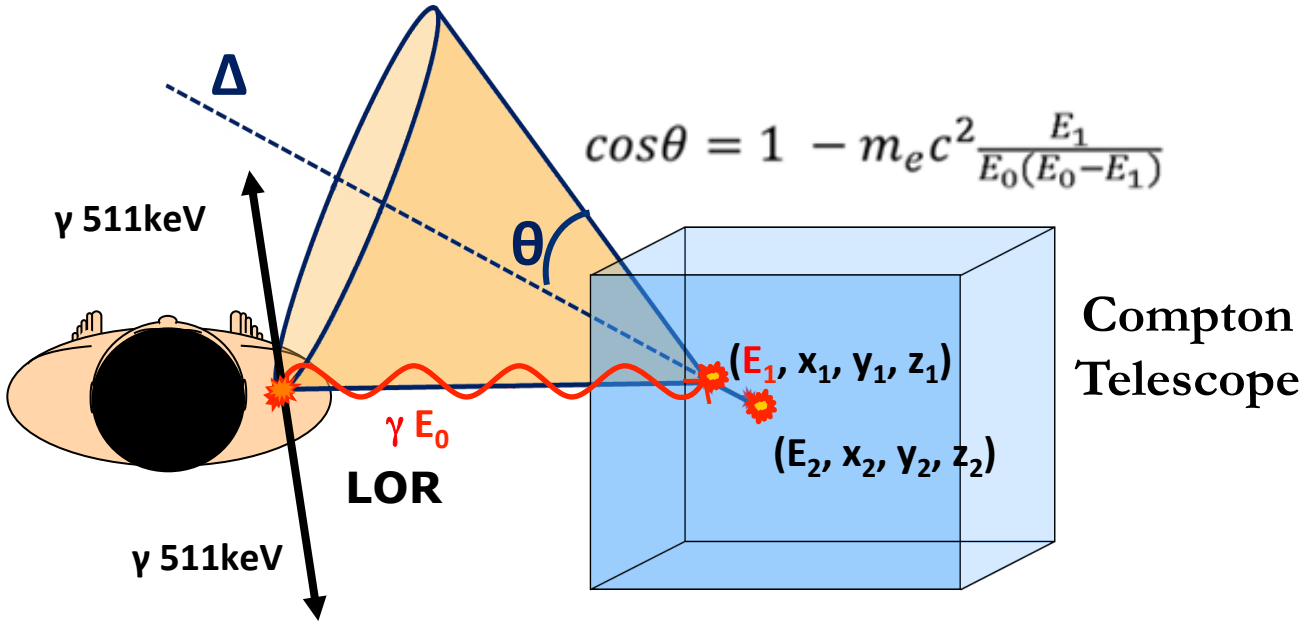
D_RD_11 : Prototype development of a positron emission tomography detector using liquid Xenon

J. Masbou, Université de Nantes

Principle of the 3γ Compton

LOR reconstruction + Compton Telescope



Reconstructed γ direction

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

- Direct 3D location of the radioactive source
- Administered activity reduction, shorter scan times

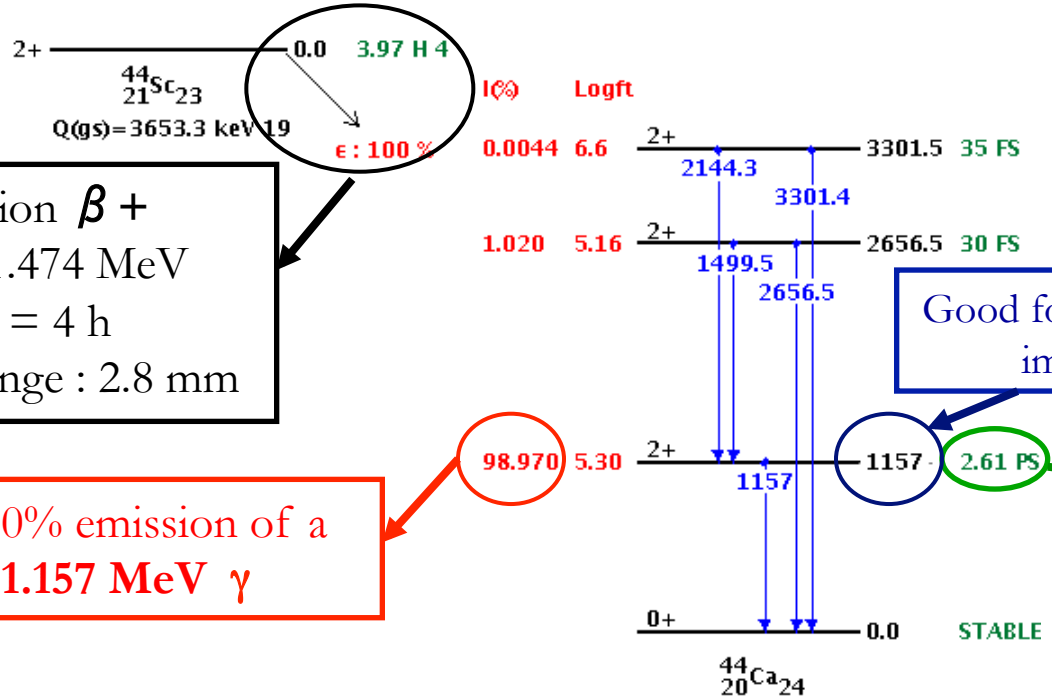
➢ **Both new medicament and new camera technology !**

3γ imaging will be investigated with 44Sc

Requires the use of a specific nucleus, which emits a **$\beta^+ + \gamma$ ray** in quasi-coincidence:

The **^{44}Sc** is our best candidate

$$^{44}_{21}Sc \xrightarrow{\beta^+\ 94.3\ \%} {}^{44}_{20}Ca + e^+ + \nu_e$$



Emission $\beta+$
E_{max} = 1.474 MeV
$T_{1/2}$ = 4 h
effective range : 2.8 mm

Good for Compton imaging

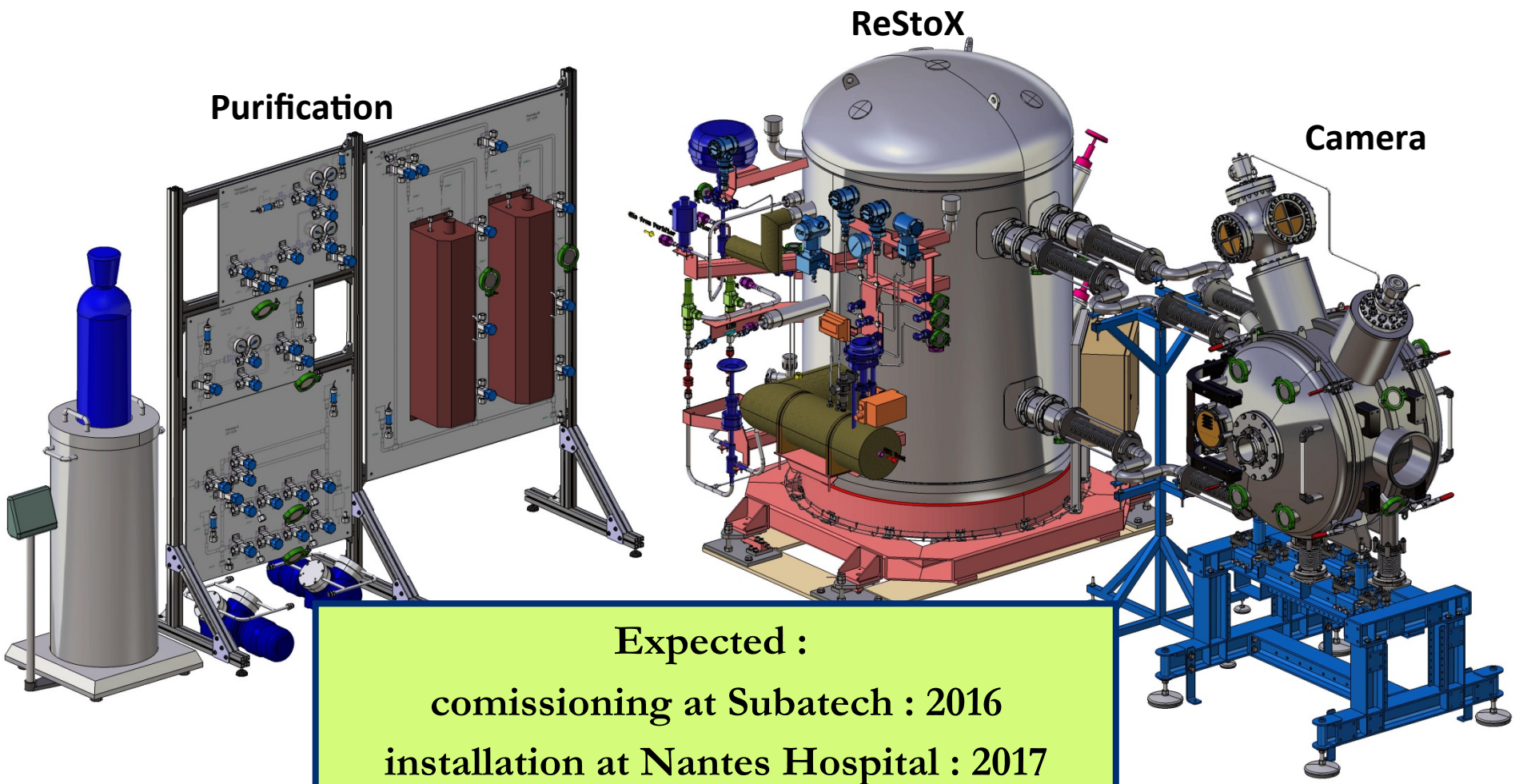
~100% emission of a **1.157 MeV γ**

Fast emission
Precise time coincidence

- **Production:** cyclotron **ARRONAX**
- **Radiopharmaceutical : CRCNA/INSERM**

➢ **Ready for tests with [^{44}Sc]-DOTA**

3γ imaging: XEMIS2 and small animal



Expected :

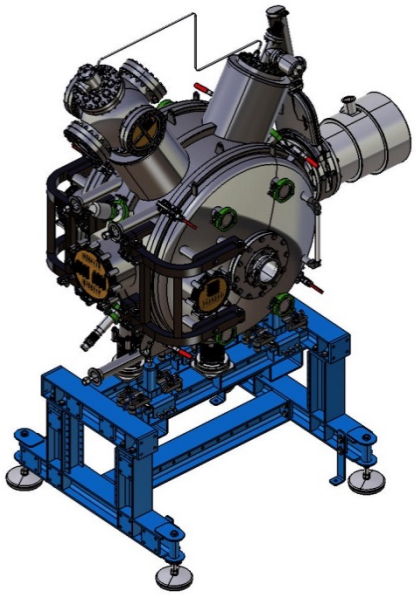
comissioning at Subatech : 2016

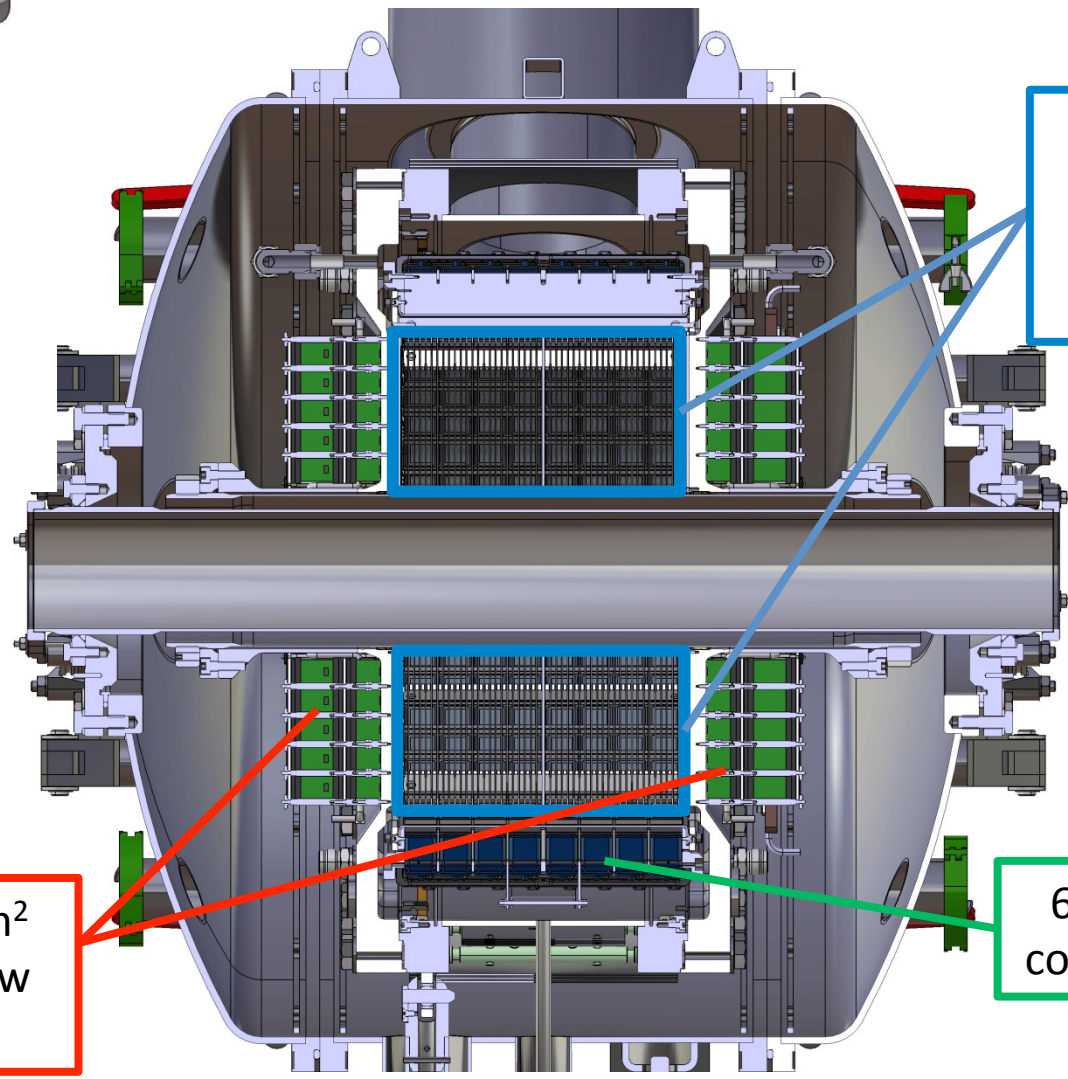
installation at Nantes Hospital : 2017

1st image : before the end of 2017

preclinical researches : until 2020

3γ imaging cameras: made of liquid xenon





LXe TPC

X2 active volume
- axial : 2 x 12 cm
- depth : 12 cm
- r_{min} : 7 cm

Ionization

2 x 10^4 3.1x3.1 mm^2 pixels with ultra low noise cold FEE

Scintillation

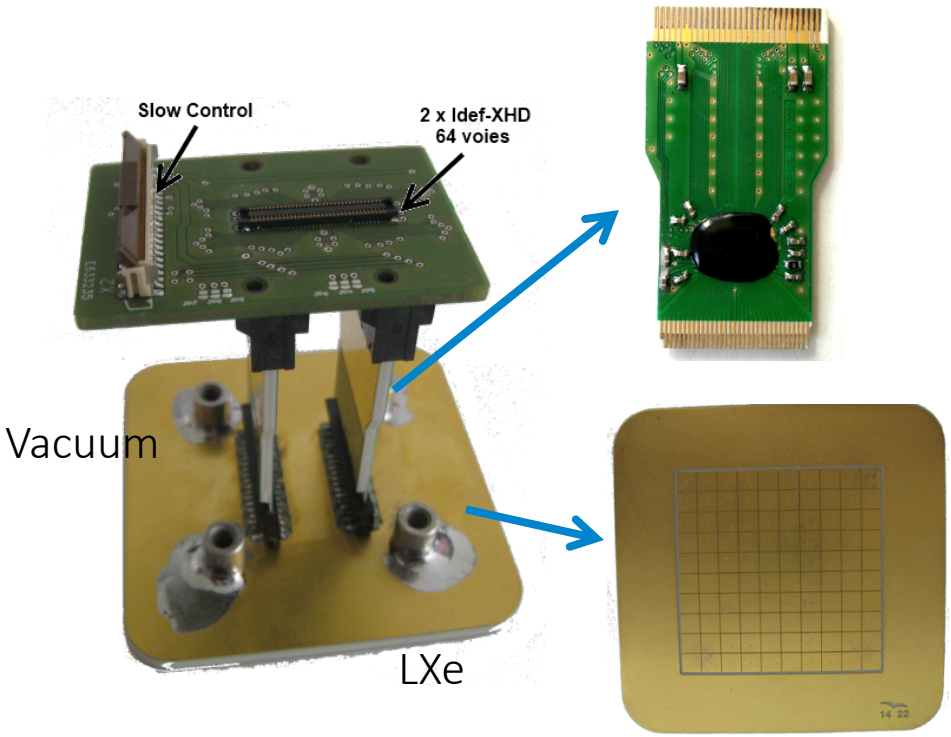
64 x 1'' PMTs in LXE covering 8 sectors in ϕ

Results with XEMIS1 : Ionization read-out

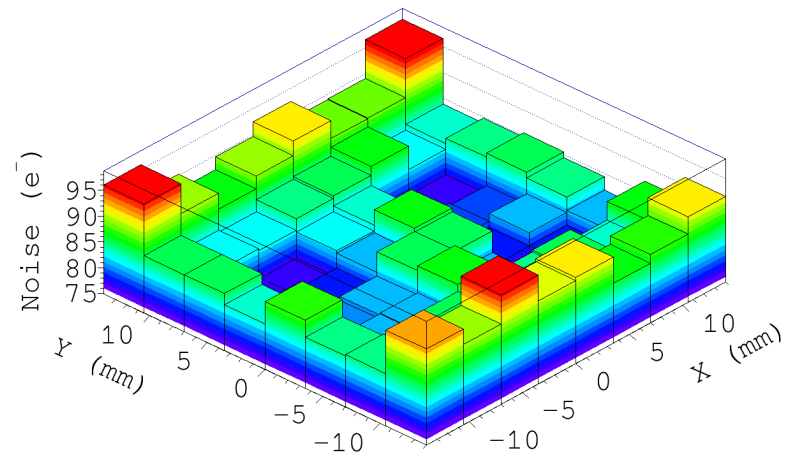
Noise : 85 +/- 5 e- (at -100 °C)

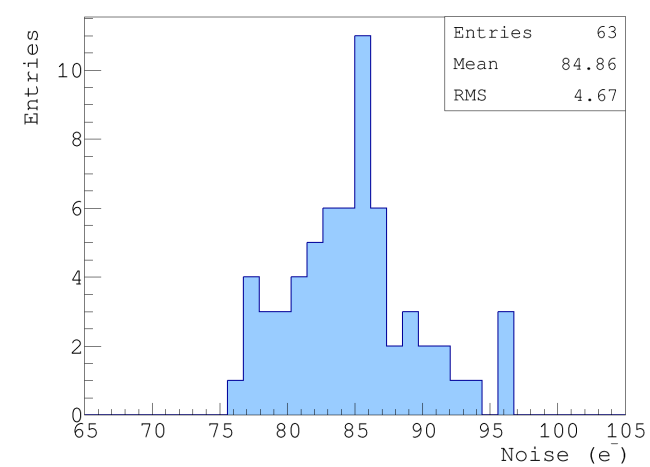
IDEF-X Asics
Developed for CdTe @ IrFU (Gevin et al. 2006)
Adapted by Subatech for LXe

511 keV (@1 kV/cm) ⇒ 27200 e-

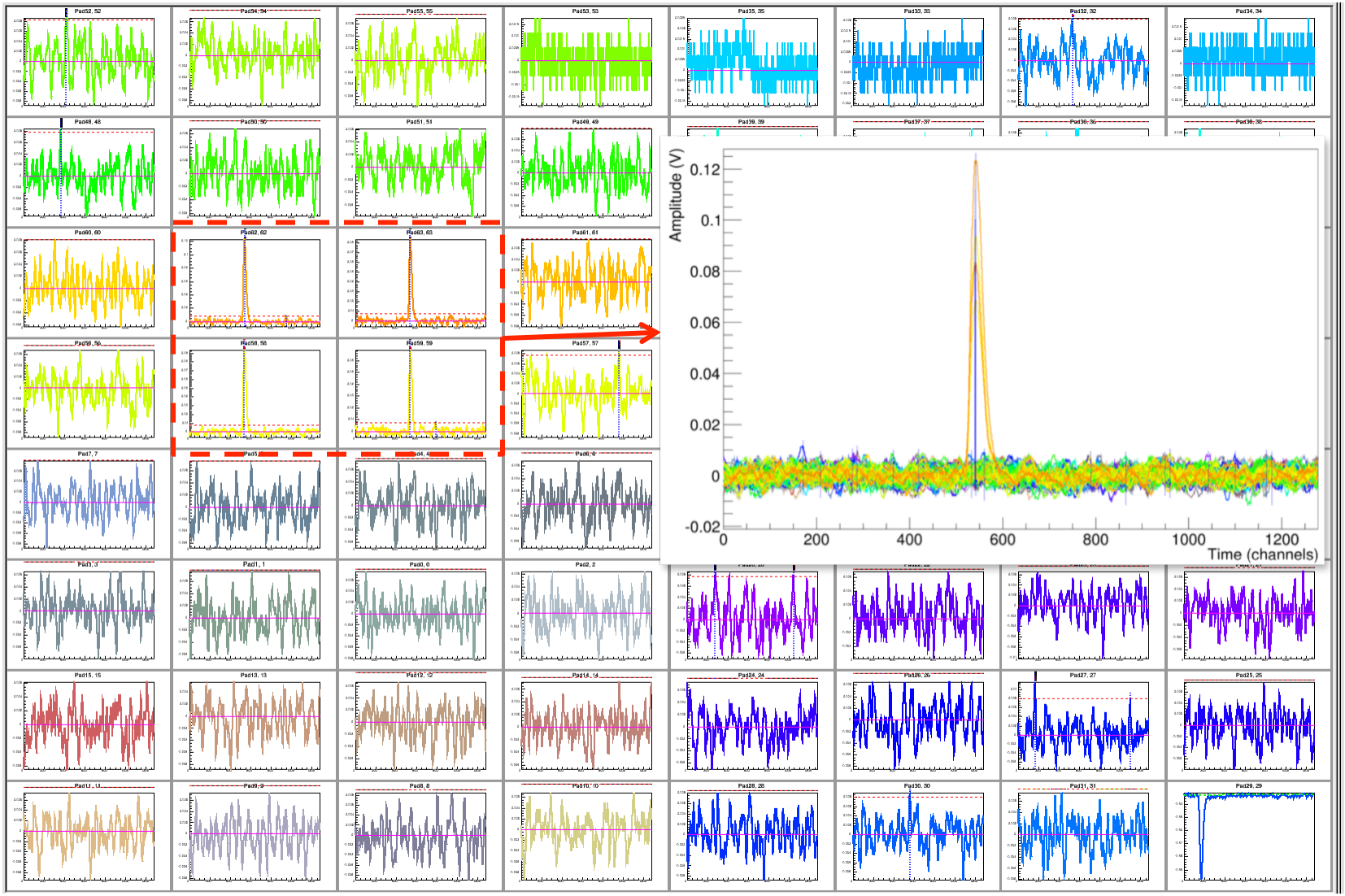


Anode 64 pixels
3.1 x 3.1 mm²

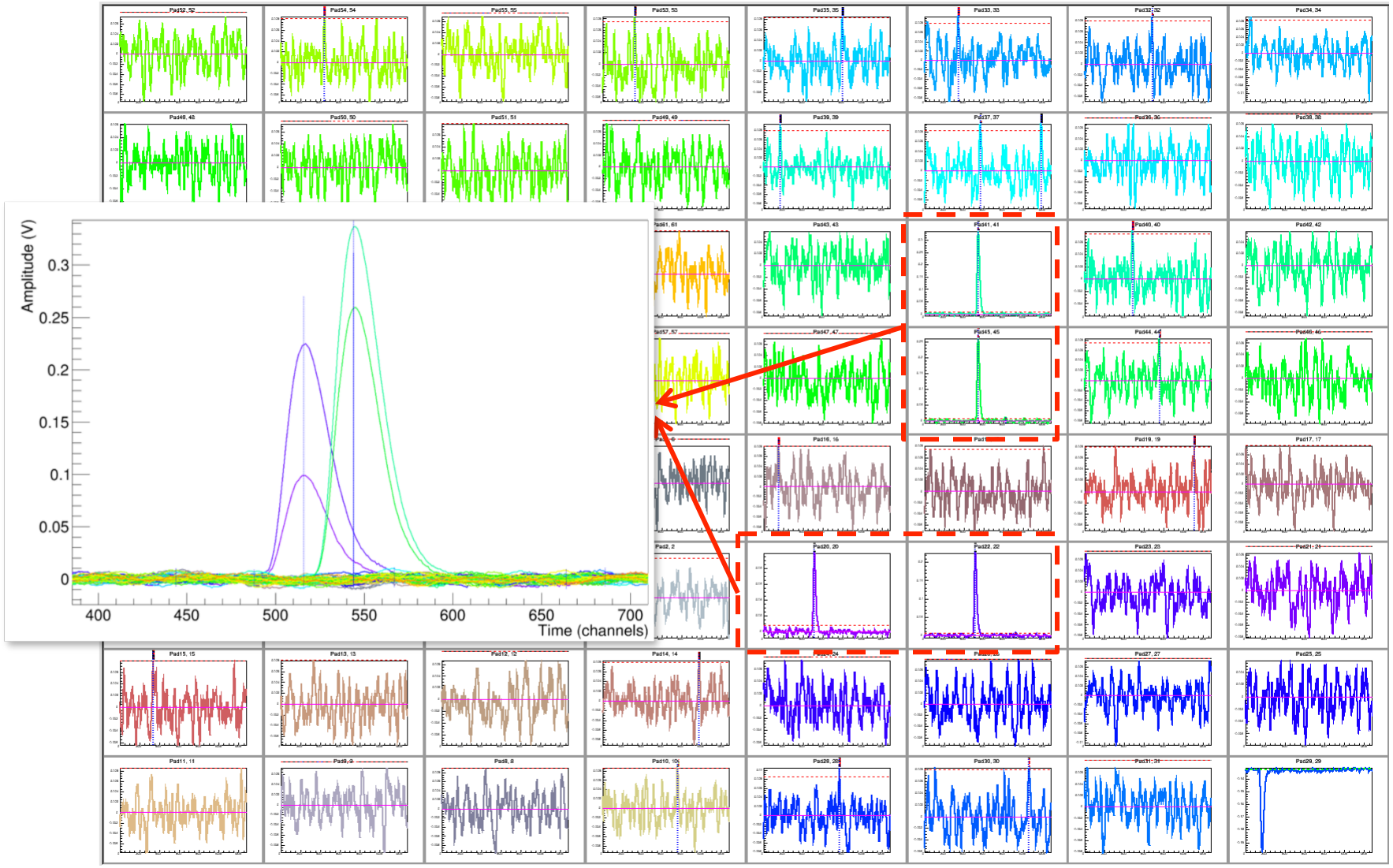




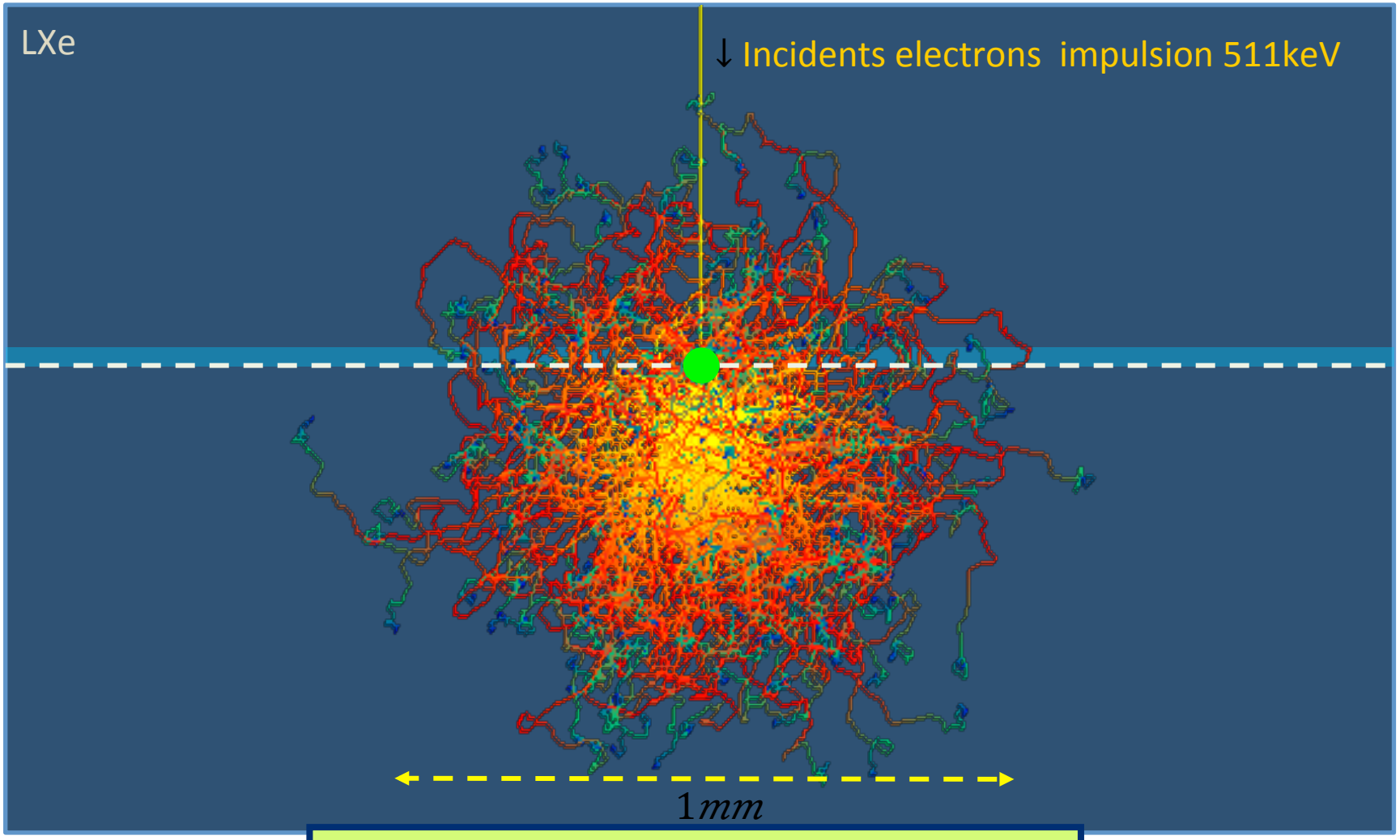
Ionization : signal @ 511 keV for Photoelectrics



Ionization : signal @ 511 keV for Compton

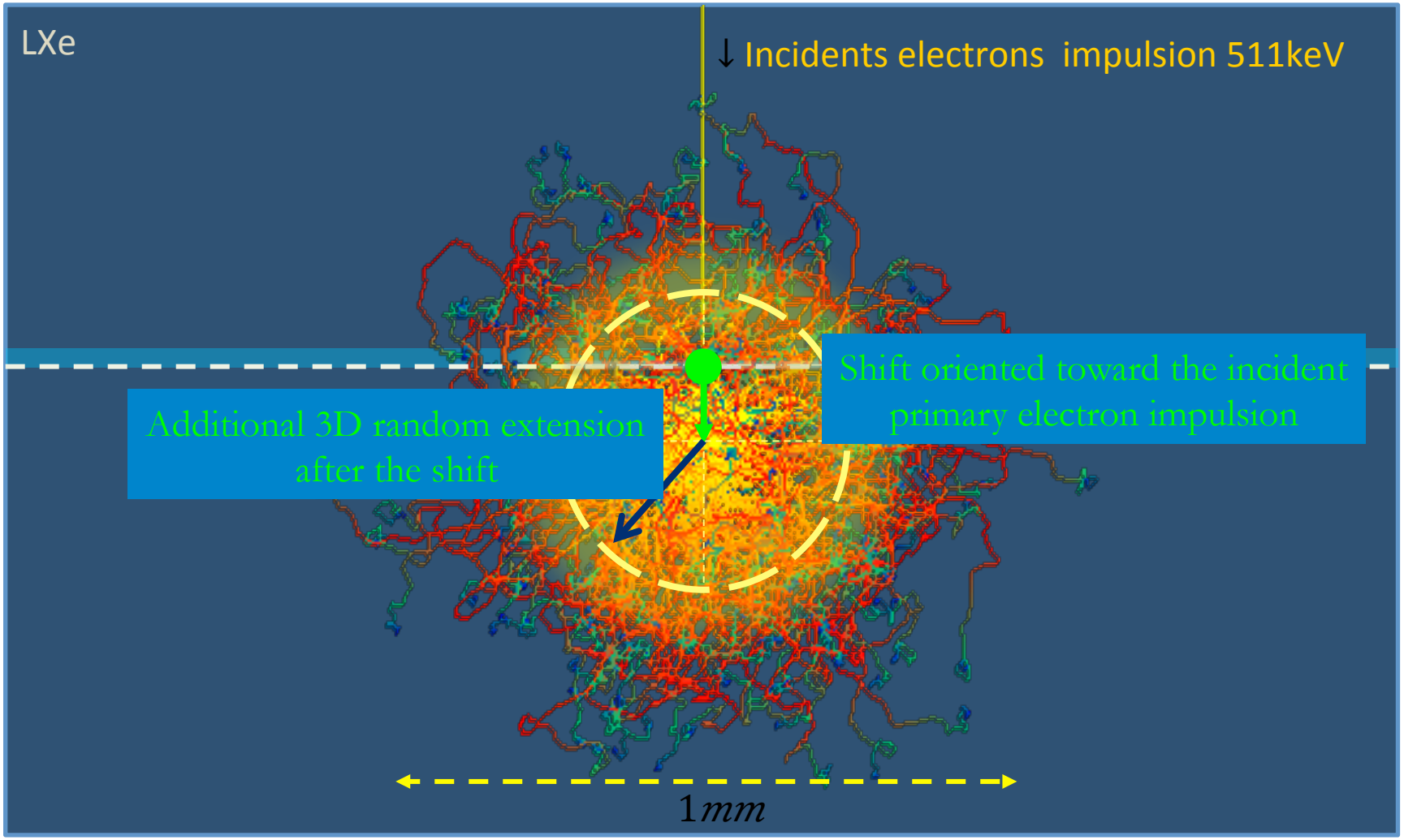


Ionization : recoil electrons in LXe with CASINO



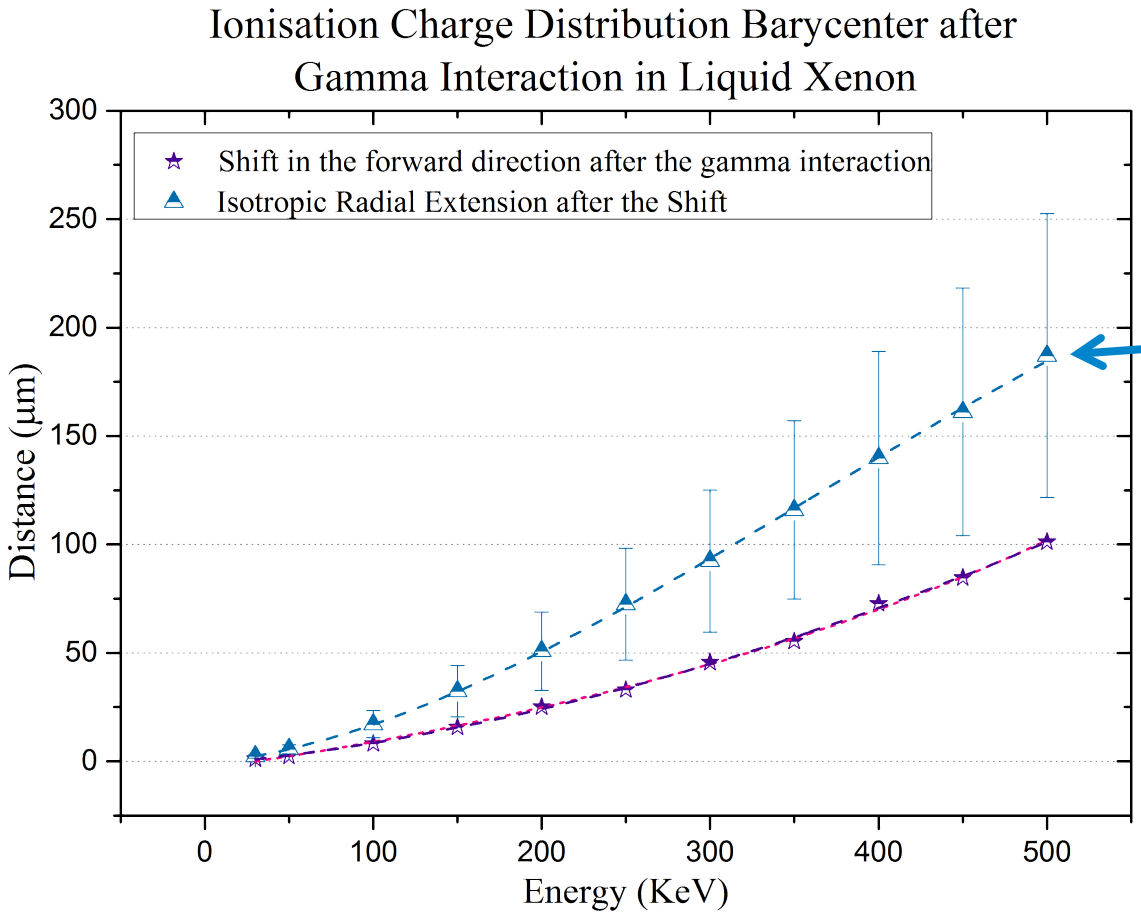
Ionization is generated on a dispersed cloud due to the chaotic trajectory of the primary electron

Ionization : recoil electrons in LXe with CASINO



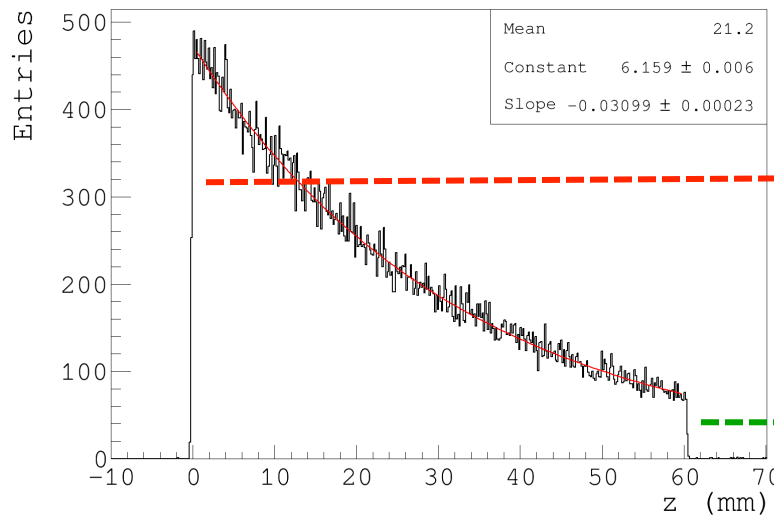
Ionization : achievable spatial resolution

Recombination model (Thomas & Imel.)

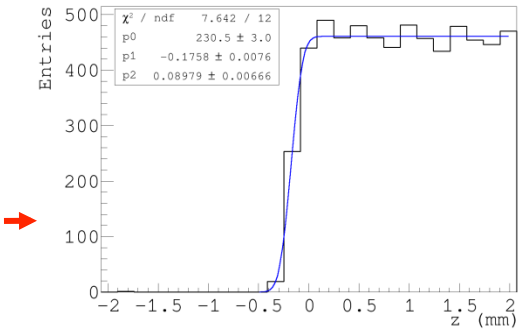


around 100 µm
in x, y, and z

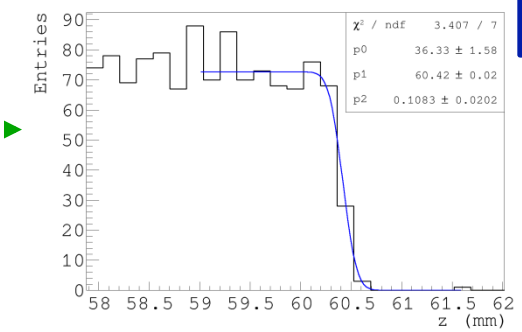
XEMIS1 : Ionization results @ 511 keV



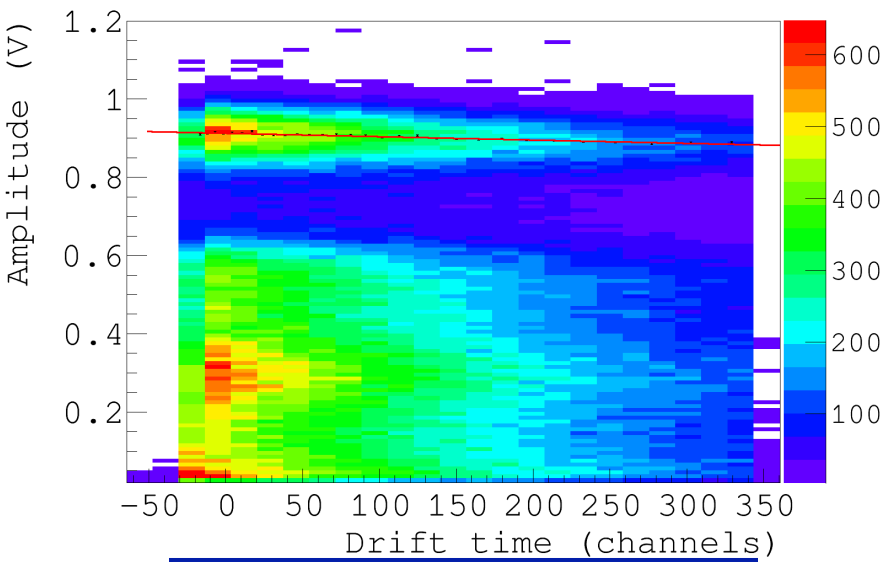
Beginning of the TPC



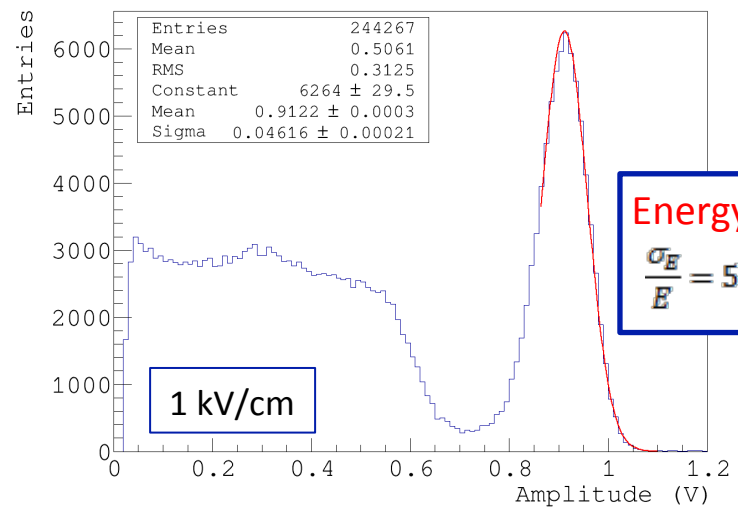
End of the TPC



DOI resolution:
~ 100 µm



Attenuation length ~ 1 m

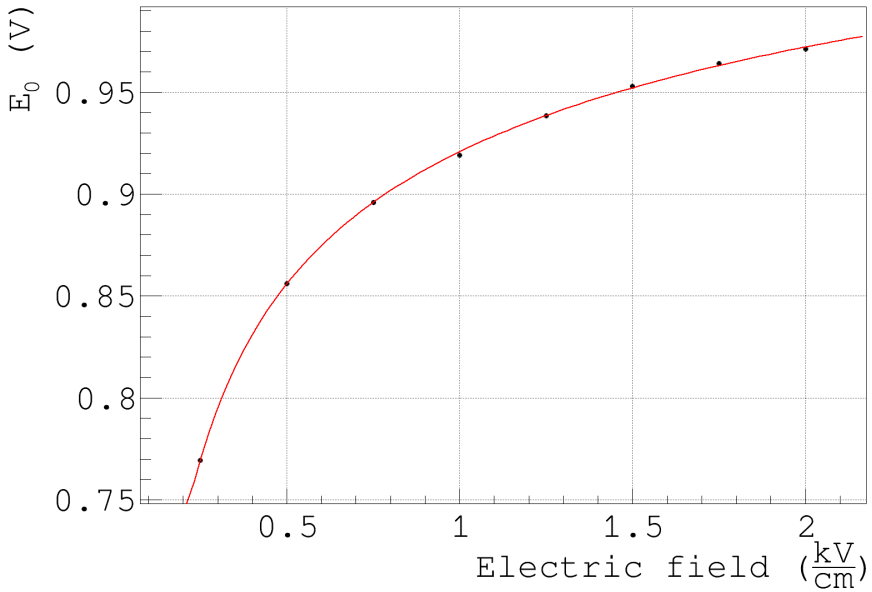


Energy resolution

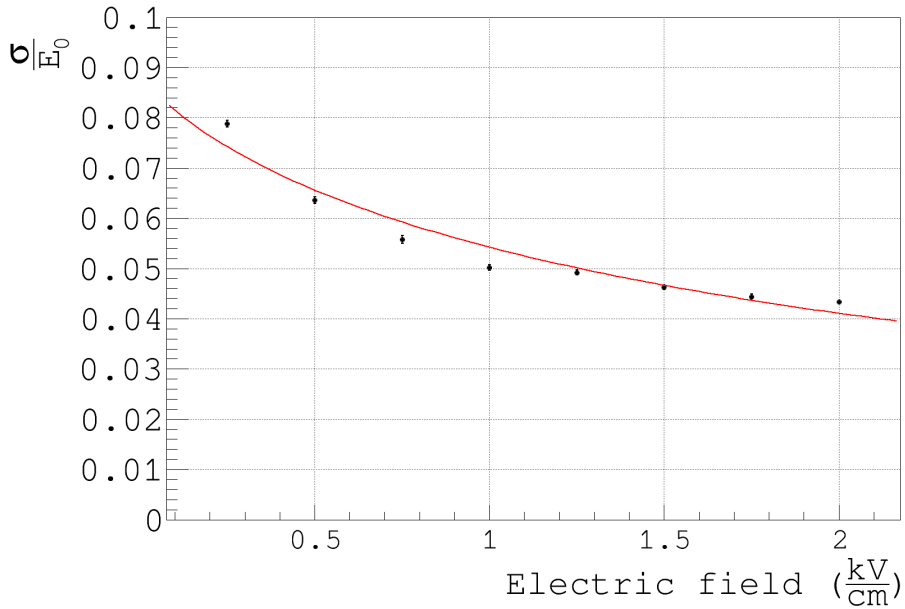
$$\frac{\sigma_E}{E} = 5.07 \pm 0.06\,\%$$

XEMIS1: Energy resolution

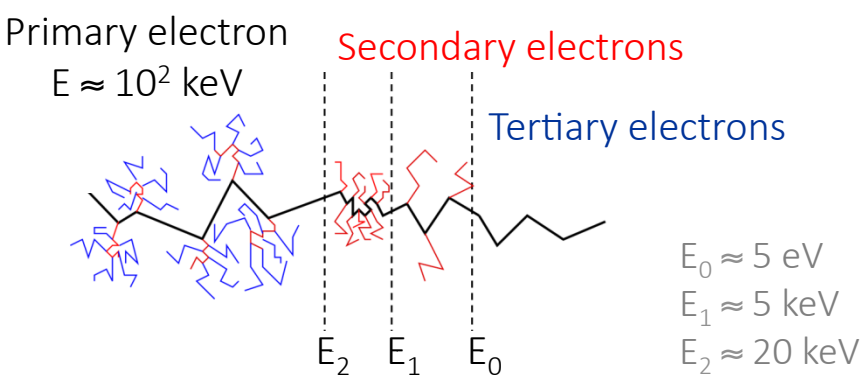
Ionization yield



Energy resolution



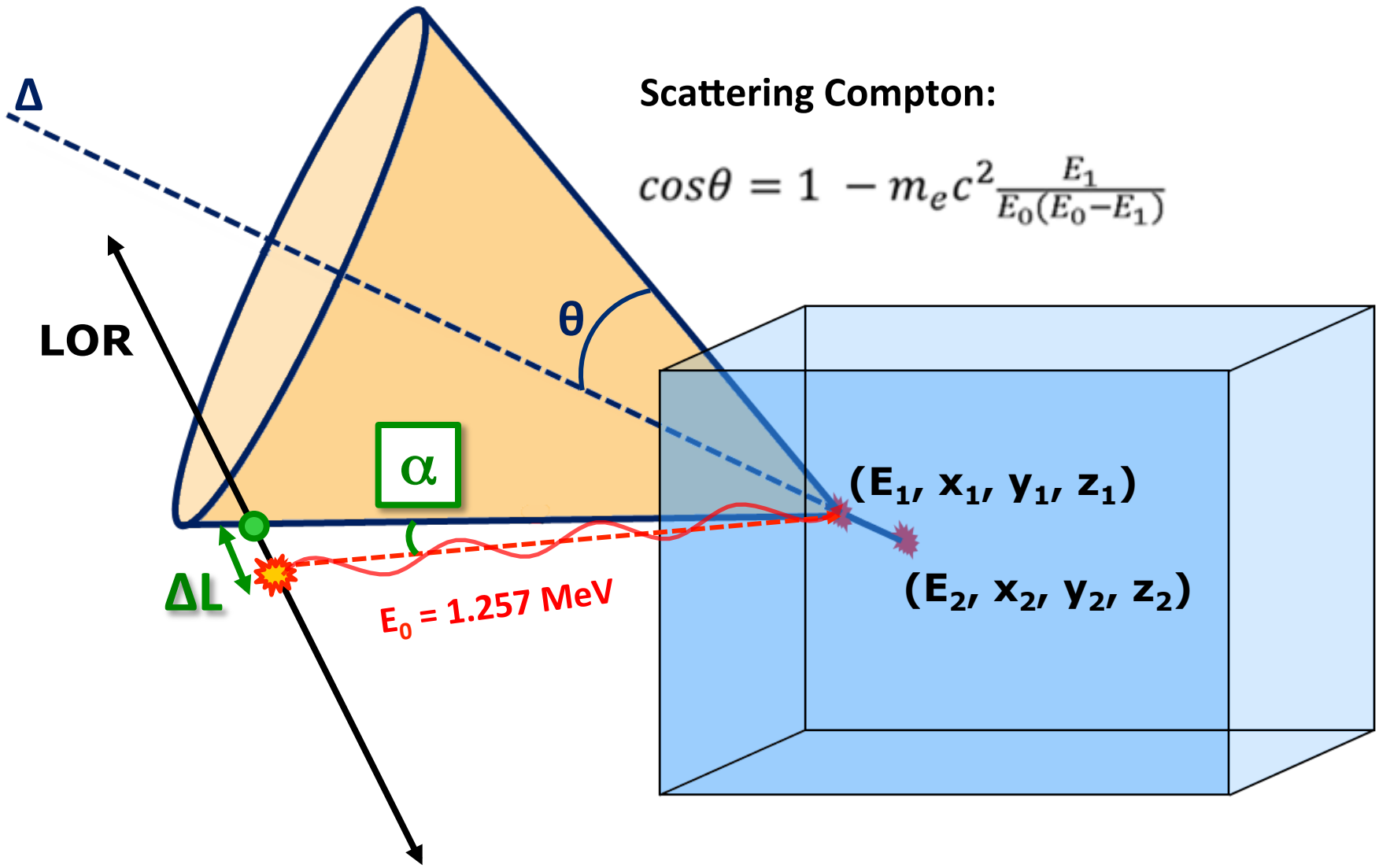
e-/ion Recombination :



Thomas et al. Model 1988 Phys. Rev. A

Best energy resolution measured for the ionization signal in LXe @ 511 keV.

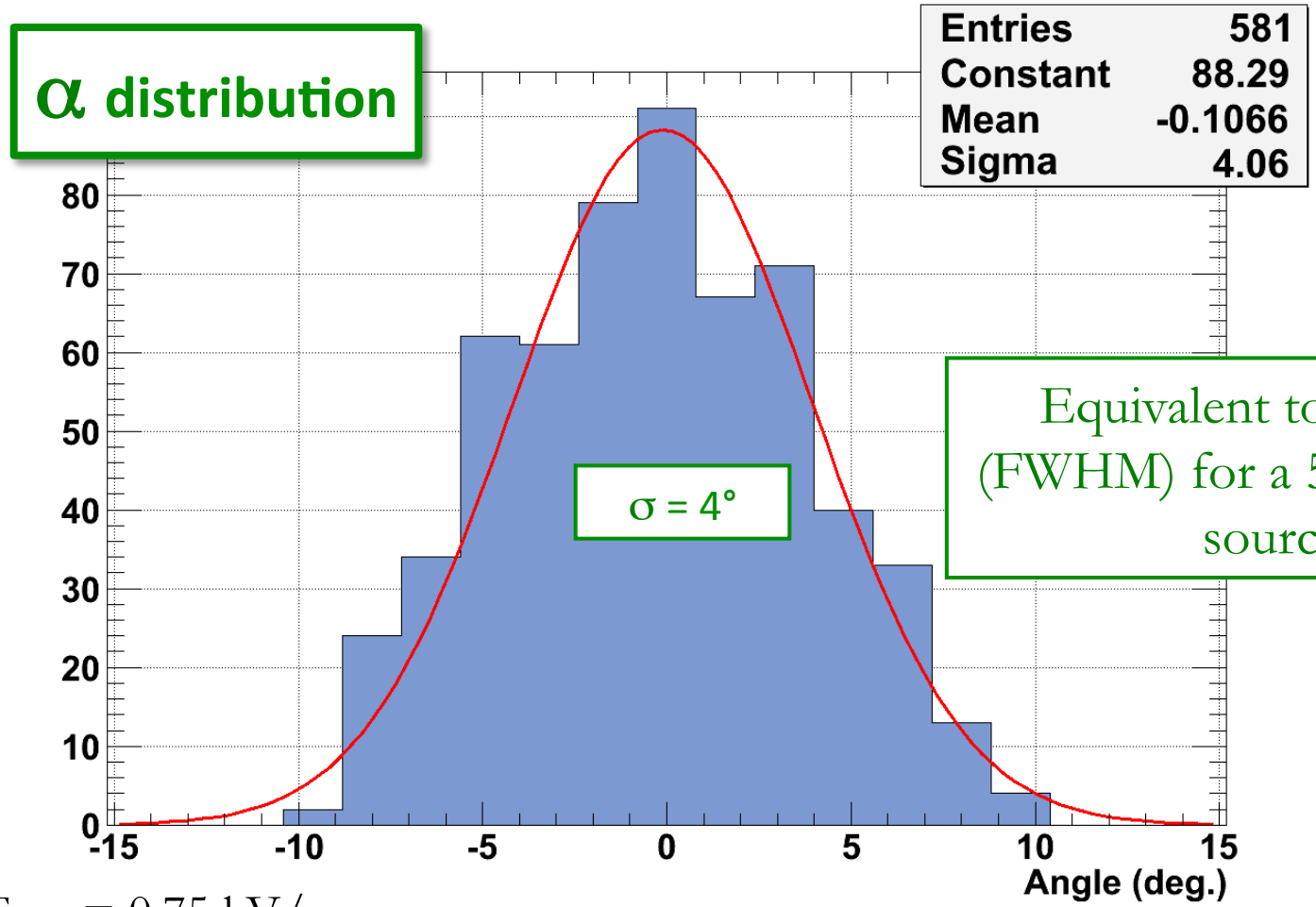
Cone – LOR intersection



Scattering Compton:

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

XEMIS1: resolution along the LOR



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

$E_{drift} = 0.75$ kV/cm

Very promising results
Improvement: E_{drift} ↑

XEMIS2

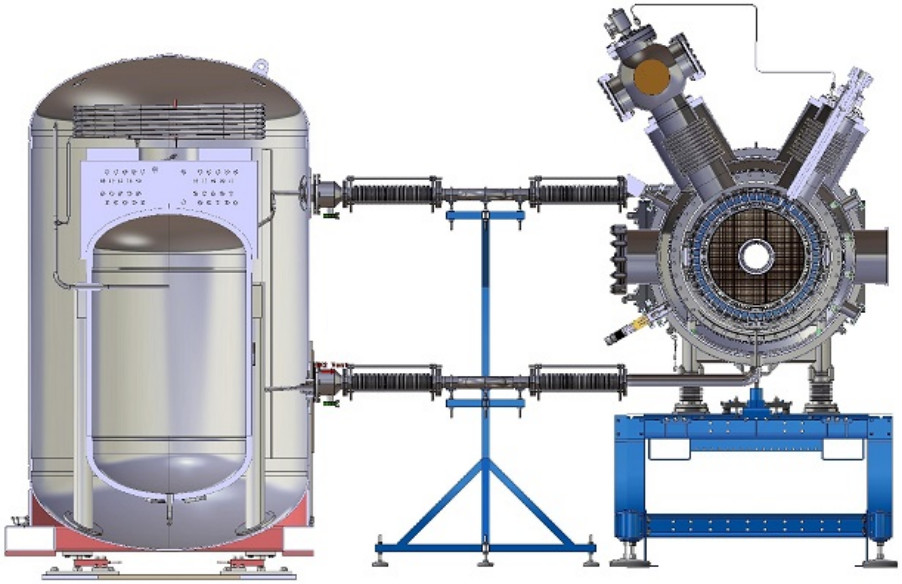
ReStoX :
Recovering and Storage system for liquid Xenon

Scientific collaboration :

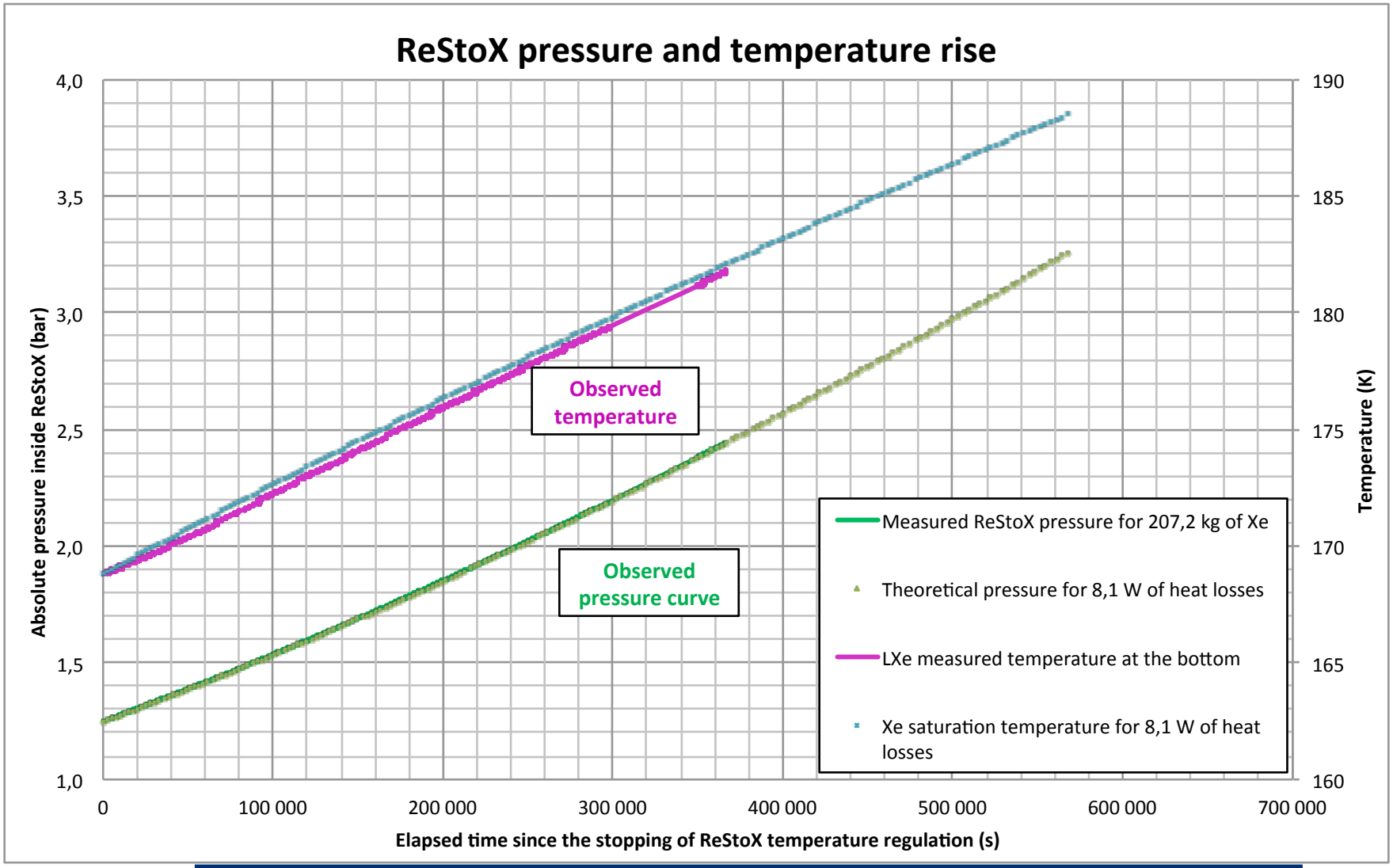
AIR LIQUIDE Subatech

Install a liquid xenon camera in a hospital ?

Xenon cryogenics of XEMIS2 :
- compact (210 kg capacity)
- safe (from RT to -110°C)
- powerfull (up to 10 kW)
- ultra clean (ppb impurities lvl)



XEMIS2: commissioning pressure rise-up



Without LN_2, RT should be reached in ~ 1 year

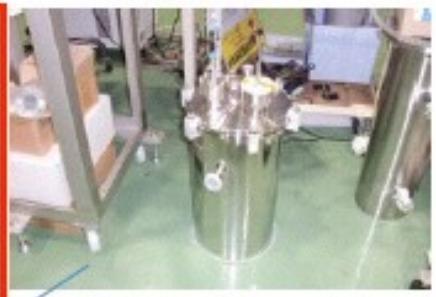
Crogenics study of LXE TPC at KEK : Stiring Cooler

Control system of cryogenics

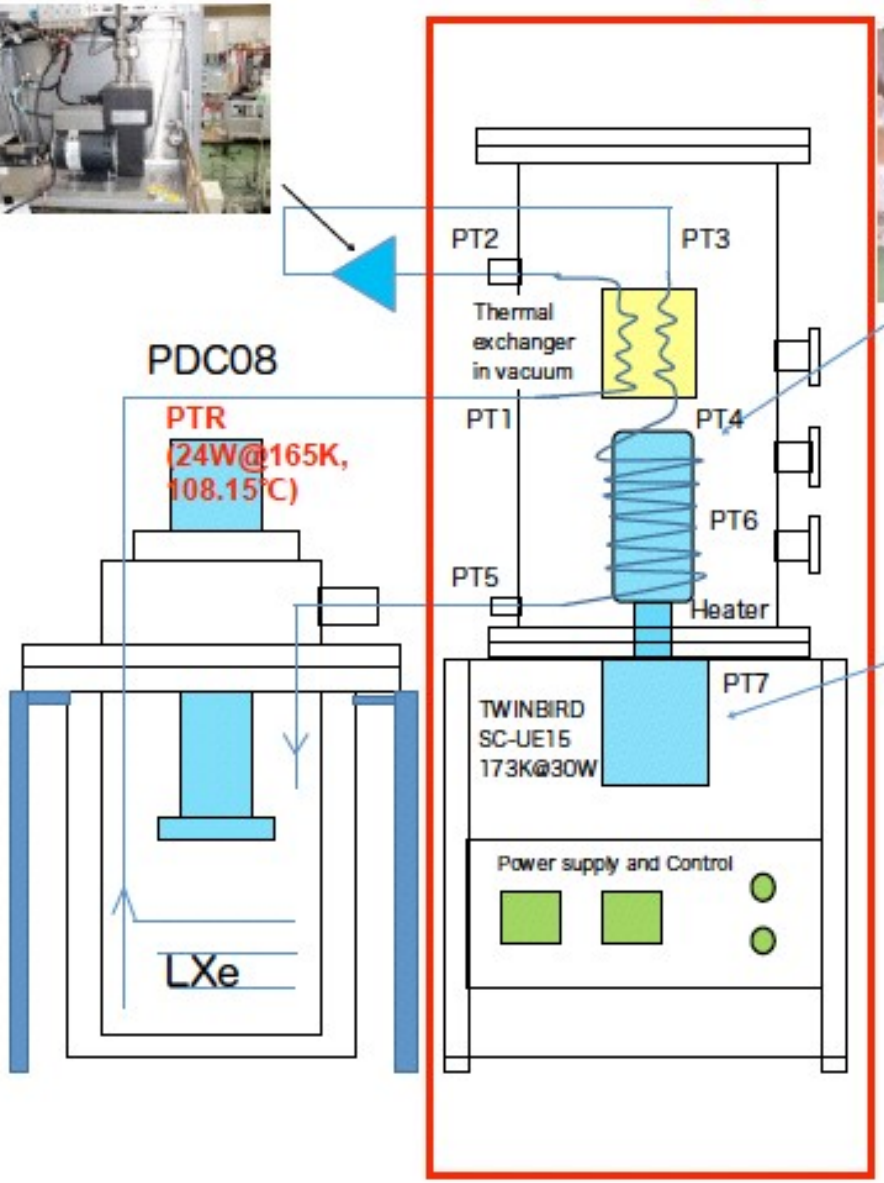
pump of the gas circulation

Xe Pre-cooling system

Heat exchanger with vacuum insulation



LXe Cryostat

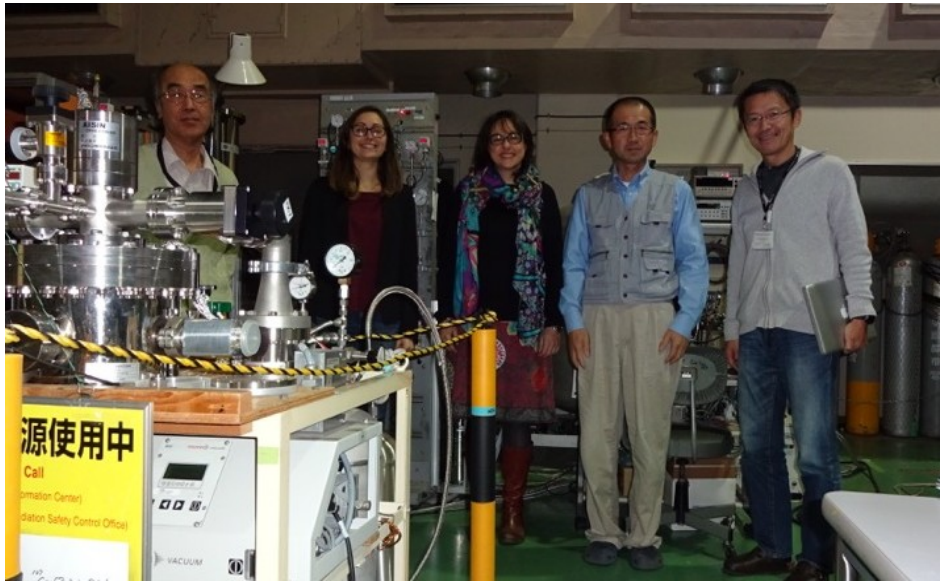


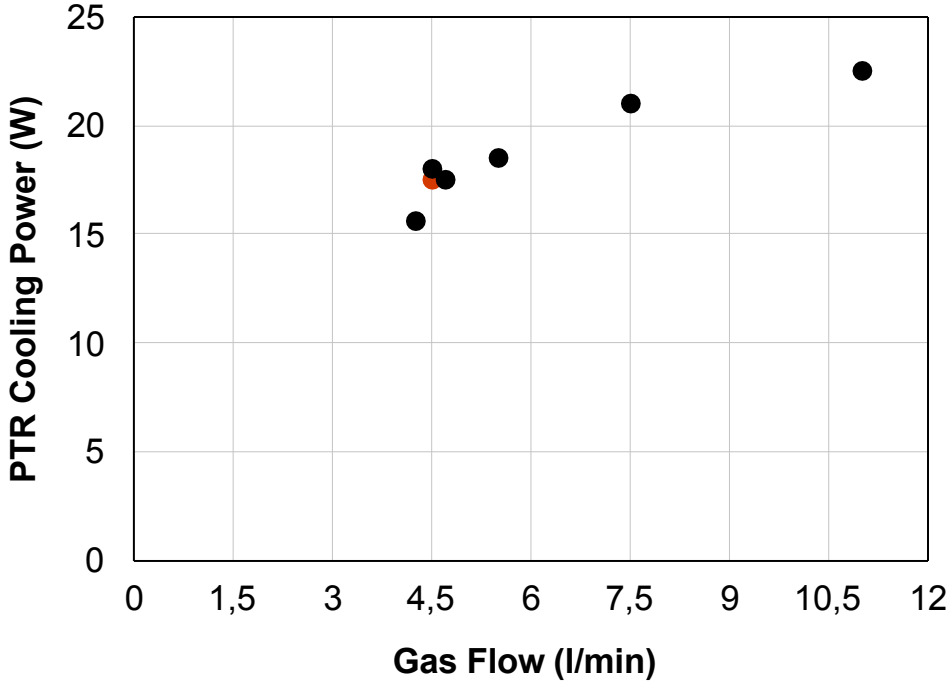
Additional cooler

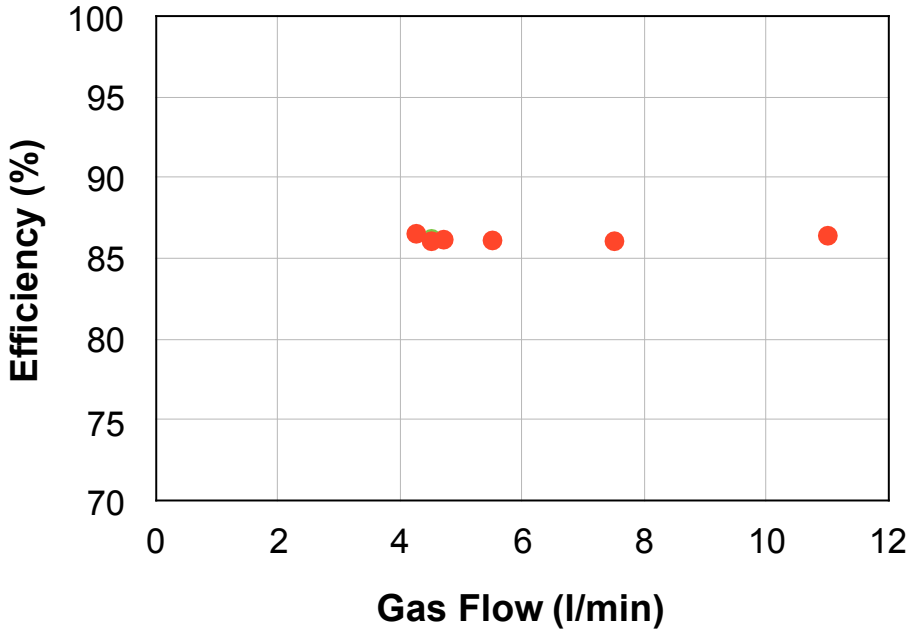
TWINBIRD SC-UE15
173K@30W

Crogenics Study of the LXE TPC at KEK

- 2 weeks of tests
- Control of stability (pressure, temperature,…)
- Measurment of Thermal Losses
- Computation of the efficiency







Conclusions

- 3γ imaging in a new approach targeting theranostics and phenotypics imaging
- It involves new technologies and a lot of innovations for the cameras design
- XEMIS covers initial Technology Readiness Level inside a scope compatible with fundamental researches frame
- Expected image qualities are very promising :
    - very low activity in the FOV
    - good spatial resolution of in all the FOV
    - fast scan of all the FOV
- **It should be considerated for precise and personnalise medecine**

Contributors

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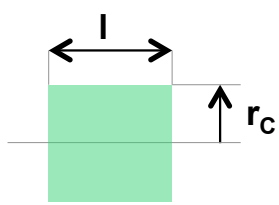
XEMIS2 complete simulation with Geant4

RAT PHANTOM

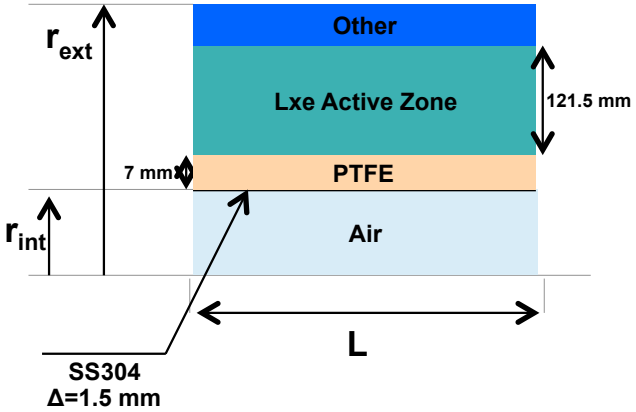
- **Geometry :**
  - Cylinder :
    - r_C = 2.6 cm
    - l = 12 cm
  - Sphere:
    - r_S = 5 mm
- **Material :**
  - Water
  - ^{44}Sc
- **Radio-Activity :**
  - Total = 20,0 kBq
  - Bkg (cylinder) = 19,5 kBq
  - Src (sphere) = 0,5 kBq
    - Uniform distribution

➡ Contrast = 15



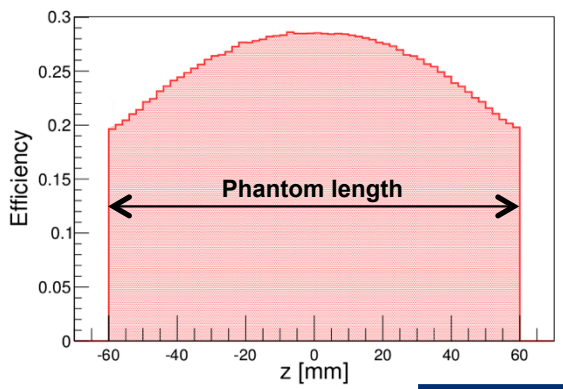
CAMERA

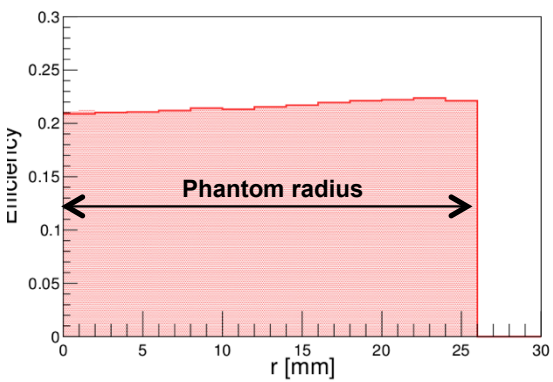
- **Geometry :**
  - Uniform Tube of LXe
    - r_{int} = 7 cm
    - r_{ext} = 19 cm
    - L = 24 cm
- **Material :**
  - Liquid Xenon
- **Acquisition time :**
  - t_A = 20 min



Detectable Event Fraction

At least 4 Hits in Lxe :
- 1 for each 511 keV photons
- 2 for 1157 keV photon





quite uniform !

XEMIS2 reconstruction strategy

Event Reconstruction Algorithm :

All simulated evts (100 %) (a)

↓

At least 4 Xenon interactions (b)

↓

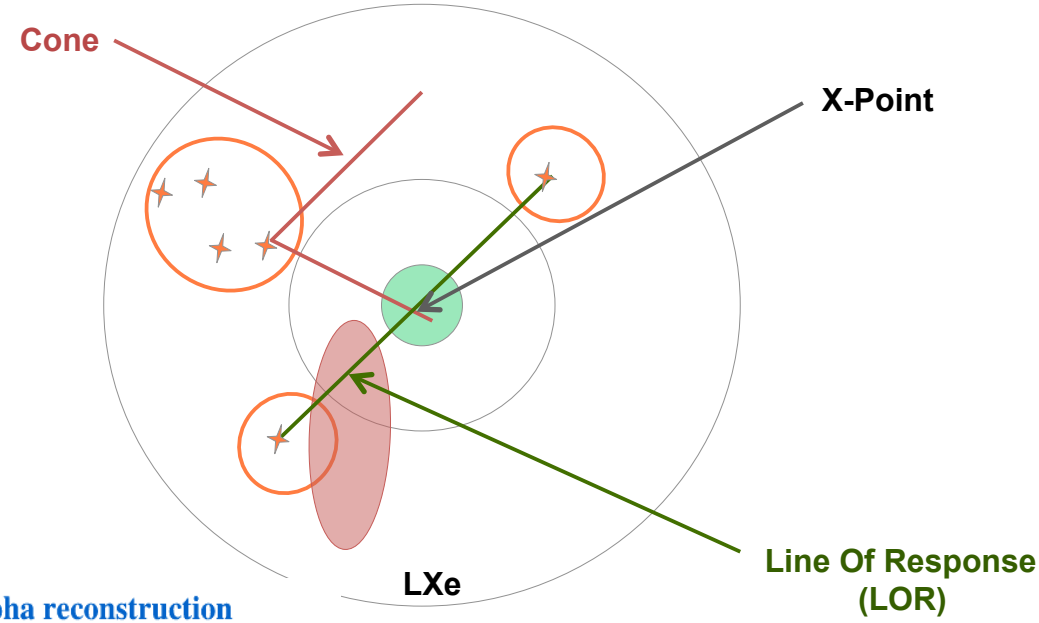
3 Reco Groups (c)

↓

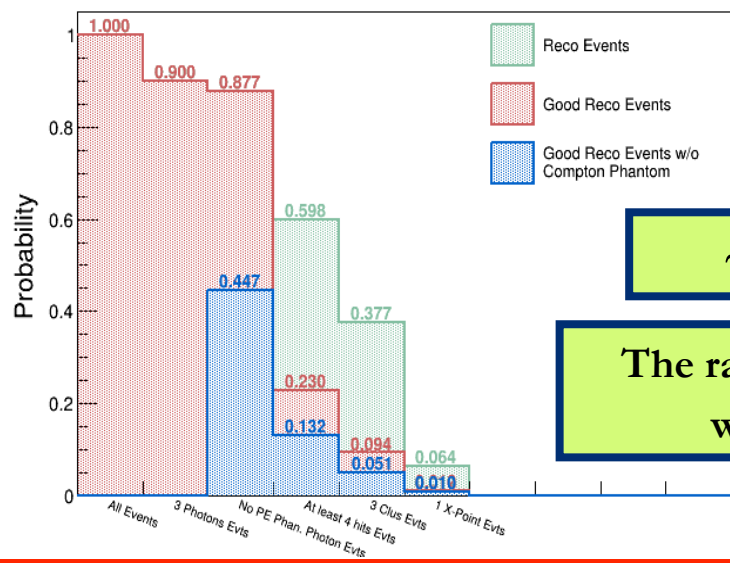
1 Flag (d)

↓

1 x-point (e)



Event evolution through Alpha reconstruction



~ 7,4 % at the end

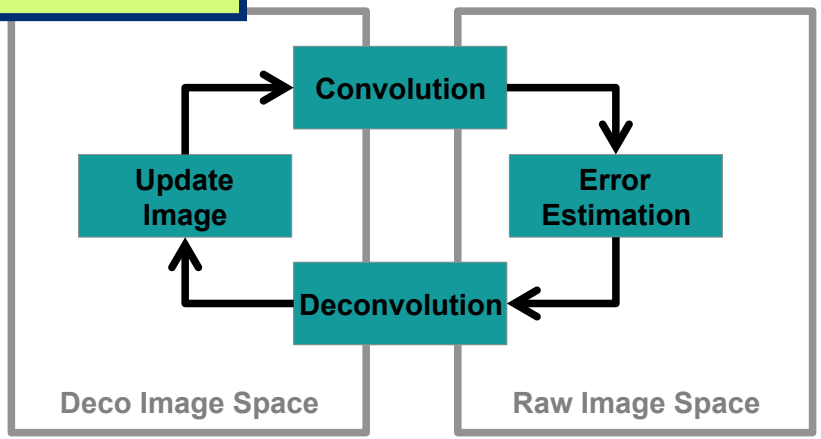
The raw image is obtained directly with the selected events

XEMIS2: deconvolution

From Direct Image to Deco Image

- **Idea :**
- **Inverse pb of convolution**
- **Points image to points image**

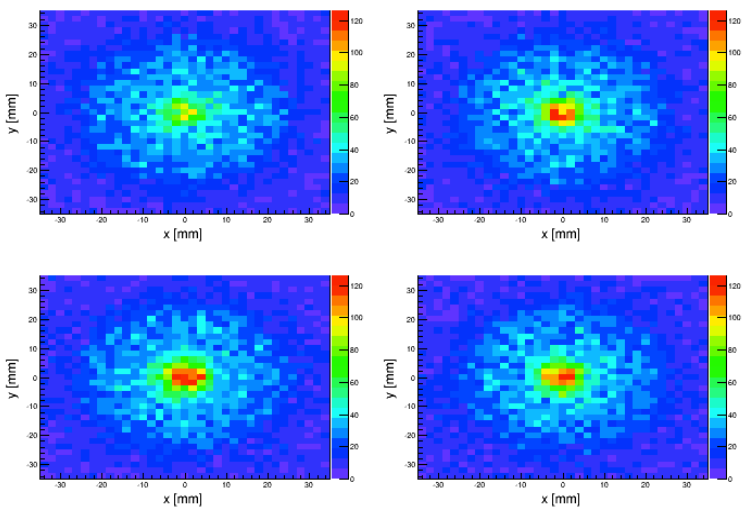
Asumption : PSF uniform in all the field of view



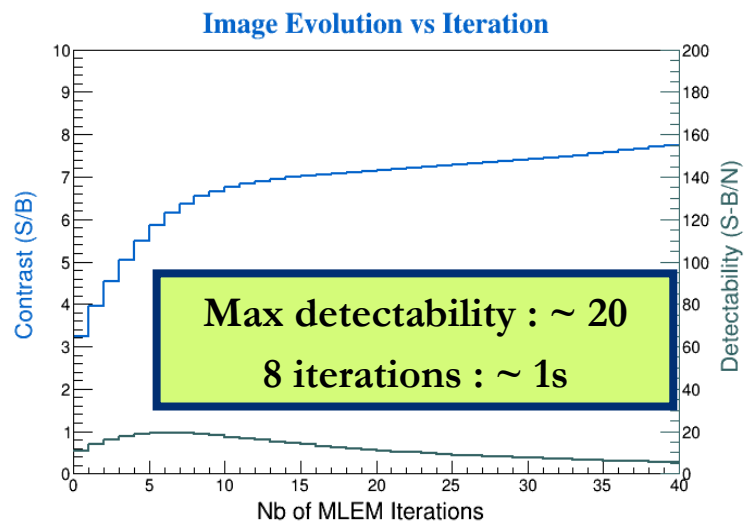
- **Algorithm :**
- **Iterative ML-EM based on Poisson Distribution**
- **Convolution in frequency domain**

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

Raw Image :

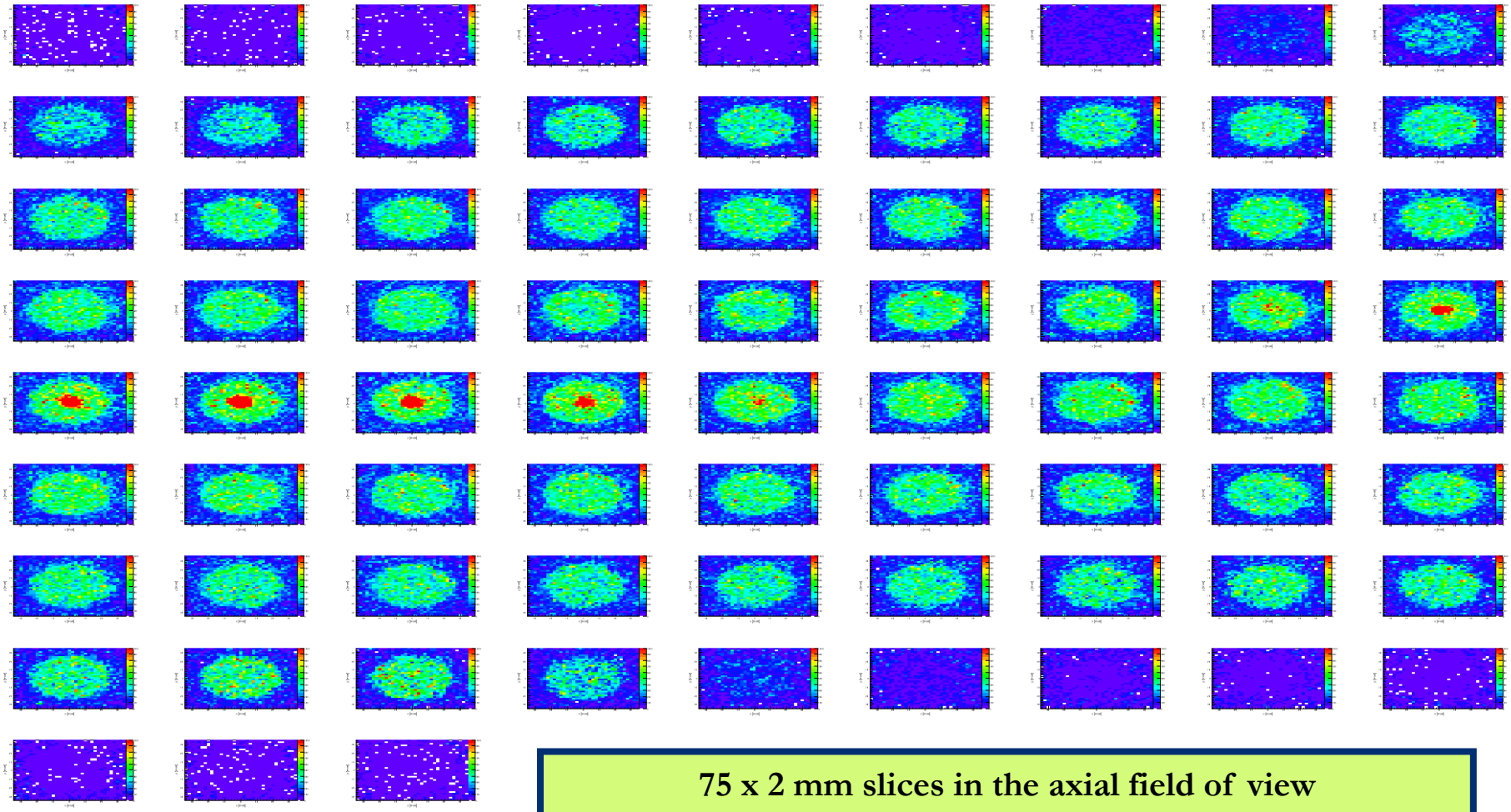


Deconvolution



XEMIS2 expected image 20 kBq, 20 mns

Raw Image

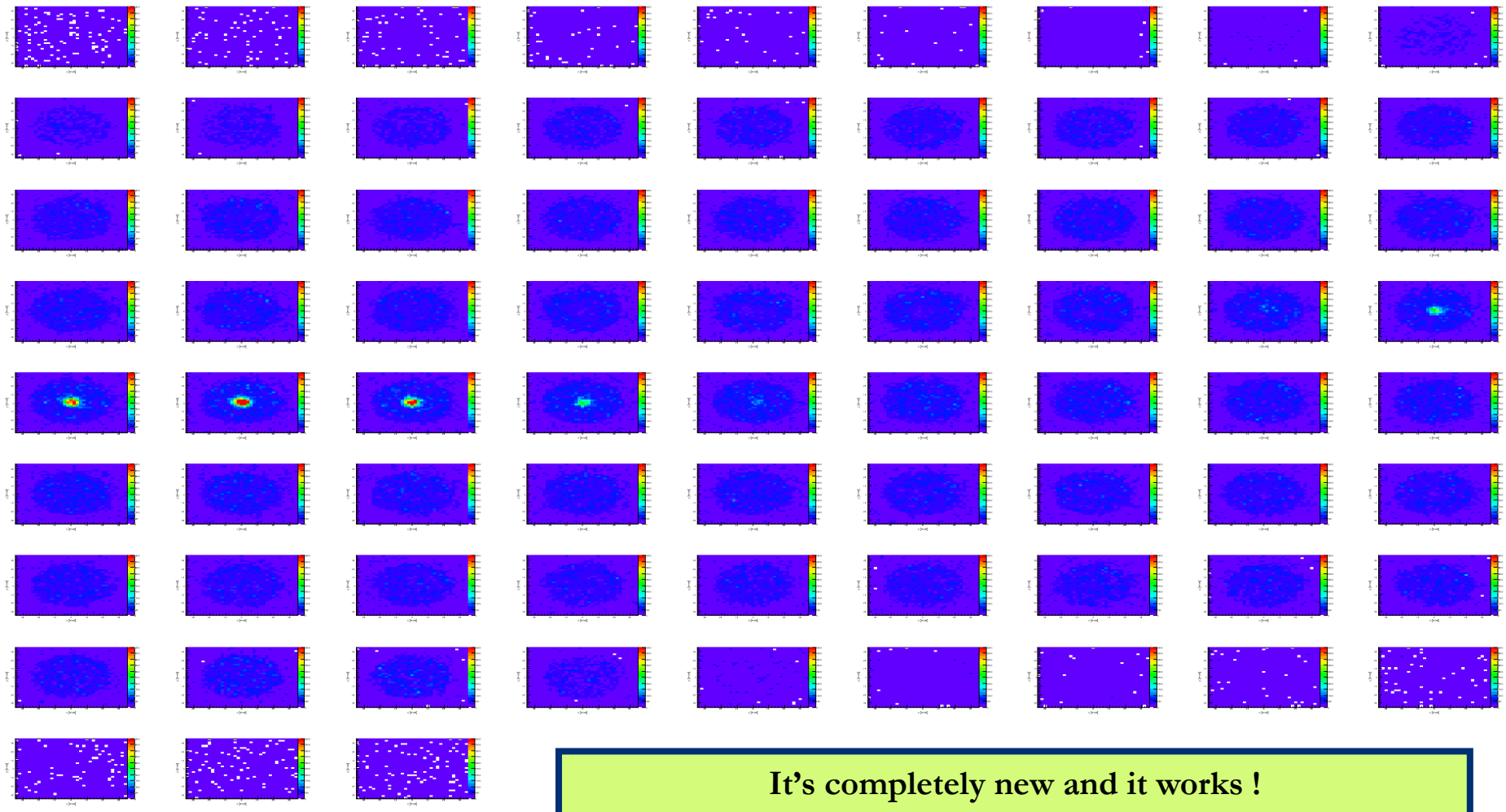


75 x 2 mm slices in the axial field of view

the contrast on the central sphere is clearly visible

XEMIS2 expected image 20 kBq, 20 mns

Deco Image



It's completely new and it works !

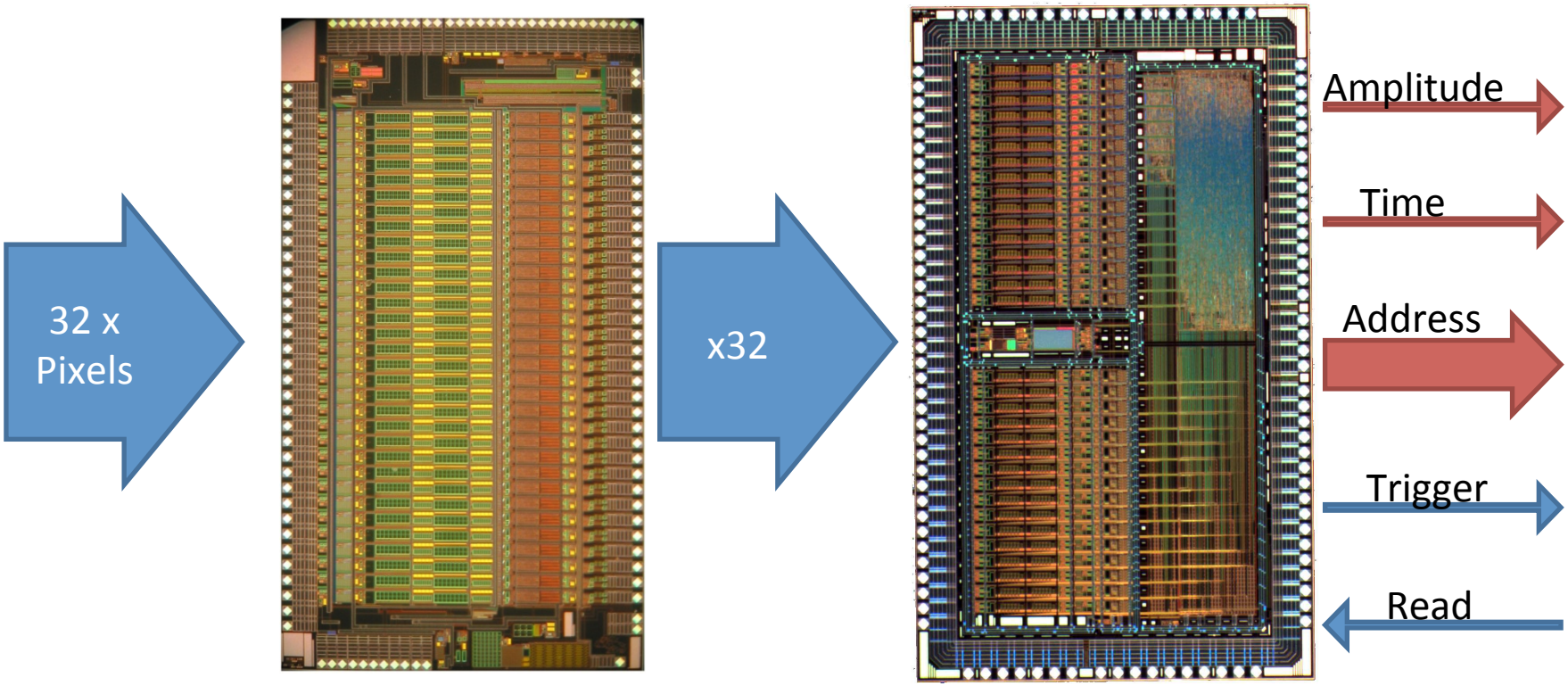
Expected resolution : [2-3 mm] on all the field of view

A lot of works for the future …

XEMIS2: DAQ for ionization

IDEF-XHD_LXe
Imaging **D**etector **F**ront-end

XTRACT
XEMIS **T**PC **R**eadout for **A**cquisition of **C**harge and **T**ime

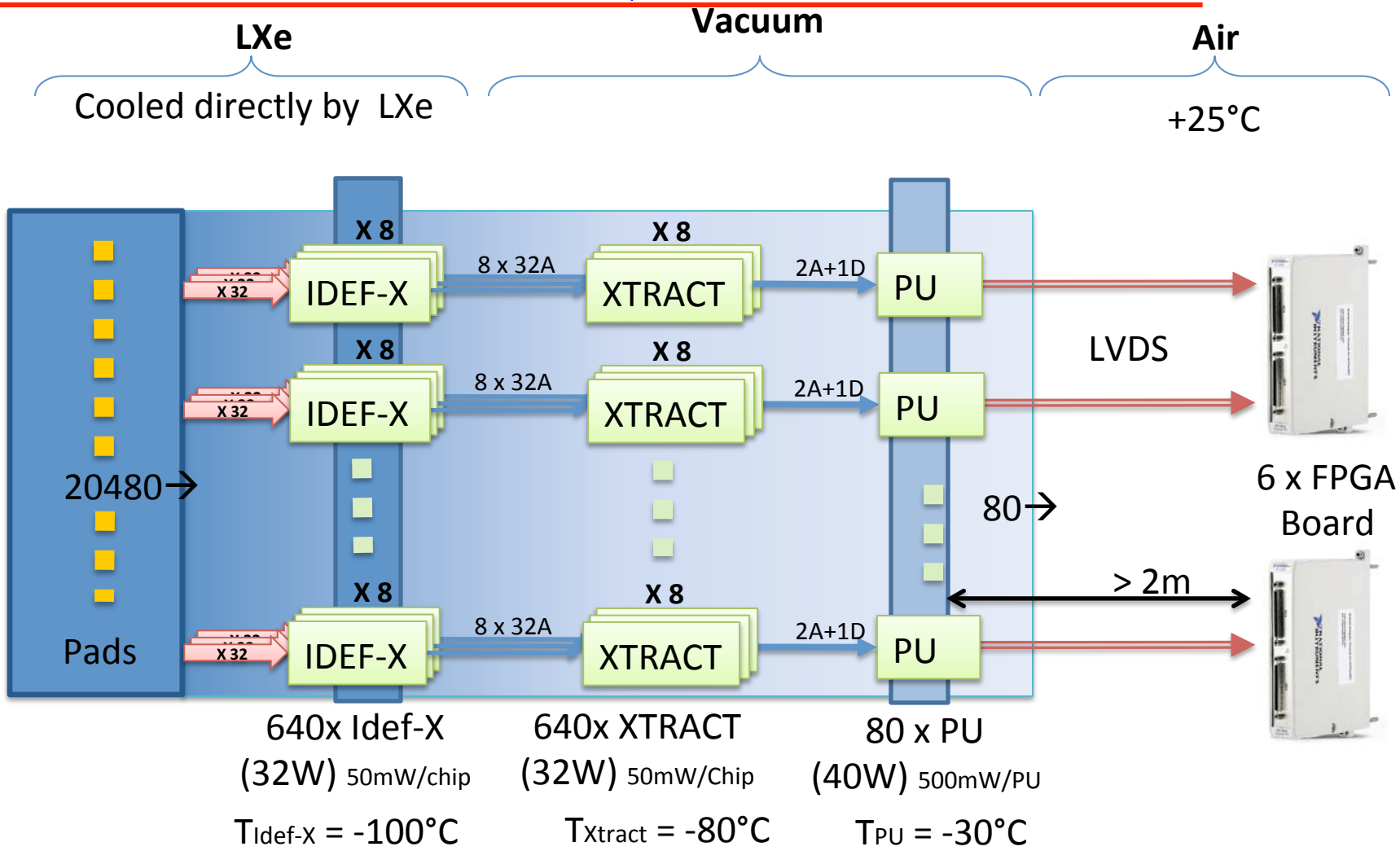


IRFU - SUBATECH

MICHRAU - SUBATECH

XTRACT v1 is on test, final version expected for 2017

XEMIS2: ionization DAQ Scheme



Challenge : Continuous read-out with negligeable dead-time

Goal : record on disc 10^4 charge and time signals/pixel/s