# INNOVATIVE DETECTOR CONCEPTS IN PET IMAGING

## investigated in the IRIS group

P. Solevi on behalf of the IRIS group

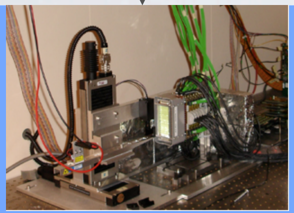
# THE IRIS GROUP

Software

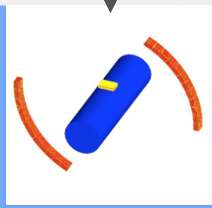
**M. Rafecas**: principal investigator
**J. Oliver**, **J. Cabello**, **P. Solevi**, **J. Gillam**: post-doctoral fellows
**M. Blume**, **K. Brzezinski**: PhD students

Instrumentation

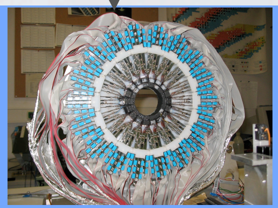
**C. Lacasta**: principal investigator
**G. Llosa**, **V. Linhart**: post-doctoral fellows
**J. Barrio**: PhD student
**V. Stankova, C. Solaz**: engineer



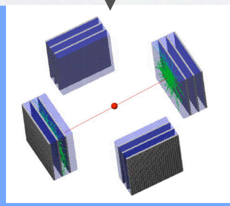
International collaboration AX-PET



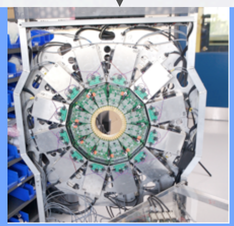
ENVISION/MADEIRA EU-project



Technische Universitat Munchen (Germany)



Universita' degli Studi di Pisa (Italy)

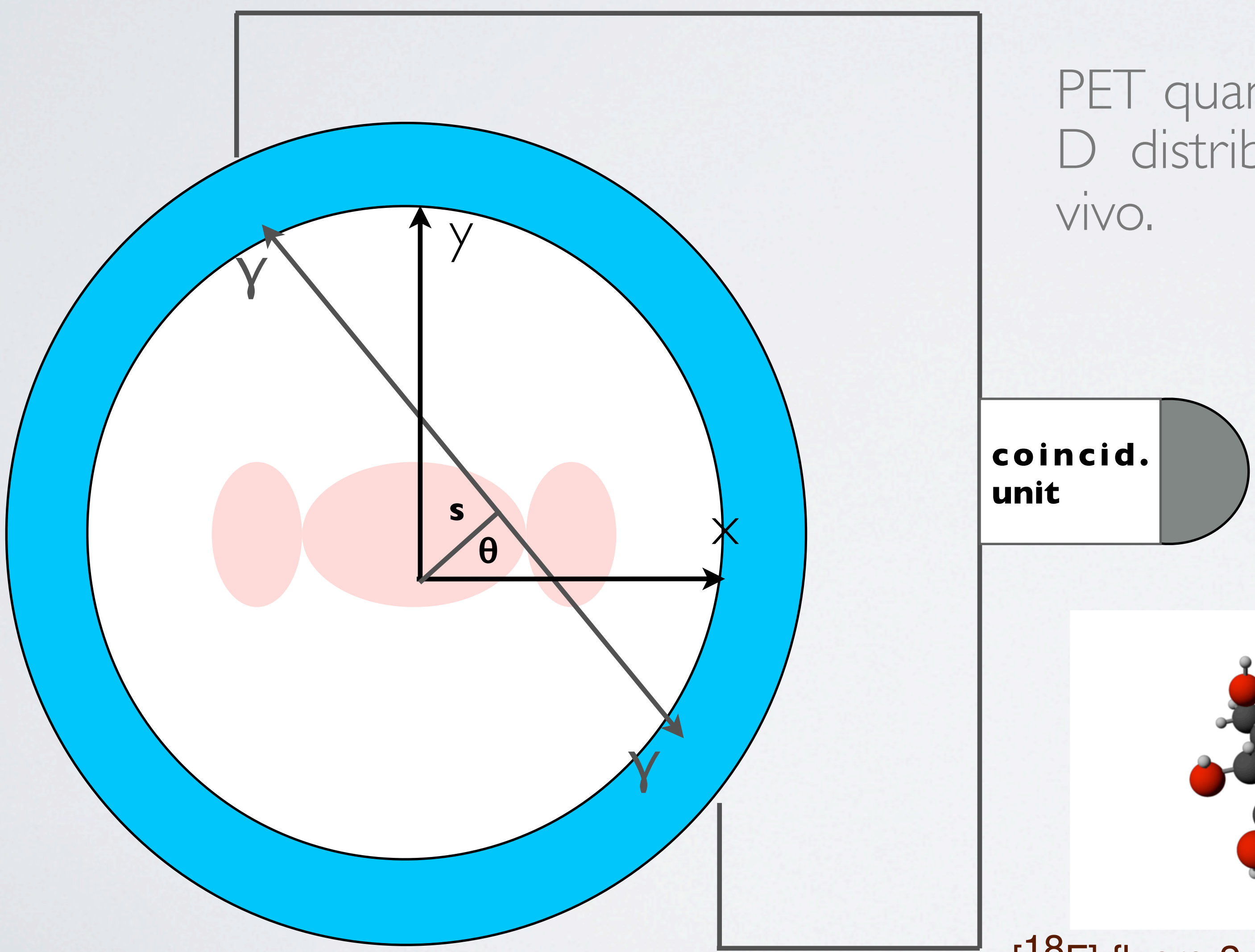


Universite' de Sherbrooke Canada

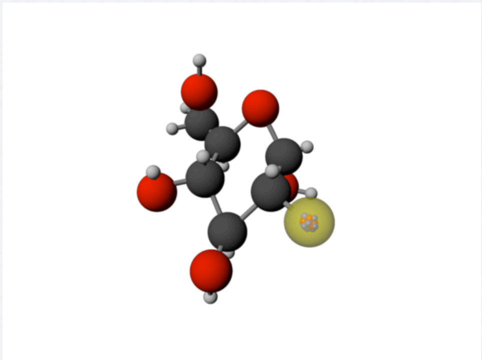
# EMISSION TOMOGRAPHY

Emission Tomography (ET) encompasses two main imaging modalities: Positron Emission Tomography (**PET**), Single-Photon Emission Computed Tomography (**SPECT**) and Compton Imaging.

ET is a functional imaging modality that combines the gamma-ray *emission* (the tracer principle) with volumetric imaging of the body (i.e. tomography).




PET quantitatively and non-invasive measures the 3-D distribution of radio-labeled biomolecules in vivo.

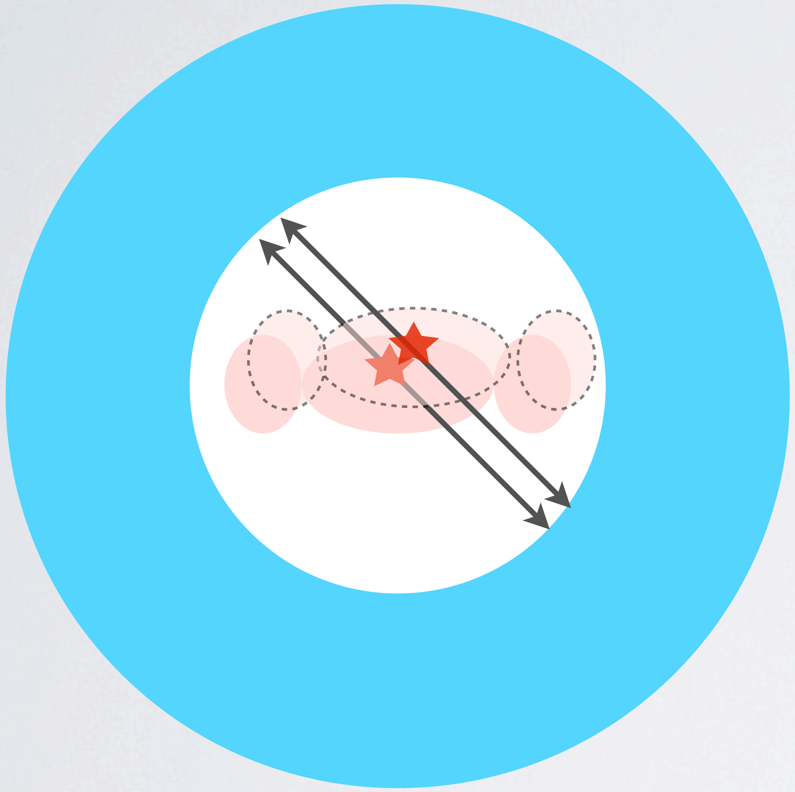


$[^{18}F]$-fluoro-2-deoxy-D-glucose

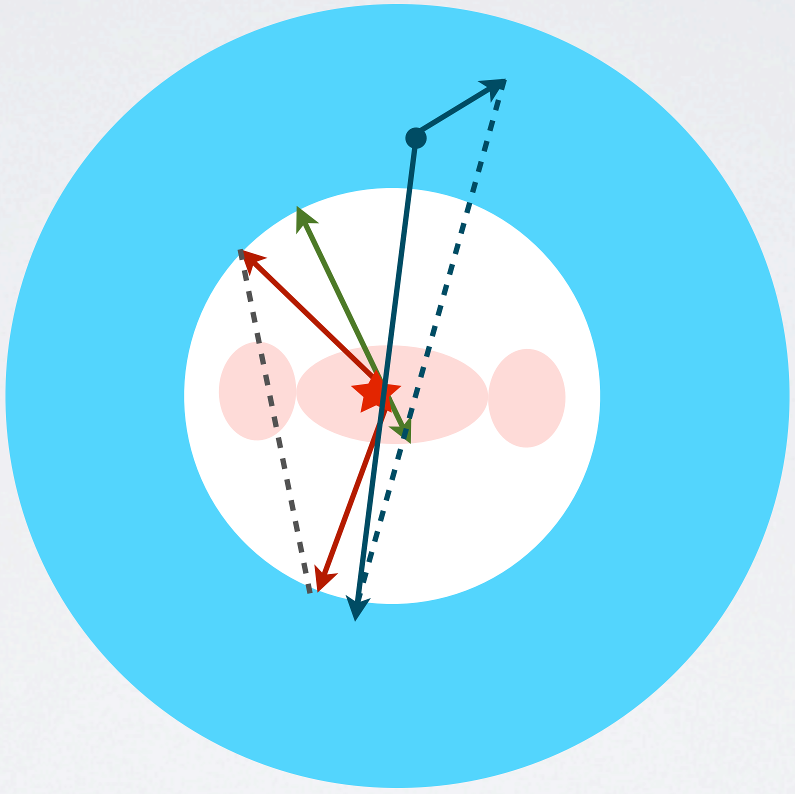
| | $T_{1/2}$ |
|---|---|
| **$^{11}C$** | **20.4 mins** |
| **$^{18}F$** | **110 mins** |
| **$^{13}N$** | **19 mins** |
| $^{68}Ga$ | 68 mins |
| $^{89}Zr$ | 8.3 days |
| $^{124}I$ | 4.2 days |
| $^{64}Cu$ | 12.6 hrs |

# PET IMAGE DEGRADATION PHENOMENA

The detected *prompt coincidences* can be of different types given the limited spatial and time resolution of PET detectors as well as the electronics readout speed.
Additionally, the patient motion can be a further source of blurring in the final image.

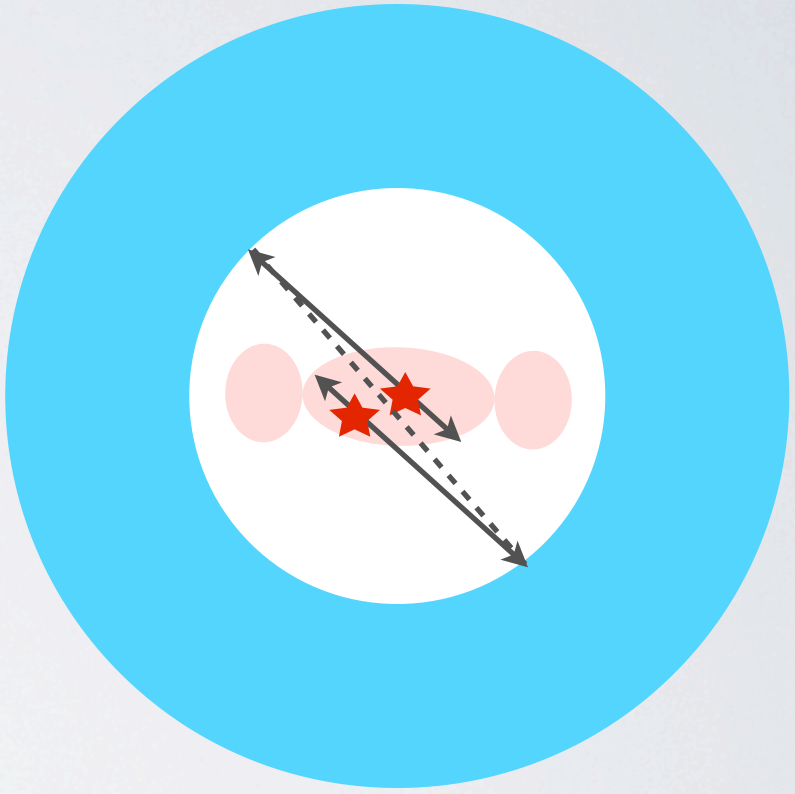


**Patient motion**



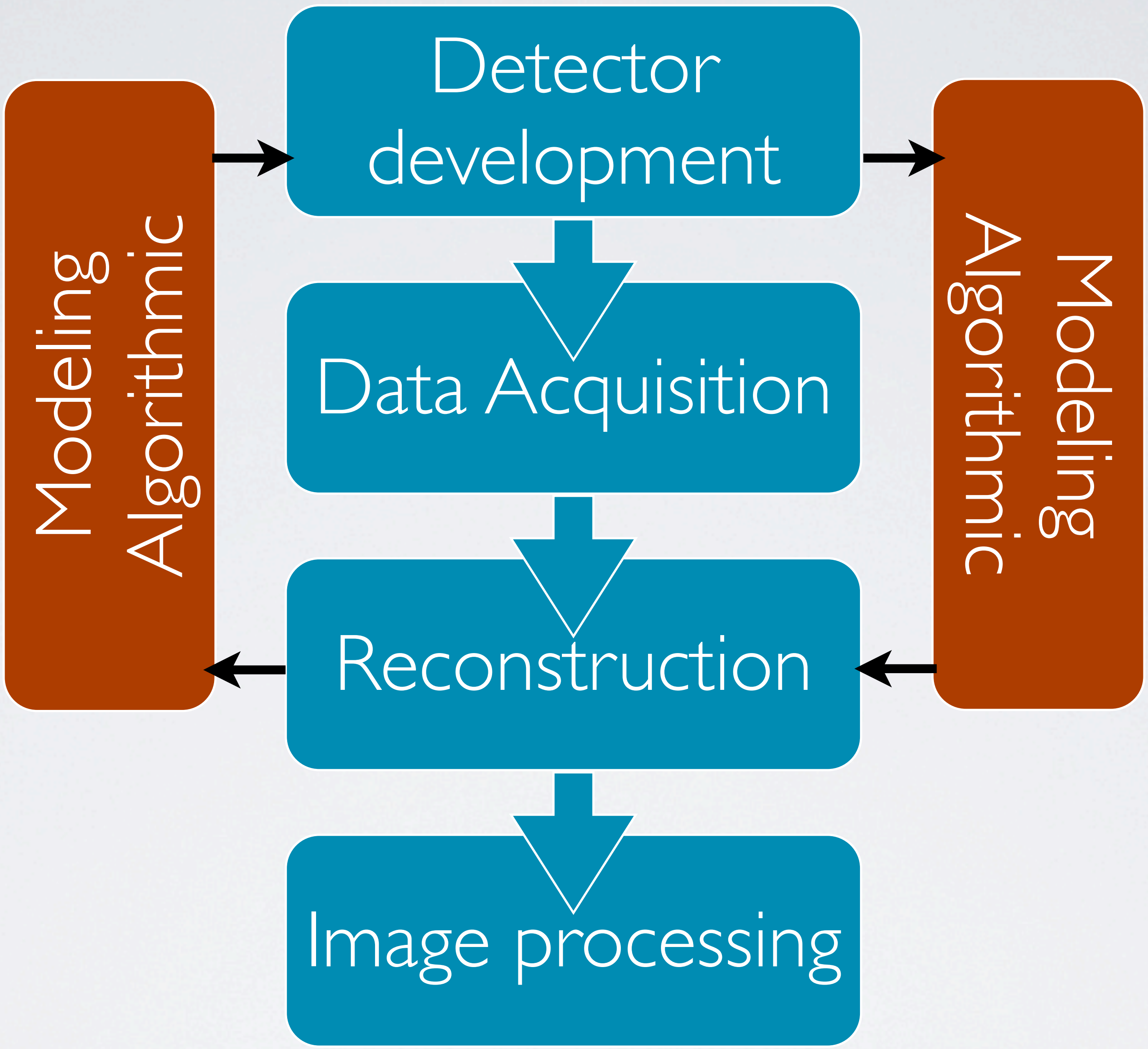
**Scattered events**

* attenuation
* scatter in the detector
* scatter in the patient body



**Random**

# PET WORKING FLOWCHART




The kernel of ET reconstruction is obtaining *volumetric* images starting from *projections* as provided by the detection system. This is a non trivial problem that yields to images whose quality depends on detector performance, acquisition modalities and the modeling/correction of physics phenomena as well as of the system response.

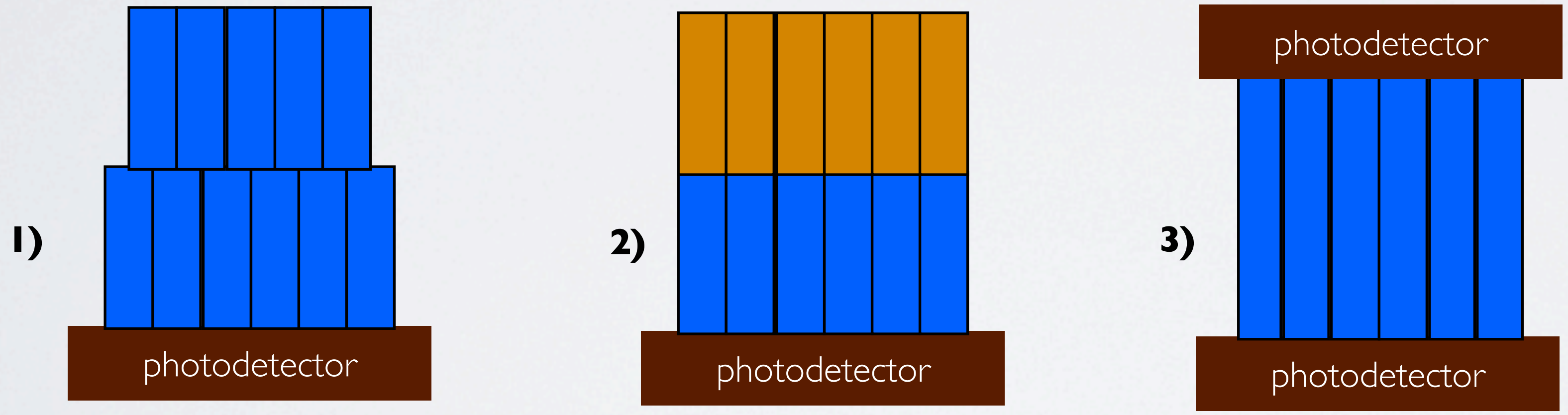
# GOALS IN PET DETECTOR DEVELOPMENTS

Innovative PET detectors try to find out new approaches to overcome the trade off between sensitivity and spatial resolution.

**High sensitivity:**
* high efficiency (thick) detectors
* high solid angle coverage i.e. small diameter and longer axial extent

**High resolution:**
* small cross section detector elements
* depth-encoding detectors

TOF-PET: increasing CNR

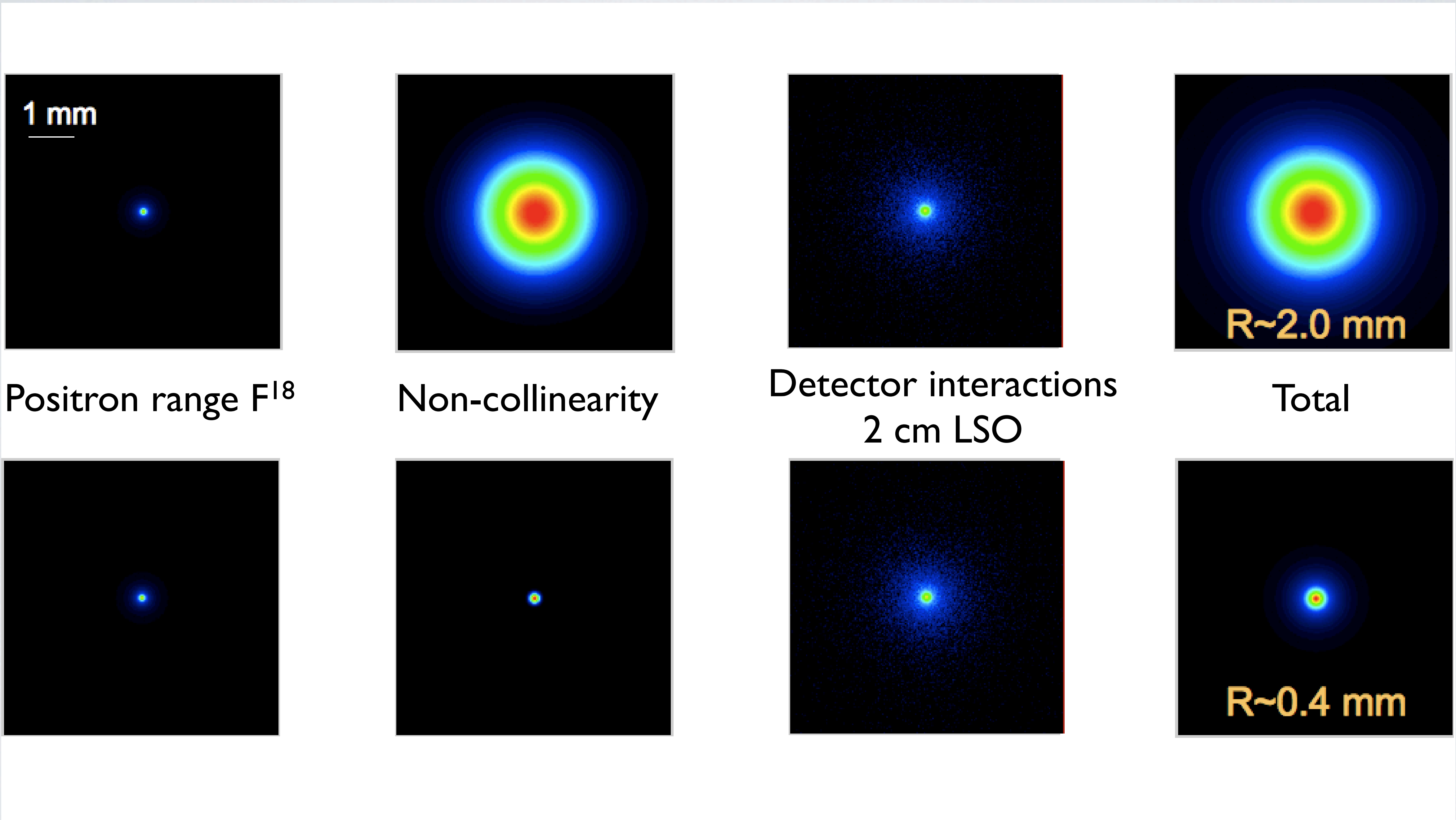



Depth encoding explored approaches:
1) offset design
2) phoswich design
3) dual end readout
1+2 provide discrete information.

Faster and high efficiency detectors as APD and SiPM as well as luminous and fast scintillators as LYSO and LaBr3 are leading choices in the PET community.

# SPATIAL RESOLUTION IN PET

Human Whole-Body Scanner (D = 80 cm)




Small Animal Scanner (D = 8 cm)

S. Cherry, UC Davis

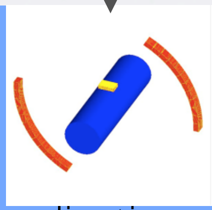
# THE IRIS GROUP

Software

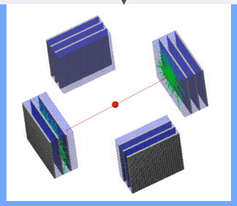
**M. Rafecas**: principal investigator
**J. Oliver**, **J. Cabello**, **P. Solevi**, **J. Gillam**: post-doctoral fellows
**M. Blume**, **K. Brzezinski**: PhD students

Instrumentation

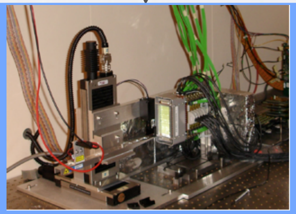
**C. Lacasta**: principal investigator
**G. Llosa**, **V. Linhart**: post-doctoral fellows
**J. Barrio**: PhD student
**V. Stankova, C. Solaz**: engineer



New imaging application and approaches: hybrid detectors and Hadrontherapy monitoring



New PET detectors concepts for 3D positioning and high sensitivity



Employment of "state of the art" ingredients: SiPM, LaBr3.

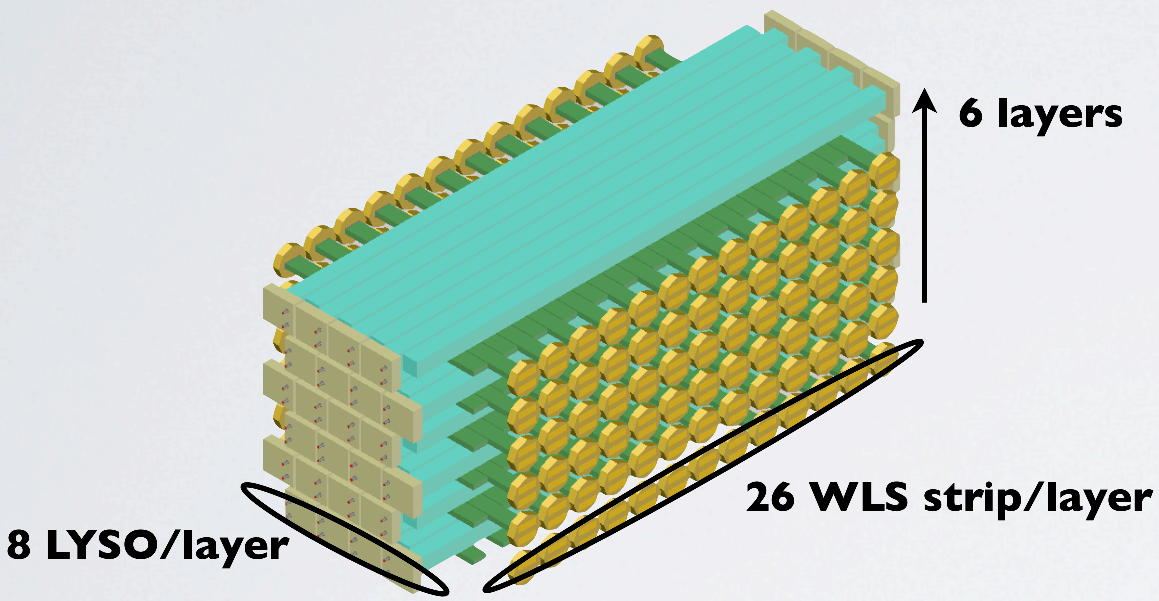
# AXPET: THE CONCEPT

AX-PET is based on a novel PET concept based on **axially oriented crystals and interleaved WLS strips**, both individually readout.

It provides:

✘ a high spatial resolution, with marginal parallax error;

✘ possibility to increase sensitivity by adding additional crystal layers.



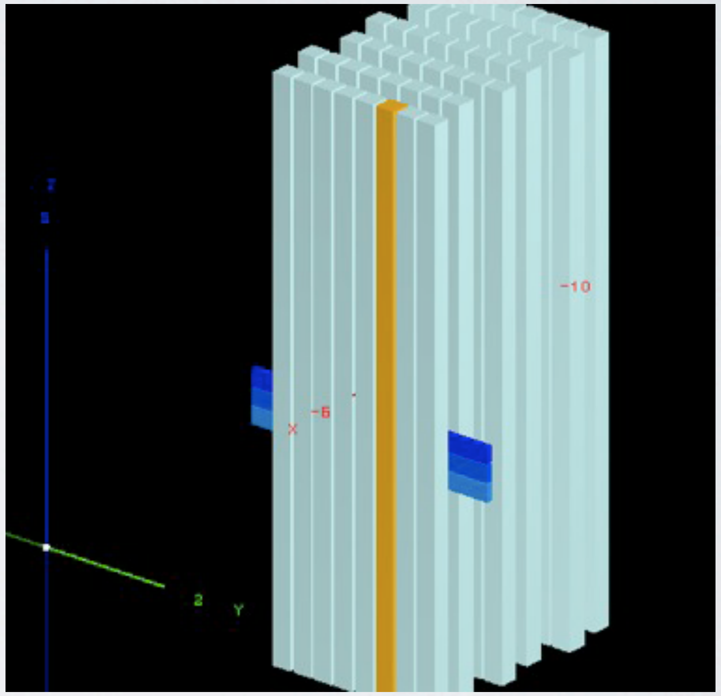
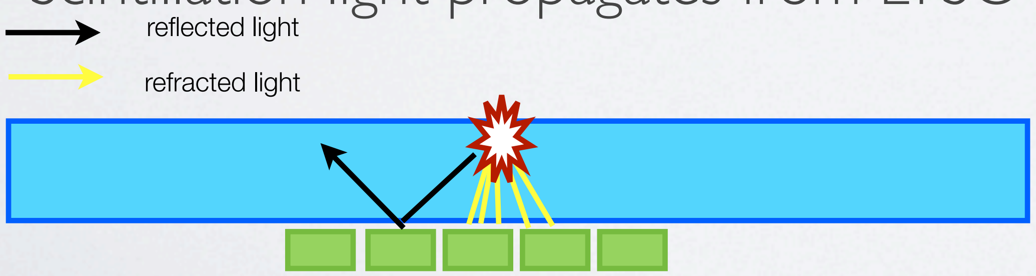



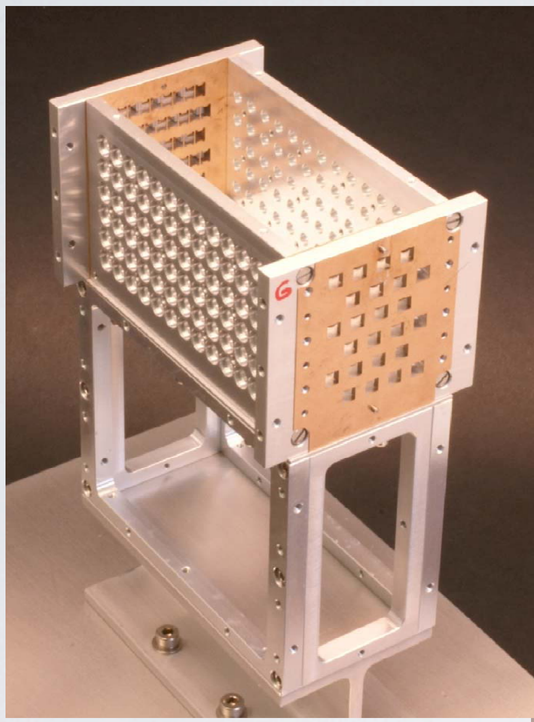
Photo-electric event from event displayer.

Scintillation light propagates from LYSO to the WLSs.



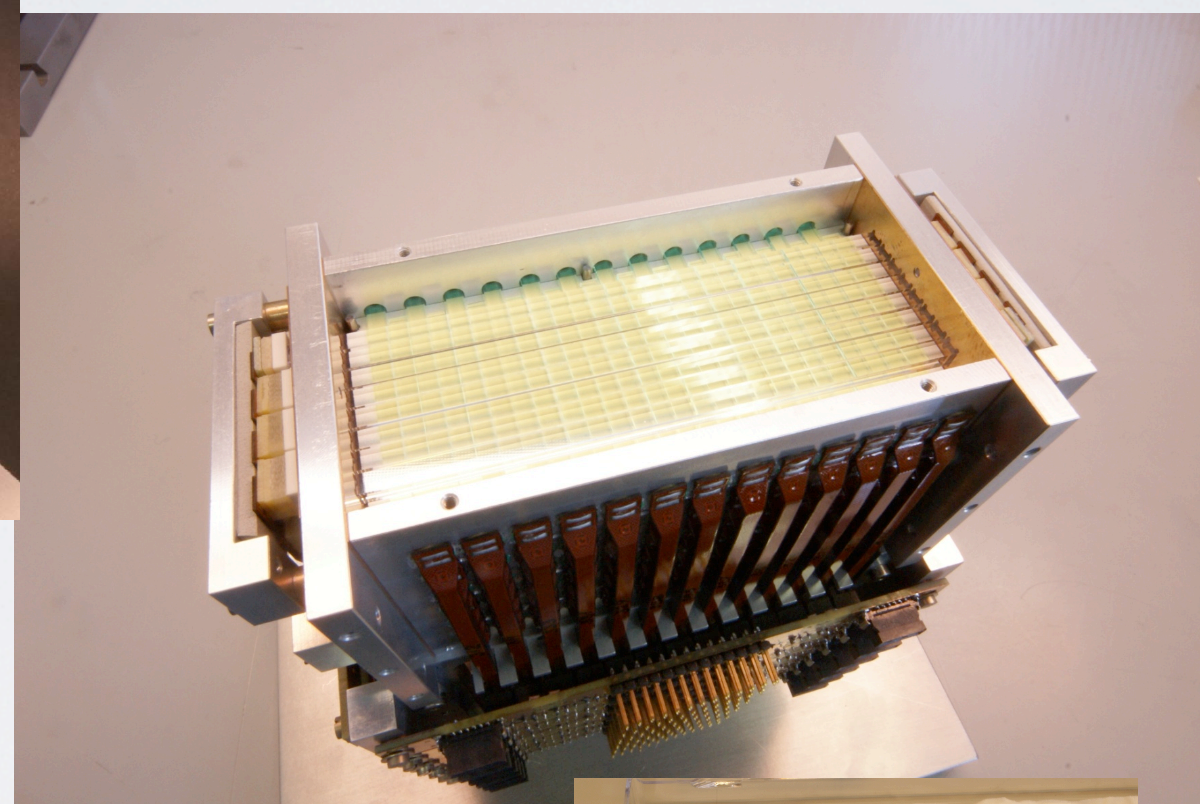

$$z_{CG}=\sum LY_i \cdot z_i / \sum LY_i$$

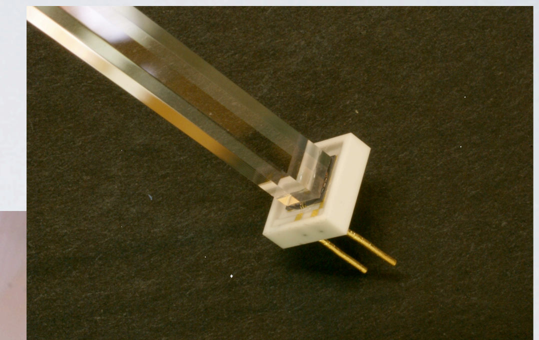
# AXPET: THE FIRST DEMONSTRATOR



Mechanics: aluminum housing to keep the crystal and WLS in place.

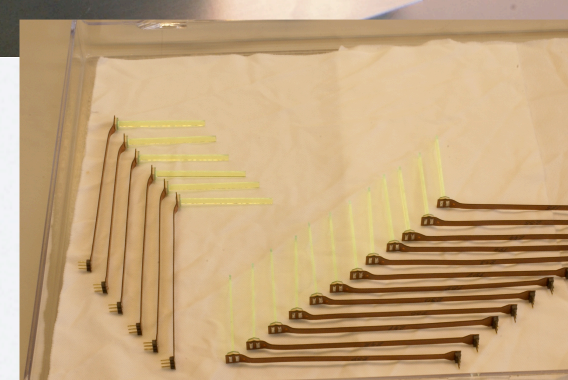
**Module I**



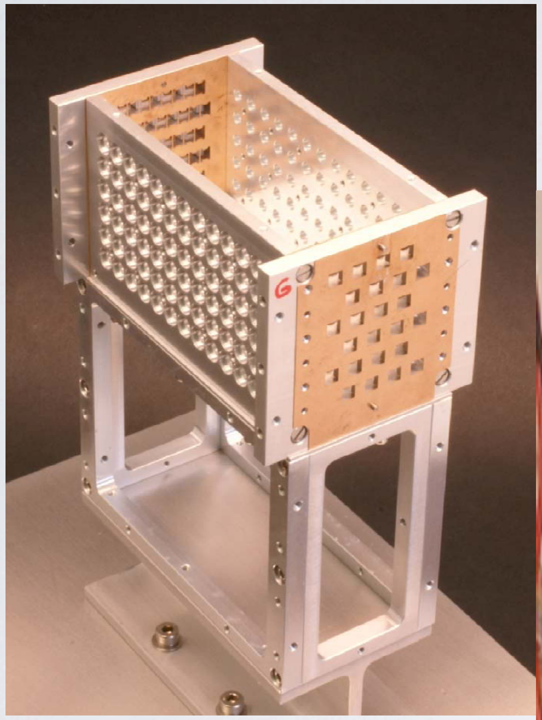


LYSO crystals from St. Gobain, 3x3x100 mm$^3$ readout by 3x3 mm$^2$ MPPC (3600 pixels).

0.9x3x40 mm$^3$ WLS strips from EJEN are readout by 1.19x3 mm$^2$ MPPC (1200 pixels).

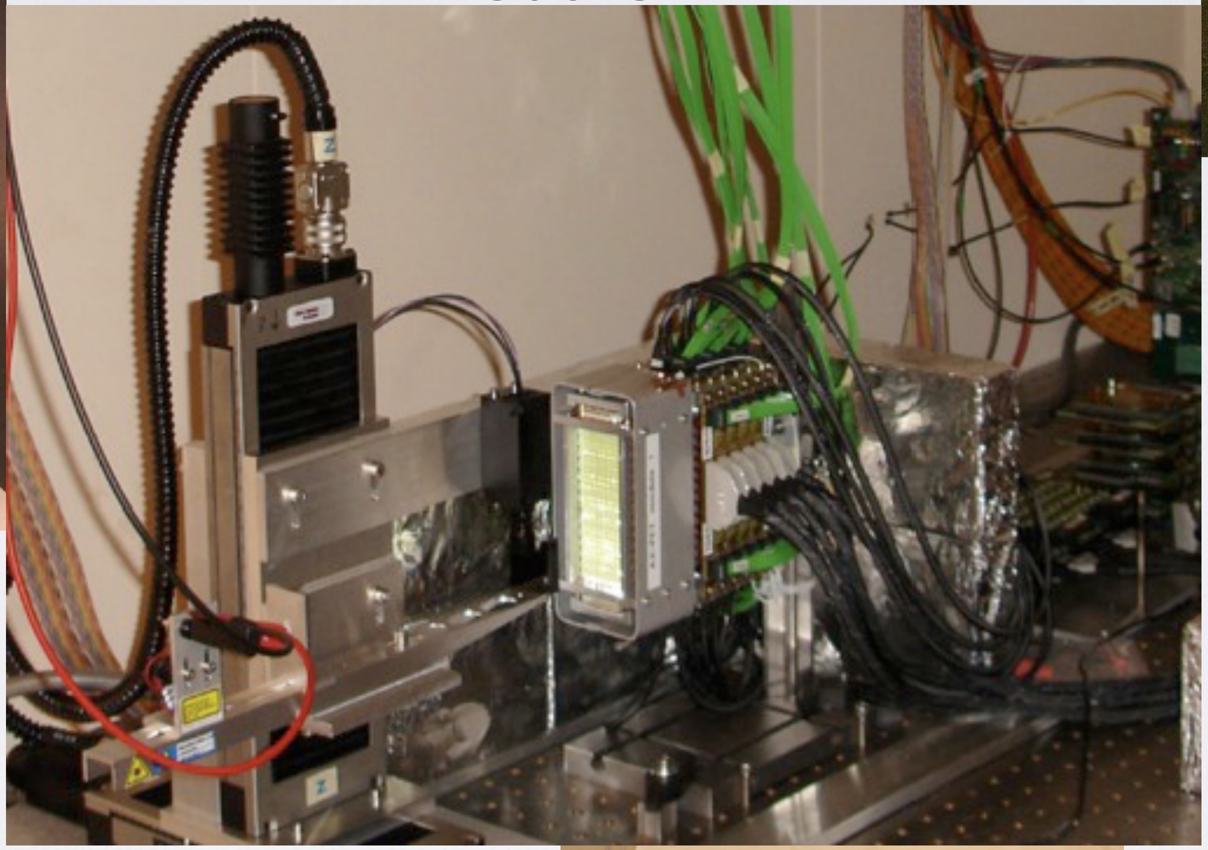


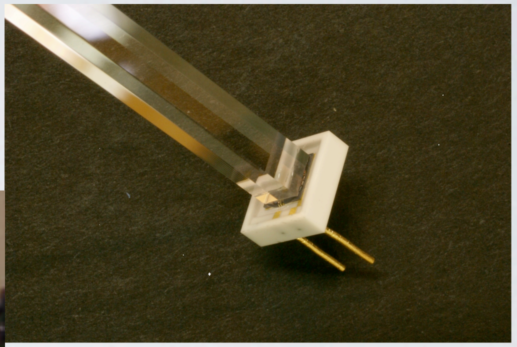
# AXPET: THE FIRST DEMONSTRATOR



Mechanics: aluminum housing to keep the crystal and WLS in place.

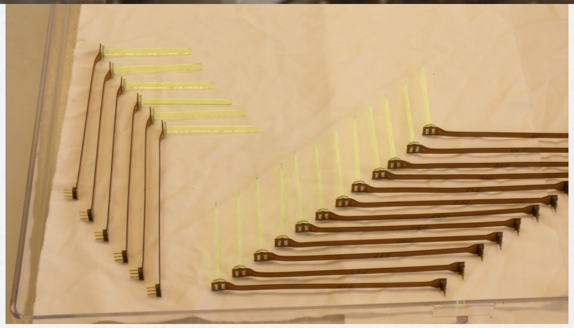
**Module I**



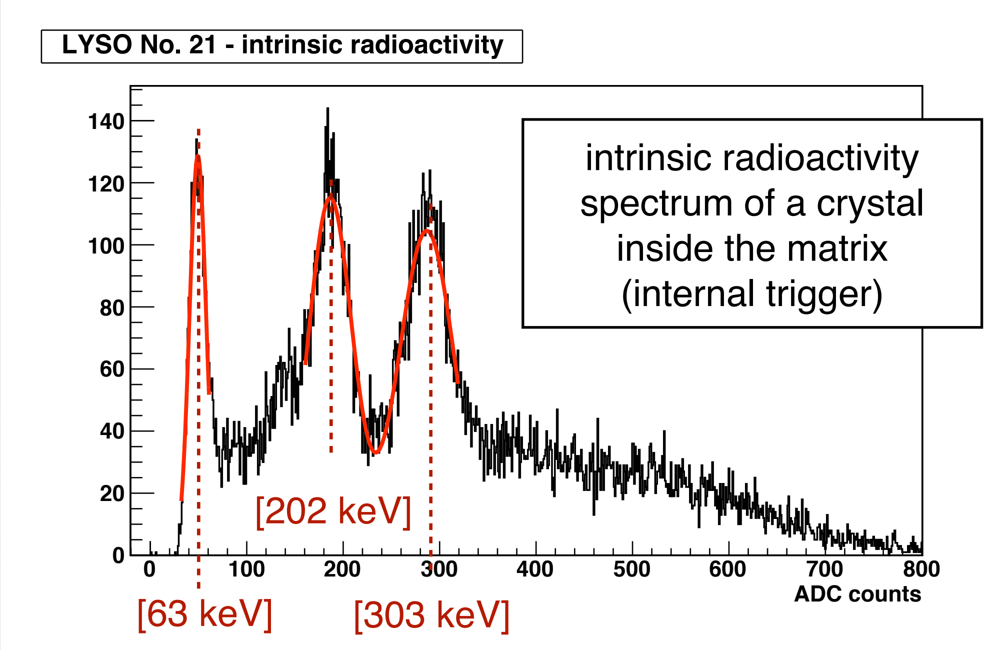


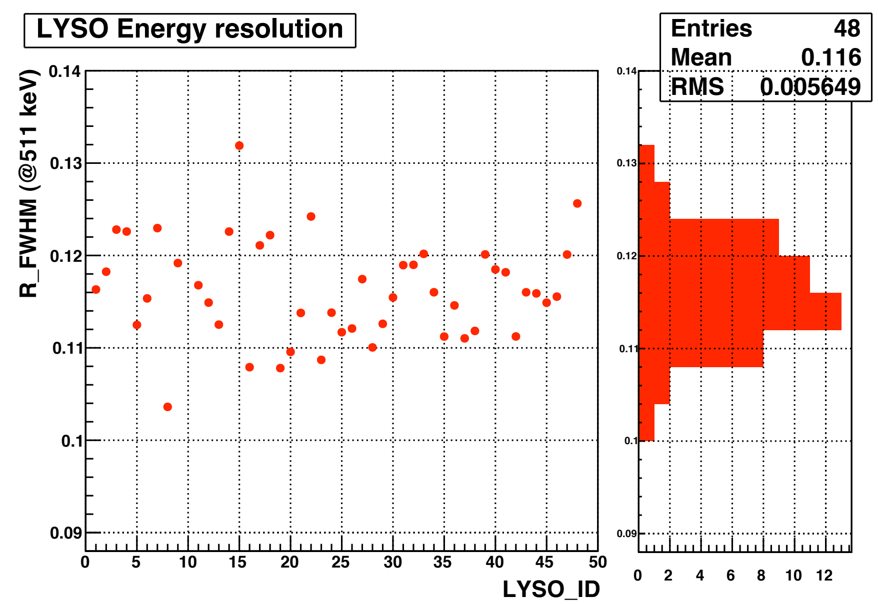
LYSO crystals from St. Gobain, 3x3x100 $mm^3$ readout by 3x3 $mm^2$ MPPC (3600 pixels).

0.9x3x40 $mm^3$ WLS strips from EJEN are readout by 1.19x3 $mm^2$ MPPC (1200 pixels).



# AXPET: DETECTOR PERFORMANCE

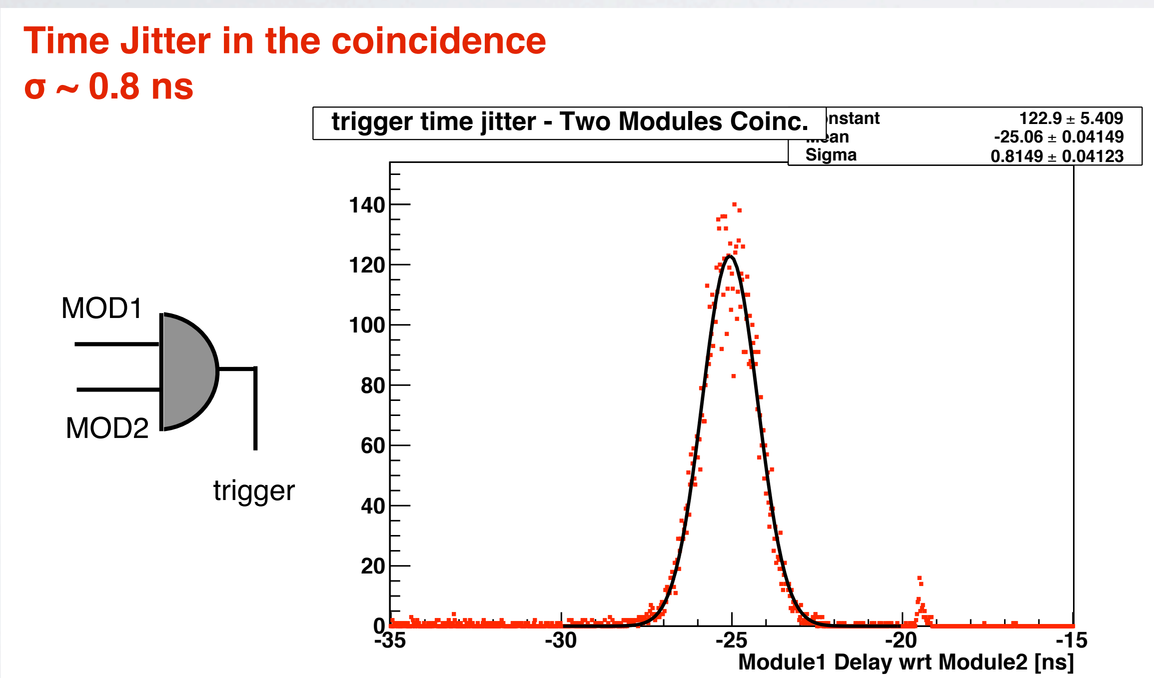


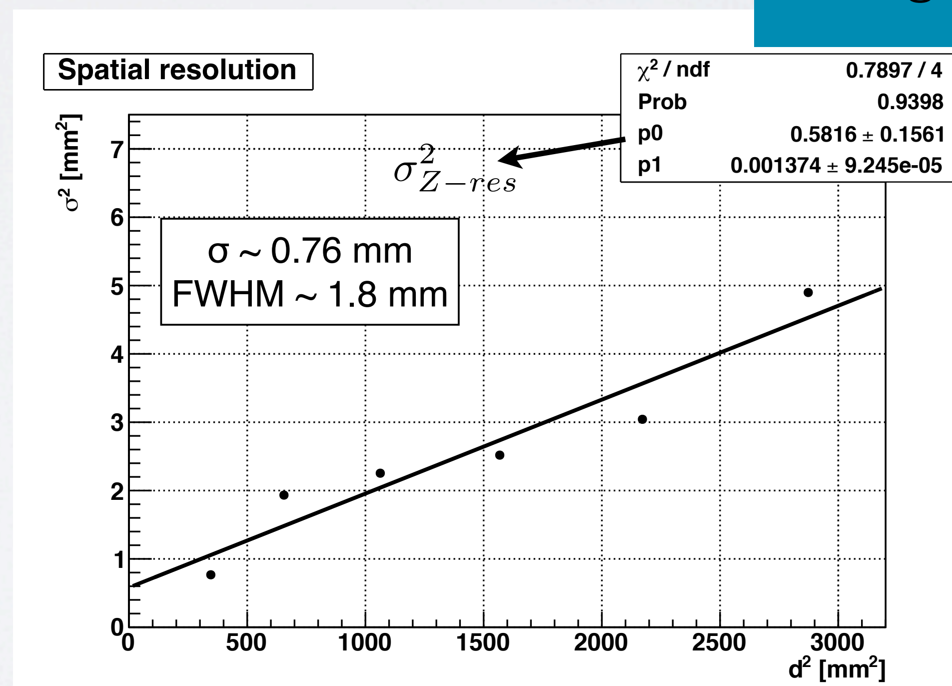




Energy calibration and non-linearity are corrected by exploiting the intrinsic radioactivity peaks.

Energy resolution in coincidence 11.6% @ 511 keV.

Timing 0.8 ns (σ)



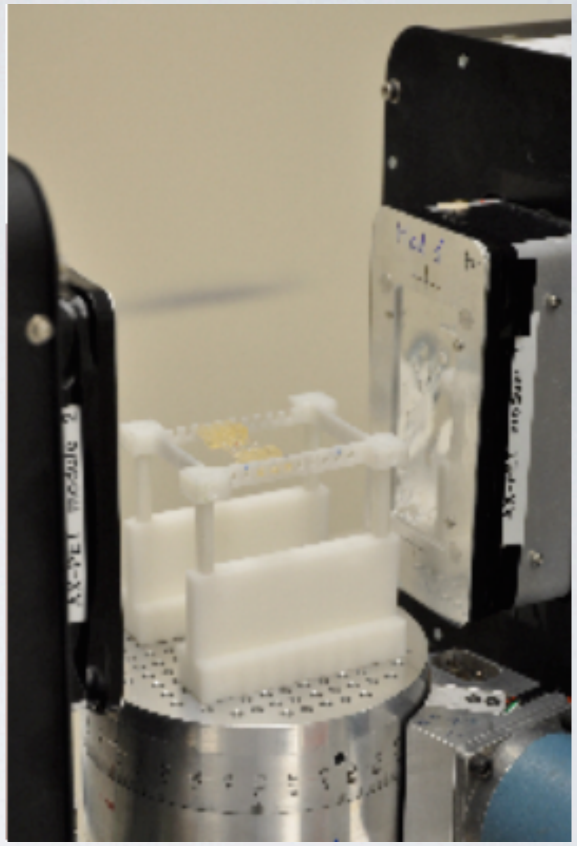



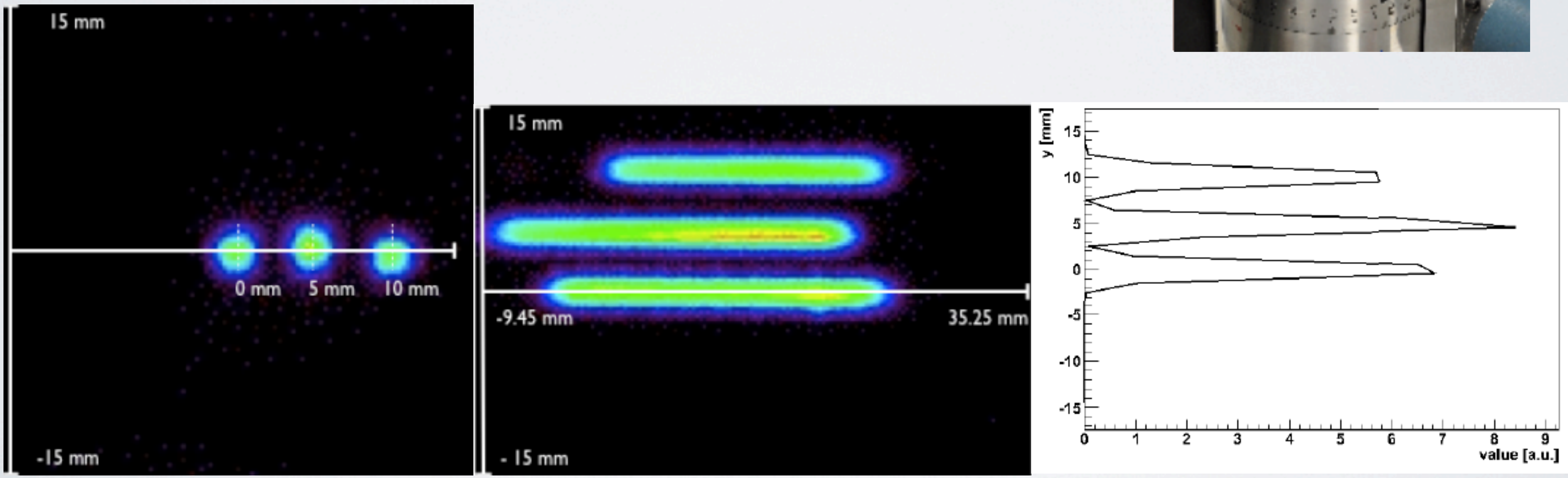

$<\sigma_x>=0.87$ mm
$<\sigma_y>=0.87$ mm
$<\sigma_z>=0.76$ mm

# AXPET: MEASUREMENTS CAMPAIGN

AXPET consisting of 2 modules set in coincidence went already through 2 measurements campaigns at the ETH pharmaceuticals lab (Zurich, Switzerland) and at the AAA - Advanced Accelerator Application company (St Genis Pouilly, France).

The measurements were addressed at exploring the imaging capabilities of our device with realistic sources (standard phantoms filled by $^{18}$F-FDG).



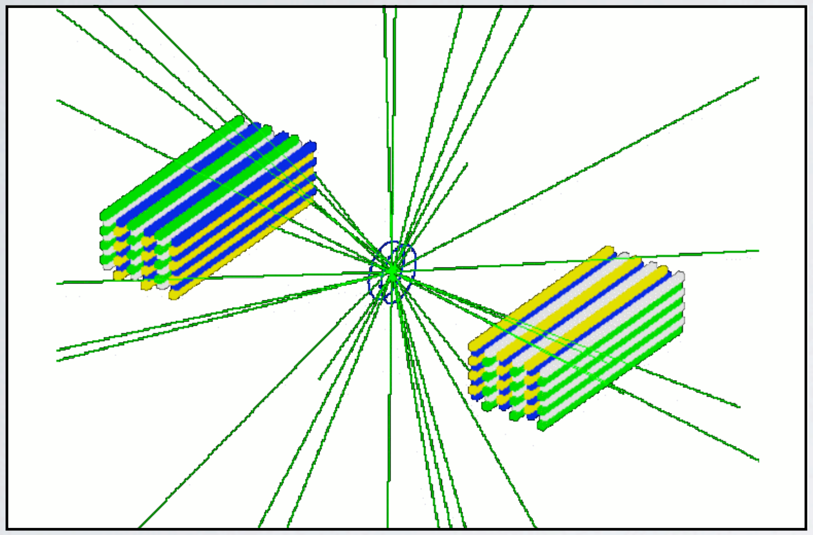


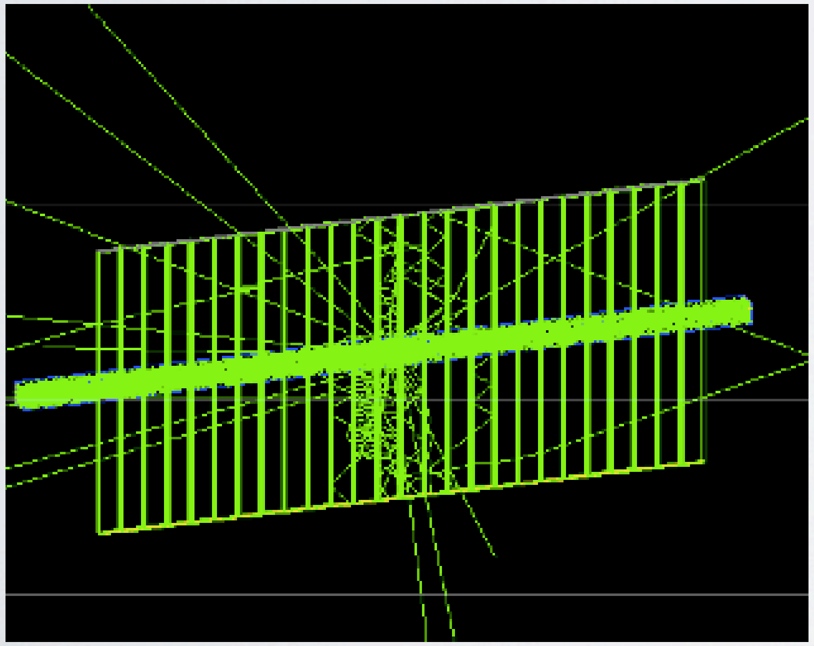

Three capillaries of 1.4 mm diameter are filled with FDG and placed on a rotary table to mimic the scanner rotation. The reconstruction is based on MLEM algorithm.

# AXPET: MONTE CARLO SIMULATIONS

Due to the unique design and concept of AXPET many efforts were invested to accurately model the system in order to support the detector development and better understand the underlying physics.

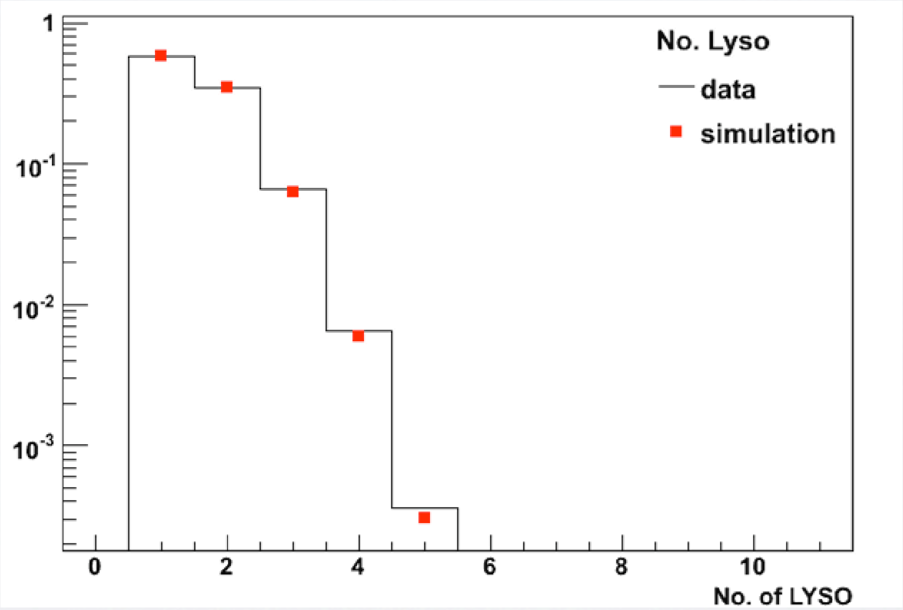
**Modeling**

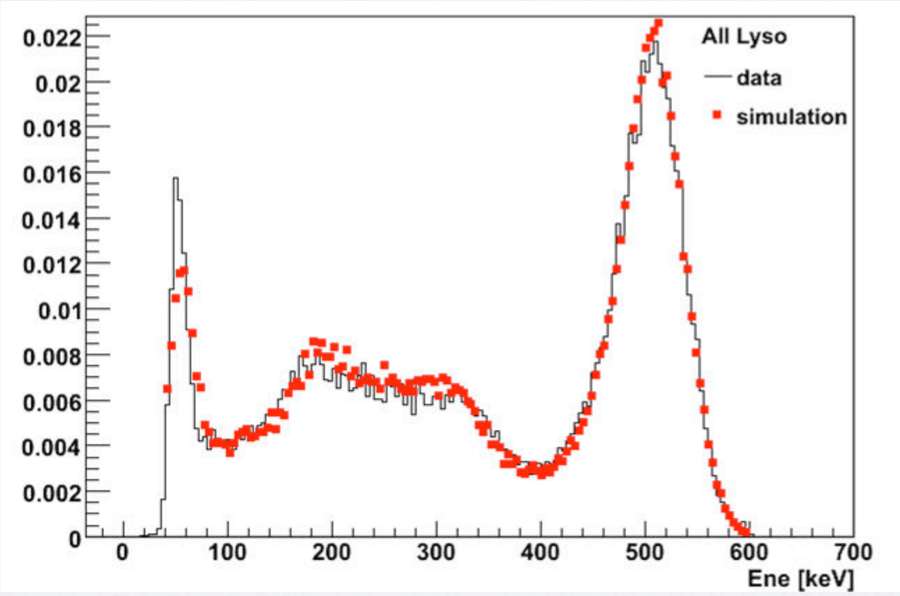




GATE and Geant4 simulations screenshots.

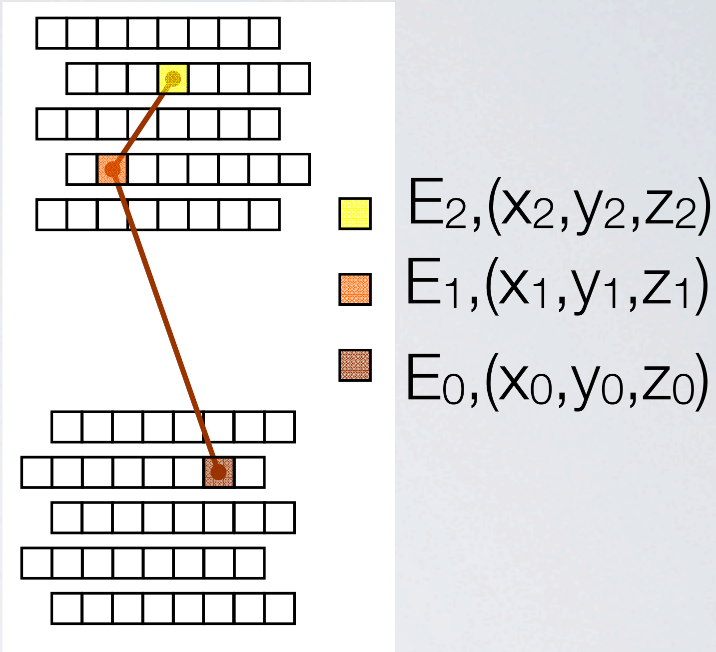
**MC Validation**




No selection on LYSO number

**Test algorithm**




Inter-Crystal Scattering events are identified and reconstructed via algorithms heavily tested and optimized over synthetic data.

Neural Network ~75% eff.
Klein-Nishina ~62% eff.

# ENVISION

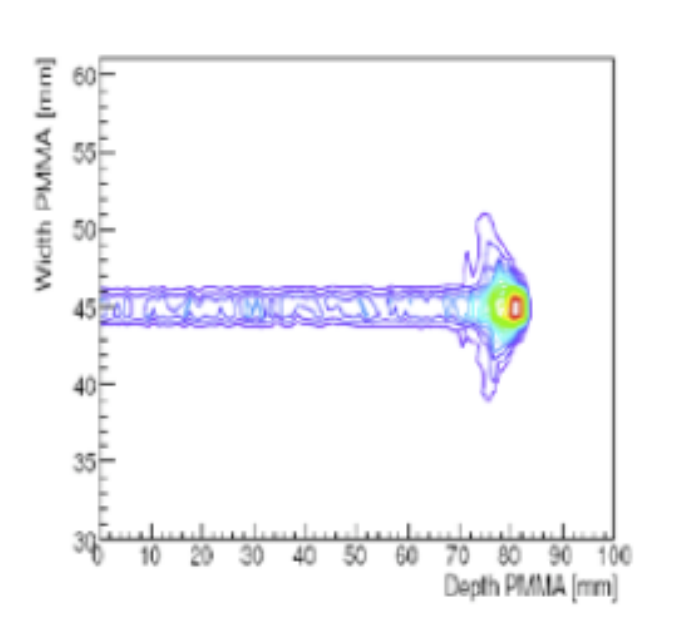
ENVISION was born from joint international efforts to develop new imaging techniques for particle tumor treatments monitoring.

**Hadrontherapy quality assurance** is based on the detection of particles directly or indirectly produced by nuclear fragmentation phenomena yielded by the incident hadron beam in the patient tissue.

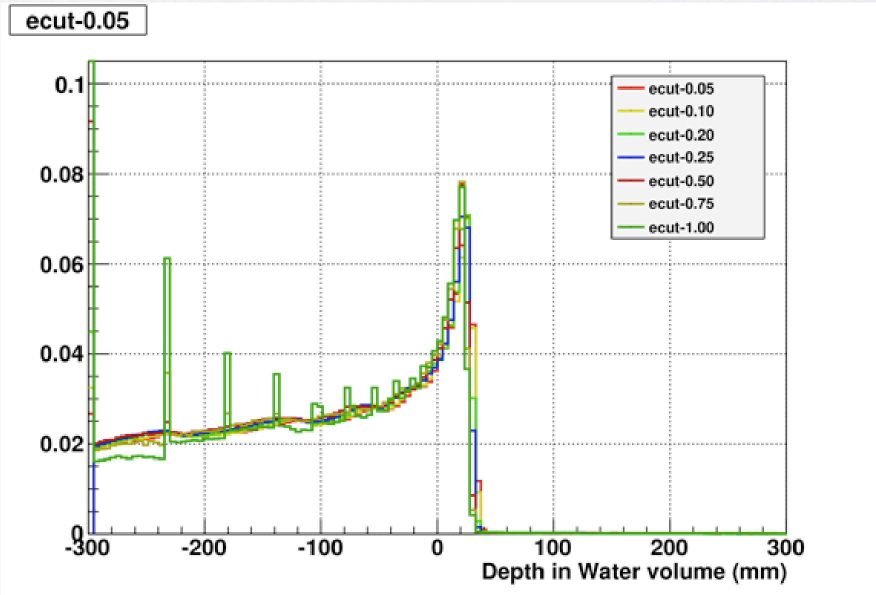
This encompasses several techniques, among these:

- In-Beam PET measuring the back-to-back gammas from the annihilation in the patient tissue of positrons emitted by unstable nuclei produced via nuclear interactions;
- Gamma-imaging of *prompt emitted gammas* (continuous energy spectrum up to 15 MeV).

The particle measured profile is correlated to the energy and path (i.e. dose profile) of the primary beam in the patient and it could provide precious feedbacks about the exits of the treatment.



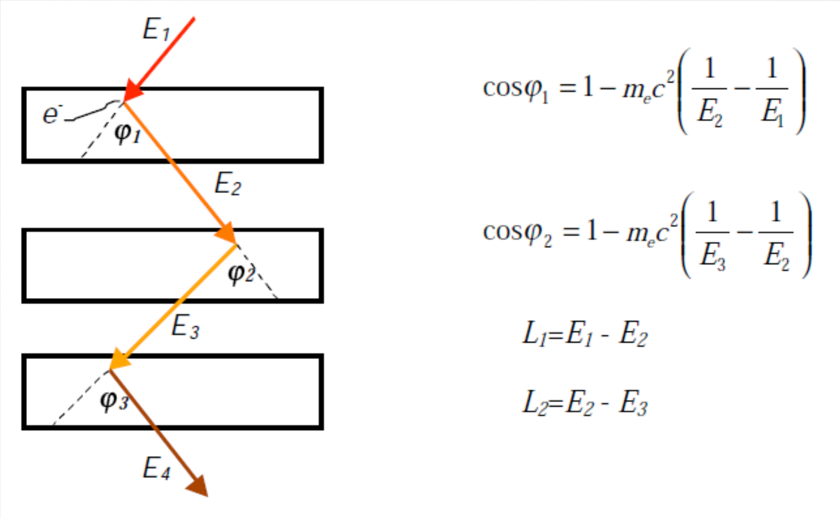

$\beta^+$ emitters profiles in PMMA as produced by 212 MeV $^{12}C$ beam.

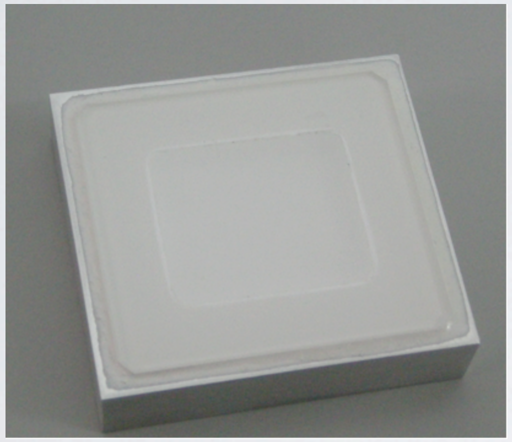



Gammas production profile by 280 MeV proton beam in water phantom.

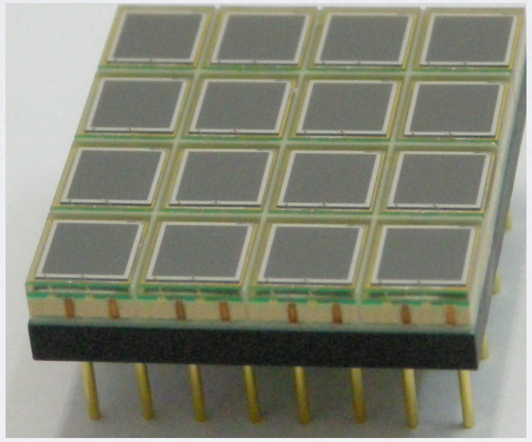
# ENVISION: THE COMPTON TELESCOPE

Prompt gammas can be detected by using a Compton telescope.
It is based on 3 layers on monolithic LaBr3 crystals (high cross section for Compton in the energy range of interest) readout by SiPM array (Hamamatsu MPPC).

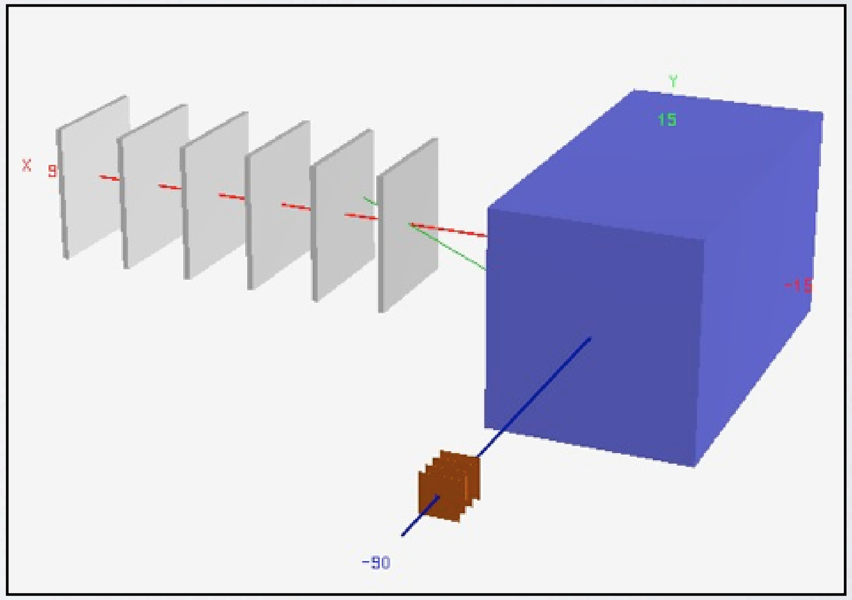


LaBr3 slab 16x18x5 $mm^3$ encapsulated by reflective material.



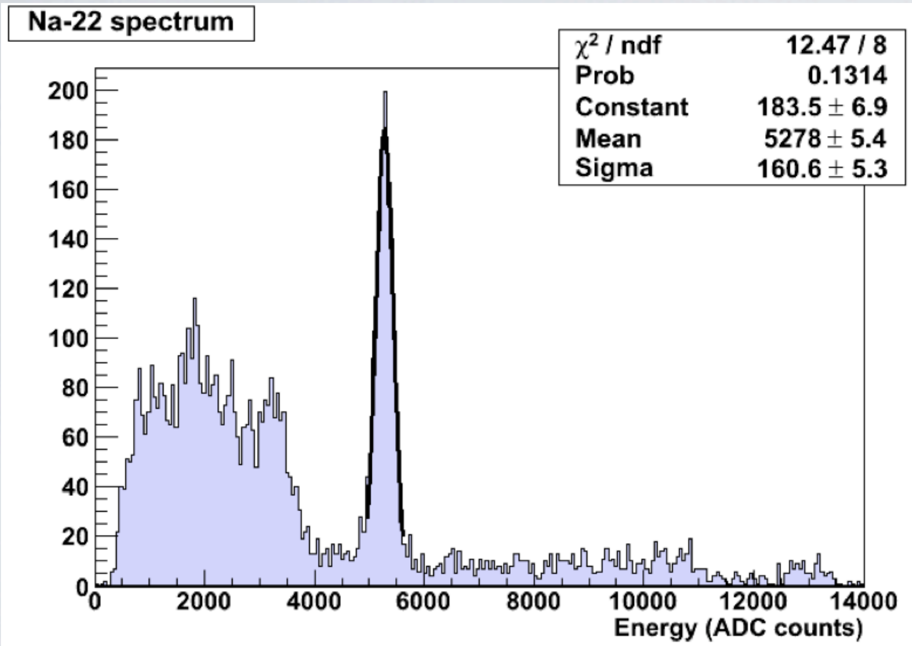
Hamamatsu 16 pixels 3x3 $mm^3$ each.



Simulated geometry based on Geant4 consisting in 6 detection layers of

Main requirements:
- good energy and spatial resolutions to properly reconstruct Compton events i.e. high LY and PDE
- good time resolution to reduce randoms i.e. fast crystal and electronics
- high Compton detection efficiency.

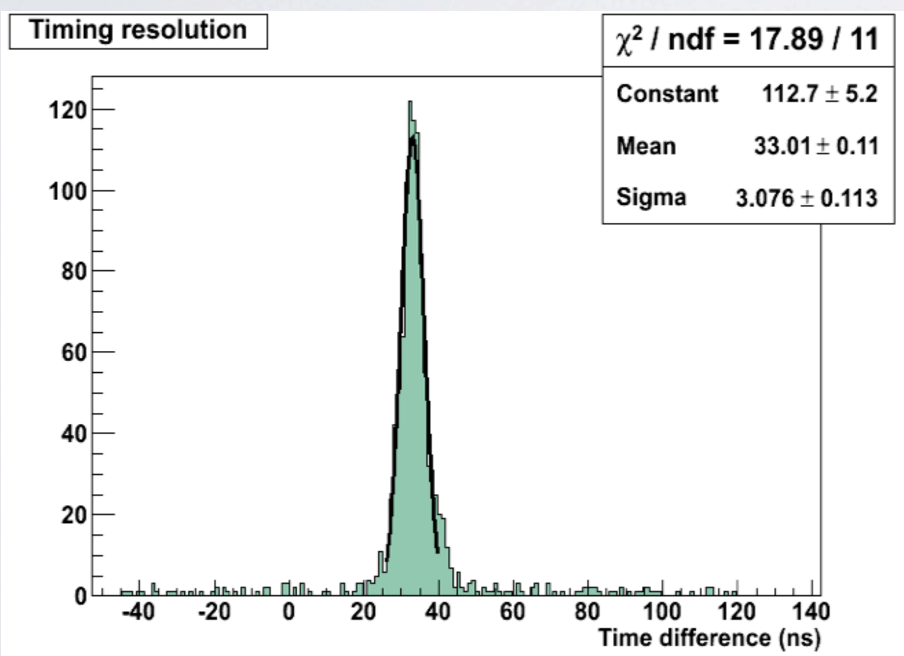
# COMPTON CAMERA: PRELIMINARY RESULTS

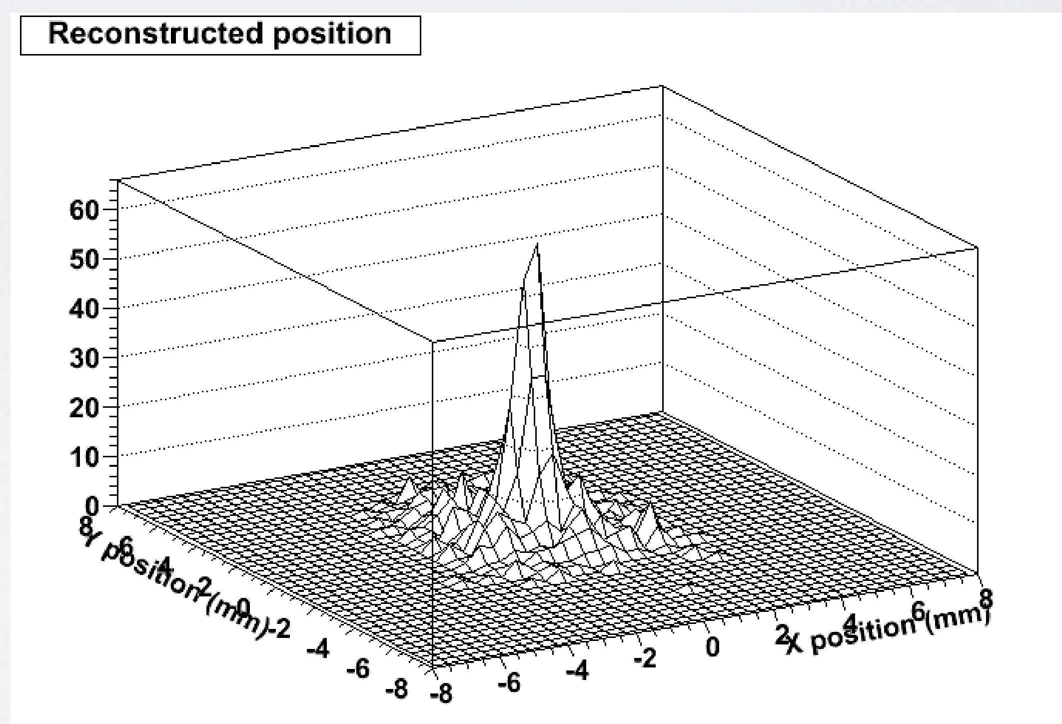



Energy resolution not in coincidence 7% @ 511 keV.

1.2 mm FWHM with Centre Of Gravity algorithm

LYSO+SiPM 7 ns FWHM



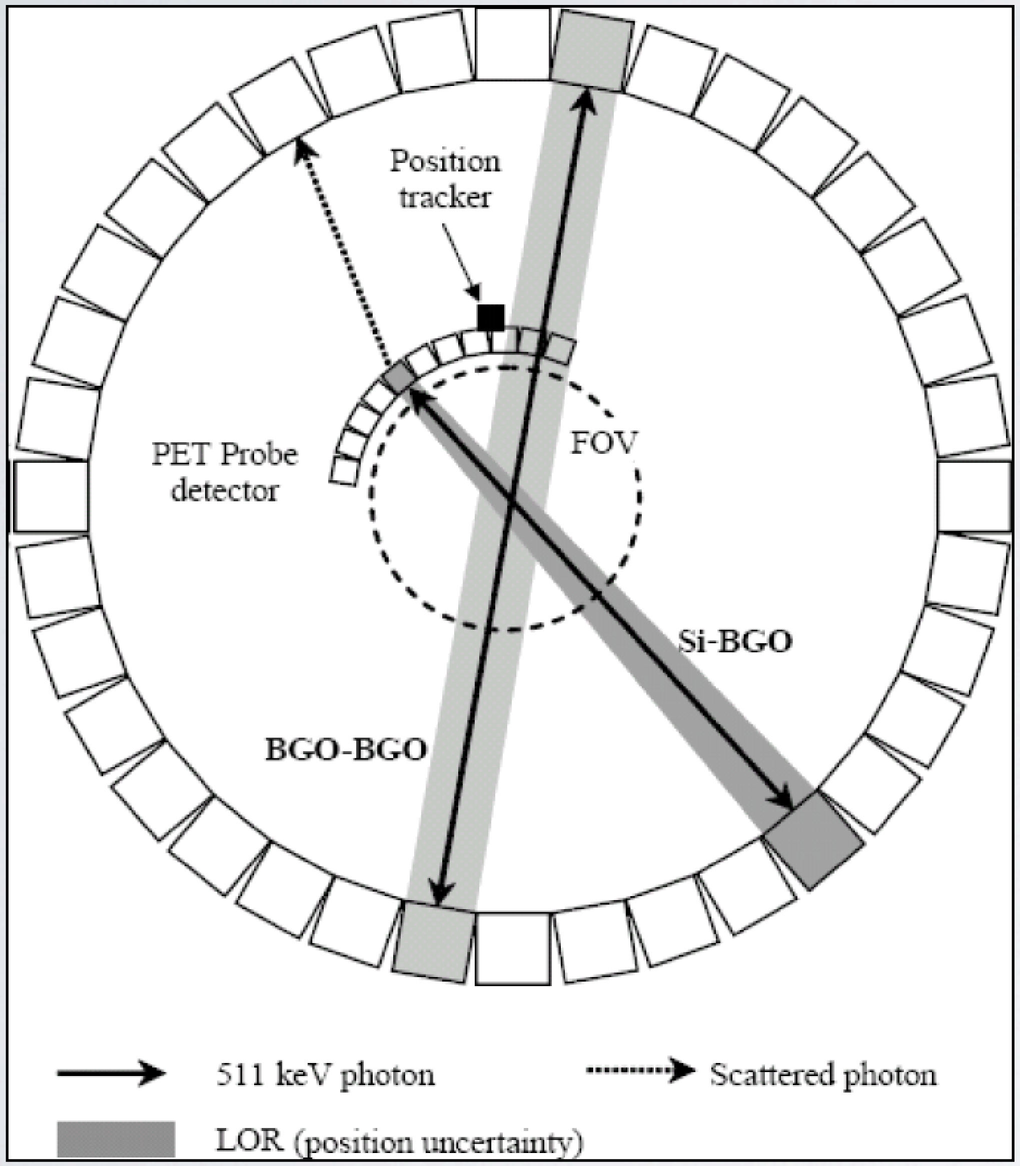




The system was successfully tested with a SPIROC ASIC 32 channels (16 used).

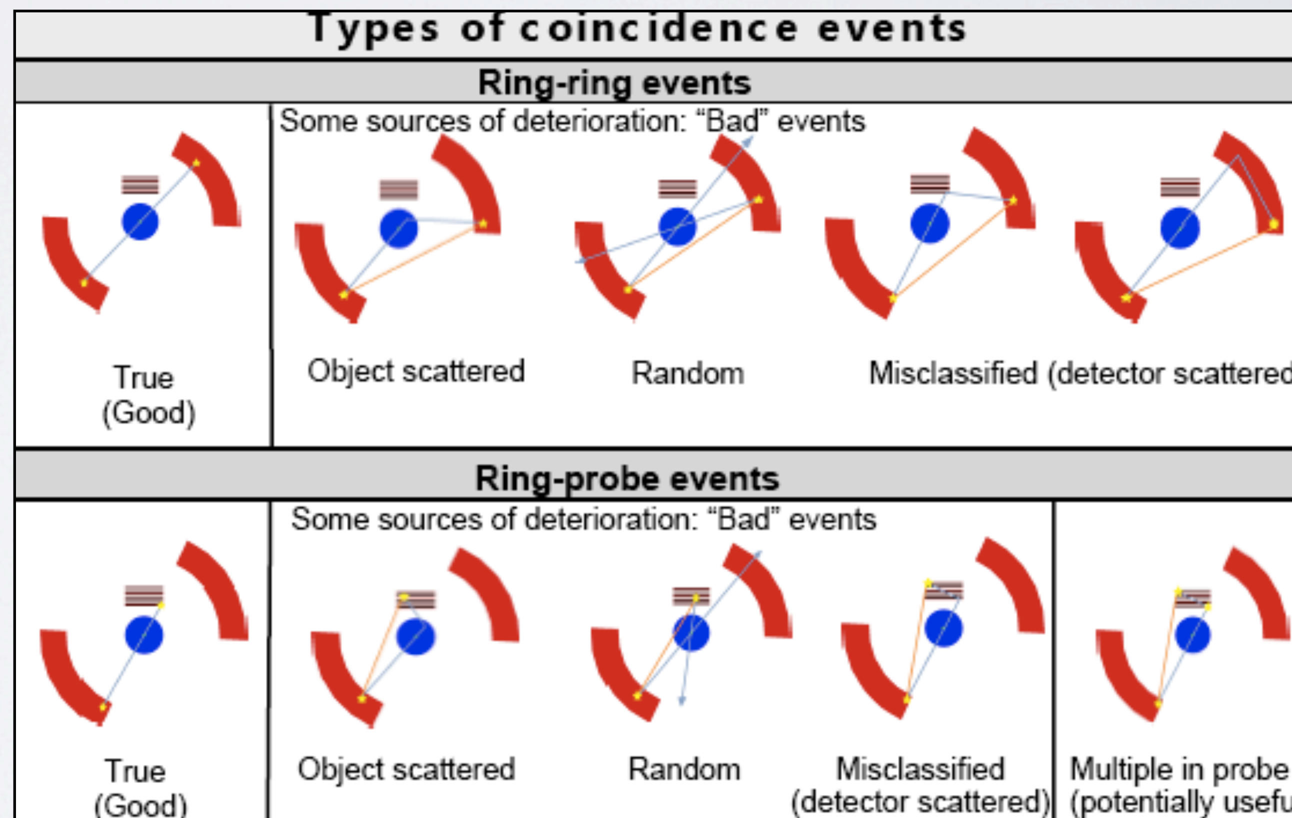
# MADEIRA: THE CONCEPT

Minimizing Activity and Dose with Enhanced Image quality by Radiopharmaceutical Administration

The MADEIRA project explores the possibility to employ a Silicon pixellated detector probe to improve the spatial resolution of a PET scanner.

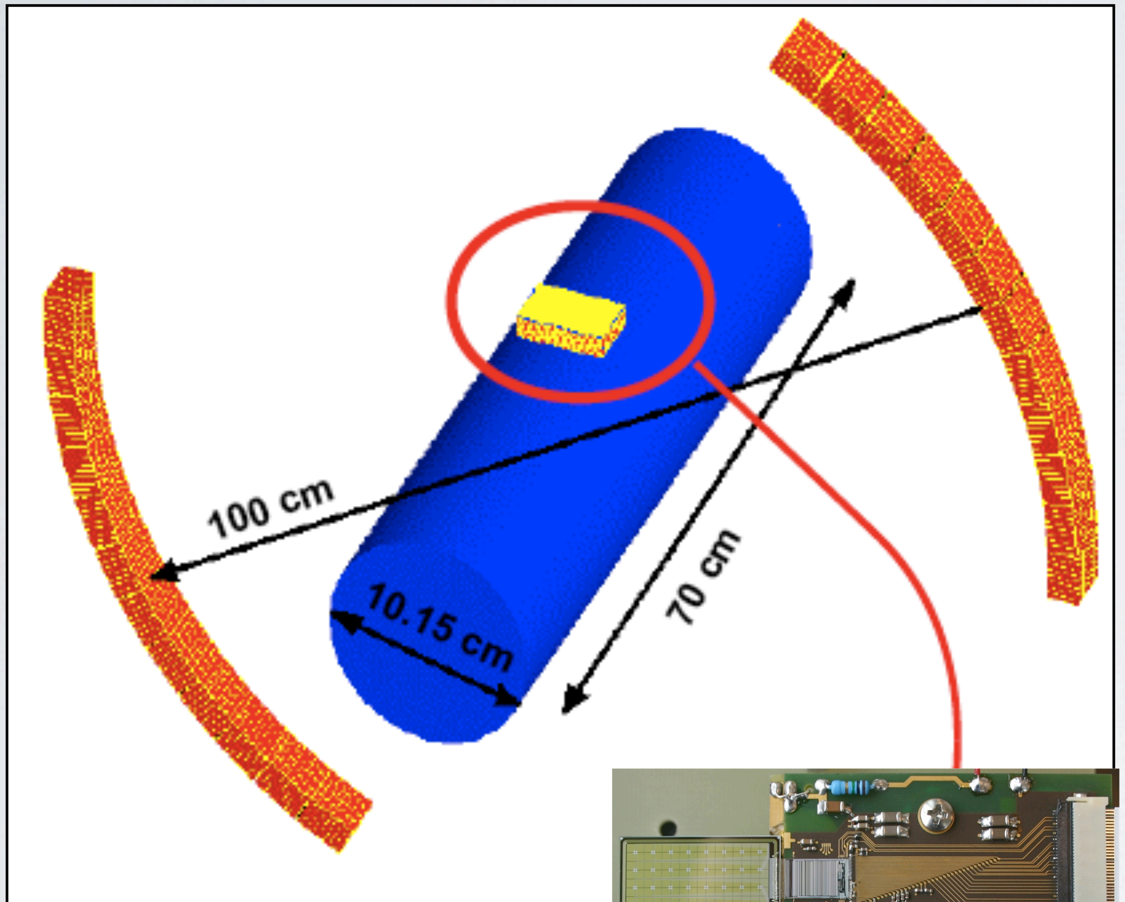


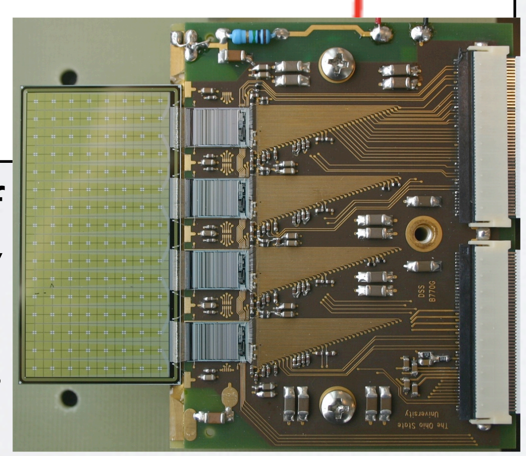

The probe is a stack of Silicon detectors set in coincidence with the PET scanner detectors. The coincidences come as different ring-probe combinations, that are explored in order to exploit the device and reduce possible degradation sources.



# MADEIRA: PRELIMINARY RESULTS

In order to optimize and characterize the system configuration, and model its physical response dedicated Monte Carlo simulations were performed by using GATE.

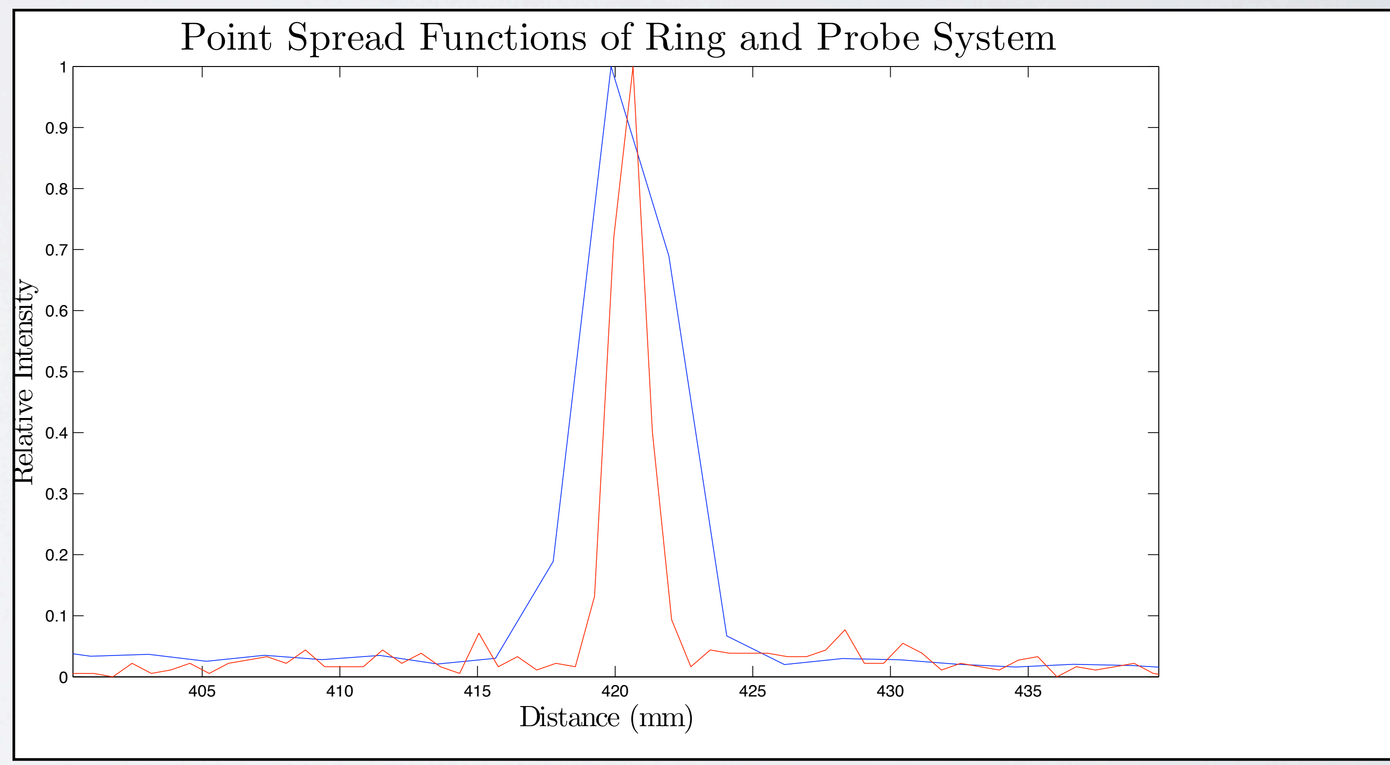


10 layers of 52 x 80 pixels of 1x1x1 $mm^3$, 1.5 keV energy resolution. Singles threshold of 20 keV and multiples thresholds at 300 keV and 400 keV.

Small amount ~5% of ring-ring events are affected by the probe, with small gain in efficiency provided by the use of the latter.

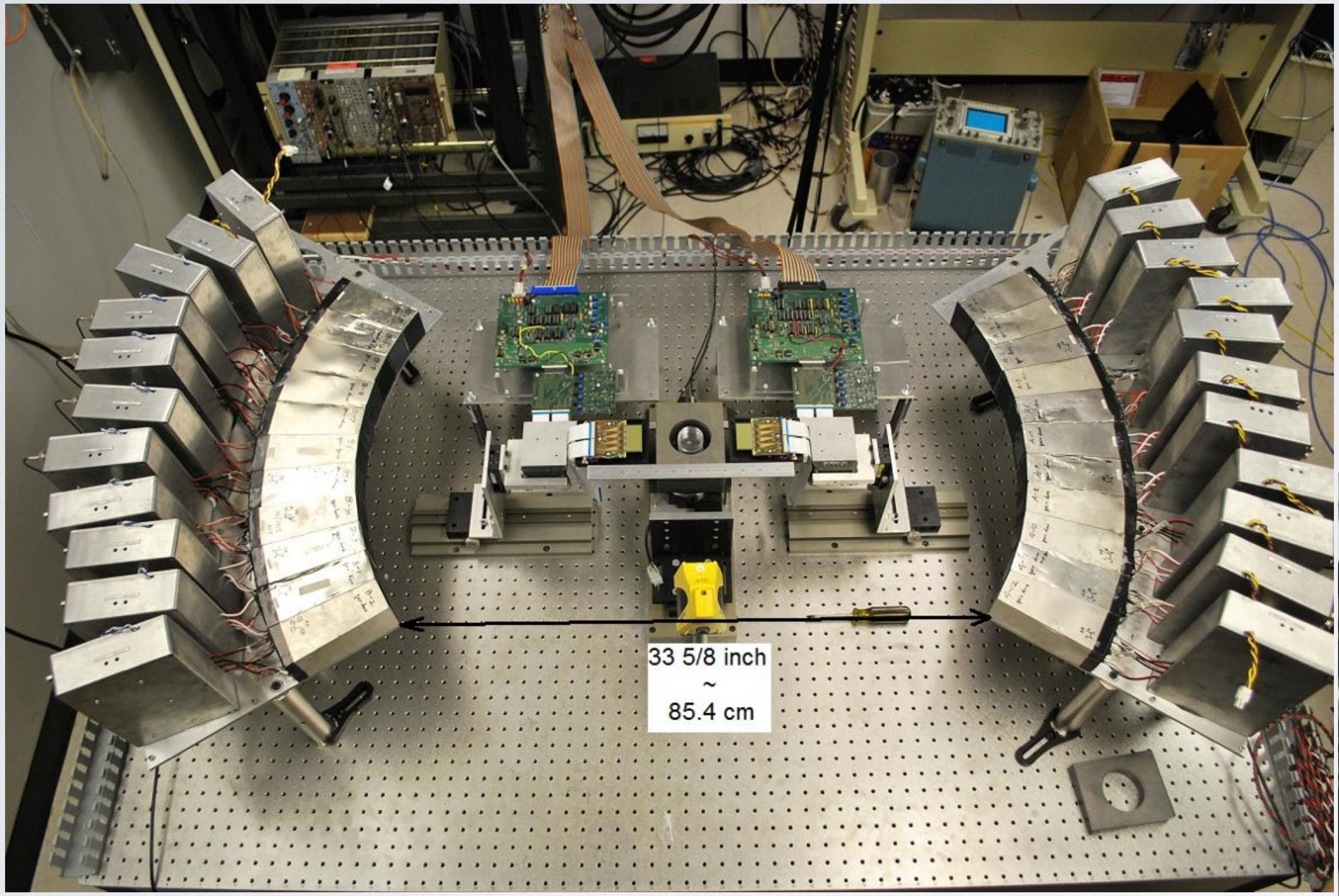
But more extensive studies proved an important gain in spatial resolution by employing the probe.

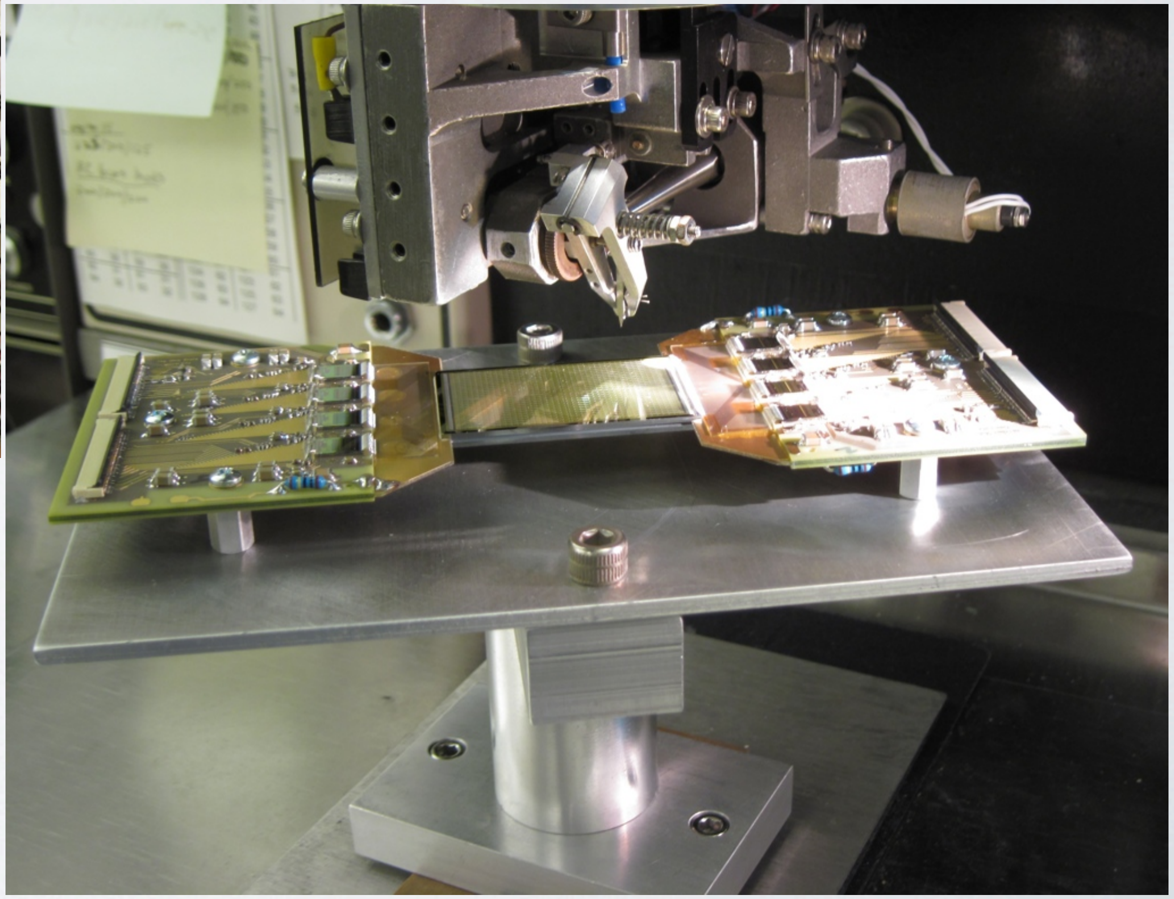



PSF of a point-like source simulated for a probe set in coincidence with a Biograph64 scanner. Blue line: ring-ring events, Red line: ring-probe events.

# MADEIRA: THE EXPERIMENTAL SETUP

A PET scanner + 2 Silicon probes setup was installed at the Medical Imaging and Physics Lab., University of Michigan. It allows coincidences ring-ring, ring-probe and probe-probe coincidences.

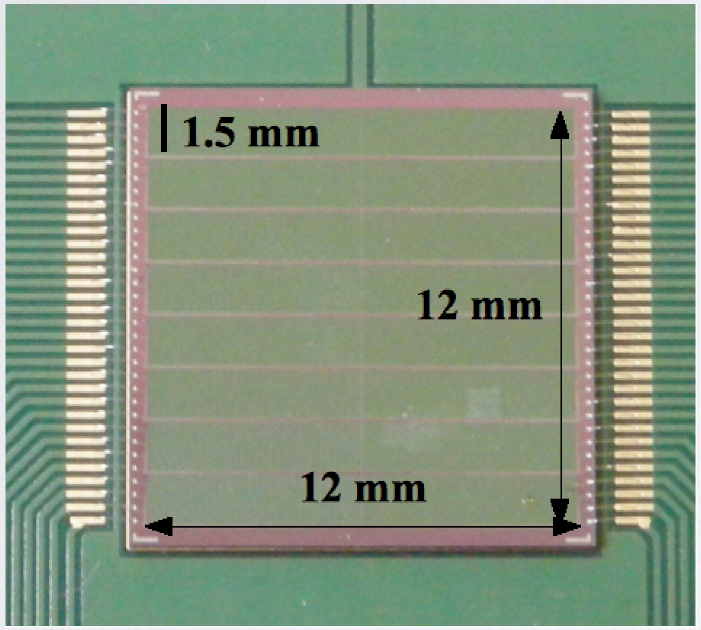


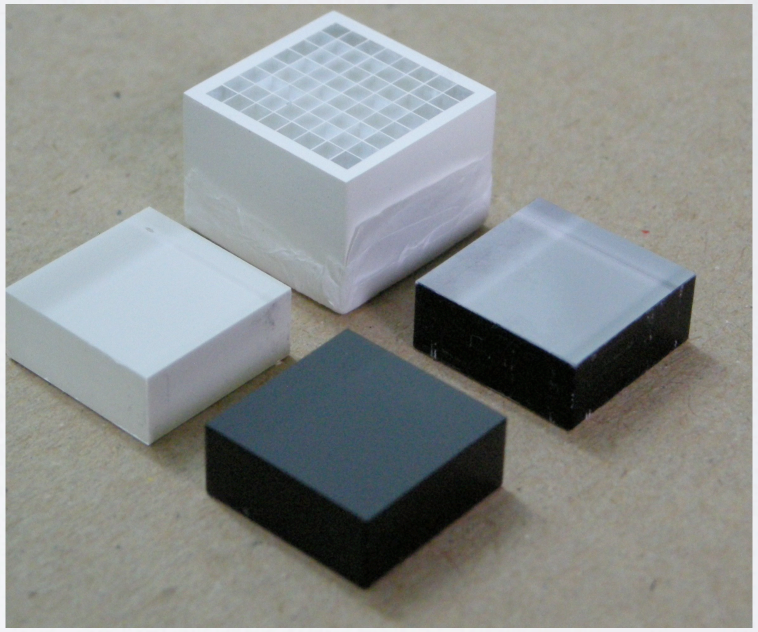



# PETETE

Conceived for a small animal PET detector, PETETE is based on a 12x12x5 $mm^3$ LYSO monolithic detector readout by a 64-pixels SiPM matrix.

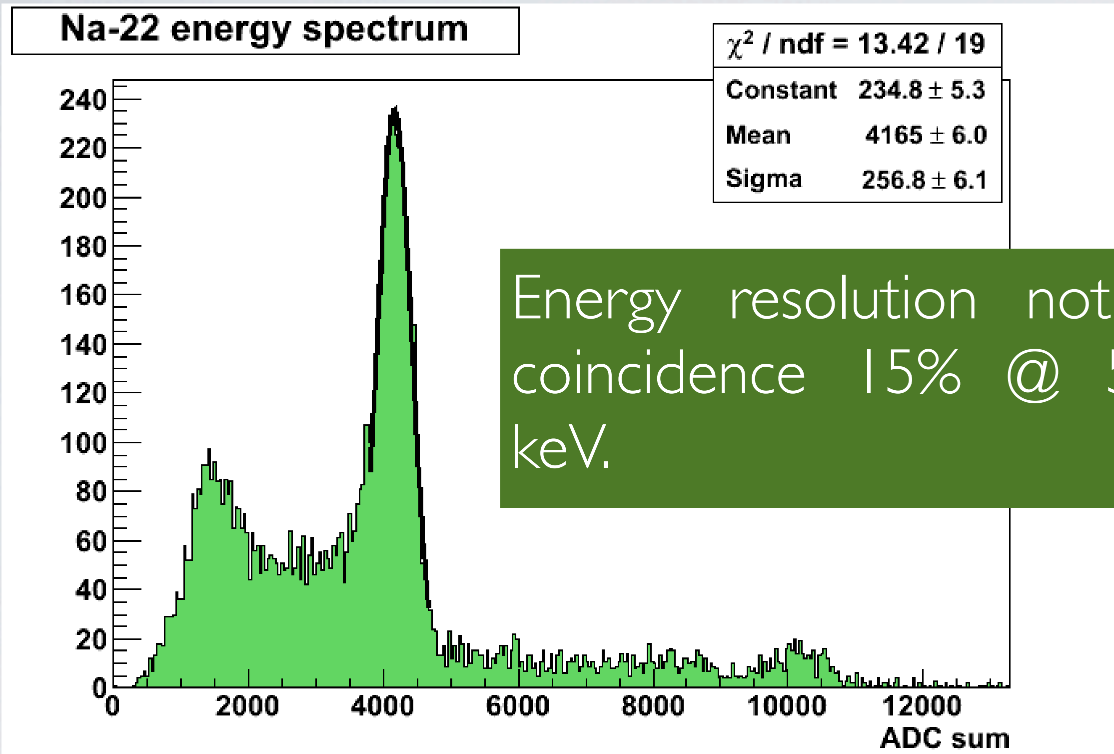
Three continuous crystals have been employed in the characterization tests: one painted black, one painted white, and one painted black on the sides and white on the back. A pixellated crystal array coupled one-to-one to the matrix has been employed to test the uniformity of the detector.

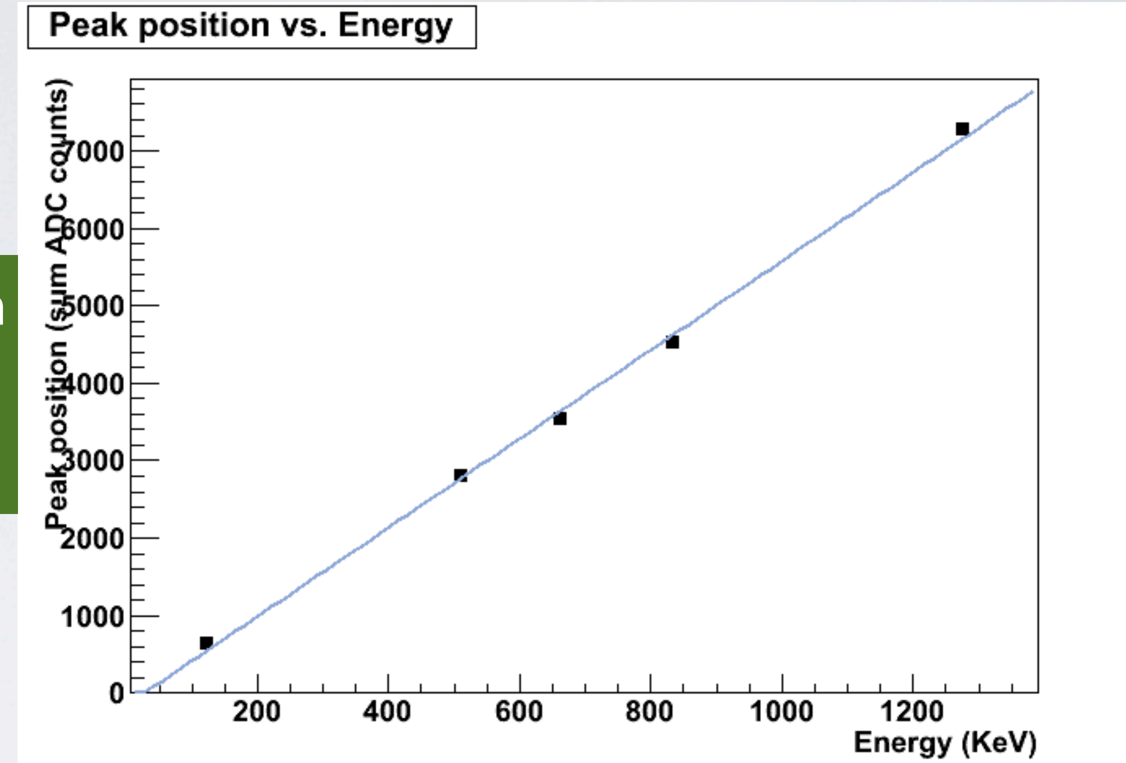


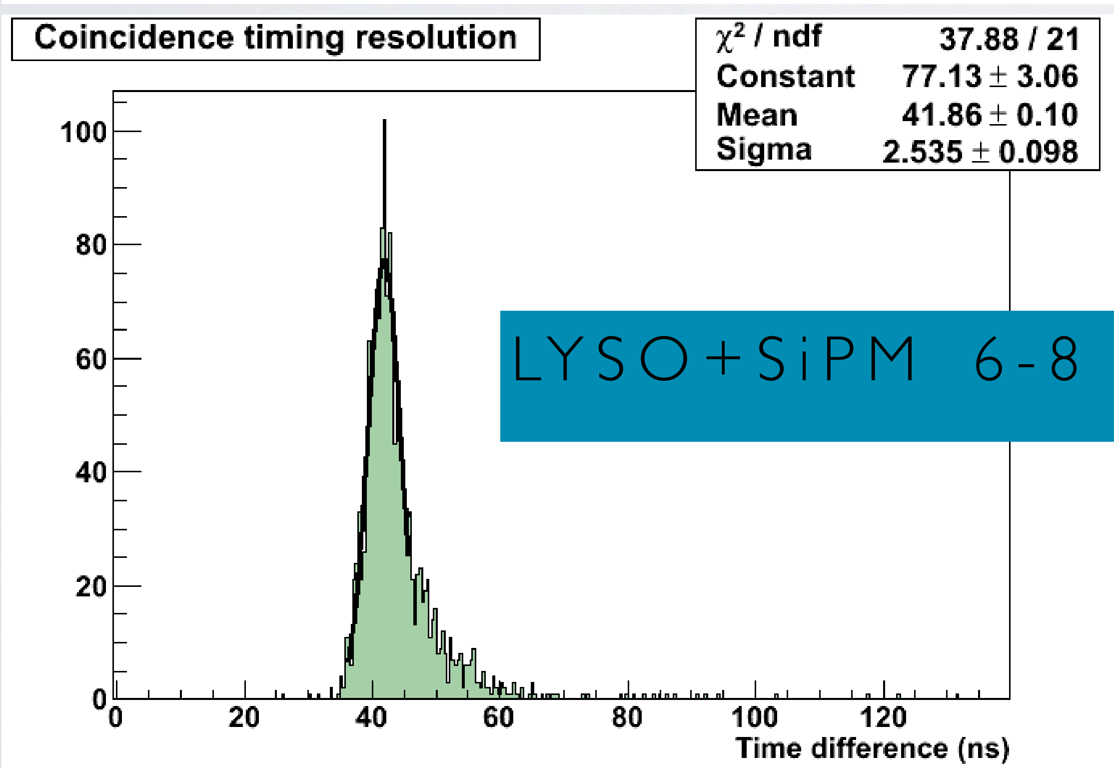
The matrices have been fabricated at FBK-irst. They consist of 64 (8x8) pixel elements in a common substrate. The pixel size is 1.5 mm x 1.4 mm, in a 1.5 mm x 1.5 mm pitch, and each pixel is composed of 840 microcells of 50μm x 50μm size.

# PETETE: DETECTOR PERFORMANCE (I)

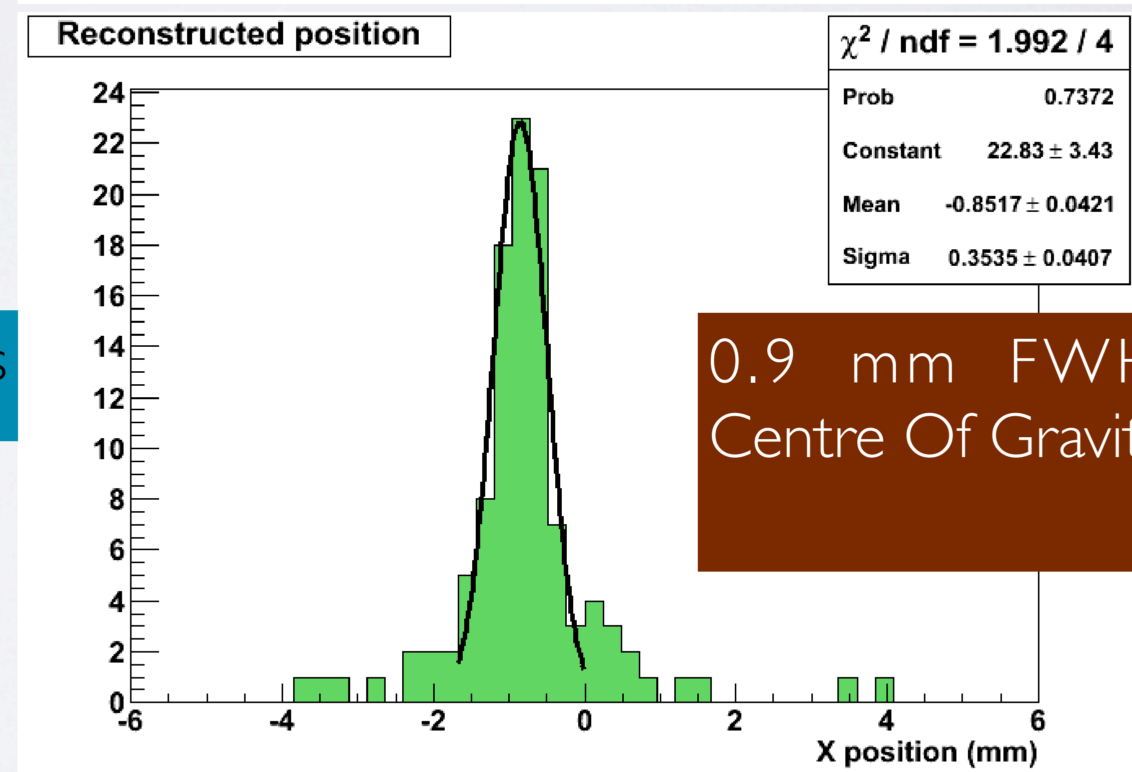



Energy resolution not in coincidence 15% @ 511 keV.



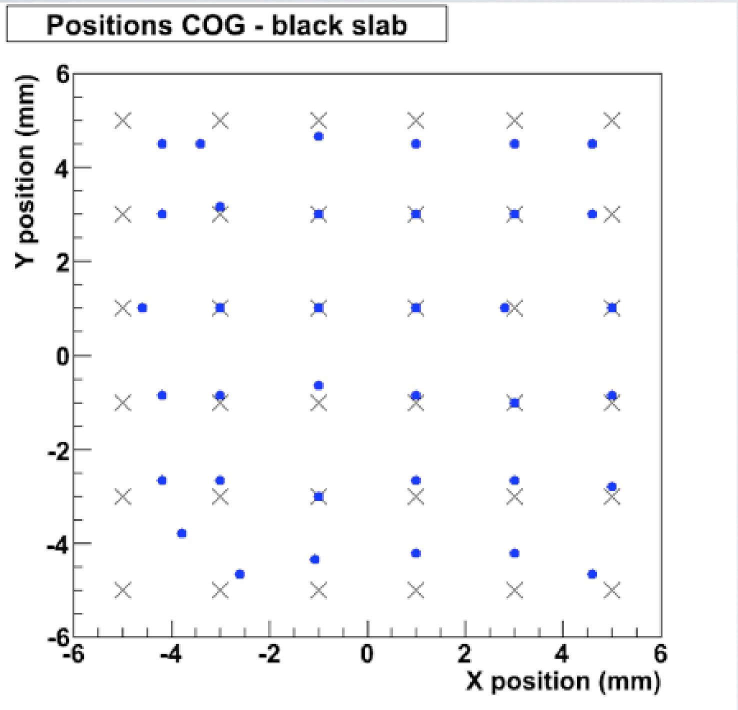

LYSO+SiPM 6-8 ns

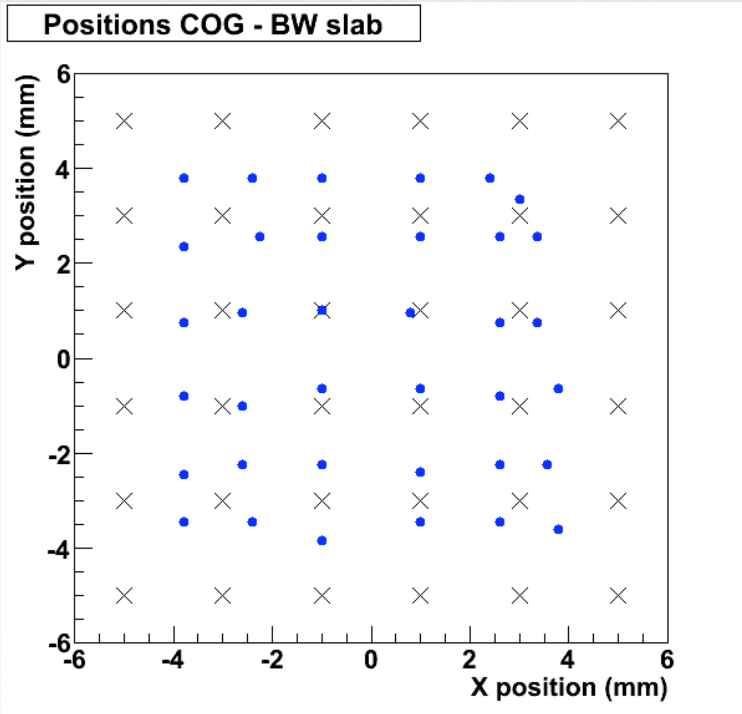


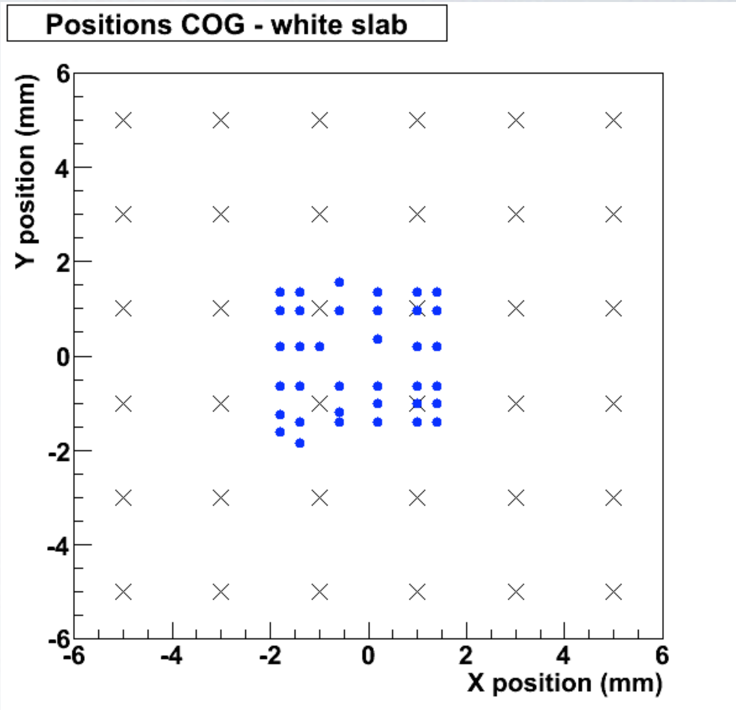

0.9 mm FWHM with Centre Of Gravity

The system was tested with a ASIC MAROC2 64 channels

# PETETE: DETECTOR PERFORMANCE (II)

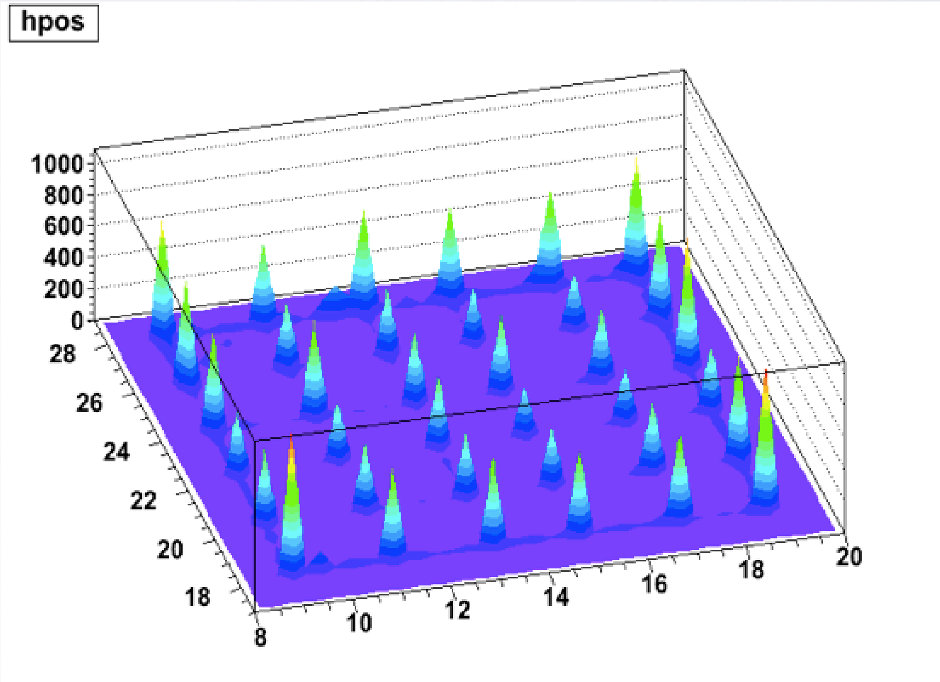



Positioning capability of the device depends on the reflective materials used to cover/treat the scintillator surfaces.

By using appropriate and more sophisticated positioning algorithms the interaction point can be properly reconstructed.



# CONCLUSIONS AND....INTRODUCTION

The devices developed by the IRIS group cover a wide range of applications, exploiting innovative approaches in order to improve both resolution and sensitivity in ET imaging.

**The detector developments needs to be supported by dedicated software in order to fully exploit the high potential.**

* Monte Carlo simulations are needed to help in **understanding the involved physics processes** and therefore support the detector development;

* Algorithms to further **model the system response** and correct for degradation effects:

* **Dedicated data format and reconstruction algorithms** considering the peculiarities of the system.