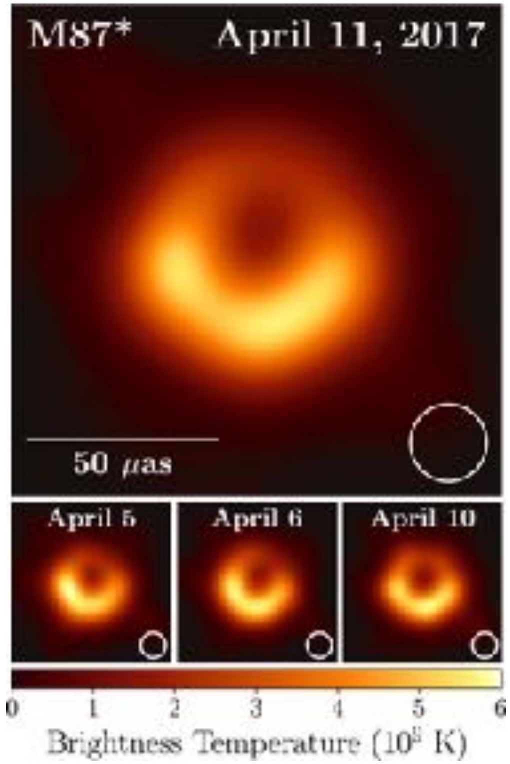
Quantum-assisted interferometers for astrometry

Andrei Nomerotski
Florida International U &
Czech Technical U

CAPADS group in Czech TU

EHT black hole image



2019 ApJL 875

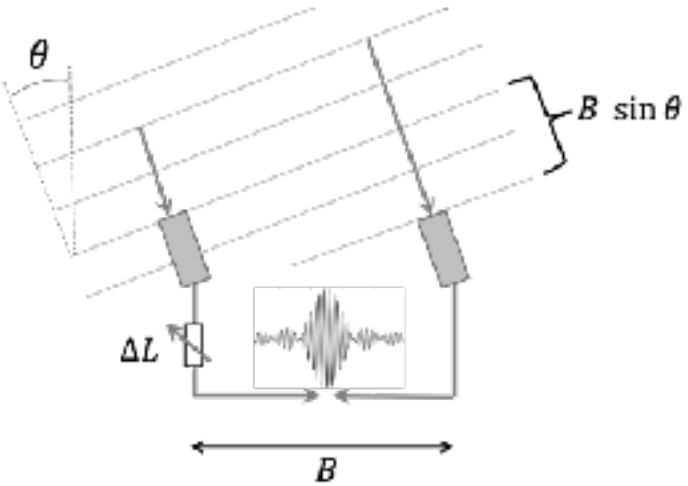
sensitive to features on angular scale

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

Black hole in the center of M87 imaged at 1.3mm

Achieved by radio interferometry with ~10000 km baselines

Radio	Optical
$\bar{n} \gg 1$	$\bar{n} \ll 1$
mode population	mode population



Can literally record entire waveform

interfere later offline

One photon at a time!

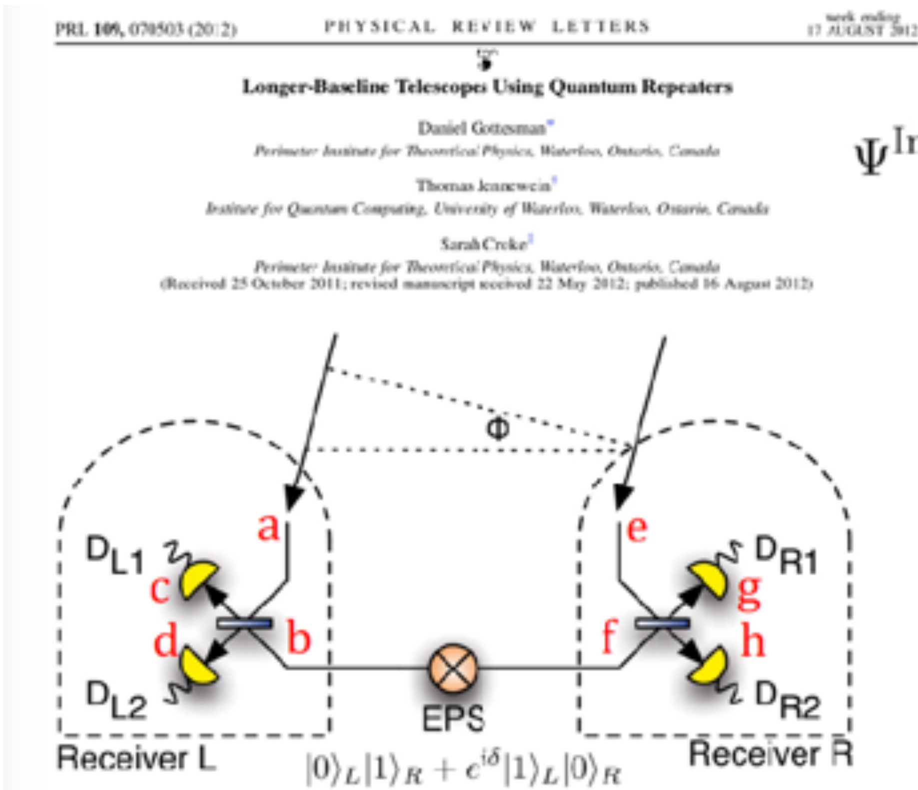
Need to bring paths to common point in real time

Need path length delayed and stabilized to better than λ

Max baselines ~ 100 m

Two-photon techniques

Second photon for quantum assist



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

Beam Splitters

$$\hat{a}^\dagger \to (\hat{c}^\dagger + \hat{d}^\dagger)/\sqrt{2} \qquad \hat{b}^\dagger \to (\hat{c}^\dagger - \hat{d}^\dagger)/\sqrt{2}$$
$$\hat{e}^\dagger \to (\hat{g}^\dagger + \hat{h}^\dagger)/\sqrt{2} \qquad \hat{f}^\dagger \to (\hat{g}^\dagger - \hat{h}^\dagger)/\sqrt{2}$$

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

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

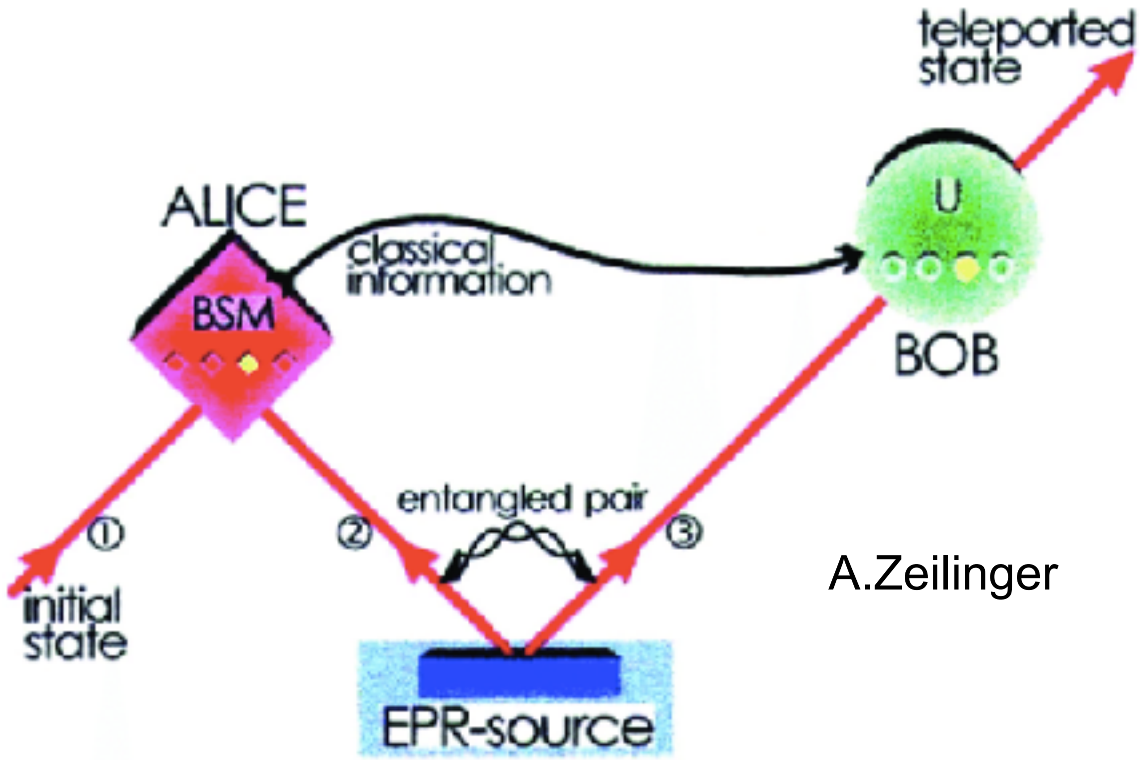
- Correlation of counters are sensitive to sky photon phase → direction
- Need to transfer the photon quantum state → can use quantum networks, this will allow long distances

- Verified experimentally in quantum optics settings: M Brown et al, PRL 131, 210801 (2023)

Quantum Network

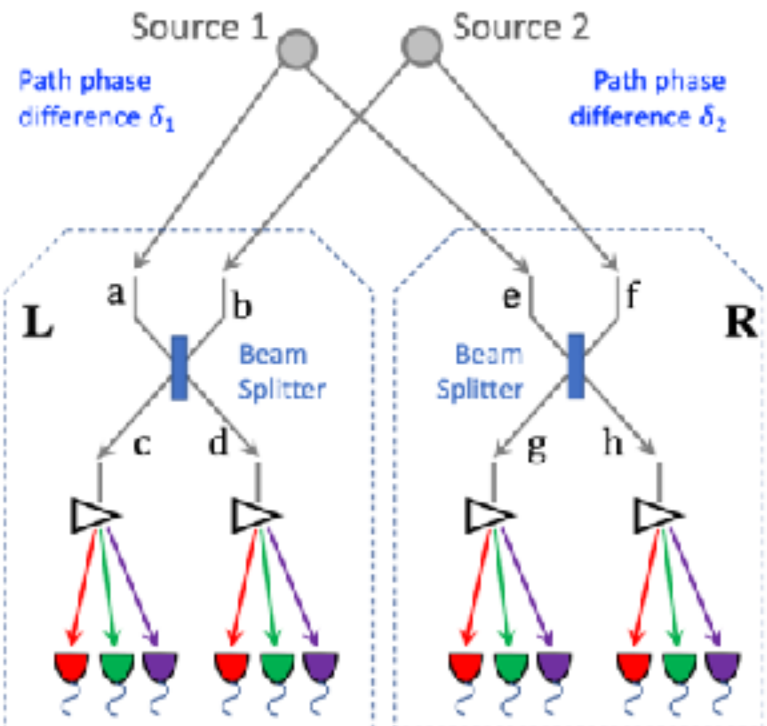
- Attenuation in fibers → need quantum repeater to reproduce qubits
  - Simple amplification will not conserve the quantum state

- 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

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

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

Rates HBT

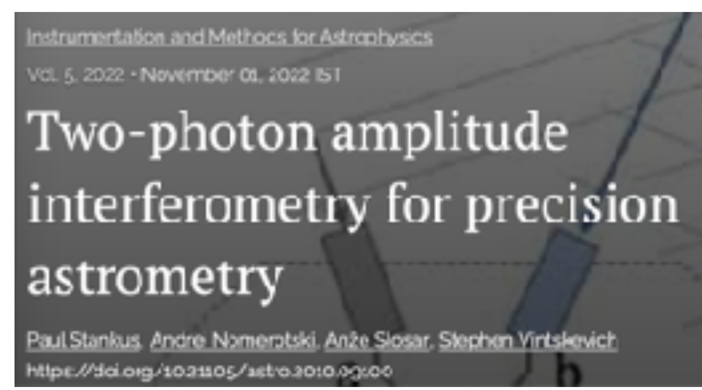
$$
A^2 \eta_1 \eta_2 T_r \left[(I_1 + I_2)^2 + I_1^2 \frac{\tau_c g_{11}}{T_r} + I_2^2 \frac{\tau_c g_{22}}{T_r} \pm \right.
$$

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

New oscillatory term!

Relative path phase difference $\delta_1 - \delta_2$ can be extracted from the coincidence rates of four single photon counters: c, d, g and f

Perfect to start exploring this approach

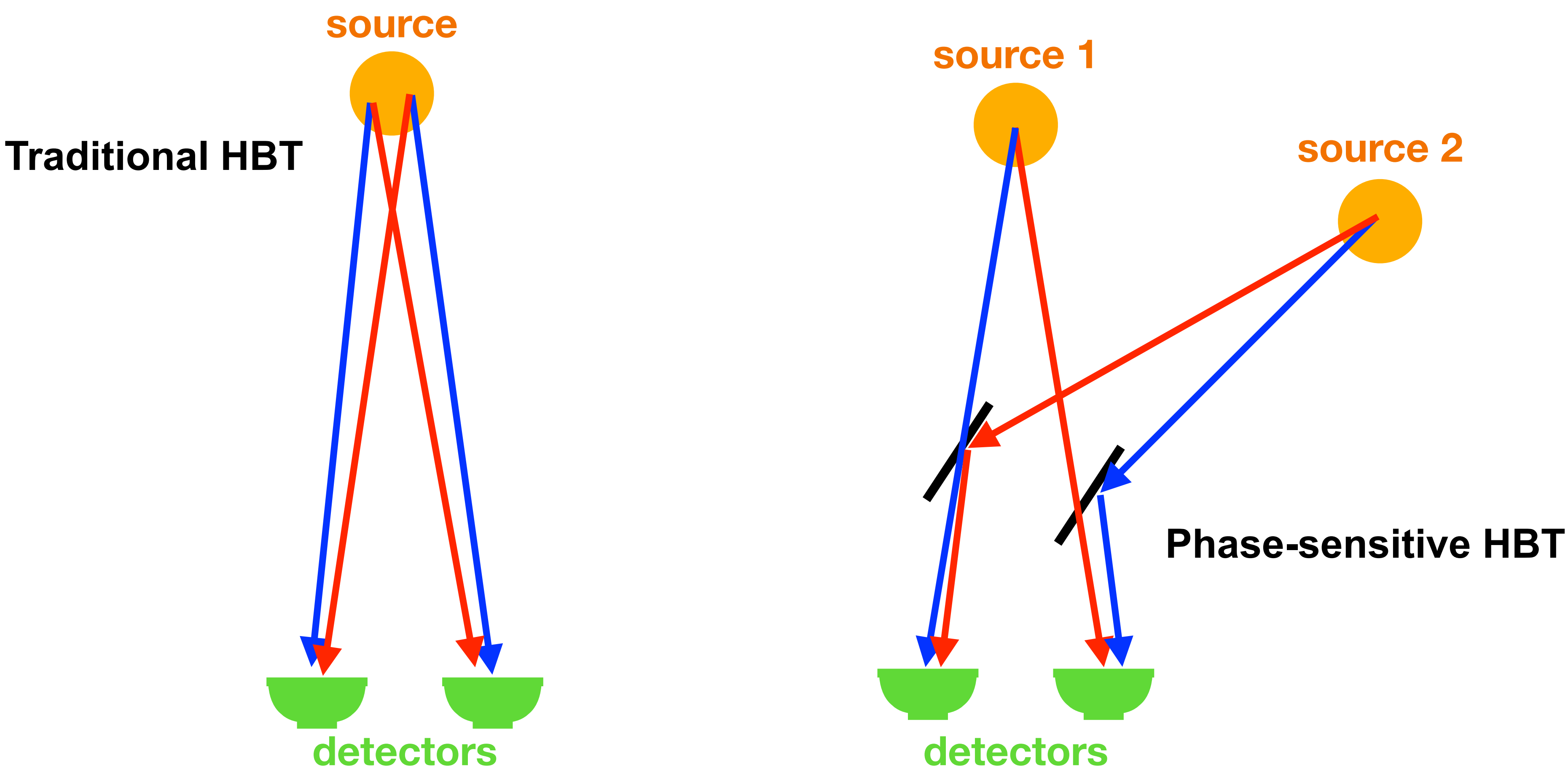


https://arxiv.org/abs/2010.09100

Hanbury Brown – Twiss Interferometry

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

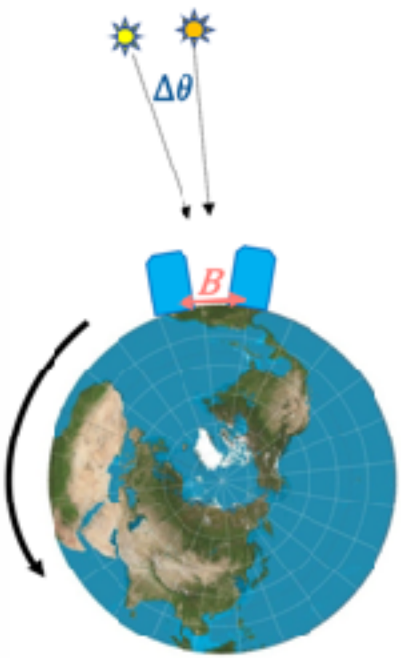
Interference produces photon bunching or HBT effect



Earth rotation fringe scan

$$\langle N(xy)\rangle = \frac{k(S_1+S_2)^2}{8}\left[1 \pm V_{2PS}\cos\left[\frac{2\pi B}{\lambda}(\sin\theta_1 - \sin\theta_2) + \frac{2\pi\Delta L}{\lambda}\right]\right]$$

This will evolve as the Earth rotates



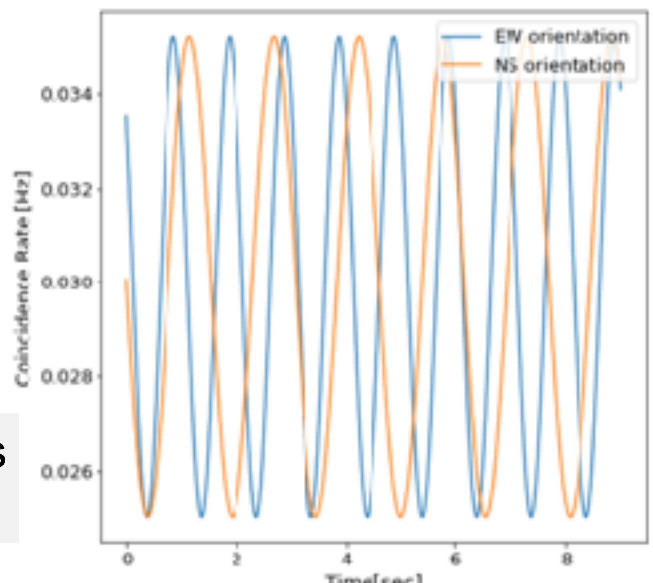
$$\langle N_{xy}\rangle(t) = \bar{N}_{xy}\left[1 \pm V\cos\left(\omega_f t + \Phi\right)\right]$$

Coincidence rates oscillate

$$\omega_f = \frac{2\pi B\Omega_\oplus \sin\theta_0}{\lambda}\Delta\theta$$

Fringe oscillation rate is a direct measure of sources' opening angle!

Can measure with high precision



example of oscillations for pair of stars

$$\sigma[\Delta\theta] \sim 10\mu as\ (\sim 10^{-11}\ rad)$$

doi.org/10.1103/PhysRevD.107.023015

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

Tang et al. *Light: Science & Applications* (2025)14:46
https://doi.org/10.1038/s41377-024-01684-y
Official journal of the CIOMP 2047-7538
www.nature.com/lsa

ARTICLE Open Access

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

Xuan Tang[1], Yunxiao Zhang[2], Xueshi Guo[2], Liang Cui[2], Xiaoying Li[2✉] and Z. Y. Ou[1✉]

Possible impact on astrophysics and cosmology

https://arxiv.org/abs/2010.09100

offers orders of magnitude better astrometry with major impact

- Parallax: improved distance ladder
- Proper star motions - sensitive to Dark Matter

- Black hole accretion disk imaging
- **Gravitational waves through coherent motions of stars - microHz range**
- Exoplanets, microlensing etc

Requirements for detectors

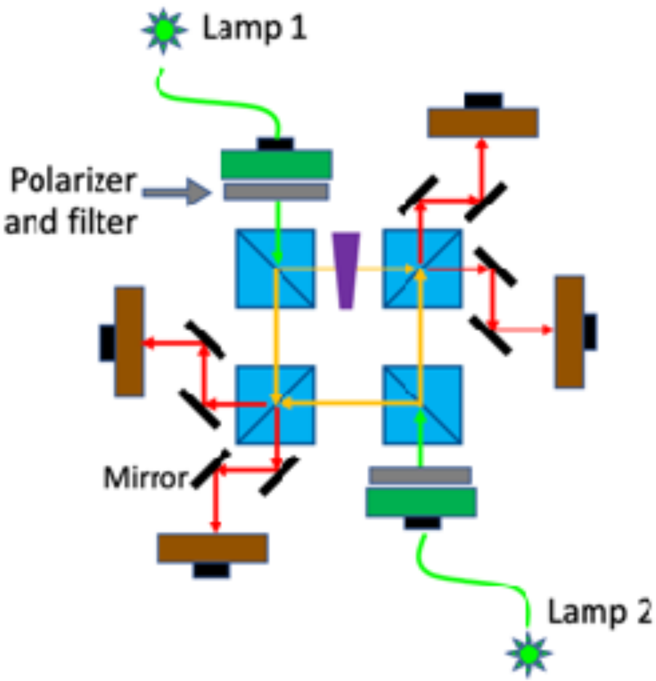
Photons must be indistinguishable so close enough in frequency and time to interfere → temporal & spectral binning :
need ~ 10 pm * 10 ps $\Delta t * \Delta E \geq \hbar/2$

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

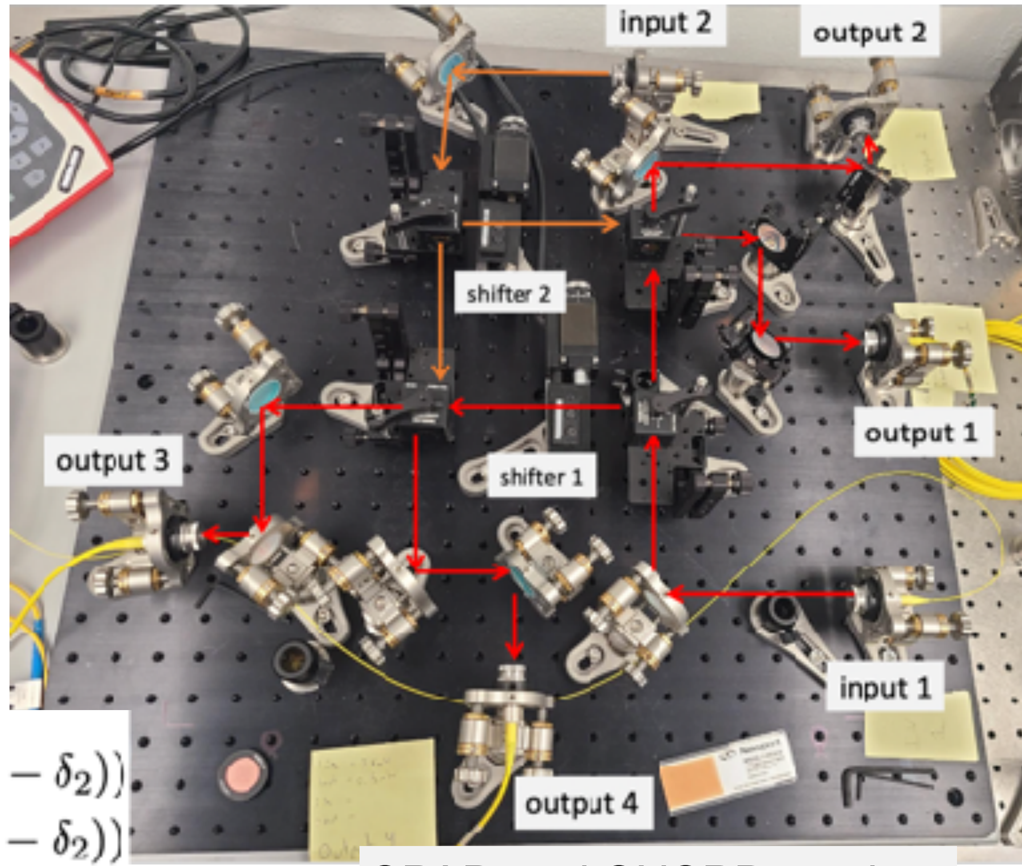
then achieve maximum contrast for HBT peaks, no resolution smearing

- 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

Benchtop Verification



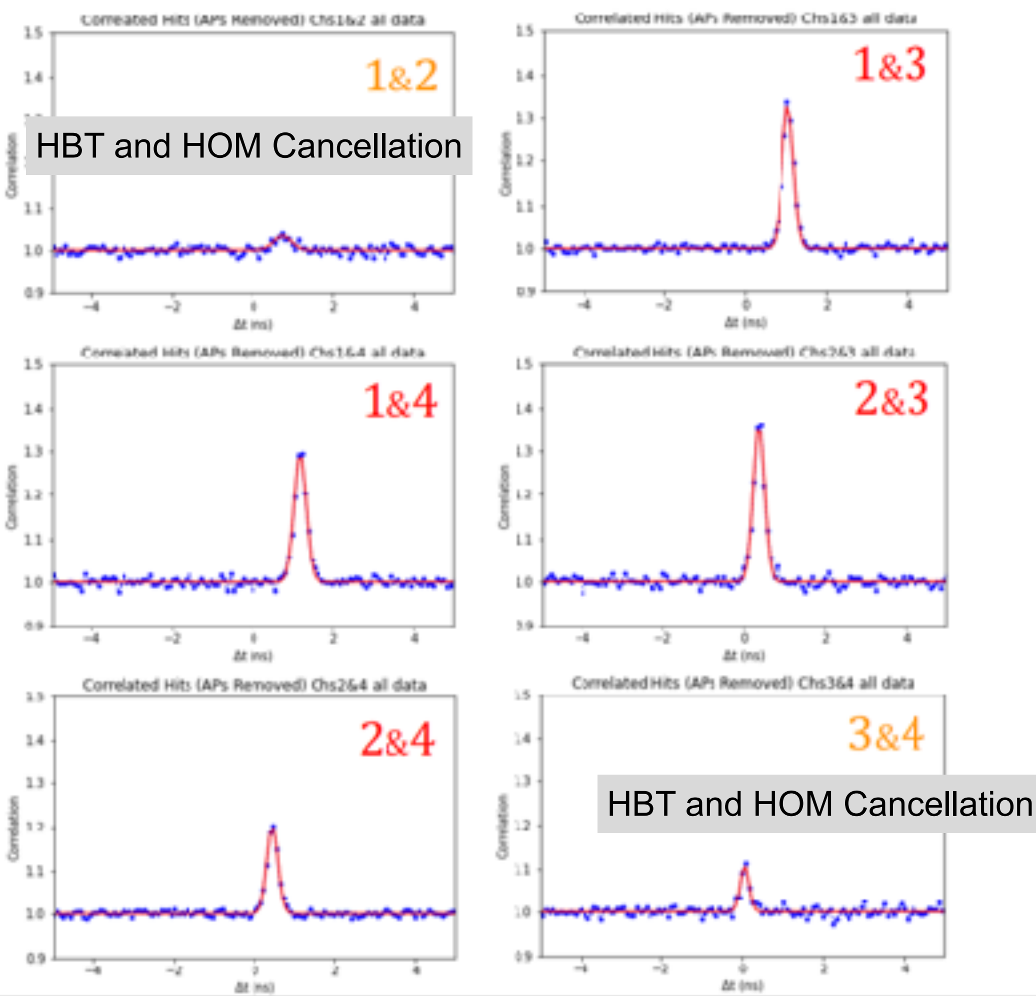
$$P(cg) = P(dh) = (1/8)(1 + \cos(\delta_1 - \delta_2))$$
$$P(ch) = P(dg) = (1/8)(1 - \cos(\delta_1 - \delta_2))$$

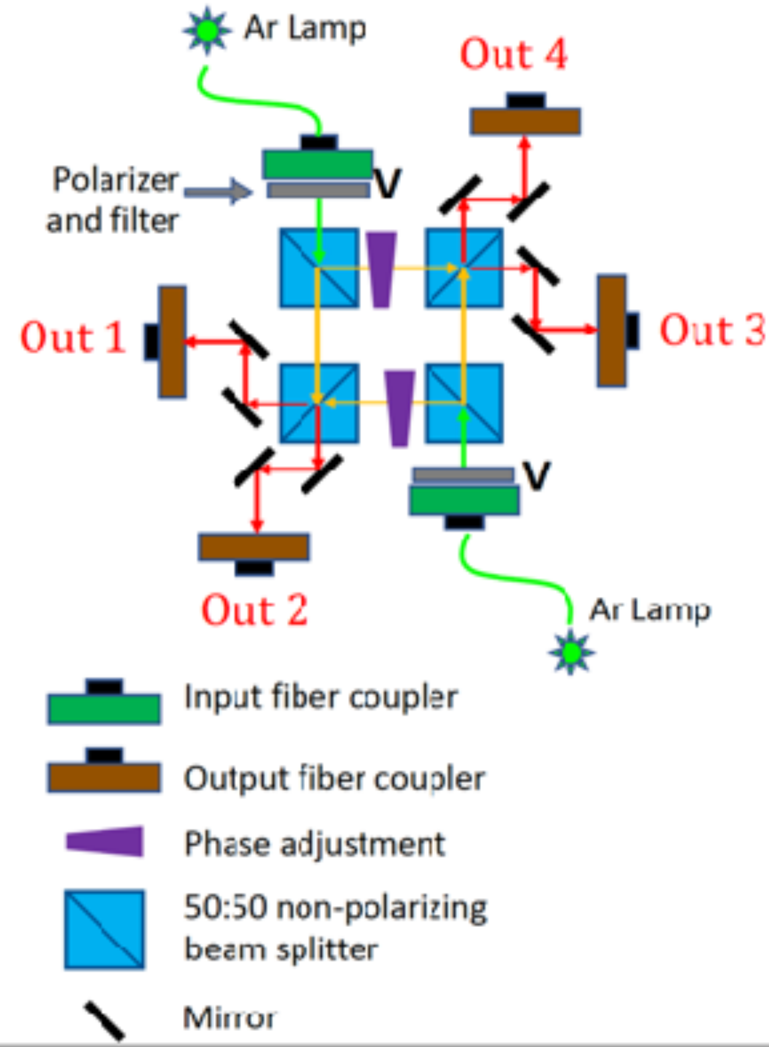


SPAD and SNSPD readout

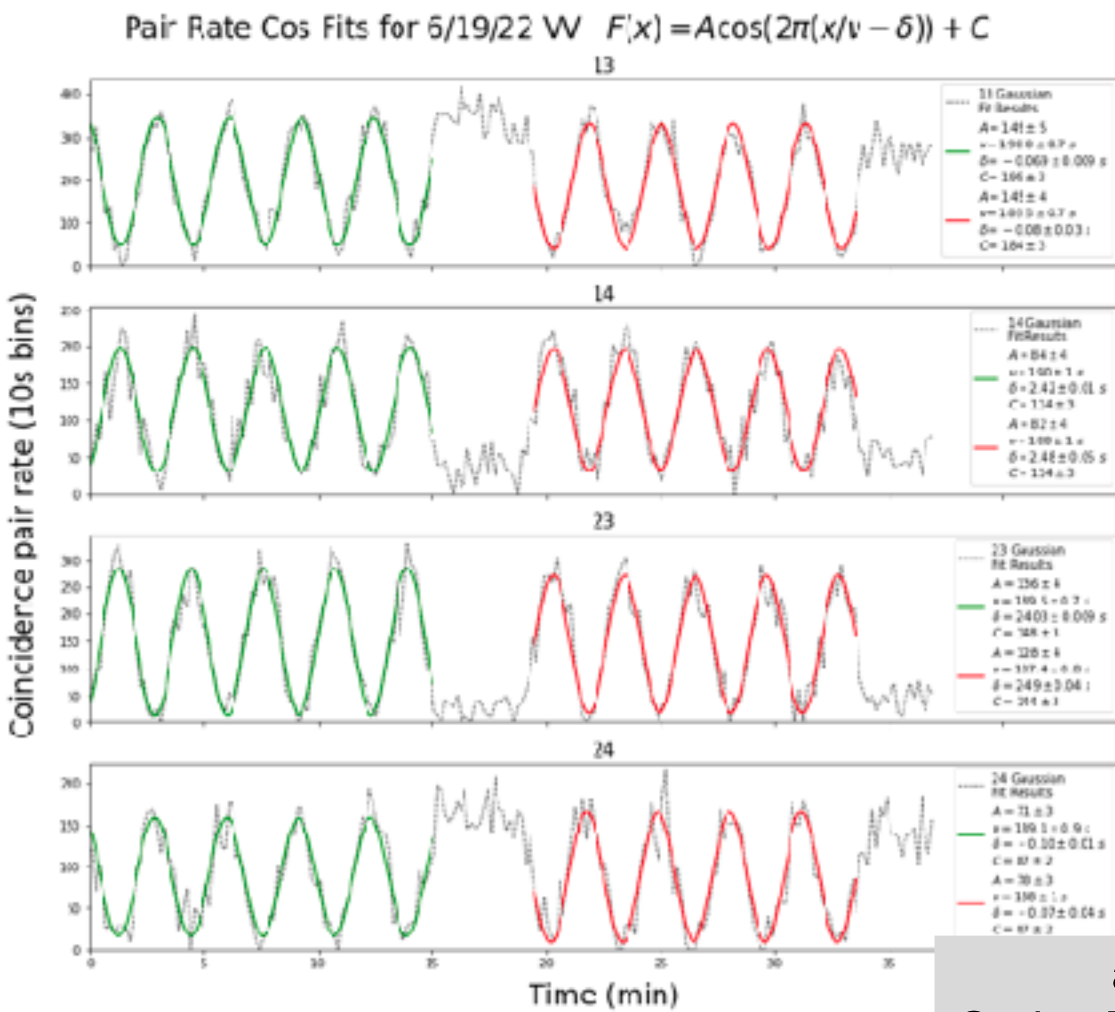
arxiv.org/abs/2301.07042
Optics Express 31, 44246-44258 (2023)

Polarized – V V





Phase dependence



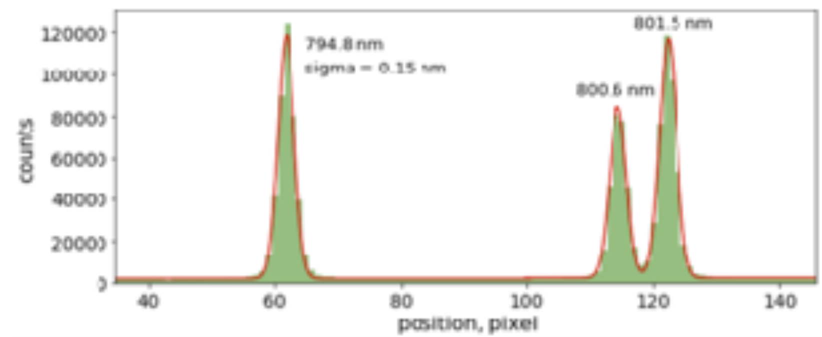
arxiv.org/abs/2301.07042
Optics Express 31, 44246-44258 (2023)

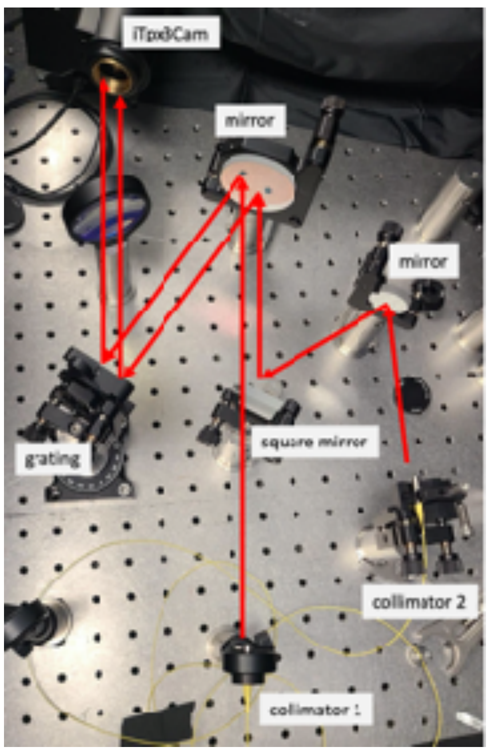
Population of HBT peaks as function of phase = phase oscillations

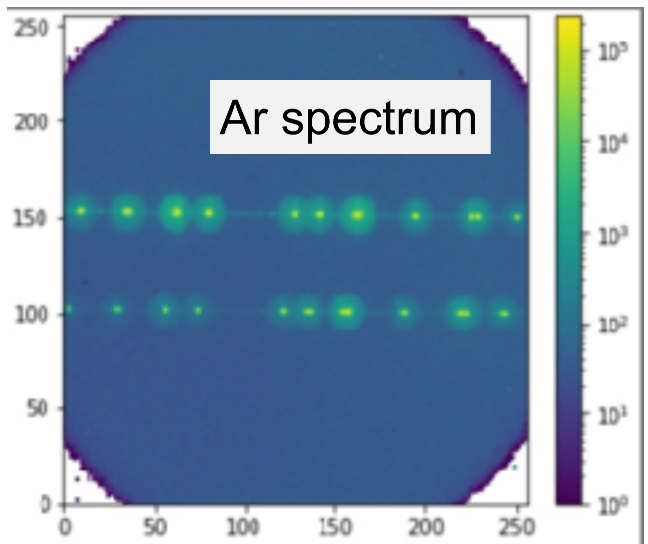
Next step: spectral binning

Spectral binning: spectrometer

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



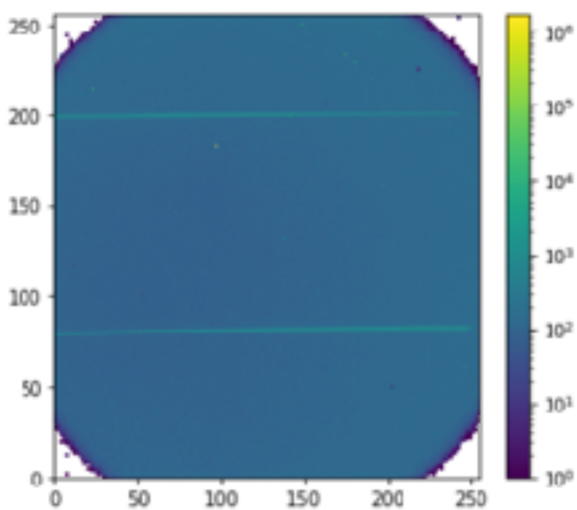


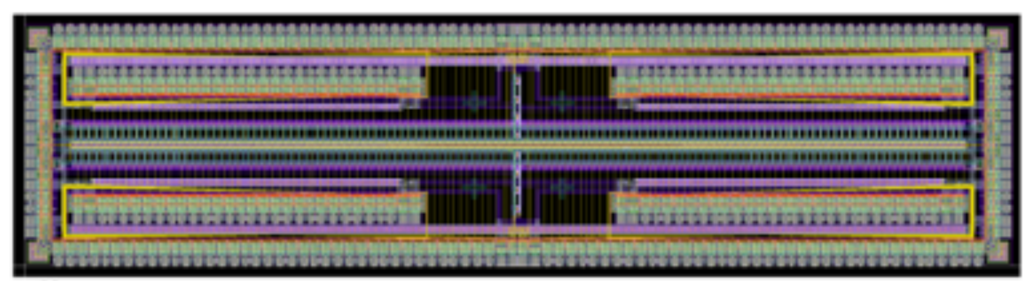


A.Nomerotski et al. Intensified Tpx3Cam, a fast data-driven optical camera with nanosecond timing resolution for single photon detection in quantum applications, arxiv.org/abs/2210.13713, published in JINST

Next steps: spectrometer based on LinoSPAD2

Diffracted photon stripe projected on to linear array





Spectrometer time resolution: 5 ns →100 ps

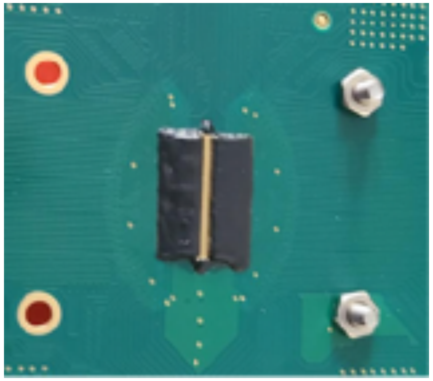
Possible technologies: SPAD

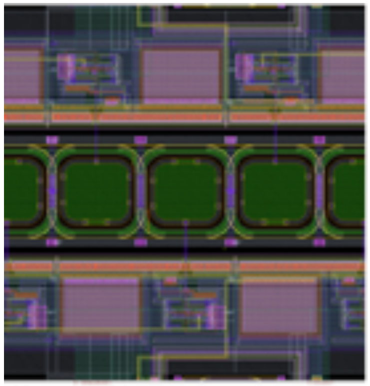
SPAD = single photon avalanche device
Semiconductor device: p-n junction with amplification

LinoSPAD2

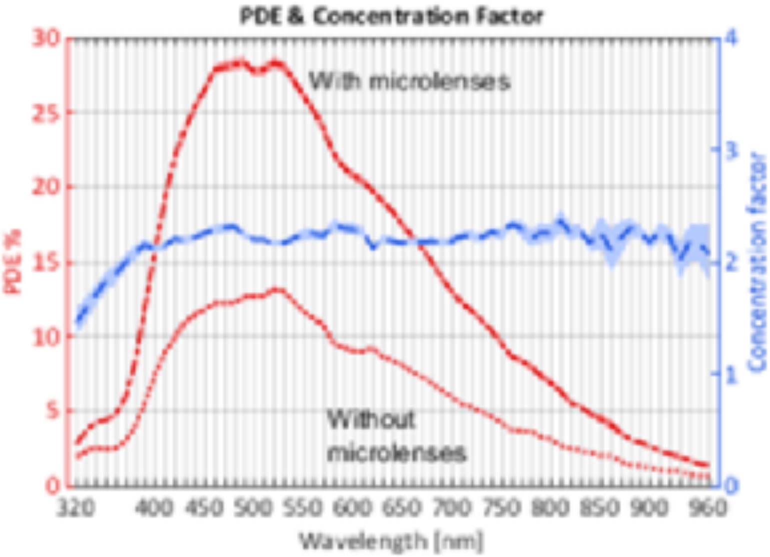
- 512 x 1 pixels
- 24 x 24 micron pixels
- Max PDE (with microlenses) ~ 30%
- 50 ps resolution

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



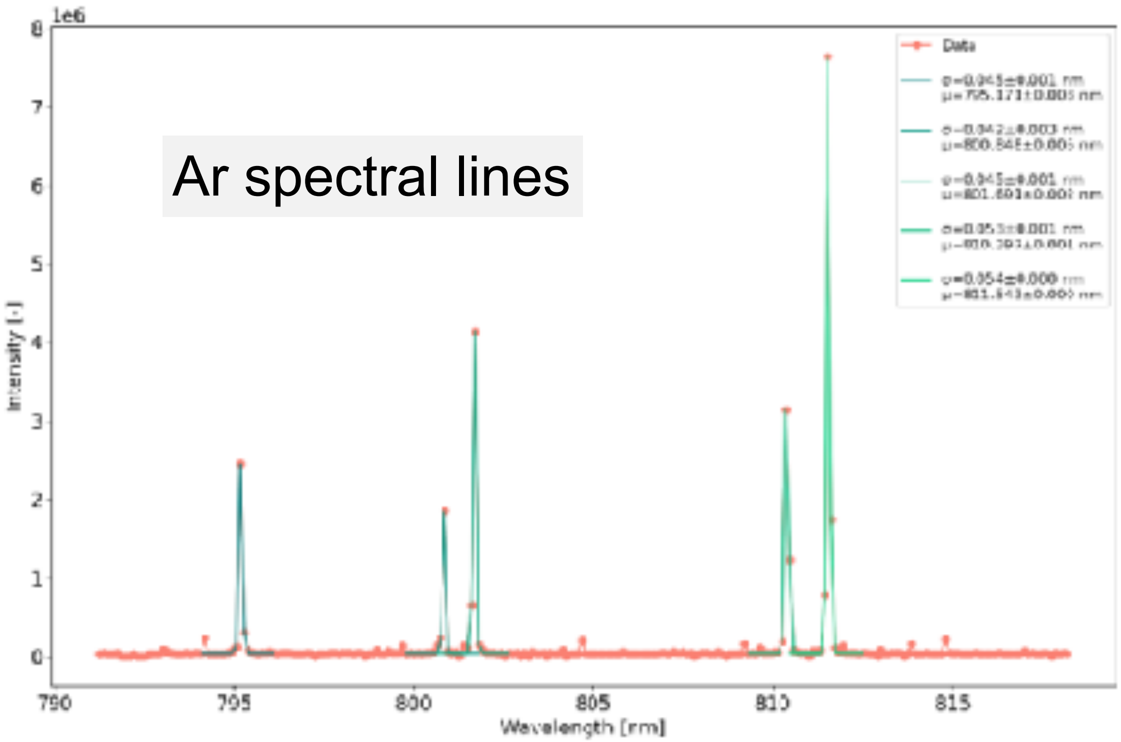


Close-up of SPADs



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.

Spectrometer with LinoSPAD2

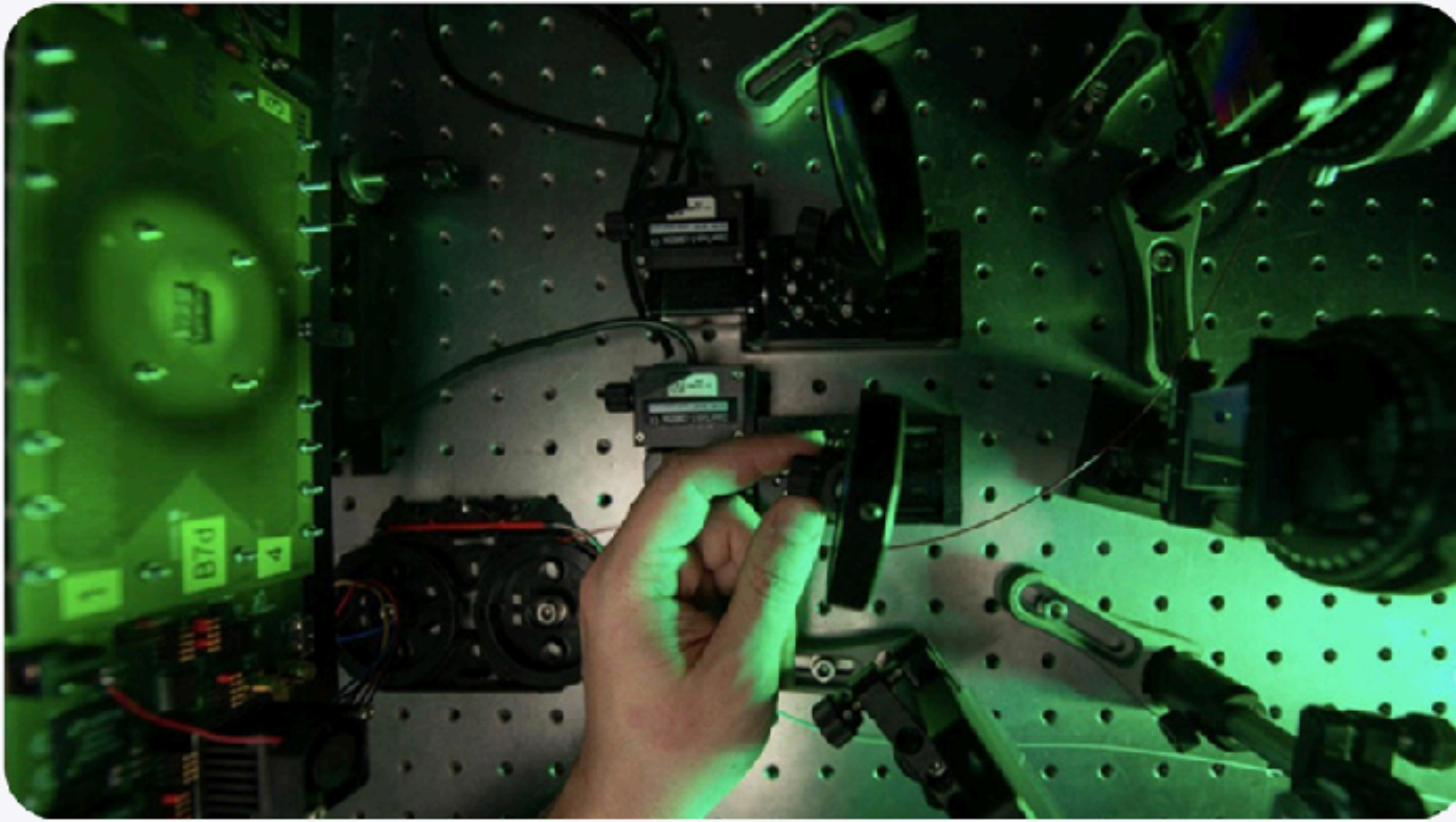


arxiv.org/abs/2304.11999

spectral resolution 0.04 nm

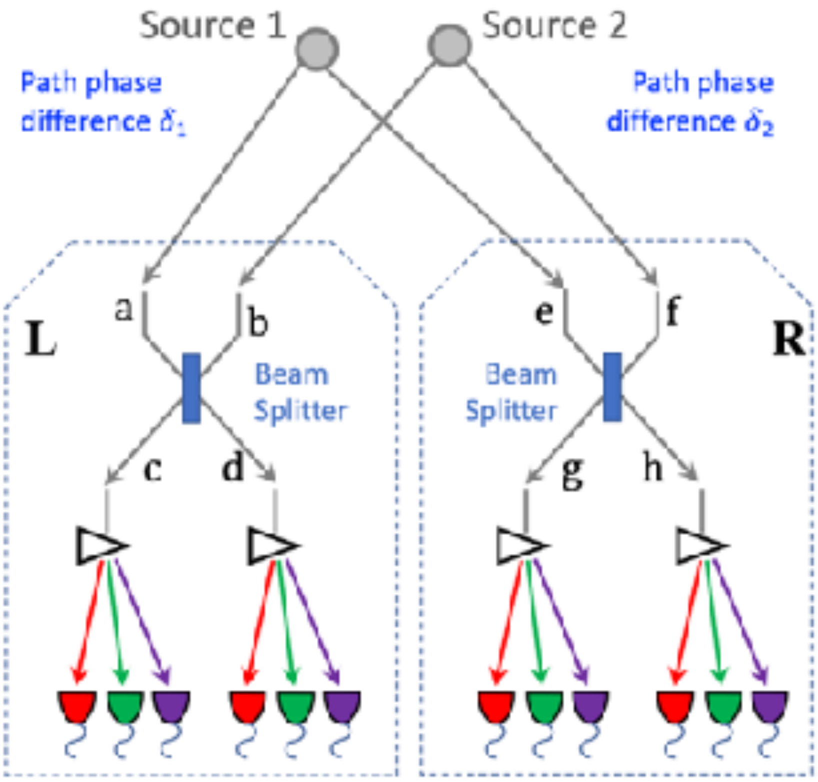
Achieved 0.04 nm spectral and 40 ps timing resolution
only x10 more than $\Delta t * \Delta E \geq \hbar/2$

Next talk



Important points for discussion

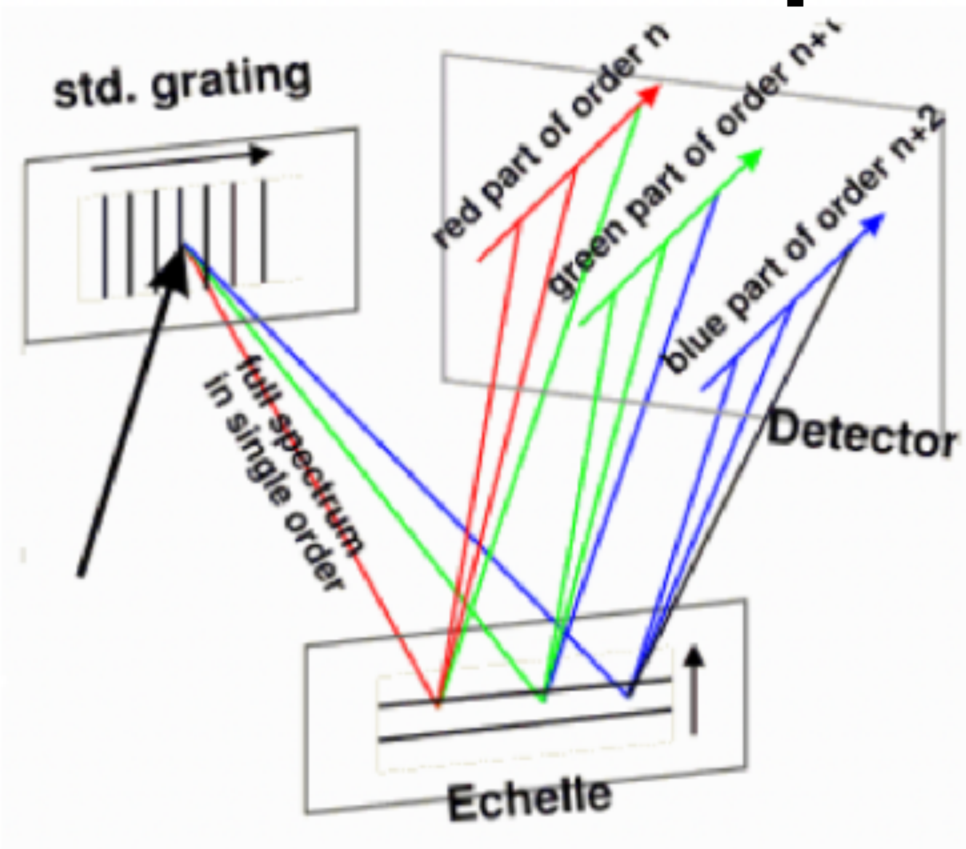
- For amplitude two-photon interferometry light needs be coupled to SMF
- This is difficult!
  5-10 micron spot, non-trivial adaptive optics
- When achieved then interference and spectrometers are easy
- Work in progress to adapt spectrometer to MMF

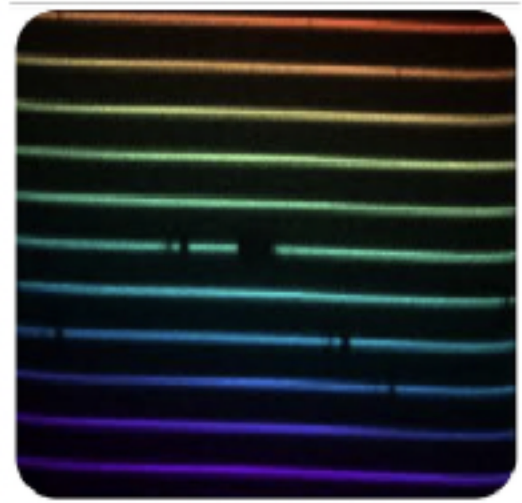


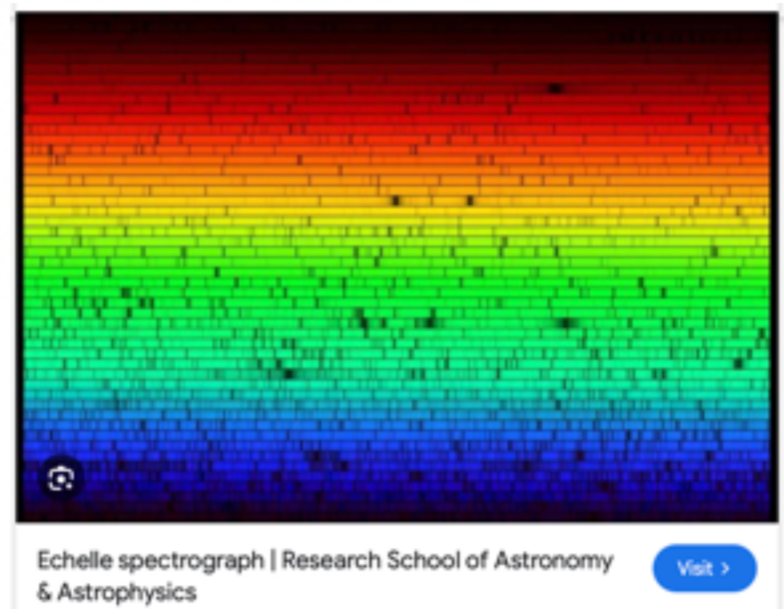
Sensor R&D

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

Echelle spectrometer





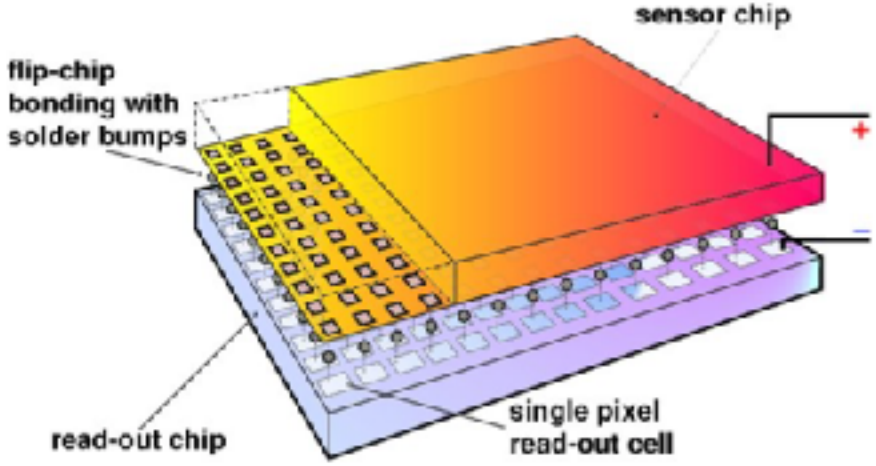


- Widely used in astronomy
- Achievable resolution ~ few pm
- **Require 2D single photon detector**

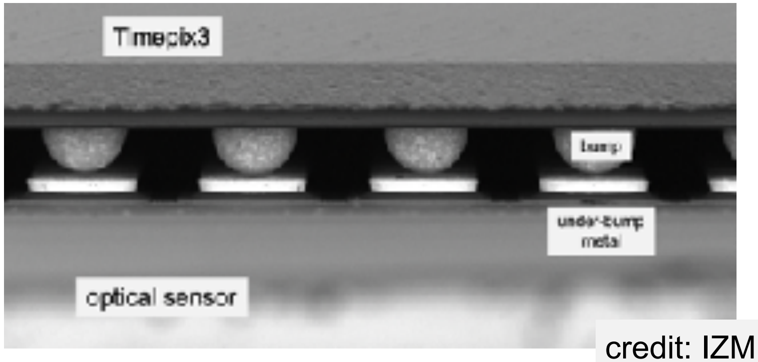
rsaa.anu.edu.au/observatories/instruments/echelle-spectrograph

Fast 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

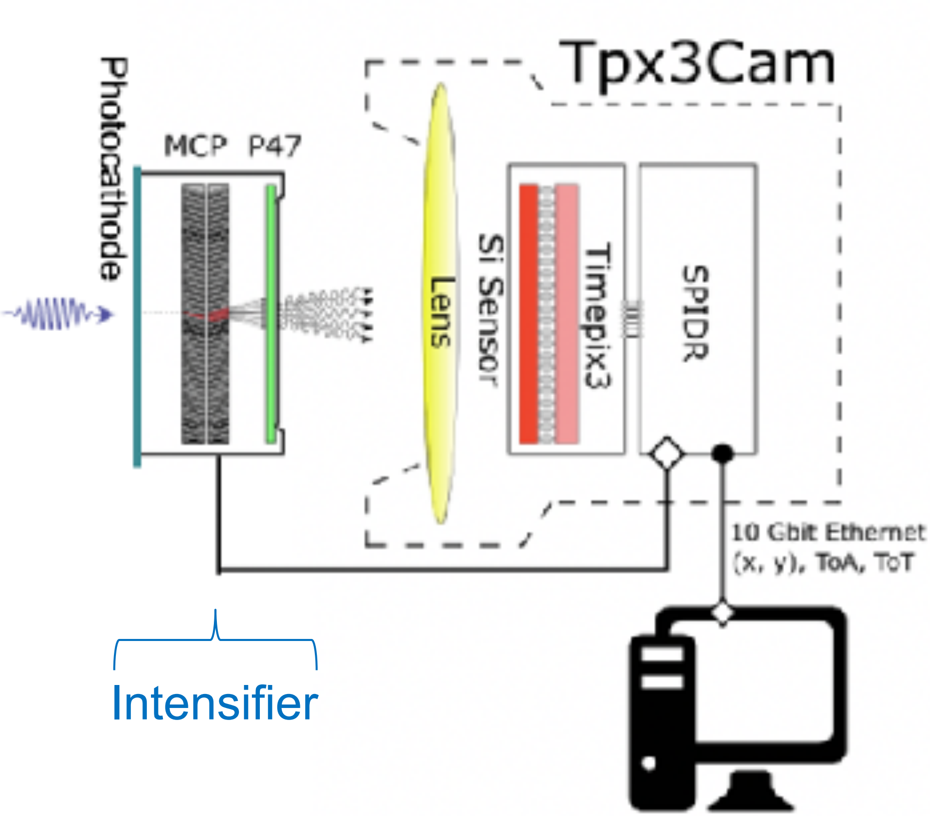
Decouple readout chip and sensor

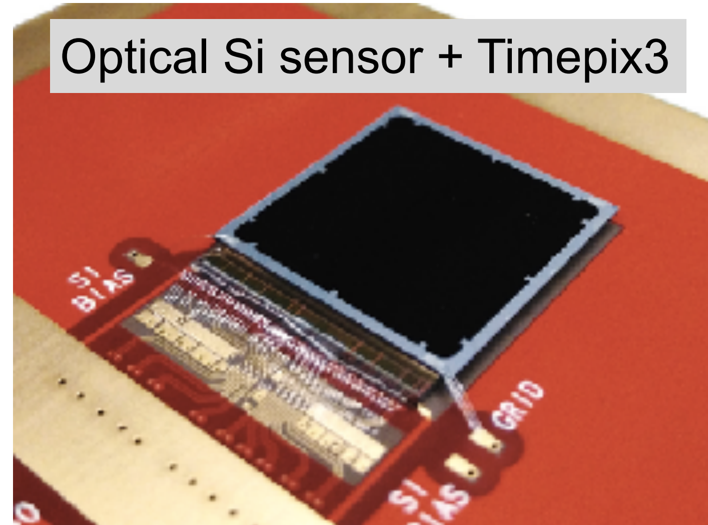
- optimize technologies for chip and sensor separately

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

→ we will use **OPTICAL** sensors

Intensified fast camera: use off-the-shelf image intensifier





Optical Si sensor + Timepix3

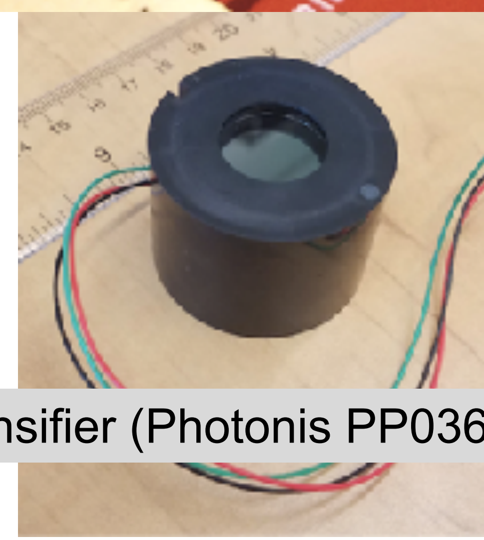


Image intensifier (Photonis PP0360EG)

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

Timepix3 → Timepix4

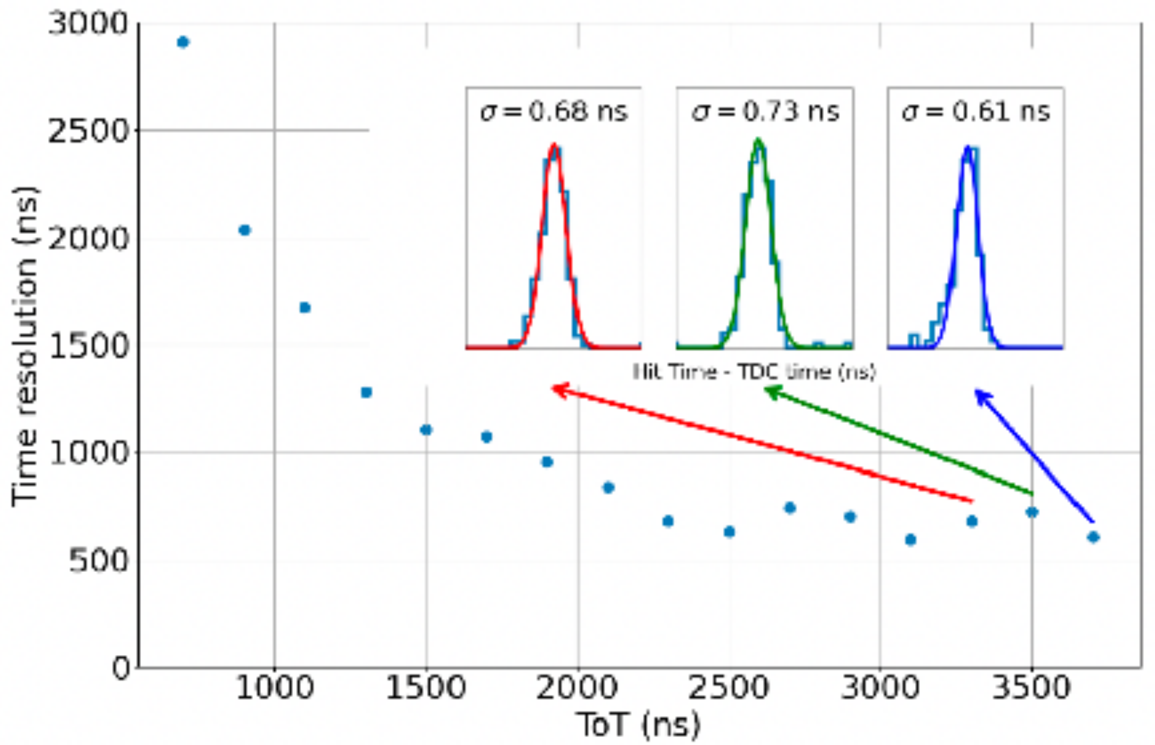
by Medipix4 collaboration

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.

First optical Tpx4 measurements

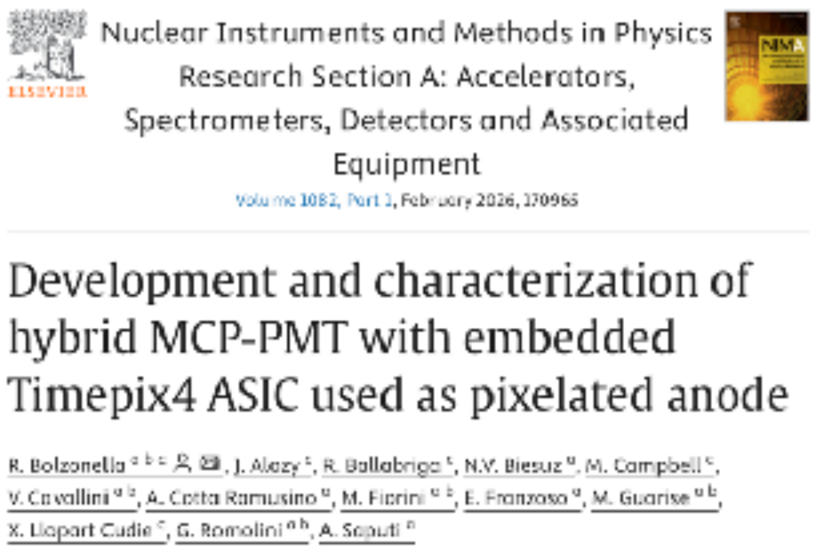


Single photon sensitive (intensified) optical Tpx4 camera

600 ps possible with high gain intensifier

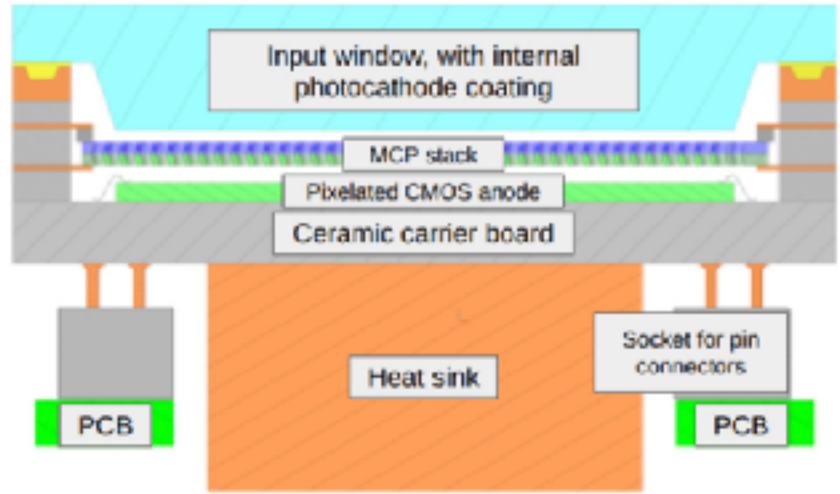
arxiv.org/abs/2509.14649

Direct detection after MCP in Timepix


Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
Volume 1082, Part 1, February 2026, 170965

Development and characterization of hybrid MCP-PMT with embedded Timepix4 ASIC used as pixelated anode

R. Bolzonella [a,b,c], J. Alozy [c], R. Ballabriga [c], N.V. Biesuz [a], M. Campbell [c], V. Cavallini [a,b], A. Cotta Ramusino [a], M. Fiorini [a,b], E. Franzoso [a], M. Guarise [a,b], X. Llopart Cudie [c], G. Romolini [a,b], A. Saputi [a]



Has been implemented before with Timepix

Time resolution 60 ps (TBC)

Limitation: photocathode QE ~ 35%

Difficulties: HV and cooling in vacuum

Direct detection after MCP via resistive anode

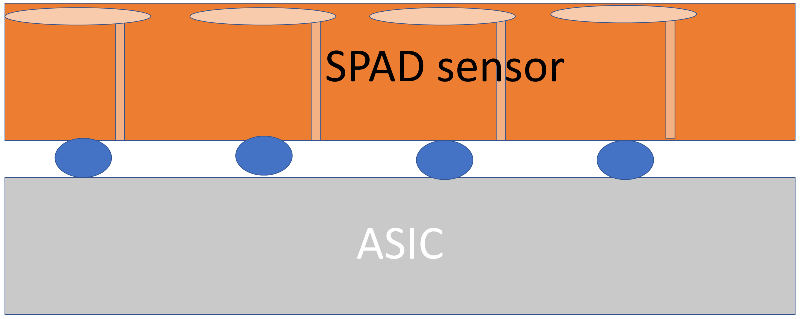
PhotonPix™ Single Photon Detector

Verena Leopold's talk

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)
  - FE not designed for large SPAD signals, good time resolution but large dead time
  - Tests with SPADs planned in 2026
- **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

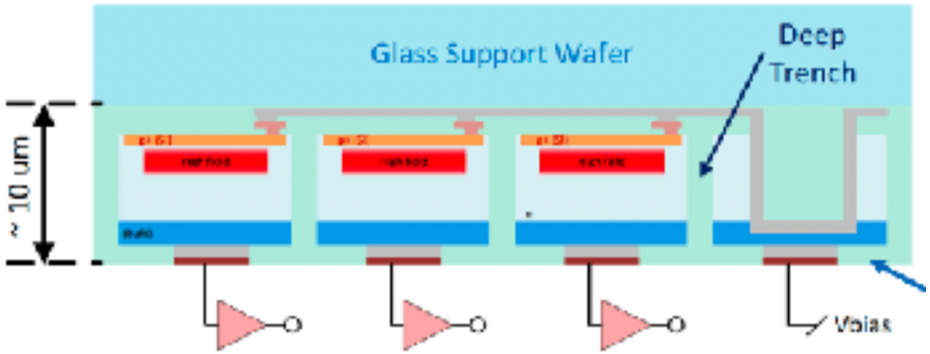


Difficulties: connectivity and cooling

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

- Timepix4 chip: 200 ps bin (RMS 60 ps)
    - FE not designed for large SPAD signals, good time resolution but large dead time
    - Tests with SPADs planned in 2026
- **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



Possible solution

SPAD in CMOS: monolithic solution with 10 ps timing

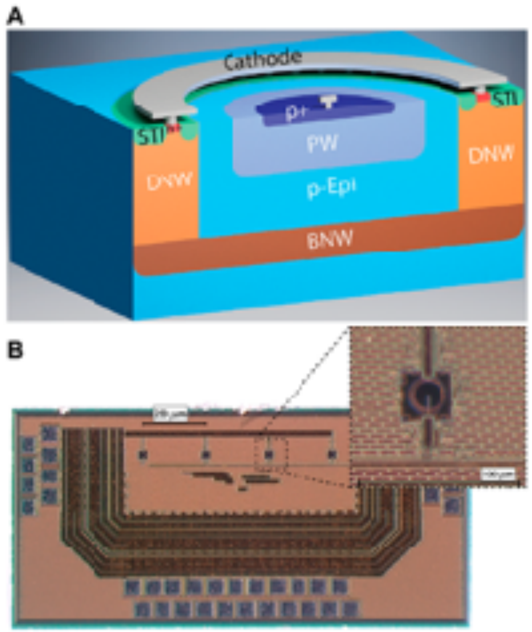
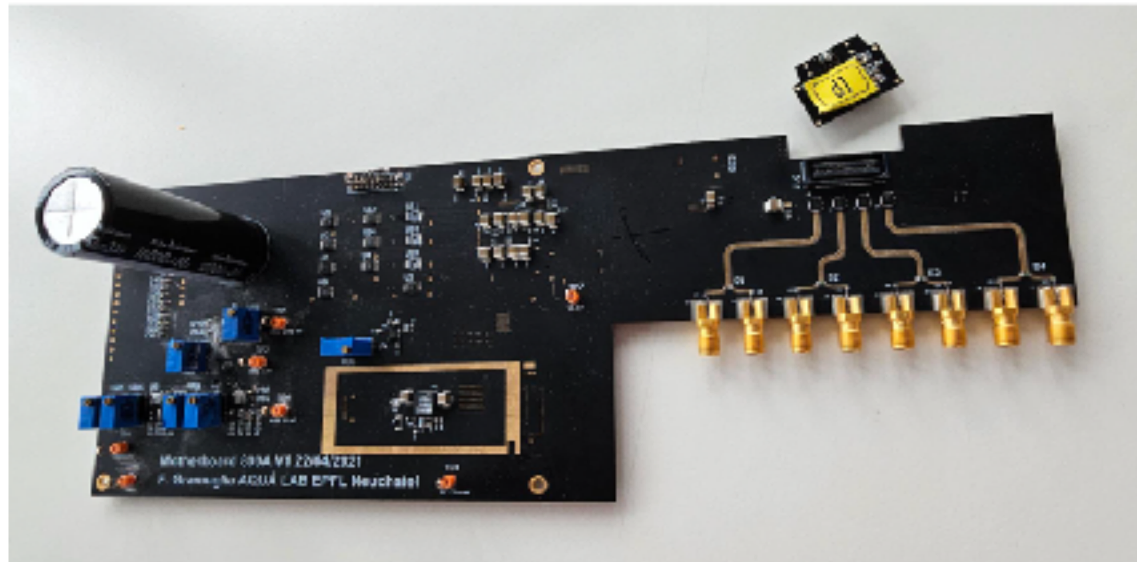


FIGURE 1 | (A): SPAD cross section. (B): Micrograph of the implemented chip embedding 25 µm diameter SPADs with integrated pixel circuit [21].



F. Gramuglia, M.-L. Wu, C. Bruschini, M.-J. Lee, and E. Charbon, A low-noise CMOS SPAD pixel with 12.1 ps SPTR and 3 ns dead time, IEEE Journal of Selected Topics in Quantum Electronics **28**, 1 (2022).

- **SuperSPAD sensor**
  - Developed in AQUA group in EPFL
  - Excellent results from QUASAR collaboration
  - 7.5 ps FWHM time resolution

- **QUASAR1 sensor** (Ivan Cardea's talk at this workshop)
  - Monolithic CMOS logic and TDCs (!)
  - Possible extension to full 2D version?

Main points to take home

- Two-photon interferometry allows independent stations over long baselines
- 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

Broad program in quantum-assisted optical interferometry ahead, efforts underway to develop new timing technologies (also needed for other applications)

Synergy in techniques and instrumentation with SII community

Acknowledgements

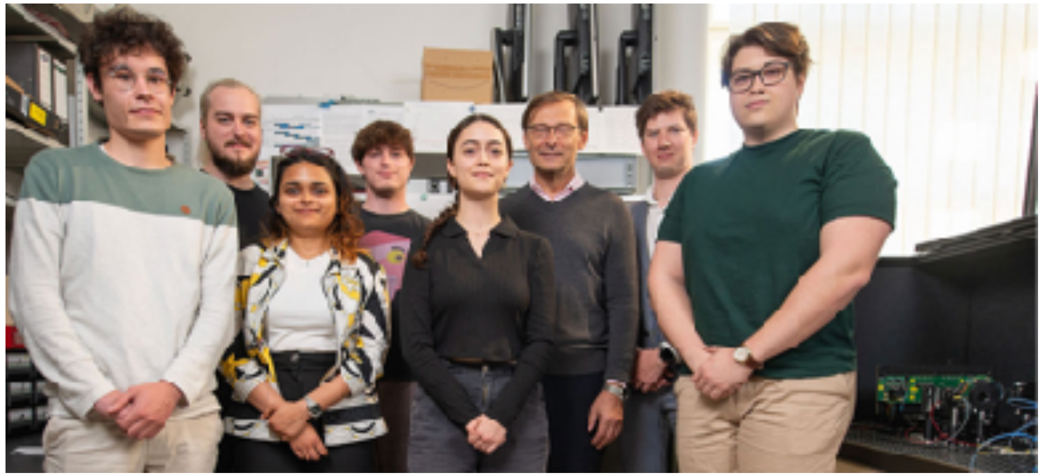
Eden Figueroa
Paul Stankus
Tom Tsang
Justine Haupt

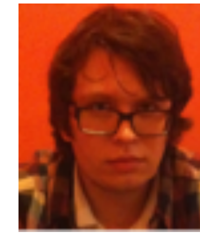
Michael Keach
Steven Paci
Alex Parsells
Jonathan Schiff
Denis Dolzhenko
Stepan Vintskevich
Anze Slosar
Zhi Chen
Jesse Crawford
Aaron Mueninghoff

Erik Hogenbirk
Martin van Beuzekom
Bram Bouwens
Erik Maddox
Duncan England
Yingwen Zhang
Raphael Abrahao
Brianna Farella
Ryan Mahon

Edoardo Charbon
Tommaso Milanese
Ermanno Bernasconi
Claudio Bruschini
Ivan Cardea

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





Thank you for your attention!

https://capads.fjfi.cvut.cz