DE LA RECHERCHE À L'INDUSTRIE

# SPADnet
# a Digital Silicon PhotoMultiplier for Positron Emission Tomography: presentation and characterization


**Eric Gros d'Aillon, CEA-LETI**

eric.grosdaillon@cea.fr

www.spadnet.eu

L. Maingault [1], E. Gros d'Aillon [*, 1], L. André [1], L. Verger [1], E. Charbon [2], C. Bruschini [3], C. Veerappan [2], D. Stoppa [4], N. Massari [4], M. Perenzoni [4], L. H. C. Braga [4], L. Gasparini [4], R. K. Henderson [5], R. Walker [5], S. East [6], L. Grant [6], B. Jatekos [7], E. Lorincz [7], F. Ujhelyi [7], P. Major [8], Z. Papp [8], and G. Nemeth [8]

*1- CEA-Leti, MINATEC Campus,Recherche Technologique, F 38054 Grenoble, France*
*2- Delft University of Technology, Delft, The Netherlands*
*3- EPFL, Lausanne, Switzerland*
*4- Smart Optical Sensors and Interfaces (SOI) Group, Fondazione Bruno Kessler (FBK), Trento, Italy*
*5-CMOS Sensors and Systems (CSS) Group, School of Engineering, The University of Edinburgh, Edinburgh, United Kingdom.*
*6-Imaging Division, STMicroelectronics, Edinburgh, United Kingdom*
*7- Budapest University of Technology and Economics, Department of Atomic Physics, Budapest, HU*
*8- Mediso Orvosi Berendezes Fejleszto es Szerviz Kft. (Mediso Ltd.),HU*


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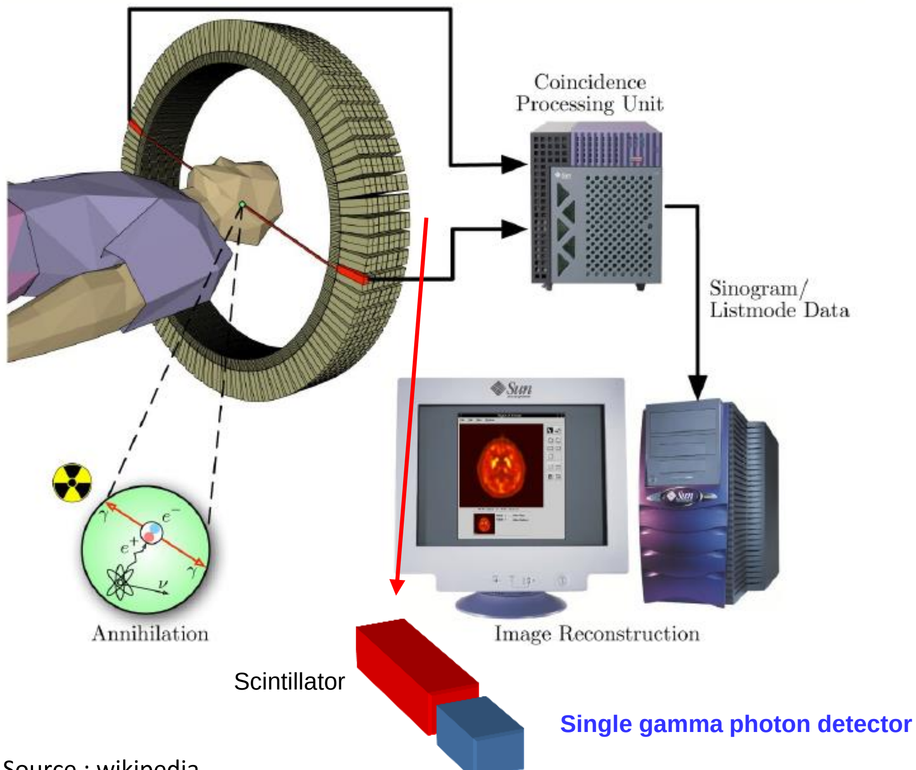
# Positron Emission Tomography

- Functional imaging of radio-isotope which emit a positron.
- Positron and electron annihilate. Two 511keV gamma photons are emitted in coincidence at 180°.
- Mainly used for oncology.



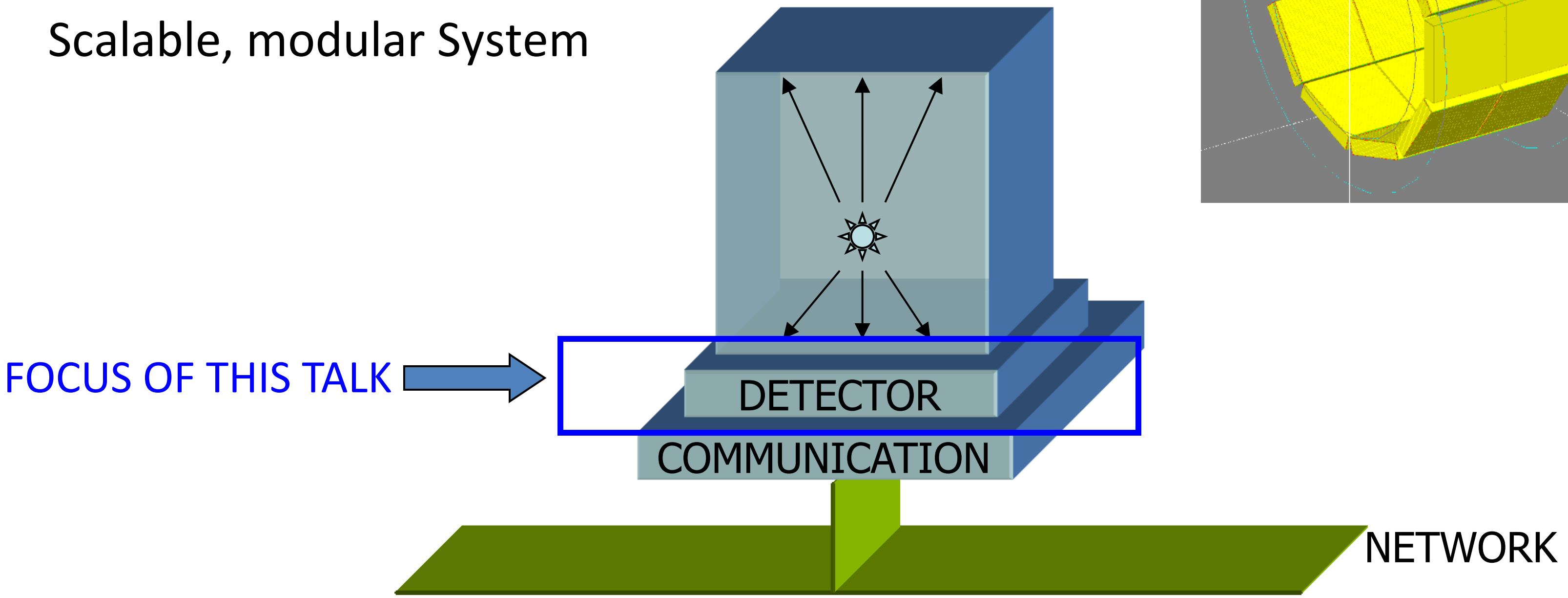

Source : wikipedia

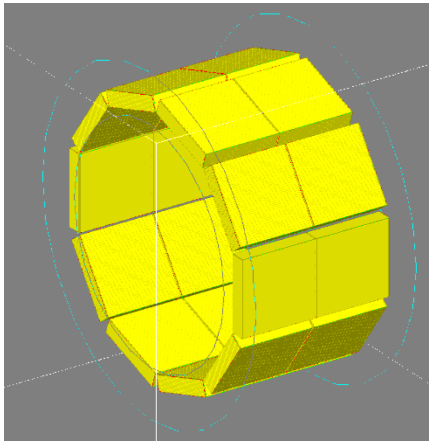
# The SPADnet Concept

Photonic Component, comprising:

- Scintillator (LYSO)
- Sensor (SiPM)
- Network (Gbps)

Scalable, modular System



# The sensor

# Sensor Requirements for PET

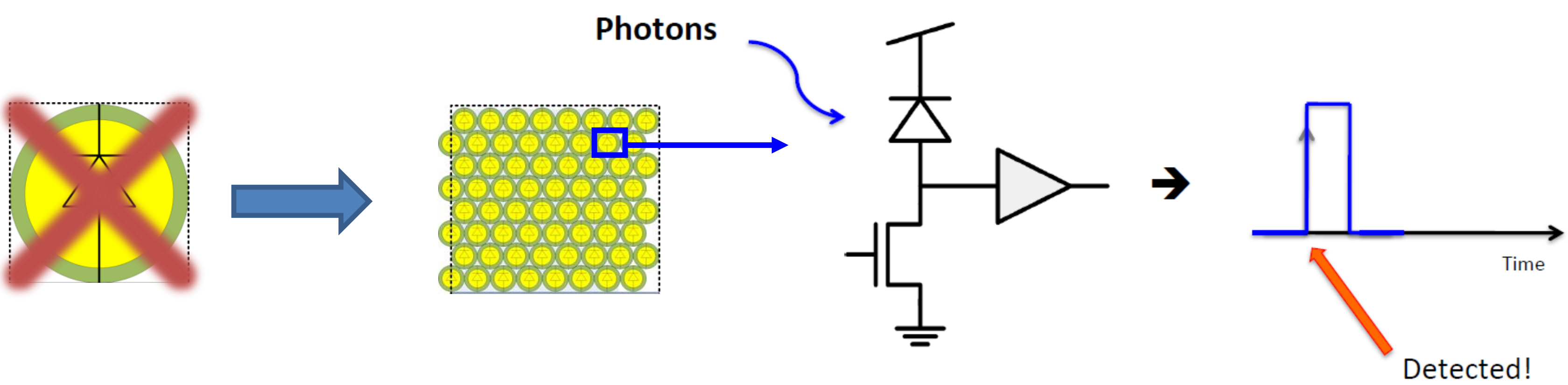
- We want to build of large format, compact, MRI compatible sensor capable of TOF-PET

- We need to measure for each gamma-ray:
  - Position Of Interaction
  - Energy
  - Time of arrival

- Proposed solution: a fast sensor sensitive to a few photons in CMOS technology
  - Small pixels → Improve spatial resolution
  - Embedded Time to Digital Converters → Time stamp more than one visible photon
  - Real-time energy output → Provide scintillation decay time information
  - Through-Silicon-Via based packaging → Extensible to large format

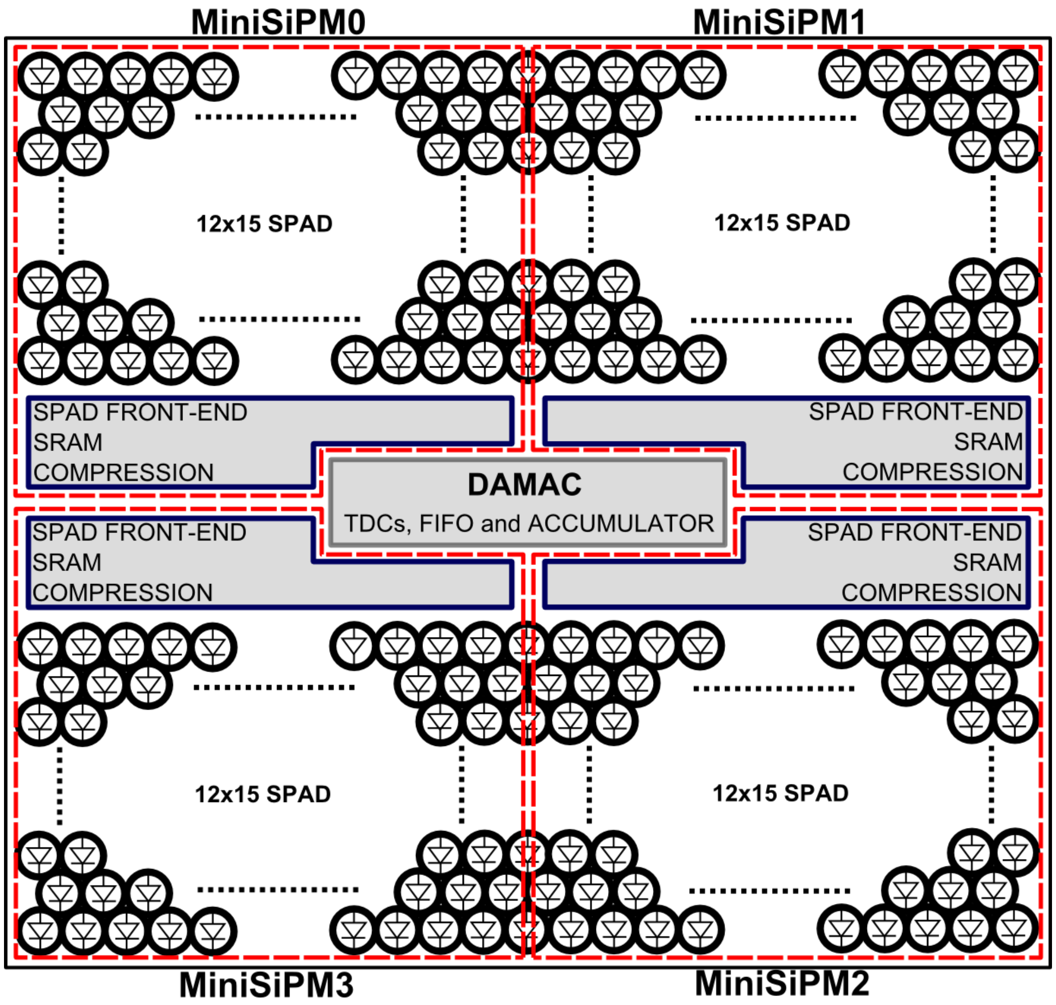
# Silicon Photomultiplier (SiPM)

- SiPM : array of Single-Photon Avalanche Diodes (SPADs)
- Each SPAD is a photodiode operating in Geiger mode
  - The number of fired SPADs is proportional to the number of incident photons
- Particularity of CMOS based SiPM
  - Digitization of the photon
  - Advanced functions could be embedded



# SPADnet Pixel Architecture

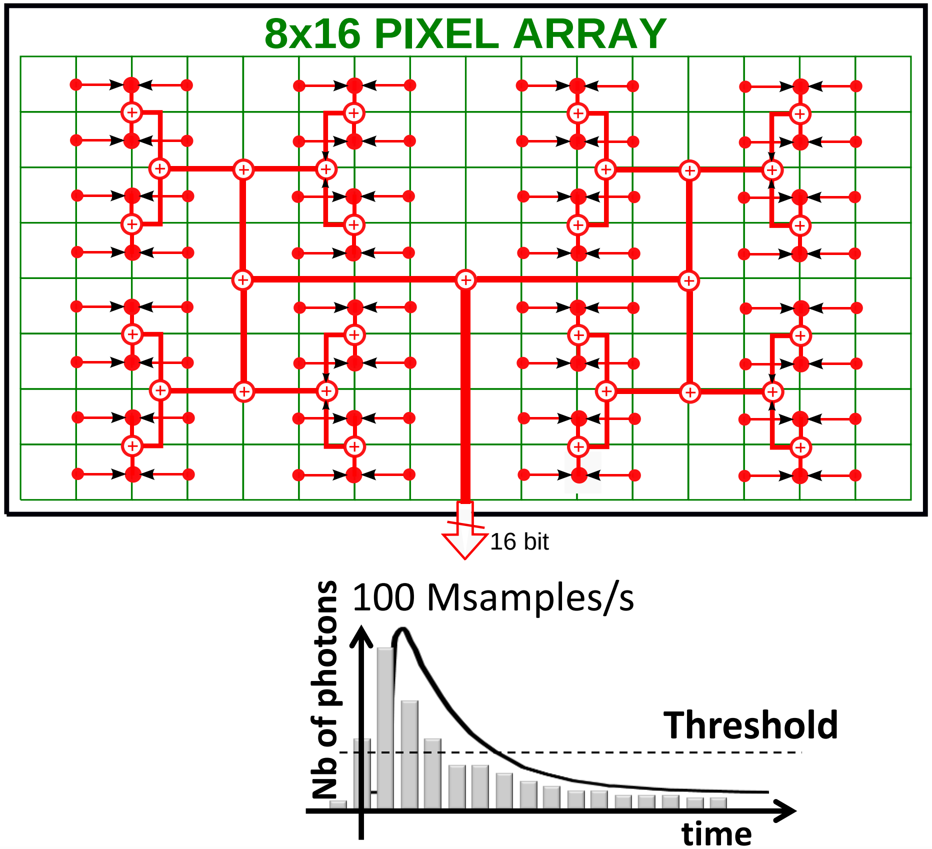
- 0.57×0.61mm pixel
- 2 x 2 mini-SiPMs (Braga et al., NSS2011)
- 720 SPADs (Walker et al., NSS 2012)
- 1 active TDC
- 43% array fill factor




For more details, see Braga *et al.*, ISSCC 2013 and Walker *et al.* IISW 2013

# Discriminating gamma event

- The chip is an array of 8x16 pixels
- Fast readout of the counted photons
- Integration is triggered by comparing the photon flux to a threshold

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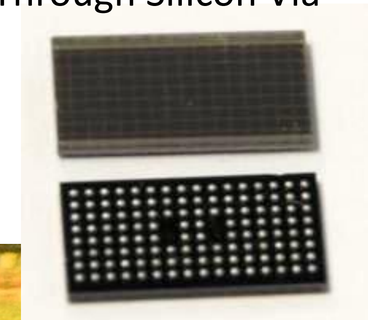
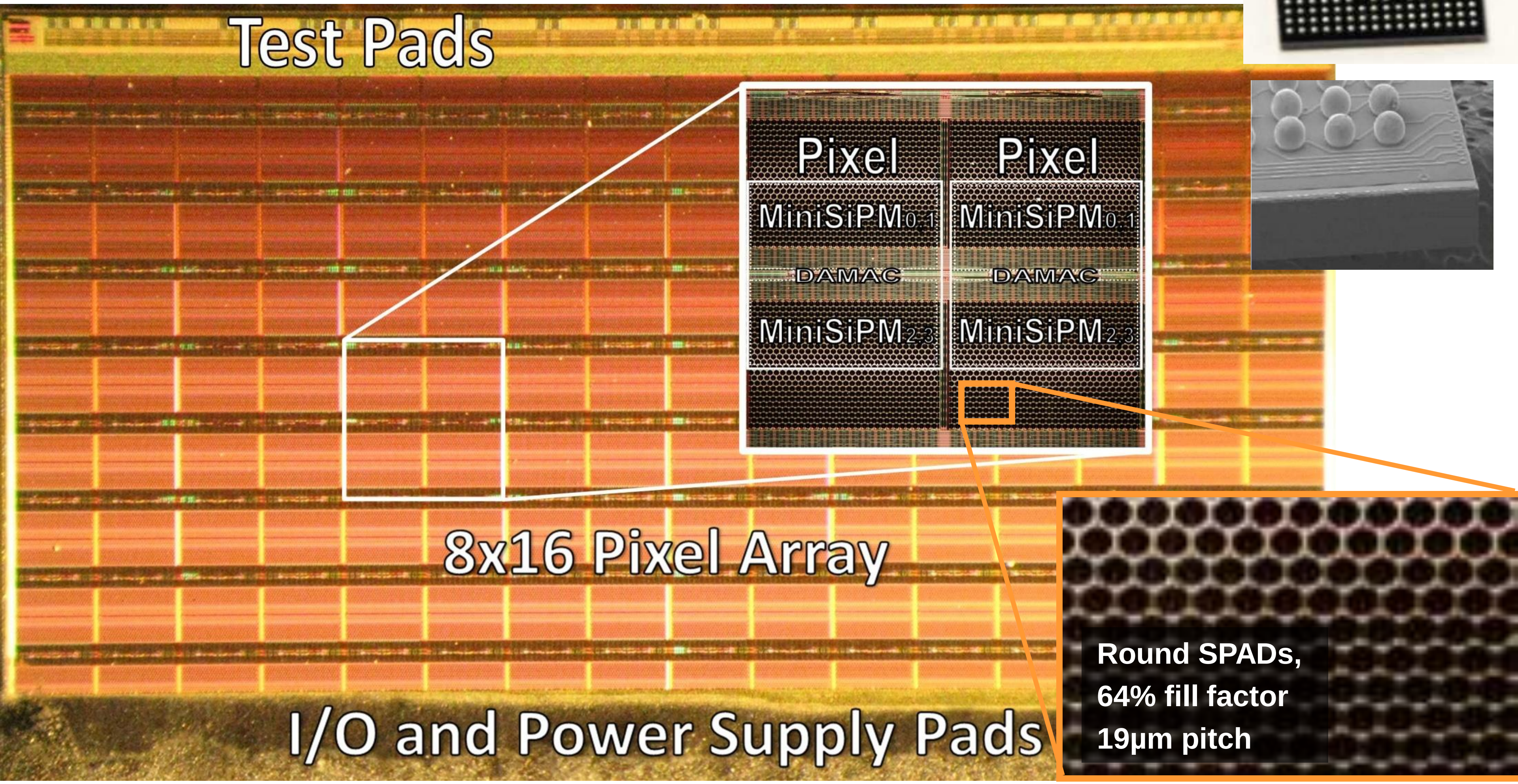
# Implemented Device

Through Silicon Via



**SPADnet1 chip :** 16x8 pixels, ~600µm pitch. 720 SPADs per pixel. 92k SPADs



# Characterization

1 – SPADs

Dark Count Rate

Dead Time

Photon Detection Probability

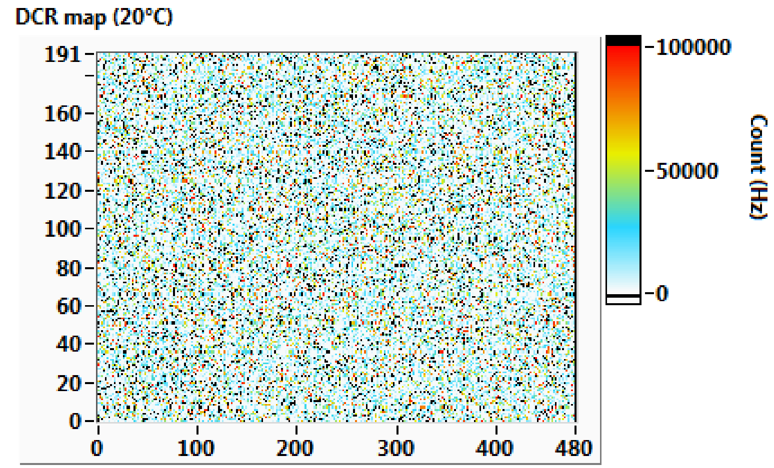
2 – Sensor

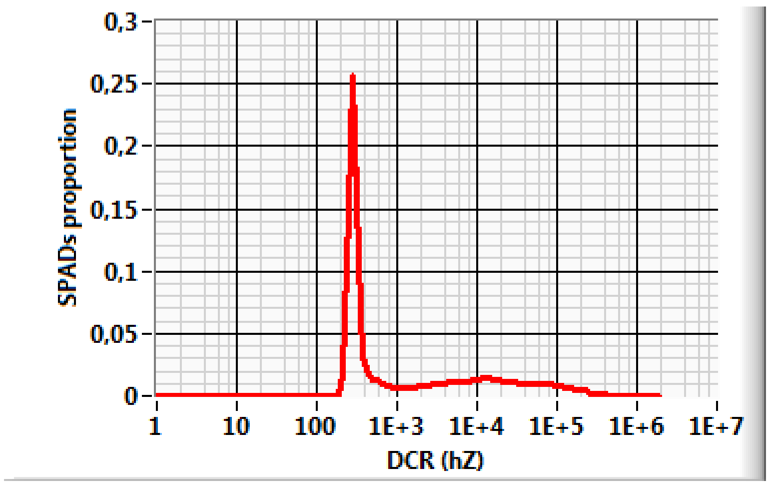
Gamma spectra

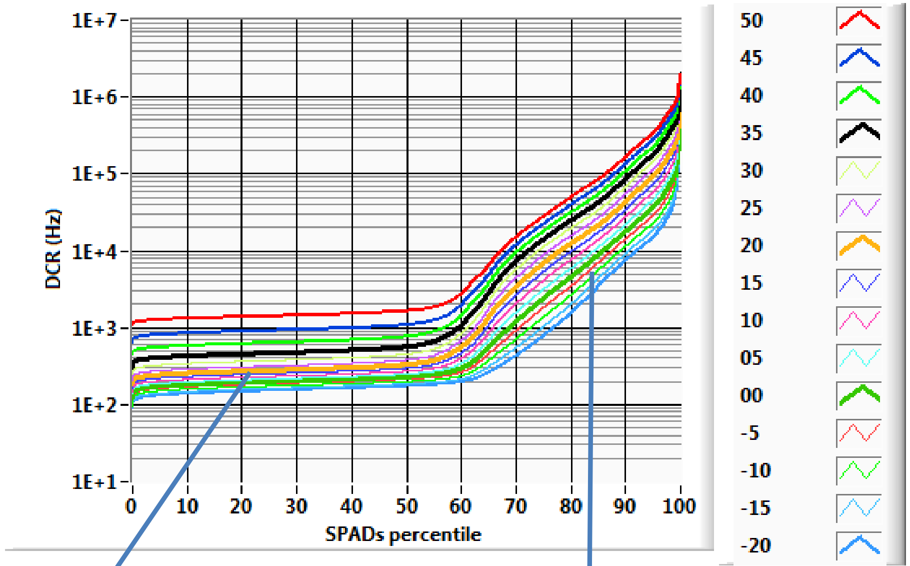
Coincidence Timing Resolution

# Dark Count Rate

- Selecting one SPAD per pixel at a time
- At 23 °C and 1.5V excess bias : median DCR = 330 Hz
- Noisy SPADs could be disabled
- DCR double every 15°C



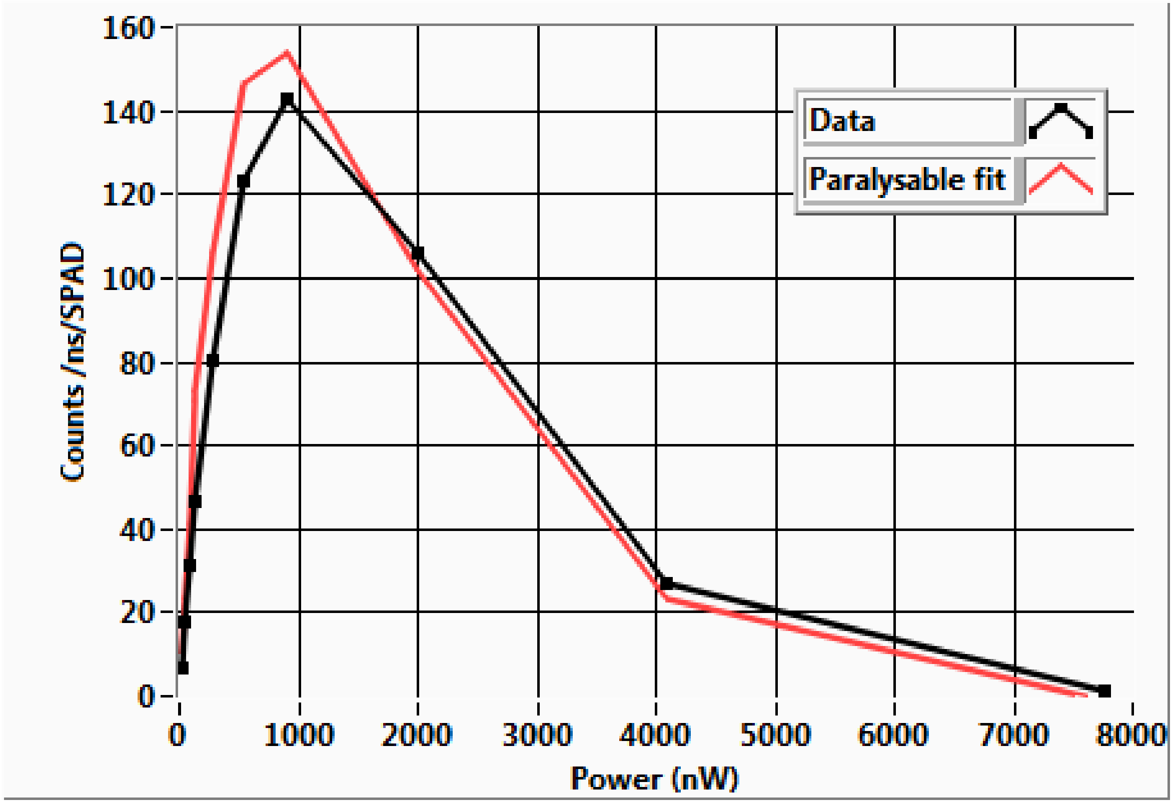




Limited by tunneling

Limited by thermally assisted Shockley-Read-Hall

# SPAD Dead Time

- Count with respect to the photon flux
- Deadtime : 50ns. Paralysable behaviour



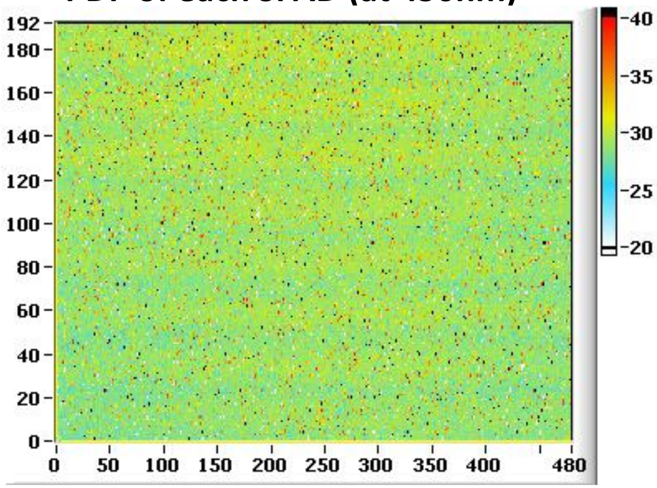

$$Counts = N_{ph}e^{-N_{ph}\tau}$$

$\tau$=50ns

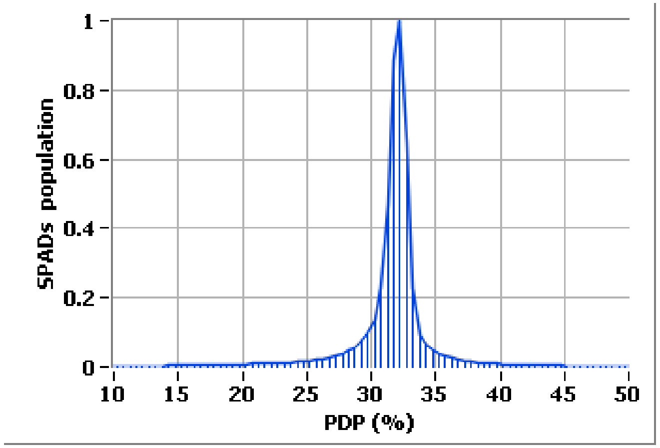
# Photon Detection Probability

- Selecting one SPAD per pixel at a time
- Peak SPAD PDP 32% at 450 nm at 20 °C and 1.5V excess bias (incl. afterpulse)

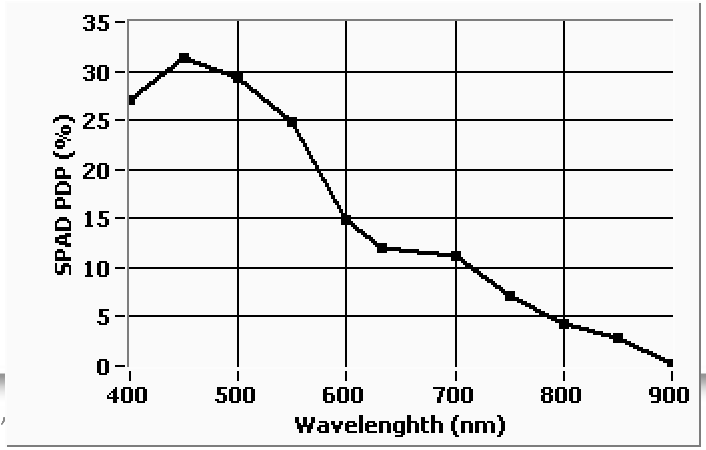
**PDP of each SPAD (at 450nm)**




**PDP histogram (at 450nm)**

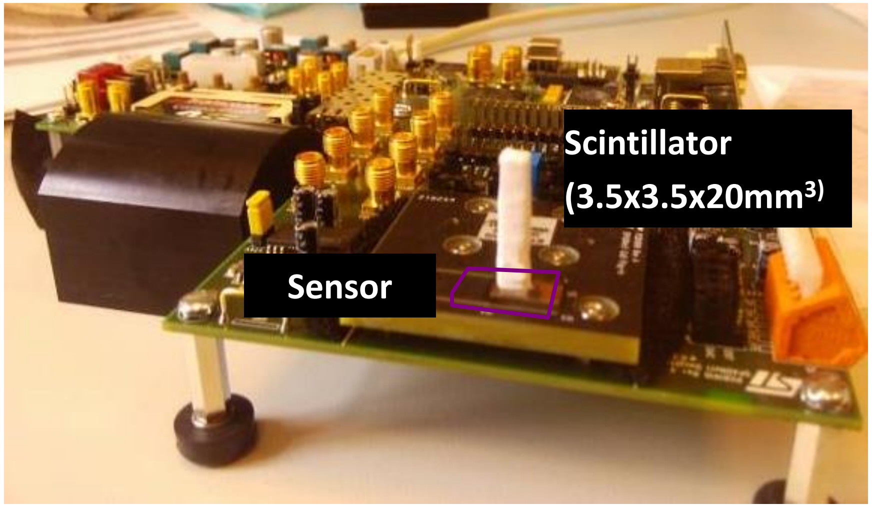



**With respect to wavelength**

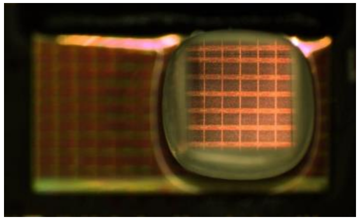


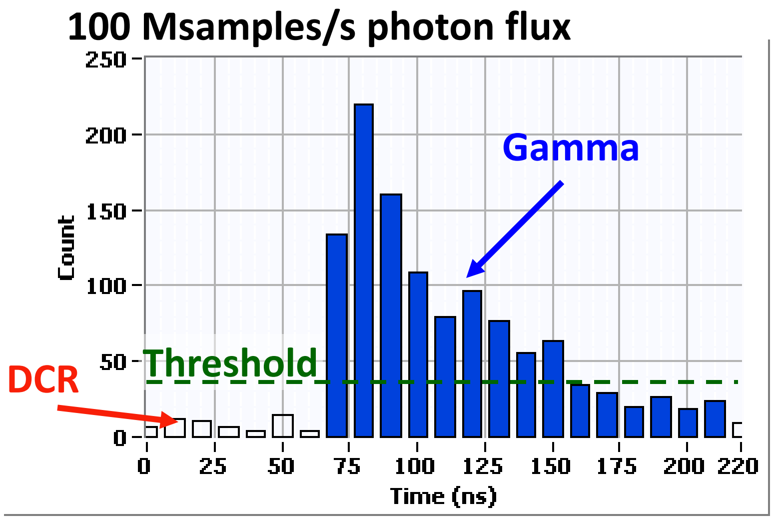
# Gamma measurements

- Single 3.5x3.5x20 $mm^3$ LYSO crystal (clinical) on 9.8x4.6$mm^2$ active area
- Teflon wrapped. Optical grease coupled.
- Room temperature. No stabilization. 1.5 V excess bias

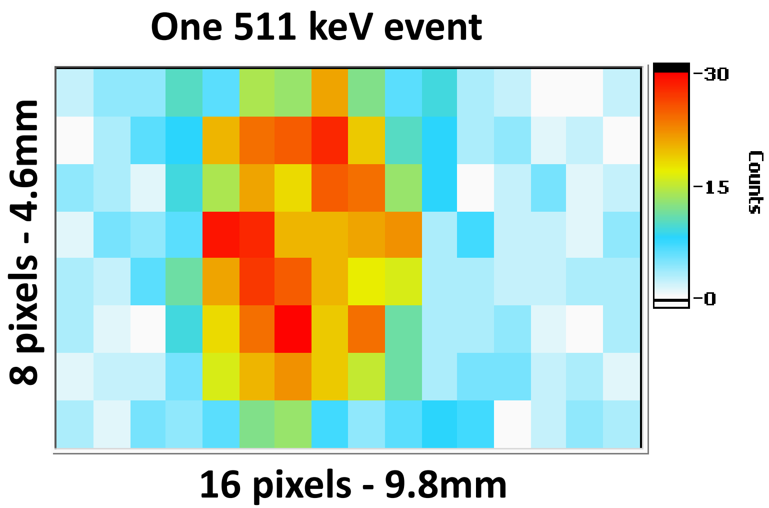


# Picture of a Gamma Event



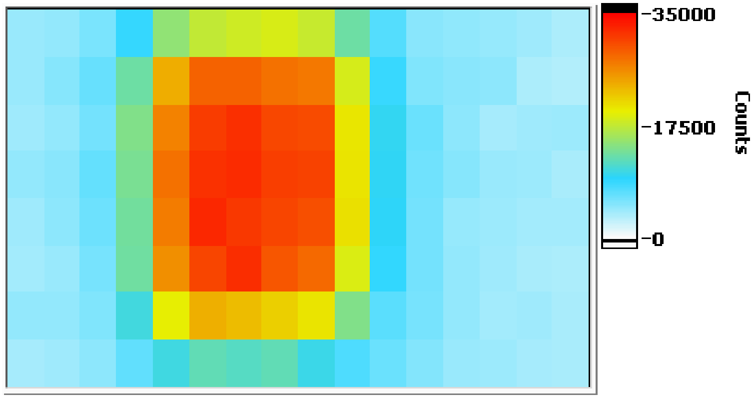



Triggering
Integration (150ns)



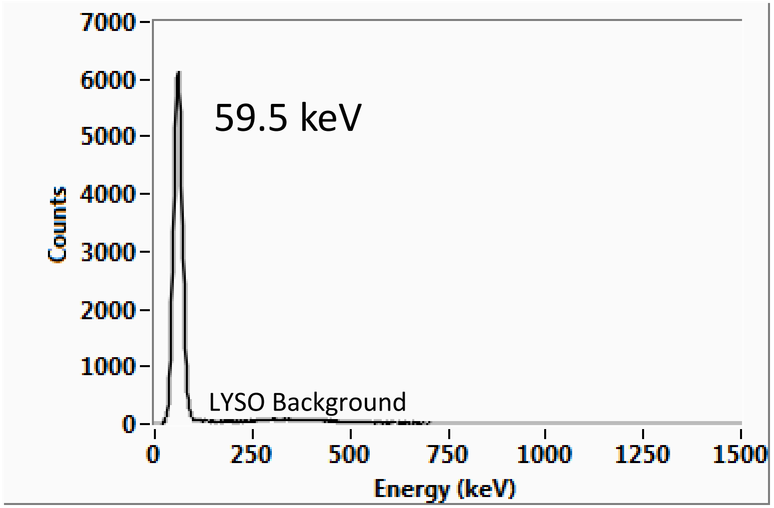

**Triggering mechanism gives robustness with respect to DCR**

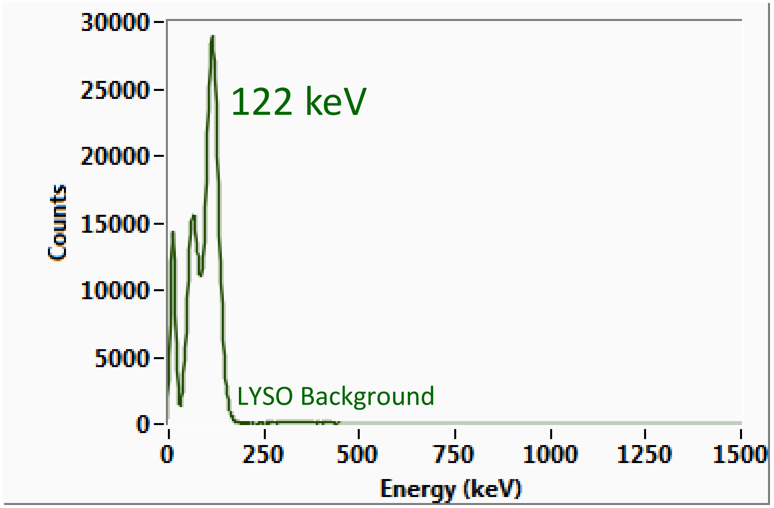
**Accumulation show the 3.5x3.5x20 LYSO needle**

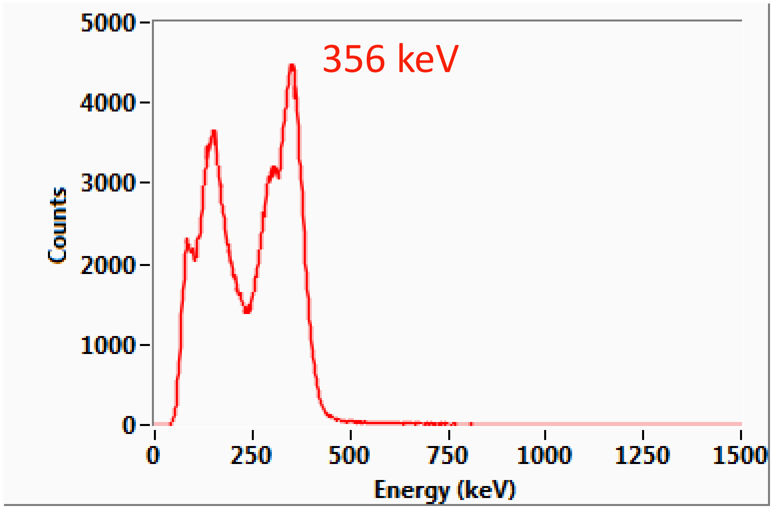


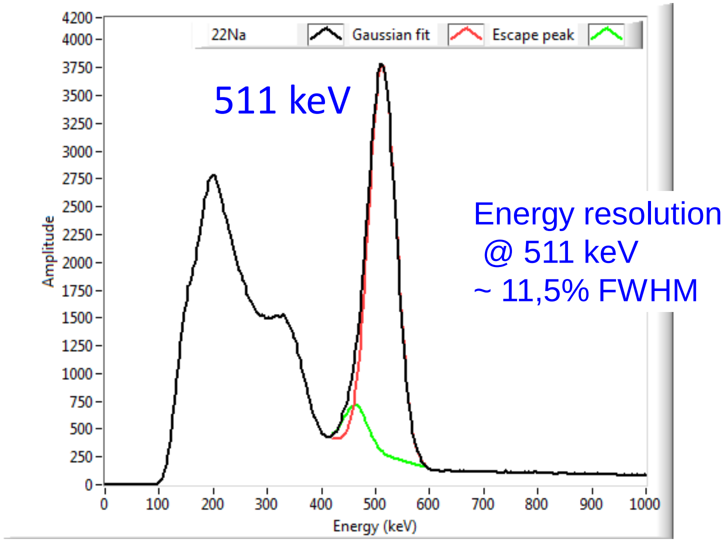
# Gamma Spectra

20°C
1.5V excess bias
80% SPAD enabled



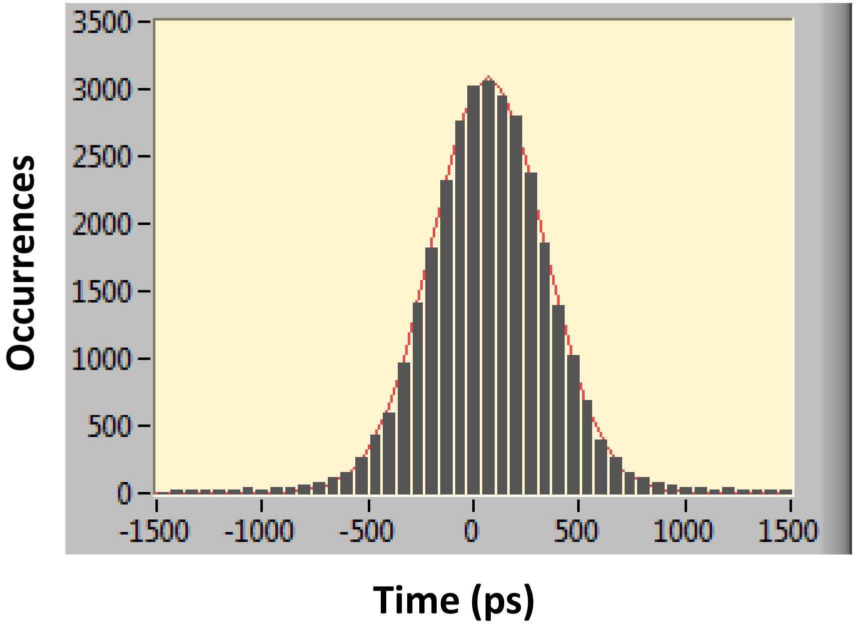



# Coincidence Resolution Time

20°C
1.5V excess bias
80% SPAD enabled

- Single 3.5x3.5x20 $mm^3$ LYSO crystal (clinical) on 9.8x4.6$mm^2$ active area
- 128 TDCs per chips enable multi-timestamp processing
- Best CRT in this experiment : 530 ps FWHM
- 288 ps obtained by Braga et al. using smaller LYSO crystals (IEEE Nucl. Sci. Symp. Conf. Rec 2013).

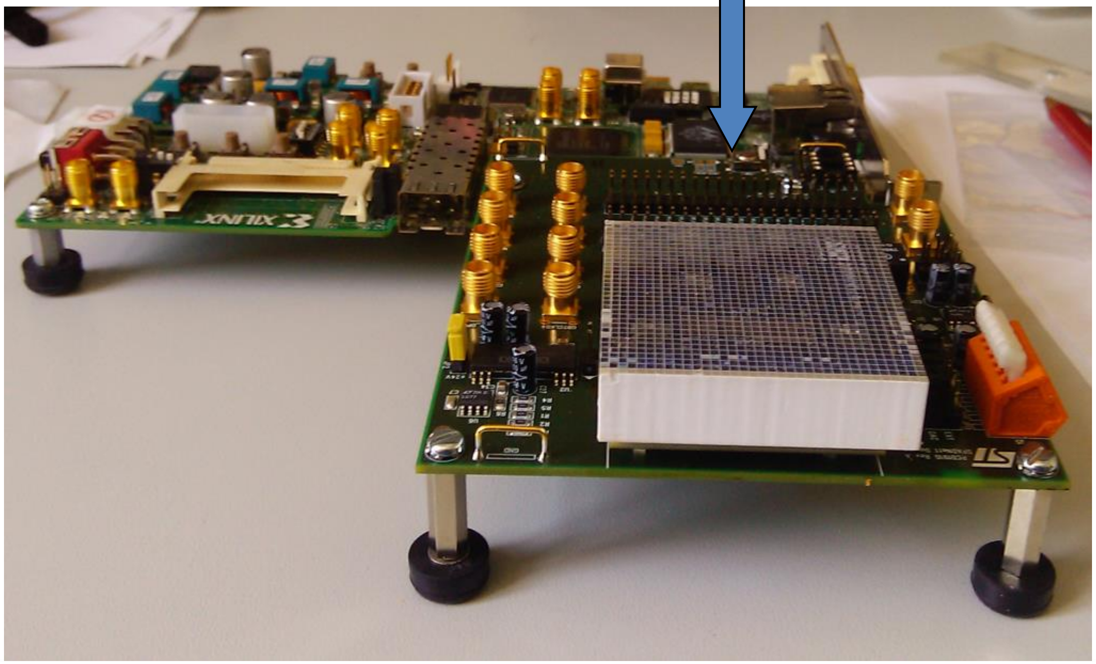


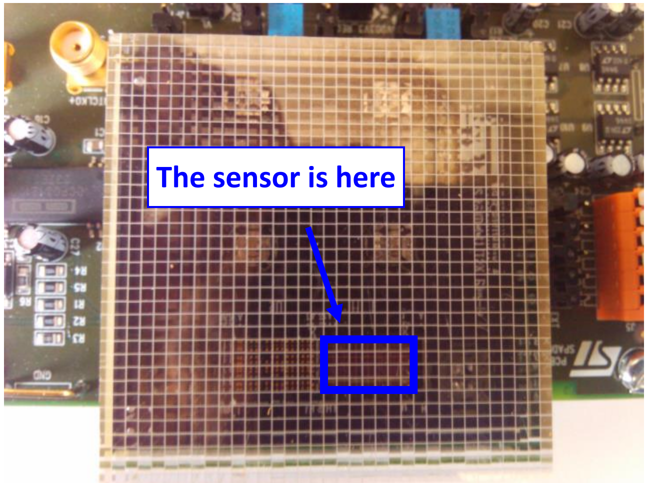
# Gamma measurements

- LYSO matrix with 35x35 pixels and 1.3mm pitch, and optical separator, 13 mm thick (preclinical) on 9.8x4.6mm² active area. Optical grease coupled. GORE® Diffuse Reflector. No alignment with pixels.
- Room temperature. No stabilization. 1.5V excess bias

Non-collimated punctual Na source

1 MBq, 10cm

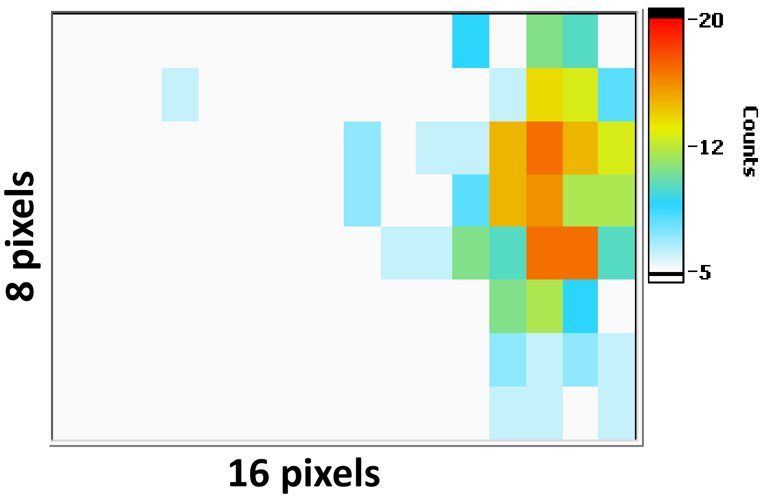




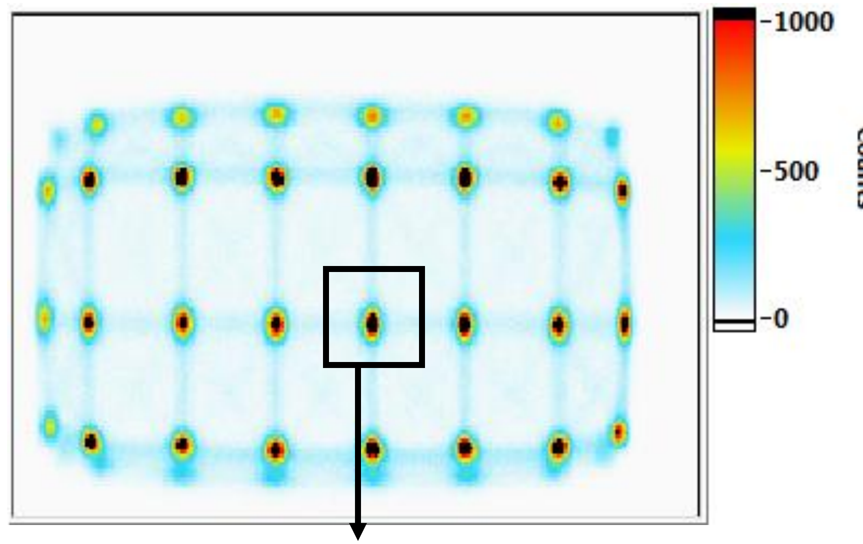
# Small needle matrix

- Post processing : Filtering noise (5 count) + centroïd

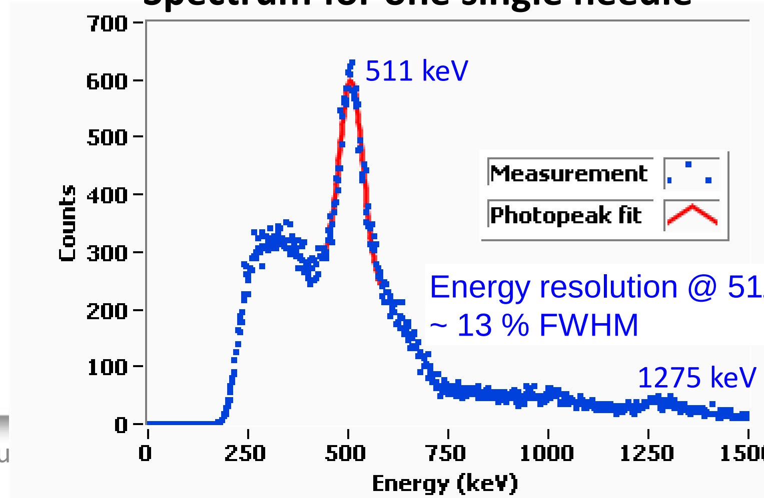
**One 511 keV event**




**Gamma accumulation**




**Spectrum for one single needle**




→ LYSO needles are clearly resolved

→ (overflow at edges)

# Conclusion and future steps

- SPADnet is a 4 sides tileable Gamma sensor in CMOS technology
- 8 x 16 pixels, 0.6 mm pitch, 92k SPAD
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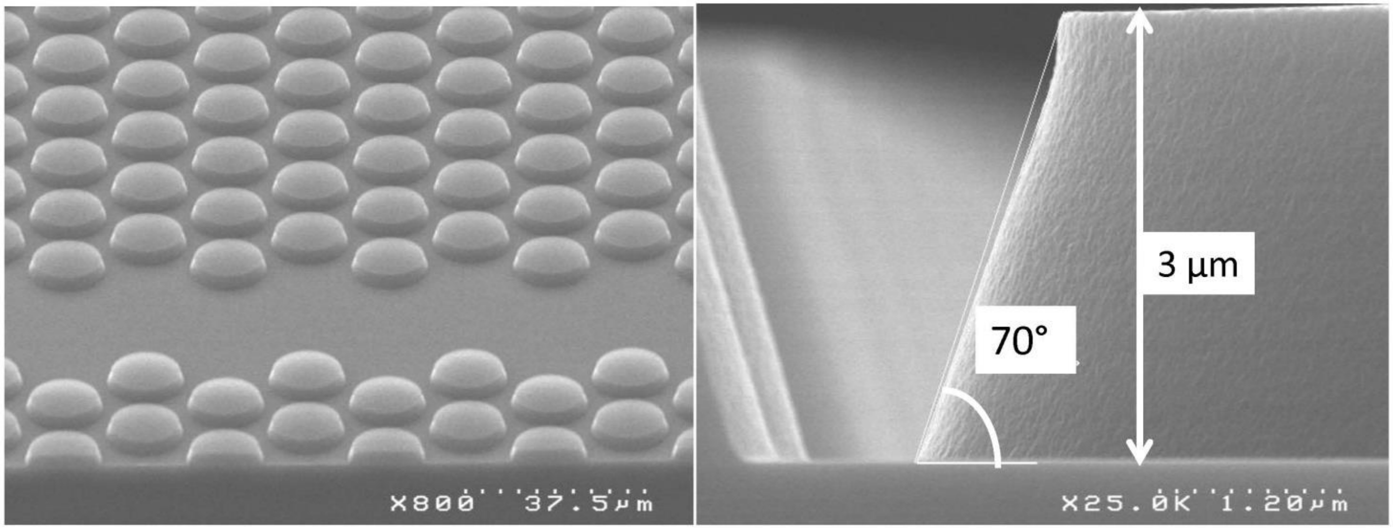
  - Optical Concentrators to recovers SPADs fill factor loss



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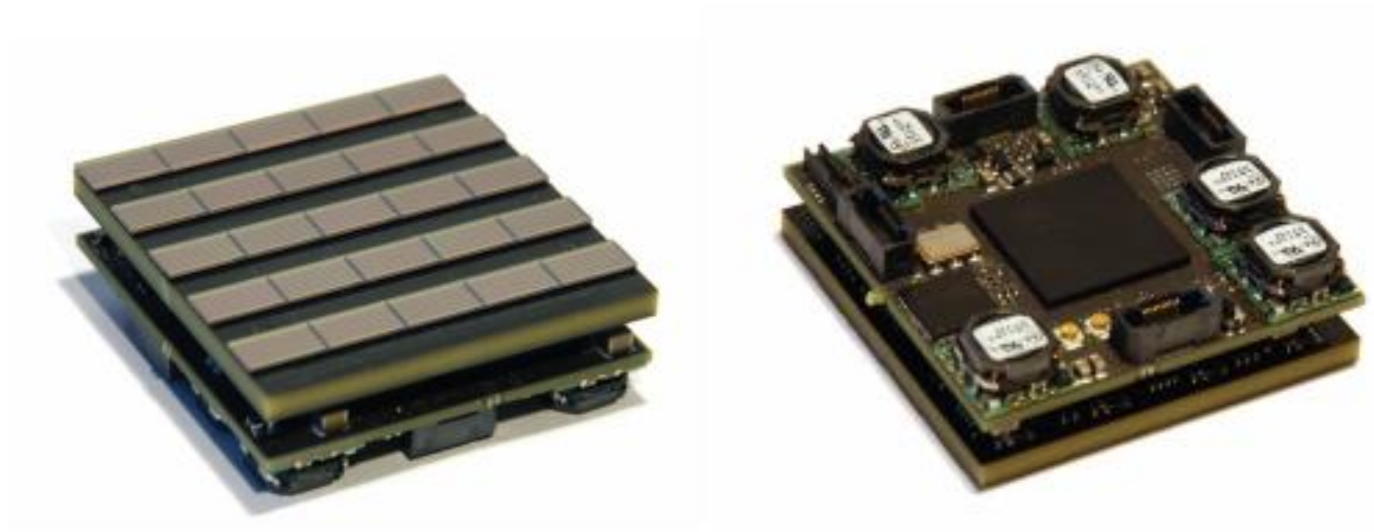

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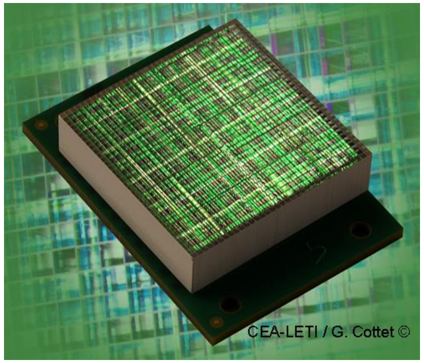


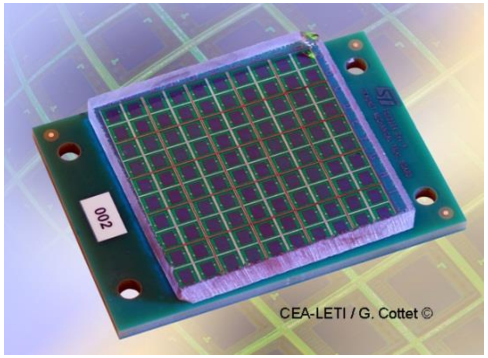


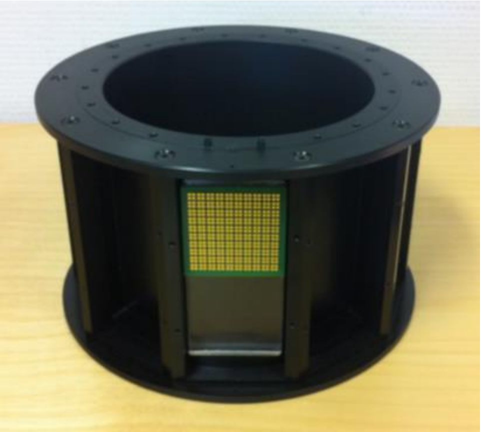

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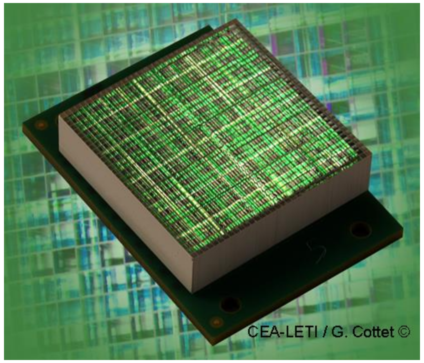
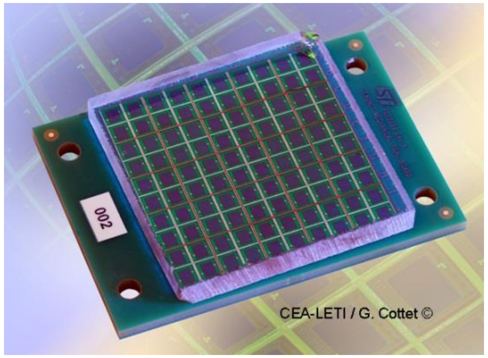
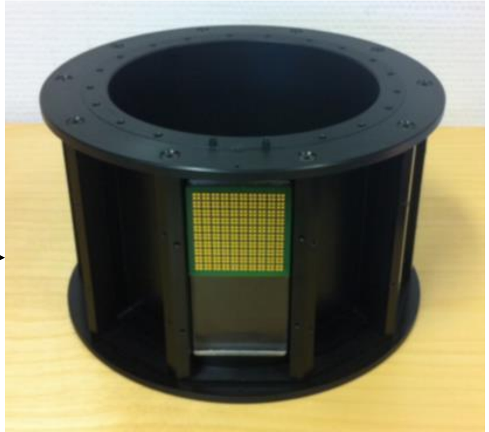
  - Second version of the SPADnet chip. 9.8 x 9.8 mm$^2$, higher fill factor



LABORATOIRE D'ÉLECTRONIQUE
ET DE TECHNOLOGIES
DE L'INFORMATION

CEA-Leti
MINATEC Campus, 17 rue des Martyrs
38054 GRENOBLE Cedex 9
Tel. +33 4 38 78 36 25

www.leti.fr

# Thanks for your attention