XEMIS: low dose 3γ medical imaging with a single-phase liquid xenon TPC

Lucía Gallego Manzano

30/01/2017

Subatech

XENON Group @ Subatech

- **Medical Imaging Applications:** XEMIS project
- **Dark Matter Research:** XENON100, XENON1T, DARWIN

XENON Group @ Subatech

XEMIS @ Subatech

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Post-doc:

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- Lucía Gallego

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Mechanical Service:

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- Jean-Sébastien Stutzmann

Electronic Service

Collaborations

CHU / INSERM

- Thomas Carlier

IRCCyN

- Imaging

KEK Japon

- R&D photodetectors

Air Liquide Advanced Technologies

- R&D liquid xenon cryogenics

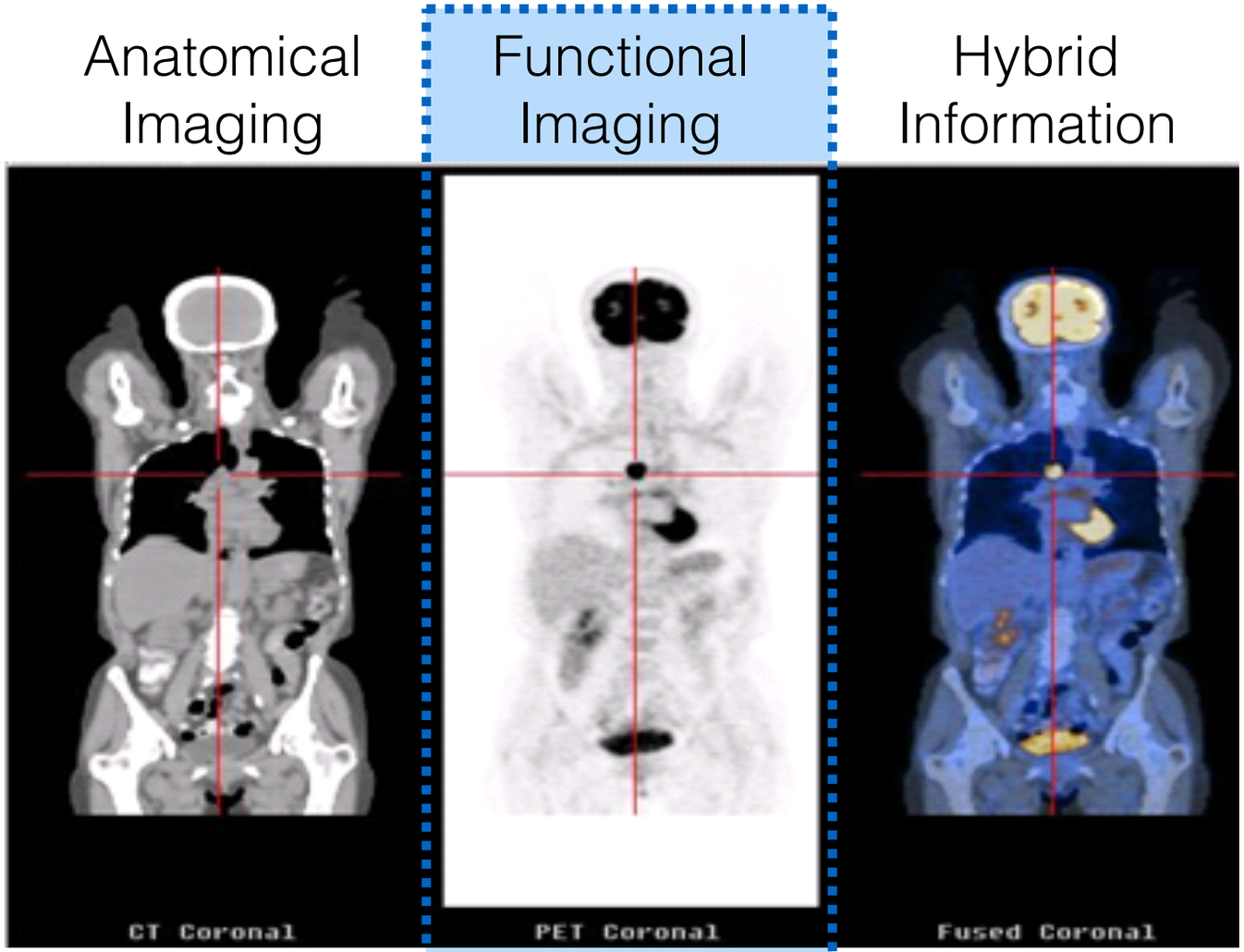
Pôle Micrhau

- R&D electronics

ARRONAX

- Radioisotope production

Medical Imaging



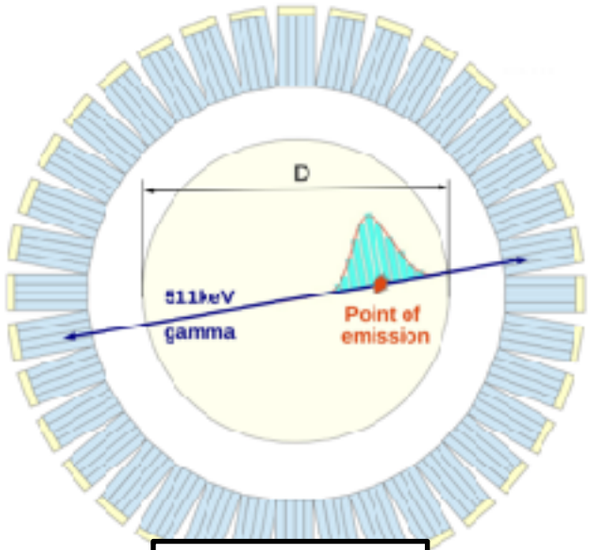
CT: Computed Tomography
PET: Positron Emission Tomography

Motivation

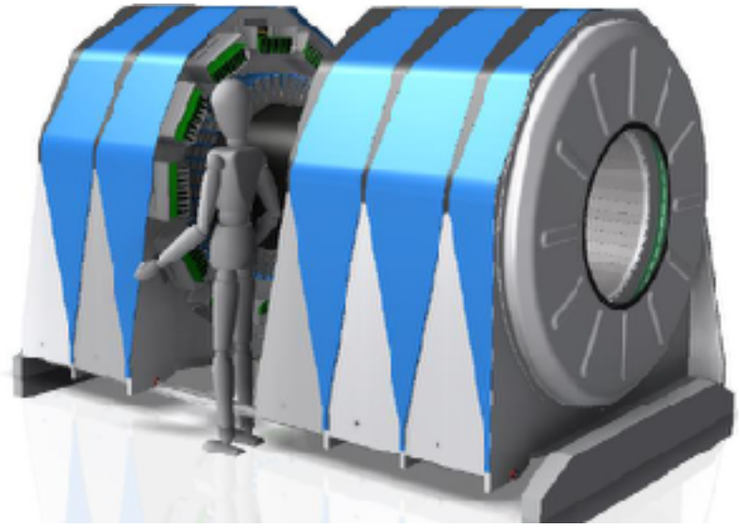
- What are the axes of tomorrow's **functional medical imaging**?
  - Early diagnosis:
    - **Better sensitivity** & specificity in disease detection
  - Personalized diagnosis and treatment:
    - Quantitative analysis → **Personalized Medicine**
  - **Lower dose** / Shorter Exam Time

- How?

  New detectors design
  - Depth of interaction
  - Time of Flight
  - Larger Field of View
  - Multi-modal imaging



TOF-PET



EXPLORER

Alternative to standard technologies?

XEMIS: XEnon Medical Imaging System

Low activity Medical Imaging (~20 kBq)

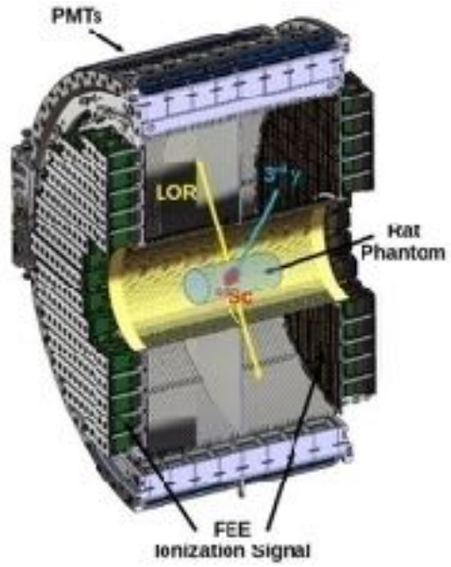
3γ imaging + Liquid xenon Compton camera

XEMIS1
R&D

XEMIS2
Small animal imaging

XEMIS3
Whole body imaging

30 kg
12 cm drift TPC



200 kg
2 x 12 cm drift TPC

From 2020

LXe clinical camera

- Neurology: ~250 kg
- Paediatrics: ~700-800 kg
- Whole body: few tons

Outline

1. 3γ Imaging and liquid xenon
2. XEMIS1: R&D
3. XEMIS2: Small animal imaging
4. Image Reconstruction
5. Conclusions

Principle of the 3γ Compton Imaging

- Radioisotope (β^+,γ) emitter in coincidence
- Direct 3D reconstruction of the source:

Line of response (LOR) + Compton cone

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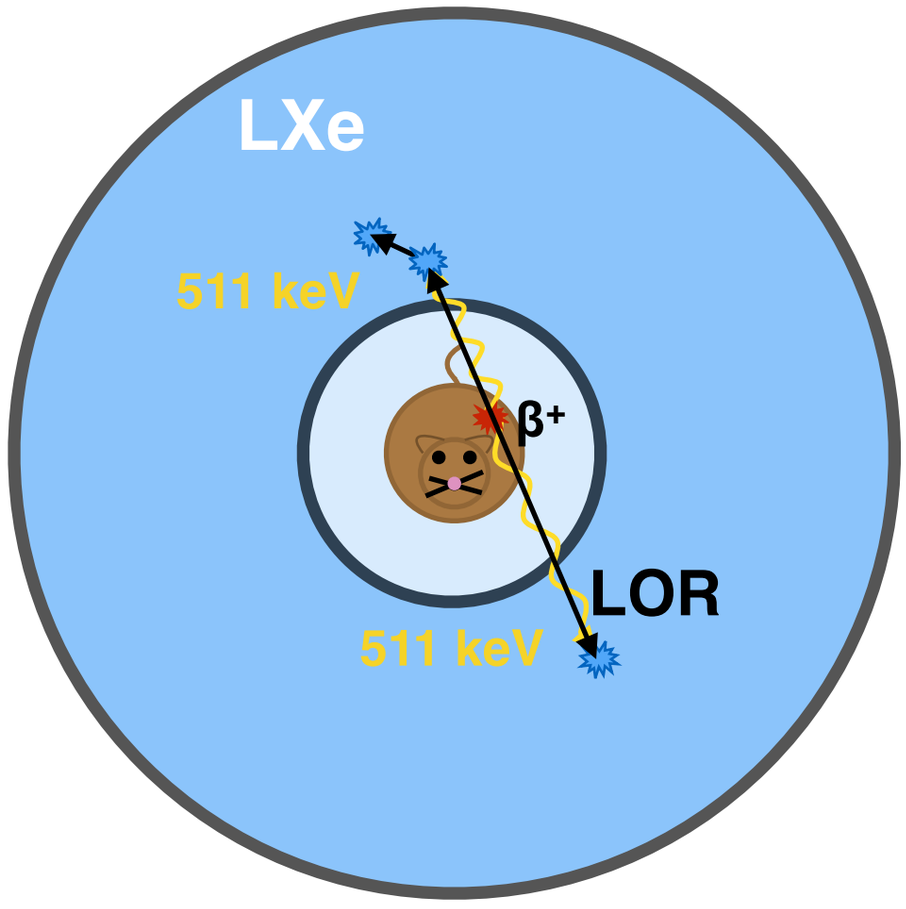


Principle of the 3γ Compton Imaging

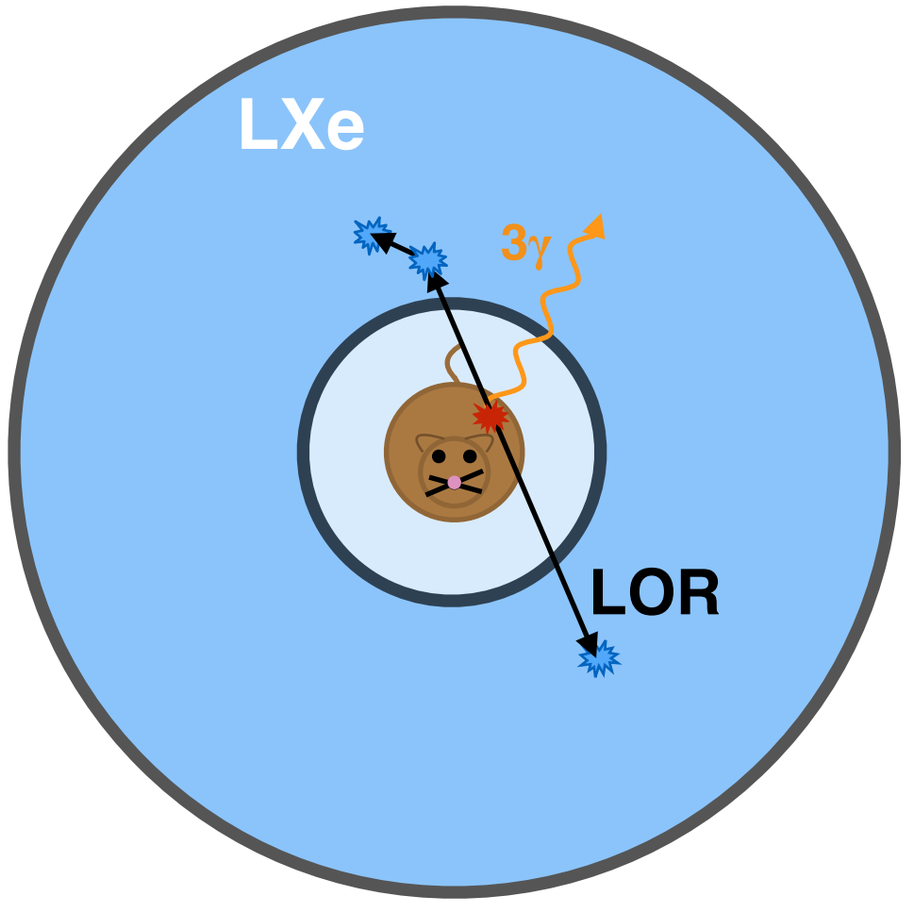
- Radioisotope (β^+,γ) emitter in coincidence
- Direct 3D reconstruction of the source:

Line of response (LOR) + Compton cone

- Reconstructed γ direction:

Compton kinematics

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



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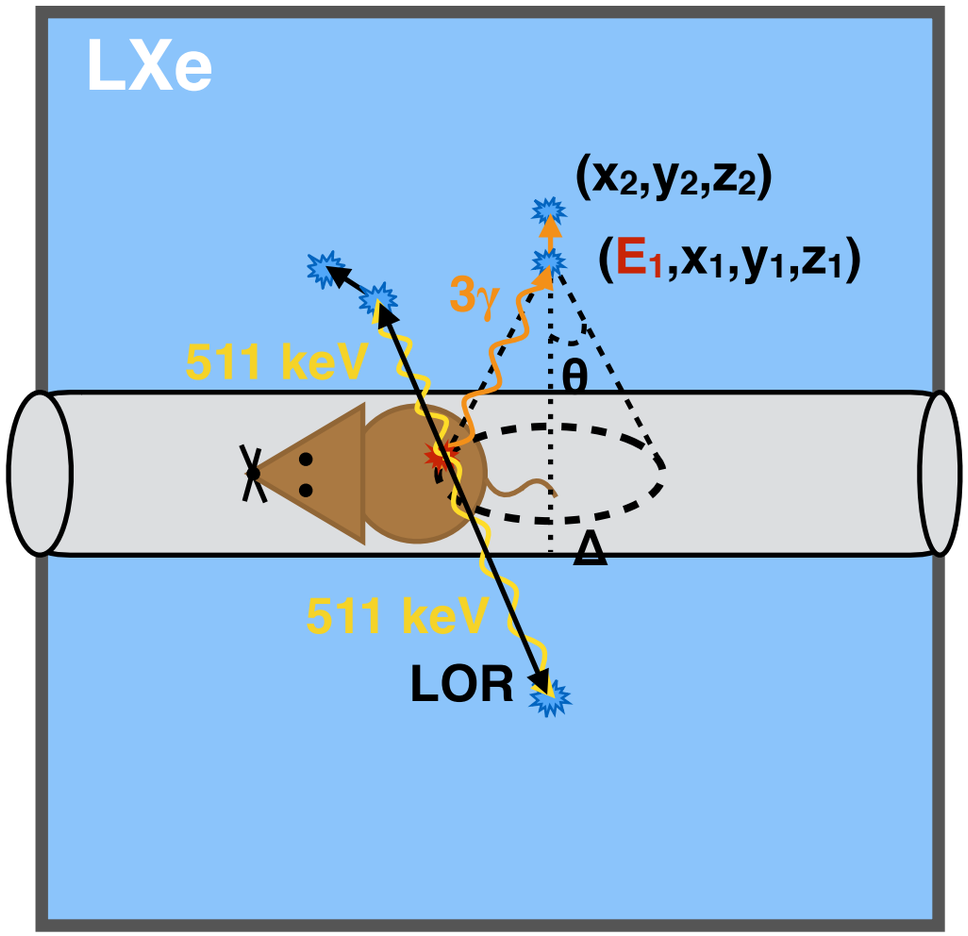
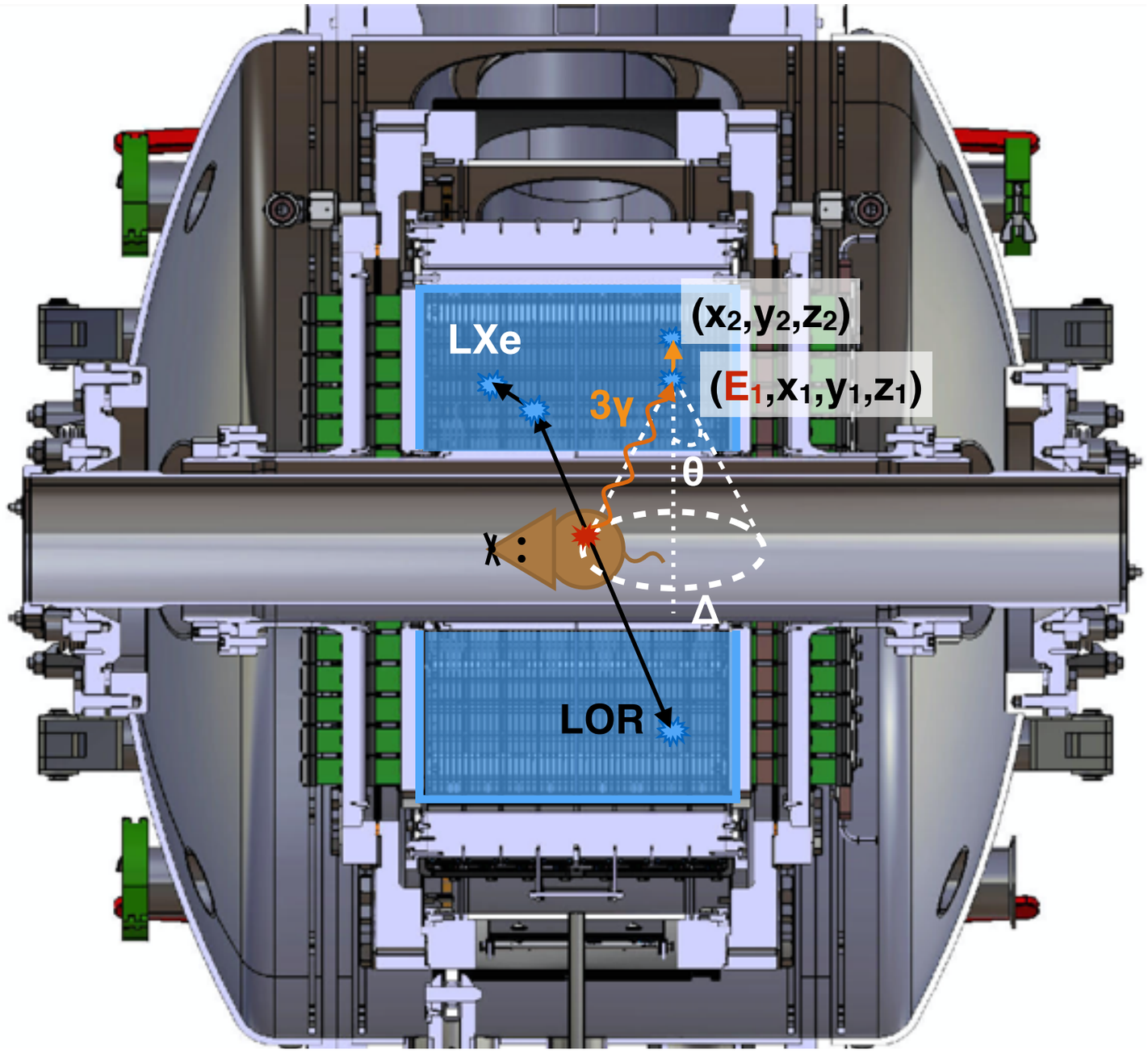
Spatial resolution ⇒ axis Δ of the cone
Energy resolution ⇒ opening angle θ



- Direct 3D location of the radioactive source
- Administered dose reduction &/or shorter scan times

3γ Imaging with XEMIS

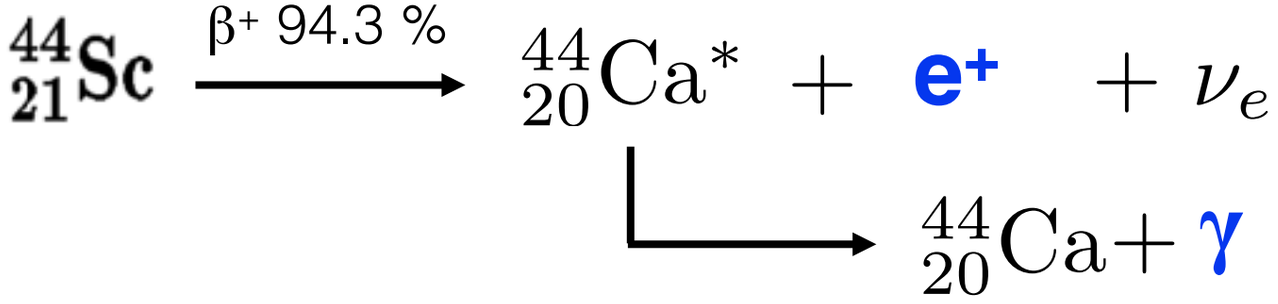


XEMIS2: A monolithic LXe cylindrical camera for small animal 3γ Compton imaging

Sc-44

Good **β+ / γ** emitter radionuclide for 3γ medical imaging: **^{44}Sc**

- Emission β+ (E_{max} = 1.474 MeV) + 1 photon of energy 1.157 MeV
- Spatial and temporal quasi-coincidence
- $T_{1/2}$ = 4 h



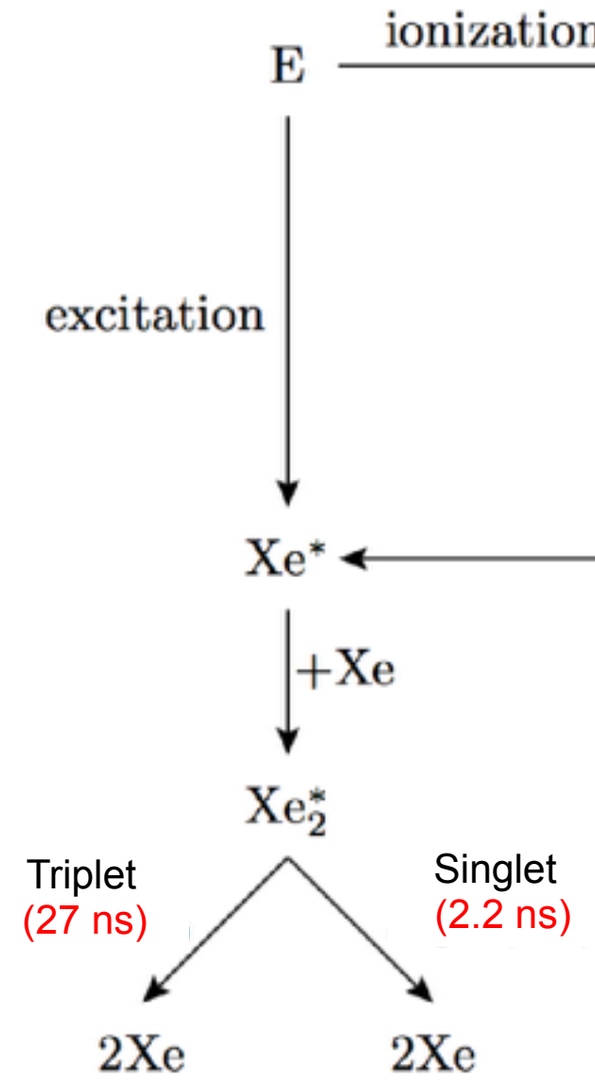
R&D { ^{44}Sc production: ARRONAX cyclotron
Radiopharmaceutical labeled with ^{44}Sc: CRCNA

Liquid Xenon as detection medium

- High stopping power (Z = 54 & ρ = 3.06 g.cm^{-3}) for γ-rays from 10 keV to 10 MeV
- Simultaneous production of a **scintillation** and an **ionization** signal
- High scintillation light yield and high ionization yield
- Scalable to large, massive and homogeneous detectors

Element	LHe	LNe	LAr	LKr	LXe
Atomic number Z	2	10	18	36	54
Average atomic weight A	4.00	20.18	39.95	83.80	131.30
Density (g.cm^{-3})	0.145	1.2	1.40	2.41	3.06
Boiling point at 1 atm (K)	4.22	27.1	87.3	119.9	165.0
Average ionization energy W (eV)	41.3	29.2	23.6	18.4	15.6
Light yield (photons/MeV)	15000	30000	40000	25000	42000

Charge and Light in liquid xenon



UV photons 178 nm

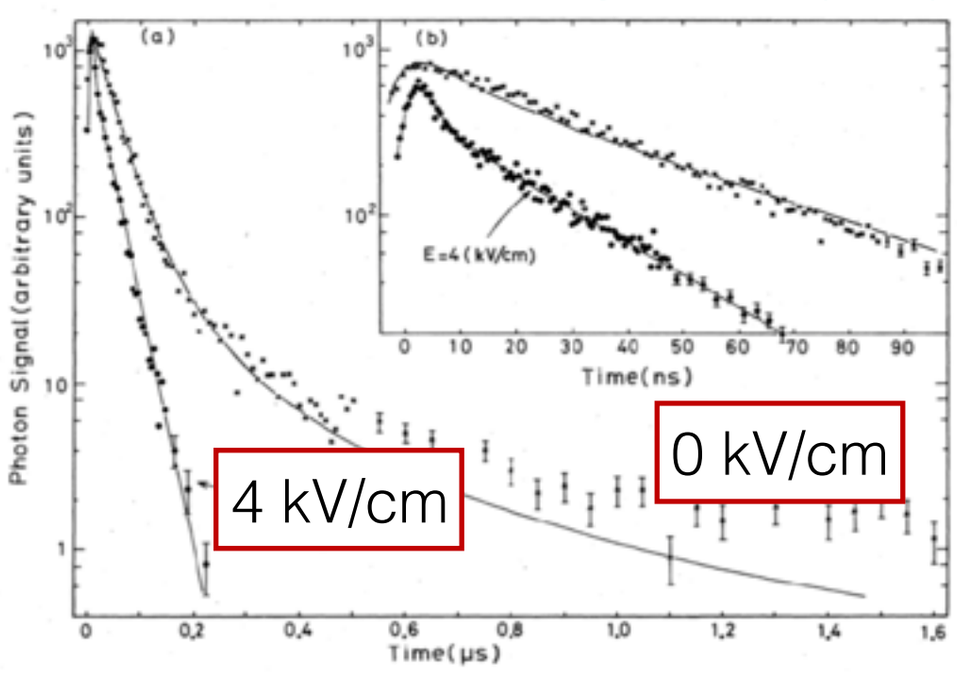
G. Plante, 2012.

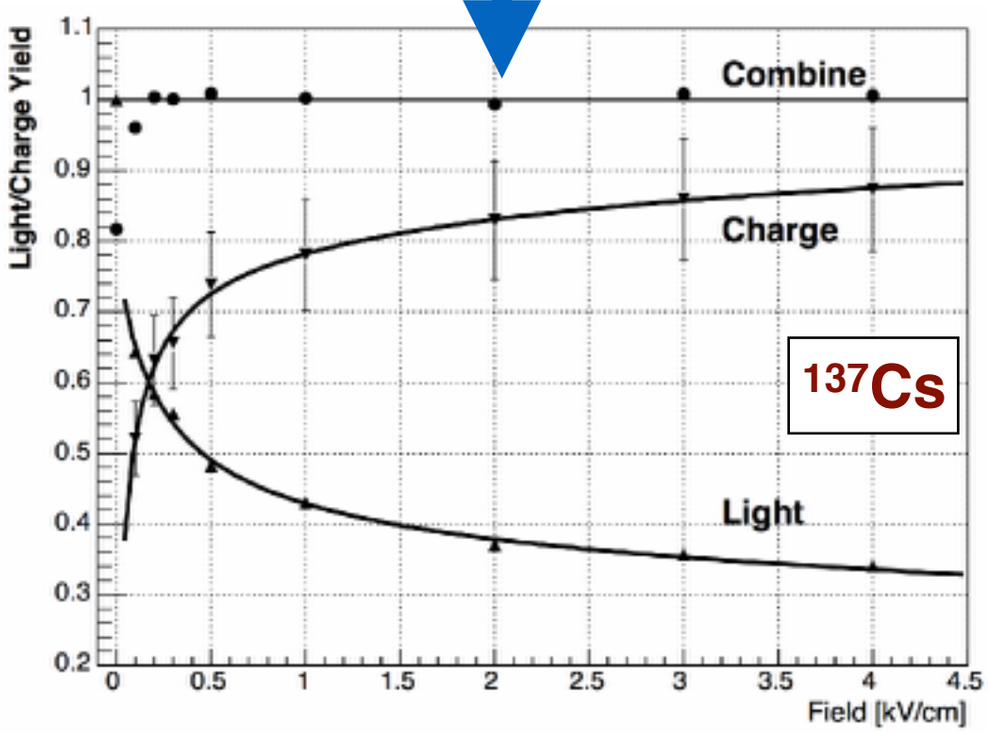
$\vec{E}$ = 0 kV/cm

Incident particle	τ_s (ns)	τ_t (ns)	τ_r (ns)	I_s/I_t
Electrons:	2.2 ± 0.3	27.0 ± 1.0	~ 45	0.05
Alpha particles:	4.3 ± 0.6	22.0 ± 1.5		0.45 ± 0.07
Fission fragments	4.3 ± 0.5	21.0 ± 2.0		1.6 ± 0.2

Electric field dependence

Kubota et al., Phys. Rev. B (1979)



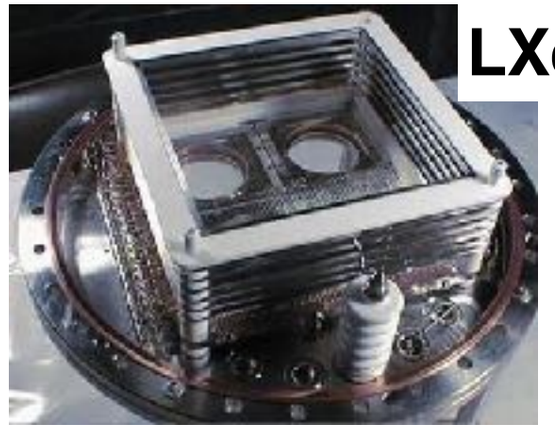


Aprile et al., Phys. Rev. B 76 (2007)

Overview

Possible applications:

- Gamma-ray astronomy
- Dark matter search
- Neutrinoless double beta decay search
- **Medical imaging**

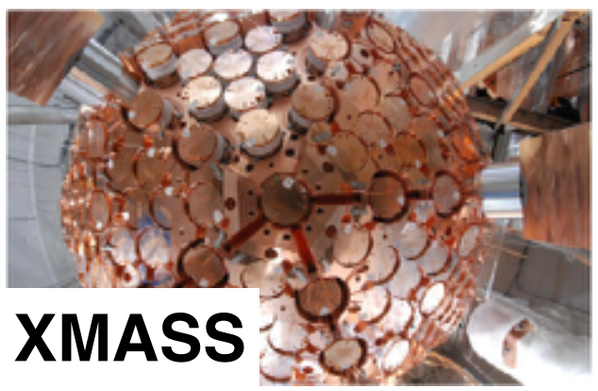


LXeGRIT

Liquid xenon based detectors:

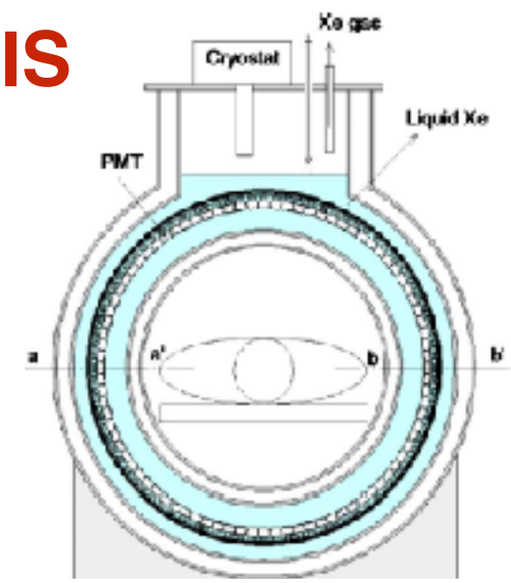
- Double-phase (LXe/GXe): XENON, LUX, ZEPLIN, Panda-X
- Single-phase (LXe):
  - Scintillation signal: XMASS, MEG
  - Ionization signal:

} LXeGRIT, **XEMIS**



XMASS

XENON1T

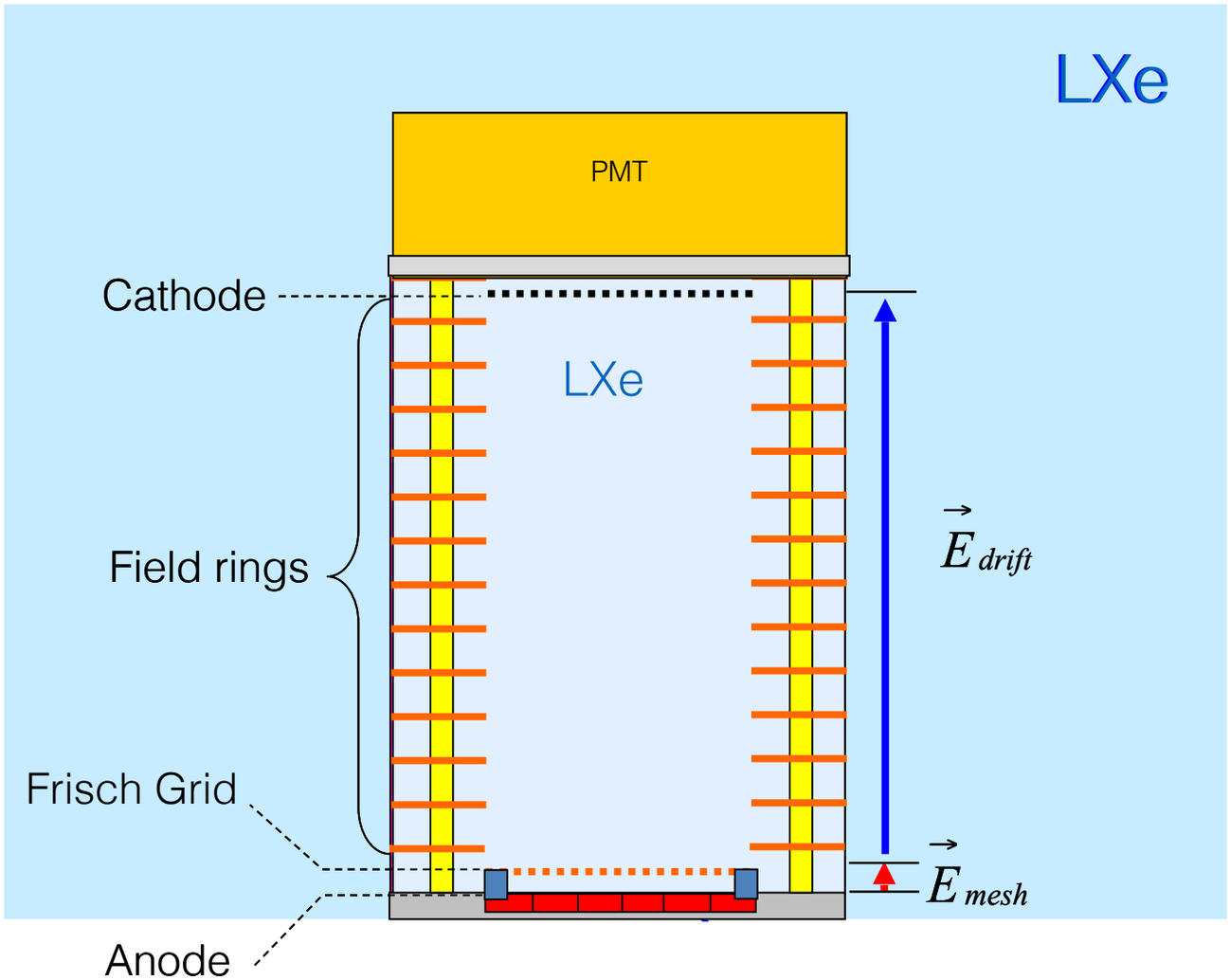


Waseda LXe TOF-PET

LUX

XEMIS: LXe Time Projection Chamber

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



Scintillation light (PMT)
t_0

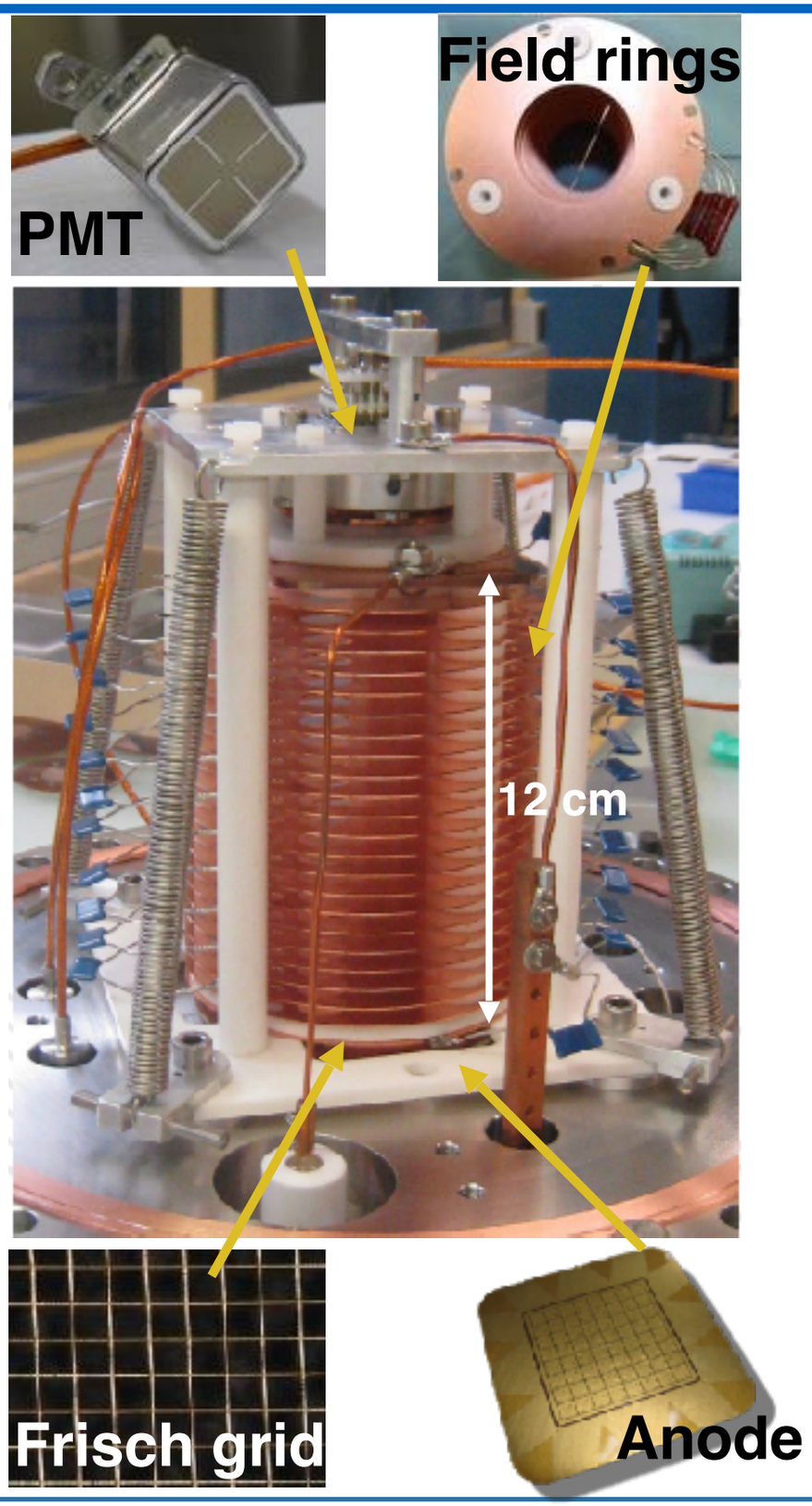
+

Ionisation
(Frisch grid, Anode, FEE)
Energy + (x, y) + t_1

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

Energy + 3D Positions
of each interaction

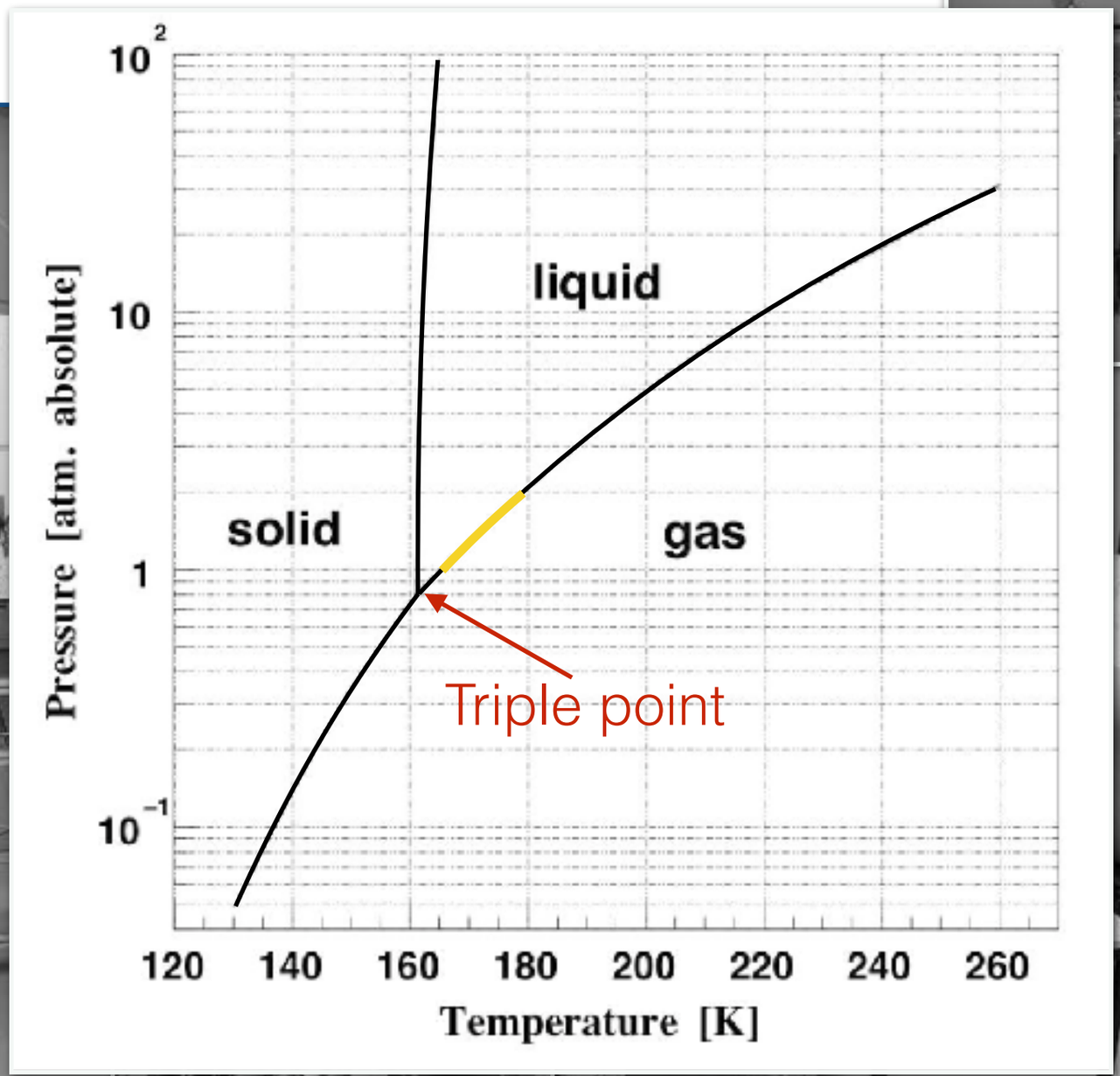
XEMIS: LXe Time Projection Chamber

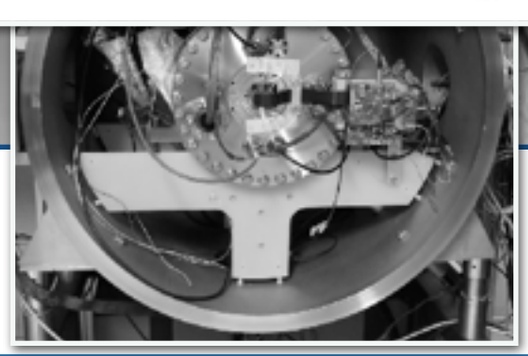


XEMIS1: R&D prototype

- 30 kg ultra pure LXe
- Active volume 12 (6) x 2.5 x 2.5 cm^3
- Field shaping rings (23)
  Homogeneous drift field up to 2.5 kV/cm
- 1” square UV sensitive PMT → Trigger
- Segmented anode (2.5 x 2.5 cm^2 active) in 64 pixels
- Frisch grid

Xenon Cryogenics



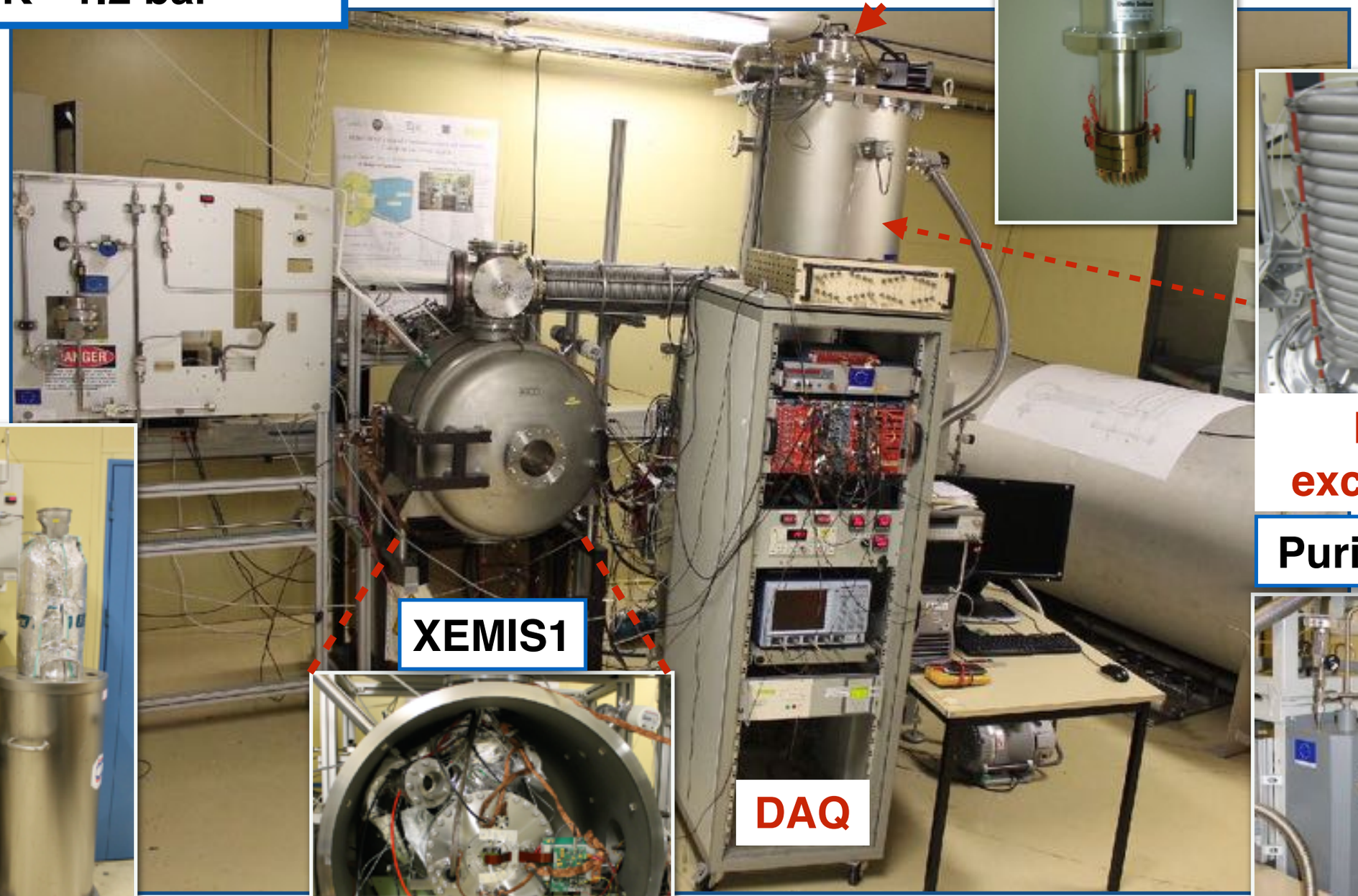


Experimental Conditions:
168 K - 1.2 bar

Narrow temperature margin of 7 K

XEMIS1 Facility

Experimental Conditions:
168 K - 1.2 bar



PTR

Liquefaction

Heat exchanger

Purification

Getters

Storage

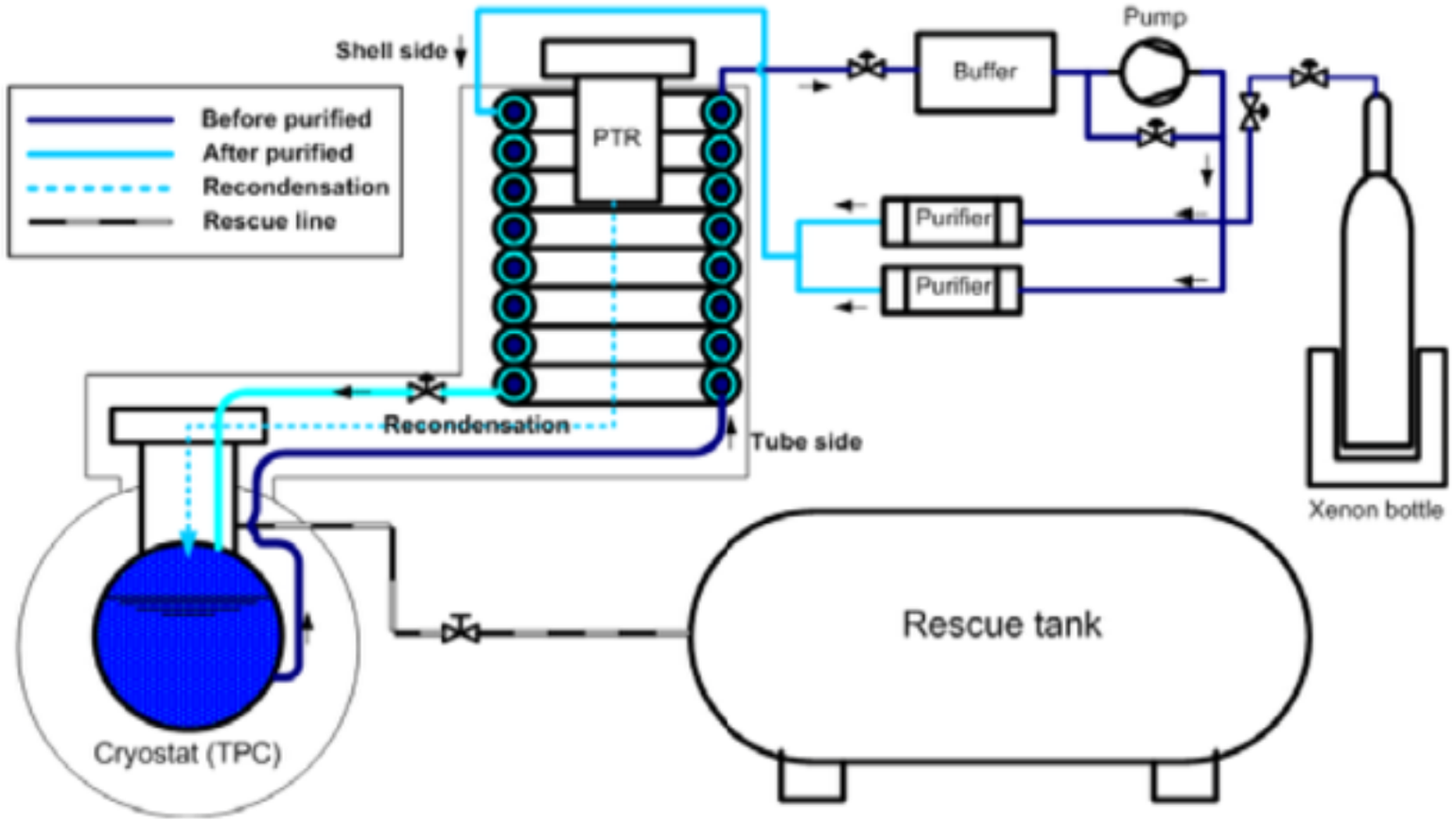
XEMIS1

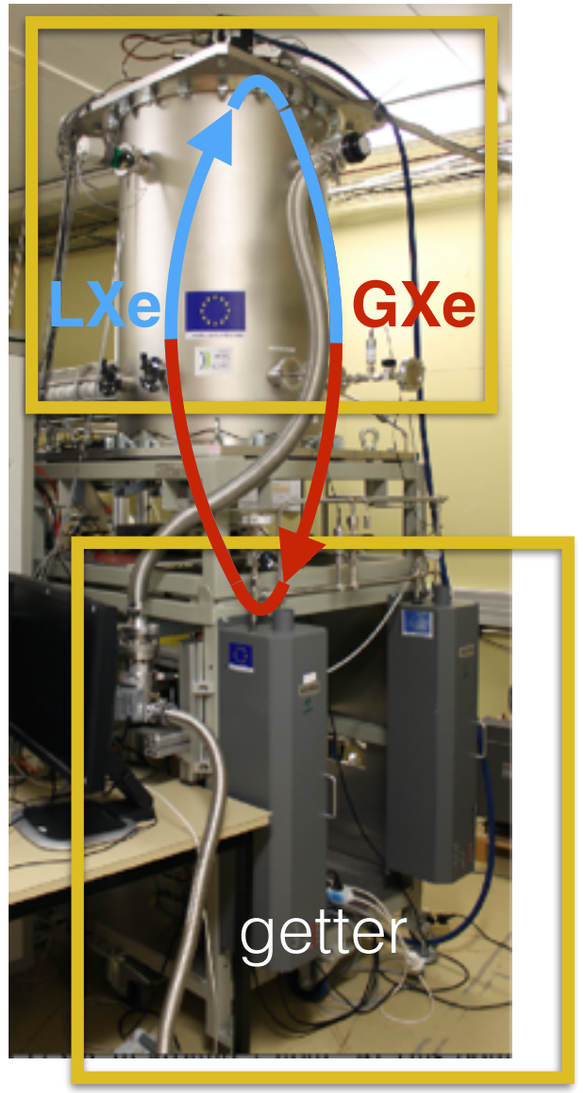
Cryostat

DAQ

Circulation and Purification

- Electronegative impurities → electron loss during drift
- Light absorbing impurities → scintillation light lost



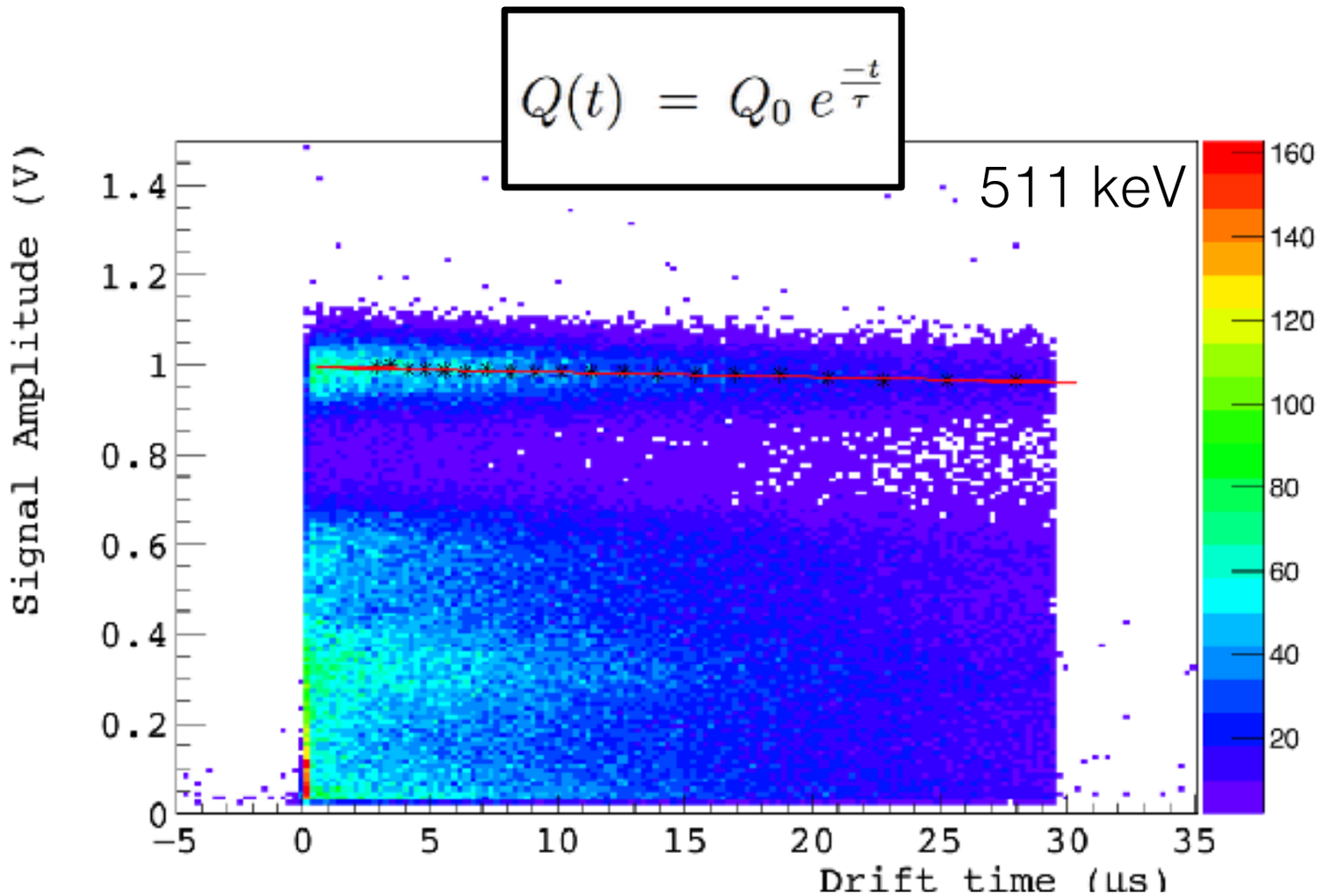


Purification rate: **30 liter/min**

Purification in gas-phase:
LXe evaporation
GXe purification
LXe recondensation

Electron Attenuation Length

Electronegative impurities → electron loss during drift



One week → Attenuation length >1 m

⬇

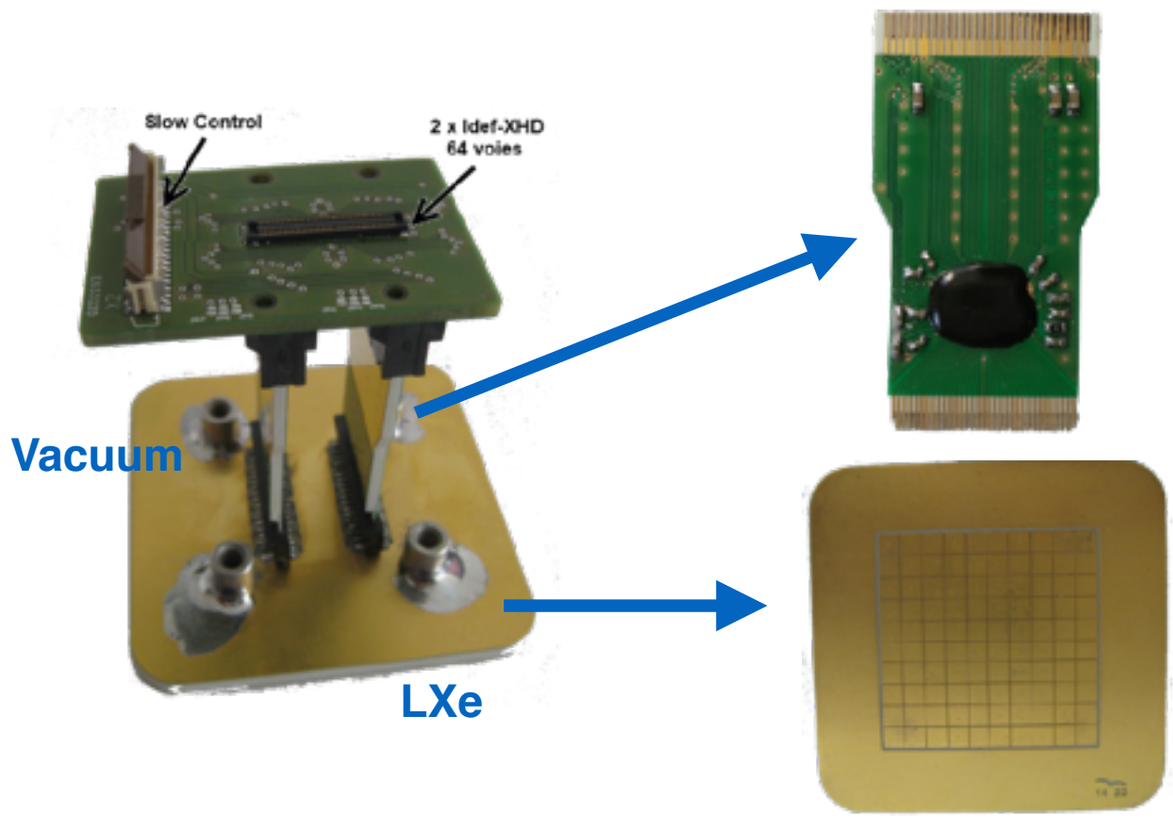
Concentration of 1 ppb O_2 equivalent

XEMIS1: Ionization Signal Readout

IDeF-X HD LXe Asics Gevin et al. 2006

Developed for CdTe @ IrFU

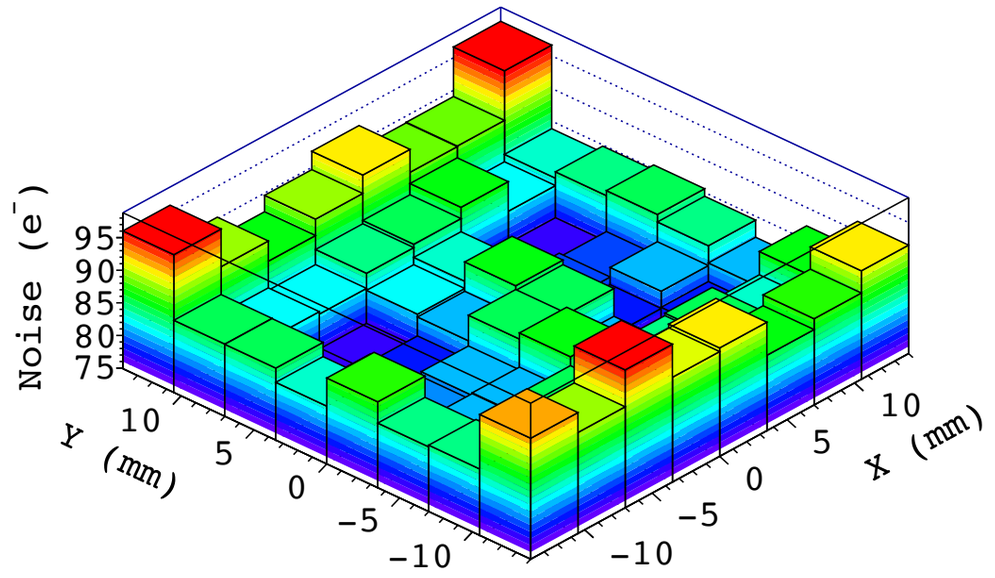
Adapted by Subatech for LXe

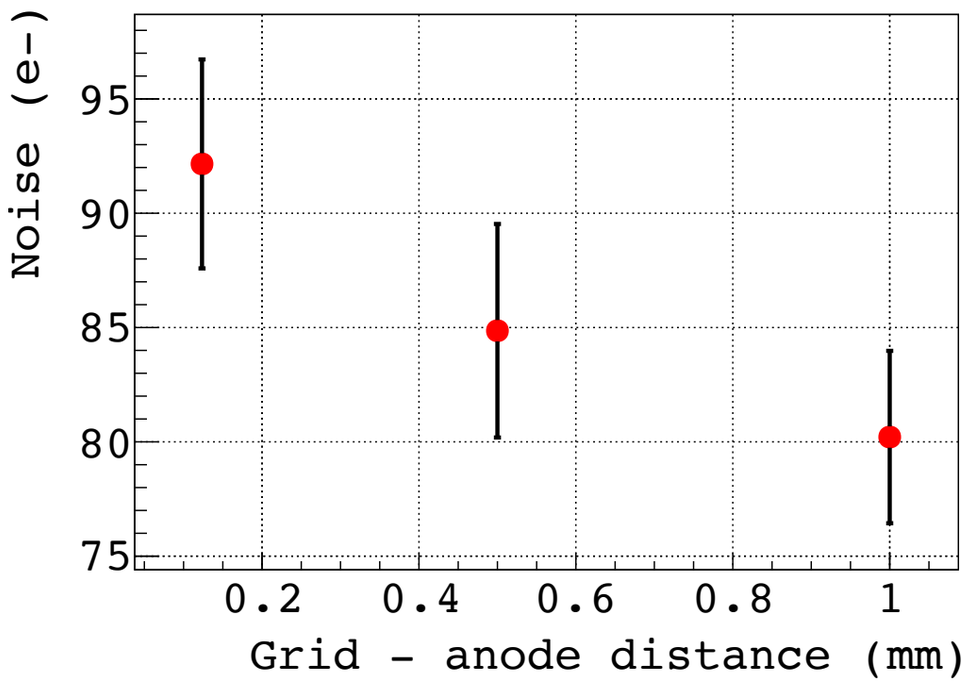


Anode 64 pixels
3.1 x 3.1 mm²

Noise < 100 e⁻ (at LXe Temp)

511 keV (@1 kV/cm) ⇒ 27200 e-

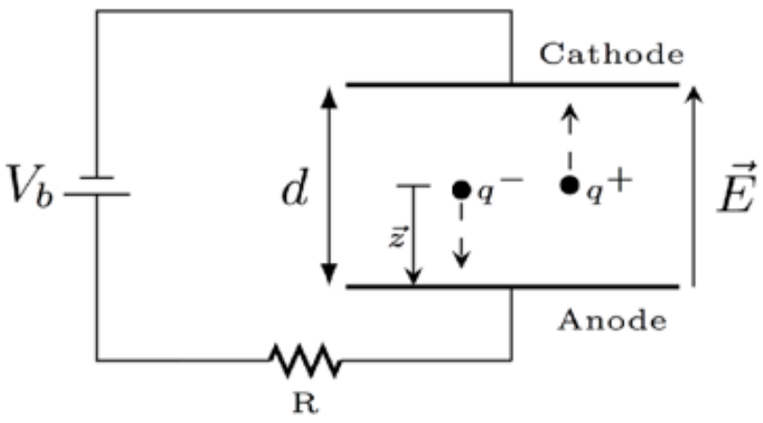


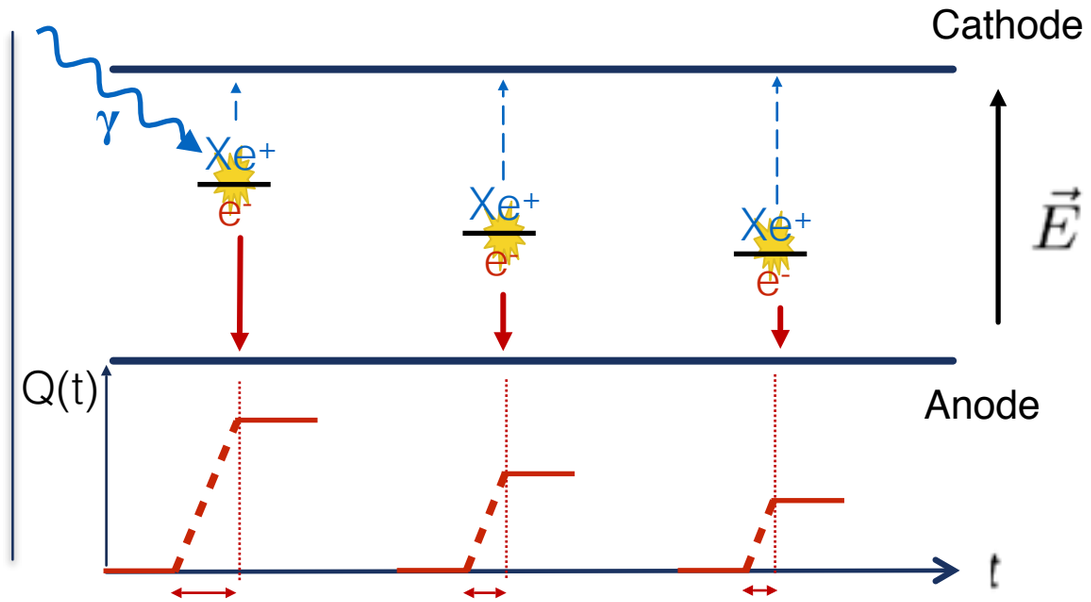


- Ultra low noise front-end electronics
- 32 channels per IDeF-X HD LXe
- Two chips → **one channel per pixel**

Gridded Ionization Chamber

- **Planar** Ionization Chamber

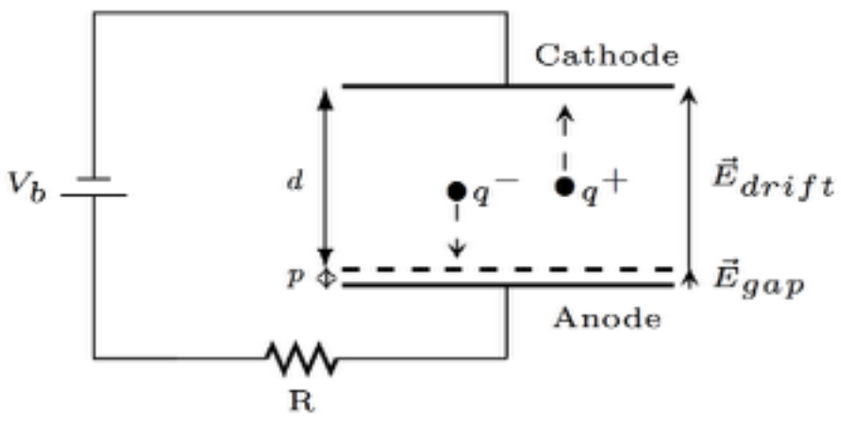


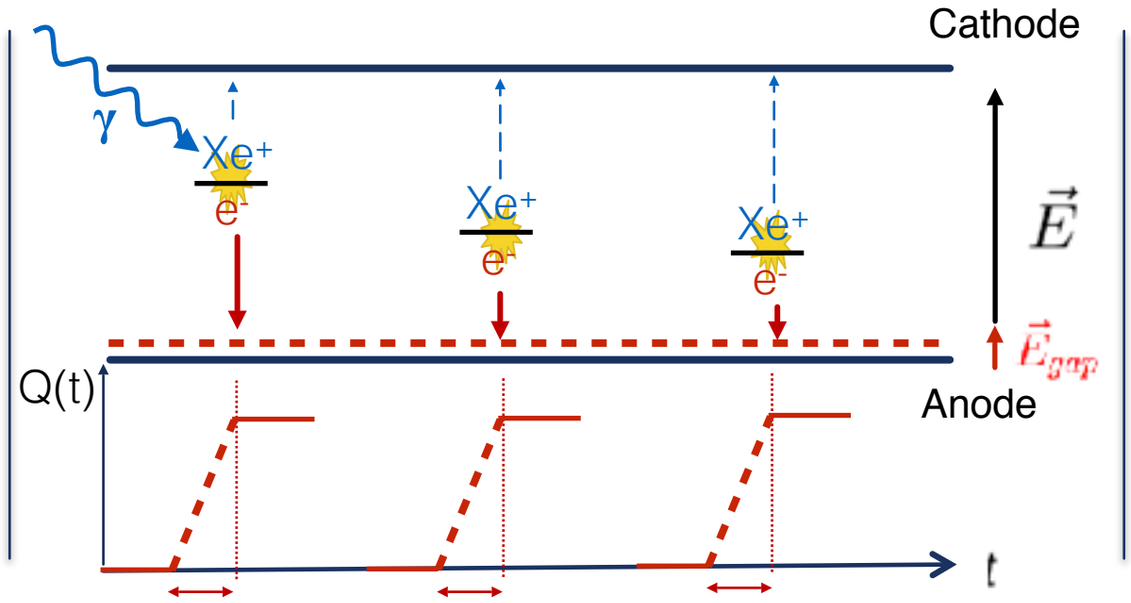


Signal depends on position

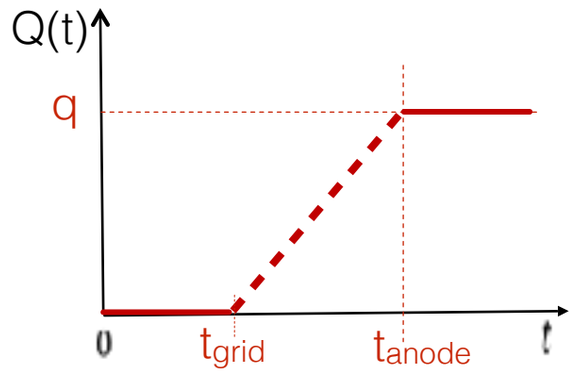
Gridded Ionization Chamber

- **Gridded** Ionization Chamber

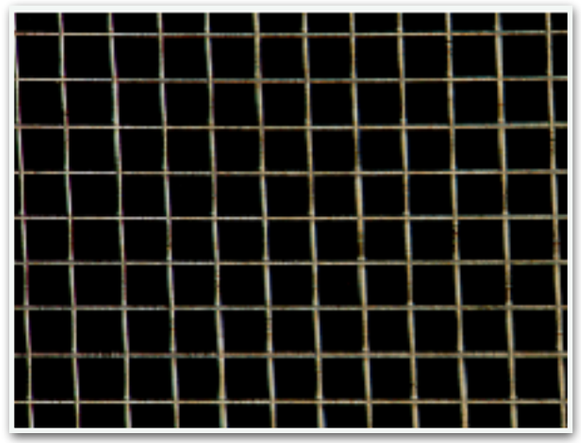




Induced charge



- The grid removes the pulse-amplitude dependence on position of interaction
- Signal induced in the anode by ionization electrons is proportional to the deposited energy



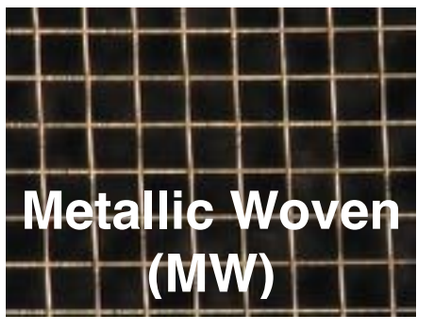
100 LPI metallic woven mesh

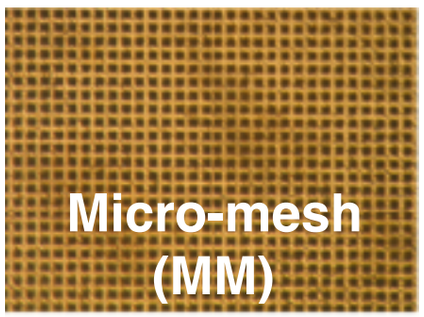
LPI: Line per Inch

Gridded Ionization Chamber

Ionization signal affected by:

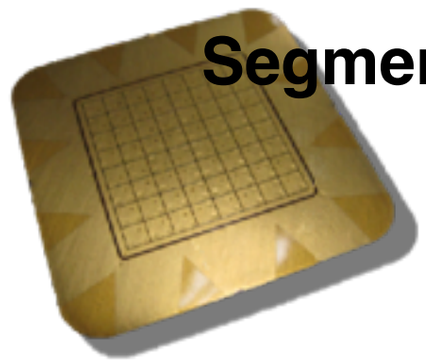
Frisch grid





- Transparency of the grid
- Efficiency of the grid

Segmented Anode

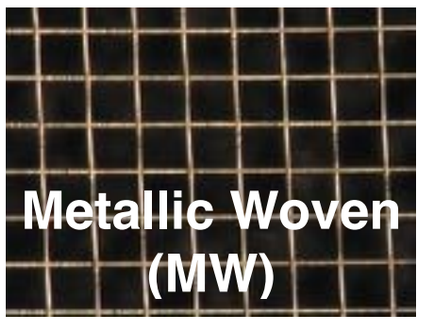


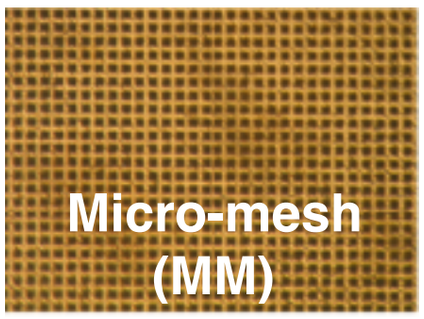
- Small pixel effect: induction in non-collecting pixels

Gridded Ionization Chamber

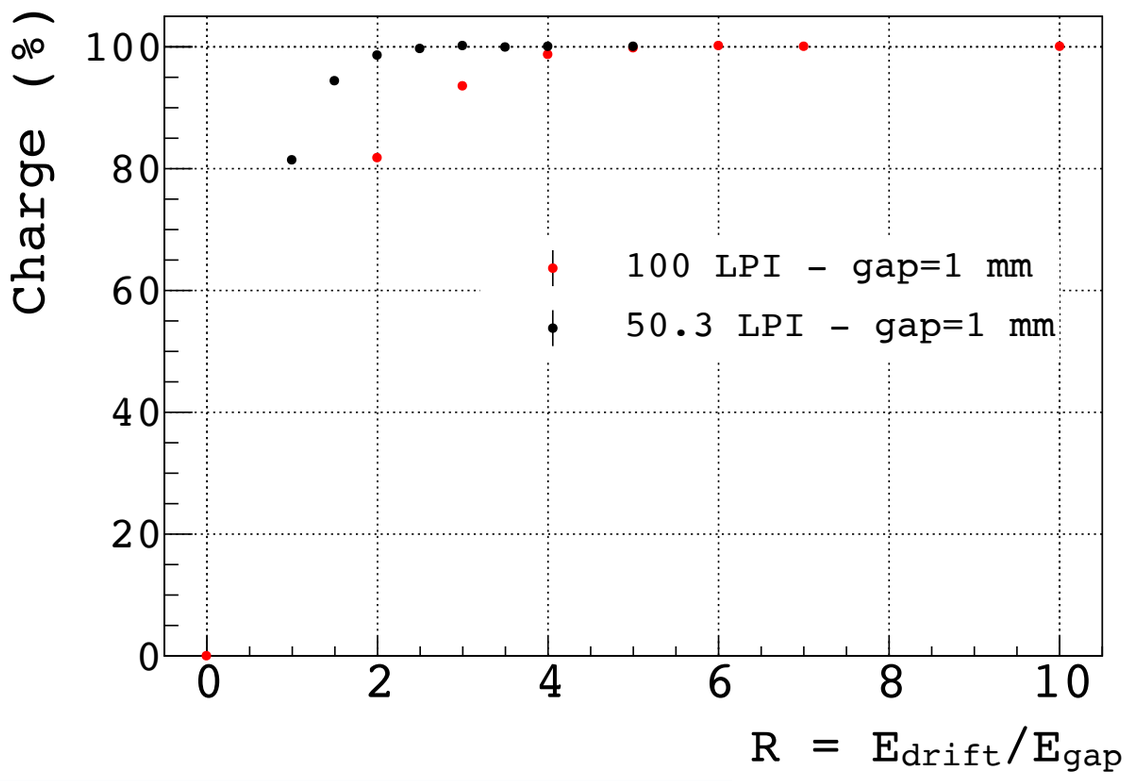
Ionization signal affected by:

Frisch grid

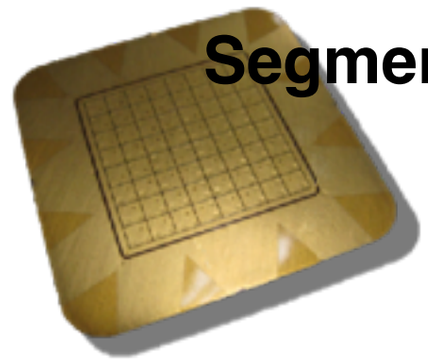




- **Transparency of the grid**
- Efficiency of the grid



Segmented Anode



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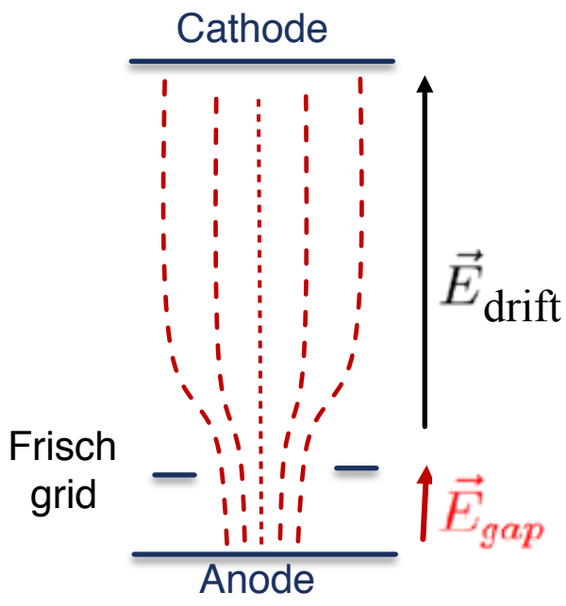
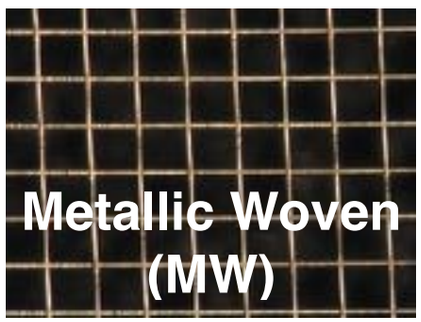
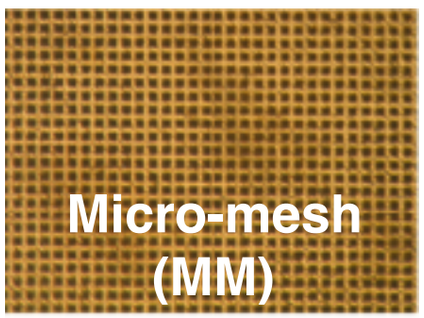


Gridded Ionization Chamber

Ionization signal affected by:

Frisch grid





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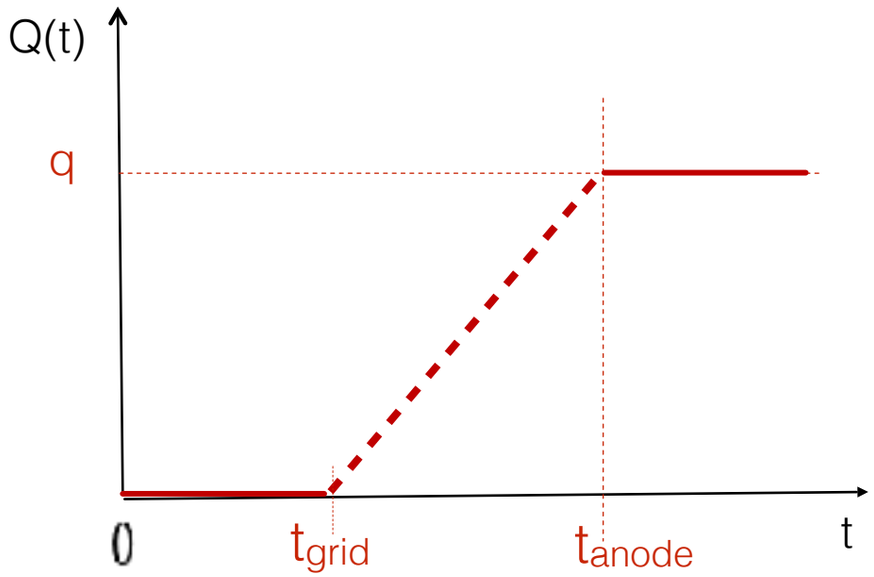
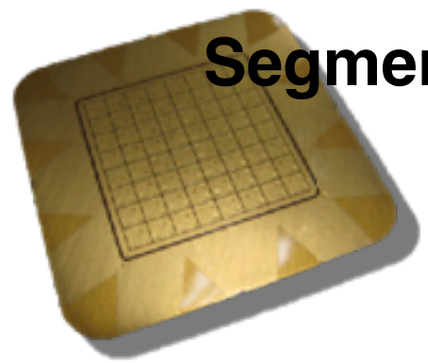


Segmented Anode

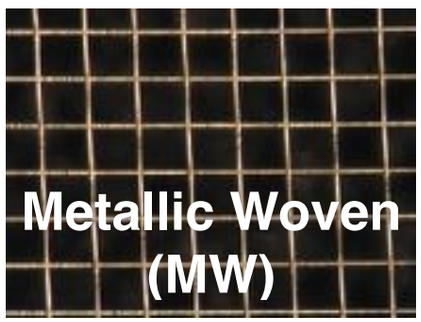


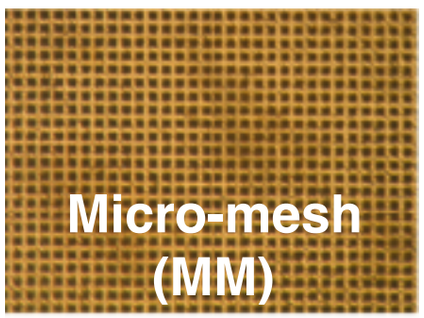
- Small pixel effect: induction in non-collecting pixels

Gridded Ionization Chamber

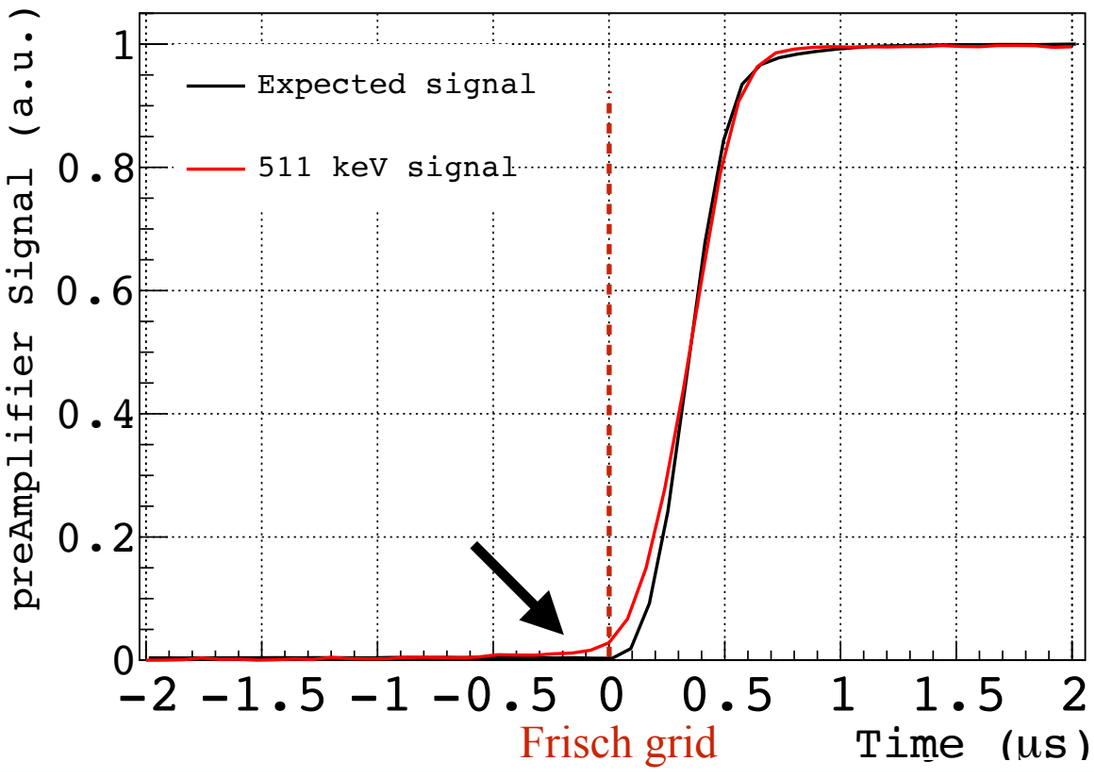
Ionization signal affected by:

Frisch grid

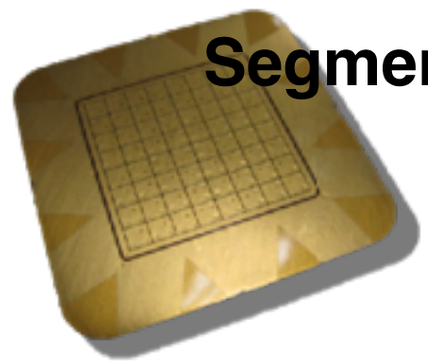




- Transparency of the grid
- **Efficiency of the grid**



Segmented Anode



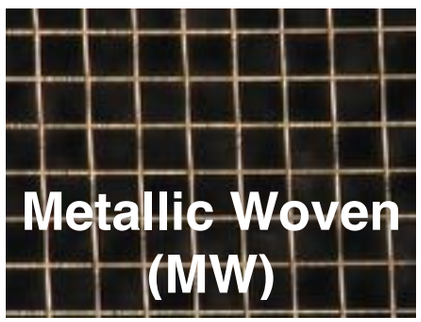
- Small pixel effect: induction in non-collecting pixels

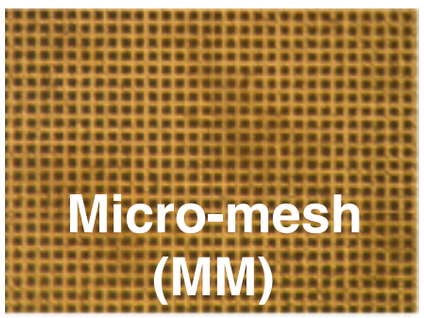
Electrons induce a current in the anode before passing through the grid

Gridded Ionization Chamber

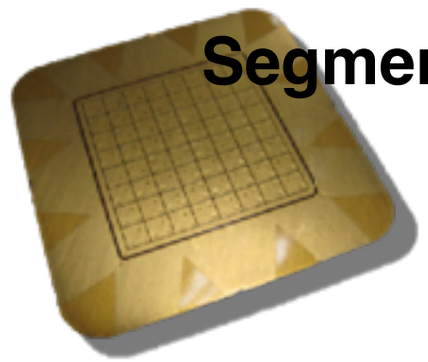
Ionization signal affected by:

Frisch grid

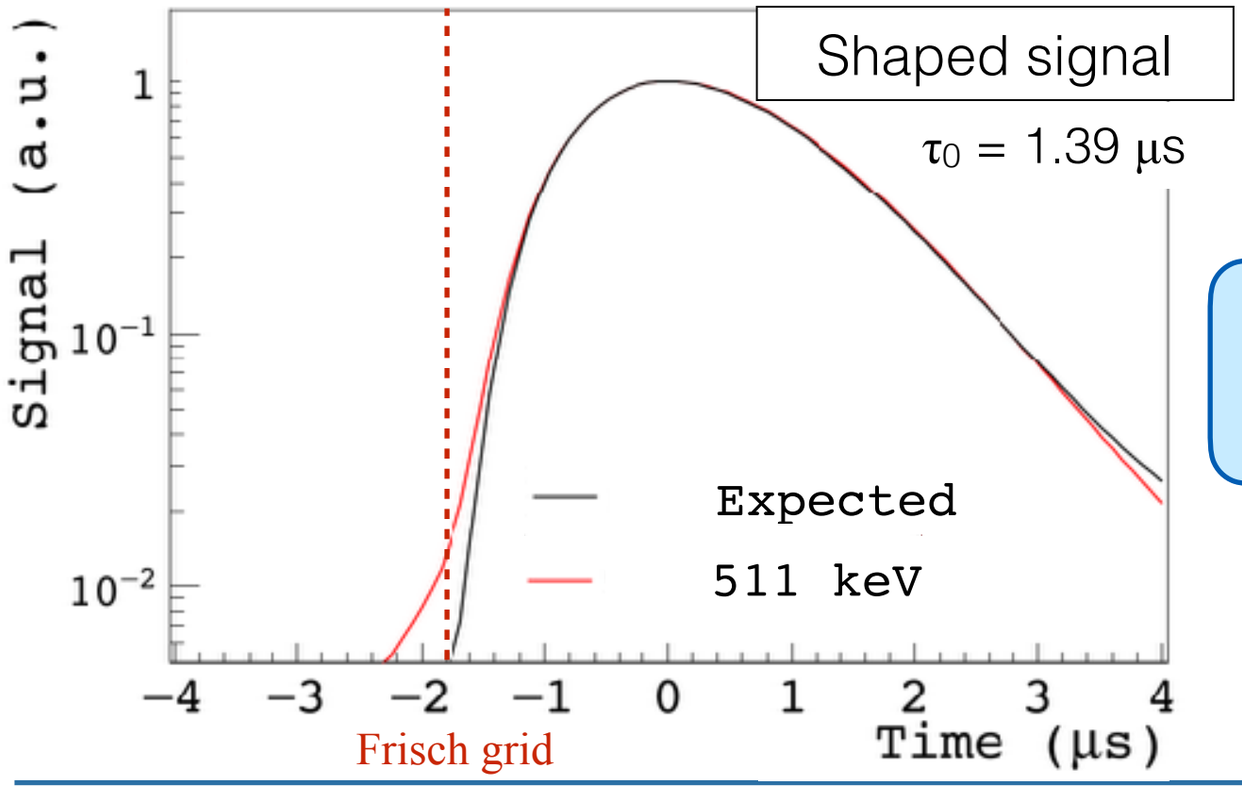




- Transparency of the grid
- **Efficiency of the grid**



- Small pixel effect: induction in non-collecting pixels

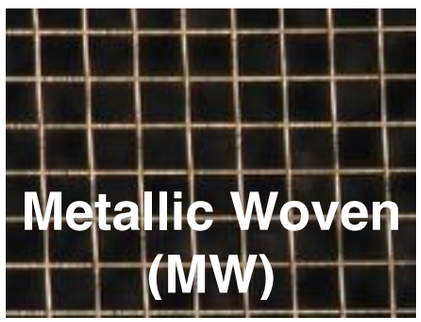


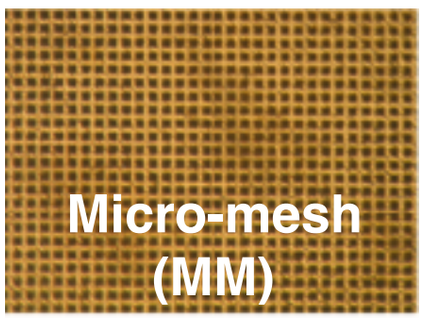
Electrons induce a current in the anode before passing through the grid

Gridded Ionization Chamber

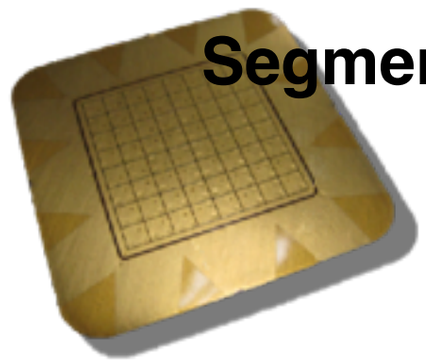
Ionization signal affected by:

Frisch grid



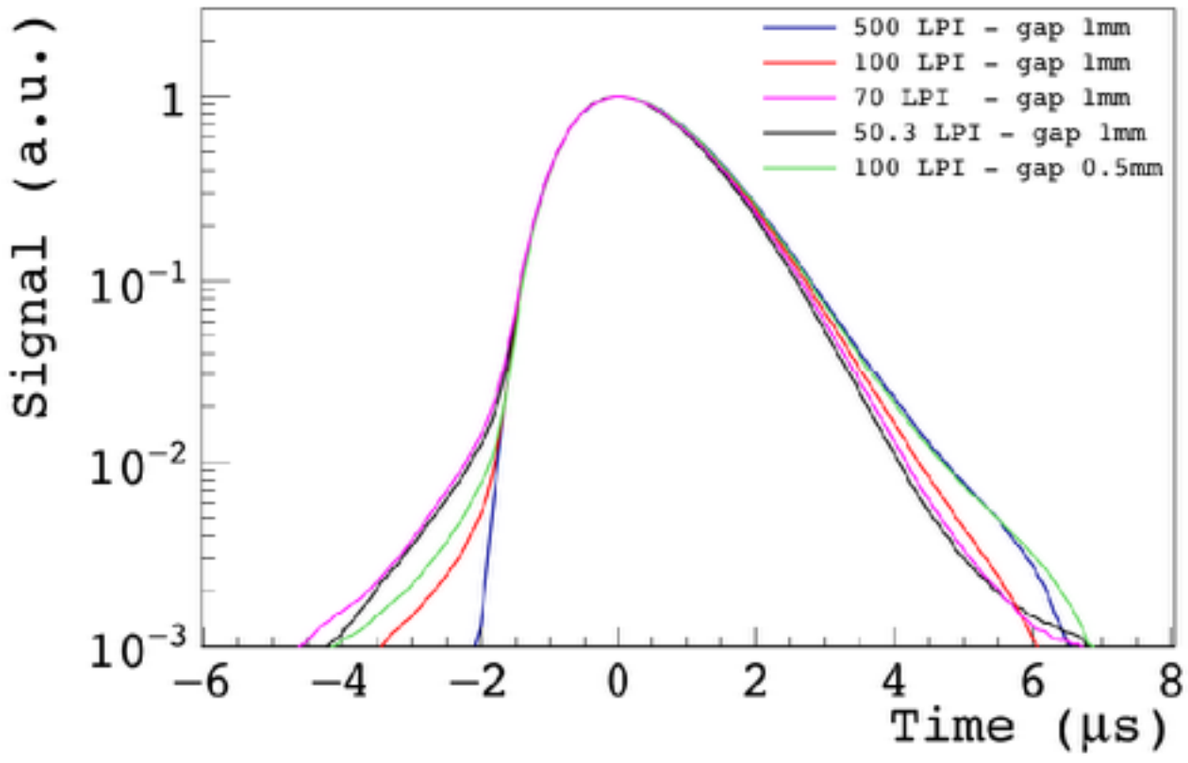


- Transparency of the grid
- **Efficiency of the grid**



Segmented Anode

- Small pixel effect: induction in non-collecting pixels

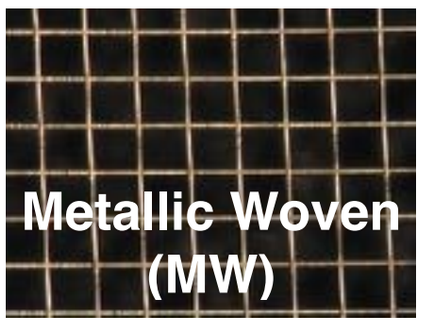


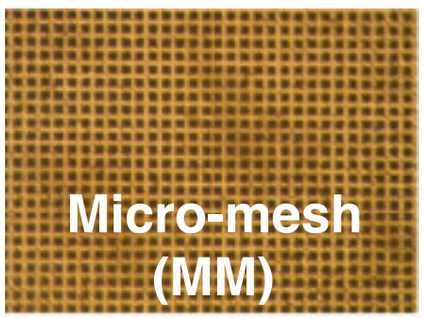
Signal depends on the type of grid

Gridded Ionization Chamber

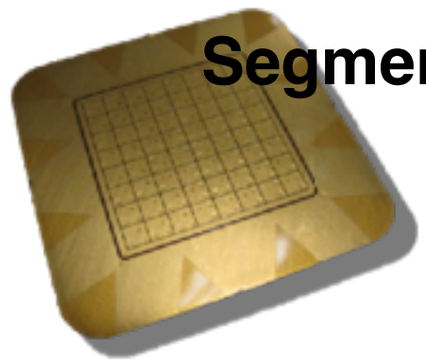
Ionization signal affected by:

Frisch grid

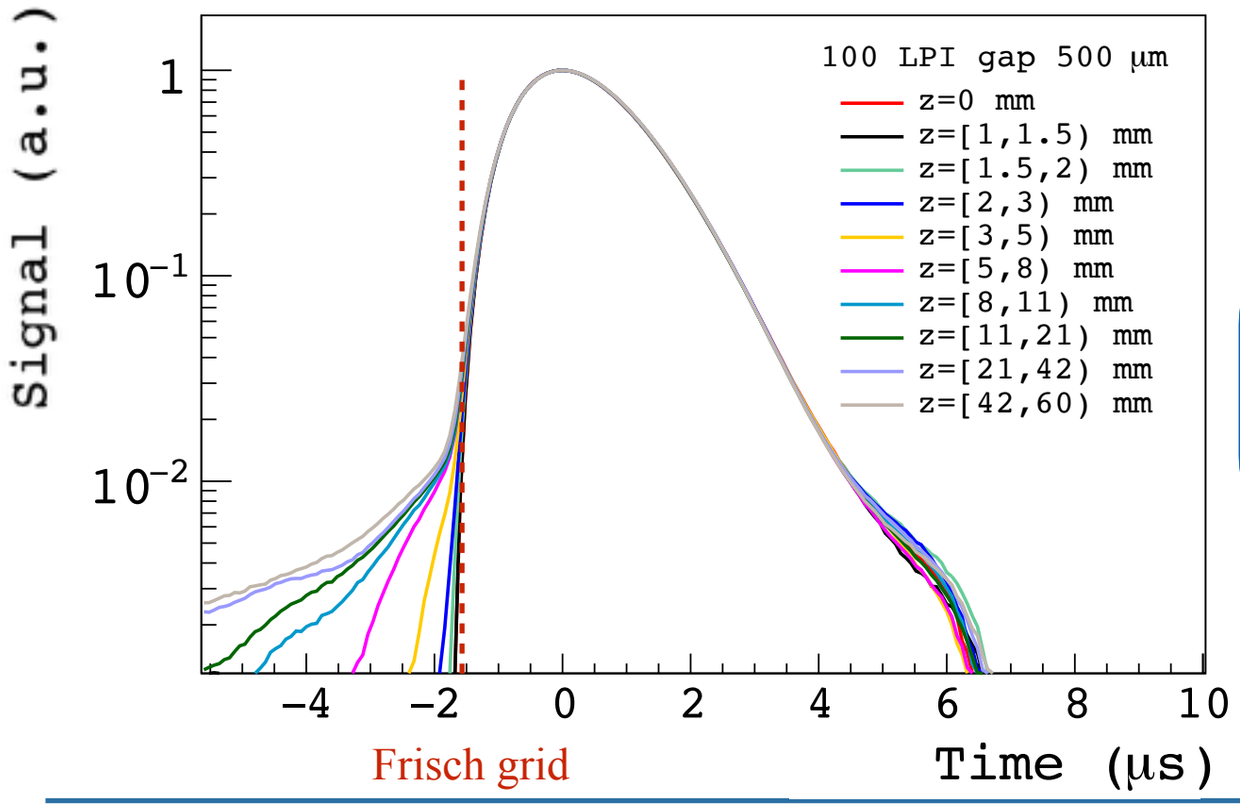




- Transparency of the grid
- **Efficiency of the grid**



- Small pixel effect: induction in non-collecting pixels

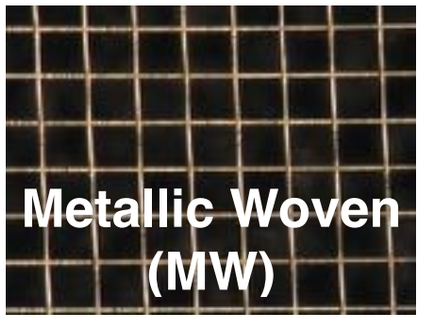


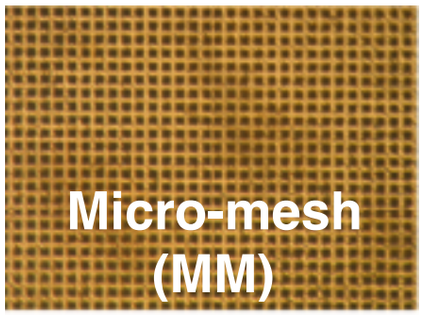
Signal depends on the position of the interaction

Gridded Ionization Chamber

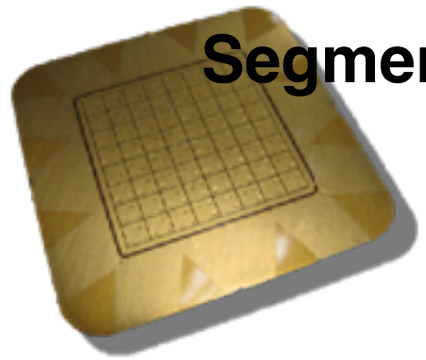
Ionization signal affected by:

Frisch grid





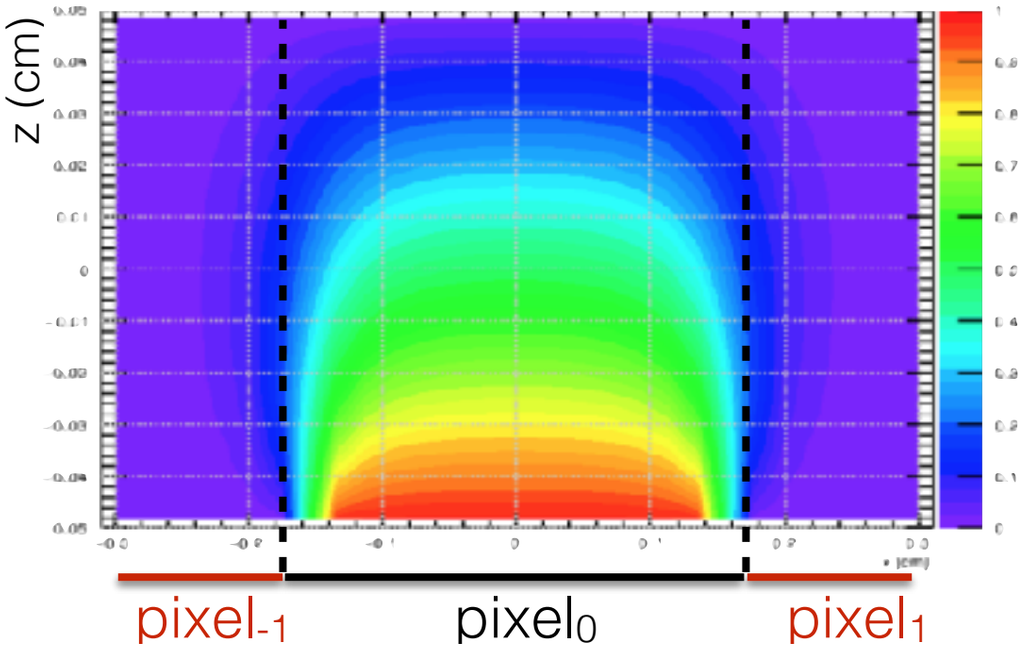
- Transparency of the grid
- Efficiency of the grid



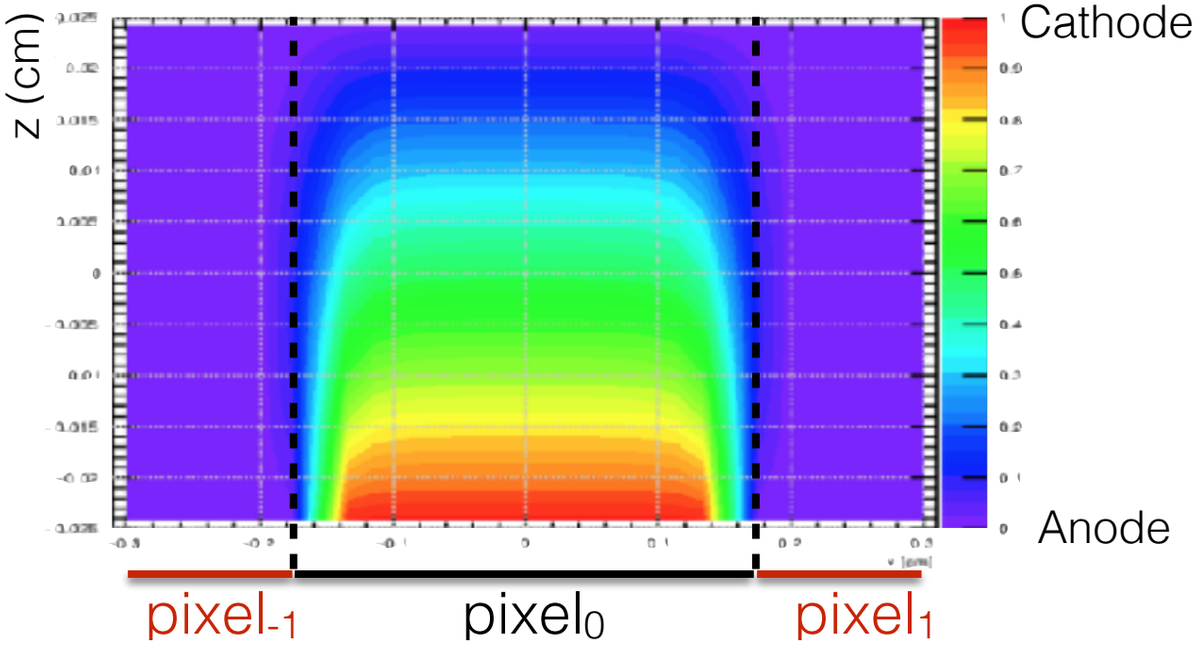
Segmented Anode

- **Small pixel effect:** induction in non-collecting pixels

gap: 1 mm



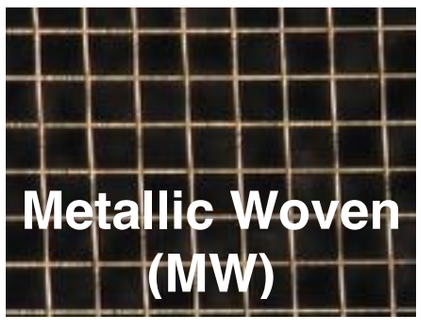
gap: 500 μm

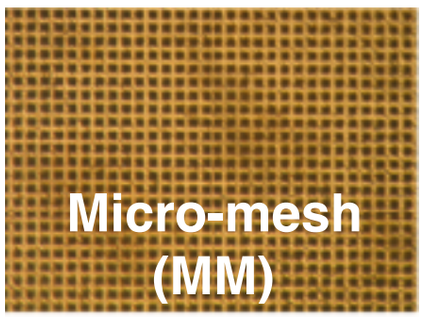


Gridded Ionization Chamber

Ionization signal affected by:

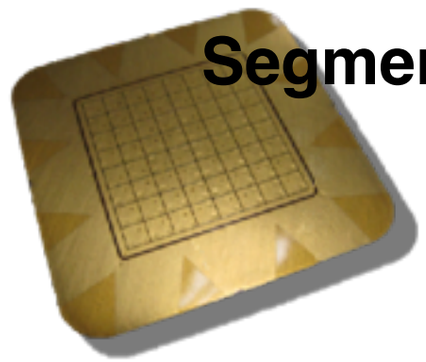
Frisch grid





- Transparency of the grid
- Efficiency of the grid

Segmented Anode



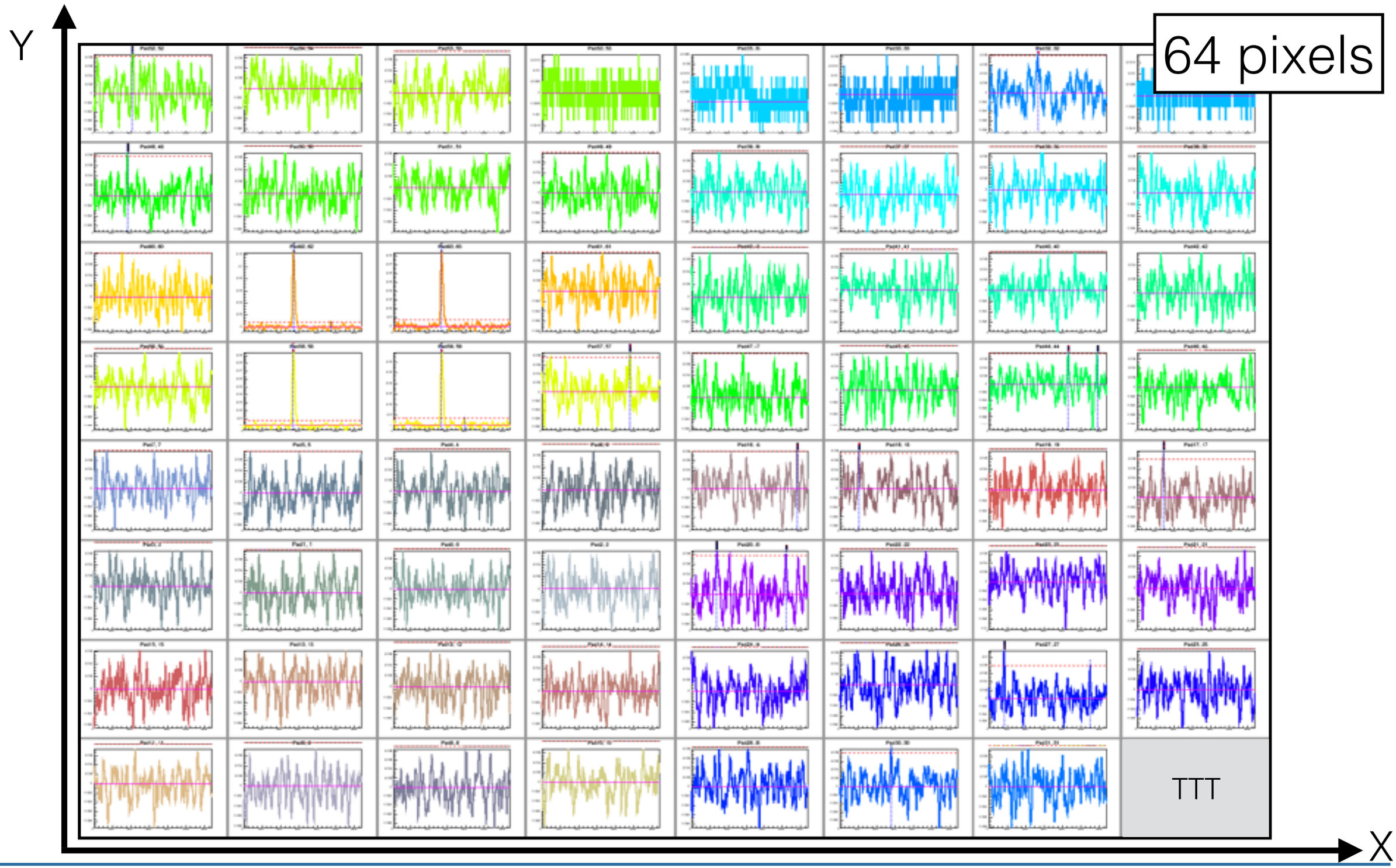
- Small pixel effect: induction in non-collecting pixels

Grid	Tech	Pitch	Thickness	Bar
500 LPI	MM	50.8 µm	5 µm	12 µm
200 LPI	MM	127 µm	5 µm	24 µm
100 LPI	MW	254 µm	50 µm	25 µm
70 LPI	MM	362 µm	5 µm	18.5 µm
50.3 LPI	MW	505 µm	60 µm	30 µm

Gap grid-anode
1 mm
500 µm
125 µm

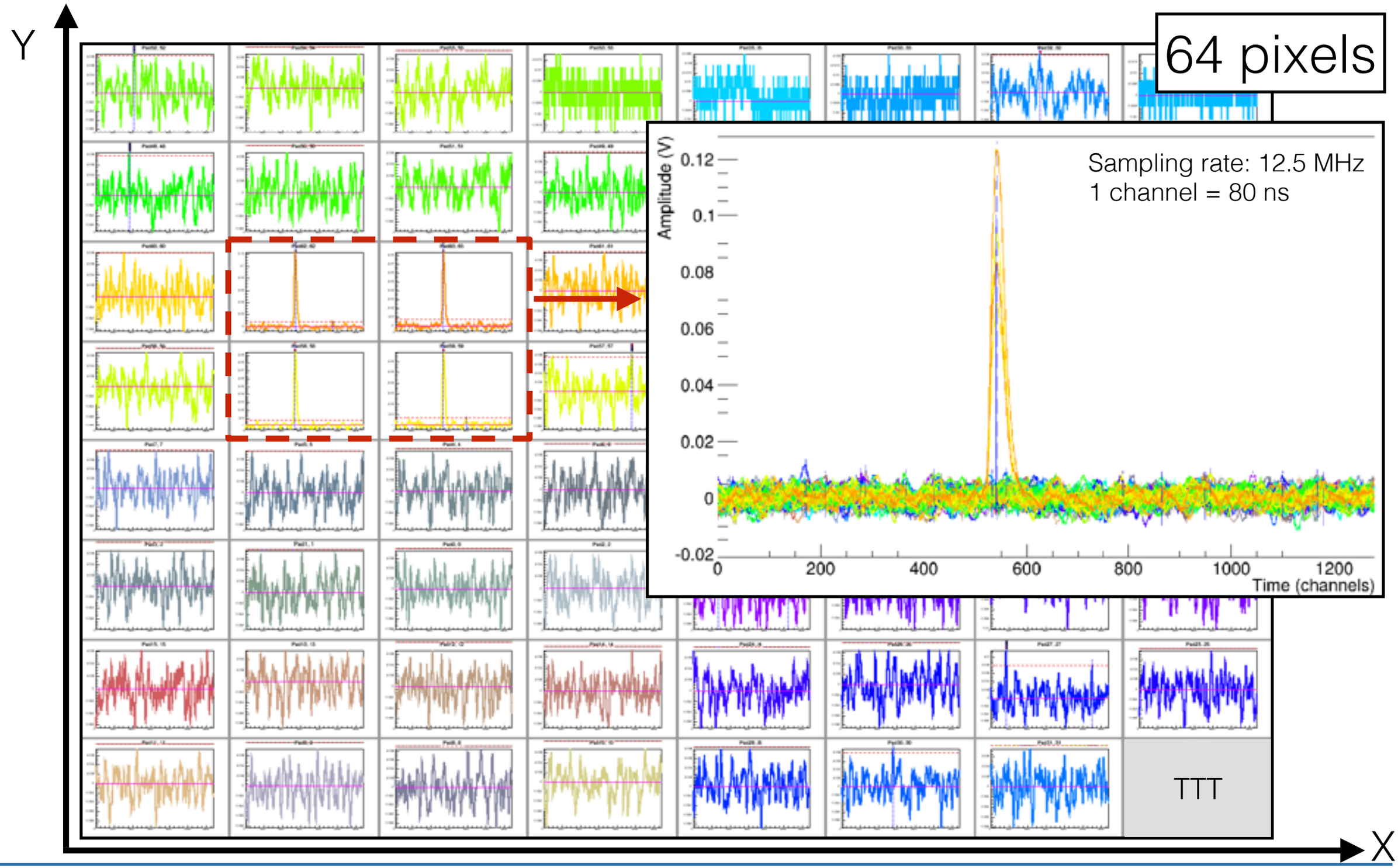
Ionisation signal @ 511 keV for Photoelectrics

Event reconstruction: Compton scattering /photoelectric effect identification



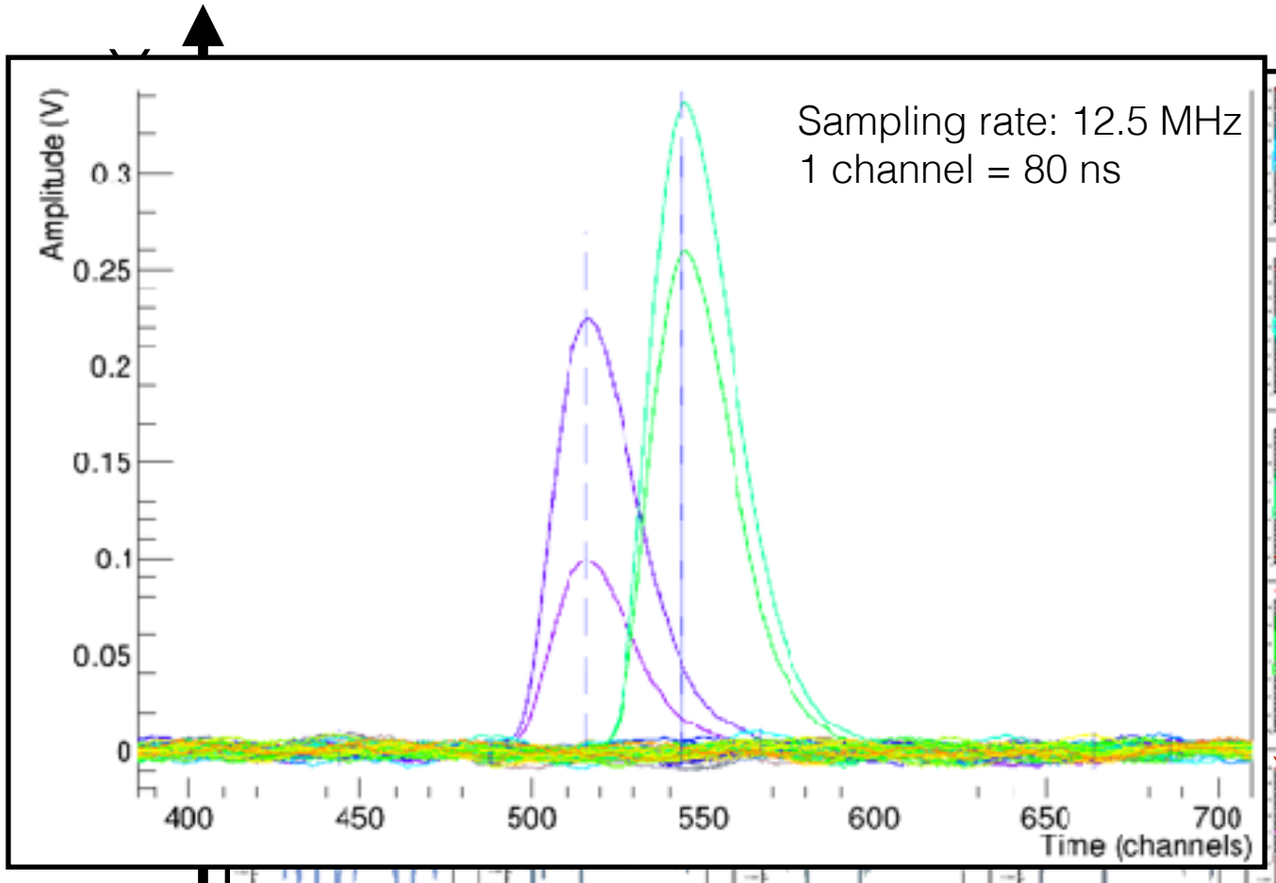
Ionisation signal @ 511 keV for Photoelectrics

Event reconstruction: Compton scattering /**photoelectric effect** identification



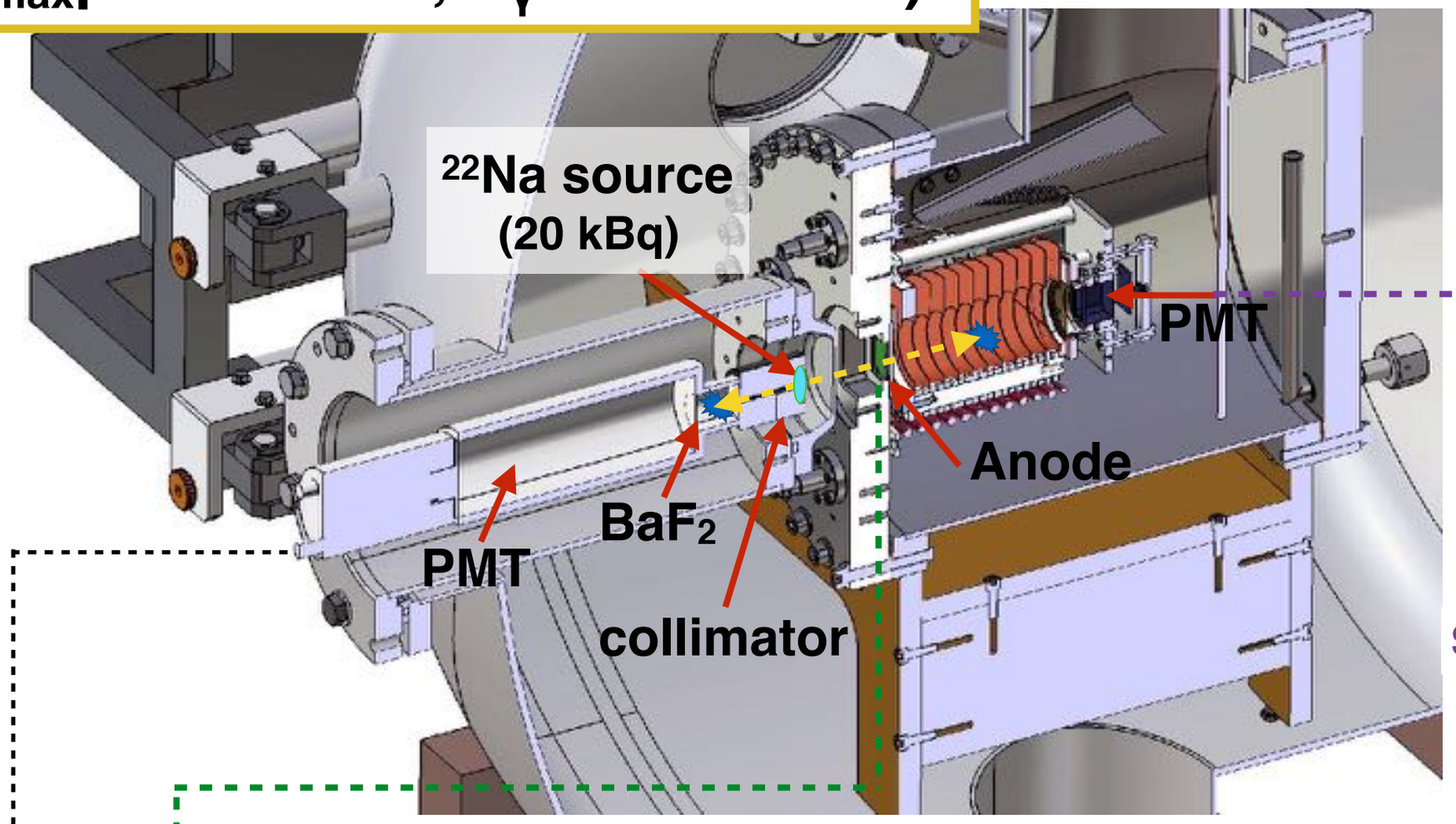
Ionisation signal @ 511 keV for Compton

Event reconstruction: **Compton scattering** /photoelectric effect identification



Experimental Set-up @ 511 keV

^{22}Na: ($E_{max}\beta^{+}$= 545 keV, E_{γ}= 1.274 MeV)



LXe
Scintillation signal

Ionization signal

Time
Coincidence

Trigger

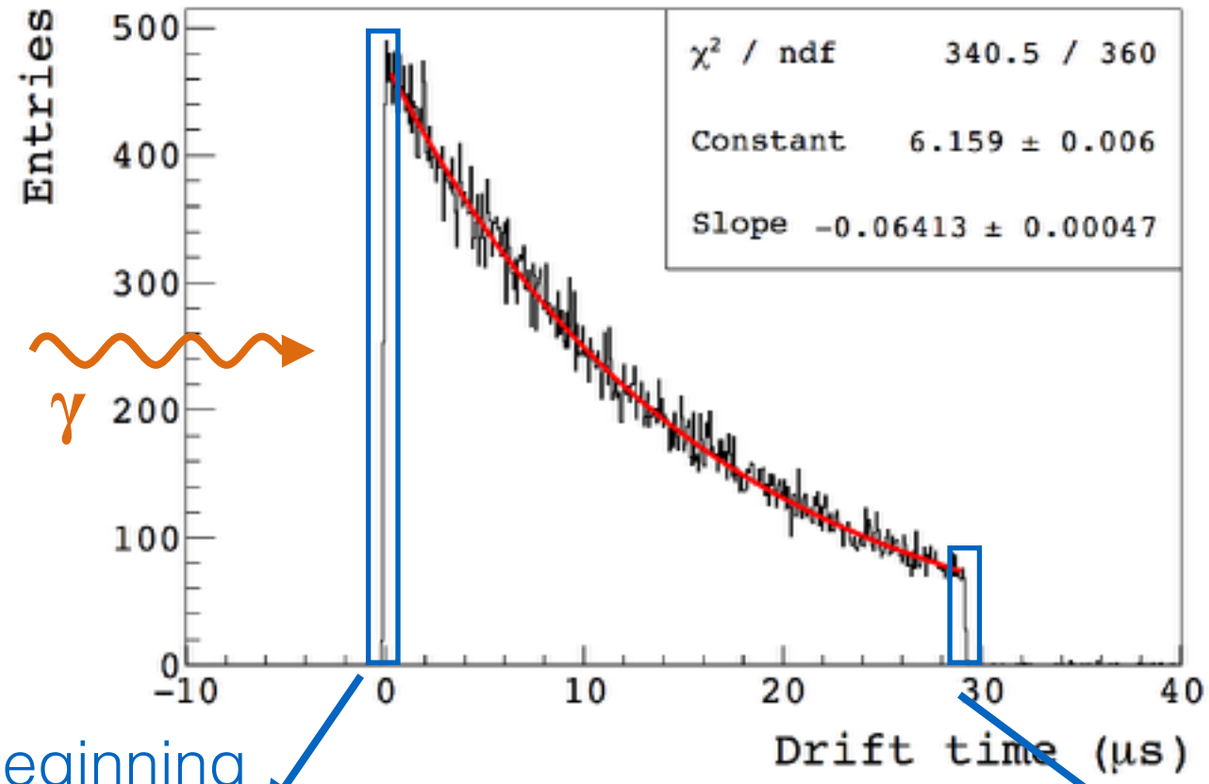
ADC

12.5 MHz digitizer

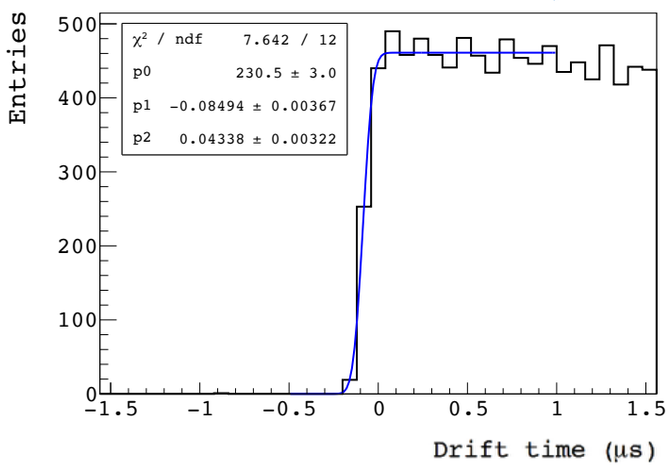
ADC

250 MHz digitizer

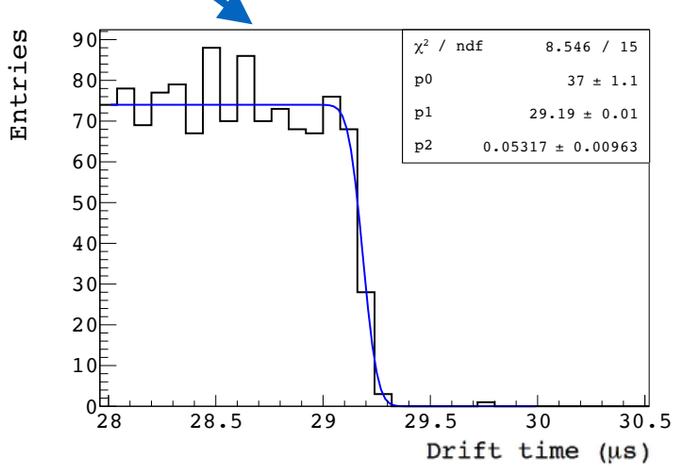
XEMIS1: Ionization results @511 keV (1 kV/cm)



Beginning

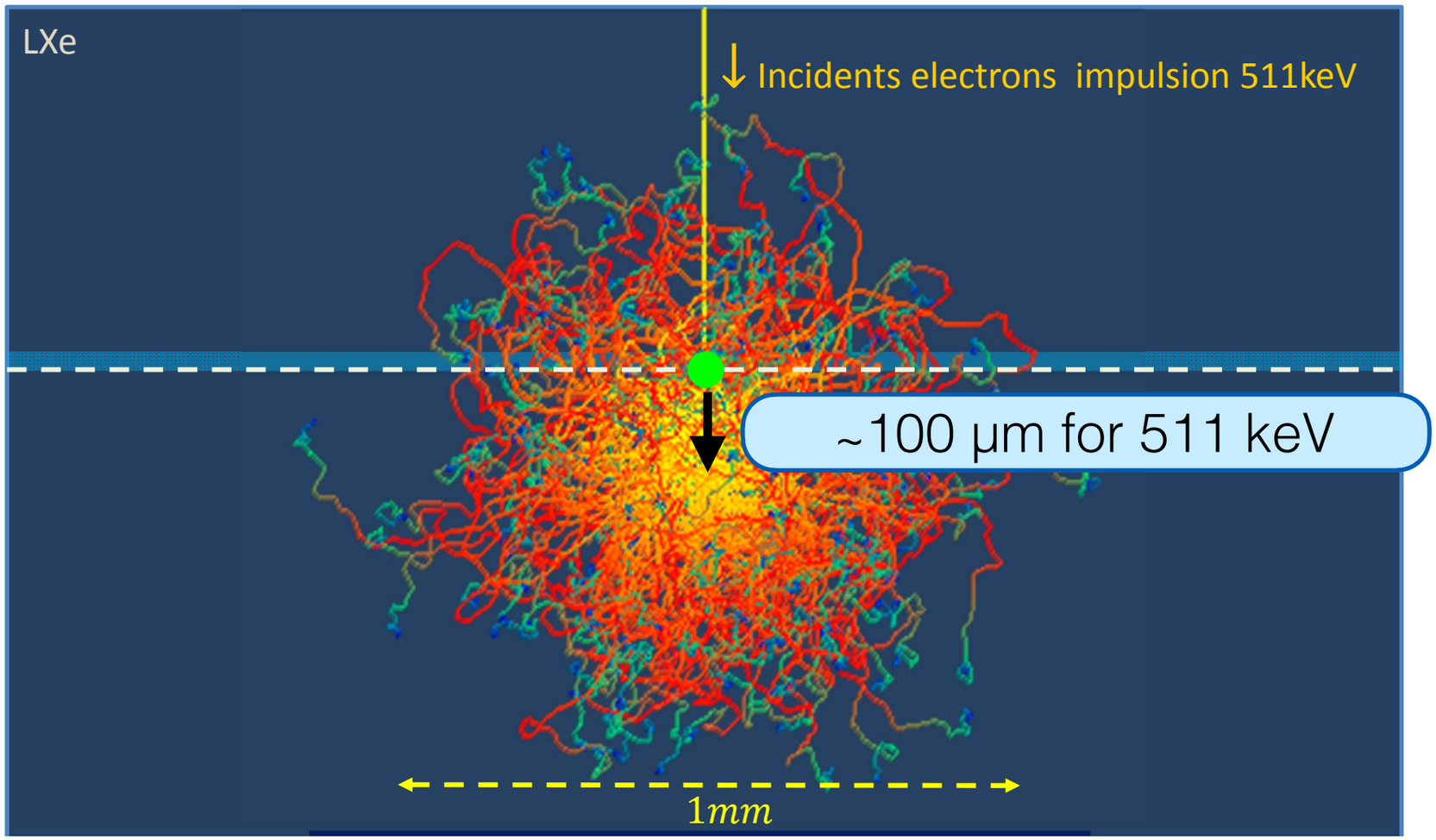


End



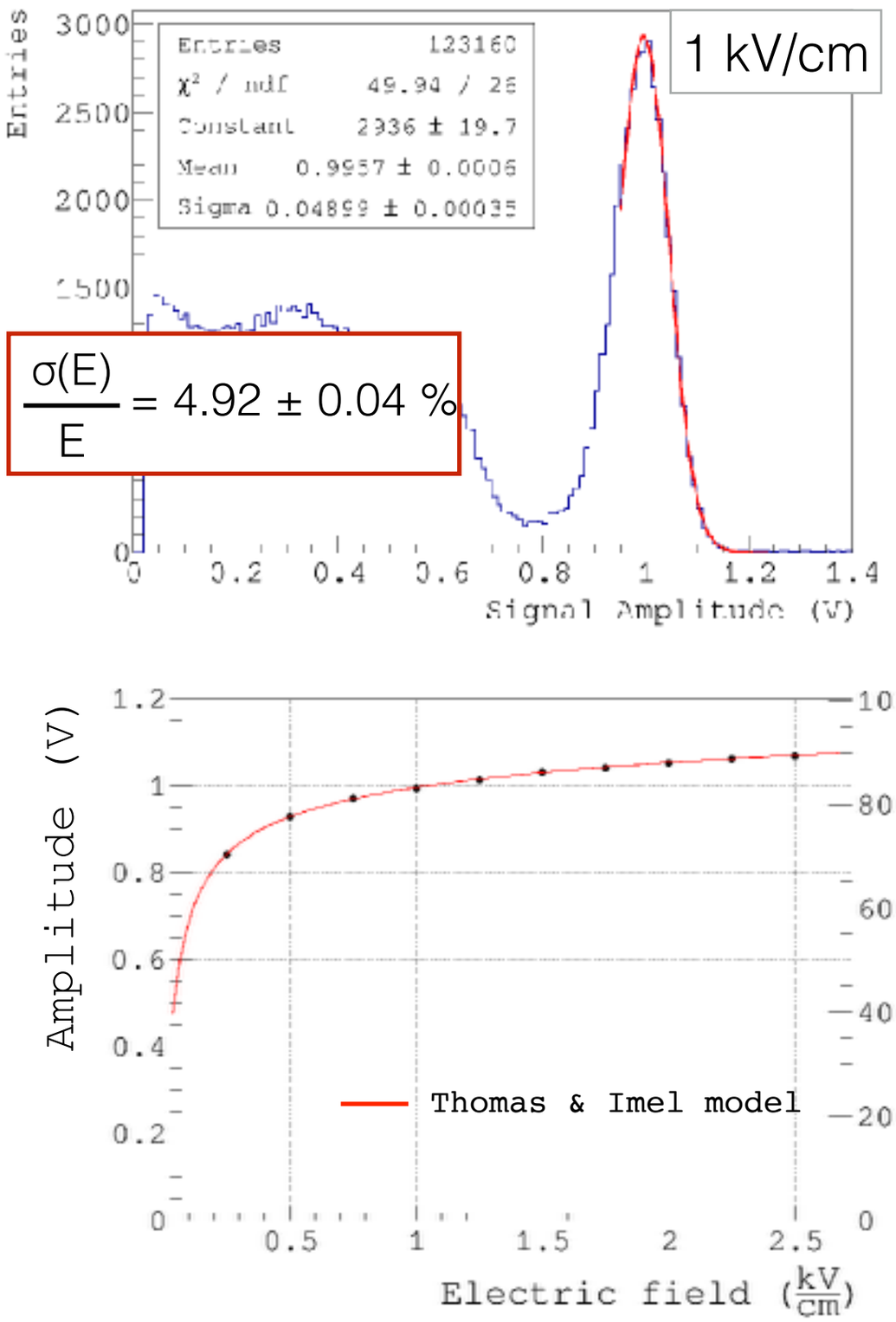
Drift time resolution: ~ 50 ns
DOI resolution: ~ 100 µm

Ionisation: recoil electrons in LXe with CASINO

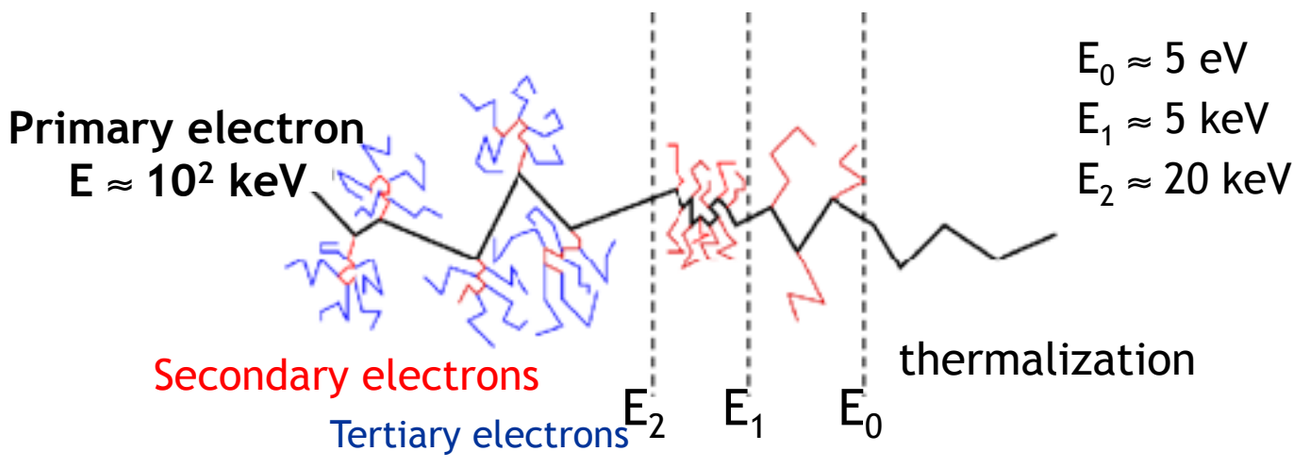


Spread of the electron cloud due to the chaotic trajectory of the primary electrons

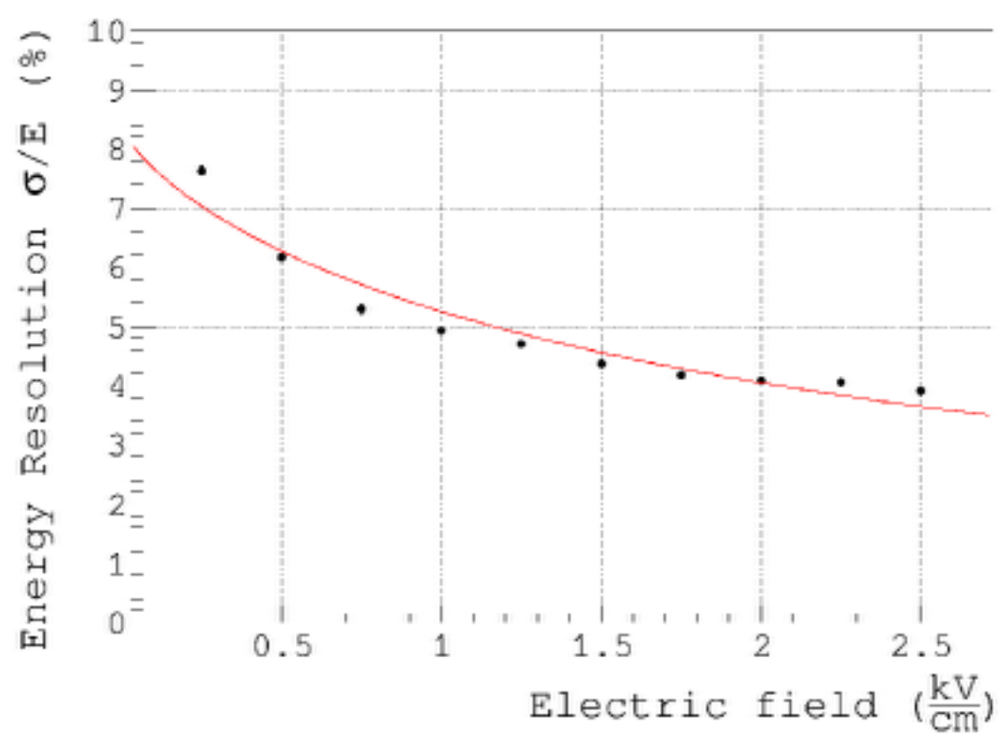
XEMIS1: Ionization results @511 keV



Recombination in LXe: Thomas and Imel model

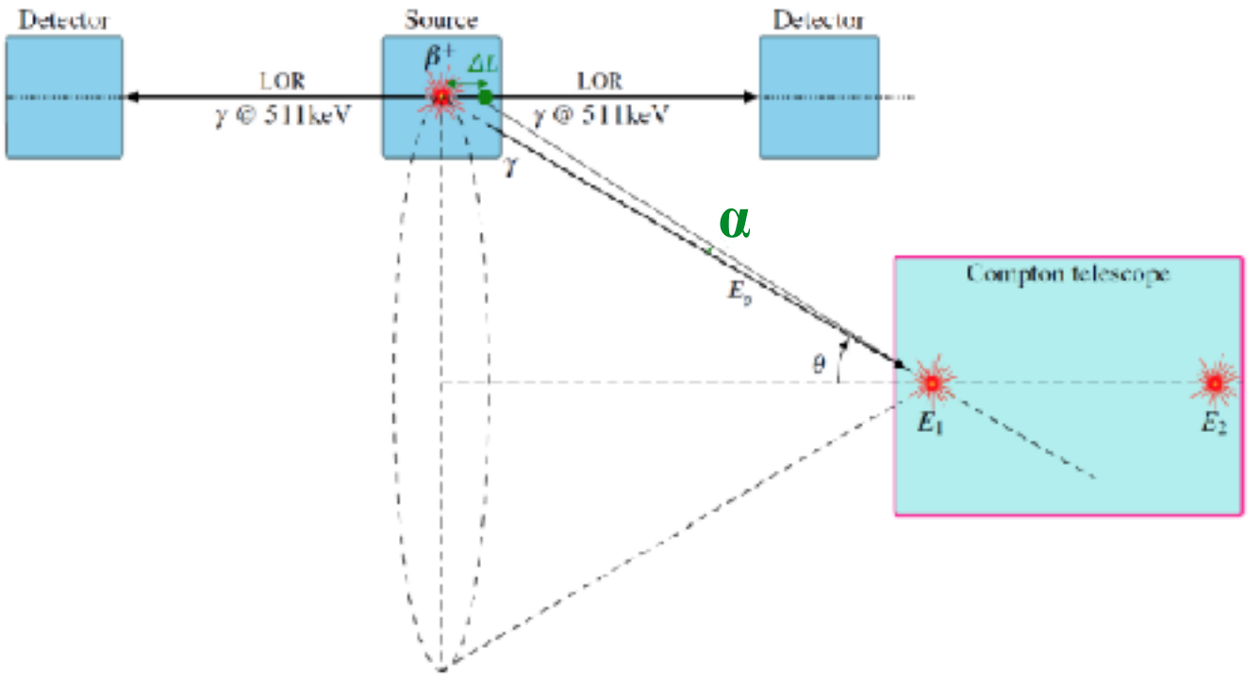


Thomas et al. 1989 Phys. Rev. A



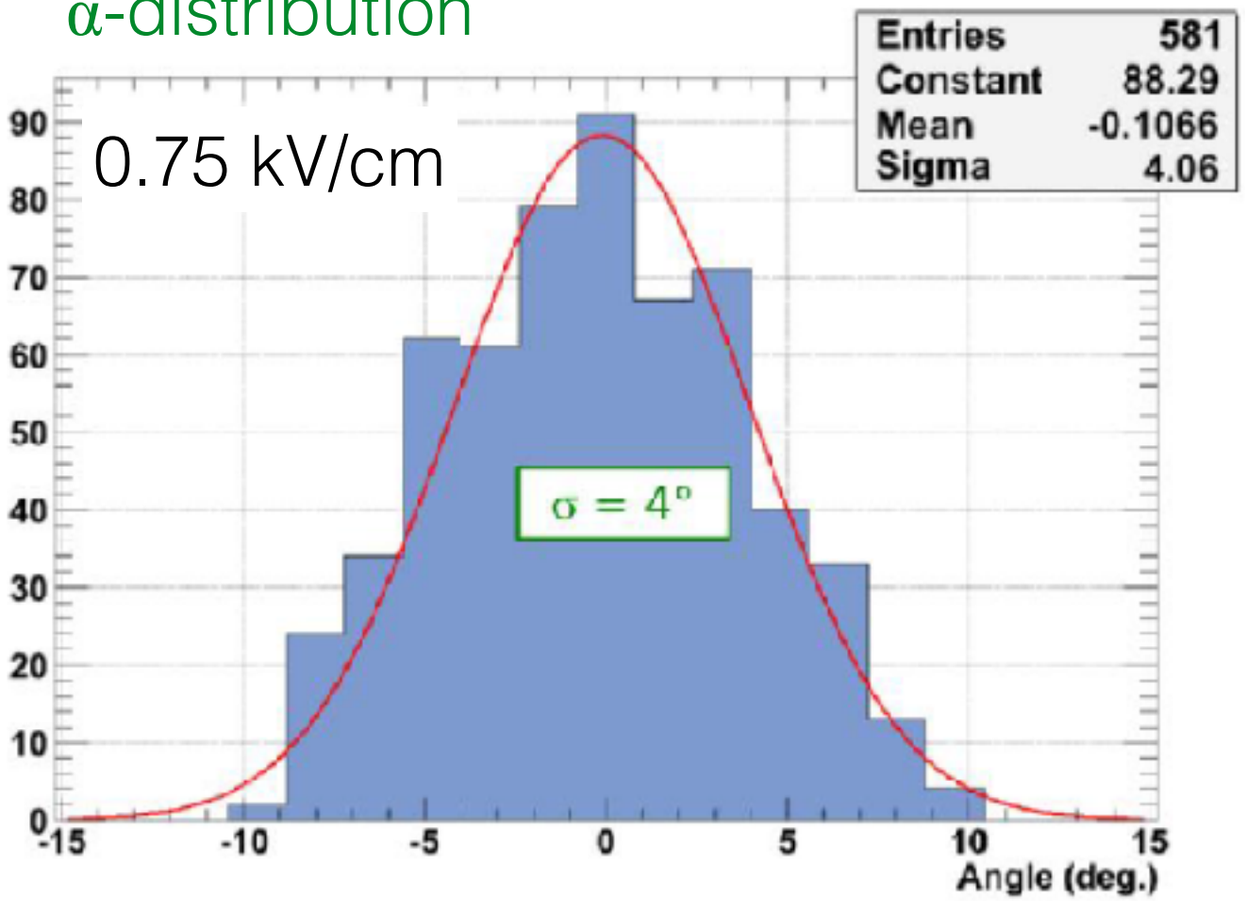
XEMIS1: Resolution along the LOR

ΔL resolution along the LOR → α



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

α-distribution



Gallego et al., NIMA (2015)

- Angular resolution limited by active area of XEMIS1
- Improvement expected at higher electric field
- XEMIS2 is the key

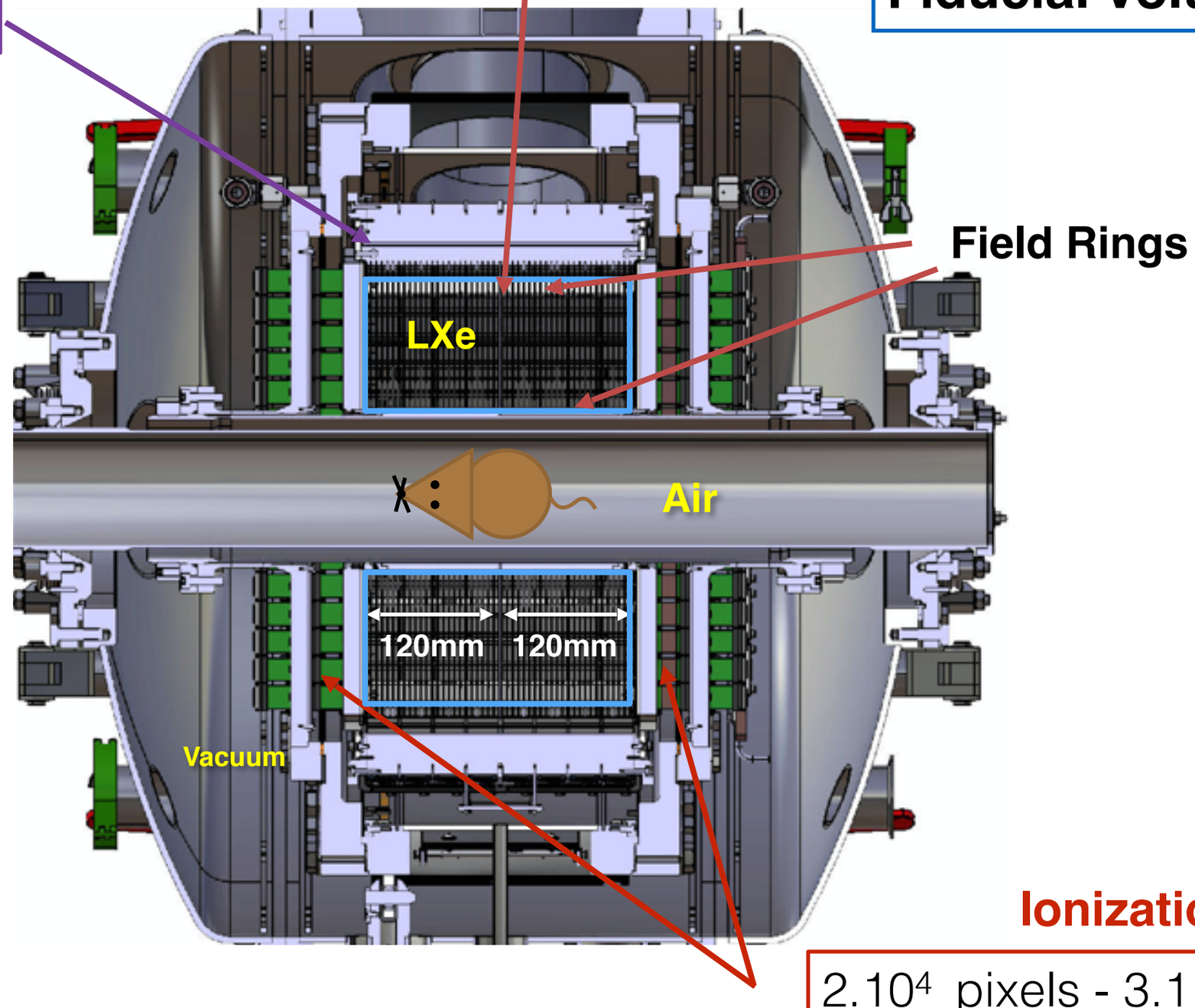
Equivalent to ΔL = 8.2 mm (FWHM) for a 5 cm distant source

XEMIS2

LXe: 200 kg
Fiducial volume ~24 L

Scintillation

380 x 1'' PMTs in LXe



High Purity LXe
at 1.2 bar (168 K)

LXe TPC

Active volume
- axial : 2 x 12 cm
- depth : 12 cm
- r_{min} : 7 cm

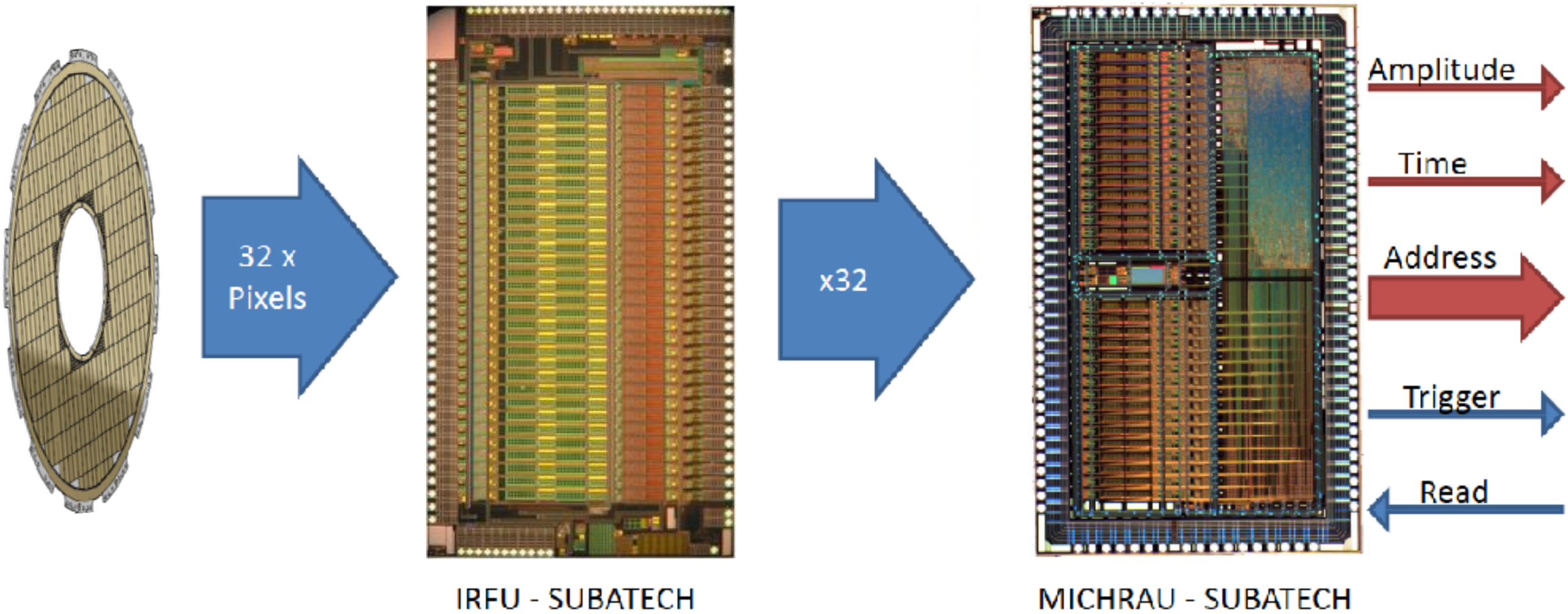
Ionization

2.10^4 pixels - 3.1 x 3.1 mm^2
Ultra low noise FEE

XEMIS2: Ionization Signal Readout

IDeF-X HD_LXe
Imaging **De**tector **F**ront-end

XTRACT: Xemis **T**PC **R**eadout for
Acquisition of **C**harge and **T**ime

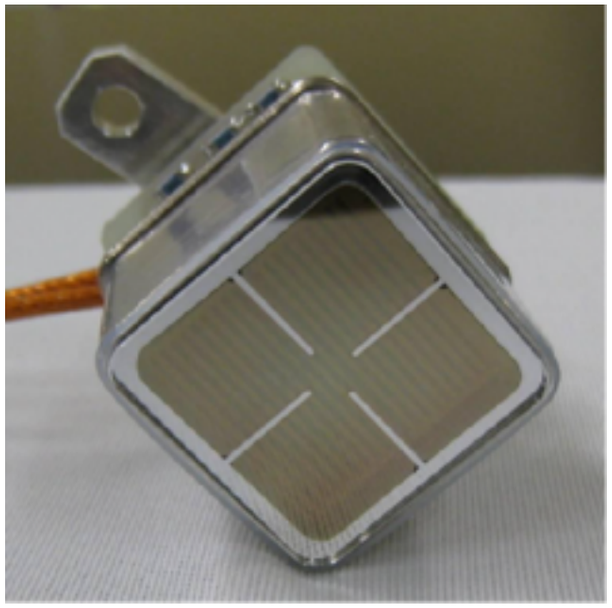


~20000 electronic channels
Challenge: continuous read-out with negligible dead-time

XTRACT v1 is on test since summer 2016. Final version expected for 2017

XEMIS2: Light Signal

Hamamatsu R7600 1” PMT



- Used as time measurement for the charge signal readout and interaction volume determination
- Developed to work at LXe temperature
- **Phase 1: 64** x 1” PMTs inside LXe covering 8 sectors in Φ
- **Future upgrade: 380** x 1” PMTs → complete coverage of the active zone

XEMIS2: Recovery and Storage of Xenon

ReStoX:
Recovery and **St**orage system **o**f **X**enon

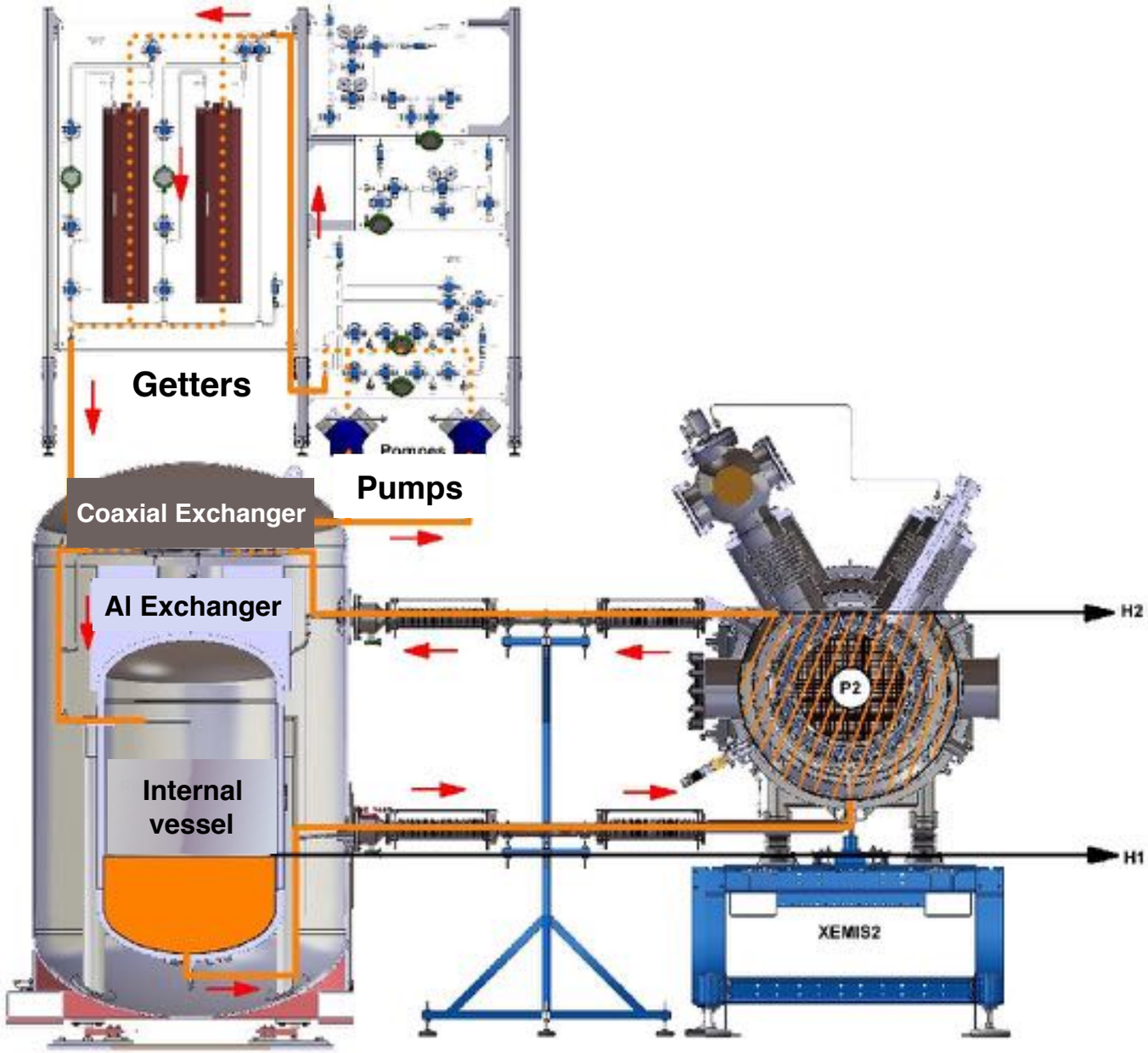
- Double walled vacuum insulated stainless steel cryostat
- Compact (210 kg capacity)
  - storage
  - distribution
  - recovering
- Safe
  - from room temp. to -110 °C
  - 71 bar design pressure
- Ultra pure LXe at 1.2 bar
  - ppb impurities level

XEMIS2: purification and re-circulation

Closed loop

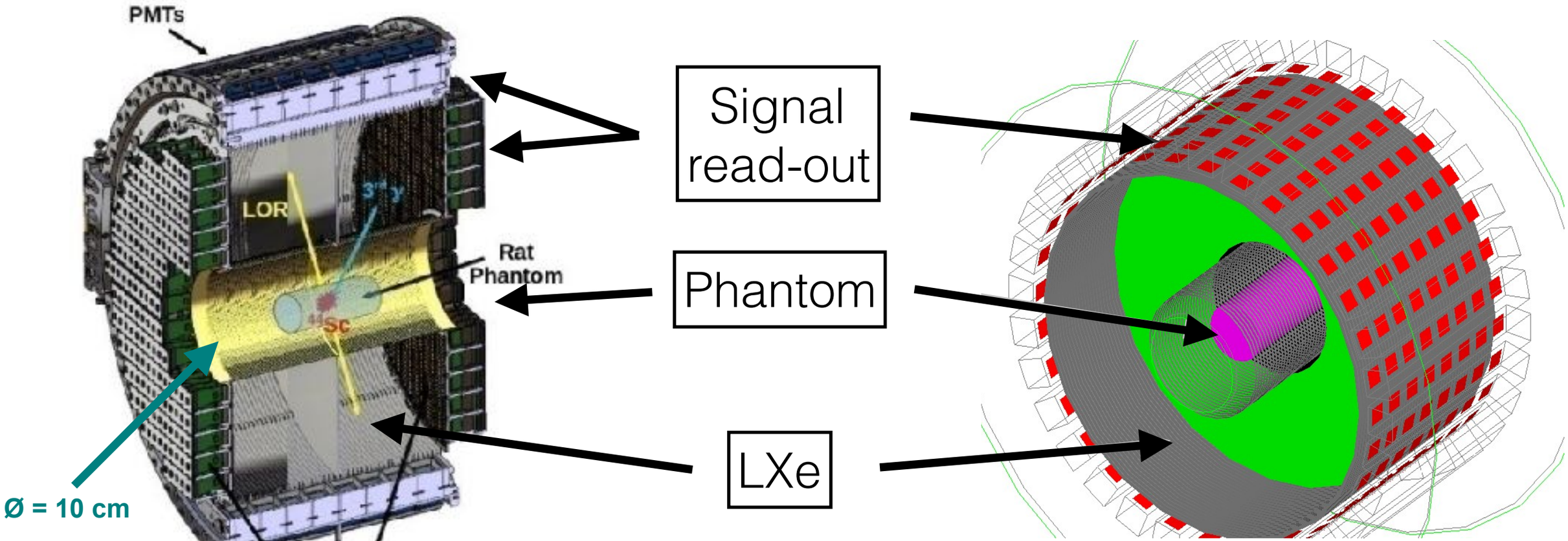
Reversible transfer ReStoX - XEMIS2

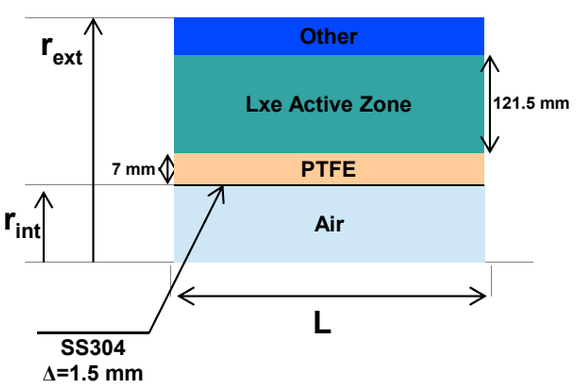
- LXe injection from ReStoX to XEMIS2
- Purification & circulation: 30 Nl/min
- Recovery from XEMIS2 to ReStoX



XEMIS2: Simulation

Complete simulation of **XEMIS2** with Geant4



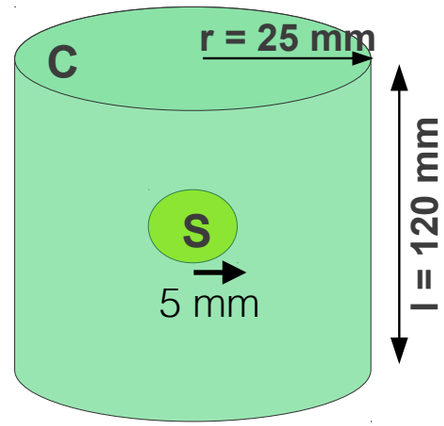


Geant 4 Gate ROOT Data Analysis Framework

XEMIS2: Simulation & Reconstruction

Input of the simulation:

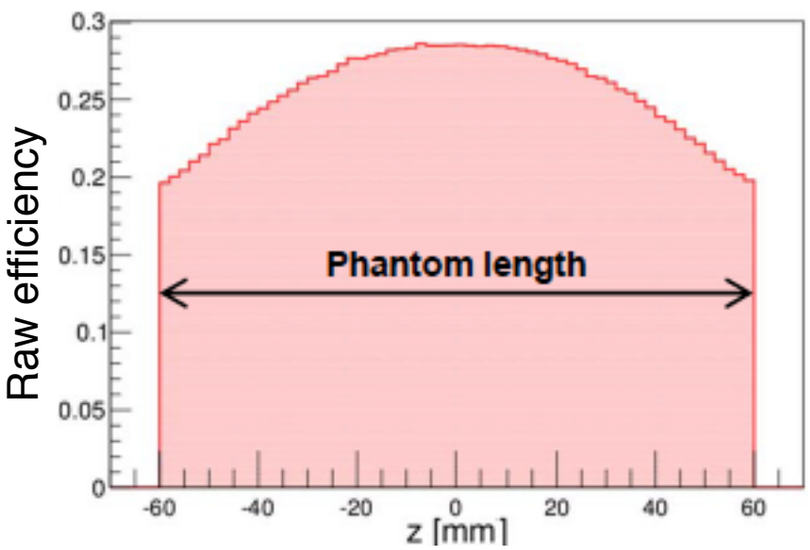
- Energy resolution: Thomas Imel model
  5% @ 511 keV
- Spatial resolution: < 1 mm (X, Y)
  ~ 0.5 mm (Z)
- Electronic noise: 100 e^- (~ 2 keV)

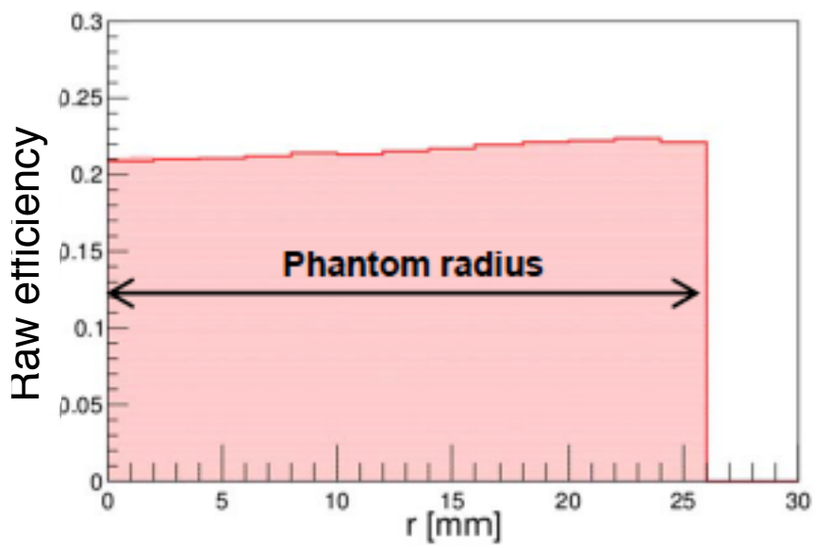


Rat phantom
Total activity: **20 kBq**
Contrast: **15**
Acquisition time: **20 min** (~24x10^{6}evts)

Submitted to Physics in Medicine and Biology

Quite uniform response of the detector!





- High sensitivity 3γ **> 7% along the FOV**
- Expected resolution along the LOR **< 1 cm**

XEMIS2: Reconstruction Algorithm

Simulated event

↓ 1st event cut

At least 4 xenon interaction

↓ Group reconstruction

3 reconstructed groups

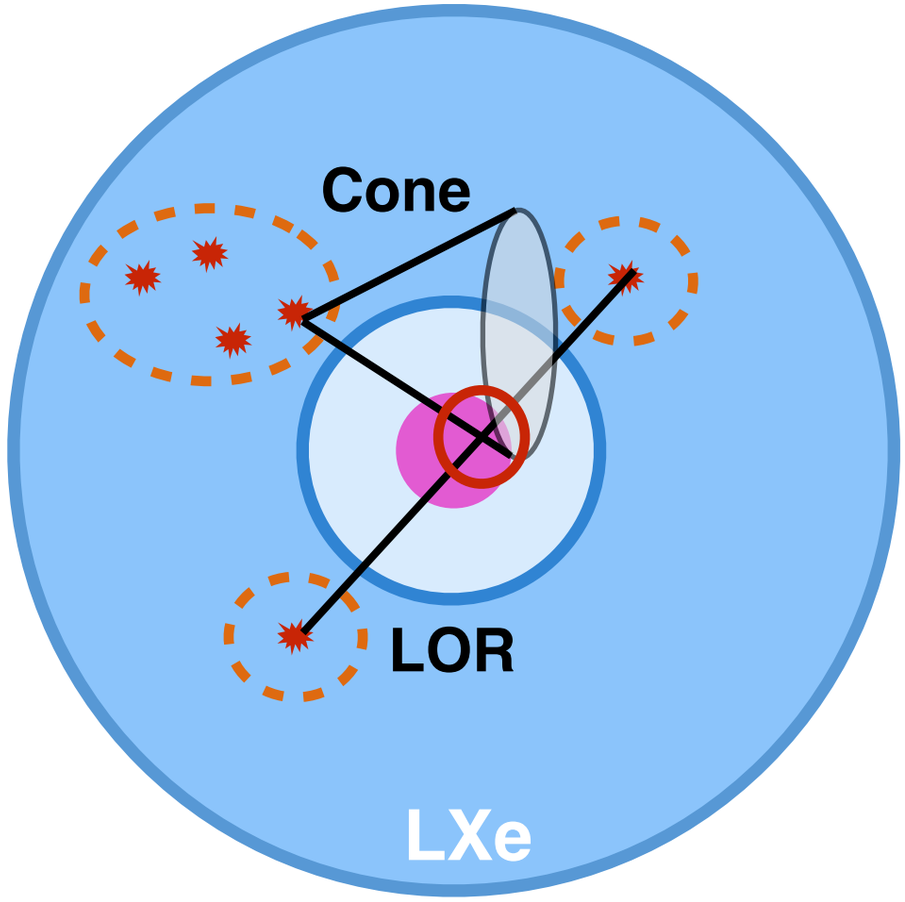
↓ Cone/LOR reconstruction

Cone/LOR intersection

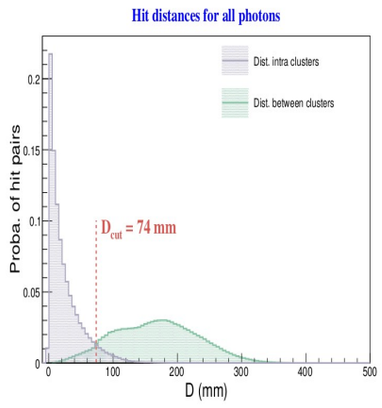
↓ Point reconstruction

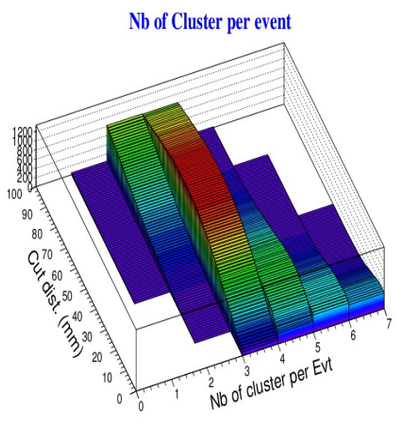
1 final point

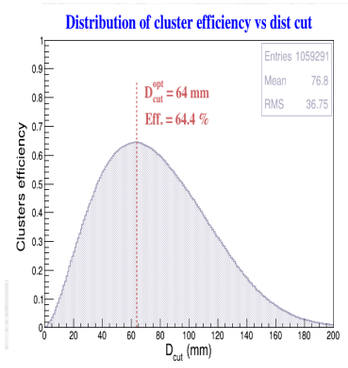
Submitted to Physics in Medicine and Biology

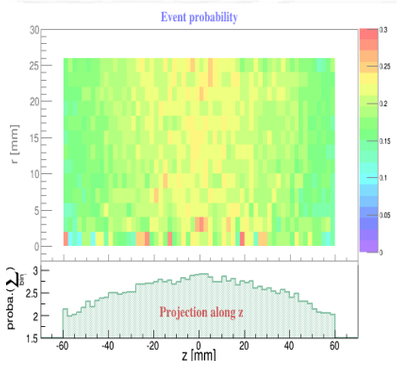


3D reconstruction of the source



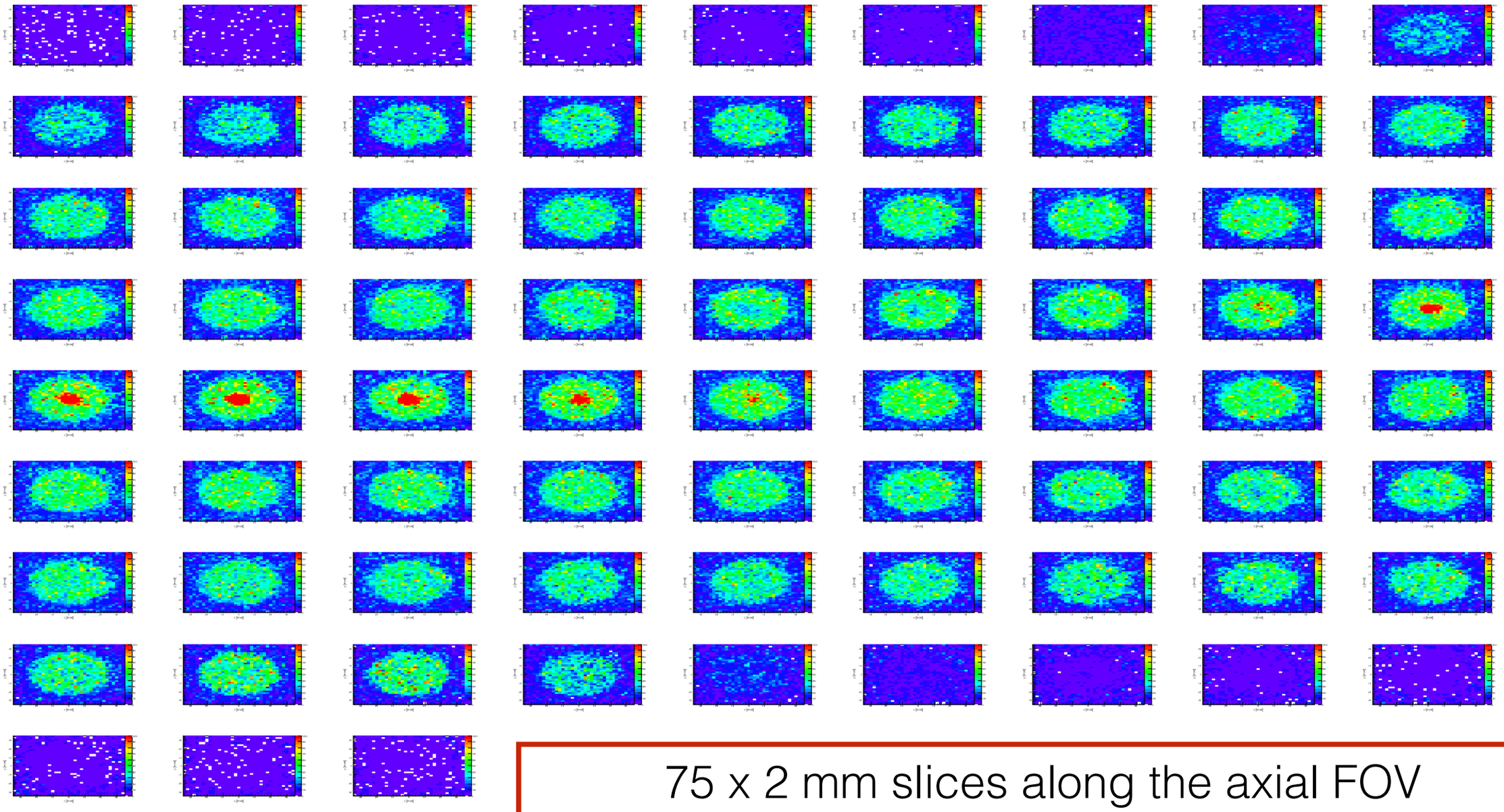






XEMIS2: Reconstruction

Raw Image



75 x 2 mm slices along the axial FOV

the contrast on the central sphere is clearly visible

XEMIS2: Deconvolution

- Idea

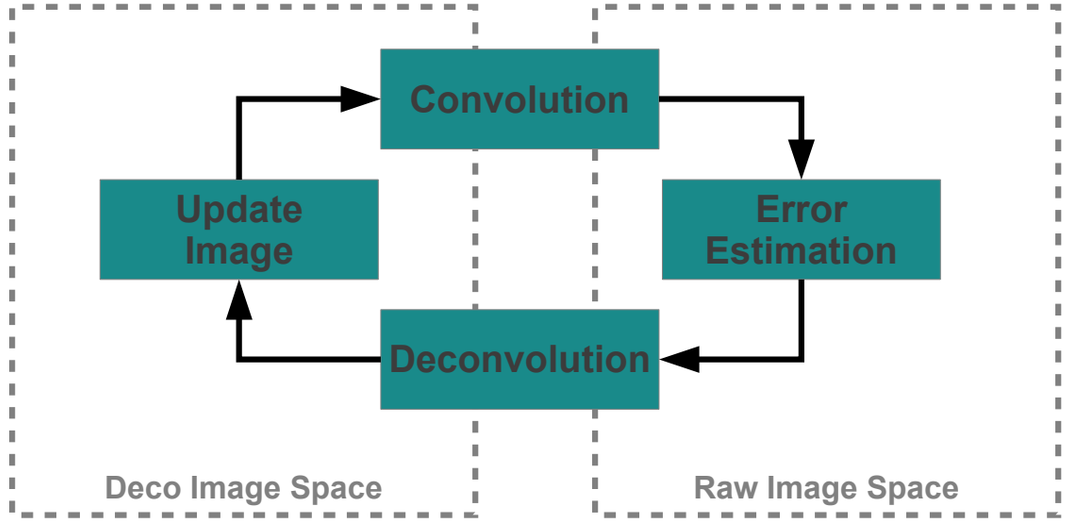
- Inverse problem of convolution

- Algorithm

- Iterative **ML-EM** based on Poisson distribution

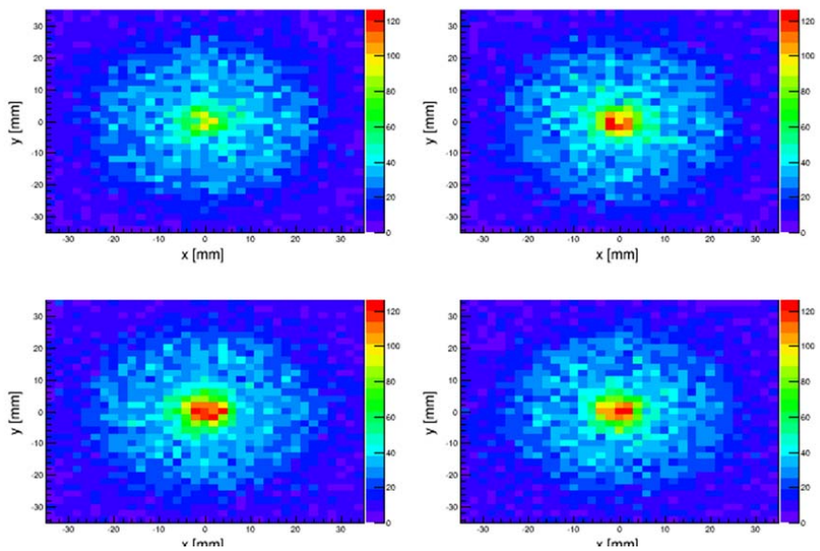
$$\lambda_i^{(n+1)} = \lambda_i^{(n)} \cdot \frac{1}{\sum f_{ij}} \sum_{j \varepsilon J} \frac{p_j}{\sum f_{kj} \lambda_k^{(n)}} \cdot f_{ij}$$

$j \varepsilon J \qquad k \varepsilon I$

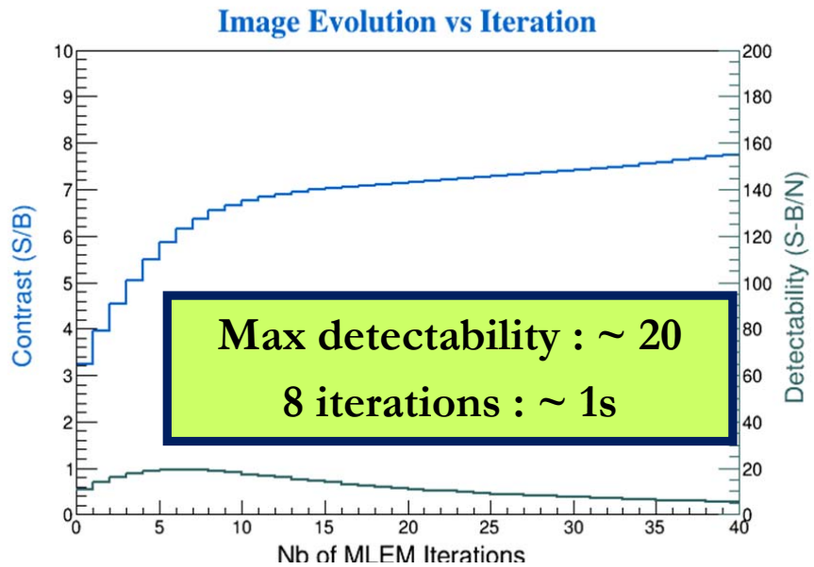


Preliminary

Raw Image :



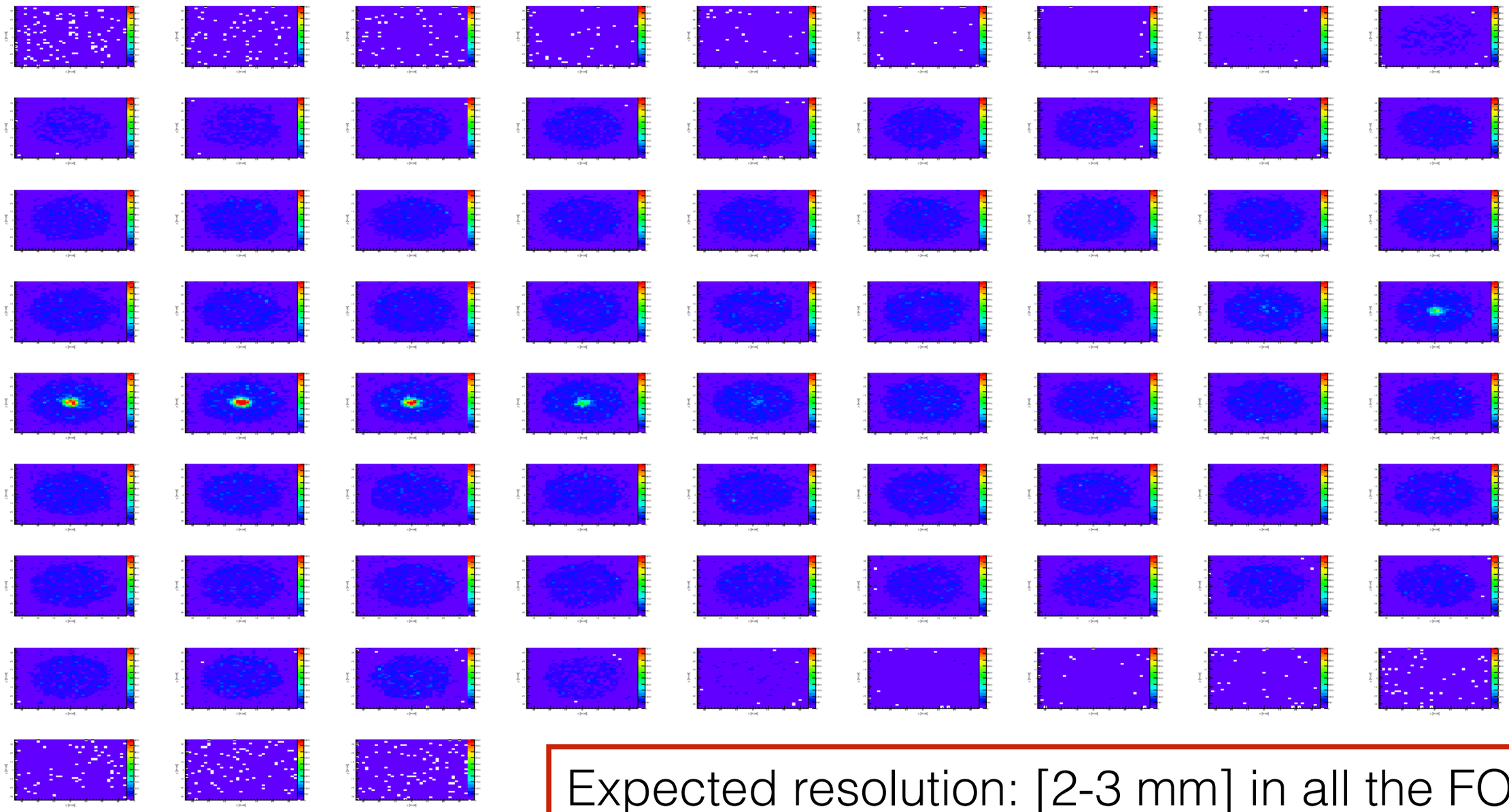
Deconvolution



XEMIS2: Deconvolution

Deconvolved Image

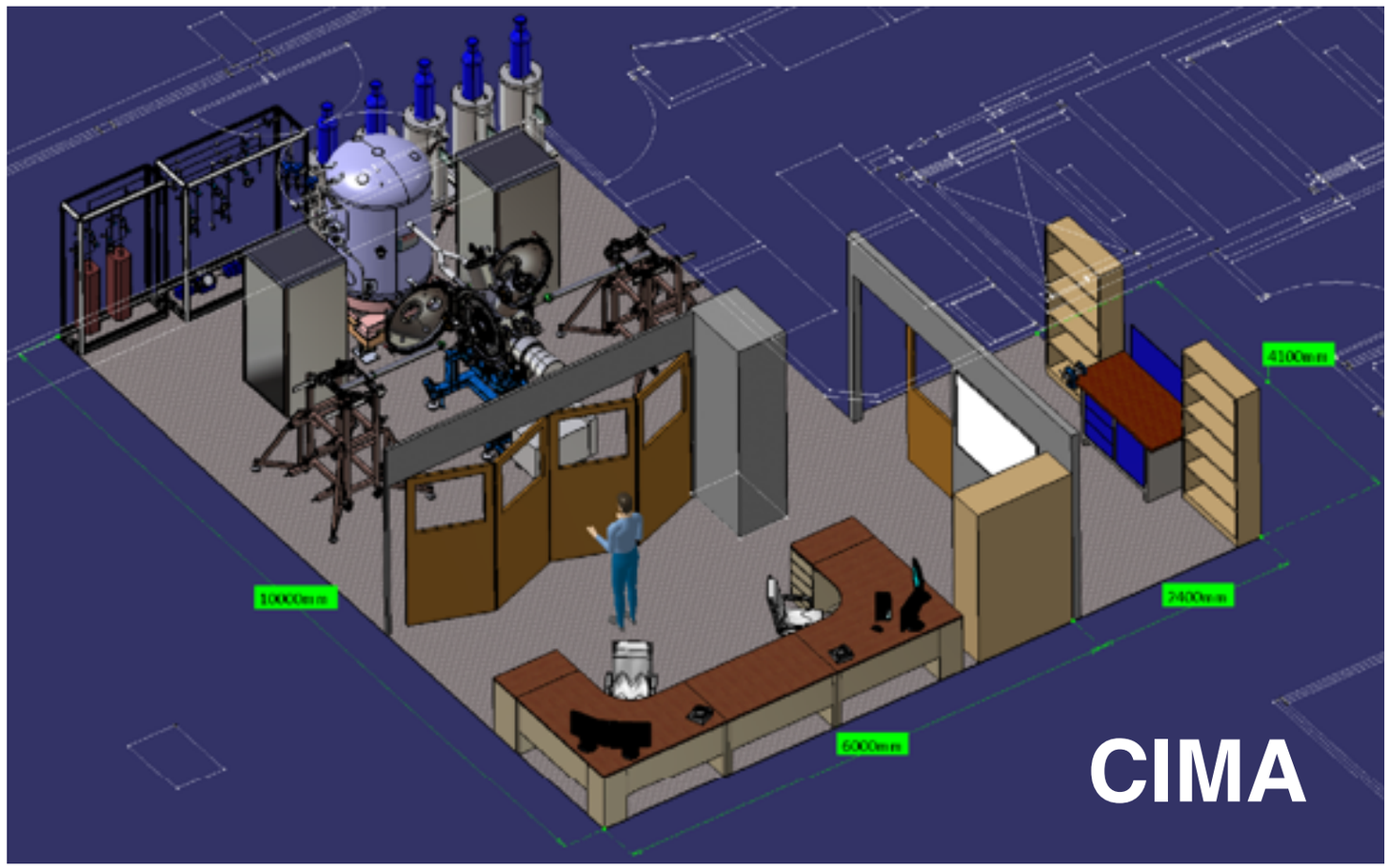
Preliminary



Expected resolution: [2-3 mm] in all the FOV

A lot of work to do…

Conclusion



Small animal imaging with XEMIS2

- Commissioning at Subatech: 2016 - 2017
- Installation at Nantes Hospital: 2017
- First **20 kBq** image: 2017
- Preclinical researches: til 2020

Thank's for your attention