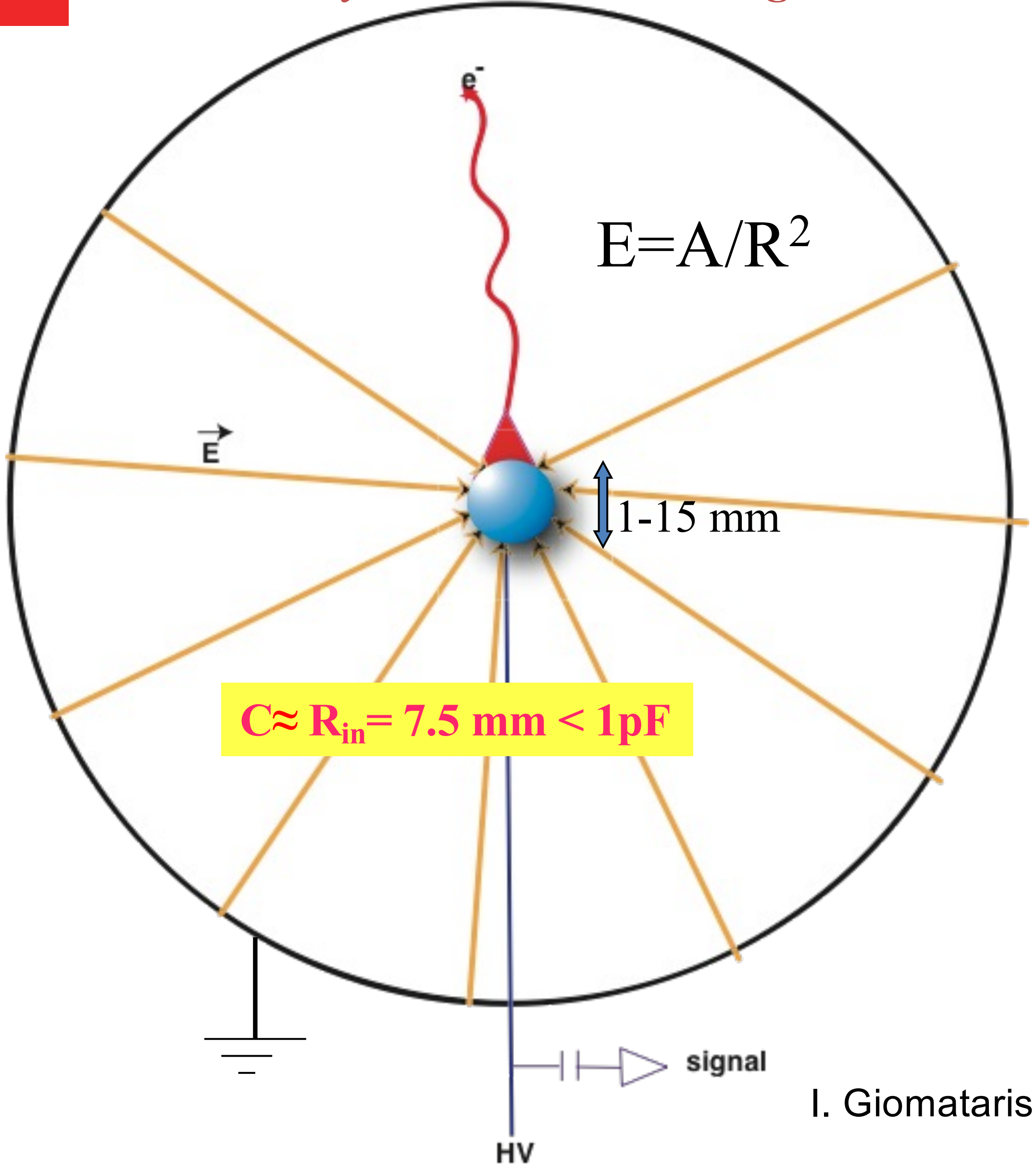
Ionization Quenching Factor (IQF) Measurements with COMIMAC in the frame of NEWS-G collaboration

C. Beaufort, O. Guillaudin, P. Knights, I. Katsioulas,
A. Dastgheibi-Fard, J-F. Muraz, D. Santos

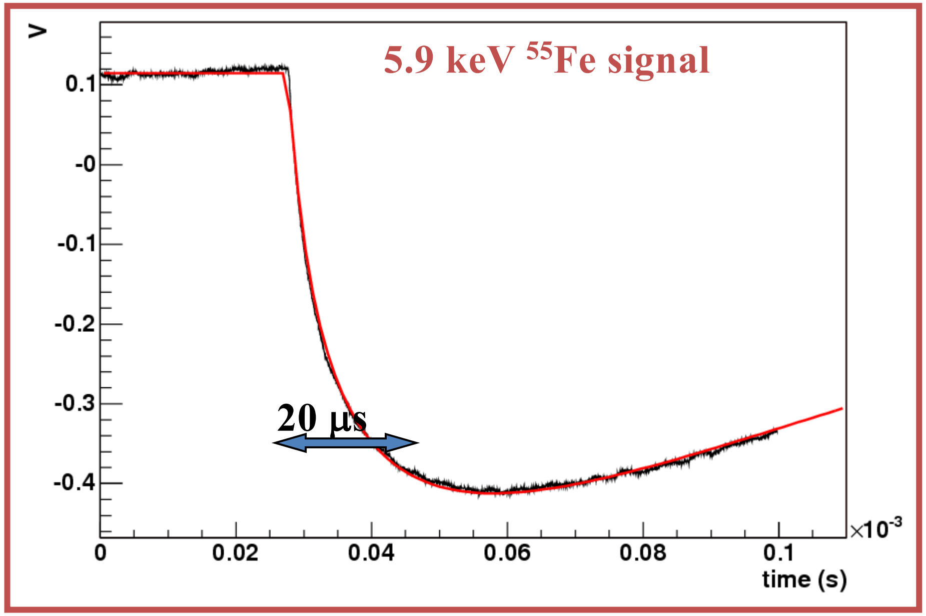
Radial TPC with spherical proportional counter read-out

Saclay-Thessaloniki-Saragoza

A Novel large-volume Spherical Detector with Proportional Amplification read-out, I. Giomataris *et al.*, JINST 3:P09007,2008

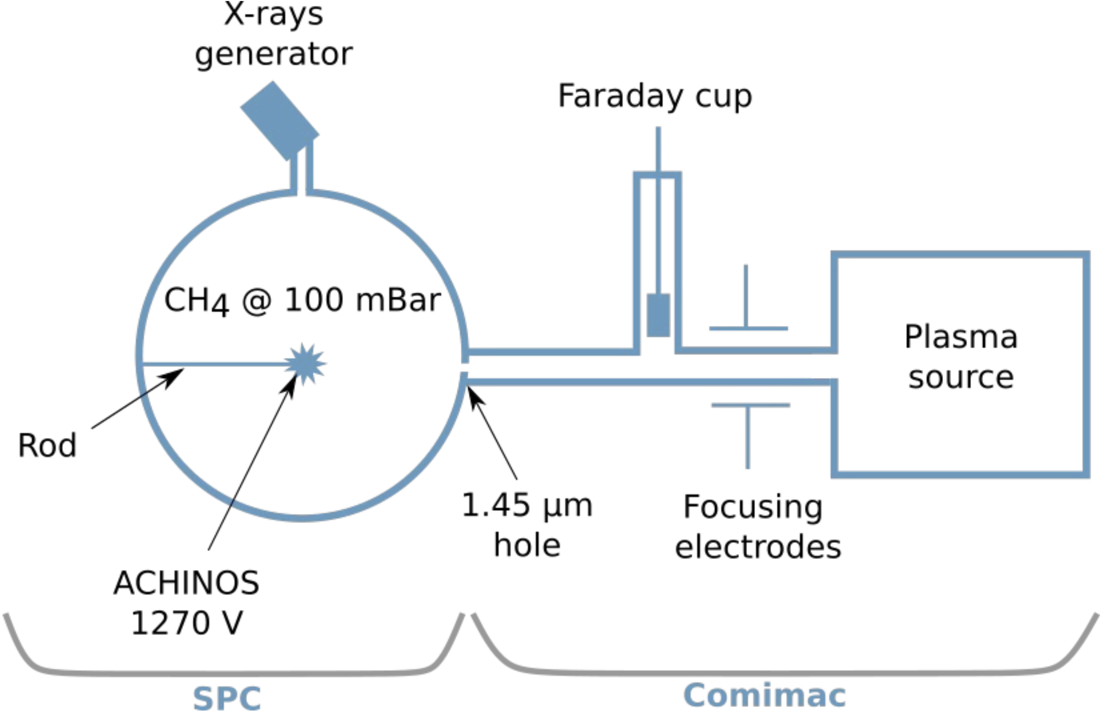


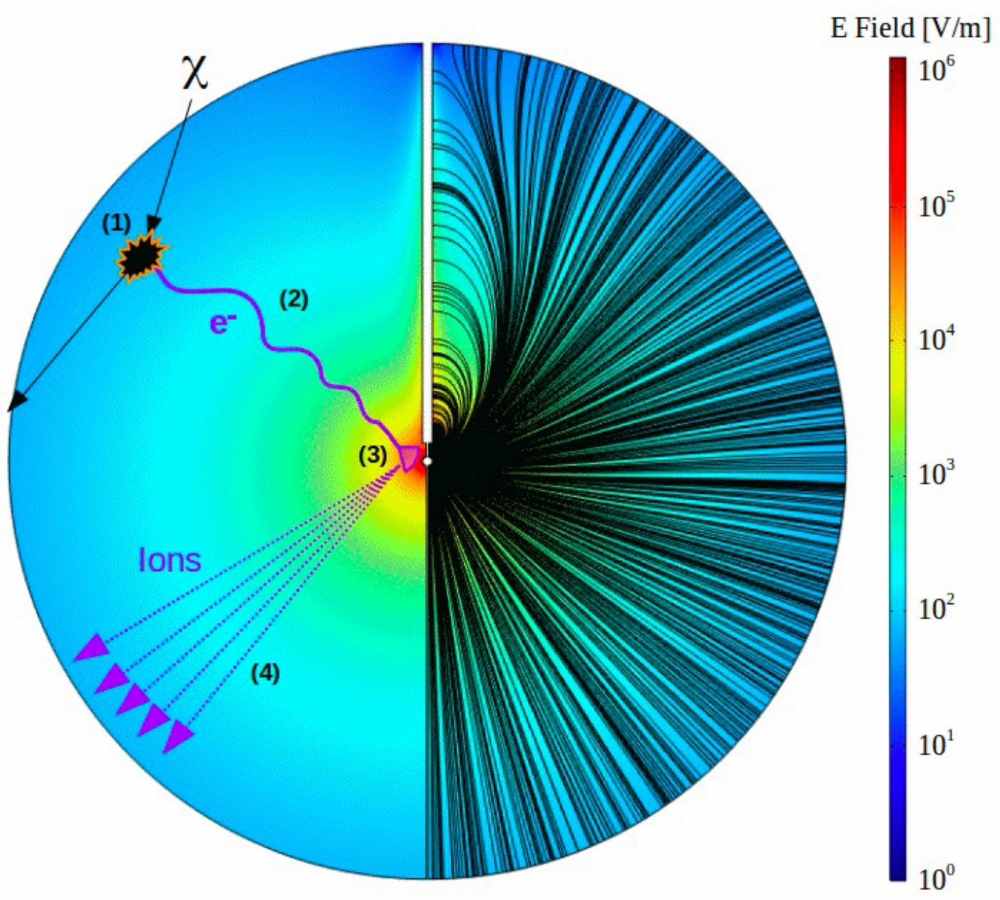
I. Giomataris (2008)

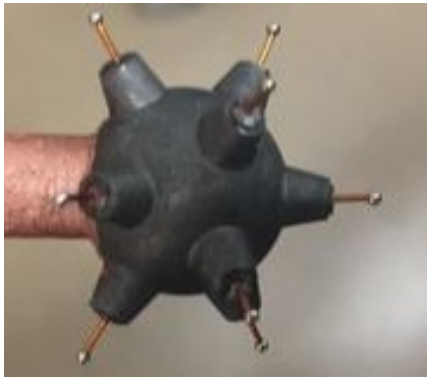


- **Simple and cheap**
- **Large volume**
- **single read-out**
- **Robustness**
- **Good energy resolution**
- **Low energy threshold**
- **Efficient fiducial cut**

S30 coupled to COMIMAC







- Table-top particle accelerator
- Send electrons and ions of known kinetic energy
- Interfaced with the detector through a 1.45 µm hole
- $IQF(E_K) = \frac{E^{ioniz}}{E_K} = \frac{f_{calib}(E_{ADU})}{E_K}$

Ions

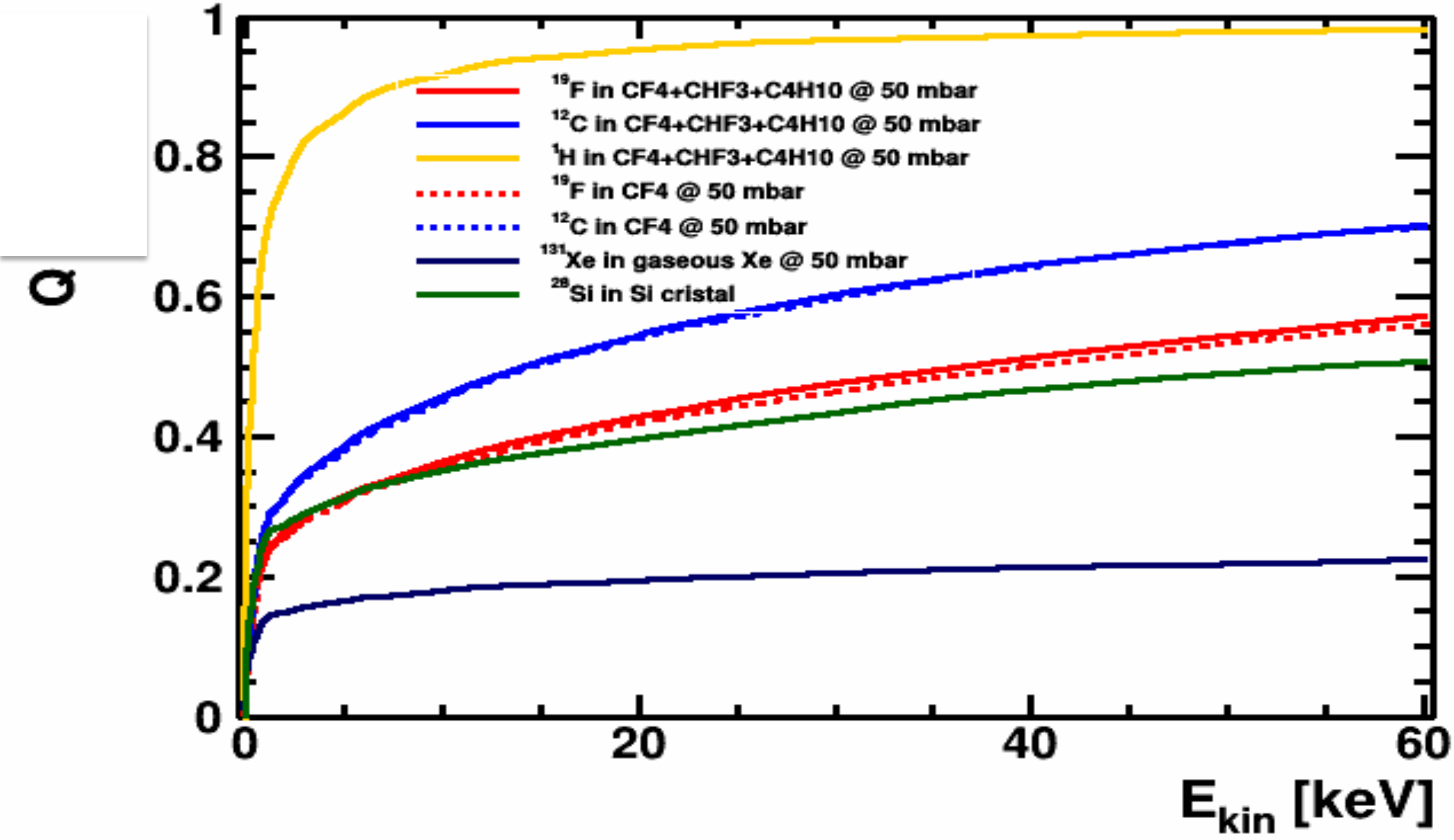
Electrons

Comimac

Ionization Quenching Factors

SRIM-Simulations (Lindhard Theory improved)

Q= Energy transfered to electrons (E_e)/Total kinetic energy



Interaction Processes during the complete slowing down of particles

B. Grosswendt et al, (1997, PTB's team)

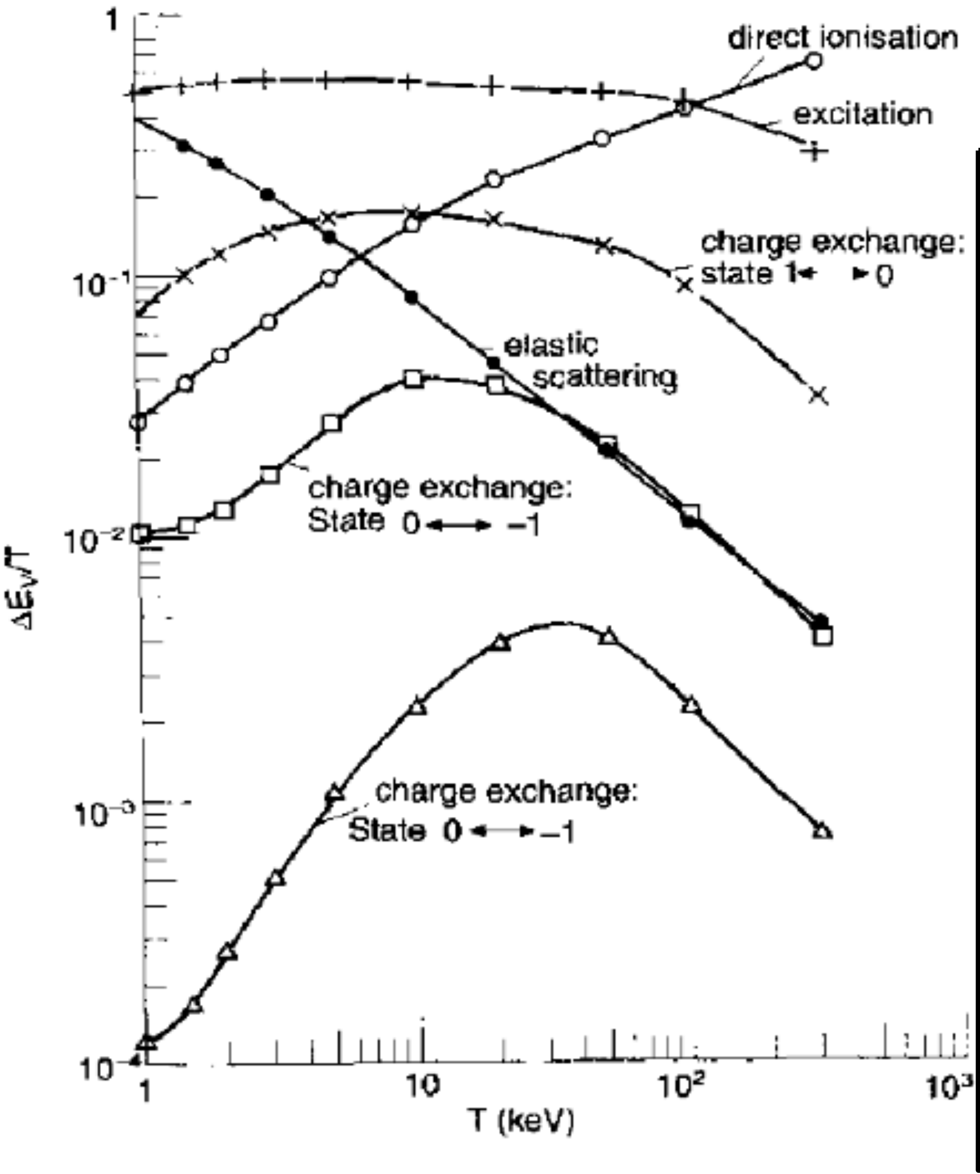


Figure 2. Fraction ΔE/T of the energy spent on possible interaction processes during the complete slowing down of primary particles of initial energy T calculated using the Monte Carlo method.

Radiation Protection Dosimetry
Vol. 70, Nos. 1–4, pp. 37–46 (1997)
Nuclear Technology Publishing

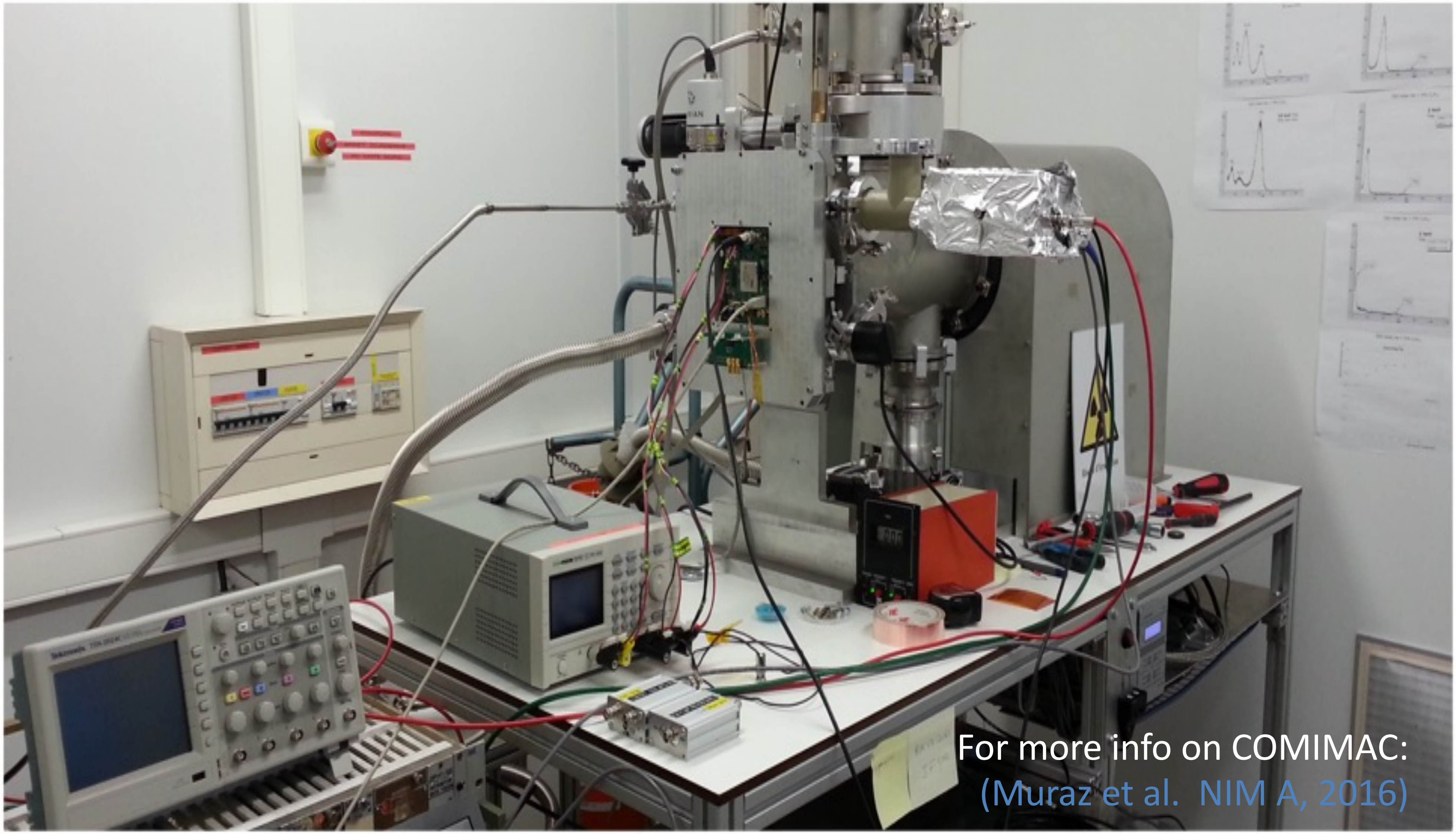
W VALUES OF PROTONS SLOWED DOWN IN MOLECULAR HYDROGEN

B. Grosswendt, G. Willems and W. Y. Baek

- Huge contribution of the excitation process! (50% between 1 keV- 100 keV)
- Elastic collisions more important than direct ionization up to 5 keV !
- Charge exchange process up to 30 keV
- Measurements performed at low pressures (4-37 mbar) keeping E/p constant and further extrapolation of p to zero to reduce the impact of diffusion and recombination !
- All these processes are even more complex with heavier particles !

The complexity of the processes forced us to try to measure the ionization available in our detector !!

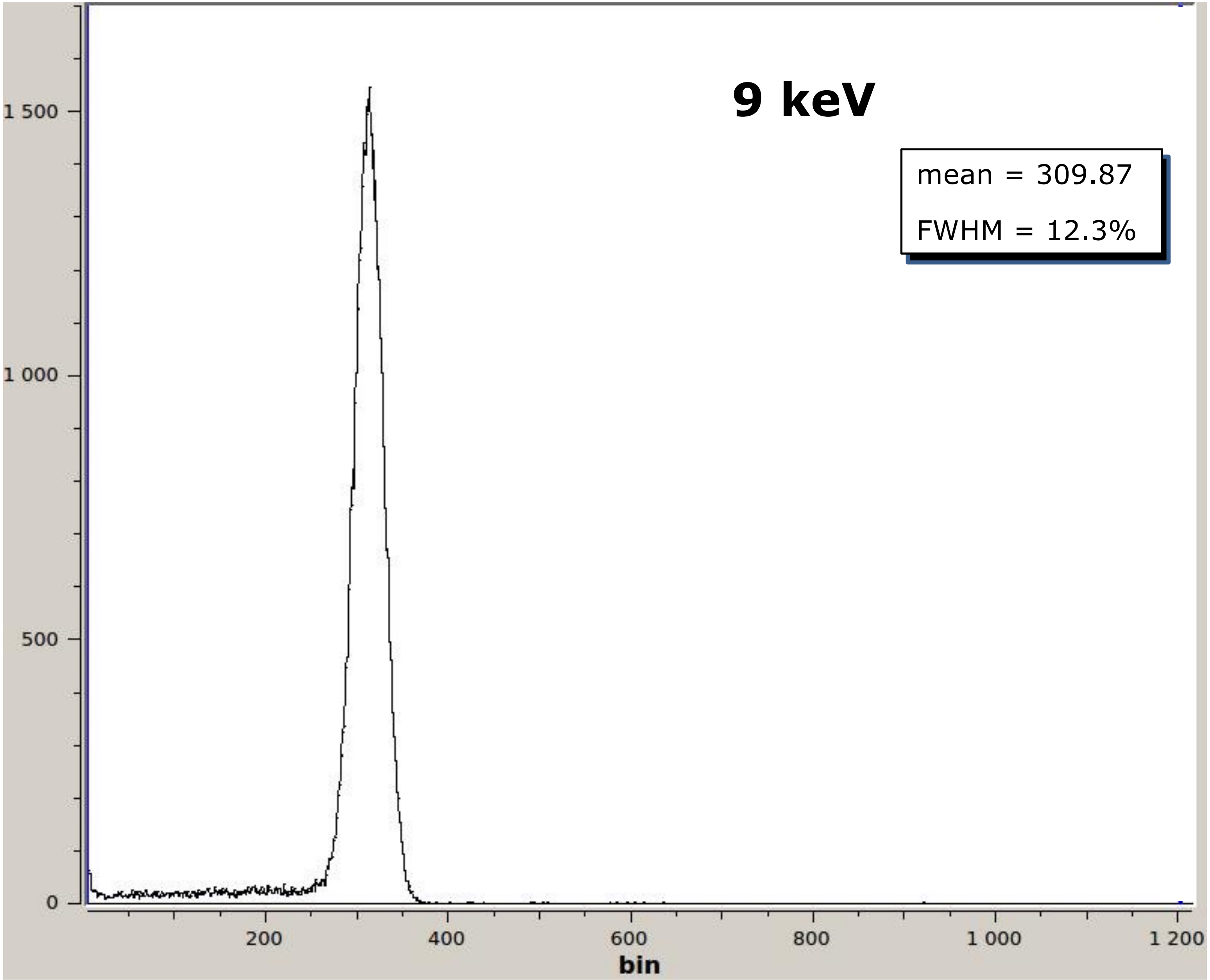
First controlled Nuclear Recoil tracks, using COMIMAC



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

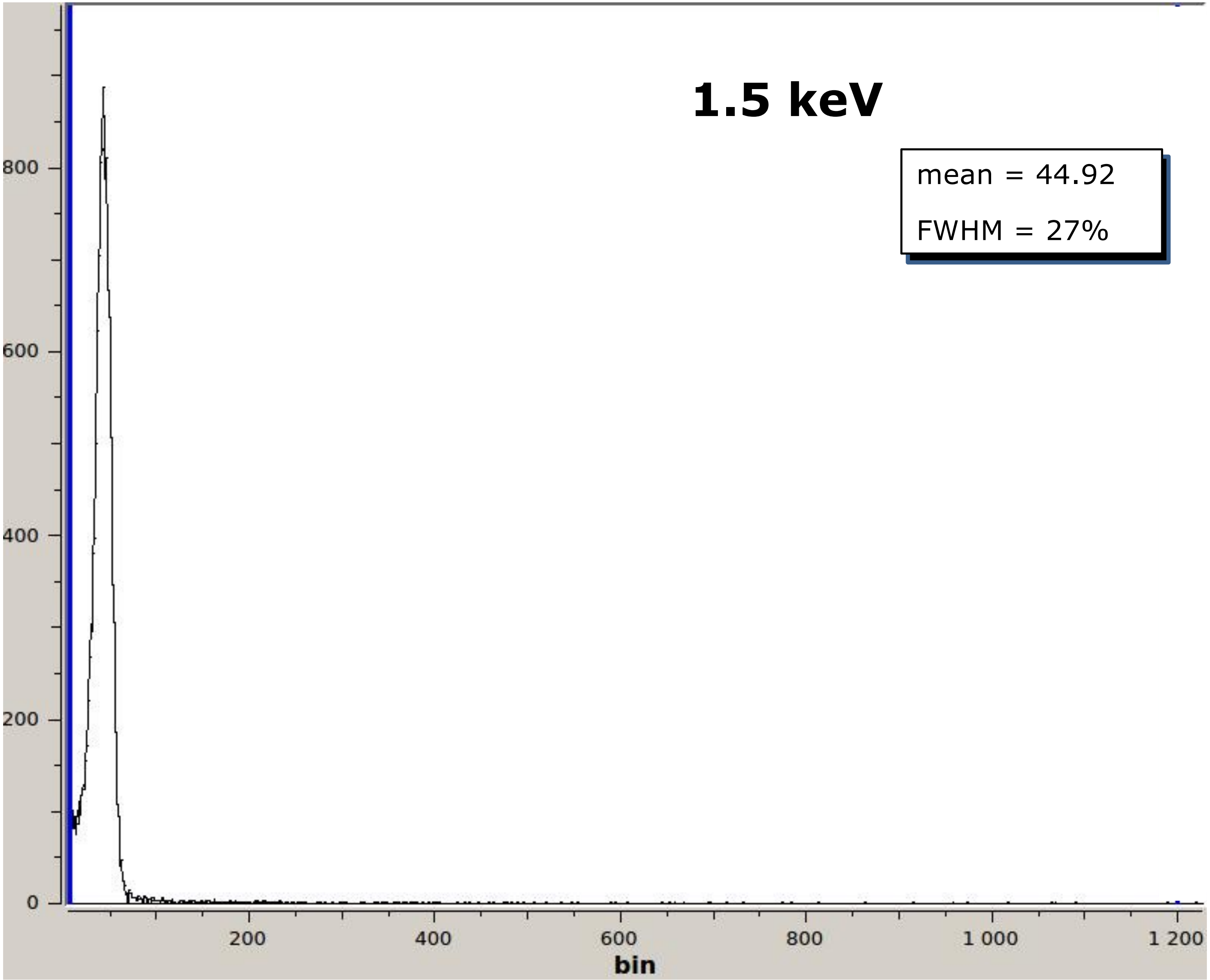
D. Santos (LPSC Grenoble)

Electrons Performance

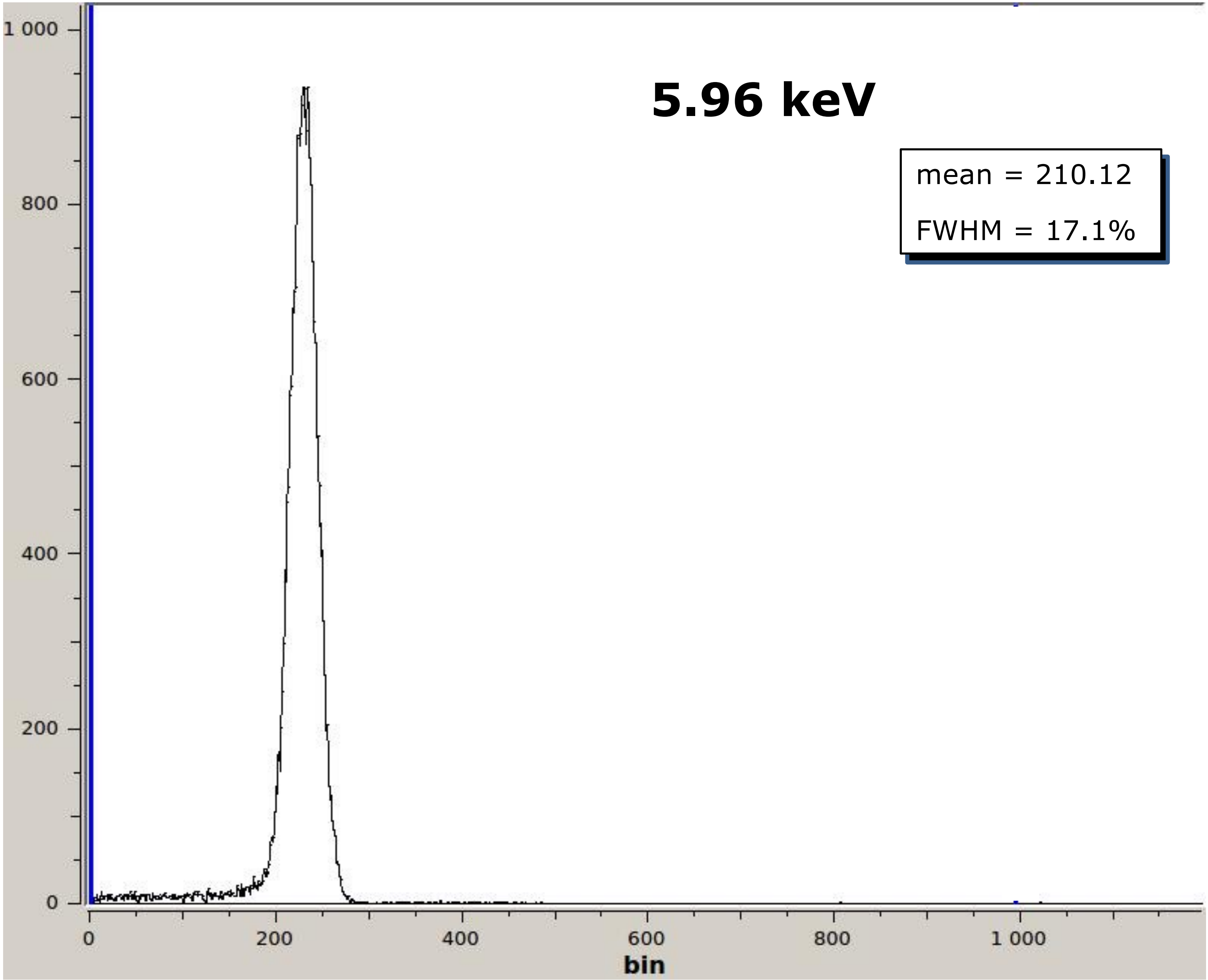


D. Santos (LPSC Grenoble)

Electrons Performance

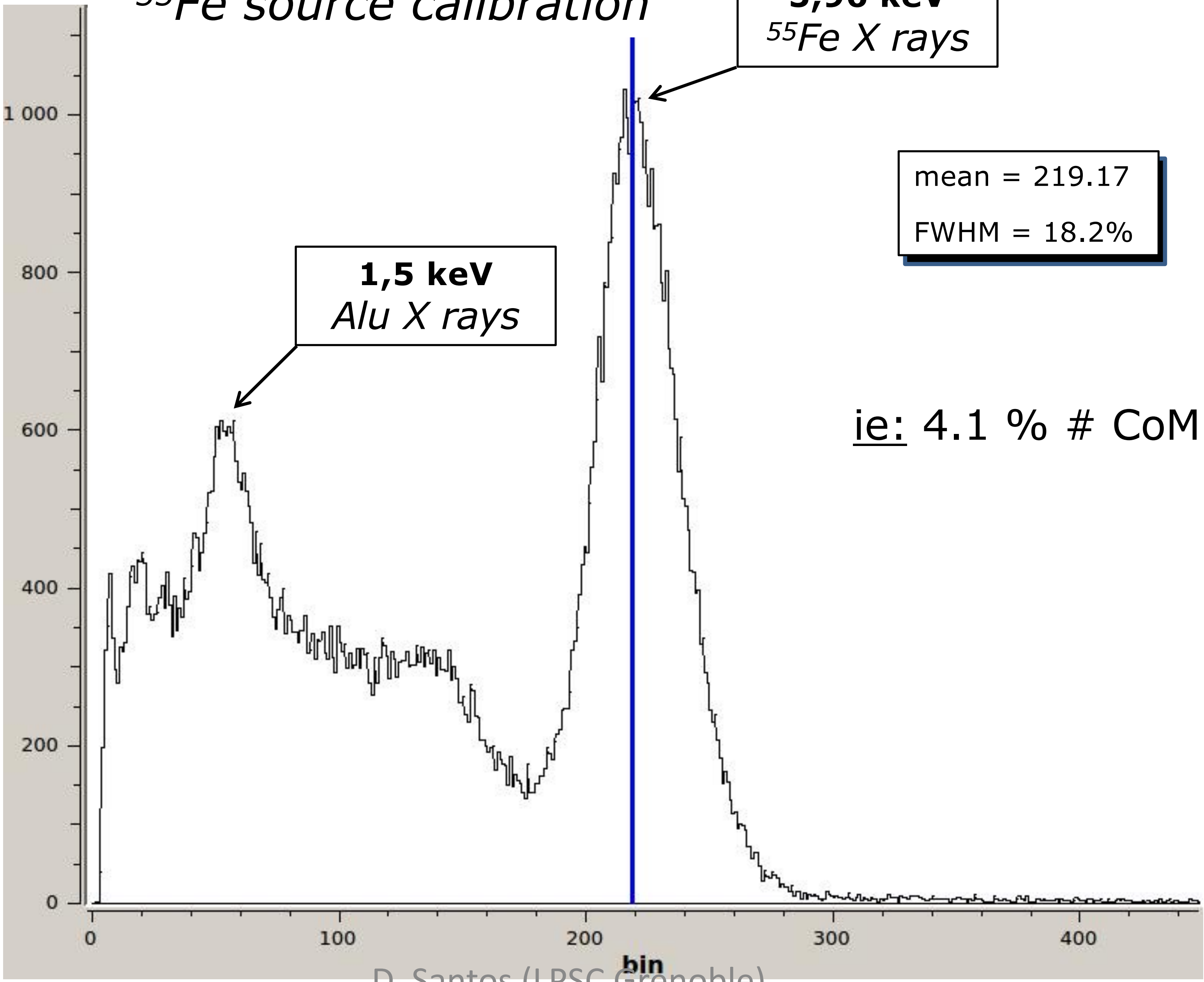


Electrons Performance



Electrons Performance

^{55}Fe source calibration



5,96 keV
^{55}Fe X rays

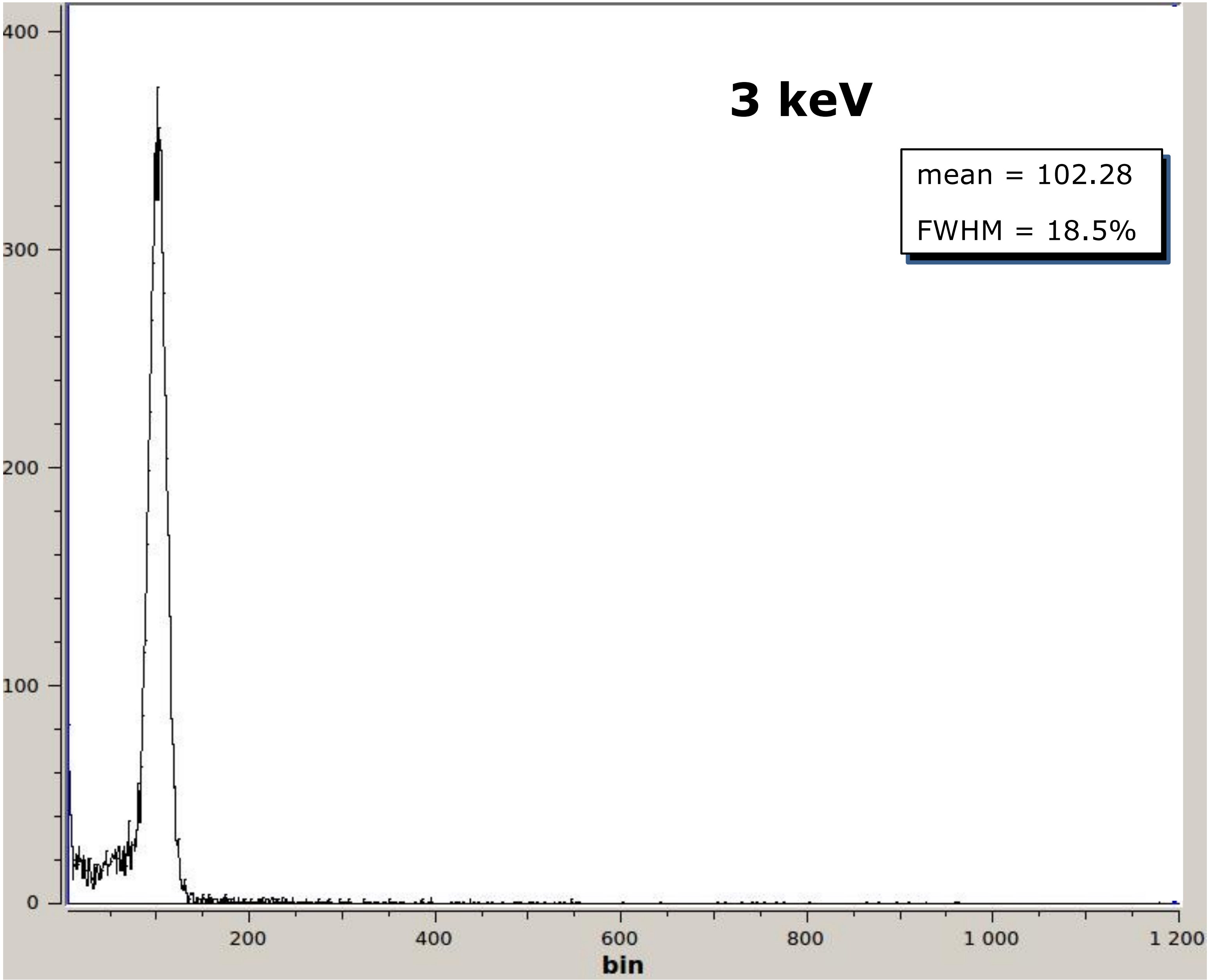
1,5 keV
Alu X rays

mean = 219.17

FWHM = 18.2%

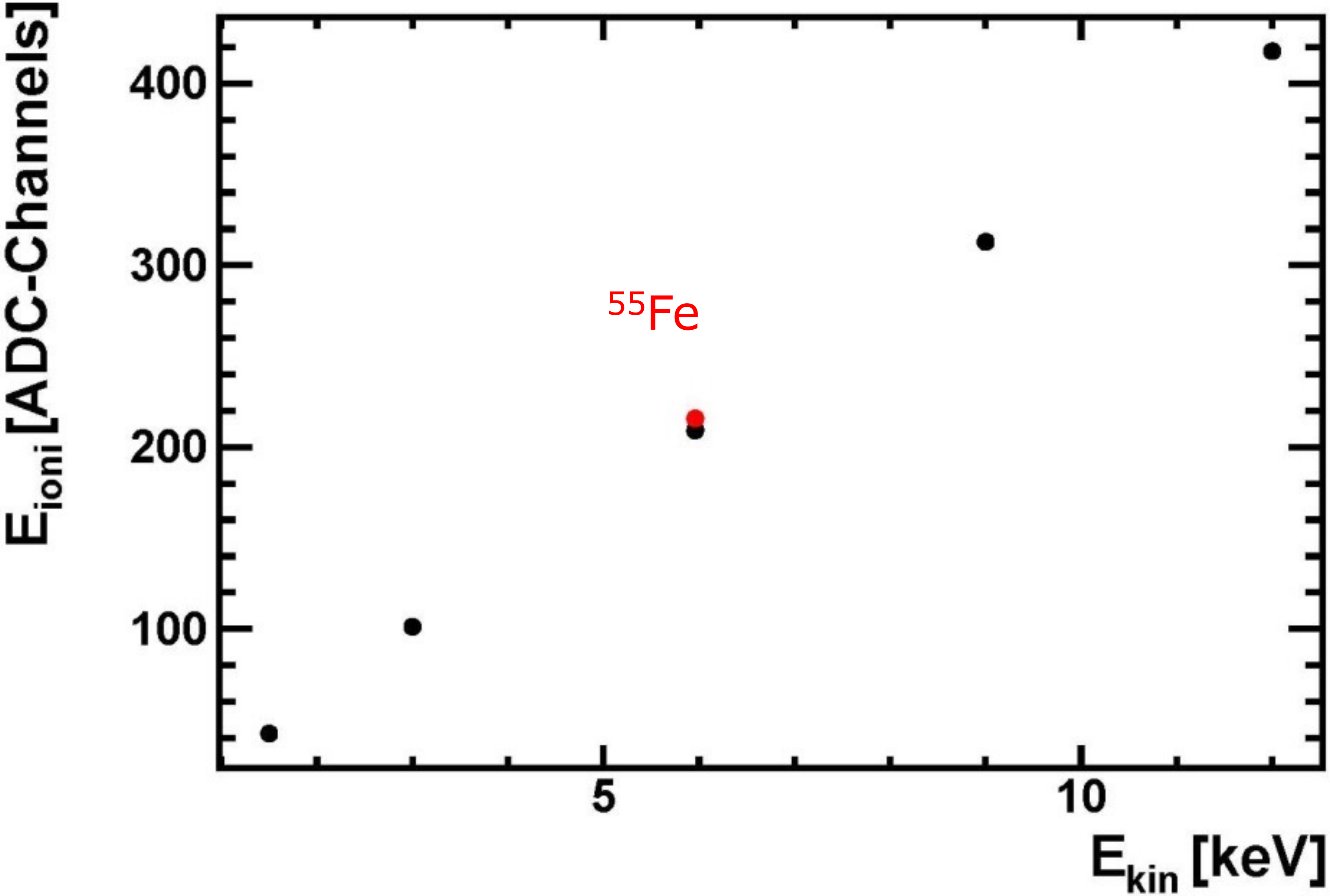
<u>ie:</u> 4.1 % # CoMimac

Electrons Performance

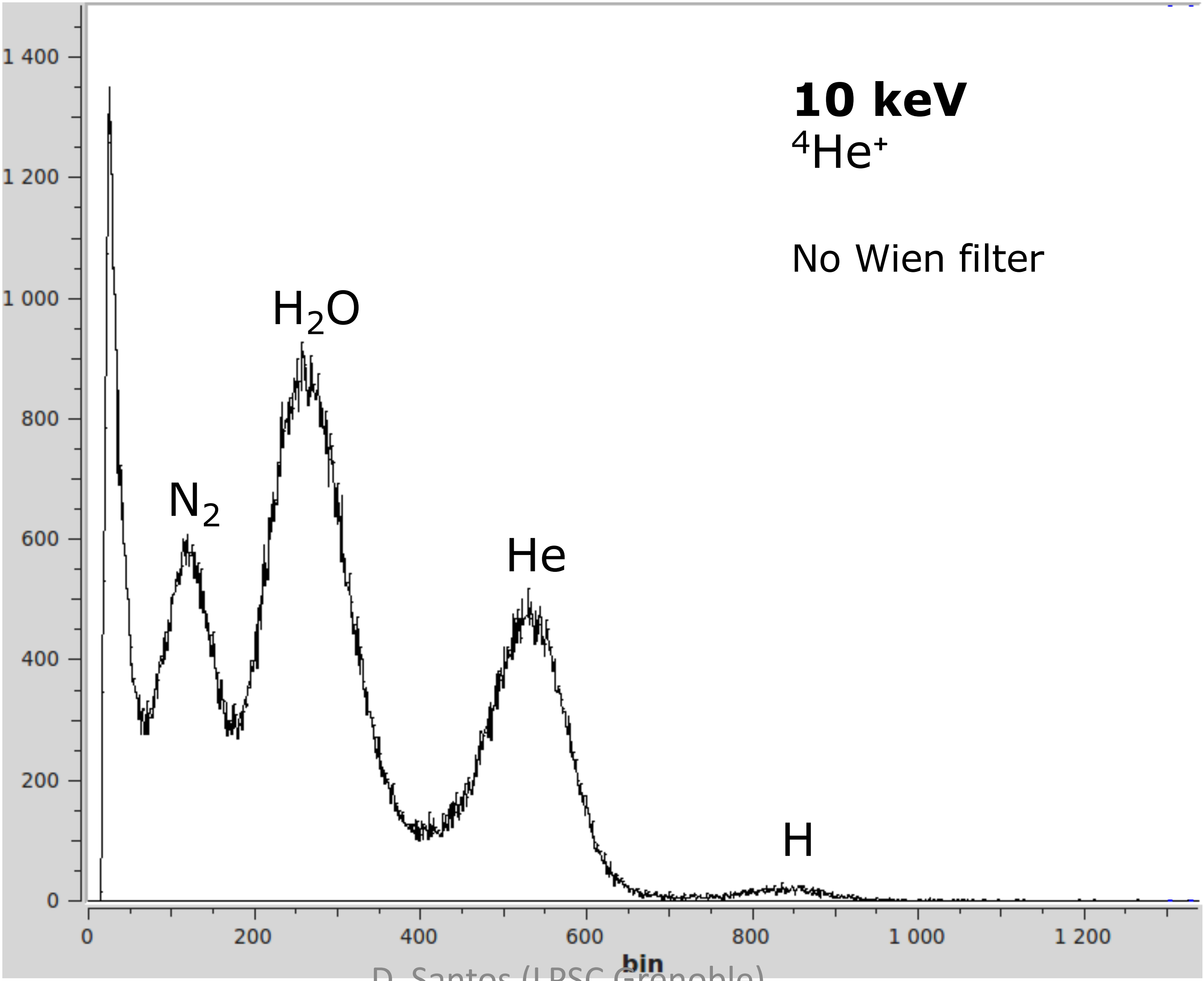


Electrons Performance

Electron Linearity response



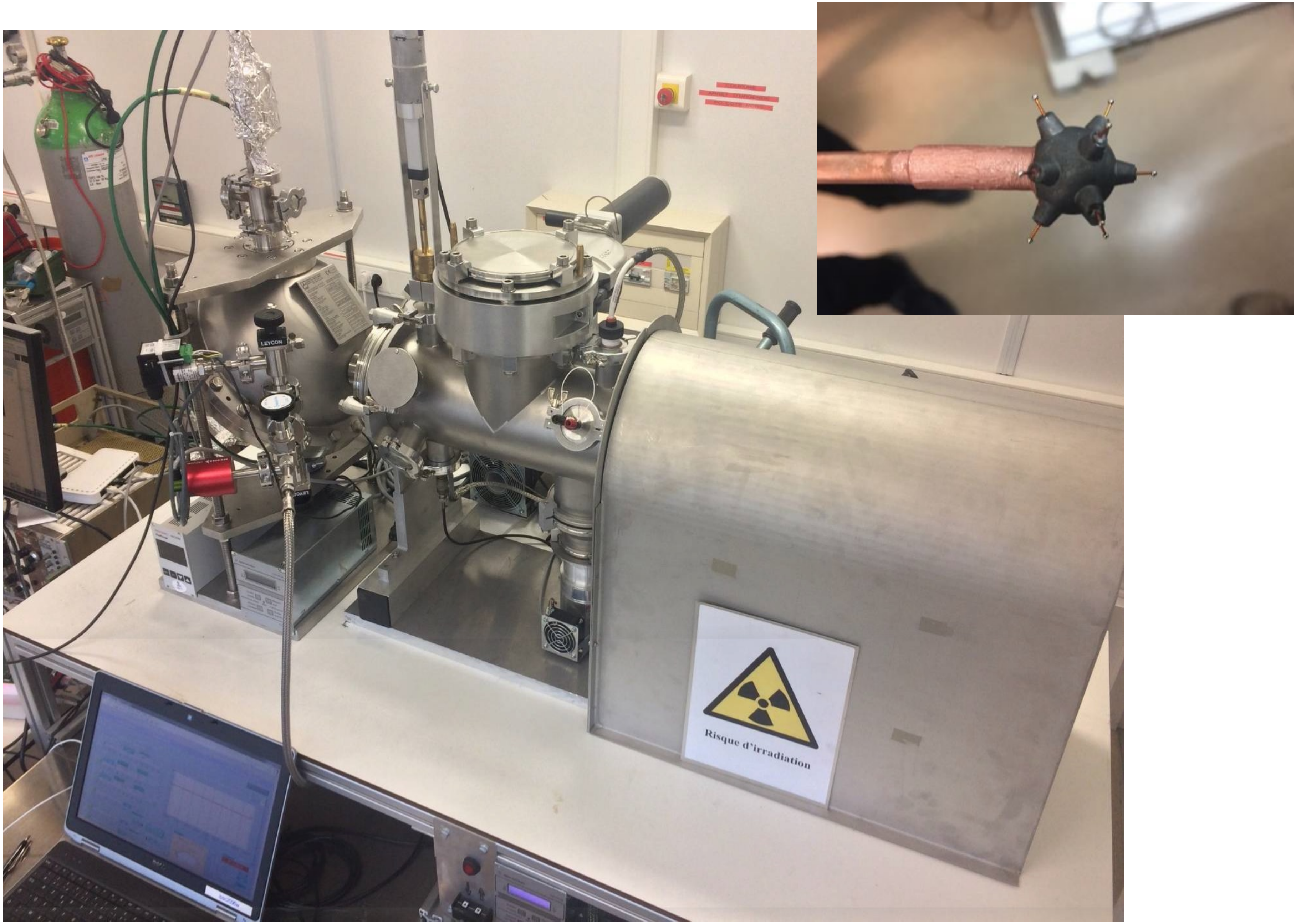
Ions Performance



10 keV
$^4He^+$

No Wien filter

S30 coupled to COMIMAC (J-F. Muraz)



Electron spectra from 1.5 to 13 keV delivered by Comimac measured by S30

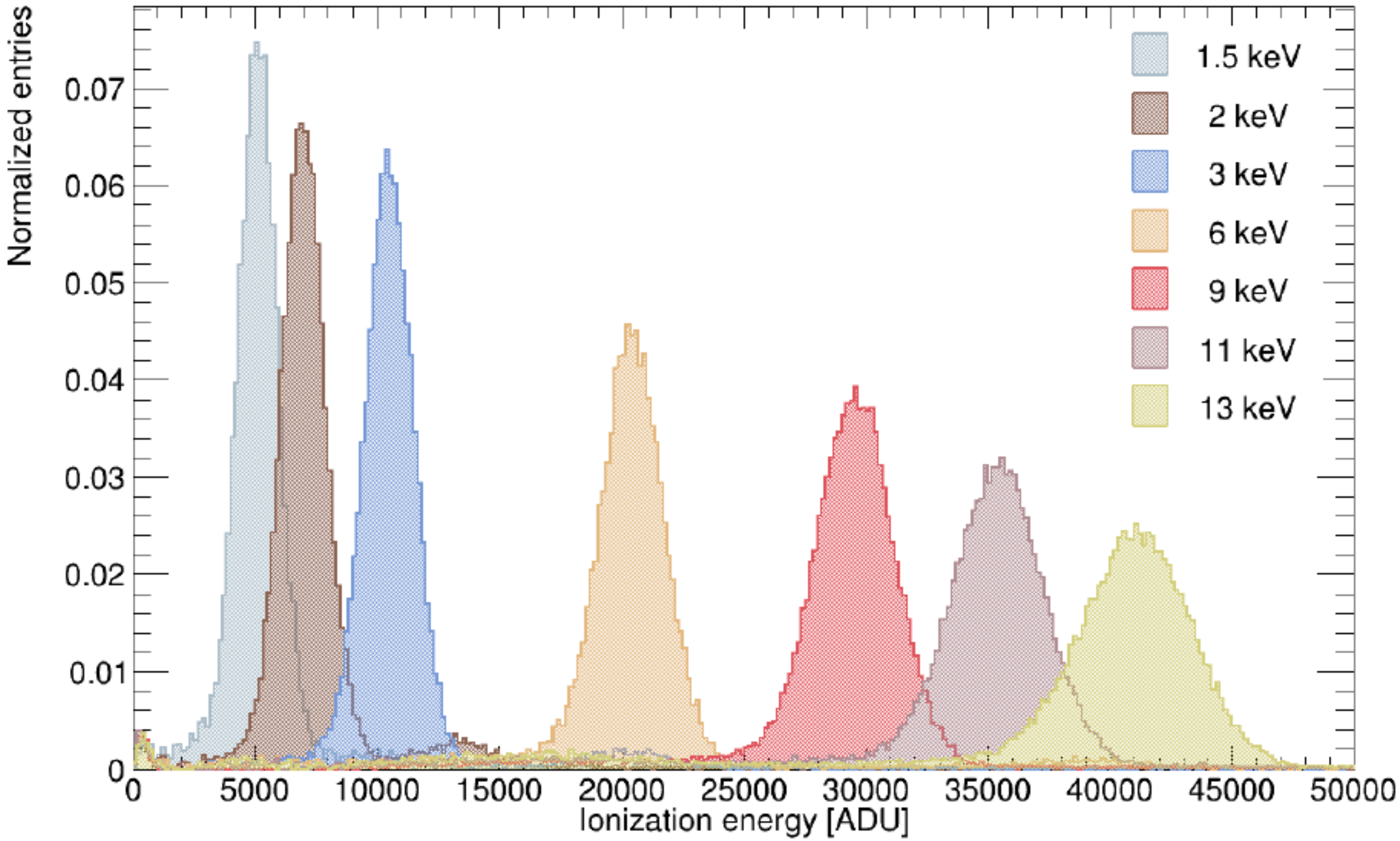


Fig. 5: Complete set of energy spectra used for the calibration of the detector response. The kinetic energy is determined by the Comimac facility. The cosmic background has been subtracted but no cut is applied.

Systematic effects : Cosmic background substraction and losses in the 13um interface hole

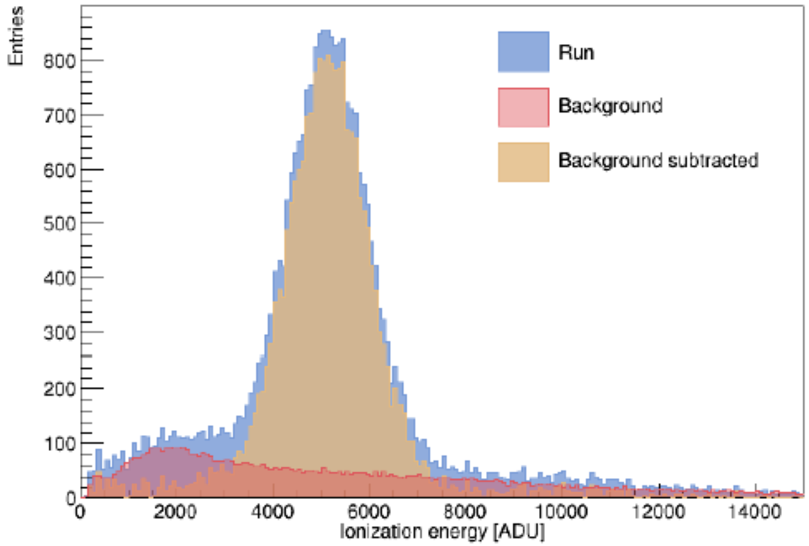


Fig. 3: Background subtraction for 1.5 keV electrons

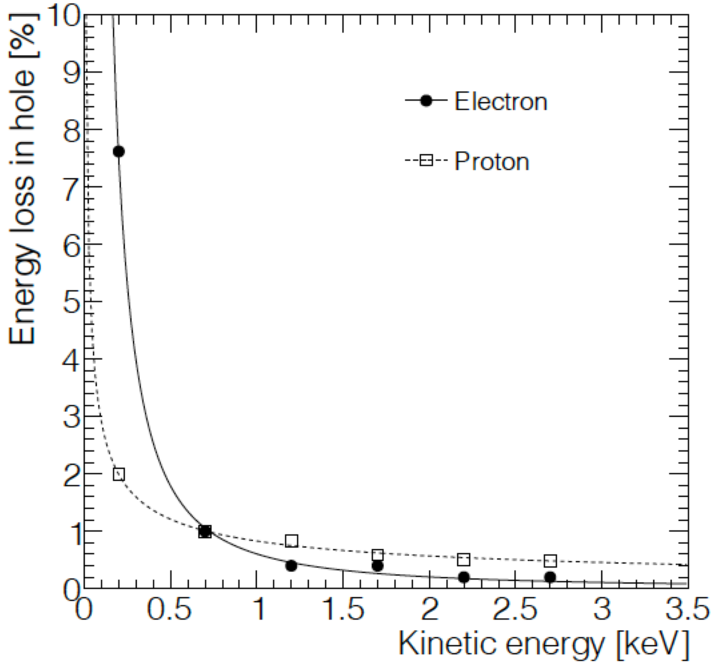
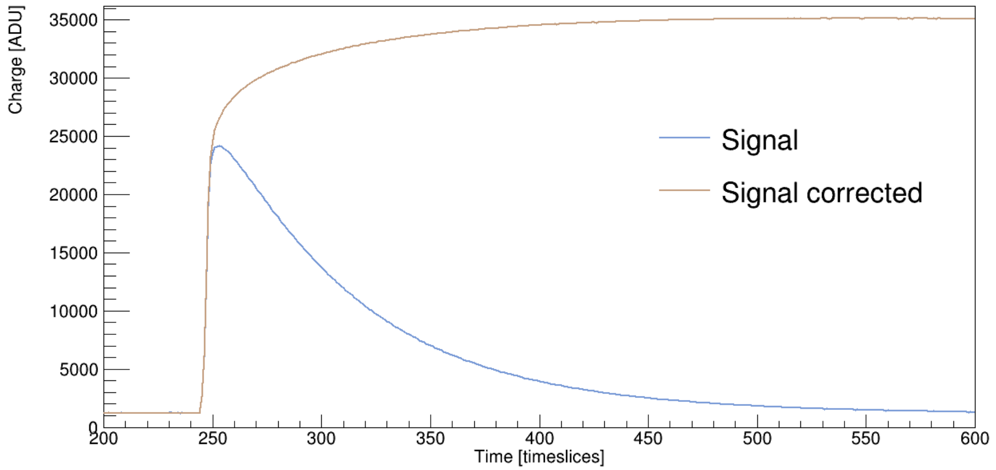


Fig. 4: Simulation of the energy loss in the Comimac's hole of diameter 1.45 μm for 100 mbar of CH_4. The fit functions are displayed.

Molflow+

Casino and SRIM



Ballistic correction (RC preamplifier)

Electron calibration

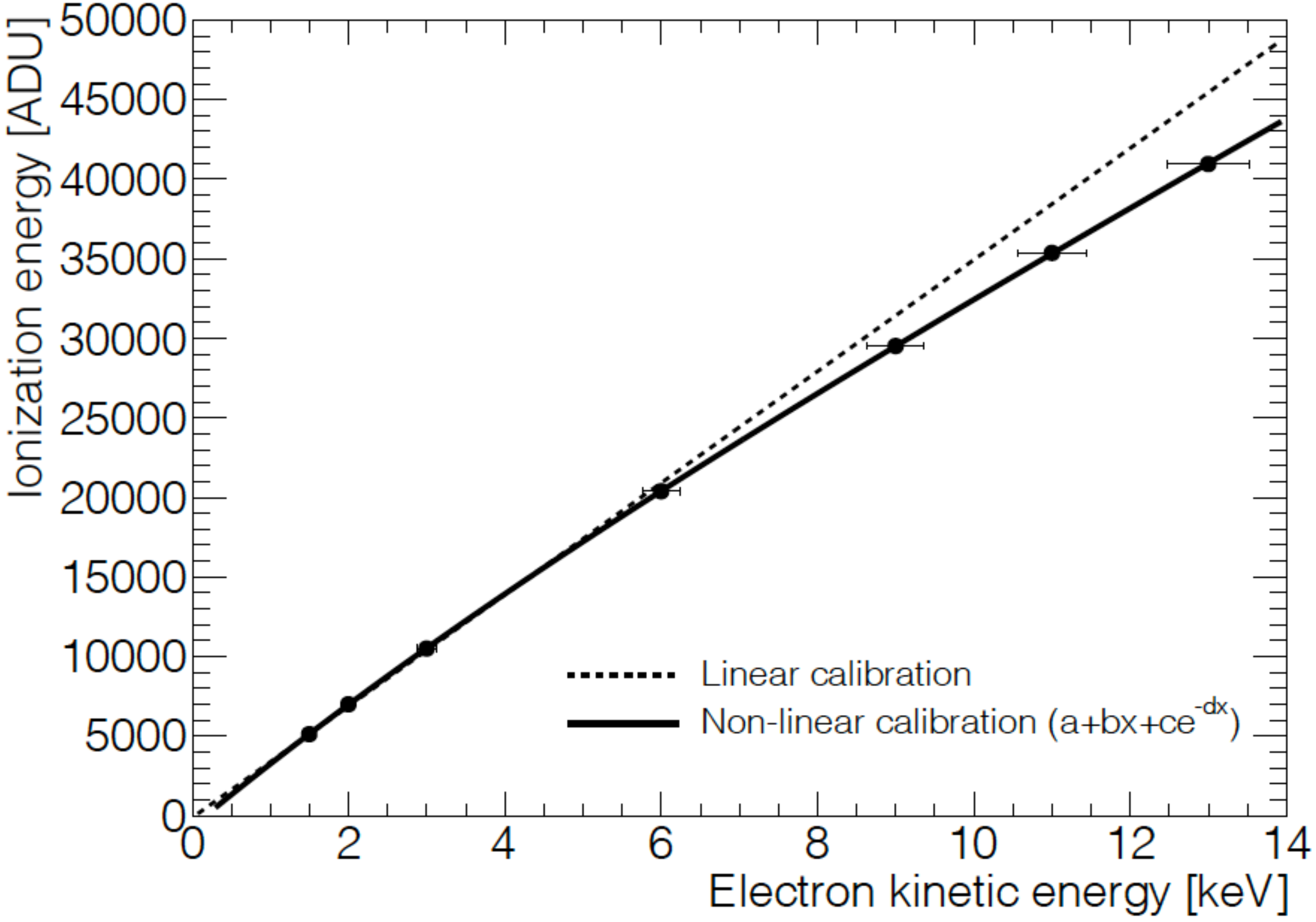


Fig. 6: Electron calibration. The dashed line represents a linear calibration passing through the first data point and having an offset of −117 ADU. The solid line is a fit with a first order polynomial function plus a decreasing exponential function. Error bars are drawn in X and Y but they are hardly visible in Y.

Proton and other species spectra from 2 to 13 keV kinetic energies !!

Provided by Comimac

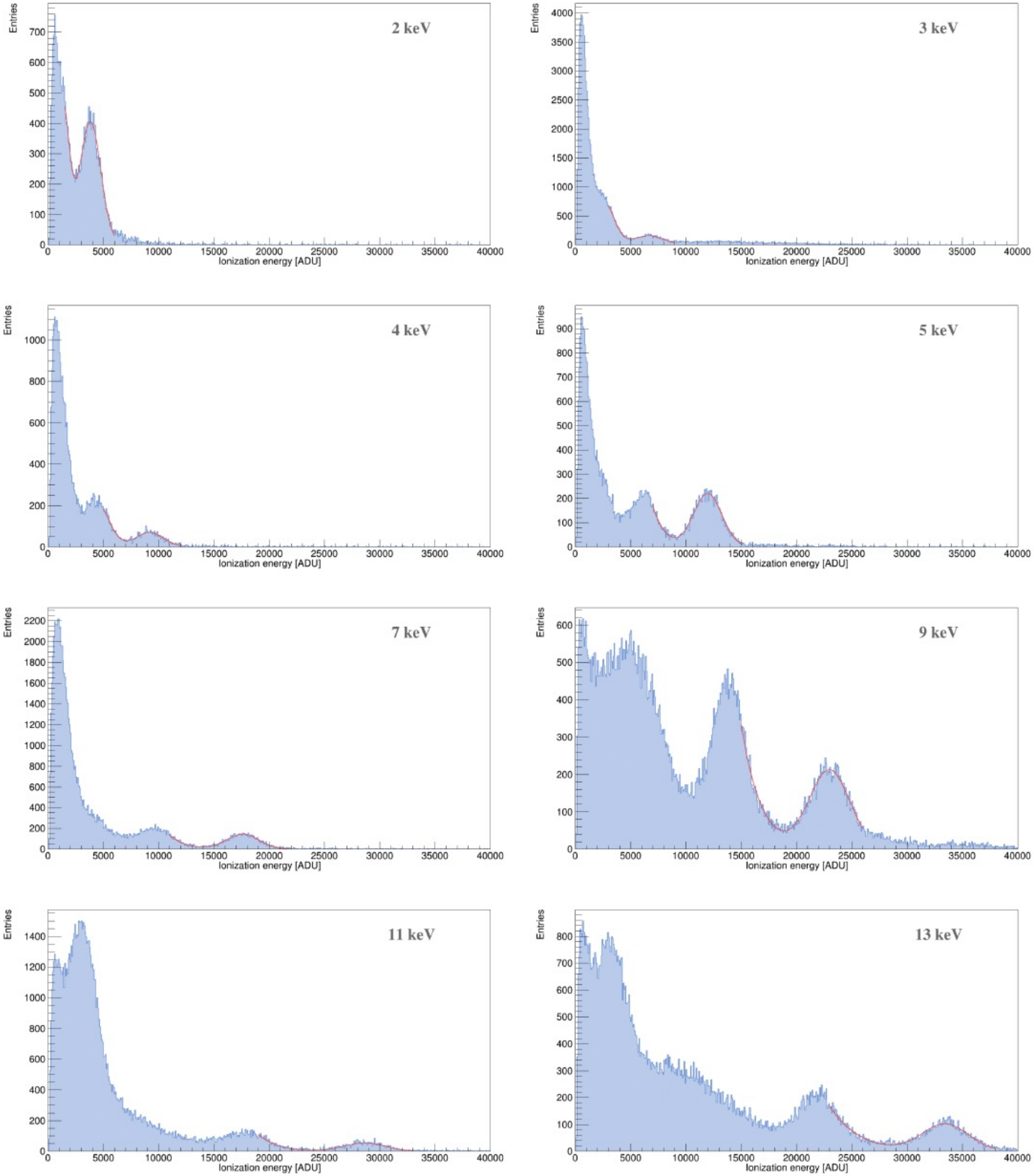
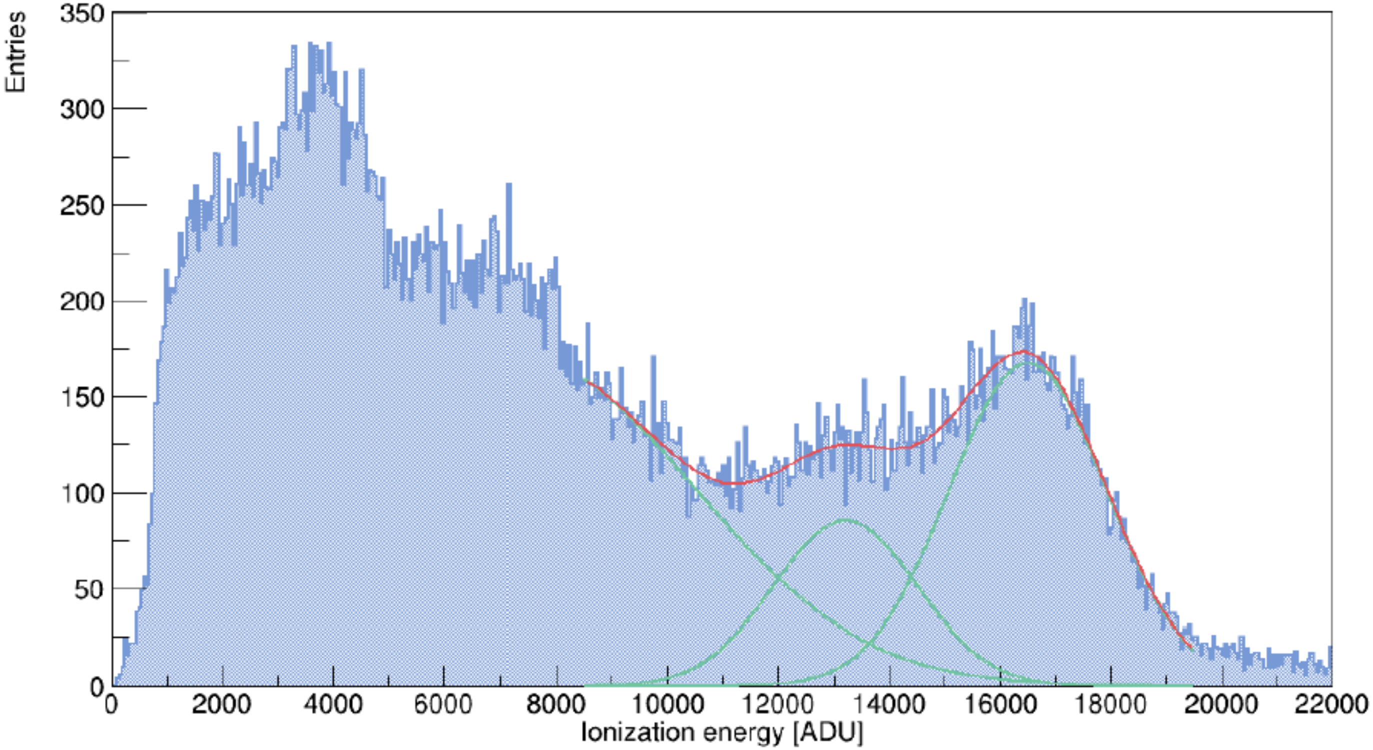


Fig. 7: Complete set of proton spectra measured at 1270 V. The fit functions of two Gaussian, used for the analysis, are shown in red. In each spectrum, the proton peak can be identified as the one with highest ionization energy. The second peak from the right corresponds to helium.

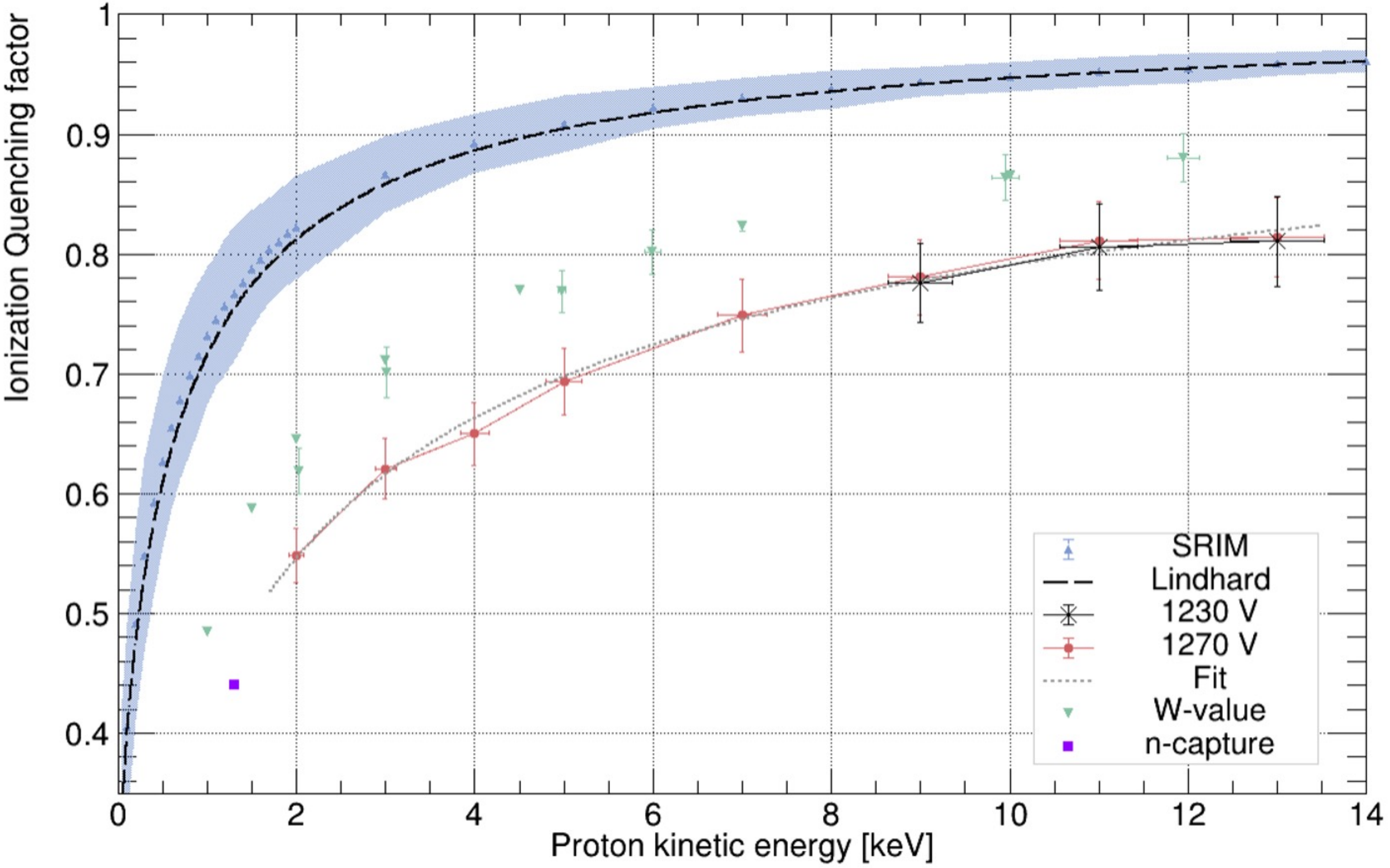
One of the more difficult tasks is to discriminate the proton from the other species, heavier ones (H_2^+, He, N, O, H_2O,…)



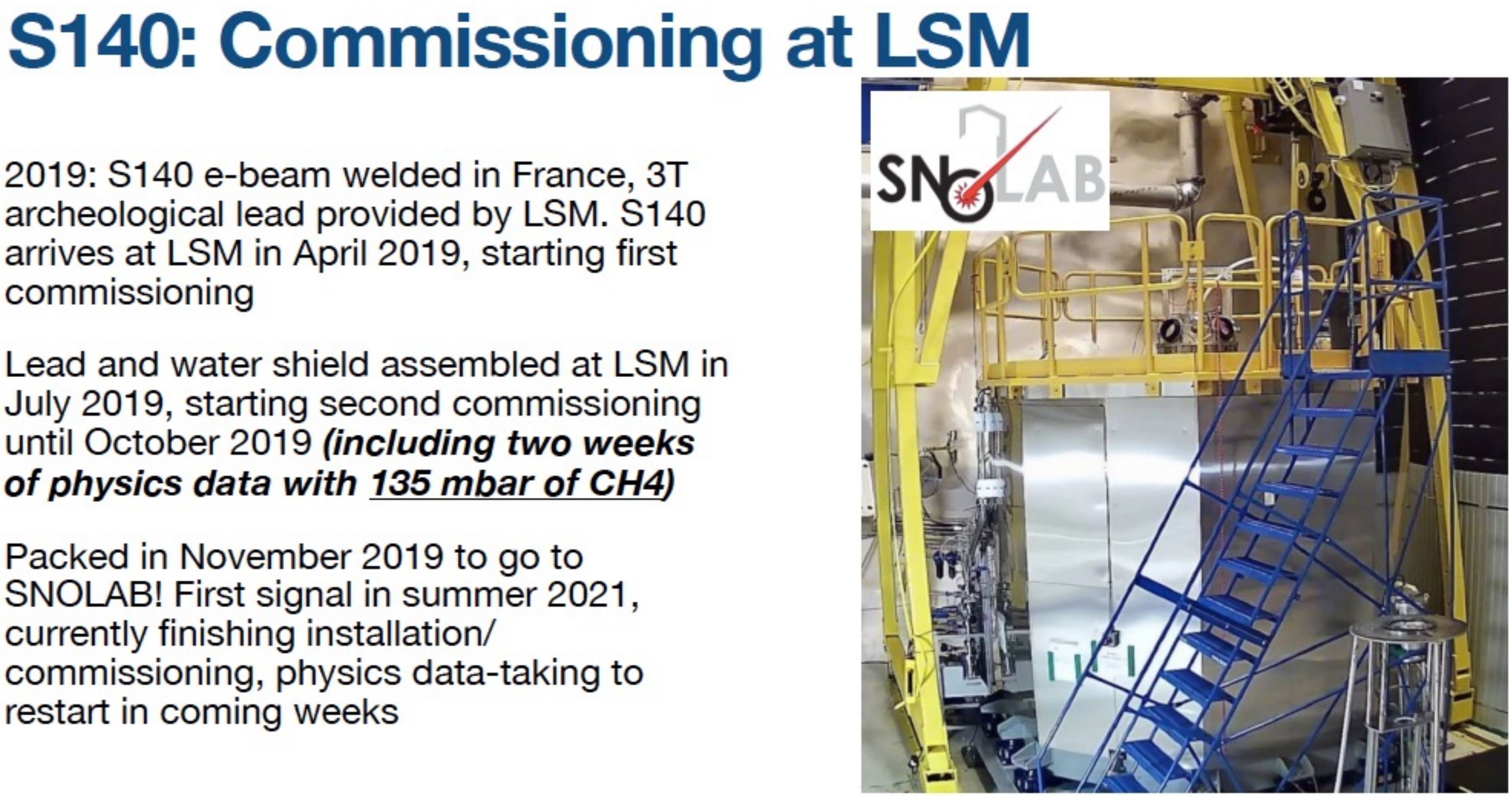
The proton, being the lightest ion, is the particle ionizing the most!

IQF Measurements of H in CH_4 at 100 mbar

EPJC 82, 1114 (2022)



NEWS-G at LSM and SNOLAB



S140: Commissioning at LSM

2019: S140 e-beam welded in France, 3T archeological lead provided by LSM. S140 arrives at LSM in April 2019, starting first commissioning

Lead and water shield assembled at LSM in July 2019, starting second commissioning until October 2019 ***(including two weeks of physics data with 135 mbar of CH4)***

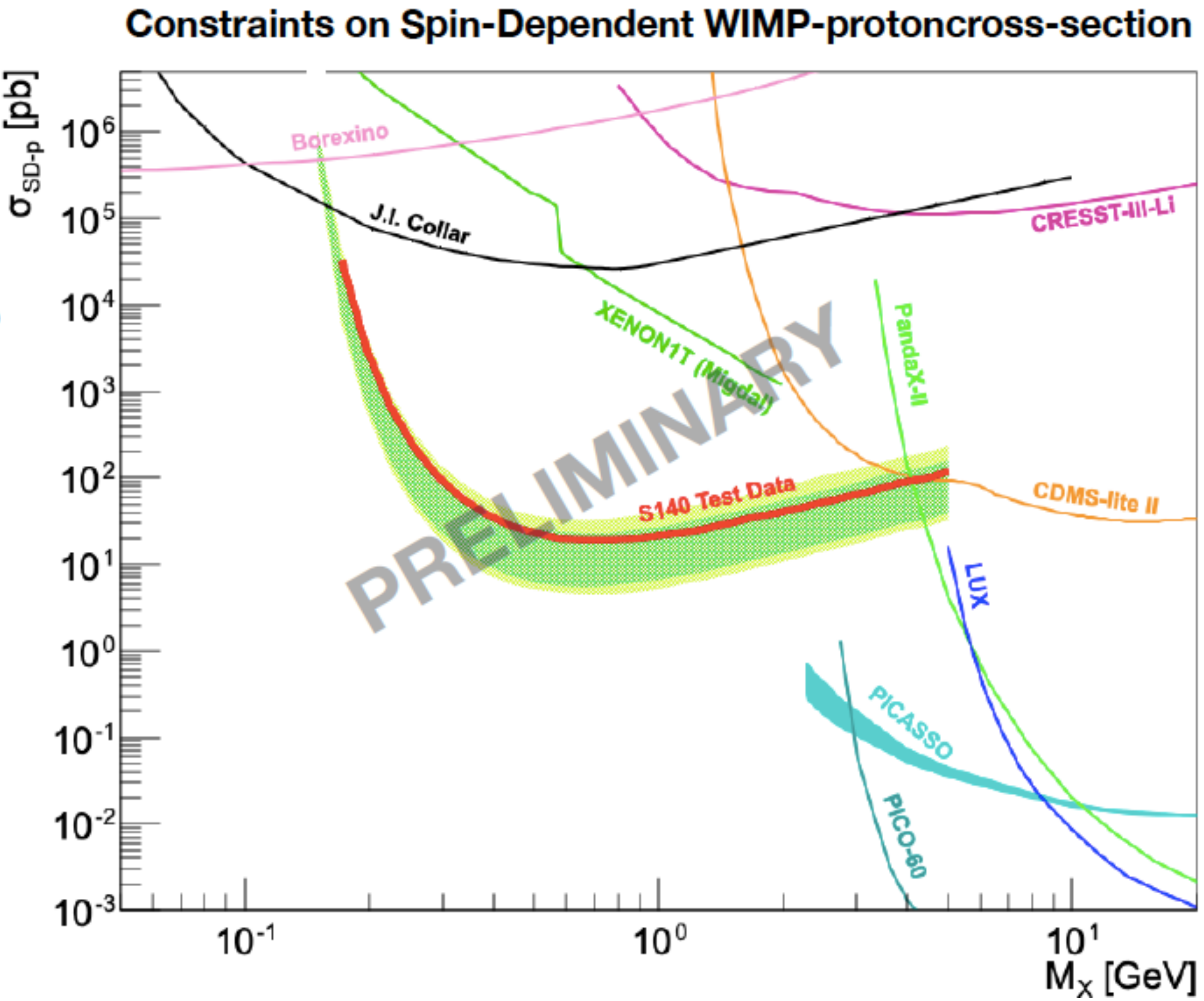
Packed in November 2019 to go to SNOLAB! First signal in summer 2021, currently finishing installation/ commissioning, physics data-taking to restart in coming weeks

From F. Vazquez de Sola's Blois presentation in May 2022

NEWS-G at LSM

New WIMP constraints

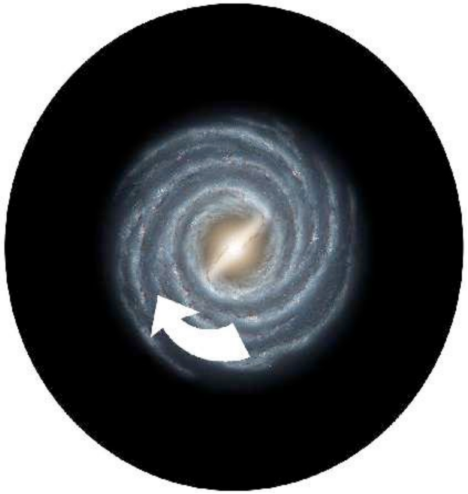
- Profile Likelihood used to generate constraints on WIMP cross-section
- Results on test data (effective 0.12 kg·day) : strongest constraint on spin-dependent WIMP-proton cross-section in 0.2-2 GeV range!
  - Final results on blind data in coming weeks



From F. Vazquez de Sola’s Blois presentation in May 2022

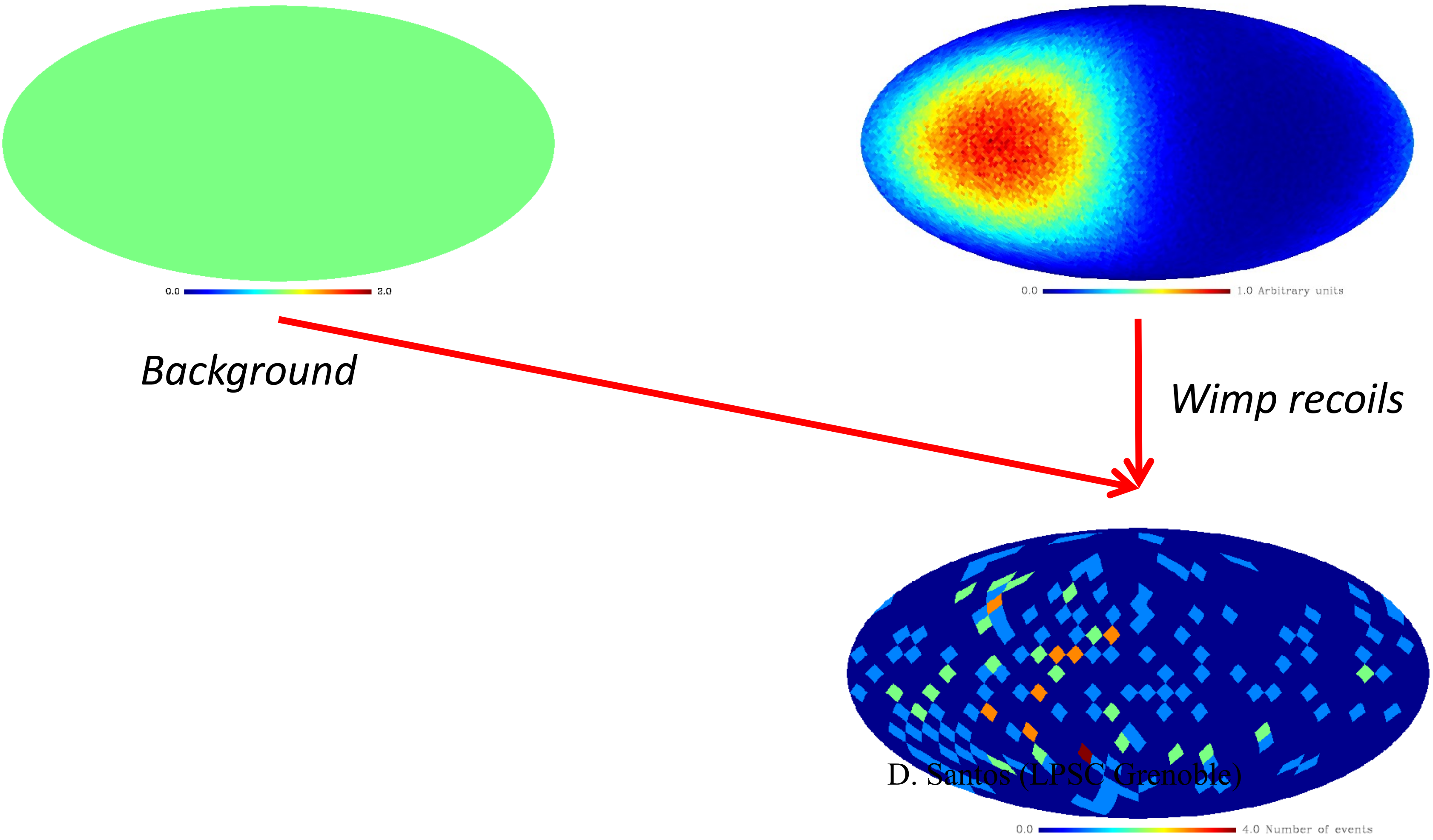
Dark Matter Directional Detection and Neutron spectroscopy with MIMAC

JCAP 08 (2022) 057, arXiv 2112.12469



Cyprien Beaufort, Olivier Guillaudin, Nadine Sauzet, D. Santos

100 WIMP evts + 100 Background evts



Background

Wimp recoils

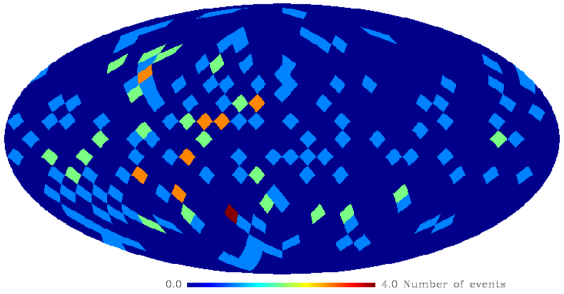
D. Santos (LPSC Grenoble)

Phenomenology: **Discovery**

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

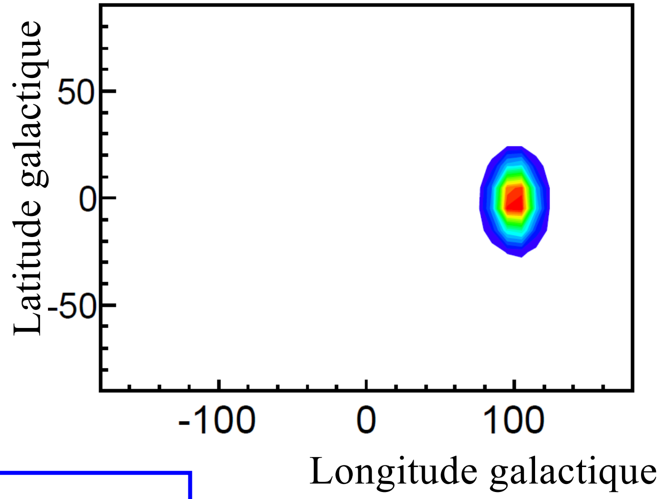
Proof of discovery: **Signal pointing toward the Cygnus constellation**

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



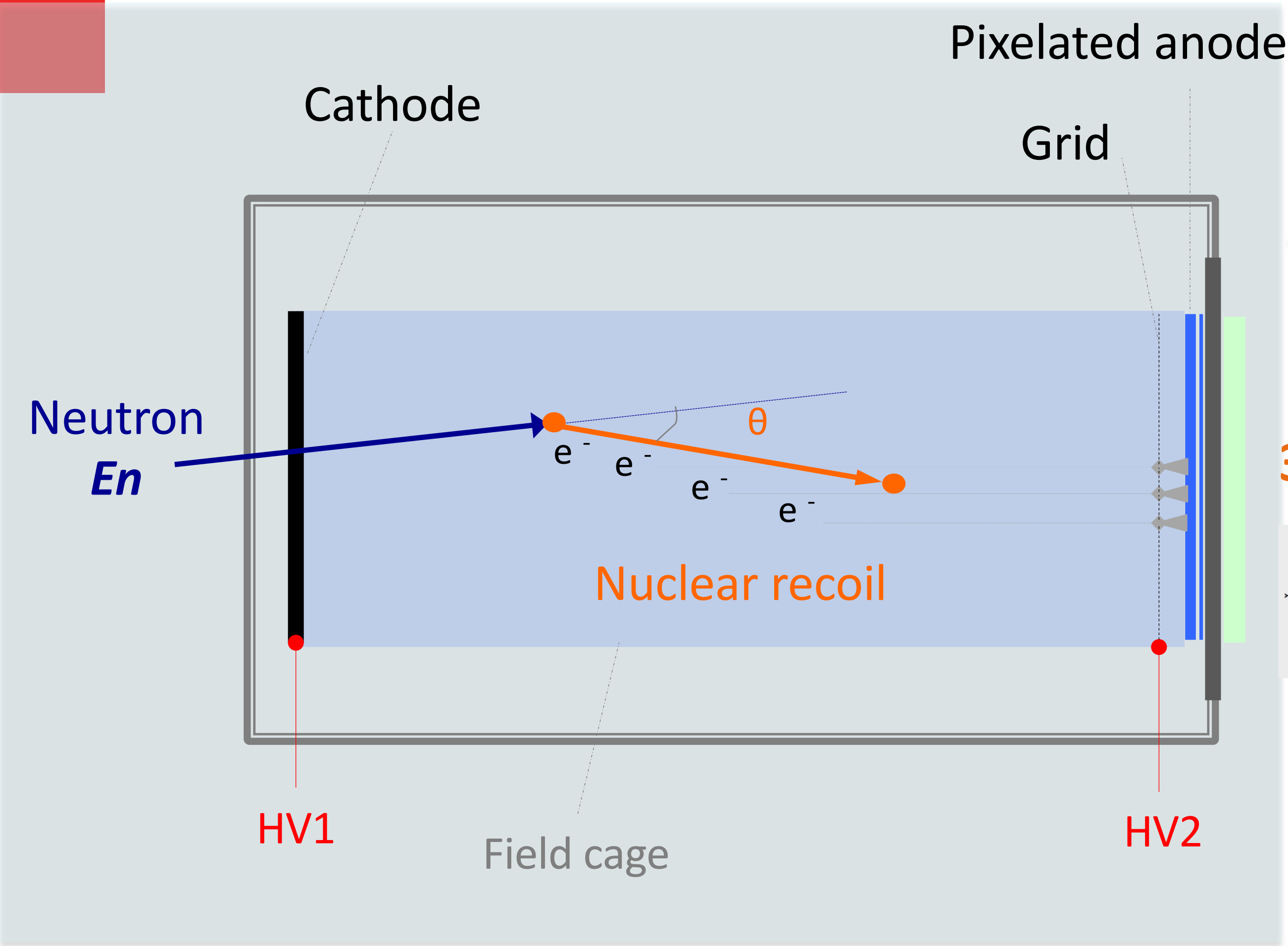
100 WIMP + 100 BKG

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

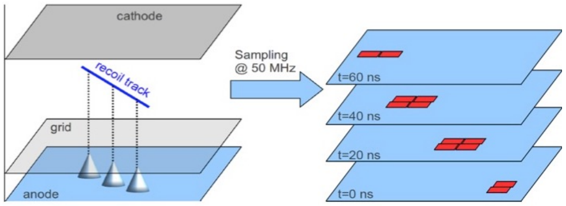


Strong correlation with the direction of the Constellation Cygnus **even with a large background contamination**

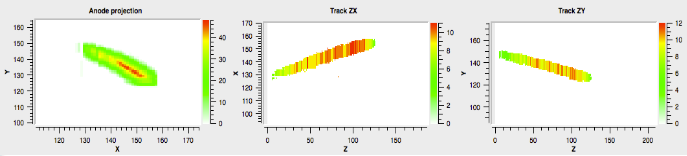
MIMAC operation principle



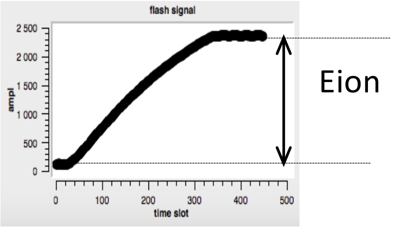
20 ns sampling :



3D recoil track ⟶ θ



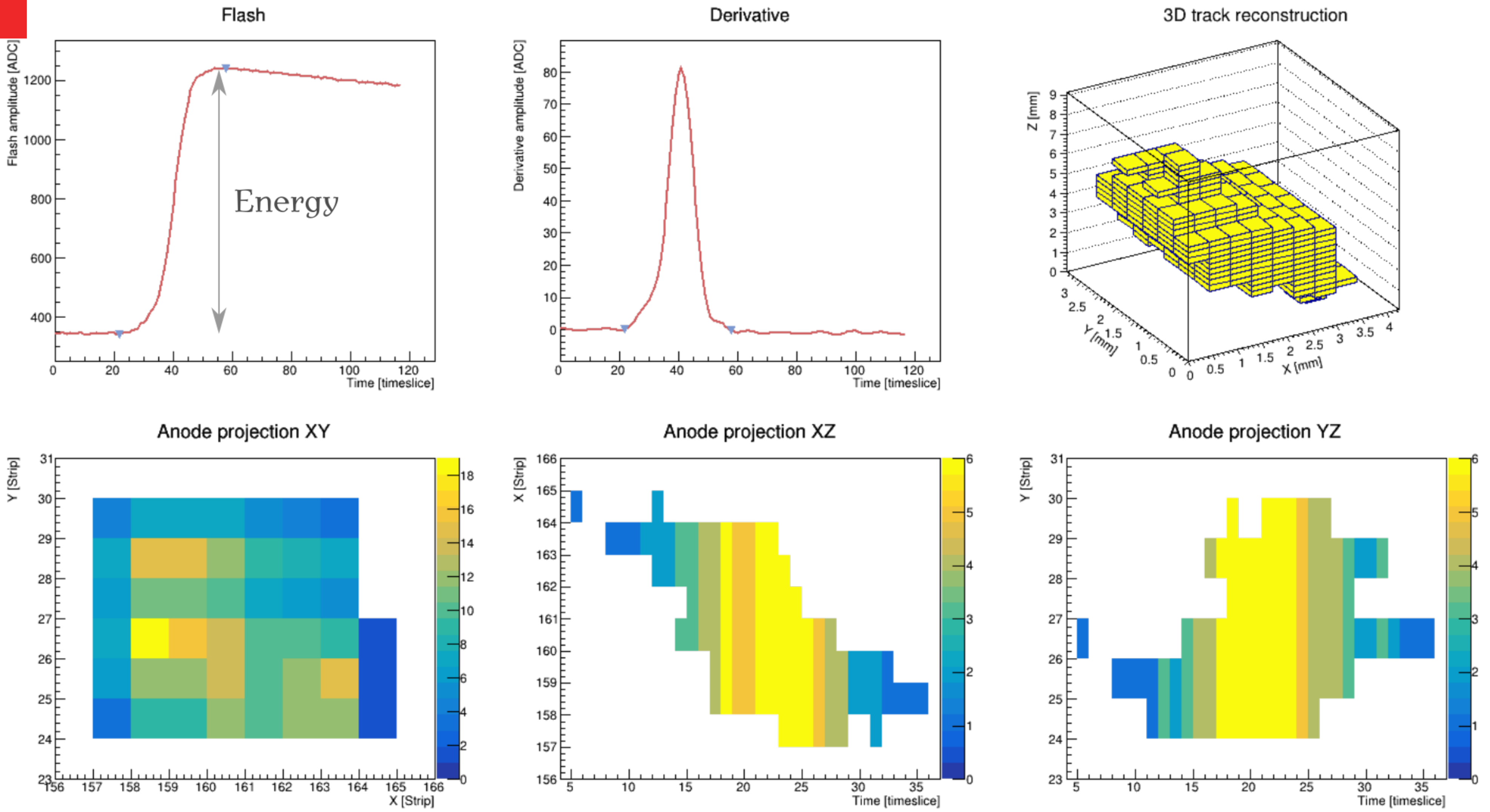
Energy deposited in ionization :



From **θ**, $\mathbf{E_{ion}}$, and the **IQF**,

*we get the neutron energy **En***

Proton recoil 3D track of 8.6 keV kinetic energy


Flash

Derivative

3D track reconstruction

Anode projection XY

Anode projection XZ

Anode projection YZ

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

– → Sampling at 50 MHz (20 ns)

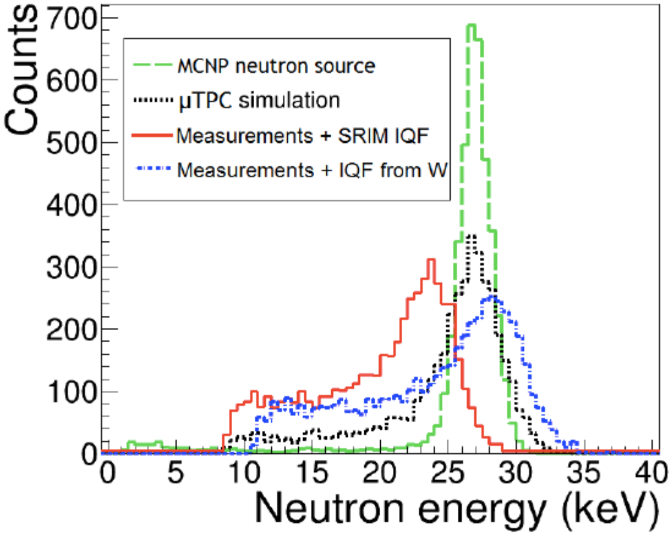
A large energy adjustable range

50% C_4H_{10} 50% CHF_3
30 mbar

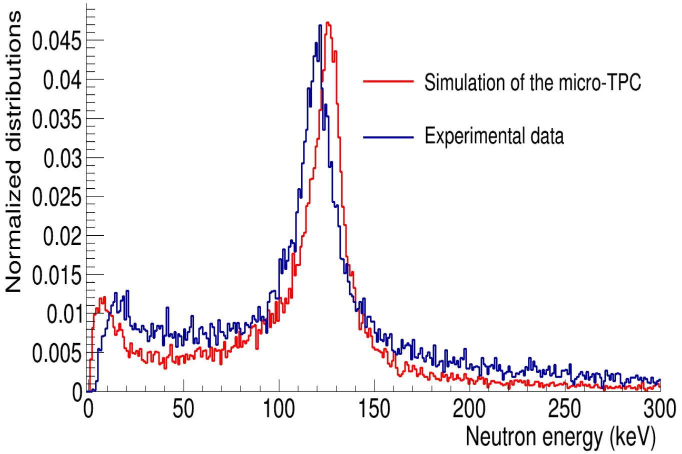
60% C_4H_{10} 40% CHF_3
50 mbar

95% ^4He 5% CO_2
700 mbar

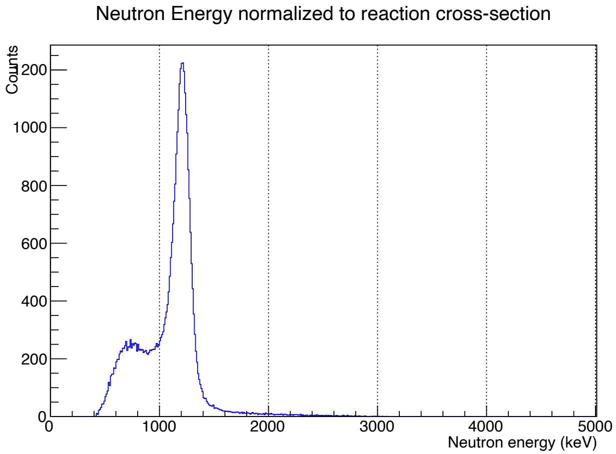
E_n=27 keV



E_n=127 keV



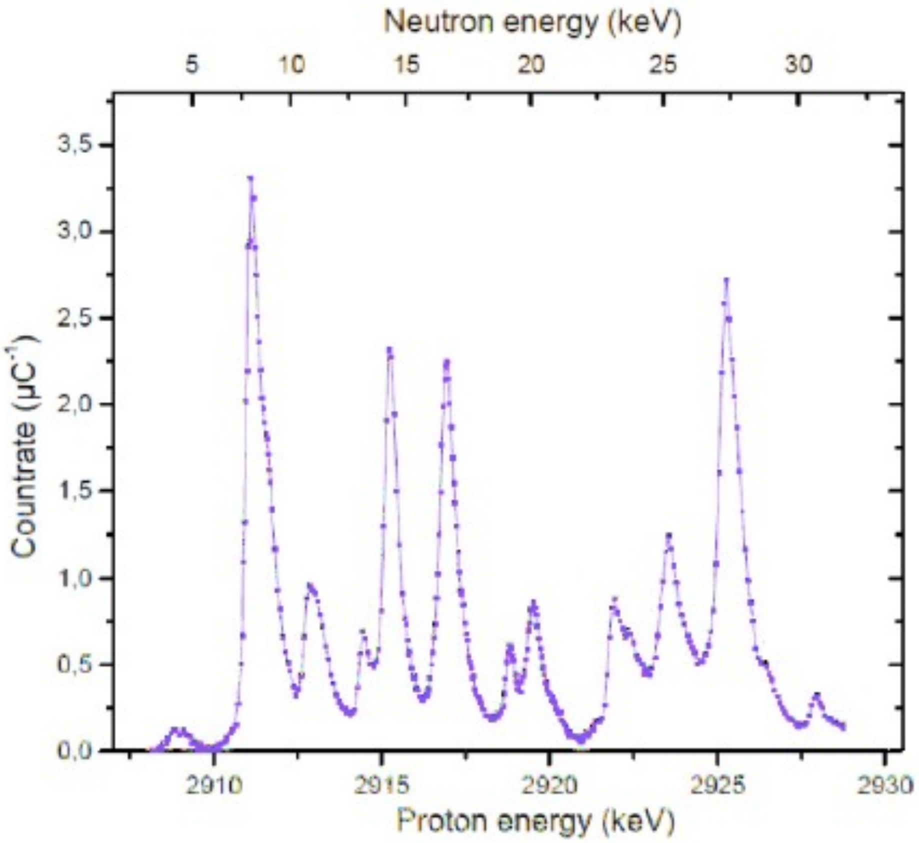
E_n=1.2 MeV



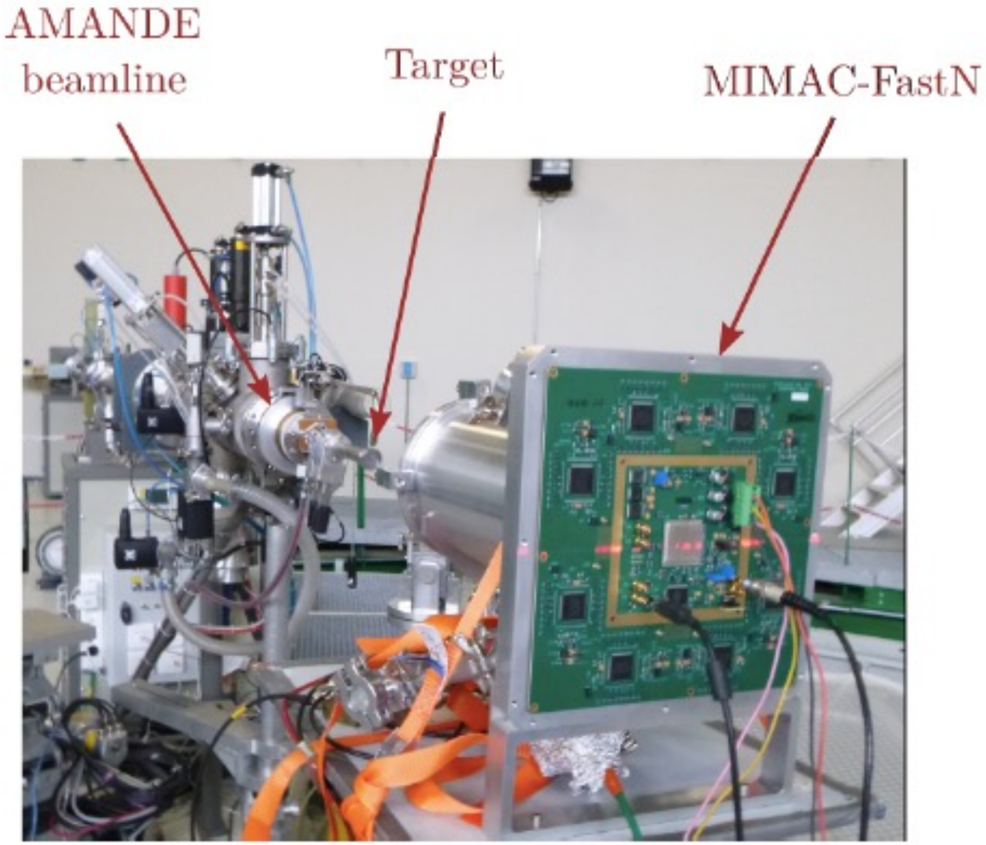
D. Maire *et al.*
« Neutron energy reconstruction and fluence determination at 27 keV with the LNE-IRSN-MIMAC µ-TPC recoil detector »
IEEE Transactions on Nuclear Science, 63(3) : 1934-1941, June 2016

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

Low energy (8 and 27 keV) monoenergetic neutron detection



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

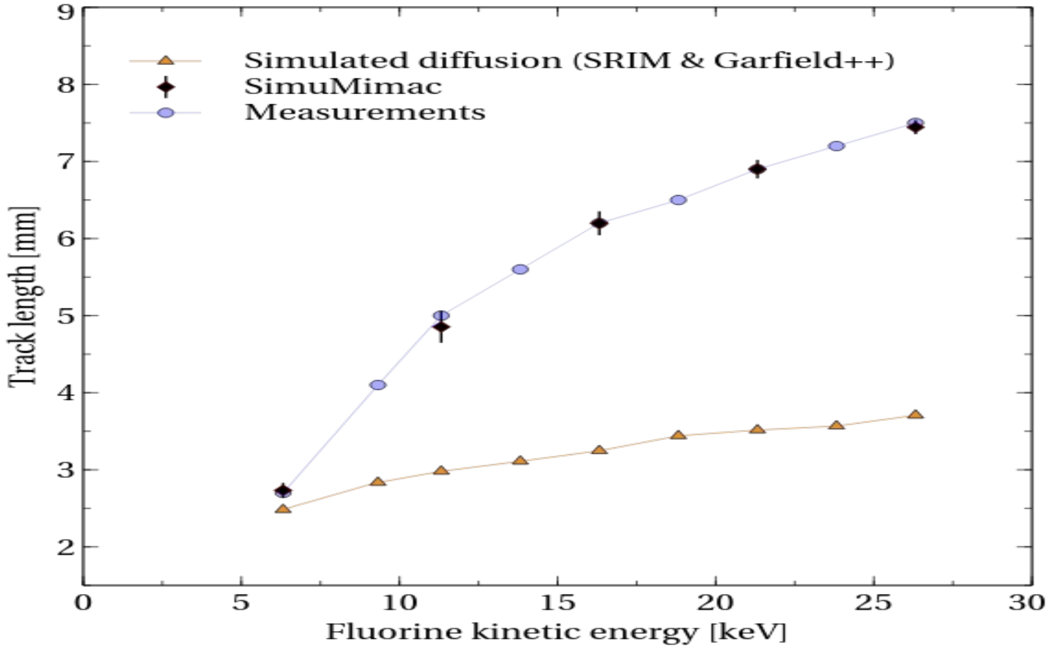


Amande facility (IRSN-LMDN) ⇒

Produce monochromatic neutron fields

Directionality at high gain - SimuMimac (1/2)

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

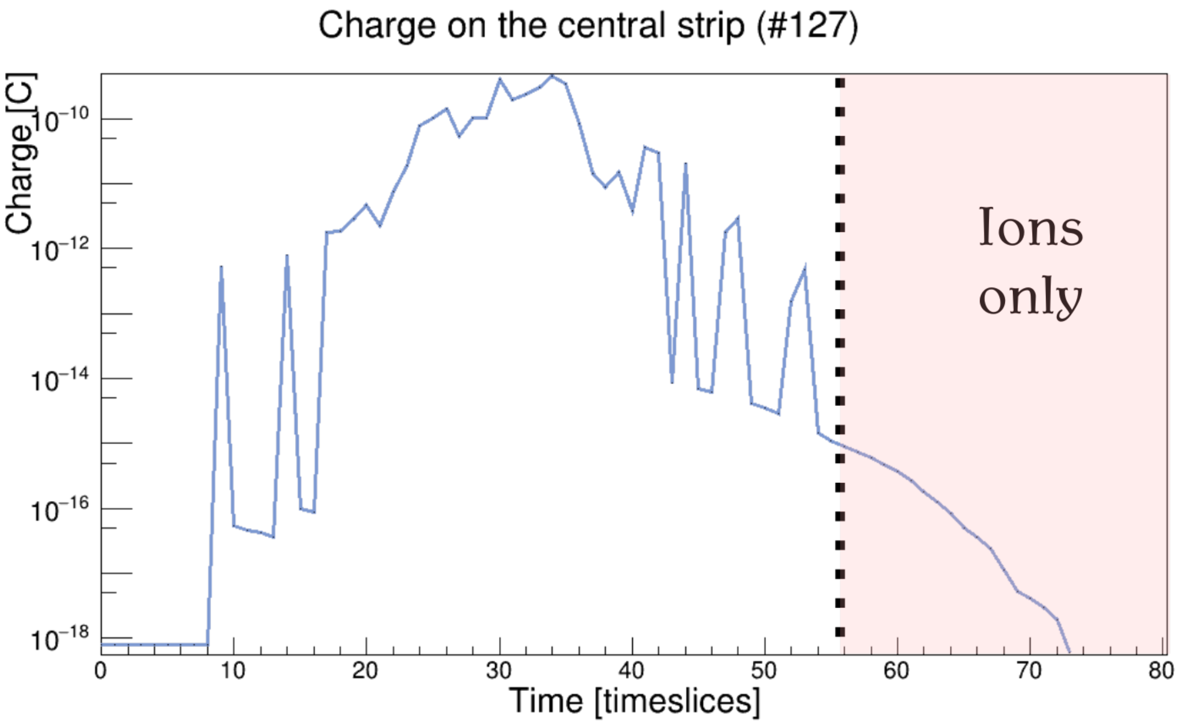
- SimuMimac agrees with the measurements
- Main difference with standard simulation code = **takes into account the current induced by the motion of the ions**

Directionality at high gain - SimuMimac (2/2)

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

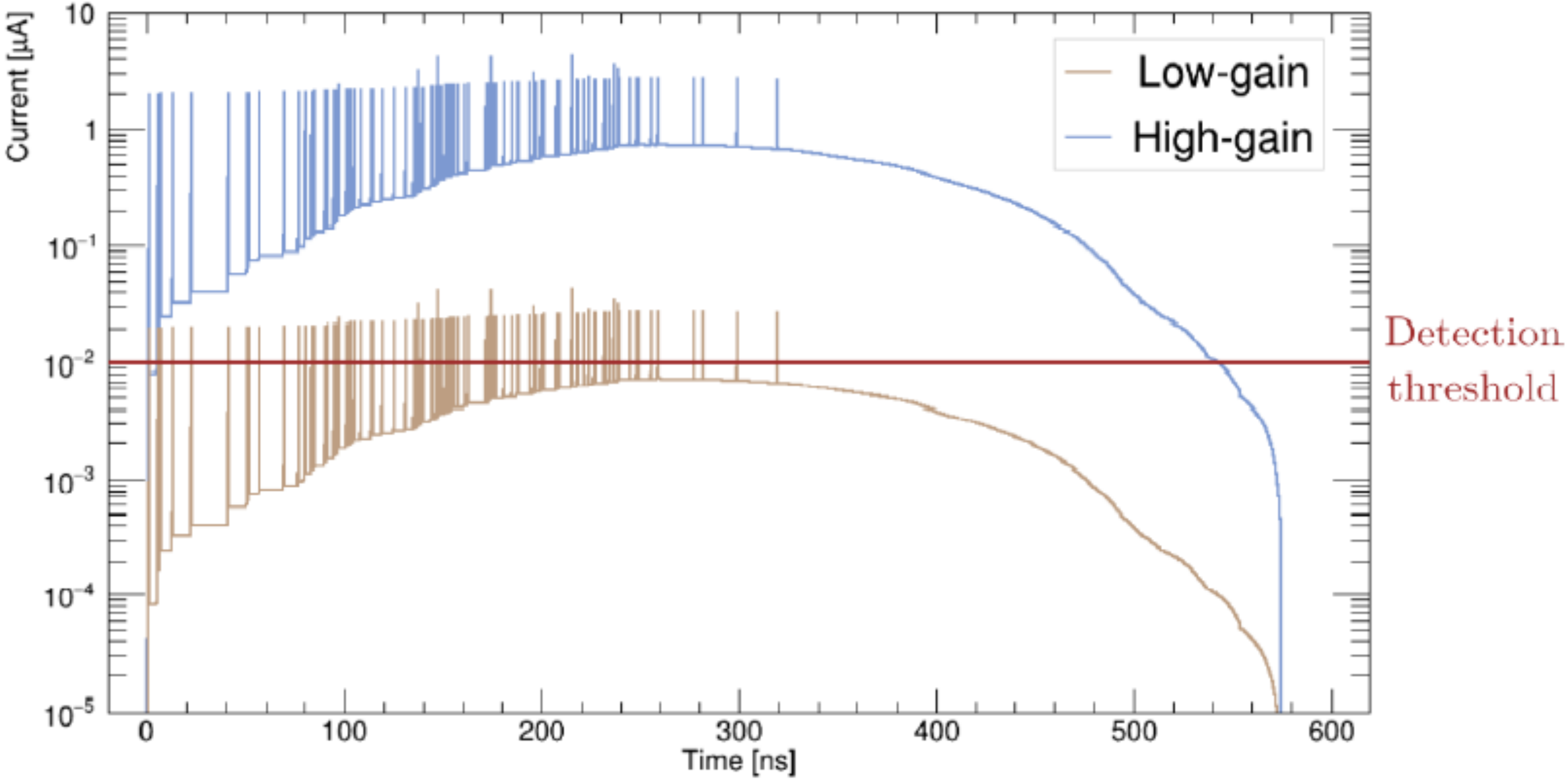
$$i(t) = \sum_{k=i,e} q_k \mathbf{E}_{w,k} \cdot \mathbf{v}_k \text{ with } \mathbf{v}_e \sim 10^3 \mathbf{v}_i$$

- 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**



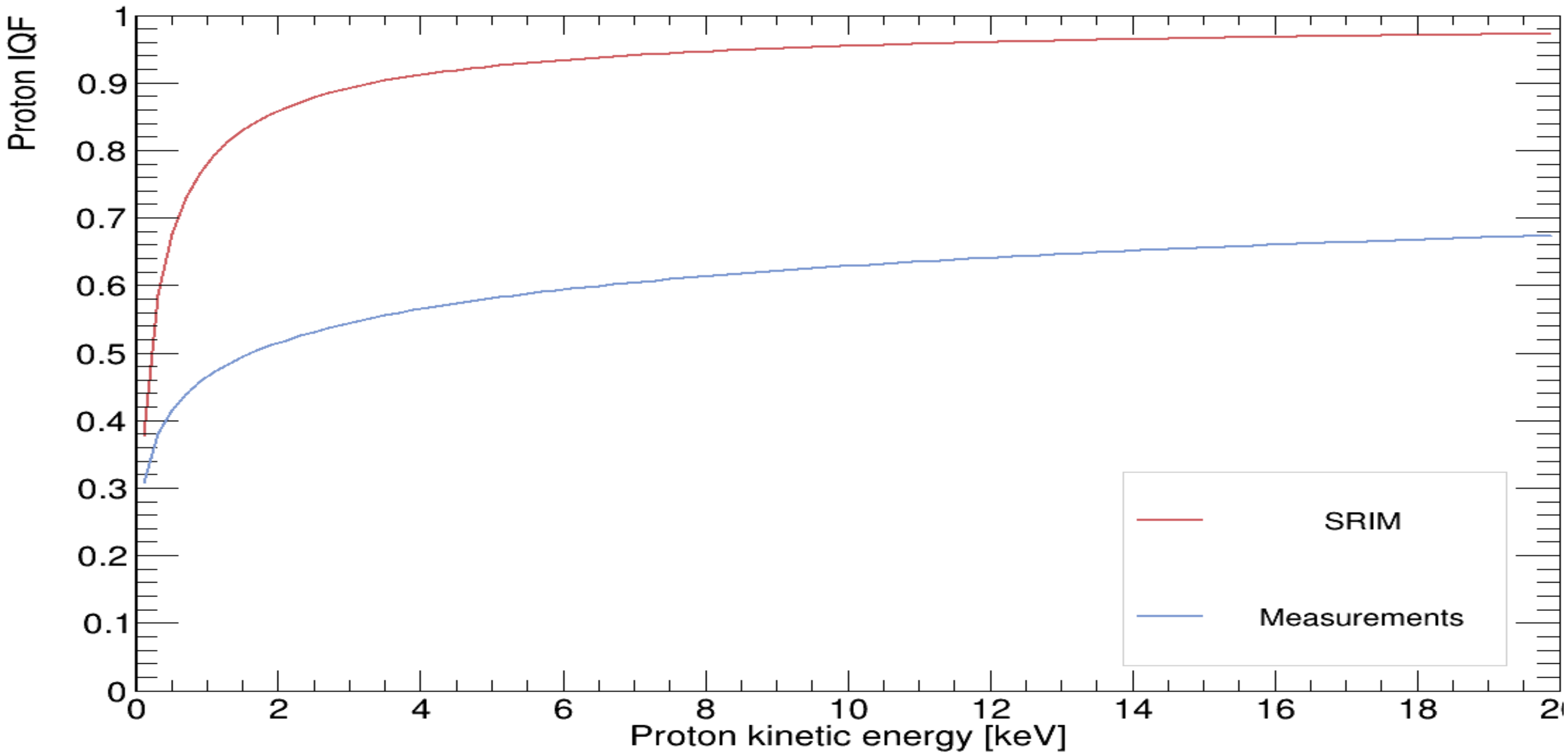
Signal contributions at high-gain (primary electrons and secondary ions)

Cyprien Beaufort et al. arxiv.org/2112.12469

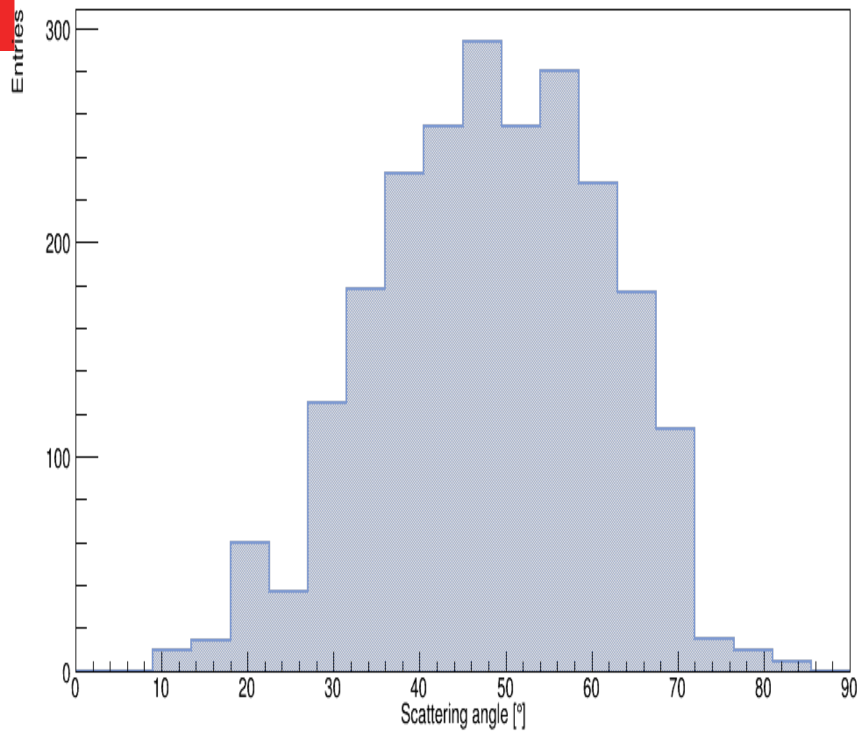


Neutron spectroscopy with MIMAC (1/2)

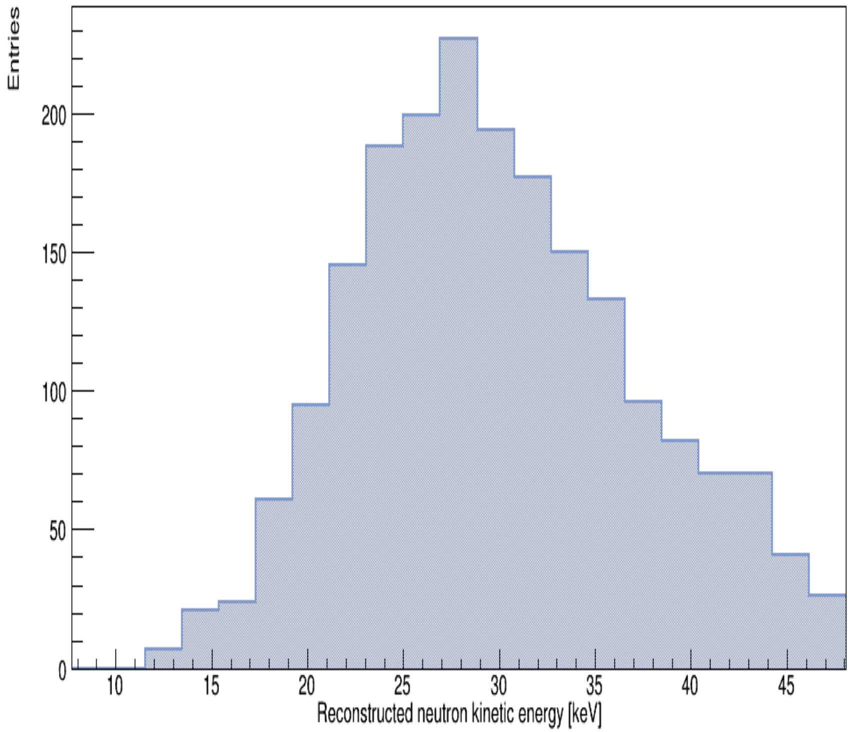
- Measurements with MIMAC in CHF_3 + 50% C_4H_{10} at 30 mbar
- The reconstruction of the kinetic neutron energy from proton recoil measurements **is very sensitive to the IQF** since neutrons induce nuclear recoils of any energy up to the kinematic limit
- As in the case of methane, **the proton IQF measured with Comimac is lower than SRIM** (40% difference at 2keV, compared with 33% difference in the methane measurements)



Directionality - Neutron spectrum reconstruction at 27 keV



Angular distribution

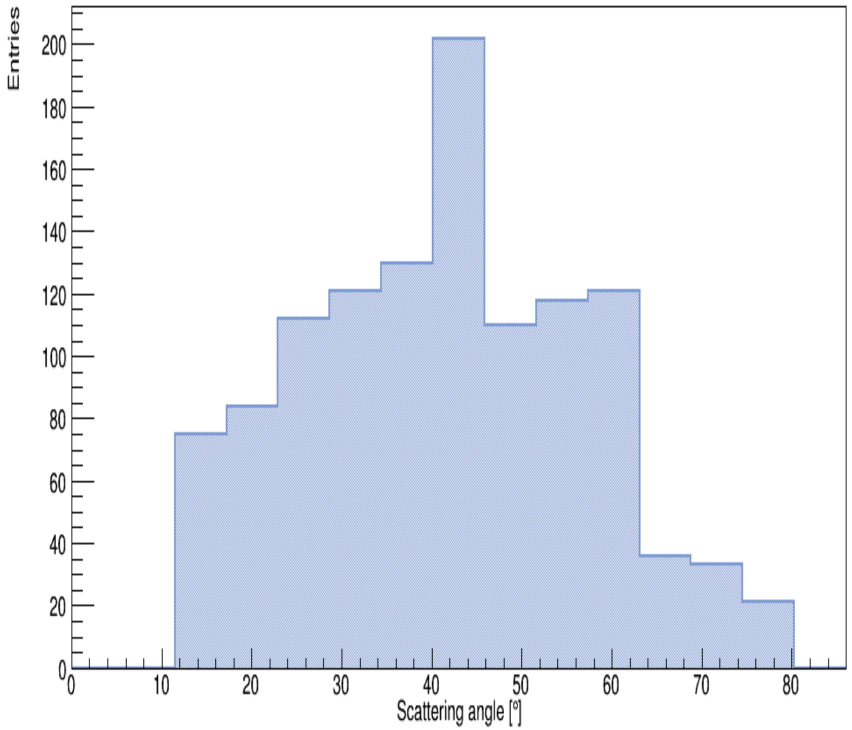


Reconstructed spectrum

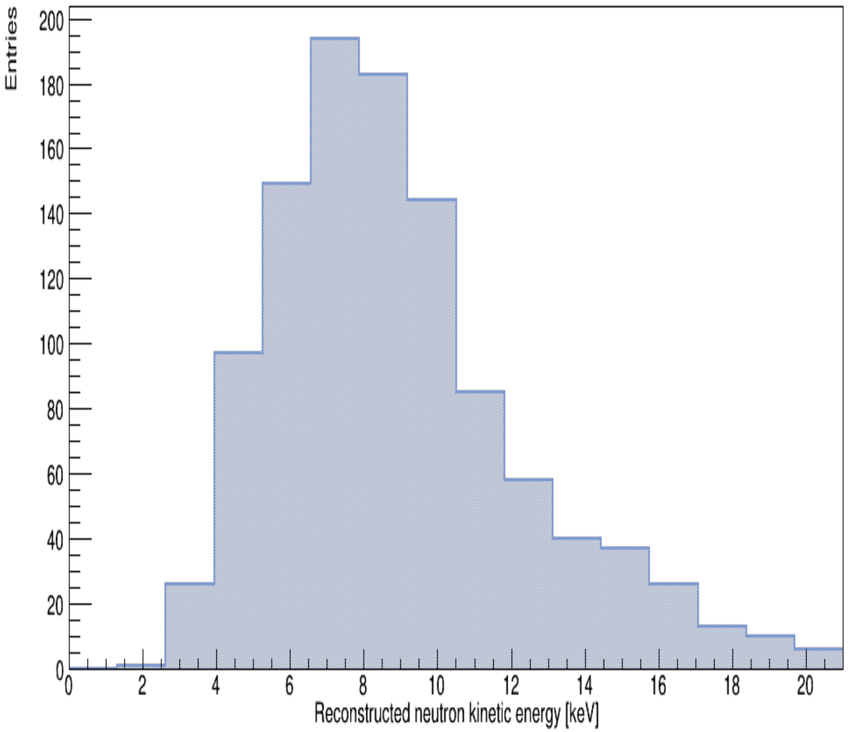
Directional performances at $27\,\mathrm{keV}$:

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

Directionality - Neutron spectrum reconstruction at 8 keV !!



Angular distribution



Reconstructed spectrum

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

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

Conclusions

i) A new method to measure the IQF in gas detectors has been validated

ii) The Directional Detection (DD) of Nuclear Recoils at low energies (E > 1 keV) is now possible

iii) The DD is a degree of freedom to cope with the Background !!

W-value measurements for low energy electrons !

W VALUES OF LOW-ENERGY ELECTRONS

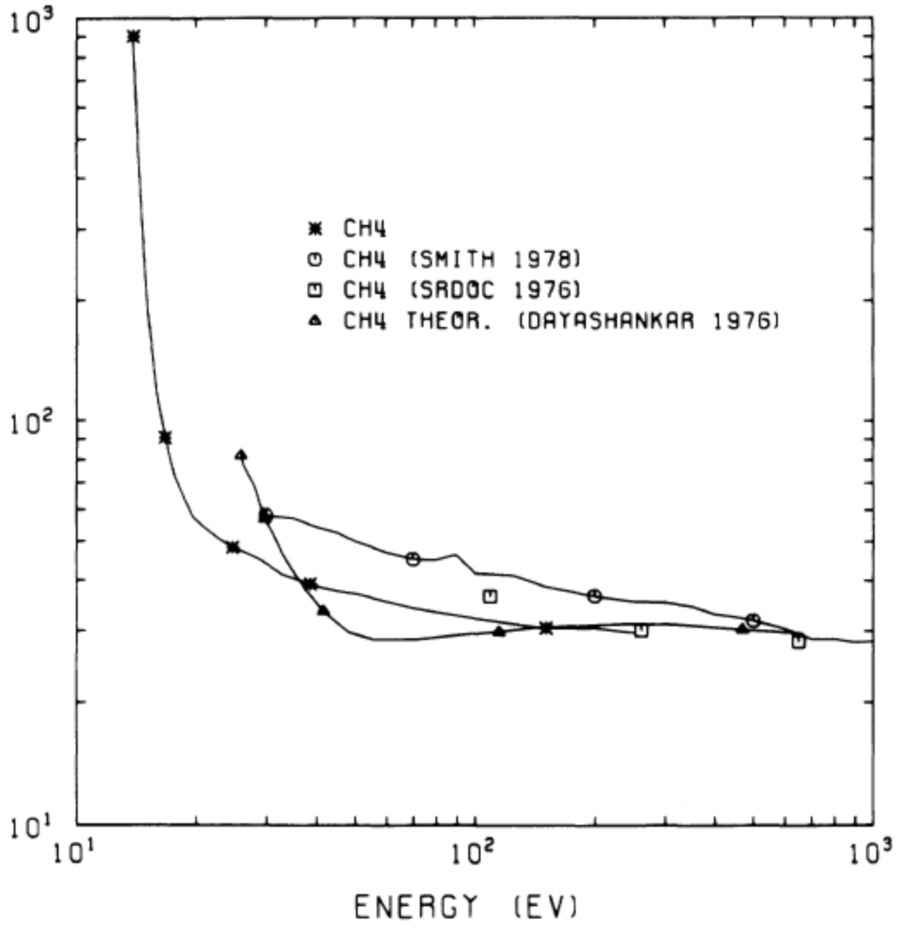
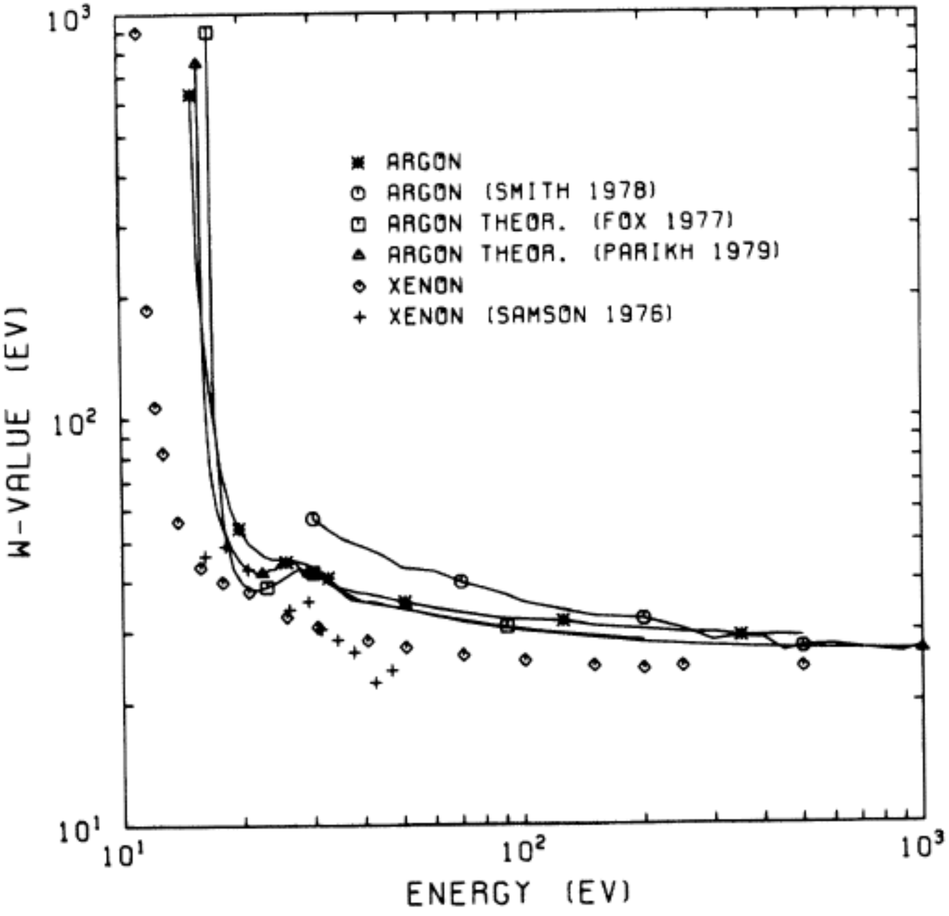


FIG. 19. Methane.

D. COMBECHER



. Argon and xenon.

LPSC Grenoble)

Measurement of W Values of Low-Energy Electrons in Several Gases

Author(s): D. Combecher

Source: *Radiation Research*, Vol. 84, No. 2 (Nov., 1980), pp. 189-218

Published by: Radiation Research Society

Stable URL: http://www.jstor.org/stable/3575293

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

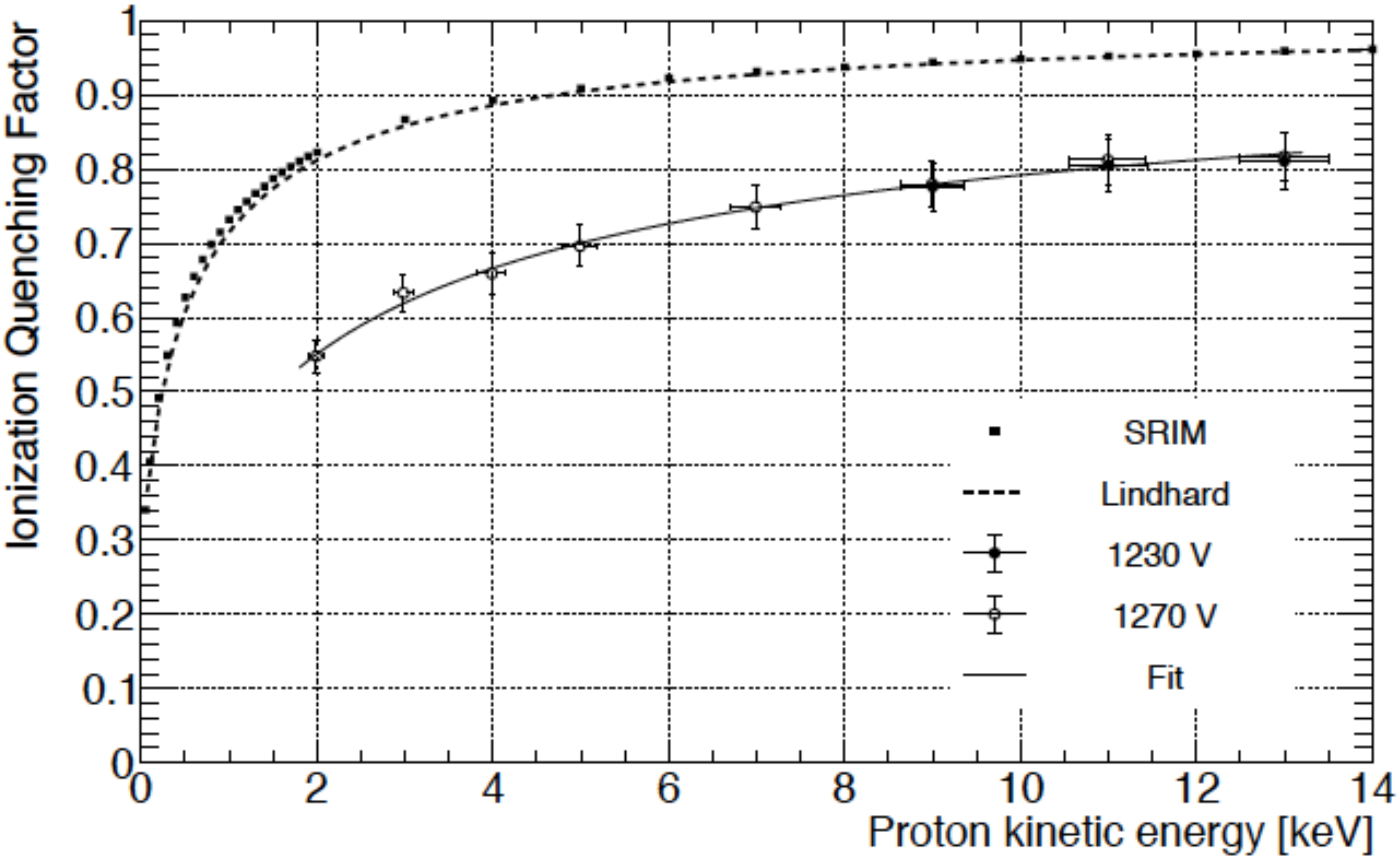
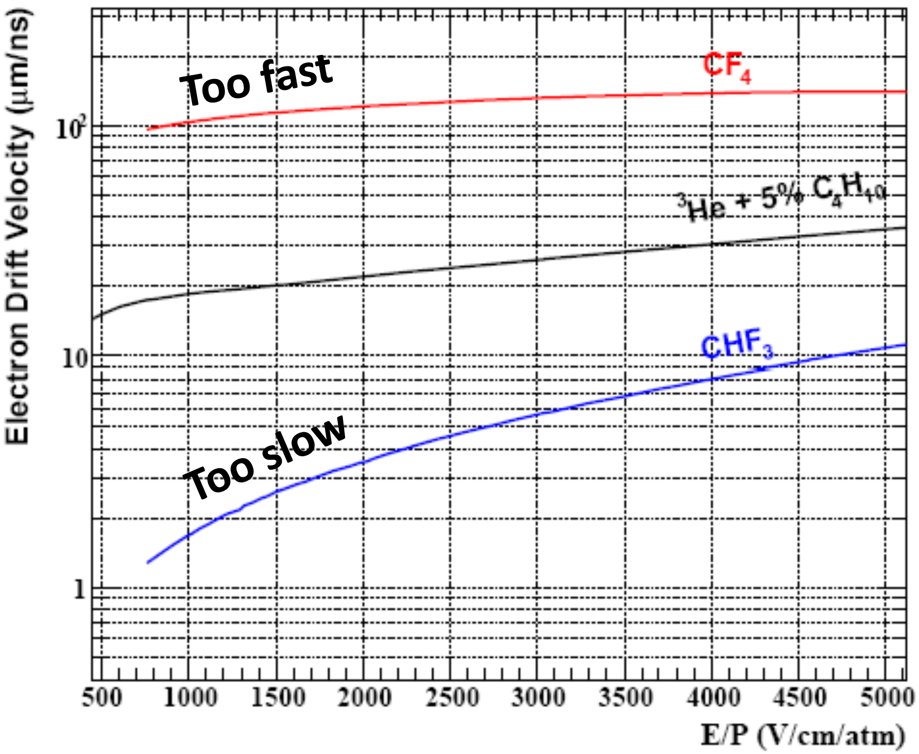
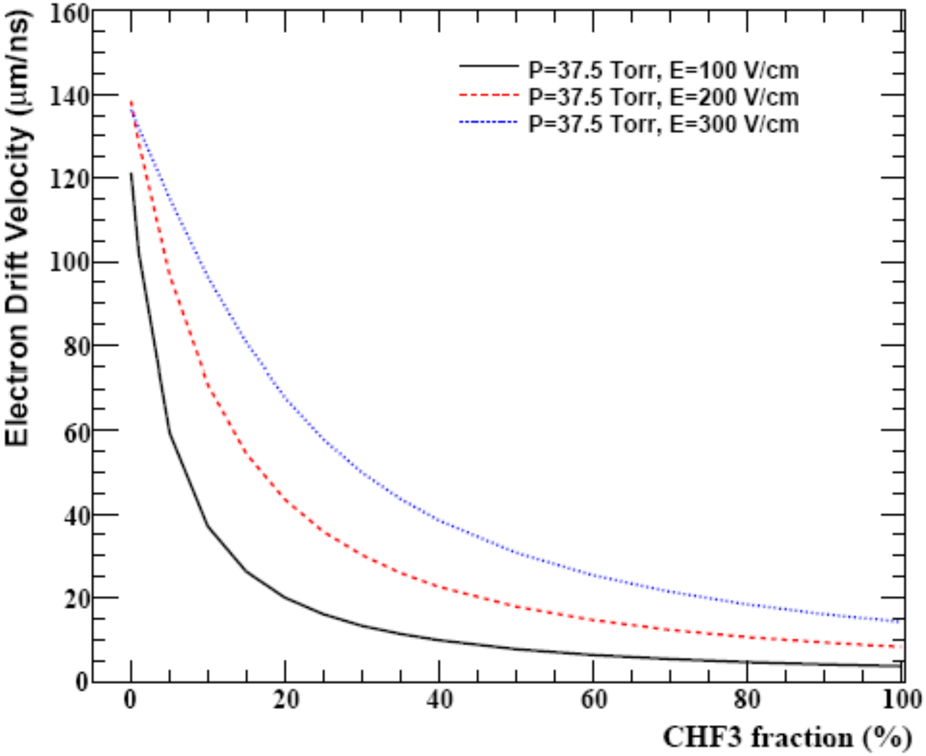


Fig. 9: Ionization Quenching Factor for protons in 100 mbar of methane. The measurements at 1230 V and 1270 V are respectively presented with black dots and white dots. Comparisons with SRIM and with the Lindhard theory are also shown.

3D Tracks: Drift velocity

Magboltz Simulation



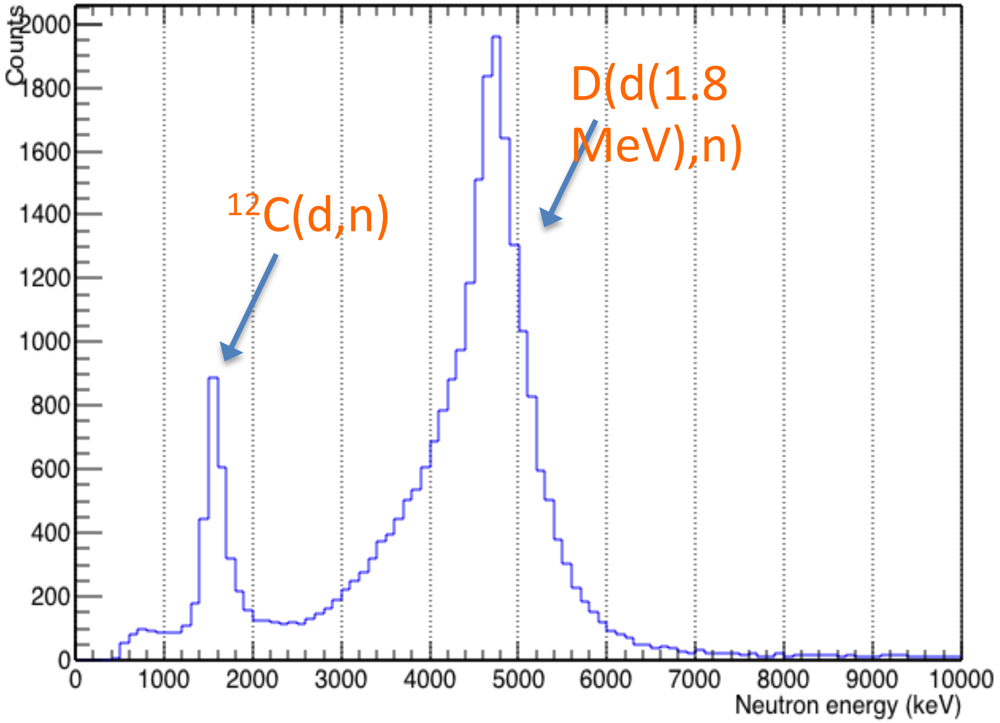


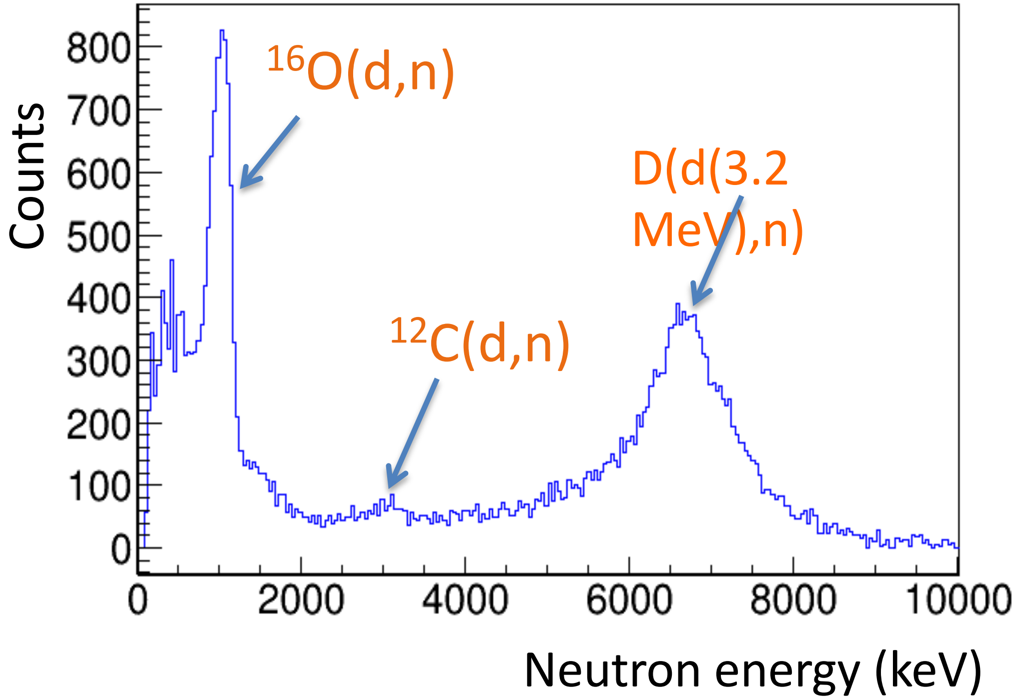
- New mixed gas MIMAC target : CF_4 + x% CHF_3 (x=30)

Monoenergetic measurements : detection of target pollution

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

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





NPL /(UK)

IRSN / AMANDE (Cadarache)

700 mbar He/CO_2 (5%)

Paper to be submitted

Polyenergetic measurement with ^{9}Be(d(1.45 MeV),n)

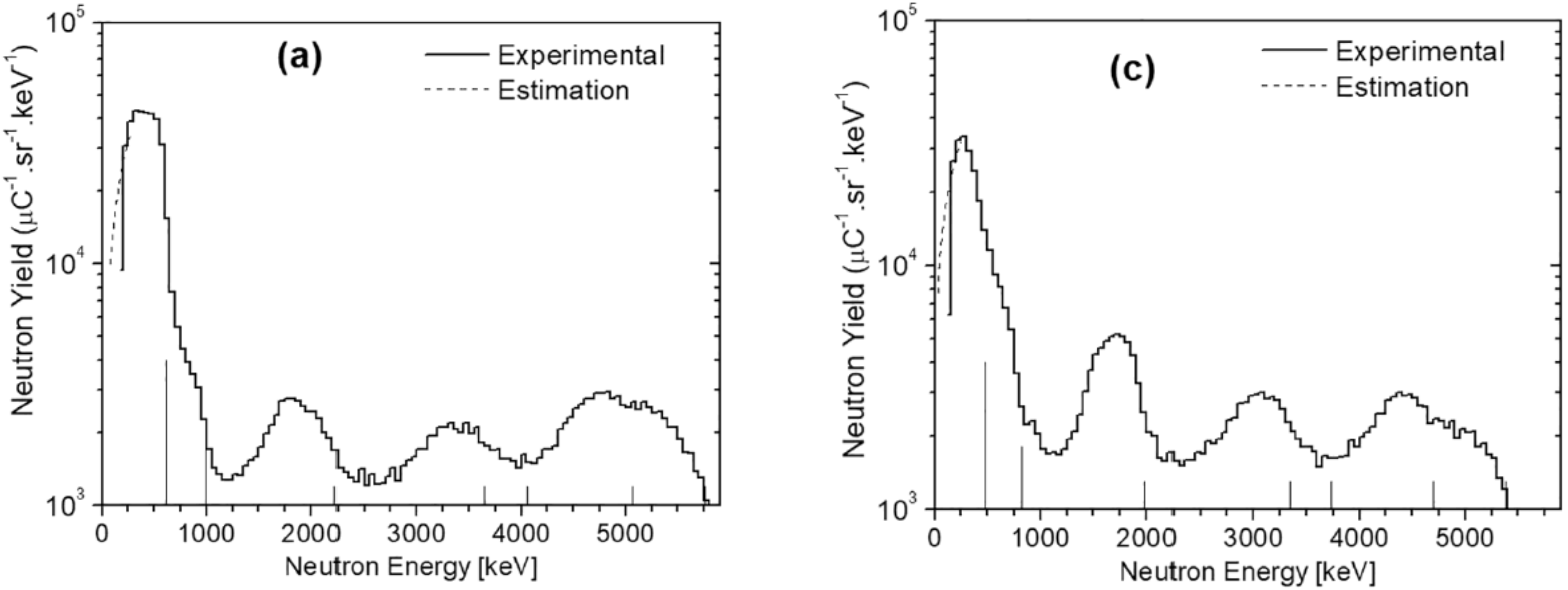
Angular distribution

INFN LNL
(Legnaro - Italy)

700 mbar
He/CO_2 (5%)

Spectrum measured at **0 deg**

Spectrum measured at **60 deg**



M.E. Capoulat, N.Sauzet *et al.*
« Neutron spectrometry of the ^{9}Be(d(1.45 MeV),n)^{10}B reaction for accelerator-based BNCT »
NIM B, vol. 445, pp. 57-62, 2019

First detection of 3D tracks of Rn progeny

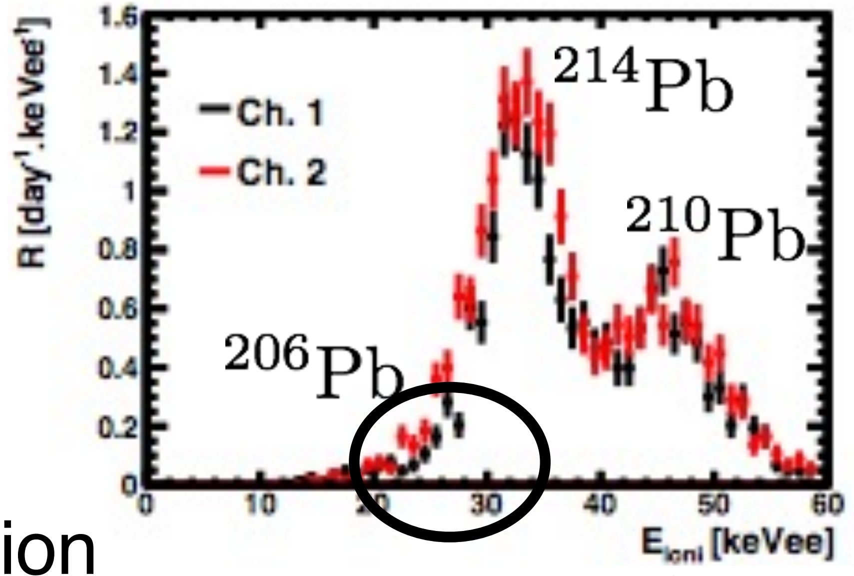
Electron/recoil discrimination

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



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