Hybrid Pixel Single Photon Detector for Quantum Applications

Innovative Solutions for Quantum Imaging and Real-Time Feedback

Shazia Farooq

25th January 2025

Outline

- **Perspectives from Academia to Industry**
- **Technological Advancements**
- **Challenges**
- **Current Gaps in the Field**

From Lab Coat to Business Suit ☺

2011
ASI was found as spin-off from NIKHEF and AMOLF in Amsterdam

2013
First deliveries of TPX-1 detectors to synchrotron customers

2017
Commercial Restructuring under new leadership

2018
Release of TPX3CAM

2020
Release of CheeTah M3 and T3 Retractables

2021
Release of CheeTah 1MP

2022
Release of 4D-STEM solutions

Release of LumaCam

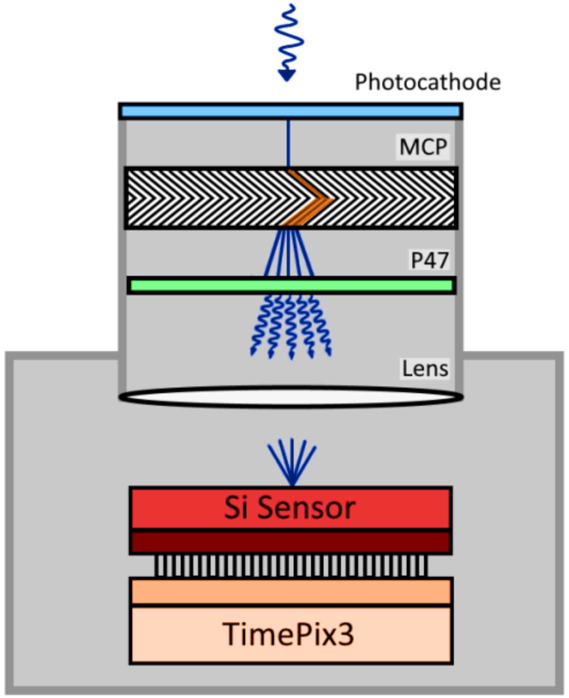
2023
Release of Phoebe

2024
Release of Hyperion

TPX3CAM: Hybrid Pixel Photon Detector

Prof. Andrei Nomerotski
(StonyBrook & BNL)

Single-Photon-Sensitive Event-Driven , Tim-Resolved 2D Detector

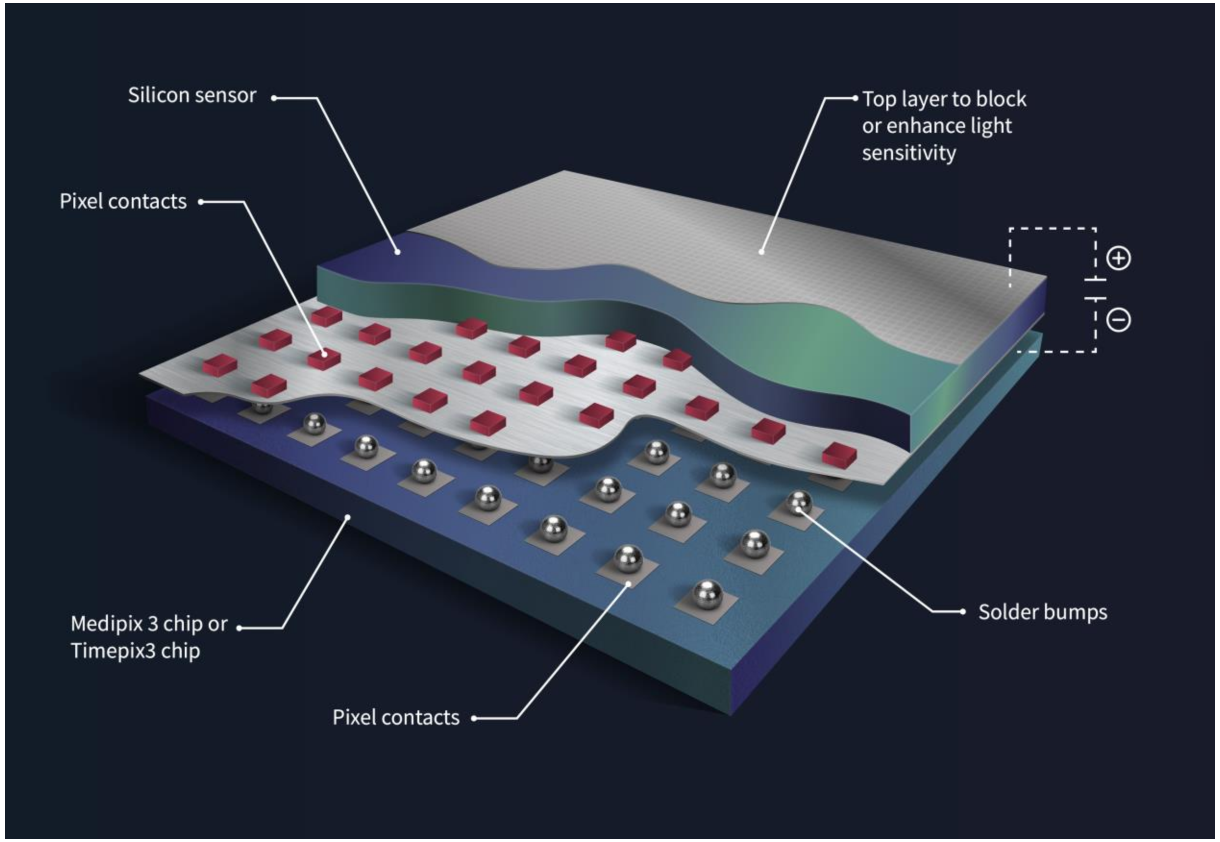


Detection of optical photons (VIS to UV range) making use of optical photon sensors:

- Conventional silicon sensor adapted to optical photons sensing
- Electron multipliers (MCP)
- Image Intensifiers

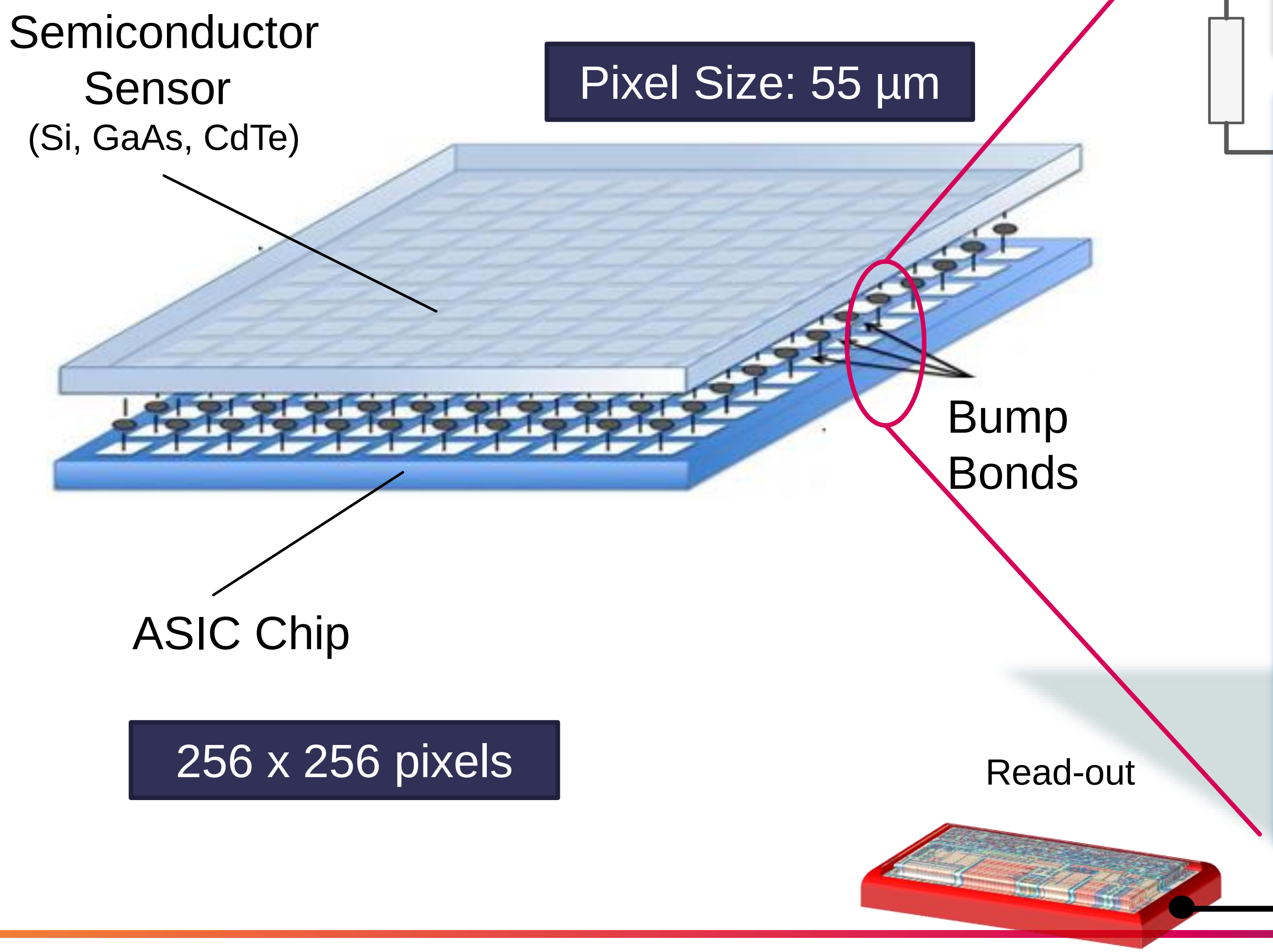
Hybrid Pixel Detectors

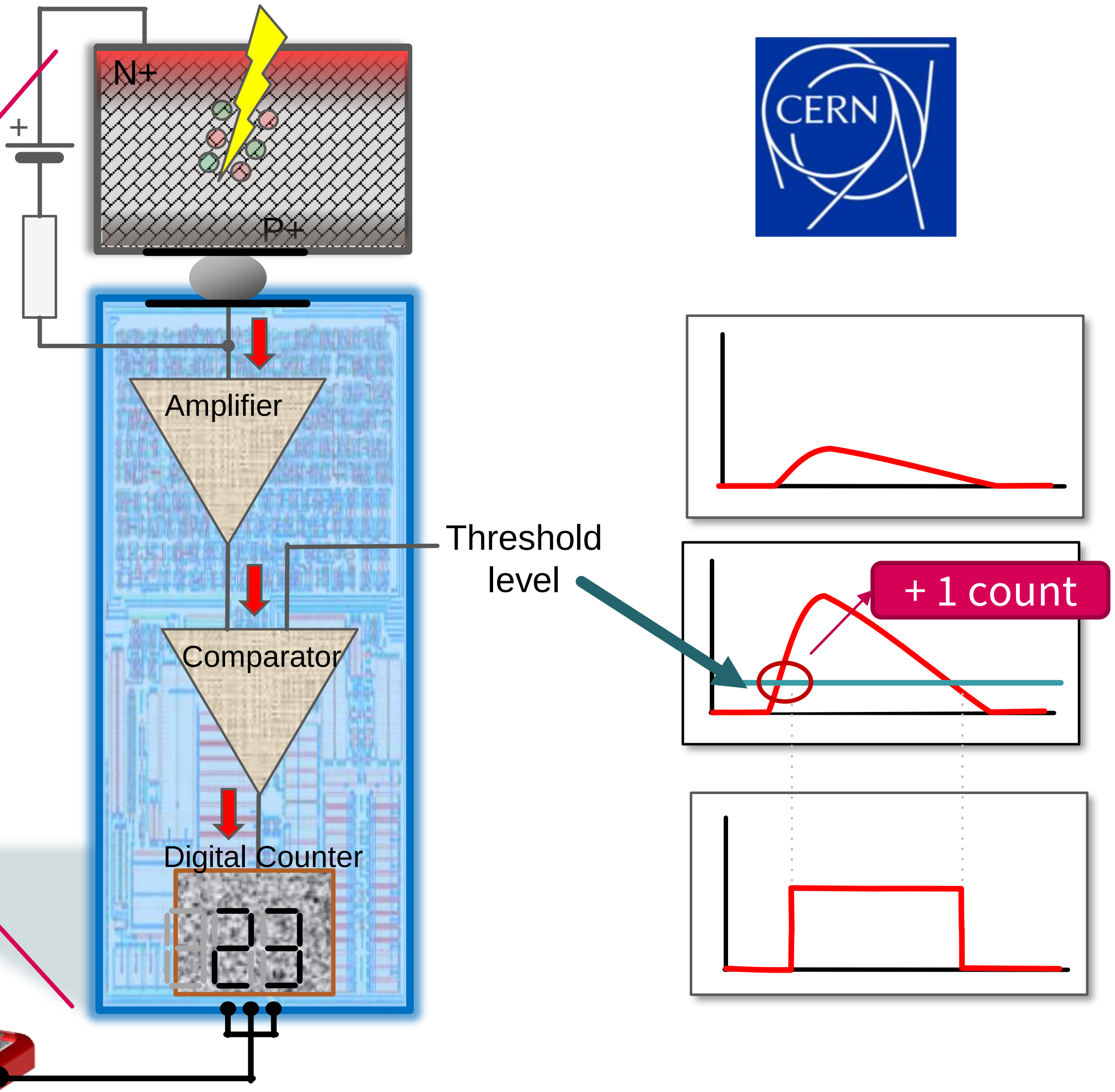
- Sensor material is separate from electronics this makes Timepix3 very robust.
- Noise Free (counting mode, thresholding)
- Ultra-sensitive (high intrinsic amplification)



Hybrid Pixel Detector

Working principle

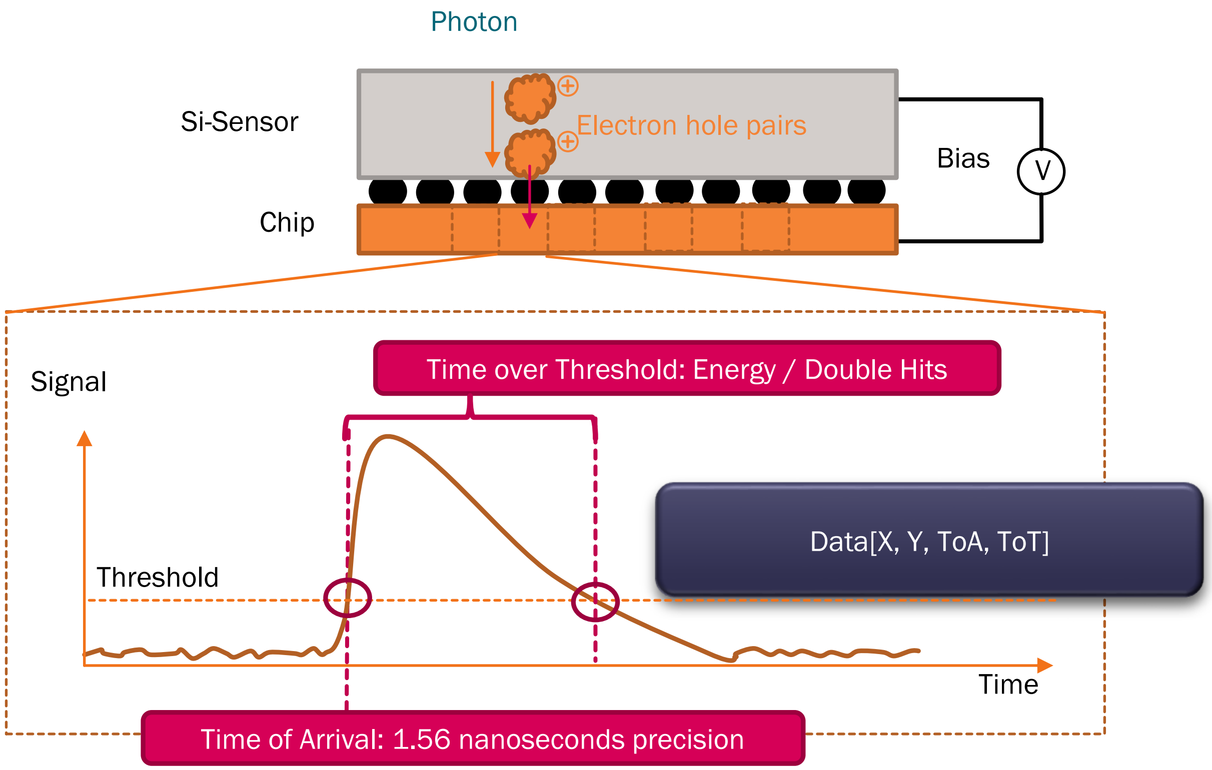




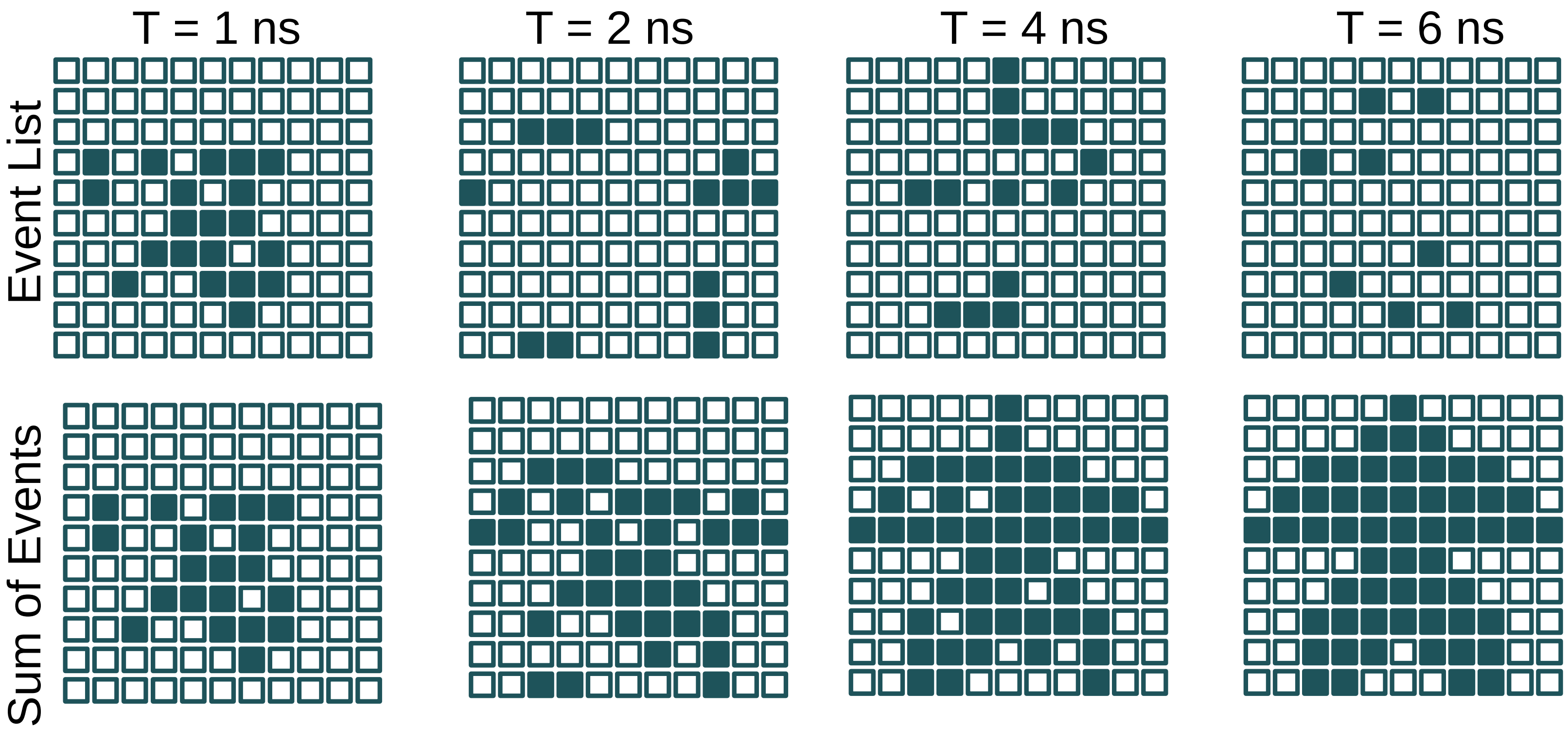
What does Timepix3 offer/enable: **ToA & ToT**

- Data-driven – direct readout of the hit
- Time of Arrival (ToA) of each electron with 1.56 ns time resolution
- Very high effective frame rates – 640 MHz
- 3D information (x,y and time)

- Measuring energy deposited (~10 -20% resolution)
- Time over Threshold (ToT) of each event with 25 ns resolution
- Measuring pile-up (multi hit)

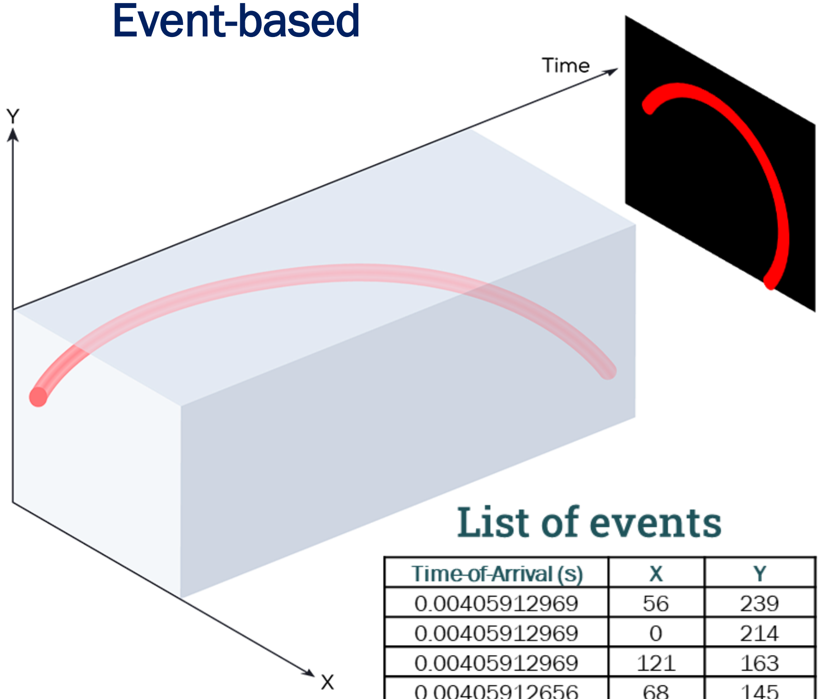


Event-based detection can also create images!



Timepix 3

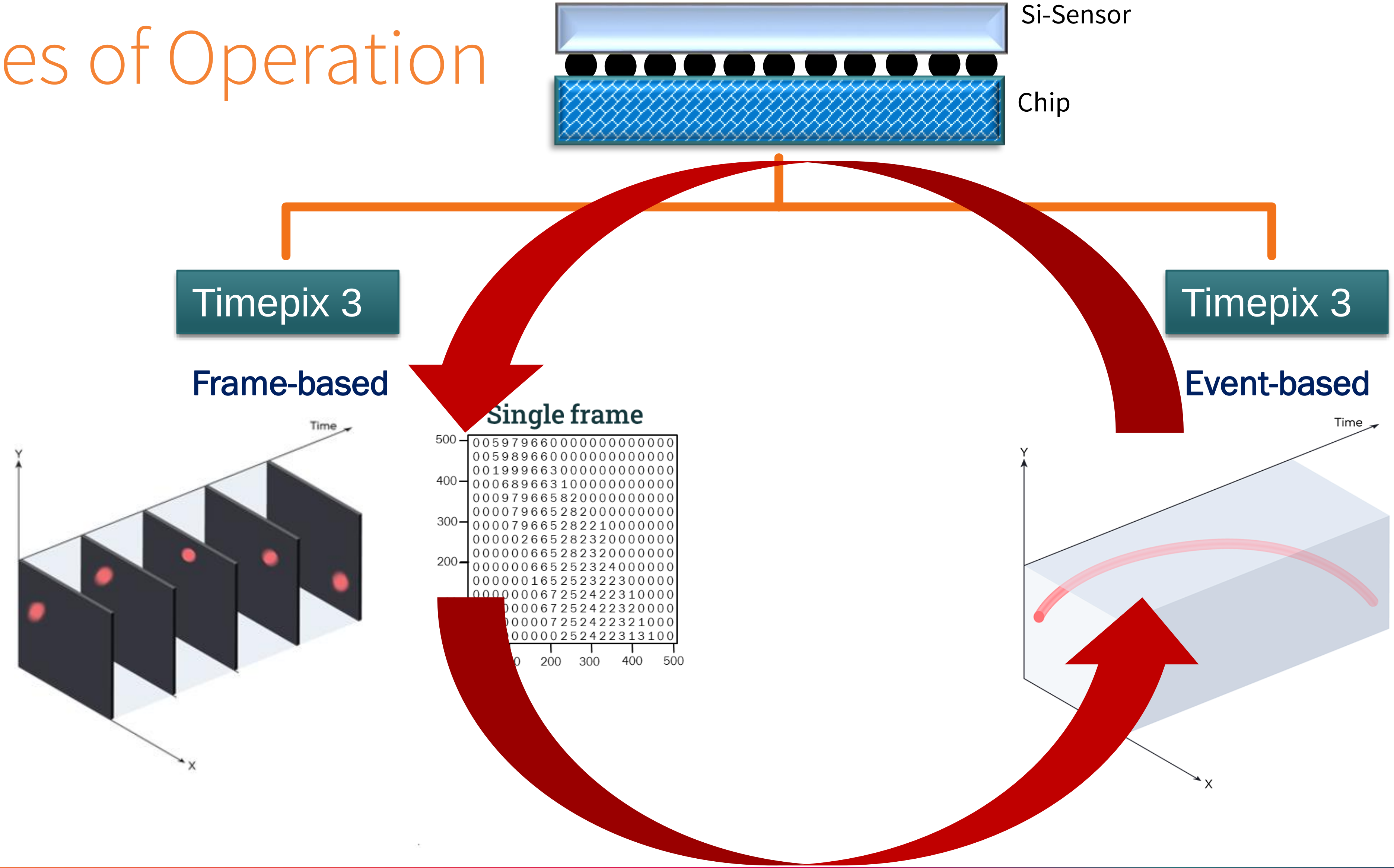
Event-based



List of events

Time-of-Arrival (s)	X	Y
0.00405912969	56	239
0.00405912969	0	214
0.00405912969	121	163
0.00405912656	68	145
0.00405920938	133	197
0.00405912500	32	98
0.00405956094	12	228

Modes of Operation



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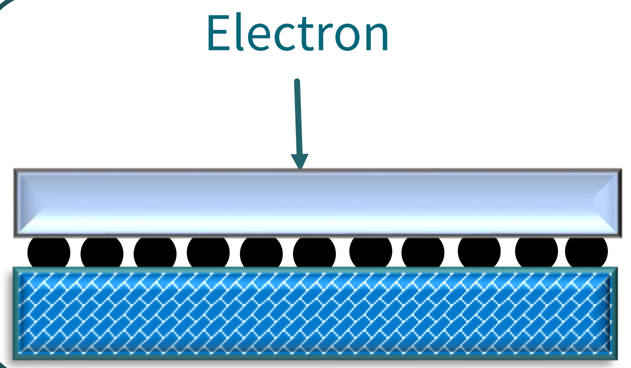
0.00405920938	133	197
0.00405912500	32	98
0.00405956094	12	228

TDC (Time to Digital conversion) input



Low voltage TTL input on TDC
Source examples:
- Pulsed laser sync
- Photon counter (e.g.SPAD)

Timepix3 Detectors

List of events

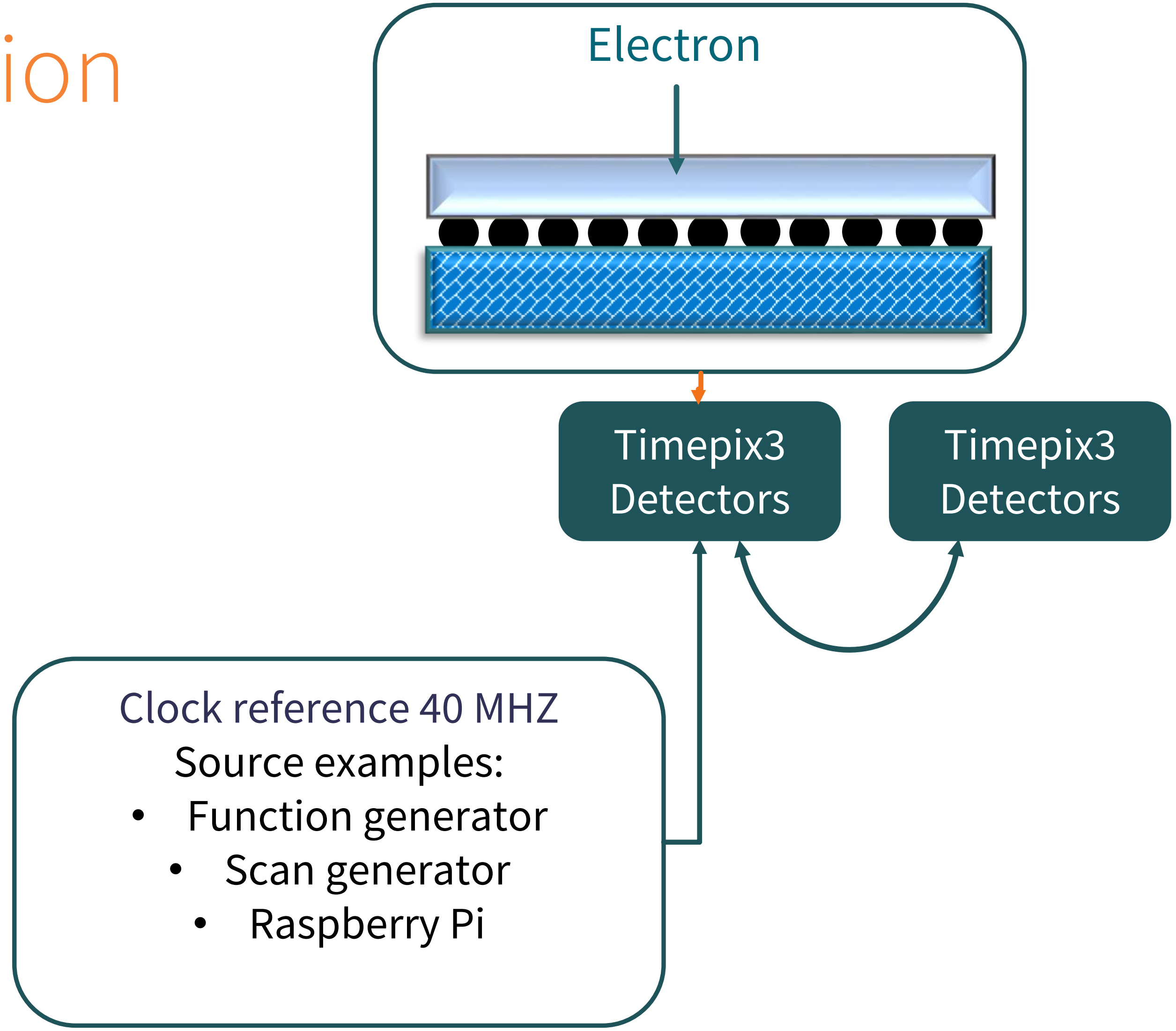
	Time-of-Arrival (s)	X	Y
TPX3	0.00405912969	56	239
TPX3	0.00405912969	0	214
TPX3	0.00405912969	121	163
TPX3	0.00405912656	68	145
TDC	0.00405912655	-	-
TPX3	0.00405920938	133	197
TPX3	0.00405912500	32	98
TXP3	0.00405956094	12	228
TDC	0.00405956096	-	-

TDC Specifications	
Time resolution	260 ps
Number of inputs	2
Trigger	Rising or falling edge or both
Maximum rate	10 MHz

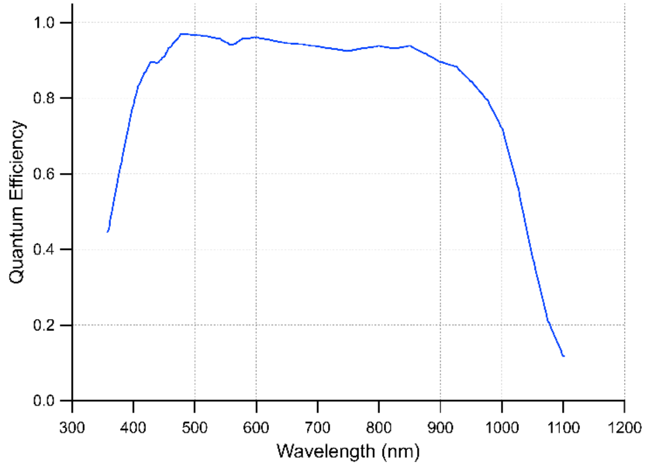
- ASI Timepix3 Detectors has two external TDC inputs with 260 ps time resolution
- These allow synchronization with arbitrary external signals
- The inputs are clock synchronized with the Timepix3
- They appear as events in the event list output

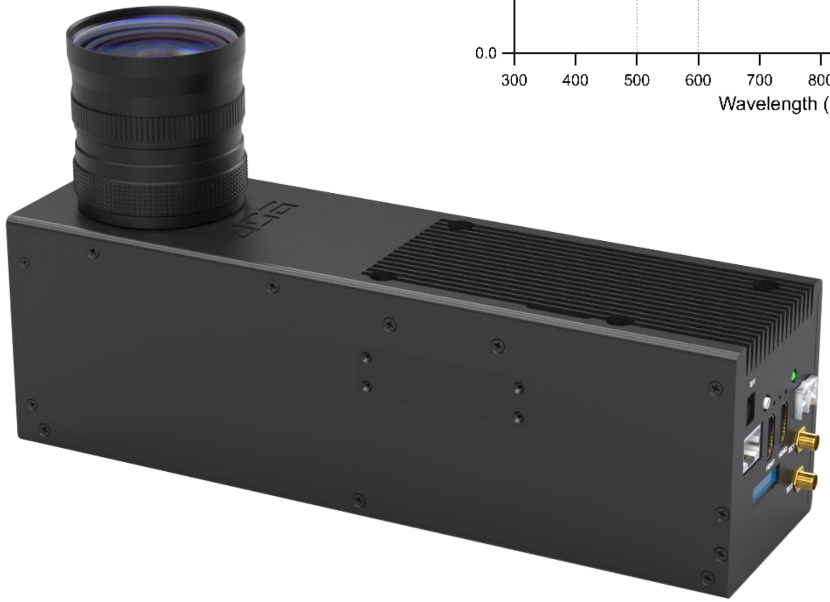
Clock synchronization

- An alternative is to synchronize the clock of the Timepix3 detectors with an external reference
- Timepix3 Detectors has a 40MHz input and output
- It is even possible to daisy-chain Timepix3 Detectors



Chronos: The Optical TPX3CAM





Key features

- Light sensitive sensor, Quantum Efficiency > 90%
- Wavelength range: 400 – 1000 nm
- Simultaneous detection of time (ToA) and intensity (ToT) in each individual pixel
- 256x256 pixel matrix, 55 µm pixel size
- Flexible optical design, ideal to observe scintillators or phosphor screens
- Event-driven detection mode with up to 80 million hits per second
- Time resolution in picosecond range (using TDC signals)
- Flexible integration via Python API or GUI

Application Specific Chronos Series

Quantum Science: Phoebe & Rhea

Neutron Detection: Telesto

Ion Detecton: Hyperion

TPX3CAM (legacy)

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ALON BOGOT, MATHIAS POLINE, MINGCHAO JI, ARNAUD DOCHAIN, ANSGAR SIMONSSON, STEFAN ROSÉN, HENNING ZETTERGREN, HENNING T. SCHMIDT, RICHARD D. THOMAS, AND DANIEL STRASSER Authors Info & Affiliations

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A. S. Losko, Y. Han, B. Schillinger, A. Tartaglione, M. Morgano, M. Strobl, J. Long, A. S. Tremsin & M. Schulz

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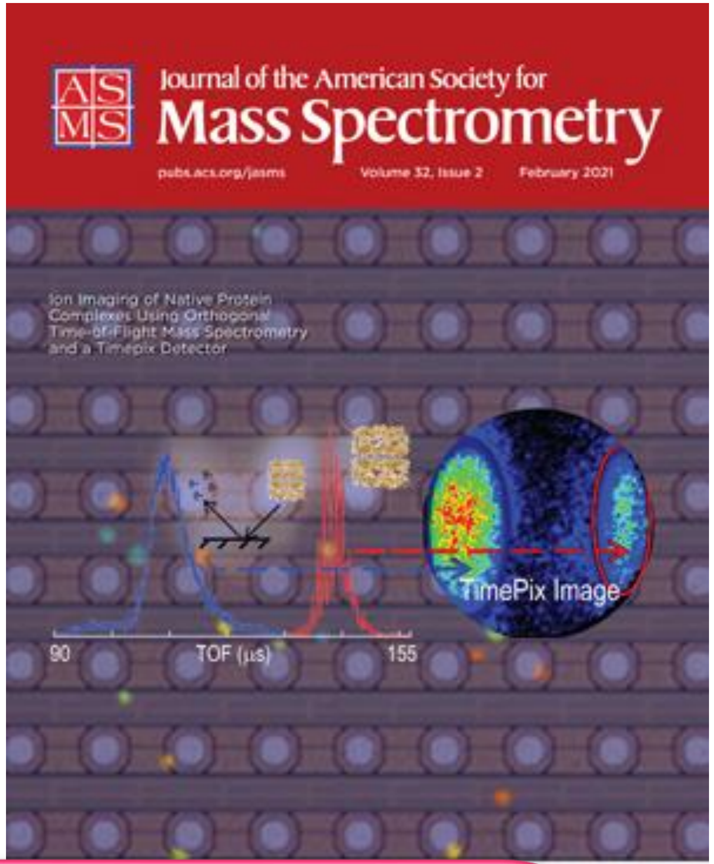


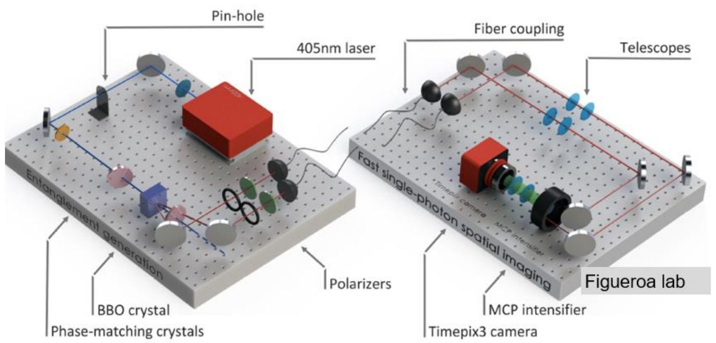
MassSpec | Quantum | VMI | Neutrons

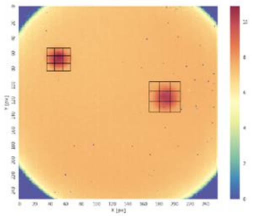
159 publications in past 5 years using TPX3CAM and Chronos

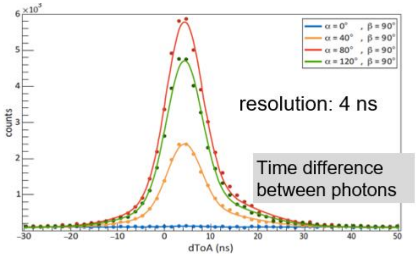
Chronos Series: Quantum Imaging

Phoebe is an intensified hybrid pixel detector based on TPX3CAM especially designed for *Quantum Science* applications.

Measuring Entanglement

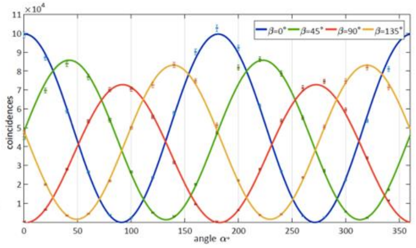






- Find coincidences, plot as function of two polarizations
- Figure of merit: S-value
  - If > 2: photons are entangled
  - max value: $2\sqrt{2} = 2.82$

Clauser-Horne-Shimony-Holt (CHSH) inequality



- Measurement:

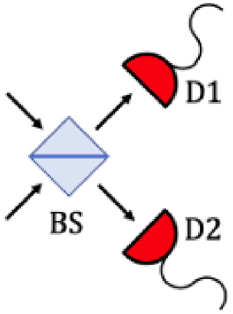
S-value = 2.72±0.02

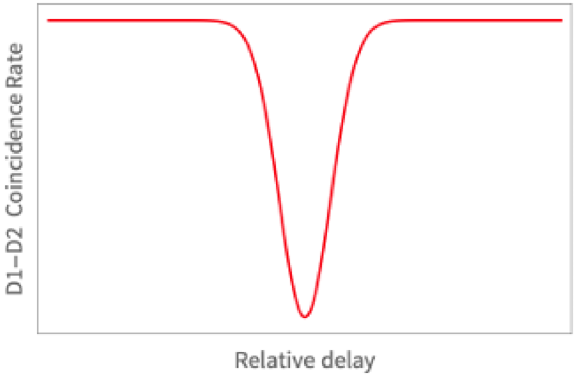
Fast camera spatial characterization of photonic polarization entanglement

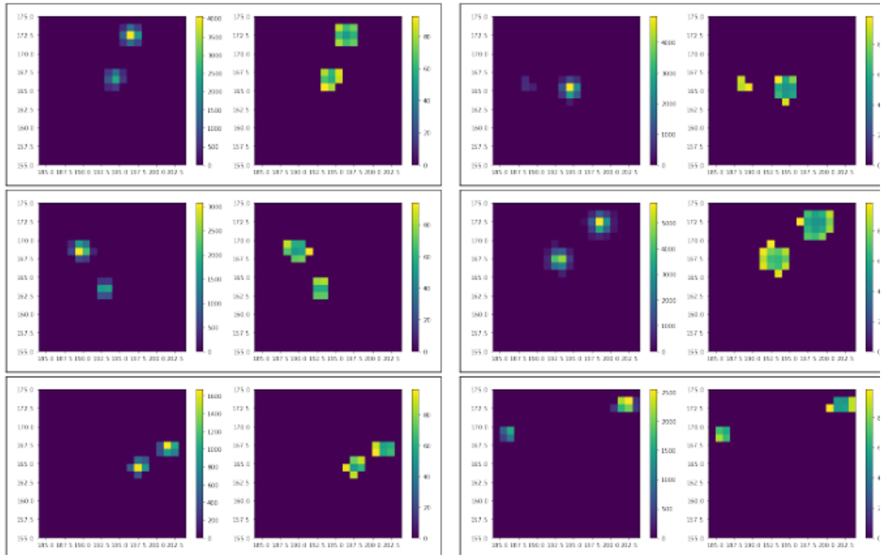
Christopher Ianzano, Peter Svihra, Mael Flament, Andrew Hardy, Guodong Cui, Andrei Nomerotski & Eden Figueroa

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

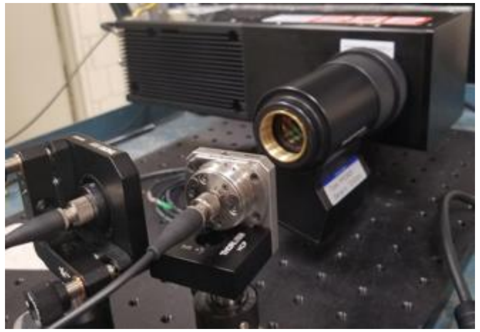
Hong-Ou-Mandel effect

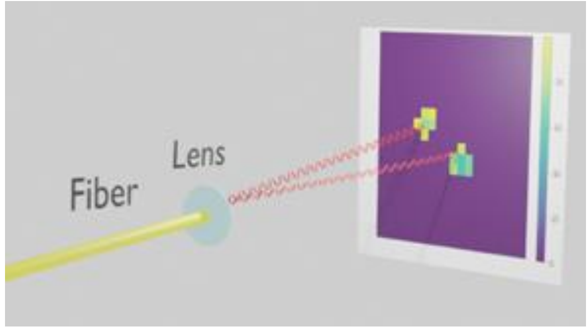






Quantum interference





https://doi.org/10.48550/arXiv.2005.07982

AMSTERDAM SCIENTIFIC INSTRUMENTS

How to achieve an extreme depth-of-field (DOF) with Phoebe: the single-photon TPX3CAM!

DOI:10.48550/arXiv.2212.12582

The Concept

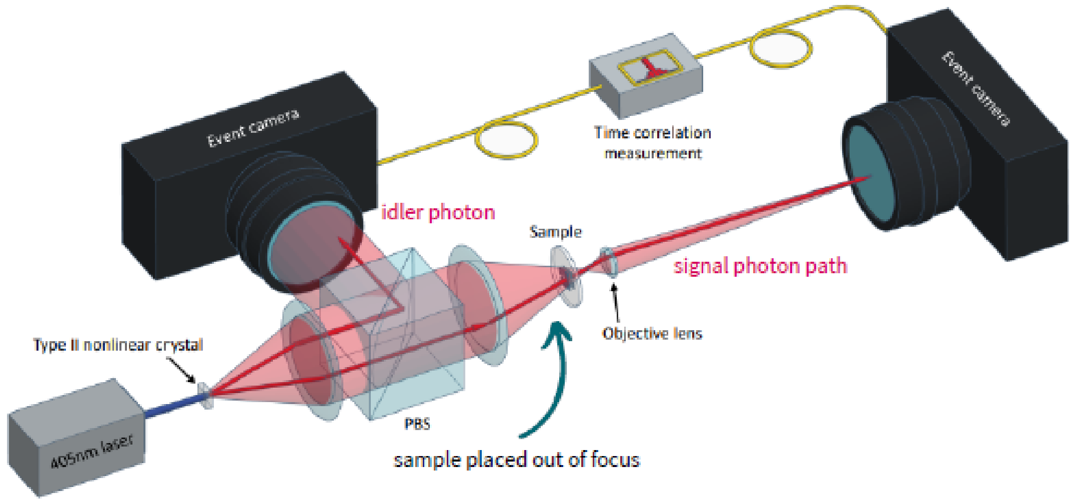


Figure 1. Conceptual setup of the Quantum correlation light-field Microscopy (QCLFM) system.

Quantum correlation light-field microscopy

- Through Spontaneous Parametric Down Conversion (SPDC) produce pairs of entangled photons: signal and idler
- Split them with a polarizing beam splitter
- Record position and time-of-arrival (TOA) of the signal photons passing through the sample
- Record the momentum and TOA of the idler photons
- Perform time-correlation analysis to identify entangled pairs
- Infer the signal's momentum information from its time-correlated partner

* The technique is insensitive to whether the target is placed before or after the objective focus.

The authors tested this technique using just **one** time-tagging event detector on a 3D scene consisting of multiple overlapping fiber strands of a thick stack of lens tissue. With a **single measurement** and digital refocusing in post-processing, they obtained the results in Fig. 2.

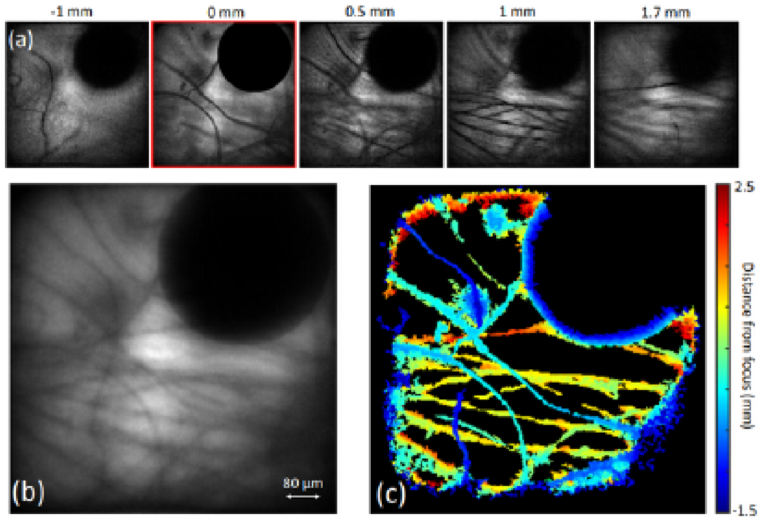


Figure 2. Refocusing of lens tissue fiber (a) Digital refocus of fiber strands at various distances from the focus. The measurement is taken in with a data acquisition time of 200 s. The empty circular region on the top right is the part of the camera used for capturing the idler photons. (b) Image showing all fiber strands brought into focus through post-processing. (c) Depth map of the fiber strands.

The Benefits

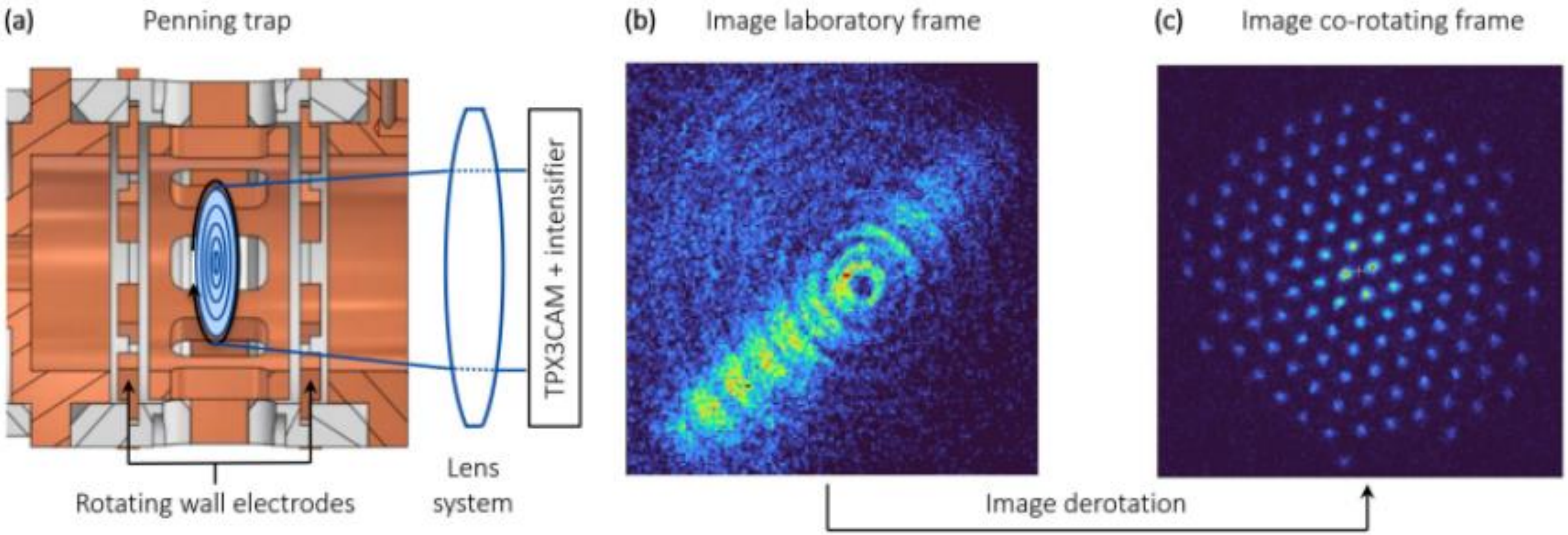
- No need to sacrifice position resolution for momentum resolution or vice versa as in conventional Light-field Microscopy (LFM) designs.
- Achieve a DOF that is ~3 times larger than that of the latest LFM designs rendering the technique excellent for volumetric biological imaging applications and 100 times better than optical microscopes.
- If spatial resolution is sacrificed (100 µm) a near-infinite DOF can be attained.
- Subpixel resolution (<55 µm) with centroiding algorithms using the TPX3CAM detection system.
- There is potential to combine this technique with other quantum imaging technologies, such as quantum lithography to achieve a resolution beyond the diffraction limit.

Crystal clear insights on the quantum states of hundreds of trapped-ion qubits with Phoebe: the single-photon TPX3CAM!

Using the time-tagging capabilities of Phoebe, researchers from the University of Sydney led by Dr Robert Wolf, capture data from rapidly spinning ions at the incredible speed of 25 kHz.

Just 10 ms later, the state of each ion is known!

Figure 1 shows the **de-rotation** of the ion crystal from the laboratory frame to a static image of all 120 trapped-ions. This image is then used as a reference image to infer the positions of the ions with machine learning techniques using Phoebe data as input.



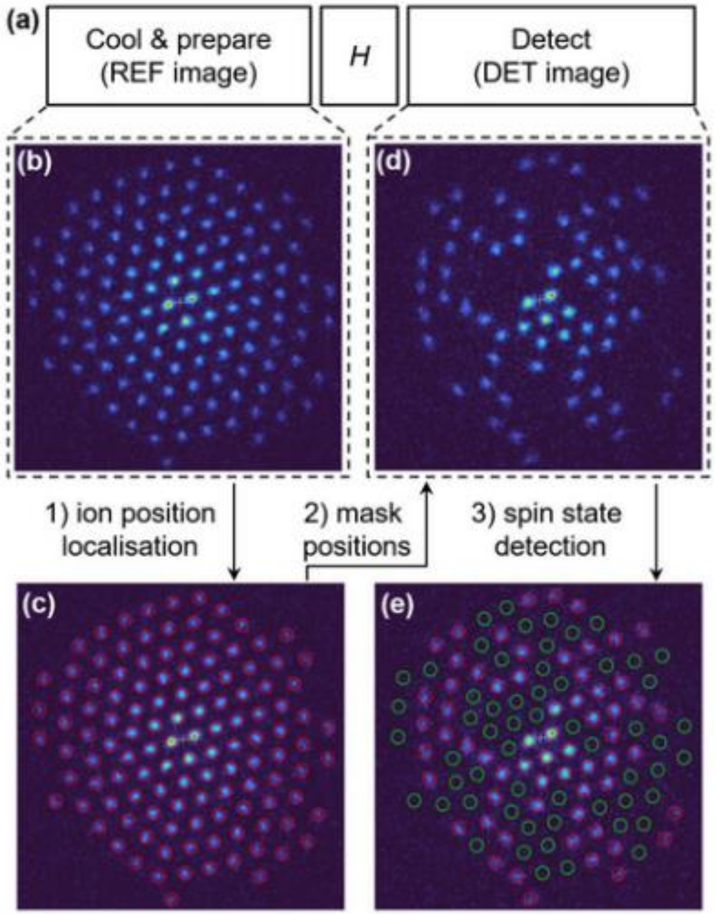
When an ion is in the **"bright"** state (|↑|) the cooling and detection lasers scatter photons, while ions in the **"dark"** state (|↓|) produce almost no fluorescence and cannot be localized. To determine their spin-state all images are compared to a reference image captured a few milliseconds before each detection sequence.

The full sequence is described in the images below:

(a) Ions are prepared in the bright state.

(b) Phoebe records single photon data to form a reference image.

(c) Data are fed to a neural network that localizes the position of each ion.



(d) The ion positions are projected onto the measurement image (DET), taken after some arbitrary interaction H.

(e) The previously found ion positions are masked to this image. Time data in each ion region can be evaluated to determine the spin state.

Direct Observation of Ion Micromotion in Paul Traps

The simultaneous time and position information of Phoebe, the single-photon TPX3CAM enables real-time monitoring of ion micromotions and characterisation of ion traps.

Experimental set-up of a Paul Trap

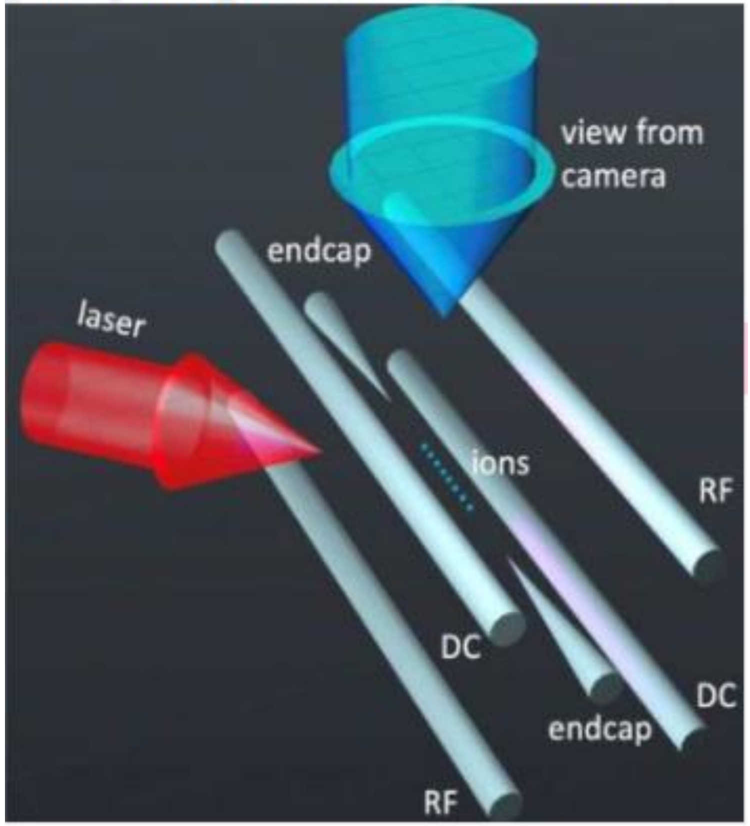
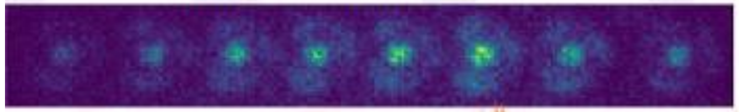


Image of eight Ba+ ions



In RF traps, the motion of the ions has 2 components:

1. **Secular motion:** slow, harmonic and predictable.
2. **Micromotion:** faster oscillation due to the RF field applied.

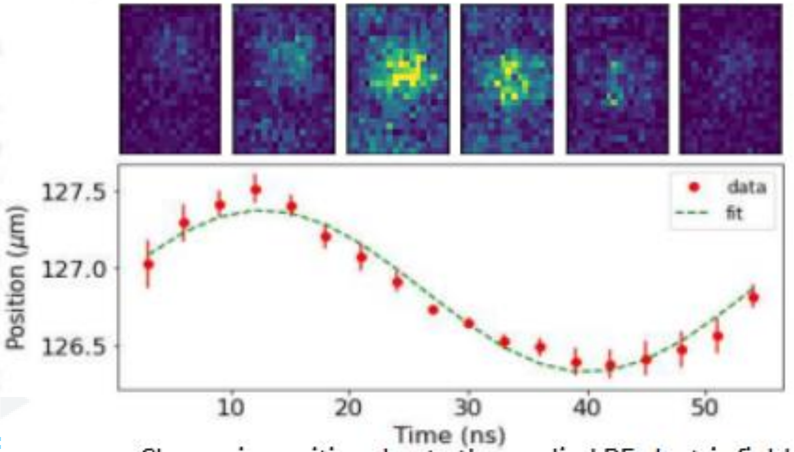
Most current techniques for micromotion detection are indirect and typically require additional optical setup or laser modifications.

Directly observing ion micromotion.

Snapshots of the sixth ion during micromotion oscillation in six time bins separated by 9 ns each. The shown statistics correspond to 3 ns time integration around the midpoint of the bin.

- **Simultaneous time & position information allows to monitor ion micro-motions**

Change in brightness due to the "Doppler shift"



Change in position due to the applied RF electric field

Observed period T = 54.79 ns - exactly the period of the trap's RF

https://doi.org/10.1103/PhysRevA.103.023105

Ongoing Projects: 2025-2026

Chronos Phoebe

256 x 256 pixels
C-Mount
1.56 ns
80 Mhits/s
TDC: 260 ps

STANDARD

Chronos Rhea

256 x 256 pixels
c-Mount
Latency optimized
TDC: 260 ps

In Progress

Chronos Phoebe T4

512 x 448 pixels
M-Mount
200 ps
1.2 Ghits/s

In Progress

Chronos Phoebe T4 +SPAD

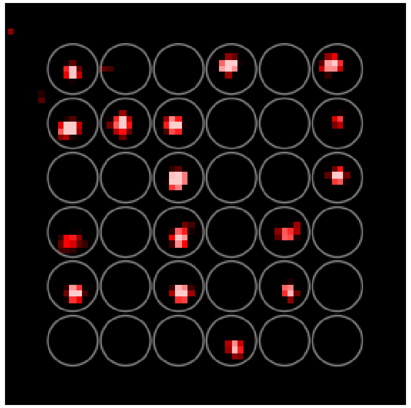
512 x 448 pixels
M-Mount
200 ps
1.2 Ghits/s

Conceptual

Chronos Series: Real-Time Feedback

Rhea is an intensified hybrid pixel detector based on TPX3CAM especially designed for *real-time feedback control* applications. Our development team is currently working on a prototype.

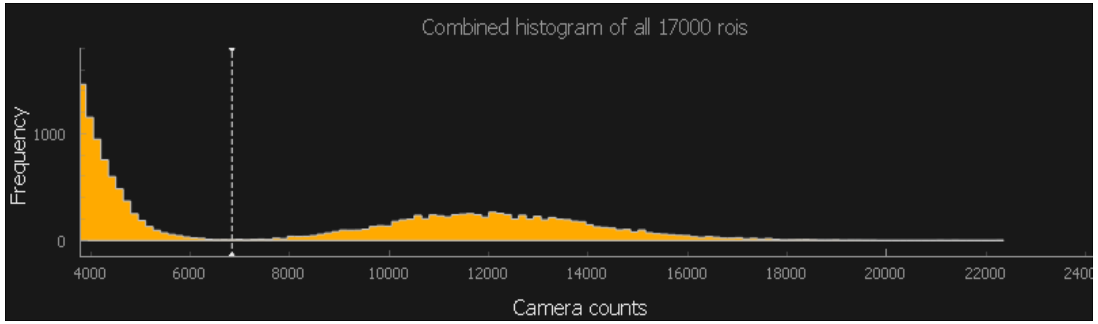
Quantum Computing with Atoms



- Quantum computing leverages particles as qubits, and in our case, we focus on **atoms**.
- Atoms function as qubits because they exhibit two distinct states—**"dark"** (logical 0) and **"bright"** (logical 1).
    - When exposed to light at a specific wavelength, atoms either reflect or do not reflect light, making their state visible in imaging.
    - This property allows us to determine whether they represent a 0 or a 1 by taking pictures and analyzing their brightness.

Application Context

- Atoms are held in **optical tweezers**, and their states (light or dark) are measured using imaging detectors.
- The key requirement in this process:
    - Capture an image of the array of atoms.
    - Identify the states (light or dark) as quickly as possible to ensure precise feedback.

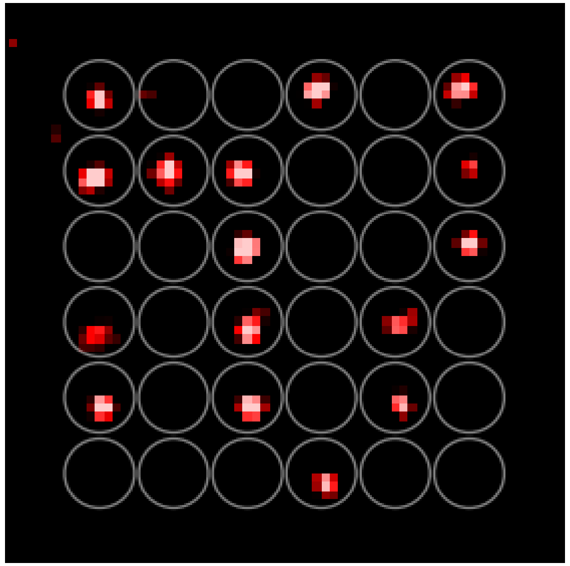


Typical fluorescence Imaging of single atoms:
- Need to collect tens of photons to clear camera noise
- Need to have a deep enough trap to tolerate heating or cool simultaneously
- Image durations (exposures): 10-100 ms
    - record is 500 us

Why Speed Matters

Fast Feedback is Critical in Quantum Systems

- Atoms' states are **unstable** and decay rapidly (e.g., within ~100 ms).
- Delays in feedback, even as little as **10 ms**, can result in a **10% loss** of quantum states.
- Speed is essential to maintain coherence and correct errors in real-time.



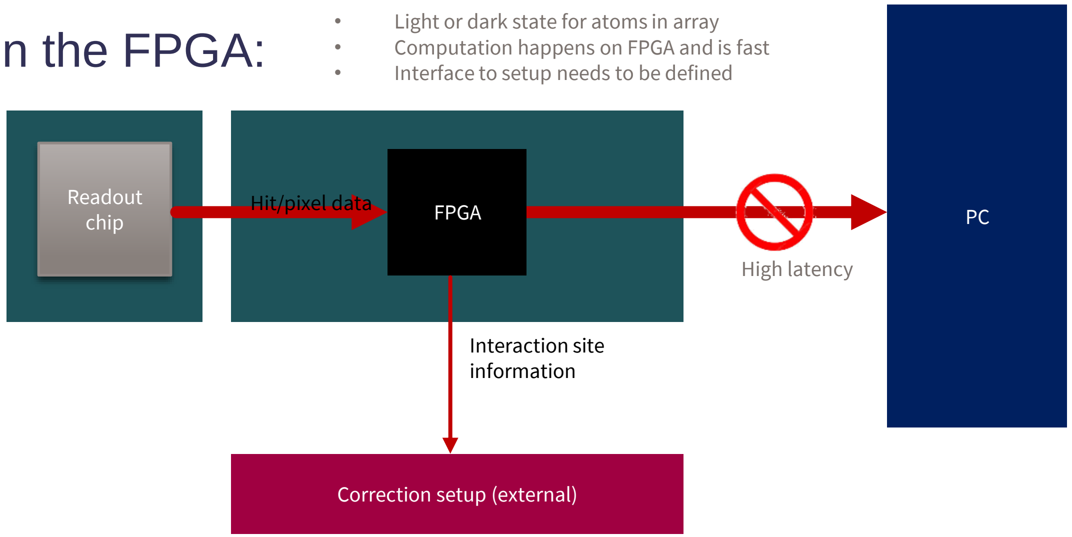
Current Workflow Challenges

- Standard systems involve these steps:
  1. Take exposure (open/close shutter).
  2. Read out data from the detector.
  3. Transfer data to the control system.
- Typical readout involves transferring data from the detector chip to an FPGA, then to a PC for processing. This can introduce critical latency.

The Innovation of Rhea

What Rhea Does

- Rhea accelerates the feedback loop by enabling **ultrafast readout and processing** of the quantum system states.
- The detector computes the **region of interest (ROI)** directly on the FPGA:
  - Determines whether each region represents a **light** or **dark** state.
  - Immediately transfers this information to the quantum control system.



•Key Innovation

- Eliminates the need for data transfer to a PC for processing.
- Reduces latency by performing computations directly on the FPGA, ensuring near-instantaneous feedback.

Challenges and Uncertain Elements

Standardization Challenges

- There is no universal standard for transferring data from detectors to quantum control setups.
- Different quantum systems (e.g., ion traps, neutral atom processors) require unique configurations.

Latency and Data Rate

- Achieving low latency is challenging due to:
  - High photon rates overwhelming the system during exposure.
  - Balancing **data-driven mode** and **frame-based mode** to ensure optimal performance.
- Developing physical electronic connections that meet the speed and reliability requirements.

Technical Barriers

- The system must manage high data rates while maintaining precision.
- Integration with diverse quantum computing setups requires adaptable solutions.

Why Rhea is Needed

Problem Rhea Solves

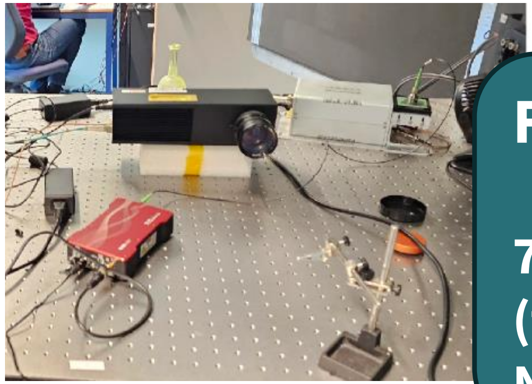
- Traditional systems face delays in transferring and processing data, which slows down real-time feedback.
- These delays lead to errors in quantum computations due to state decay.

Rhea's Solution

- Implements **low-latency processing** directly at the detector level.
- Provides immediate feedback to the quantum control system, enhancing error correction and system reliability.

A little Sneak Peek at our current project

Optical TPX4...(in progress)



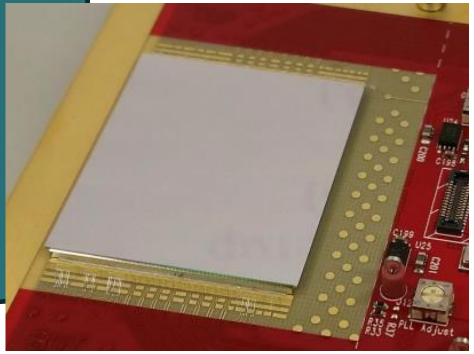
First optical TPX4 signals

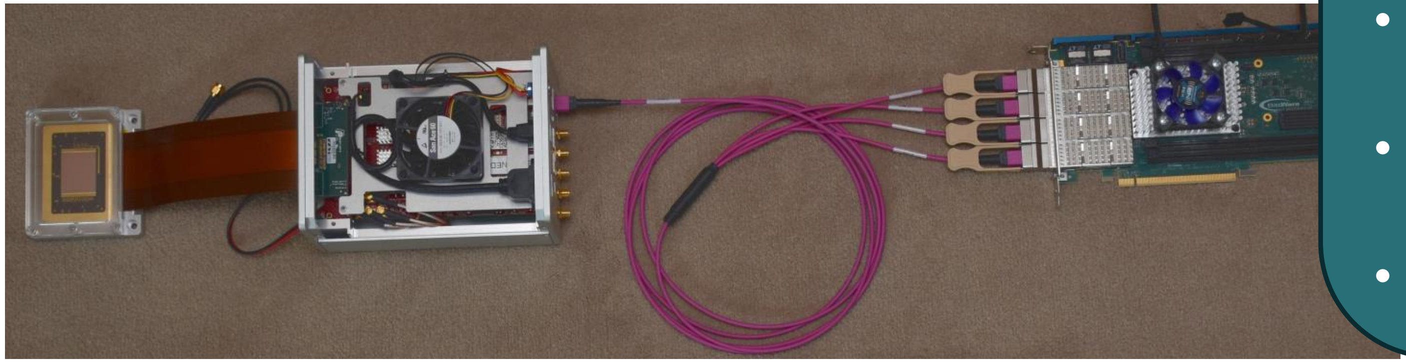
70 ps pulsed laser (thanks to Andrei Nomerotski)

The max rate is 1.2 Ghits/s.

195ps time bin

For experiments where High hit rate and large area detection system and much faster time-resolution is required





TPX4 Full rate Data Pipeline

- **16 GWT links from TPX4 chip (2.56 Gb/s for now, 5.12 Gb/s later)**
- **2 x FireFly → 16 fibers on MPO → 4 x QSFP → BittWare card**
- **16 receivers → packet builders → Wupper interface → memory**
- **Serval: merge streams → sort → split**

Technical Challenges in Development

Non-Technical Challenges in Development

- Securing long-term R&D funding.
- Aligning R&D expenses with scalability.
- Managing academic collaborations alongside industrial schedules. (UvA)
- Bridging the talent gap in quantum expertise.
- Ensuring access to specialized materials and manufacturing techniques.
- Identify companies for integration into the quantum industry sector.
- Transitioning from academia-focused sales to targeting the broader industry in the quantum domain.
- Identifying what appeals to a larger market in the quantum sector.
- Developing strategies for effective networking within the industry.

ASI Effort's in Quantum Domain

Rhea Project Collaboration
Partnering with the University of Amsterdam (UvA) to advance quantum research.

Quantum Delta NL Grant
Proud recipients of this prestigious grant to support groundbreaking quantum initiatives.

Active Collaborations with QBN
Strengthening ties with the Quantum Business Network to drive innovation and ecosystem development.

Upcoming QBN Event
Hosting the next Quantum Business Network event in Q4 2025.

Let's collaborate to push the boundaries of quantum technology!