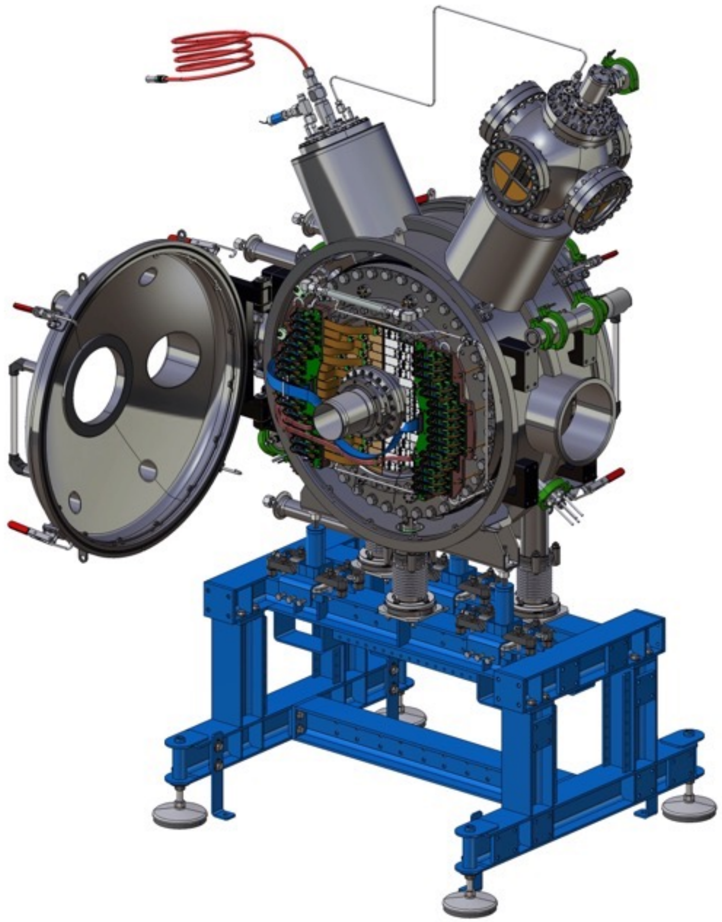


Xenon Medical Imaging System (XEMIS)

Dominique Thers (dominique.thers@subatech.in2p3.fr)
SUBATECH Laboratory

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

France-Australia Joint Program

XERD – DM – ν

XEnon Time Projection Chambers: **R&D** for Future Generation Experiments, searching for **D**ark **M**atter and investigating the nature of neutrinos (ν)

Monthly Oz-France meetings organized by Theresa Fruth (Sydney)

French PI
Sara Diglio
SUBATECH/CNRS

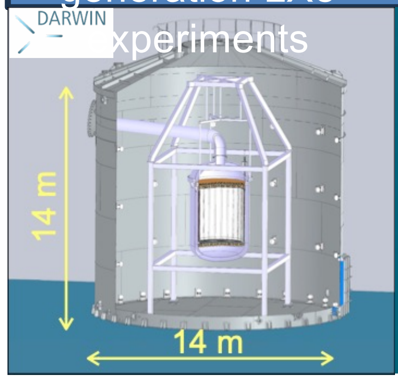
4 Joints PhDs SUBATECH – Melbourne
- Marina Bazyk (2021 – 2024)
- Owen Stanley (2022 – 2025)
- Lorenzo Principe (2022 – 2025)
- Ananthakrishnan Ravindran (2023 – 2026)

2 Postdocs strongly committed
- Yajing Xing (SUBATECH)
- Robert James (Melbourne)

Phill (Melb), Celine (Sydney), Dominique (SUBATECH), Ciaran (Sydney), Jayden (Melb), Luca (LPNHE), …

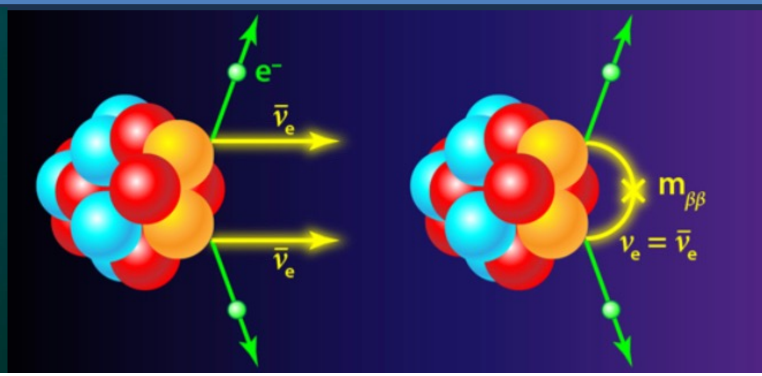
Australian PI
Elisabetta Barberio
Melbourne

Future generation LXe experiments

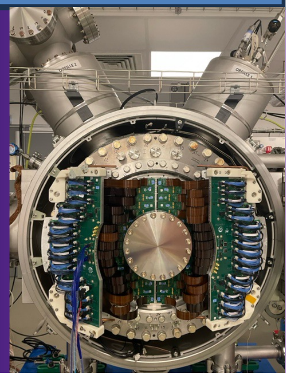


Dark Matter searches

Neutrinoless Double Beta Decay



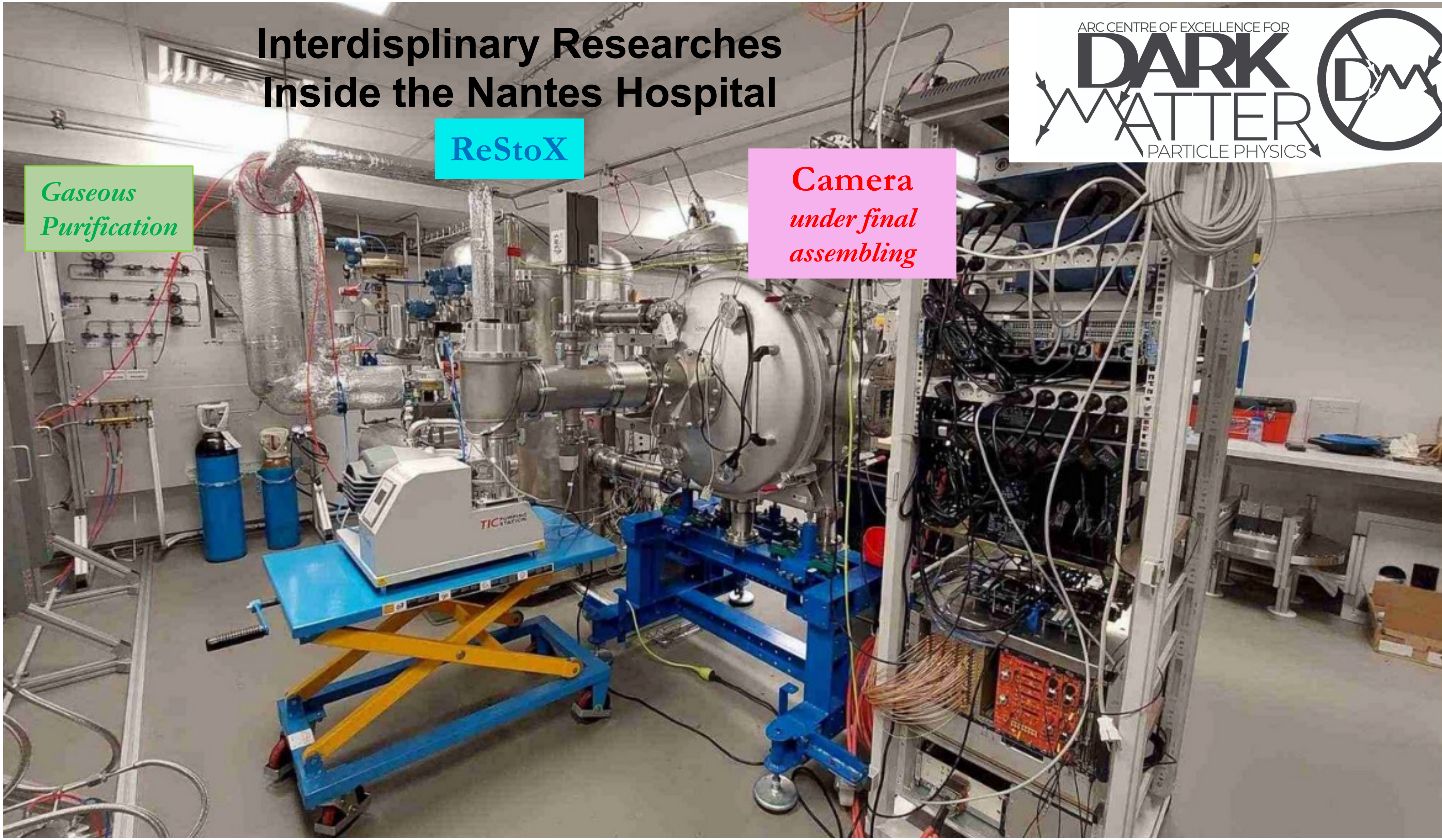
LXe technology



Nantes in France

ARC CENTRE OF EXCELLENCE FOR
DARK MATTER
PARTICLE PHYSICS

Interdisplinary Researches Inside the Nantes Hospital



PET world race for personalized medicine

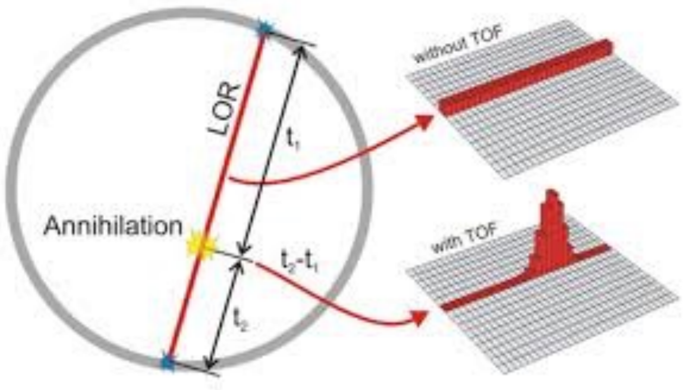
PET/Total body

- Increase FOV (Field Of View)
- Explorer: increase axial FOV of PET camera

2m axial FOV

PET/Time Of Flight

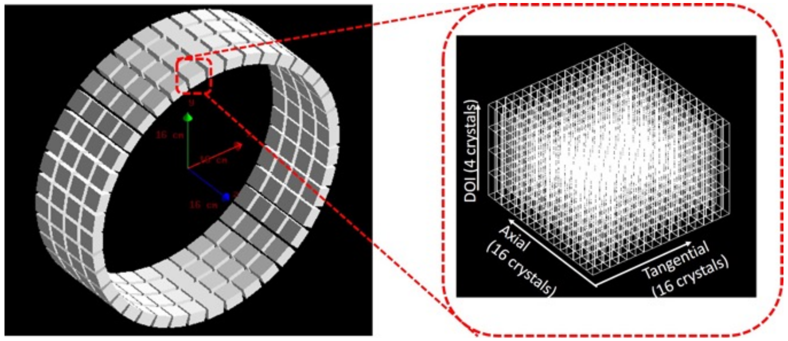
- Reduce Length of LOR (Line Of Response)
- Very good time resolution of detectors



10 ps challenge

PET/Depth Of Interaction

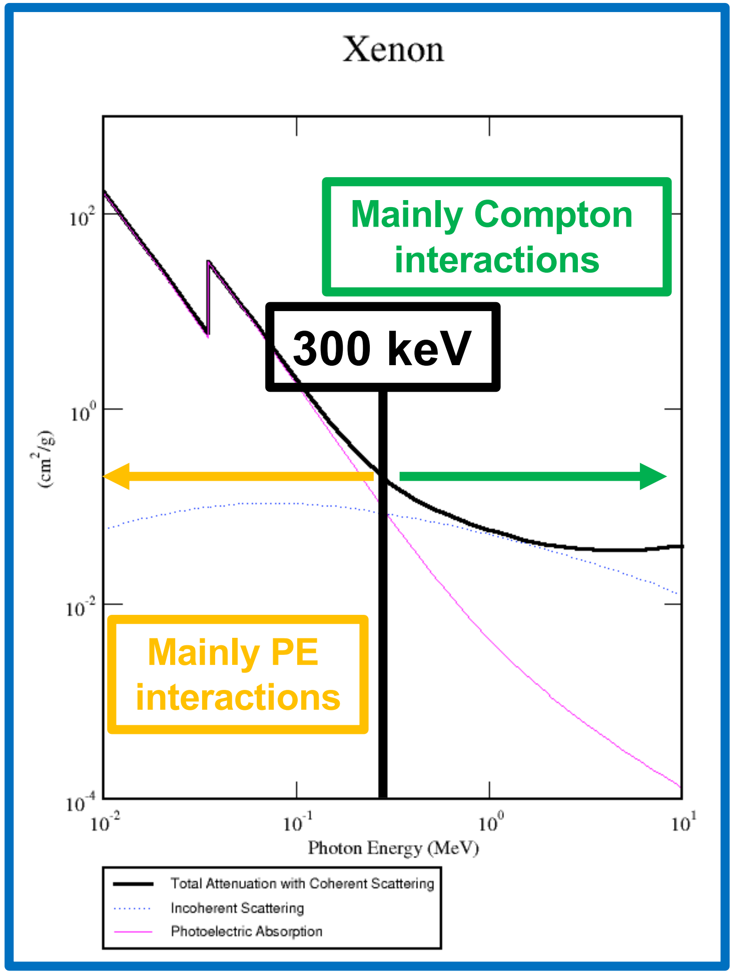
- Reduce Parallax effects on the whole FOV with precise DOI measurement
- Depth segmentation



DOI for parallaxe recovering

Smaller dose, faster exam, dynamical imaging
But only "photo-pic fraction" detection
Compton imaging is neglected

Compton interactions dominates HE γ-rays interaction



NIST:XCOM

Some basic considerations:

@ 511 keV: Compton/PE = 73/21
@ 1 MeV: Compton/PE = 90/8

γ-rays interaction length is also increasing more and more (max at 4 MeV thanks to pair production):

@ 511 keV: 3.4 cm
@ 1 MeV: 5.9 cm

Efficient Compton camera should be monolithic and large enough

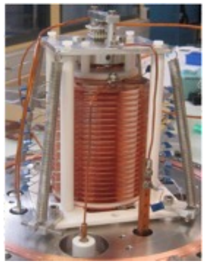
Stay actually the main driver for HE Compton Cameras and XEMIS future

XEMIS (XENON MEDICAL IMAGING SYSTEM)

- Total Body, TOF like, parallax free 3γ medical imaging technique
- High Rate Single Phase LXe Time Projection Chamber
- XEMIS2 first Compton telescope with LXe installed in Hospital

Done

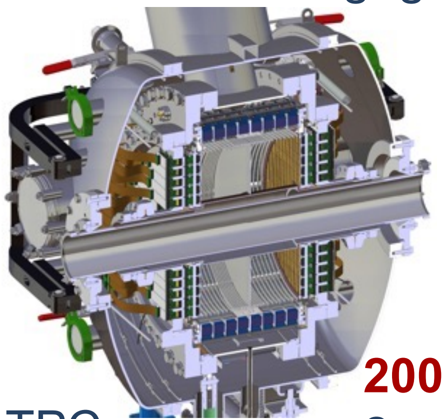
XEMIS1
R&D Prototype



30 kg
6 (12) cm drift TPC

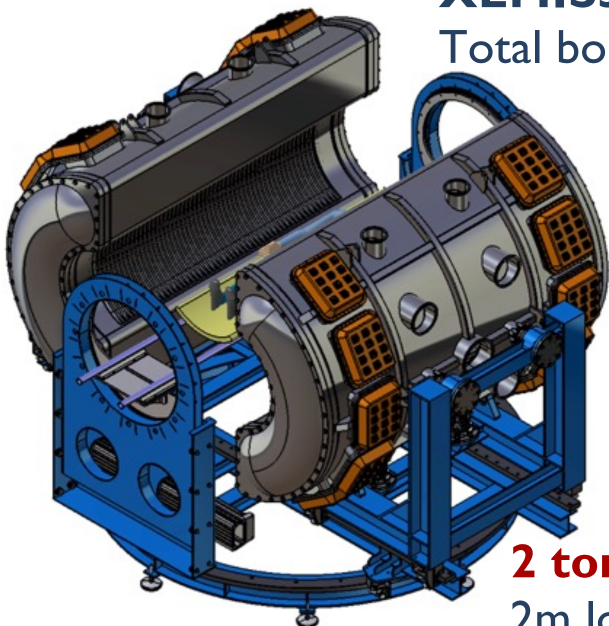
Under installation at Nantes CHU

XEMIS2
Small animal imaging



200 kg
2 × 12 cm drift TPC

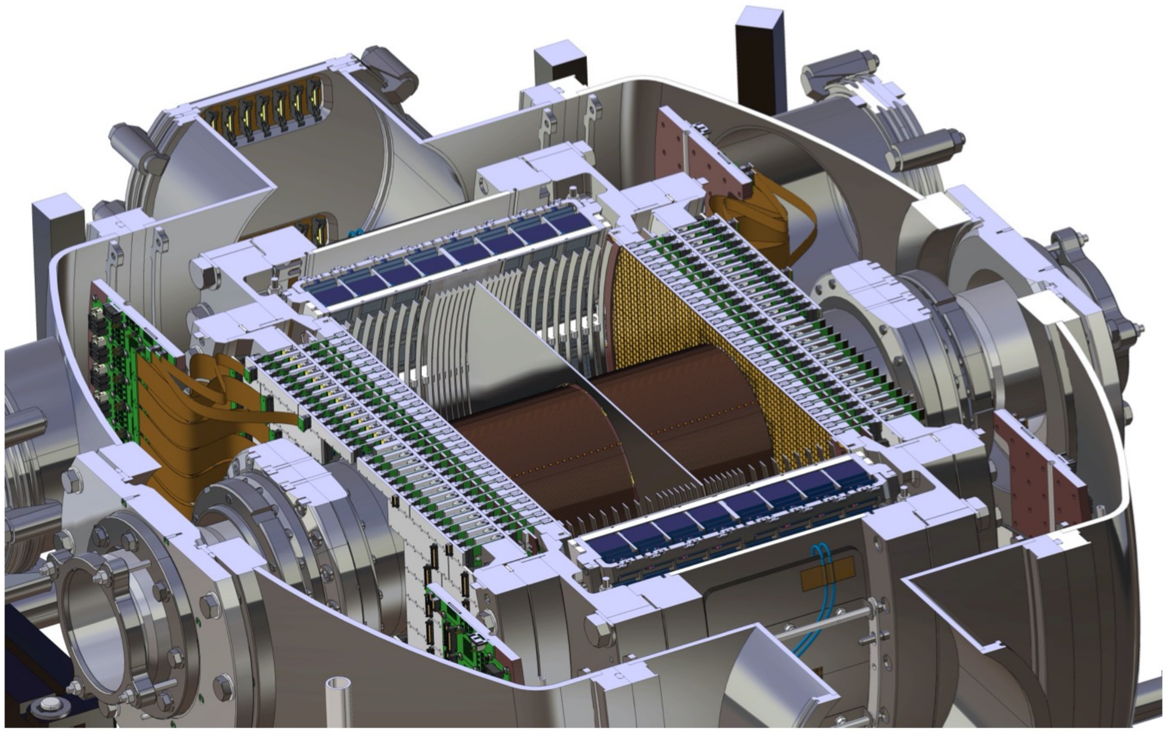
XEMIS3
Total body imaging

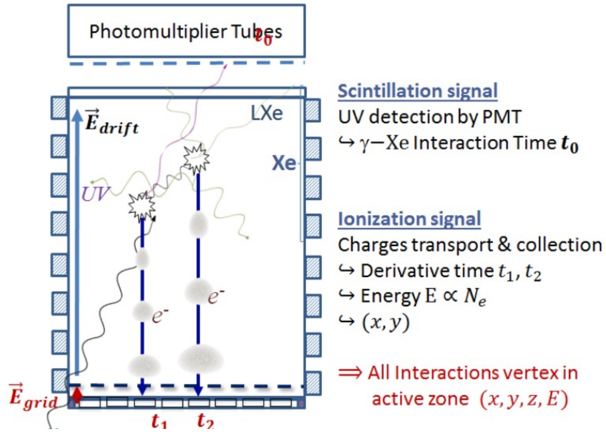


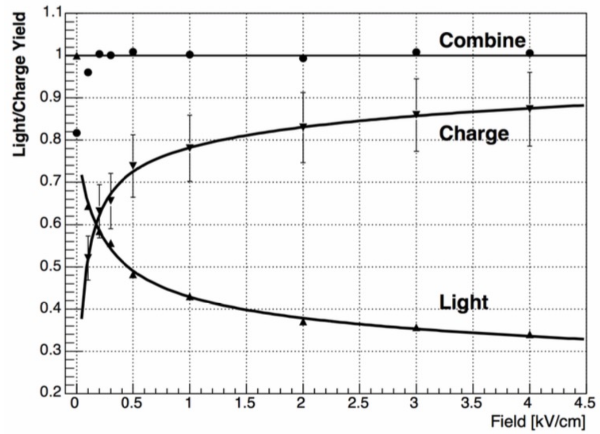
2 tons
2m long
12 cm drift TPC

2010 — **2023** — **Final goal**

Parallax free with LXe TPC used as ionization chamber for Compton imaging



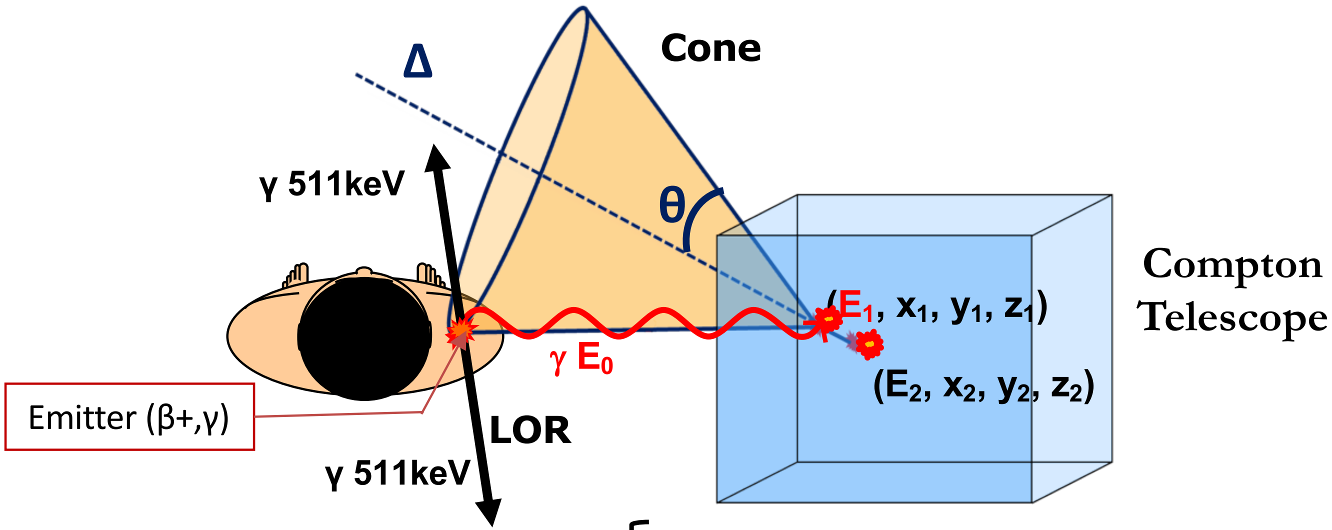




From E. Aprile et al., "Observation of Anti-correlation between Scintillation and Ionization for MeV Gamma-Rays in Liquid Xenon," Physical Review B, vol. 76, 2007.

No parallax effect with monolithic 70 kg active LXe TPC
Goal : 100 µm X,Y and Z spatial resolution on Compton/Photoelectric vertices position

3γ imaging : Monolithic Compton telescope and 3γ emitter for "TOF-TEP like"

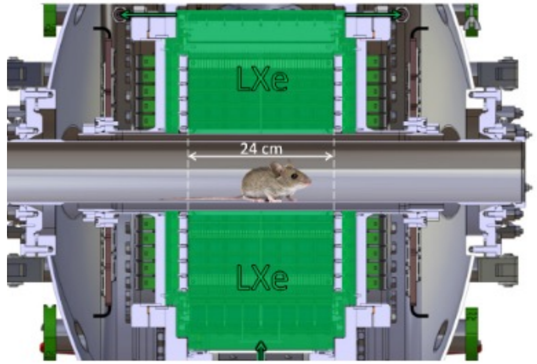


Reconstructed γ direction
- Spatial resolution ⇒ cone axis (Δ)
- Energy resolution ⇒ opening angle (θ)

Direct 3D location of the radioactive source: res. along LOR < 1 cm (FWHM) for small animal FOV

XEMIS2 goals:
50 ps "TOF like" with 5-10% global sensitivity
thanks to good spatial and energy resolution (only ns time resolution)

XEMIS2 LXe handling

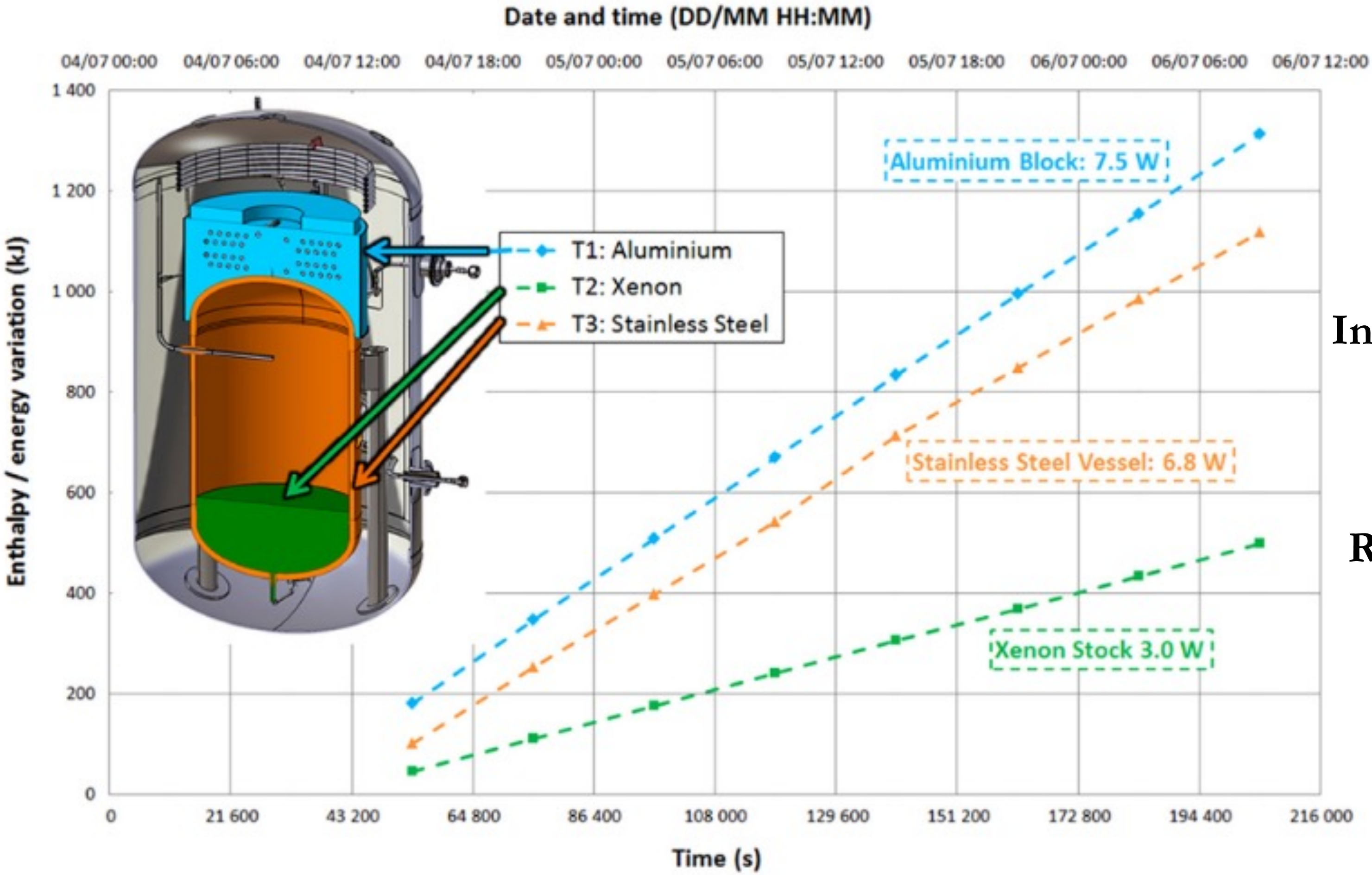


Max Xe flow: 30 nl/mn

Scientific Collaboration
Air Liquide
Cooling with LN_2
300 kg Aluminum Head
Internal Pressure 0-70 bars
200 kg Xe capacity

Low P vessel: 2 bars max
Xenon : 200 kg total
Active mass: 70 kg
Photodetectors
and FEE inside LXe

Warm up ReStoX test with LXe

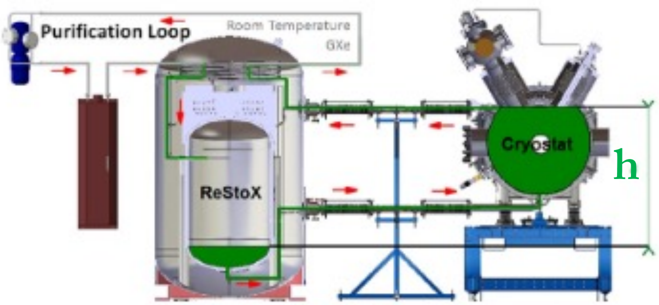


ReStoX

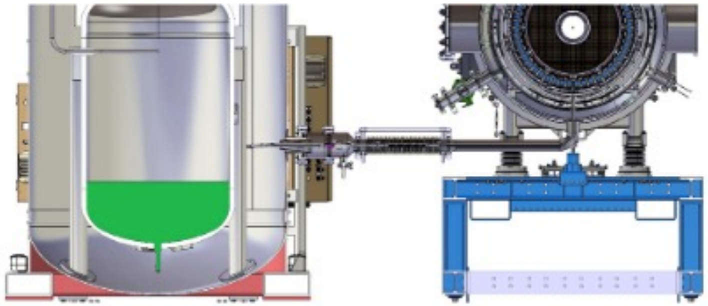
Insulation : vacuum and pearlite
Head load < 20 W with LXe
Cooling max: 5 kW

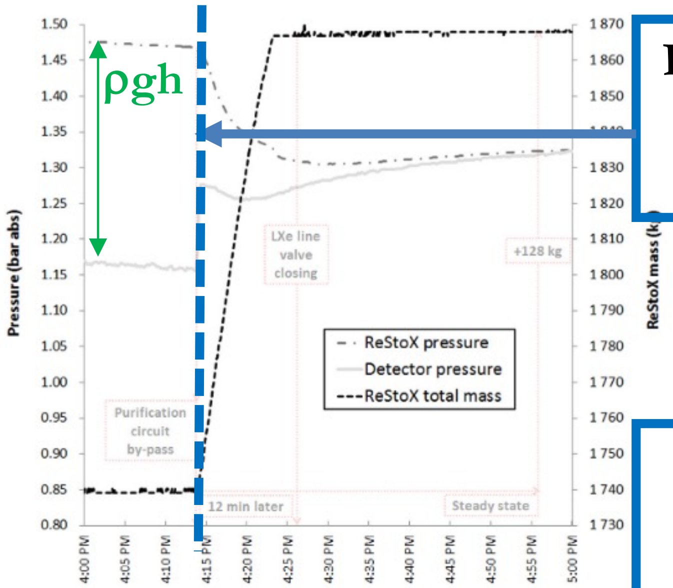
Regulation thanks to LN_2 flow
and internal pressure

XEMIS2 cryogenics commissioning



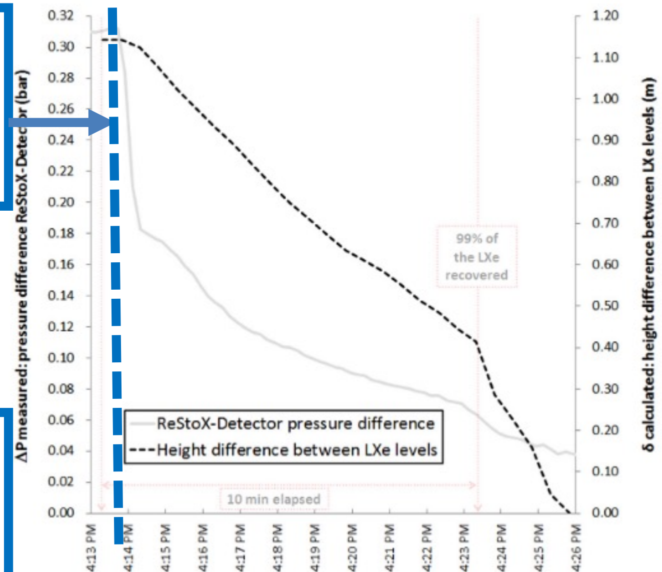
Gravity assisted recovery





Purification Circuit By-pass

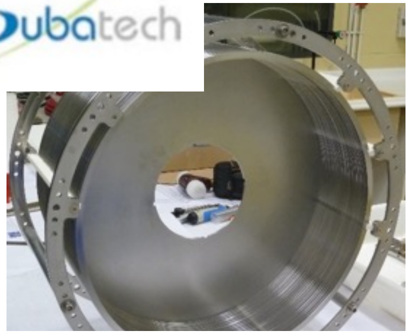
No more LXe in the camera 10 mn later



Very safe (subcooled LXe transfer) and Fast Xe mass flow rate: close to 1 ton·h−1 achieved in operation

Work automatically without human assistance

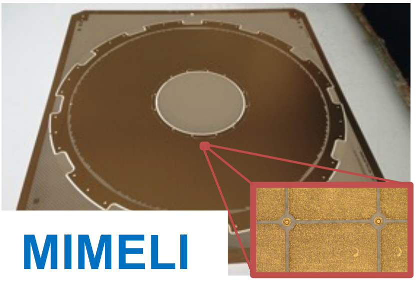
XEMIS2: High Purity LXe Compton Camera



LXe TPC

Active volume ~70 kg
- axial : 2 x 12 cm
- radius: 7 -> 19 cm

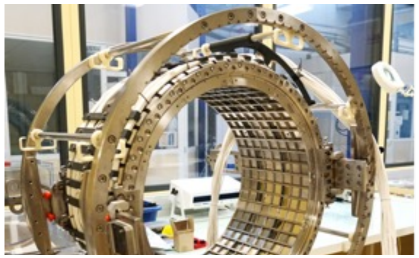
Central cathode



MIMELI

Charge readout

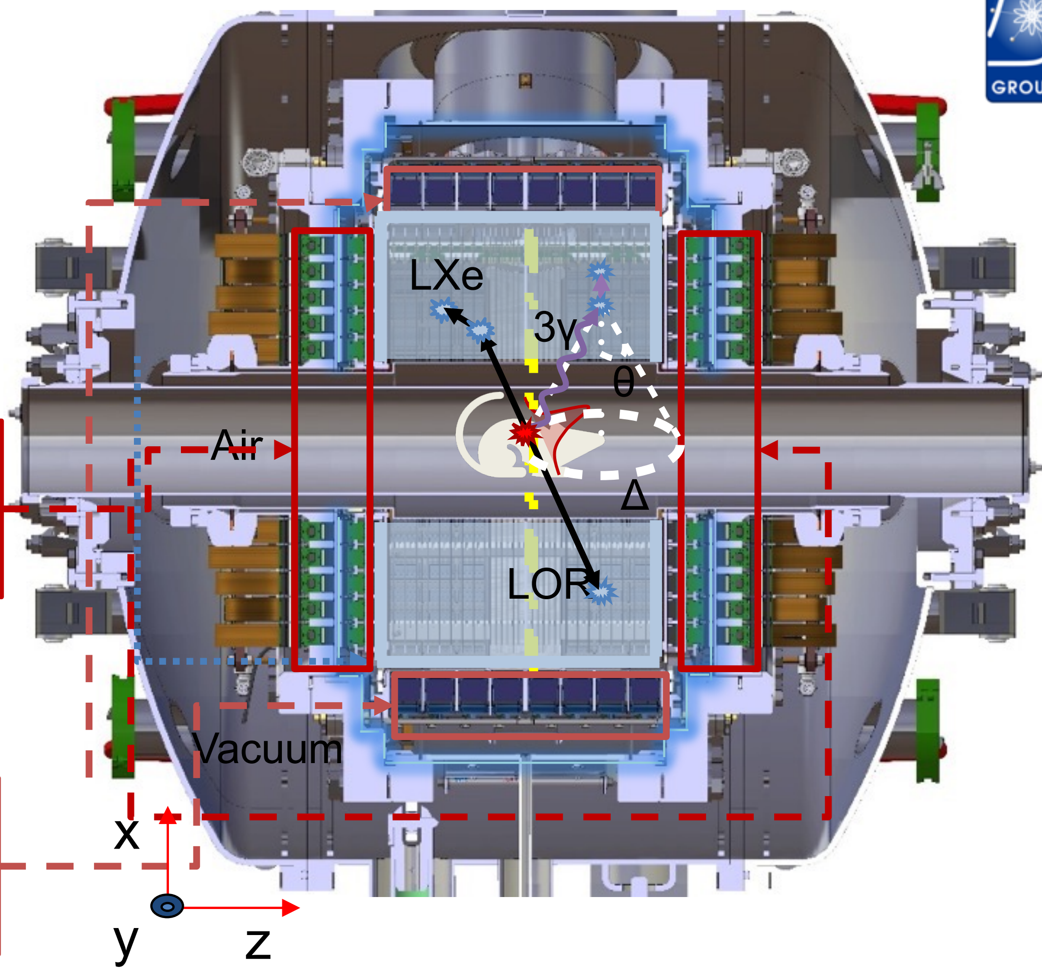
2×10^4 3.1×3.1 mm^2 pixels with ultra-low noise cold FEE



PMTs & Support

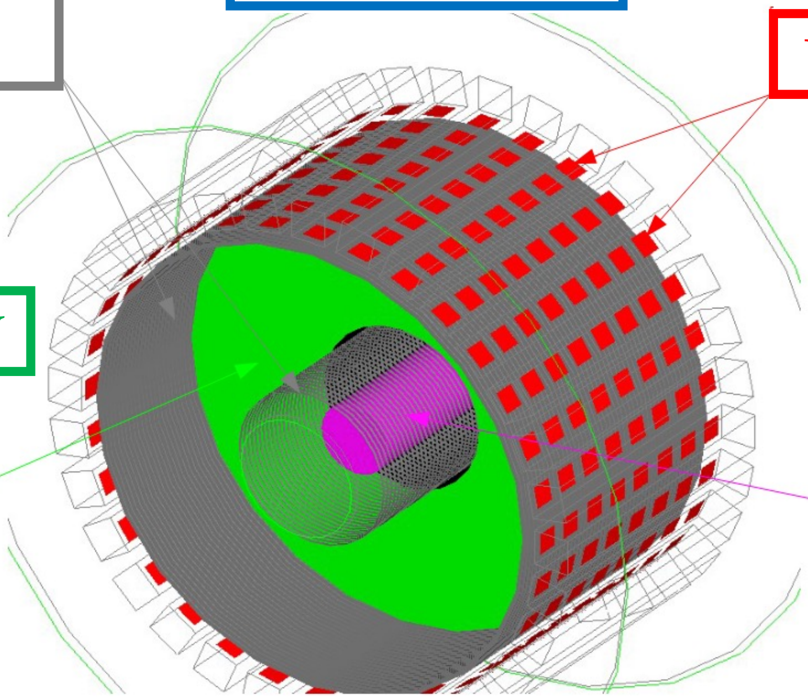
Light readout

64 x 1'' Hamamatsu PMTs in LXe
Cover 32 sectors in ϕ



Full Gate/GEANT4 simulation
High sensitivity 3γ > 7% along the FOV

G4 framework for XEMIS2 simulation and γ reconstruction



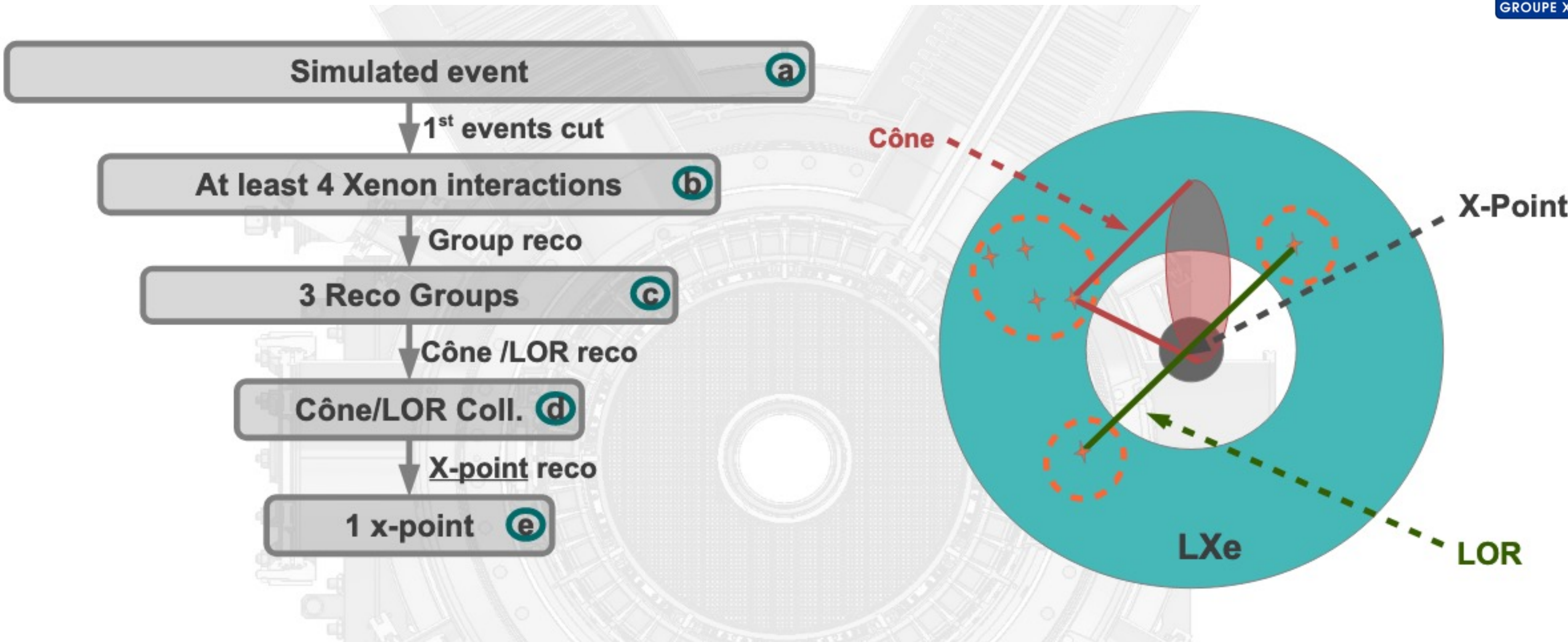
All processes for γ-rays activated but

No tracking for electron recoils
No X-rays, no Auger electrons

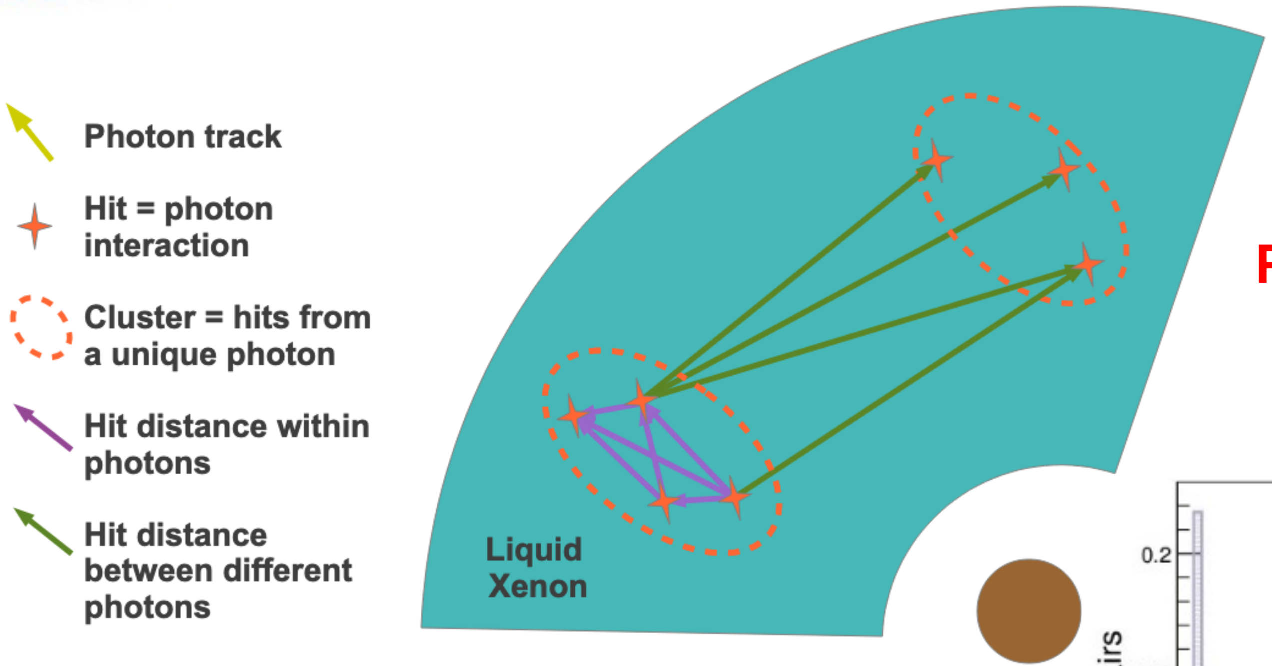
Event by event simulation with parametrization of light and charge yields

Used to test reconstruction and deconvolution algorithms for 3γ imaging

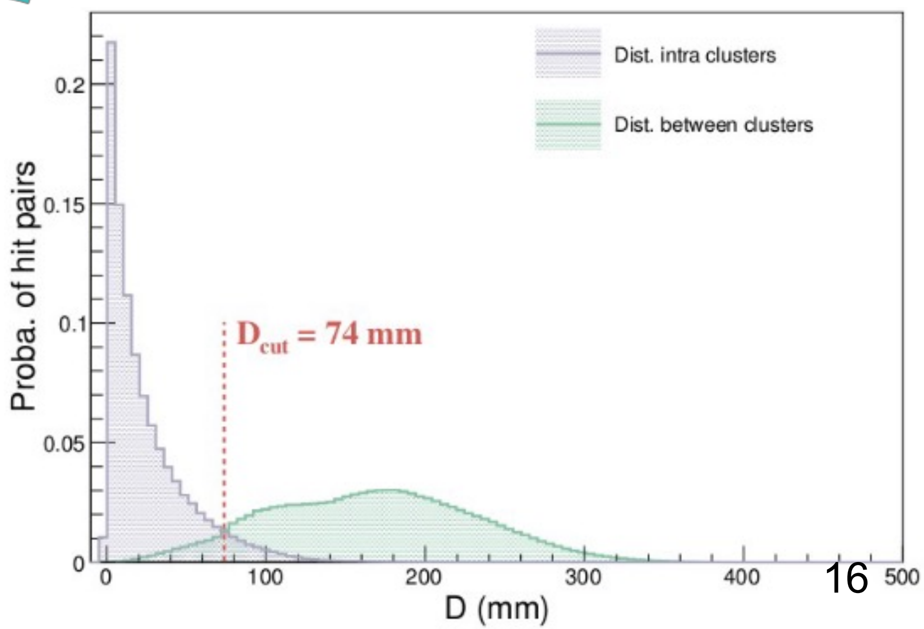
Main steps for the 3γ events selection



Electronics recoils clustering for γ matching



Preliminary studies done for ^{44}Sc emitter and Rat Phantom

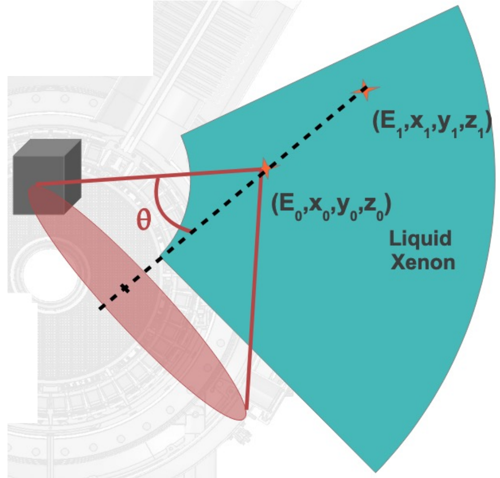


Naïve γ clustering based on Distance between hits
One reco group for each cluster

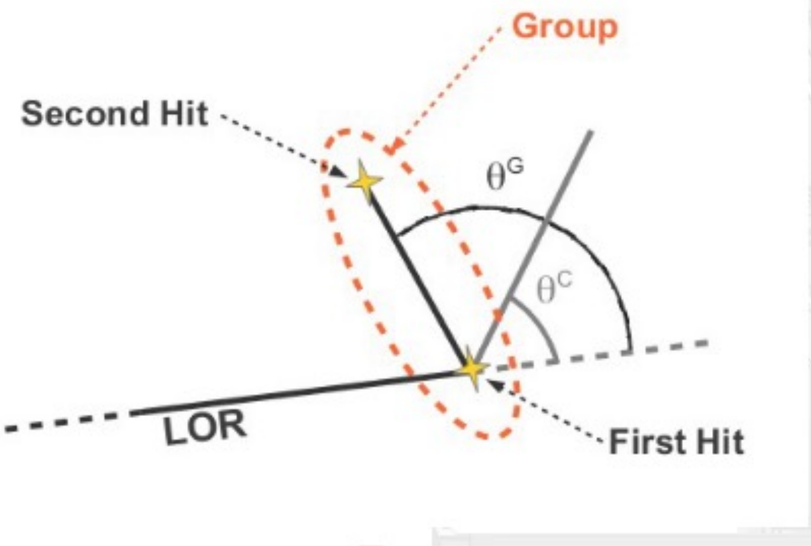
3rd γ Cone and LOR reconstruction

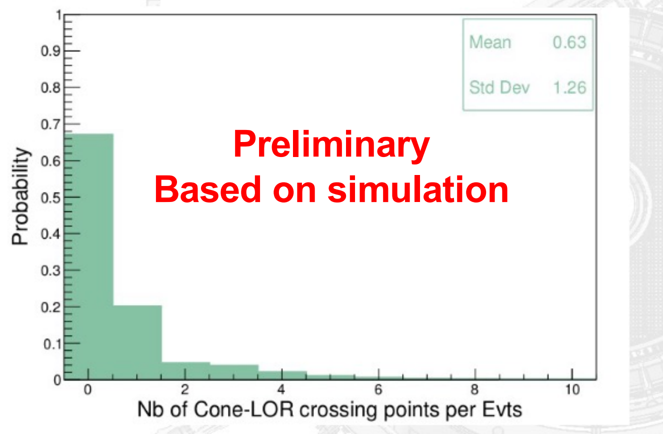
Based on topological considerations:

Compton Edge Threshold
γ range in LXe
Geometrical vs Compton angles comparison
Cone-LOR xPoint inside the XEMIS2 FOV



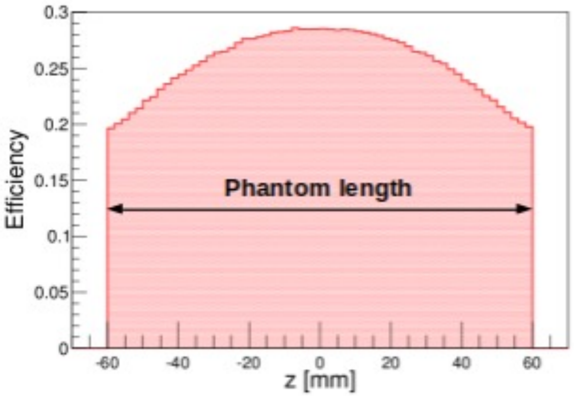
$$\theta^C = \arccos\left[1 - m_e c^2\left(\frac{E_{dep}}{E_i(E_i - E_{dep})}\right)\right]$$

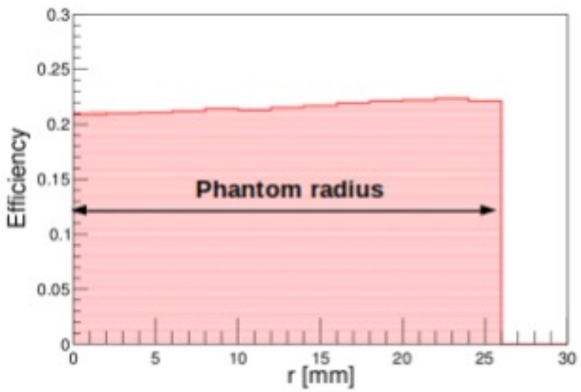




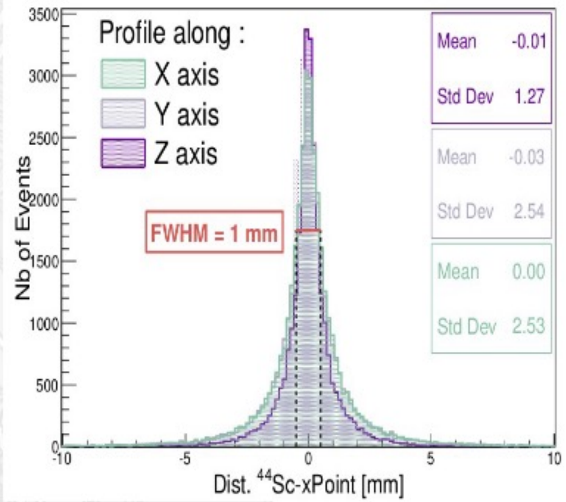
3γ sensibility variation and resolution

Preliminary
Based on simulation

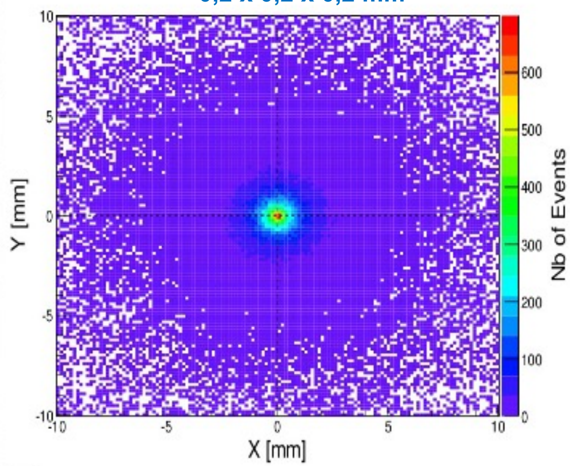




Preliminary
Based on simulation



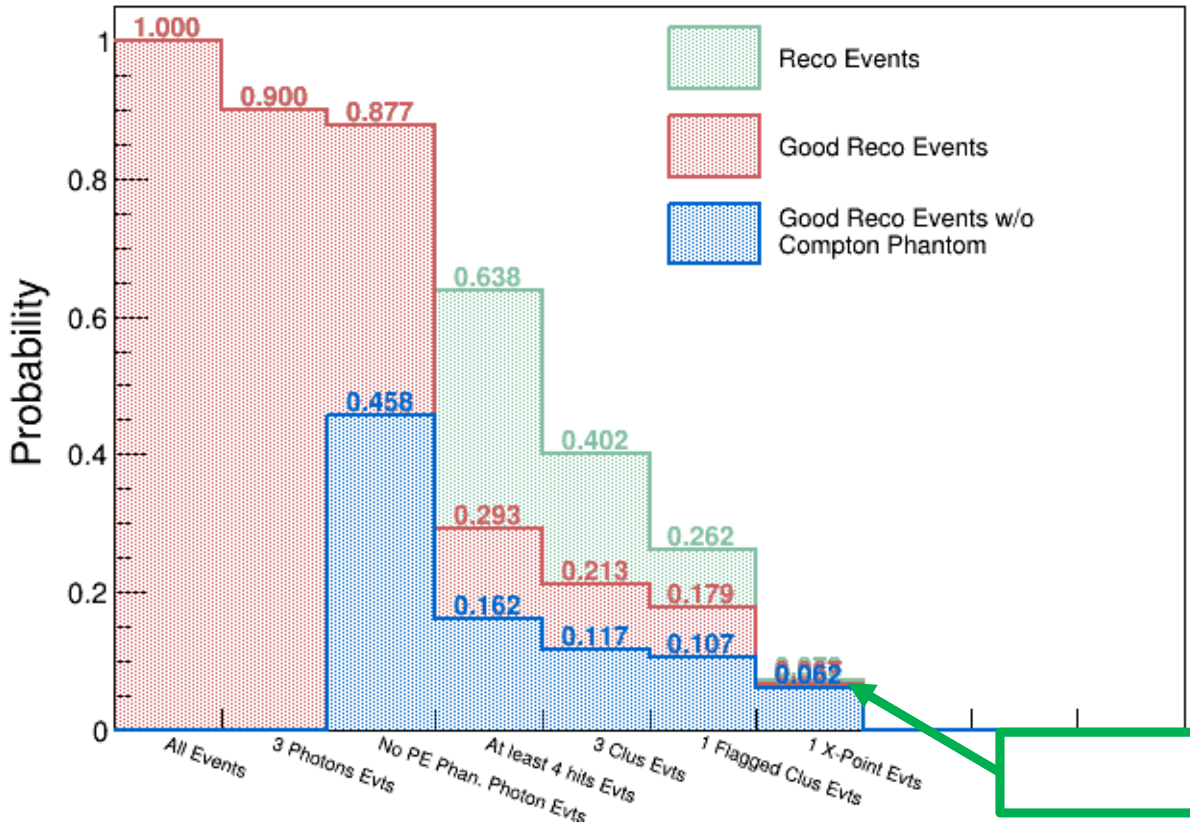
Ideal voxels for infinite statistics
0,2 x 0,2 x 0,2 mm^3



Good uniformity for Resolution and Sensibility in the whole FOV of XEMIS2

3γ sensibility variation and resolution

Event evolution through reconstruction



Preliminary
Based on 12cm long 5cm diameter Rat Phantom simulation with ^{44}Sc labeling

Promising total sensibility after reconstruction with quite small scatter fraction

72 kcps/MBq expected

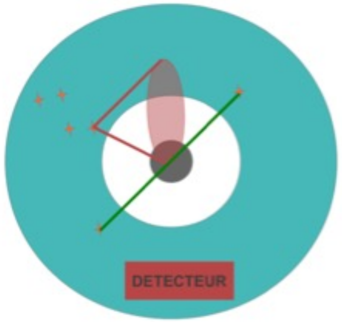
Much still to be optimized for the future, place for research and progress in the 3γ reconstruction

3γ Expected image with

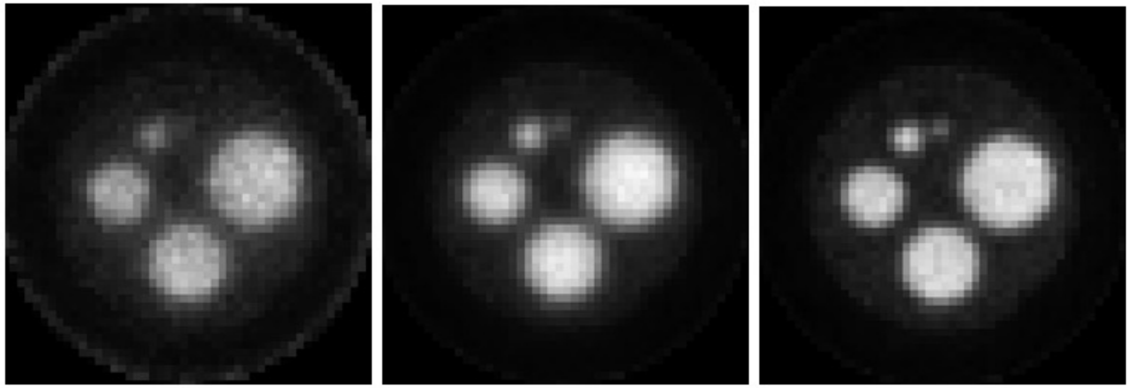
TOF-PET ML-EM reconstruction algorithms

Based on simulated datas

Cylindrical rat phantom (diameter 7 cm, length 12 cm)
2, 4, 8, 10, 12 mm radius hot sphere (^{44}Sc contrast 15)
Activity limited to 20 kBq, 20 mns exposure



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



XEMIS2 PET | XEMIS2 3γ "TOF = 100 ps" | XEMIS2 3γ "TOF = 50 ps"

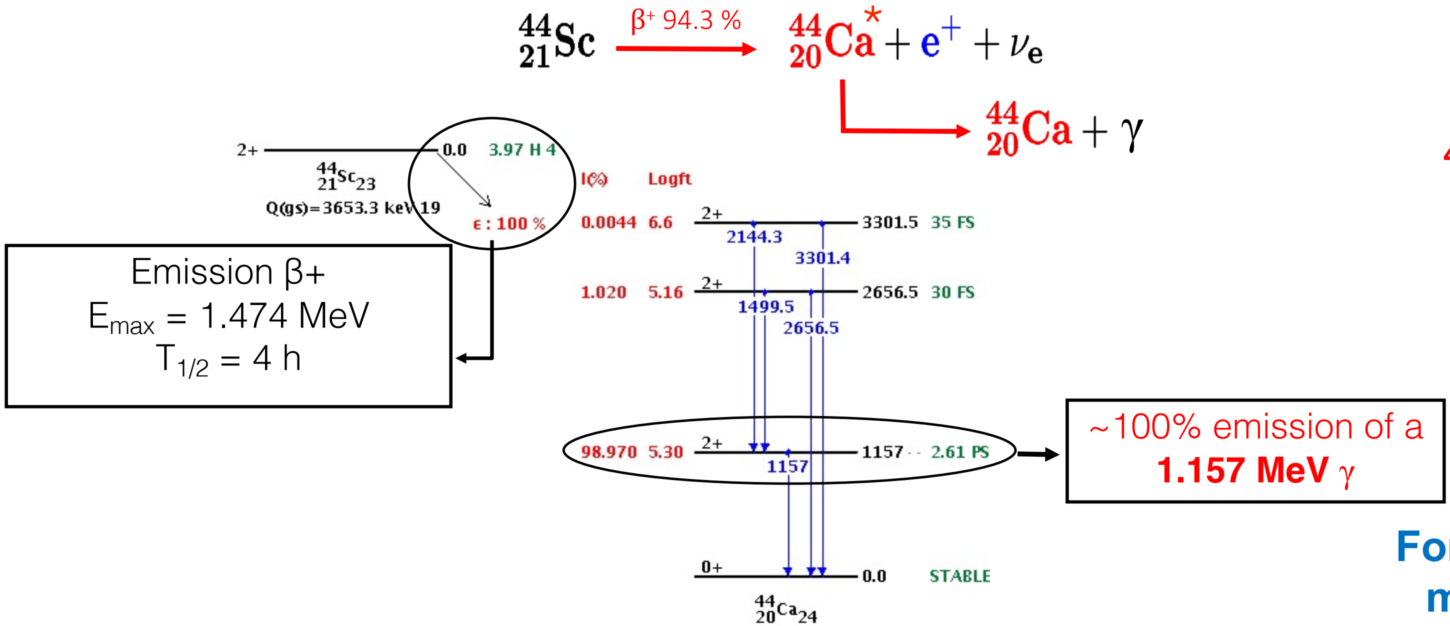
Promising results for all modalities
Reconstruction with CASToR open source
Reconstruction software available

Also, very similar images obtained with 3γ PSF and matrix system based deconvolution algorithms (with CRCINA at Nantes)

XEMIS2, ^{44}Sc labeling

In collaboration with Nantes INSERM CRCINA and GIP ARRONAX

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



^{44}Sc can also be produced by ^{44}Ti generator

Operations at CIMA:

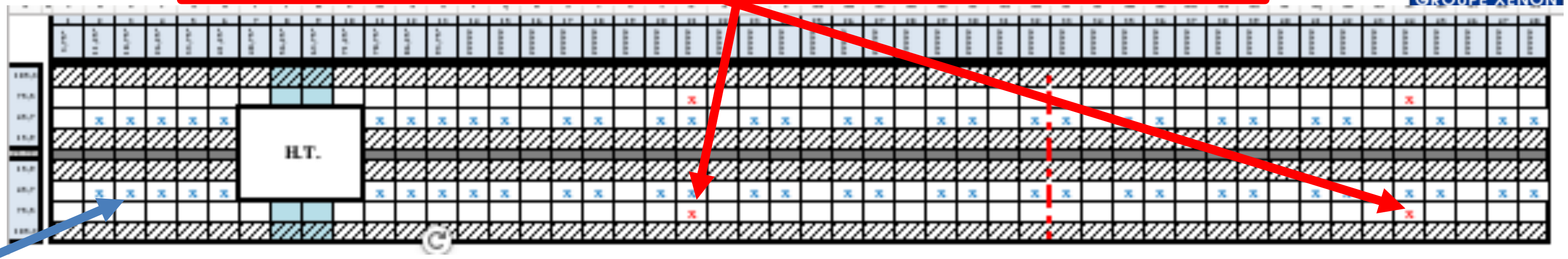
For ^{44}Sc labeling, generator will be mainly used (up to 20 MBq/day)

Images with ^{44m}Sc will be also proposed, production at ARRONAX with ^{44}Ca target.

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

S1 Prompts scintillation light detection with 1 inch PMTs

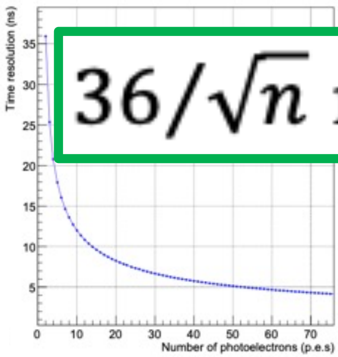
Gain calibration with 4 photo diodes installed on the support



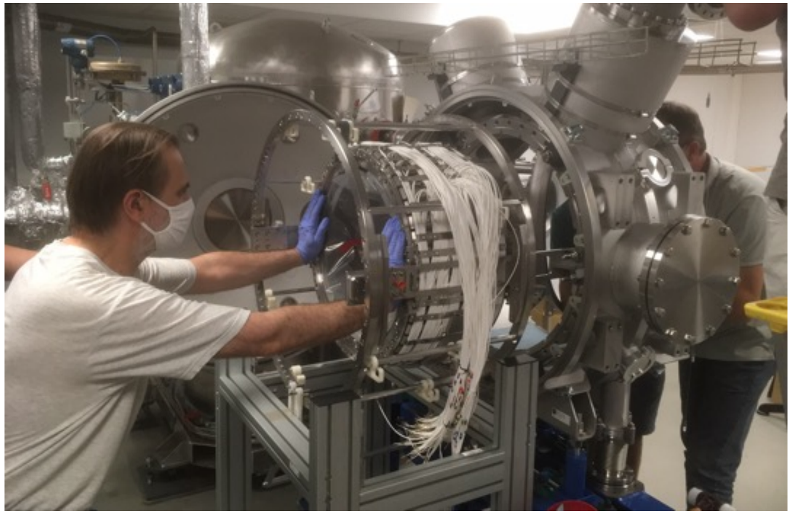
64 1" PMTs to cover ϕ acceptance
QE 32%

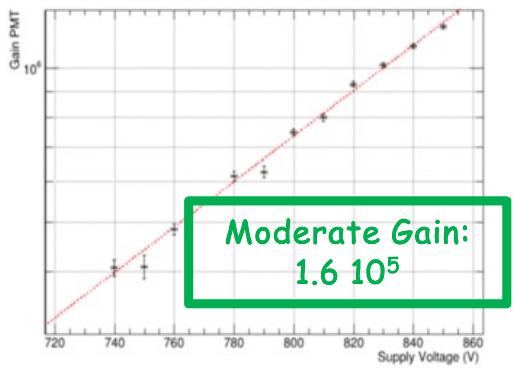
Incident particle	τ_s (ns)	τ_t (ns)	τ_r (ns)	I_s/I_t
Electrons	2.2 ± 0.3	27.0 ± 1.0	~ 45	0.05

Time resolution dominated by LXe in XEMIS2



$36/\sqrt{n}$ ns





Moderate Gain: 1.6 10^5

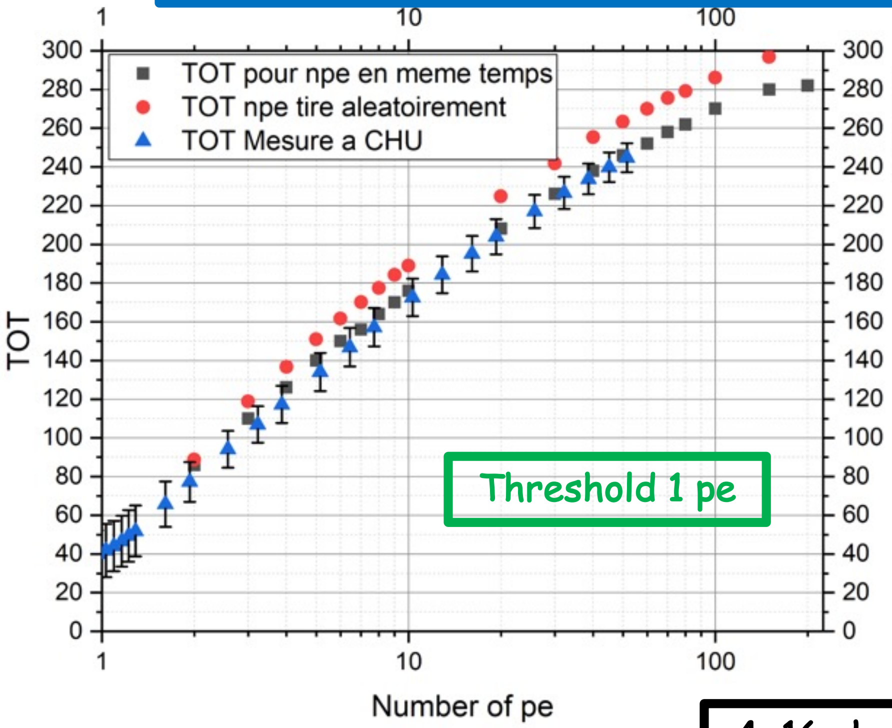
More than 15 fired PMTs with 3γ event
Mainly with a small number of photons
Between 1 and 10 pe/PMT expected
(reflection not considered)

Prompts scintillation XEMIS2 DAQ

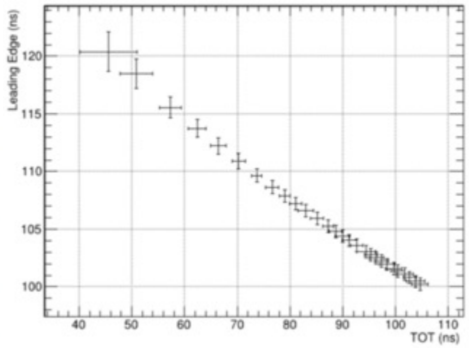
Each PMT is self-triggered, signal digitized with leading and trailing edge times measurement (200MHz)

Serial LVDS link up to SPARTAN FPGA, Continuous DAQ with max rate of 10^6 signals/s/PMTs

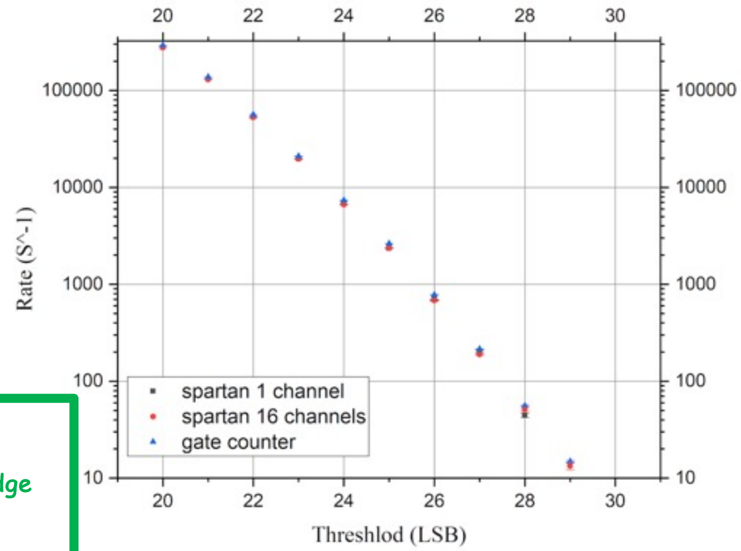
50 Go for 20 mns image at 20 kBq



Threshold 1 pe



σ_t: 2-3 ns from electronics/PMT with l_{edge} and TOT correction LXe contribution only



Up to 10^6 S1/s/PMT on disk

4x16 channels discrete cards "home made"

Light detection is "cheap" on XEMIS2: ns resolution/evt and 64 channels

Ionization measurement in XEMIS2

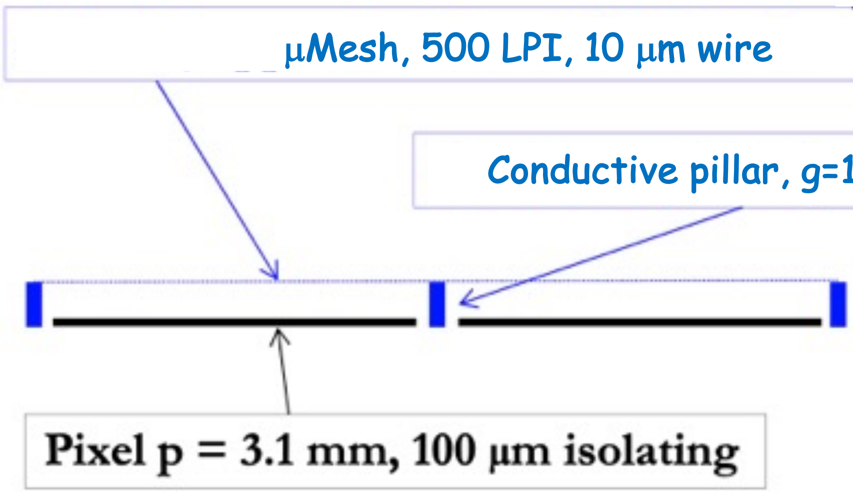
LXe ionization chamber properties very powerful (LXeGRIT, Exo, …) for 10 keV-MeV recoils electrons

Most of experiments use fast digitizers, not realistic for high rate and large number of pixels.

Technical option taken by XEMIS projects: just one sample for charge and one for time

Two main worries: Frish grid efficiency and induction on non-collecting electrodes

Development of new Micro-Pattern electrodes for electron collection



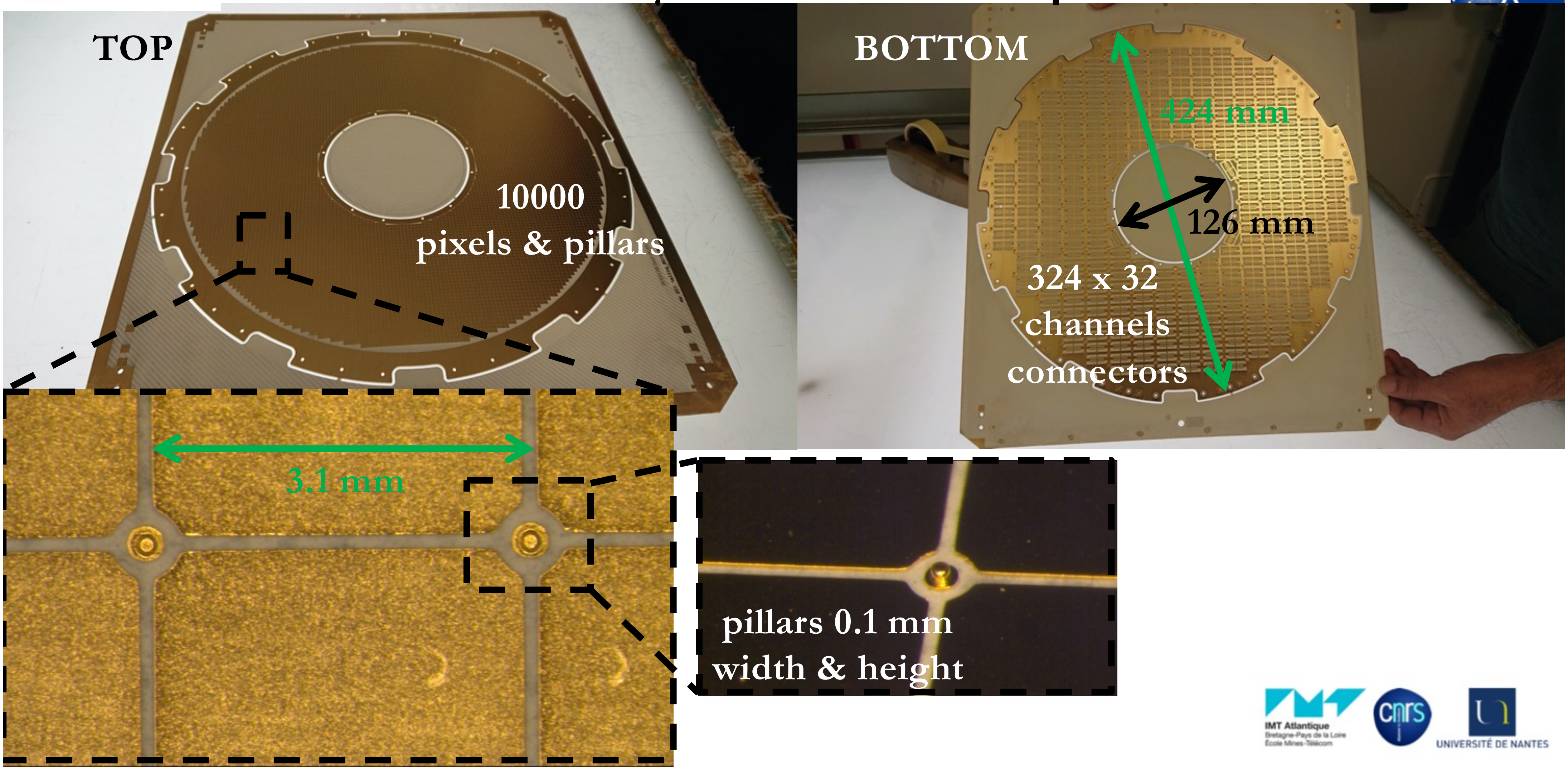
MIMELI

MIcro MEsh for Liquid Ionization chamber

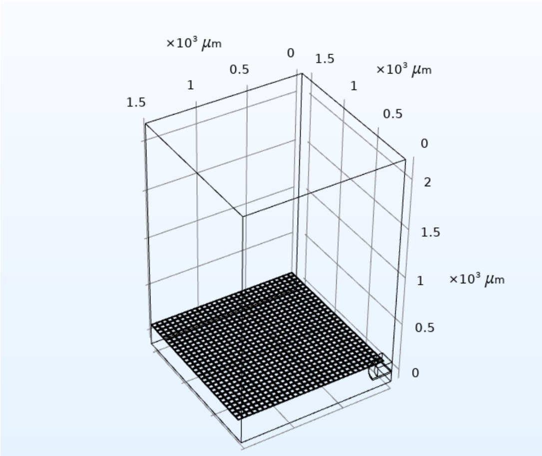
microstructure to stabilize induced current

Negligible induction on neighbors pixels ($g/p < 5\%$)
Excellent Frisch grid efficiency (500 LPI μMesh)
Stable on long term (more than 1 year accumulated test)
Scalable on large surface …

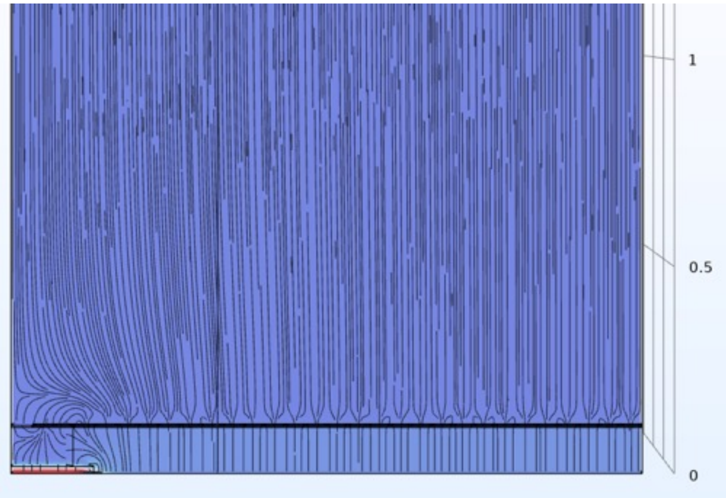
XEMIS2 MIMELI anodes fabricated by CERN
Gaseous μPattern detector dpt

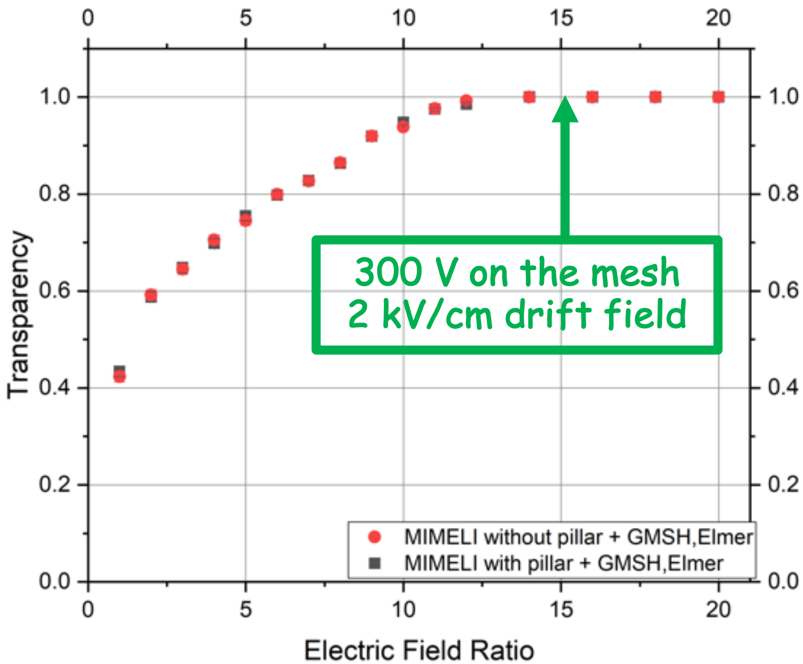


Ionization electrons collection with MIMELI



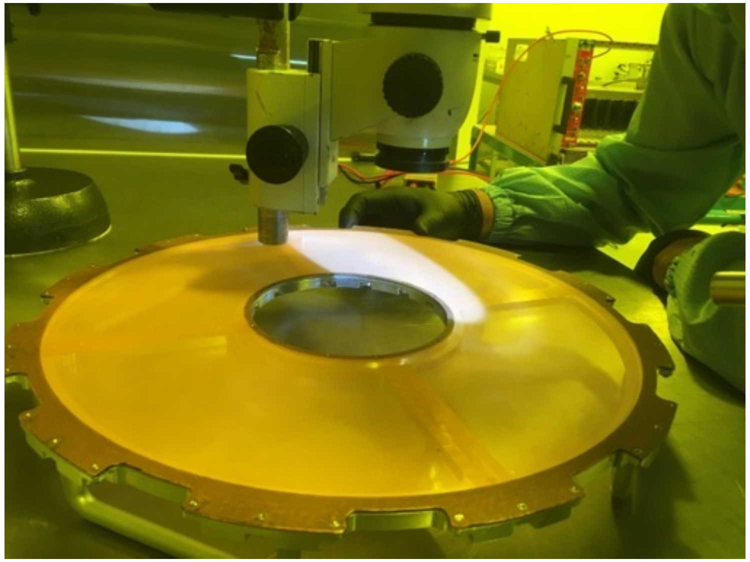
3D finite elements simulation with GMSH, Elmer and Garfield for the diffusion

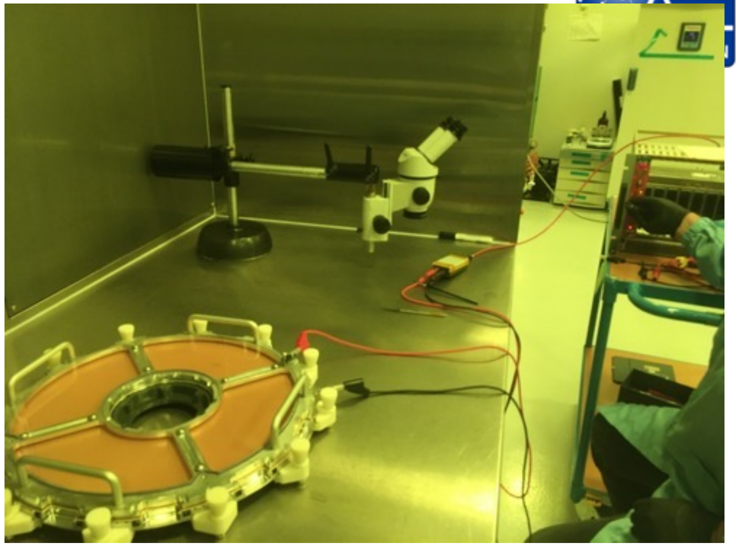




The conductive pillar is so small that it doesn't contribute to electron loss when field ratio is enough to focalize them in μMesh holes

MIMELI Micromesh assembling at CERN





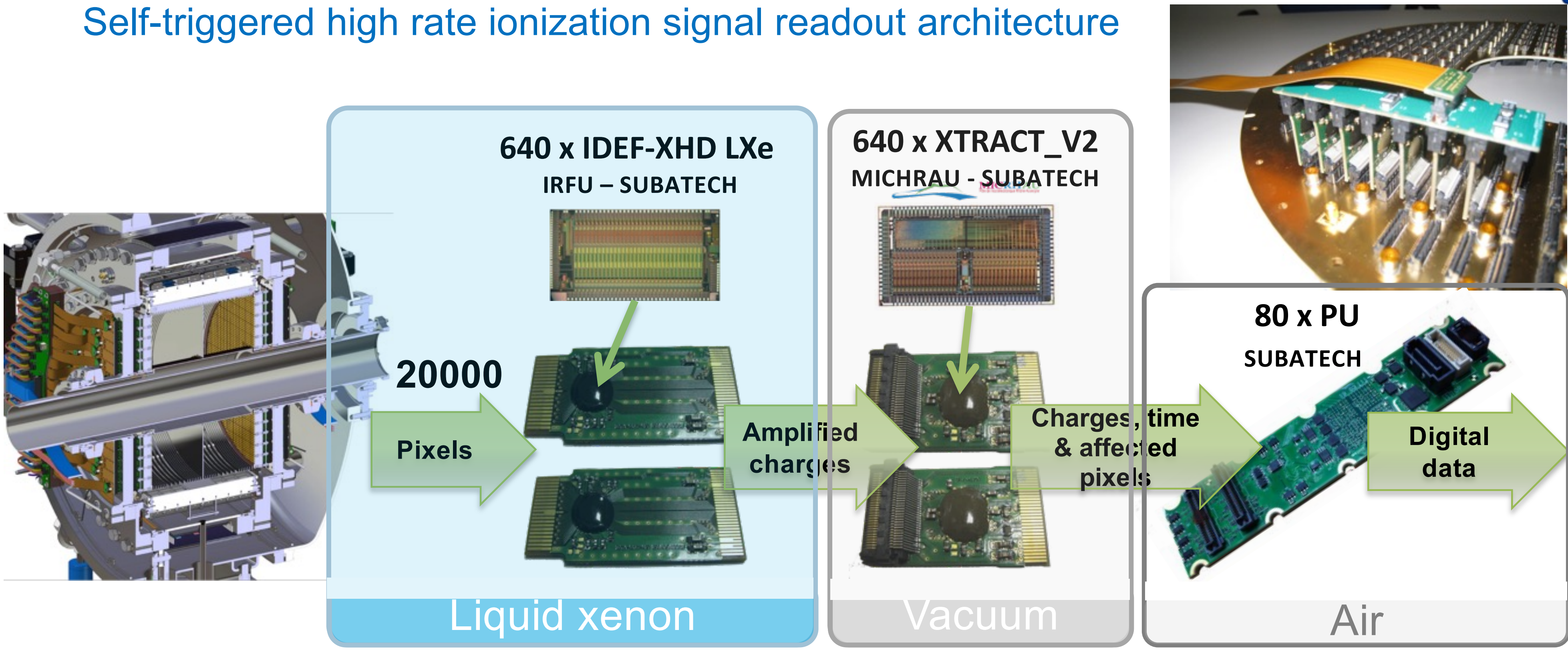
3 main steps:
- Anode and mesh washing with demineralized water
- Baking in high vacuum
- Assembling and HV test on dry air

μMeshes with copper GEM-HD geometry also assembled

XEMIS2 charge read-out electronics

The known DAQ system cannot meet the requirements for use in LXe

Self-triggered high rate ionization signal readout architecture

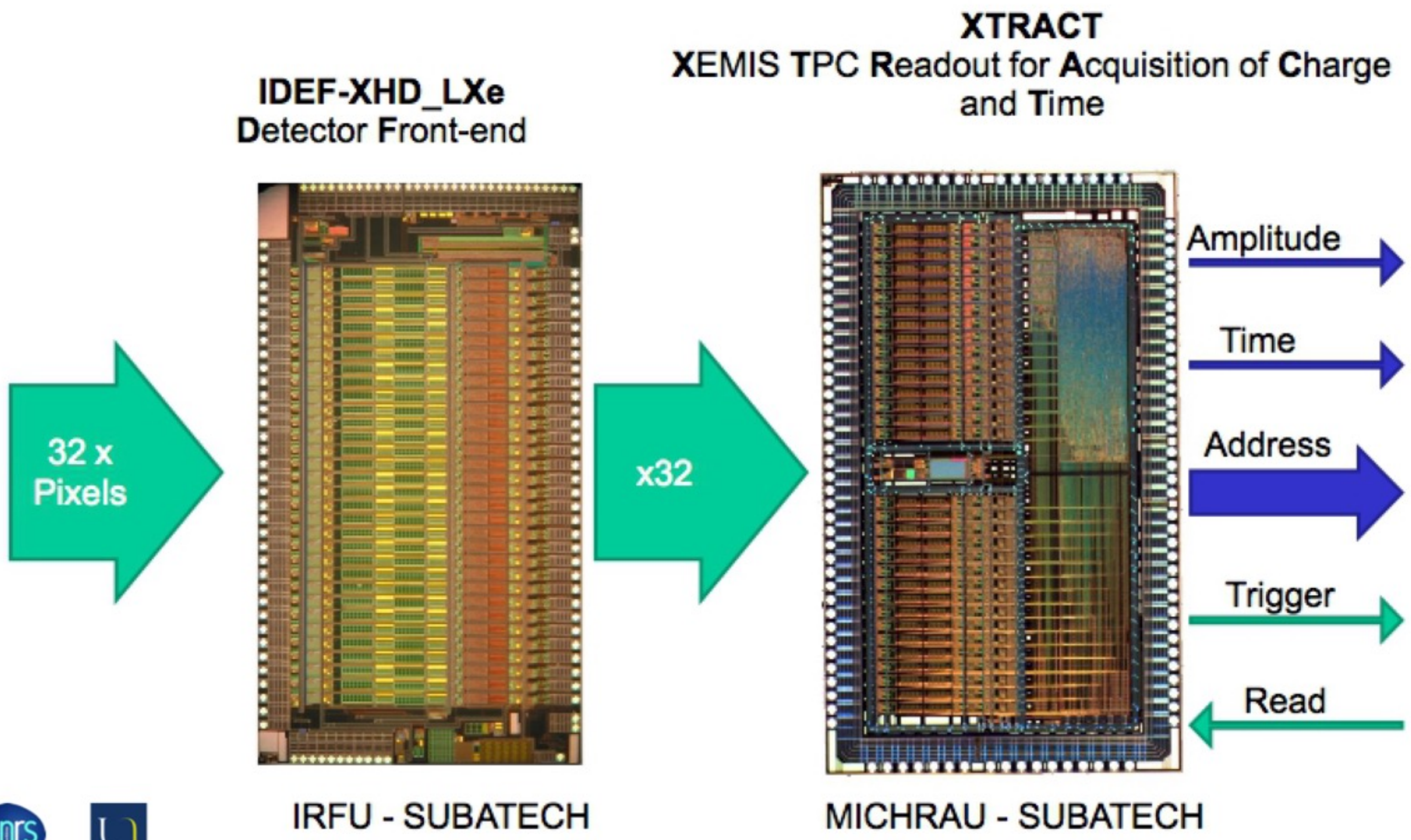


Cold Front-end electronic to reduce the electronic noise

only 1 amplitude and 1 time per ionization pulse escape from the cryostat

only 2 data lines/PU escape the vacuum (to the air) for all the measured charges

XEMIS2 contains specific ASICS



XEMIS2 charge electronics test bench at Subatech

Test bench at RT with all the chain from Idef-XHD_LXe to storage disc

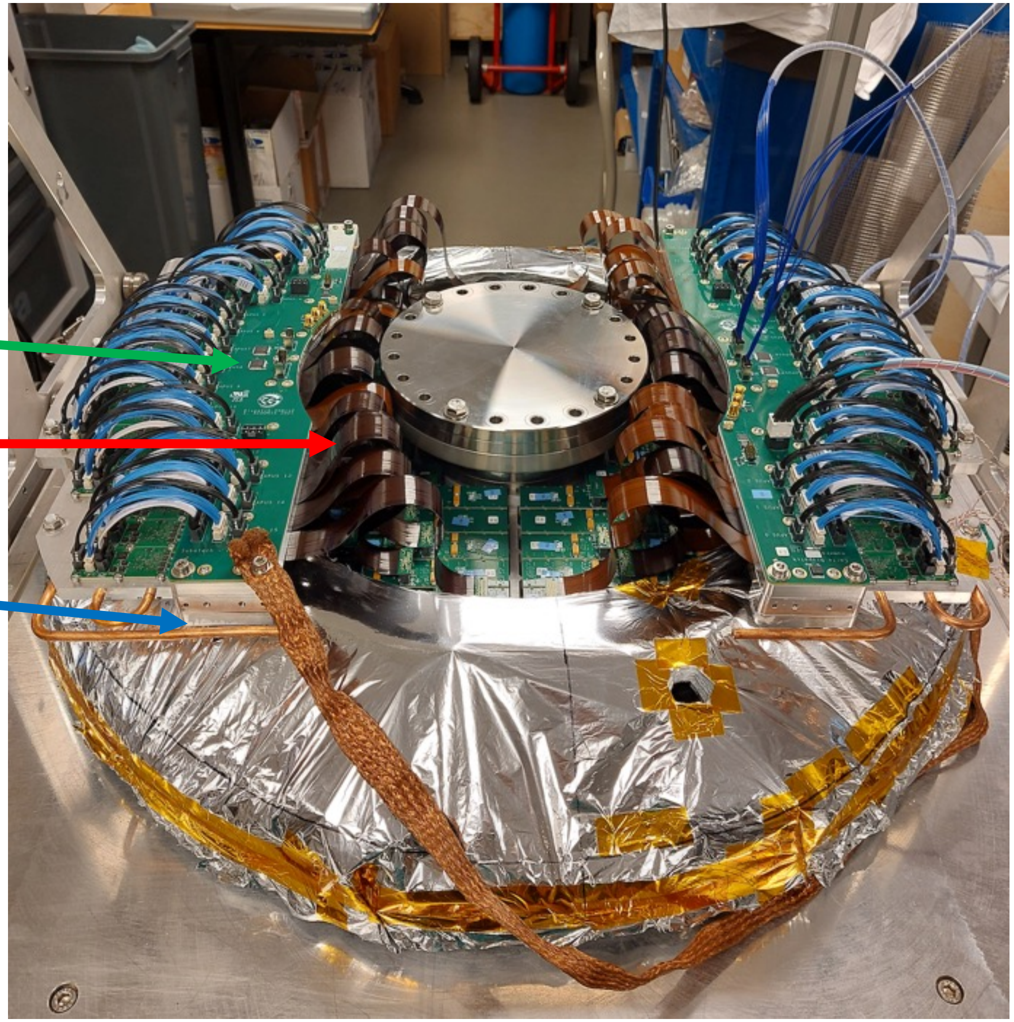
1 End-cap : Around 10 000 channels

32 PU cards in vacuum

Cold electronic to PU card with 32 Stripped Kapton flex

PU cards cooled with external cold water recirculation system (10W expected leak connected on LXe per endcap)

1 Spartan charge per ½ endcap outside the cryostat at RT

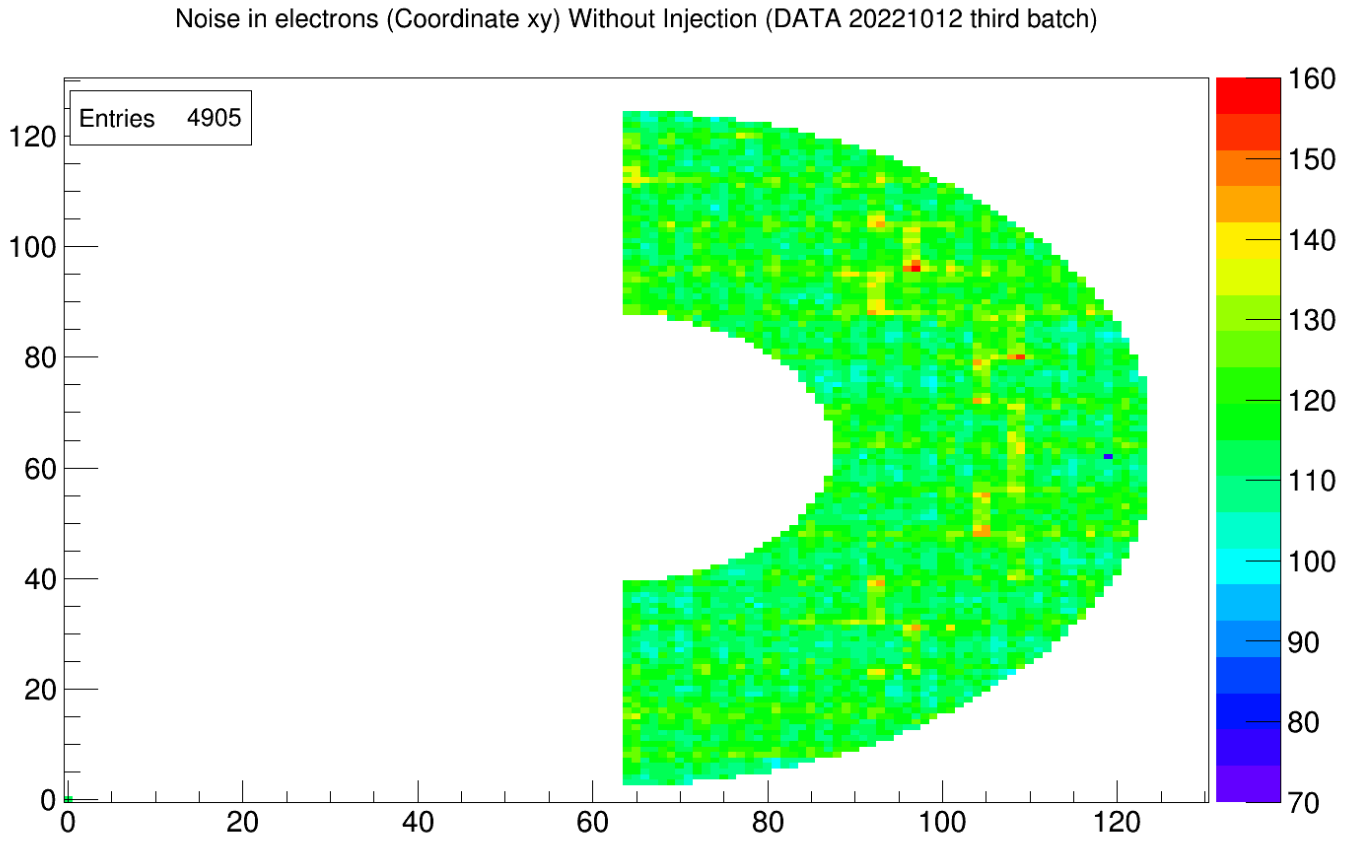


XEMIS2 noise measurement on charge electronics at RT

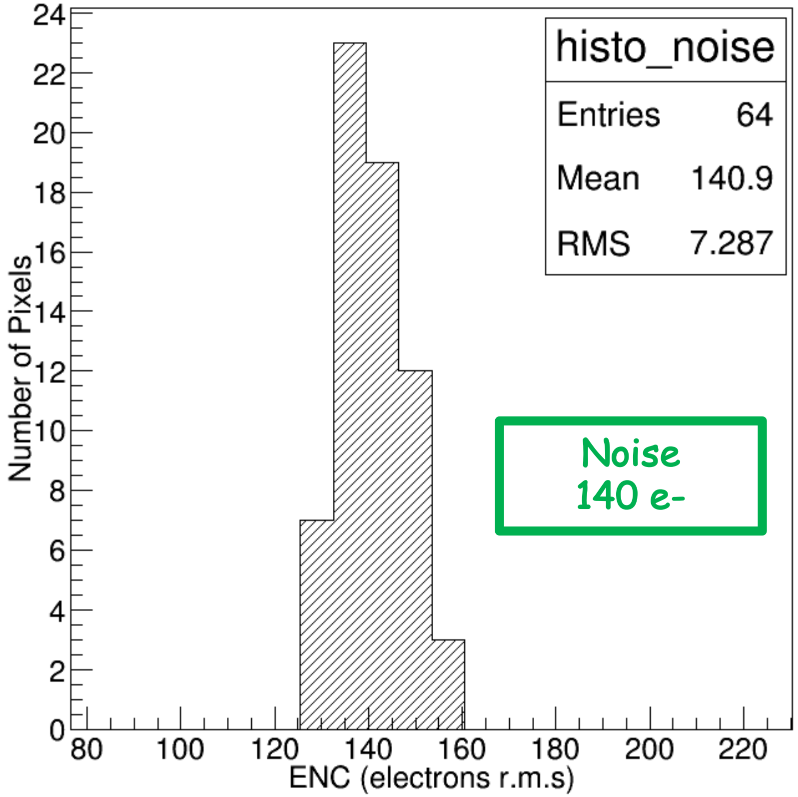
Used to:

- identify Connectix problem
- identify pick-up
- validate each component before installation inside the cryostat
- test setting and calibration processes
- validate μmesh insulation with 50V DDP in nitrogen chamber

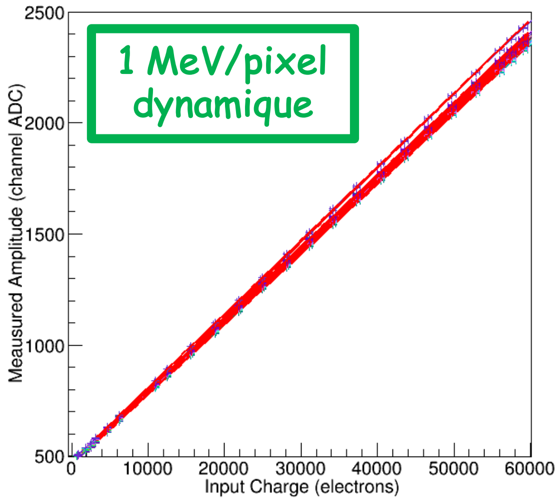
Second endcap in assembling

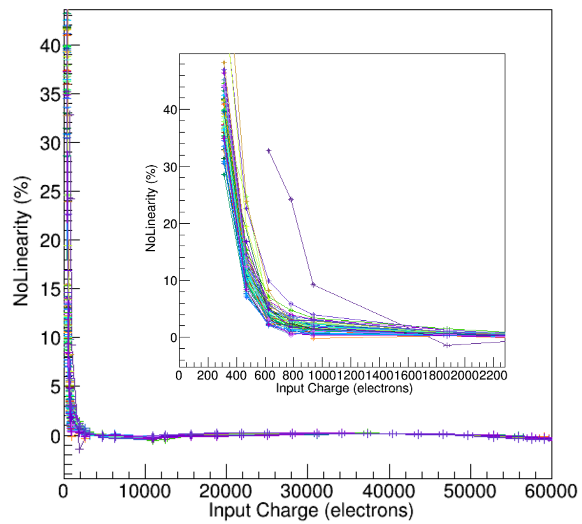


COLD Test with 64 pixels on XEMIS1
MIMELI+Idef-XHD_LXe+XTRACT+PU on XEMIS1 (64 channels)
2 kV/cm



Charge measurement calibration

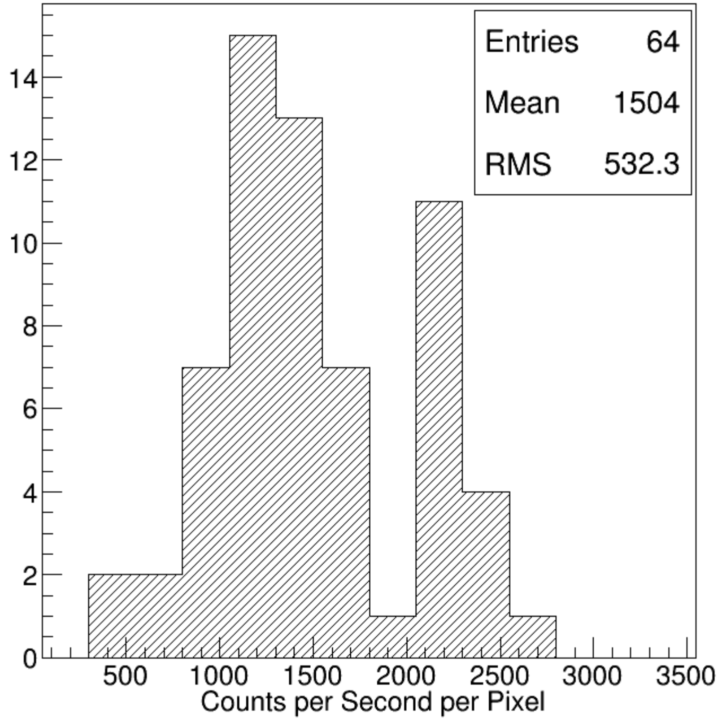


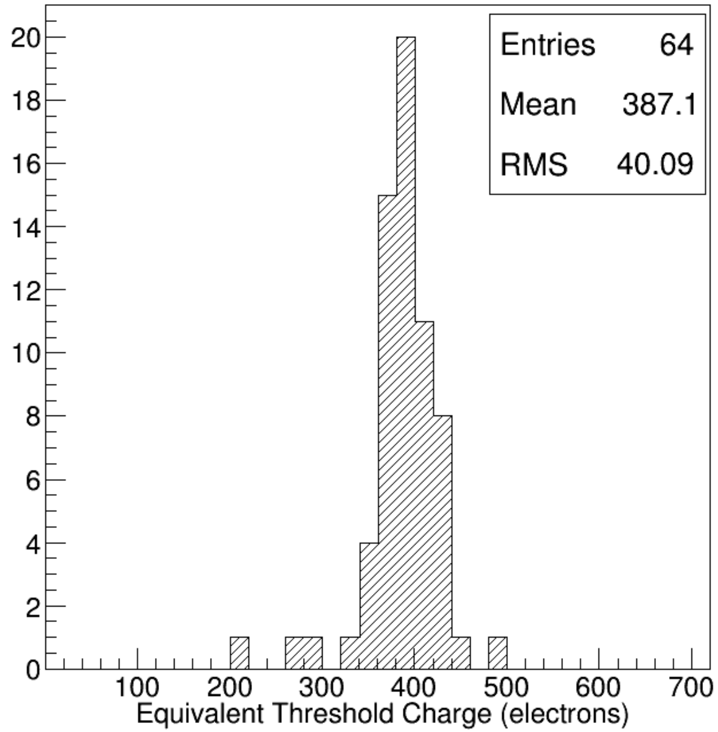


Noise : a little bit more than expected (100 e-)
Linearity : impressive (less than 1 σ_{noise})

COLD Test with 64 pixels on XEMIS1
MIMELI+Idef-XHD_LXe+XTRACT+PU on XEMIS1 (64 channels)
2 kV/cm

Rate and self-triggered channels

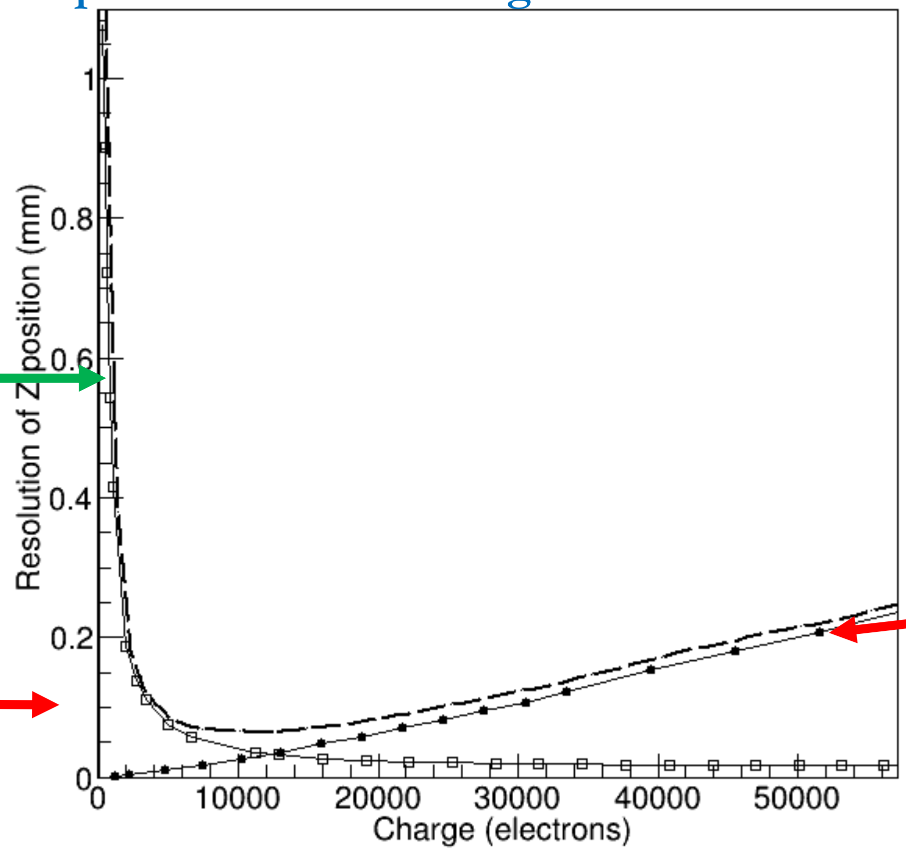




Threshold : close to 3 σ_{noise} on each channels
Counting rate : more than 10^3 ionization/s/p charge and time on disk

COLD Test with 64 pixels on XEMIS1
MIMELI+Idef-XHD_LXe+XTRACT+PU on XEMIS1 (64 channels)
2 kV/cm

Spatial resolution along drift direction

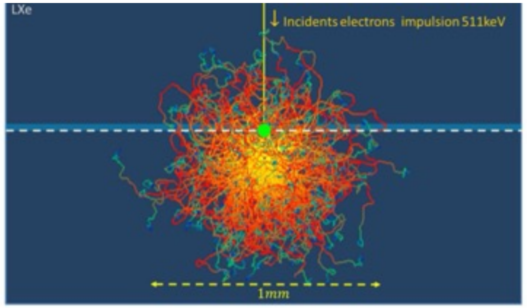


v_{drift} = 2,1 mm/µs
jitter on charge and light contributions

100 microns !

Electron Range contribution

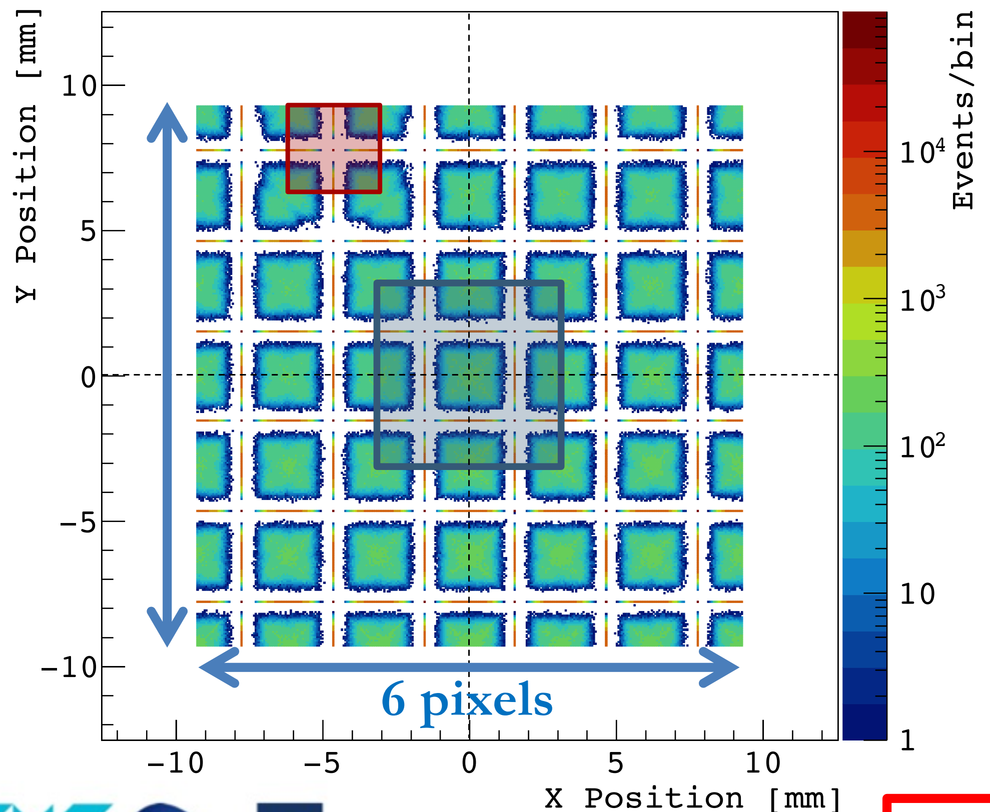
Geant4 v10.4
Electron recoils in LXe
T=511 keV

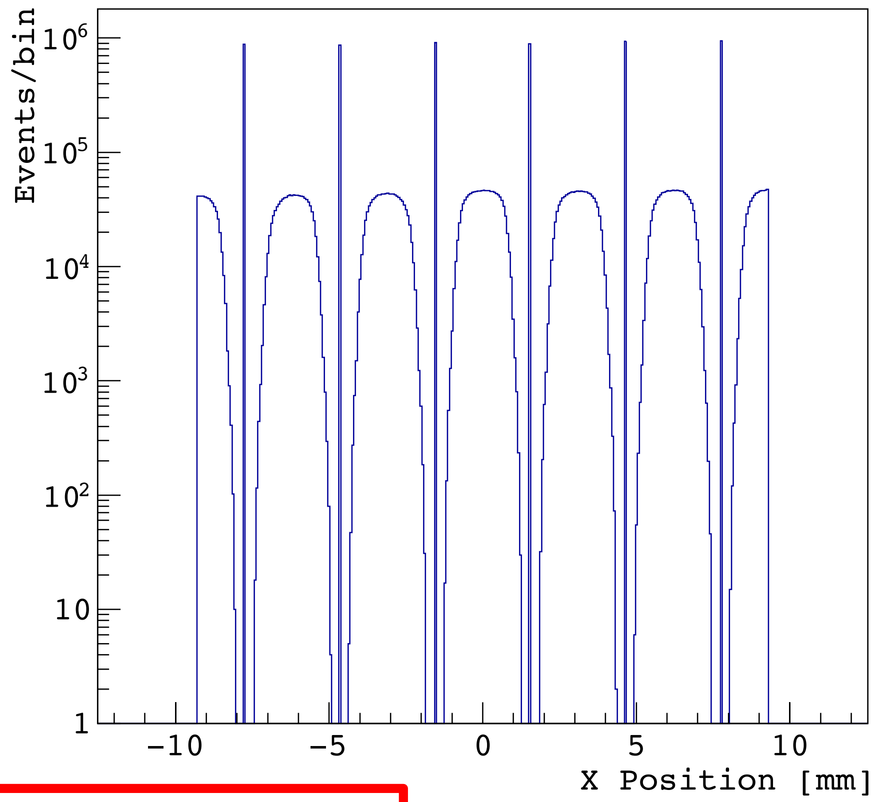


0,1 mm from 4000 to 30000 electrons, ie between 60 and 500 keV

COLD Test with 64 pixels on XEMIS1
MIMELI+Idef-XHD_LXe+XTRACT+PU on XEMIS1 (64 channels)
2 kV/cm

Spatial resolution transverse to the drift direction





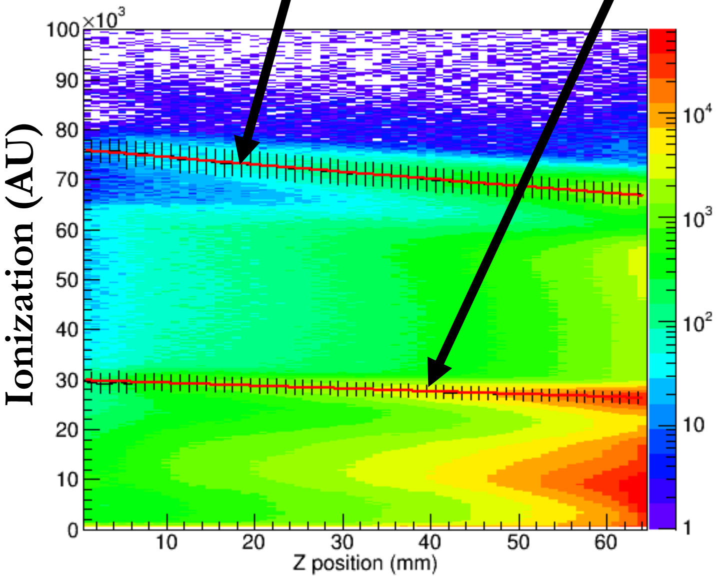
100 microns @ 511 keV!

COLD Test with 64 pixels on XEMIS1
MIMELI+Idef-XHD_LXe+XTRACT+PU on XEMIS1 (64 channels)
2 kV/cm

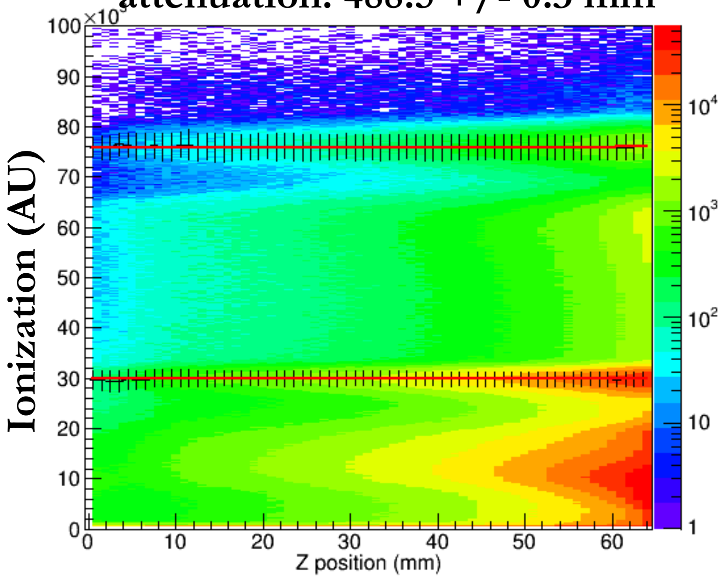
Energy resolution with single scatter and ^{22}Na source

1274 keV

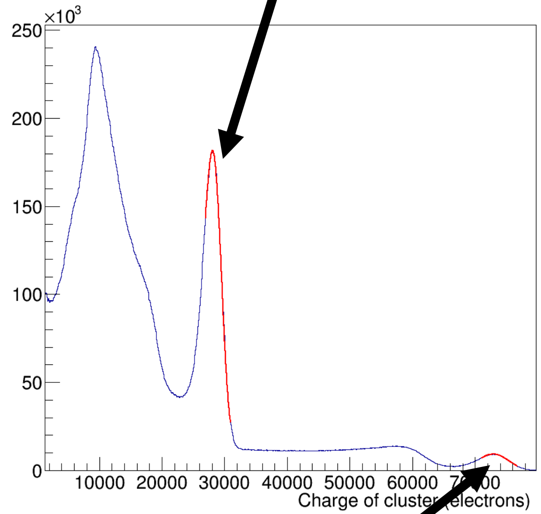
511 keV



attenuation: 488.5 +/- 0.3 mm

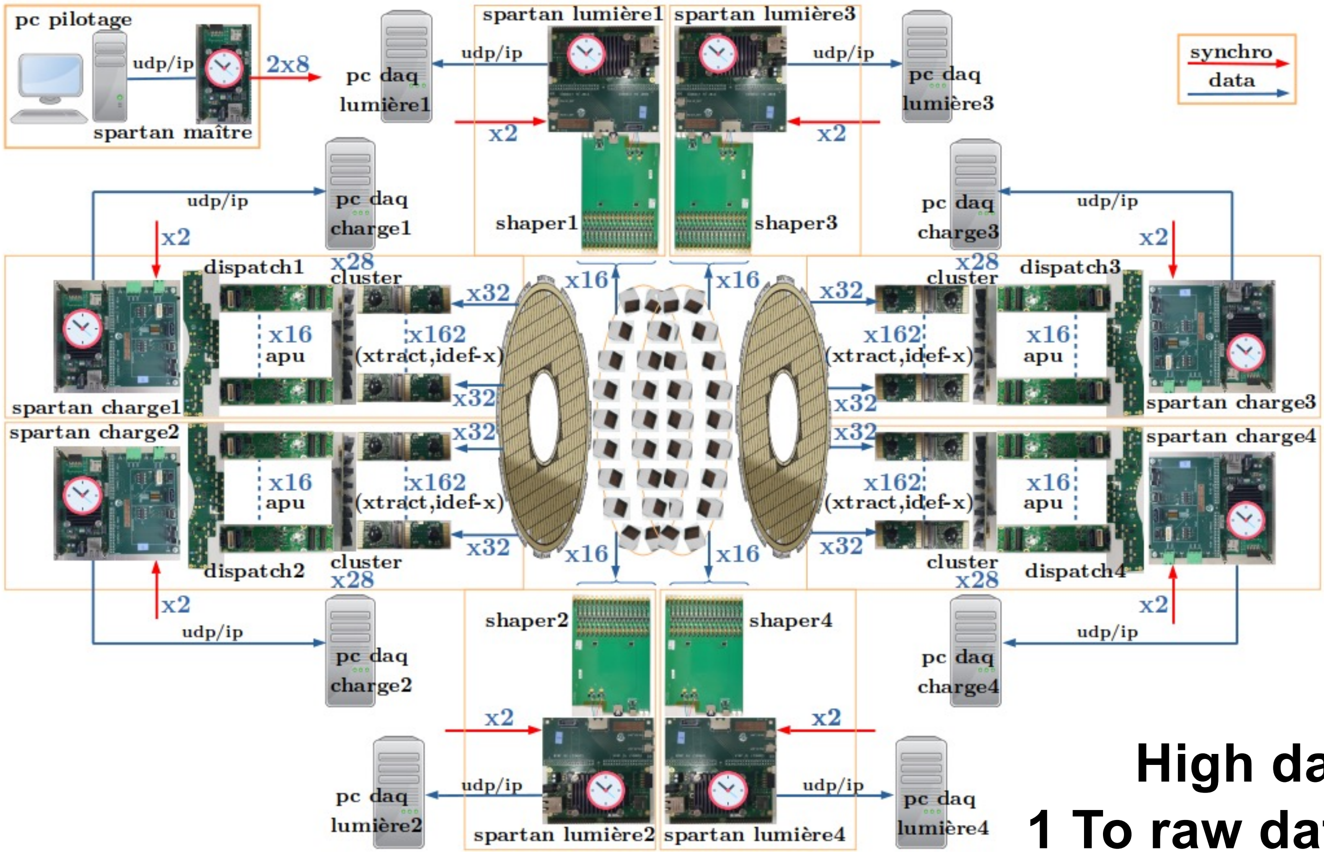


4.78% @ 511 keV



2.81% @ 1274 keV

XEMIS2 DAQ
From detector to disk



Synchronization with 200 MHz clock
No external trigger

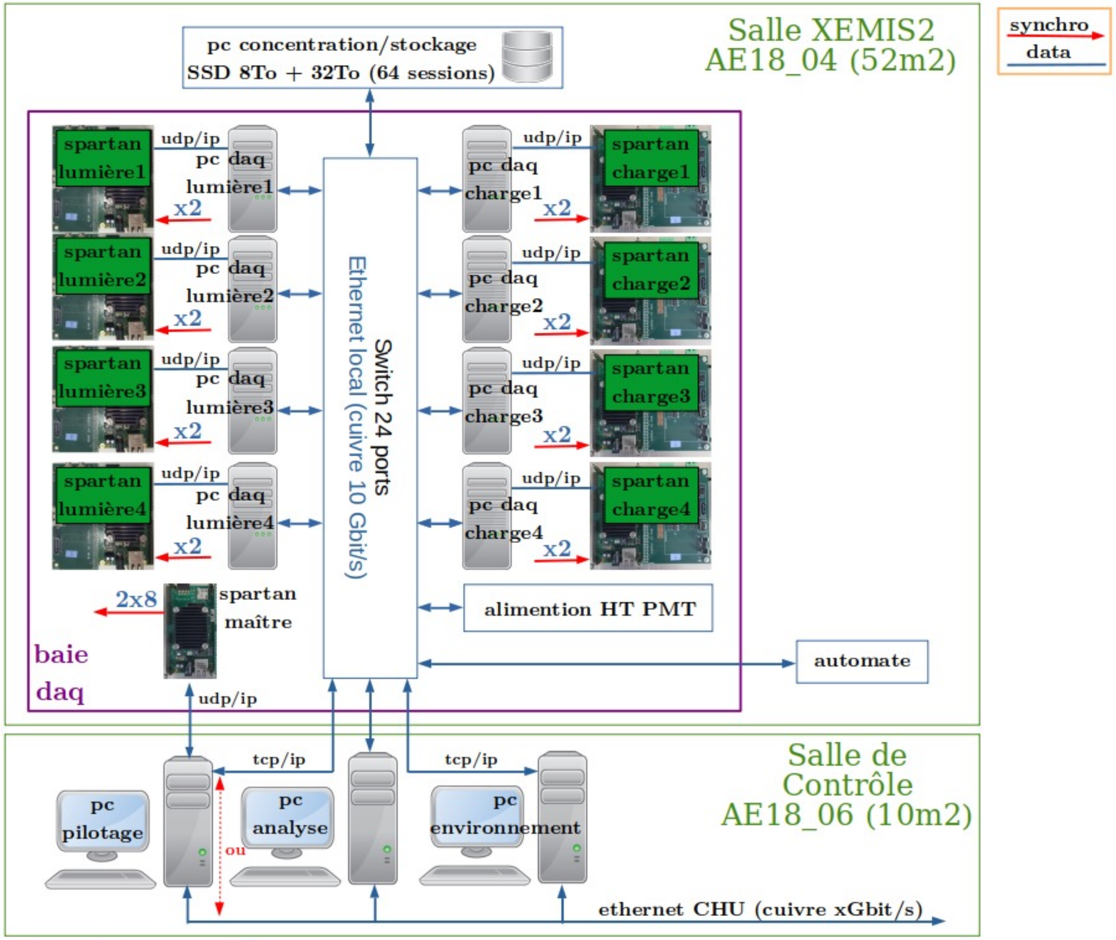
Light signal:
leading edge and TOT up to 1 Mevts/s per channel on 64 self triggered channels

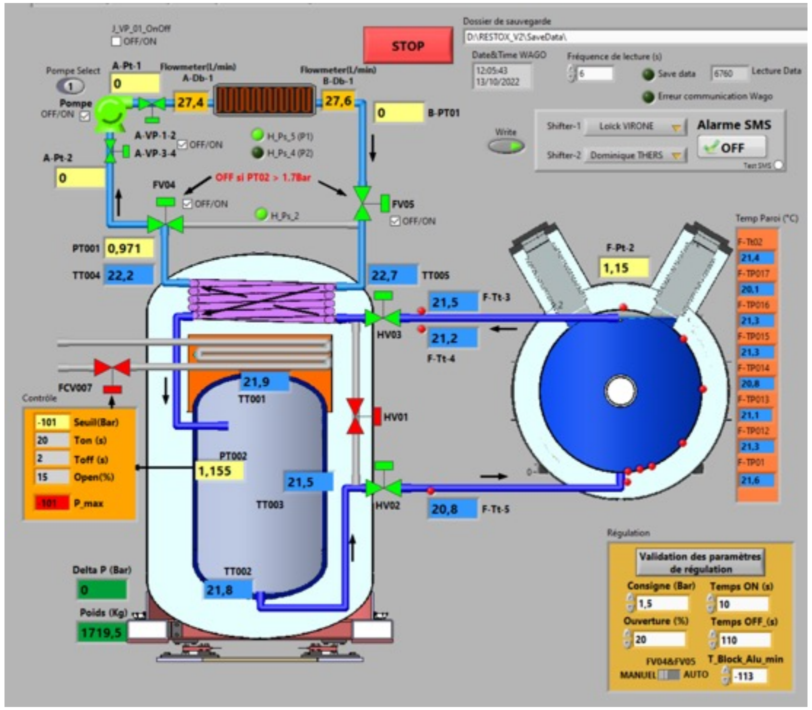
Charge signal:
time and amplitude up to 3 kevts/s per channel on 20k self triggered channels

High data flow rate and transfer:
1 To raw data expected on disk in 20 mns

XEMIS2 DAQ is ready

XEMIS2 DAQ infrastructure at CIMA

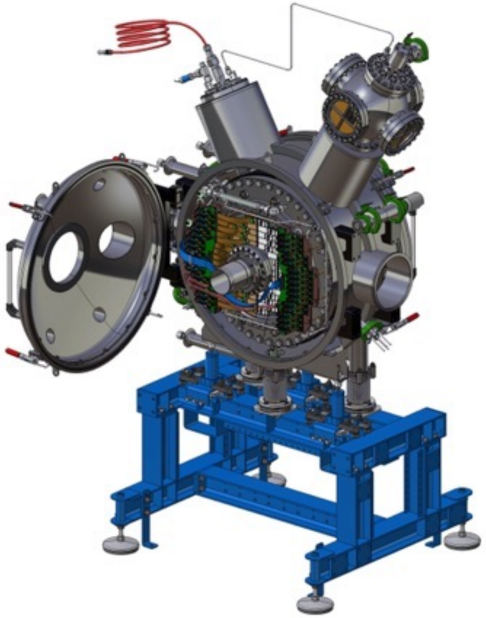




XEMIS2, research program

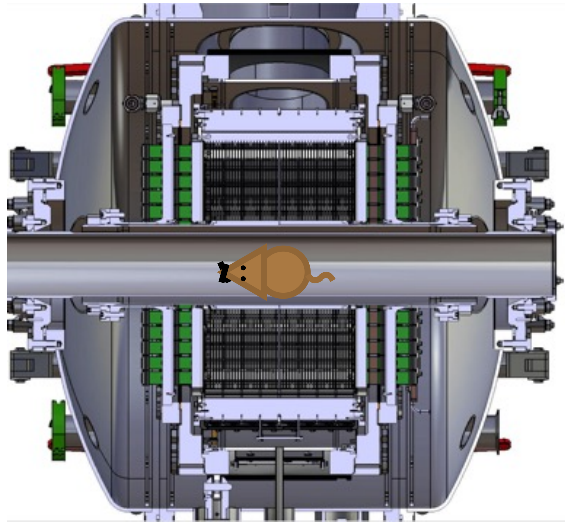
In collaboration with Nantes INSERM CRCINA
and Nantes GIP ARRONAX

3γ image with 20 kBq of ^{44}Sc activity in the Field of View



XEMIS2 technology

First Monolithic Compton telescope
dedicated to medical imaging



Timeline : scientific exploitation in 2024