

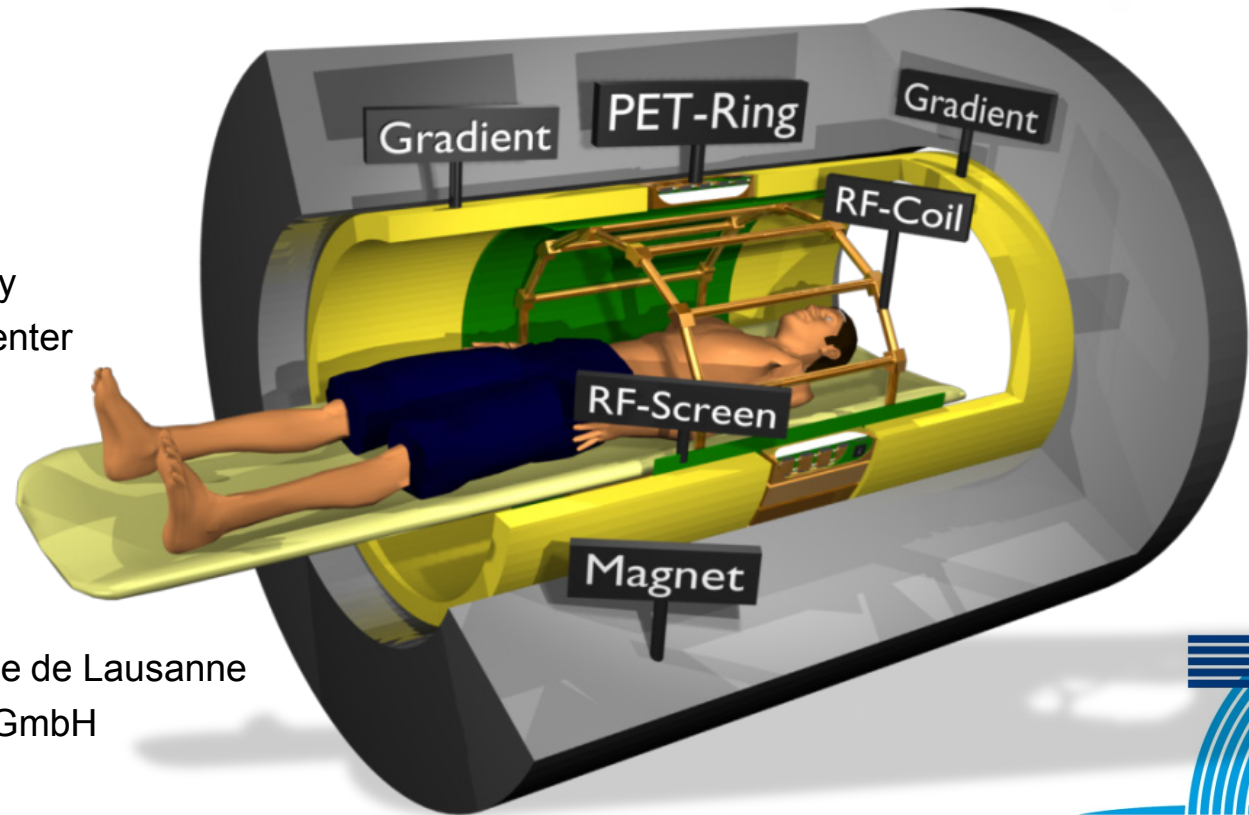
Initial Experience with Digital SiPMs in Detectors for Time-of-Flight PET

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PhotoDet 2012, Orsay, 14-Jun-2012

SUBLIMA project

Whole-body TOF-PET / MRI

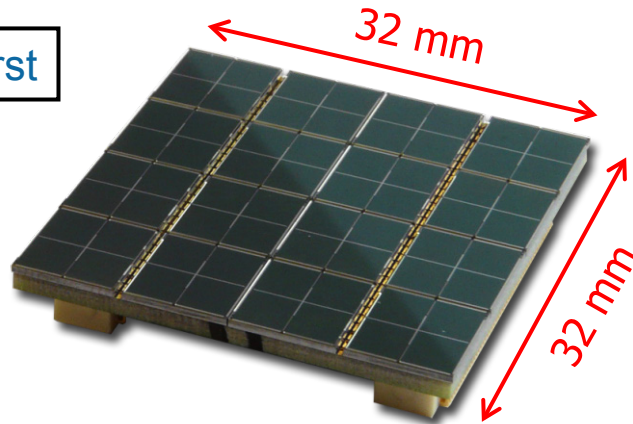


Philips Research
Delft University of Technology
Leiden University Medical Center
University of Heidelberg
University of Ghent
King's College London
Fondazione Bruno Kessler
University of Pennsylvania
Ecole Polytechnique Fédérale de Lausanne
Micro Systems Engineering GmbH
Technolution BV

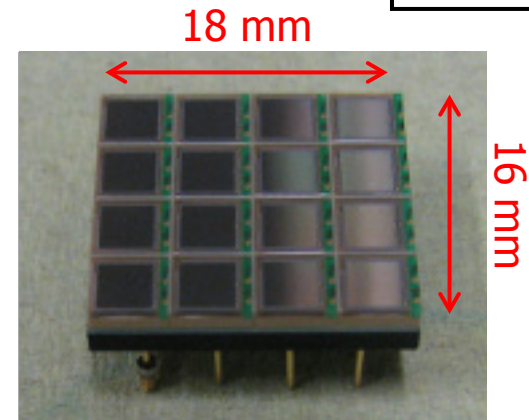


SiPM arrays – some examples

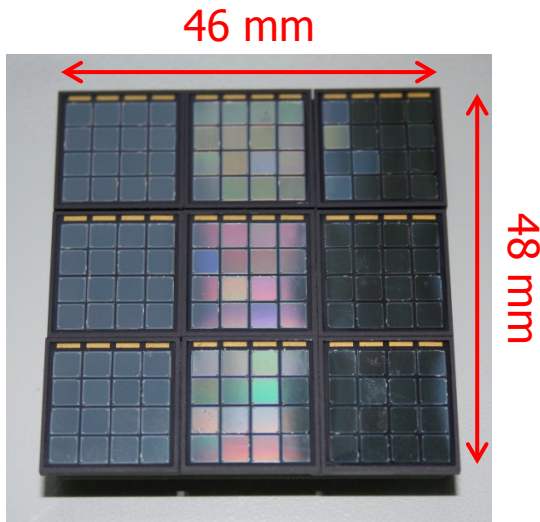
FBKirst



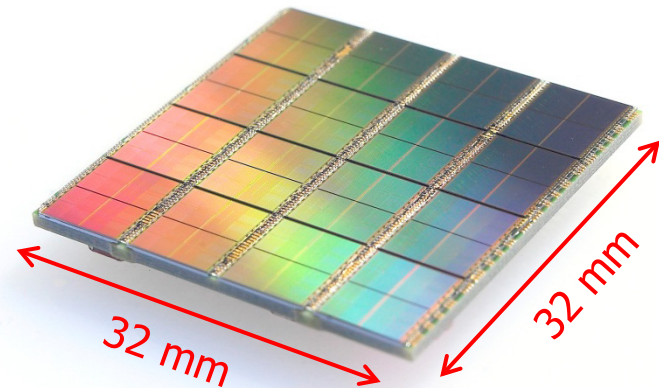
Hamamatsu



SensL



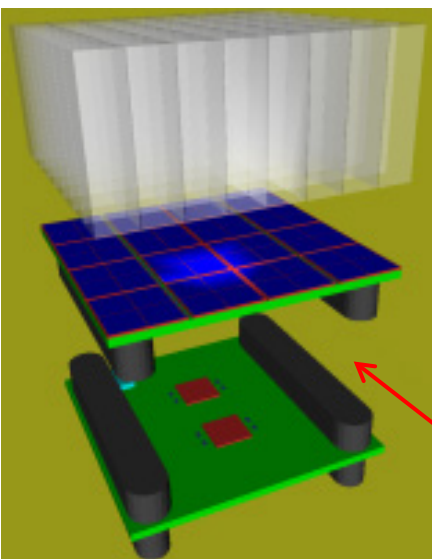
Philips Digital Photon Counting



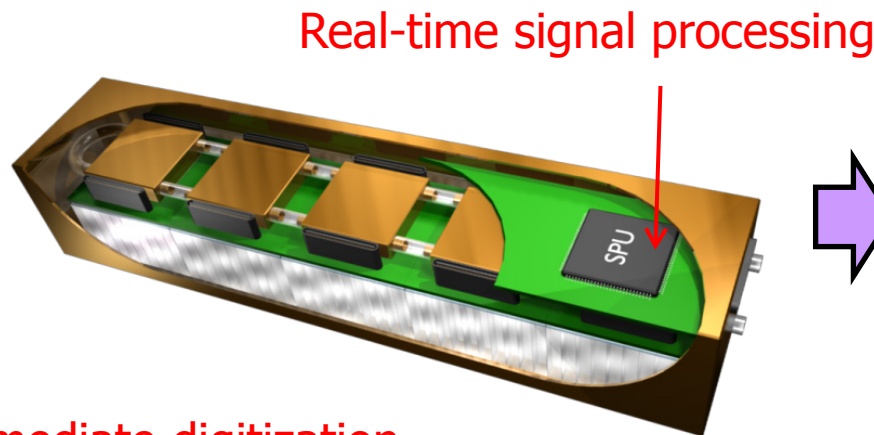
Individual readout of array elements => position-sensitive light sensor

Digital PET system

- Local position decoding and time-stamping
 - no limit on no. of channels, no loss of information
- Real-time DOI correction of timing and spatial information
- Fast, accurate & repeatable system calibration and time alignment



Detector

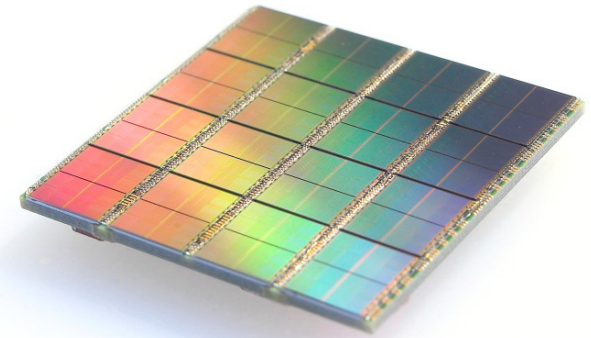


Module

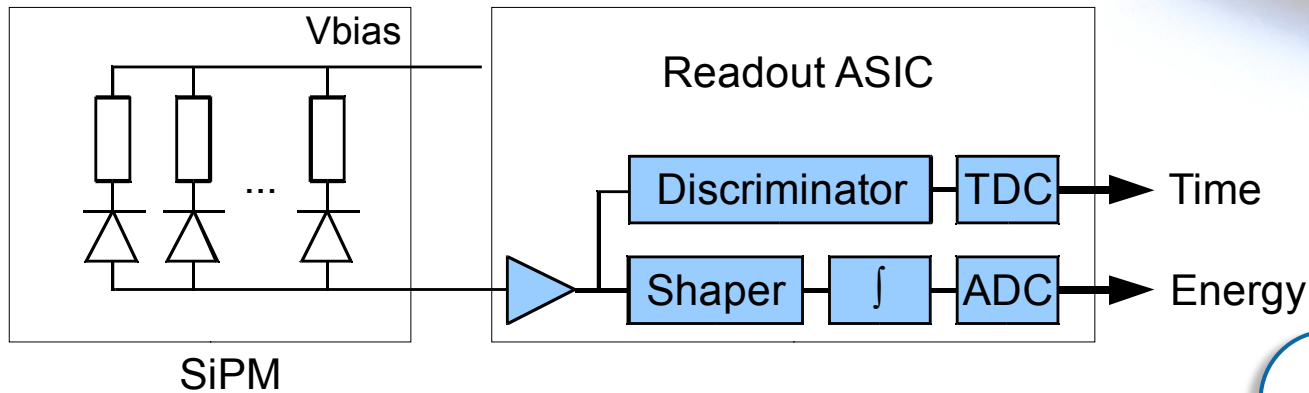


System

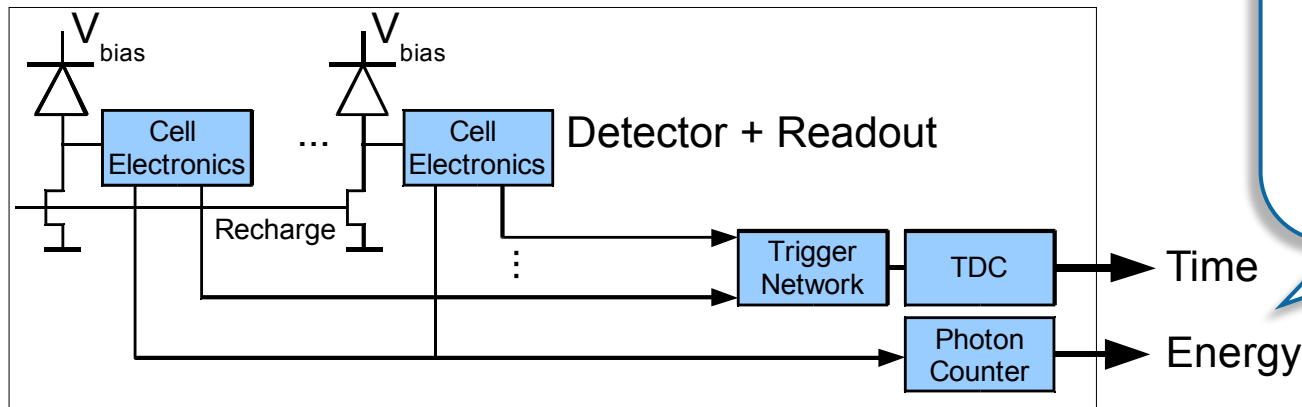
Digital SiPMs



Analog Silicon Photomultiplier



Digital Silicon Photomultiplier

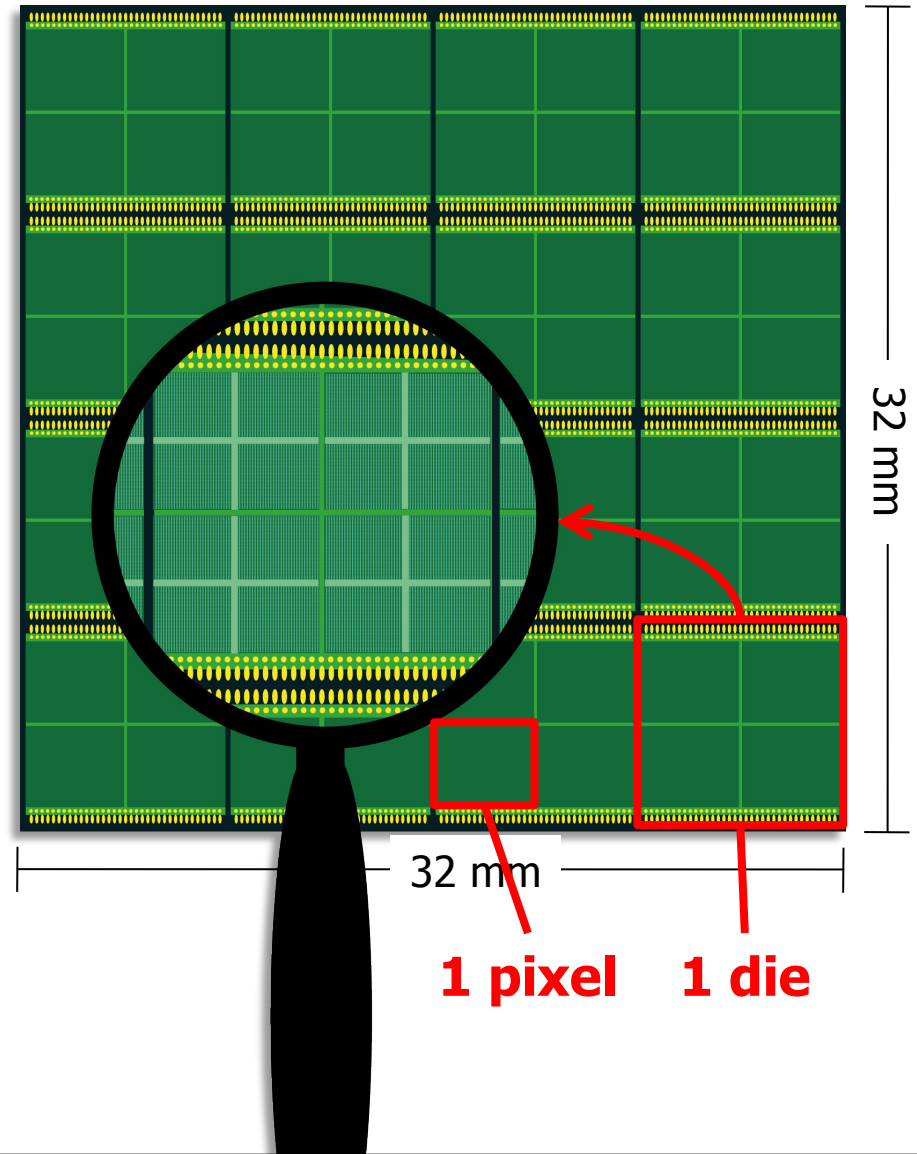


dSiPM provides a digital timestamp and the photon count for each light pulse, without the need of any analog front-end electronics

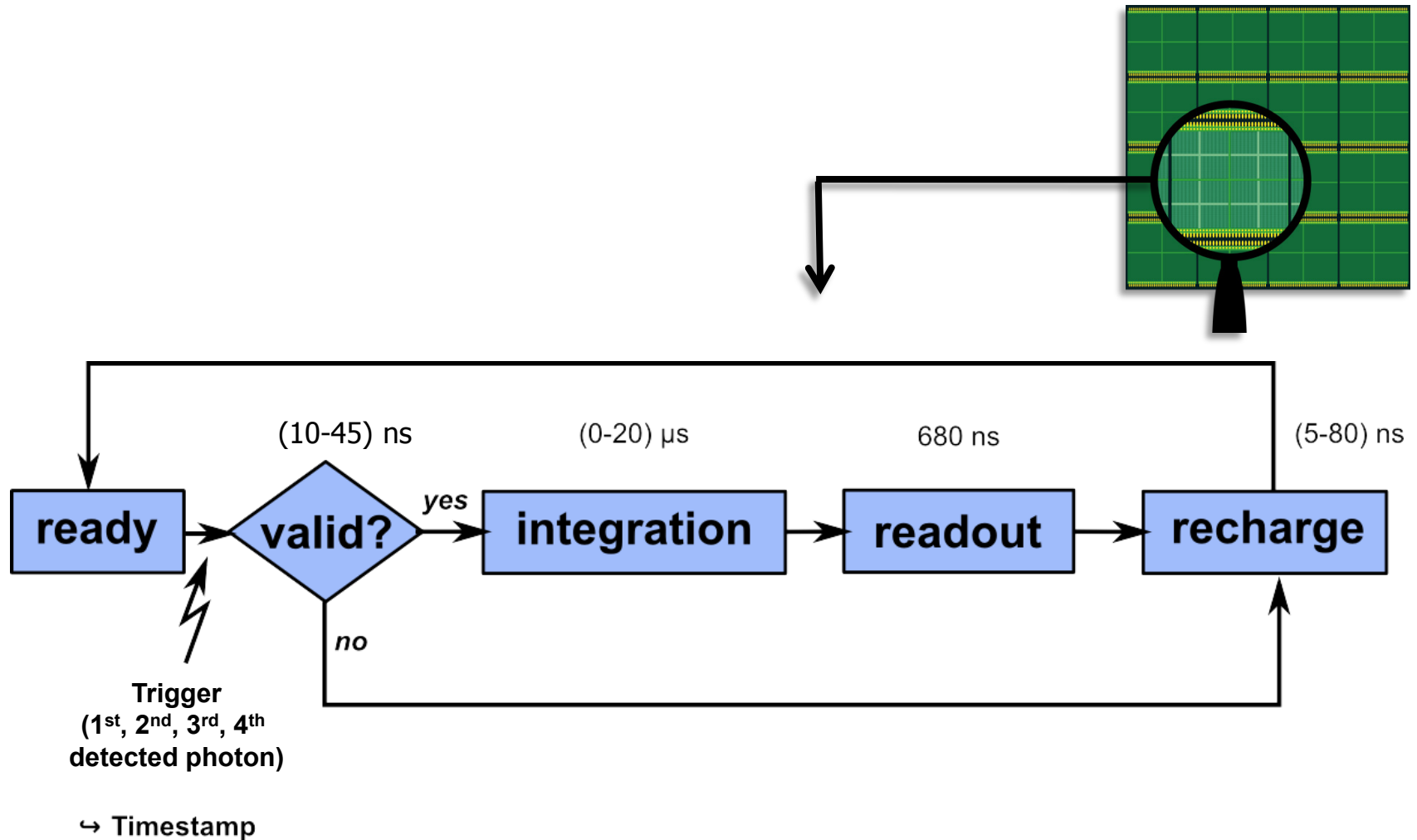
dSiPM array

- dSiPM pixels: 64 (8x8)
- Microcells per pixel:
 - 6396 (DPC-6400-44-22)
 - 3200 (DPC-3200-44-22)
- Silicon dies: 16 (4x4)
- Sub-pixels per pixel: 4 (2x2)
- Array size: 32 mm x 32 mm

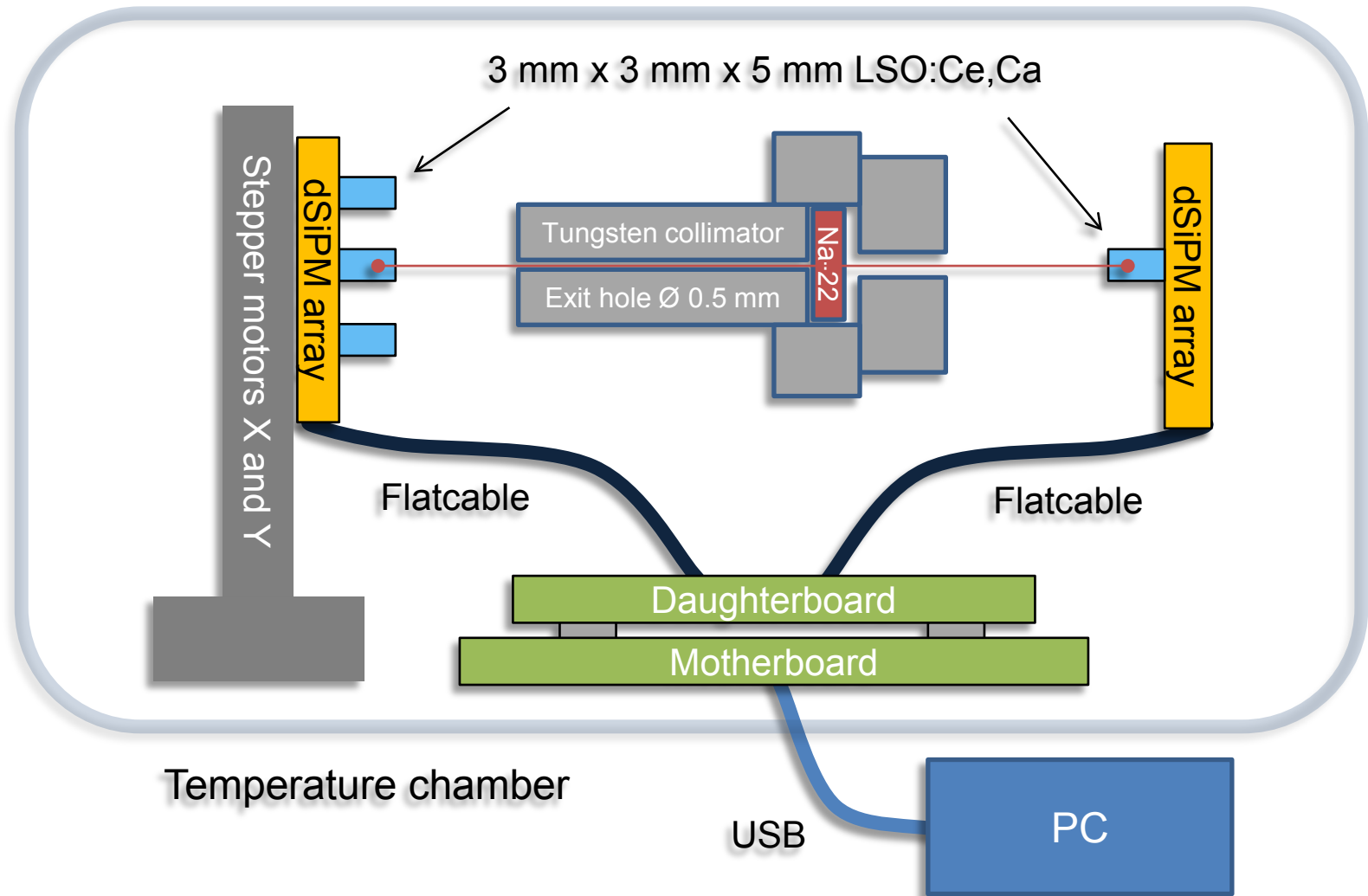
Magnifying glass shows 1 Si die



dSiPM trigger and validation logic



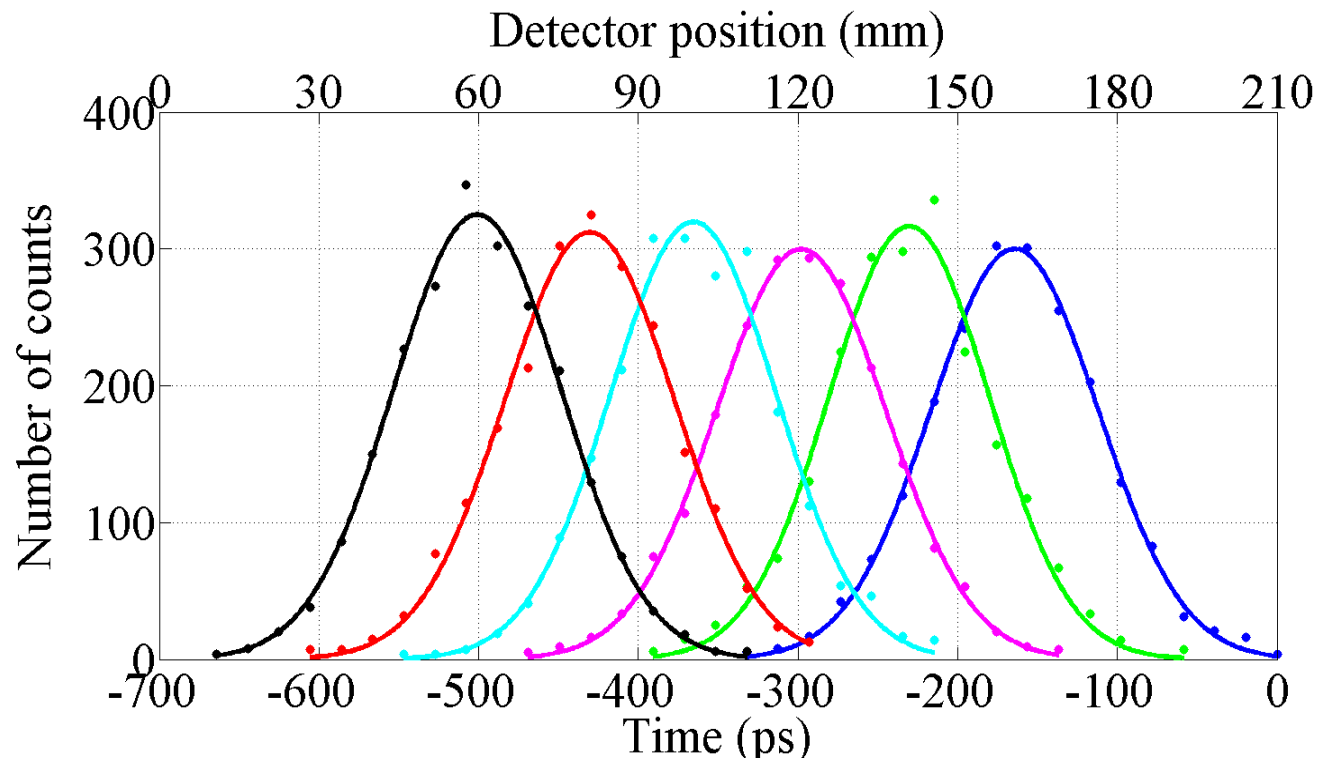
Test setup: initial timing measurements



Timing resolution

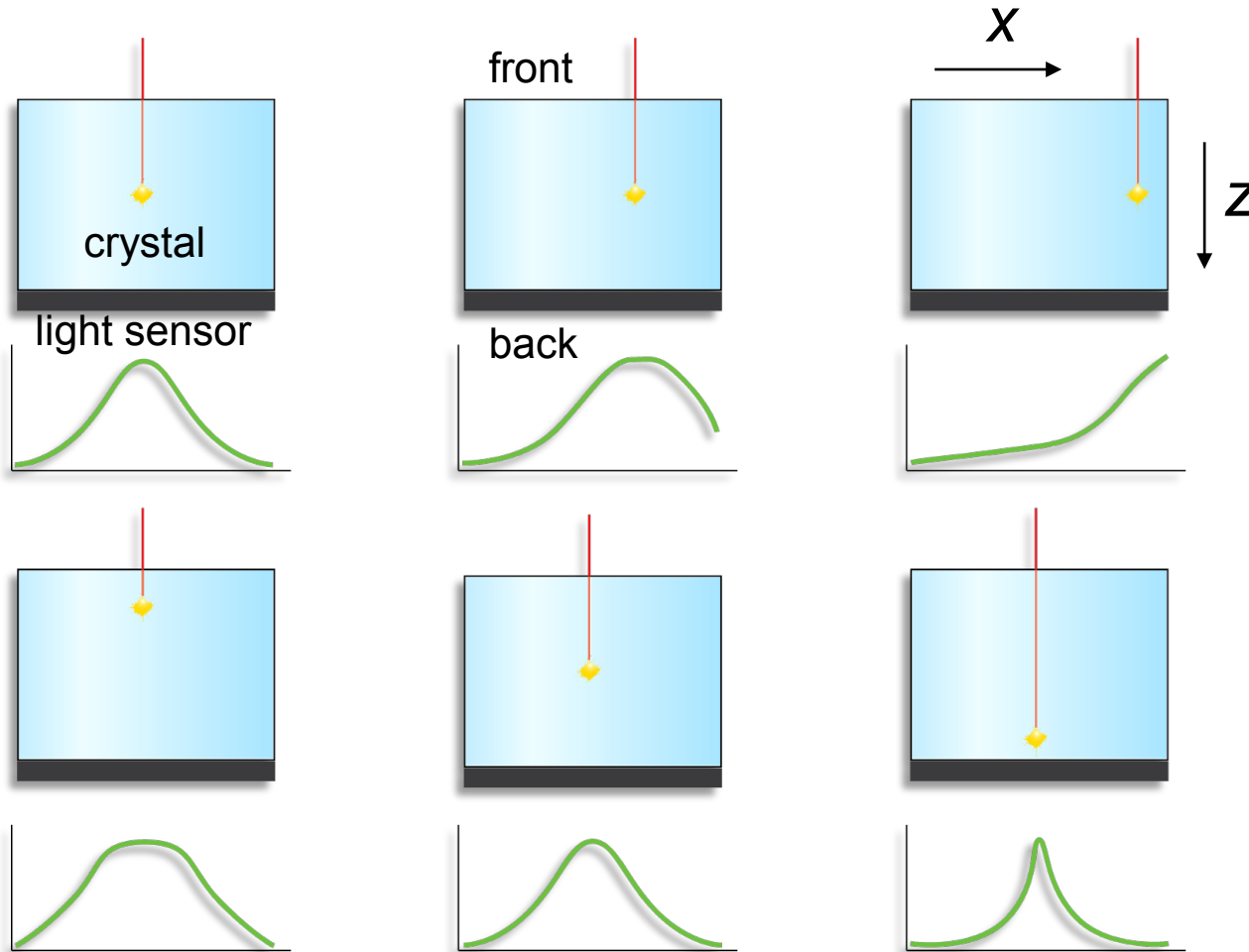
Two coincident detectors:

- DPC-3200-44-22 dSiPM arrays
- 3 x 3 x 5 mm³ LSO:Ce,Ca crystals



Timing spectra at different positions of one of the two detectors. The step size is 20 mm. The average coincidence resolving time (CRT) is **123 ps FWHM**.

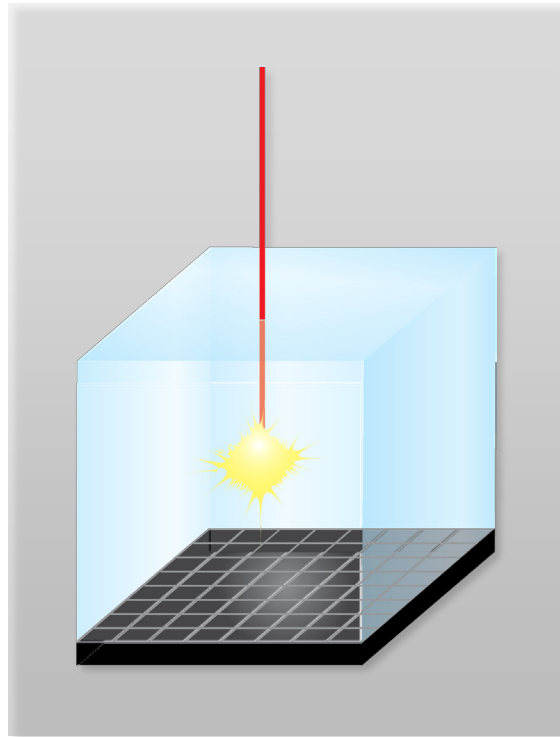
Monolithic scintillator detectors



Light distribution depends on the entry point on the front surface...

...and on the depth of interaction (DOI).

Monolithic scintillator detectors



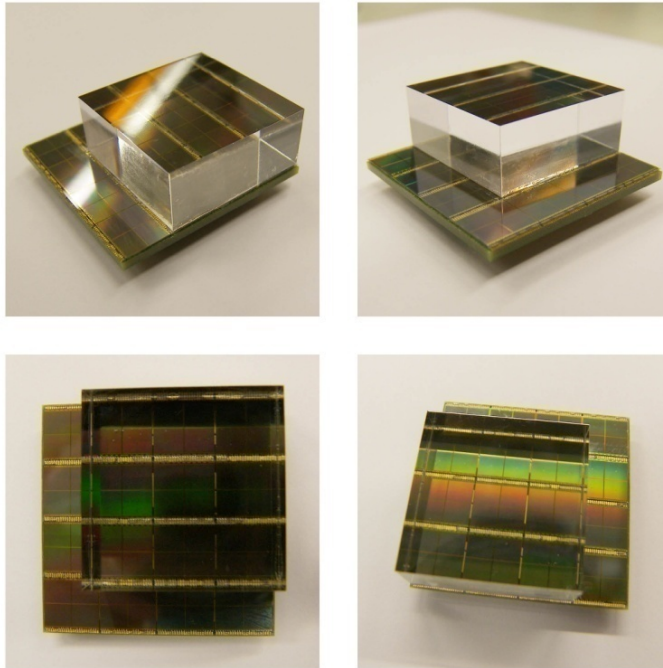
Compared to segmented crystals:

- Intrinsic depth of interaction (DOI), even with single-sided readout
- High sensitivity (100% packing fraction)
- Easier crystal surface processing and detector assembly
- Fewer reflections of scintillation photons before reaching sensor
 - Fewer losses
 - Smaller transient time spread

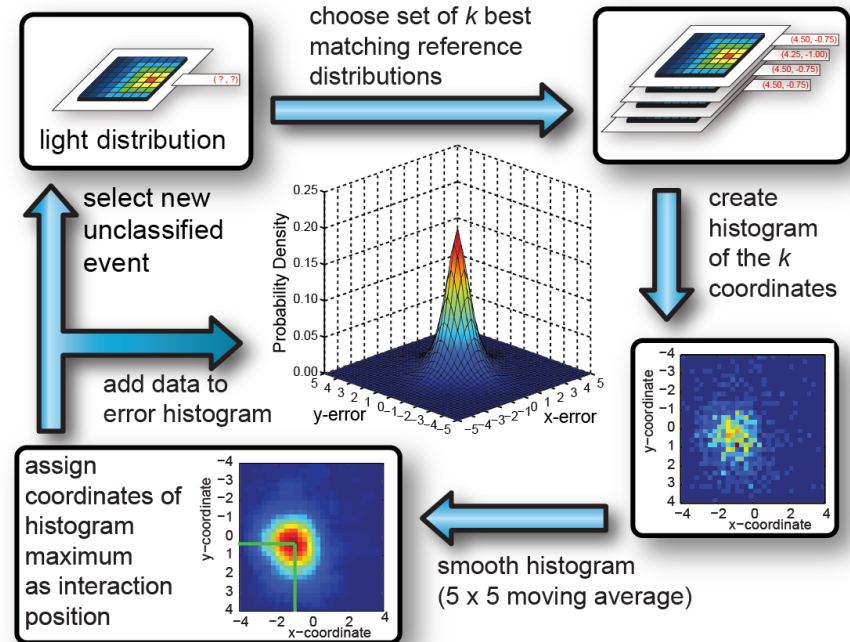
=> intrinsically better characteristics?

The monolithic scintillator 2.0

Monolithic TOF/DOI detector with improved performance due to Ca co-doped LSO scintillator, **digital photon counting (dSiPM)**, and optimized readout algorithms



24 mm x 24 mm x 10 mm LSO:Ce,Ca scintillator on PDPC digital SiPM array

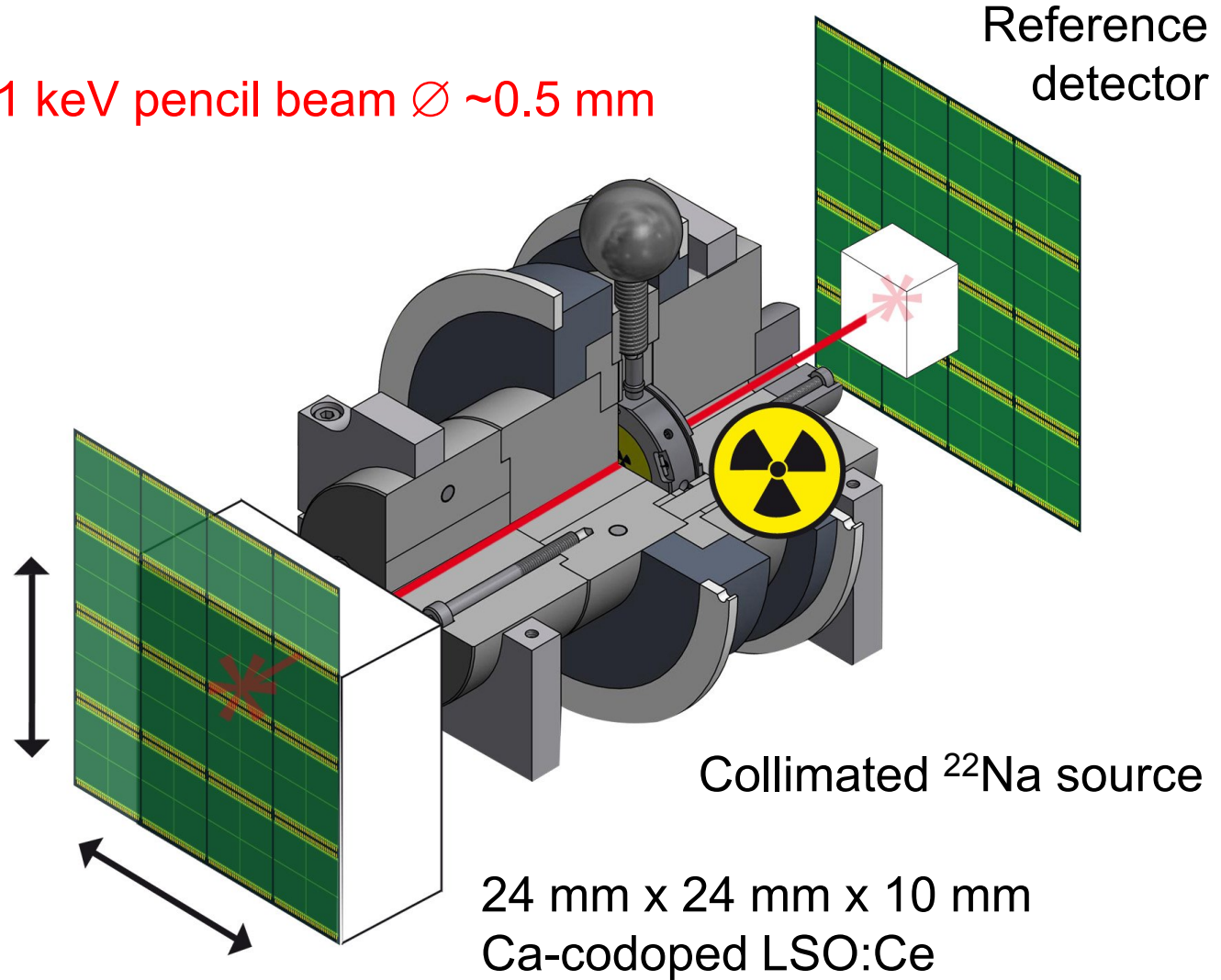
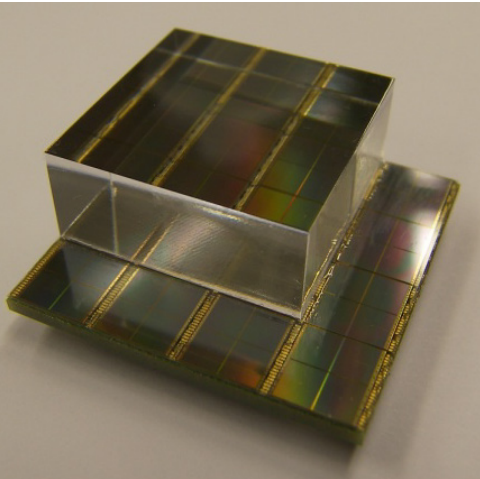


Faster & more accurate nearest-neighbour algorithm, H.T. van Dam et al, IEEE Trans Nucl Sci 58, 2139-2147, 2011

Setup: 2 dSiPMs in coincidence

Scanning 511 keV pencil beam $\varnothing \sim 0.5$ mm

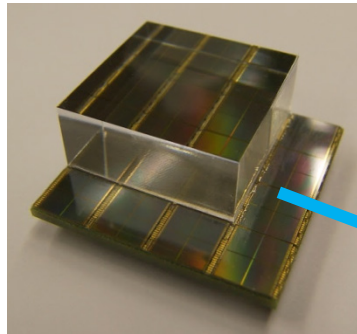
dSiPM array +
monolithic
scintillator



Collimated ^{22}Na source

24 mm x 24 mm x 10 mm
Ca-codoped LSO:Ce

Test setup dSiPM-based detectors

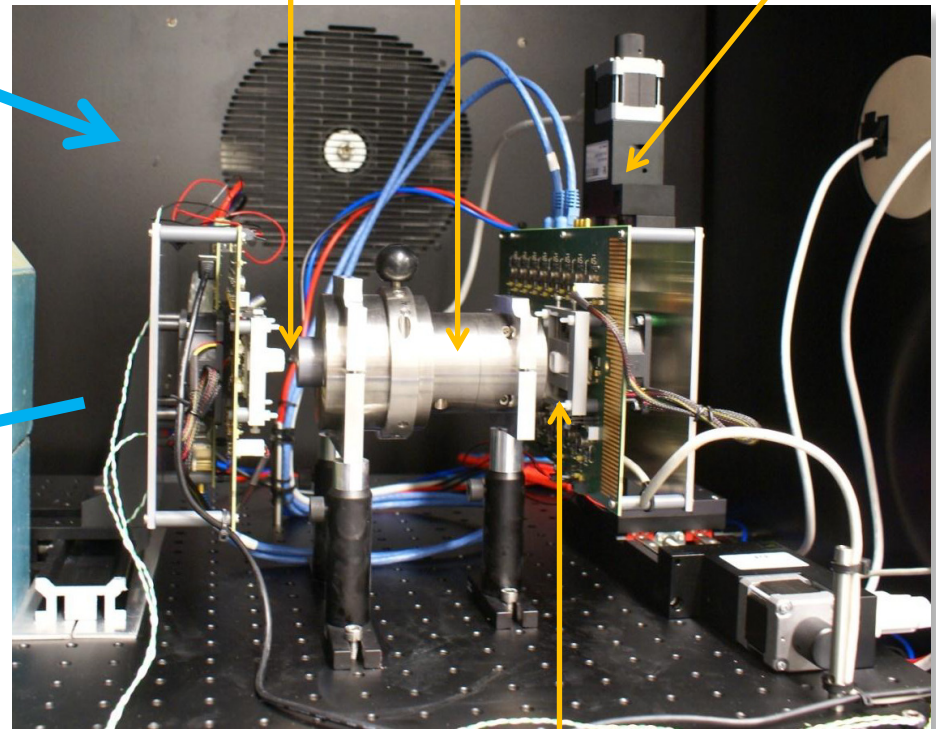


Temperature cabinet

Reference detector

Collimator

X-Y stage

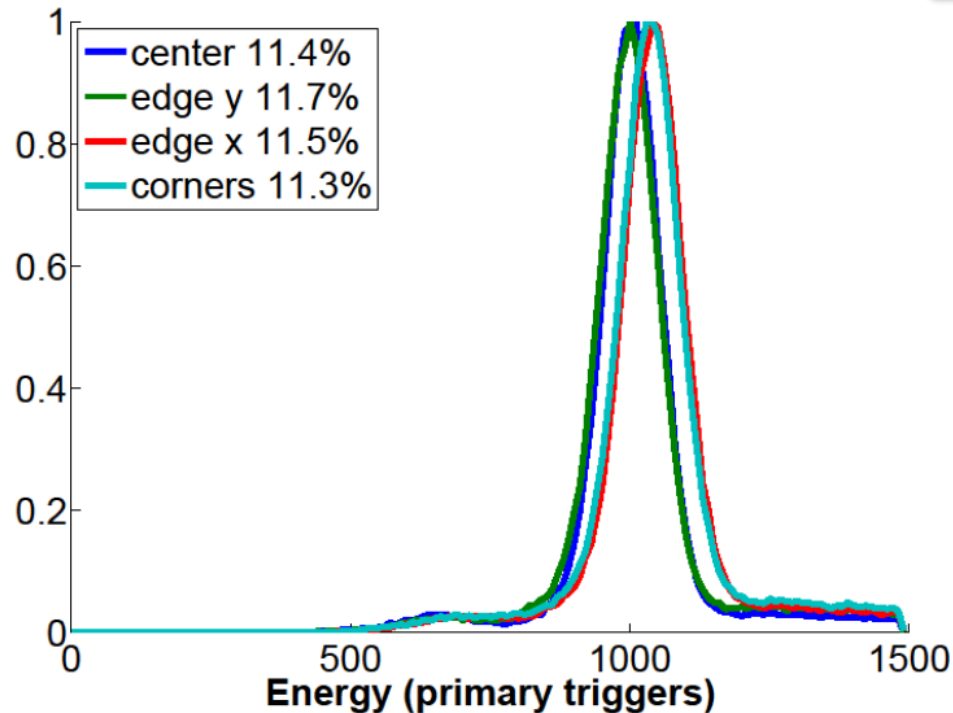
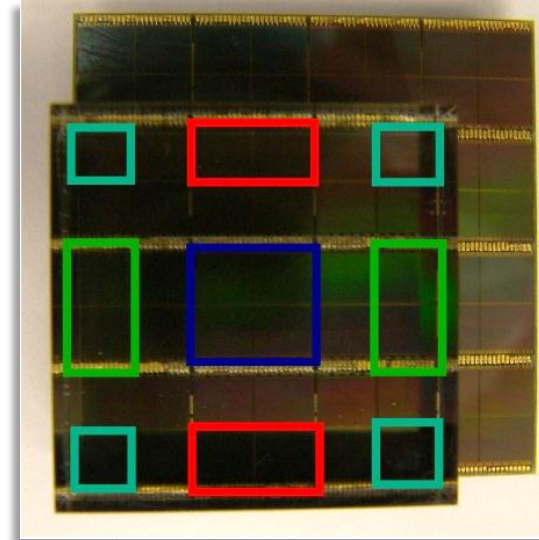


24 mm x 24 mm x 10 mm monolithic LSO:Ce,Ca on PDPC array



Energy resolution

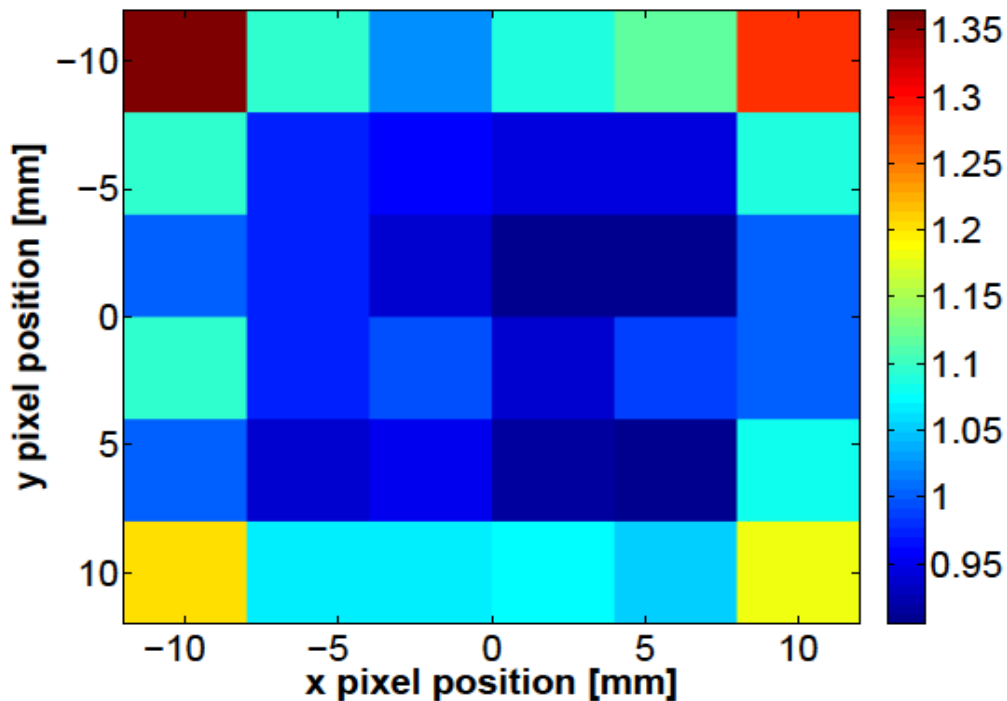
- 24 mm x 24 mm x 10 mm Ca-codoped LSO:Ce
- PDPC DPC-6400-44-22 dSiPM array
- Average energy resolution: ~11.5% FWHM
- Negligible saturation



Sub-mm spatial resolution

10 mm thick crystal

Position resolution FWHM,
averaged over 4 mm x 4 mm areas

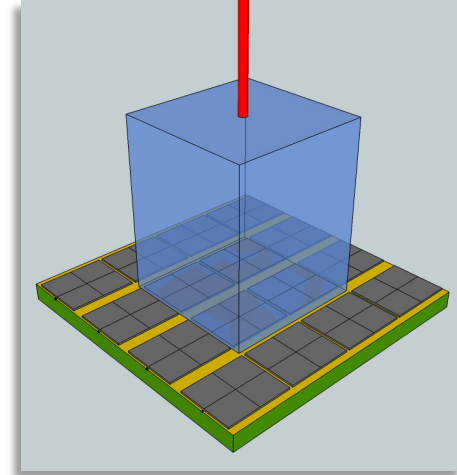


- 24 x 24 x 10 mm³ LSO:Ce,Ca
- DPC-6400-44-22 array
- Smoothed k-NN method*
100 reference events per calibration position
- Measured at 0 °C
- Crystal average:
 - **0.98 mm FWHM**
 - 2.31 mm FWTM
- Uncorrected for beam width

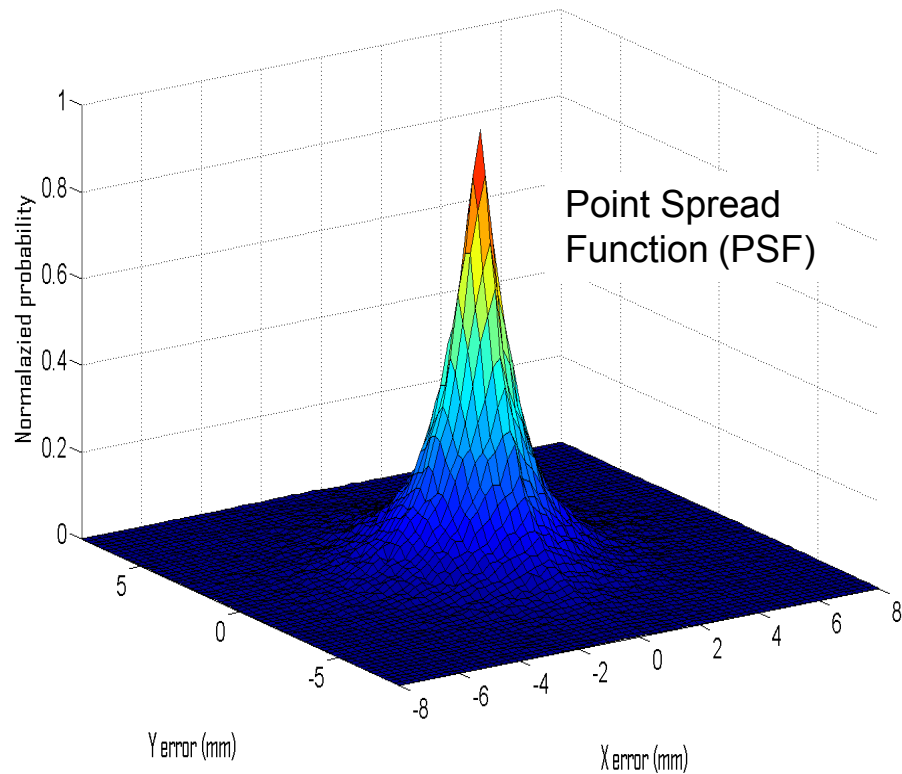
* *H.T. van Dam et al, IEEE Trans Nucl Sci 58, 2139-2147, 2011*

Spatial resolution

20 mm thick crystal



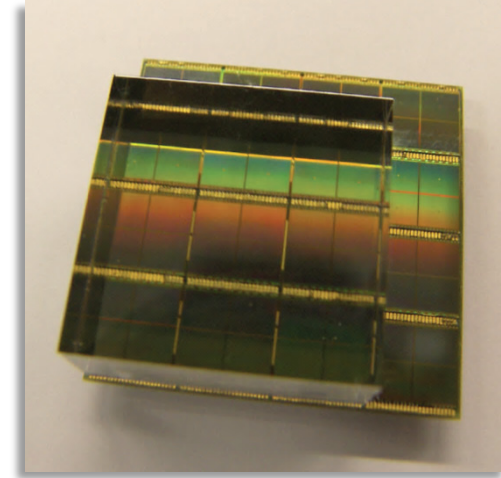
- 16 x 16 x 20 mm³ LSO:Ce,Ca
- DPC-3200-44-22 array
- Smoothed k-NN method*
 $n_{\text{ref}} = 100$
- Measured at -25 °C
- Crystal average:
 - **x: 1.89 mm FWHM**
 - **y: 1.79 mm FWHM**
- Uncorrected for beam diameter



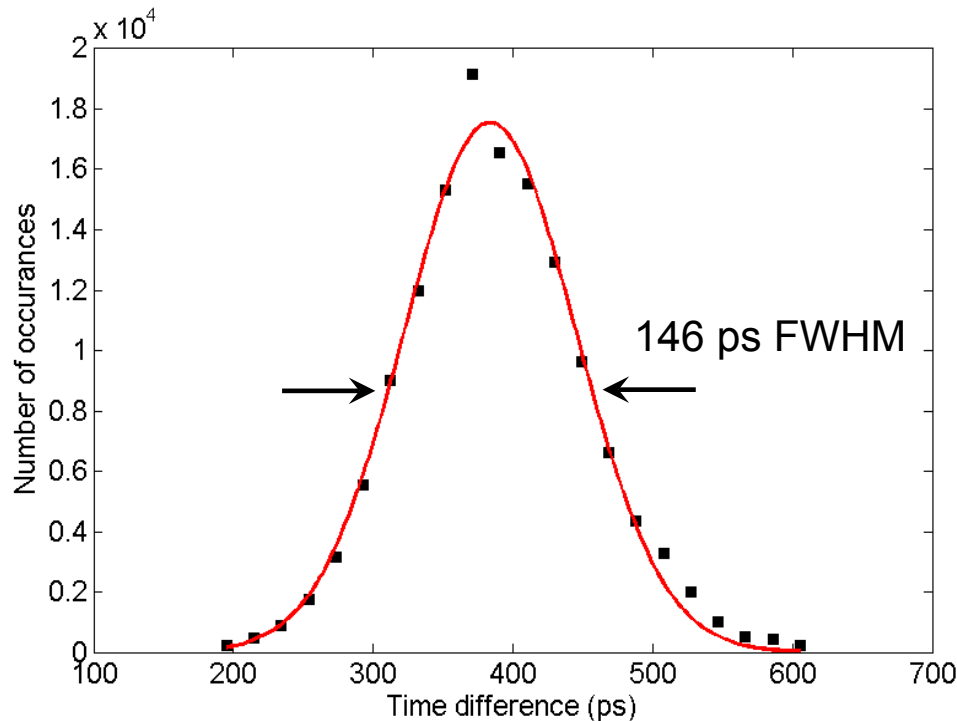
* H.T. van Dam et al, *IEEE Trans Nucl Sci* 58, 2139-2147, 2011

Coincidence resolving time

10 mm thick crystal



CRT for 2 detectors: 167 ps FWHM



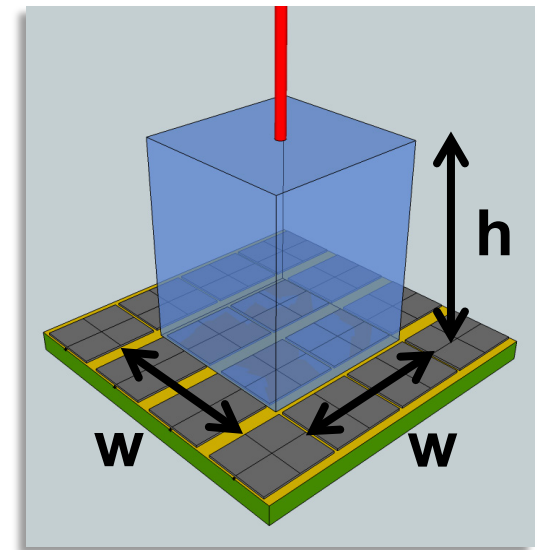
Timing measurement against 85 ps FWHM reference detector

- 24 x 24 x 10 mm³ LSO:Ce,Ca
- DPC-3200-44-22 array
- Measured at -25 °C
- Corrected for electronic skews of individual Si dies (50 ps laser measurement)
- Corrected for mean optical transit time, given the (x,y) interaction position

CRT for different monolithic crystal sizes

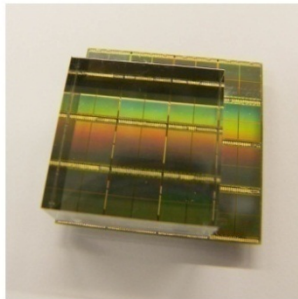
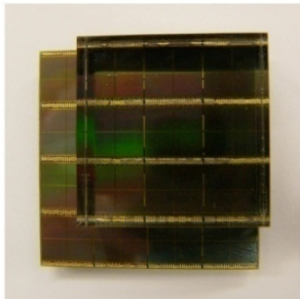
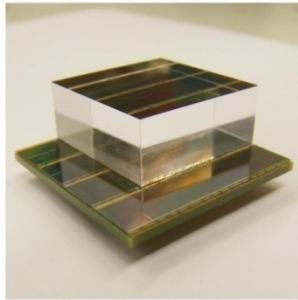
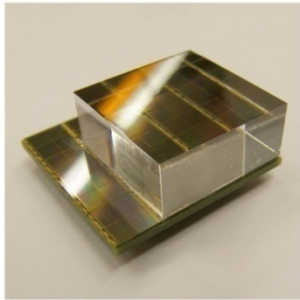
FWHM coincidence resolving time of two identical detectors in coincidence, for different crystal footprints ($w \times w$) and heights (h)

	$h = 10 \text{ mm}$	$h = 20 \text{ mm}$
$w = 16 \text{ mm}$	165 ps	199 ps
$w = 24 \text{ mm}$	167 ps	198 ps



LSO:Ca, Ce + DPC-3200-44-22 dSiPM array

Sub-mm resolution, TOF & DOI !



Summary of first results with LSO:Ce,Ca monolithic scintillators on digital SiPM arrays:

- Coincidence resolving time ≤ 200 ps FWHM
- < 1 mm FWHM resolution (height = 10 mm)
- < 2 mm FWHM resolution (height = 20 mm)
- 11% - 12% FWHM energy resolution
- Intrinsic depth-of-interaction (DOI) information

\Rightarrow A highly promising detector concept for clinical PET/CT and PET/MRI

Thank You