MIMAC

MIcro-tpc MAtrix of Chambers

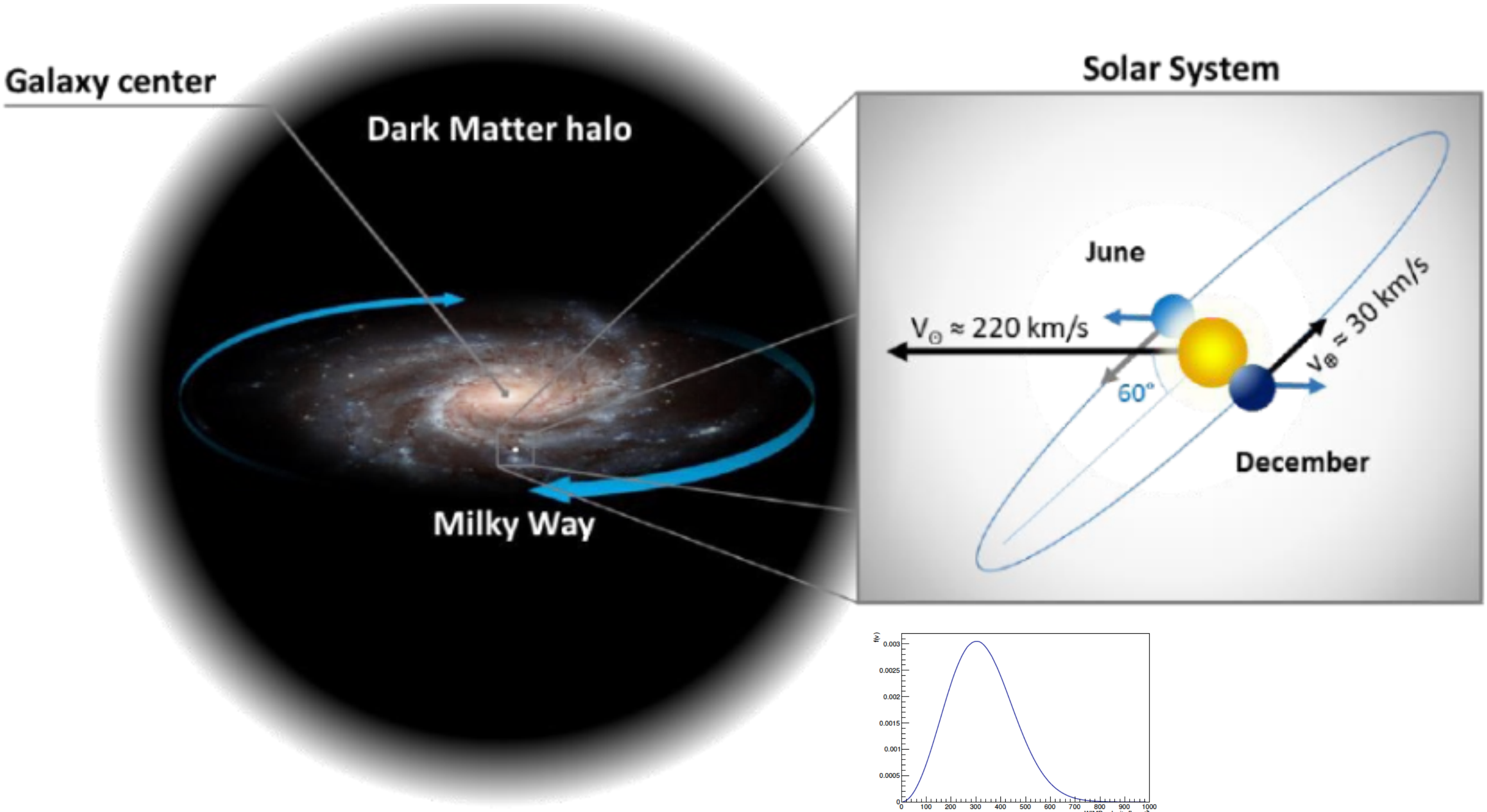
for 3D-Directional Dark Matter detection

Daniel Santos

LPSC-Grenoble

October 23rd 2023

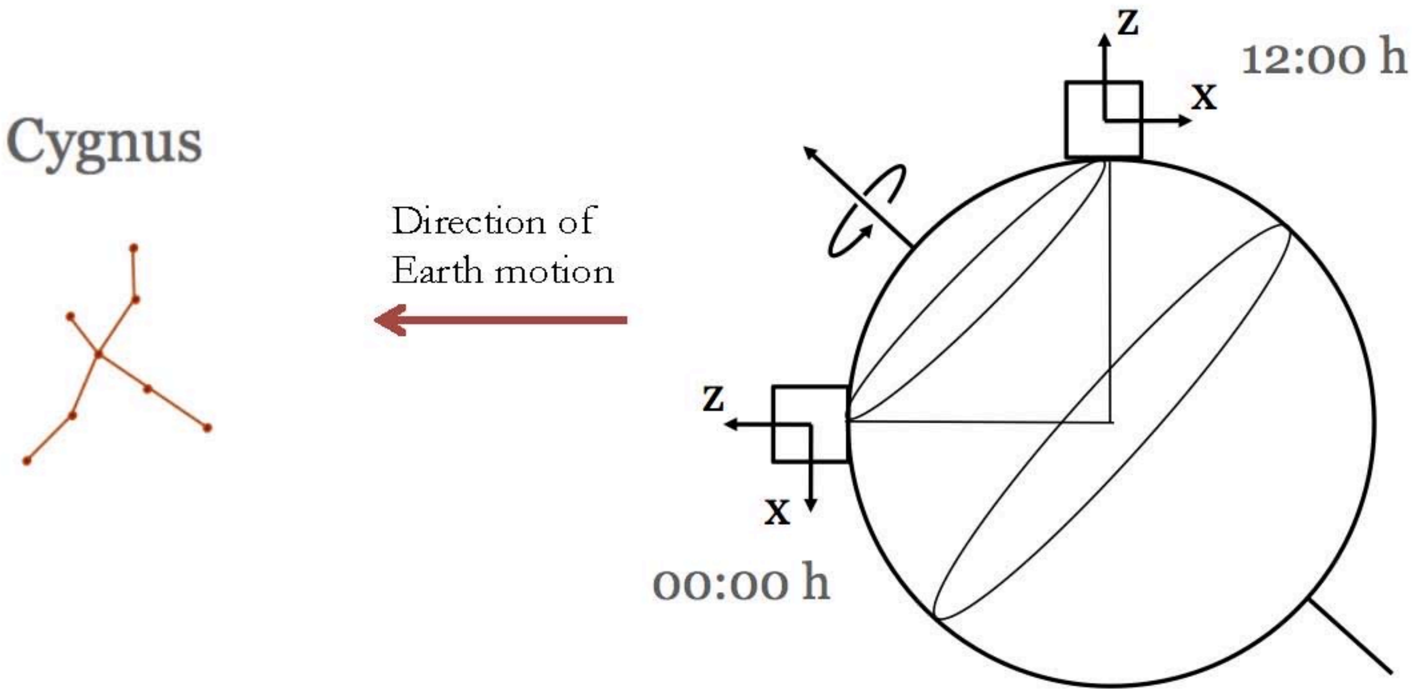
Directional detection principle



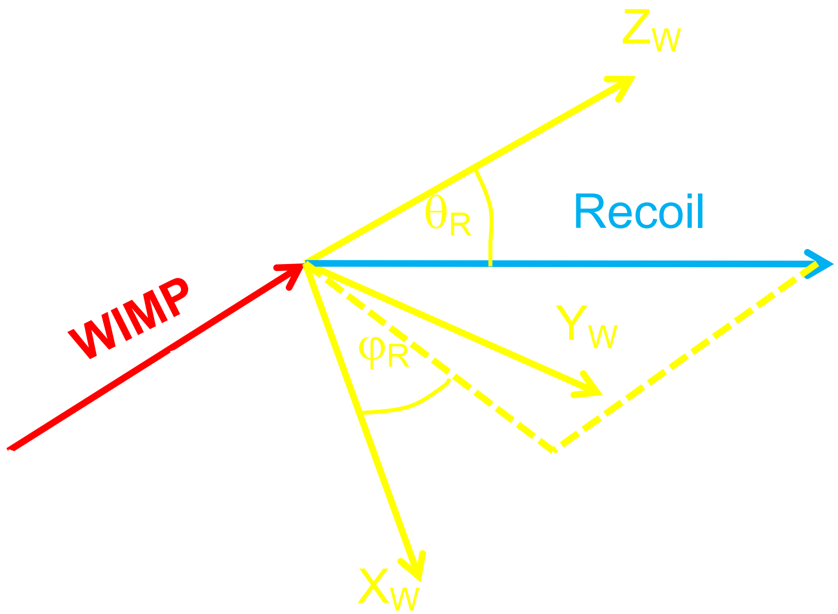
The only signature able to correlate the rare events in a detector to the DM galactic halo !!

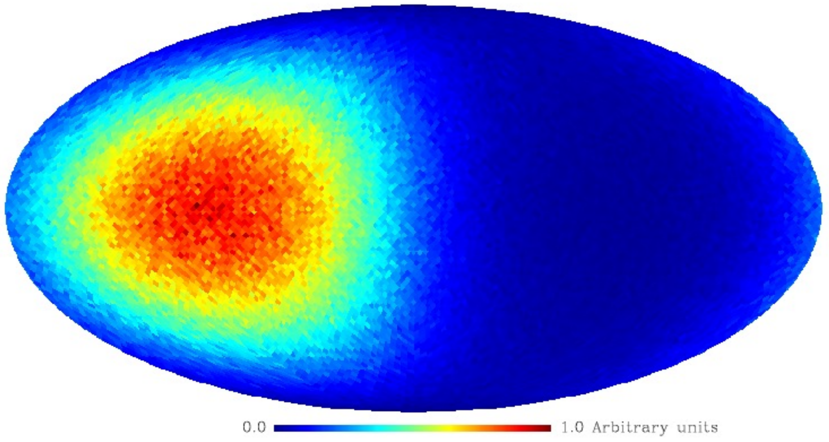
Angular modulation of WIMP flux

Modulation is sidereal (tied to stars) not diurnal (tied to Sun)



There are many "angles" for nuclear recoils… 3D tracks are needed…

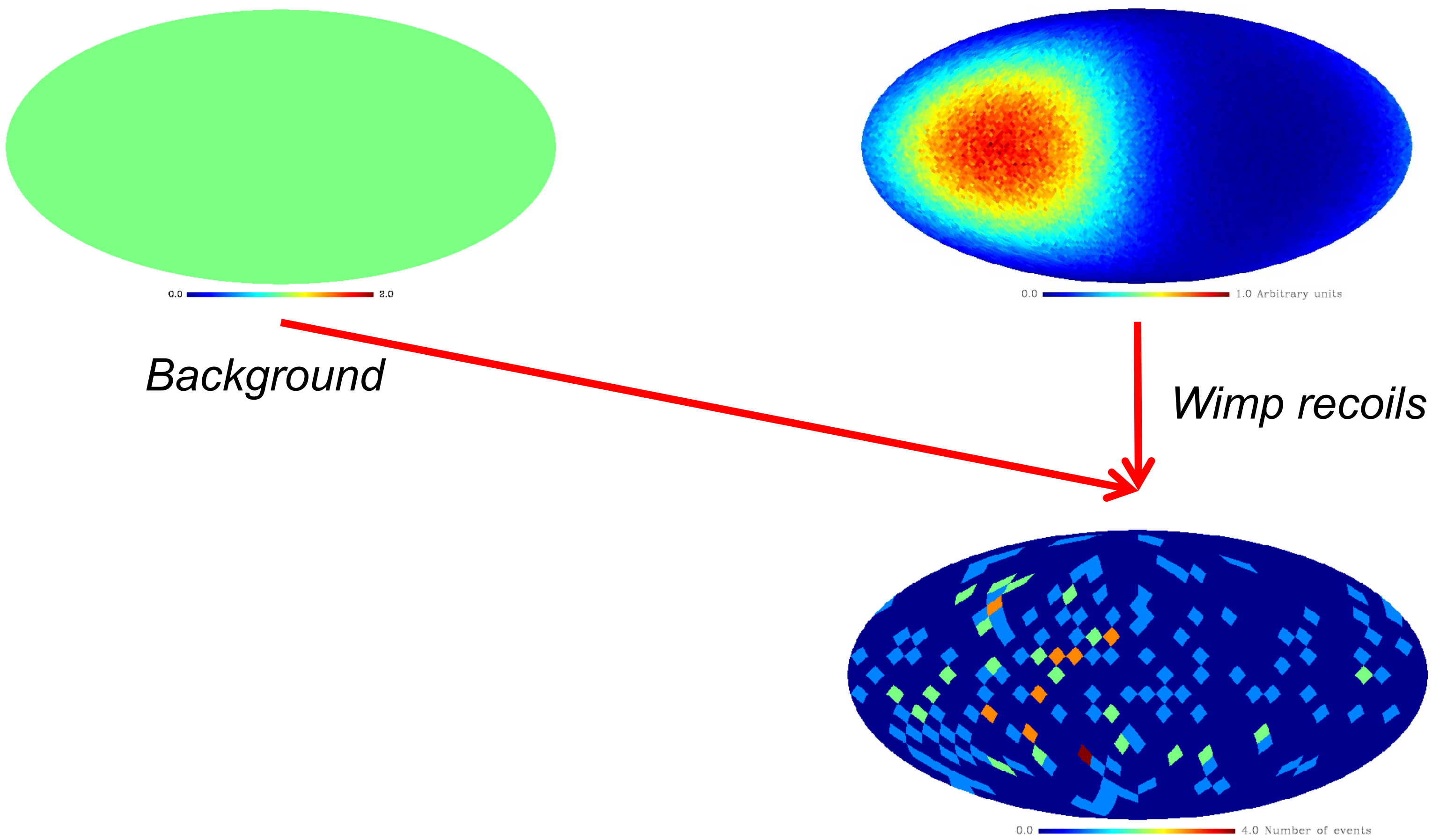




Map of recoils in galactic coordinates (HealPix)

Robust with respect to Background events

100 WIMP evts + 100 Background evts

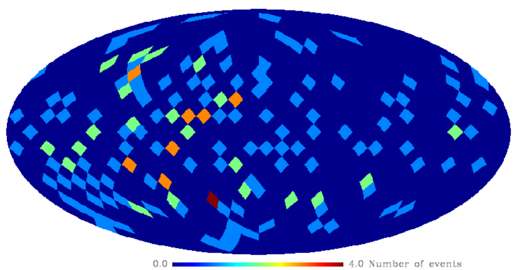


Phenomenology: Discovery

J. Billard *et al.*, PLB 2010
J. Billard *et al.*, arXiv:1110.6079

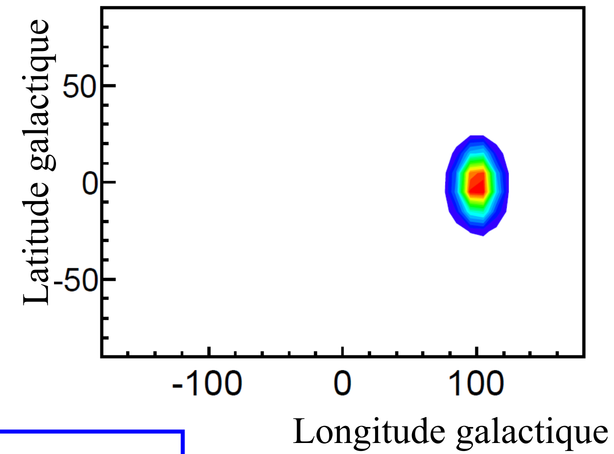
Proof of discovery: **Signal pointing toward the Cygnus constellation**

Blind likelihood analysis in order to establish the galactic origin of the signal



100 WIMP + 100 BKG

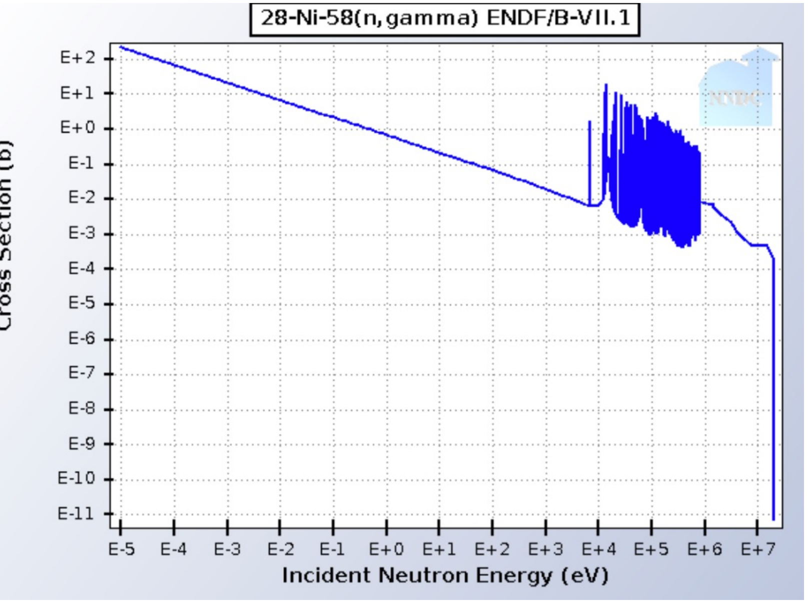
$$\mathscr{L}(\ell, b, m_\chi, \lambda)$$



Strong correlation with the direction of the Constellation Cygnus **even with a large background contamination**

A complex background will always be there.

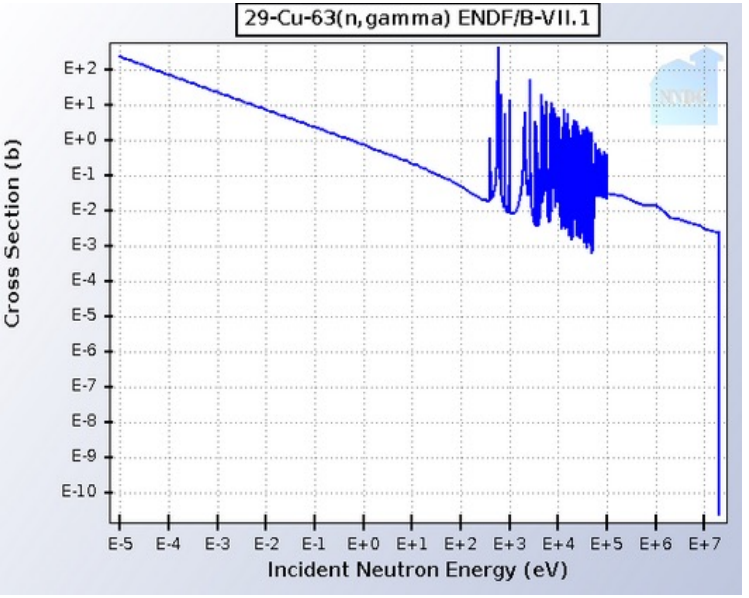
Lower the energy even more uncertain will be.

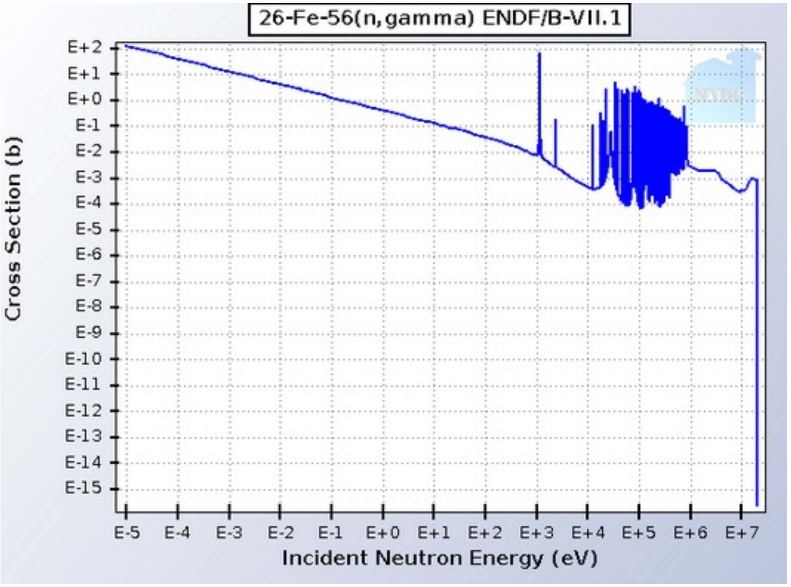


Neutron capture in materials used to build our detectors

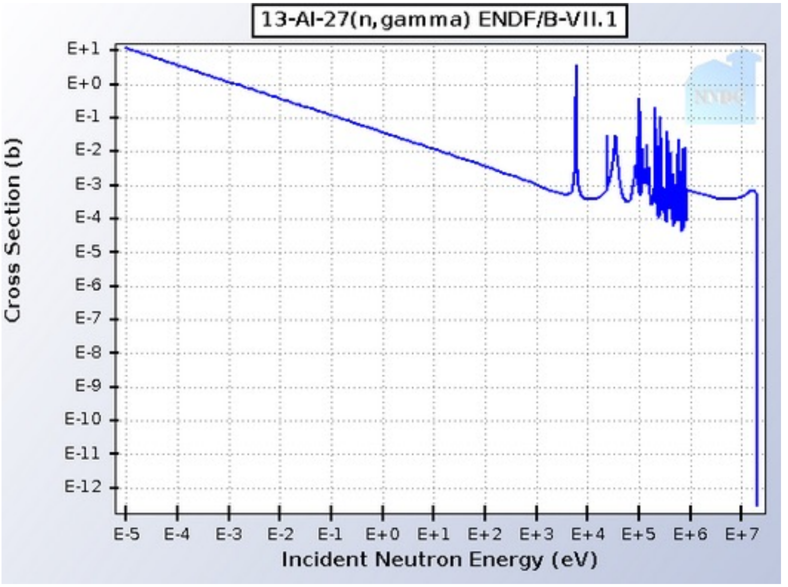
^{58}Ni, ^{63}Cu

^{56}Fe, ^{27}Al

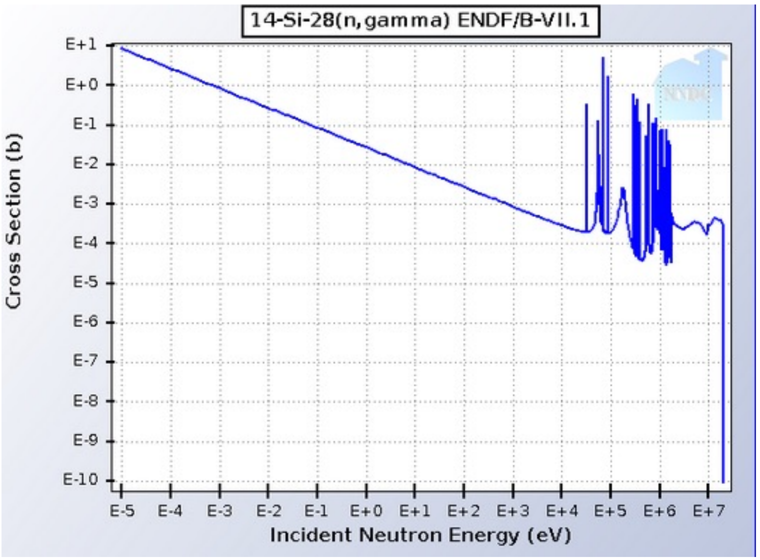




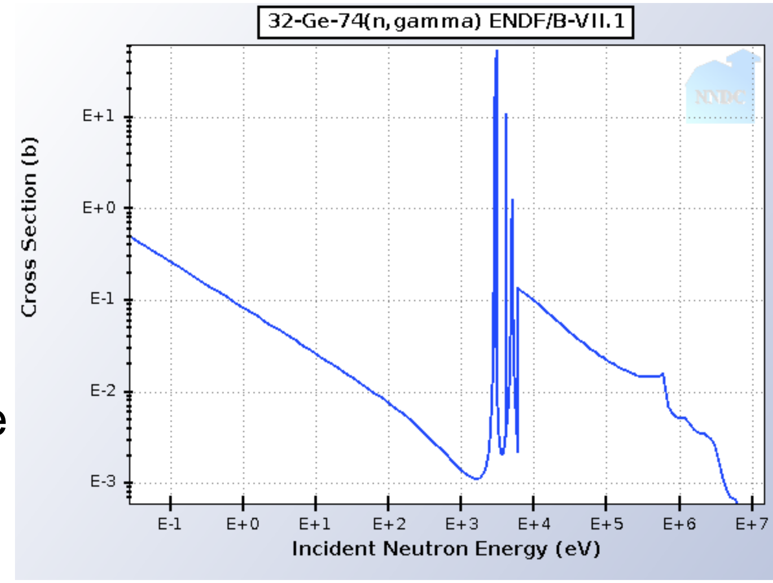
Showing a lot of resonances starting at less than 1 keV… Producing gamma-rays source of many electrons !!



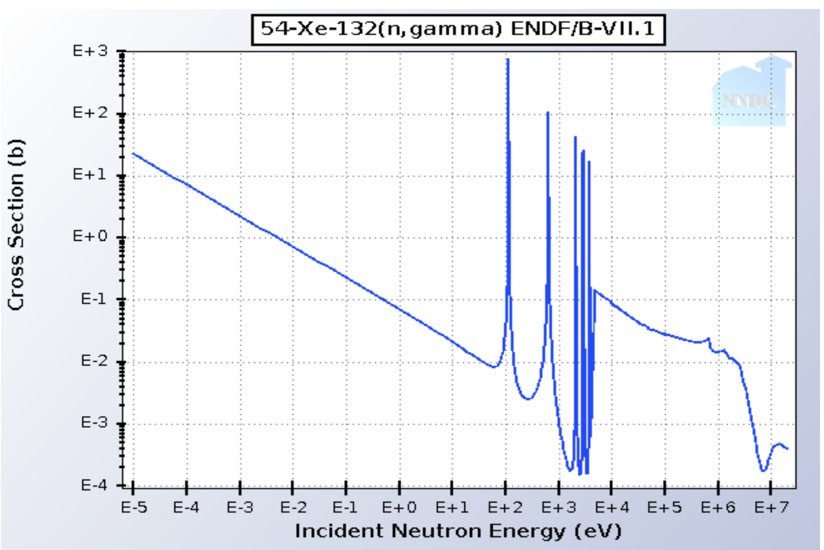
Even the **target nuclei** are a source of such gamma-rays by neutron capture, difficult to prevent from entering inside



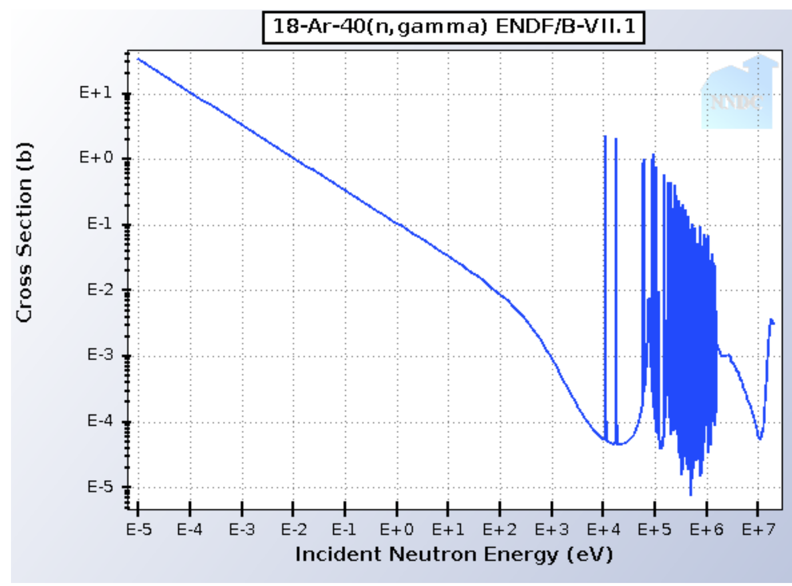
^{28}Si



^{74}Ge

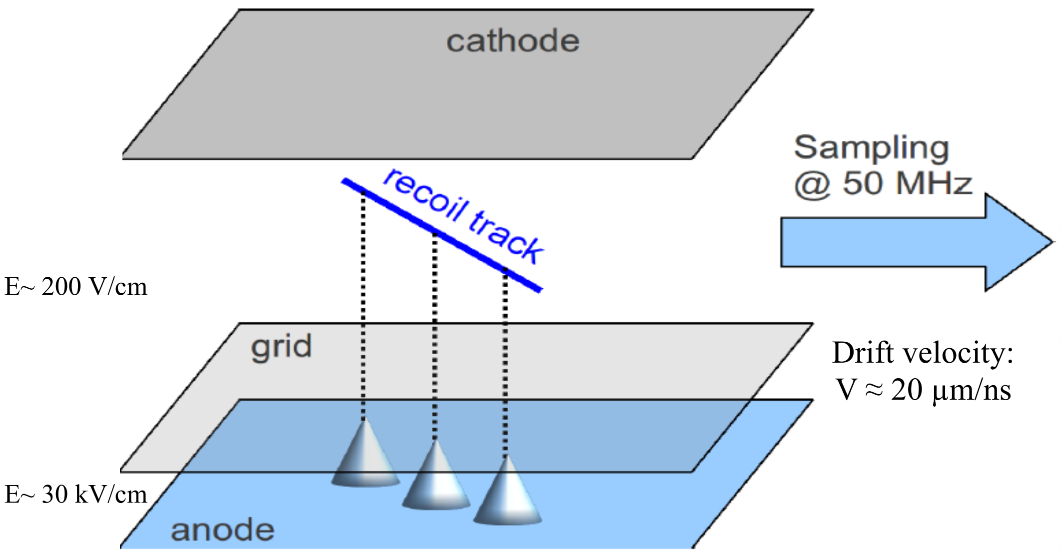


^{132}Xe

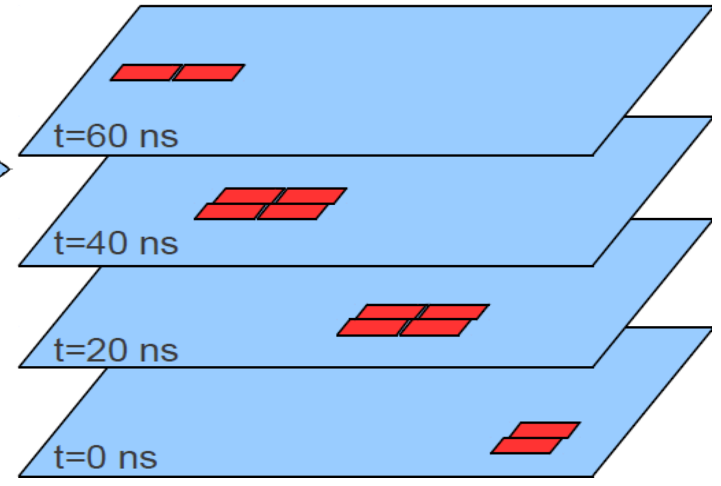


^{40}Ar

MIMAC: Detection strategy



Scheme of a MIMAC µTPC



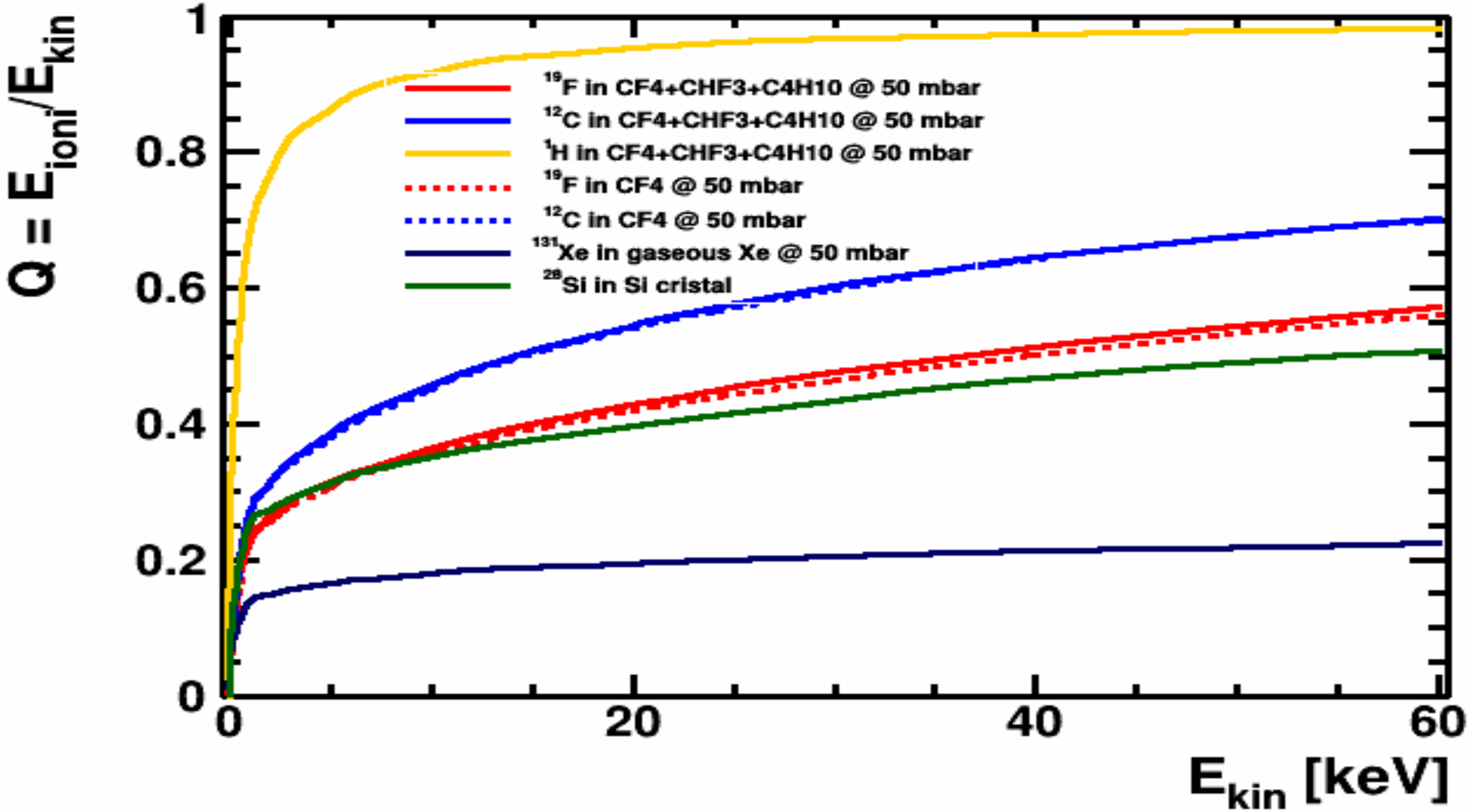
Evolution of the collected charges on the anode

Measurement of the ionization energy:

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

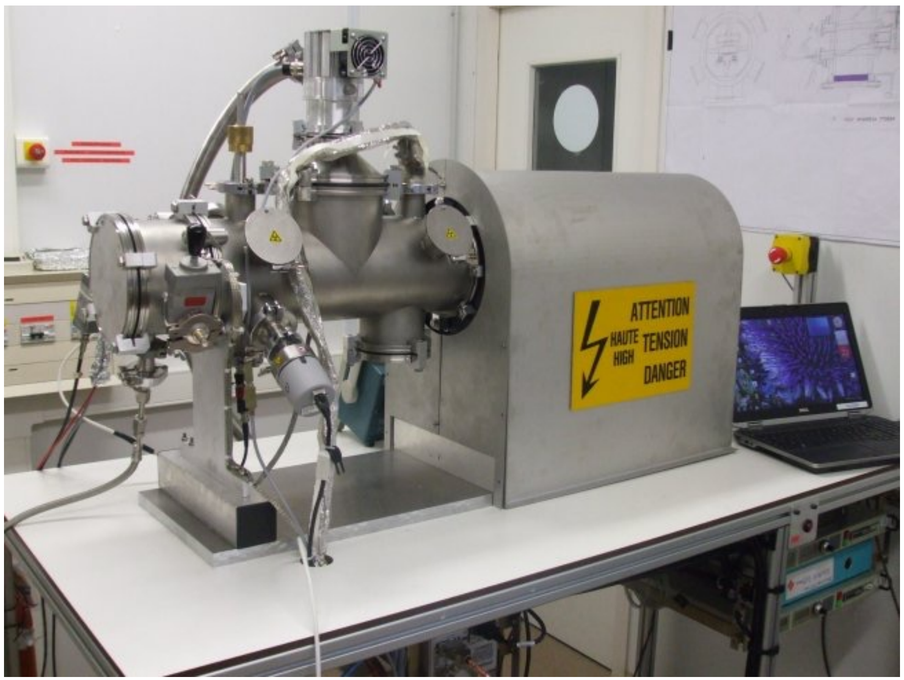
Ionization Quenching Factors

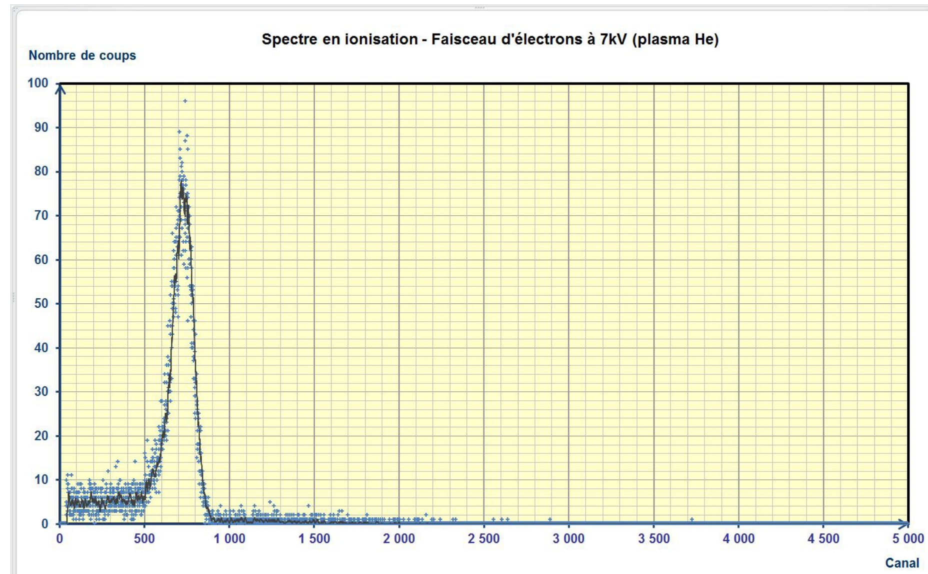
SRIM-Simulations (LPSC)



Portable Ionization Quenching Facility (COMIMAC)

(Electrons and Nuclei of known energies)





Electrons of 7 keV

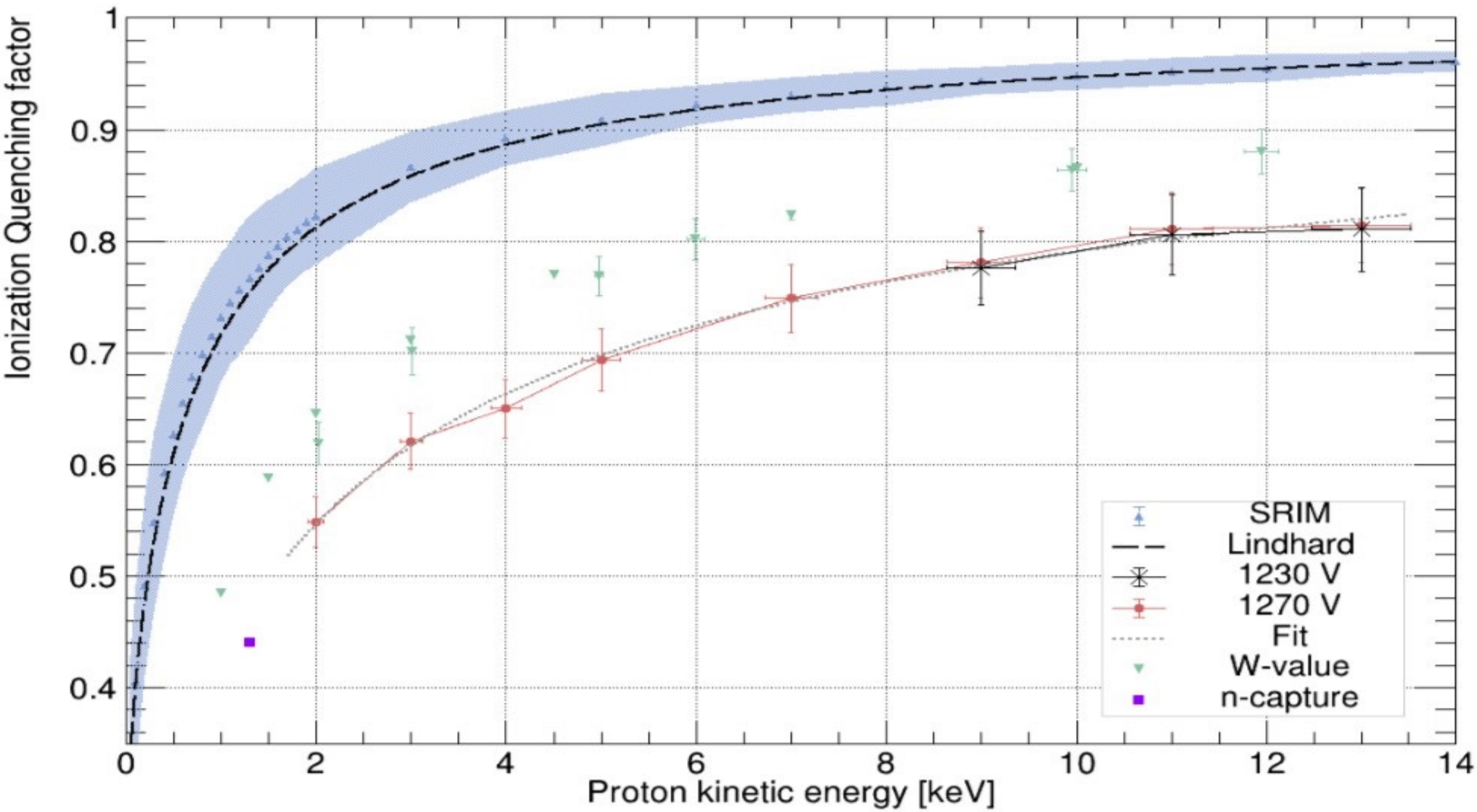
In a gas detector the IQF depends on the gas mixture and on its « quality »!

For more information on COMIMAC: J-F. Muraz et al. NIM A, 2016

COMIMAC-IQF measurements of H in CH_4 compared with simulations

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

IQF



Nuclear recoil calibration with neutrons

Neutron monochromatic field:

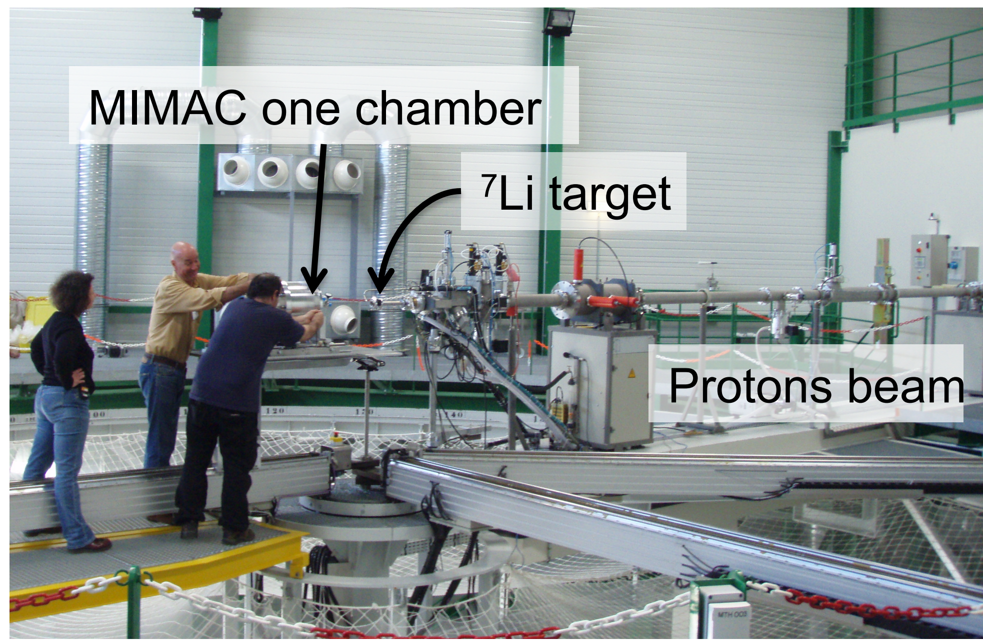
AMANDE facility at IRSN of Cadarache

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

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

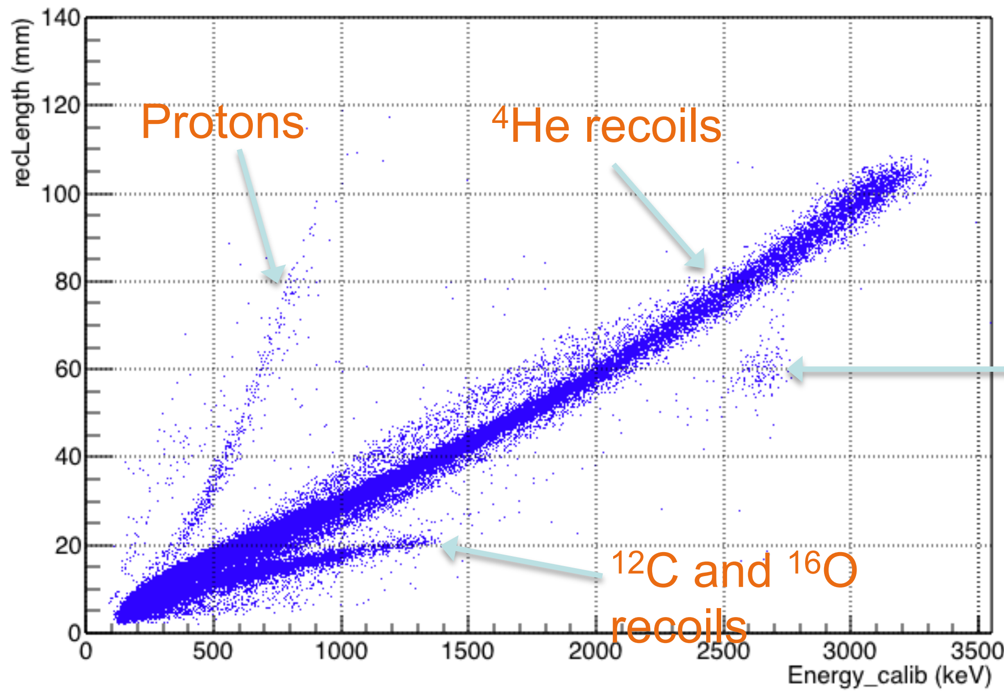
Electron Calibration:

with electrons of COMIMAC facility



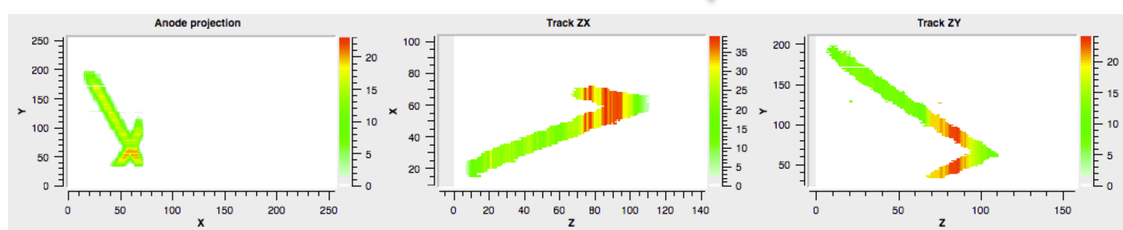
Selection of ^{4}He nuclear recoils : D(d(1.8 MeV),n)

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



700 mbar He/CO_2 (5%)

^{16}O(n,α)^{13}C

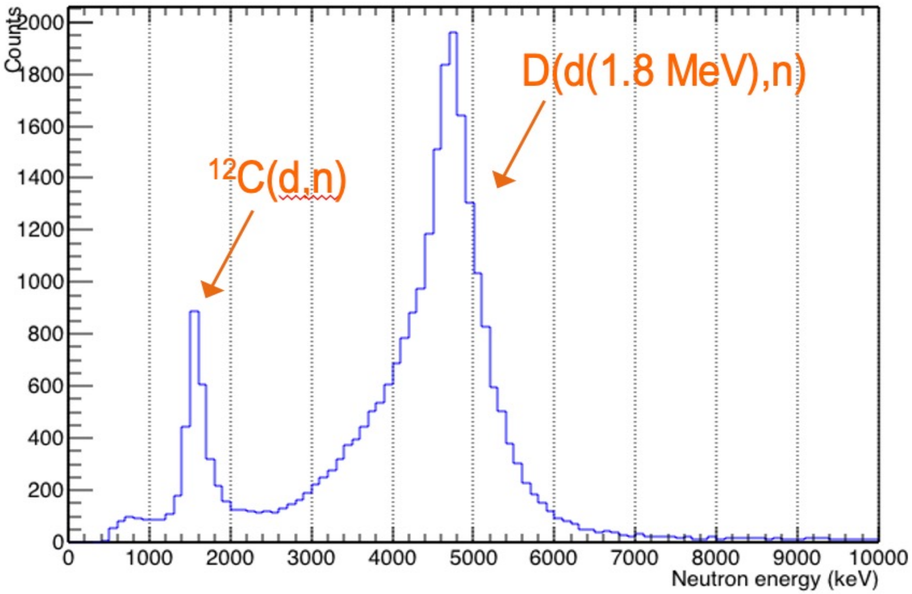


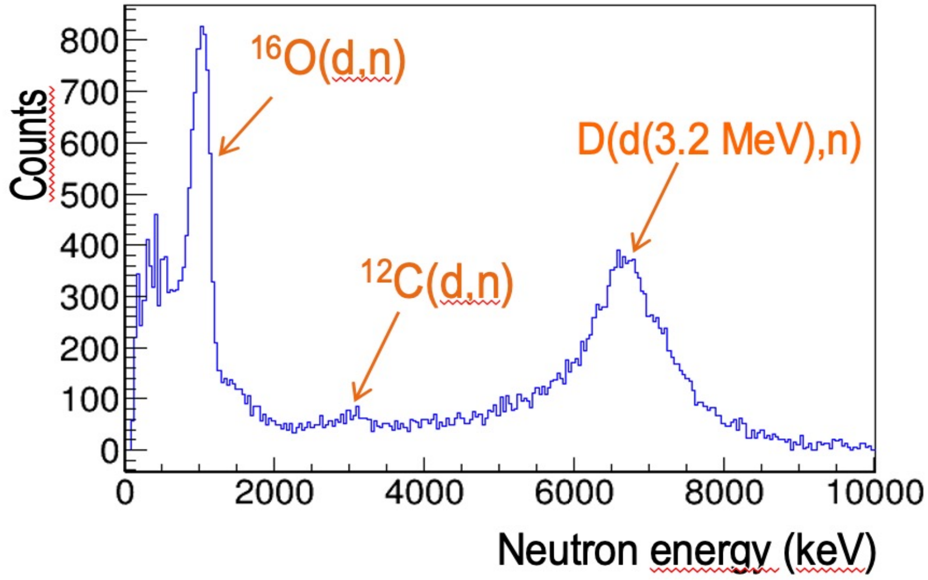
IRSN /AMANDE (Cadarache)

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





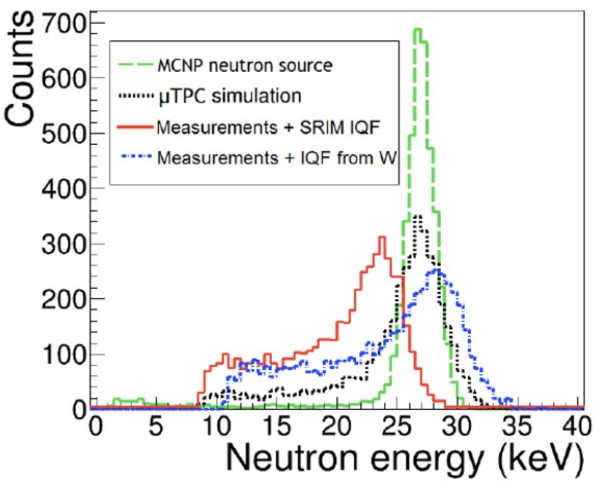
NPL /(UK)

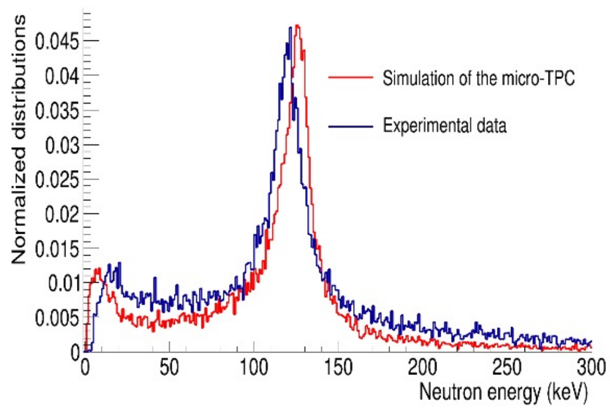
700 mbar He/CO_2 (5%)

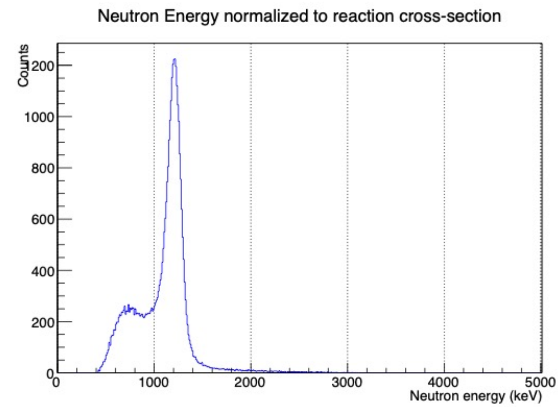
IRSN / AMANDE (Cadarache)

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

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

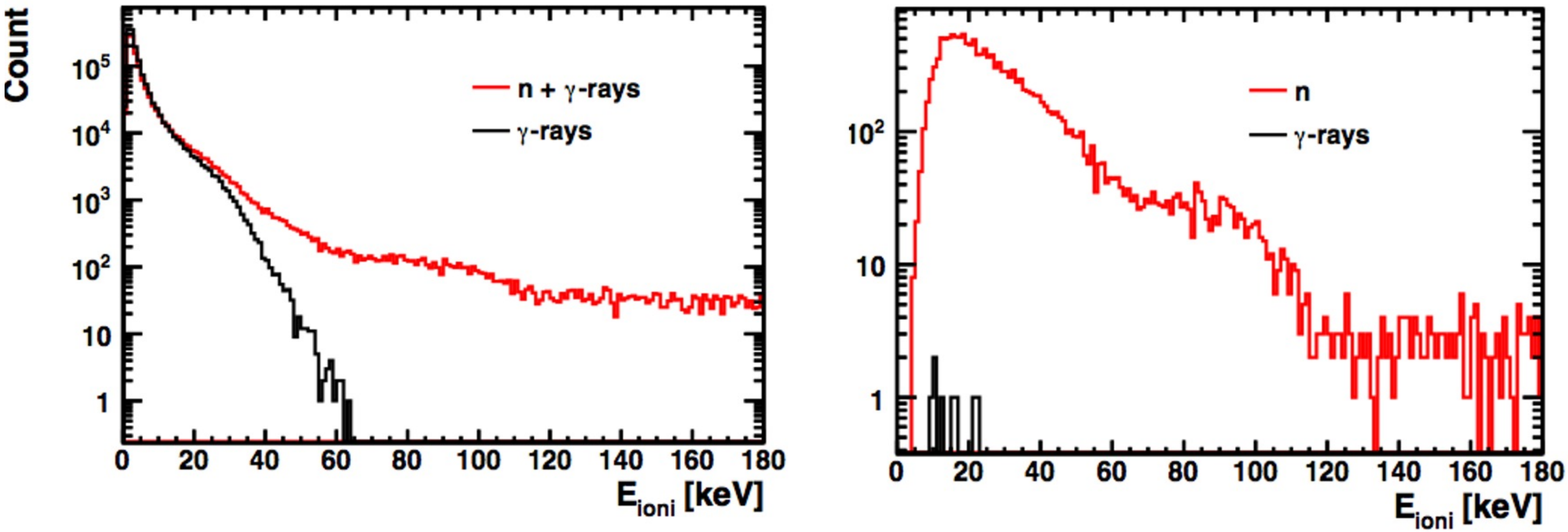
D. Maire *et al.*
« First measurement of a 127 KeV neutron field with a µ-TPC spectrometer »
Nuclear Science, IEEE Transactions, 61(2014) 2090

Electron-recoil Discrimination

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

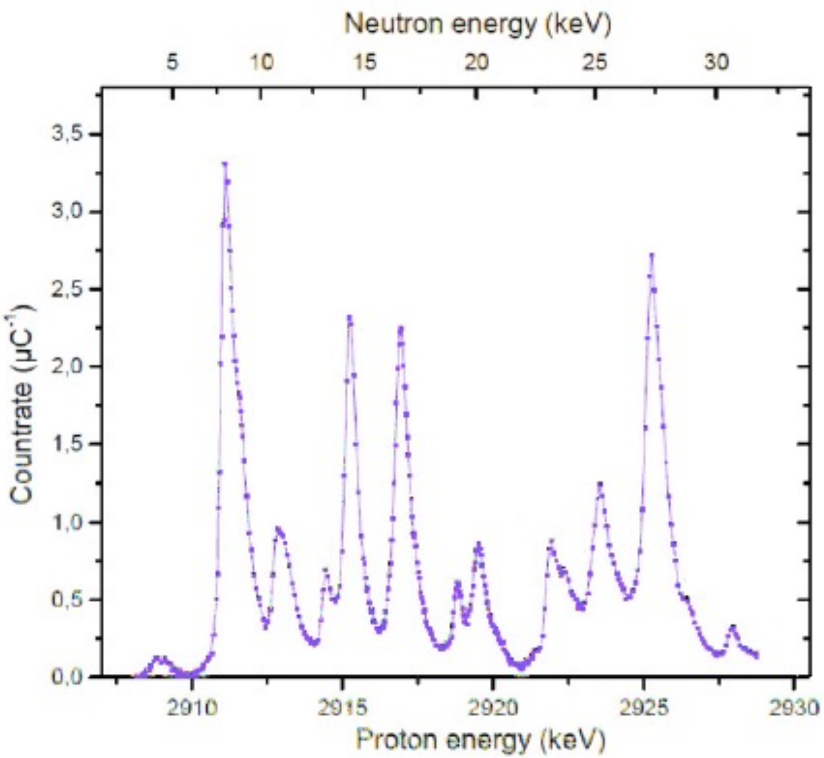
Neutrons → F , C, H, nuclear recoils

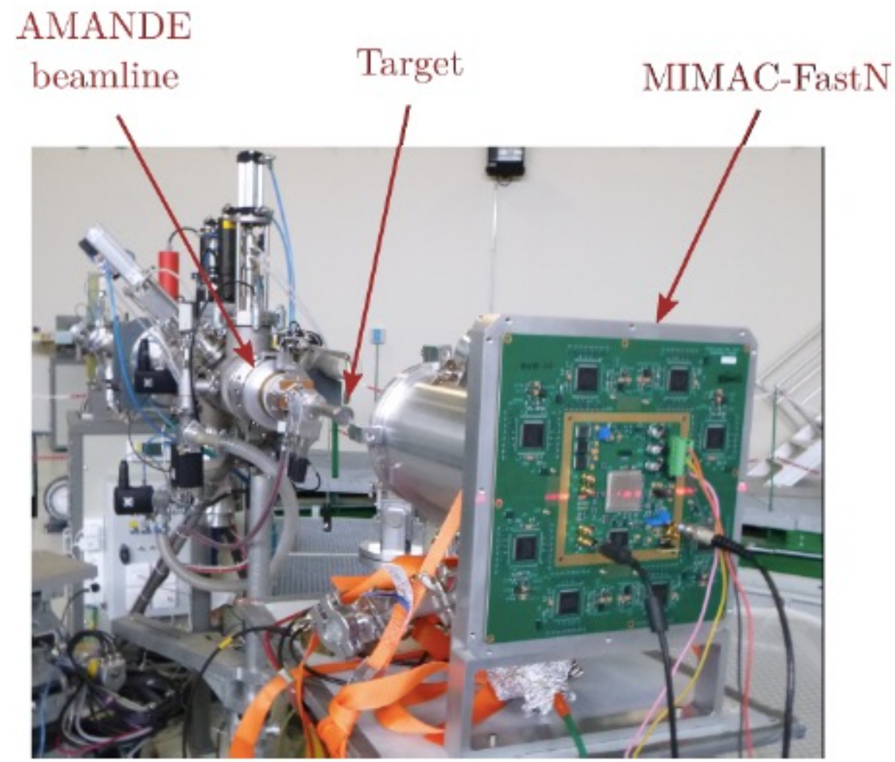
$\gamma - \text{rays}$ → Electrons



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

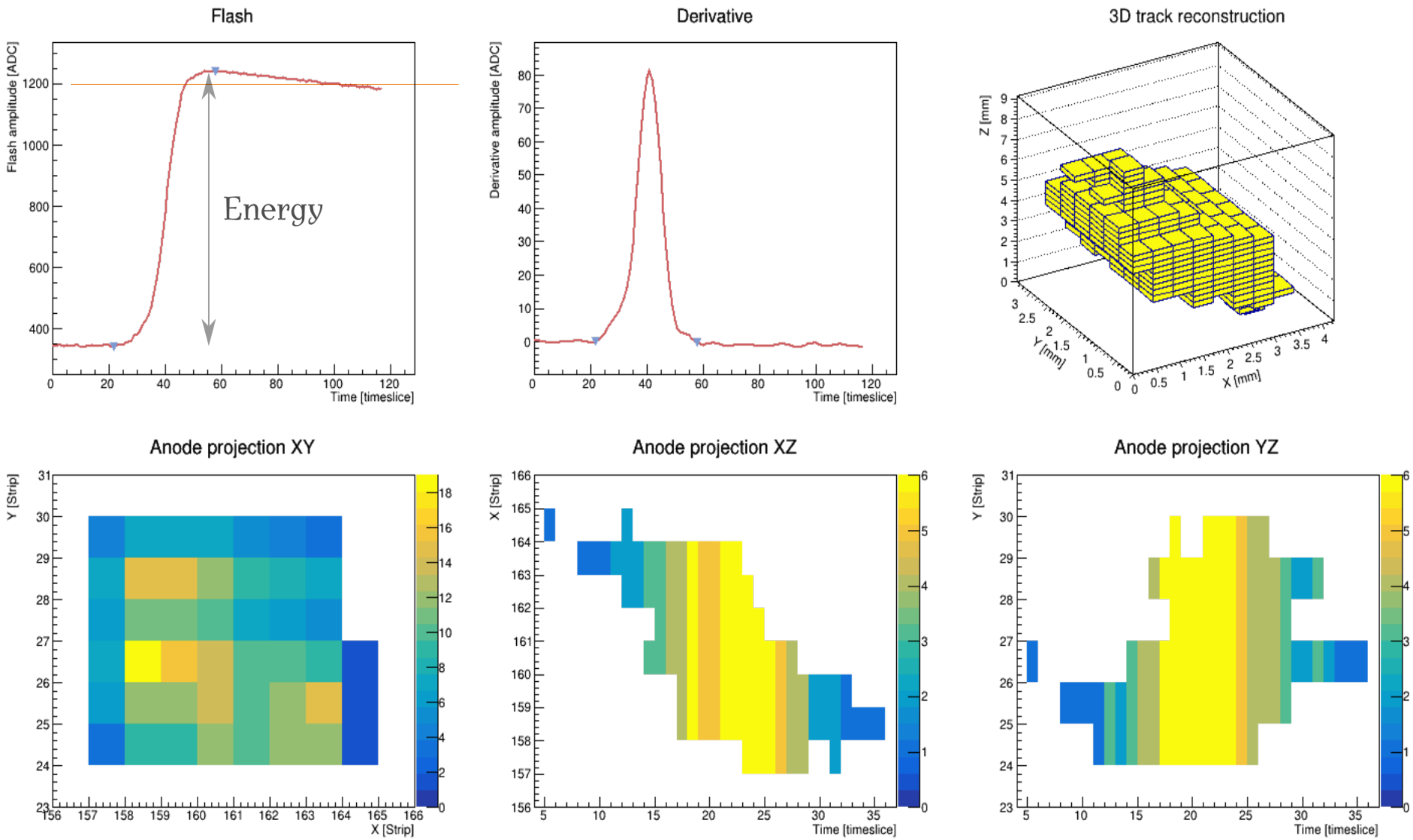
Low energy (8 and 27 keV) mono-energetic neutron spectroscopy





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

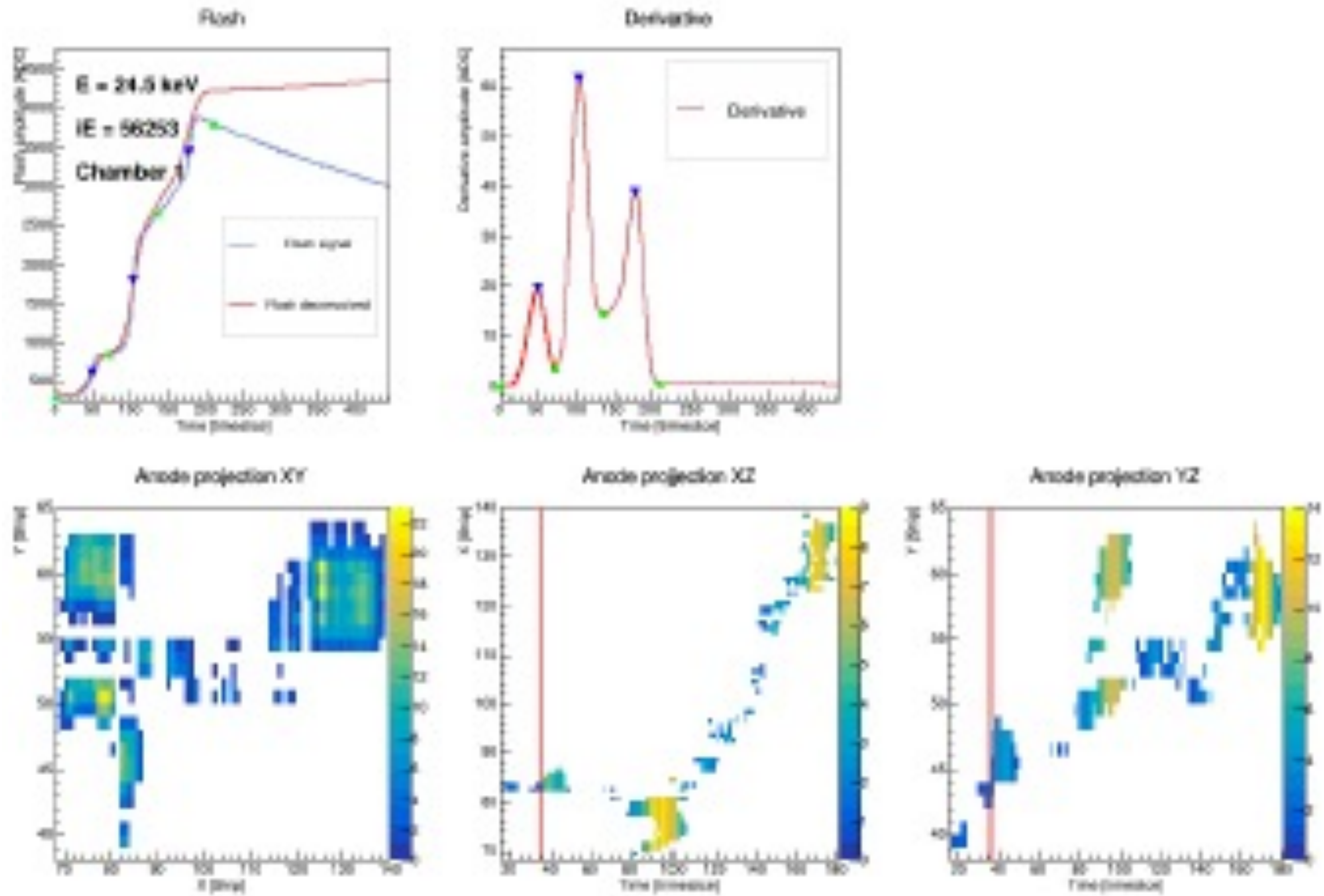
Example of a proton recoil of $6\ \mathrm{keV_{ee}}$ ($8.6\ \mathrm{keV_{nr}}$)



– → Sampling at 50 MHz (20 ns)

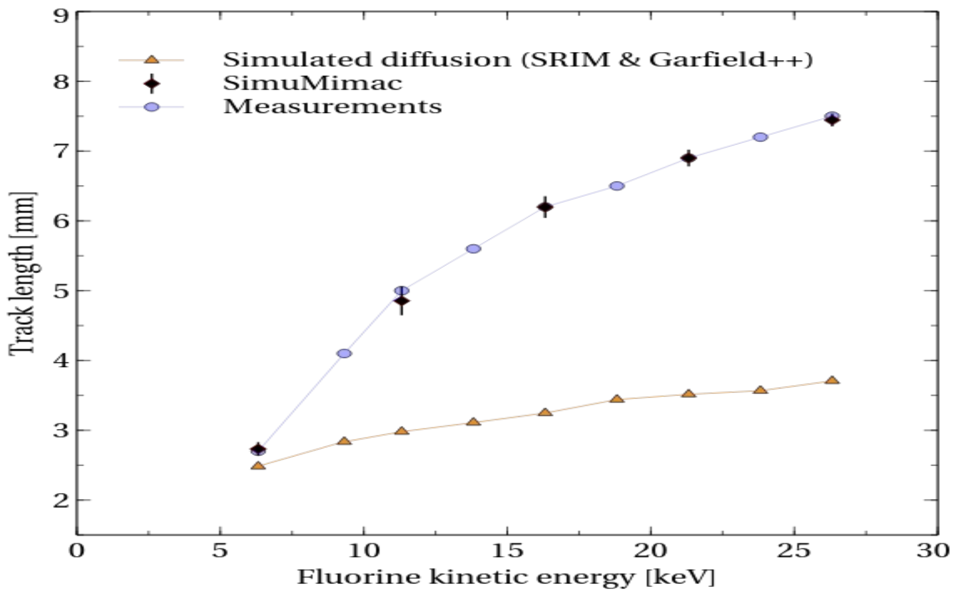
C_4H_{10} +. 50% CHF_3 at 30 mbar

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



Directionality at high gain – SimuMimac

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



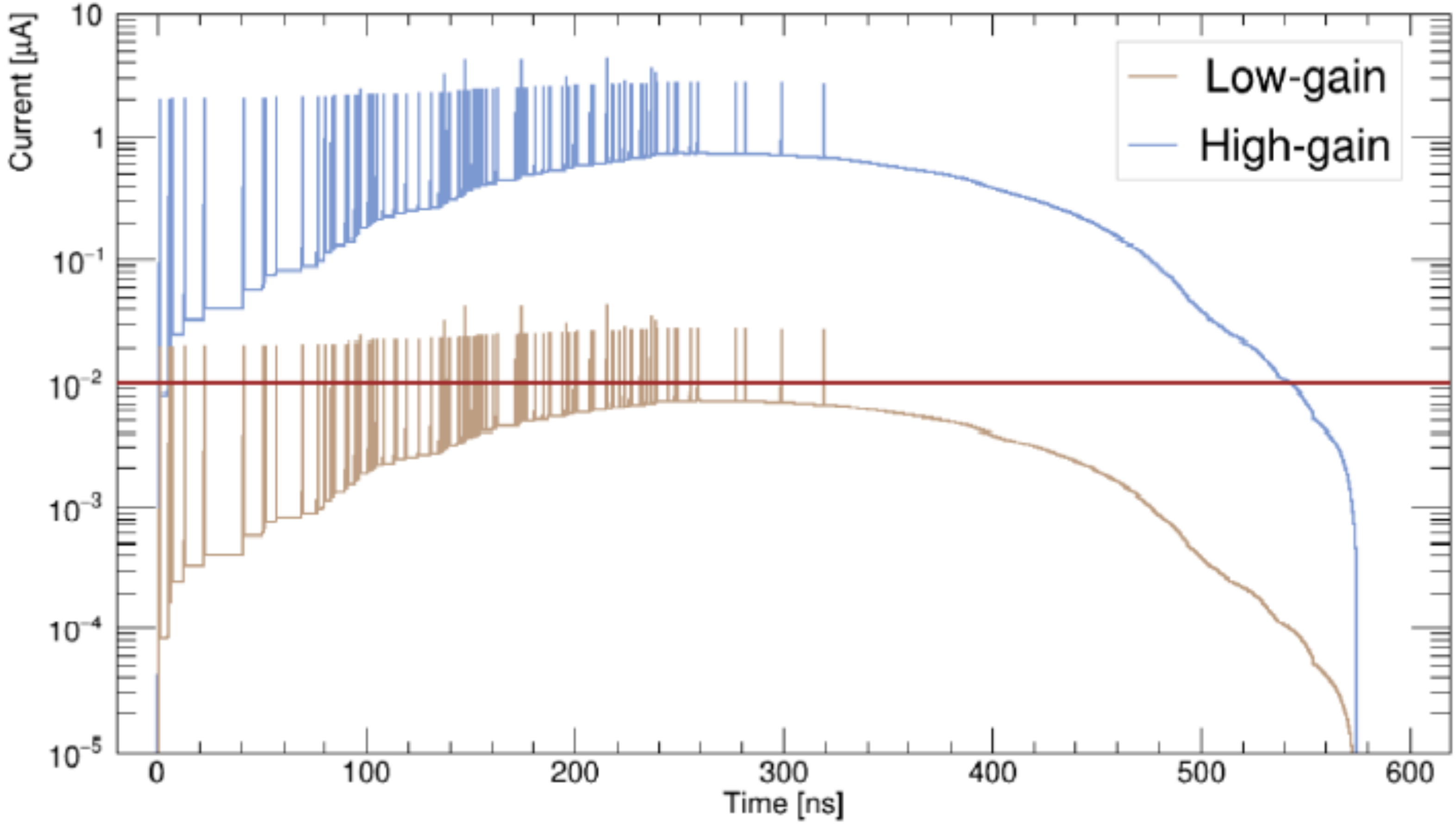
Measured and simulated fluorine track lengths

We developed SimuMimac **(C.Beaufort 2021)**, a simulation tool based on SRIM and Garfield++ to model the physics of the detector from the primary electron cloud to the signal formation

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

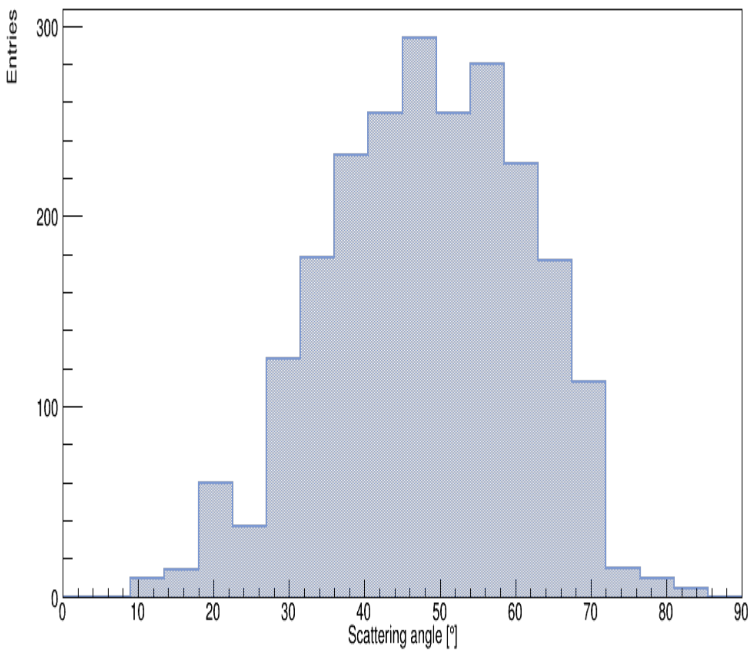
Signal contributions at high-gain (primary electrons and secondary ions)

Cyprien Beaufort et al. arxiv.org/2112.12469

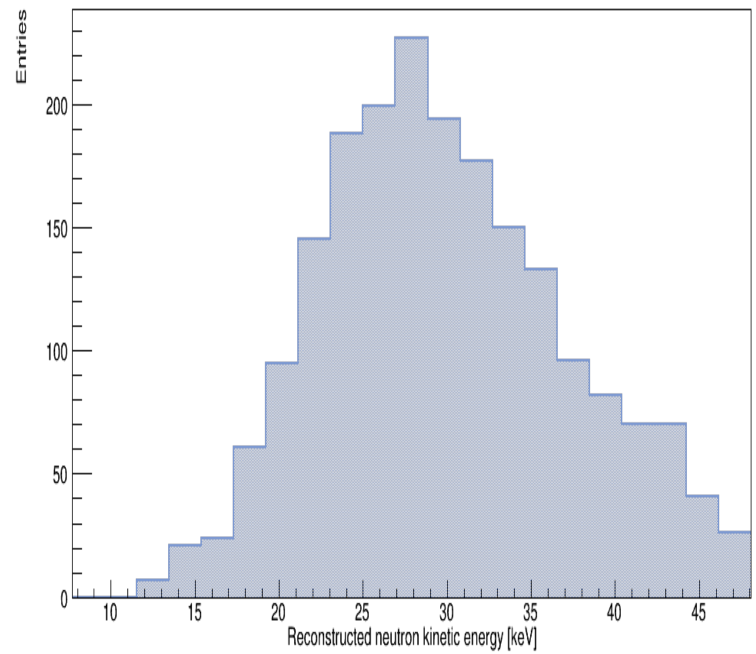


Detection threshold

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



Angular distribution



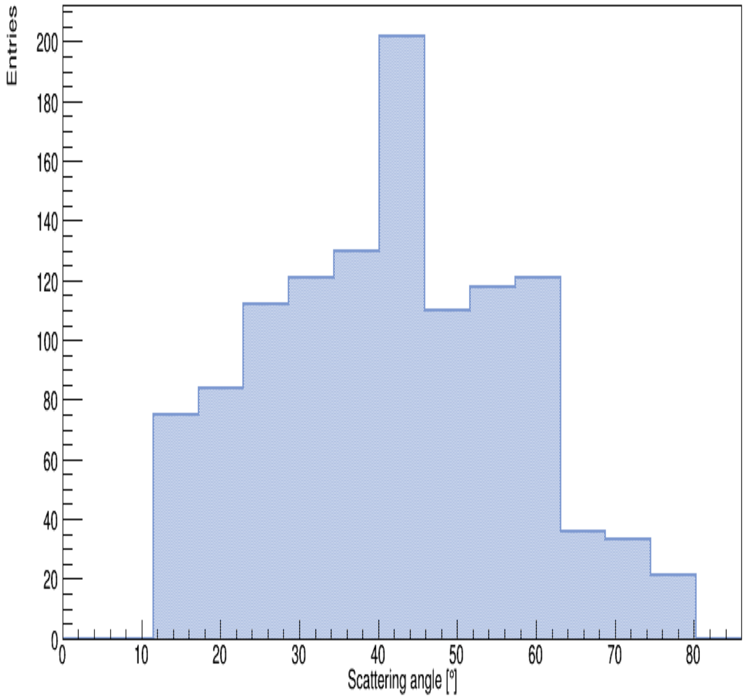
Reconstructed spectrum

Directional performances at 27 keV:

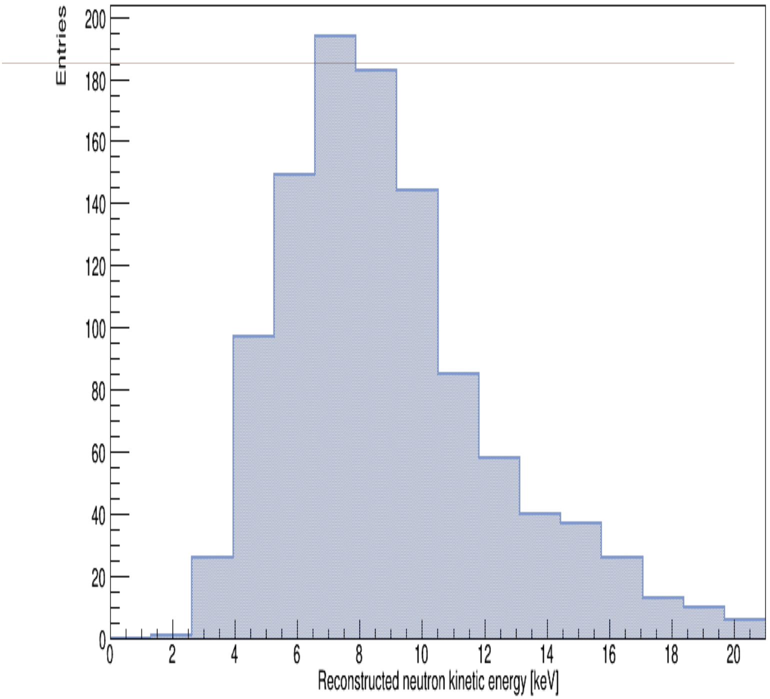
- **Energy reconstructed agrees within 2.5%** with the energy of the monoenergetic neutron field
- **Angular resolution better than 10°**

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

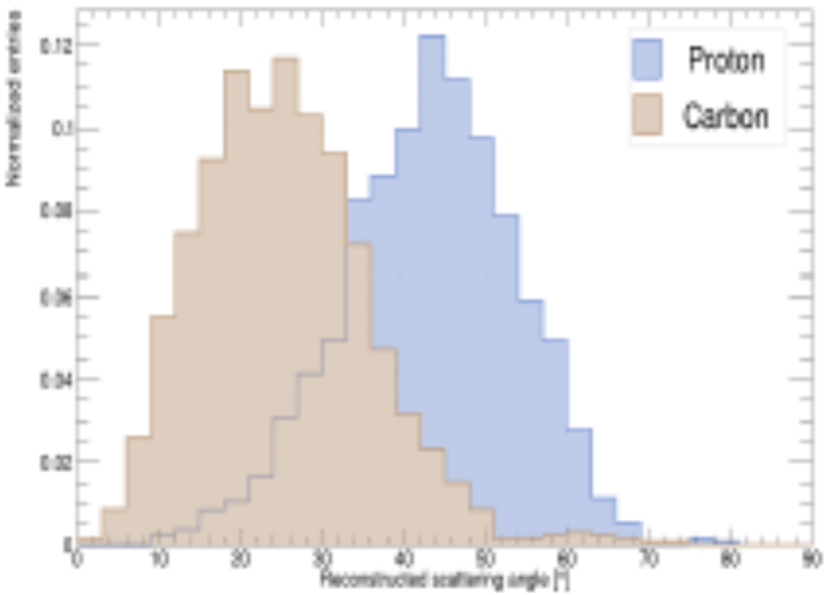
Directional performances at $8\,\mathrm{keV}$:

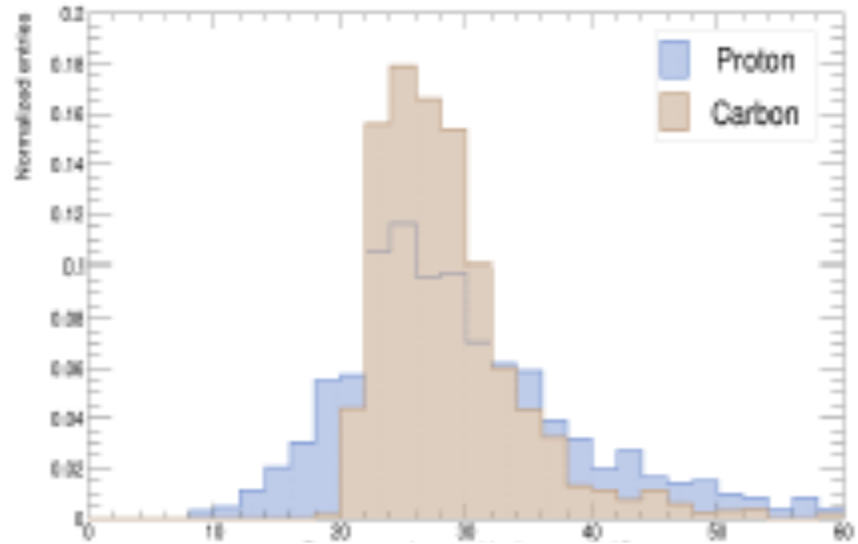
- Energy reconstructed agrees within 4.0% and angular resolution better than 15°

Cyprien Beaufort et al. JCAP08(2022)057

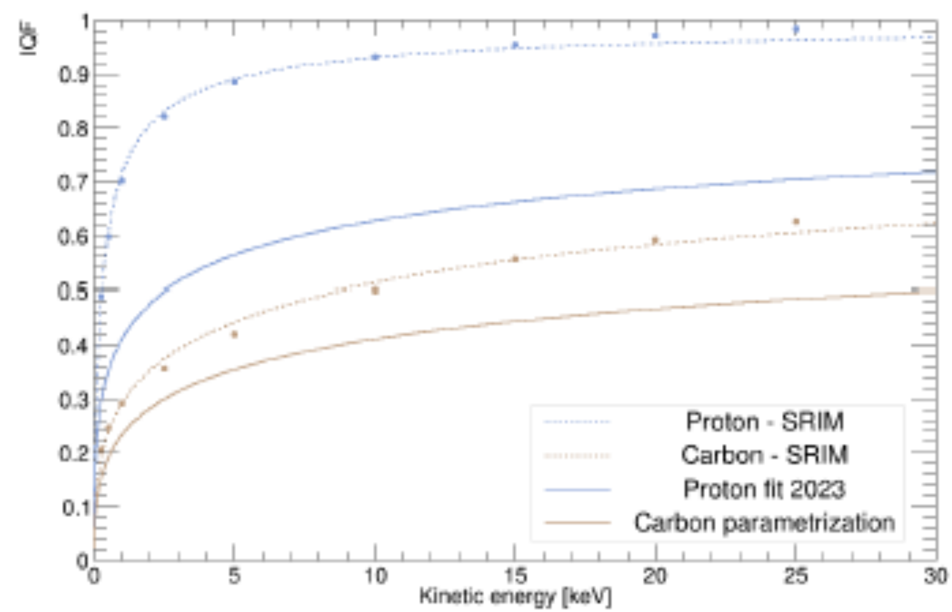
From proton and carbon recoils at 27 keV

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

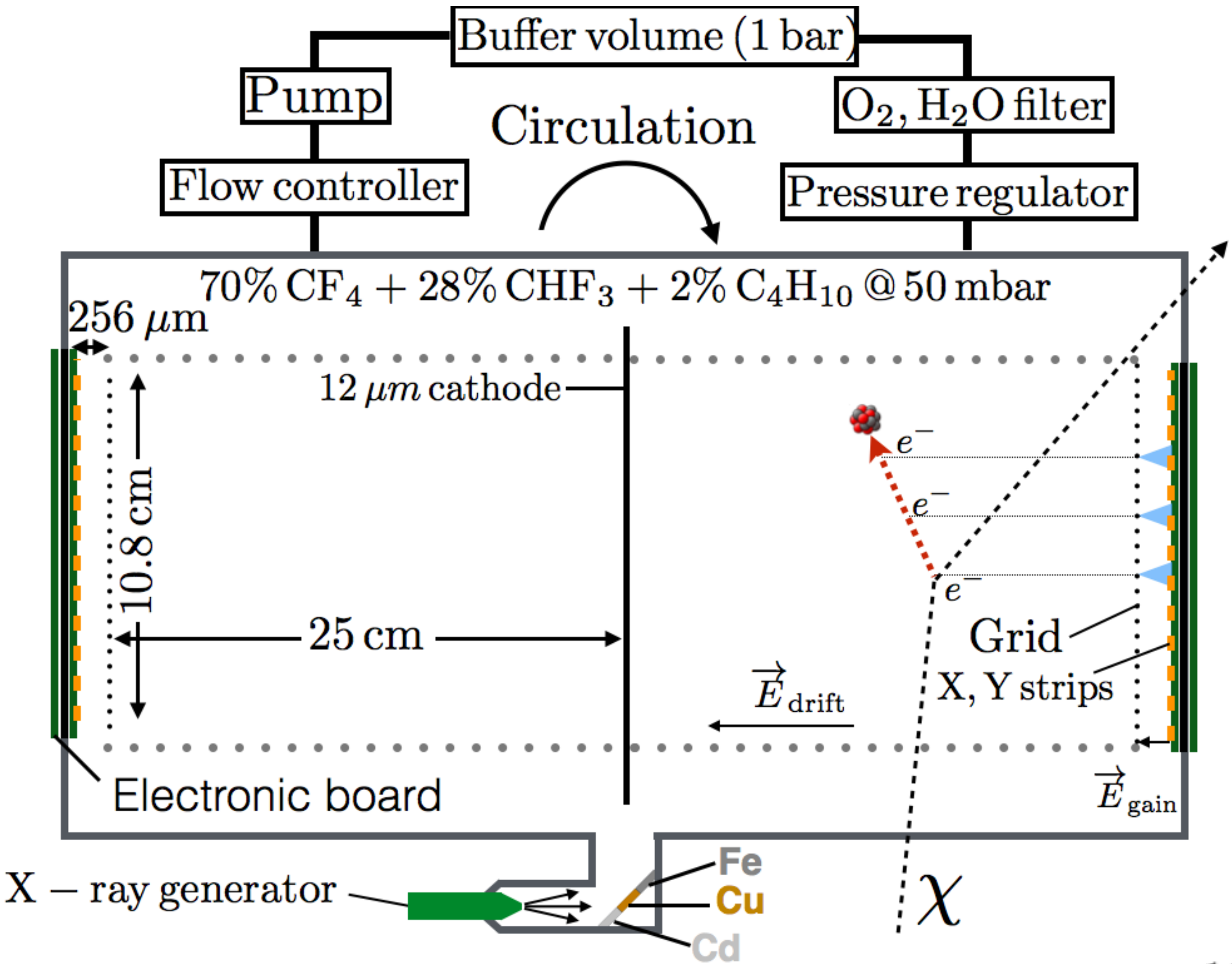


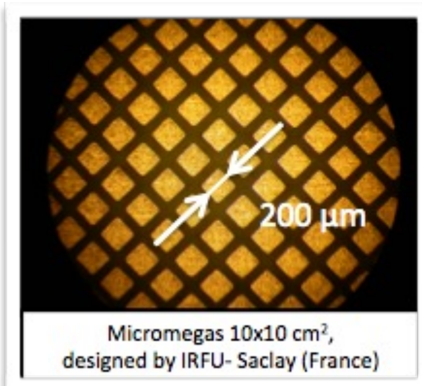


Only possible having the Ionization quenching factor measurements…



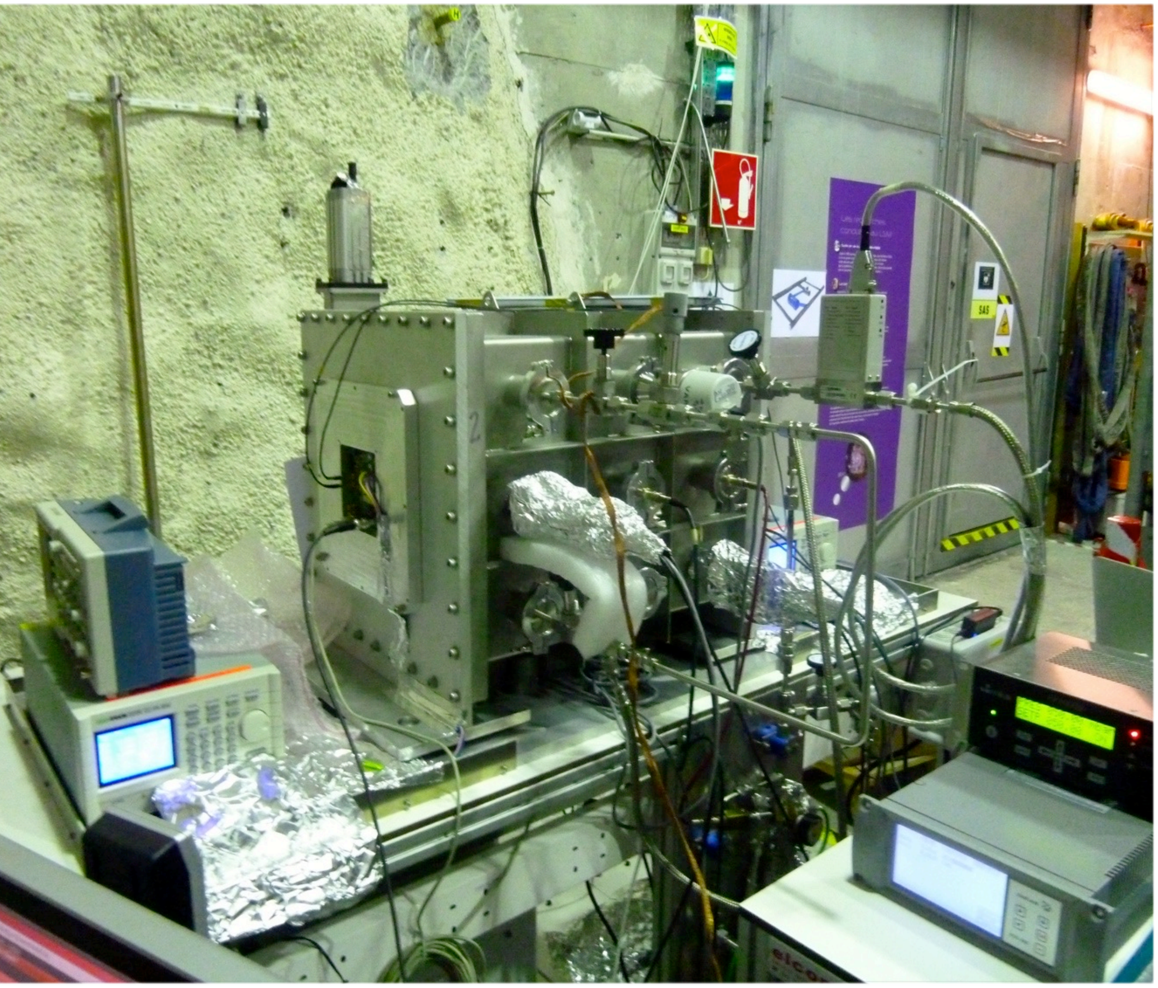
MIMAC-bi-chamber module prototype





MIMAC Target: ^{19}F

- Light WIMP mass
- Axial coupling



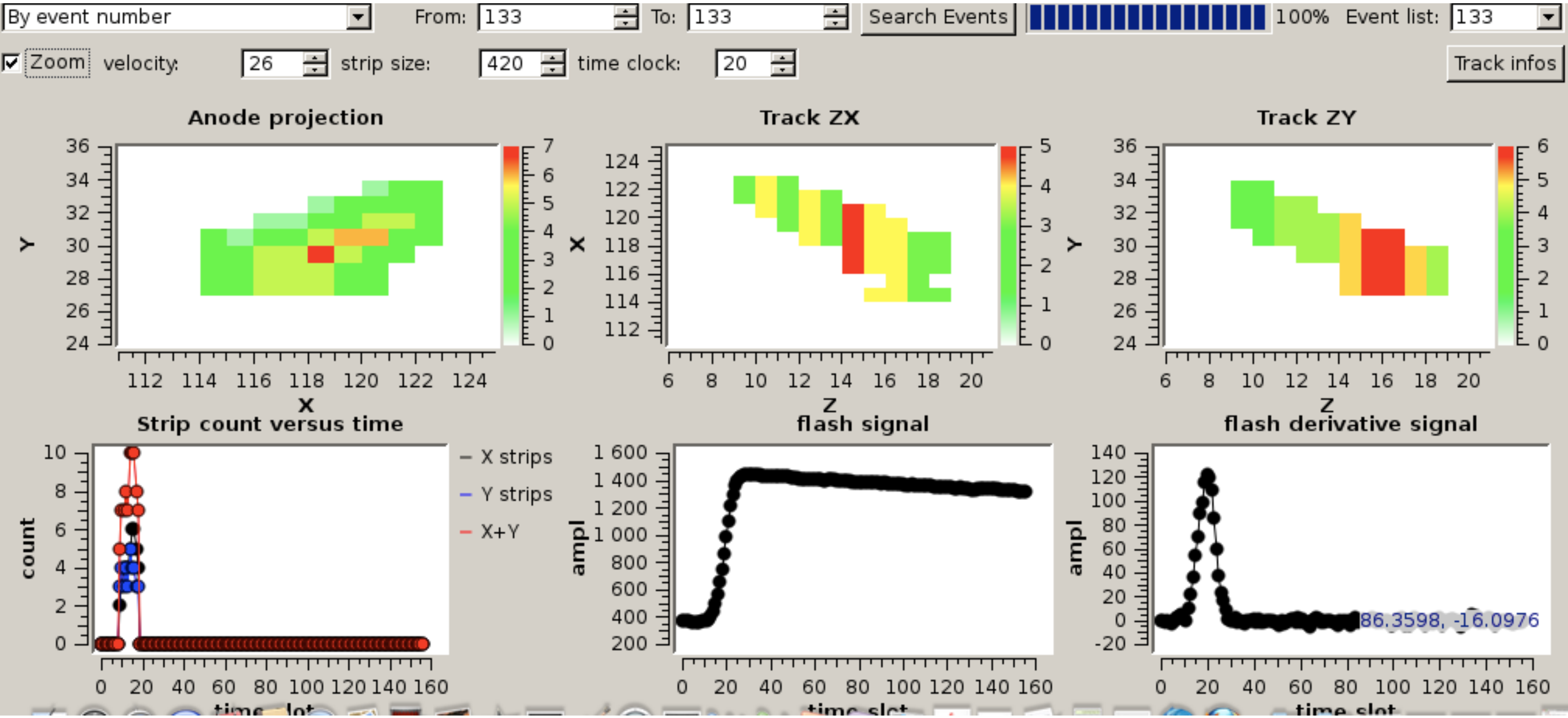
MIMAC (bi-chamber module)at Modane Underground Laboratory (France)
since June 22nd 2012.
Upgraded June 2013, and
June 2014 till February 2018

-working at 50 mbar
(CF_4+28% CHF_3 + 2% C_4H_{10})

-in a permanent circulating mode
-Remote controlled
and commanded
-Calibration control twice per week

Since then upgraded with new detectors and with the Cathode signal. Reinstall at LSM in 09/22

A "very interesting recoil event" (~ 34 keVee)



Radon Progeny

^{222}Rn chain:

- 4 β-decays

→ Electron event (background)

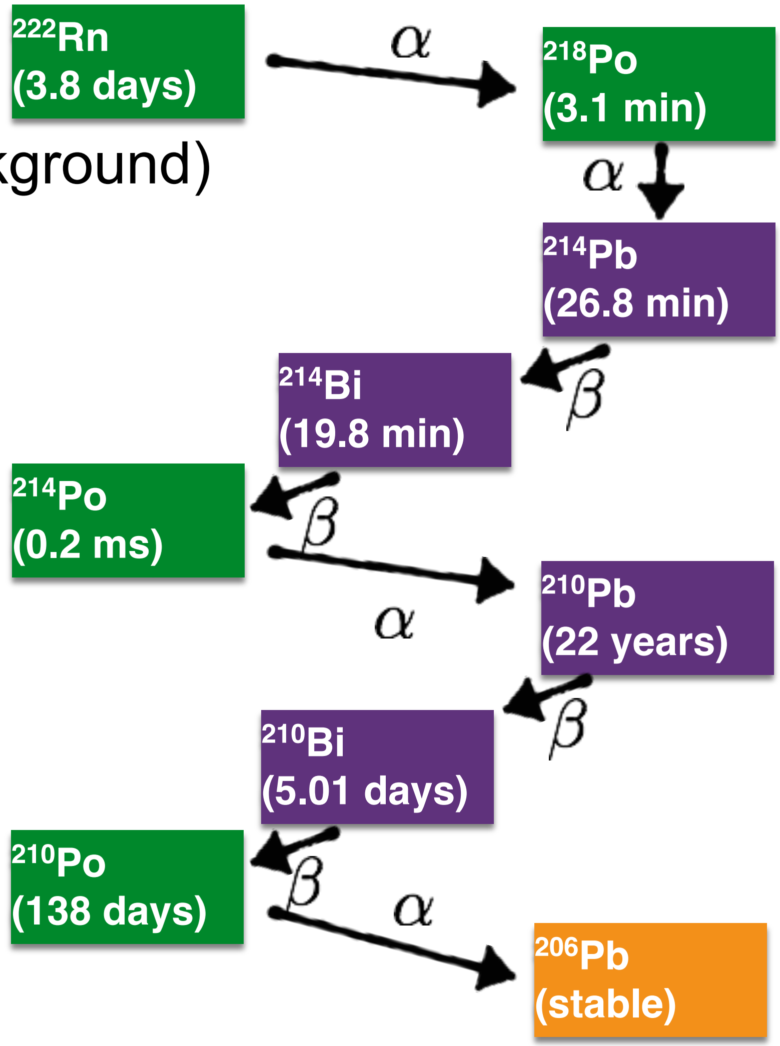
- 4 α-decays

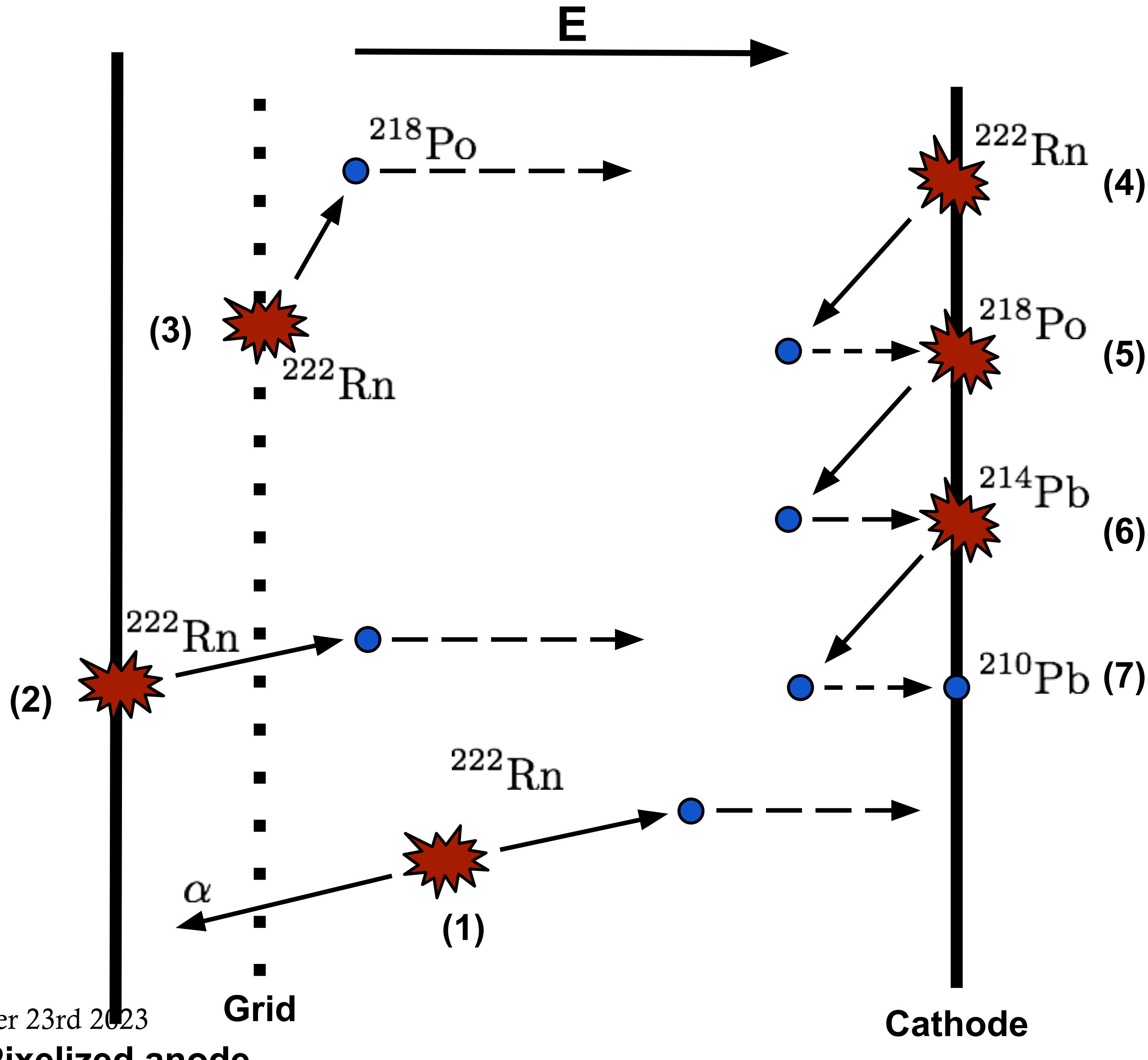
→ α-particle emission: $E_\alpha \sim 5\,\mathrm{MeV}$ → Saturation

→ Daughter nucleus recoil (surface event):

Parent	Daughter	E_{recoil}^{kin} [keV]	E_{recoil}^{ioni} [keV]
^{222}Rn	^{218}Po	100.8	38.23
^{218}Po	^{214}Pb	112.3	43.90
^{214}Po	^{210}Pb	146.5	58.78
^{210}Po	^{206}Pb	103.1	39.95

Simulation (SRIM)

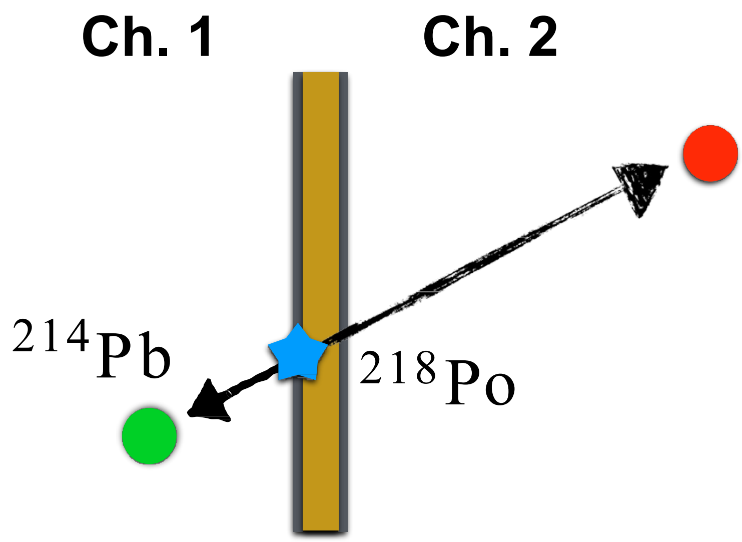


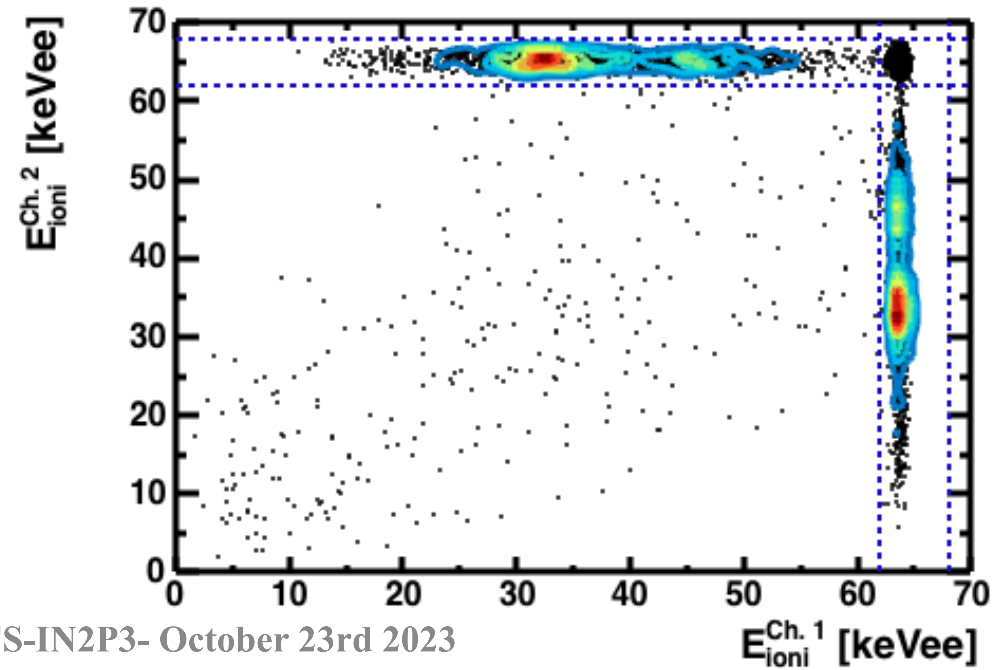


D. Santos (LPSC Grenoble)

RPR: « In coincidence » events

Chamber coincidences:





3D tracks from nuclear recoil of radon progeny detection

First detection of 3D tracks of Rn progeny

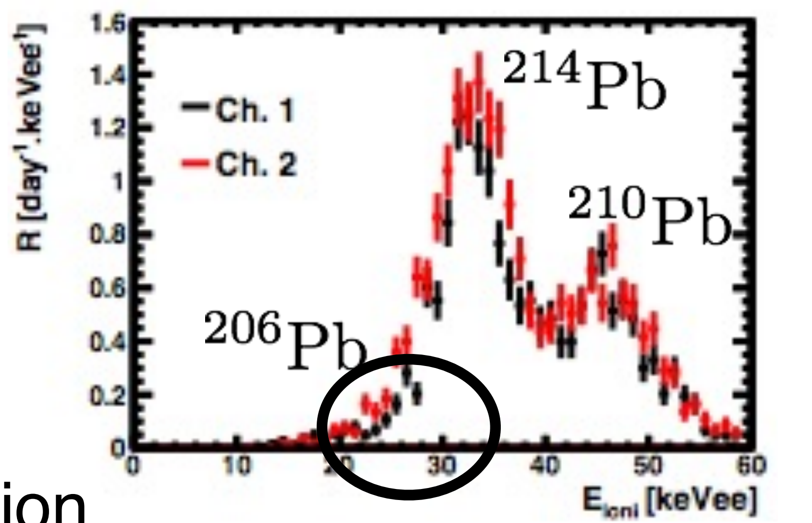
Electron/recoil discrimination

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

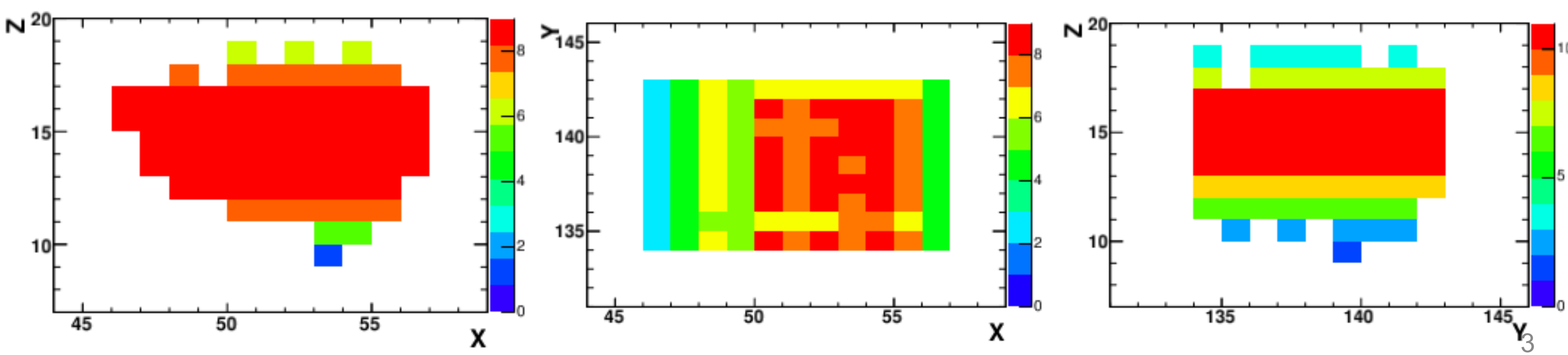
First measurement of 3D nuclear-recoil tracks coming from radon progeny

⟶ MIMAC detection strategy validation

Nuclear recoil spectra



$R_{^{206}\mathrm{Pb}} \sim 0.25\,\mathrm{day}^{-1}.\mathrm{keVee}^{-1}$

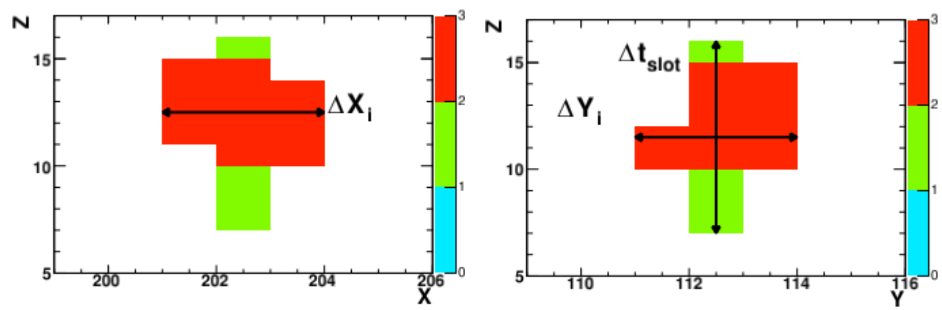


RPR events occur at different positions in the detector…

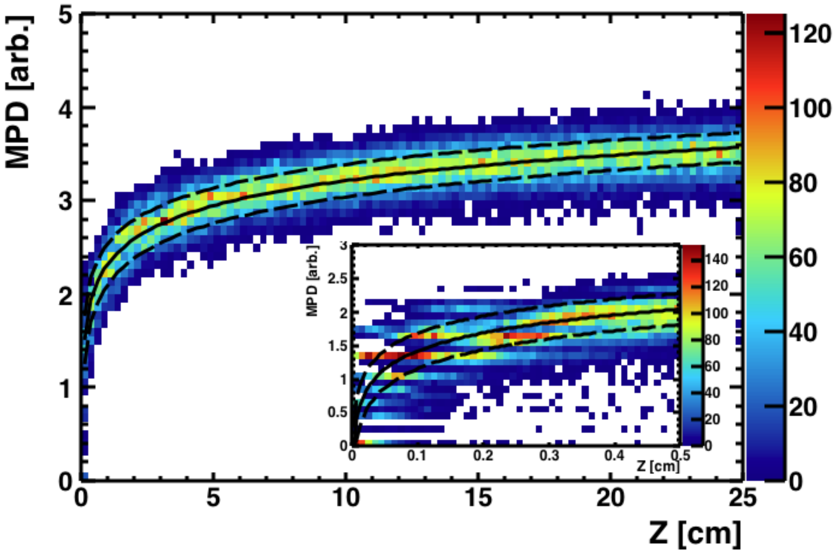
$$z_0 \longleftrightarrow \text{Diffusion}$$

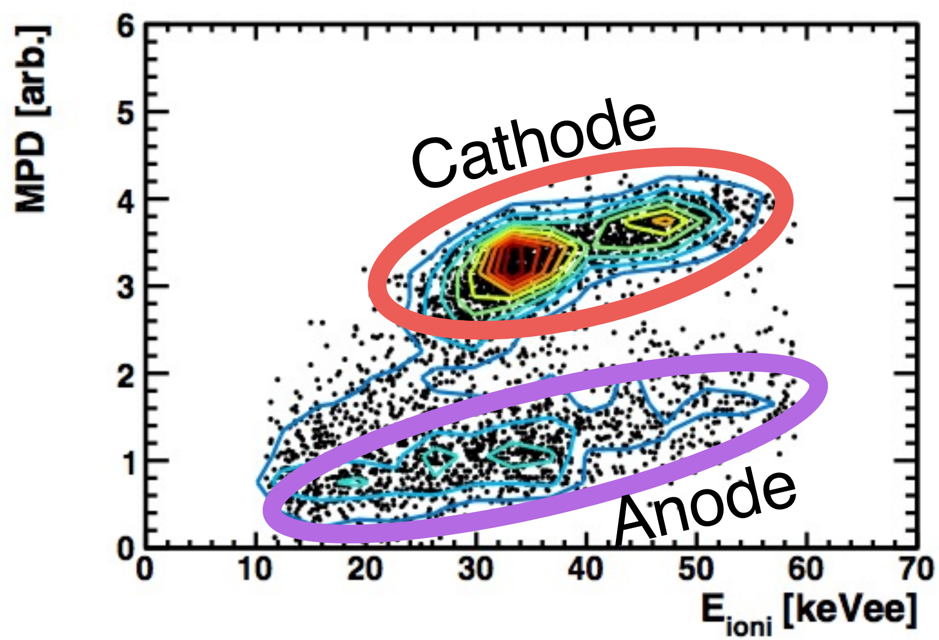
$$\begin{cases} D_T = 237.9\,\mu\text{m}/\sqrt{\text{cm}} \\ D_L = 271.5\,\mu\text{m}/\sqrt{\text{cm}} \end{cases}$$

« Grid » event



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

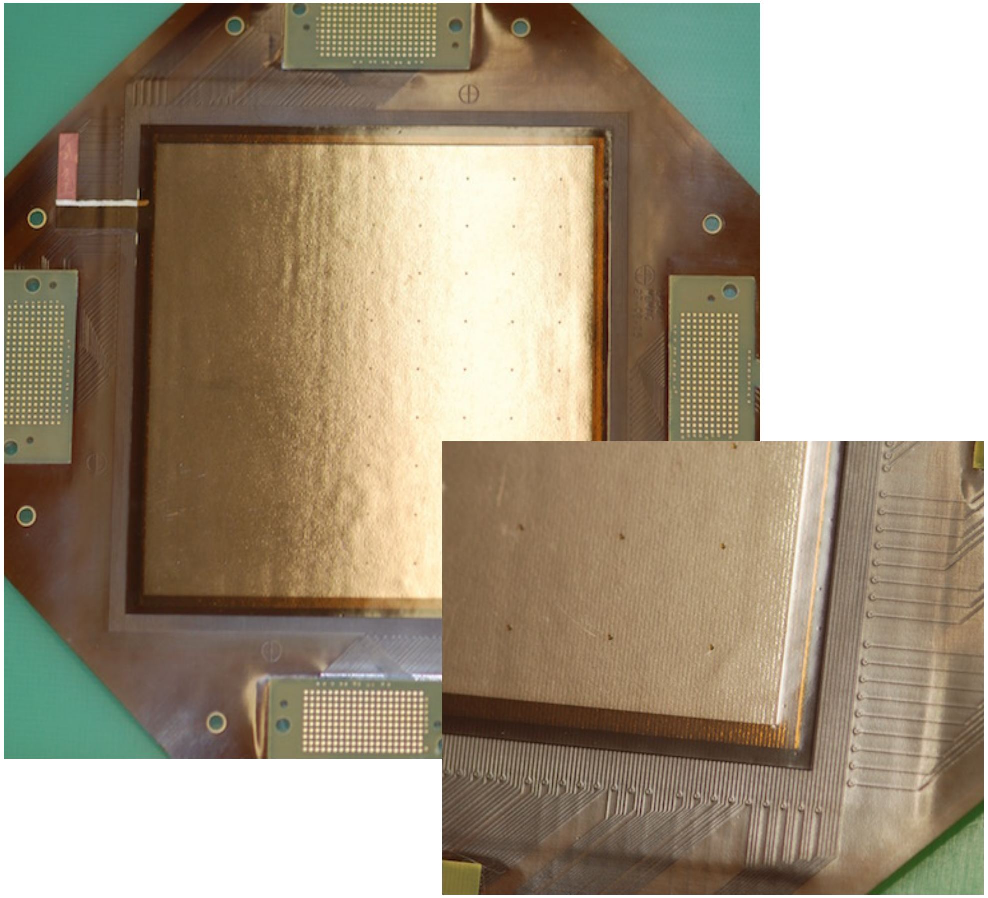


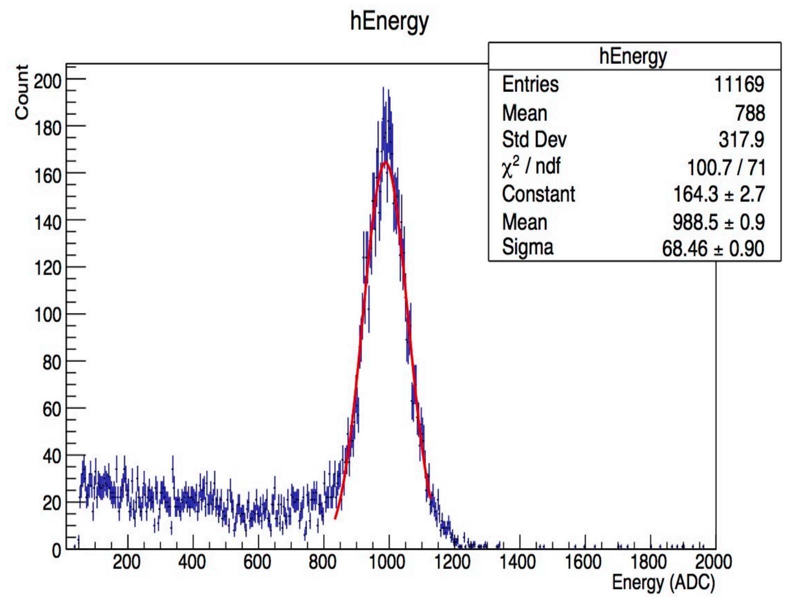


Bi-chamber-512 module
(with the Cathode Signal and
the new low background 10 cm detectors)
installed in february 2023

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

New MIMAC low background detector





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

Kapton micromegas readout
Piralux Pilar

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

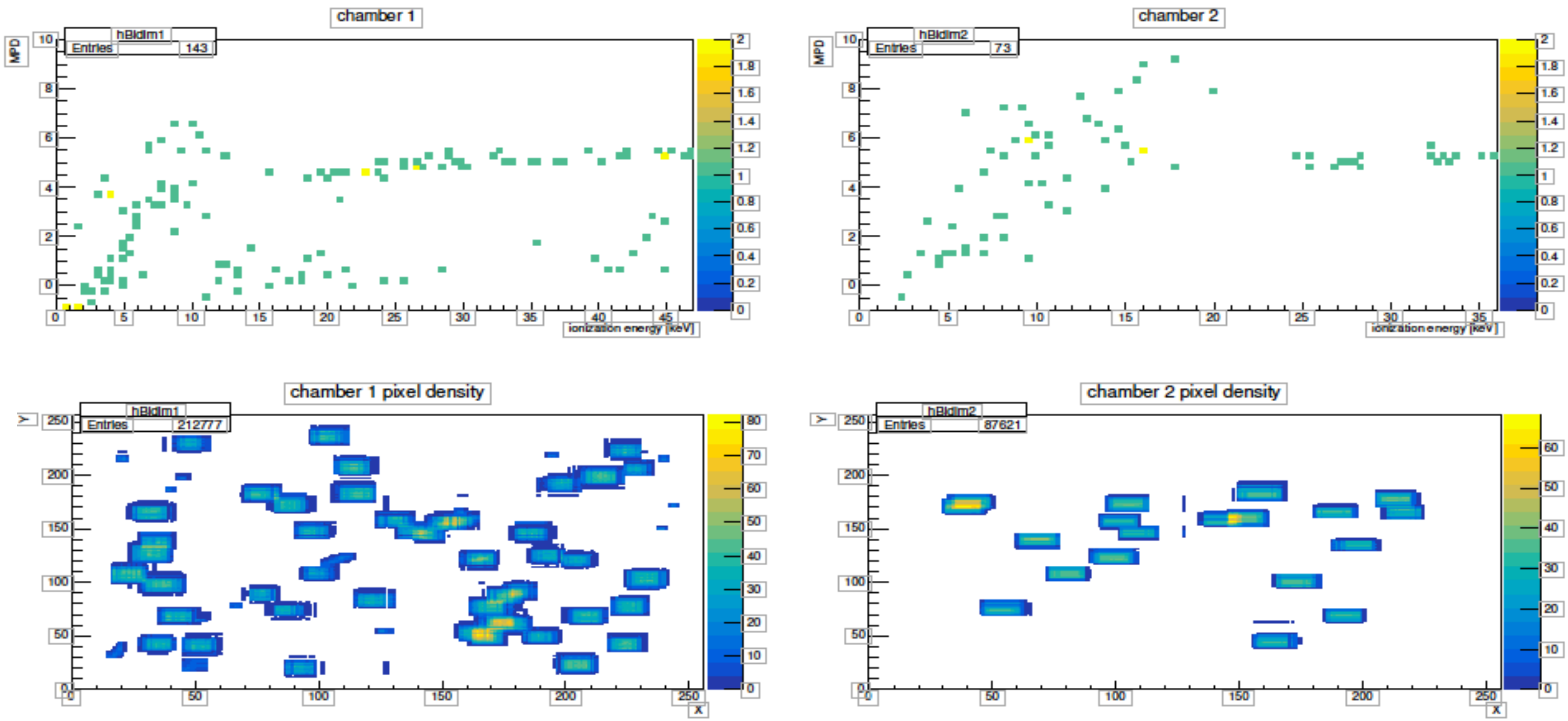
The first physics run of the Bi-chamber in february 2023 at Modane

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.

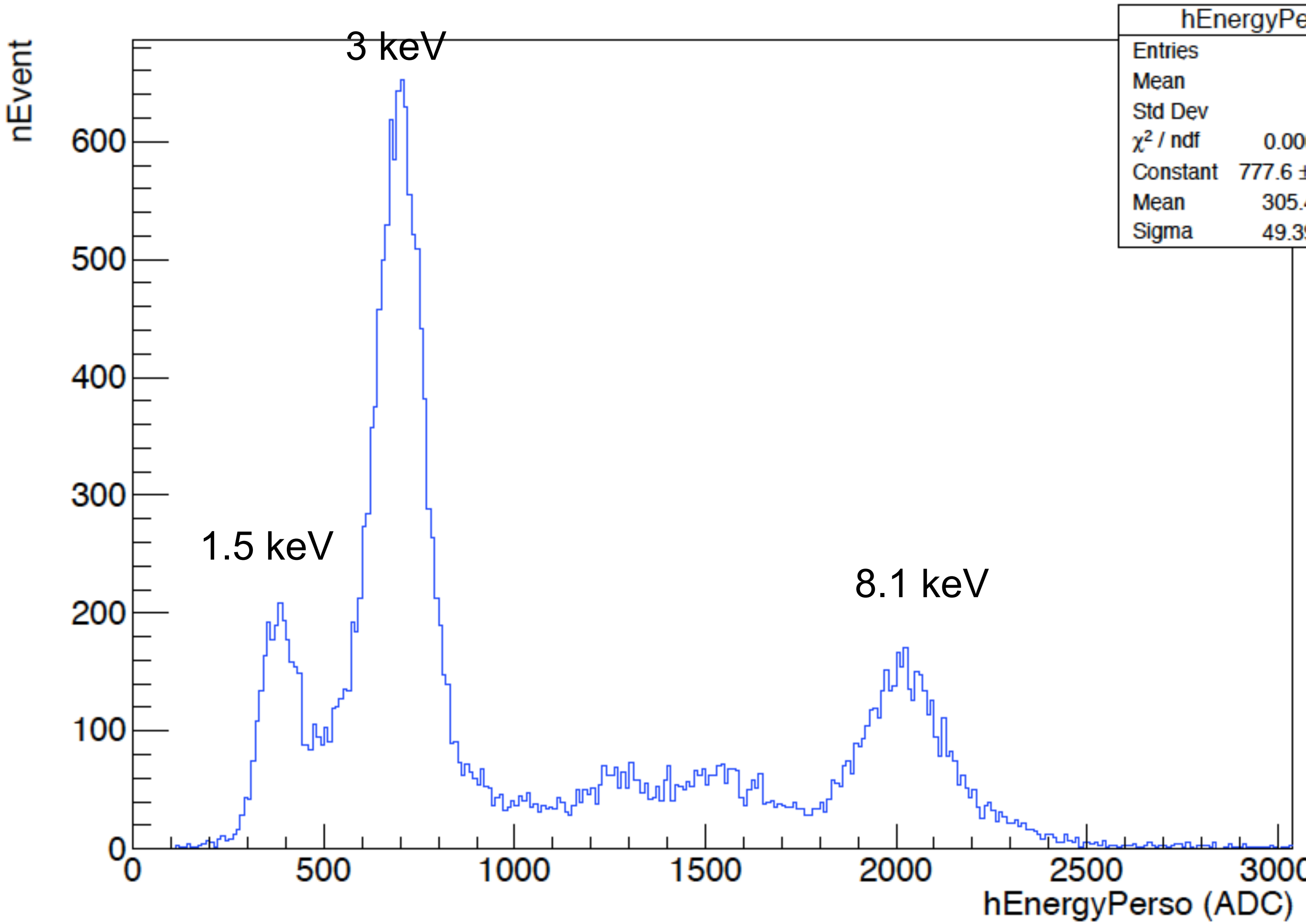
Improvement of the new detector showing very few Rn progeny contributions



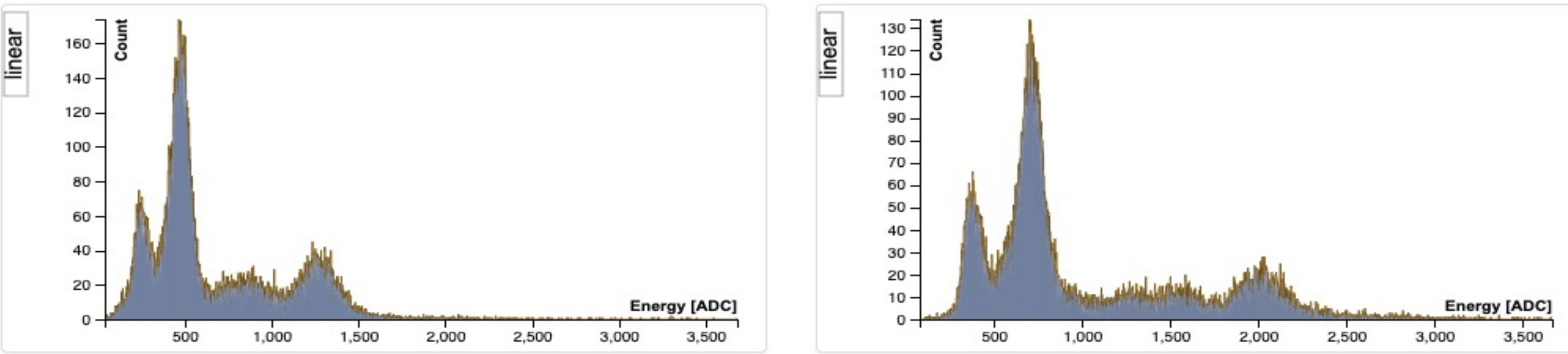
(a) In chamber 1. (b) In chamber 2.

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

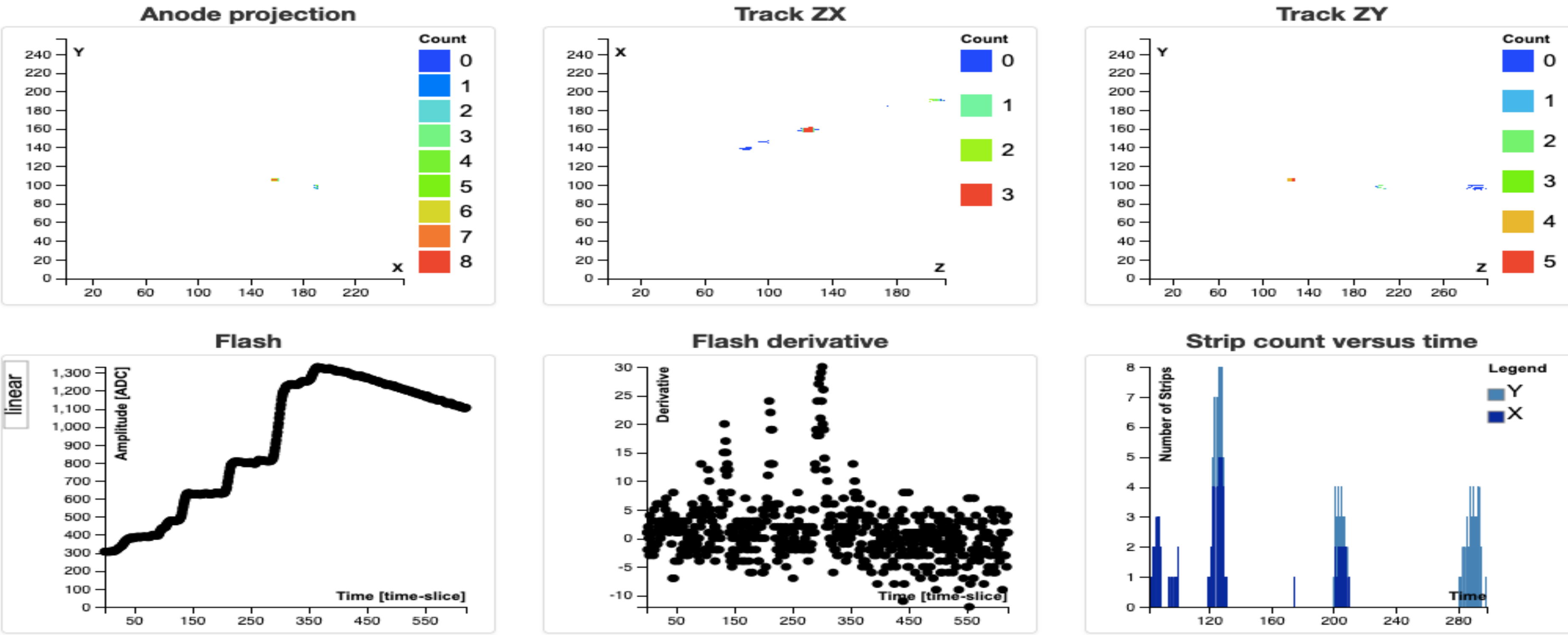
X-ray Calibration of the new detector Bi-chamber Module at 500 V, 3000V drift



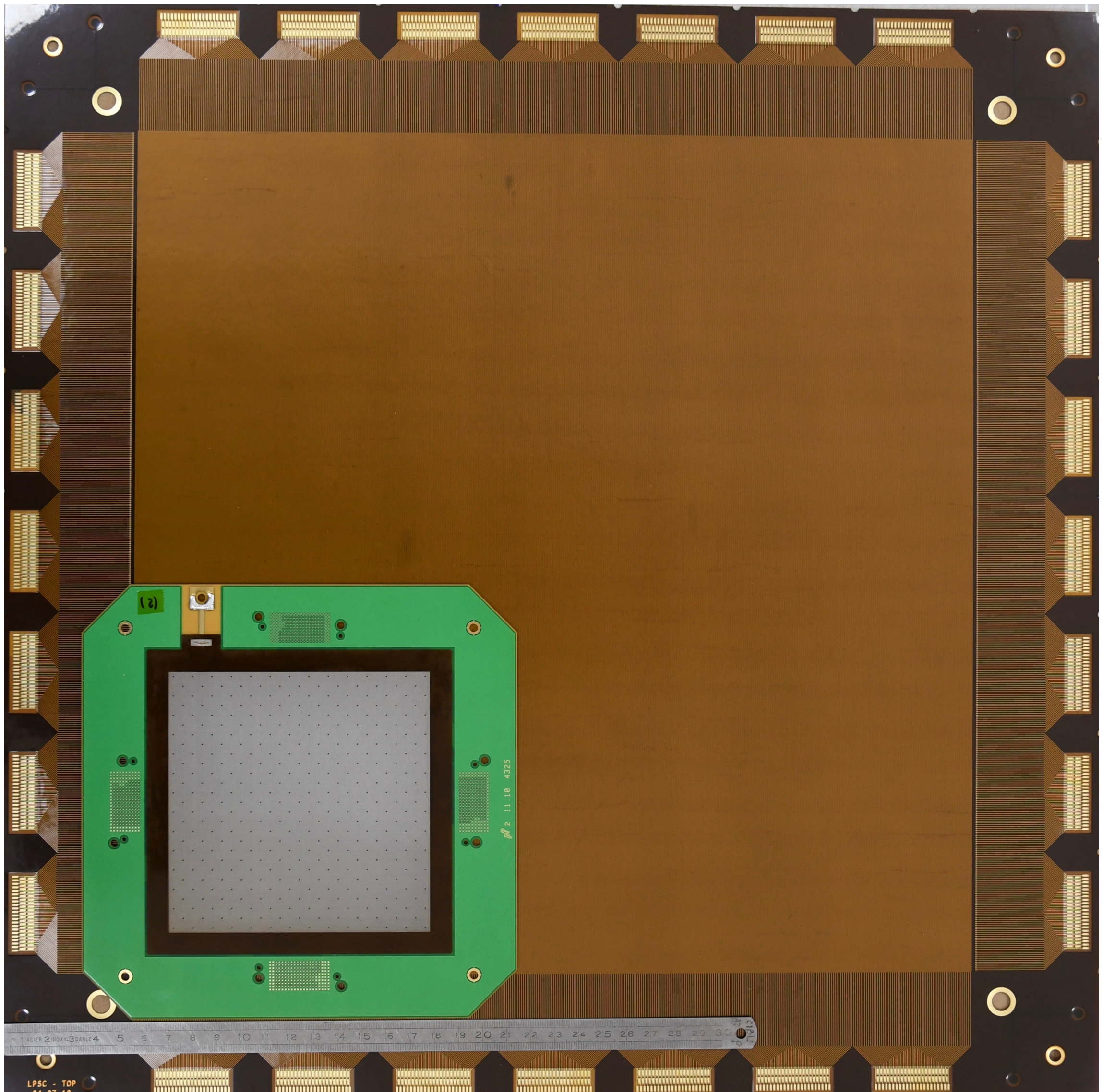
X-ray calibration of both chambers simultaneously

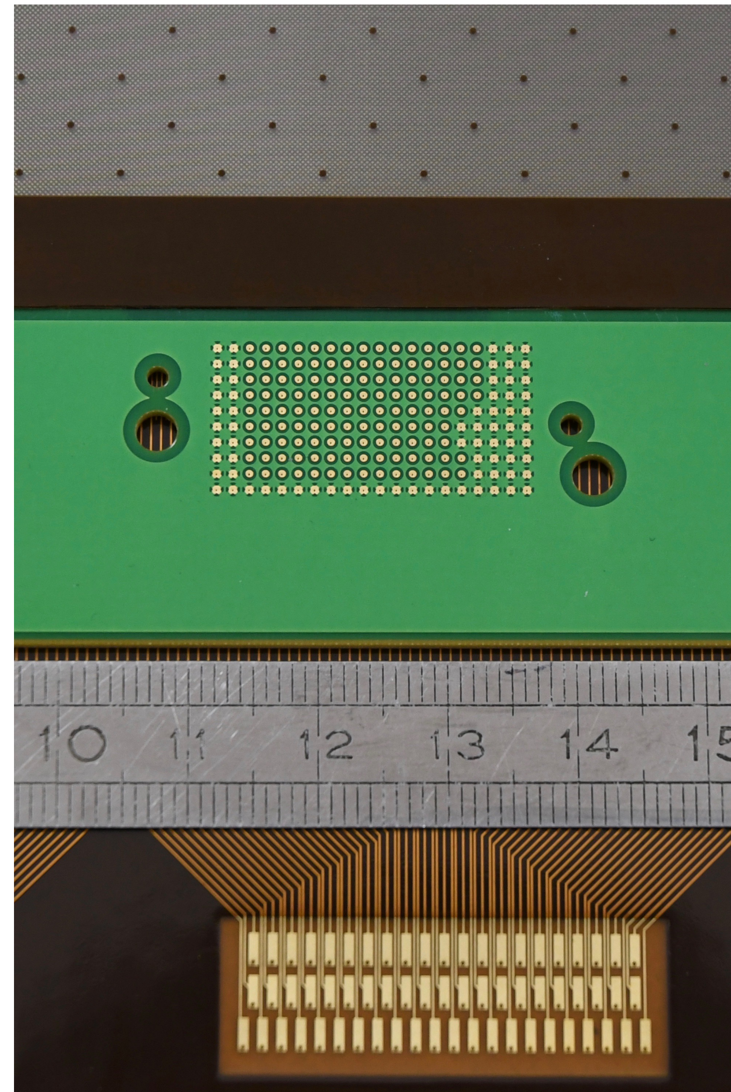


A typical electron event in the chamber 2



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

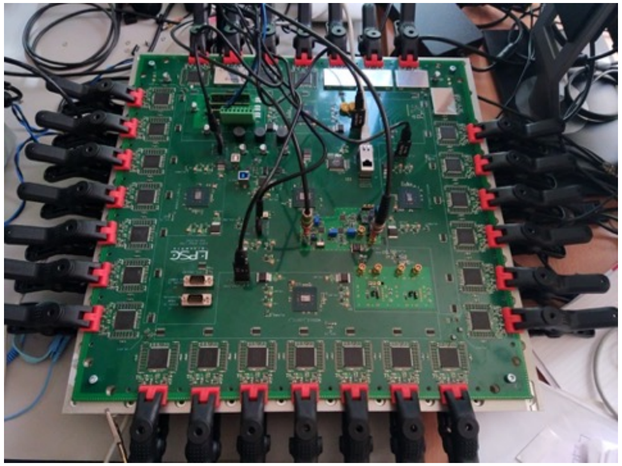


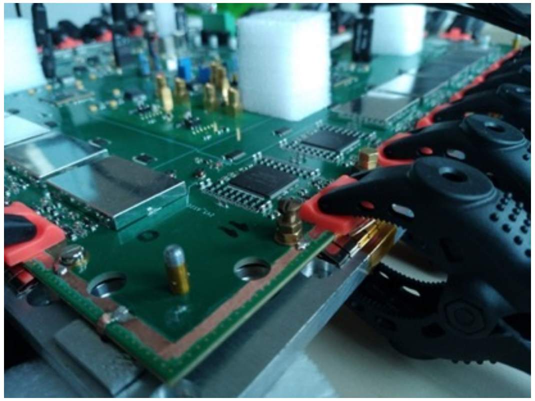


TRAVAUX RÉALISÉS

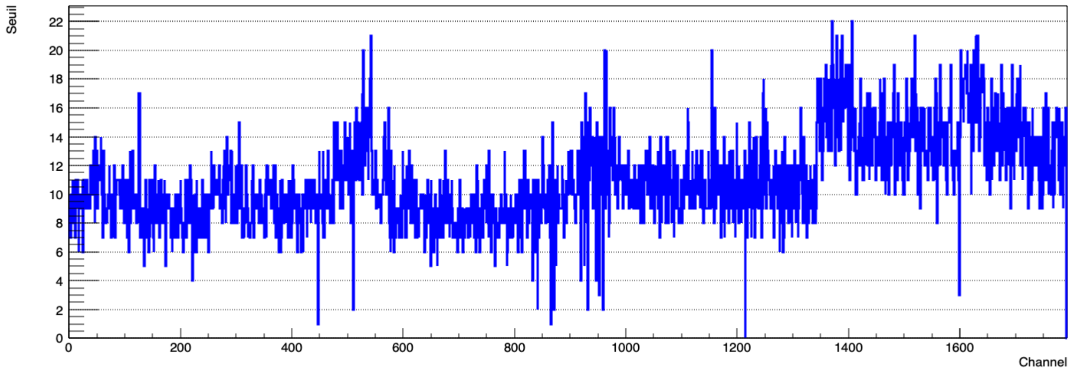
Fonctionnement de la carte électronique sur table seule	✓
Couplage de la carte électronique avec le détecteur 35 x 35 cm, sur table	✓

- Synchronisation des ASIC et des FPGA,
- Programmation des FPGA,
- Soft de reconstruction des pistes (nouveau routage carte+détecteur),
- Adaptation soft d'acquisition pour tests, et intégration protocole Ethernet,
- Résolution de problématiques CEM (blindages, conductivité entre les masses,…)
- Caractérisation du bruit électronique intrinsèque,
- Tests de déclenchement sur événement simulé.



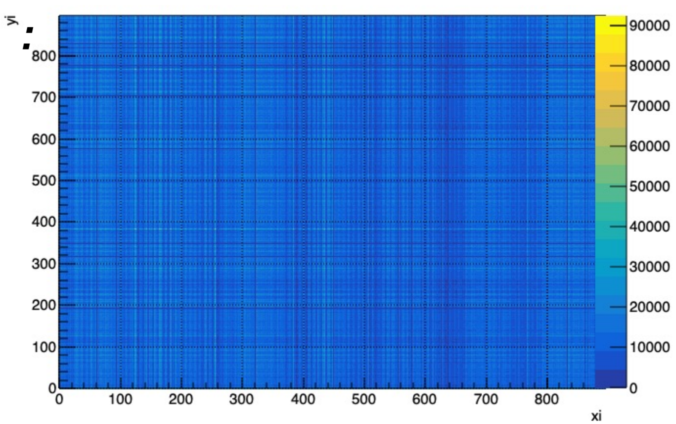


Valeurs des seuils de déclenchement des pistes, issues des mesures de bruit après travail CEM (autocalibration) :

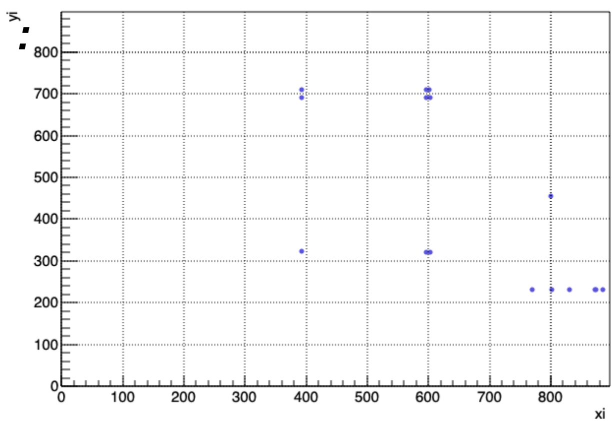


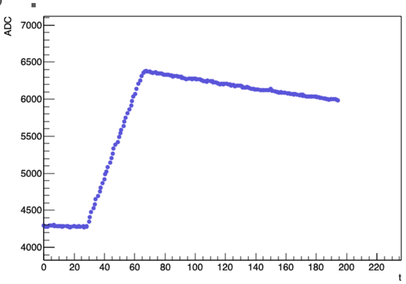
Déclenchement des pistes pendant l'acquisition de 4000 signaux de 600 ns :

***Avant** autocalibration*



***Après** autocalibration*



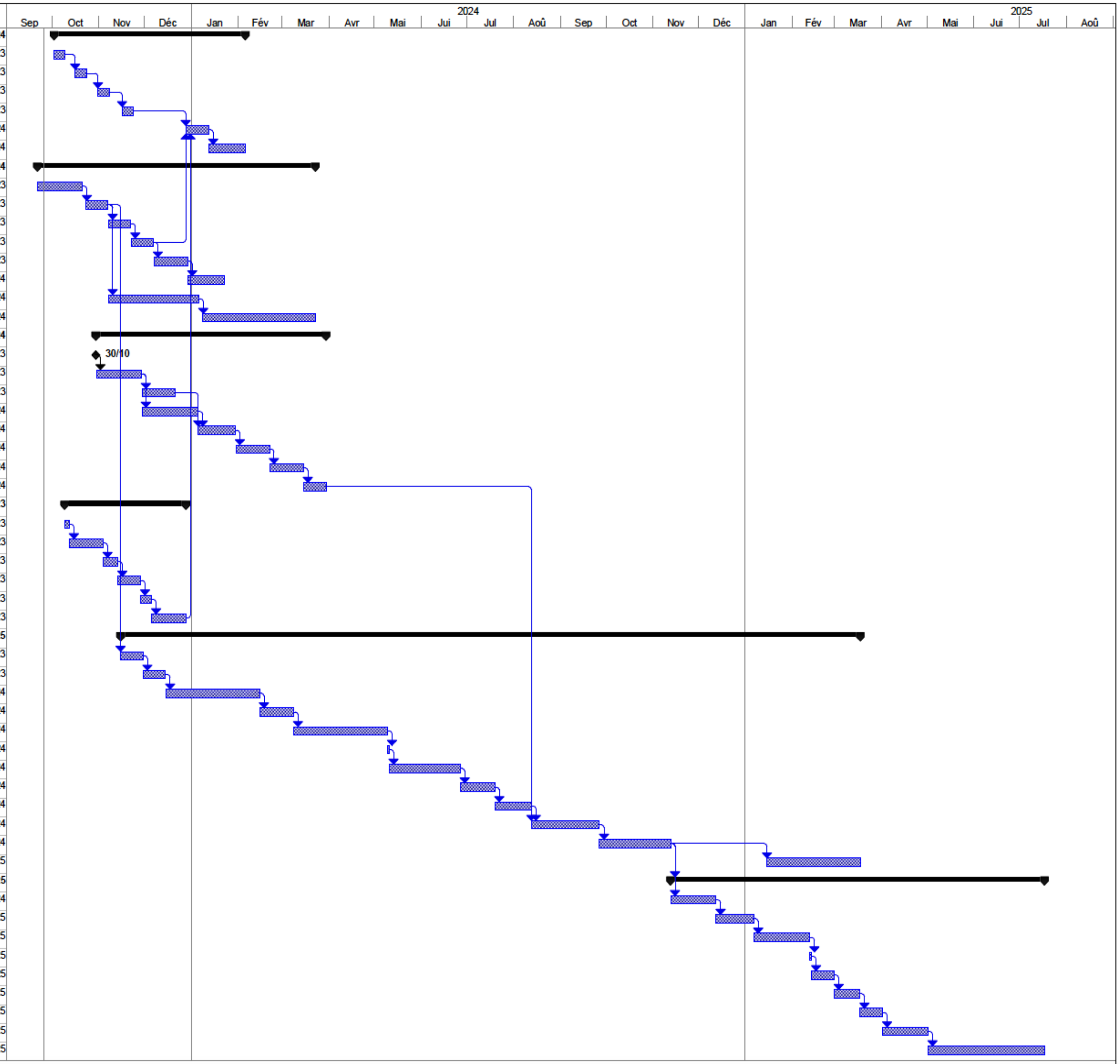


Signal injecté

→ Prochaine étape : tests avec de vrais événements

The different tasks foreseen in the next two years between the LPSC and the Chinese partners.

N°	Nom de la tâche	Durée	Début	Fin
1	**Prototypage Détecteur PCB 35x35 cm**	**82,55 jours?**	**Lun 02/10/23**	**Lun 05/02/24**
2	Collage interface rigide	5 jours	Lun 02/10/23	Lun 09/10/23
3	Reprise plaque de fermeture	5 jours?	Lun 16/10/23	Lun 23/10/23
4	Montage sur Bichambre	5 jours	Mar 31/10/23	Mar 07/11/23
5	Test d'étanchéité	5 jours	Jeu 16/11/23	Jeu 23/11/23
6	Test sous gaz (30 mbar à 1 bar)	10 jours	Jeu 28/12/23	Ven 12/01/24
7	Mesure du gain (stabilité, homogénéité,...)	15 jours	Ven 12/01/24	Lun 05/02/24
8	**Mise au point carte 1792 voies**	**120 jours?**	**Jeu 21/09/23**	**Ven 22/03/24**
9	Réglage des seuils et réduction bruit	20 jours?	Jeu 21/09/23	Ven 20/10/23
10	Test de déclenchement sur table	10 jours	Lun 23/10/23	Lun 06/11/23
11	Montage mecanique sur détecteur	10 jours?	Mar 07/11/23	Mar 21/11/23
12	Test connectique et HT	10 jours	Mer 22/11/23	Mer 06/12/23
13	Test PAC sur Carte	15 jours	Jeu 07/12/23	Ven 29/12/23
14	Mesure du bruit de fond en cosmique et avec sources	15 jours?	Ven 29/12/23	Lun 22/01/24
15	Appro composant Carte 2	40 jours?	Mar 07/11/23	Ven 05/01/24
16	Cablage carte 1792 voie n° 2	50 jours?	Lun 08/01/24	Ven 22/03/24
17	**Alimentation HT et BT**	**100 jours**	**Lun 30/10/23**	**Ven 29/03/24**
18	Finalisation de la conception de la carte	0 jour	Lun 30/10/23	Lun 30/10/23
19	Routage PCB	20 jours	Lun 30/10/23	Mar 28/11/23
20	Fabrication PCB	15 jours	Mer 29/11/23	Jeu 21/12/23
21	Appro composants	25 jours	Mer 29/11/23	Ven 05/01/24
22	Cablage Carte	15 jours	Ven 05/01/24	Lun 29/01/24
23	Test sur table	15 jours	Mar 30/01/24	Mer 21/02/24
24	Mise en boitier	15 jours	Mer 21/02/24	Jeu 14/03/24
25	Tests finaux	10 jours	Ven 15/03/24	Ven 29/03/24
26	**Cage de champ et connectique 40x40**	**53 jours**	**Lun 09/10/23**	**Jeu 28/12/23**
27	Mise en plan de la structure cage de champ	3 jours	Lun 09/10/23	Jeu 12/10/23
28	Commande et réception pièces	15 jours	Jeu 12/10/23	Ven 03/11/23
29	Soudure composant cages de champ	5 jours	Ven 03/11/23	Lun 13/11/23
30	Collage cathode Mylar	10 jours	Lun 13/11/23	Mar 28/11/23
31	Montage / Intégration	5 jours	Mar 28/11/23	Mar 05/12/23
32	Tests HT sous gaz	15 jours	Mar 05/12/23	Jeu 28/12/23
33	**Prototypage Détecteur Bas Bruit 35x35 cm (Chine)**	**317,27 jours?**	**Mer 15/11/23**	**Lun 17/03/25**
34	Fabrication des Kapton à la dimension	10 jours?	Mer 15/11/23	Mer 29/11/23
35	Collage des Kapton sur semelle Cuivre	10 jours	Jeu 30/11/23	Jeu 14/12/23
36	Contrôle dimensionnel (aller retour Chine)	40 jours?	Ven 15/12/23	Mer 14/02/24
37	Dépôt resistifs (Ge)	15 jours	Jeu 15/02/24	Ven 08/03/24
38	Collage grille	40 jours?	Ven 08/03/24	Jeu 09/05/24
39	Récepetion prototype Bas bruit	1 jour?	Jeu 09/05/24	Ven 10/05/24
40	Collage sur interface rigide (Alu)	30 jours	Ven 10/05/24	Mer 26/06/24
41	Test connectique	15 jours	Mer 26/06/24	Ven 19/07/24
42	Test détanchéité	15 jours	Ven 19/07/24	Lun 12/08/24
43	Test de fonctionnement (Grenoble LPSC)	30 jours	Lun 12/08/24	Jeu 26/09/24
44	Comparatif PCB / Bas Bruit	30 jours?	Jeu 26/09/24	Mar 12/11/24
45	Test de fonctionnement Modane	40 jours?	Mer 15/01/25	Lun 17/03/25
46	**Fabrication lot Détecteur Bas bruit (Chine)**	**161 jours?**	**Mar 12/11/24**	**Jeu 17/07/25**
47	Fabrication des Kapton	20 jours	Mar 12/11/24	Jeu 12/12/24
48	Collage Kapton Sur semelle Cuivre	15 jours	Jeu 12/12/24	Lun 06/01/25
49	Réalisation des Bulk	25 jours	Lun 06/01/25	Mer 12/02/25
50	Réception détecteurs Bas Bruit	1 jour?	Mer 12/02/25	Jeu 13/02/25
51	Collage sur interface rigide (Alu)	10 jours	Jeu 13/02/25	Ven 28/02/25
52	Test connectique	10 jours	Ven 28/02/25	Lun 17/03/25
53	Test détanchéité	10 jours	Lun 17/03/25	Mar 01/04/25
54	Test de fonctionnement (Grenoble LPSC)	20 jours	Mar 01/04/25	Jeu 01/05/25
55	Test Fonctionnement (Modane LSM)	50 jours	Jeu 01/05/25	Jeu 17/07/25

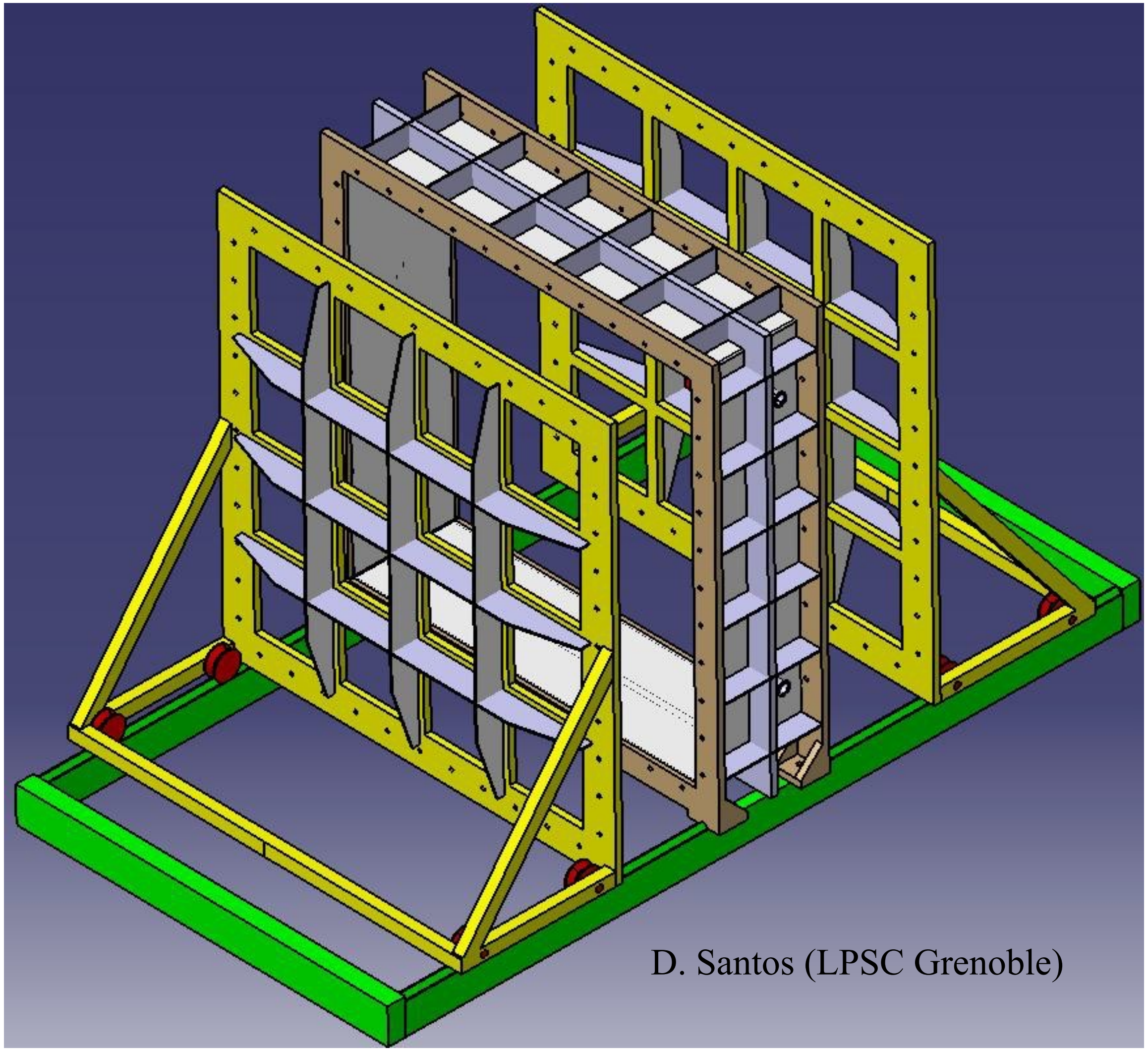


MIMAC – $1m^3$ = 16 bi-chamber modules (2x 35x35x26 cm^3)

New technology anode 35cmx35cm

New electronic board (1792 channels)

Only one big chamber



D. Santos (LPSC Grenoble)

MIMAC (MIcro-tpc MAtrix of Chambers)

LPSC (Grenoble) : D. Santos, C. Beaufort (CDD), F.Naraghi

- 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
(spectroscopie neutronique métrologique)

Prototype hosted in **IHEP (Beijing-China)**: **ZhiminWang , Changgen Yang**
USTC (University of Science and Technology of China, Hefei) Zhiyong Wang

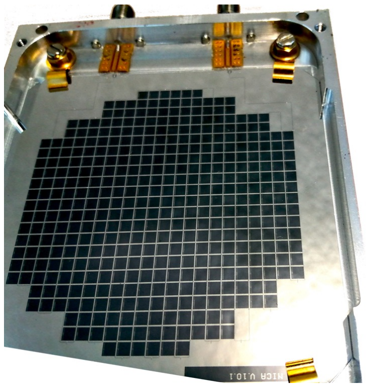
Conclusions

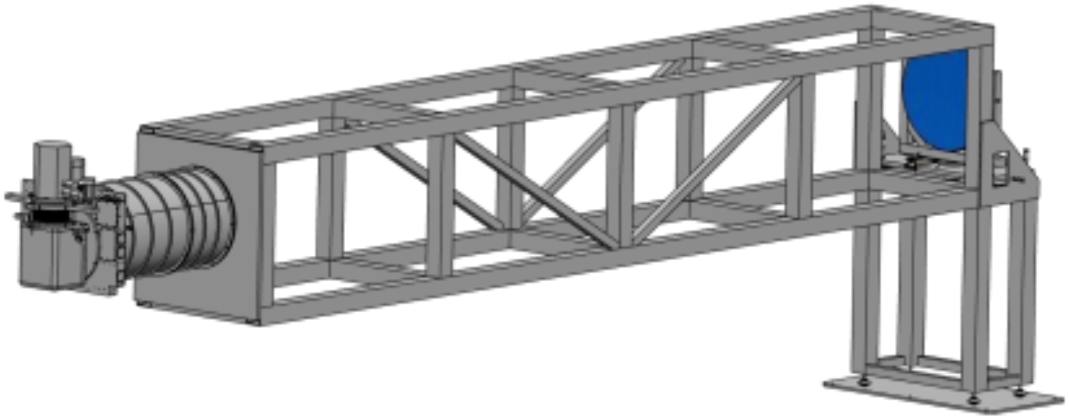
- **MIMAC** has opened new possibilities in the DM search and Neutron spectroscopy.
- At low energies giving a lot of flexibility on targets, pressure, energy range…
- Ionization quenching factor measurements have been determined experimentally showing an important differences with respect to simulations !
- 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 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 is not made of Wimps... The directional detection will also be needed to convince us that we understand what we've detected…**

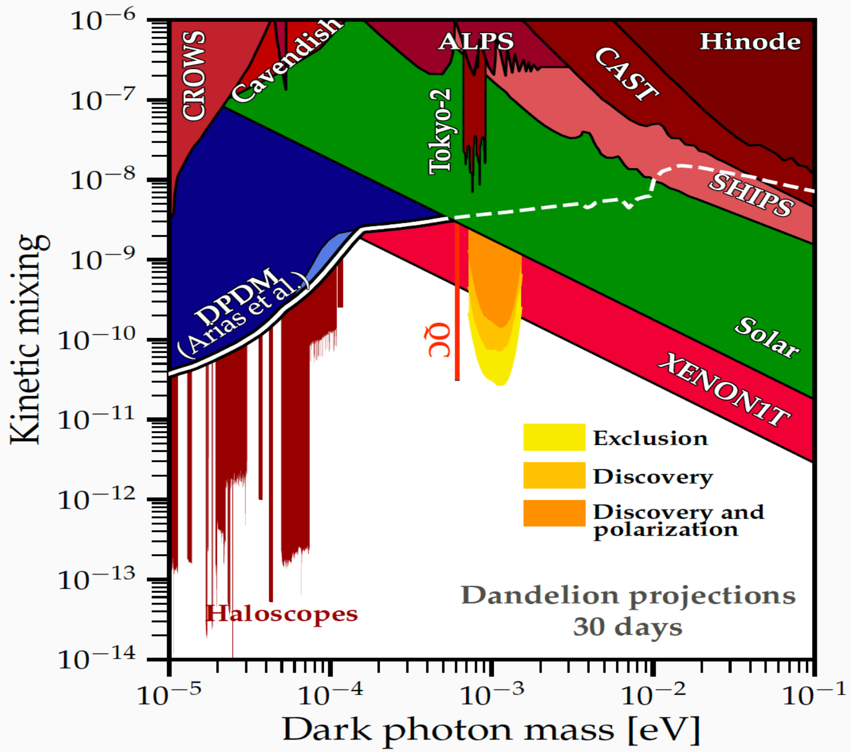
DArk photoN DirEctionaL detectION(Dandelion) at 1 meV

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:

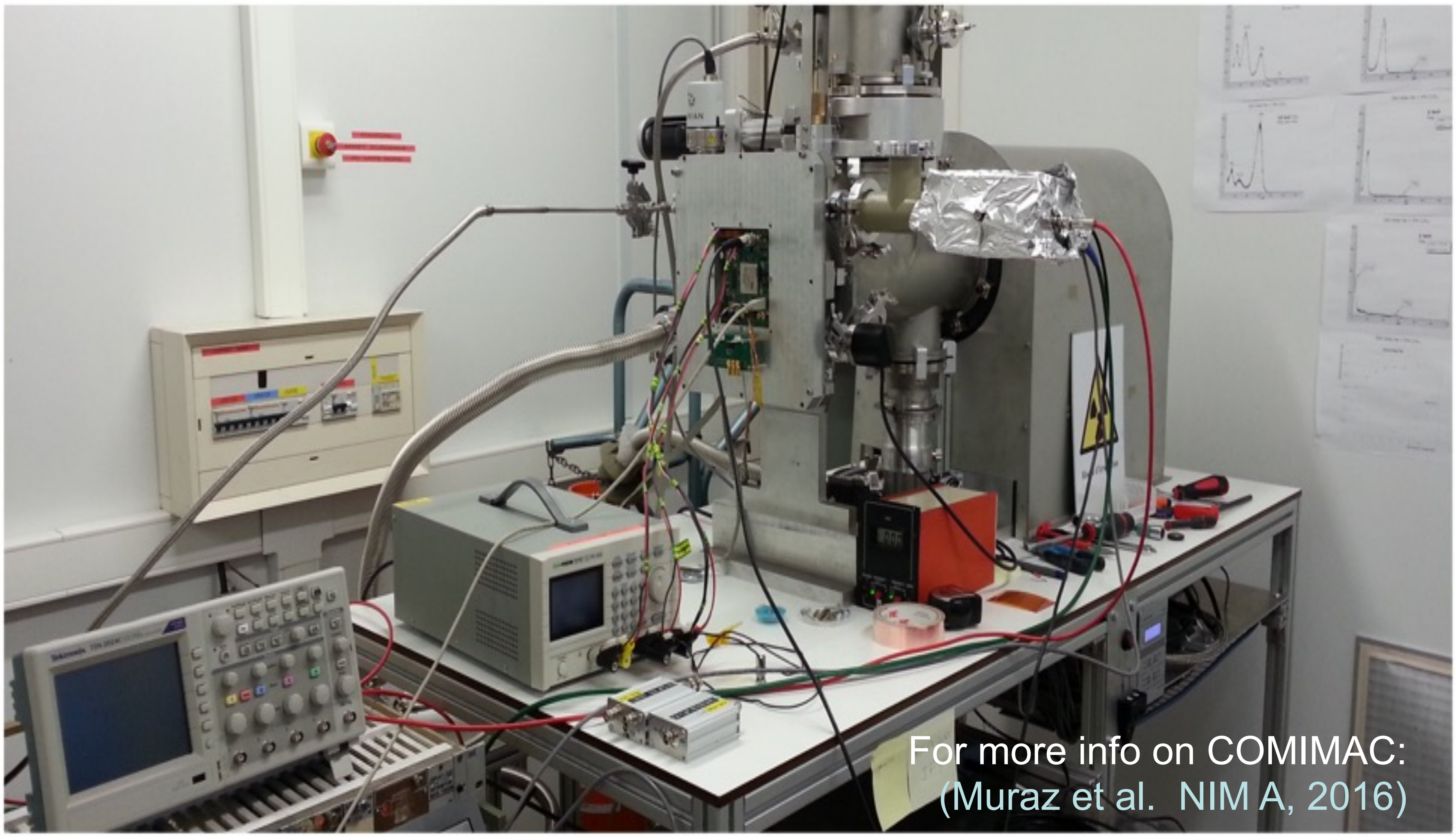
The directional detection leads to an **unprecedented discovery potential**

DISCOVERY AND POLARIZATION:

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

Preprint sent today to arXiv

First controlled Nuclear 3D tracks, using COMIMAC

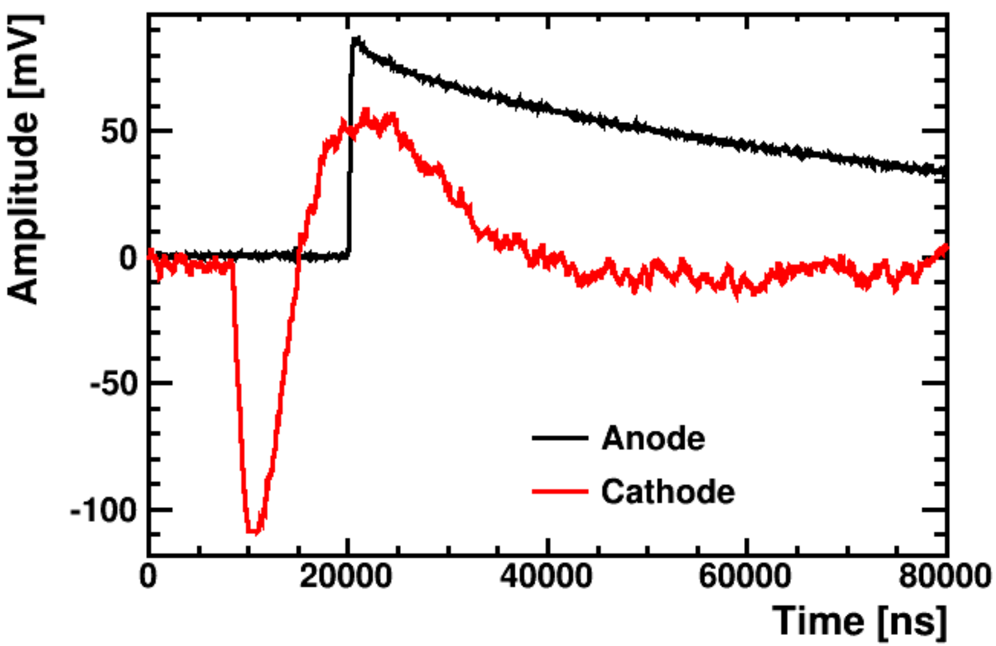


Directional experiments around the world

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)

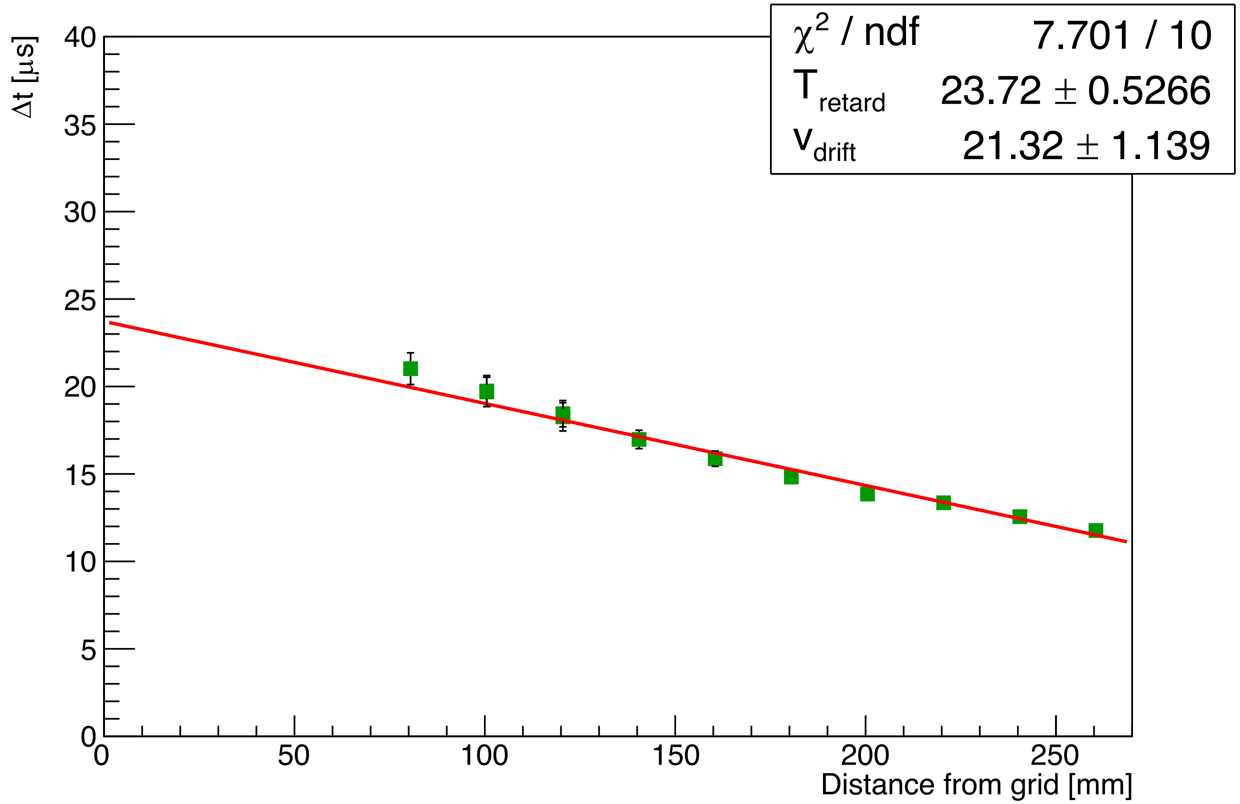
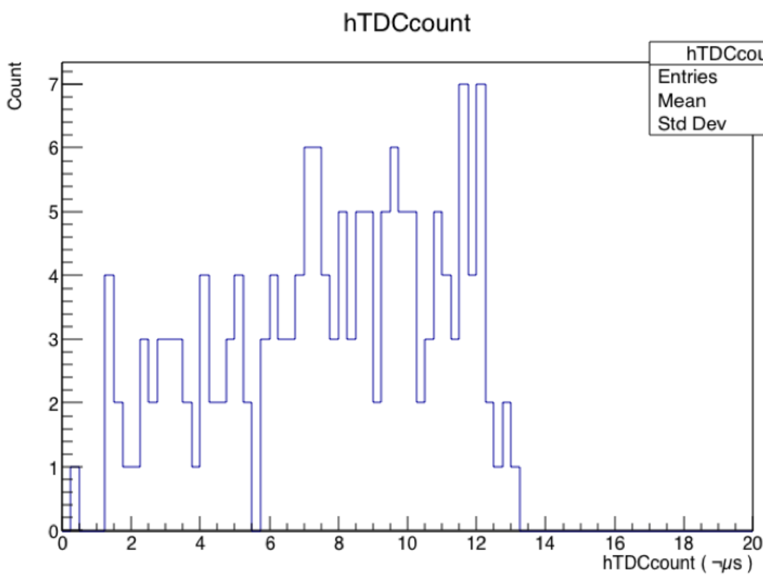


Figure 4. Measure of the time differences (TAC) between the grid signal and the delayed cathode signal in the "START Grid" configuration, as a function of the distance of the α source from the anode (green points) ; error bars correspond to the standard deviation of the mean. A linear fit of these points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

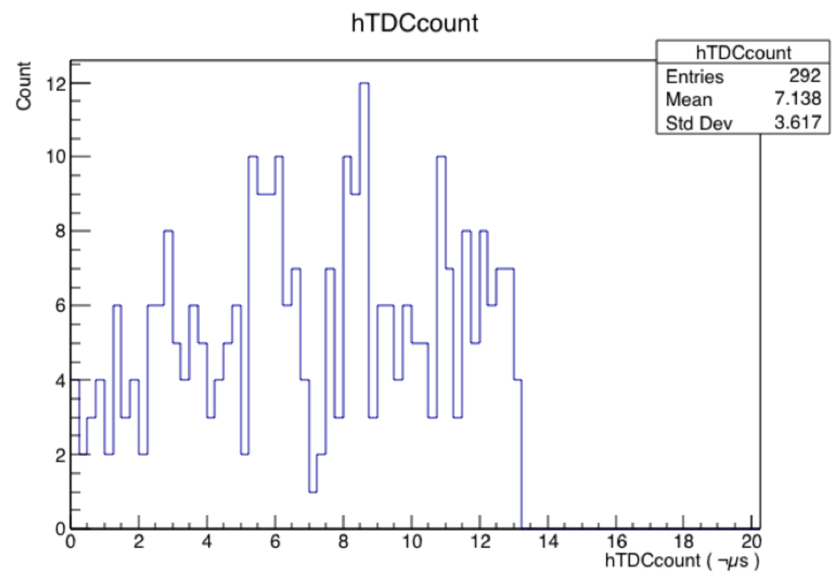
First Cathode Signals from the MIMAC bichamber background

(O. Guillaudin, D.S. et al.)

Chamber 1

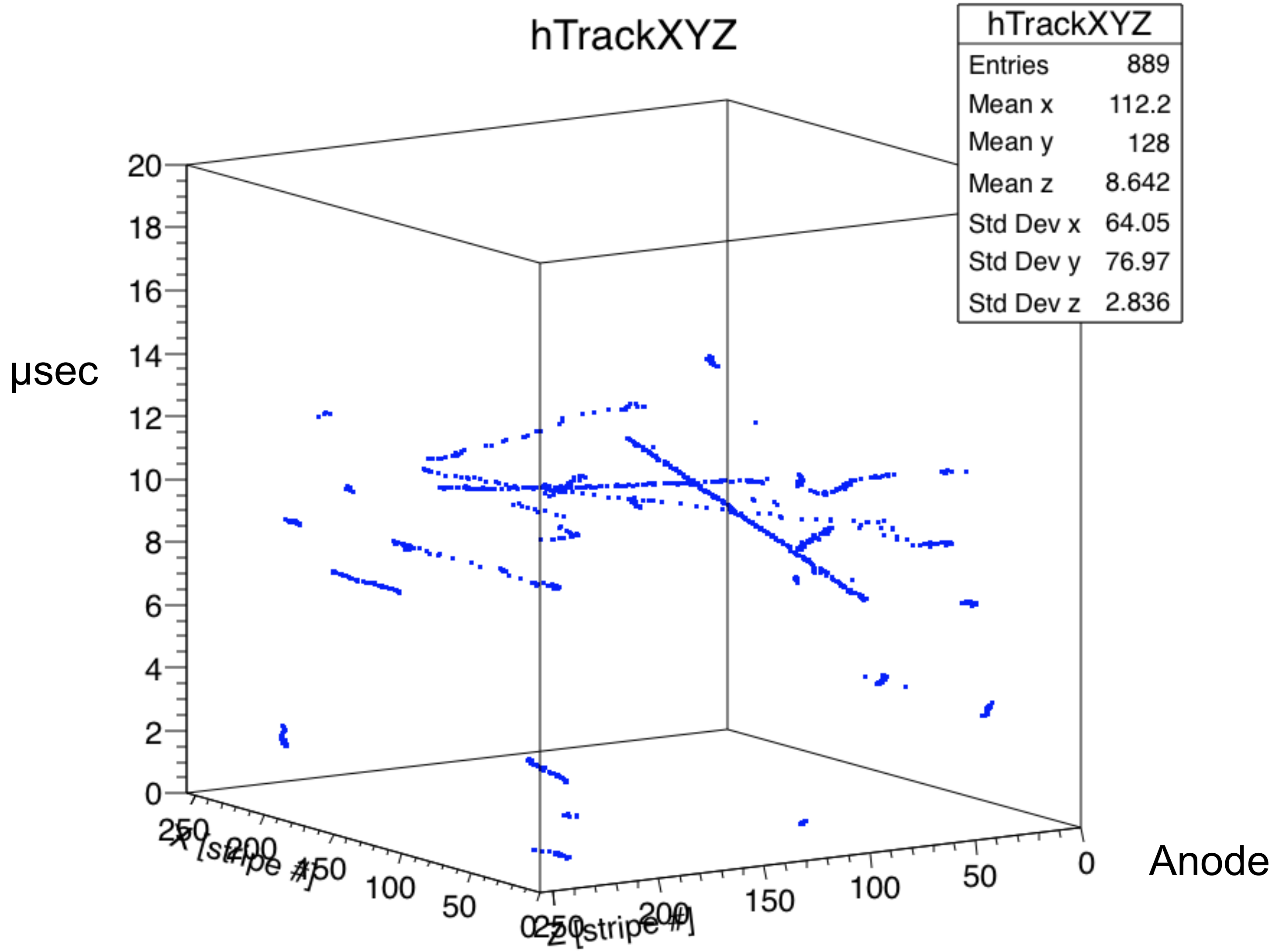


Chamber 2

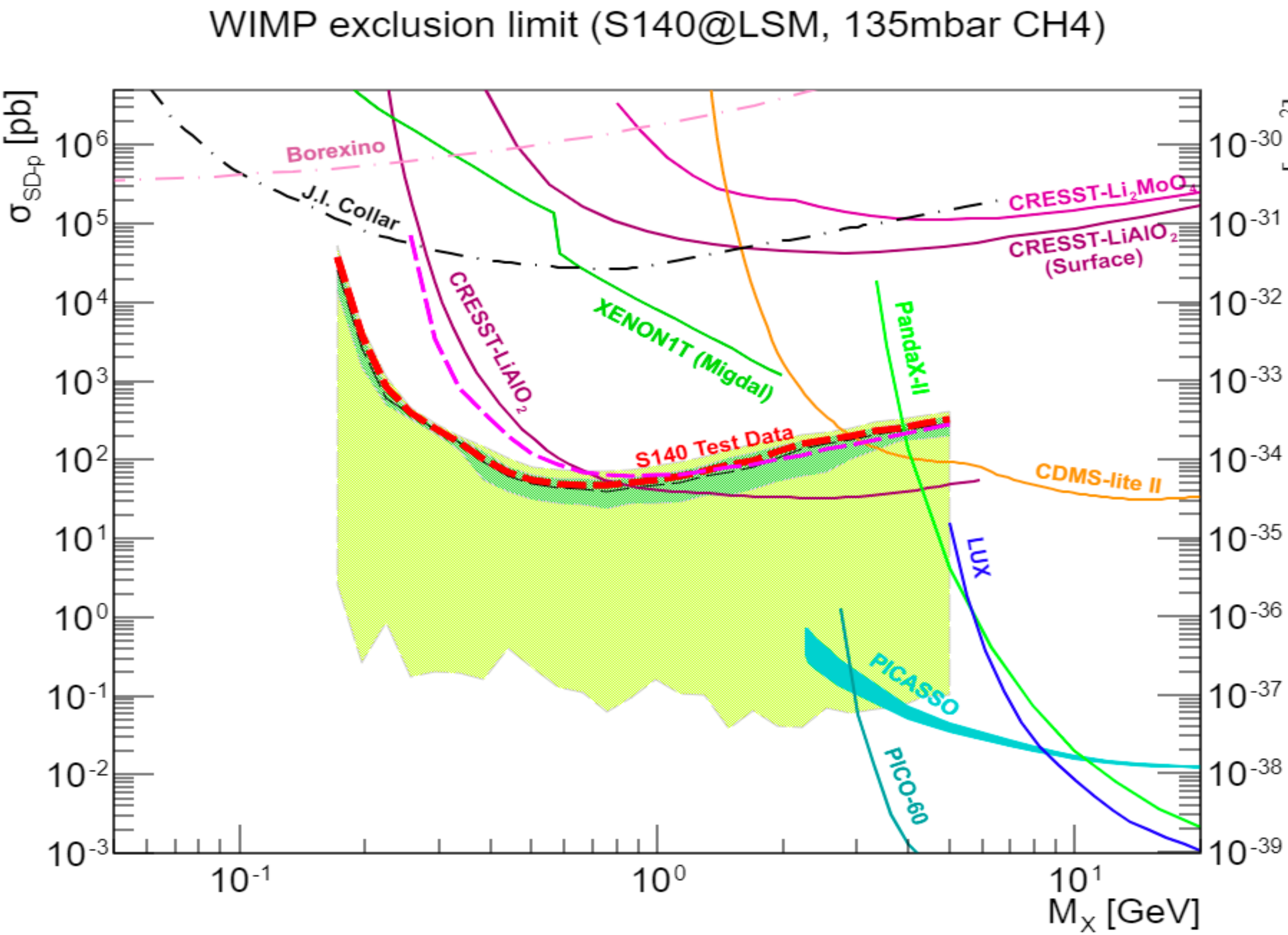


Measuring the time between the “event production” and the avalanche signal !!
Covering the 26 cm drift distance (13 us x 20 um/ns) !!

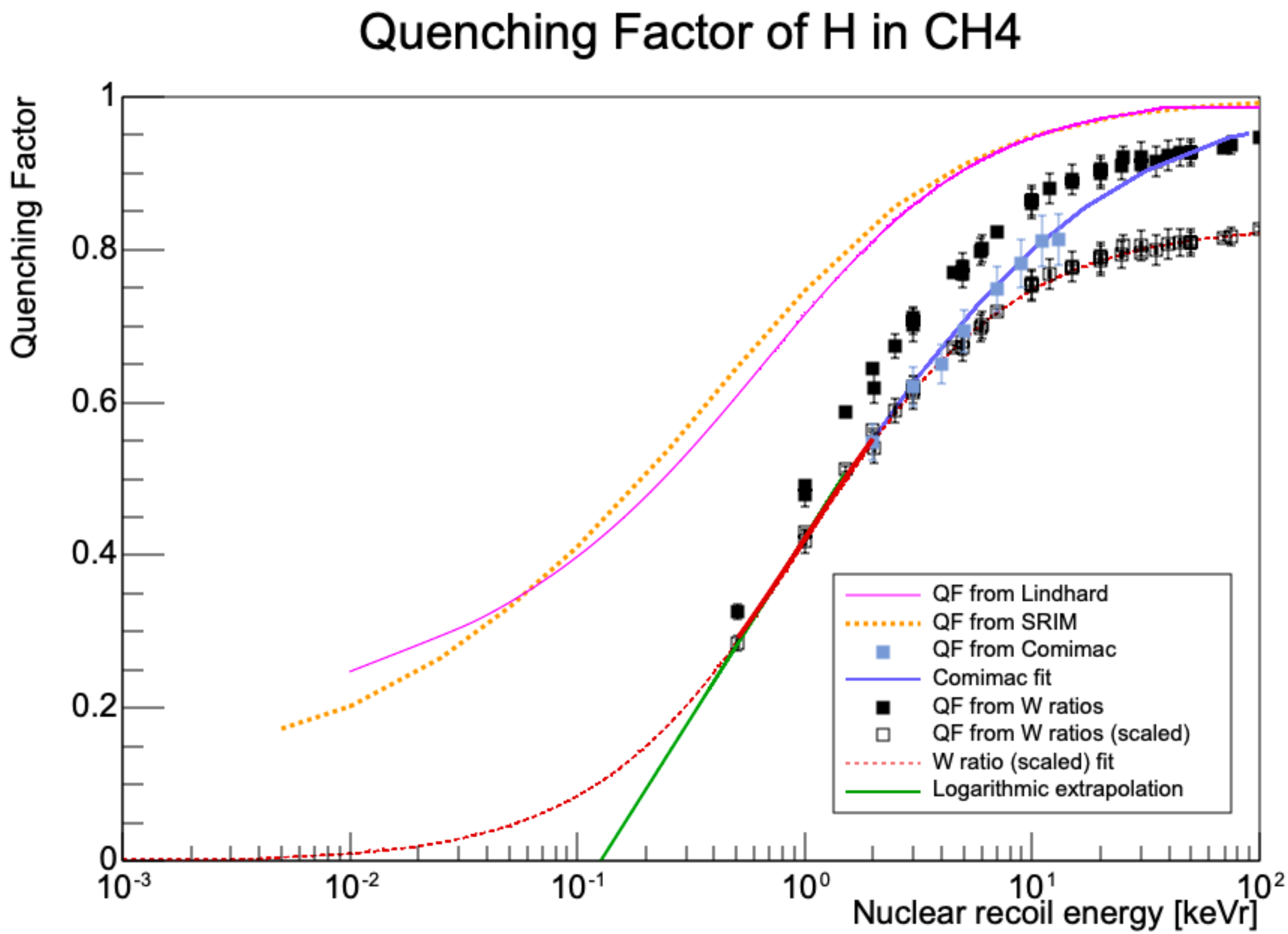
3D event-localization in MIMAC



NEWS-G (LSM results) (A spherical Gas detector)

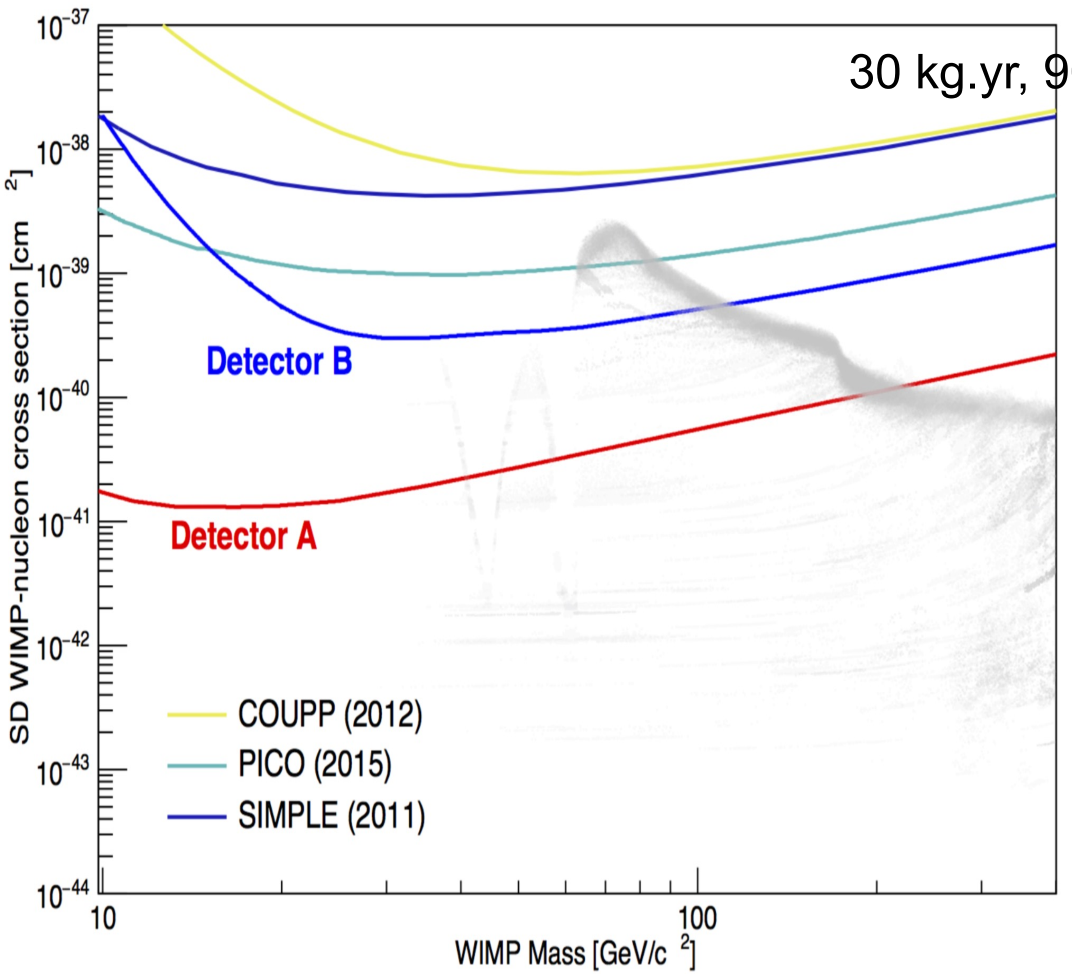


ble)



Quenching Factor of H in CH4
Quenching Factor
1
0.8
0.6
0.4
0.2
0
10-3
10-2
10-1
100
101
102
Nuclear recoil energy [keVr]
QF from Lindhard
QF from SRIM
QF from Comimac
Comimac fit
QF from W ratios
QF from W ratios (scaled)
W ratio (scaled) fit
Logarithmic extrapolation

MIMAC-Exclusion limits

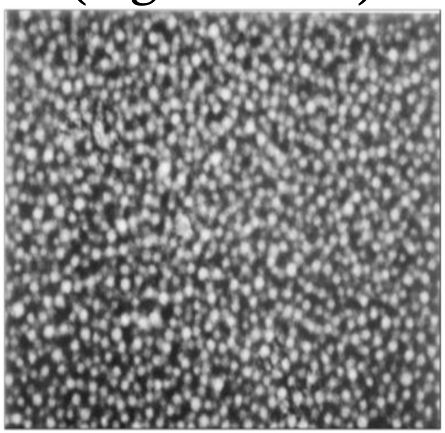


A: 5 keV (threshold)
no background
3D track with head-tail
angular resolution 20°

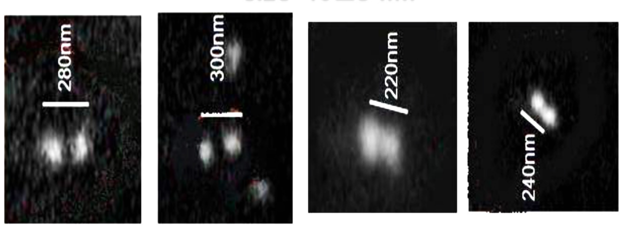
B: 20 keV
background= 10evt/kg yr
angular resolution 50°
3D with no head-tail

Directional detection: comparison of strategies

- Emulsion layers target = C (low masses), Ar, Br, Kr (high masses)

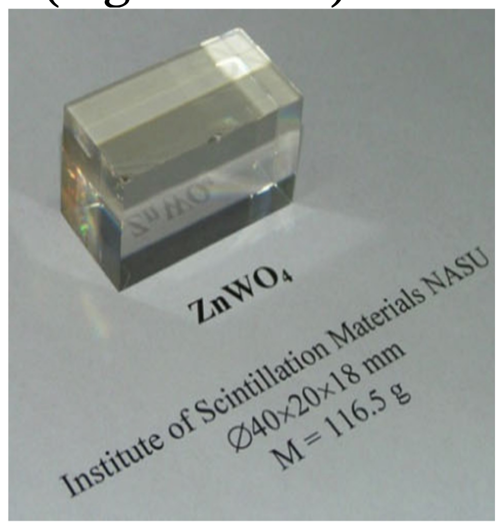


size 40±9 nm



D'Ambrosio et al. 2014

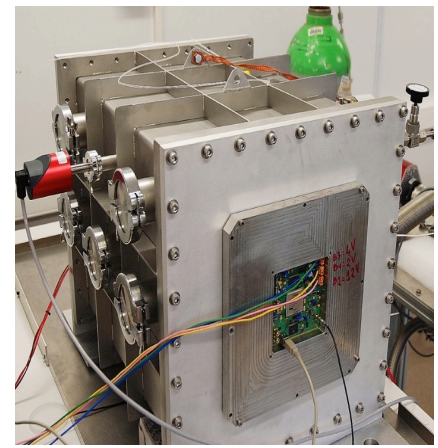
- Anisotropic crystals target = O (low masses), Zn, W (high masses)

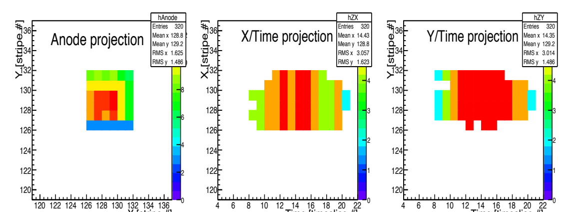


No tracks ; only statistical distributions (!)

Capella et al. 2013

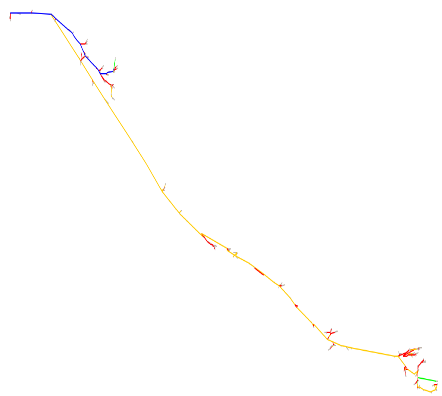
- Low pressure TPCs target = F





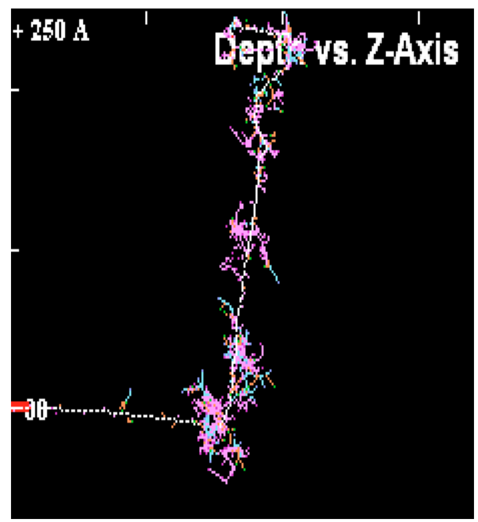
Directional detection: comparison of strategies

- Emulsion



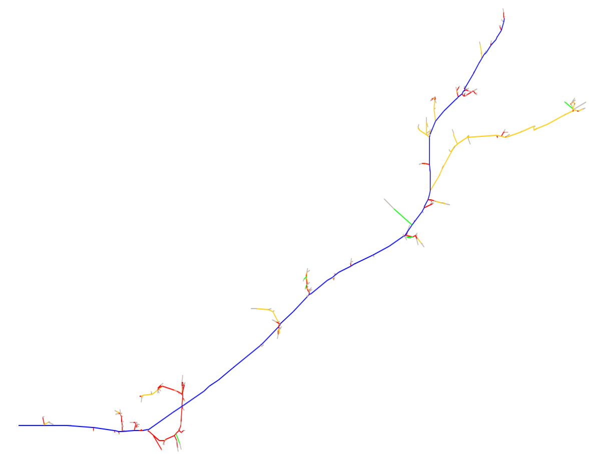
~100 nm

- Anisotropic crystals



~10 nm

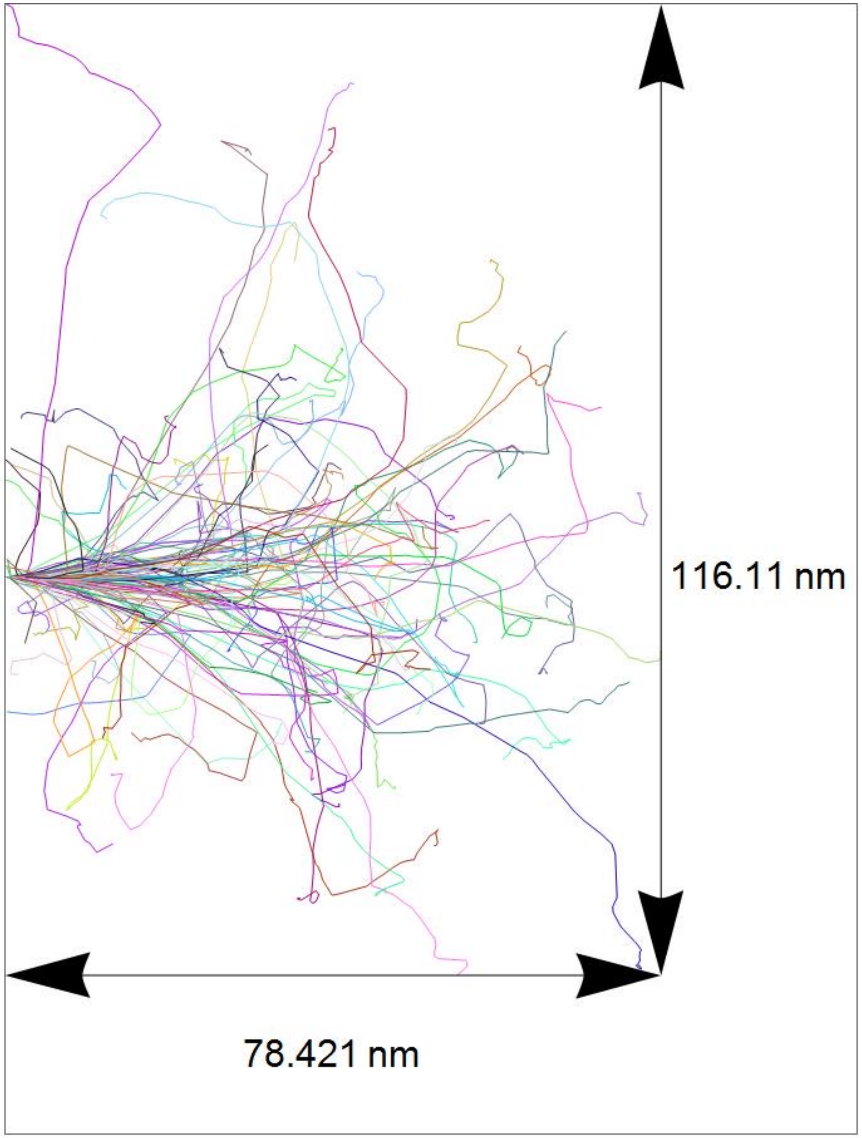
- Low pressure TPCs



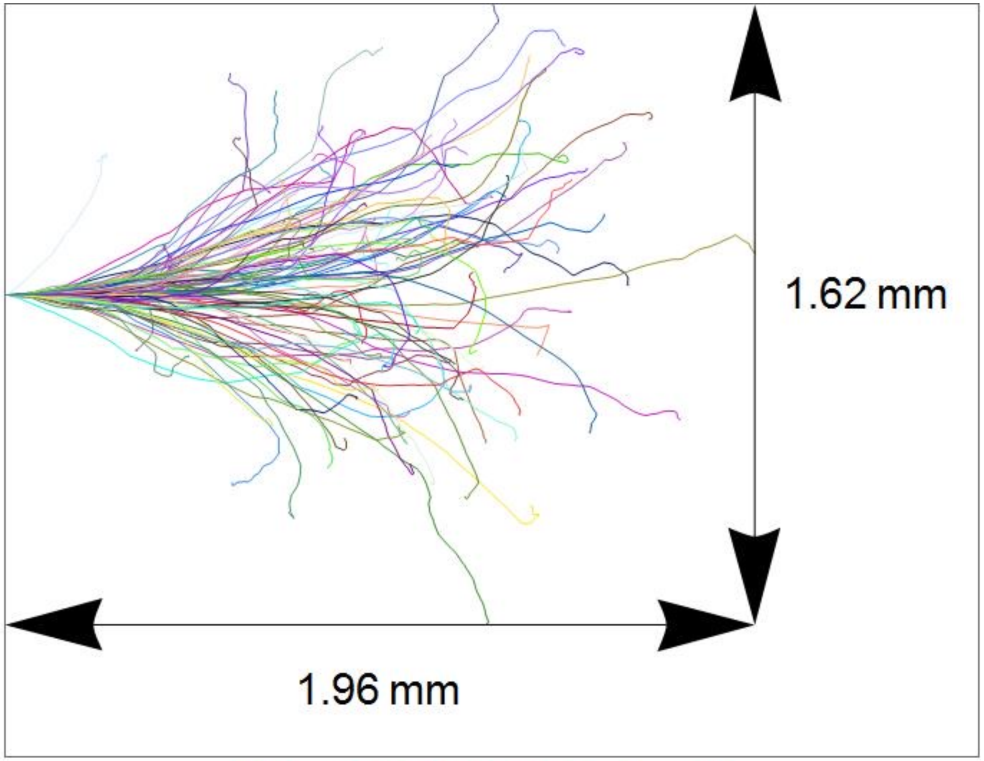
~1 mm
(10^5 times longuer !!)

(SRIM simulations)

SRIM simulations…

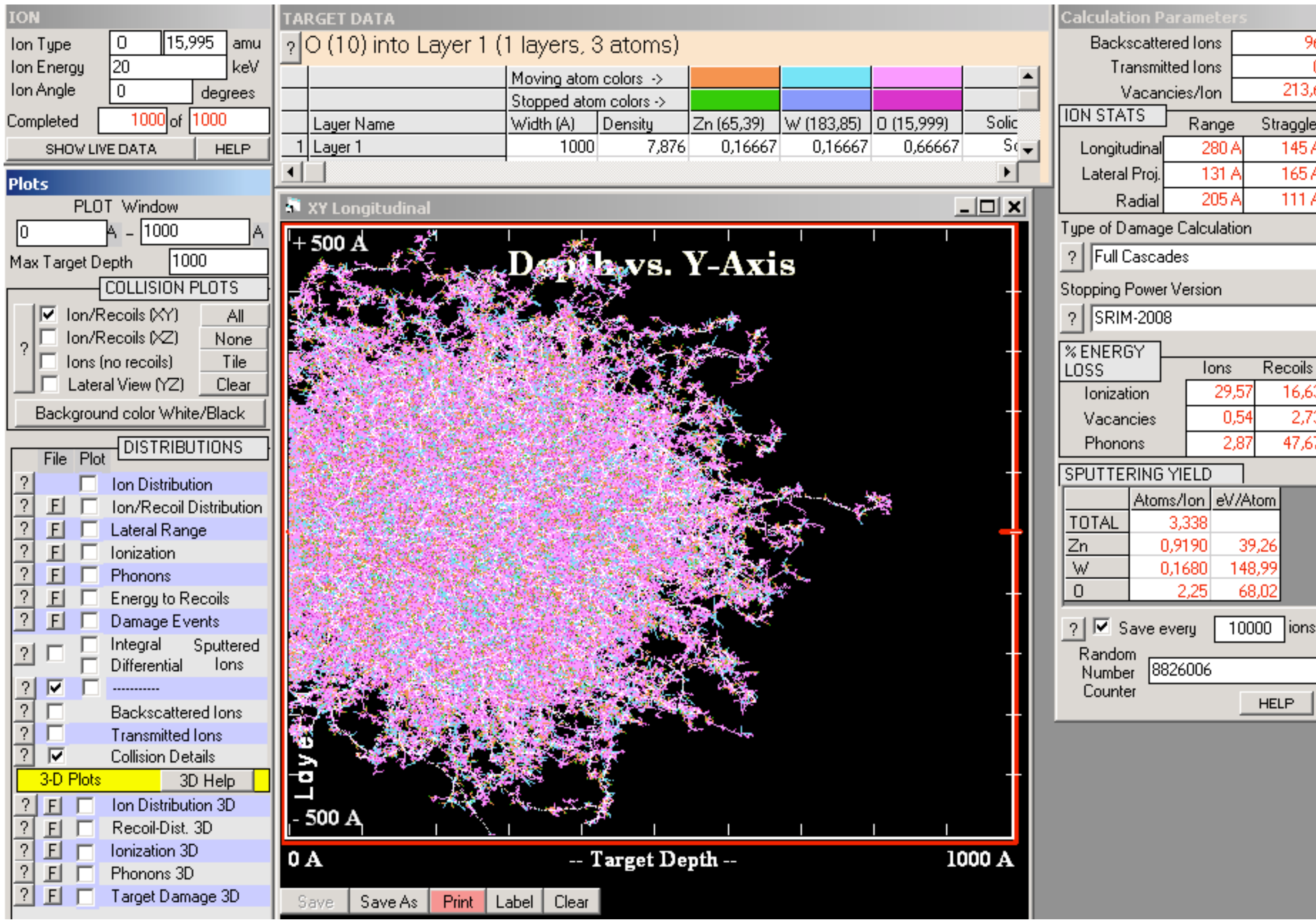


O in Crystal (29keV)

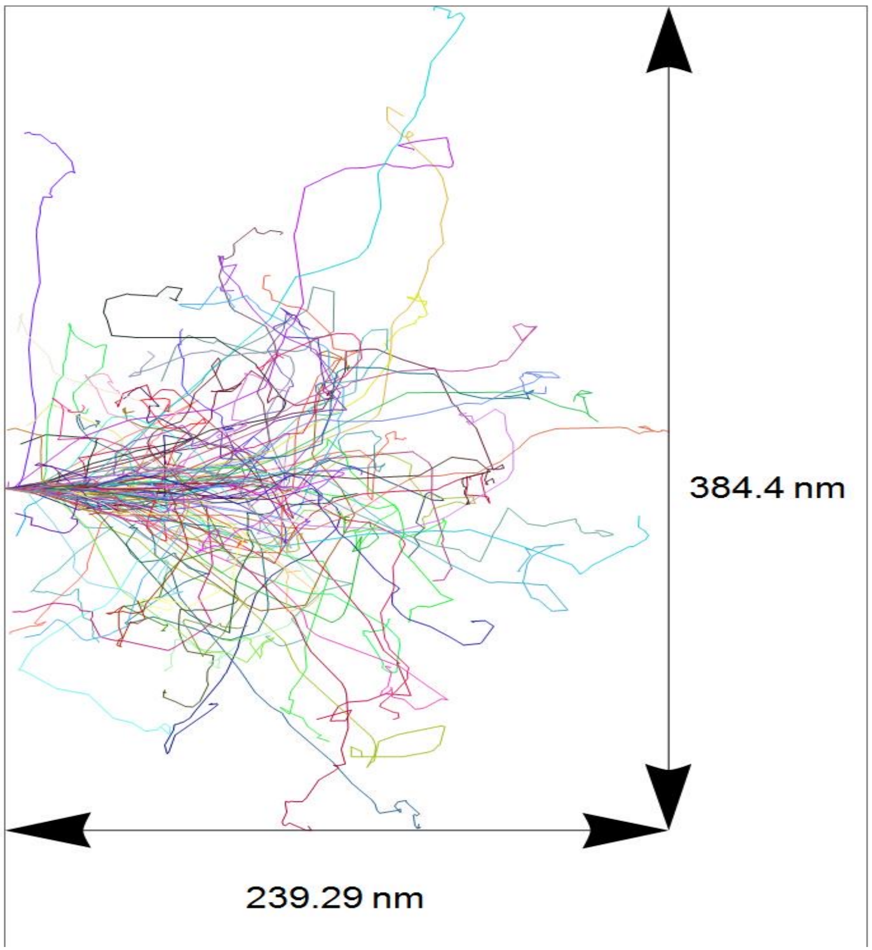


F in MIMAC (34keV)

SRIM simulation of O (20 keV) in ZnO_4W
showing the secondary recoils

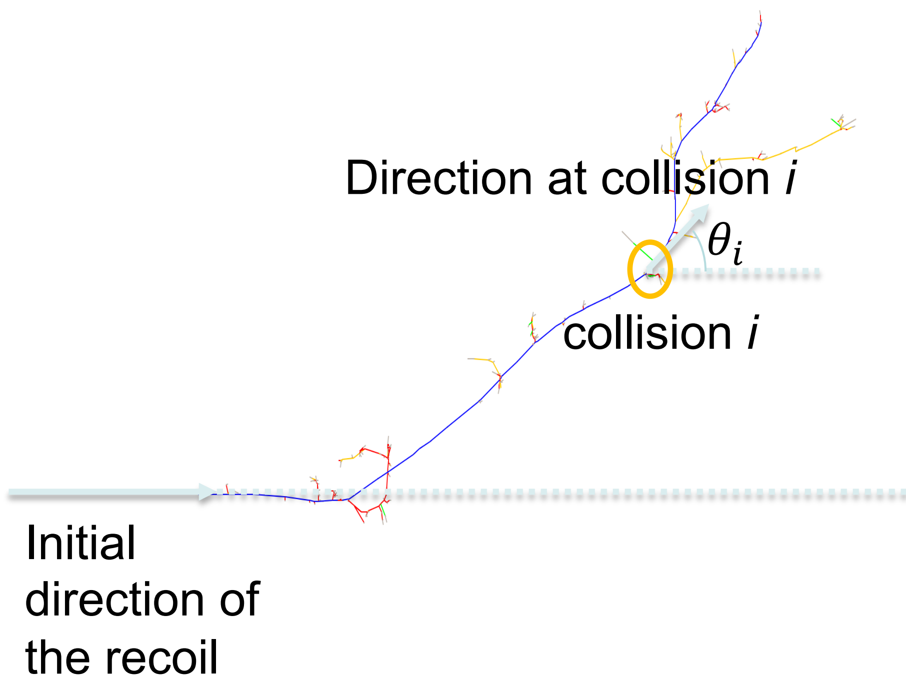


C (22 keV) in emulsion (SRIM simulation)

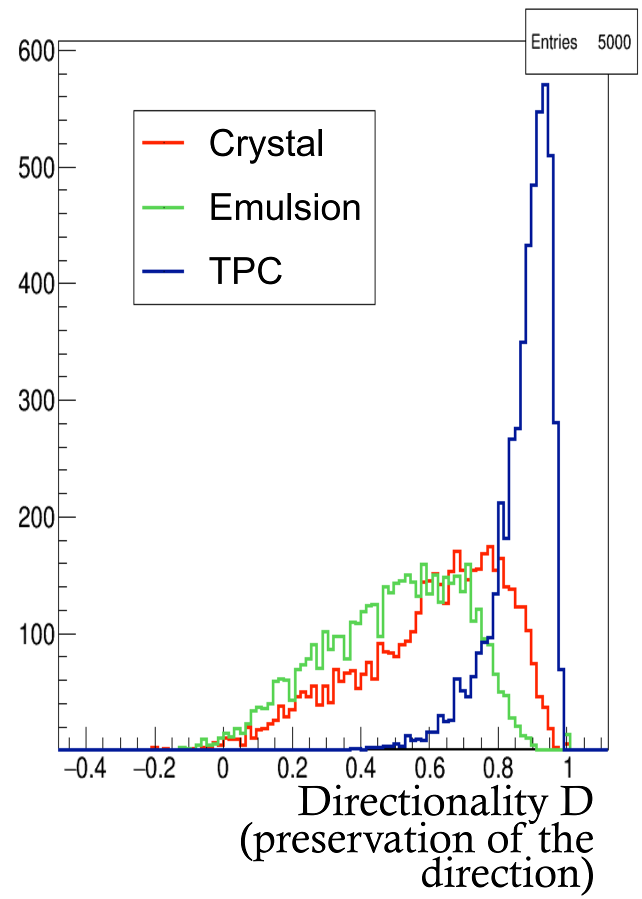


In emulsions and solids the transverse development is in general greater than the longitudinal !!

Directional detection: Directionality 'D'



$$D = \frac{\langle\cos(\theta)\cdot E\rangle_{track}}{\langle E\rangle_{track}} = \frac{\sum_{i=0}^{N_{collisions}} \cos(\theta_i)\cdot E_i}{\sum_{i=0}^{N_{collisions}} E_i} = \frac{\sum_i \cos(\theta_i)\cdot E_i}{N_{collisions}\cdot\langle E\rangle_{track}}$$

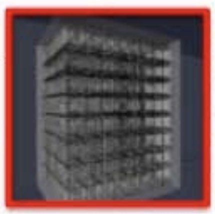


For more information on the comparison:
Couturier et al. (in preparation)

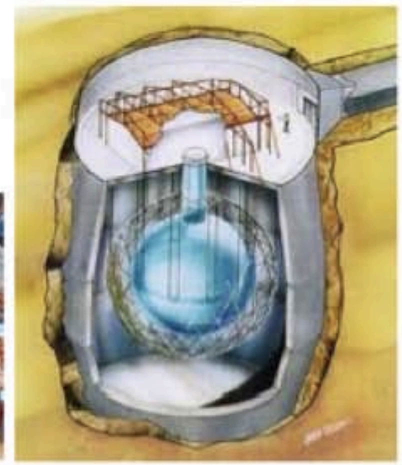
How big is a 1 tonne directional detector?

14 m x 14 m x 14 m
directional dark matter
detector

Mini-
BooNE



MINOS



SNO

Super-Kamiokande

TPC directional detectors

	DRIFT	MIMAC	NEWAGE	DMTPC
	Boulby	Modane	Kamioka	SNOLAB
Gas mix	73%CS2 +25%CF4 +2%O2	70%CF4 +28%CHF3 +2%C4H10	CF4	CF4
Current volume	800 L	6 L	37 L	1000 L
Drift	ion, 50 cm	e□ , 25 cm	e□ , 41 cm	e□ , 27 cm
Threshold (keVee)	20	1	50	20
Readout	Multi-Wire Proportional Counters	Micromegas	micro-pixel chamber +GEM	CCD

Adapted from Mayet et al. [arXiv:1602.03781]