MIMAC -35cm
3D-Directional Direct Detection for Dark Matter Search and Neutron Spectroscopy

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Zhiyong Zhang, Charling Tao, Daniel Santos

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MIMAC (MIcro-tpc MAtrix of Chambers)

LPSC (Grenoble) : D. Santos, Ilias Ourahou (PhD), F. Malek, F. Naraghi

- SDI : **O. Guillaudin, N. Sauzet**
- Electronics : **O. Bourrion, C. Hoarau, E. Lagorio**
- Data Acquisition: **G. Dargaud**
- COMIMAC (quenching) **: J-F. Muraz**

CCPM (Marseille): C. Tao, J. Busto

IRSN- LMDN (Cadarache): M. Petit, T. Vinchon (neutron spectroscopy)

IHEP (Beijing-China): Wang Zhimin

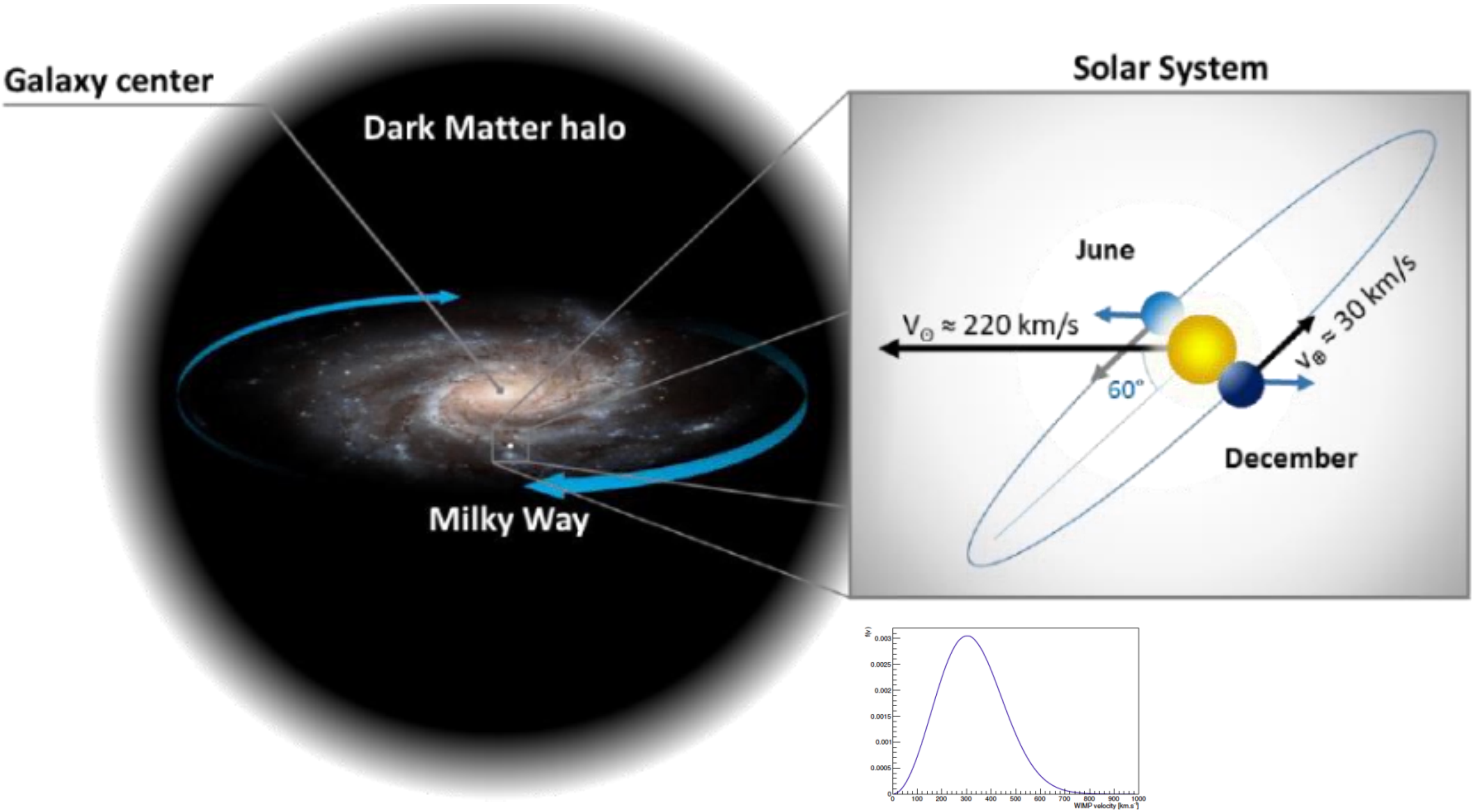
USTC (University of Science and Technology of China, Hefei): Zhang Zhiyong

SJTU(Shanghai Jiao tong University): Wang Shaobo, Han Ke, Zhou Ning, Tao Yi

TSINGHUA University (Beijing-China): Yue Qian (China JinPing underground Laboratory (CJPL))

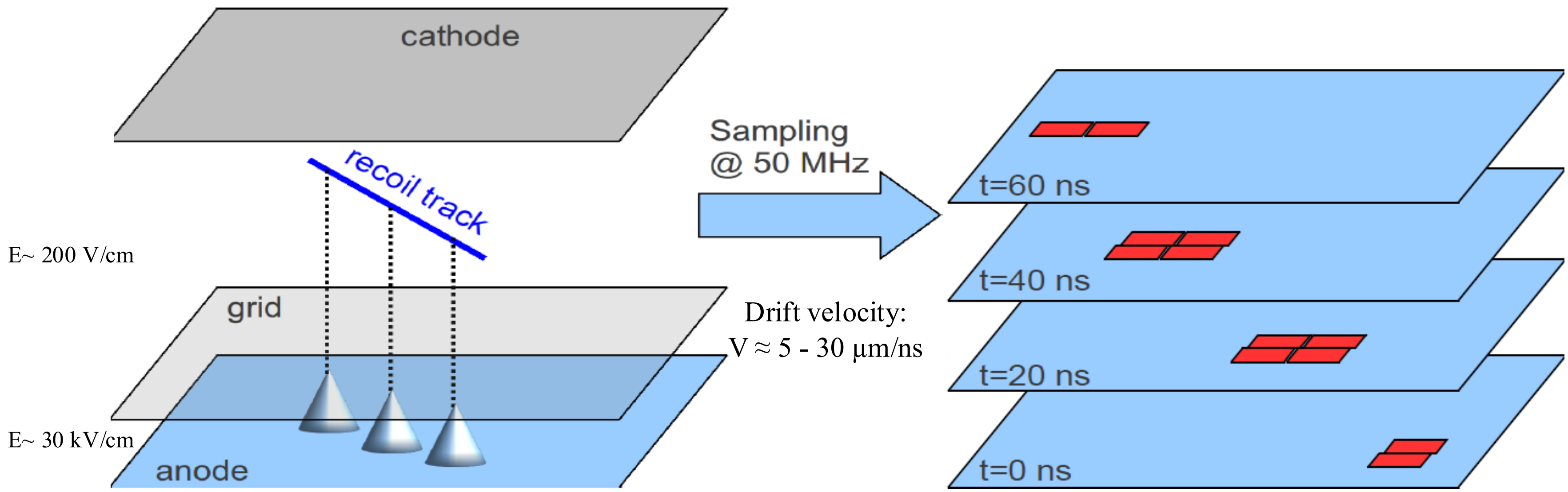
SHAO(Shanghai Astronomical Observatory): Shan Huan Yuan

Dark Matter Directional detection principle



The only signature able to correlate the rare events in a detector to the DM galactic halo !!

MIMAC: Detection strategy



Scheme of a MIMAC μTPC

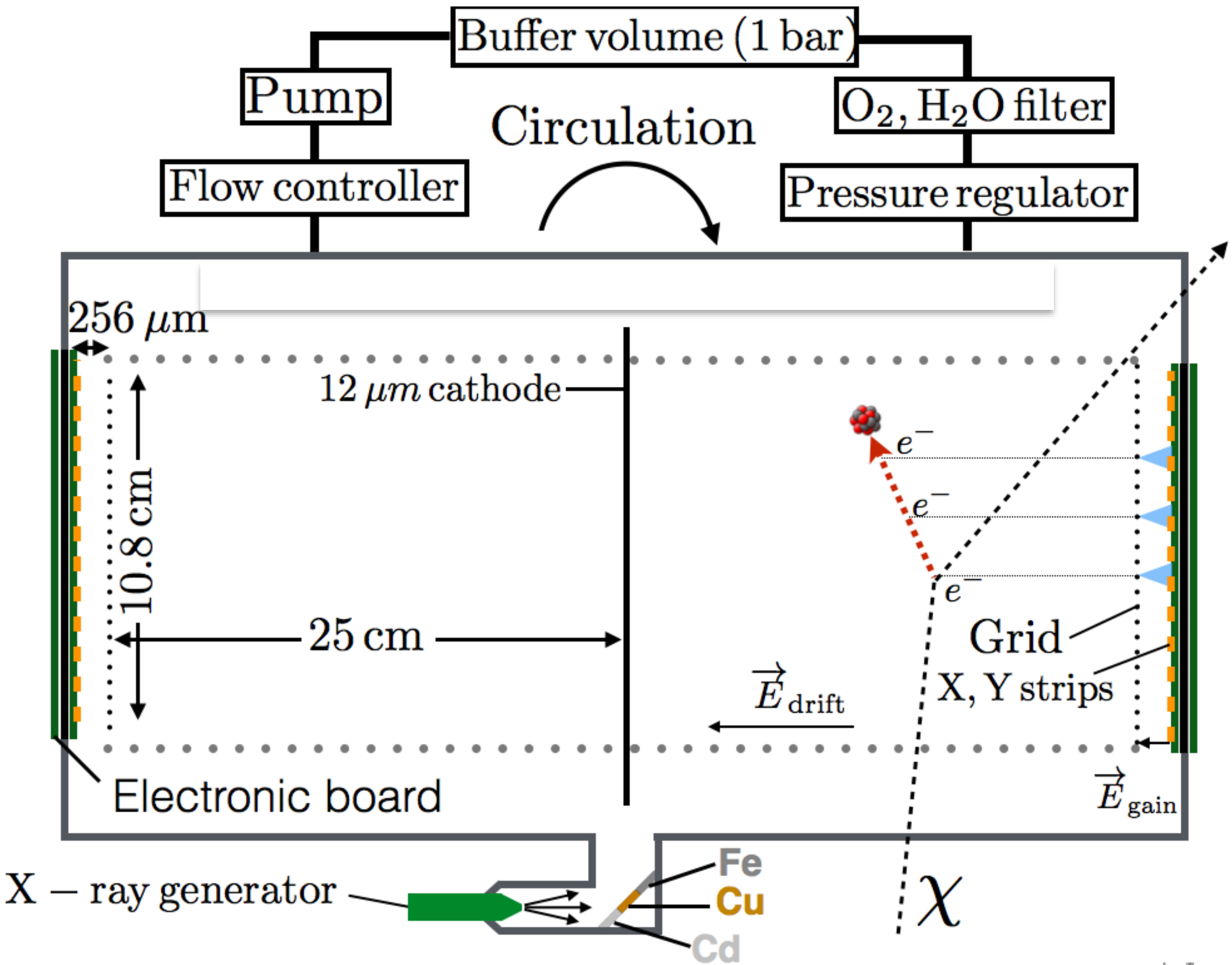
Evolution of the collected charges on the anode

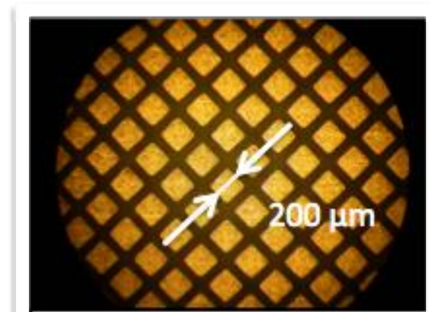
Measurement of the ionization energy:

Charge integrator connected to the mesh coupled to a FADC sampled at 50 MHz

MIMAC-10cm-bi-chamber module

C_4H_{10} + 50% CHF_3 at 30 mbar



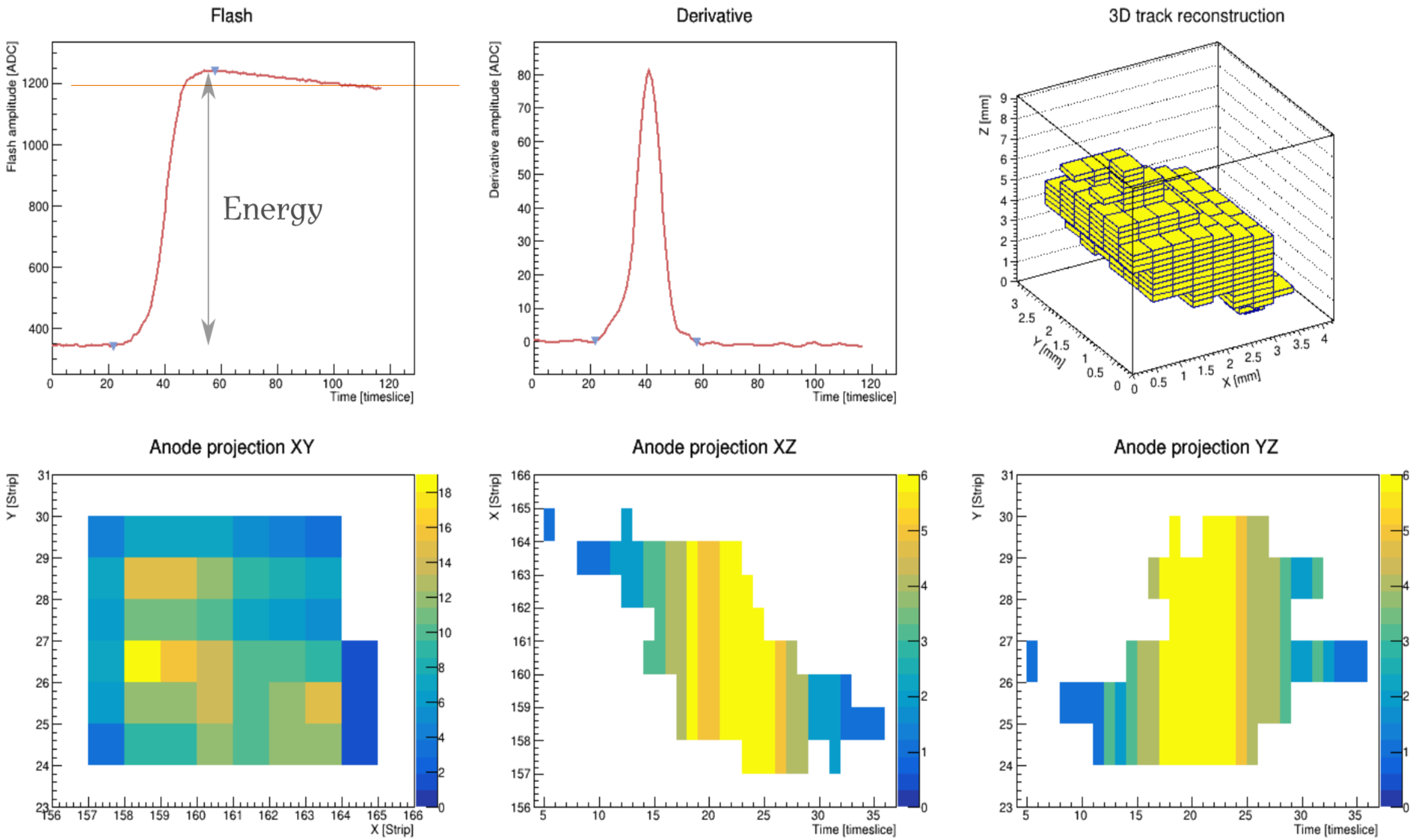


Micromegas 10x10 cm², designed by IRFU- Saclay (France)

MIMAC Target: H, ^{19}F

- Light WIMP mass
- Axial coupling

Example of a proton recoil of $6\ \mathrm{keV_{ee}}$ ($8.6\ \mathrm{keV_{nr}}$)



-→ Sampling at 50 MHz (20 ns)

C_4H_{10} +. 50% CHF_3 at 30 mbar

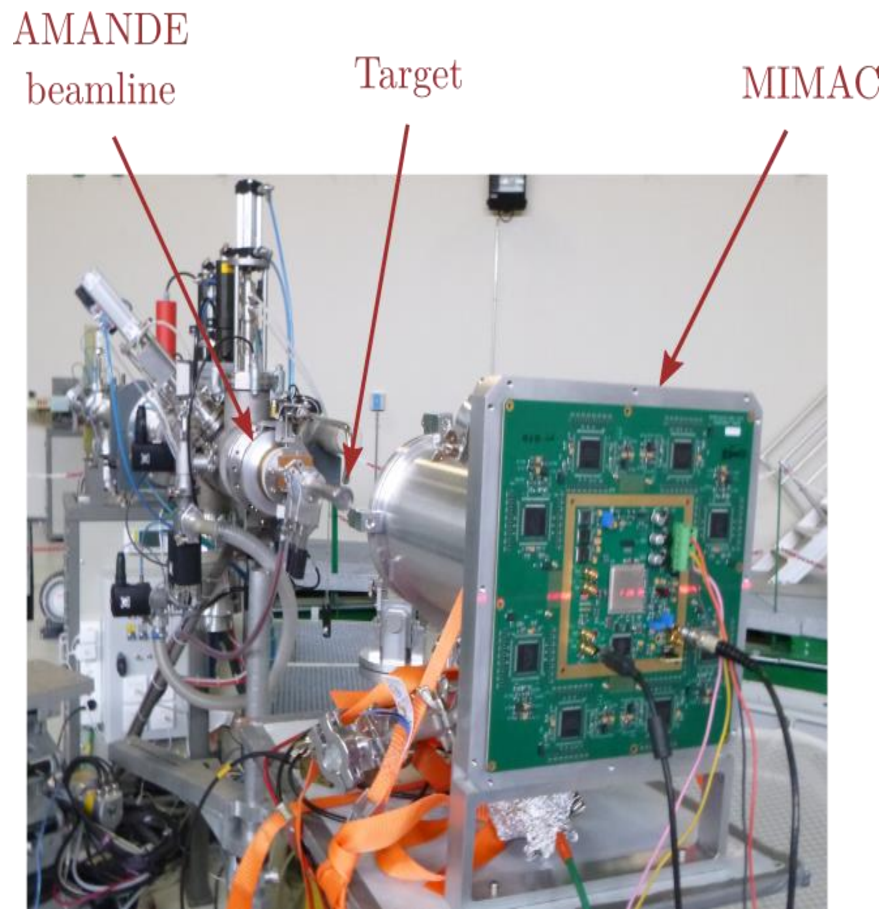
Demonstration of directional detection with mono-energetic neutron fields

- For the low energy range (keV), the AMANDE facility (ASNR (ex-IRSN)-Cadarache) provides mono-energetic neutron fields

- The energy of the mono-energetic neutron field is defined by the angle of **each nuclear recoil** track with respect to the neutron direction…

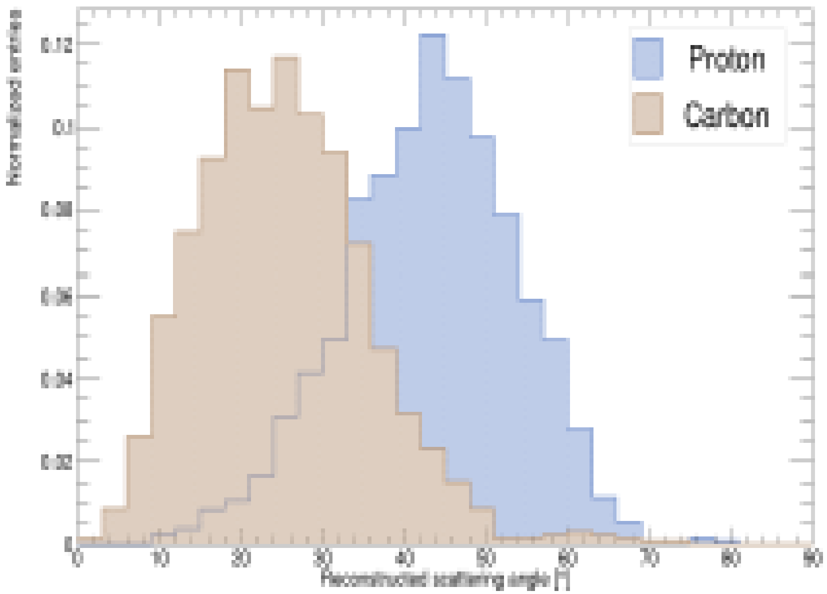
But the ionization energy of the recoil is different of its kinetic energy…

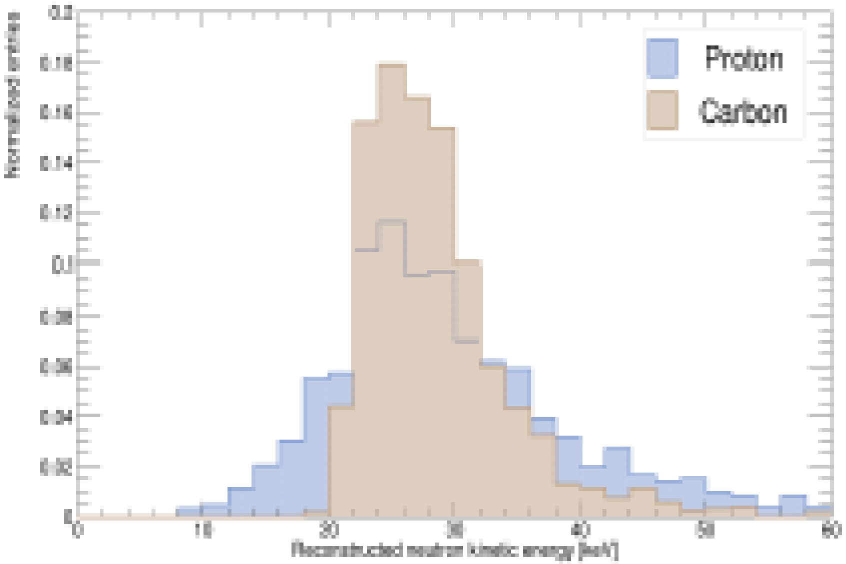
It is quenched !!



At low energies… 27 keV neutron field
Proton and carbon recoils give quite the same neutron energy !

C. Beaufort *et al* 2024 *JINST* **19** P05052, arXiv:2312.12842

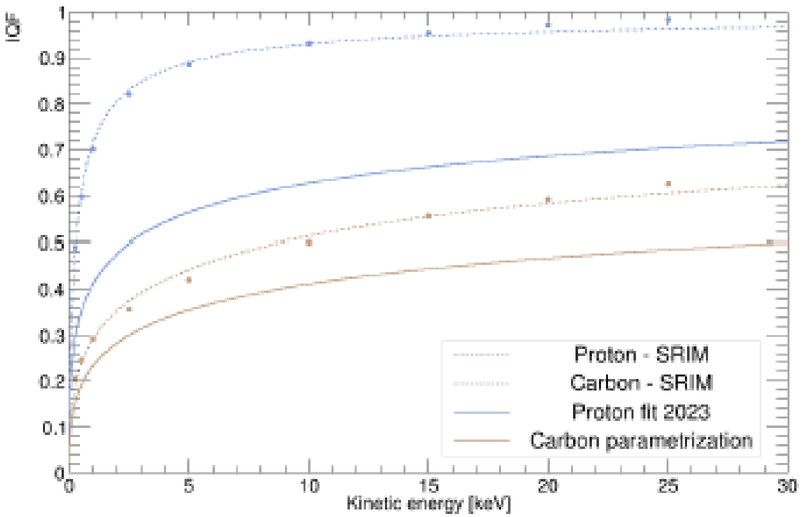




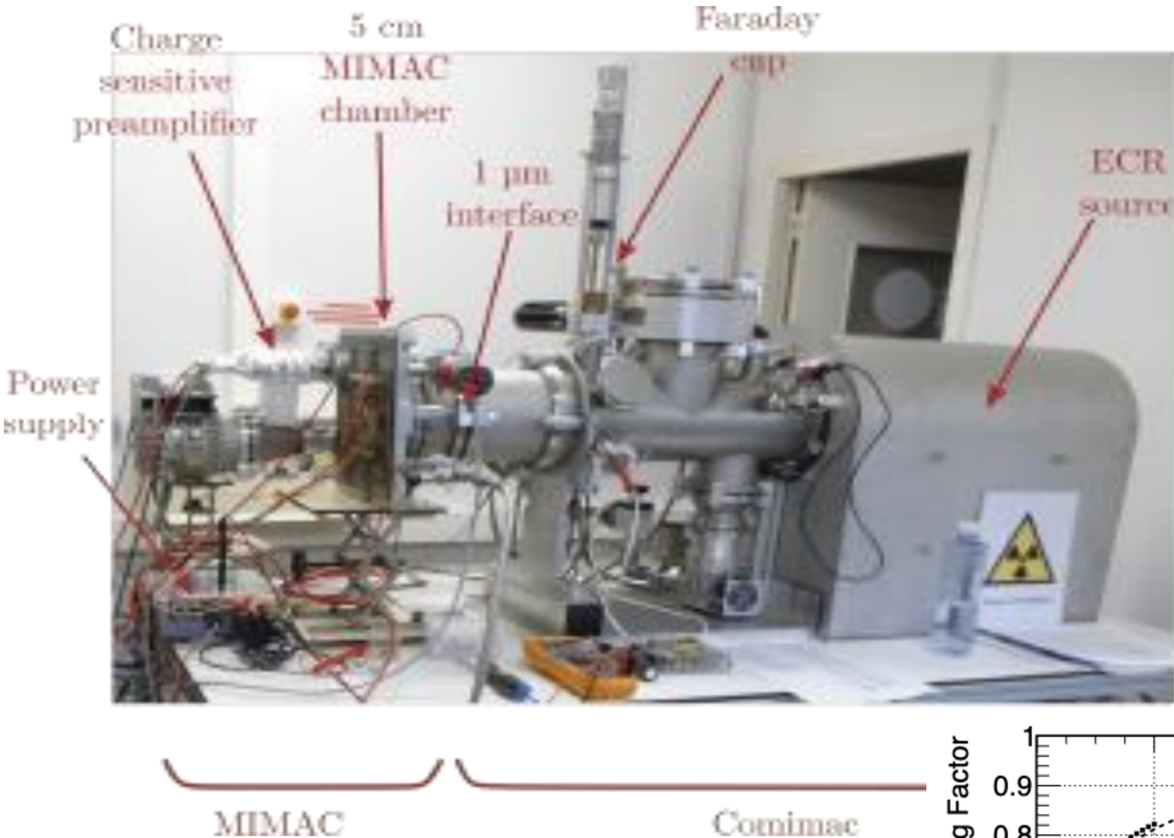
The kinetic energy is reconstructed with :

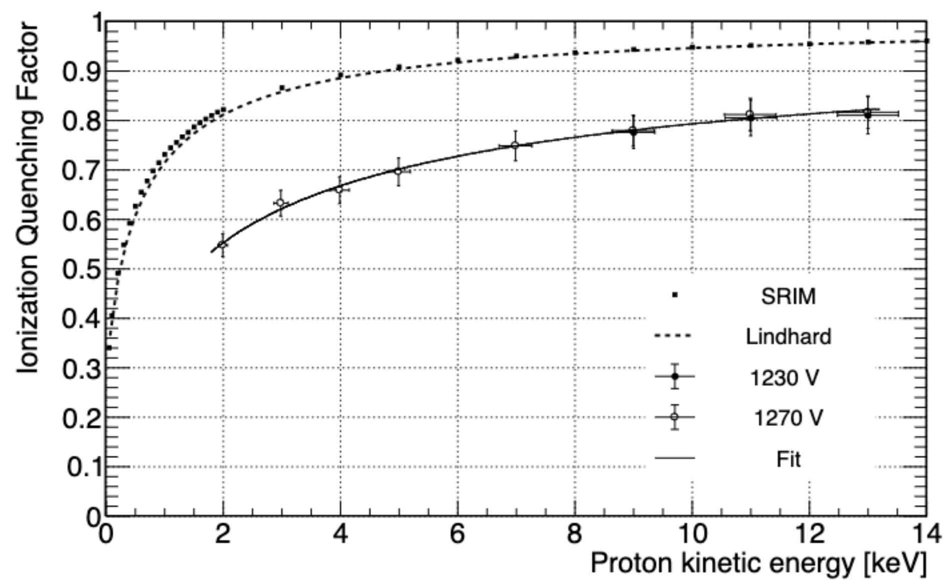
- the Ionization quenching factor measured by COMIMAC

- understanding the ion contribution to the signal



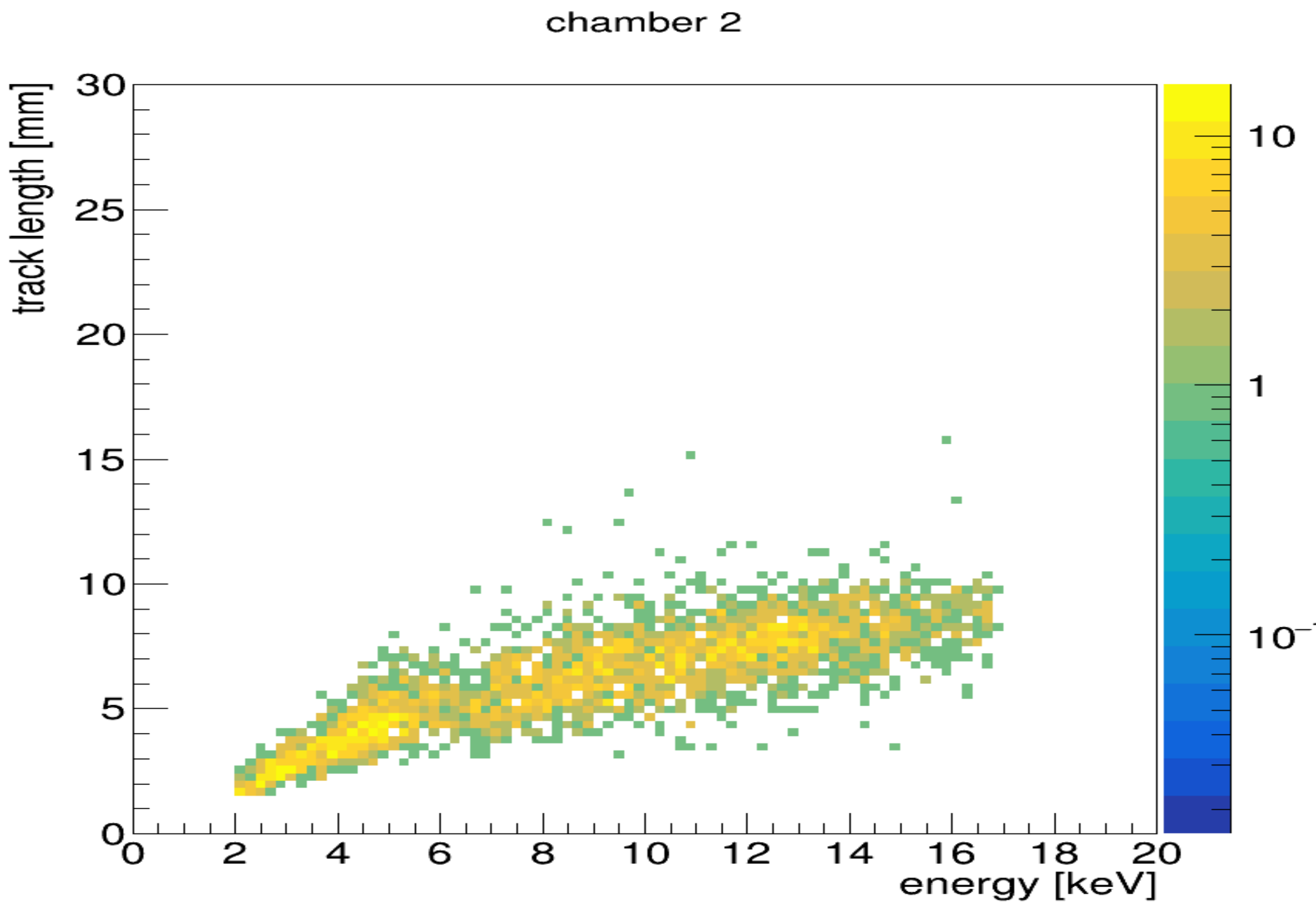
COMIMAC facility for IQF measurements





Balogh, L., Beaufort, C. *et al.*
Measurements of the ionization efficiency of protons in methane.
Eur. Phys. J. C **82**, 1114 (2022).

Proton recoil track lengths produced by a mono-energetic neutron field of 27 keV as a function of their ionization energy

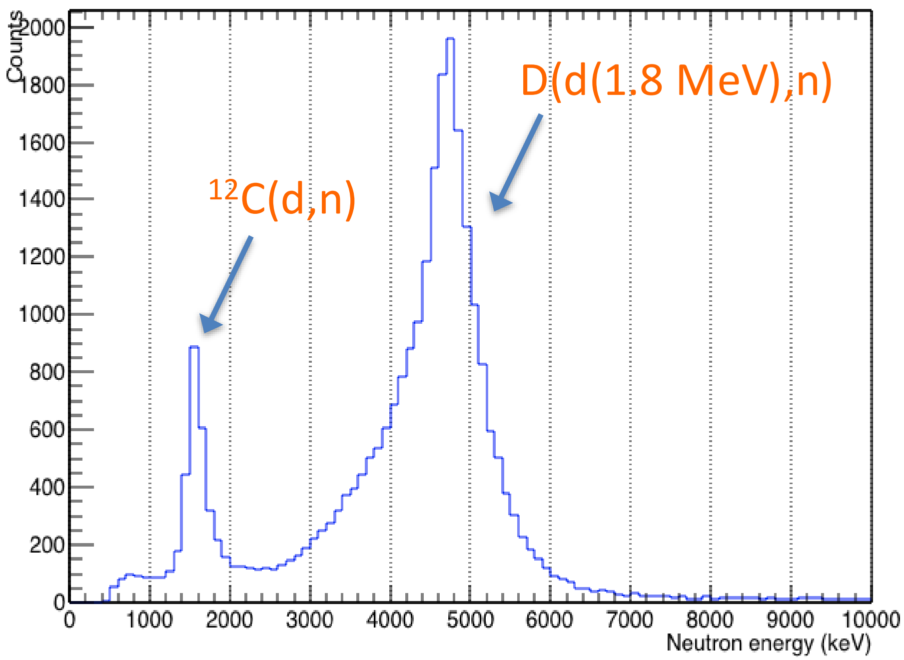


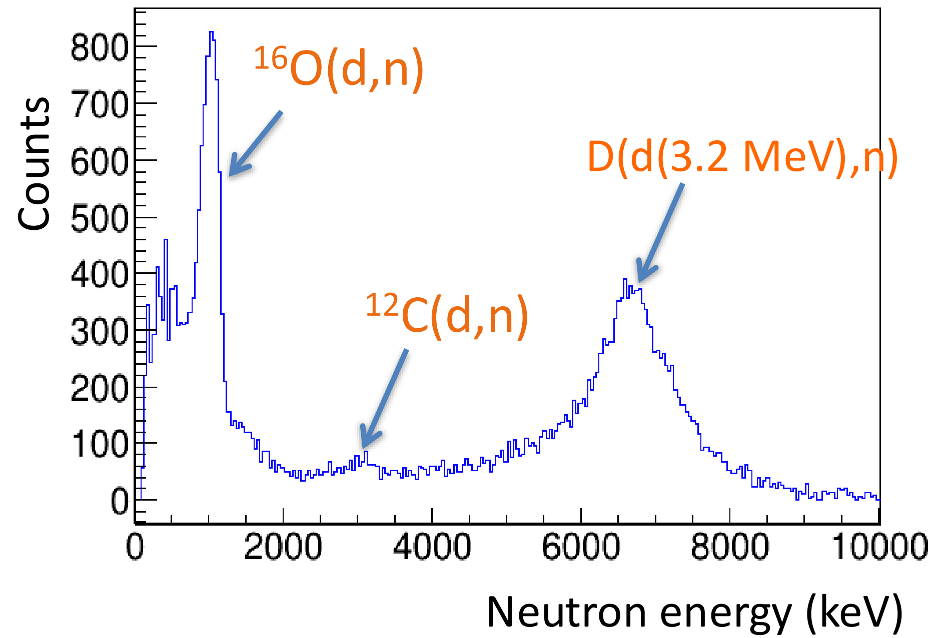
These H^+ recoils are very useful in characterizing the nuclear recoils searched for DM detection

Monoenergetic measurements : detection of target pollution

D(d(1.8 MeV,n) : neutrons of 5 MeV

D(d(3.2 MeV,n) : neutrons of 6.5 MeV





NPL /(UK)

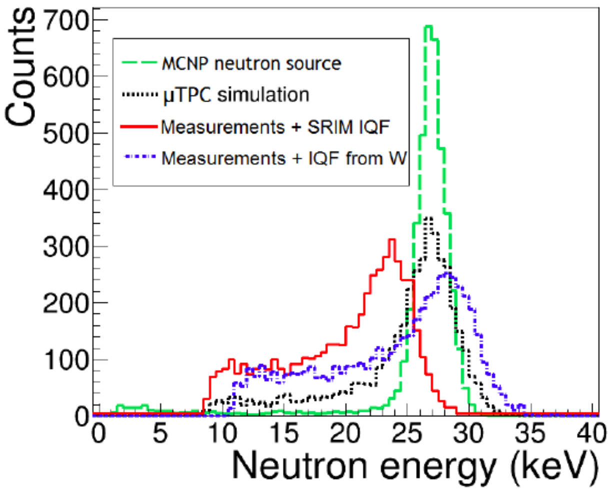
700 mbar He/CO_2 (5%)

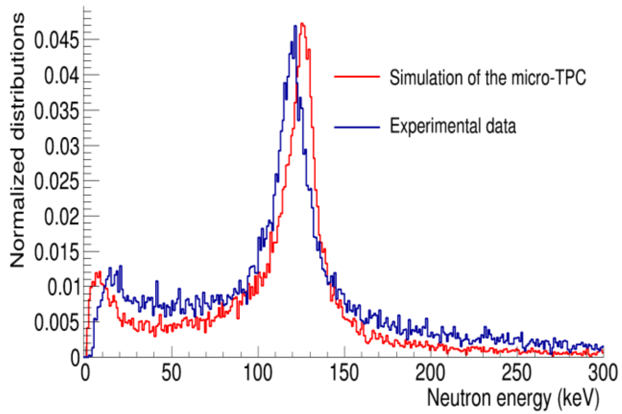
IRSN / AMANDE (Cadarache)

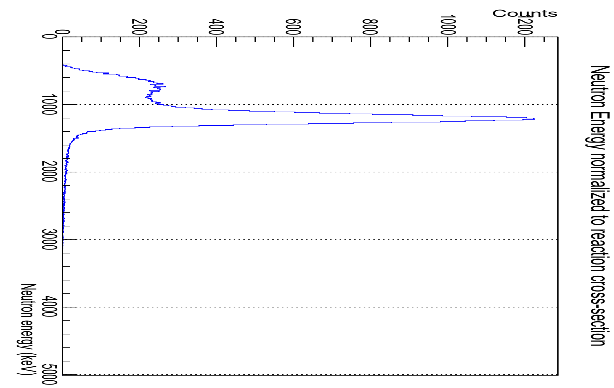
Fast neutron spectroscopy from 1 MeV up to 15 MeV with Mimac-FastN, a mobile and directional fast neutron spectrometer, N. Sauzet , D. Santos, O. Guillaudin, G. Bosson, J. Bouvier, T. Descombes, M. Marton, J.F. Muraz, NIM A 965 (2020) 163799

A large energy range of neutron fields

50% C_4H_{10} 50% CHF_3 30 mbar	60% C_4H_{10} 40% CHF_3 50 mbar	95% ^4He 5% CO_2 700 mbar
E_n=27 keV	***E_n=127 keV***	***E_n=1.2 MeV***







D. Maire *et al.*
« Neutron energy reconstruction and fluence determination at 27 keV with the LNE-IRSN-MIMAC µ-TPC recoil detector »
IEEE Transactions on Nuclear Science, 63(3) : 1934-1941, June 2016

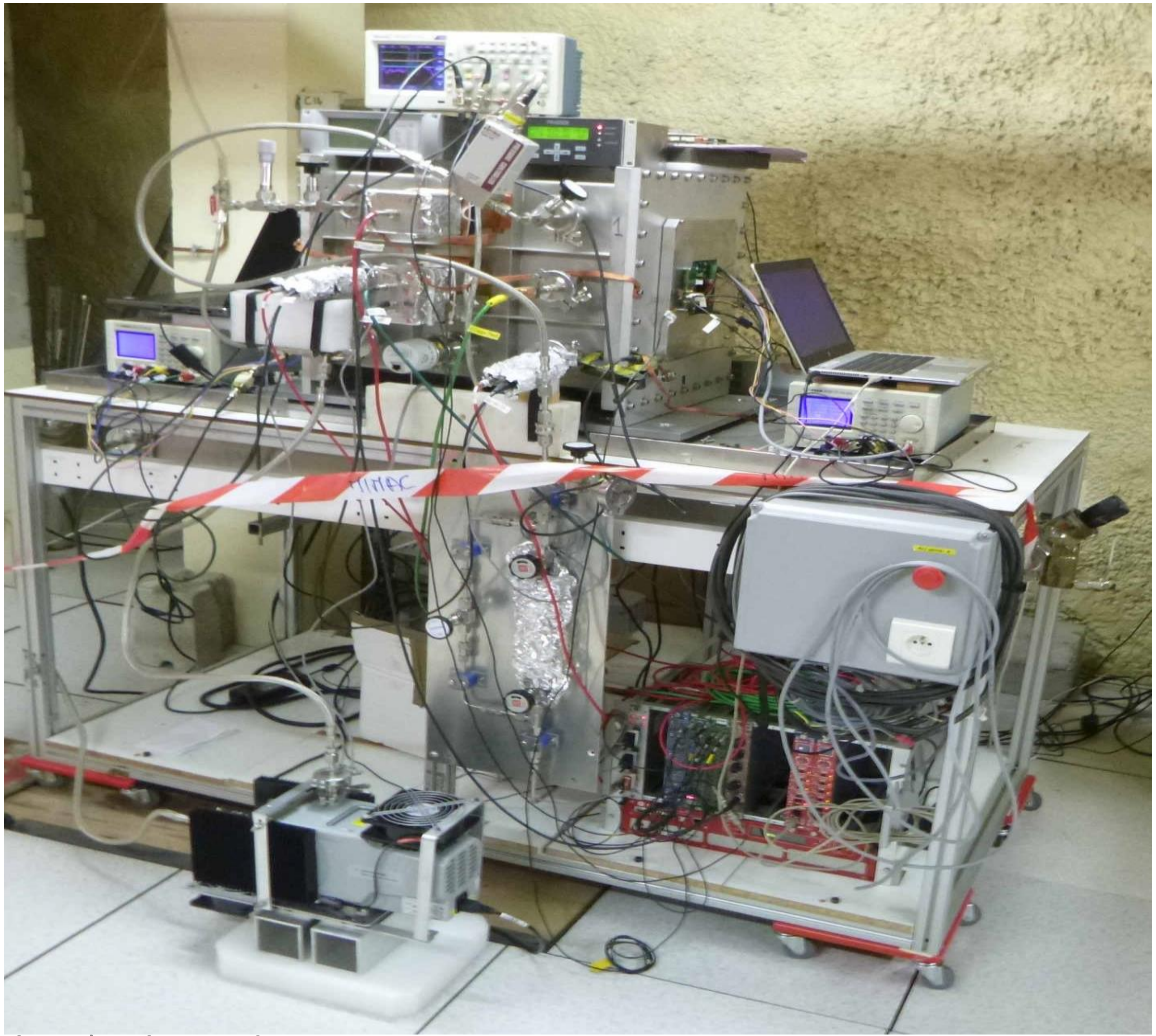
D. Maire *et al.*
« First measurement of a 127 KeV neutron field with a µ-TPC spectrometer »
Nuclear Science, IEEE Transactions, 61(2014) 2090

Bi-chamber-512 module
(with the Cathode Signal and
the new low background 10 cm detectors)

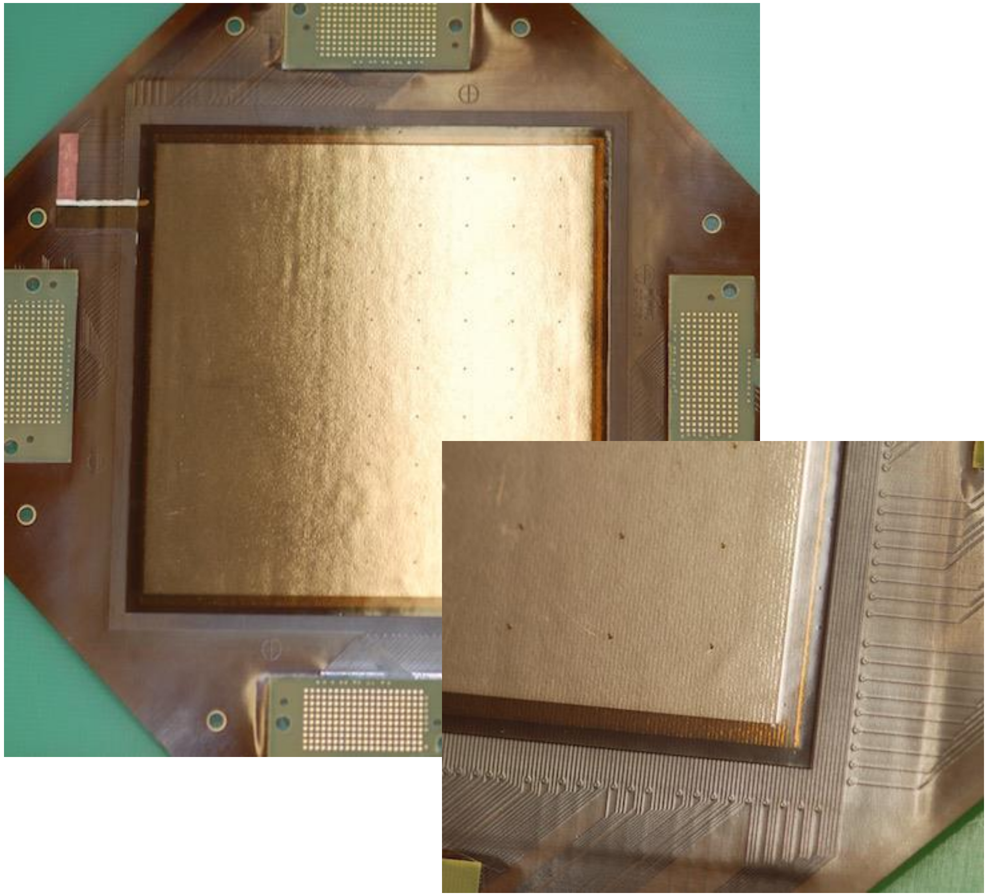
- working at 30 mbar (C_4H_{10}+50% CHF_3)
- Permanent circulating mode
- Remote controlled and commanded
- A periodic calibration by an X-ray generator

Installed in February 2023

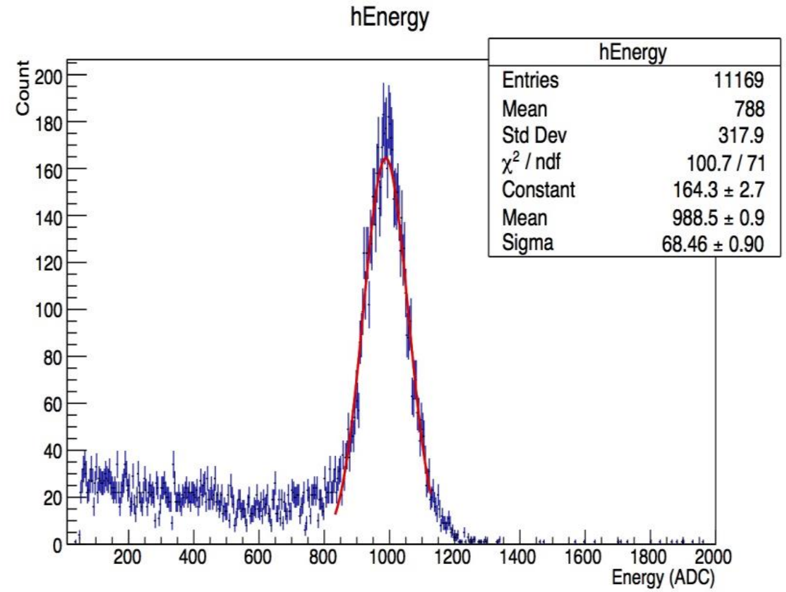
MIMAC at LSM



New MIMAC low background detector



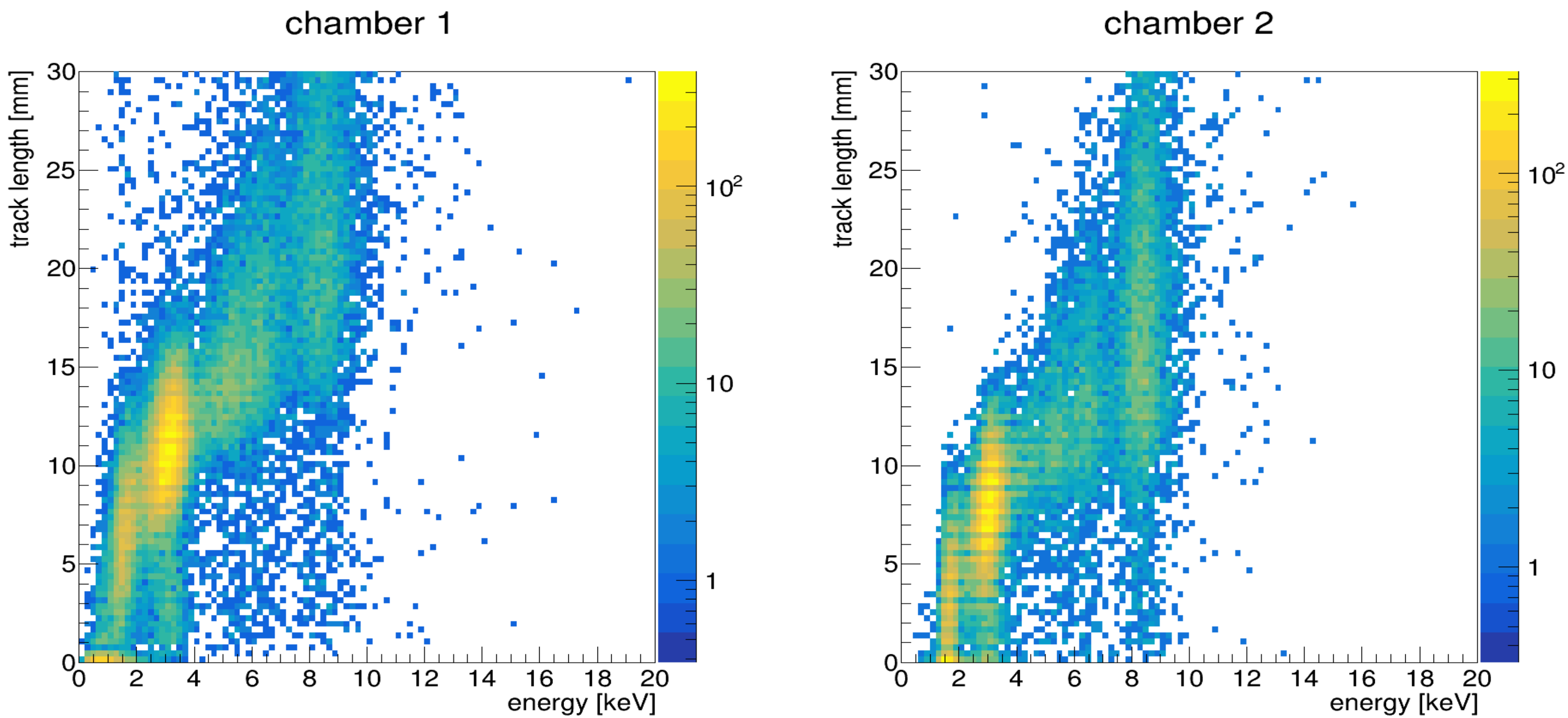
Kapton micromegas readout
Piralux Pilar



Gaz : MIMAC 50 mbar
HT grille : -560 V
Drift field : -150 V/cm

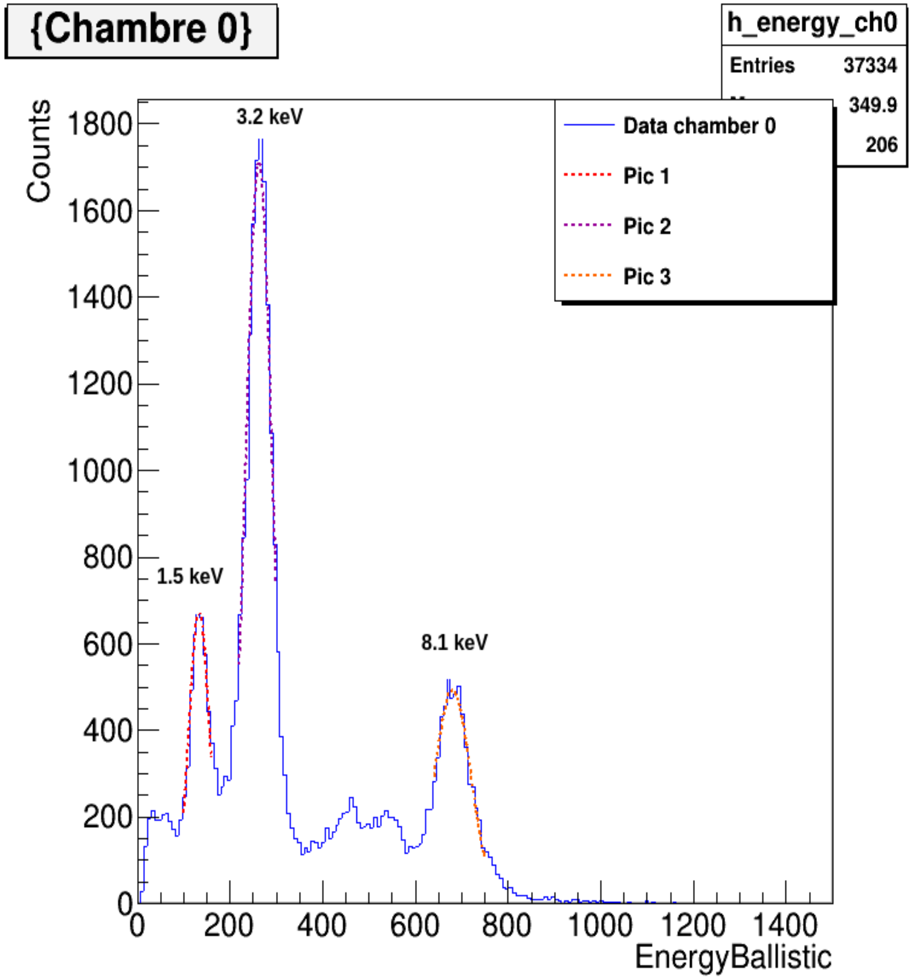
16,3 % FWHM (6 keV)
Gain ~25 000
Energy threshold <1 keV

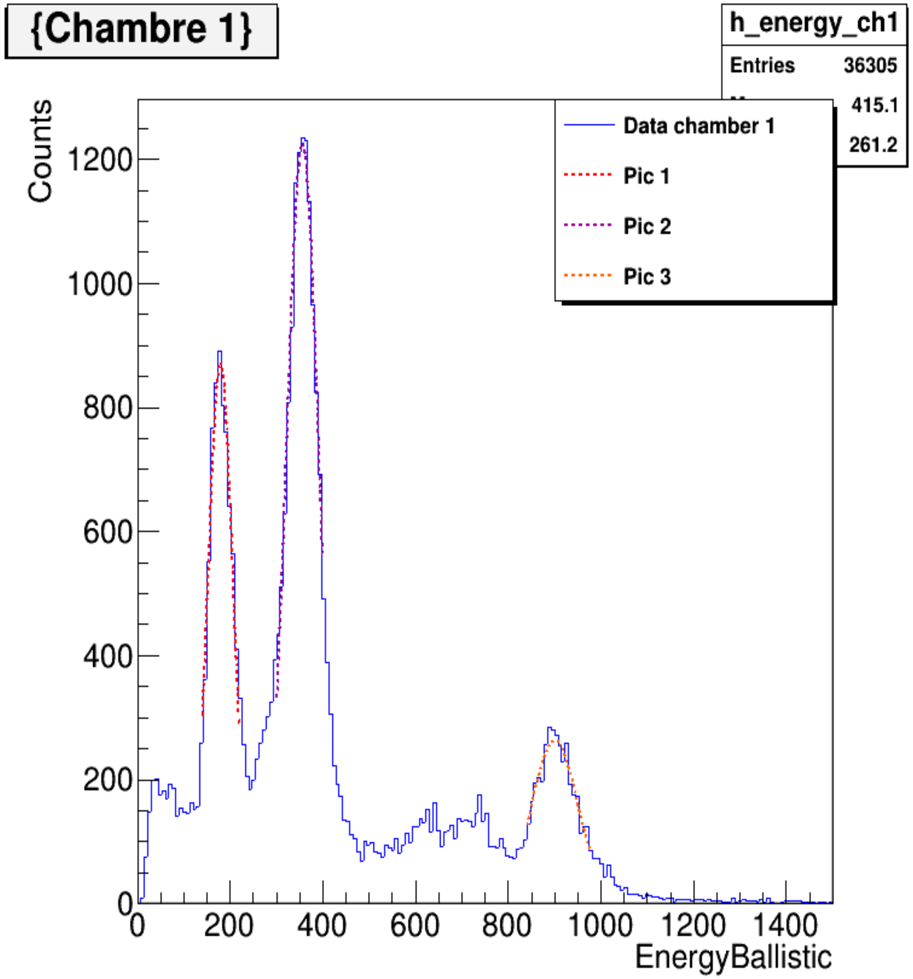
Electron track lengths produced by X-rays as a function of their energy



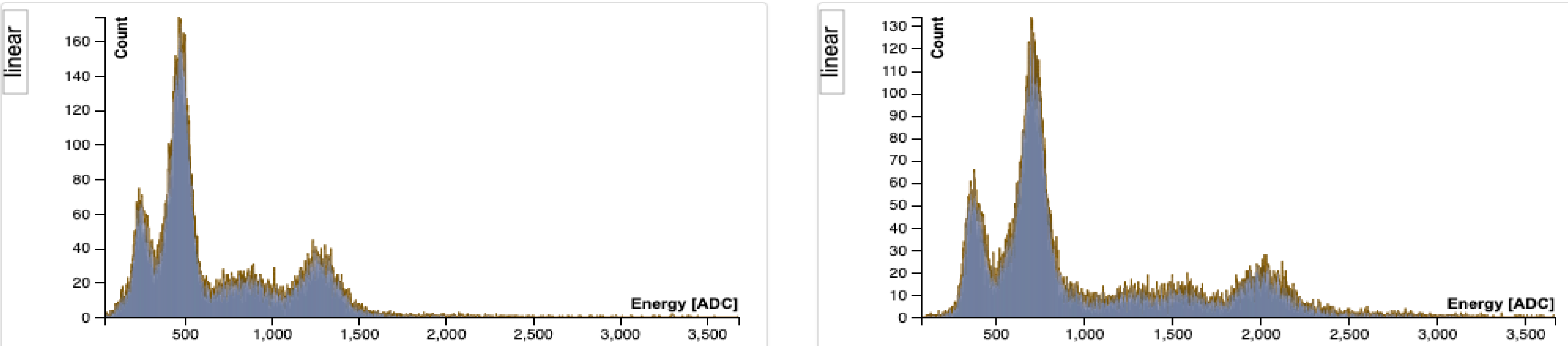
These electron tracks are very useful in the electron vs. nuclear recoil discrimination

Energy Calibration of both chambers

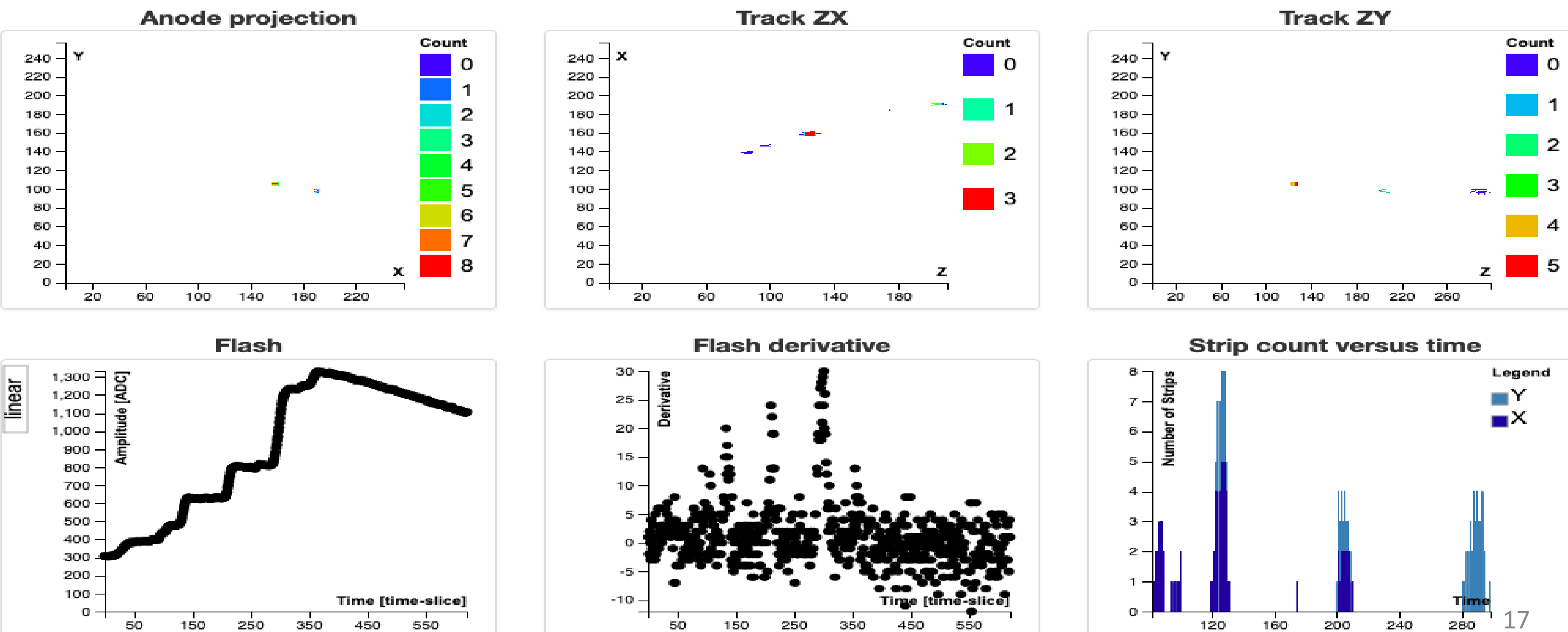




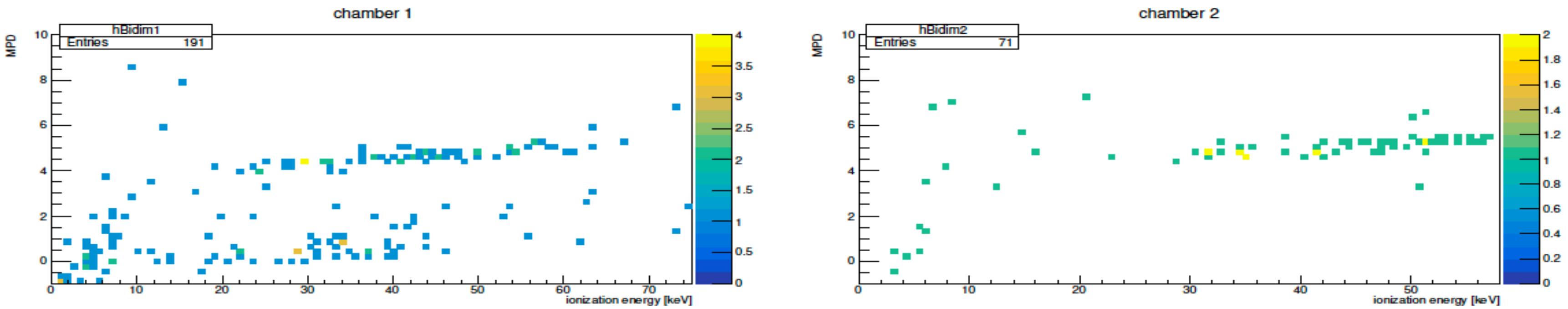
X-ray calibration of both chambers simultaneously



A typical electron event in the chamber 2

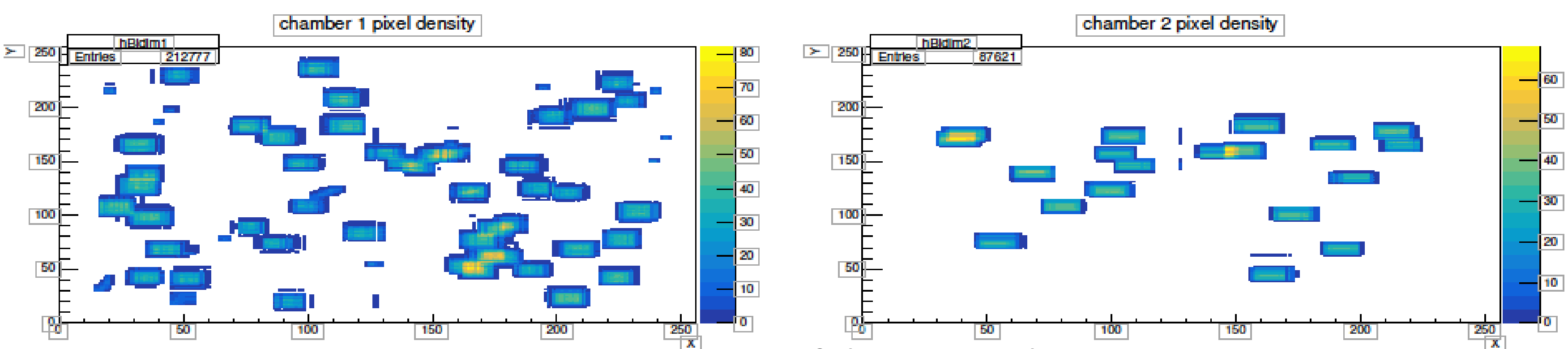


The first physics run of the Bi-chamber in february 2023 at Modane
Chamber 1(old detector)- Chamber 2 (new 10 cm detector)
127 h analysed at moderate gain (470 V)
Only recoils after the BDT, mainly from the Rn progeny.
The new detector shows few Rn progeny contributions



(a) In chamber 1. **(b)** In chamber 2.

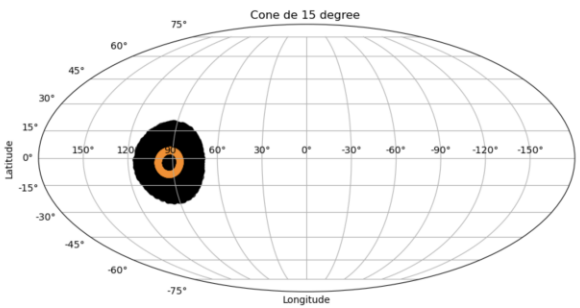
Figure 7.16.: MPD as a function of the energy in the background selection using the BDT at Modane, from runs with a gain covering an energy range of up to 70 keV.



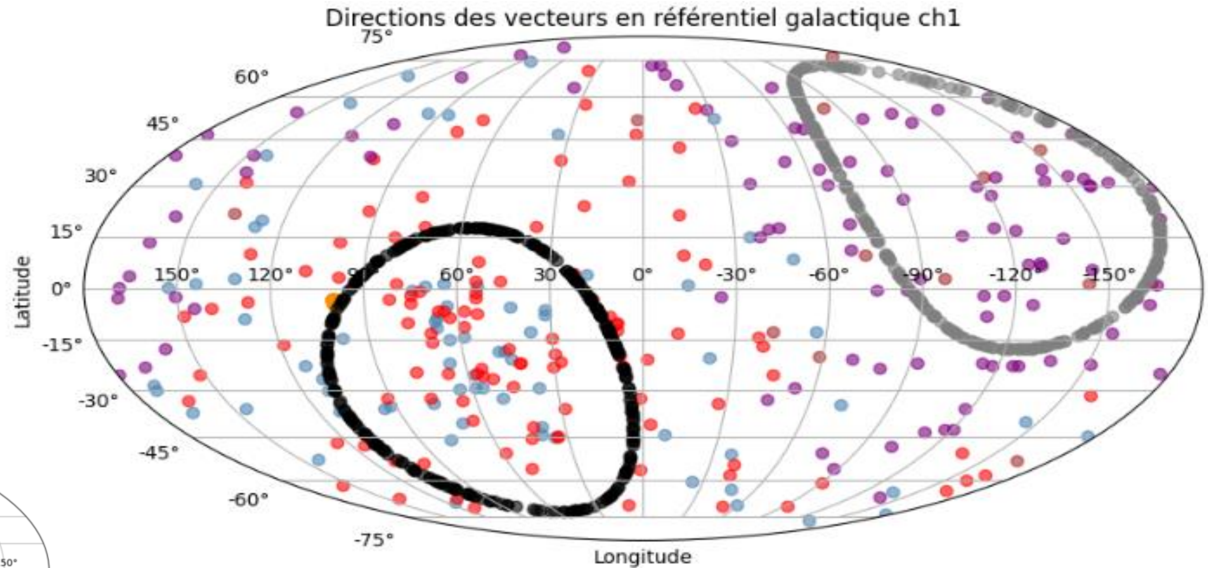
X-Y projections of the 3D tracks

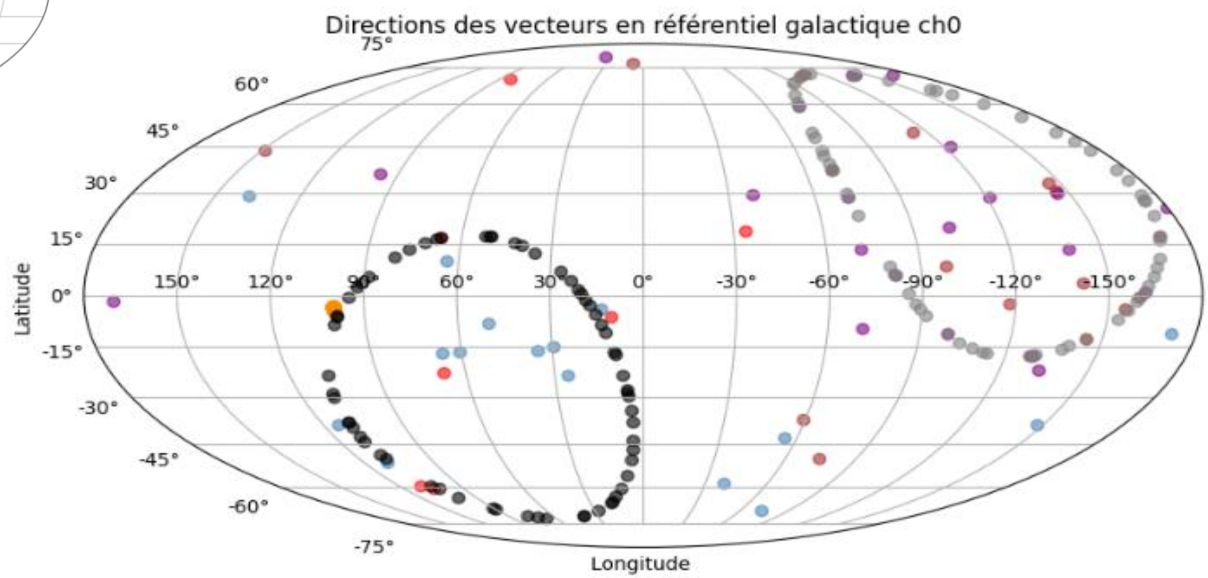
(a) In chamber 1. **(b)** In chamber 2.

Galactic Map showing the recoil events projections compared with the WIMP direction (orange)



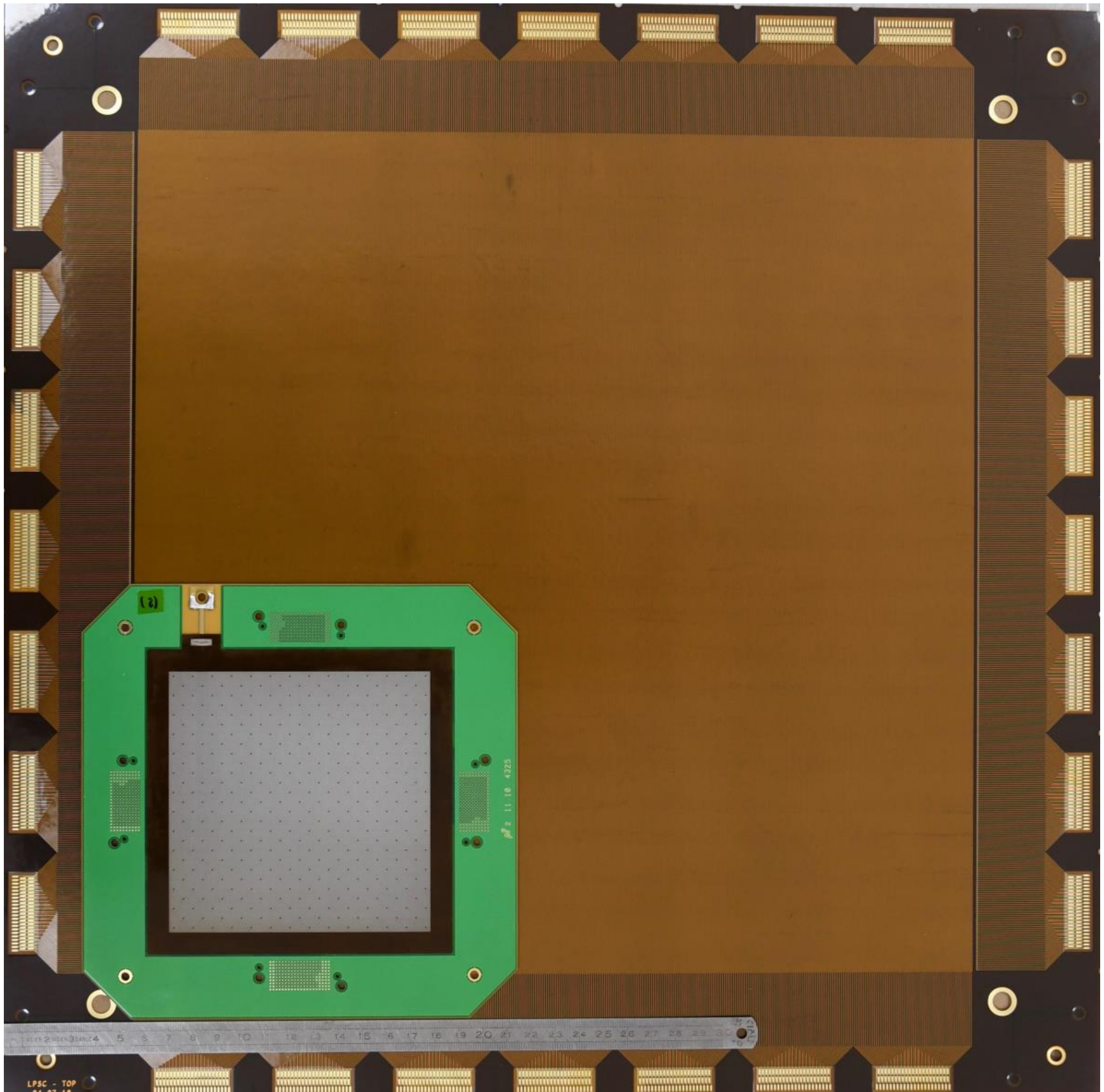
The black points show the orthogonal cathode direction
and the grey points the orthogonal anode direction

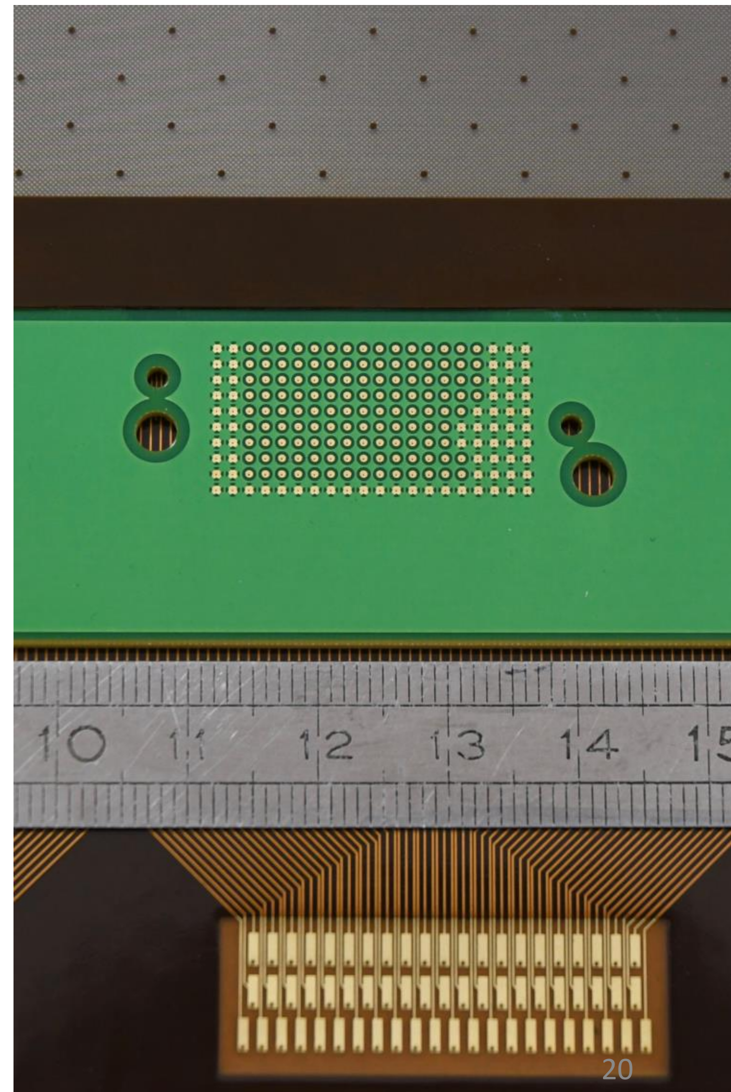




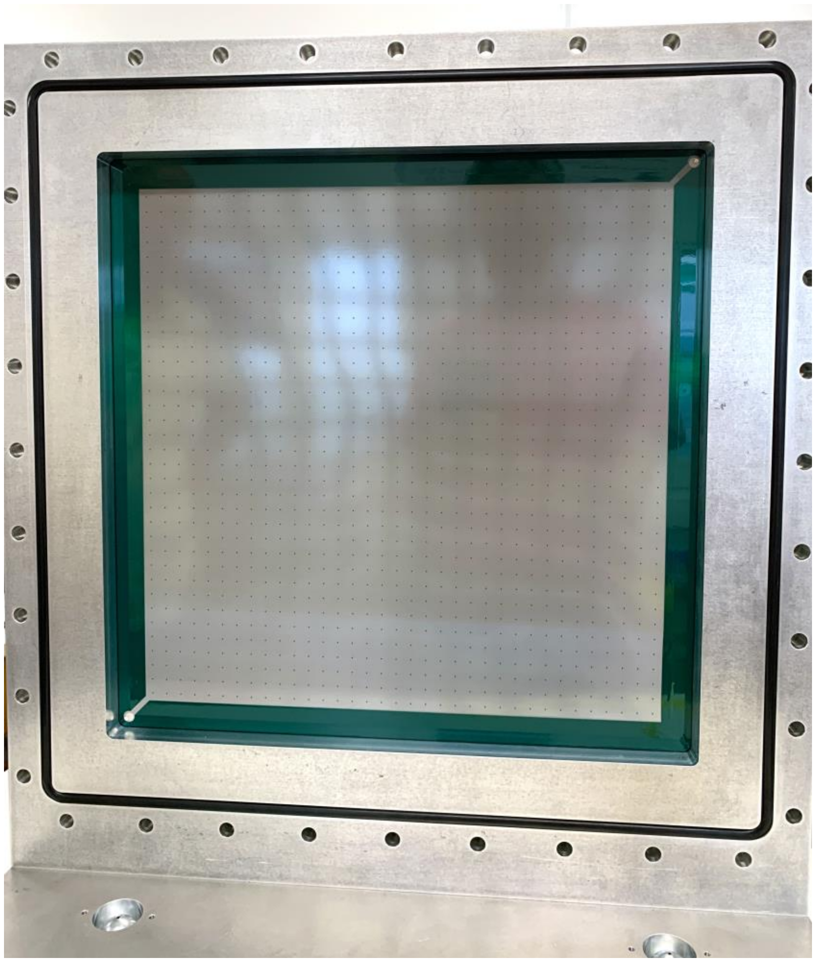
I. Ourahou et al. (2025)

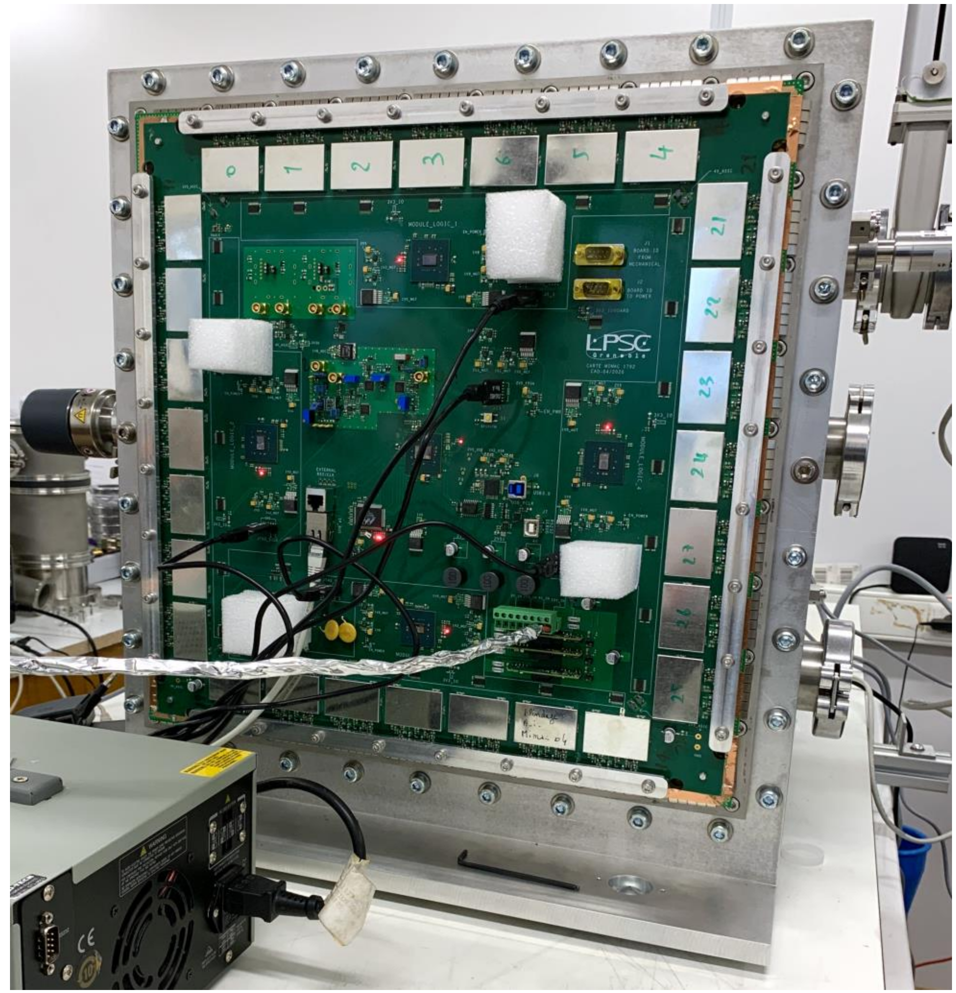
The **new 35 cm "new technology" MIMAC** detector compared to the old one



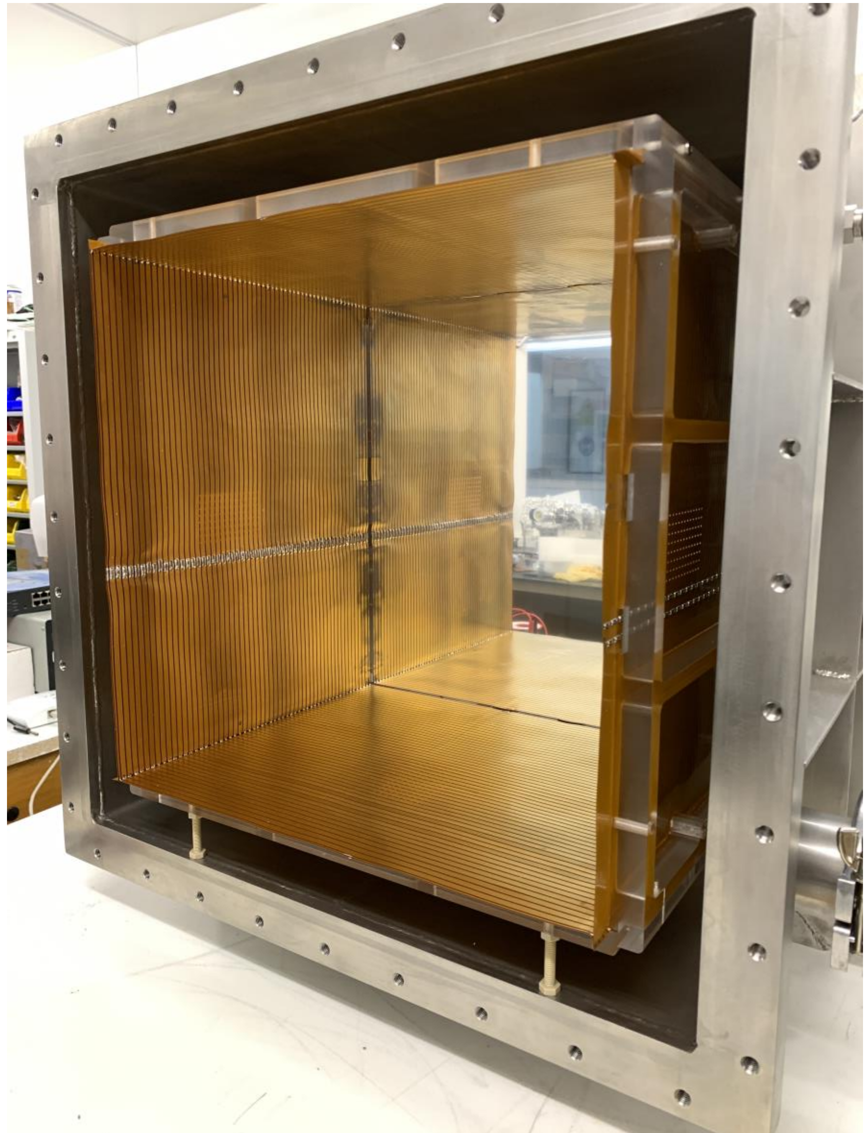


The new detector (35cm side, PCB) is mounted in the bi-chamber at the LPSC-Grenoble



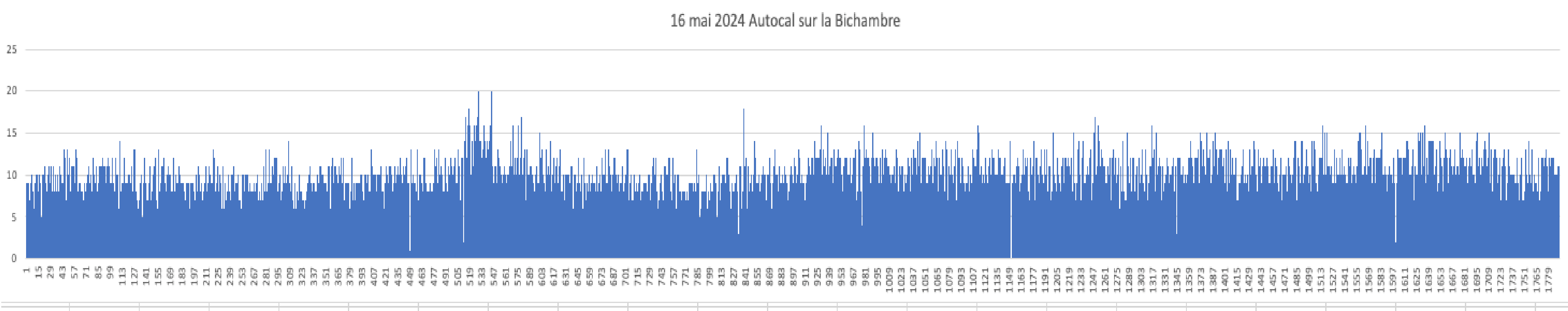


The MIMAC-35cm field cage



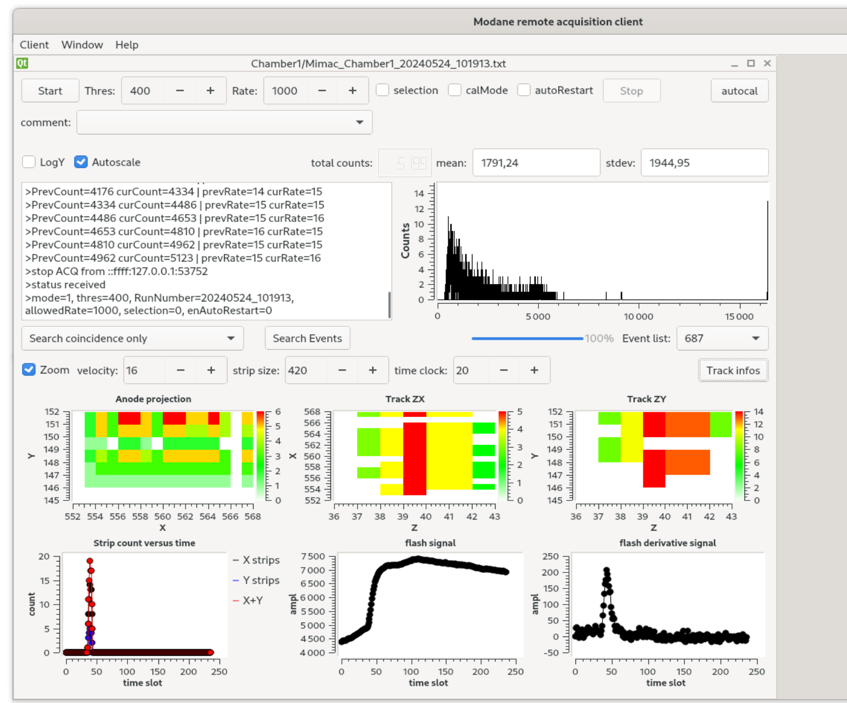
AUTOCALIBRATION OF THE 1792 (896 + 896) CHANNELS

1792 threshold values from the autocalibration defined by the intrinsic electronic noise on each strip.

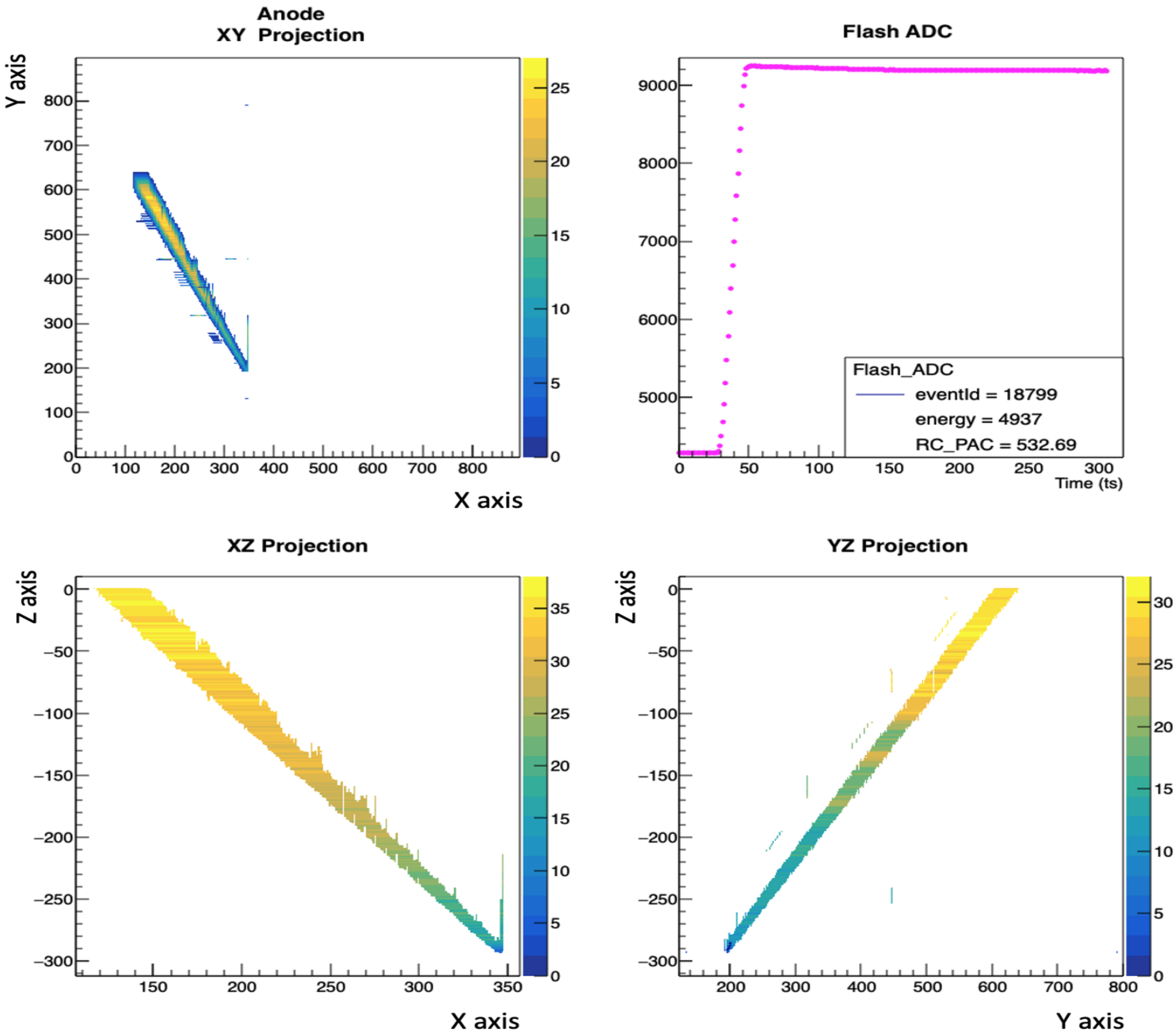


C_4H_{10} (30 mbar)

The first events with 3D tracks, of the background at Grenoble (May 24th 2024)



An alpha event from ^{222}Rn progeny



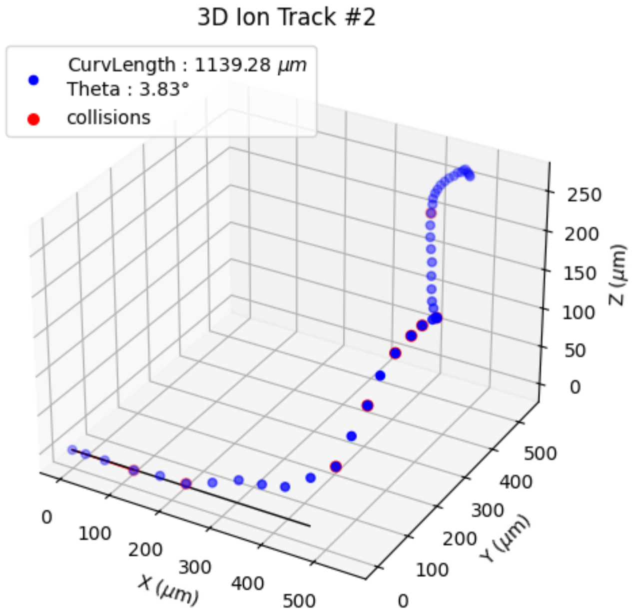
Exploring a large portion of the pixelated anode

35 x 35 cm^2

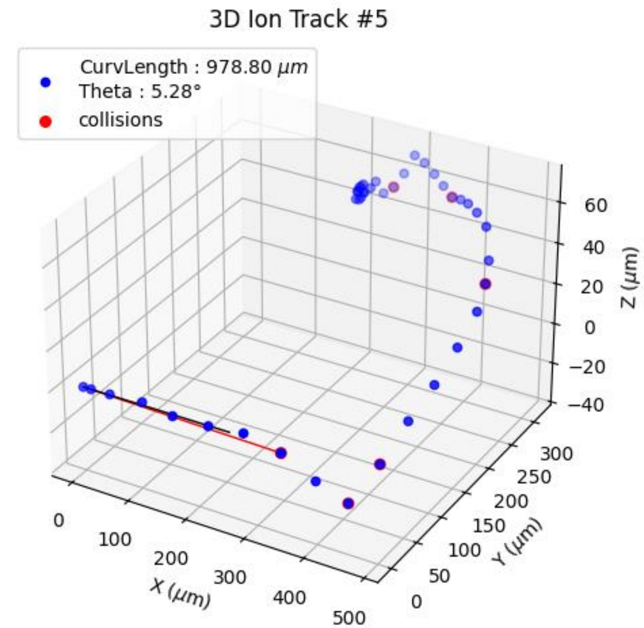
X and Y as a function of time every 20 ns

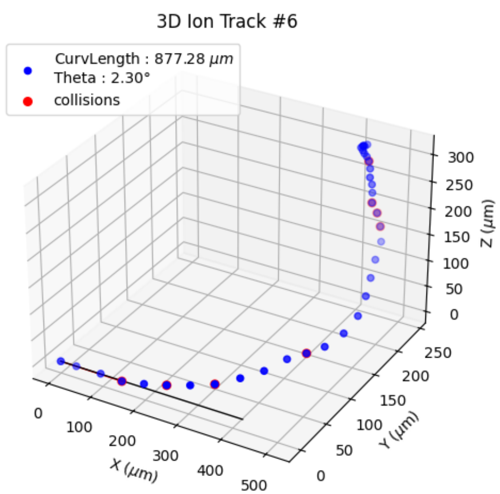
Deuteron Recoils from the neutron capture on H
H(n,gamma)^{2}H

SRIM 3D track simulations- pure C_4H_{10} at 30 mbar



$E_{kinetic}$= 1.29 keV

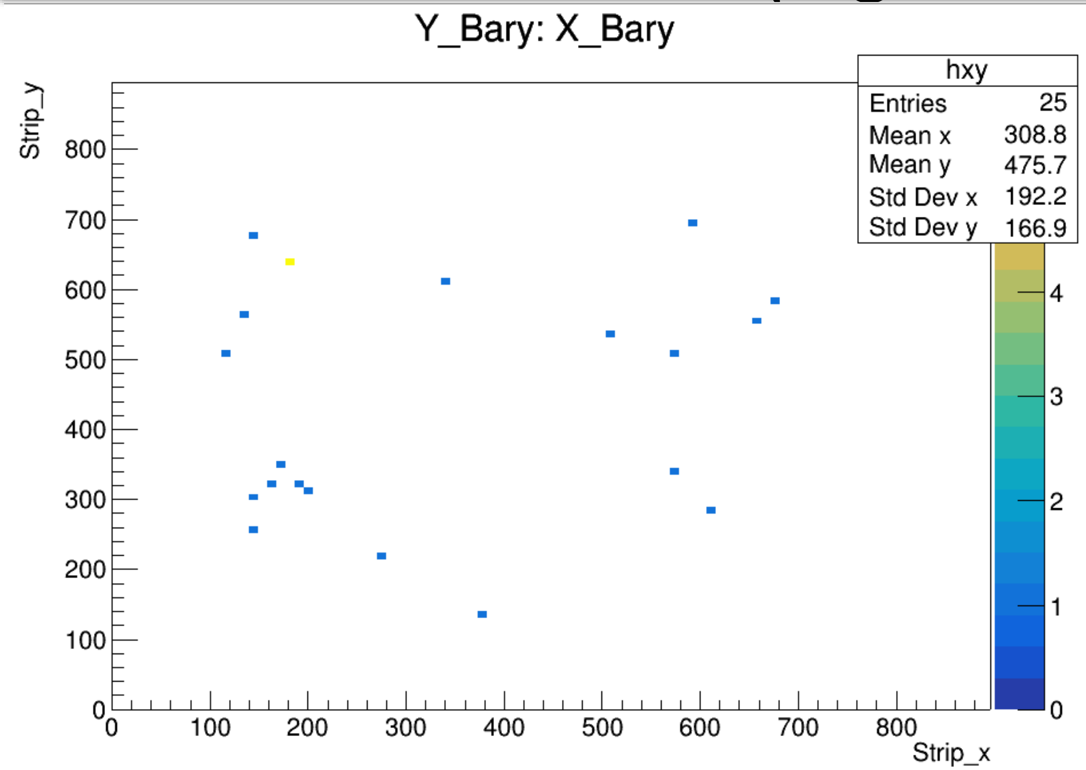




P. Louis-Cistec et al. (2025)

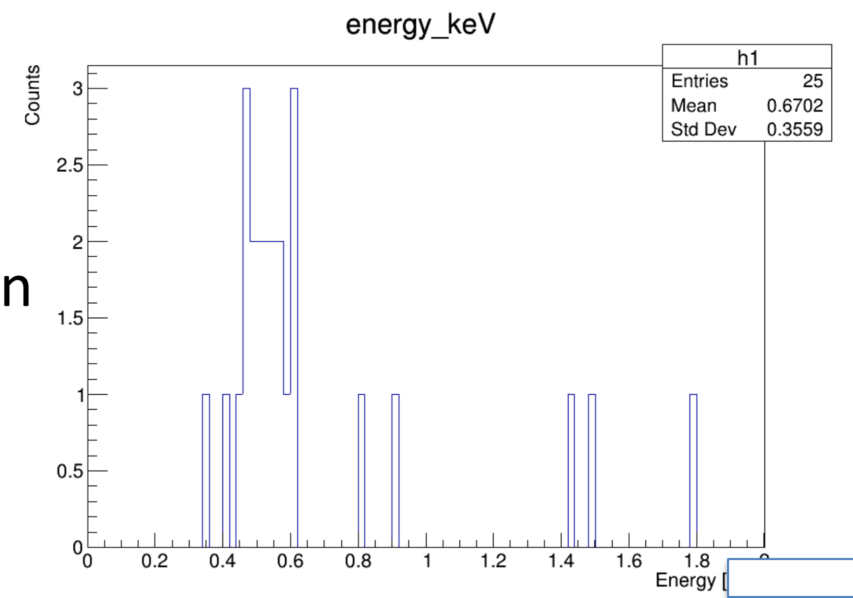
Only the « tail »
of the tracks has to
be considered as
the « directionality »

Deuteron Recoils from the neutron capture on H
$H(n,\gamma)^2H$



C_4H_{10} pure Gas at 30 mbar

25 events from 6 10^6 total background events
in 64 hours at LPSC-Grenoble



Ionization Quenched events of Deuteron recoils mainly at 1.29 keV !!

New Micromegas (35cm) on Kapton/Copper made by Chinese USTC team (Hefei)

With the cooper interface

The future… MIMAC – 1m^3

16 bi-chamber modules (2x 35x35x25 cm^3)

New technology anode
35cmx35cm

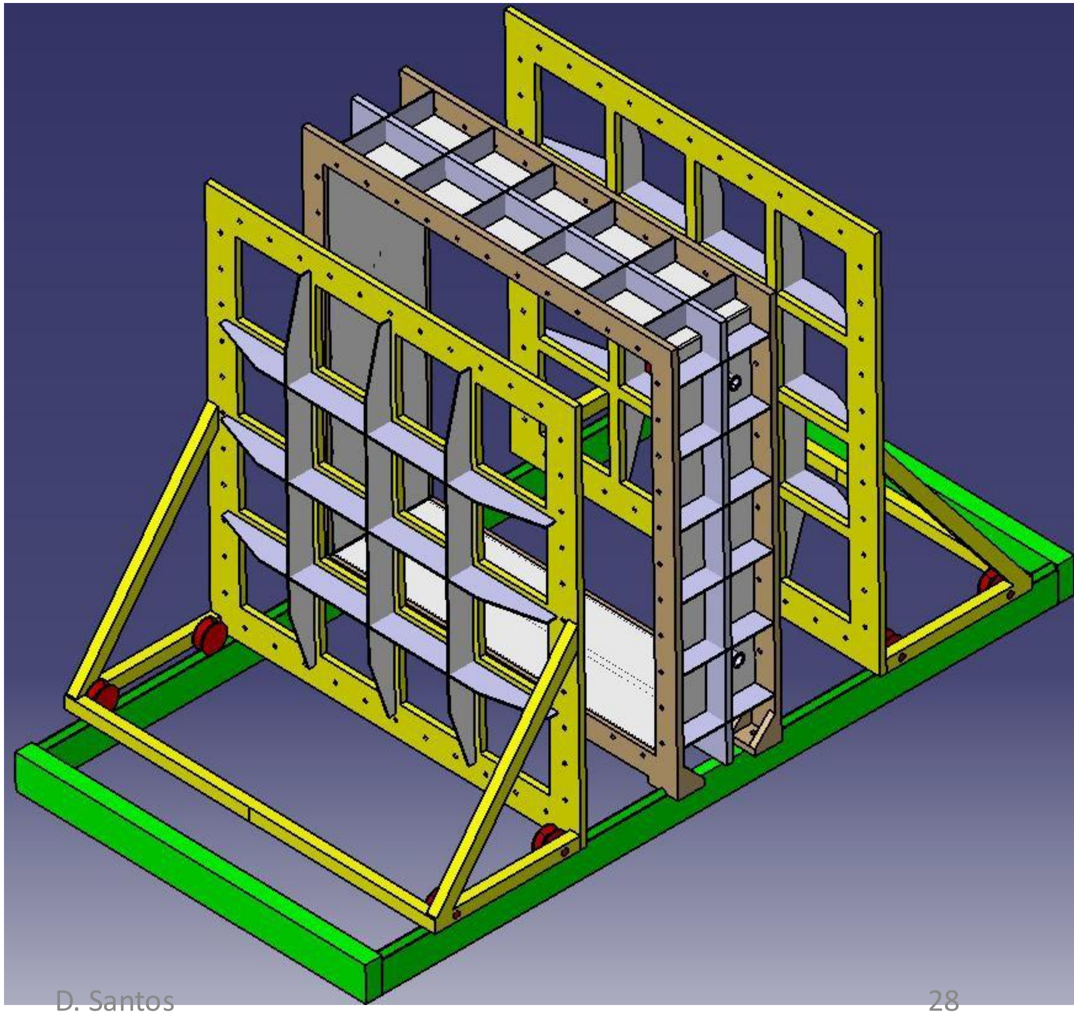
New electronic board
(1792 channels)

Only one big chamber with
4 field cages inside

First 1 m^3 at Modane
by the end of 2027

Second 1 m^3 at Jinping
by the end of 2028

financed by the Chinese partners?

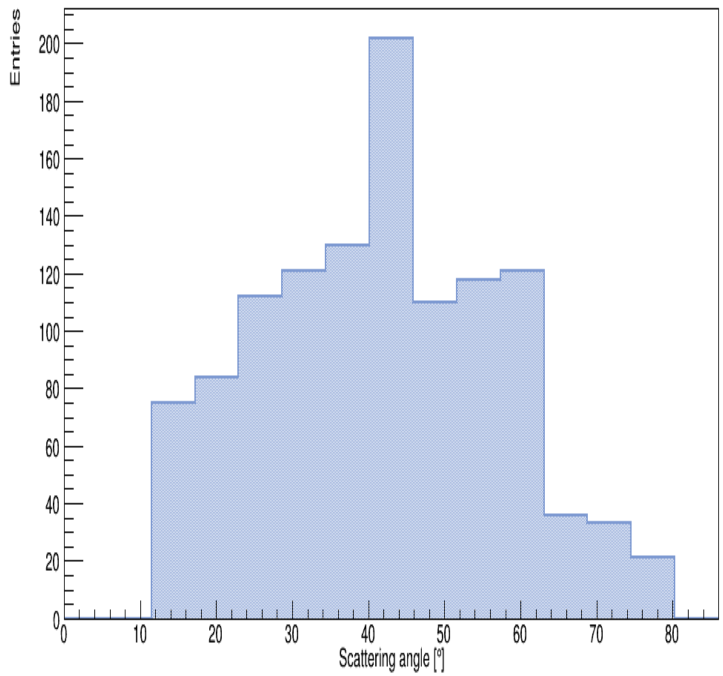


Conclusions

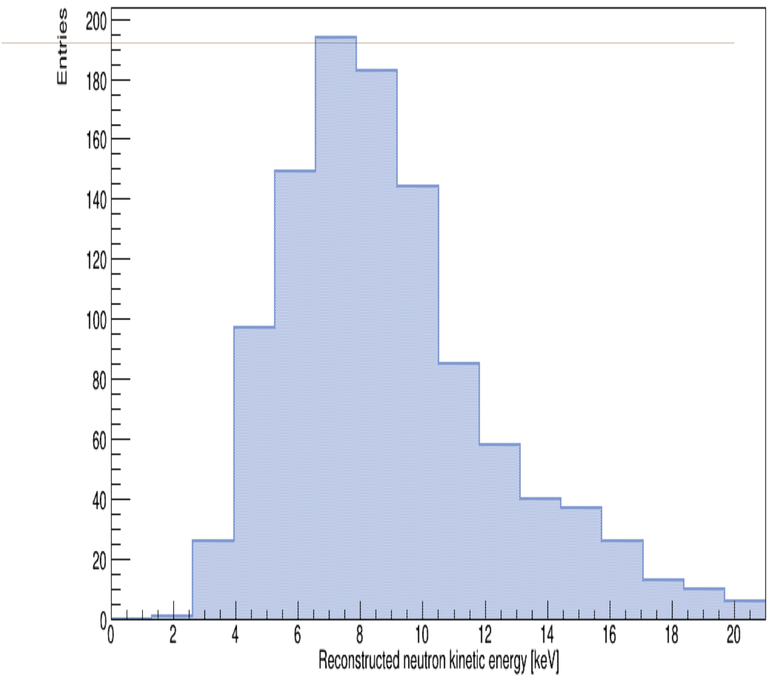
- MIMAC has developed an important know-how on 3D nuclear recoil directional detection from 300 eV up to 15 MeV and even more…
- The nuclear recoil directional detection is the observable needed to go beyond the neutrino floor for DM search, providing the galactic signature
- The 35 x 35 cm^2 will be the elemental brick to build a big directional detector… for a broad purpose in physics…

A new degree of freedom is available in « low-energy » particle detection: **the 3D-directionality**

Mono-energetic neutron field (8 keV)
Neutron spectrum reconstruction from proton recoils



Angular distribution



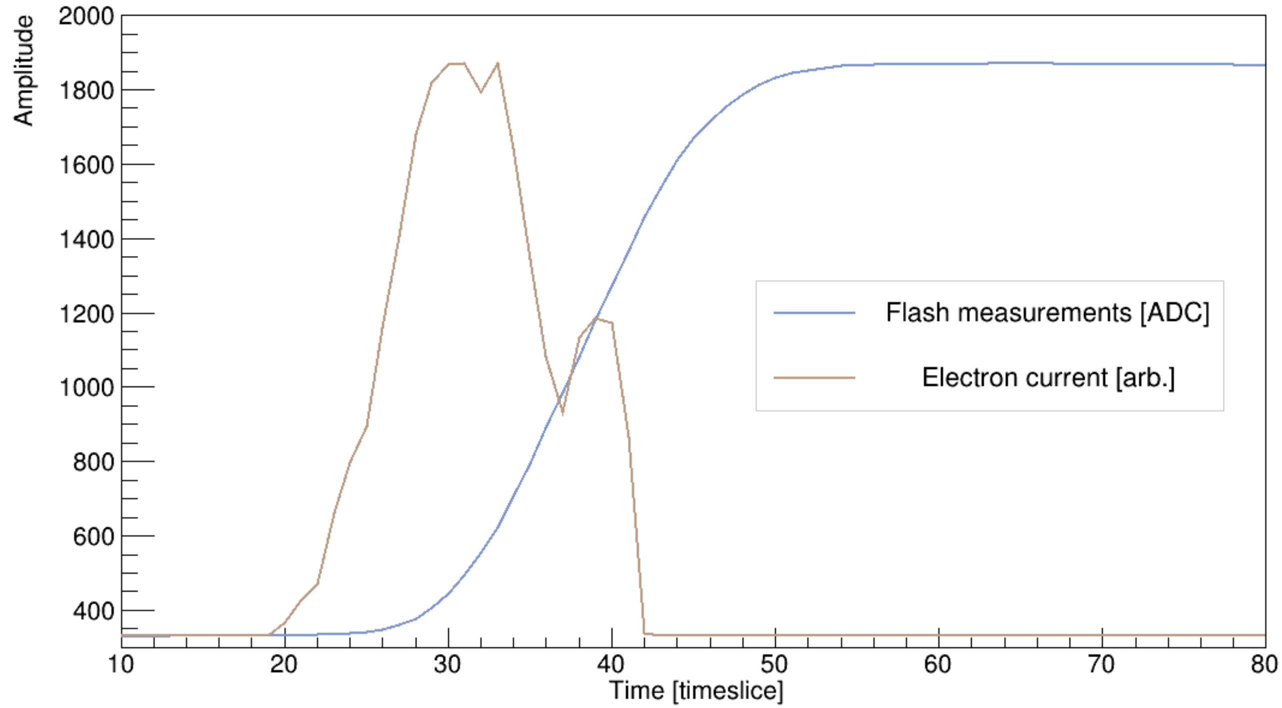
Reconstructed spectrum

Directional performances at 8 keV:

- Energy reconstructed agrees within 4.0% and angular resolution better than 15°

Cyprien Beaufort et al. JCAP08(2022)057

Directionality – Head-tail recognition



Deconvolution on measured 10 keV proton

- The deconvolution gives access to the time distribution of the primary electrons cloud

  $=\Rightarrow$ fine structure of the primary cloud

  $=\Rightarrow$ **Head-tail recognition**

C. Beaufort *et al* 2024 *JINST* **19** P05052, arXiv:2312.12842

3D tracks of Rn progeny

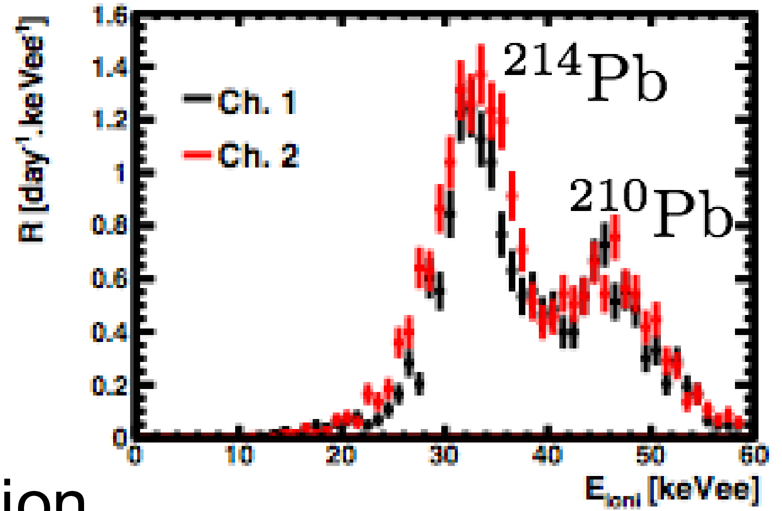
Electron/recoil discrimination

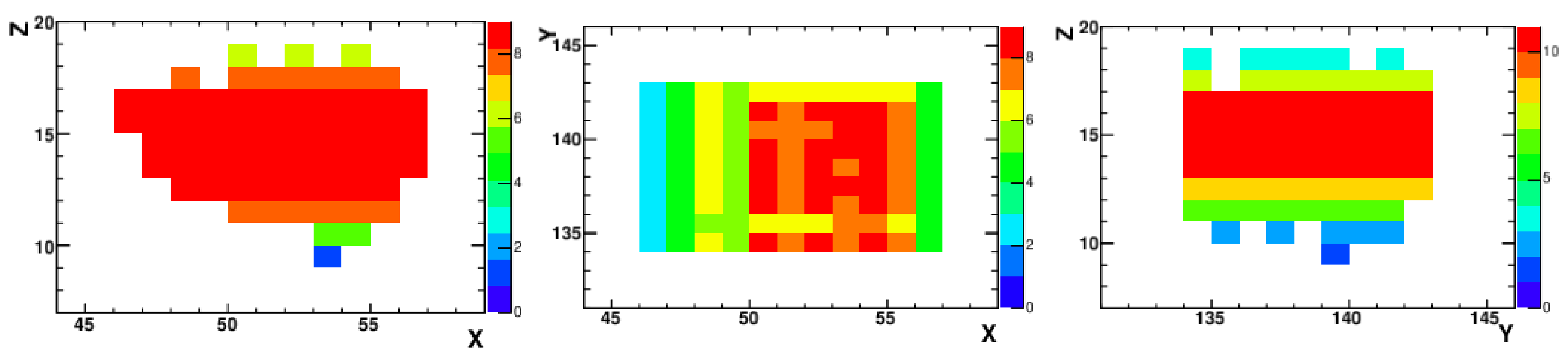
Mesure: $$\begin{cases} E_{ioni}(^{214}\mathrm{Pb}) = 32.90 \pm 0.16\,\mathrm{keVee} \\ E_{ioni}(^{210}\mathrm{Pb}) = 45.60 \pm 0.29\,\mathrm{keVee} \end{cases}$$

First measurement of 3D nuclear-recoil tracks coming from radon progeny

⟶ MIMAC detection strategy validation

Nuclear recoil spectra



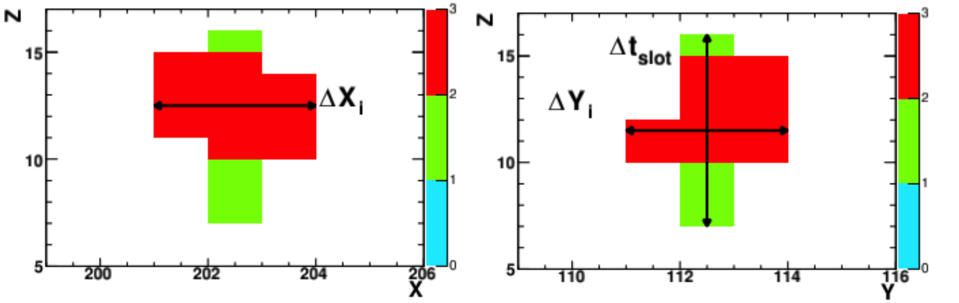


RPR events occur at different positions in the detector…

$$z_0 \longleftrightarrow \text{Diffusion}$$

$$\begin{cases} D_T = 237.9\,\mu\text{m}/\sqrt{\text{cm}} \\ D_L = 271.5\,\mu\text{m}/\sqrt{\text{cm}} \end{cases}$$

« Grid » event



Mean Projected Diffusion: $\overline{\mathcal{D}} = \ln\left(\overline{\Delta X} \times \overline{\Delta Y}\right)$