MIMAC

MIcro-tpc MAtrix of Chambers

for Directional Dark Matter detection and Axion-Like-Particle Exploration

Daniel Santos

LPSC-Grenoble

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MIMAC (MIcro-tpc MAtrix of Chambers)

LPSC (Grenoble) : D. Santos, C. Beaufort (Ph.D), F.Naraghi , O. Guillaudin, N. Sauzet,

- Electronics : **G. Bosson (r), J. Bouvier (r), J.L. Bouly, L.Gallin-Martel, F. Rarbi, Cairo Caplan (CDD)**
- 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)

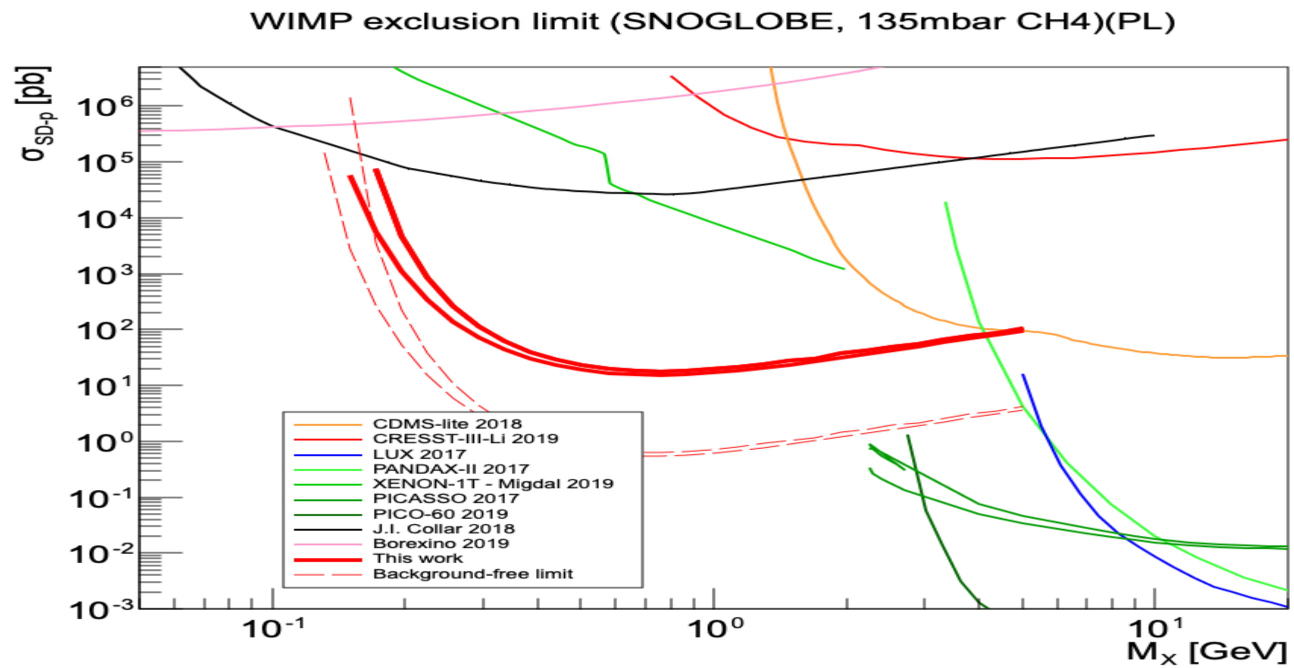
Prototype hosted in **IHEP (Beijing-China)**: **ZhiminWang , Changgen Yang**

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

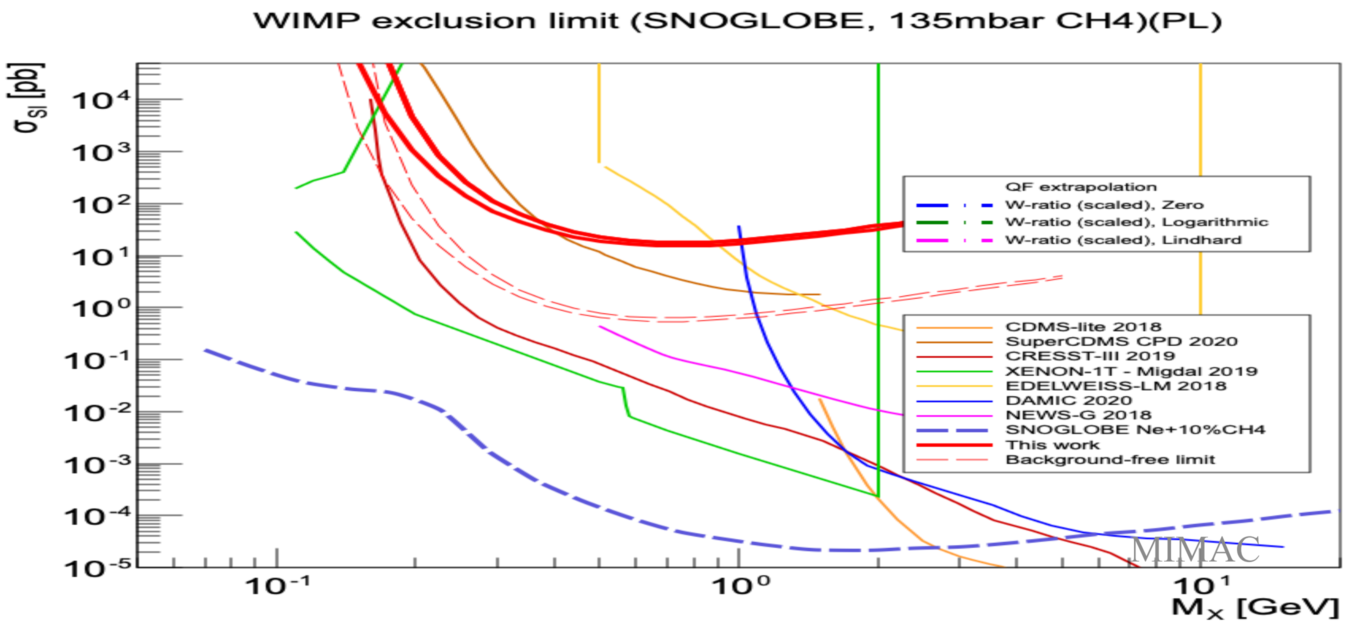
Non-directional detector

Exclusion limits (SD-p)

To be published…

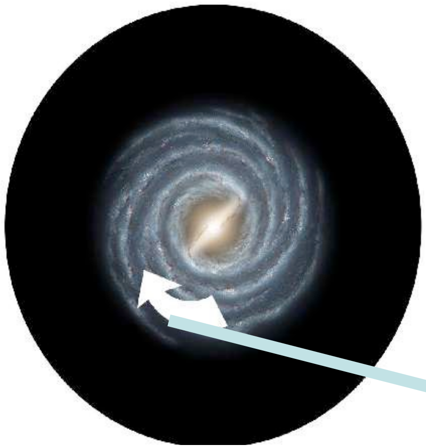


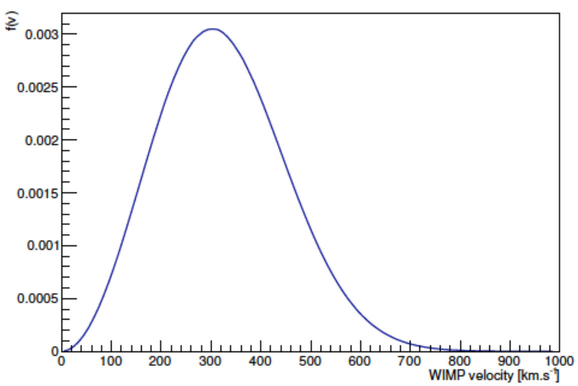
Exclusion limits (SI)

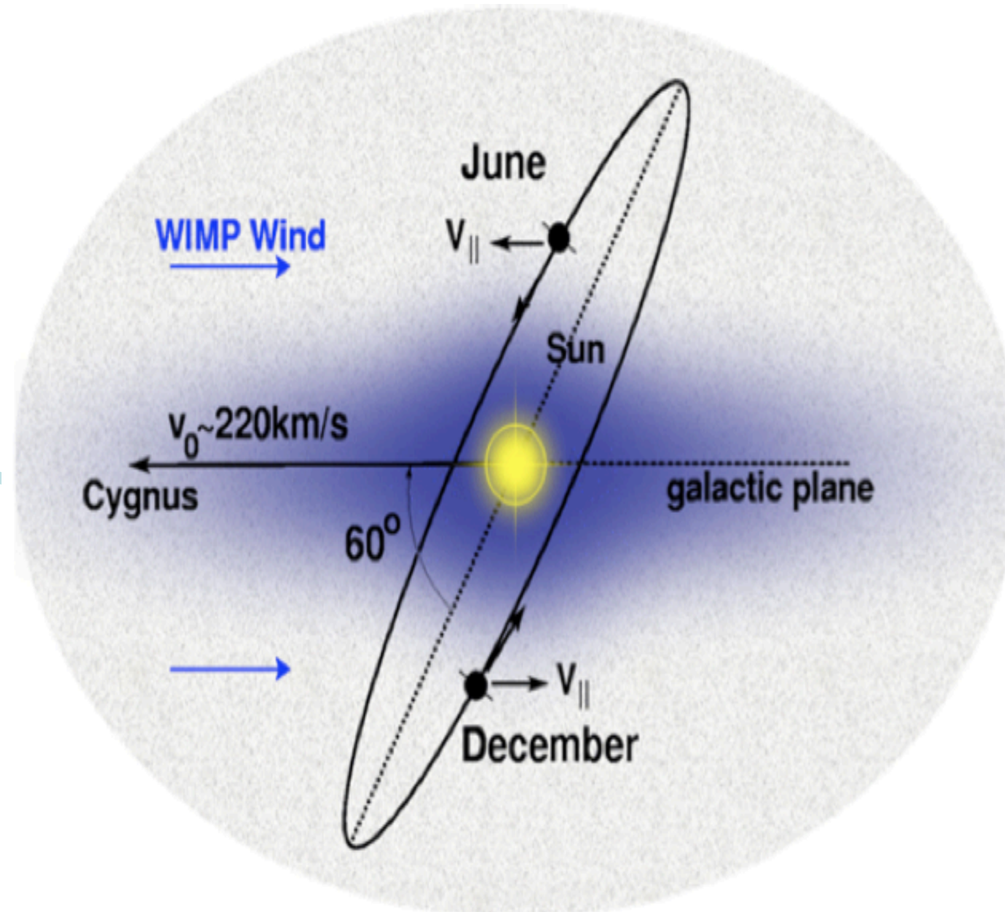


MIMAC

Directional detection: principle



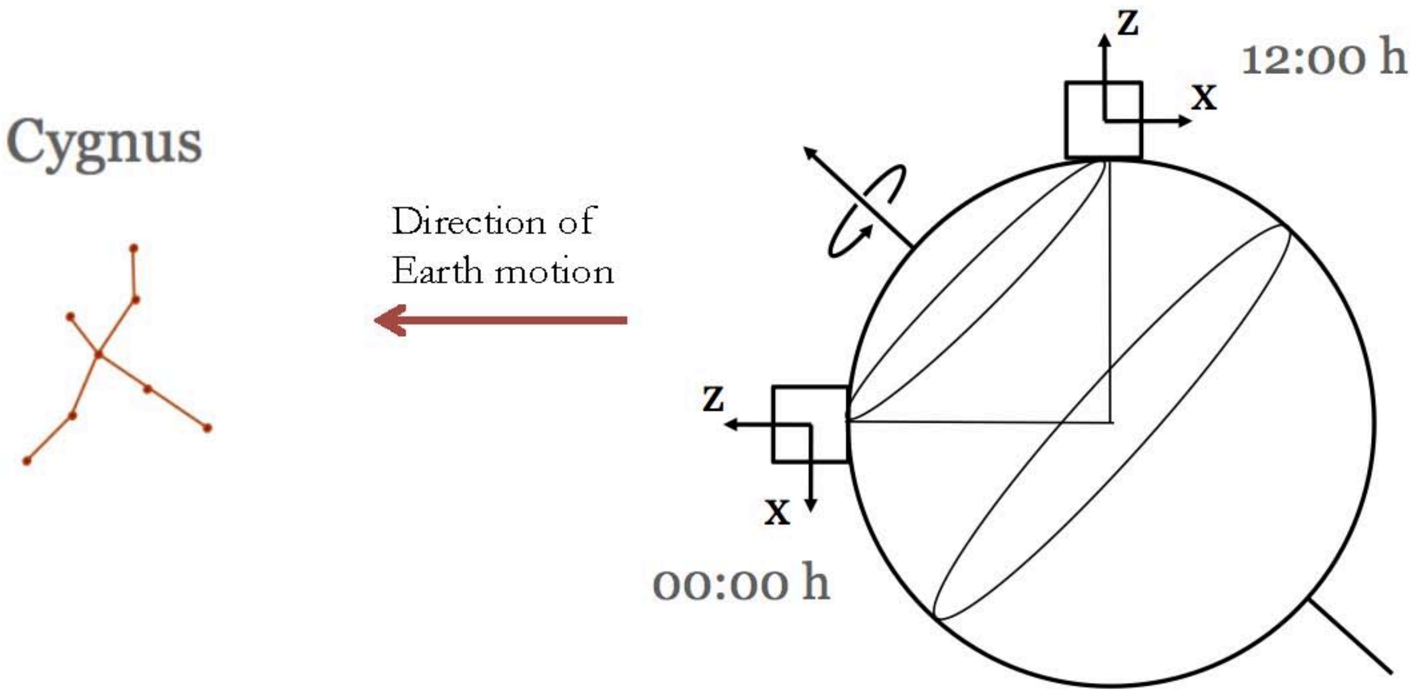




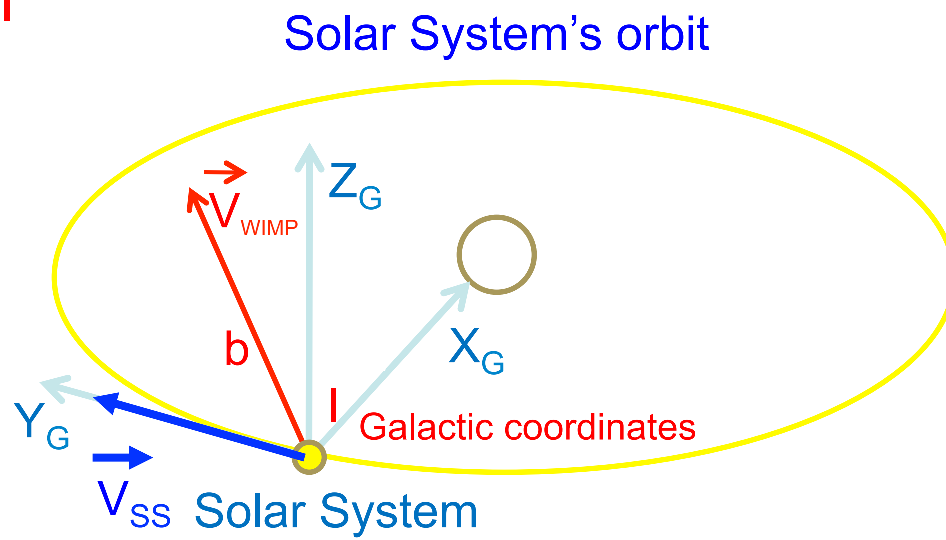
The signature able to correlate the rare events in a detector to the galactic halo !!

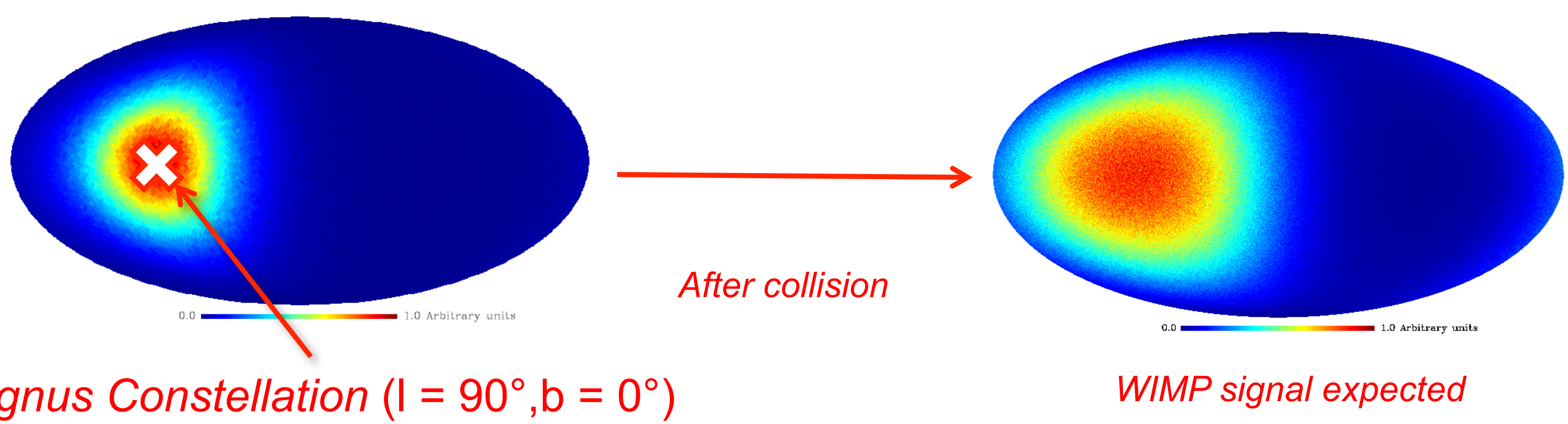
Angular modulation of WIMP flux

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

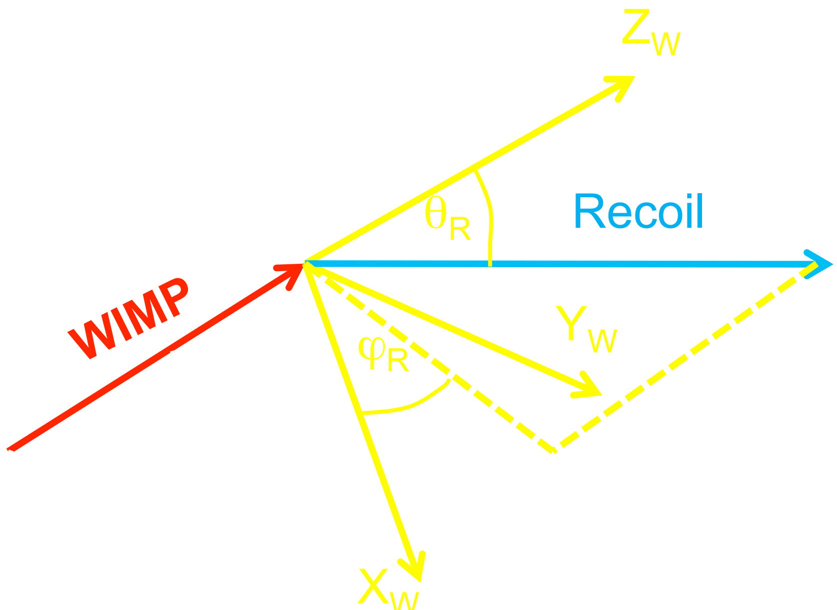


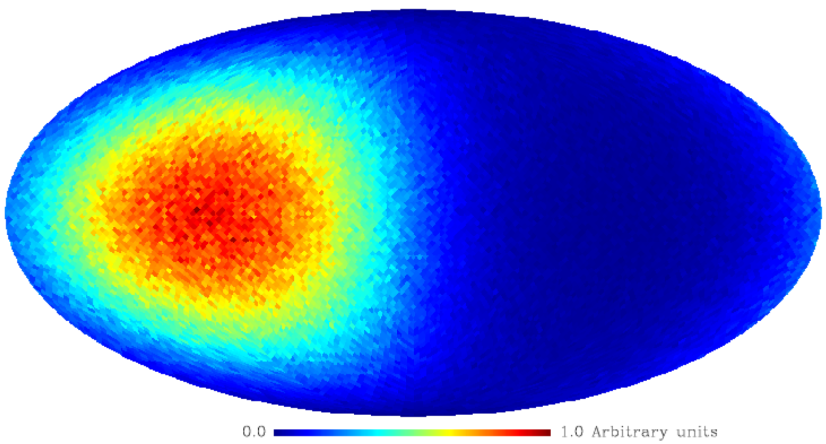
WIMP signal


Solar System's orbit
$\vec{V}_{WIMP}$
Z_G
b
X_G
l
Galactic coordinates
Y_G
$\vec{V}_{SS}$
Solar System


0.0
1.0 Arbitrary units
After collision
Cygnus Constellation (l = 90°,b = 0°)
WIMP signal expected

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



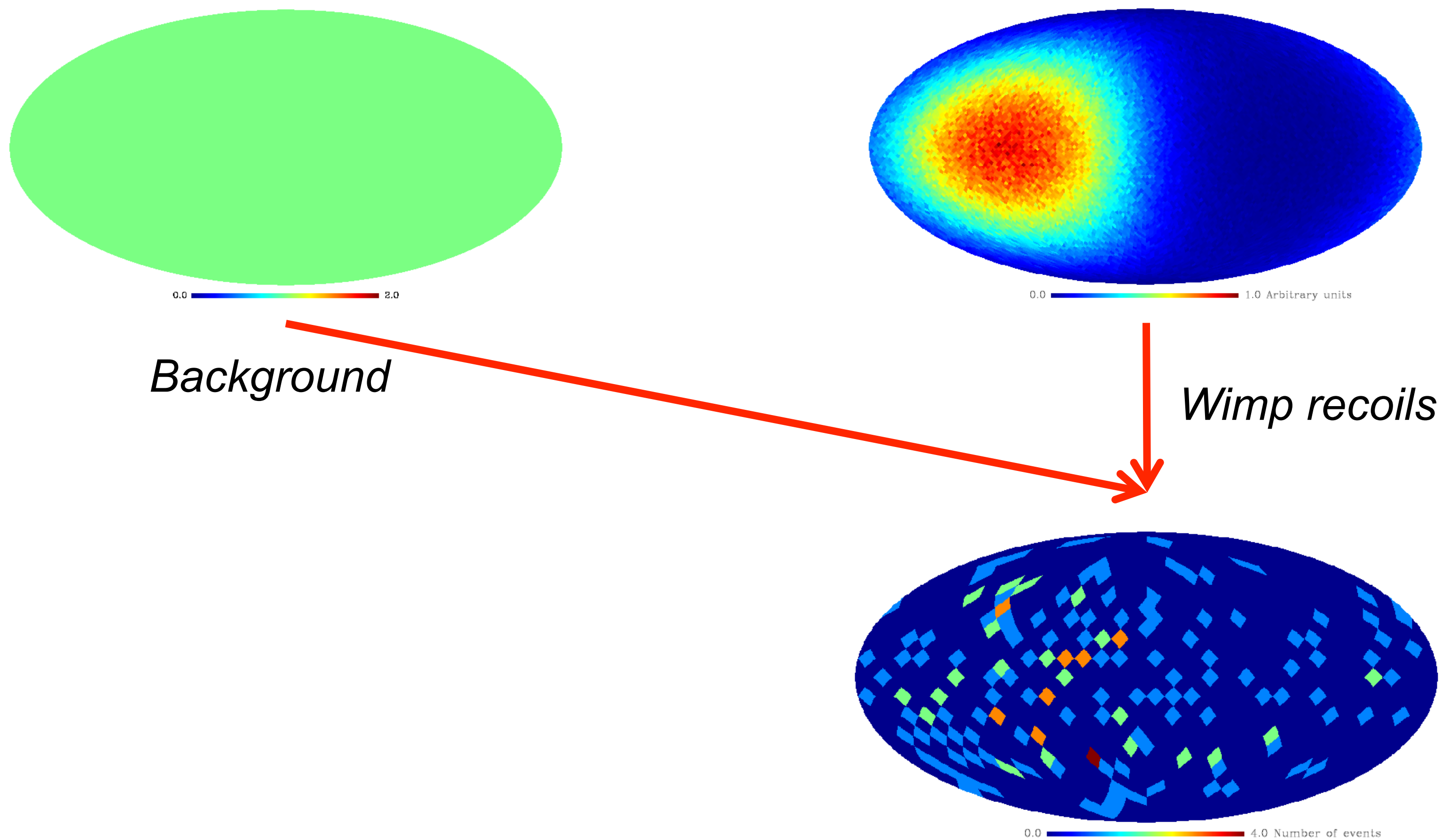


Map of recoils in galactic coordinates (HealPix)

10^8 Events with E_R = [5,50] keV

Robust with respect to Background events

100 WIMP evts + 100 Background evts

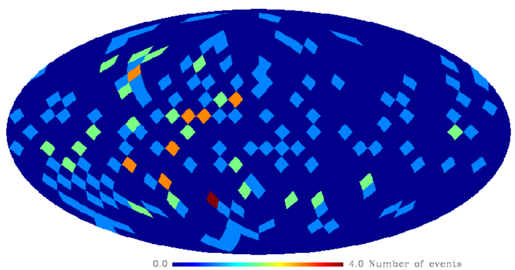


Phenomenology: Discovery

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

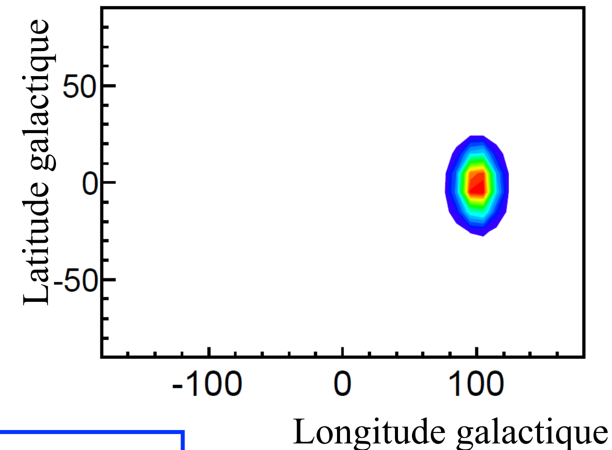
Proof of discovery: **Signal pointing toward the Cygnus constellation**

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



100 WIMP + 100 BKG

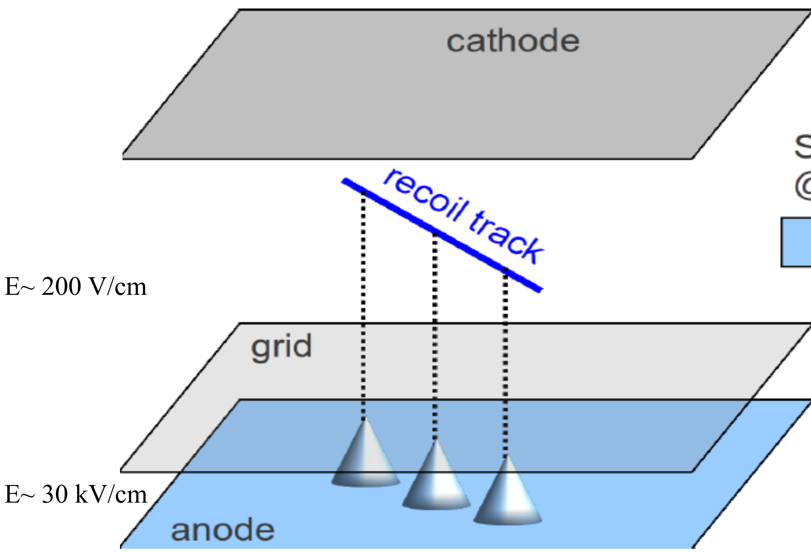
$$\mathscr{L}(\ell, b, m_\chi, \lambda)$$



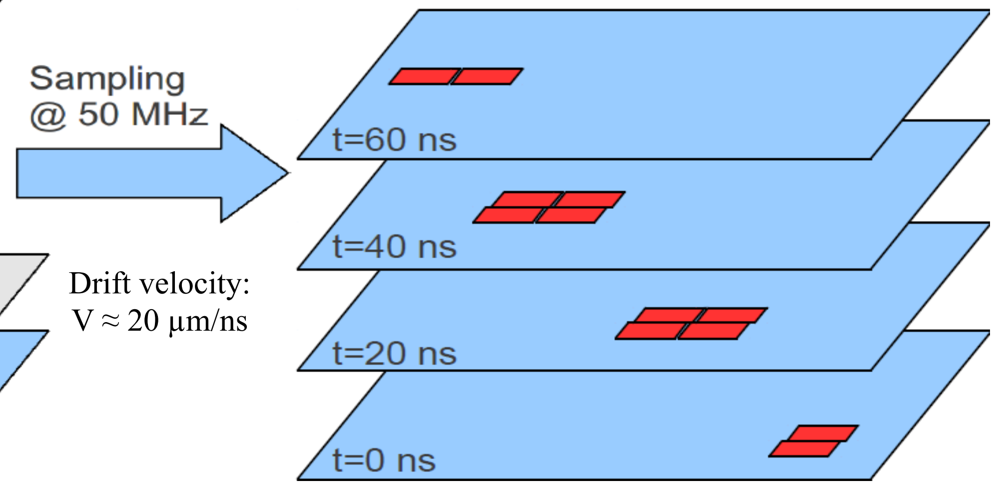
Strong correlation with the direction of the Constellation Cygnus **even with a large background contamination**

Directional experiments around the world

MIMAC: Detection strategy



Scheme of a MIMAC μTPC

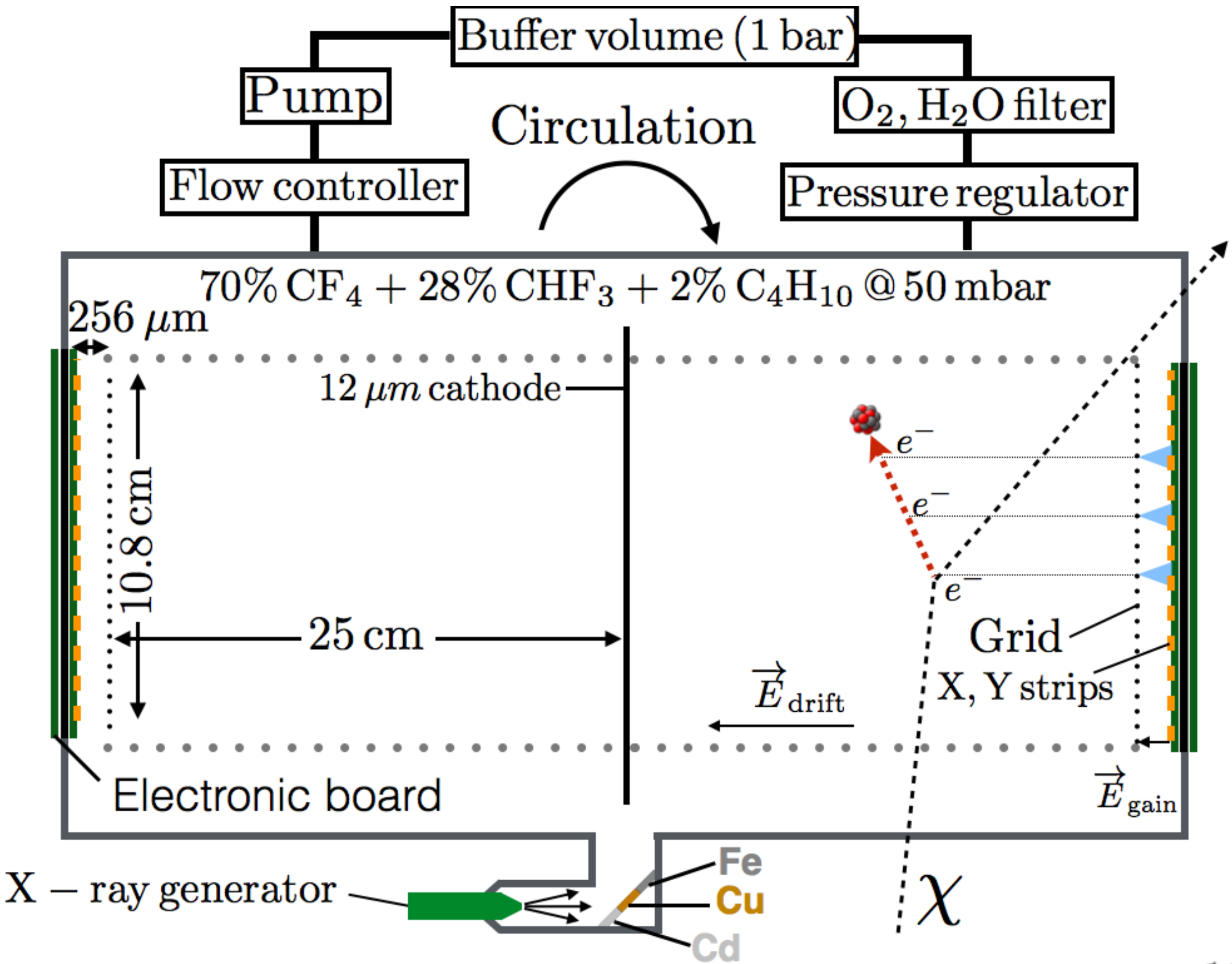


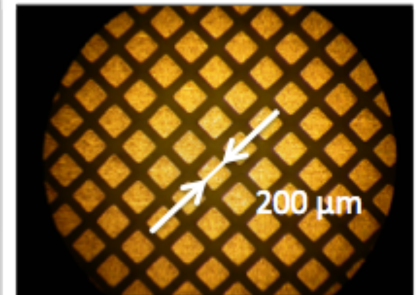
Evolution of the collected charges on the anode

Measurement of the ionization energy:

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

MIMAC-bi-chamber module prototype





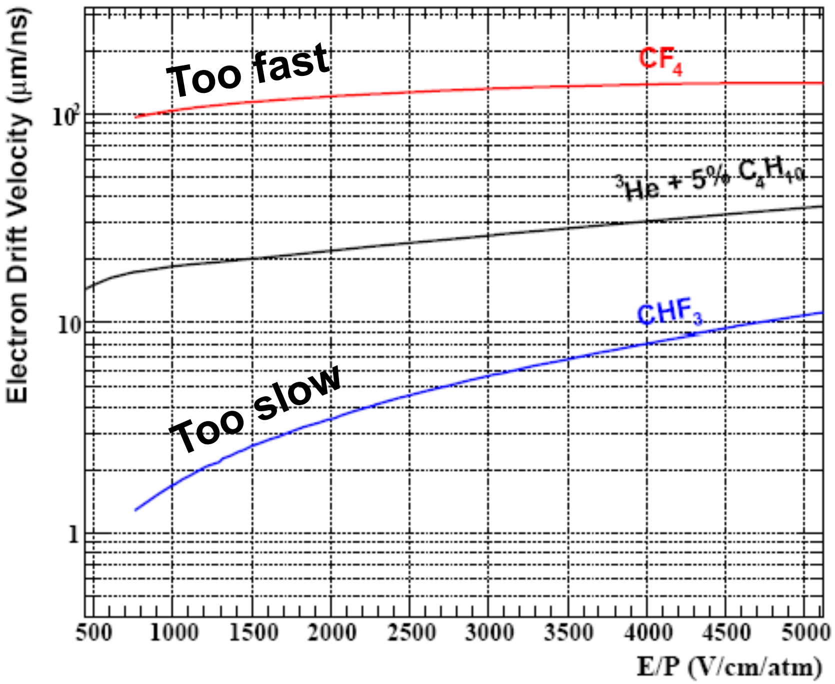
Micromegas 10x10 cm², designed by IRFU- Saclay (France)

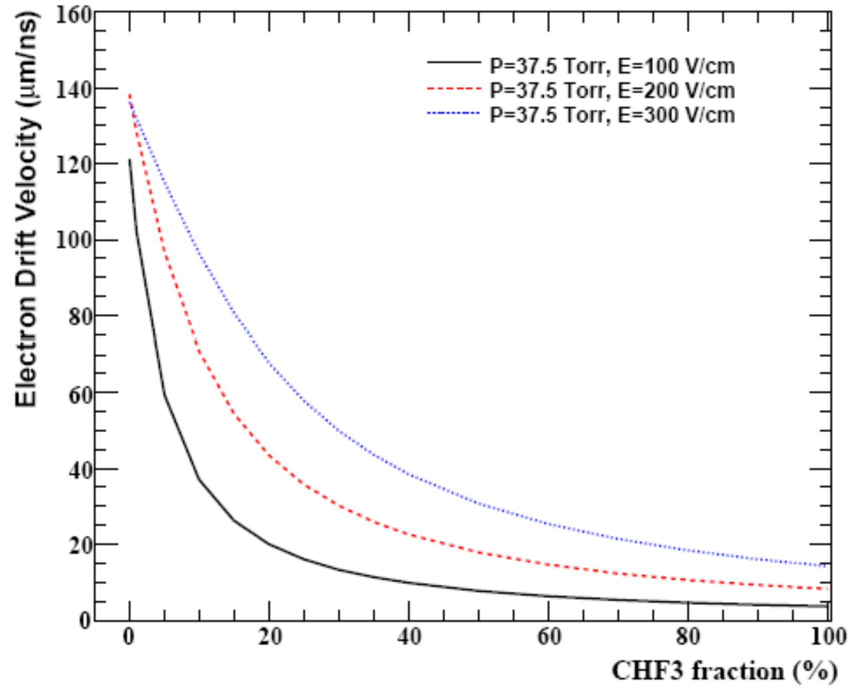
MIMAC Target: ^{19}F

- Light WIMP mass
- Axial coupling

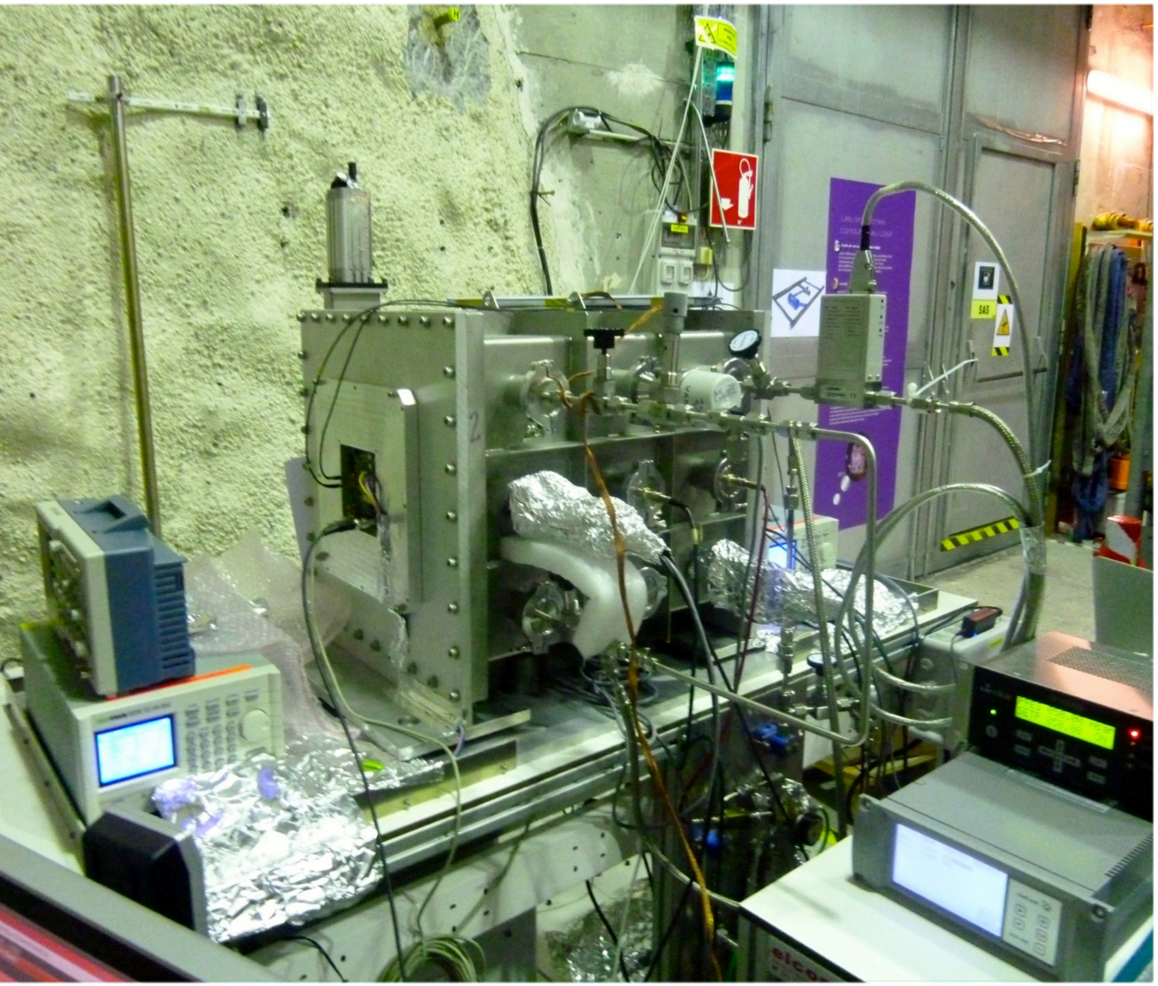
3D Tracks: Drift velocity

Magboltz Simulation





- New mixed gas MIMAC target : CF_4 + x% CHF_3 (x=30)



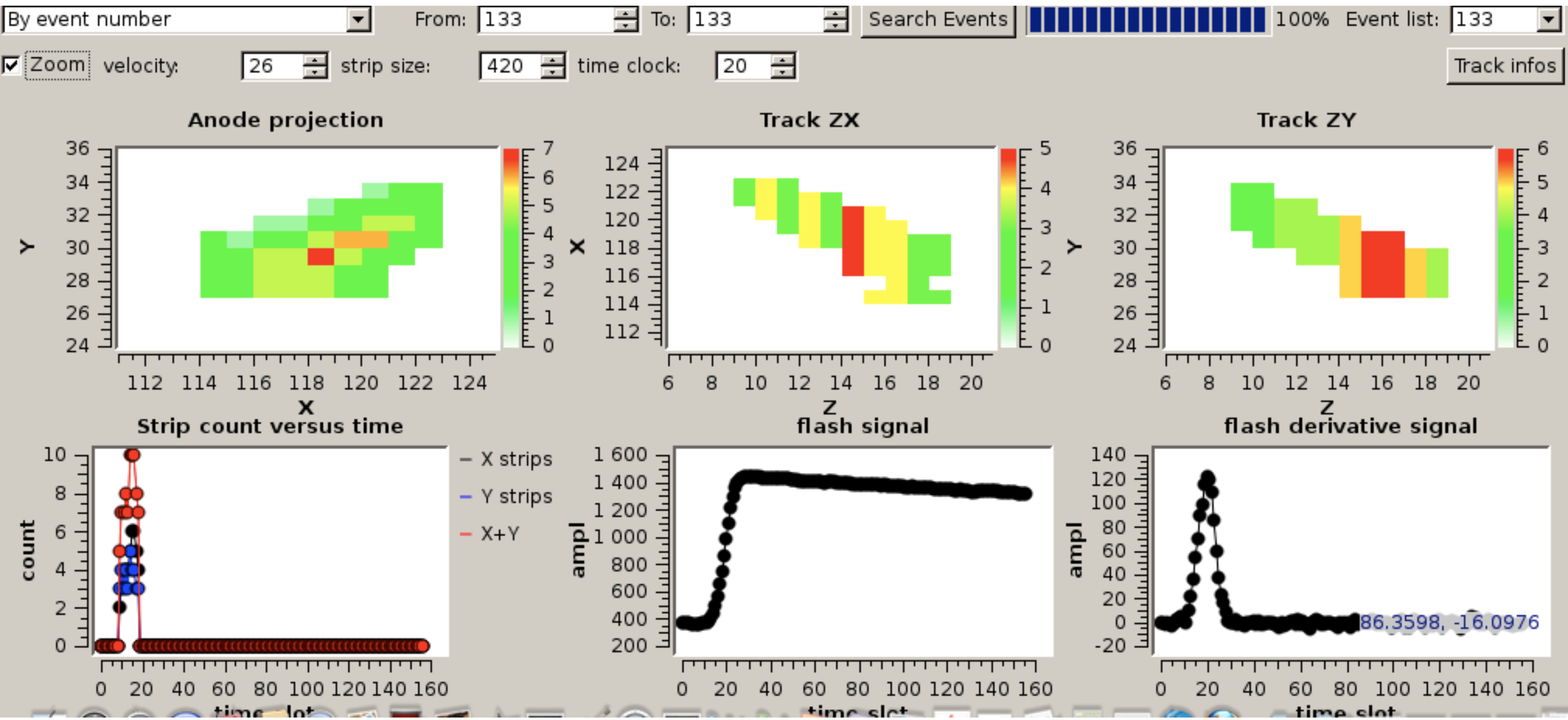
MIMAC (bi-chamber module)at Modane Underground Laboratory (France)
since June 22nd 2012.
Upgraded June 2013, and
June 2014 till February 2018

-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

$\longrightarrow$ Electron event (background)

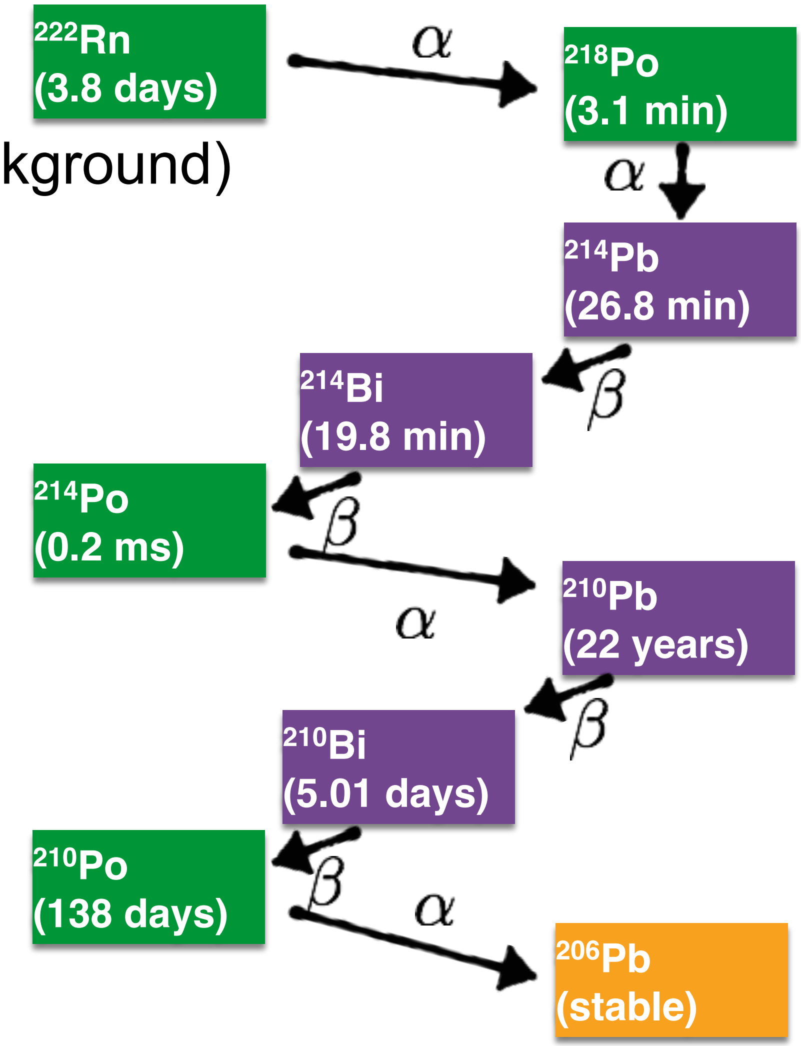
- 4 α-decays

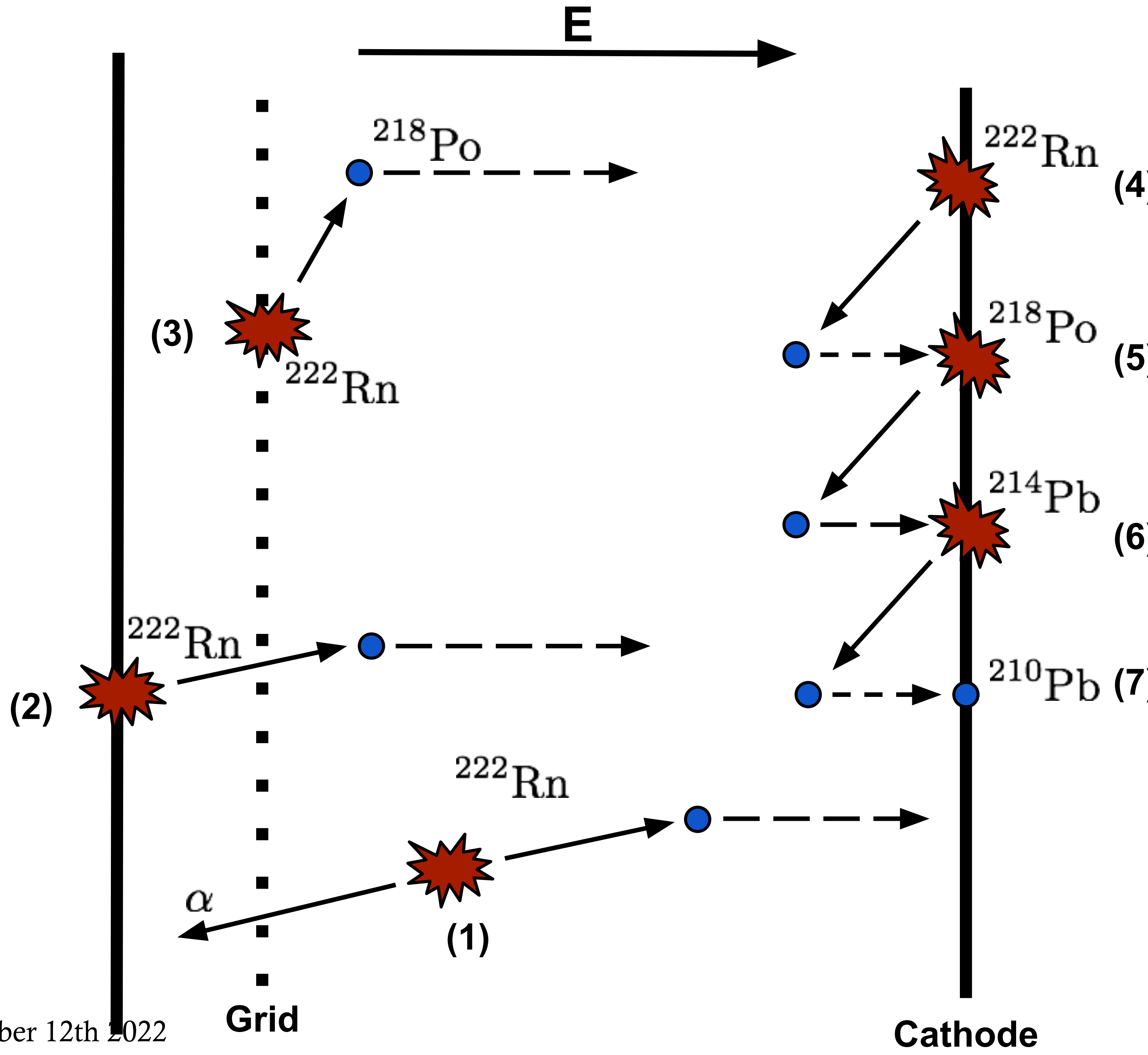
$\longrightarrow \alpha$-particle emission: $E_\alpha \sim 5\,\mathrm{MeV} \longrightarrow$ Saturation

$\longrightarrow$ 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

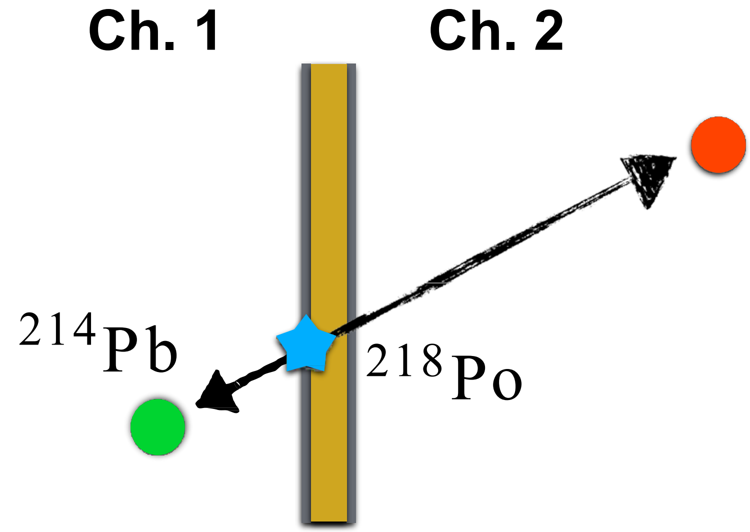
Simulation (SRIM)

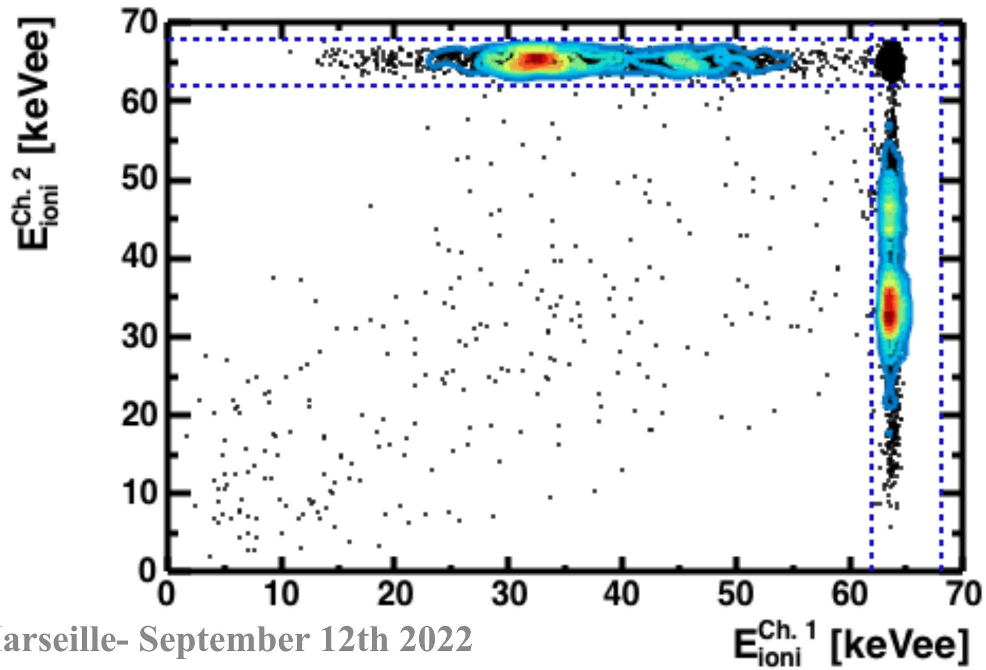



E
$^{218}\mathrm{Po}$
$^{222}\mathrm{Rn}$
(4)
(3)
$^{222}\mathrm{Rn}$
$^{218}\mathrm{Po}$
(5)
$^{214}\mathrm{Pb}$
(6)
$^{222}\mathrm{Rn}$
(2)
$^{210}\mathrm{Pb}$
(7)
$^{222}\mathrm{Rn}$
α
(1)
Grid
Cathode
Pixelized anode

RPR: « In coincidence » events

Chamber coincidences:

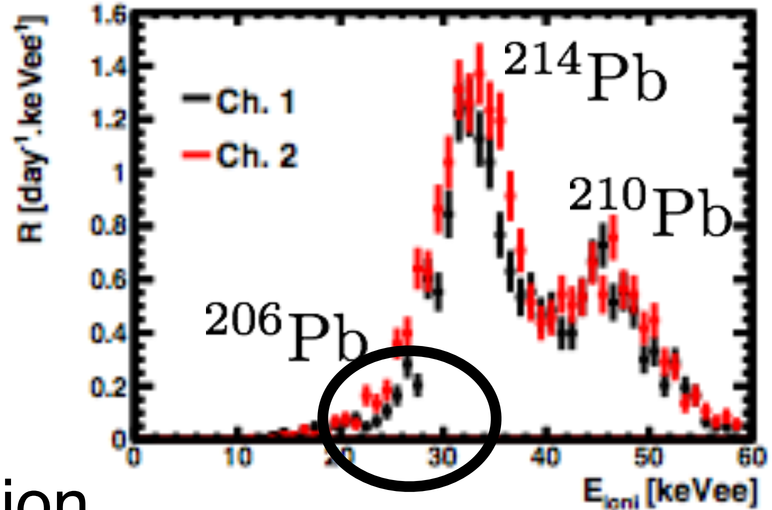




3D tracks from nuclear recoil of radon progeny detection

First detection of 3D tracks of Rn progeny

Nuclear recoil spectra



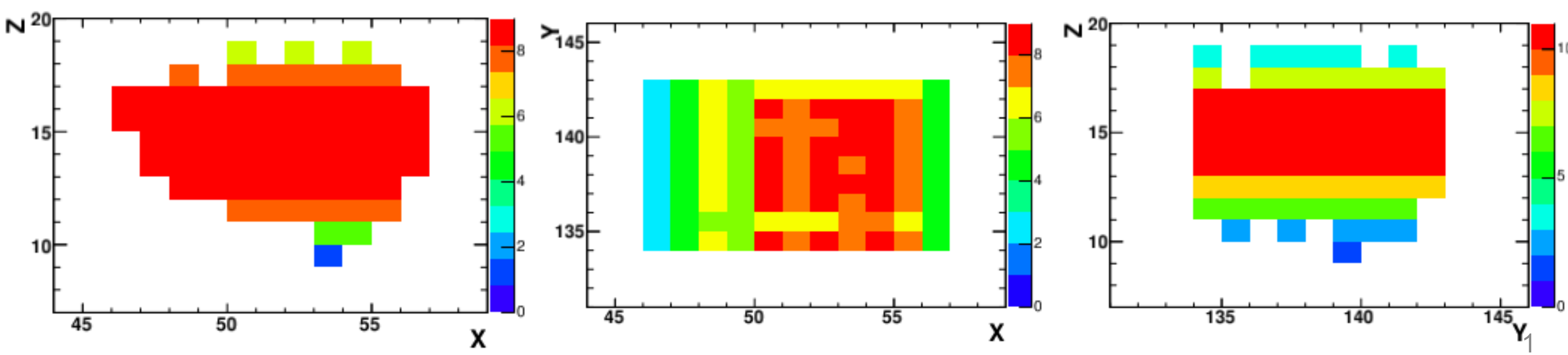
$R_{^{206}\mathrm{Pb}} \sim 0.25\,\mathrm{day}^{-1}.\mathrm{keVee}^{-1}$

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

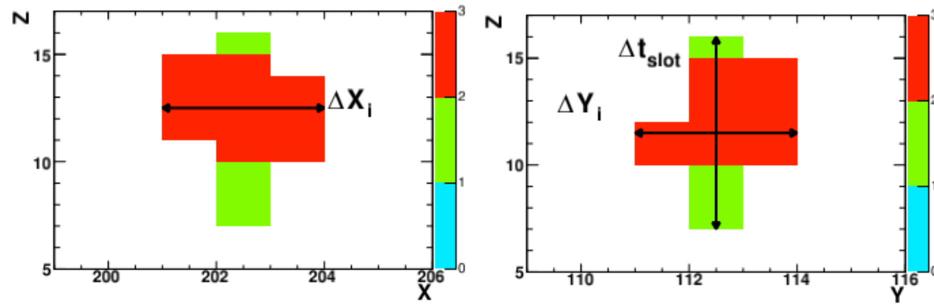


RPR events occur at different positions in the detector…

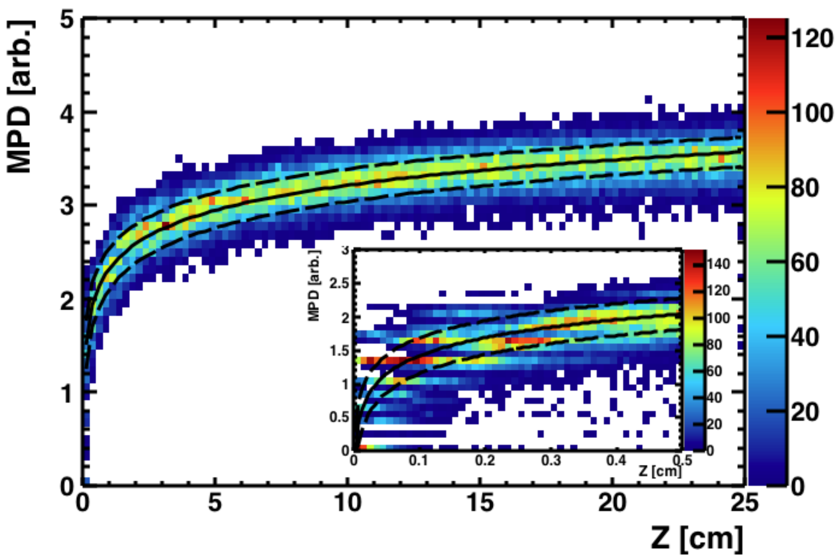
$$z_0 \longleftrightarrow \text{Diffusion}$$

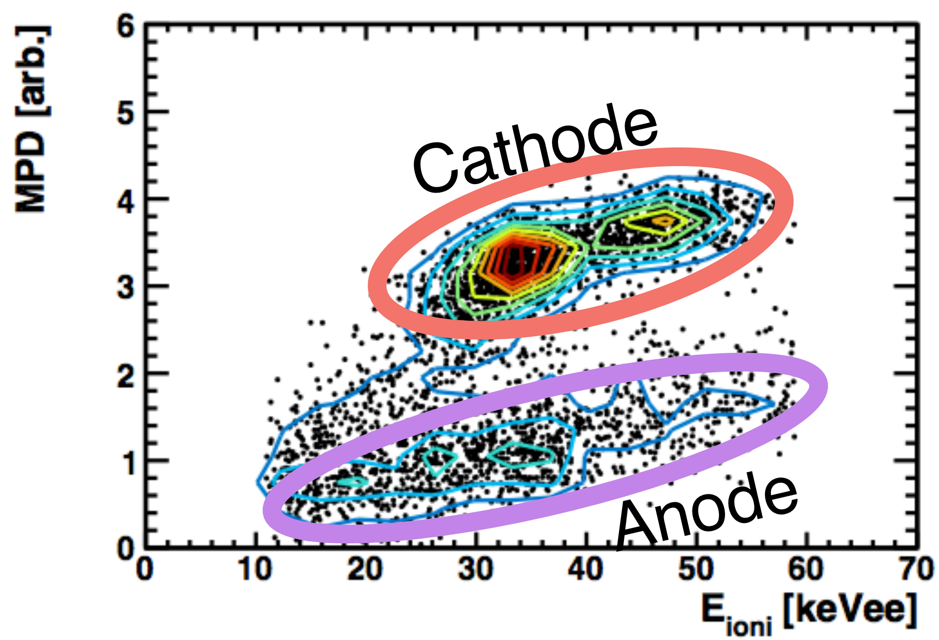
$$\begin{cases} D_T = 237.9\,\mu\text{m}/\sqrt{\text{cm}} \\ D_L = 271.5\,\mu\text{m}/\sqrt{\text{cm}} \end{cases}$$

« Grid » event



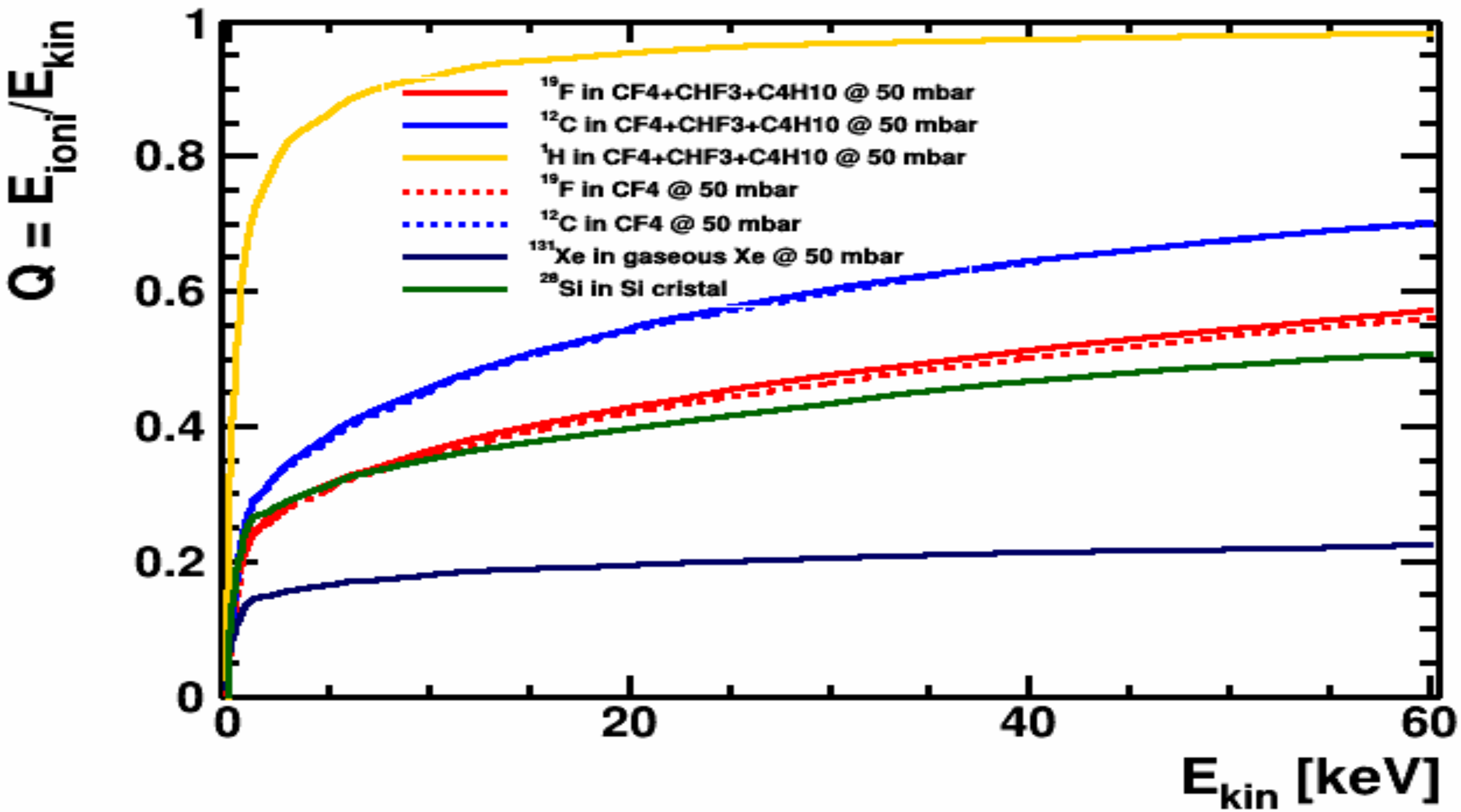
Mean Projected Diffusion: $\overline{\mathcal{D}} = \ln\left(\overline{\Delta X} \times \overline{\Delta Y}\right)$





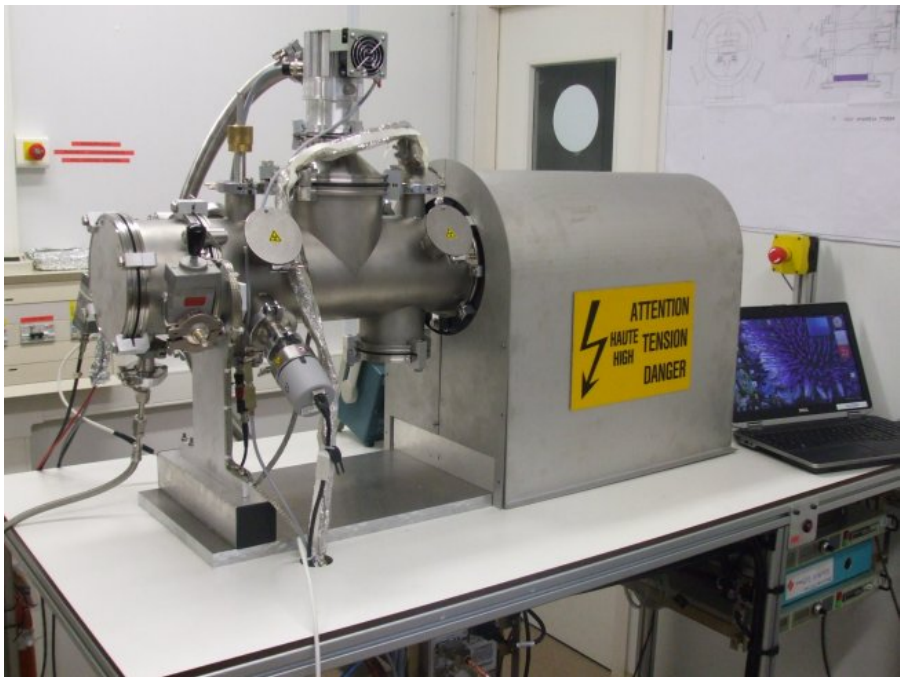
Ionization Quenching Factors

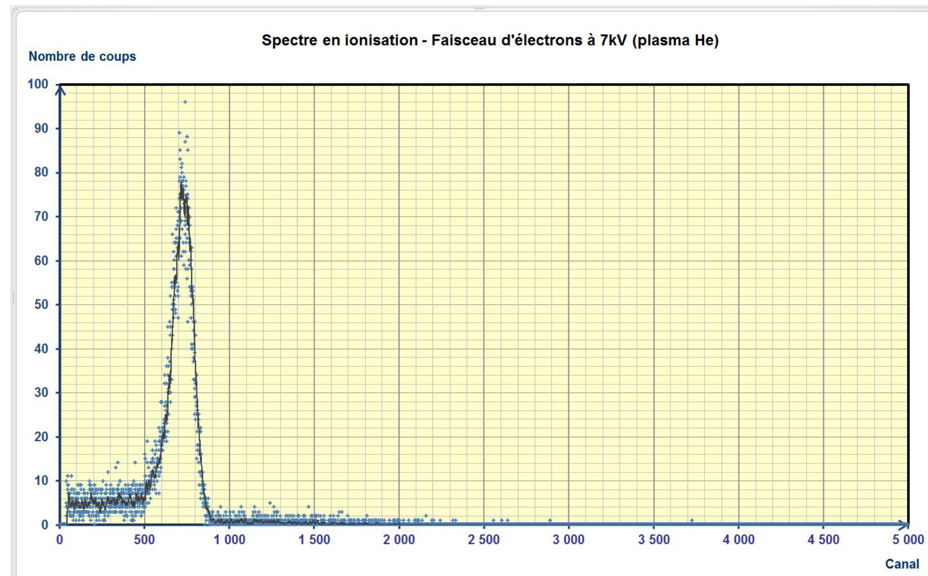
SRIM-Simulations (LPSC)



Portable Quenching Facility (COMIMAC)

(Electrons and Nuclei of known energies)

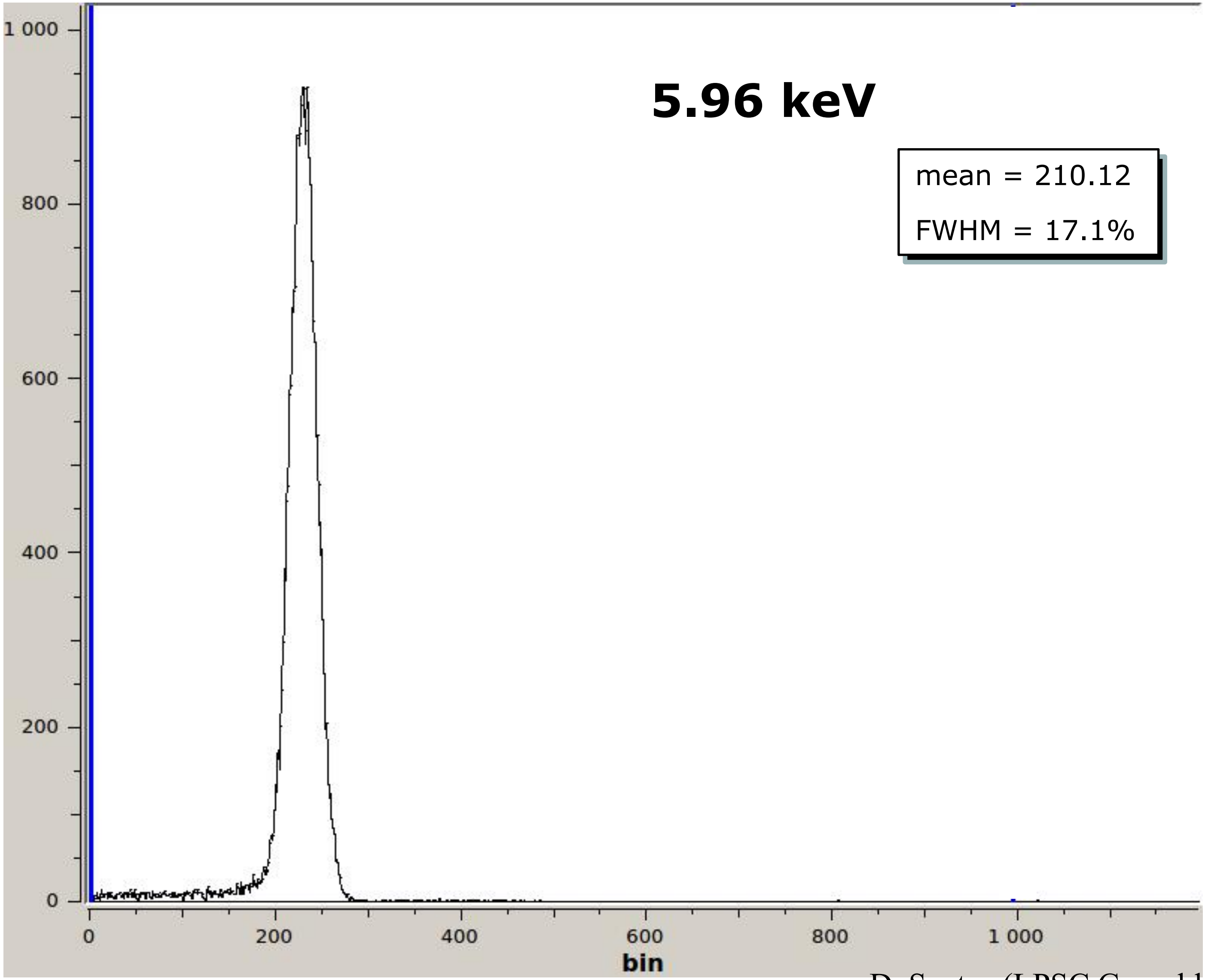




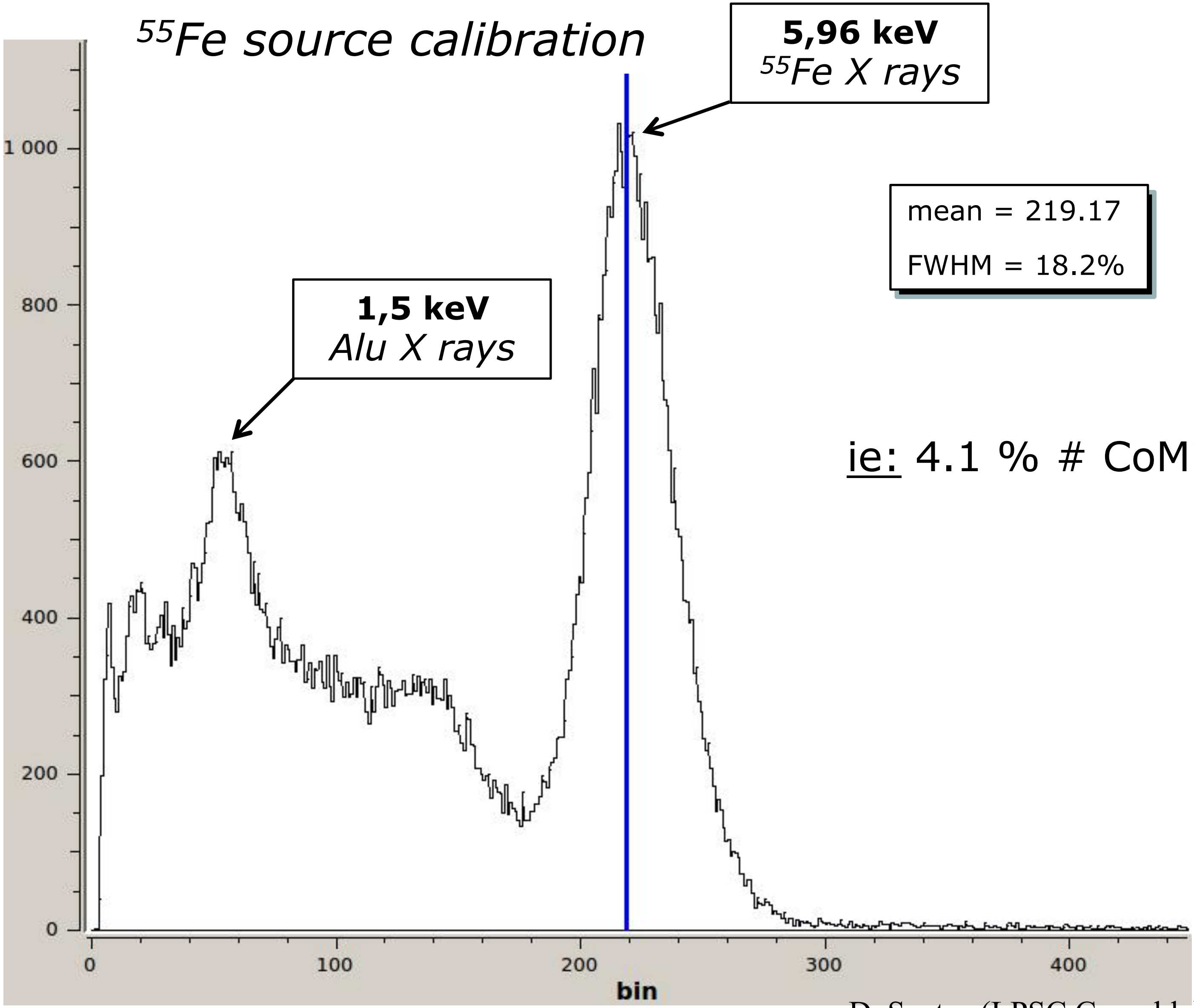
Electrons of 7 keV

In a gas detector the IQF depends strongly on the quality of the gas.
The IQF needs to be measured periodically (in-situ) in a long term run experiment.

Electrons Performance

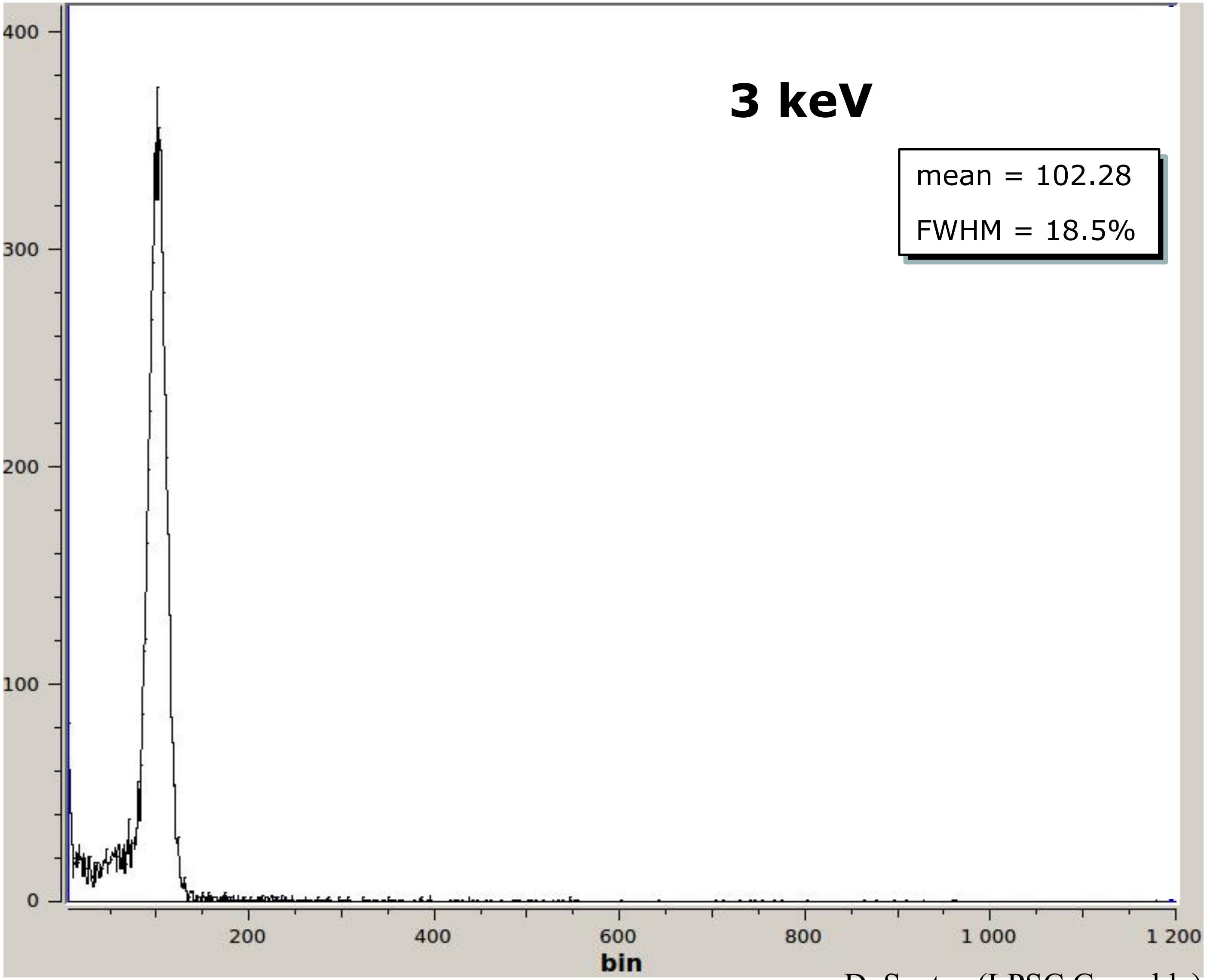


Electrons Performance

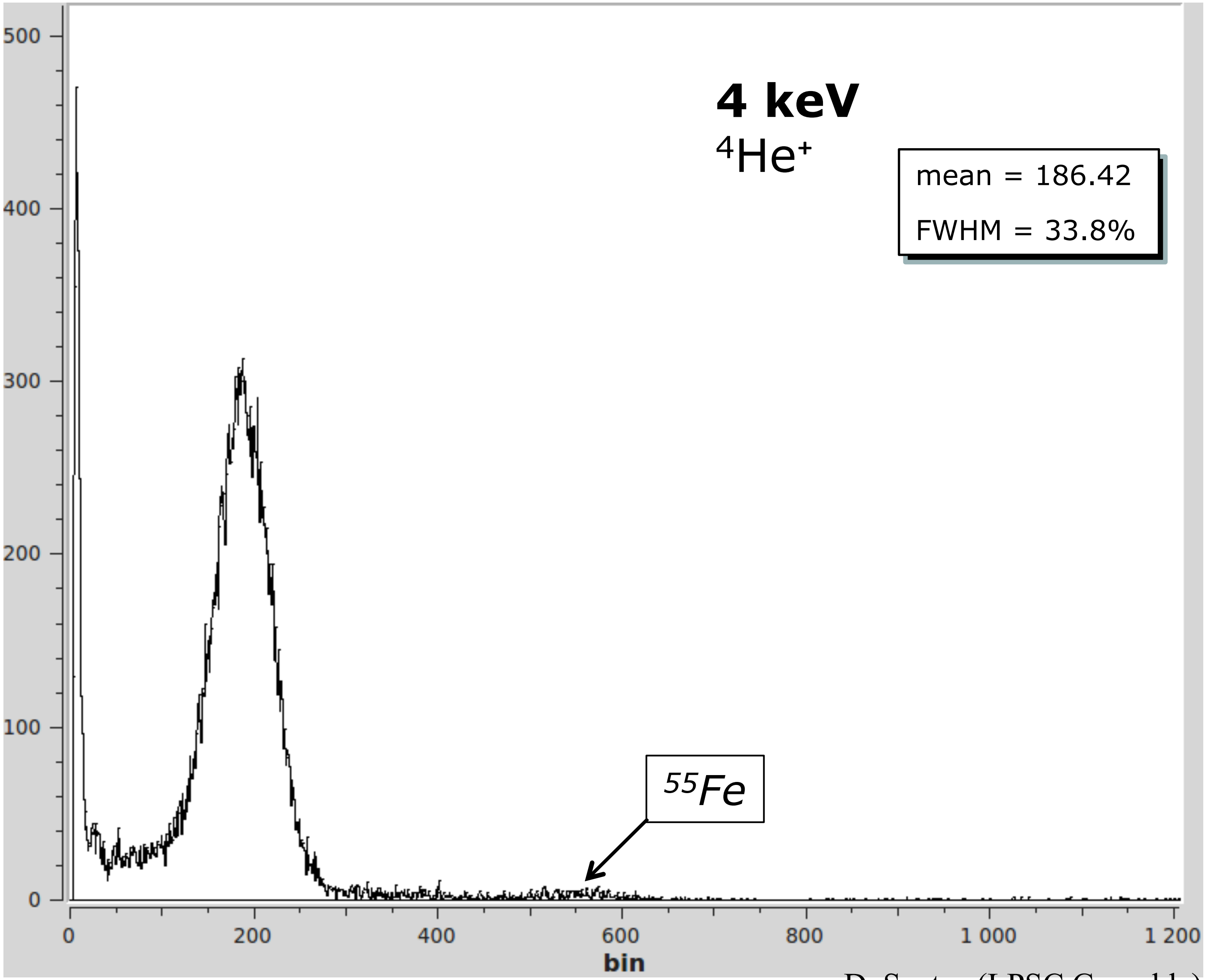


ie: 4.1 % # CoMimac

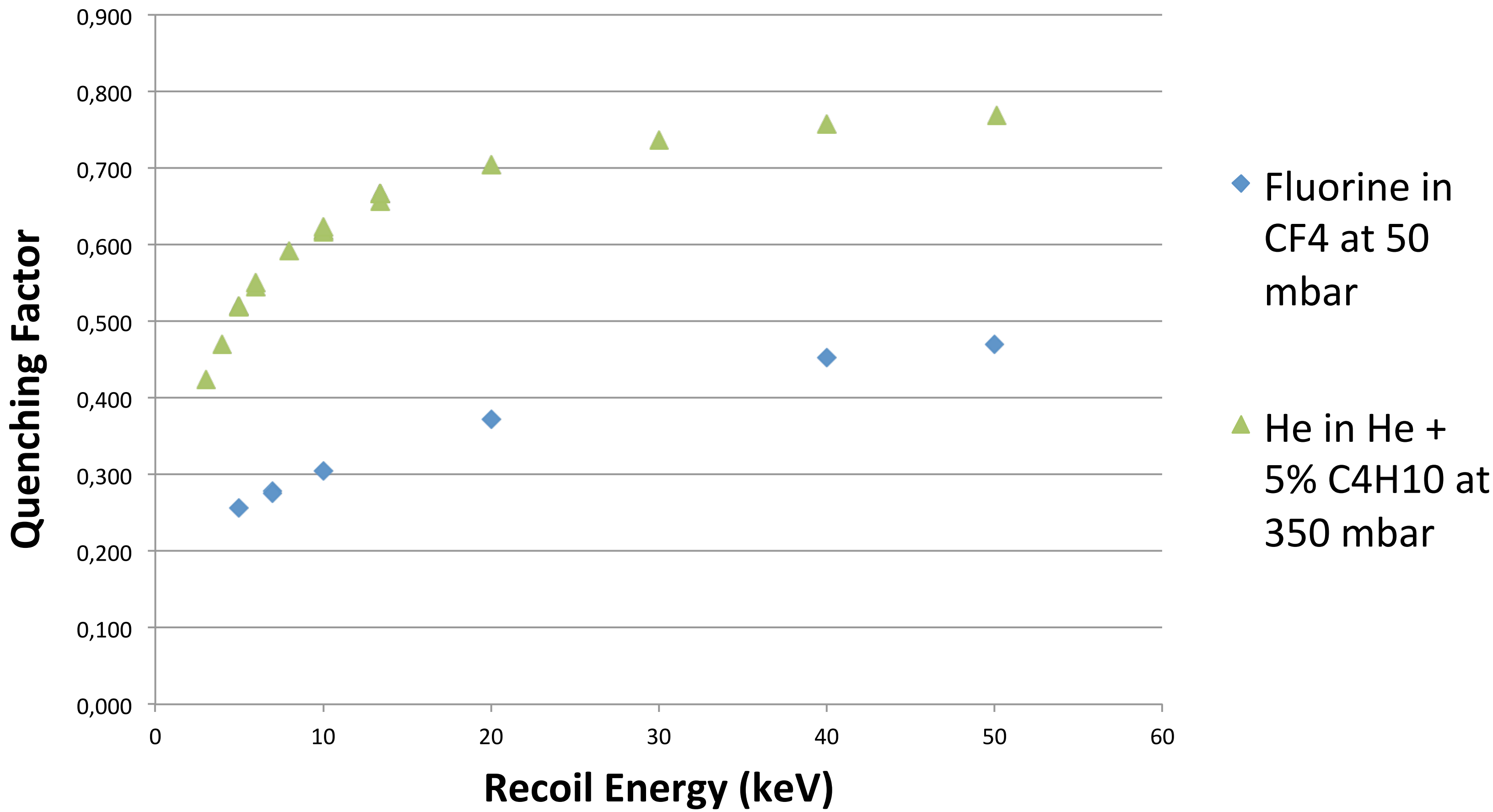
Electrons Performance



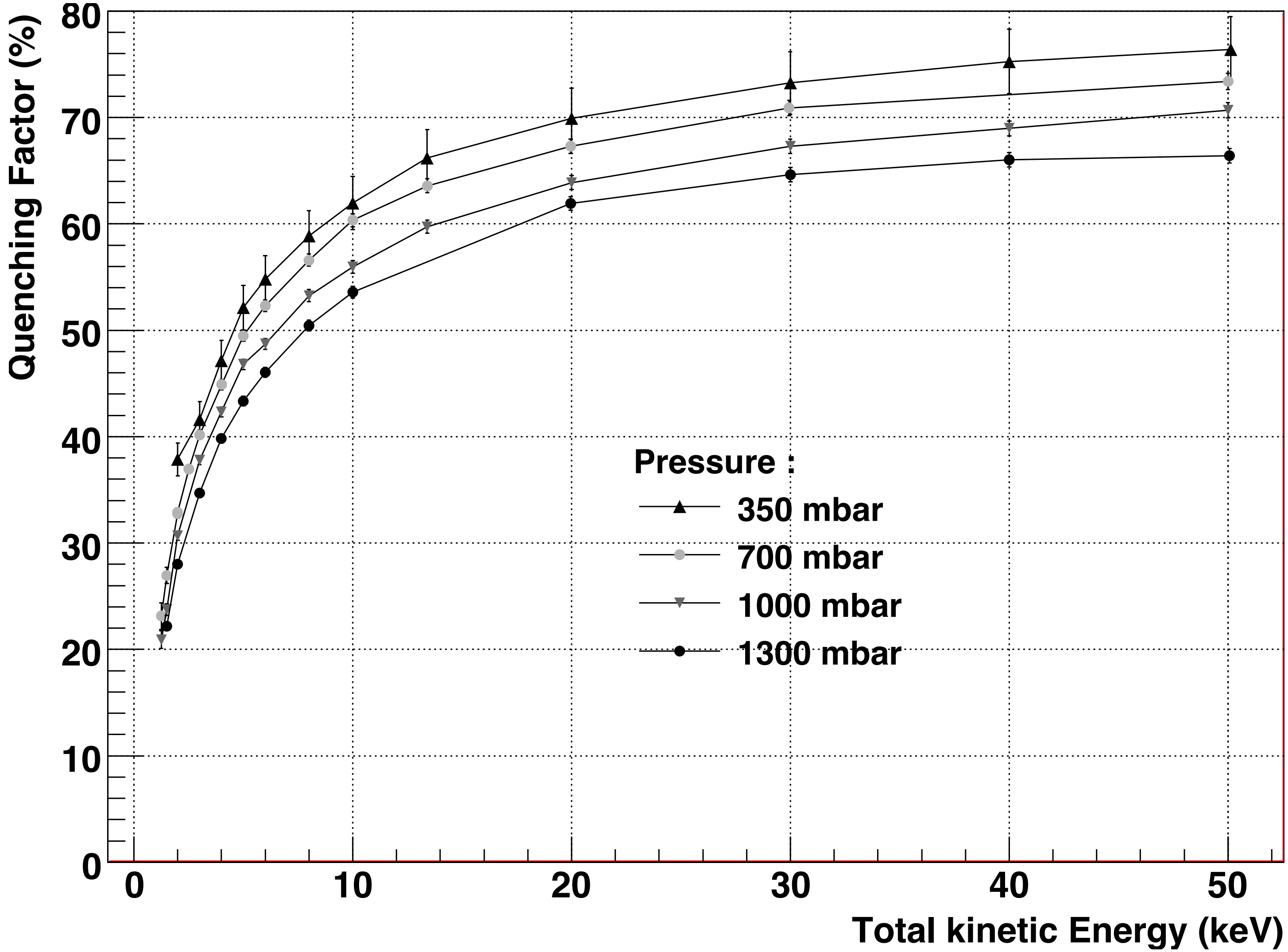
Ions Performance



Ionization Quenching Factor for Fluorine in pure CF4 at 50 mbar



IQF in ^{4}He + 5% isobutane for different pressures!!



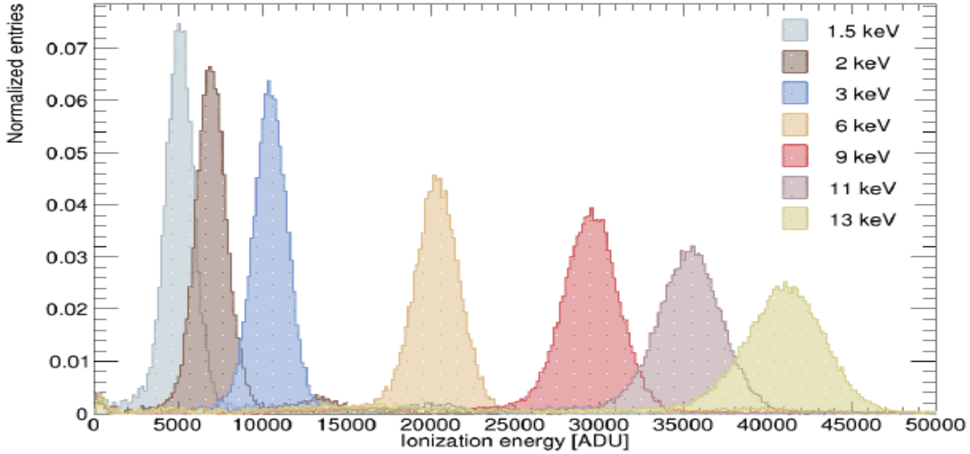
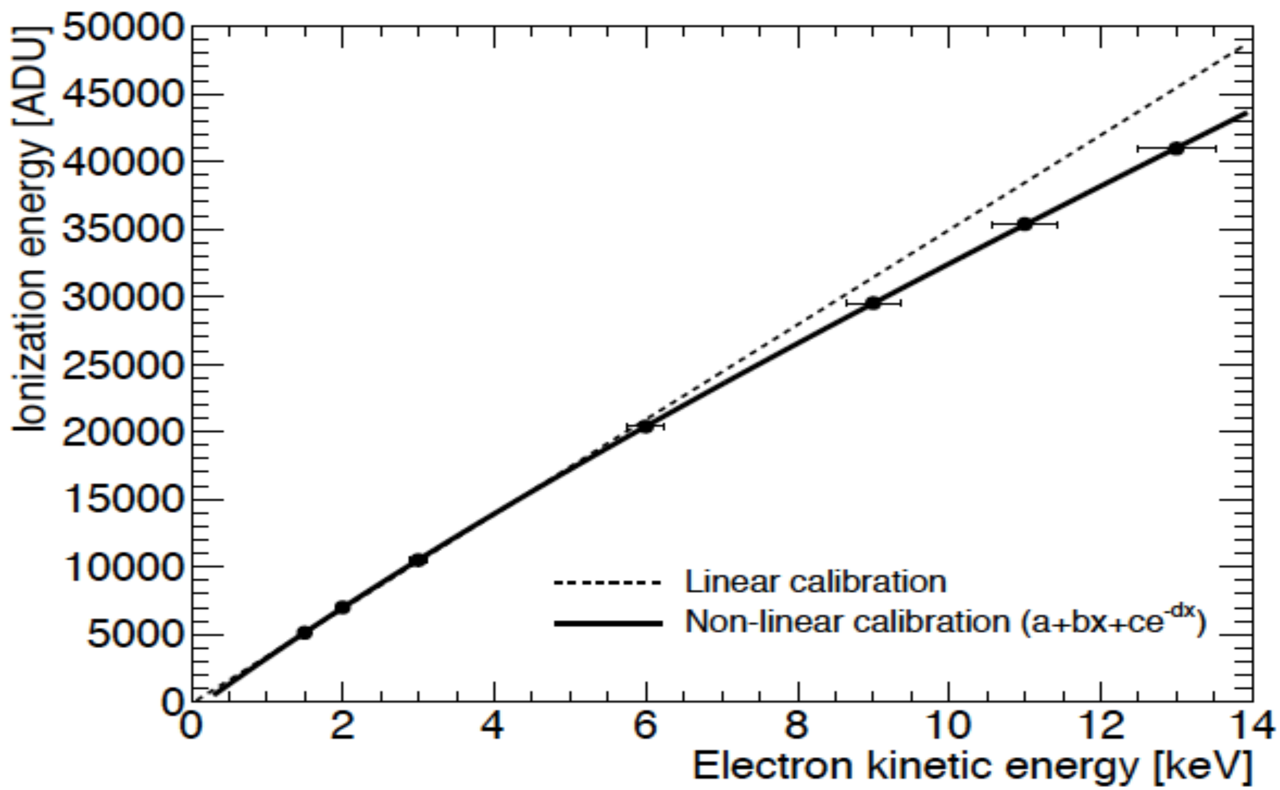


Fig. 5: Complete set of energy spectra used for the calibration of the detector response. The kinetic energy is determined by the Comimac facility. The cosmic background has been subtracted but no cut is applied.

Electron Calibration with COMIMAC of a 30 cm diameter Sphere with an akinos sensor

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 to be published in EPJ-C)

Ionization Quenchin Factor Measurements with COMIMAC
(NEWS-G collaboration, arXiv 2201.09566 to be published in ERJ-C)

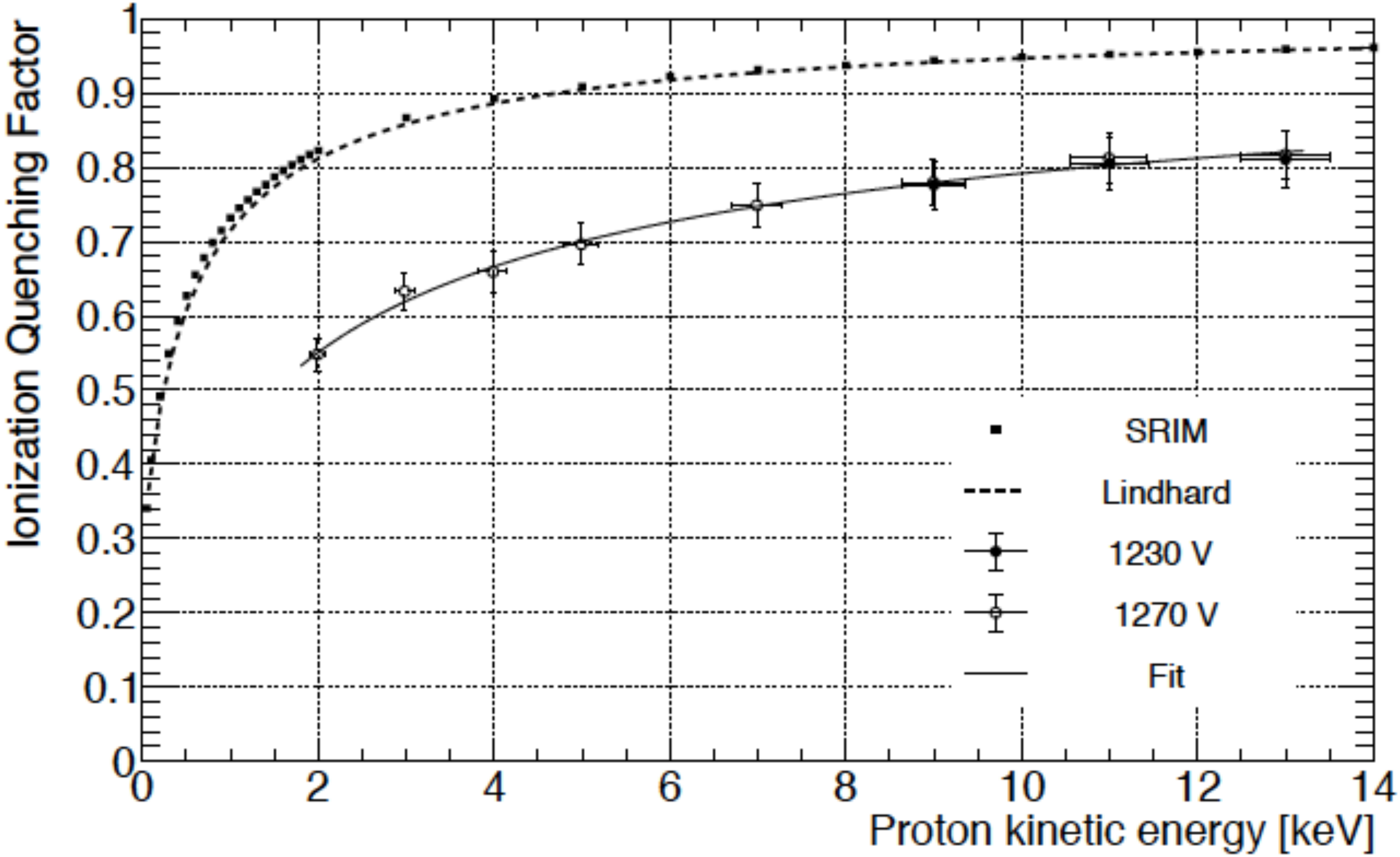
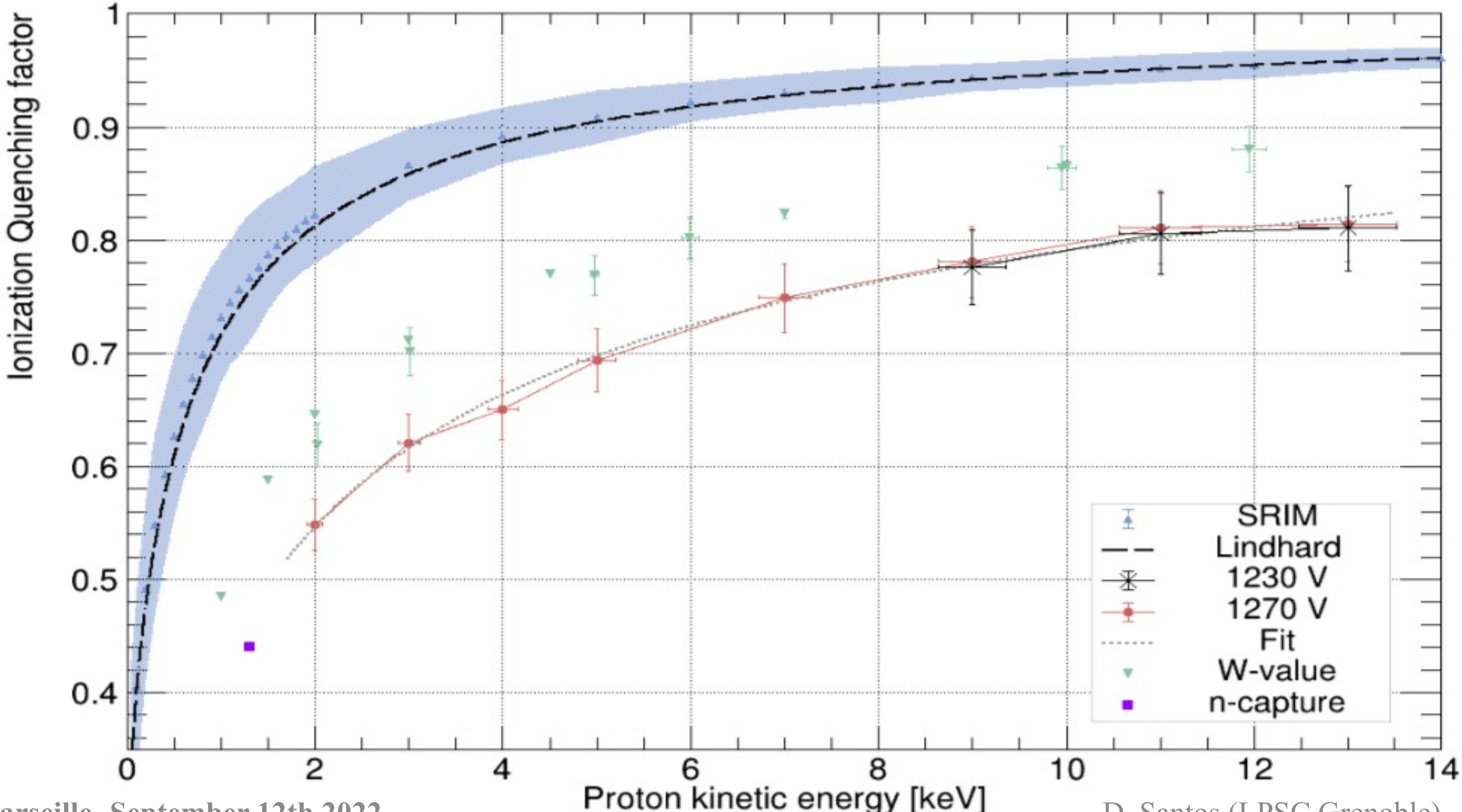


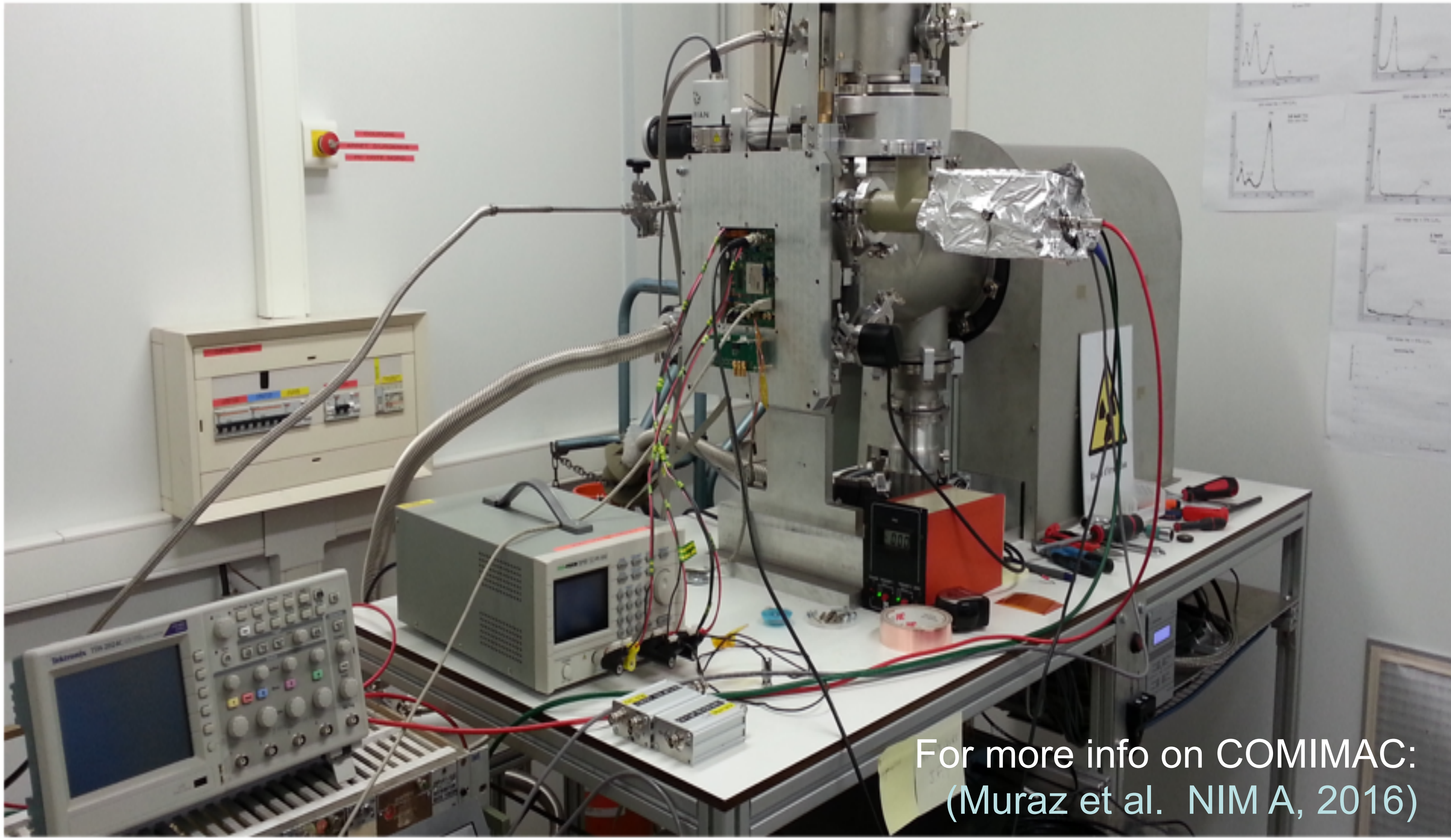
Fig. 9: Ionization Quenching Factor for protons in 100 mbar of methane. The measurements at 1230 V and 1270 V are respectively presented with black dots and white dots. Comparisons with SRIM and with the Lindhard theory are also shown.

Compared with our IQF measurements in CH_4 is just an overestimation…

IQF



First controlled Fluorine tracks, using COMIMAC

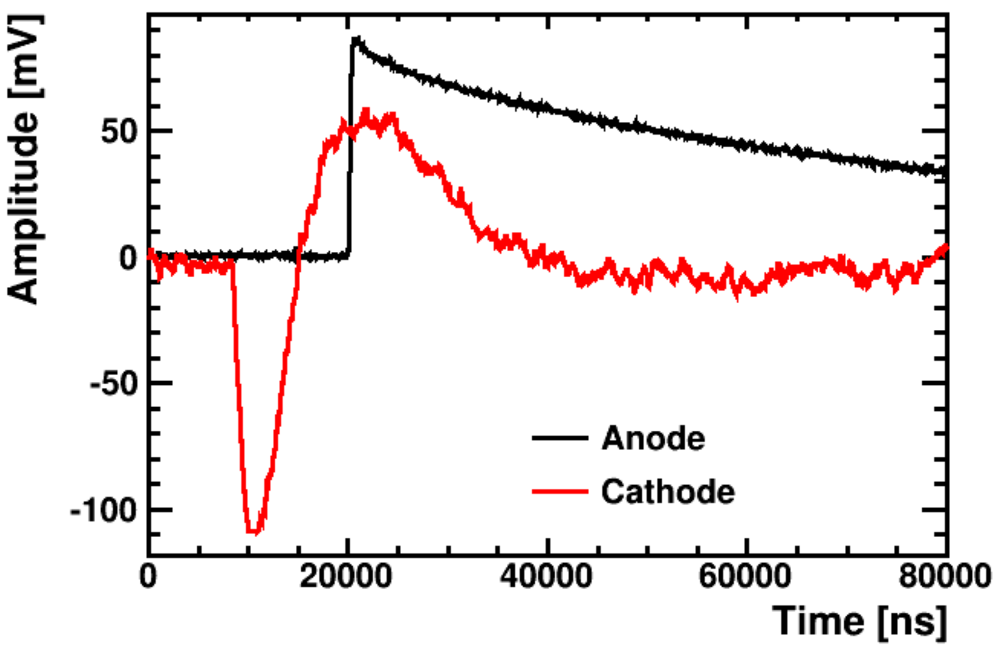


For more info on COMIMAC:
(Muraz et al. NIM A, 2016)

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)

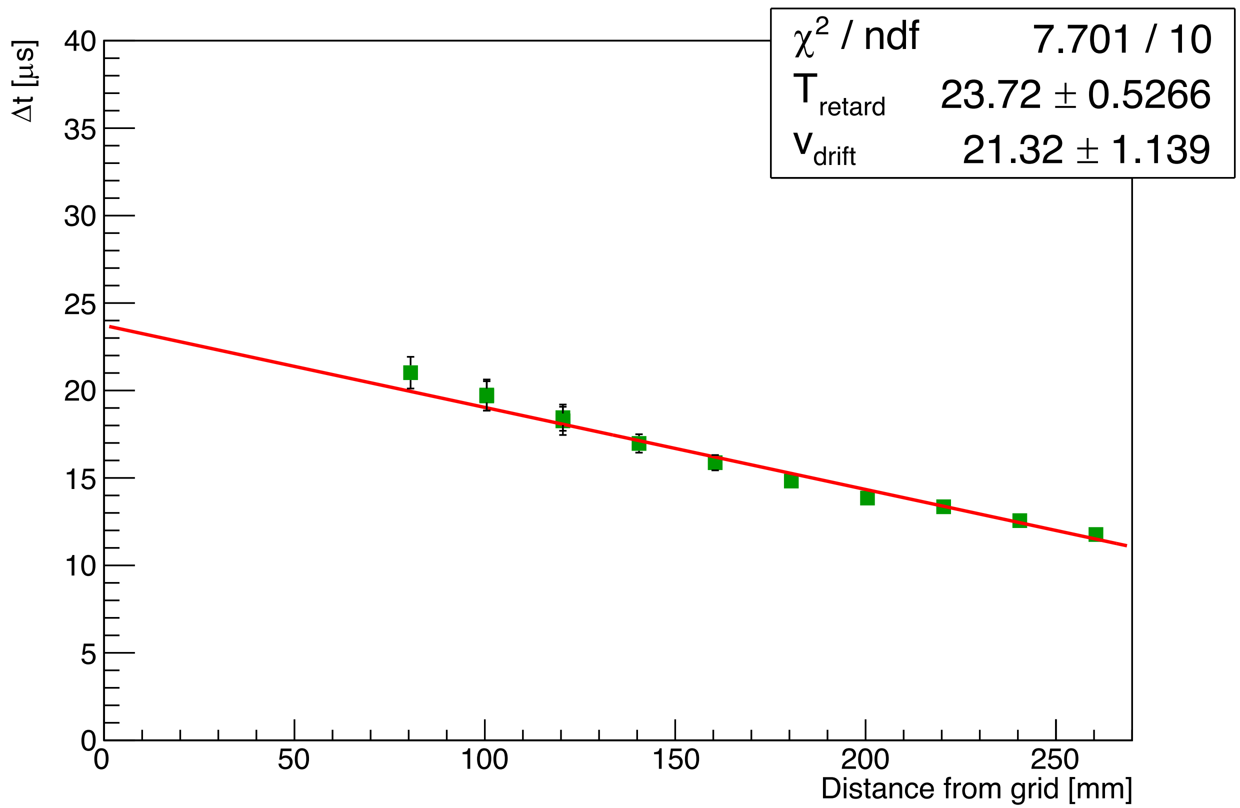
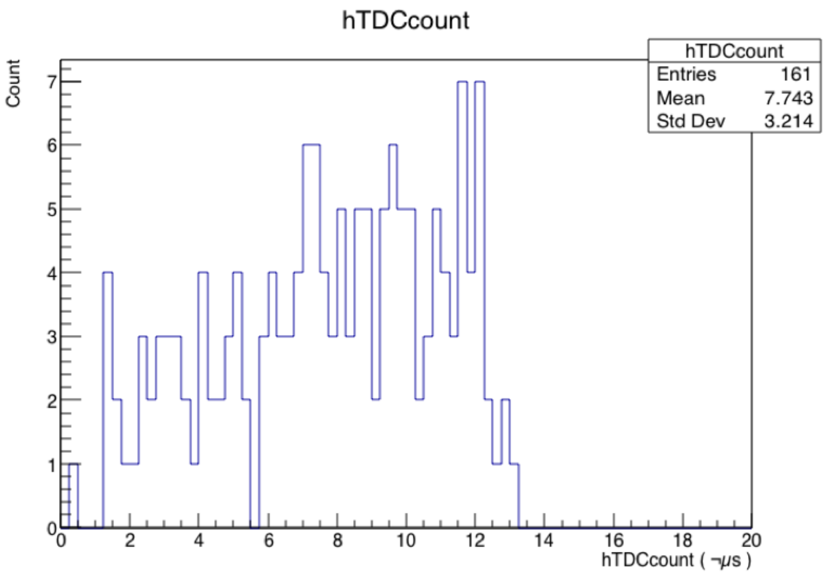


Figure 4. Measure of the time differences (TAC) between the grid signal and the delayed cathode signal in the "START Grid" configuration, as a function of the distance of the α source from the anode (green points) ; error bars correspond to the standard deviation of the mean. A linear fit of these points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

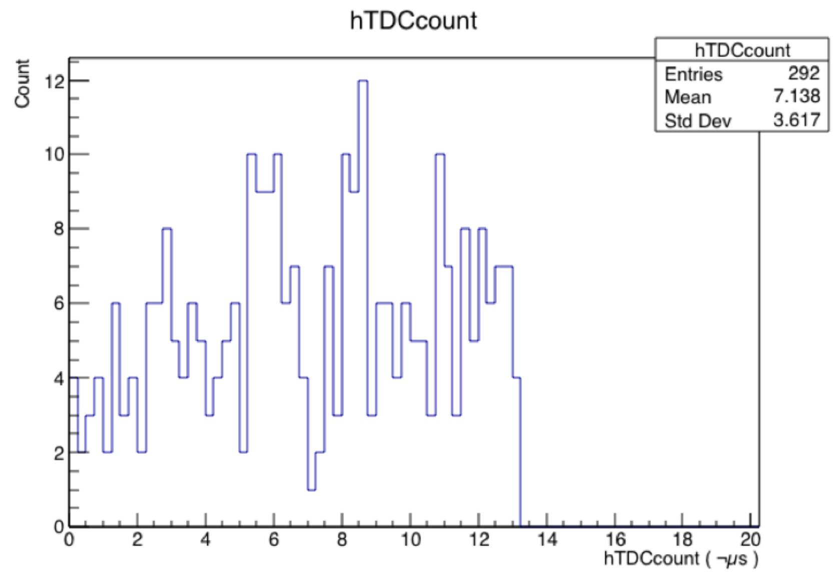
First Cathode Signals from the MIMAC bichamber background

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

Chamber 1

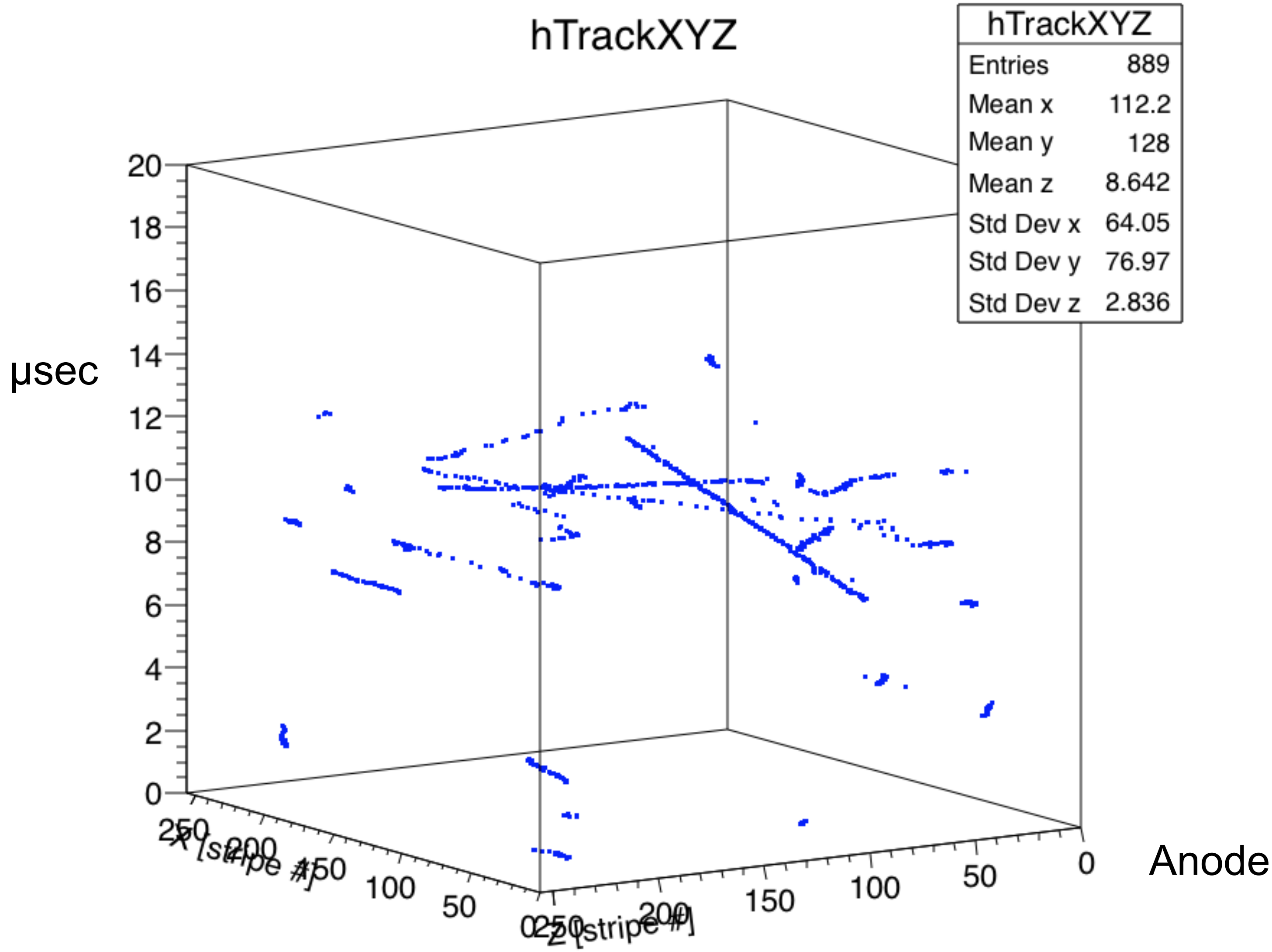


Chamber 2

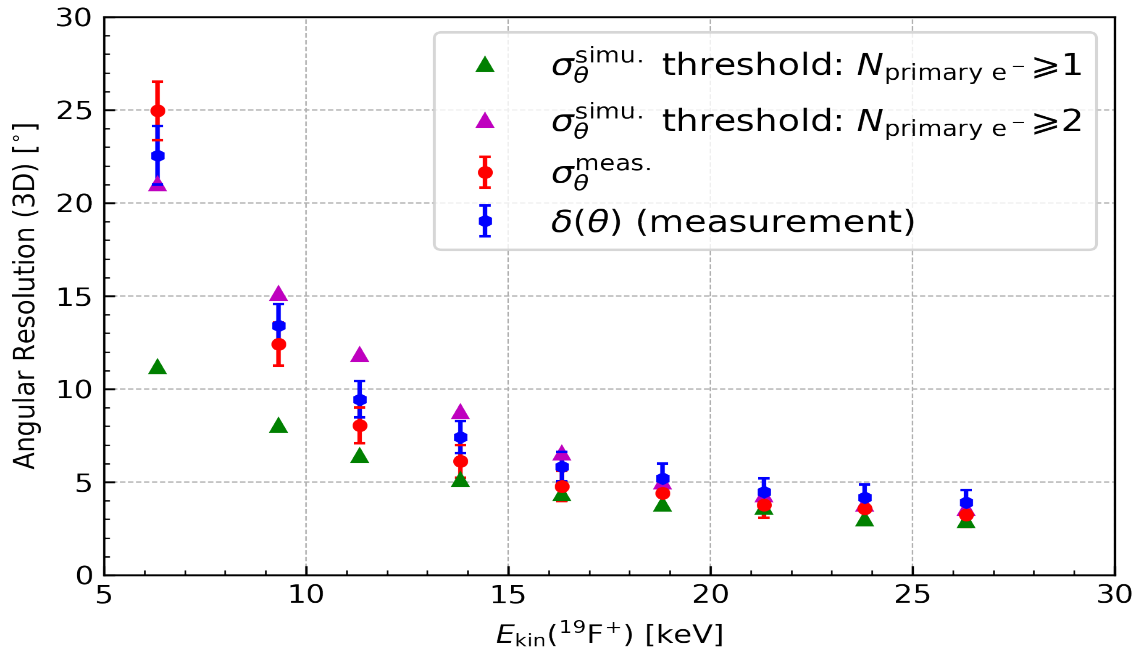


Measuring the time between the “event production” and the avalanche signal !!
Covering the 26 cm drift distance (13 us x 20 um/ns) !!

3D event-localization in MIMAC



Directionality at high gain - Diffusion and angular resolution



Measured and simulated angular resolution at 0°

Tao Yi *et al.*, 2003.11812

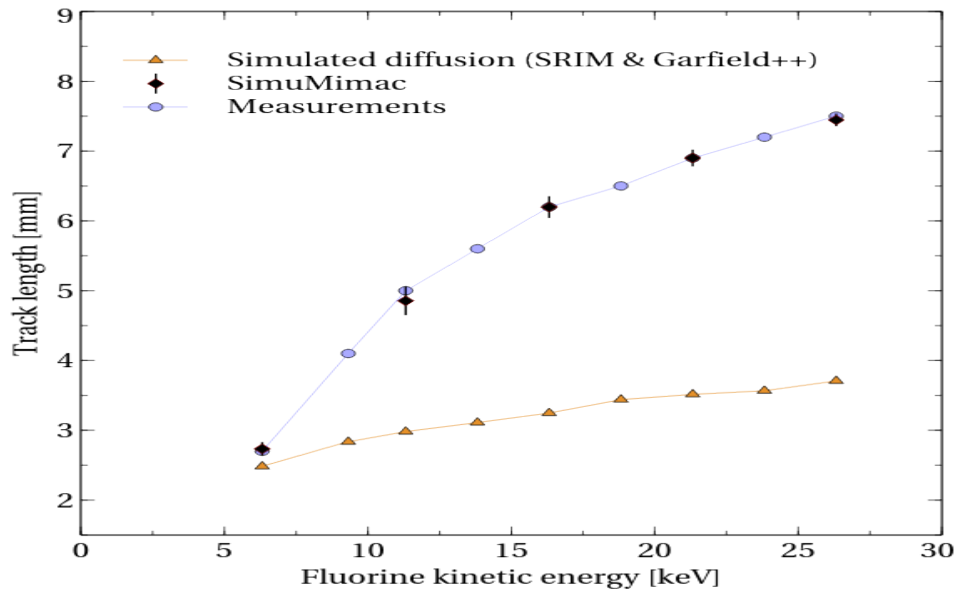
For fluorine ions, we measured an angular resolution below 10° for $E_K >$ 10 keV

$=\Rightarrow$ **Twice better than requirements** for a directional detector (Billard *et al.*, 1110.6079)

$=\Rightarrow$ 0° is the optimal configuration, the resolution must now be determined at any angle

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

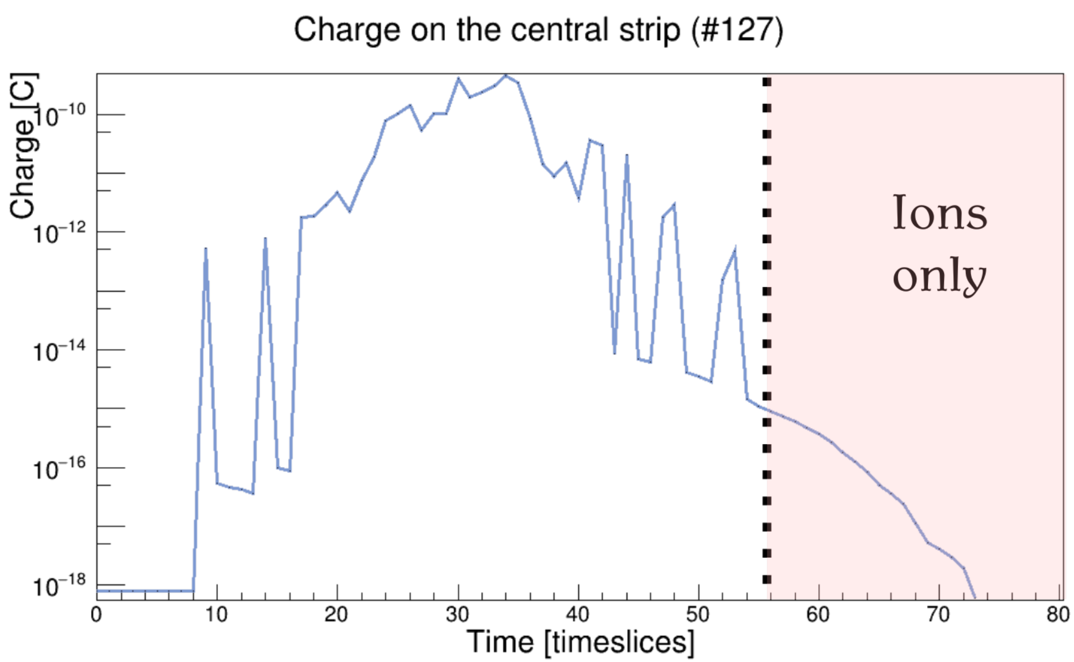
- SimuMimac agrees with the measurements
- Main difference with standard simulation code = **takes into account the current induced by the motion of the ions**

Directionality at high gain – SimuMimac

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

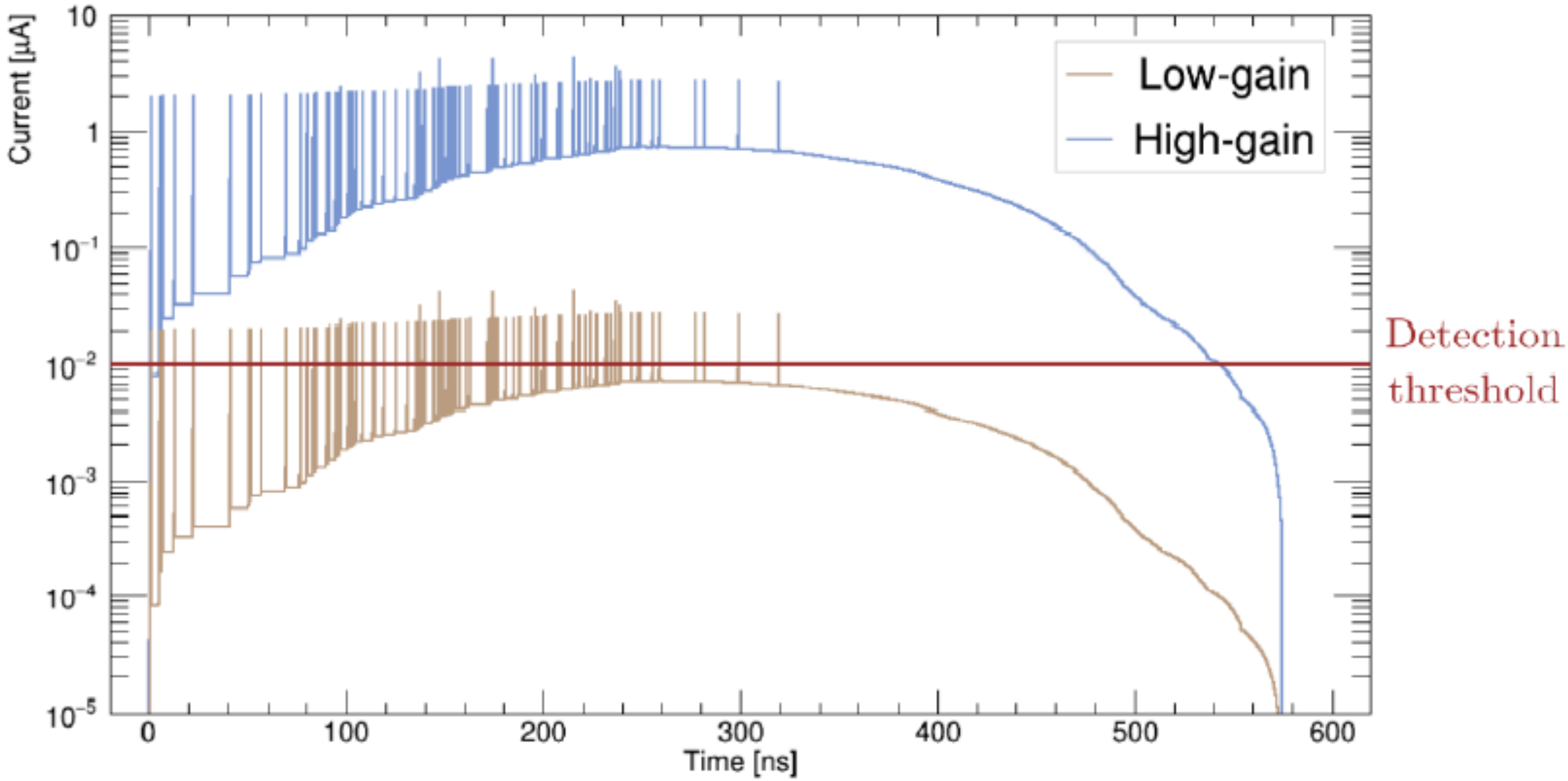
  $$i(t) = \sum_{k=i,e} q_k \mathbf{E}_{w,k} \cdot \mathbf{v}_k \text{ with } \mathbf{v}_e \sim 10^3 \mathbf{v}_i$$

- 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**

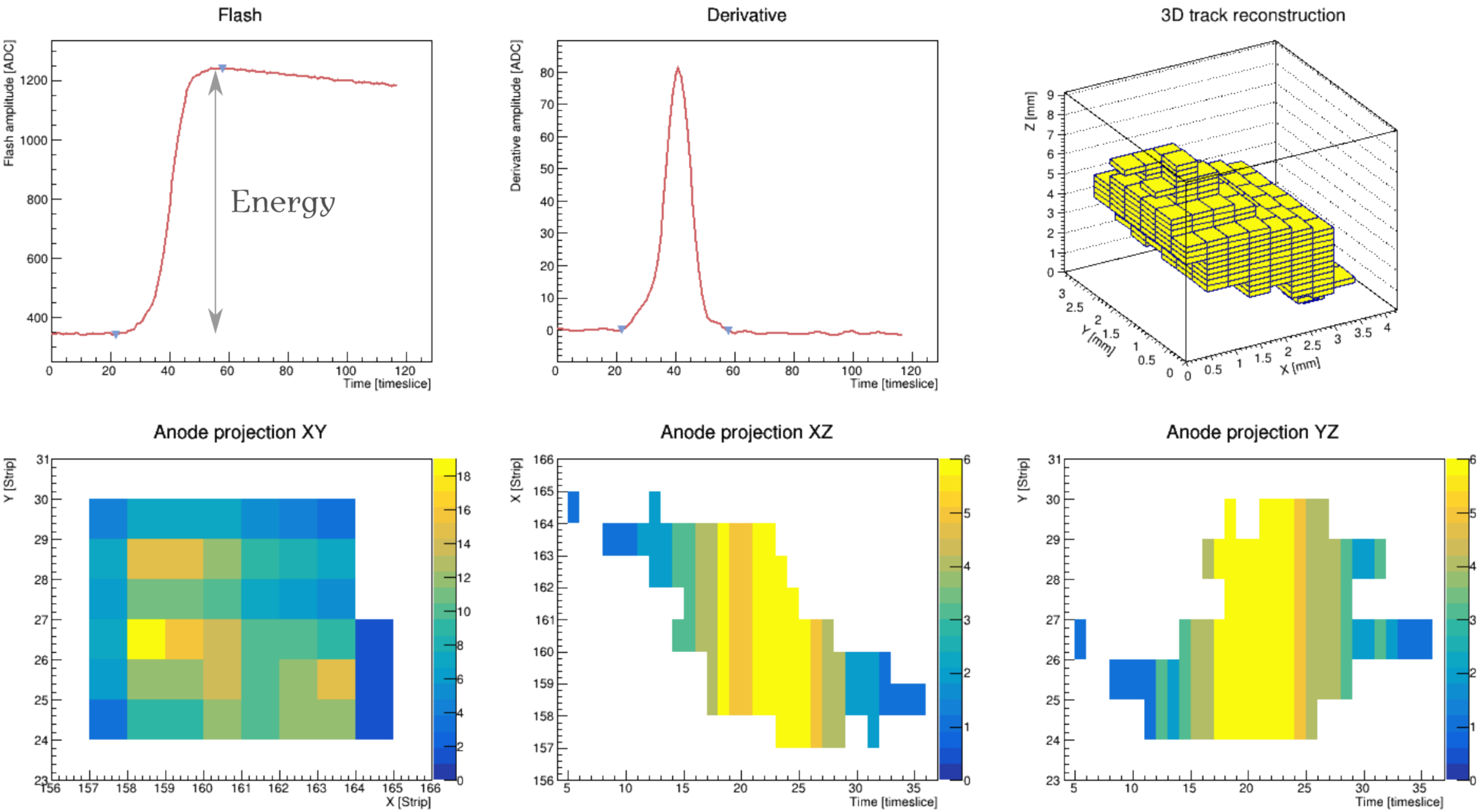


D. Santos (LPSC Grenoble)

Signal contributions at high-gain
(primary electrons and secondary ions)
Cyprien Beaufort et al. arxiv.org/2112.12469

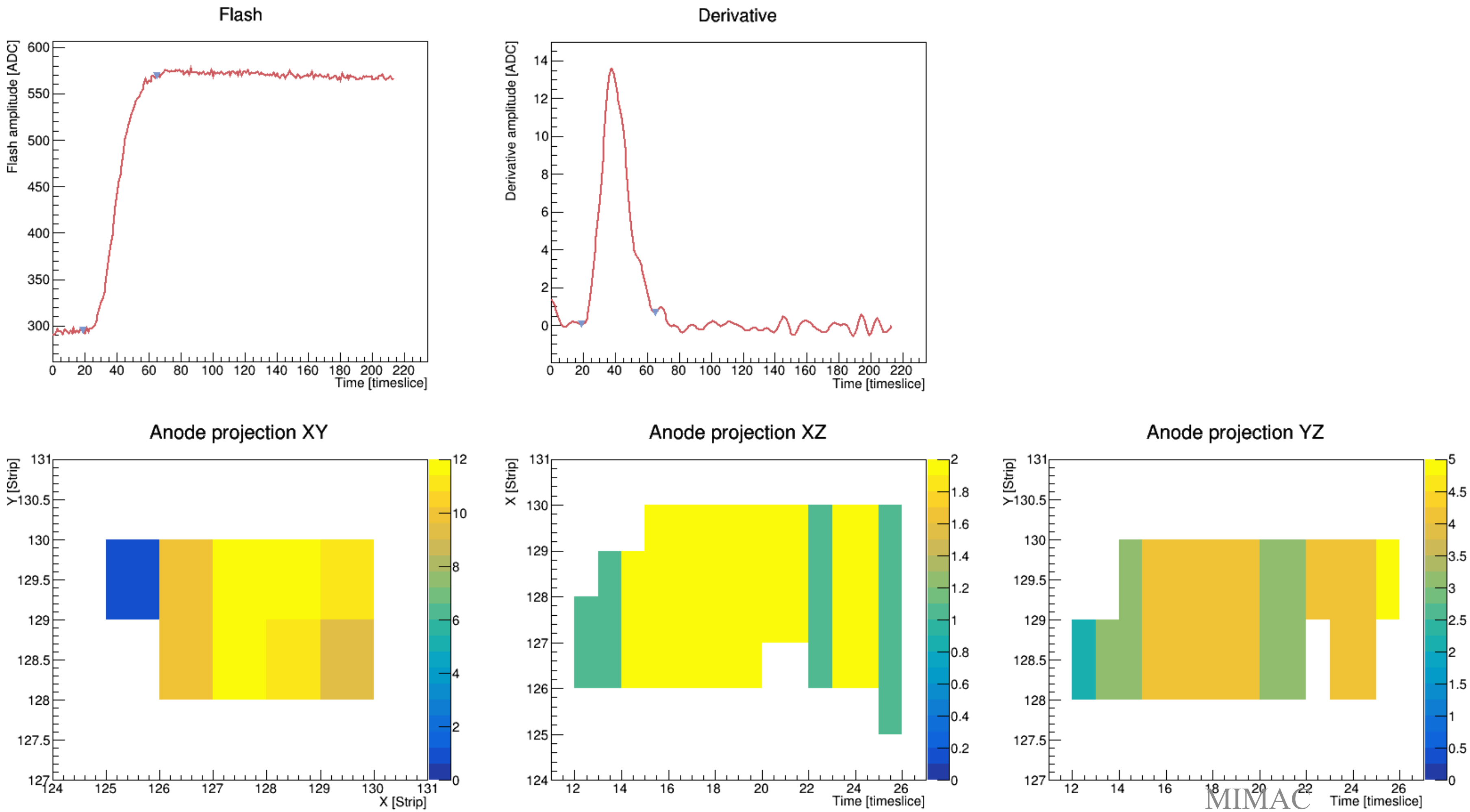


Example of a proton recoil of $6\ \mathrm{keV_{ee}}$ $(8.6\ \mathrm{keV_{nr}})$



$-\rightarrow$ Sampling at 50 MHz (20 ns)

150 eV 3D- Electron track produced by COMIMAC detected by one MIMAC chamber (C_4H_{10}+50% CHF_3) at 30 mbar



MIMAC

Nuclear recoil calibration with neutrons

Neutron monochromatic field:

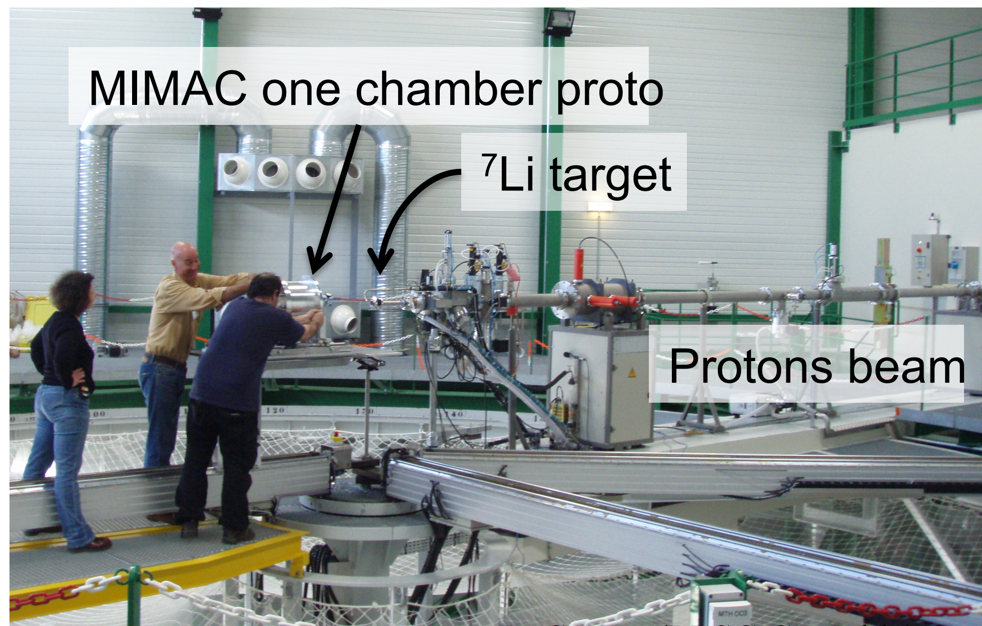
AMANDE facility at IRSN of Cadarache

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

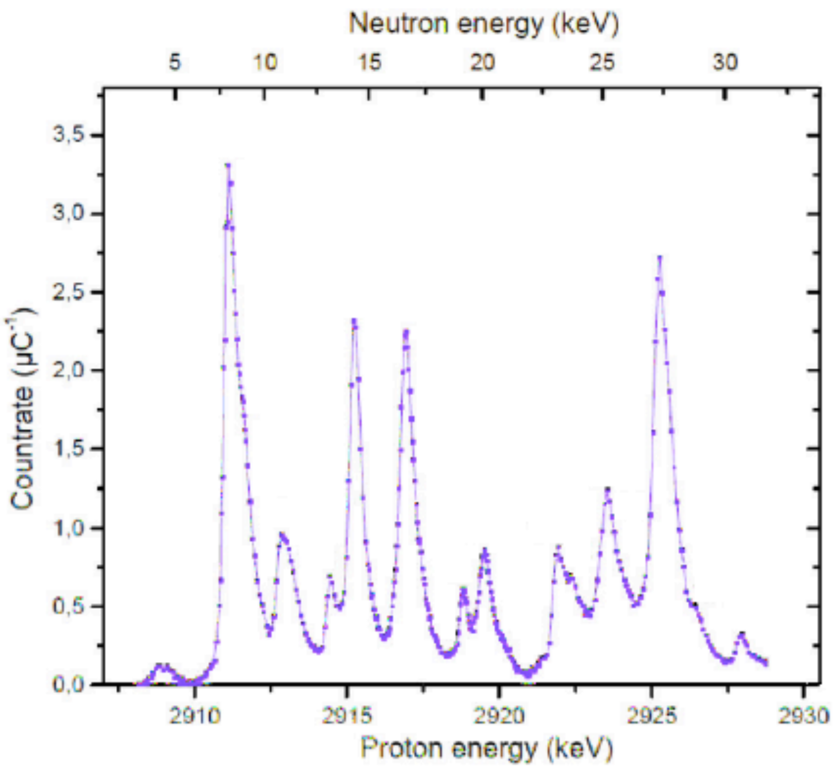
$$E_{\mathrm{Re}coil} = 4\frac{m_n m_R}{(m_n + m_R)^2} E_{neutron} \cos^2\theta$$

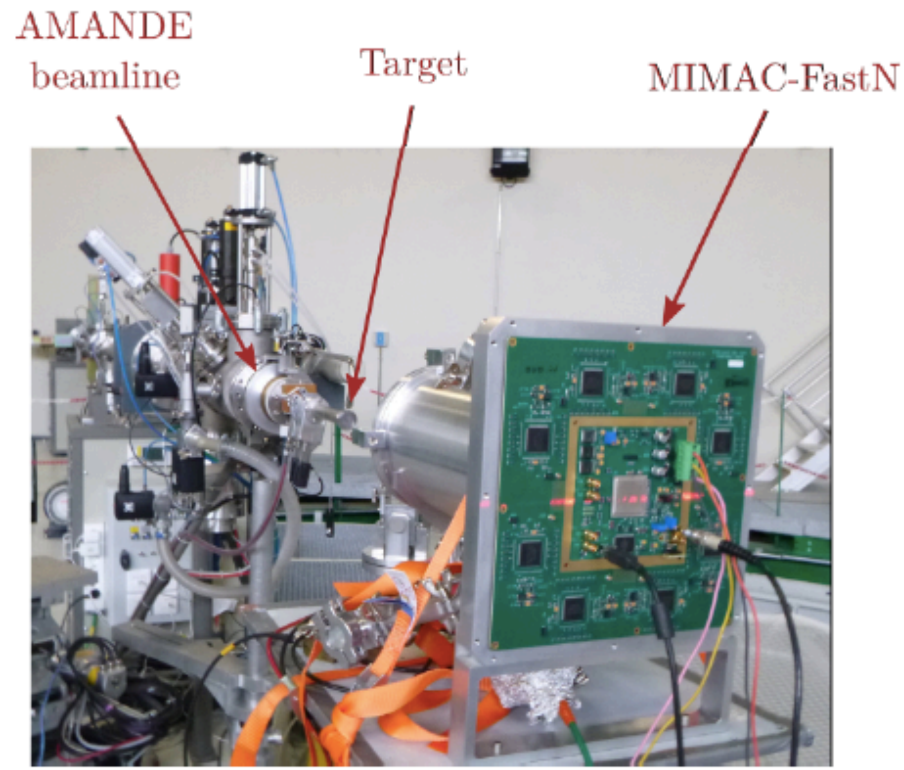
Electron Calibration:

^{55}Fe (5.9 keV) and ^{109}Cd (3.1 keV) sources



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

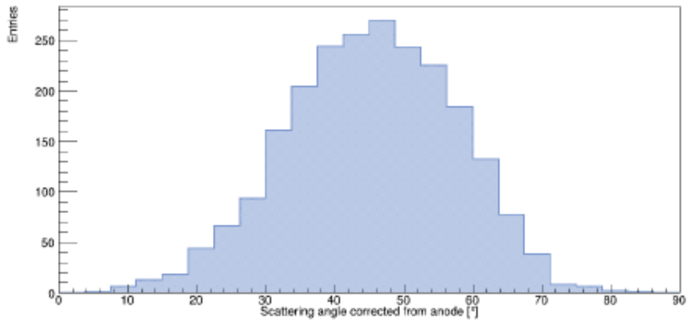


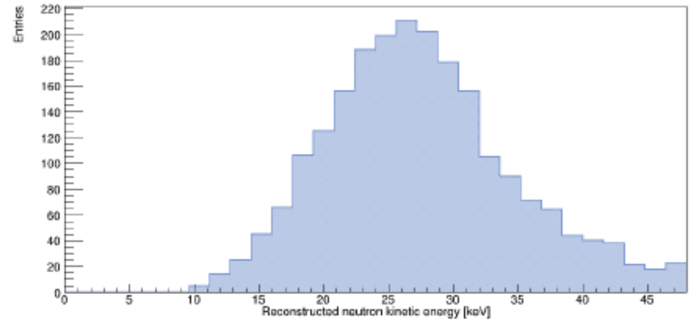


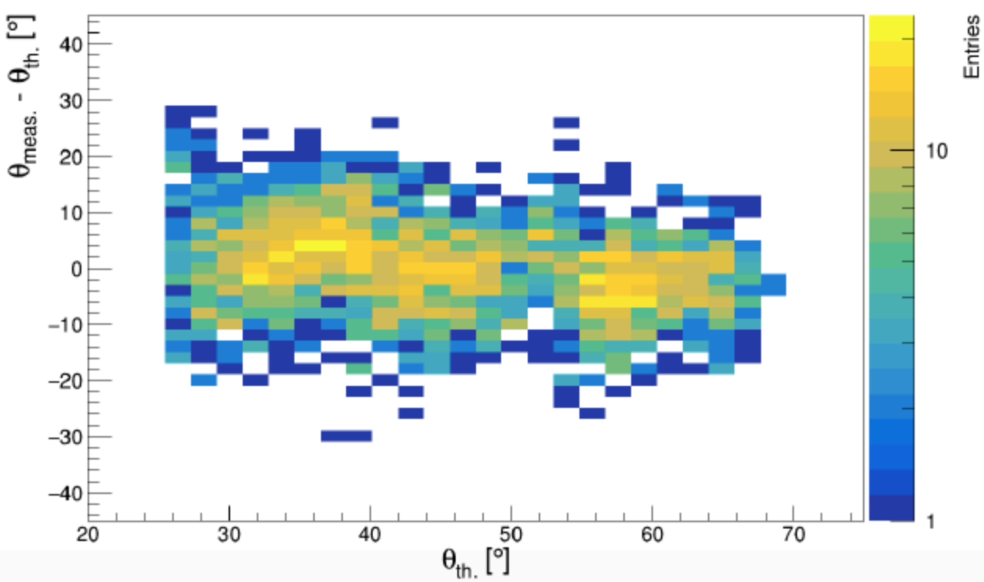
$^{45}Sc(p,n)$ neutron resonances

Proton recoil Angular Distribution produced by 27 keV neutrons

Cyprien Beaufort et al, https://arxiv.org/abs/2112.12469

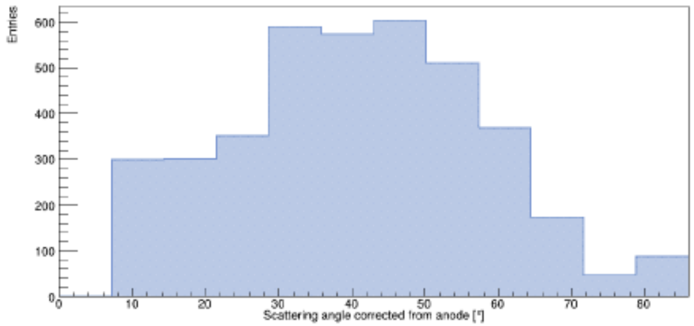


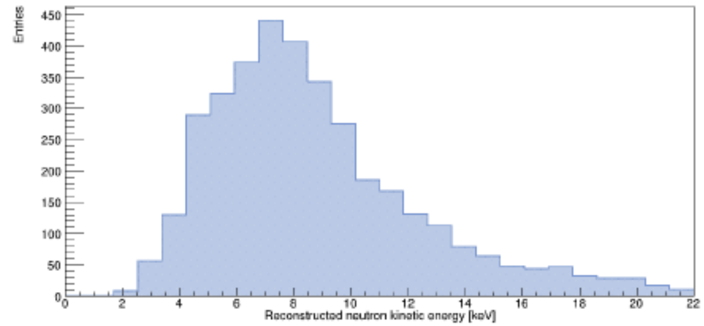


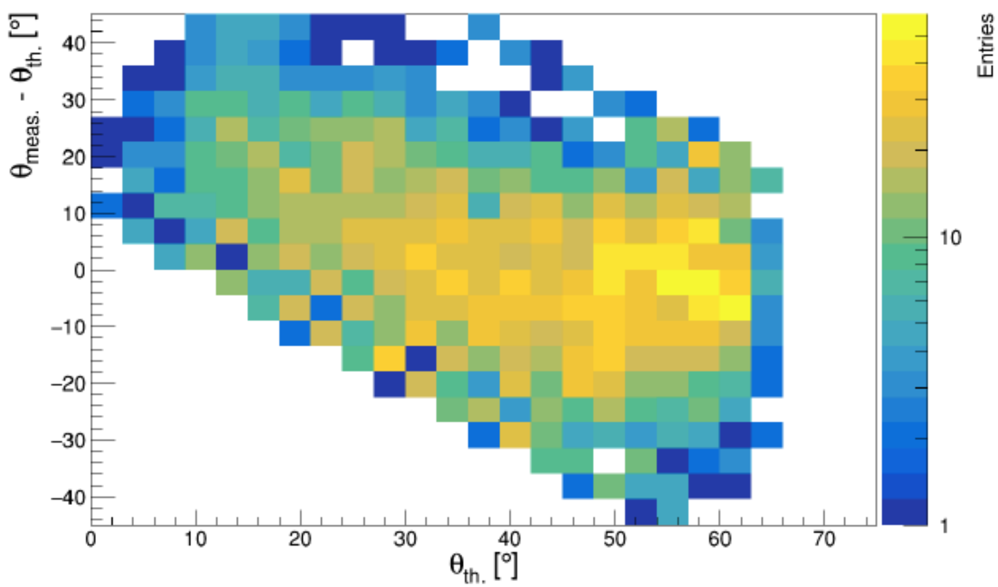


Proton recoil Angular Distribution produced by 8 keV neutrons

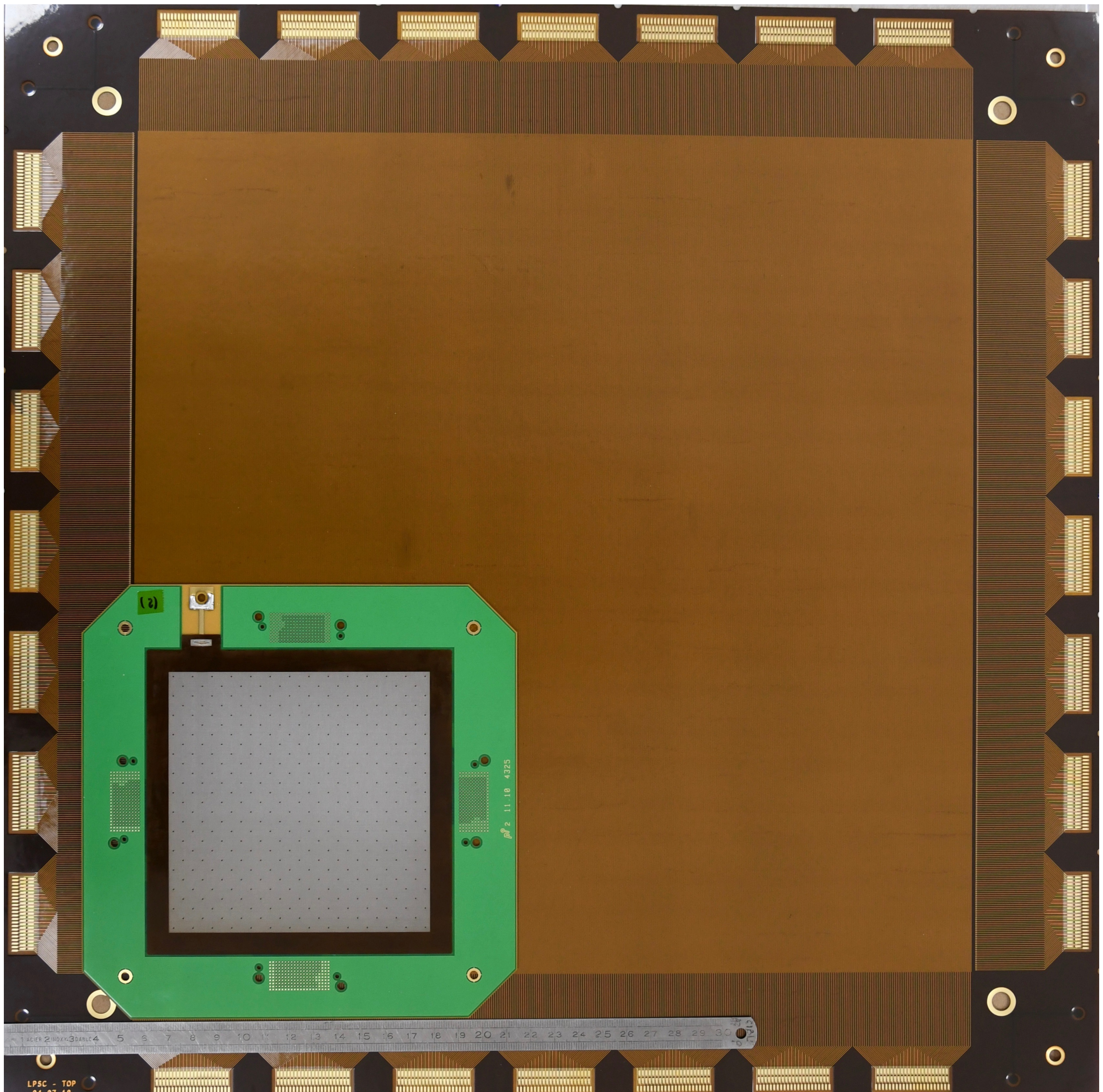
Cyprien Beaufort et al.,arxiv.org/2112.12469

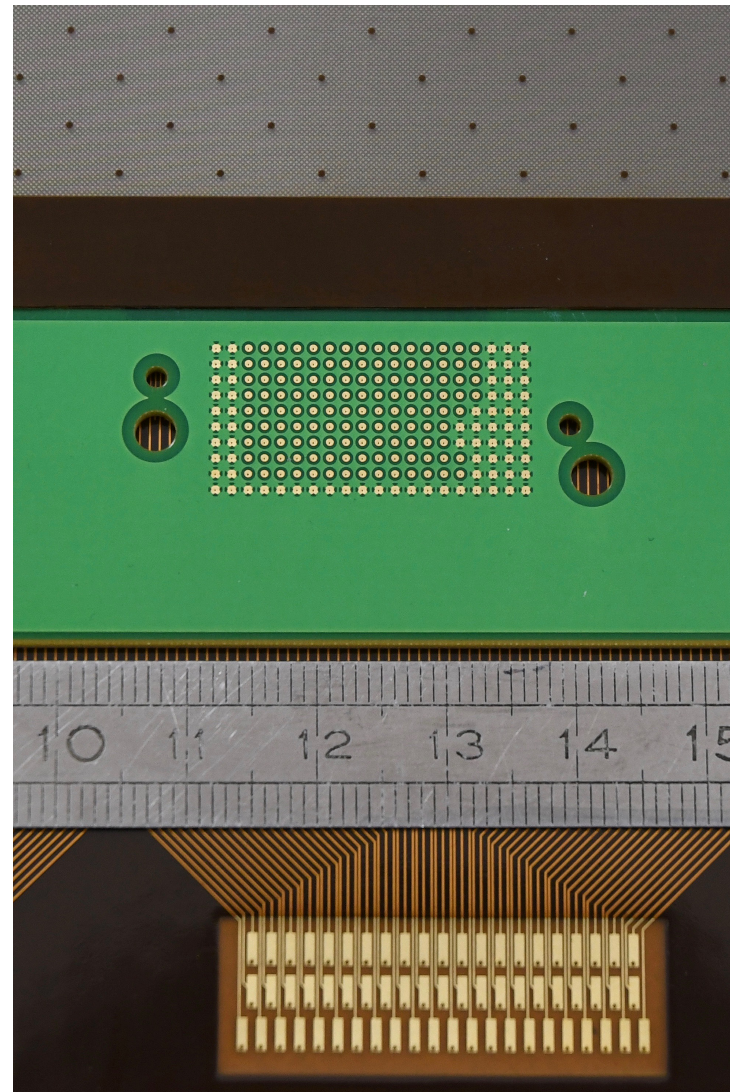




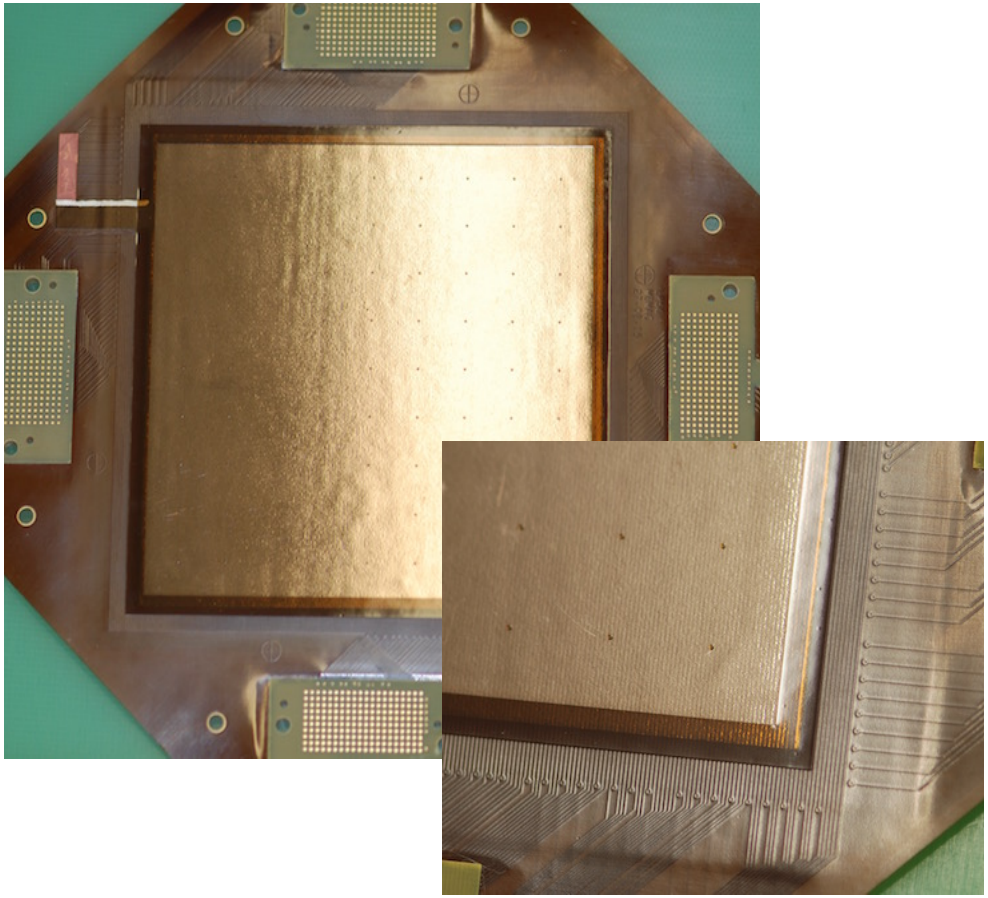


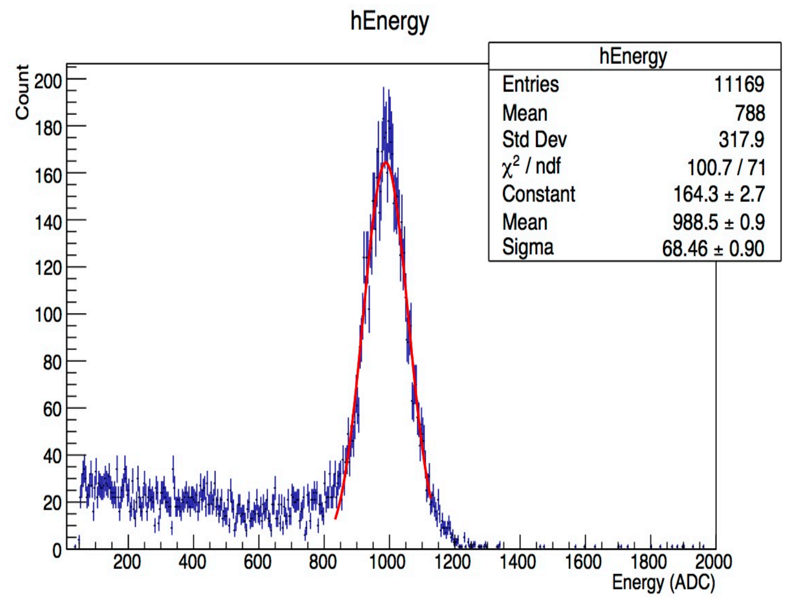
The new 35 cm “new technology” MIMAC detector compared to the old one





New MIMAC low background detector



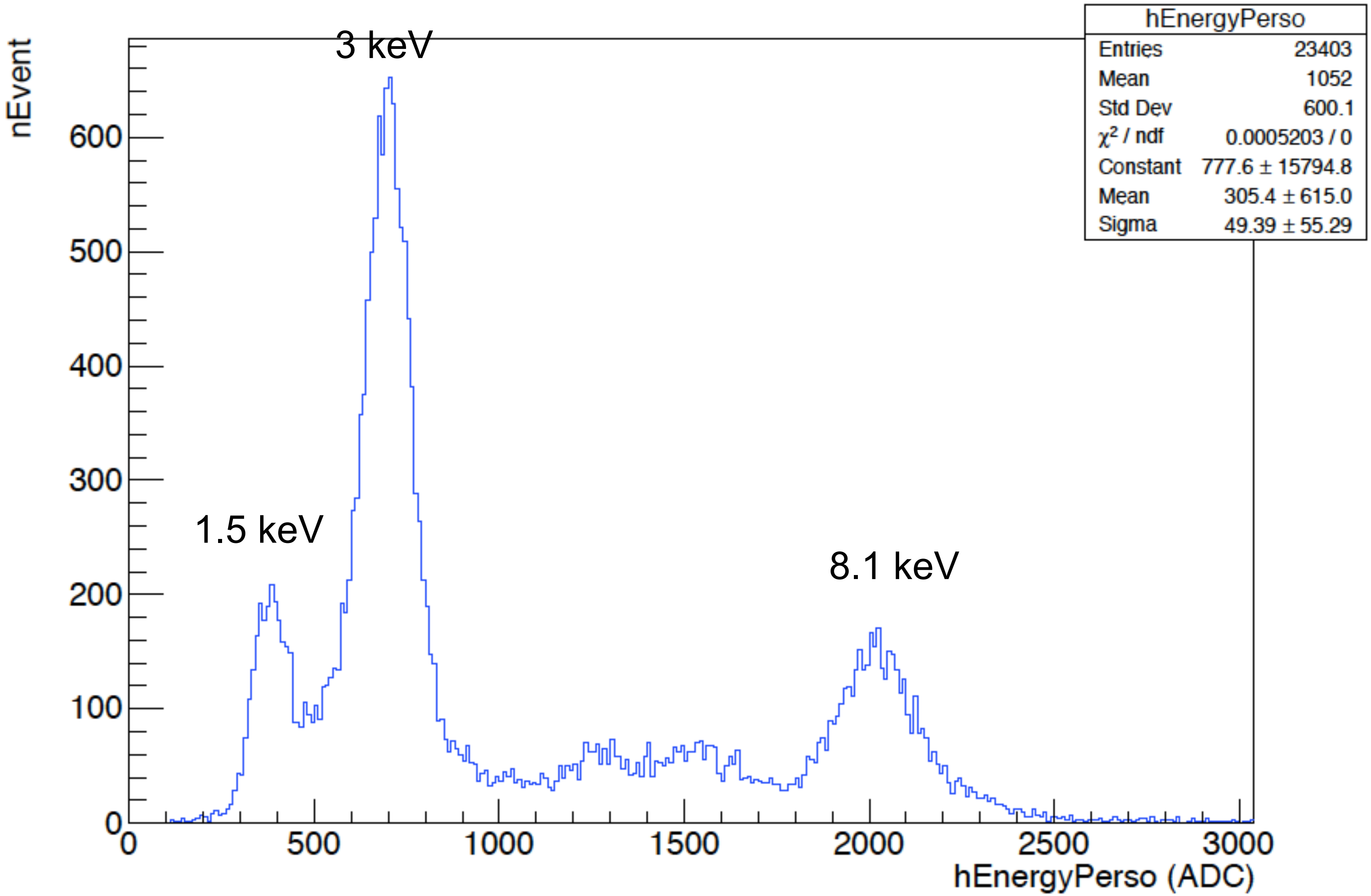


Kapton micromegas readout
Piralux Pilar

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

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



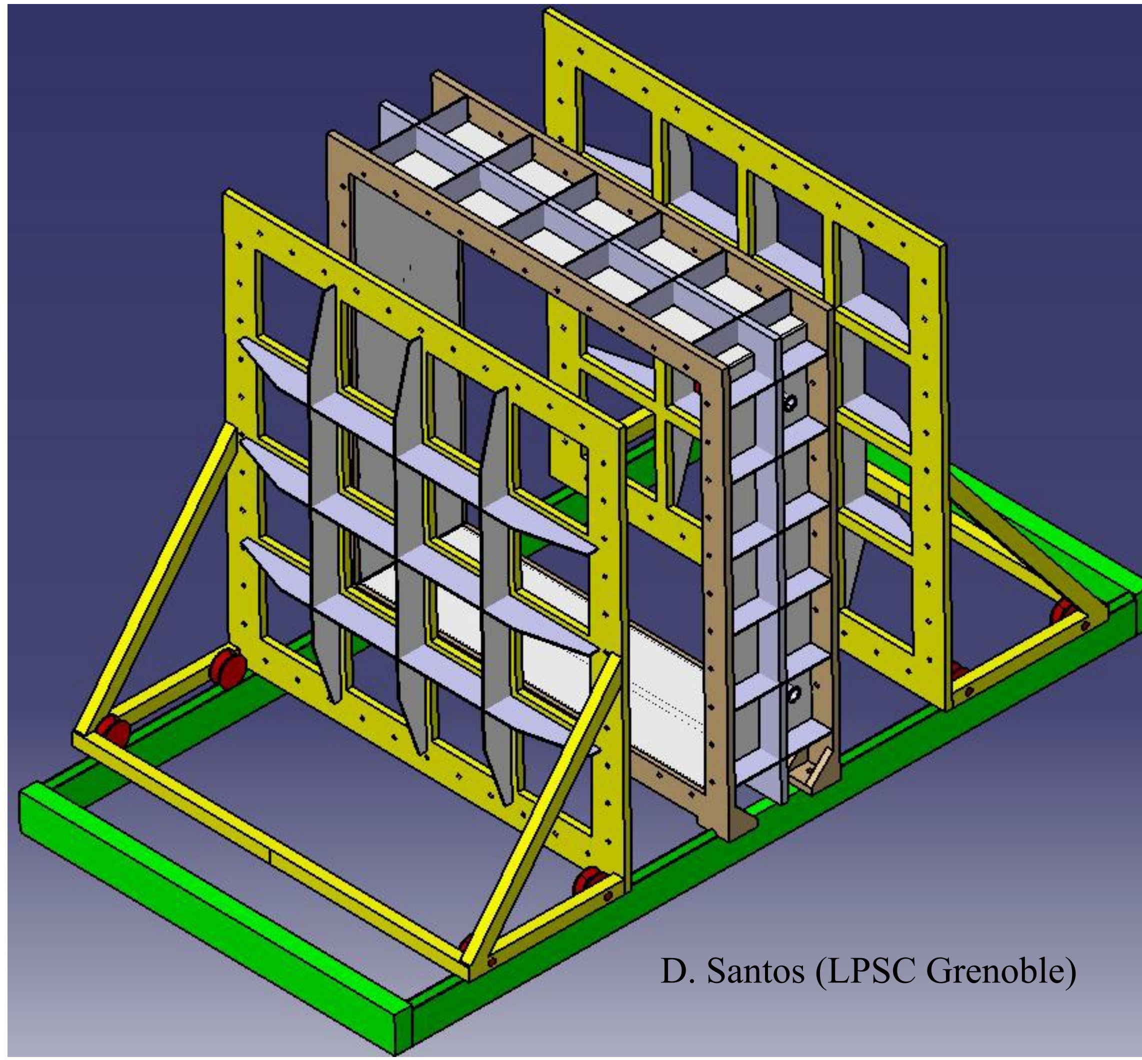
MIMAC – $2m^3$ = 16 bi-chamber modules (2x 35x35x52 cm^3)

New technology anode 35cmx35cm

Stretched thin (12 um) grid at 512um.

New electronic board (1792 channels)

Only one big chamber



Conclusions

- **MIMAC** has openned new possibilities in the DM research, Axion-Like Particles, Neutron spectroscopy and other fields.
- At low energies giving a lot of flexibility on targets, pressure, energy range…
- Ionization quenching factor measurements have been determined experimentally and they can be checked in-situ.
- 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 detector (a needed signature for DM discovery) has been validated.**
- **Large active volumes with a high 3D spatial resolution will open new windows beyond the neutrino floor…**