



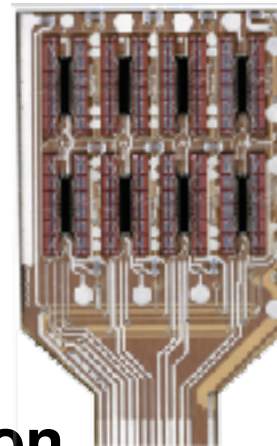
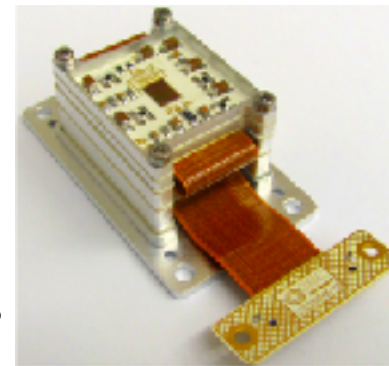
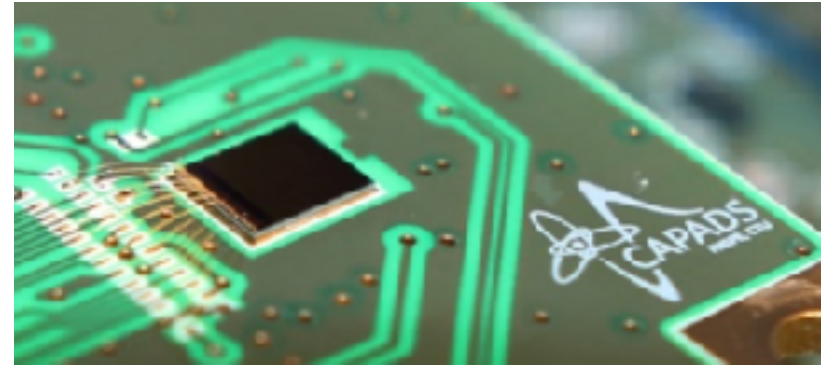
Probing Photon Indistinguishability with Fast Spectrometers

Andrei Nomerotski

Czech Technical University
CAS Institute of Physics

Strasbourg, 8 October 2026

CAPADS group in Czech TU



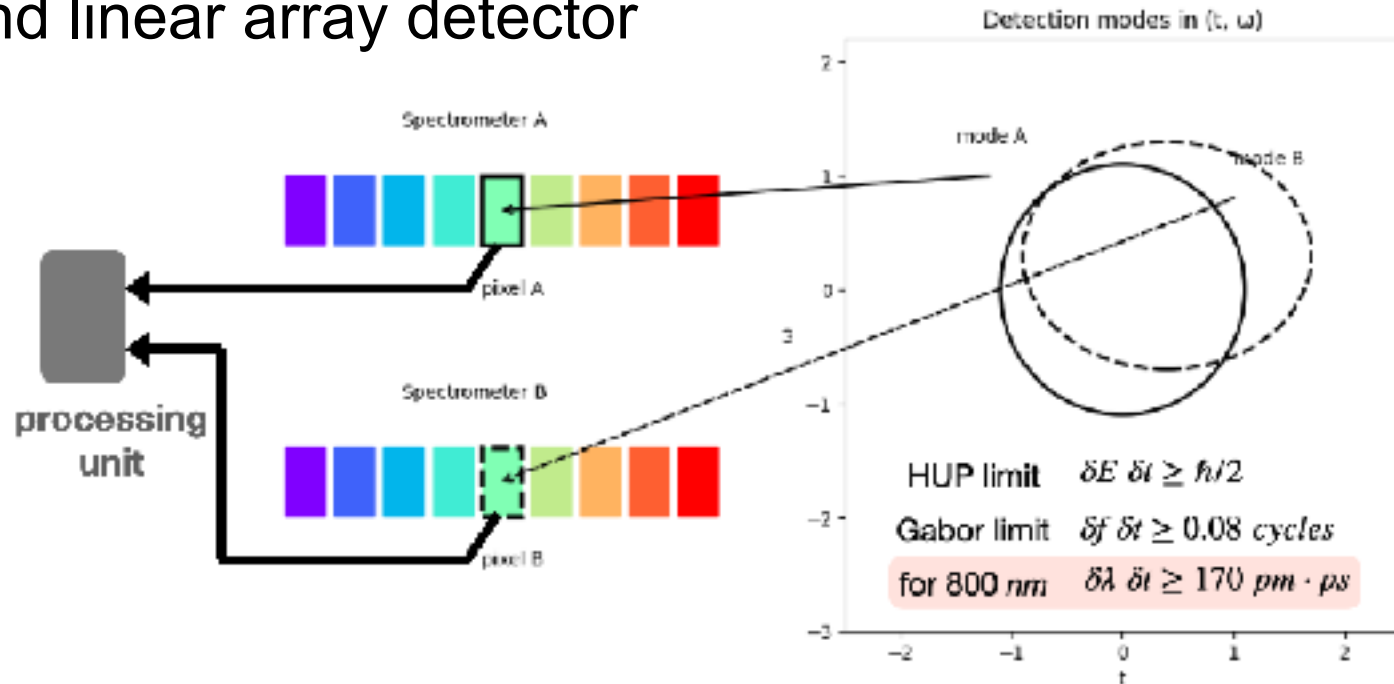
Group is involved in several projects including OCTOPUS

- Hybrid detectors : PHpix/PH32
- MAPS: X-Chip-04 & SpacePix3
- Si, SiC sensors with onsemi

Quantum Sensing is a new direction

Photon Indistinguishability

Spectrometers based on diffraction grating
and linear array detector



If resolutions are good enough two photons hitting the same pixel are indistinguishable →

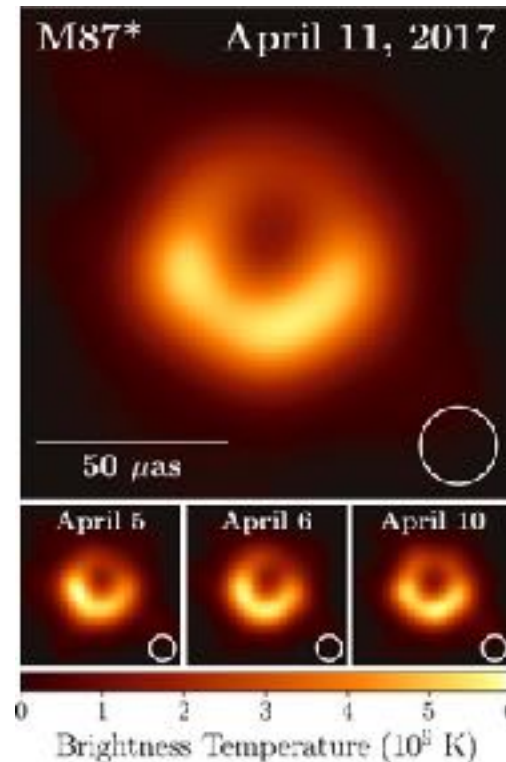
$$\Delta E \Delta t \geq \frac{\hbar}{2} \quad (\text{within HUP})$$

only indistinguishable photons can interfere →
can probe **interference effects**

Outline

- **Science motivation - stellar intensity interferometry**
- **Instrument requirements - fast single photon detectors**
 - Timepix3/4 cameras and SPAD arrays
- **Spectral multiplexing at Heisenberg-Gabor limit**
- **More quantum applications of fast cameras**
- **Future directions for fast imaging**
- **Probing photon indistinguishability**

Event Horizon Telescope black hole image



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

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

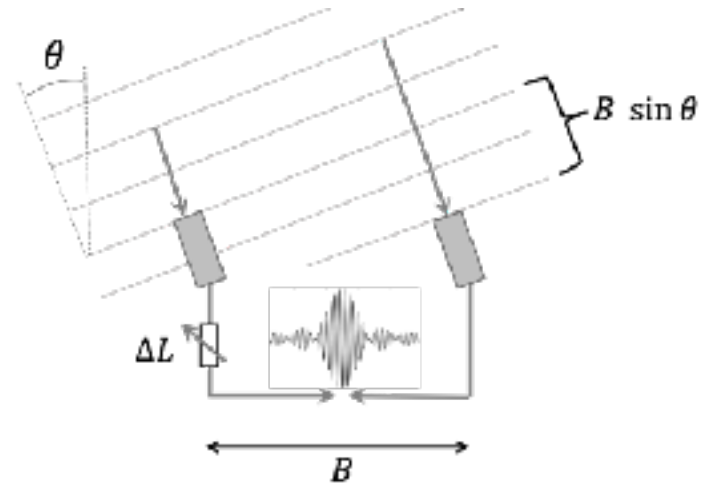
mode population

Can literally record entire waveform
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 delayed and
stabilized to better than λ**

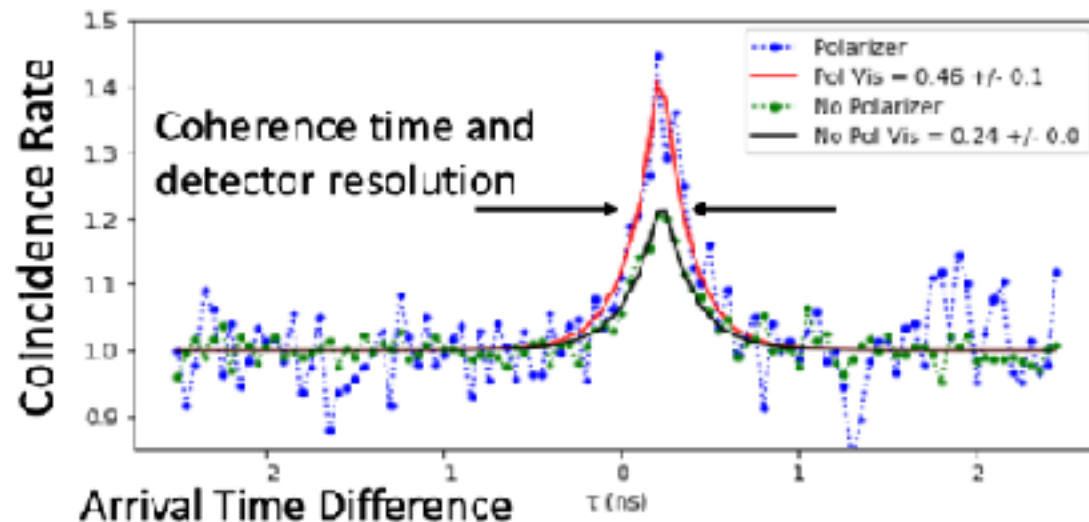
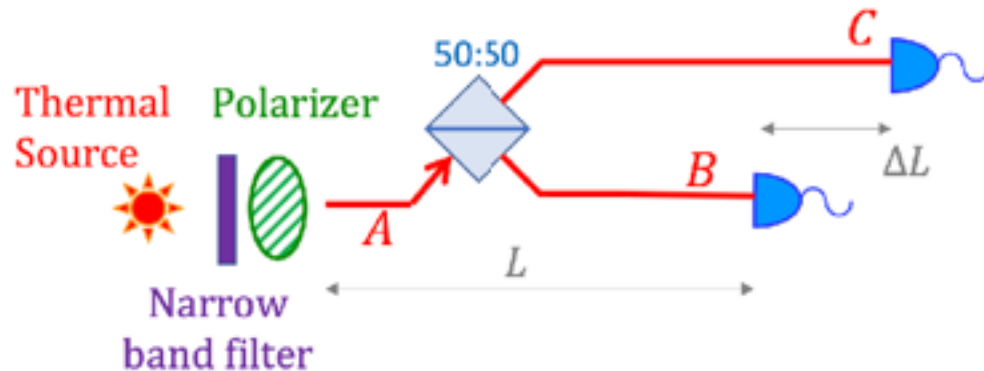
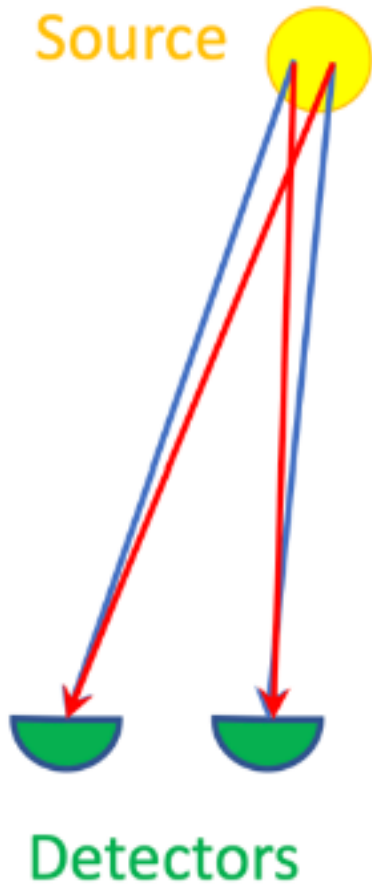
Max baselines ~ 100 m

Two-photon techniques

Hanbury Brown - Twiss effect

If points are close enough two options of photons paths are coherent = photon phases not so different and they interfere

Interference produces photon bunching or HBT effect



Stellar Intensity Interferometry



Stellar intensity
interferometer at
Narrabri, Australia, 1968

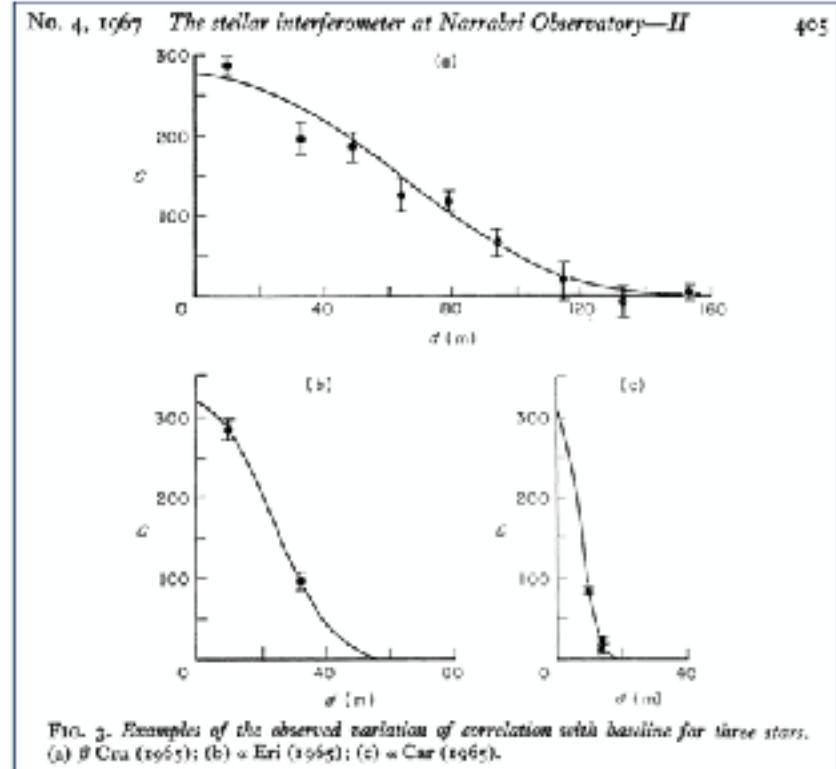
arXiv.org > astro-ph > arXiv:1810.08023

Astrophysics > Instrumentation and Methods for Astrophysics

Intensity Interferometry revival on the Côte d'Azur

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

(submitted on 18 Oct 2018)



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

renewed interest due to progress in fast detectors!

Second photon for quantum assist

PRL 106, 070503 (2012)

PHYSICAL REVIEW LETTERS

week ending
17 AUGUST 2012

Longer-Baseline Telescopes Using Quantum Repeaters

Daniel Gottesman¹

Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada

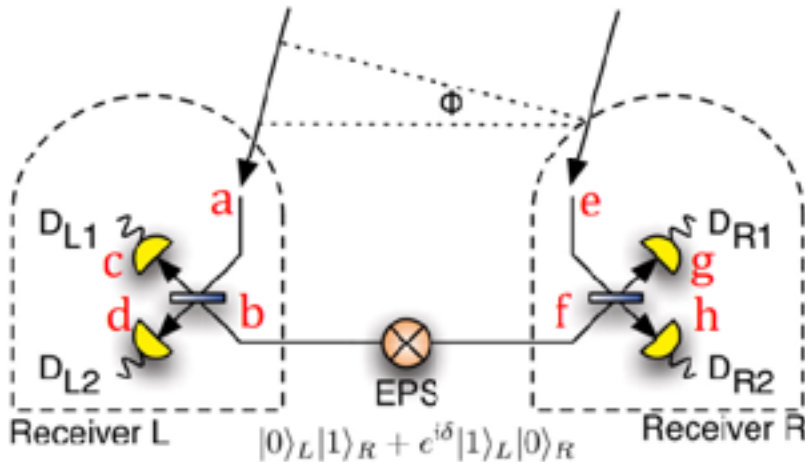
Thomas Jennewein²

Institute for Quantum Computing, University of Waterloo, Waterloo, Ontario, Canada

Sarah Croke¹

Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada

(Received 25 October 2011; revised manuscript received 22 May 2012; published 16 August 2012)



$$\Psi^{\text{Initial}} = \psi_1 \psi_2 = \frac{1}{2} \underbrace{(\hat{a}^\dagger + e^{i\delta_1} \hat{e}^\dagger)}_{\text{Sky photon}} \underbrace{(\hat{b}^\dagger + e^{i\delta_2} \hat{f}^\dagger)}_{\text{Ground photon}}$$

Beam
Splitters

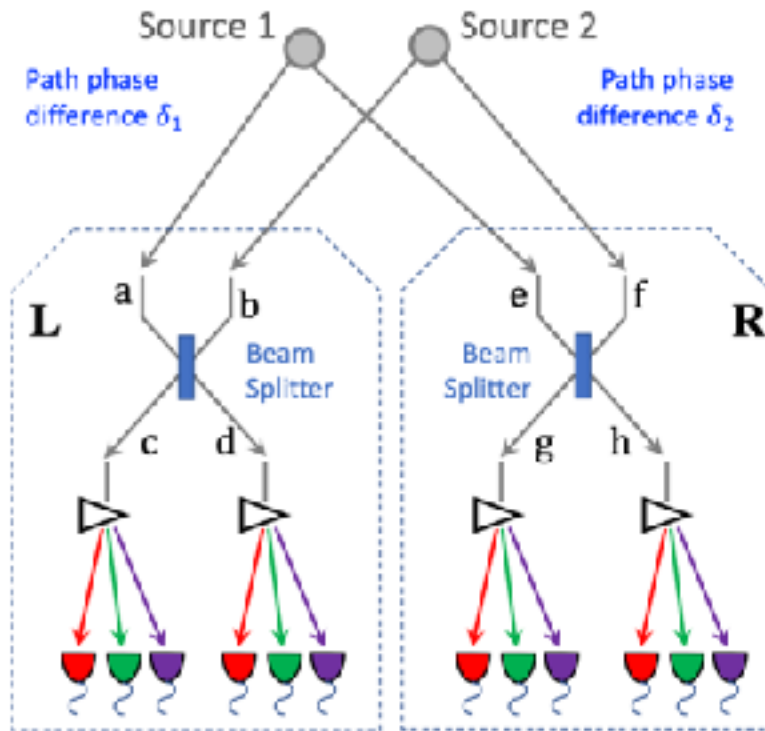
$$\begin{aligned} \hat{a}^\dagger &\rightarrow (\hat{c}^\dagger + \hat{d}^\dagger)/\sqrt{2} & \hat{b}^\dagger &\rightarrow (\hat{c}^\dagger - \hat{d}^\dagger)/\sqrt{2} \\ \hat{e}^\dagger &\rightarrow (\hat{g}^\dagger + \hat{h}^\dagger)/\sqrt{2} & \hat{f}^\dagger &\rightarrow (\hat{g}^\dagger - \hat{h}^\dagger)/\sqrt{2} \end{aligned}$$

$$\Psi^{\text{Output}} = (1/4)(\hat{c}^\dagger \hat{c}^\dagger - \hat{d}^\dagger \hat{d}^\dagger + e^{i(\delta_1 + \delta_2)}(\hat{g}^\dagger \hat{g}^\dagger - \hat{h}^\dagger \hat{h}^\dagger) + (e^{i\delta_1} + e^{i\delta_2})(\hat{c}^\dagger \hat{g}^\dagger - \hat{d}^\dagger \hat{h}^\dagger) + (e^{i\delta_1} - e^{i\delta_2})(\hat{c}^\dagger \hat{h}^\dagger + \hat{d}^\dagger \hat{g}^\dagger))$$

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

- Measure photon quantum state at one station → teleport the sky photon to 2nd station
- Coincidences of counters are sensitive to sky photon phase → direction
- Need to transfer the photon quantum state → can use quantum networks, this will allow long distances

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



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

Full QFT calculation

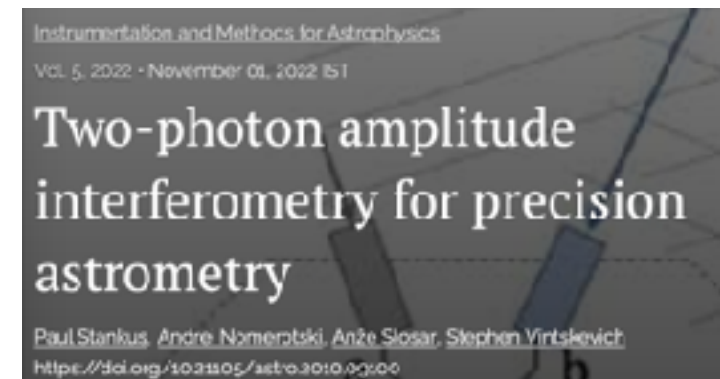
$$\begin{aligned}
 N_c(xy) &= \eta_1 \eta_2 A^2 \int_0^{T_r} P_{L,R,\tau}^{\text{two photons}} d\tau = \\
 &A^2 \eta_1 \eta_2 T_r \left[\text{Rates} \left((I_1 + I_2)^2 \right) + \text{HBT} \left(I_1^2 \frac{\tau_c g_{11}}{T_r} + I_2^2 \frac{\tau_c g_{22}}{T_r} \right) \pm \right. \\
 &\left. 2I_1 I_2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

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

Perfect to start exploring this approach

Want to do it in spectral bins - gain $\sqrt{\#ofbins}$



<https://arxiv.org/abs/2010.09100>

Requirements for detectors

Photons must be indistinguishable so close enough in frequency and time to interfere → temporal & spectral binning :

need $\sim 10 \text{ pm} * 10 \text{ ps}$ $\Delta t * \Delta E \geq \hbar/2$

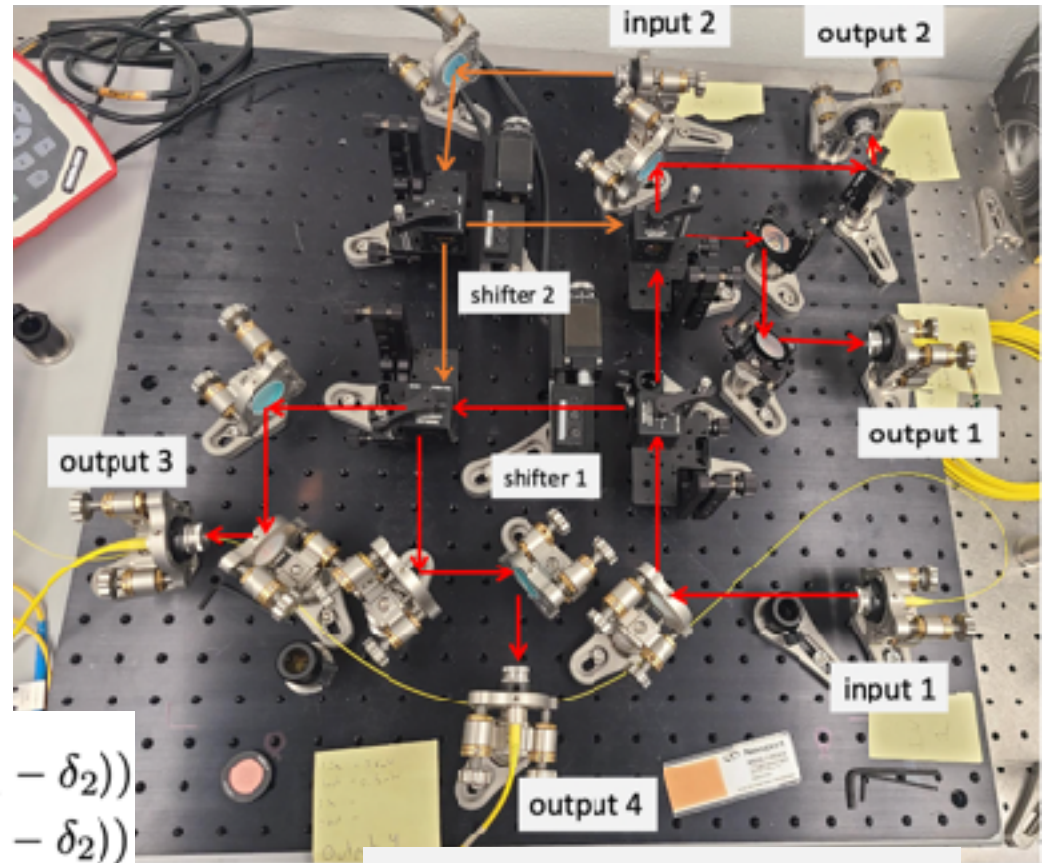
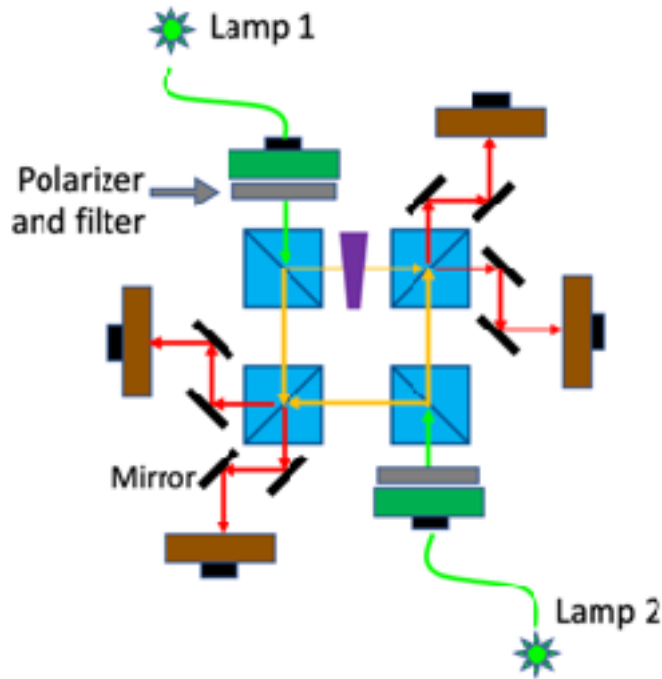
**Need fast spectrometers
at Heisenberg Uncertainty Principle limit
(or Fourier limit, or Heisenberg-Gabor limit)**

then achieve maximum contrast for HBT peaks, no resolution smearing

- Fast imaging techniques are the key
 - Promising technologies: **SPADs**, SNSPDs
 - Target 10 - 100 ps resolution
- Spectral binning: diffraction gratings, echelle spectrometers
- High photon detection efficiency: SNSPDs

Benchtop Verification

used a narrow argon line: 794.8 nm

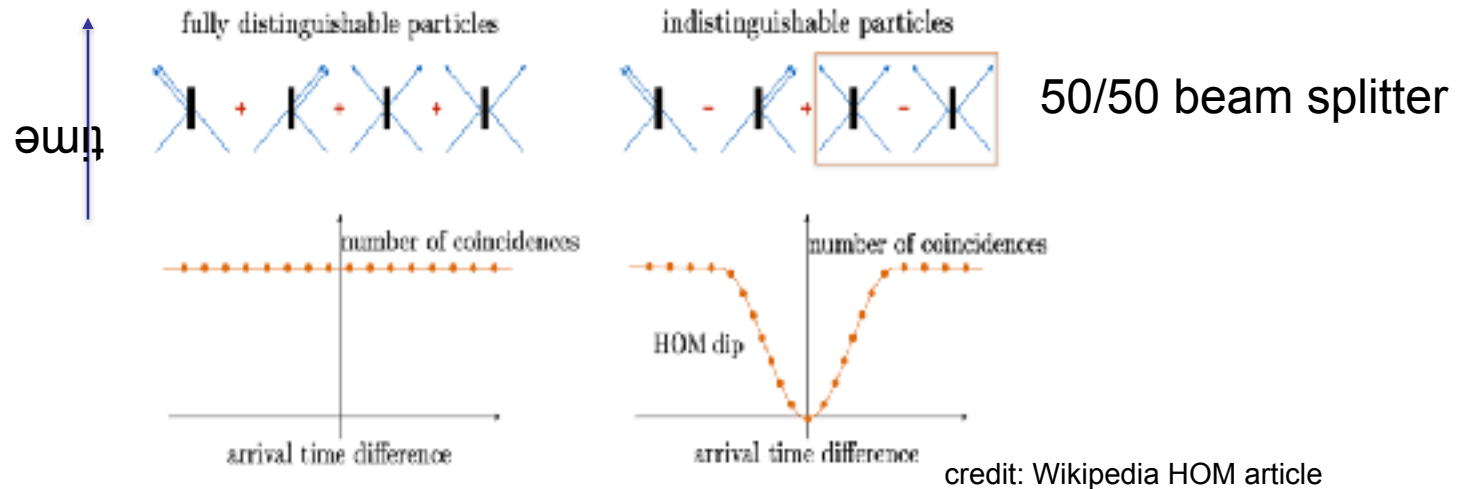


$$P(cg) = P(dh) = (1/8)(1 + \cos(\delta_1 - \delta_2))$$
$$P(ch) = P(dg) = (1/8)(1 - \cos(\delta_1 - \delta_2))$$

SPAD and SNSPD readout

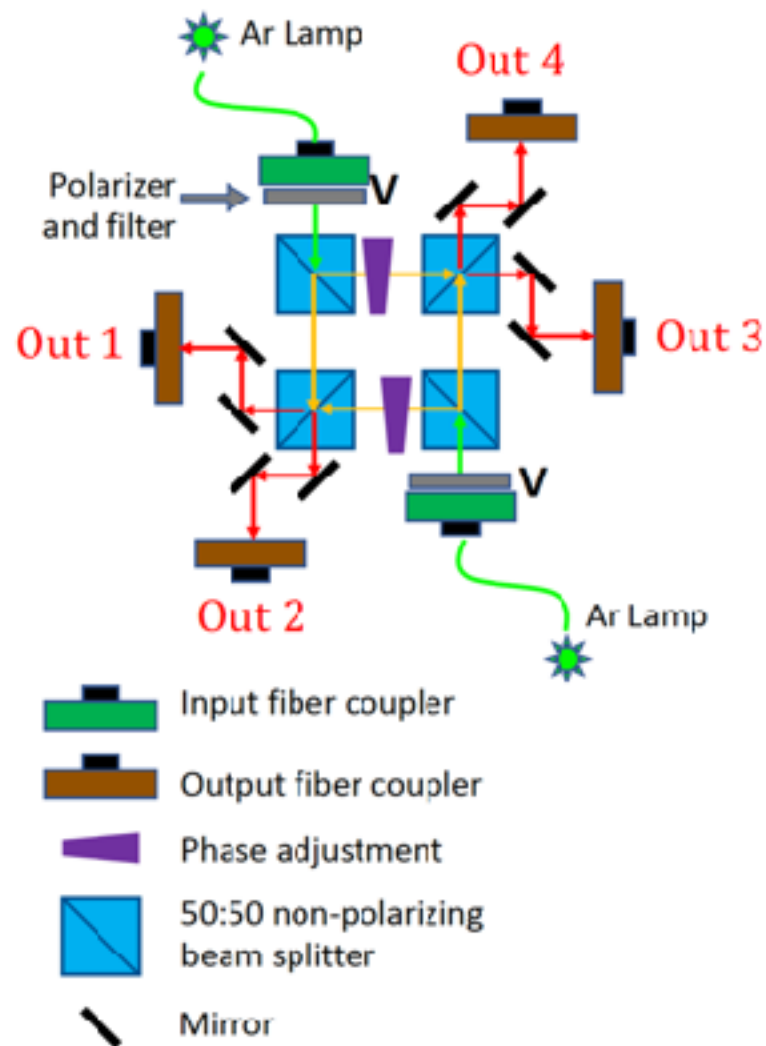
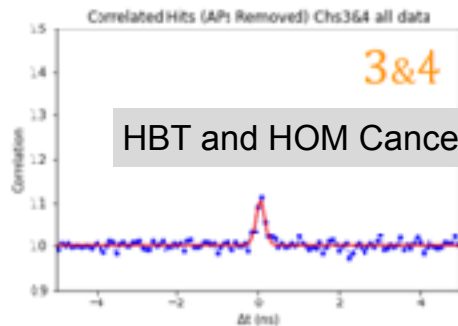
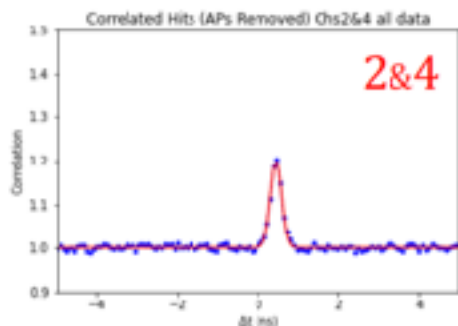
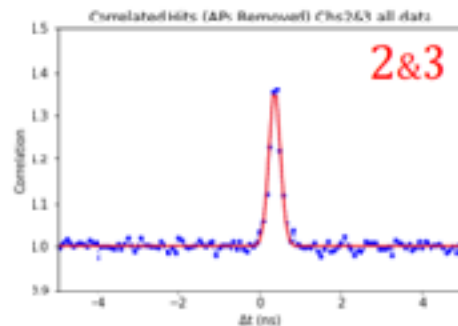
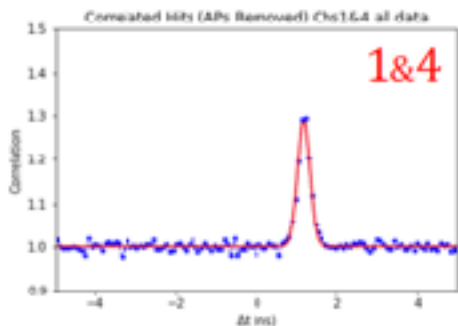
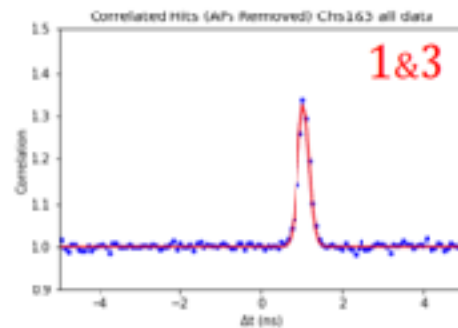
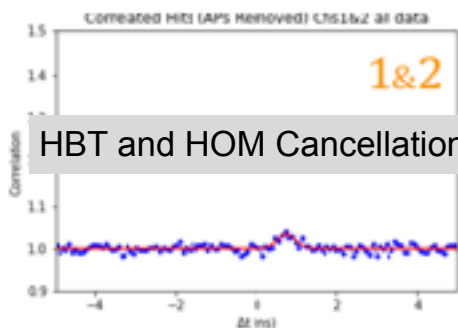
arxiv.org/abs/2301.07042
Optics Express 31, 44246-44258 (2023)

Hong-Ou-Mandel effect

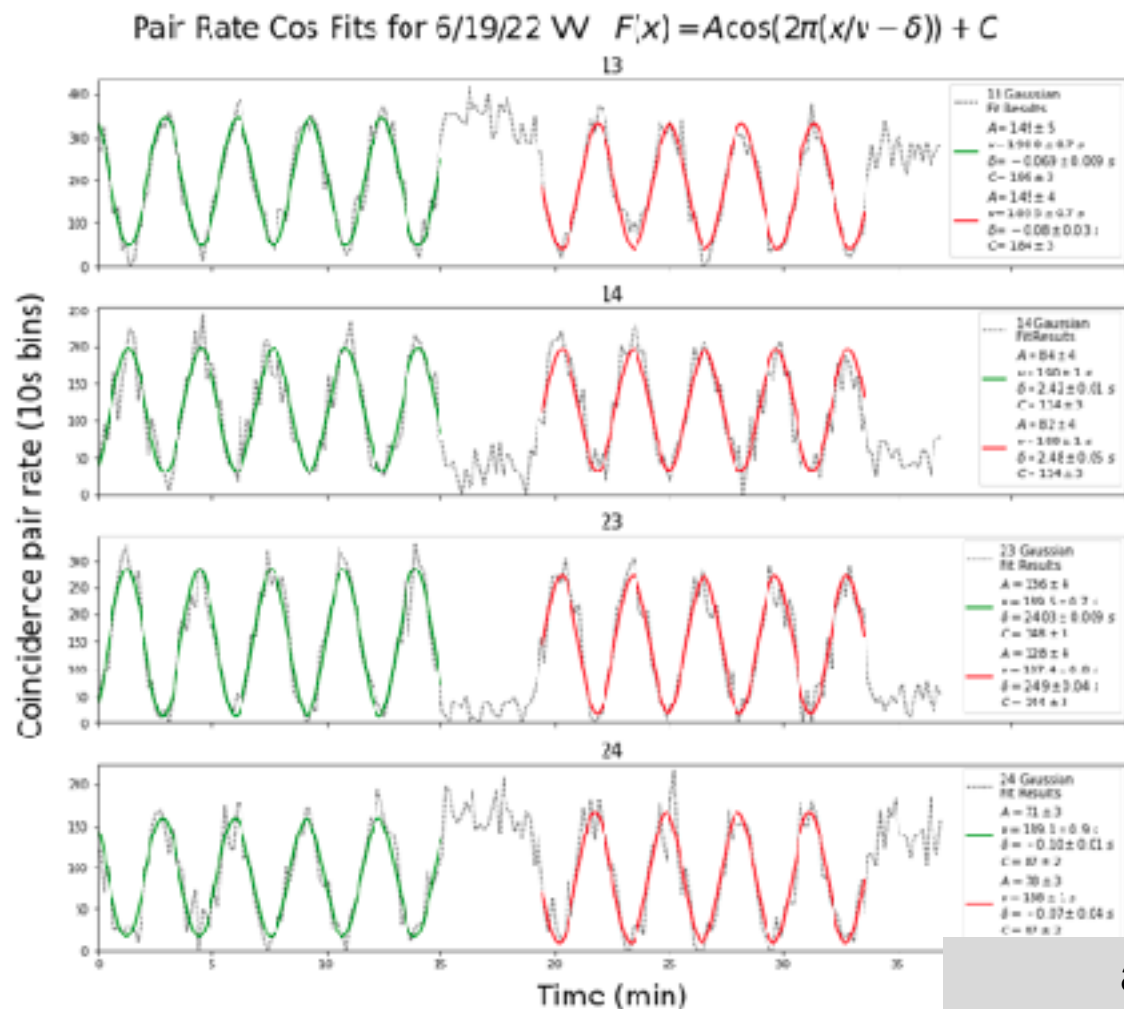


HOM dip for coincidences of two outputs

Polarized – V V



Phase dependence



arxiv.org/abs/2301.07042
 Optics Express 31, 44246-44258 (2023)

Population of HBT peaks as function of phase = phase oscillations

Related Ideas

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

M.R. Brown, M. Allgaier, V. Thiel, J.D. Monnier, M.G. Raymer and B.J. Smith, *Interferometric Imaging Using Shared Quantum Entanglement*, *Physical Review Letters* **131** (2023) .

Tang et al. *Light: Science & Applications* (2025)14:46
<https://doi.org/10.1038/s41377-024-01684-y>

Official journal of the OOWP 2847 7538
www.nature.com/lsa

ARTICLE

Open Access

Phase-dependent Hanbury-Brown and Twiss effect for the complete measurement of the complex coherence function

Xuan Tang¹, Yunxiao Zhang², Kueshi Guo², Liang Cui², Kaoping Li^{2,§} and Z. Y. Ou^{1,§}

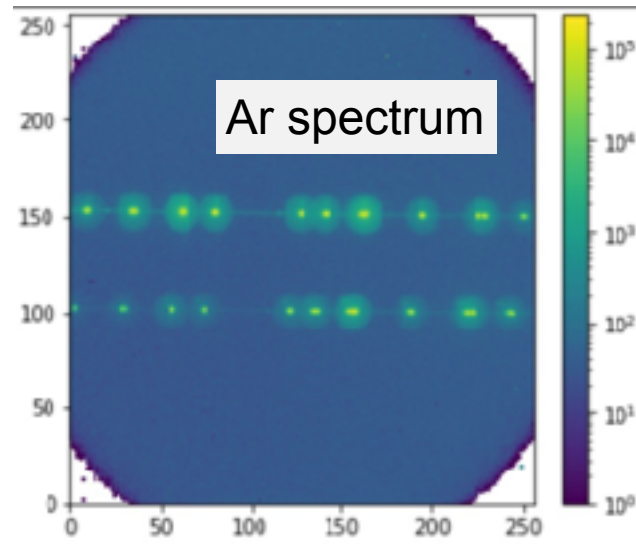
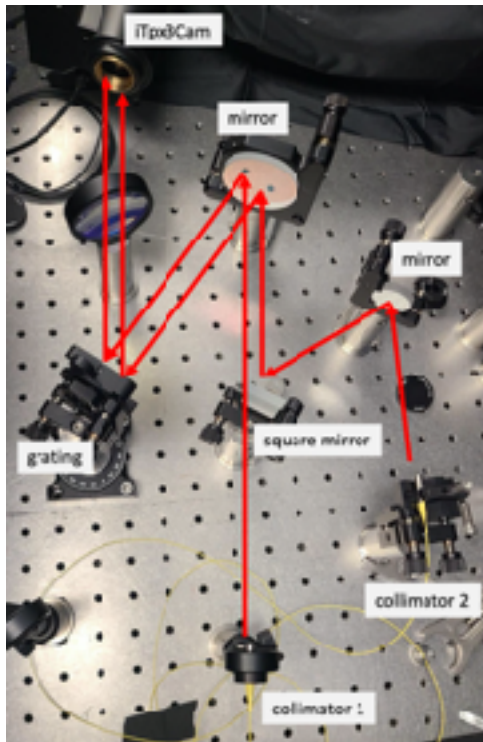
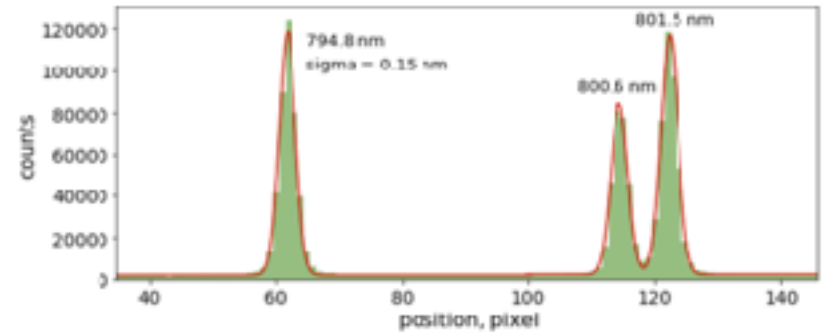
Entanglement Assisted Non-local Optical Interferometry in a Quantum Network

P.-J. Stas,^{2,*} Y.-C. Wei,^{1,*} M. Sirotni,^{1,2,*} Y. Q. Huan,² U. Yazlar,^{1,3}
F. Abdo Arias,¹ E. Knyazev,¹ G. Baranes,^{1,3} B. Machielse,^{4,5} S. Grandi,⁶ D. Riedel,⁵
J. Borregaard,² H. Park,^{1,7} M. Lončar,⁴ A. Suleymanzade,^{1,8} and M. D. Lukin^{1,7}

Next step: spectral binning

Spectral binning: spectrometer

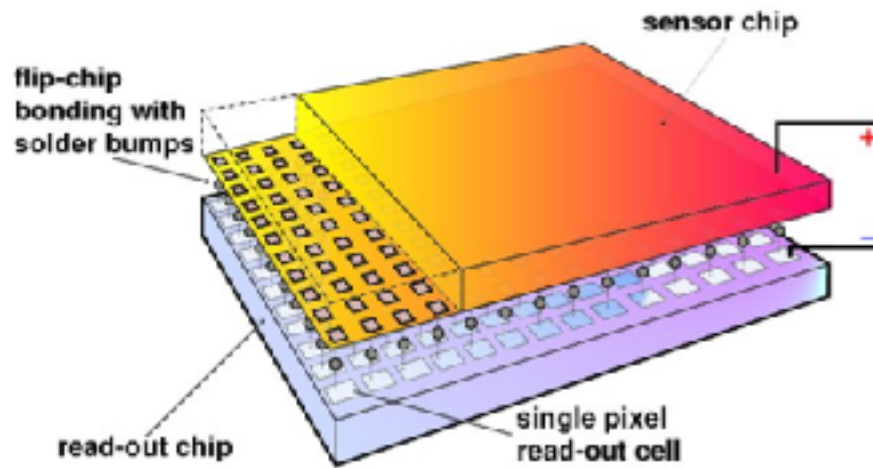
Two beams of thermal photons $\rightarrow$ diffraction grating
Based on intensified Tpx3Cam, ns time resolution



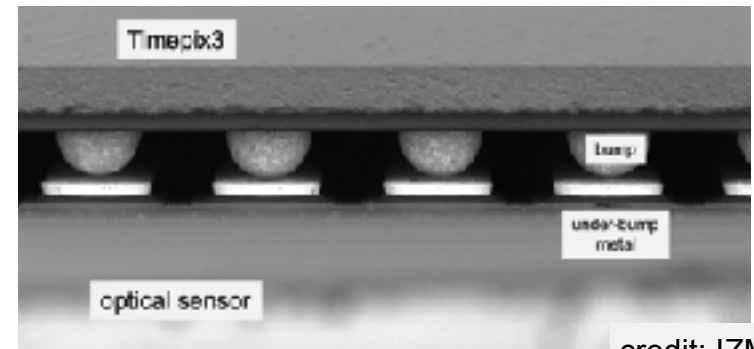
A.Nomerotski et al. Intensified Tpx3Cam, a fast data-driven optical camera with nanosecond timing resolution for single photon detection in quantum applications, arxiv.org/abs/2210.13713, published in JINST

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

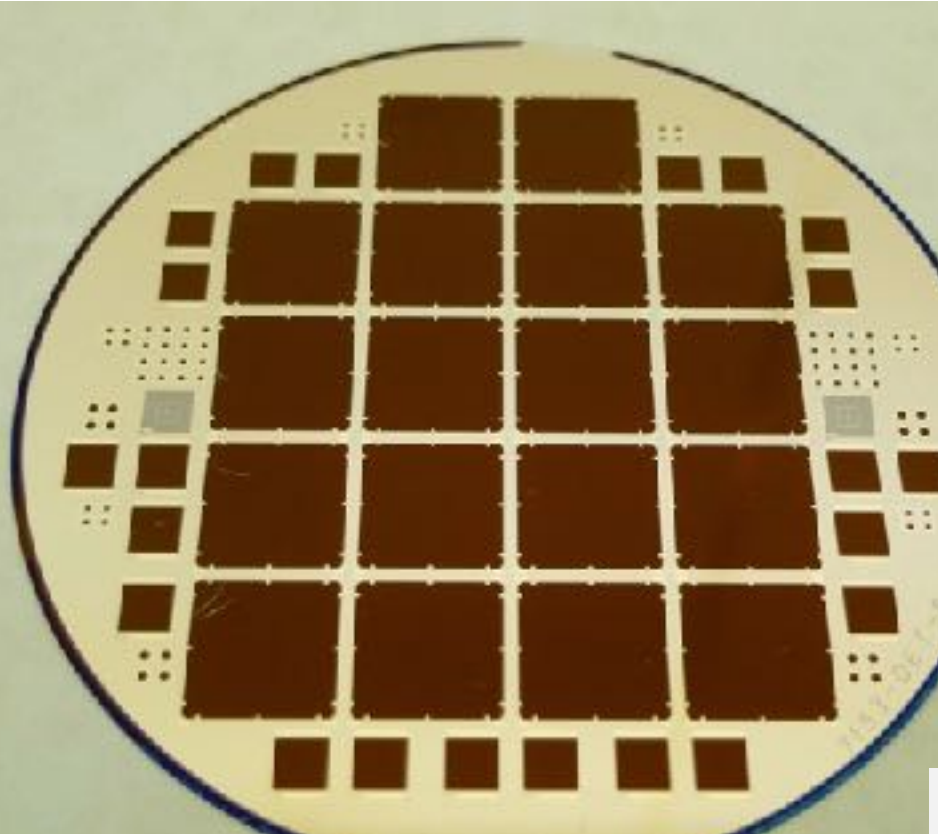
Decouple readout chip and sensor

- optimize technologies for chip and sensor separately

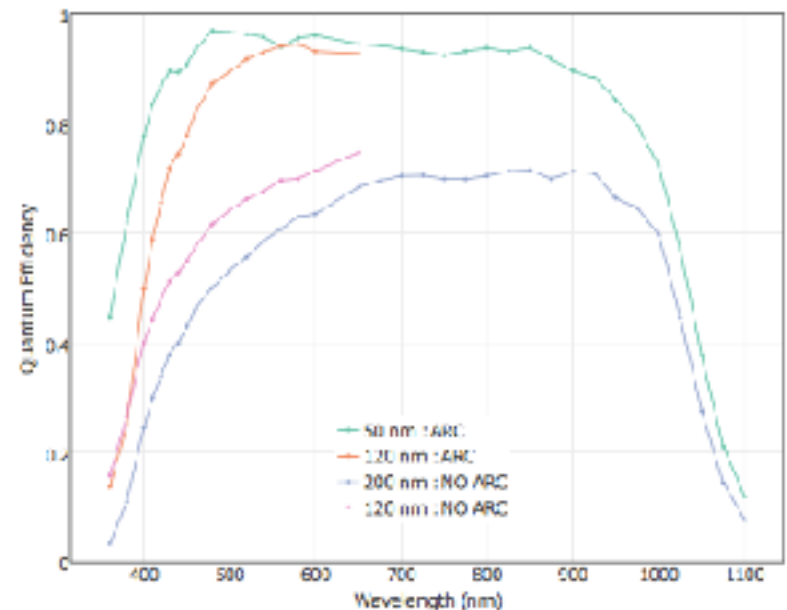
Use different sensors with same readout, versatile approach for x-rays (Si, CZT)

→ we will use **OPTICAL** sensors

Thin window optical sensors



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



High QE

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.

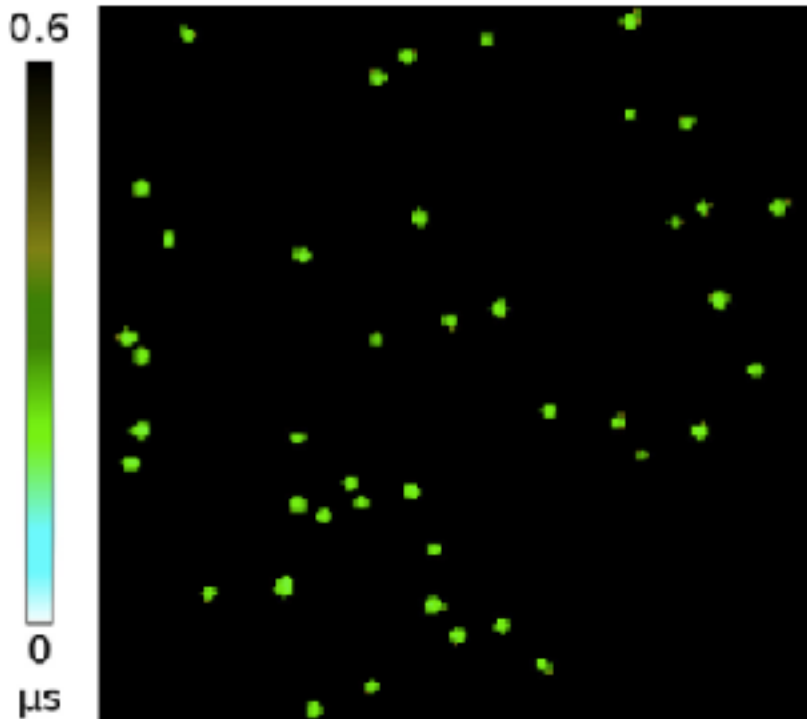
First produced at CNM (Barcelona) in 2015

Surface preparation is very important, inspired by astronomical CCDs (LSST)

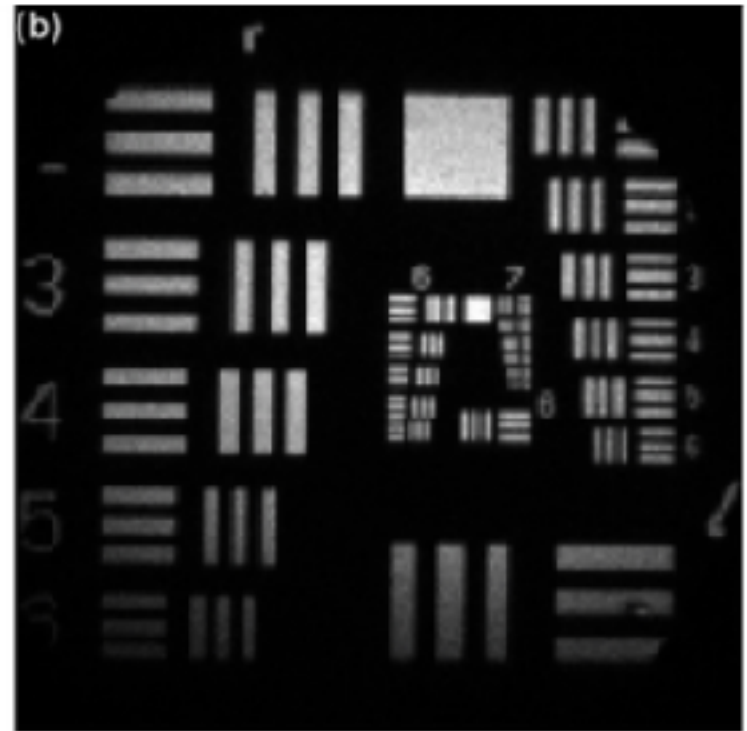
Imaging with photon counting

Photons appear as standalone objects $\leftrightarrow$ 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 replaced by
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

Particle Physics and Quantum

In PP: detect particles as objects collision per collision (= fast) then form **observables for collision based 'events'** like transverse momentum, invariant mass etc

Same ideas are now applicable to optical photons - detect them as objects, then evaluate correlators or other estimators (entanglement certifiers?) pair by pair (so 'event' by 'event'). This **should give better performance compared to integrating over long time** and subtracting background.

Peter Svihira, Yingwen Zhang, Paul Hockett, Steven Ferrante, Benjamin Sussman, Duncan England, Andrei Nomerotski; Multivariate discrimination in quantum target detection. *Appl. Phys. Lett.* 27 July 2020; 117 (4): 044001. <https://doi.org/10.1063/5.0012429>

Accidental coincidences in camera-based high-dimensional entanglement certification

RAPHAEL GUITTER ^{1,*}, BAPTISTE COURME ^{1,2}, CHLOÉ VERNIÈRE ¹, PETER SVIHRA ³, ANDREI NOMEROTSKI ³ AND HUGO DEFLENNE ¹

R.Guitter et al, Opt. Lett. 50, 7532-7535 (2025)

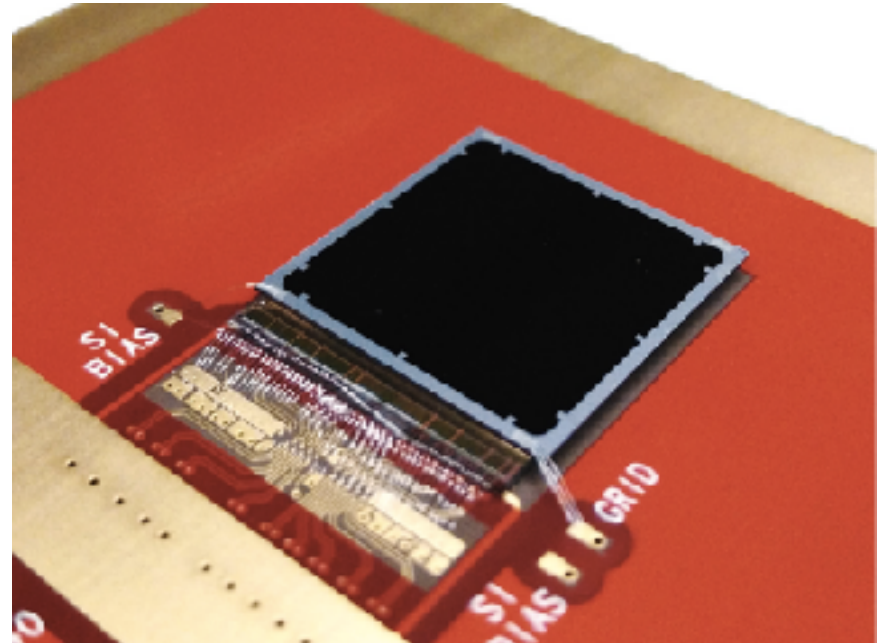
Timepix3 Camera → Tpx3Cam

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, $\sim 1\mu\text{s}$ 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.

Intensified camera: use off-the-shelf image intensifier

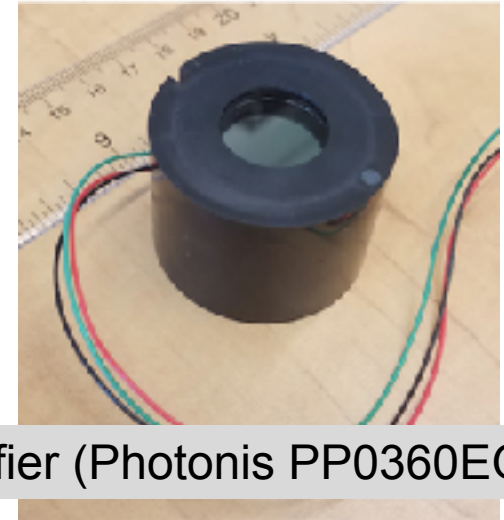
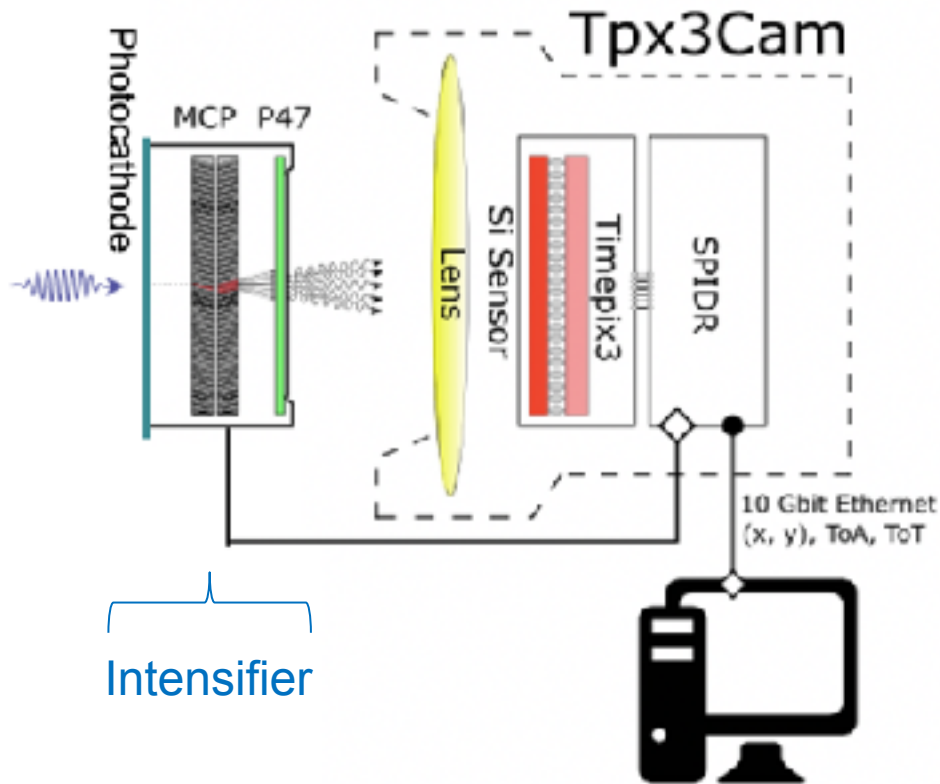


Image intensifier (Photonis PP0360EG)

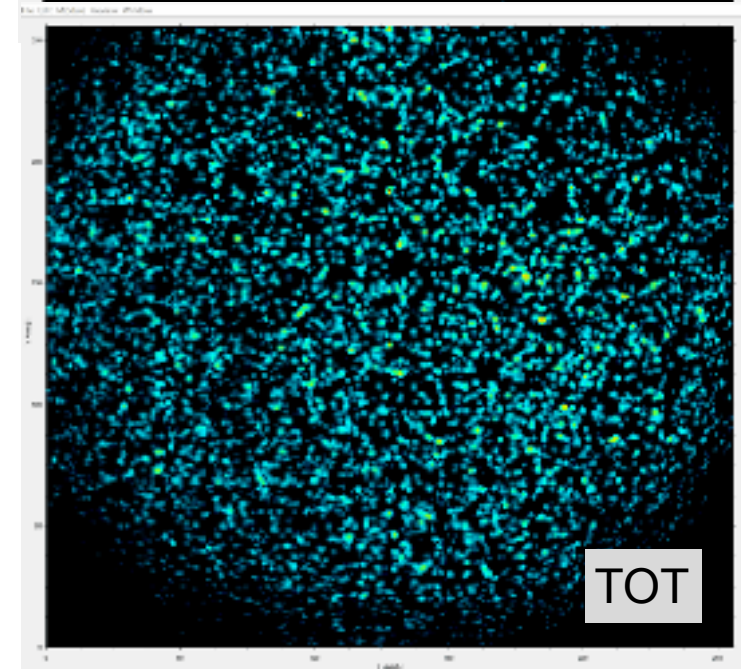
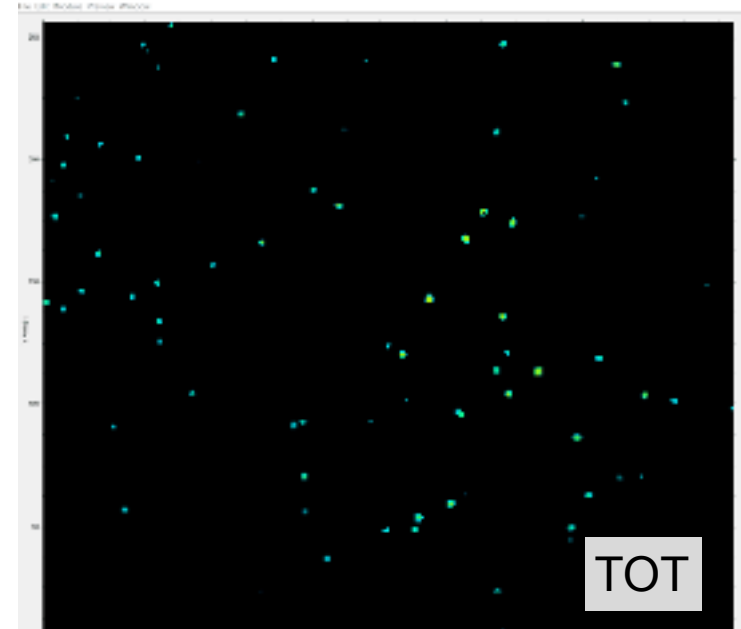
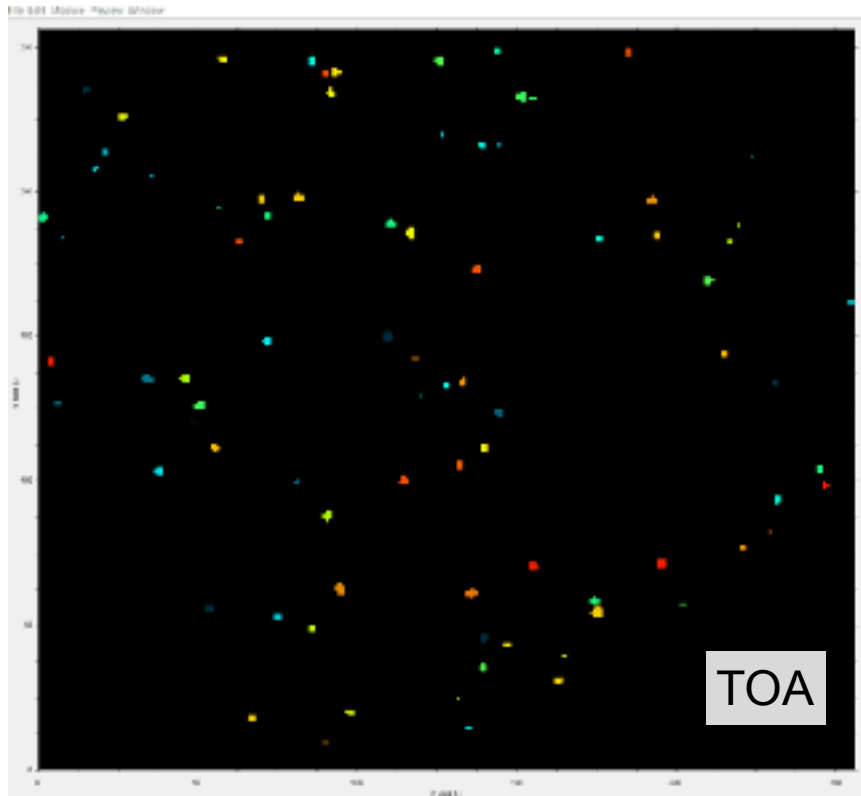
Cricket@



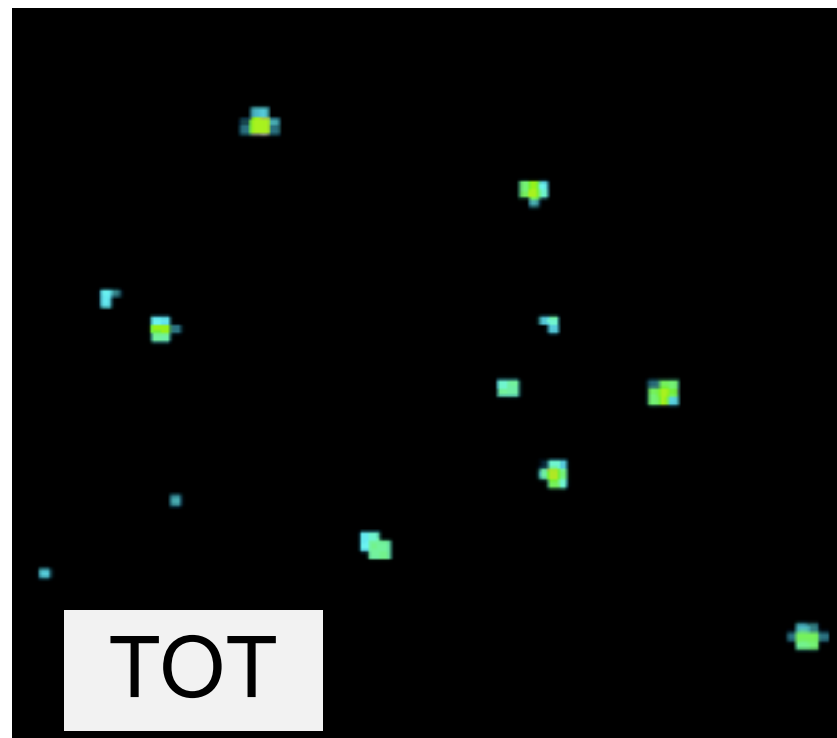
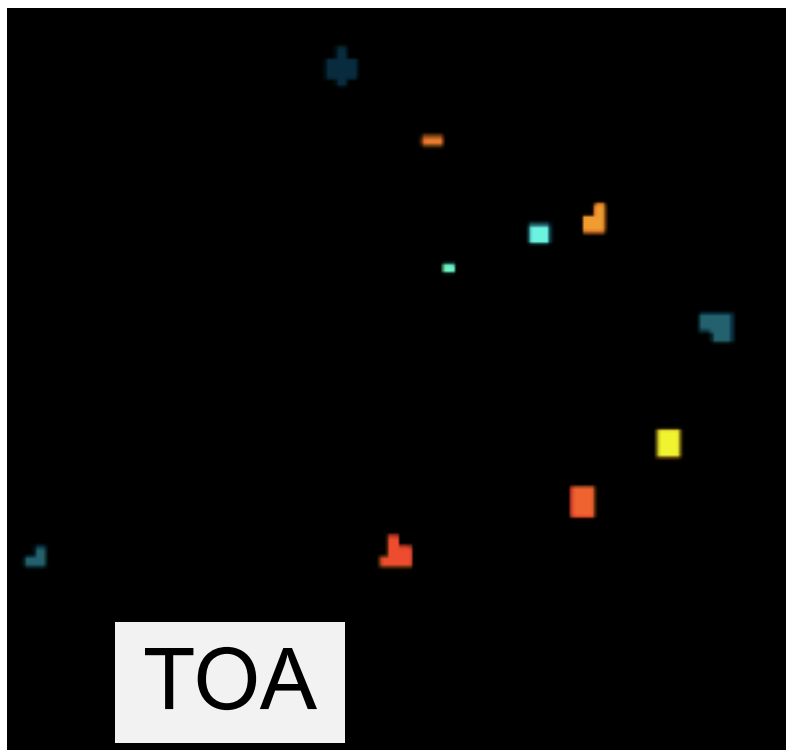
Intensified cameras are common:
iCCD
iCMOS cameras

Single Photons in Tpx3Cam

1 ms slice of data
1.5ns time-stamping



Tpx3Cam + intensifier by Photonis

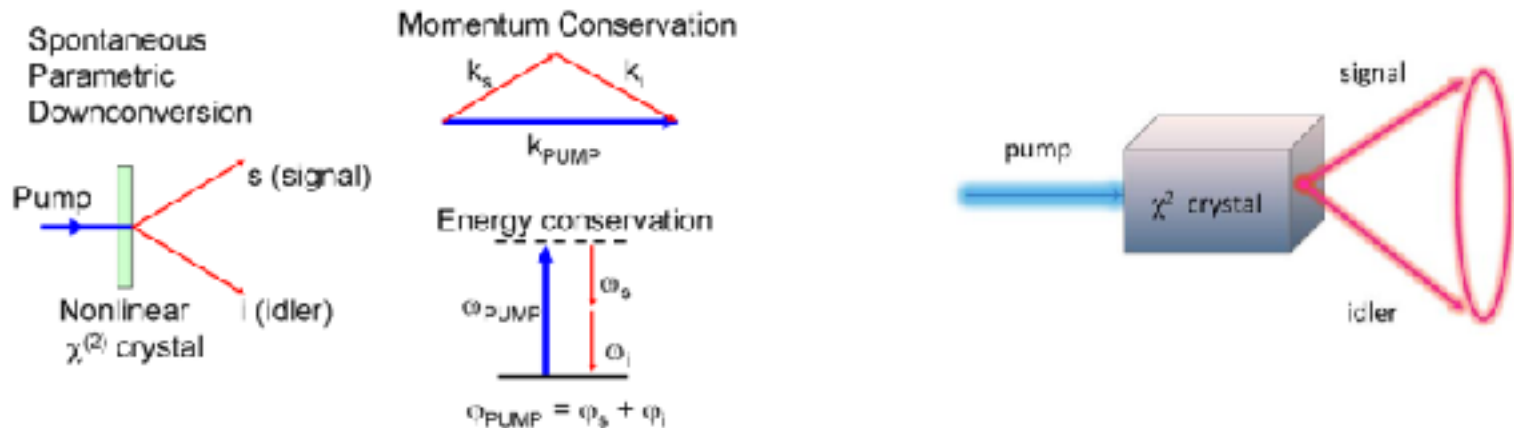


Each photon is a cluster of pixels
à 3D (x,y,t) centroiding

Spatial resolution: 0.1 pixel / photon

Time resolution: < 1 ns / photon

Quantum photon sources - spontaneous parametric down-conversion (SPDC) sources

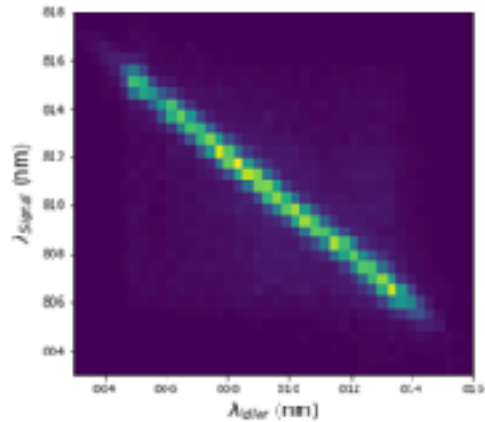


Produce two photons correlated (sometimes entangled) in

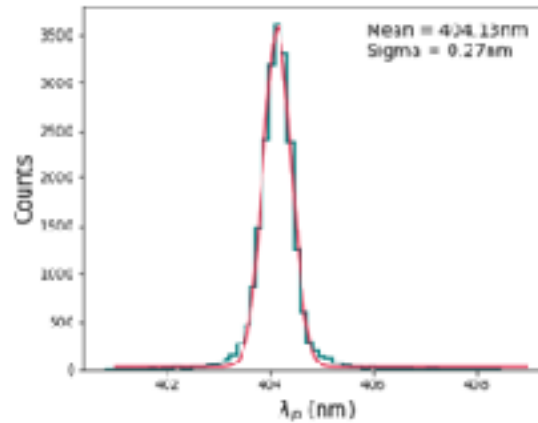
1. Time
2. Position
3. Energy

SPDC source in spectrometer

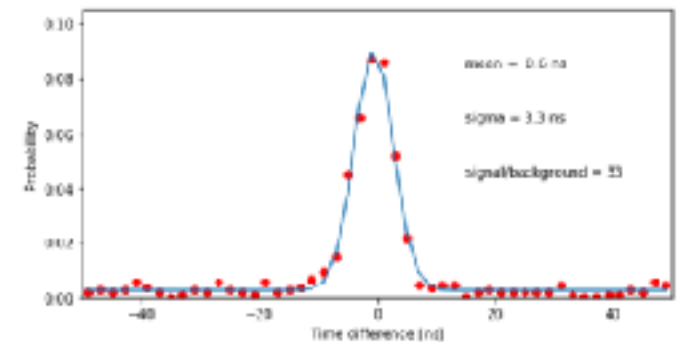
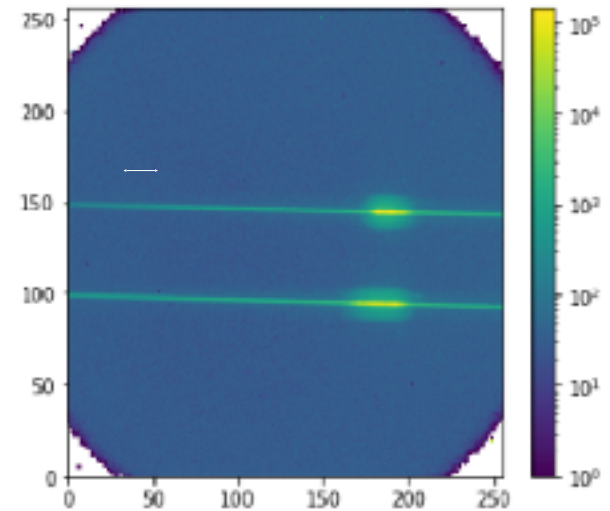
signal & idler in spectrometer



wavelength
anti-correlation
for photon pairs



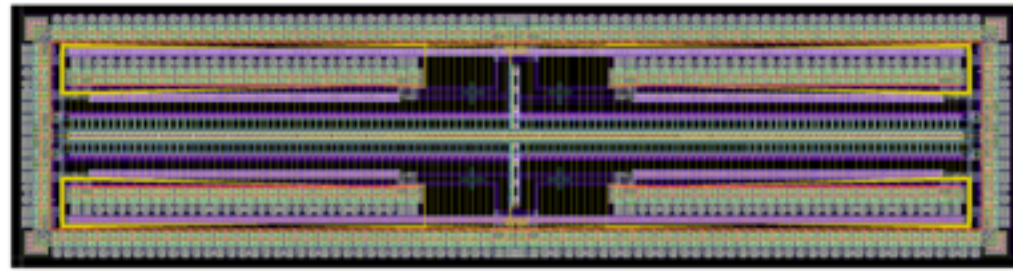
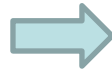
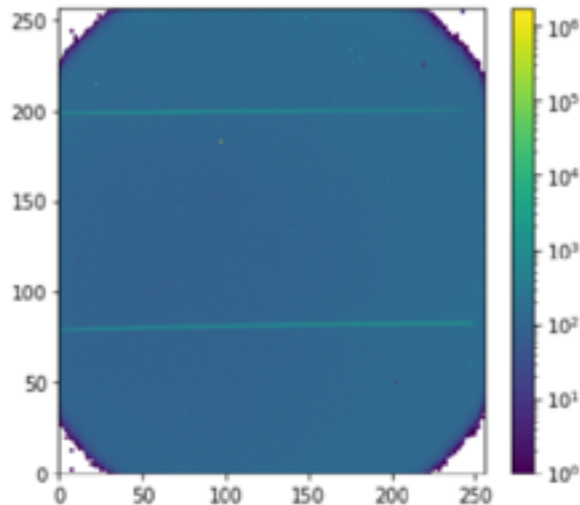
pump
wavelength



time coincidences

Next steps: spectrometer based on LinoSPAD2

Diffracted photon strip projected on to linear array



Spectrometer time resolution: 5 ns $\rightarrow$ 50 ps

Possible technologies: SPAD

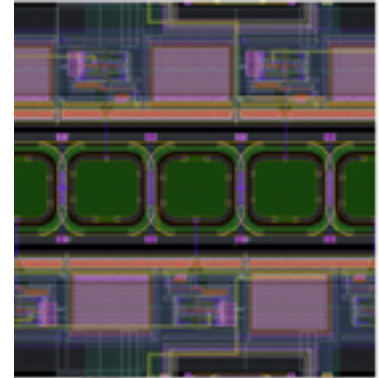
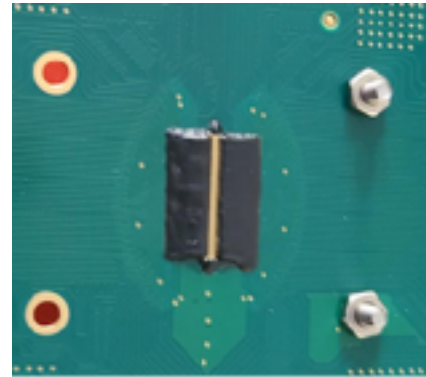
SPAD = single photon avalanche device

Semiconductor device: p-n junction with amplification

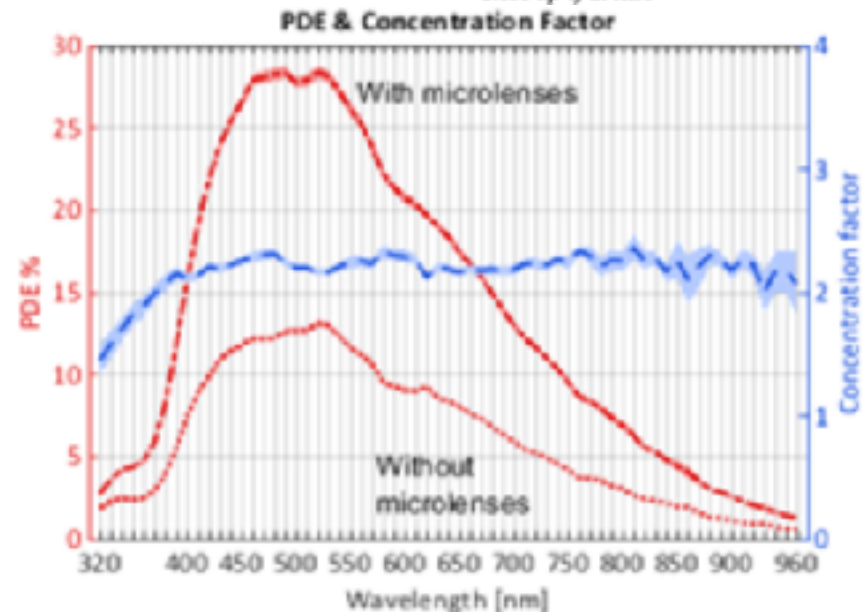
- 512 x 1 pixels
- 24 x 24 micron pixels
- Max PDE (with microlenses) ~ 30%
- 50 ps resolution

Developed in EPFL (Switzerland)
AQUA group (E.Charbon)

LinoSPAD2

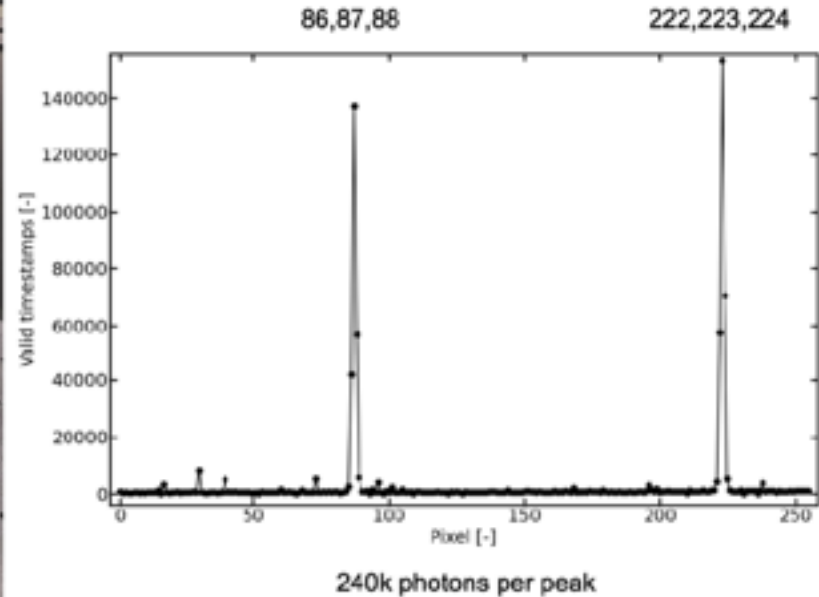
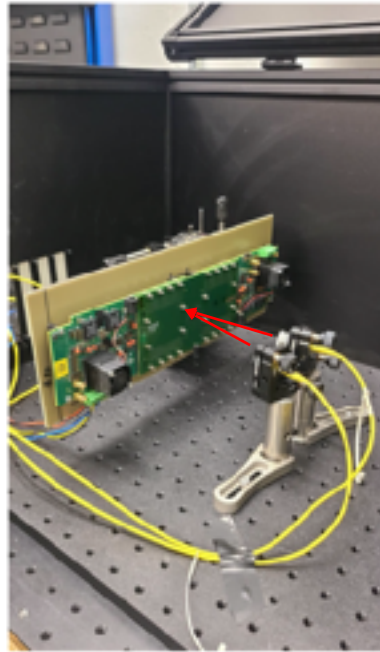
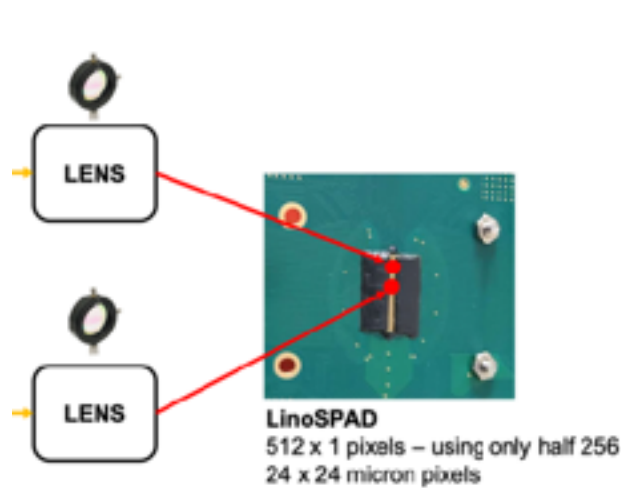


Close-up of SPADs



C. Bruschini et al, Linospad2: a 512x1 linear spad camera, in Quantum Sensing and Nano Electronics and Photonics XIX, vol. 12430, pp. 126–135, SPIE, 2023.

SPAD arrays with 50 ps resolution

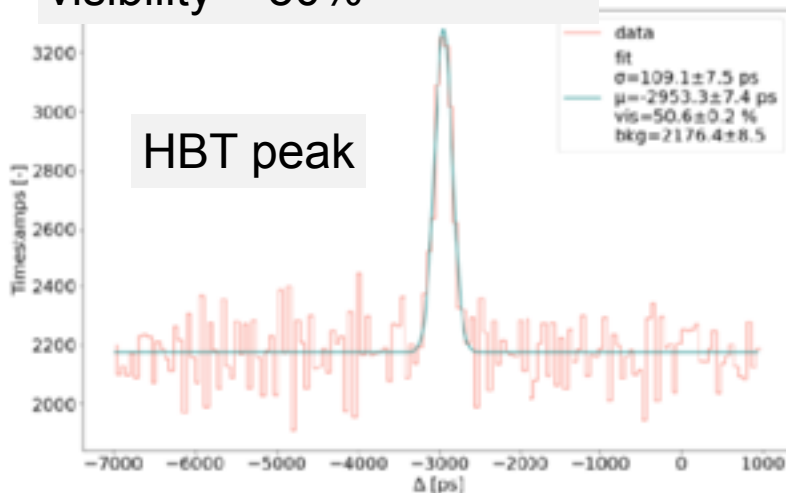


time difference, $\sigma=110$ ps
visibility = 50%

Two beams from Ar lamp + polarizer after beamsplitter

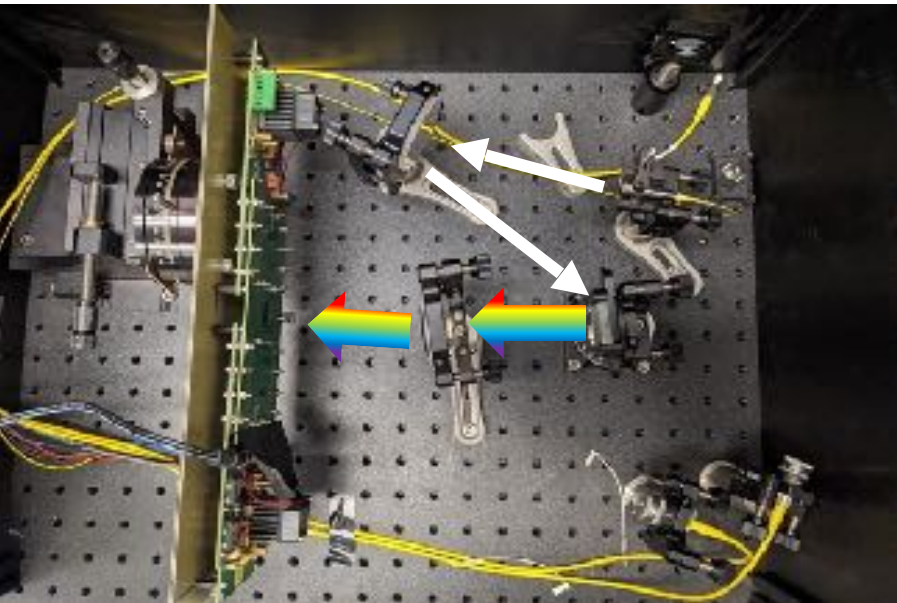
arxiv.org/abs/2406.15323
arxiv.org/abs/2406.13959

Next step: HBT in spectral bins for broadband light

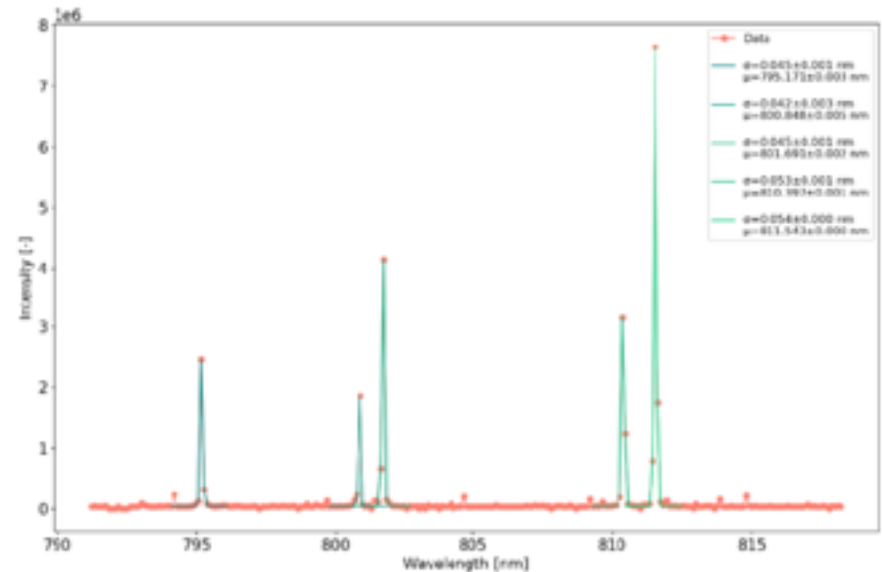


Spectrometer with LinoSPAD2

Used Ar lamp coupled to SM fiber



Ar spectral lines



spectral resolution 0.04 nm

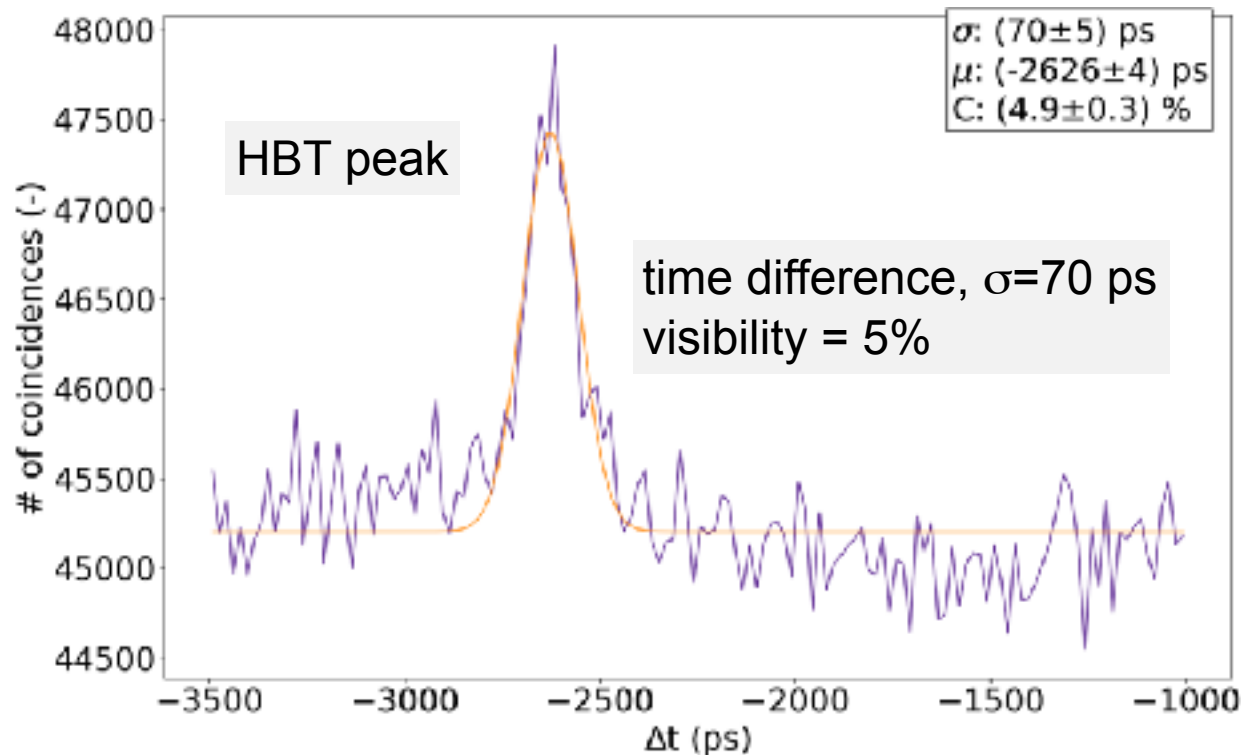
arxiv.org/abs/2304.11999

34

Achieved 40 pm spectral and 40 ps timing resolution

Broadband HBT peak

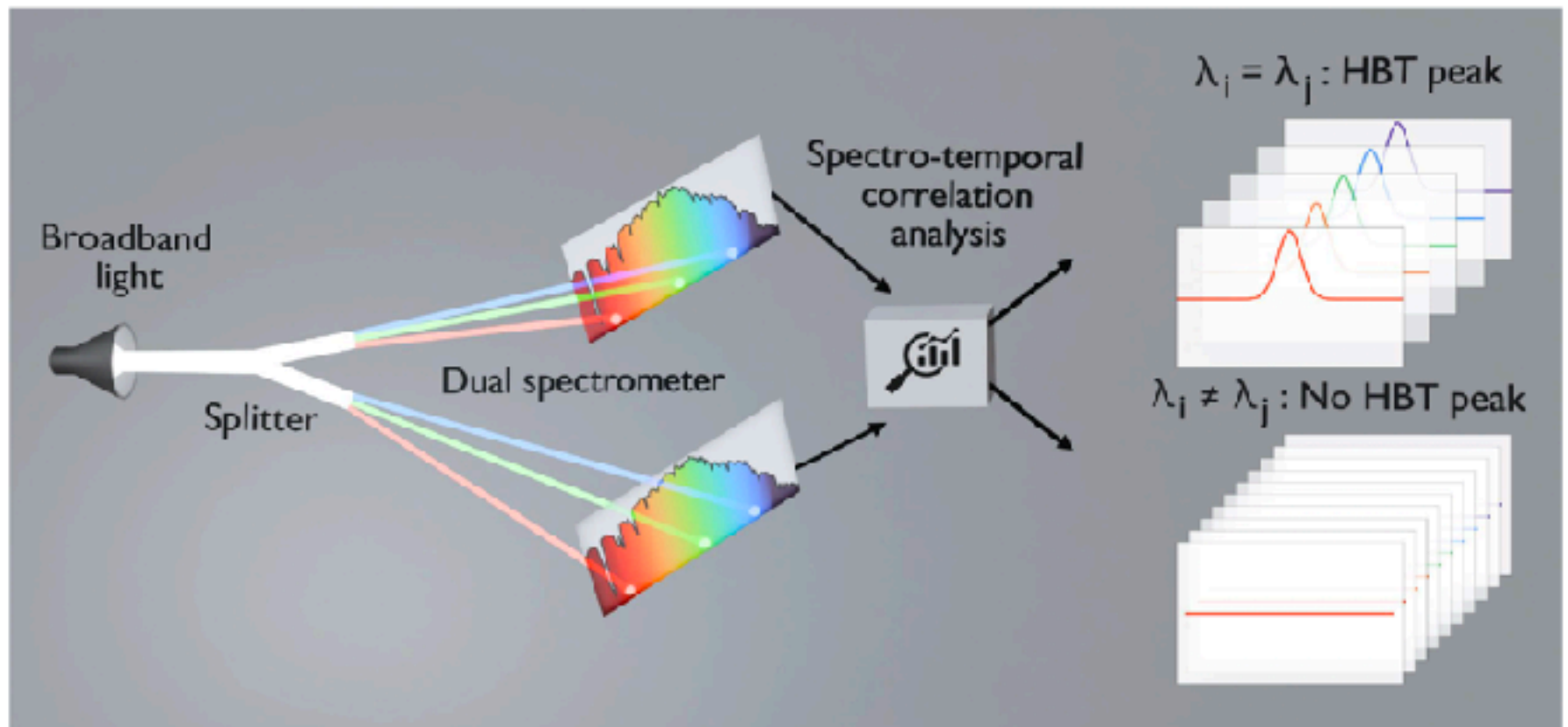
Two beams from bright LED + 0.1 nm filter + polarizer



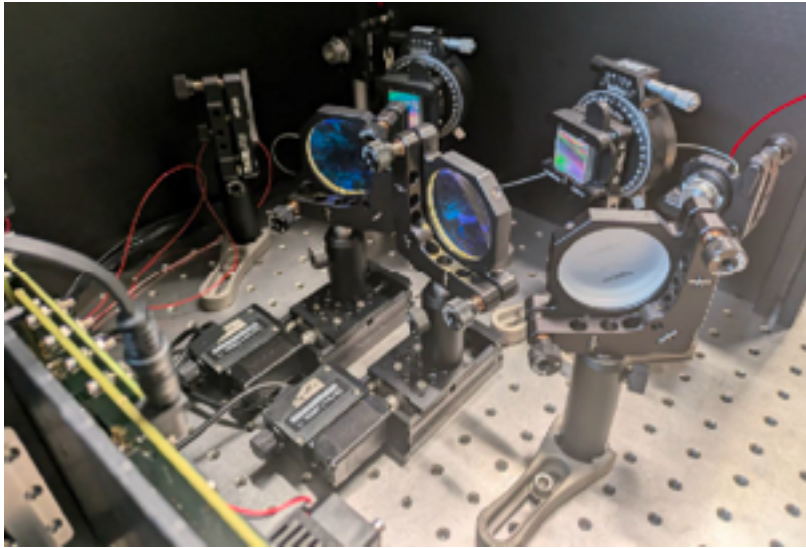
arxiv.org/abs/2509.05649

Next step: do it in spectrometer in spectral bins

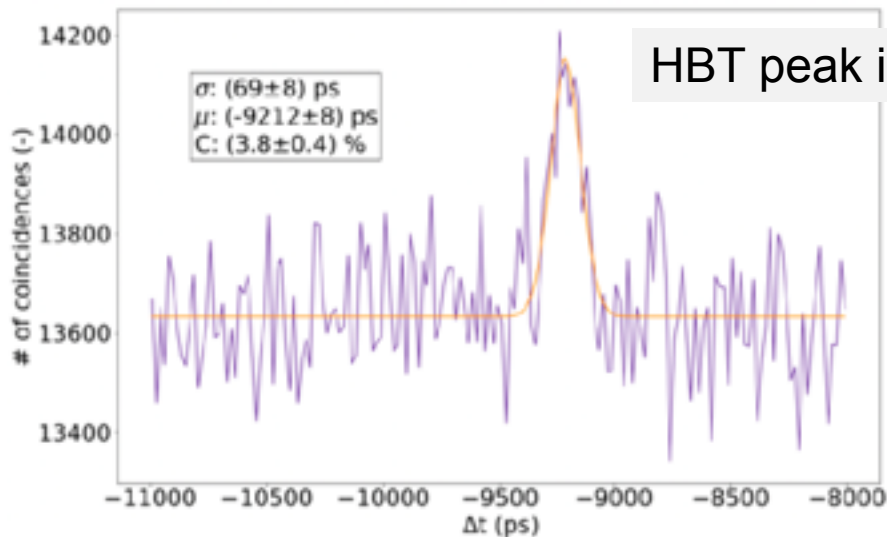
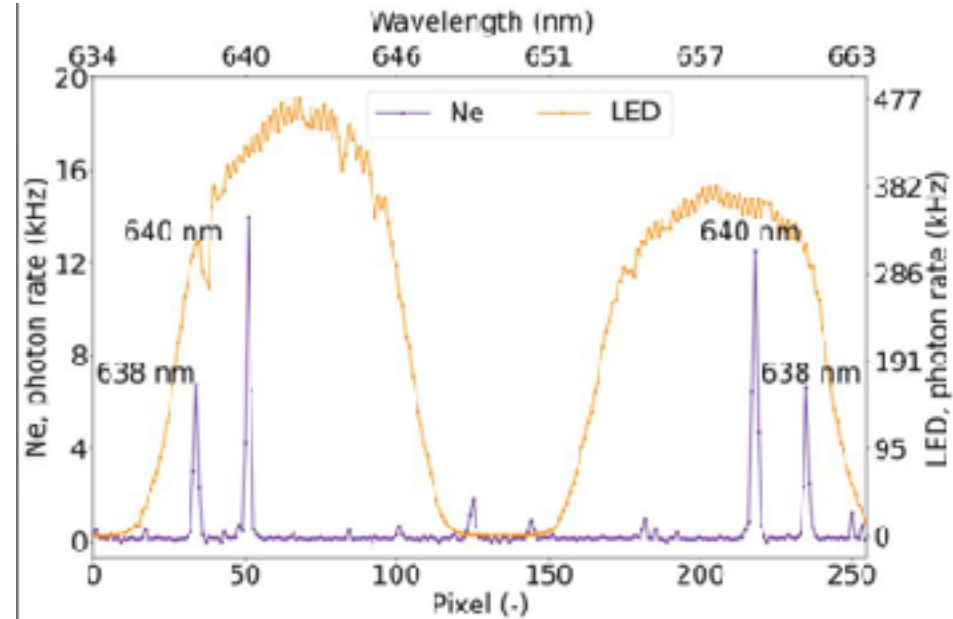
The idea



Colored HBT peaks in LinoSPAD2



dual spectrometer in Prague



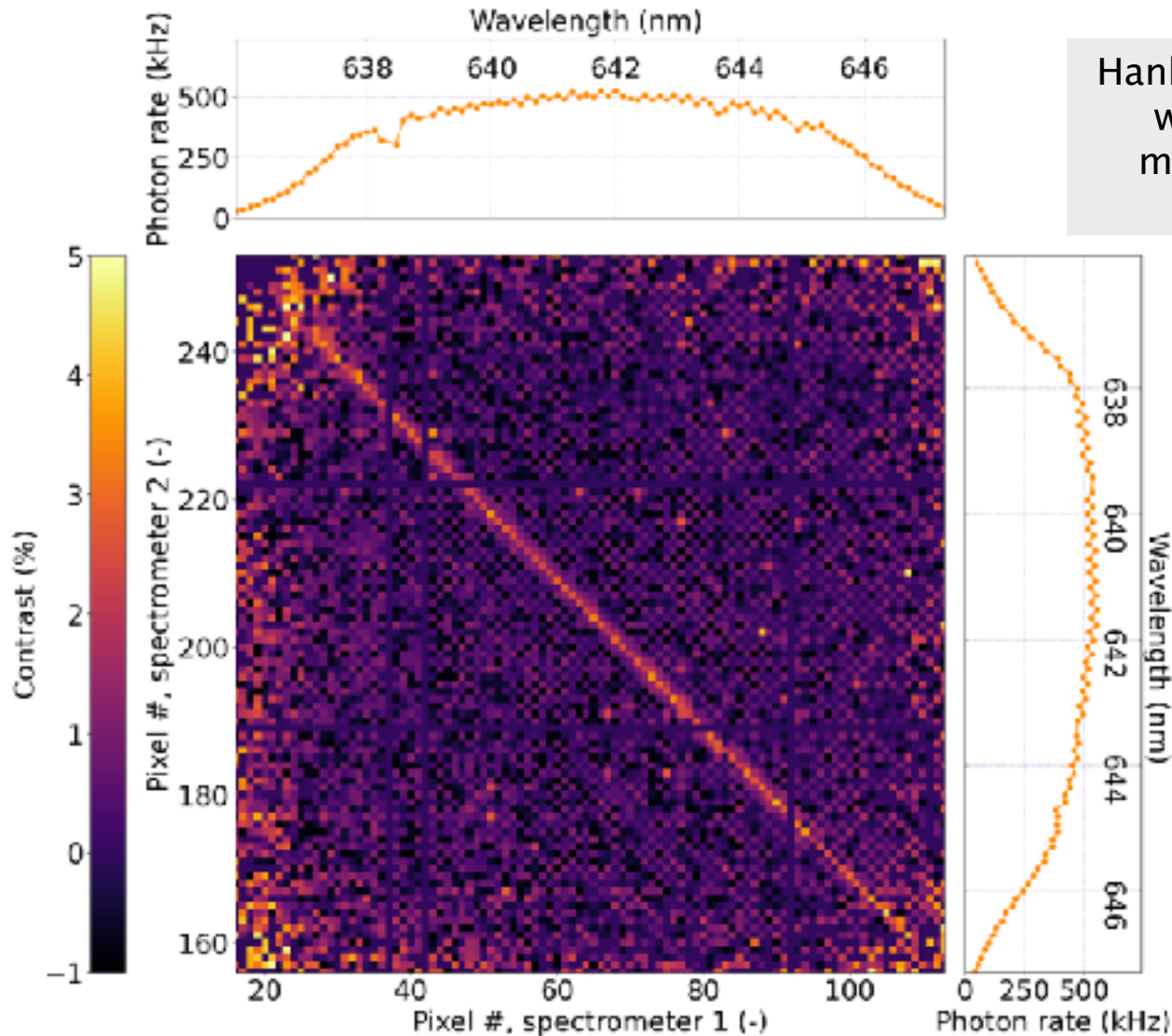
HBT peak in two spectral bins

time difference, $\sigma=70 \text{ ps}$
visibility = 3.8%

arxiv.org/abs/2509.05649

Spectral multiplexing in 100 x 0.1nm bins!

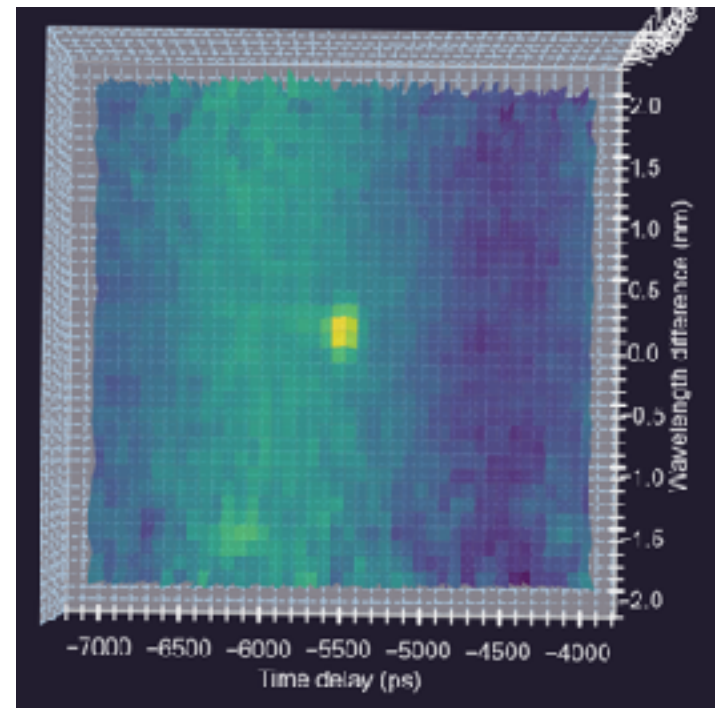
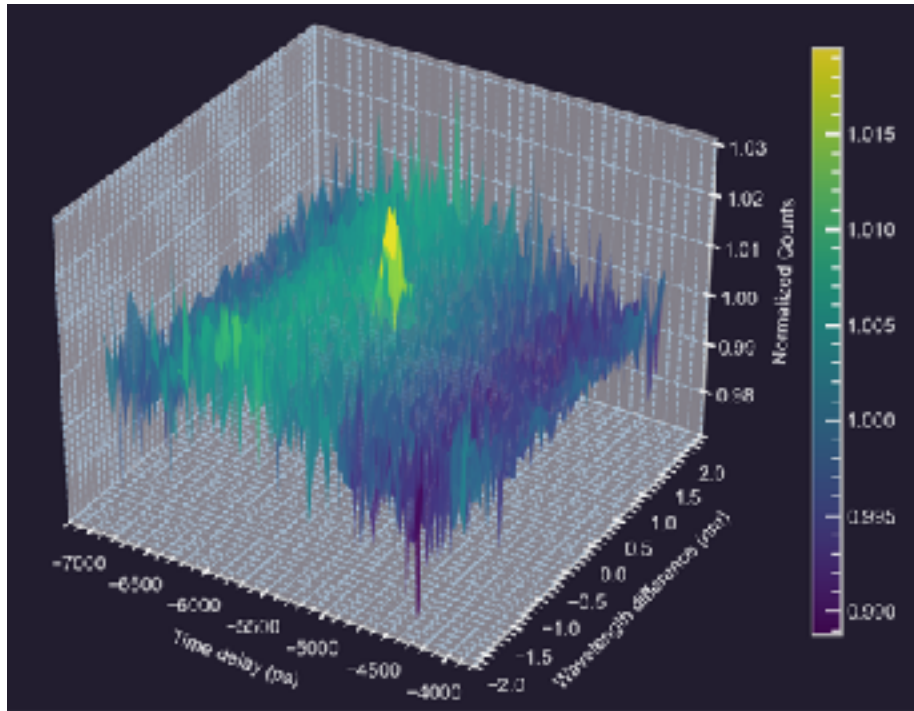
Contrast of HBT peak in spectral bins



Hanbury Brown-Twiss interference
with massively parallel spectral
multiplexing for broadband light
S.Kulkov et al

arxiv.org/abs/2509.05649

Spectral-temporal correlation



peak $dt \cdot d\lambda$ @ 5.5 ns $\cdot$ 0.0 nm

Heisenberg-Gabor limit (or Fourier limit)

$$\Delta E \Delta t \geq \frac{\hbar}{2}; \quad \Delta f \Delta t \geq \frac{1}{4\pi}$$

40 pm

40 ps

14.7x

Ways to improve



Echelle
spectrometer

Faster
detectors:
superSPAD,
SNSPD

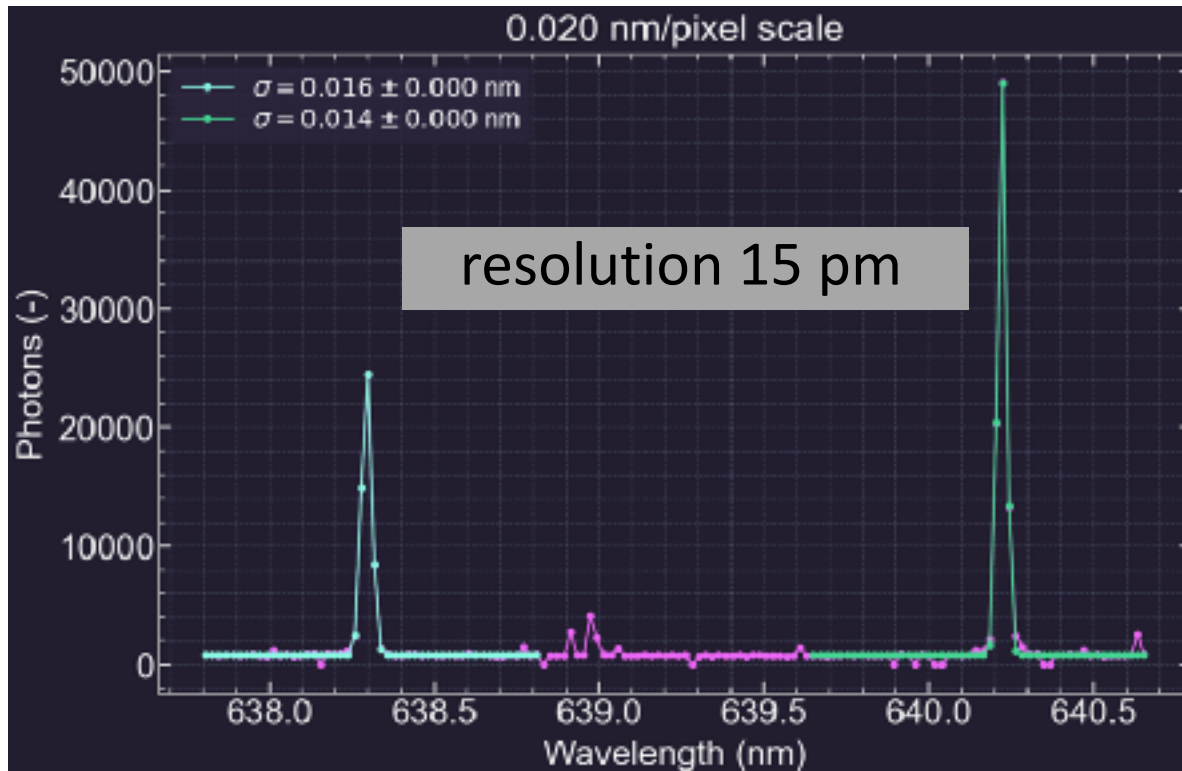
Contrast of HBT peak

$$C_j \approx \frac{1}{4\pi \Delta f \Delta t}, \text{ at the H-G limit contrast} = 100\%$$

Improving spectrometers

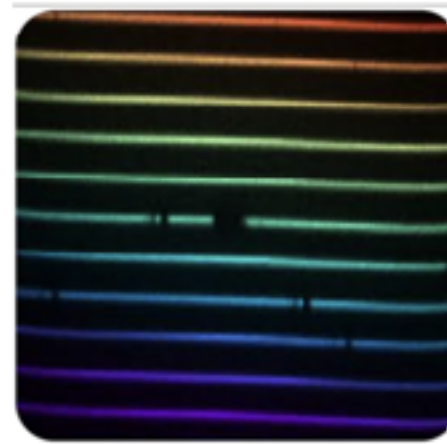
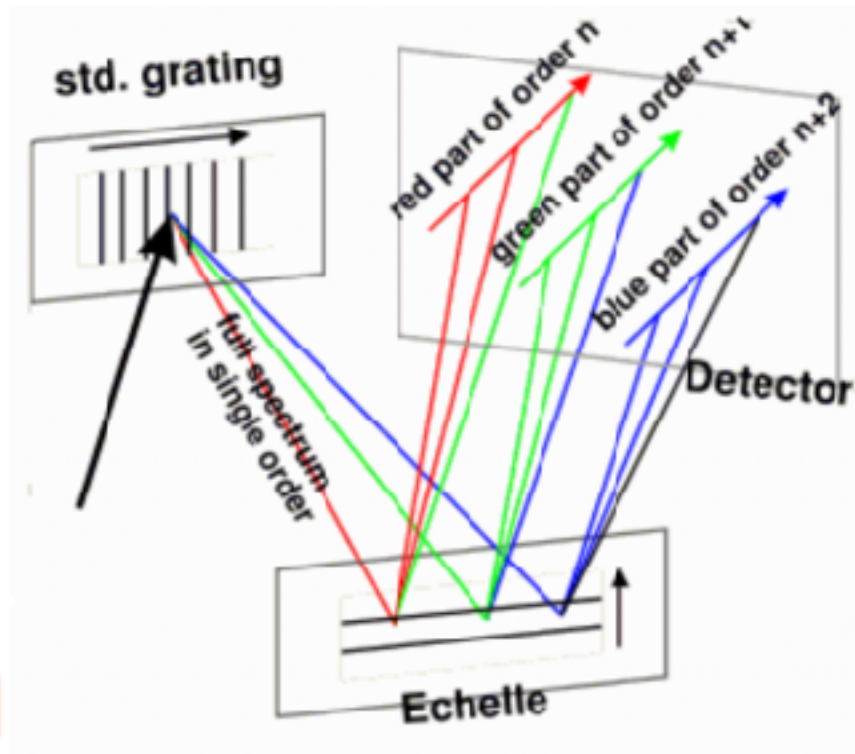
Ideas for spectrometers which can provide few pm resolution

Spectrometer improvements

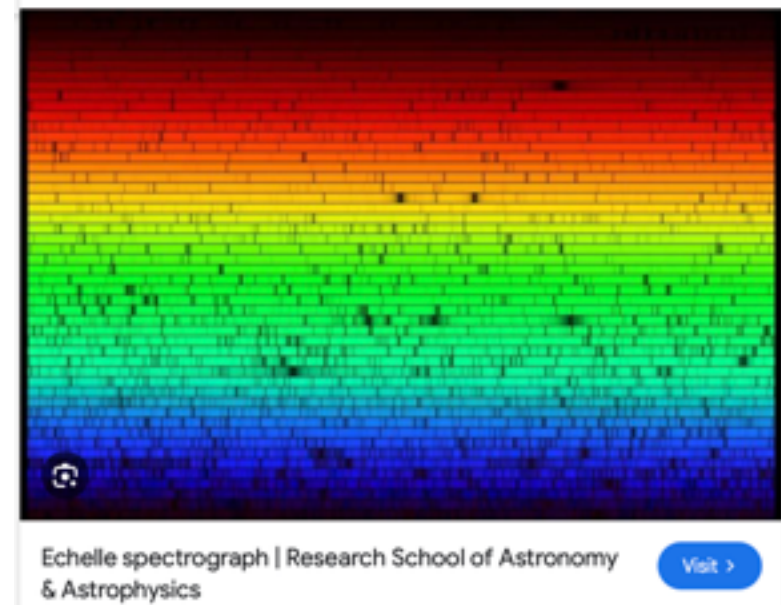


- More standard improvements: 40 pm $\rightarrow$ 15 pm
- Wider beam, denser grating, smaller pixel scale

Echelle spectrometer

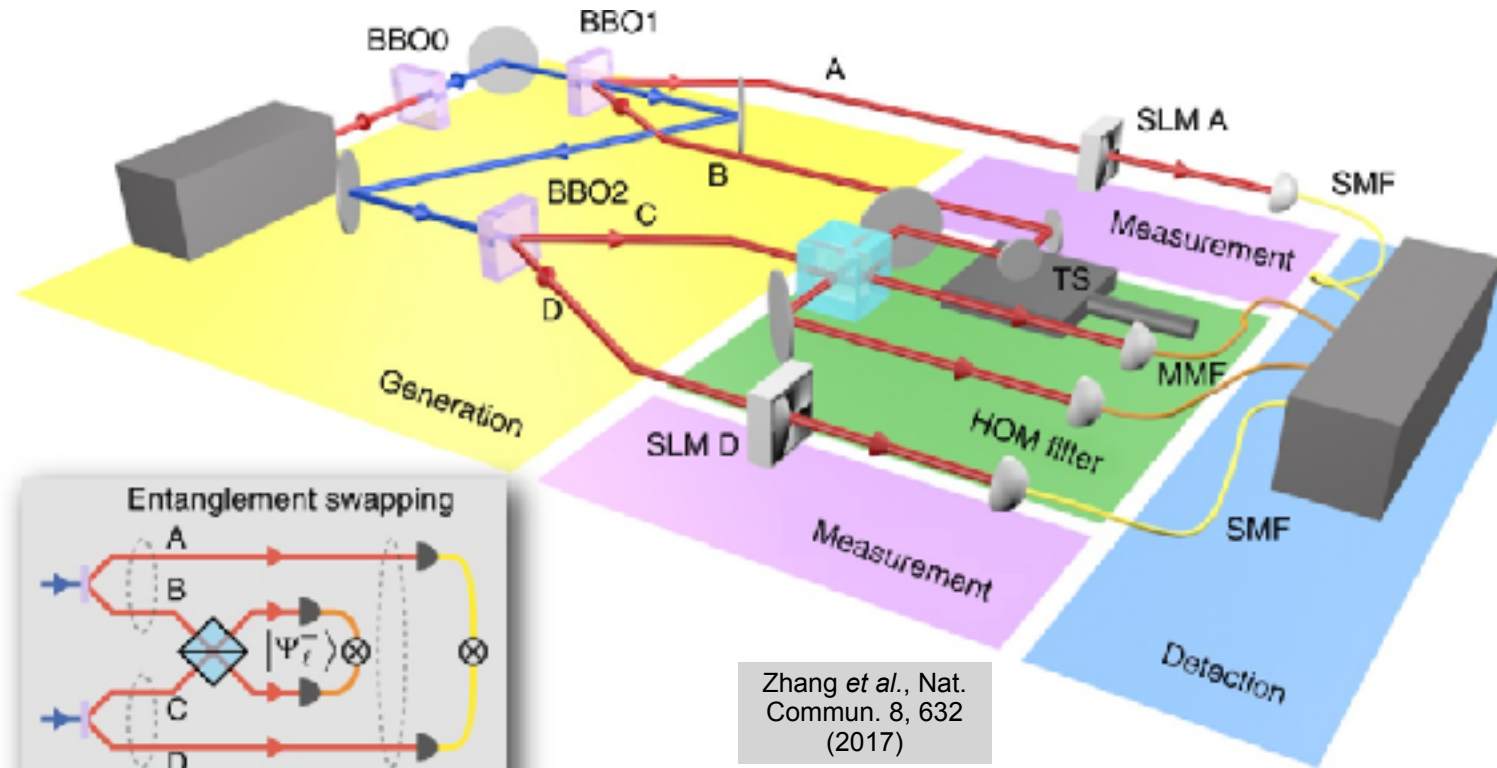


- Widely used in astronomy
- Achievable resolution $\sim$ few pm
- **Require 2D single photon detector**



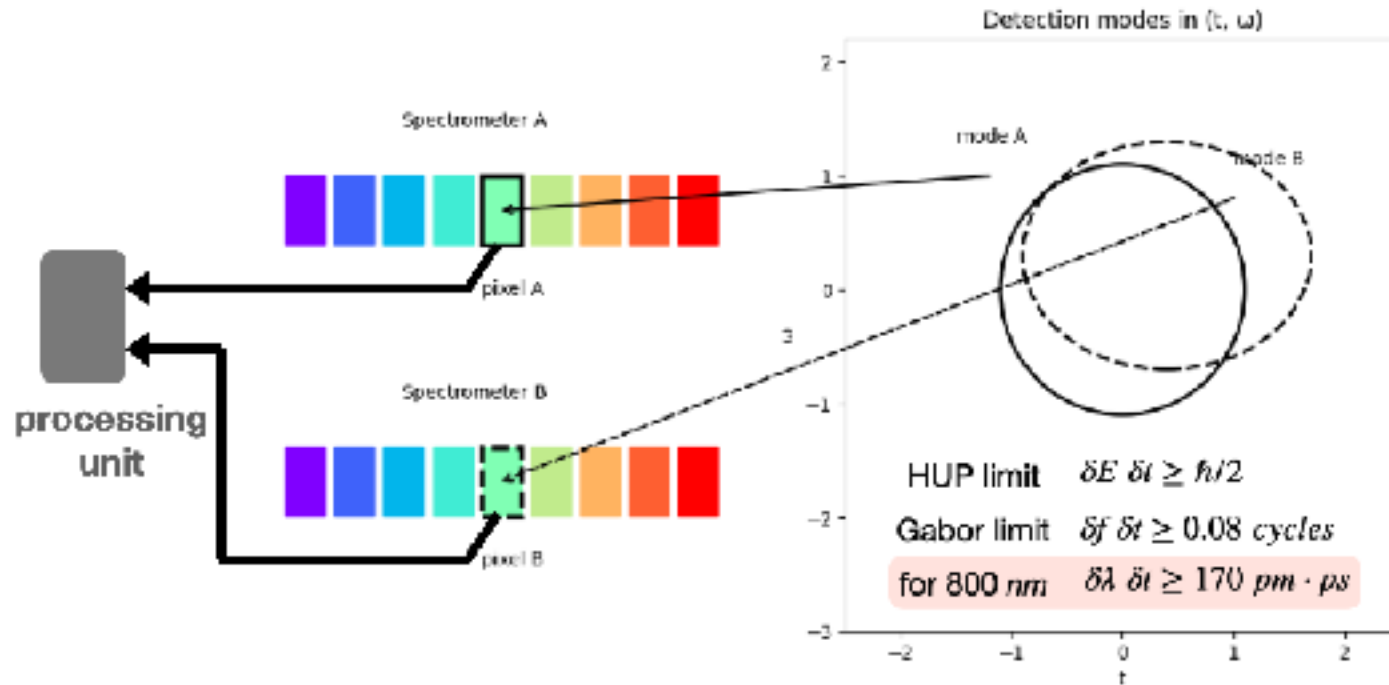
Another application: Quantum Networks

Entanglement swapping scheme with two SPDC sources



- 256 pixels $\Rightarrow$ 128 Bell state measurements $\Rightarrow$ ~2 orders of magnitude faster swap rate
- Next step: demonstrate HOM in spectral bins

Photon indistinguishability



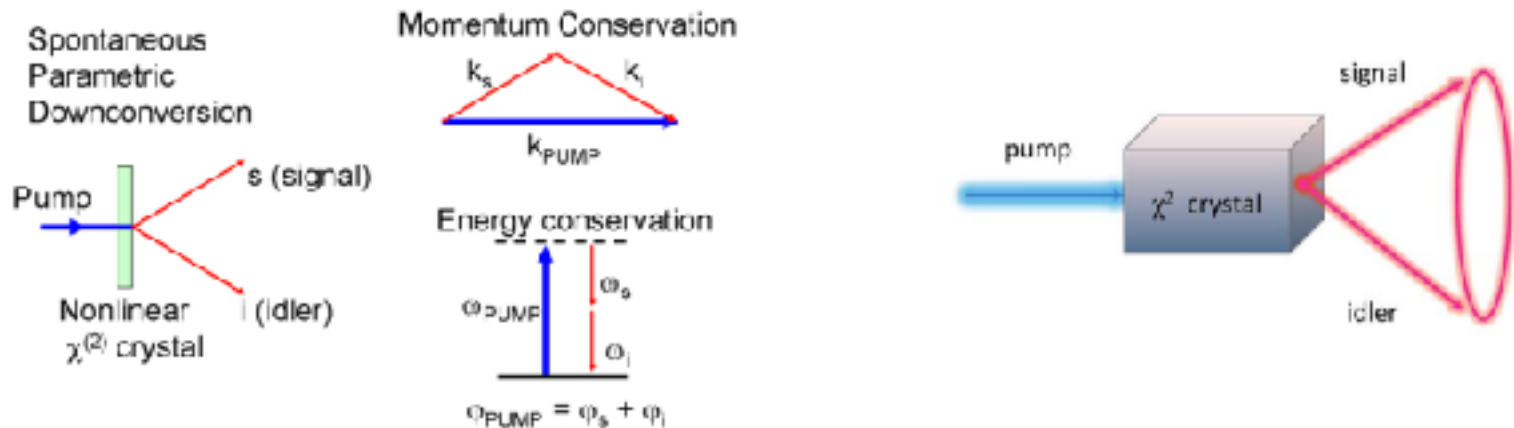
Single pixel corresponds to a single $(\delta t, \delta f)$ mode →
probing of photon indistinguishability → two-photon interference effects

- Scalable architecture
- Possible implementation in real-time : reduction of logged data
- Can be extended to multi-photon correlations
- Photon counting capability at pixel level could be an important advantage

Quantum Optics applications with time stamping of single photons

Some examples how nanosecond scale resolution is
used in Quantum Optics

Quantum photon sources - spontaneous parametric down-conversion (SPDC) sources

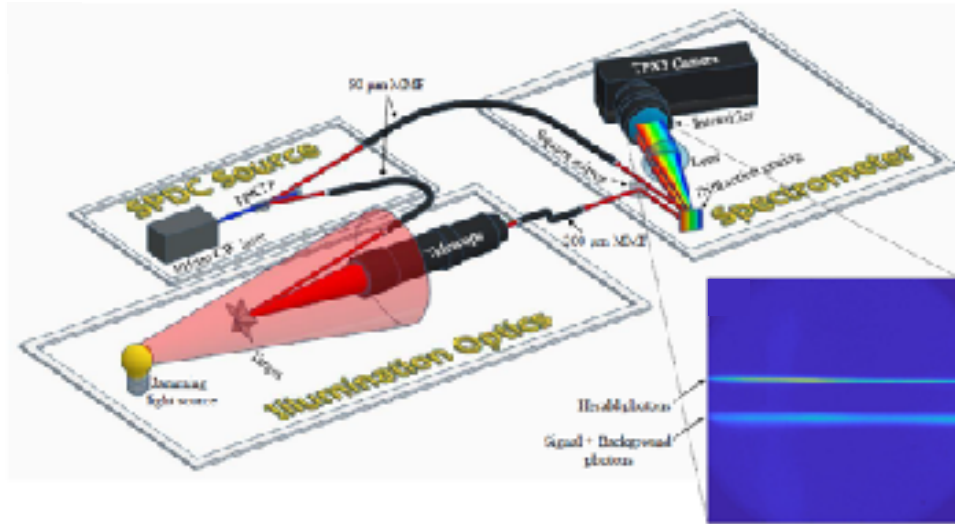


Produce two photons correlated (sometimes entangled) in

1. Time
2. Position
3. Energy

Multidimensional Quantum Illumination

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

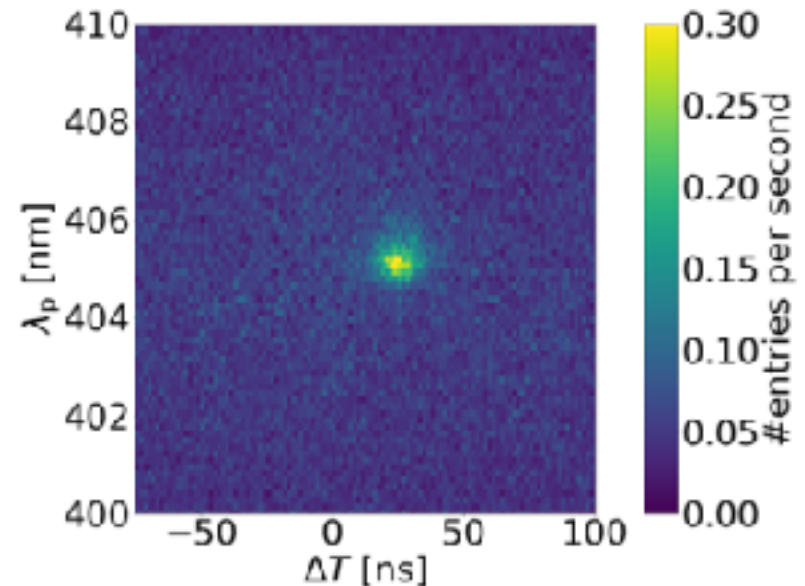


Y Zhang, D England, A Nomerotski, P Sviha et al,
Multidimensional quantum-enhanced target
detection via spectrotemporal-correlation
measurements, Physical Review A 101 (5), 053808

Note that here the time resolution is needed to find
coincidences with good S/B

→ no requirement to be near Heisenberg-Gabor limit

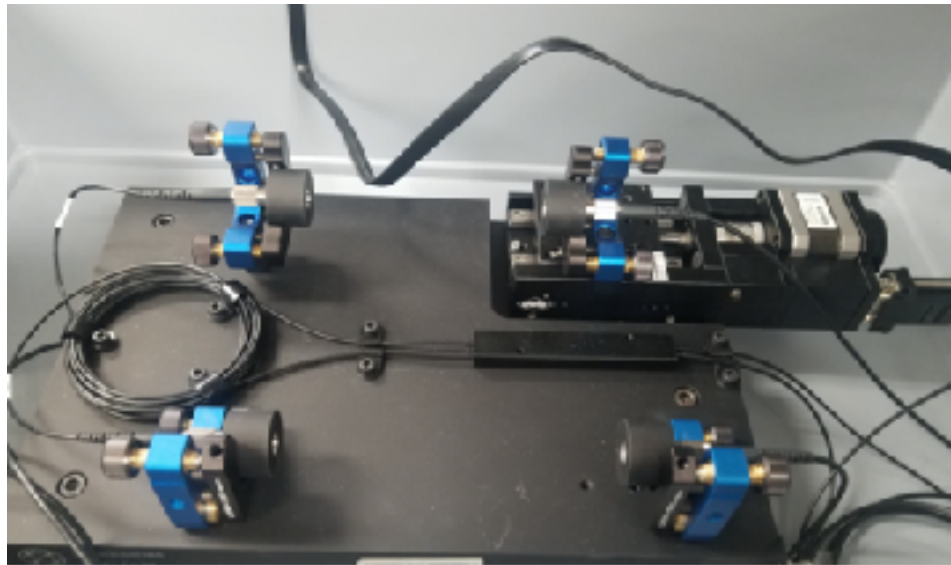
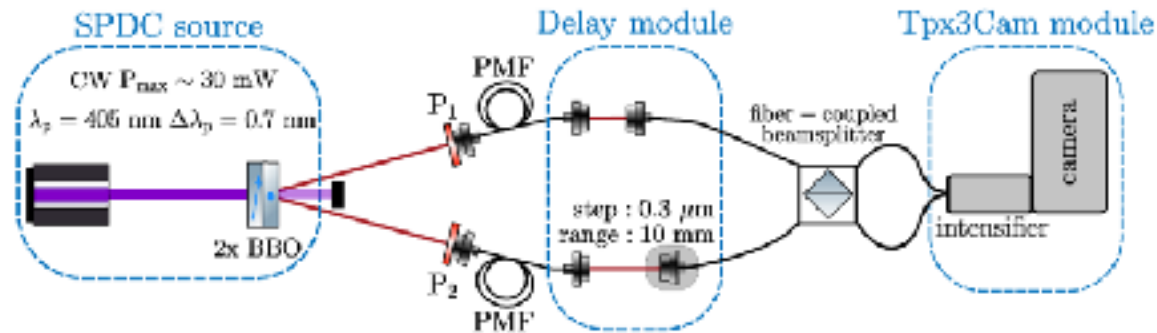
$$\delta\lambda * \delta t \sim 5 \text{ ns} * 0.5 \text{ nm}$$



Pump photon wavelength vs time difference

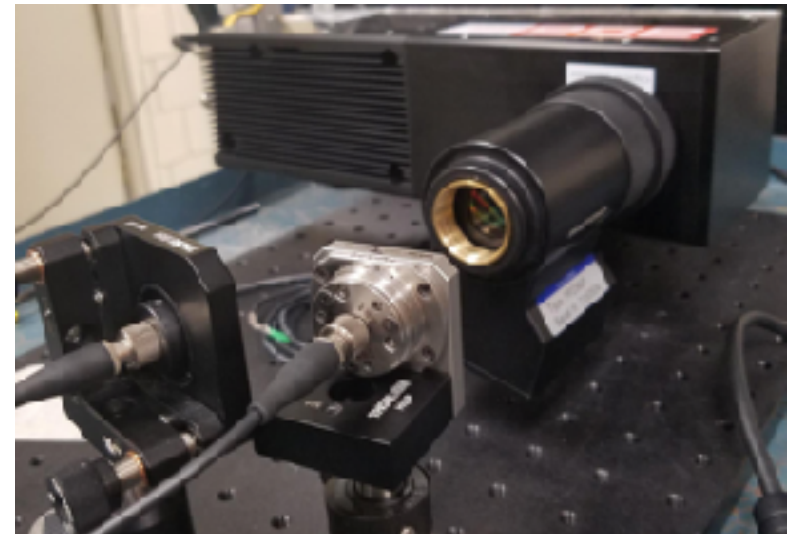
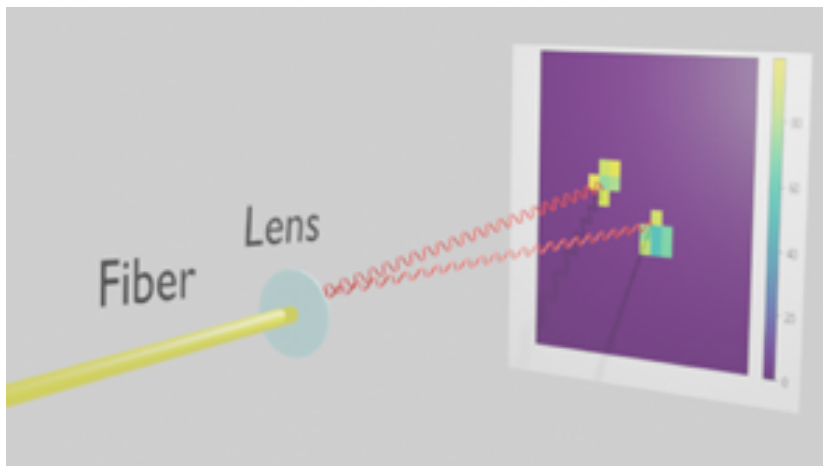
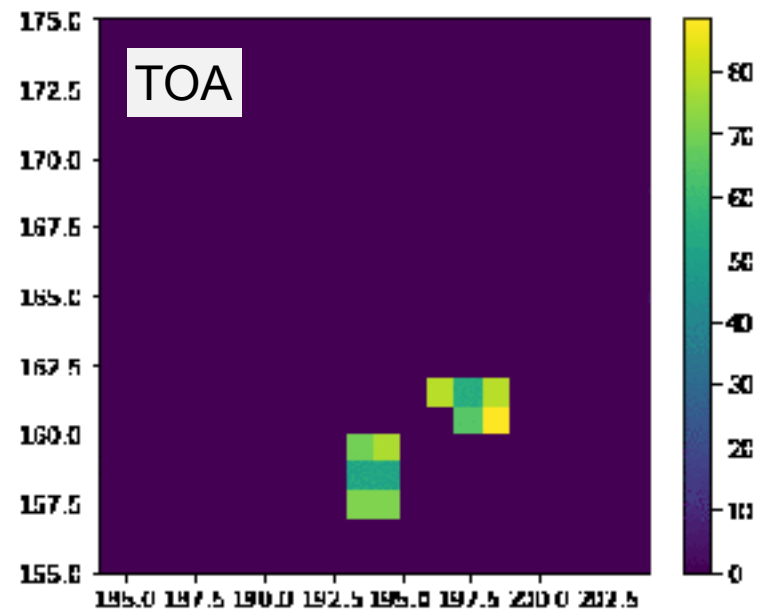
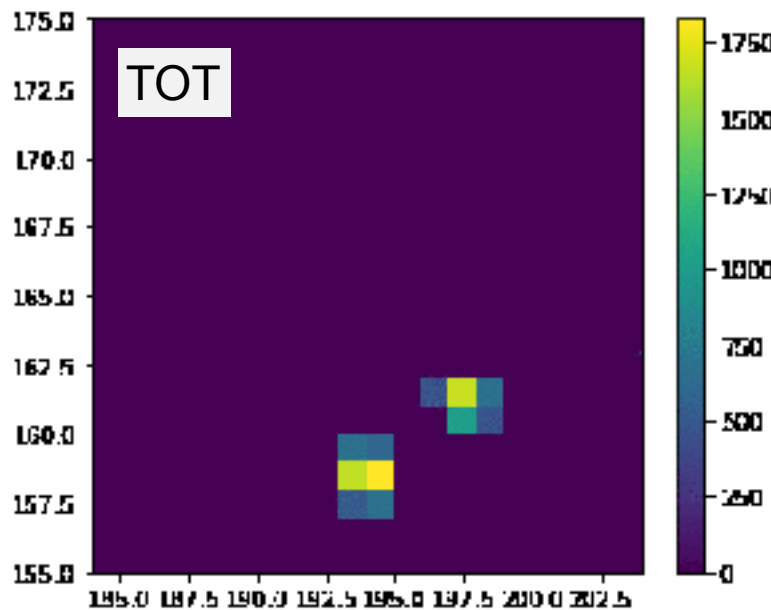
P Sviha et al, Multivariate Discrimination in Quantum
Target Detection, Appl. Phys. Lett. **117**, 044001 (2020)

HOM Setup

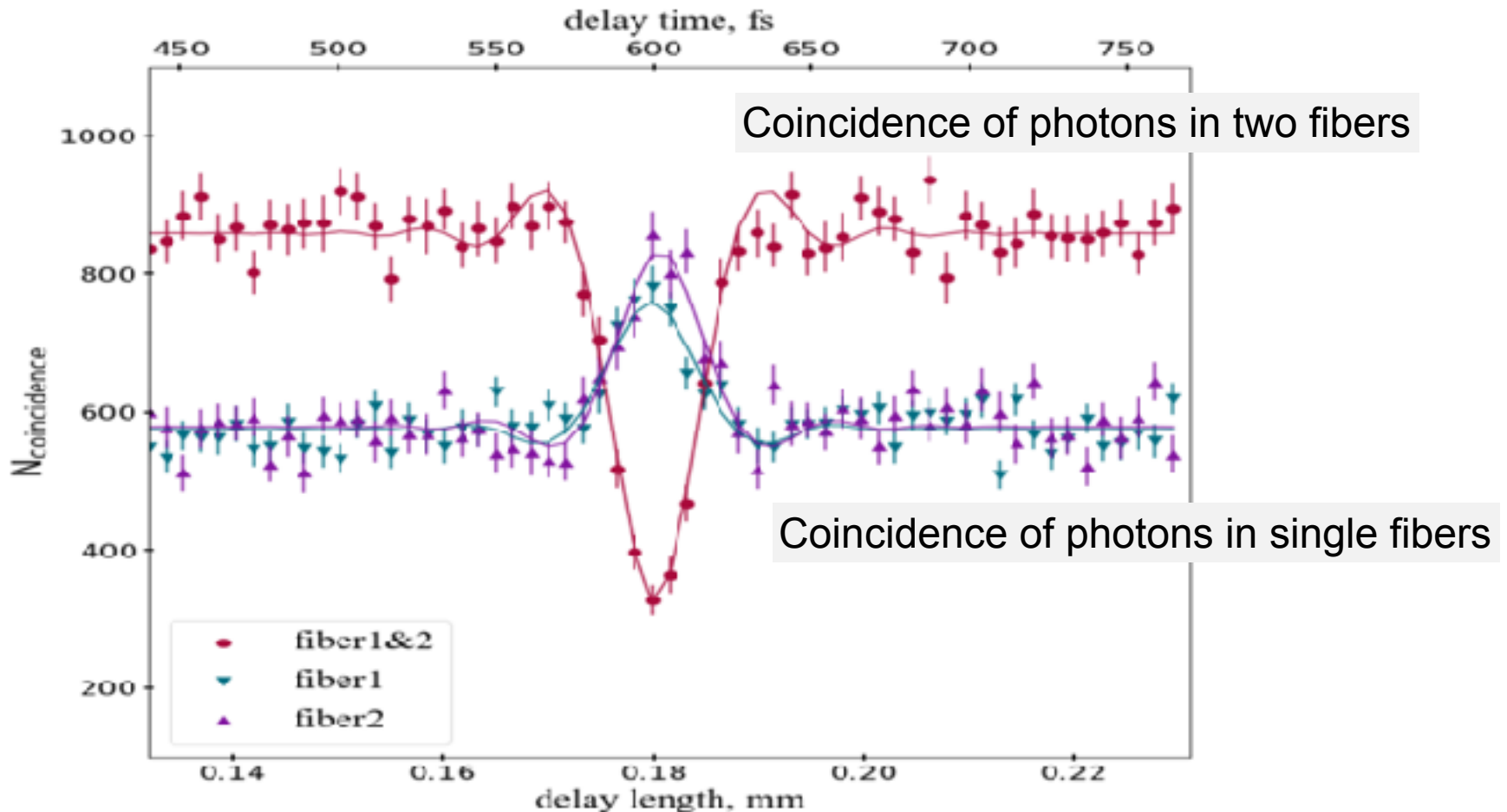


A. Nomerotski, M. Keach, P. Stankus, P. Svihra, and S. Vintskevich,
“Counting of hong-ou-mandel bunched optical photons using a fast pixel
camera,” arXiv:2005.07982 (2020).

Examples of bunched HOM photons

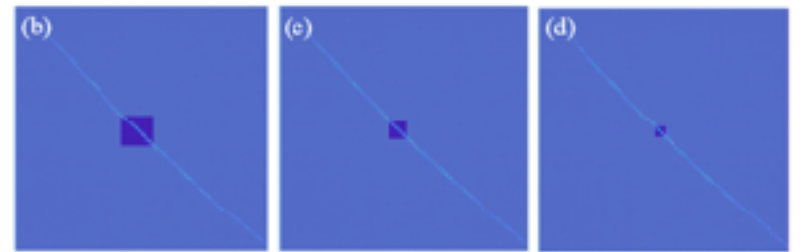
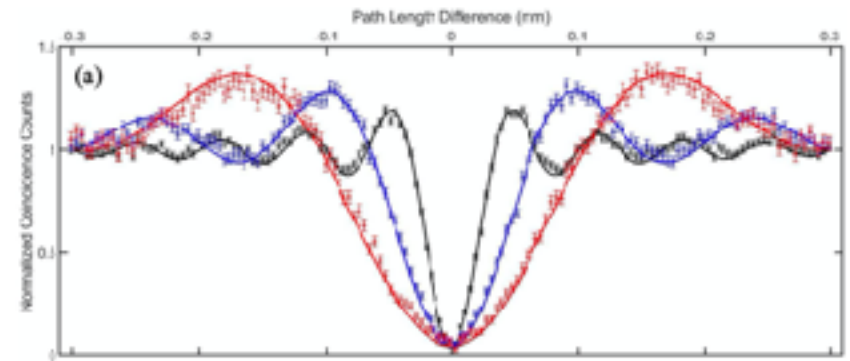
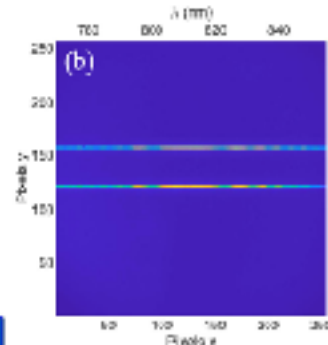
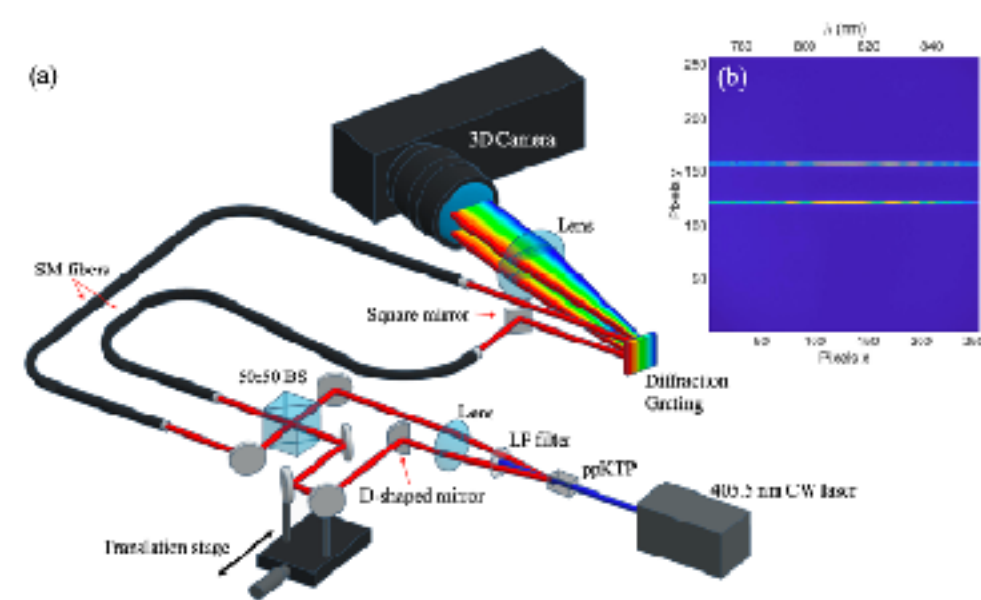


Hong-Ou-Mandel effect

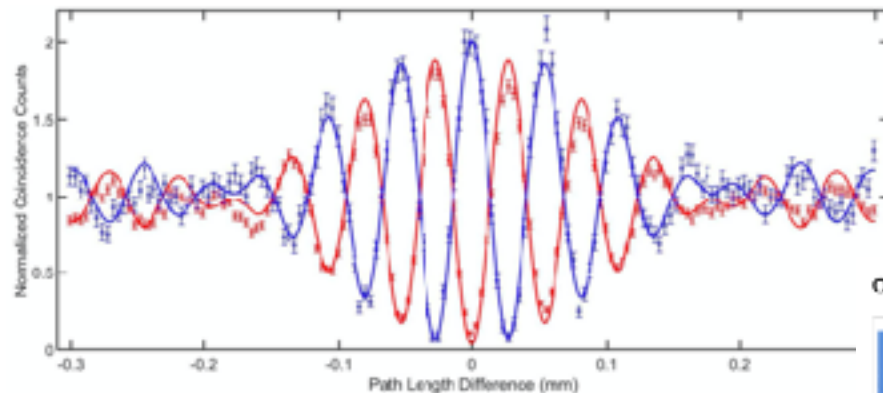


A. Nomerotski, M. Keach, P. Stankus, P. Svihra, and S. Vintskevich,
“Counting of hong-ou-mandel bunched optical photons using a fast pixel
camera,” arXiv:2005.07982 (2020).

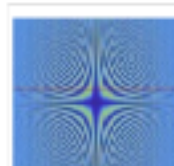
HOM effect with post-selection



10, 5, 3 nm post-selection filters



Optics Express, Vol. 25, Issue 18, pp. 28217-28227 (2017) - <https://doi.org/10.1364/OE.25.028217>

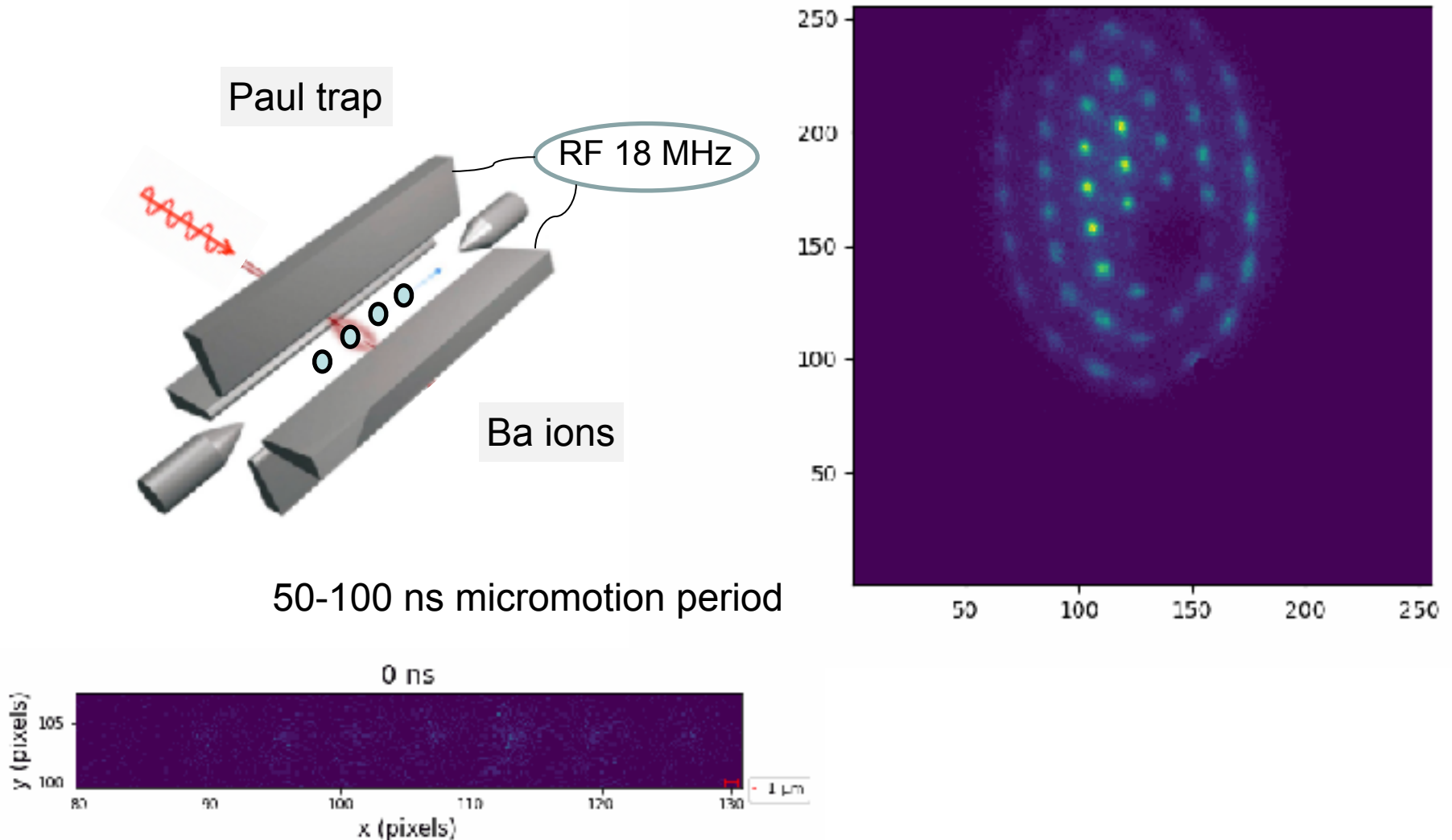


High speed imaging of spectral-temporal correlations in Hong-Ou-Mandel interference

Yingwen Zheng, Duncan England, Andrei Nemerovski, and Benjamin Sussman

2 nm filters at 805 nm and 817 nm.

1- and 2-D ion crystals

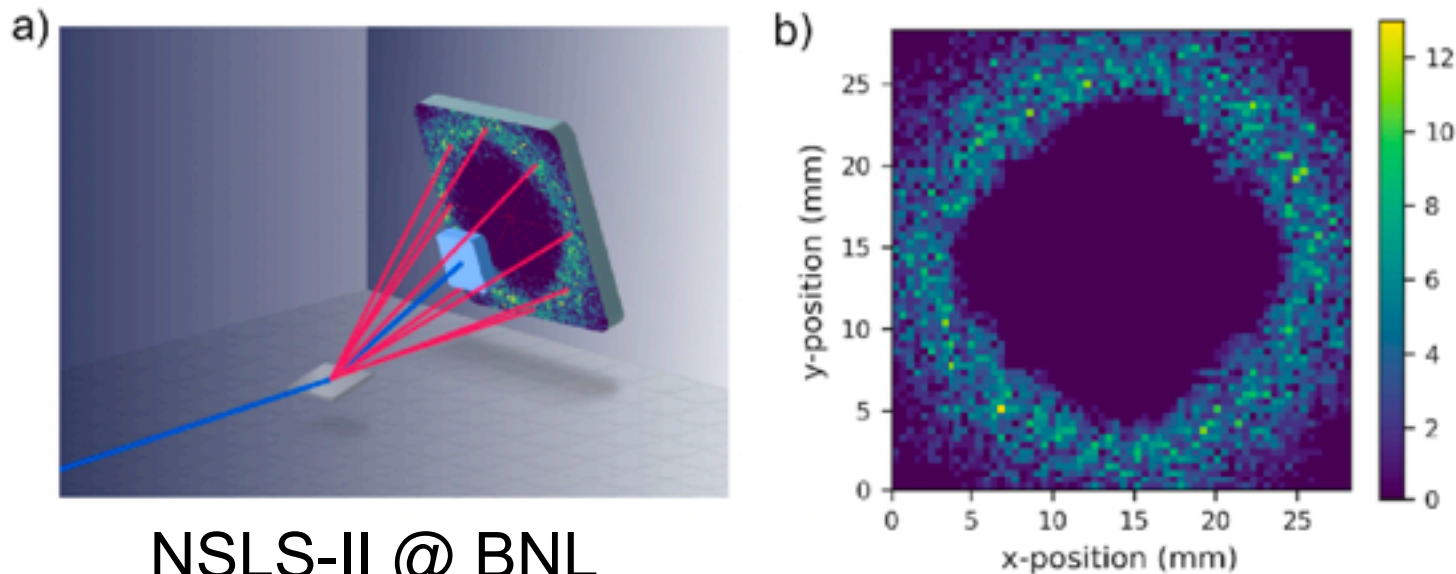


Direct Observation of Ion Micromotion in a Linear Paul Trap

[Liudmila A. Zhukas](#), [Maverick J. Millican](#), [Peter Svihra](#), [Andrei Nomerotski](#), [Boris B. Blinov](#), arxiv: 2010.00159
Phys. Rev. A **103**, 023105 (2021).

x-rays

Down-conversion of x-rays



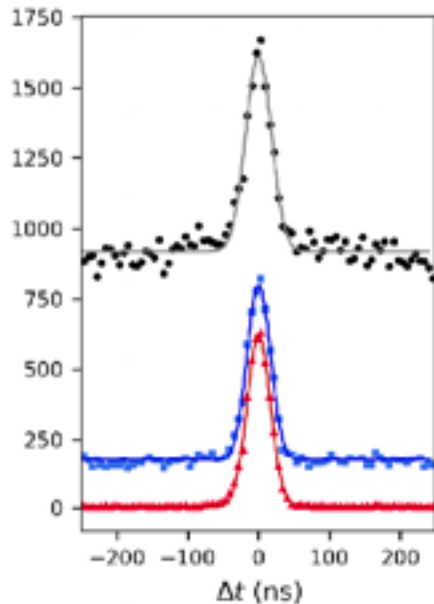
NSLS-II @ BNL

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 $\Delta\theta = 0.022^\circ$ with a total count of 4,145 photon pairs. Analyses of the spatial and spectral structures follow.

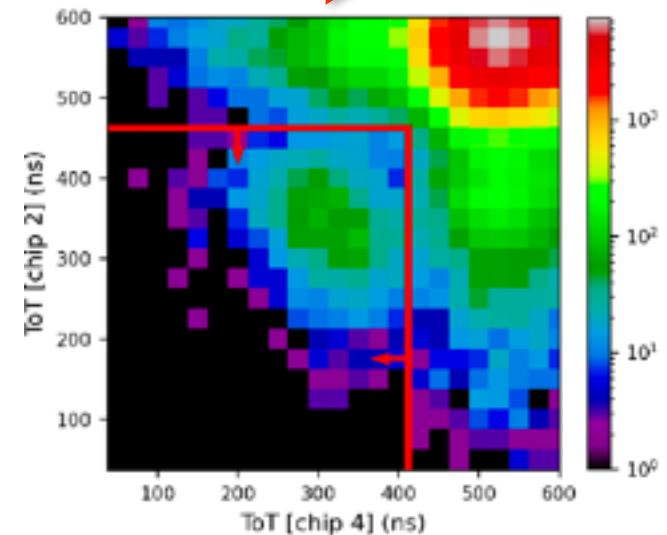
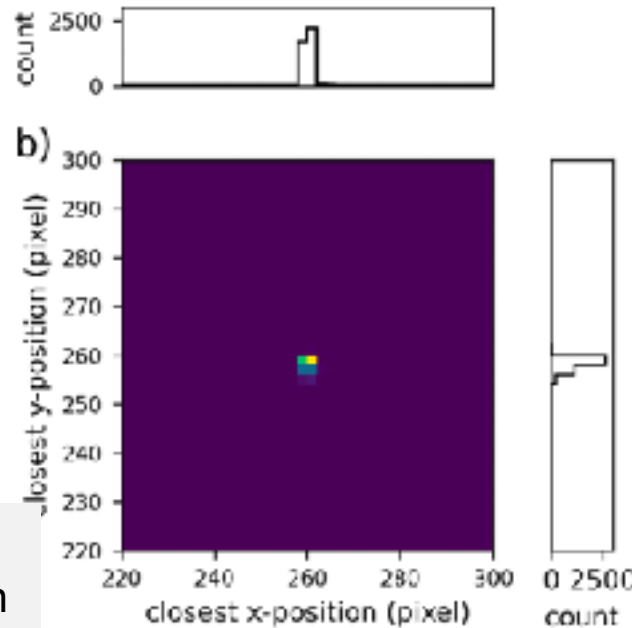
first imaging of x-ray cone
record rate of pair detection $\sim$ few Hz

arxiv.org/abs/2310.13078
J.Goodrich et al, Optica 13, 135-142 (2026)

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



18 ns resolution due to variation of conversion depth



TOT correlation
poor resolution

Motivation: x-ray detectors with good timing and energy resolutions

Scope: entanglement studies for x-rays

[All](#) [3D/2D](#) [VR & AR](#) [Specialty Imaging](#) [Diagnostic Ultrasound](#) [Fetal/FM](#) [U-ULI](#) [HEM](#) [4D-STEM](#) [HEER](#) [SDD](#) [XRD](#) [SEM](#) [SAC](#) [SFC](#) [Neutron Scattering](#)

Europe 8	Miscellaneous	Tide Projector Channel	Germany	FM & Radio Spectrometry	Software	Tide Projector Channel	Europe 8
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Search...

Category	Publication	Author	Link
Quantum ZooKeeper	Real quantum device imaging with a single-photon sensitive time-clamping camera	A. Rando et al. Optics Publishing (2022)	20
Quantum Visions	Quantum Estimation of Beamforming Expanding the Wavelength Bandwidth Limit	Y. Zhang et al. IEEE Electrical Systems (2022)	20
Quantum Science	High-dimensional programmable photonic circuits with microcavities	M. G. Amini et al. Adv. Sci. (2022)	20
Quantum	An internal submillimeter laser cavity based on a three-dimensional microcavity structure	A. Gholami et al. Opt. Rev. (2022)	20

[illegible][illegible]

55 papers with Tpx3Cam on quantum topics!

Sensor R&D

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

Timepix3 → Timepix4

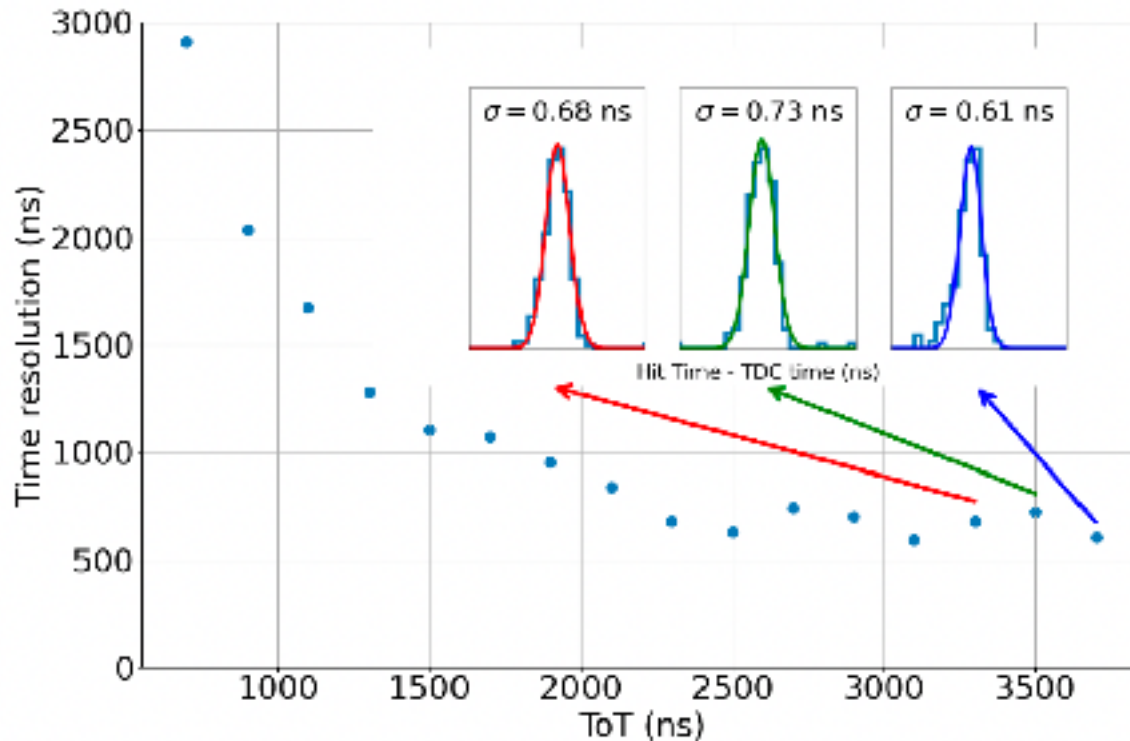
by Medipix4 collaboration

X. Llopart

		Timepix3	Timepix4
Technology		IBM 130nm	TSMC 65nm
Pixel Size		55 x 55 μm	$\leq 55 \times 55 \mu\text{m}$
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.

First optical Tpx4 measurements



Single photon sensitive (intensified) optical Tpx4 camera

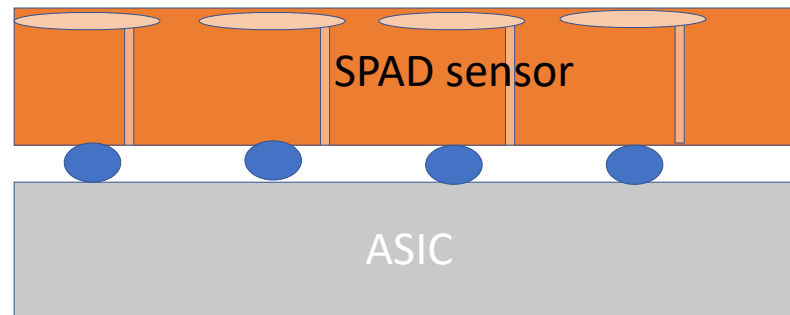
600 ps possible with high gain intensifier

arxiv.org/abs/2509.14649

Erik Hogenbirk *et al* 2026 *JINST* **21** P02004

20 ps timing in 2D

- 20 ps timing is needed for next round of CERN experiments in 10 years, there will be lots of investment in fast ASICs
- **Hybrid SPAD detector**
- Timepix4 chip: 200 ps bin (RMS 60 ps)
- **PicoPix chip: 40 ps bin**
 - Full size, will be used in one of CERN big experiments (LHCb)
 - Will have a SPAD compatible version
- Hybrid detector: SPAD + PicoPix



Difficulties: connectivity and cooling

Main points to take home

- Two-photon interferometry allows long baselines for stellar intensity interferometry
- New ideas suggest quantum sensing technology can dramatically enhance astrometric precision, requires spectrometers and single photon cameras with 10 ps resolution
- Promising results with 40 ps & 40 pm spectrometers, not far from Heisenberg-Gabor limit
- Lots of synergy and applications in quantum optics
- Ideas how to improve the detectors and how to probe photon indistinguishability

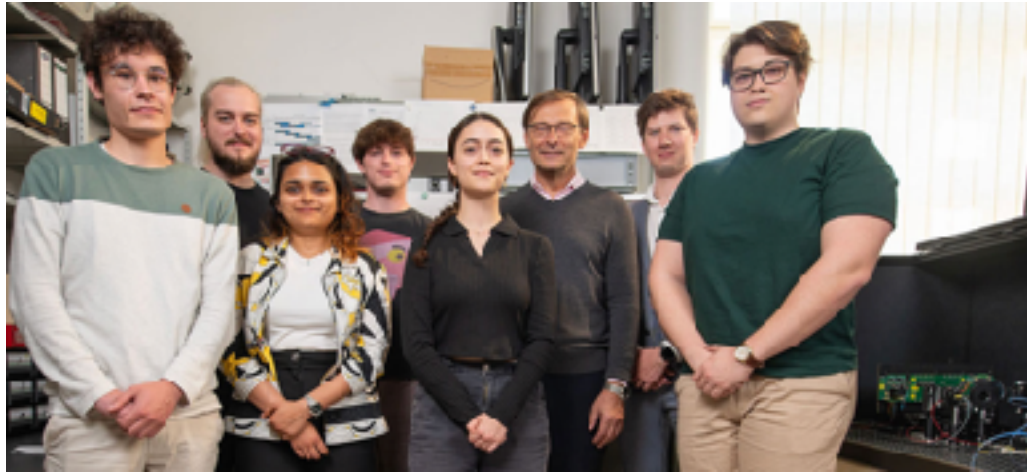
“The great advances in science usually result from new tools rather than from new doctrines”

Freeman Dyson (1923-2020)

Eden Figueroa
Paul Stankus
Tom Tsang
Justine Haupt

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Brianna Farella
Ryan Mahon



Edoardo Charbon
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Ermanno Bernasconi
Claudio Bruschini
Ivan Cardea

Peter Svihra
Michal Marcisovsky
Sergei Kulkov
Jakub Jirsa
Lou-Ann de Sousa
Dmitri Sevaev
Ondra Matoušek
Sarlote Simsone



Thank you for your attention!



<https://capads.fjfi.cvut.cz>

Quantum Mechanics

Two miracles:

1) wave-particle duality

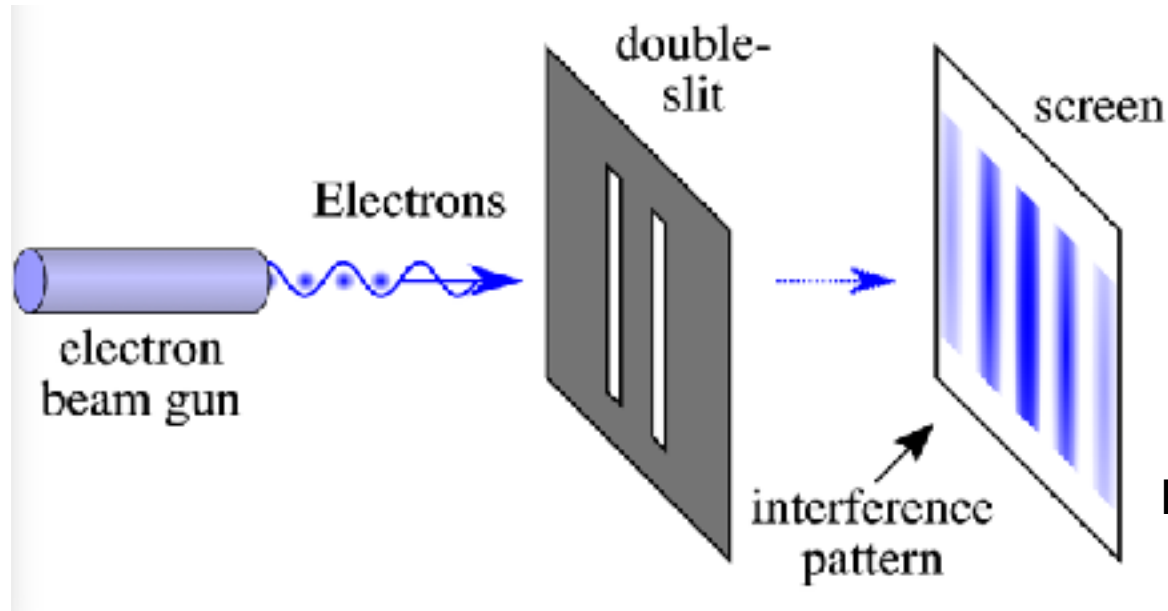
2) entanglement

**They both are dictated by experiment, this is the way
the Nature works**

Everything else follows from them

1) Wave - Particle Duality

Applicable to single particles



From Wikipedia

Experiment tells us that particles are similar to waves, even if you shoot them slowly, one by one

Consequences of wave-particle duality

Superposition principle: add amplitudes (of wave function) as for waves. Then $I \propto |A|^2$

Interference is consequence of wave nature of particles, single particle can interfere with itself

Quantization is property of all confined waves - plucked string can only make discrete frequencies

Heisenberg Uncertainty Principle

Similar to Fourier transform limit: infinite sine corresponds to a single frequency but finite wave duration will correspond to finite bandwidth

$$\Delta w \Delta t \geq \frac{1}{2}$$

$$\Delta E \Delta t \geq \frac{\hbar}{2}$$

