TEMPUS: a Timepix4-based detector system for Photon Science

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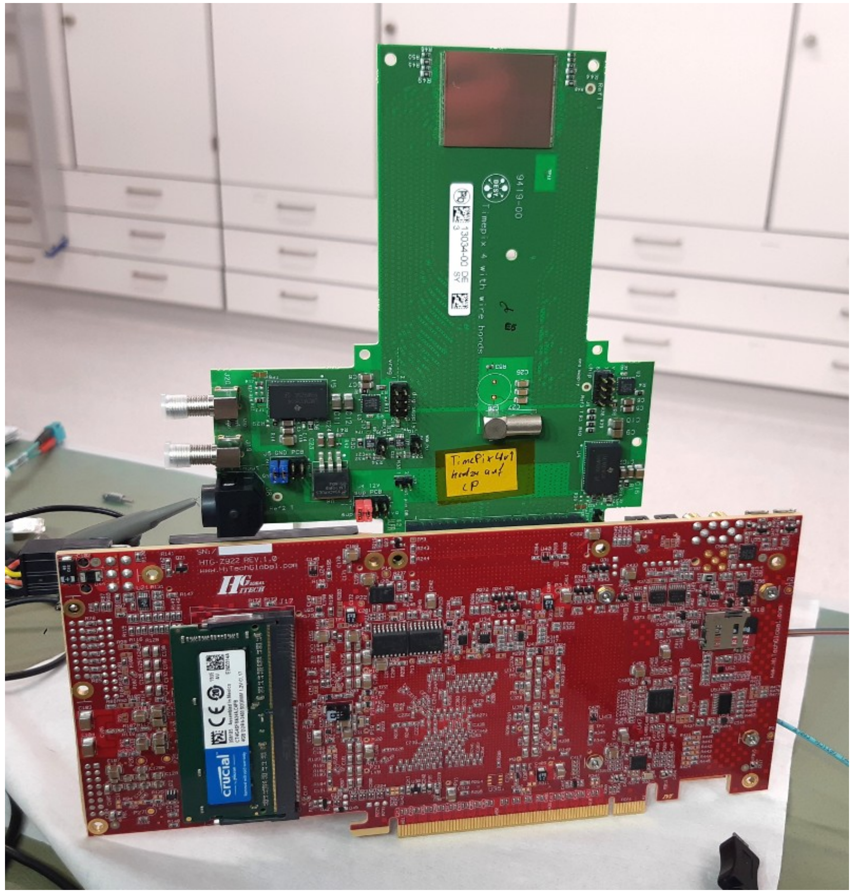


HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

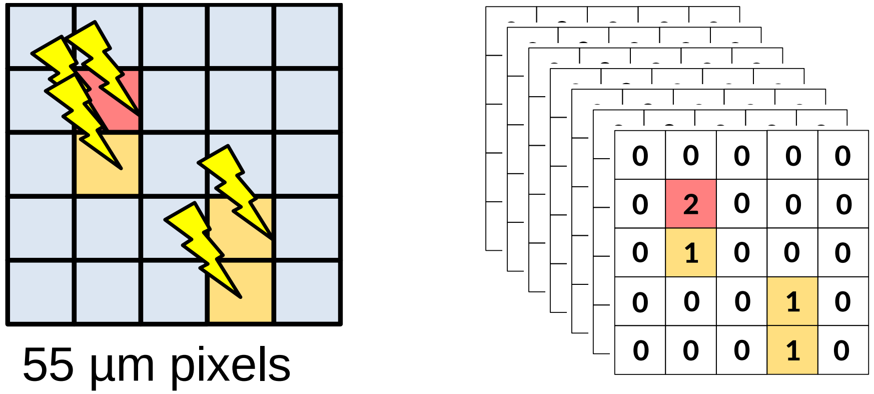
Timepix4 readout chip – key features

> Developed by CERN, Nikhef and IFAE on behalf of Medipix4 collaboration – TSMC 65nm
  - Timepix4v2 received from foundry in Sept 2021

Photon counting and frame readout (like Medipix3)

Detector

Frame readout



55 µm pixels

- 40 kHz frame rate CRW (8 bit depth)
- ~ 4x10^6 counts/pixel/s

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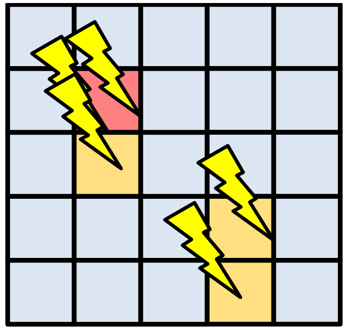

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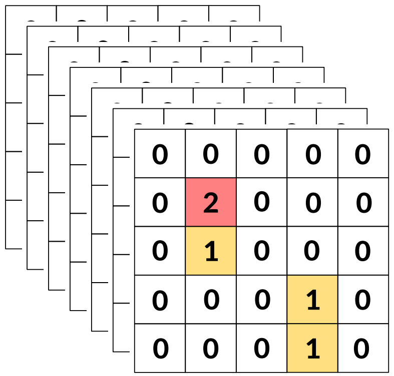

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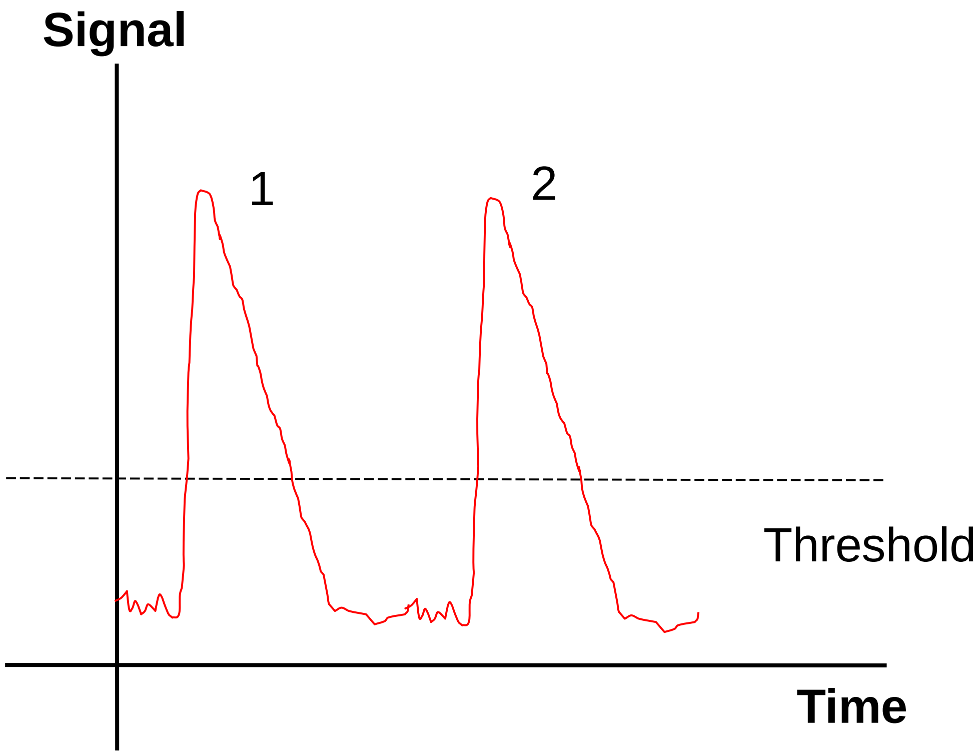

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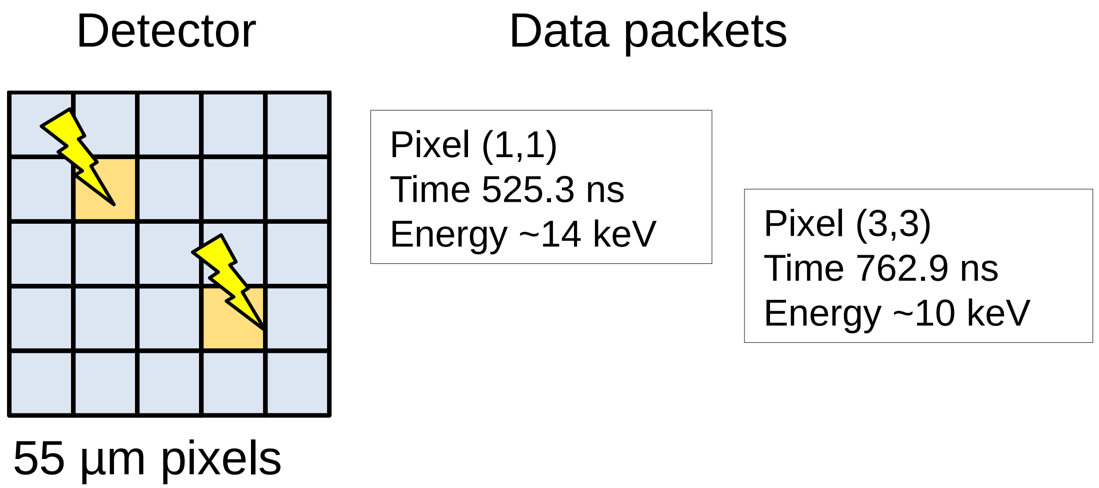
Time-stamping and event-by-event readout (like Timepix3)



- Event rate: ~10^9 events/s in 512 x 450 pixel chip
- Up to 150 ps RMS time resolution (sensor dependent)
- ~ 2 keV energy resolution

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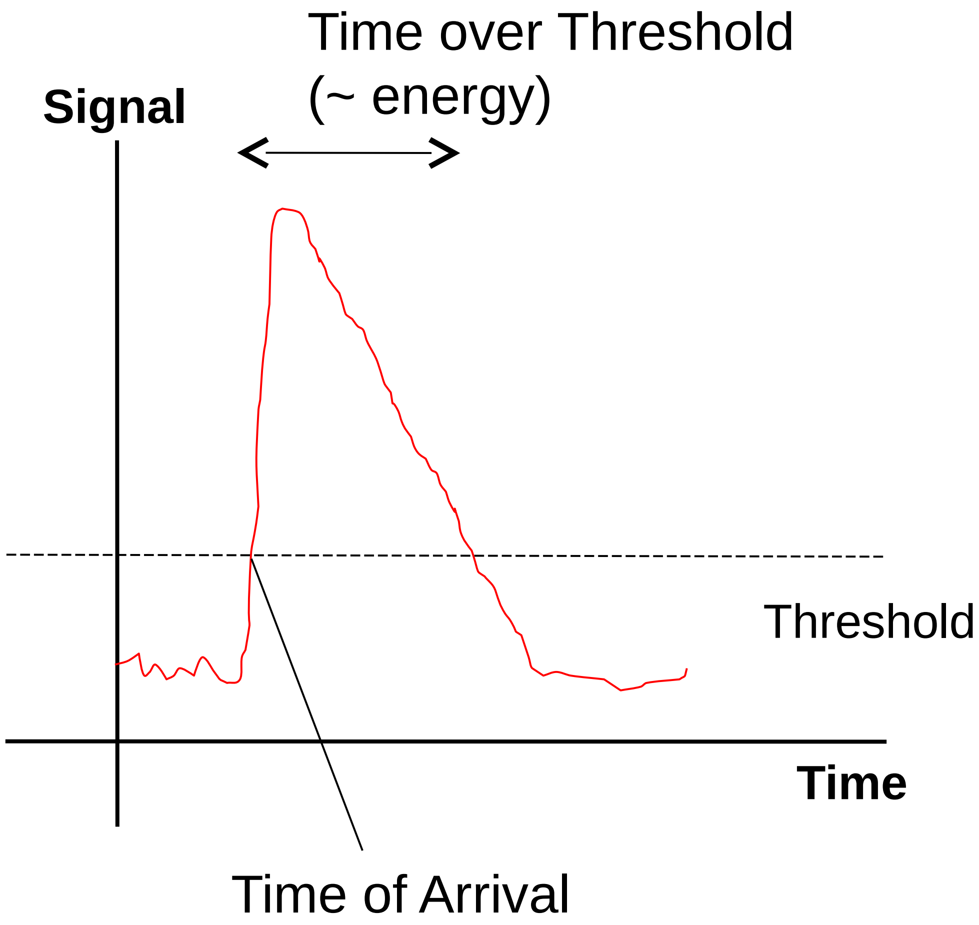

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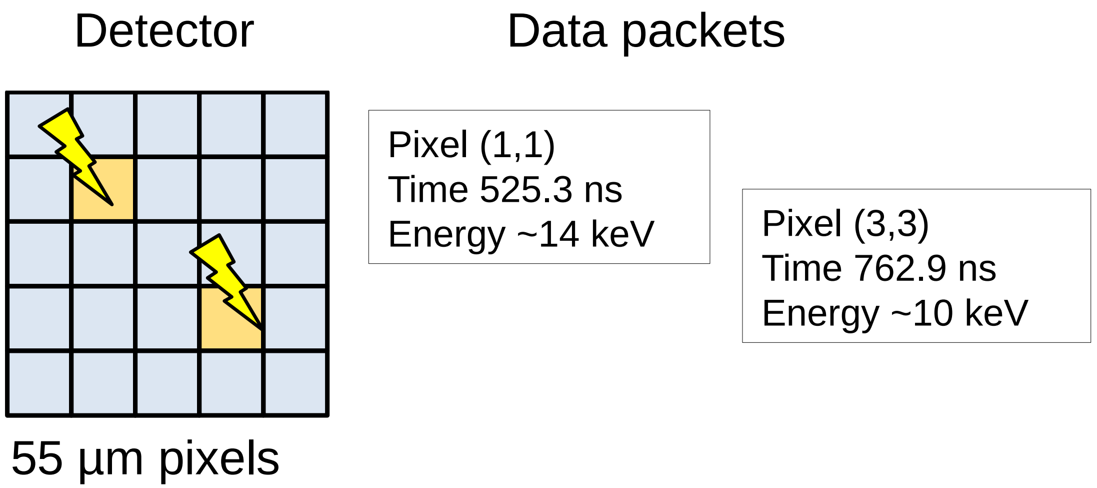

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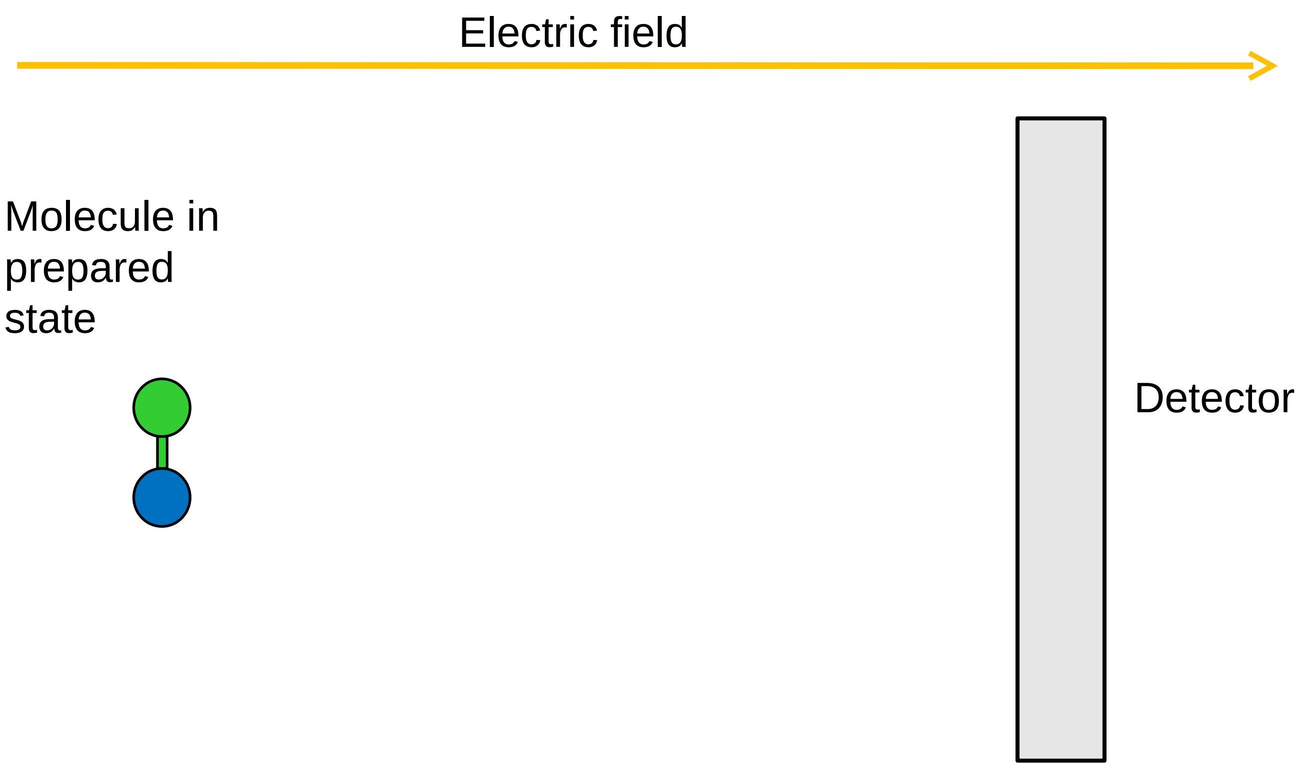
Specifications: Timepix3 vs. Timepix4

			Timepix3 (2013)	Timepix4 (2019/20)	
Technology			IBM 130 nm – 8 metal	TSMC 65 nm – 10 metal	
Pixel size			55 x 55 µm	55 x 55 µm	
Pixel arrangement			3-side buttable 256 x 256	4-side buttable (TSV) 512 x 448	3.5 x
Sensitive area			1.98 cm^2	6.94 cm^2	
Readout modes	Data driven (tracking)	Mode	ToT and TOA		
		Event packet	48-bit	64-bit	
		Max rate	< 43 Mhits/cm^2/s	357.6 Mhits/cm^2/s	8 x
		Pix rate equiv.	1.3 kHz/pix average	10.8 kHz/pix average	
	Frame Based (imaging)	Mode	Count: 10 bit + iToT	Count: 8 or 16 bit CRW	
		Frame	Zero suppressed (with pix addr)	Full frame (no pix addr)	
		Max count rate	82 Ghits/cm^2/s	~ 800 Ghits/cm^2/s	10 x
		Max frame rate	N/A (worst case: 0.8ms readout)	80 kHz CRW	
TOT energy resolution			< 2 keV	< 1 keV	2 x
Time resolution			1.56 ns	~ 200 ps	8 x
Readout bandwidth			≤ 5.12 Gbps (8 x 640 Mbps)	≤163.8 Gbps (16 x 10.2 Gbps)	32 x
Target minimum threshold			< 500 e$^-$	< 500 e$^-$	

Ion detection (Controlled Molecule Imaging)



Thanks to Melby Johny, Sebastian Trippel, Hubertus Bromberger, Jochen Küpper

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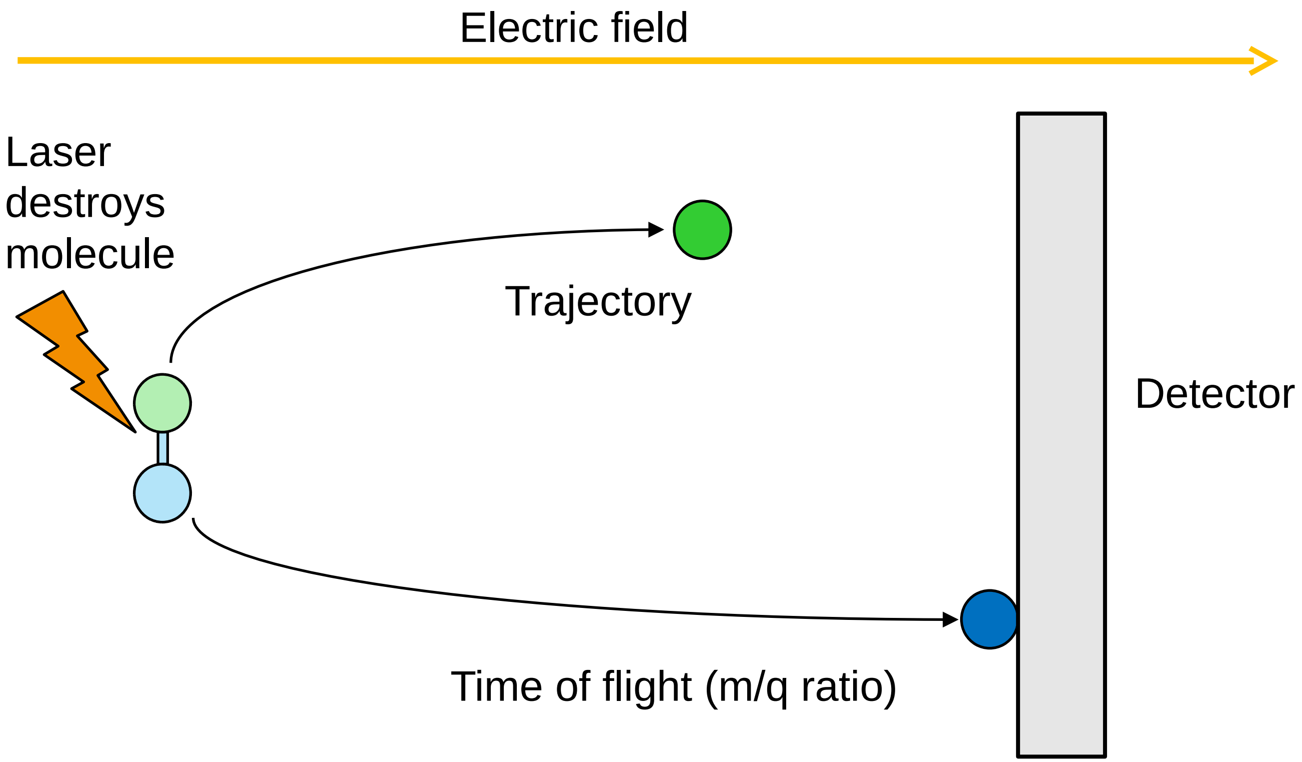

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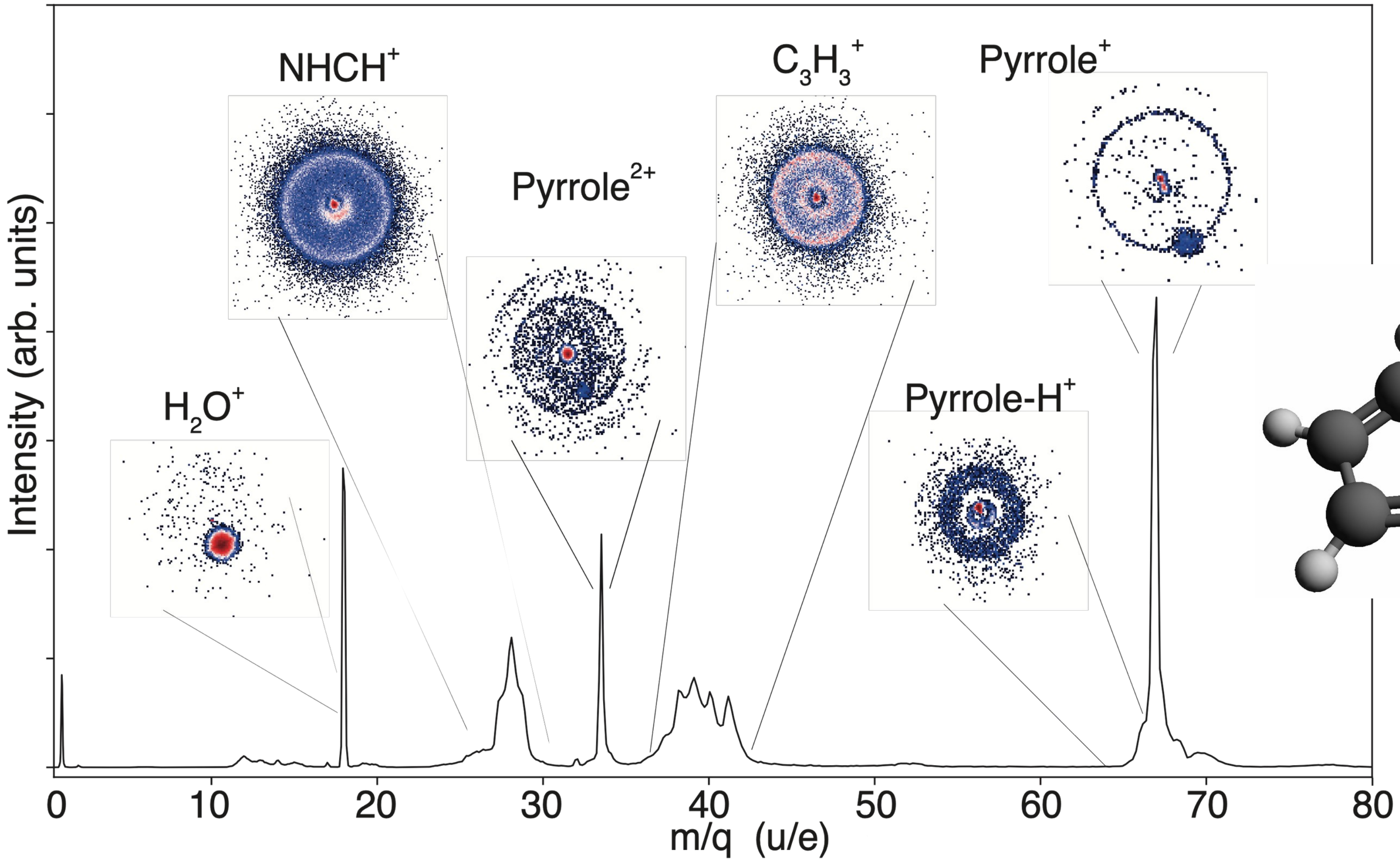
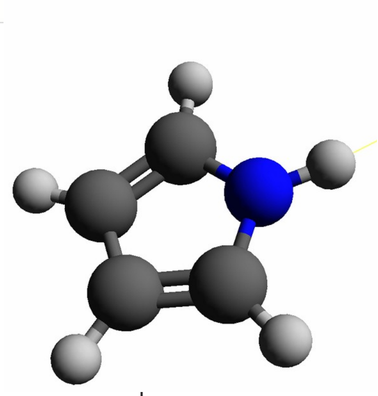
Coulomb explosion imaging of Pyrrole

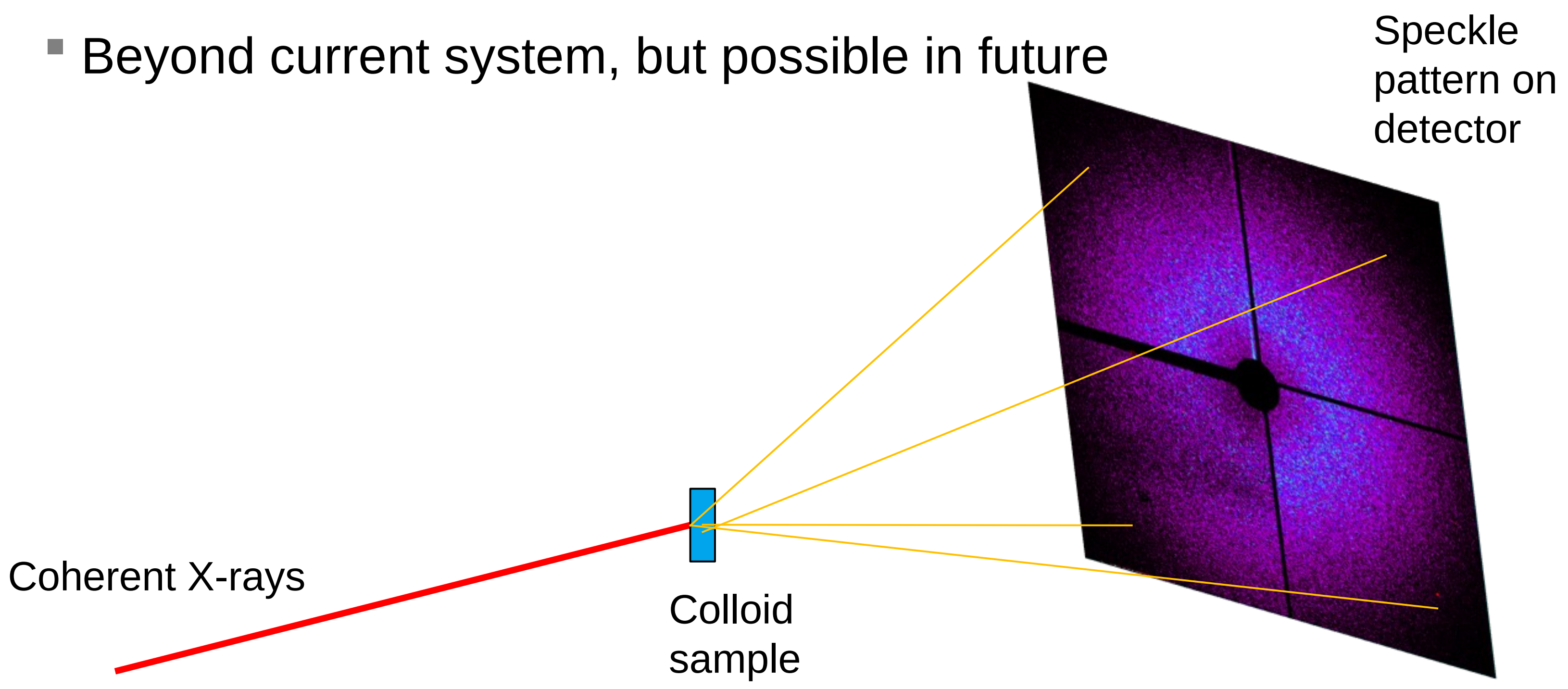
~2 ns (std dev) time resolution





X-ray photon correlation spectroscopy (XPCS) at P10

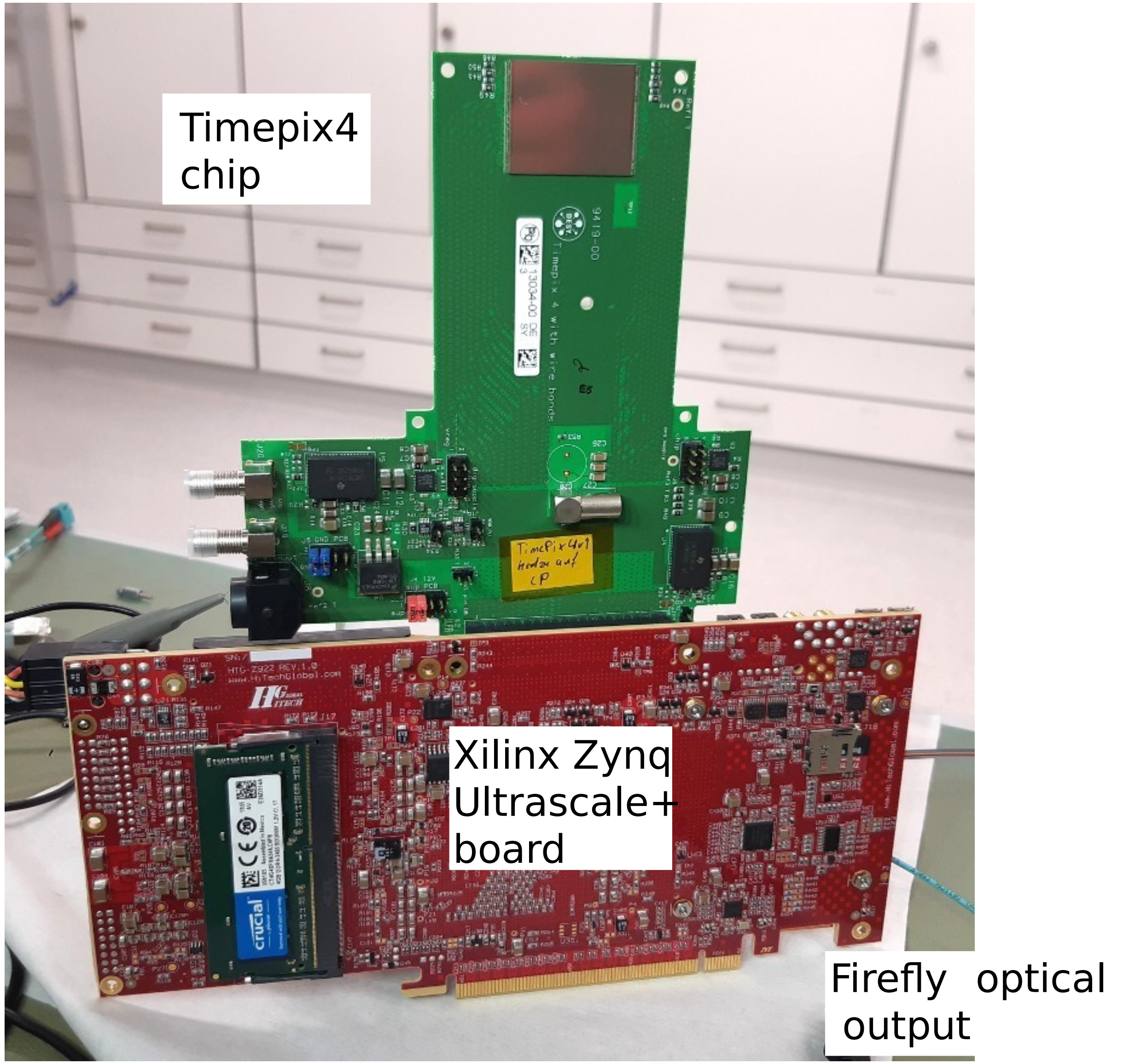
- Fluctuation of speckle pattern over time reveals dynamics of sample
    - At PETRA-IV, XPCS could reach 100 ns time resolution!
- Typical experiment has ~2×10^7 hits/s in detector
    - Beyond current system, but possible in future



Thanks to Fabian Westermeier, Ruth Livingstone, Michael Sprung

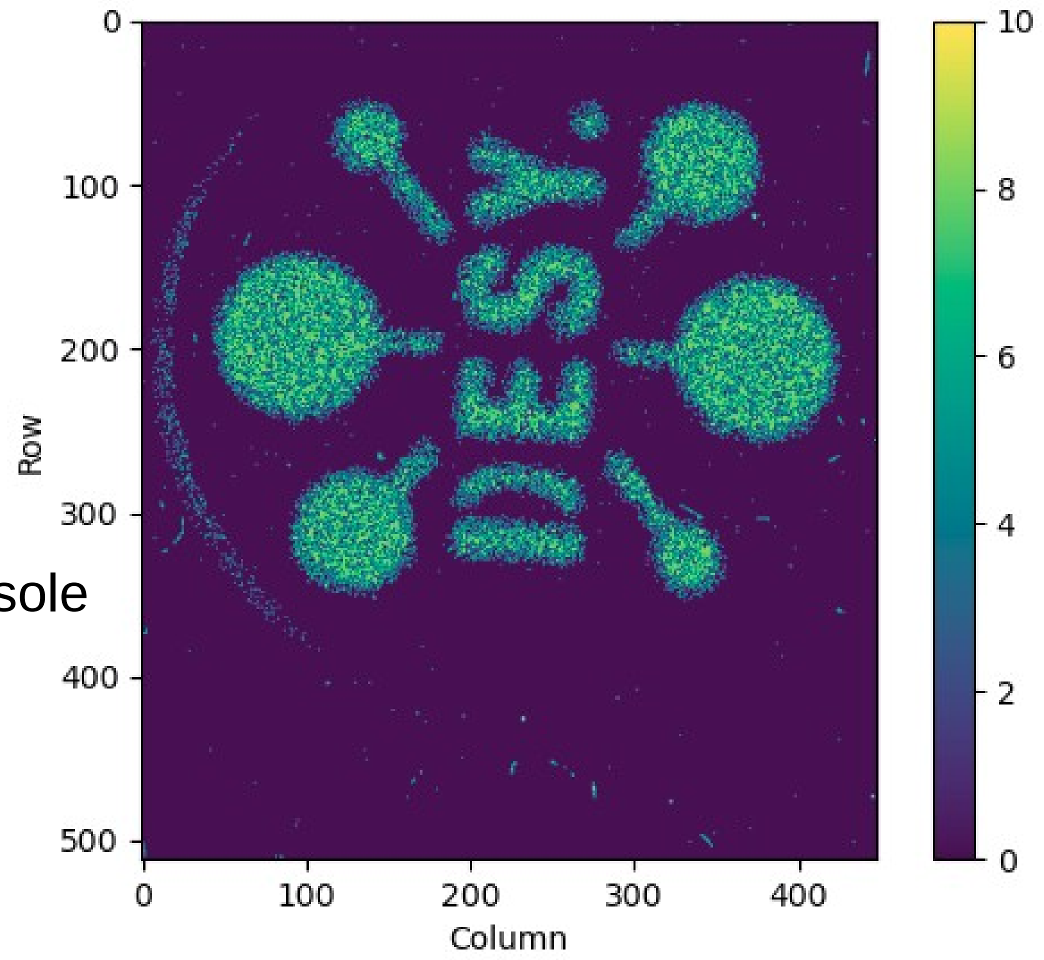
DESY single chip prototype

- Single-chip Timepix4 board connected to off-the-shelf Xilinx board
  - Zynq Ultrascale+ with FPGA fabric and 4-core CPU
- Parallel readout of 16 high-speed links from chip, each up to 5 (or 10) Gbit/s
  - Specialised transceivers on Zynq
- Daughterboard offering 2 x 100 GBE links over “Firefly” optical cable
  - Challenge of dealing with ~ 160Gbits/s



Current status – readout development

- Data read out over the control link
  - Example – first image taken using a 55Fe source and a DESY logo target
  - Limited to ~ 5000 hits/second
- High speed data links already operational
  - Real data transfer tests planned upcoming days
- Basic software for taking data
  - Remotely connect to Zynq and control from Python console
  - CMI already working in a Pymepix implementation
- External triggering is operational
  - Different triggering schemes are being implemented
- Dummy data transfer over 100 GBE links



Data reception and processing in PC

> Started work with Xilinx FPGA accelerator cards

- Data reception with 2 x 100 Gigabit Ethernet
- Buffering in high-bandwidth memory
- Data correction in FPGA fabric
  - Programming in C++ (Xilinx High Level Synthesis)
- PCIe4.0 transfer to server PC

> Started work on data reduction algorithms throught machine learning:

– Talk later today by Vahid Rahmani

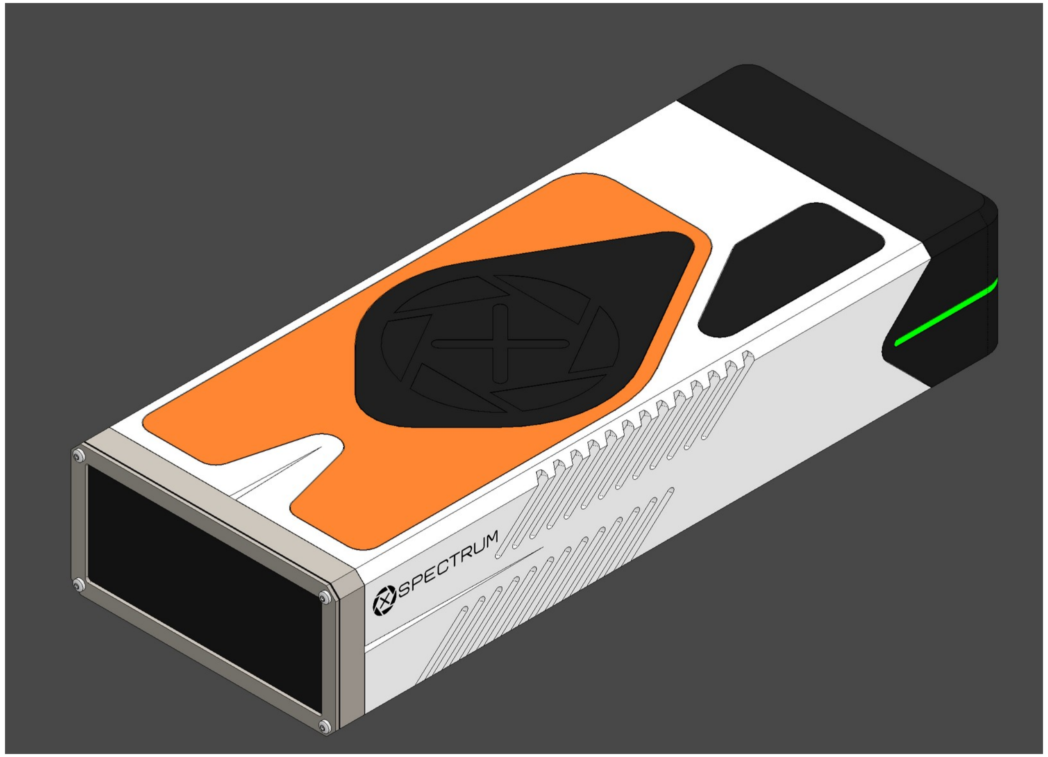
Outlook: multi-chip, multi-module systems

> Goal – large, continuous detector area

> Tileable building block: 3-chip module

> Readout board with Zynq Ultrascale+ SoC

> Ultimate goal – TSVs to eliminate wire bonds
   – TSV run started at Fraunhofer IZM (Berlin)and LETI (Grenoble) by Medipix4 collaboration

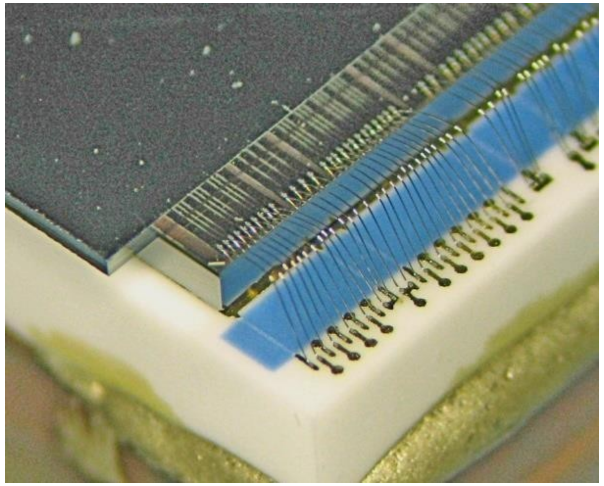


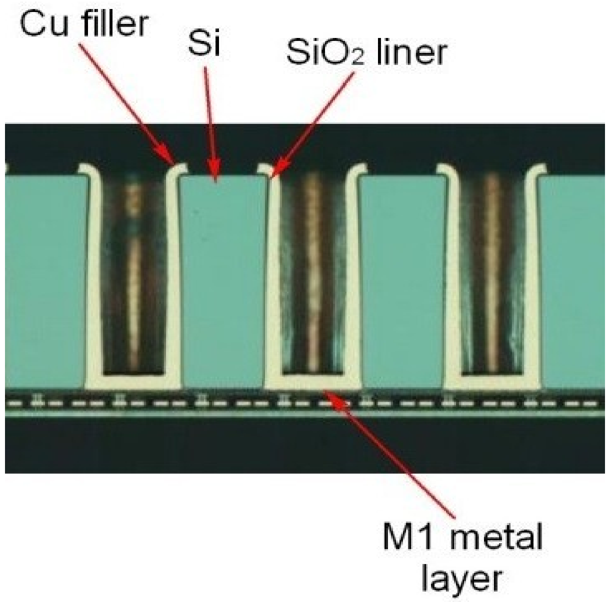
3-chip detector head
1344 x 512 pixels

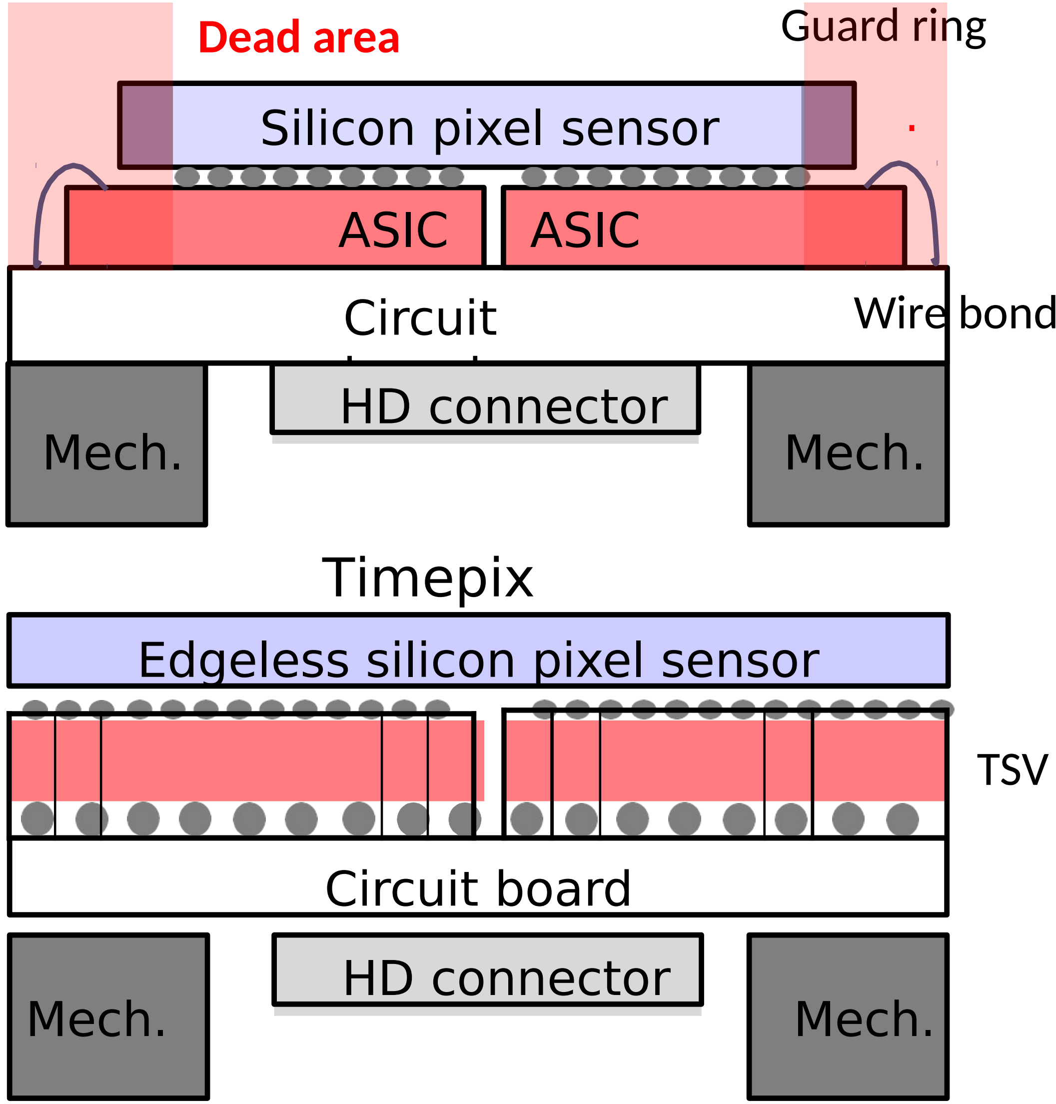
X-SPECTRUM

Outlook: multi-chip, multi-module systems

- Improved 4-side butting with Through Silicon Vias (TSVs)
  - Full chip surface is covered with pixels
  - Rerouting in metal layers creates space for periphery
  - Improved TSV landing pads, redundant inputs, extra power TSV connections in center of chip







Conclusions

- Current LAMBDA systems ~ 2 kHz frame rates and large areas
- Current Timepix3 systems ~ 5ns time resolution with limited hit rate
  - Suitable for CMI and proof-of-principle work at PETRA III

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- Improved photon counting and time stamping modes:
  - Higher frame rate
  - Hit rate compatible with more PETRA experiments
  - Much higher time resolution possible

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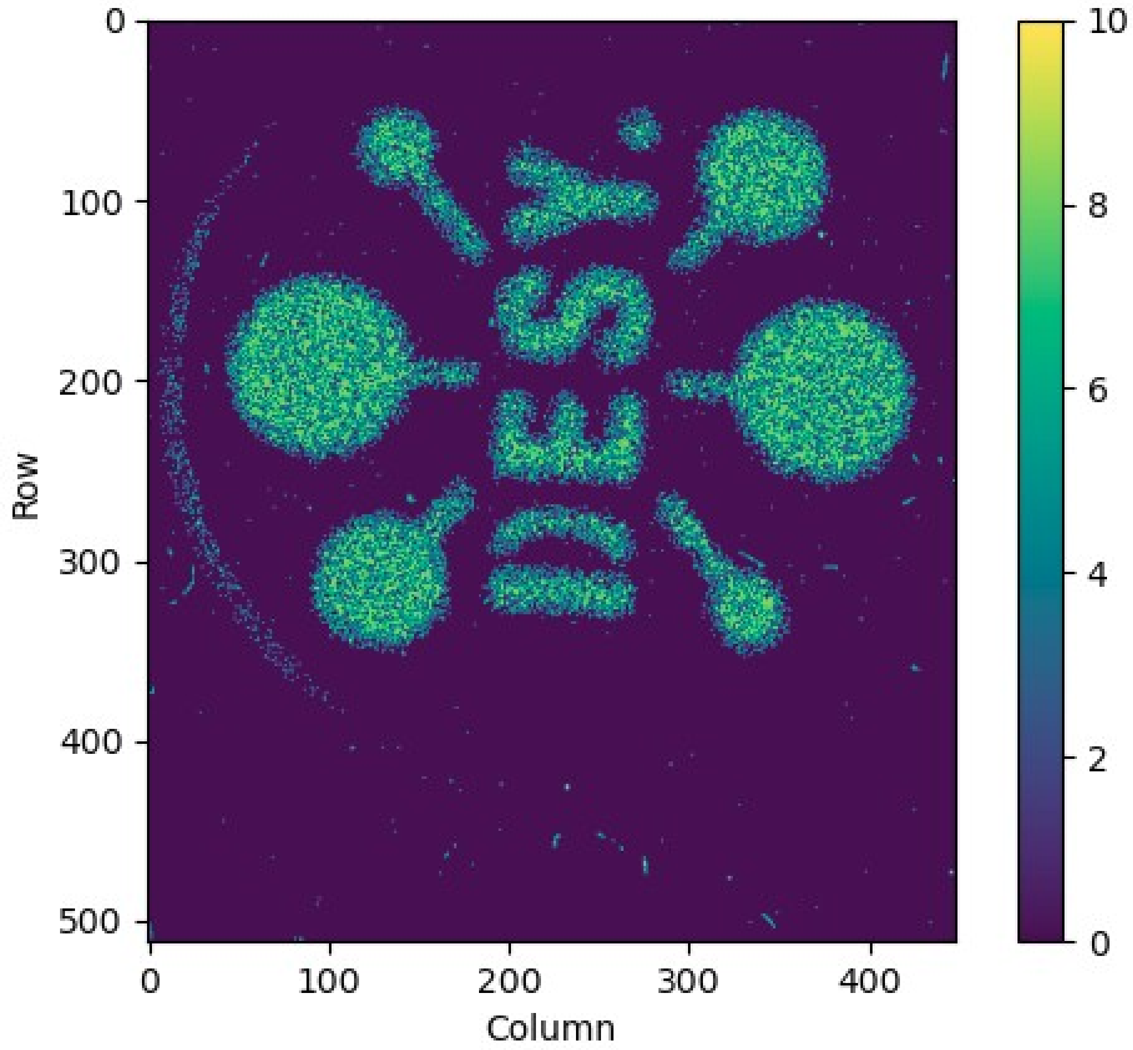
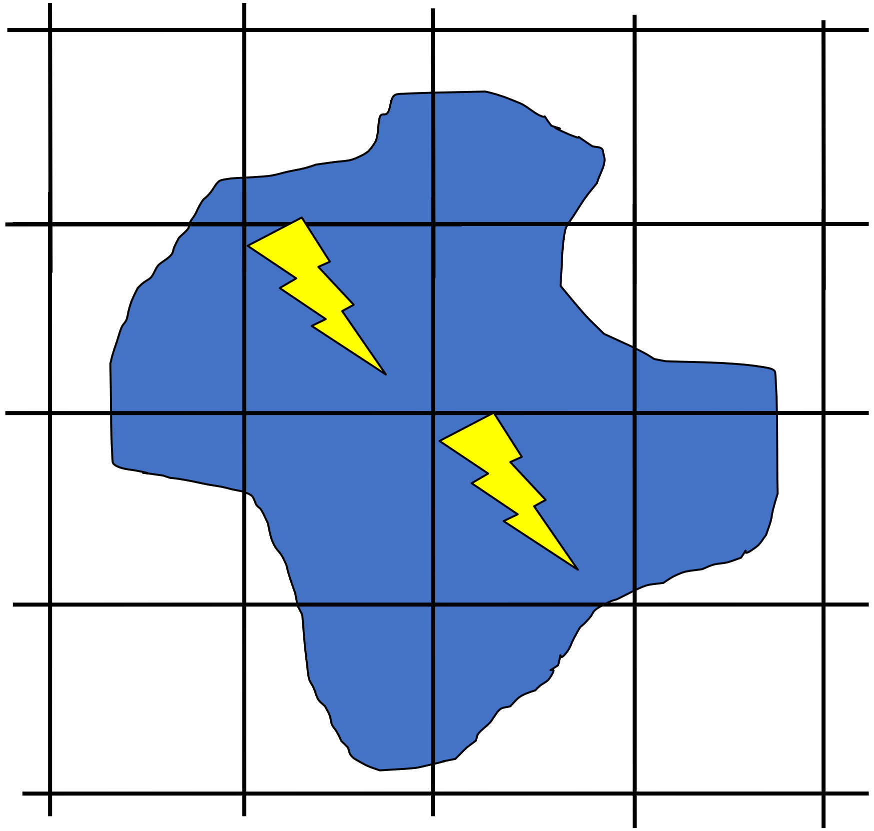


Time resolution for XPCS



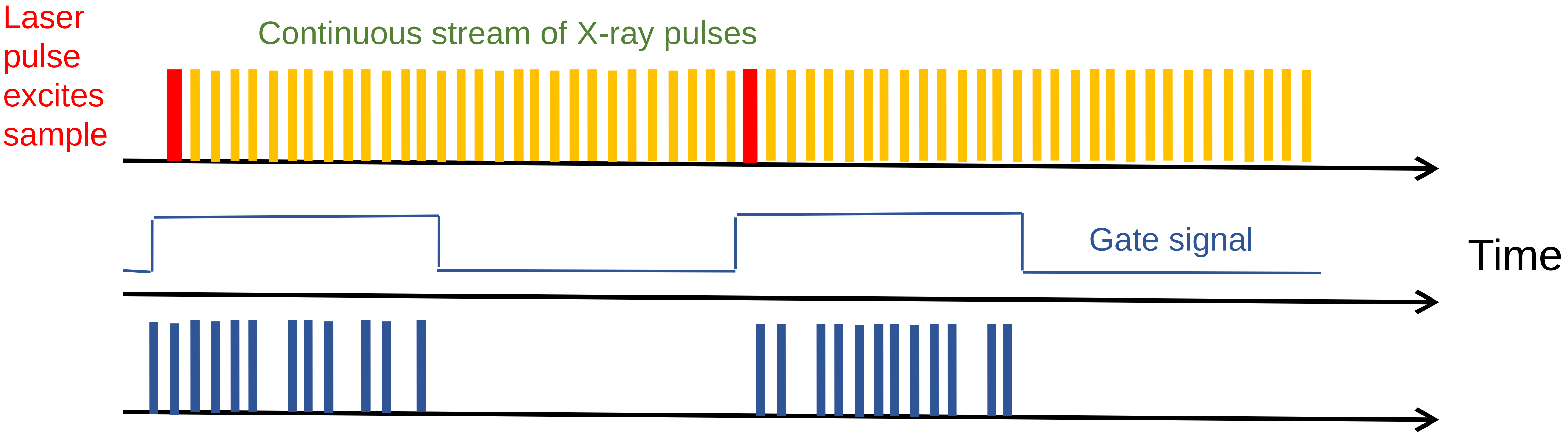
- If speckles are spread across multiple pixels, we could in principle find autocorrelations down to 10 ns timescales
- Otherwise, limited to ~350 ns recovery time

Pixel (1,1)
Energy ~8 keV
Time 10 ns

Pixel (2,2)
Energy ~8 keV
Time 20 ns

X-ray pump probe experiments

- Could continuously record photon hits with 10 ns bunch spacing
- Data rate can be kept down by selecting useful signal
  - Electronic shutter selects time window
  - Pixel masking can create arbitrary regions of interest



Each hit timestamped with Timepix4

X-ray tube pump-probe experiments with Timepix3 at Nanolab

- MgO sample probed with 1W laser pulses – measure changes in peak amplitude
- 1 hr 40 mins of X-ray tube data, binned to 10 ns
- Thanks to Simon Chung and Vedran Vonk