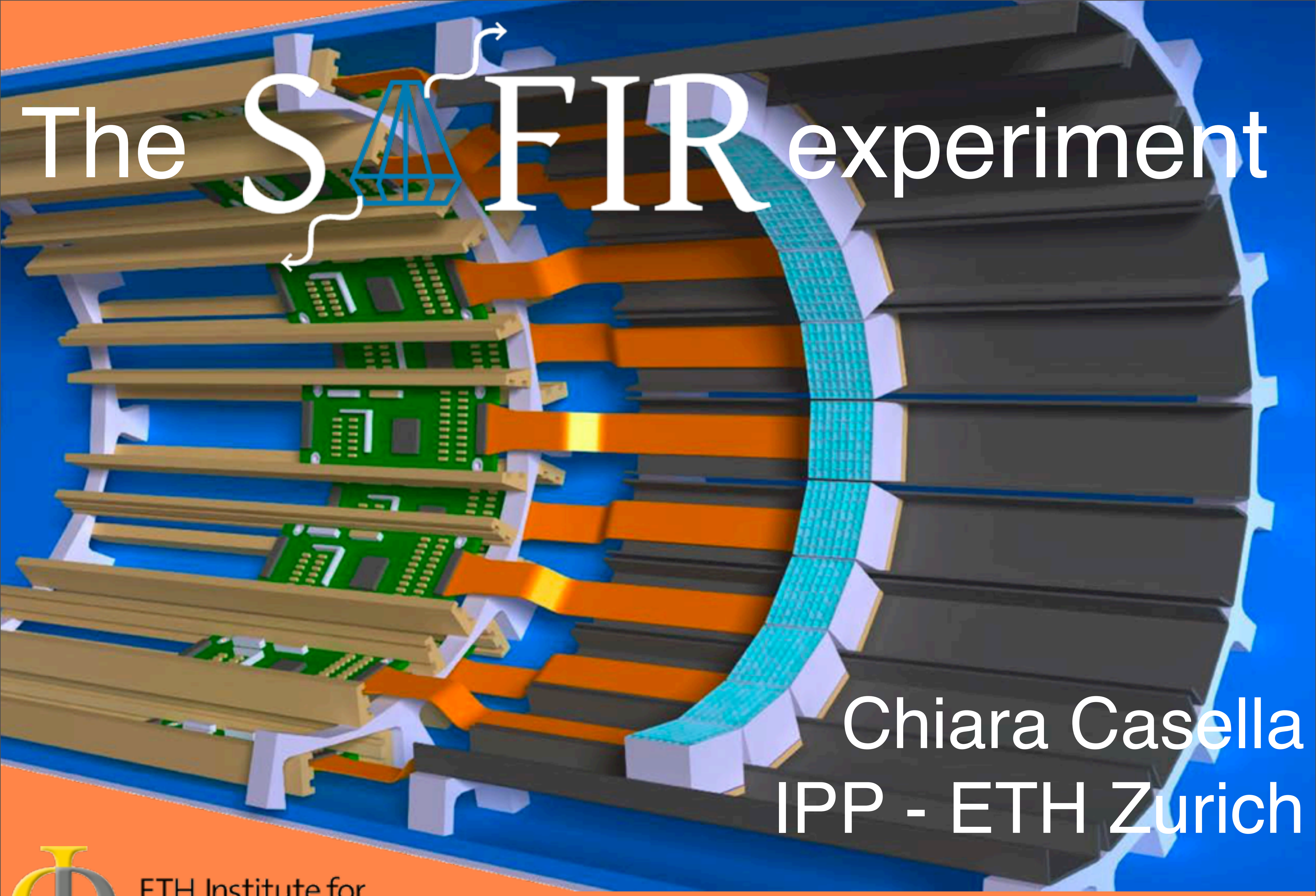
The SAFIR experiment

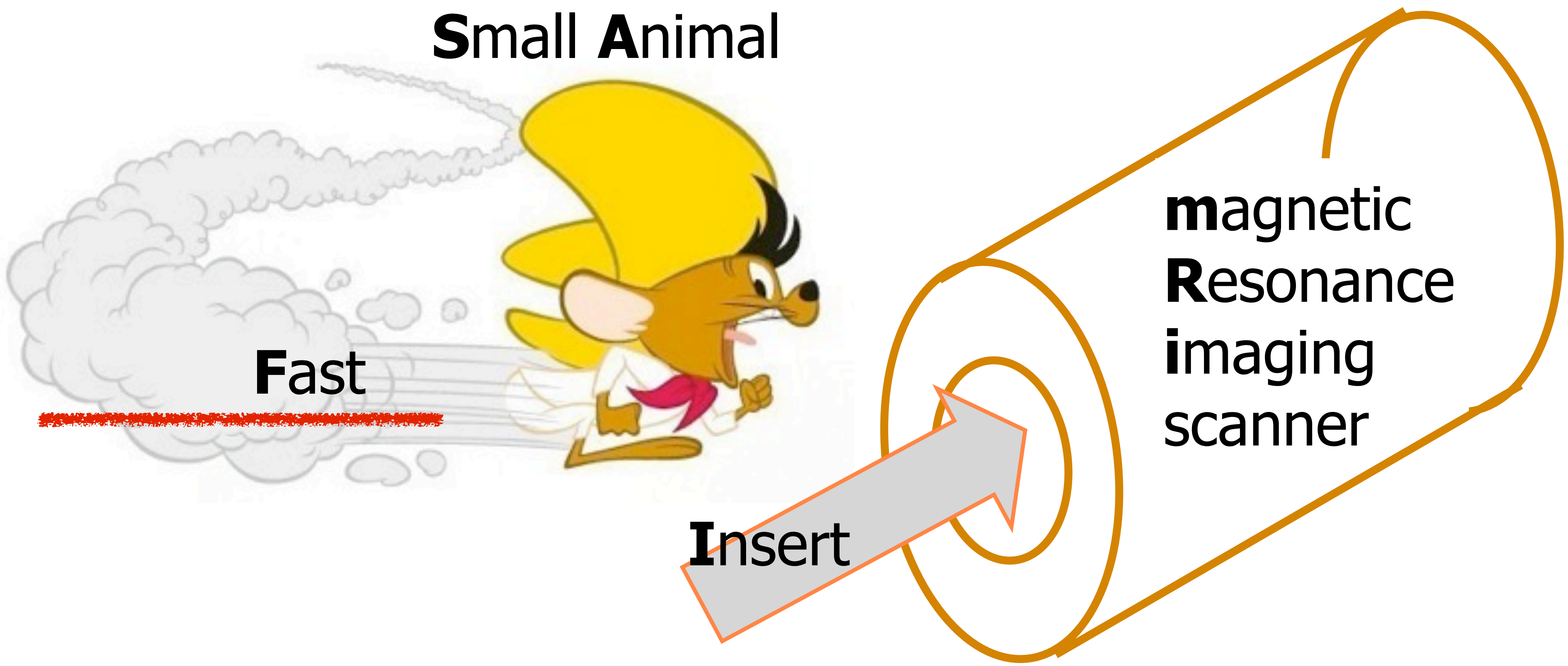


Chiara Casella
IPP - ETH Zurich

ETH Institute for
Particle Physics

UCL HEP seminar
London, 26.02.2016

SAFIR : Small Animal Fast Insert for mRi



R&D project in

Positron Emission Tomography (PET) instrumentation

for pre-clinical hybrid PET / MRI acquisitions

Outline

Define the context :

- PET basics
- multimodal PET/CT and PET/MRI
- short digression with a historical approach

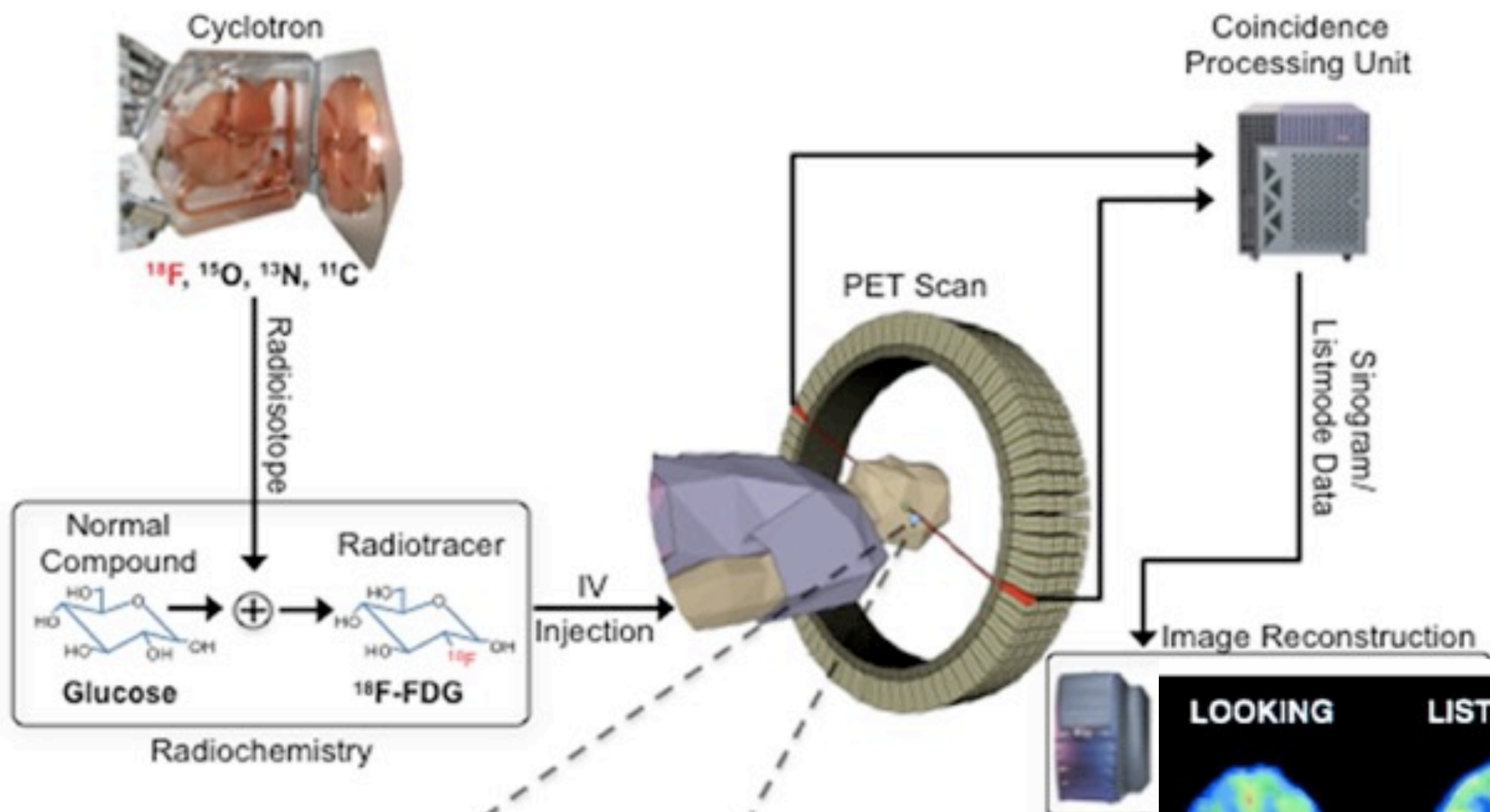
SAFIR :

- SAFIR goal
- detector design
- simulations
- image reconstruction
- characterization of the hardware components
  - SiPM
  - scintillator crystals
  - readout ASIC chips (high rate tests)
- future plans

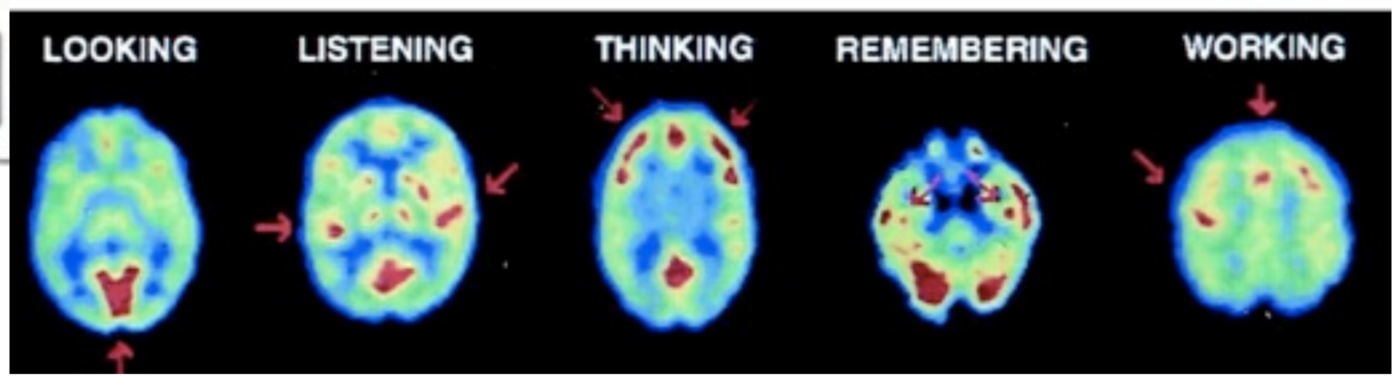
Conclusions


Setting the stage...

PET : Positron Emission Tomography



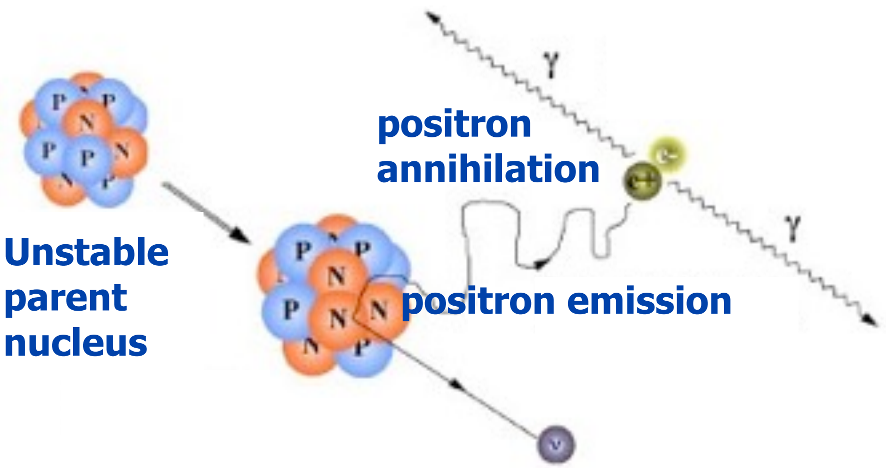
nuclear medicine imaging technique for **in-vivo functional** analysis



map of the radiotracer concentration

result : image of **functional** processes in the body

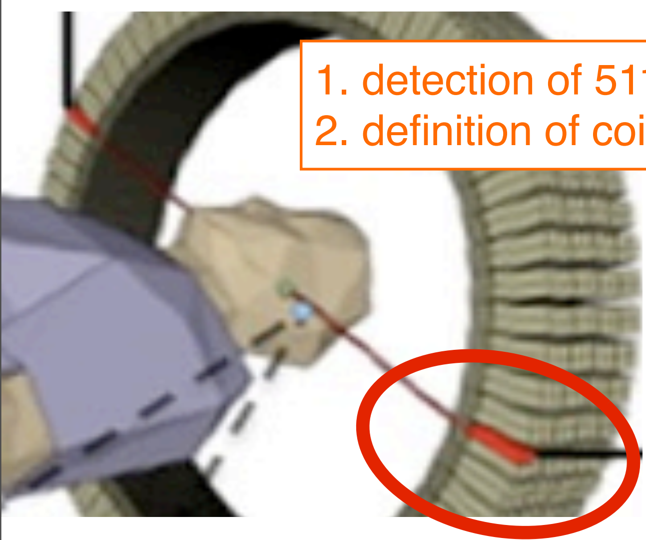
PHYSICS PRINCIPLE



$p \rightarrow n + e^+ + \nu_e$ **positron (e^+) emission :** β^+ decay

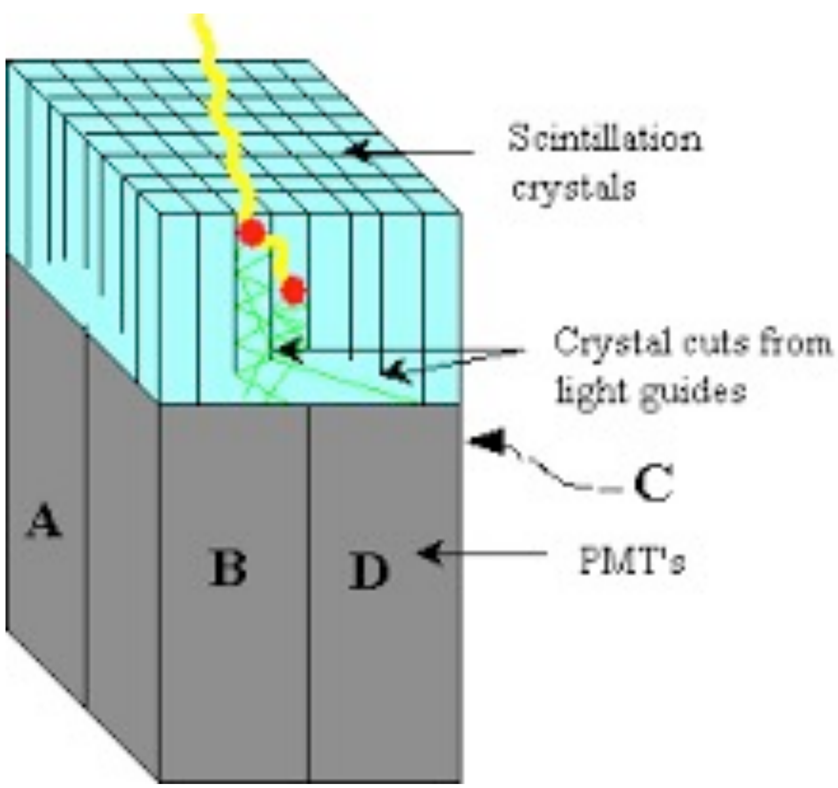
$e^+ e^- \rightarrow \gamma\gamma$ **positron (e^+) annihilation** => 2 collinear γ photons of E = 511keV each

PET detection principle



most widely adopted detection technique :

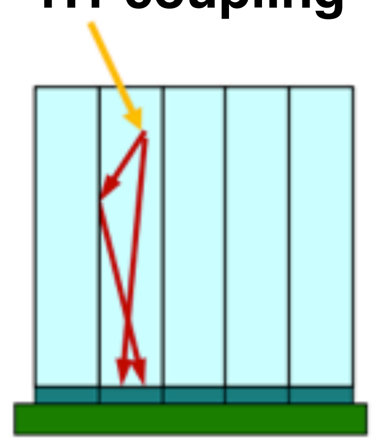
- **inorganic scintillators**
  mostly L(Y)SO [Lu based crystals]
- **photosensors**
  traditionally PMT (block detector)
  now Silicon based photodetectors (APD/SiPM)



BLOCK DETECTOR configuration

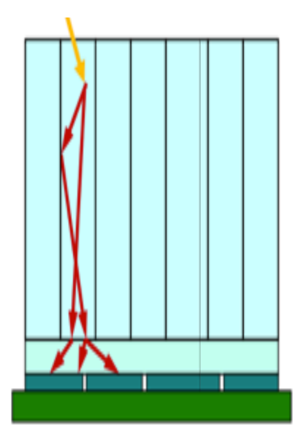
different approaches of xtal/photosensors coupling

pixelated xtals
1:1 coupling



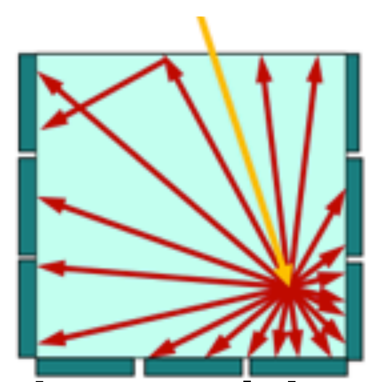
good ΔE/E
good time resol.
large signals

pixelated xtals
+ light sharing
=> Center of Gravity



high spatial resol.
small signals
increased data rate

monolitic
=> Center of Gravity

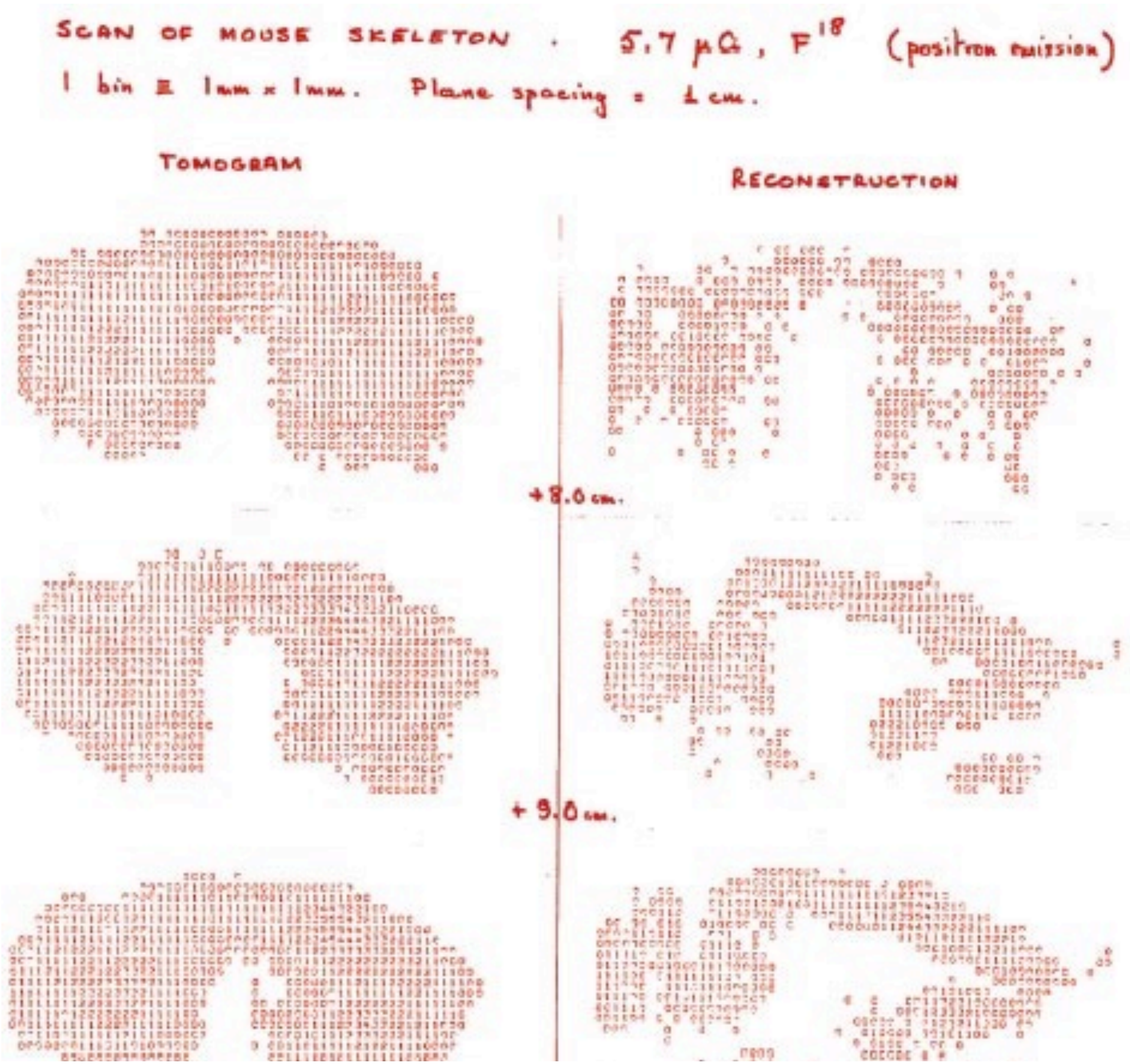


higher spatial resol.
smaller signals
largest data rate

CLINICAL

PRE-CLINICAL (small animals)

Early PET images (at CERN)



RAW DATA RECORDED IN THE DETECTORS

RECONSTRUCTED IMAGES

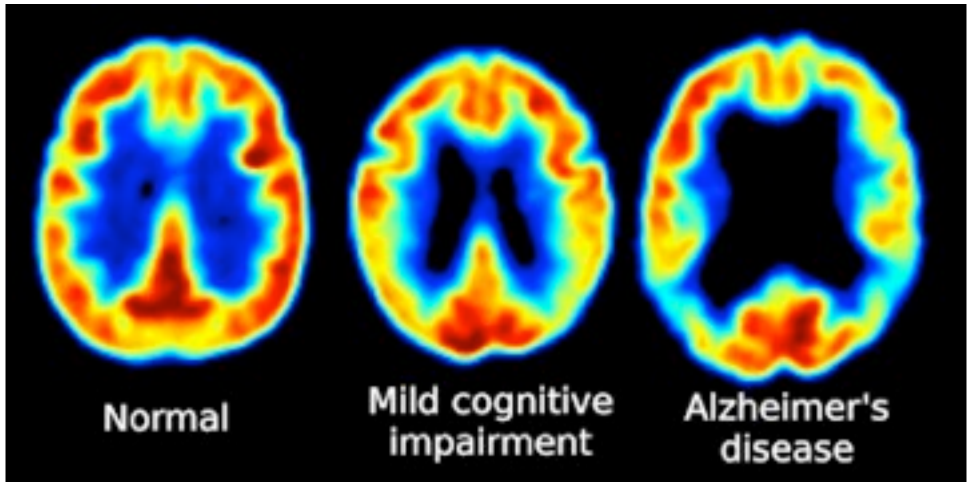
D. Townsend, A. Jeavons
CERN, 1977

first reconstructed image of the skeleton of a mouse injected with 18-F

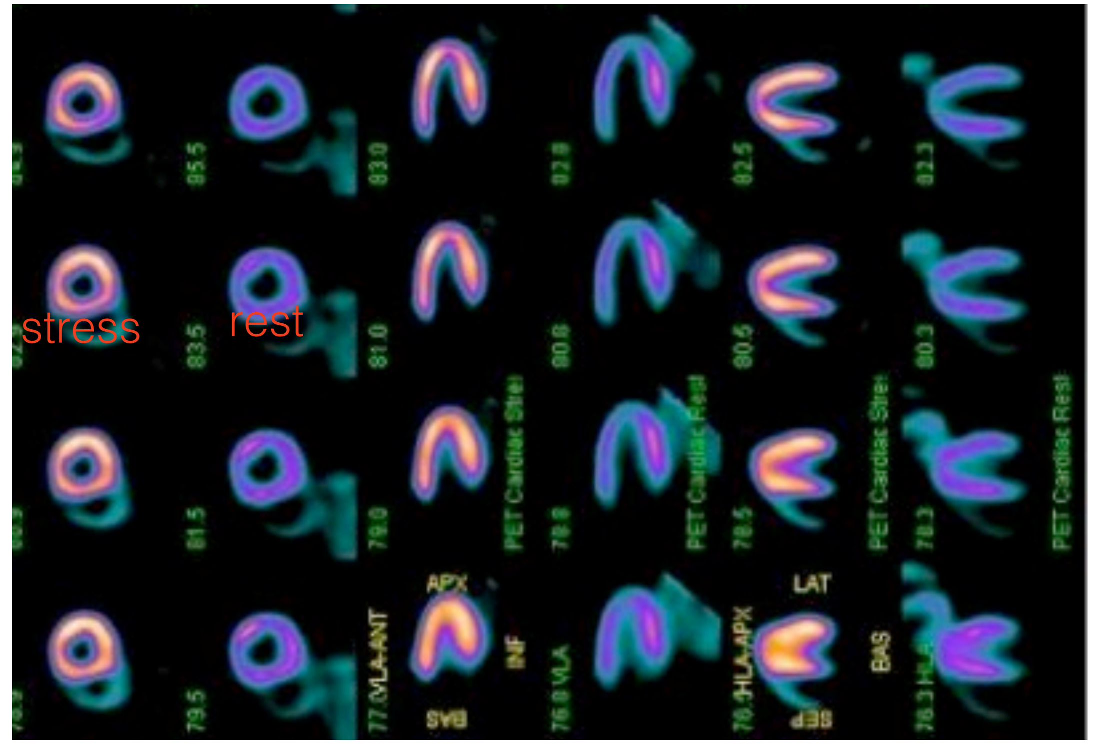
detector :
HIDAC i.e. wire chamber
(from G. Charpak)

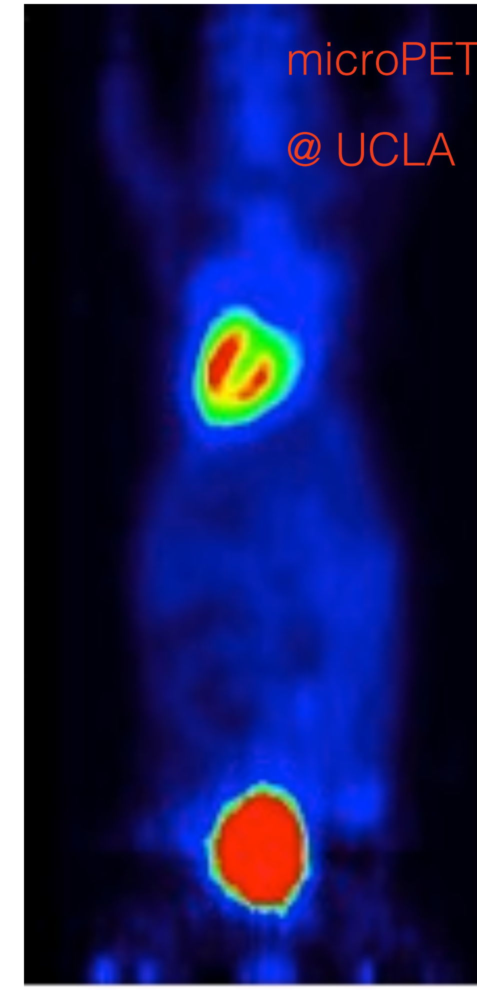
"You are indeed correct that the birth of PET is somehow controversial"
(D. Towsend)

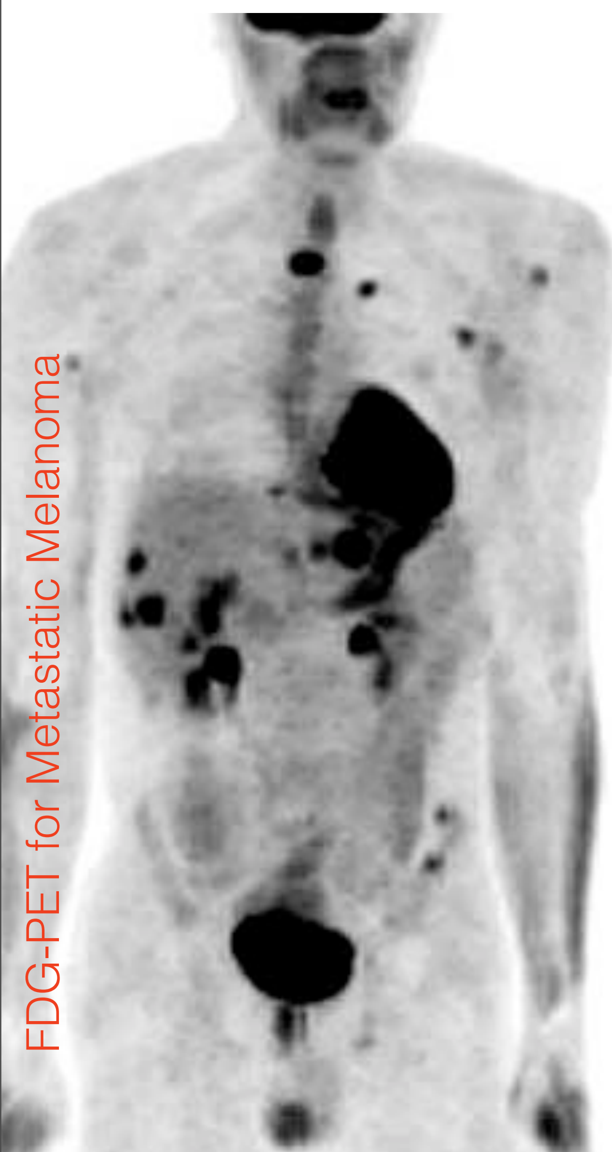
Randomly selected PET images



myocardial perfusion (Rb-82) in a normal patient







FDG-PET for Metastatic Melanoma

F-18 young rat imaged with the AX-PET

huge domain of applications
both in **clinical** and **pre-clinical** fields

- full body / brain /or organs-specific
- oncology (diagnosis, tumor staging)
- study of neurogererenative diseases
- psychology
- cardiac functioning monitoring
- in-beam monitoring in hadron-therapy
- medical research
- pharmacokinetics
- development of new tracers
- ...

Skeleton of a mouse injected with 18-F at CERN

D. Townsend, A. Jeavons
CERN, 1977

35 years later...

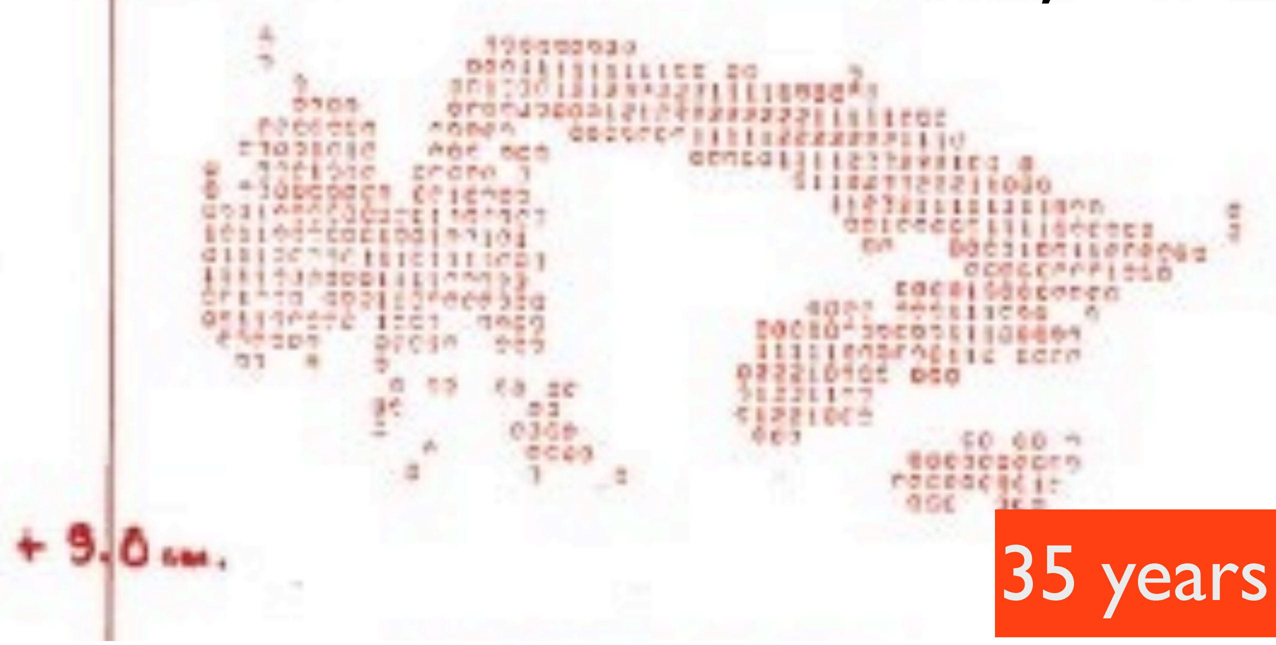
remarkable development!!

Most important factors that contributed to this :

- **instrumentation development** [great boost from HEP : calorimetry / new crystals / new photodetectors / electronics]
- **computing power** [improved reconstruction algorihtms]
- **radio-chemistry** [FDG-based radiomarkers]
- **PET / CT** (Computed Tomography)

Skeleton of a mouse injected with 18-F at CERN

D. Townsend, A. Jeavons
CERN, 1977



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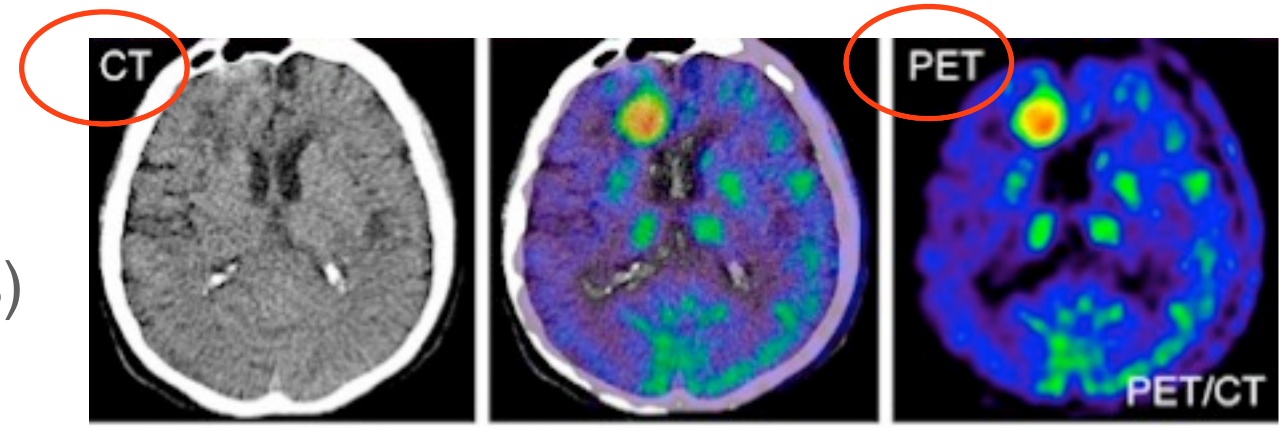
PET and CT: a perfect fit



- idea: combine **functional imaging from PET** with **morphological imaging from CT** (X-rays) (D. Townsend)

- born in the clinical domain (first commercial PET/CT scanner: 2001)
- 2006 : no more stand-alone PET !

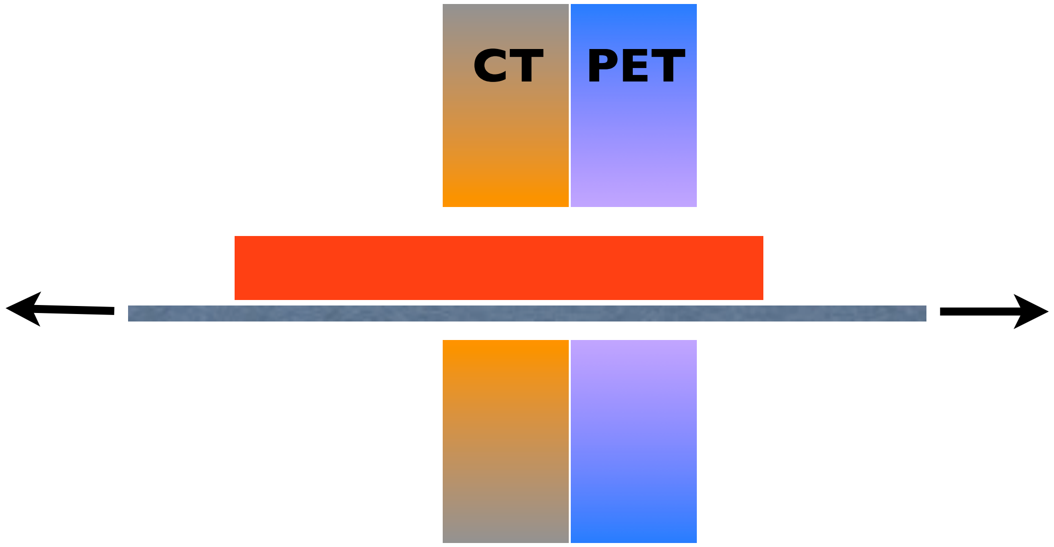
A revolution in medical imaging !

- clinical evaluation (~ 10 years) => **importance of co-registered anatomical information at high resolution with functional data**

- immediately recognized by-product :

  CT generates the attenuation correction map needed for PET to be quantitative (instead of lengthy transmission scans)

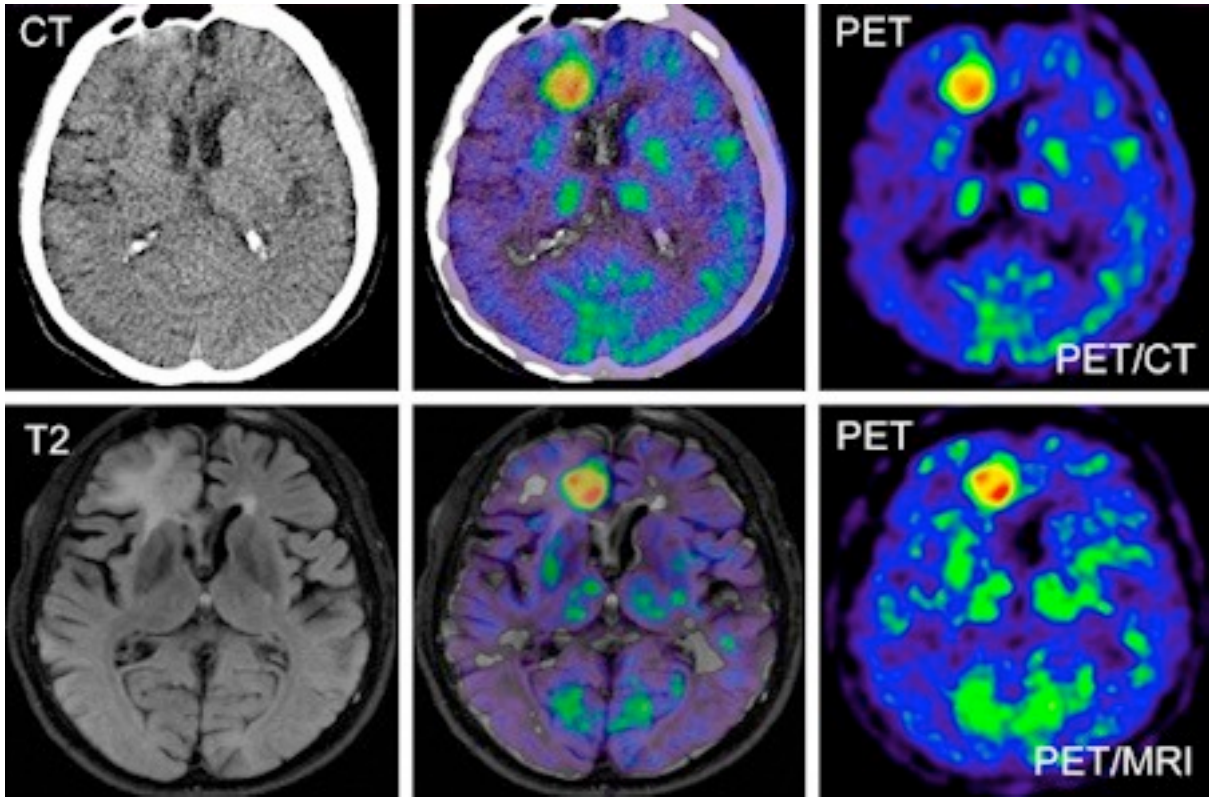
PET/CT :
- Localization
- CT-based attenuation correction



- the 2 devices mounted sequentially (essentially unmodified) in a common gantry
- translational patient bed

PET and MRI: an even better fit ? - PART I

MRI : **M**agnetic **R**esonance **I**maging also provides morphological information



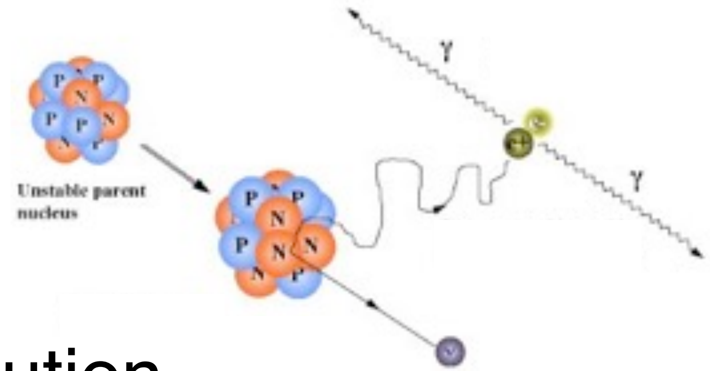
<u>Anatomical counterpart for PET:</u>

CT

or

MRI ?

Advantages of PET/MRI vs PET/CT :



- high soft-tissue contrast (brain)
- no additional dose (kids)
- reduction in positron range => improved spatial resolution
- possibility of simultaneous acquisition
  => no temporal mismatch (organs movements)

PET and MRI: an even better fit ? - PART II

MRI is also **functional** - full complementary to PET

Two examples :

[1] **MRS (Magnetic Resonance Spectroscopy)**

- study tissue metabolism with 13C-labelled substrates
- MRS: high chemical specificity in identifying different metabolites
- MRS: low sensitivity (or interference with methabolism processes)

if **11C** -labelled => **MRS + PET**

[2] **CBF - Cerebral Blood Flow**

- importance of constant delivery of oxygen in the brain
- CBF mechanisms are not yet completely understood
- CBF used as surrogate of neural activity in MRI => functional MRI

if **15O**-H2O => **fMRI + PET**

t1/2(O-15) ~ 2 mins
changes of CBF up to 20% in time scales of seconds
=> high temporal resolution needed

Hybrid PET / MRI

Great potential for PET/MRI to become the dominant nuclear imaging technique

- **MRI as the anatomical counterpart of PET** (with advantages wrt CT)
- **Functional capabilities of MRI (fMRI)**

1 + 1 > 2!

The potential of PET/MRI is fully exploited when :

- **fully simultaneous** (time / space correlation) => PET **inside** the MR bore
- **dynamic studies**

But...

PET / MRI is **technically very challenging !**

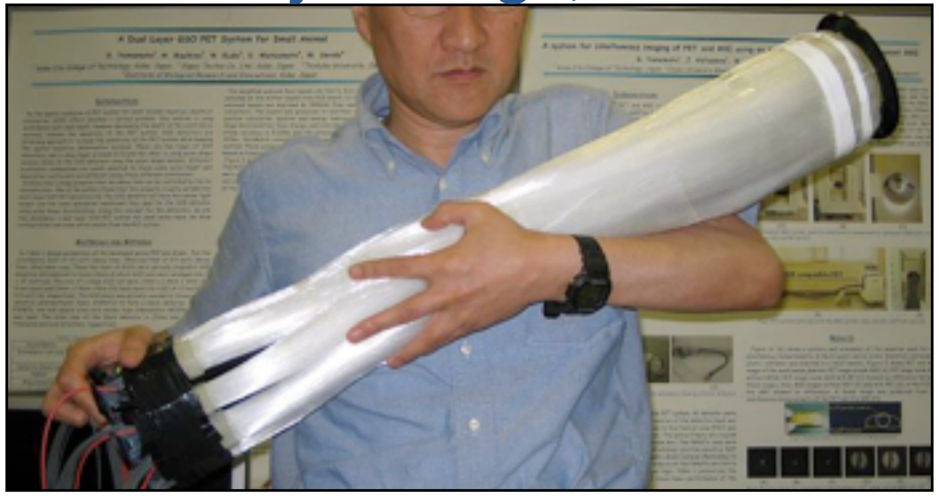
- **Mutual non-interference of the two modalities**
  - PET must work into MRI (no PMT ; heating / vibrations; electronics interference)
  - MRI must be undistorted by PET
- **Limited space available**

difficult, but possible

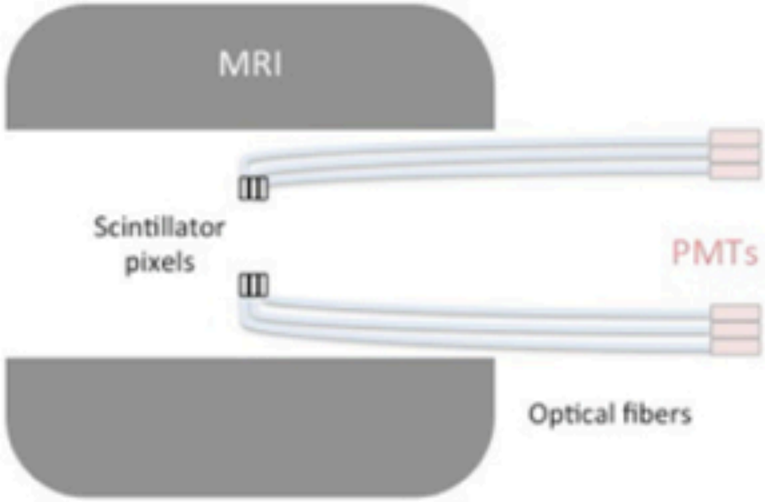
Possible, thanks to the revolution in photodetection

PMT
high gain
good timing
not MR compatible

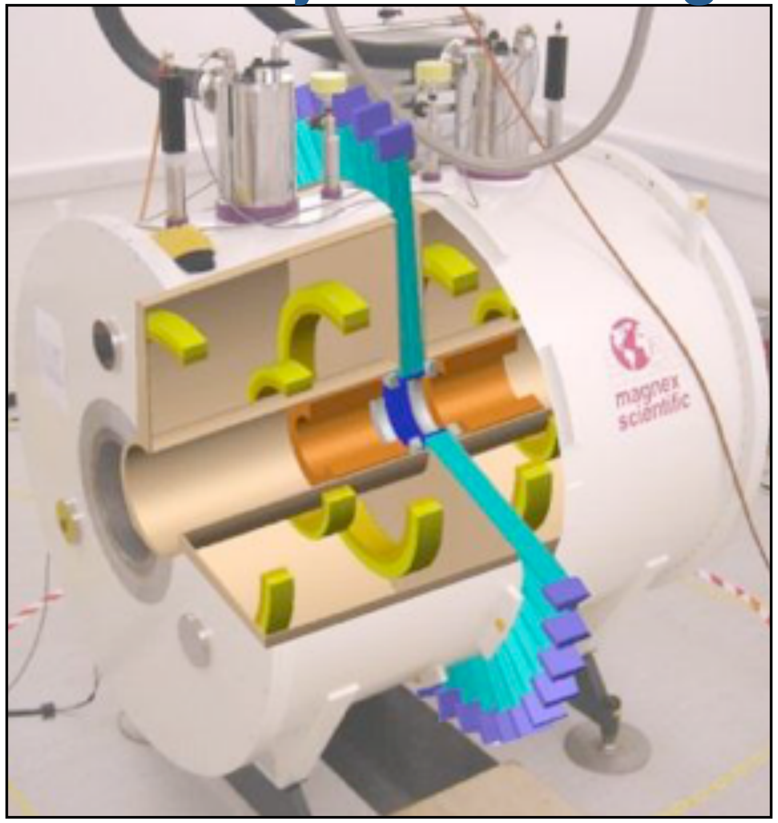
Kobe City College, Osaka University



fibers + PS-PMT
Axial ~ 0.5 cm



University of Cambridge



split magnet
fibers + PMT
Axial ~ 7 cm

Possible, thanks to the revolution in photodetection

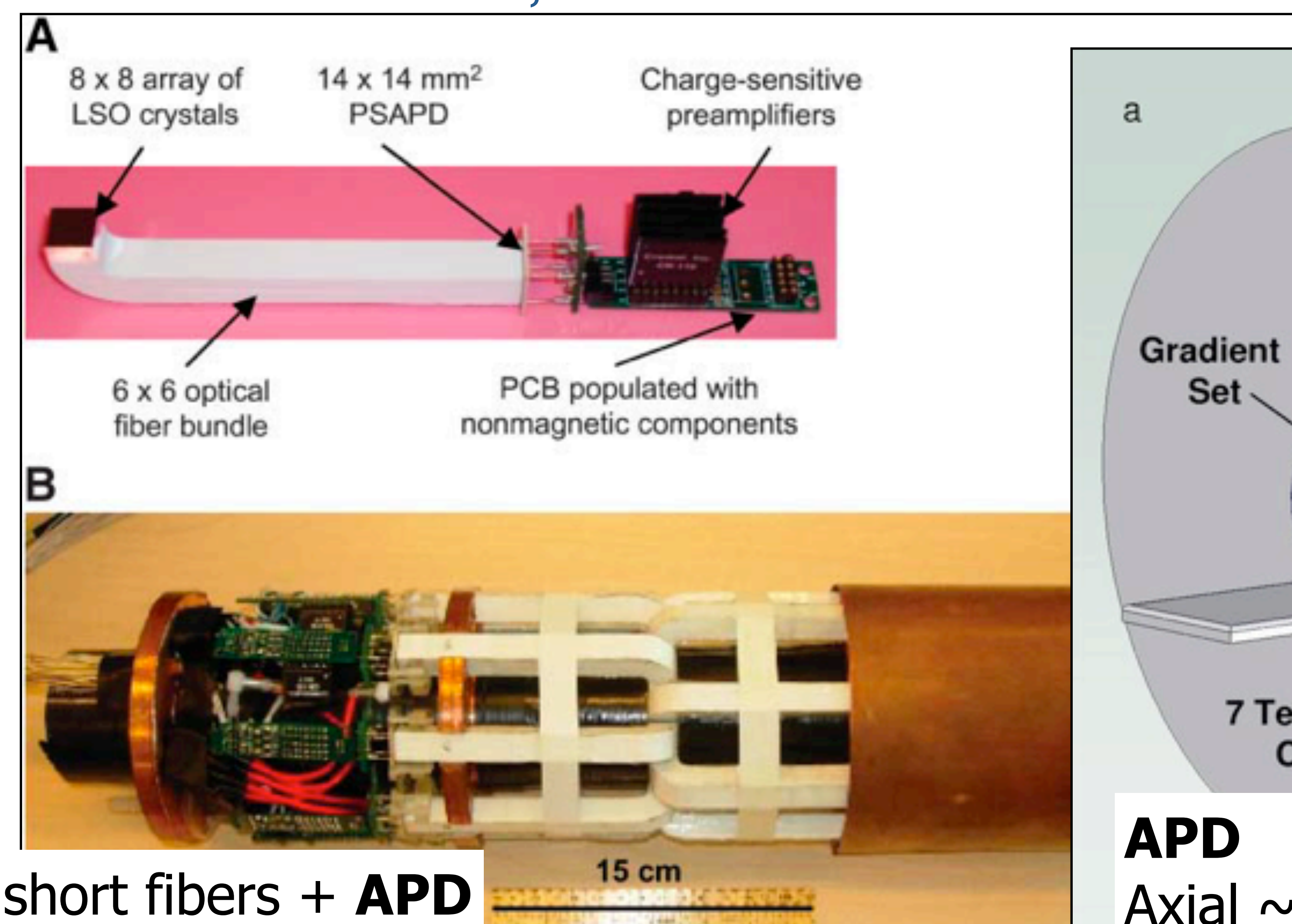
PMT
high gain
good timing
<u>not MR compatible</u>

⇨

APD (Avalanche Photo Diodes)
insensitive to magnetic field / compact /
low gain
=> worse timing perfs
=> need of very low noise FE electronics

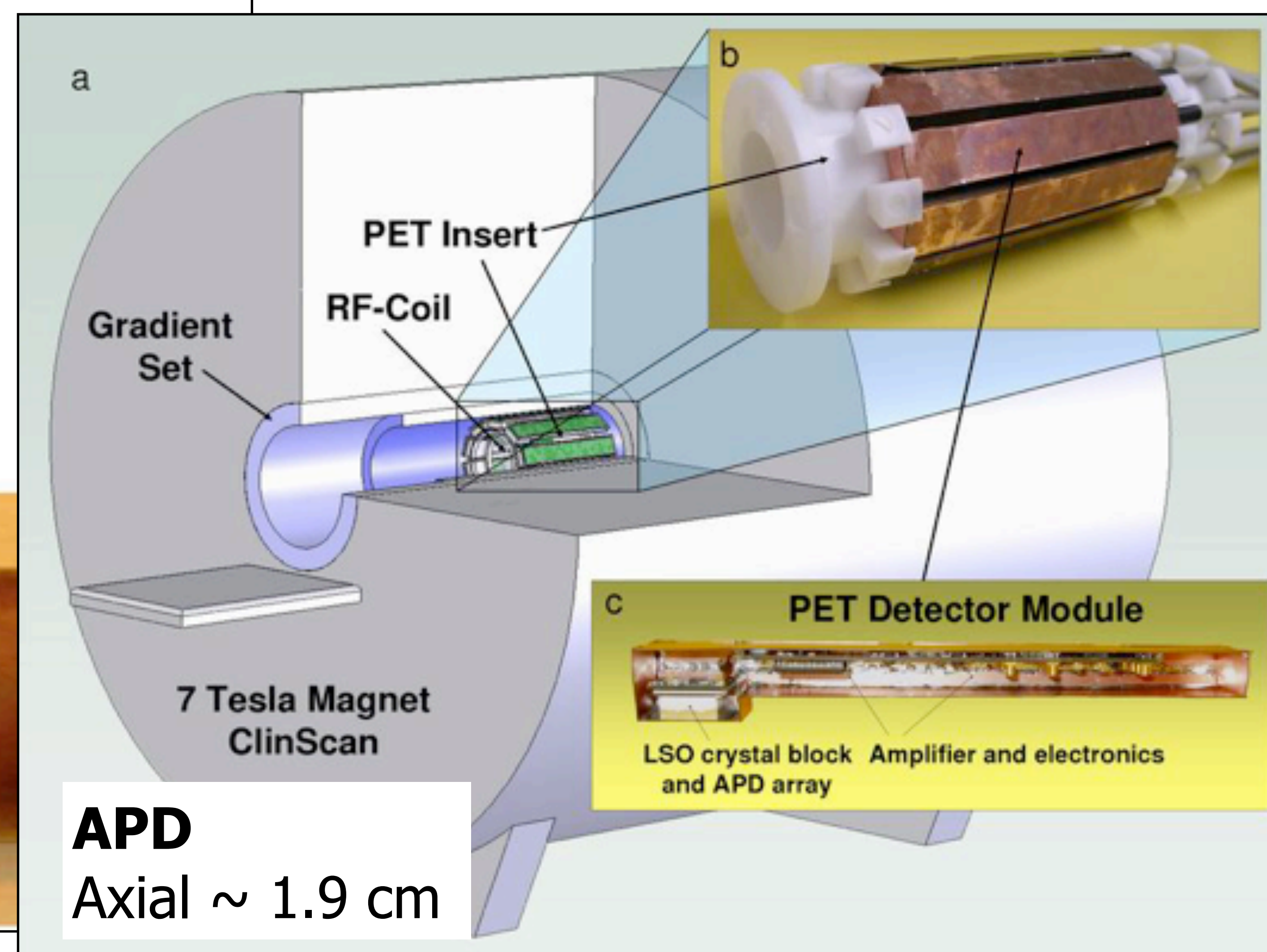
relevant examples of **pre-clinical simultaneous** PET/MRI that have been used for **in-vivo analysis**

UC Davis, California



short fibers + **APD**
Axial ~ 1.4 cm

University of Tuebingen, Germany



APD
Axial ~ 1.9 cm

Possible, thanks to the revolution in photodetection

PMT
high gain
good timing
not MR compatible

⇨

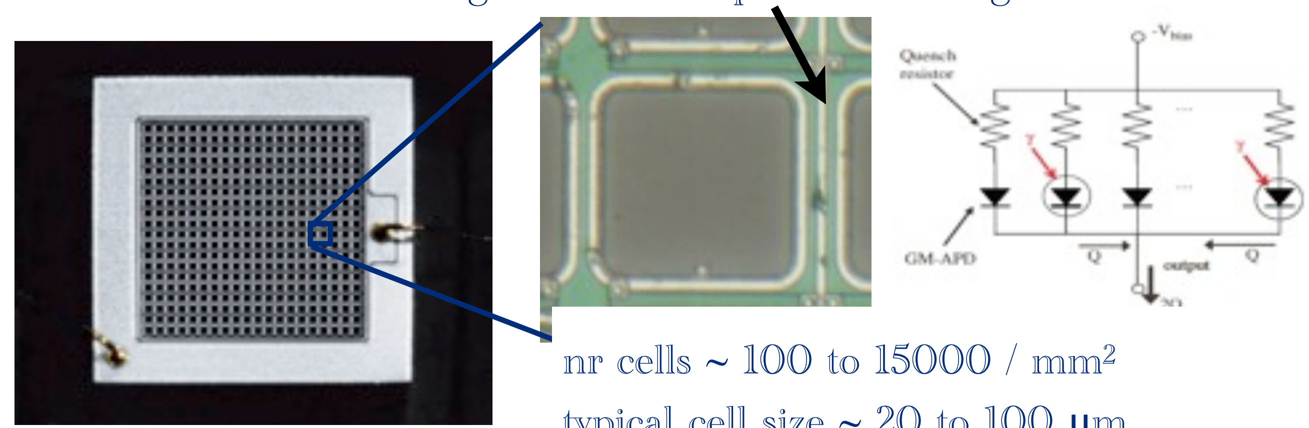
APD (Avalanche Photo Diodes)
insensitive to magnetic field / compact /
low gain
=> worse timing perfs
=> need of very low noise FE electronics

⇨

SiPM (Silicon PhotoMultipliers)

SiPM is the dominating technique for all new PET developments

single APD cell operated in Geiger mode



nr cells ~ 100 to 15000 / mm^2
typical cell size ~ 20 to 100 µm

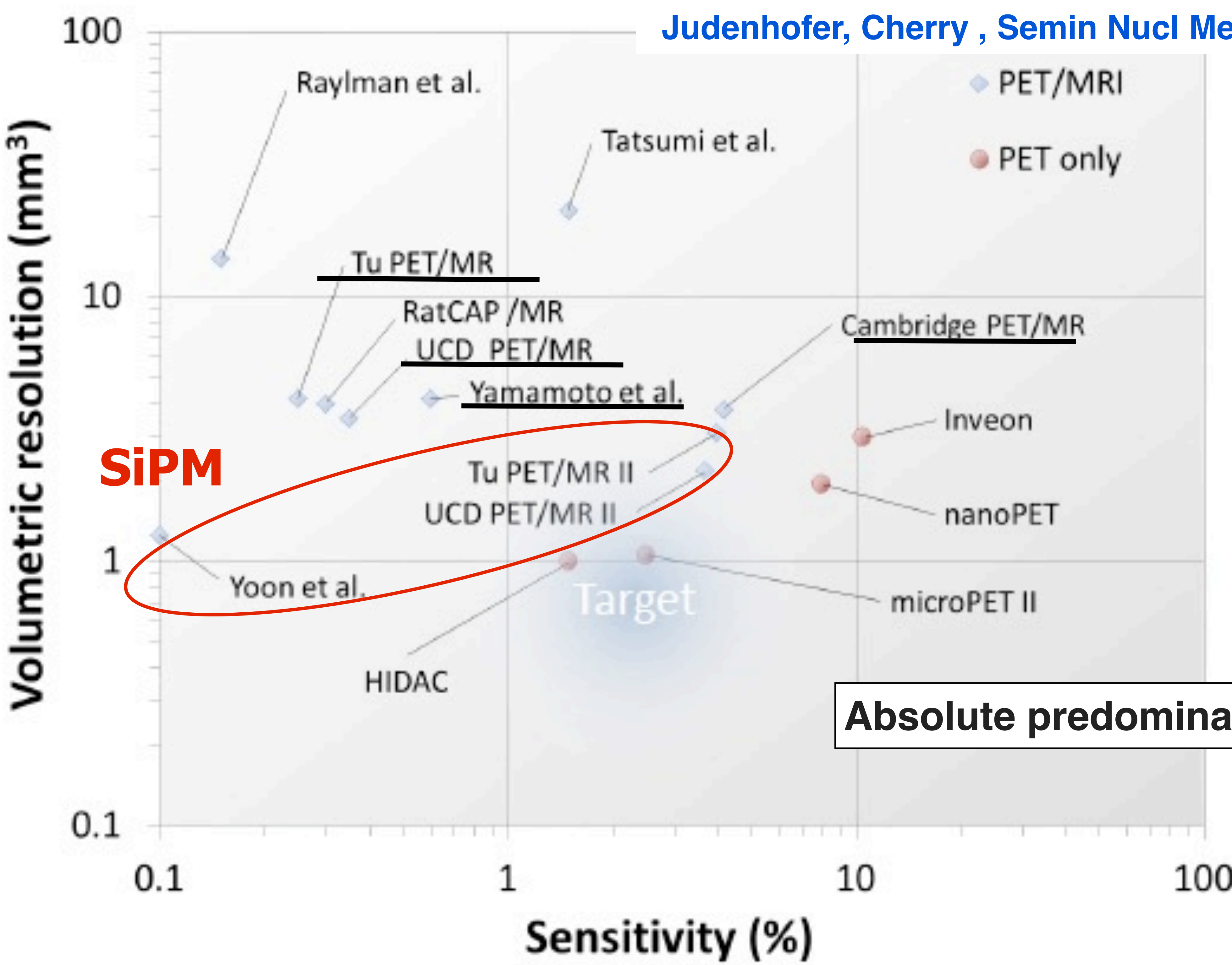
:-) ...Advantages :

- insensitive to magnetic field
- compact
- gain ~ PMT => excellent timing resolution + no need of very special care in the FE
- high PDE
- low bias voltage
- exist in arrays of increasing dimensions

:-(...Disadvantages
- temperature dependence of the gain => stability issues (Temp, Vbias) / cooling
(- dark counts)
- non - linearity

Overview of current small animal PET and PET/MRI

Judenhofer, Cherry , Semin Nucl Med 2013; 43(1):19-29



Absolute predominance of PET/MRI

Trend : improve sensitivity and spatial resolution

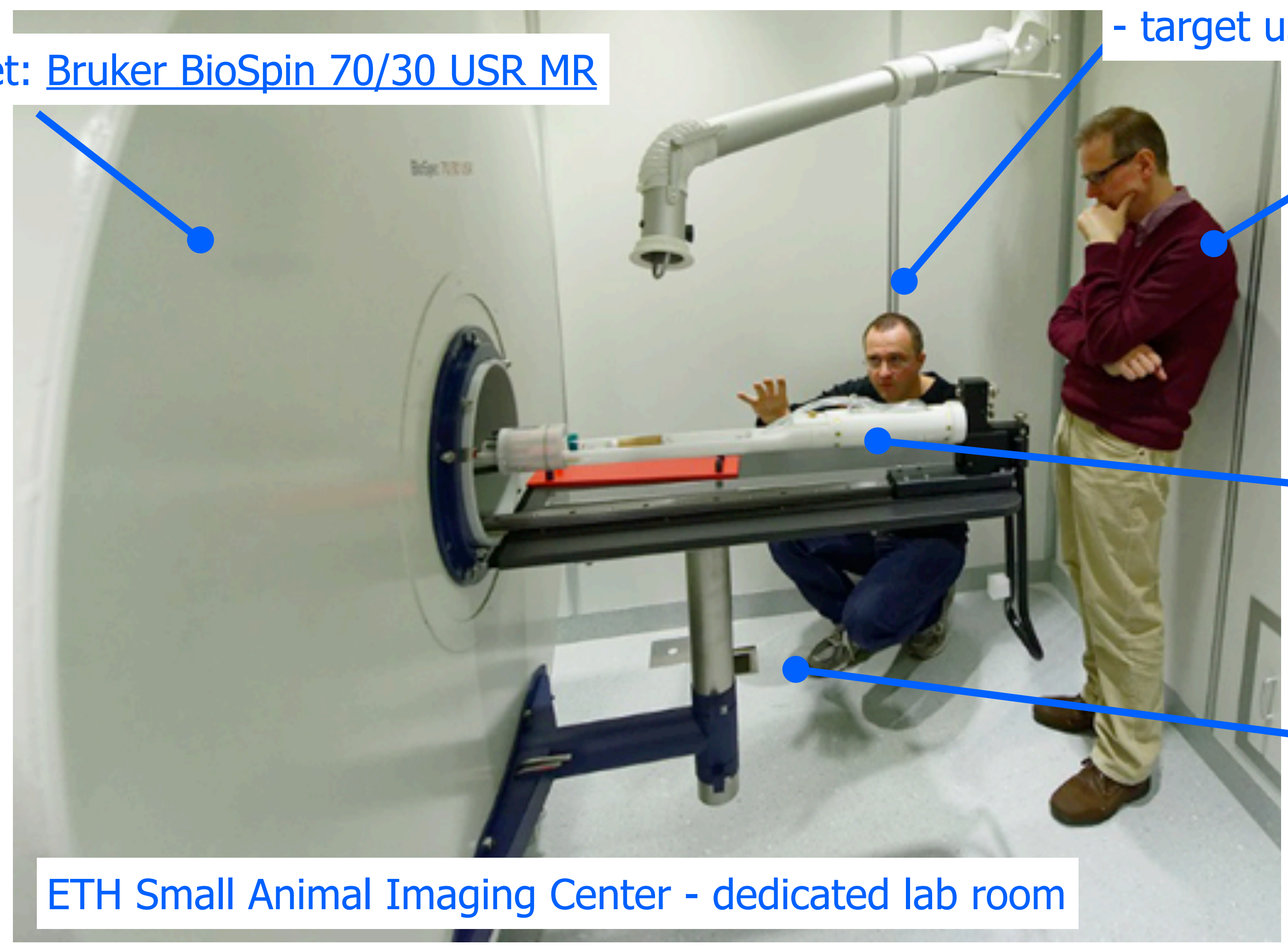

SAFIR

SAFIR : GOAL

Small Animal Fast Insert for mRi :

- **pre-clinical PET / MRI**
- **fully simultaneous**
- **<u>unprecedented high temporal resolution</u>**
  (acquisition duration of the order of a few seconds - at high repetion rate)
- **<u>dynamic studies</u> of various biological processes**
  (e.g. blood perfusion - cerebral blood flow with O-15)

^{15}O : t1/2 ~ 2 mins ; changes in tracer concentration ~ 20% in secs



<u>ETH / UniZh IBT (Institute of Biomedical Engineering)</u>
- target user of the detector

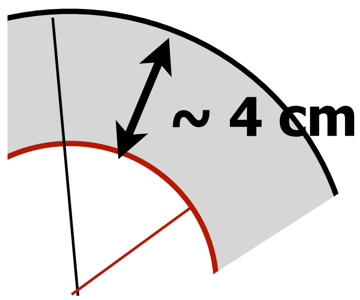
<u>ETH IPP (Institute for Particle Physics)</u>
- detector conception, construction, commissioning...

space for the insert

direct tubing connection to the cyclotron hall (mainly for 15-O)

Detector requirements

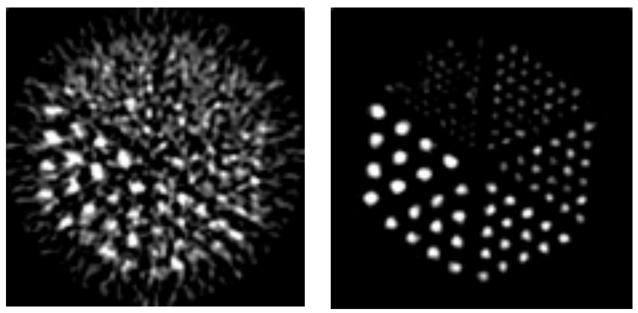
limitations from the existing magnet



Challenging detector requirements => DETECTOR DESIGN

- Geometrical constraints — **∅inner ~ 120 mm - ∅outer = 200 mm**
- Good spatial resolution — **R ~ 2 mm FWHM**
- **MRI- compatibility**
- Dynamic acquisition, **few seconds temporal resolution**

=> poor statistics - poor image quality



→ **high sensitivity: S ~ 5%** (at photopeak)

→ high injected activities **up to ~ 500 MBq** [standard pre-clinical ~ 50 MBq]

→ Randoms contribution!

small coincidence window (<ns)

excellent coinc. time resolution CRT ~ 300 ps FWHM

[same as in clinical TOF-PET, without being TOF-PET!]

→ readout and DAQ system

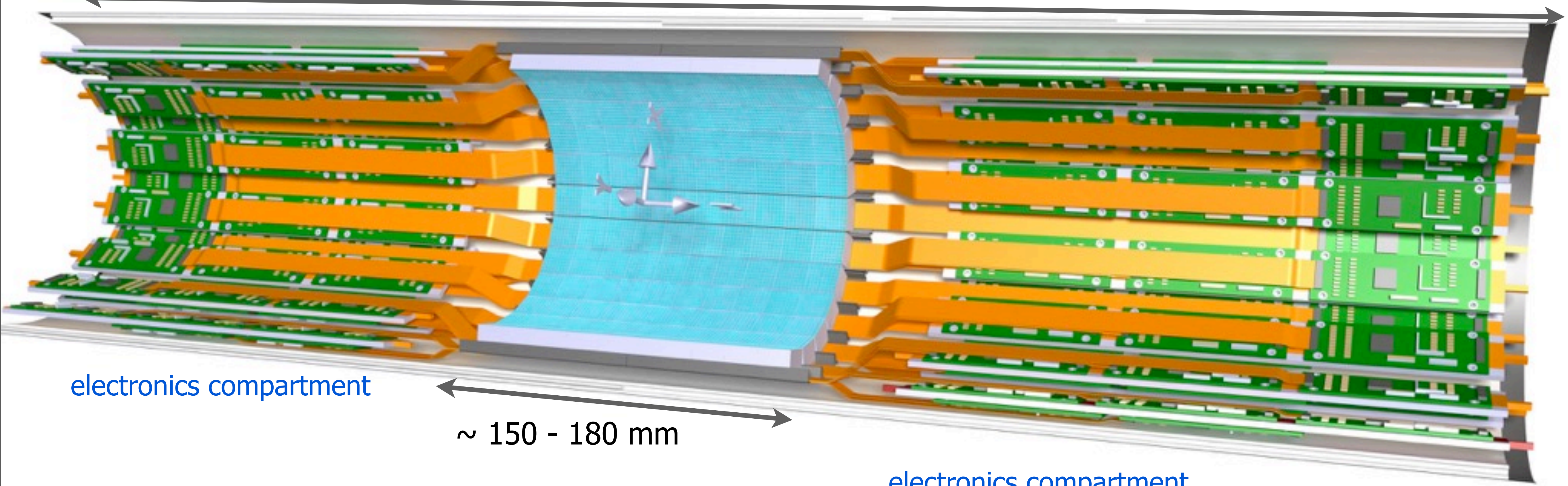
min. deadtime and pileup

1:1 coupling xtal/SiPM
high channel number
high channel density

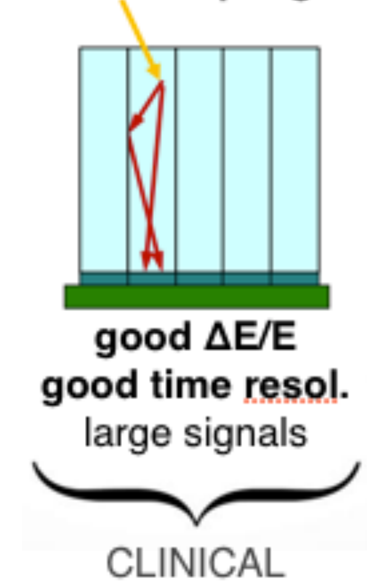
high rate/channel
~ 10 kHz/mm²

SAFIR design concept

sketch of 1/2 detector
design not yet finalized!

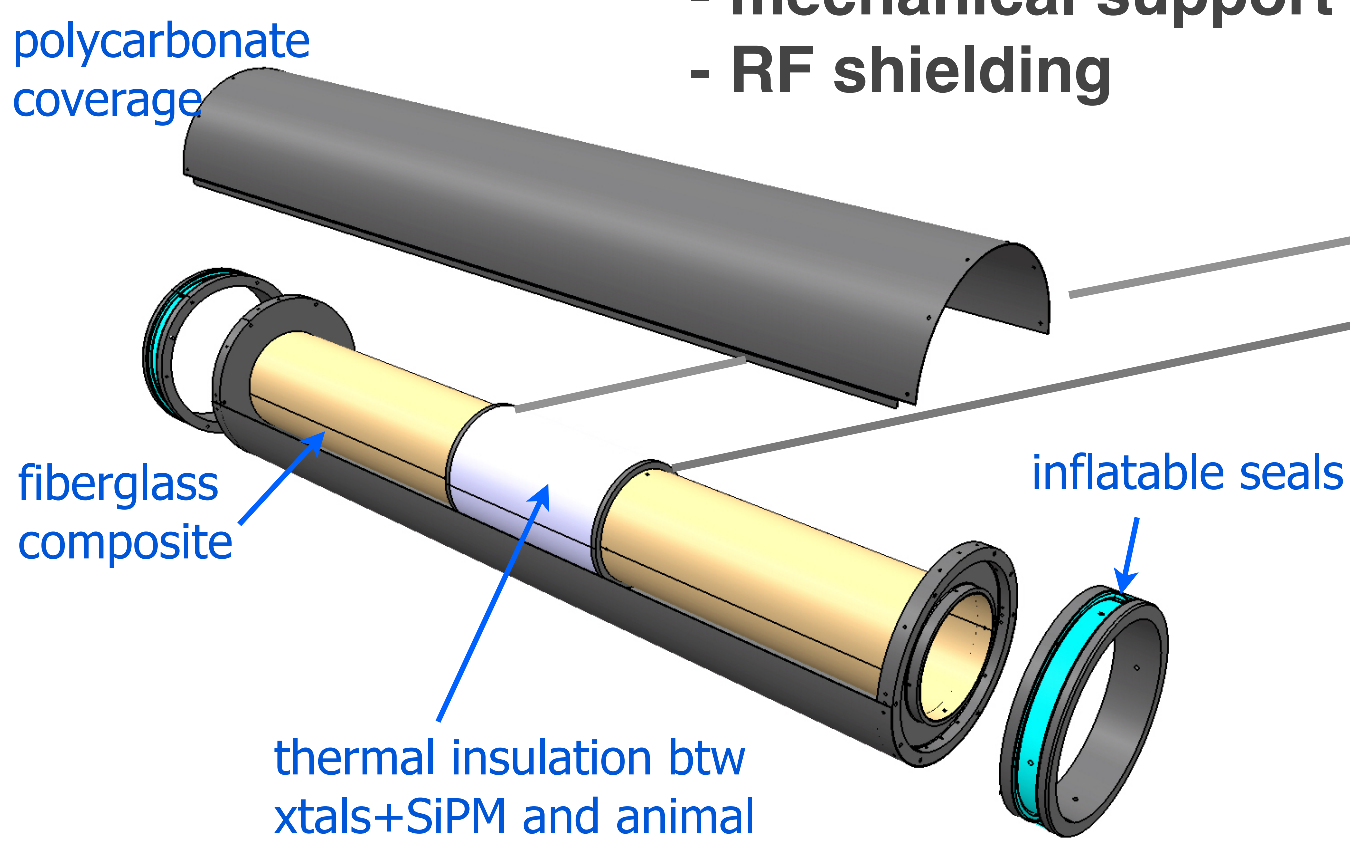


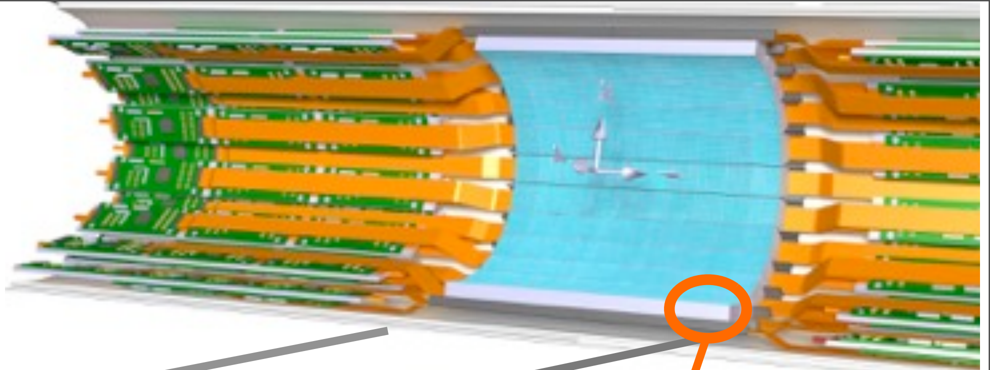
- radial arrangement of crystal matrices with 1:1 coupling to SiPM arrays
- LSO-type (LYSO, LSO:Ca...) crystal matrices
- modular structure of crystals
- ring structure / several modules per ring
- rings stacked axially to provide the axial FOV coverage



Mechanics for the insert

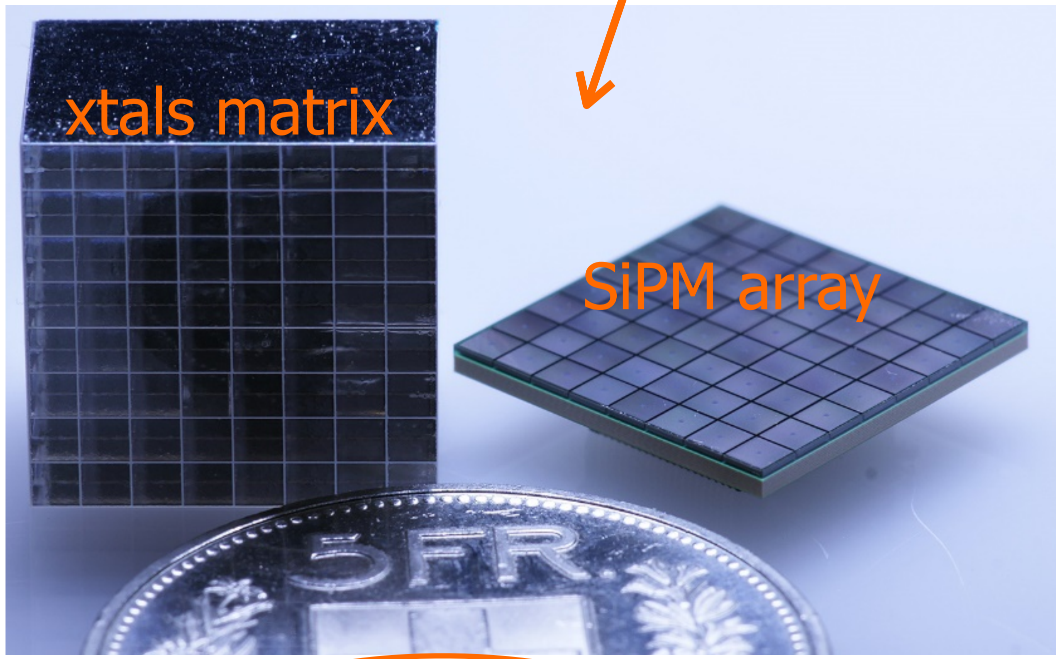
- mechanical support
- RF shielding





Reference design

- not necessarily the final design
- one possible configuration for the detector based on commercially available components



- xtals : (2.1 x 2.1 x 12) mm^3 , **2.2 mm pitch**
- **matrices 8x8**

- 24 modules / ring
- 10 rings (axially stacked) : FOVax ~ 180mm
- Inner radius ~ 60 mm
- 15360 readout channels

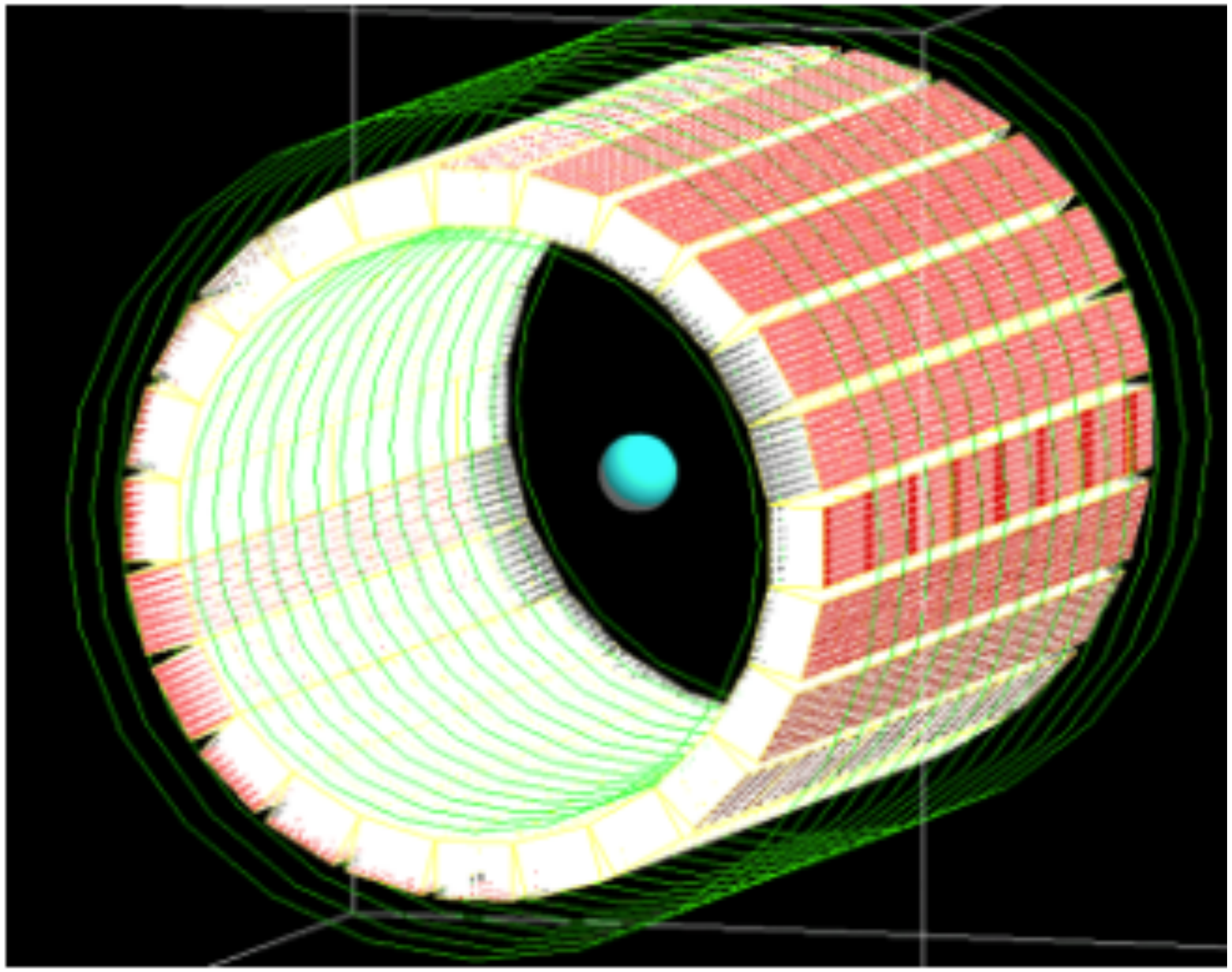
- **8x8 matrices**
- **pitch = 2.2 mm**

Reference design : needed for simulations

SAFIR SIMULATIONS

- custom simulation framework
- native **Geant4**

- DETECTOR
  - **'reference' design geometry**
  - **gaussian time smearing**
    σ = 90 ps => CRT ~ 300 ps fwhm
  - **gaussian energy blurring**
    ΔE/E ~ 20% fwhm



according to
NEMA standard (NU 4-2008) :
1. Noise Equivalent Count Rate (NECR)
2. Sensitivity
3. Spatial resolution

NEMA **(National Electrical Manufacturer Association)**: standardized methodology to evaluate the performance of a scanner independently on the specificity of the designs.

sources and phantoms used in simulations according to NEMA prescriptions

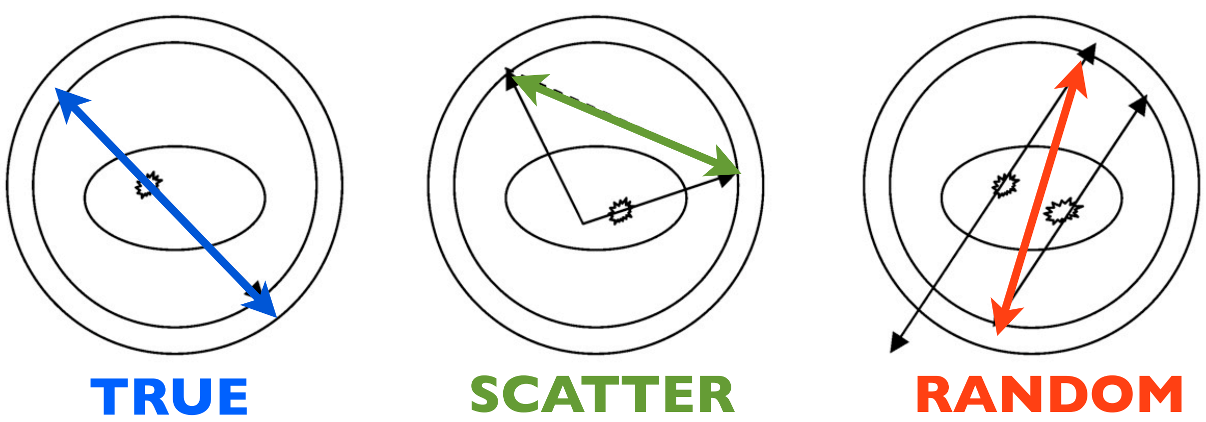
Quantity	Phantom Material	Phantom Shape	Source	Activtiy (MBq)
NECR	High-density polyethylene	Mouse-like (cylinder, l=70 mm, d=25 mm)	^{18}F line (l=60 mm)	10, 25, 50, 100, 200, 300, 400, 500, 700, 1000
Sensitivity	Acryl	Cube (1 cm x 1 cm x 1 cm)	^{22}Na point-like	0.1
Spatial resolution	Acryl	Cube (1 cm x 1 cm x 1 cm)	^{22}Na point-like	0.1

NECR (Noise Equivalent Count Rate)

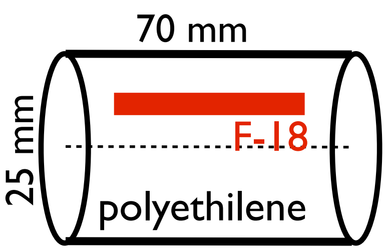
- **figure of merit in PET (counting statistics)**

- NECR = rate of ‘true’ coincidences normalized to the total number of coincidences

NECR = T² / (T+S+R)

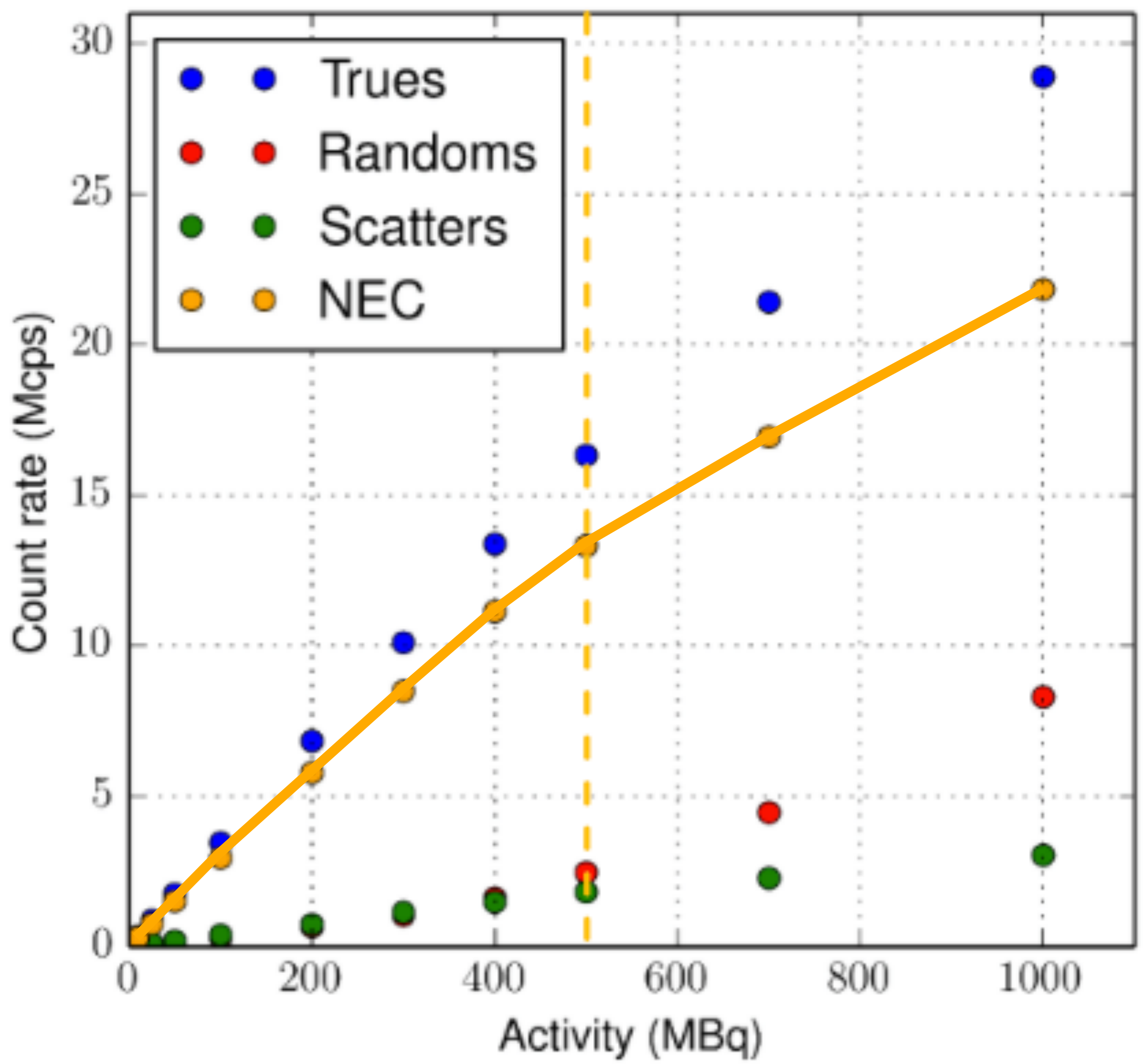


NEMA prescriptions :



mouse cylindrical phantom with line source at different activities

from simulated data
(with reference design geometry)

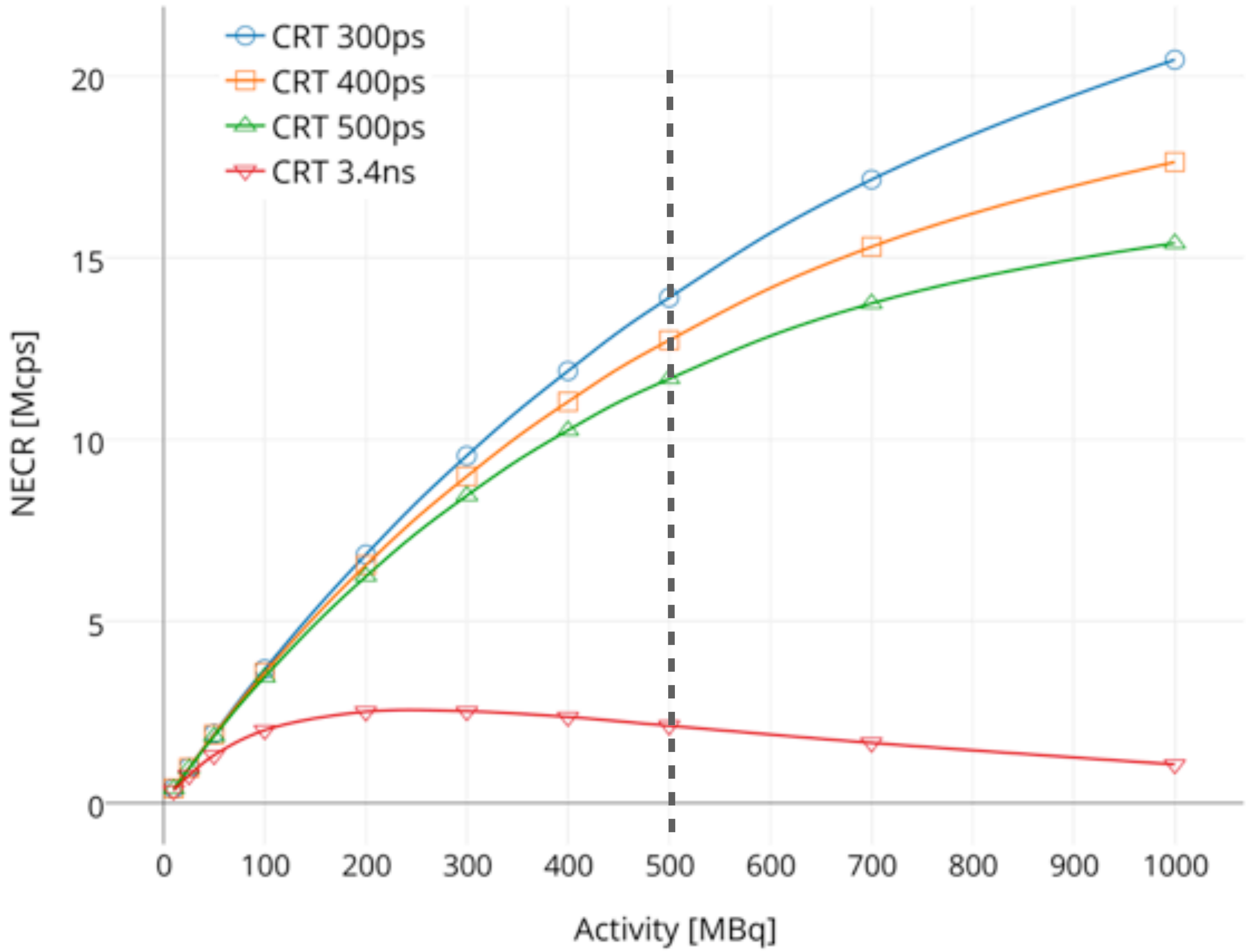


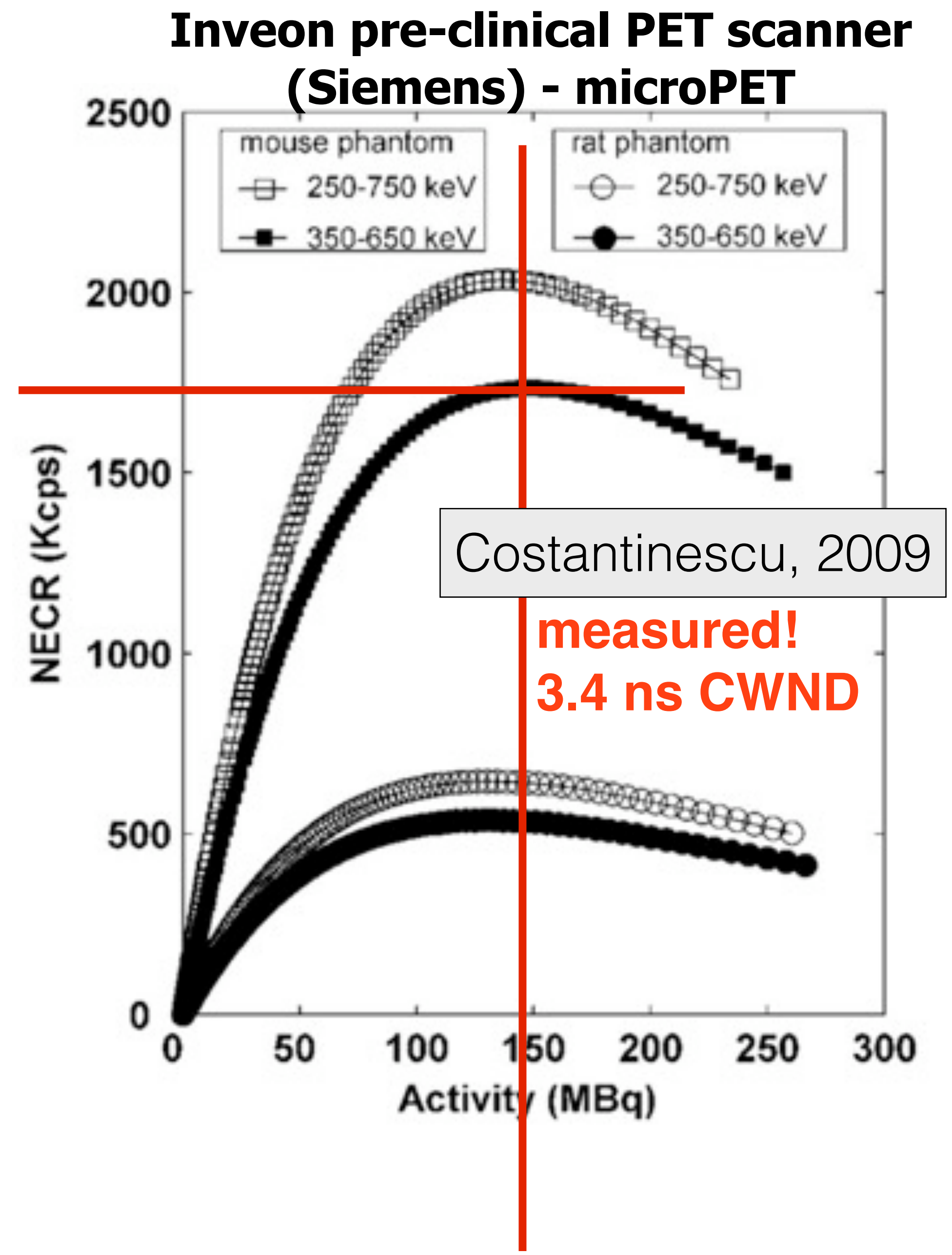
- higher **NECR value** => higher ratio of good events (T) to the overall detected events (T, R, S) i.e. S/N

- larger activity **peak value** => capability to handle higher activities without being dominated by the randoms + scatters

NECR (Noise Equivalent Count Rate) vs CRT

strong impact of the timing resolution on the NECR





=> Feasibility of the SAFIR concept

with **CRT ~ a few 100's ps** (<500 ps) and at **Act ~ 500 MBq**

(1) still far from being dominated by randoms

(2) NECR ~ x6/7 'standard NECR' at activities (~ 50 MBq) (i.e. 1 min => 10 secs)

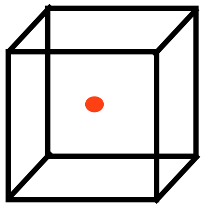
Sensitivity

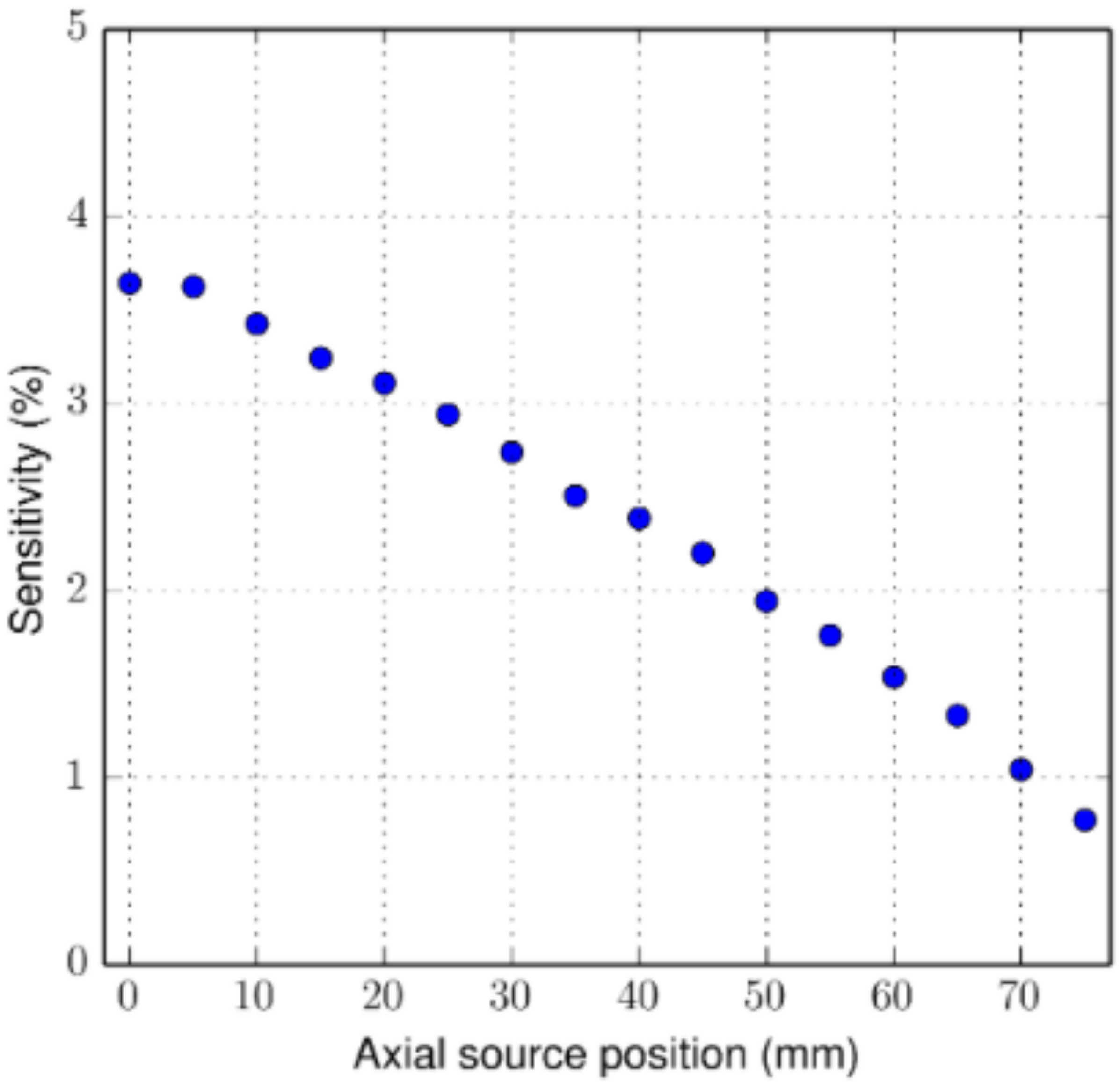
from simulated data
(with reference design geometry)

Sensitivity = N_detected_coincs / N_annihilations - at photopeak

N_detected coincs & N_annihililations defined according to NEMA standard

- NEMA phantom : 1cm³ acrylic with 22-Na point source at the center
- low activity (Act = 100 kBq)
- at different axial distances





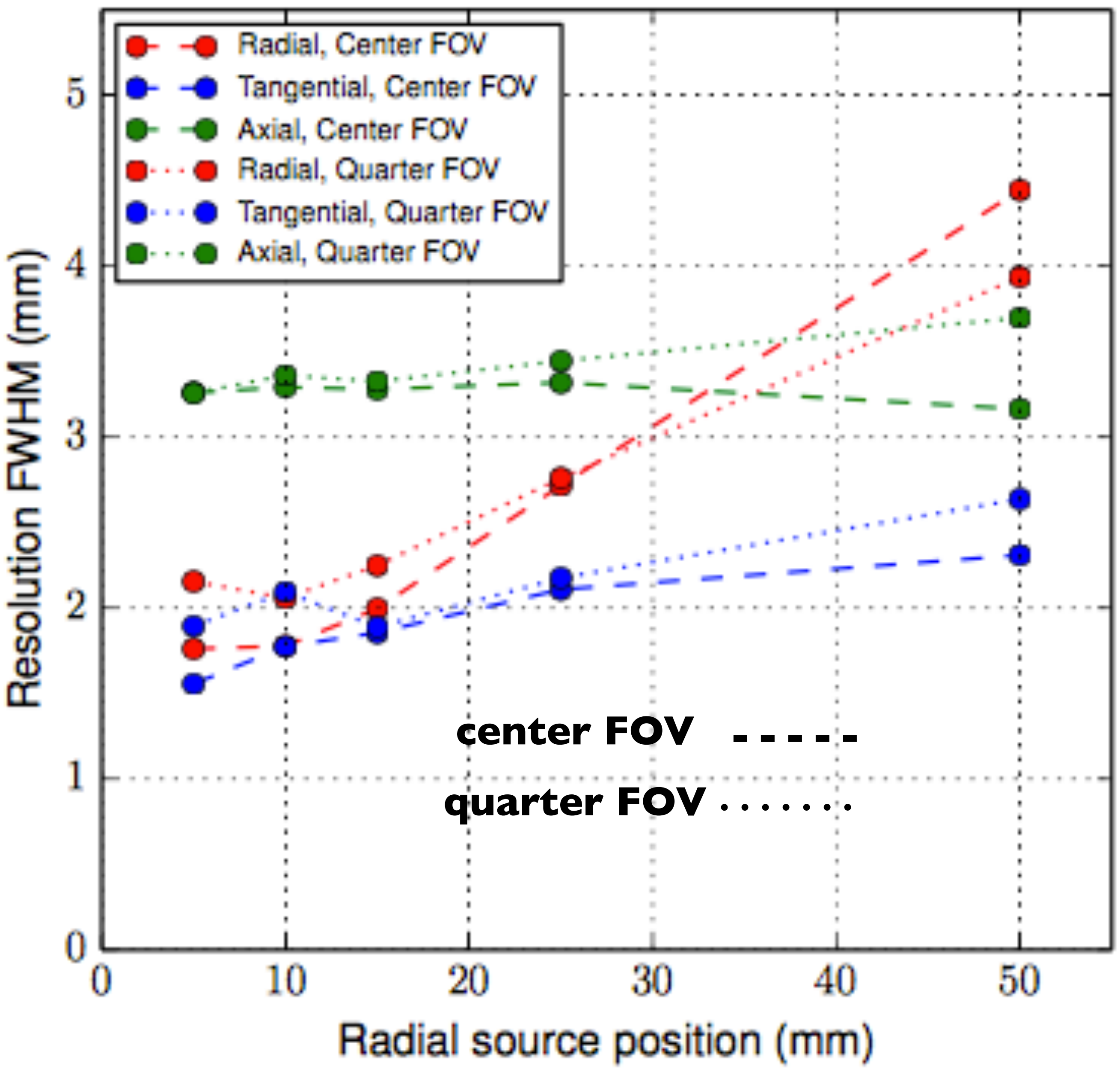
S_peak ~ 3.8% (at photopeak)

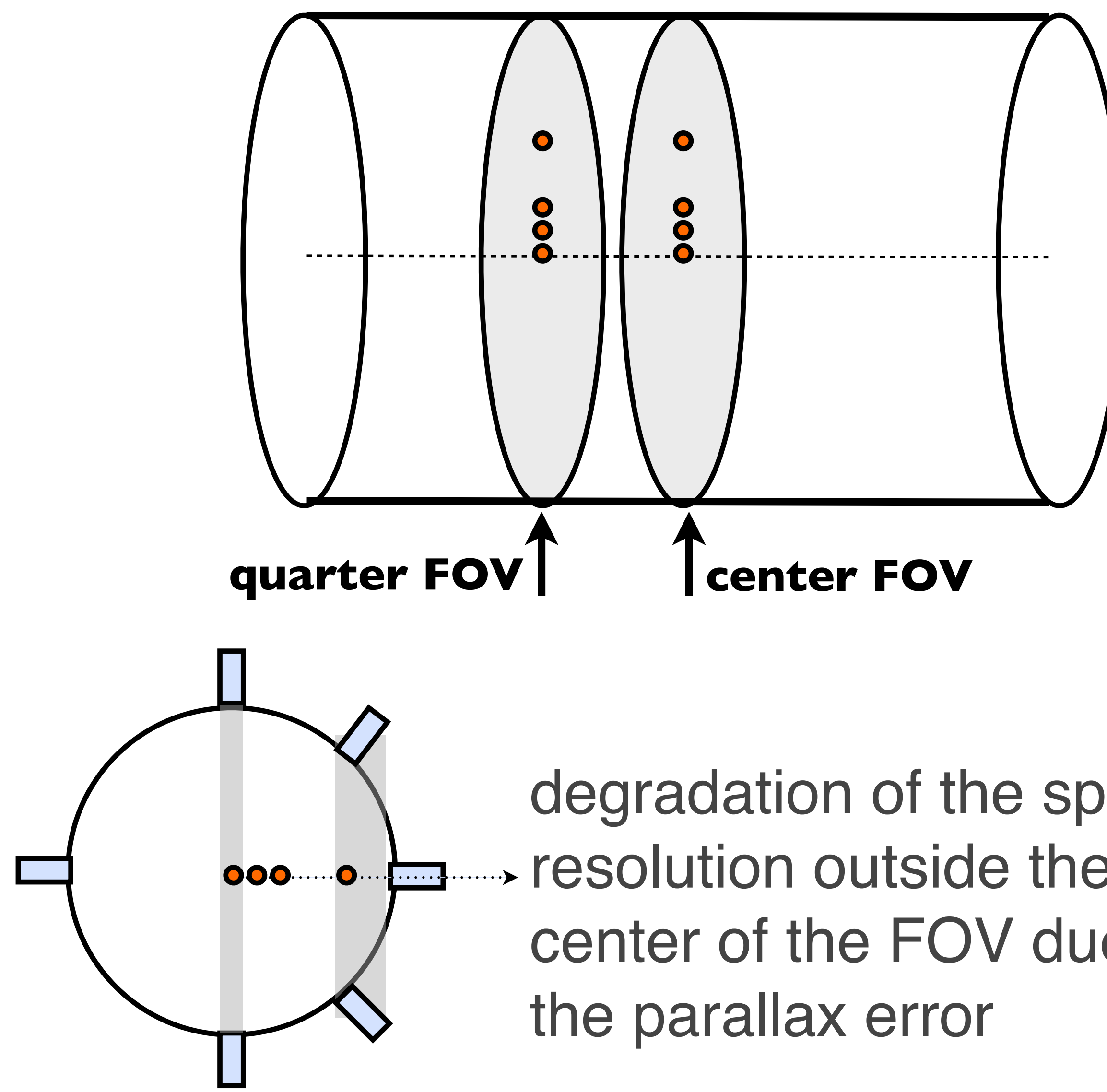
- Large solid angle coverage (~ 85%) => **Very good sensitivity**

- expected to increase with the inclusion of ICS (Inter-Crystal Scattering) events

Spatial resolution

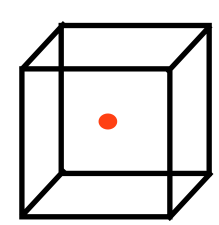
from simulated data
(with reference design geometry)





degradation of the spatial resolution outside the center of the FOV due to the parallax error

- NEMA phantom : $1 cm^3$ acrylic with 22-Na point source at the center
- low activity (Act = 100 kBq)
- <u>at different radial distances in two different axial positions</u>



Resolution ~ 2mm FWHM (at center of FOV)

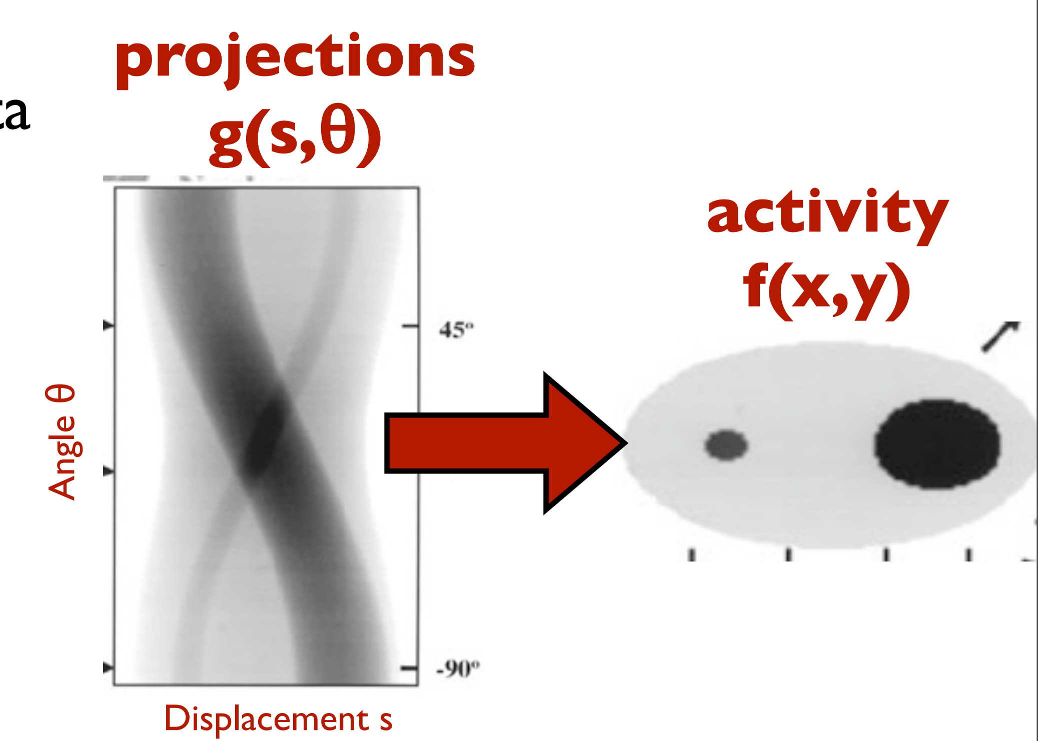
SAFIR image reconstruction

STIR (Software for Tomographic Image Reconstruction)
- Open Source software (C++)
- libraries for image reconstruction and manipulation of projection data
- several reconstruction algorithms already implemented

Goal :
recover the activity distribution, starting from the acquired data

Data :
LOR of the various coincidence events i.e. **projections**
(typically organized in "sinograms")

f(x,y) => g(s,θ) : data taking (projection)
g(s,θ) => f(x,y) : back projection



Two different approaches :

ANALYTICAL METHOD

- Filtered Back Projection (FBP) :
  1) Fourier analysis of the projection data
  2) Different weight to different frequencies ("filtering")
  3) "Back-Project"

- **simple and fast / less accurate**

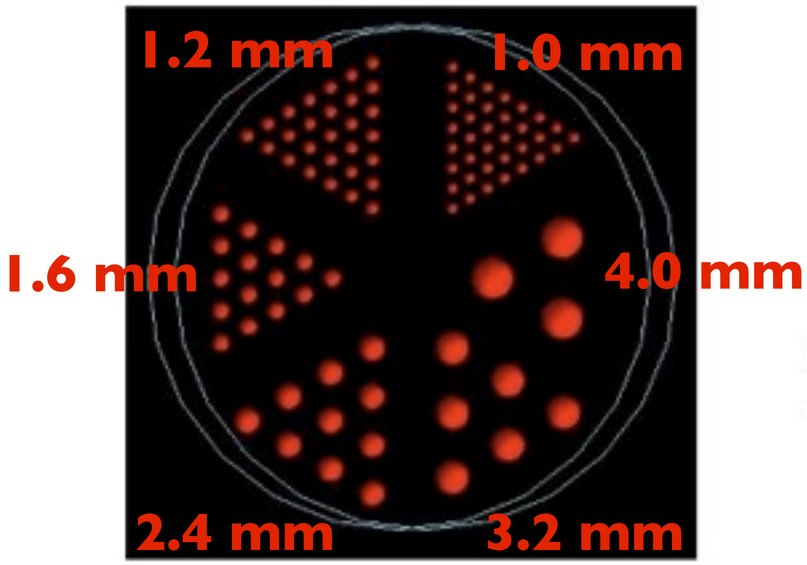
ITERATIVE METHOD

- optimization procedure until the best estimate of the source is found (several optimization strategies exist)
- it requires the accurate model of the emission and detection processes
- **slow and CPU consuming**
- **accurate reconstruction**

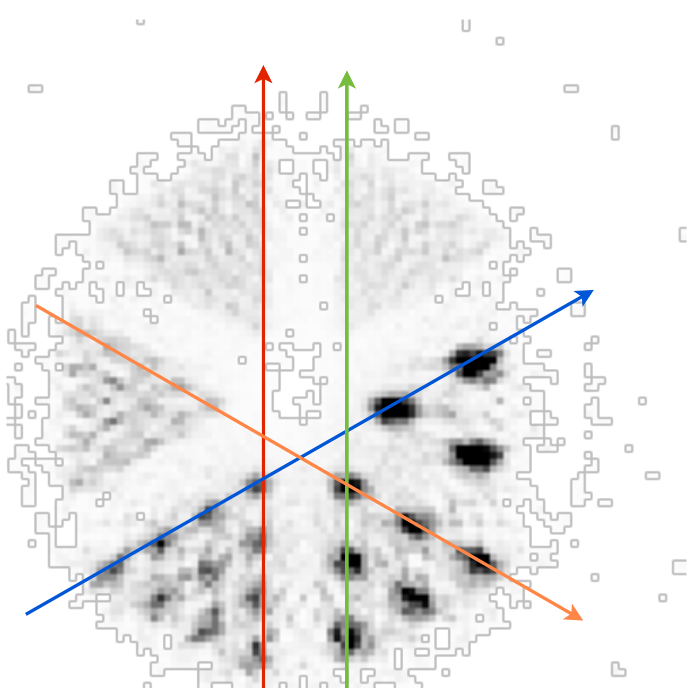
SAFIR image reconstruction (static)

Derenzo phantom - no background

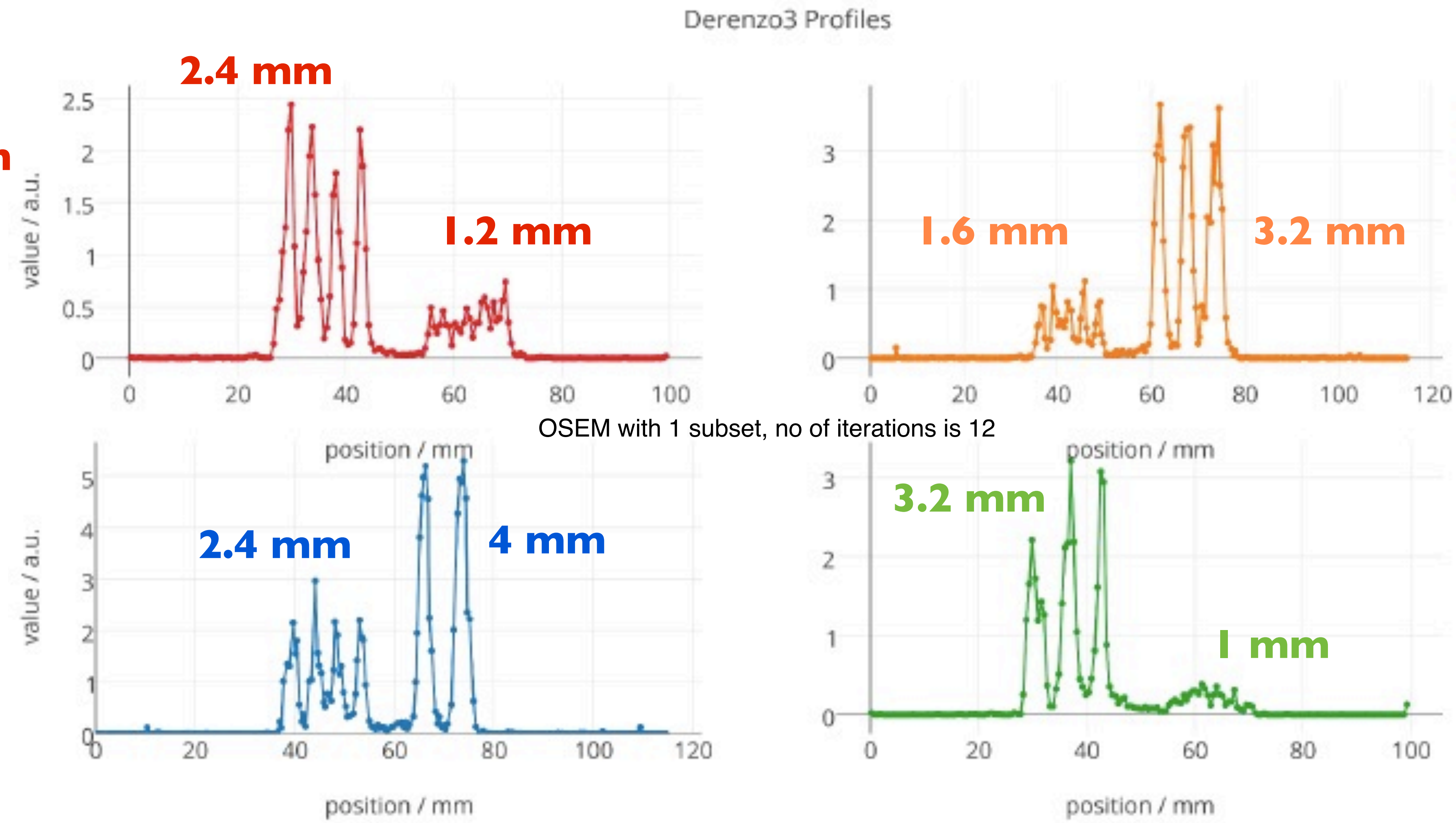
- iterative (OSEM - 1 subset - 12 iterations)
- 1 sec data
- 500 M decay events
- “best case scenario”



simulated (input)



reconstructed



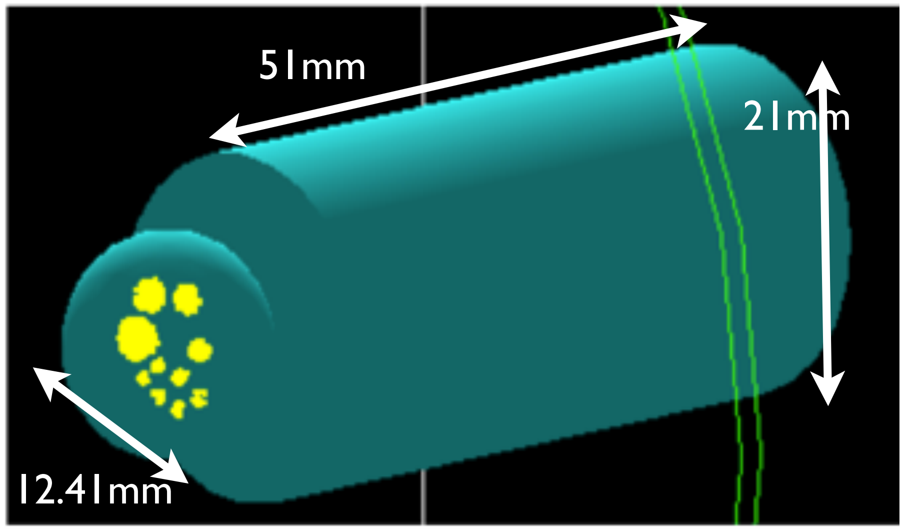
=> Image reconstruction :

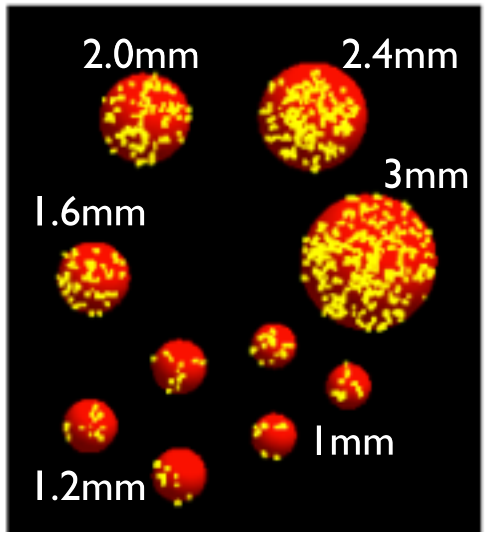
- up to 1.6 mm structures are ~ resolvable

SAFIR image reconstruction - plans

Currently ongoing activities :

- simplified mouse phantom with realistic activity concentrations

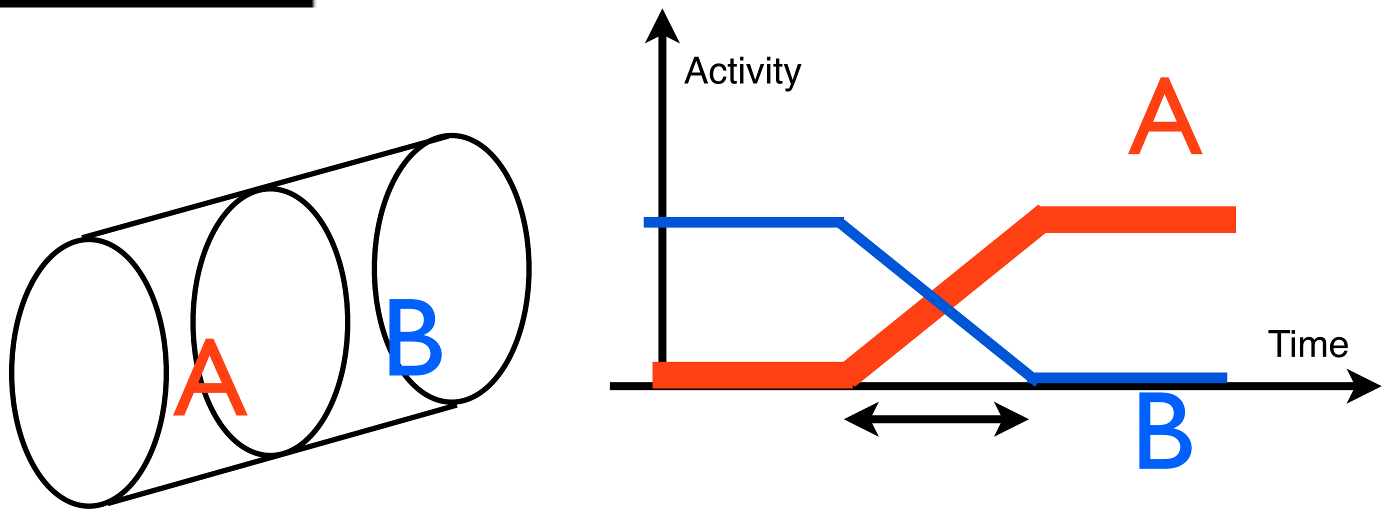




body / brain / spheres

- towards dynamic reconstruction
  time slicing of the transient region

  division of the full data set into a time
  sequence of data frames



- future : from frame-based reconstruction to 4D reconstruction algorithms

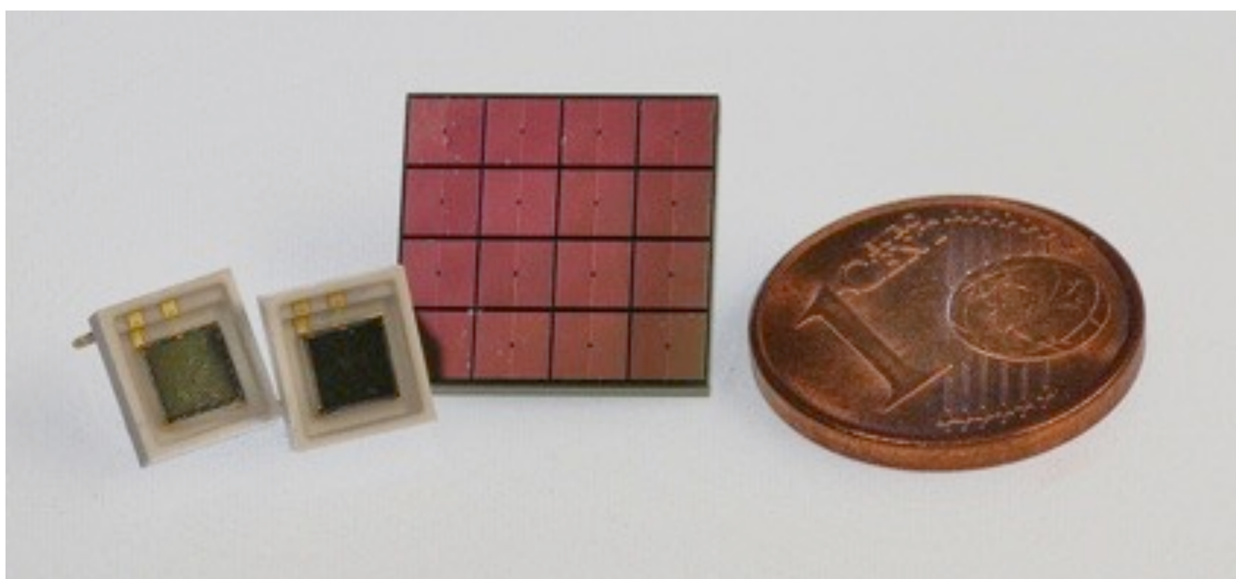
Characterization of hardware components

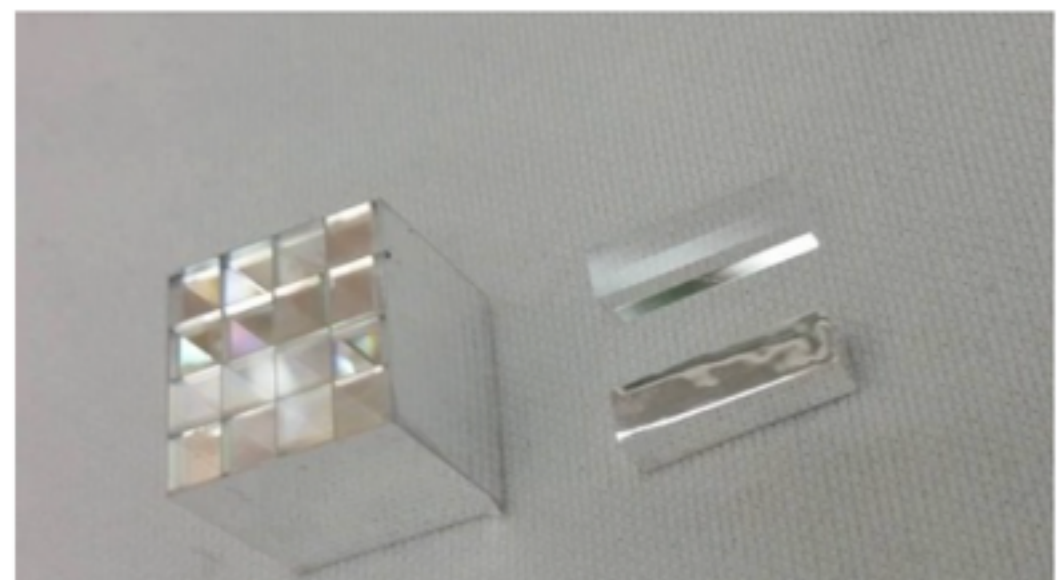
Hardware components:

- **SiPMs**
- **crystals**
- **readout chips for SiPM**

A few samples of arrays in the ‘reference’ design (i.e. 8x8 arrays, pitch 2.2 mm) have been procured only recently

Tests done so far : on individual crystals / SiPM or 4x4 arrays (3.2 mm pitch)

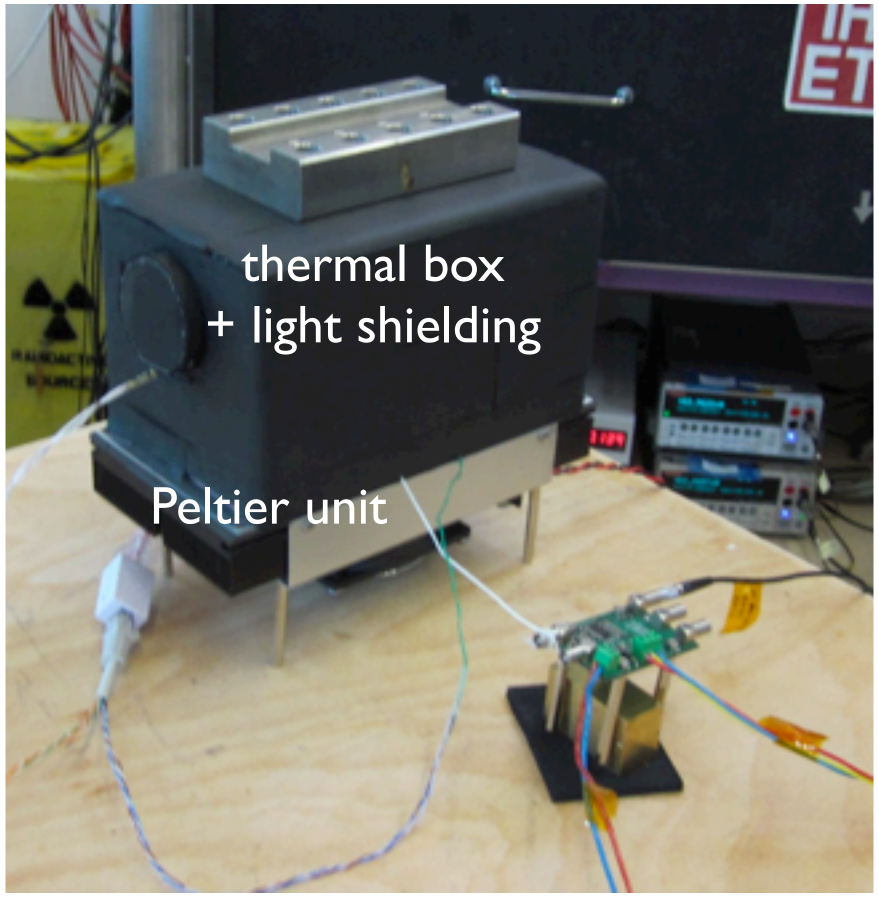


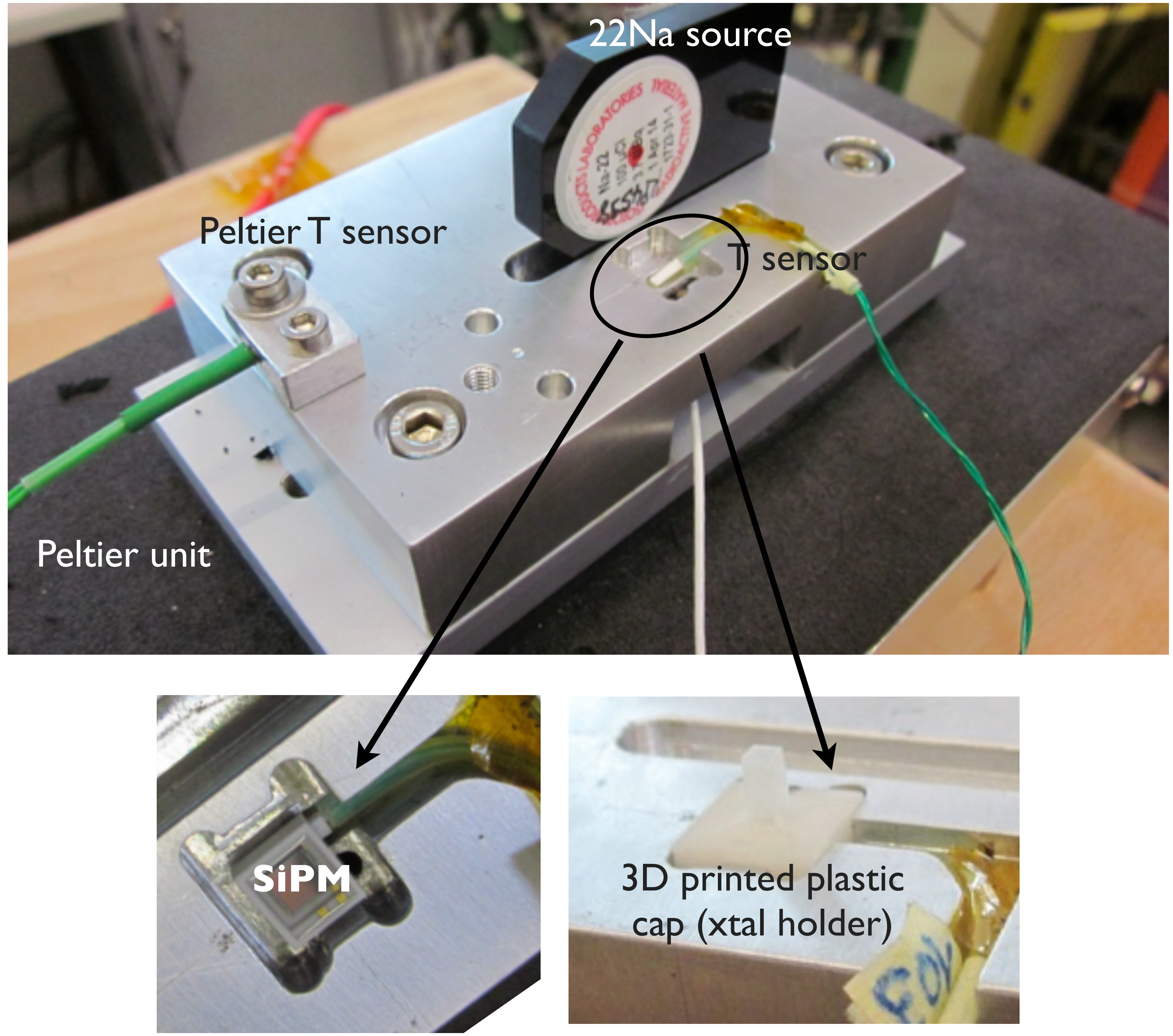


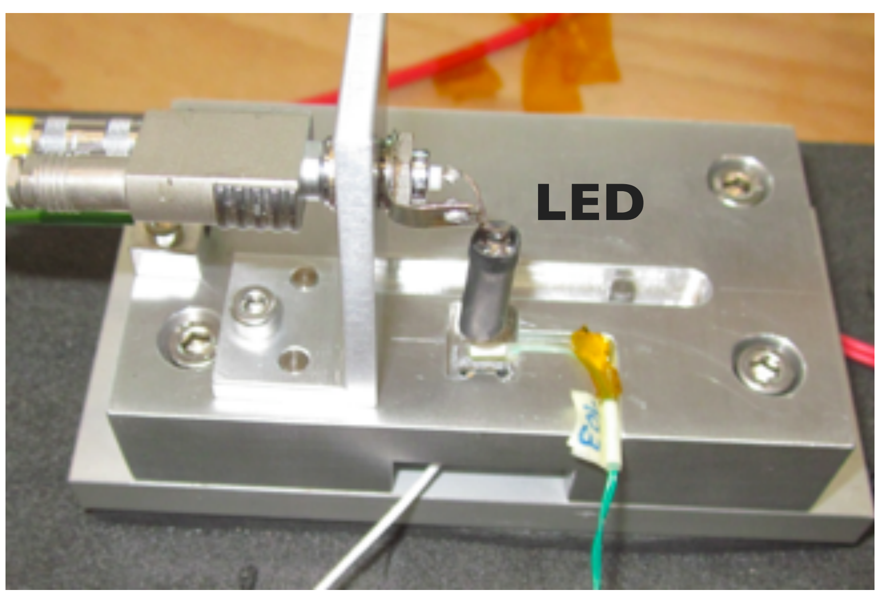
Both individual crystals and matrices :

LYSO (Hilger)
LYSO (Agile)
LFS (Hamamatsu)
LSO & LSO:Ca (SiPAT) - only on single crystals

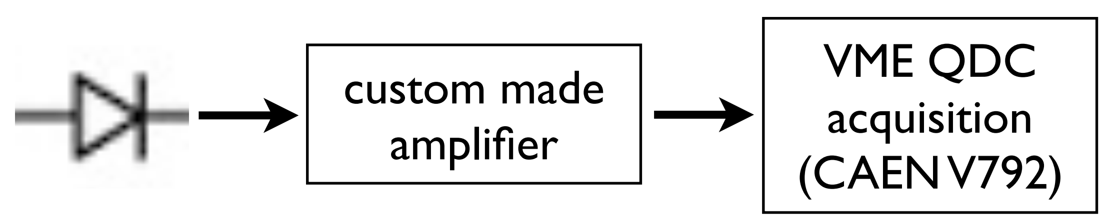
Analogue characterization SiPM / crystals







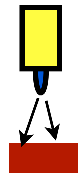
same setup used with LED on bare SiPM
for single photoelectrons detection

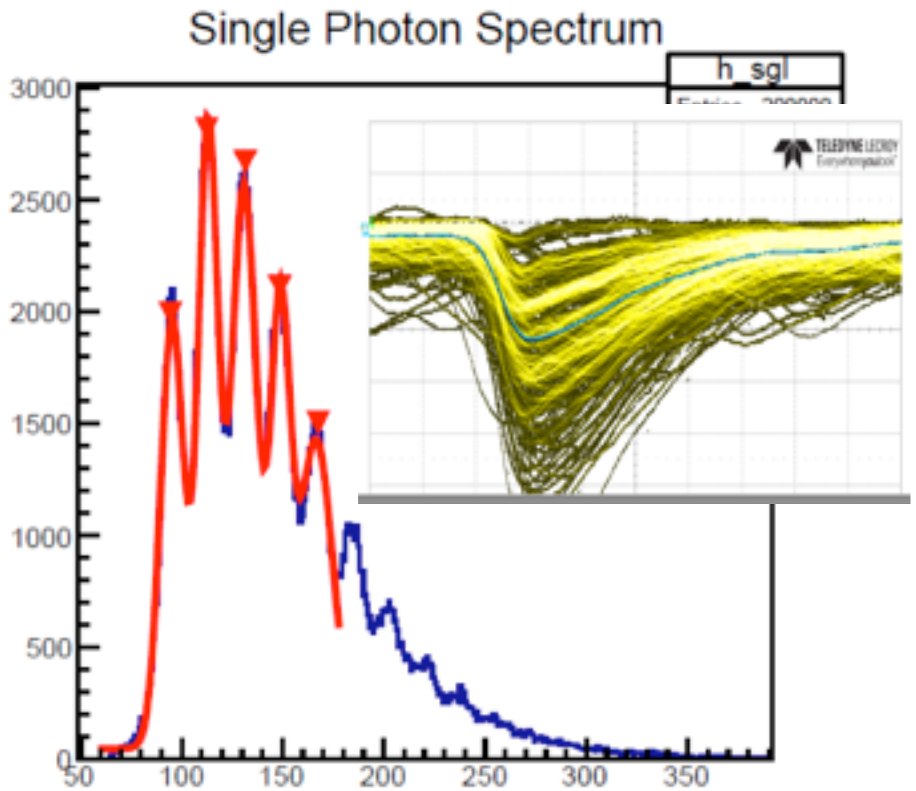


analogue readout chain

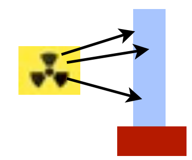
Analogue characterization SiPM / crystals

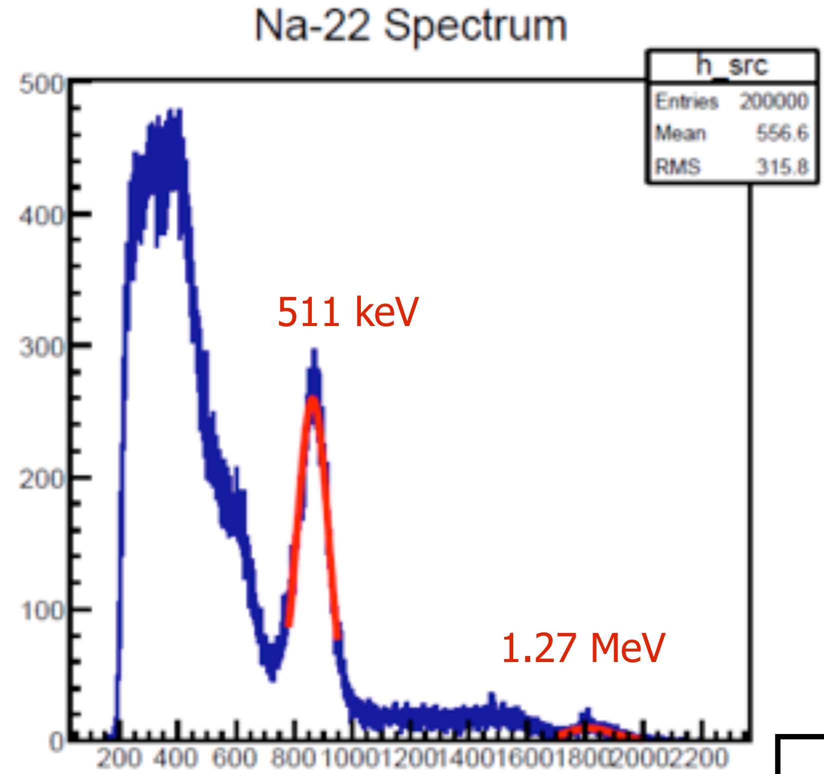
LED (no crystal)



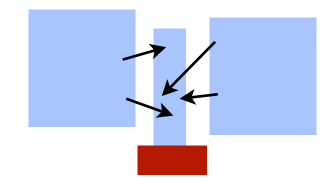


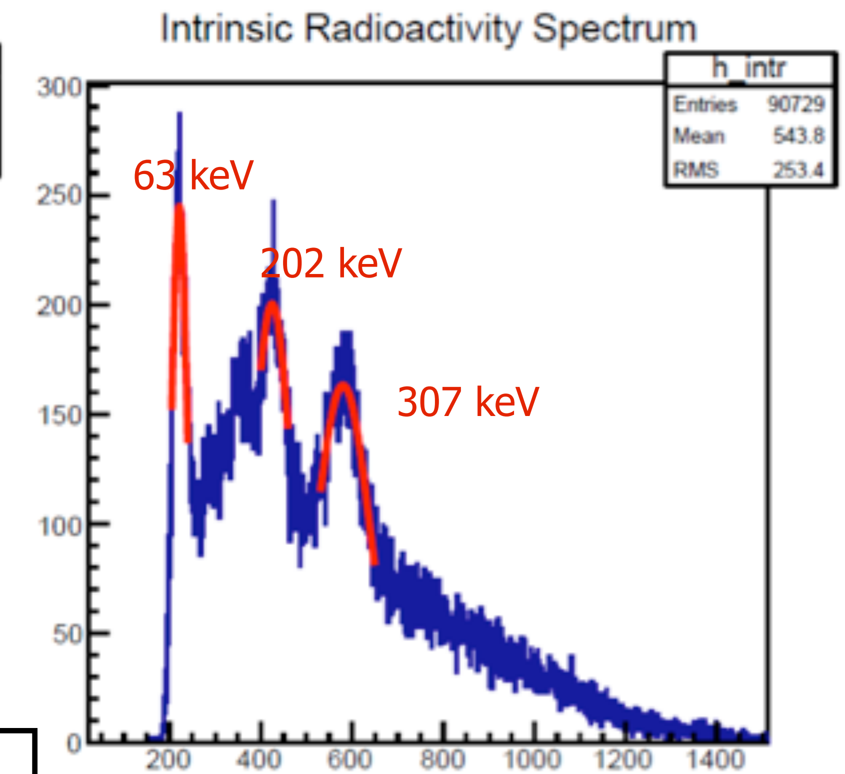
22Na (with crystal)



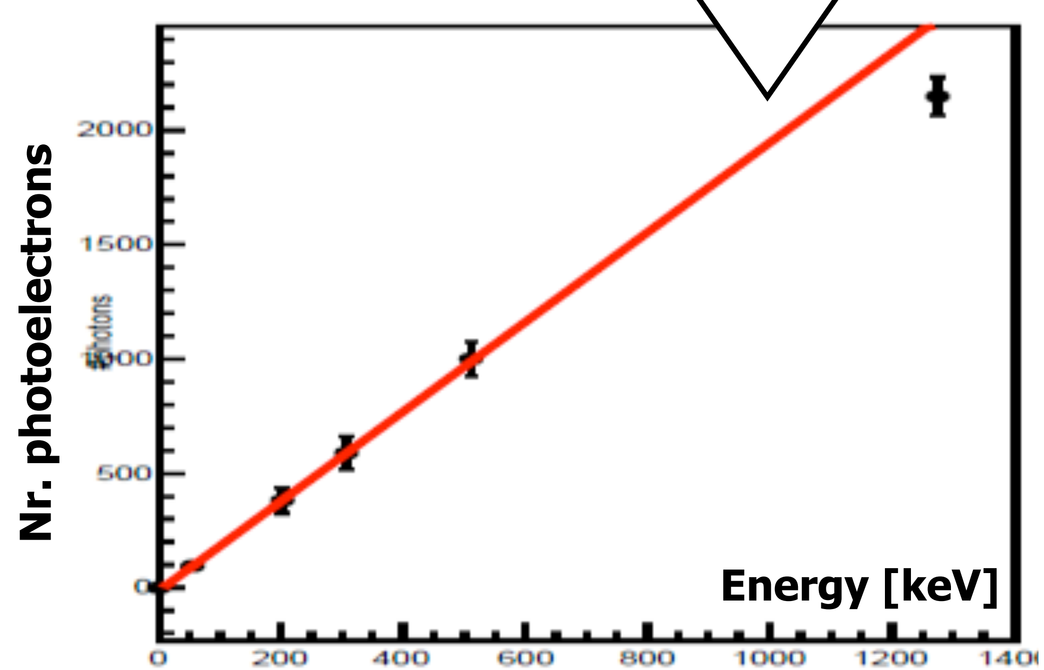


external LYSO (with crystal)





Calibration
[ADC counts / pe]



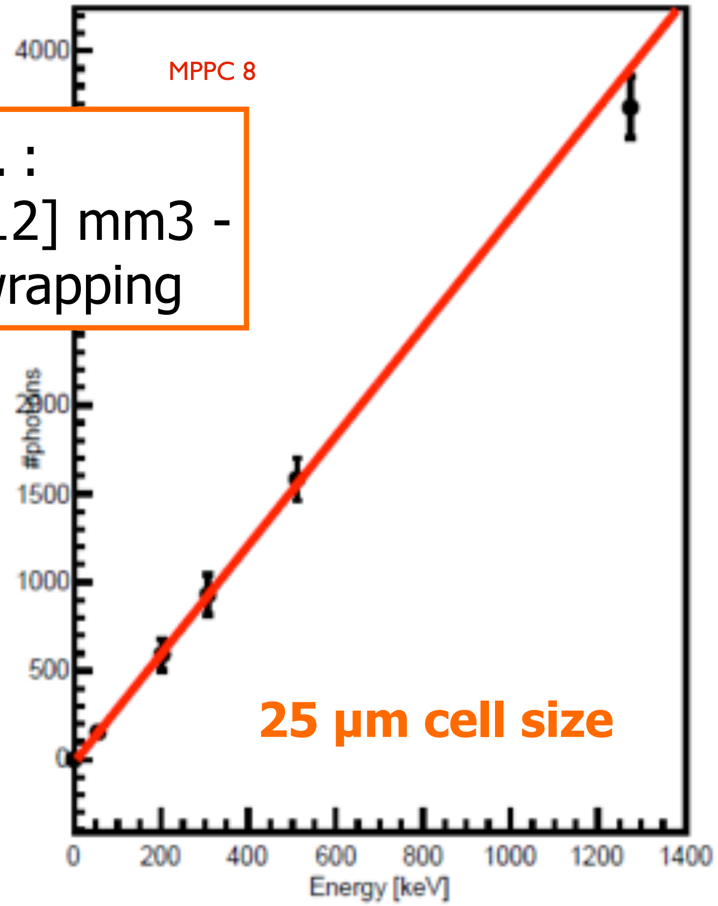
L(Y)SO crystals **(1.5 x 1.5 x 12) mm³**

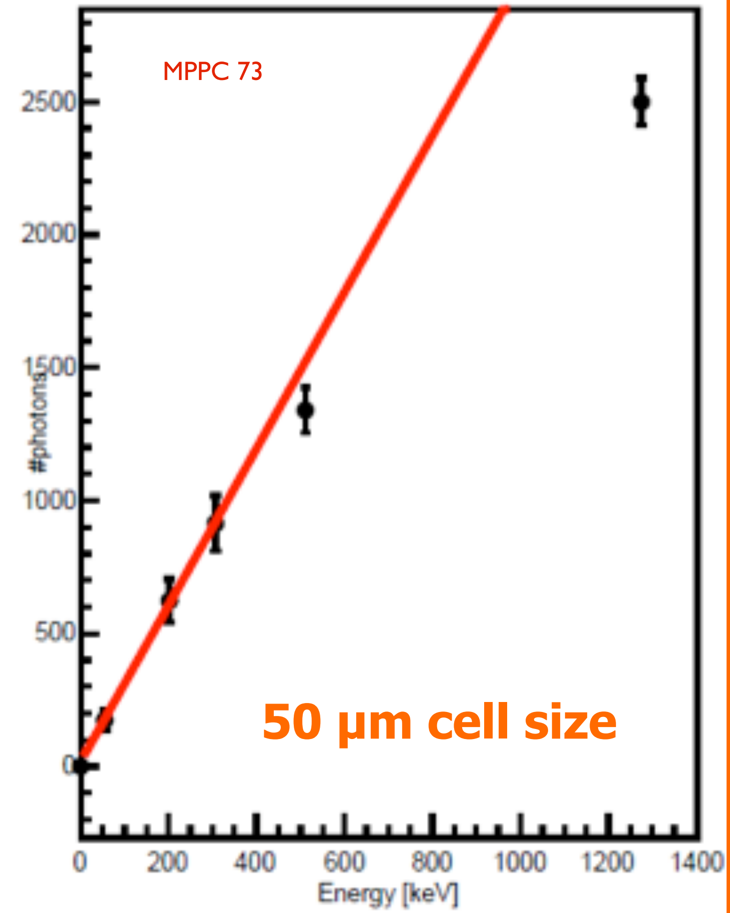
Analogue characterization SiPM / crystals

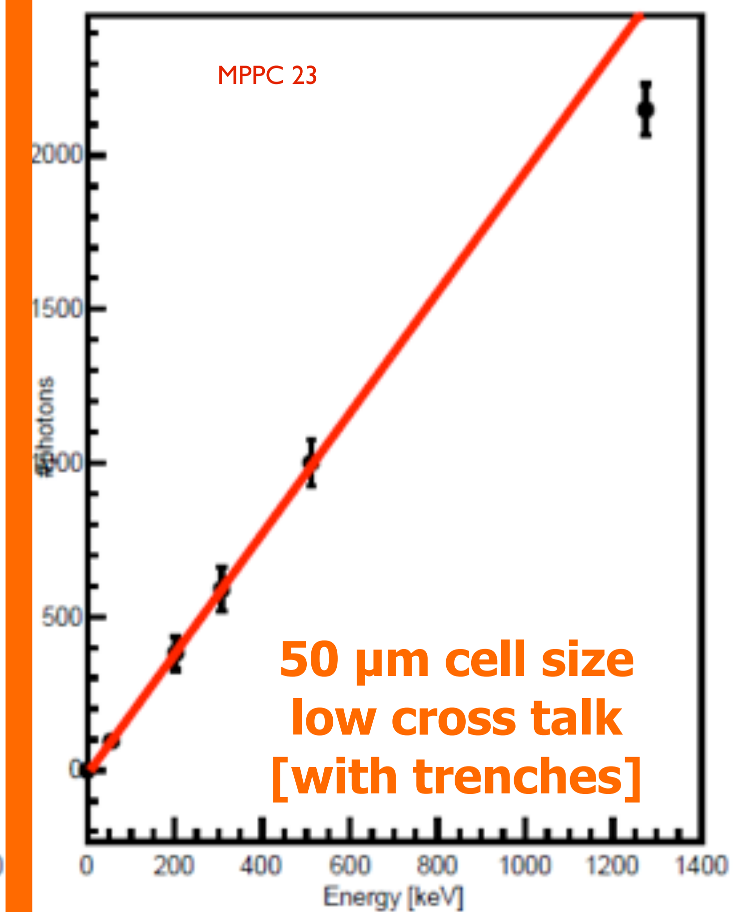
XTAL :
[1.5 x 1.5 x 12] mm3 - with ESR wrapping

SiPM :
[3x3] mm^2
Hamamatsu

nr photoelectron vs energy







Light yield at the photopeak

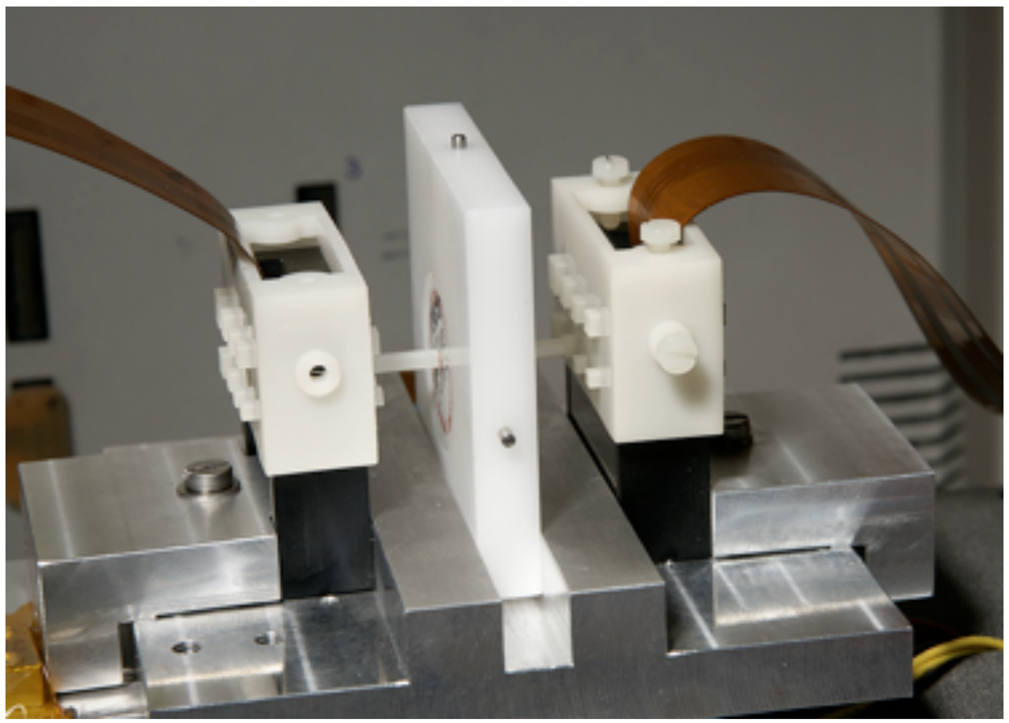
AGILE **LYSO**	~ 2000	~ 1700	~ 1400
SIPAT **LSO**[*]	~ 1600	~ 1400	~ 1000
SIPAT **LSO:Ca**	~ 1300	~ 1100	~ 900

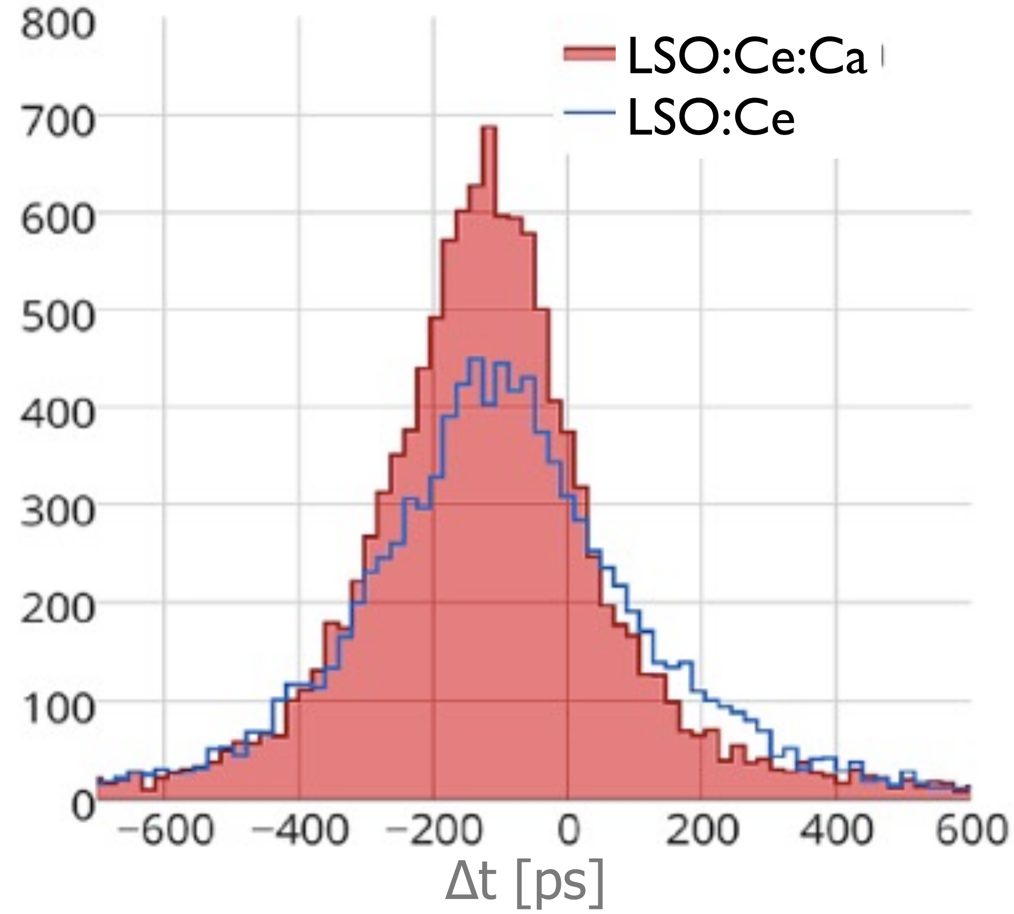
[*] = plots

~ 1000 - 1500 pe's @ 511 keV
different saturation response depending on the adopted SiPM type

Timing properties of different crystals

- different types of crystals
- pairs of crystals tested with **digital SiPM (Philips)**
- direct comparison of coincidence time resolution





LSO Ca-codoped

measured CRT

Crystal	measured CRT	
1.5 x 1.5 x 12 mm3 - Sipat **LSO:Ce**	**[446 +/- 5.2] ps**	
← 1.5 x 1.5 x 12 mm3 - Sipat **LSO:Ce : Ca**	**[329.7 +/- 1.5] ps**	**25% improvement wrt undoped**
1.5 x 1.5 x 12 mm3 - Sipat **LSO:Ce : Ca** + **wrapped** crystal (ESR) and optical coupling between crystals and photosensors (**grease**)	**[228.1 +/- 1.5] ps**	**30 % improvement wrt bare**

LSO Ca-codoped are better in terms of timing <u>BUT DIFFICULT TO PROCURE in large quantity</u>

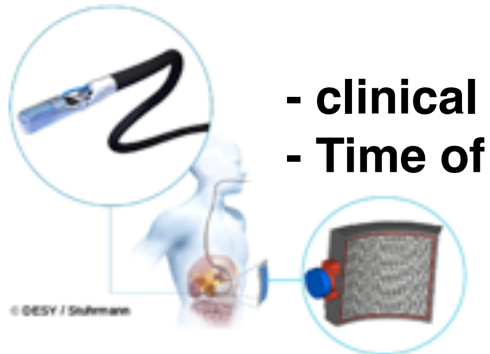
Readout ASIC chip

measure **time and energy**
on **individual channels**
with **very good timing perfs**

Out of the many existing SiPM readout chips options :

- **ToFPET(v1) ASIC** (developed at LIP - Lisbon) Rolo et al, JINST8 C02050
- **STiC v3.1 ASIC** (developed at KIP - Heidelberg) Harion at el, JINST9 C02003

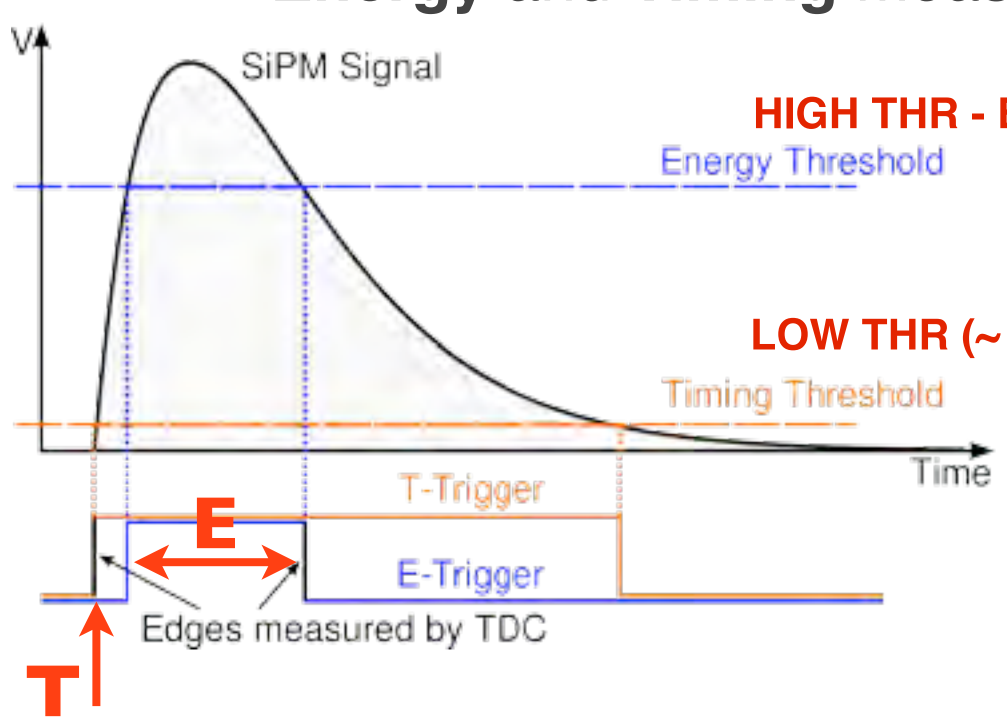
Both developed within the Endo-TOFPET-US project



- clinical
- Time of Flight !

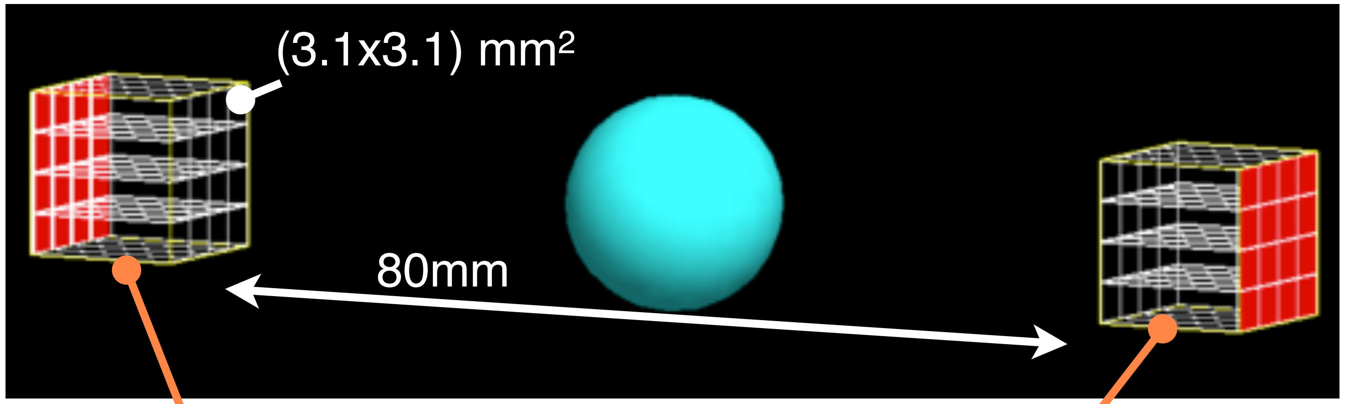
	EndoTOFPETUS	SAFIR
readout for SiPM and Xtals matrices	✔	✔
measure time and energy	✔	✔
timing resolution	✔ excellent (CRT ~ 200 ps FWHM)	✔ very good (CRT < 500 ps FWHM)
high channel density	✔	✔
low power consumption	✔	✔
high rate capabilities		✔

Energy and **Timing** measurements through the **Time Over Threshold logic**



64 channels/ASIC
mixed mode : analogue FE (ampli, discri) + digitization / LVDS output
same logic - different implementations

High rate test with TOFPET and STiC ASICs



at University Zurich Hospital
(daily 18-F production)

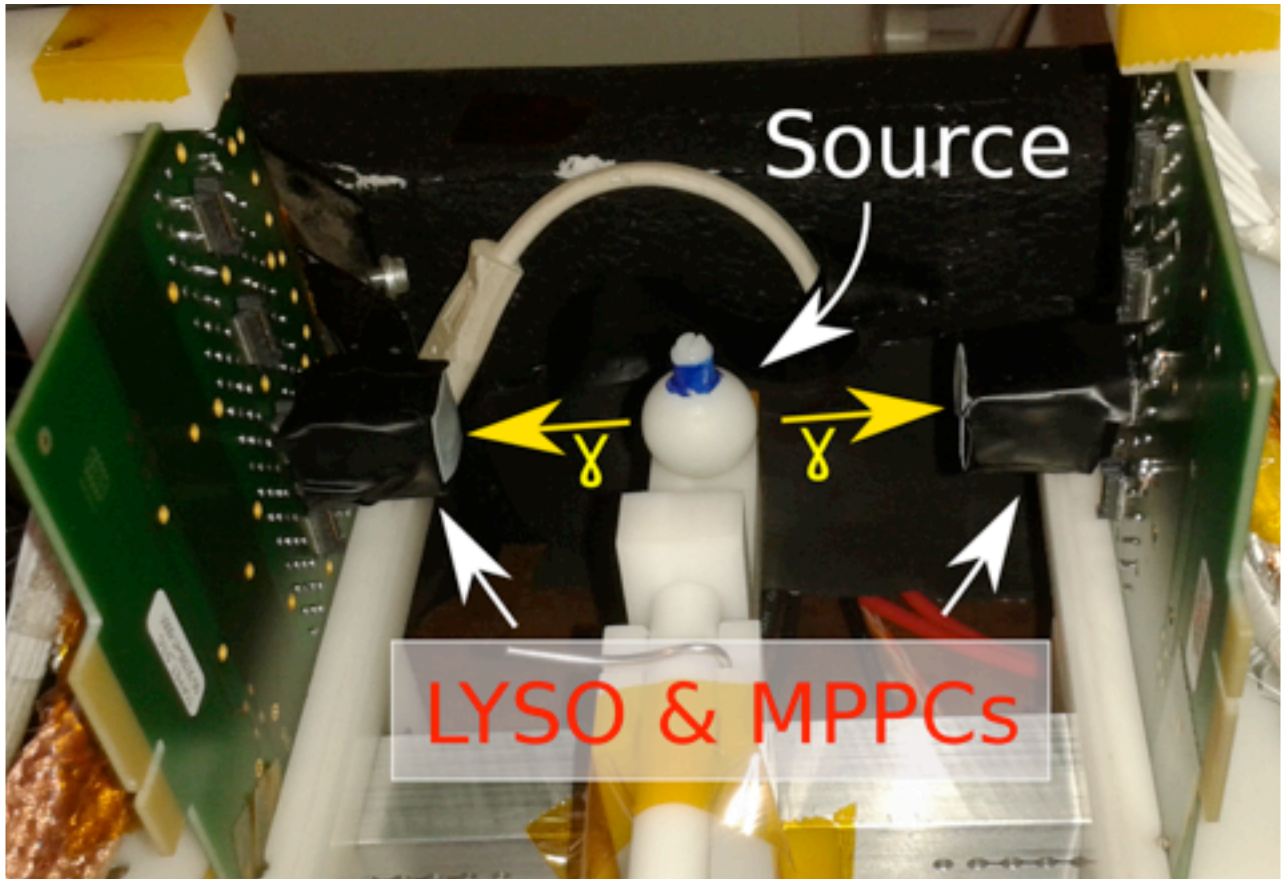
- Activity : **ball phantom** [⌀ = 11mm] **filled with FDG** [$t_{1/2}$ 18-F ~ 120 mins]
- Activities up to 500 MBq

- **2 matrices [xtals + SiPM arrays] - 4x4 channels**
  - Hamamatsu S12642-0404PB-50 : 4x4 ch, TSV, 3x3 mm2 sensor size, 3.2 mm pitch
  - LYSO crystals (Agile) : 4x4 xtals, (3.1 x 3.1 x 12) mm3 each, ESR wrapping / separation (100 um thick)

i.e. existing commercial components - different form factors and distances wrt SAFIR reference design
- reduced nr of channels/chip

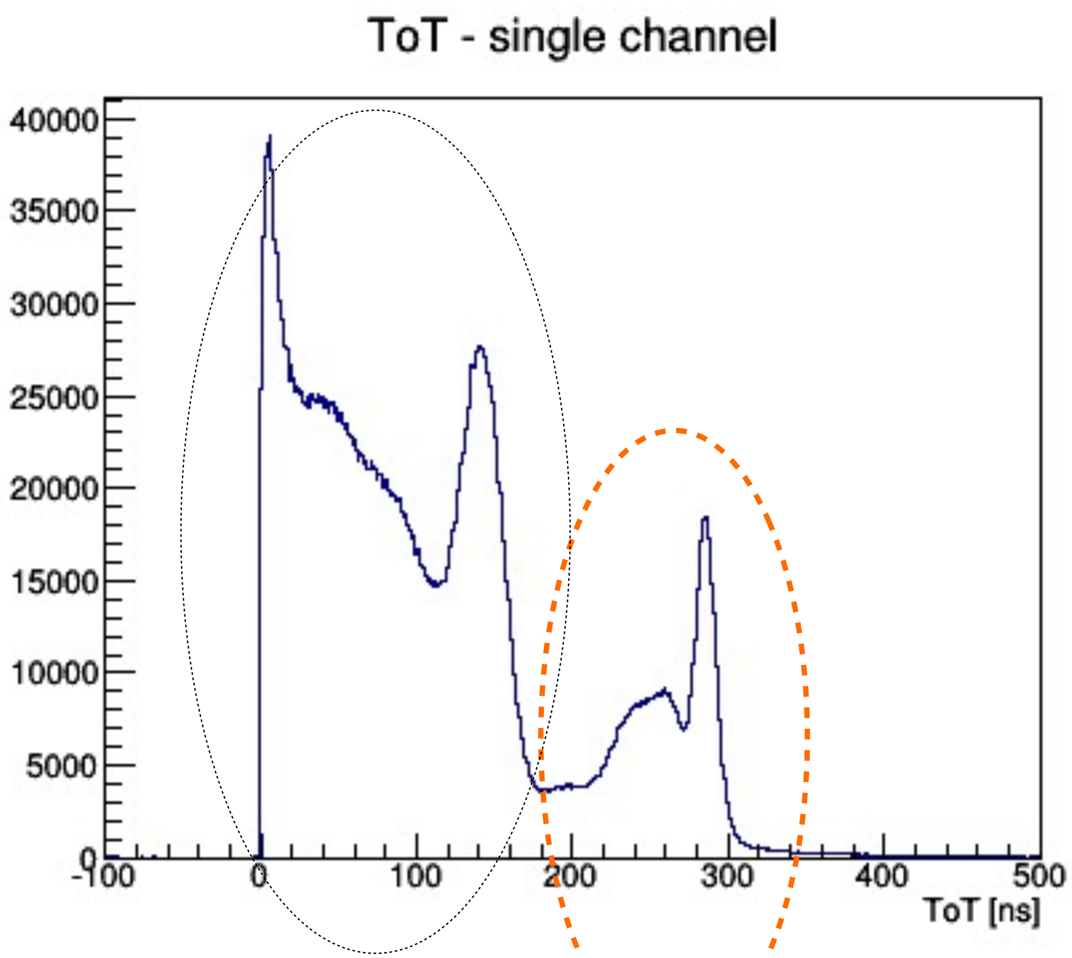
- operated in coincidence
- same matrices used alternatively for the TOFPET and the STiC setup
- 2 identical parallel setups in a thermal box

- ToT spectrum
- Rate capabilities
- CRT performance



TOFPET performance : ToT and Rate

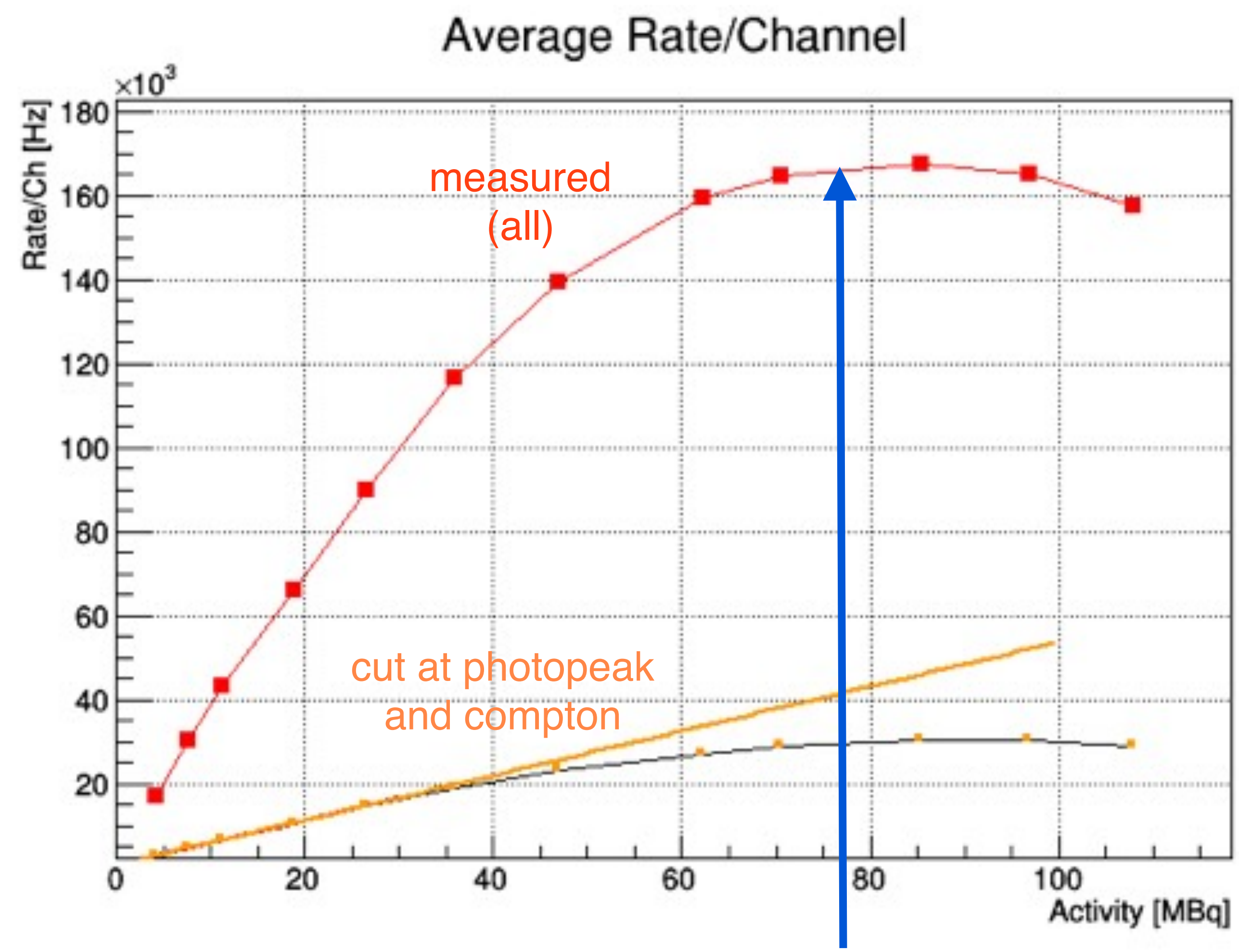
Time Over Threshold



photopeak and Compton scattering of the interacting 511 keV gamma

Low Energy contribution due to important cross talk effect in the crystal matrix

Rate performance



500 MBq SAFIR-equivalent

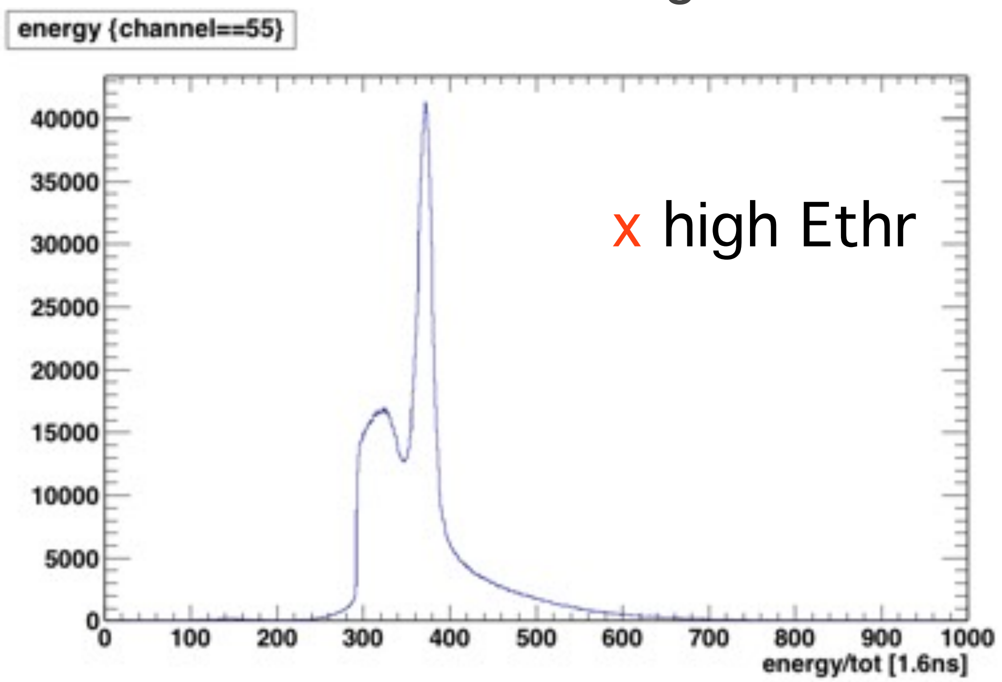
(scaled by size of xtals and F2F distance)

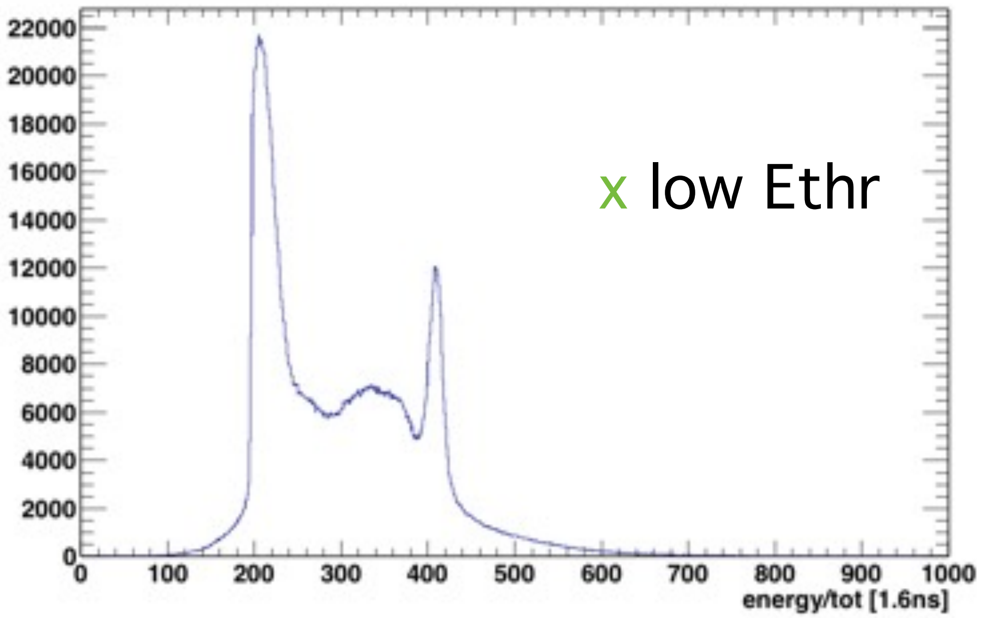
- **up to 160 kHz/channel**
- **then : saturation effect**
- not linear anymore at SAFIR equivalent point
- low energy contribution significantly impacts the total rate/channel

STiC performance : ToT and Rate

Time Over Threshold

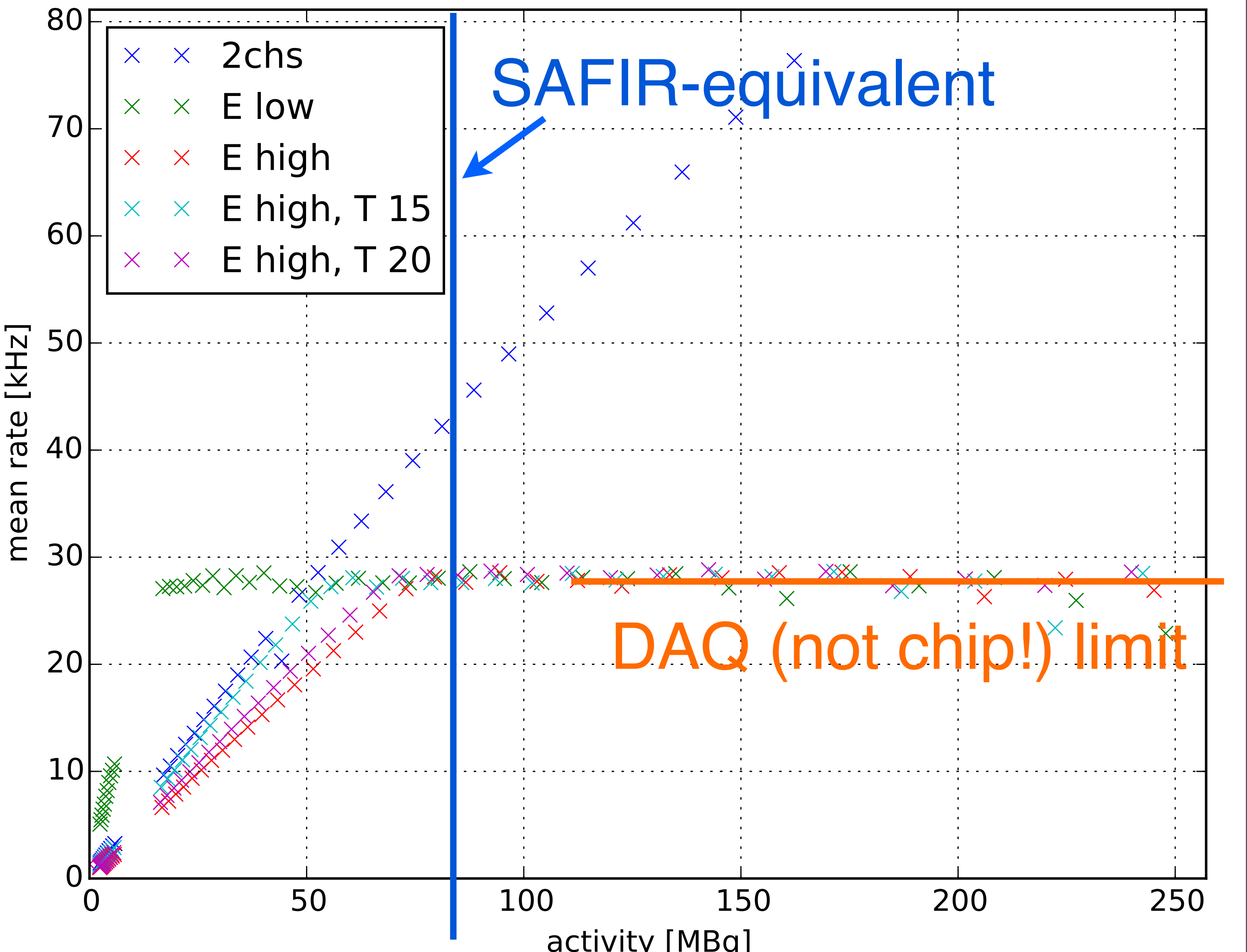
Flexibility in adjusting THRESHOLDS over a broad range!





+ **linearization** circuitry in the ToT

Rate performance

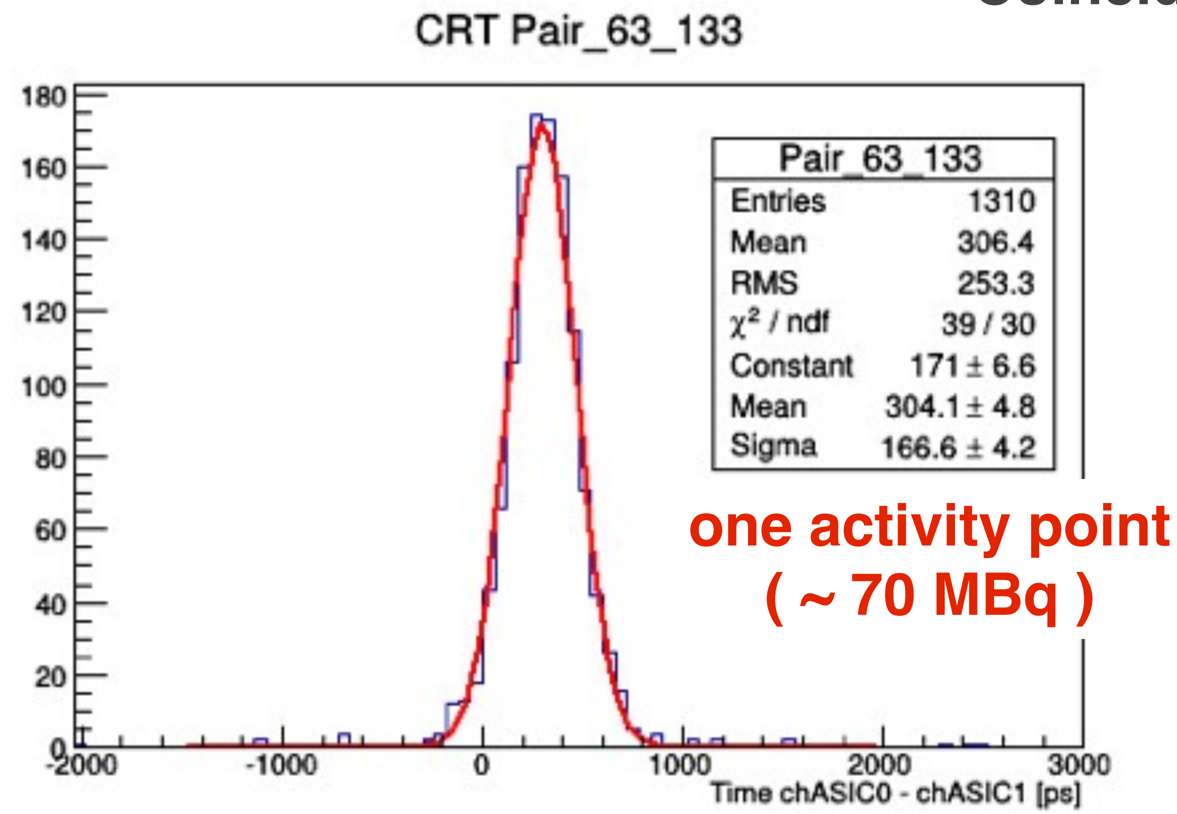


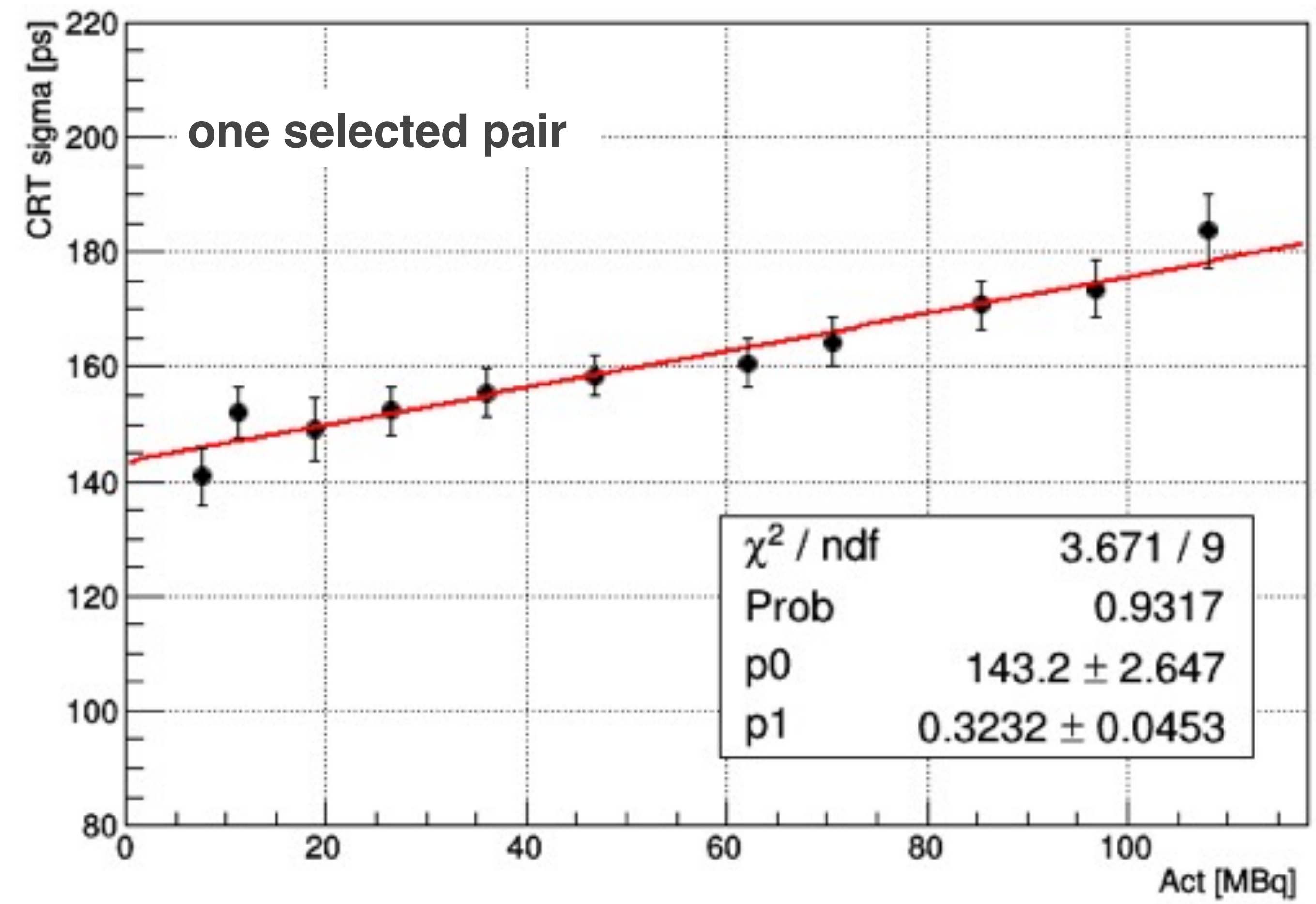
- DAQ (**USB link**) limit ~ 700 kHz (total)
- different Ethr in ToT => different slopes in rate/ch vs activity

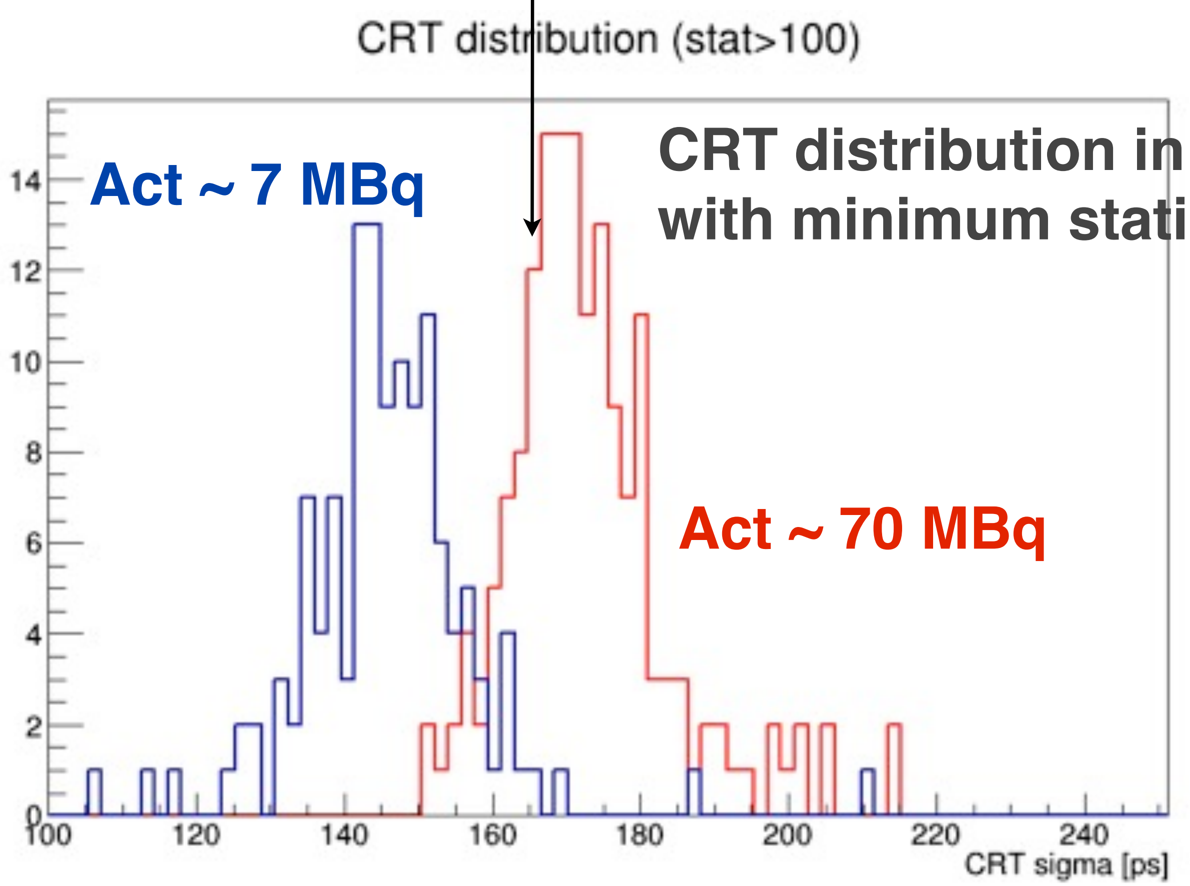
- 2 channels test :
  - demonstrates high rate chip capabilities (>> SAFIR req)
  - ~ 40 kHz/channel at SAFIR-equivalent (as from MC)

TOFPET performance : CRT

Coincidence Time Resolution (CRT) - one selected pair







CRT distribution in all pairs with minimum statistics

CRT performance

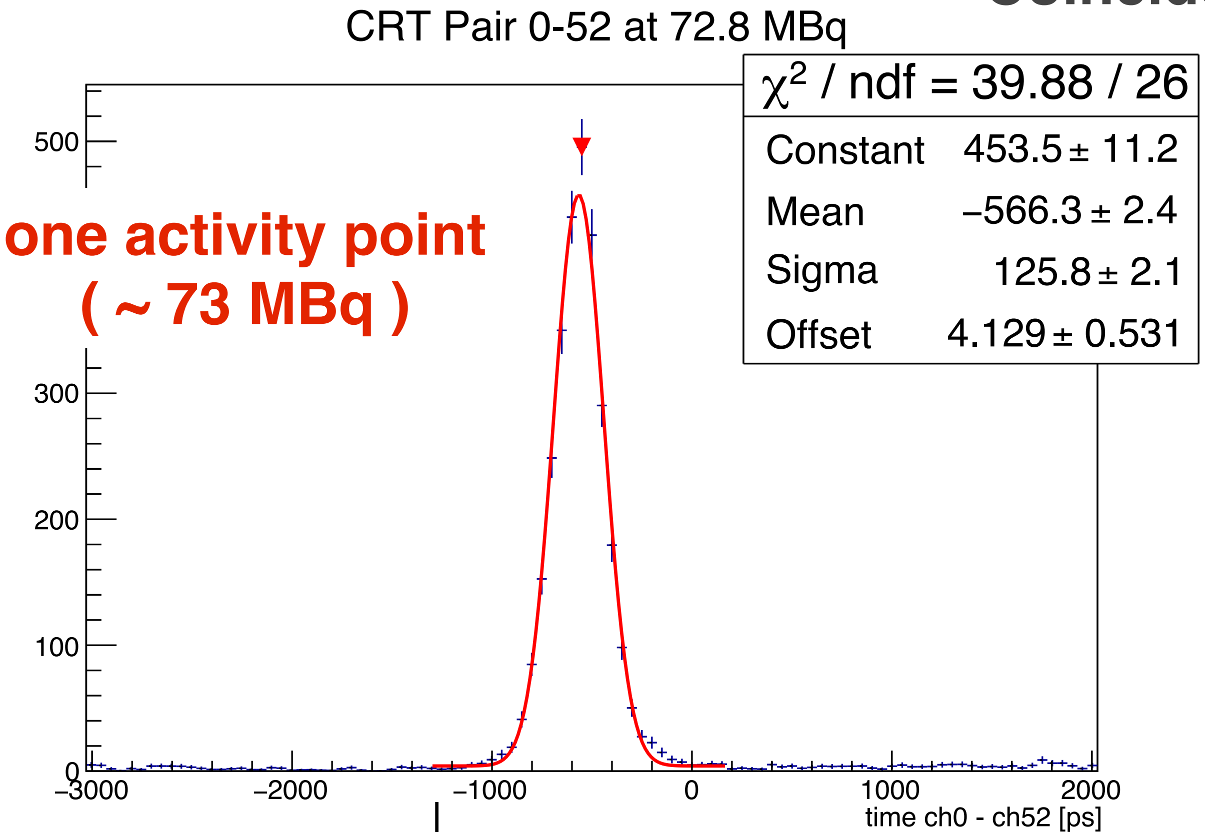
linear degradation of CRT with increasing activities

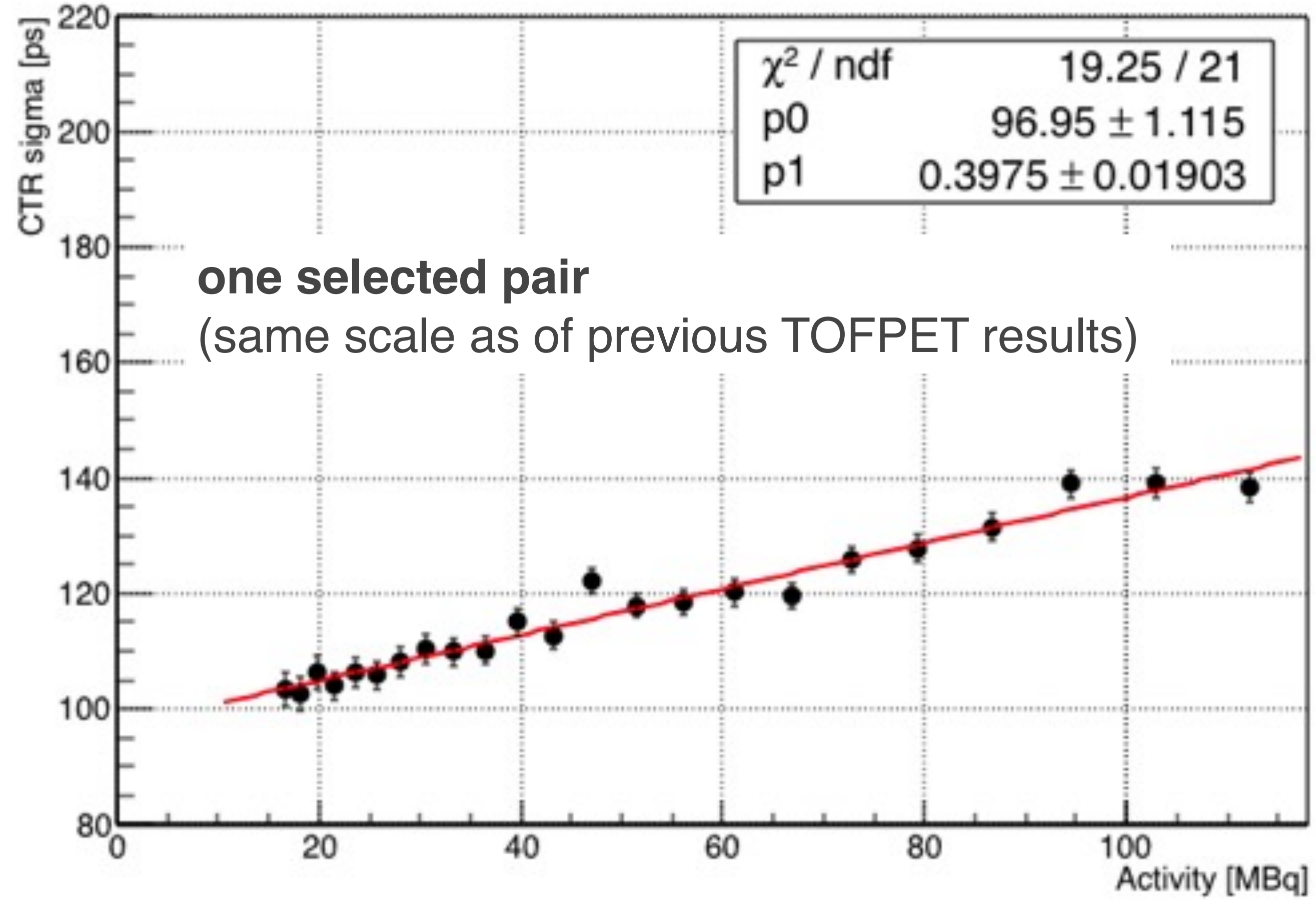
< CRT > @ Act ~ 7 MBq => 330 ps FWHM

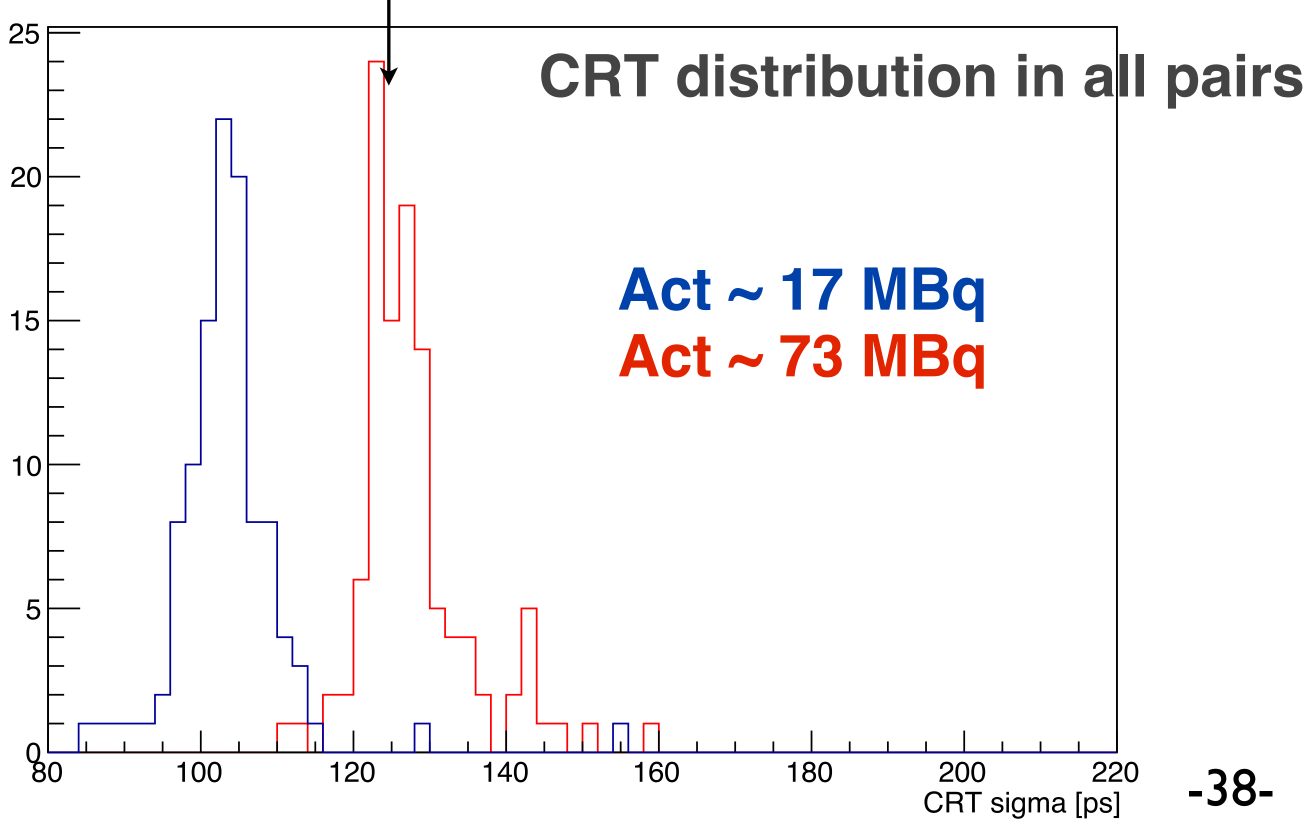
< CRT > @ Act ~ 70 MBq => **400 ps FWHM [~ 500 MBq SAFIR-equivalent]**

STiC performance : CRT

Coincidence Time Resolution (CRT) - one selected pair







CRT performance

linear degradation of CRT with increasing activities

< CRT > @ Act ~ 17 MBq => 240 ps FWHM

< CRT > @ Act ~ 70 MBq => **300 ps FWHM [~ 500 MBq SAFIR-equivalent]**

TOFPET and STiC as possible readout for SAFIR

Results from the High Rate Test :

- **Significant low energy contribution in the ToT distribution** in the tested setup [Agile matrices + Hamamatsu SiPM] (**cross-talk effect btw xtals**)
- Need to cut on those events <=> reduce bandwidth occupancy
- Need to have a **high validation threshold:**
  - **STiC(v3.1) : ok**
  - **TOFPET(v1) : no**

- **Rate capabilities :**
  - SAFIR requirement : ~ 40 kHz/channel (with 2x2 mm2 detector size as in reference design)
  - **excellent rate performance (>> SAFIR reqr.)** both for STIC(v3) and TOFPET(v1)

- **Coincidence Timing Resolution :**
  - SAFIR requirement : CRT ~ 300-500 ps FWHM
  - **very good CRT in the full range of explored activities**
    - **STiC(v3.1) CRT ~ 300 ps FWHM** at 500 MBq SAFIR-equiv.
    - **TOFPET(v1) CRT ~ 400 ps FWHM** at 500 MBq SAFIR-equiv.
  - Still under study : deterioration of the CRT with increasing activity
    - $\Delta\sigma/\Delta Act$ ~ 30-40 ps / 100 MBq (100 MBq in HighRateTest setup ~ 650 MBq SAFIR)
    - but does not compromise the CRT perfs

=> STiC is considered a valid candidate for SAFIR readout

PETA module

alternative option for SAFIR

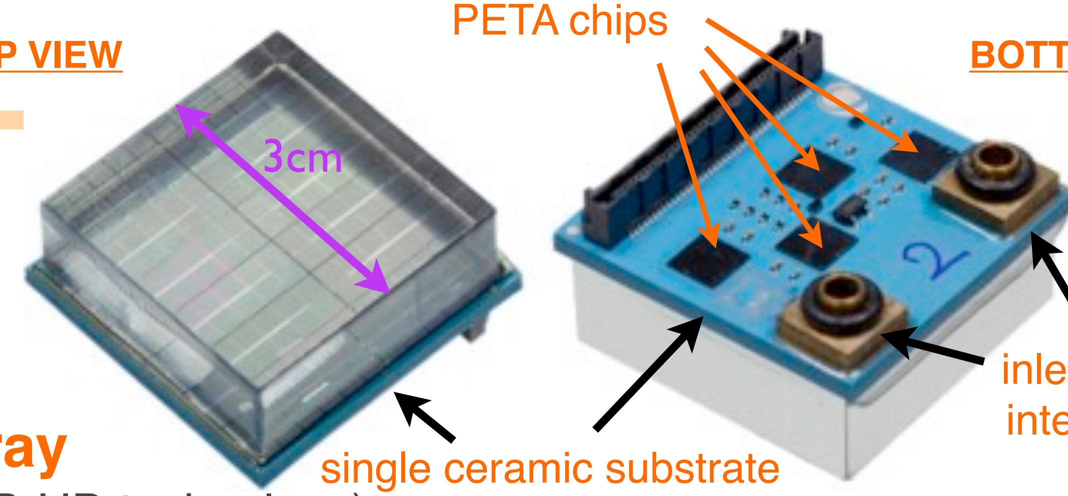
- **compact module for TOF in PET [crystals, SiPM array, RO chip]**

I. Sacco et al: 10.1016/j.nima.2015.11.004 [in press]

- developed within the Sublima project
- based on the PETA chip

TOP VIEW

BOTTOM VIEW



SiPM array

- FBK (RGB-HD technology)
- 12x12 channels
- (2.25 x 2.25 x10) mm3
- 2.5 mm pitch
- wire-bonded SiPM dies

Crystals

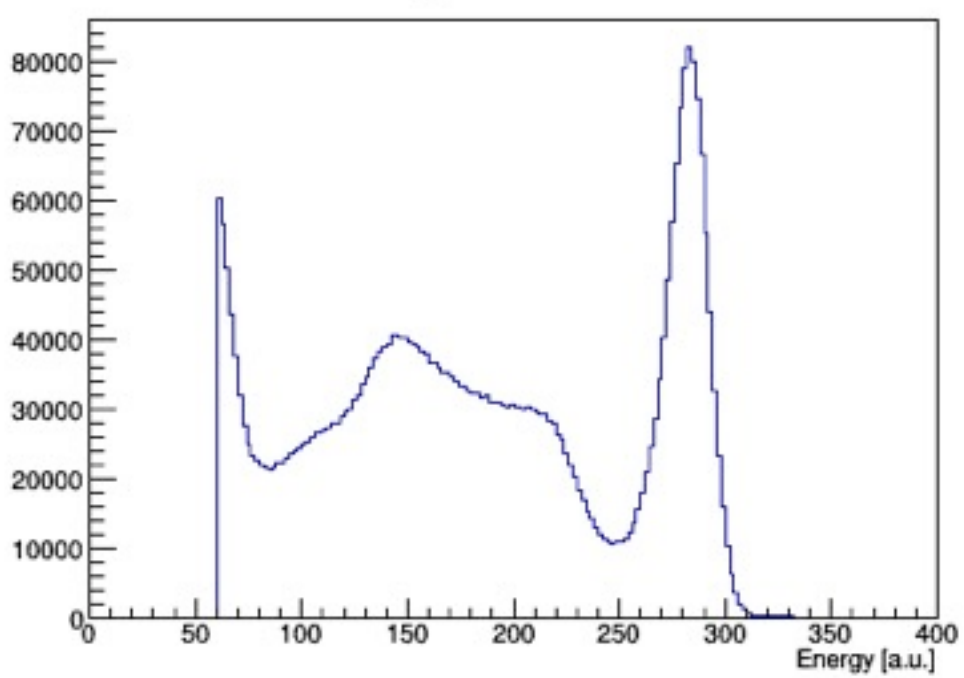
- LYSO + ESR/Alu/ESR

Readout chip

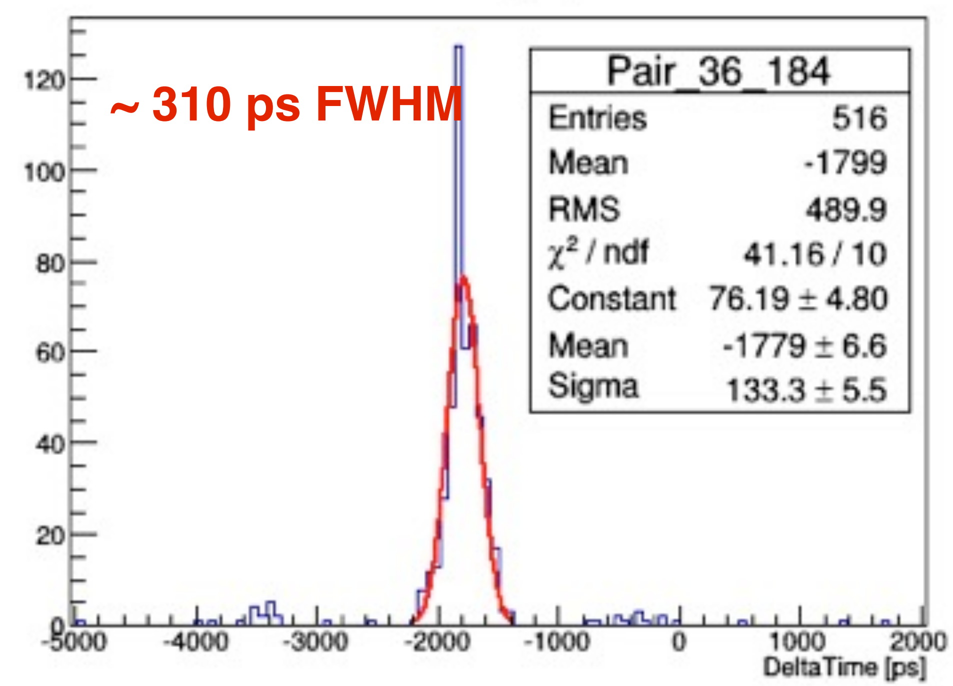
- PETA5 chip (x4/module)
- Position Energy Time ASIC
- 32 channels / chip
- bump-bonded ASIC
- **Time (discri + TDC)**
- **Amplitude (charge input integr.)**

Tests with high activity (one chip/module)
2 modules coincidences

single channel



CRT single pair



although only by preliminary tests **PETA is considered a valid candidate for SAFIR readout**

SAFIR future steps

Bruker BioSpin 70/30 MRI-scanner
already commissioned and in use at ETH Zurich

1. Two small scale prototypes

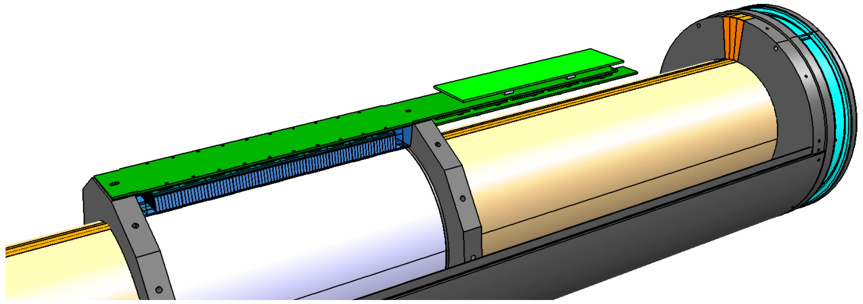
- **two modules coincidence setups**
  - **in the final mechanical arrangement**
  - **inside the MR-bore**

  * **PETA modules**
  * 2 modules (12x12)
  * xtal size : (2.25x2.25x12) mm3

  * **STIC chip RO**
  * 2 matrices (8x8)
  * xtals size : (2.1x2.1x12)mm3
  * “reference design”

- test high rate performance
- test full MR-compatibility

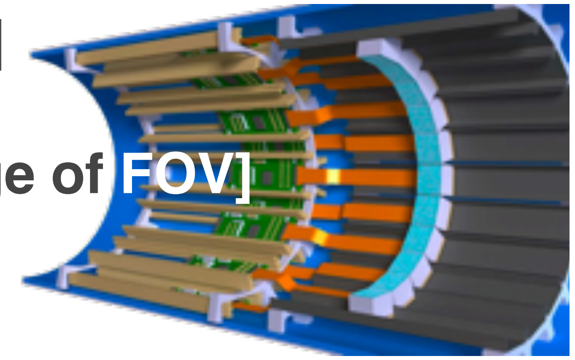
- now : building / commissioning the needed readout electronics
- expected - prototypes ready: May 2016 - tests : 2nd half 2016



The same support foreseen for the full system will be used in the two small scale prototypes

2. First full ring

- choice of the readout solution
- extension to one full ring [same geometry of xtals and SiPM as in prototype]
- development and tests of 4D reconstruction algorithms
- **full tomographic acquisitions for dynamic studies [but limited coverage of FOV]**
- expected : 2017



3. Final SAFIR detector

- design to be confirmed / tuned also on first full ring experience (e.g. maybe improve the spatial resolution with new developed detector heads)
- full commissioning ... towards ~ secs acquisitions!!!

conclusions

Conclusions

I have described the **SAFIR detector concept** and **its progress status**
(software and hardware activities)

SAFIR: **unconventional detector for hybrid PET/MRI acquisition with the dedicated goal of dynamic and simultaneous imaging at unprecedented temporal resolutions**
(target user: ETHZ/UniZh Institute of Biomedical Engineering)

Peculiarities of the detector :

500 MBq activity (wrt standard ~ 50 MBq)

excellent time resolutions : CRT ~ 300 - 500 ps FWHM (w/o being a TOF-PET)

heavy usage of SiPM sensors
(not peculiar to SAFIR, but standard nowadays in PET developments)

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(not peculiar to SAFIR, but standard nowadays in PET developments)

What you were probably wondering at the beginning of this talk:

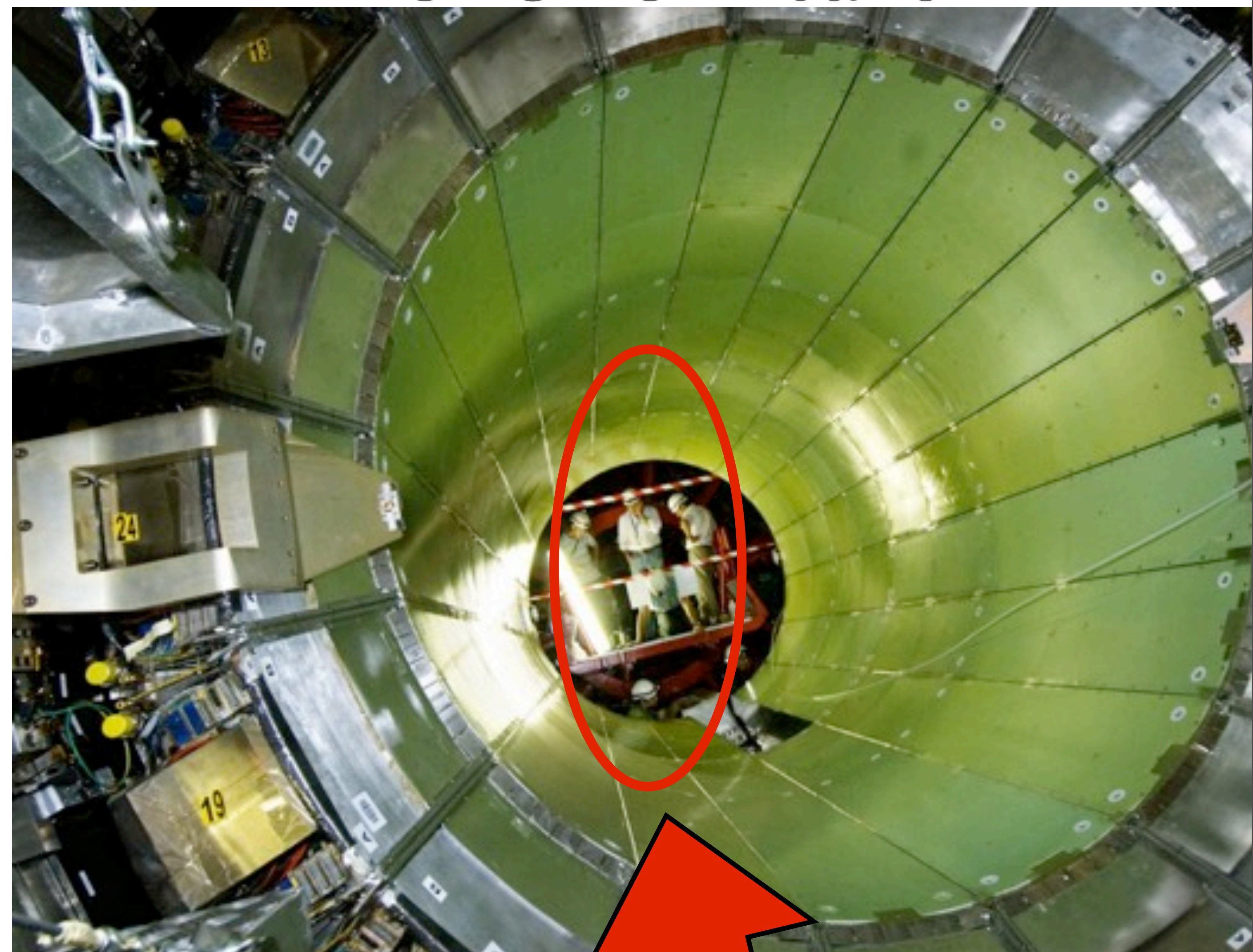
" Small Animals??? PET???
Magnetic resonance???
What all this has to do with a HEP Department seminar ???"

Keywords of these slides :

calorimetry (measurement of gamma energy with crystals) ; scintillators ; photosensors ; operation in magnetic field ; SiPM ; readout ASIC chips ; high data rate ; fast DAQ ; 10's kchannels

Inveon preclinical PET scanner

CMS ECAL barrel



many more similarities than it might look at first glance !

but not in the size!

SAFIR collaboration

Institute for Particle Physics - ETH :
R. Becker, C. Casella, D. Di Calafiori, G. Dissertori, L. Djambazov, M. Droge, C. Haller,
A. Howard, M.Ito, P. Katheri, J. Fischer, W. Lustermann, U. Roeser

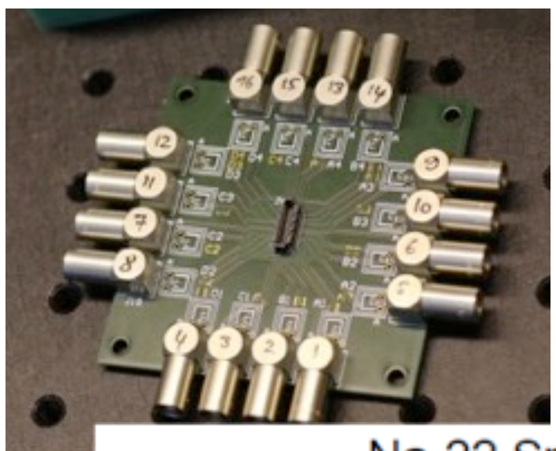
Institute for Biomedical Engineering - ETH:
M. Rudin

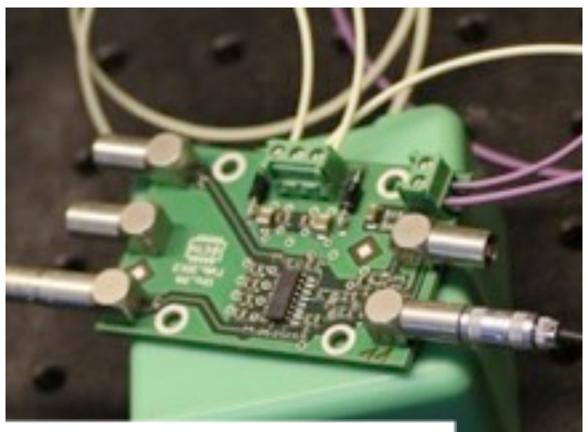
Institute for Pharmacology and toxicology - University Zurich :
A. Buch, G. Warnock, B. Weber

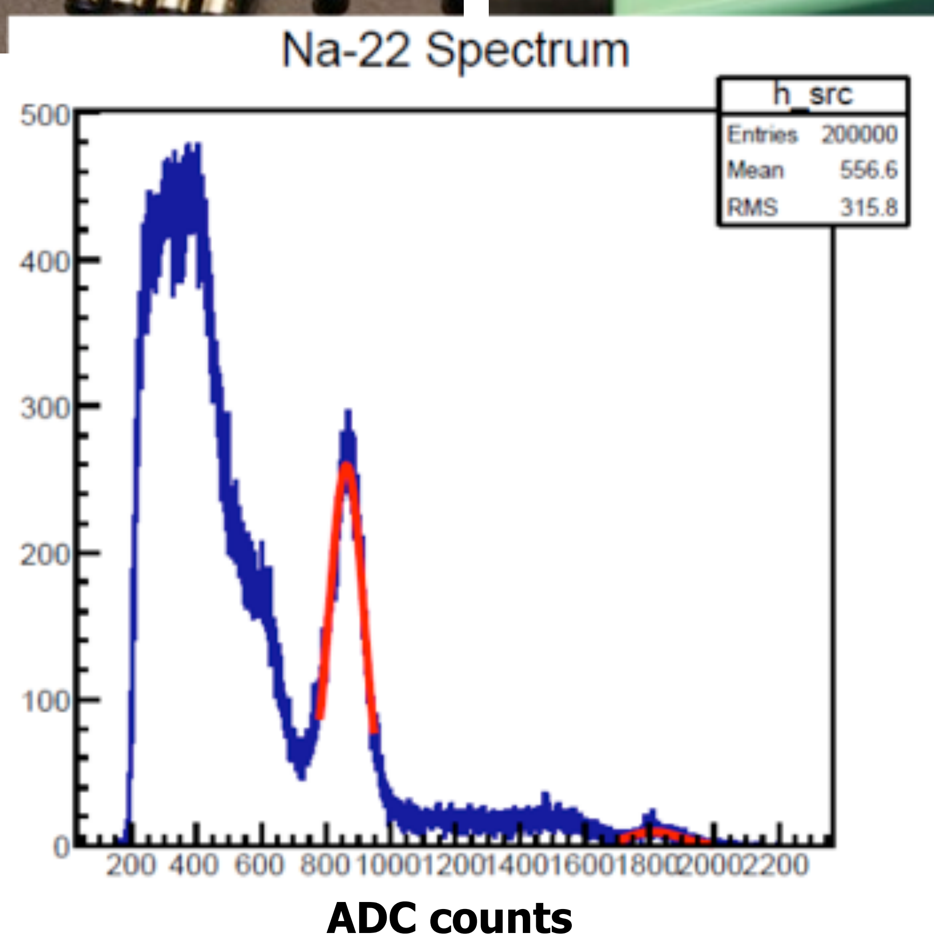
University of Valencia, IFIC :
J. Oliver

Lab tools

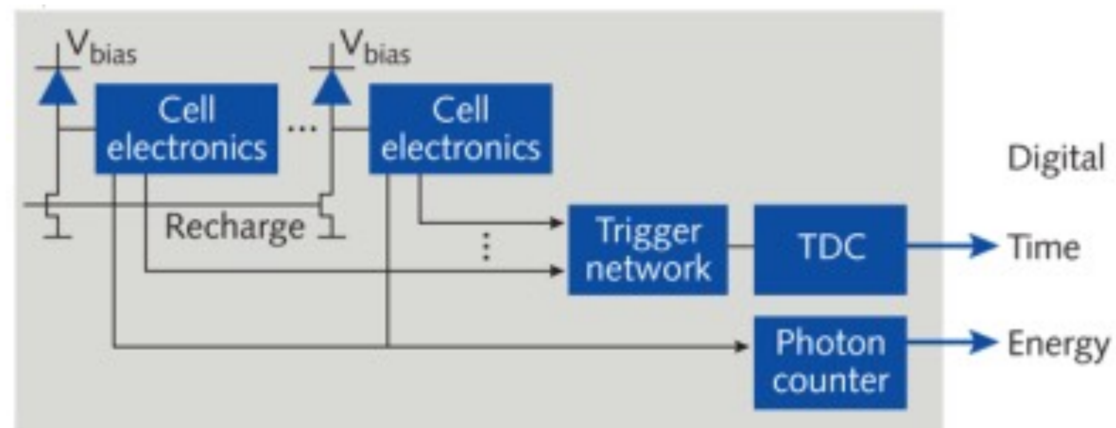
- **analogue readout chain**



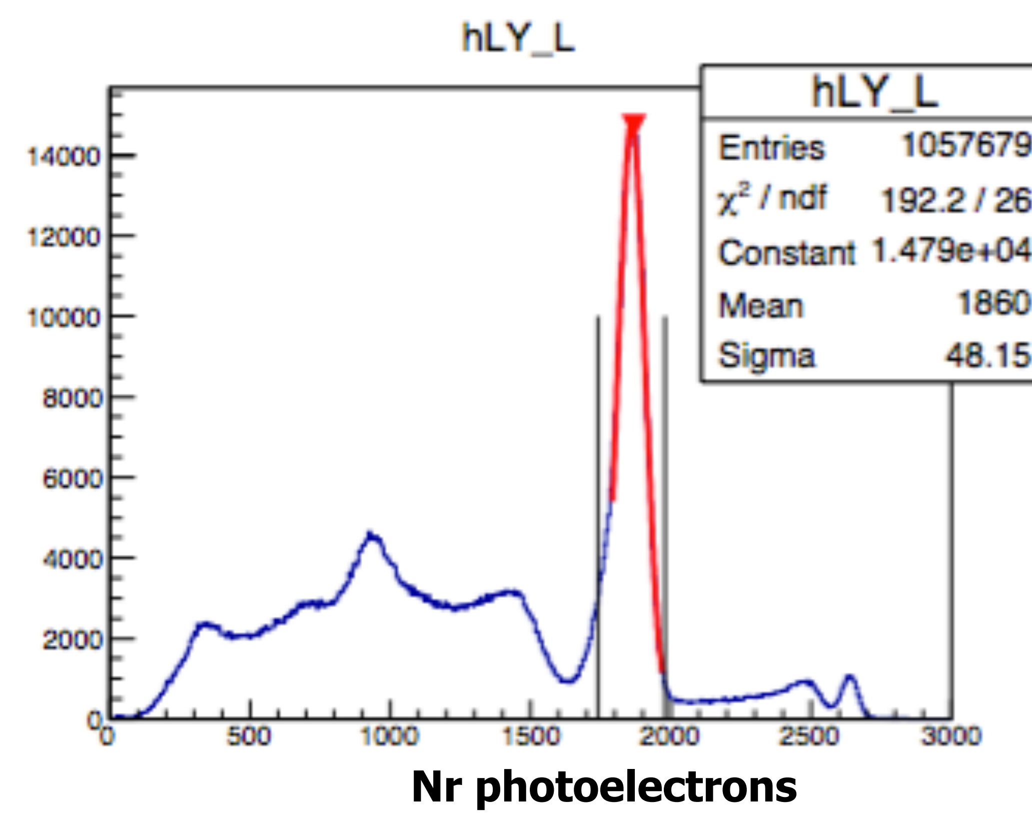




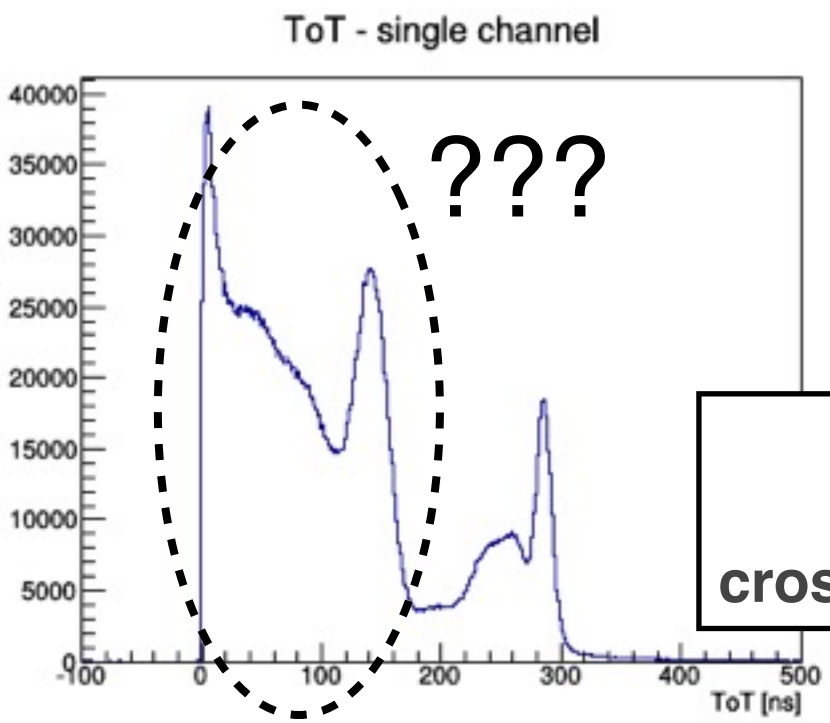
- **Digital SiPM (Philips)**
  - fully digital implementation of SiPM
  - the electronics for each cell implemented on the same Si substrate of the sensor
  - high resolution TDC (19.5 ps resolution)



Very good tool for :
- photon counters
- coincidence timing measurements

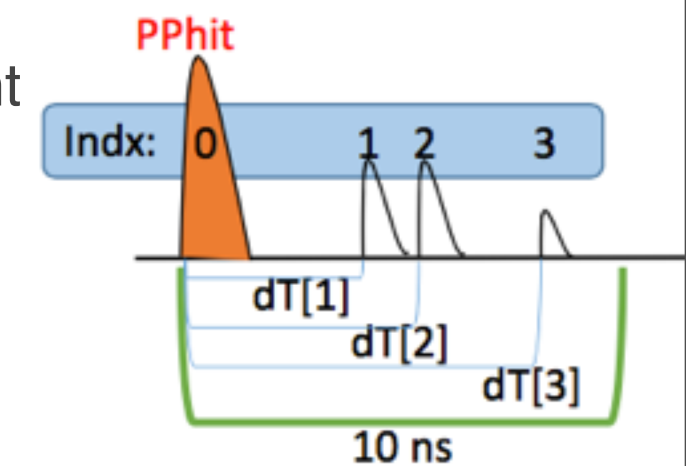


TOFPET performance : low energy contribution

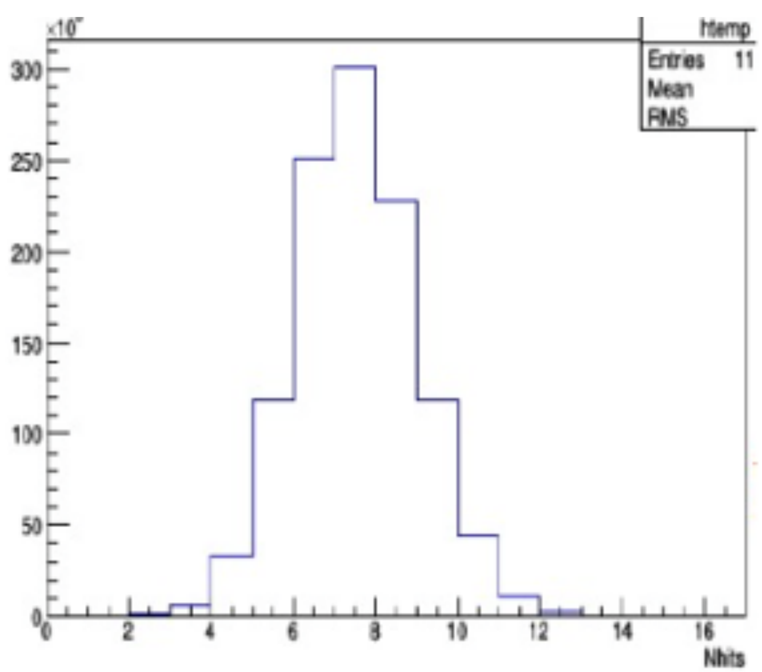


Dedicated analysis on “coincidence events” :

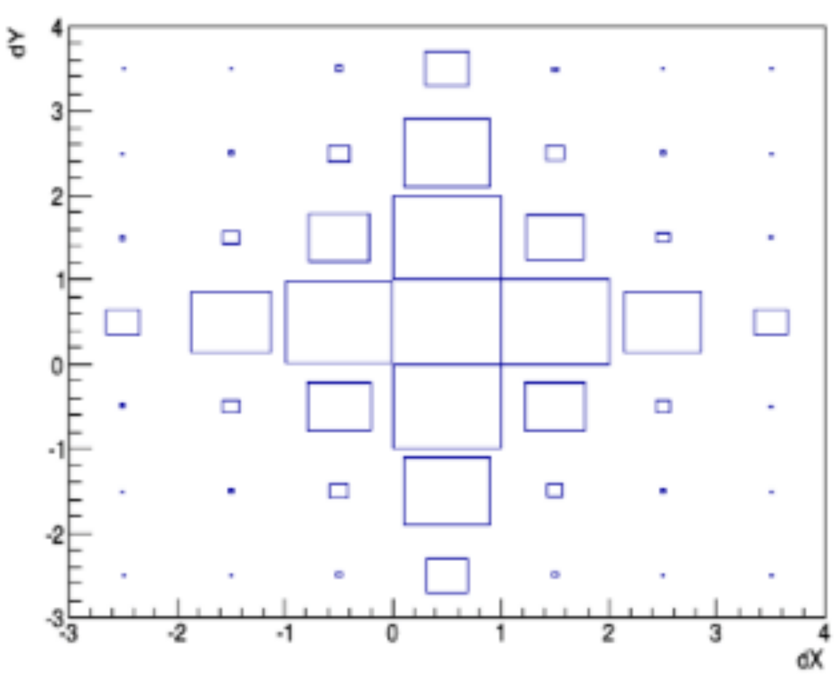
- 10 ns duration coincidence window
- within the same matrix
- started by a photopeak event



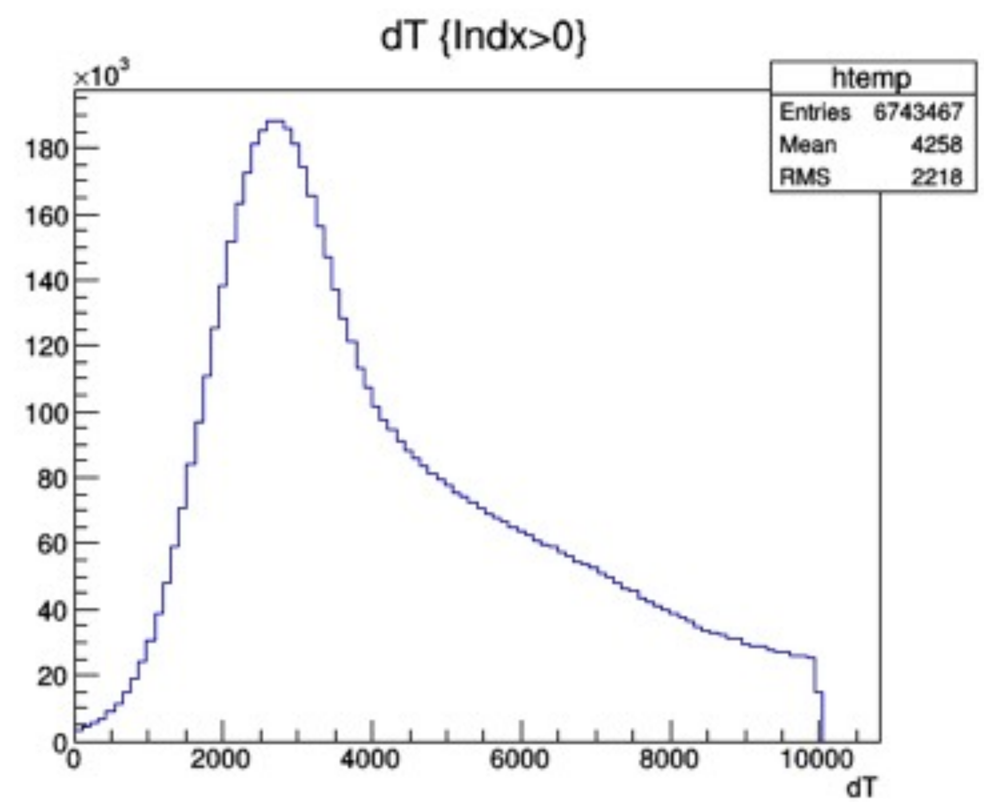
Low Energy contribution :
due to a
cross talk effect in the crystal matrix



Average nr of hits **<N>~7**

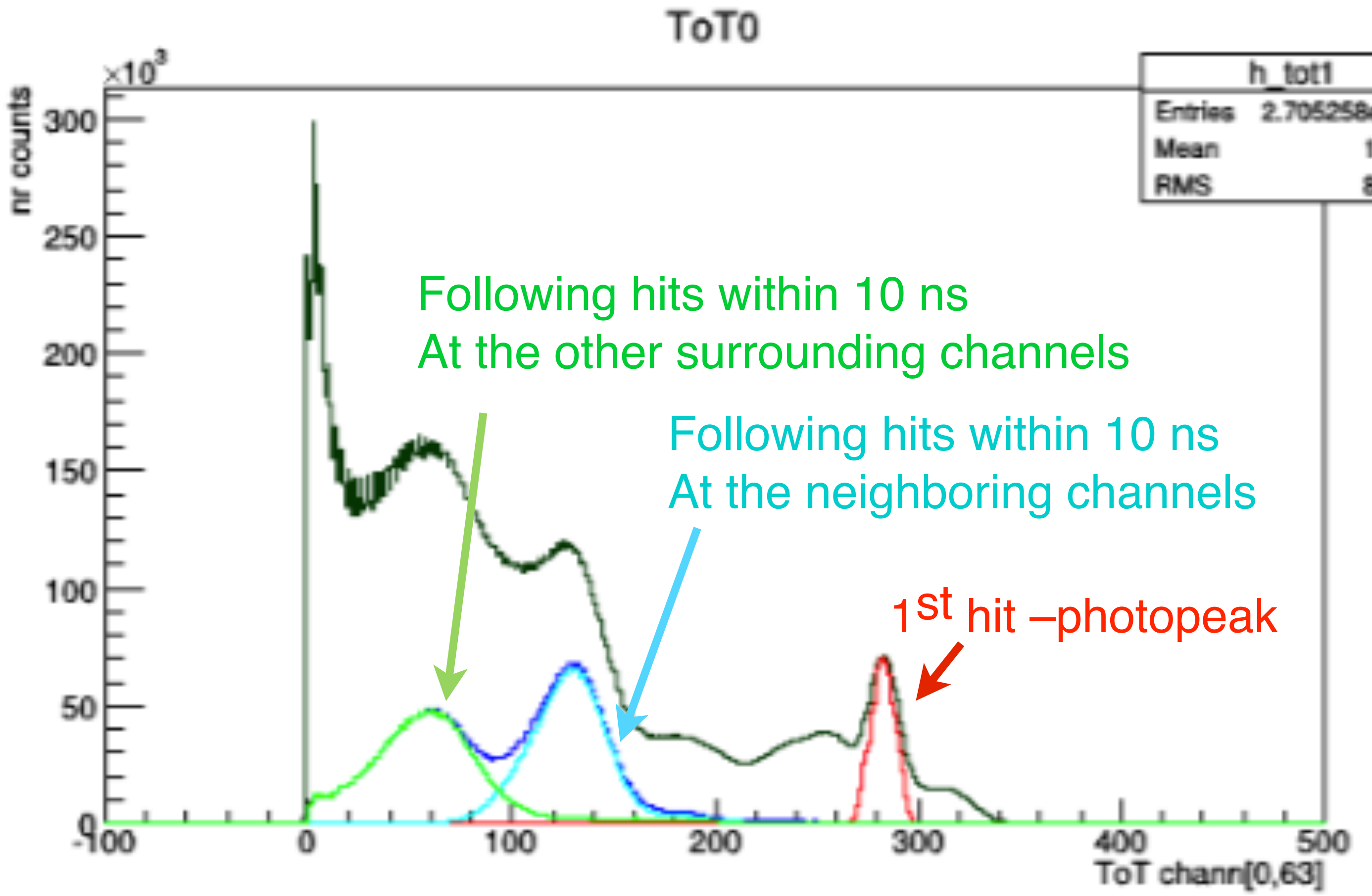


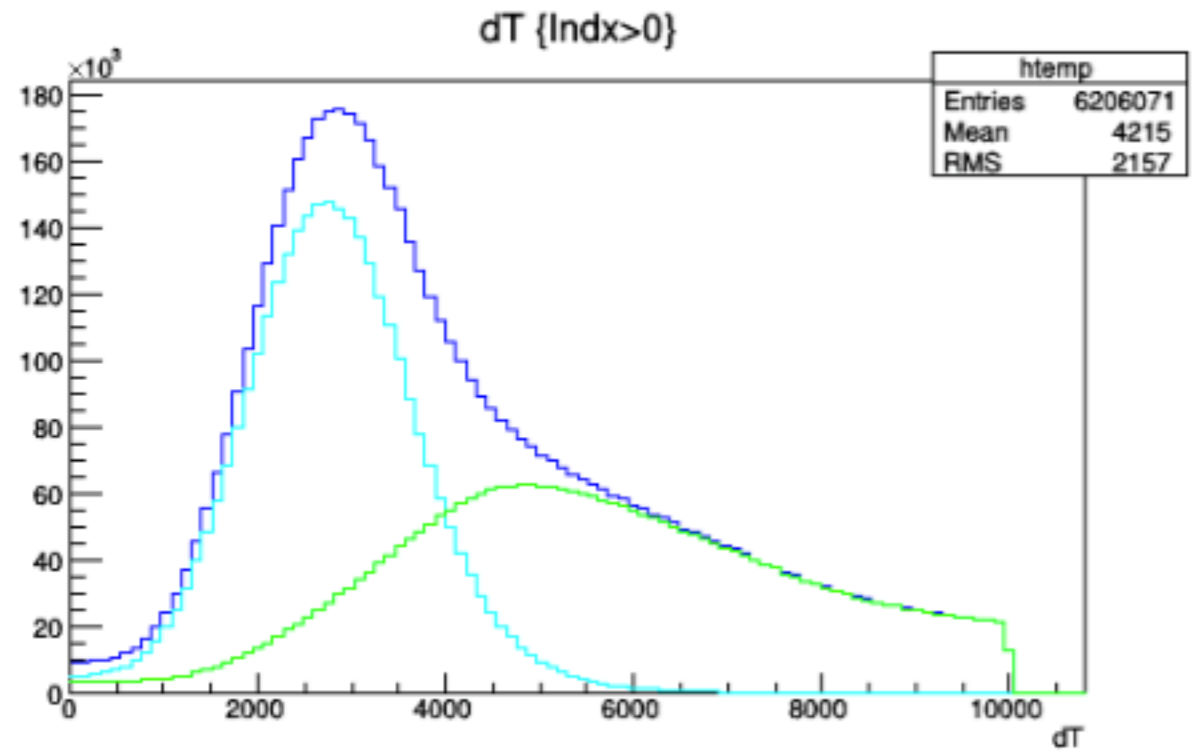
Geometrical correlation
direct neighbors
neighbors to neighbors

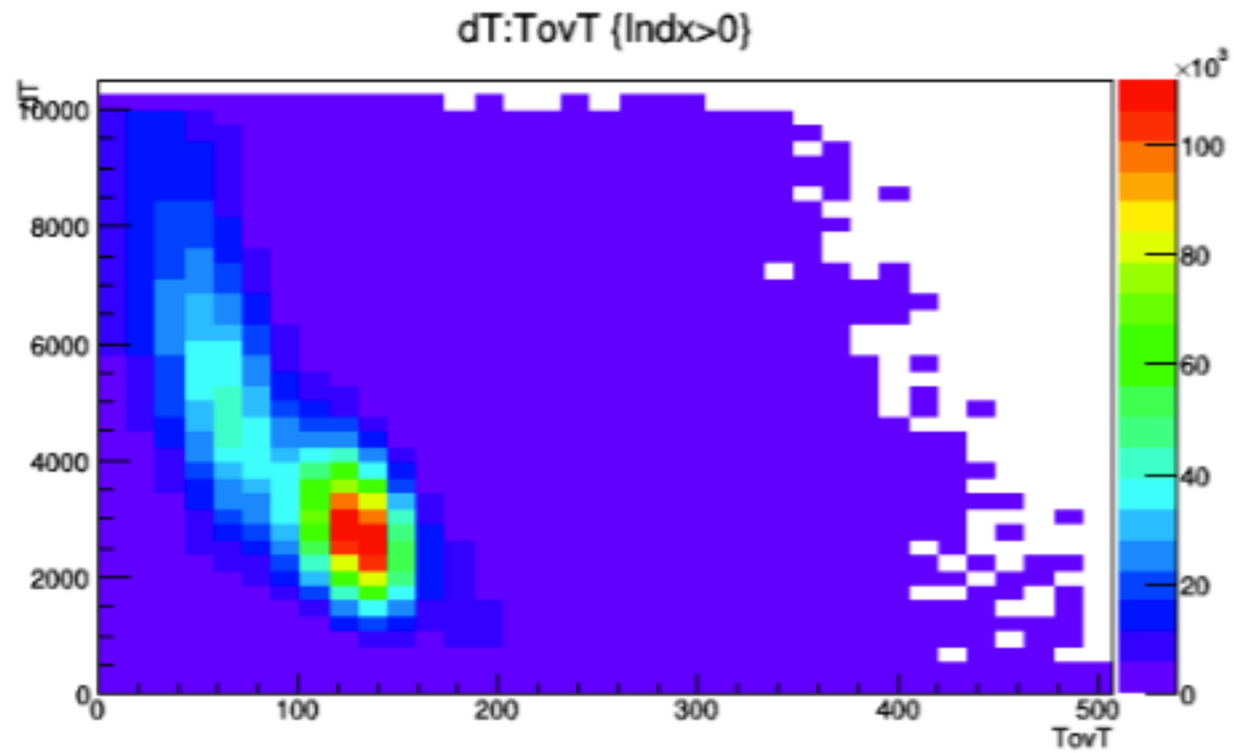


Time difference wrt photopeak hit

TOFPET performance : low energy contribution







Low energy contribution

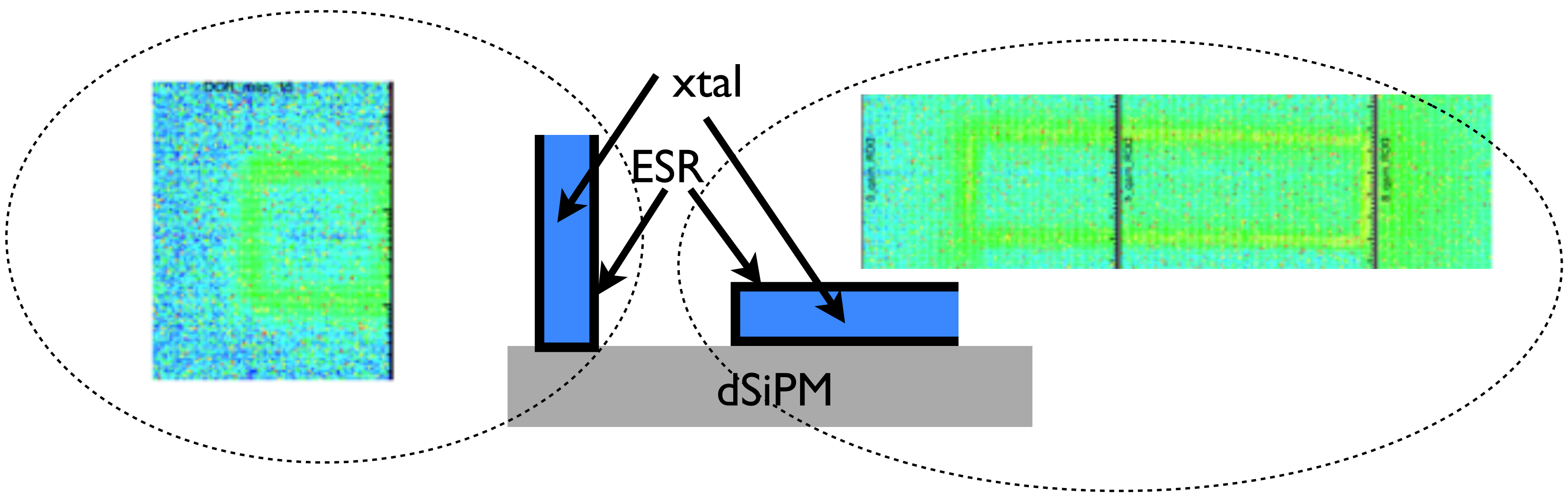
=> There is **LIGHT CORRELATED WITH THE PHOTOPEAK EVENTS** everywhere in the matrix

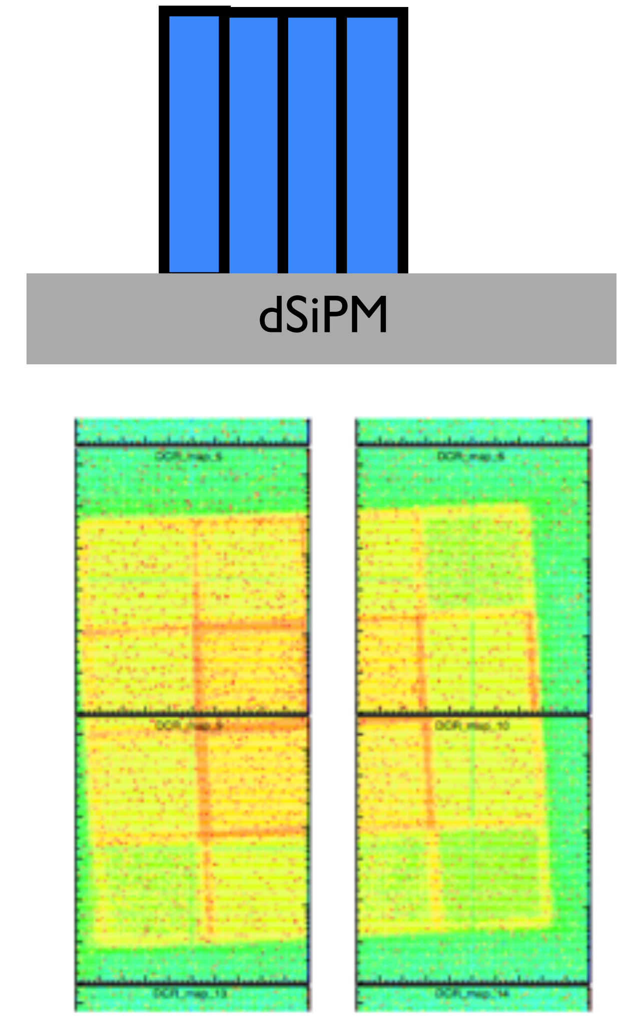
Where does it come from?

- **Escaping by the ESR (non-continuous) wrapping**

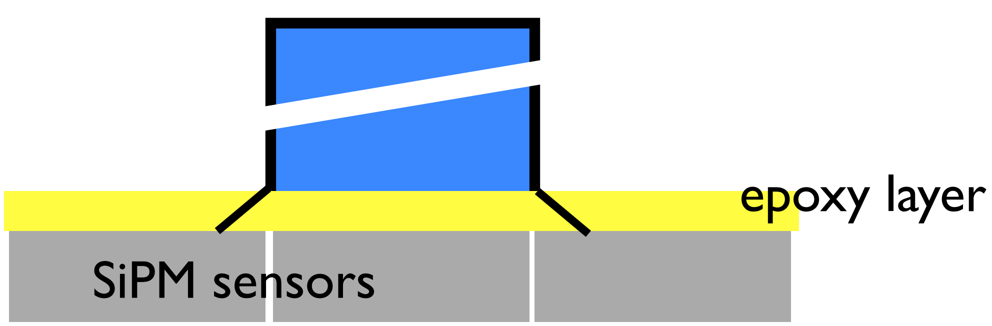
  by DSiPM (Philips) "dark count maps"

  obtained with crystals on the DSiPM surface and 22Na source





- **SiPM epoxy thickness [also modeled in simulations!]**

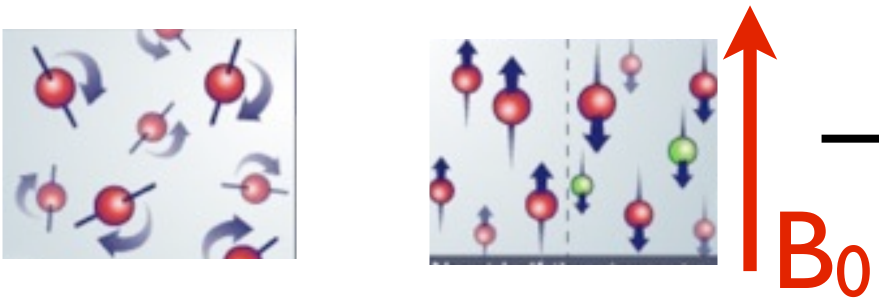


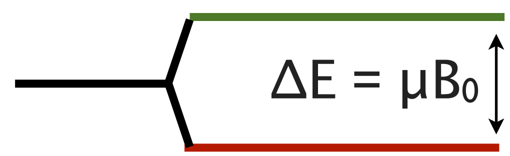
- **cross-talk between SiPM channels of the array (not related with the crystals) ?**

Magnetic Resonance Imaging (MRI)

- physics basis : **Nuclear Magnetic Resonance (NMR) :** absorption and re-emission of energy by nuclei at their own resonance frequency

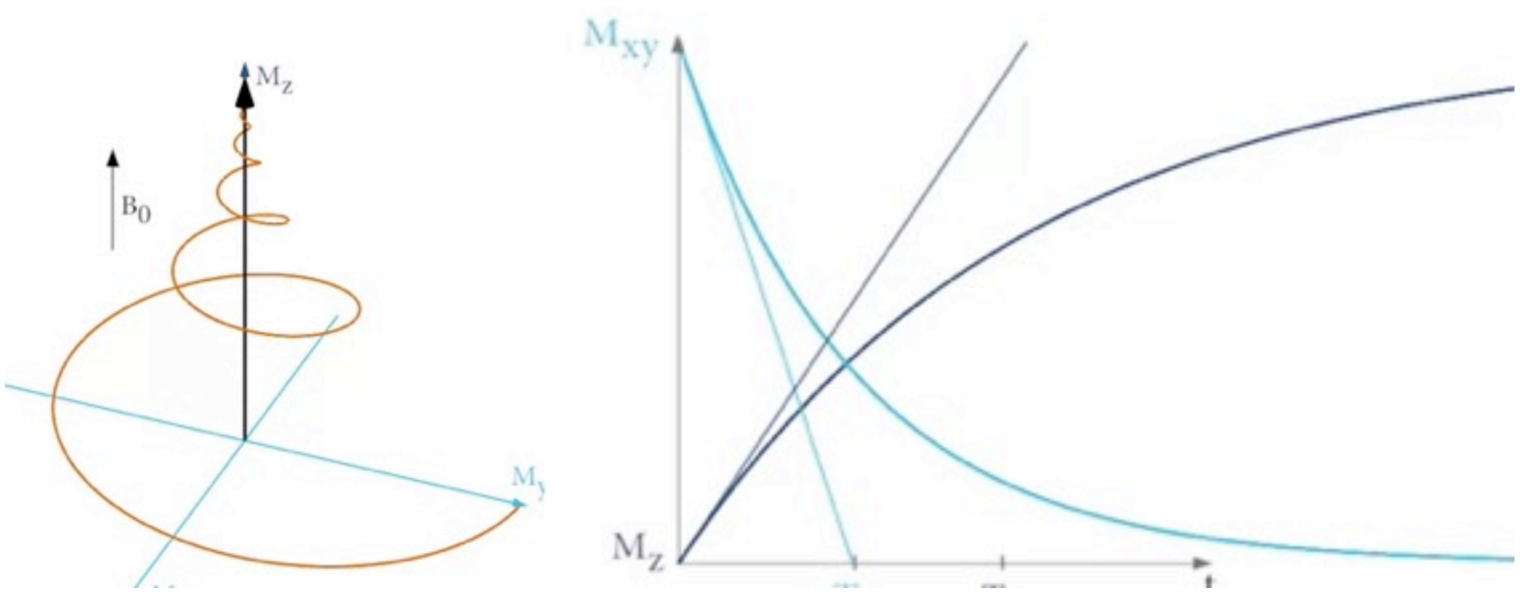
- **H** : most abundant element in the body => primary focus of MRI: **H spins**



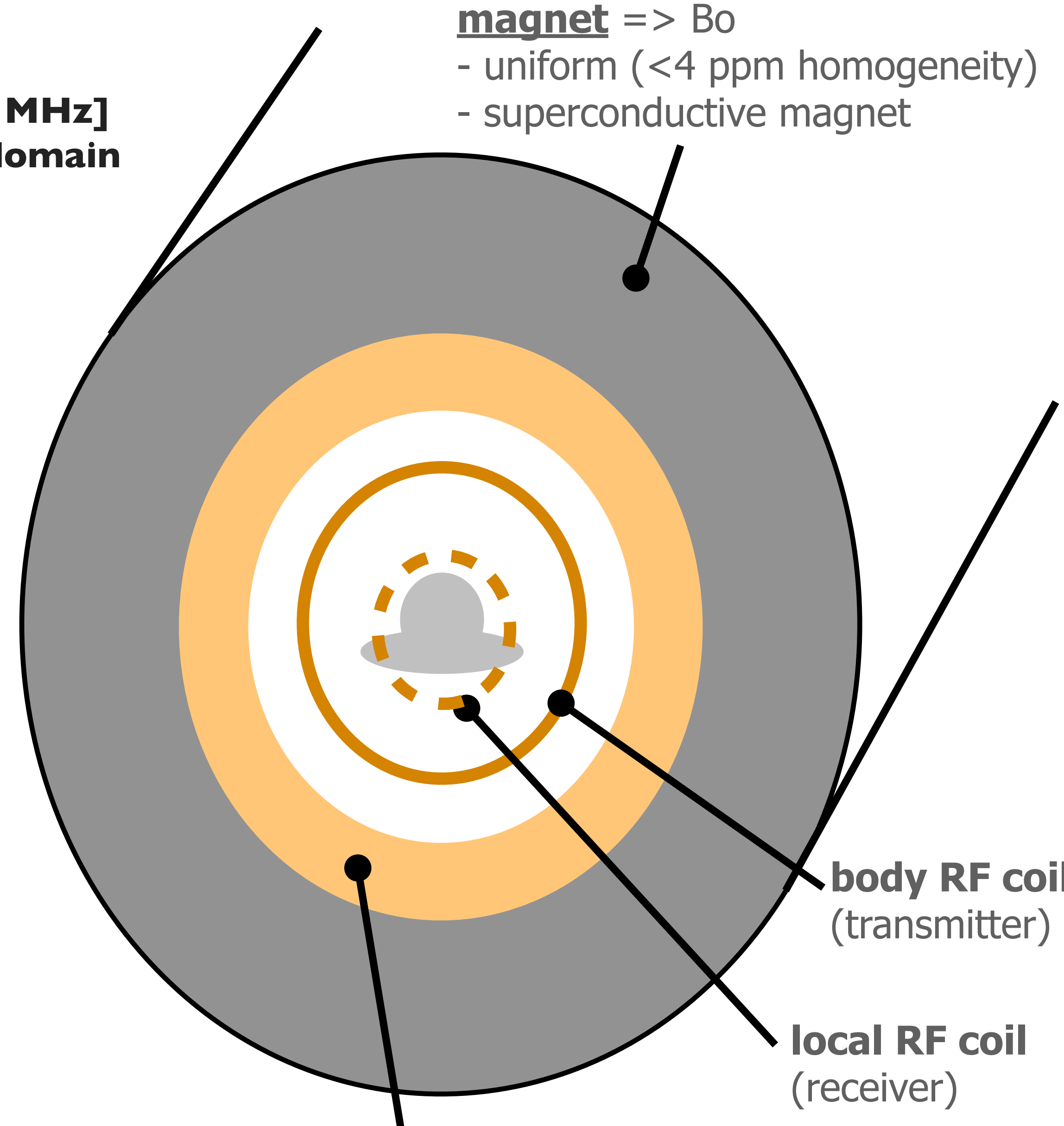


[~ 100 MHz]
i.e RF domain

- B_0 => net magnetization M_0 (prop. to p density) //B_0
- RF on => Spin Flip => Transverse magnetization
- RF off => relaxation [T_1, T_2 time const]



M_0 , T_1, T_2 are tissue dipendent !!!



result: map of local transfer magnetization => morphological

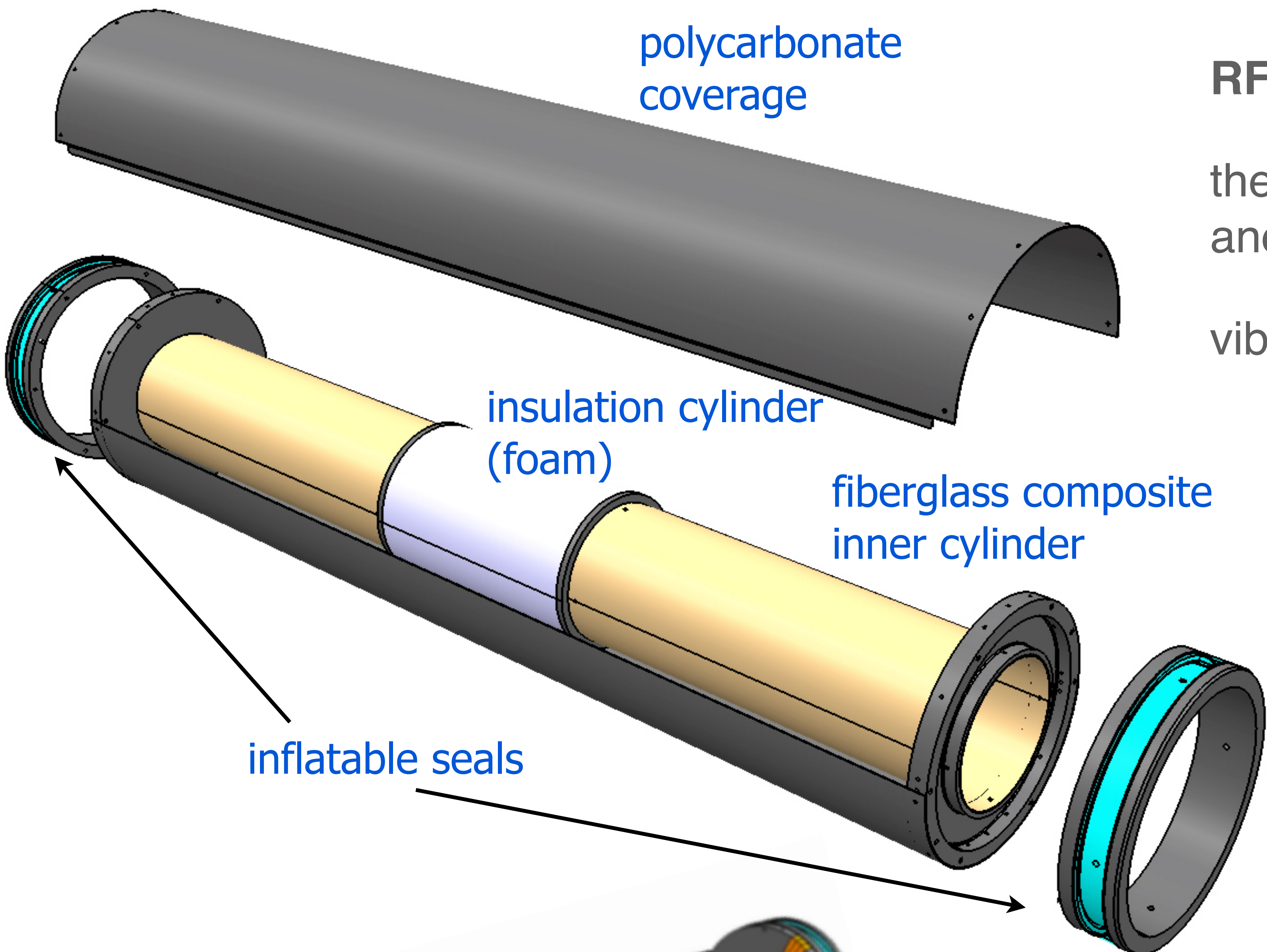
Mechanics for the insert

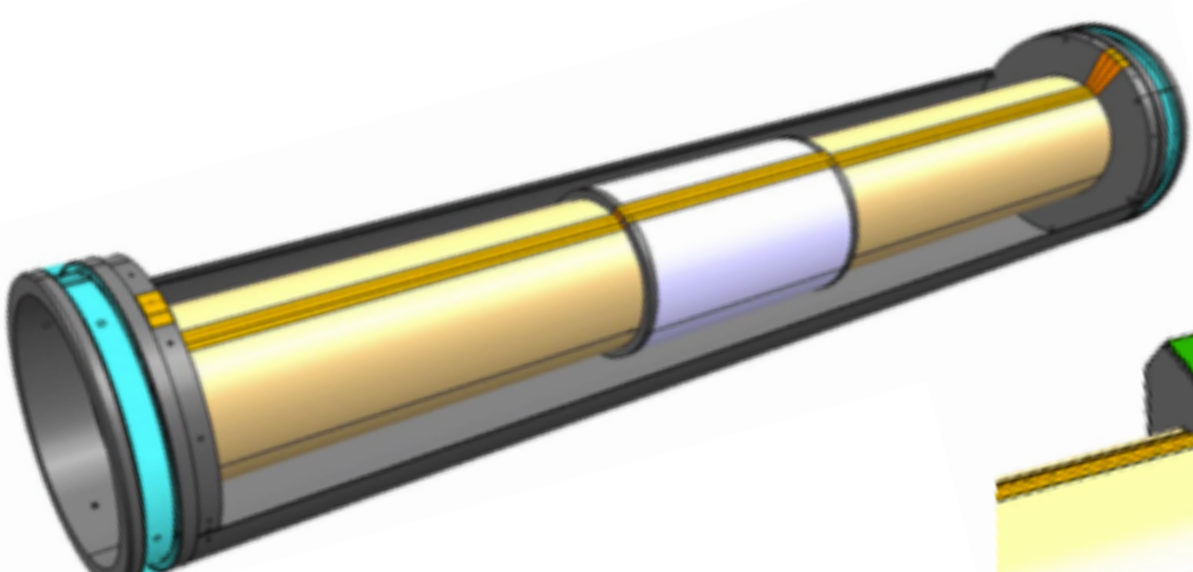
mechanical structure

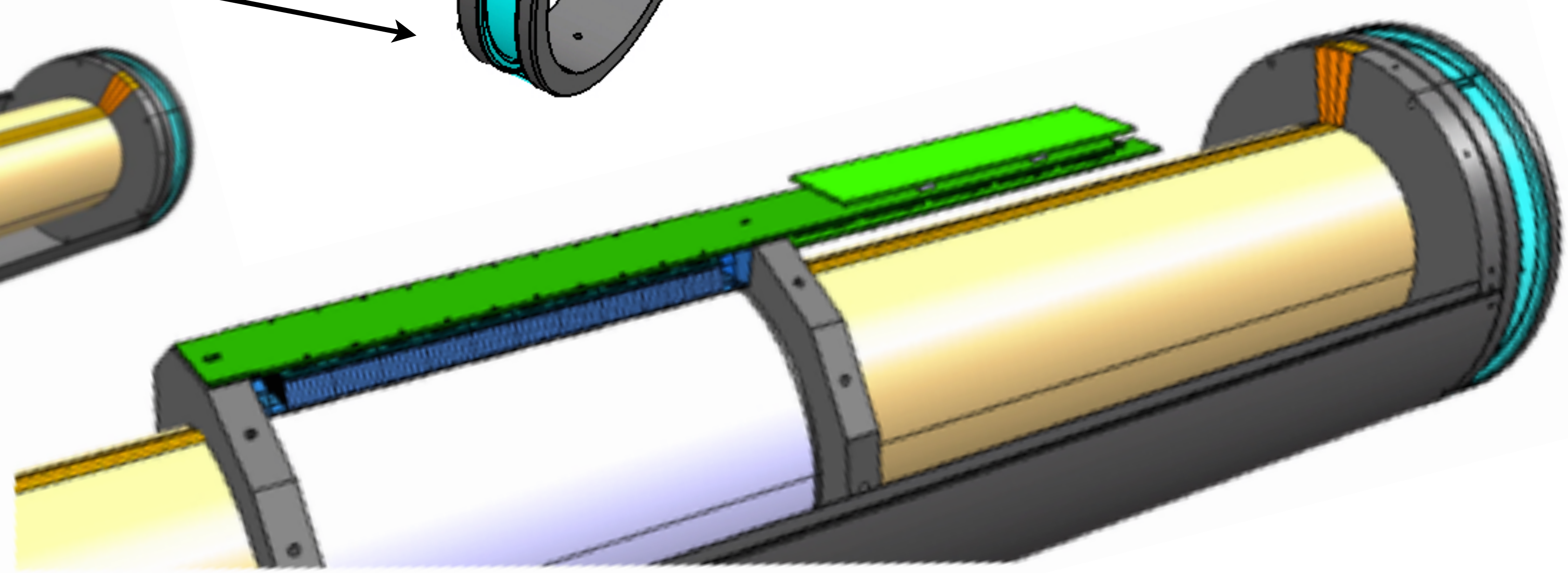
RF shielding (copper tape strips)

thermal insulation btw xtals/SiPM and animal

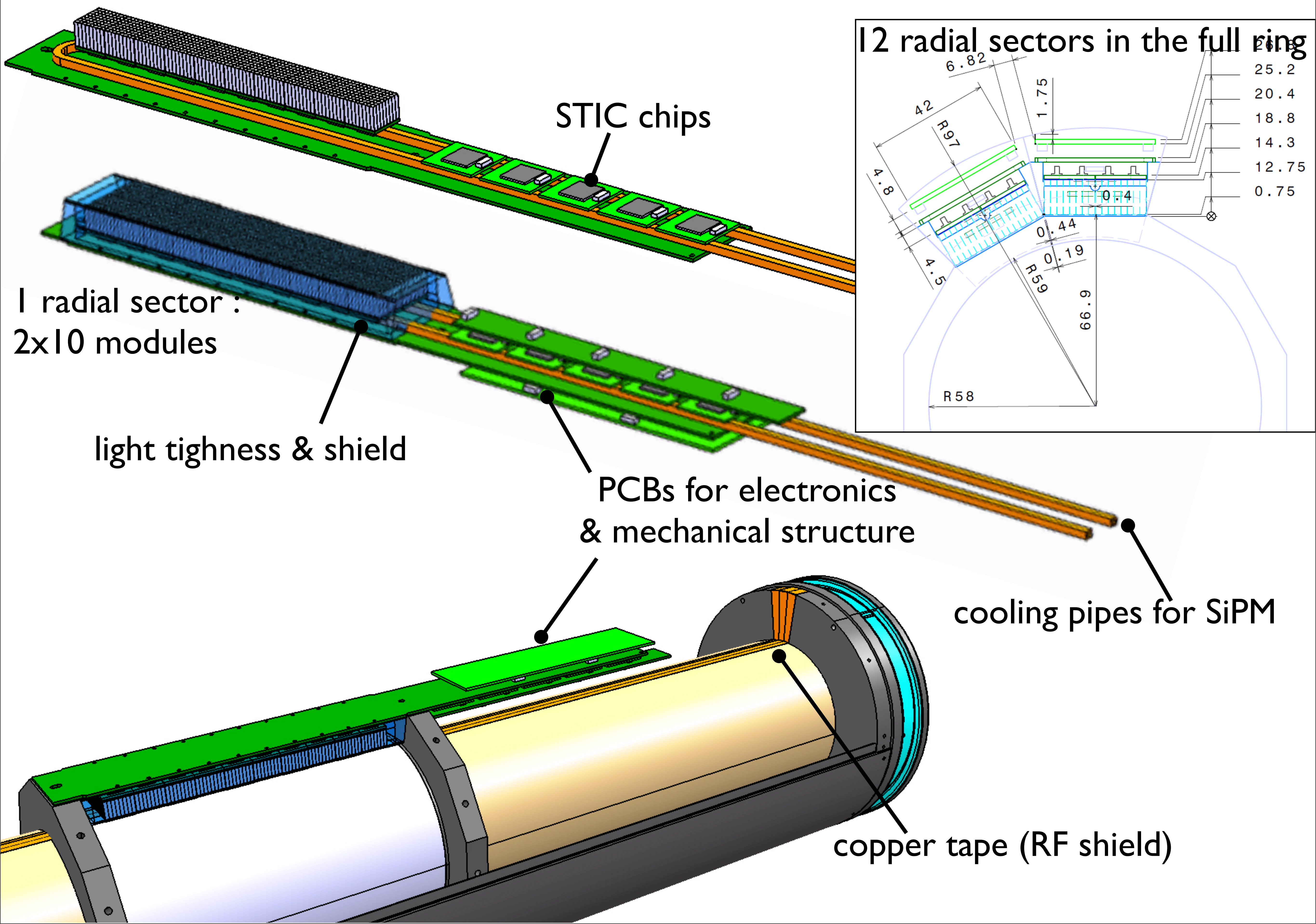
vibration absorption



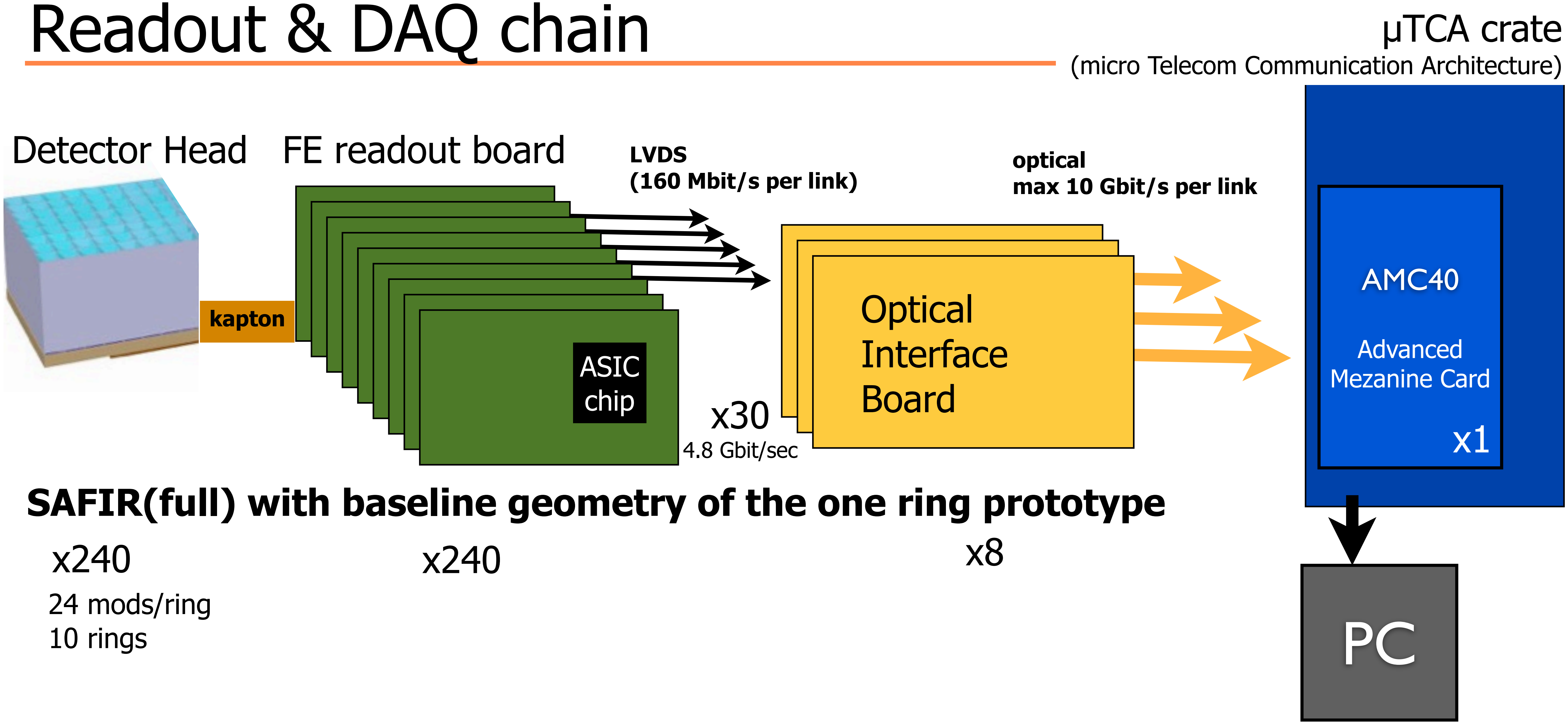


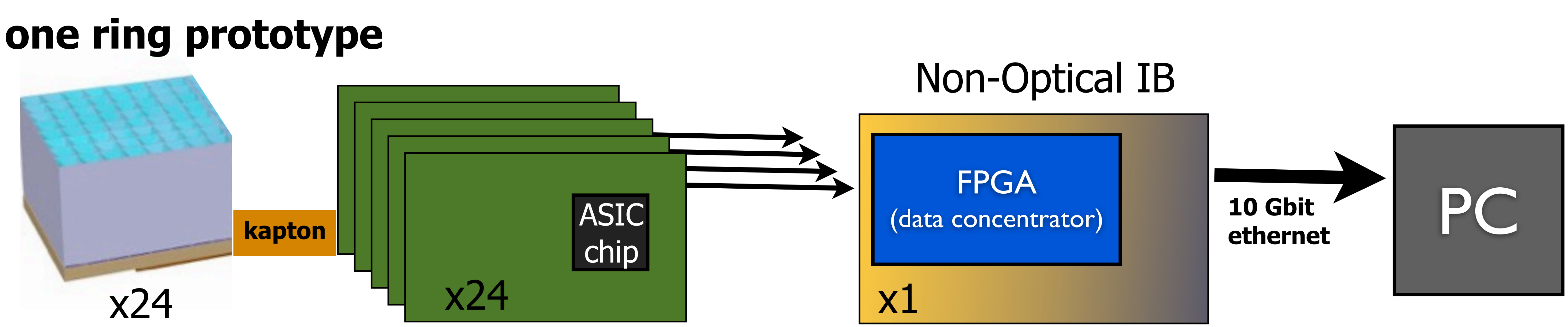


Extension of the prototype (STIC RO) to a full system



Readout & DAQ chain





SINOGRAM

representation in (s,Φ) coordinates of all the LOR emitted from a given point in the FOV

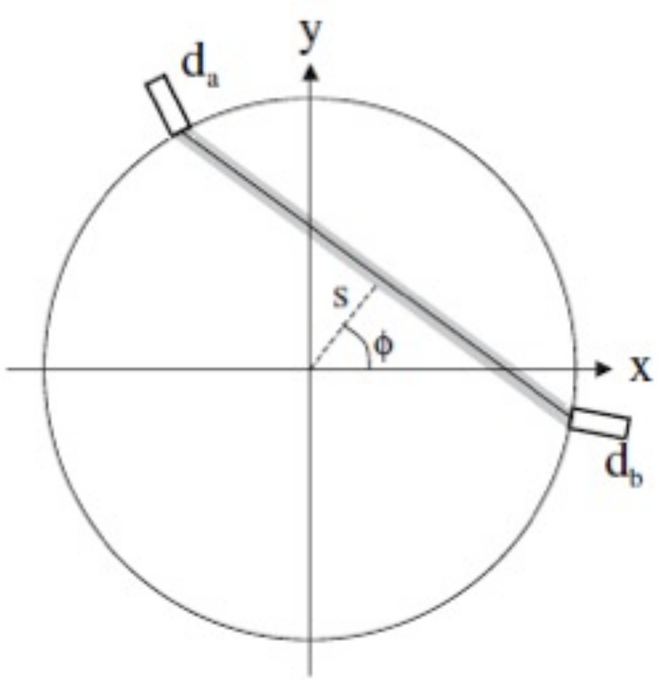
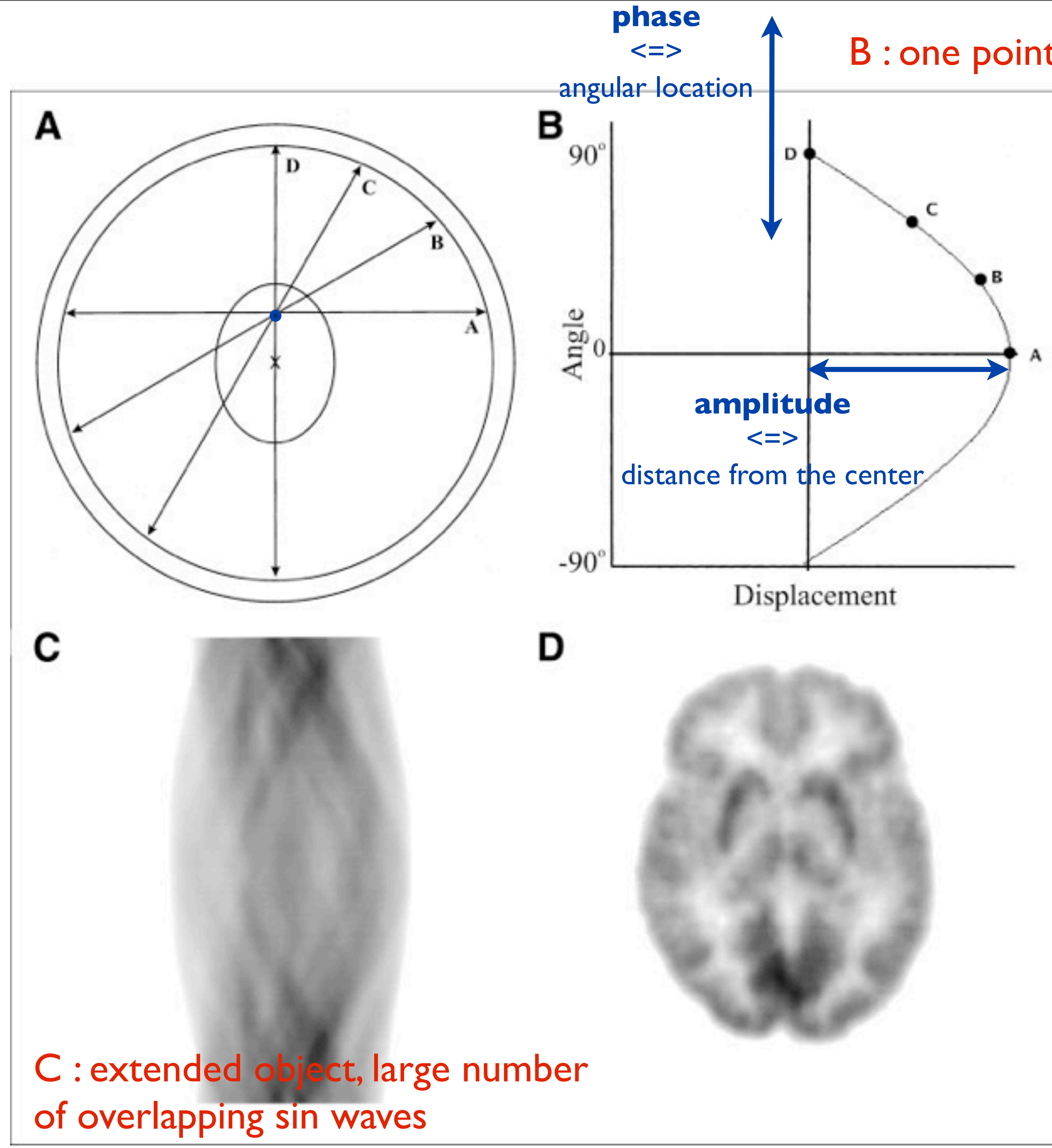
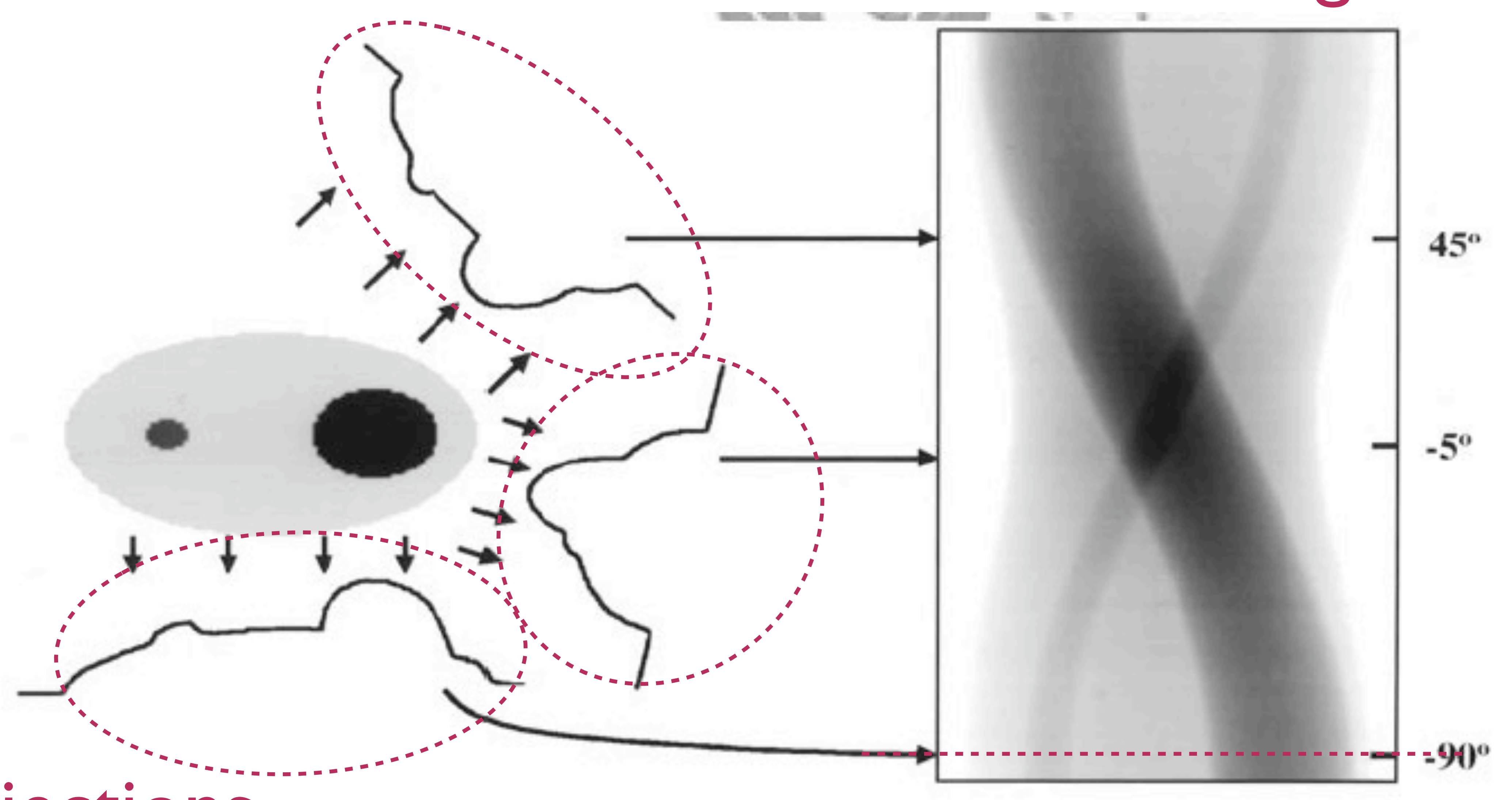


Figure 4.1. Schematic representation of a ring scanner. A tube of response between two detectors d_a and d_b is represented in grey with the corresponding LOR, which connects the center of the front face of the two detectors. The sinogram variables s and ϕ define the location and orientation of the LOR.



Frederic H. Fahey, J. Nucl. Med. Technol. June 1, 2002 vol. 30 no. 2

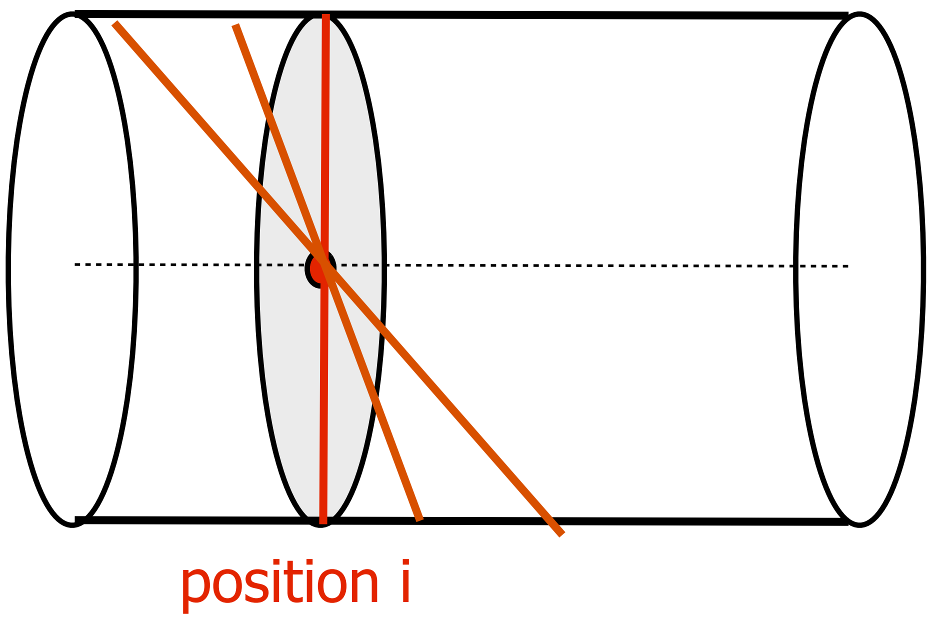
sinogram

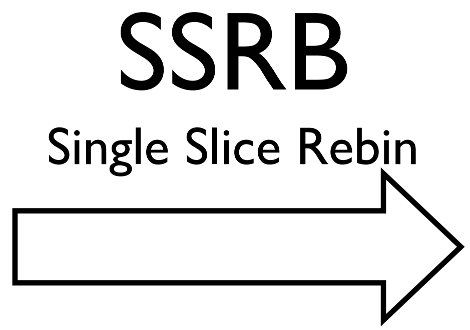


projections

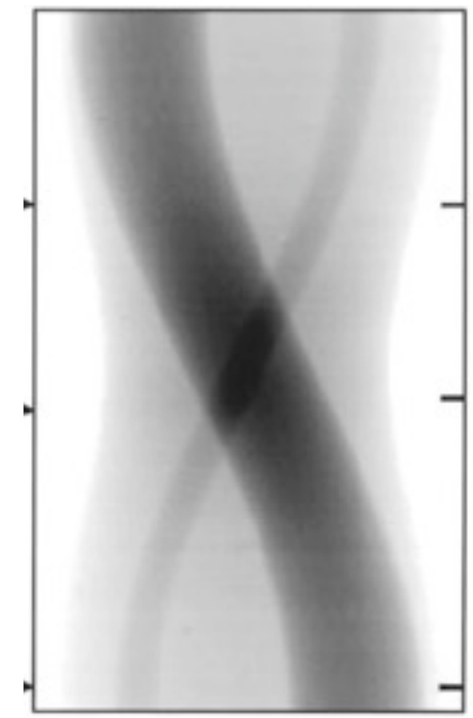
each row in a sinogram is the projection along the angle associated with that row

Single Slice Rebin [SSRB]





1! sinograms for each i position

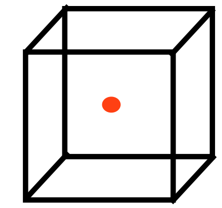


- for each source position (i) :
  the full set of sinograms is rebinned to a single 2D sinogram
  approximation - but acceptable near the center of the scanner and for small apertures

Spatial resolution - NEMA prescription

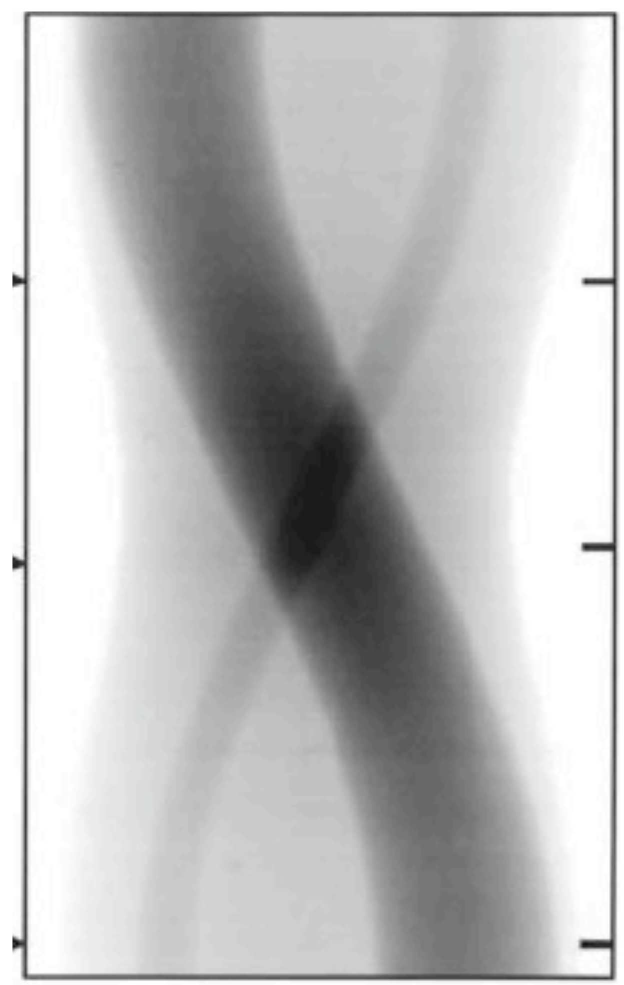
- phantom : $1cm^3$ acrylic with 22-Na point source at the center
- low activity (Act = 100 kBq)

- moved axially / transaxially (5 mm steps)



- for each source position (i) :

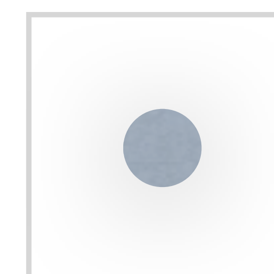
  a full set of sinograms for each axial position (accounting for all oblique configurations) rebinned into one single sinogram [SSRB]



1! sinograms for each i position

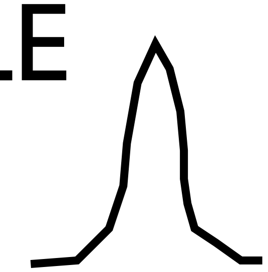
FBP

Filtered back projection



LINE PROFILE

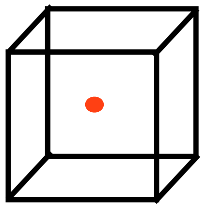
=> Resolutions



Sensitivity - NEMA prescription

Sensitivity = N_detected_coincs / N_annihilations

- phantom : 1cm^3 acrylic with 22-Na point source at the center
- low activity (Act = 100 kBq)



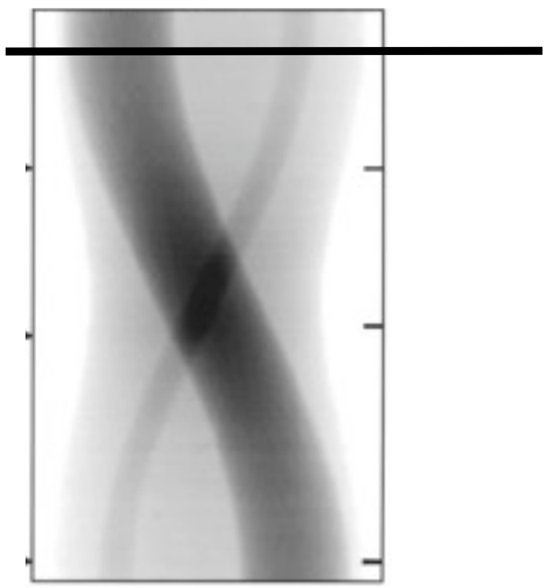
- moved axially over the full FOV

- for each source position (i) :
  10000 **true** coincidences detected
  acquisition duration : time t_i
  N_annihilations (i) = Act * BR(=0.90) * t_i

- **N_detected_coincs** : through reconstructed sinograms

- for each source position (i) :

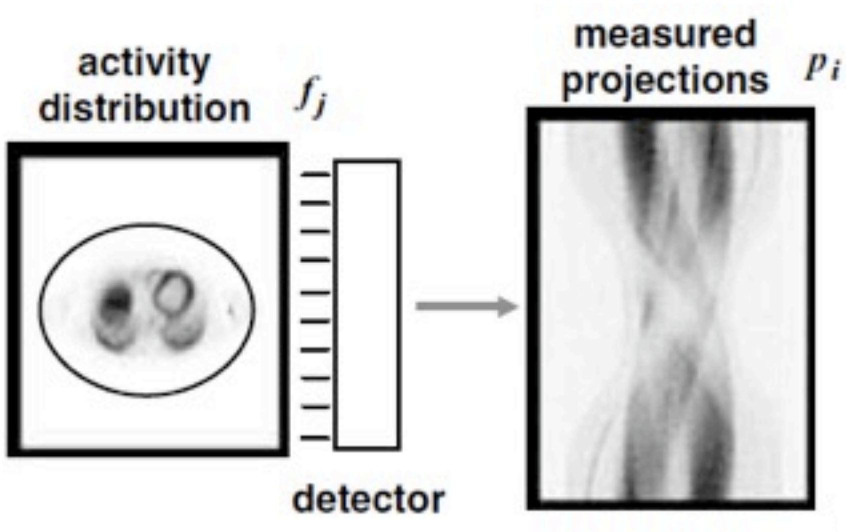
  a full set of sinograms
  for each axial position
  (accounting for all
  oblique configurations)
  rebinned into one single
  sinogram [SSRB]



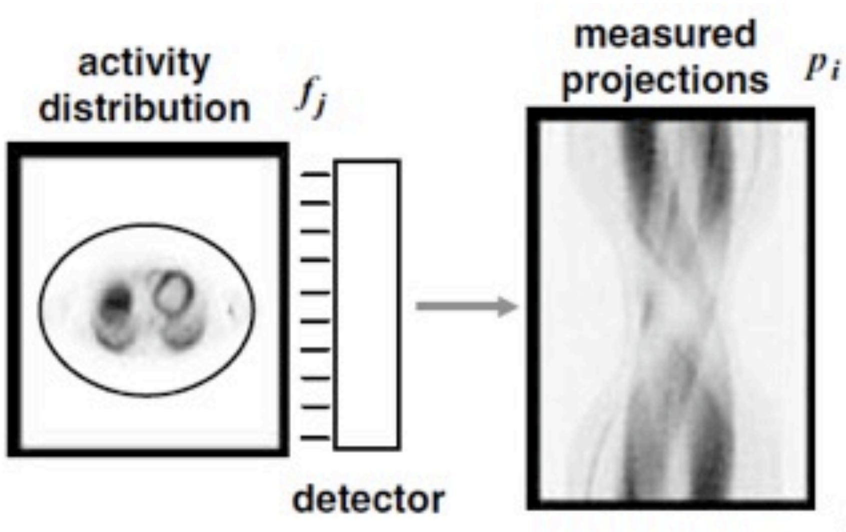
row j :
  find max
  sum counts around max (1cm)

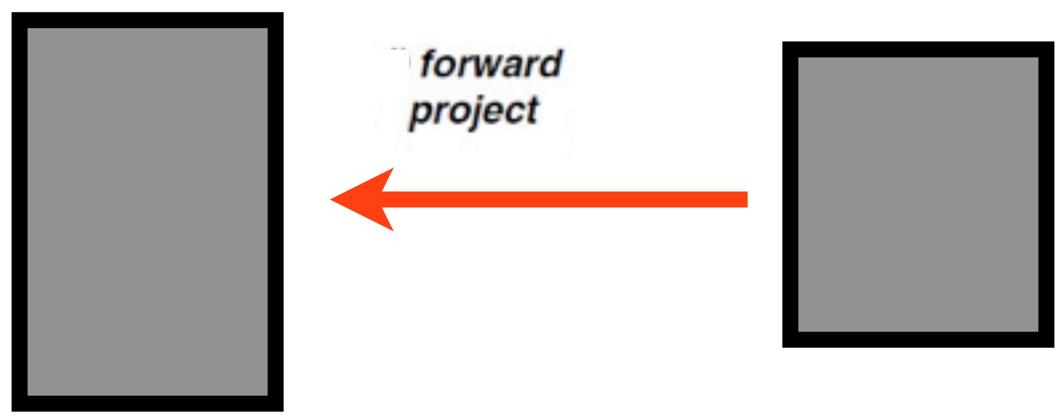
N_detected (i) = Sum_j counts

Iterative reconstruction method



Iterative reconstruction method

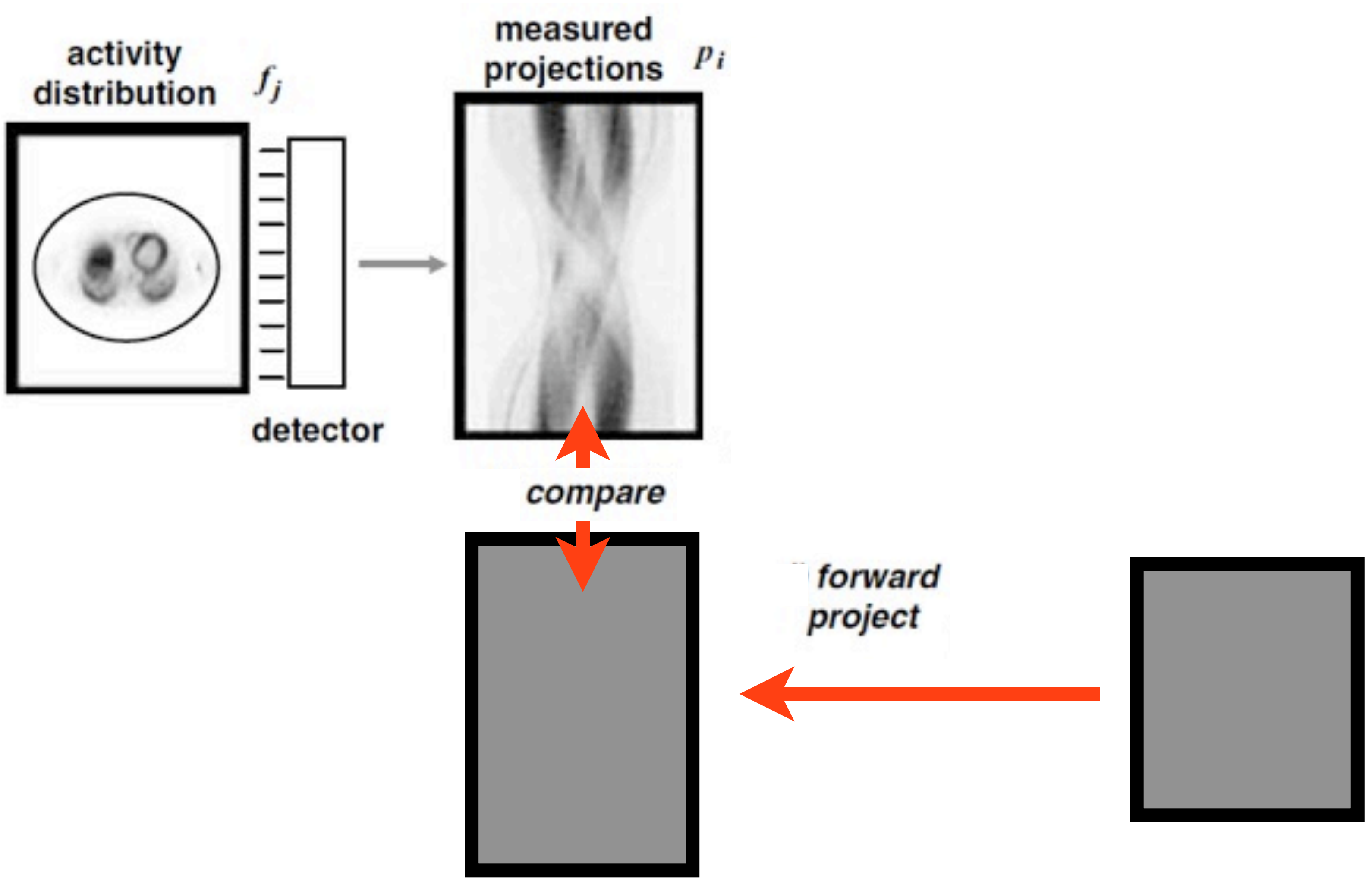




(1)
initial estimate of the
object count distribution
(typically: uniform)

(2)
obtain the projection that would
derive from such an object

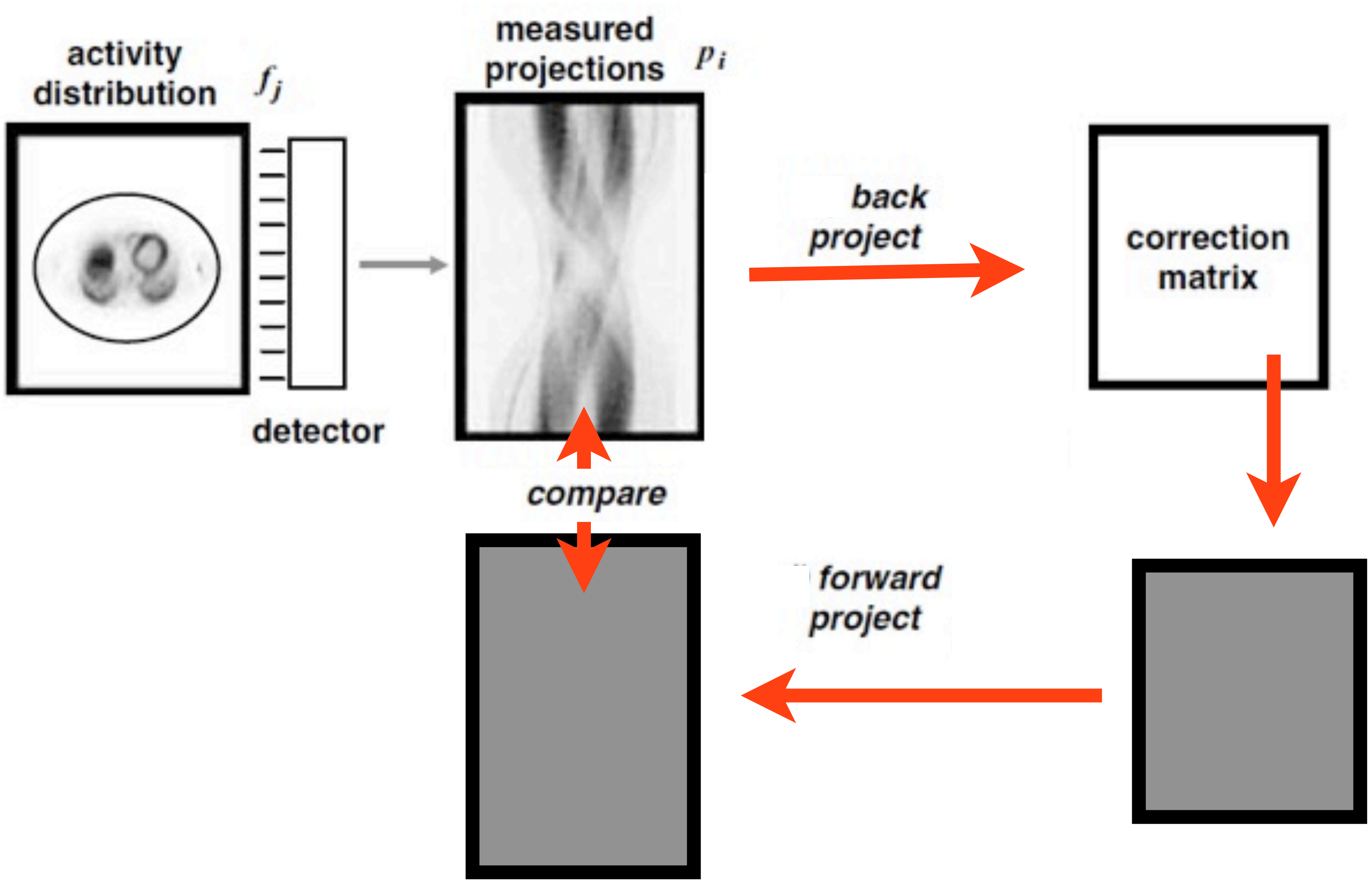
Iterative reconstruction method



(1)
initial estimate of the object count distribution (typically: uniform)

(2)
obtain the projection that would derive from such an object

Iterative reconstruction method

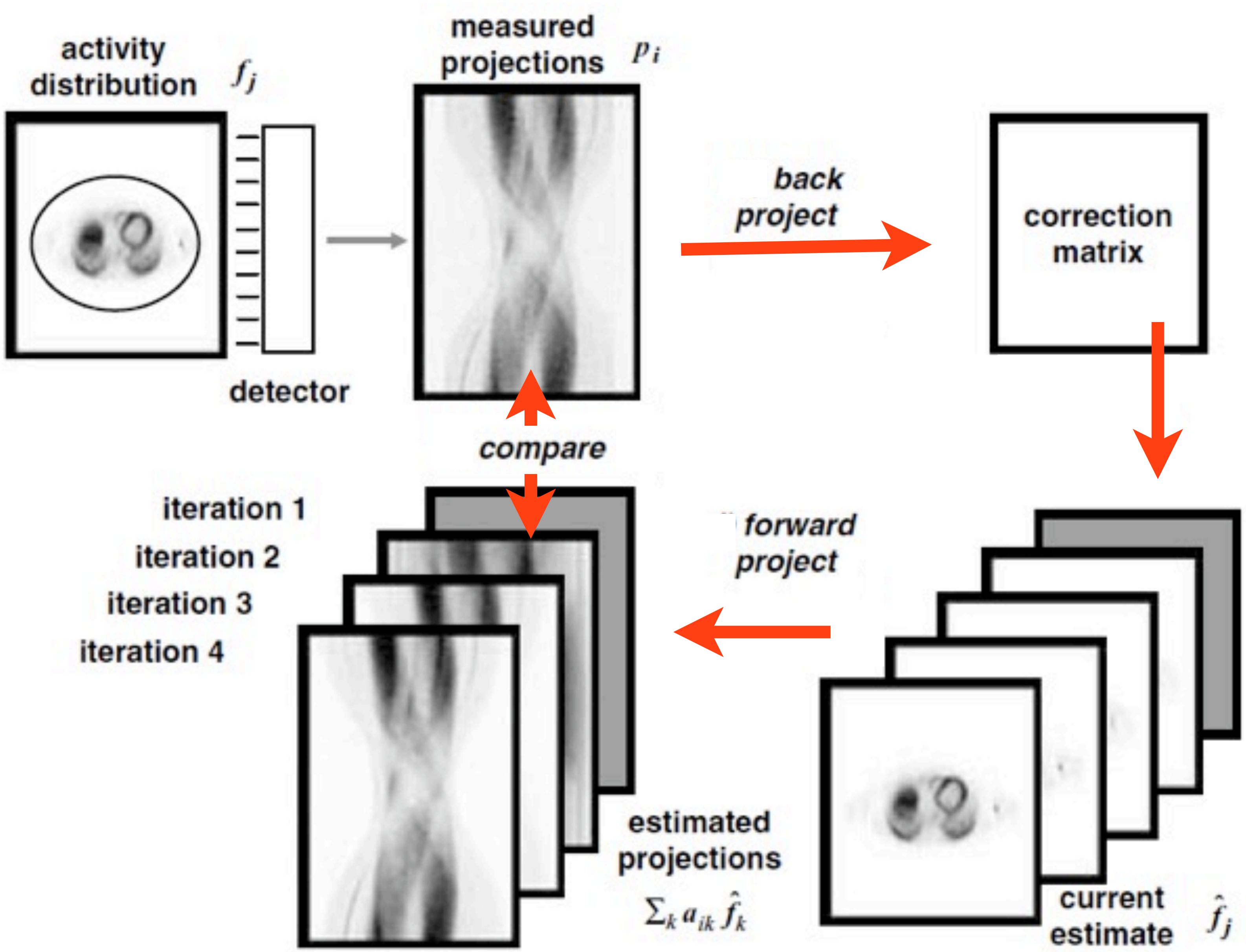


build up correction coefficients

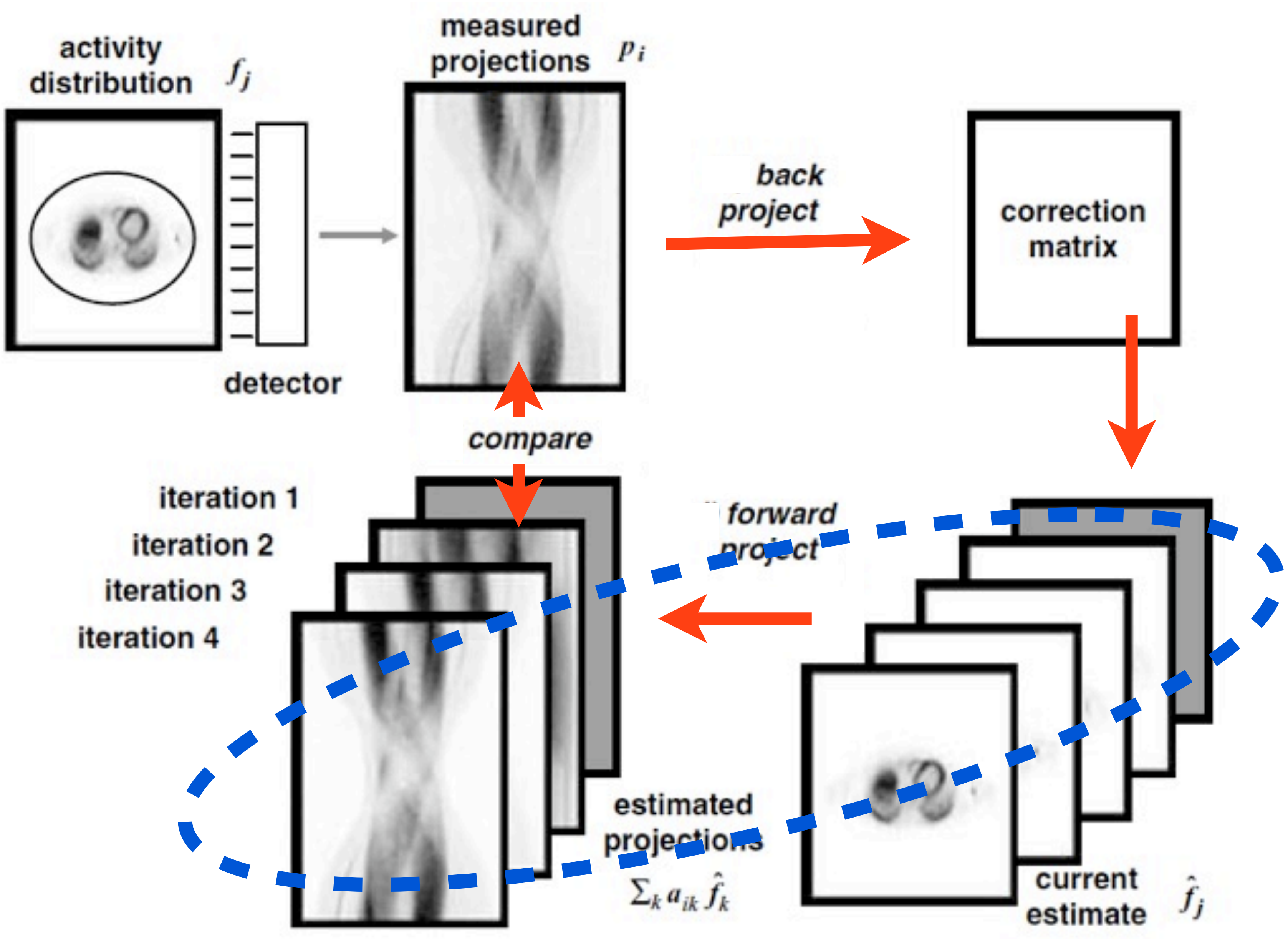
(1)
initial estimate of the object count distribution (typically: uniform)

(2)
obtain the projection that would derive from such an object

Iterative reconstruction method

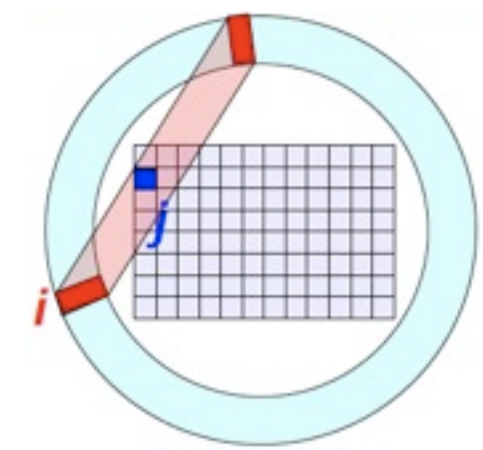


Iterative reconstruction method



requires a description of the physical model of emission and detection processes :

SYSTEM MATRIX Mij



probability of the activity in the j-voxel to be detected by the i-LOR

includes :
- **geometry** description
- **physics** (e.g. : attenuation)
- **variable fraction of the voxel** contributes to the counts
- **...**

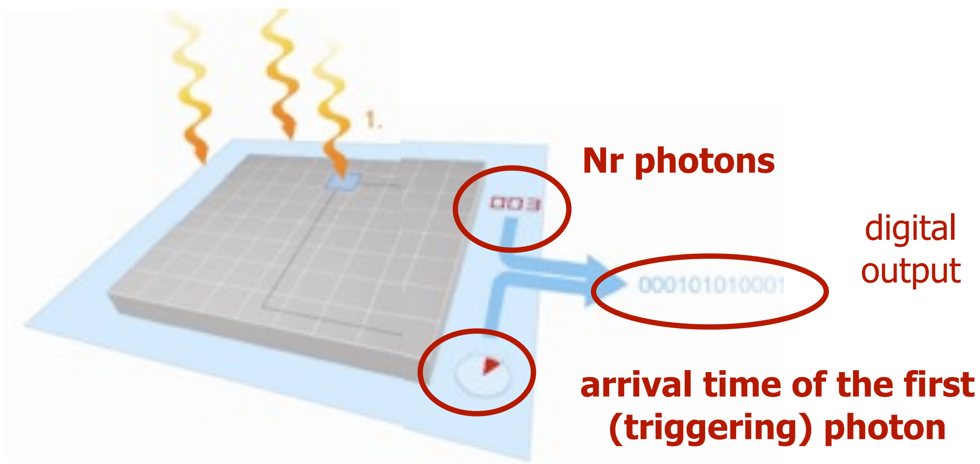
out of the many possible iterative methods **AX-PET** uses **ML-EM**

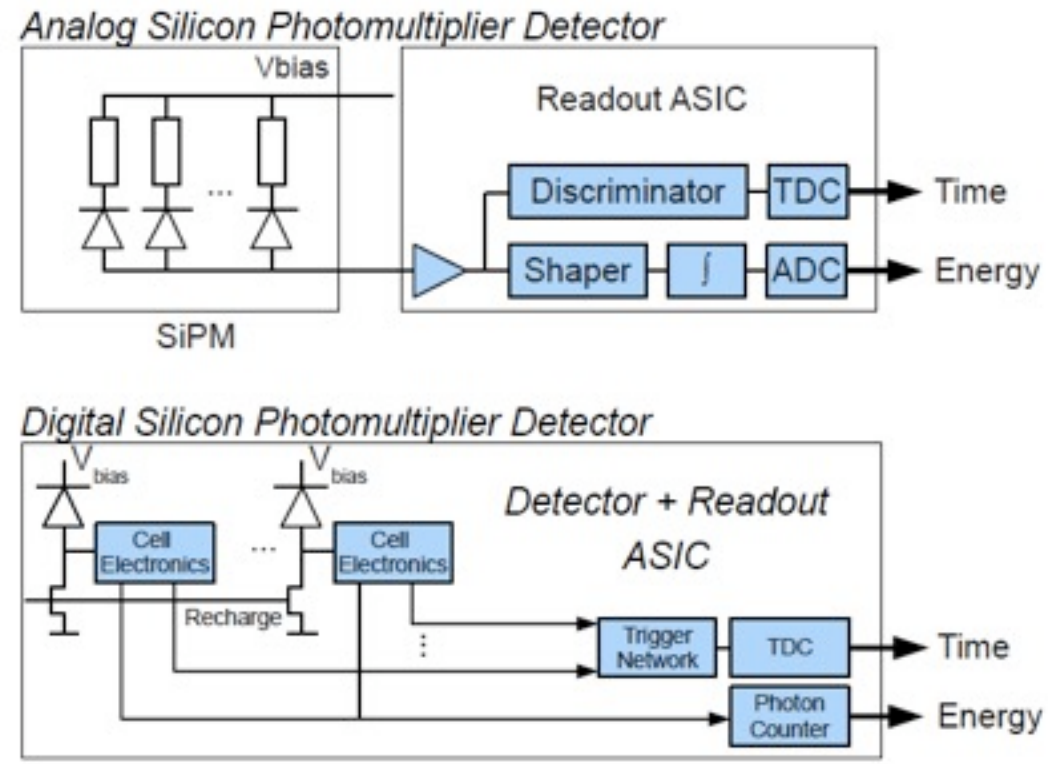
↙ **M**ax **L**ikelihood ↘ **E**xpectation **M**aximization

two steps per iteration :
(1) Expectation **step** : form the likelihood of any reconstructed image given the measured data
(2) Maximization **step** : find the image with the greatest likelihood

dSiPM : Digital SiPM (Philips)

- fully digital implementation of SiPM
- electronics on the same Si substrate as for the sensor
- on-board TDC (19.5 ps resolution)

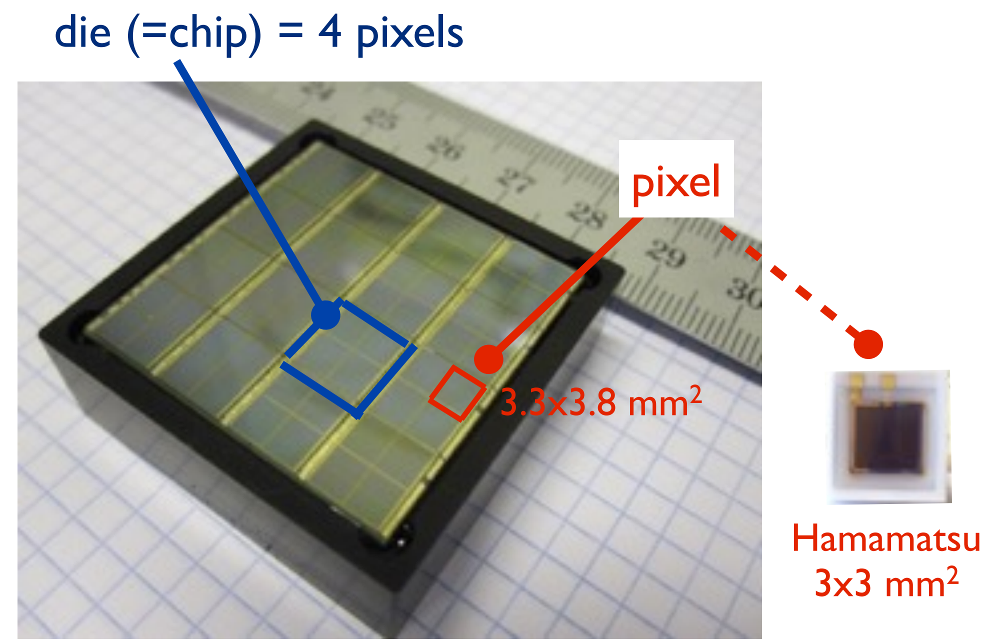




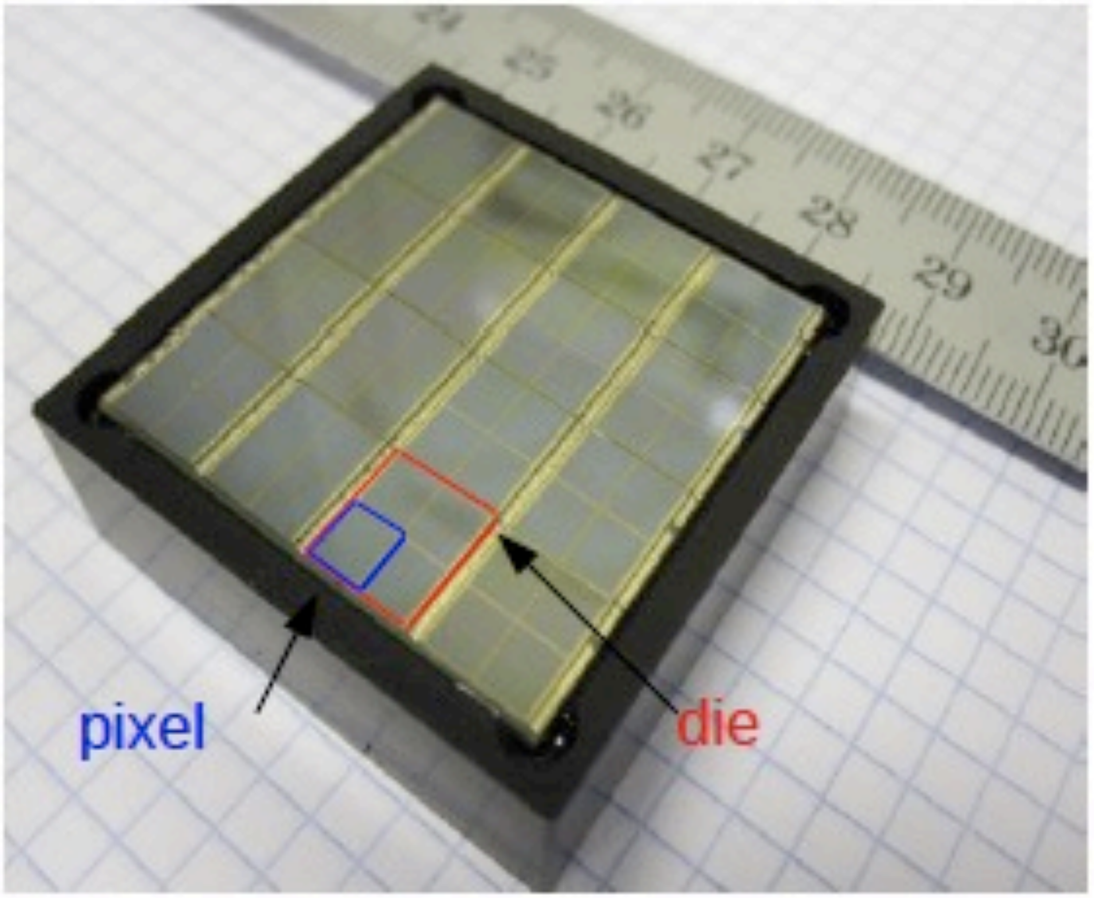
T. Frach

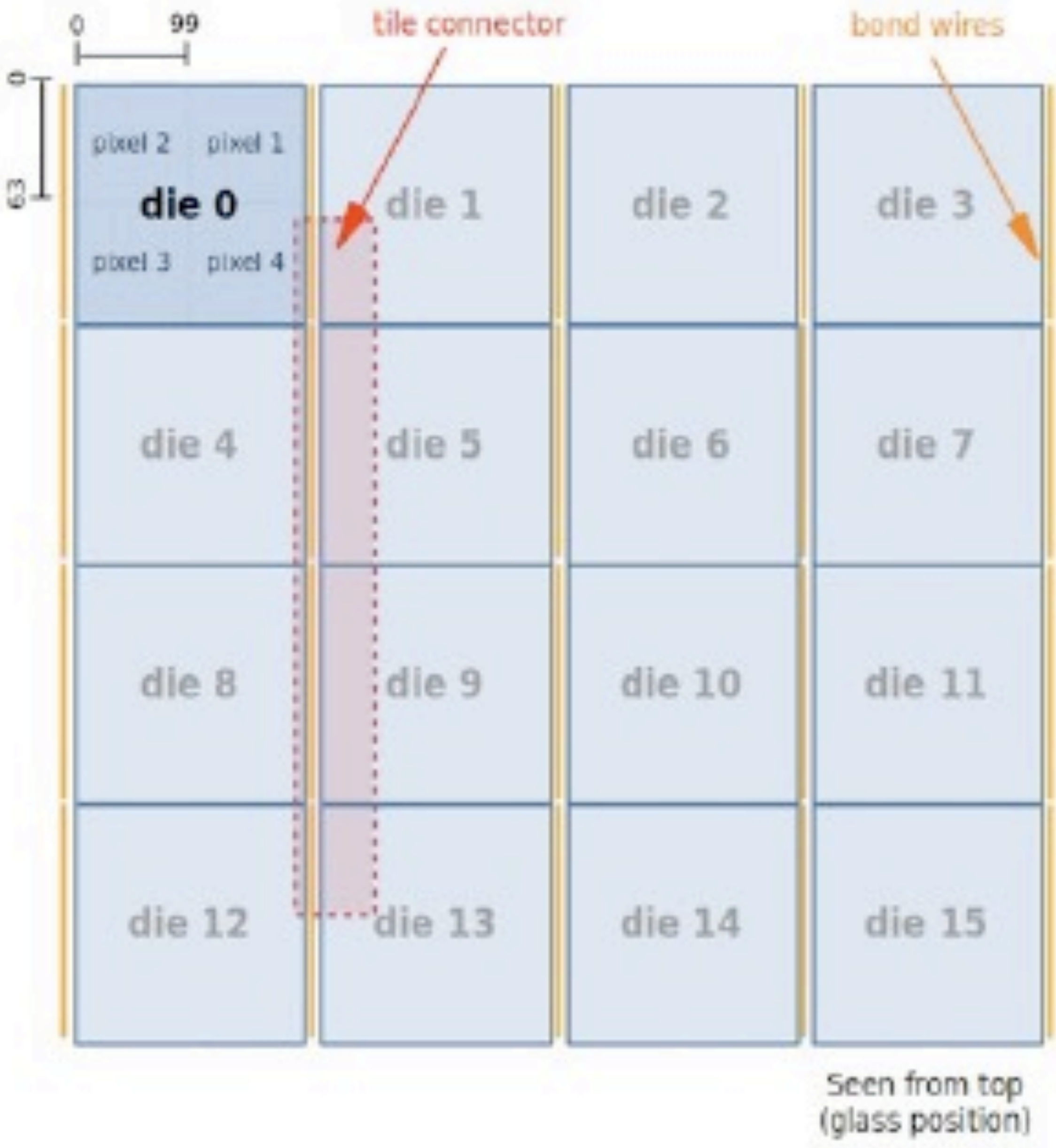
interest of dSiPM for PET applications :

- **High resolution timing information** => TOF-PET
- **Integration** (bias supply included, amplifier, TDC, photon counter)
- **Compactness**
- Early digitization of the output => **Low noise**
- Digital => **Temperature and gain stability less critical** wrt analogue
- Fast active quenching => no Afterpulses.
- Possibility to disable individual cells => **Reduction in the dark count rate** (but lower PDE)
- MRI compatible



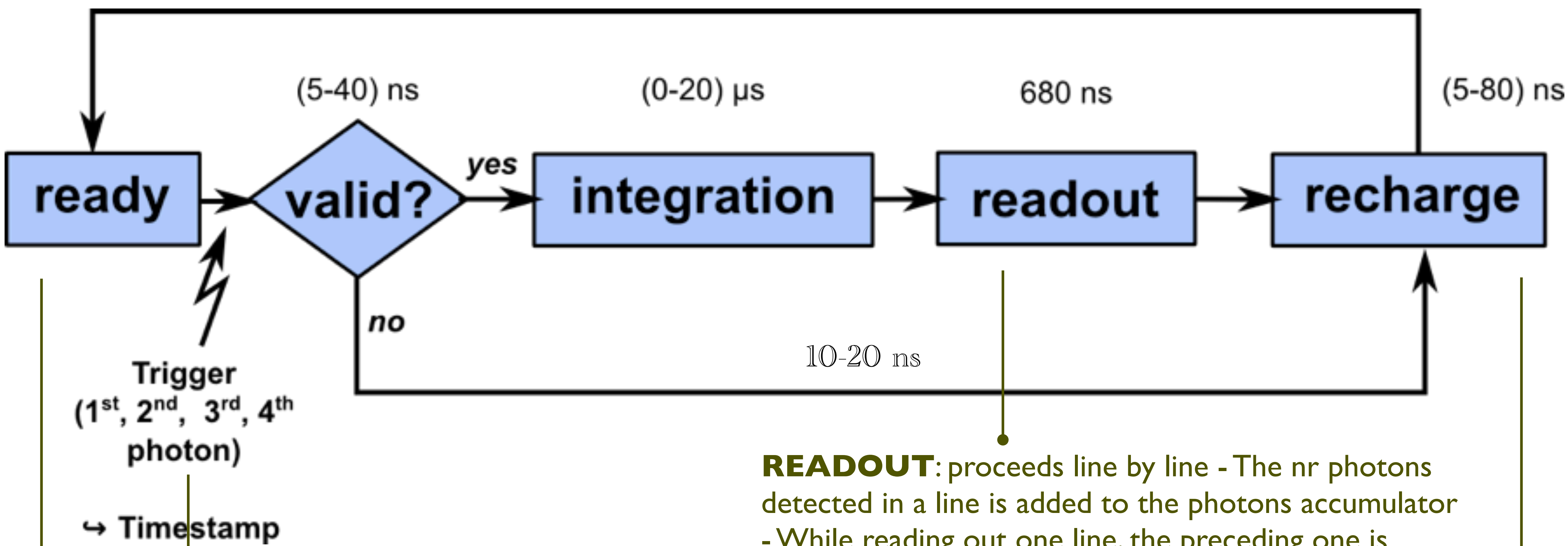
- 8x8 pixel matrix
- Each pixel contains 3200 (DLS3200) or 6400 (DLS6400) cells
- Pixel is 3.2 x 3.8 mm^2 (close to MPPC size)
- Digital device, i.e the output is directly the number of detected photons
- Each event is made of:
  - Die ID
  - timestamp
  - #photons in each pixel composing the die





Digital Silicon Photomultiplier (D-SiPM)

pixel (i.e. 3200/6400 diodes) state machine :



higher **trigger** level: better control of the system dead time but loss of time resolution

READOUT: proceeds line by line - The nr photons detected in a line is added to the photons accumulator - While reading out one line, the preceding one is recharged
Sensor is still sensitive during readout => ~1/2 readout time still contributes to the integration time

READY :
all diodes charged above breakdown
recharge transistors open

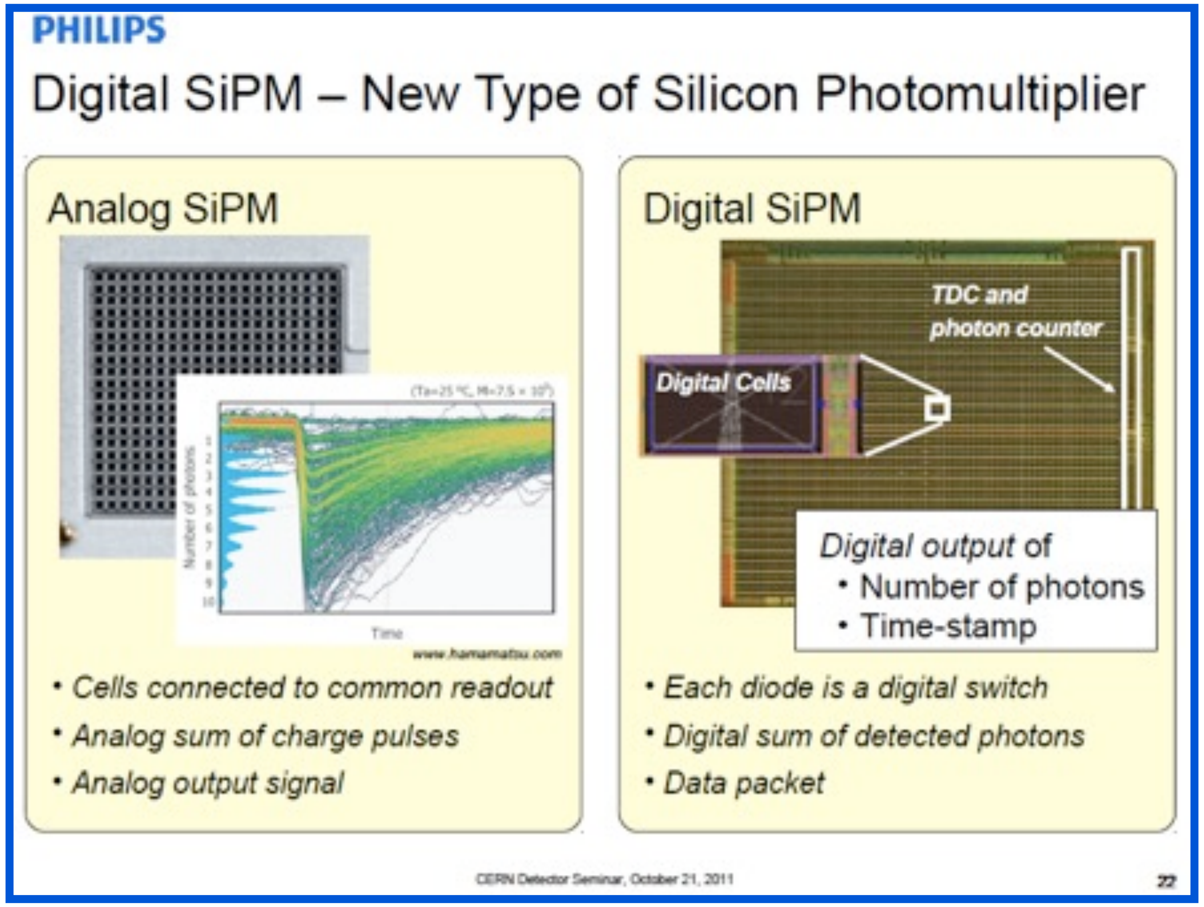
RECHARGE / RESET :
global pixel recharge
TDC reset

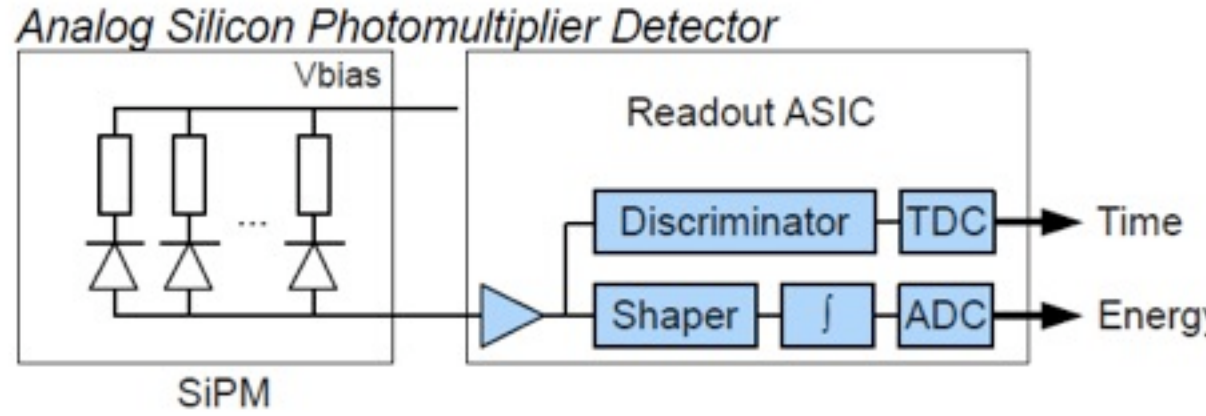
If the trigger is validated, the full readout starts - Σ < 1 µs => Rates ~ MHz can be sustained

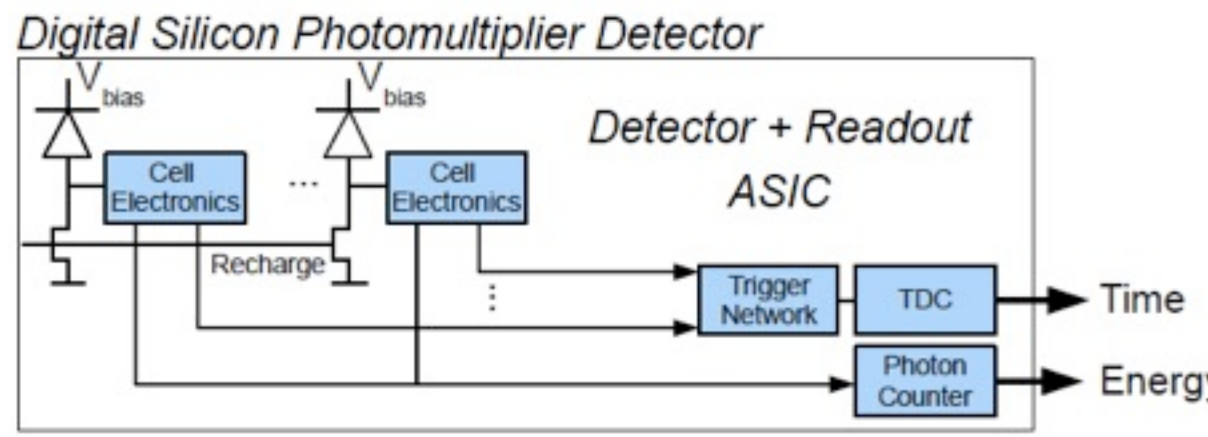
Every non-validated trigger leads to the recharging of all cells. **Without cooling, the device can loose efficiency/availability.**

Digital vs Analogue SiPM

SiPM : intrinsically already a "digital" device







Advantages of digital vs analogue:
- integration (bias supply, amplifier, TDC, photon counter)
- compactness
- (very good timing resolution)
- early digitization of the cell output => low noise
- digital => Temp and Gain stability less critical
- fast active quenching => no afterpulses
- possibility to deactivate individual noisy cells => low dark count rate

Shared limitations digital / analogue :
- limited nr of cells => saturation
- high dark count rates

Drawbacks:
- cooling advisable / needed
- long readout time (~ 1 μs) over a quite large detector surface (8x8 mm2) => deadtime / availability issues
- lack of flexibility: readout functionality is designed into the sensor; in case of mismatch with the needs expensive FPGA/sensor modifications required