Optical camera with Timepix4 readout for single photon imaging

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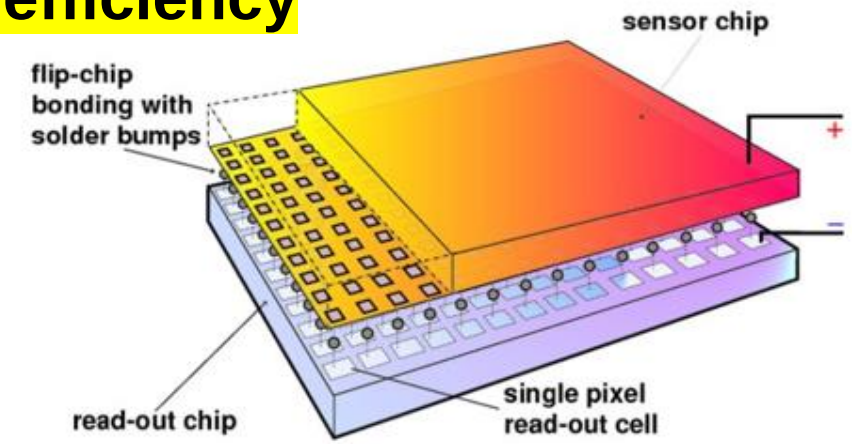
IWORID 2026

Hybrid pixel detectors

- Have roots in R&D for LEP/LHC vertex detectors
- Decouple readout chip and sensor
  - Optimize technologies for chip and sensor separately
  - Use same readout ➡ **swap sensors**; versatile approach for x-rays (Si, CZT)
- **Per pixel timing + charge + spatial information**
- We use **optical sensors with high quantum efficiency**

M. Fisher-Levine and A. Nomerotski 2016 JINST 11 C03016

Google scholar 115 citations



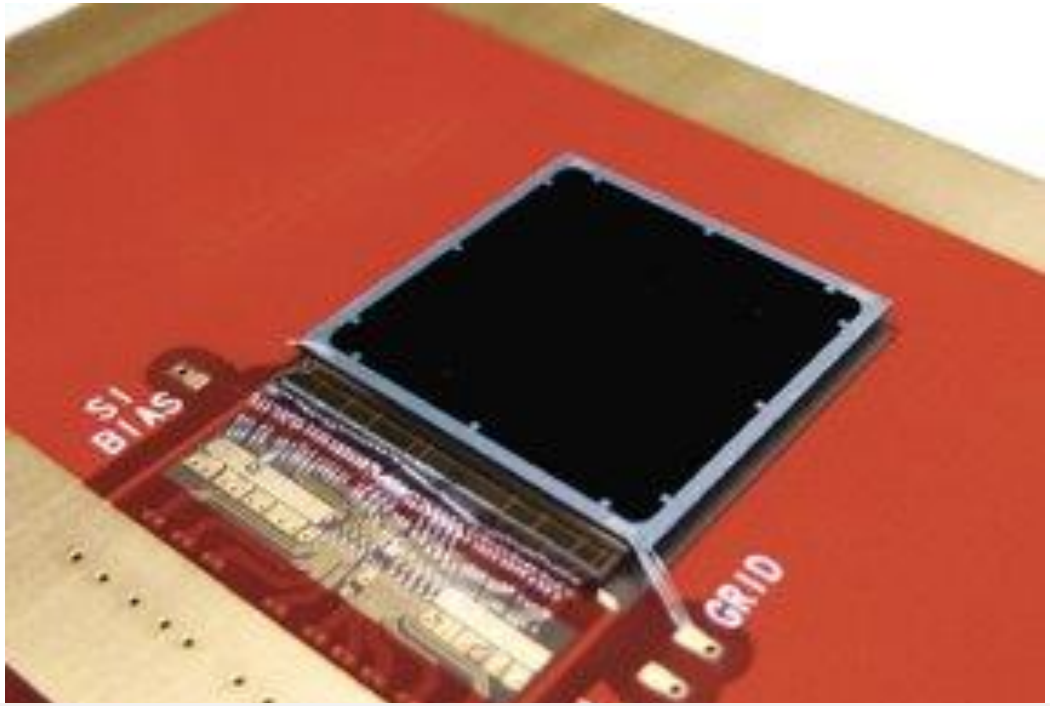
Lukas Tlustos and Erik H. M. Heijne, Performance and limitations of high granularity single photon processing X-ray imaging detectors, in CERN proceedings (2005)

Hybrid optical cameras

- Based on Timepix3 and Timepix4 chips by Medipix/Timepix 3/4 collaborations
- Data-driven measurement of Time of Arrival (**ToA**) and Time over Threshold (**ToT**)

Camera = sensor + ASIC + readout

- Optical sensor with 90% QE for 400-950 nm
- Timepix3
  - **256x256 pixels**, 55 µm pixel size
  - **1.56 ns** time bin
  - **80** Mpx/s
- Timepix4
  - **448×512 pixels**, 55 µm pixel size
  - **0.195 ns** time bin
  - **1.2** Gpx/s
- SPIDR readout



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 Tpx3Cam

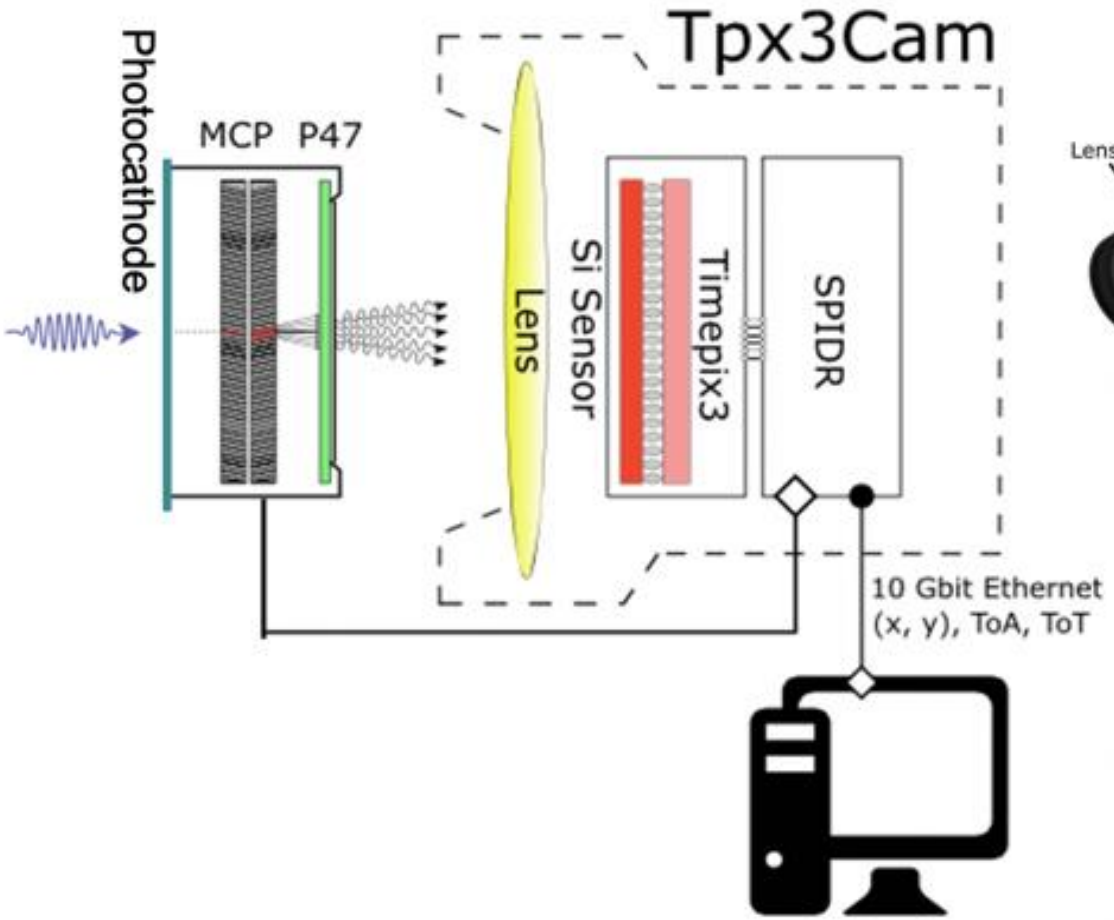
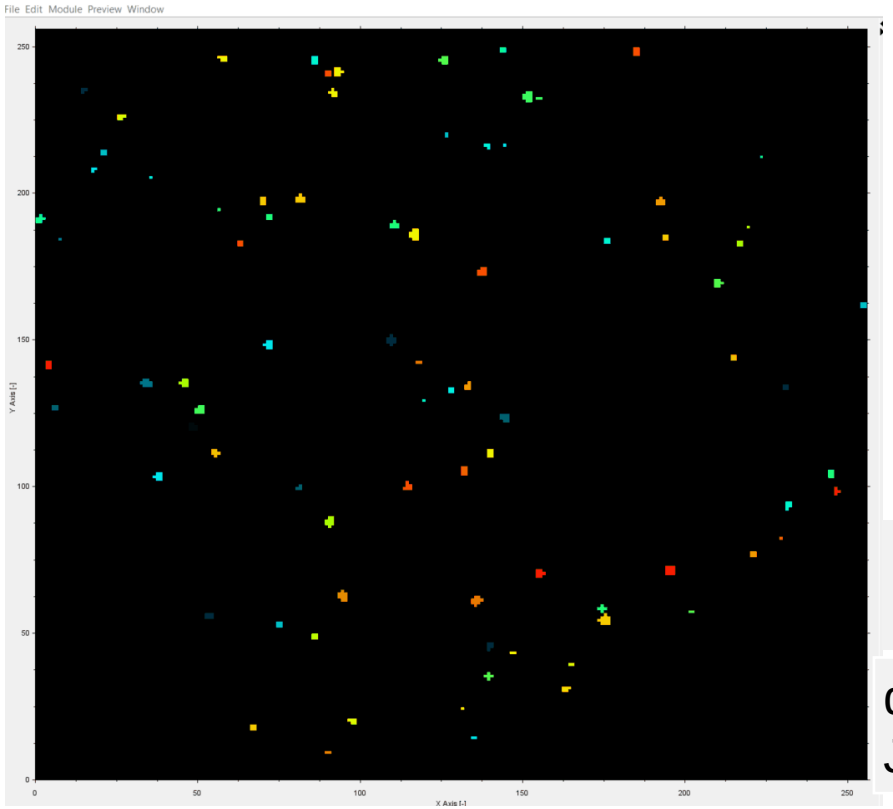


Image intensifier (Photonis PP0360EG)

Cricket@

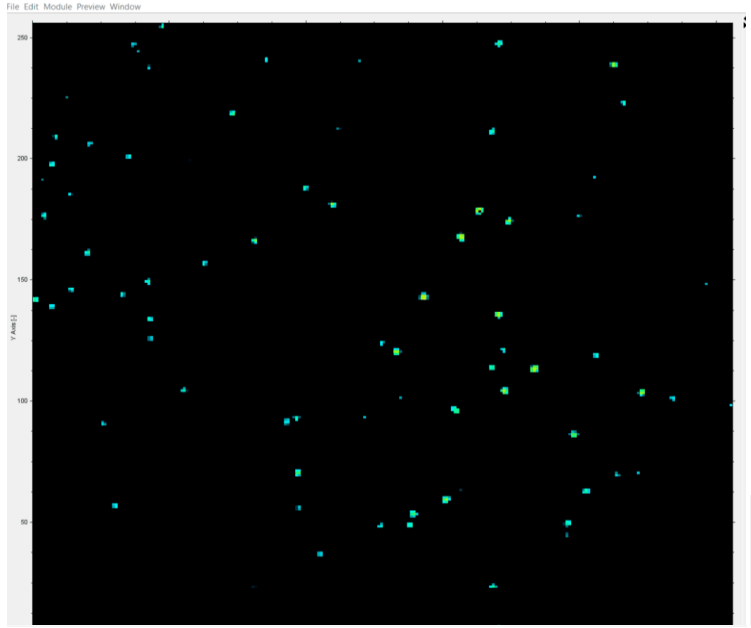
Single photons in Tpx3Cam

- 1 ms slice of data
- 1.5ns time-stamping

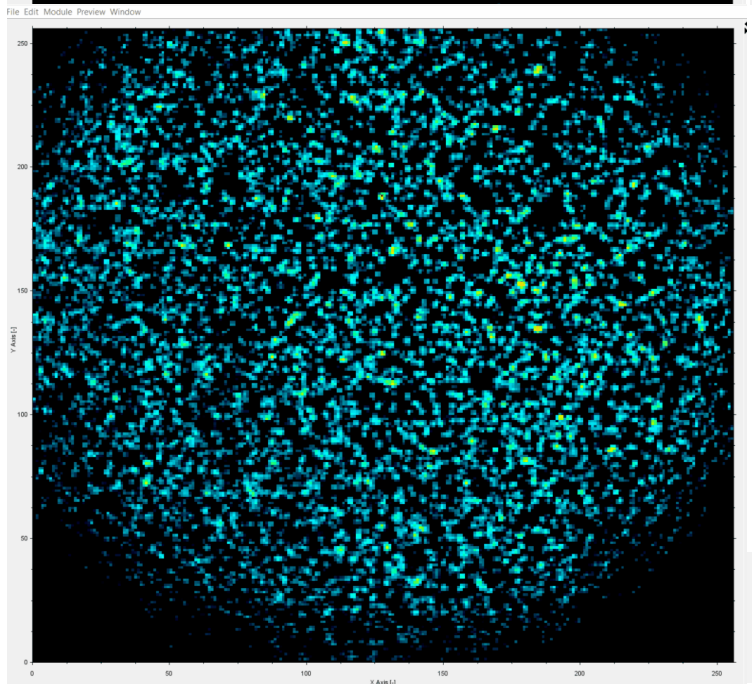


TOA

data taken by
J. Long (ASI)



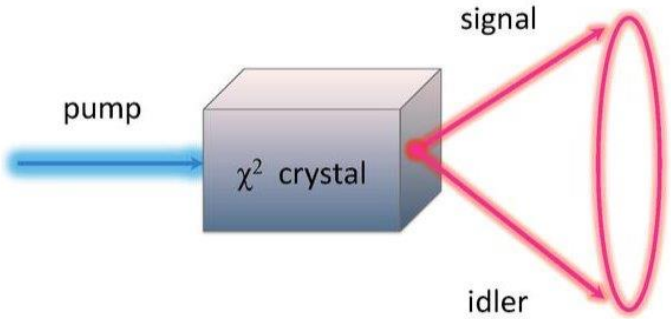
TOT

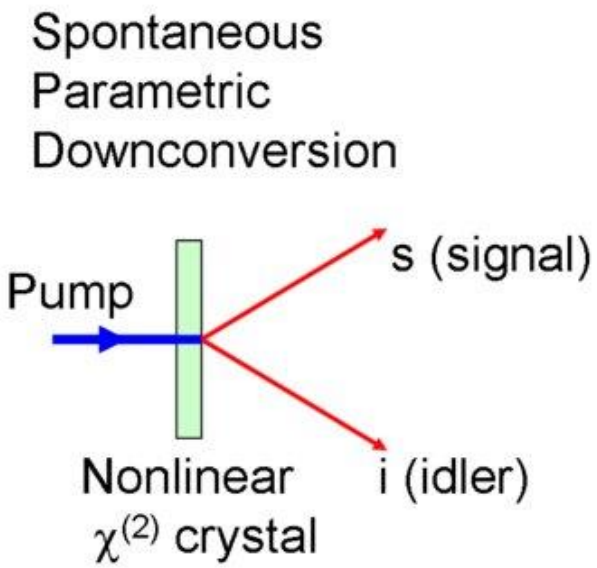


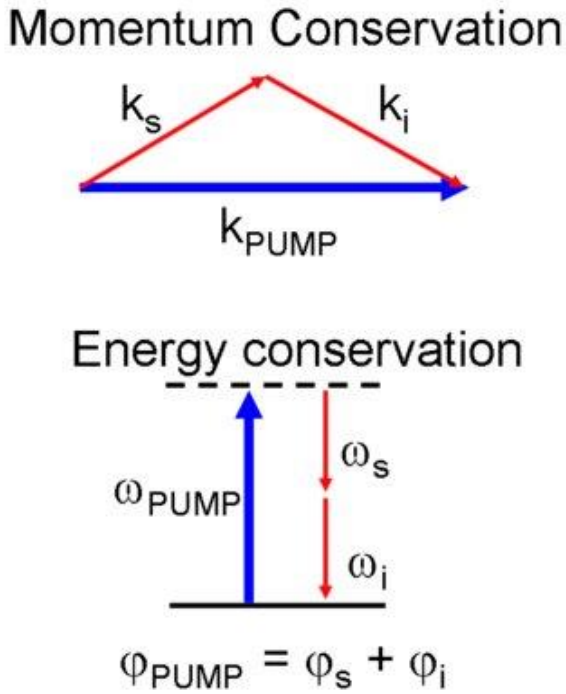
TOT

Quantum application

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







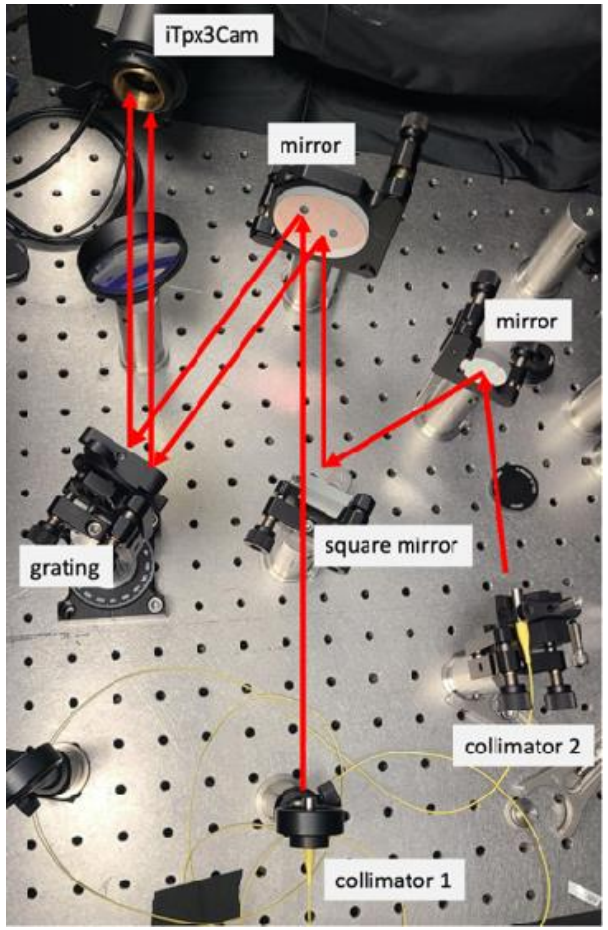
- Produce two photons correlated (sometimes entangled) in
  1. Time
  2. Position
  3. Energy

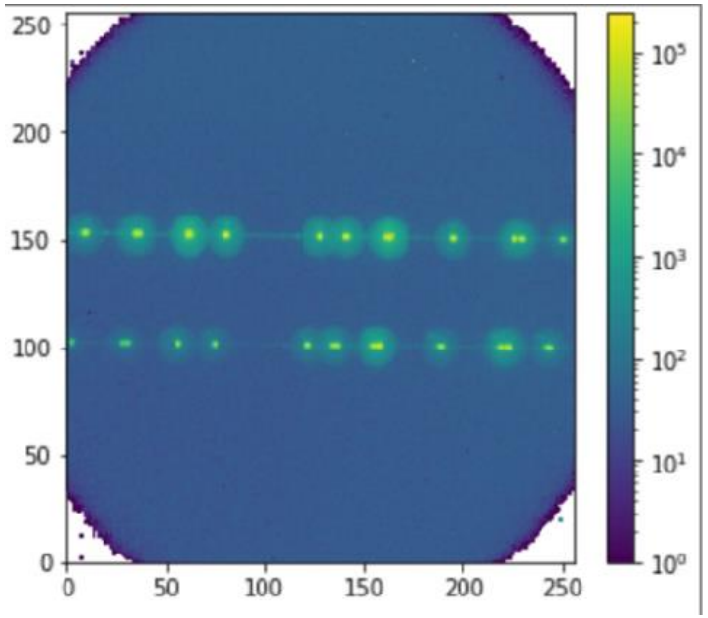
en.wikipedia.org/wiki/Spontaneous_parametric_down-conversion

Spectrometer

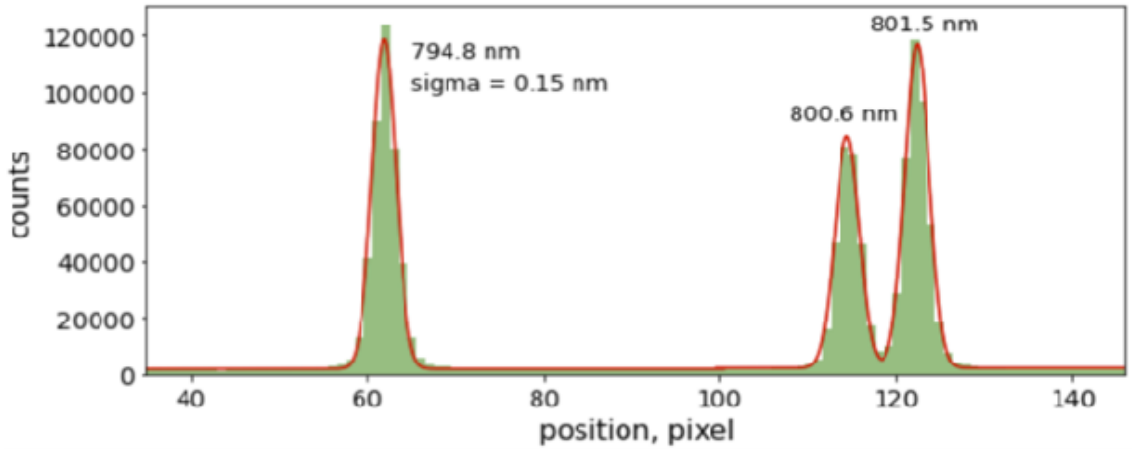
- Two beams of photons ➡ diffraction grating
- Based on intensified Tpx3Cam, ns time resolution

QR publication





Ar spectrum

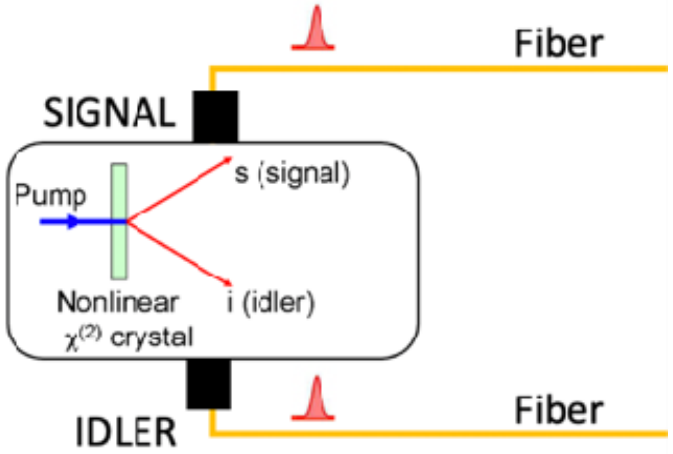


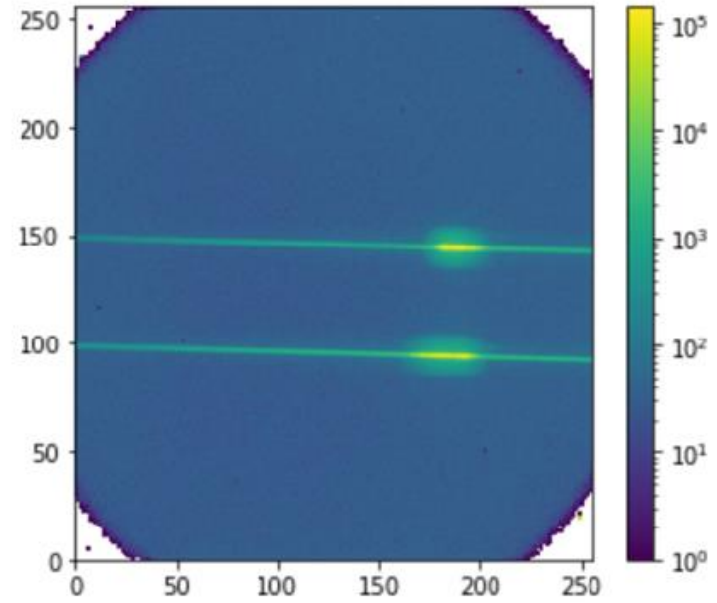
spectral resolution for Ar lines ~0.15 nm

A.Nomerotski et al. Intensified Tpx3Cam, a fast data-driven optical camera with nanosecond timing resolution for single photon detection in quantum applications, https://iopscience.iop.org/article/10.1088/1748-0221/18/01/C01023, published in JINST

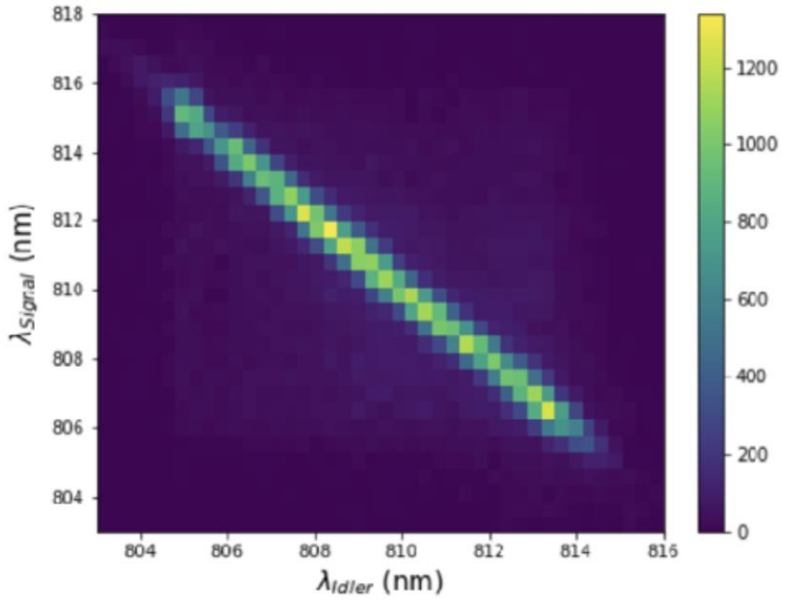
SPDC source in spectrometer

- Both signal and idler have 810 nm
- No filter was used
- Similar idea as before

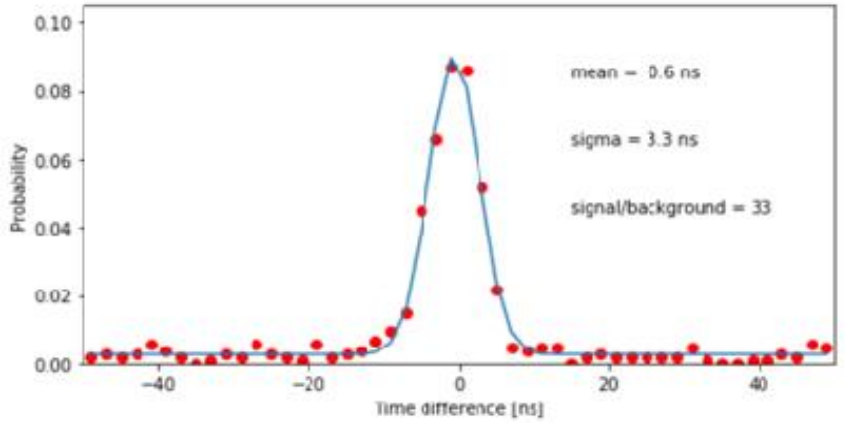




wavelength anti-correlation for photon pairs



time coincidences



B Farella, G Medwig, R A Abrahao, A Nomerotski, *AIP Advances* 14, 045034 (2024) doi.org/10.1063/5.0168423

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Publications

All 3DED VMI & Mass Spectrometry Quantum Science FLIM/PLIM U-EELS UEM 4D-STEM LEEM EBSD XRD XRM SAXS XPCS Neutron Science
Timepix4 Miscellaneous Time Projection Chamber Dosimetry VMI & Mass Spectrometry Software Time Projection Chamber Timepix 4

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Category	Publication	Author	Link
Quantum Science	Fast quantum ghost imaging with a single-photon-sensitive time-stamping camera	A. Mavian et al. Optica Publishing (2025)	
Quantum Science	Quantum-Enhanced Beam Tracking Surpassing the Heisenberg Uncertainty Limit	Y. Zhang et al. APS Physical (2025)	
Quantum Science	High-dimensional programmable photonic circuits with structured media	M. G Ammendola et al. ArXi	
Quantum Science	Accidental coincidences in camera-based high-dimensional entanglement certification	R. Guitter et al. arXiv (2025)	
Quantum Science	Biphoton state reconstruction via phase retrieval methods	N.Dehghan et al. Optica Pu	
Quantum Science	Engineering quantum states from a spatially structured quantum eraser.	Carlo Schiano et al. Sci. Ad	
Quantum Science	Background resilient quantitative phase microscopy using entangled photons	Yingwen Zhang et al. arXiv	
Quantum Science	Quantum light-field microscopy for volumetric imaging with extreme depth of field	Yingwen Zhang et al. Phys.	
Quantum Science	Nonlocal transfer of high-dimensional unitary operations	Dilip Paneru et al. arXiv (20	
Quantum Science	Individual-Ion Addressing and Readout in a Penning Trap	Brian J. McMahon et al. AP Journals (2024)	
Quantum Science	Generation of the Complete Bell Basis via Hong-Ou-Mandel Interference	Xiaoqin Gao et al. arXiv (20	
Quantum Science	Intensified Tpx3Cam, a fast data-driven optical camera with nanosecond timing resolution for single photon detection in quantum applications	A. Nomerotski et al. IOP Sc	
Quantum Science	Characterisation of a single photon event camera for quantum imaging	V. Vidyapin et al. Nature (2	
Quantum Science	Snapshot hyperspectral imaging with quantum correlated photons	Y.Zhang et al. Optica (2023)	
Quantum Science	Study of afterpulsing in optical image intensifiers	R Mahon et al. arXiv (2023)	
Quantum Science	Spectral characterization of a SPDC source with a fast broadband spectrometer	B Farella et al. arXiv (2023)	
Quantum Science	Experimental Work Towards an Individually-Addressed-Ion Penning Trap Quantum Simulator	B McMahon et al. Bulletin Physical Society (2023)	
Quantum Science	Full spatial characterization of entangled structured photons		
Quantum Science	Full spatial characterization of entangled structured photons		
Quantum Science	Stability of 3D Optical Topologies and Reconstruction of Strongly Correlated Bi-photon States	SF Dehghan Manshadi et al. Uottawa (2023)	
Quantum Science	Interferometric imaging of amplitude and phase of spatial biphoton states	D Zia et al. Nature Photonics (2023)	
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Quantum Science	Efficient site-resolved imaging and spin-state detection in dynamic two-dimensional ion crystals	RN Wolf et al. arXiv (2023)	
Quantum Science	Micromotion-synchronized pulsed Doppler cooling of trapped ions	A Kato et al. Physical Review A (2023)	
Time Projection Chamber	ARIADNE+ Large Scale demonstration of fast optical readout	A Lowe et al. MDPI Physical Sciences Forun (2023)	
Quantum Science	Towards Quantum Telescopes: Demonstration of a Two-Photon Interferometer for Quantum-Assisted Astronomy	J Crawford et al. arXiv (2023)	
Quantum Science	Quantum correlation light-field microscope with extreme depth of field	Y. Zhang et al. Arxiv. (2022)	
Quantum Science	Reconfigurable phase contrast microscopy with correlated photon pairs	H. Hodgson et al. AIP Publishing (2022)	
Quantum Science	High-speed imaging of spatiotemporal correlations in Hong-Ou-Mandel interference	X Gao et al. Optica Publishing Group (2022)	
Quantum Science	Observation of Nonclassical Photon Statistics in Single-Bubble Sonoluminescence	M. Rezaee et al. Arvix (2022)	
Quantum Science	Ray tracing with quantum correlated photons to image a three-dimensional scene	Y. Zhang et al. Phys. Rev. A (2022)	
Quantum Science	Quantum-Assisted Optical Interferometers: Instrument Requirements	A. Nomerotski et al. Optical and Infrared Interferometry and Imaging VII (2022)	
Quantum Science	Ray tracing with quantum correlated photons to image a three-dimensional scene	Y Zhang et al. Physical Review A (2022)	
Quantum Science	Trapping and cooling two-dimensional crystals of barium ions	A Kato et al. ProQuest (2022)	
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Quantum Science	Direct observation of ion micromotion in a linear Paul trap	L. A. Zhukas et al. Physical Review A (2021)	
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Quantum Science	Fast imaging of single photons in quantum assisted optical interferometers	A Nomerotski et al arXiv (2021)	
Quantum Science	Time-stamping and counting of single photons using fast camera	A Nomerotski et al. IEEE Xplore (2021)	
Quantum Science	Quantum-Assisted Optical Interferometry	A Parsells, J Schiff et al. Quantastro (2021)	
Quantum Science	Novel Methods in Trapped-Ion Quantum Computing: Single-Photon-Sensitive Time-Resolving Camera, Sympathetic Cooling, and Qutrit	L Zhukas et al. ProQuest (2021)	
Quantum Science	Direct observation of ion micromotion in a linear Paul trap	LA Zhukas et al. Physical Review A (2021)	
Quantum Science	Multivariate discrimination in quantum target detection	P. Svihra et al. Applied Physics Letters (2020)	
Quantum Science	Fast camera spatial characterization of photonic polarization entanglement	C. Ianzano et al. Scientific Reports (2020)	
Quantum Science	Counting of Hong-Ou-Mandel Bunched Optical Photons Using a Fast Pixel Camera	A. Nomerotski et al. Sensors (2020)	
Quantum Science	Multidimensional quantum-enhanced target detection via spectrotemporal-correlation measurements	Y. Zhang et al. Physical Review A (2020)	
Quantum Science	Spatial and temporal characterization of polarization entanglement	A Nomerotski et al Journal of Quantum (2020)	
Quantum Science	Imaging and time stamping of photons with nanosecond resolution in Timepix based optical cameras	A. Nomerotski. Nuclear Instruments and Methods in Physics Research (2019)	
Quantum Science	Multidimensional quantum illumination via direct measurement of spectro-temporal correlations	Y. Zhang et al. arXiv (2019)	
Quantum Science	Spatial characterization of photonic polarization entanglement using a Tpx3Cam intensified fast-camera	C Ianzano et al. arXiv (2018)	
Quantum Science	Characterization of TimepixCam, a fast imager for the time-stamping of optical photons	A. Nomerotski et al. Journal of Instrumentation (2017)	
Quantum Science	TimepixCam: a fast optical imager with time-stamping	M. Fisher-Levine and A. Nomerotski. Journal of Instrumentation (2016)	

55 papers with Tpx3Cam on quantum topics!

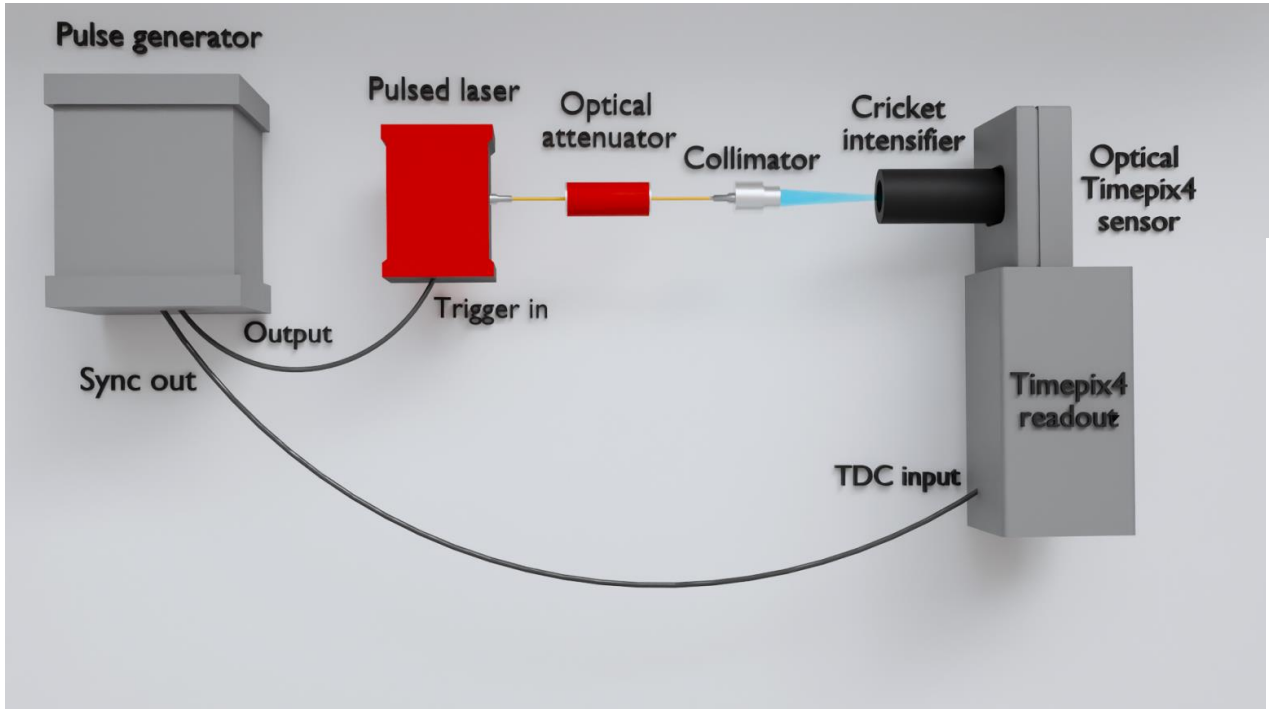
AMSTERDAM SCIENTIFIC INSTRUMENTS

Optical Tpx4Cam

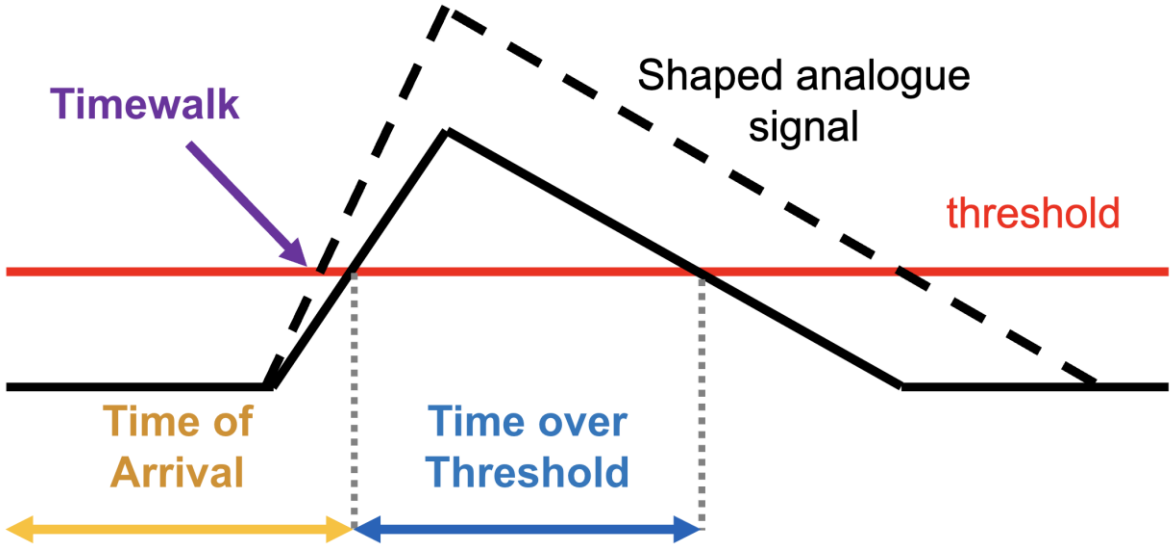
Tpx4Cam overview

- Compared to Tpx3Cam
  - Time binning improvement 1.56 ns → **0.195 ns**
  - Expected improvement in timing resolution
- Current possible limitation: P47 intensifier rise time ~ 7 ns (also MCP, photocatode)
- Detector response dominates over TPX4 timing precision
- Purpose of this study: quantify the scintillator/intensifier limit on achievable time resolution

Intensified camera Tpx4Cam



- 450 nm pulsed laser with 90 ps width
- Attenuated to operate with single photons



https://iopscience.iop.org/article/10.1088/1748-0221/21/02/P02004

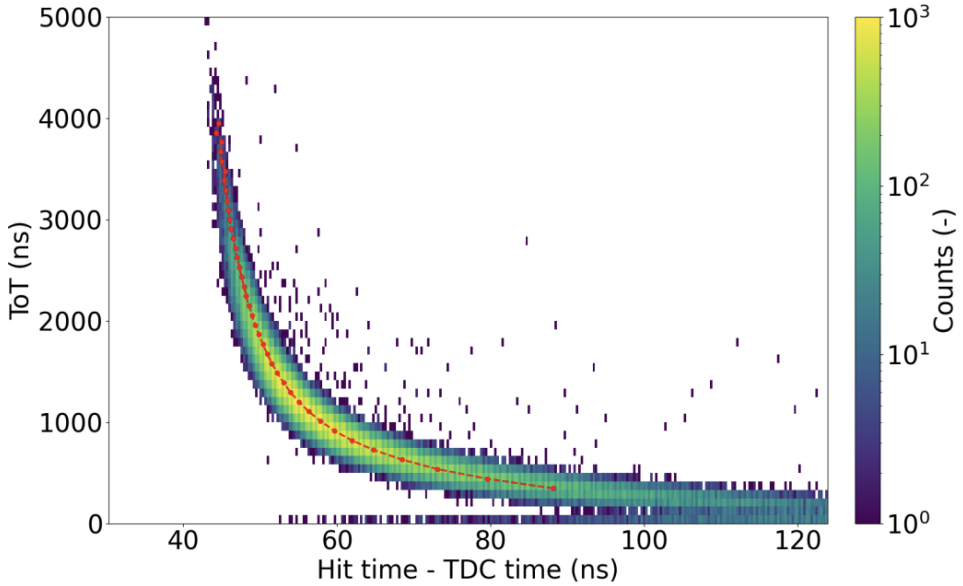
QR publication

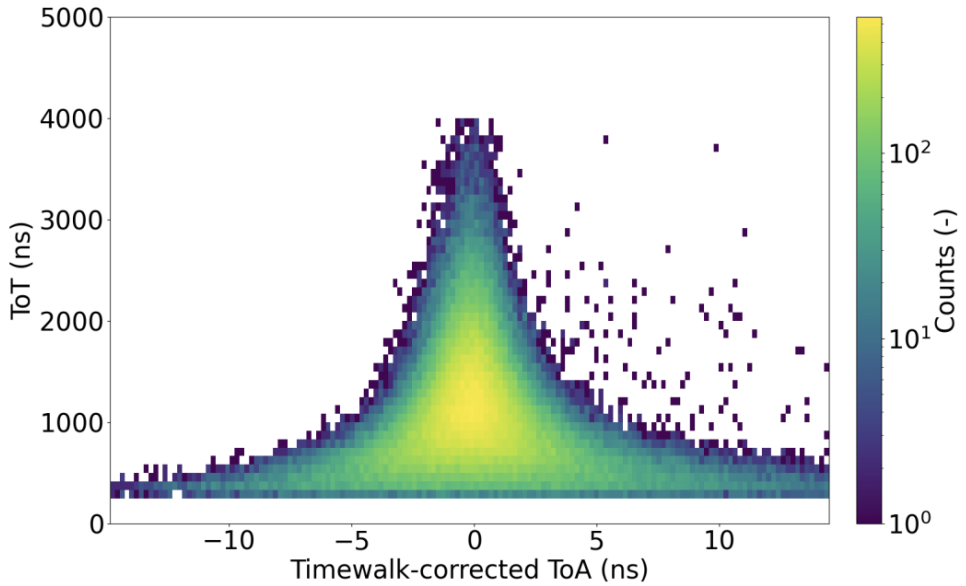
Timewalk correction

https://iopscience.iop.org/article/10.1088/1748-0221/21/02/P02004

- Dependence of timing resolution on signal amplitude
- Correction procedure:
  - Slice ToT axis
  - Fit a gaussian for each slice
  - Read off the mean values and subtract (per slice)

QR publication

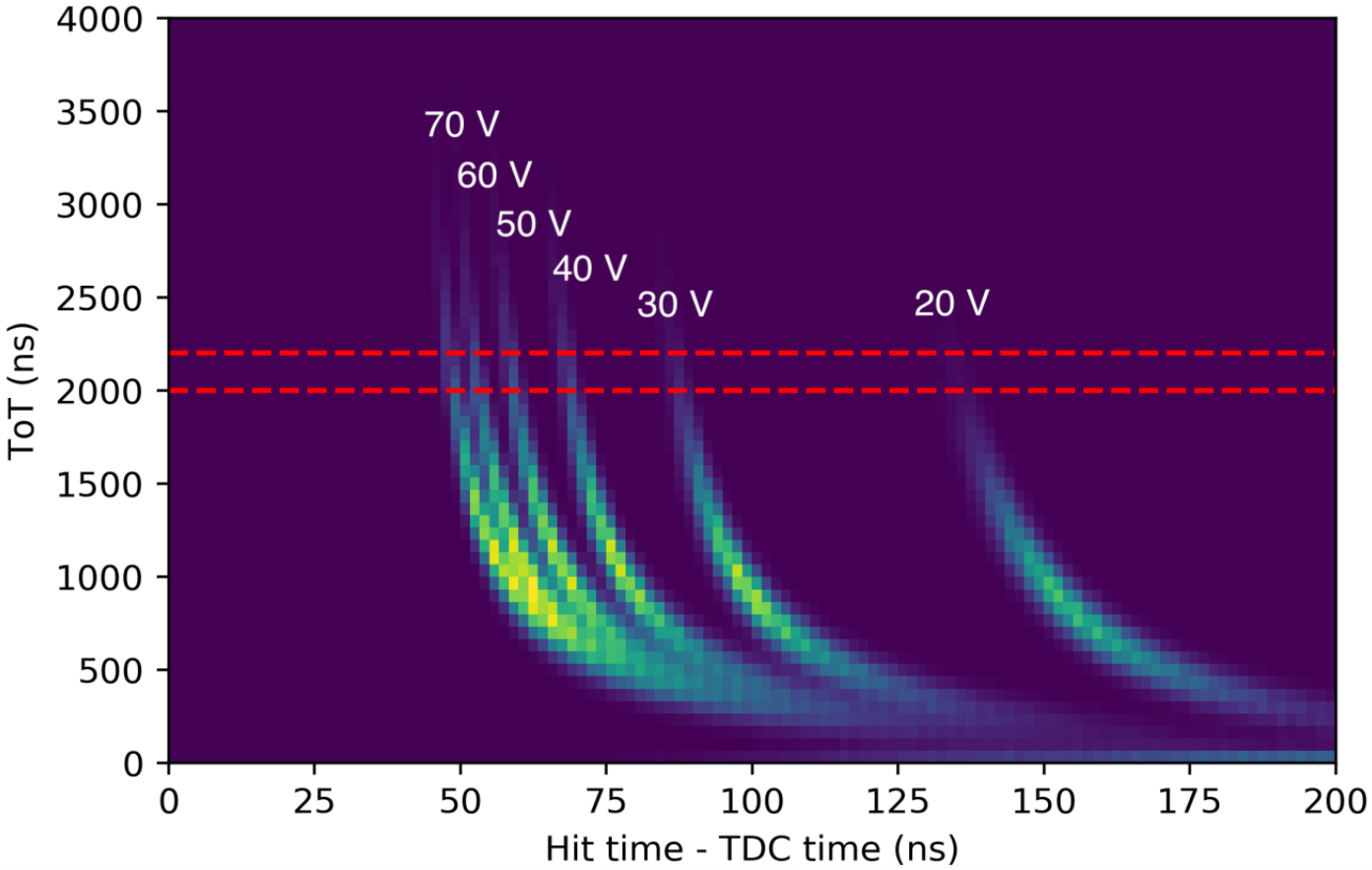




Intensified camera Tpx4Cam

- Drift in silicon ~20-30 ns depends on bias
- Best performance at higher bias and highest ToT

https://iopscience.iop.org/article/10.1088/1748-0221/21/02/P02004



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ToT vs resolution

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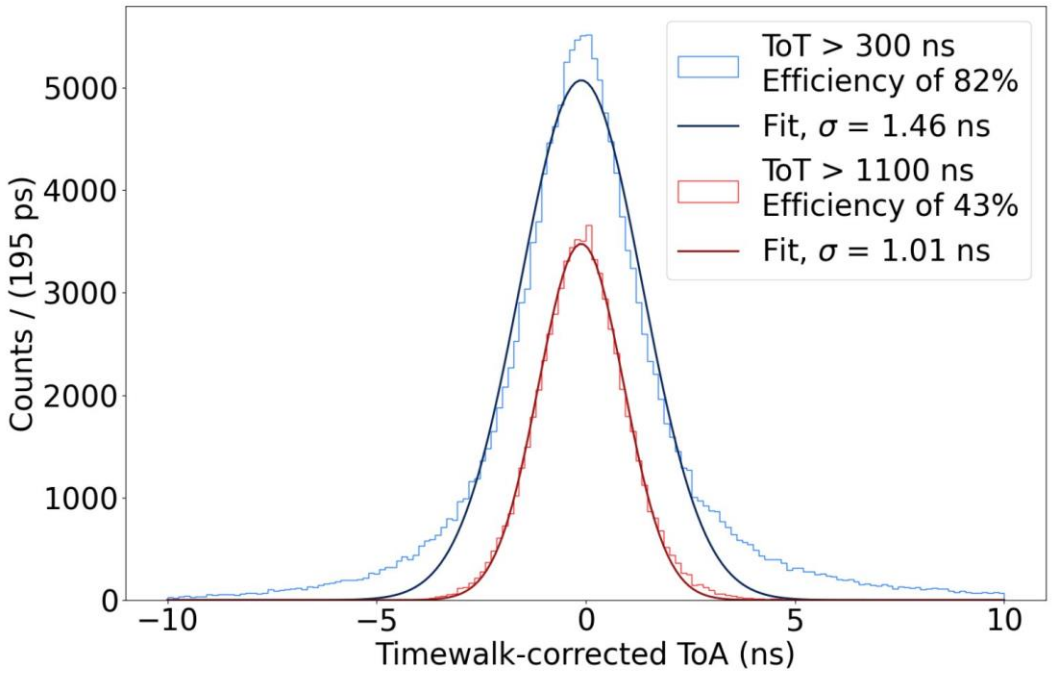
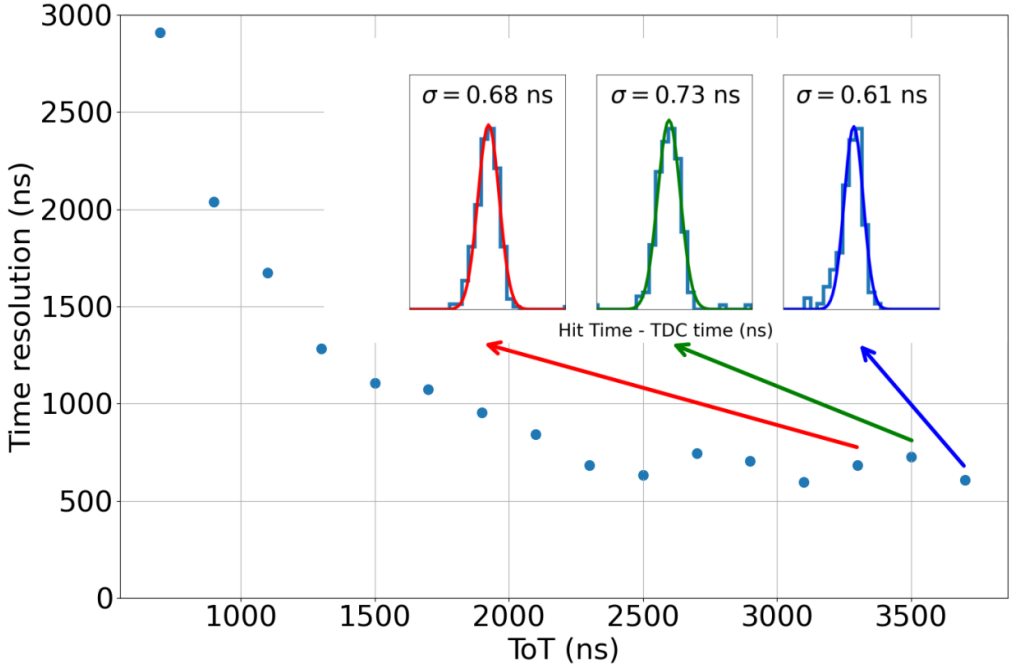




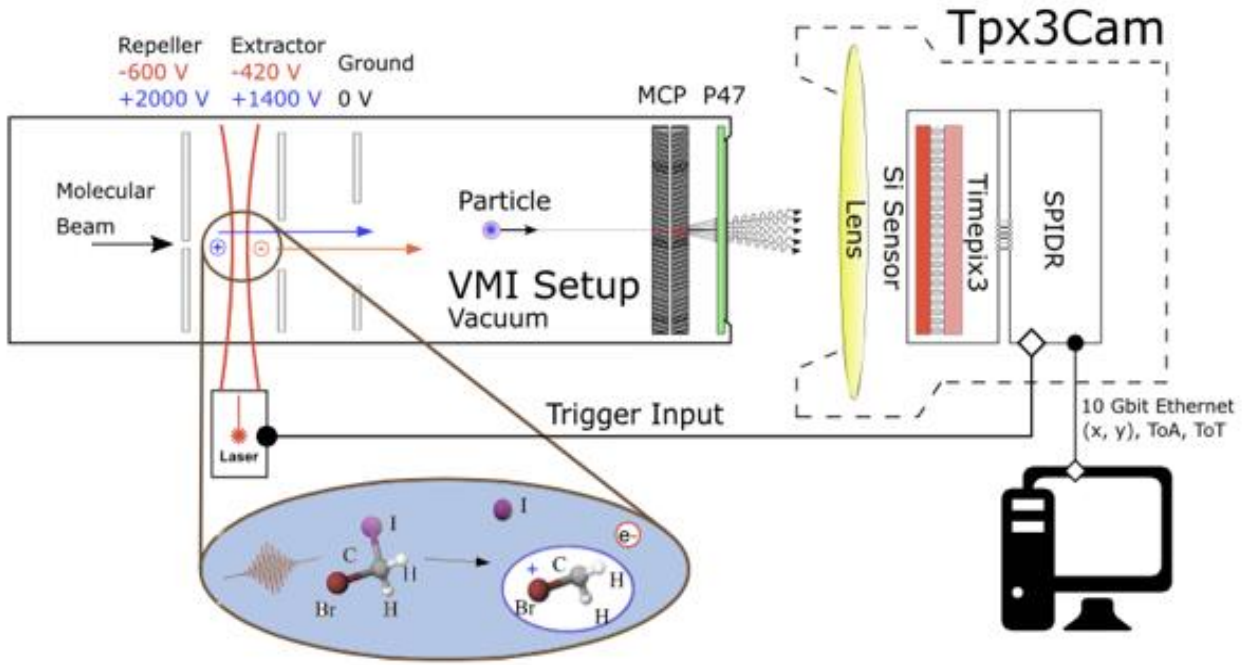
QR publication

- Best time resolution achieved 600 ps
- Depends on ToT, require high gain intensifier (reached saturation)

Ion Imaging

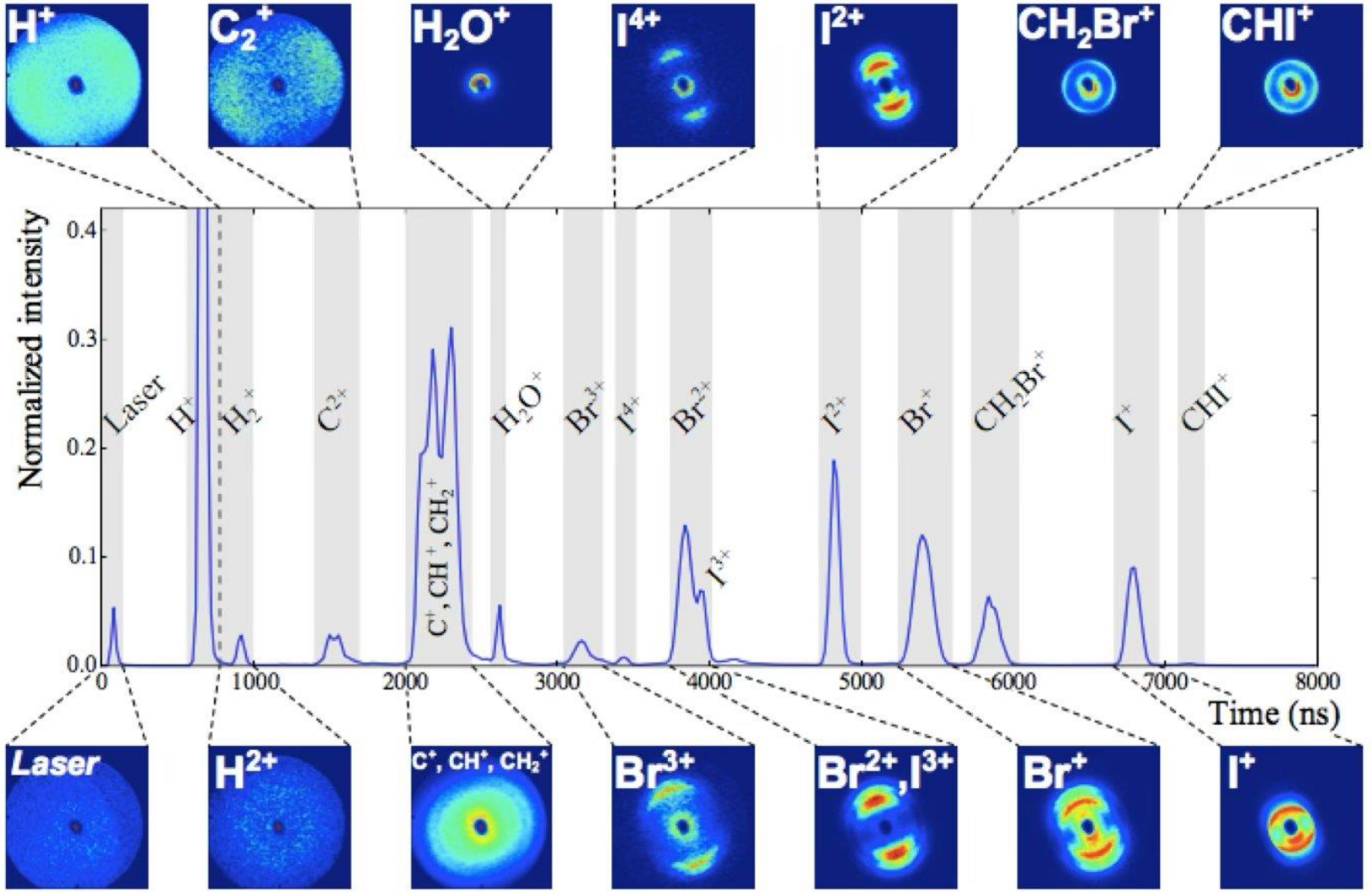
Imaging mass spectrometry

- Create ions
- Detect with MCP + P47
- MCP typically has **higher** gain
- Measure ToF
- **ToF ~ m/z**



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)

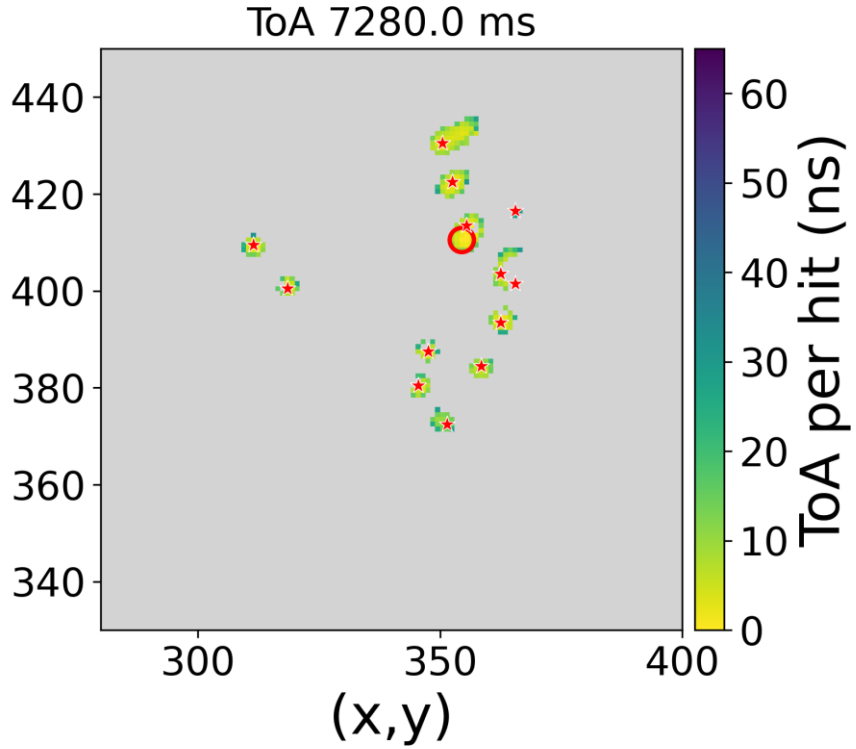
Google Scholar 153 citations

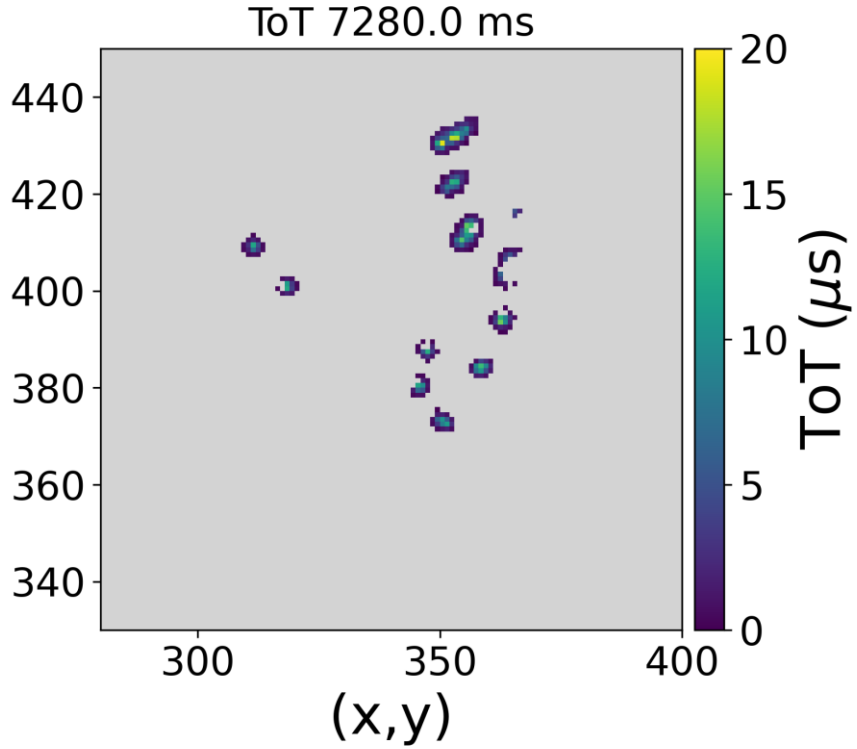


6. M. Fisher-Levine, R. Boll, F. Ziaee, C. Bomme, B. Erk, D. Rompotis, T. Marchenko, A. Nomerotski and D. Rolles: *'Time-Resolved Ion Imaging at Free-Electron Lasers Using TimepixCam'*. Journal of Synchrotron Radiation.(2018) 25 https://doi.org/10.1107/S16005775170

Secondary ion mass spectrometry (SIMS)

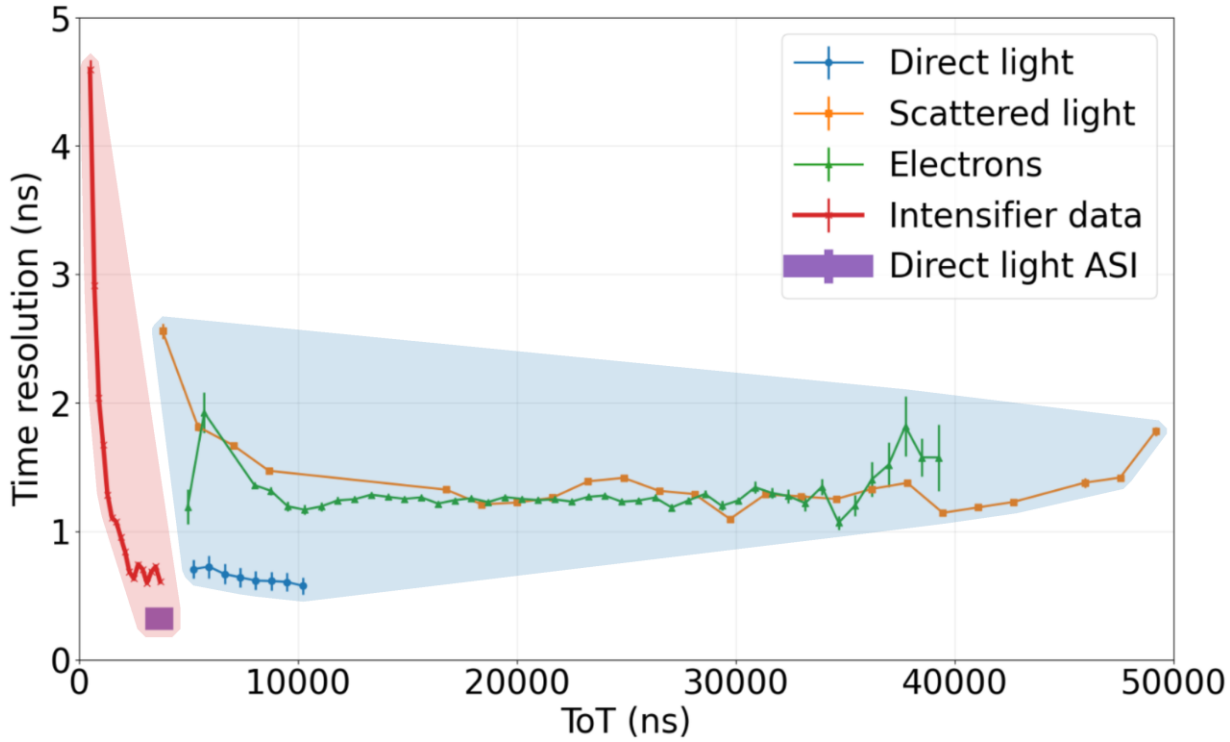
- **In+** ion imaging with MCP and P47
- For our studies used high ToT
- ToA is visualised relative to the first hit in an isolated ion shower





ToT vs resolution

- Data from 90 ps pulsed laser:
  - Measured with intensifier
- Pulsed fs laser data:
  - Scattered light
  - Electrons



- ToT ~ 50 µs, much larger than for intensifier data (red)
- BUT: Complex experimental setup with different contributions to timing resolution
- Currently 1.2 ns resolution, work in progress to understand contributions

Conclusion

- Tpx3Cam is widely used in multiple applications requiring time-resolved imaging of photons, electrons, ions, neutrons etc.

- First results from intensified Tpx4Cam with **600 ps resolution!**

- First Tpx4Cam results for ion imaging and mass spectrometry

- Further characterization performed

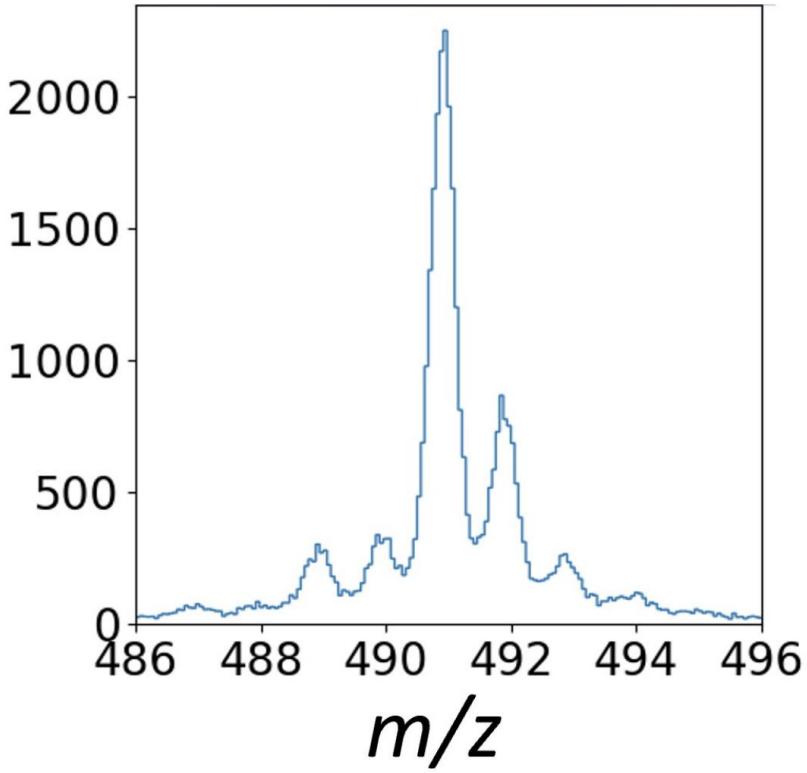
- Resolution limited by P47 scintillator in intensifier

Thank you for your attention!

CAPADS detectors

https://capads.fjfi.cvut.cz

Backup

Secondary ion mass spectrometry (SIMS)

- C_{60}^{+} fulleren gun bombarding target plate
- Secondary ions are kicked out from the sample
- They travel through ion optics, MCP (high gain!) and P47 scintillator
- No intensifier is used here
- Converted light gets projected onto the Tpx4Cam
- **ToF** ion separation **~ m/z**
- in SIMS z=+1, so mass is basically ToF