Fast time-stamping of single photons for quantum applications

Andrei Nomerotski, Czech TU & FIU

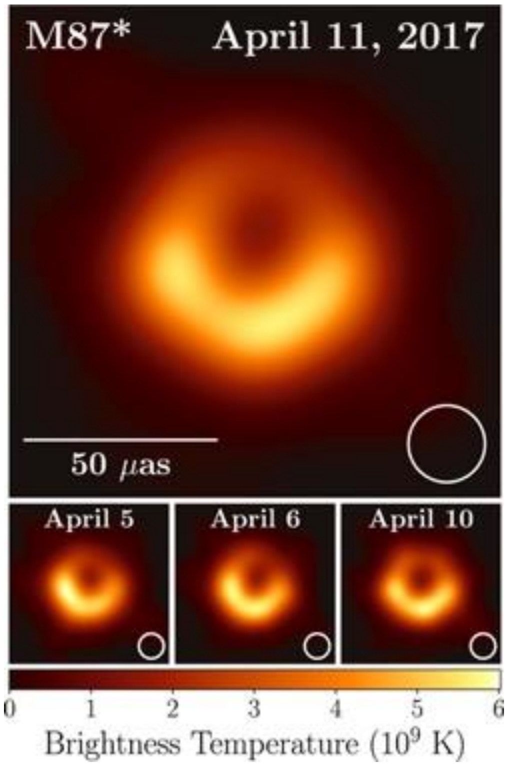
Will talk about

- Science motivations of fast Imaging

- Astrophysics
- Quantum sciences

- Current technologies and future directions

Astronomy picture of the decade



2019 ApJL 875

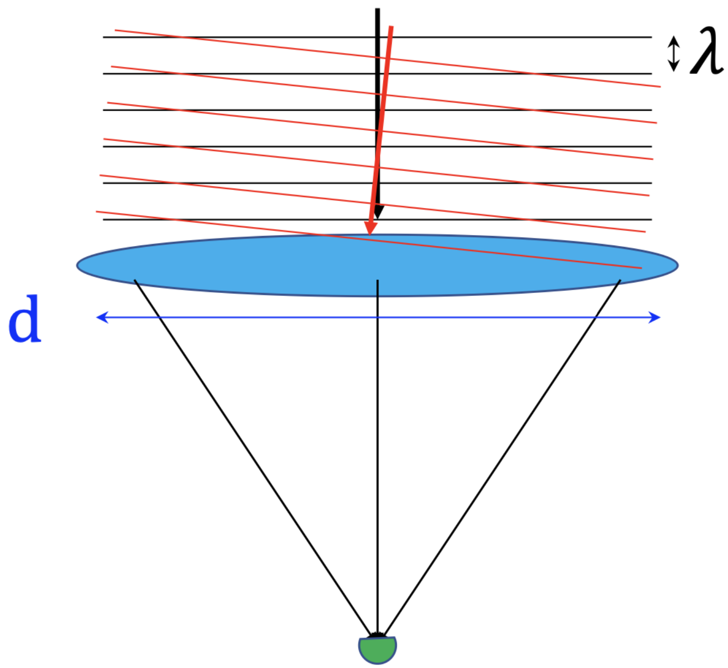
sensitive to features on angular scale

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

Black hole in the center of M87 imaged at 1.3mm

Achieved by radio interferometry with ~10000 km baselines

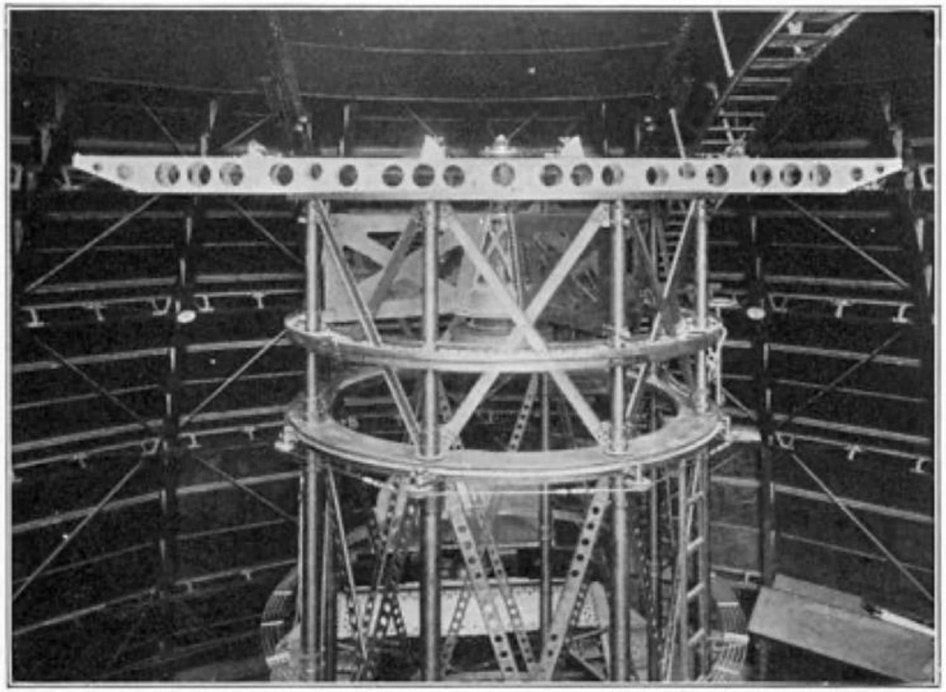
Single Aperture: Diffraction Limit



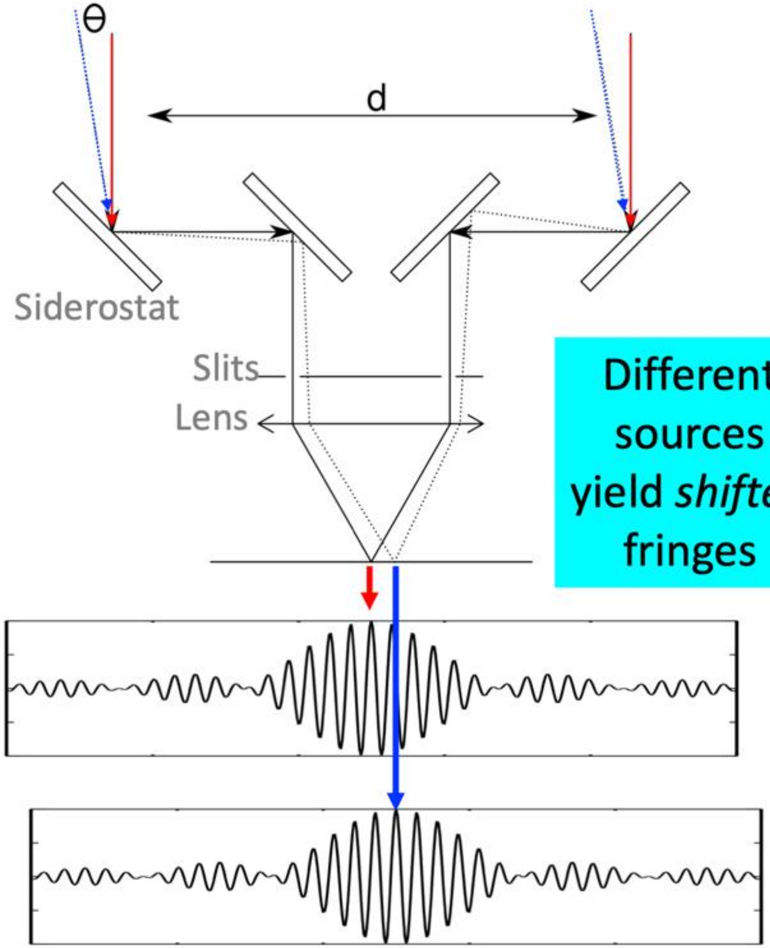
A single detector/pixel point will collect intensity from a range of angles. The limit of this angular range is $\Delta\theta \sim \lambda/d$ after which the wavefront will interfere with itself destructively across the aperture. Therefore any single-aperture telescope cannot resolve features with angular size smaller than λ/d

Classical interferometery

In classical times



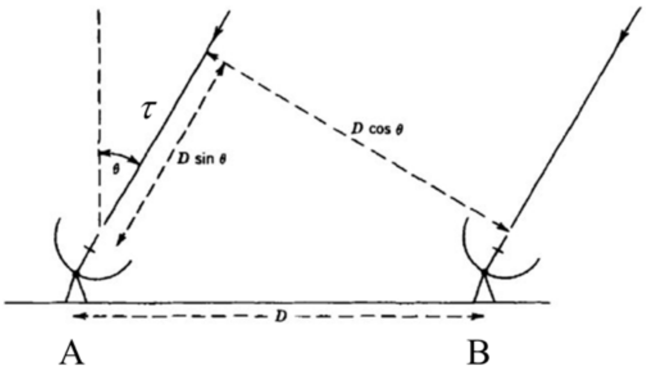
Michelson Stellar Interferometer at Mt. Wilson c. 1920, after original idea by Michelson & Fizeau c. 1890



Different sources yield *shifted* fringes

Radio

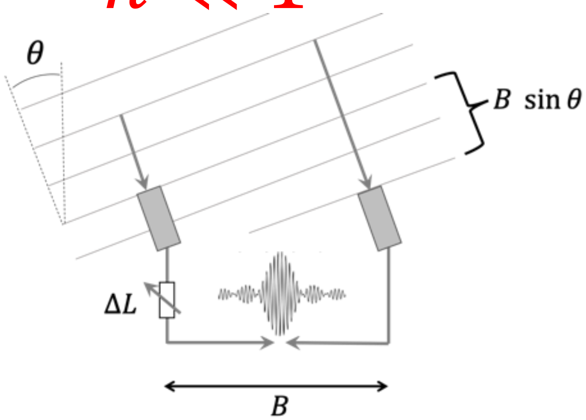
$\bar{n} \gg 1$ mode population



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

Optical

$\bar{n} \ll 1$ mode population



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

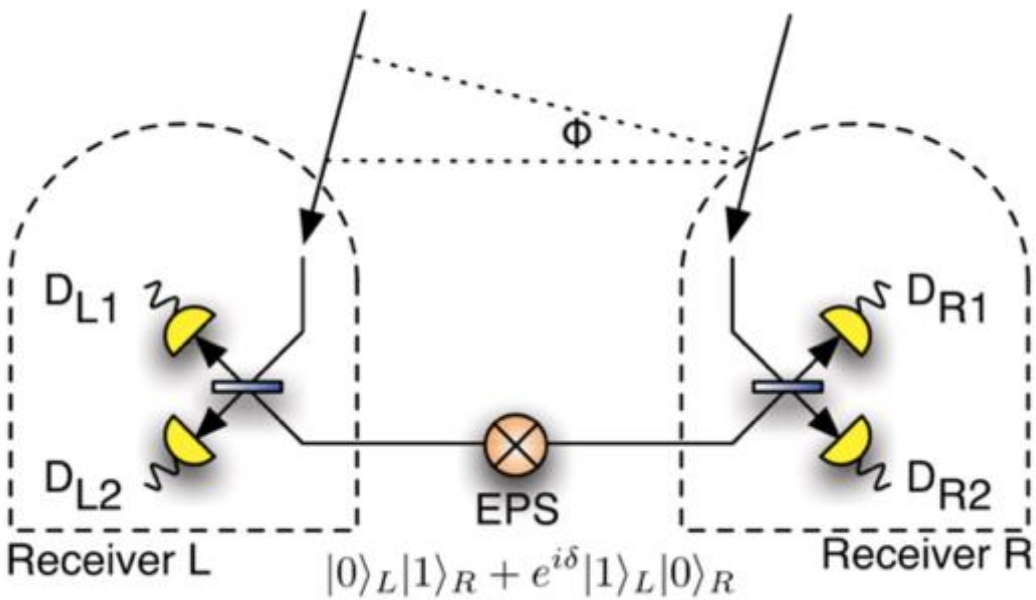
Accuracy ~ 1 mas

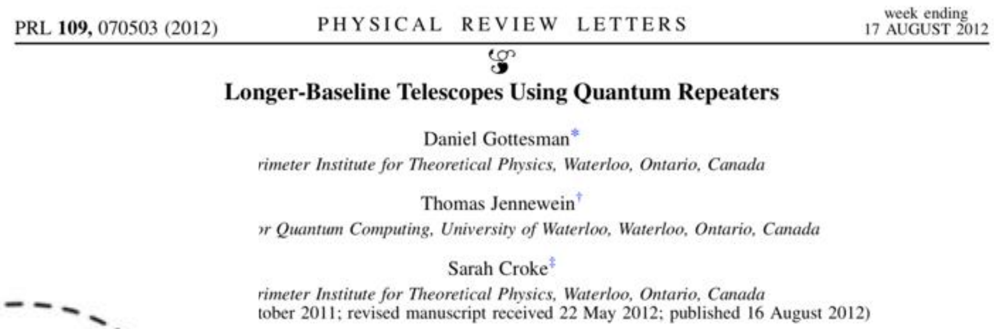
Max baselines to ~ 100 m

Two-photon techniques

Second photon for quantum assist

Quantum (two-photon) interferometer





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

Longer-Baseline Telescopes Using Quantum Repeaters

Daniel Gottesman*
rimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada

Thomas Jennewein†
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Sarah Croke‡
rimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada

tober 2011; revised manuscript received 22 May 2012; published 16 August 2012)

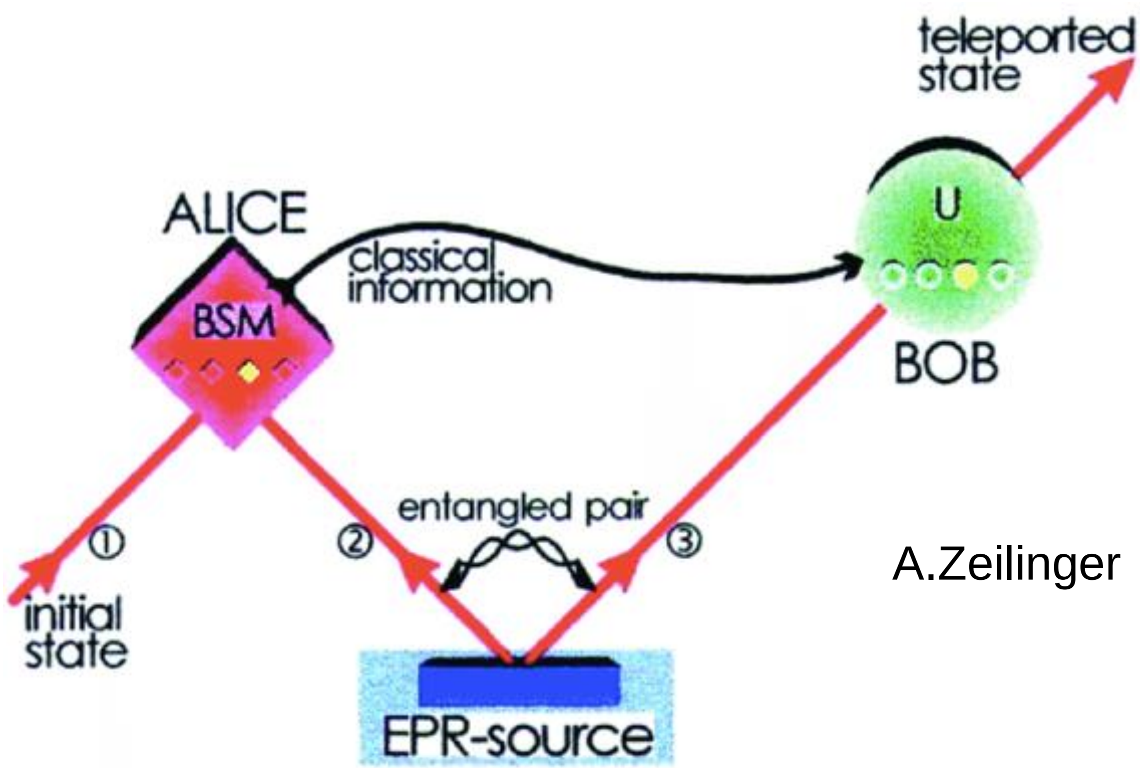
$$\Delta\theta \sim \frac{\lambda}{b}$$

- Coincidences of counters in two stations are sensitive to phase → to direction
- Measure photon wave function at one station so effectively teleport the sky photon to the other station
- Need to transfer the photon quantum state → can use quantum networks, this will allow long distances, orders of magnitude better resolution, great impact

Quantum Network

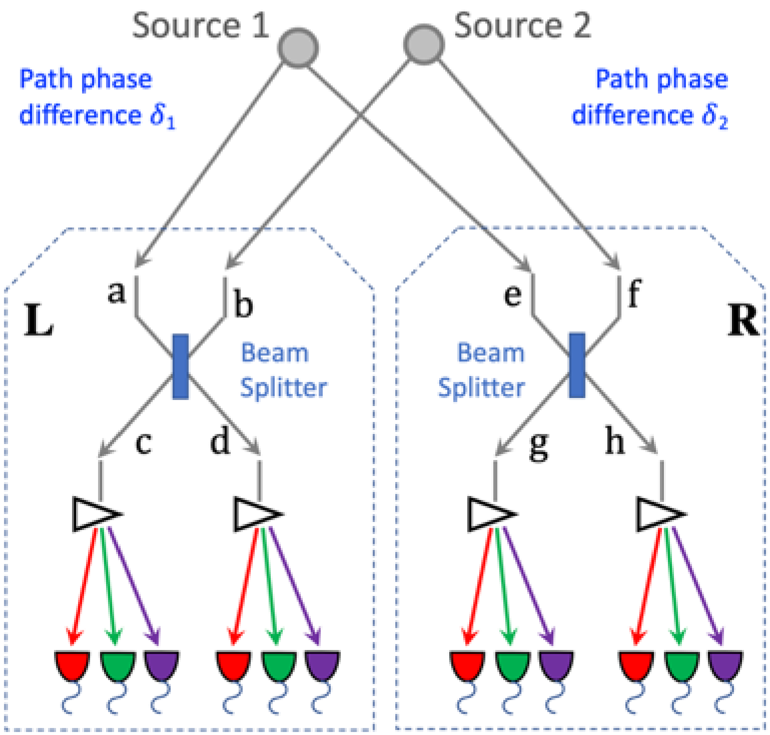
- Attenuation in fibers → need quantum repeater to reproduce qubits
  - Simple amplification will not conserve the quantum state

- 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

New ideas extending original proposal




Instrumentation and Methods for Astrophysics

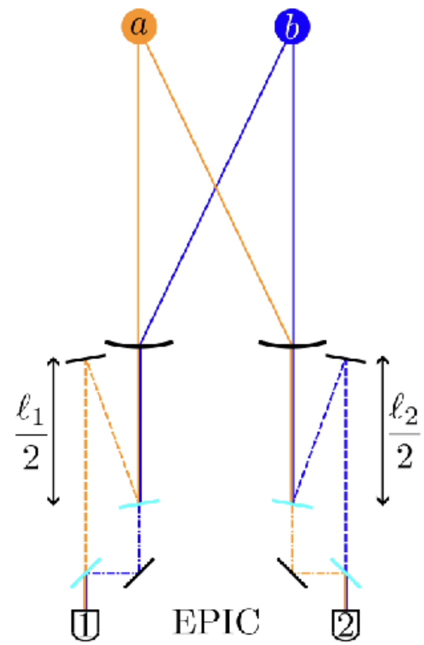
Vol. 5, 2022 · November 01, 2022 IST

Two-photon amplitude interferometry for precision astrometry

Paul Stankus, Andrei Nomerotski, Anže Slosar, Stephen Vintskevich

https://doi.org/10.21105/astro.2010.09100

arxiv.org/abs/2010.09100



Astrometry with Extended-Path Intensity Correlation

Ken Van Tilburg,[1,2,*] Masha Baryakhtar,[3,†] Marios Galanis,[4,‡] and Neal Weiner[1,§]

[1] *Center for Cosmology and Particle Physics, Department of Physics, New York University, New York, NY 10003, USA*

[2] *Center for Computational Astrophysics, Flatiron Institute, New York, NY 10010, USA*

[3] *Department of Physics, University of Washington, Seattle WA 98195, USA*

[4] *Perimeter Institute for Theoretical Physics, Waterloo, Ontario N2L 2Y5, Canada*

(Dated: July 10, 2023)

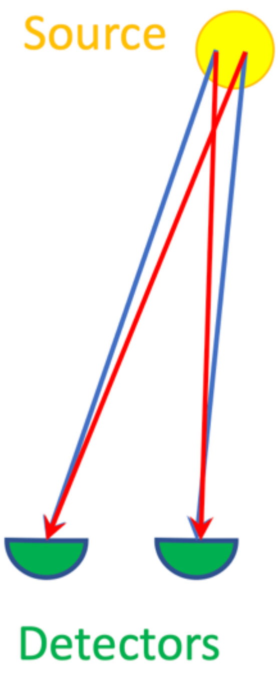
arxiv.org/abs/2307.03221

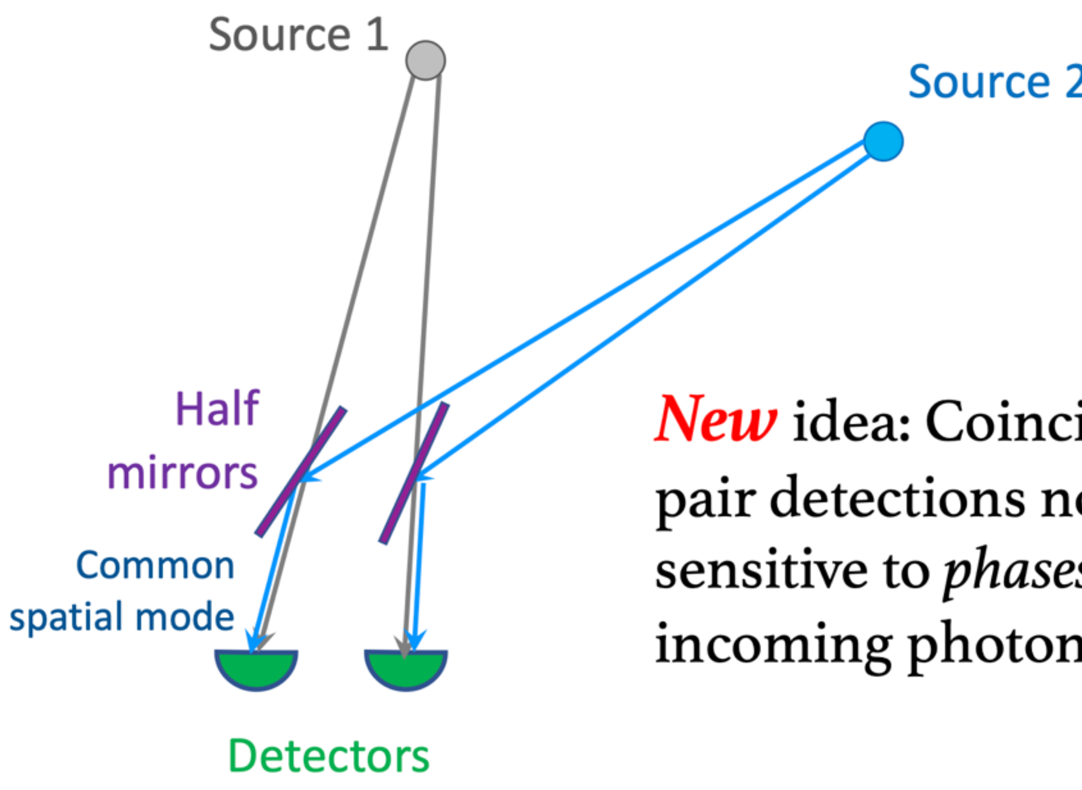
Extensions of Stellar Intensity Interferometry bridging to quantum-enhanced ideas

Perfect to start exploring this approach

Hanbury Brown – Twiss Interferometry

HBT with two sources?





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

Stellar Intensity Interferometry

arXiv.org > astro-ph > arXiv:1810.08023

Astrophysics > Instrumentation and Methods for Astrophysics

Intensity Interferometry revival on the Côte d'Azur

Olivier Lai, William Guerin, Farrokh Vakili, Robin Kaiser, Jean Pierre Rivet, Mathilde Fouché, Guillaume Labeyrie, Etienne Samain, David Vernet

(Submitted on 18 Oct 2018)

No. 4, 1967 *The stellar interferometer at Narrabri Observatory—II* 405

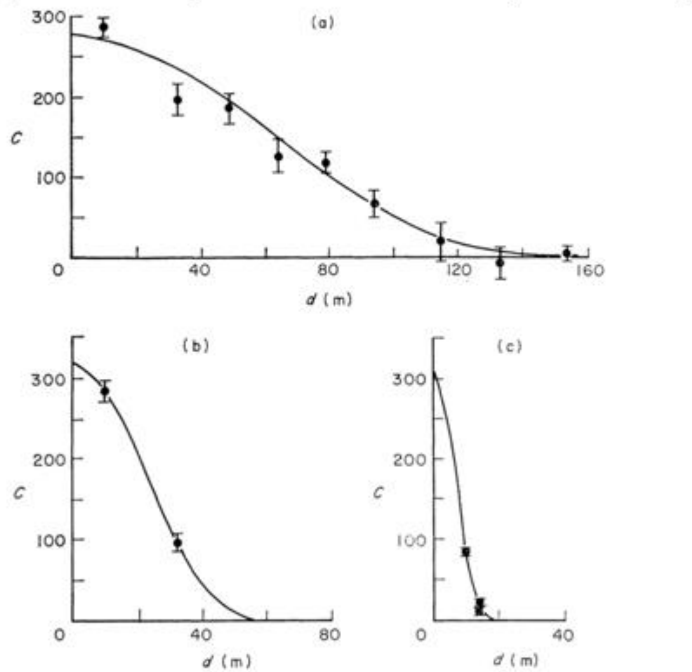


FIG. 3. *Examples of the observed variation of correlation with baseline for three stars.* (a) β Cru (1965); (b) α Eri (1965); (c) α Car (1965).

Hanbury Brown, Davis, Allen, Rome; MNRAS **137**, (1967) p393-417

renewed interest due to progress in fast detectors!

Requirements for detectors

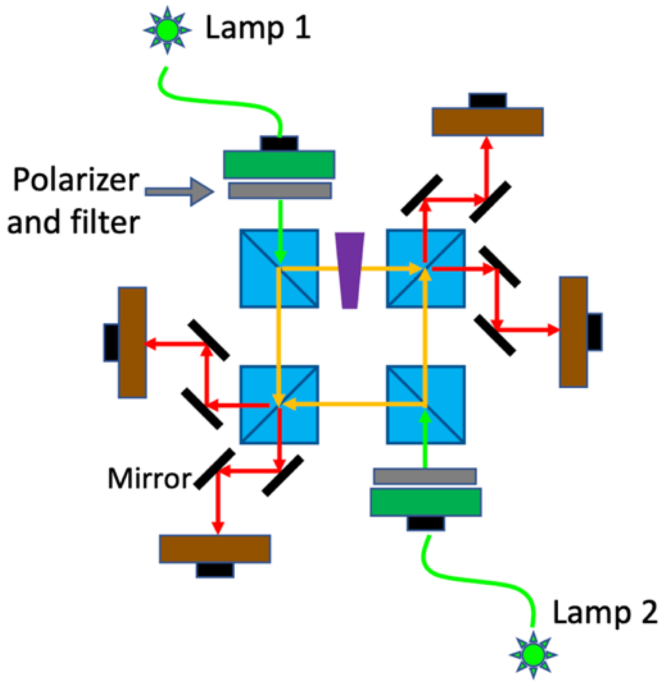
Photons must be indistinguishable so close enough in frequency and time to interfere → temporal & spectral binning :
need ~ 0.02 nm * 10 ps

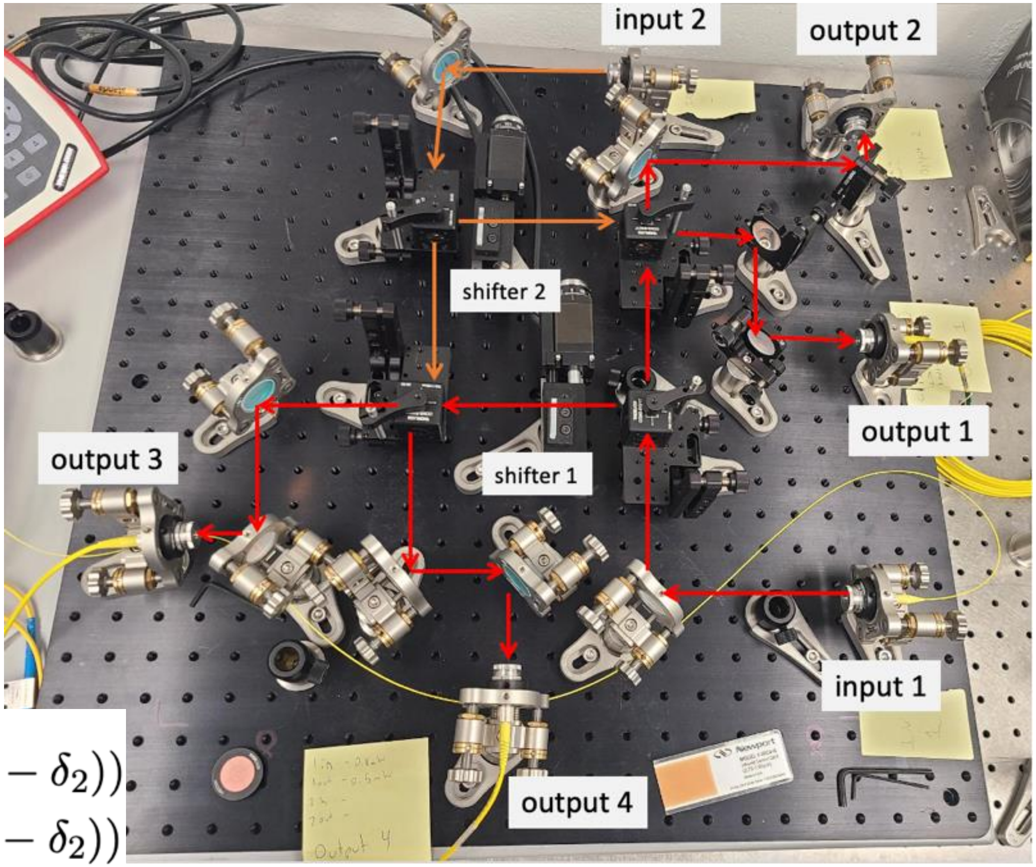
$$\Delta t * \Delta E \geq \hbar/2$$

Fast spectrometers at Heisenberg UP limit

- Fast imaging techniques are the key
  - Promising technologies: **SPADs**, SNSPDs
  - Target 1-100 ps resolution
- Spectral binning: diffraction gratings
- High photon detection efficiency

Benchtop Verification



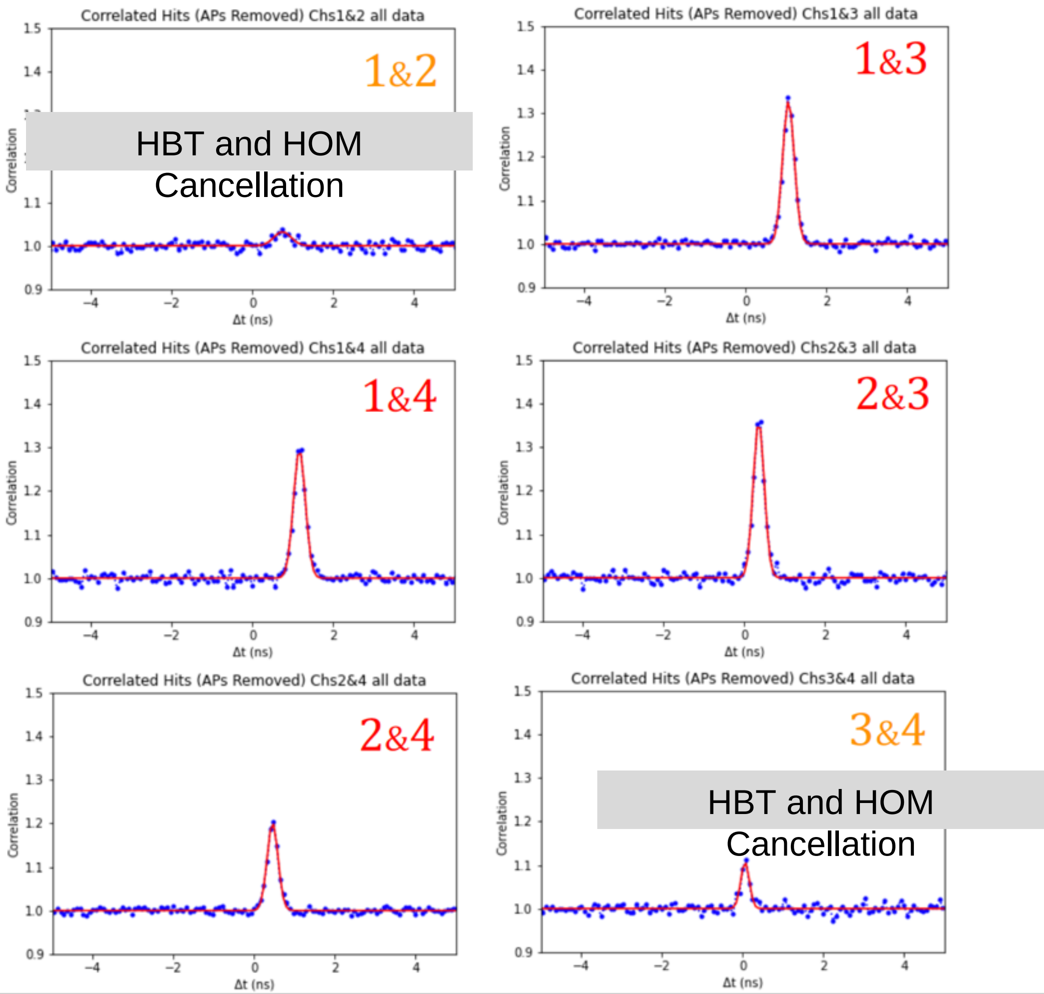


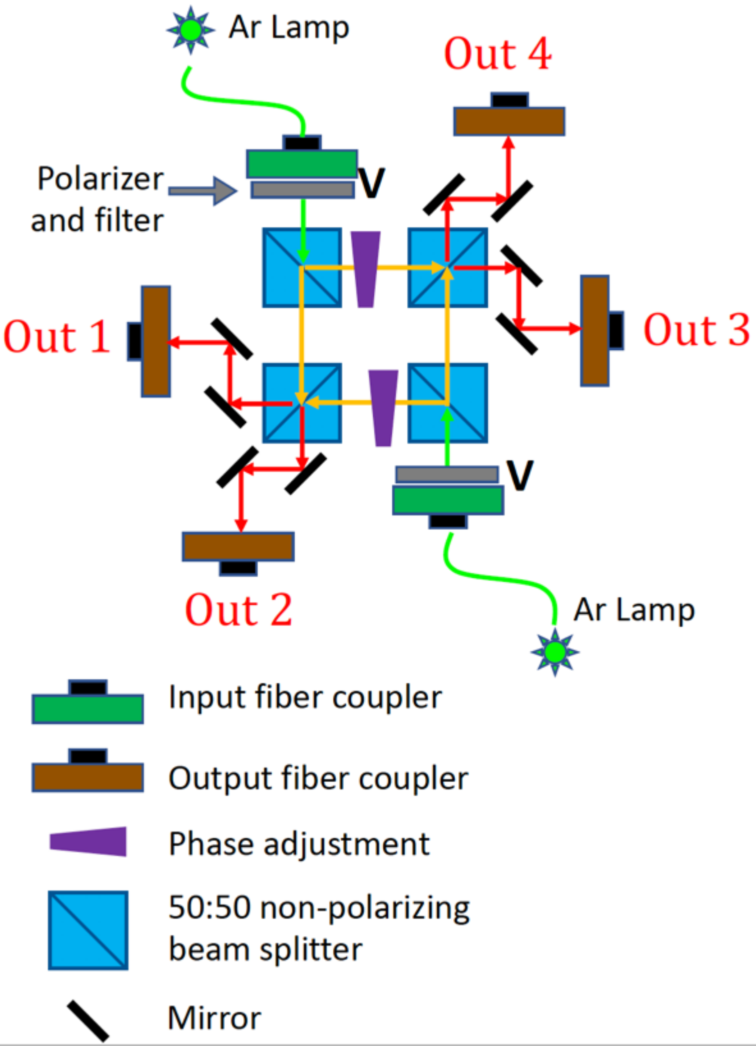
$$P(cg) = P(dh) = (1/8)(1+\cos(\delta_1-\delta_2))$$
$$P(ch) = P(dg) = (1/8)(1-\cos(\delta_1-\delta_2))$$

SPAD and SNSPD readout

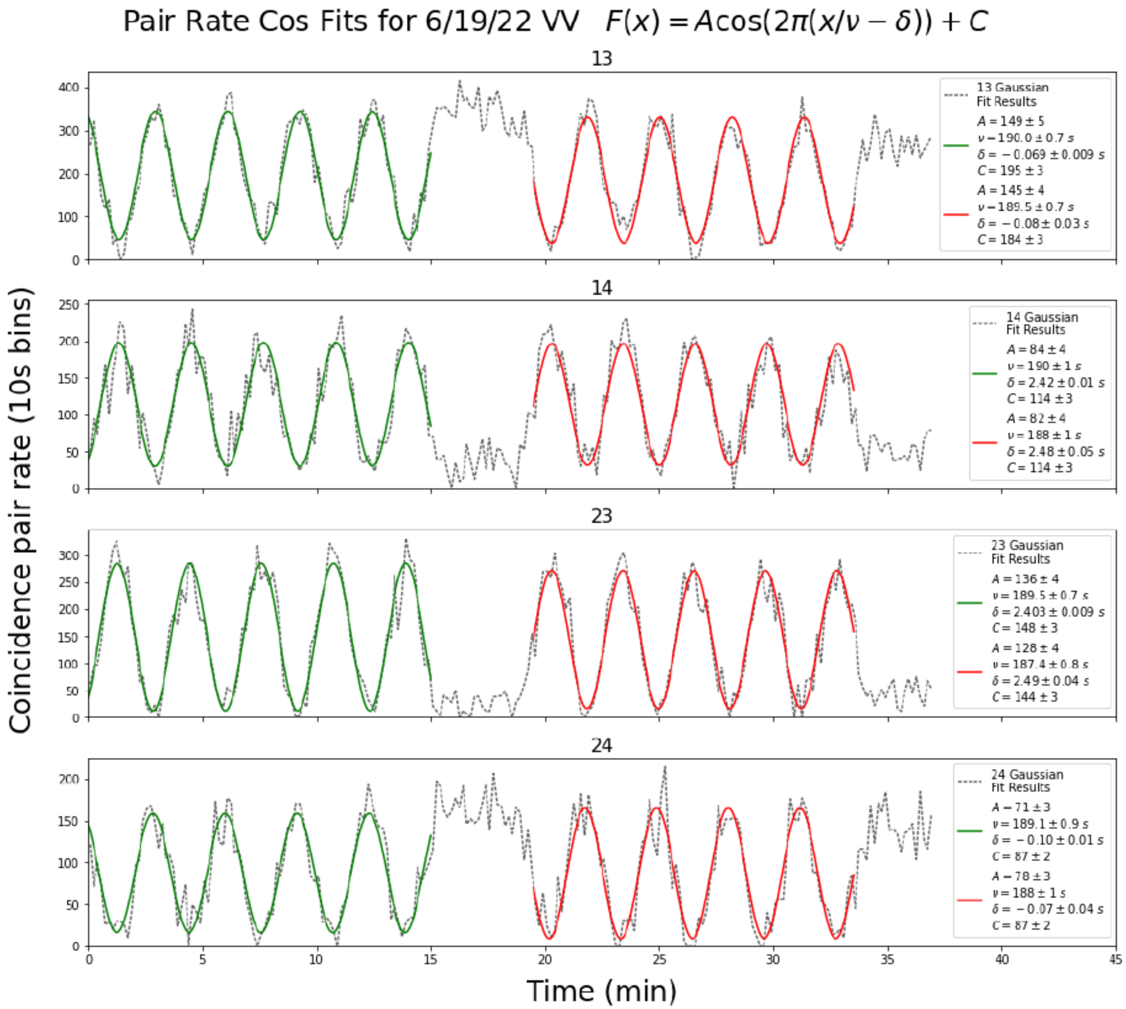
arxiv.org/abs/2301.07042
published in Optics Express

Polarized – V V





Phase dependence

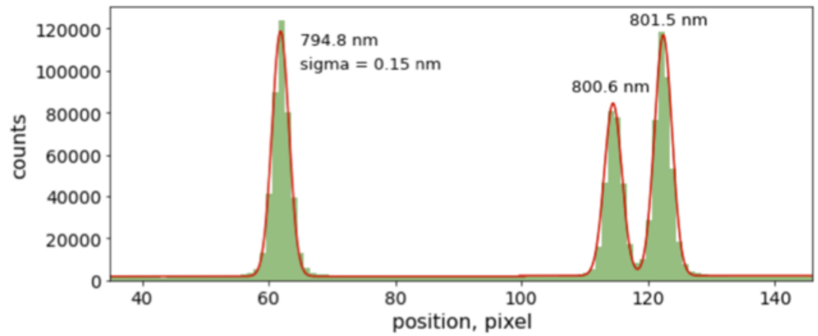


Population of HBT peaks as function of phase = phase oscillations

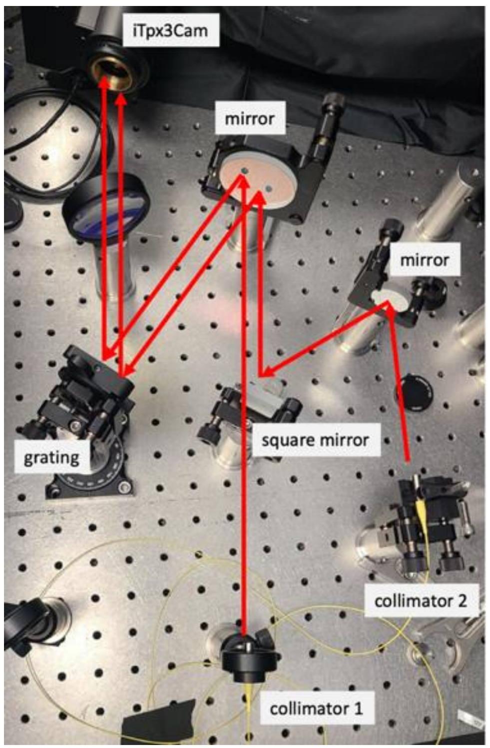
Next step: spectral binning

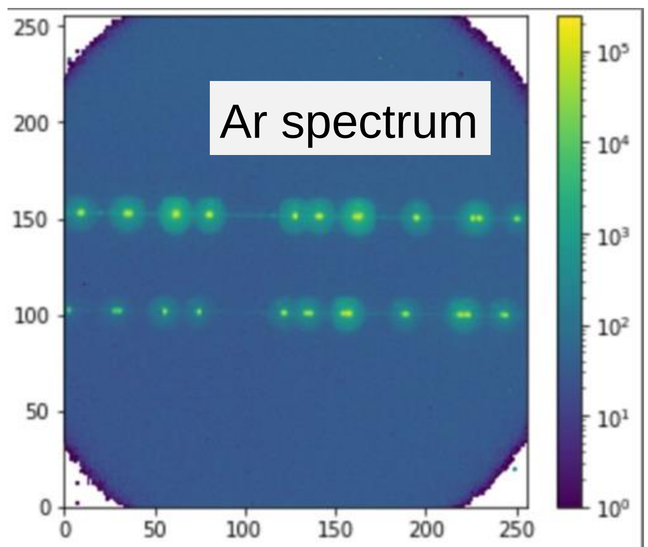
Spectral binning

Two beams of thermal photons → diffraction grating
Based on intensified Tpx3Cam, ns time resolution



spectral resolution for Ar lines ~0.15 nm

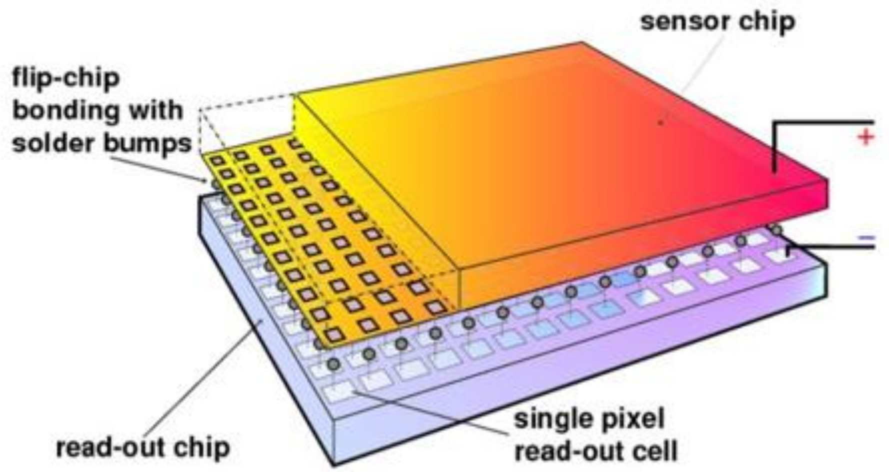




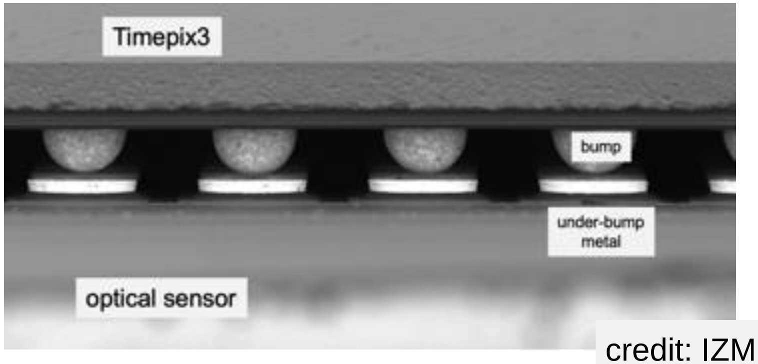
A.Nomerotski et al. Intensified Tpx3Cam, a fast data-driven optical camera with nanosecond timing resolution for single photon detection in quantum applications, arxiv.org/abs/2210.13713, published in JINST

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

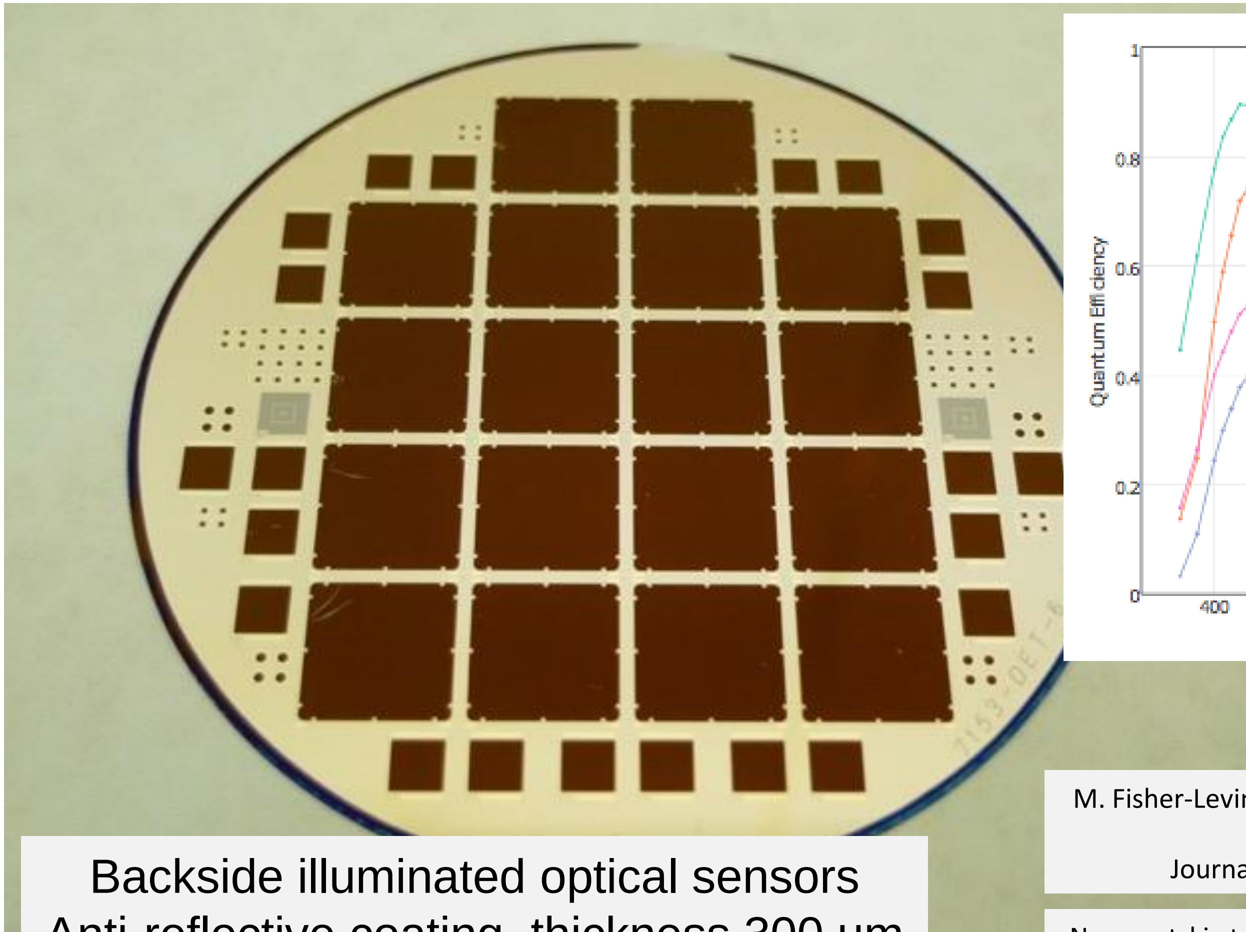
Decouple readout chip and sensor

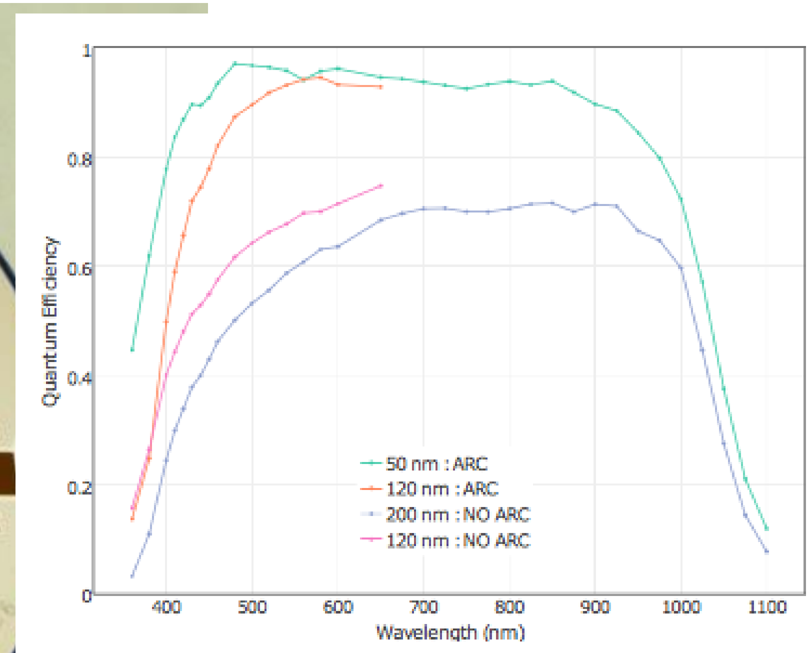
- optimize technologies for chip and sensor separately

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.

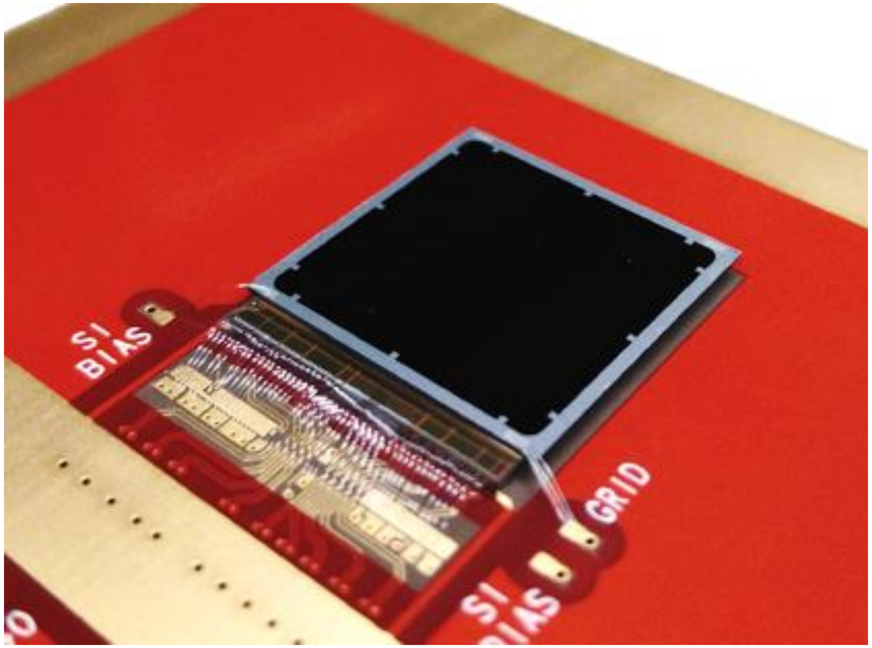
Developed at BNL, first produced at CNM (Barcelona, Spain) in 2015
Surface preparation is very important, inspired by astronomical CCDs (LSST)

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



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.

Intensified camera: use off-the-shelf image intensifier

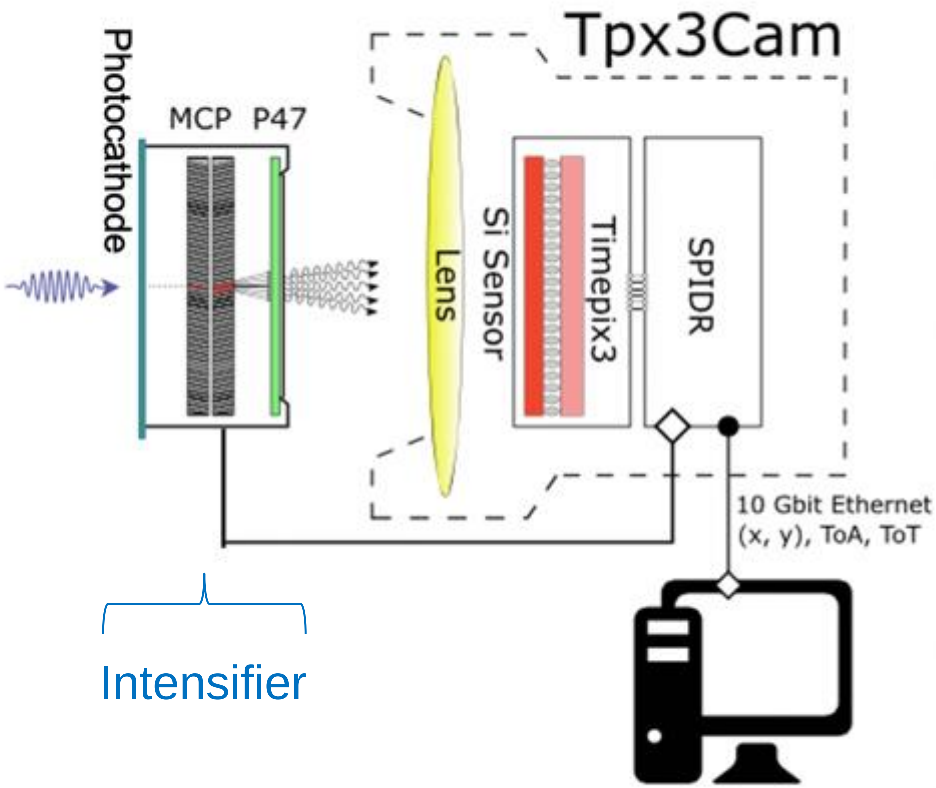
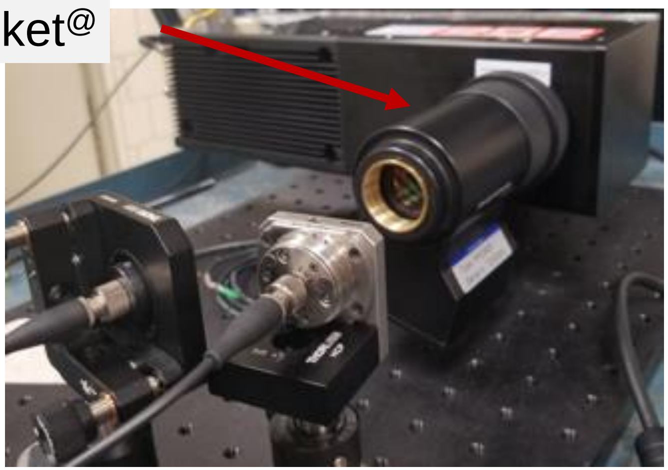


Image intensifier (Photonis PP0360EG)

Cricket@

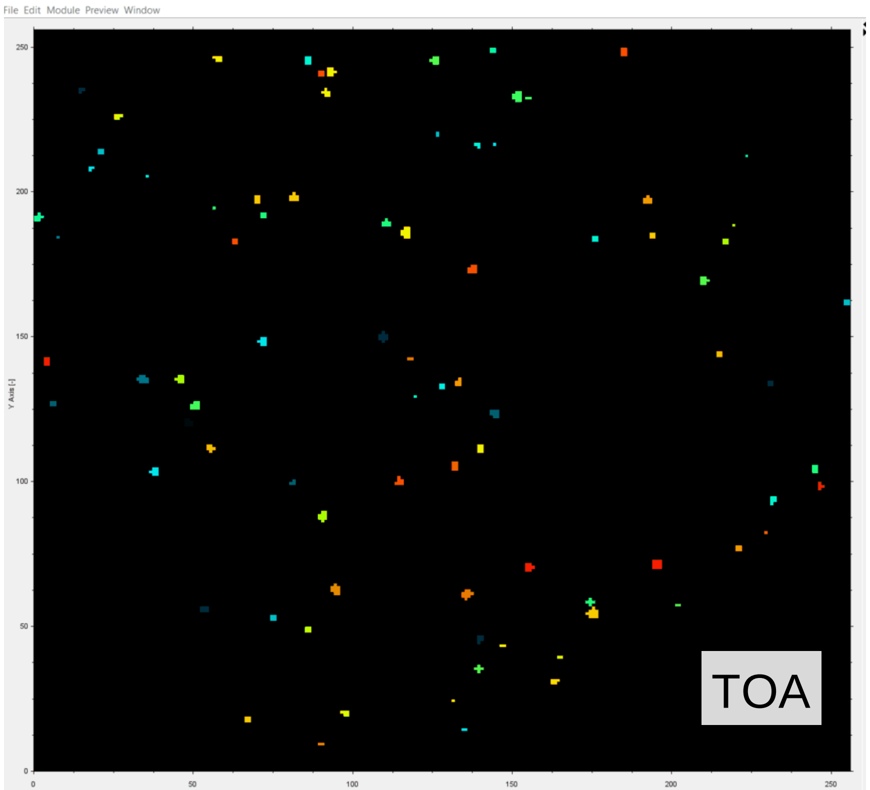


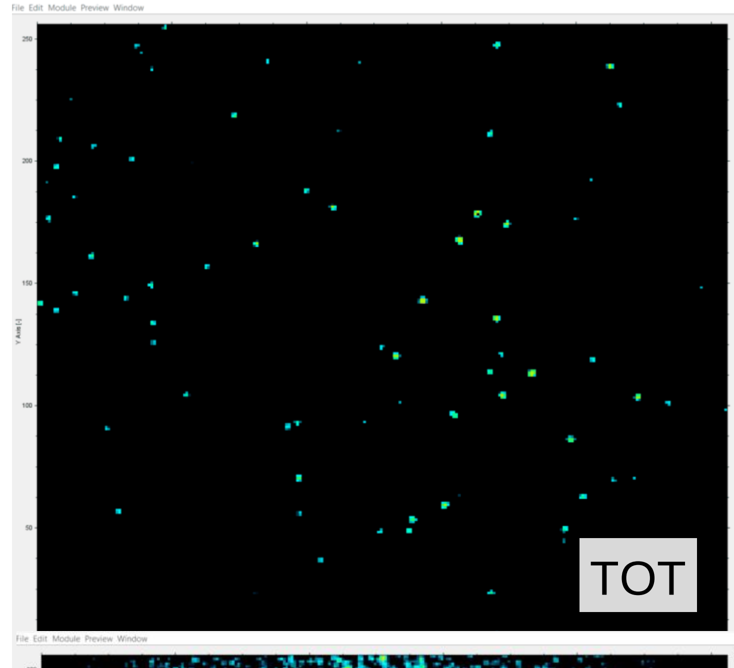
Intensified cameras are common:

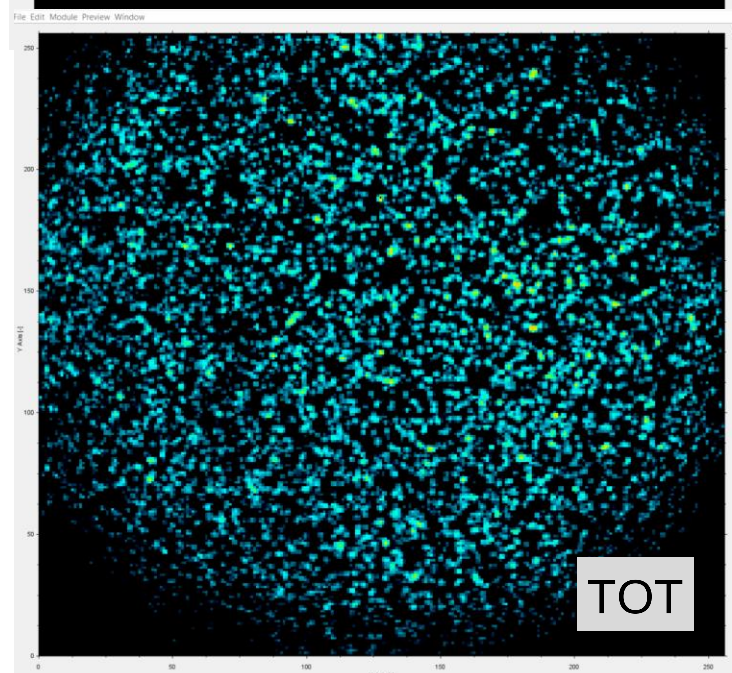
- iCCD
- iCMOS cameras

Single Photons in Tpx3Cam

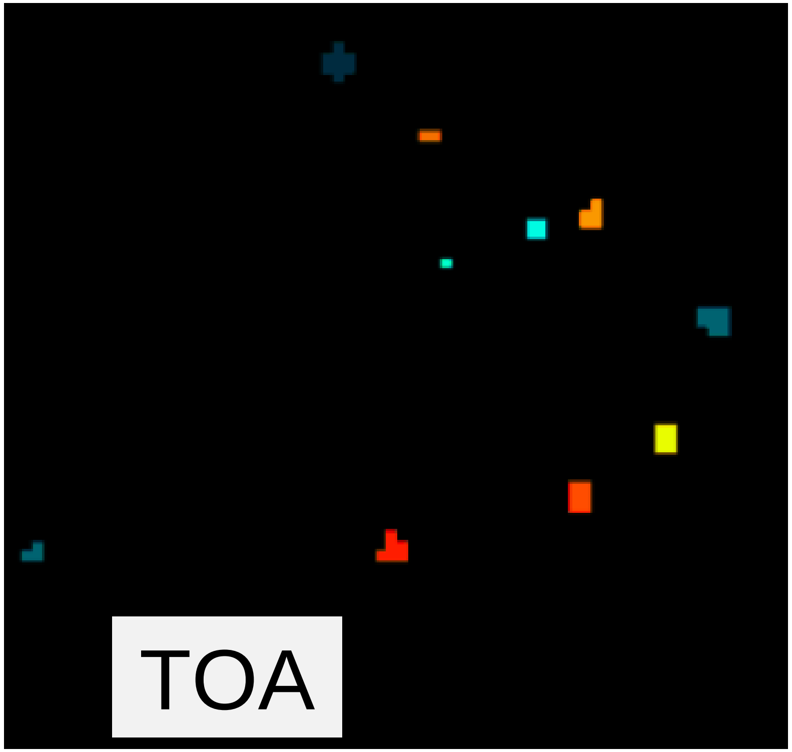
1 ms slice of data
1.5ns time-stamping

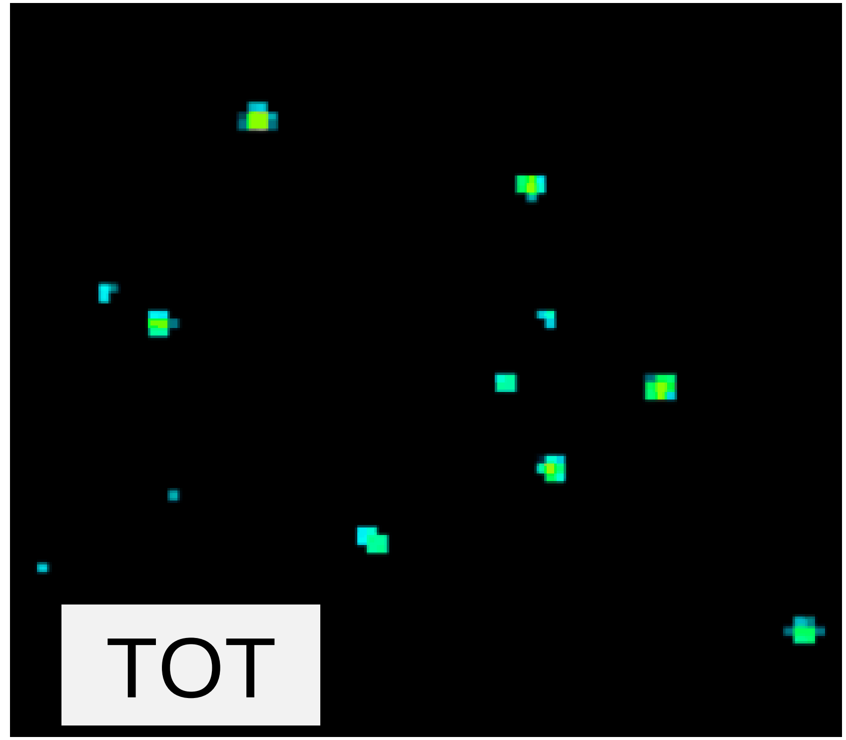






Tpx3Cam + intensifier by Photonis





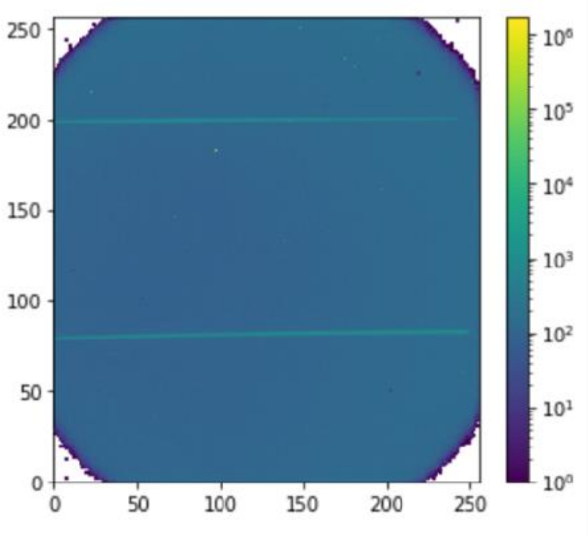
Each photon is a cluster of pixels
à 3D (x,y,t) centoiding

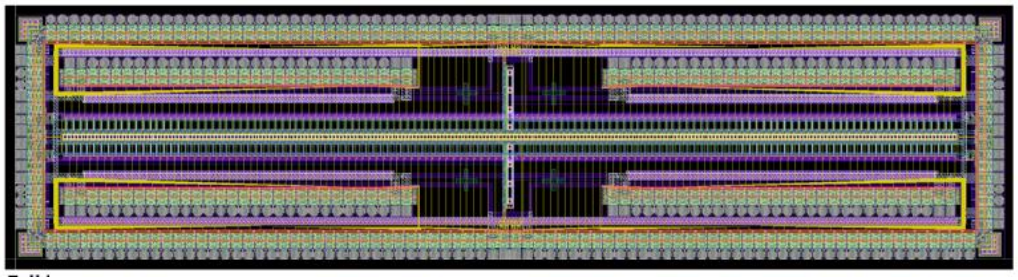
Spatial resolution: 0.1 pixel / photon

Time resolution: < 1 ns / photon

Next steps: spectrometer based on LinoSPAD2

Diffracted photon stripe projected on to linear array



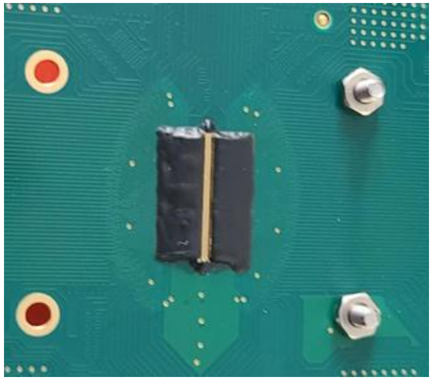


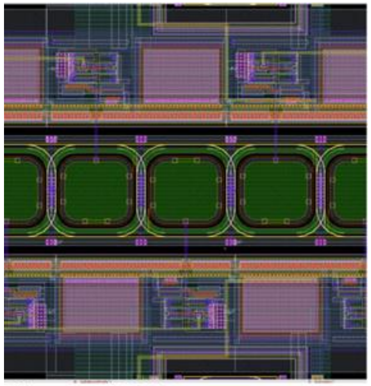
Spectrometer time resolution: 5 ns →100 ps

Possible technologies: SPAD

SPAD = single photon avalanche device
Semiconductor device: p-n junction with amplification

LinoSPAD2

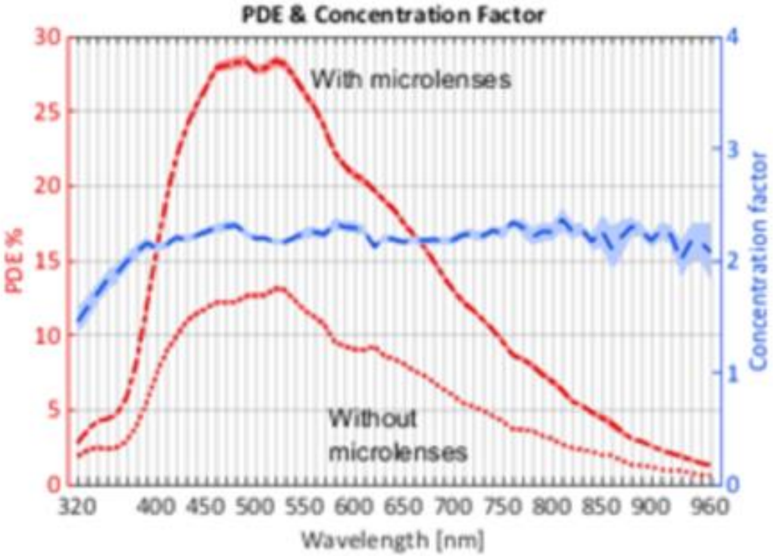




Close-up of SPADs

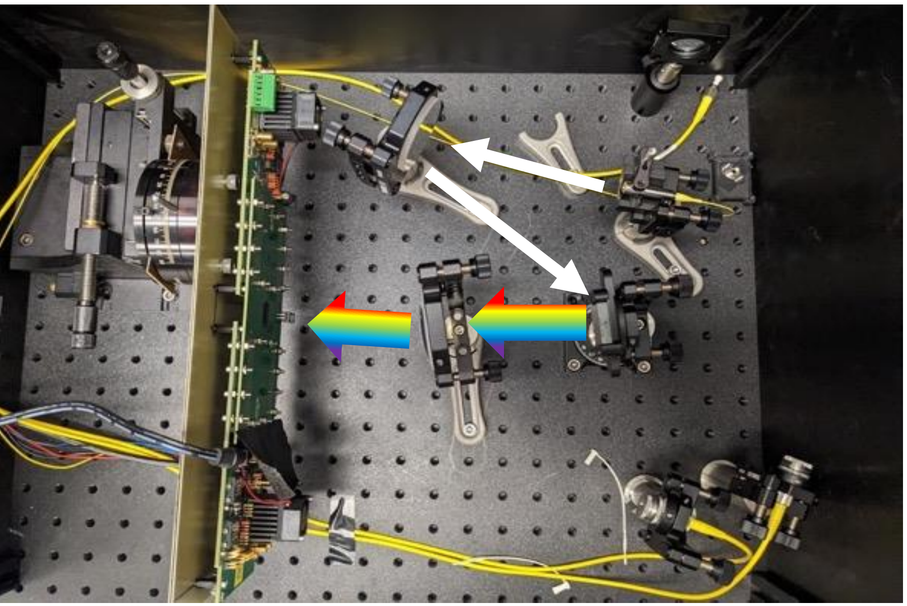
- 512 x 1 pixels
- 24 x 24 micron pixels
- Max PDE (with microlenses) ~ 30%
- 50 ps resolution

Developed in EPFL (Switzerland)



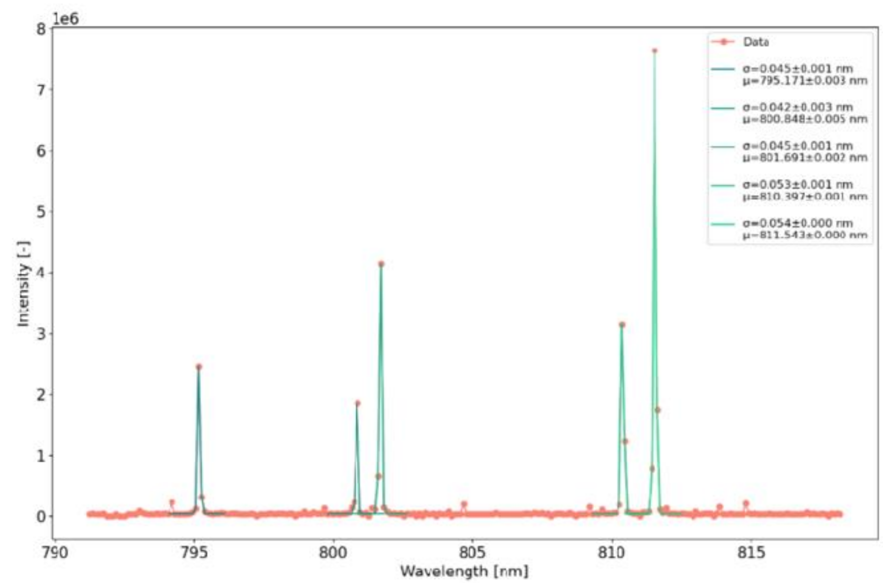
Spectrometer with LinoSPAD2

Used Ar lamp coupled to SM fiber



arxiv.org/abs/2304.11999

Ar spectral lines



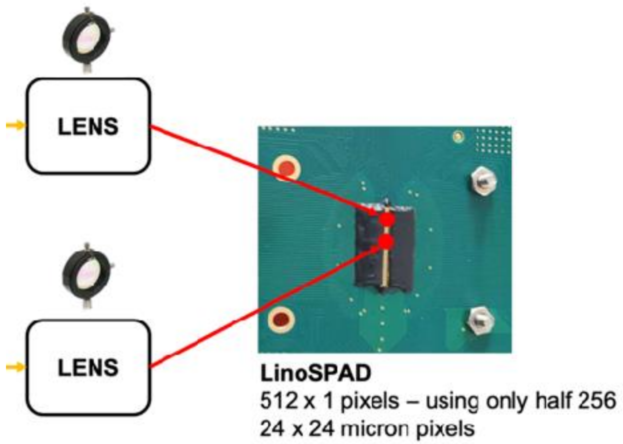
spectral resolution 0.04 nm

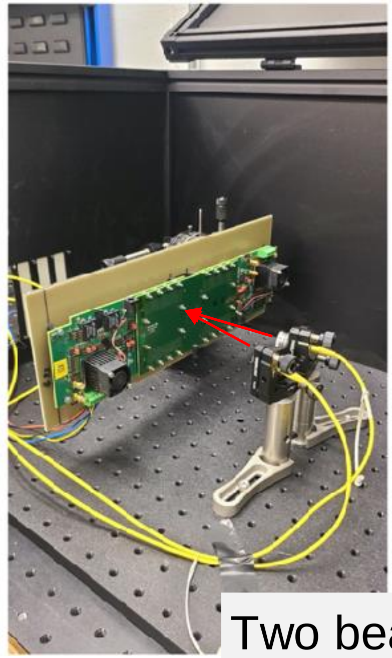
arxiv.org/abs/2304.11999

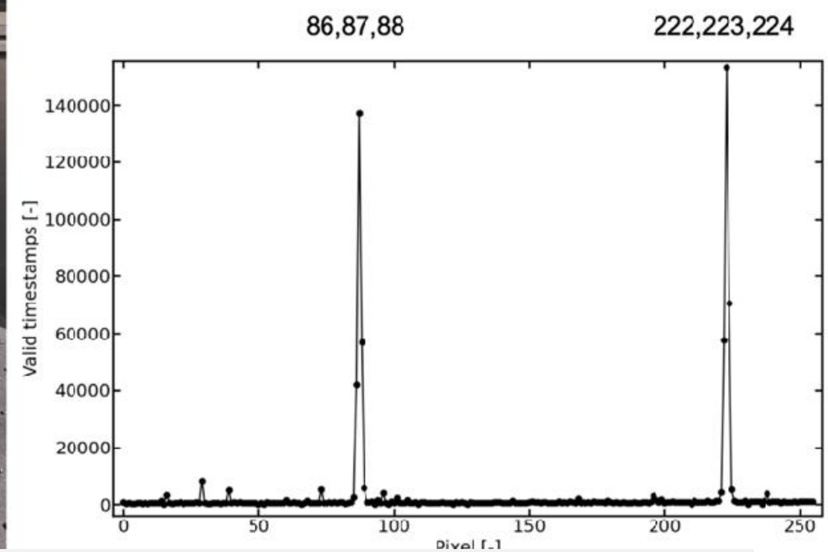
Achieved 0.04 nm spectral and 40 ps timing resolution

only x10 more than $\Delta t * \Delta E \geq \hbar/2$

HBT peaks in LinoSPAD2

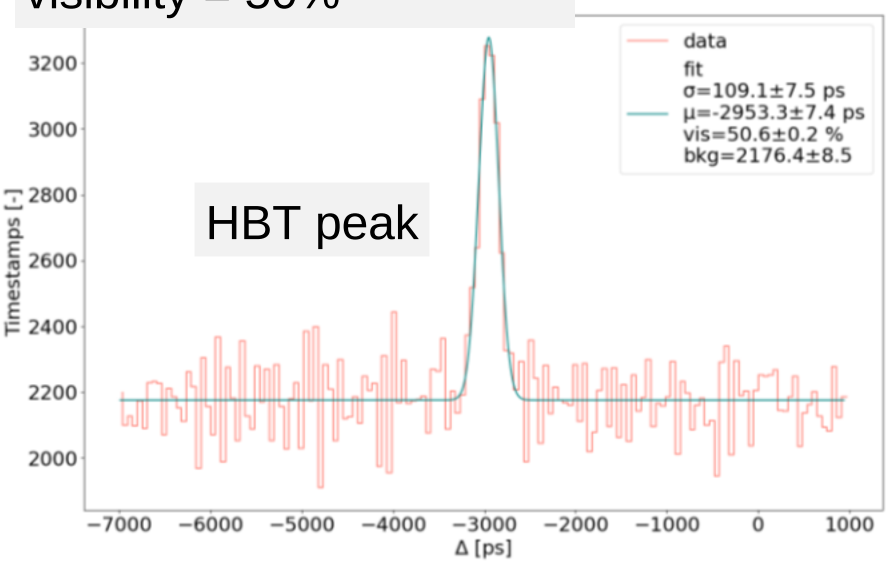






Two beams from Ar lamp + polarizer after beamsplitter

time difference, σ=110 ps
visibility = 50%

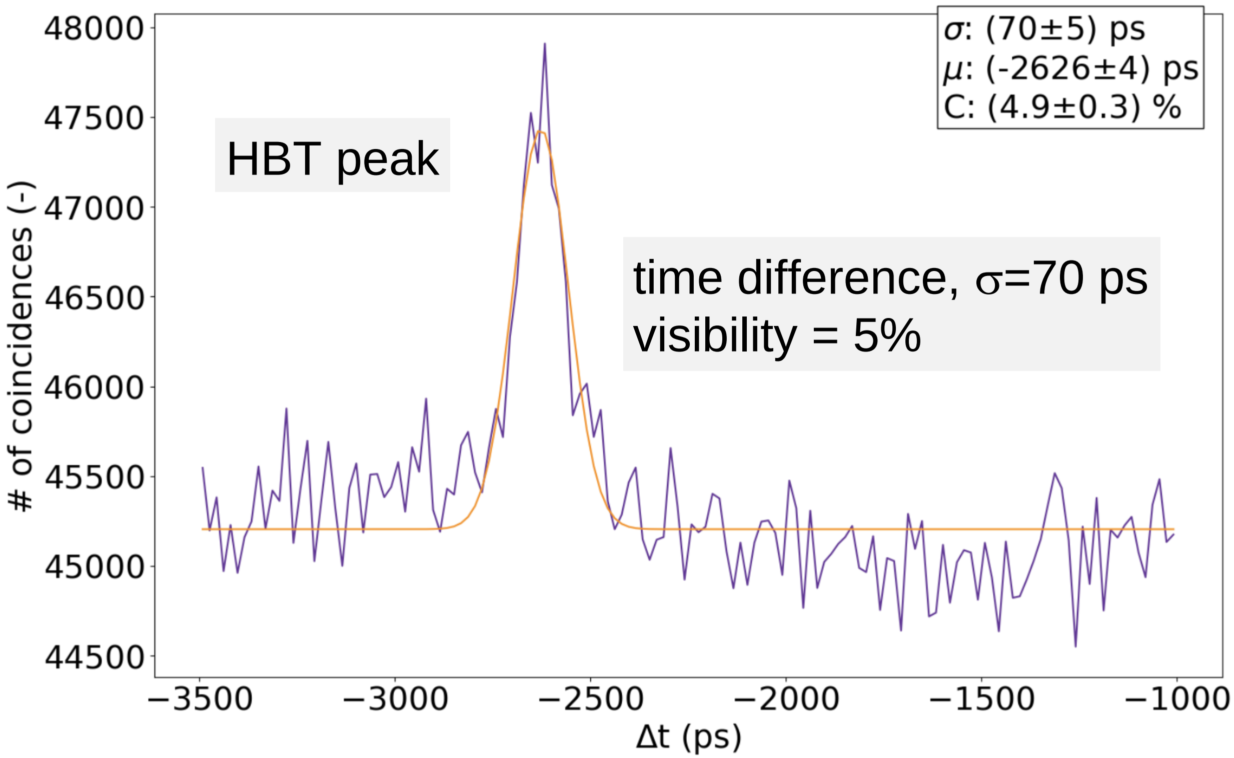


HBT peak

Next step: HBT in spectral bins for broadband light

Broadband HBT peak

Two beams from bright LED + 0.1 nm filter + polarizer

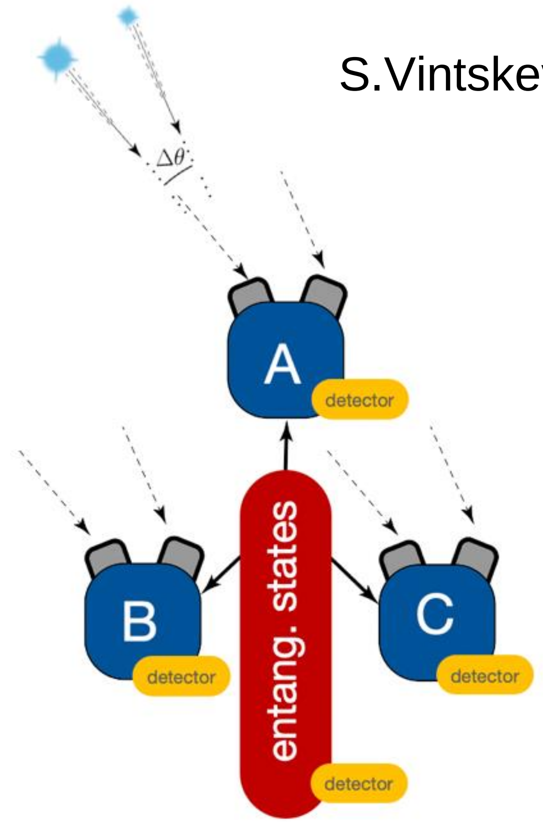


Next step: do it in spectrometer in spectral bins

Developing the quantum

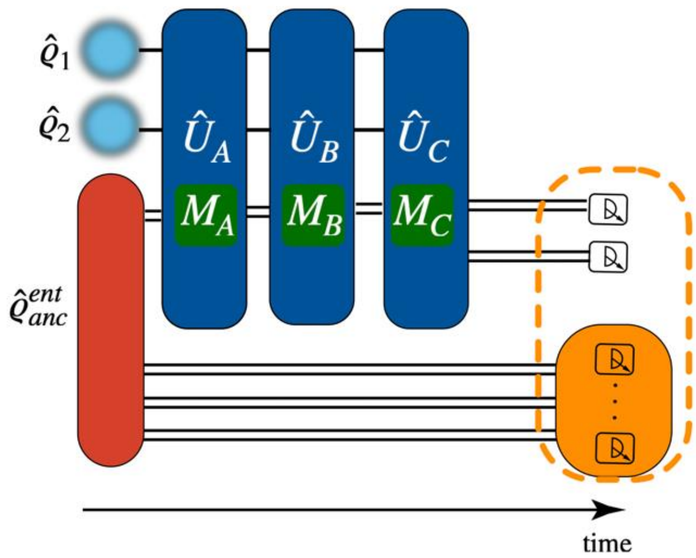
Use multi-partite entanglement (ex W or GHZ states) distributed between multiple stations and quantum protocol to process information in noisy environment

S.Vintskevich et al



Geometry: 2 stars + A,B,C telescope stations + source of entangled photon states + detectors

Quantum protocol circuit



Quantum protocol evaluates experimental observables

Common approaches with quantum sensing and quantum metrology

Classification of four-qubit entangled states via machine learning

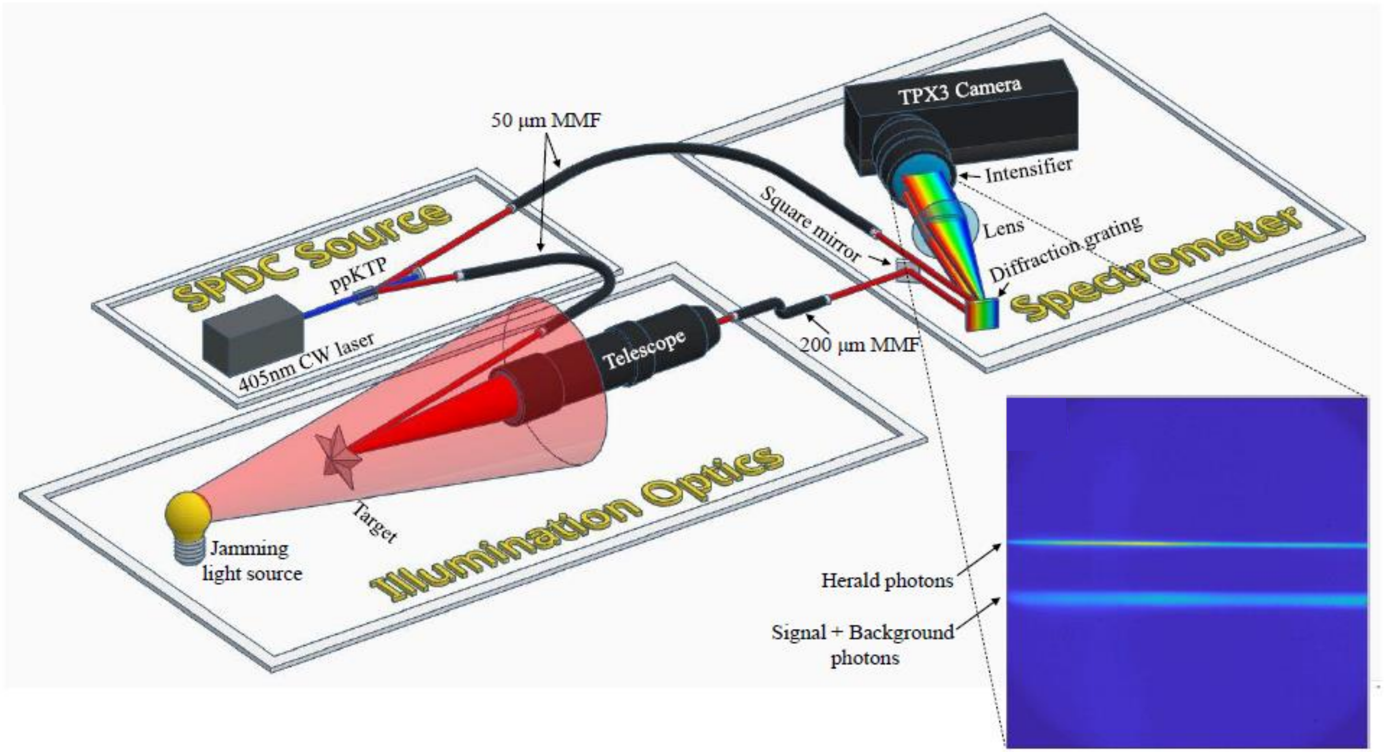
S. V. Vintskevich, N. Bao, A. Nomerotski, P. Stankus, and D. A. Grigoriev
Phys. Rev. A **107**, 032421 – Published 23 March 2023

Quantum Optics applications with time stamping of single photons

Some examples how nanosecond scale resolution is used in Quantum Optics

Multidimensional Quantum Illumination

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



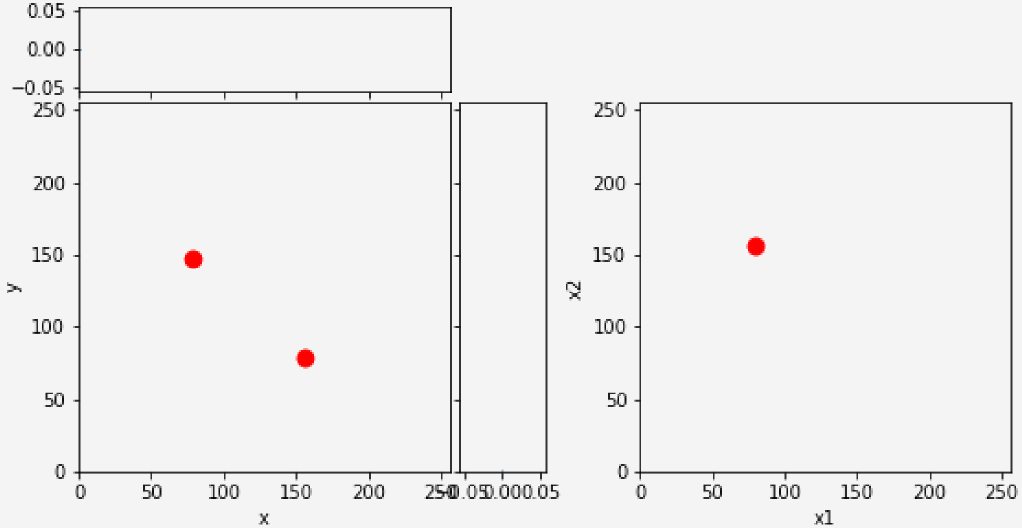
Y Zhang, D England, A Nomerotski, P Svihra et al, Multidimensional quantum-enhanced target detection via spectrotemporal-correlation measurements, Physical Review A 101 (5), 053808

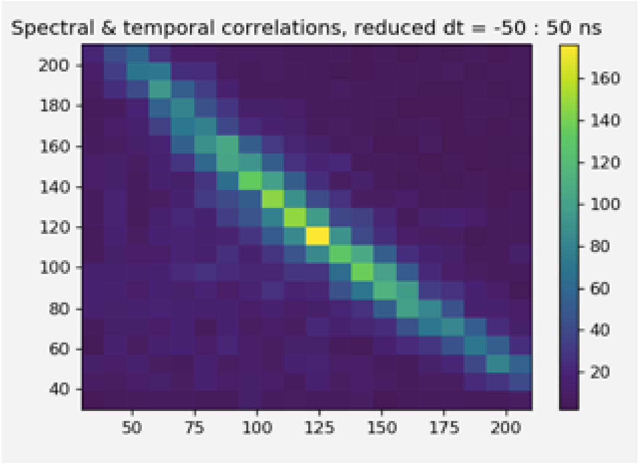
P Svihra et al, Multivariate Discrimination in Quantum Target Detection, Appl. Phys. Lett. **117**, 044001 (2020)

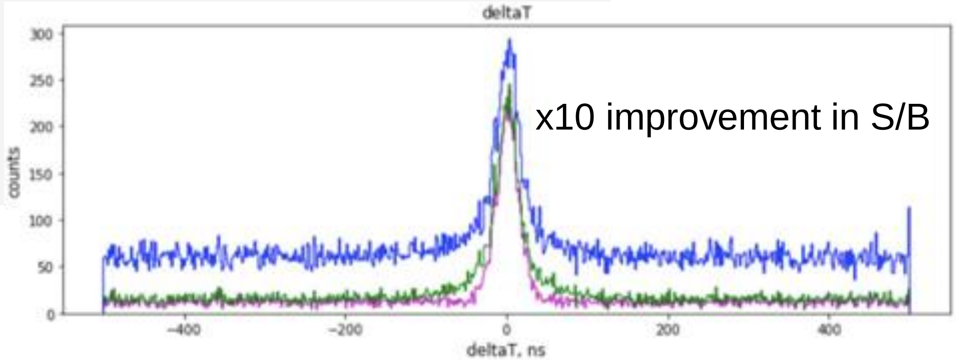
$\delta\lambda * \delta t$ ~ 5 ns * 0.5 nm

Pump photon wavelength & time difference

Spectral and temporal correlations





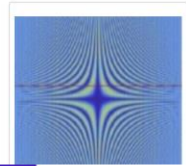


x10 improvement in S/B

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

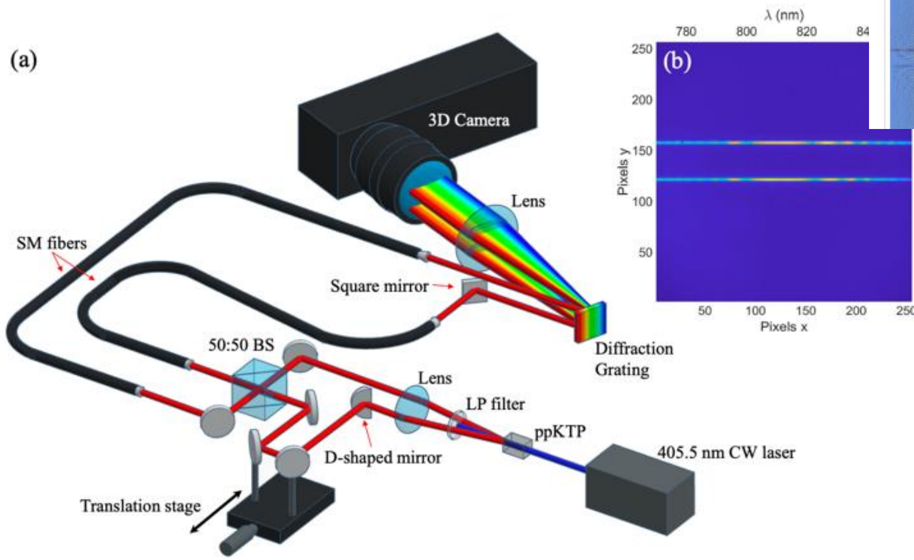
HOM effect with post-selection

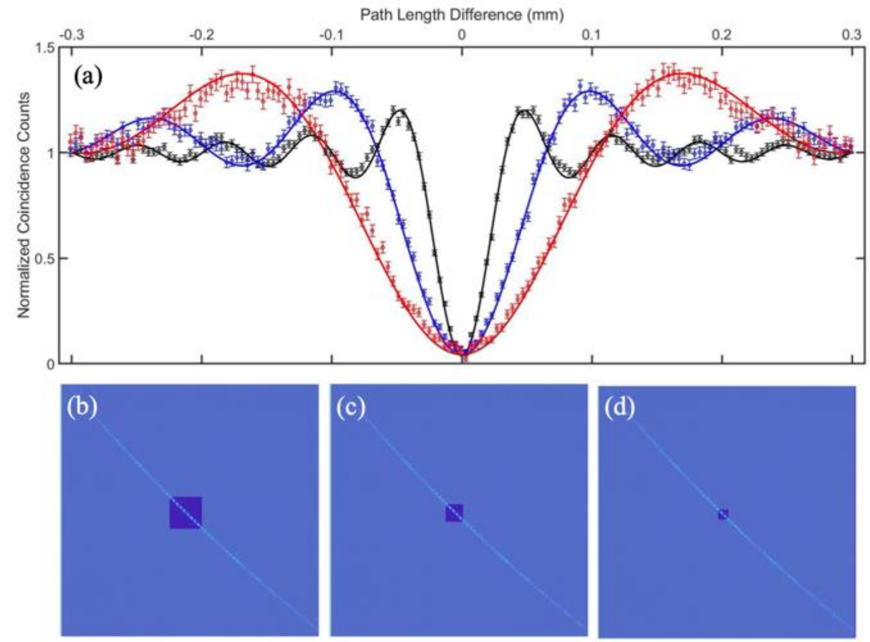
Optics Express Vol. 29, Issue 18, pp. 28217-28227 (2021) • https://doi.org/10.1364/OE.432191

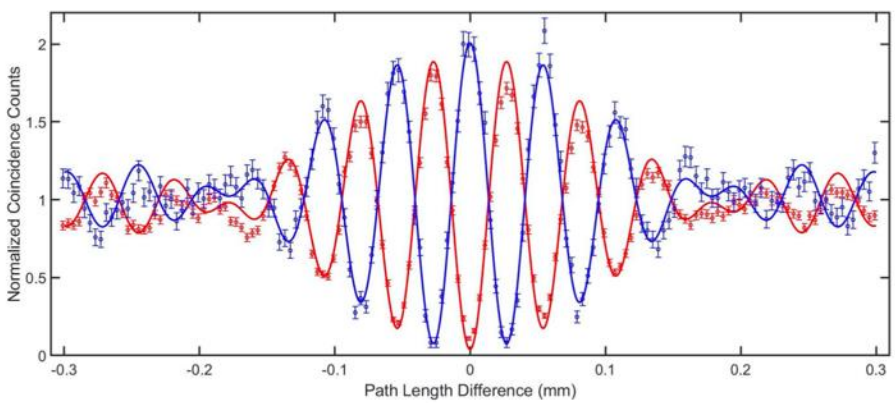


High speed imaging of spectral-temporal correlations in Hong-Ou-Mandel interference

Yingwen Zhang, Duncan England, Andrei Nomerotski, and Benjamin Sussman



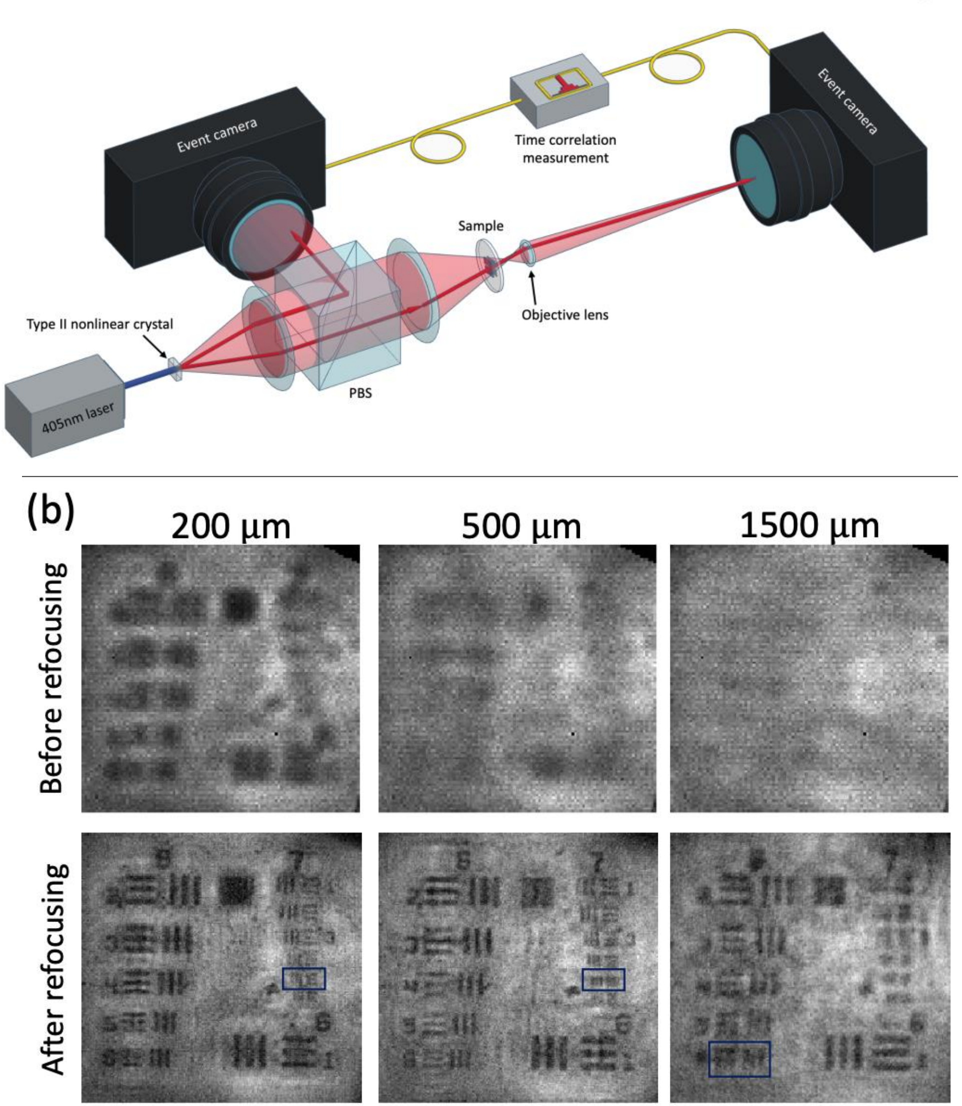




2 nm filters at 805 nm and 817 nm.

10, 5, 3 nm post-selection filters

Quantum light-field microscope



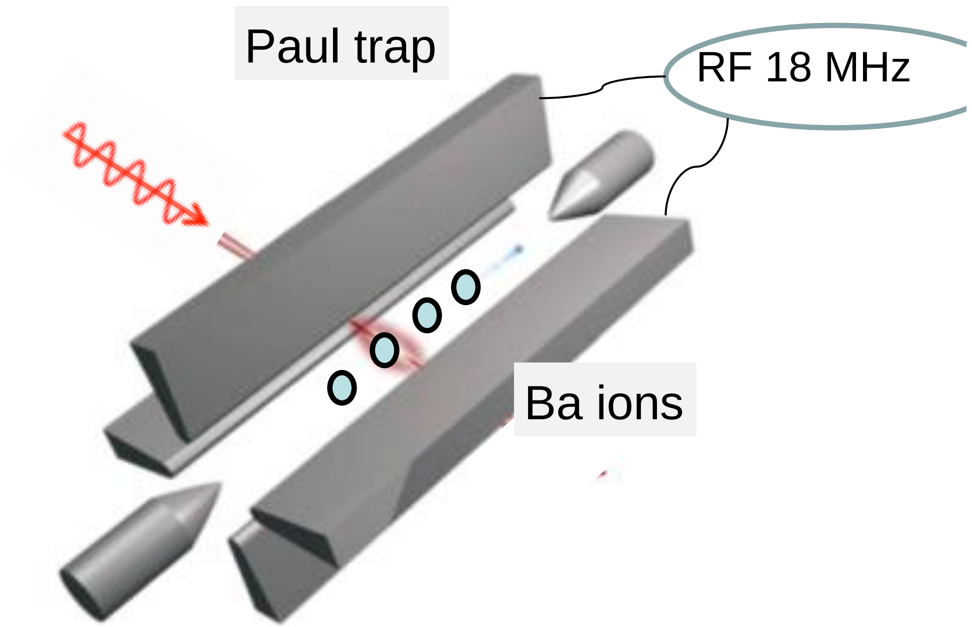
- Ottawa group
- Use one photon for position and one photon for angle information
- This allows refocussing at arbitrary distance

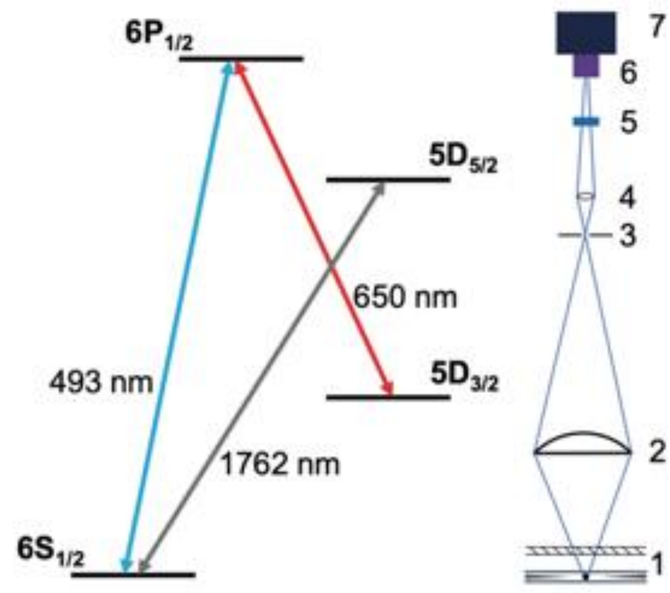
Quantum correlation light-field microscope with extreme depth of field

Yingwen Zhang,[1,2,*] Duncan England,[2,†] Antony Orth,[2] Ebrahim Karimi,[1,2] and Benjamin Sussman[1,2]
[1]*Nexus for Quantum Technologies, University of Ottawa, K1N 6N5, ON, Ottawa*
[2]*National Research Council of Canada, 100 Sussex Drive, Ottawa ON Canada, K1A0R6*

Imaging of trapped ions

Time resolved qubit manipulation (Blinov group, UWash)

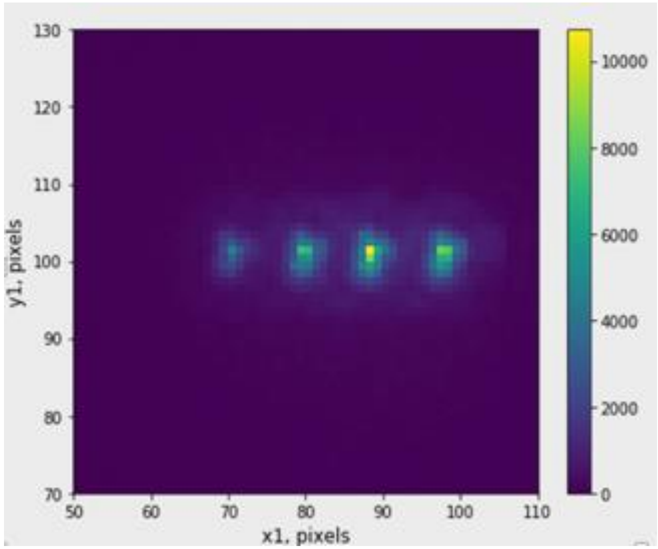


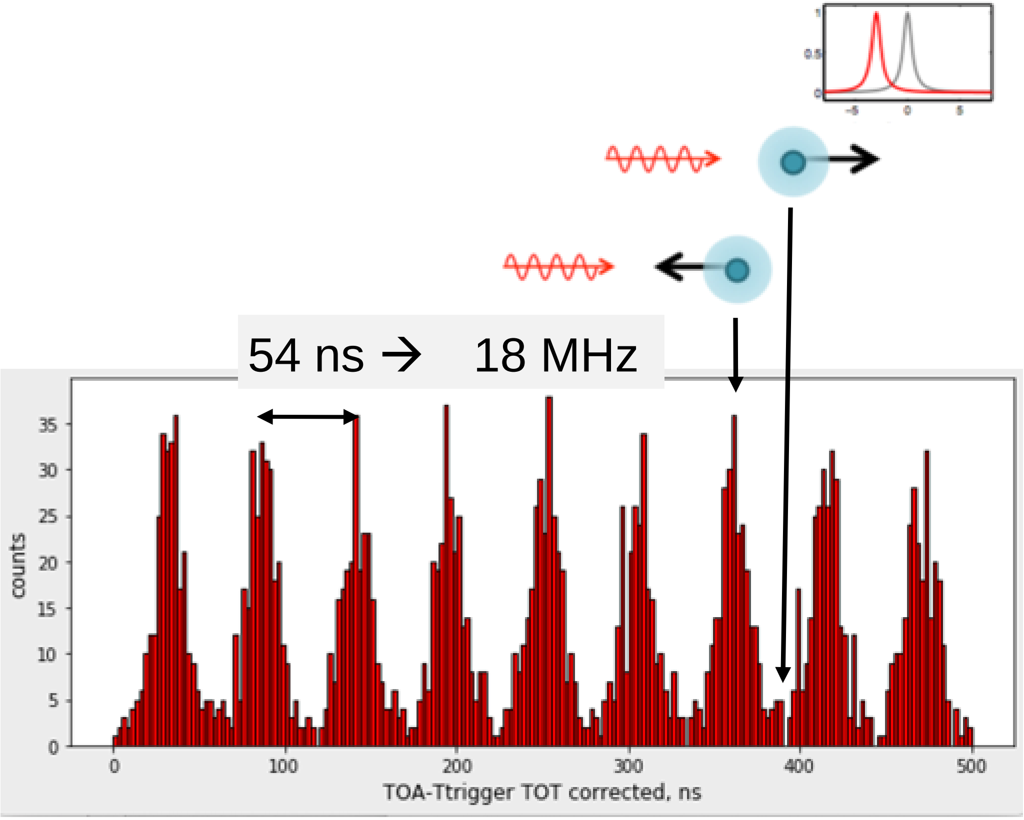


Register 493 nm photons to probe dark/bright state of ion = state of qubit register

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

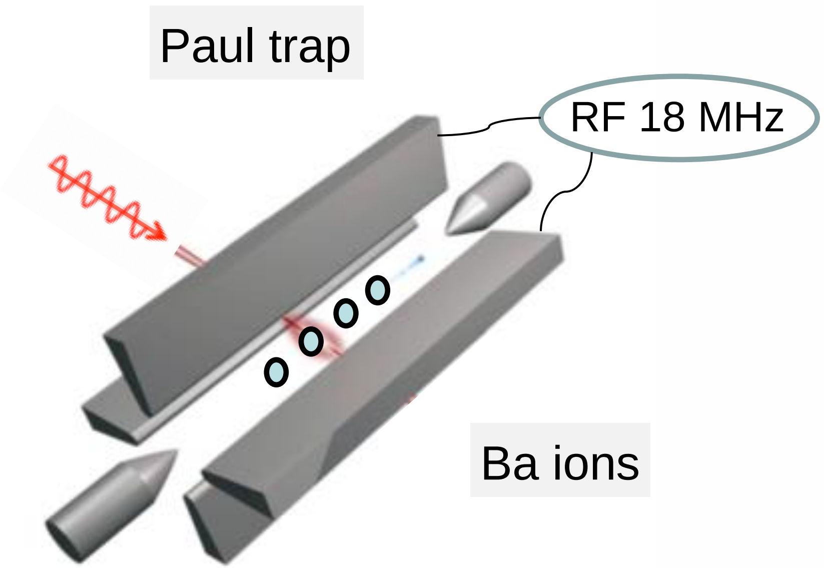


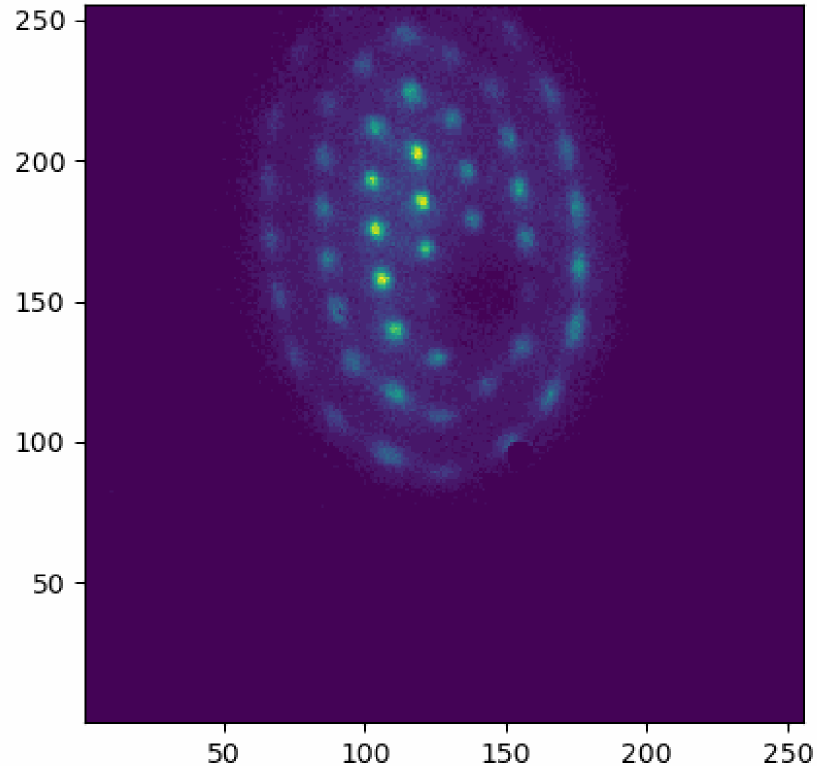


- Emission rate oscillations due to Doppler shift of laser light wrt moving ion
- Simultaneous time & position information allows to monitor ion micro-motions
- Powerful technique to characterize traps

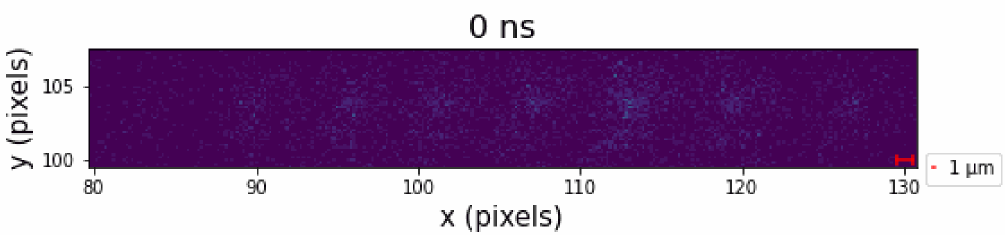
Direct observation of ion micromotion in a linear Paul trap,
L.Zhukas, M.Millican, P. Svihra, A. Nomerotski, B.Blinov, https://arxiv.org/abs/2010.00159,
Phys. Rev. A **103**, 023105 (2021).

1- and 2-D ion crystals





50-100 ns micromotion period



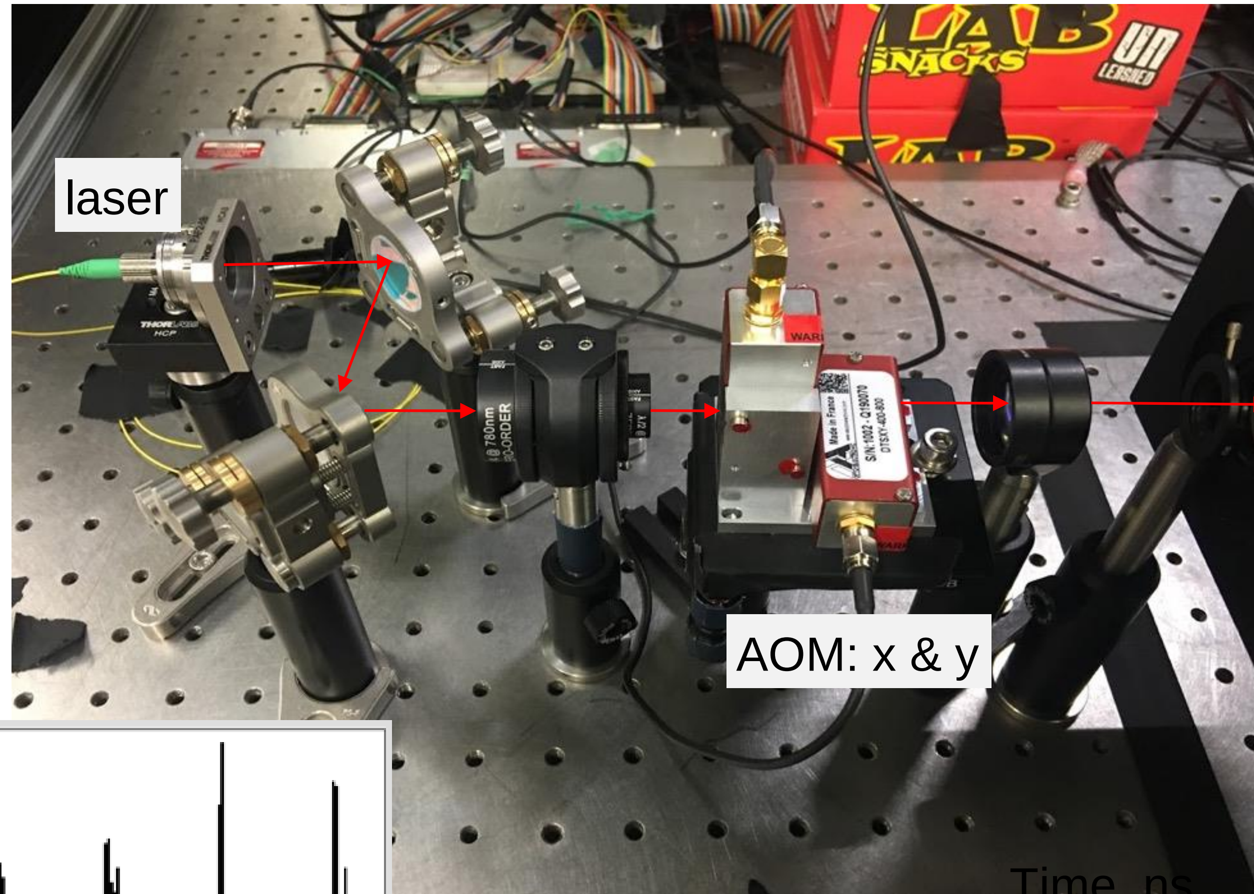
Scalability

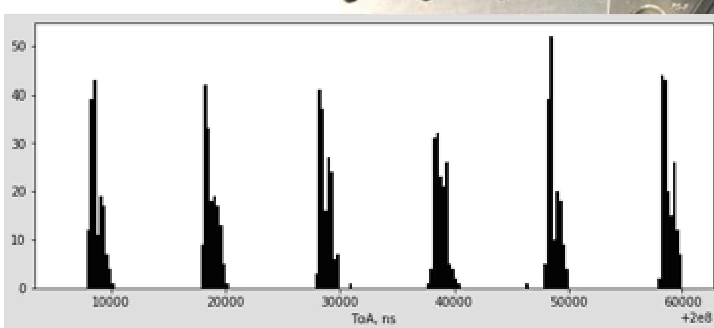
Tpx3Cam supports 10MHz single photon rate :

= 10 x 10 x 100kHz beams

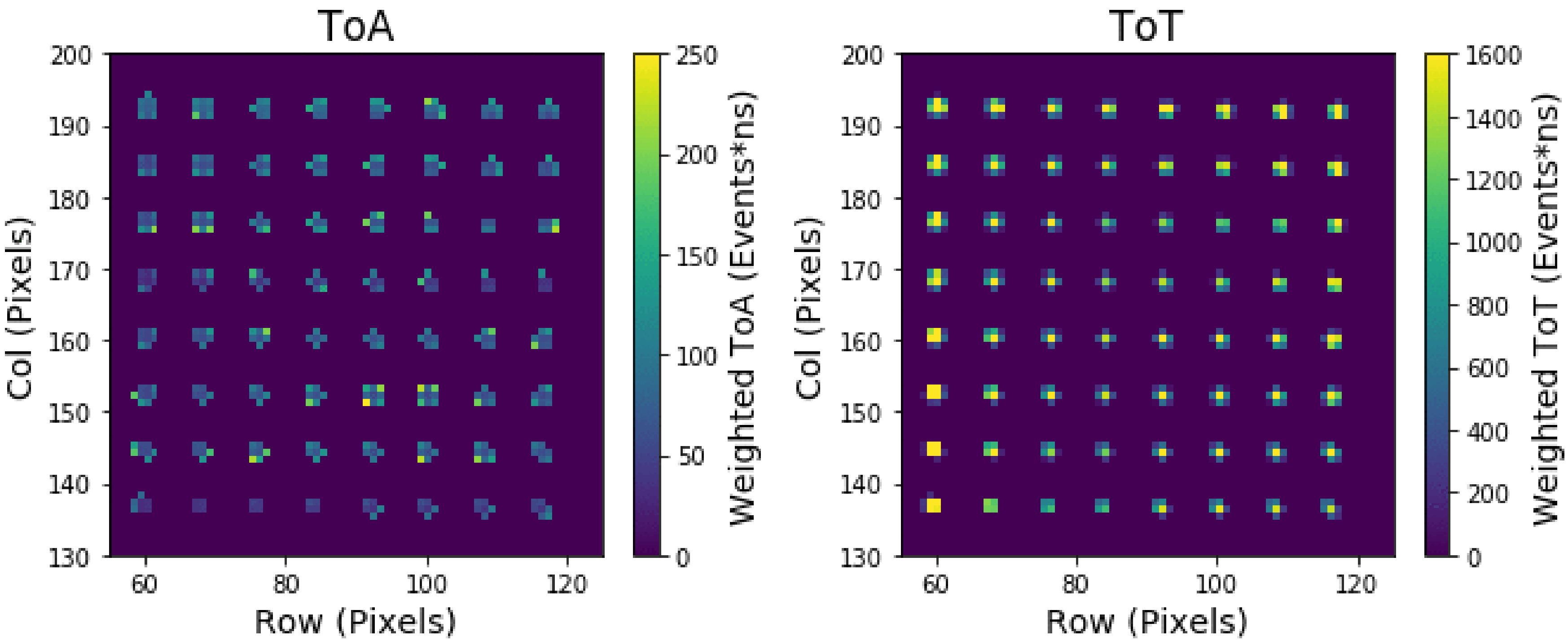
Photon router:

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





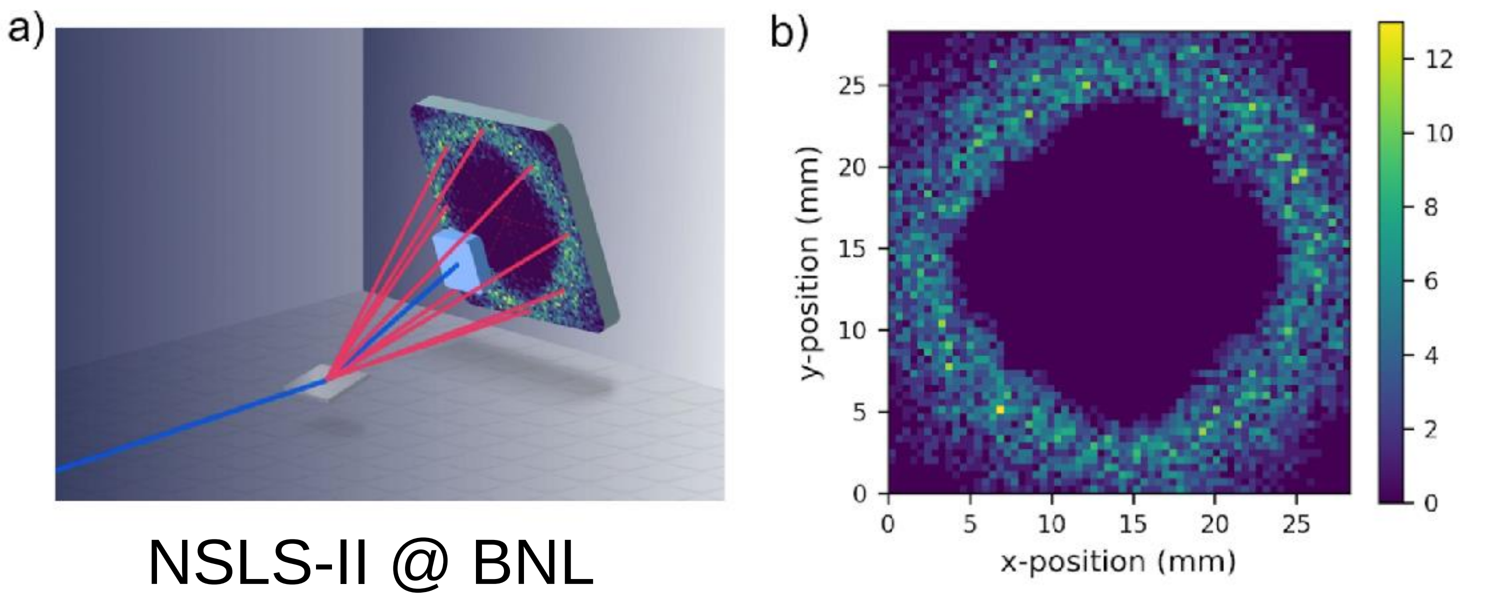
Scalability



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

Quantum x-rays

Down-conversion of x-rays



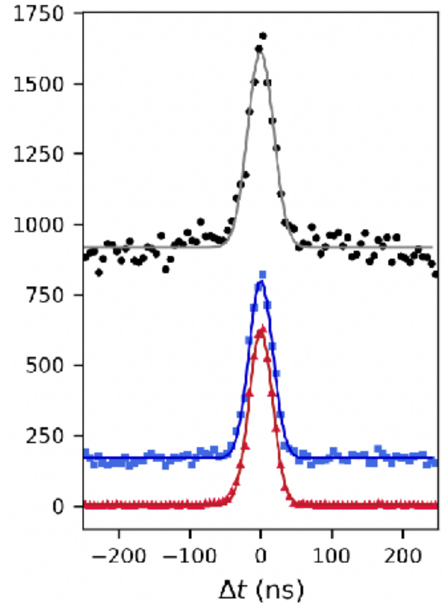
NSLS-II @ BNL

Fig. 1 Conceptual experimental schematic and the final observed SPDC structure. a, A conceptual schematic of the experiment, which shows that the Bragg reflection of a pump incident upon (111) diamond, with a small detuning, can generate down-converted X-ray pairs around the diffracted pump. A tantalum beamstop is played to obscure flooding the detector with diffracted pump photons. **b,** The detected SPDC photons after isolation from background scattering using a robust filtering process. The results are from a one hour exposure at $\Delta\theta = 0.022°$ with a total count of 4,145 photon pairs. Analyses of the spatial and spectral structures follow.

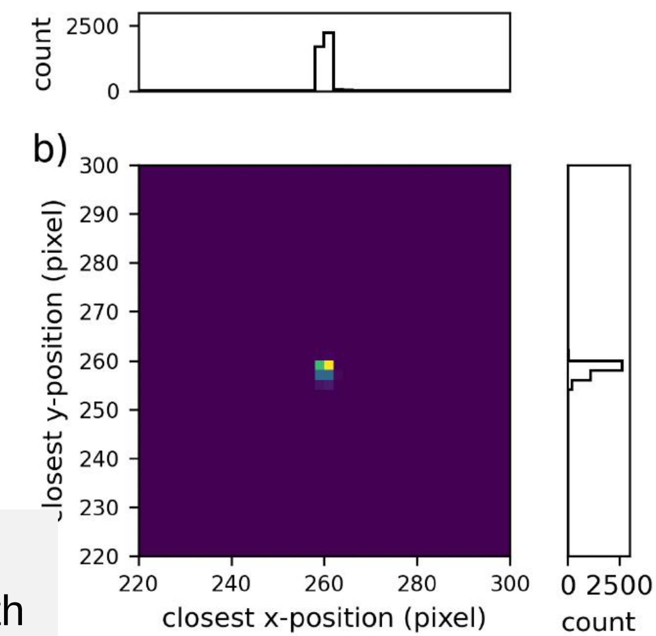
first imaging of x-ray cone
record rate of pair detection ~ few Hz

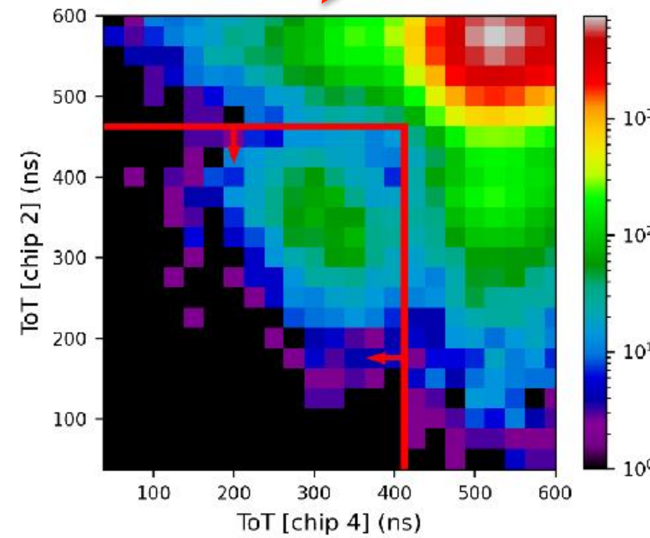
arxiv.org/abs/2310.13078
arxiv.org/abs/2412.09833

Detected simultaneously 3 types of correlations: time, spatial & energy



18 ns resolution due to variation of conversion depth





TOT correlation poor resolution

Motivates x-ray detectors with good timing and energy resolutions

arxiv.org/abs/2310.13078
arxiv.org/abs/2412.09833

Scope: entanglement studies for x-rays

Sensor R&D

Ideas for 2d imaging sensors which can provide 20 ps resolution

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**

X. Llopart, J. Alozy, R. Ballabriga, M. Campbell, R. Casanova, V. Gromov, E.H.M. Heijne, T. Poikela, E. Santin, V. Sriskaran, L. Tlustos, and A. Vitkovskiy. Timepix4, a large area pixel detector readout chip which can be tiled on 4 sides providing sub-200 ps timestamp binning. *Journal of Instrumentation*, 17(01):C01044, January 2022.

External amplification in MCP

Direct detection after MCP in Timepix

12TH INTERNATIONAL CONFERENCE ON POSITION SENSITIVE DETECTORS
12 - 17 SEPTEMBER 2021
UNIVERSITY OF BIRMINGHAM, BIRMINGHAM, UK

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*

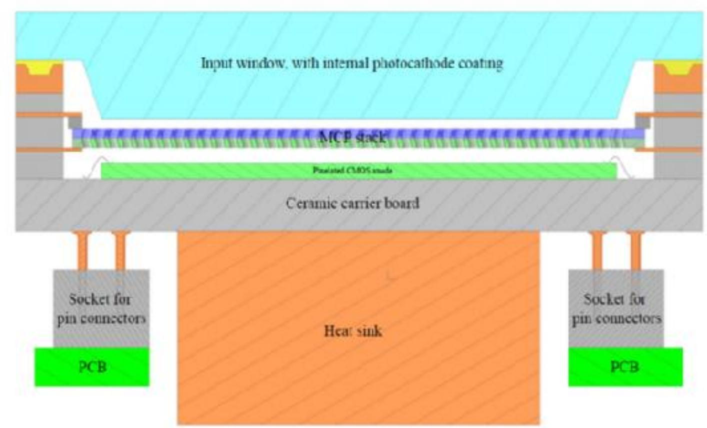


Figure 1. Cutaway schematic view of the detector assembly.

Has been implemented before with Timepix

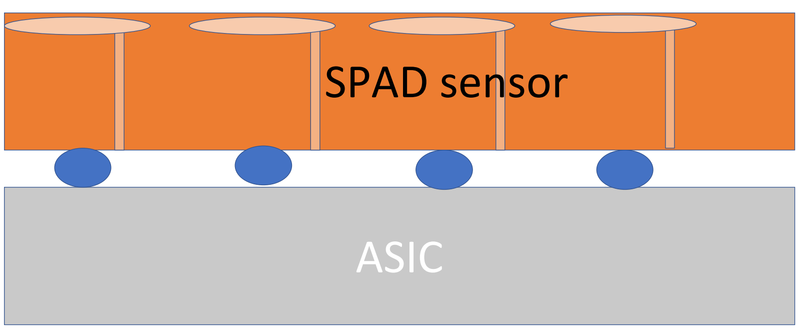
Limitation: photocathode QE ~ 35%

Hybrid SPADs: 20 ps timing

- 20 ps timing is needed for next round of CERN experiments in 10 years, there will be lots of investment in fast ASICs

- example: Timespot1 chip
  - 32 x 32
  - 50 ps
  - 55 micron pitch

- Hybrid detector: SPAD + 20 ps chip



Timespot1: A 28 nm CMOS Pixel Read-Out ASIC for 4D Tracking at High Rates

Sandro Cadeddu,[a,1] Luca Frontini,[b,c] Adriano Lai,[a] Valentino Liberali,[b,c] Lorenzo Piccolo,[d] Angelo Rivetti,[d] Jafar Shojaii,[e] Alberto Stabile[b,c]

[a] *INFN Sezione di Cagliari, 09042 Monserrato, Italy*
[b] *Università degli Studi di Milano, Dipartimento di Fisica, 20133 Milano, Italy*
[c] *INFN Sezione di Milano, 20133 Milano, Italy*
[d] *INFN Sezione di Torino, 10125 Torino, Italy*
[e] *Swinburne University of Technology and University of Melbourne, Victoria, Australia*

E-mail: sandro.cadeddu@ca.infn.it

Abstract: We present the first characterization results of Timespot1, an ASIC designed in CMOS 28 nm technology, featuring a 32 × 32 pixel matrix with a pitch of 55 µm. Timespot1 is the first-born small-size prototype, conceived to read-out fine-pitch pixels with single-hit time resolution below 50 ps and input rates of several hundreds of kilohertz per pixel. Such experimental conditions will be typical of the next generation of high-luminosity collider experiments, from the LHC run5 and beyond. Each pixel of the ASIC has been endowed with a charge amplifier, a discriminator, and a Time-to-Digital Converter with time resolution around 30 ps and maximum read-out rates (per pixel) of 3 MHz. To respect system-level constraints, the timing performance have been obtained keeping the power budget per pixel below 40 µW. The ASIC has been tested and characterised in laboratory concerning its performance in terms of time resolution, power budget and sustainable rates. The ASIC will be hybridized on a matched 32 × 32 pixel sensor matrix and will be tested under laser beam and Minimum Ionizing Particles in the laboratory and at test beams. In this paper we present a description of the ASIC operation and the first results obtained from characterization tests concerning its performance in tracking measurements.

Keywords: Front-end electronics for detector readout, Timing detectors, VLSI circuits

[1] Corresponding author.

Main points to take home

- Quantum-assisted two-photon interferometry dramatically enhance astrometric precision with great impact on astro science
- **Requires single photon cameras with 10 ps scale resolution**

Broad program in quantum-assisted optical interferometry ahead, efforts underway to develop new timing technologies

This will be useful in many fields including the quantum

- Entangled x-rays motivate pixels with simultaneously good timing resolution (nsec) and good energy resolution (few %)

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Yingwen Zhang
Boris Blinov
Mila Zhukas
Maverick Millican
Alex Kato
Peter Svihra
Michal Marcisovsky
Sergei Kulkov
Jakub Jirsa
Lada Radmacherova
Lou-Ann Pestana de Sousa
Raphael Abrahao
Brianna Farella
Ryan Mahon

Edoardo Charbon
Tommaso Milanese

Main publications

- Original idea: https://doi.org/10.21105/astro.2010.09100
- Earth rotation fringe scanning: doi.org/10.1103/PhysRevD.107.023015
- Experimental proof of principal: https://arxiv.org/abs/2301.07042
- Fast spectrometer: https://iopscience.iop.org/article/10.1088/1748-0221/18/01/C01023

Looking for graduate students and postdoc for quantum astronomy projects

Talk to me andrei.nomerotski@cvut.cz or

peter.svihra@cern.ch

Thank you for your attention!

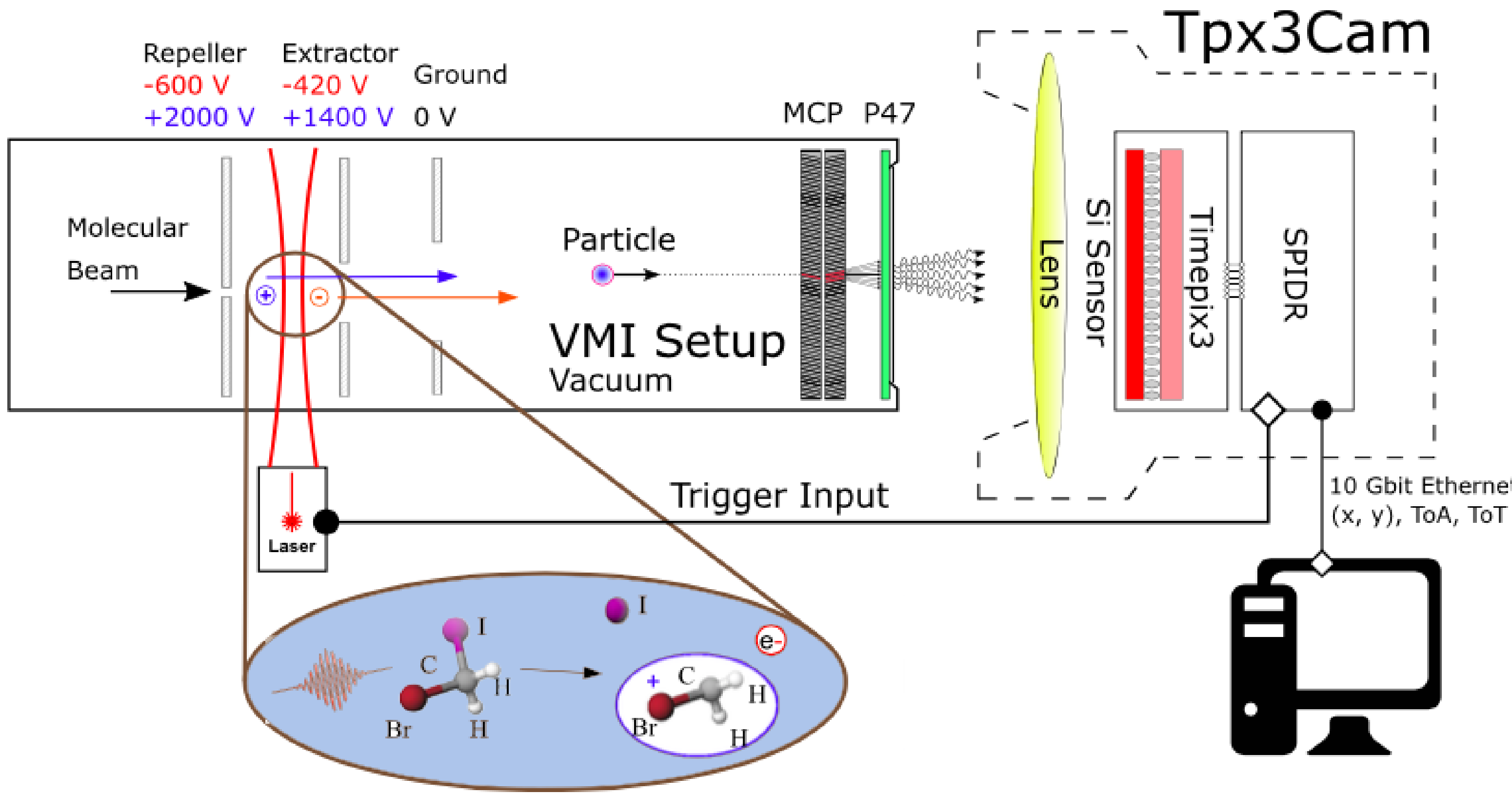
https://capads.fjfi.cvut.cz

Spares

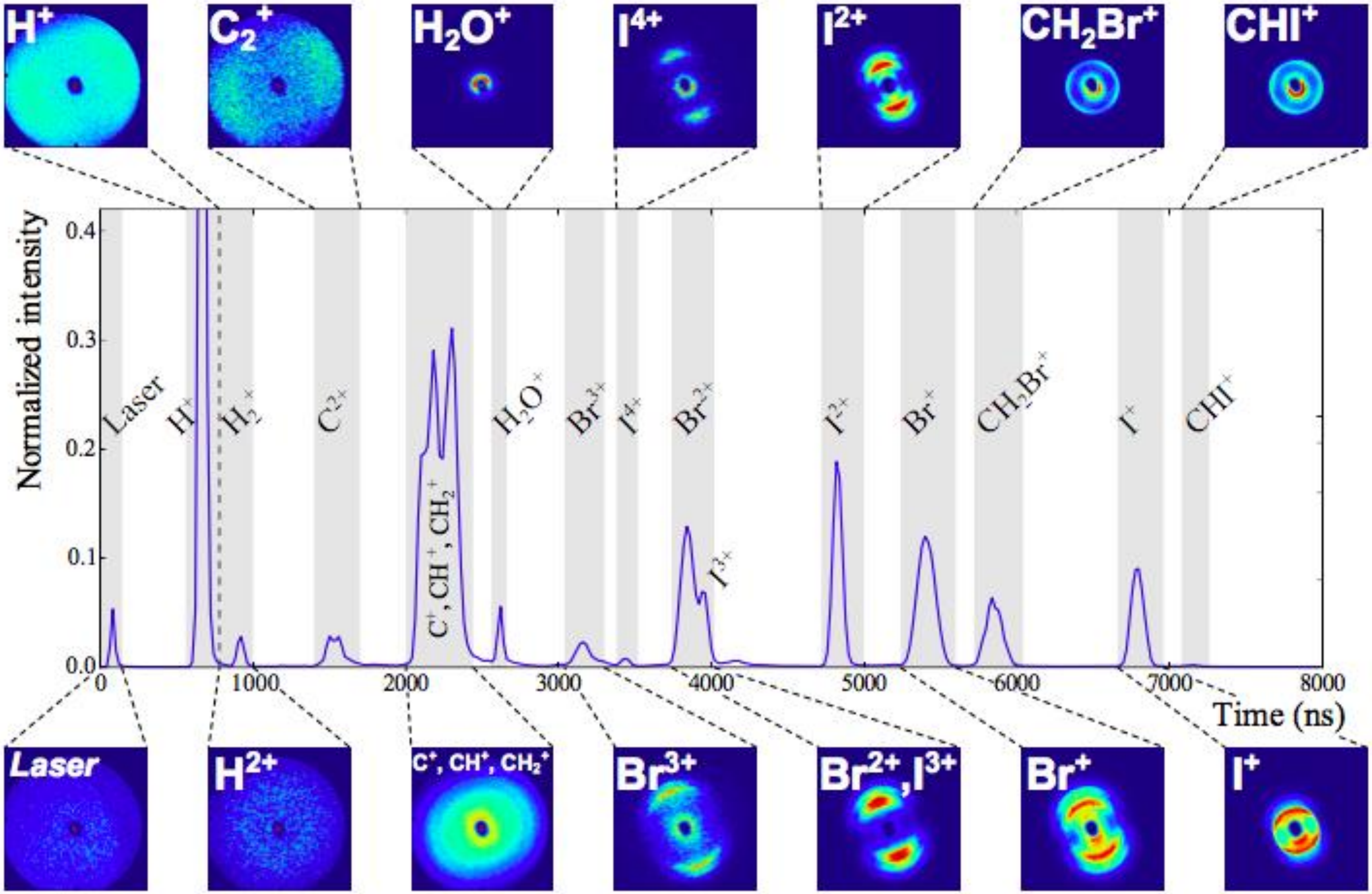
More applications of fast imaging

- Mass Spectroscopy
- Atomic Probe Tomography
- Lifetime imaging
- Neutron imaging
- High Energy Physics

Imaging Mass Spectroscopy



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)



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

Optical readout for LAr TPC

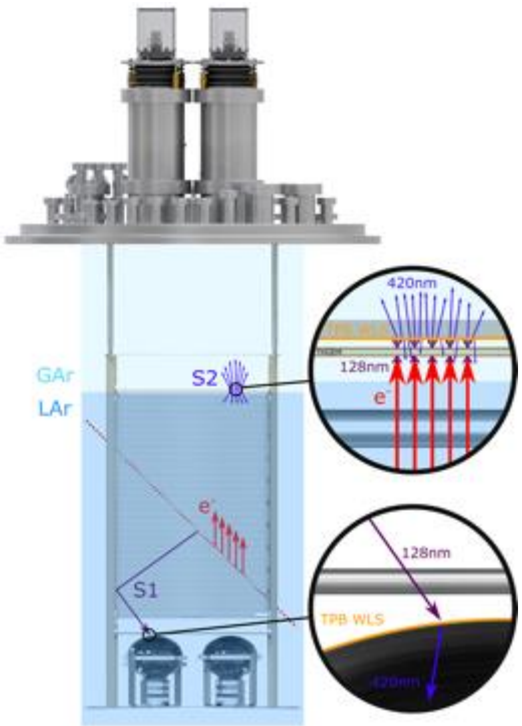
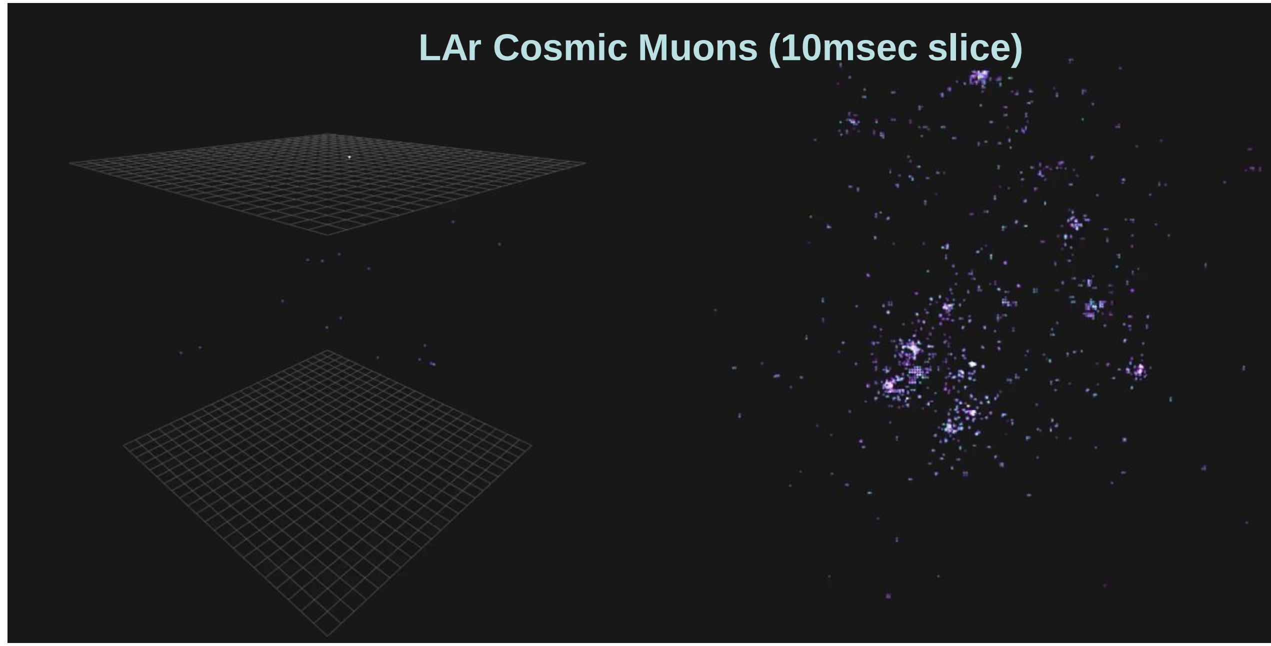


Image light from avalanches in gas phase in THGEM



TPX3Cam on ARIADNE 1-ton dual phase Liquid argon TPC

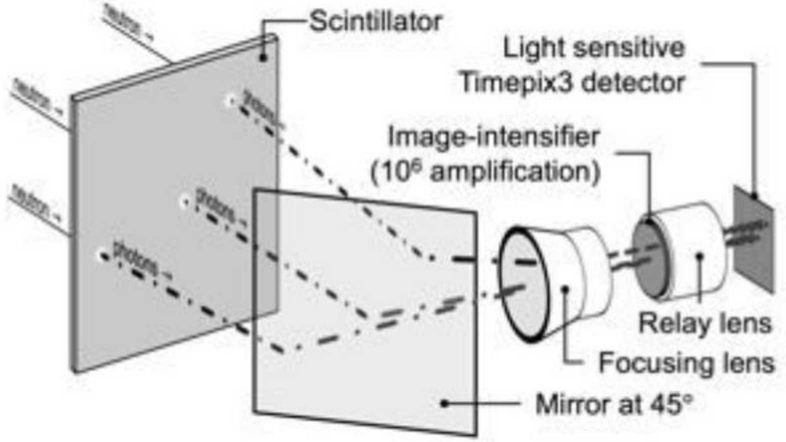
hep.ph.liv.ac.uk/ariadne/index.html
Kostas Mavrokoridis et al

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

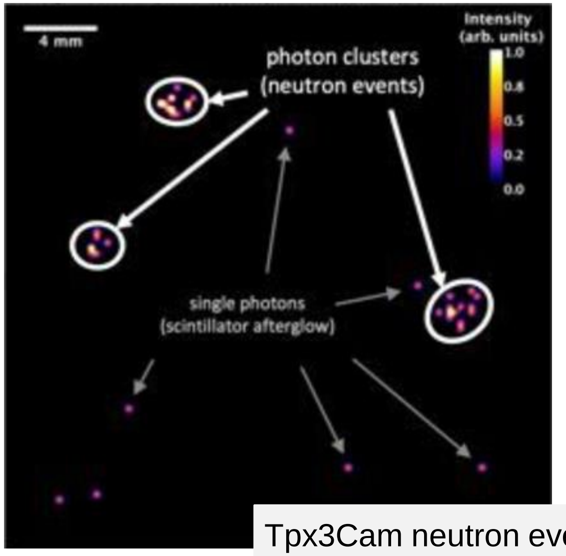
A. Roberts et al., 2019 First demonstration of 3D optical readout of a TPC using a single photon sensitive Timepix3 based camera *JINST* **14** P06001

Neutron detection with Tpx3Cam

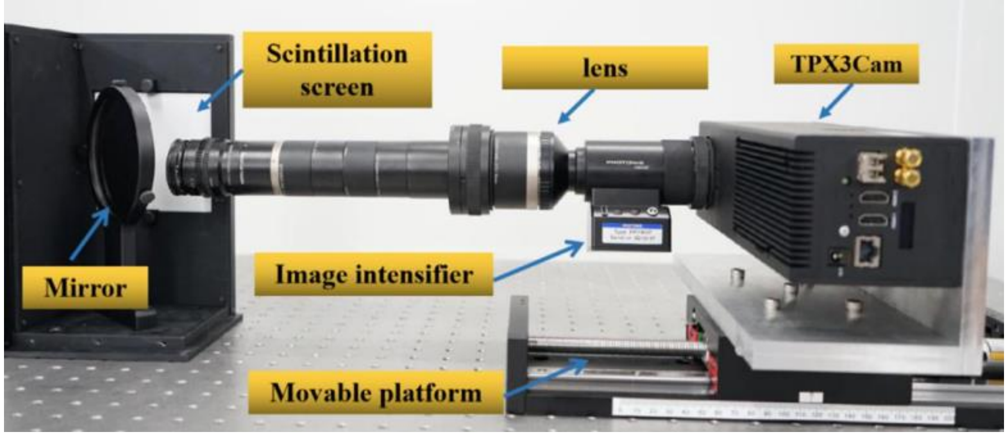
- ^{6}Li-based scintillator
- Neutrons produce alphas
- Time resolved



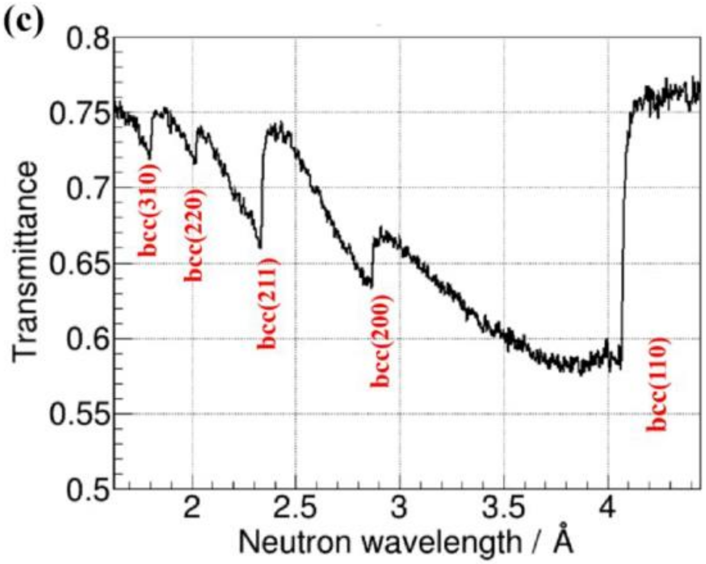
A.Losko et al, DOI:10.21203/rs.3.rs-257513/v1



Tpx3Cam neutron event display



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



Material characterization with Bragg edges