Multi-dimensional discrimination in quantum imaging

Andrei Nomerotski
Brookhaven National Lab, Upton NY, USA

Sensing with Quantum Light 2020

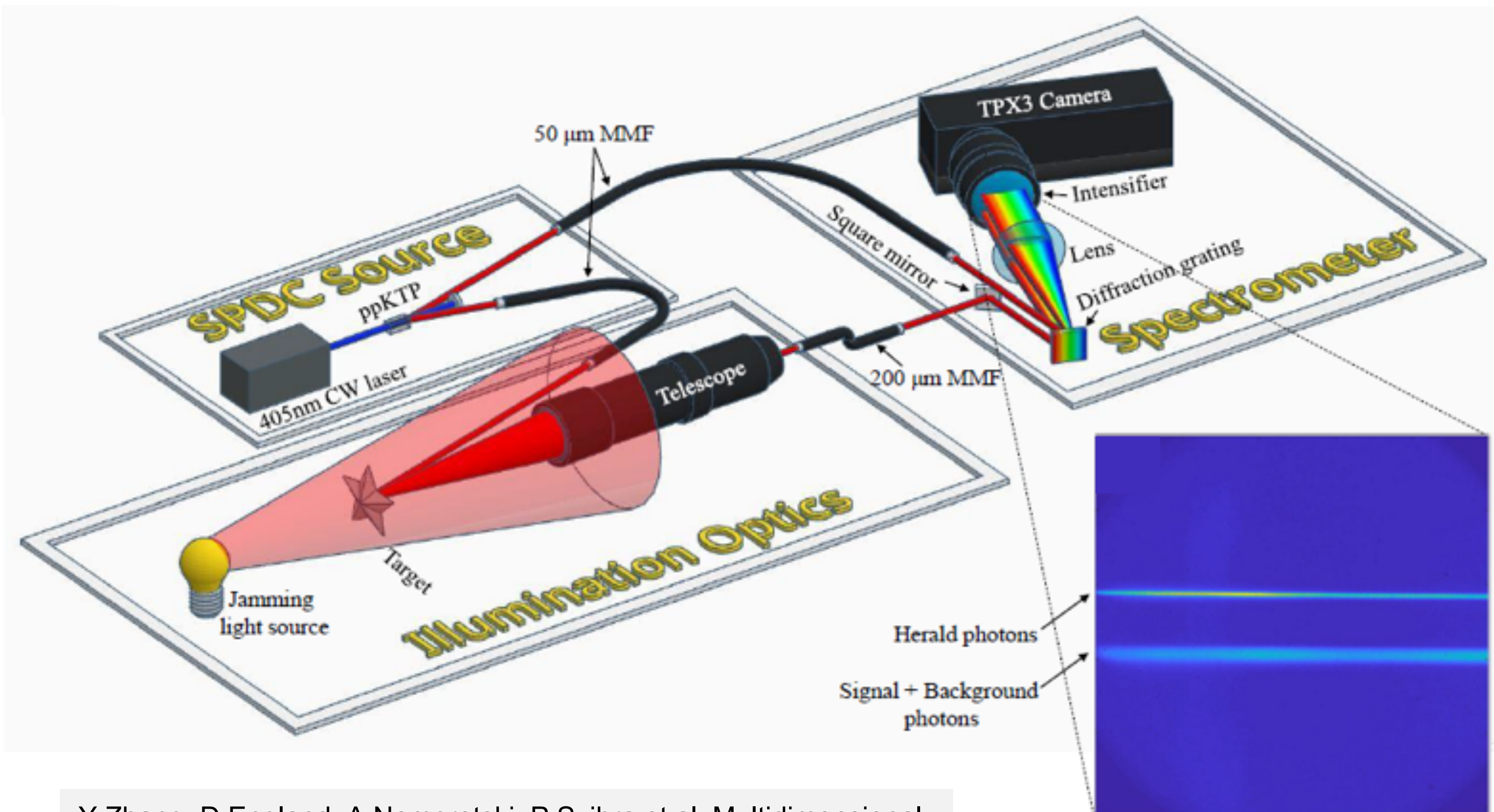
Sept. 6th – 9th 2020, Berlin

Outline

- Quantum enhanced target detection
  - Data-driven fast camera
- Multi-dimensional signal discrimination
- Other applications of fast imaging in quantum optics and QIS

Quantum-Enhanced Target Detection

In collaboration with NRC Ottawa group – Duncan England, Yingwen Zhang et al



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

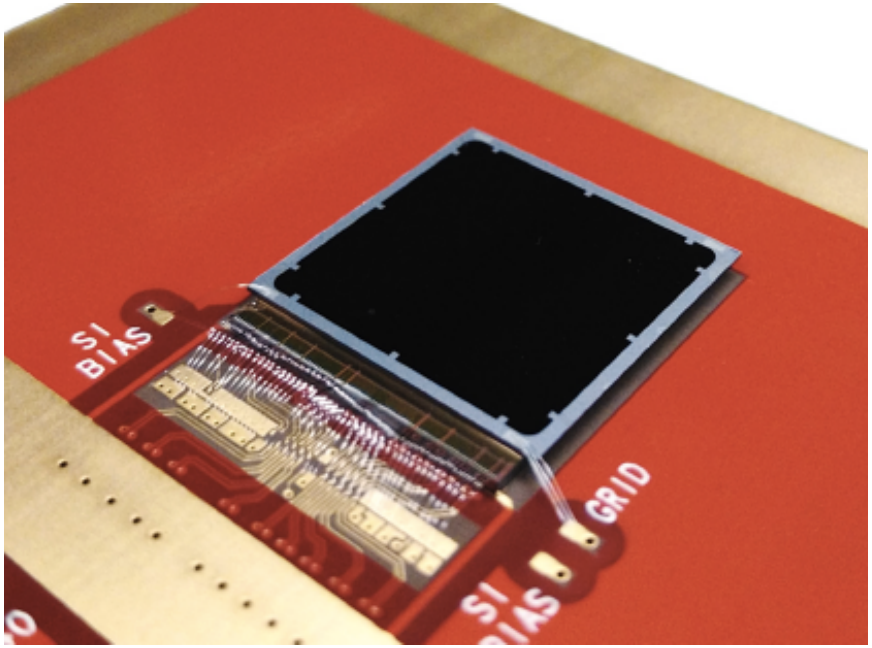
Timepix3 Camera → Tpx3Cam

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

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

- 1.56 ns timing resolution
- Data-driven readout, 600 e min threshold, 80 Mpix/sec, no deadtime

- each pixel independently measures both time and flux
- ~1μs pixel deadtime when hit



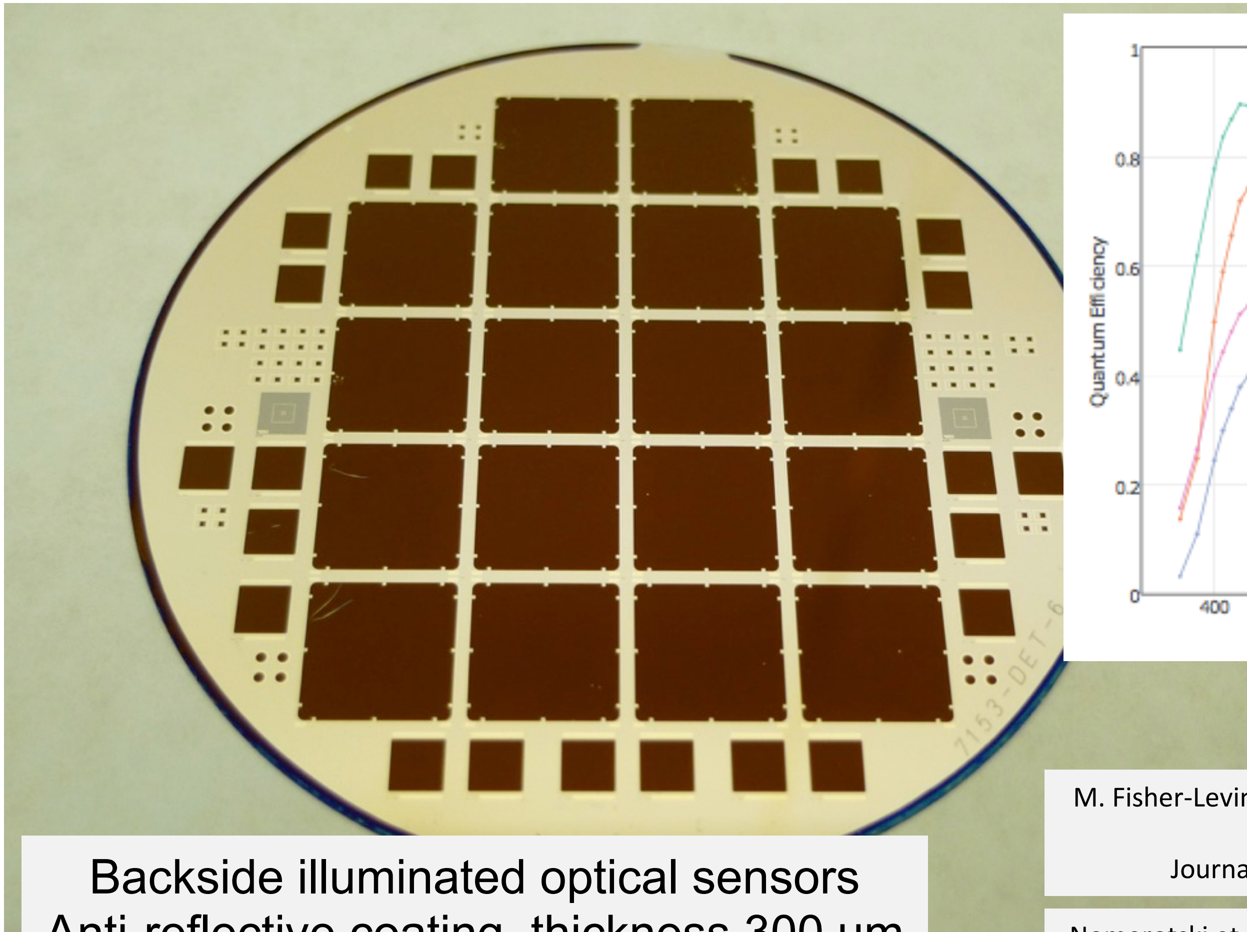
Optical sensor is bump-bonded to chip

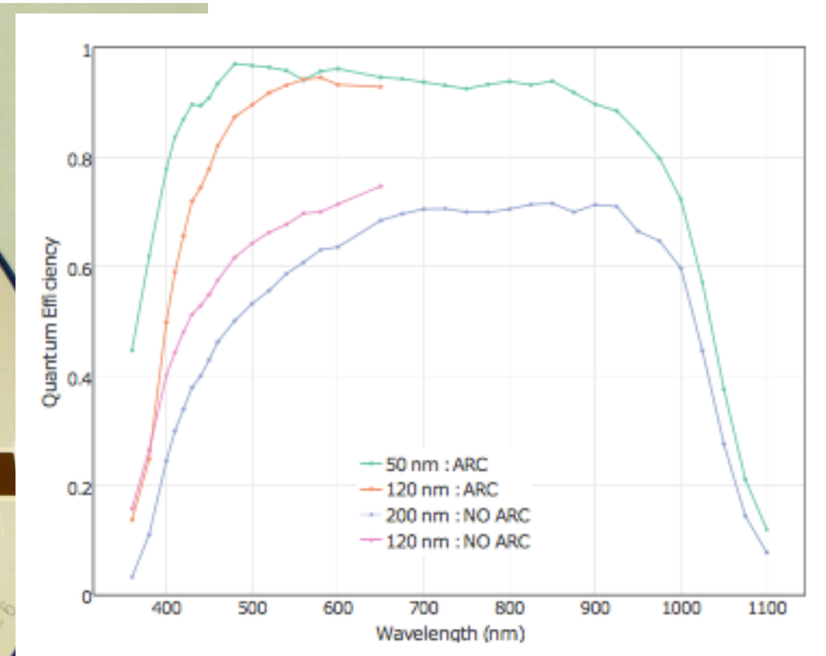
Use existing x-ray readouts:
SPIDR (Nikhef, ASI)
www.amscins.com

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

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

Thin window optical sensors





High QE

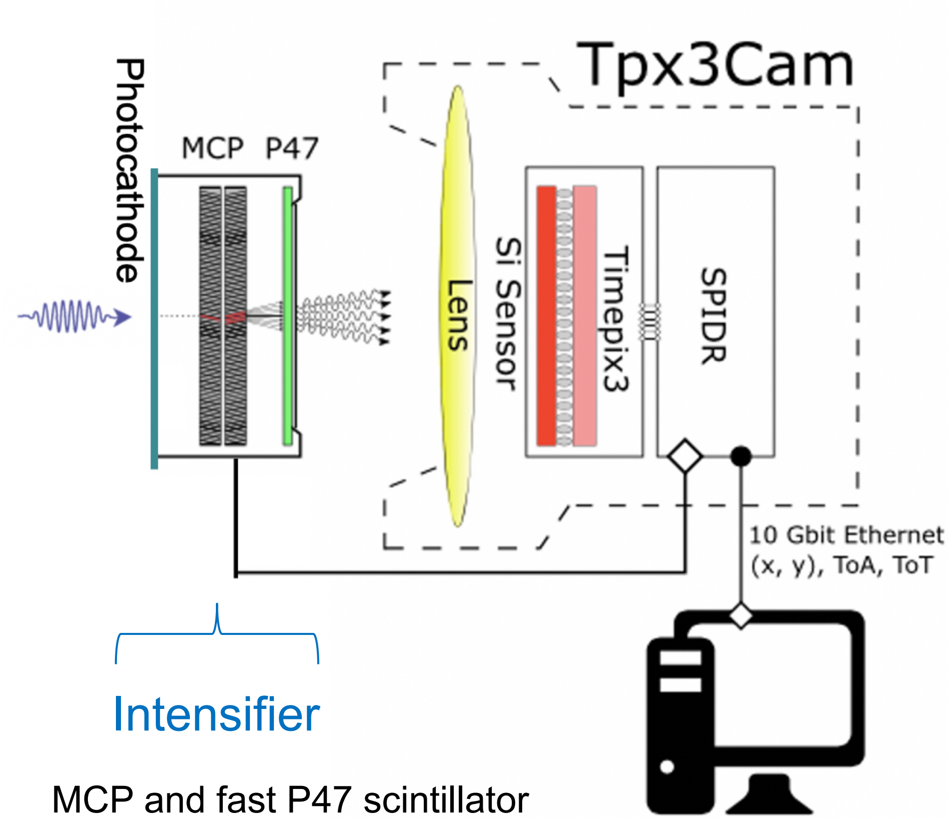
Backside illuminated optical sensors
Anti-reflective coating, thickness 300 um

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

Intensified camera: use off-the-shelf image intensifier



Intensifier

MCP and fast P47 scintillator support ns time resolution

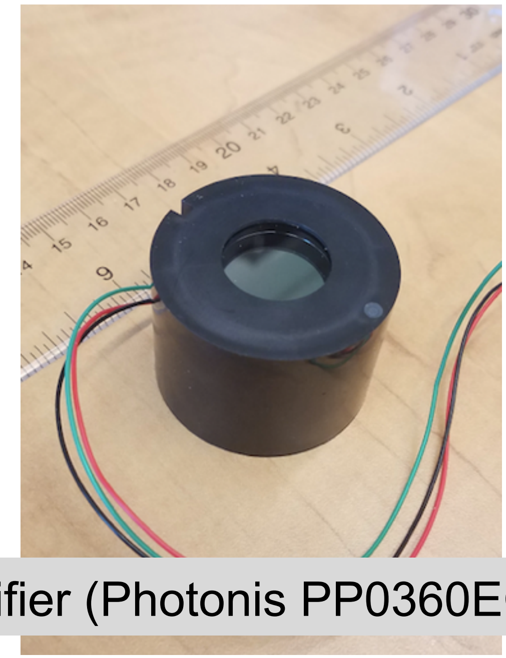
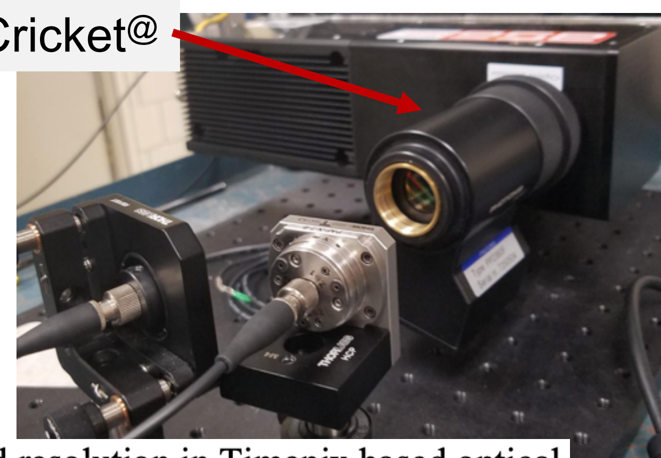


Image intensifier (Photonis PP0360EG)



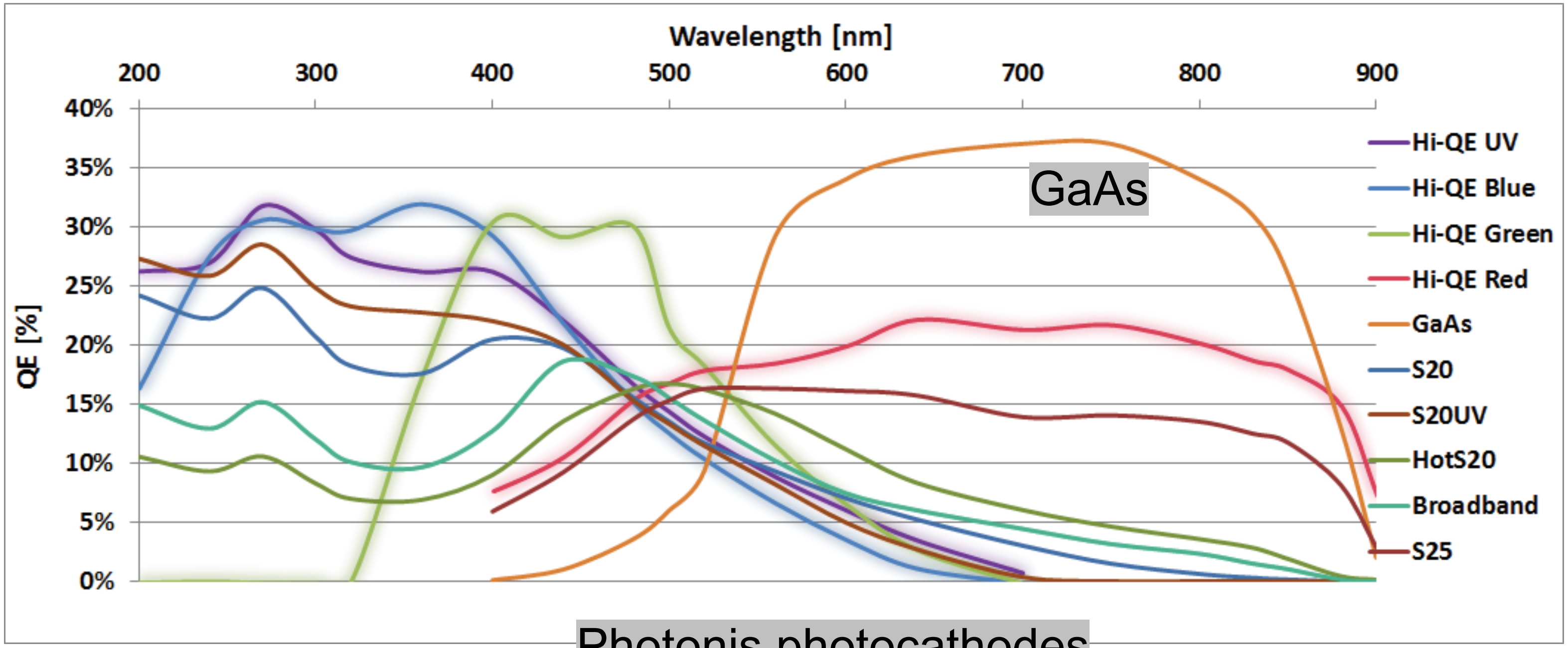
Cricket@

Single photon sensitive!

Imaging and time stamping of photons with nanosecond resolution in Timepix based optical cameras, A. Nomerotski, Nuclear Instruments and Methods Section A, 937, 26 (**2019**).

Photocathodes

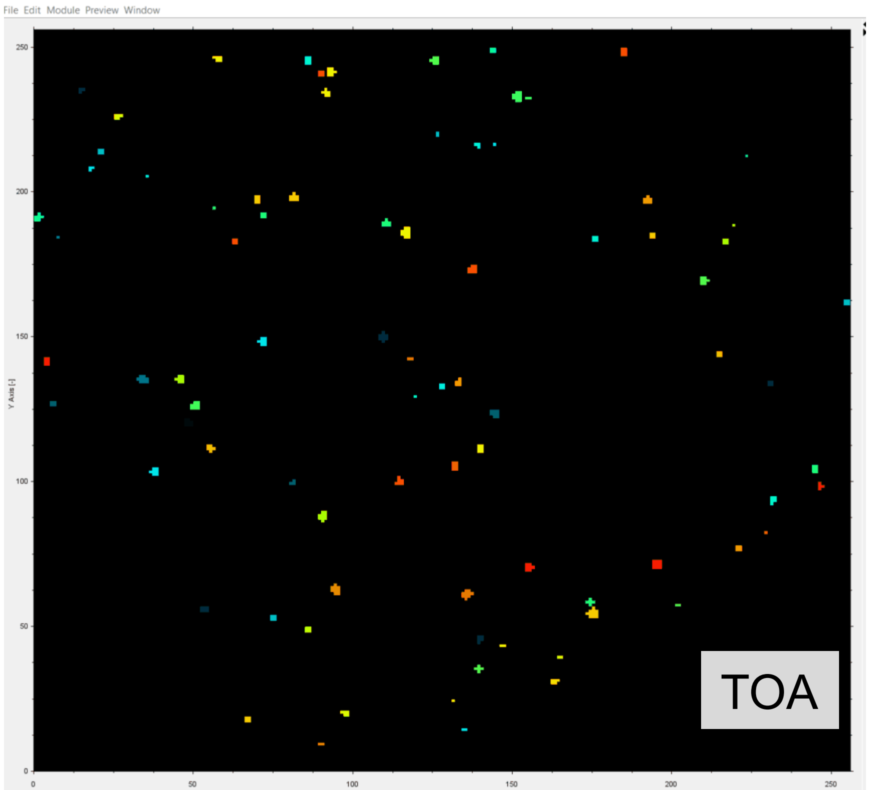
Can choose any wavelength



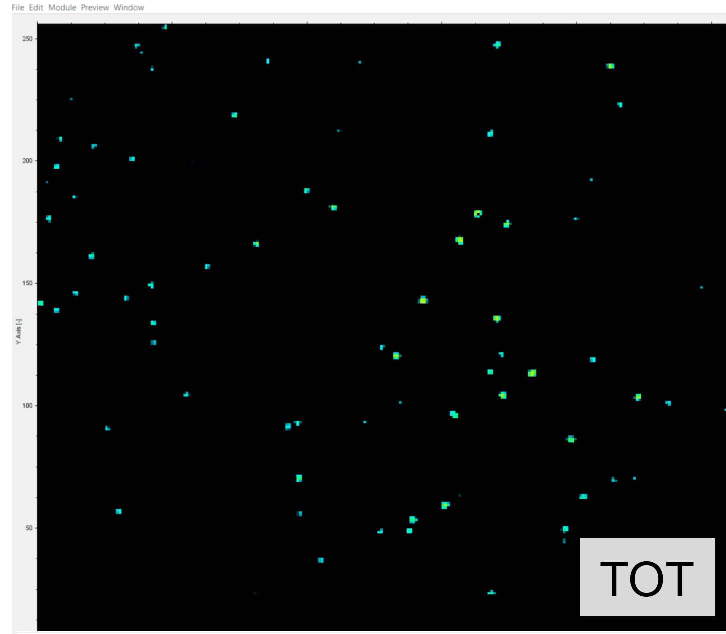
Photonis photocathodes

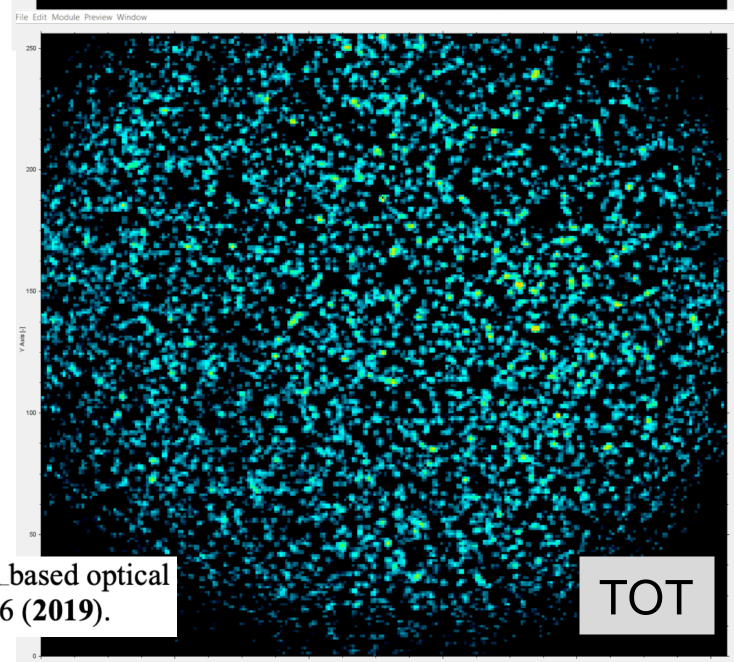
Single Photons in Tpx3Cam

1 ms slice of data
1.5ns time-stamping

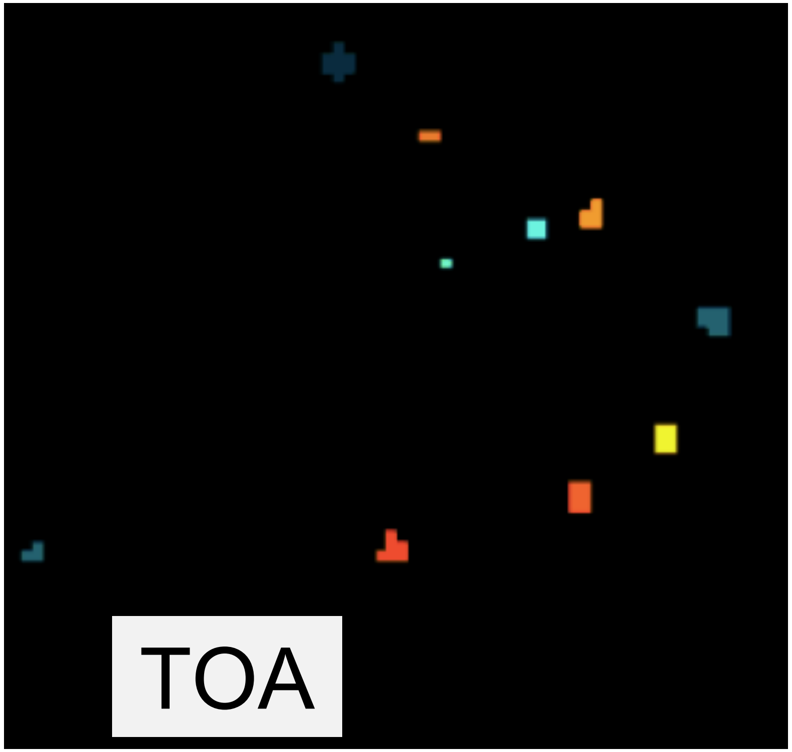


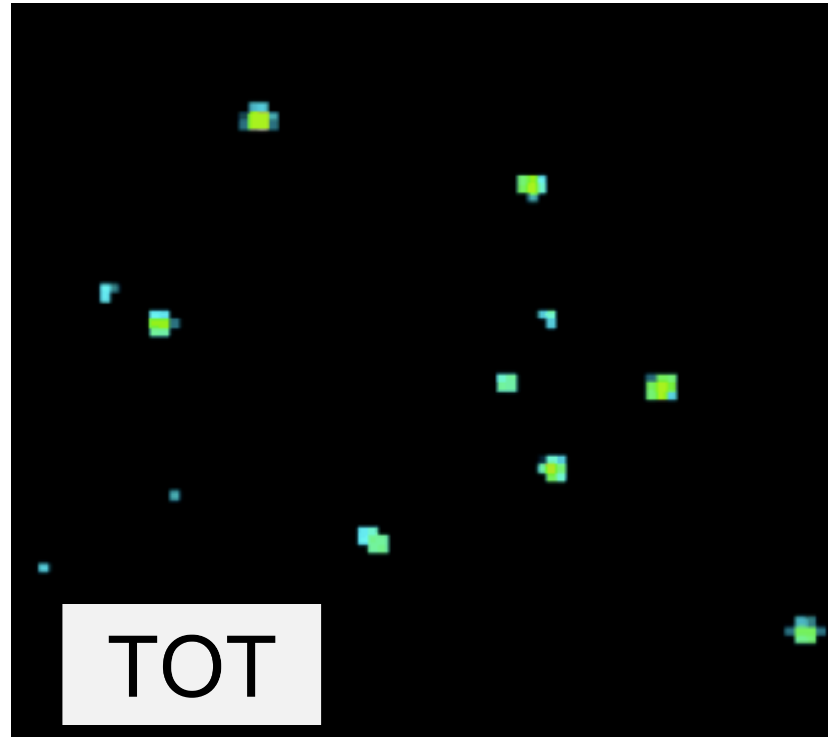
Tpx3Cam + intensifier by Photonis





Imaging and time stamping of photons with nanosecond resolution in Timepix based optical cameras, A. Nomerotski, Nuclear Instruments and Methods Section A, 937, 26 (**2019**).





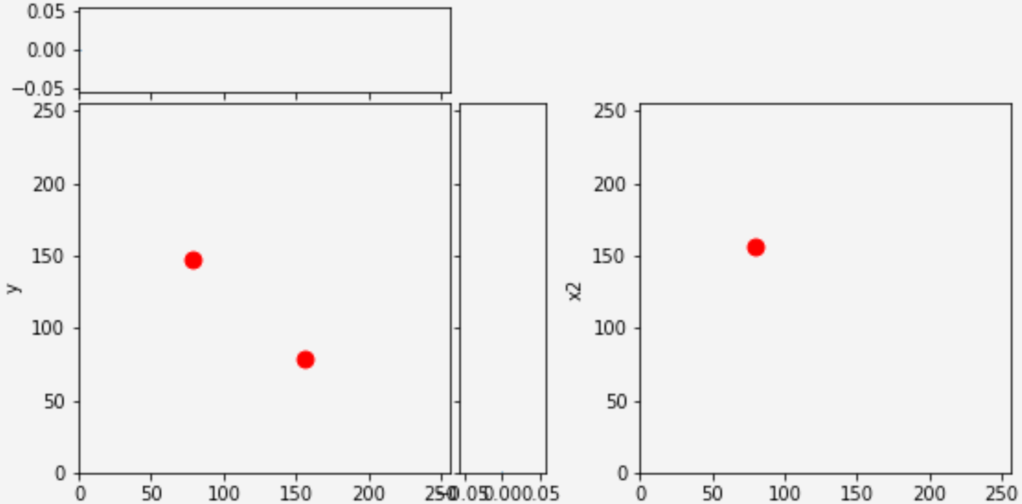
Each photon is a cluster of pixels
→ 3D (x,y,t) centoiding

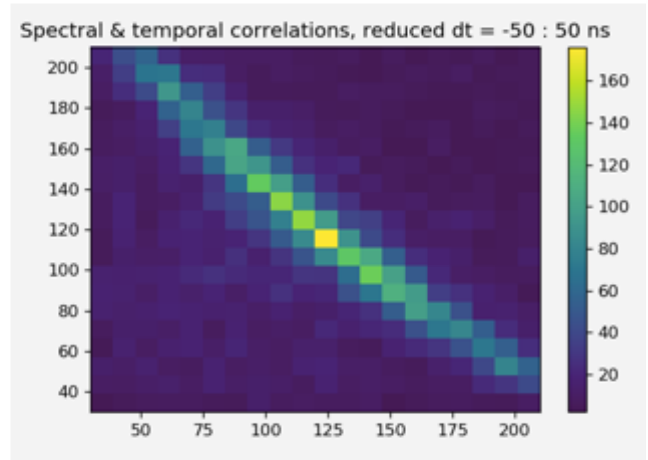
Spatial resolution: 0.1 pixel / photon

Time resolution: < 1 ns / photon

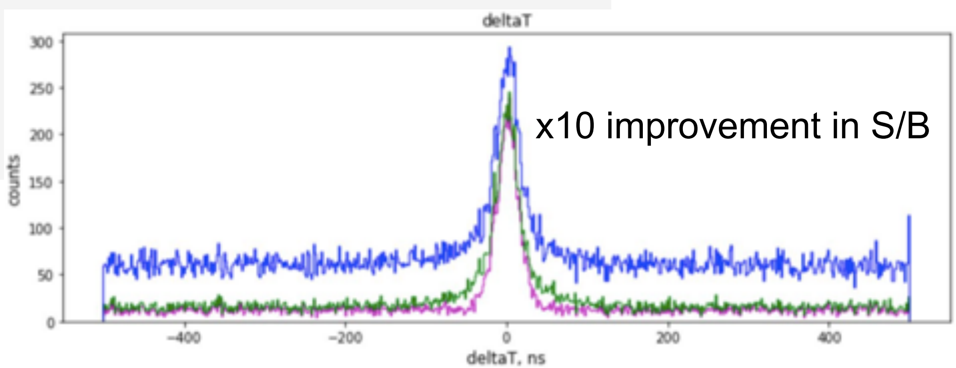
Zhao et al, Coincidence velocity map imaging using Tpx3Cam, a time stamping optical camera with 1.5 ns timing resolution, Review of Scientific Instruments 88 (11) (2017) 113104.

Spectral and temporal correlations





temporal and spectral information is available pair by pair



SNR improvement achieved by straightforward box selections on time difference and sum energy → can do better with optimal discrimination

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

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

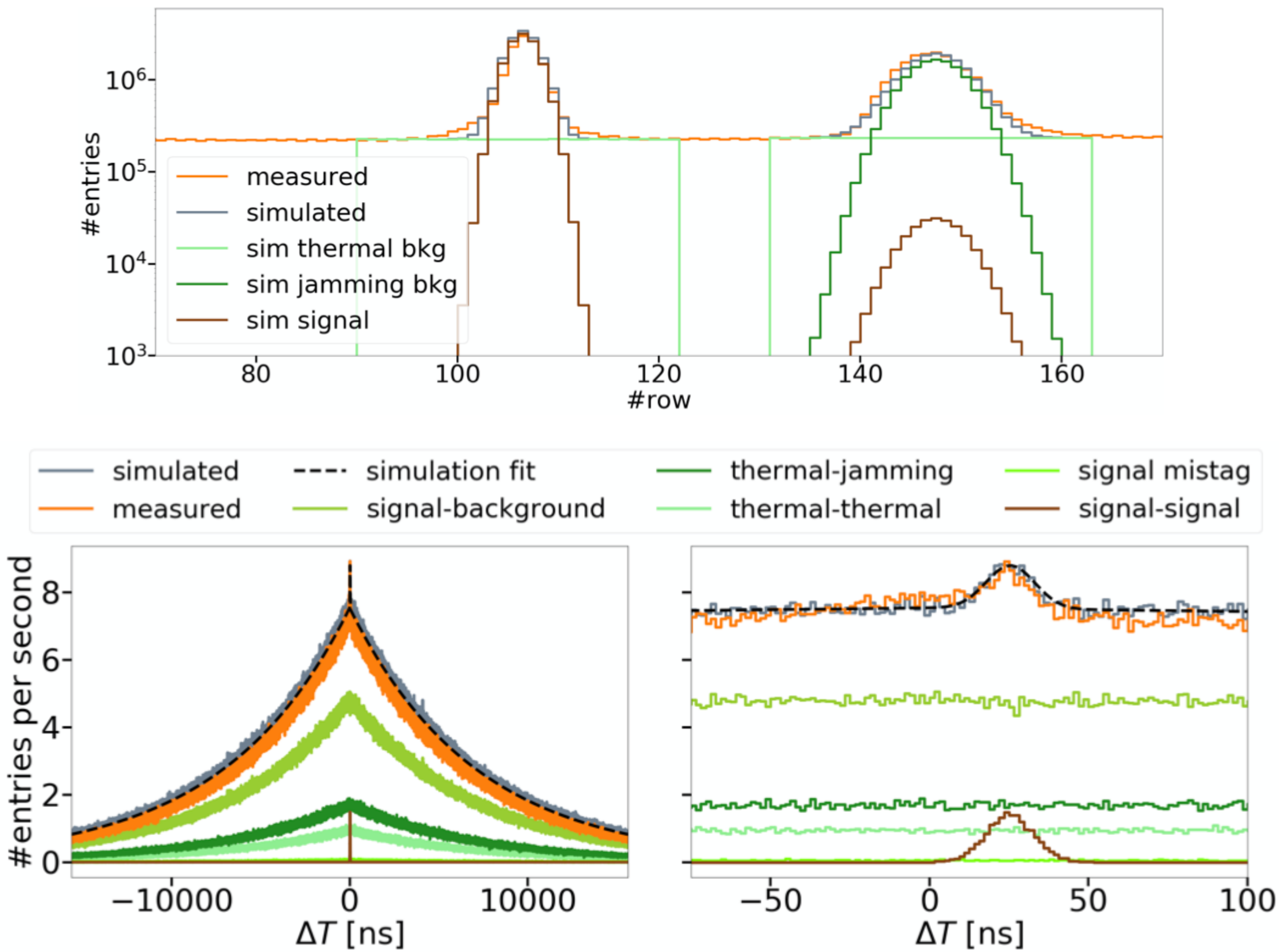
Likelihood ratios

Simple discriminant technique popular in HEP

- Optimal if variables are independent
- Need to know distributions for signal and bkg

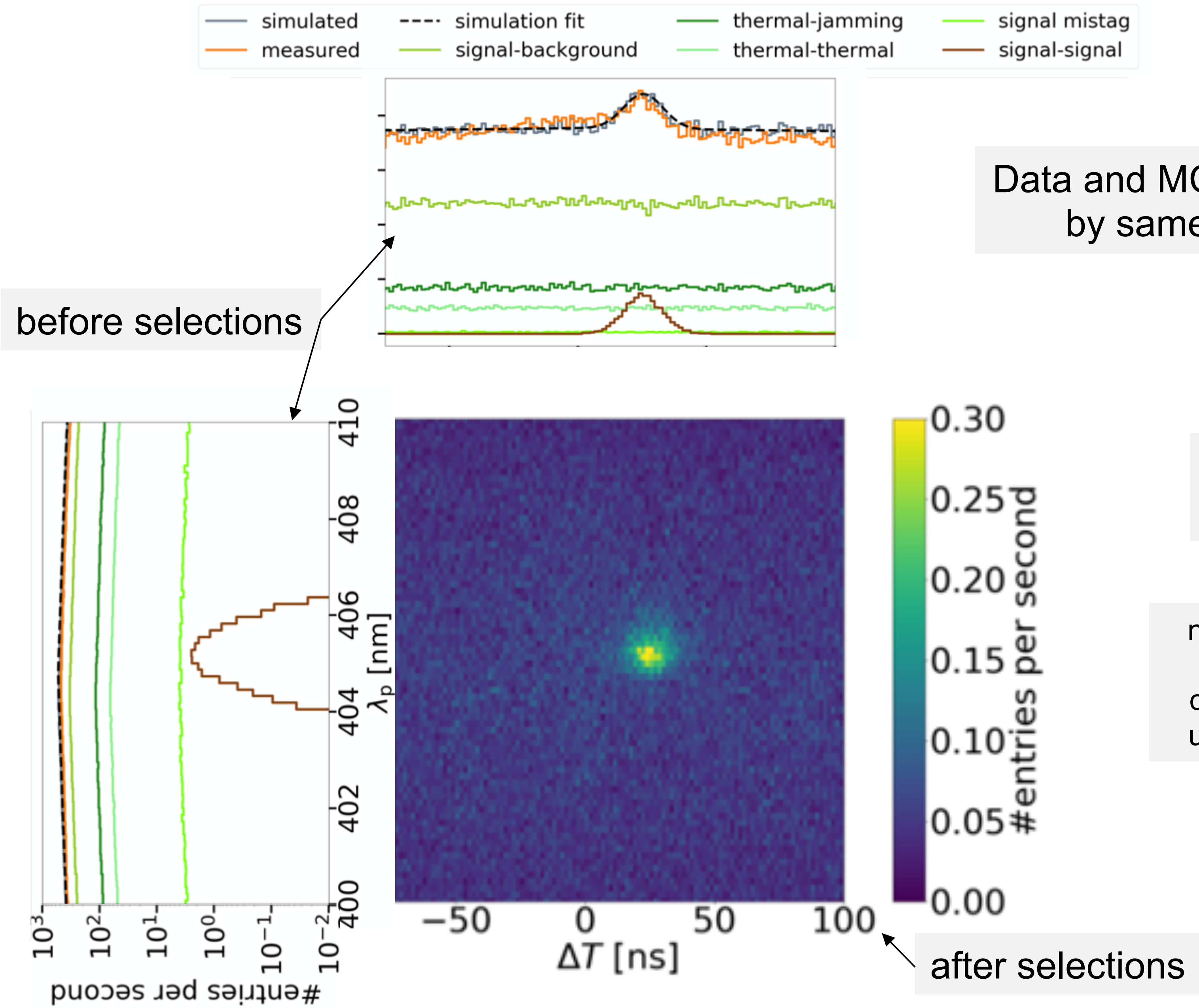
Nowadays replaced in HEP by neural nets, boosted decision trees and other discriminants

Monte-Carlo Modelling



MC model was tuned to the data

2D λ_p vs ΔT distribution



Data and MC are processed by same algorithms

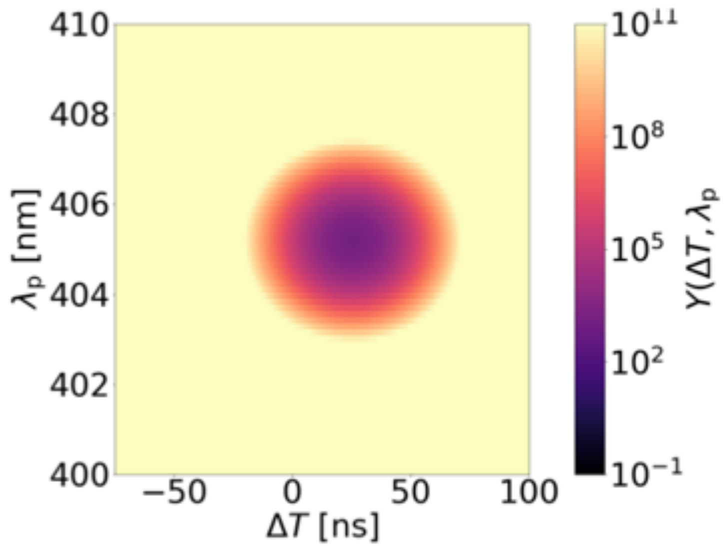
$\delta\lambda_p$ = 0.36 nm
δT = 7.5 ns

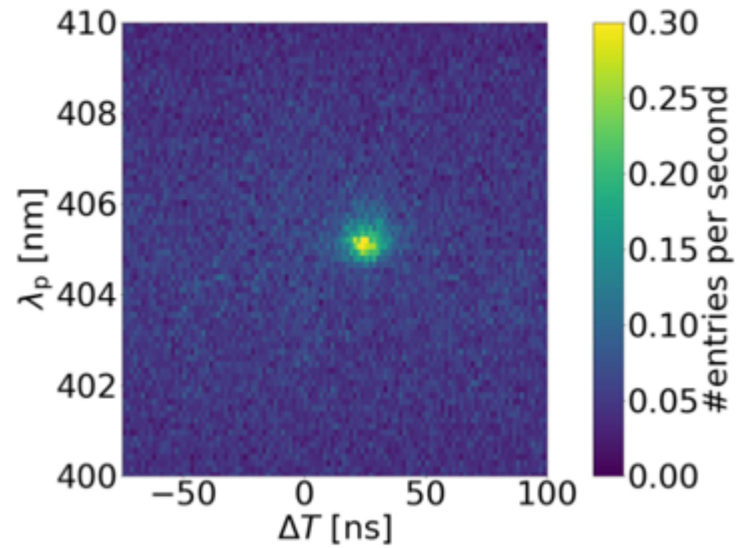
not sensitive (yet) to energy-time correlations through uncertainty principle

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

$$\frac{hc}{\lambda_{\mathrm{p}}} = \frac{hc}{\lambda_{\mathrm{h}}} + \frac{hc}{\lambda_{\mathrm{s}}}$$





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

Pump photon wavelength vs delta T

Likelihood ratios

$$Y(\lambda_{\mathrm{p}}, \Delta T) \equiv Y(Y_{\lambda_{\mathrm{p}}}, Y_{\Delta \mathrm{T}}) = Y_{\lambda_{\mathrm{p}}} \cdot Y_{\Delta \mathrm{T}}$$

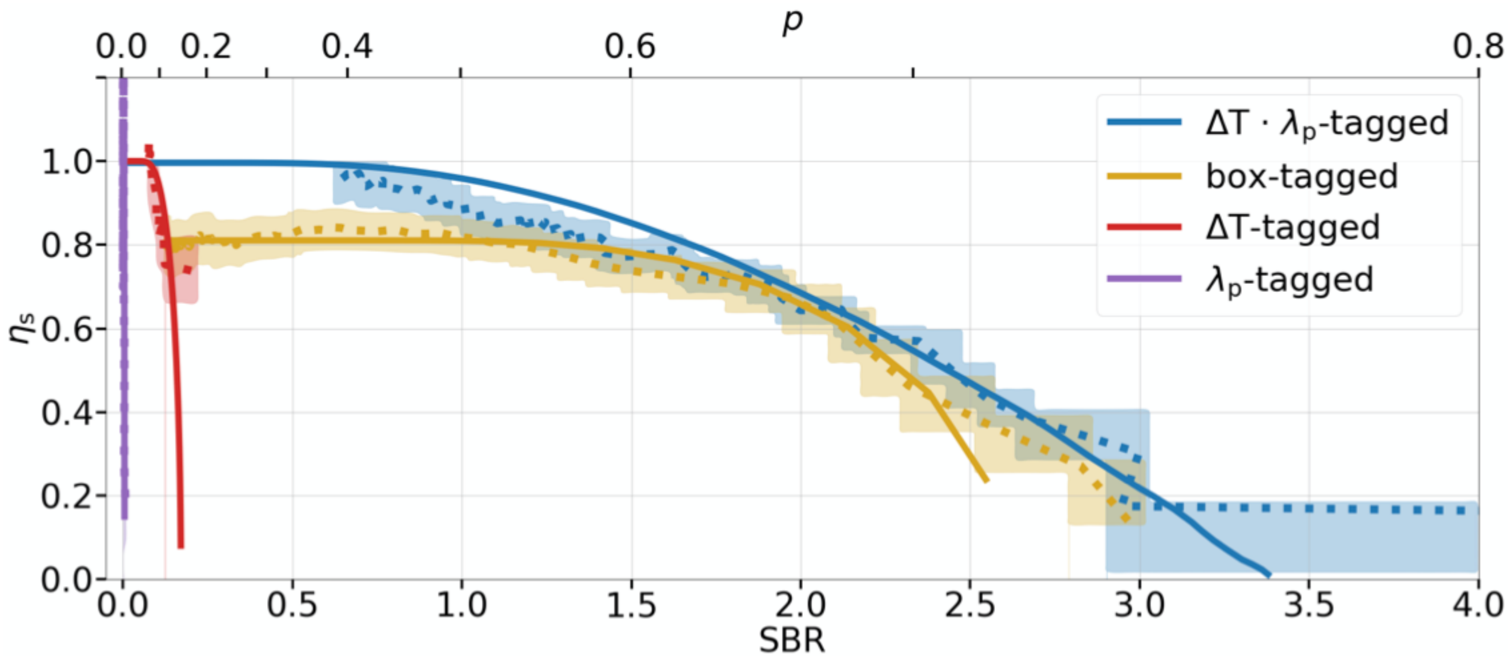
P Svihra, Y Zhang et al, Multivariate Discrimination in Quantum Target Detection, arXiv preprint arXiv:2005.00612
Appl. Phys. Lett. **117**, 044001 (2020)

Discriminant performance

Each point corresponds to certain Y selection

Sample purity $p = S/(S + B)$

Selection Efficiency

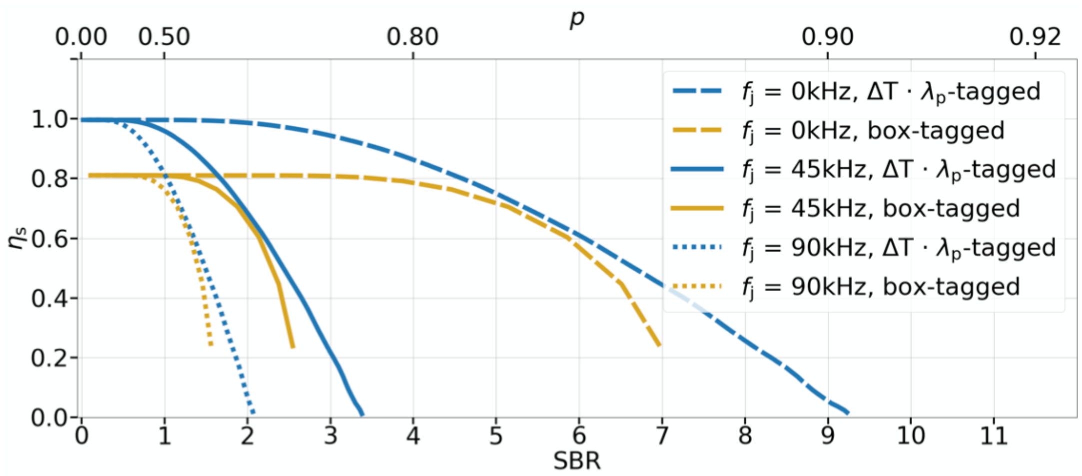


26% improvement of SBR

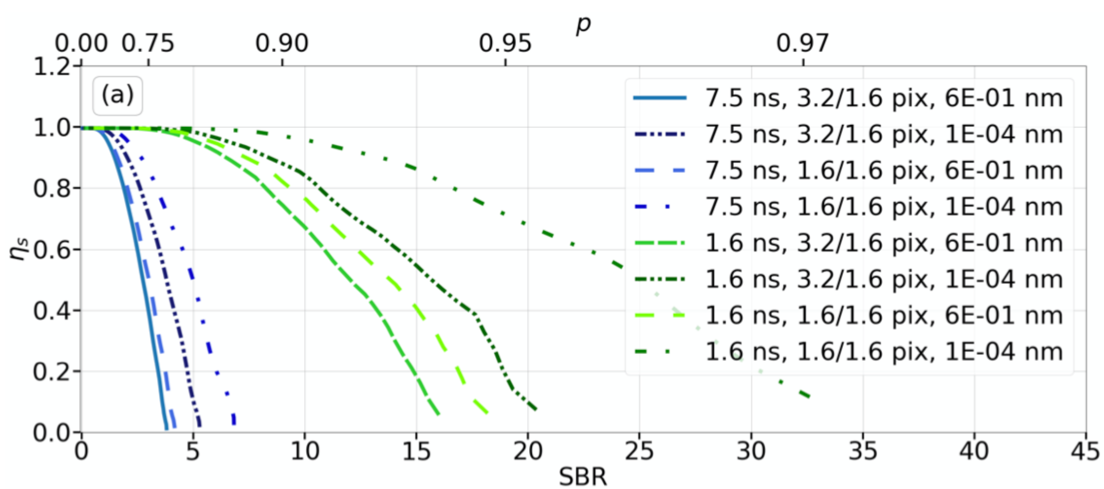
P Svihra, Y Zhang et al, Multivariate Discrimination in Quantum Target Detection, arXiv preprint arXiv:2005.00612 Appl. Phys. Lett. **117**, 044001 (2020)

Projected performance

Can vary resolutions and rates and check performance



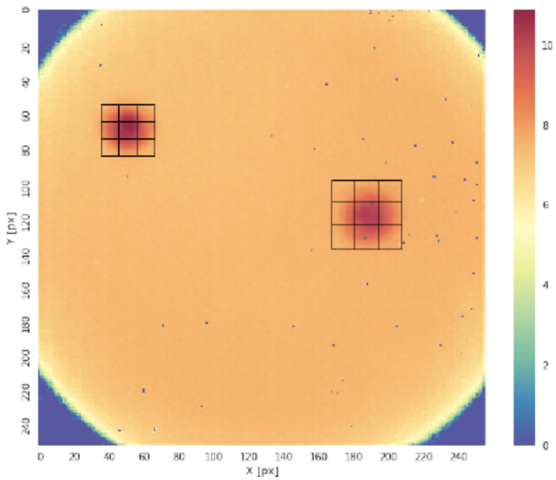
change of jamming rate

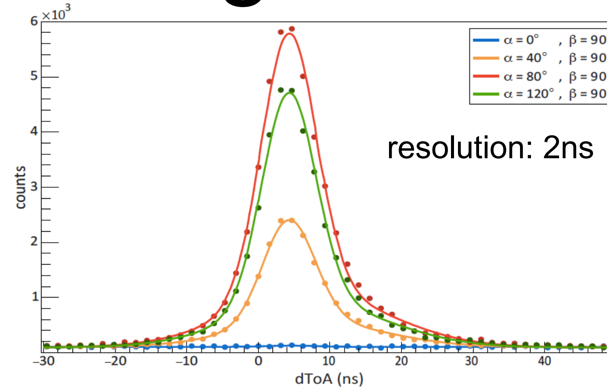


change of temporal
and spectral resolutions

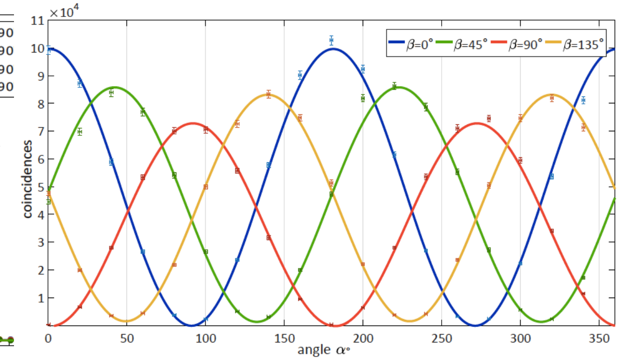
Other applications of fast imaging in quantum optics and QIS

Spatial characterization of polarization entanglement



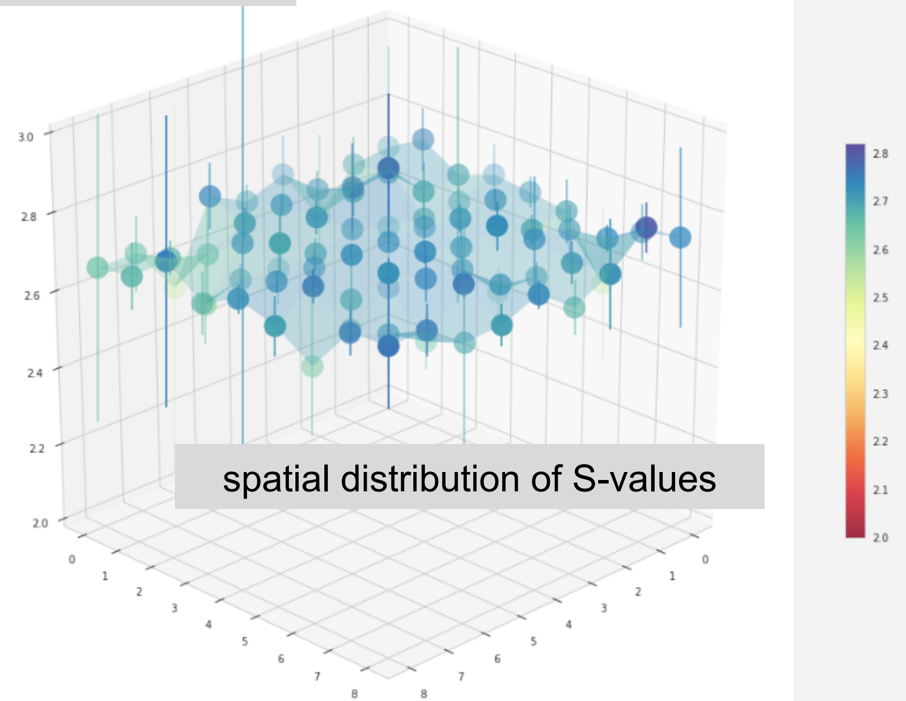


Time difference between photons



Polarization angle

- Find coincidences for SPDC pairs, plot as function of two polarizations
- S-value = 2.72±0.02
- Measure S-value for 81 combinations of subareas



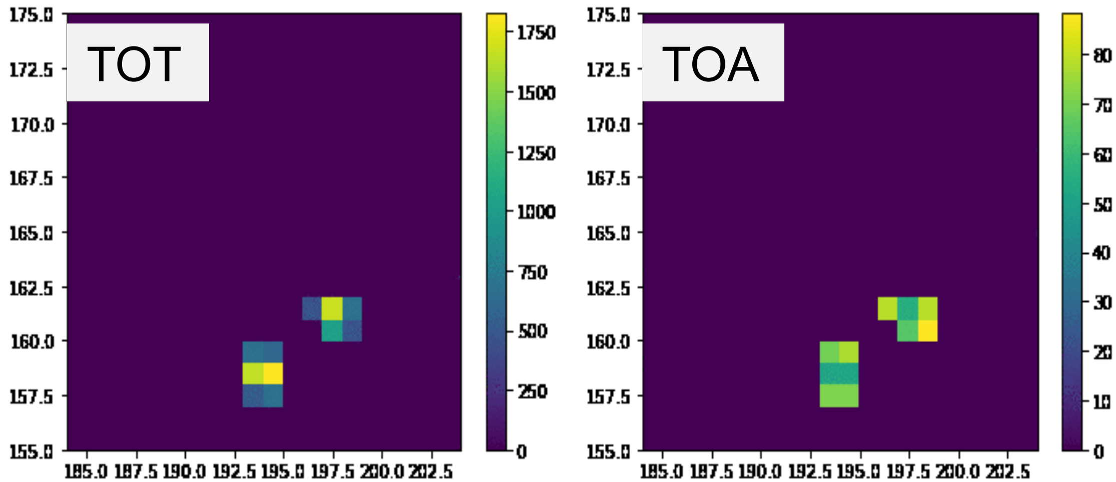
spatial distribution of S-values

Fast camera spatial characterization of photonic polarization entanglement

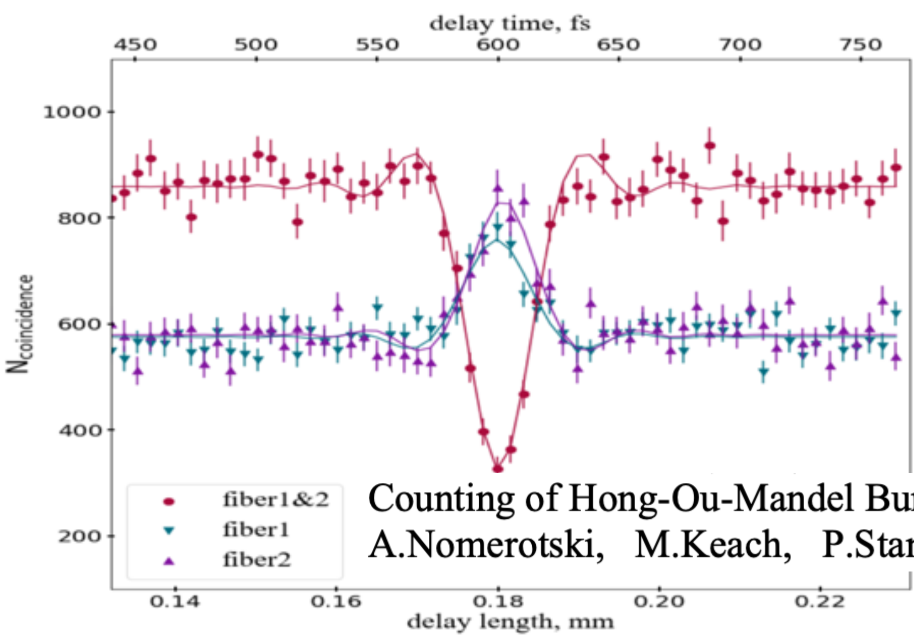
Christopher Ianzano, Peter Svihra, Mael Flament, Andrew Hardy, Guodong Cui, Andrei Nomerotski & Eden Figueroa

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

Counting of HOM bunched pairs



Pairs of bunched photons in Tpx3Cam

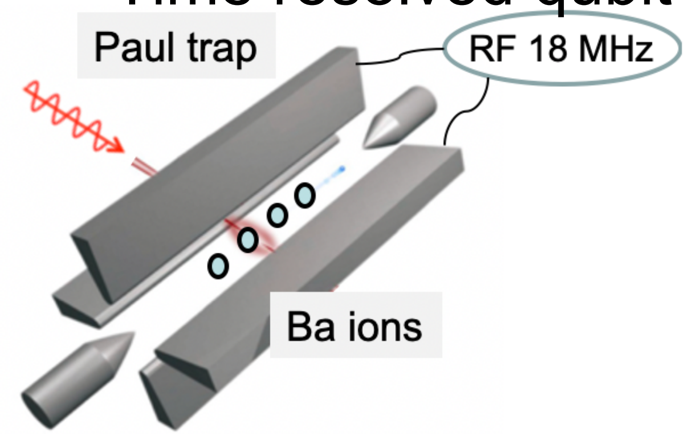


HOM dip for coincidences and bunching in single fibers

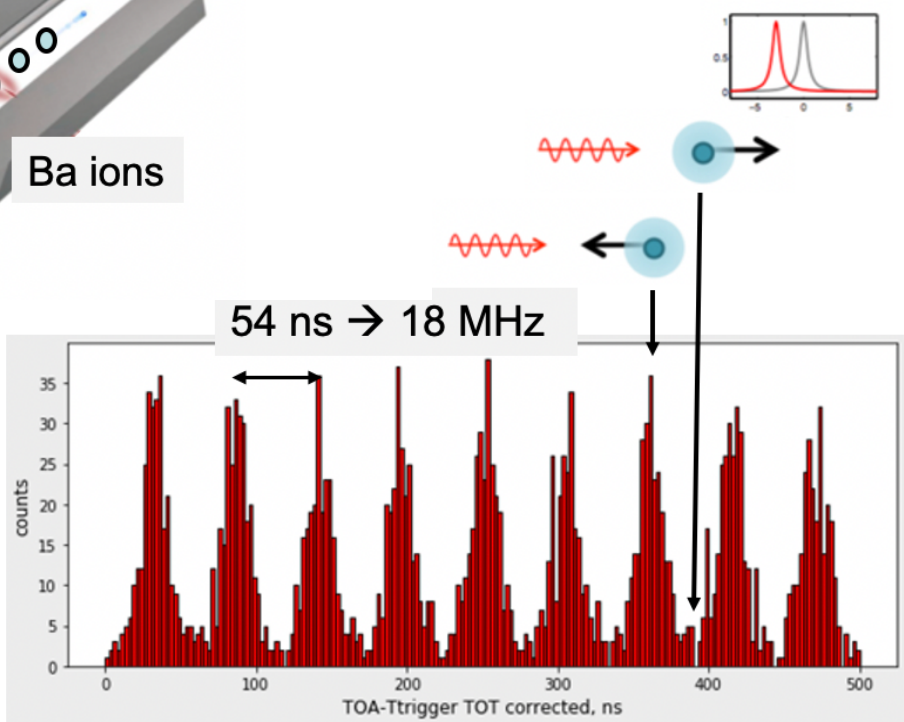
Counting of Hong-Ou-Mandel Bunched Optical Photons Using a Fast Pixel Camera, A.Nomerotski, M.Keach, P.Stankus, P.Svihra, and S.Vintskevich, *Sensors* **2020**, *20*, 3475.

Imaging of trapped ions

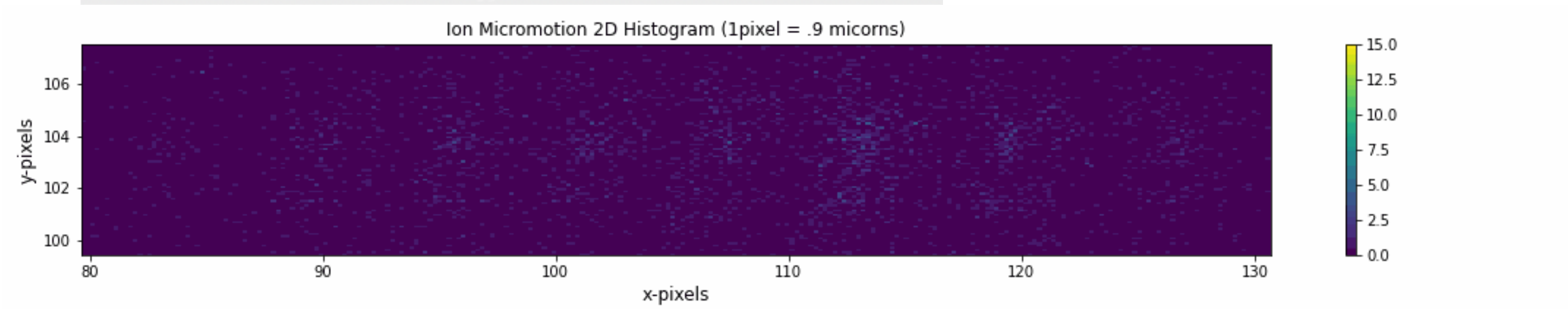
Time resolved qubit manipulation (Blinov group, UWash)



- Register 493 nm photons to probe dark/bright state of ion
- Emission rate oscillations due to Doppler shift of laser light wrt moving ion



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



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
- Both position and temporal information is available photon by photon with no deadtime at 10's MHz rate → allows to implement multi-dimensional approaches
- Variety of applications in quantum optics and QIS

Acknowledgements

Eden Figueroa
Paul Stankus
Tom Tsang
Justine Haupt
Mael Flament
Guodong Cui
Sonali Gera
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