XEMIS: A liquid xenon detector for medical imaging

Lucia GALLEGO

01 – 07 – 2014

Outline

- Introduction
  - The XEMIS (Xenon Medical Imaging System) project
- 3γ Imaging technique
- XEMIS1: R&D
- XEMIS2: Small animal imaging
- Conclusions and Perspectives

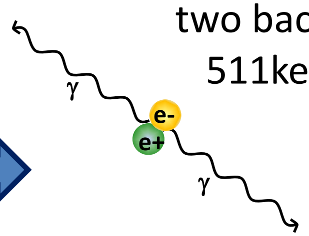
Functional Medical Imaging

Functional imaging:

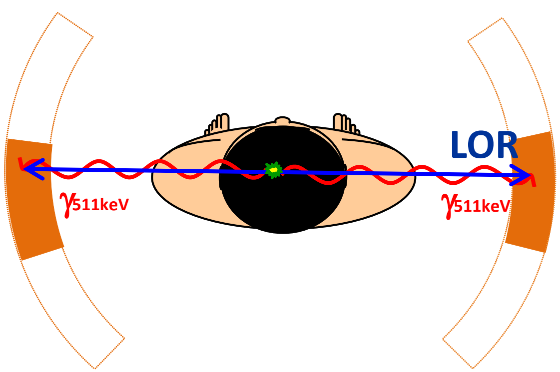
- **Physiological information**
- SPECT, **PET**…

positron – emitting radionuclides

Emission
two back-to-back
511keV γ-rays



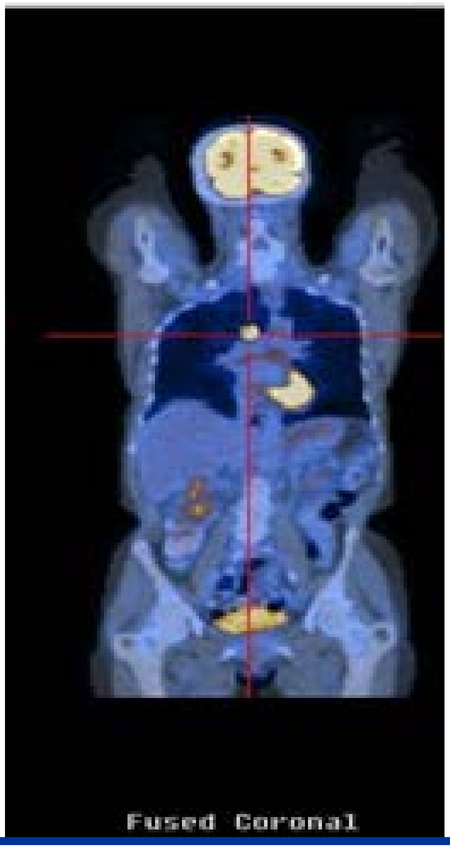
positron – electron
annihilation



Gamma detector

Image reconstruction

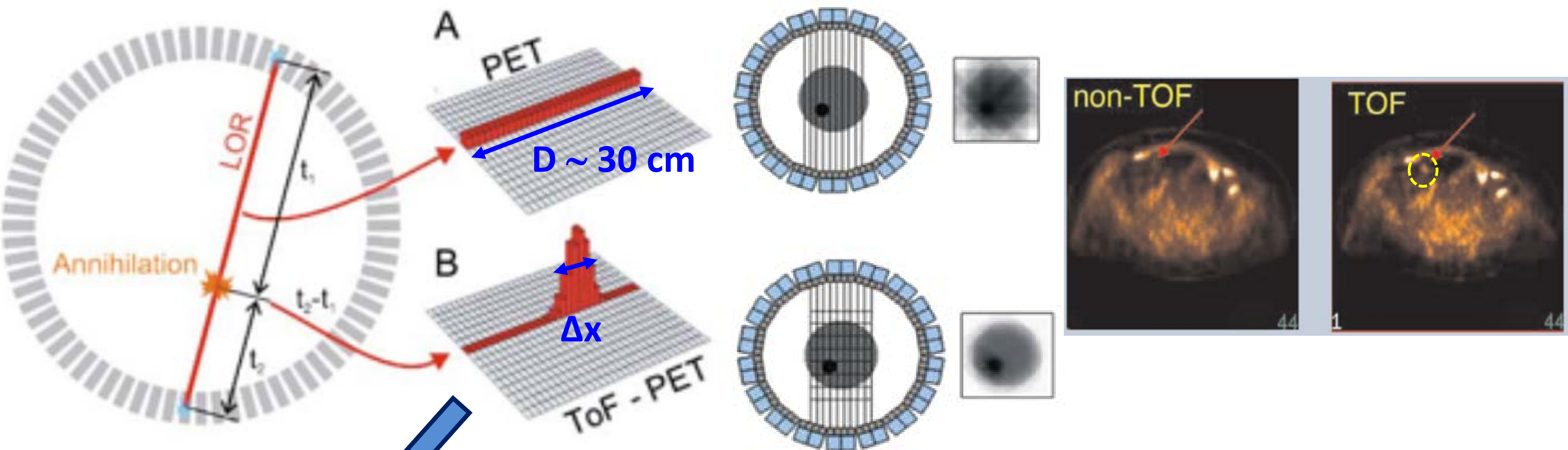
Hybrid Information

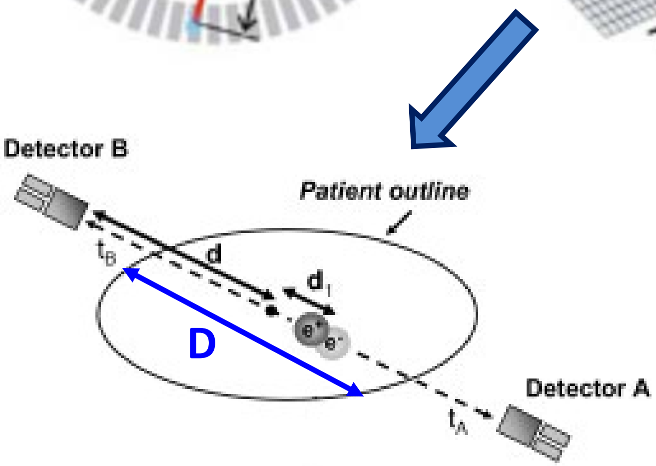


Anatomical/ Functional

CT/PET

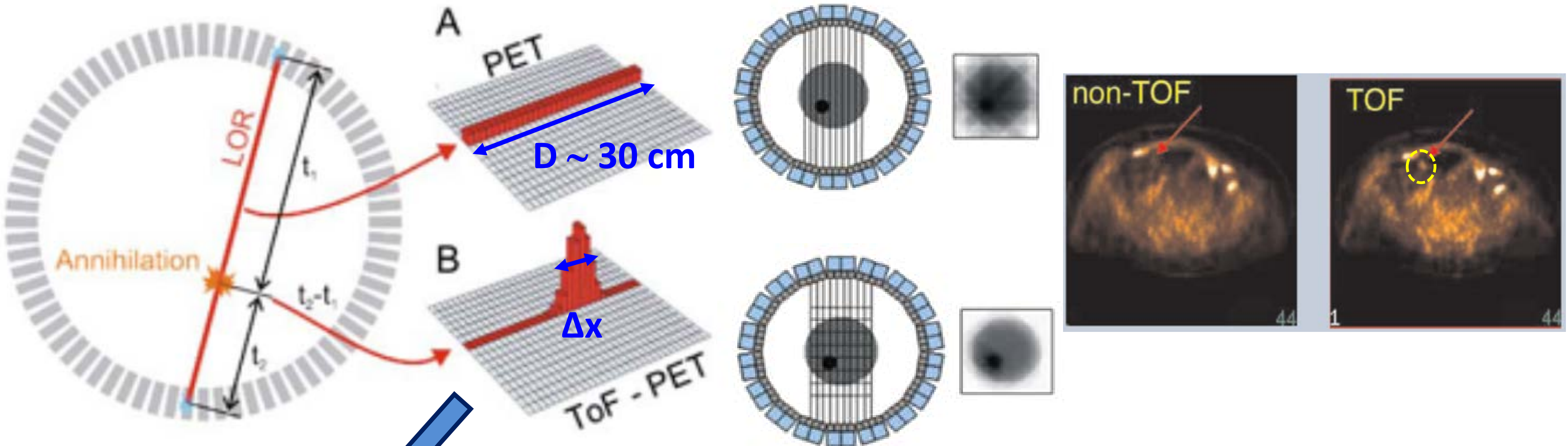
PET / TOF PET

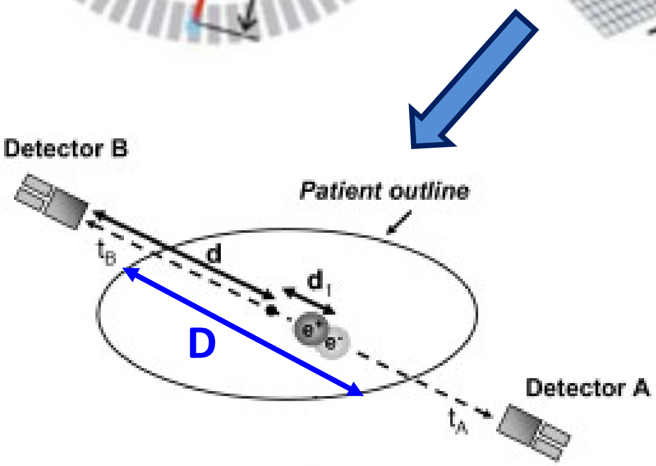




- Better Signal to Noise Ratio → Better contrast
- Low administered dose
- Shorter scan times
- Actual temporal resolution **500 ps** ➔ **Δx = 7.5 cm** (FWHM) at the center of the FOV

PET / TOF PET





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- Actual temporal resolution **500 ps** ➔ **Δx = 7.5 cm** (FWHM) at the center of the FOV

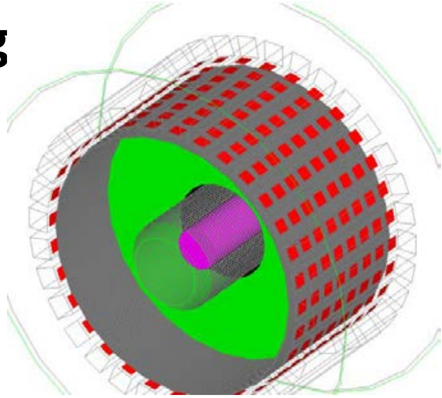
Motivation: reach a Δx = 1cm

Any alternative to TOF PET?

XEMIS Project

XEMIS: XEnon Medical Imaging System

- Propose a new functional nuclear imaging technique based on the detection in coincidence of **3** gamma rays → **3γ Imaging**



  - **Direct 3D location of the radioactive source**
  - **Administered dose reduction**
  - **Shorter scan times**

Development of a new detector framework based on a liquid xenon Compton camera

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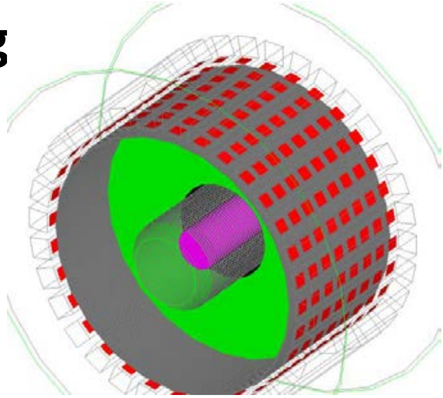

  - **Direct 3D location of the radioactive source**
  - **Administered dose reduction**
  - **Shorter scan times**

Development of a new detector framework based on a liquid xenon Compton camera

- Main phases of the project:
  1. Proof of the feasibility of the 3γ imaging technique (XEMIS1) ✓
  2. Study of its capability for small animal imaging (XEMIS2) • • •
  3. Application in human body imaging

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  - The XEMIS project
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- XEMIS2: Small animal imaging
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Principle of the 3γ Imaging Technique

- Requires the use of a specific radioisotope, which emits a β^+ **+ γ ray** in quasi-coincidence:

The ^{44}**Sc** is a good candidate

ARRONAX

^{44}Sc :

- β^+(**Emax = 1.474 MeV**)
- γ(**E_0 = 1.157 MeV**)

($T_{1/2}$ = 4 h)

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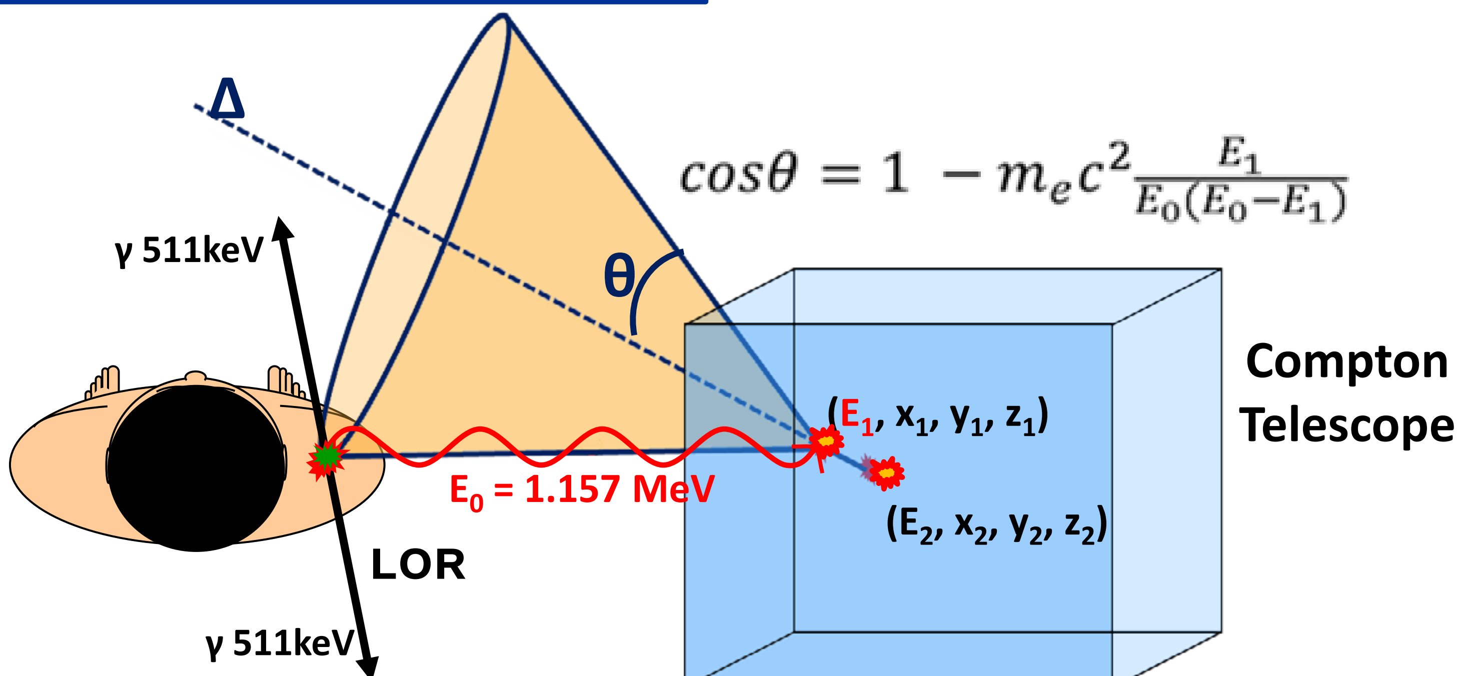
- Principle:

LOR reconstruction + Compton Telescope



Why liquid xenon?

	Neon	Argon	Krypton	Xenon
Atomic number	10	18	36	54
Density (g/cc)	1.2	1.4	2.4	3
Boiling Point (K)	27.1	87.3	119.8	165.0
Light yield (UV/MeV) $(\vec{E} = 0)$	30000	40000	25000	42000
Ionization yield (/MeV) $(\vec{E} = \infty)$	46000	42000	49000	64000
Decay Time (ns)	10, 15400	6.3, 1500	7.0, 85	2.2 , 27 , 45
Wavelength (ns)	85	128	150	175

J.A. Nikkel et al. 2012 JINST

LXe provides:

- Simultaneous production of a scintillation and an ionization signal
- Simpler cryogenics
- Fast decay, high scintillation light yield and high ionization yield

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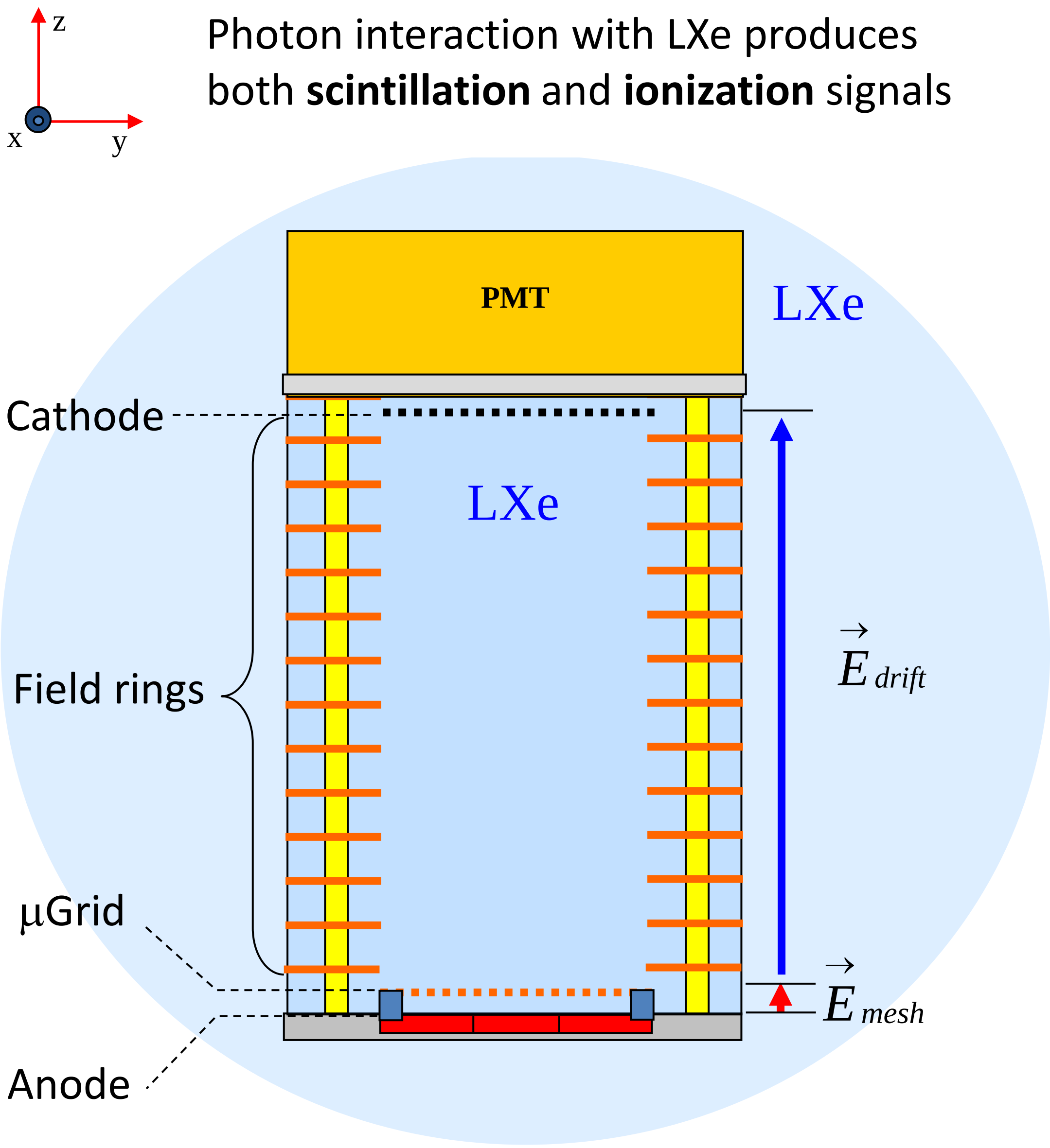
3D position information

⇩

γ direction → Compton Telescope

Liquid Xenon TPC

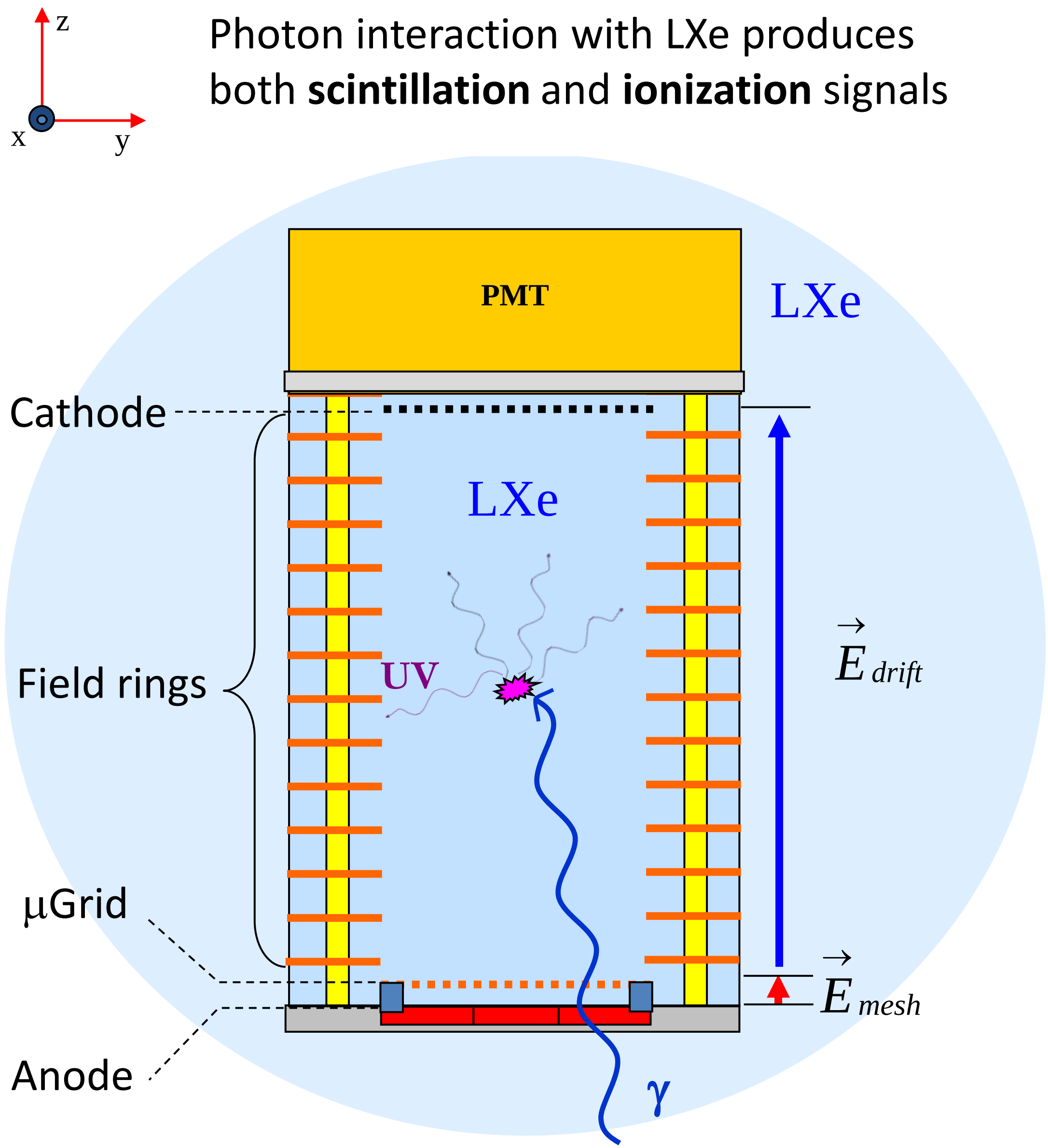
Photon interaction with LXe produces both **scintillation** and **ionization** signals



Liquid Xenon TPC

Photon interaction with LXe produces both **scintillation** and **ionization** signals

Scintillation light (PMT)
t_0



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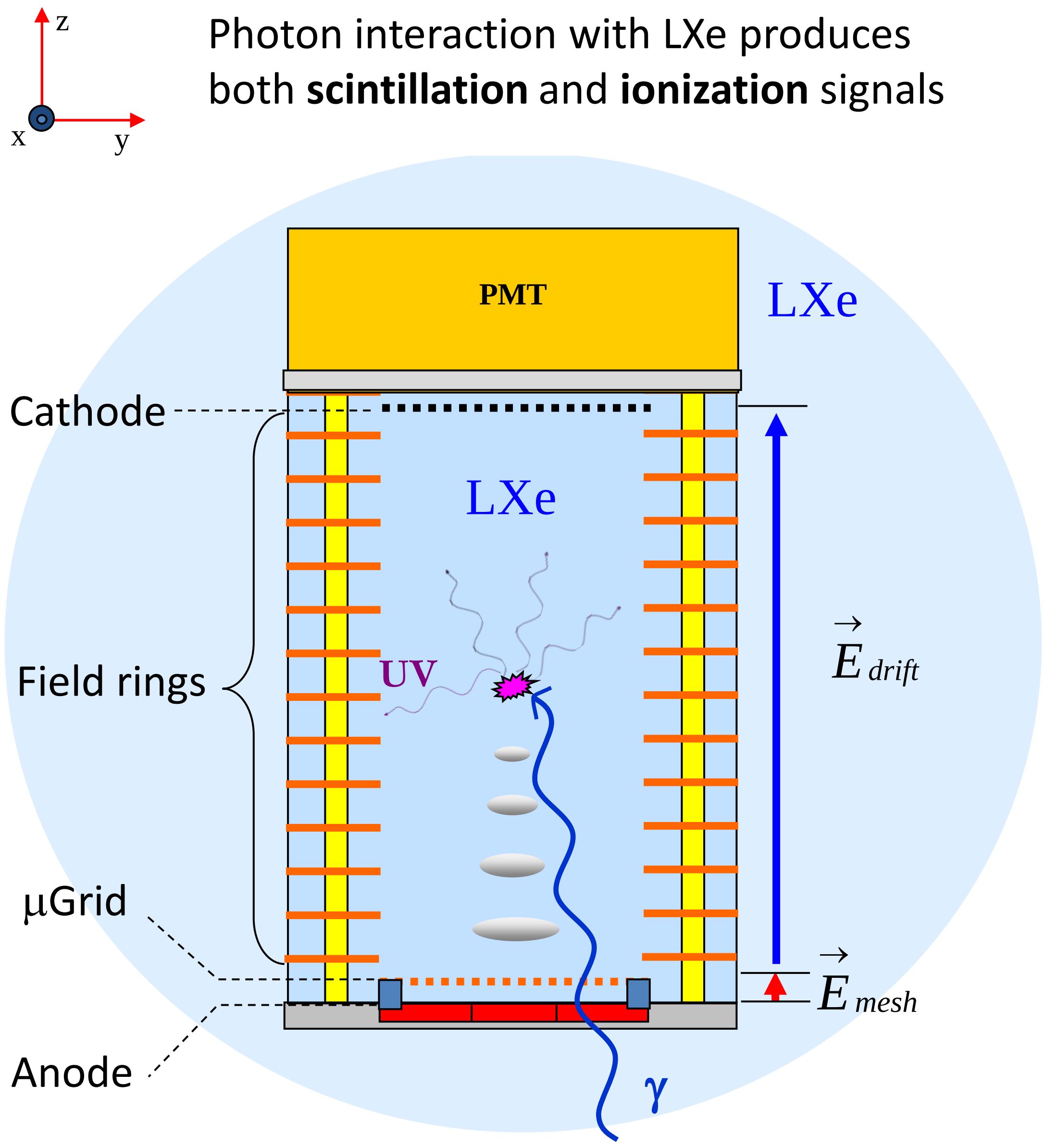


Scintillation light (PMT)

t_0

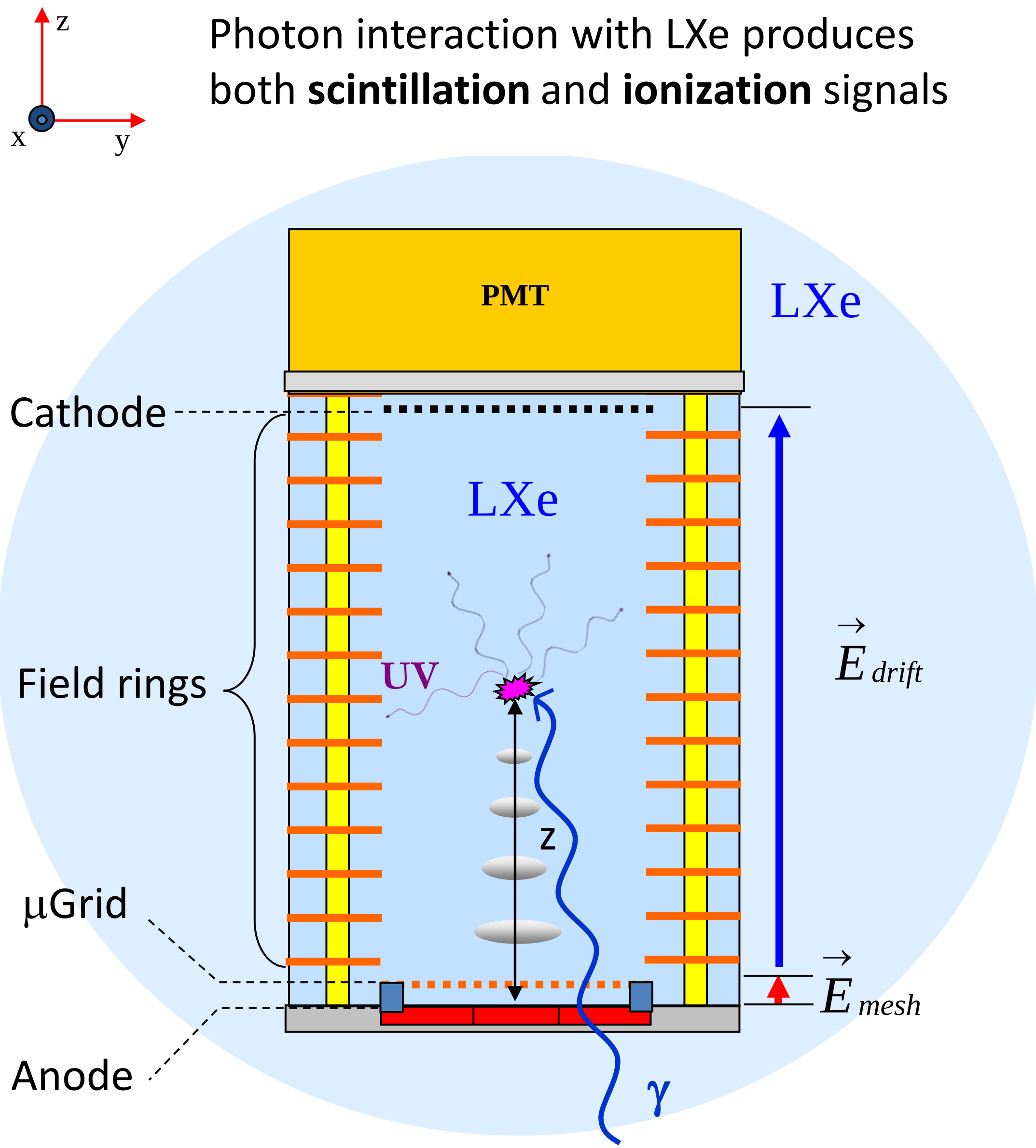
+

Ionization

(FEE + micromegas)

Energy + (x, y) + t_1

Liquid Xenon TPC



Photon interaction with LXe produces both **scintillation** and **ionization** signals

Scintillation light (PMT)
t_0

+

Ionization
(FEE + micromegas)
Energy + (x, y) + t_1

V_{drift} known
(T,E) = cst
$Z = v_{drift} \cdot (t_1 - t_0)$

Energy + 3D Position of each interaction

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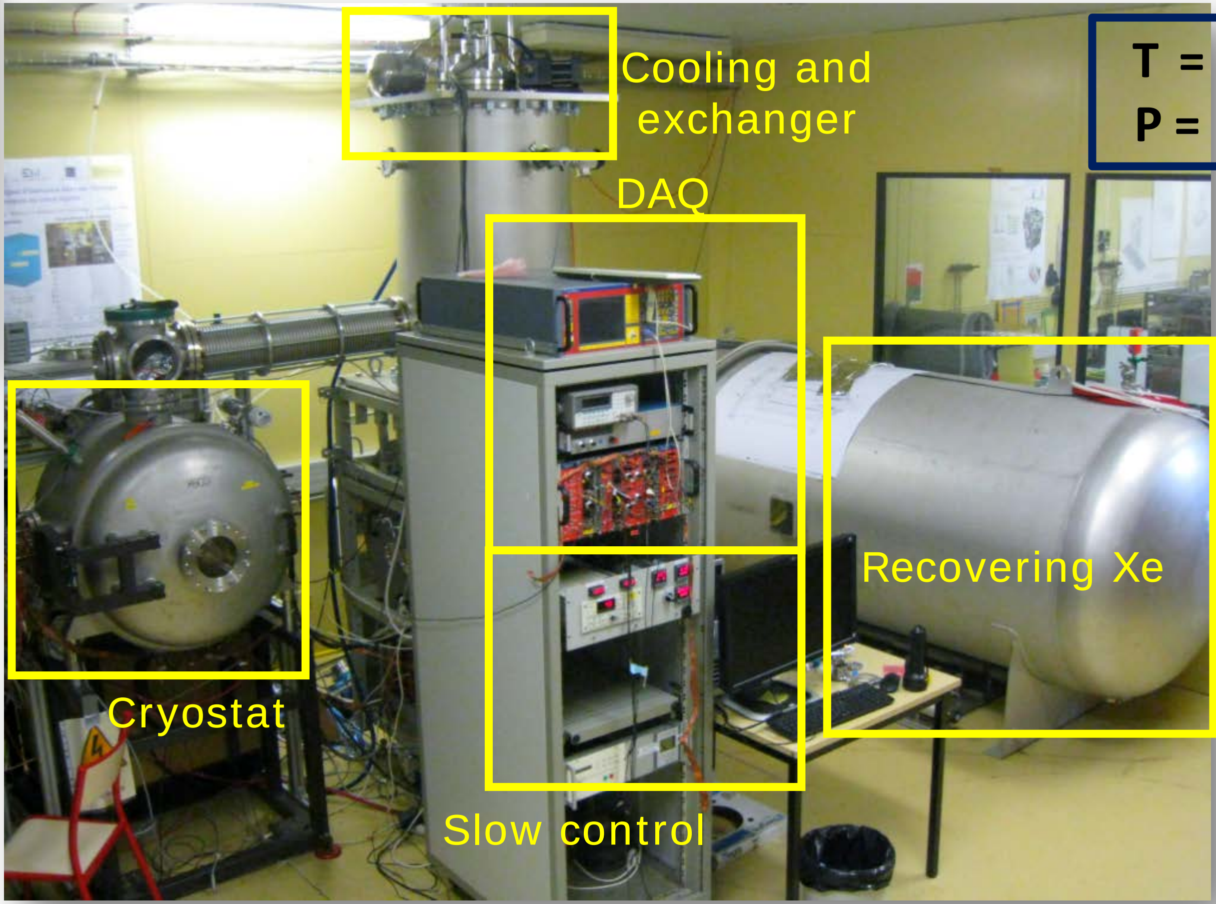
XEMIS1 Facility

30 kg LXe

Experimental study of the feasibility of the 3γ imaging technique and the use of liquid xenon as a perfect candidate for gamma detection.



T = 165 K
P = 1 bar

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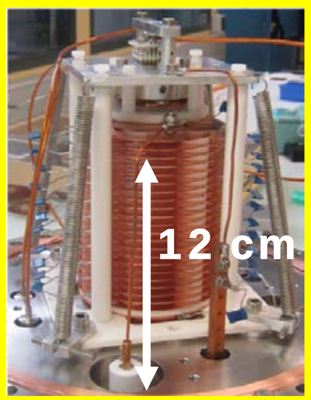
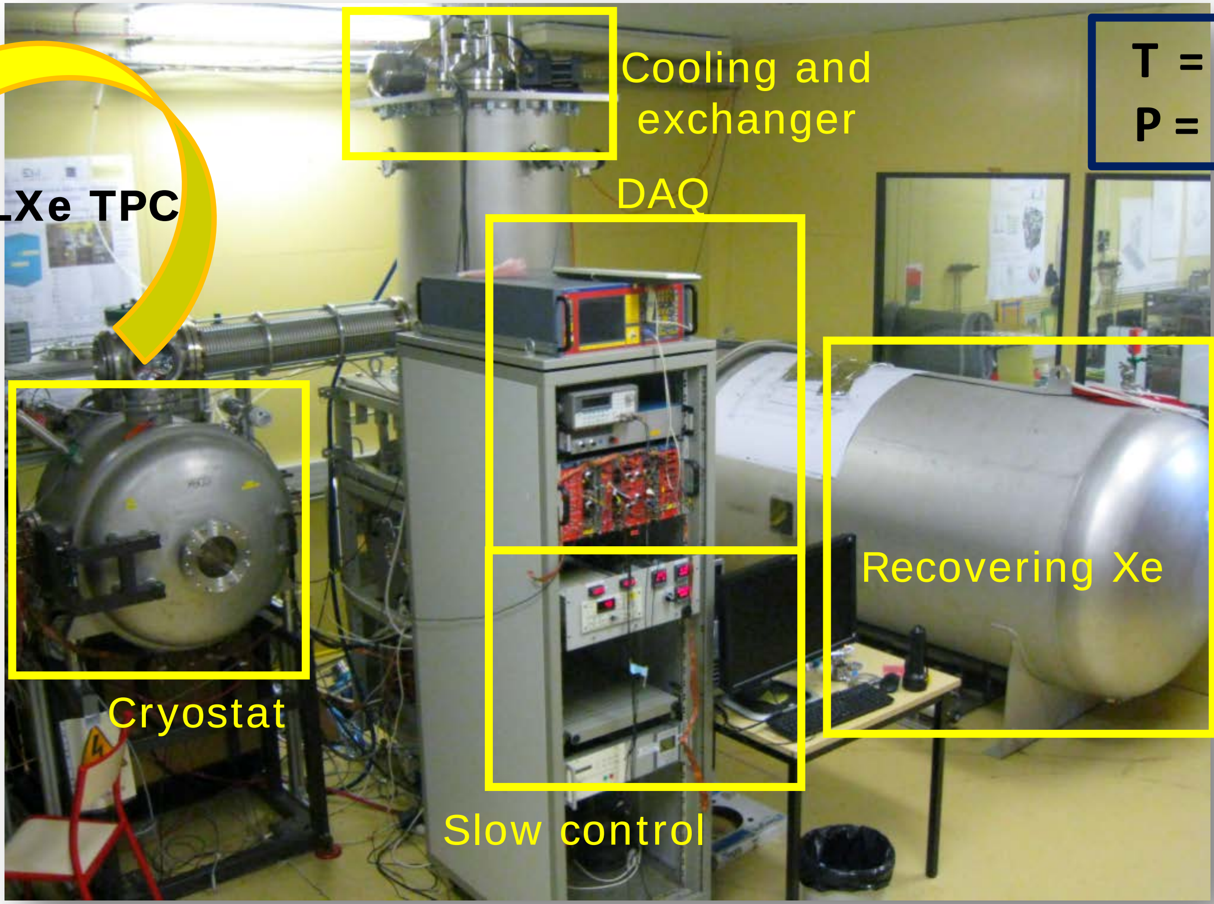


LXe TPC



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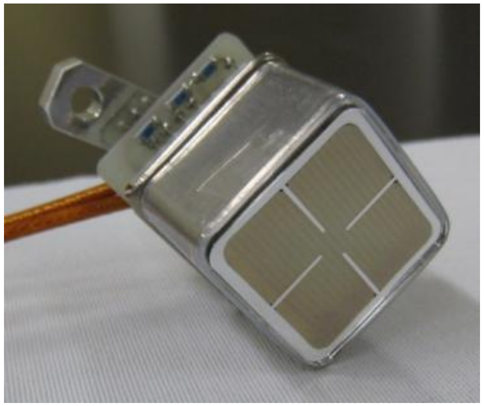
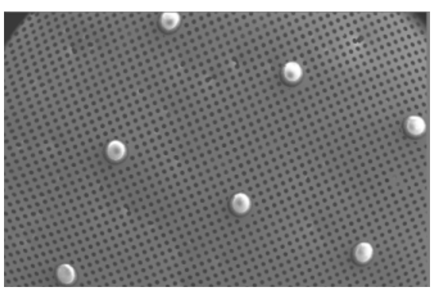
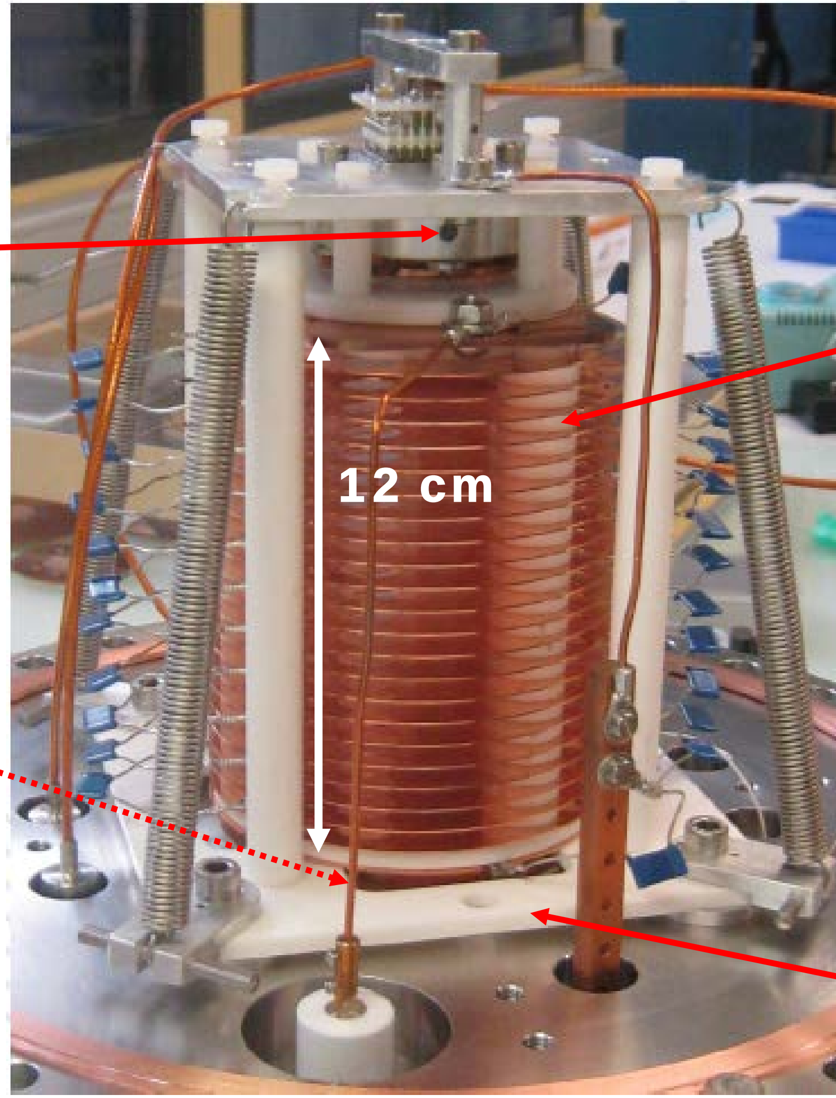
XEMIS1 TPC



PMT
Hamamatsu R7600 – 1’’

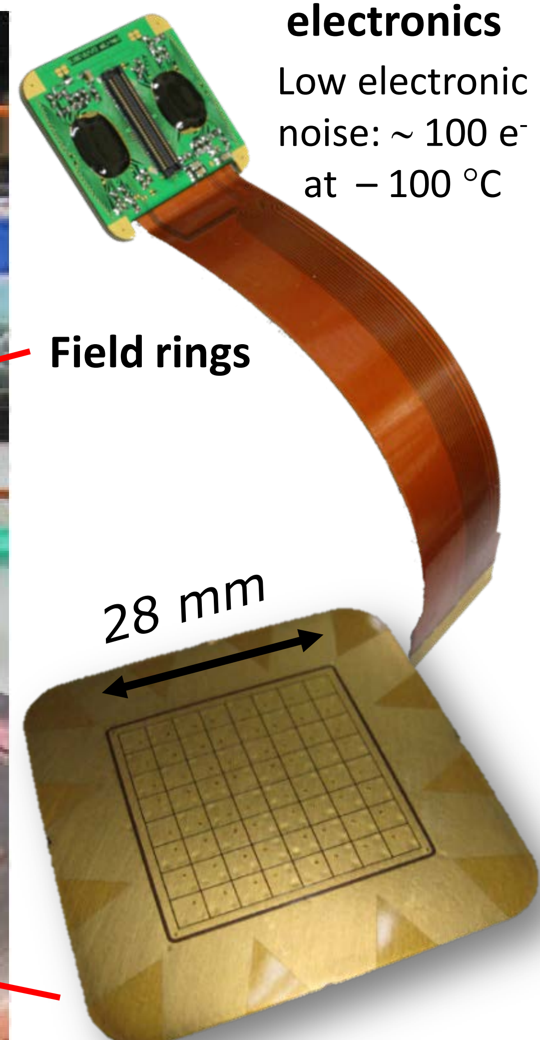
Micromegas Grid





Readout electronics

Low electronic noise: ~ 100 e^- at – 100 °C



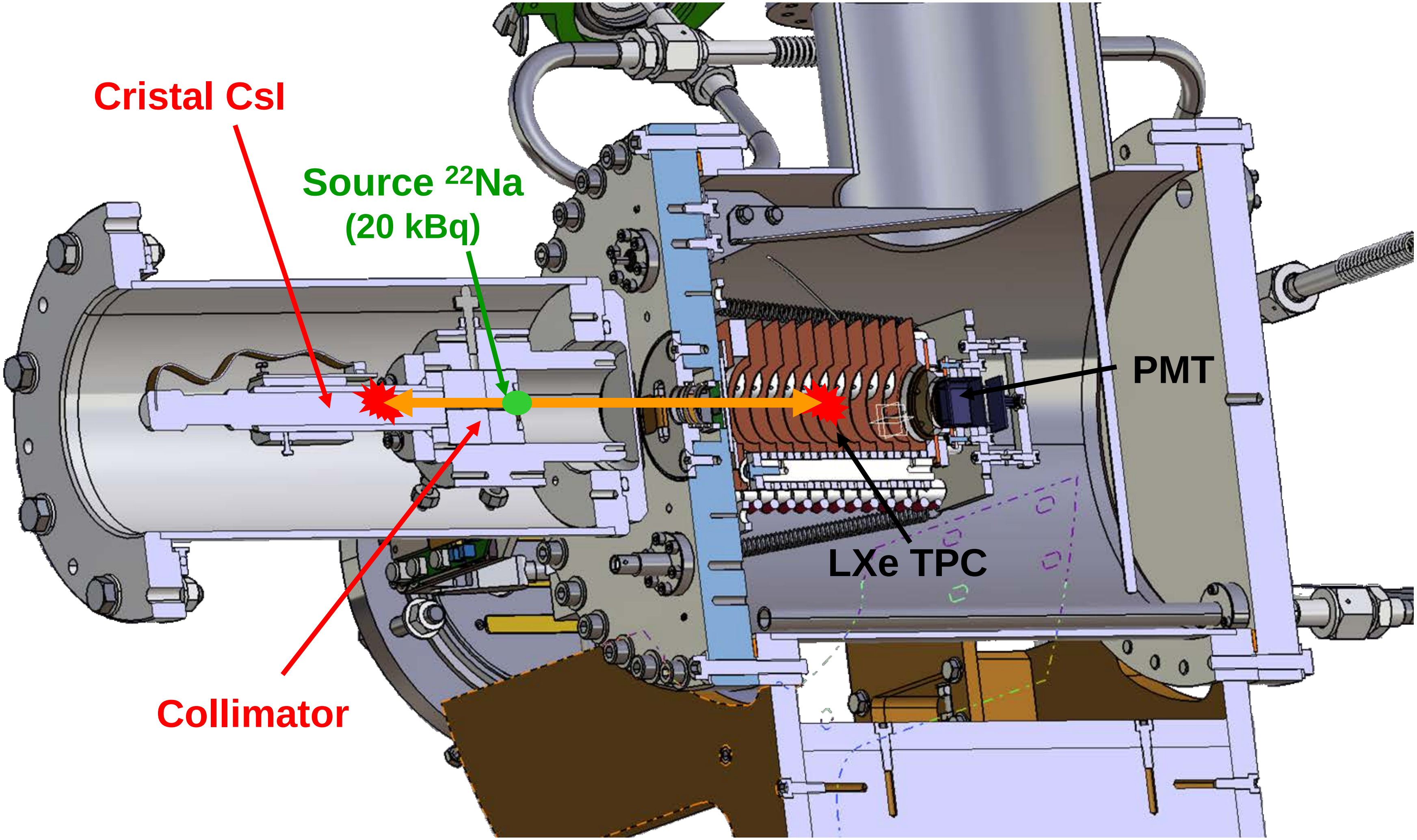
Field rings

64 pixels anode
3.5 x 3.5 mm^2 pixel

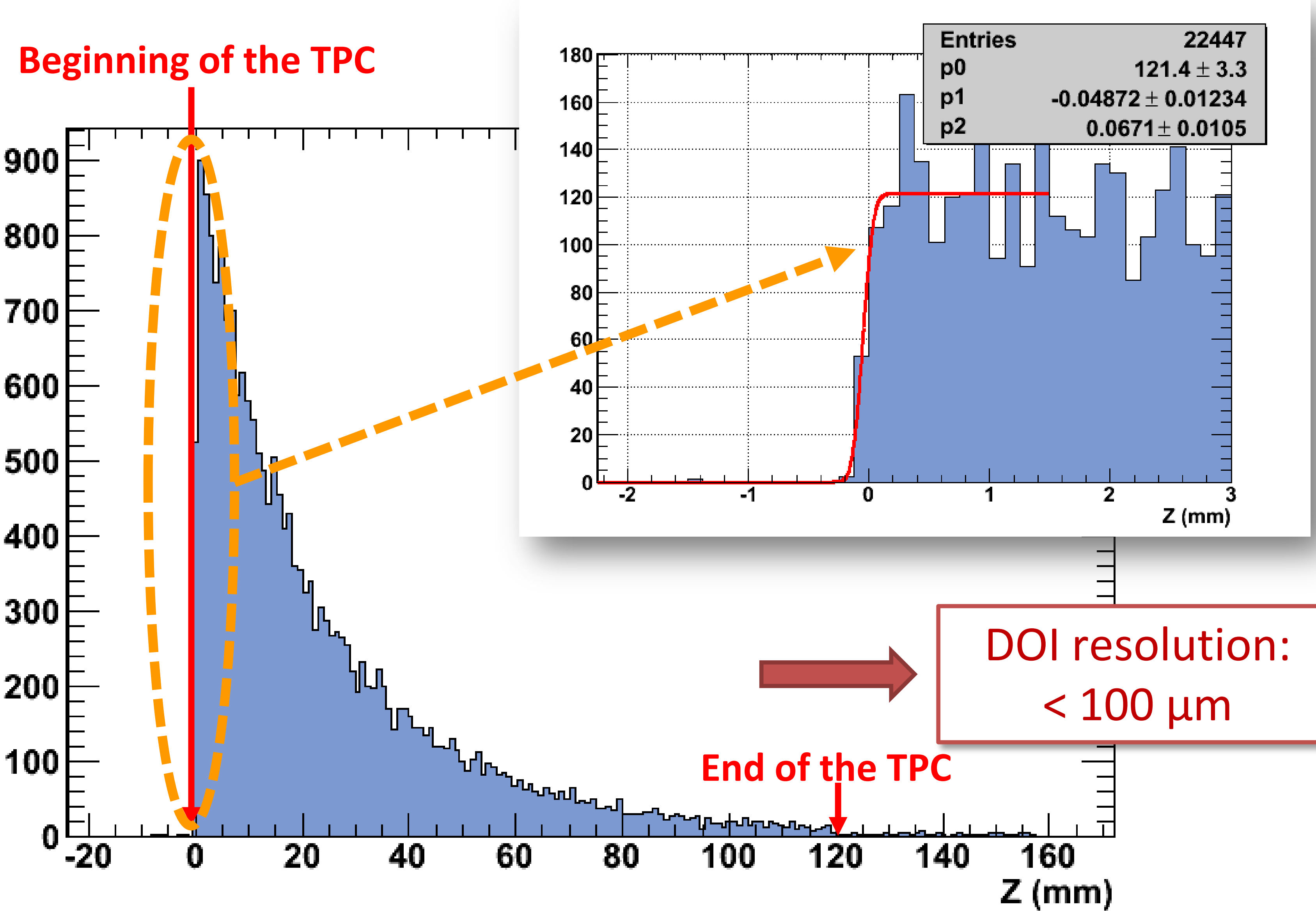
511 keV Calibration

^{22}Na source (20 kBq)

($E_{max}\beta^{+}$= 545 keV, E_{γ}= 1.257 MeV)



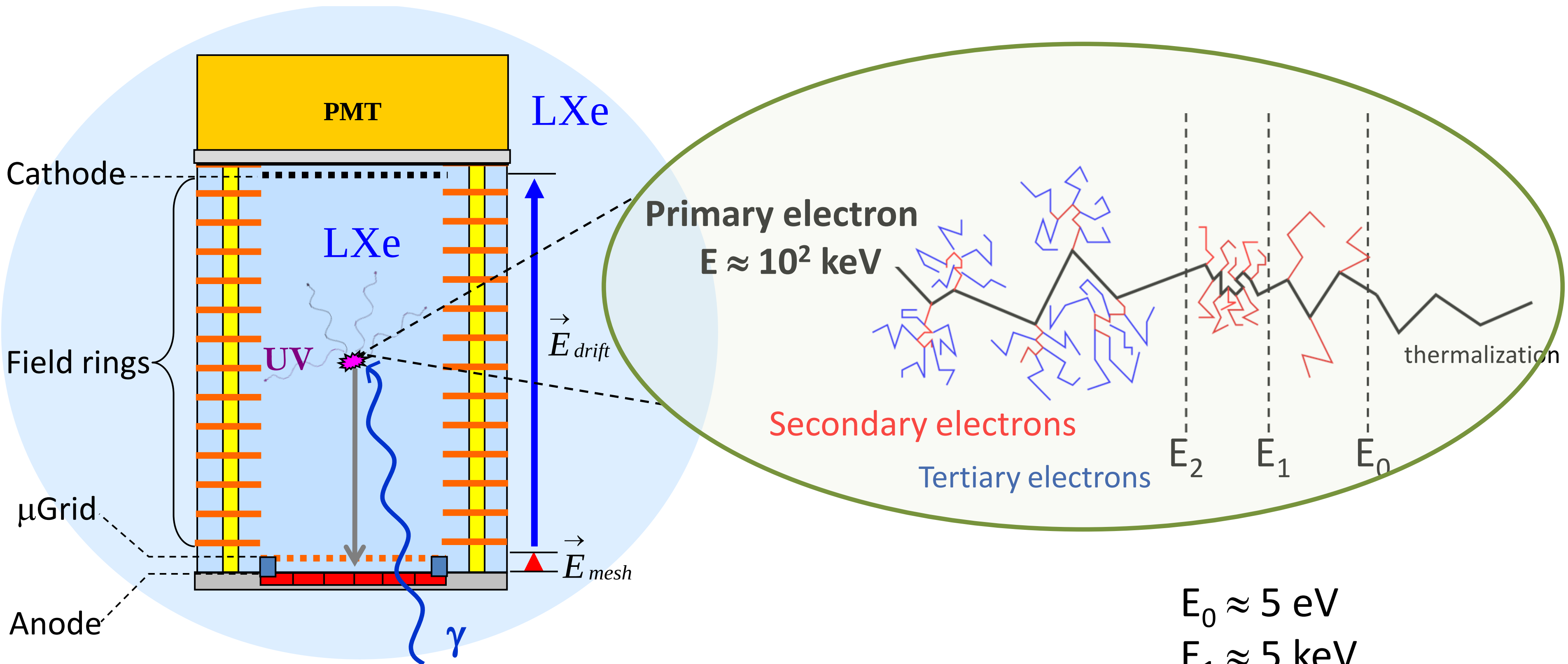
Depth of Interaction (@511 keV)



DOI resolution:
< 100 µm

Energy Fluctuations

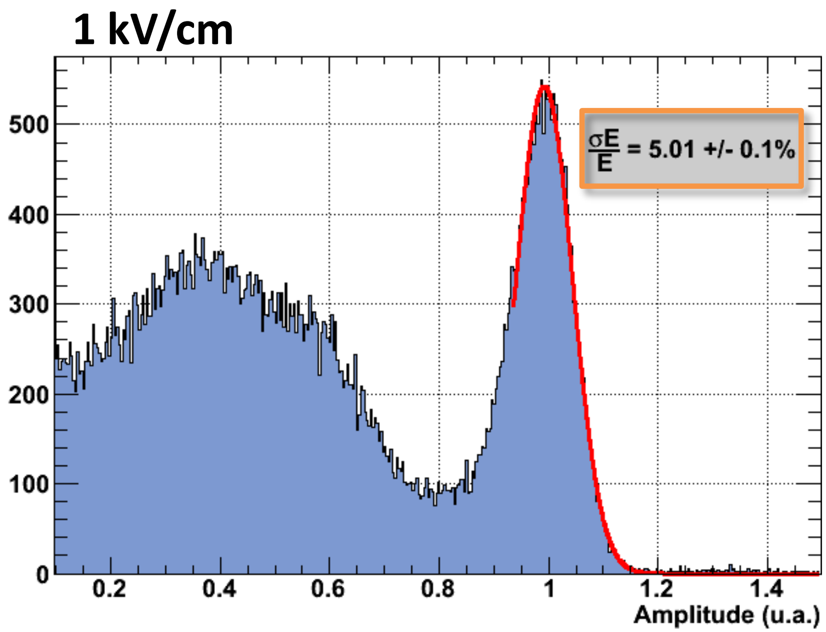
Charge density fluctuations caused by changes in the production of δ electrons affects the energy resolution → Thomas model.

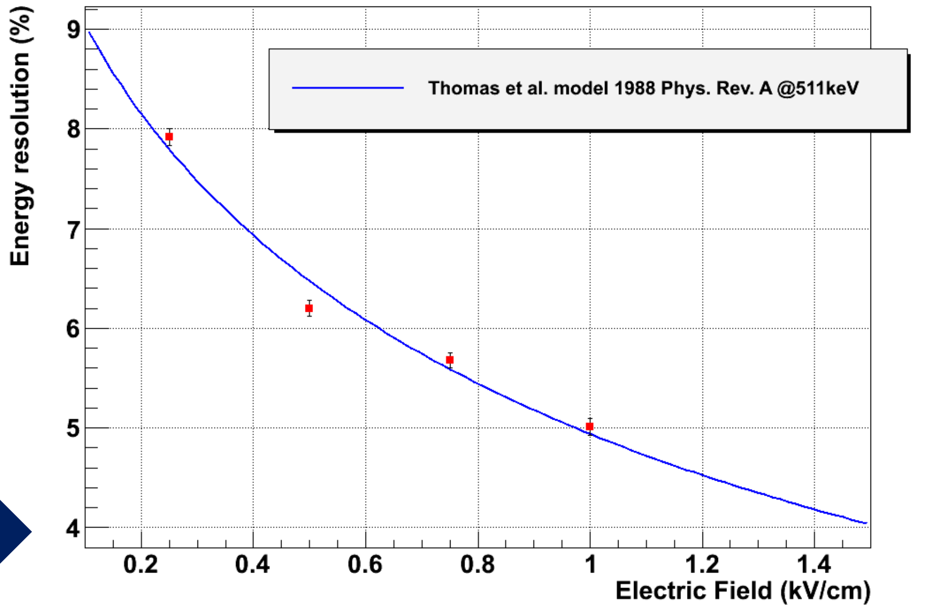


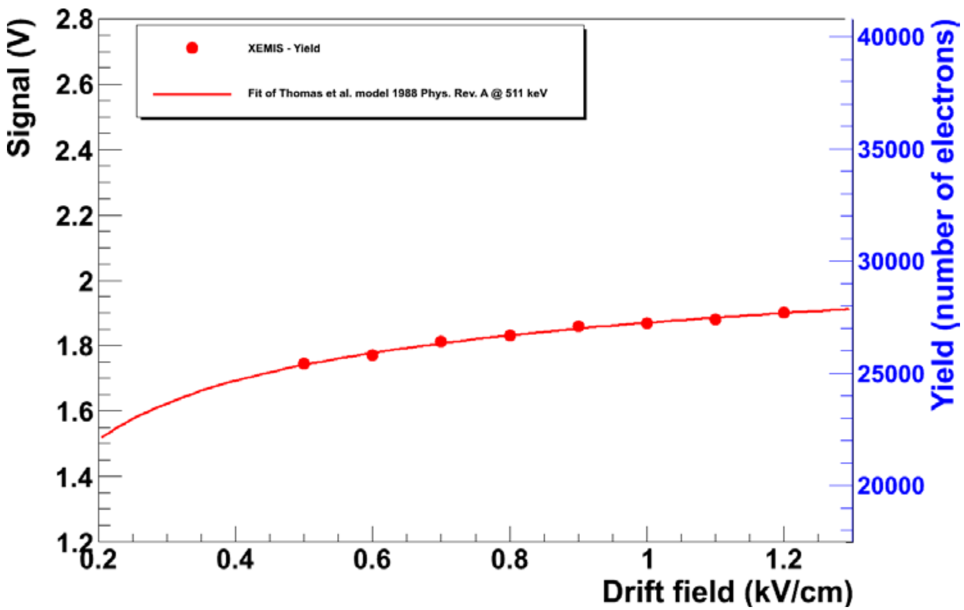
$E_0 \approx 5$ eV
$E_1 \approx 5$ keV
$E_2 \approx 20$ keV

Thomas et al. Model 1988 Phys. Rev. A

Energy Resolution (@511 keV)



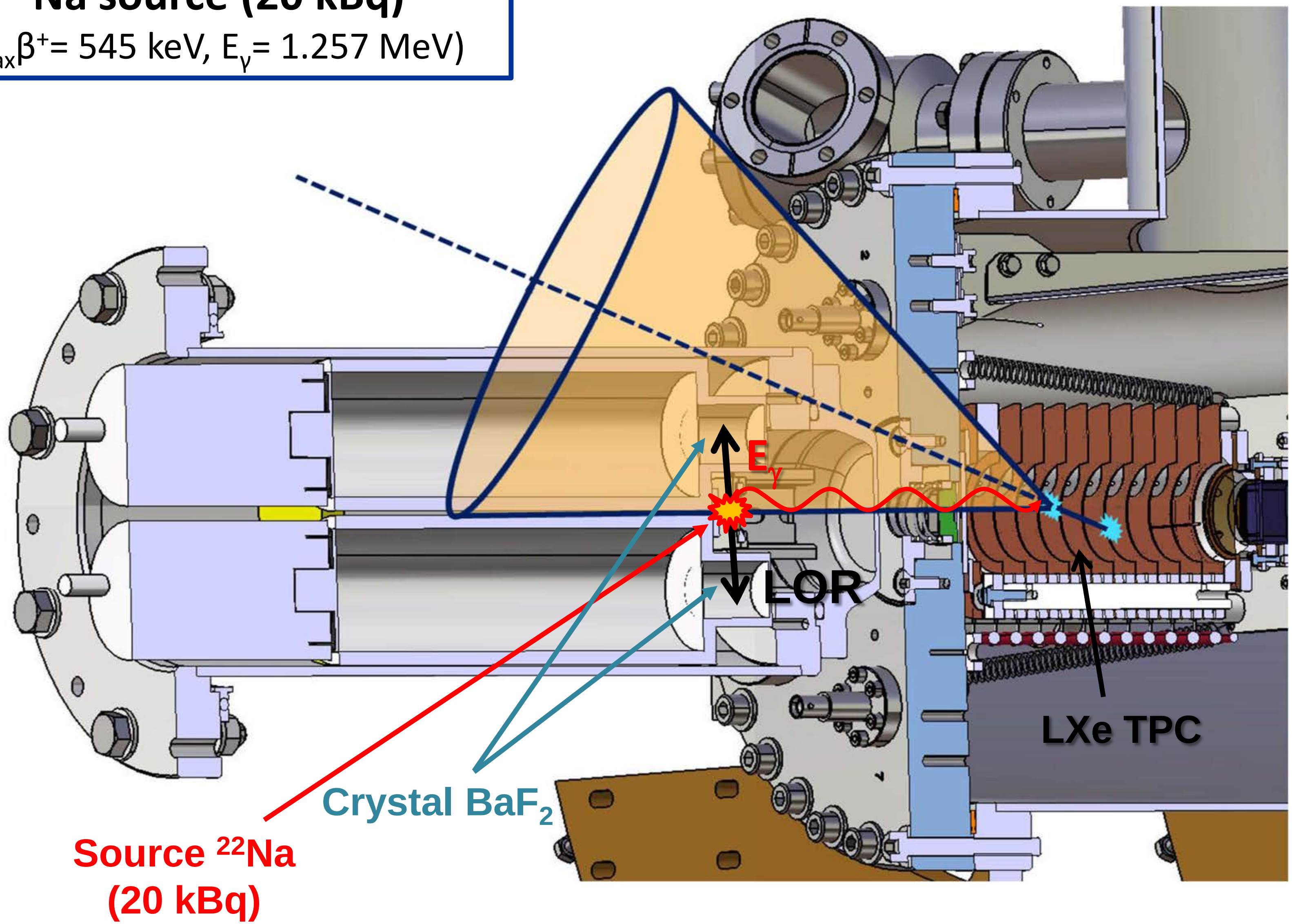




Very promising for Compton imaging

Cone LOR intersection

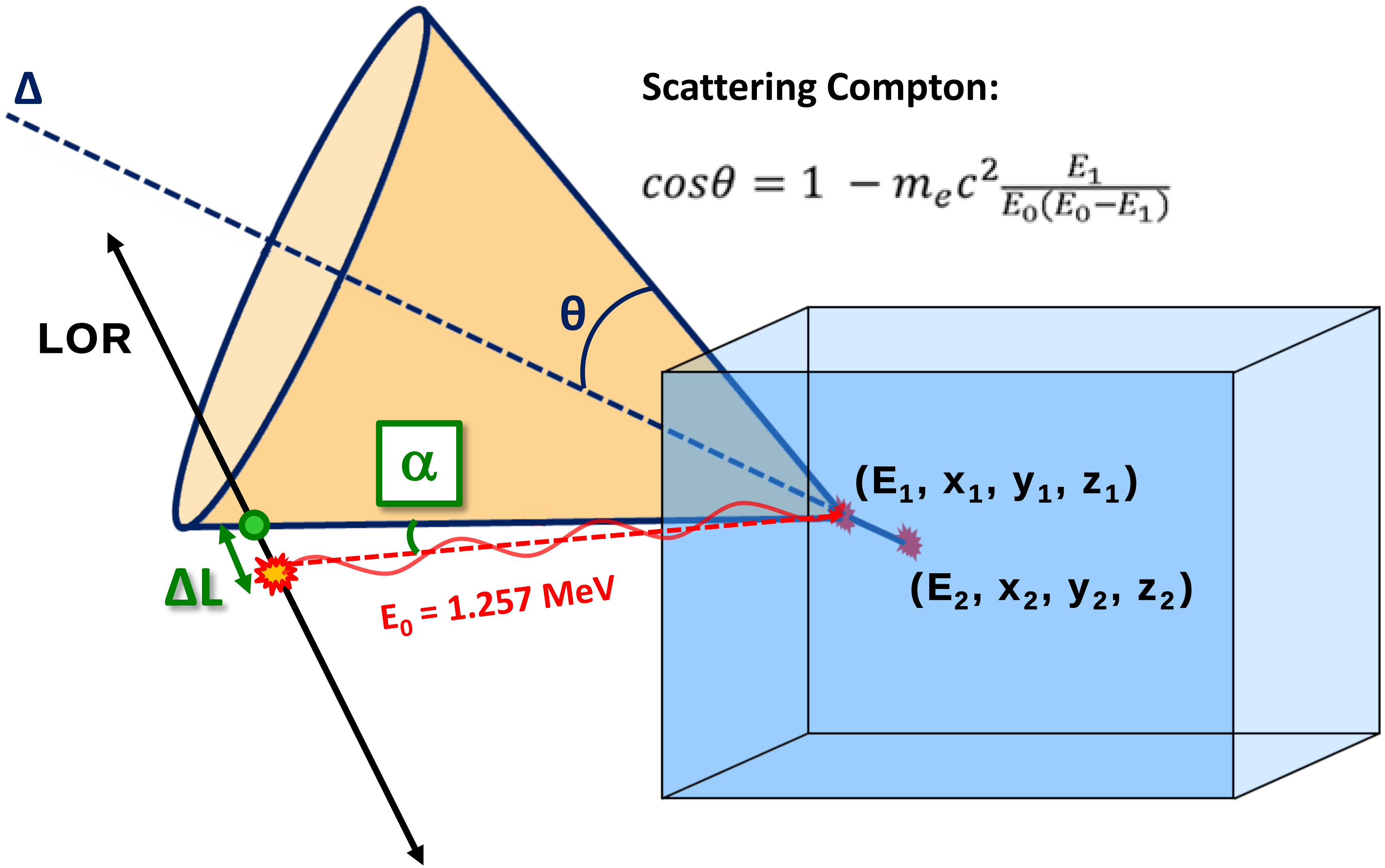
^{22}Na source (20 kBq)
($E_{max}\beta^{+}$= 545 keV, E_{γ}= 1.257 MeV)



Cone LOR intersection

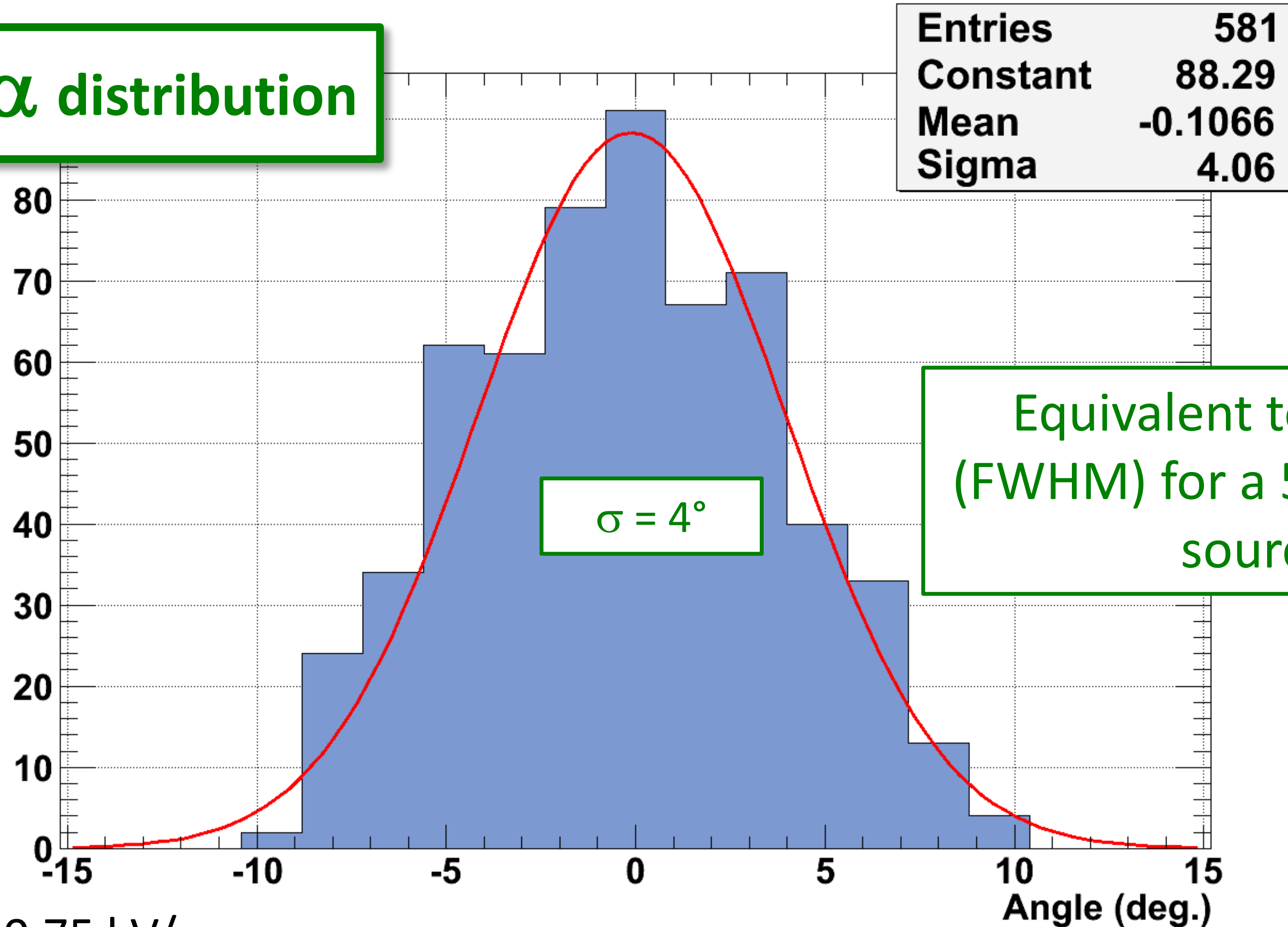
Scattering Compton:

$$cos\theta = 1 - m_e c^2 \frac{E_1}{E_0(E_0 - E_1)}$$



Resolution along the LOR

α distribution



σ = 4°

Equivalent to 8,2 mm (FWHM) for a 5 cm distant source

E = 0.75 kV/cm

It works! Very promising

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- **XEMIS2: Small animal imaging**
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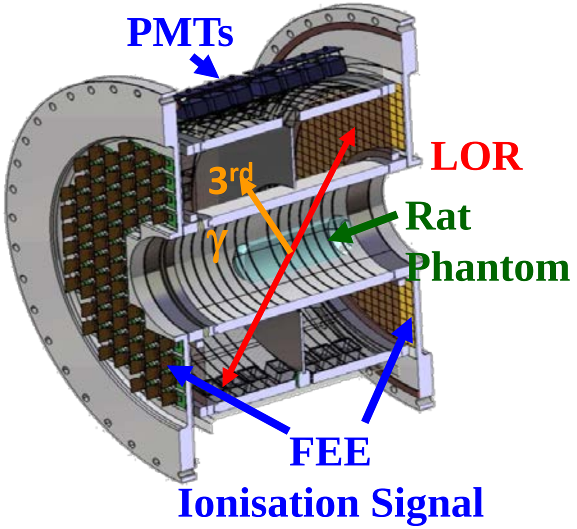
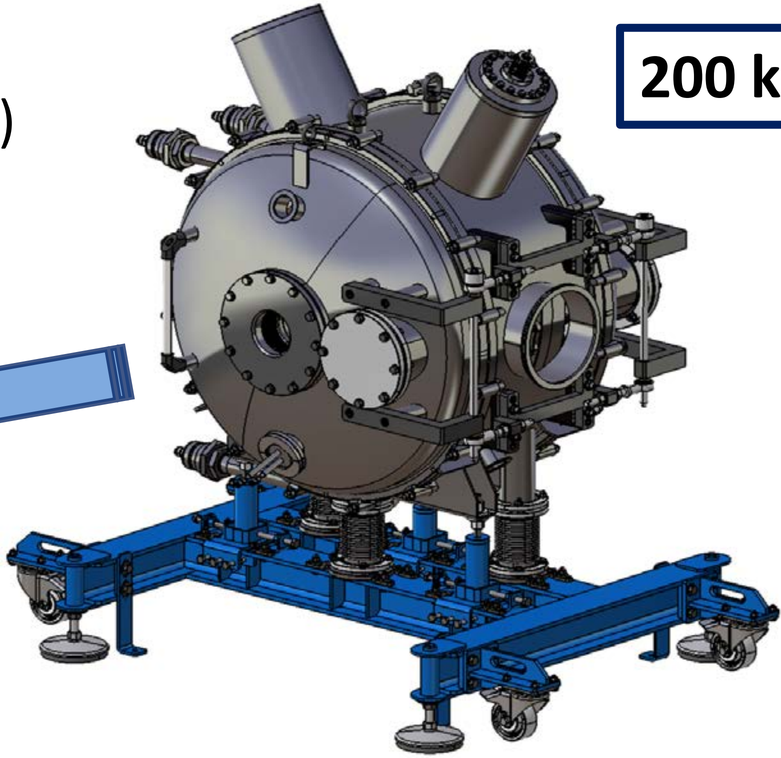
XEMIS2 Prototype

Full liquid xenon cylindrical camera dedicated to small animal imaging

- Active radius : 7 < r < 19 cm
- 1'' photo-sensors : 348 (50 at first)
- FEE ionisation channels : 25 000





200 kg LXe

- Advanced simulation with GATE since 2012
- Design study 2013
- Construction 2014
- Installation at Nantes Hospital in 2015

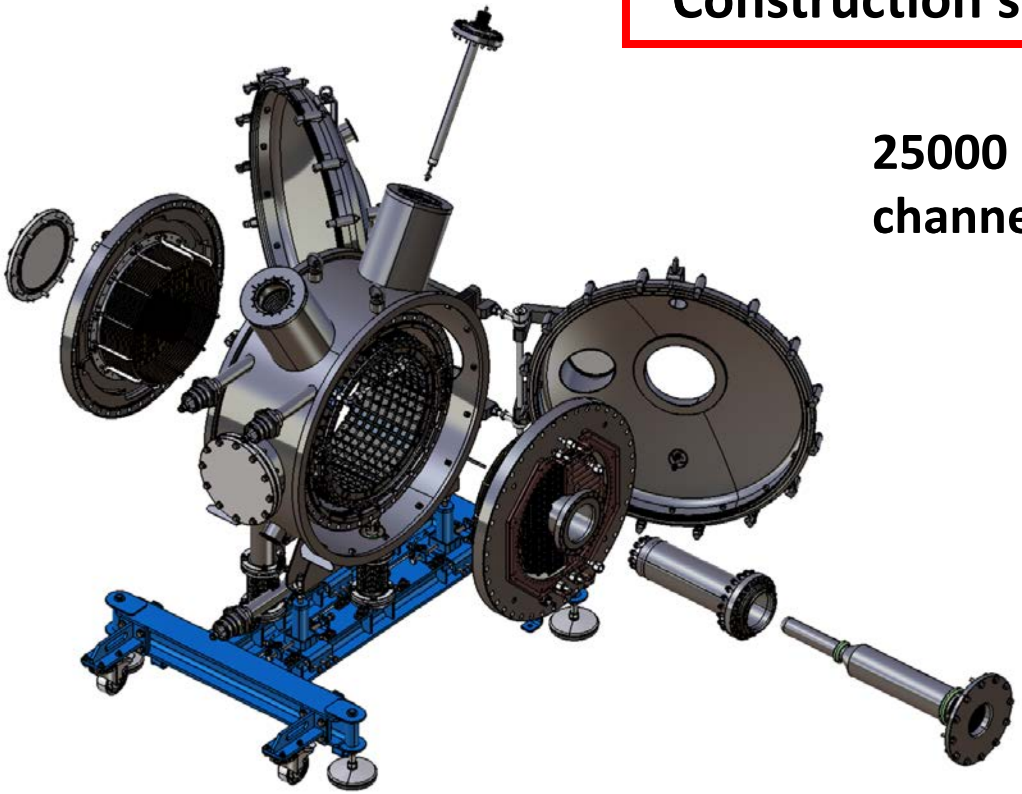
AIR LIQUIDE

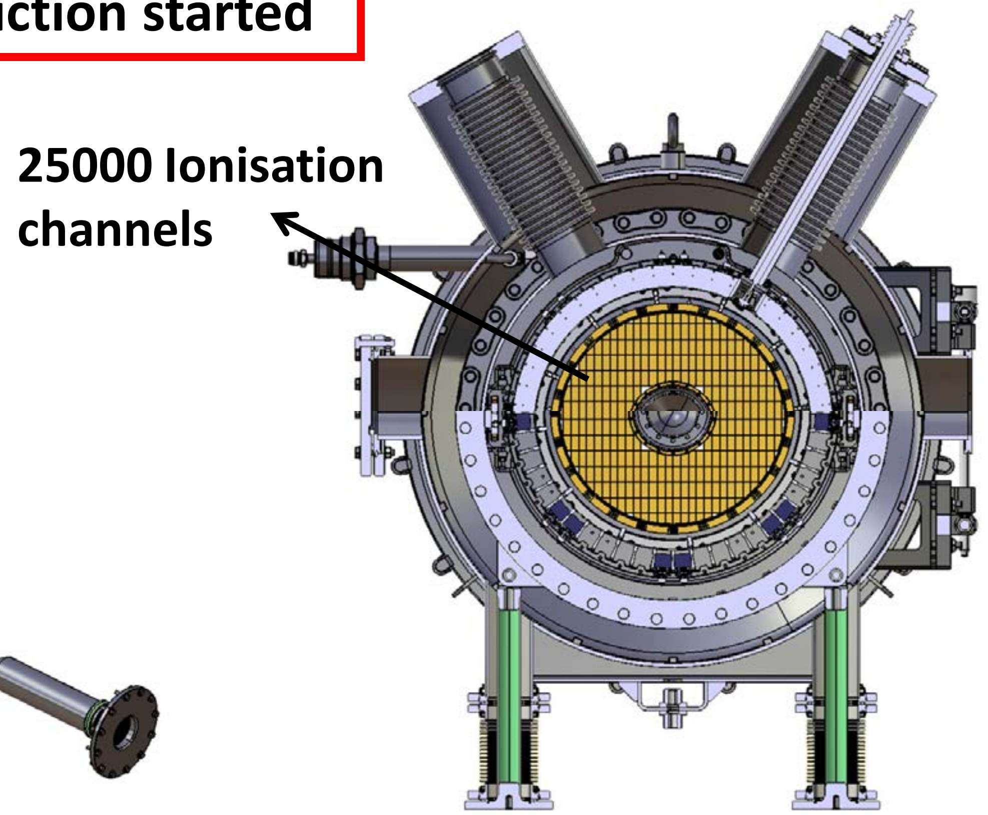
CENTRE HOSPITALIER UNIVERSITAIRE DE NANTES

Inserm

XEMIS2 Cryostat

Detail studies ended
Construction started





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Data treatment simulation

XEMIS1

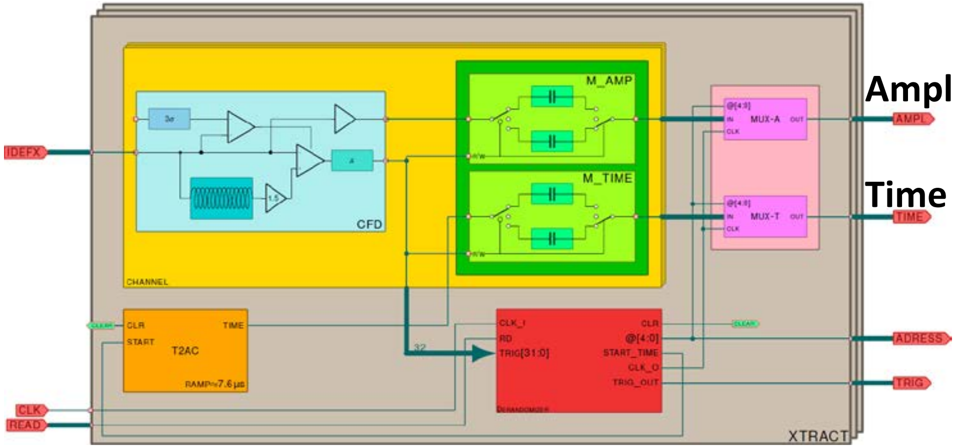
Output signal: continuous sampling 12.5 MHz → 64 channels x 102.2 μs → 2Gb/hour

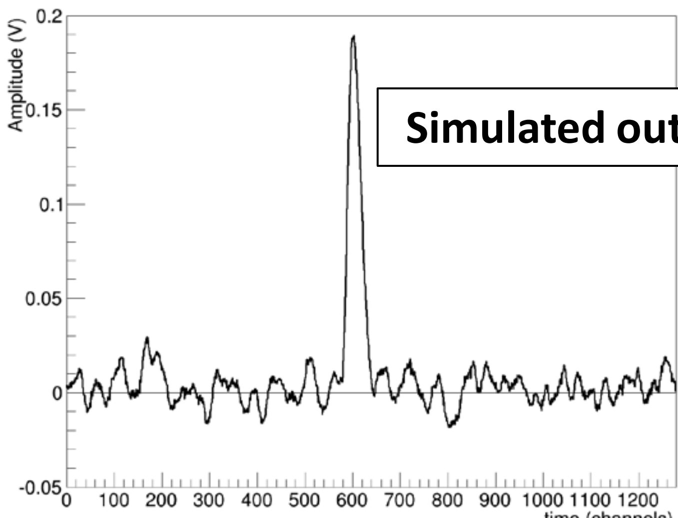
XEMIS2

- Anode: **25000** pixels
- Analog ASIC (XTRACT): signal **amplitude** and **time** registration

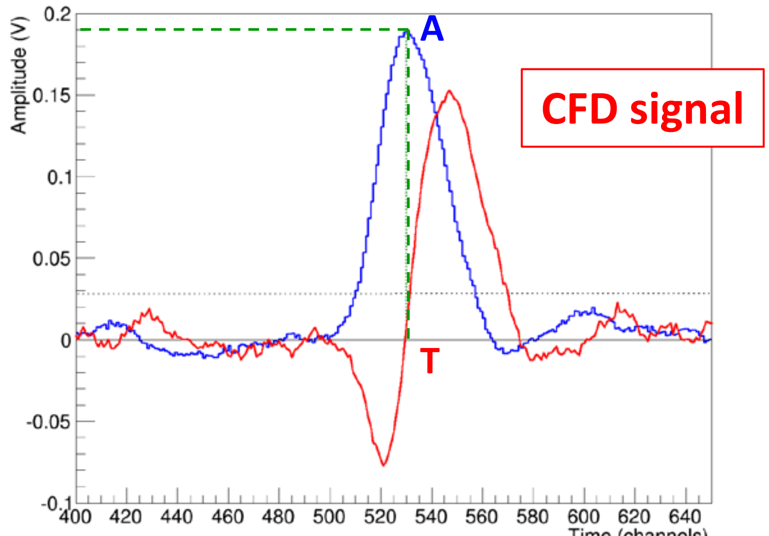
⇓

- **Constant Fraction Discrimination** (CFD)
- Optimal discriminator threshold level

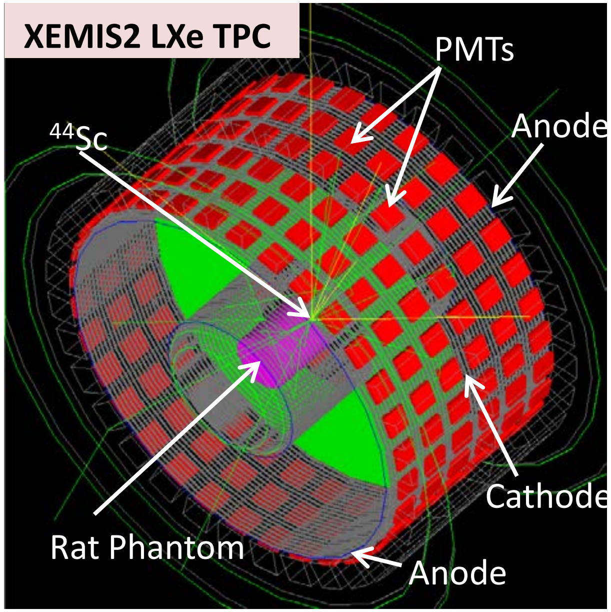




Simulated output signal



XEMIS2 Design



Geometry and response simulation with Geant4 and GATE

Objective: Precision along LOR **~ 1 cm (FWHM)**

- Energy resolution ⇨ 5% @ 511 keV
- Spatial resolution ⇨ < 1 mm (X, Y)
  ~ 0.5 mm (Z)

} XEMIS1

Sensitivity ≈ 5% ⟹ **Very high sensitivity**

OpenGATE collaboration: *http://www.opengatecollaboration.org/*

Image Reconstruction

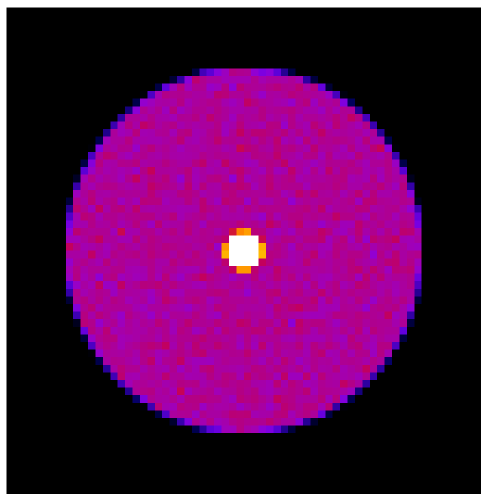
Image Reconstruction: 3γ + reconstruction algorithm

GATE simulation:

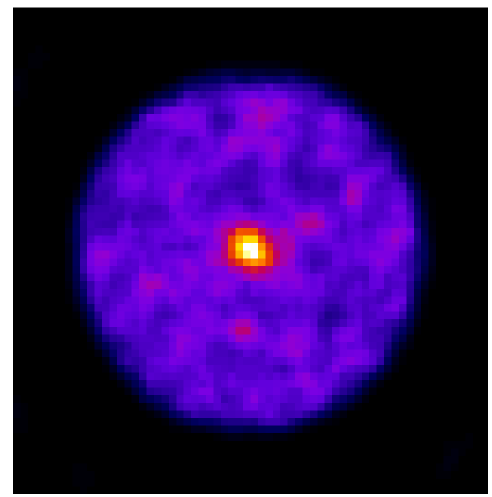
- ^{44}Sc source located at the center of the camera
- **Low activity: 20 kBq inside the phantom**
- **Acquisition time 20 minutes**

50 times less of activity than MICRO-PET for small animal imaging!

Simulated Image



Reconstructed Image



Conclusion and Perspectives

XEMIS1

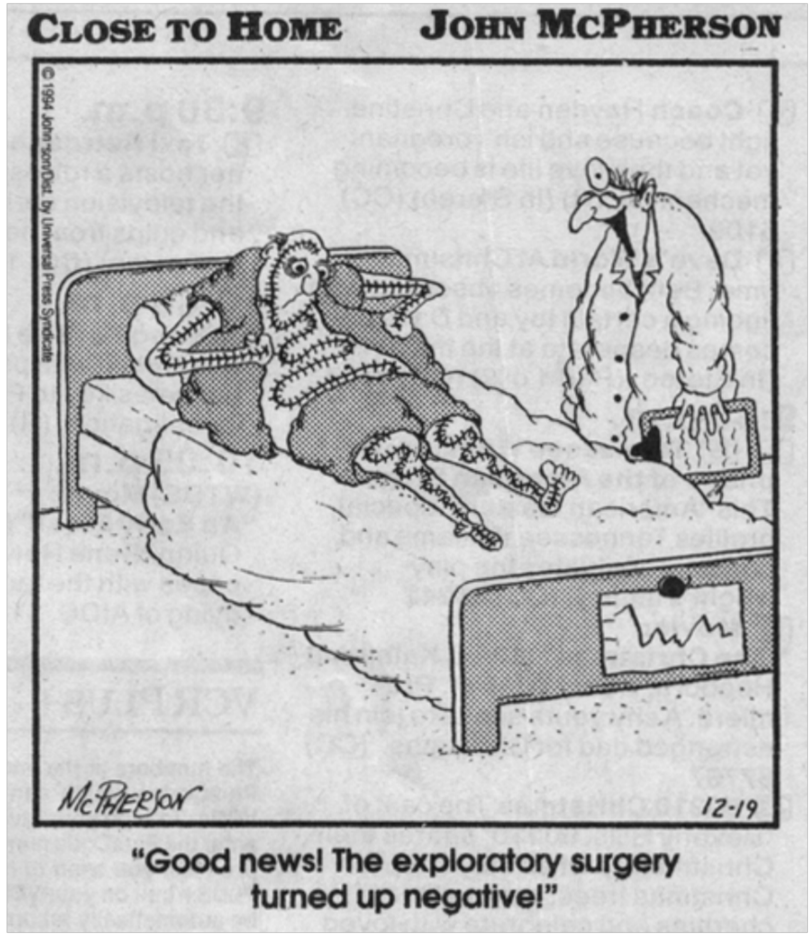
"Technical" proof of the feasibility of the 3γ imaging technique

- Very good results for the ionization signal in liquid xenon have been obtained with XEMIS1.

XEMIS2

- A complete simulation of XEMIS2 using Geant4 shows very promising results for the sensitivity, energy and spatial resolutions.
- Simulated tomographic reconstructed images reveal the possibility of imaging a whole animal in a short time with a very low injected activity.
- Design phase is already finished and the R&D for the upgrade of XEMIS2 is starting $\rightarrow$ **installation at Nantes Hospital in 2015.**

Thank you for your attention



"Good news! The exploratory surgery turned up negative!"

Acknowledges:

Cancéropôle Grand ouest
Nantes Métropole
Région PAYS DE LA LOIRE
ANR
INSTITUT NATIONAL DU CANCER

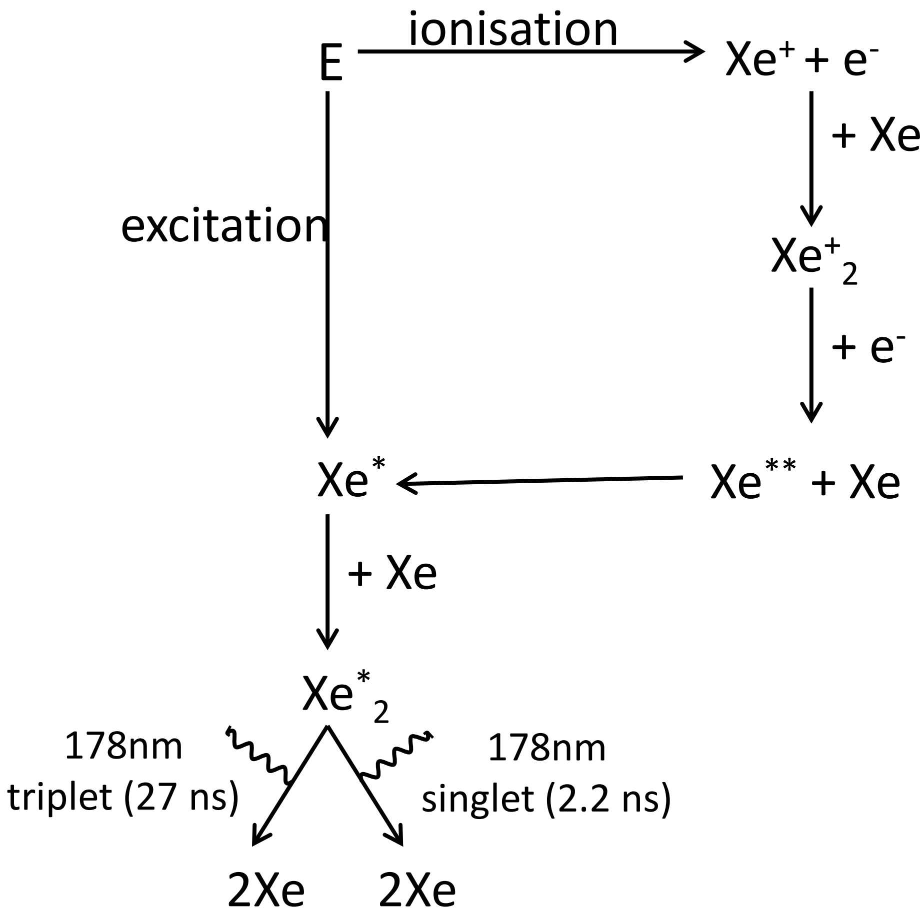
Backup

Why Liquid Xenon?

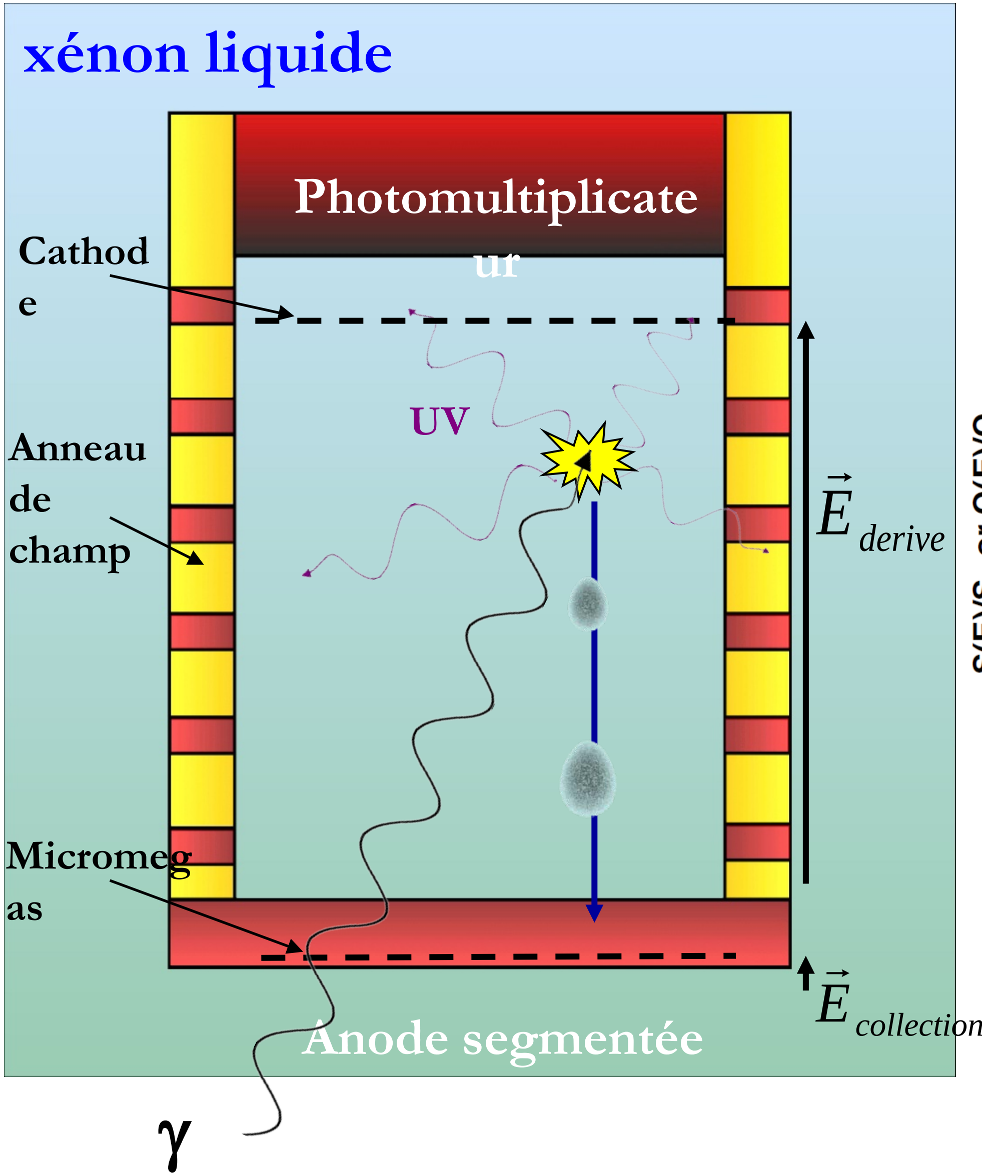
Attractive properties as detector medium:

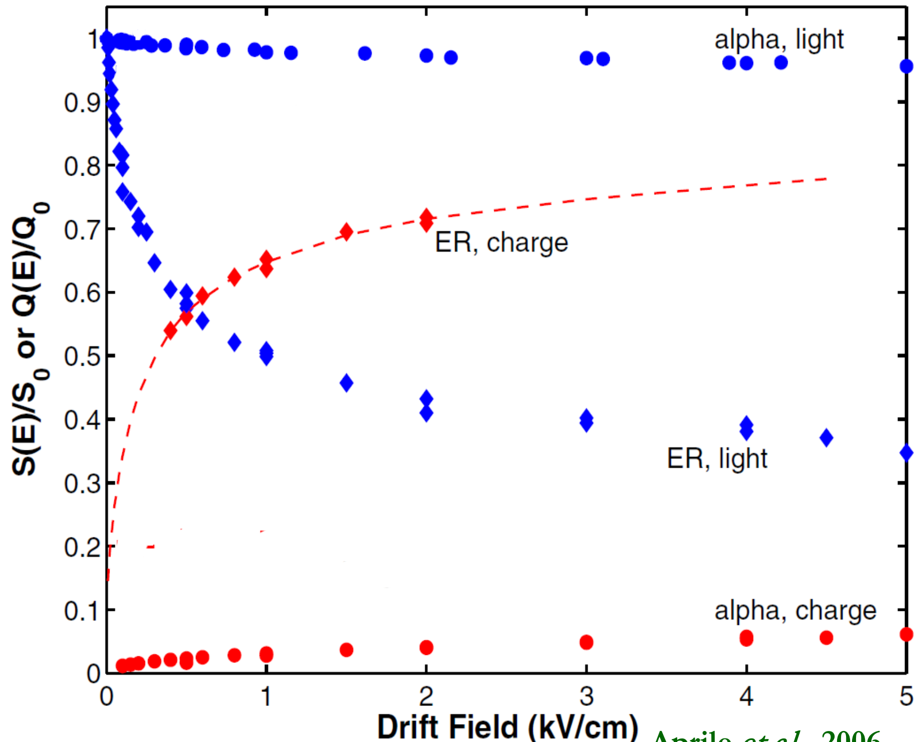
- **High density**: 3 g/cm^3 and high **atomic number**: Z = 54
- → high stopping power for 1 MeV γ-rays → compact detector
- **High scintillation yield**: 42 000 UV photons/MeV at 175 nm
- **High ionization yield**: 64 000 electron-ion pairs/MeV (W_{LXe} = 15.6 eV)
- **High electron drift velocity** (v = 2 mm/μs) and **low diffusion** → excellent spatial resolution
- **Liquid state** → large monolithic detector at reasonable cost
- **Boiling point**: 165 K → warmer that other liquid materials as N_2 or Ar
- → "easy" cryogenics
- **Event localization in 3D** → time projection chamber (TPC)

Why Liquid Xenon?



Liquid Xenon TPC



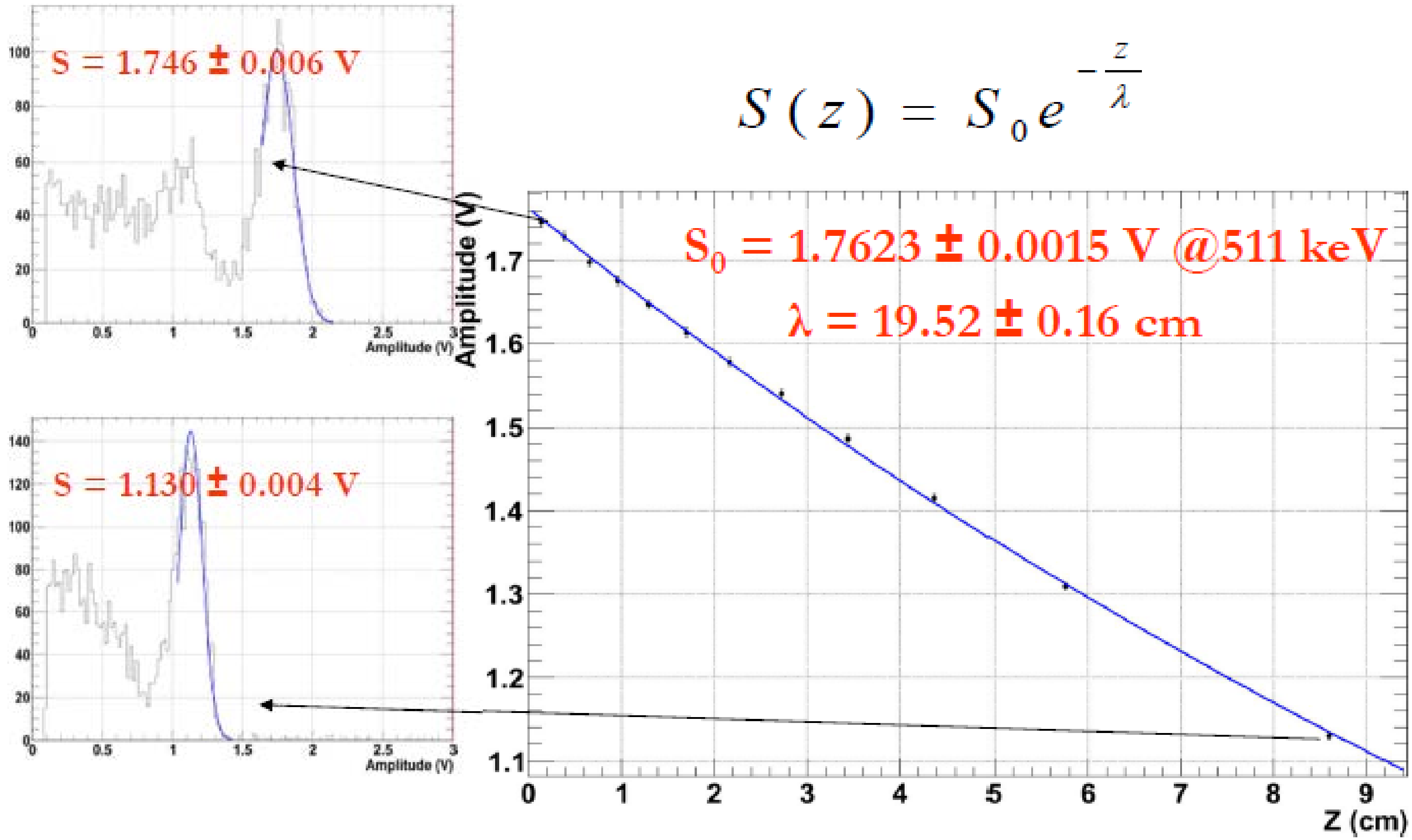


Aprile *et al.*, 2006

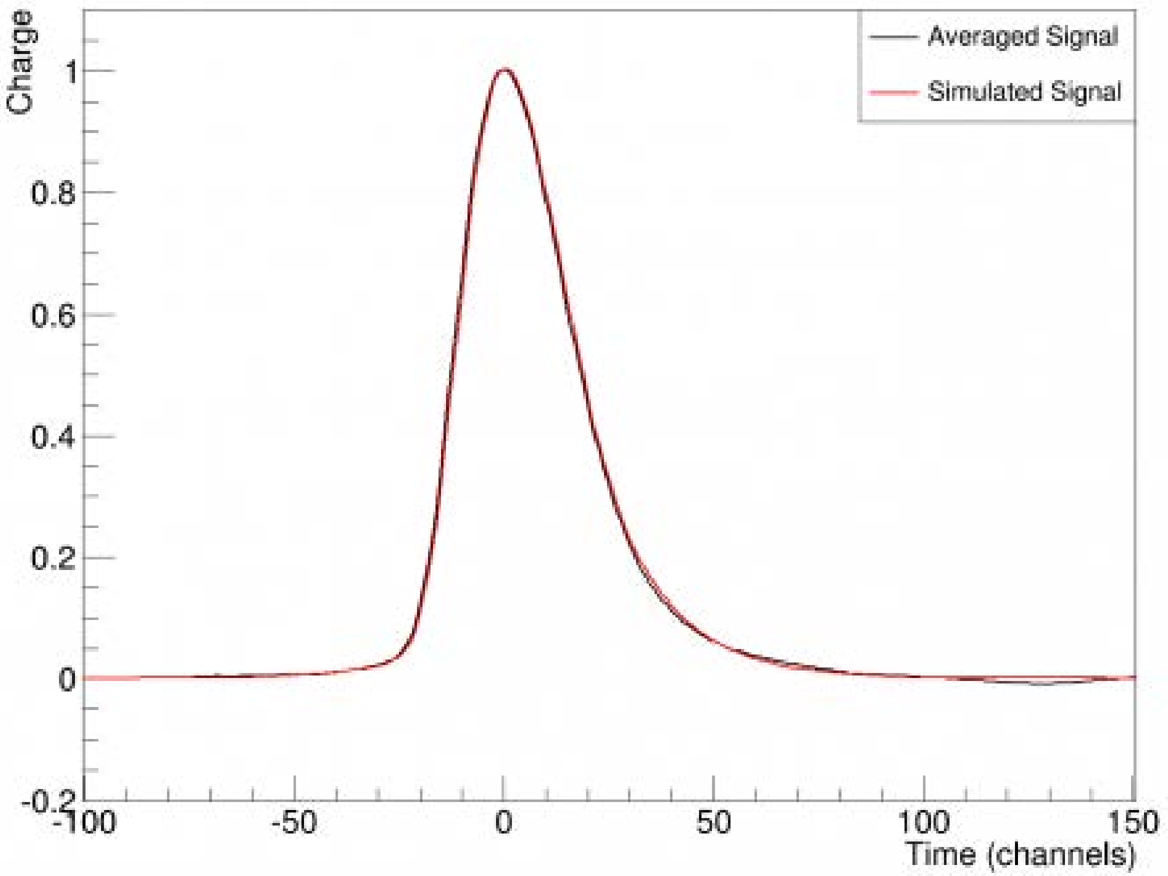
Purity of the Liquid Xenon

Electronegative impurities absorbed electrons drifting in LXe

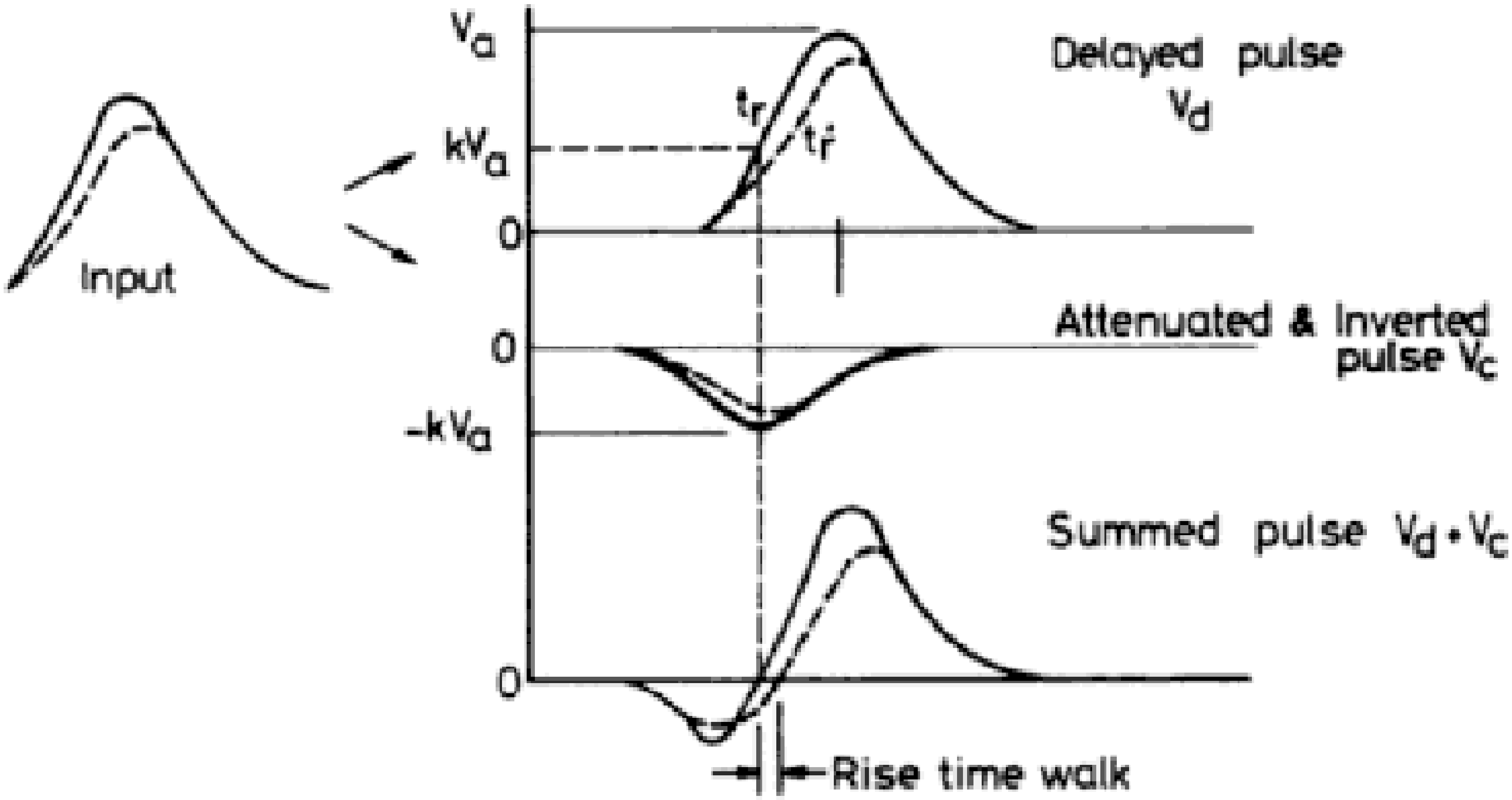
$$S(z) = S_0 e^{-\frac{z}{\lambda}}$$



Data treatment simulation

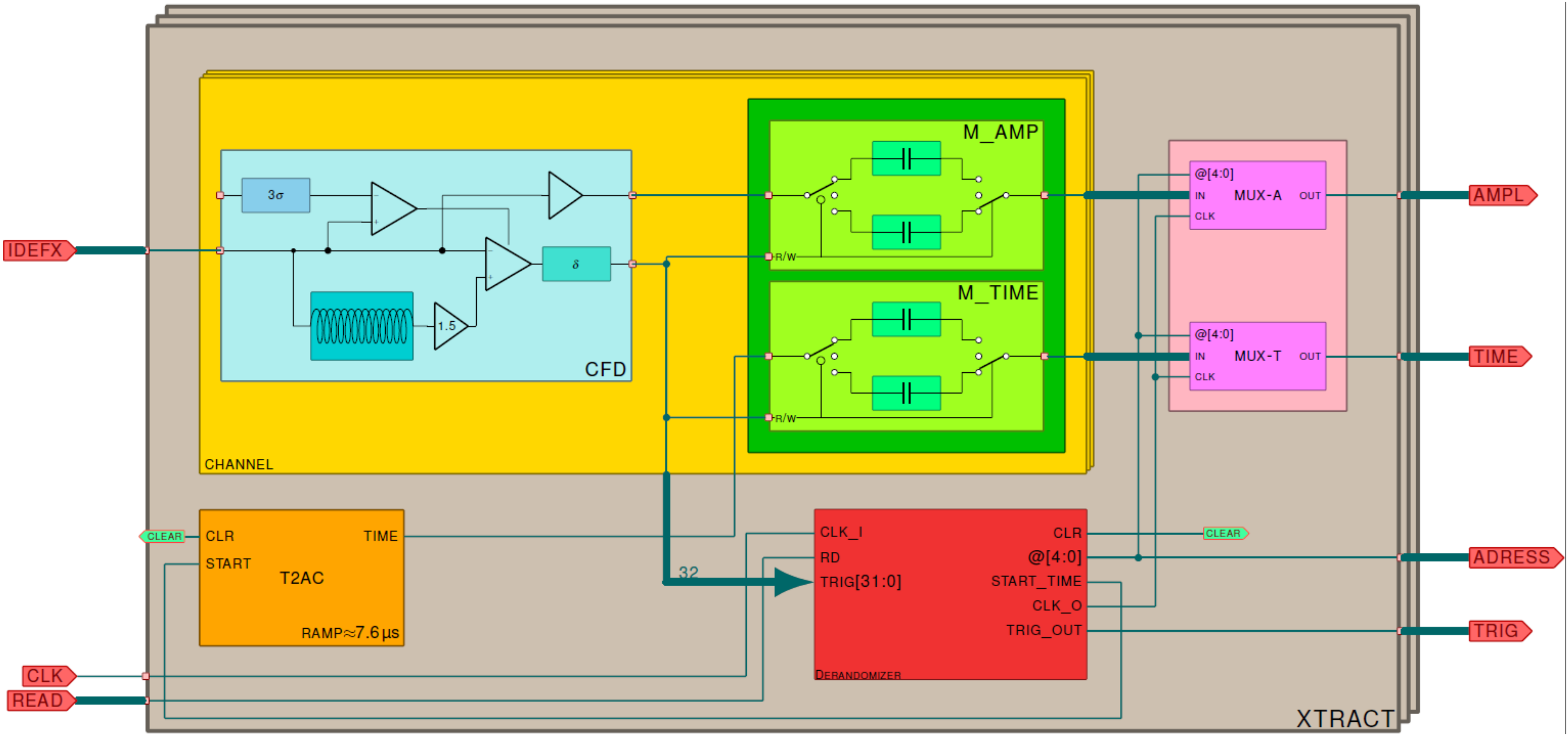


Data treatment simulation



W.R. Leo. Tehcniques for Nuclear and Particle Physics Experiments. Springer-Verlag

Data treatment simulation



Data treatment simulation