

# XEMIS2 Compton detector for 3-photon medical imaging

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Workshop GdR Mi2B

November 30 – December 1, 2021 @ CPPM Marseille

## Context

### Motivation

XEMIS project

Liquid xenon

3-photon imaging



**Personalized medicine:**  
smaller dose  
faster exam  
better sensitivity ...

Detector technologies  
based on solid scintillators



Alternative technologies  
combining all advantages?

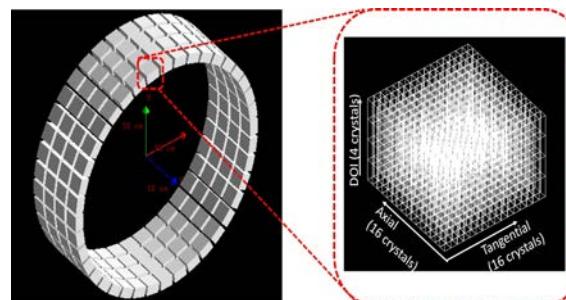
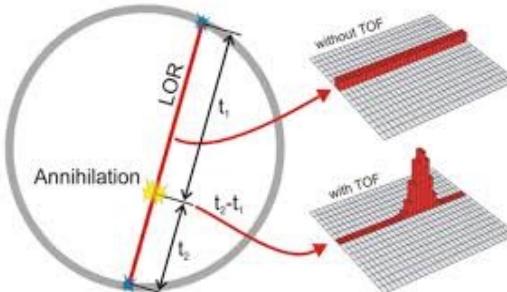


## Detector technology advances in PET imaging

### TB-PET/Total-body Increase FOV

Increase axial FOV of PET camera

*R. D. Badawi et al., First Human Imaging Studies with the EXPLORER Total-Body PET Scanner, J Nucl Med 2019; 60:299–303.*



### TOF-PET/Time Of Flight Shorten length of LOR

Detectors with very good CTR

*P. Lecoq, Pushing the Limits in Time-of-Flight PET Imaging, IEEE Trans. Rad. Plasma Med. Sc., Vol 1, No 6, Nov. 2017.*

### DOI-PET/Depth Of Interaction Reduce Parallax effects

Precise DOI measurement on the whole FOV  
*Eiji Yoshida et al., Development of a Whole-Body Dual Ring OpenPET for in-Beam PET, IEEE Transactions on Radiation and Plasma Medical Sciences ( Volume: 1 , Issue: 4 , July 2017 ).*

## Context

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Liquid xenon

3-gamma imaging



Alternative technologies  
combining all advantages?

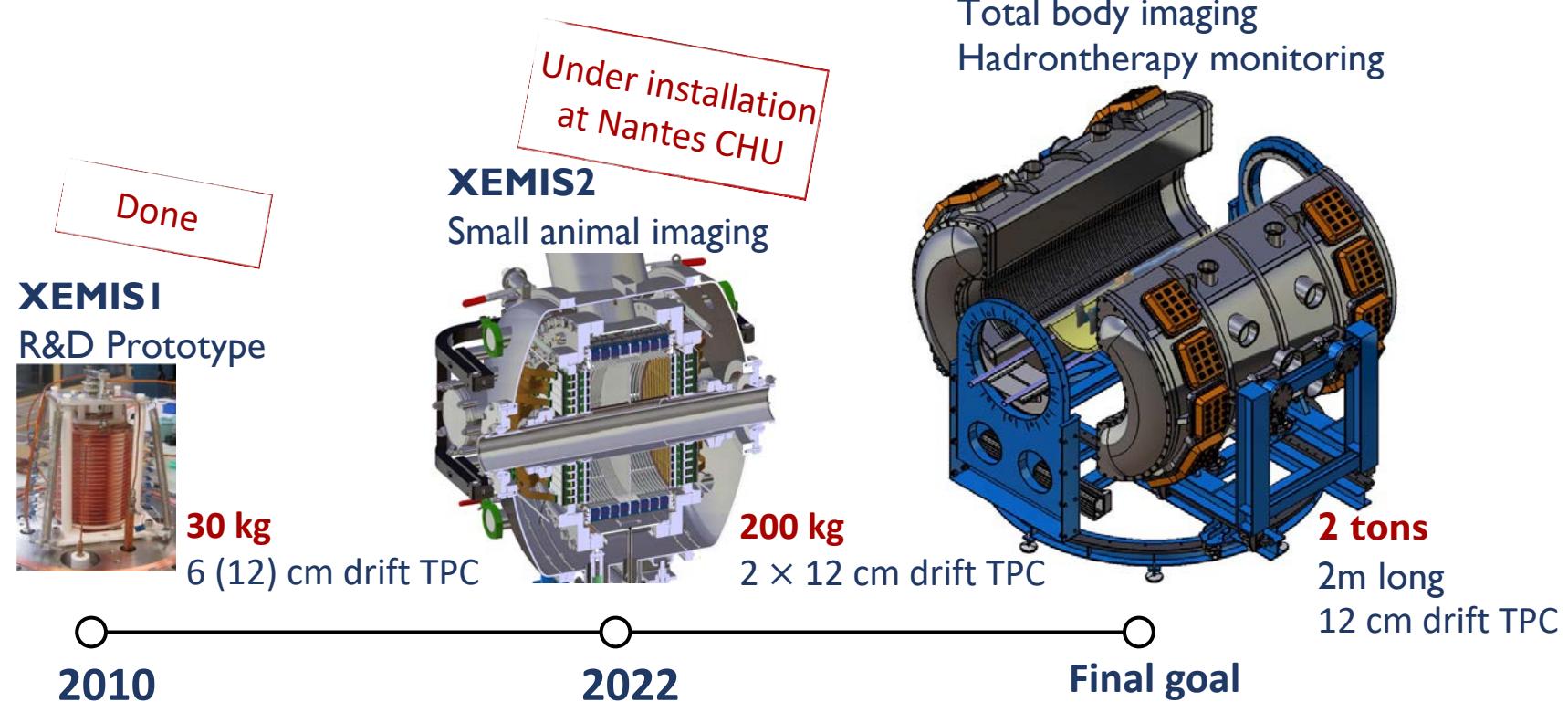
XEMIS

HOW?

- Liquid xenon Compton camera
- 3-photon imaging

## XEMIS (XEnon Medical Imaging System)

- Total Body, TOF like, parallax free medical imaging technique
- High Rate Single Phase LXe Time Projection Chamber
- XEMIS2 already the biggest Compton telescope with LXe ever done



## Context

Motivation  
XEMIS project  
Liquid xenon  
3-photon imaging

### XEMIS

Monolithic | Homogeneous | scalable  
 → Increase efficiency & FOV  
 DOI measurement  
 → Parallax free

## Emerging monolithic radiation detection medium

- ✓ High stopping power ( $Z = 54$  &  $\rho = 3.06 \text{ g.cm}^{-3}$ ) for  $\gamma$ -rays from 10 keV to 10 MeV
- ✓ Simultaneous production of the **scintillation** and **ionization** signals
- ✓ High scintillation light yield and high ionization yield

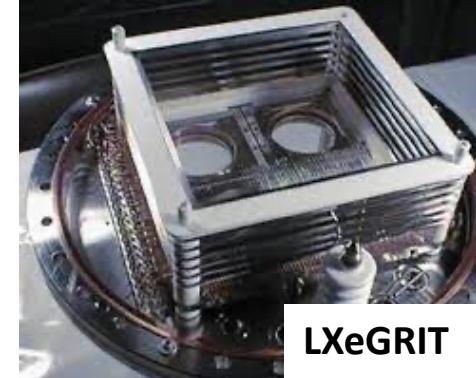
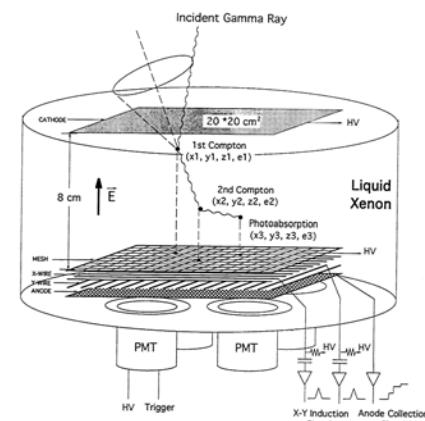


**Scalable to large, massive and homogeneous detectors**

XENON, LUX, Panda-X, nEXO, XMASS, MEG ... ...

in the researches of

$\gamma$ -ray astronomy / Dark matter/  $0\nu\beta\beta$  ...



Single phase **liquid xenon Compton telescope** for MeV energy cosmic  $\gamma$ -ray imaging

Goetzke, L. W., Aprile, E., Anthony, M., Plante, G., & Weber, M. (2017), 103007.



**Precise vertex position measurement**

# Context

Motivation  
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Liquid xenon

## 3-photon imaging

### XEMIS

Monolithic | Homogeneous | scalable  
 → Increase efficiency & FOV  
 DOI measurement  
 → Parallax free  
 “TOF-like” PET imaging  
 → Direct 3D source location



5

# 3-photon imaging: “TOF-like” PET



**Direct 3D source location:**  
 Line of Response & Compton Cone Intersection (LCCI)

- $(\beta^+, \gamma)$  emitter in quasi-coincidence:

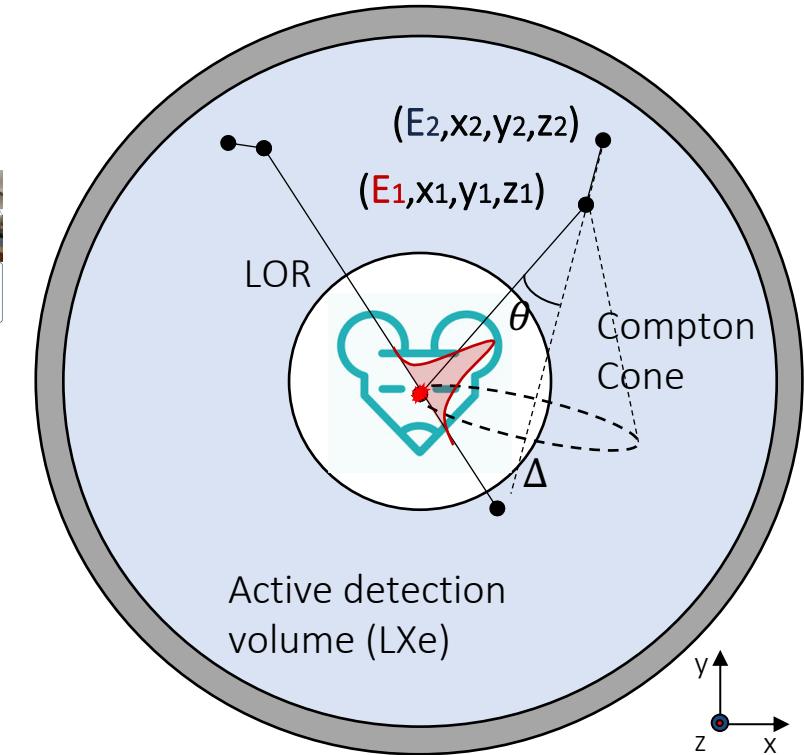
↪  $^{44}\text{Sc}$  {  $\beta^+$  ( $E_{\text{max}} = 1.472$  MeV)  
 $\gamma$  ( $E_0 = 1.157$  MeV)  
 $T_{1/2} = 4$  h



- $\gamma$  direction reconstruction :

↪ Compton kinematics

$$\cos\theta = 1 + m_e c^2 \left( \frac{1}{E_\gamma} - \frac{1}{E_1} \right)$$



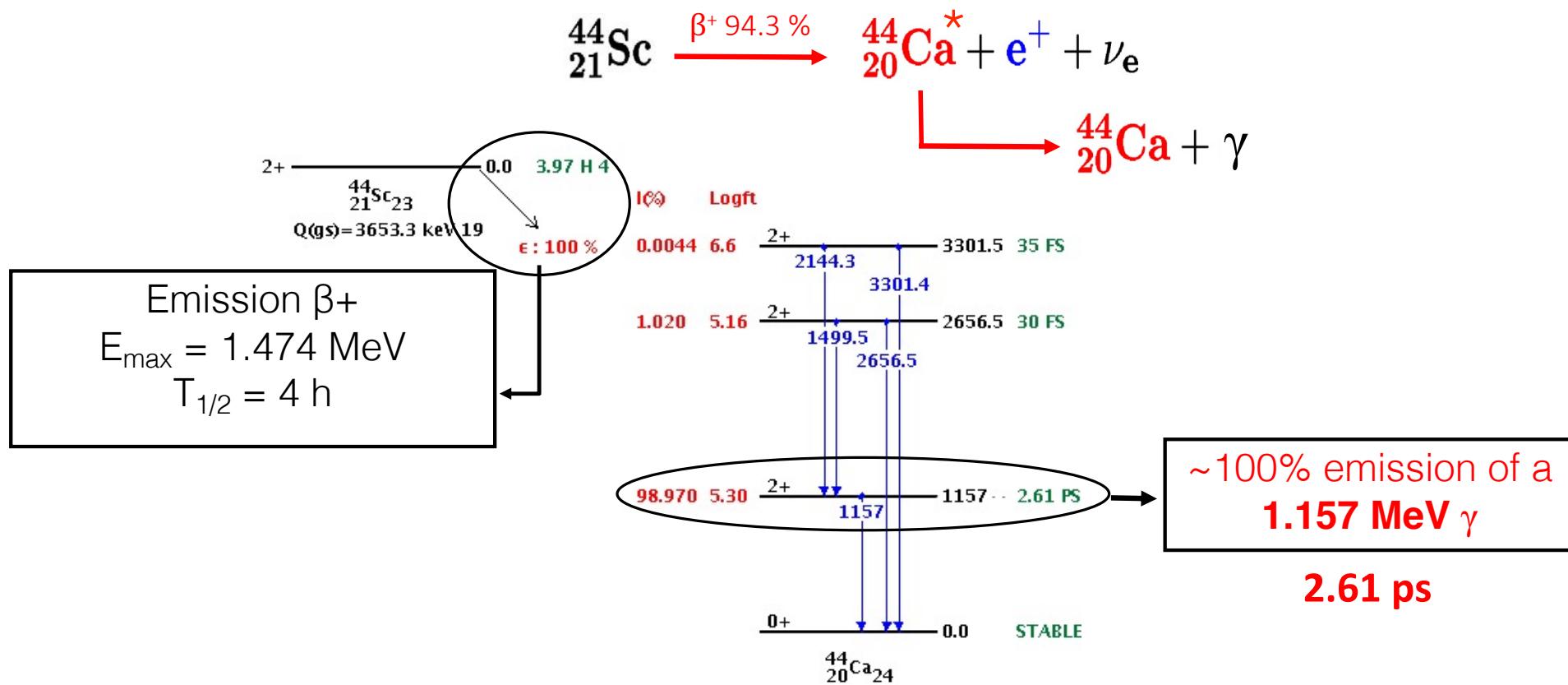
**Image quality**

**Angular resolution of  $2^\circ$  @ 1 MeV**

Axis  $\Delta$  of the cone ⇒ **Spatial resolution  $\sim 100 \mu\text{m}$  in 3D**

Opening angle  $\theta$  ⇒ **Energy resolution  $2\sim 3\%$  @  $\sim 1$  MeV**

# Good $\beta^+$ / $\gamma$ emitter radionuclide for 3 $\gamma$ medical imaging: $^{44}\text{Sc}$



R&D

{
   
 $^{44}\text{Sc}$  production: ARRONAX cyclotron
   
 Radiopharmaceutical labeled with  $^{44}\text{Sc}$ : CRCNA



30/11/2021-01/12/2021 | CPPM Marseille

Experimental facility

Working principle

Detector design

Data acquisition system

Conceived and Developed  
@ SUBATECH



ReStoX LXe cryogenic station:  
Liquid xenon storage and  
security operation in hospital

Commissioning @ SUBATECH

Subatech  Air Liquide



Installation @ Nantes CHU



Experimental facility  
Working principle  
Detector design  
Data acquisition system

### Scintillation signal (SS ↔ S1)

VUV scintillation light (178 nm)

$\gamma$ -Xe → **Interaction Time  $t_0$**

### Ionization signal (IS ↔ S2)

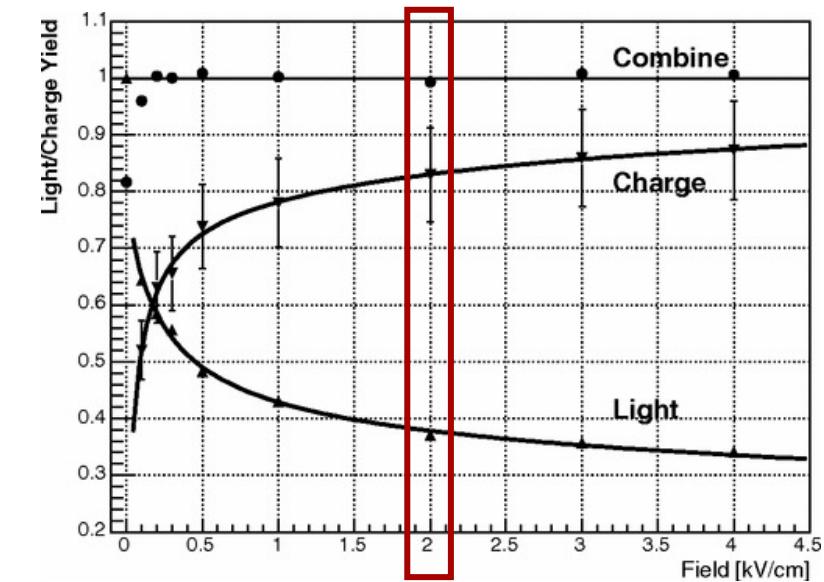
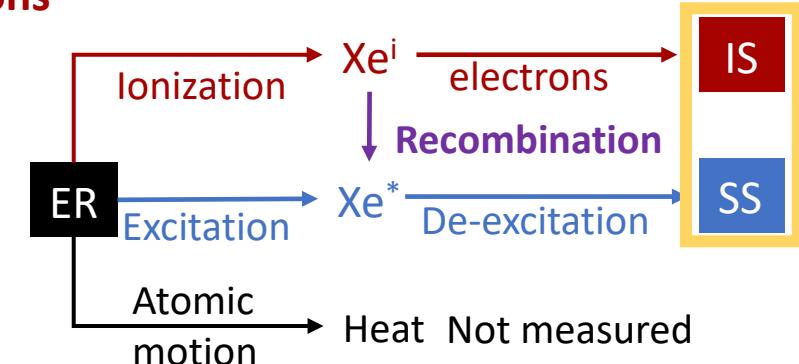
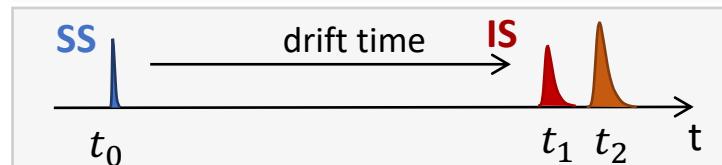
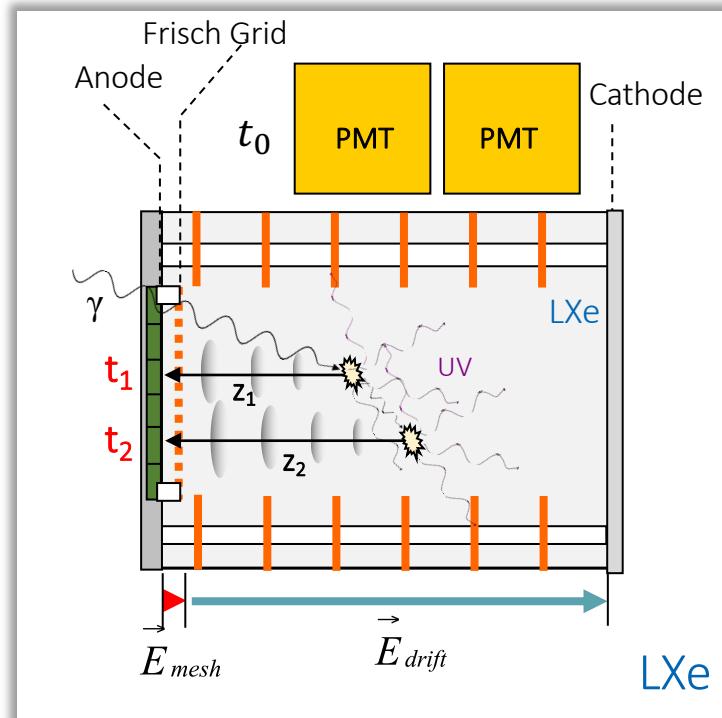
Charge transport and collection

→ **Interaction vertex ( $x, y, z, E$ )**

→ **Vertex separation**

## Liquid Xenon Time Projection Chamber

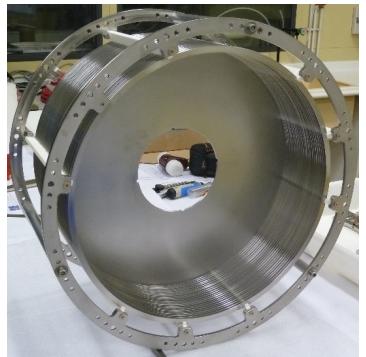
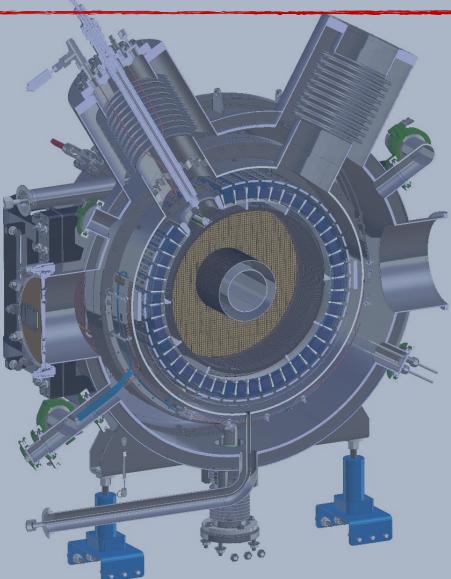
Particle interaction in the active volume produces prompt  
**scintillation light** and **ionization electrons**



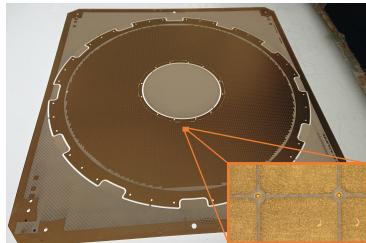
**High electric field 2 kV/cm**  
**Energy measurement thanks to high charge yield**

Experimental facility  
Working principle  
Detector design  
Data acquisition system

**Objective:**  
low activity (20 kBq) small animal imaging in 20 minutes (first phase) with same image quality with PET



**Central cathode**



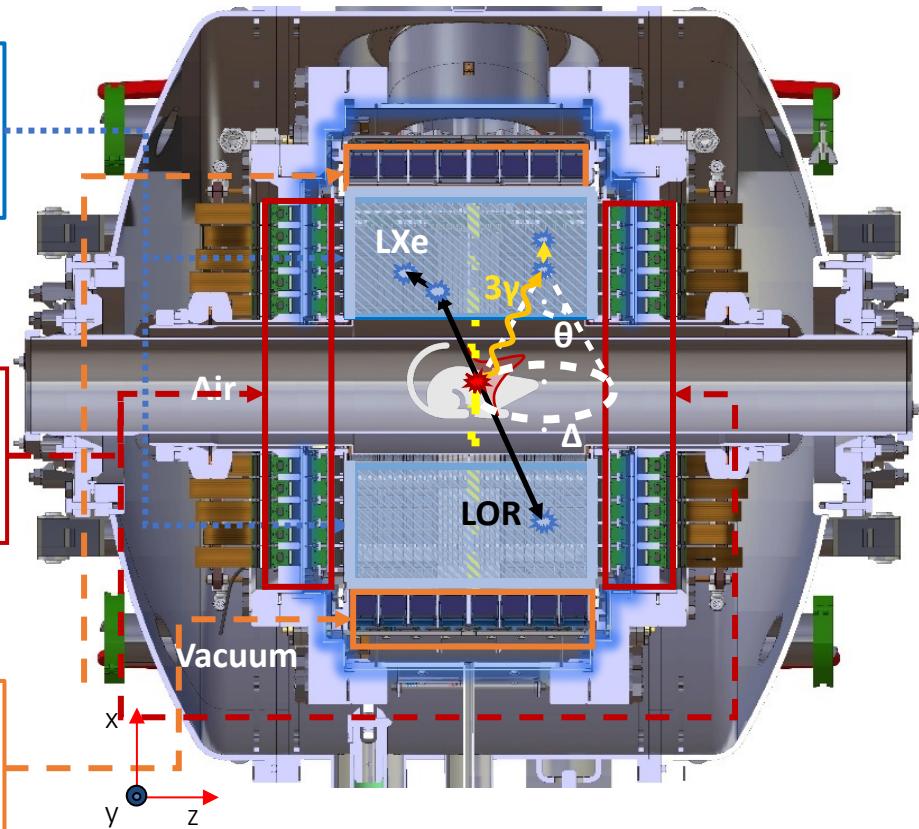
**MIMELI**



**PMTs & Support**

## XEMIS2 camera for small animal imaging

**High Purity LXe Compton Camera**  
at 1.2 bar (168 K) with 200 kg LXe



**LXe TPC**

Active volume ~24 L  
- axial : 2 x 12 cm  
- radius: 7 -> 19 cm

**Charge readout**

2 x 10<sup>4</sup> 3.1 x 3.1 mm<sup>2</sup> pixels with ultra-low noise cold FEE

**Light readout**

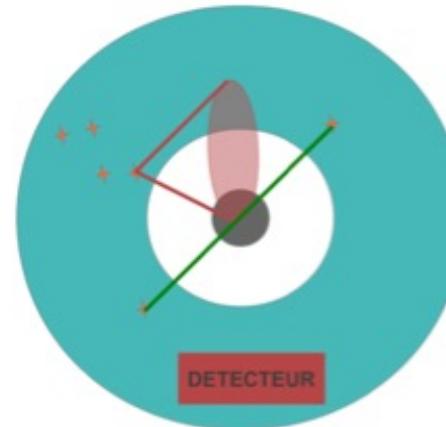
64 x 1'' Hamamatsu PMTs in LXe  
Cover 32 sectors in  $\phi$

Full Gate/GEANT4 simulation  
High sensitivity  $3\gamma > 7\%$  along the FOV

Experimental facility  
Working principle  
Detector design  
Data acquisition system

Activity as low as 20 kBq  
should be enough!

\*\* Better resolution should  
be obtained with  
 $3\gamma$  imaging reconstruction



ML-EM  
Reconstruction  
Algorithms

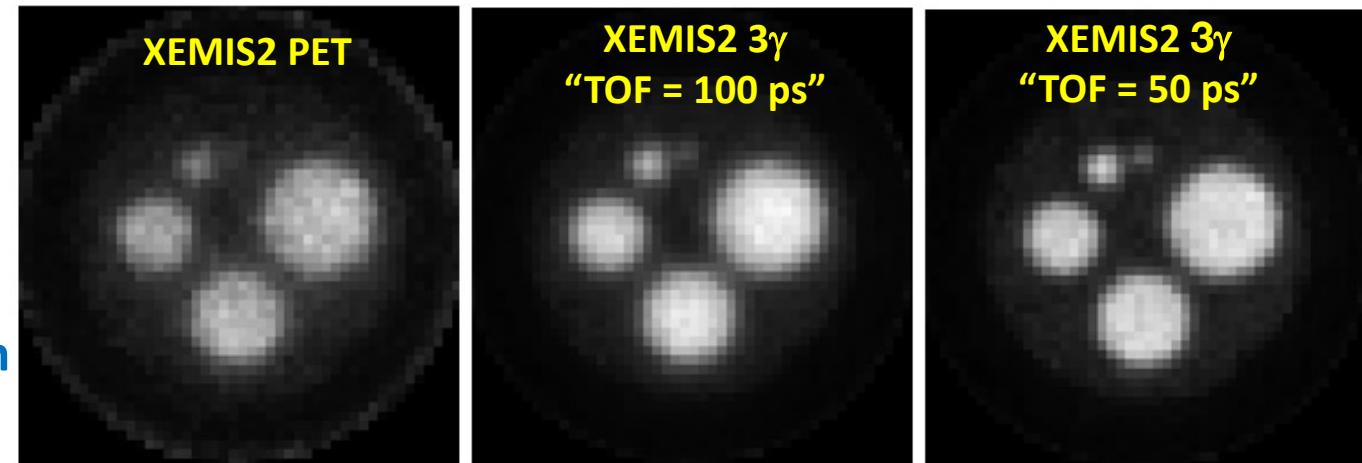
## Reconstruction TOF-PET with CASToR open source

- $3\gamma$  Scandium-44 tracer simulation
- Full camera design simulated with Geant4
- Detector fully simulated
- LOR and cone reconstructed for Crossing point computing

20 kBq, 20 mns exposure

2, 4, 8, 10, 12 mm radius hot sphere ( $^{44}\text{Sc}$  contrast 15)

Debora Giovagnoli's PhD, Nov. 2020



D. Giovagnoli et al., "A Pseudo-TOF Image Reconstruction Approach for Three-Gamma Small Animal Imaging," in IEEE Transactions on Radiation and Plasma Medical Sciences, vol. 5, no. 6, pp. 826-834, Nov. 2021.

Experimental facility  
Working principle  
Detector design  
Data acquisition system

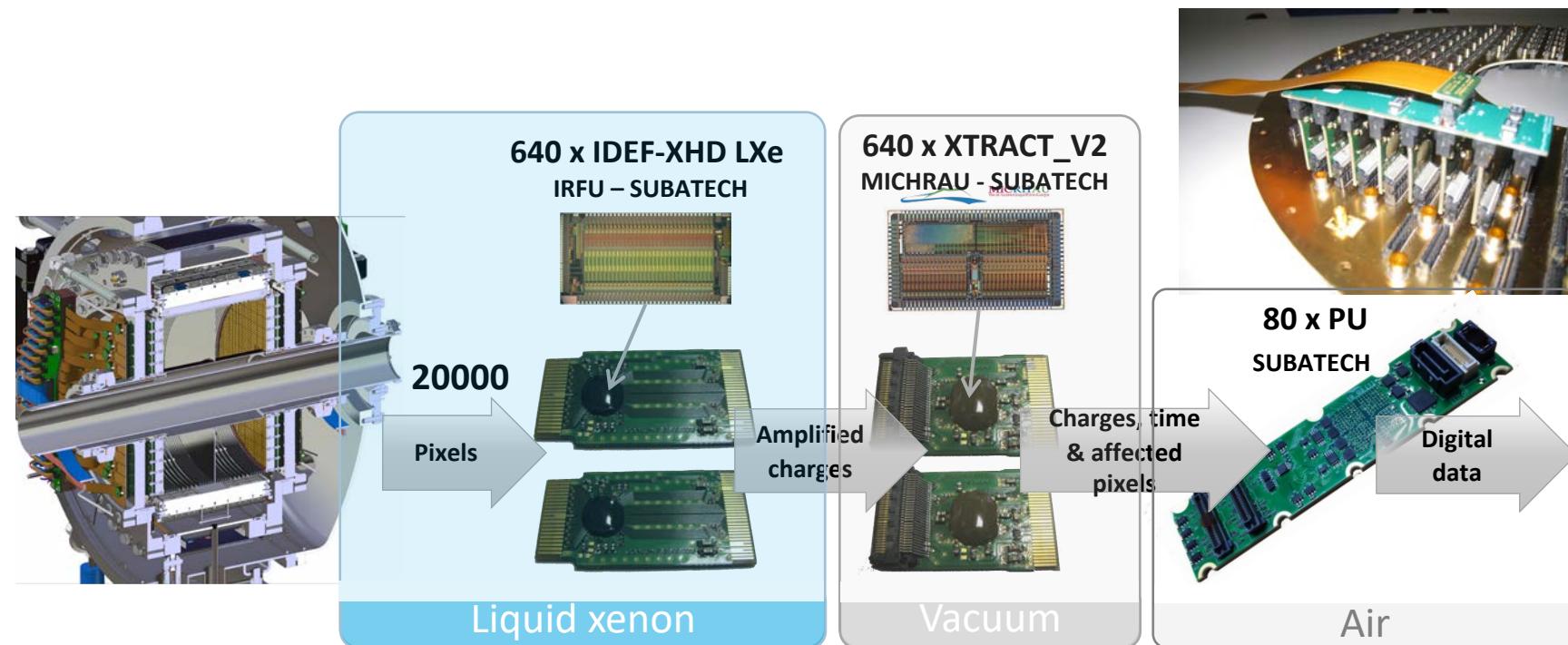


### XEMIS2 small animal imaging 20 kBq – 20 mns

Low activity image  
→ good measurement efficiency  
→ High frequency signals readout  
with processible data flow

## High Rate DAQ for LXeTPC

The commercial DAQ system cannot meet the requirements for use in LXe  
Self-triggered ionization signal readout architecture



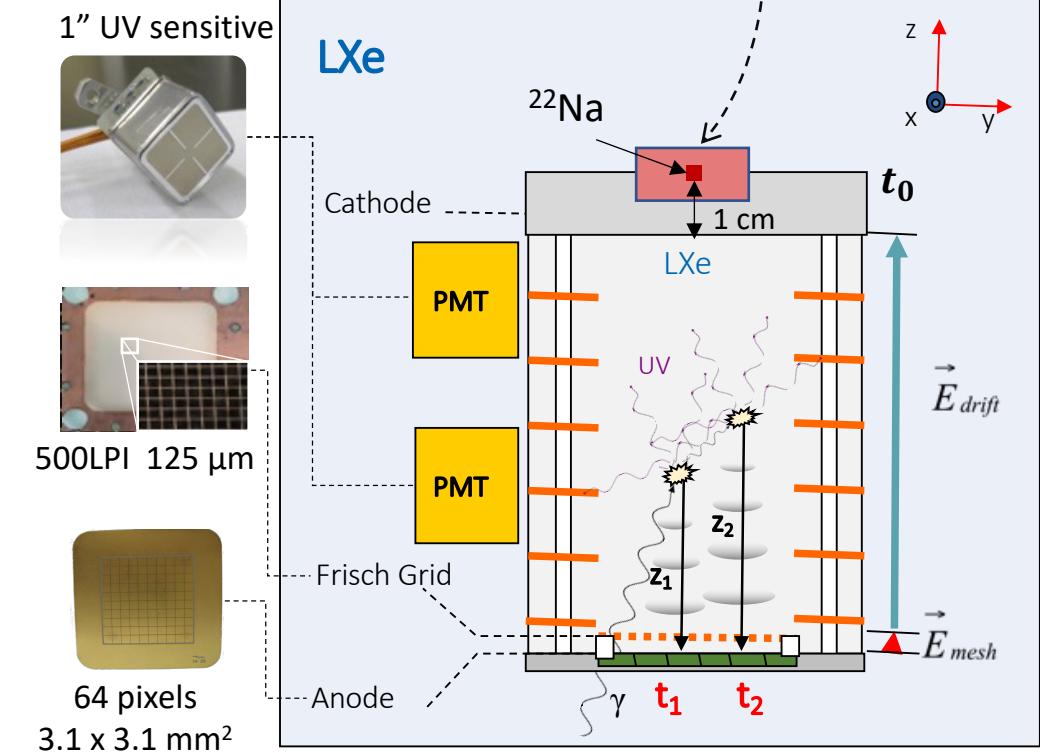
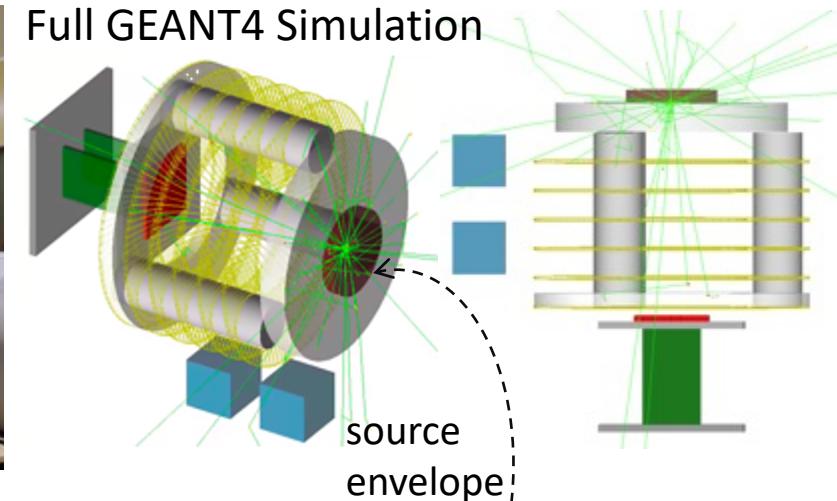
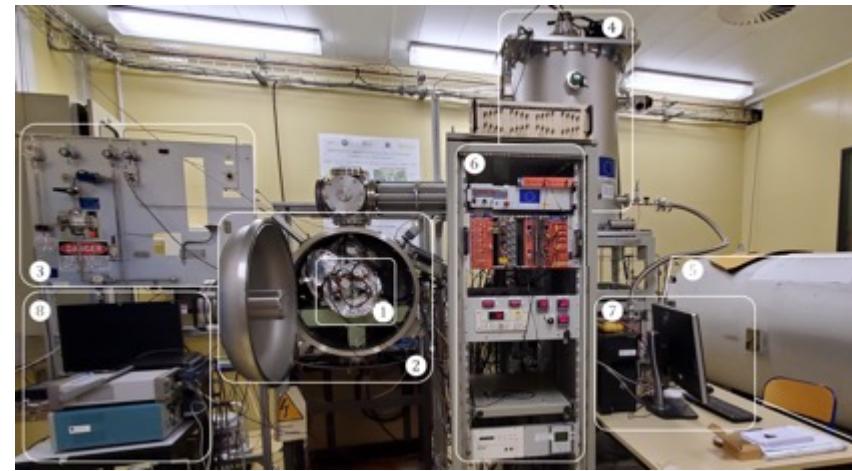
Cold Front-end electronic to reduce the electronic noise  
only **1 amplitude** and **1 time** per ionization pulse escape from the cryostat  
only **2 data lines** escape the vacuum (to the air) for all the measured charges

## XEMIS1 experimental setup

- XTRACT adjustment & calibration
- Photoelectric peak calibration
- Compton Geometric calibration

### XEMIS1 TPC characteristics

- **30 kg** ultra pure LXe
- Active volume **6.5 x 2.5 x 2.5 cm<sup>3</sup>**
- **2 x 1"** square UV sensitive PMT
- Segmented anode – **MIMELI**  
2.5 x 2.5 cm<sup>2</sup> active in **64 pixels**
- Frisch grid – **500 LPI Micromesh**
- **6** Field shaping rings (**gap 1cm**) for homogeneous drift field of **2 kV/cm**
- **Source↔active zone = 1 cm**

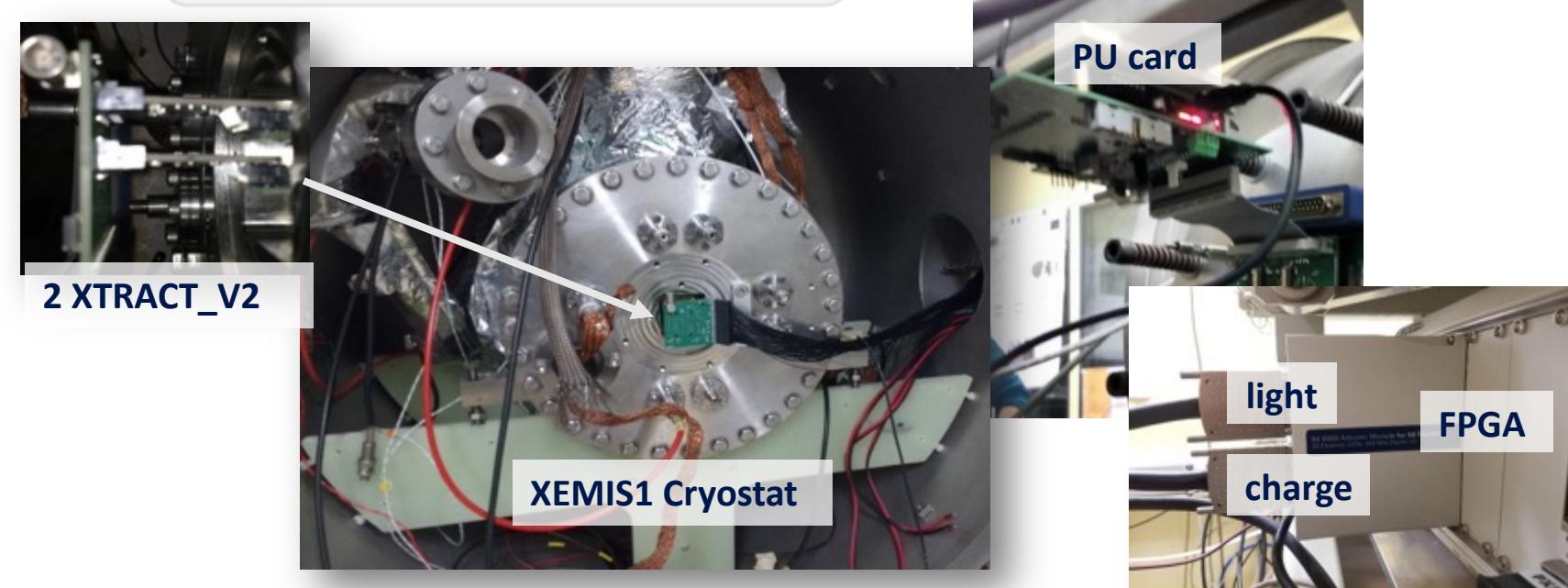
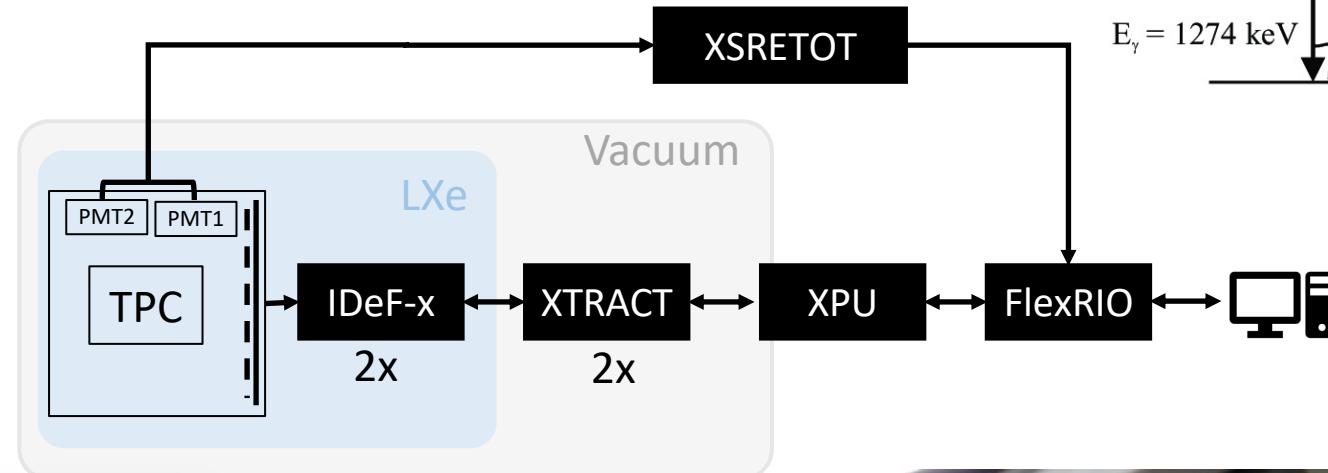
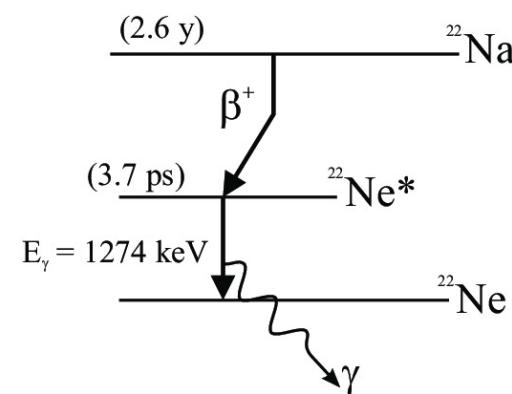


## XEMIS1 experimental setup

- XTRACT adjustment & calibration
- Photoelectric peak calibration
- Compton Geometric calibration

## Novel DAQ electronic prototype

$^{22}\text{Na}$ : ( $E_{\text{max}}\beta^+ = 545 \text{ keV}$ ,  $E_\gamma = 1.274 \text{ MeV}$ ) **3 gamma emitter**



## Energy resolution

Z resolution

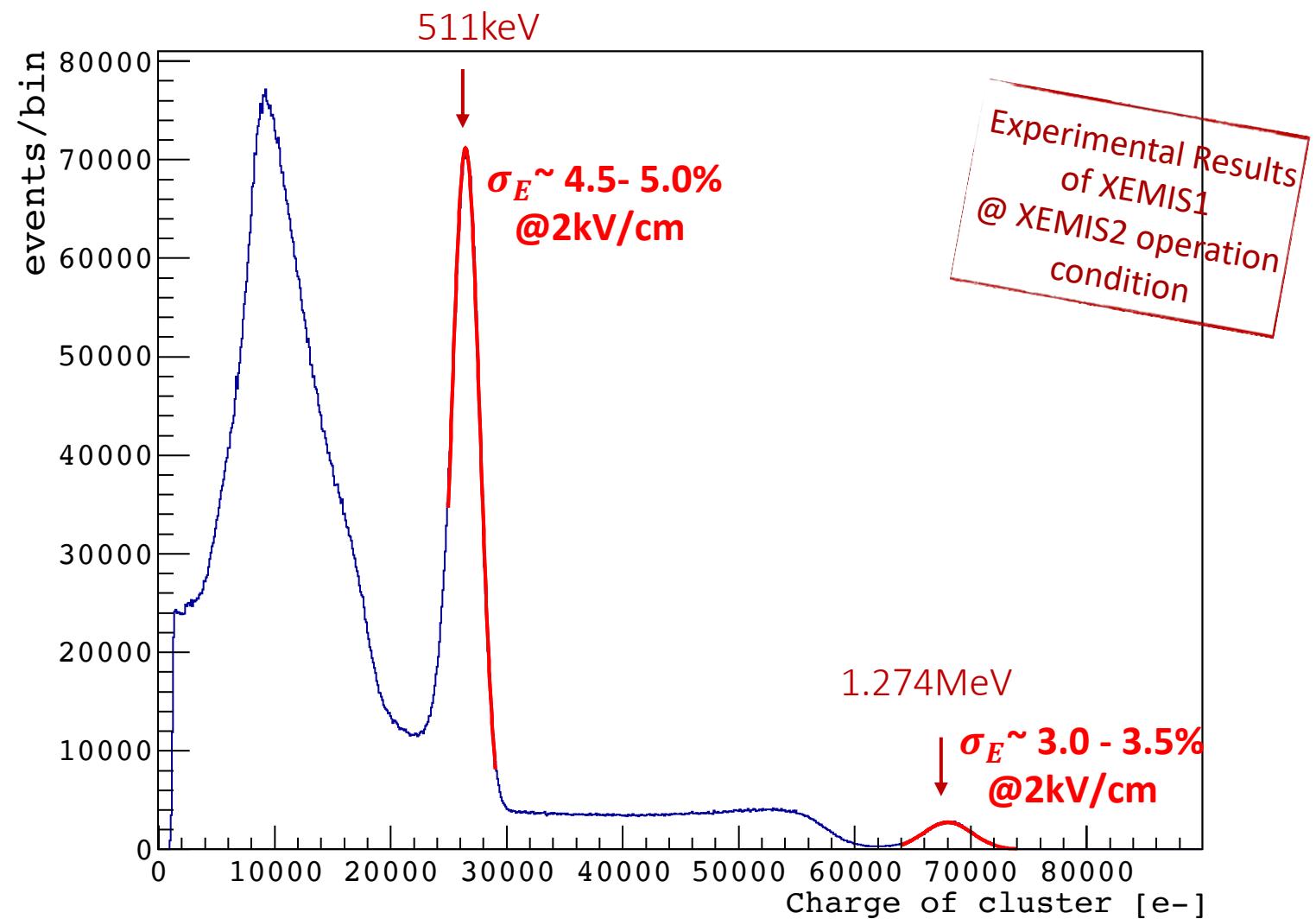
XY resolution

Angular resolution

Asymmetric events distribution in the PE peak

-> scattered  $\gamma$ -ray

-> overlapping physics interactions

Energy resolution with single scatter and  $^{22}\text{Na}$  source

# Results

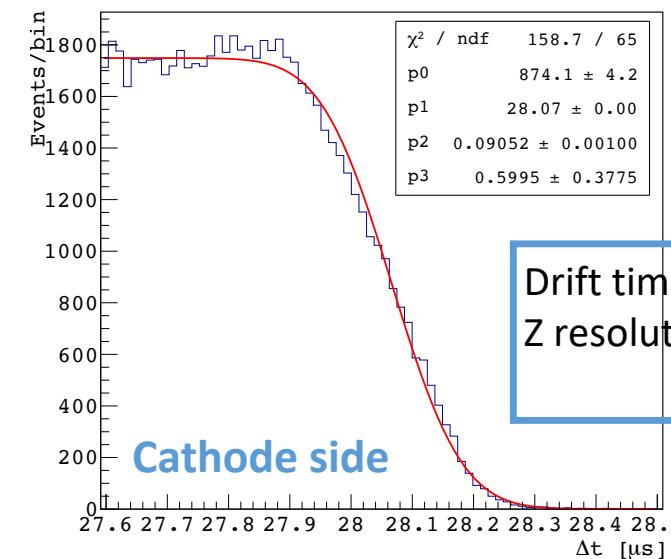
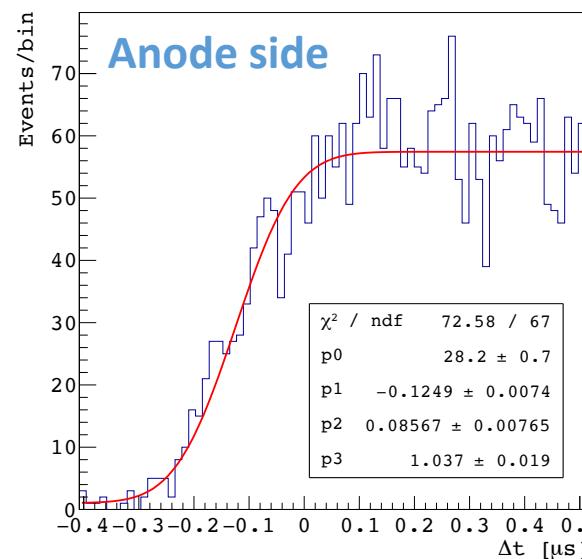
Energy resolution  
Z resolution  
XY resolution  
Angular resolution

$$v_{drift} = 2.3(1) \text{ mm}/\mu\text{s}$$

Z resolution of detector is much better than 300  $\mu\text{m}$  allows us to observe the electron range effect

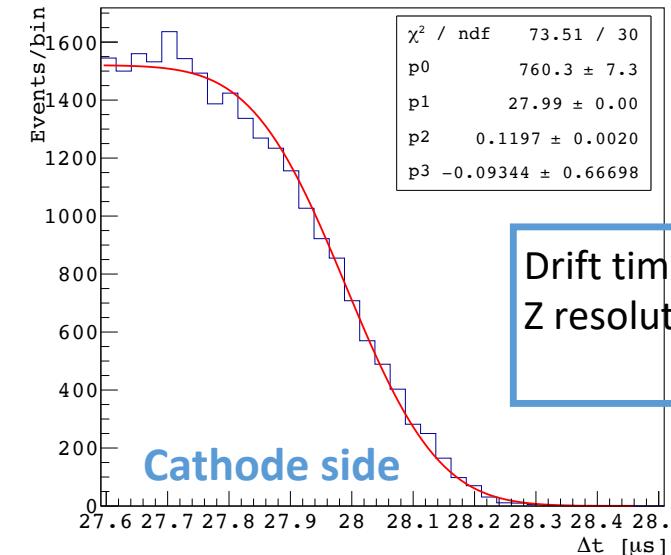
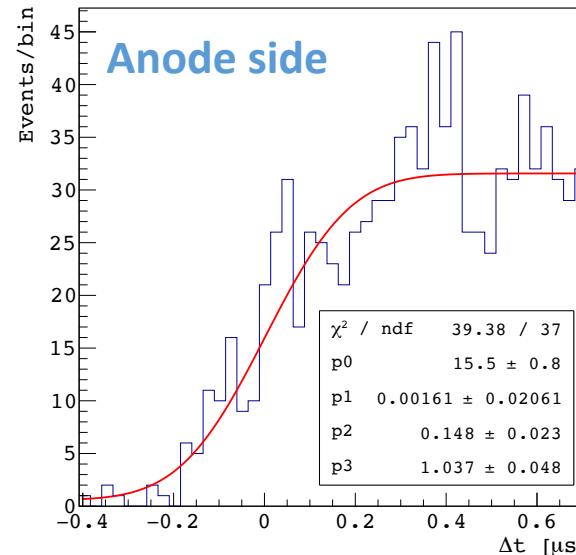


## Photoelectric events of 511 keV LXe@2 kV/cm



Drift time resolution: ~ 90 ns  
Z resolution + range electrons:  
~ 200  $\mu\text{m}$

## Photoelectric events of 1.274 MeV LXe@2 kV/cm



Drift time resolution: ~ 130 ns  
Z resolution + range electrons:  
~ 300  $\mu\text{m}$

*Experimental Results  
of XEMIS1  
@ XEMIS2 operation  
condition*

# Results

Energy resolution

Z resolution

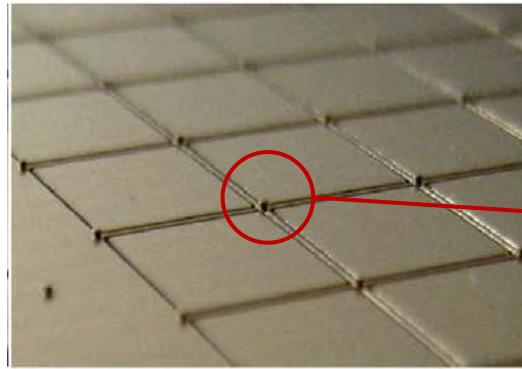
**XY resolution**

Angular resolution

Big challenges for assembling  
and electronics !

Each default/error will be  
visible, here one XTRACT  
Zc channel is out of range

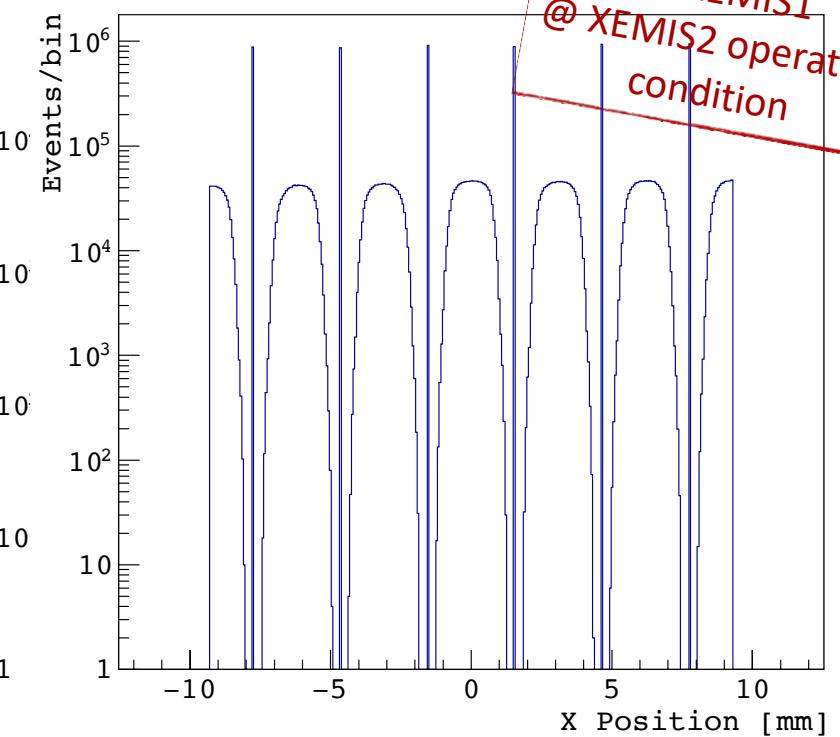
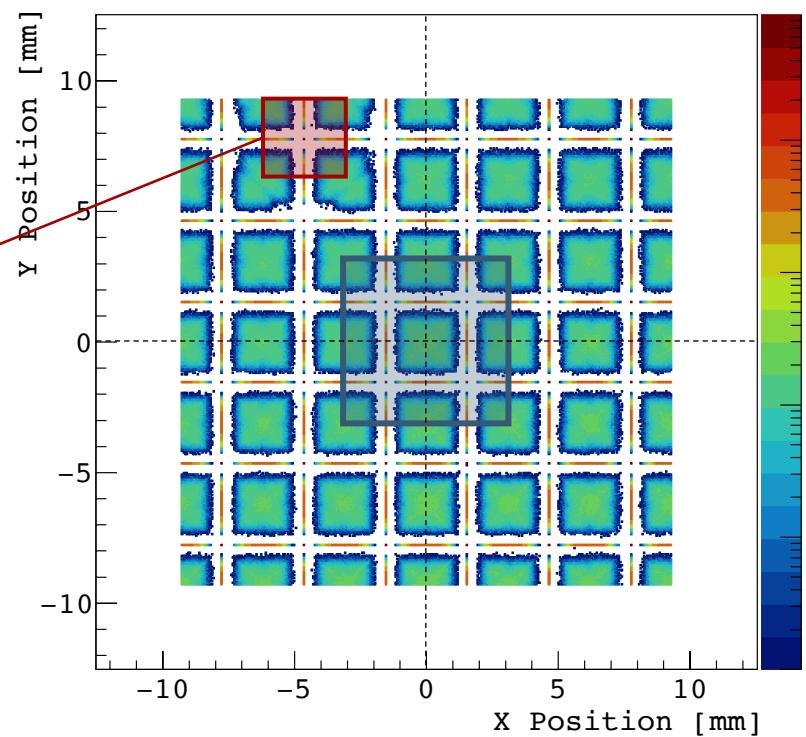
## MIMELI Technology



**µMesh (copper,  $d \sim 10 \mu\text{m}$ , 500 Line Per Inch-LPI)**

**Conductive pillar ( $g \sim 130 \mu\text{m}$ )**

**Pixel  $p = 3.1 \text{ mm}$ ,  $100 \mu\text{m}$  isolating**



*Experimental Results  
of XEMIS1  
@ XEMIS2 operation  
condition*

# Results

Energy resolution

Z resolution

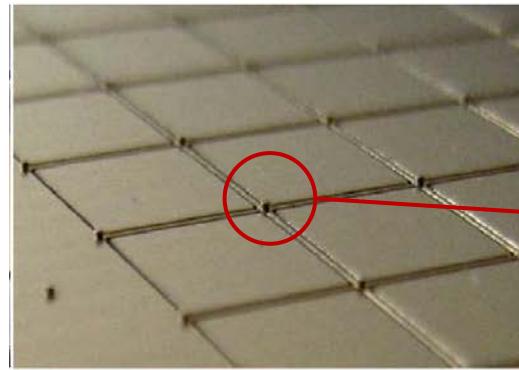
**XY resolution**

Angular resolution

Resolution of single multiplicity:  
 $< 500 \mu\text{m}$

Resolution of multi-pixel events:  
 $\sim 150 \mu\text{m}$

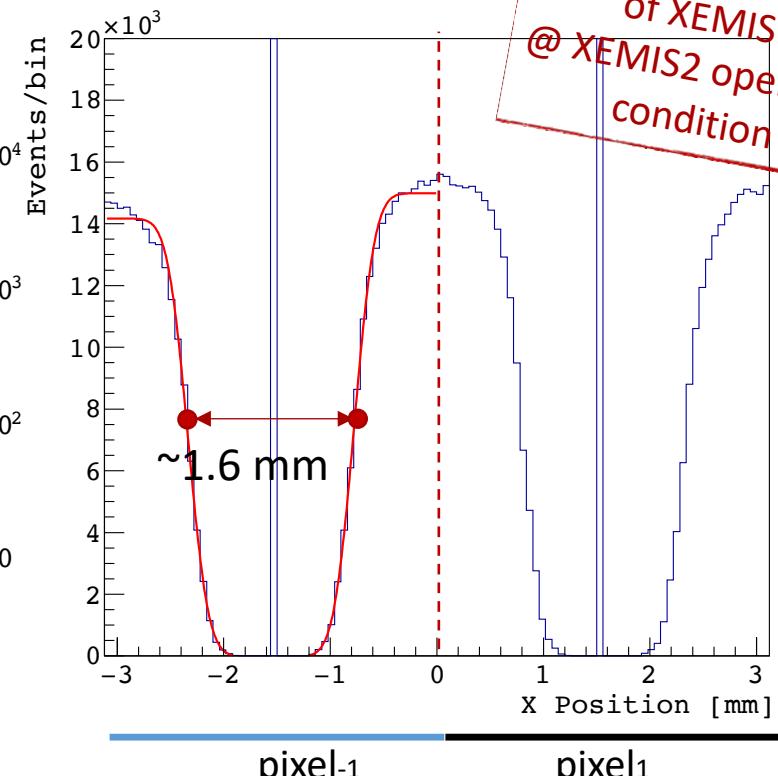
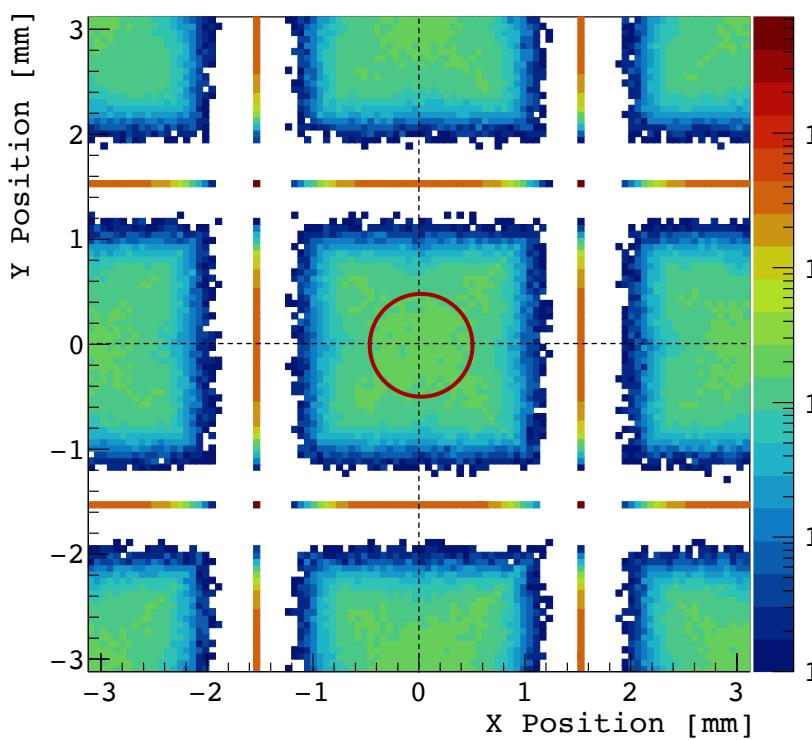
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**$\mu\text{Mesh}$  (copper,  $d \sim 10 \mu\text{m}$ , 500 Line Per Inch-LPI)**

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# Results

Energy resolution

Z resolution

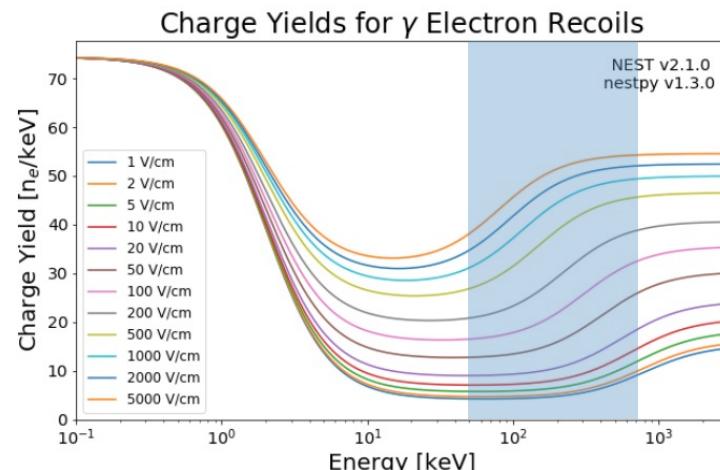
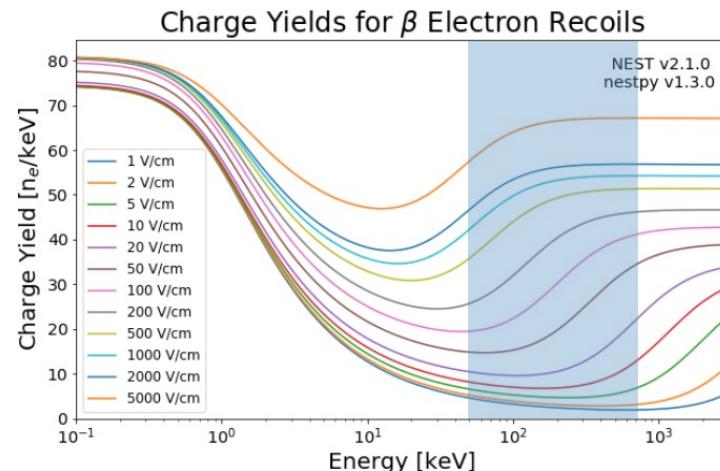
XY resolution

Angular resolution

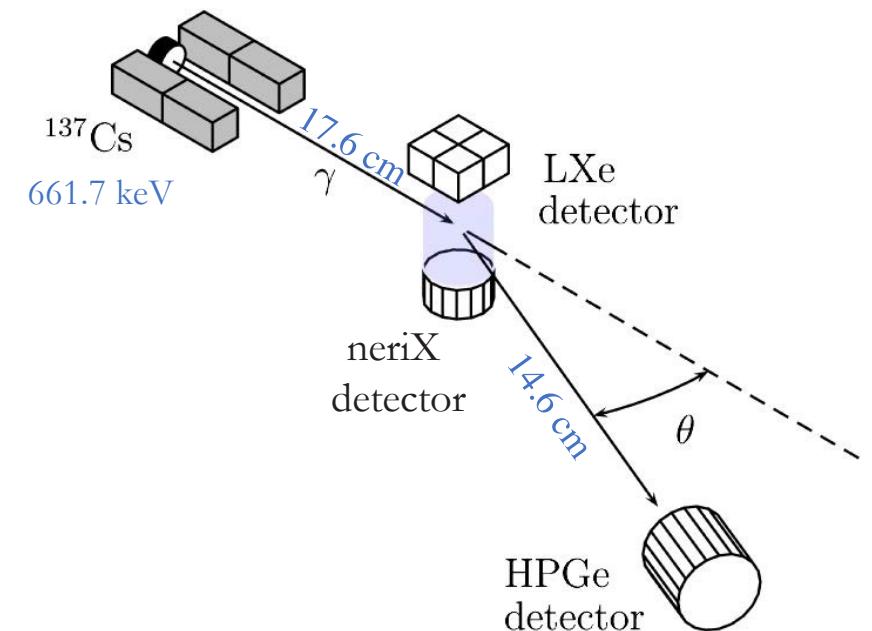
Good angular resolution ( $\sim 1$  MeV)  
 $\text{@ } \theta \in 10^\circ \text{ to } 60^\circ$   
 $\rightarrow 40 \text{ keV to } 600 \text{ keV}$

## Compton Geometric Angle Calibration (CGAC)

### No-linear ER charge yield in LXe



### Compton coincidence measurements



#### HPGe detector:

- precise scattered  $\gamma$ -ray energy measurement
- Big distance between source and detector:
- Good geometric angle resolution

# Results

Energy resolution

Z resolution

XY resolution

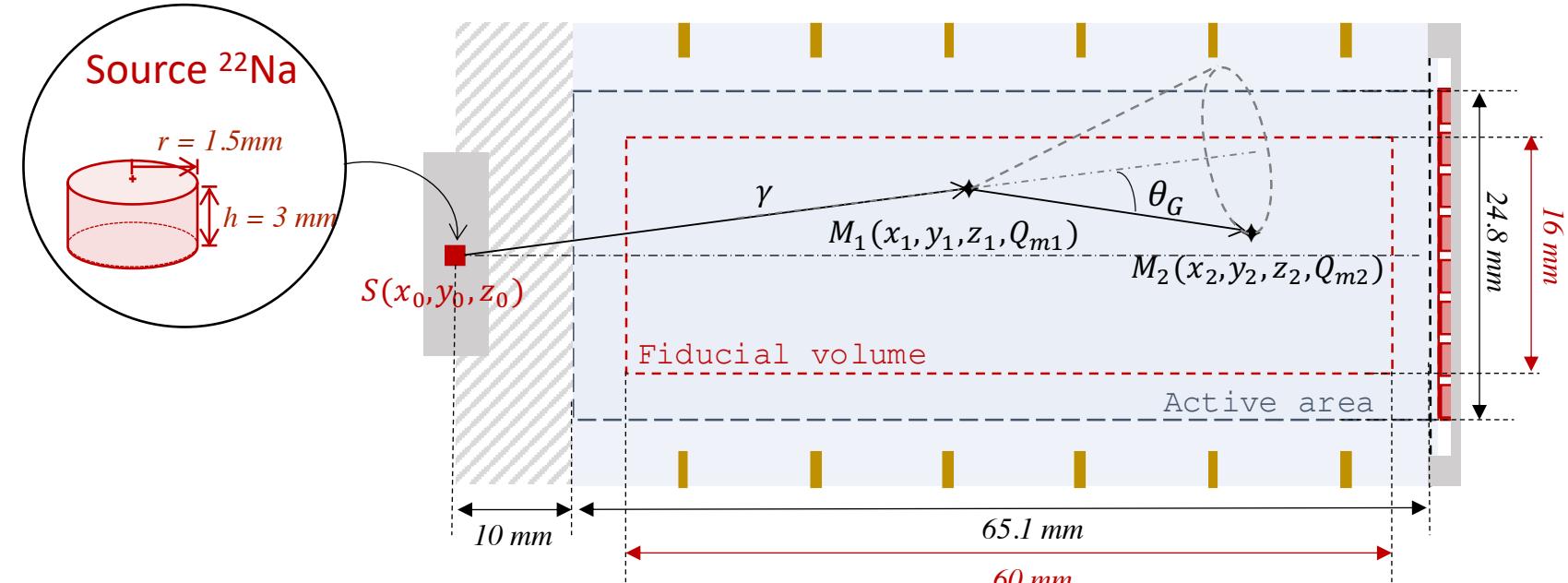
Angular resolution

Thanks to the high spatial resolution of XEMIS

Limits of the experimental setup:

- Small scale of detector
- Size of source – non point-like
- Distance between source and detector

## CGAC concept @ XEMIS1



### Compton Geometric Angular Calibration

$$\theta^G = \arccos(\vec{u} \cdot \vec{v}) \Rightarrow E_e^G = \frac{E_\gamma^2 (1 - \cos \theta^G)}{mc^2 + E_\gamma (1 - \cos \theta^G)} \Rightarrow Q_i^G \leftrightarrow Q_i^m$$

Vertex position  
measurement

Compton  
kinematic

Charge yield  
Nest

Calibration  
Sequence selection



Energy resolution

Z resolution

XY resolution

Angular resolution

Calorimetered and no  
Calorimetered events with  
Good sequence

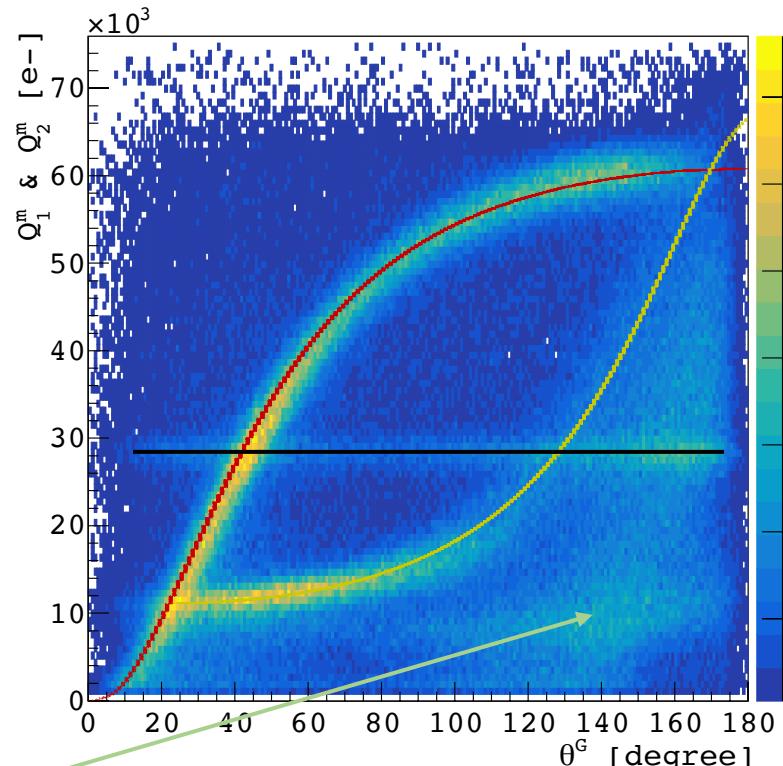
Calorimetered events with  
false sequence

Mix of 511 keV events

No Calorimetered events  
with false sequence

## CGAC Results of 1.274 MeV g-ray @ XEMIS1

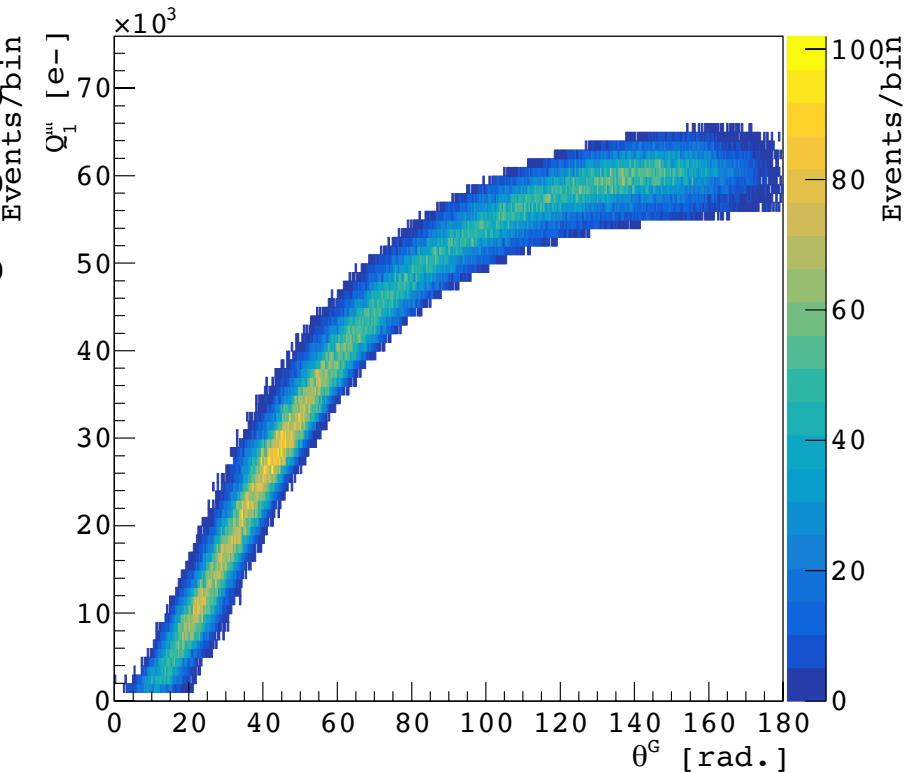
## Detector acceptance



$$E_{tot} > 600 \text{ keV} \quad \Delta D > 6 \text{ mm}$$

**Total acceptance:**  
All 180° Compton angle reconstruction!

## Compton scatter sequence selection



$$\Delta Q = |Q^m - Q^G| < 3 \times \sigma_Q$$

$$\sigma_Q^2 = \sigma_{Q_{nest}}^2 + \sigma_{Q_{\theta_G}}^2 + \sigma_{Q_{noise}}^2$$

# Results

Energy resolution

Z resolution

XY resolution

Angular resolution

Limited by the detector  
and source size

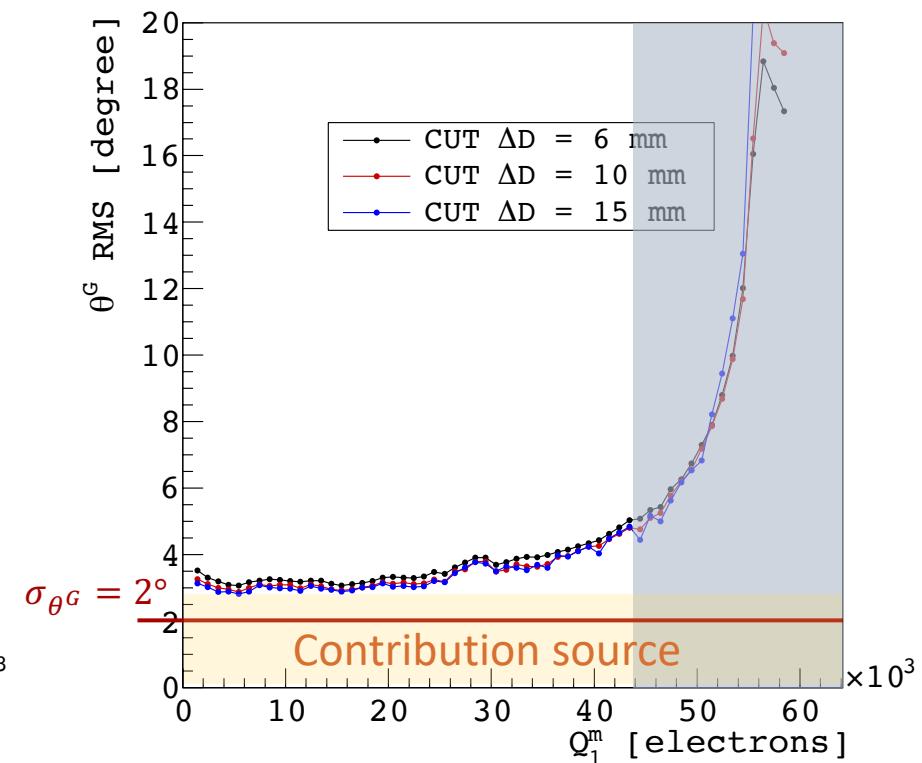
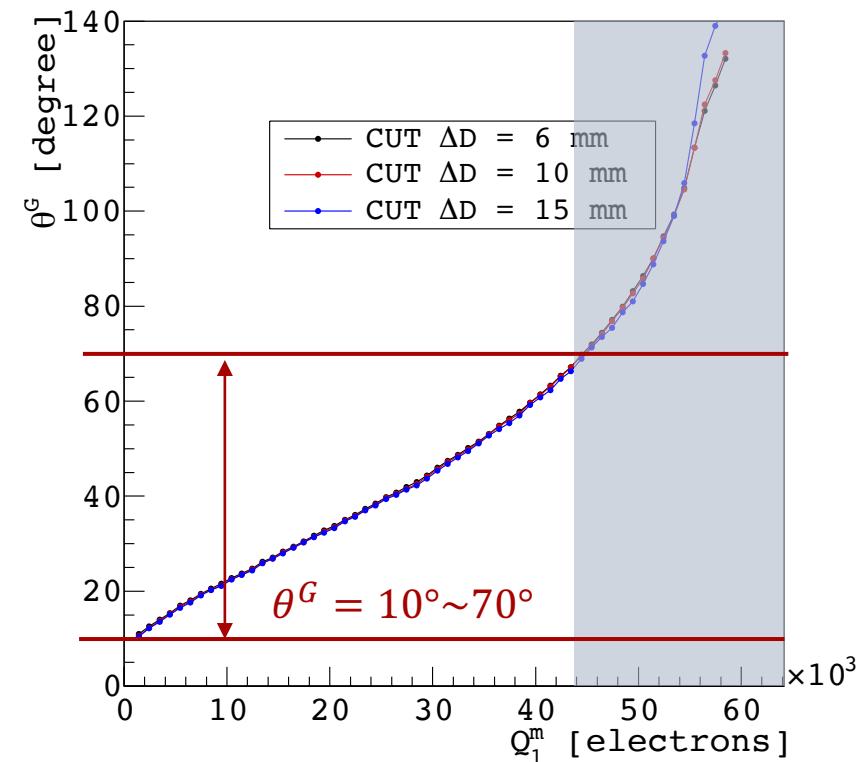
Adapted experimental setup  
is required !

Better results with XEMIS2

## CGAC Results of 1.274 MeV g-ray @ XEMIS1

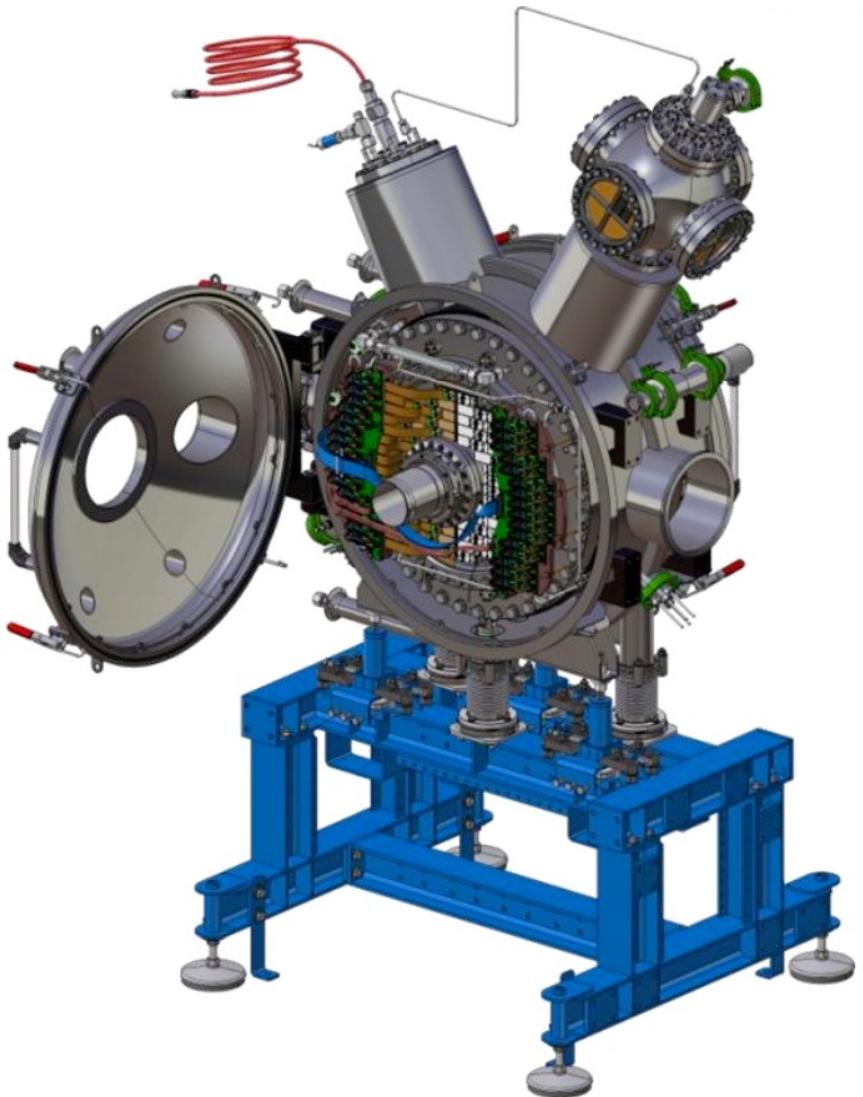
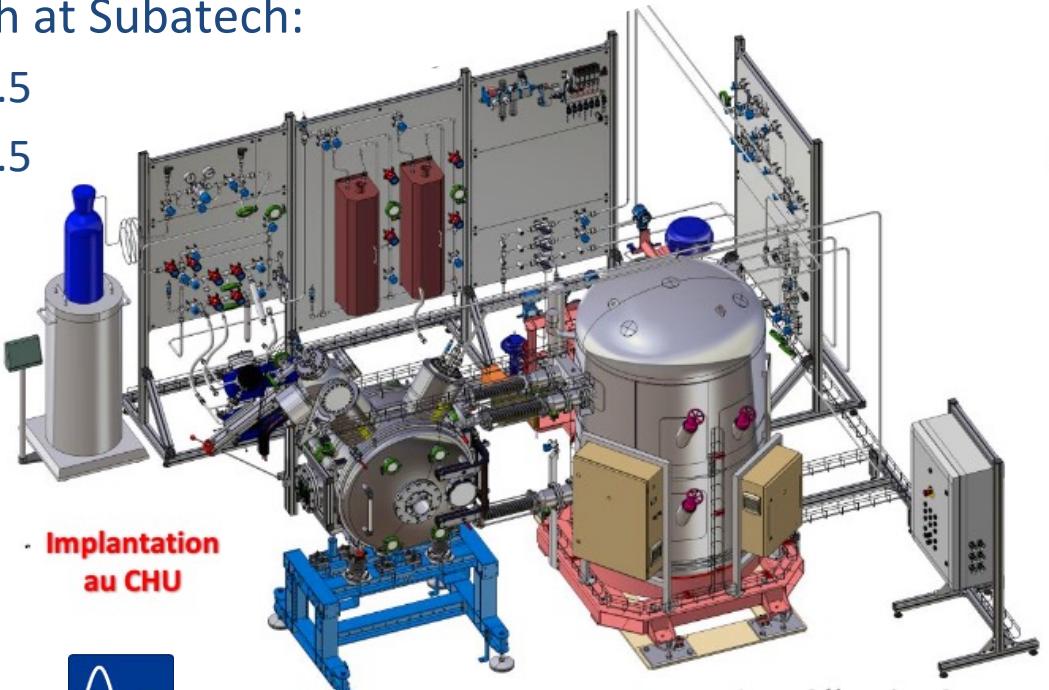
**Directly Compton angle reconstruction with measured charge !**

**Possible correct reconstruction angle range  $10^\circ \sim 70^\circ$**

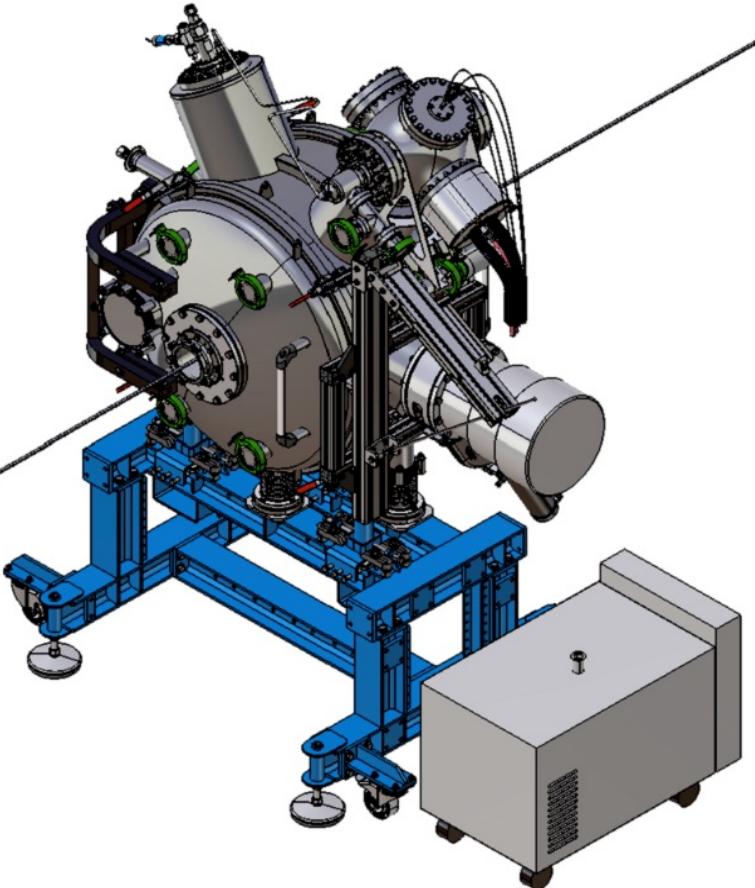


## XEMIS2 installation : general view

- Delayed, initially targeted for end of 2020
- New exceptional funding from Pays de la Loire and Subatech for 2021/22
- Challenging Goals :
  - March 2022, end of the installation
  - Autumn 2022, beginning of the exploitation
- ETP Research at Subatech:
  - 2021 : 10.5
  - 2022 : 11.5



## Investigation on other applications:



### Passive MOX Control with XEMIS

First studies done during 2021 M2 internship  
PhD : from 1<sup>st</sup> December 2021

Unique advanced passive control capacities of XEMIS technology should help significantly for MOX assembling

Experimental measurements planed with XEMIS2 at Nantes hospital (with radioactive sources)  
“XEMOX” camera technology and know how to transfer in case of success

Thank you for your attention !



XEMIS2 installation @ Nantes CHU