MIMAC

MIcro-tpc MAtrix of Chambers
for 3D-Directional Dark Matter detection
and
Neutron Spectroscopy

Daniel Santos

LPSC-Grenoble

CYGNUS-Sidney, December 15th 2023

MIMAC (MIcro-tpc MAtrix of Chambers)

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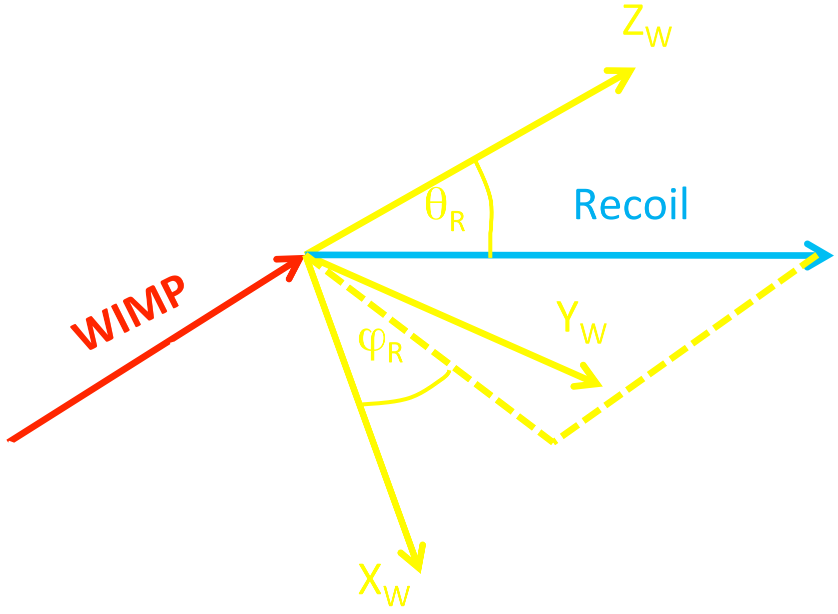
- SDI : **O. Guillaudin, N. Sauzet**
- Electronics : **E. Lagorio, O. Bourrion**
  G. Bosson (r (2020)), J. Bouvier (r (2020)), J.L. Bouly (r (2023)),
- Data Acquisition: **T. Descombes**
- COMIMAC (quenching) : **J-F. Muraz**

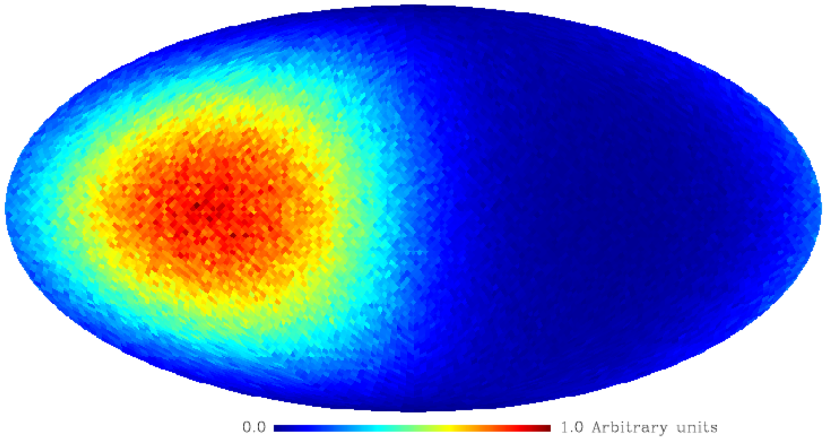
CCPM (Marseille): J. Busto, C. Tao

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

IHEP (Beijing-China): ZhiminWang , Changgen Yang
USTC (University of Science and Technology of China, Hefei) Zhiyong Wang
SJTU (Shanghai Jiao Tong University) Yi Tao (post-doc)

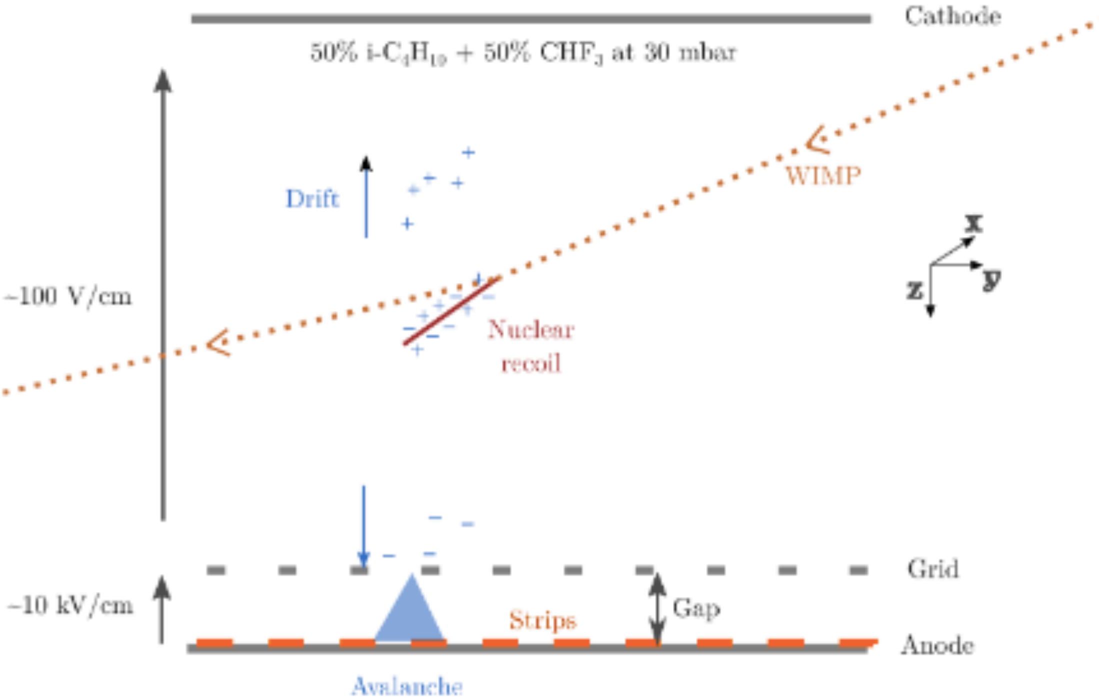
There are many "angles" for describing nuclear recoil angular distributions
3D tracks are needed…

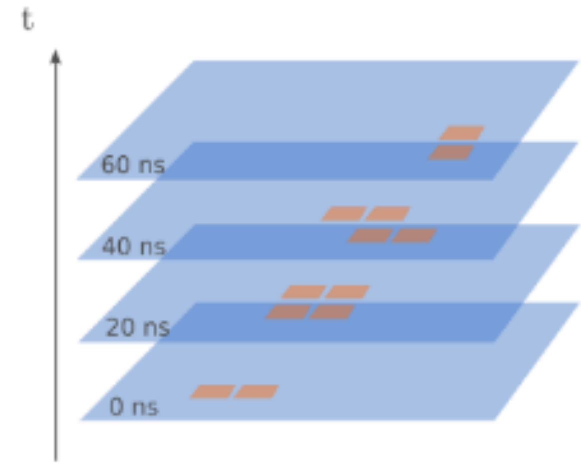




Map of recoils in galactic coordinates (HealPix)

MIMAC detection principles





Drift velocity = 11 um/ns

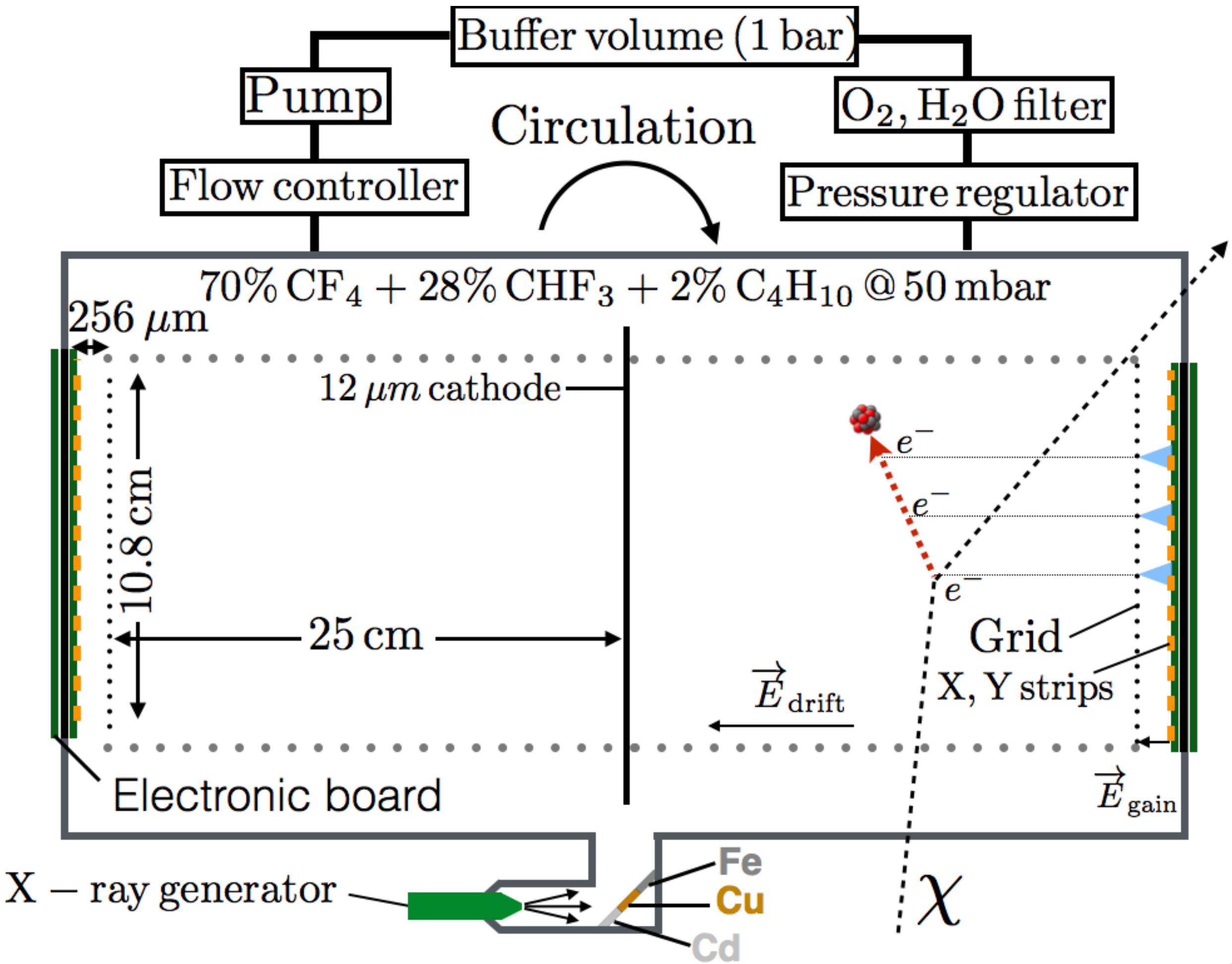
Measurement of the ionization energy:

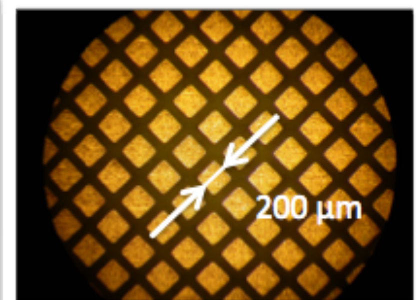
Charge integrator connected to the mesh coupled to a FADC sampled at 50 MHz

+ **Cathode signal**

+ **Ionization Quenching Factor measurements**

MIMAC-bi-chamber module





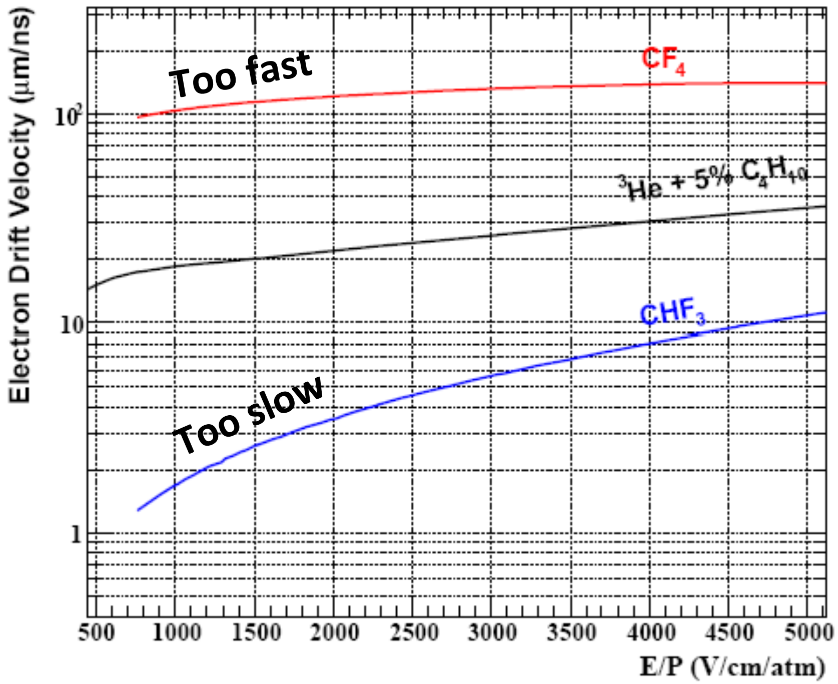
Micromegas 10x10 cm², designed by IRFU- Saclay (France)

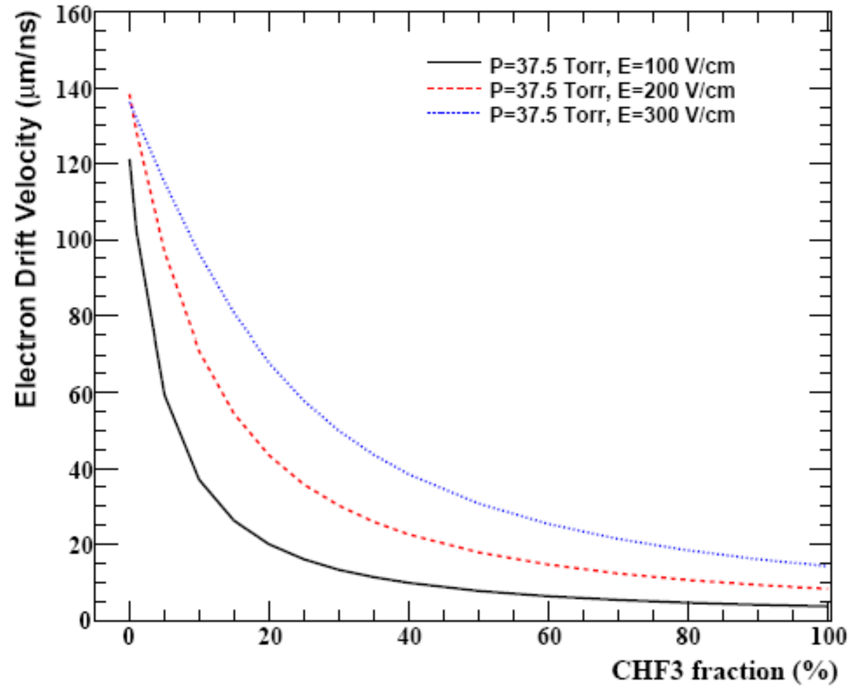
MIMAC Target: $^1H, ^{19}F$

- Light WIMP mass
- Axial coupling

3D Tracks: Drift velocity

Magboltz Simulation

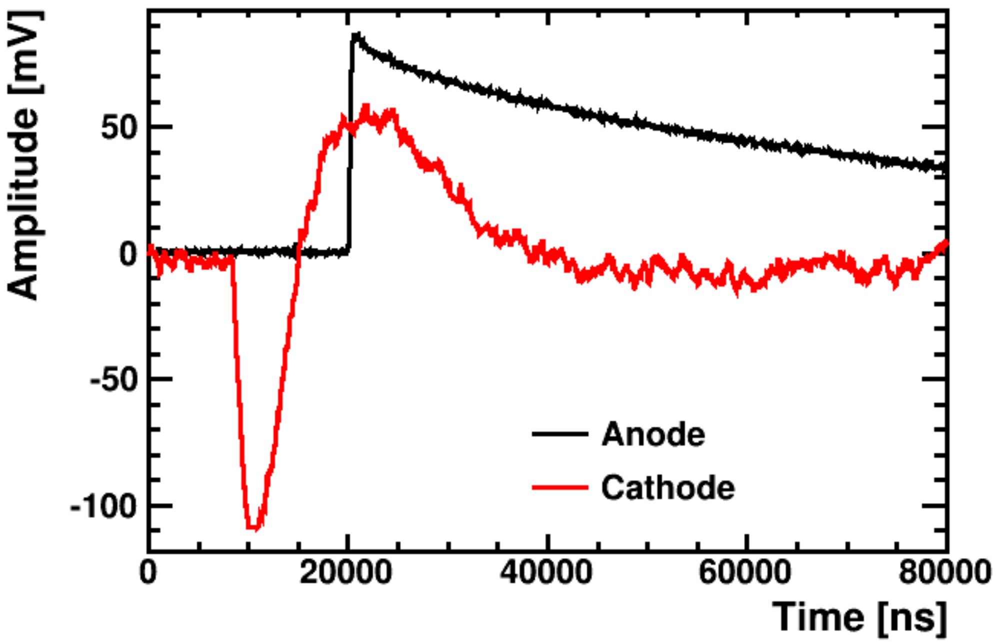




- New mixed gas MIMAC target : CF_4 + 28% CHF_3
- Other mixed gas used recently: C_4H_{10} + 50% CHF_3

Cathode Signal to place the 3D-track

The cathode signal is produced by the primary electrons drift. It is produced before the anode signal produced by the avalanche.
(C. Couturier,Q. Riffard, N. Sauzet et al. (2017))



Measurement in a MIMAC chamber of an alpha passing through the active volume parallel to the cathode at 10 cm distance.

MIMAC-Cathode Signal measurements giving the drift velocity of primary electrons !!

(C. Couturier, Q. Riffard, N. Sauzet et al. 2017)

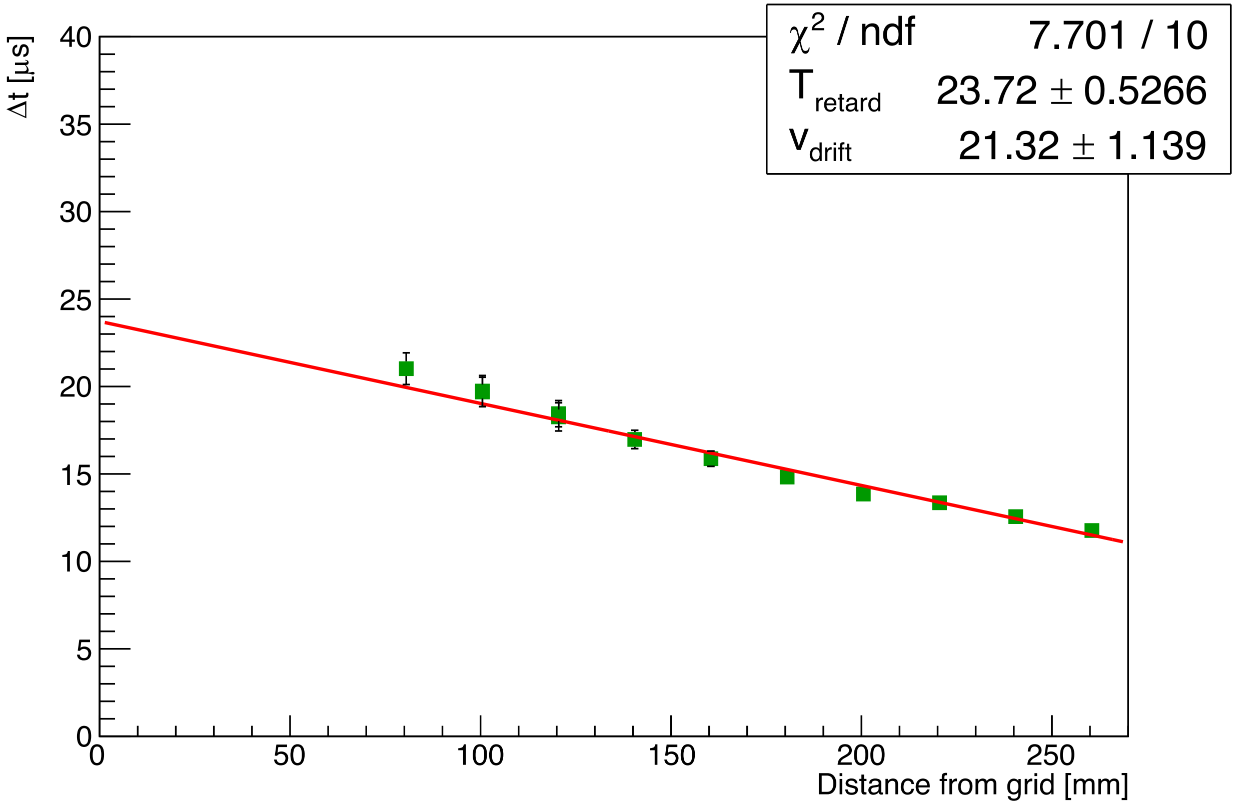
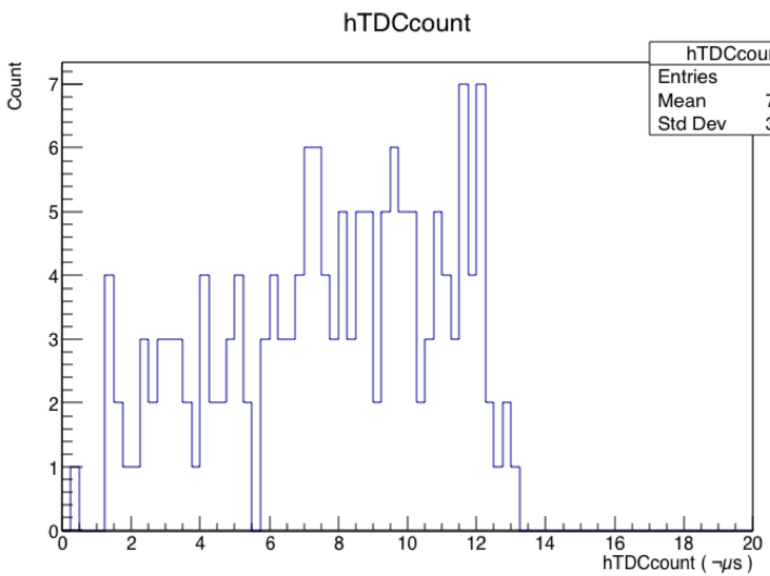


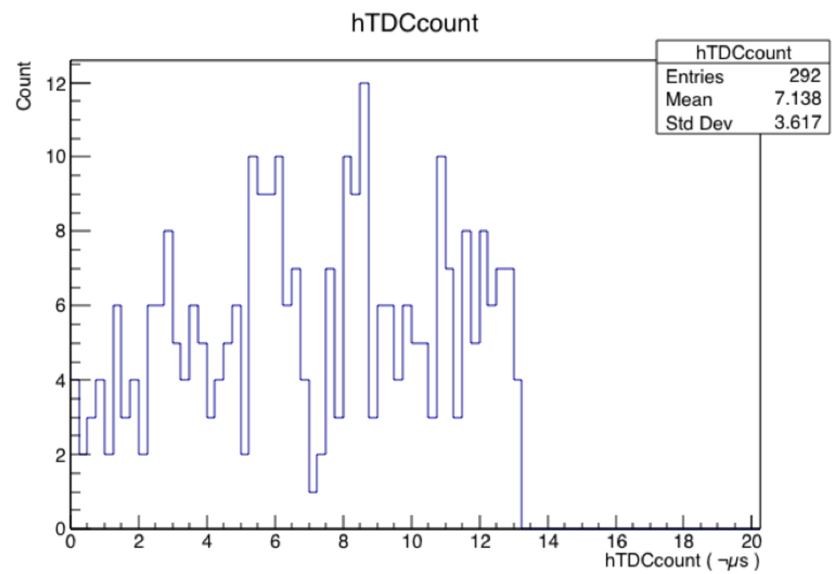
Figure 4. Measure of the time differences (TAC) between the grid signal and the delayed cathode signal in the "START Grid" configuration, as a function of the distance of the α source from the anode (green points) ; error bars correspond to the standard deviation of the mean. A linear fit of these points is superimposed in red and provides the values of the drift velocity and the additional delay.

First Cathode Signals from the MIMAC bichamber background
(O. Guillaudin, D.S. et al.)

Chamber 1

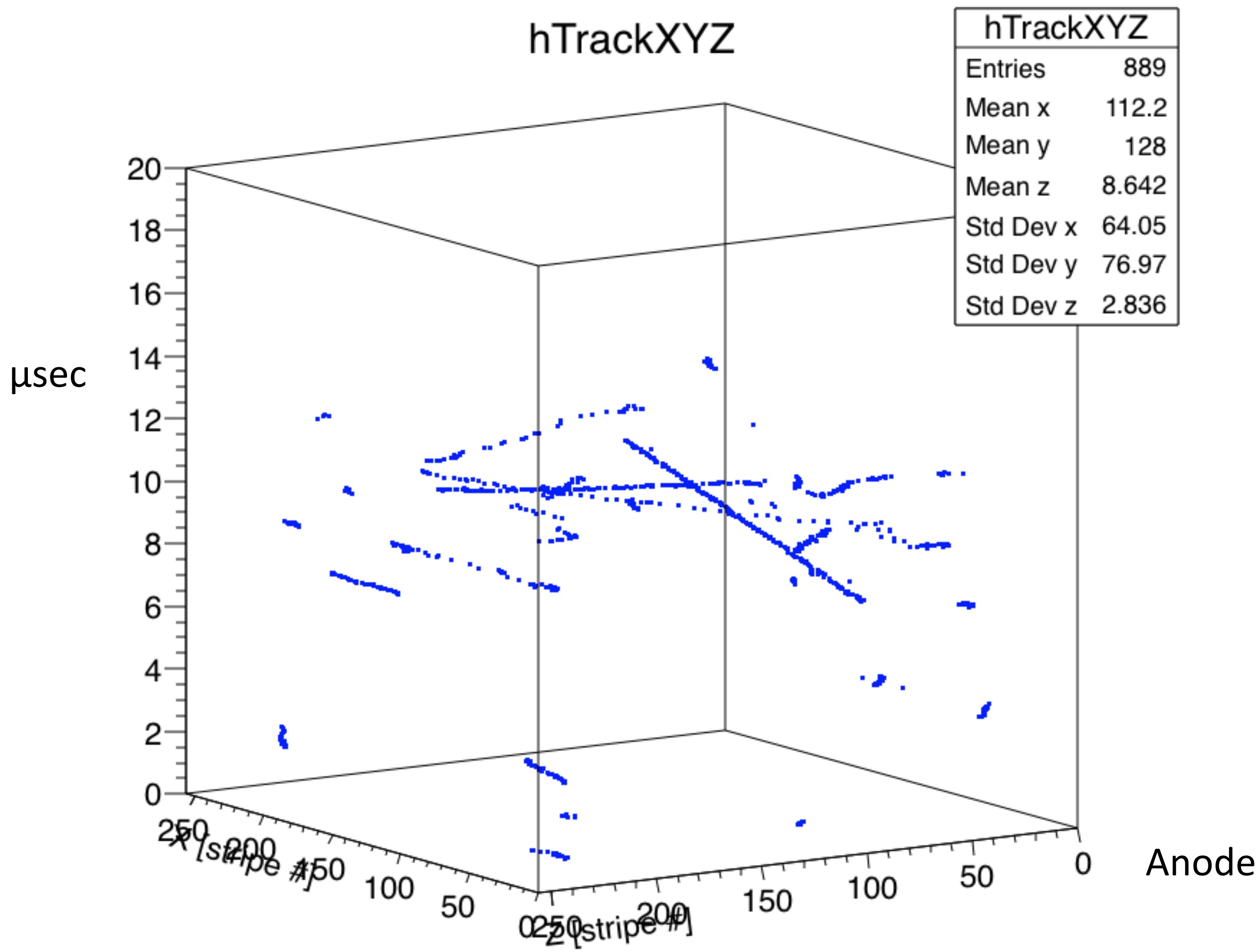


Chamber 2



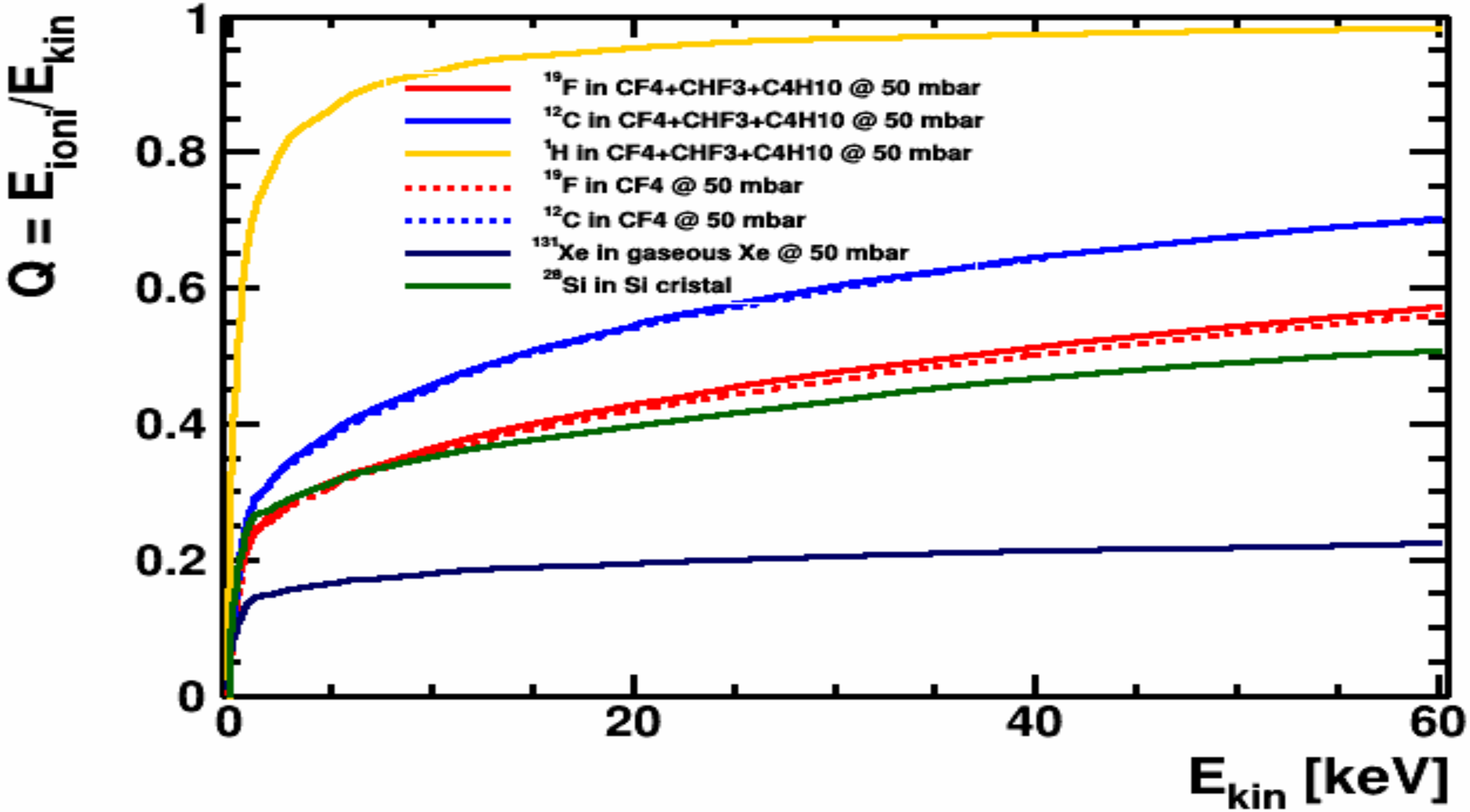
Measuring the time between the “event production” and the avalanche signal !!
Covering the 26 cm drift distance (13 us x 20 um/ns) !!

3D event-localization in MIMAC



Ionization Quenching Factors

SRIM-Simulations (LPSC)



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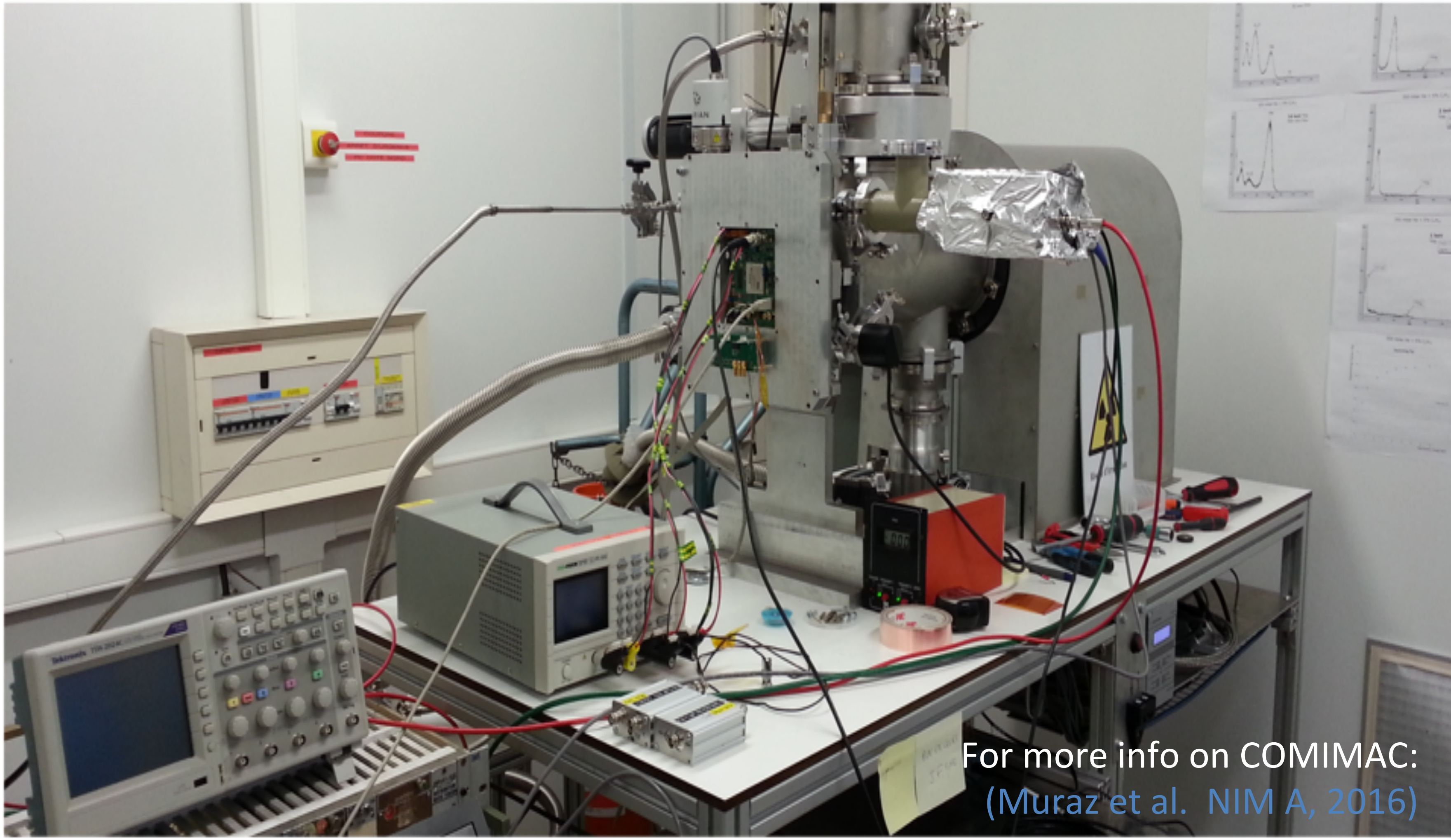
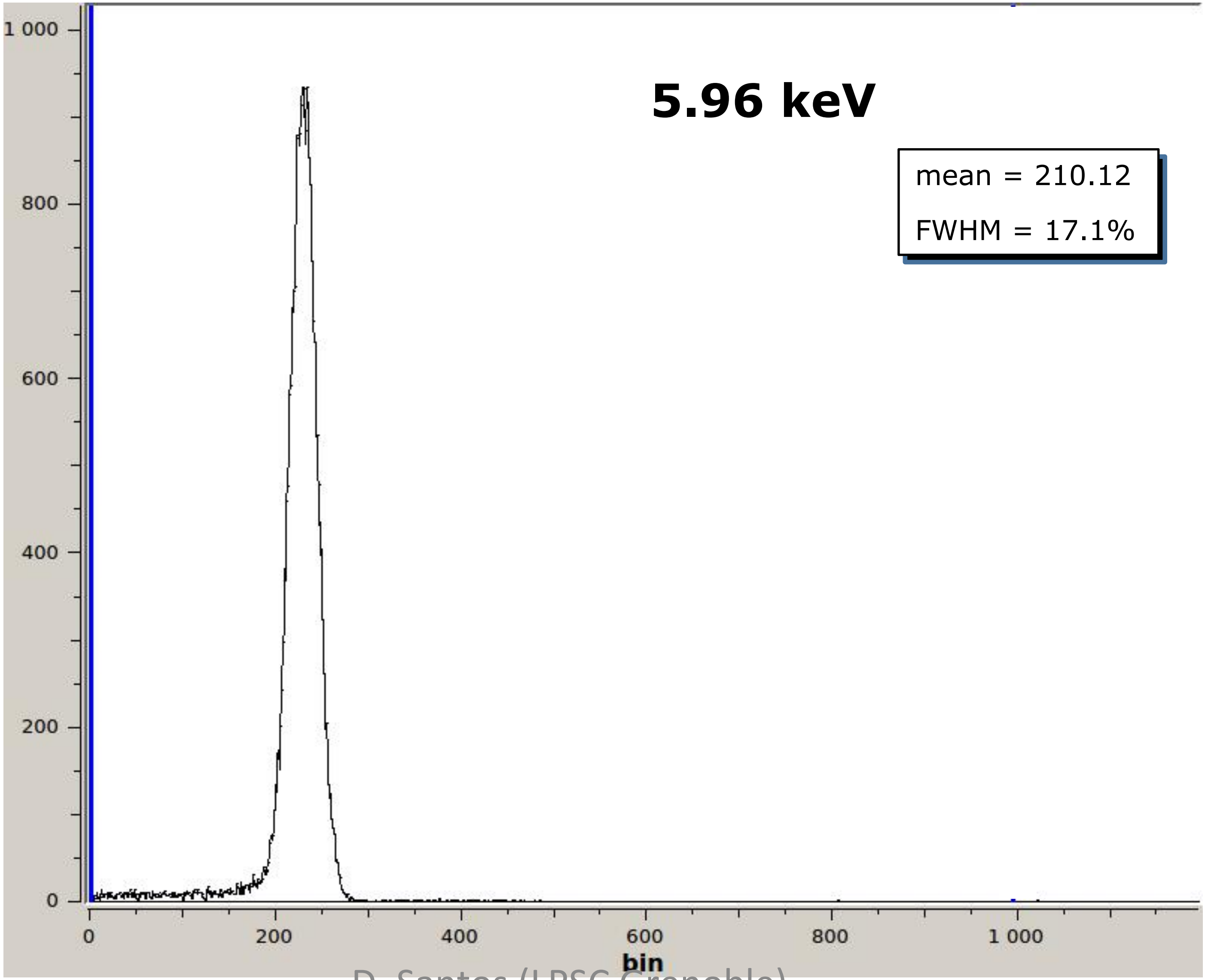
Nuclear and electron 3D-tracks, produced by COMIMAC

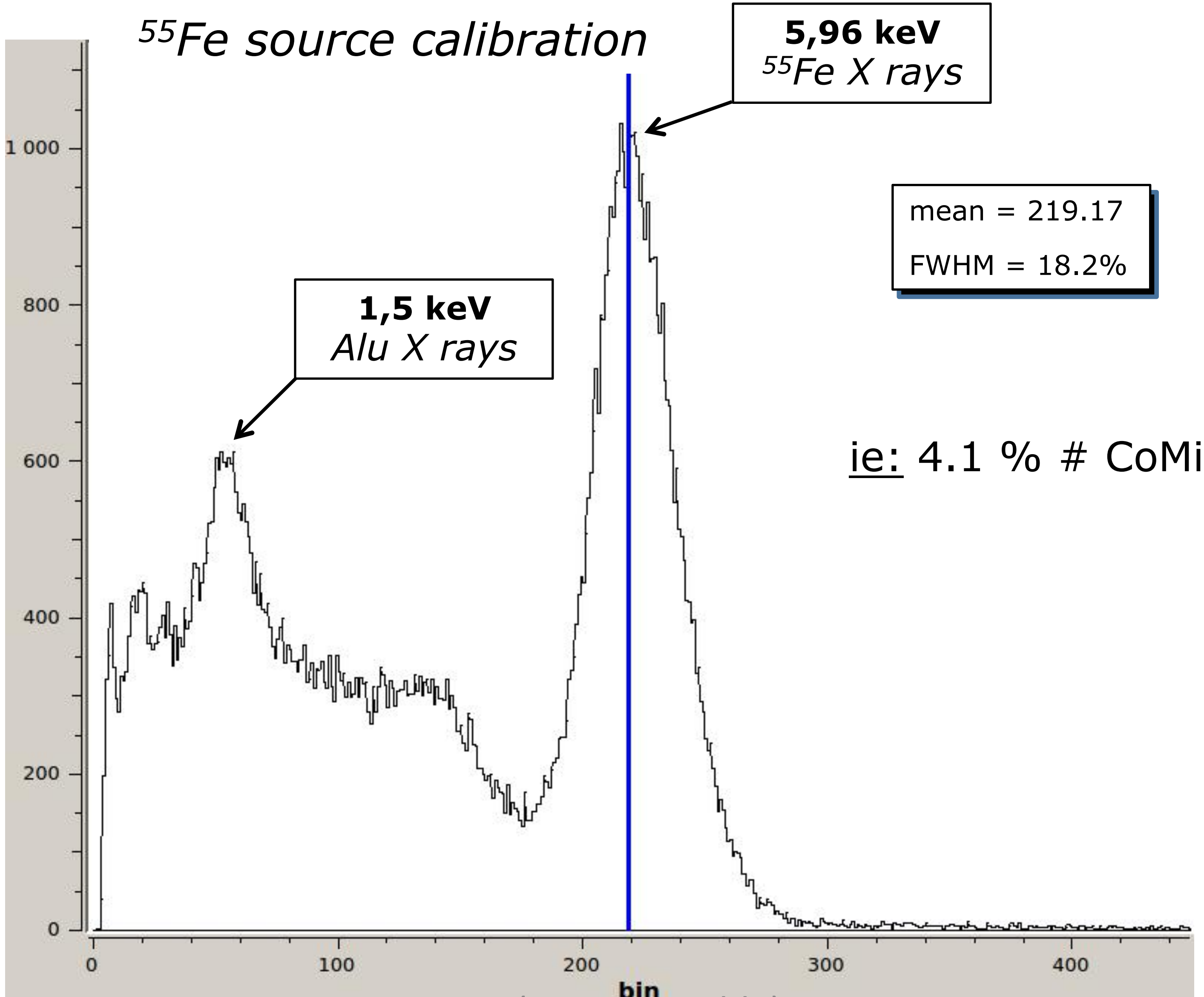


For more info on COMIMAC:
(Muraz et al. NIM A, 2016)

Electrons Performance

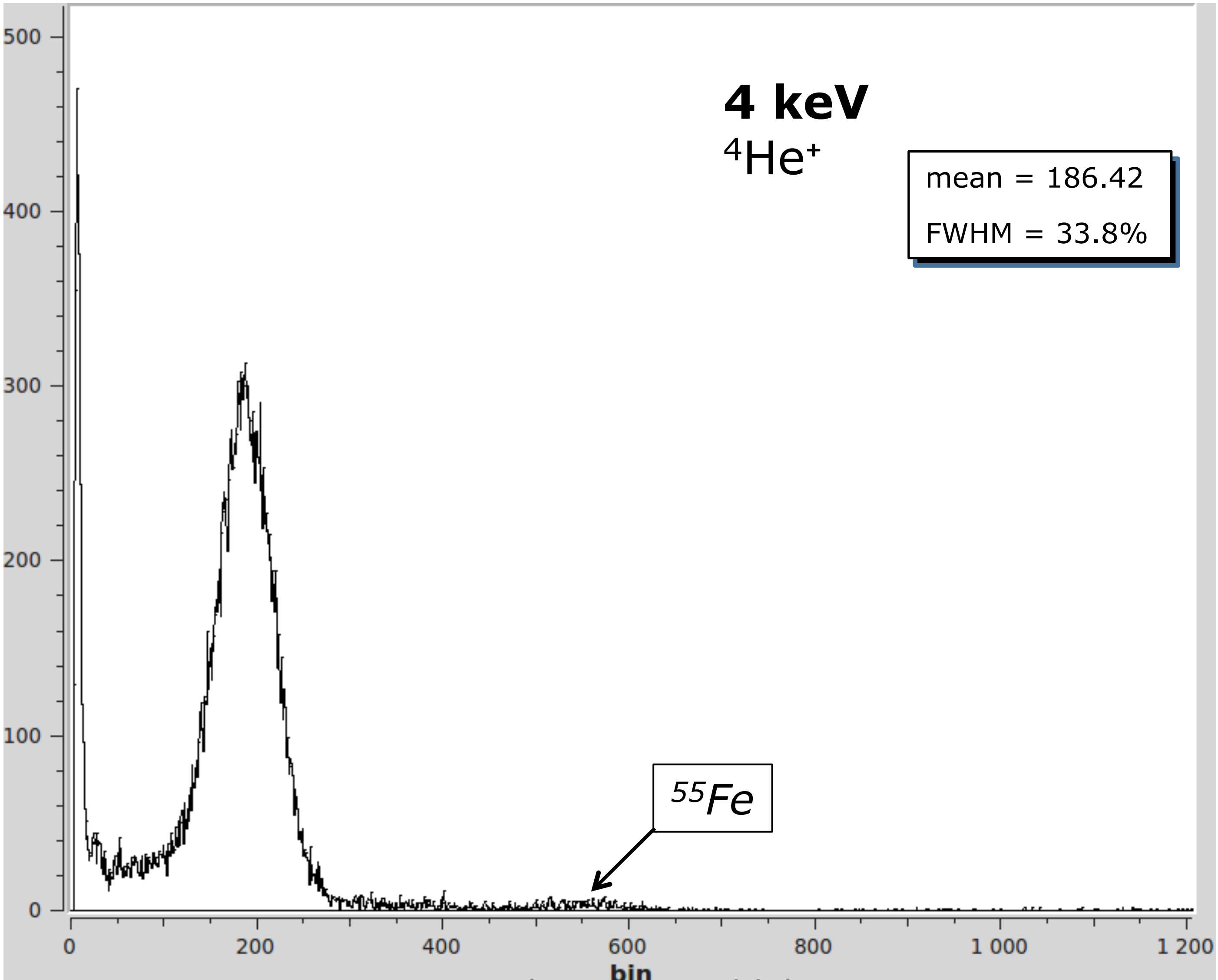


Electrons Performance

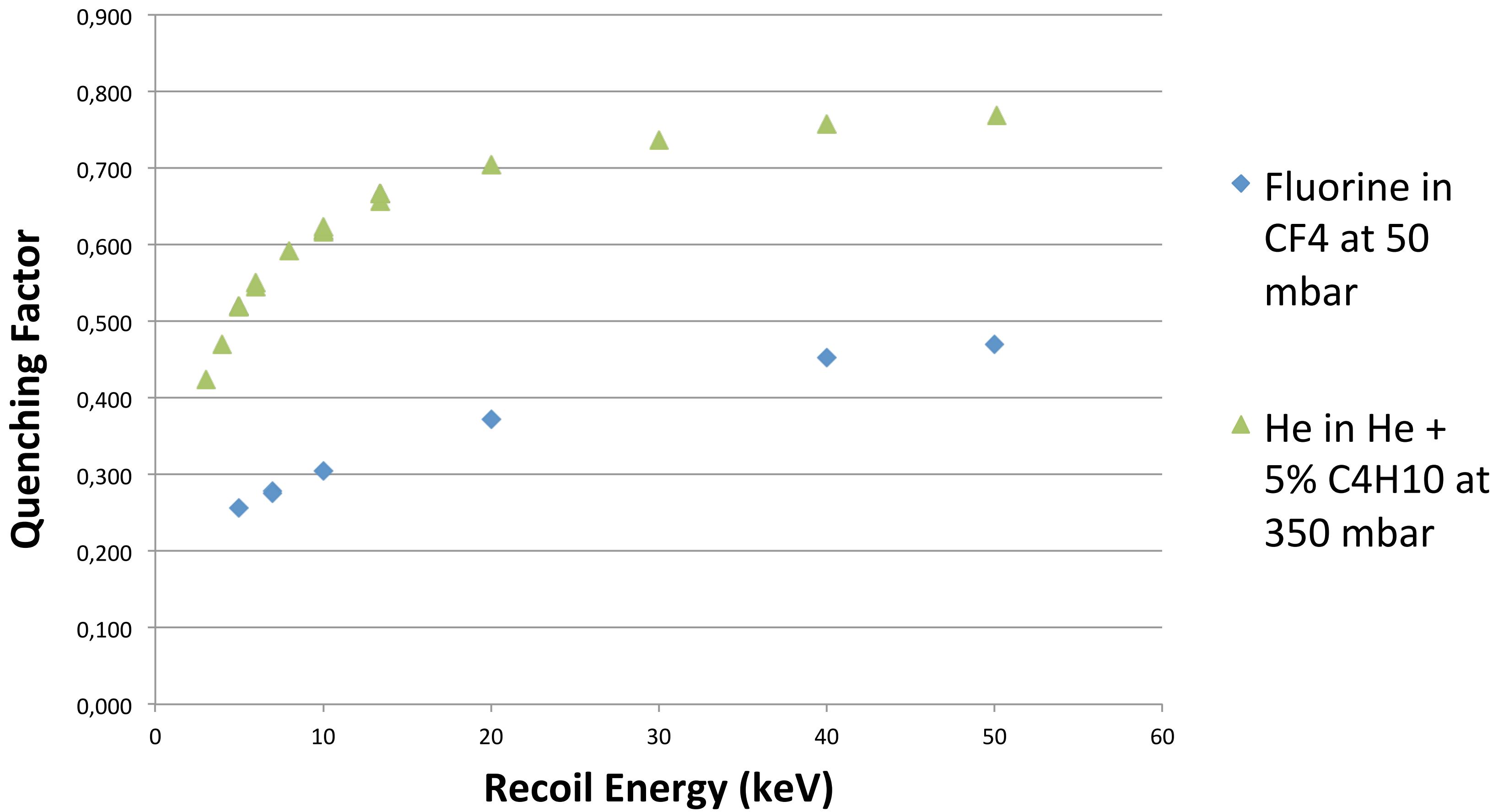


ie: 4.1 % # CoMimac

Ions Performance



Ionization Quenching Factor for Fluorine in pure CF4 at 50 mbar



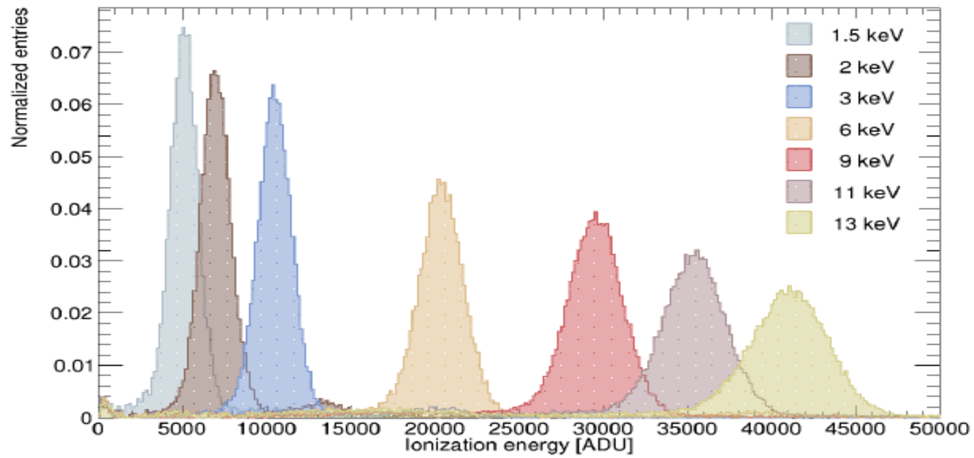
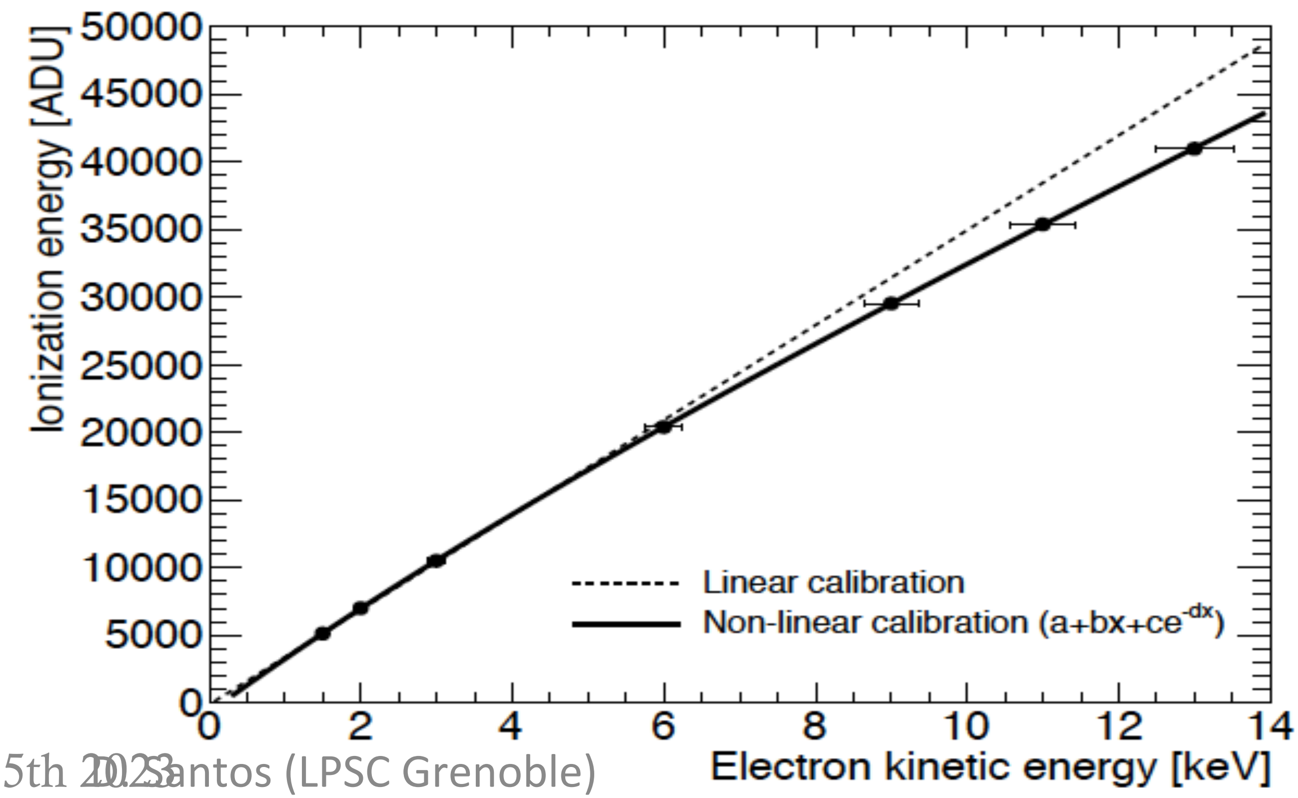


Fig. 5: Complete set of energy spectra used for the calibration of the detector response. The kinetic energy is determined by the Comimac facility. The cosmic background has been subtracted but no cut is applied.

Electron Calibration with COMIMAC of a 30 cm diameter Sphere with an akinos sensor (NEWS-G)

Non-linearity at energies higher than 4 keV probably due to screening charge effect of previous avalanches on the primary electron avalanches.

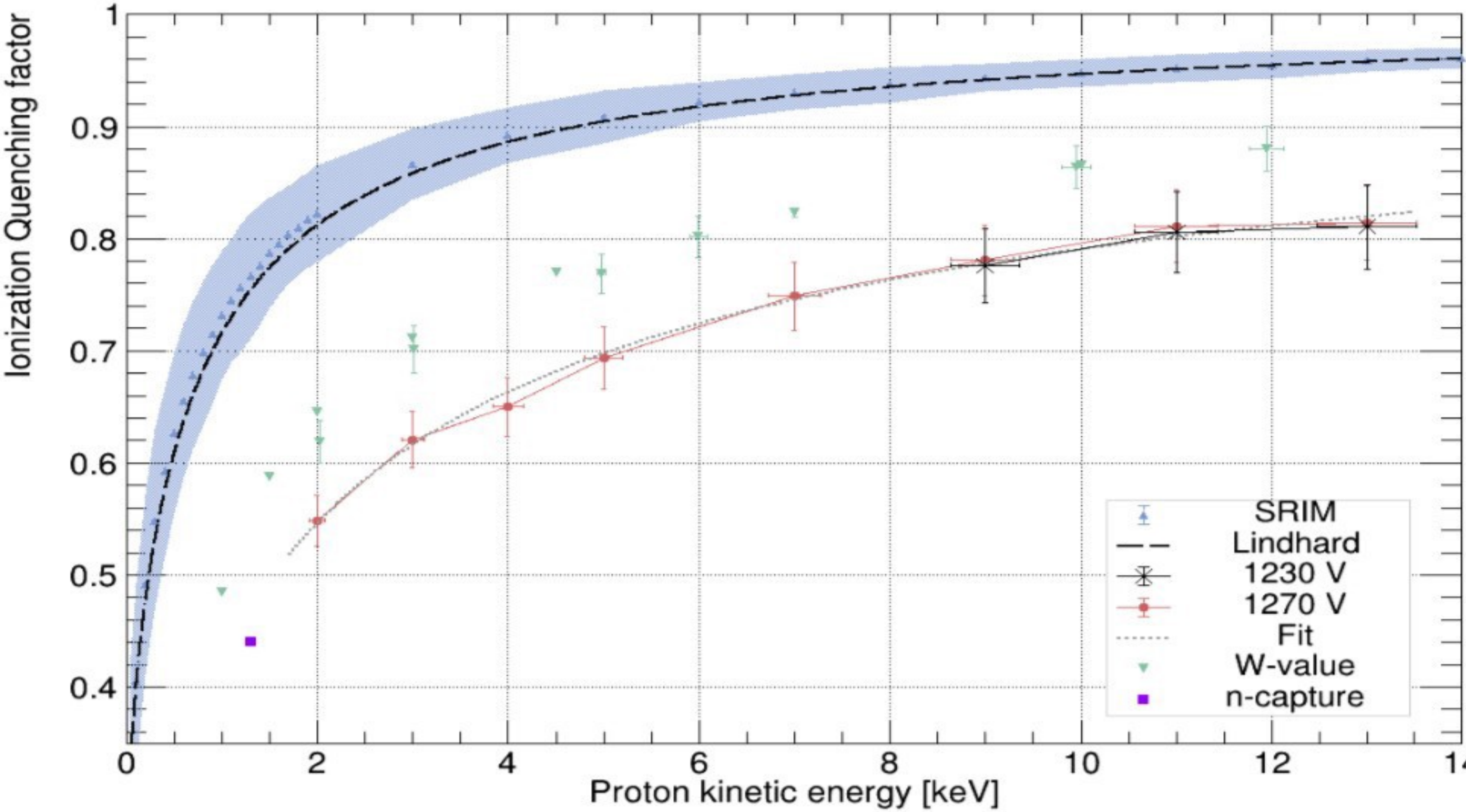
(NEWS-G collaboration, arXiv 2201.09566 published in EPJ-C)



COMIMAC-IQF measurements of H in CH_4 compared with simulations

NEWS-G collaboration, arXiv 2201.09566, published in ERJ-C (2022)

IQF



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Nuclear recoil calibration with neutrons

Neutron monochromatic field:

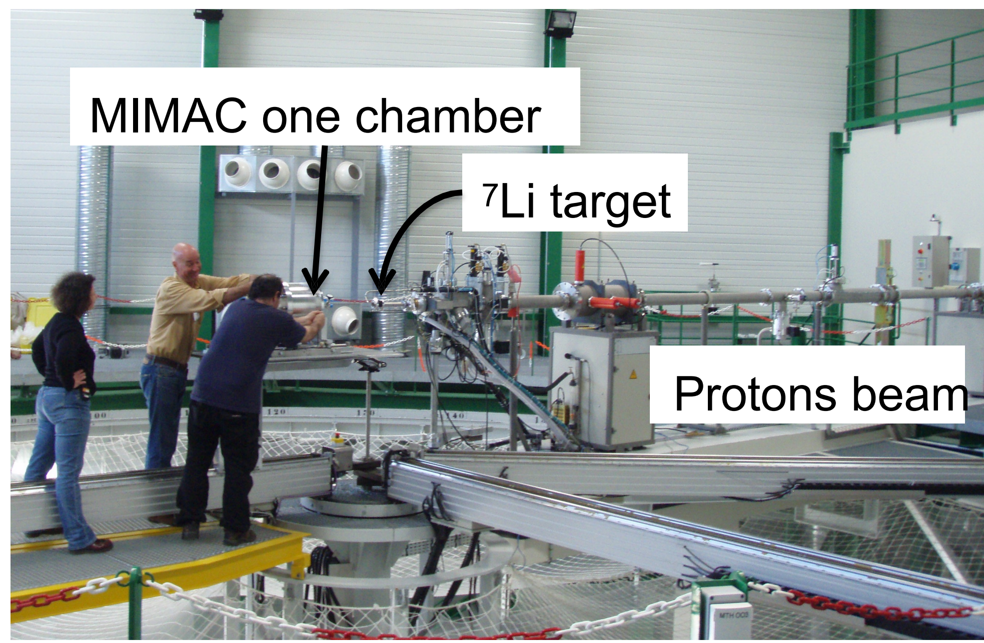
AMANDE facility at IRSN of Cadarache

- **Neutrons with a well defined energy from resonances of nuclear reaction**

$$E_{\text{Recoil}} = 4\frac{m_n m_R}{(m_n + m_R)^2} E_{neutron} \cos^2\theta$$

Electron Calibration:

with electrons of COMIMAC facility



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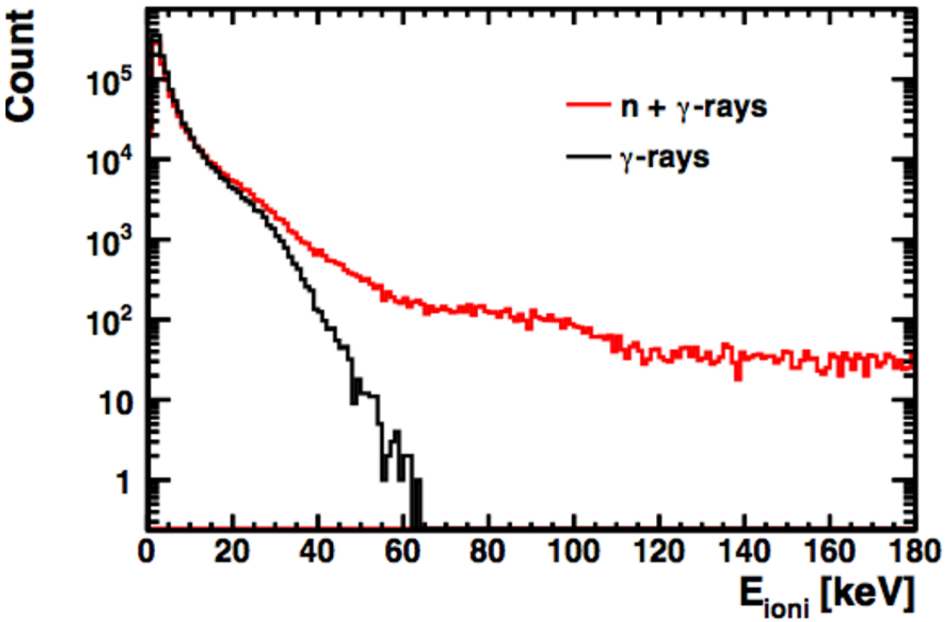
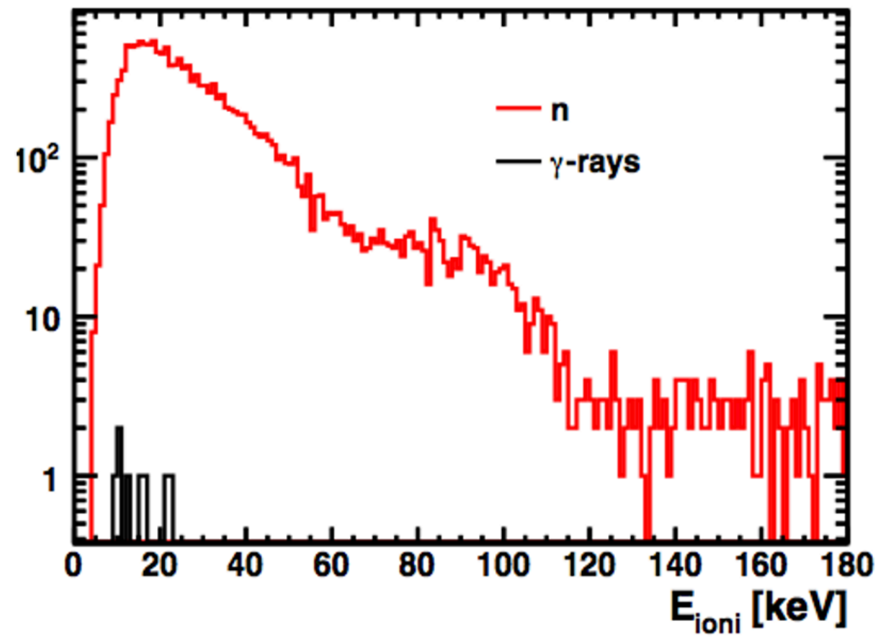
Electron-recoil Discrimination

^{7}Li (p,n (565 keV)) nuclear reaction

Neutrons → F , C, H, nuclear recoils

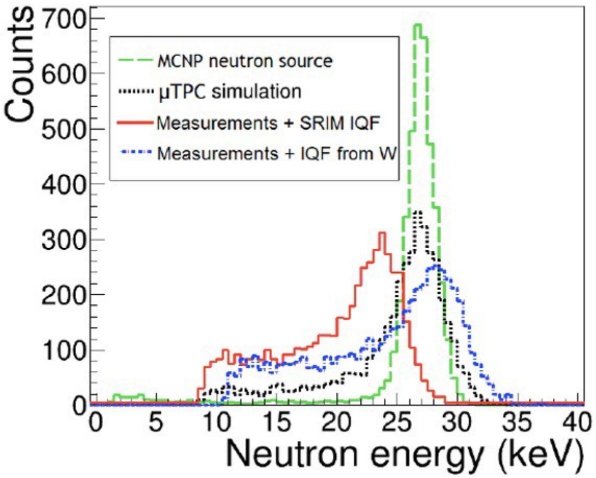
$\gamma - \text{rays}$ → Electrons

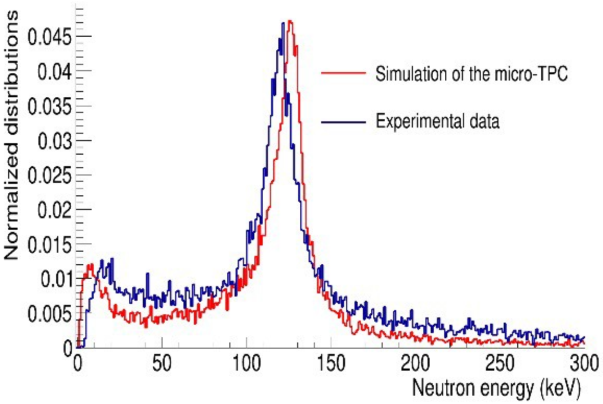


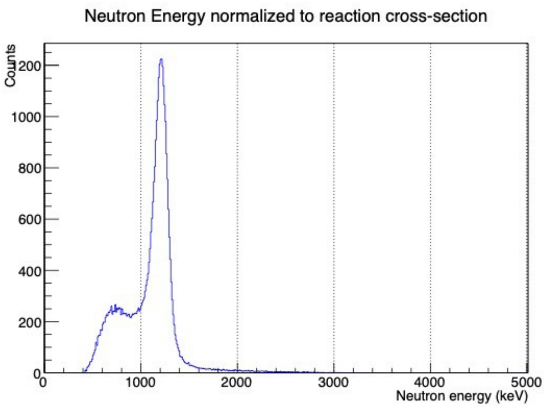


$N_{acpt}/N_{tot} = 1.1 \times 10^{-5}$ electron integrated rejection

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

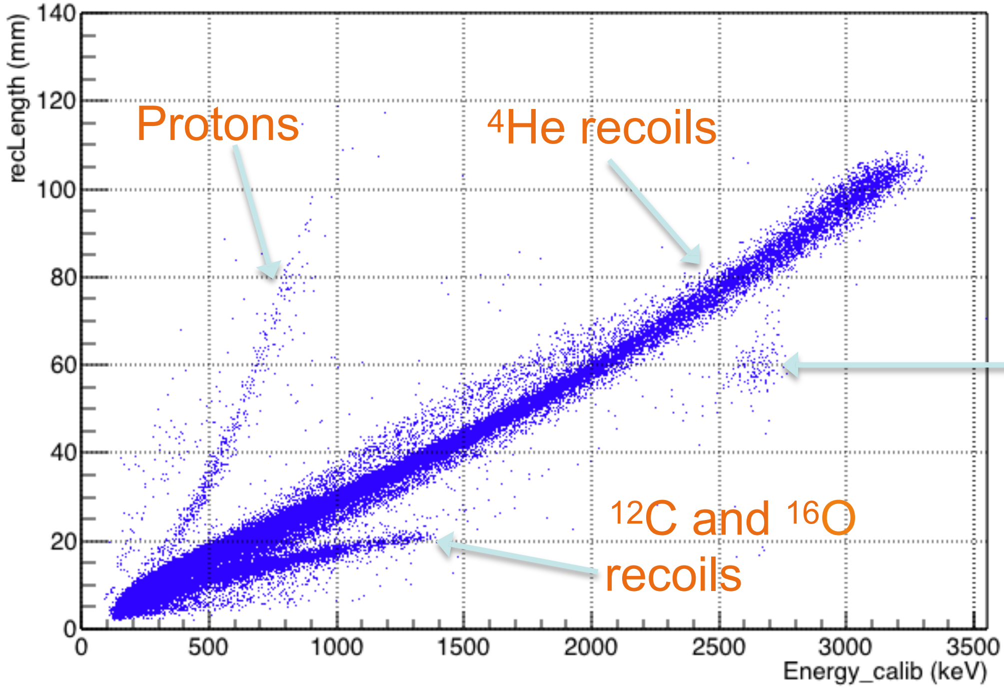
D. Maire *et al.*
« First measurement of a 127 KeV neutron field with a µ-TPC spectrometer » Nuclear Science, IEEE Transactions, 61(2014) 2090

D. Santos (LPSC Grenoble)

D. Santos (LPSC Grenoble)

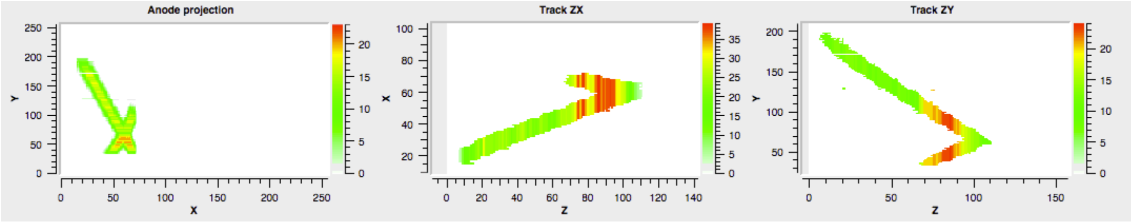
Selection of ^{4}He nuclear recoils : D(d(1.8 MeV),n)

Discrimination from protons, ^{12}C, ^{16}O, and (n,α) reactions



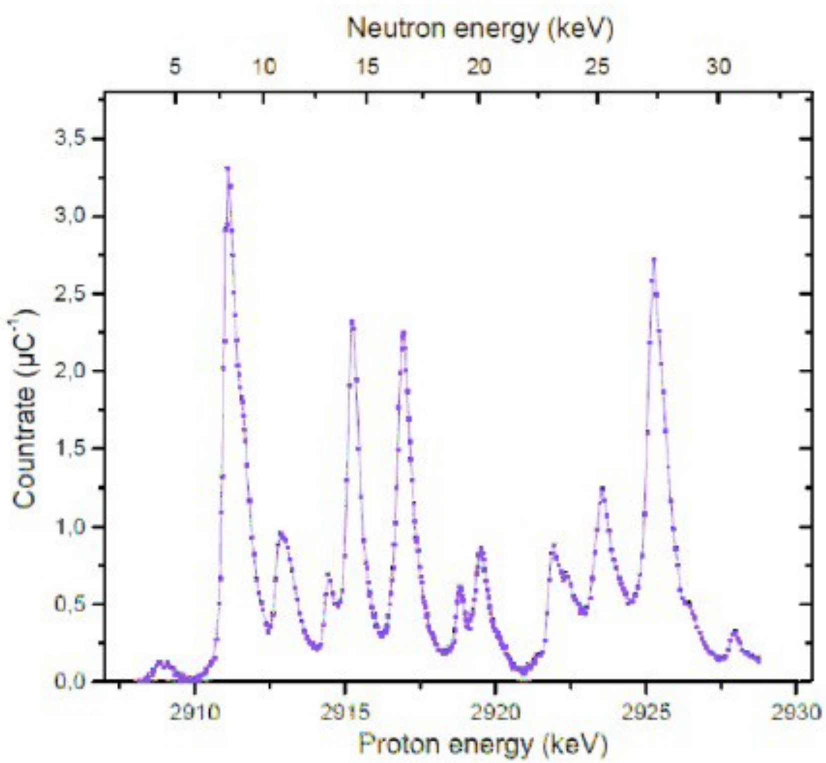
700 mbar He/CO_2 (5%)

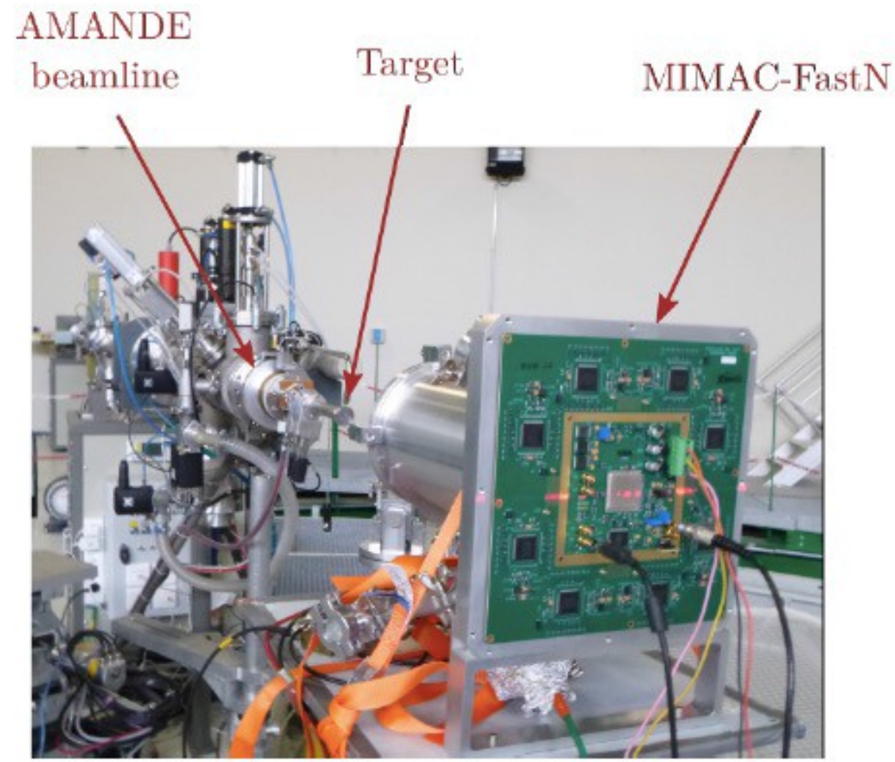
^{16}O(n,α)^{13}C



IRSN /AMANDE (Cadarache)

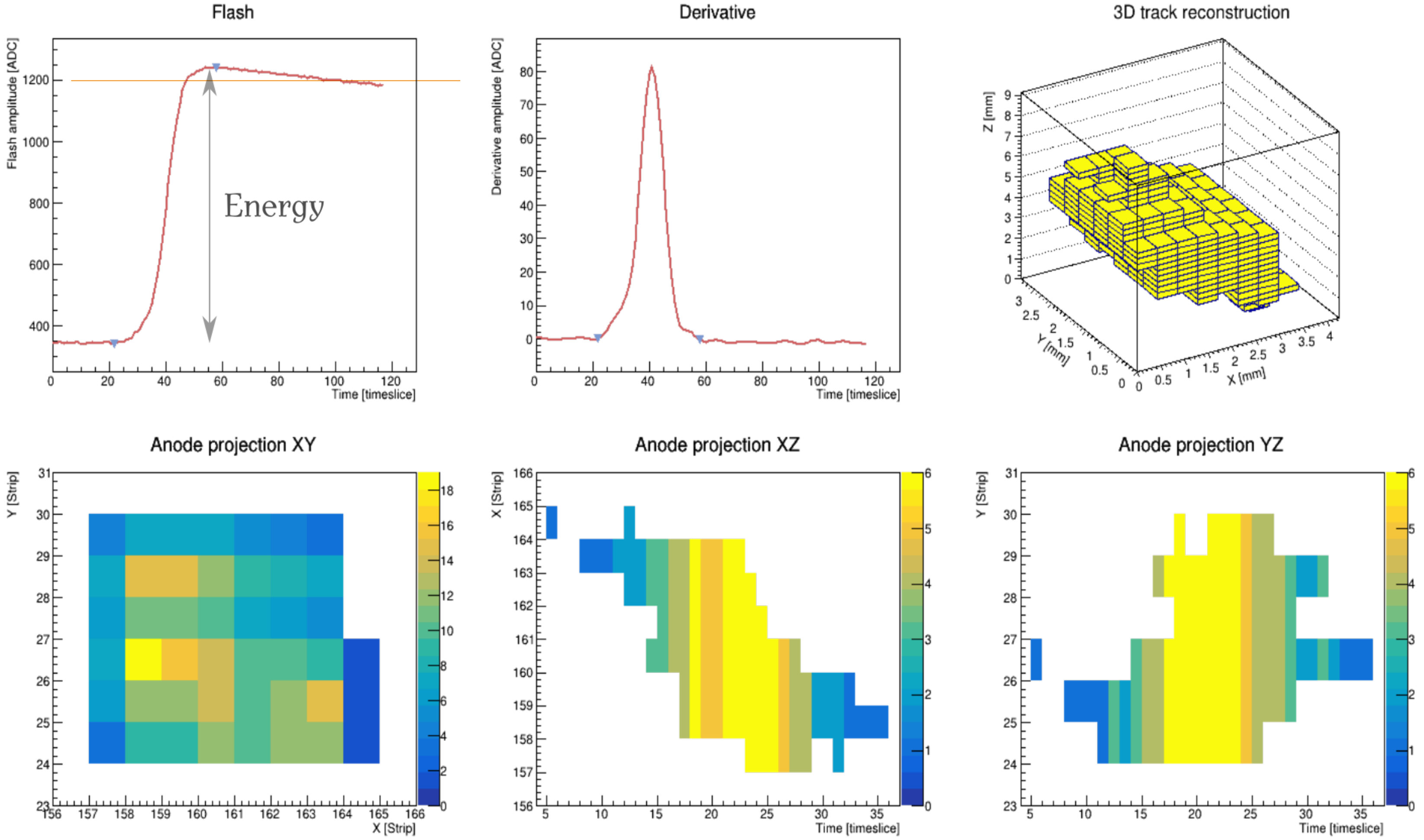
Low energy (8 and 27 keV) mono-energetic neutron spectroscopy





$^{45}Sc(p,n)$ neutron resonances

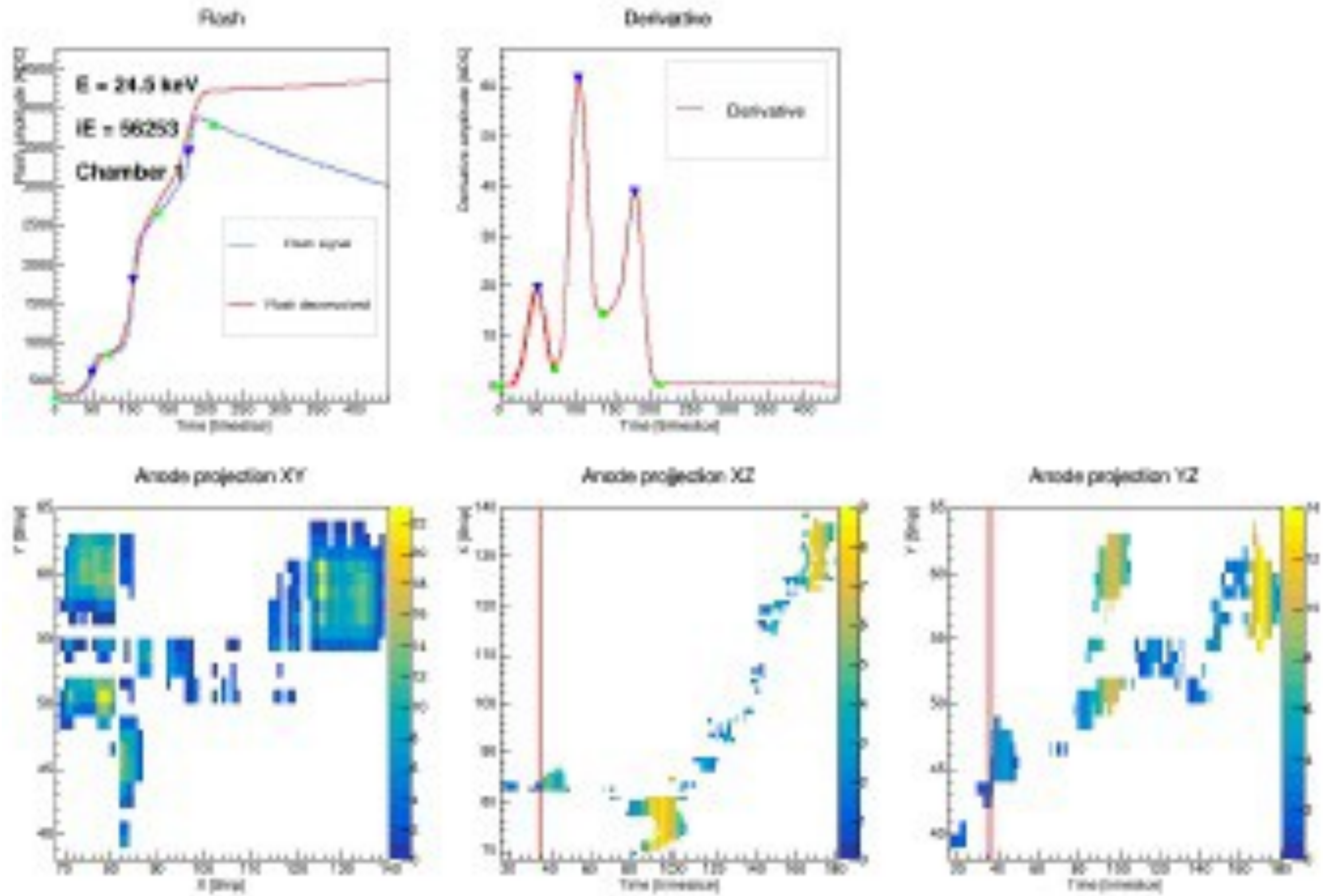
Example of a proton recoil of $6\ \mathrm{keV_{ee}}$ ($8.6\ \mathrm{keV_{nr}}$)



- → Sampling at 50 MHz (20 ns)

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

Event display of an « electron event» with a total measured ionization energy of 24.5 keV



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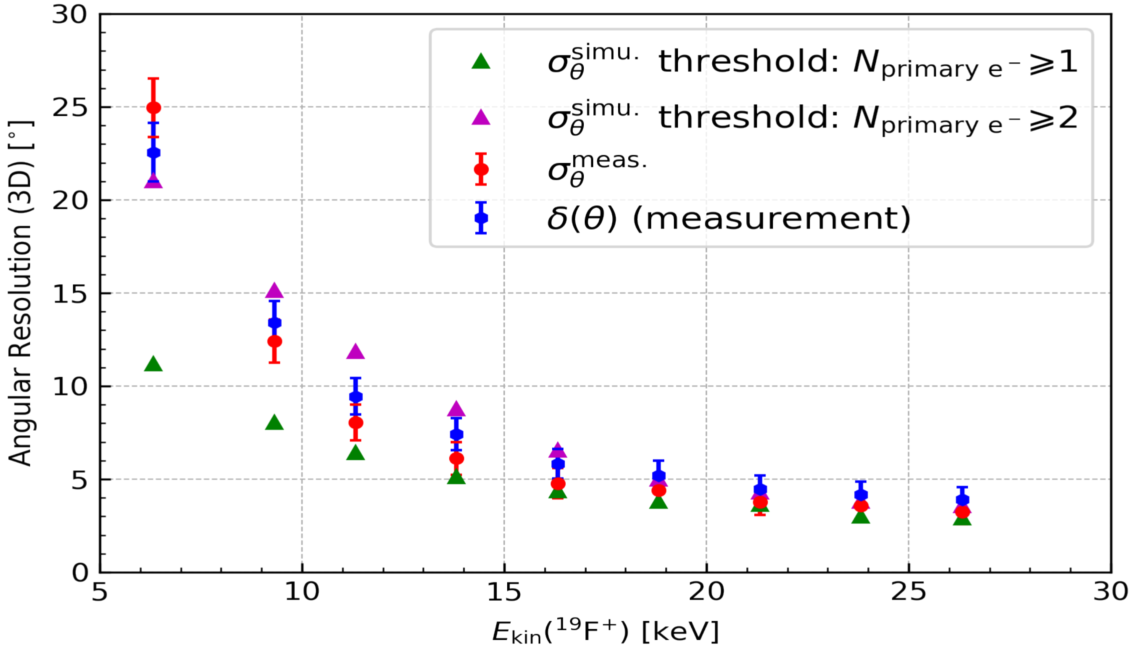
Directionality at high gain - Diffusion and angular resolution



Measured and simulated angular resolution at 0°

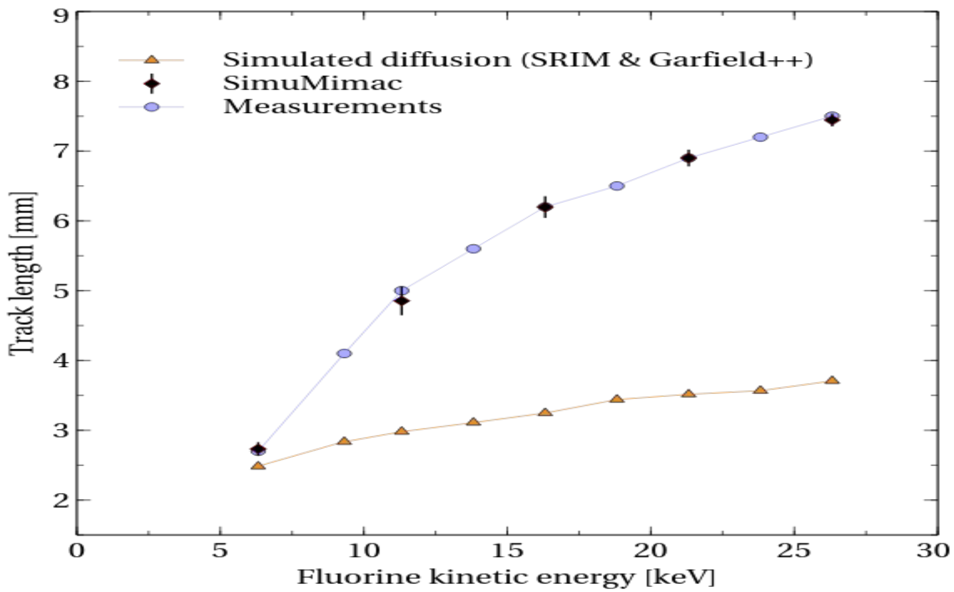
Track length measurement of 19F+ ions with the MIMAC Dark Matter directional detector
Y.Tao, C. Beaufort, I. Moric, Ch. Tao, D. Santos et al. NIMA (2021)985, 164569

Dark Matter Directionality Detection performance of the Micromegas-based μTPC MIMAC detector
Y.Tao, C. Beaufort, I. Moric, Ch. Tao, D. Santos et al. NIMA (2022)1021, 165412

For fluorine ions, we measured an angular resolution below 10° for $E_K >$ 10 keV
$= \Rightarrow$ **Twice better than requirements** for a directional detector (Billard *et al.*, 1110.6079)

Directionality at high gain – SimuMimac

At high-gain, **measurements and simulations used to strongly disagree**



Measured and simulated fluorine track lengths

We developed SimuMimac, a simulation tool based on SRIM and Garfield++ to model the physics of the detector from the primary electron cloud to the signal formation

Cyprien Beaufort *et al* JCAP08(2022)057

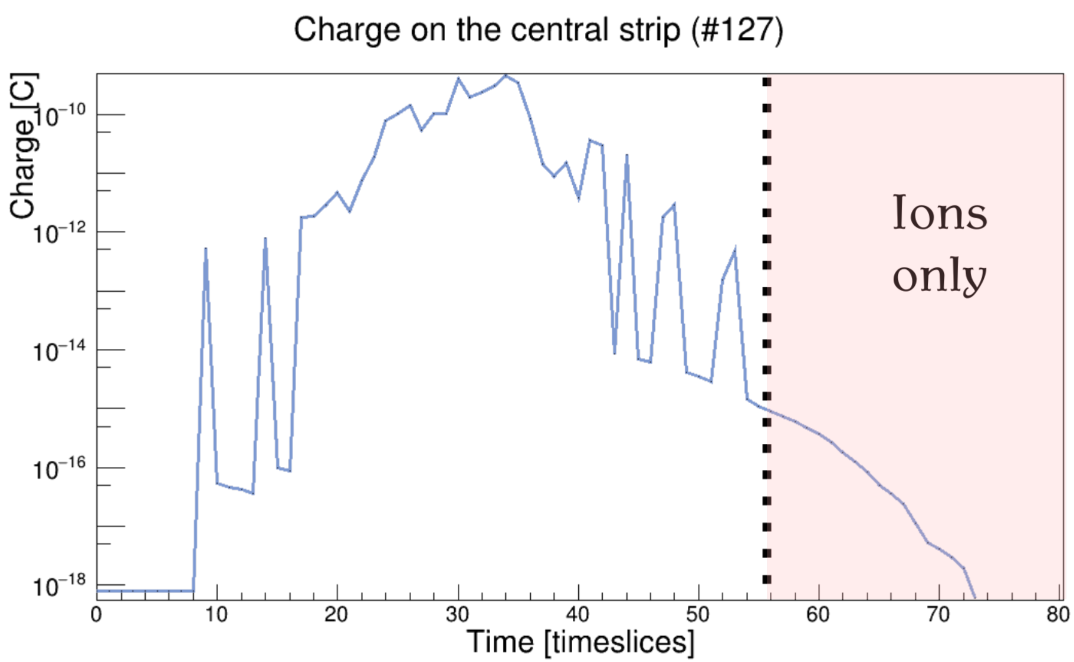
- SimuMimac agrees with the measurements
- Main difference with standard simulation code = **takes into account the current induced by the motion of the ions**

Directionality at high gain – SimuMimac

- Current induced by the charges (*Ramo theorem*):

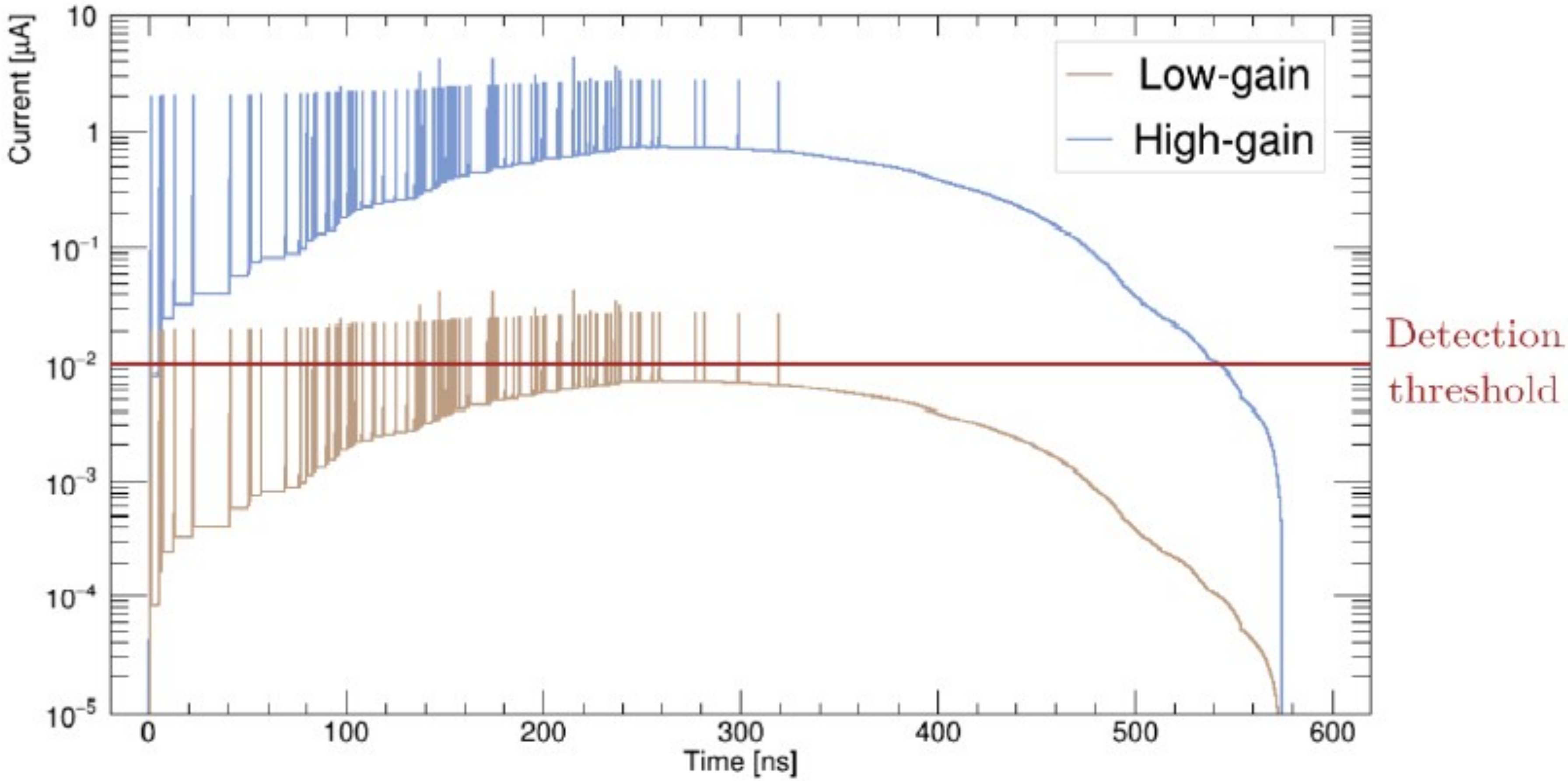
$$i(t) = \sum_{k=i,e} q_k \mathbf{E}_{w,k} \cdot \mathbf{v}_k \text{ with } \mathbf{v}_e \sim 10^3 \mathbf{v}_i$$

- Ions induce smaller currents than electrons but they remain longer in the gap
- At large gain, the ionic contribution
  - is non-negligible
  - **elongates the signal**



Signal contributions at high-gain
(primary electrons and secondary ions)

Cyprien Beaufort et al. arxiv.org/2112.12469



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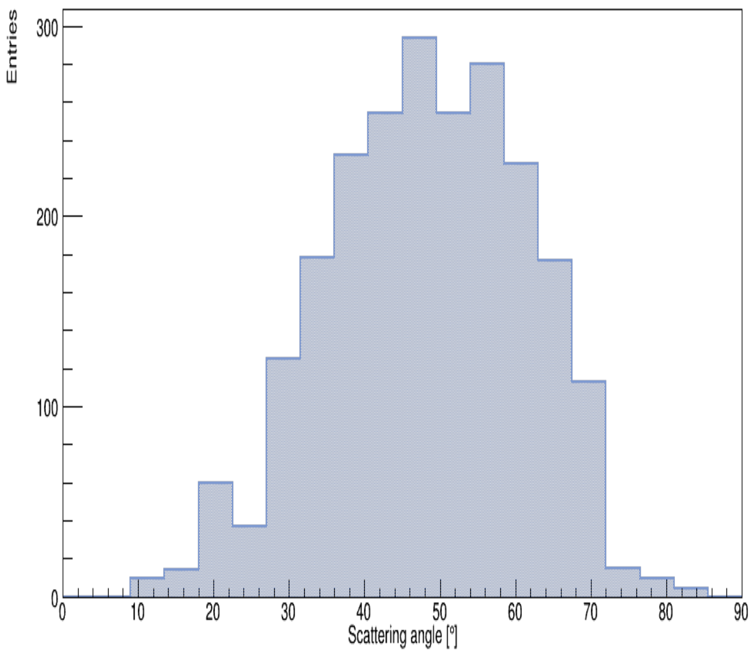
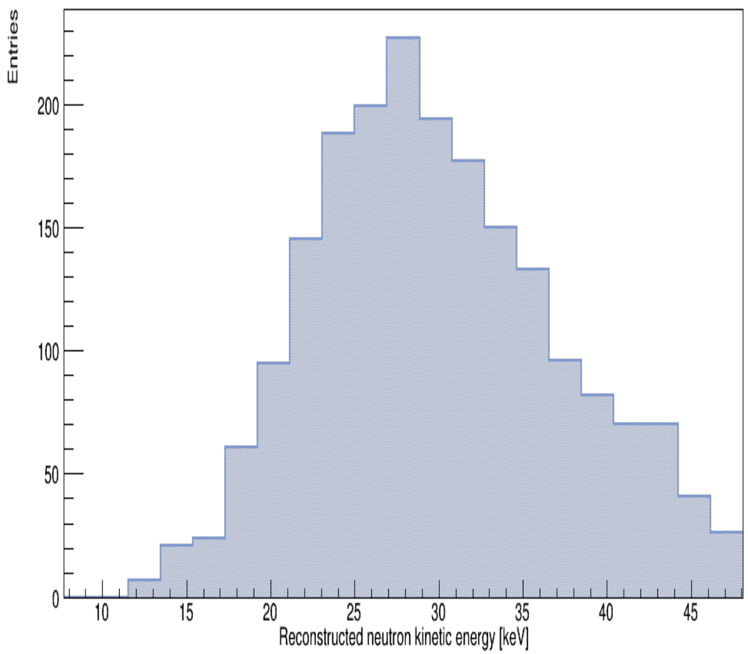
Directionality – Mono-energetic (27 keV)
Neutron field spectrum reconstruction



Angular distribution



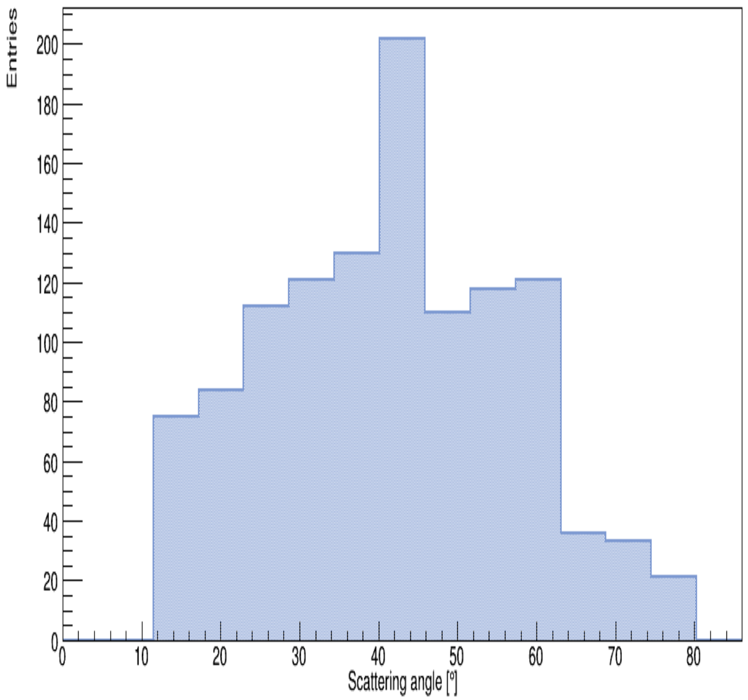
Reconstructed spectrum

Directional performances at 27 keV:

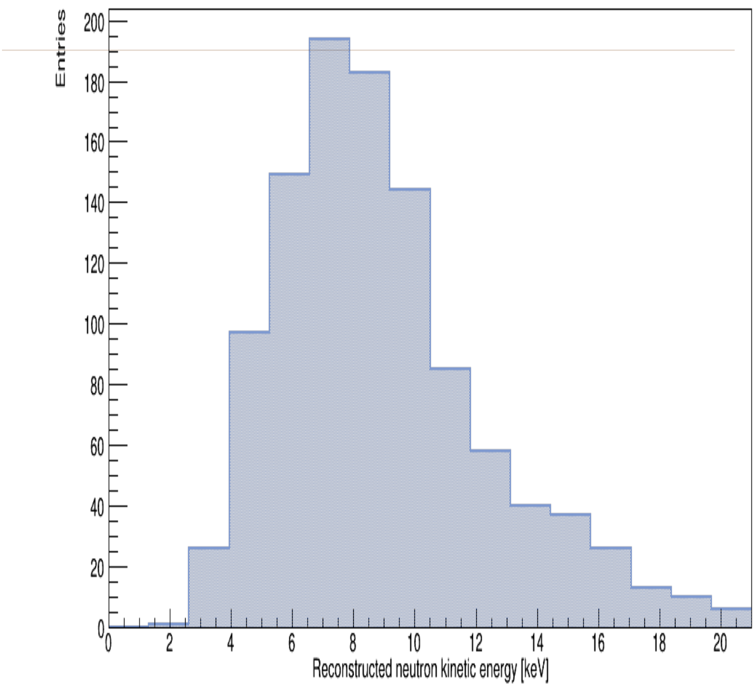
- **Energy reconstructed agrees within 2.5%** with the energy of the monoenergetic neutron field
- **Angular resolution better than 10°**

Directionality and head-tail recognition in the keV-range with the MIMAC detector by deconvolution of the ionic signal, Cyprien Beaufort et al. JCAP08(2022)057

Directionality – Mono-energetic (8 keV)
Neutron field spectrum reconstruction



Angular distribution



Reconstructed spectrum

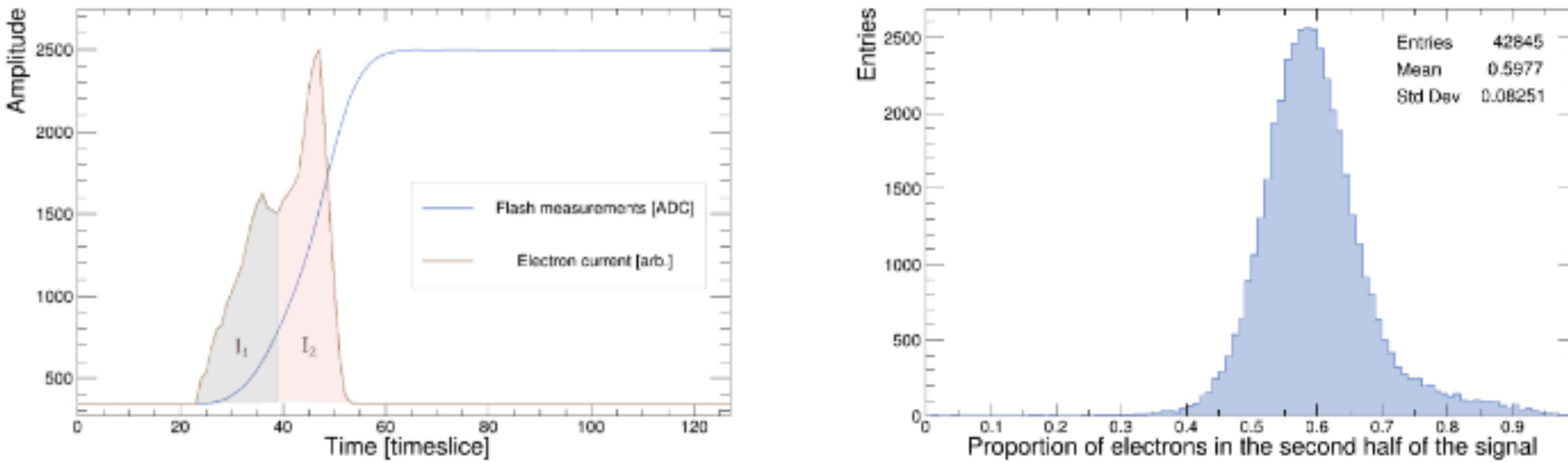
Directional performances at 8 keV:

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

Cyprien Beaufort et al. JCAP08(2022)057

Head-tail measurements by deconvolution of the Flash-ADC signal

Cyprien Beaufort et al. JCAP08(2022)057



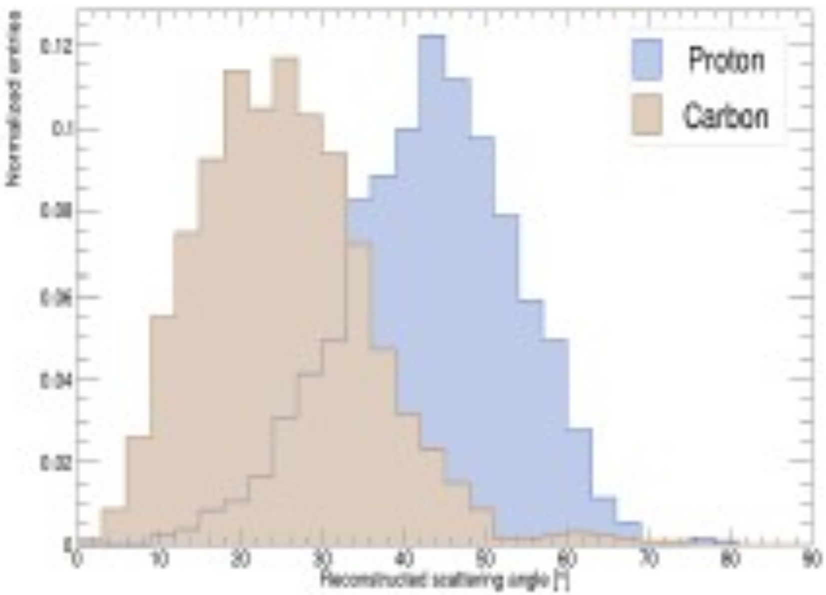
(a) Example of a measured event. The electron current has been scaled to appear as high as the Flash signal.

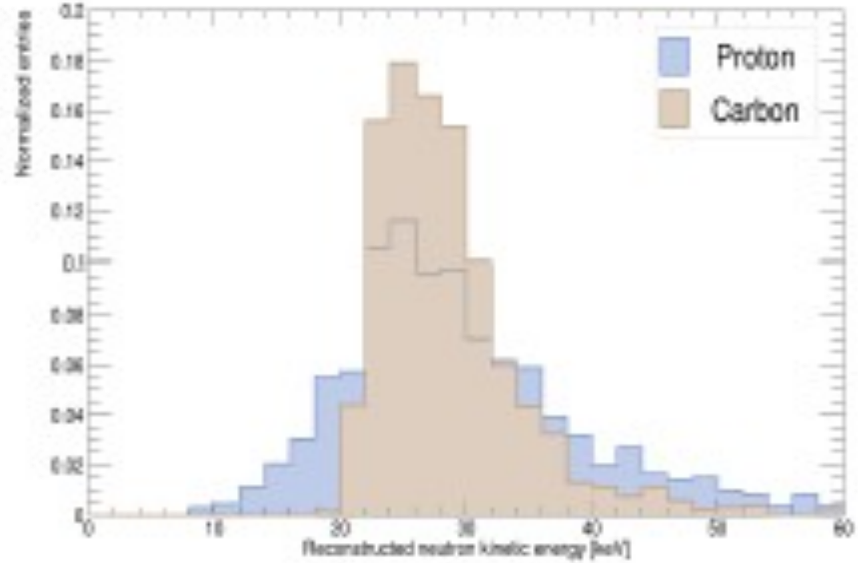
(b) Histogram of the proportion of electron current located in the second half of the signal for the entire run.

Figure 10: The asymmetry of the time distribution of the electronic current measured for 13 keV protons sent by Comimac in a mixture of 50% i-C_4H_{10} + 50% CHF_3 at 30 mbar. In the left panel, the filled areas correspond to the integrals, I_1 and I_2, of the electron current in the first and the second half of the signal, respectively. In the right panel, the proportion plotted is defined as $I_2/(I_1 + I_2)$. In this situation, since the ions are sent at the cathode, the last timeslices correspond to the first interactions of the track (*i.e.* to the tail).

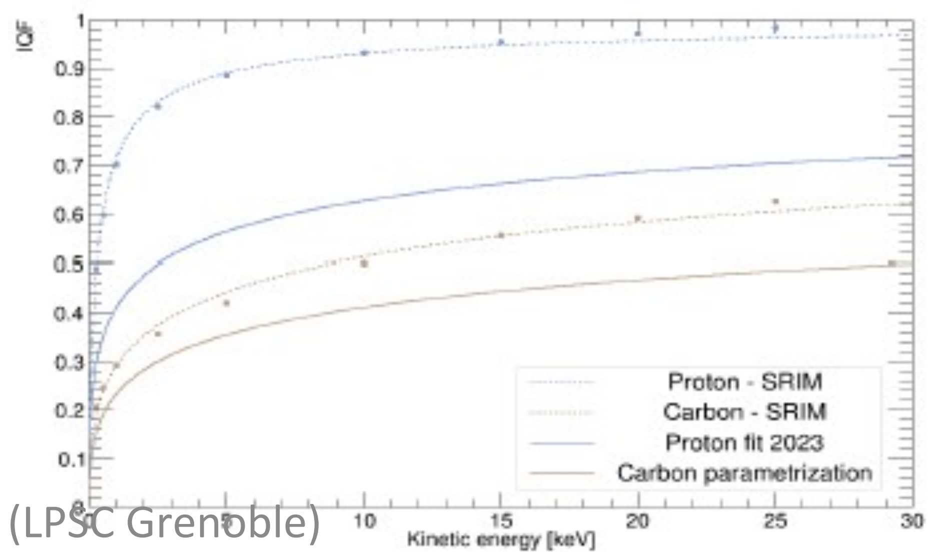
From proton and carbon recoils at 27 keV

C. Beaufort et al. (2023, to be published)





Only possible having the Ionization quenching factor measurements to get the neutron kinetic energies !!



A bi-energetic neutron field produced by $^{7}Li\ (p,n)^{7}Be$ nuclear reaction near threshold (1.881 MeV) !

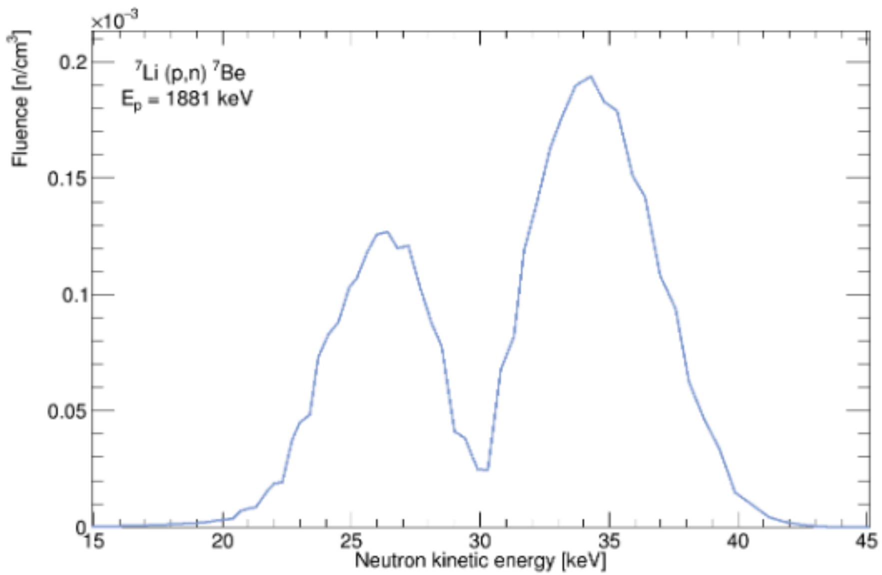


Figure 8. Simulation of the neutron fluence at the detector position as a function of energy in the conditions of the AMANDE 2023 campaign when sending a proton energy on the LiF target.

Simulation of the Neutron fluence at the detector position (C. Beaufort et al. (2023) to be submitted)

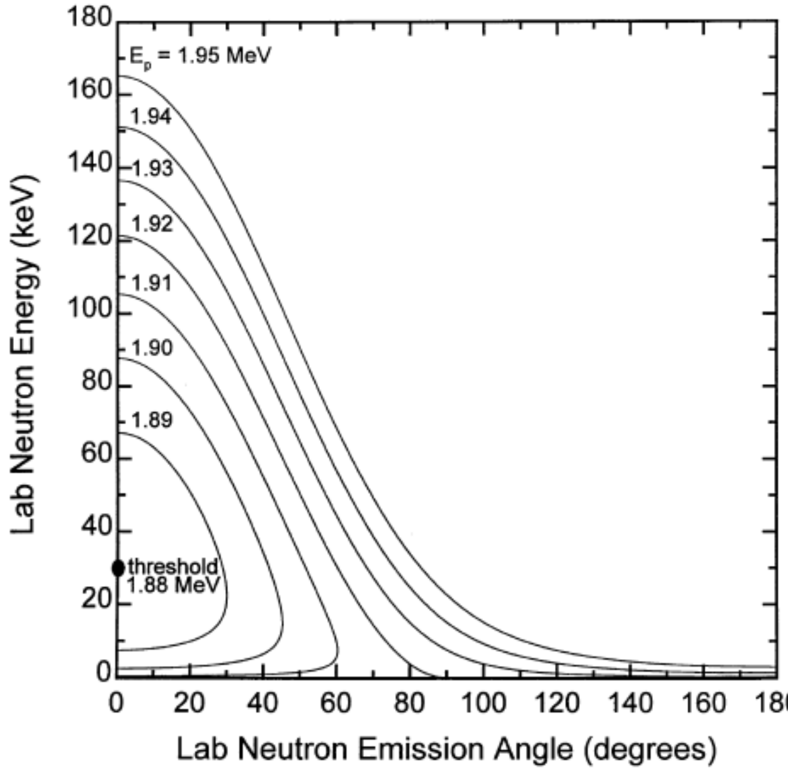


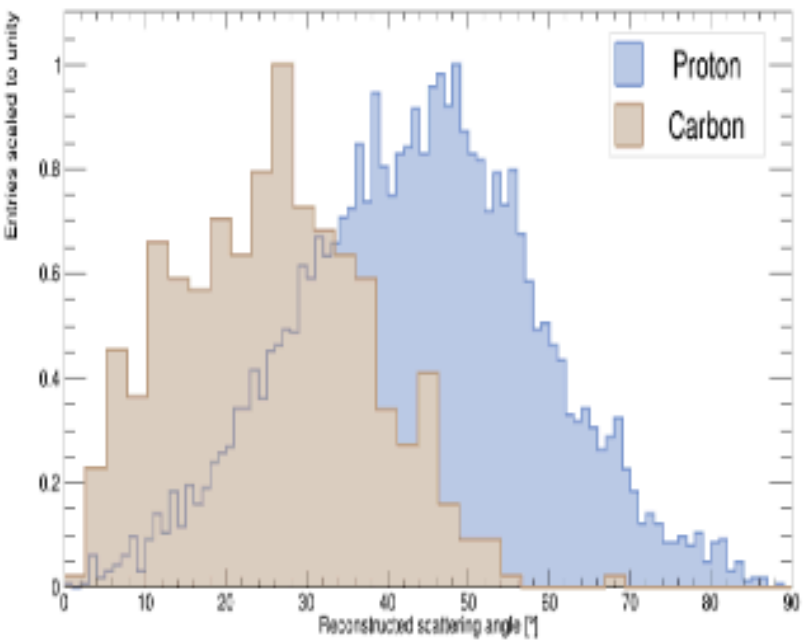
Fig. 1. Proton energy contours for a thick lithium target.

Lee & Zhou, NIMB (1999)

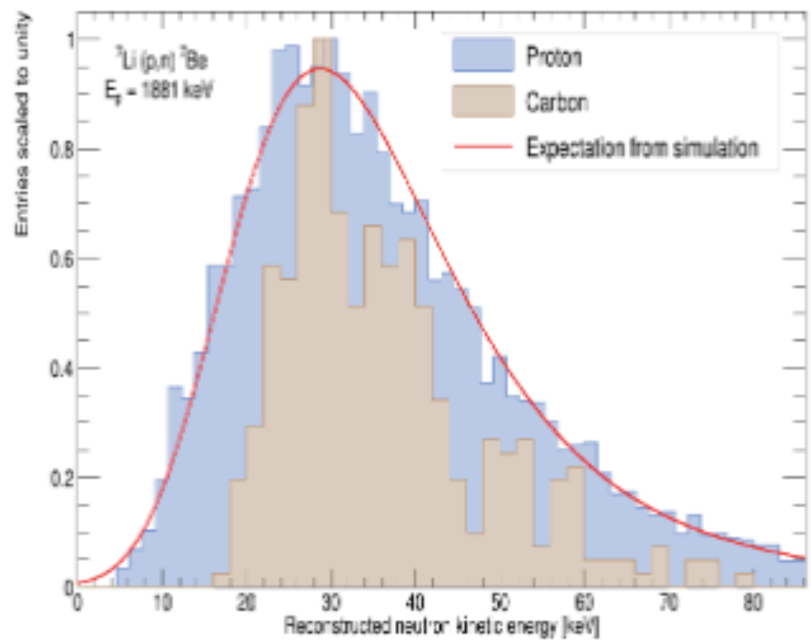
A bi-energetic neutron field produced by $^{7}Li\,(p,n)^{7}Be$ nuclear reaction at 1.881 MeV

Neutron spectrum by MIMAC from hydrogen and carbon nuclear recoils

C. Beaufort et al. (2023, next week on arXiv !!)

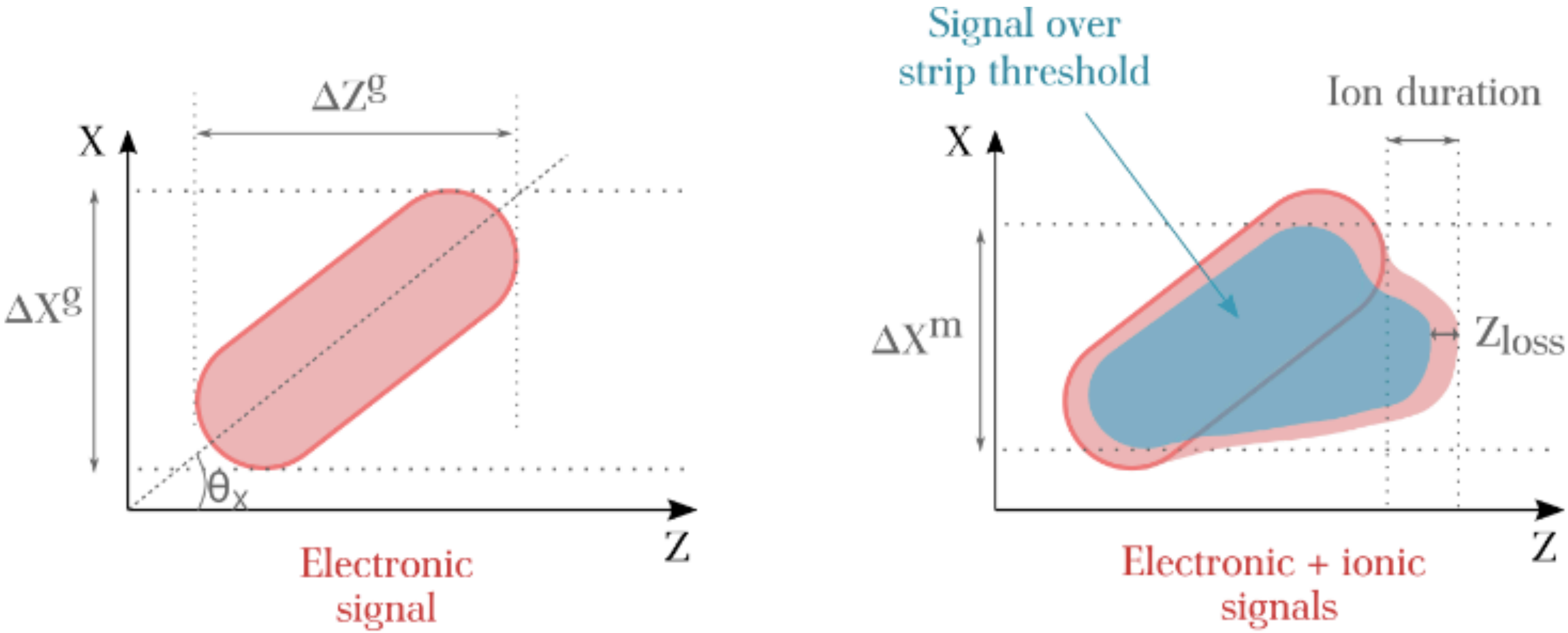


Nuclear Recoil Angular distributions



Neutron Spectra from proton and carbon recoils

High gain 3D track analysis method (C.Beaufort et al. 2023)



Z$_{loss}$= « time » during which the Flash-ADC continues to detect a signal on the grid whereas the anode strips are no longer fired

$$\tan\theta_X = \tan\theta\,\cos\phi \qquad \tan\theta_Y = \tan\theta\,\sin\phi\ .$$

$$\tan\theta_X = \frac{\Delta X^g}{\Delta Z^g}\frac{D_L}{D_T} \simeq \frac{\Delta X^m}{\Delta Z^g}\frac{D_L}{D_T}\left(\gamma\frac{Z_{\text{loss}}}{\text{Ion duration}}\right)^{\delta}$$

High gain 3D track analysis method

i) The parameters γ and δ are fixed by using a reference dataset from a mono-energetic neutron field, in our case the 27 keV dataset.

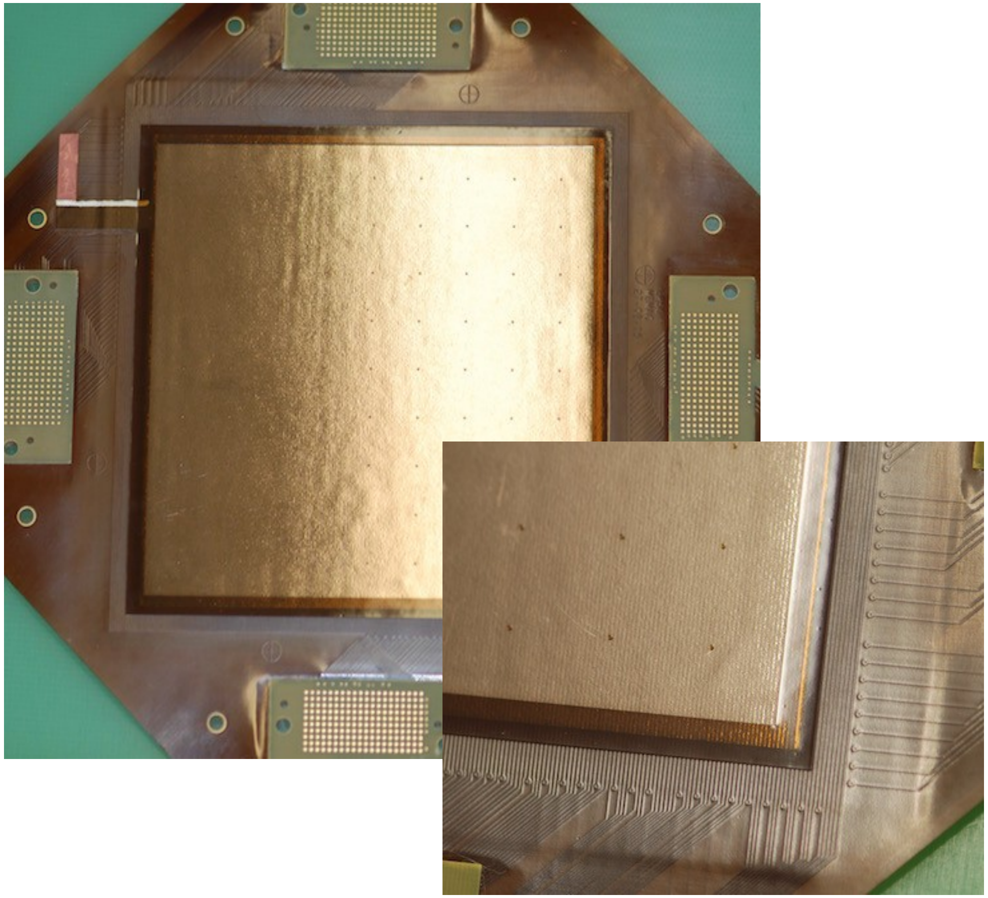
ii) The directional reconstruction from the Flash-ADC in a previous work has already validated the calibration, the IQF, and the electron-recoil discrimination.

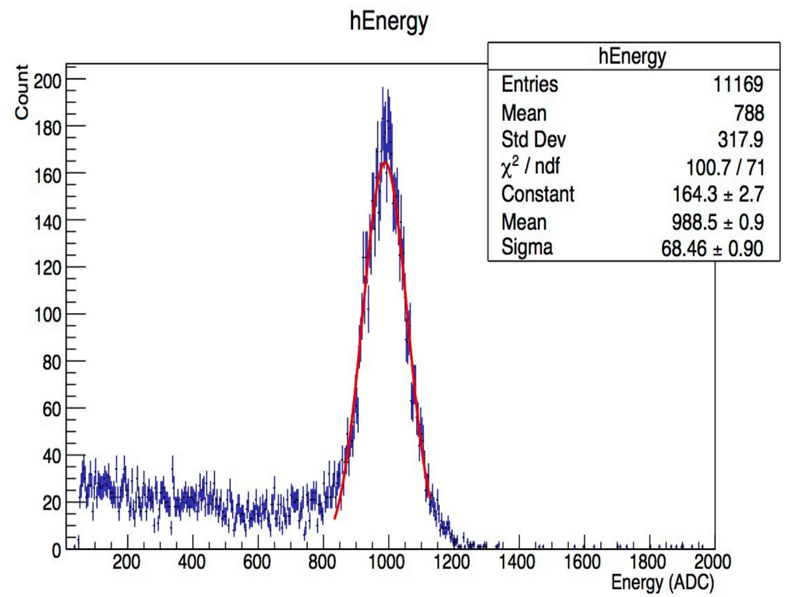
iii) Due to the mono-energetic field, we expect the value of $\cos^2\theta/Ep_K$ to be constant and equal to 1/En, where Ep_K and En are the kinetic energies of the proton recoil and of the neutron, respectively

iv) This lead to a mean estimation of the parameters to $\gamma = 5/3$ and $\delta = 5/4$.

While this method relies on experimentally fixed parameters, we will see that it leads to consistent results with the three datasets considered at multiple energies and gain, and equally for proton or carbon recoils. It requires a reference measurement with a mono-energetic neutron field to calibrate the γ and δ parameters.

New MIMAC low background detector





Kapton micromegas readout
Piralux Pilar

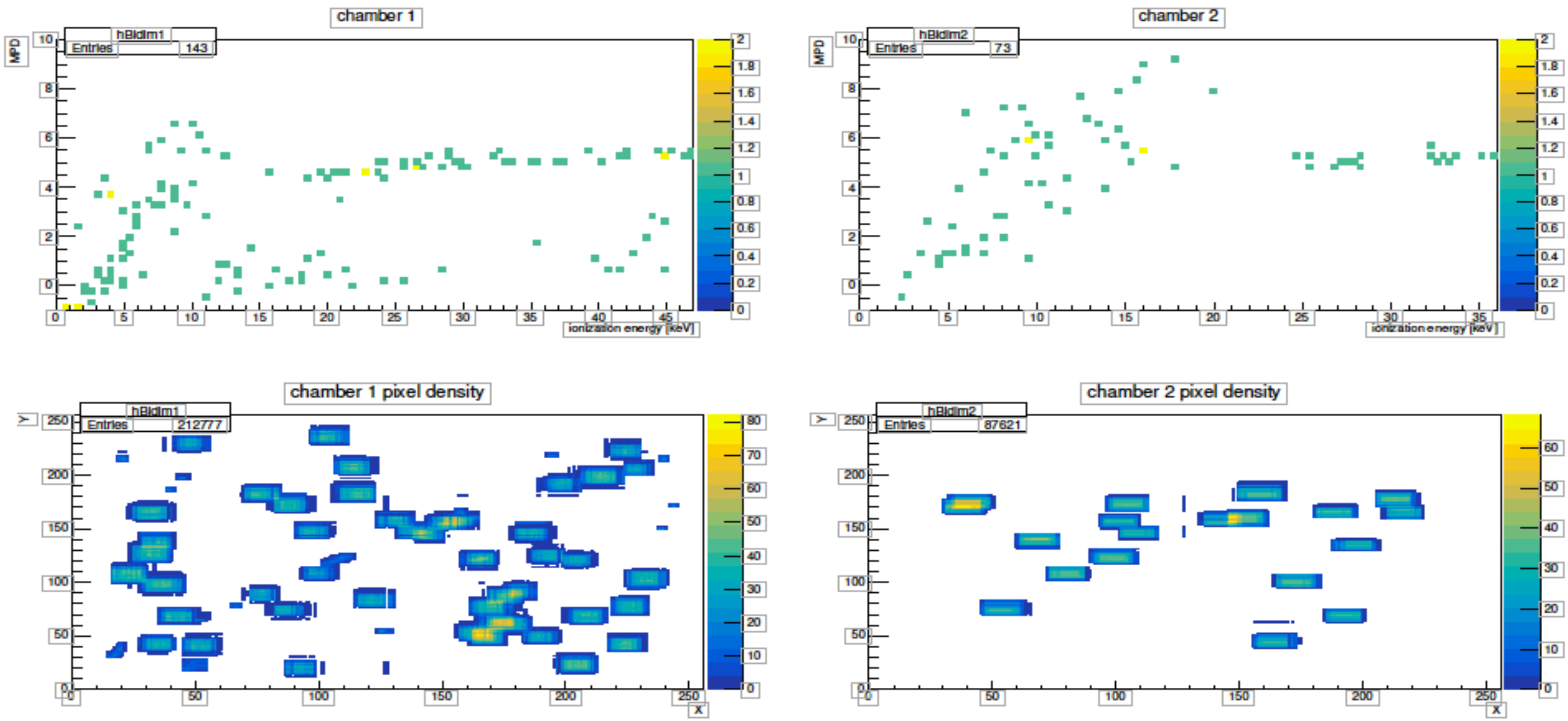
Gaz : MIMAC 50 mbar
HT grille : -560 V
Drift field : -150 V/cm

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

Bi-chamber-512 module
(with the Cathode Signal and
the new low background 10 cm detectors)
installed in february 2023

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

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

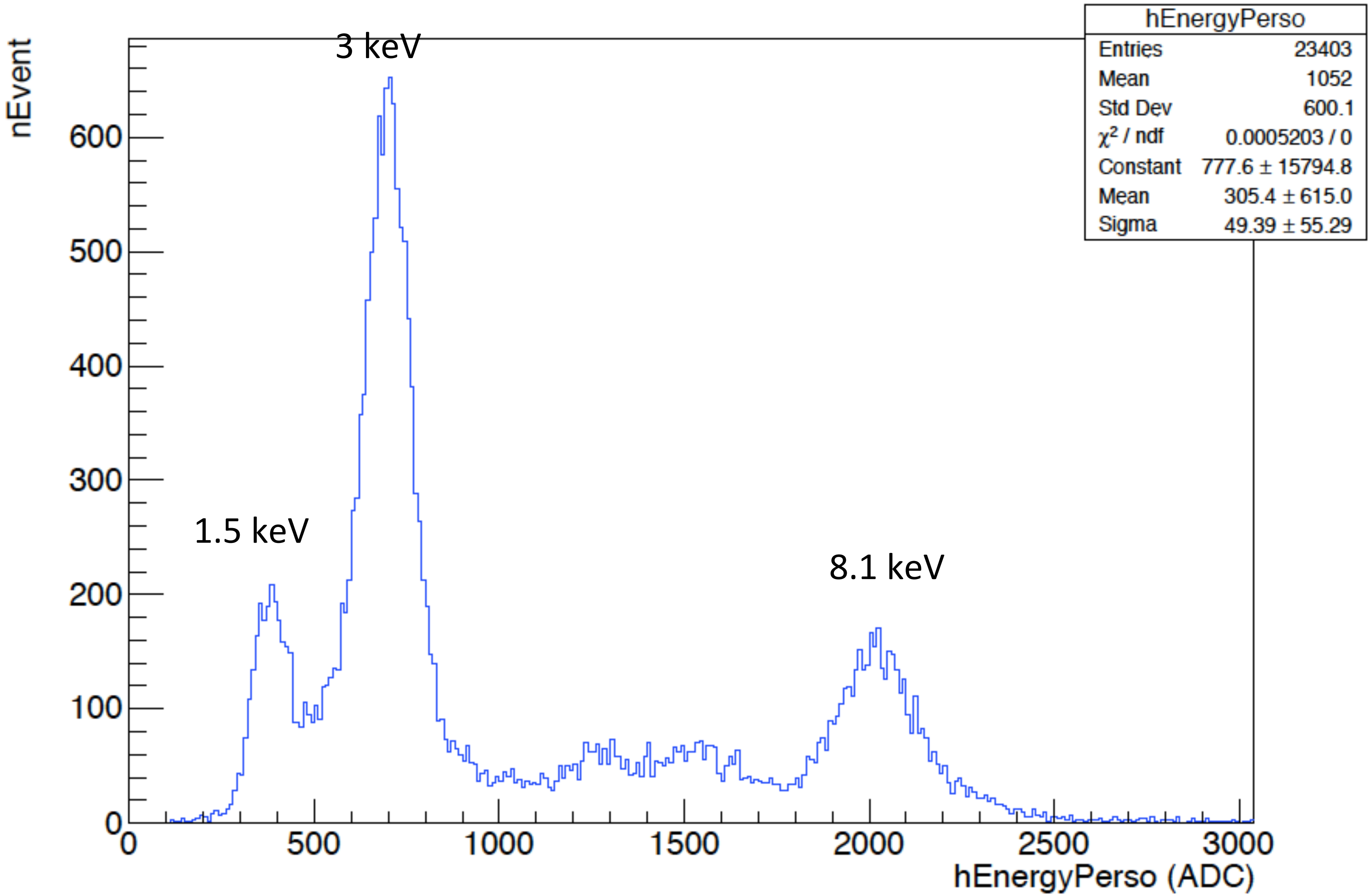


(a) In chamber 1.

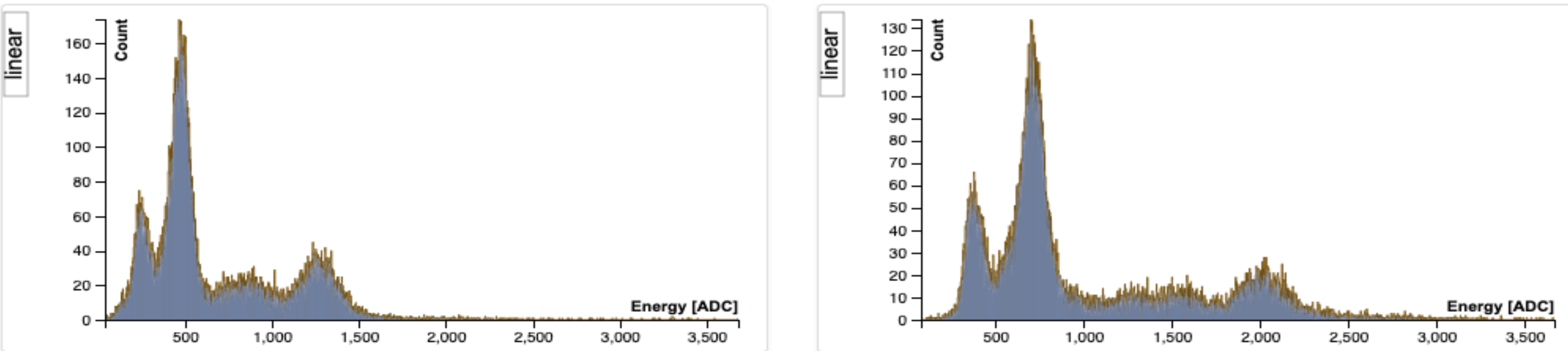
(b) In chamber 2.

Each recoil will be compared with the WIMP « wind » direction at the time of the event

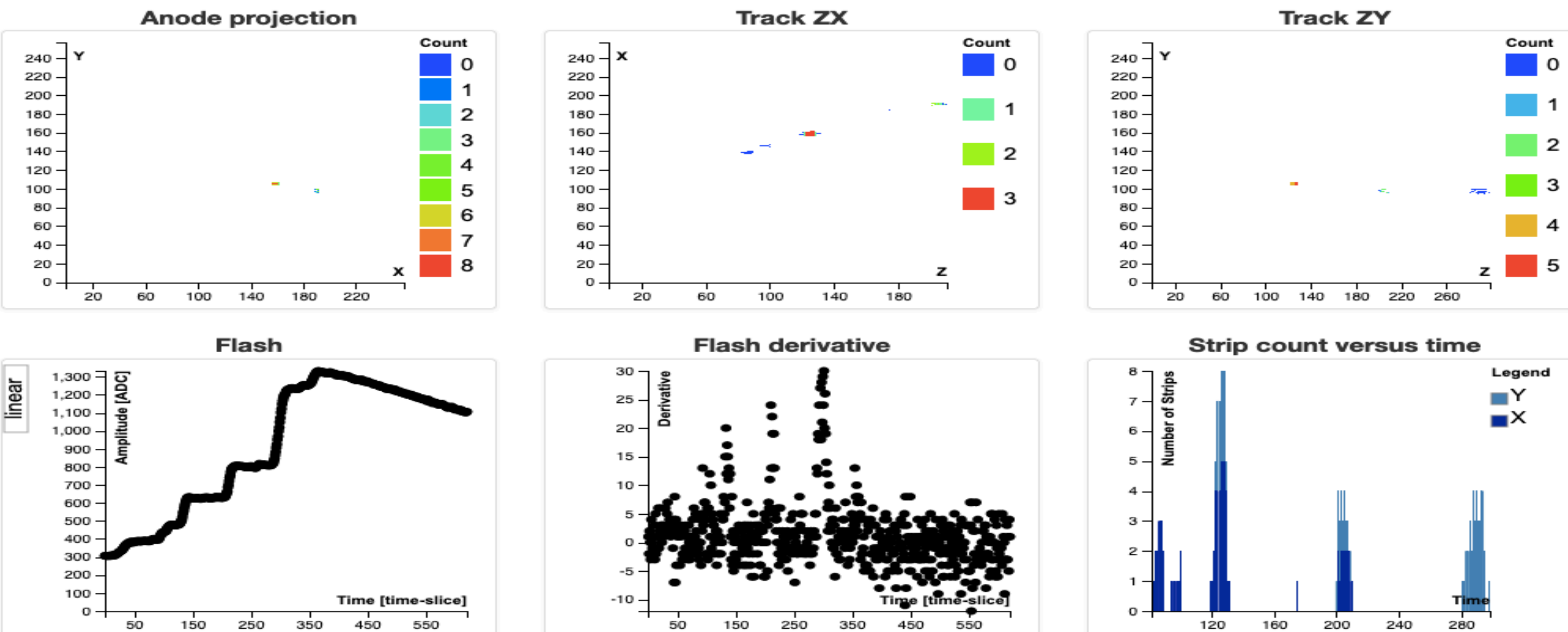
X-ray Calibration of the new detector Bi-chamber Module at 500 V, 3000V drift



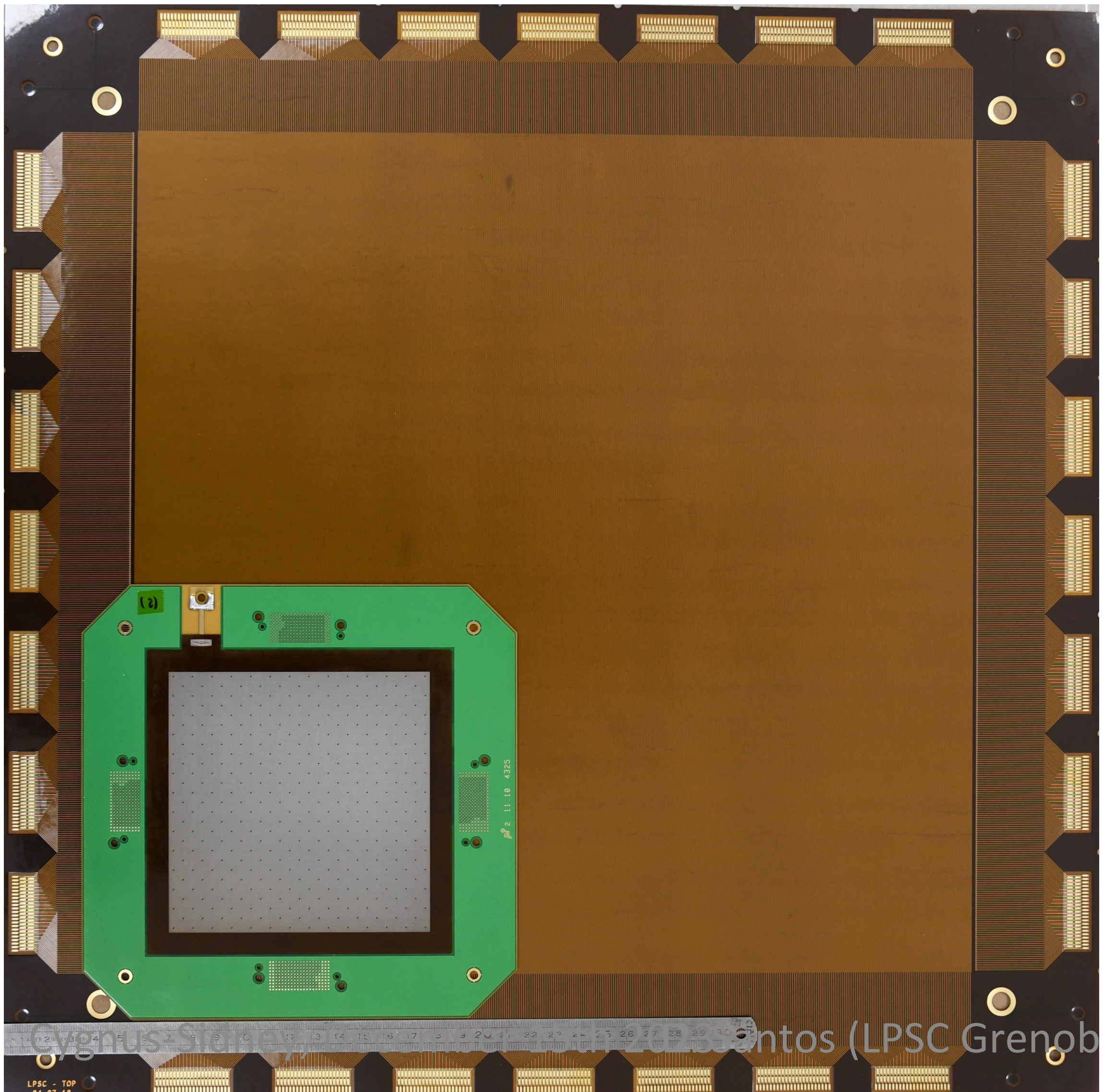
X-ray calibration of both chambers simultaneously

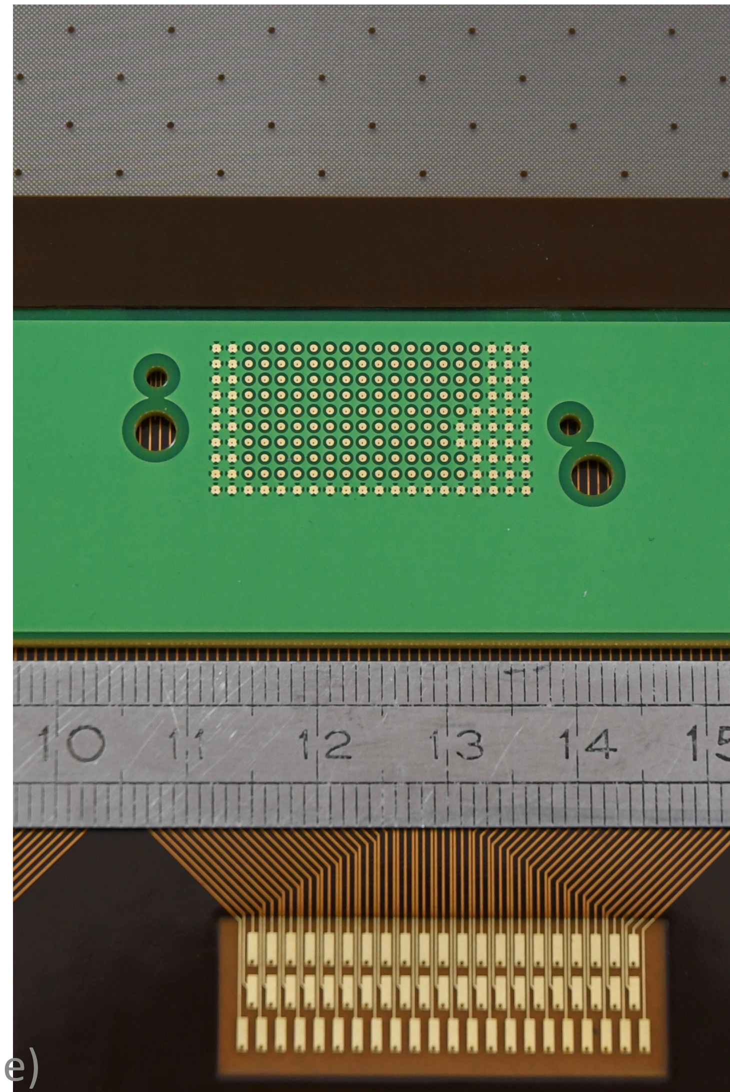


A typical electron event in the chamber 2



The new 35 cm “new technology” MIMAC detector compared to the old one

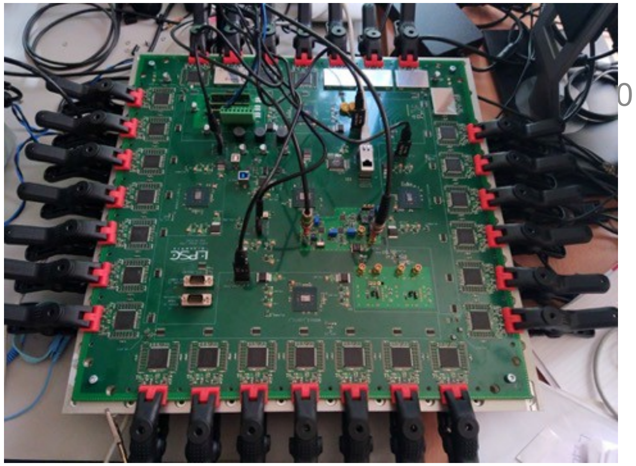


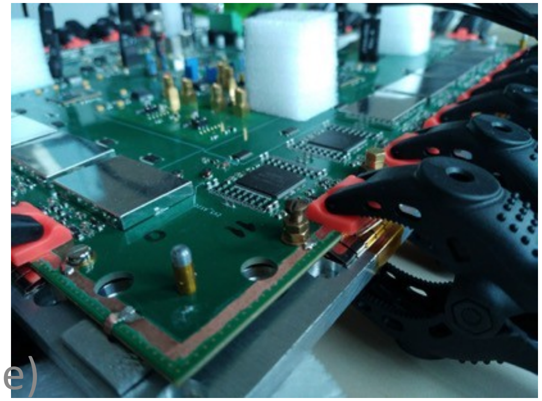


NEW-1792 channels Electronic Board

Operation of the electronic board on table	✓
Coupling of the electronic board with the detector 35 x 35 cm	✓

- ✓ Synchronization of ASICs and FPGAs
- ✓ FPGA programming
- ✓ Track reconstruction software
  (new map+detector routing)
- ✓ Soft acquisition adaptation for tests
- ✓ Ethernet protocol integration
- ✓ Resolution of EMC issues
- ✓ Characterization ofintrinsic electronic noise
- ✓ Trigger tests on simulated events





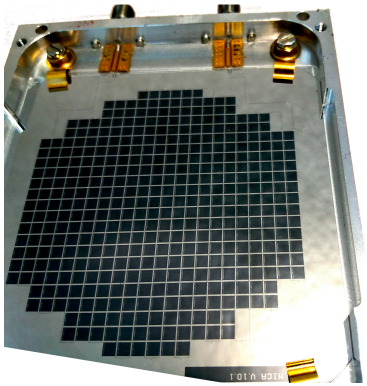
Conclusions

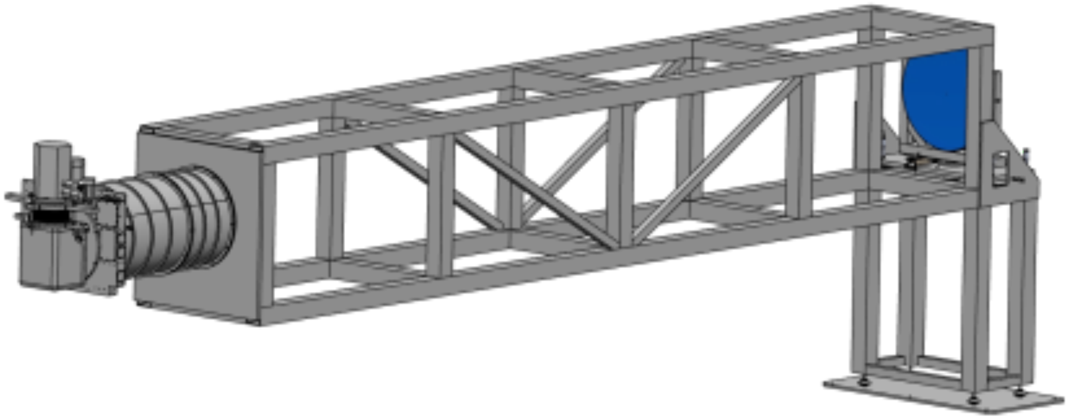
- **MIMAC** has opened new possibilities in the directional DM search and Neutron spectroscopy.
- Mainly at low energies giving a lot of flexibility on targets, pressure, energy range…
- Ionization quenching factor measurements have been determined experimentally showing an important differences with respect to simulations !
- 3D nuclear recoil tracks from Rn progeny have been observed and can be used for calibration at 30 keV nuclear recoil range.
- New degrees of freedom are available to discriminate electrons from nuclear recoils.
- Angular resolution and directional studies of 3D nuclear tracks are now possible at the keV range.
- A new generation of high-definition DIRECTIONAL detectors (a needed signature for DM discovery) has been validated.
- Large active volumes, with the new 35x35 cm^2 detector, with a high 3D spatial resolution will open new windows beyond the neutrino floor and at low mass Wimps
- **If the DM were not made of Wimps... The directional detection will also be needed to convince us that we understand what we've detected…**

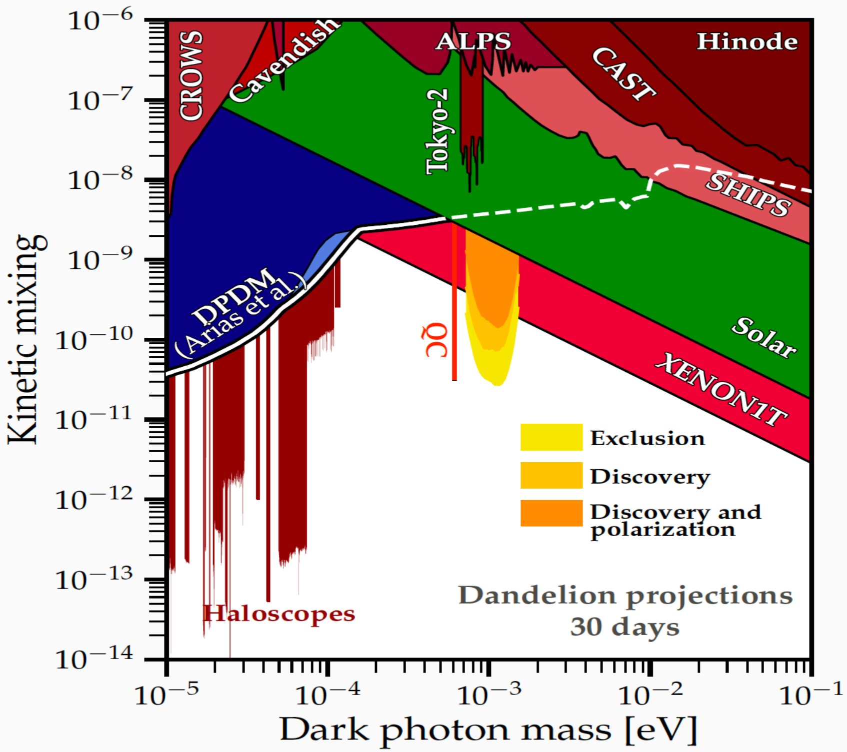
DArk photoN DirEctionaL detectION(Dandelion) at 1 meV

C. Beaufort, M. Bastero-Gil, A. Catalano, D-S. Erfani-Harami,
O. Guillaudin, D. Santos, S. Savorgnano, and F. Vezzu

418 pixels
Kid-Matrix







EXCLUSION:

A 30-day measurement would improve by **more than one order of magnitude** the existing limits

DISCOVERY:

The directional detection leads to an **unprecedented discovery potential**

DISCOVERY AND POLARIZATION:

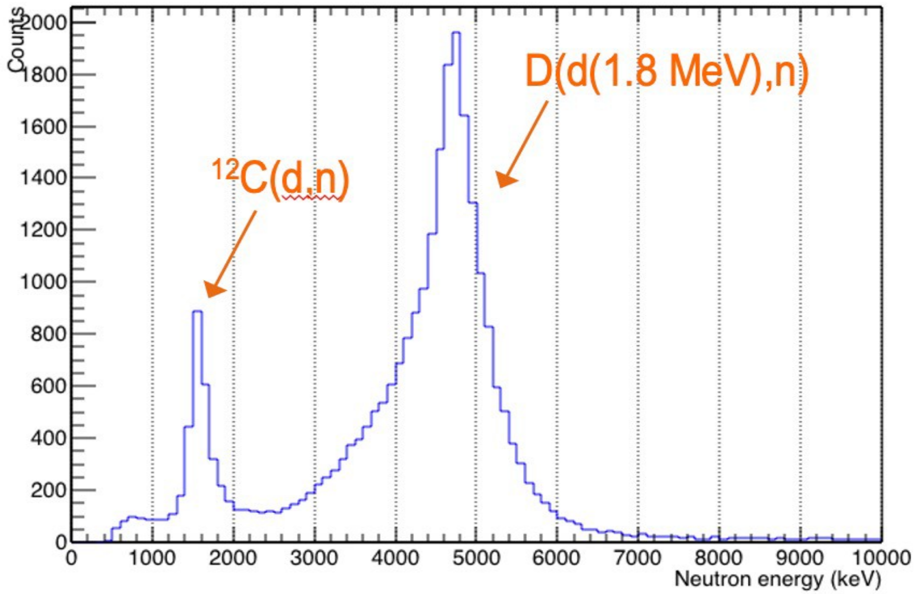
The detection of a DP could allow the **identification of its polarization**

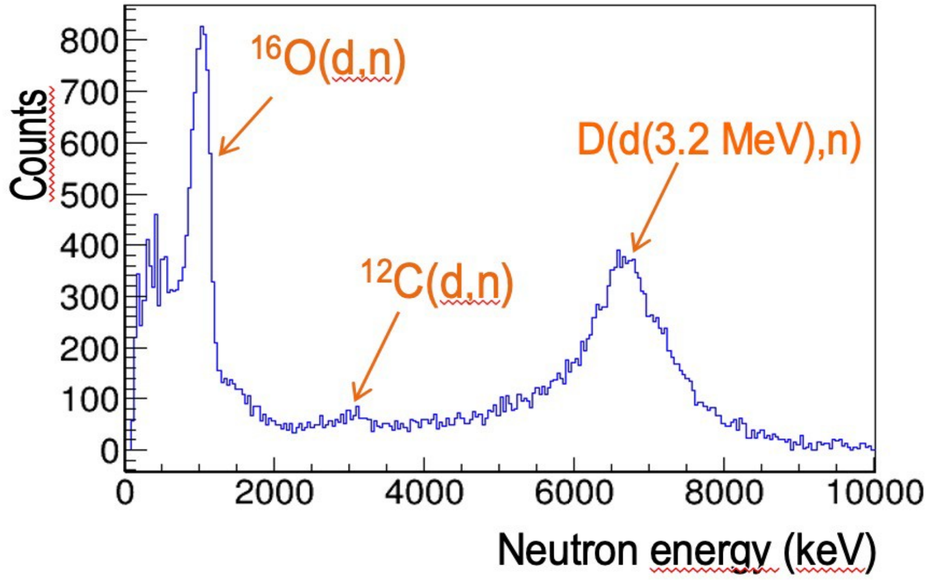
arXiv:2310.16505

Monoenergetic measurements : detection of target pollutions

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

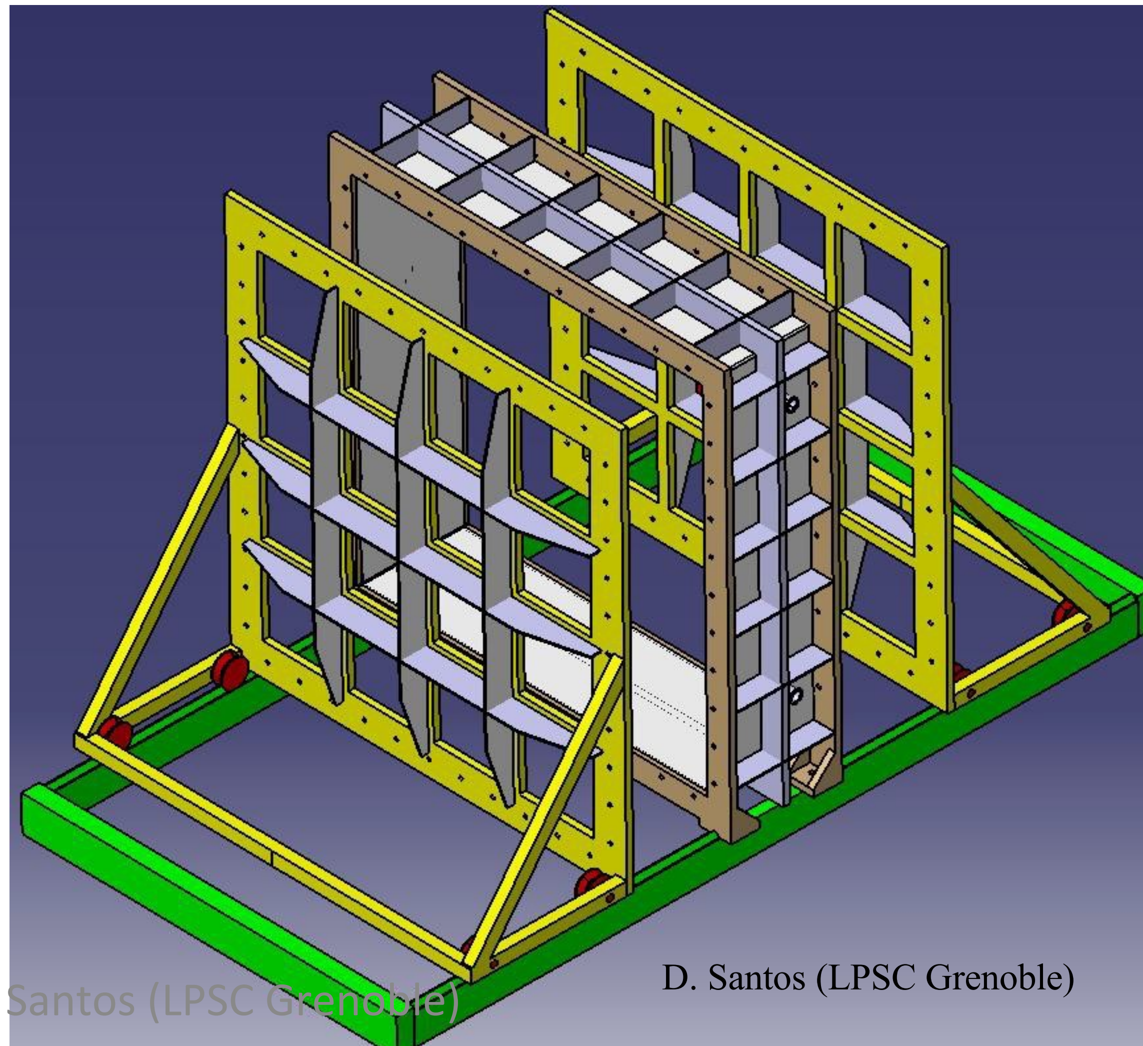
D. Santos (LPSC Grenoble)

MIMAC – 1m^3 = 16 bi-chamber modules (2x 35x35x26 cm^3)

New technology anode 35cmx35cm

New electronic board (1792 channels)

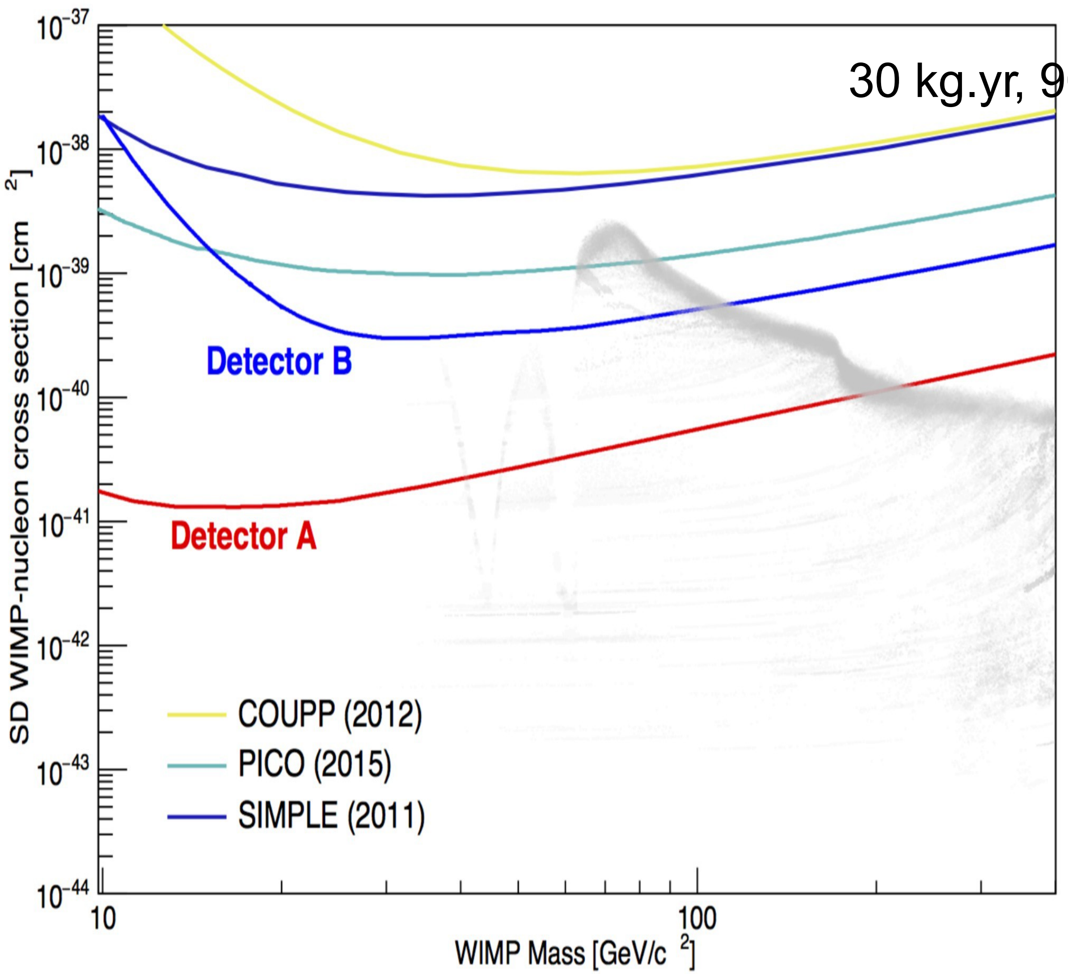
Only one big chamber



D. Santos (LPSC Grenoble)

D. Santos (LPSC Grenoble)

MIMAC-Exclusion limits



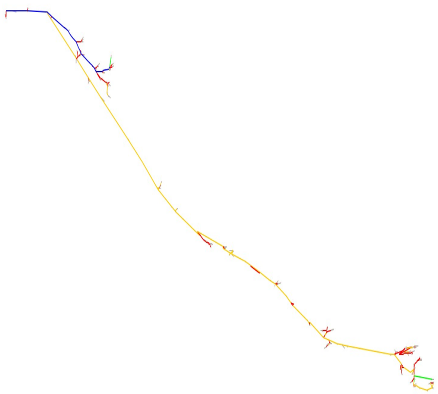
A: 5 keV (threshold)
no background
3D track with head-tail
angular resolution 20°

B: 20 keV
background= 10evt/kg yr
angular resolution 50°
3D with no head-tail

D. Santos (LPSC Grenoble)

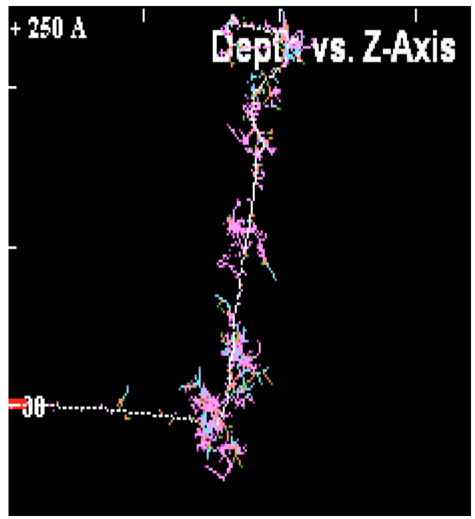
Directional detection: comparison of strategies

- Emulsion



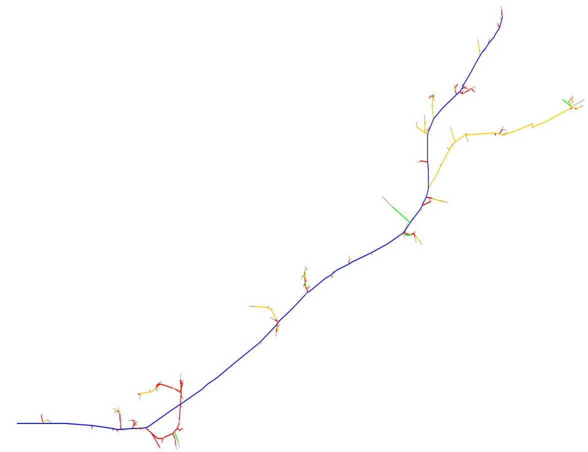
~100 nm

- Anisotropic crystals



~10 nm

- Low pressure TPCs



~1 mm
(10^5 times longuer !!)

(SRIM simulations)

D. Santos (LPSC Grenoble)