TEMPUS Detector: Recent Developments and Applications

DESY FS-DS

Photon Science Detector Group

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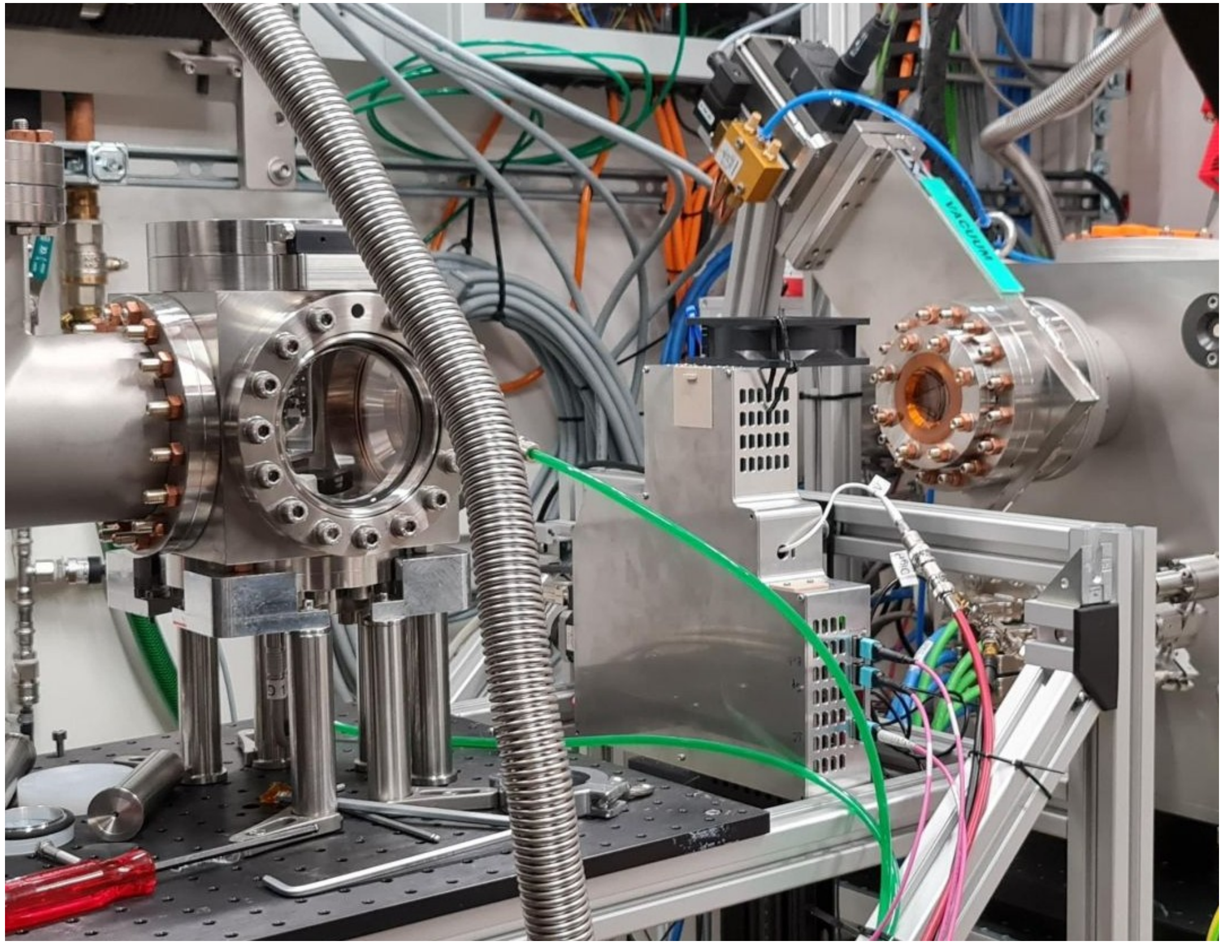
The TEMPUS X-ray Detector System

Goal & Concept

- Detector system developed at DESY for time-resolved X-ray science
- Detector upgrade for PETRA-III and PETRA-IV, also suitable for other x-ray beamlines
- Hybrid pixel detector system, based on Timepix4:
  - Single chip 2.8 x 2.5 cm
  - 55 um pixel pitch
  - Combines improved characteristics from Medipix3 and Timepix3
  - Provides sub-nanosecond timing and energy measurements



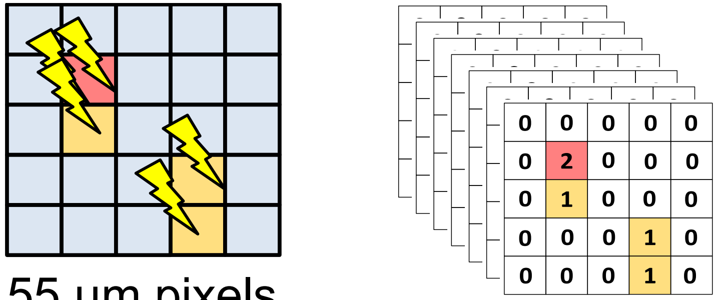
The Timepix4 Readout Chip

Operation modes

1) Photon counting and frame readout

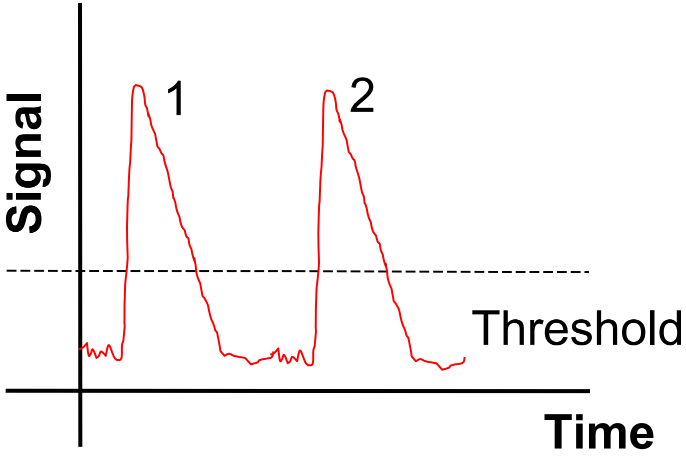
Detector

Frame readout



55 µm pixels

- 40 kHz frame rate CRW (8 bits)
- ~ 1.5×10^{6} counts/pixel/s



2) Time-stamping and event-driven readout

Detector

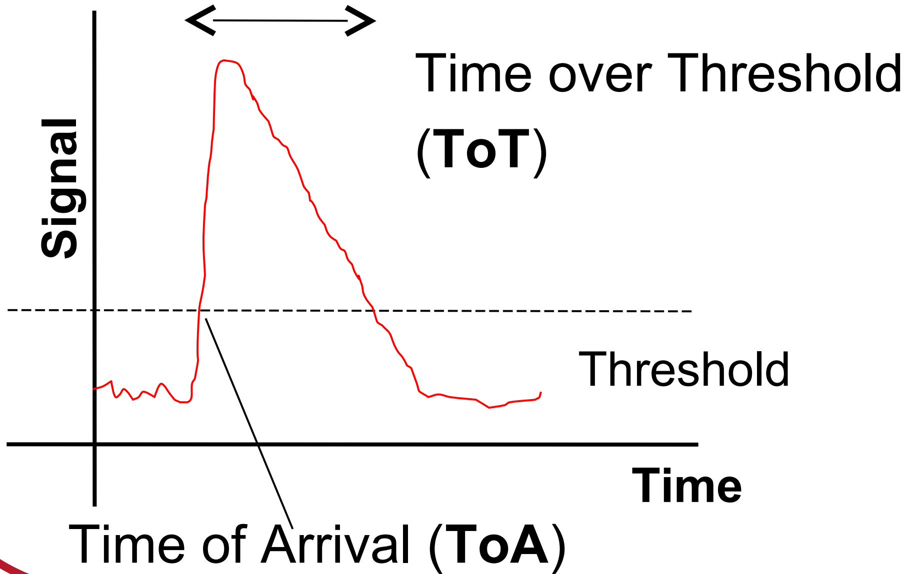
Data packets

Pixel (1,1)
Time 525.3 ns
Energy ~14 keV

Pixel (3,3)
Time 762.9 ns
Energy ~10 keV

55 µm pixels

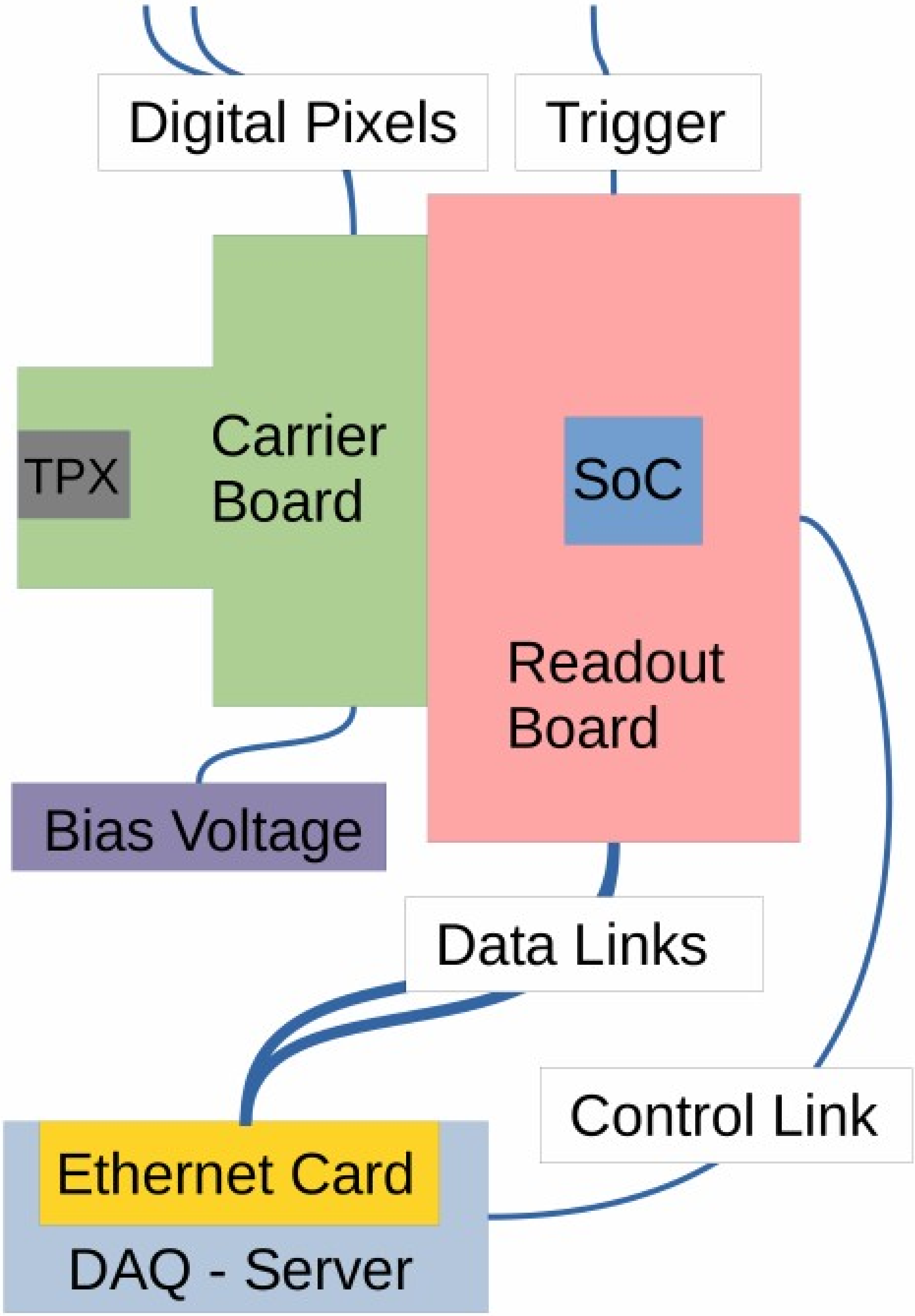
- X-rays ~ ns time resolution
- ~ 1×10^{9} counts/chip/s



The TEMPUS X-ray Detector

System description – planned specs

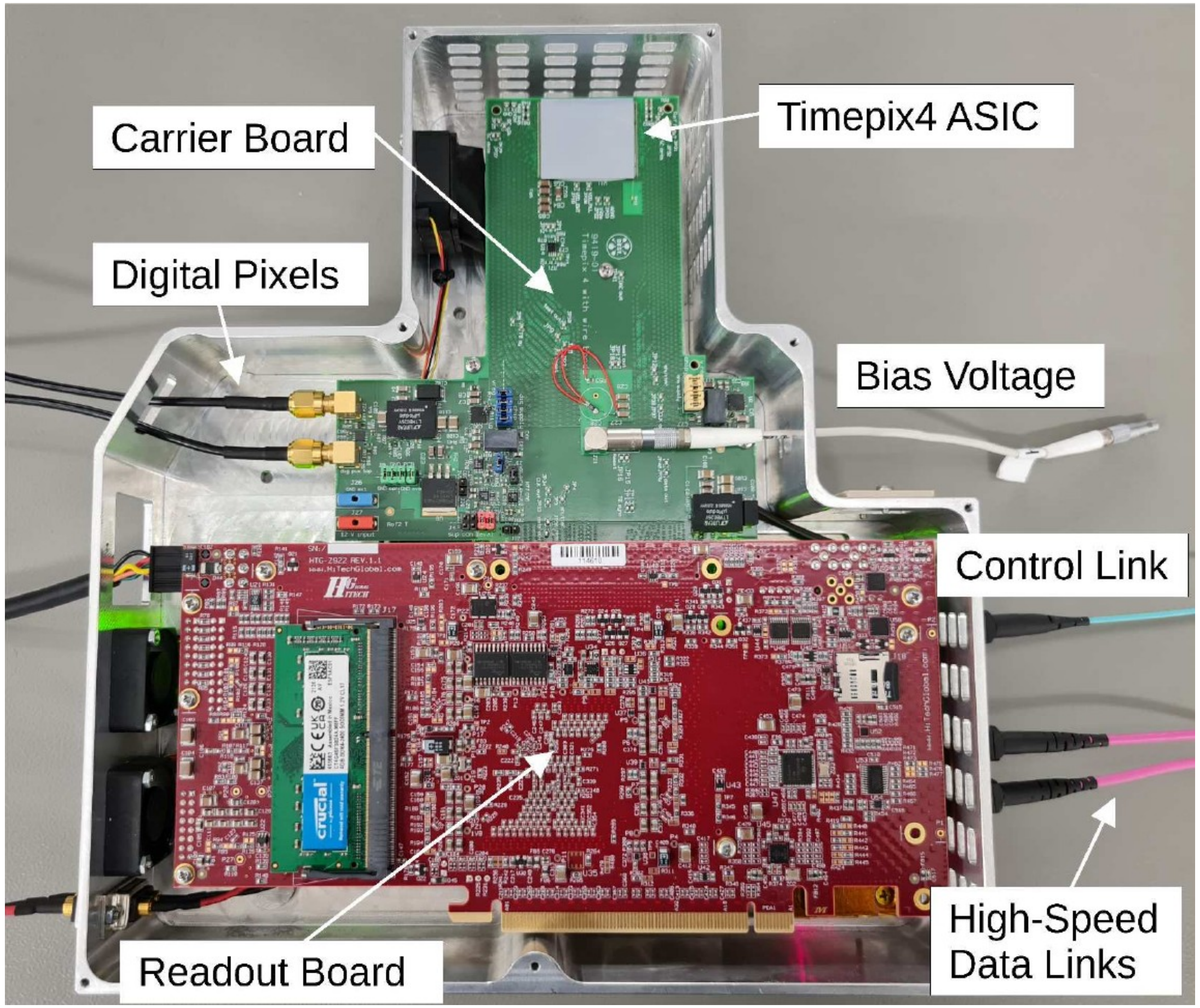
- Single-chip Timepix4 mounted on carrier board
  - Parallel readout of 16 GWT high-speed links from chip, each up to 5 (or 10) Gbit/s
- Connected to off-the-shelf Xilinx board with FPGA and 4-core CPU
- Daughterboard offering 2 x 100 GBE links over “Firefly” optical cable



Latest Developments

Current status and on-going work

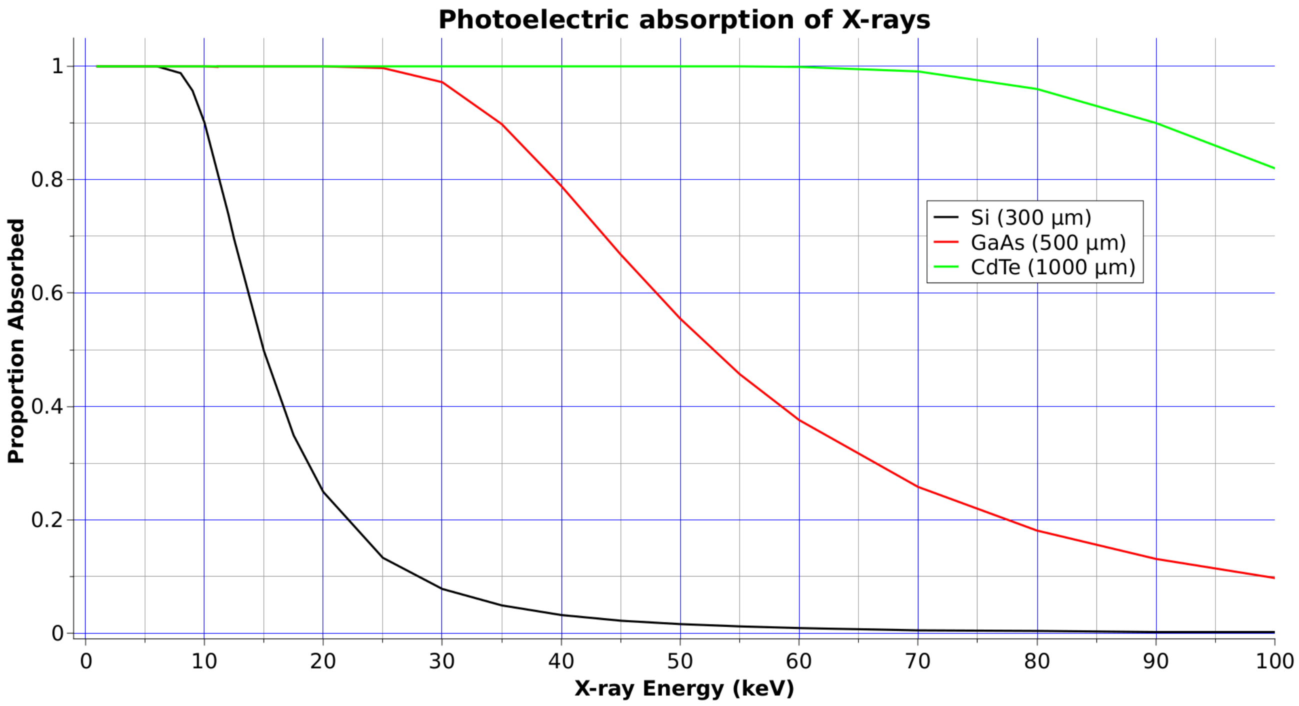
- Improve cooling with Peltier element
- Better stability of parallel readout with GWT links:
  - 2 links running at 2.56 Gbps
  - 16 links running at 1.28 Gbps
- Improvements in control software
- Configuring test pulses for energy calibration
- Clustering algorithm
- Data saving using Rust
  - Limitations at very high rates (e.g. 16-link readout)



J. Correa et al. (2024). **J. Synchrotron Rad. 31**. https://doi.org/10.1107/S1600577524005319

Latest Developments

Available Systems

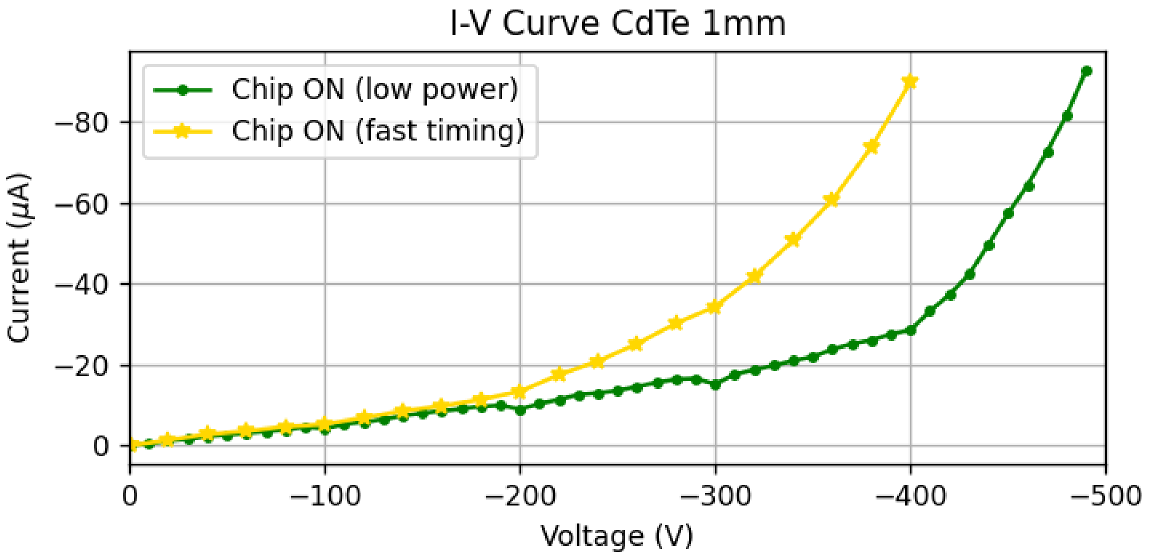


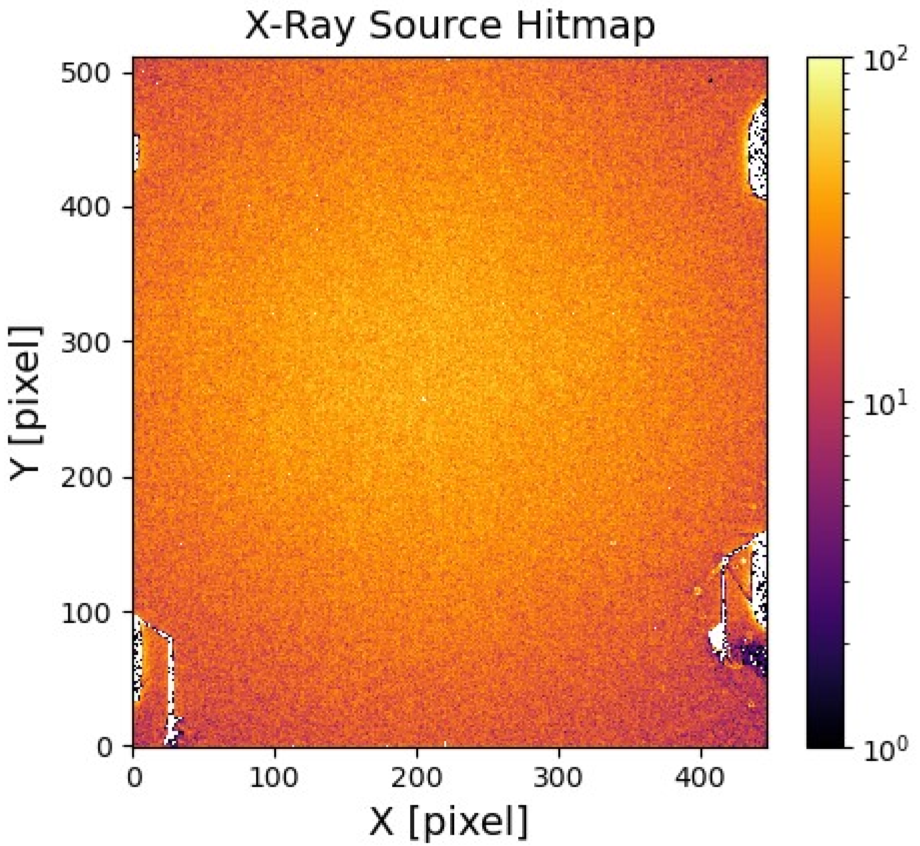
- Silicon Sensors (hole-collecting)
  - 500 um thick → increased probability of interaction
  - 300 um thick → better timing
  - 300 um thick with a thin entrance window (TEW) → visible light
- CdTe Sensor (electron-collecting)
  - 1 mm thick
    - → Larger energy range interaction
    - → More localized X-ray absorption, improving consistency of drift time

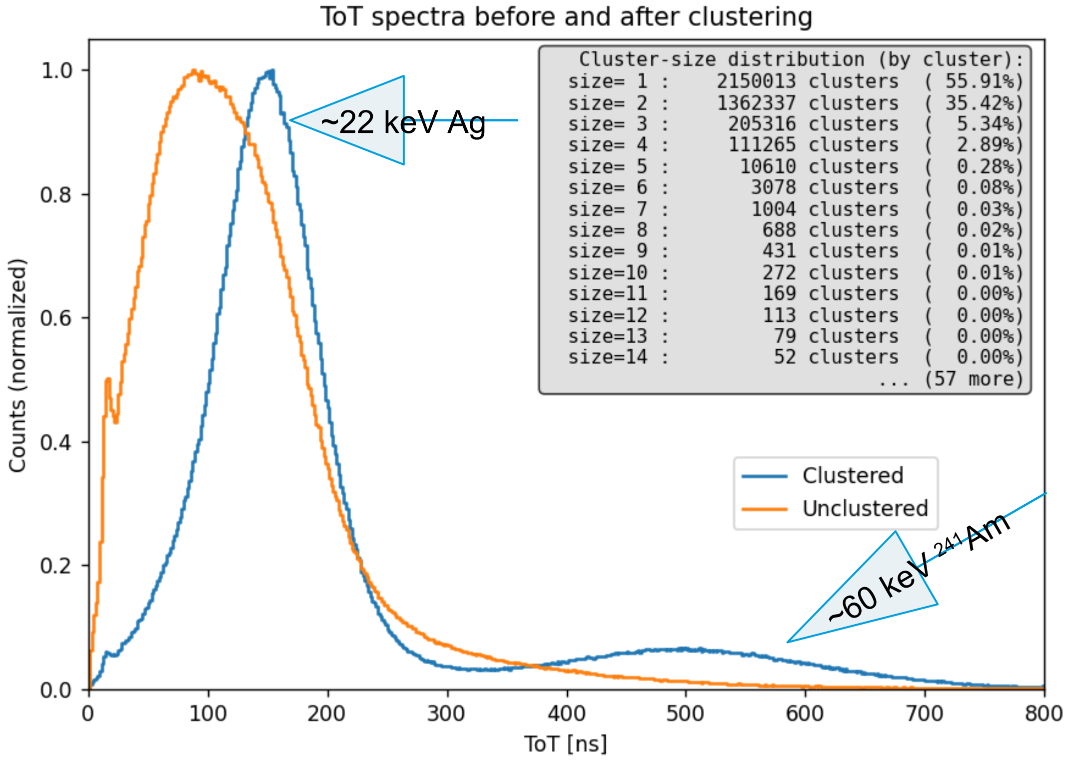
Latest Developments

CdTe System

- Leakage current dependent on configuration
- Hitmap → “disconnected” pixels
- Detectable 60 keV peak from ^{241}Am source



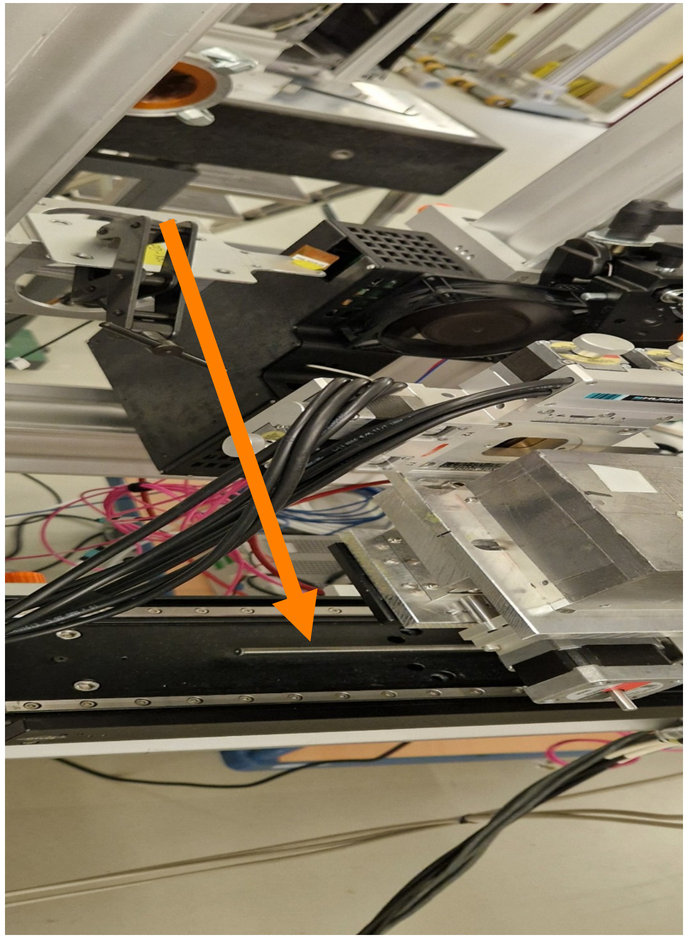




Latest User Experiment

Nuclear Resonance Scattering

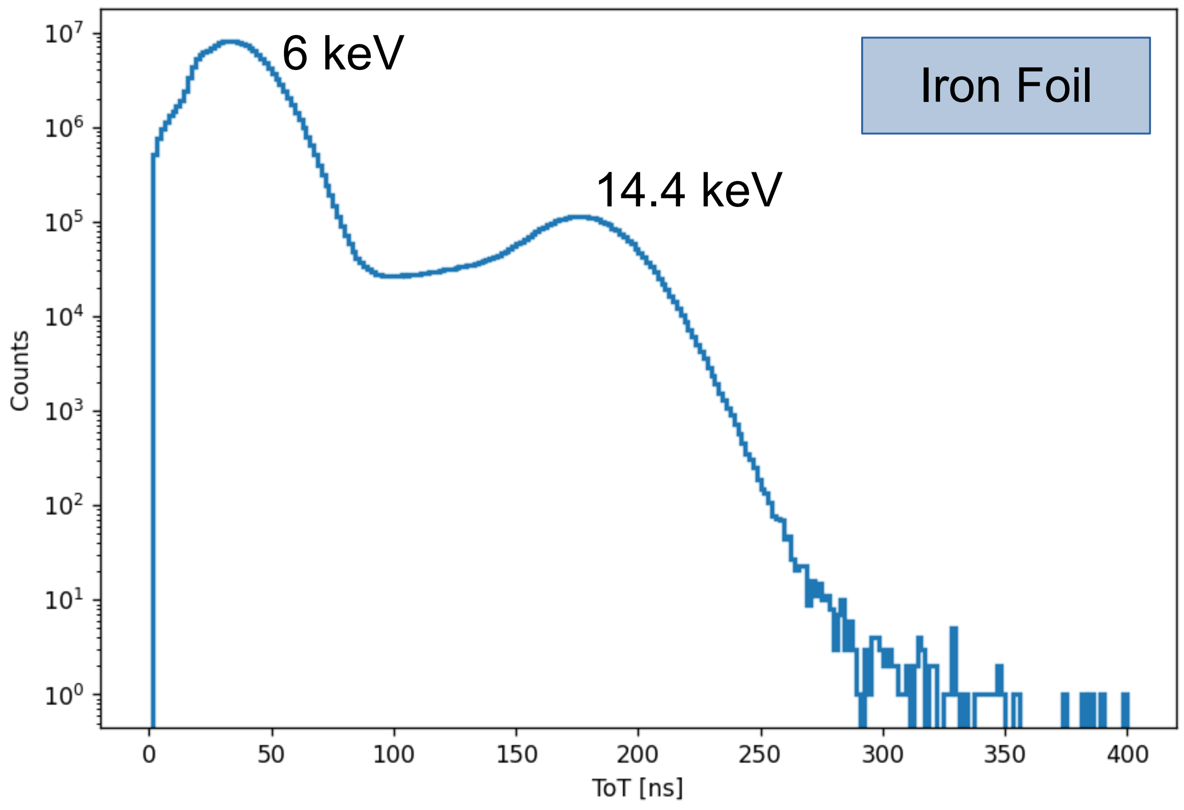
- Latest campaign at P01 in August 2025
- Probe internal structure of atomic nuclei by using resonant absorption and **re-emission of photons**
- X-ray beam: **14.4 keV**
- Samples: iron (**~6 keV**) and copper (**~8 keV**) foils
- All tests done in incoherent geometry (90 deg to incident beam)
- Two different detectors:
  - 1mm CdTe sensor @ -250 V bias
  - 300 um Si sensor TEW @ 200 V bias
- Time of arrival (ToA) relative to bunch trigger / revolution clock
- **Goal: measure time-delayed photons from nuclear excitation**

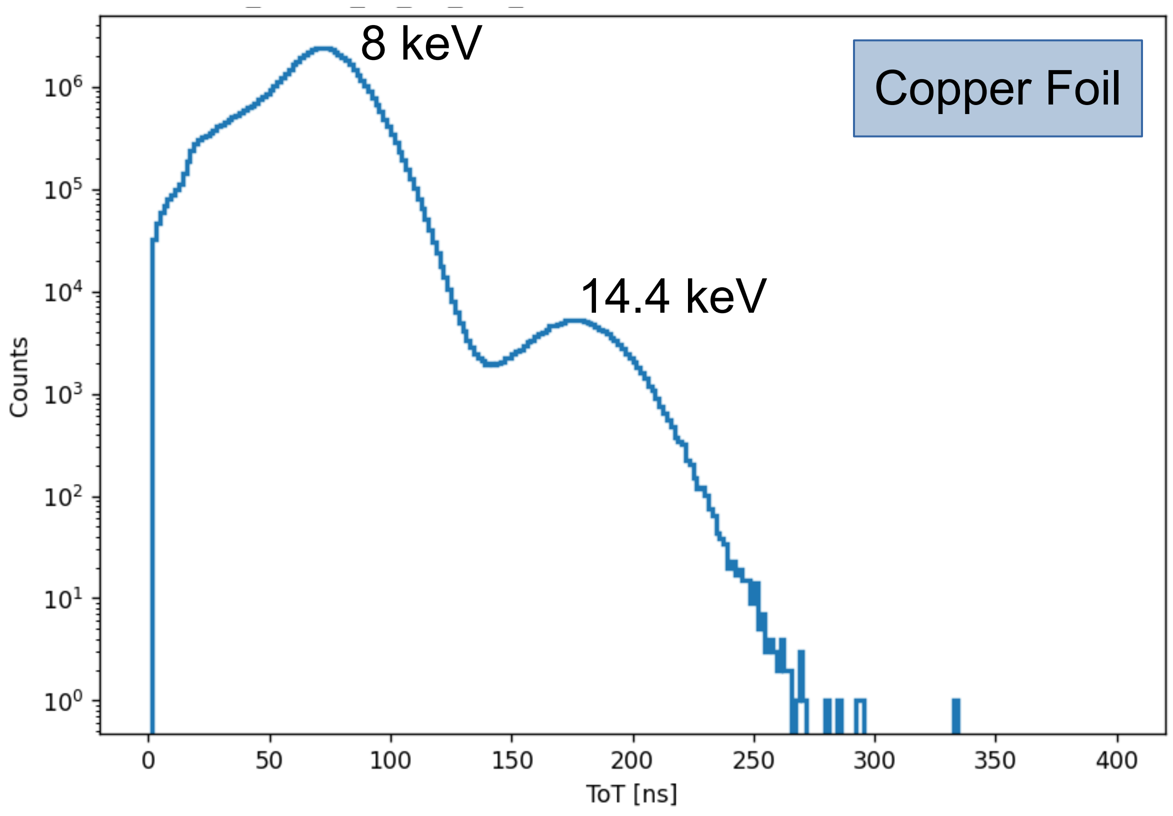


Nuclear Resonance Scattering – Preliminary Results

Time-over-threshold (ToT) Measurements

- **Si 300 um TEW**
- Photopeaks from main beam and from target foil are well distinguished
- No energy calibration yet

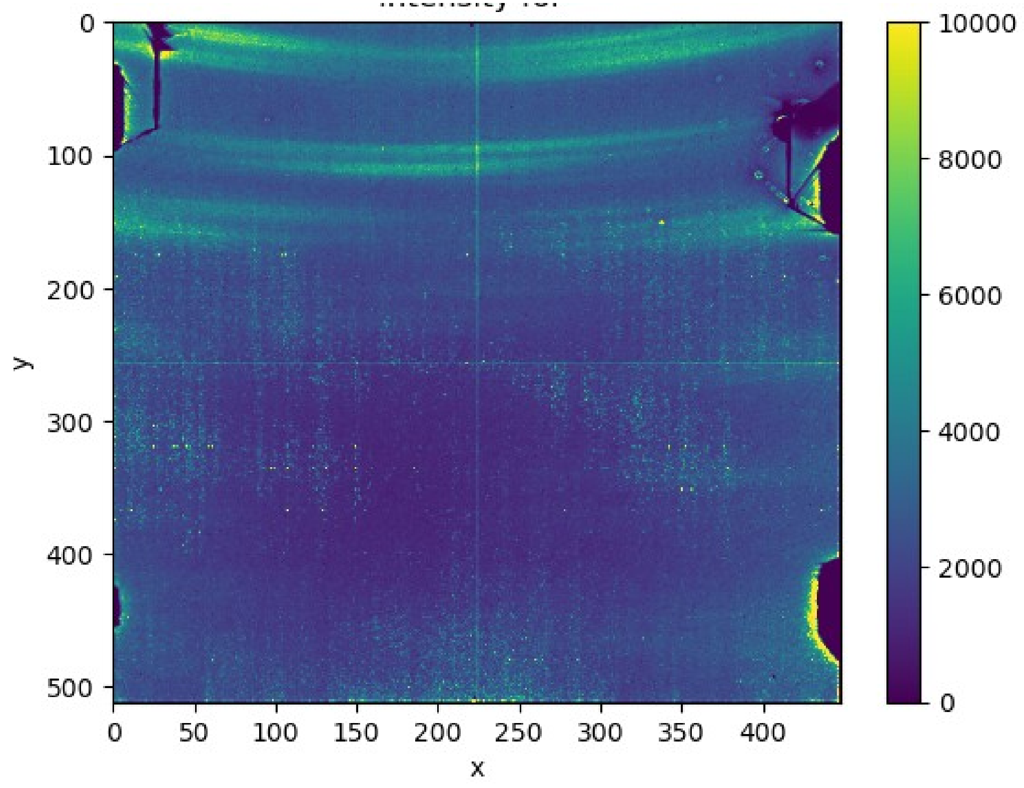


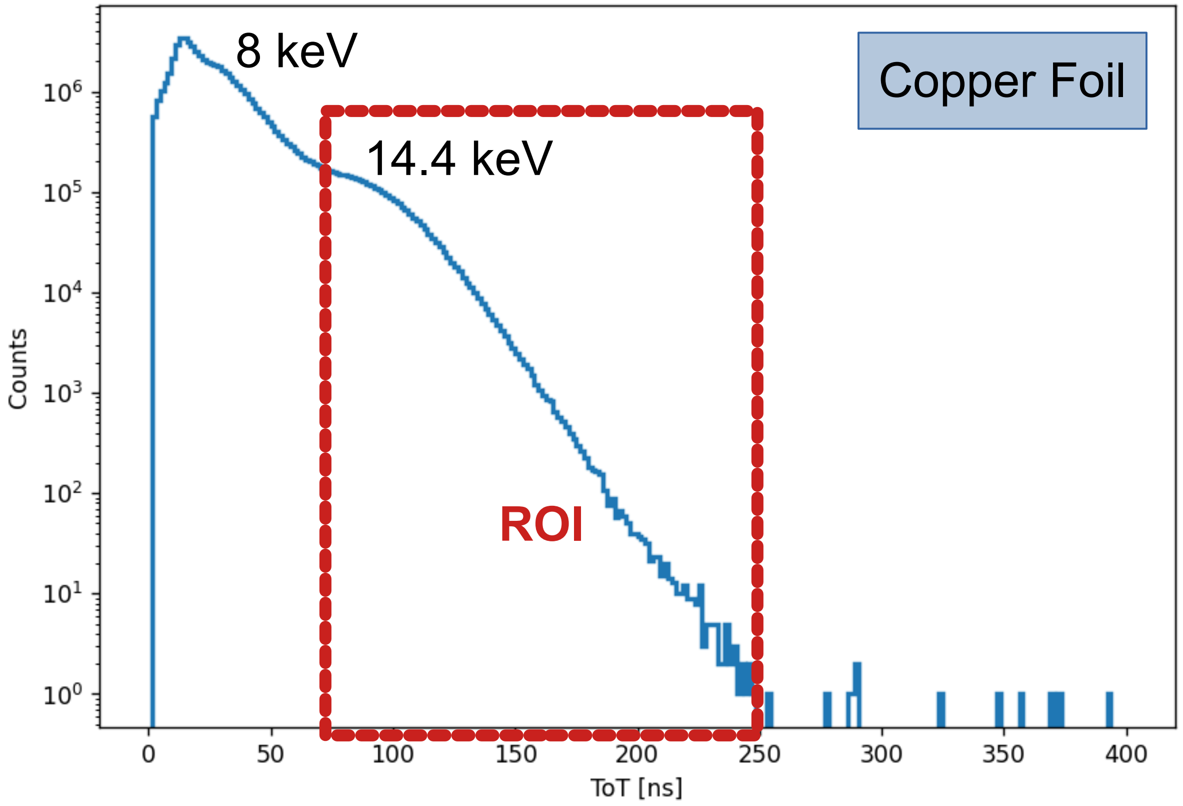


Nuclear Resonance Scattering – Preliminary Results

Time-over-threshold (ToT) Measurements

- **CdTe 1mm**
- The 2 photopeaks (from main beam and from copper foil) are difficult to distinguish
- Clustering does not improve the spectrum → likely too high threshold



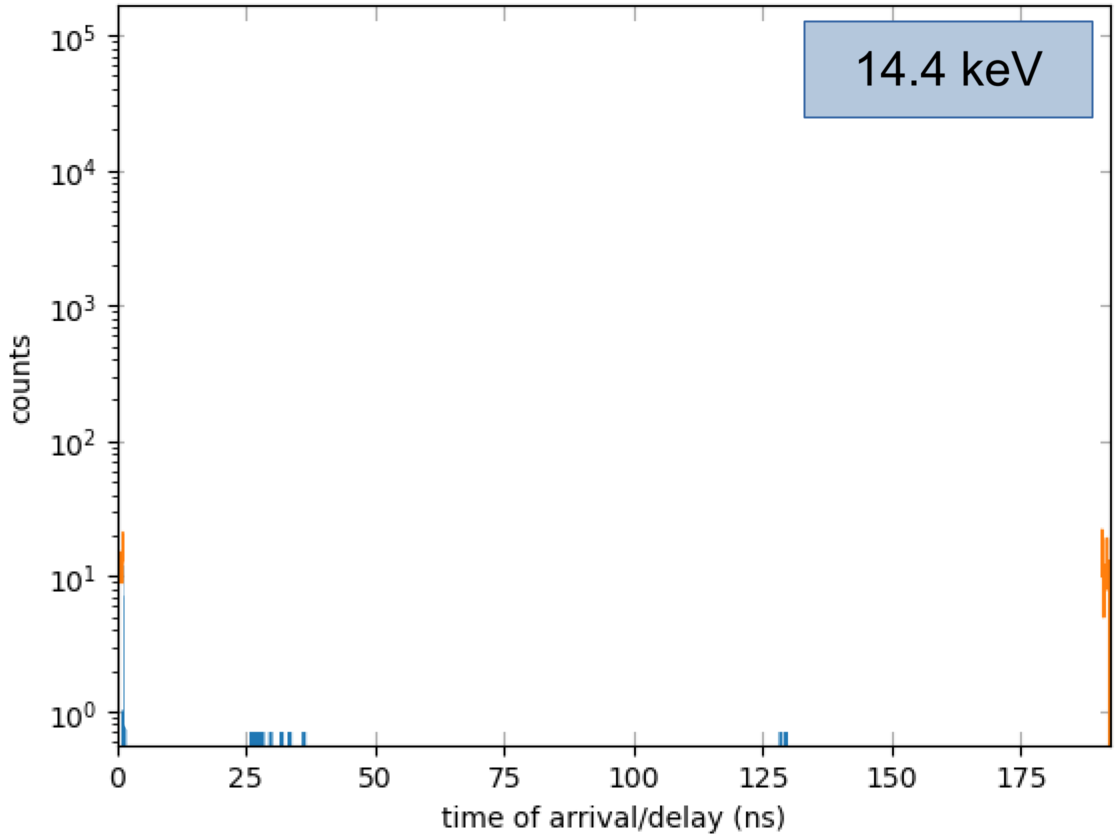


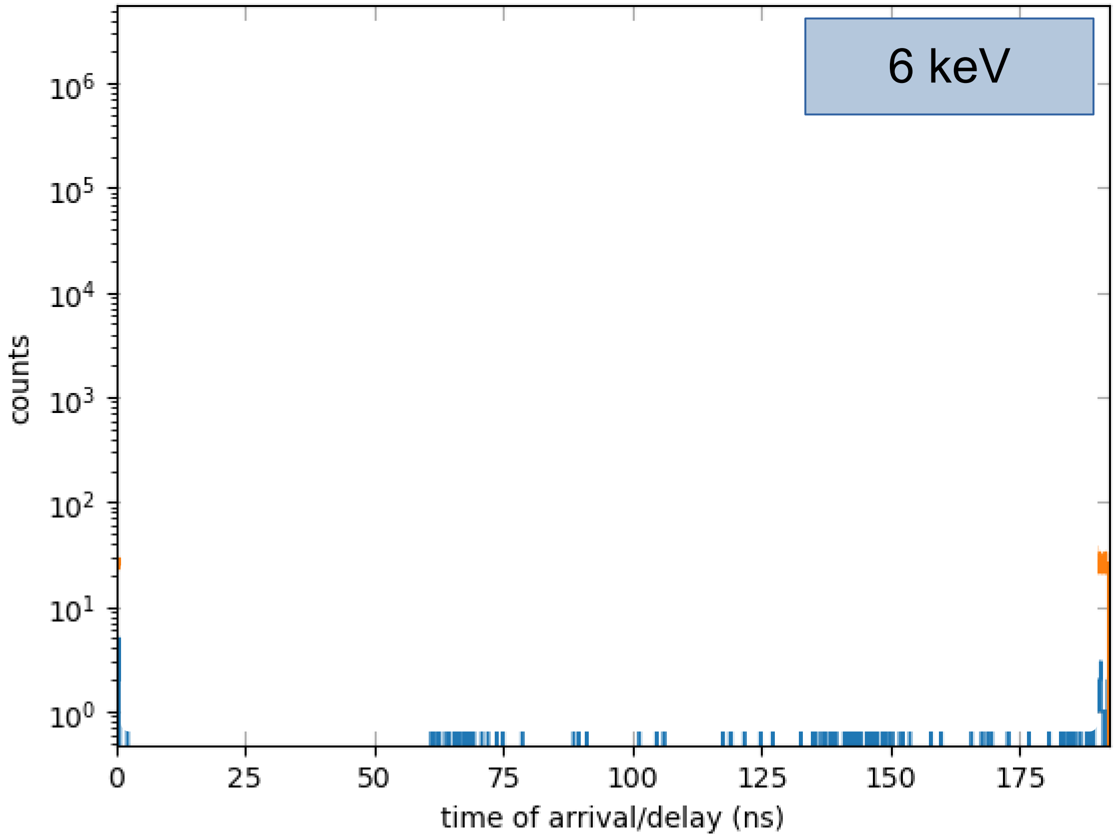
DESY.

Nuclear Resonance Scattering – Preliminary Results

Time-of-arrival (ToA) Measurements

- **Si 300 um TEW**, iron foil
- ROI to select photopeaks
- Resonance **OFF** and **ON** (delayed photons)

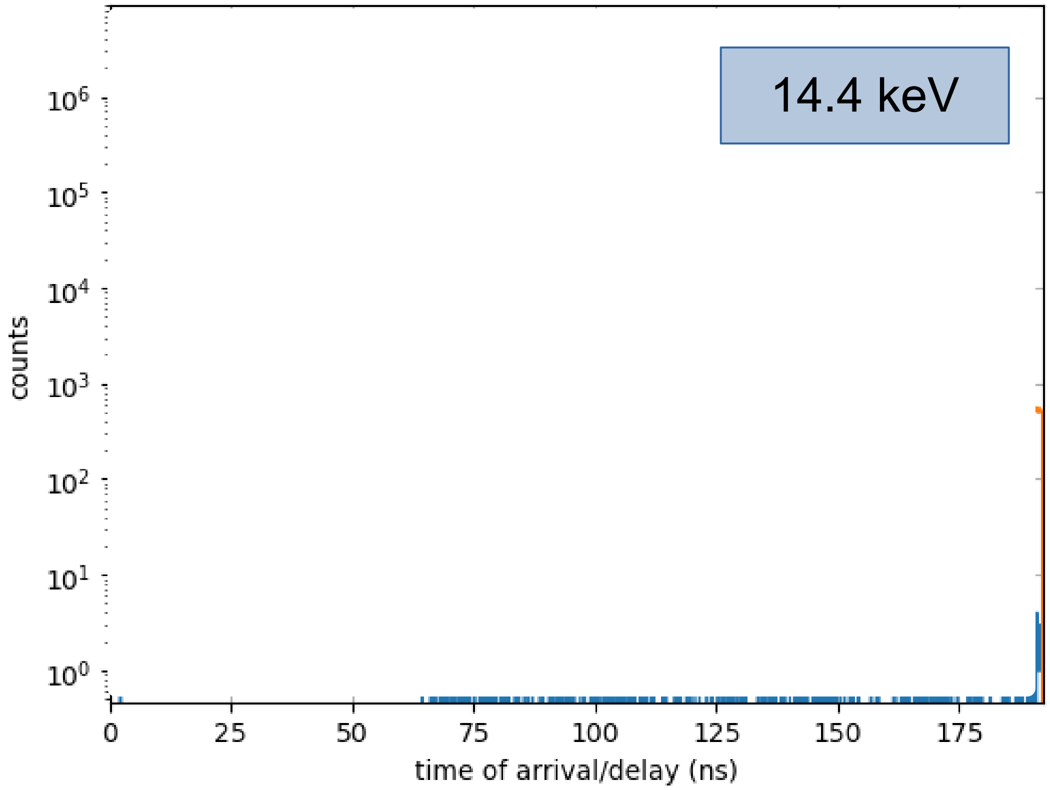




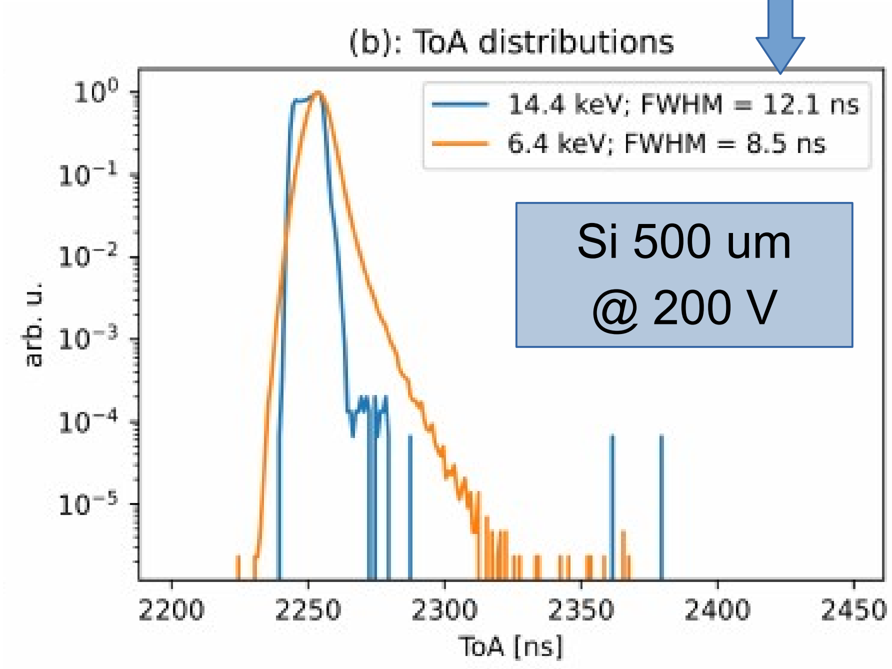
Nuclear Resonance Scattering – Preliminary Results

Time-of-arrival (ToA) Measurements

- **CdTe 1 mm**
- Resonance **OFF** and **ON** (delayed photons)
- No calibration or clustering yet



Almost 2x better timing!



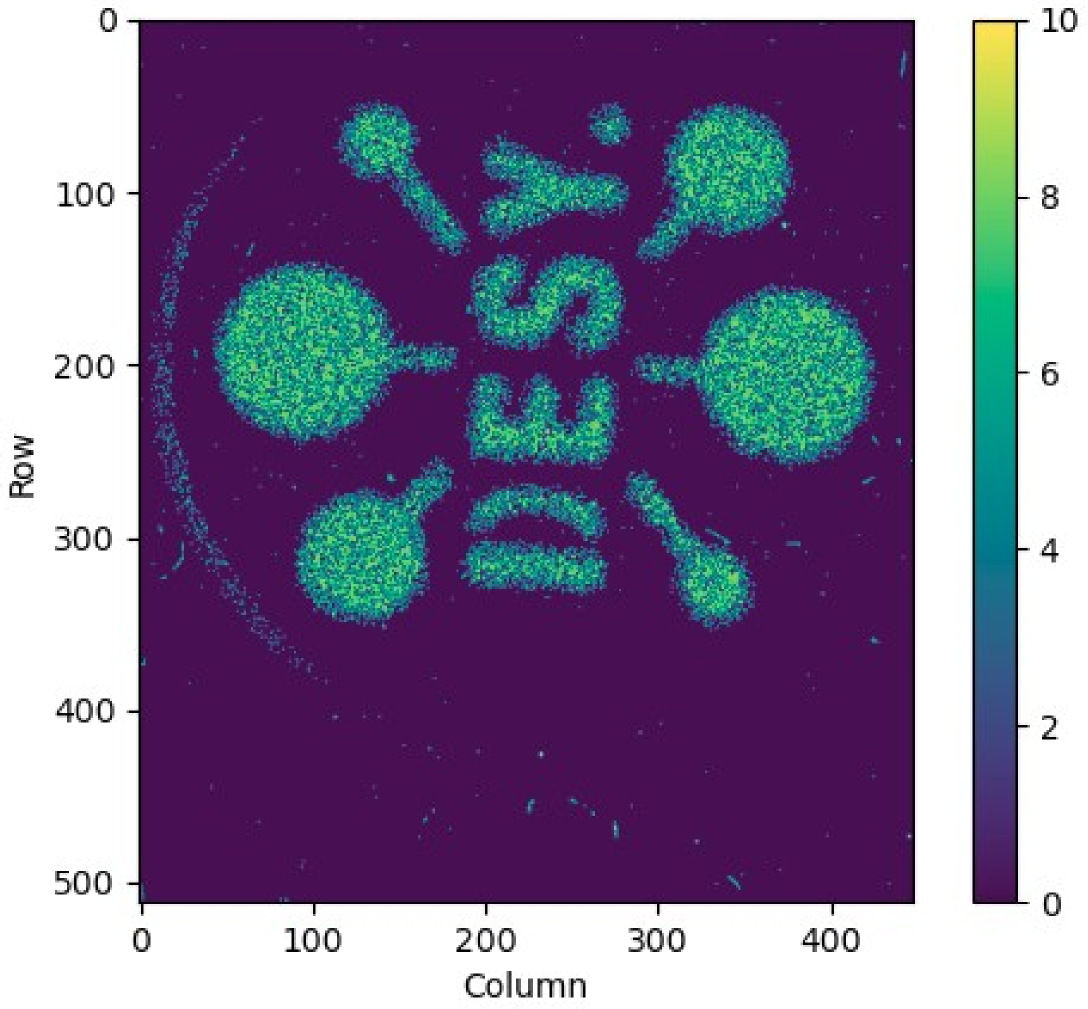
The TEMPUS X-ray detector

Summary / Outlook

- A **single-chip Timepix4-based prototype** is being developed by DESY
  - Reach the **limits of the chip** and **introduce the event-driven** readout in photon-science
  - Different systems available
  - Achieved **O(~ns)** timing resolution
- Applications with strong interest in this system: **NRS**, XPCS, Parametric Down Conversion, AMO...
- Next steps:
  - 3 Beamtimes at ESRF in November
  - Energy and time calibration
  - Use of **alternative sensors** such as **high-Z** materials and **LGADs**:
    - **Expand the photon energy range** of current system
    - Overcome the silicon sensor **time resolution** limitations for X-rays

Acknowledgments

Collaborators



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Backup Slides

TEMPUS

The Timepix4 readout chip

Comparison with Timepix3

			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$^-$	

Some comments on the time resolution

Time jitter

TOA resolution

Signal for
12 keV
photon

> **Variation in timing due to noise or variability in instant signal**, this depends on peaking time of amplifier response

Timepix4 ASIC time resolution; measured by CERN with internal test pulses

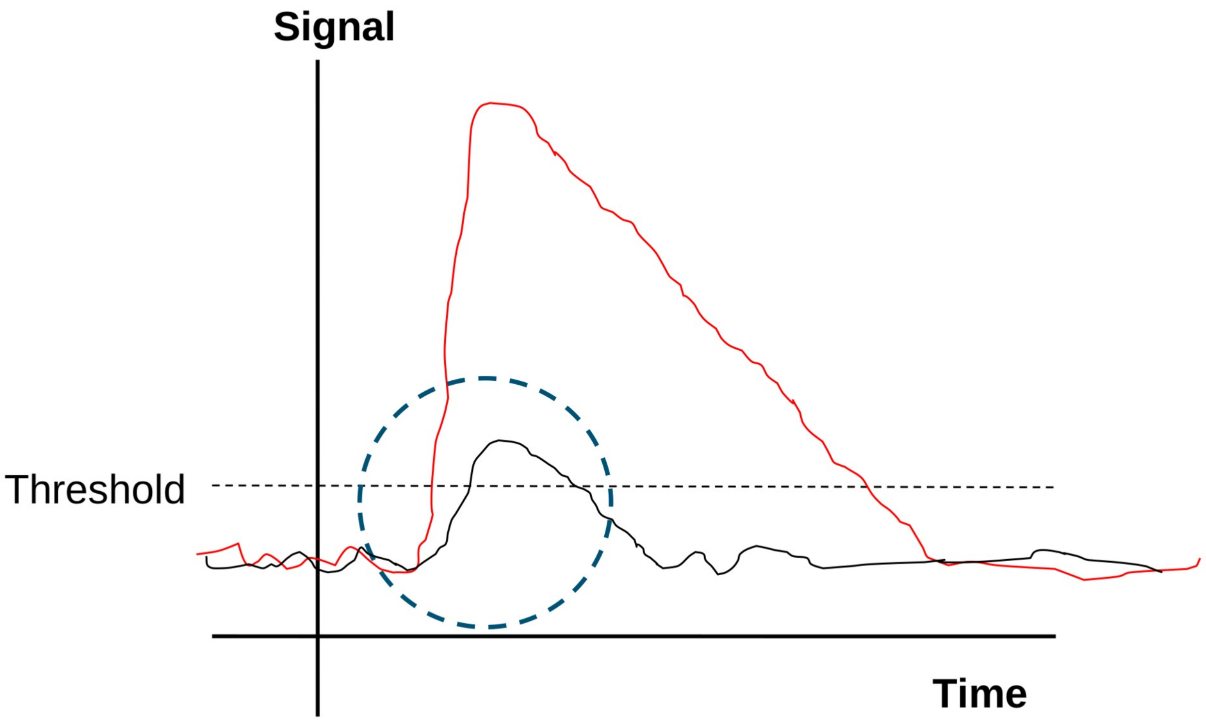
Note; in Si, 3.6 keV energy generates 1000 e-h pairs

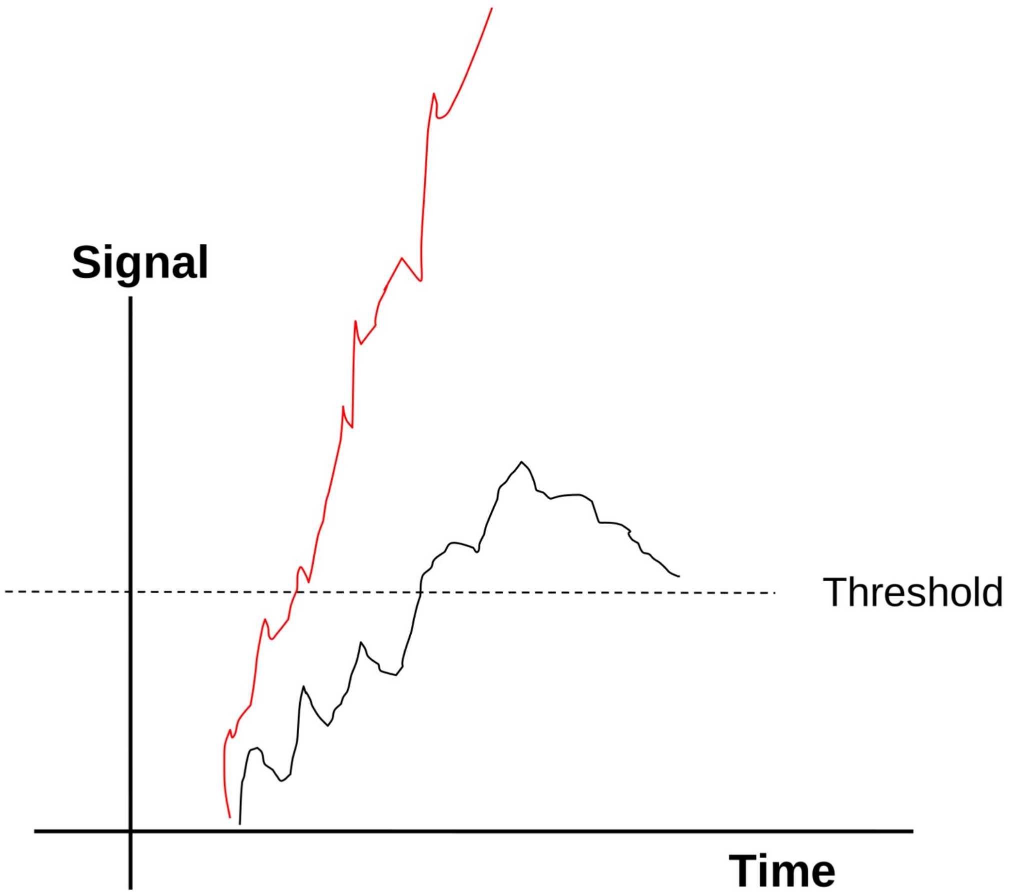
~0.7 ns FWHM for 12 keV photons

Some comments on time resolution

Timewalk

- Time delay before signal reaches threshold
  - Assuming instant signal, this depends on peaking time of amplifier response

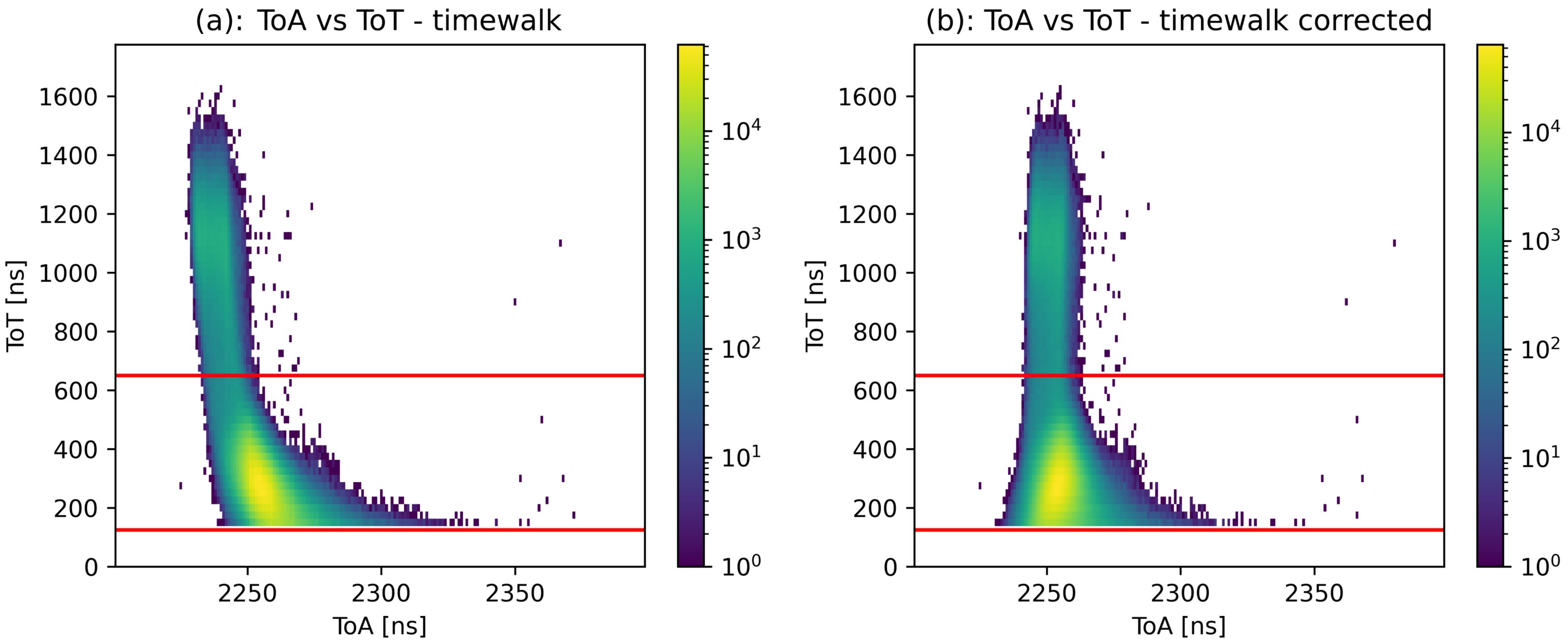




Some comments on the time resolution

First Experiments @ ESRF

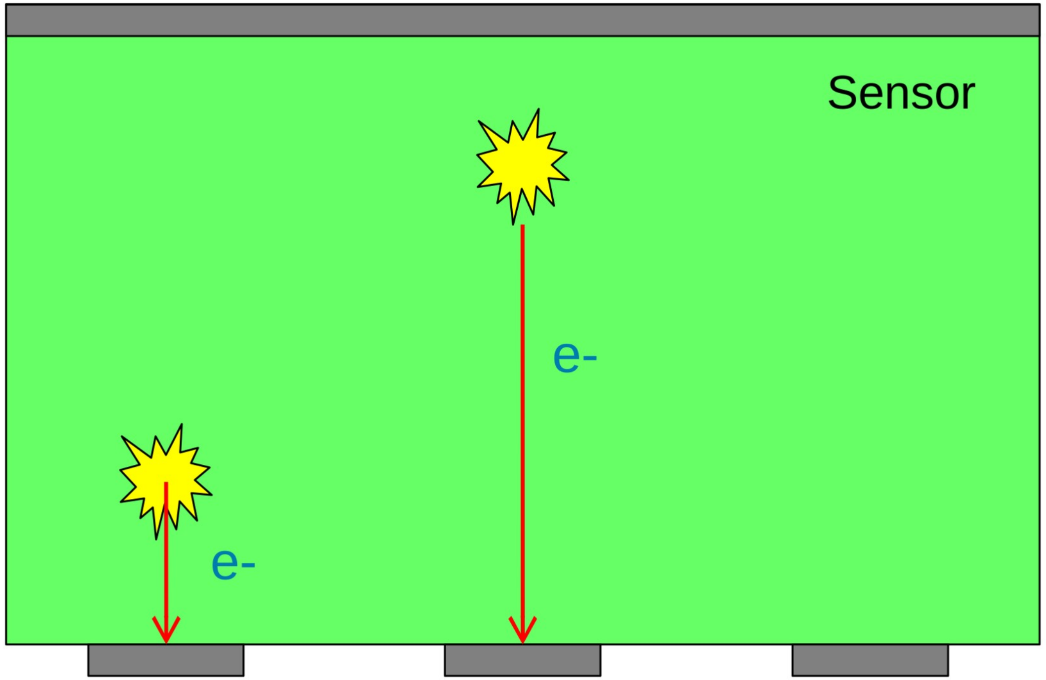
- Time-walk correction
  - Helped to improved the time resolution obtained



Some comments on the time resolution

Signal speed

- Absorption depth leads to time variation of signal pulse
- Resulting time variation depends on both **absorption profile** and **carrier velocity**

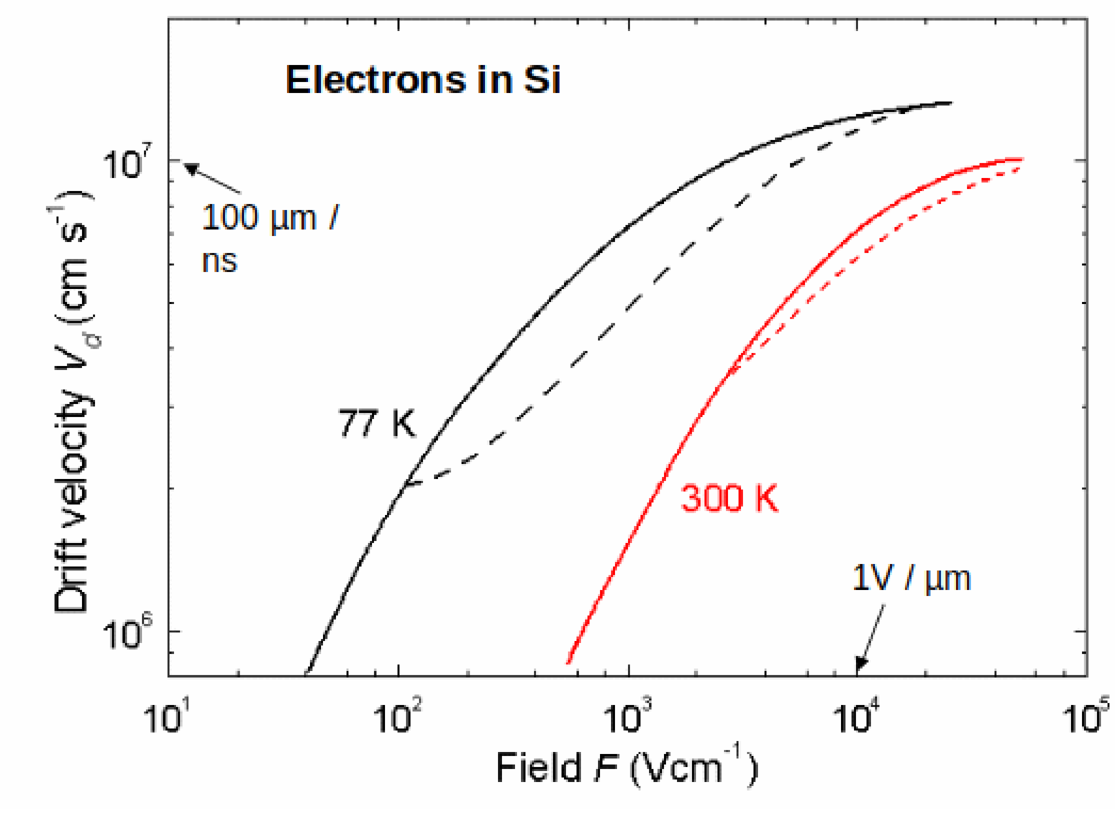


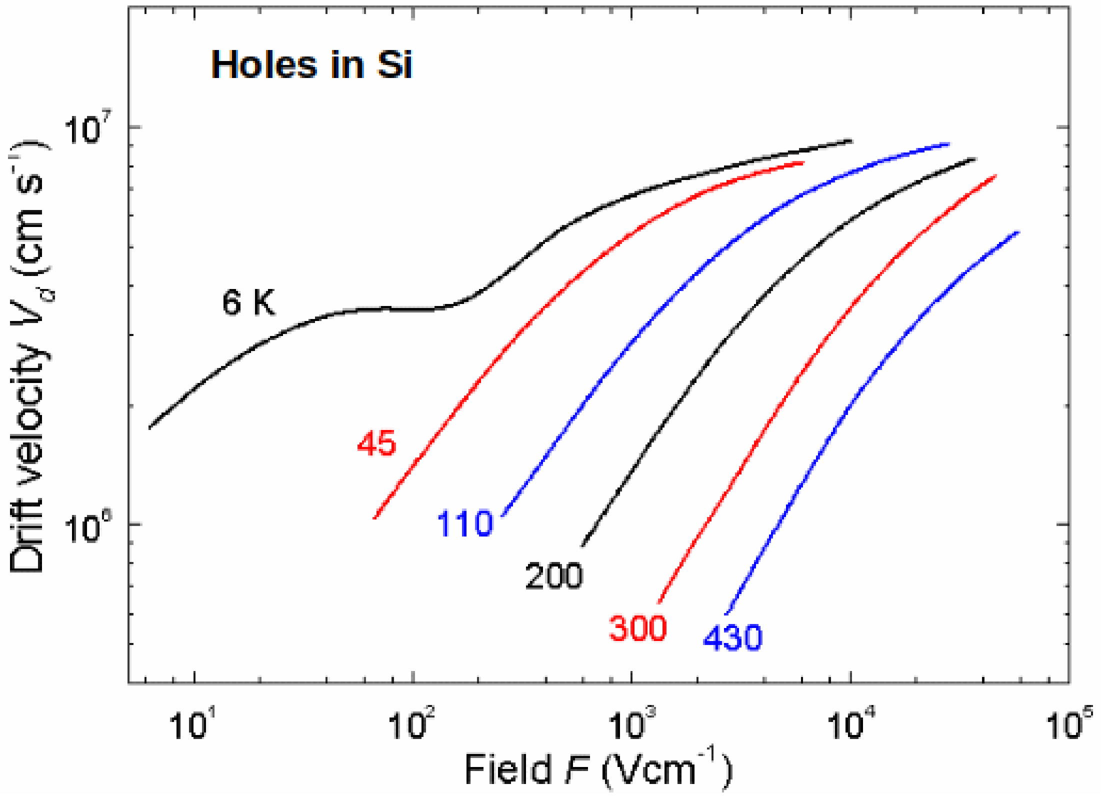
Electrons drift to readout

Some comments on the time resolution

Time resolution in Si sensors

- **Drift velocity depends on carrier type** (electron or hole) and **field strength**
- Hole-collecting sensor, 300 µm thickness, 100 V bias -> **20 ns** max drift time
- Electron-collecting sensor, 300 µm thickness, 300 V bias -> **5 ns** max drift time (~1.5 ns RMS)

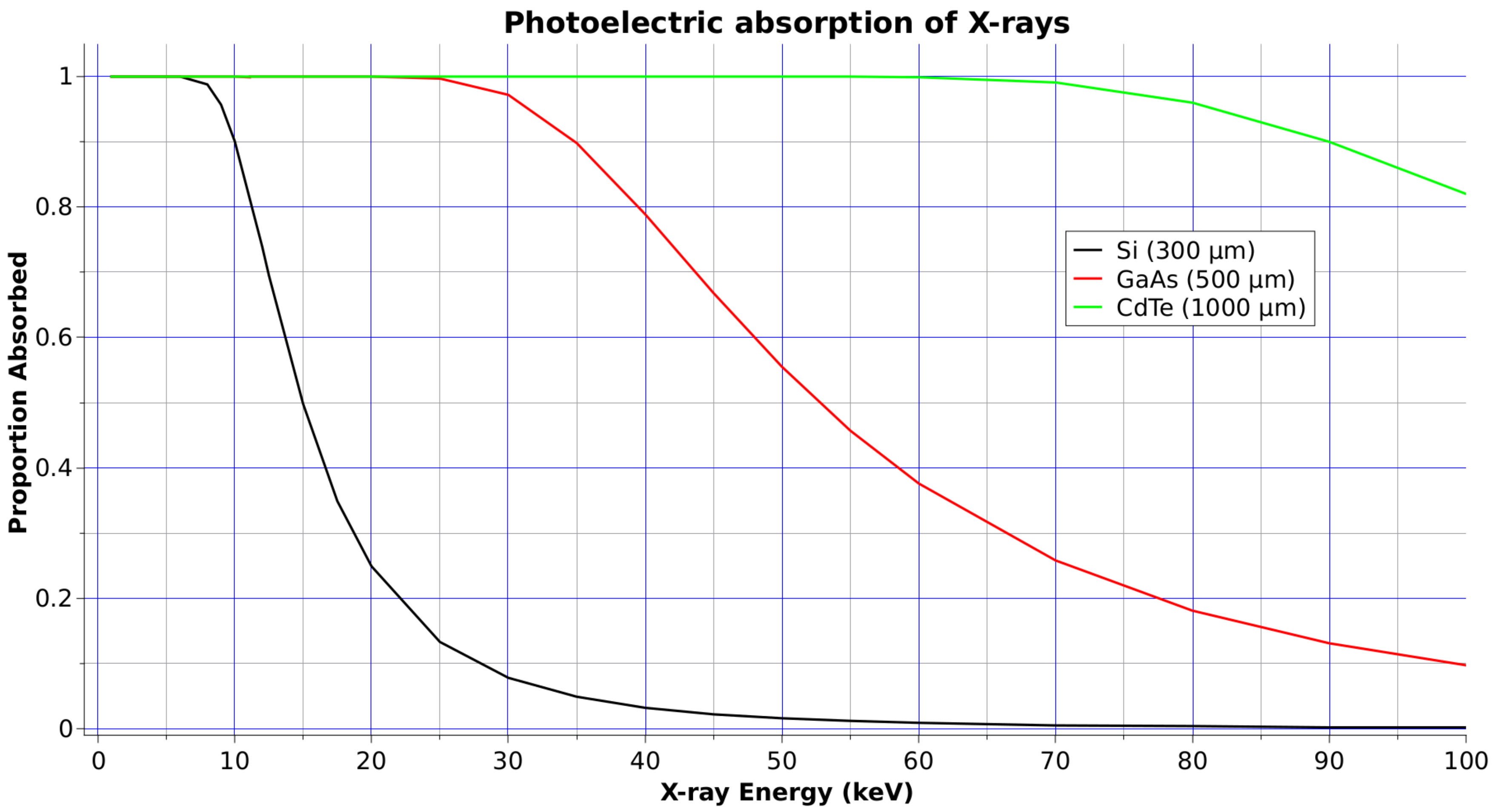




Some comments on the time resolution

High-Z materials

- High-Z materials can offer more localized X-ray absorption, improving consistency of drift time



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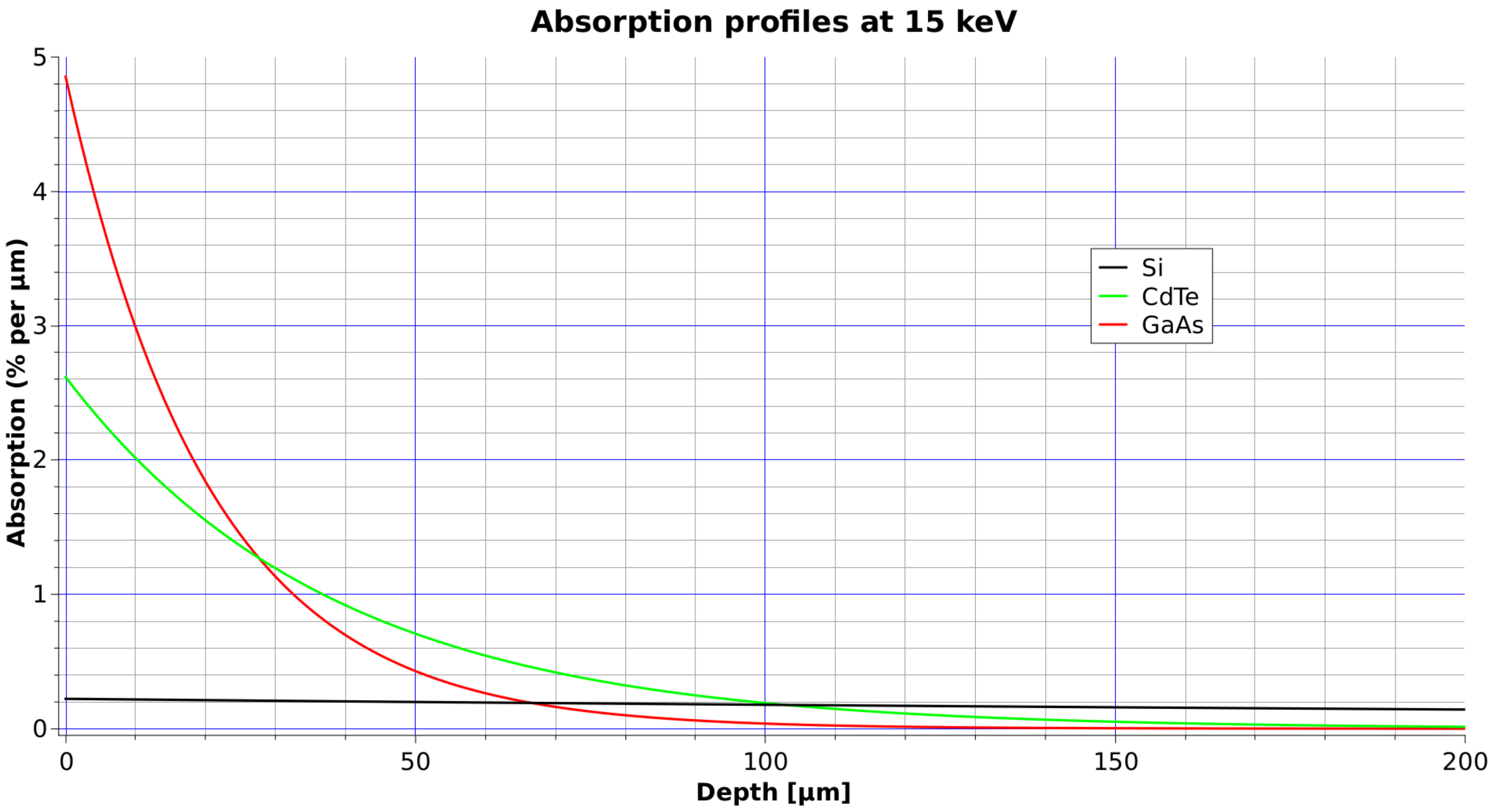
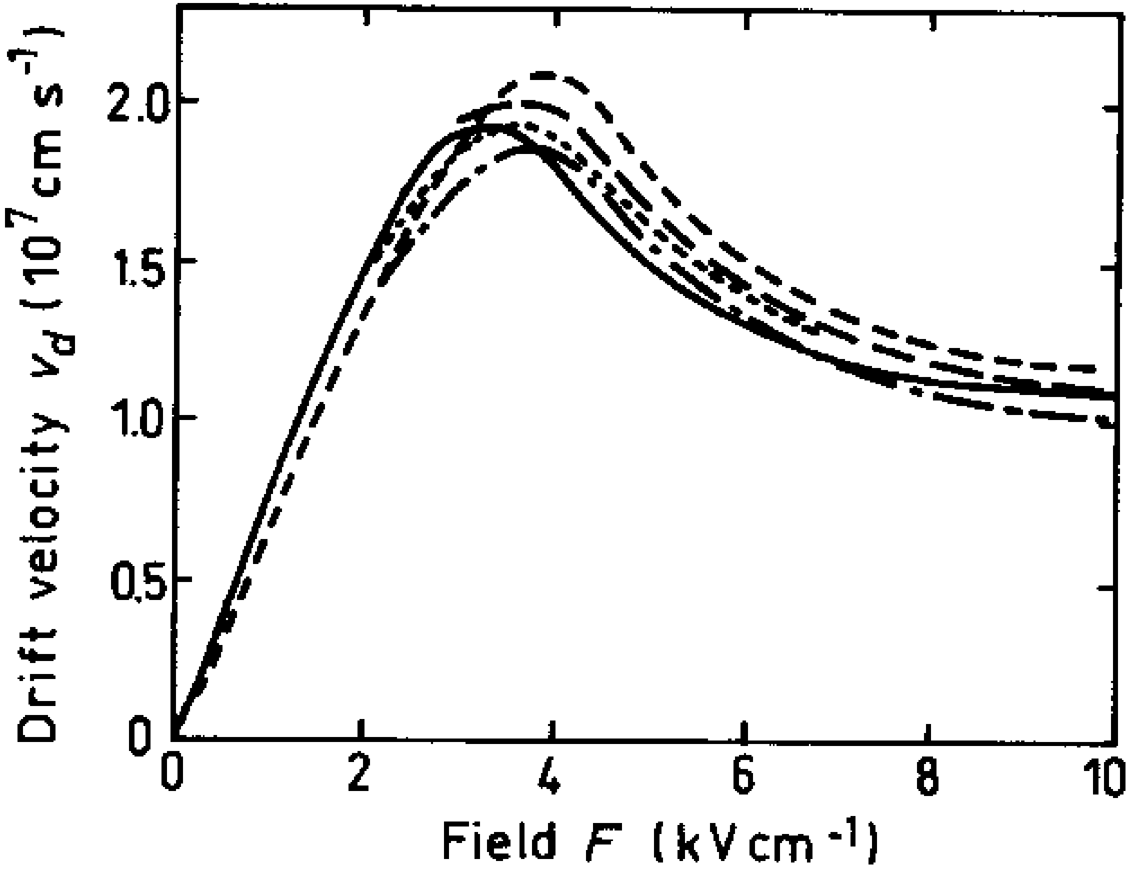
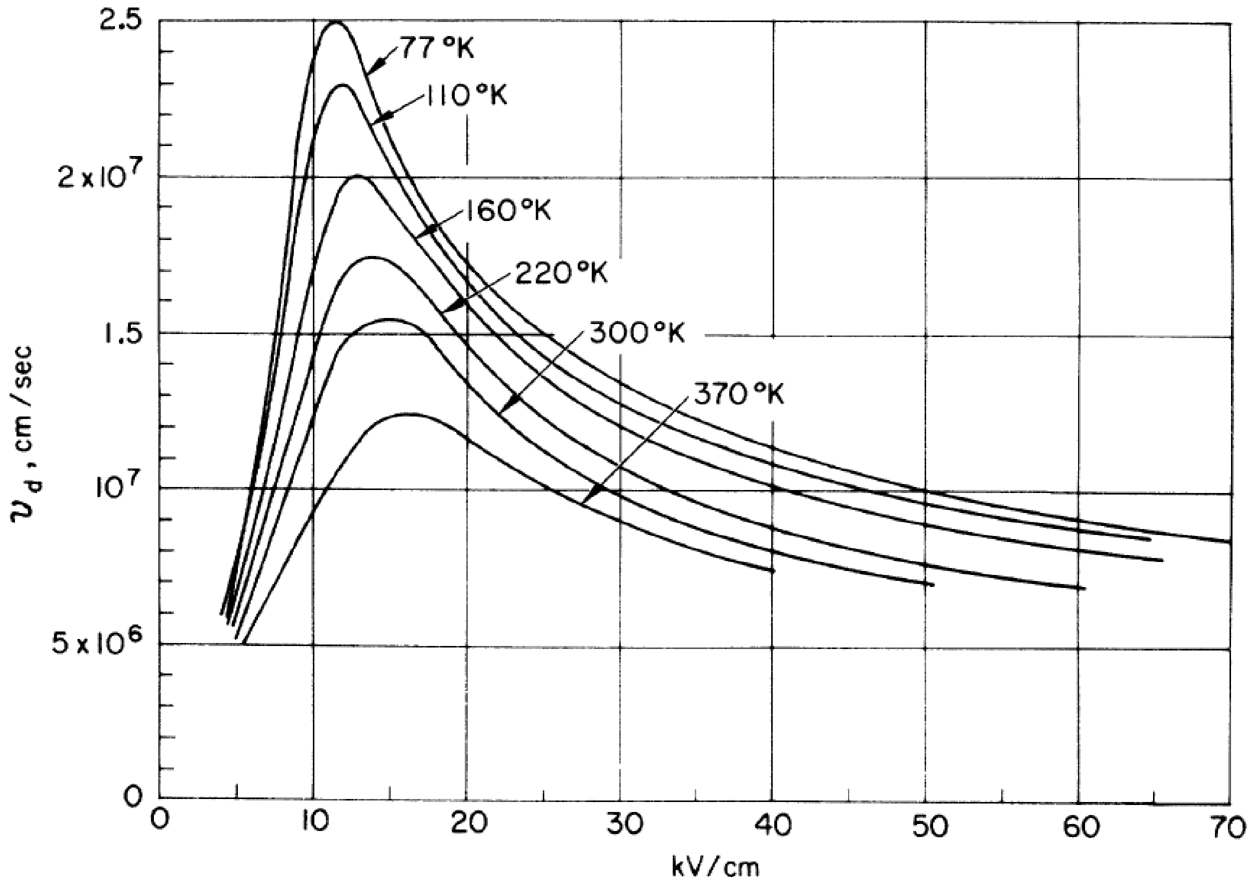


Some comments on the time resolution

Carrier mobility in high-Z semiconductors

- GaAs – high saturation velocity with “sweet spot” at ~4 kV/cm field (i.e. 200V with 500μm sensor)
- CdTe – comparable behaviour to electron-collecting Si, though high sensor thickness requires higher potential for given field strength (e.g. 500V bias for 5e6 cm/s velocity)





Some comments on the time resolution

Estimated drift time behaviour in different sensors

15 keV photons

	Si (h+), 300 µm, 100V	Si (e-), 300 µm, 300V	CdTe, 1000 µm, 500V	GaAs, 500 µm, 200V
RMS variation	2.86 ns	1,43 ns	0,76 ns	0,12 ns
Mean diff variation	2.46 ns	1,23 ns	0,56 ns	0,09 ns

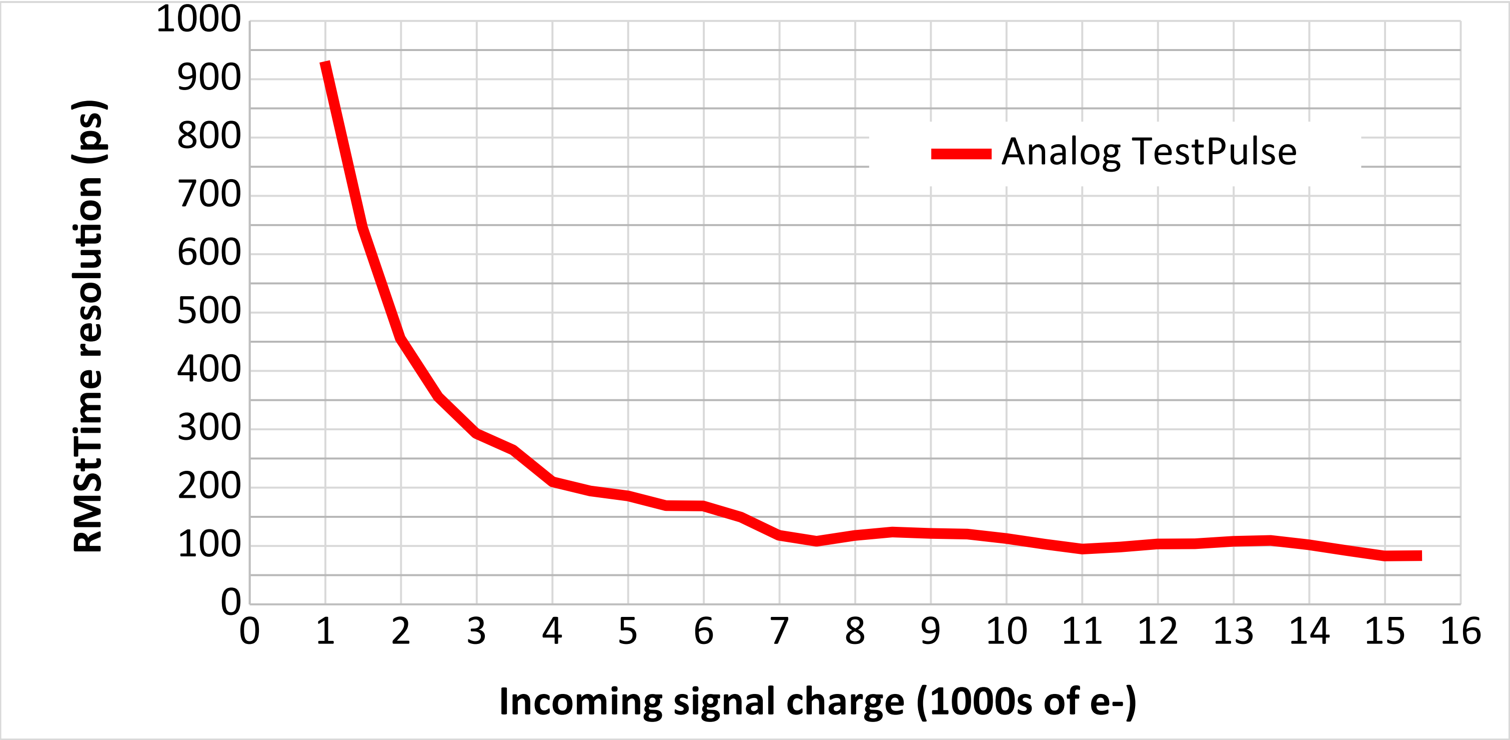
17.5 keV photons

	Si (h+), 300 µm, 100V	Si (e-), 300 µm, 300V	CdTe, 1000 µm, 500V	GaAs, 500 µm, 200V
RMS variation	2.88 ns	1,44 ns	1,16 ns	0,18 ns
Mean diff variation	2.48 ns	1,24 n	0,85 ns	0,13 ns

Some comments on the time resolution

Effects of material on signal magnitude and time jitter

- Mean electron-hole pair generation energy varies between materials, affecting time jitter:
  - Si – 3.6 eV per pair -> 4170 e at 15 keV -> 200 ps RMS jitter
  - CdTe – 4.45 eV per pair -> 3370 e at 15 keV -> 275 ps RMS jitter
  - GaAs – 4.2 eV per pair -> 3570 e at 15 keV -> 250 ps RMS jitter

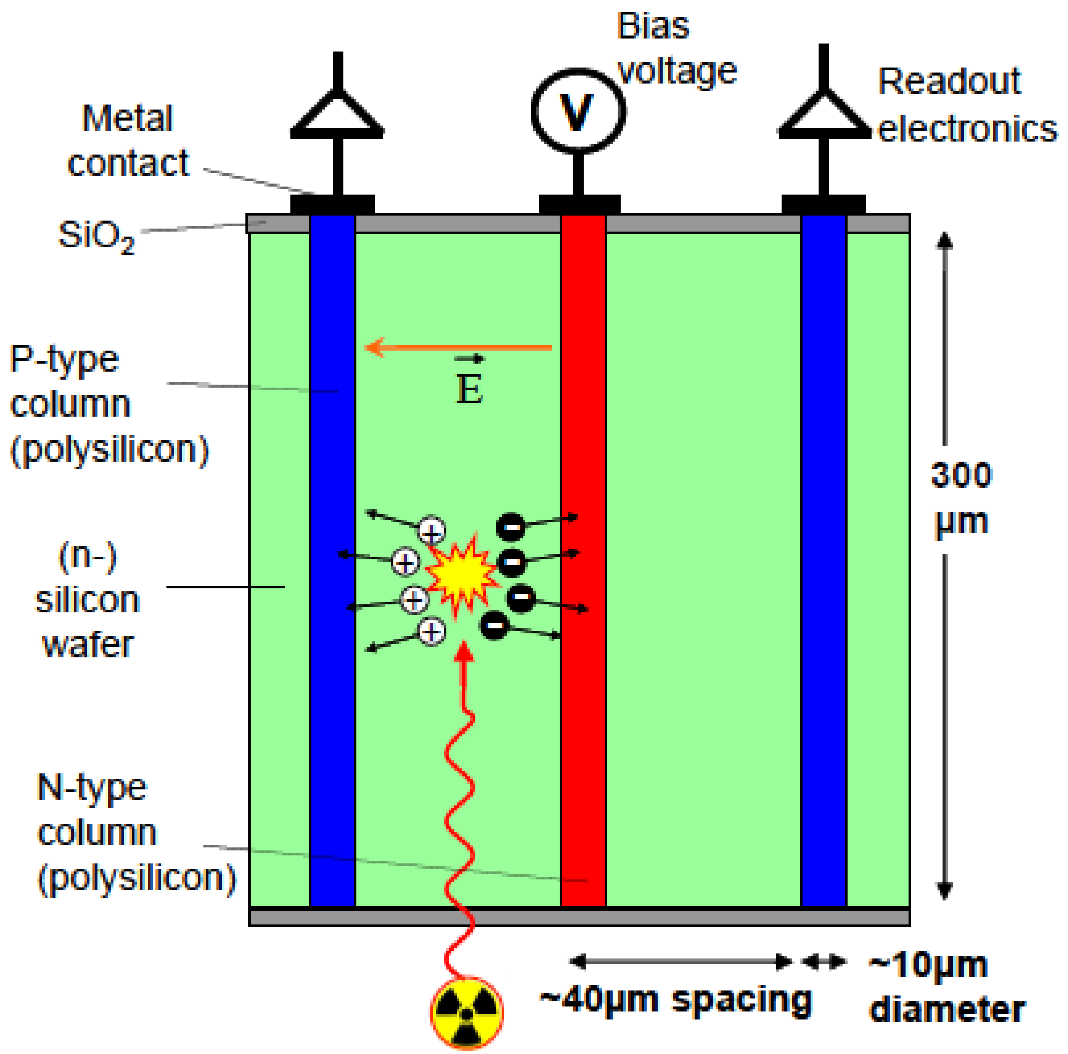


Time jitter would be main limiting factor for GaAs time resolution

Some comments on the time resolution

3D Silicon detectors

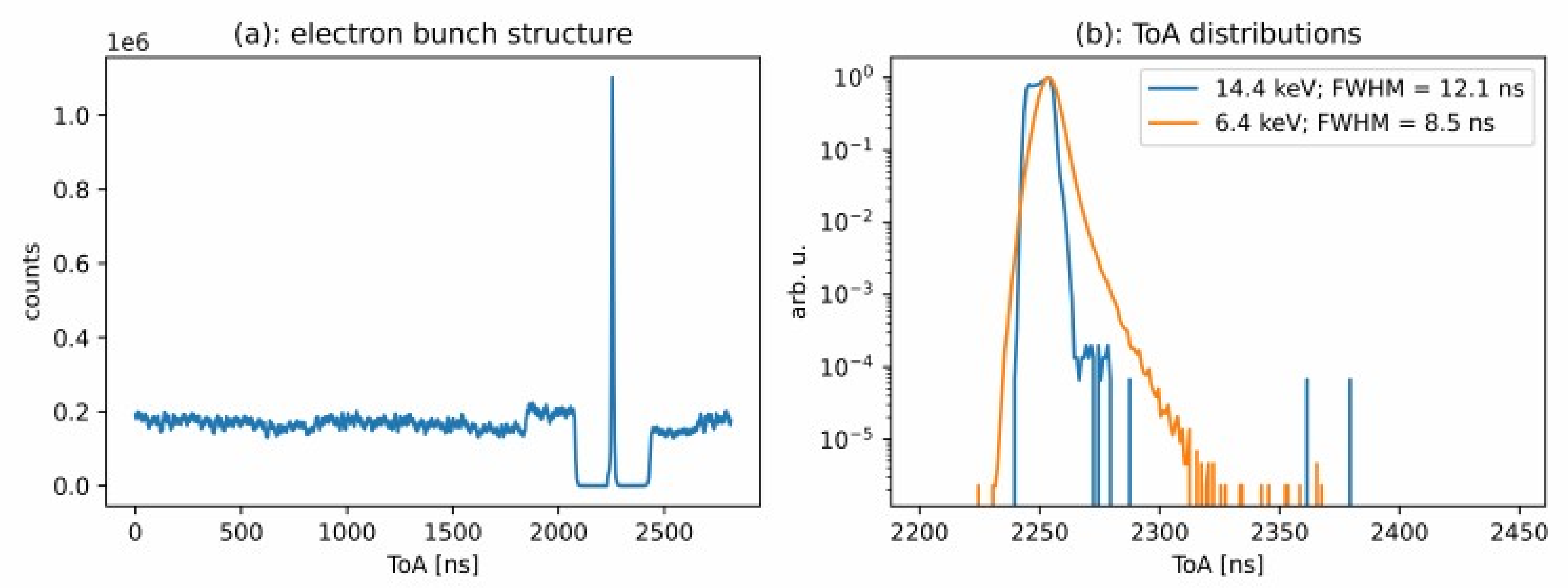
- Electrode columns pass through Si substrate
  - Up to 300 µm thickness
  - ~40 µm drift distance in Timepix4
  - Reduced charge sharing
- Time resolution:
  - 0.8 ns max collection time (~0.25 ns RMS)
  - Time jitter depends on energy
    - 0.25 RMS ns for 14.4 keV
- Detectors already used at ATLAS



TEMPUS detector system first users beamtimes

First Experiments @ ESRF

- Campaign at ID14 in February on Nuclear Resonance Scattering
  - Improved sensor bias (300 um, **200V**) and use of high-speed data links (1 x 1.28 Gbps)



Energy Calibration

Overview

Clustering

- Groups neighboring hits in space + time into single events
- Recovers energy from charge-sharing that would otherwise be split across pixels
- Produces cleaner ToT distributions with sharper peaks

ToT Analysis

- Construct histograms of clustered ToT values
- Peaks correspond to characteristic X-ray energies
- Gaussian fitting applied to determine peak positions
- Extracts precise ToT values that can be matched to known energies

Building Calibration Curve

- Collect ToT photopeak from different energies
- Build a relation ToT ↔ Energy
- Applied per pixel to correct response variations across the matrix
- Needed for improving time resolution (eg. Timewalk correction)

Clustering

Handling charge sharing

Charge Sharing

- Energy from one photon spreads into multiple neighboring pixels
- Clustering recombines these hits into a single physical event

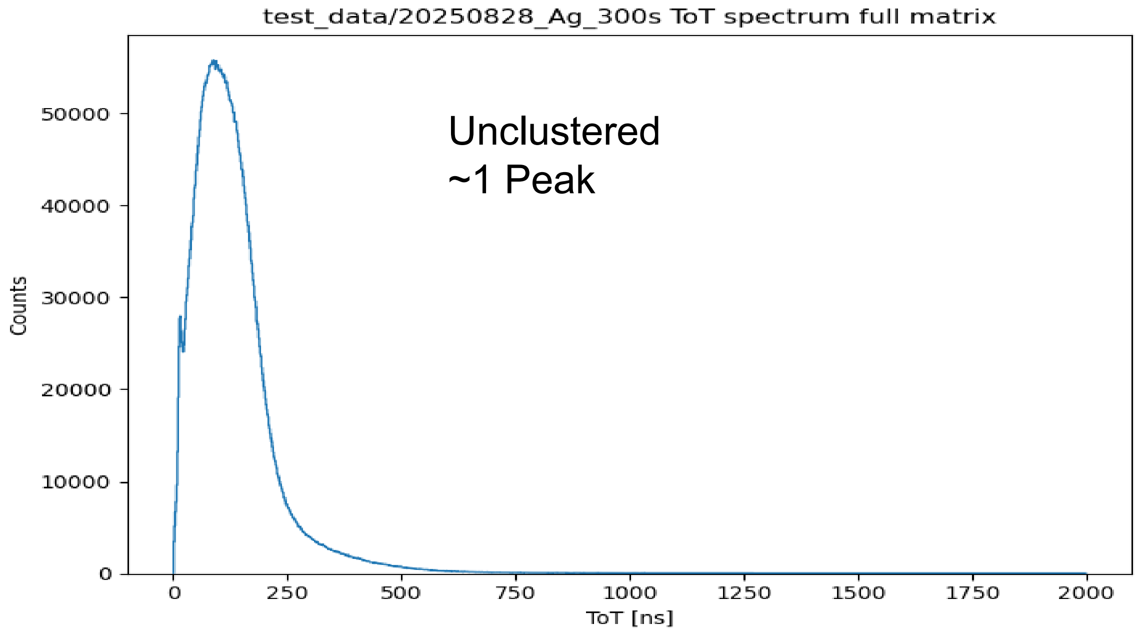
DBSCAN

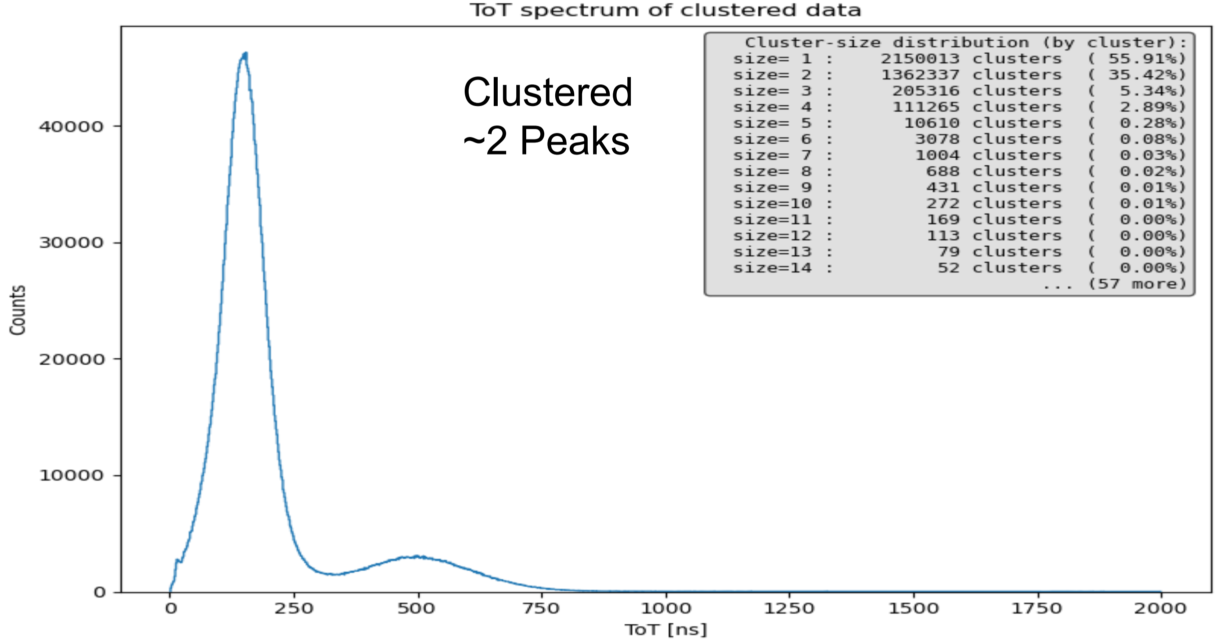
- Density-based clustering: forms a cluster if points have enough neighbors within ε
- ε (eps): max separation to count as neighbors (units: px, px, ns/50)
- Distance in 3D (x, y, t') with scaled time:

  $d = ((\Delta x)^2+(\Delta y)^2+(\Delta ToA/toa\_scale)^2)^{1/2}$

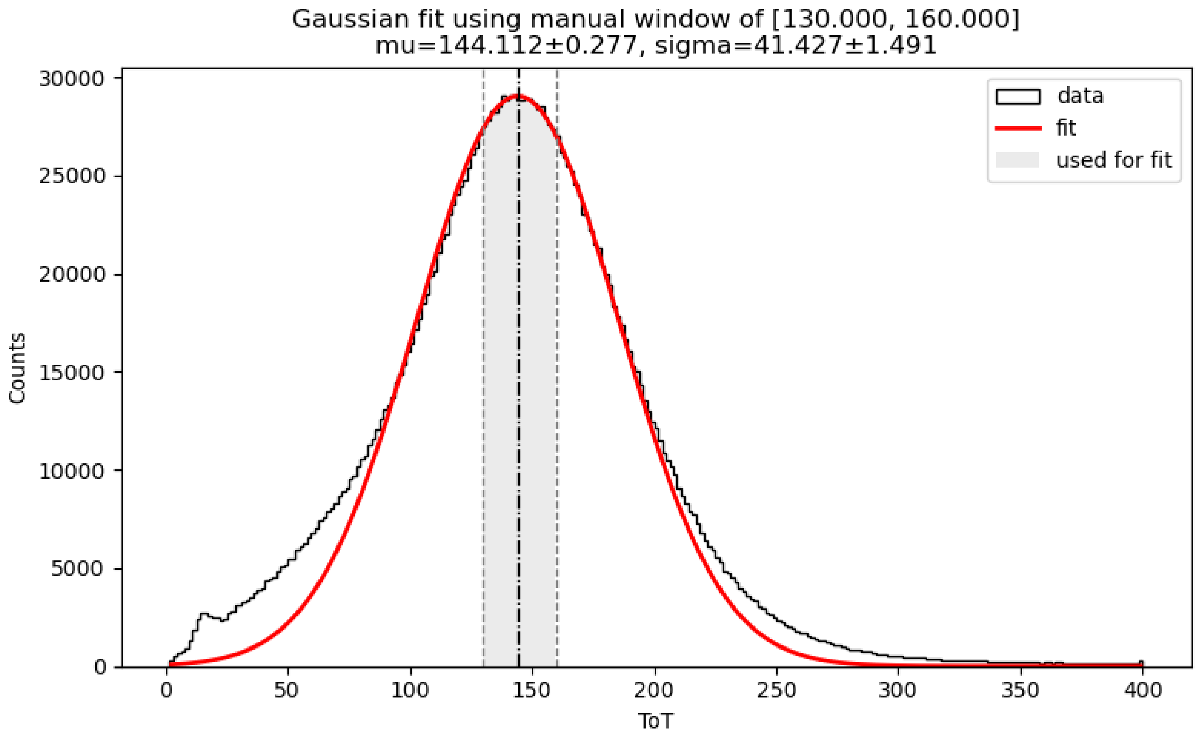
Handling Large Data Volume

- Enabled Parallelization inside DBSCAN
- Utilized built in ball tree algorithm to speed up neighbor queries
- Chunking by ToA to reduce memory/runtime





ToT Spectrum Analysis



Fitting the photopeak

- Build clustered ToT histogram
- Select fit window around the peak (exclude tails/Covariant Peaks)
- Fit Gaussian

Seed parameters from full matrix

- Estimate global seeds from full-matrix spectrum: μ_0 = mode/centroid of global peak, σ_0 from FWHM
- Reuse these seeds for faster per-pixel fits

Iterate per pixel

- For each pixel with sufficient stats:
  - build histogram
  - apply same fit window
  - fit Gaussian
- Require $N_{events} \geq N_{min}$ (e.g., 300–500) to fit reliably
- Below threshold → skip/flag pixel

Store photopeak center

- Save μ (ToT_ns) per pixel for the corresponding energy for the data

Build Calibration Curve

Preliminary Findings

- Collect calibration points by repeating ToT analysis at multiple known photon energies.
- Parametric calibration function used in Timepix:
  $$ToT(E) = aE + b - c / (E - t)$$
  - *a* linear slope term (how ToT grows with energy)
  - *b* offset (baseline shift)
  - *c* curvature term (corrects non-linearity, especially at low energy)
  - *t* effective threshold parameter (shifts the curve near threshold)
- In practice:
  - At higher energies, the relation is almost linear (dominated by *a* and *b*).
  - At lower energies, *c* and *t* adjust for threshold effects and front-end non-linearities
- Calibration done pixel-by-pixel to correct variations across the 512 × 448 matrix.
- Test pulse data is needed to fully determine the calibration curve, especially the low-energy part.