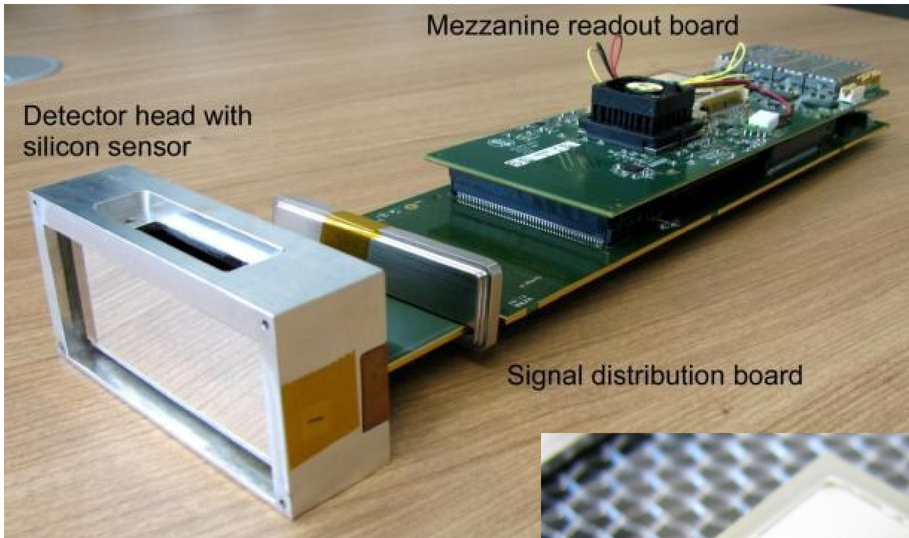
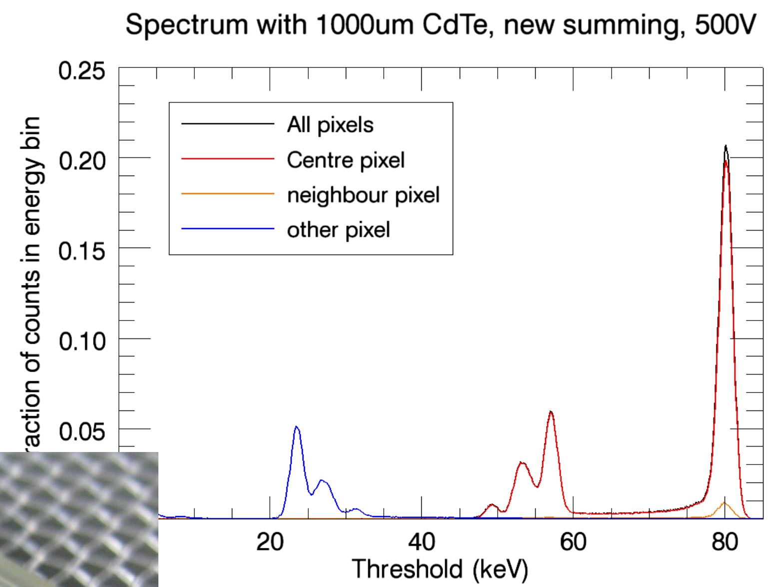
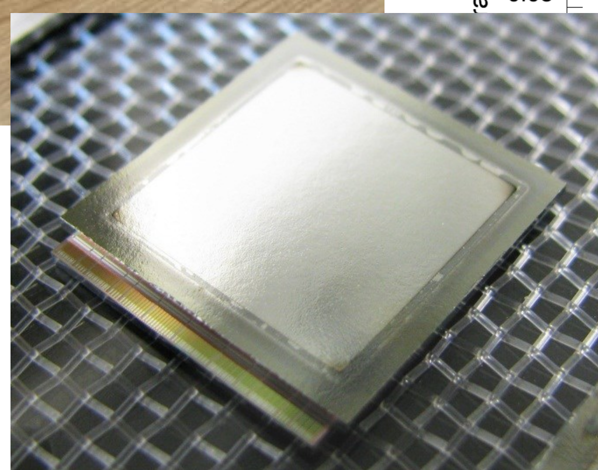
LAMBDA, High-Z sensors and the HORUS simulation tool

David Pennicard - *DESY*





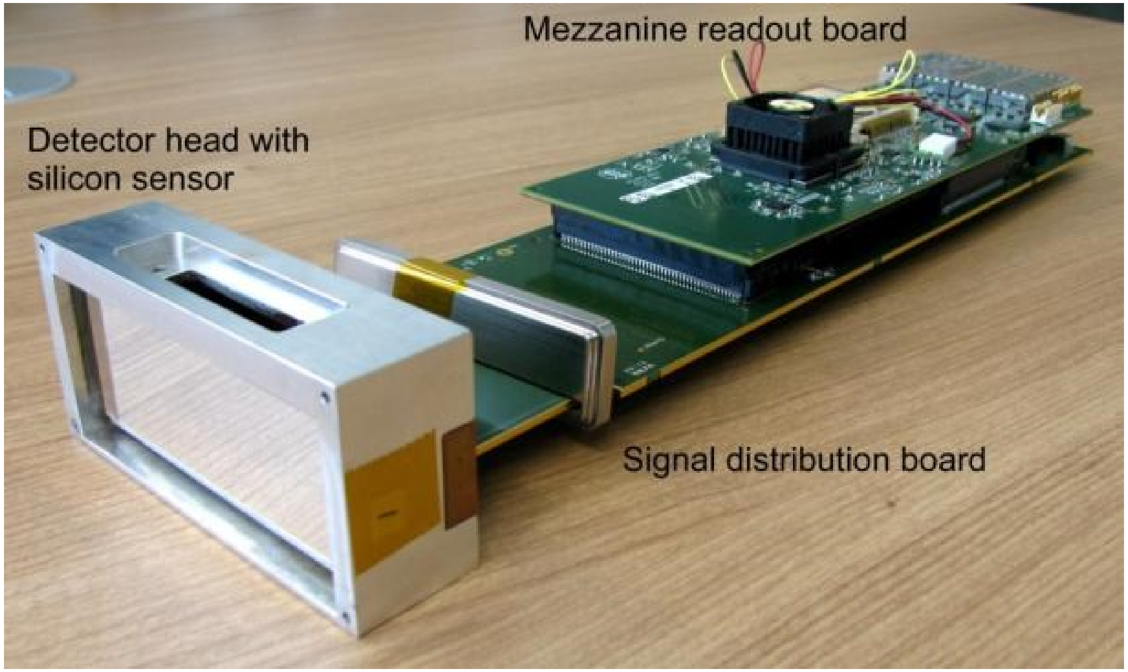


Overview

- LAMBDA (Large Area Medipix3-Based Detector Array)
  - Photon-counting detector for PETRA-III
  - Basis for high-Z sensor development
- High-Z pixel detector development
  - Germanium
  - Gallium arsenide
  - Cadmium telluride
- HORUS simulation tool
  - Medipix and high-Z sensor example

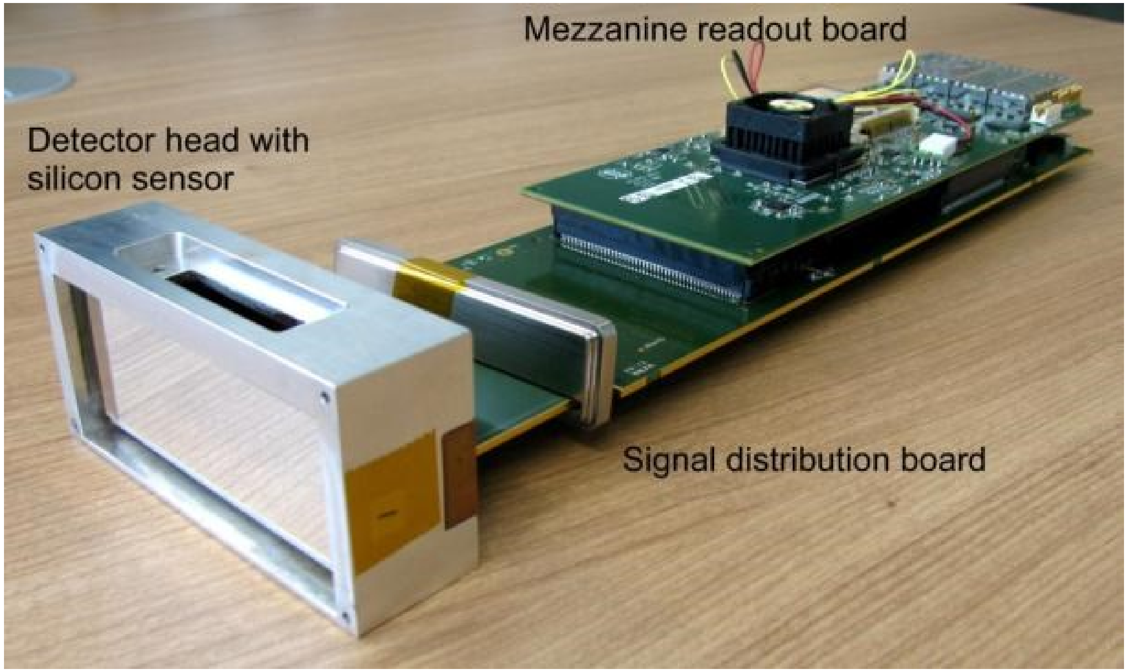
Large Area Medipix3-Based Detector Array (LAMBDA)

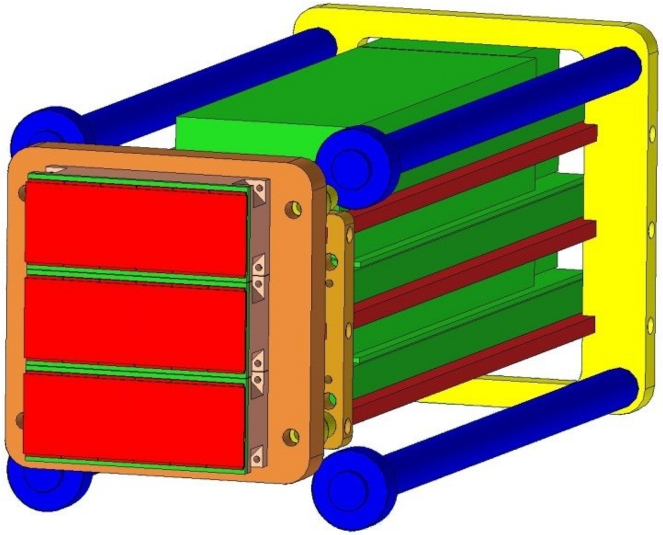
- David Pennicard, Sergej Smoljanin, Sabine Lange, Bernd Struth, Helmut Hirsemann, Milija Sarajilic, Heinz Graafsma – DESY
- Michael Epple – Technical University of Munich
- Thanks to the Medipix3 collaboration



Large Area Medipix3-Based Detector Array (LAMBDA)

- Photon-counting hybrid pixel detector based on Medipix3 chip
- 55µm pixel size, tileable layout 1536 x 512 pixels (85mm x 28 mm)
- High-speed readout up to 2000 frames per second (in progress)
- Compatible with high-Z sensor materials

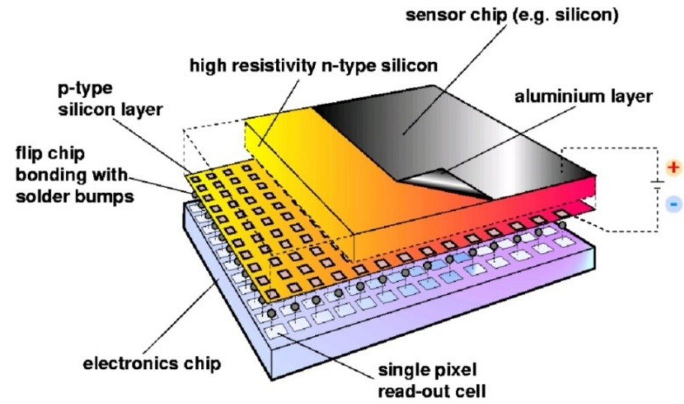




3-module system

Medipix3 readout chip

- CERN-led collaboration (20 institutes)
  - Flexible design
  - 256 by 256 array of 55µm pixels

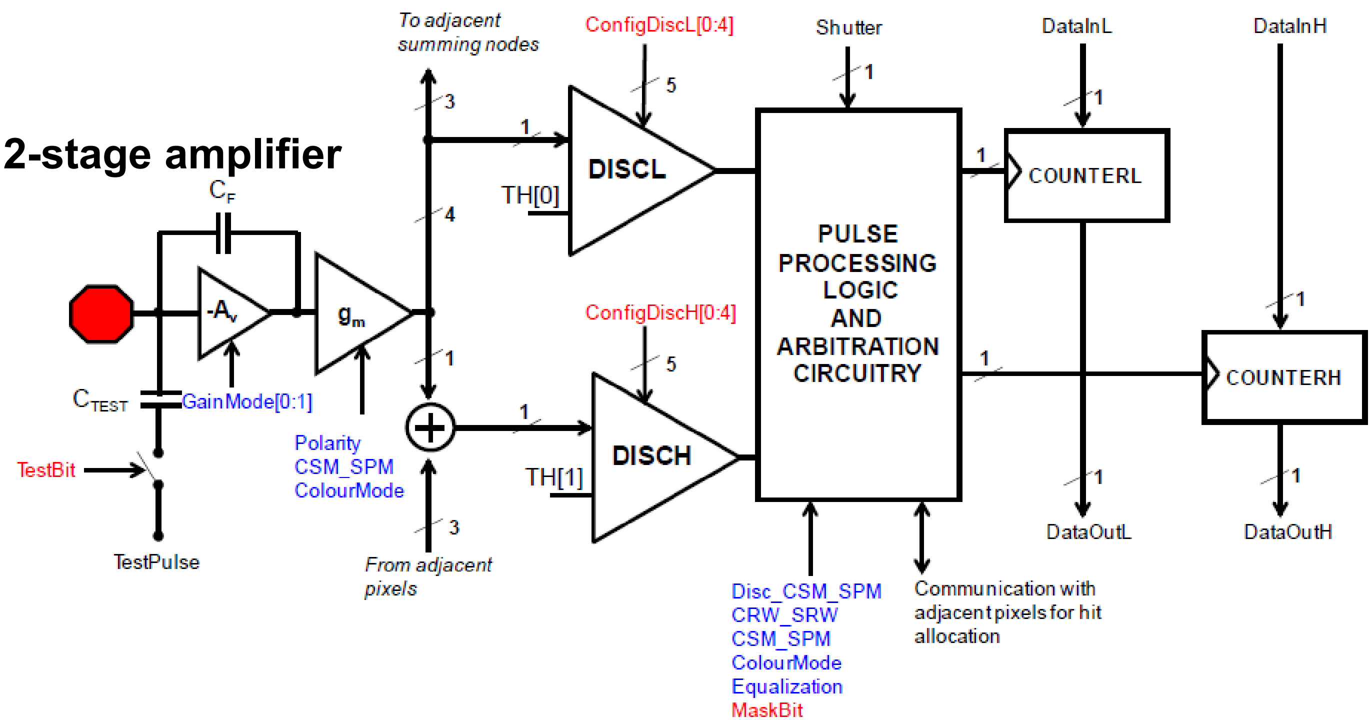


2 photon-counting thresholds available

Interpixel communication

2-stage amplifier

2 x 12-bit counters per pixel

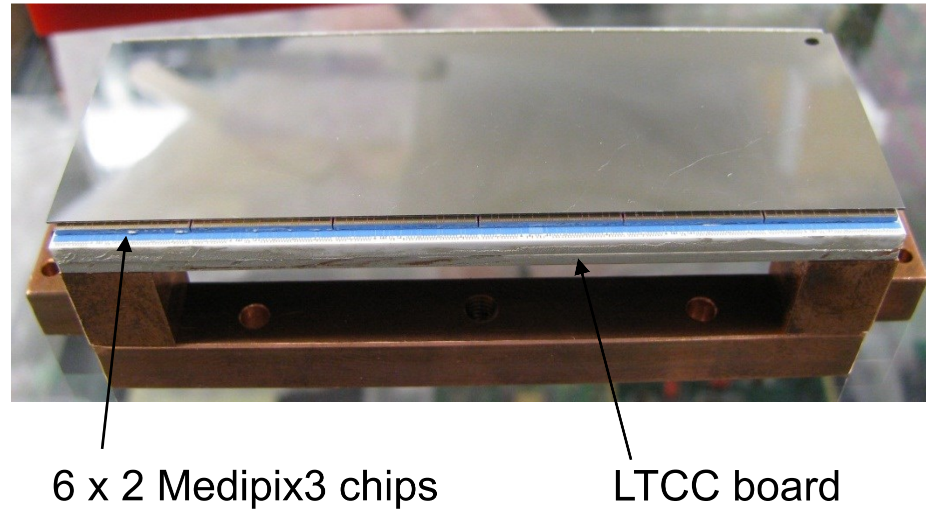


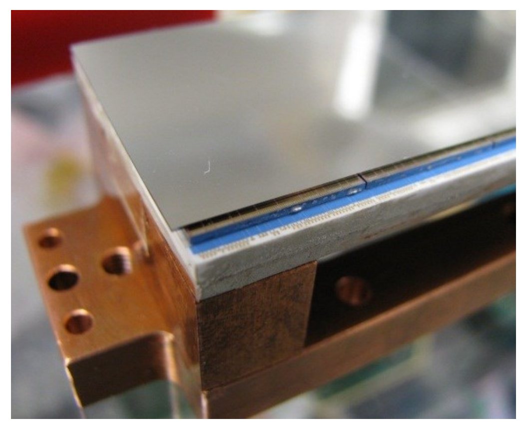
Medipix3 readout chip

- Synchrotron use – 2 counters for deadtime-free operation
  - 2000 frames per second with 200MHz readout & 12-bit depth
  - 4000 frames per second (+?) with 6-bit depth
- But also possible to have 24 bit counter depth, multiple energy bins …
- Charge summing compensates charge sharing (more later in simulation part)

Detector head

- 6 by 2 chips (1536 by 512 pixels)
  - Large Si sensor
    - 300µm Si sensor here
  - 2 x “Hexa” high-Z sensors
- Ceramic circuit board (LTCC)
  - Good match to semiconductor CTE
  - Cooling through thermal vias
- 500-pin connector on board
  - Full parallel readout (8 LVDS data outputs per chip)





High-speed electronics

- DESY high-speed readout card (also used for AGIPD and PERCIVAL)
  - Virtex-5 FPGA with PowerPC
  - Up to 4 * 10 Gigabit Ethernet links
  - DDR2 RAM (8GB)
- “Signal distribution” board connects to det. head
  - Space for vacuum barrier with germanium detector

10GE links

Connector to det. head

Power / trigger in

High-speed electronics

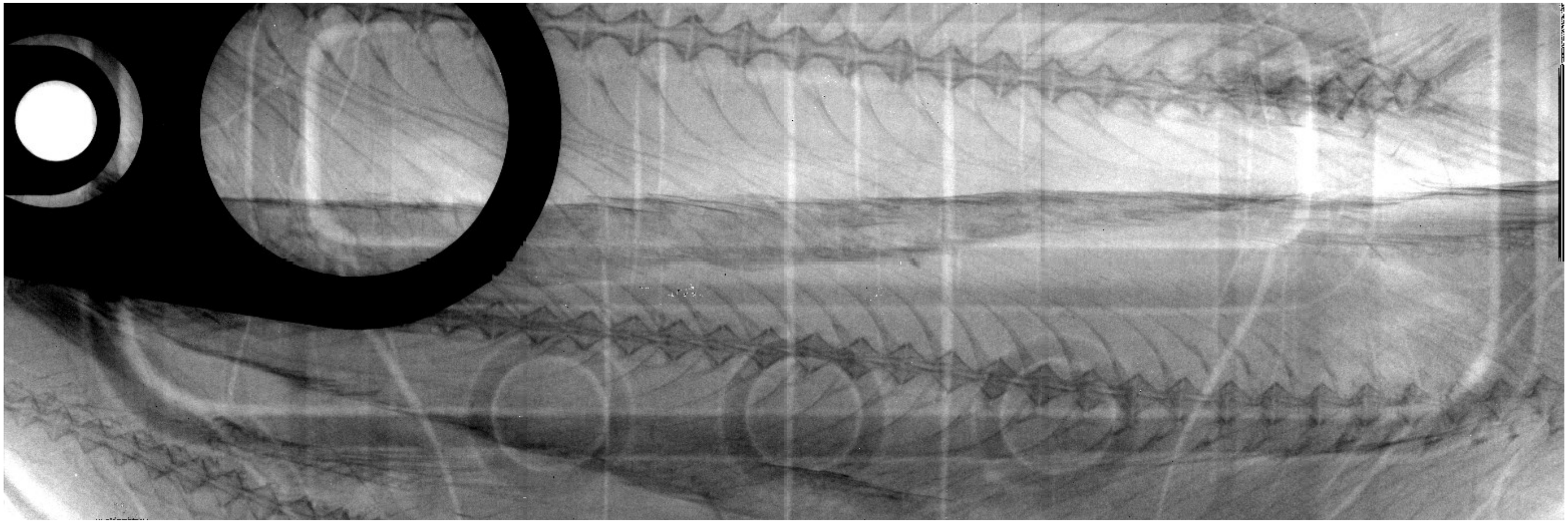
- Firmware development
  - 1 GE link for control and monitoring
  - Currently 1 x 10G readout
    - Recently tested at 750 fps
  - Plan 3 x 10G readout for 2000 fps
- Data rate challenge!
  - Get ~1GB/s with one 10GE link
  - Rely on server PC with 256GB RAM
  - Limited run period before writing data to disk at lower speed

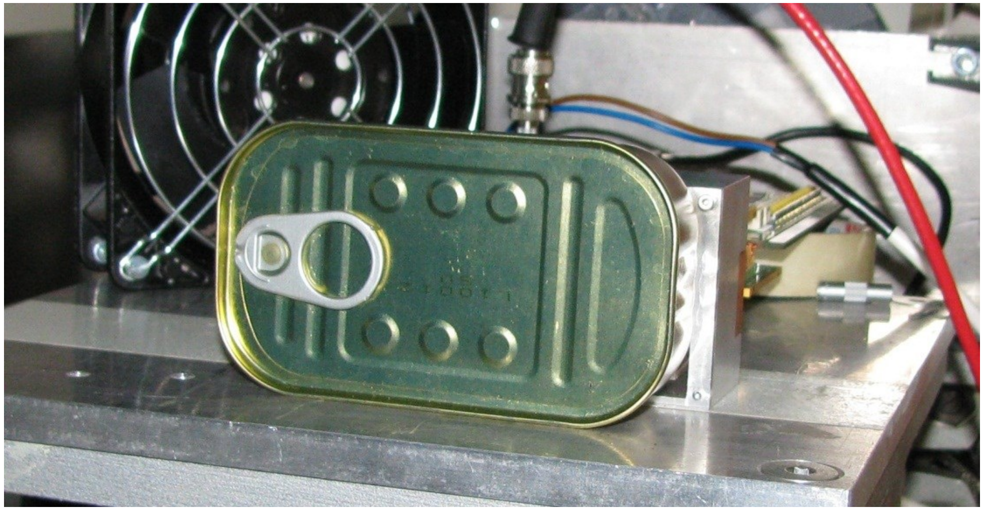
10GE links

Connector to det. head

Power / trigger in

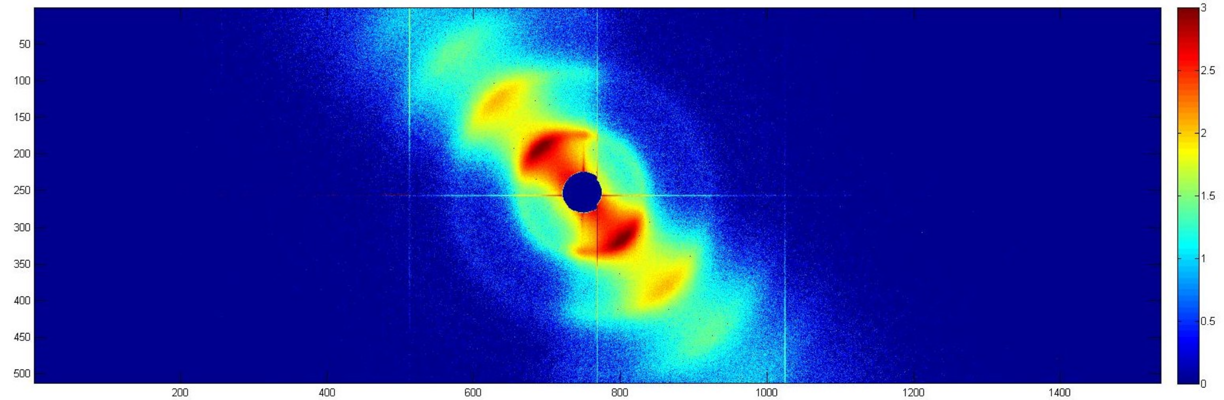
Test results with Si module





Work with LAMBDA detector

- Rheology experiments at PETRA P10
  - Taking advantage of small pixel size
- Plan to use in XPCS (P10) and SAXS (P03) experiments
  - Small pixel size and high frame rate
- Tests with high-Z sensors also planned
- Currently working on more modules, and multimodule systems



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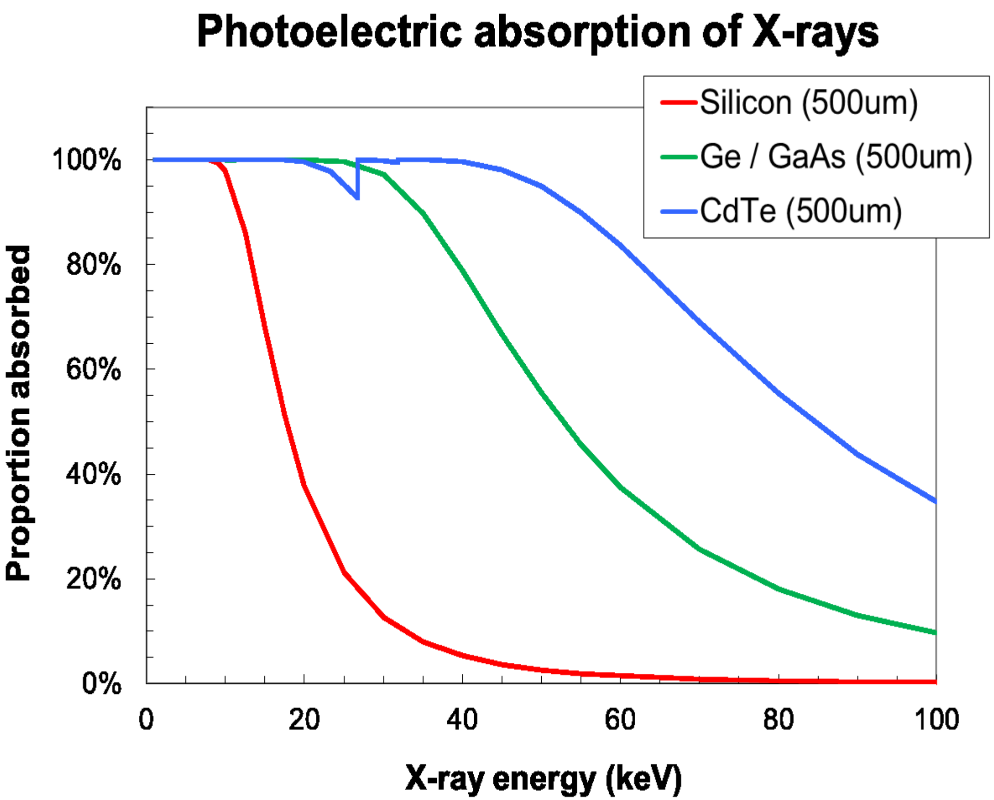
High-Z pixel detectors

- Aim: replace silicon sensor in LAMBDA with high-Z semiconductor
  - Combine high QE with hard X-rays, high frame rate, high signal-to-noise
- Investigating different materials in collaboration with other institutes and industry
  - Germanium
  - Gallium arsenide
  - Cadmium telluride



Germanium pixel development

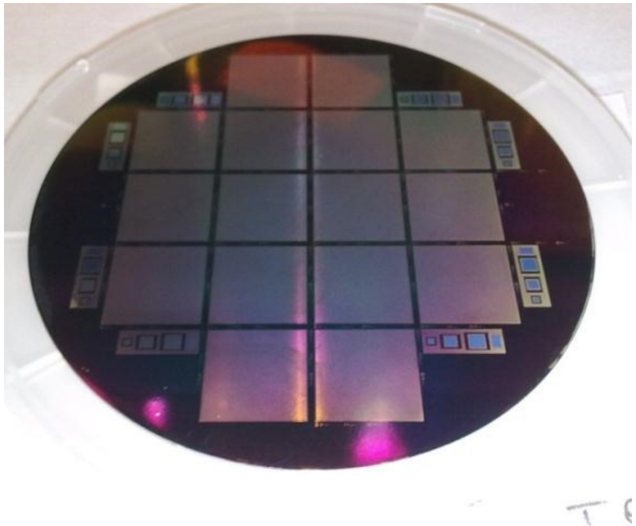
Canberra France (Lingolsheim): M Lampert, M Zuvic, J Beau

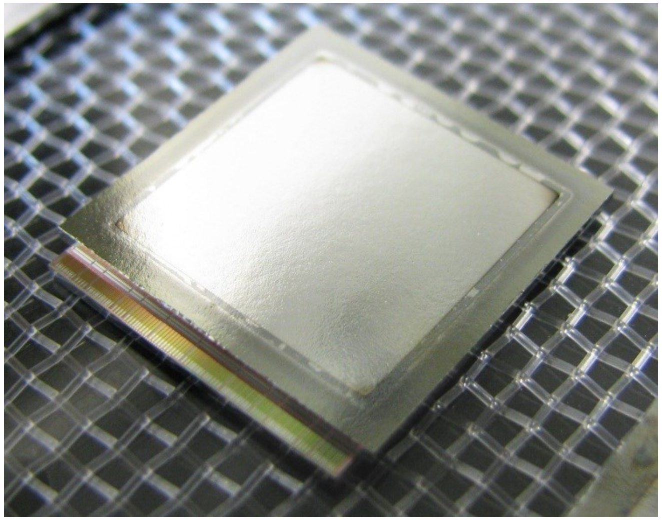
Fraunhofer IZM (Berlin): T Fritzsch, R Jordan, M Rothermund

- High-purity, high uniformity 90 mm Ge wafers available
- Cooled operation needed to reduce leakage current and allow depletion
  - Small pixel and photon counting mean LN_2 temp not necessary
    - Canberra reported **-80°C** needed for good depletion
  - However, cooling *power* relatively high (~1W per chip)
  - Lambda module designed to be cooled
- *Fine pixellation and bump-bonding needed to be developed*

Pixelated Ge detector production

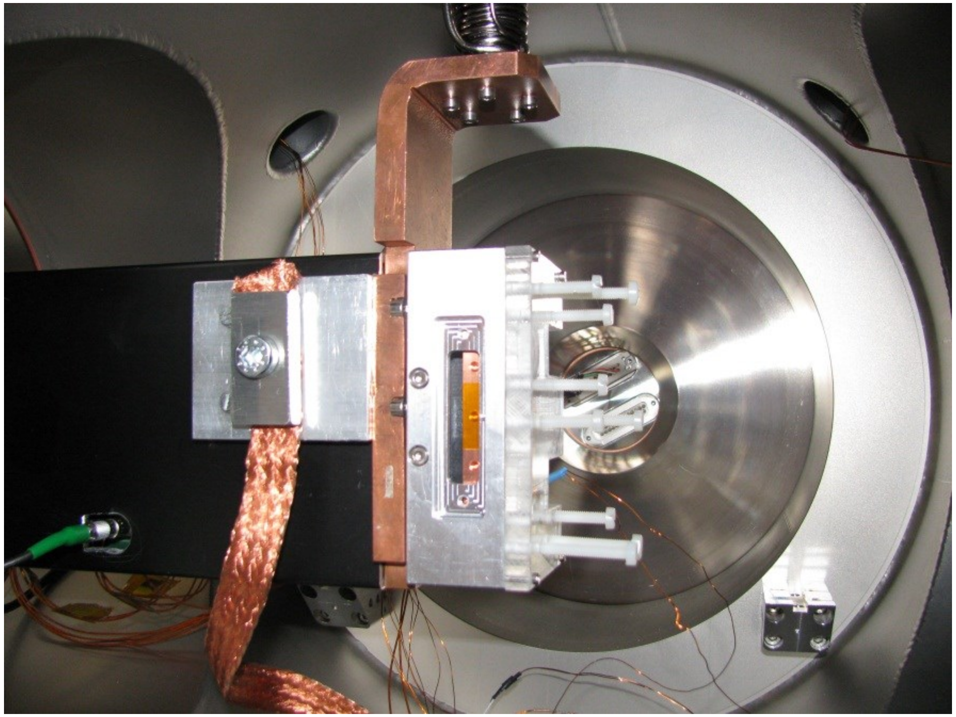
- Sensors produced by Canberra France based on existing strip technology
- 2 high purity Ge wafers produced
  - 16 Medipix3 singles per 90mm wafer
  - 55µm pixel size
  - ~700um thick
  - Electron readout
- Indium bump bonding at Fraunhofer IZM (Berlin)
  - Low-temperature process necessary to avoid damage to Ge
  - Ductility of indium prevents cracking of bonds during cooling





Testing of germanium sensors

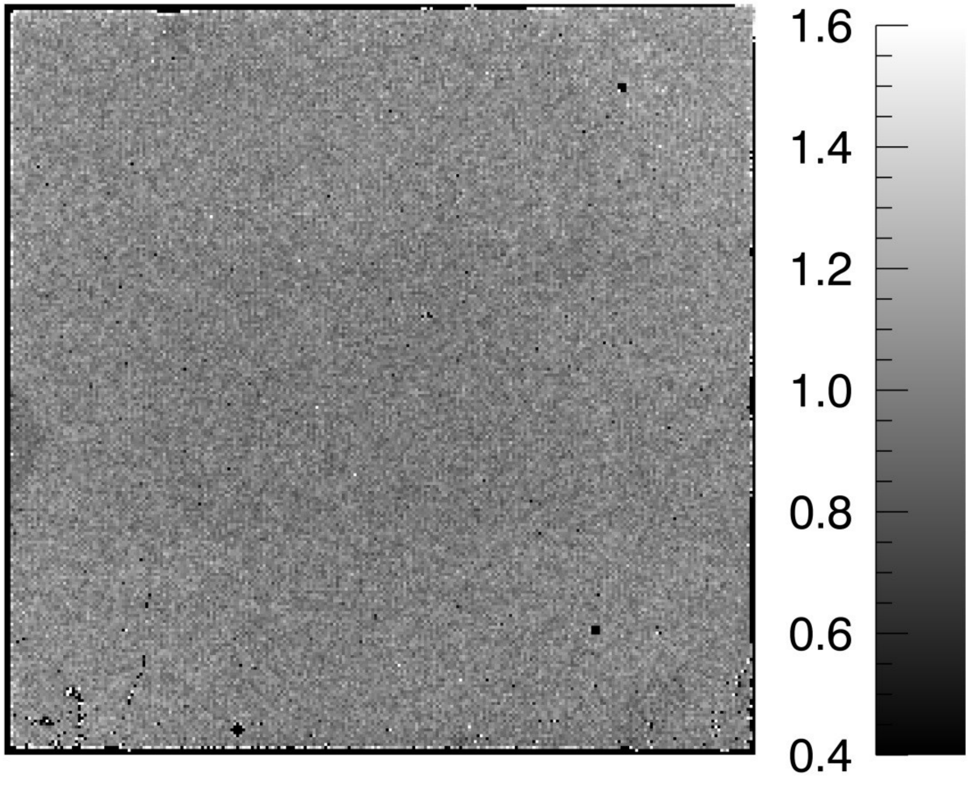
- Batches bonded to Medipix3.0 and Medipix3RX chips
  - Results from most Medipix3RX shown (very recent!)
- Mounted on standard LAMBDA ceramic board
- Full system mounted in vacuum chamber
- Cryotiger cooling
- Tested with miniature X-ray tube (Ag target)



Recent tests with Medipix3RX chips

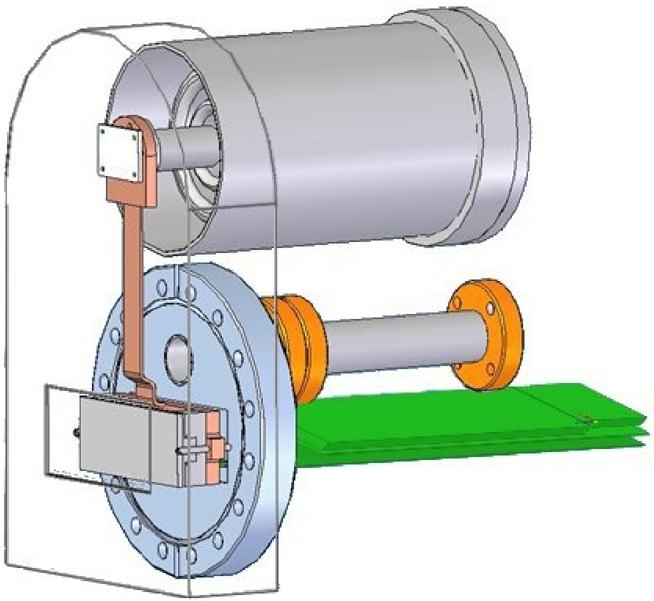
- Tested around -100ºC to -110ºC, 100V bias
- High pixel yield, generally uniform response
  - Edge pixels nonfunctional due to excessive leakage current

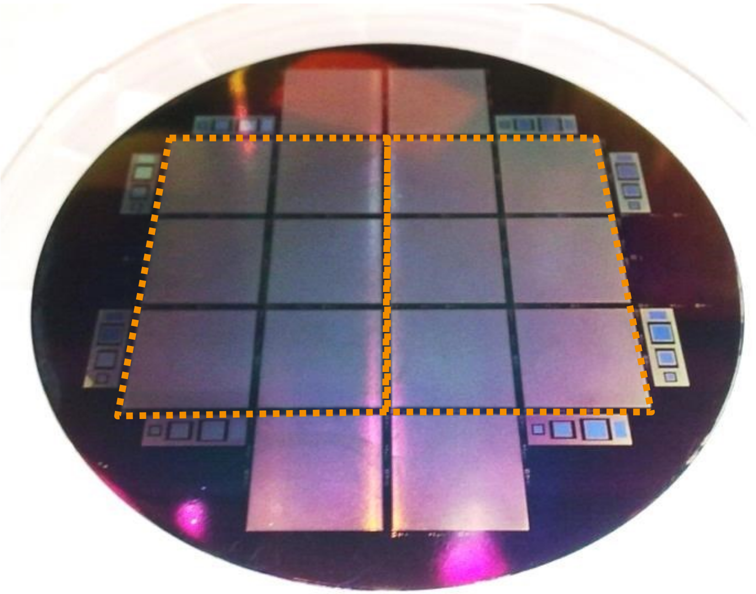
Flat illumination, Ag tube



Next steps with germanium

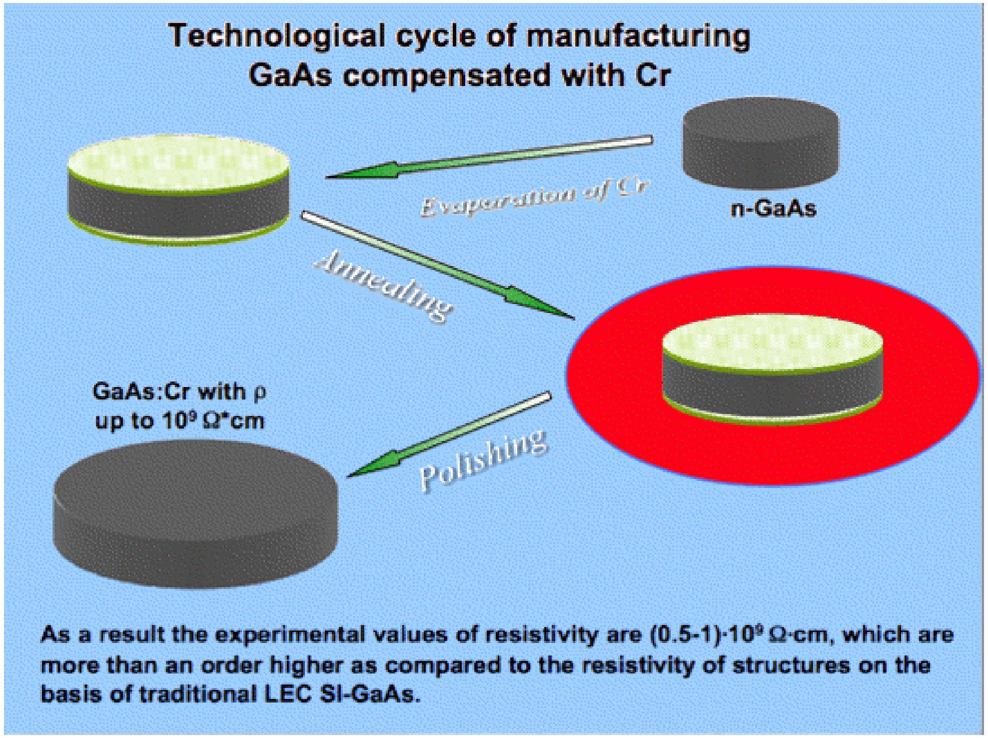
- Mechanics with high-speed readout outside vacuum
  - Vacuum barrier on signal distribution board
- Production of hexa sensors (3 x 2 chip, 768 x 512 pixel)
  - 2 per 90mm wafer
  - Requires overhaul of cooling system





Gallium arsenide

- GaAs already widely-used semiconductor
- Standard crystal growth can't produce detector-grade material
  - Either low resistivity or very short carrier lifetime
  - Various solutions tried
- Chromium compensation method at RID Ltd, Tomsk

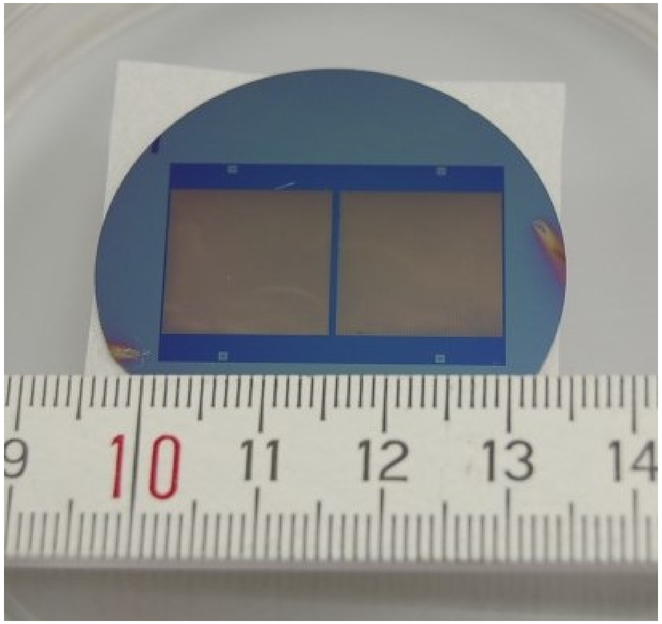


Galapad project (GaAs LArge Pixel Array Detector)

- German-Russian partnership project
  - RID Ltd (Tomsk) and JINR (Dubna) produce sensors
    - O Tolbanov, A Tyazhev, G Shelkov
  - FMF (University of Freiburg) bump-bond to Medipix
    - A Zwerger, A Fauler, T Baumbach, S Procz, M Fiederle
  - KIT (Karlsruhe) and DESY characterize and build readout system
    - E Hamann, A Cecilia

GaAs sensor production

- Single-chip devices
  - 256 x 256 pixels, 55µm pixel size
  - 500µm thickness, linear I-V response to -400V
  - Timepix or Medipix3.0 readout so far (Medipix3RX on the way)
- Hexa (3 x 2 chip) devices on 3” wafers in production

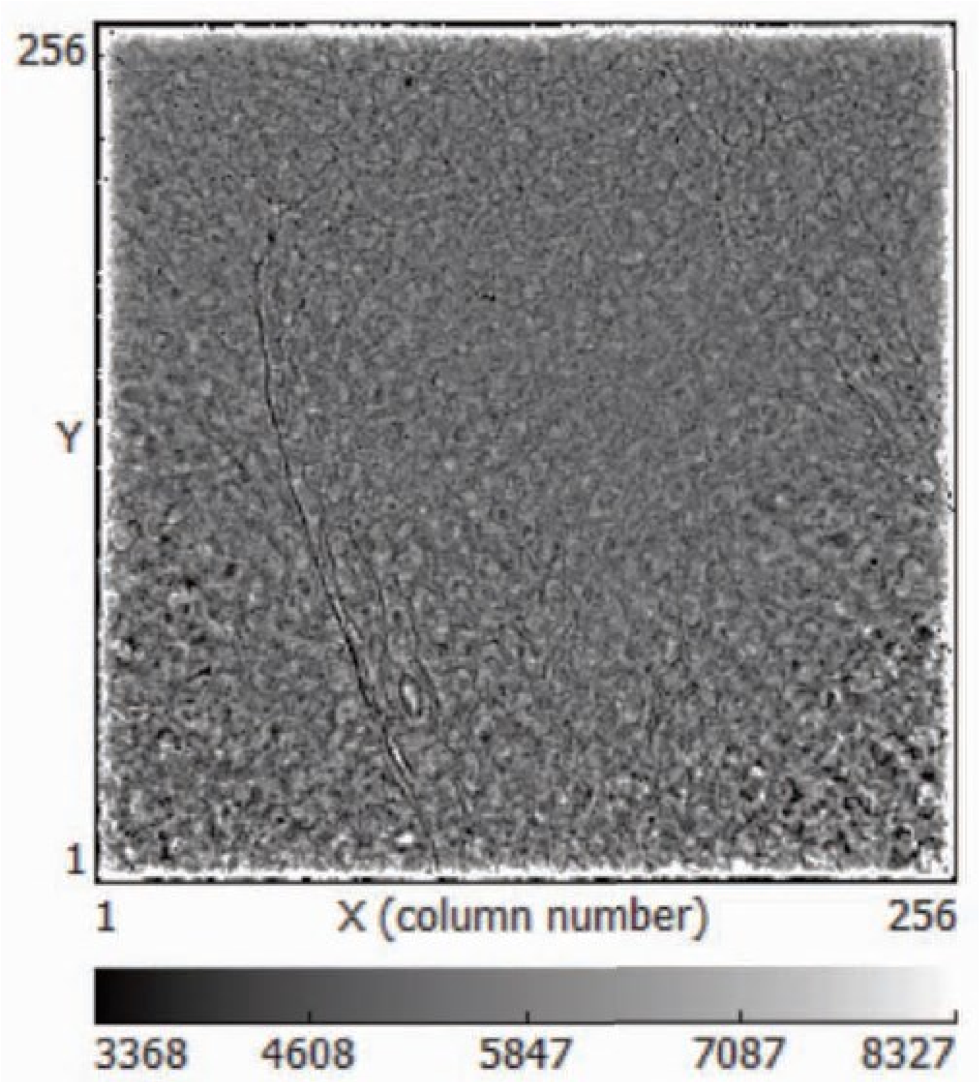


Test results with GaAs

- High pixel yield
- Poor uniformity in original image
  - Cell structure reflects growth process
  - (Probably) varying mobility-lifetime product
- Non-uniformities are stable and can be flat-field corrected reliably

Thanks to Simon Procz, Alex Fauler and Michael Fiederle (FMF / University of Freiburg)

Flat field image



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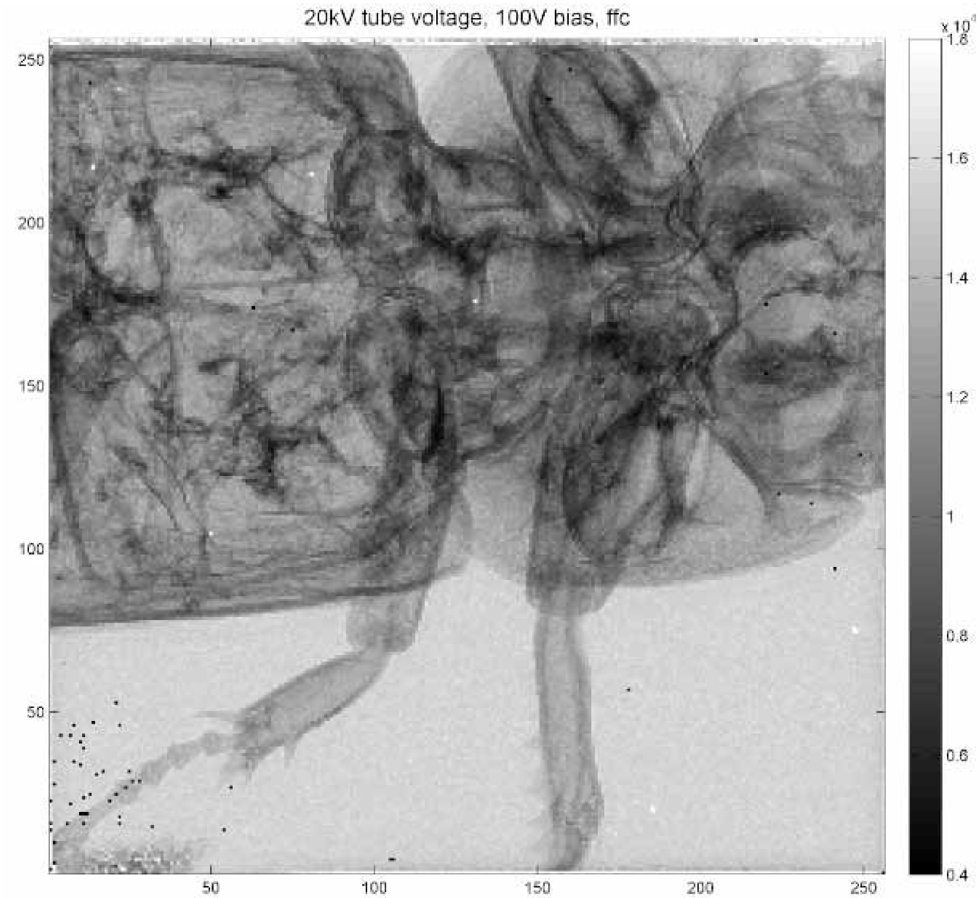
Flat-field corrected image of insect

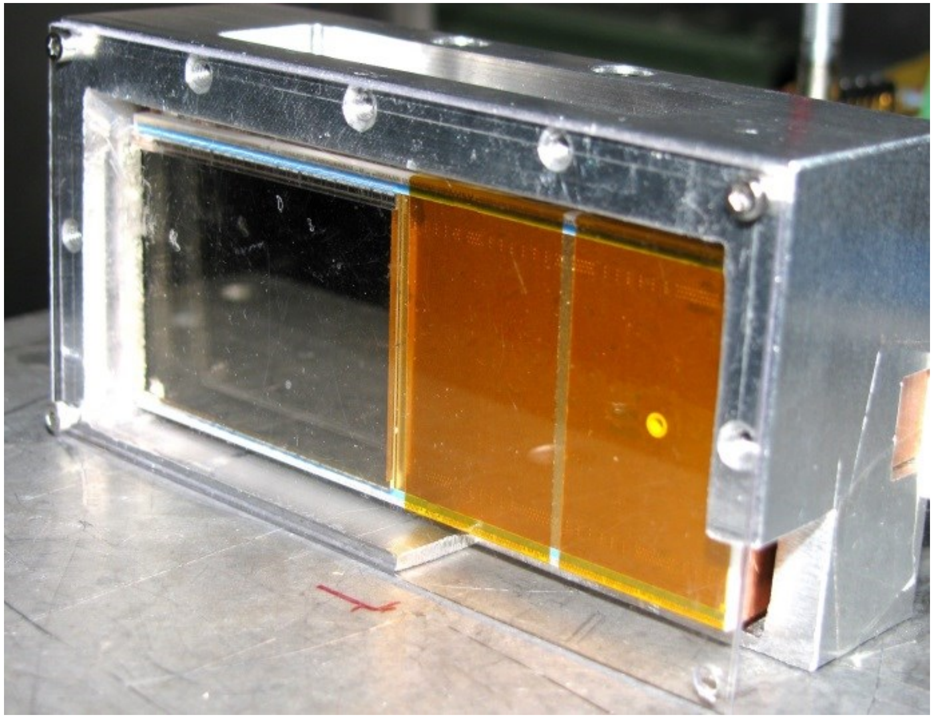


Cadmium Telluride

- Longer-established technology for high-Z hybrid pixel detectors
  - Resistivity and carrier transport properties quite good
  - Still room for improvement in sensor uniformity
- Acrorad CdTe wafers
  - 3” wafers available
- Sensor production and bonding at FMF, Freiburg
  - Previously produced Medipix2, Timepix with CdTe
  - Ohmic contacts used to improve stability
    - Schottky junctions prone to polarization

Cadmium telluride sensor

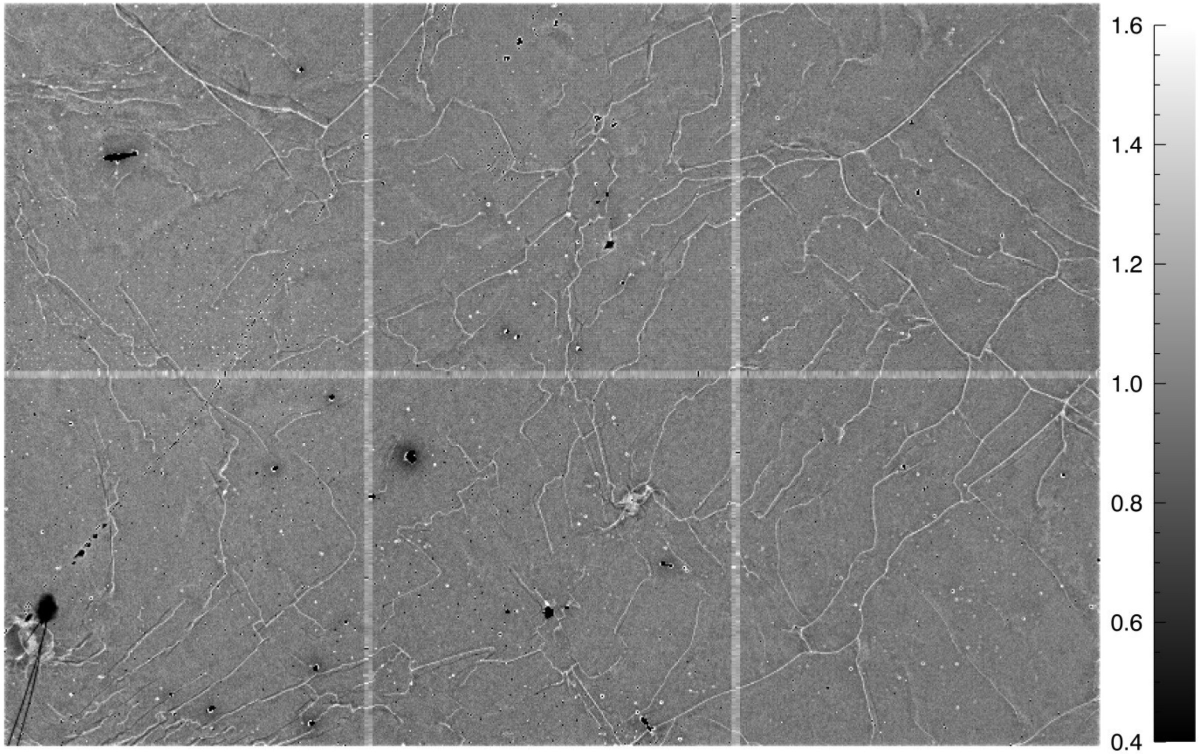
- “Hexa” (3 x 2 chip) module with Medipix3RX received
  - 55µm pixels, 768 x 512 array
- Tested with LAMBDA readout system



Cadmium telluride sensor results

- Various nonuniformities: boundaries (correctable) and blobs of dead pixels
- Some change in nonuniformities over time – not fully tested

Flat image response with 40kV Mo tube



Cadmium telluride sensor results

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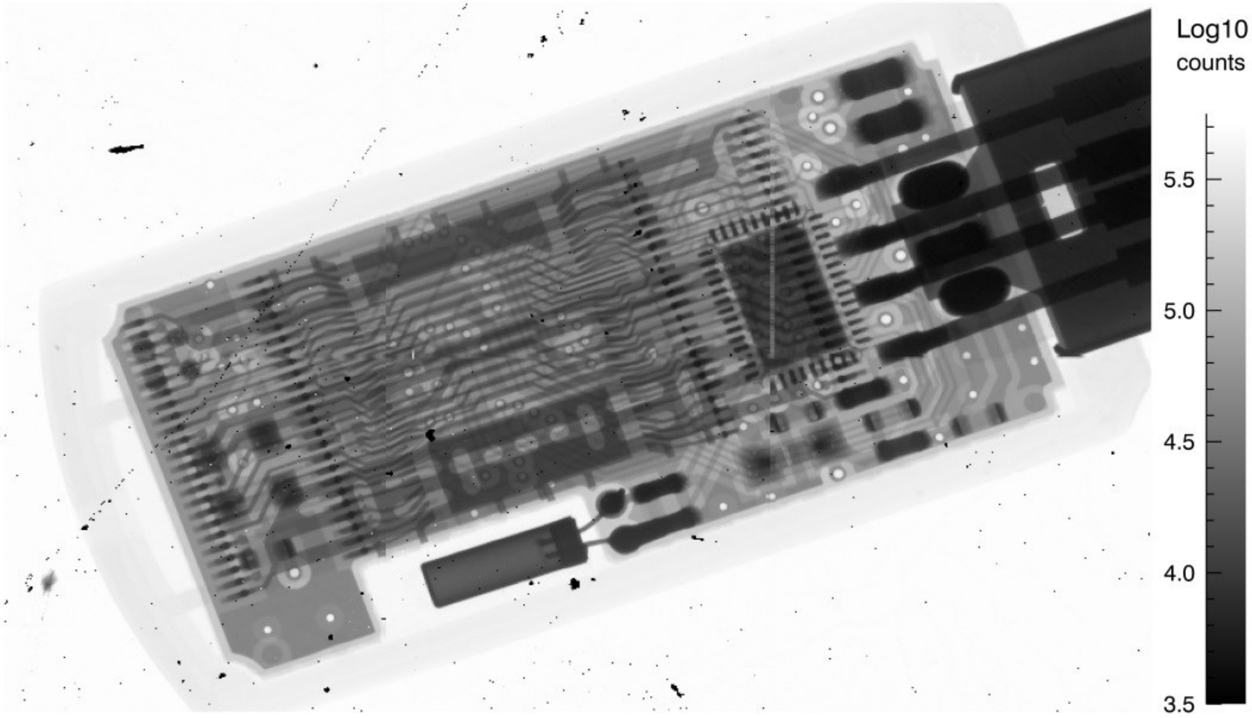
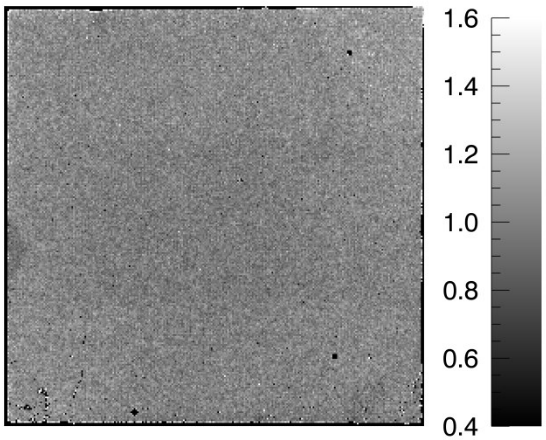
Flat-field corrected image of USB stick



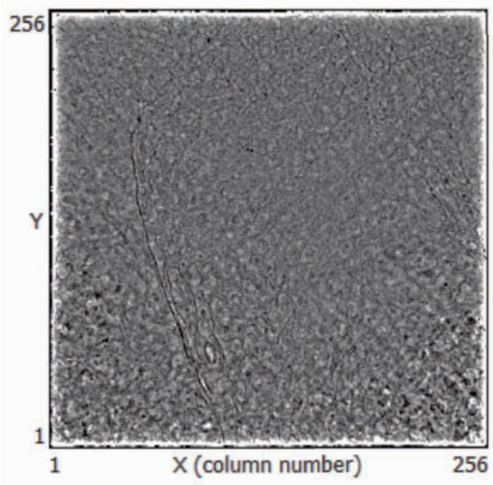
High-Z sensors

- All materials could be used for experiments
- Each material has strengths and weaknesses
  - Germanium technology now works – but high cooling power for large systems
  - GaAs – widespread but correctable nonuniformity – what results will we get with monochromatic beam?
  - CdTe – most well-established, still some problems with uniformity and stability

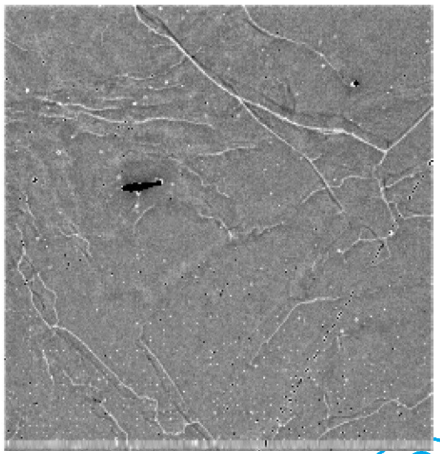
Ge



GaAs



CdTe



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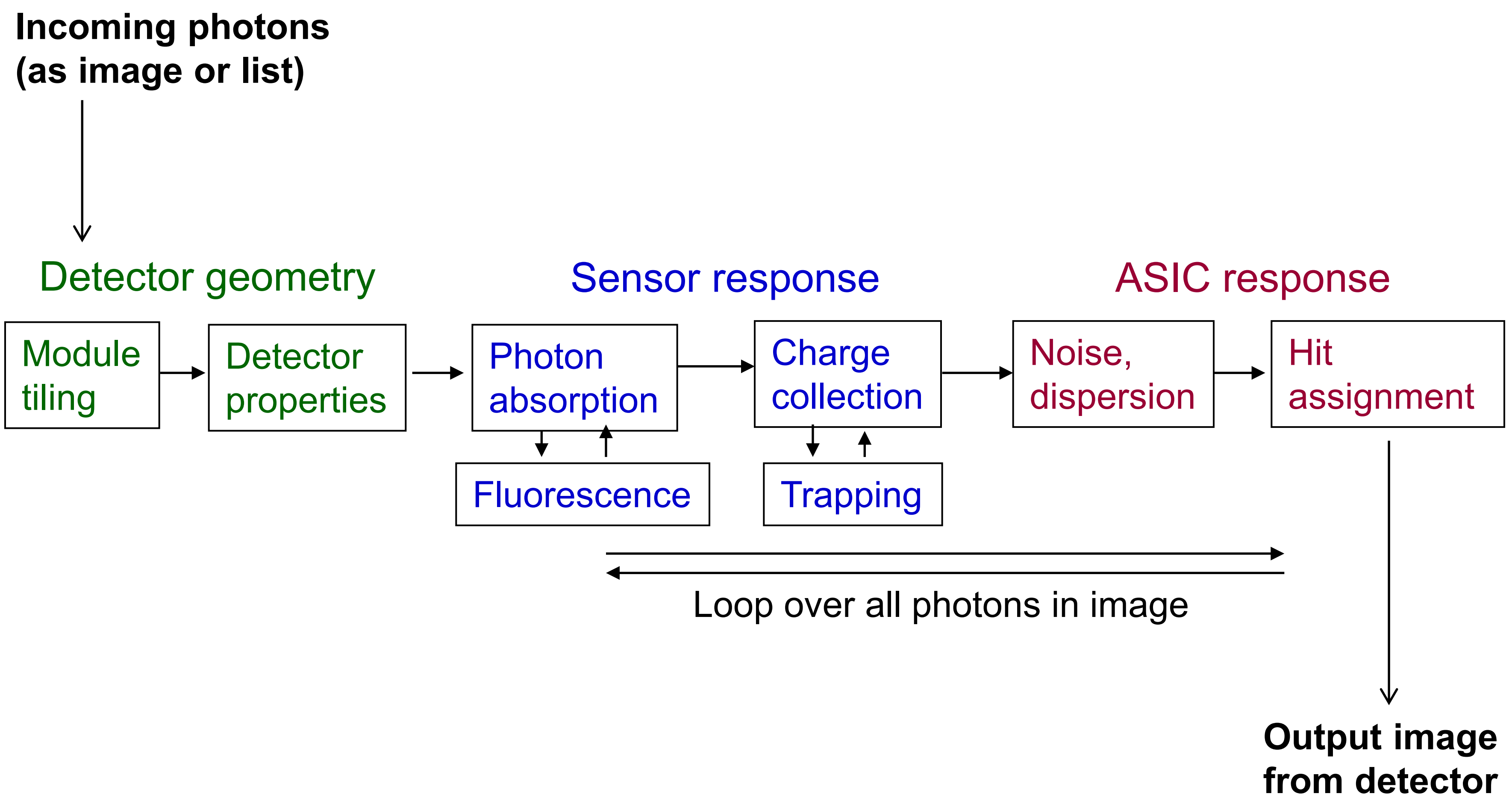
HORUS detector simulation toolkit

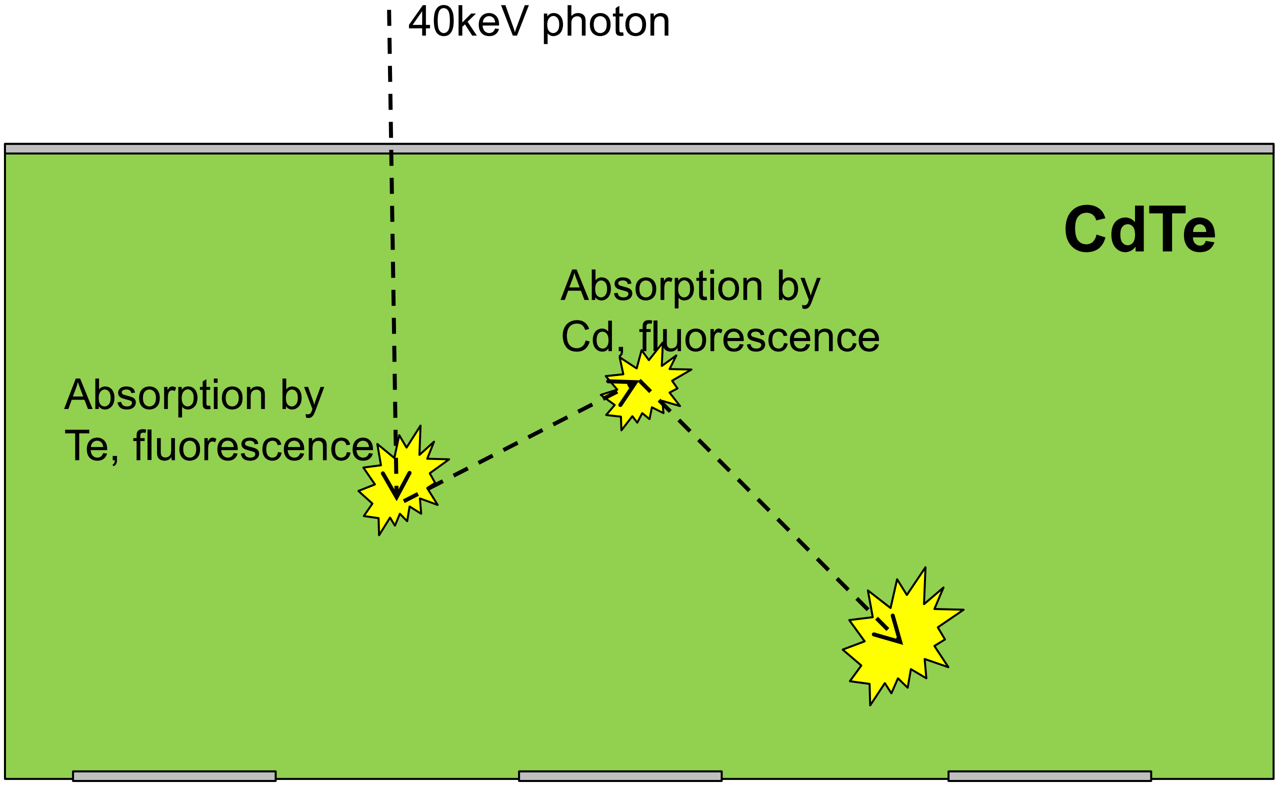
- HORUS – HPAD Output Response fUnction Simulator
  - Originally developed by Guillaume Potdevin for AGIPD (XFEL) detector
  - Expanded by Julian Becker and me for general purpose use
- Aim: Fast and flexible simulation of detector and experiment
  - Evaluate different detector designs
  - Determine which aspects of detector have biggest impact on performance
  - Hopefully uncover surprises
- Written using IDL (Interactive Data Language – Matlab-like)
  - Monte Carlo approach
  - Relatively simple models
    - Not finite-element physics model of sensor behaviour
    - Not aimed at maximum precision (though results generally good)

Typical simulation flow (photon counting detector)



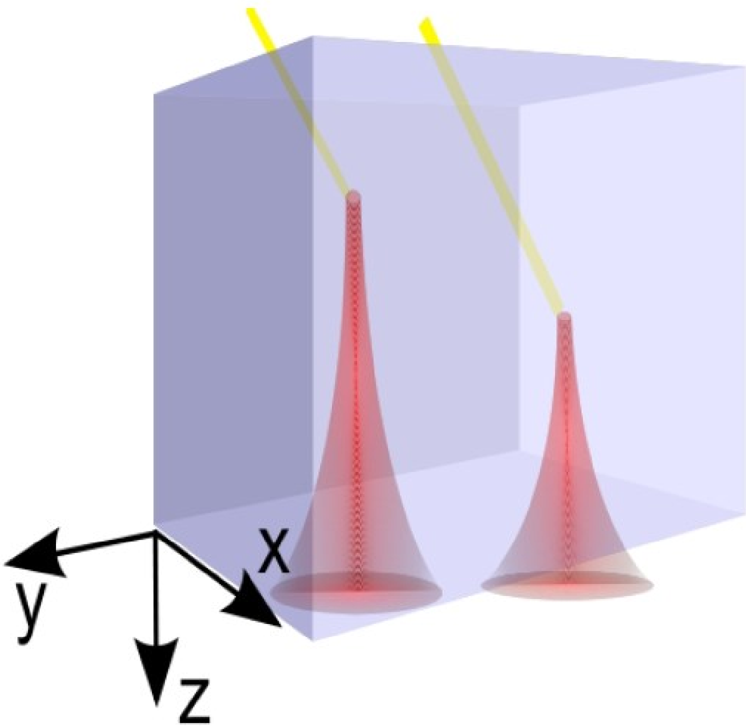
Absorption of photon in sensor

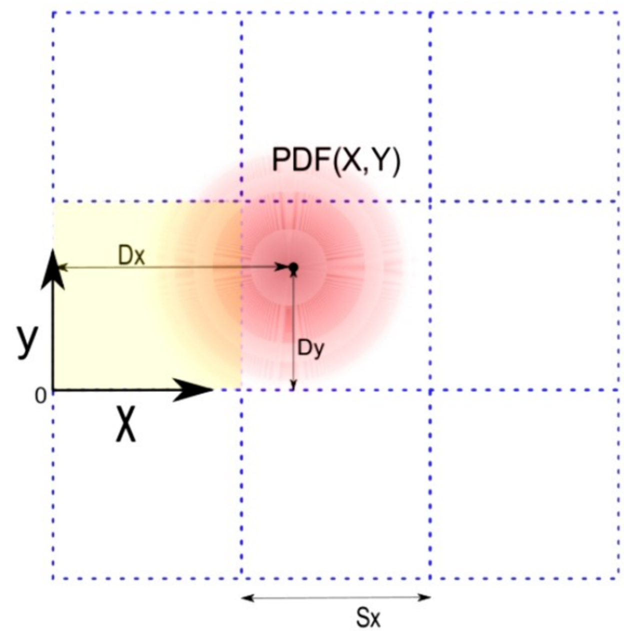
Photoelectric absorption, fluorescence, Compton scattering



Charge collection model

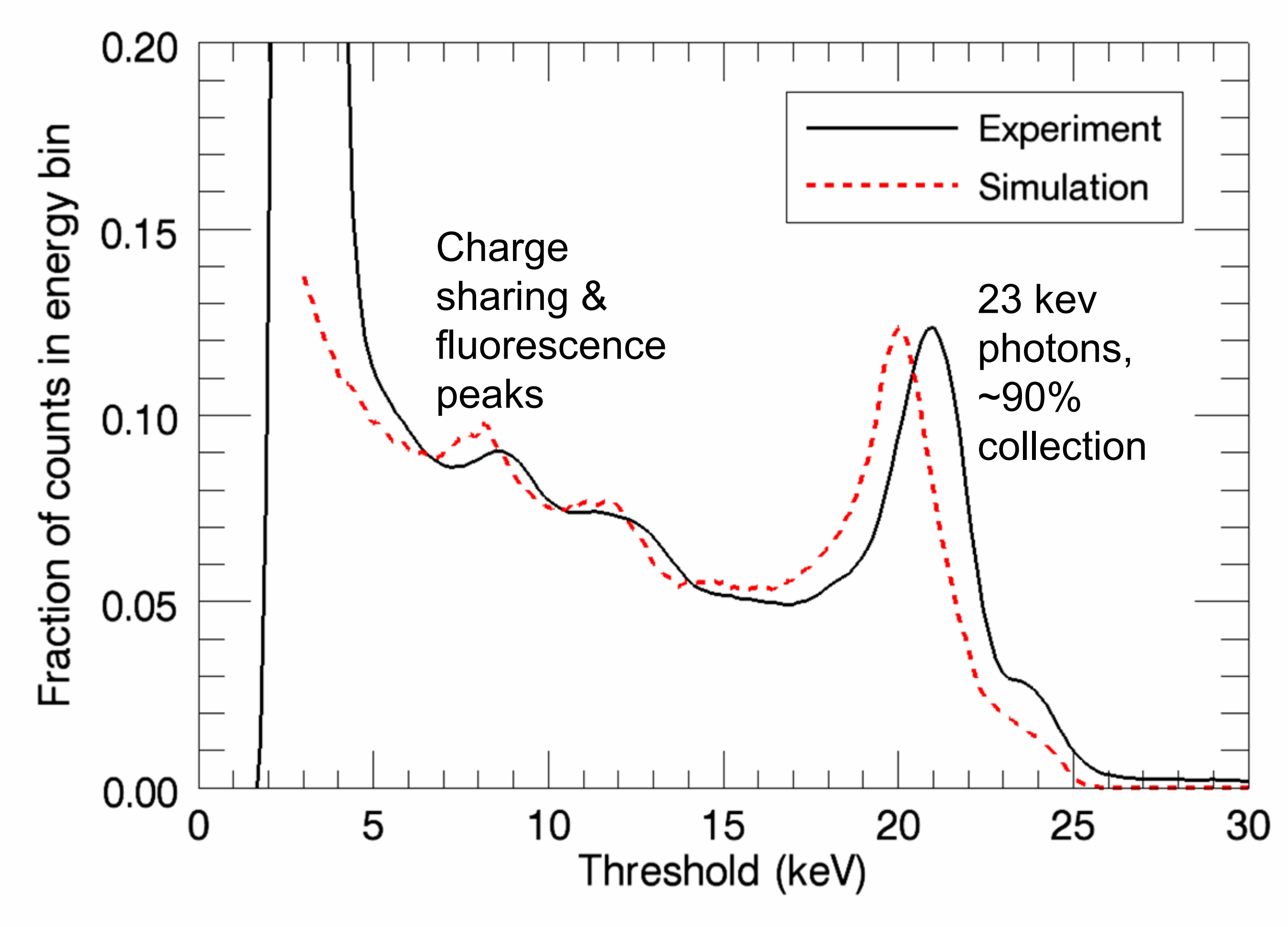
- Collection time calculated (based 1-D field model)
- Gaussian charge cloud (diffusion from a point)
- Charge distribution integrated over pixels
- Charge trapping effects based on simple analytical weighting field





Test simulation – 300um GaAs detector with Medipix2

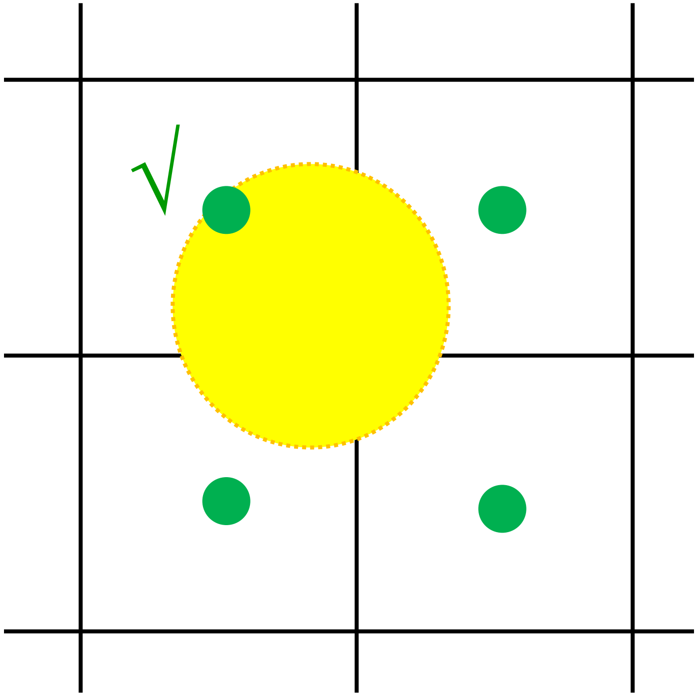
- Good agreement with experiment using reported material properties and readout chip performance (e.g. 10ns electron lifetime)



L. Tlustos, G. Shelkov and O. P. Tolbanovc 2011, NIMA 633 (1), p103-107

Will charge summing improve our performance

- **Feature of Medipix3RX chip**
  - Medipix3.0 charge summing had bug (reproducable in HORUS)
- 2 thresholds
- A low threshold is applied to each individual pixel
- If more than one is above threshold, the highest signal suppresses the others
- Then, a hit is registered if at least one neighbouring summing node is above its threshold



Single-pixel response used to perform arbitration

Charge summing in Medipix3RX

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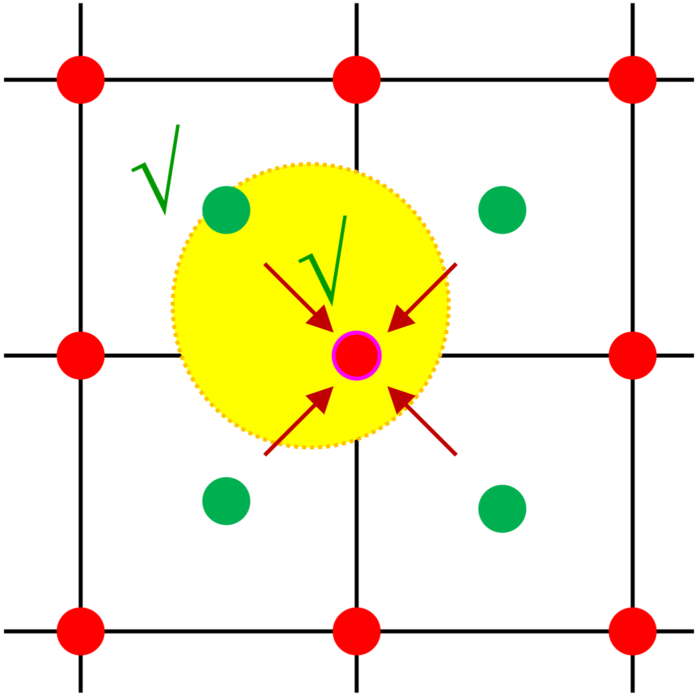
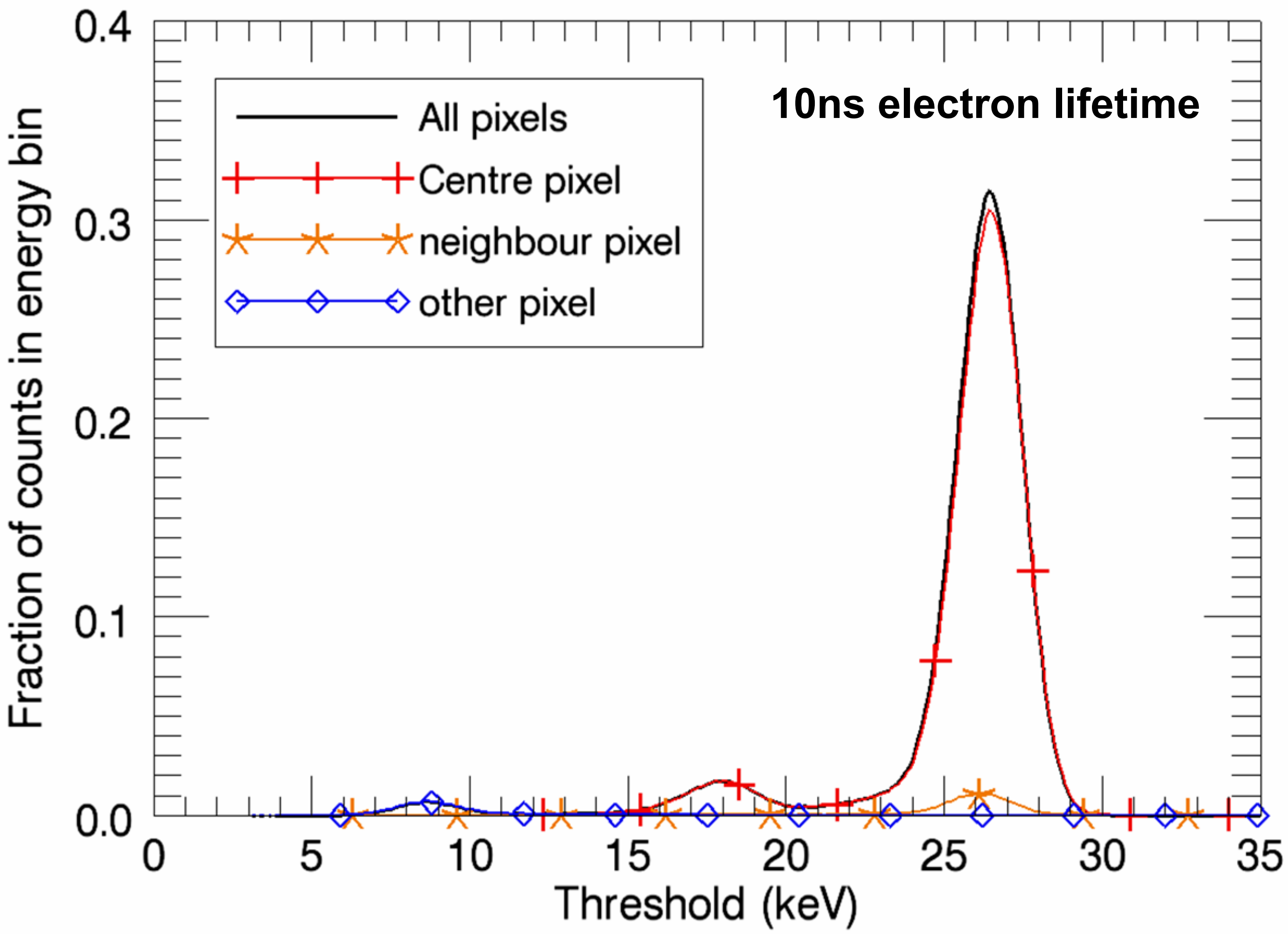


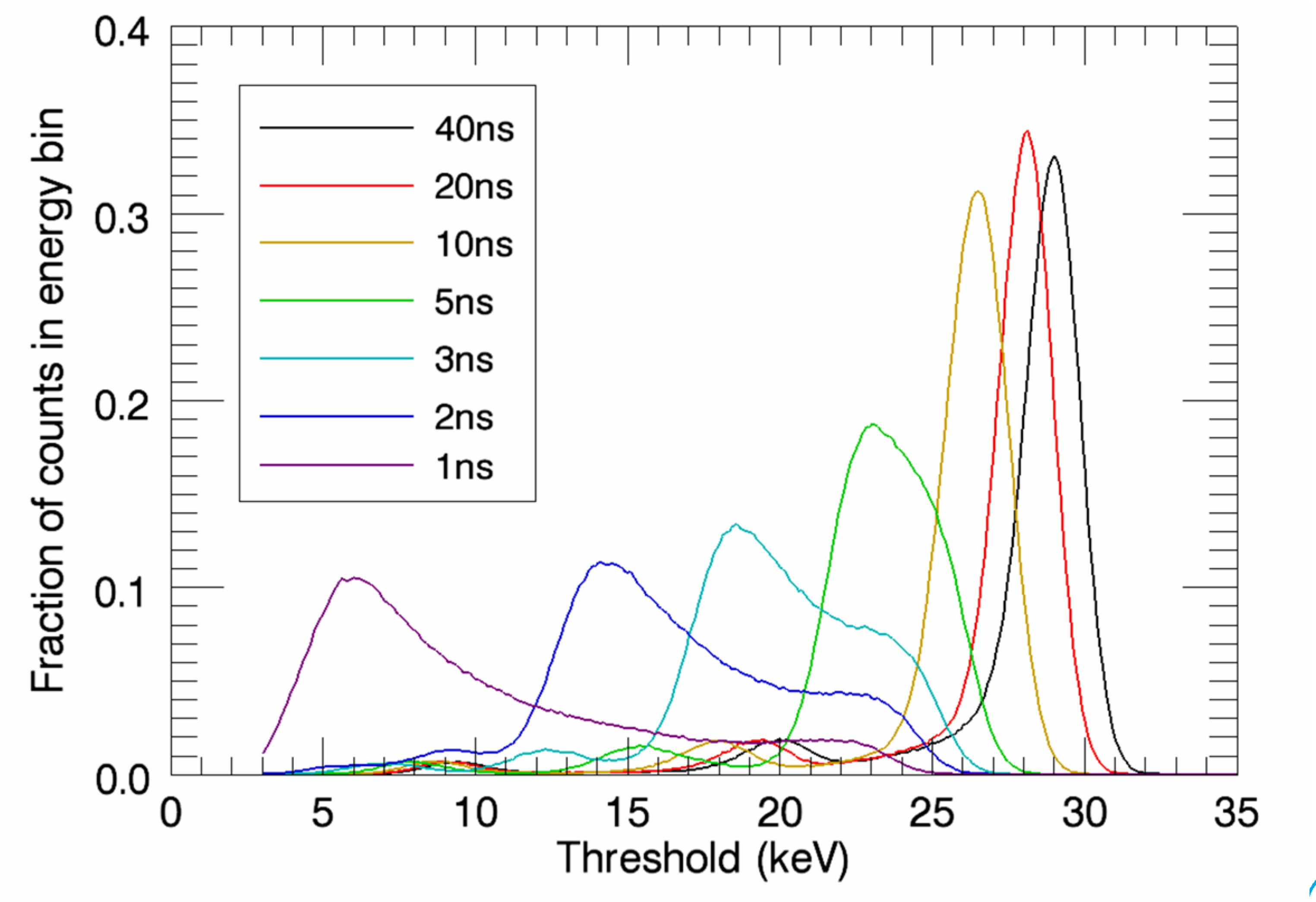
Then, hit registered if at least one summing node over threshold

GaAs detector plus charge summing



GaAs detector plus charge summing

> Variation in trapping time should have less effect on count rate



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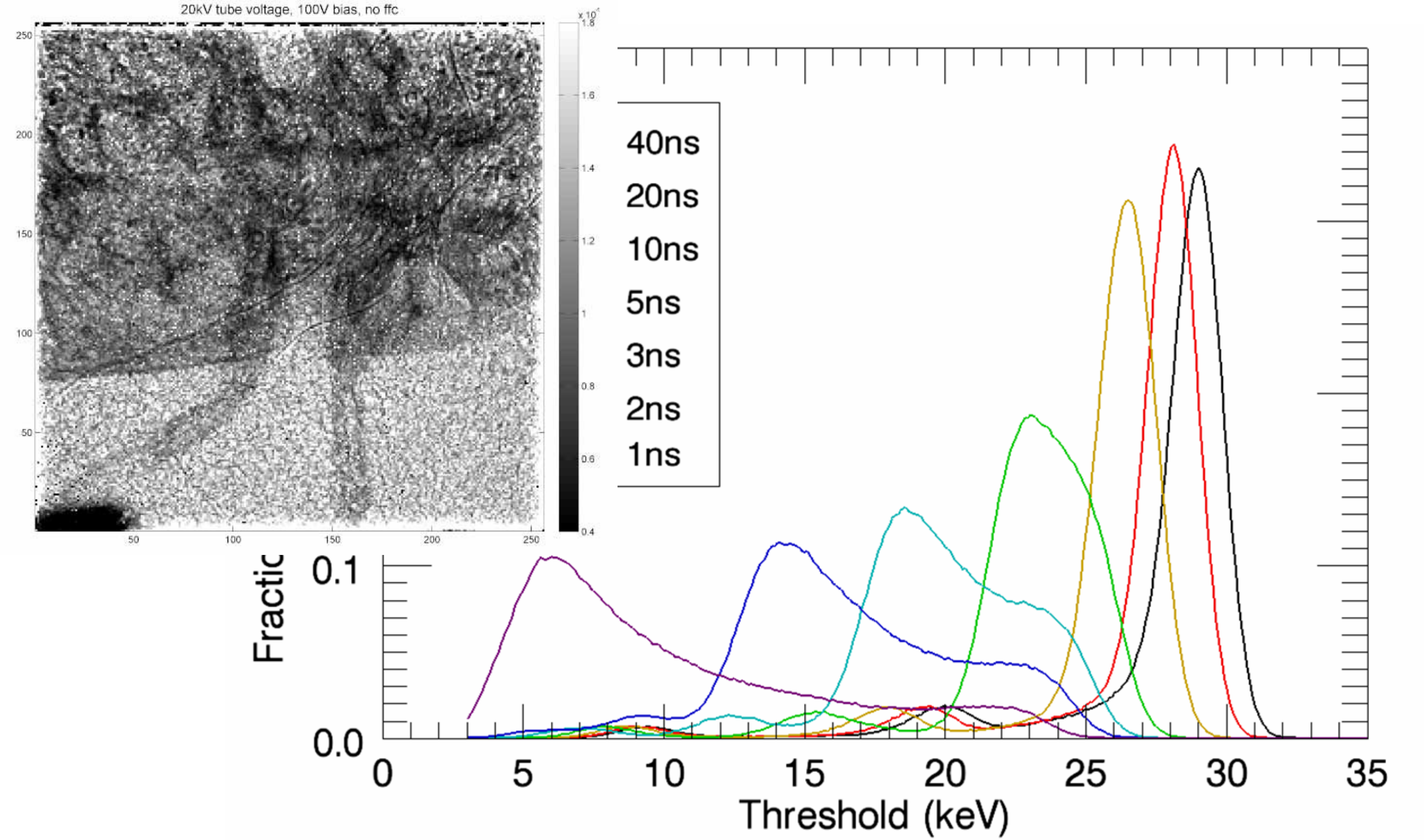

Summary

- Monte Carlo detector simulation using relatively simple models
  - Aimed at flexible simulation of full detector systems
  - Not detailed finite elment physics models
- Our code is available for use
  - Already used with Medipix, AGIPD, CSPAD (Cornell), LPD (RAL, UK)
  - david.pennicard@desy.de, julian.becker@desy.de

> Thanks for listening