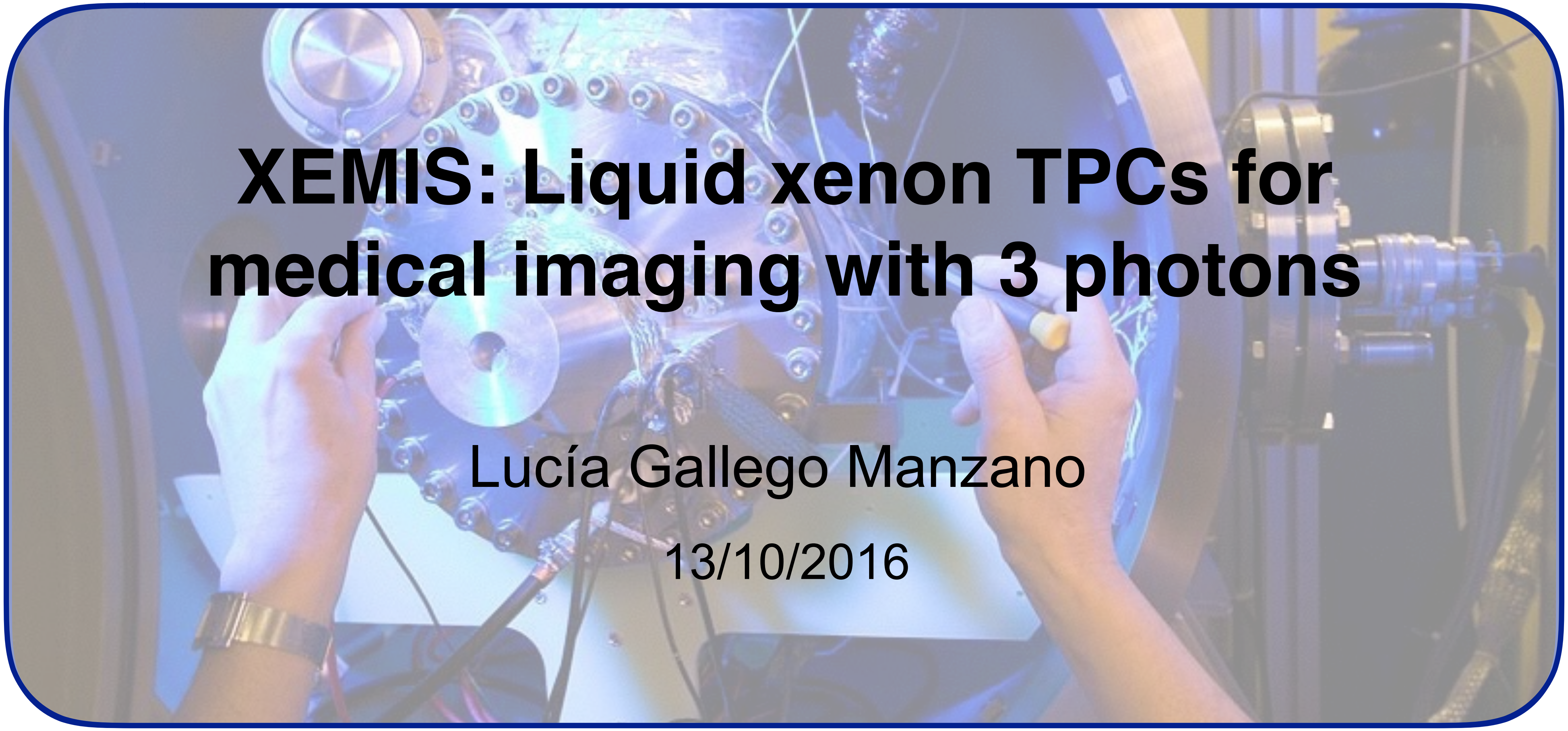
Instrumentation Days on Gaseous Detectors 2016



XEMIS: Liquid xenon TPCs for medical imaging with 3 photons

Lucía Gallego Manzano

13/10/2016

Outline

1. XENON group and the XEMIS project
2. 3γ Imaging
3. XEMIS1: R&D
4. XEMIS2: Small animal imaging
5. Conclusions

XENON Group @ Subatech

- **Medical Imaging Applications:** XEMIS project
- **Dark Matter Research:** XENON100, XENON1T, DARWIN
- **R&D in photo-detectors & liquid xenon cryogenics**

XENON Group @ Subatech

XEMIS @ Subatech

- Dominique Thers
- Jean-Pierre Cussonneau
- Eric Morteau

Post-docs:

- Nicolas Beaupere
- Lucía Gallego

PhD students:

- Loïck Virone
- + 3 new PhD students this year: Y. Xing, Y. Zhu and D. Giovagnoli

Mechanical Service:

- Jean-Sébastien Stutzmann
- Patrick Le Ray

Electronic Service

Collaborations

CHU / INSERM

- Thomas Carlier

KEK Japon

- R&D photodetectors

Air Liquide Advanced Technologies

- R&D liquid xenon cryogenics

Pôle Micrhau

- R&D electronics

ARRONAX

- Radioisotope production

IRCCyN

- Imaging

XEMIS: XEnon Medical Imaging System

Low activity Medical Imaging (~20 kBq)

3γ imaging

Radioisotope (β^+, γ) for functional imaging: **^{44}Sc**

Liquid xenon Compton camera

Time projection chamber (TPC)

XEMIS1

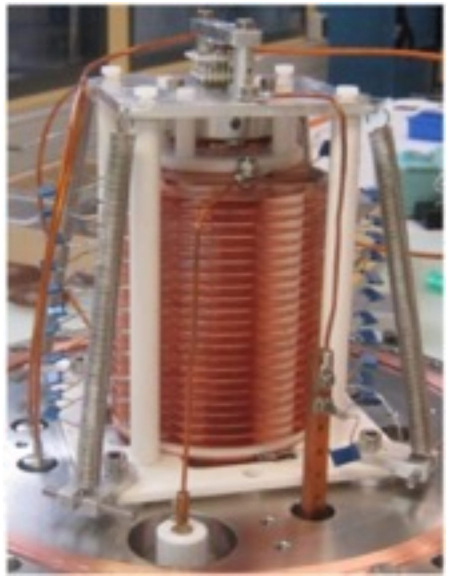
R&D

XEMIS2

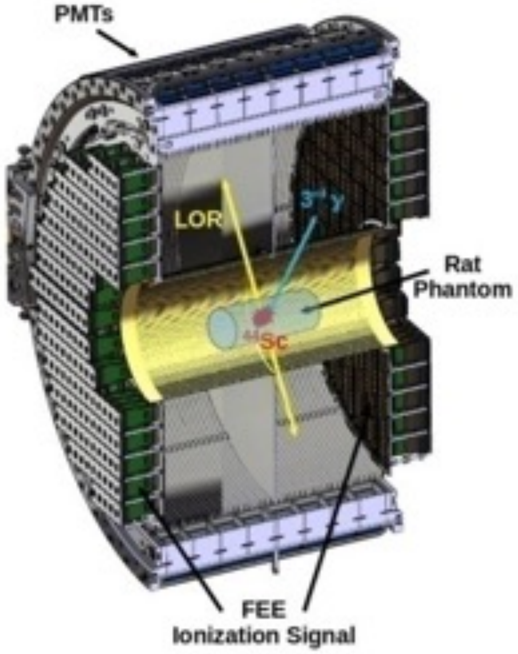
Small animal imaging

XEMIS3

Human body imaging



30 kg



200 kg

From 2020

LXe clinical camera

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

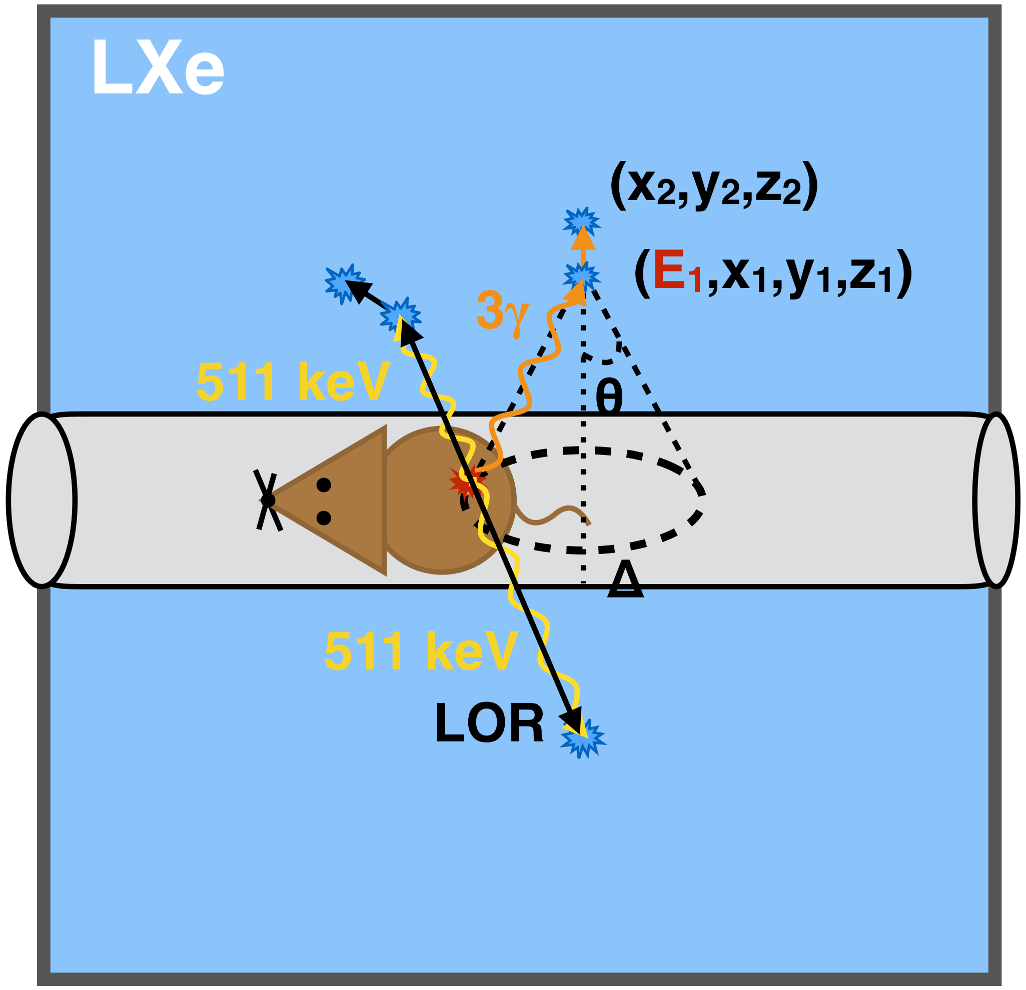
Principle of the 3γ Compton Imaging

- Radioisotope (β^+,γ) emitter in coincidence: ^{44}**Sc**

β^+ (E_{max} = 1.472 MeV)
γ (E_0 = 1.157 MeV)
$T_{1/2}$ = 4 h

- Direct 3D reconstruction of the source:

Line of response (LOR) + Compton cone



- Reconstructed γ direction:

Compton kinematics

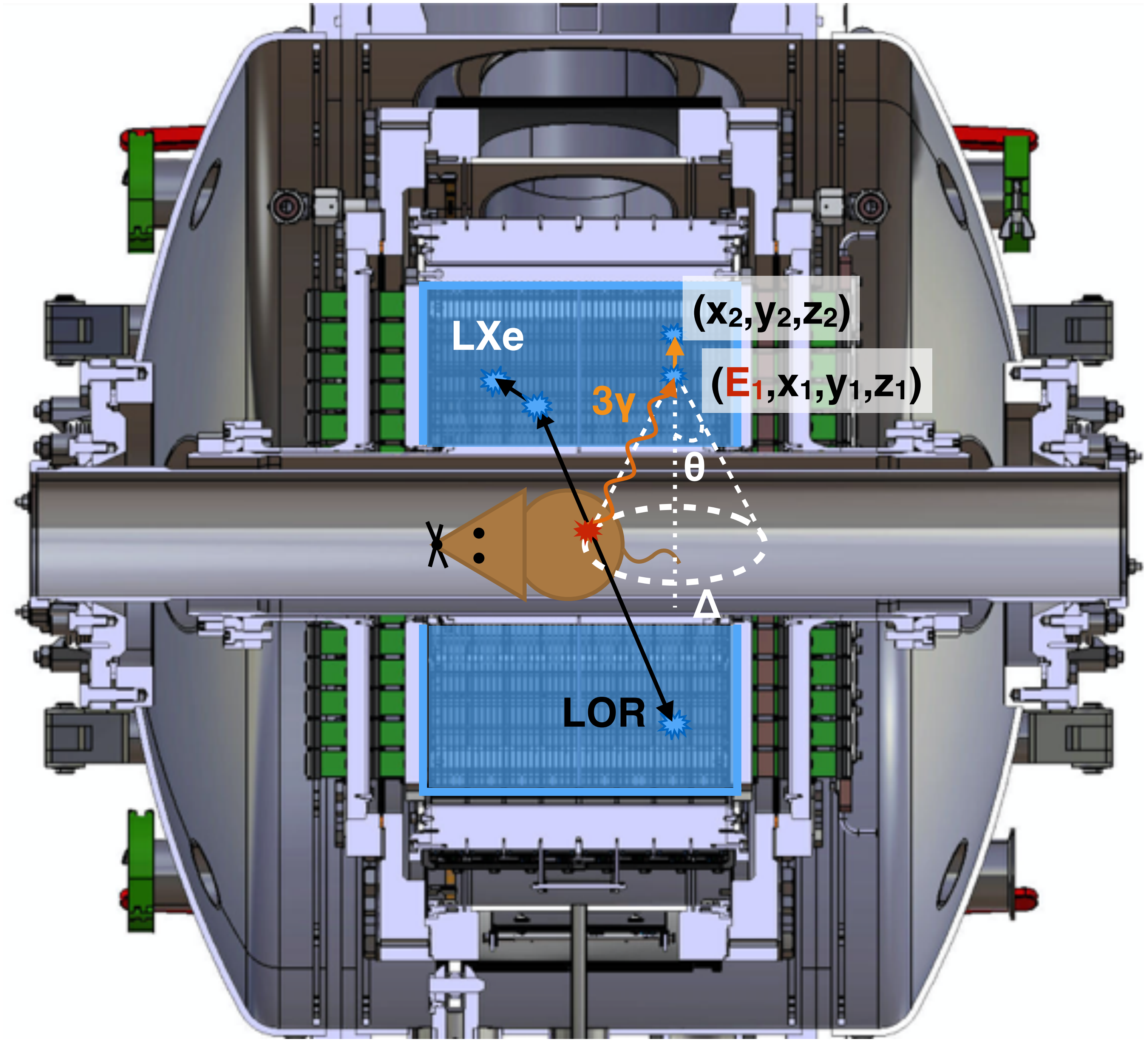
$$\cos\theta = 1 + m_e c^2 \left(\frac{1}{E_\gamma} - \frac{1}{E_1} \right)$$

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

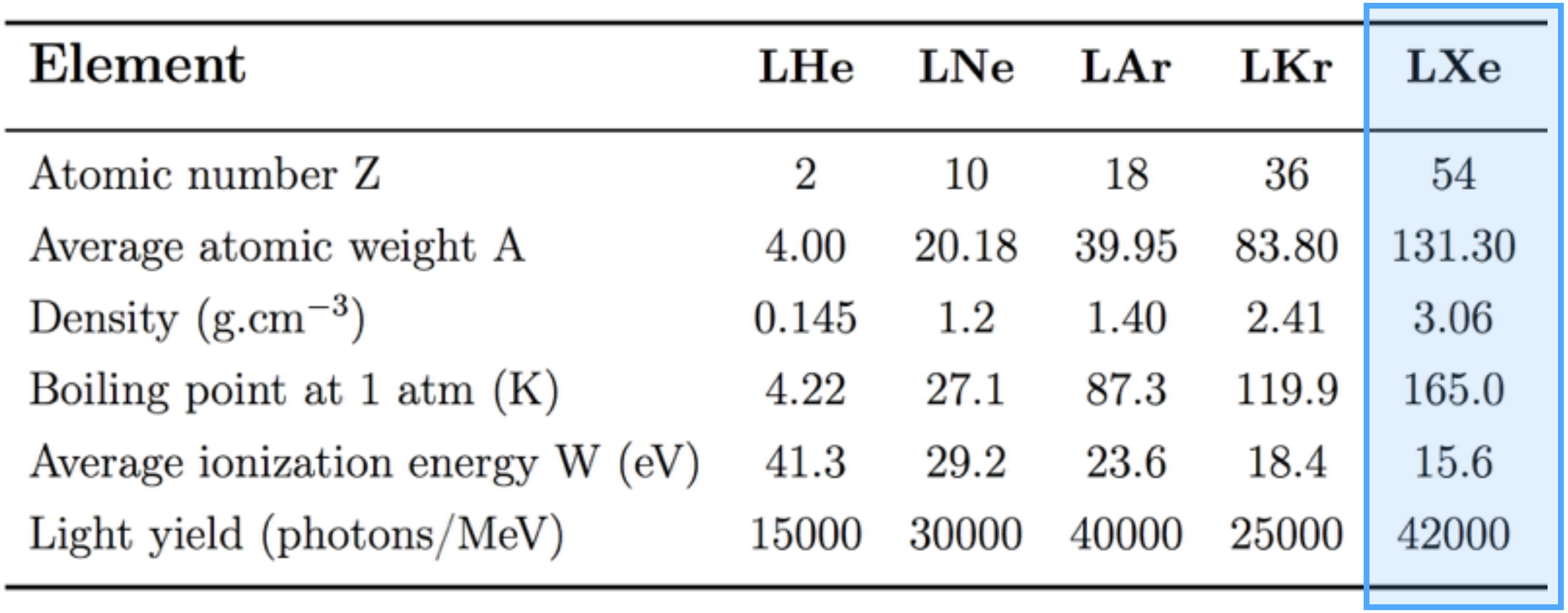
3γ Imaging with XEMIS

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



Liquid Xenon as detection medium

- High stopping power ($Z = 54$ & $\rho = 3.06$ g.cm^{-3}) for γ-rays from 10 keV to 10 MeV
- Simultaneous production of a **scintillation (178 nm)** and an **ionization** signal
- High scintillation light yield and high ionization yield
- Scalable to large, massive and homogeneous detectors

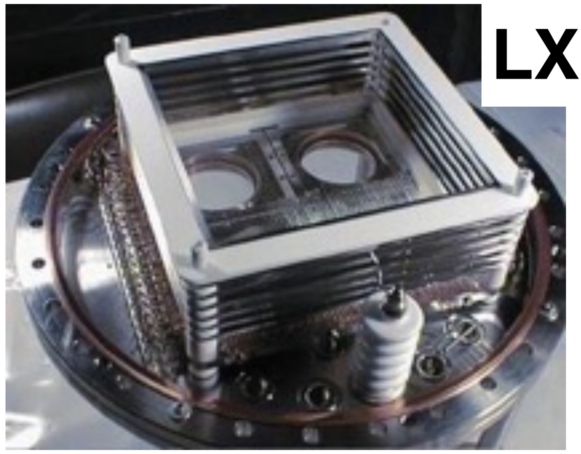


Element	**LHe**	**LNe**	**LAr**	**LKr**	**LXe**
Atomic number Z	2	10	18	36	54
Average atomic weight A	4.00	20.18	39.95	83.80	131.30
Density (g.cm^{-3})	0.145	1.2	1.40	2.41	3.06
Boiling point at 1 atm (K)	4.22	27.1	87.3	119.9	165.0
Average ionization energy W (eV)	41.3	29.2	23.6	18.4	15.6
Light yield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

Liquid Xenon as detection medium

Possible applications:

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

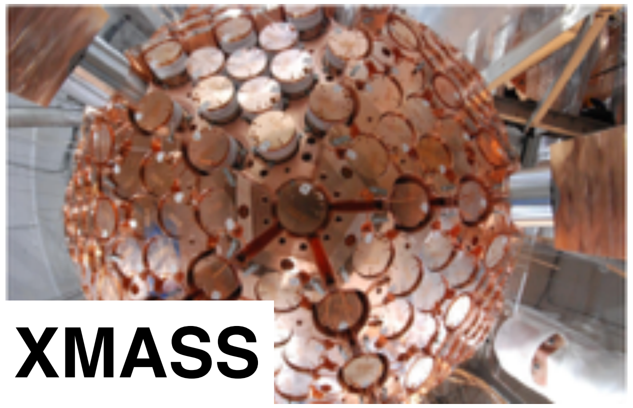


LXeGRIT

Liquid xenon based detectors:

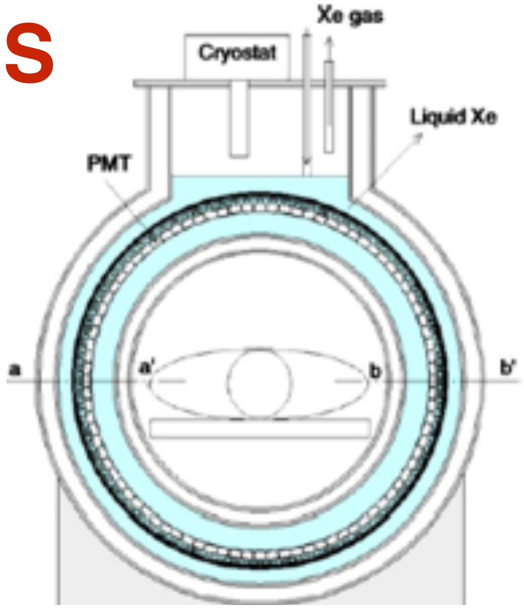
- Double-phase (LXe/GXe): XENON, LUX, ZEPLIN, Panda-X
- Single-phase (LXe):
  - Scintillation signal: XMASS
    MEG
  - Ionization signal:

} LXeGRIT, **XEMIS**



XMASS

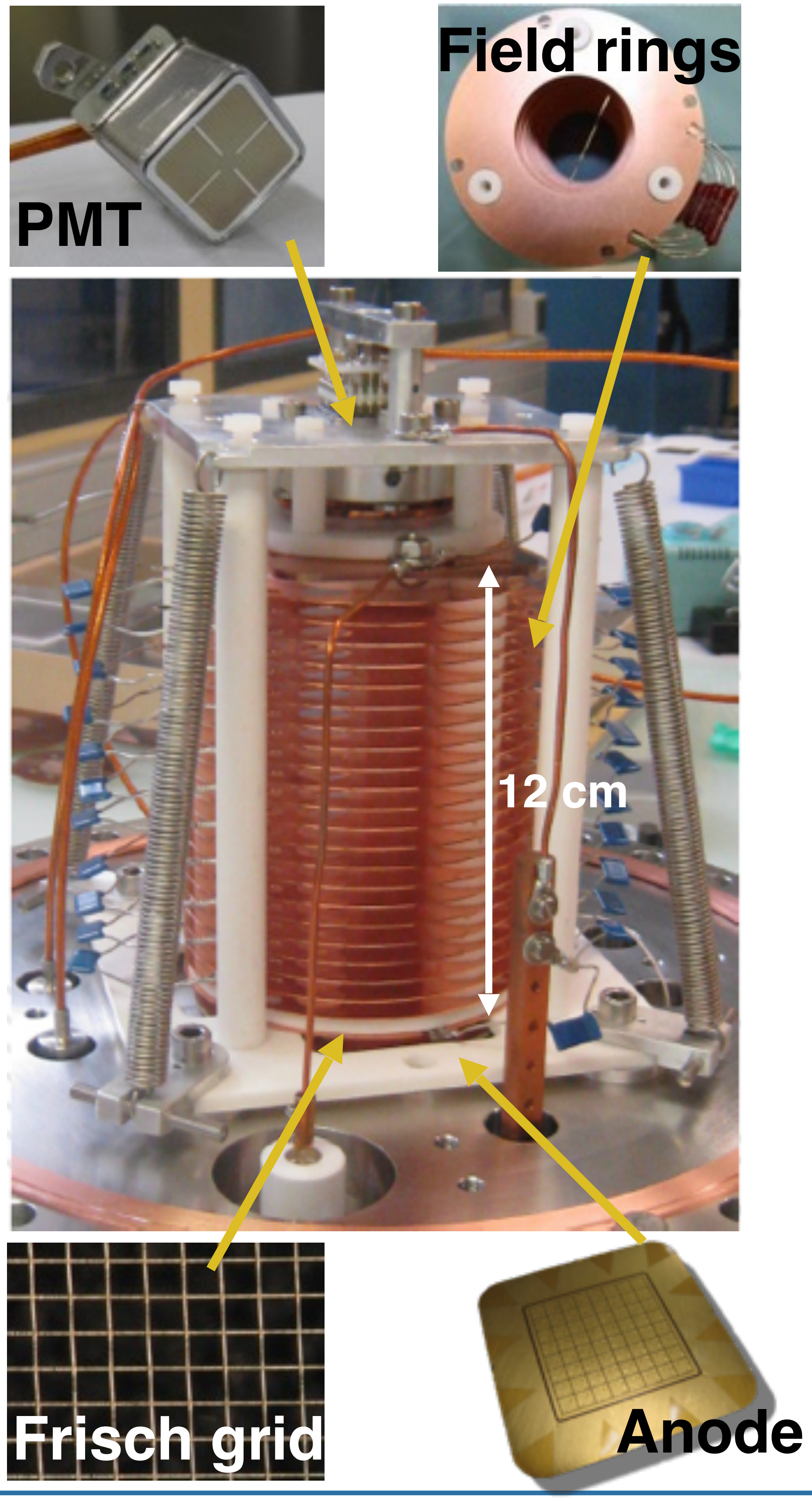
XENON1T



Waseda LXe TOF-PET

LUX

XEMIS1 Time Projection Chamber

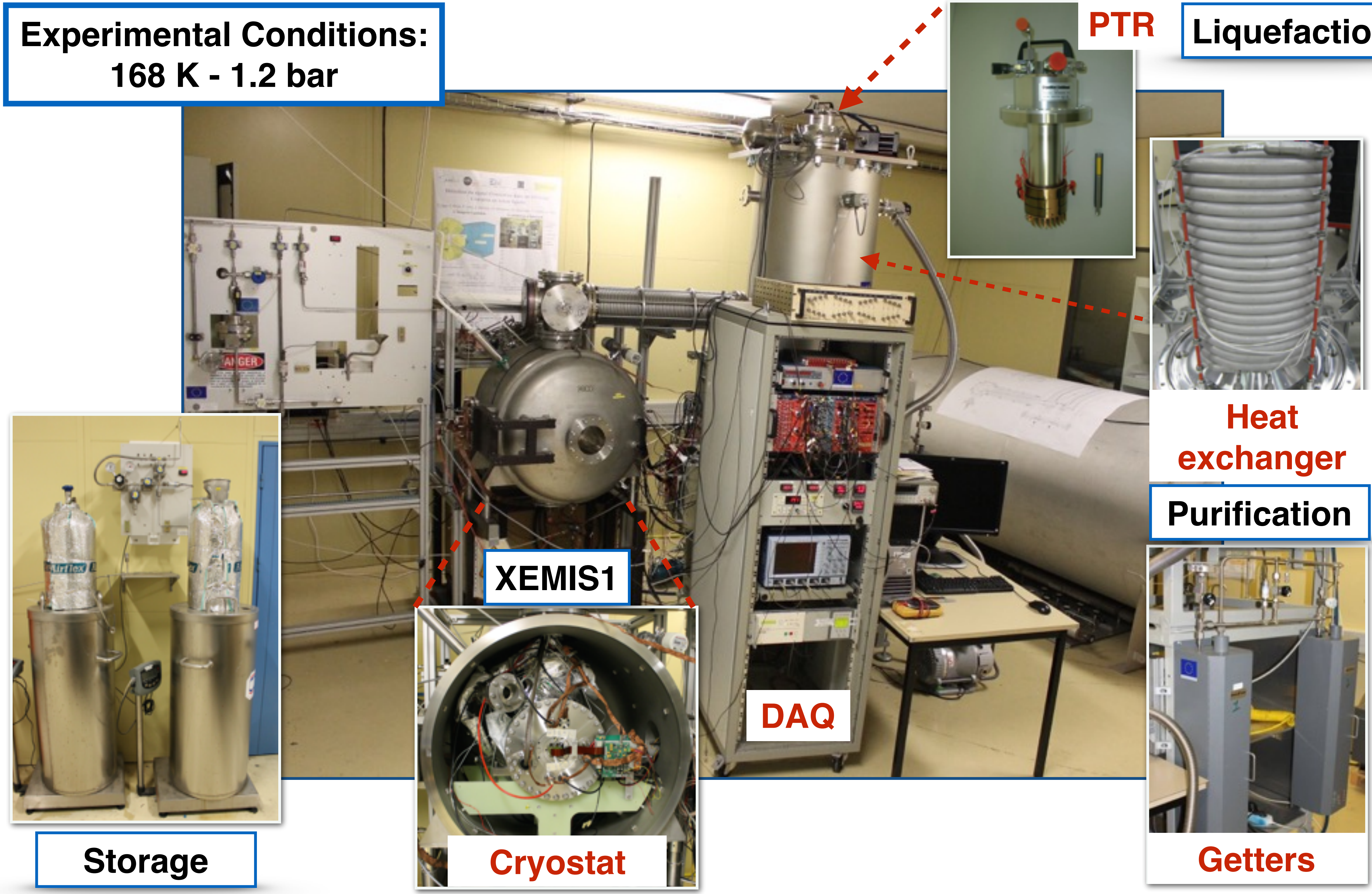


- 30 kg ultra pure LXe
- Active volume 12 (6) x 2.5 x 2.5 cm^3
- 1” square UV sensitive PMT → Trigger
- Segmented anode (2.5 x 2.5 cm^2 active) in 64 pixels
- Frisch grid. Gap 0.5 (1) mm
- Field shaping rings (23) for homogeneous drift field up to 2.5 kV/cm

Energy + 3D Positions of each interaction

XEMIS1 Facility

Experimental Conditions:
168 K - 1.2 bar



Liquefaction

PTR

Heat exchanger

Purification

Getters

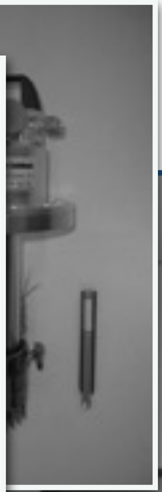
XEMIS1

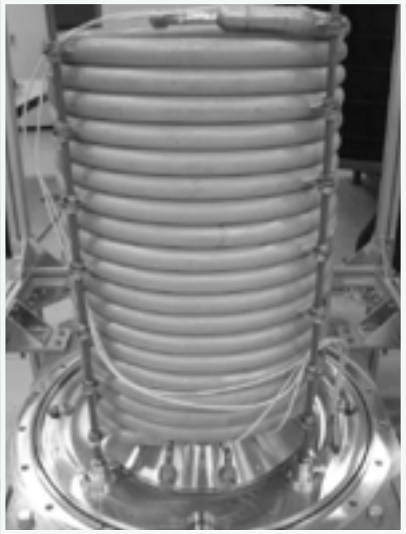
Cryostat

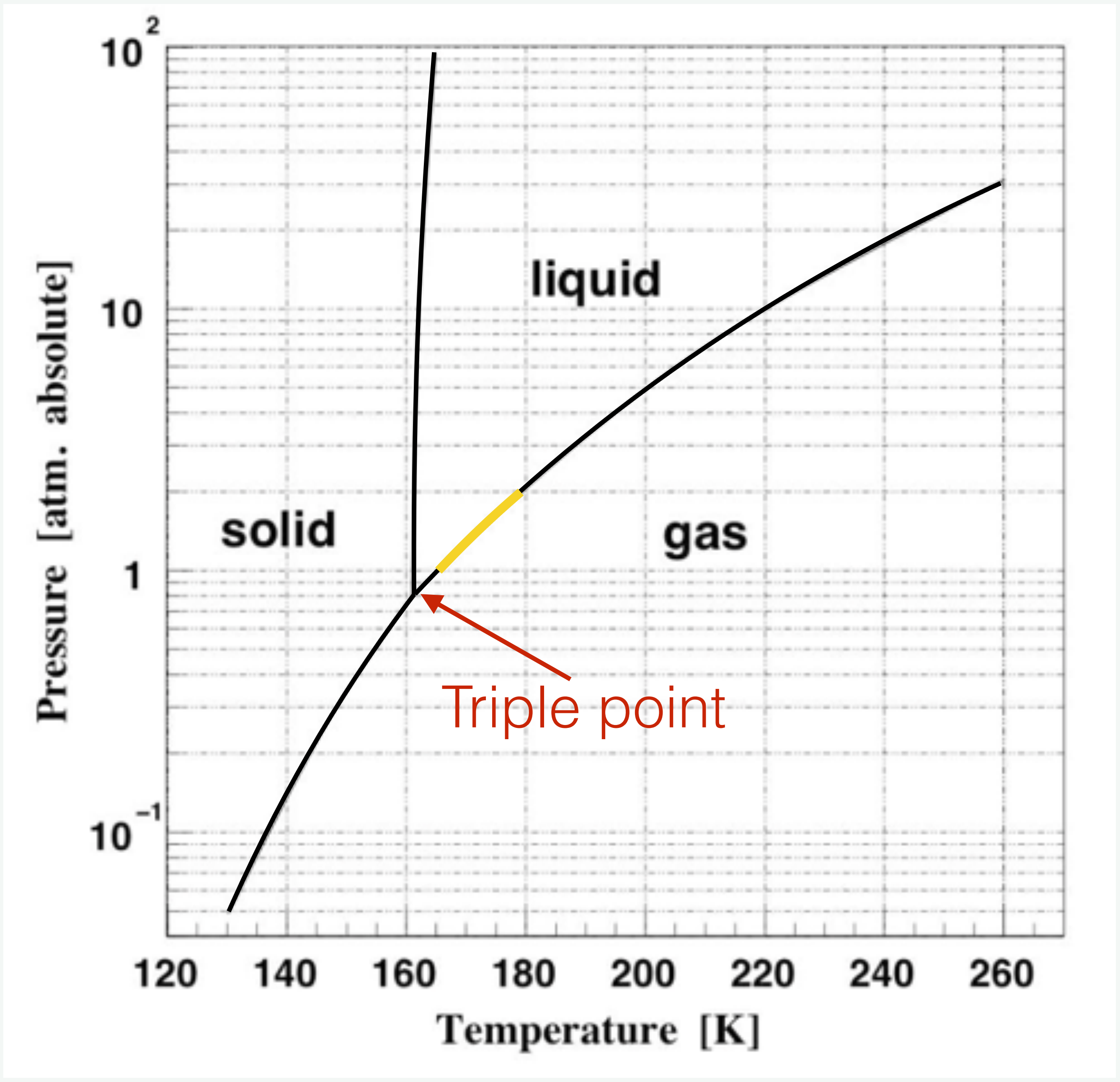
DAQ

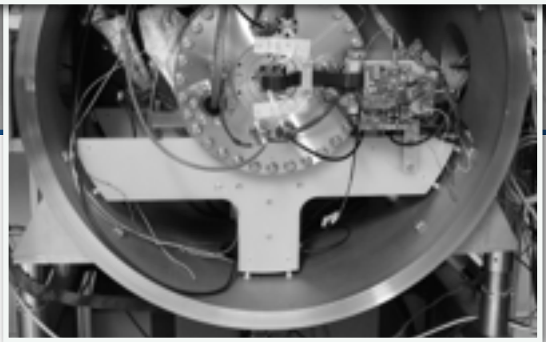
Storage

Xenon Cryogenics





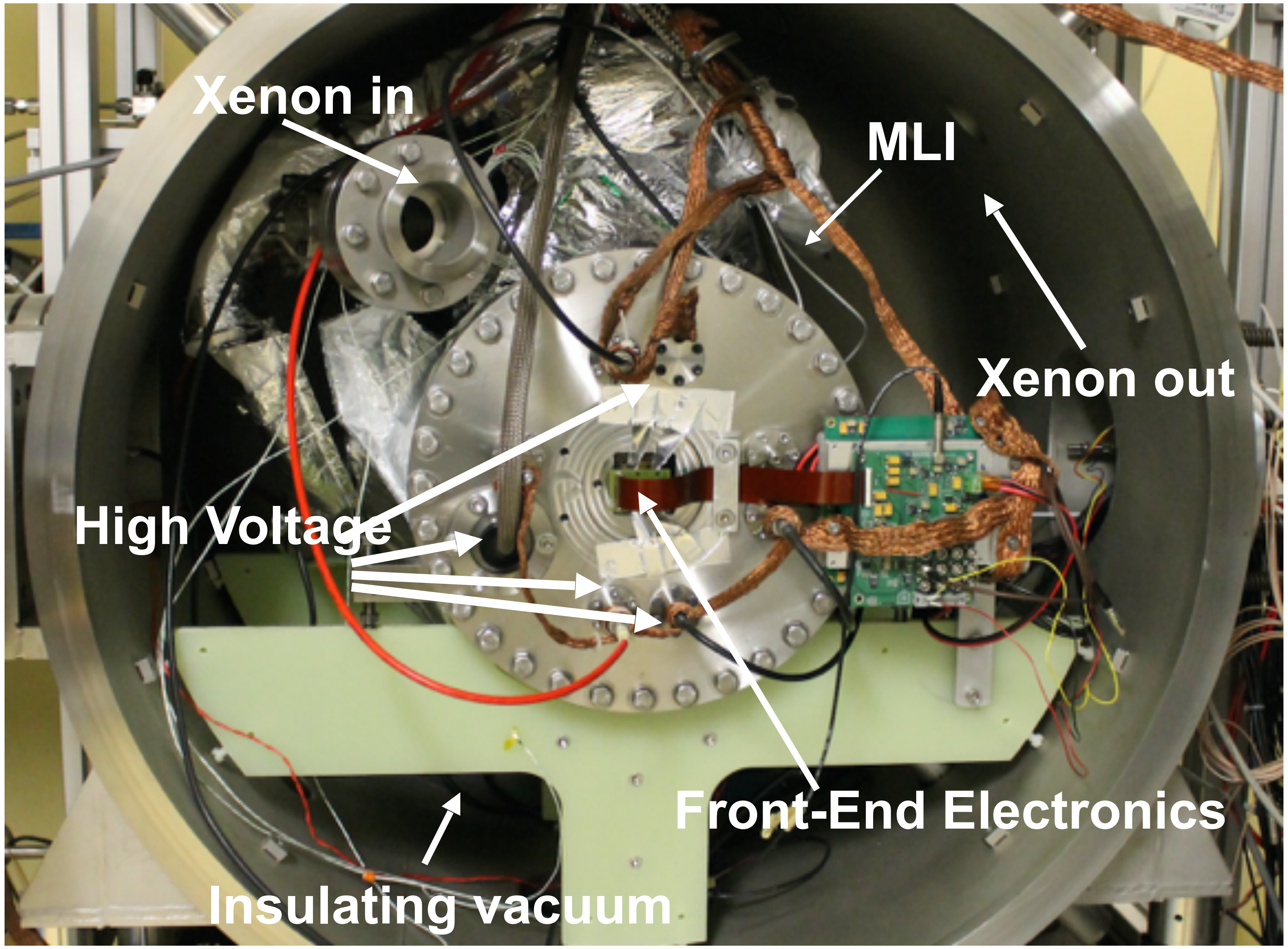




Experimental Conditions:
168 K - 1.2 bar

Narrow temperature margin of 7 K

XEMIS1 TPC



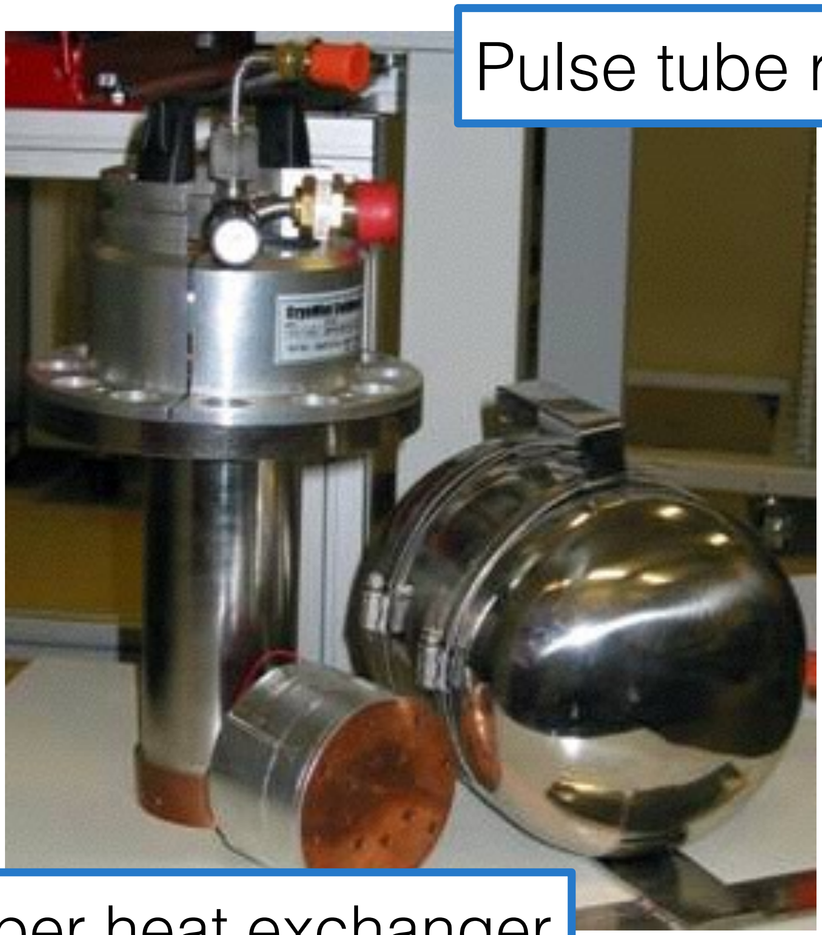
Stainless steel components are cleaned with an ultrasonic bath and drying (> 200 °C)

Ultrasonic cleaner

- Assembly in a clean room
- Maximum limitation of heat exchanges (thermal leak ~ 40 W)
- Dynamic vacuum: 10^{-8} bars

Pre-cooling and Liquefaction

KEK
HIGH ENERGY ACCELERATOR RESEARCH ORGANIZATION

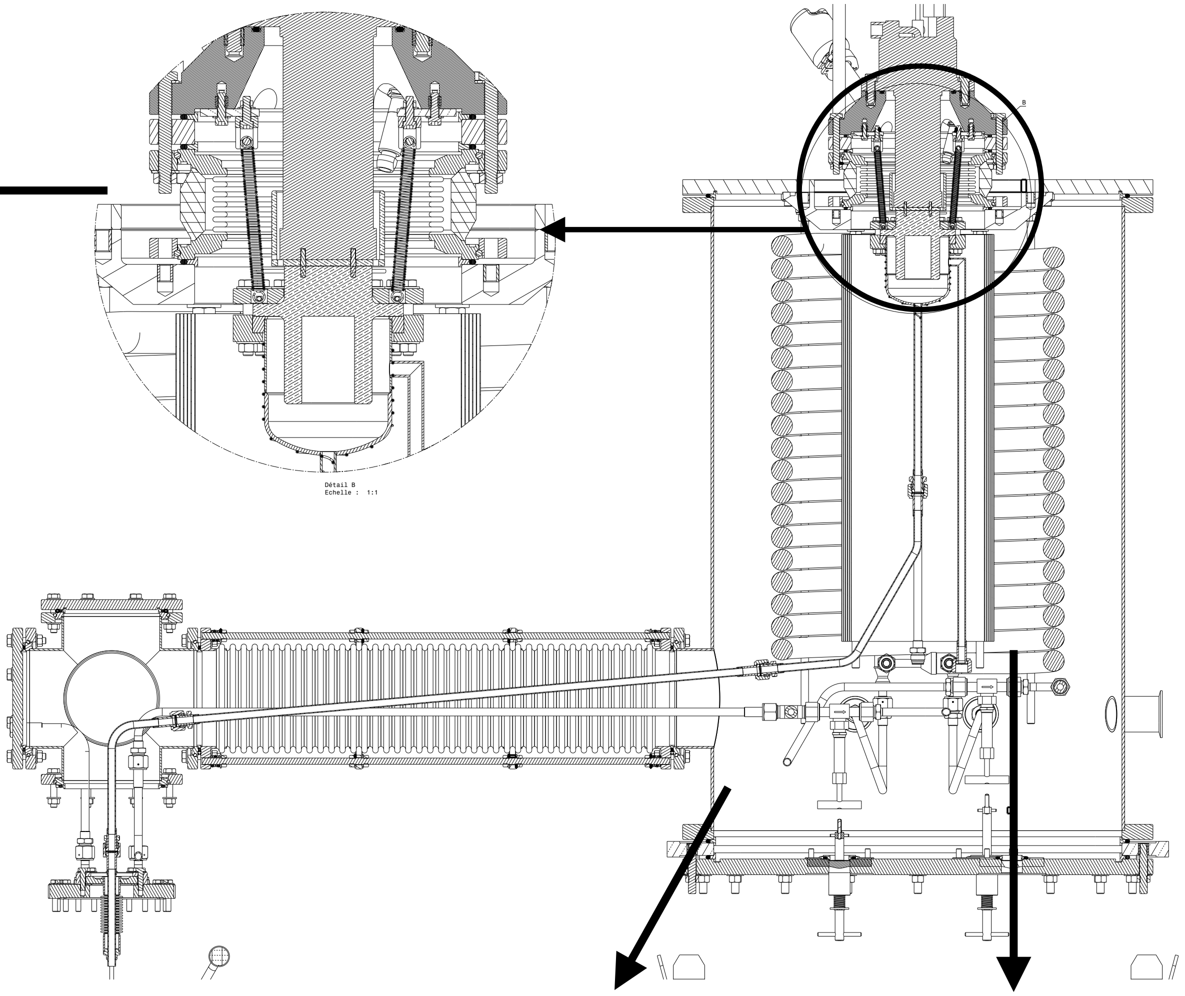


Pulse tube refrigerator

P = 180 W
at 165 K

Copper heat exchanger

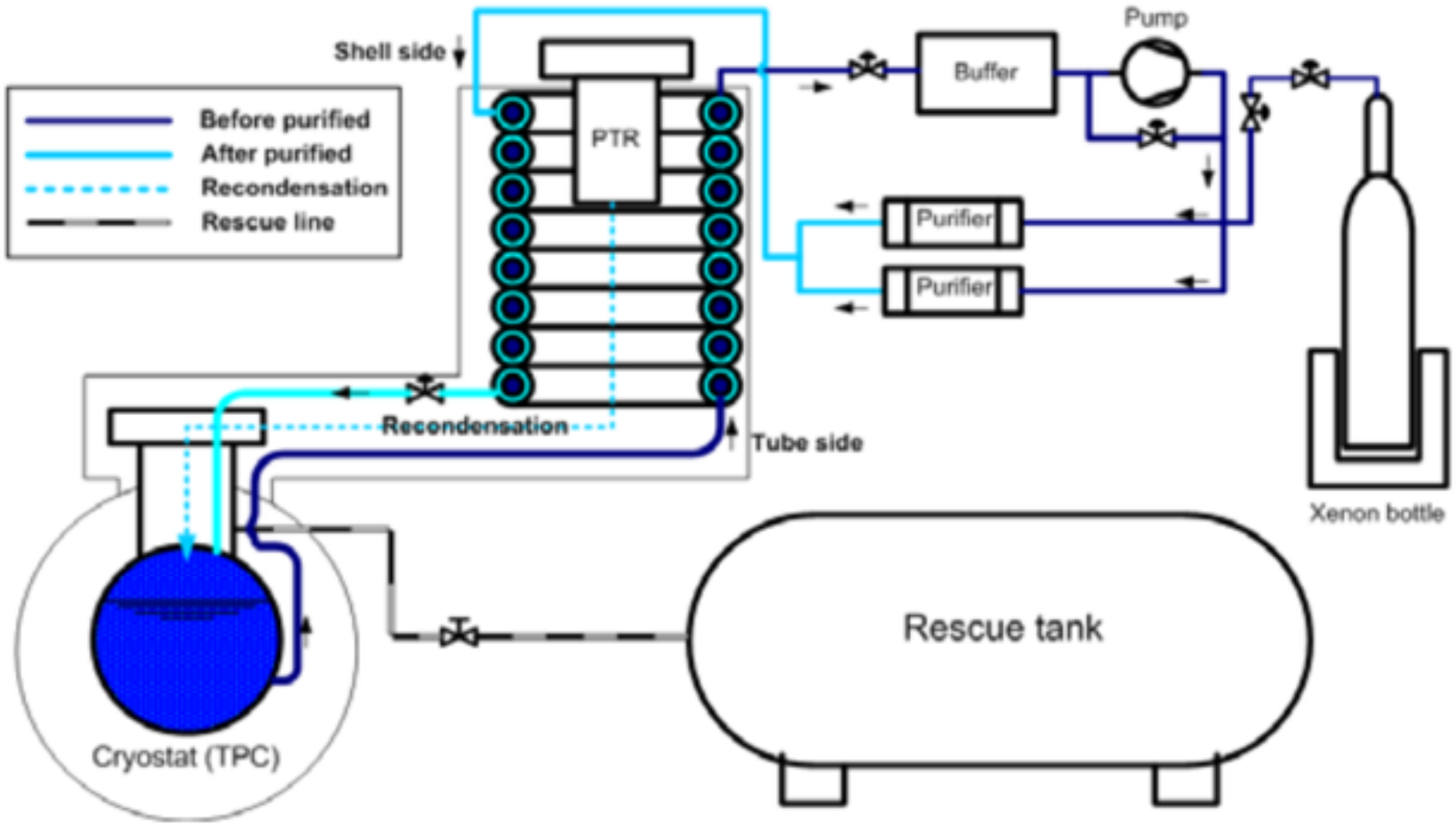
Haruyama et al., 2000

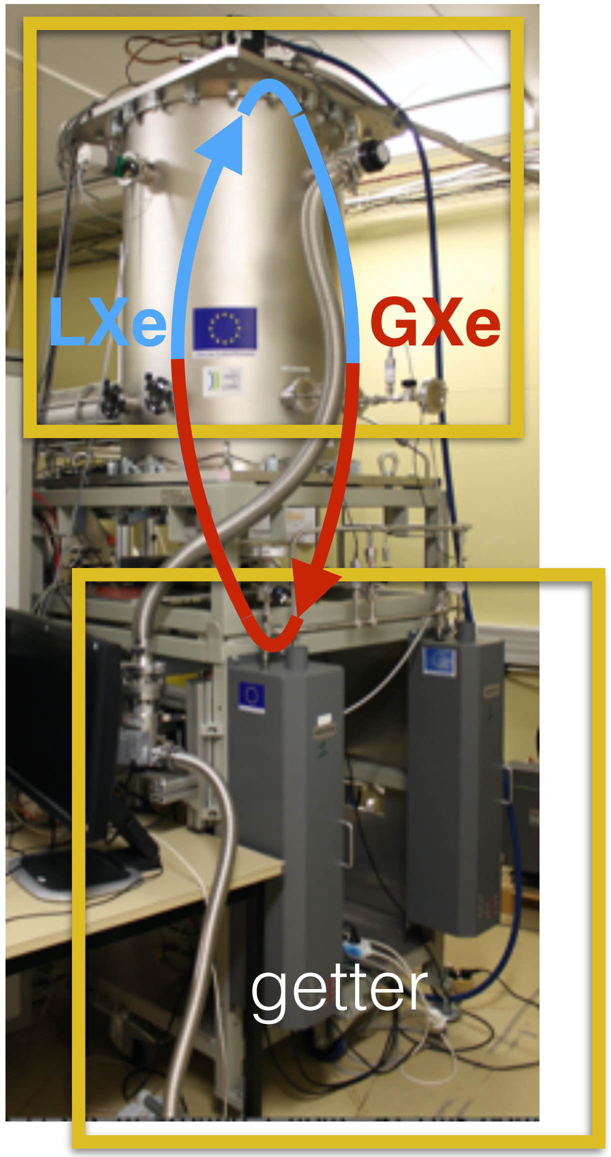


- Pre-cooling : < 1 day
- Liquefaction: 1 day
- Liquefaction rate : ~ 6 liters / min

Circulation and Purification

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





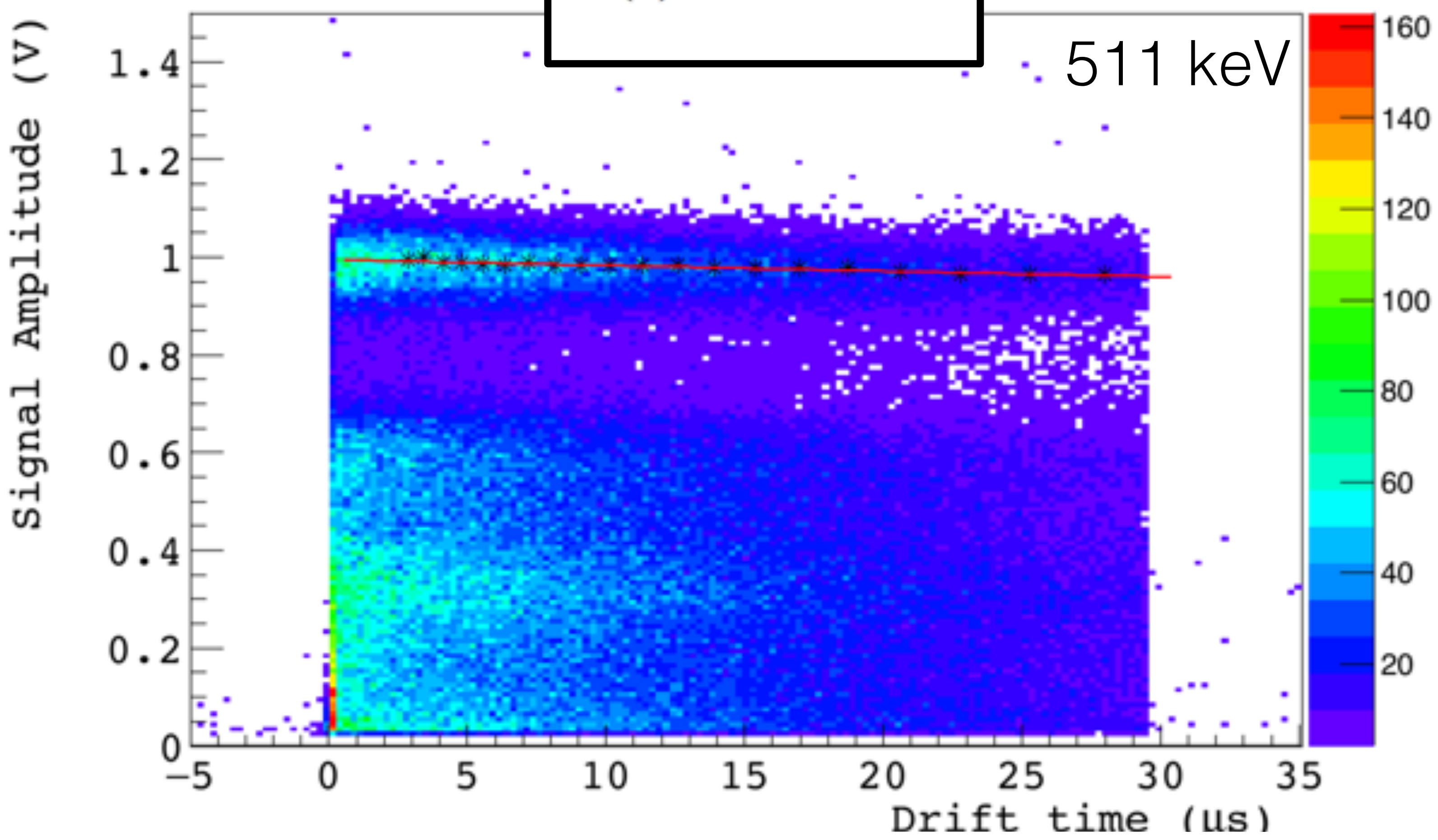
Purification rate: **30 liter/min**

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

Electron Attenuation Length

Electronegative impurities → electron loss during drift

$$Q(t) = Q_0 \, e^{\frac{-t}{\tau}}$$



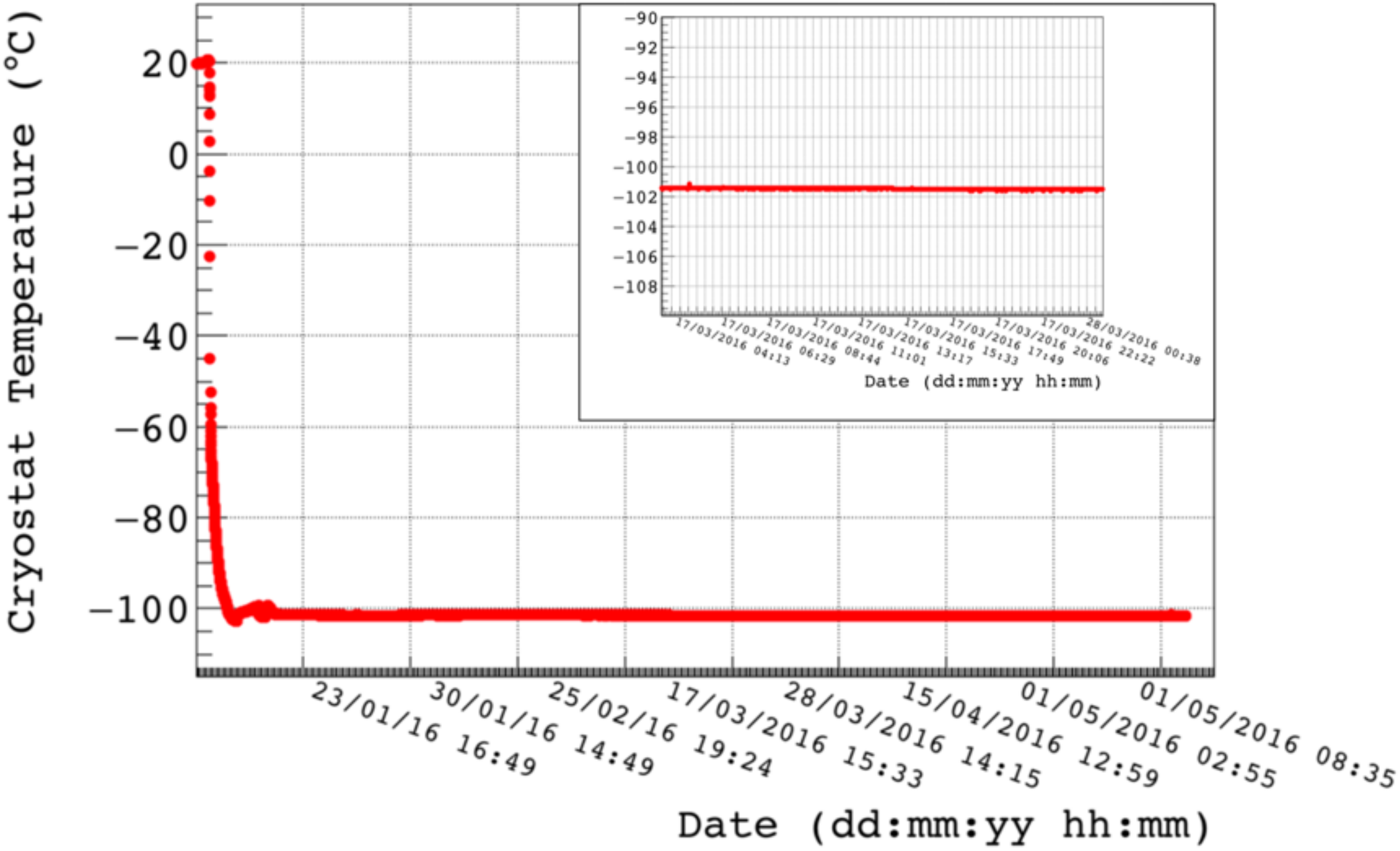
One week → Attenuation length >1 m

⬇

Concentration of 1 ppb O_2 equivalent

Temperature and Pressure Stability

Very good temperature and pressure stability during long data-taking periods



Temperature and Pressure Stability

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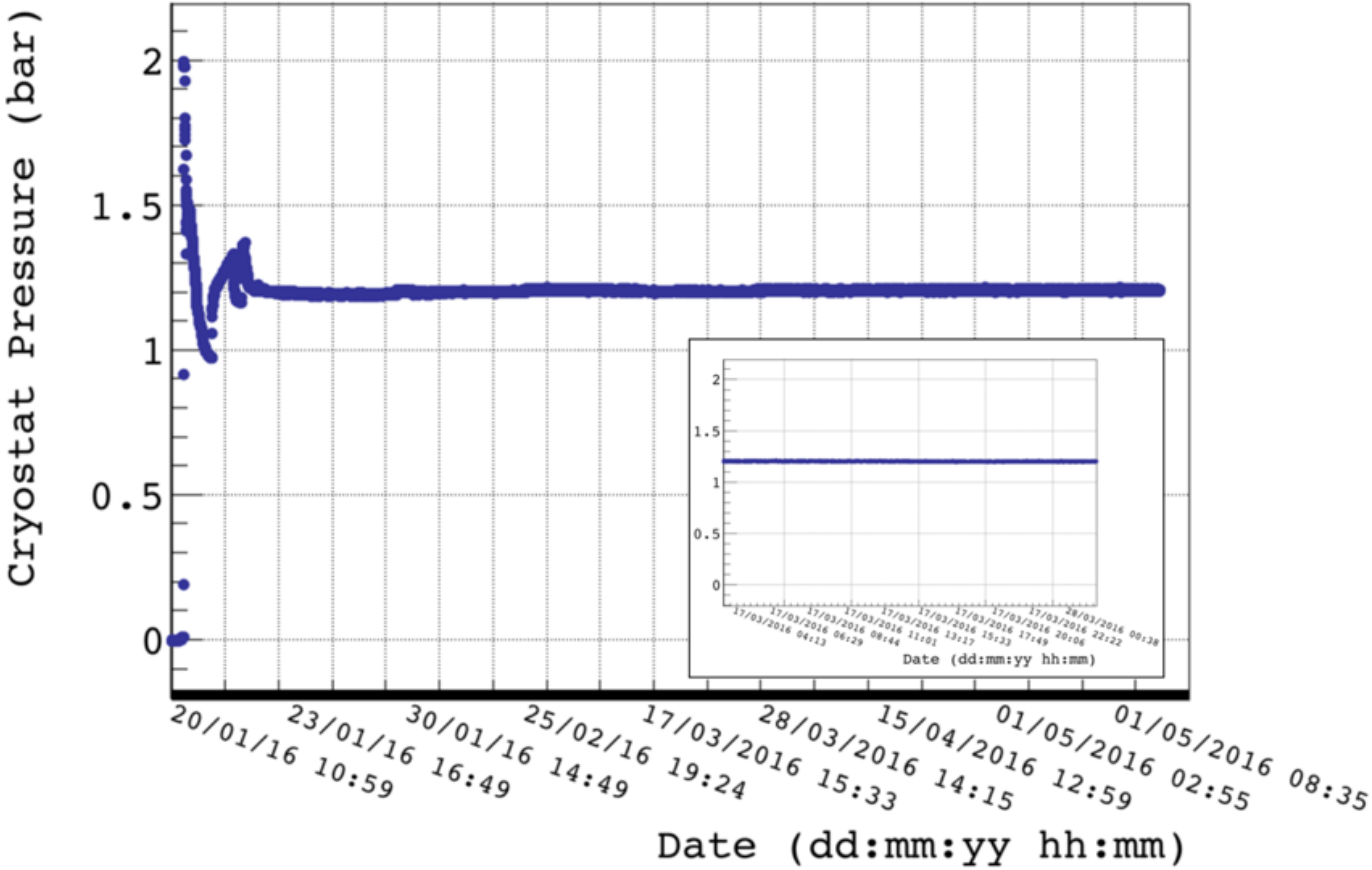
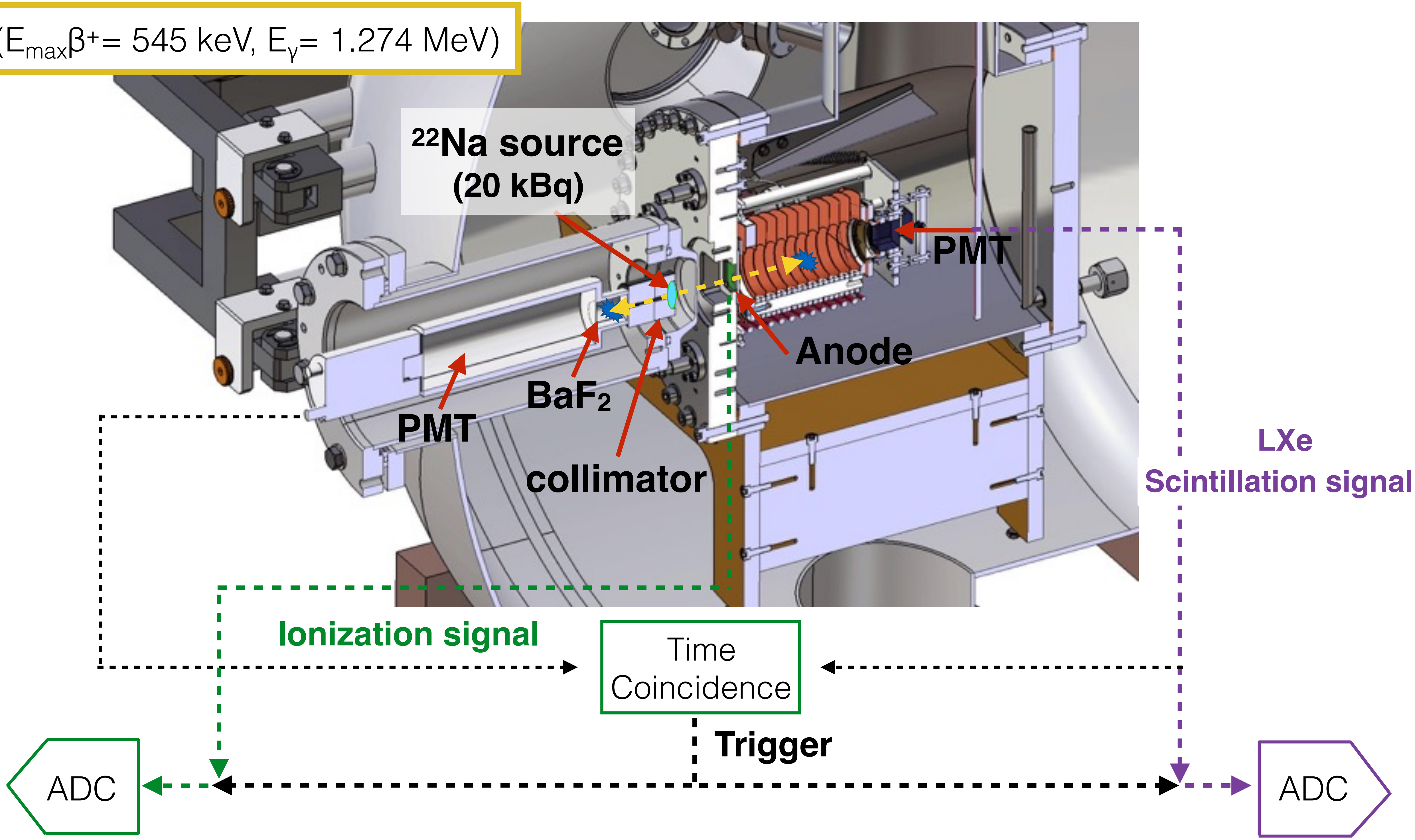


Experimental set-up @ 511 keV

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



^{22}Na source (20 kBq)

BaF$_2$

PMT

collimator

Anode

PMT

LXe Scintillation signal

Ionization signal

Time Coincidence

Trigger

ADC

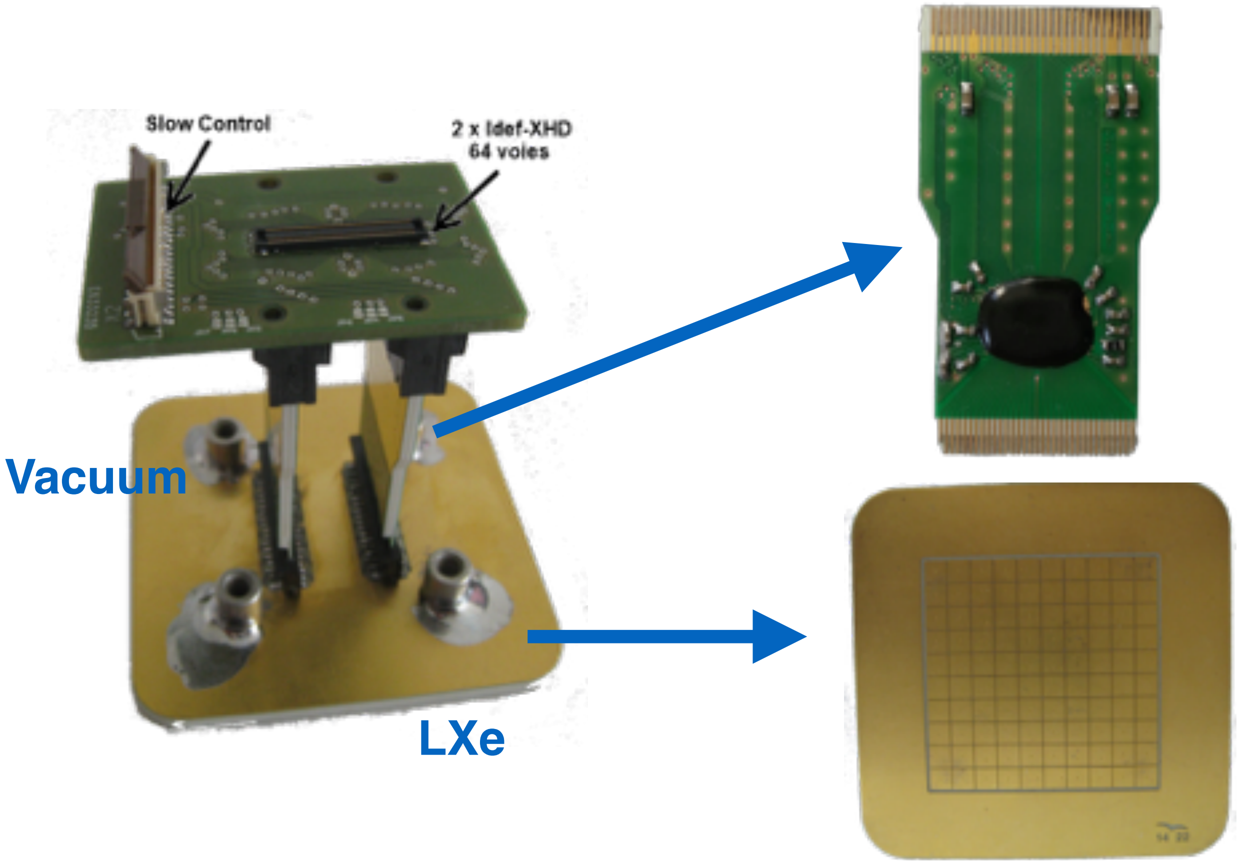
ADC

Sampling 80 ns
12.5 MHz digitizer

Sampling 4 ns
250 MHz digitizer

Ionization Signal Readout

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



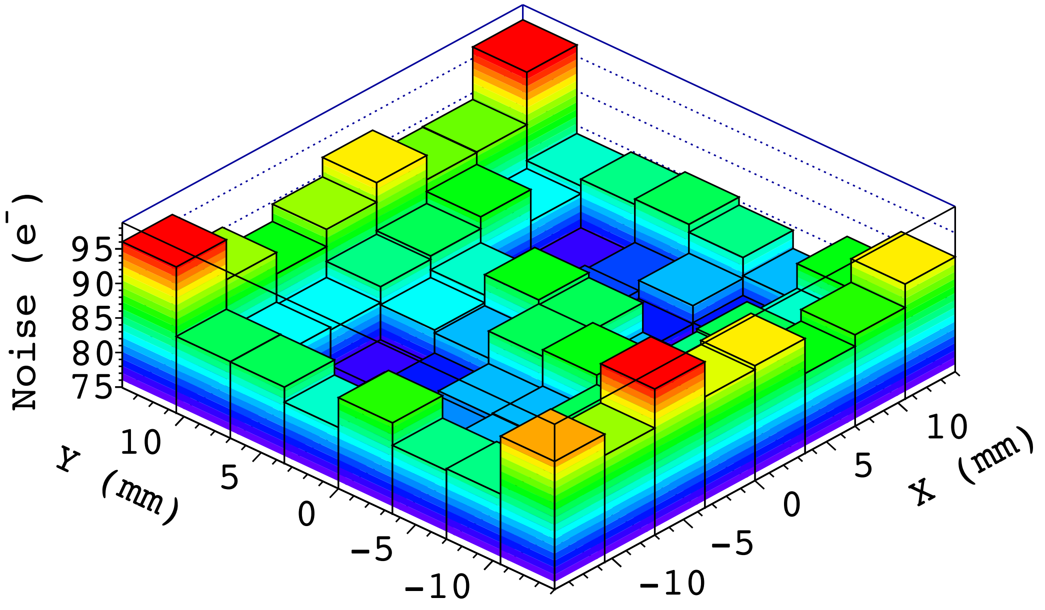
Anode 64 pixels
3.1 x 3.1 mm^2

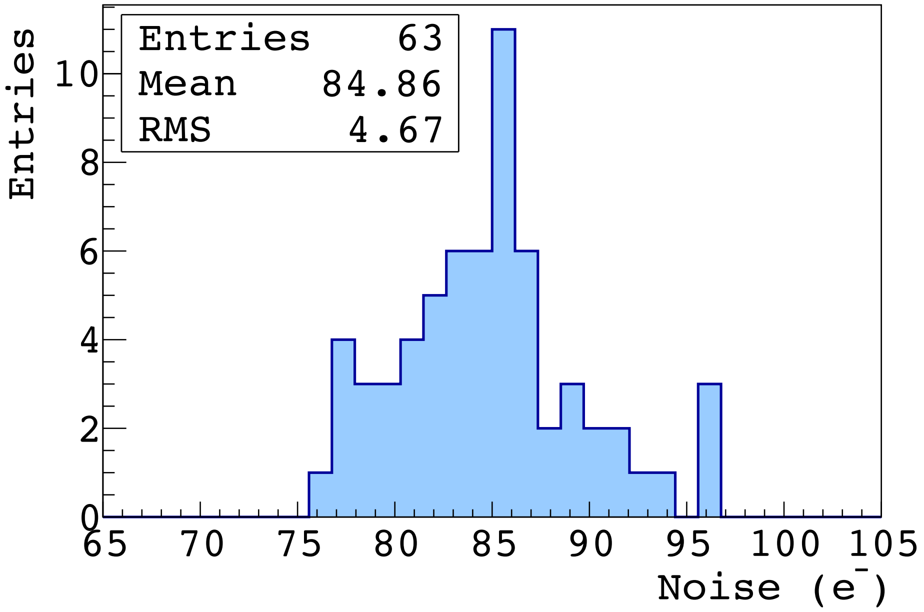
- Ultra low noise front-end electronics
- 32 channels per IDeF-X HD LXe
- Two chips → **one channel per pixel**

Good linearity and stability

Noise: 85 +/- 5 e^- (at LXe Temp)

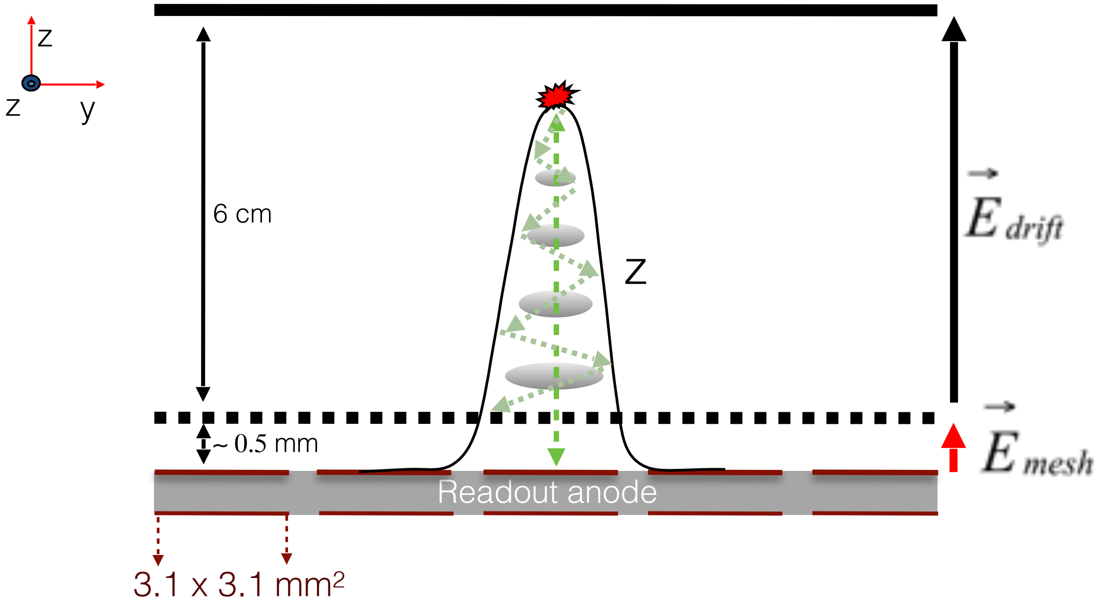
511 keV (@1 kV/cm) ⇒ 27200 e-





Electron Diffusion

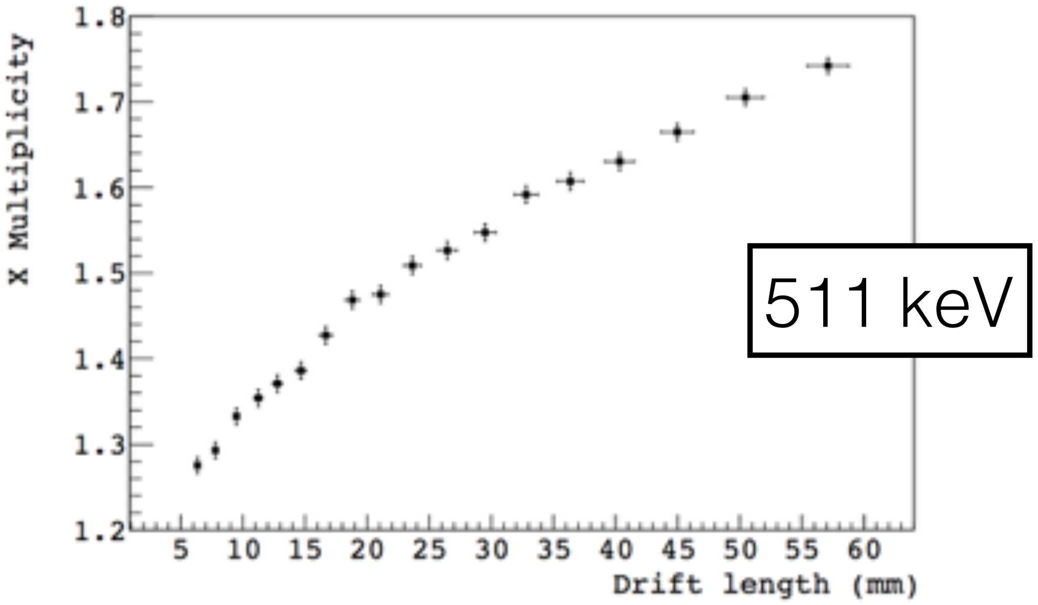
Electron Diffusion → Spread electron cloud → non-negligible probability that the electron cloud would fire multiple neighboring pixels



$$f(x,y) = \frac{1}{4\pi D_T.t_{drift}}\, exp\left(-\frac{x^2+y^2}{4D_T.t_{drift}}\right)$$

D_T : diffusion coefficient

Spread electron cloud: $\sigma_t = \sqrt{2\, D_T\, t_{drift}}$

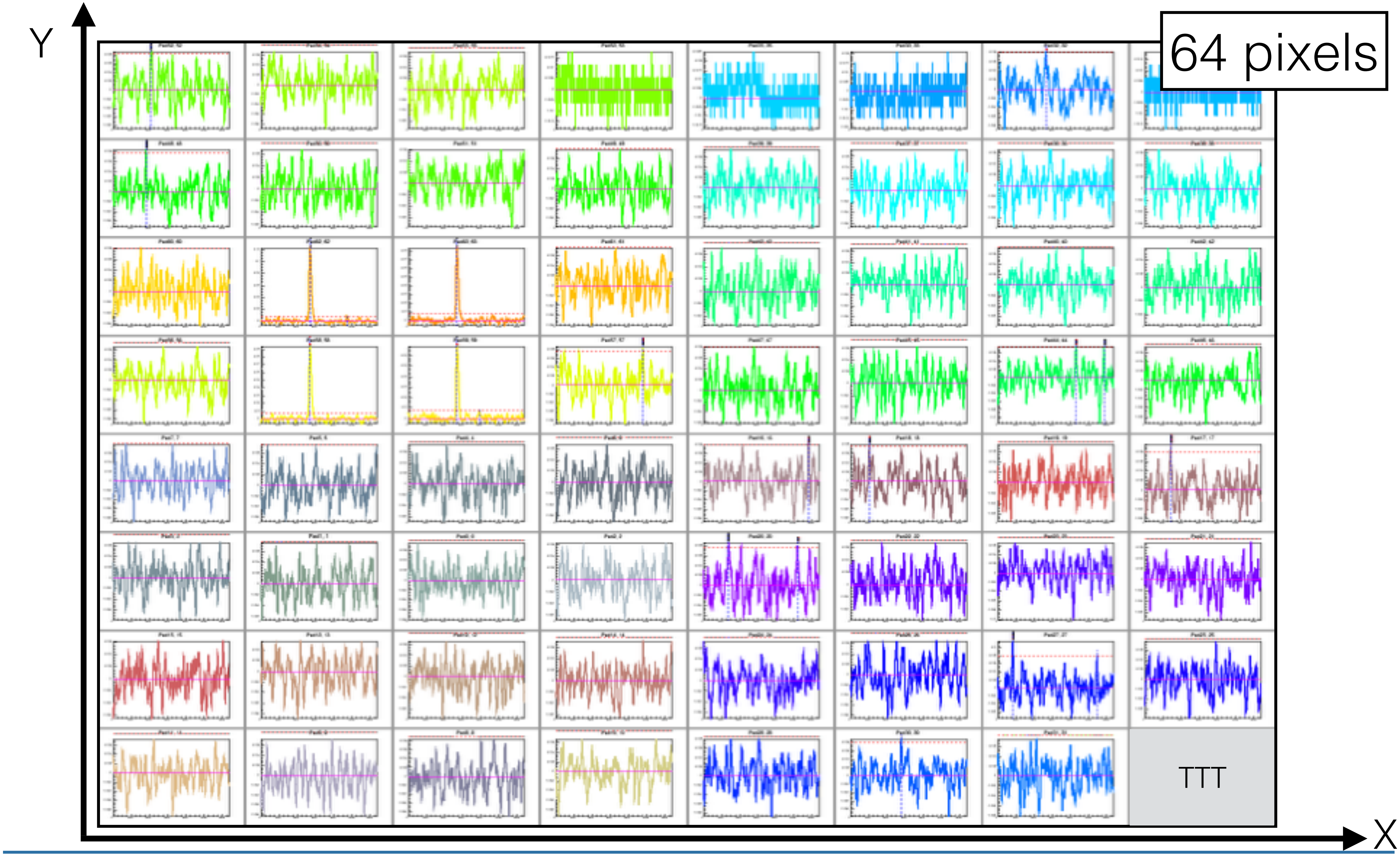


Transverse diffusion (@1kV/cm)

σ_t ~ 200 µm x √(cm)

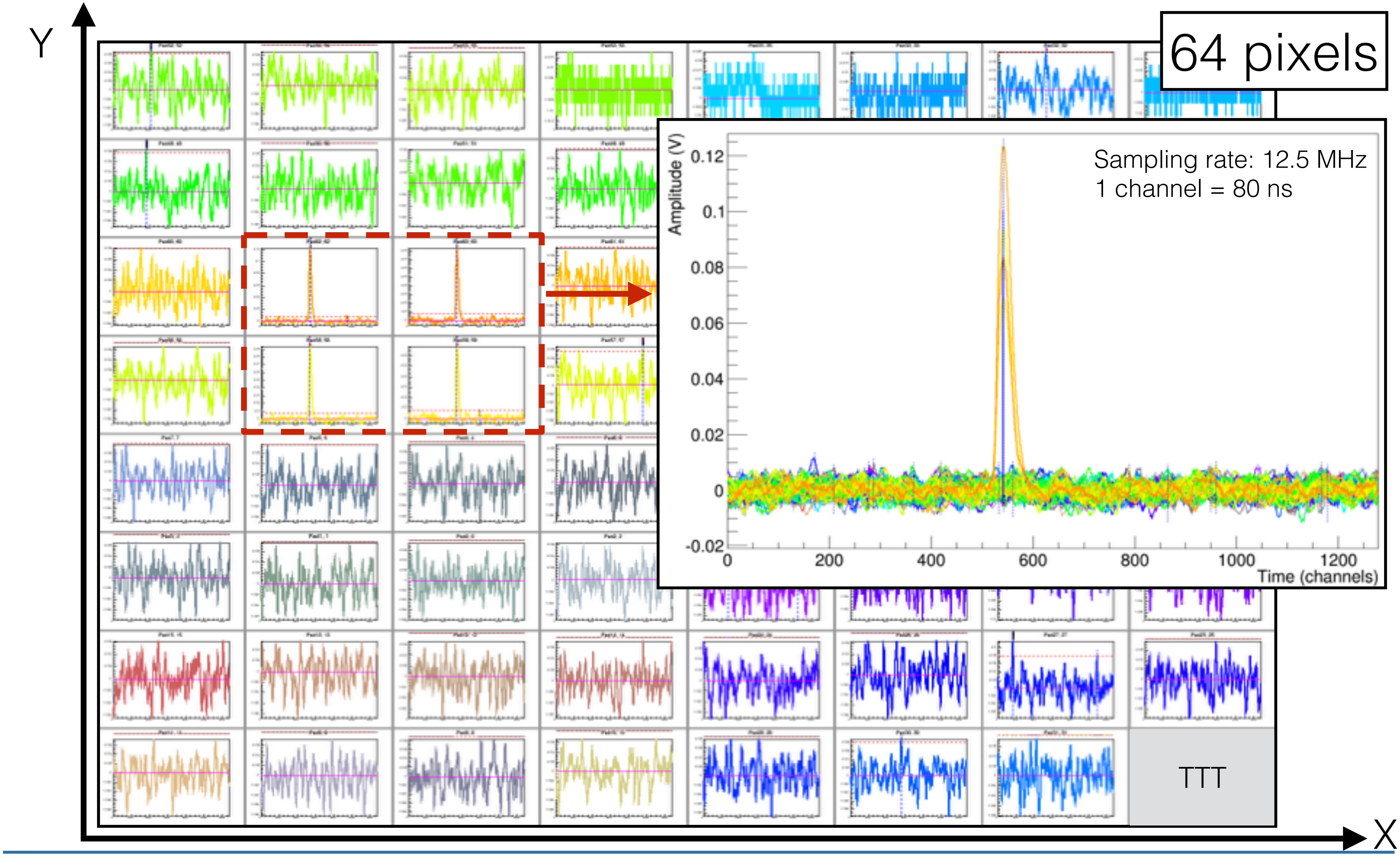
Event Topology @ 511 keV

Event reconstruction: Compton scattering /photoelectric effect identification



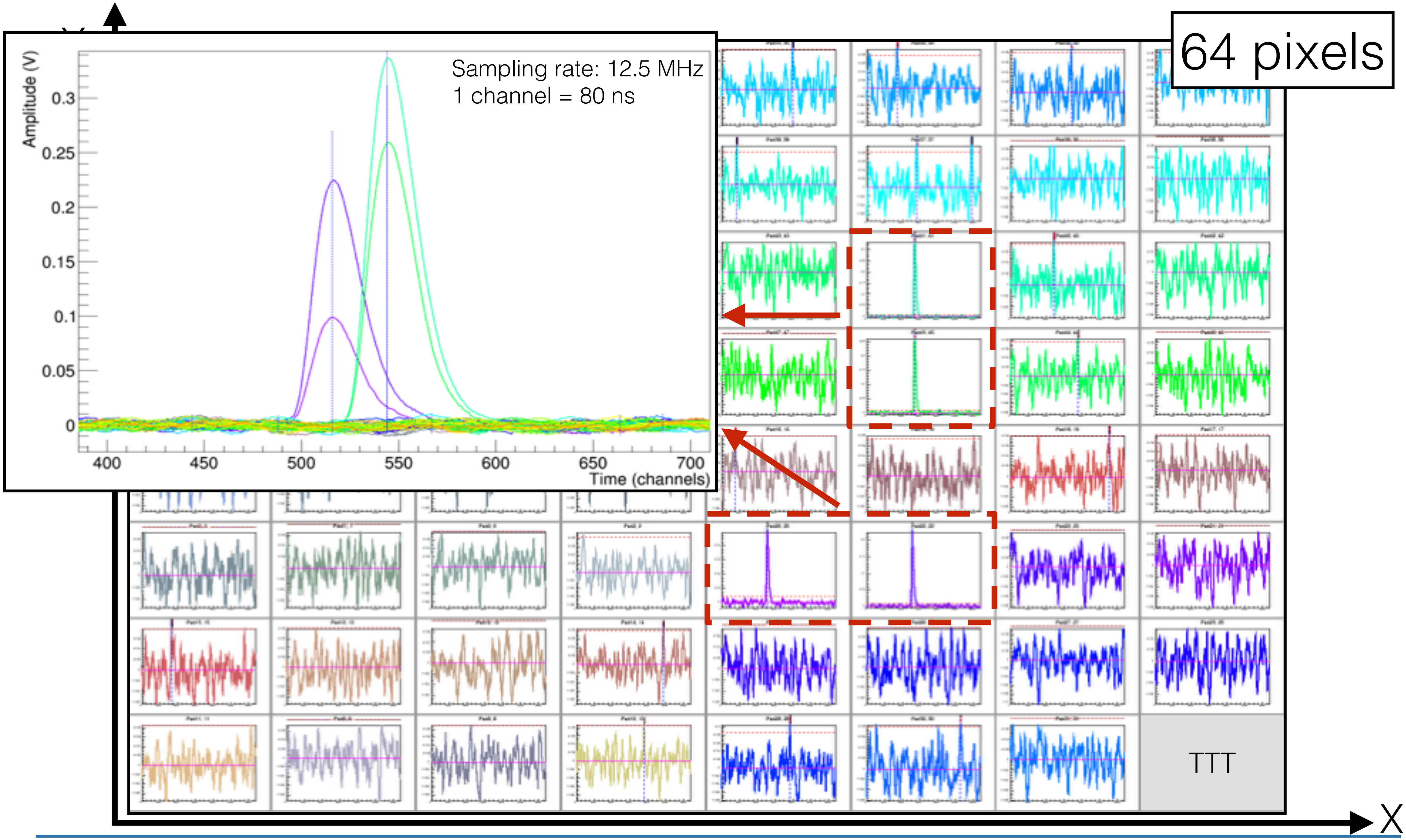
Event Topology @ 511 keV

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



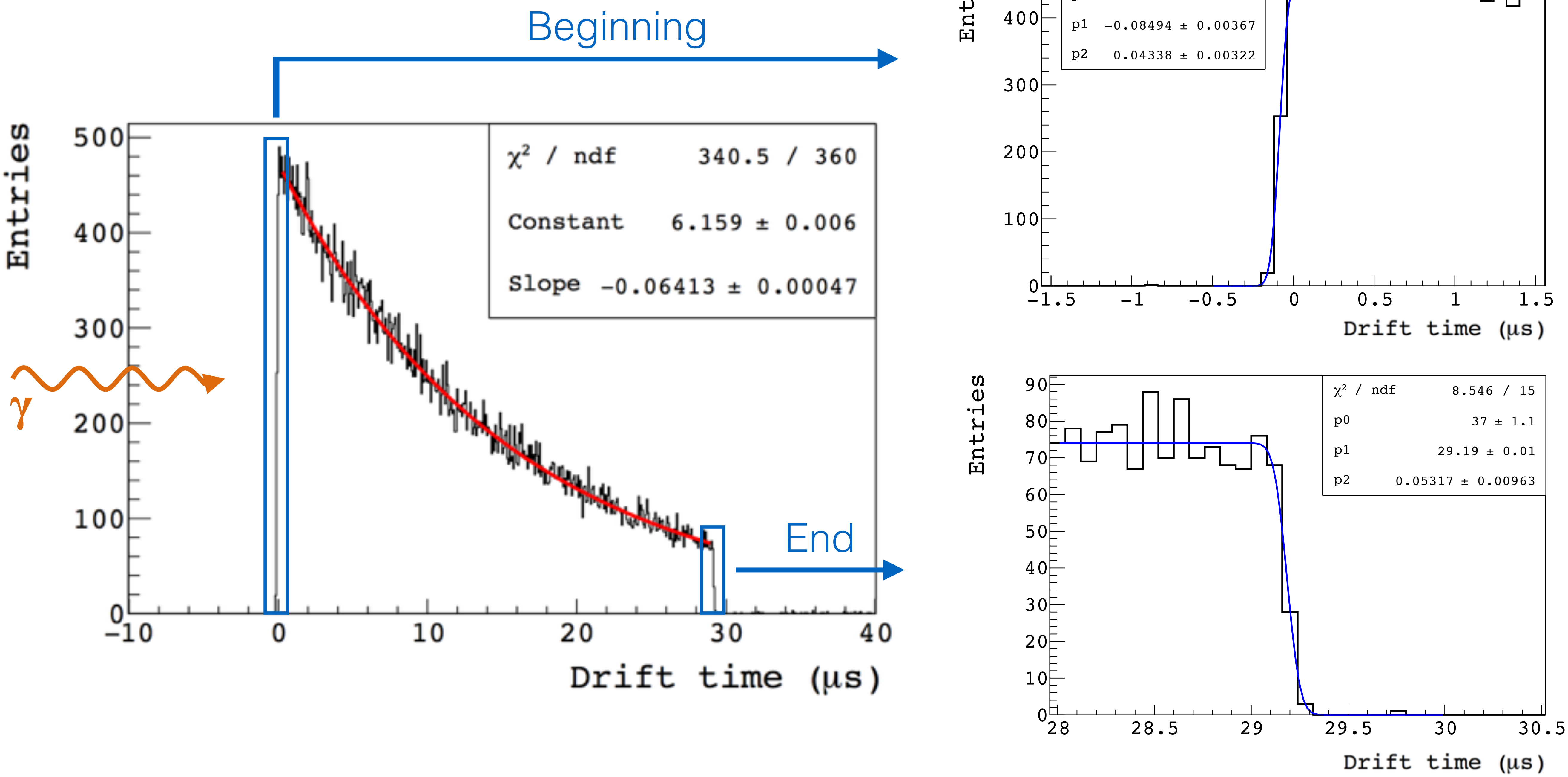
Event Topology @ 511 keV

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



Depth of Interaction @ 511 keV

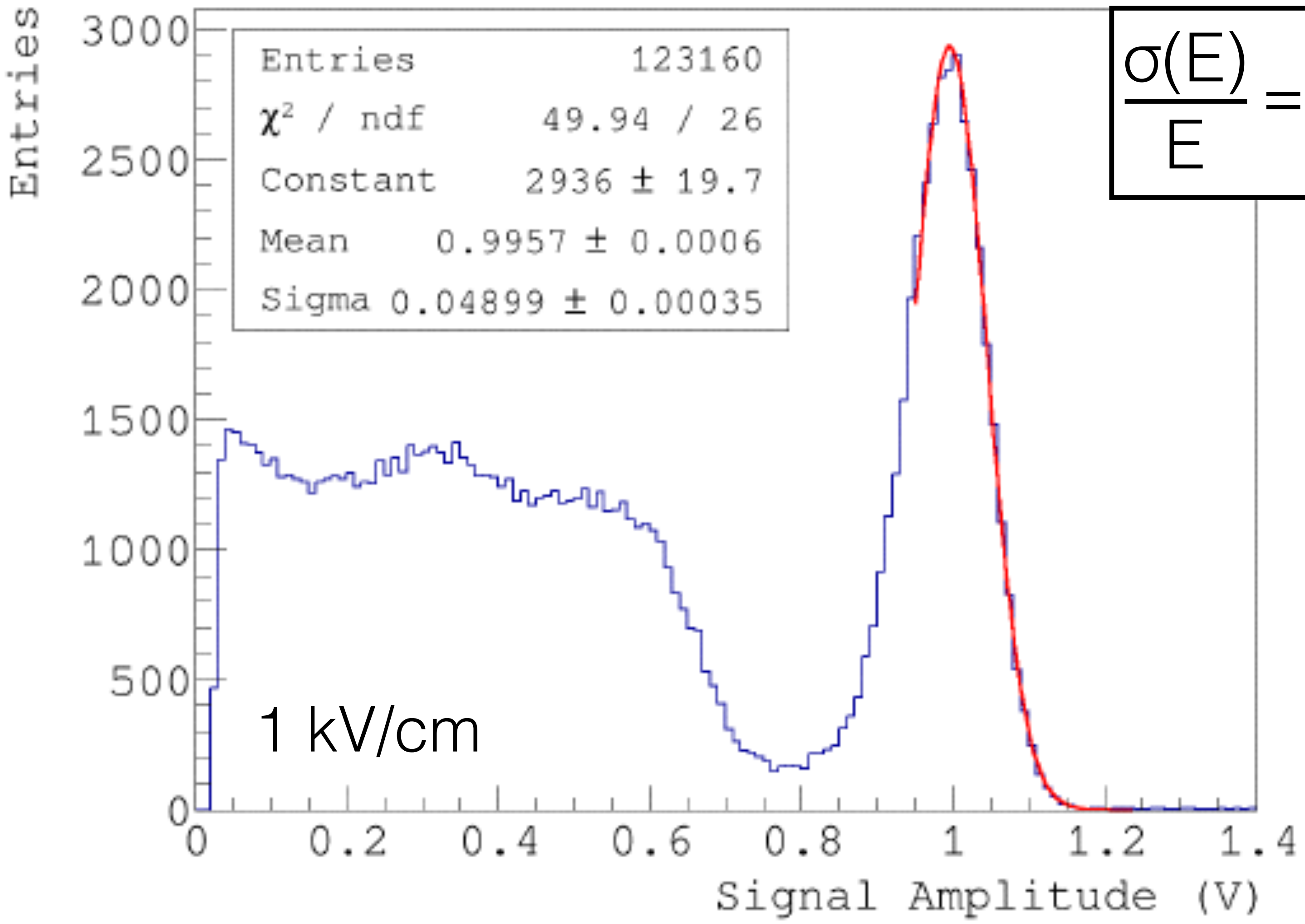
Photoelectric events @ 511 keV and 1 kV/cm



Drift time resolution: ~ 50 ns

Z resolution: ~ 100 μm

Energy Resolution@ 511 keV



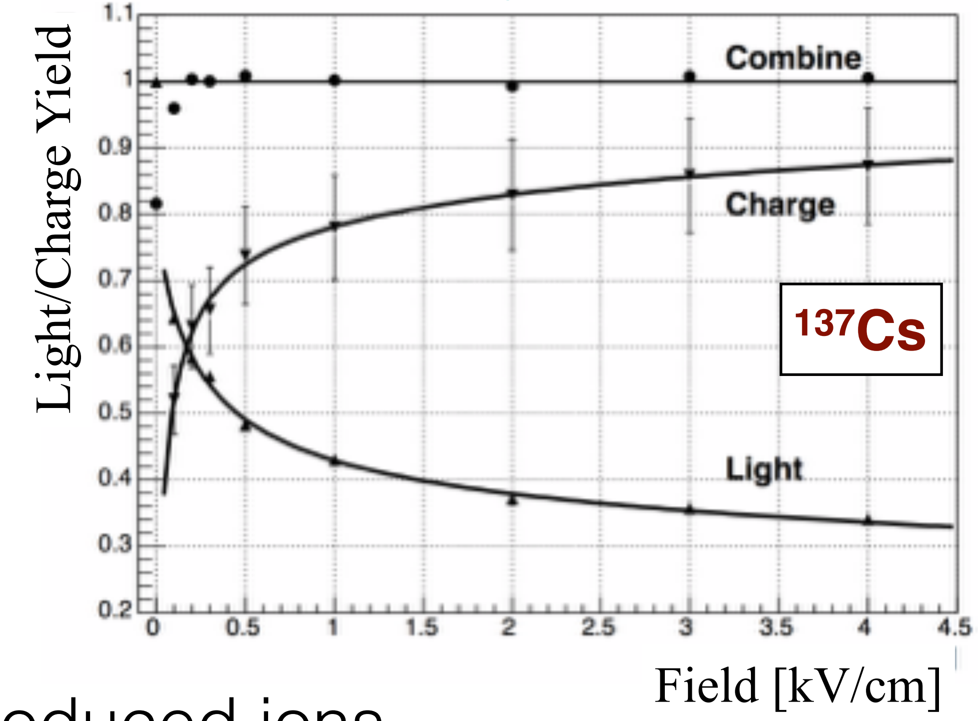
$$\frac{\sigma(E)}{E} = 4.92 \pm 0.04\ \%$$

Excellent energy resolution measured with the ionization signal in LXe

Electron-Ion Recombination

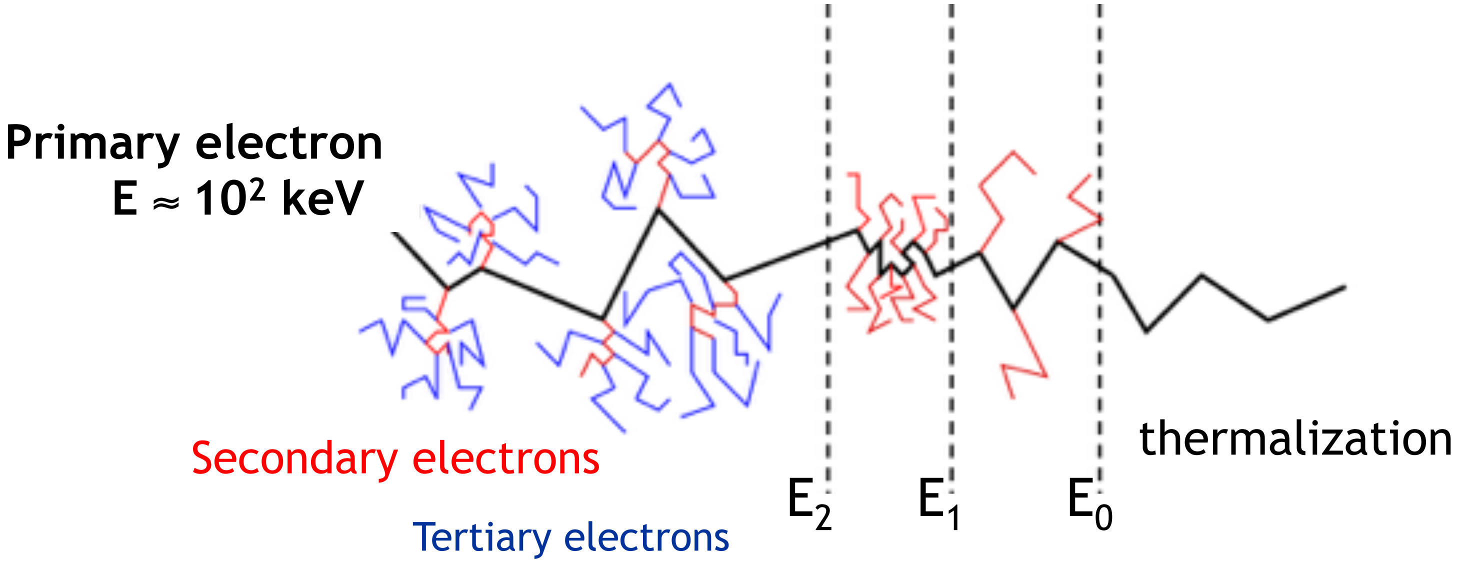
- Electron-ion recombination ⇒ loss of primary ionisation
- Fraction of light and charge depends on:
  - Density of ionisation
  - **Applied electric field**
  - Deposited energy

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



Recombination in LXe:

Thomas and Imel model: depends on the number of produced ions



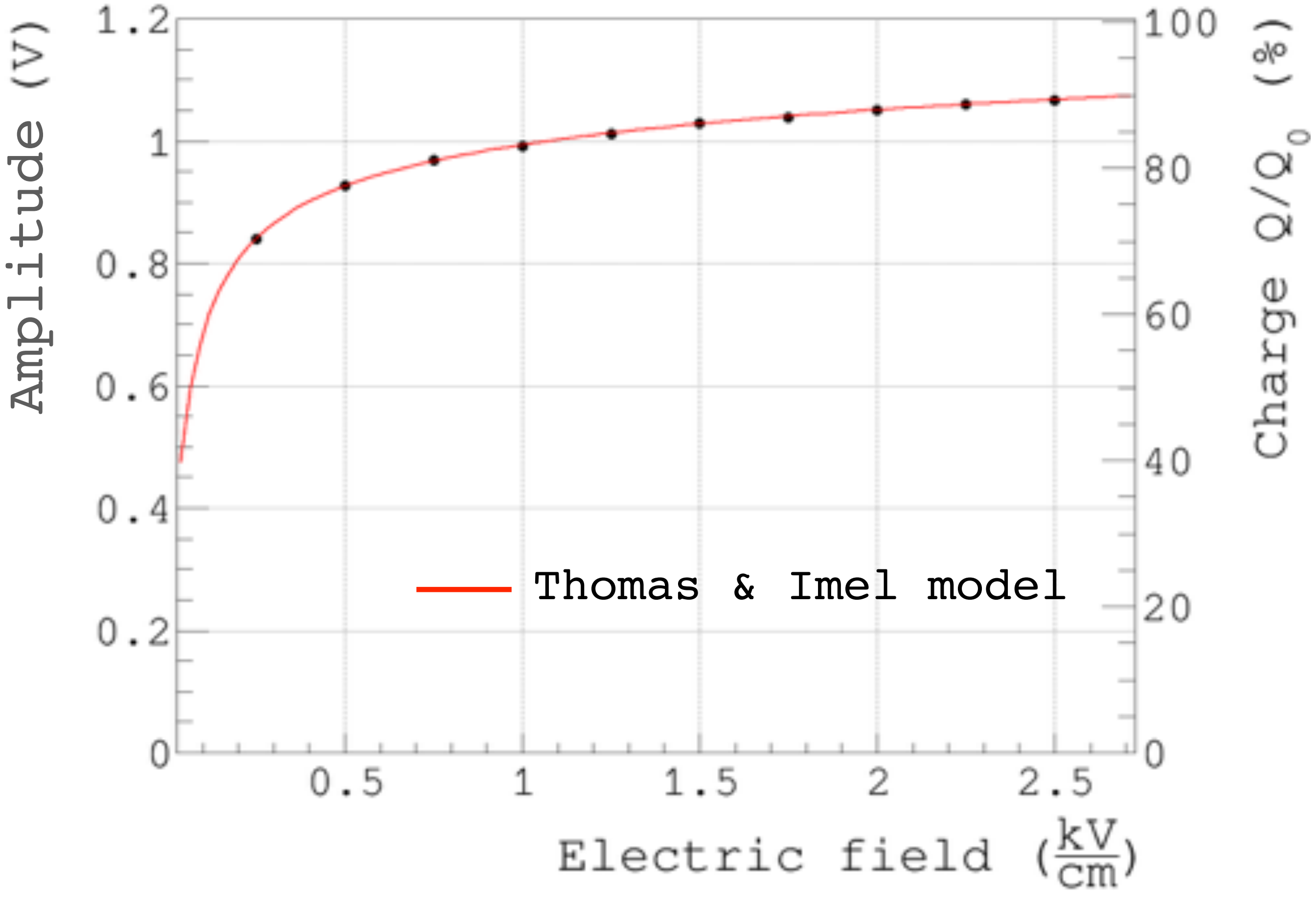
$E_0 \approx 5$ eV
$E_1 \approx 5$ keV
$E_2 \approx 20$ keV

Thomas et al. 1989 Phys. Rev. A

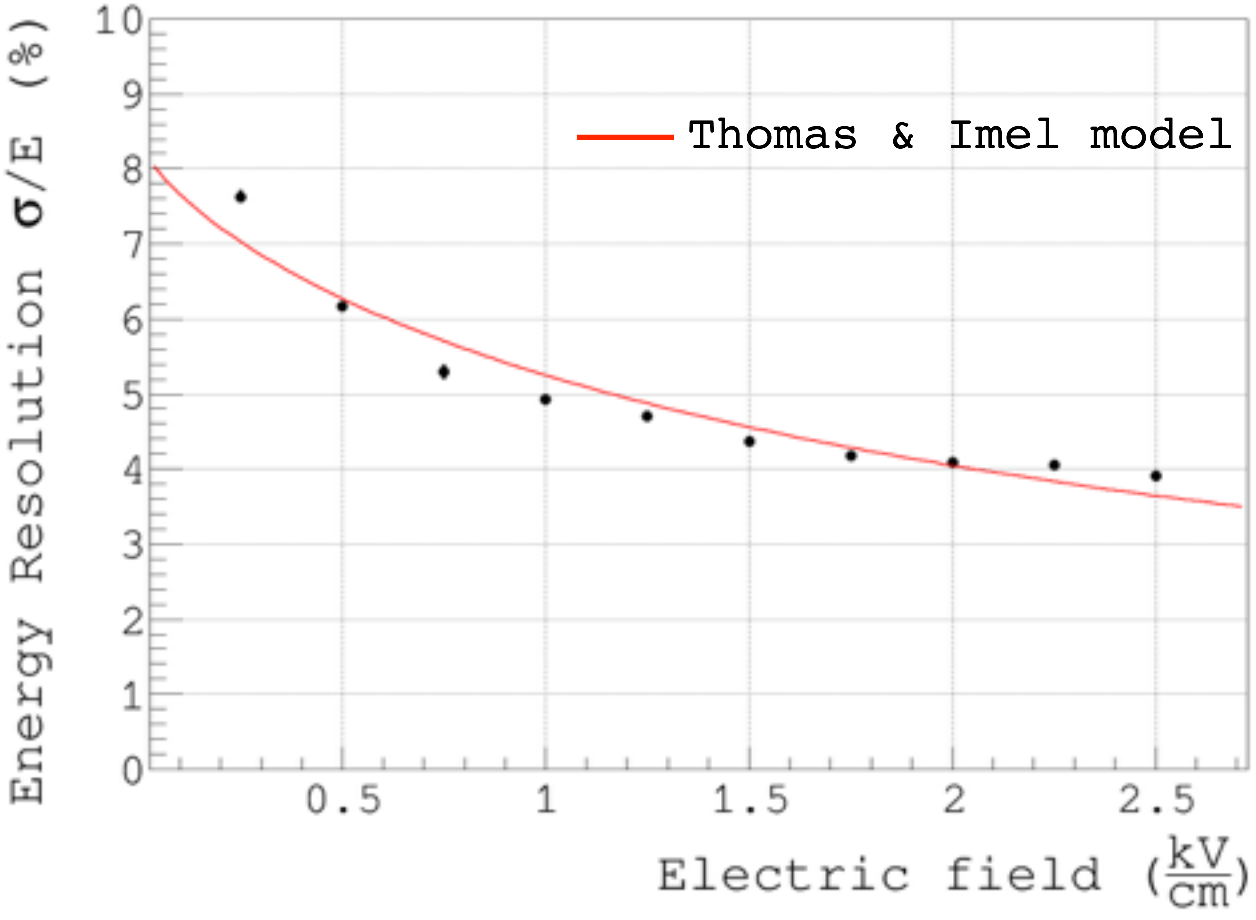
Adapted from T. Oger, 2012

Electric Field Dependence

Ionization charge yield



Energy resolution σ(E)/E (%)



$$\boxed{\frac{\sigma(E)}{E} = 3.92\ \%\ \text{at}\ 2.5\ \text{kV/cm}}$$

Recombination:

- Ionization saturates at high electric field (~10% recombination at 2 kV/cm)
- Energy resolution increases with the electric field

$Q_0 = E_0 / W$ with W average energy to create an electron-ion pair (15.6 eV in LXe)

Electron-Ion Recombination

NEST: The Noble Element Simulation Technique

Recombination model depends on the energy:

Thomas-Imel model: short tracks (low energy):

number of electrons

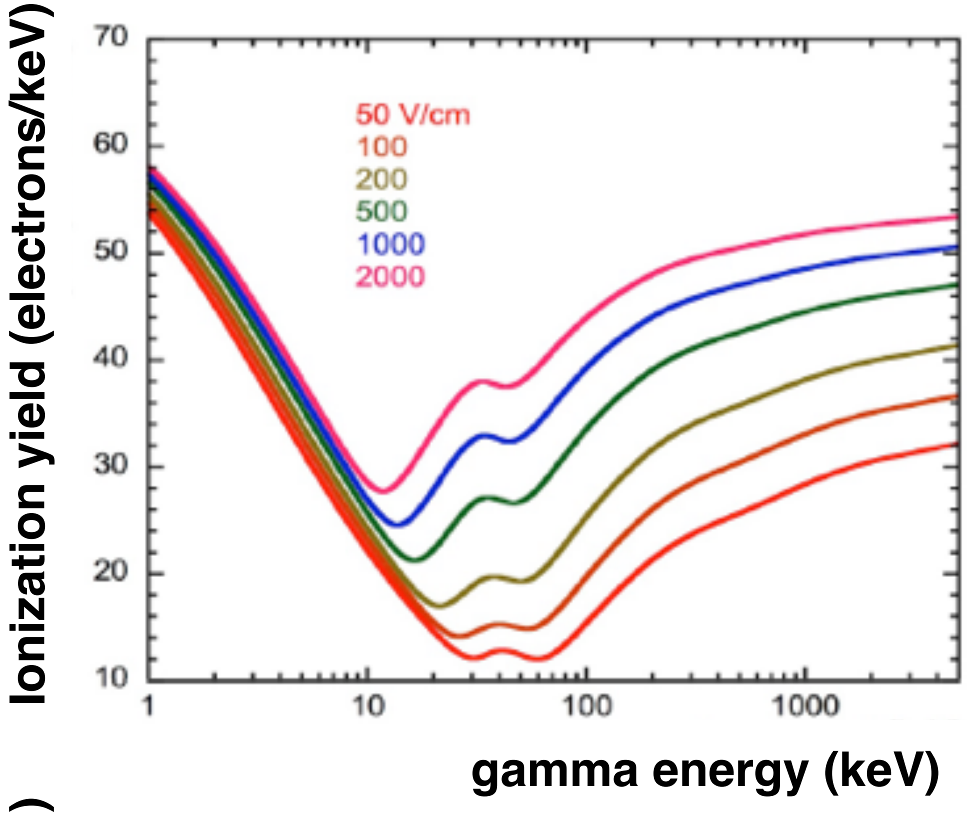
$$r = 1 - \frac{\ln(1+\xi)}{\xi}, \quad \xi \equiv \frac{N_i \alpha'}{4a^2 v}$$

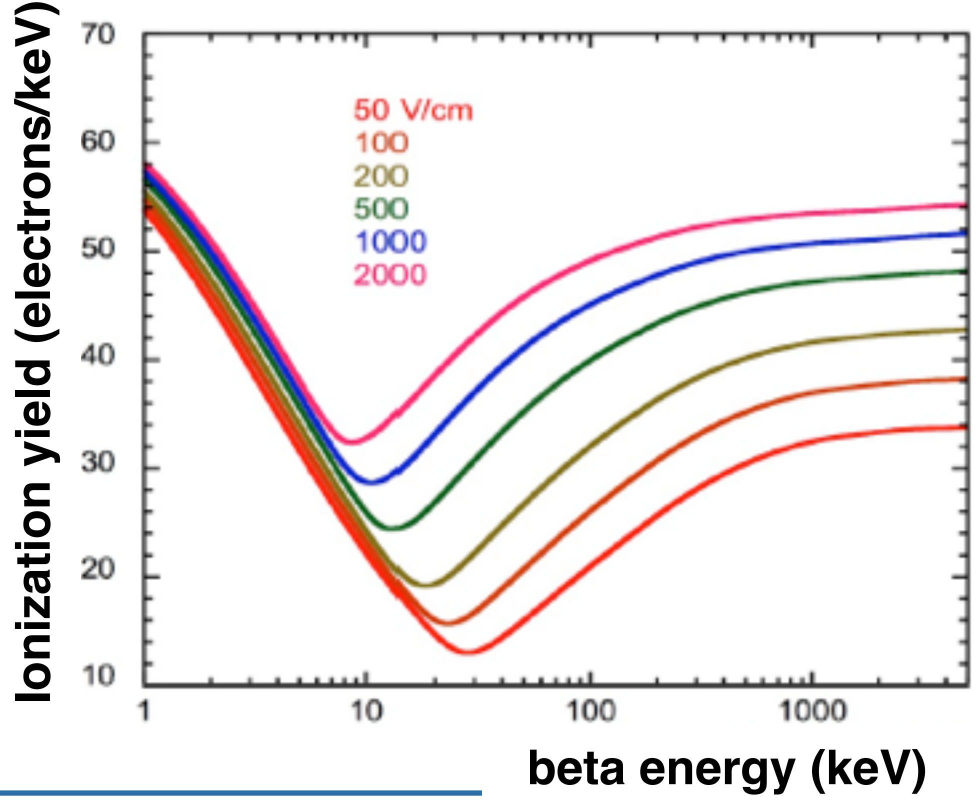
Doke-Birks law: long tracks (high energy):

energy loss

$$r = \frac{A\frac{dE}{dx}}{1+B\frac{dE}{dx}} + C, \quad C = 1 - A/B$$

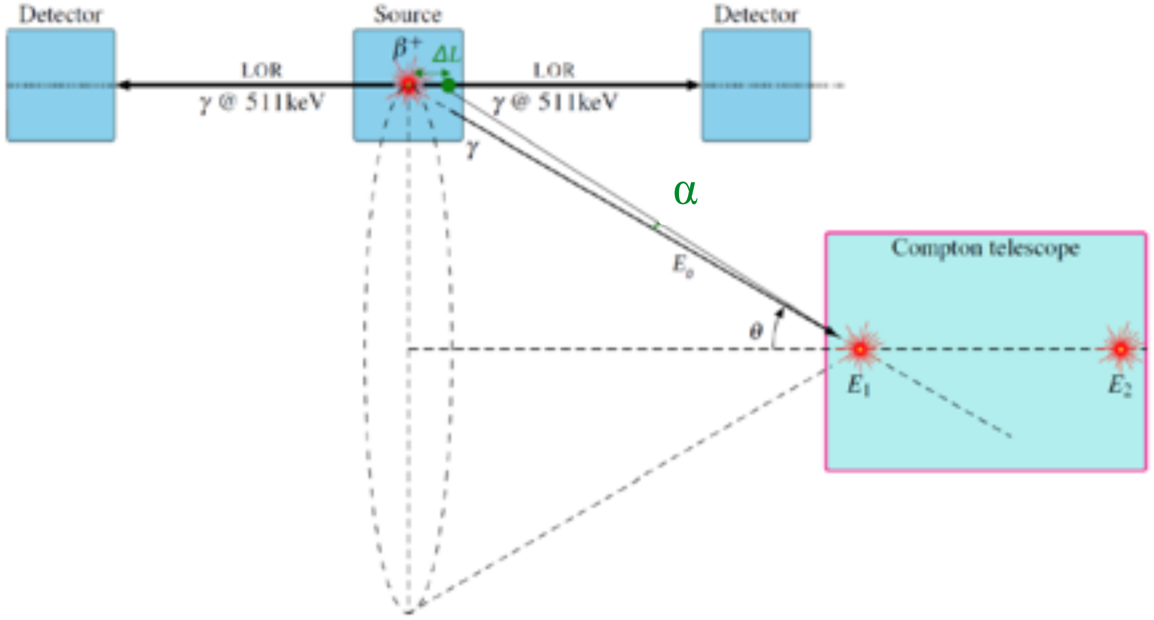
NEST, JINST (2011)





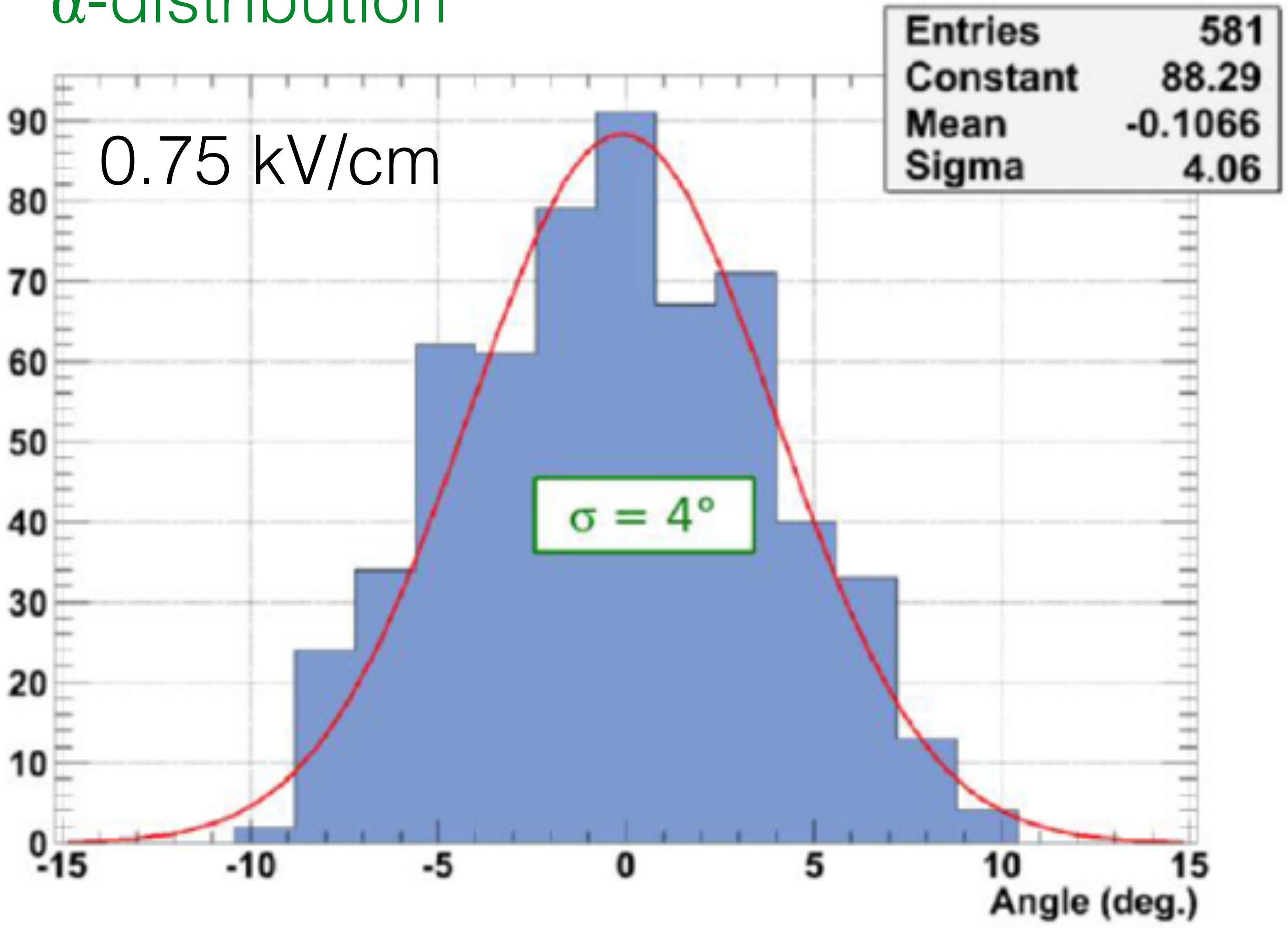
Angular Resolution

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

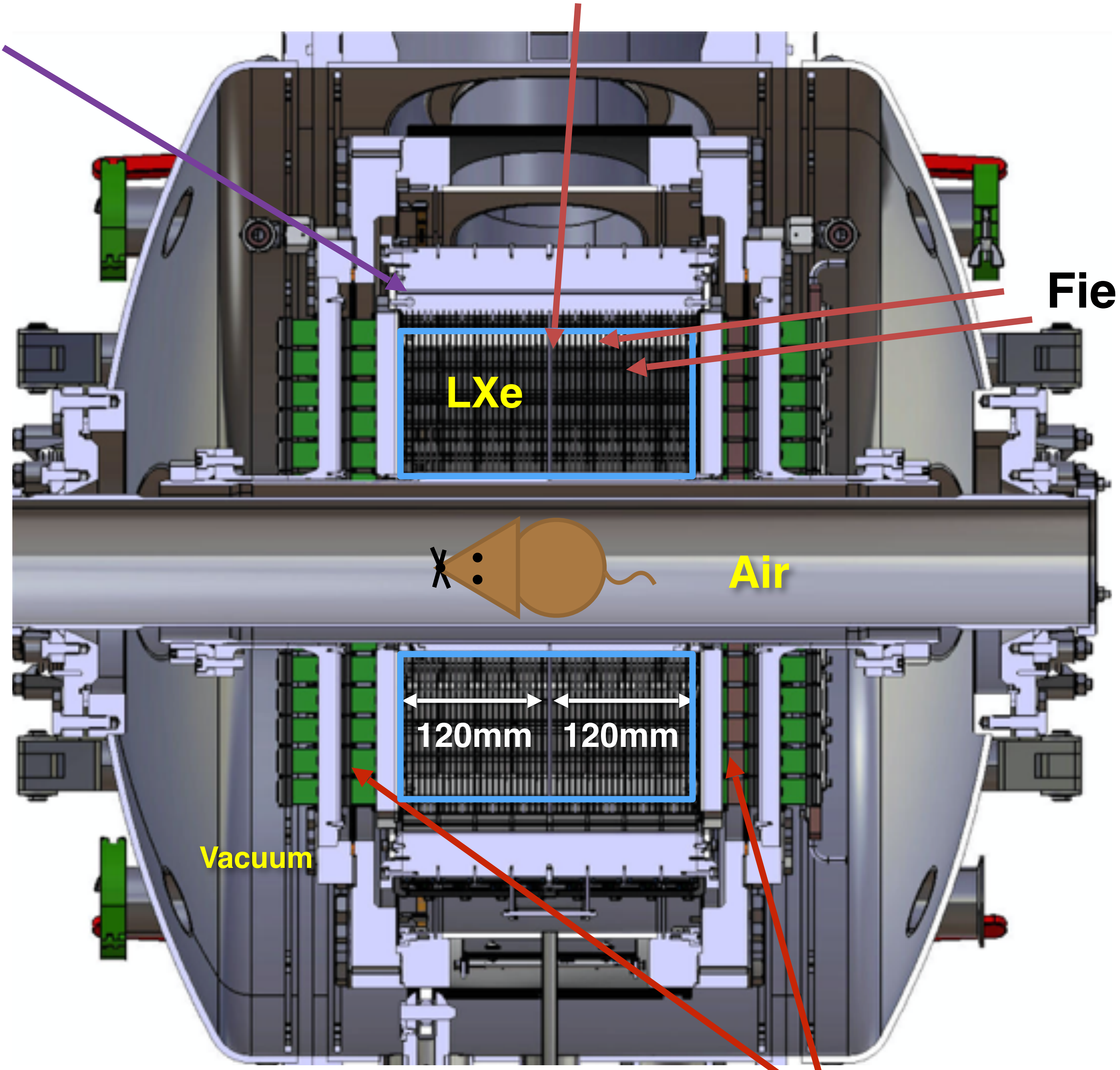
Equivalent to 8.2 mm (FWHM) for a 5 cm distant source

XEMIS2

LXe: 200 kg

Scintillation

380 x 1'' PMTs in LXe



LXe TPC

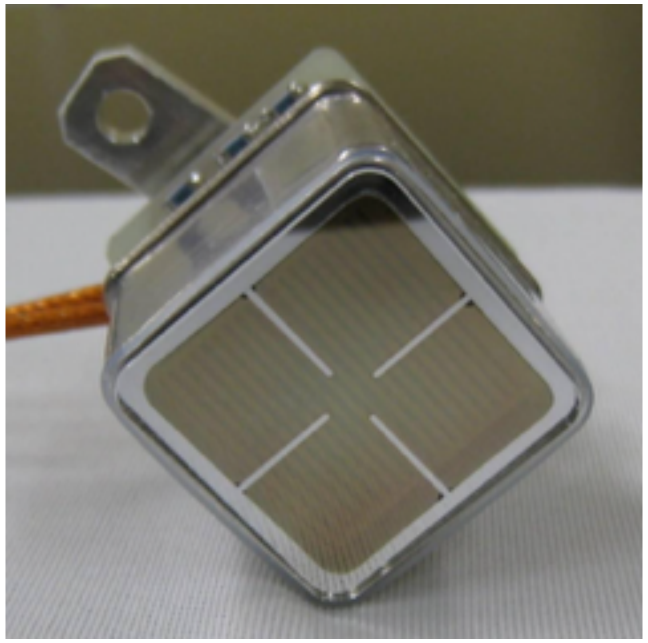
Active volume
- axial : 2 x 12 cm
- depth : 12 cm
- r_{min} : 7 cm

Ionization

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

XEMIS2: Light Signal

Hamamatsu R7600 1” PMT

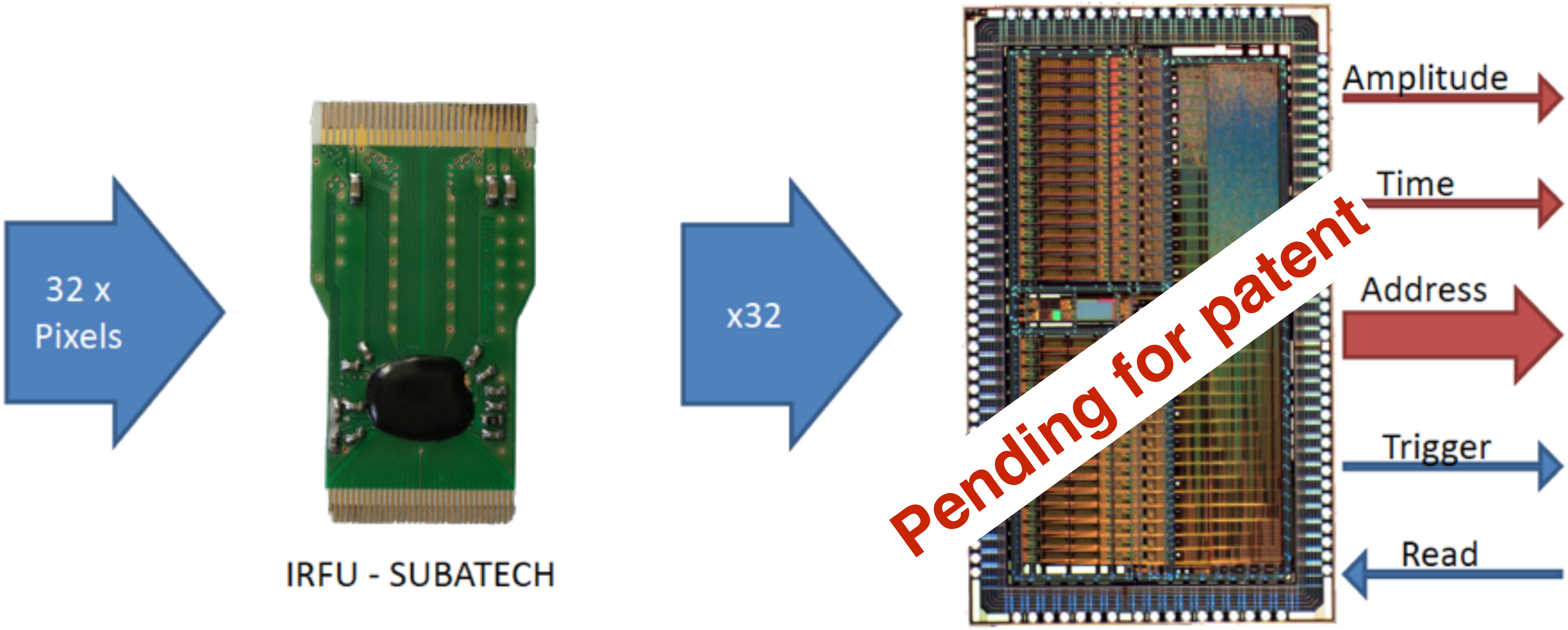


- Used as time measurement for the charge signal readout and interaction volume determination
- Developed to work at LXe temperature
- Temperature stability: Gain independent of temperature in the T = [-110, -106] °C range
- High gain and linear behavior with supply voltage between 760 to 900 V
- **Phase 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: Ionization Signal Readout

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

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



IRFU - SUBATECH

MICHRAU - SUBATECH

XTRACT v1 is on test. Final version expected for 2017

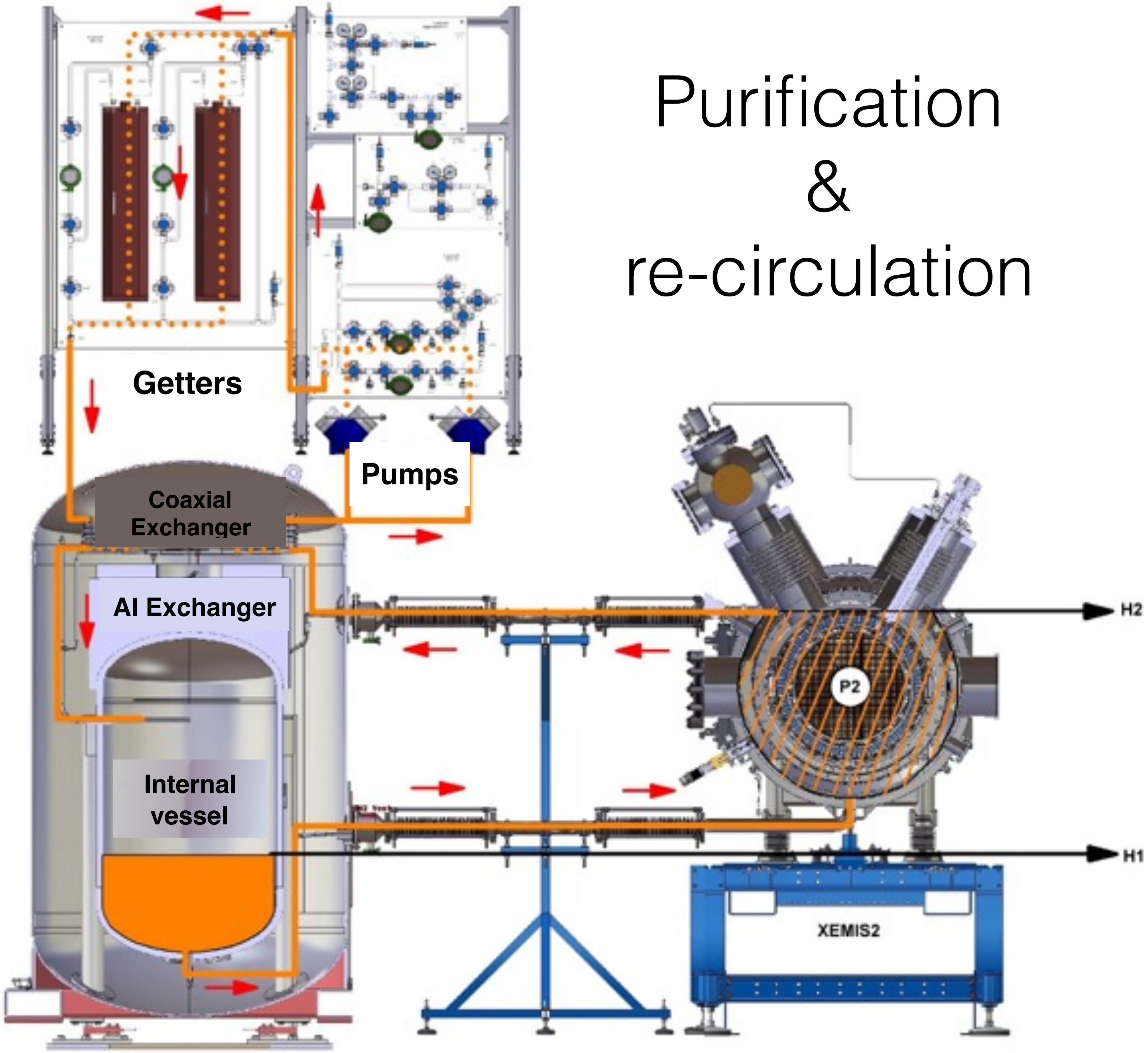
~20000 electronic channels
Challenge: continuous read-out with negligible dead-time

XEMIS2: Recovery and Storage of Xenon

ReStoX:
Recovery and Storage
system for LXe

- Compact (210 kg capacity)
  - \- storage
  - \- distribution
  - \- recovering
- Safe
  - \- from room temp. to -110 °C
- Ultra pure LXe at 1.2 bar
  - \- ppb impurities level

XEMIS2: purification and re-circulation

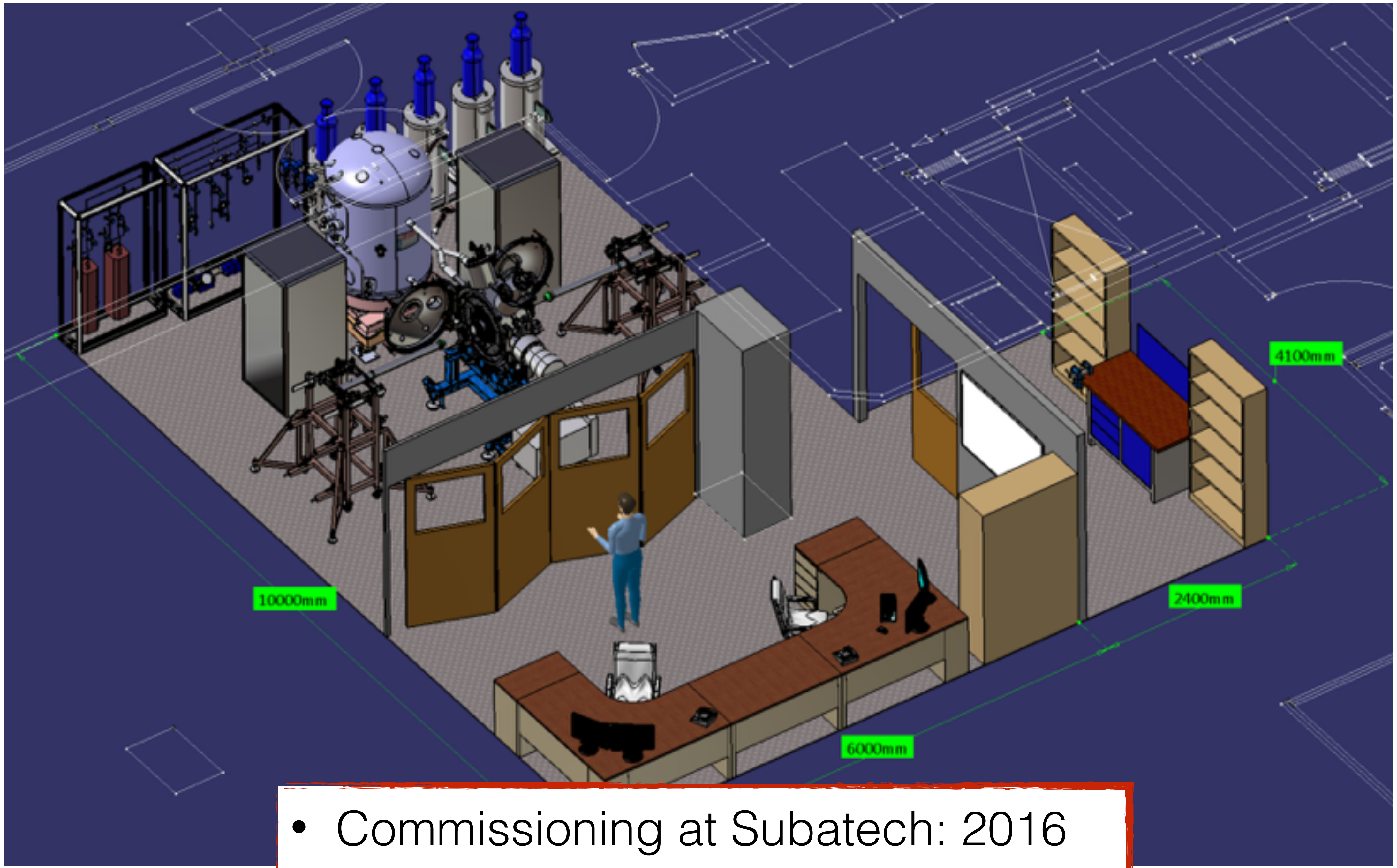


Purification
&
re-circulation

ReStoX

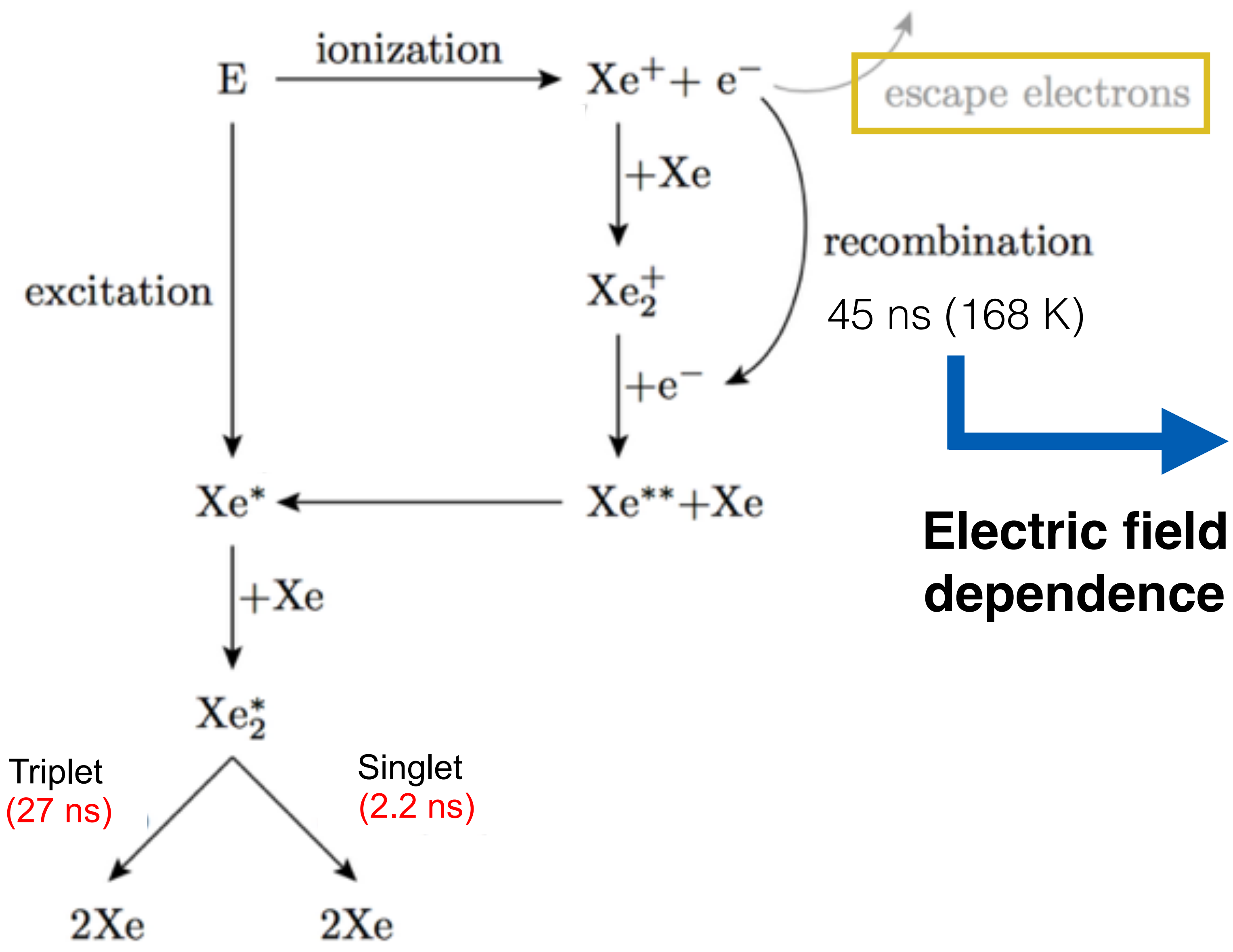
XEMIS2

Overview



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

Charge and Light in liquid xenon



E

ionization

$Xe^+ + e^-$

escape electrons

$+Xe$

Xe_2^+

recombination

45 ns (168 K)

$+e^-$

excitation

Xe^*

$Xe^{**} + Xe$

$+Xe$

Xe_2^*

Triplet (27 ns)

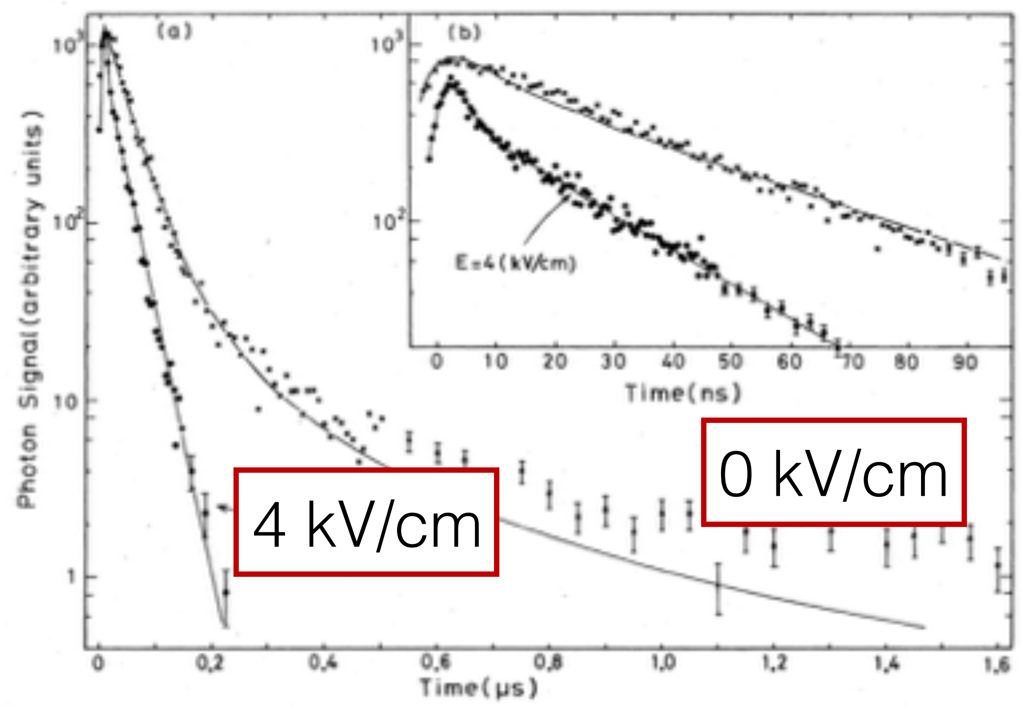
Singlet (2.2 ns)

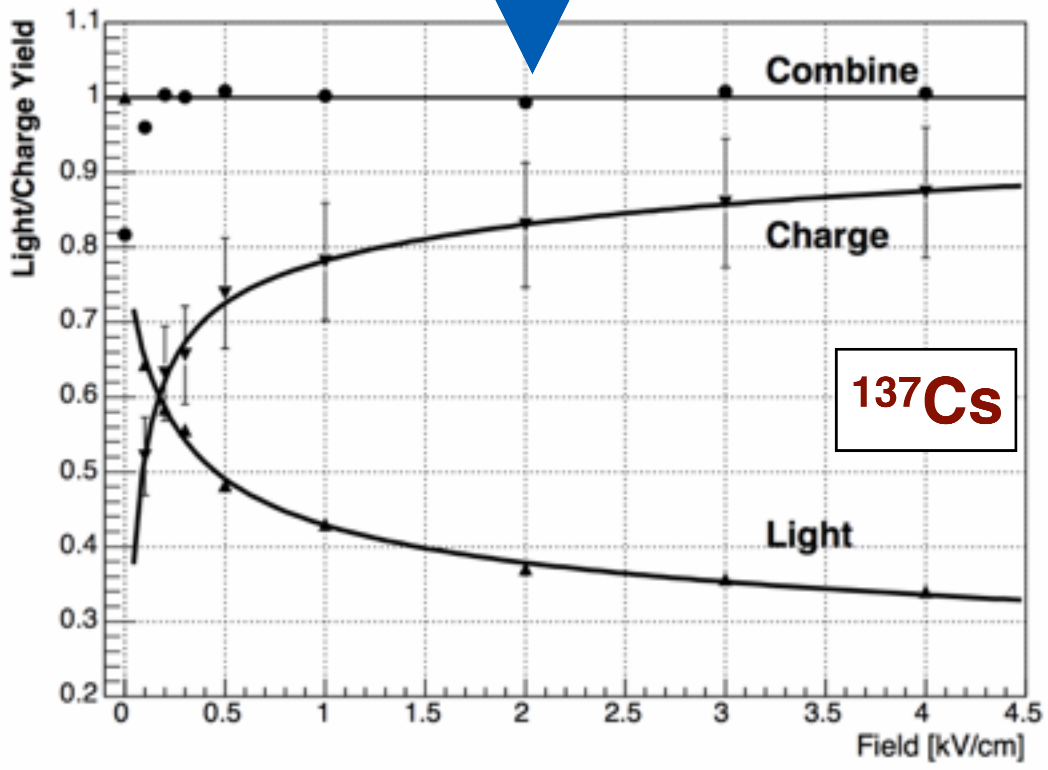
2Xe

2Xe

Electric field dependence

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





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

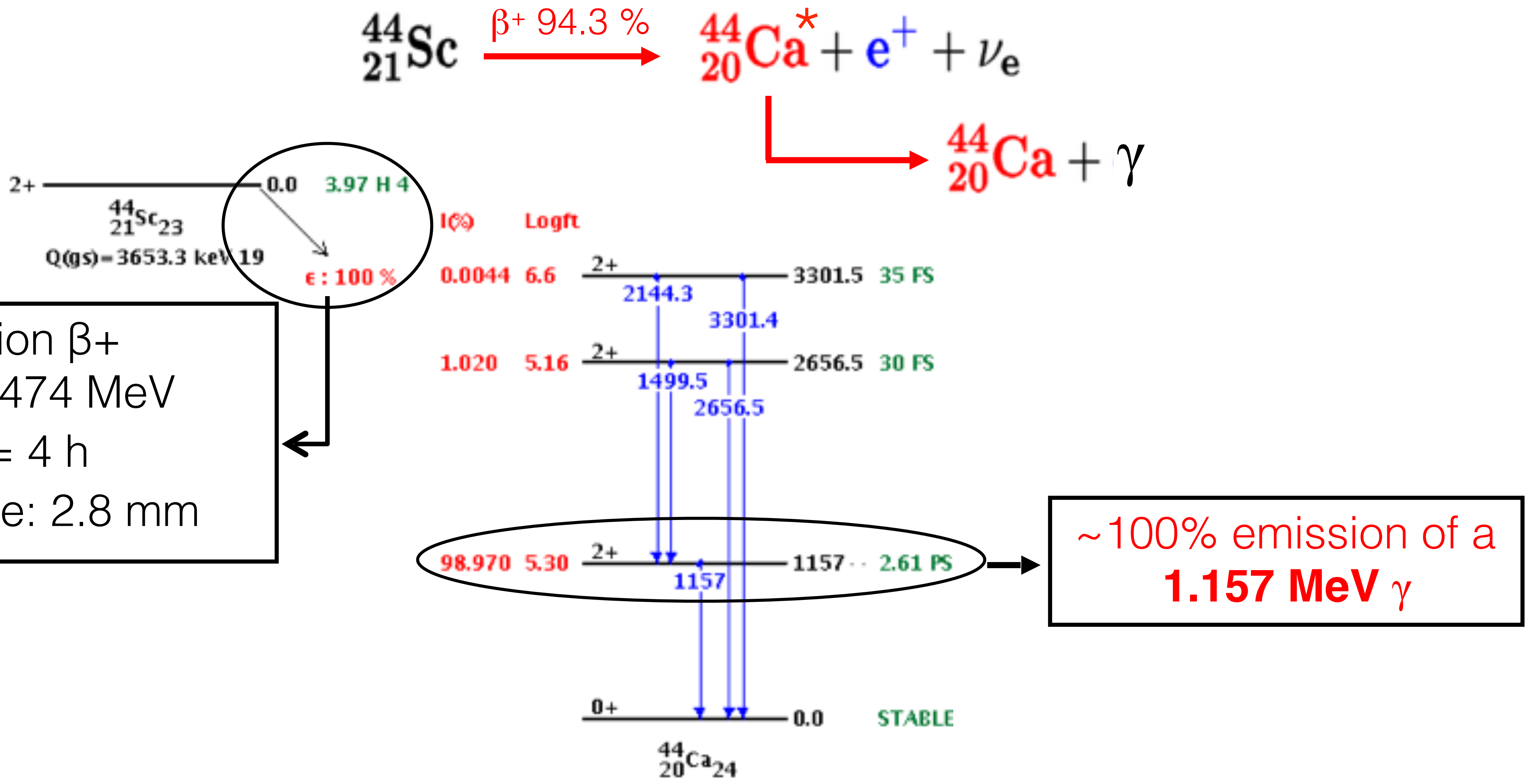
UV photons 178 nm

$\vec{E} = 0$ 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

Sc-44

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



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

$$\to {}^{44}_{20}\text{Ca} + \gamma$$

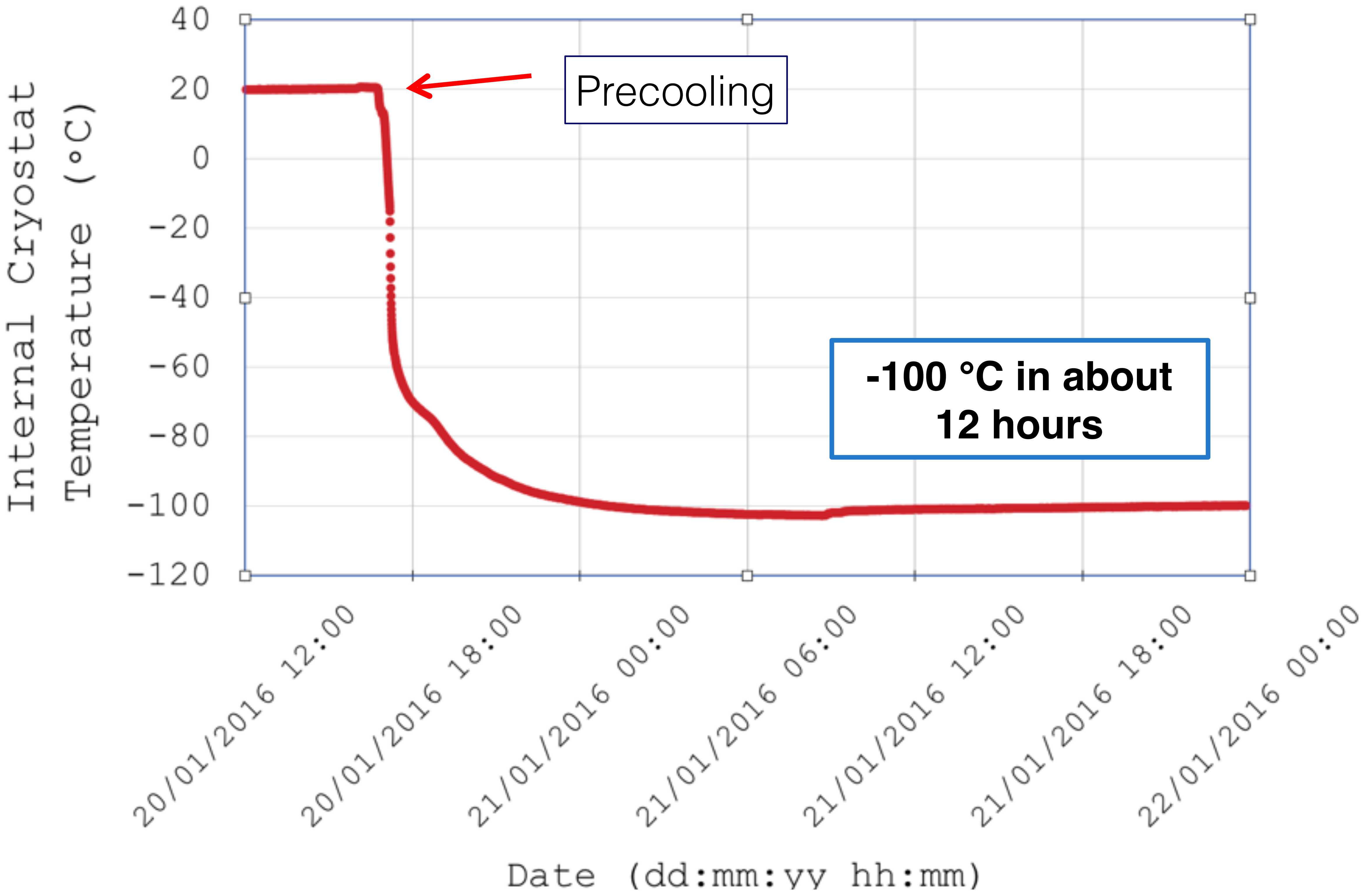
Emission β+
E_{max} = 1.474 MeV
$T_{1/2}$ = 4 h
effective range: 2.8 mm

~100% emission of a
1.157 MeV γ

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

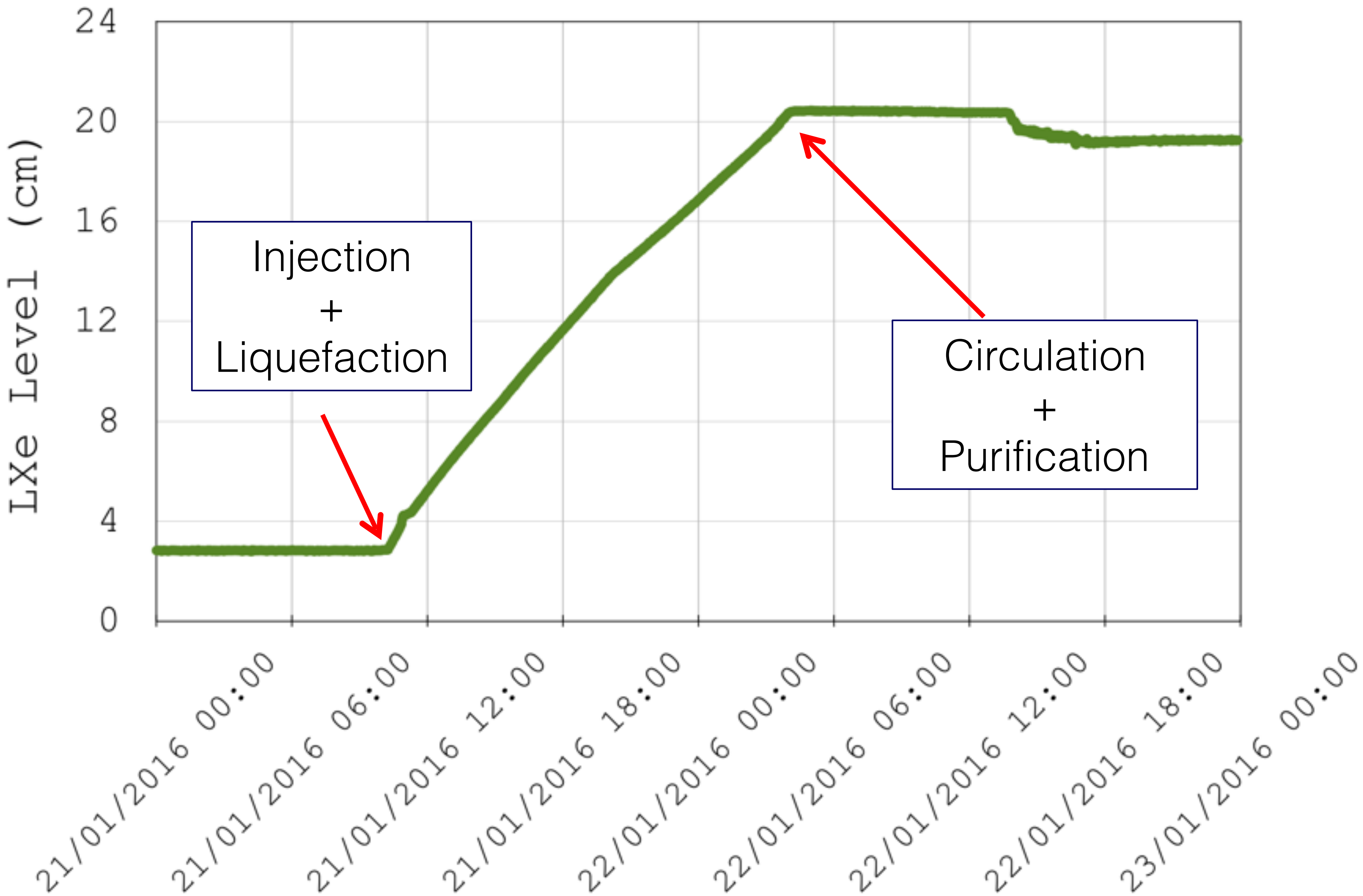
ARRONAX
CENTRE HOSPITALIER UNIVERSITAIRE DE NANTES
Inserm

Pre-cooling



-100 °C in about 12 hours

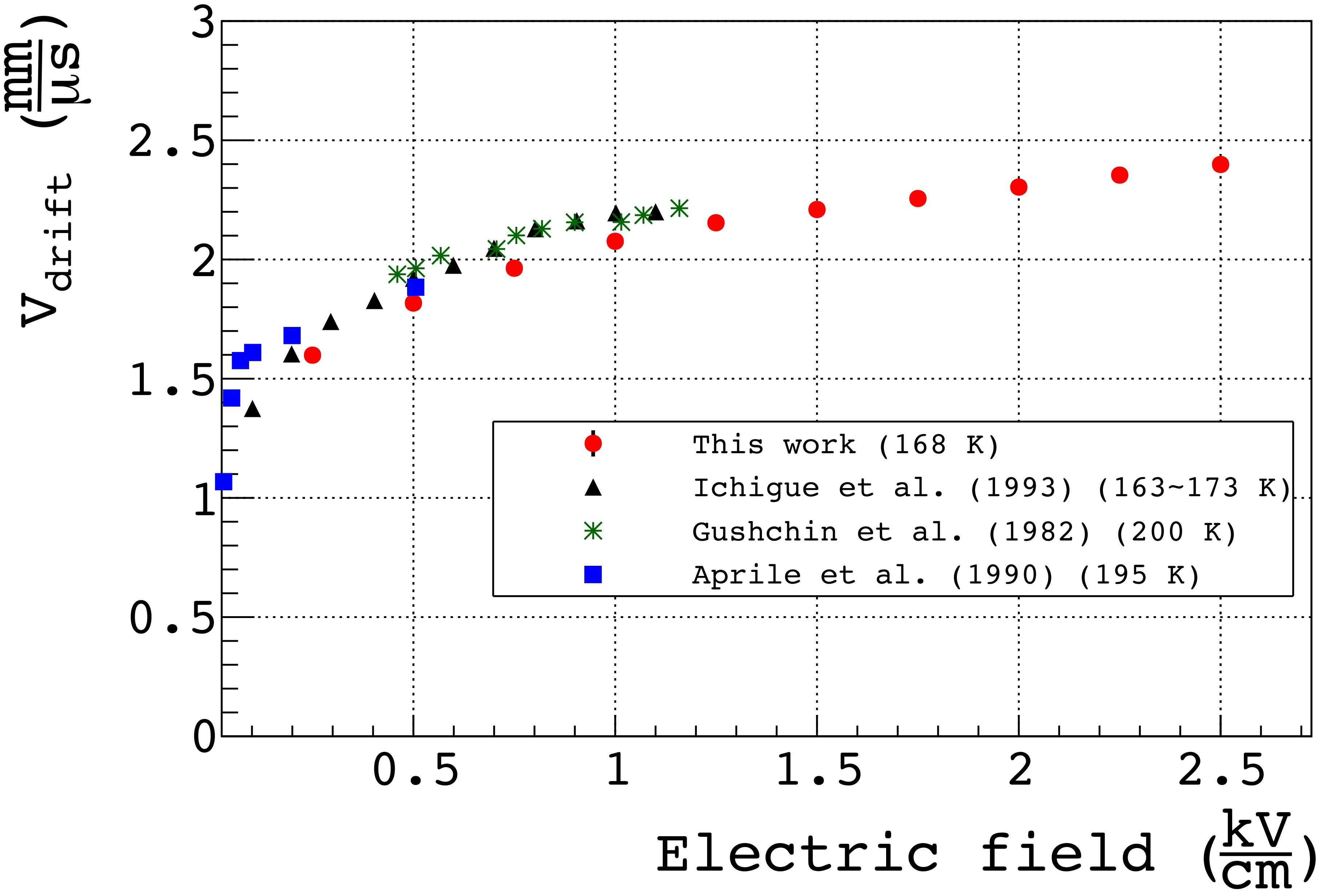
Liquefaction



Injection
+
Liquefaction

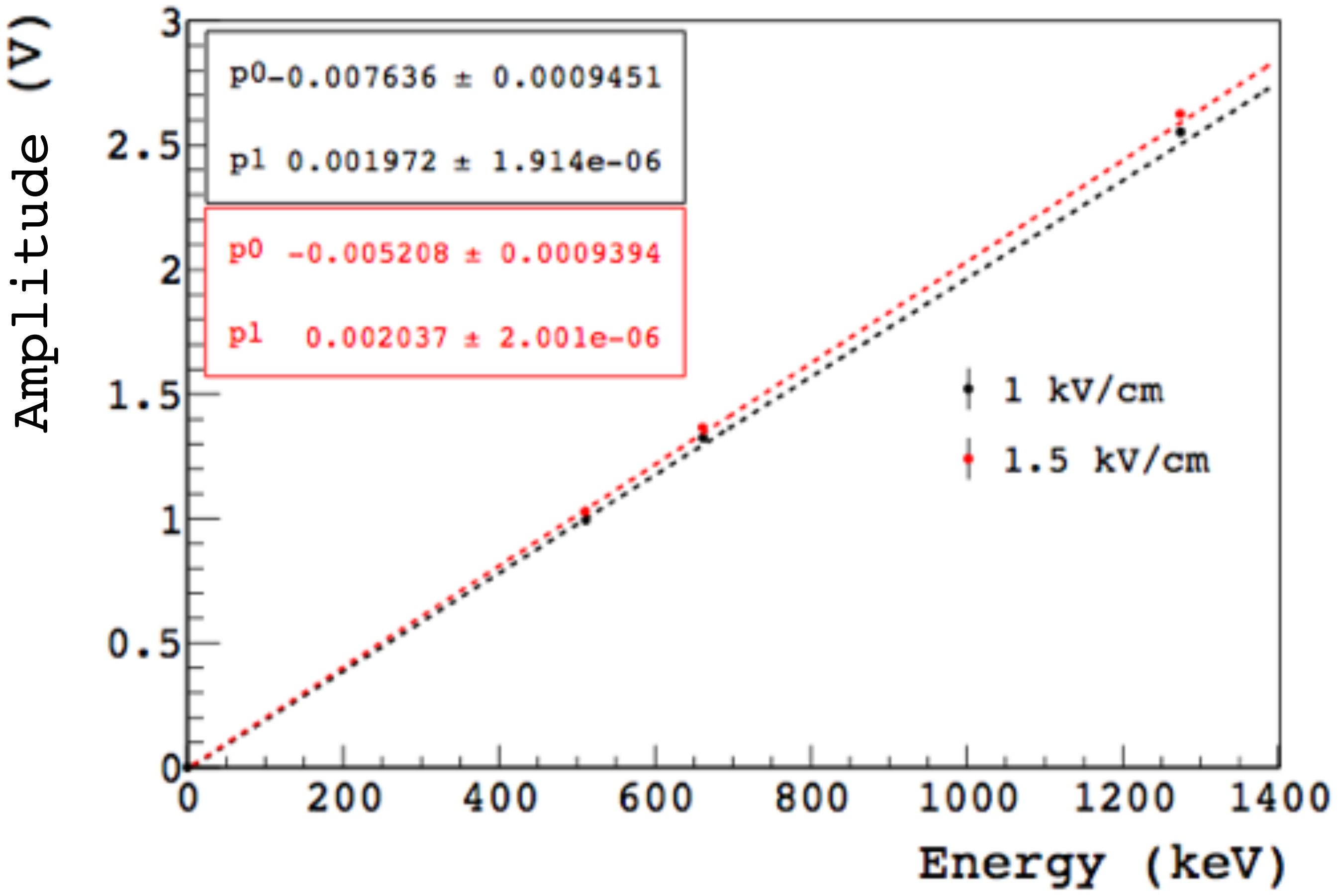
Circulation
+
Purification

Electron Drift Velocity

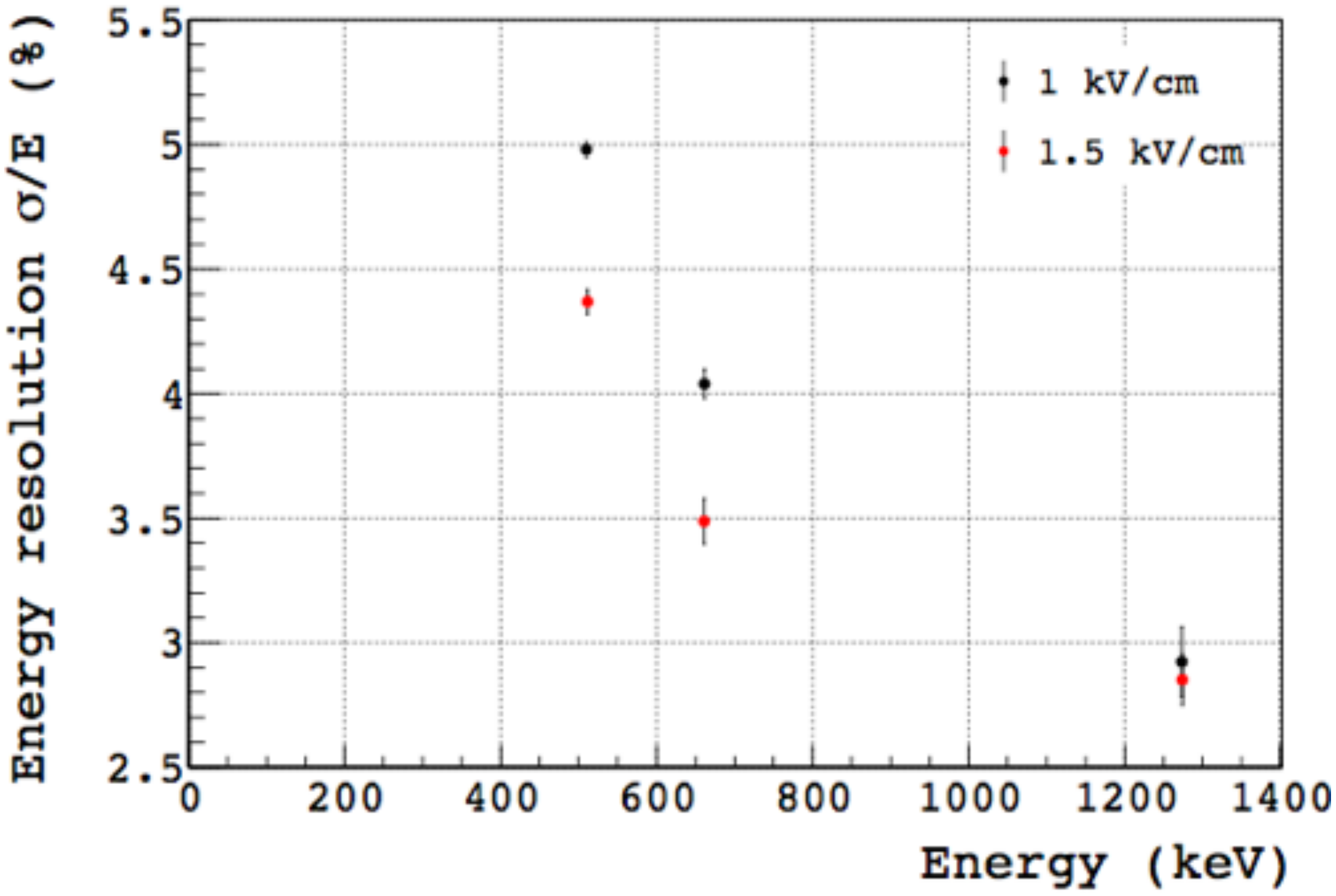


- Electron drift velocity increases with electric field
- Expected drift velocity saturation at high electric fields ~ 3 kV/cm

Spectral Response and Energy Calibration



Ionization charge yield

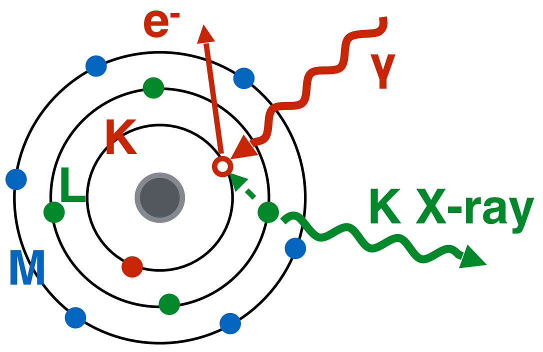


Energy resolution σ(E)/E (%)

- Non-linear energy dependence (~2% at 1274 keV and 1 kV/cm)
- Expected non-linearity of ~30% at low energies (30 keV) → NEST
- Non-linear behaviour with type of interaction → X-ray emission

  - γ-ray ≠ electronic recoil

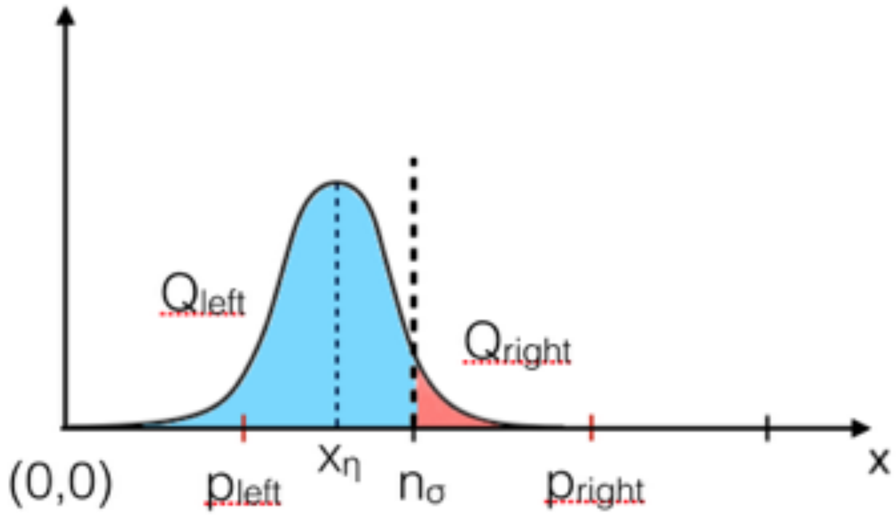
  - photoelectric effect ≠ Compton scattering

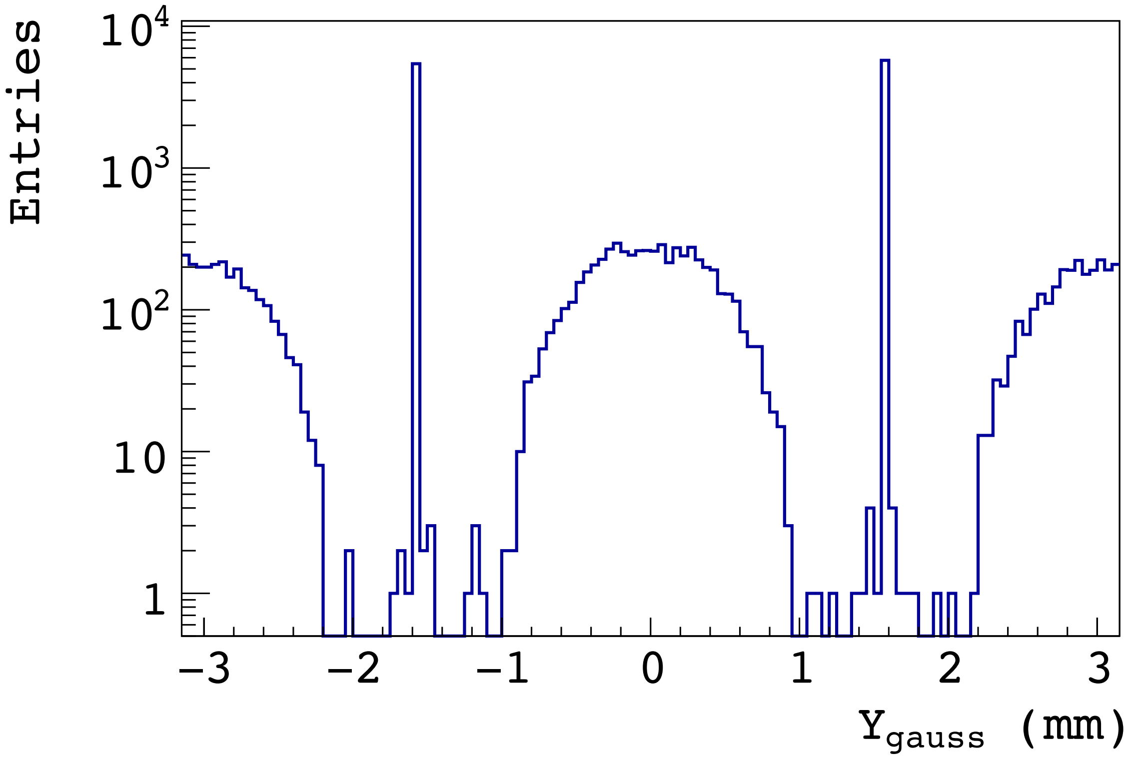


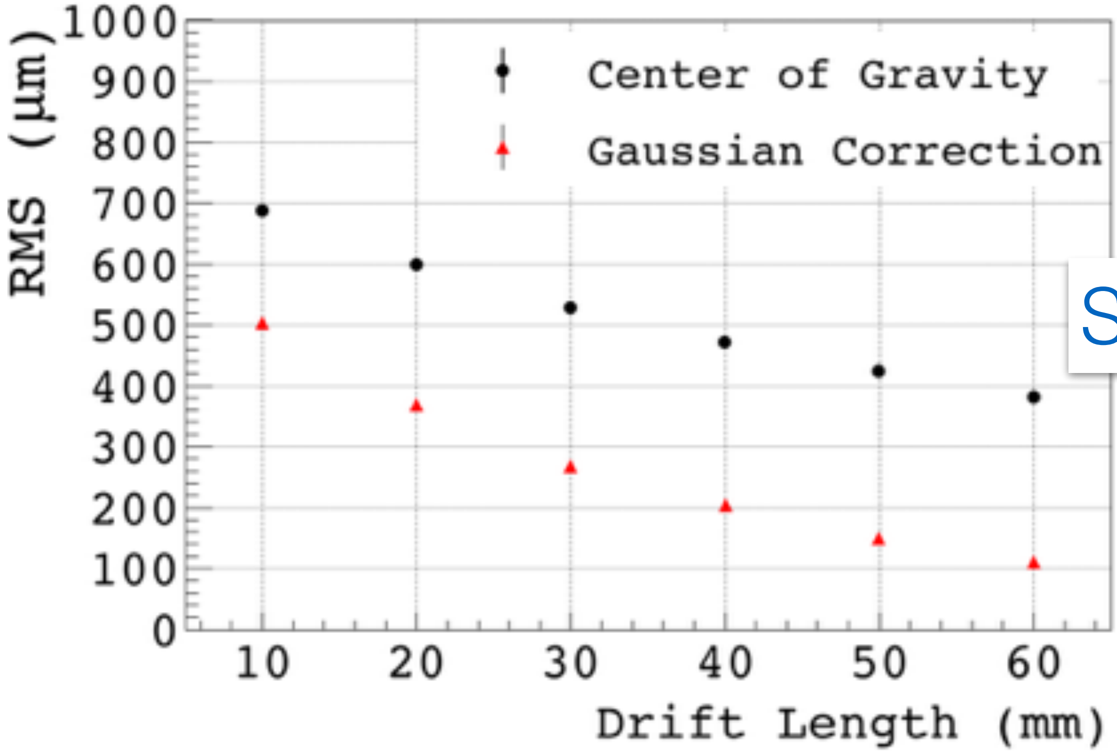
XY Resolution

- Center of gravity is not a good estimator of the position

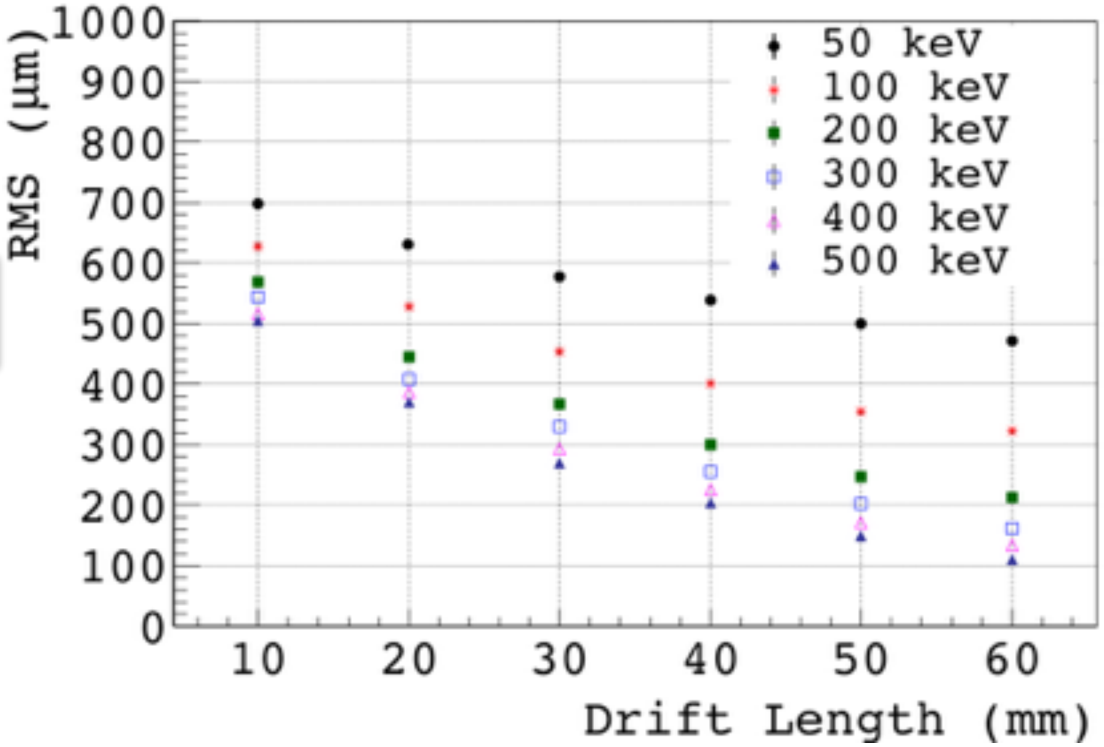
Charge distribution : **Gaussian**





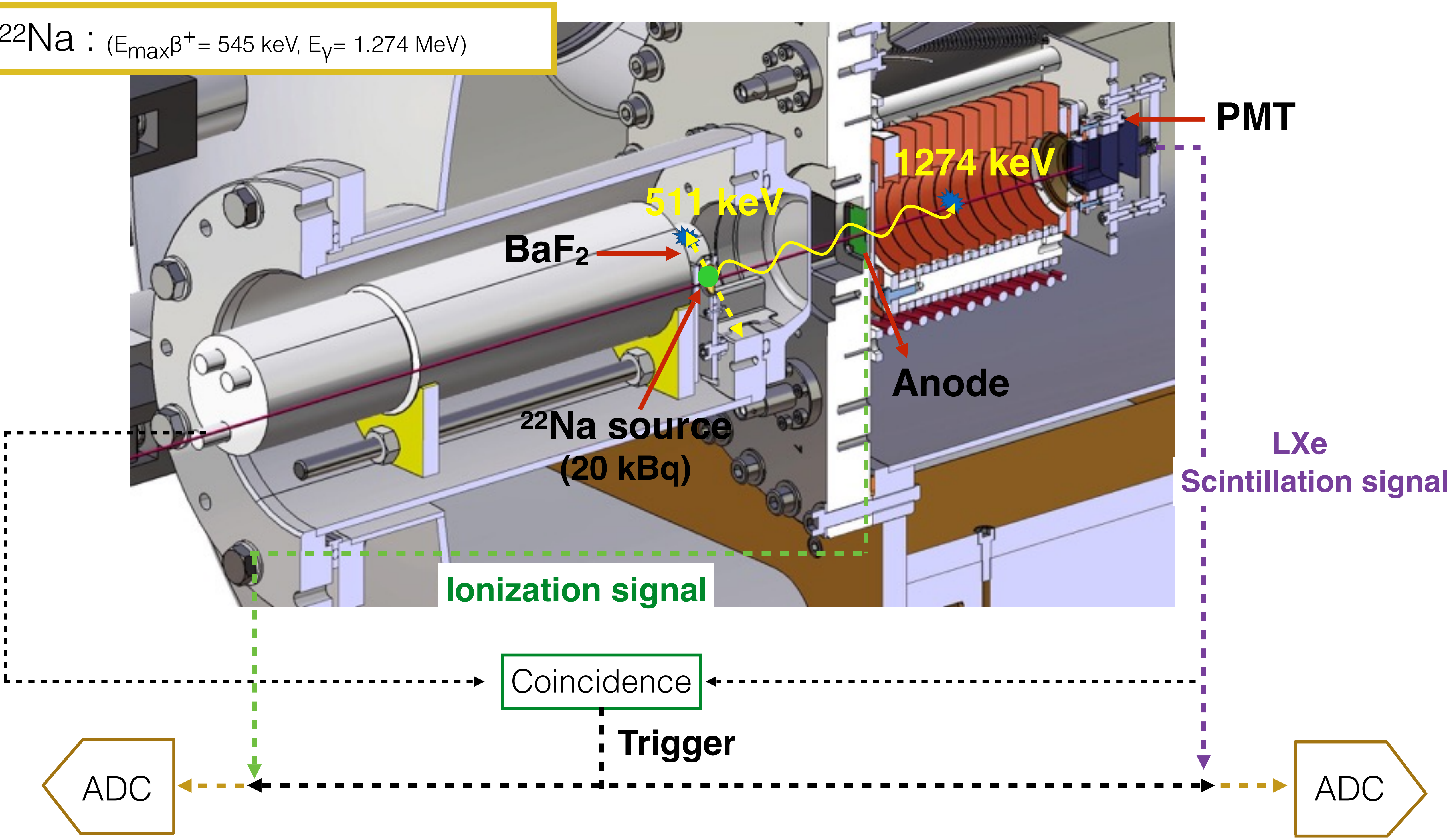


Simulation



Experimental Set-up @ 1274 keV

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



Clock 80 ns
102 µs

Clock 4 ns
2 µs