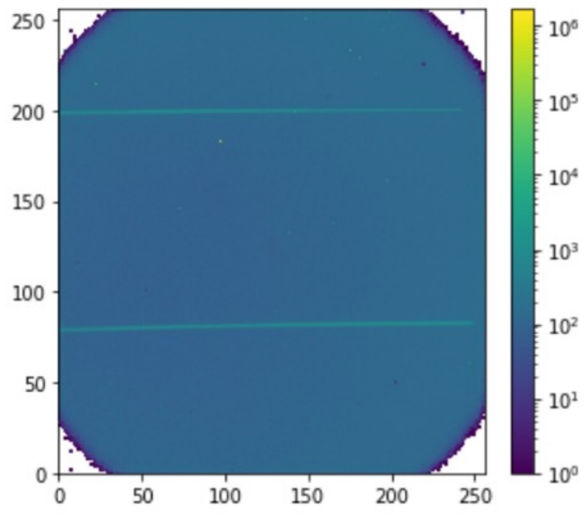
Superconducting nanowire single-photon detectors

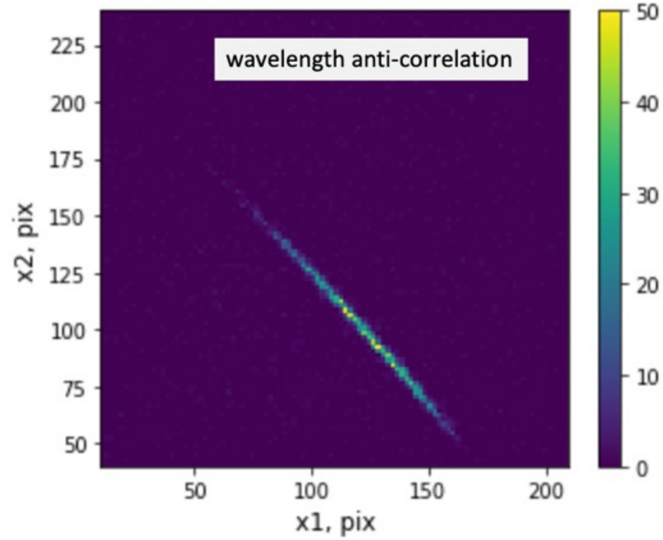


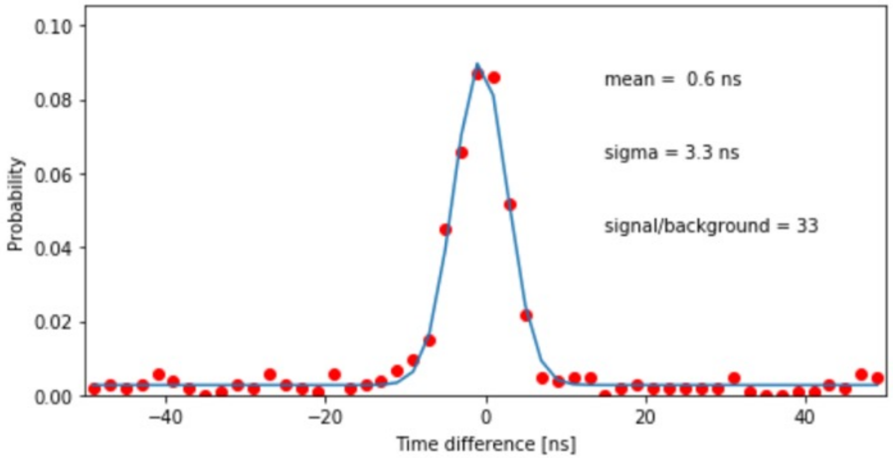
Supported by DOE HEP QuantISED program

Current setup at BNL: SPDC source as spectrometer characterization tool

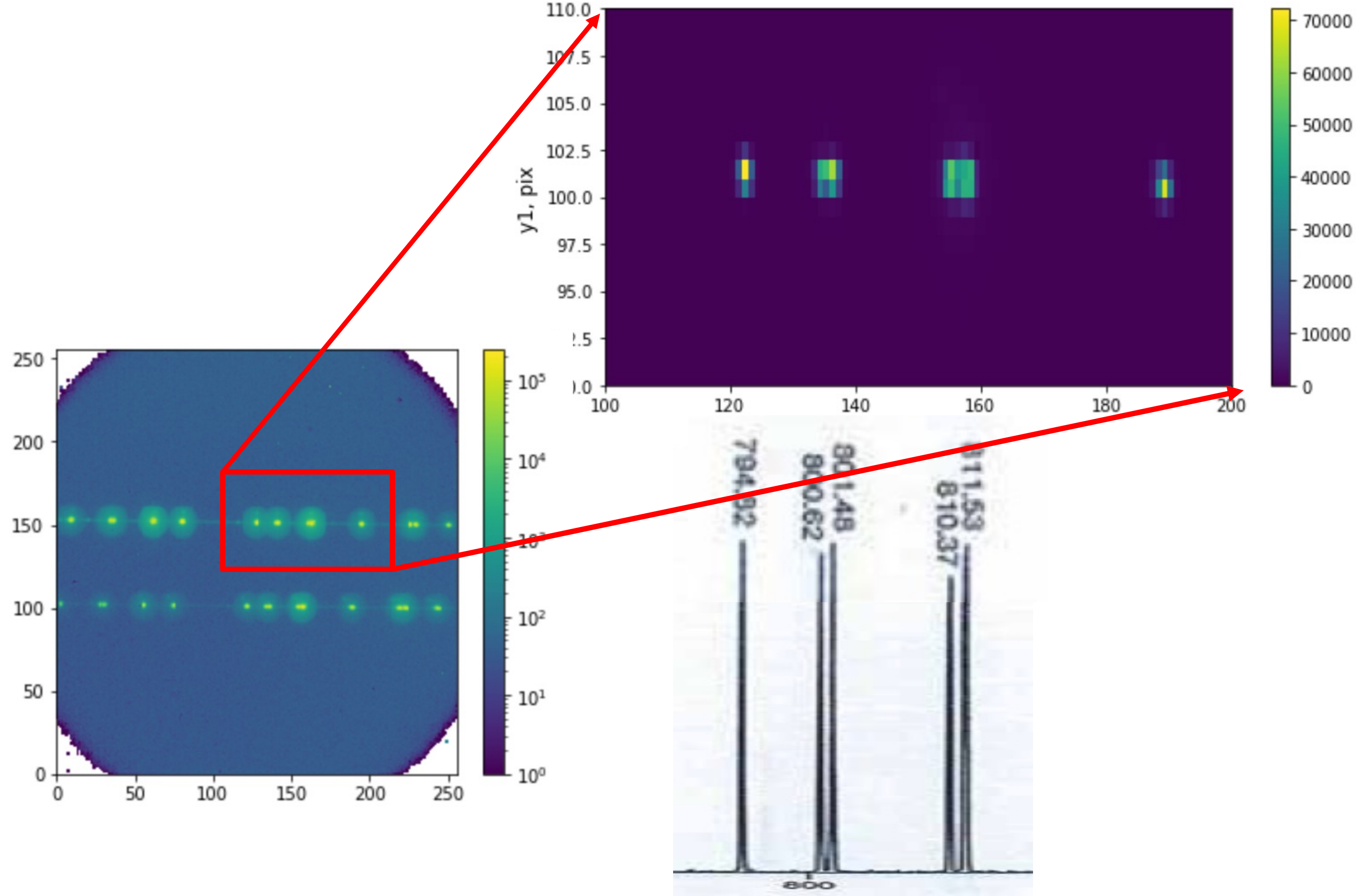








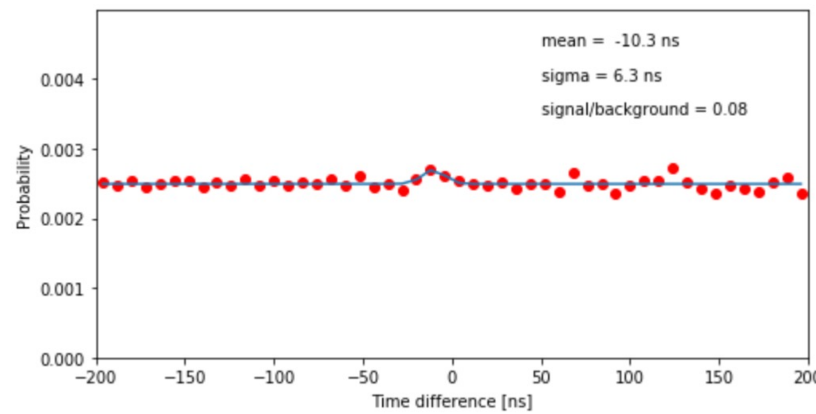
Argon lamp spectrum



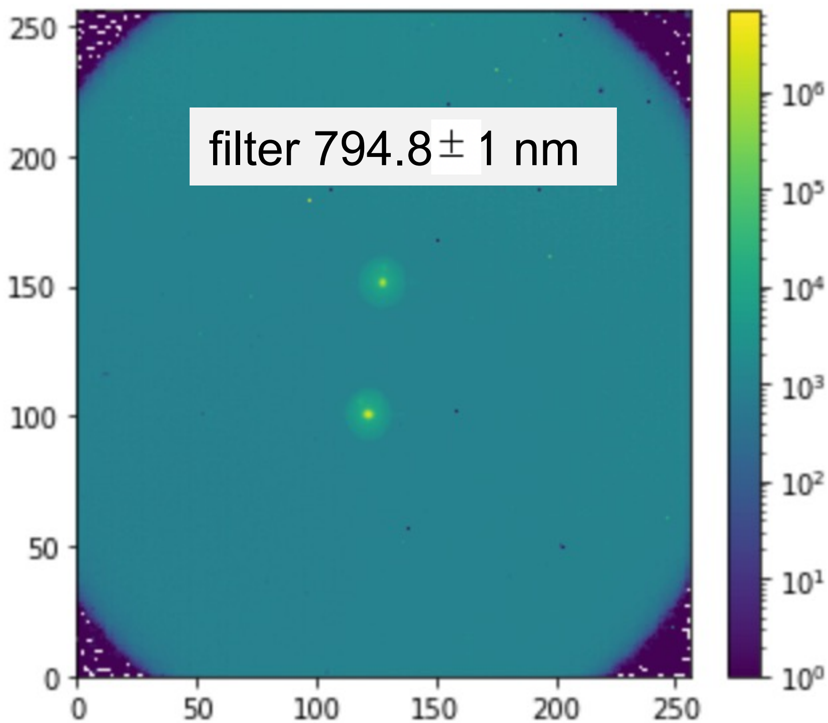
0.2 nm resolution

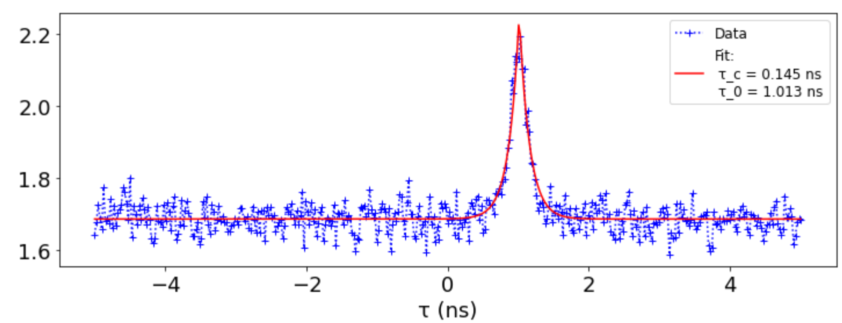
794.8 nm line

HBT peak with 5 ns resolution? no



6 ns resolution

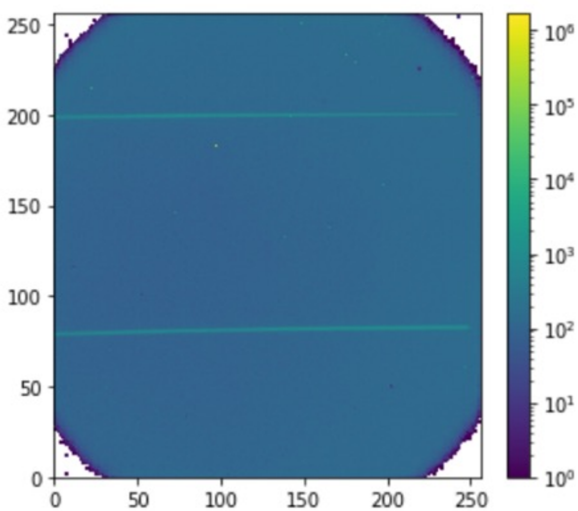


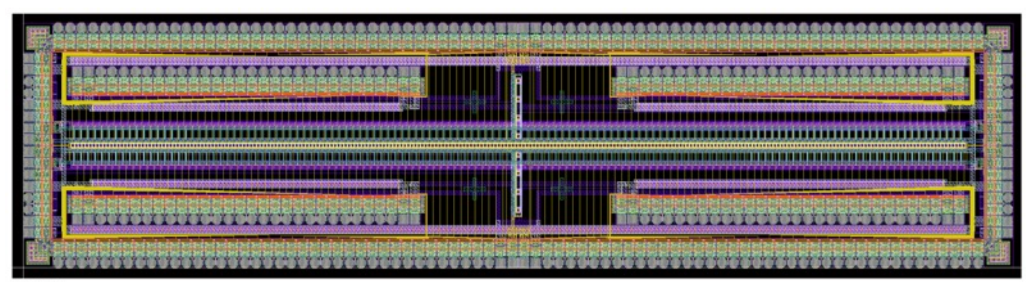


150 ps resolution

Next steps: spectrometer based on LinoSPAD2

Two diffracted photon stripes projected on to single linear array

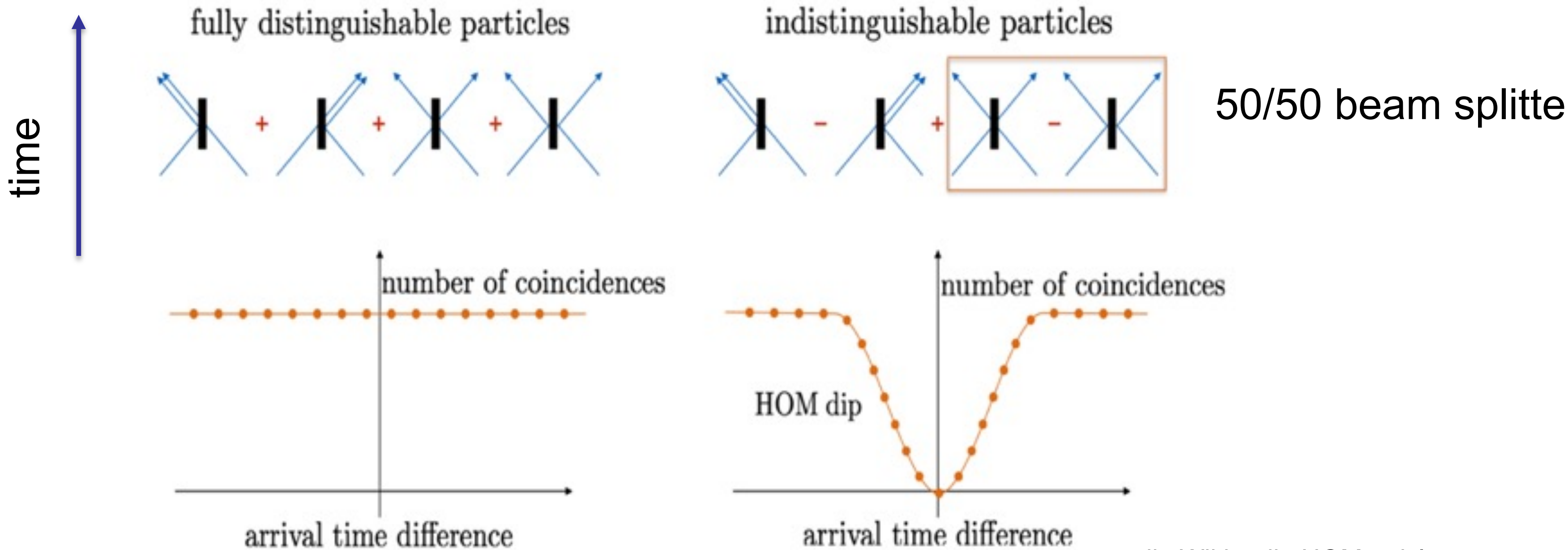




Spectrometer time resolution: ns → 100 ps

More Quantum Imaging

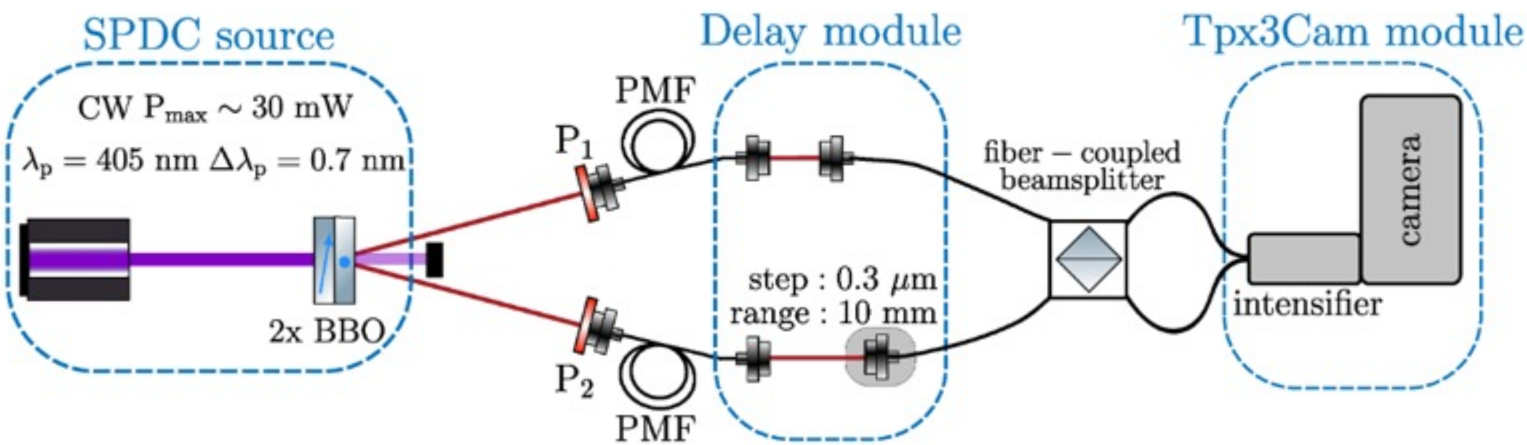
Hong-Ou-Mandel effect

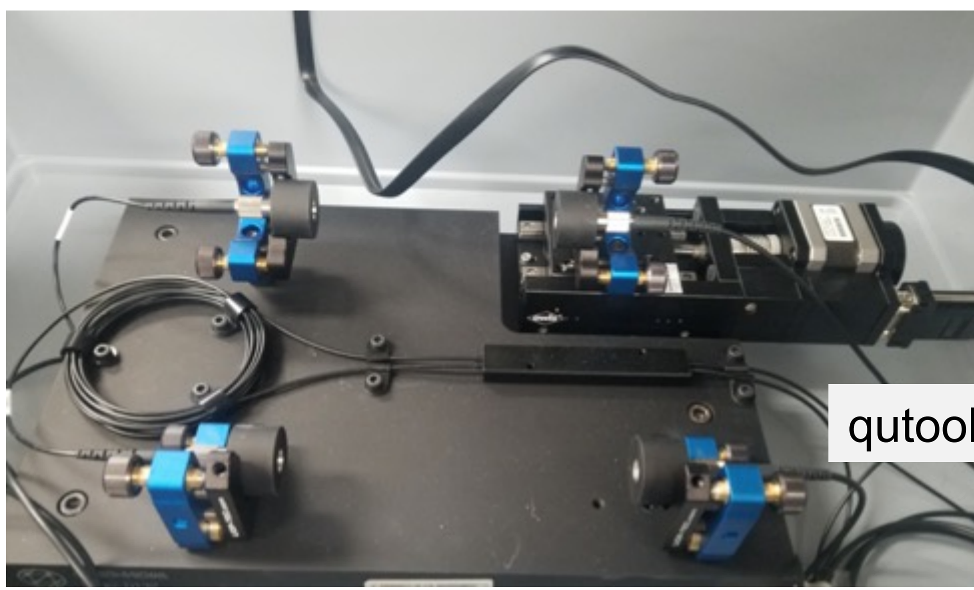


credit: Wikipedia HOM article

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

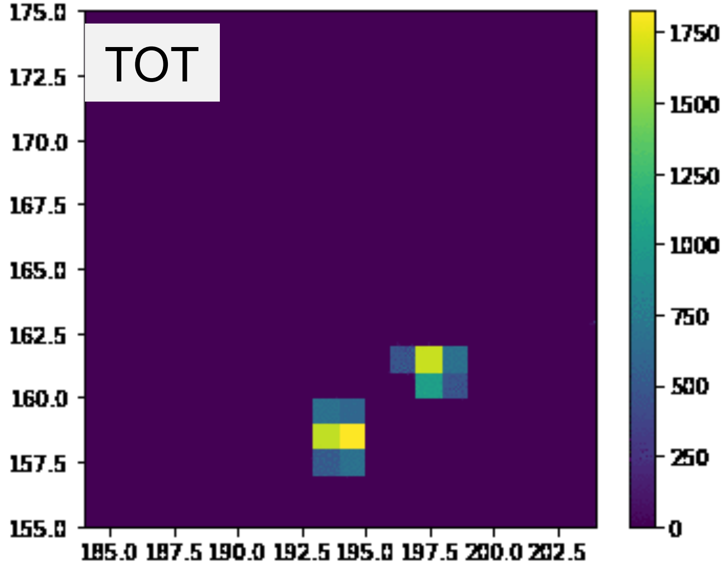
HOM Setup

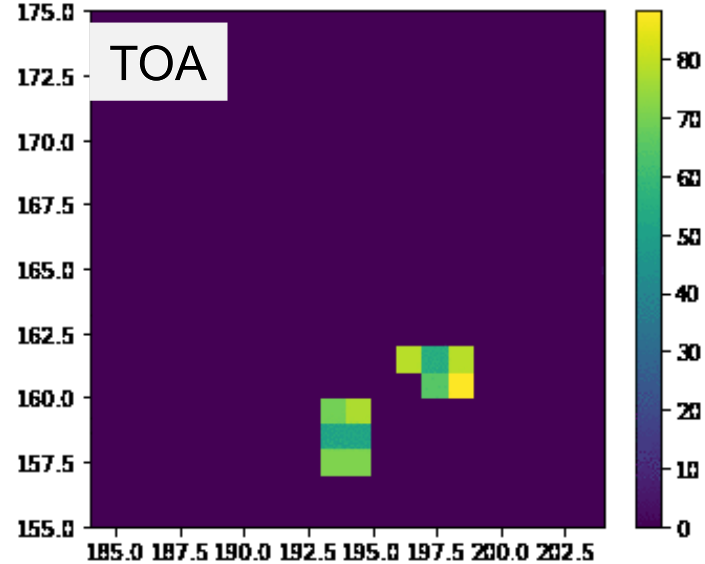


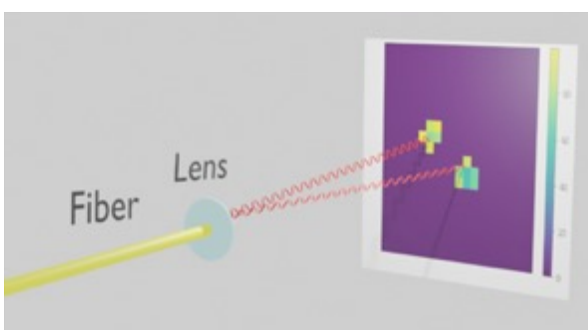


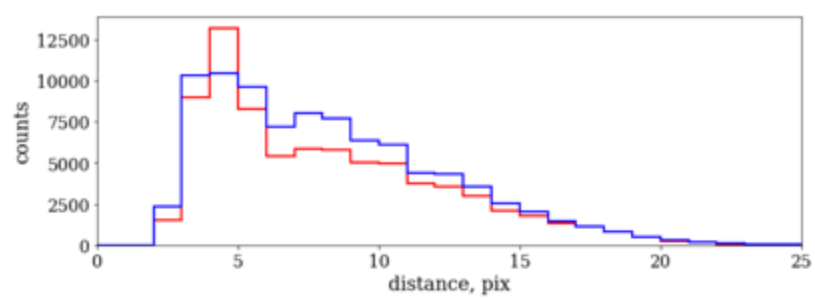
qutools.com

Examples of bunched HOM photons





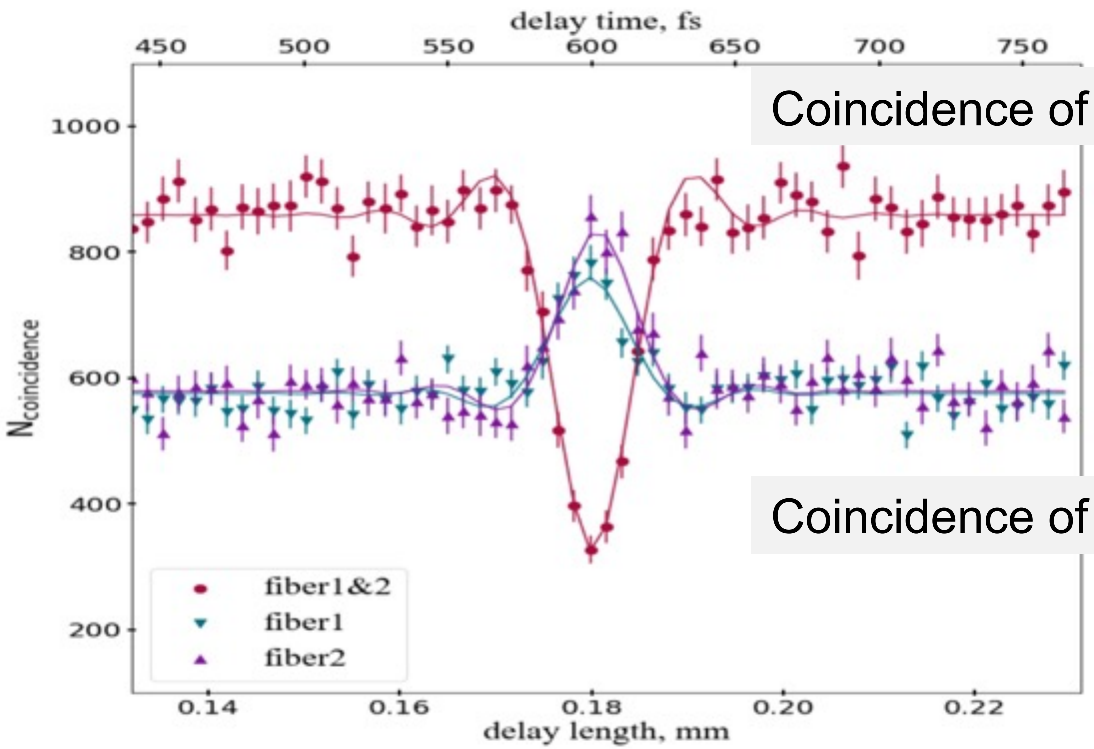




Distance between two photons, pix

Hong-Ou-Mandel effect

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



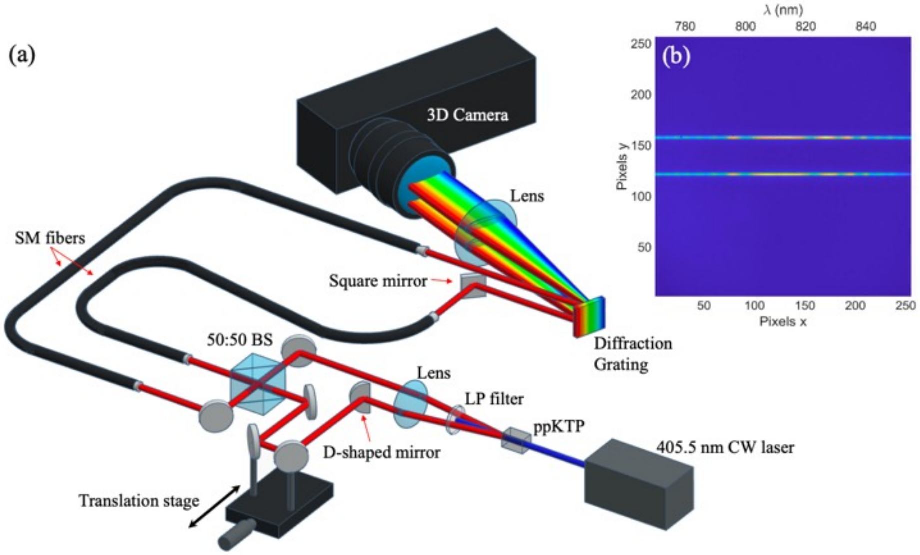
Coincidence of photons in two fibers

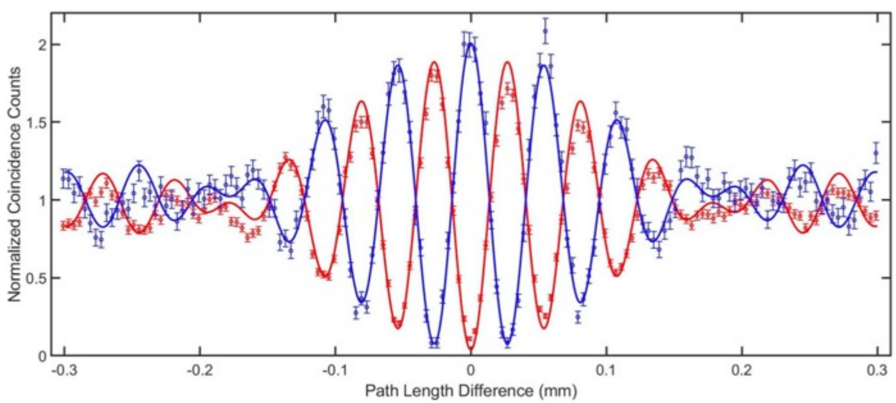
Coincidence of photons in single fibers

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).

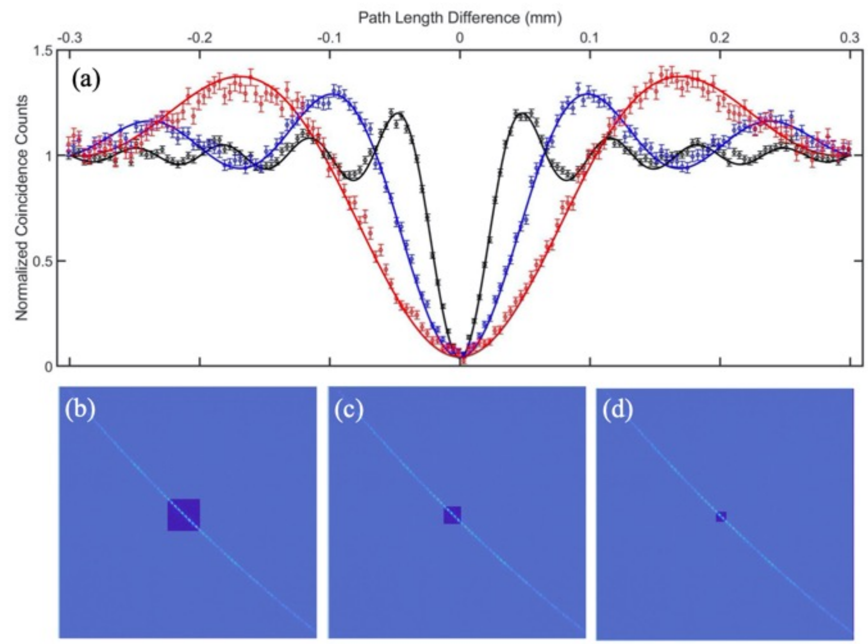
HOM effect with post-selection

In collaboration with NRC (Ottawa) D.England, Y.Zhang et al





2 nm filters at 805 nm and 817 nm.

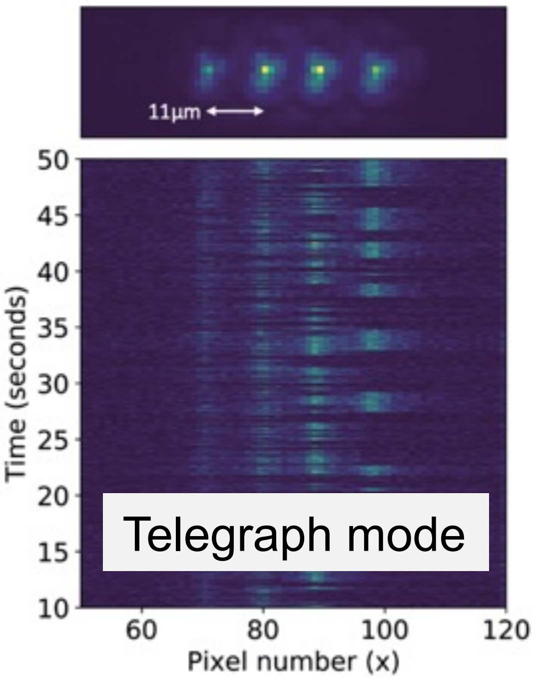


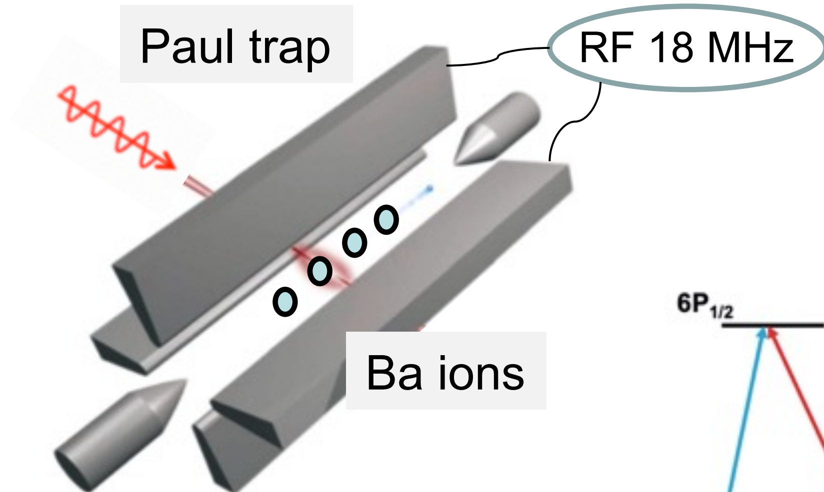
10, 5, 3 nm post-selection filters

More quantum imaging

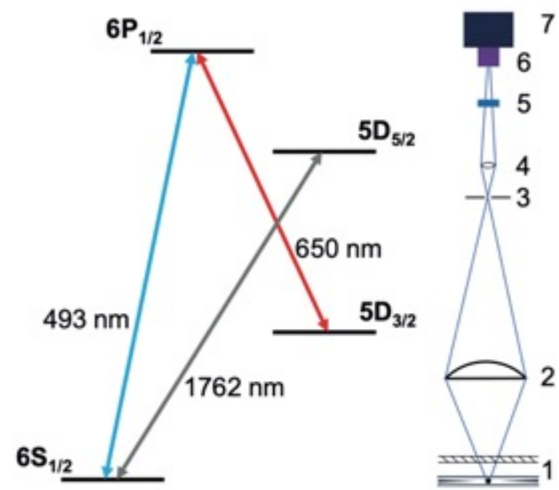
Imaging of trapped ions

Time resolved qubit manipulation (Blinov group, UWash)





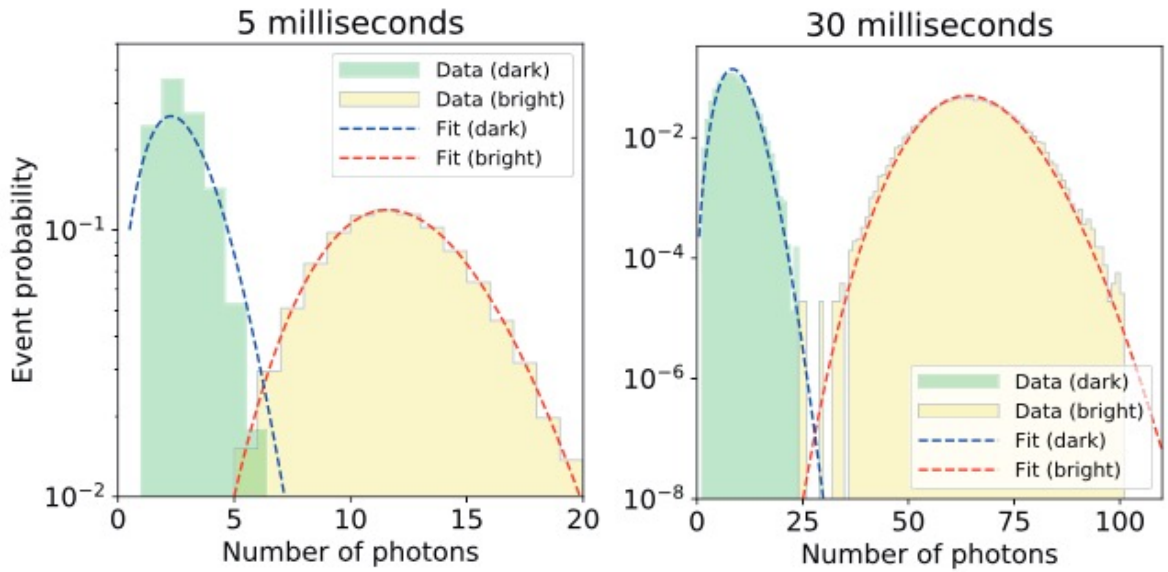
Boris Blinov
Mila Zhukas



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

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

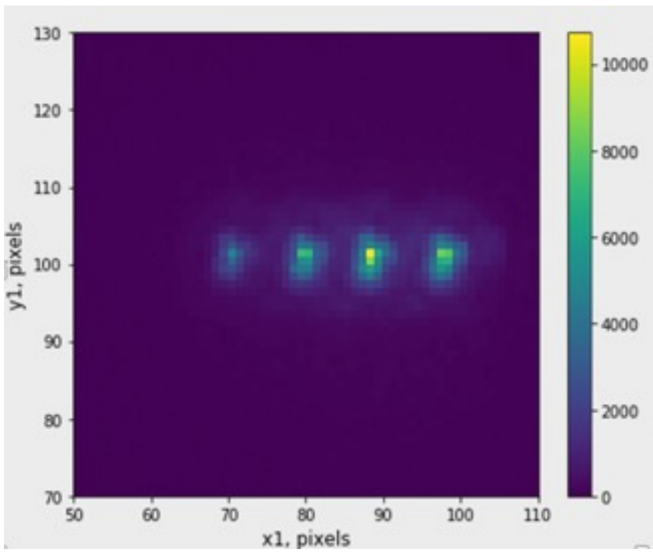
Qubit detection error

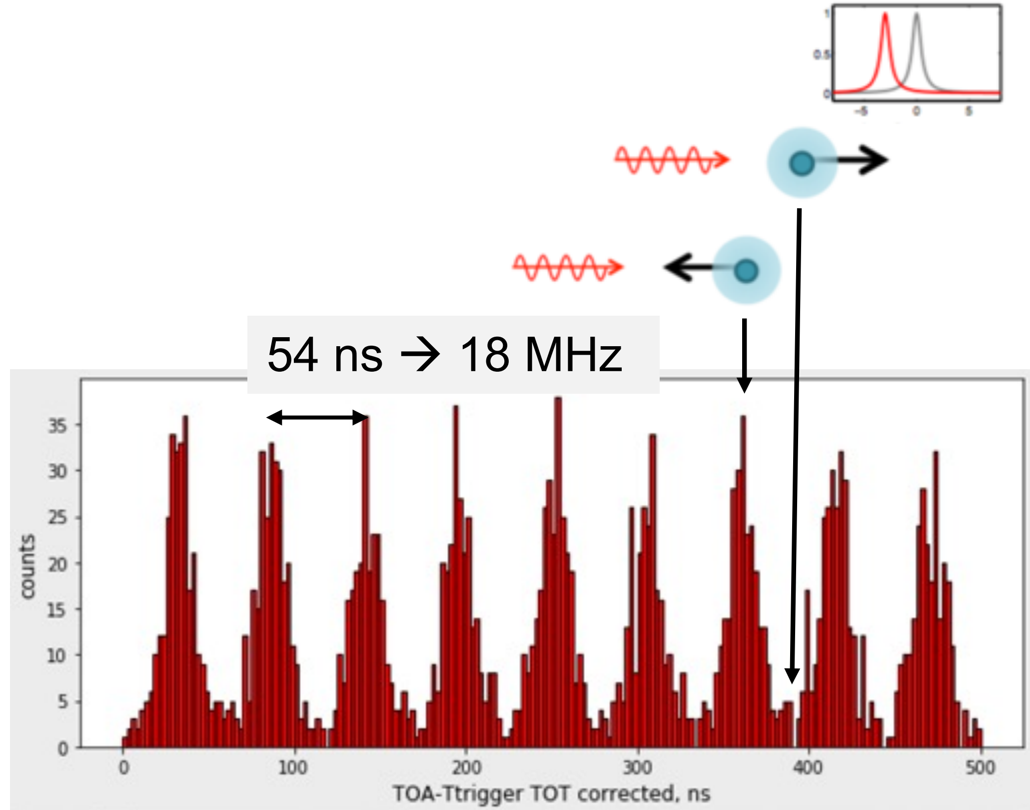


Fast Simultaneous Detection of Trapped Ion Qubit Register with Low Crosstalk, M.Zhukas, P.Svihra, A.Nomerotski, B.Blinov, arxiv.org/abs/2006.12801

single qubit detection error: ~ 5 ppm

Time resolved ion oscillations



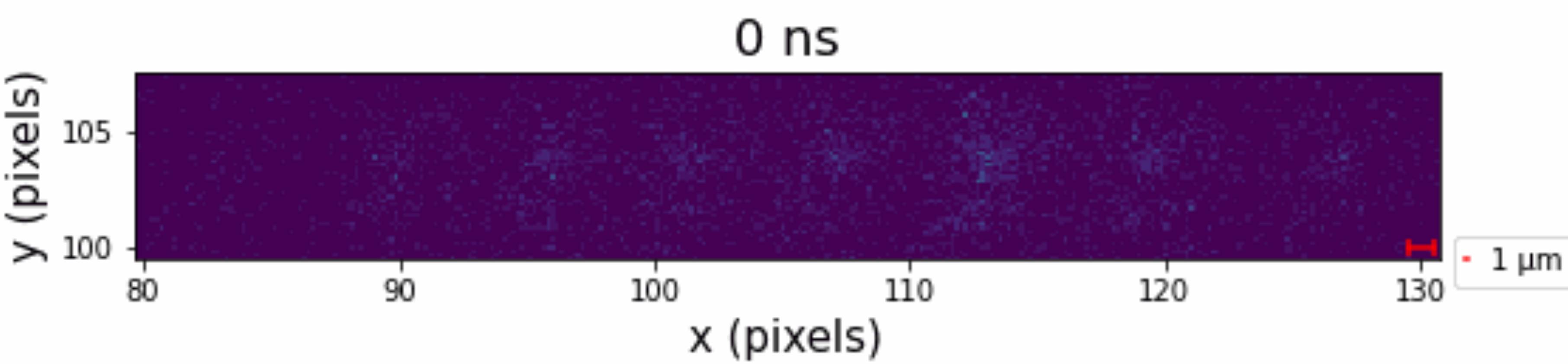


- Emission rate oscillations due to Doppler shift of laser light wrt moving ion
- Simultaneous time & position information allows to monitor ion micro-motions
- Powerful technique to characterize traps

Direct observation of ion micromotion in a linear Paul trap,
L.Zhukas, M.Millican, P. Svihra, A. Nomerotski, B.Blinov, https://arxiv.org/abs/2010.00159,
Phys. Rev. A **103**, 023105 (2021).

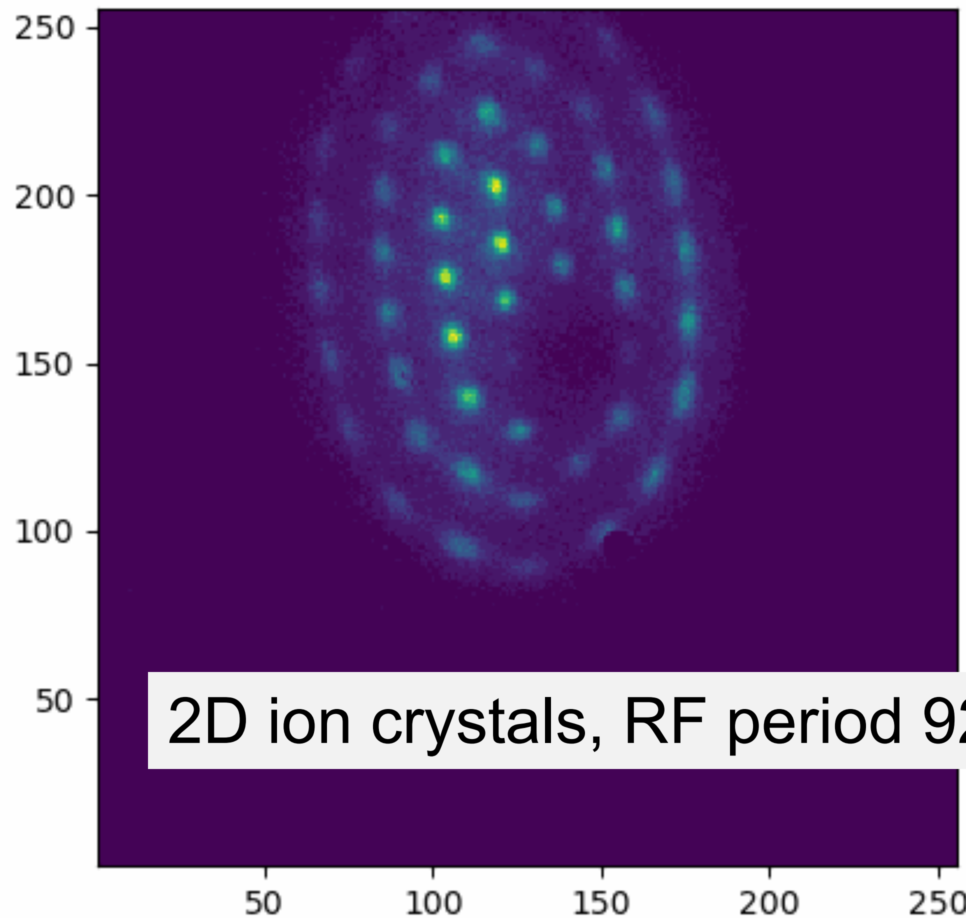
Ion micromotion

- 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
Phys. Rev. A **103**, 023105 (2021).

Ion micromotion in 2D



2D ion crystals, RF period 92 ns

A.Kato et al, Two-tone Doppler cooling of radial two-dimensional crystals in a radiofrequency ion trap, arxiv.org/abs/2111.05829; Phys. Rev. A **105**, 023101

HEP applications

TPX3Cam on ARIADNE 1-ton dual phase Liquid argon TPC

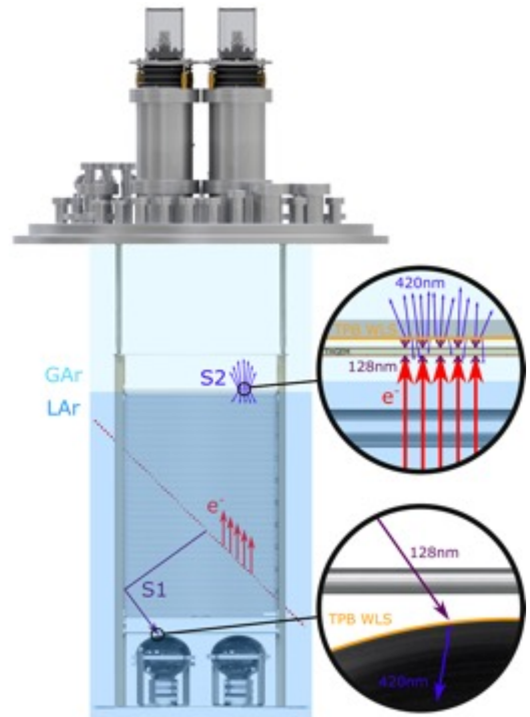
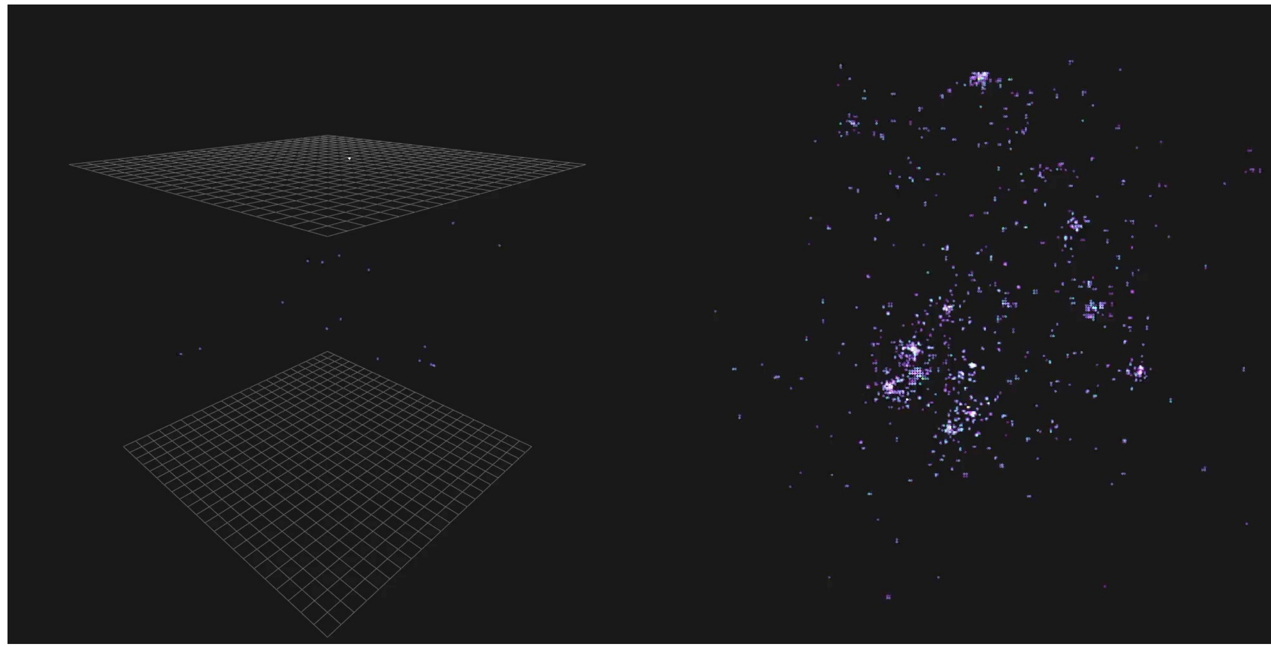


Image light from avalanches in gas phase in THGEM

LAr Cosmic Muons (10msec slice)

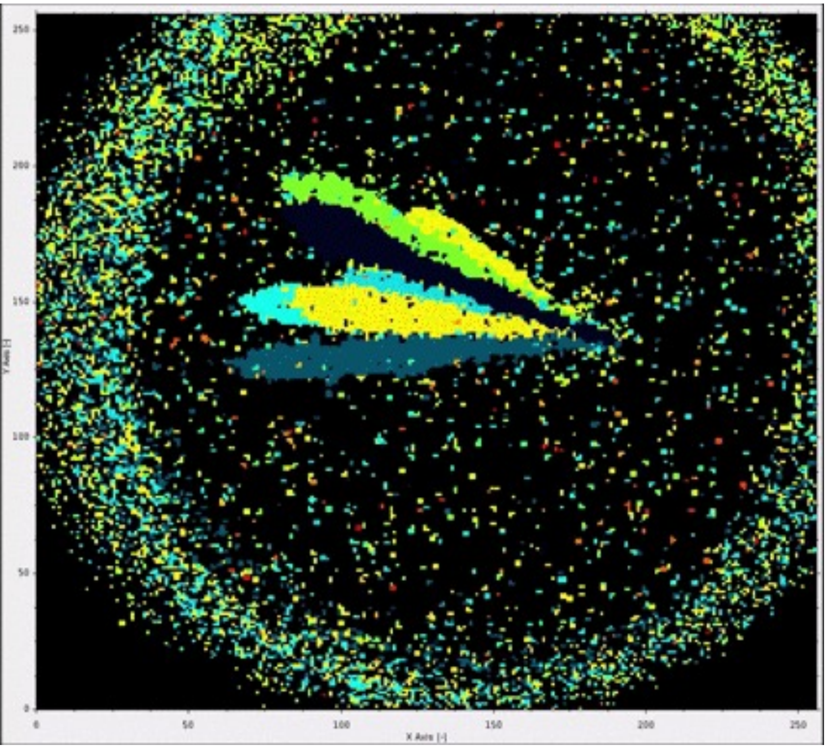


hep.ph.liv.ac.uk/ariadne/index.html
Kostas Mavrokoridis et al

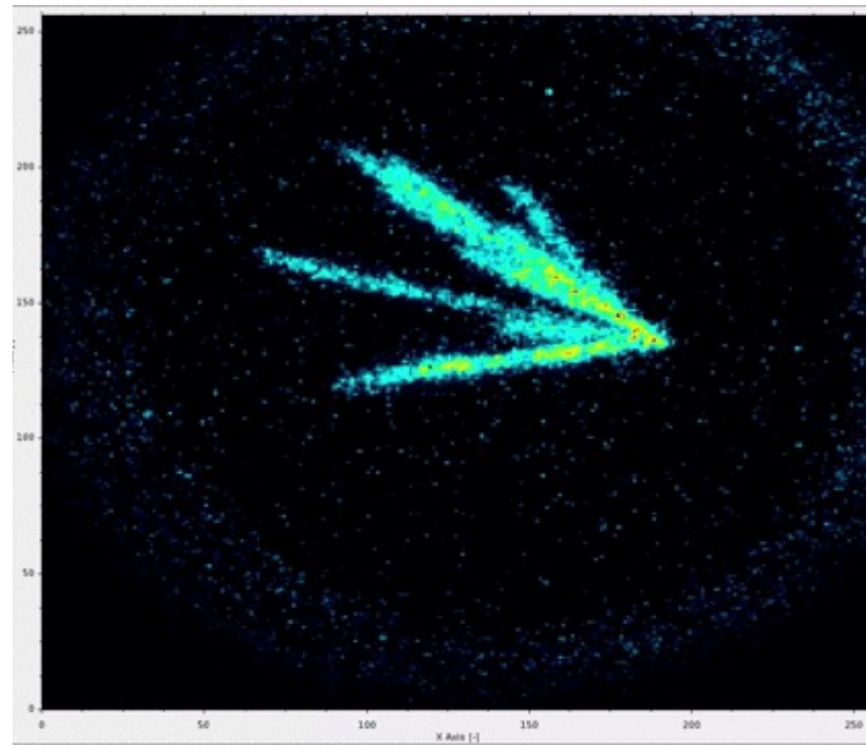
D. Hollywood et al, 2020 ARIADNE—A novel optical LArTPC: technical design report and initial characterisation using a secondary beam from the CERN PS and cosmic muons *JINST* **15** P03003

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



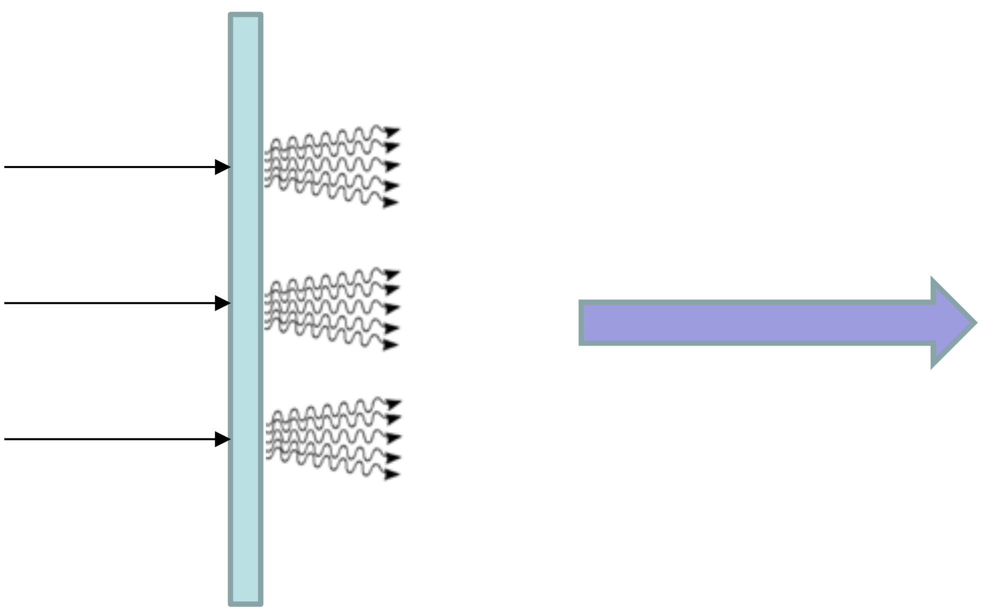
Color = TOT

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, …

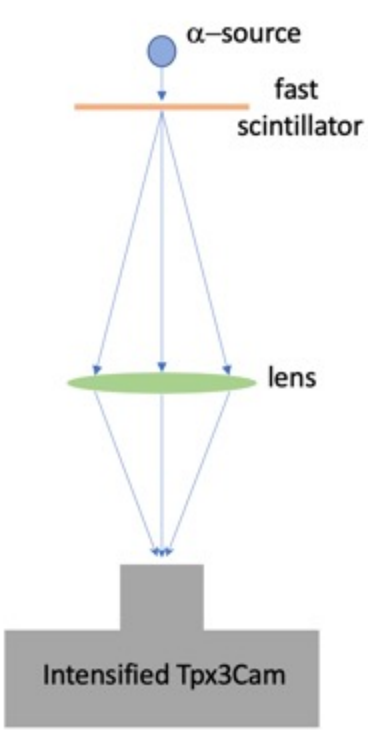
Thin fast scintillator



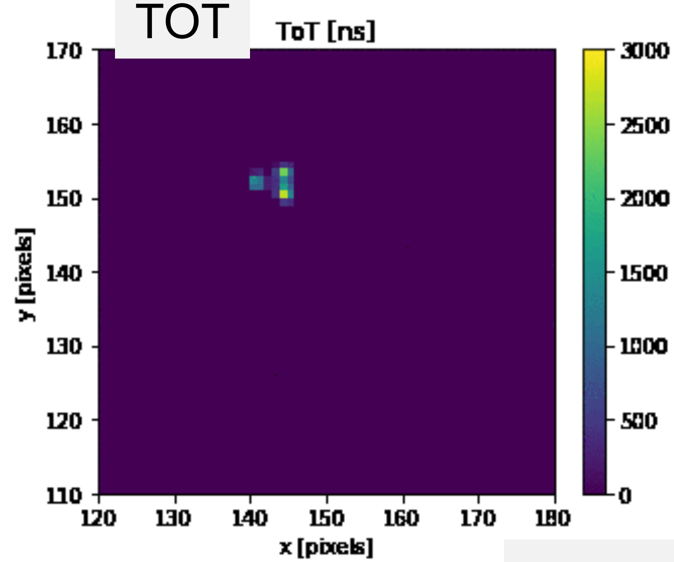
Difficulty: light collection efficiency (but it's single photon sensitive)
Advantage: outside of the beam, around the corner (with mirrors)

Alphas in LYSO in Tpx3Cam

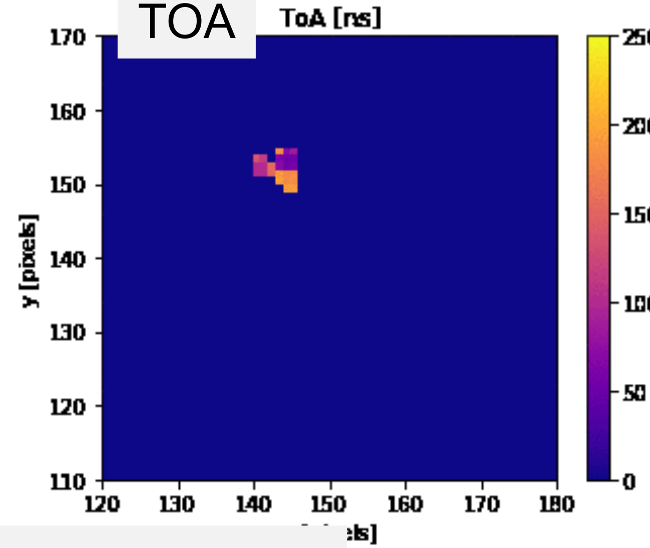
Am241 5.5 MeV alphas
LYSO 0.5 mm thickness



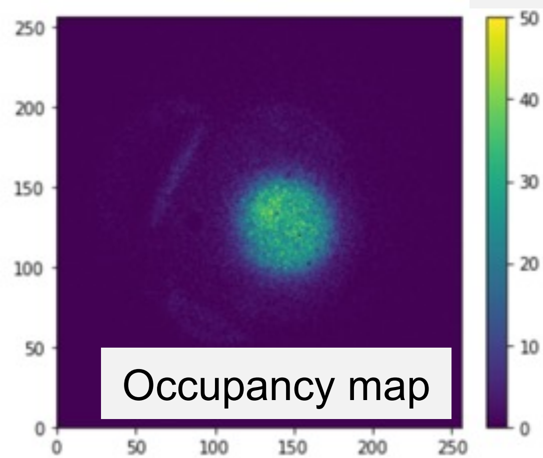
TOT



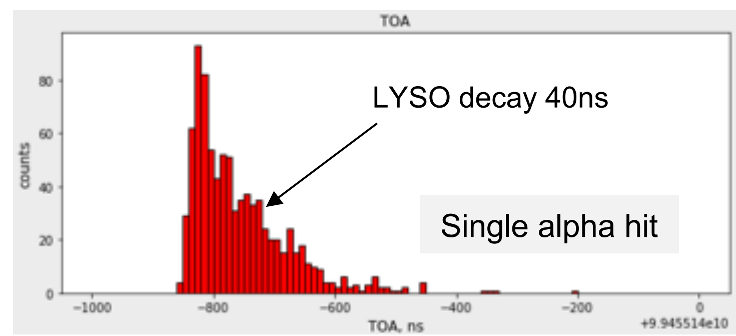
TOA



Alpha hits in Tpx3Cam



Occupancy map



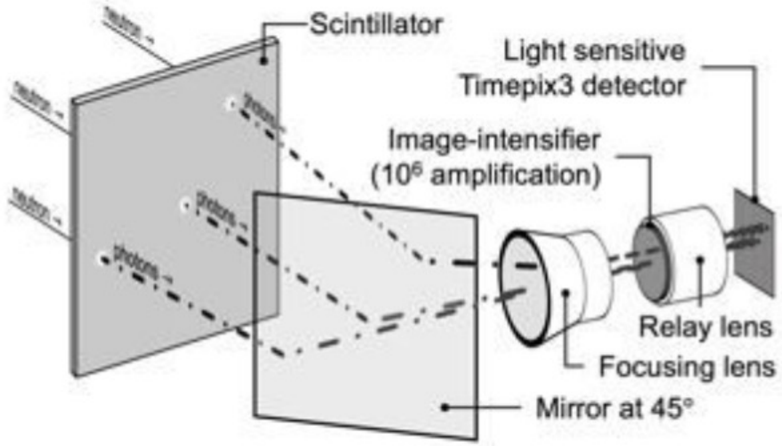
Single alpha hit

TOA, ns

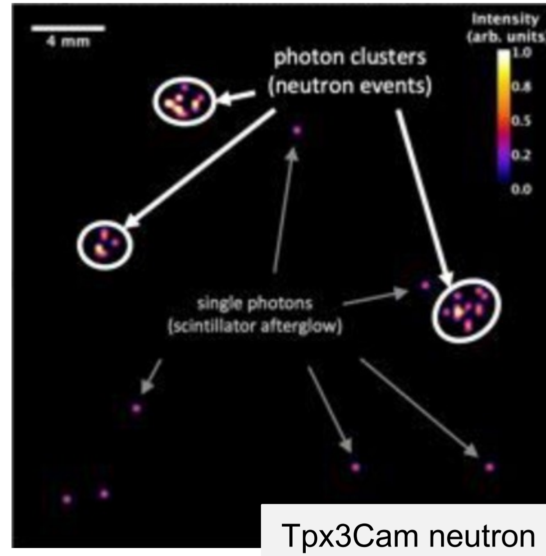
Novel imaging technique for α-particles using a fast optical camera G. D'Amen *et al* 2021 *JINST* **16** P02006

Neutron detection with Tpx3Cam

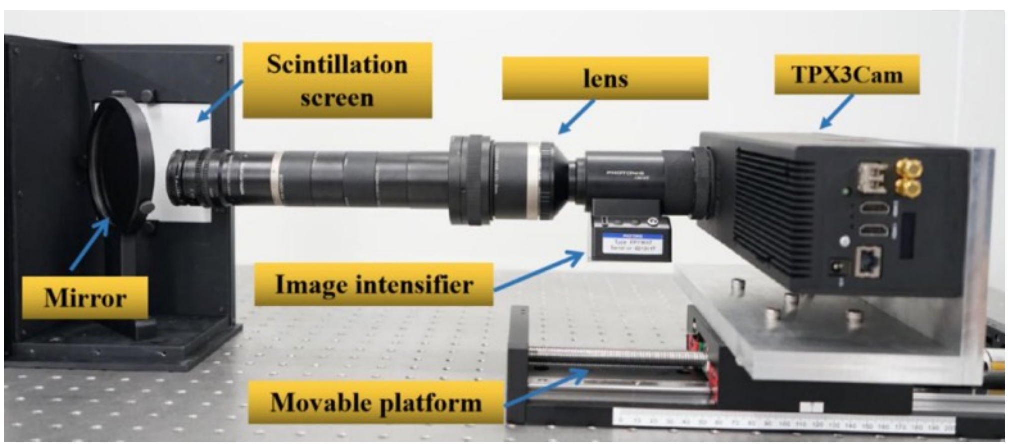
- ^{6}Li-based scintillator
- Neutrons produce alphas
- Time resolved



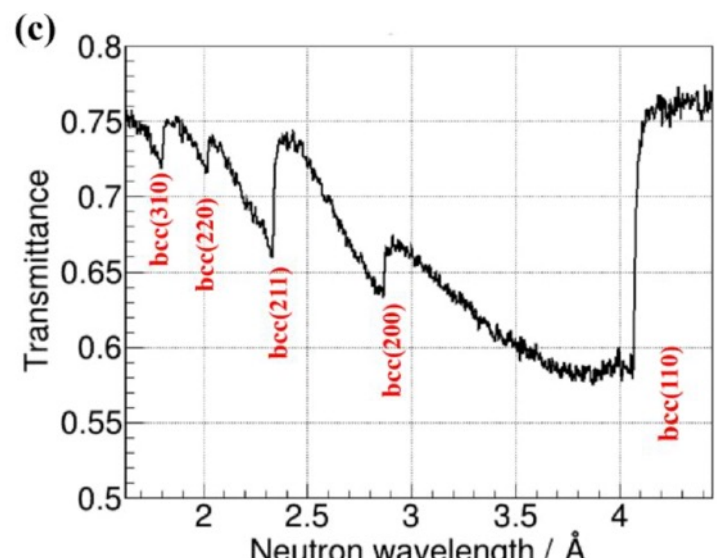
A.Losko et al, DOI:10.21203/rs.3.rs-257513/v1



Tpx3Cam neutron event display



J.Yang et al, arxiv.org/abs/2102.13386



Material characterization with Bragg edges

Future directions

Timepix3 → Timepix4

by Medipix4 collaboration

X. Llopart

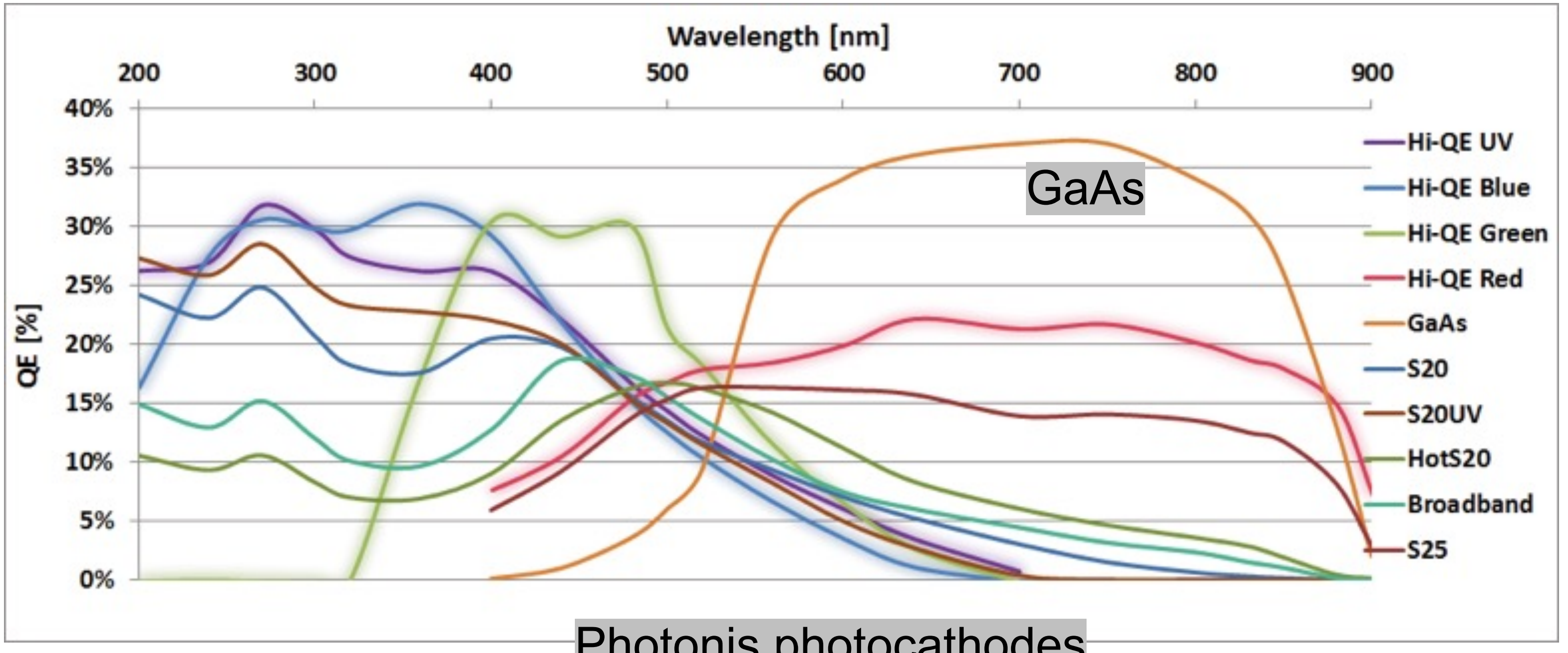
		Timepix3	Timepix4
Technology		IBM 130nm	TSMC 65nm
Pixel Size		55 x 55 μm	≤ 55 x 55 μm
Pixel arrangement		3-side buttable 256 x 256	4-side buttable 256 x 256 or bigger
Operating Modes	Data driven	PC (10-bit) and TOT (14-bit)	CRW: PC and iTOT (12...16-bit)
	Frame based	TOT and TOA	
Zero-Suppressed Readout	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 with triggering capabilities,
- 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

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

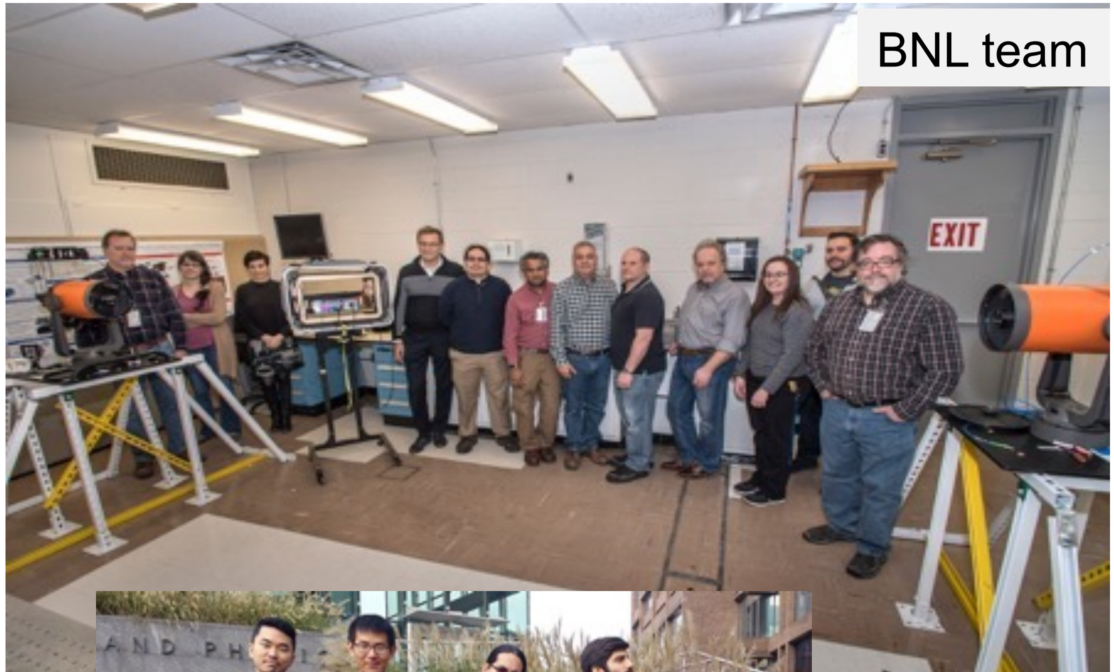
- New technologies for fast single photon detection → hot topic in quantum applications

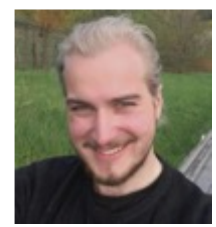
Acknowledgements

Eden Figueroa
Paul Stankus
Tom Tsang
Justine Haupt
Mael Flament
Guodong Cui
Sonali Gera
Dimitros Katramatos
Michael O'Connor
Gabriella Carini
Anand Kandasamy
Michael Keach
Steven Paci
Alex Parsells
Jonathan Schiff
Denis Dolzhenko
Stepan Vintskevich
Anze Slosar
Zhi Chen
Jesse Crawford
Rom Simovitch

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

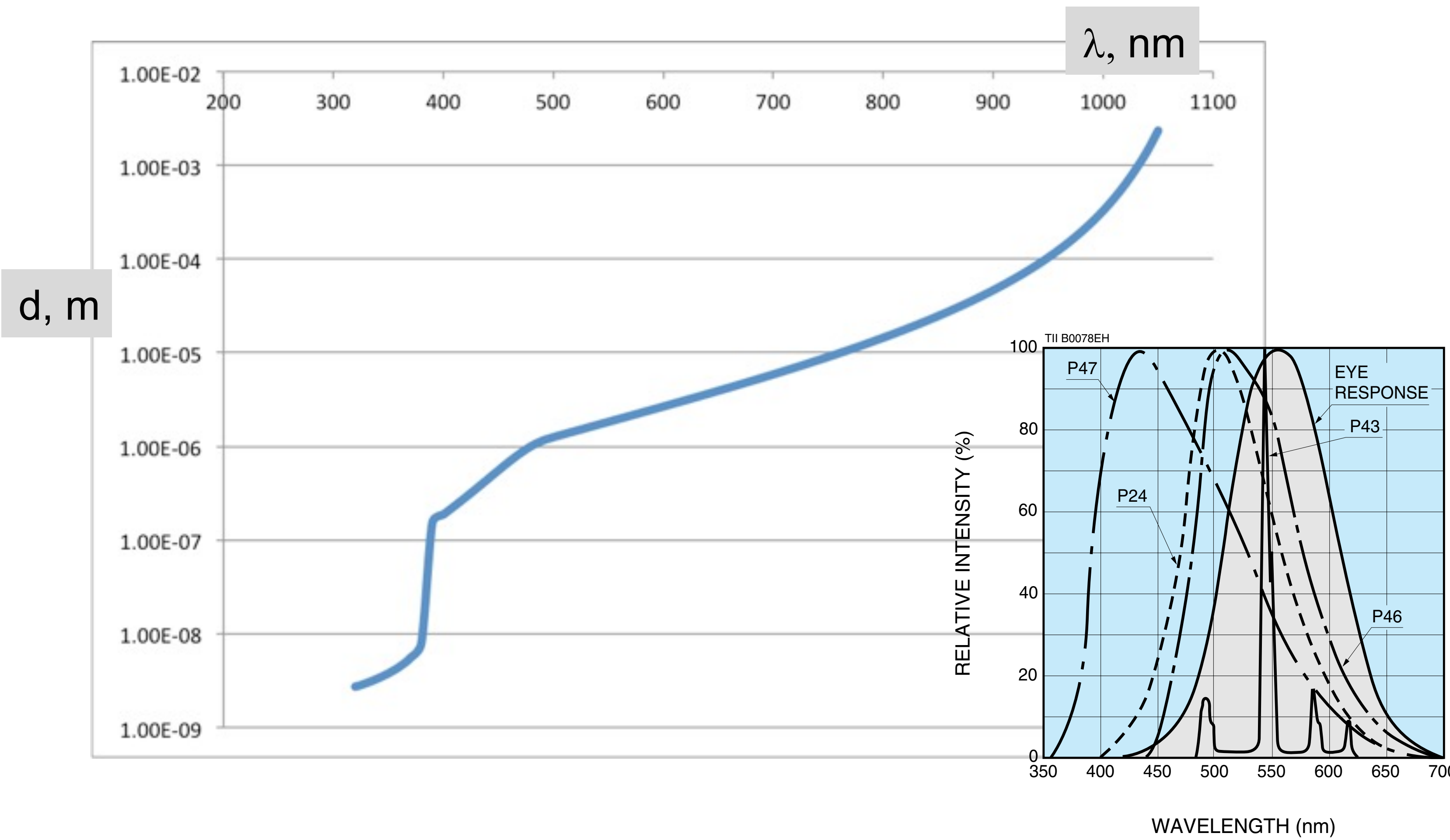
Peter Svihra
Michal Marcisovsky



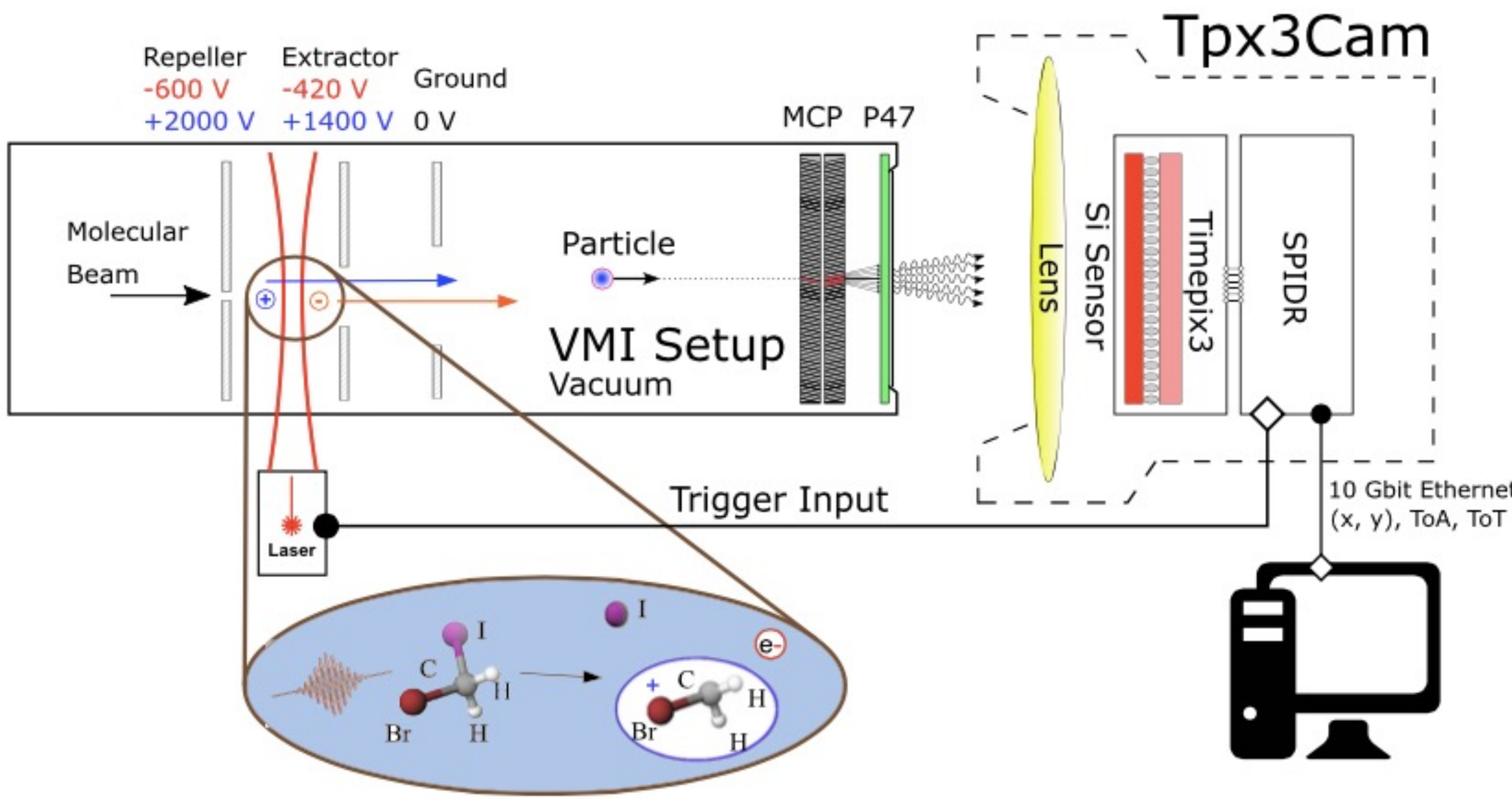


Photon absorption in silicon

- 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

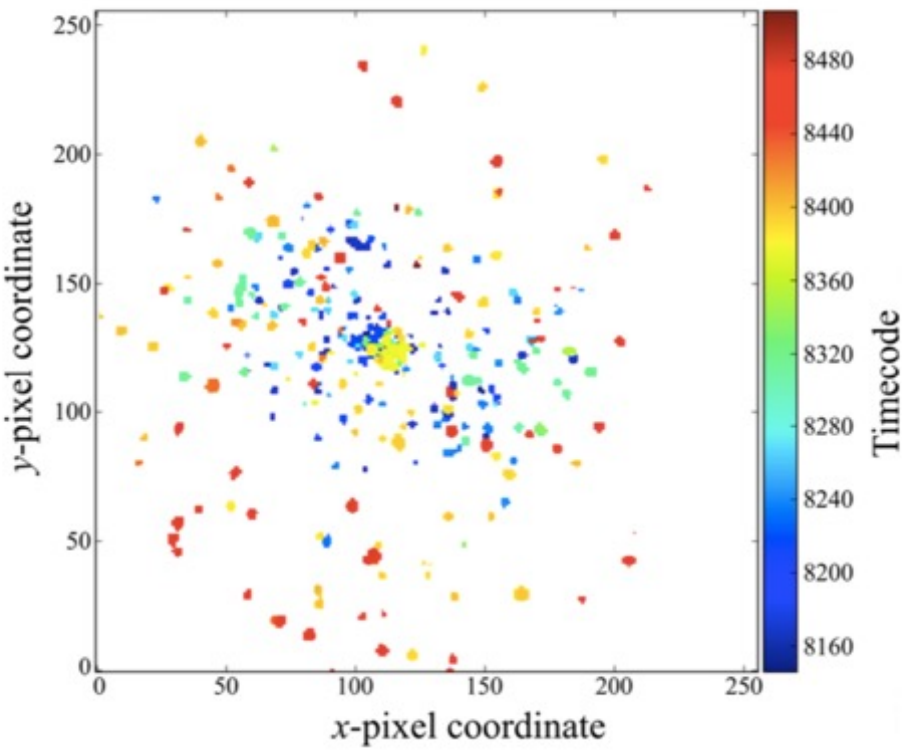


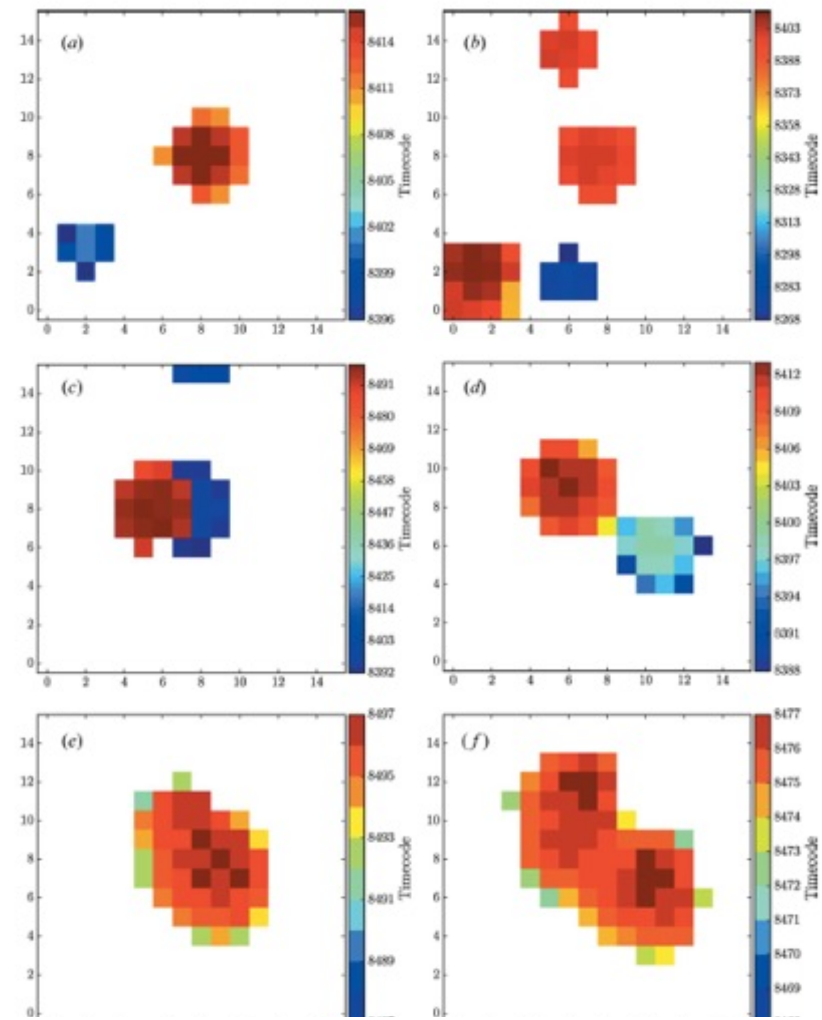
Ion Imaging



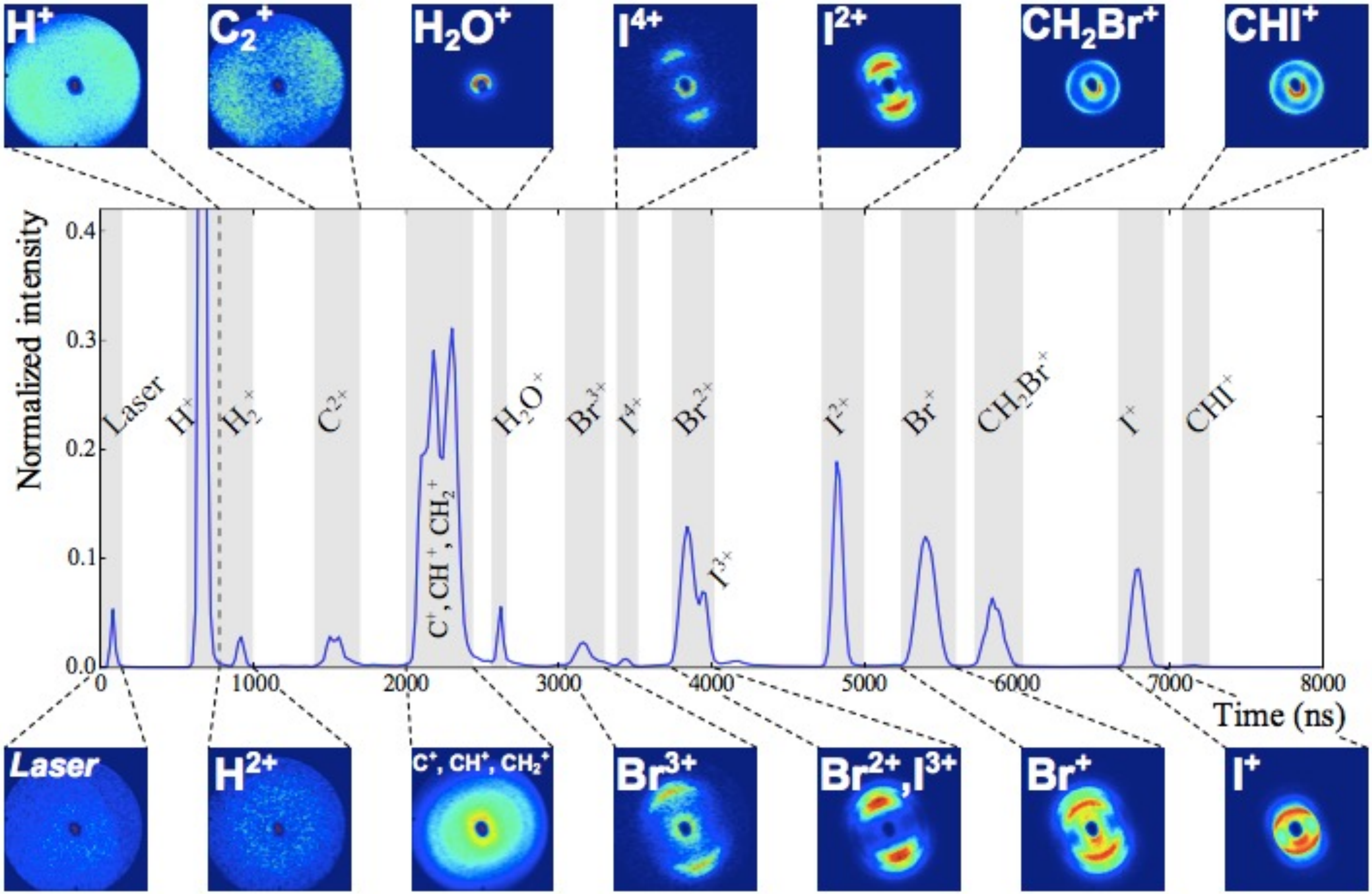
5. A. Zhao, M. van Beuzekom, B. Bouwens, D. Byelov, I. Chakaberia, Ch. Cheng, E. Maddox, A. Nomerotski, P. Svihra, J. Visser, V. Vrba and T. Weinacht: '*Coincidence velocity map imaging using Tpx3Cam, a time stamping optical camera with 1.5 ns timing resolution*'. Rev Sci Instrum. 88(11), 10.1063/1.4996888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

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

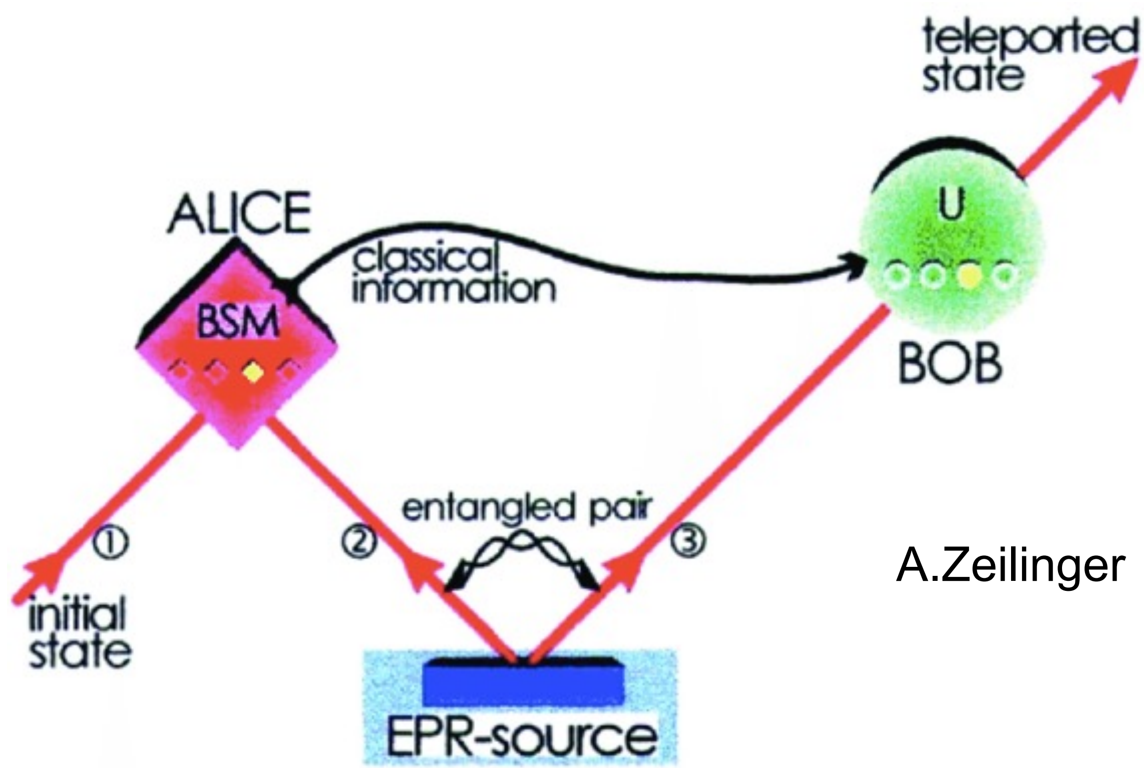


6. M. Fisher-Levine, R. Boll, F. Ziaee, C. Bomme, B. Erk, D. Rompotis, T. Marchenko, A. Nomerotski and D. Rolles: '*Time-Resolved Ion Imaging at Free-Electron Lasers Using TimepixCam*'. Journal of Synchrotron Radiation.(2018) 25 https://doi.org/10.1107/S16005775170

Quantum Network

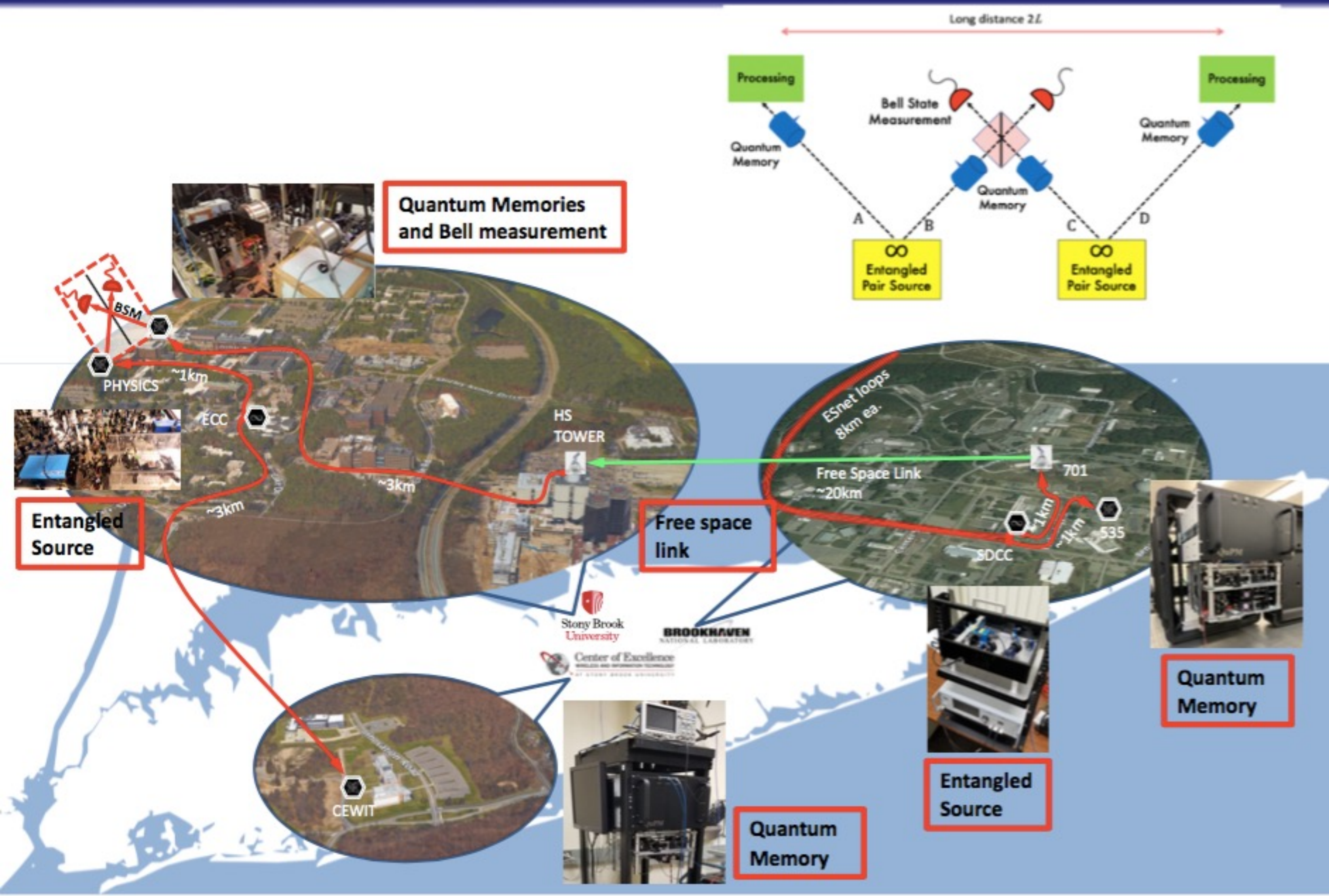
- Attenuation in fibers → need quantum repeater to reproduce qubits
  - Simple amplification will not conserve the quantum state

- 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, or teleport photon)

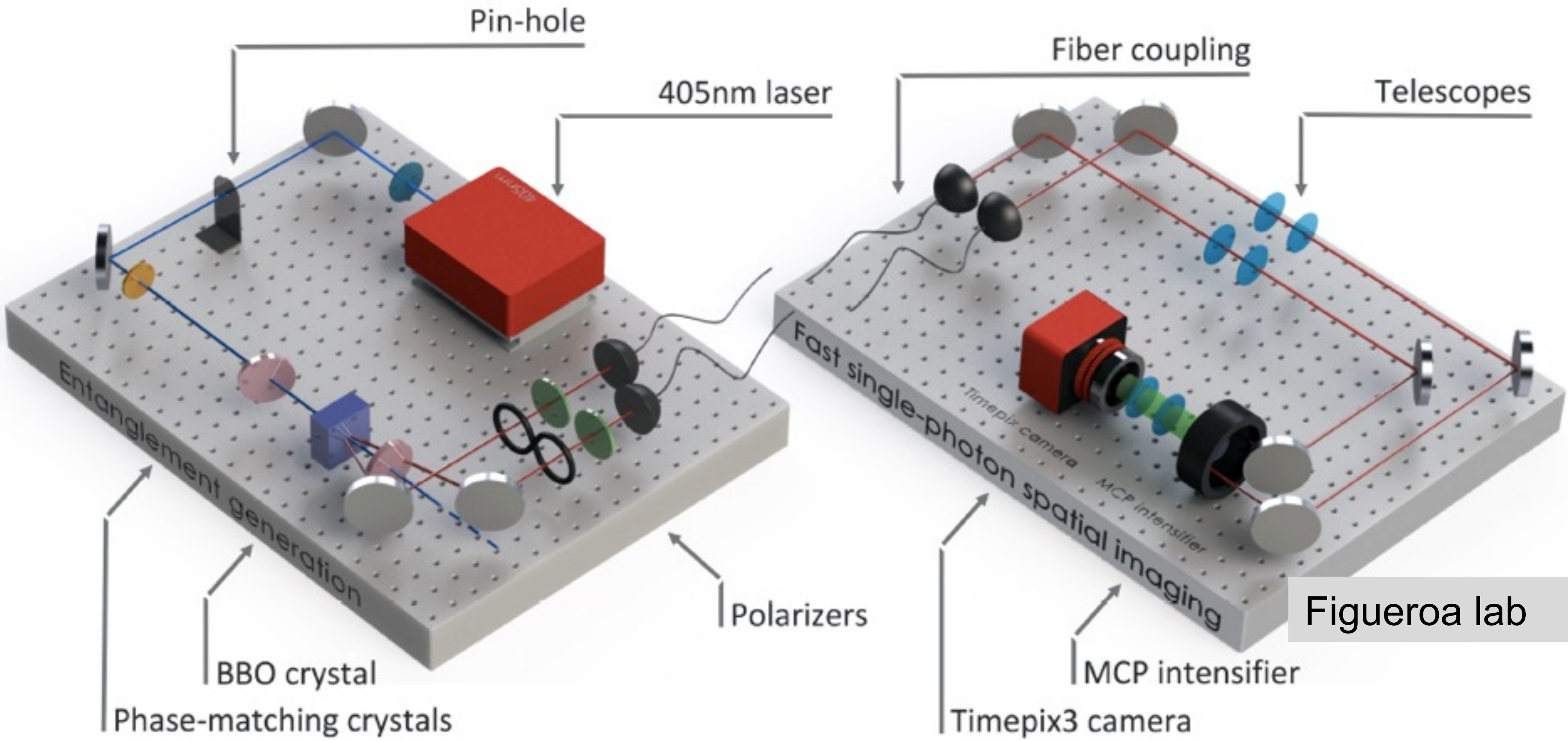


A.Zeilinger

SBU BNL Quantum repeater test bed

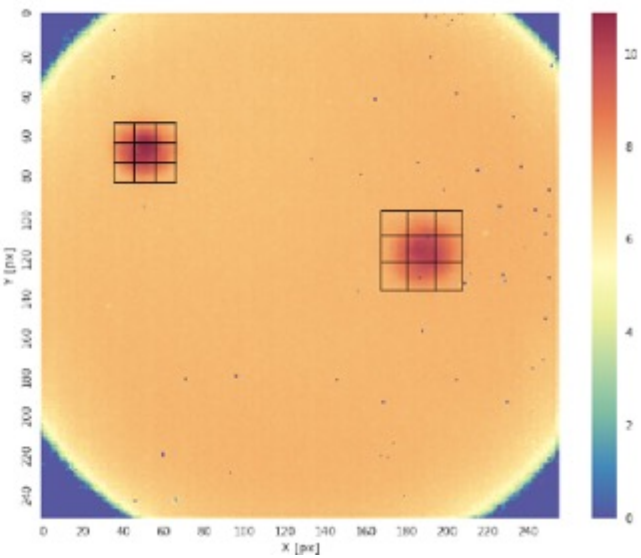


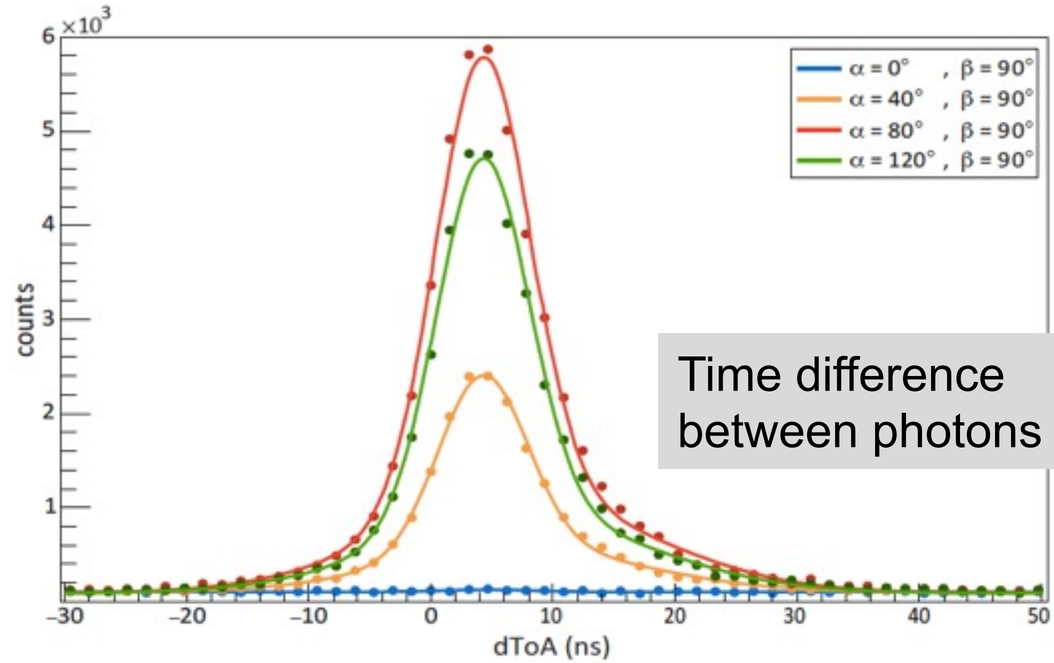
Characterization of Single Photon Down-Conversion Source



Figueroa lab

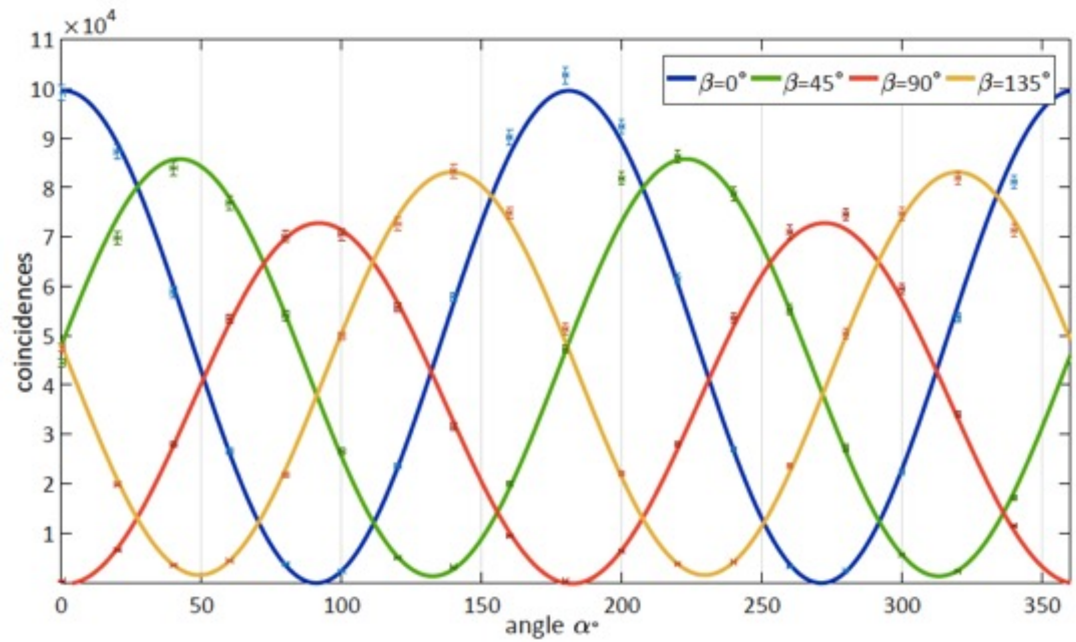
qubit: use H, V photon polarization states $$|\phi^{\pm}\rangle = \frac{(|HH\rangle \pm |VV\rangle)}{\sqrt{2}}$$





Time difference between photons

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

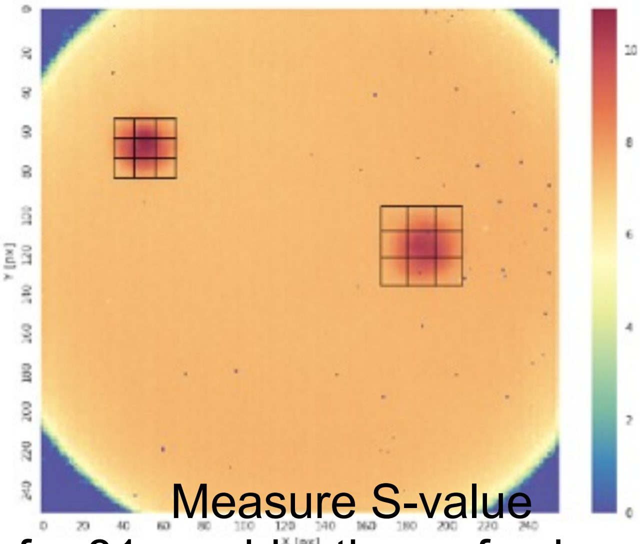


- Measurement:

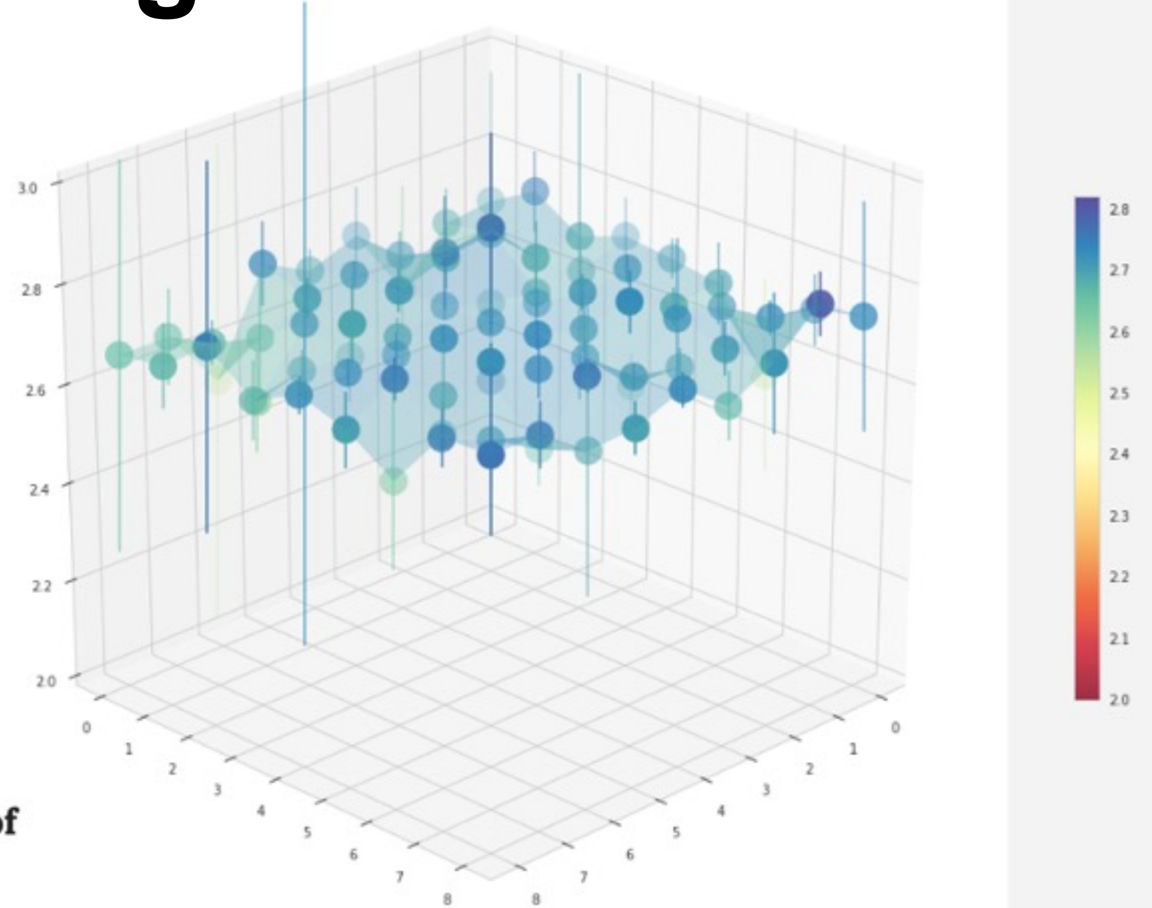
S-value = 2.72±0.02

Time resolution: 2ns

Spatial characterization of entanglement



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

Imaging enables scalability

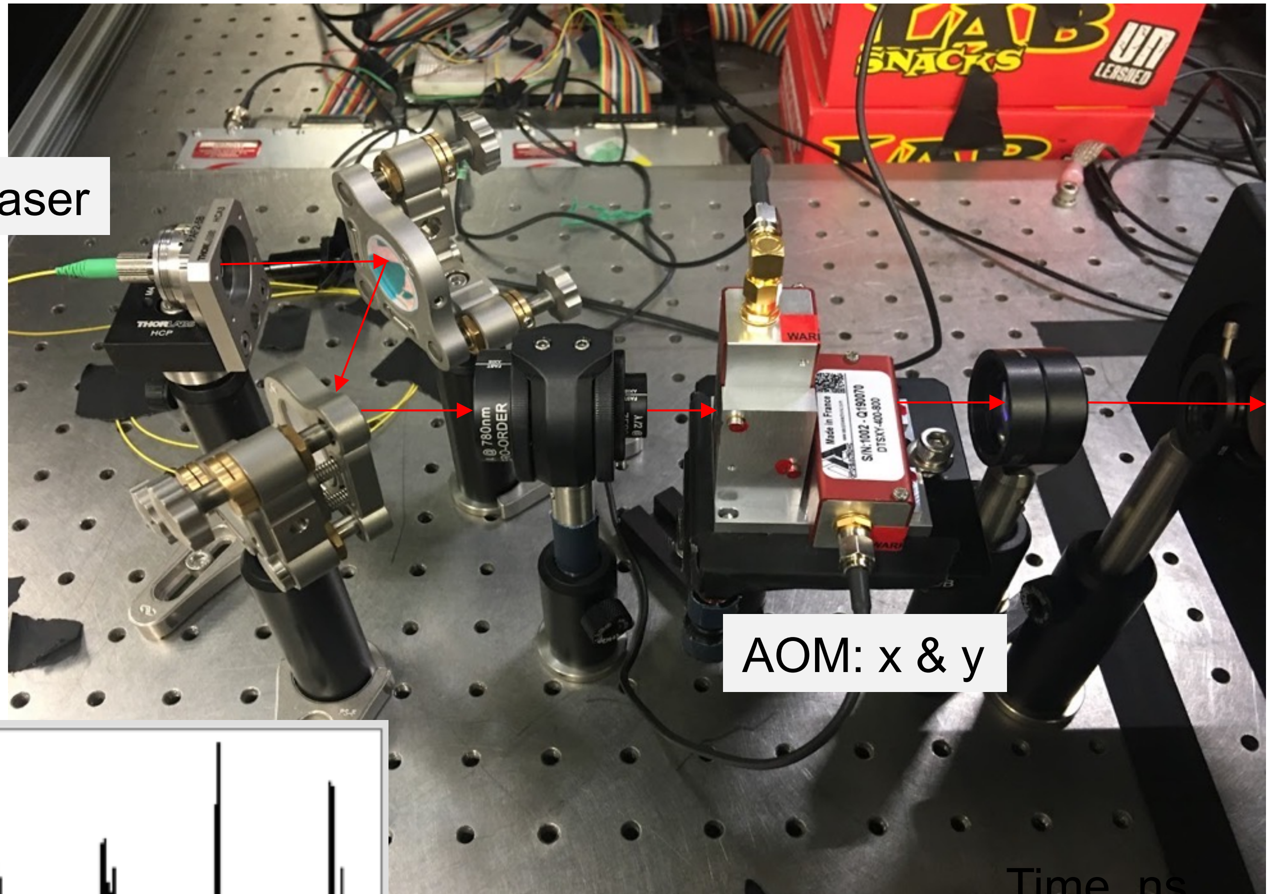
Scalability

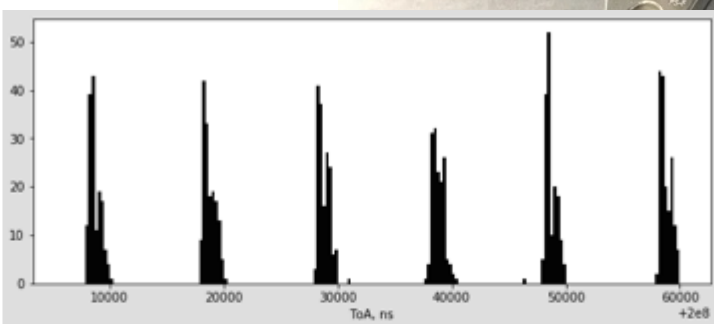
Tpx3Cam supports 10MHz single photon rate :

= 10 x 10 x 100kHz beams

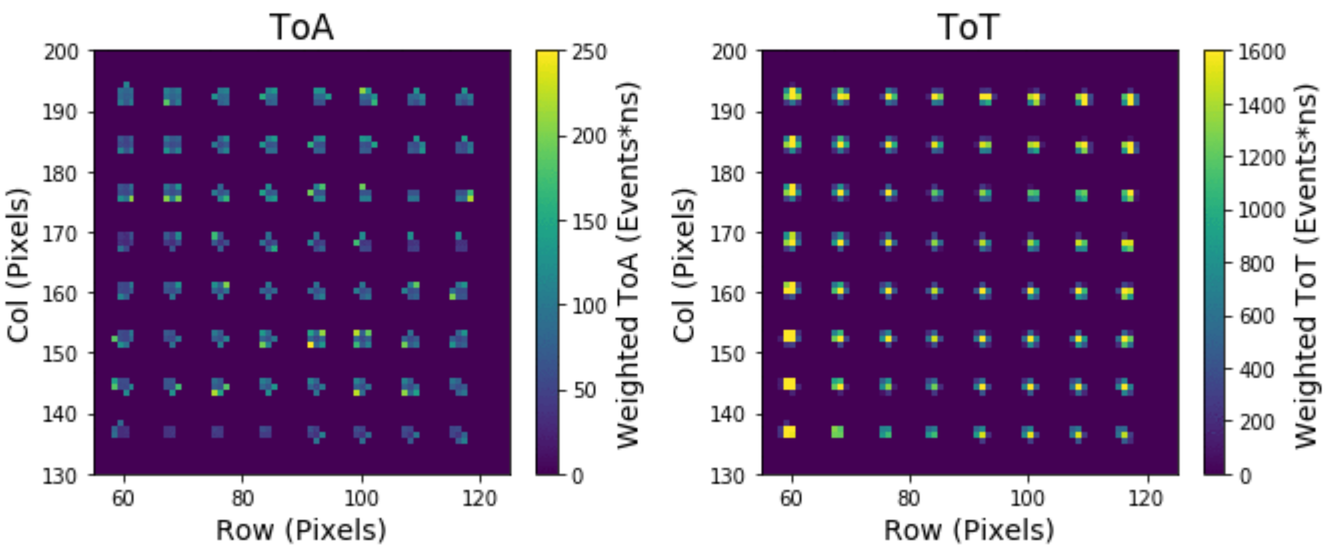
Photon router:

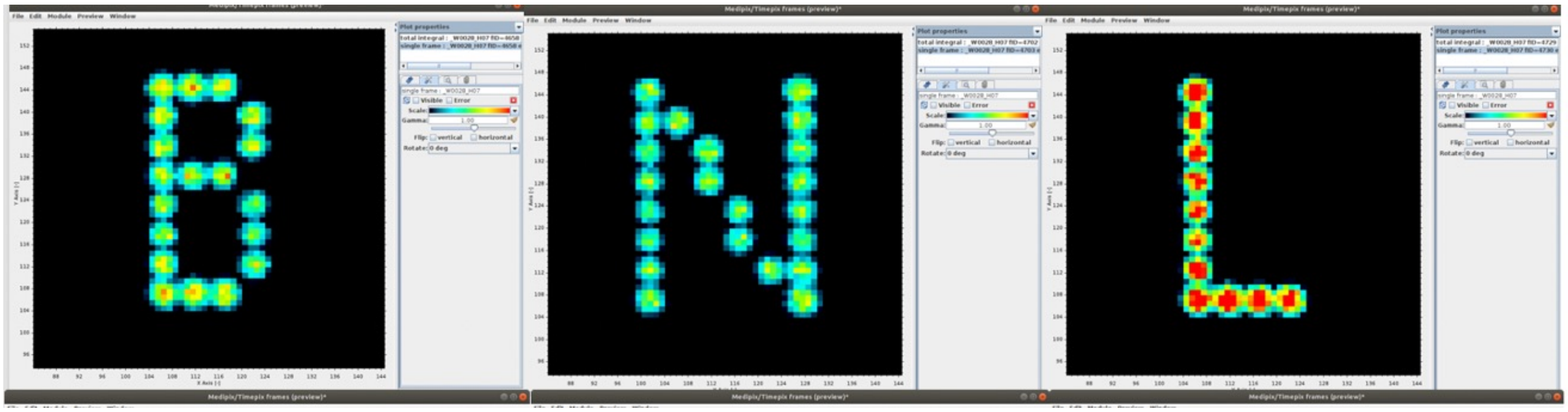
- Used acousto-optical modulators to create 8x8 grid
- Arbitrary routing between spots
- 10 ns time resolution, 1 μs switching





Scalability

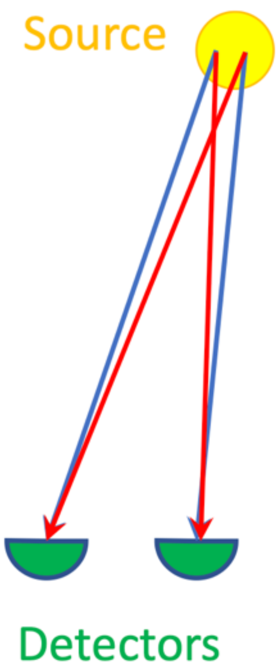


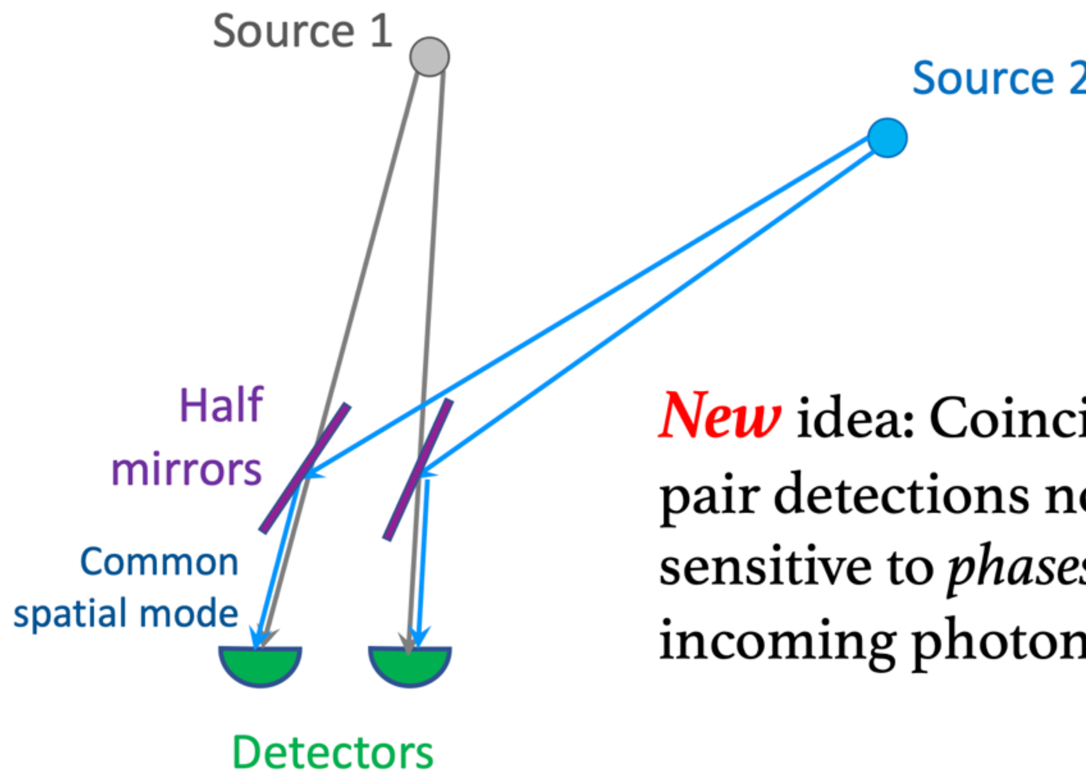


Goal: storage of multiple qubits in single ^{87}Rb cell

Hanbury Brown – Twiss Interferometry

HBT with two sources?





New idea: Coincident pair detections now sensitive to *phases* of incoming photons

Possible impact on astrophysics and cosmology

https://arxiv.org/abs/2010.09100

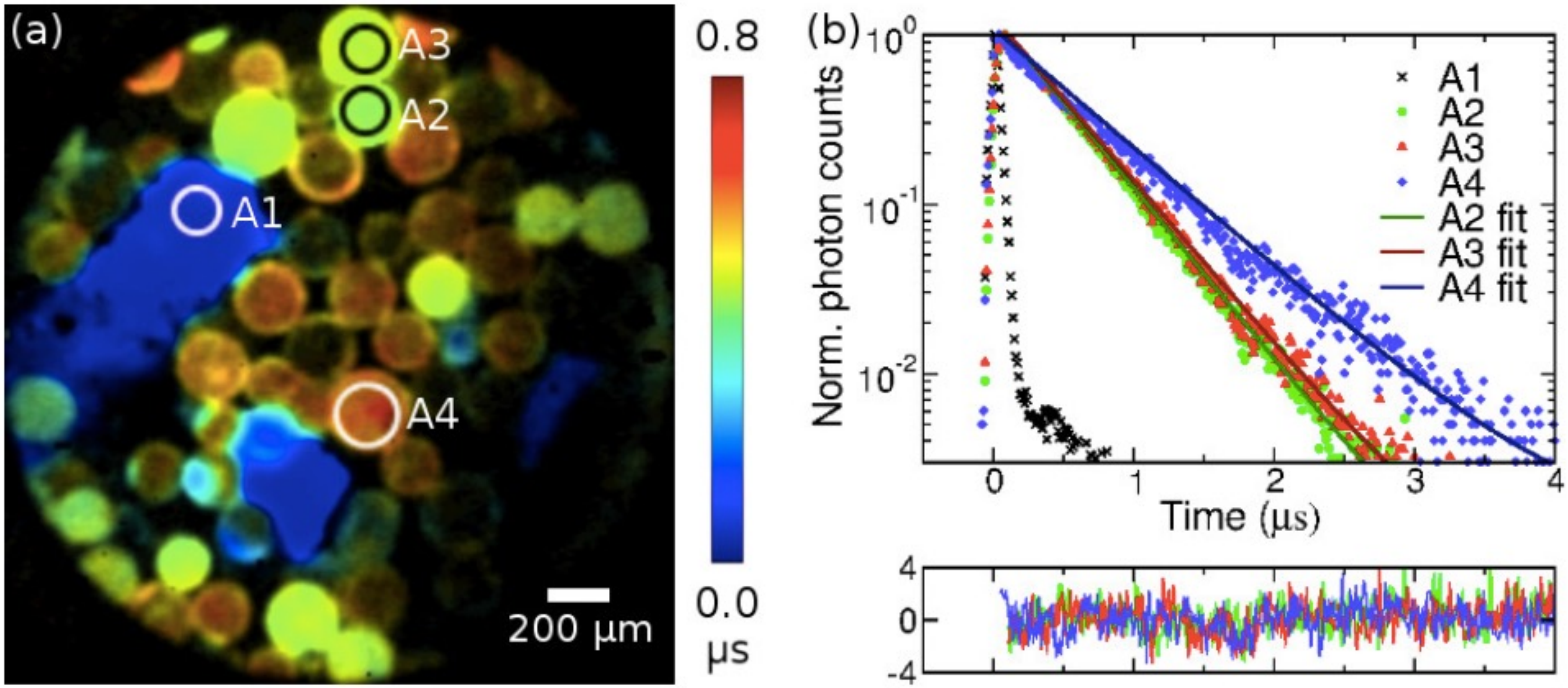
offers orders of magnitude better astrometry with major impact

- Parallax: improved distance ladder (DE)
- Proper star motions (DM)
- Microlensing, see shape changes (DM)

- Black hole imaging
- Gravitational waves, coherent motions of stars
- Exoplanets

Lifetime Imaging

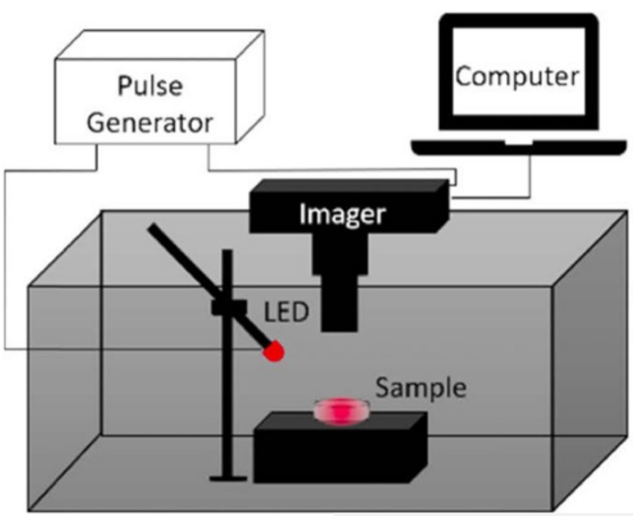
Lifetime imaging with ns timing

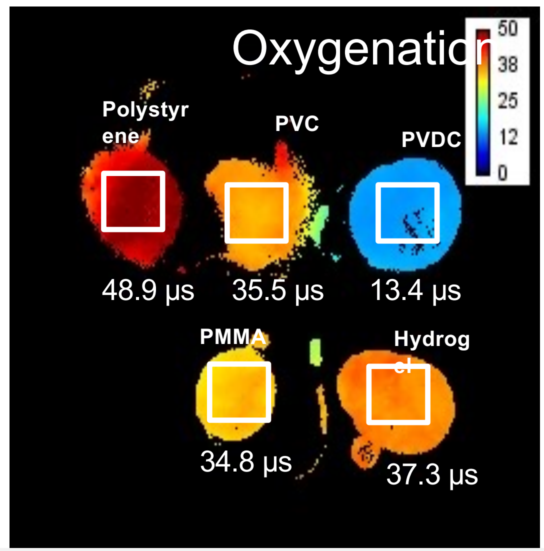


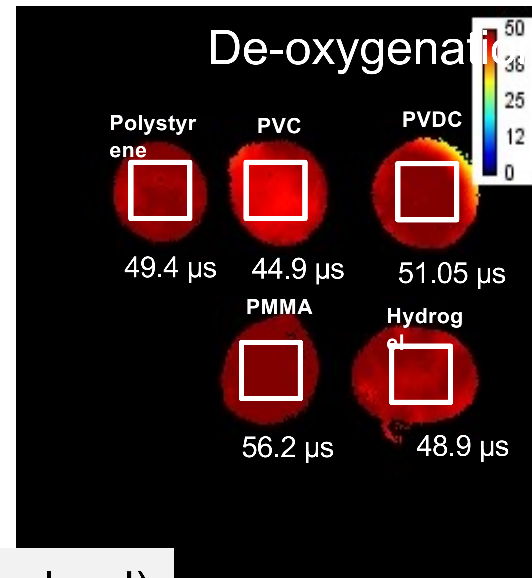
L. M. Hirvonen, M. Fisher-Levine, K. Suhling, and A. Nomerotski: *'Photon counting phosphorescence lifetime imaging with TimepixCam'*. Rev. Sci. Instrum. 88, 013104 (2017).

Lifetime imaging with oxygen sensors

Sensor lifetime depends on oxygen concentration
→ in-vivo monitoring of oxygen in tissues







Papkovski group, University College Cork (Ireland)

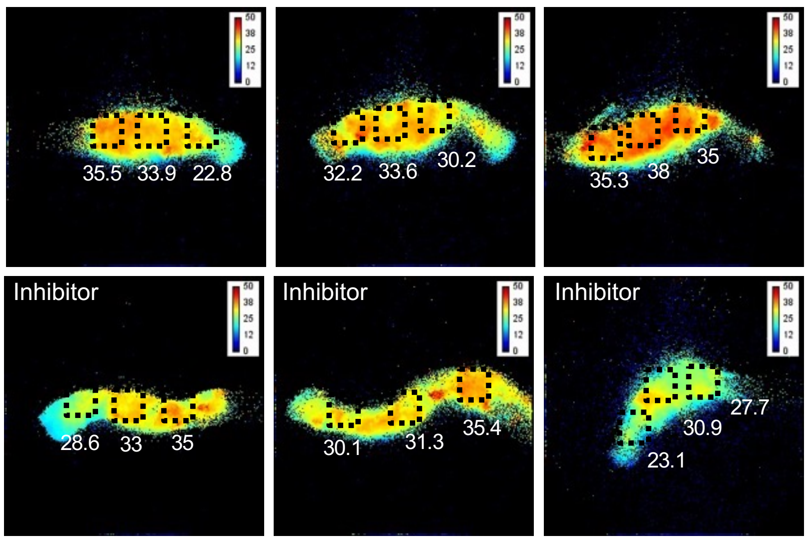
<u>Oxygenation and Deoxygenation of PtBp Solid State sensors</u>

New luminescence lifetime macro-imager based on a Tpx3Cam optical camera,
R Sen et al, Biomedical optics express 11 (1), 77-88 (2020)

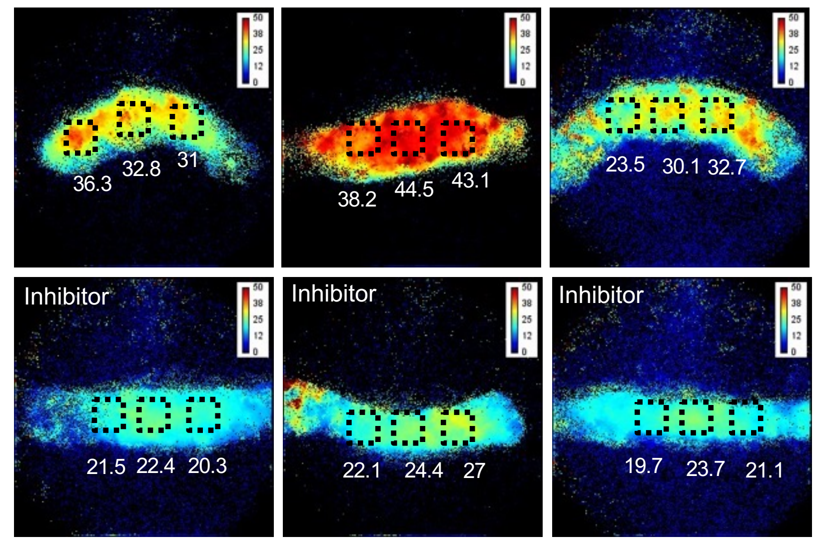
Measurements with biosamples

<u>Intraluminal application (Mice2)</u>

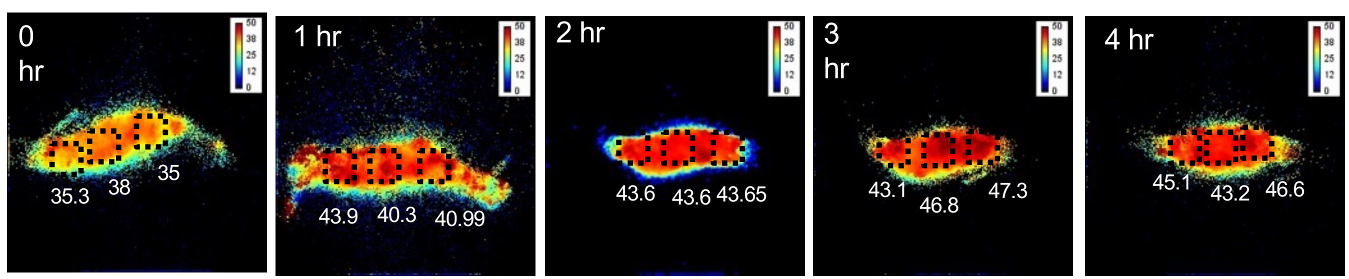
Large Intestine



Small Intestine



Large Intestine Time Lapse



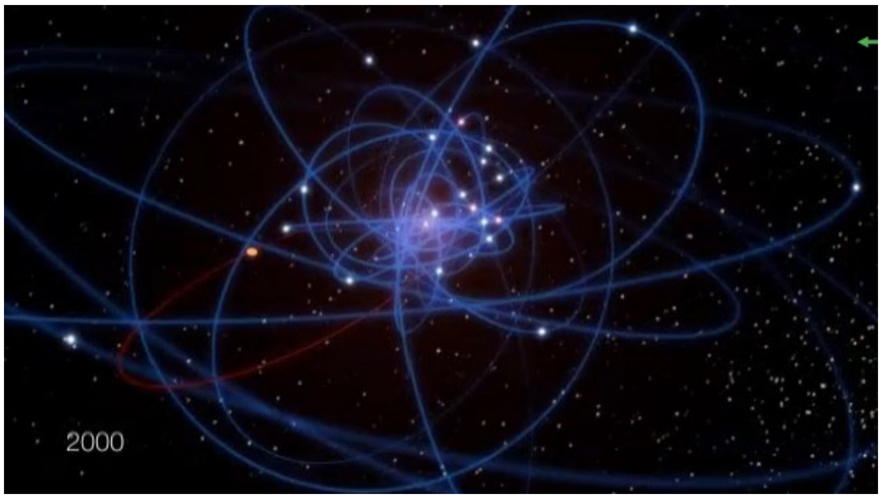
Papkovski group, University College Cork (Ireland)

Mapping O_2 concentration in ex-vivo tissue samples on a fast PLIM macro-imager, R Sen et al, Scientific reports 10 (1), 1-11 (2020)

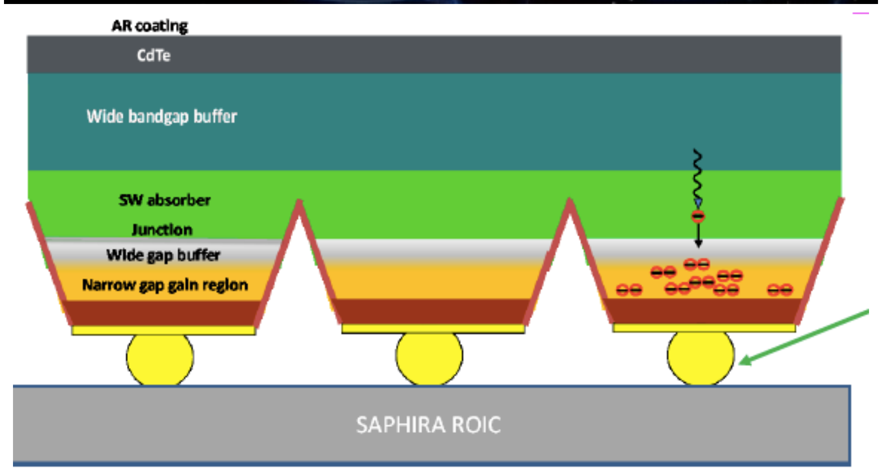
Single photon imagers for NIR

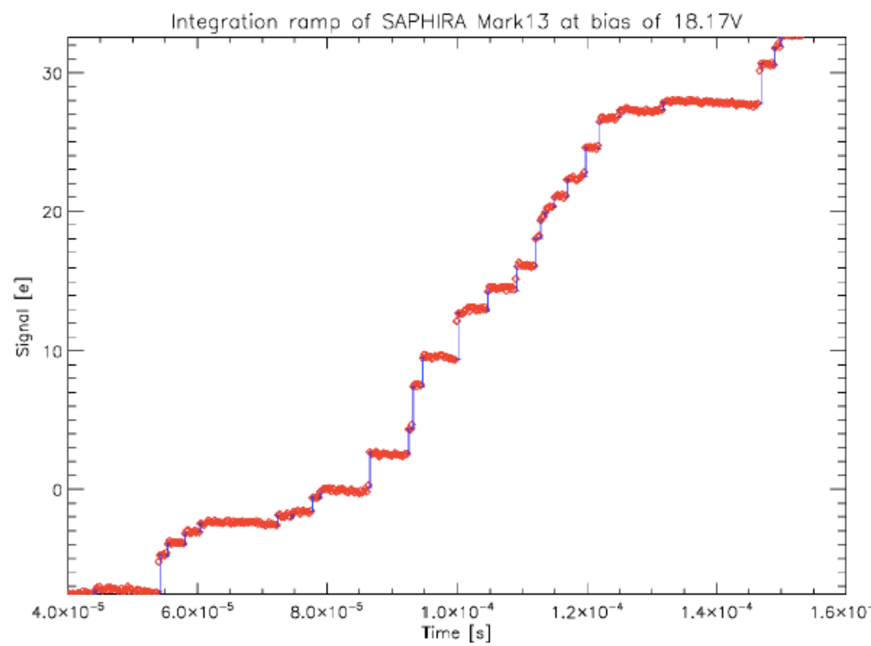
HgCdTe sensors with avalanche amplification

– developed for astronomers to study the black hole in our Galaxy



- pure electron amplification
- “noiseless” gain > 1000
- sub-e noise @ 5 MHz, QE ~= 80%
- suitable for telecom wavelength 1660 nm
- single photon counting
- Compatible with fast timing





320x256 diode array, Saphira readout ASIC

Baltimore SDW 2017 Gert Finger