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

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iWoRiD 2022

International Workshop
23rd iWoRiD
on Radiation Imaging Detectors

23rd International Workshop on
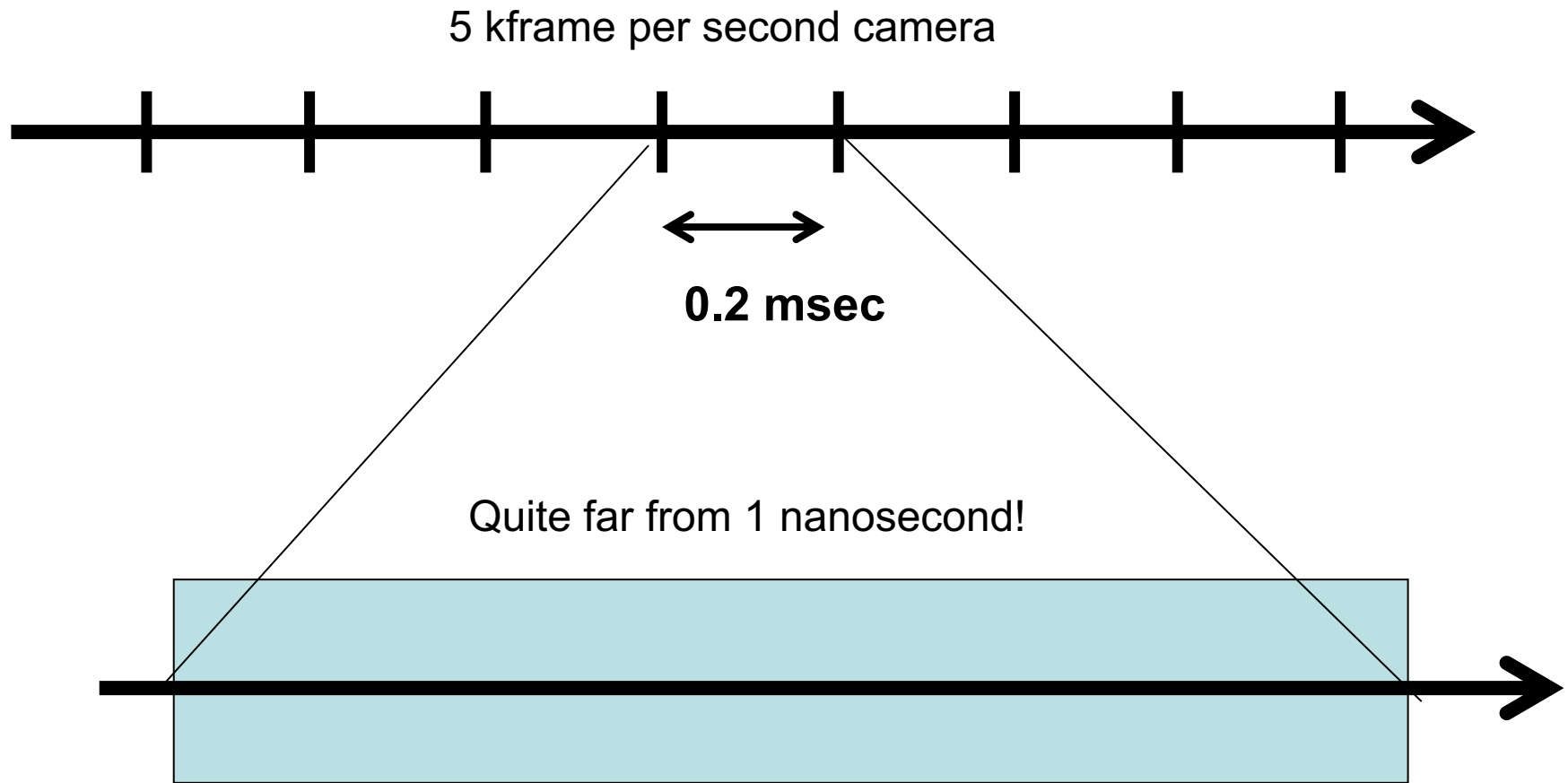## Radiation Imaging Detectors
26 – 30 June 2022
Riva del Garda, Italy

Will talk about

- Fast, data driven approach to optical imaging

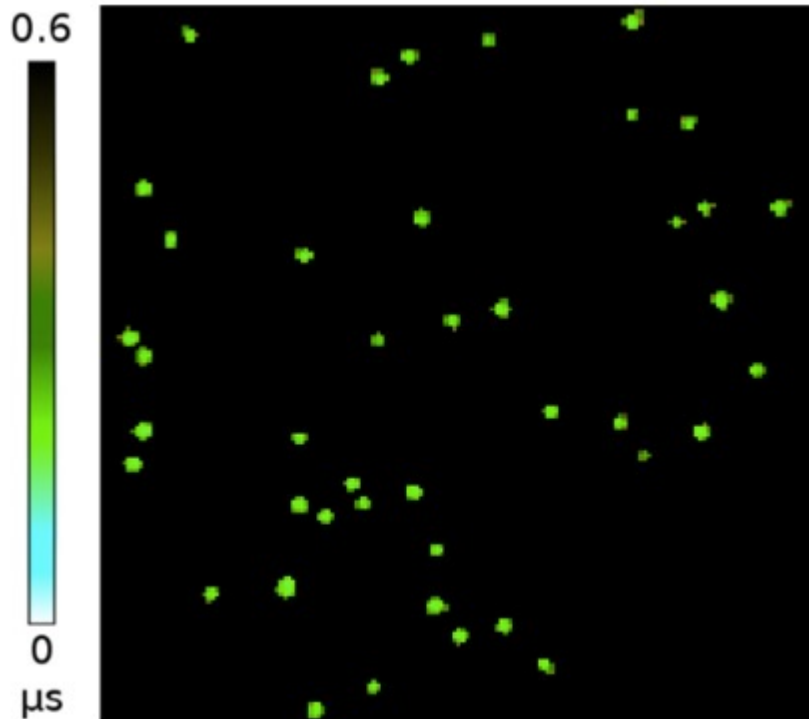- Quantum applications
- Quantum assisted telescopes

Optical cameras: normally signal is integrated in a slice of time and whole frame is read out
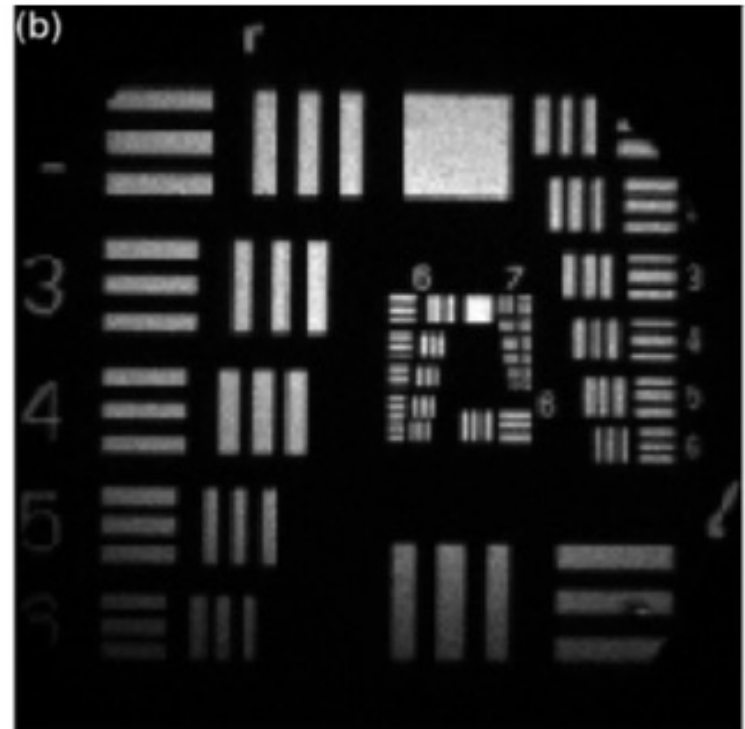
5 kframe per second camera

0.2 msec

Quite far from 1 nanosecond!

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
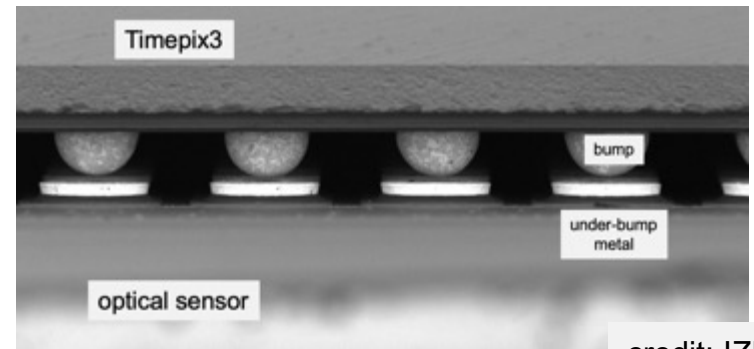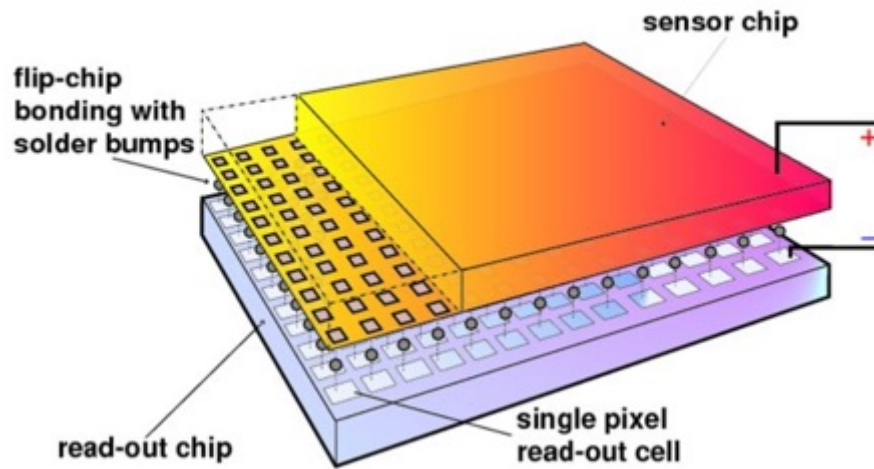
Also: PImMS1 & PImMS2 – monolithic version with different architecture

PImMS, a fast event-triggered monolithic pixel detector with storage of multiple timestamps, JJ John et al, Journal of Instrumentation 7 (08), C08001 (2012)

Timepix Optical Cameras

Hybrid pixel detectors
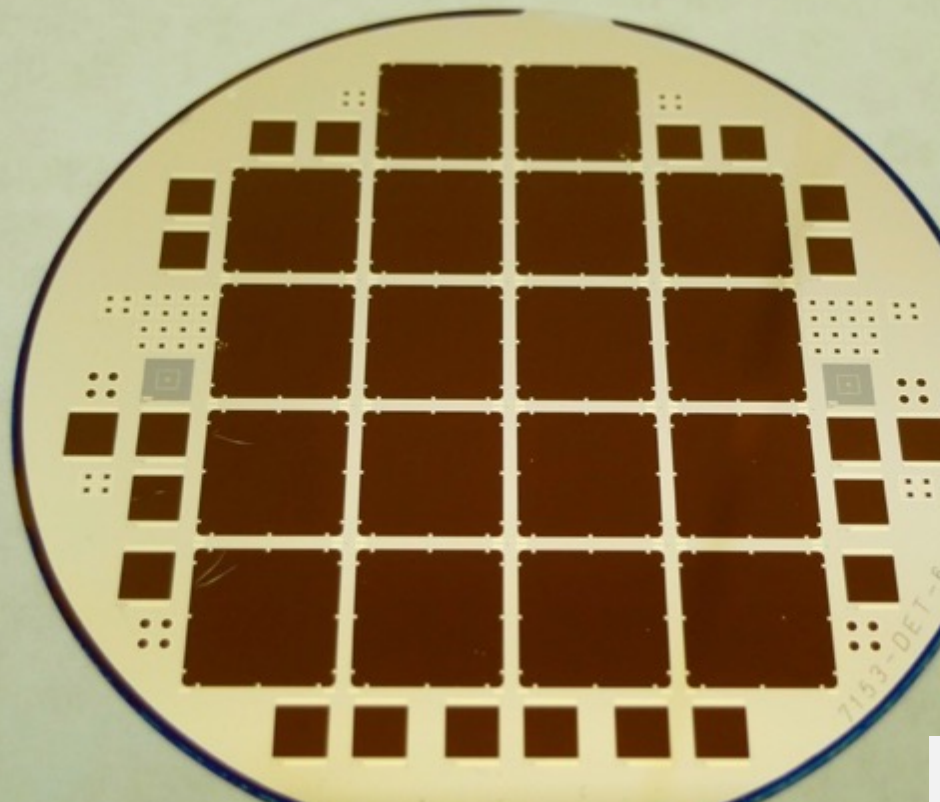
Have roots in R&D for LEP/LHC vertex detectors

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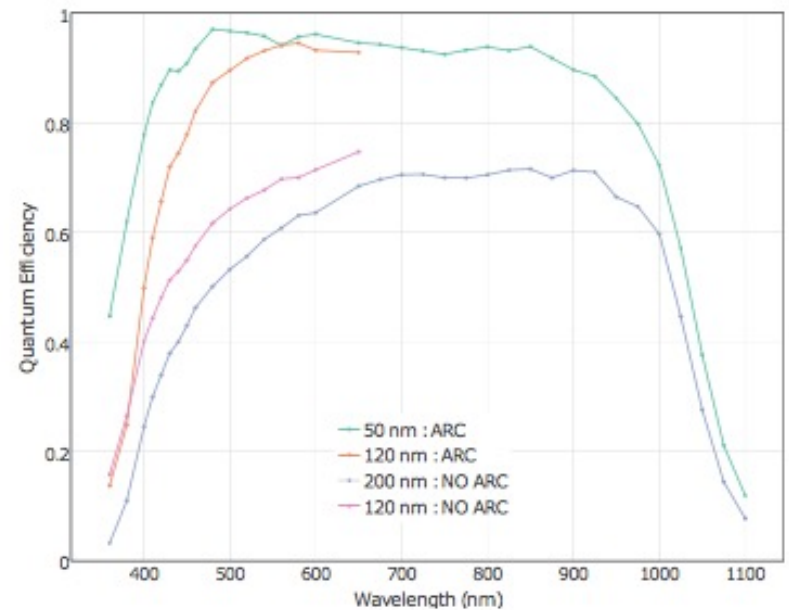

credit: IZM

- 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)
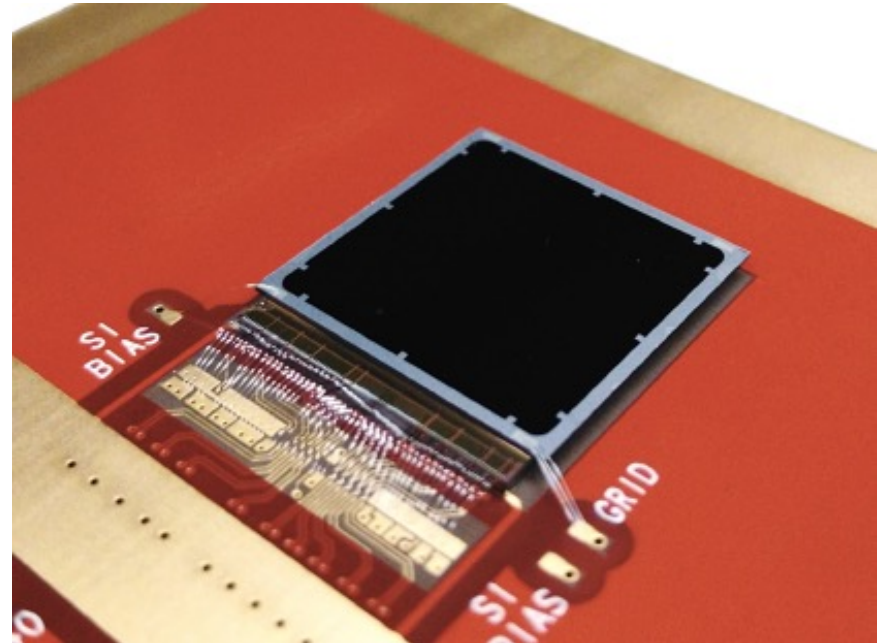
Timepix3 Camera → Tpx3Cam

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)

Single (optical) photons
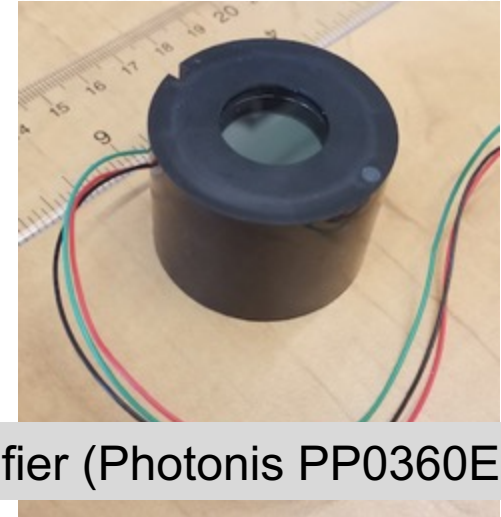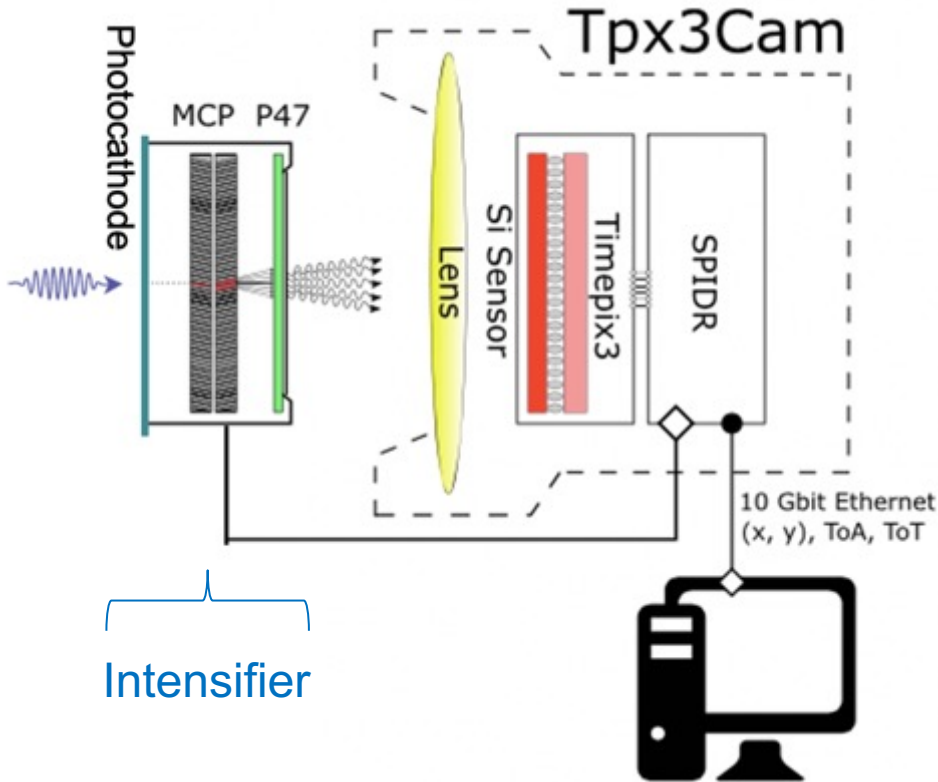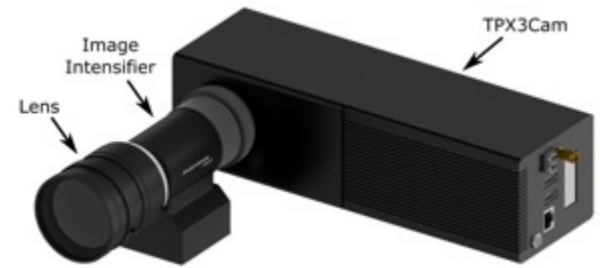
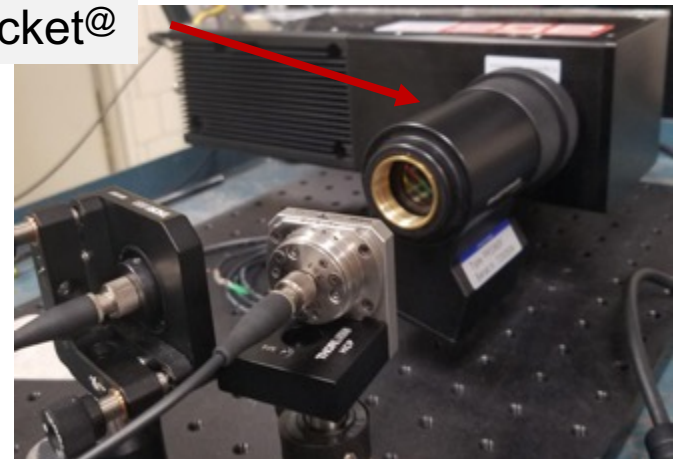# Intensified camera: use off-the-shelf image intensifier

Tpx3Cam

Photocathode

MCP P47

Lens

Si Sensor

Timepix3

SPIDR

10 Gbit Ethernet (x, y), ToA, ToT

Intensifier

Image intensifier (Photonis PP0360EG)

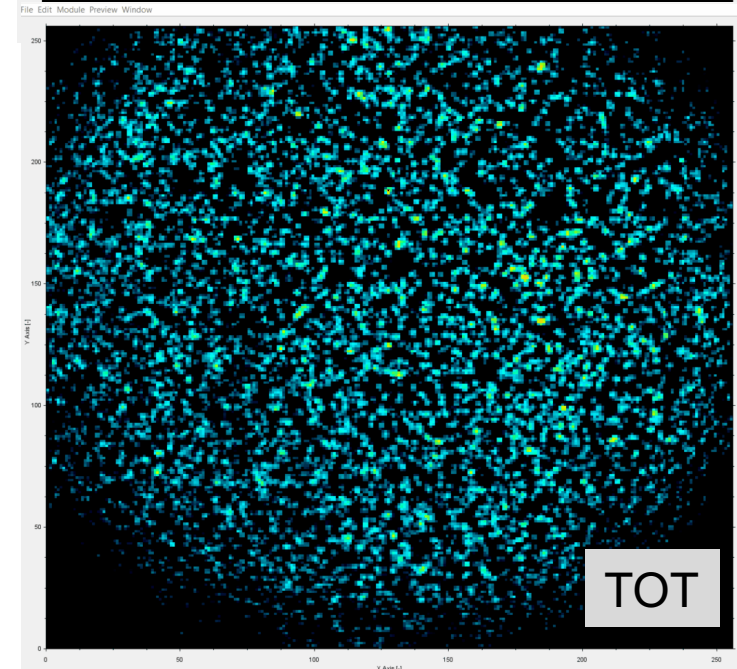Cricket@
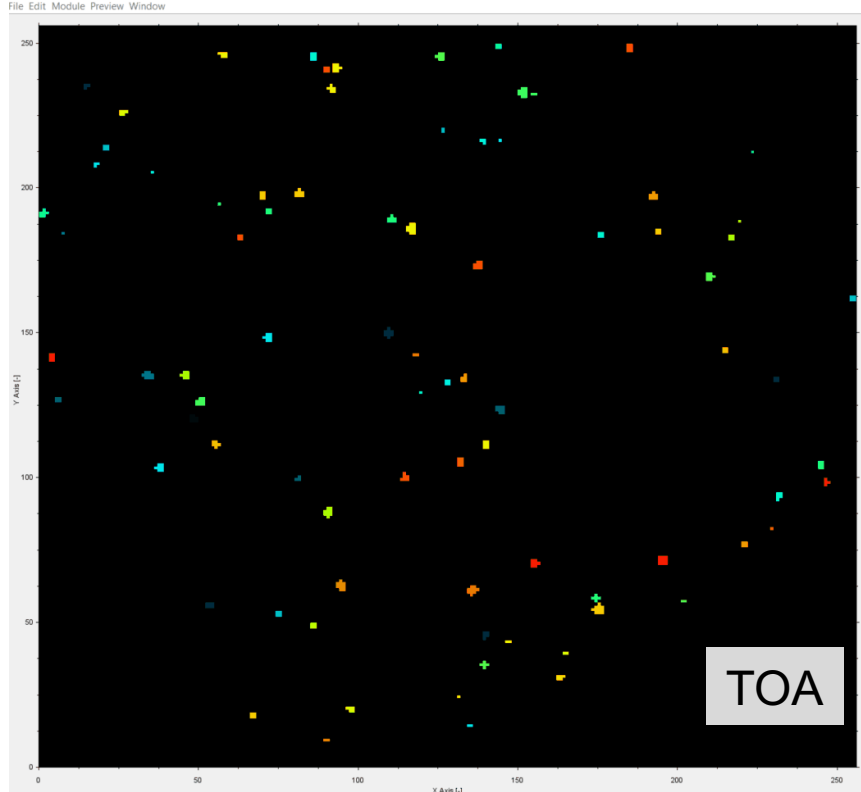
Intensified cameras are common:
iCCD
iCMOS cameras

Choice of photocathodes

Photonis photocathodes
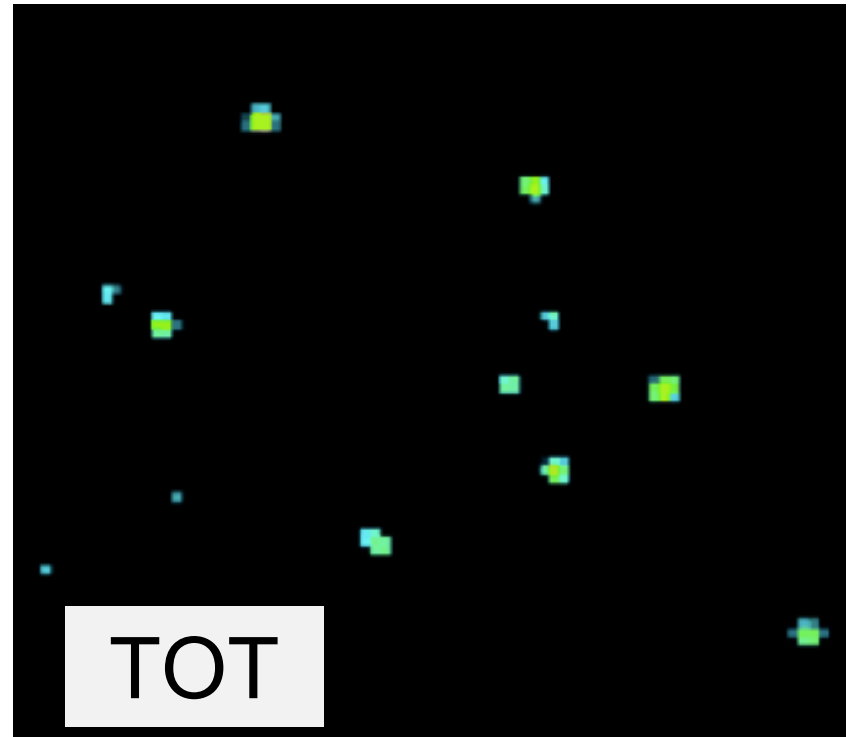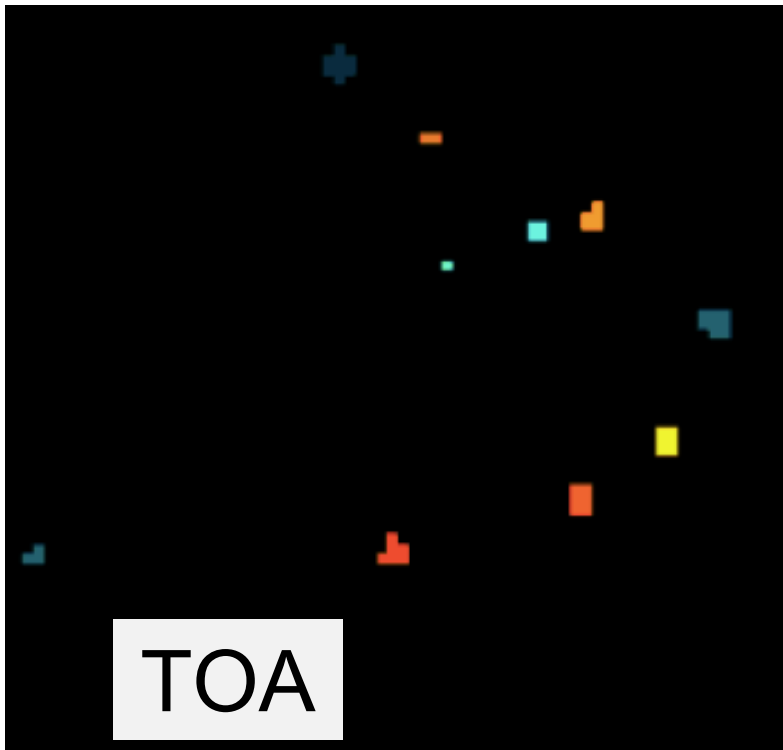
Single Photons in Tpx3Cam

1 ms slice of data
1.5 ns time-stamping

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

TOA

TOT

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 imaging

- High Energy Physics applications
- Neutron imaging

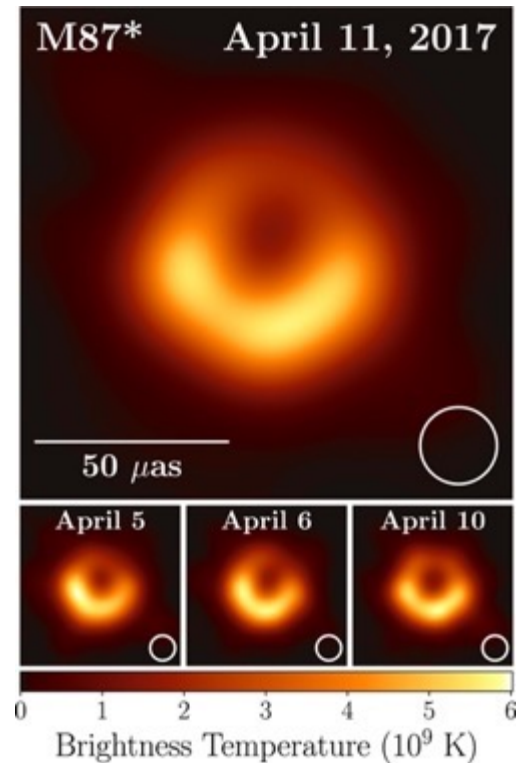- Lifetime imaging
- Ion imaging

Quantum Applications

Quantum Astrometry

Idea: employ quantum entanglement to improve precision of optical interferometers

Astronomy picture of the decade

M87*   April 11, 2017

50 μas

April 5   April 6   April 10

0 1 2 3 4 5 6
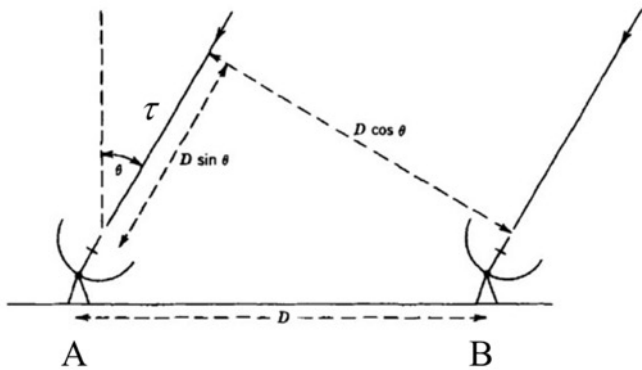Brightness Temperature (10^9 K)

sensitive to features
on angular scale

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

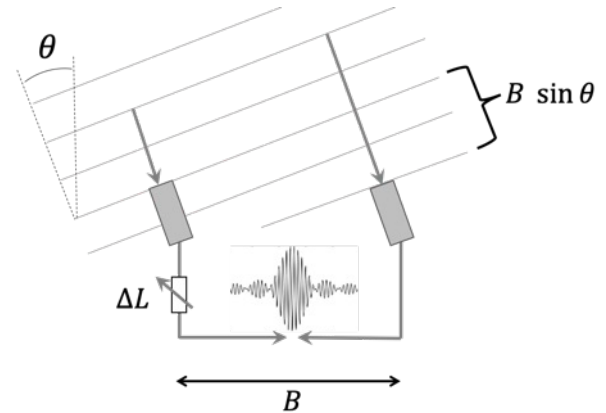2019 ApJL 875

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

Quantum (two-photon) interferometer

Daniel Gottesman[*]
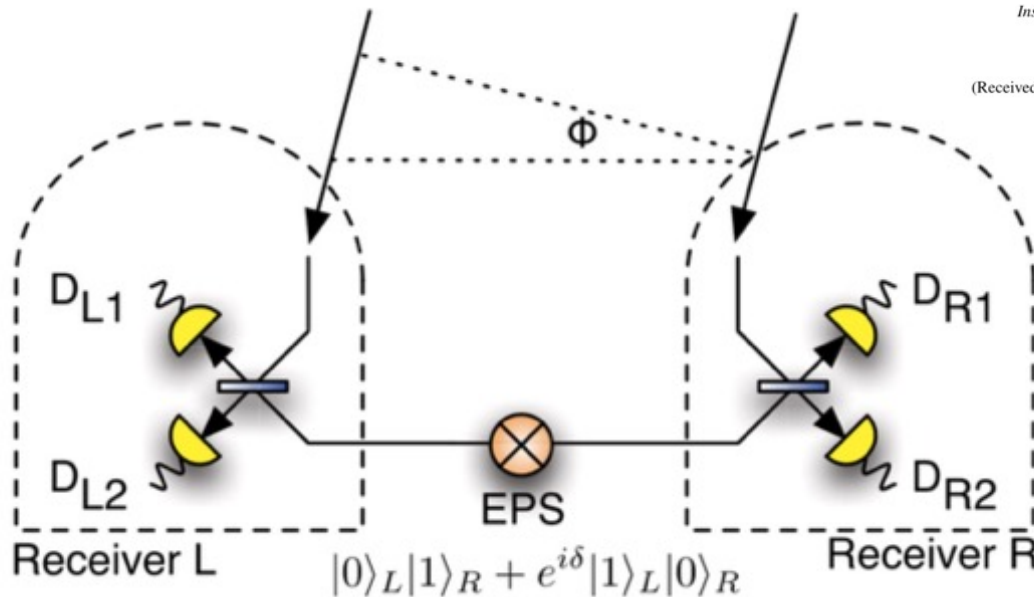Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada

Thomas Jennewein[†]
Institute for Quantum Computing, University of Waterloo, Waterloo, Ontario, Canada

Sarah Croke[‡]
Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada

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

D_{L1} D_{R1}
D_{L2} D_{R2}
Receiver L   Receiver R
EPS

$$|0\rangle_L|1\rangle_R + e^{i\delta}|1\rangle_L|0\rangle_R$$

- 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

Source 1   Source 2

Path phase difference δ_1

Path phase difference δ_2

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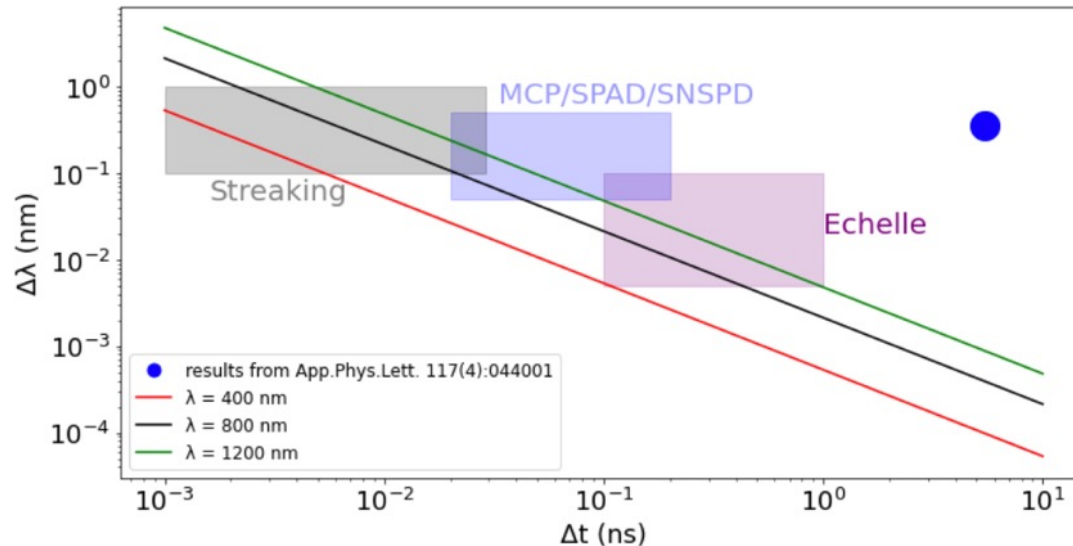P(ch) = P(dg) &= (1/8)(1 - \cos(\delta_1 - \delta_2))
\end{aligned}
$$

L   a   b   Beam Splitter   Beam Splitter   e   f   **R**

c   d   g   h

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**

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

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

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
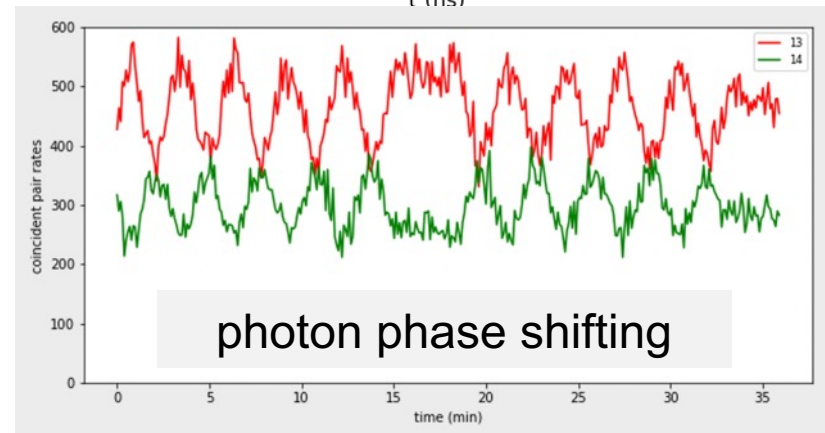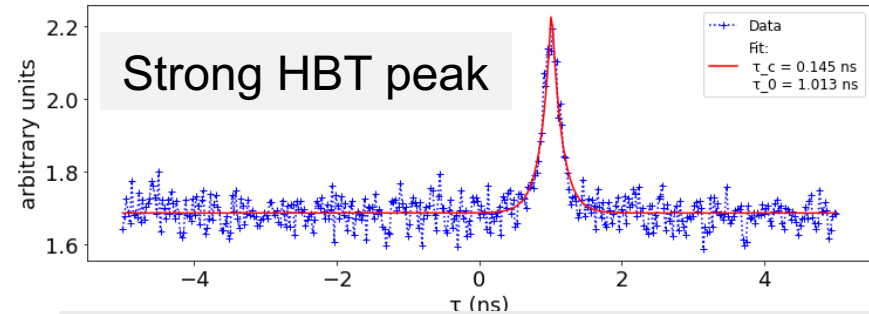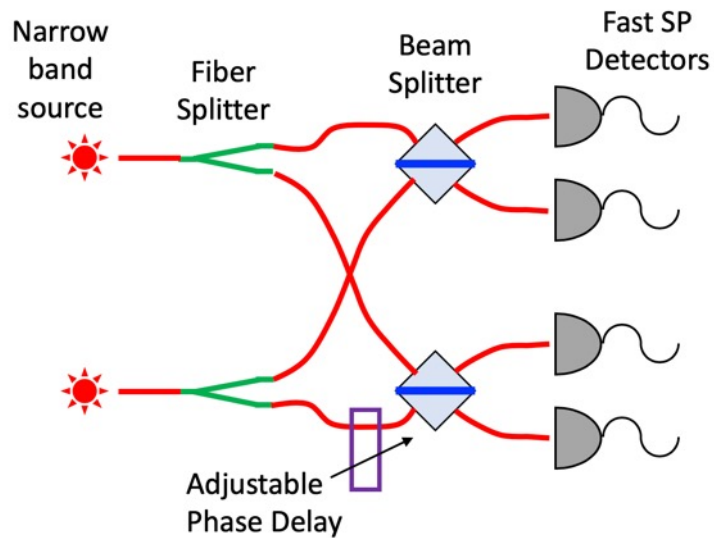- Allows to start exploring this approach experimentally

Requirements for detectors

- Photons must be indistinguishable = close enough in frequency and time to interfere
  → temporal & spectral binning: need ~ **20 ps * 0.1 nm** for 800 nm

- Fast imaging techniques are the key: target 1-100 ps resolution
- Spectral binning: diffraction gratings, Echelle spectrometers

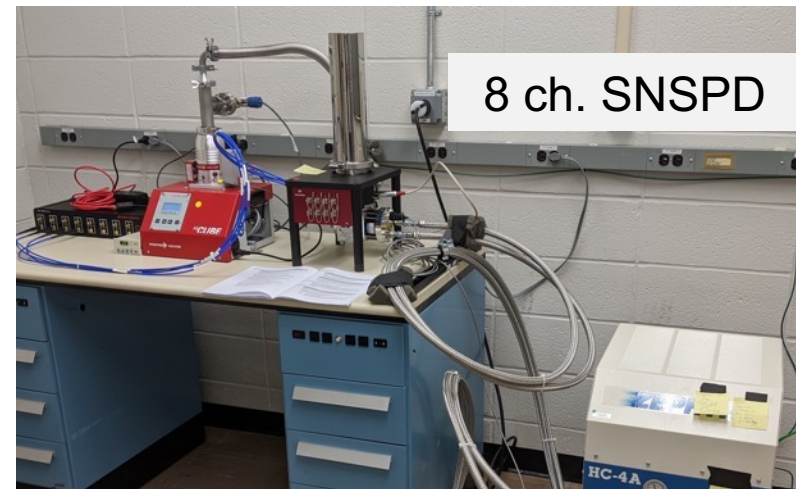- Photon detection efficiency: high
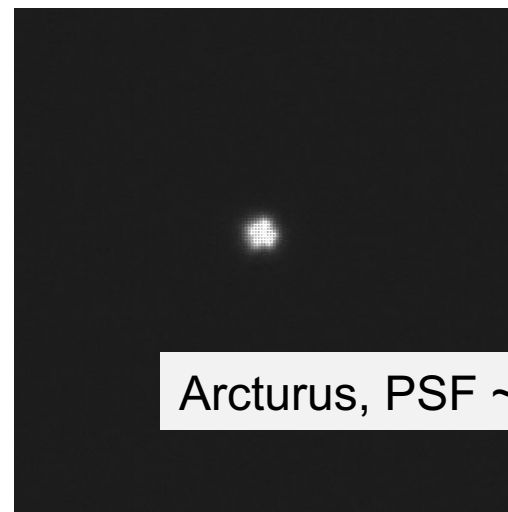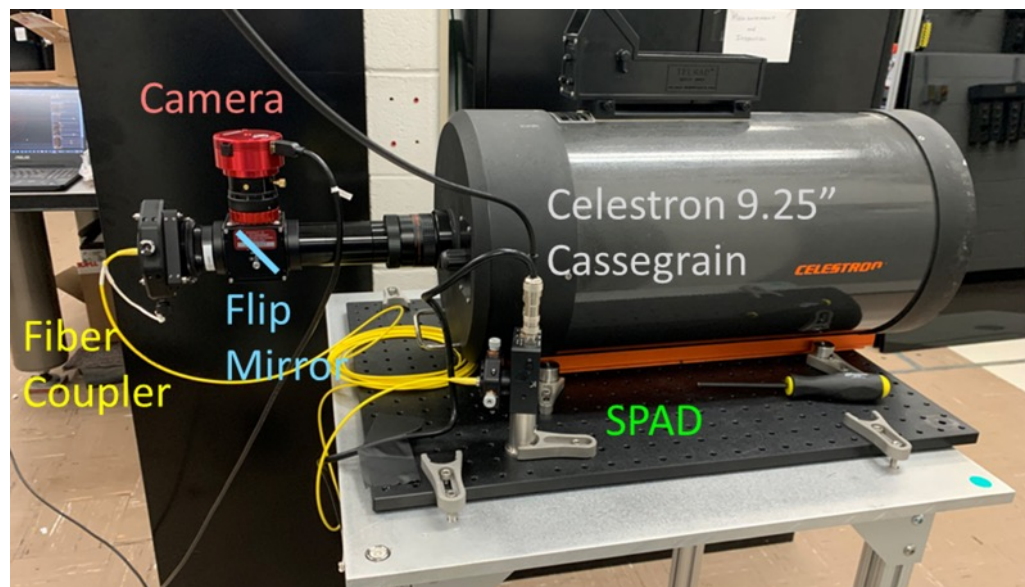
Experiments in progress

Narrow band source — Fiber Splitter — Beam Splitter — Fast SP Detectors — Adjustable Phase Delay

Strong HBT peak

$\tau_c = 0.145$ ns
$\tau_0 = 1.013$ ns

photon phase shifting

8 ch. SNSPD

Bench-top model of two-photon interferometry

Ar vapor lamps with ultra-narrow band filters
Superconducting nanowire single-photon detectors
See correlations of counters as expected

A.Nomerotski et al, arxiv.org/abs/2107.09229

On-sky experiments in progress

Camera

Fiber Coupler

Flip Mirror

Celestron 9.25" Cassegrain

SPAD

Arcturus, PSF ~ 1 arcsec

Chen, Stankus, Nomerotski, Slosar, Vintskevich, Astrometry in two-photon interferometry using Earth rotation fringe scan, arxiv.org/abs/2205.09091

Spectroscopic binning

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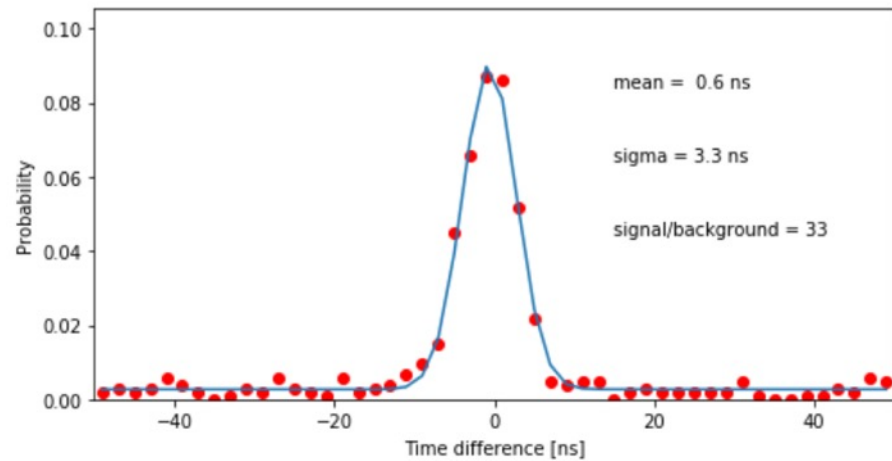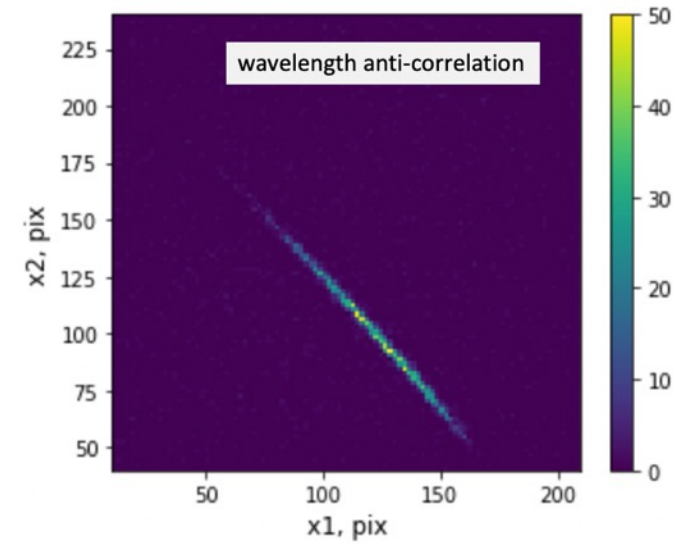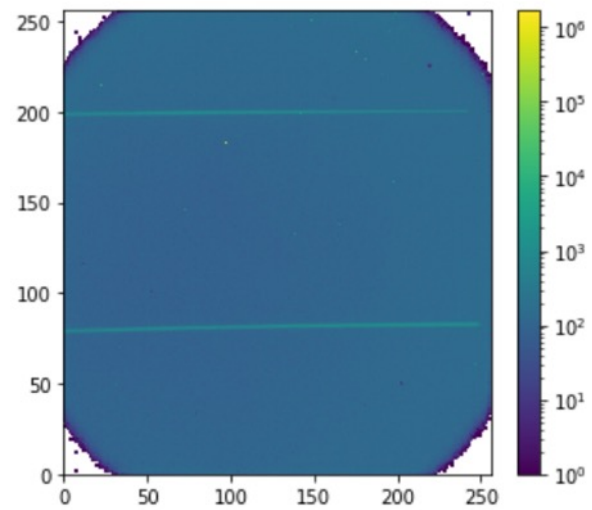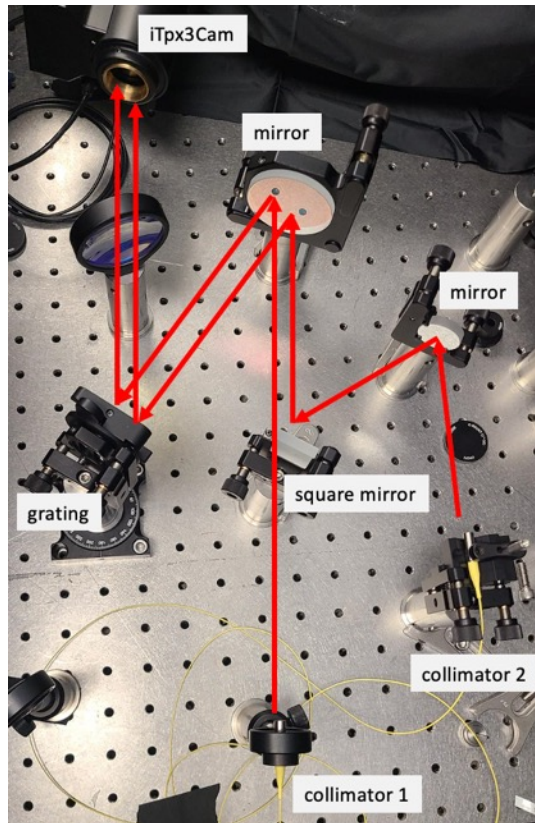

$\delta\lambda * \delta t \sim 5$ ns * 0.5 nm

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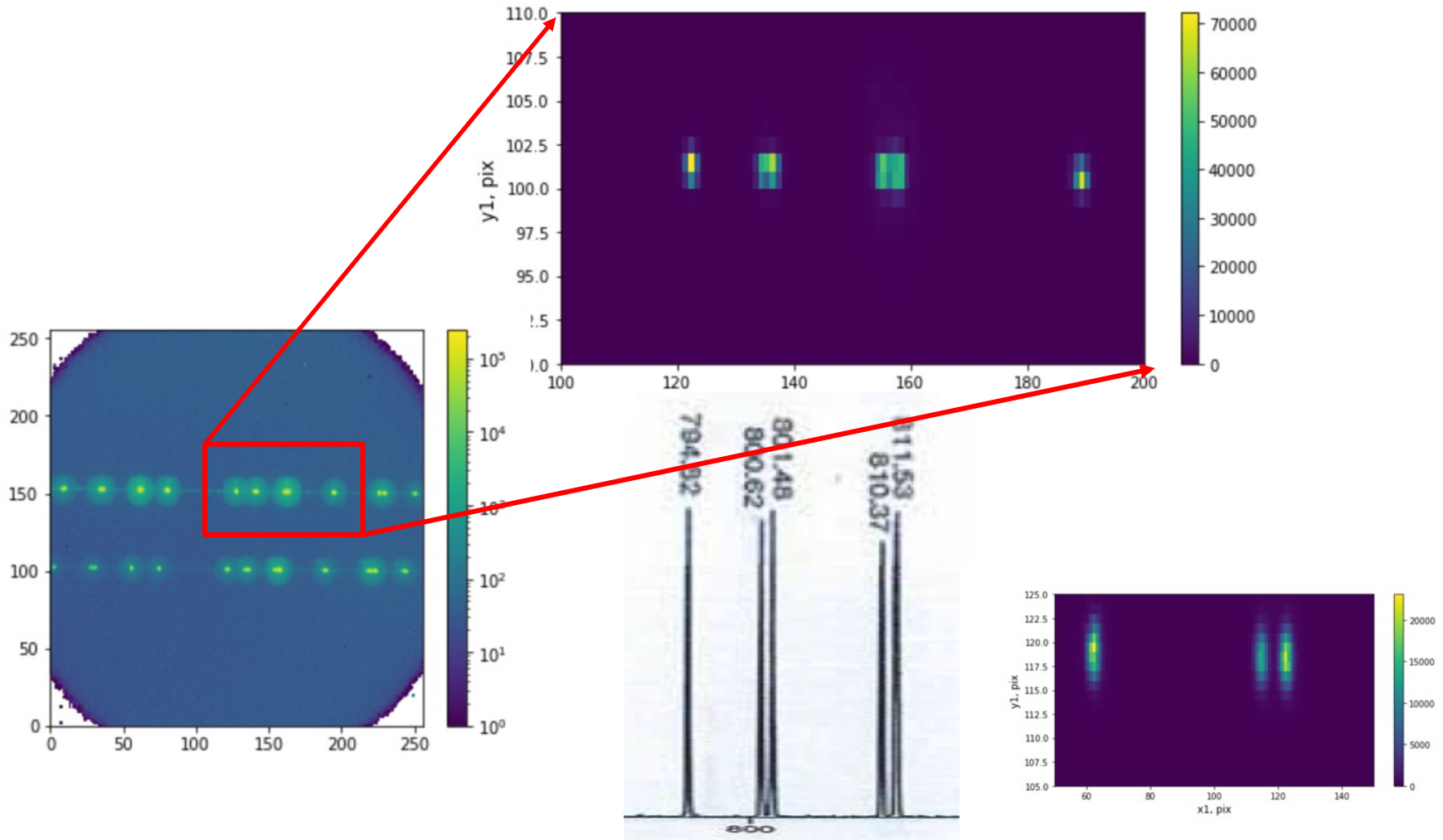
P Svihra et al, Multivariate Discrimination in Quantum Target Detection, Appl. Phys. Lett. **117**, 044001 (2020)

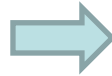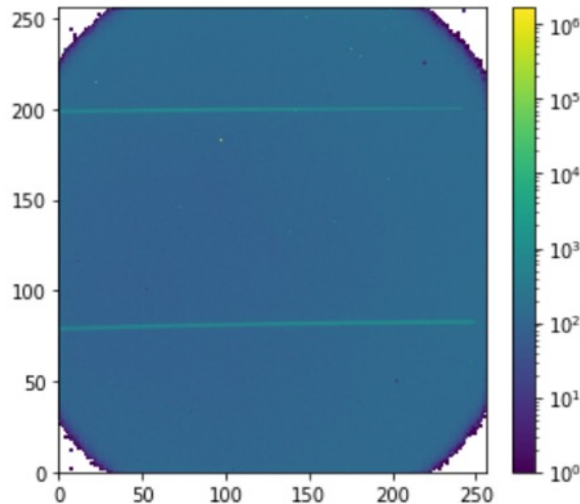# Current setup at BNL: SPDC source as spectrometer characterization tool
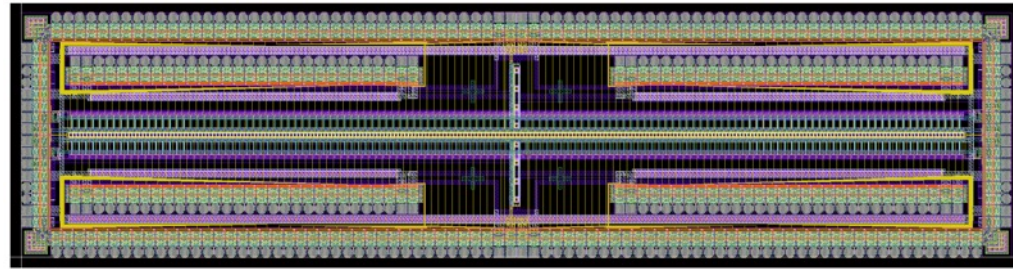
Argon lamp spectrum

better magnification:
0.1 nm resolution

Next steps: spectrometer based on LinoSPAD2

Diffracted photon stripes projected on to single linear array

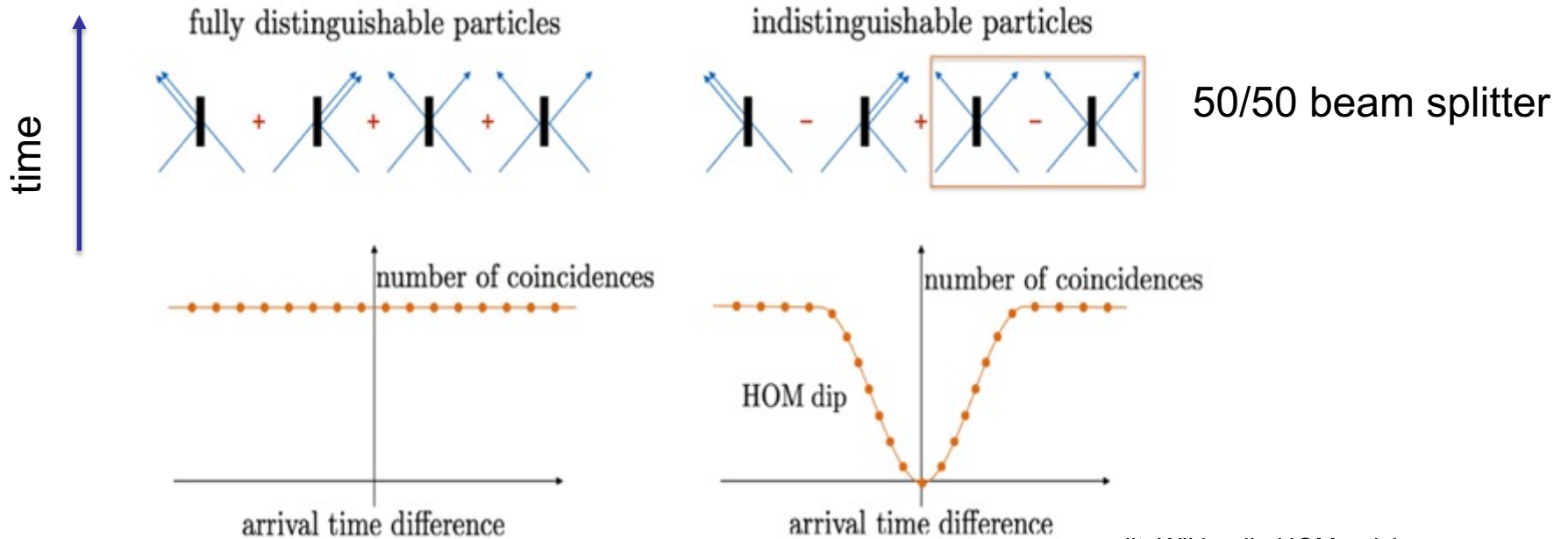Collaboration with E.Charbon EPFL LinoSPAD2

Spectrometer time resolution: ns → 100 ps

Take home message: two-photon interference requires fast imaging ~10-100 ps

More Quantum Imaging

Hong-Ou-Mandel effect

fully distinguishable particles

indistinguishable particles

50/50 beam splitter

time

number of coincidences

arrival time difference
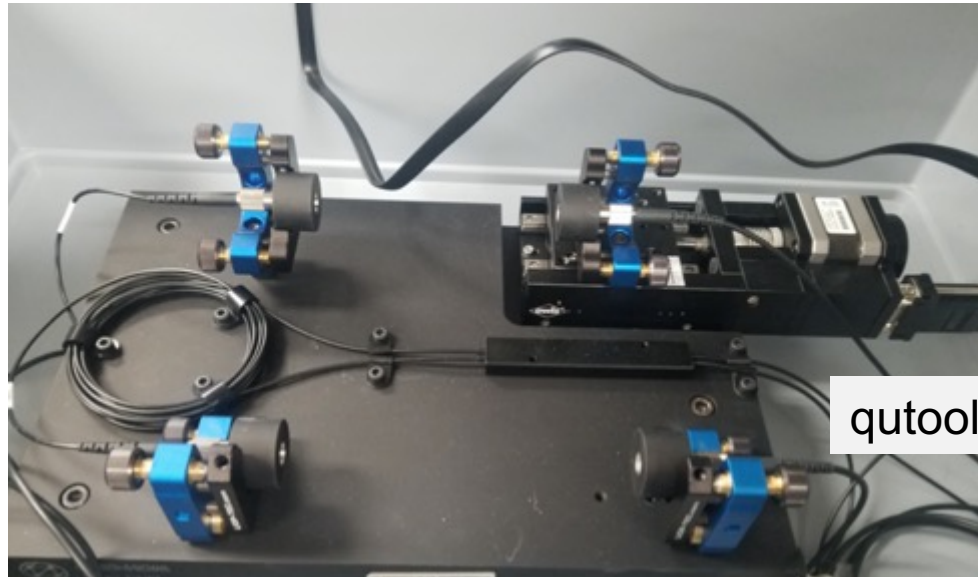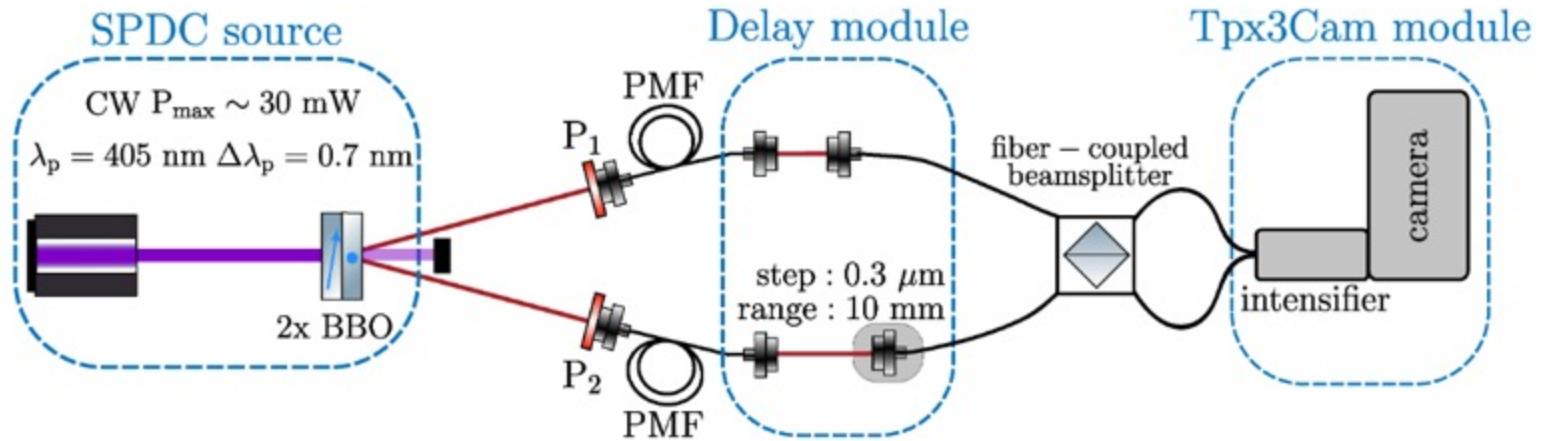
number of coincidences

HOM dip

arrival time difference

credit: Wikipedia HOM article

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

HOM Setup

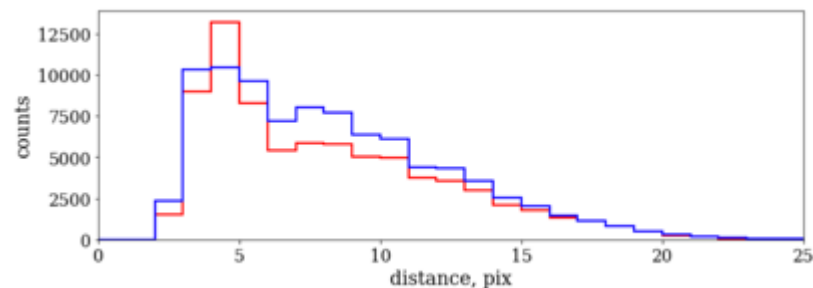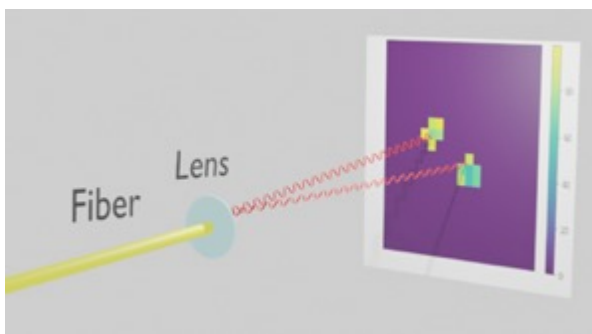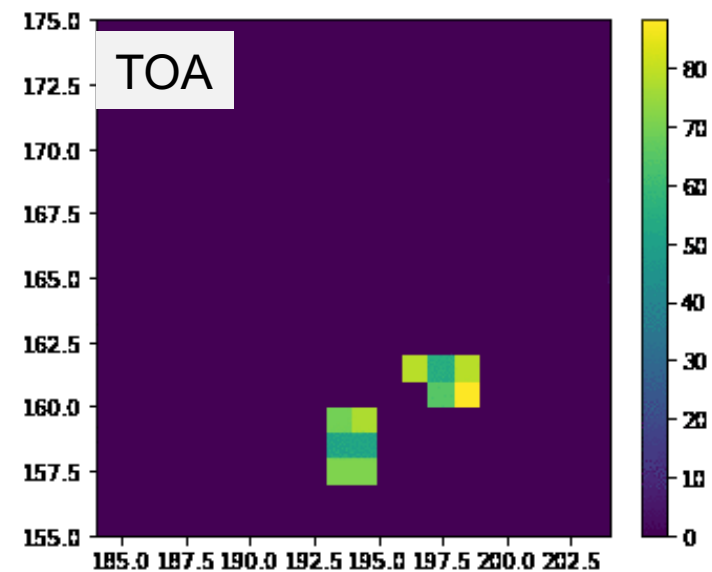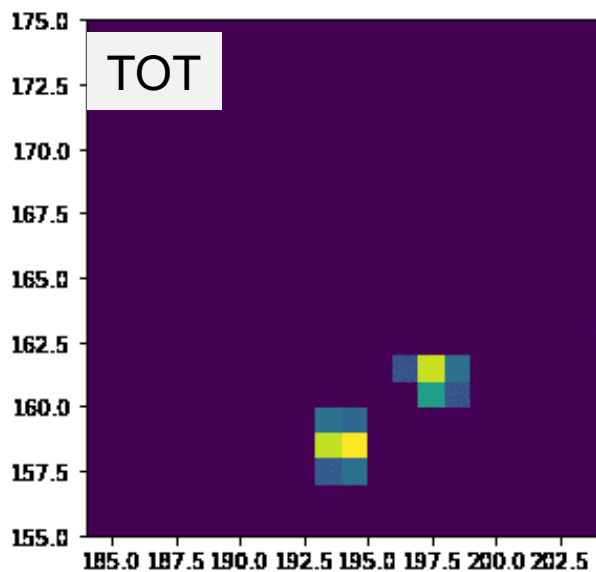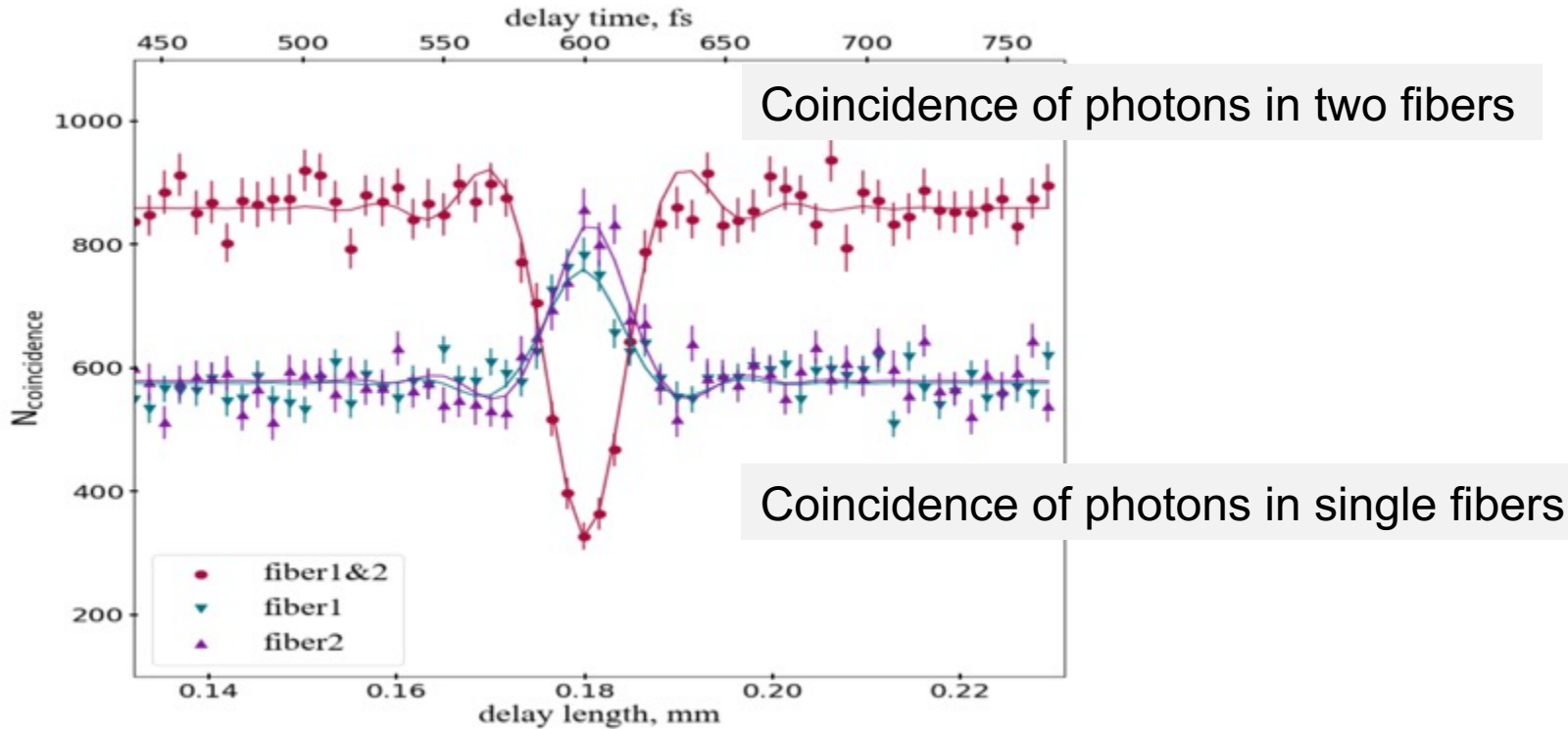# Examples of bunched HOM photons

Distance between two photons, pix

Hong-Ou-Mandel effect
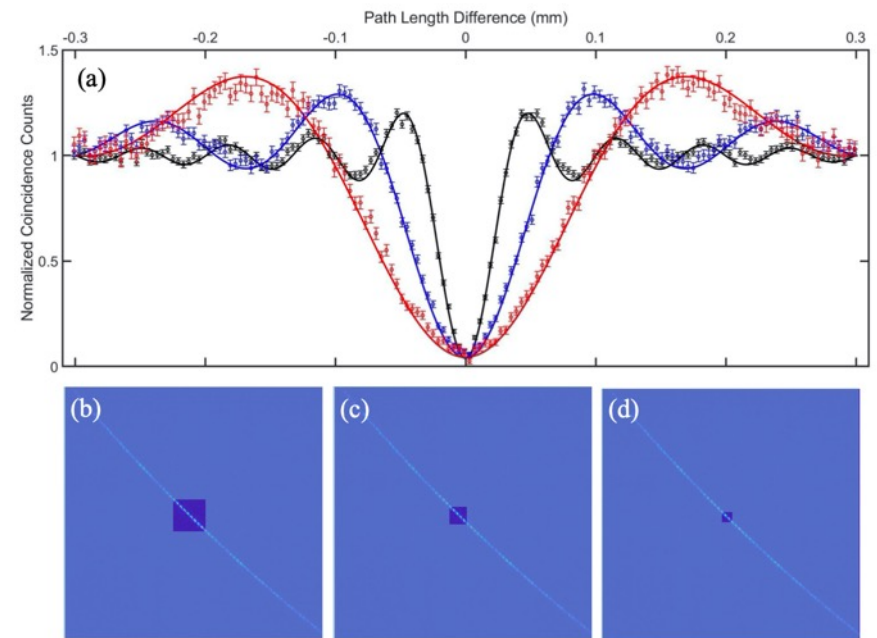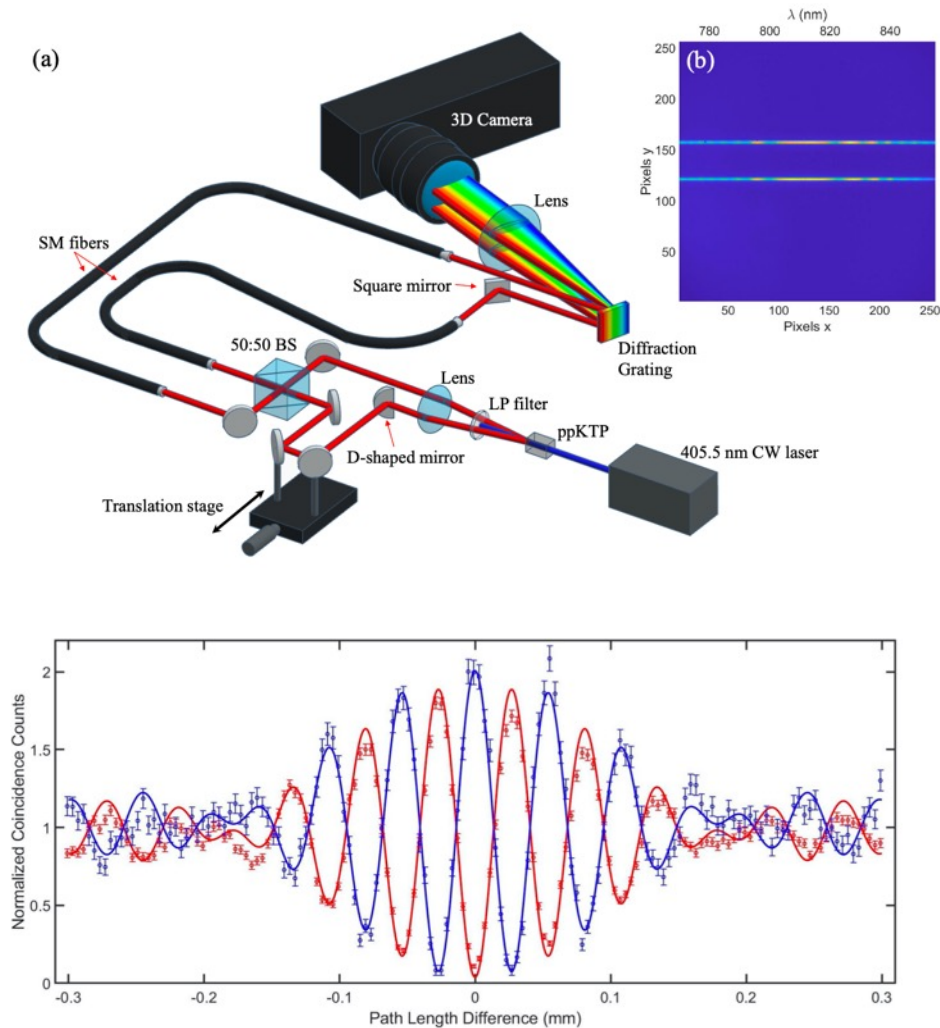
$$f(d - d_0) = \frac{3}{4\sqrt{\pi}} \int dy \, [\text{sinc}(y^2)]^2 \, e^{-iy \frac{\sqrt{4\log 2}(d - d0)}{\text{FWHM}}}$$

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.
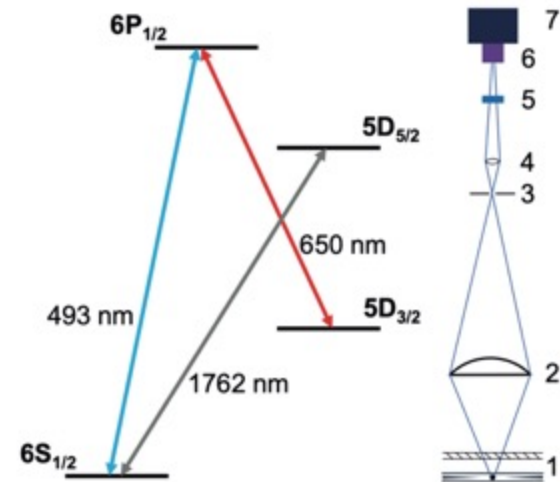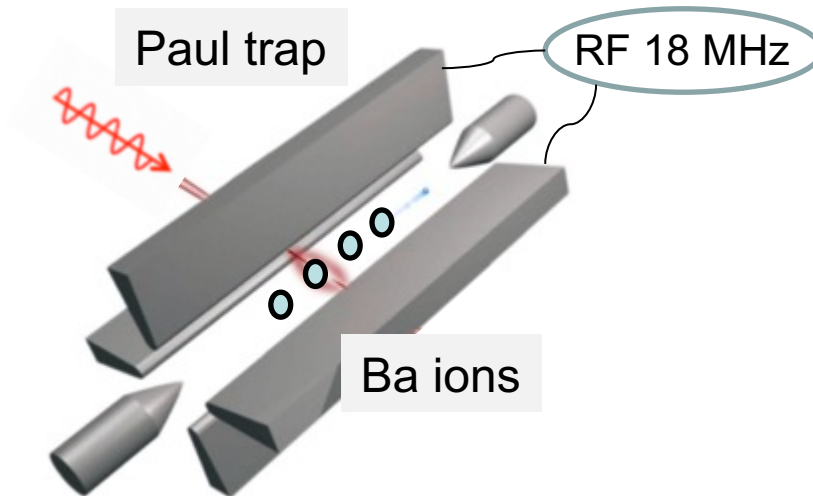
10, 5, 3 nm post-selection filters

More quantum imaging

other recent publications on quantum optics which used Tpx3Cam

- **High-speed imaging of spatiotemporal correlations in Hong-Ou-Mandel interface**
  Xiaoqin Gao et al. Optics Express, 30(11) 19456 (2022)

- **Observation of Nonclassical Photon Statistics in Single-Bubble Sonoluminescence**
  M. Rezaee et al. *Arvix* (2022)

- **Ray-tracing with quantum correlated photons to image a 3D scene**
  Y. Zhang et al. *Phys. Rev. A* (2022)

- **Tera-mode of Spatiotemporal N00N States**
  X. Gao et al. Optics Express, 30(11) 19456 (2022)
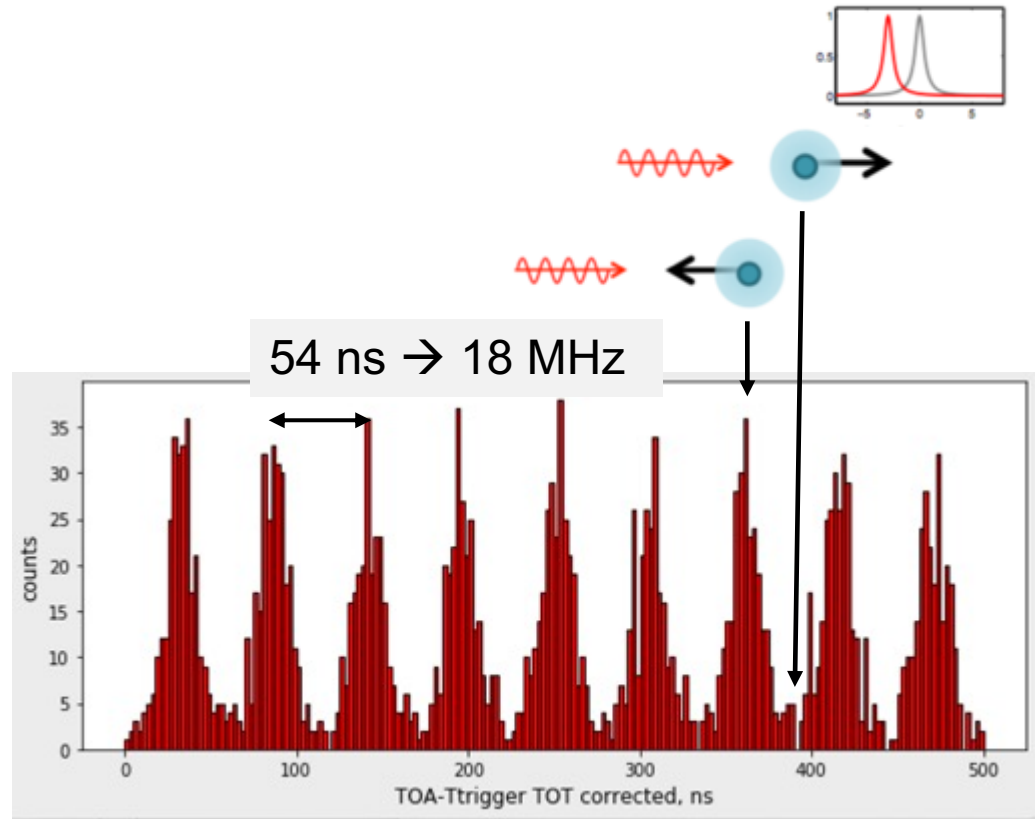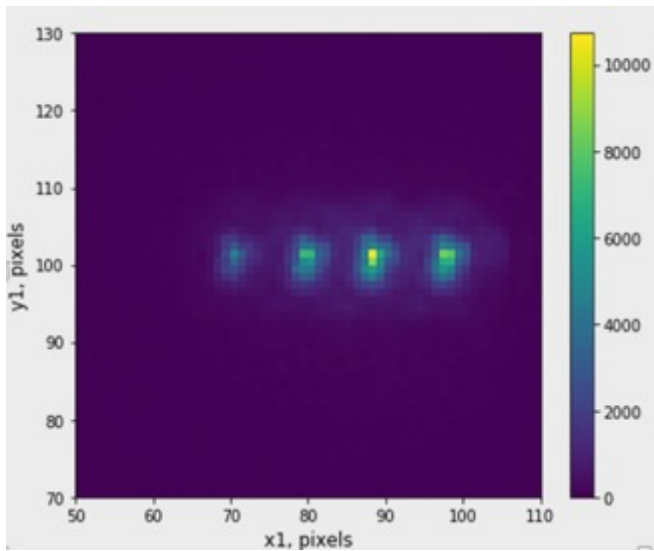
Imaging of trapped ions

Time resolved qubit manipulation (Blinov group, UWash)

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

Time resolved ion oscillations
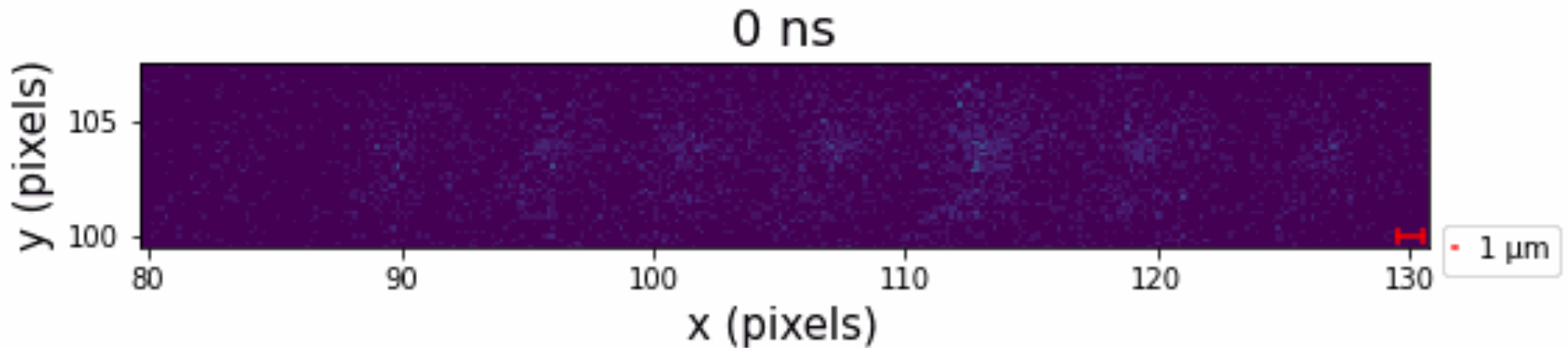

54 ns → 18 MHz

- 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

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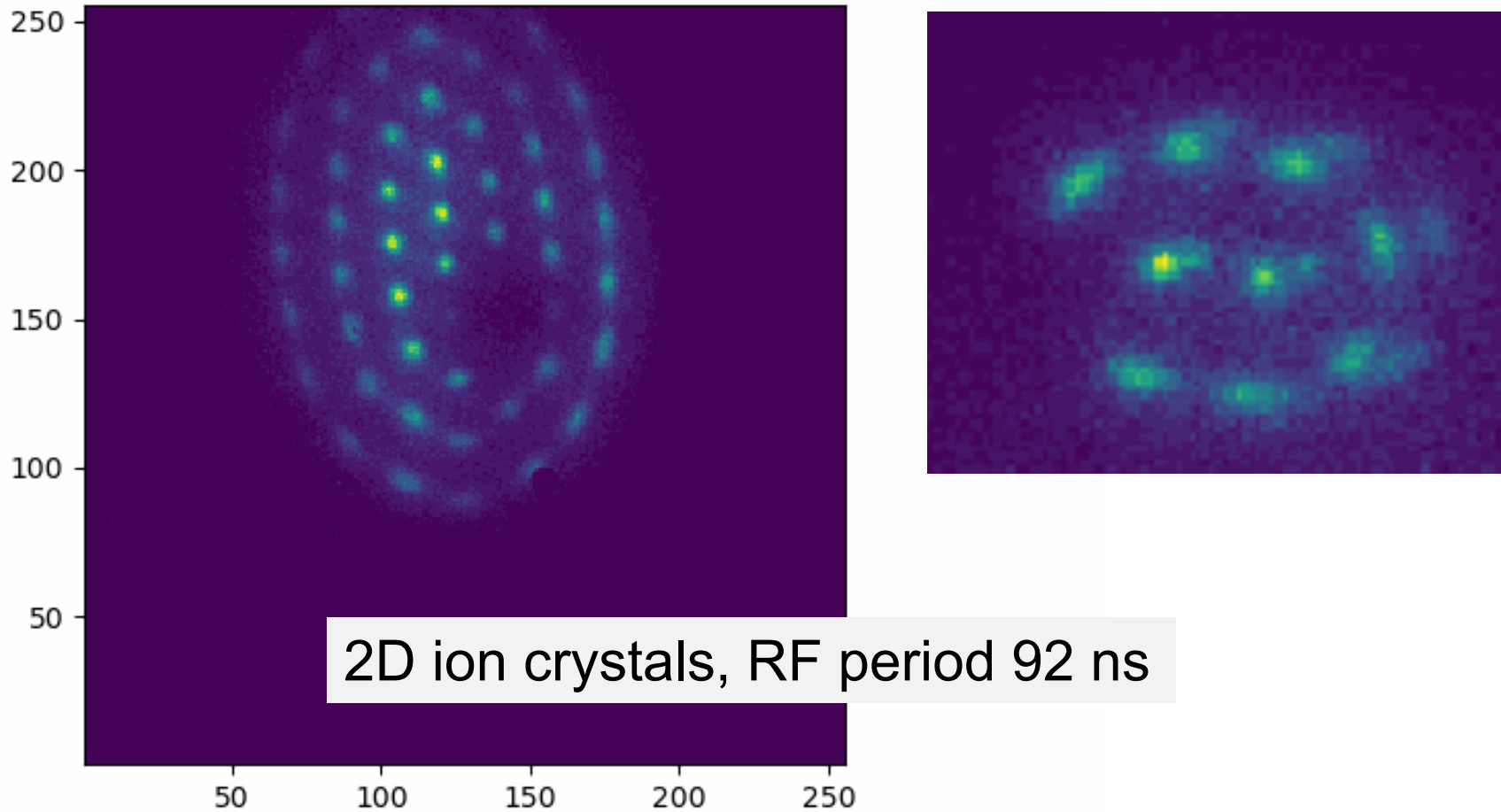
Ion micromotion

- 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

L.Zhukas, M.Millican, P.Svihra, A.Nomerotski, B.Blinov, Direct observation of ion micromotion in a linear Paul trap, https://arxiv.org/abs/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
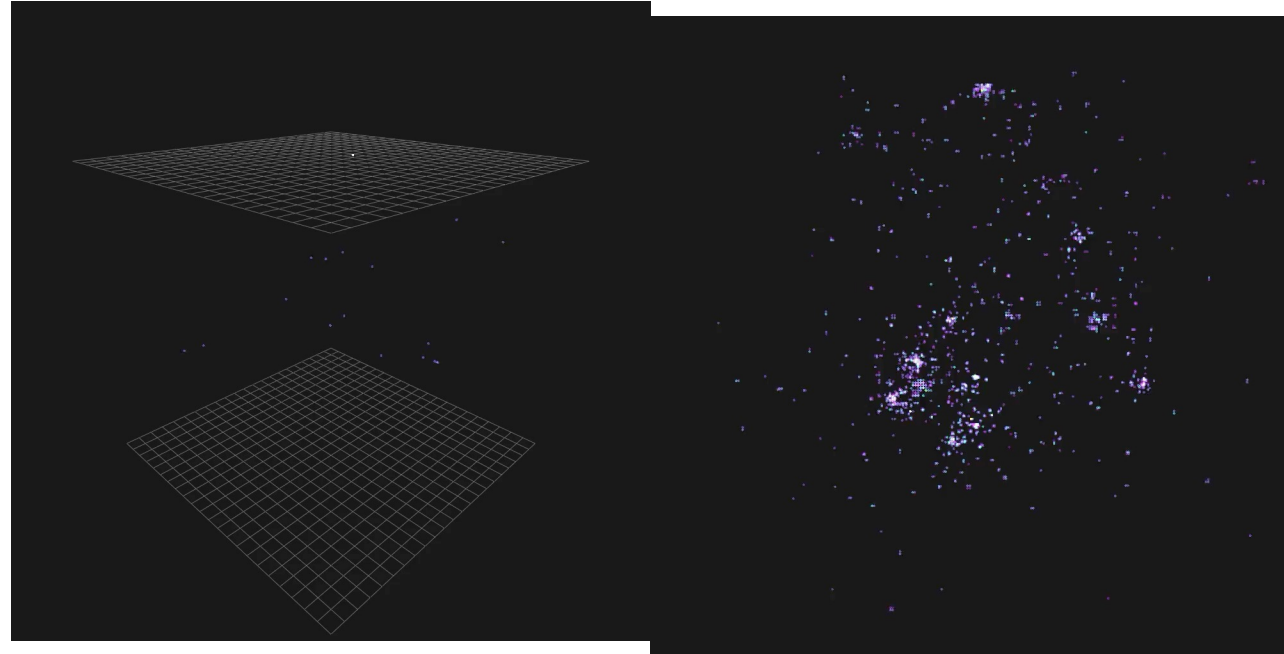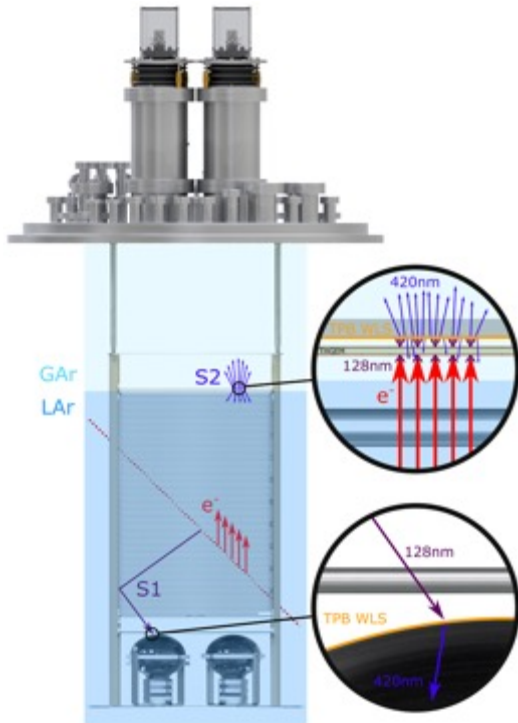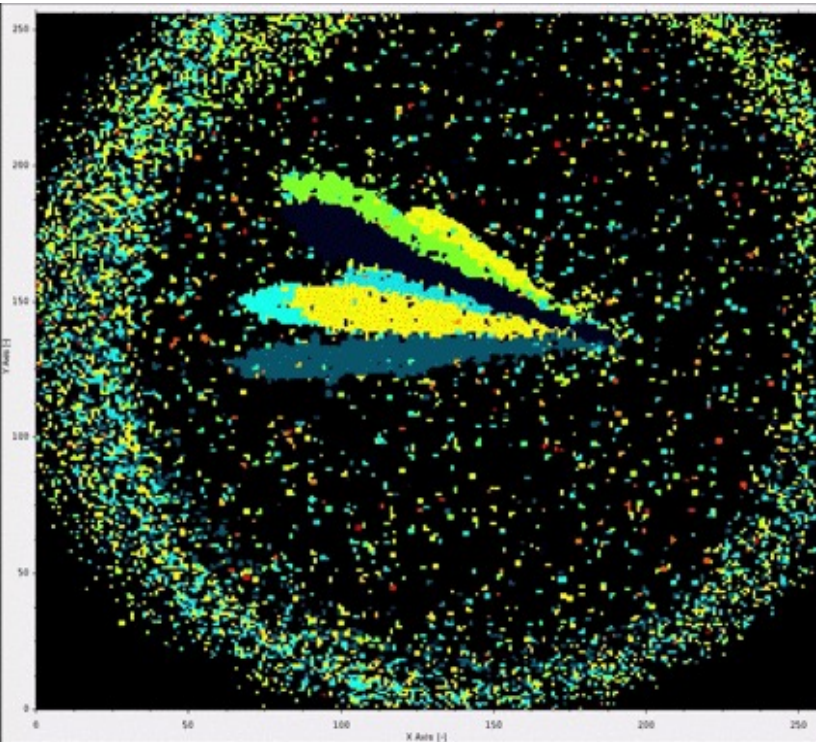
LAr Cosmic Muons (10msec slice)

Image light from
avalanches in gas phase
in THGEM

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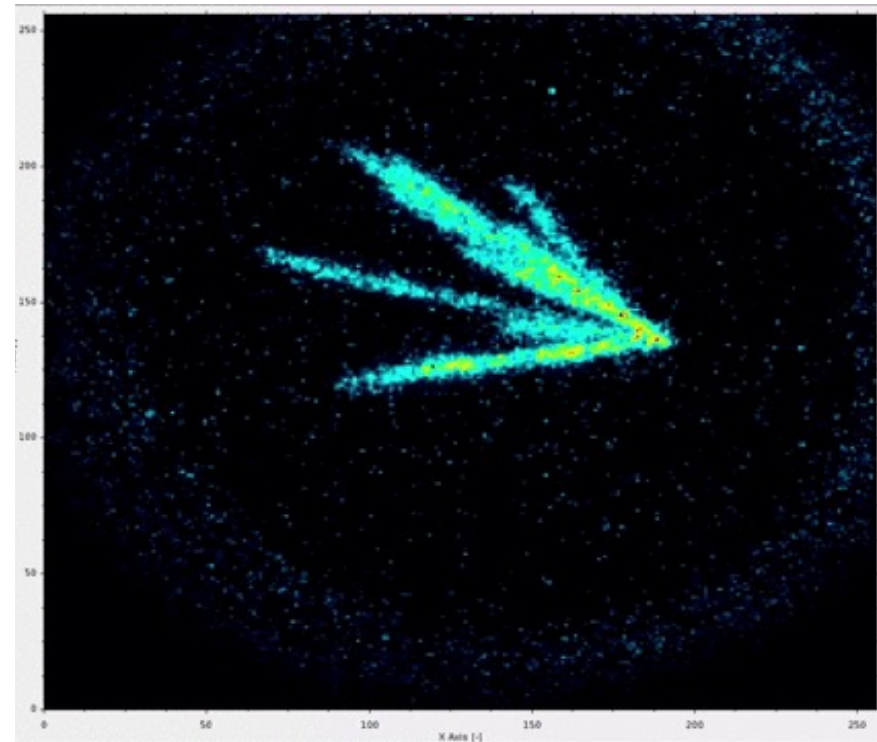Kostas Mavrokoridis et al

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
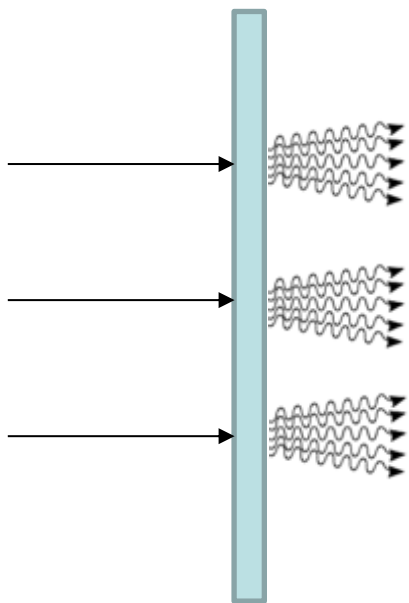

Color = TOA

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

- Flashes in scintillator are imaged by intensified Tpx3Cam
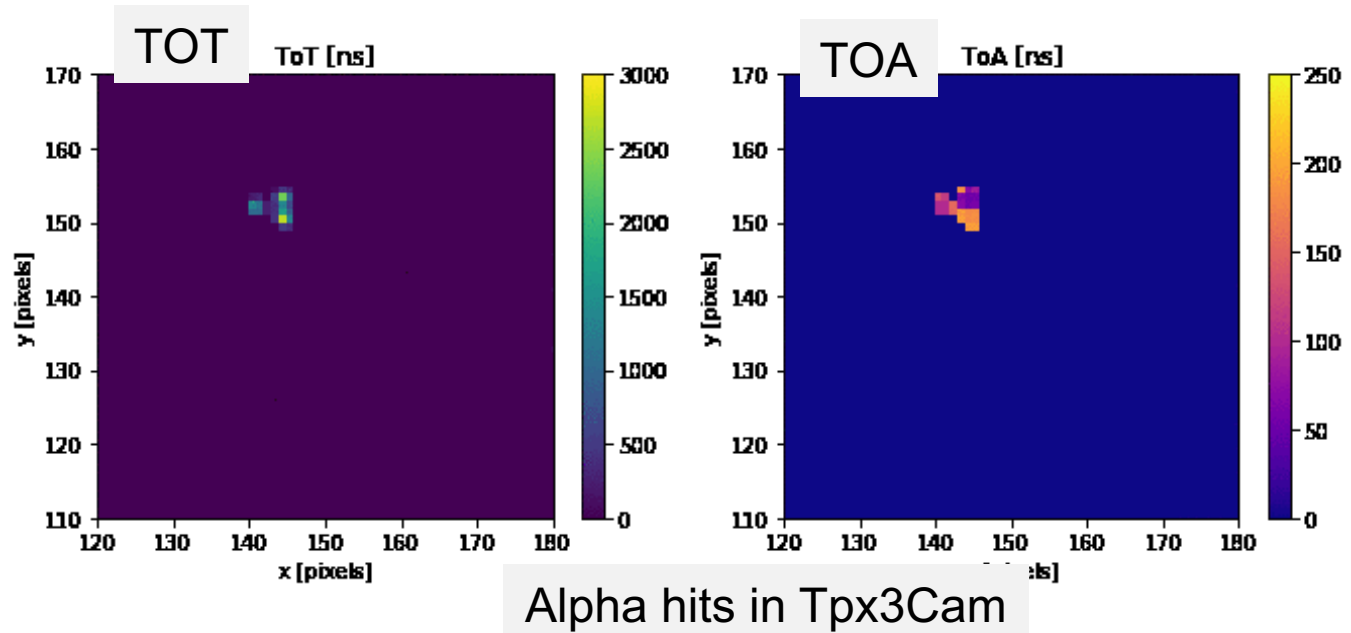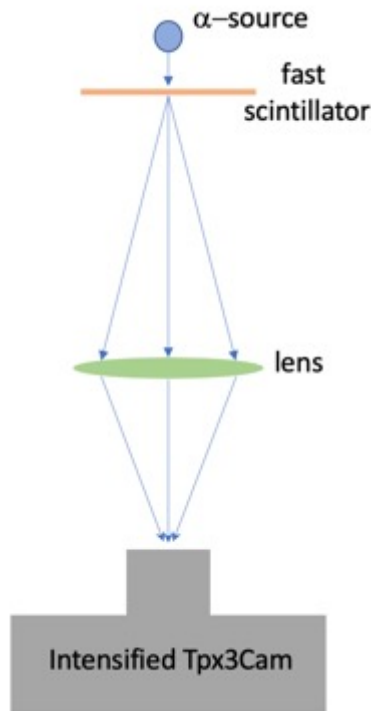- Alphas, hard x–rays, neutrons, …

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

Novel imaging technique for thermal neutrons using a fast optical camera

Tianqi Gao[a,*], Gabriele D'Amen[b], Sergey Burdin[c], Mohammad Alsulimane[c], Paul Campbell[a], Cinzia Da Via[a,d], Andrei Nomerotski[b], Adam Roberts[c], Peter Svihra[a], Jon Taylor[c], Alessandro Tricoli[d]

[a]School of Physics and Astronomy, The University of Manchester, Manchester M13 9PL, the UK
[b]Brookhaven National Laboratory, Upton NY 11973, USA
[c]Department of Physics, University of Liverpool, Liverpool L1 8JX, the UK
[d]Physics and Astronomy Department, Stony Brook University 100 Nicolls Rd, Stony Brook, NY 11794, United States

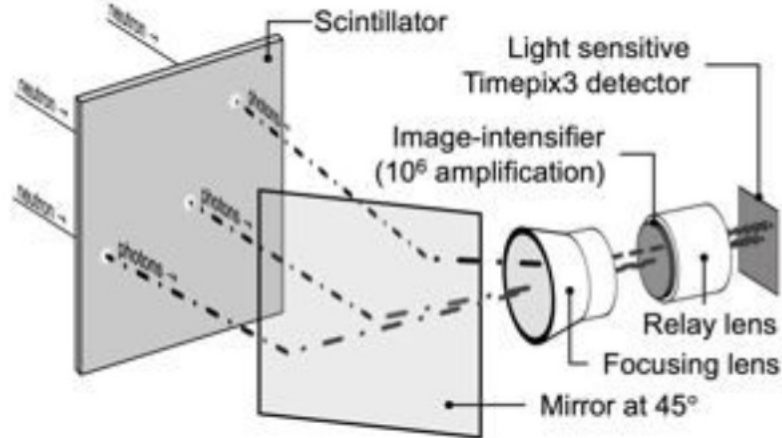Neutron detection paper submitted to NIM

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

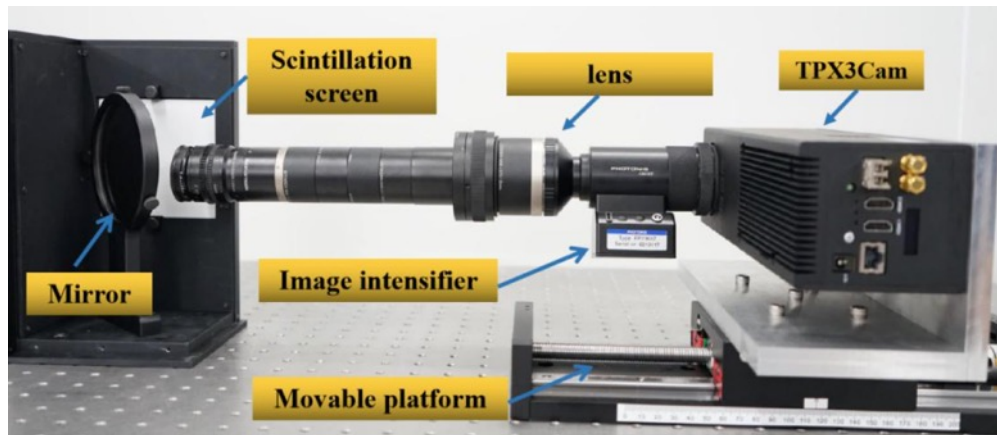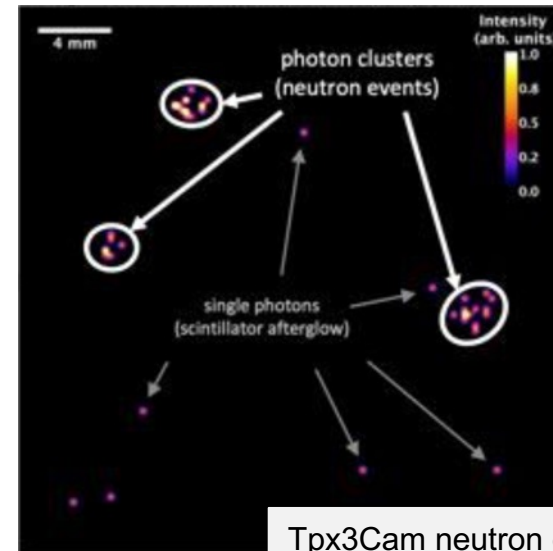# Neutron detection with Tpx3Cam

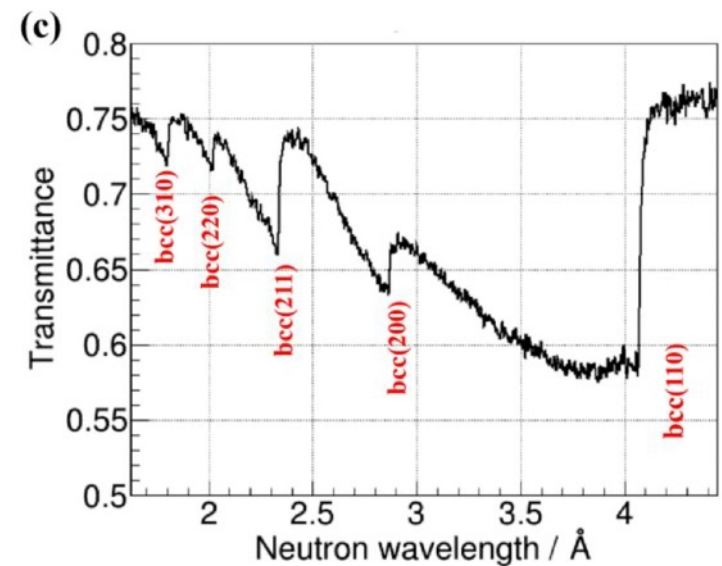- ^{6}Li-based scintillator
- Neutrons produce alphas
- Time resolved

Tpx3Cam neutron event display

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

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

X. Llopart et al., *Timepix4, a large area pixel detector readout chip which can be tiled on 4 sides providing sub-200 ps timestamp binning*, JINST **17** (2022) C01044
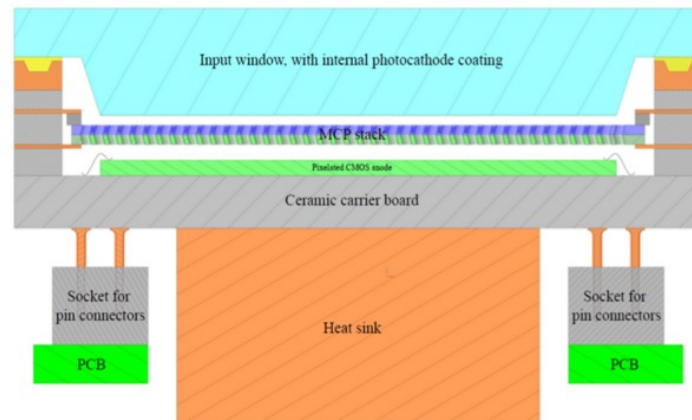
Direct MCP → Timepix detection

Development of a single-photon imaging detector with pixelated anode and integrated digital read-out

J. A. Alozy[a] N. V. Biesuz,[b] M. Campbell[a] V. Cavallini[c,b] A. Cotta Ramusino[b] M. Fiorini[c,b] M. Guarise[c,b] X. Llopart Cudie[a]

[a] CERN, Geneva, Switzerland
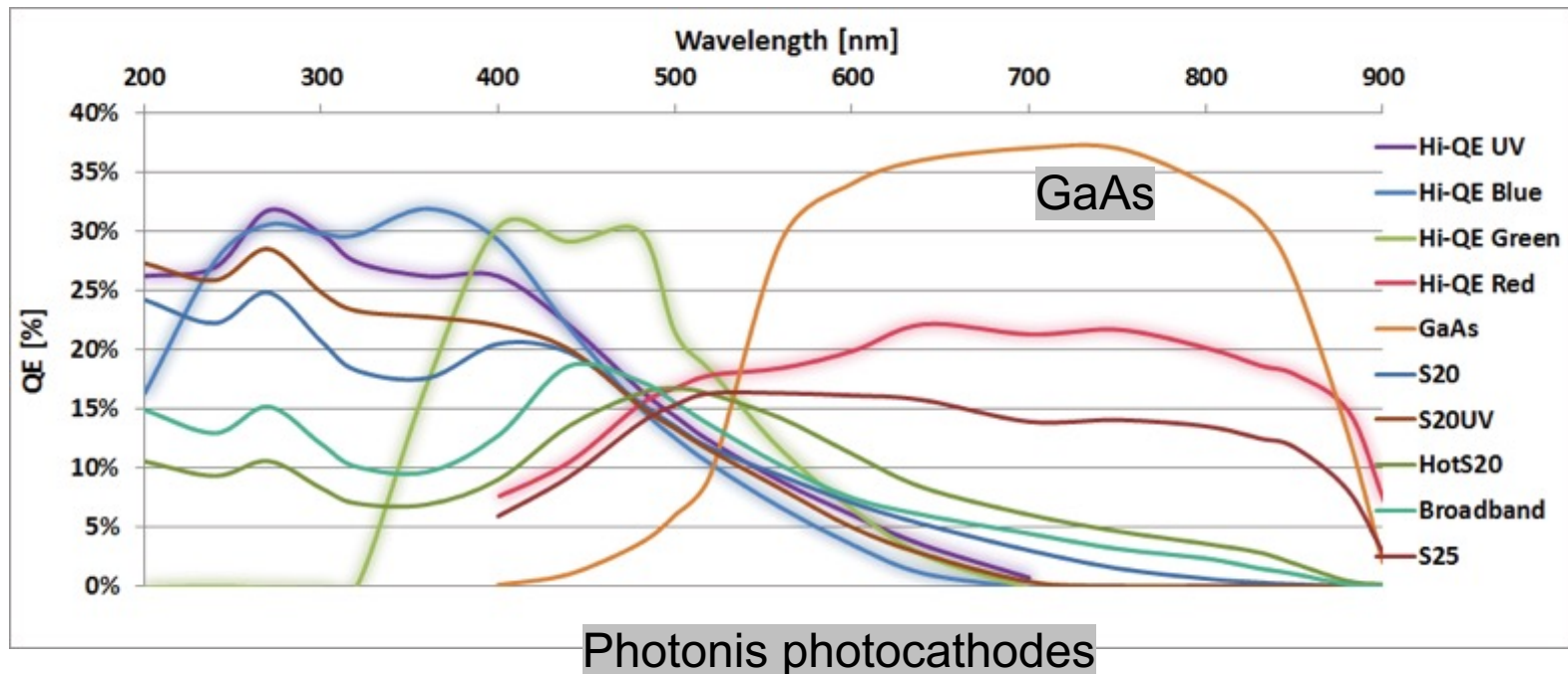[b] Istituto Nazionale di Fisica Nucleare sezione di Ferrara, Ferrara, Italy
[c] Università di Ferrara, Ferrara, Italy

Figure 1. Cutaway schematic view of the detector assembly.

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

- Can we build a hybrid (SPAD + Timepix4.1) camera?

Summary

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

  Works well for sparse data
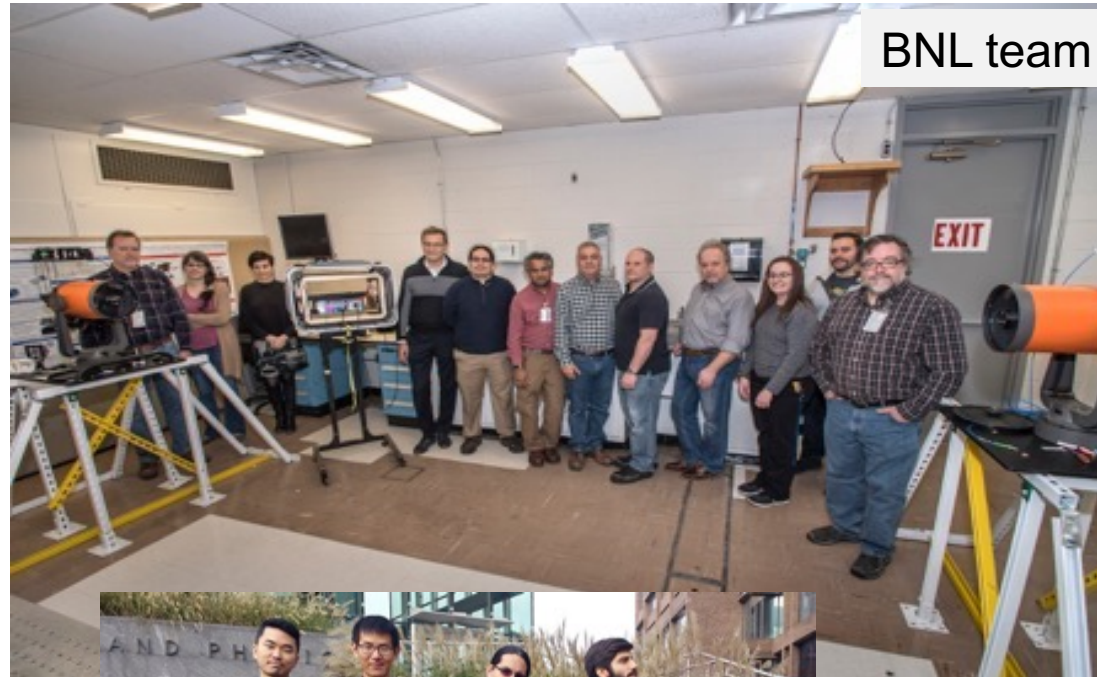
  Needs intelligent pixels with complex functionality

- 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

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Jingming Long
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Erik Maddox
Jord Prangsma
Duncan England
Yingwen Zhang
Boris Blinov
Mila Zhukas
Maverick Millican
Alex Kato

Peter Svihra
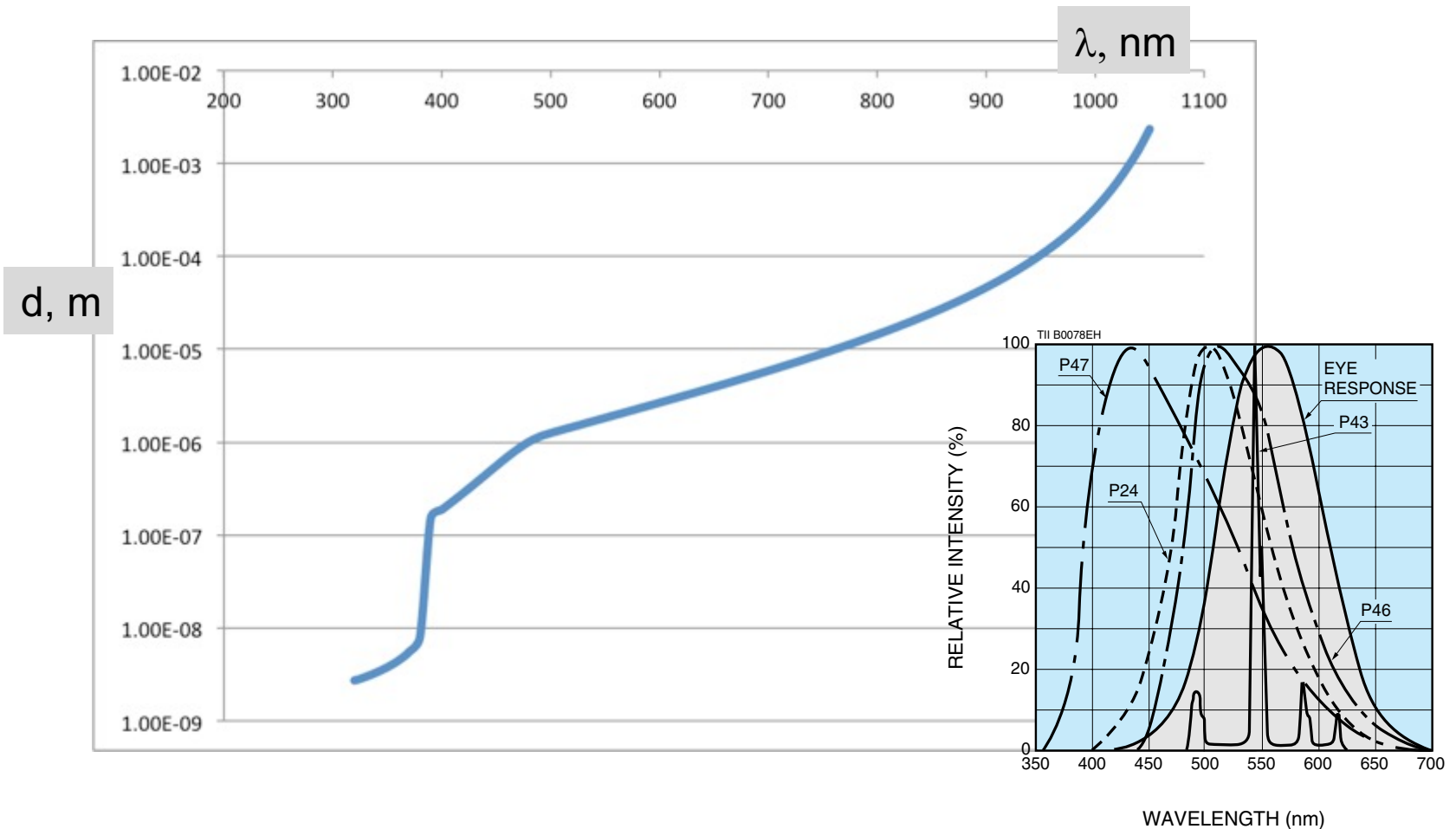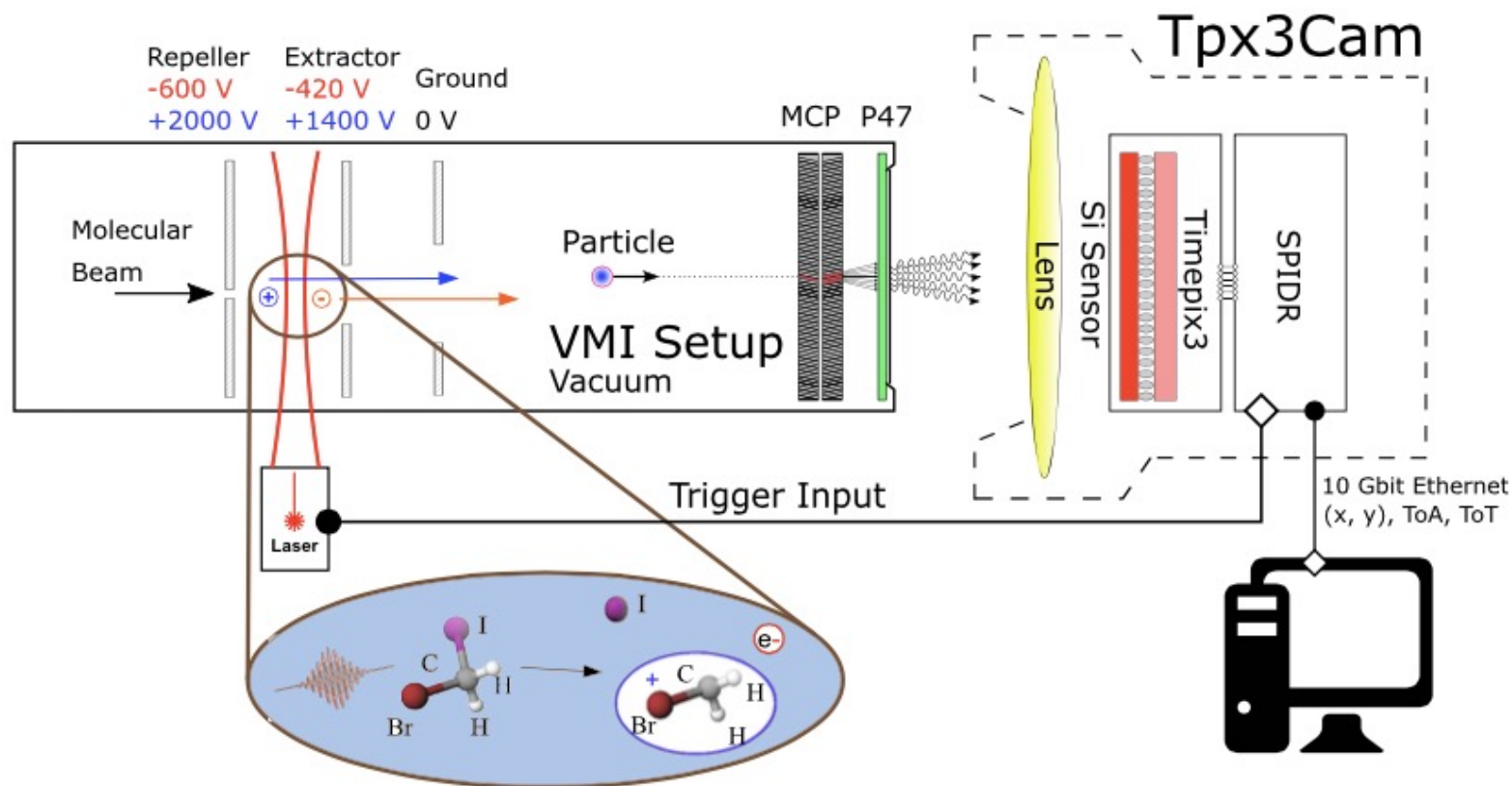Michal Marcisovsky
Sergei Kulkov

BNL team

SBU team

spares

Photon absorption in silicon

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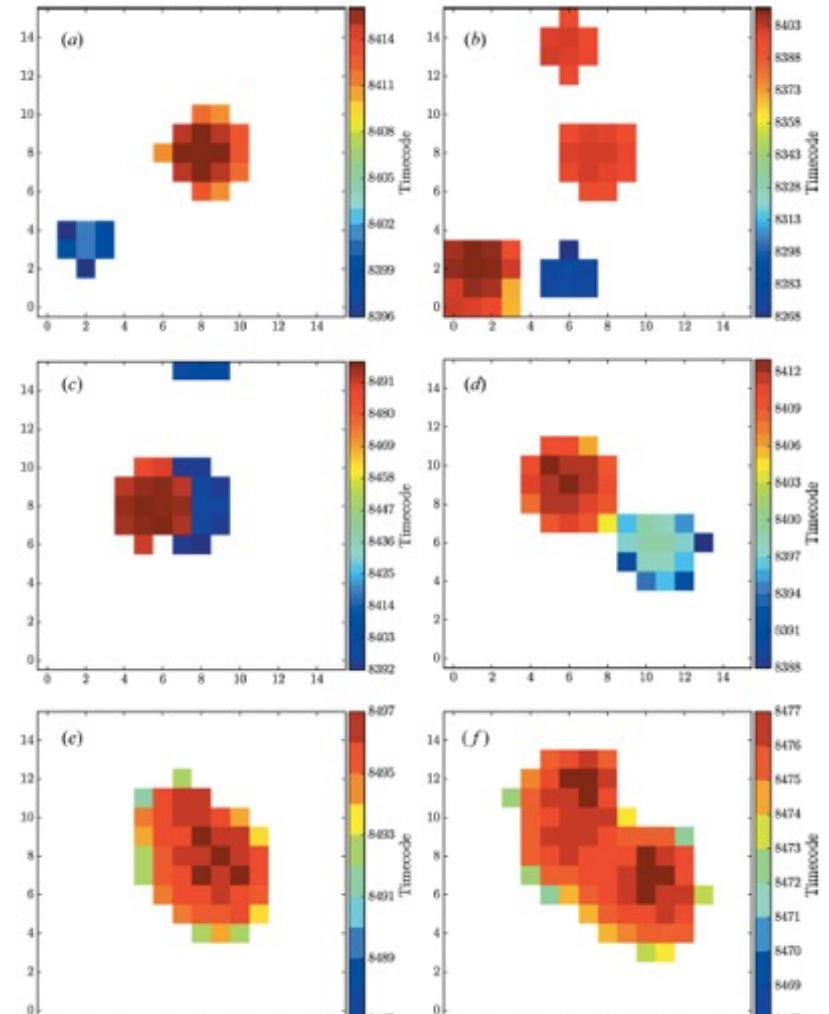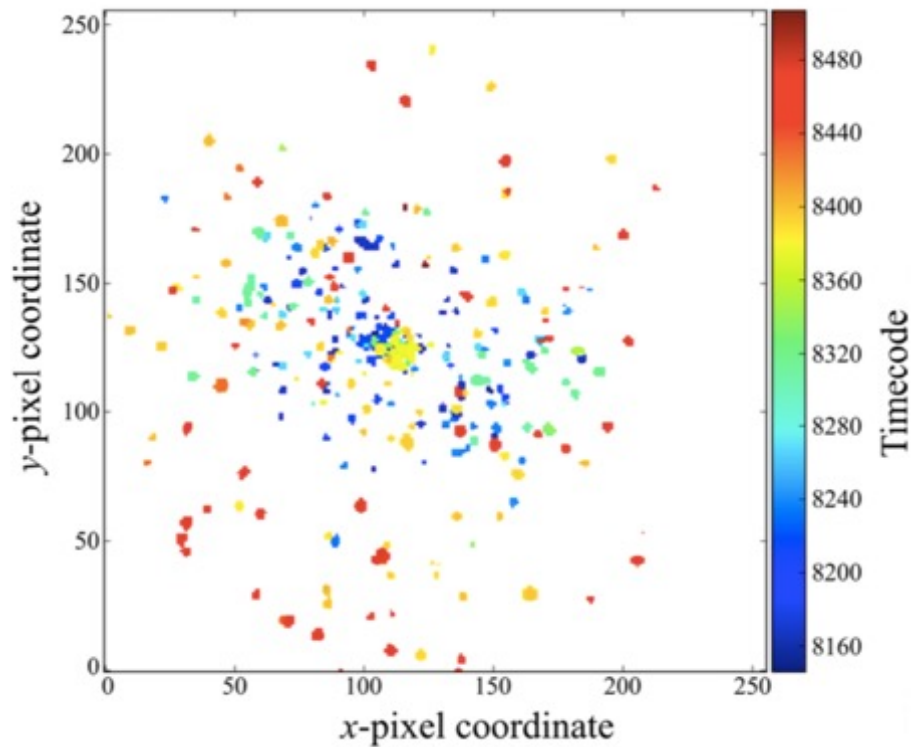- ~1 um for 500 nm, ~10 um for 800 nm
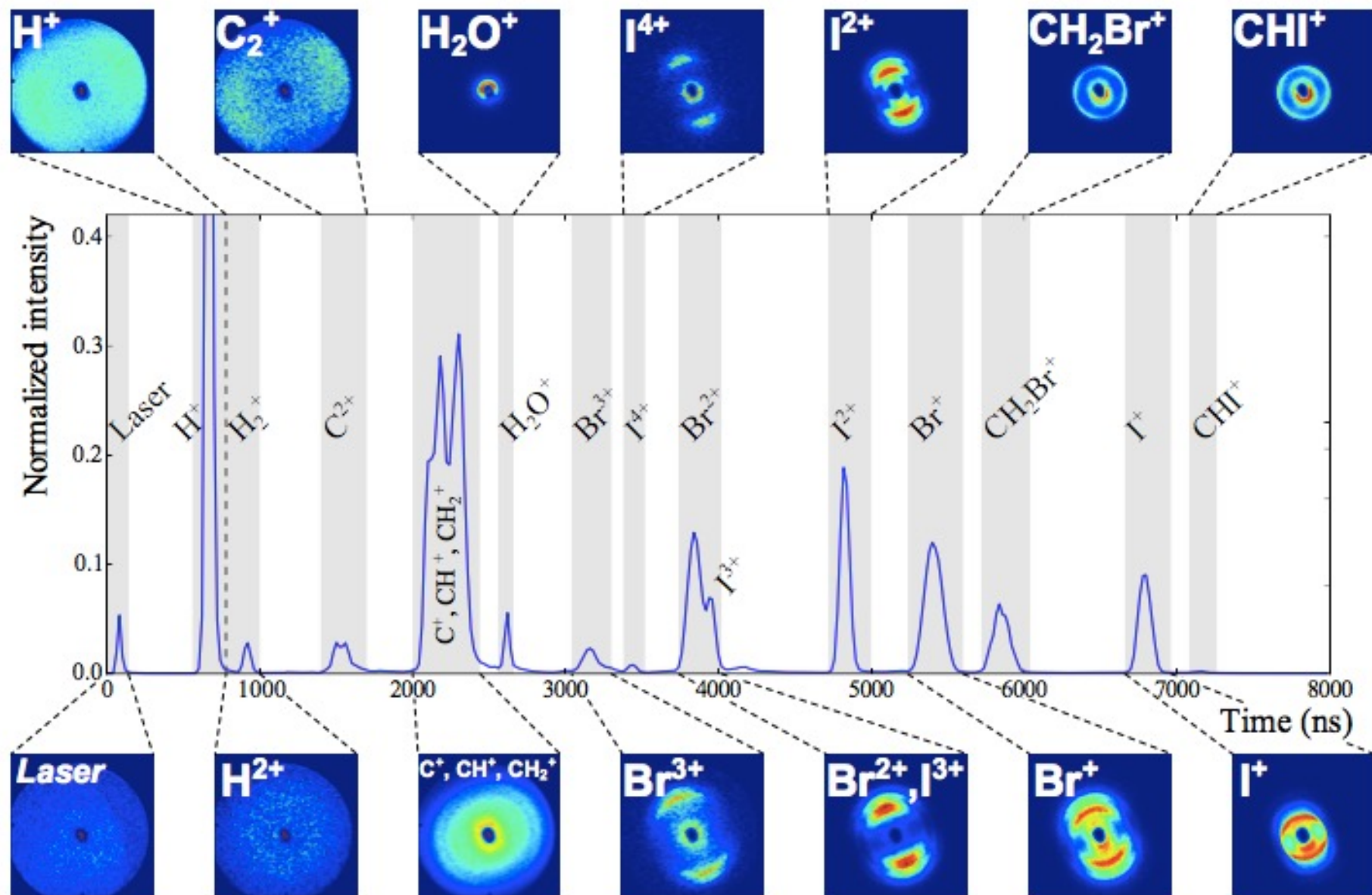
Ion Imaging

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)
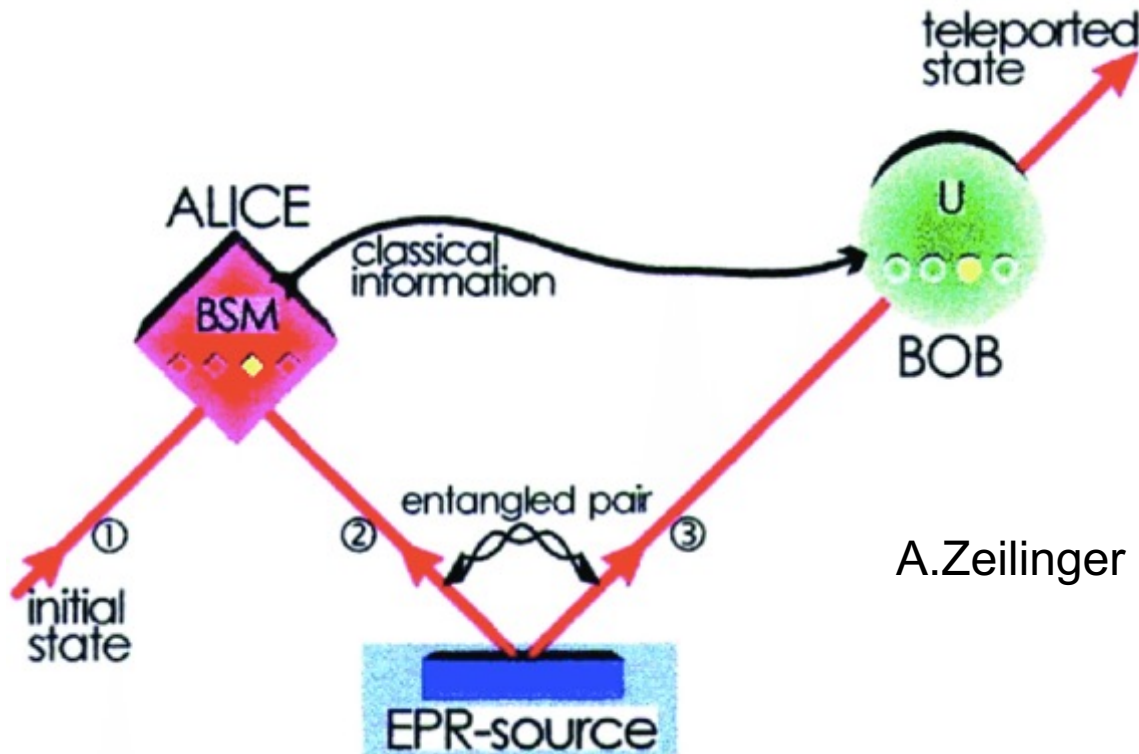
Ions in TimepixCam

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
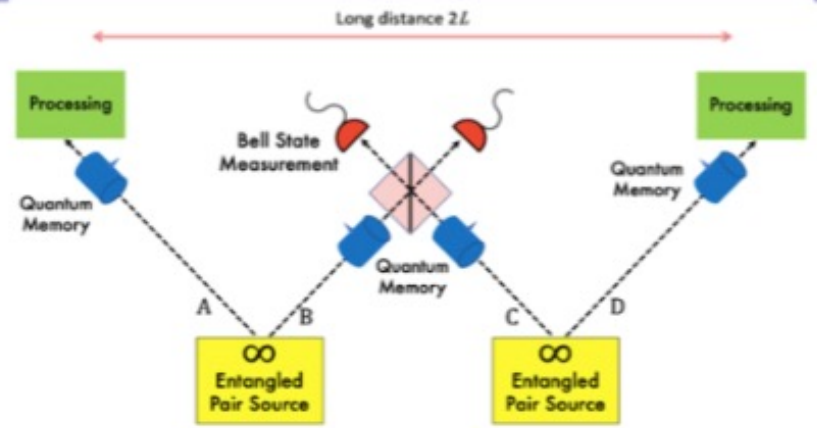
Figure labels (top row): H^+, C_2^+, H_2O^+, I^{4+}, I^{2+}, CH_2Br^+, CHI^+

Plot axis labels: Normalized intensity (y-axis, 0.0 to 0.4), Time (ns) (x-axis, 0 to 8000)

In-plot labels: Laser, H^+, H_2^+, C^{2+}, C^+, CH^+, CH_2^+, H_2O^+, Br^{3+}, I^{4+}, Br^{2+}, I^{3+}, I^{2+}, Br^+, CH_2Br^+, I^+, CHI^+

Figure labels (bottom row): Laser, H^{2+}, C^+, CH^+, CH_2^+, Br^{3+}, Br^{2+}, I^{3+}, Br^+, I^+

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)
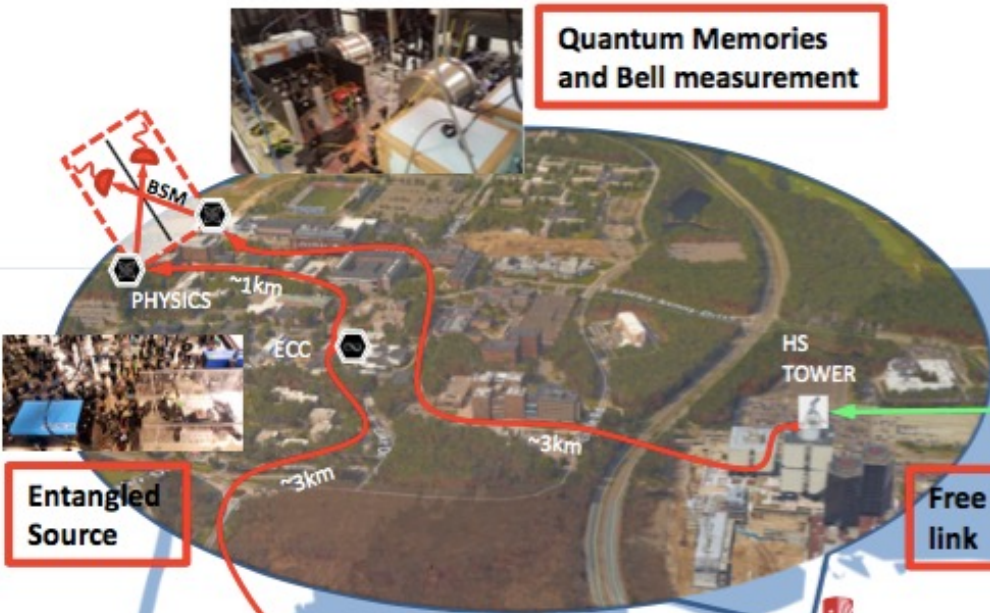

A.Zeilinger

SBU BNL Quantum repeater test bed

Characterization of Single Photon Down-Conversion Source

qubit: use H, V photon polarization states

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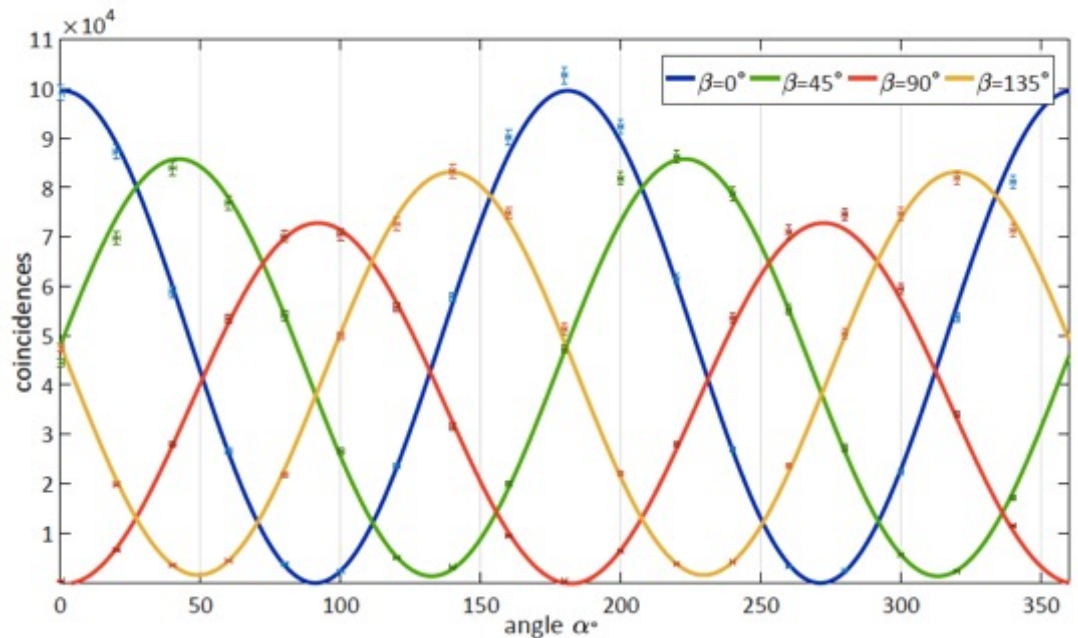
Time difference between photons

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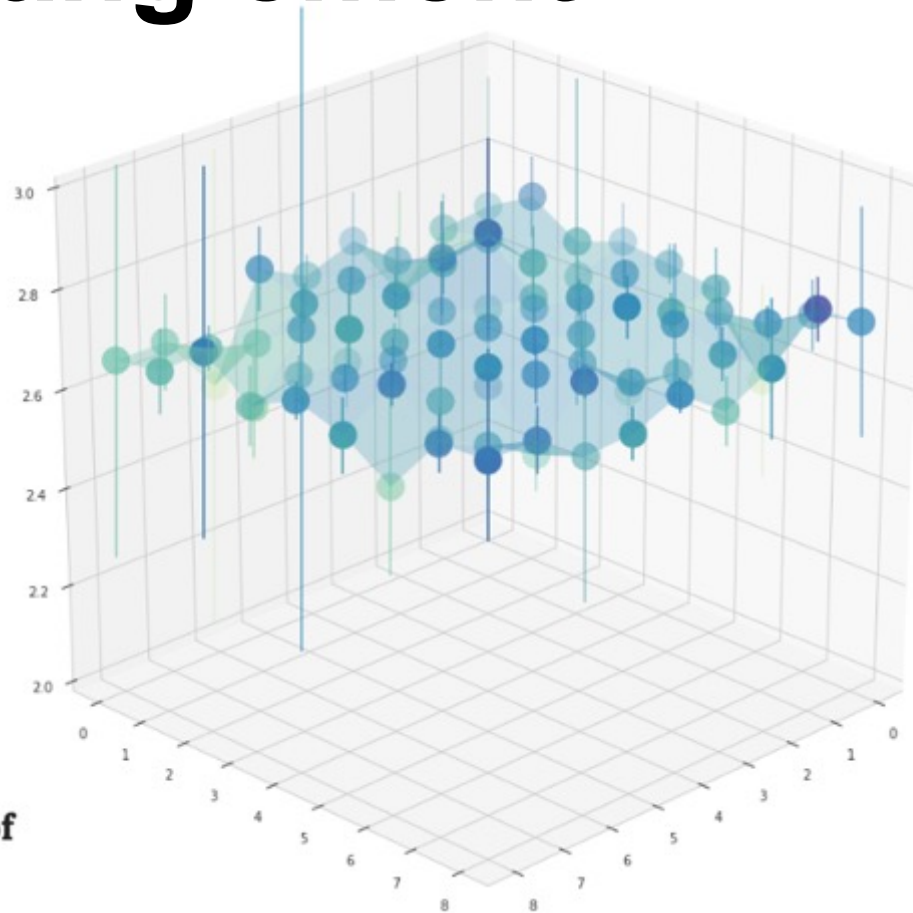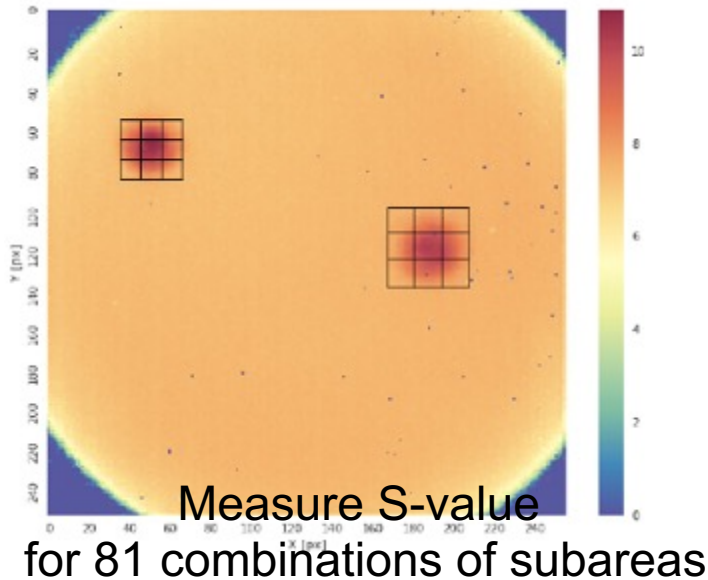 - If > 2: photons are entangled
  - max value: $2\sqrt{2} = 2.82$

- Measurement:

  S-value = 2.72$\pm$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 ✉

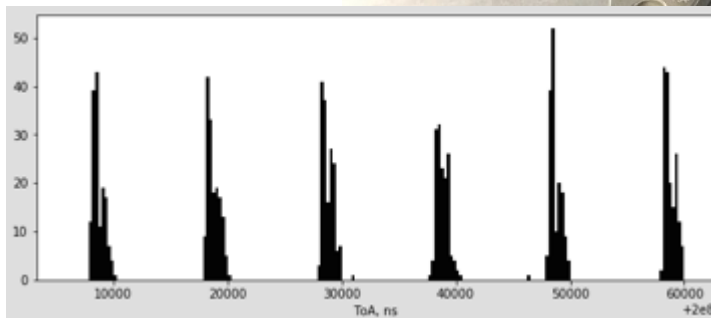Scientific Reports **10**, Article number: 6181 (2020) | Cite this article

Imaging enables scalability

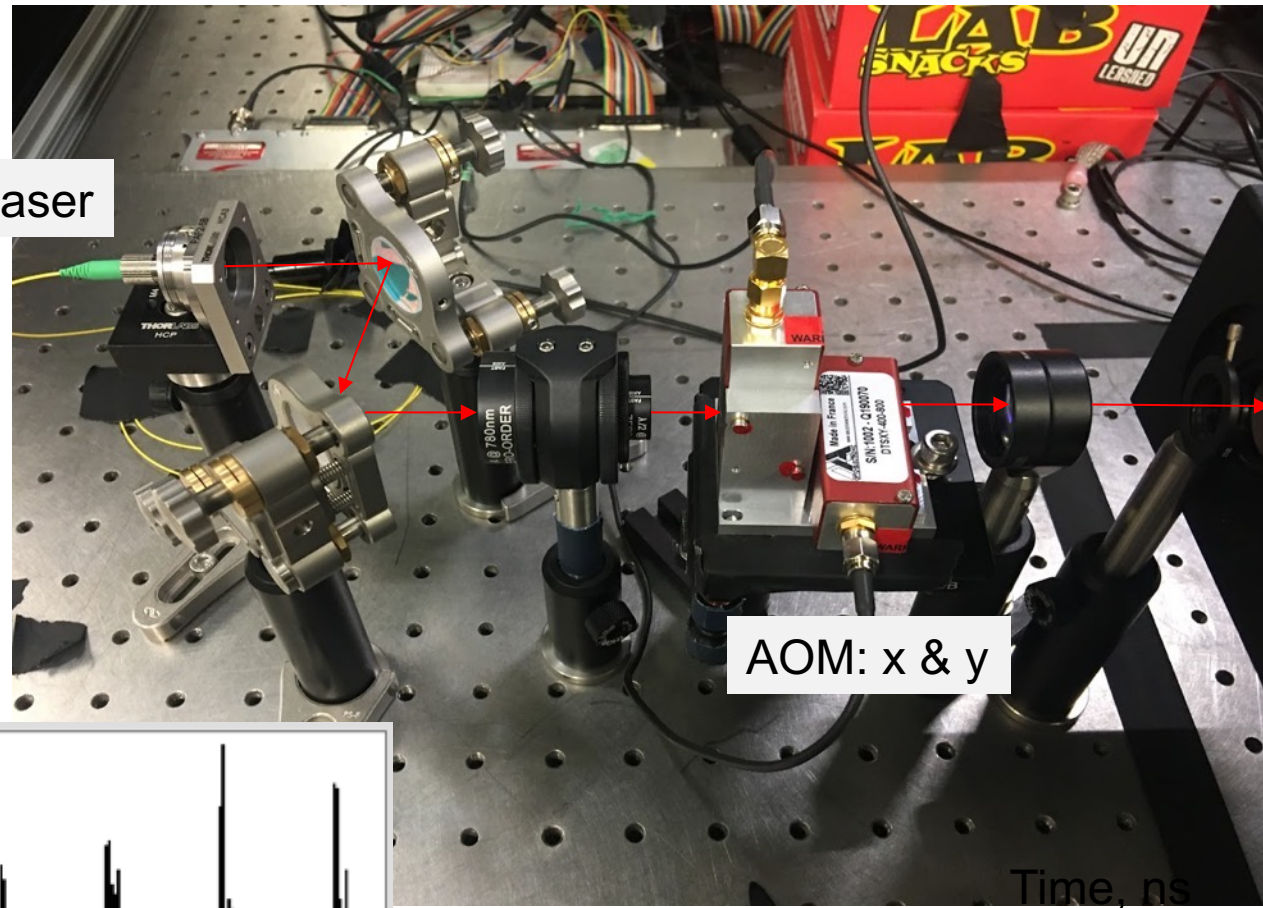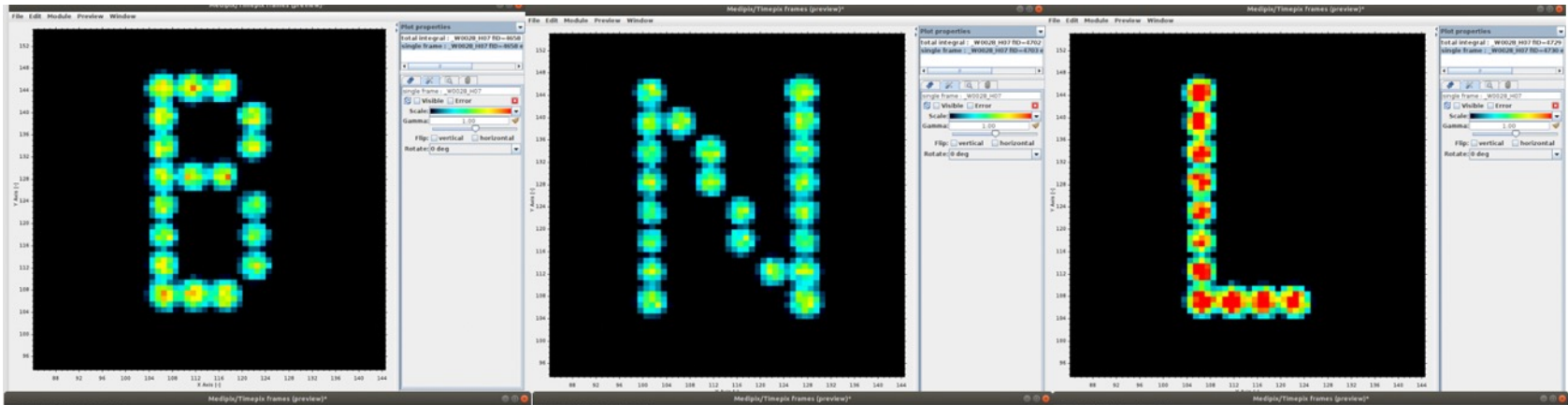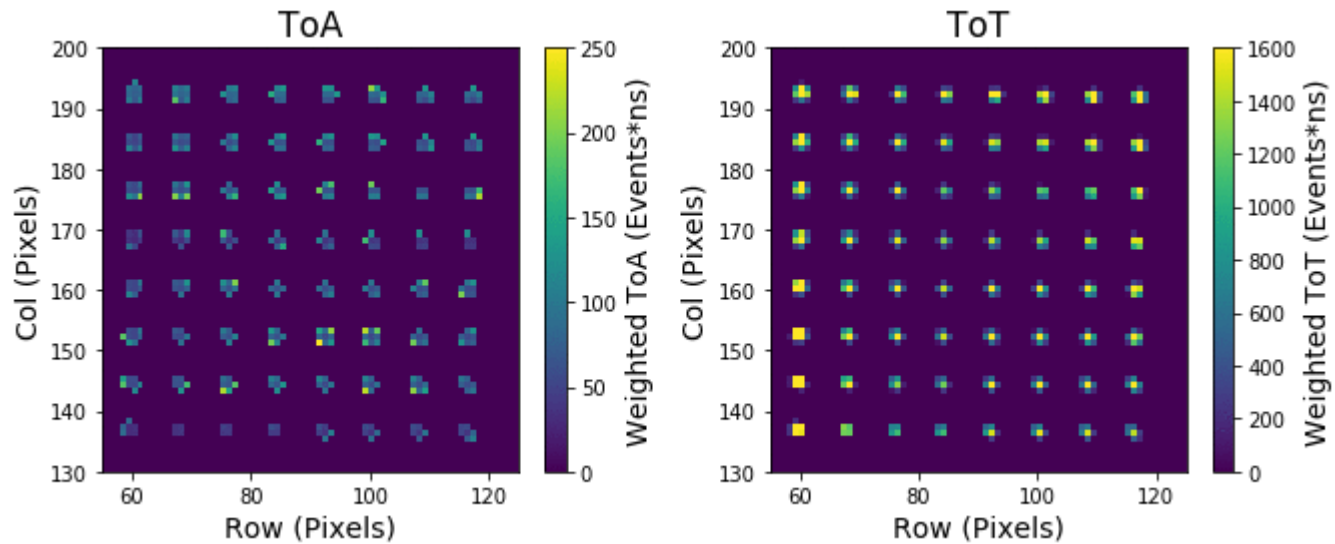# Scalability

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

Photon router:

- Used acousto-optical modulators to create 8x8 grid

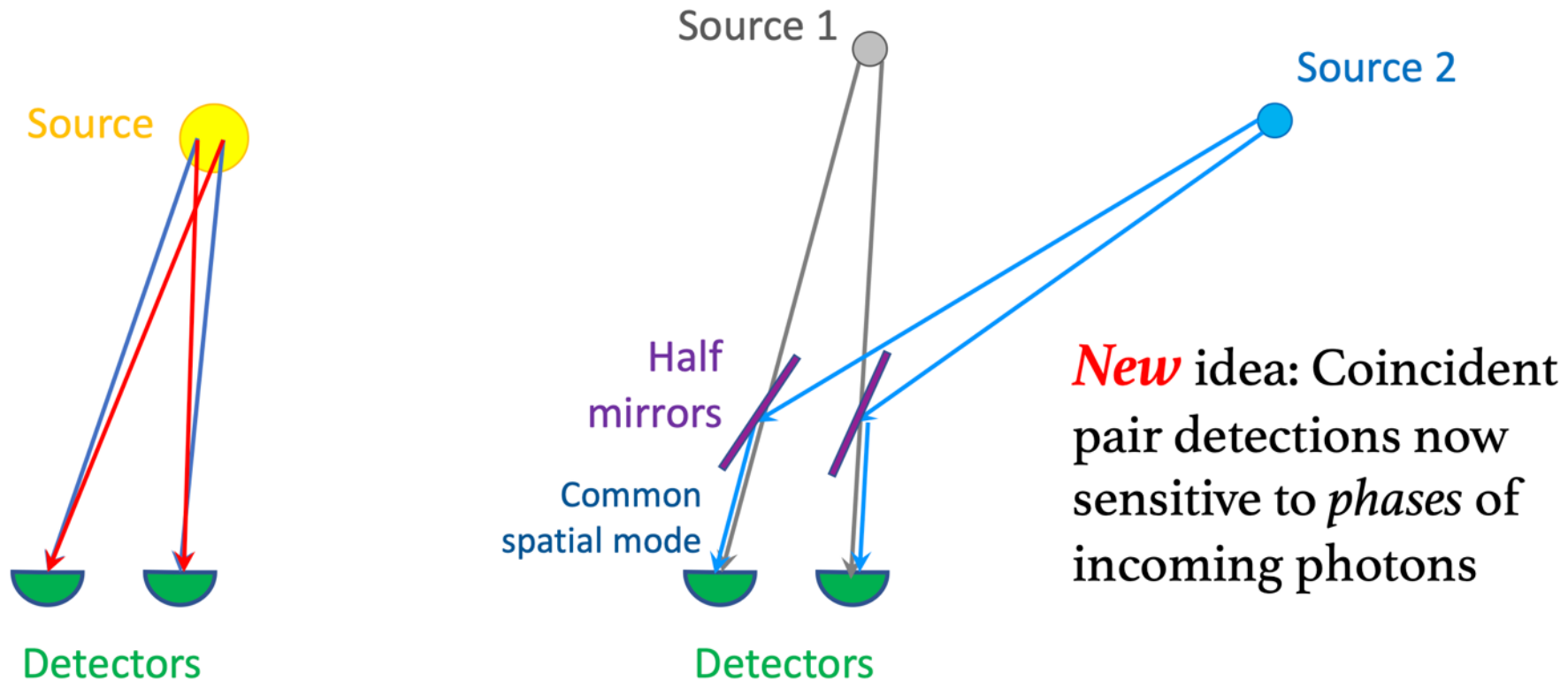- Arbitrary routing between spots

- 10 ns time resolution, 1 μs switching

laser

AOM: x & y

Time, ns

Scalability

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

Hanbury Brown – Twiss Interferometry

HBT with two sources?
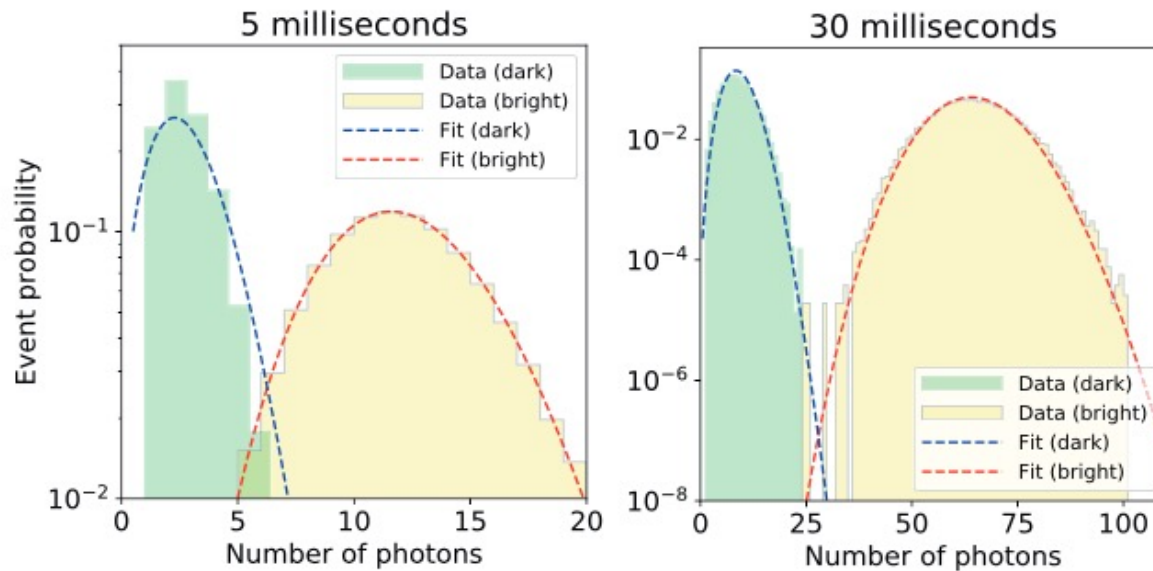
Possible impact on astrophysics and cosmology

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
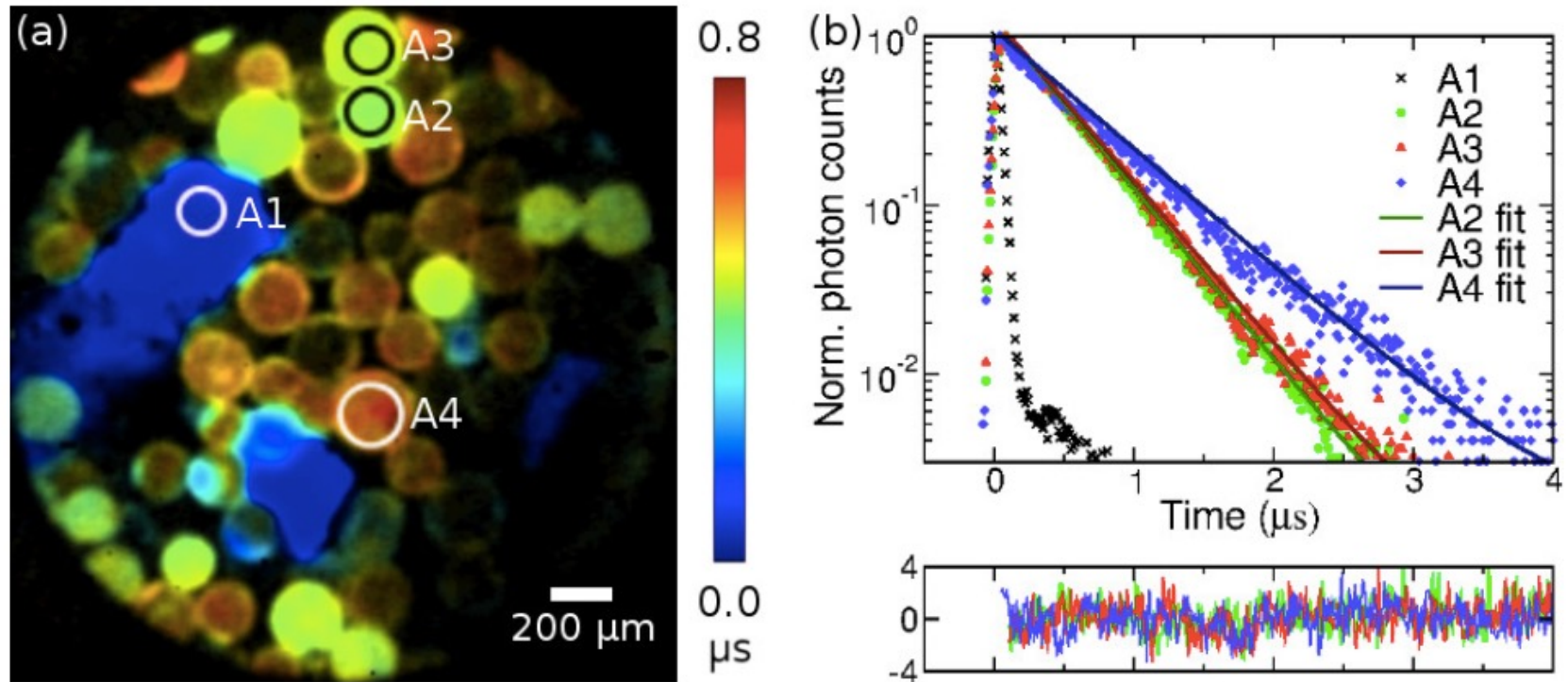- Exoplanets

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
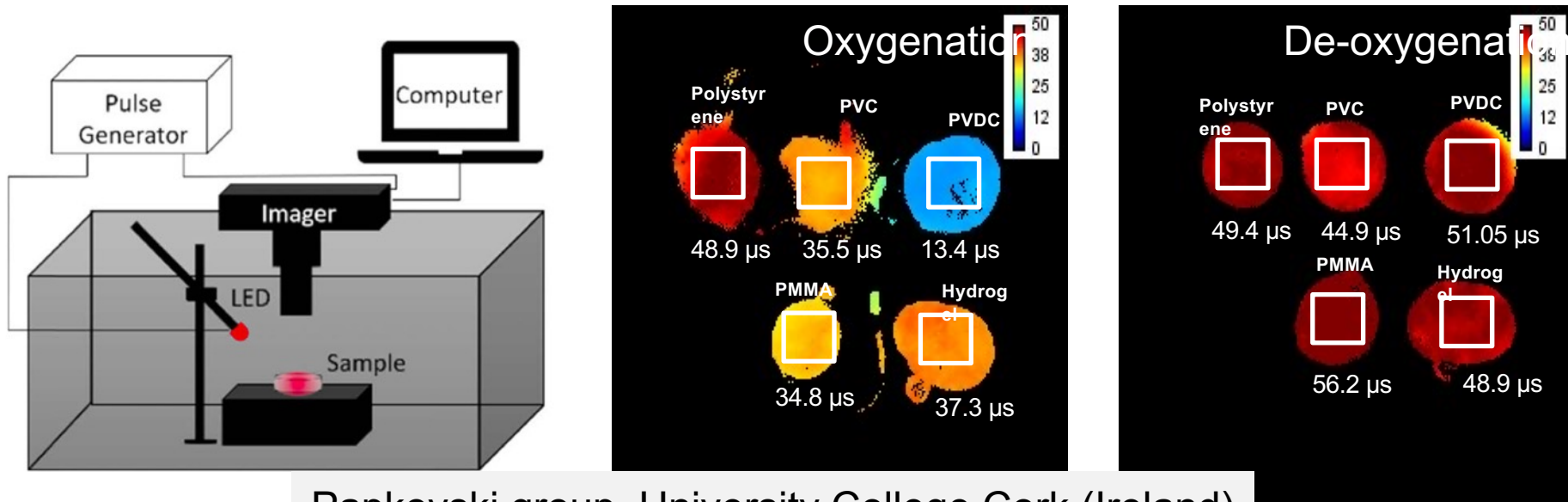
Lifetime Imaging

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

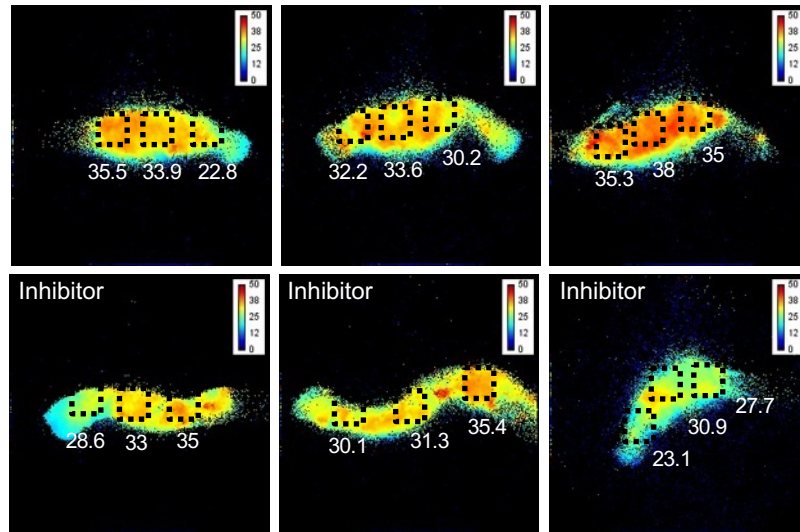Papkovski group, University College Cork (Ireland)

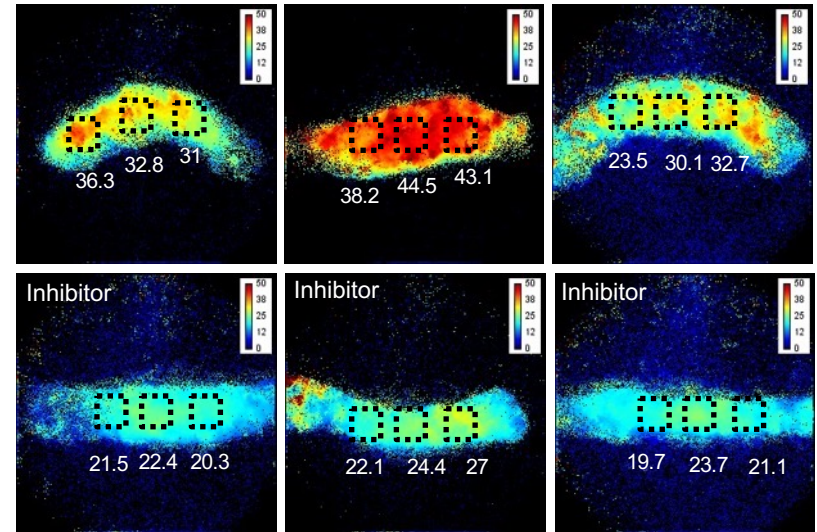Oxygenation and Deoxygenation of PtBp Solid State sensors

Measurements with biosamples
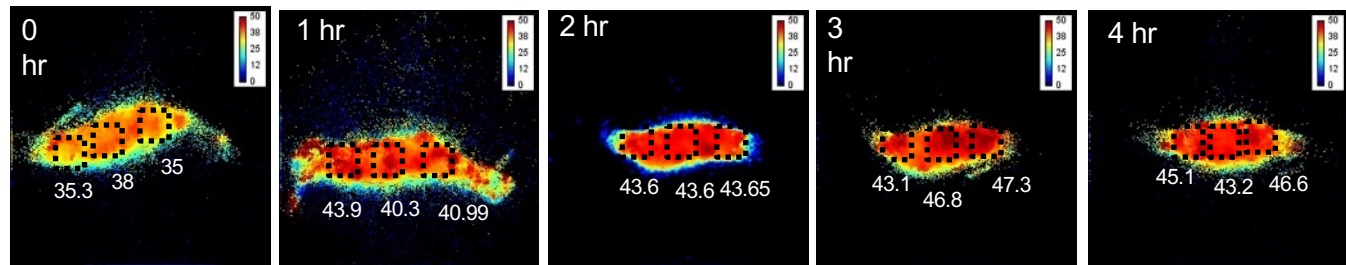
Intraluminal application (Mice2)

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)