MIMAC

MIcro-tpc MAtrix of Chambers

for Directional Dark Matter Detection and Neutron Spectroscopy...

Charling Tao,

CPPM Marseille and Universtié Aix Marseille

and Daniel Santos

LPSC-Grenoble and Université Grenoble-Alpes

People involved in 2018

LPSC (Grenoble) : D. Santos, F.Naraghi , N. Sauzet (CDD)

-Technical Coordination, Gas circulation and detectors : **O. Guillaudin**

- Electronics : **G. Bosson, J. Bouvier, J.L. Bouly, L.Gallin-Martel, F. Rarbi**
- Data Acquisition: **T. Descombes**
- Mechanical Structure : **J. Giraud**
- COMIMAC (quenching) : **J-F. Muraz**

IRFU (Saclay): P. Colas, I. Giomataris

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

Tsinghua University (Beijing-China): C. Tao, I. Moric (post-doc), Y. Tao (Ph.D)

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

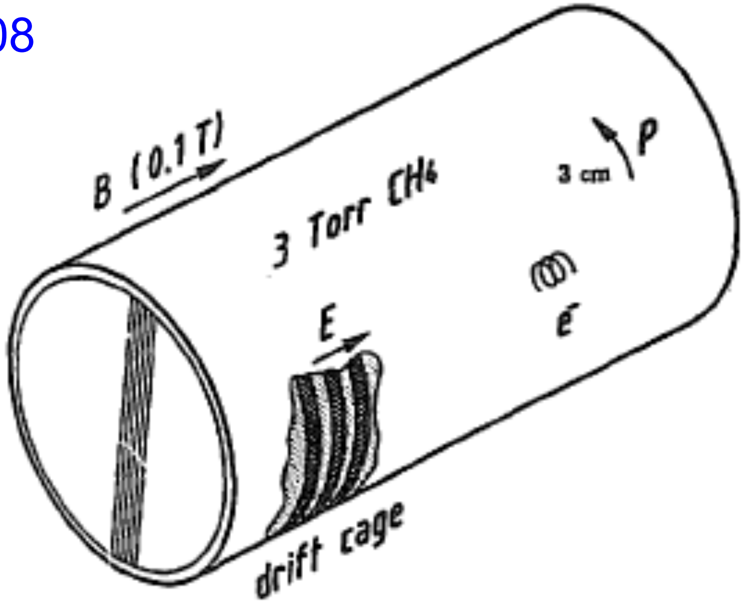
Neutron facility (AMANDE) :

IRSN (Cadarache): V. Lacoste, B. Tampon (Ph. D.)

Many other people : Julien Billard, Quentin Riffard, Zhou Ning, Dai Changjiang, Wang Qing…

An old idea:
Dark matter detection with hydrogen proportional counters

G. Gerbier, J. Rich, M. Spiro, C. Tao
Nuclear Physics B - Proceedings Supplements
Volume 13, February **1990,** Pages 207-208

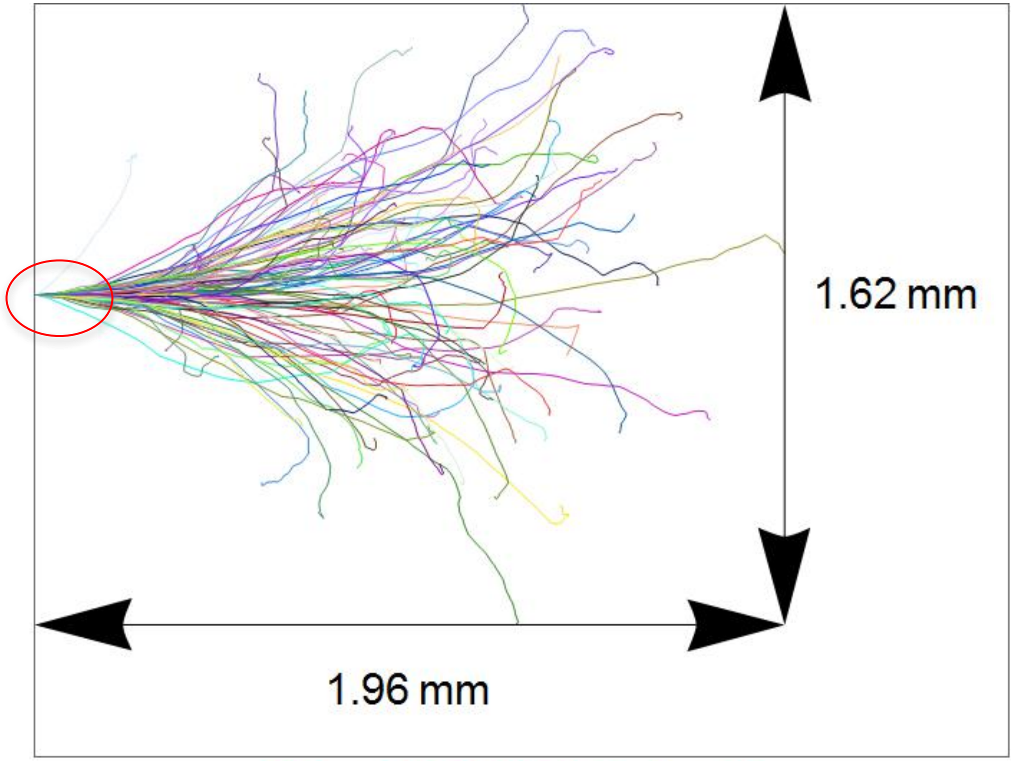


Problems: - technical : low pressure, short track length expected
- Is DM Cold? N-body simulations issues

➔ **Astrophysics**

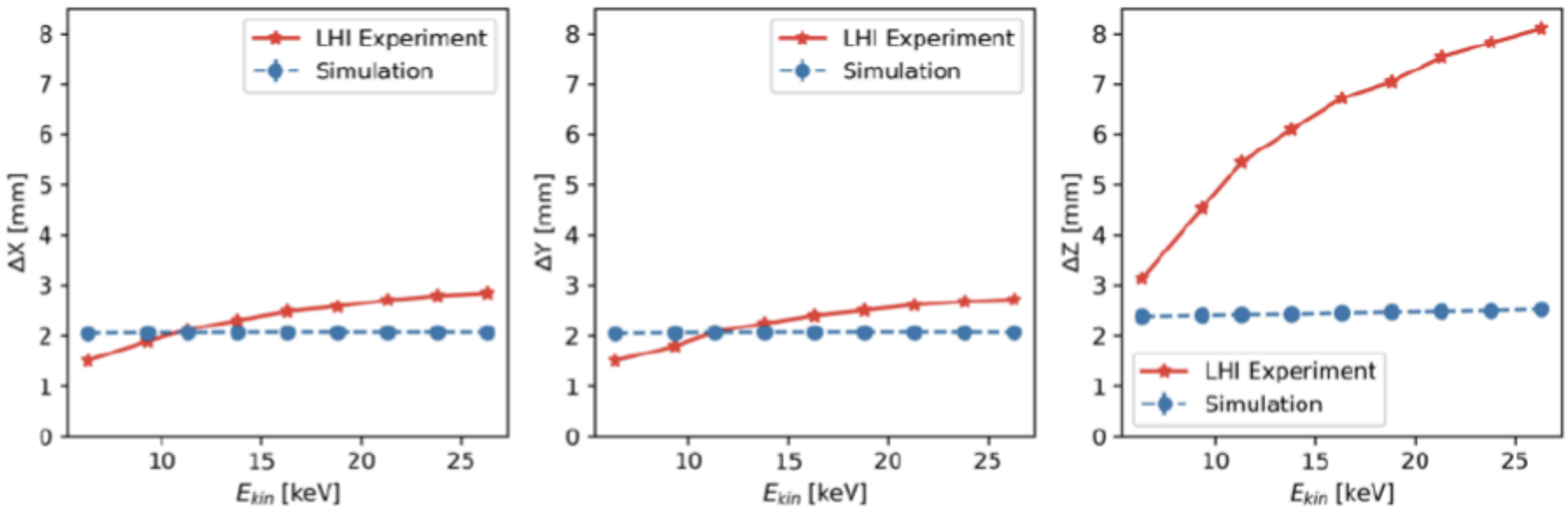
SRIM simulations

For directionality : zoom on track head



F in MIMAC (34keV)

Simulations had been misleading us!



Factor of > 6 longer tracks in real experiments !

More later on our latest results with LHI ion source !

Breakthough in 2011:
5-10 x lower drift velocity possible

Add 30% CHF3 to the standard CF4 gaz

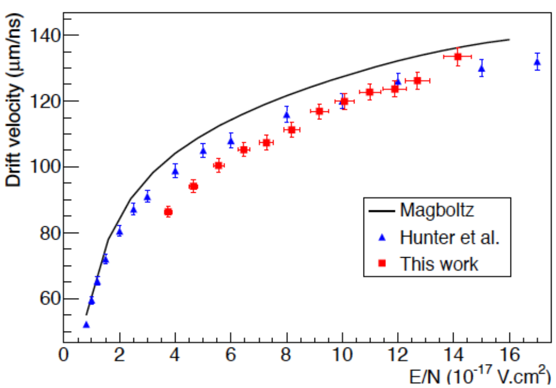


Figure 10. *Electron drift velocity measurement v_d (µm/ns) in a pure CF_4 gas at 50 mbar as a function of E/N (10^{-17} Vcm^2), for an amplification field $E_a = 14.5$ kV/cm. The data (red squares) have been obtained with the likelihood analysis strategy. We also present the Magboltz simulation (black line) and previous experimental data (blue triangle) [38].*

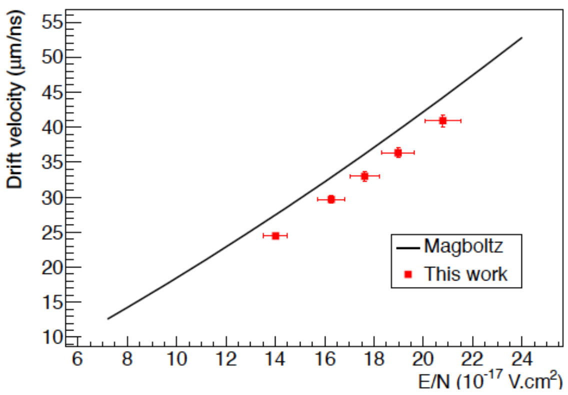


Figure 11. *Electron drift velocity measurement v_d (µm/ns) in a 70%CF_4 + 30%CHF_3 gas mixture at 50 mbar as a function of E/N (10^{-17} Vcm^2), for an amplification field $E_a = 15.6$ kV/cm. The data (red squares) have been obtained with the likelihood analysis strategy. We also present the Magboltz simulation (black line). To our knowledge there is no other experimental data with this gas mixture.*

Billard et al.   1305.2360

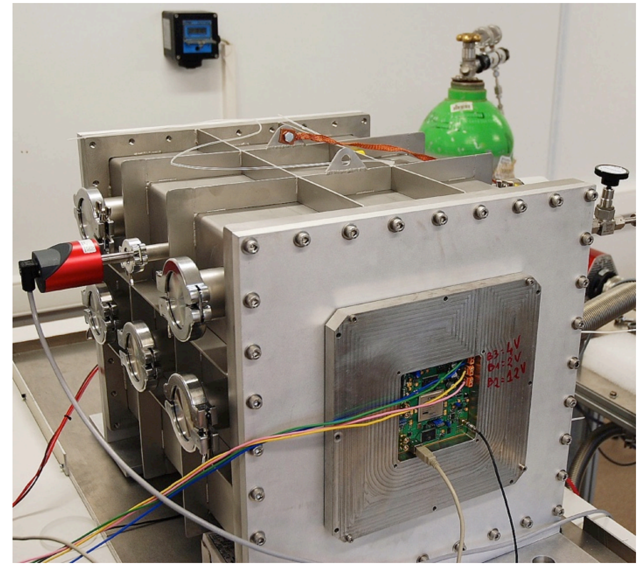
Angular resolution < 20deg: R&D studies for requirements

Billard et al 2010

- Measurable track length
- Measurable directionality
- Head-tail separation
- Ion/electron separation
- Quenching factor
- Reconstruction of initial recoil angle
- ,…

The MIMAC project

The MIMAC DM Directional Detector



A low pressure multi-chamber detector

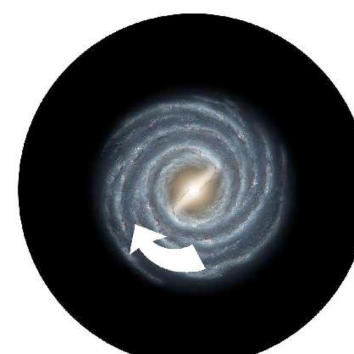
- Energy and 3D Track measurements
- Matrix of chambers (correlation)
- μTPC : Micromegas technology

MIMAC main Target:

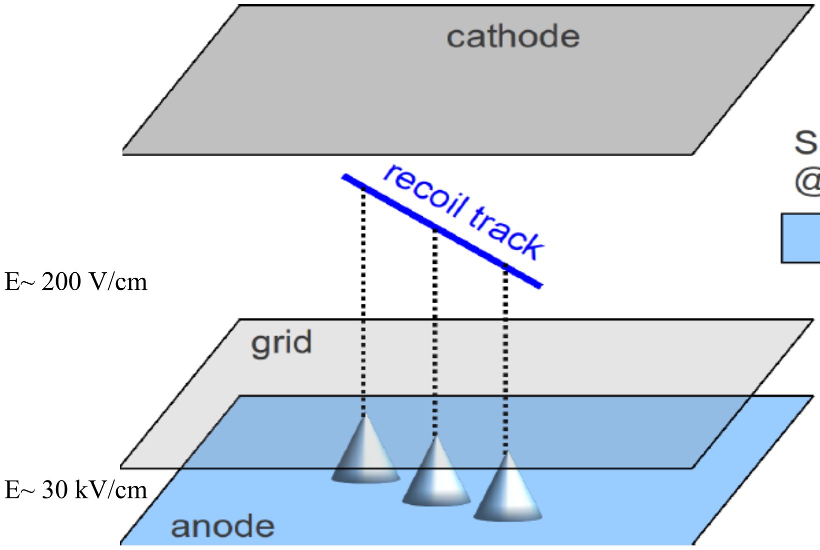
$^{19}\mathrm{F}$
- Light WIMP mass
- Axial coupling

Bi-chamber module
2 x (10.8x 10.8x 25 cm^3)
Now in THCA

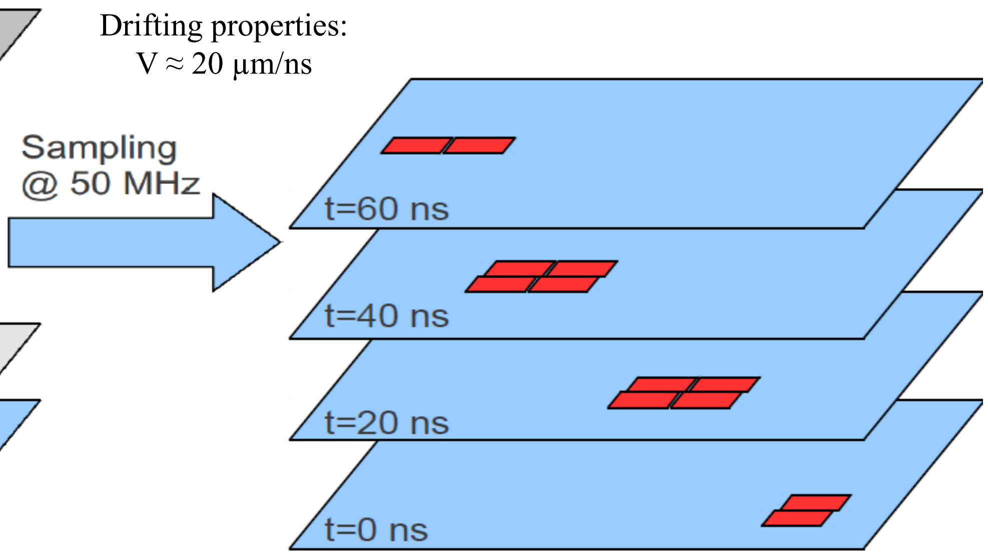
<u>Strategy:</u>
- Directional direct detection
- Energy (Ionization) AND 3D-Track of the recoil nuclei
- Prove that the signal "comes from Cygnus "



MIMAC measurement principle



Scheme of a MIMAC μTPC



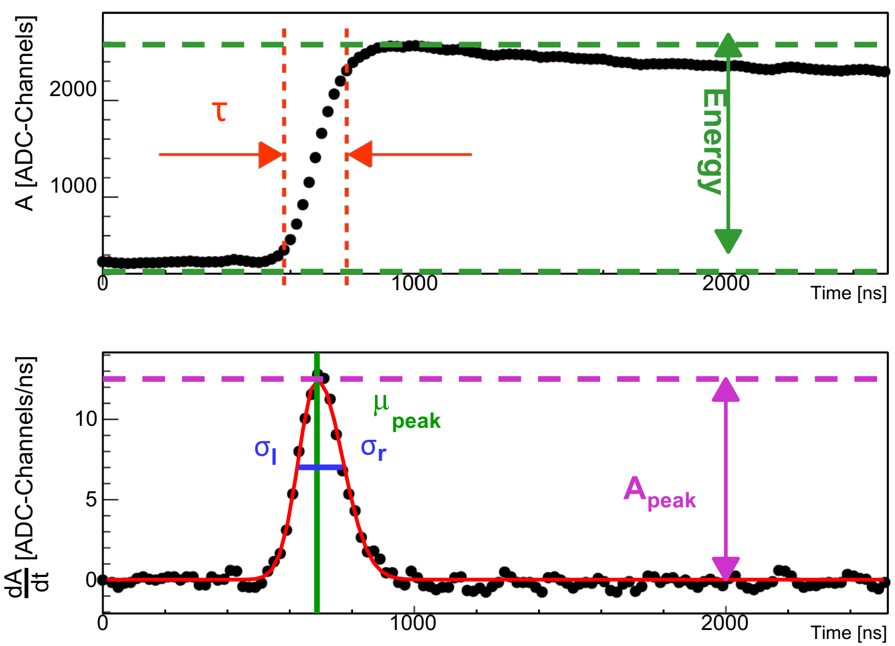
Evolution of the collected charges on the anode

- ***Micromegas detector***
- ***ionization energy:*** Charge integrator connected to the mesh coupled to a FADC sampled at 50 MHz

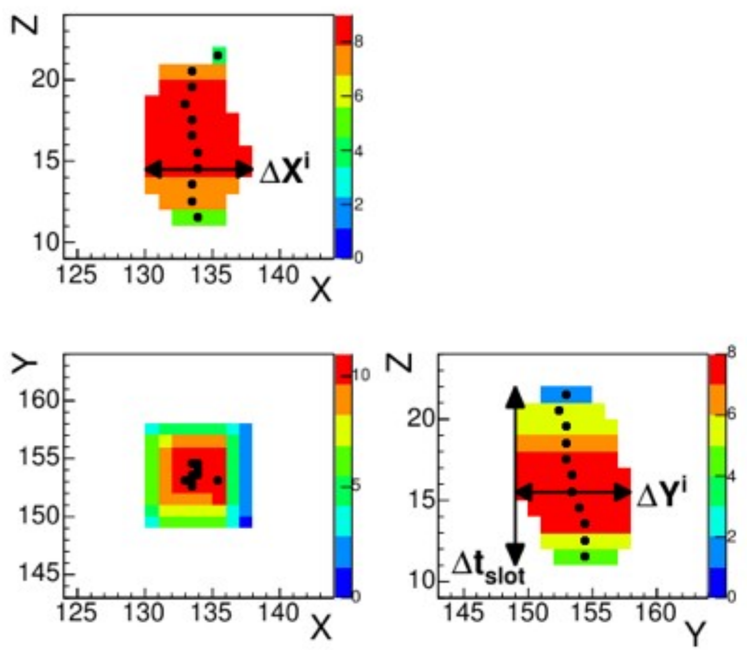
MIMAC readout

Dedicated fast electronics (self-triggered)
Based on the MIMAC chip (64 channels)

preamplifier signal + FADC: Energy

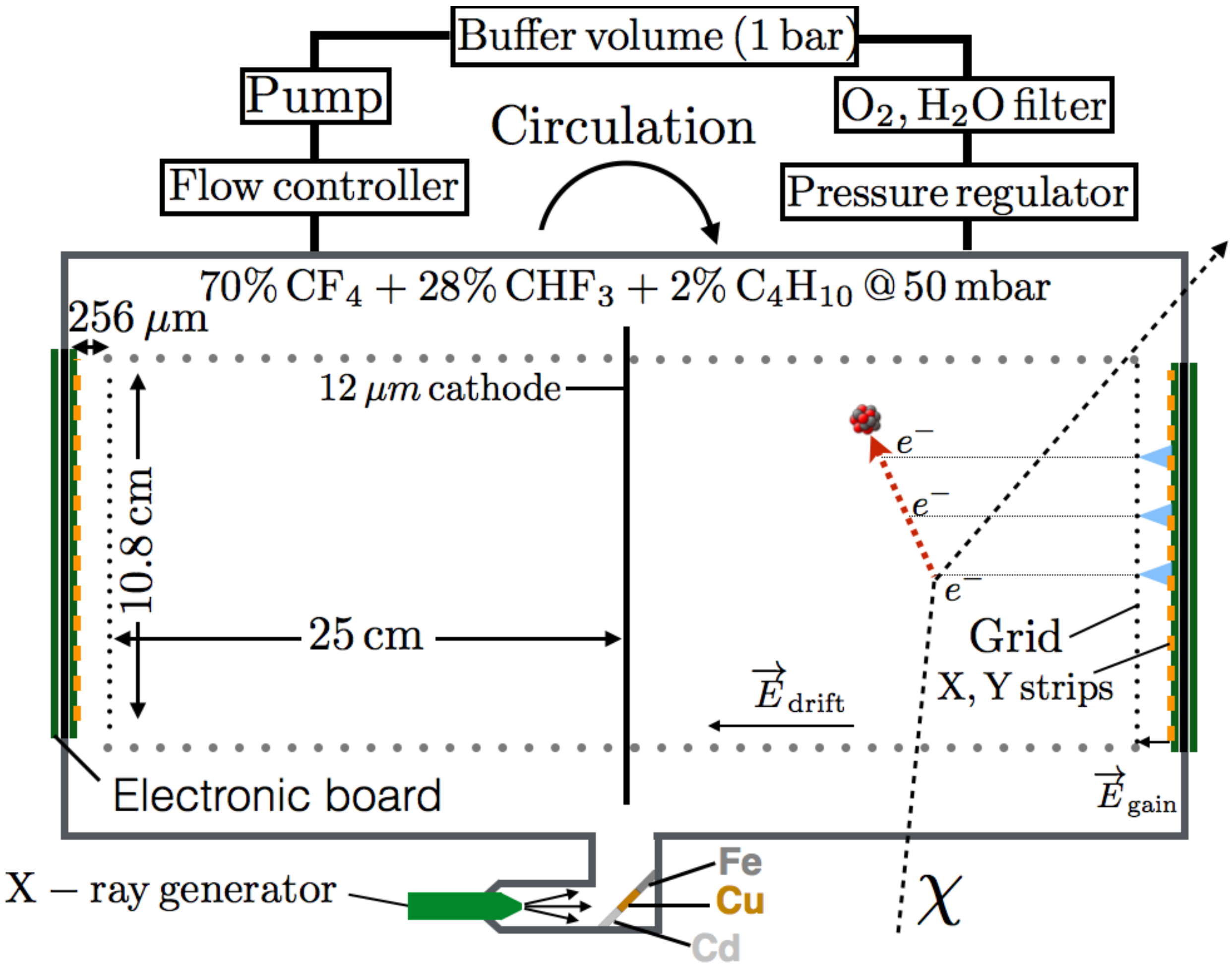


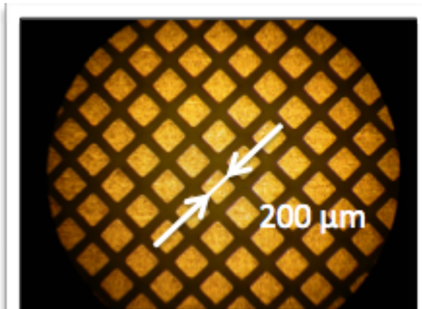
3D - track



MIMAC-bi-chamber module prototype

two chambers : one cathode 10cm x10 cmx 25 cm



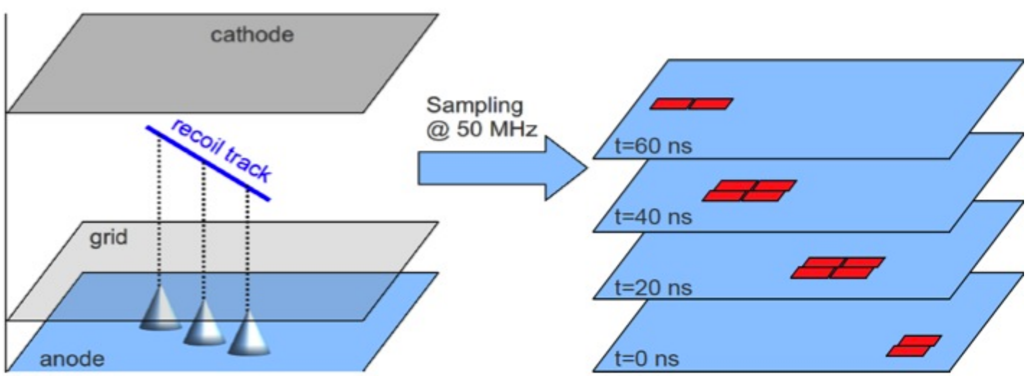


Micromegas 10x10 cm², designed by IRFU- Saclay (France)

MIMAC Bi-chamber prototype

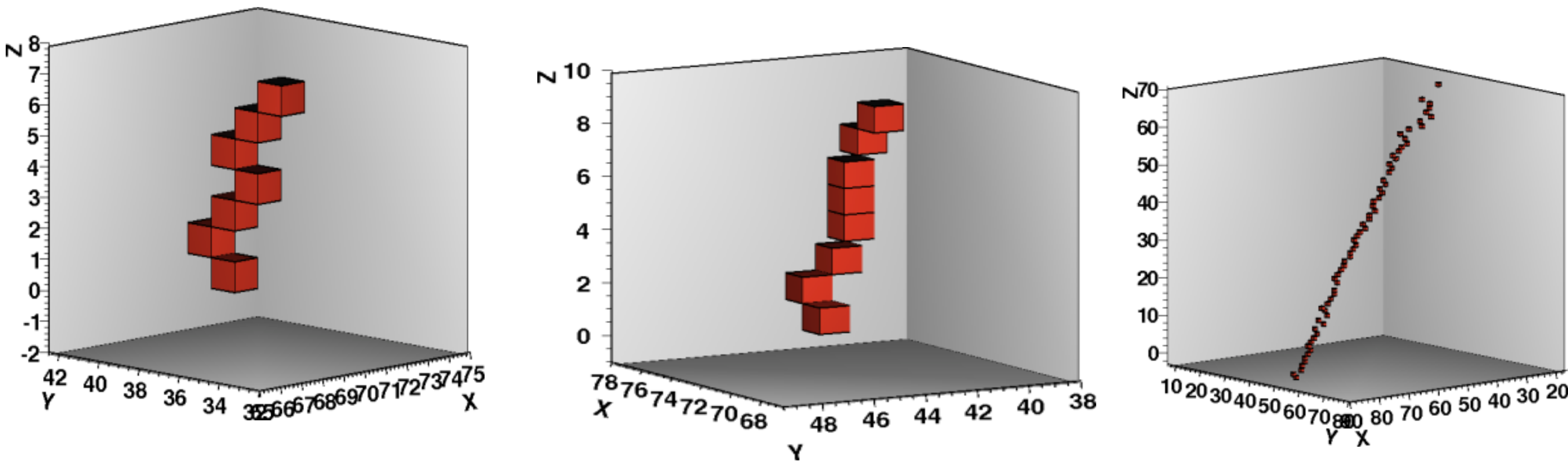
- two chambers : one cathode 10cm x10 cmx 25 cm
- $70\%CF_4 + 28\%CHF_3 + 2\%C_4H_{10}$ at a pressure of 50mbar.
- The primary electron- ion pairs : grid of **a bulk micromegas**; avalanche in a very thin gap (256 μ).
- Special electronics developed by LPSC Grenoble
- Track reconstruction : anode read every 20 ns. 3D track reconstructed, from the consecutive number of images

arxiv 1311.0616



Some tracks in MIMAC prototype

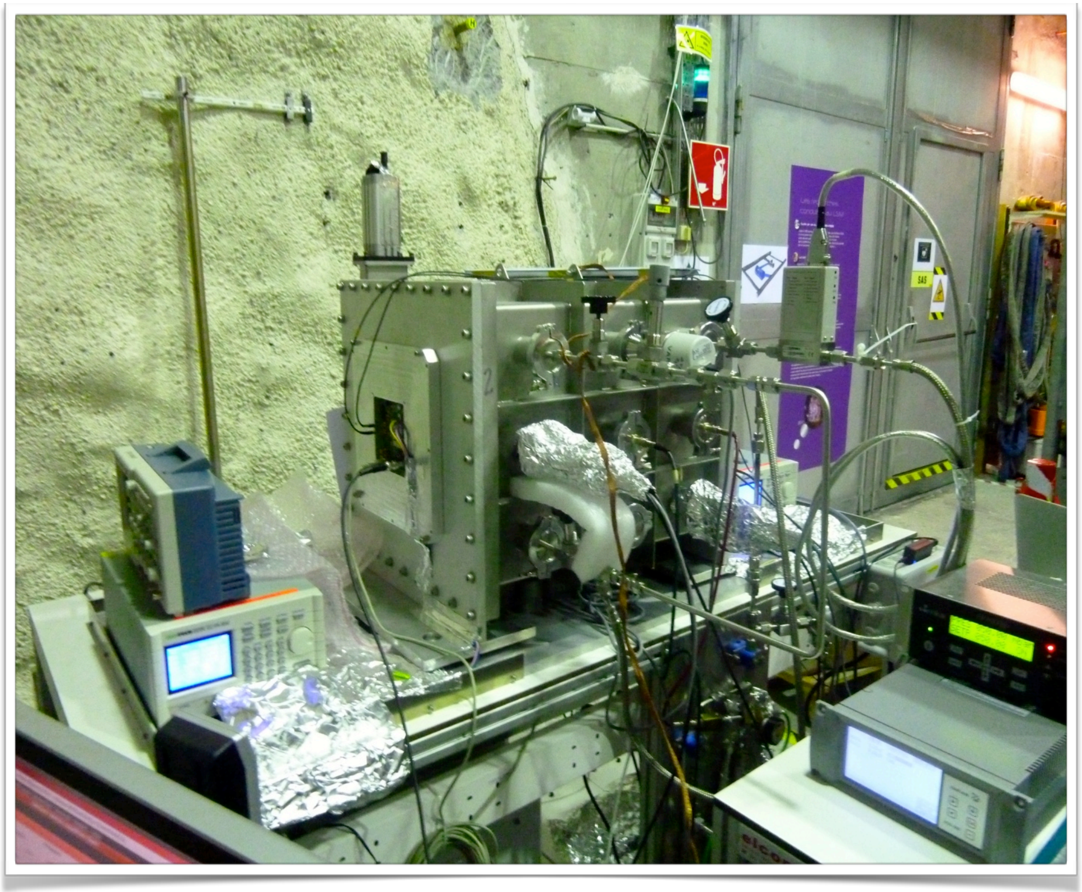
from measurements in Cadarache (AMANDE monoenergetic neutron facility)



8 keV hydrogen nucleus in 350 mbar 4He+5%C4H10, a fluorine nucleus leaving 50 keV in ionization in 55 mbar (70% CF4 + 30% CHF3) and a 5.5 MeV alpha particle in 350 mbar 4He+5%C4H10

Santos et al. 1304.2255

MIMAC first bi-chamber module at Modane Underground Laboratory (France)



since June 22nd 2012.
Upgraded in June 2013, and
in June 2014.

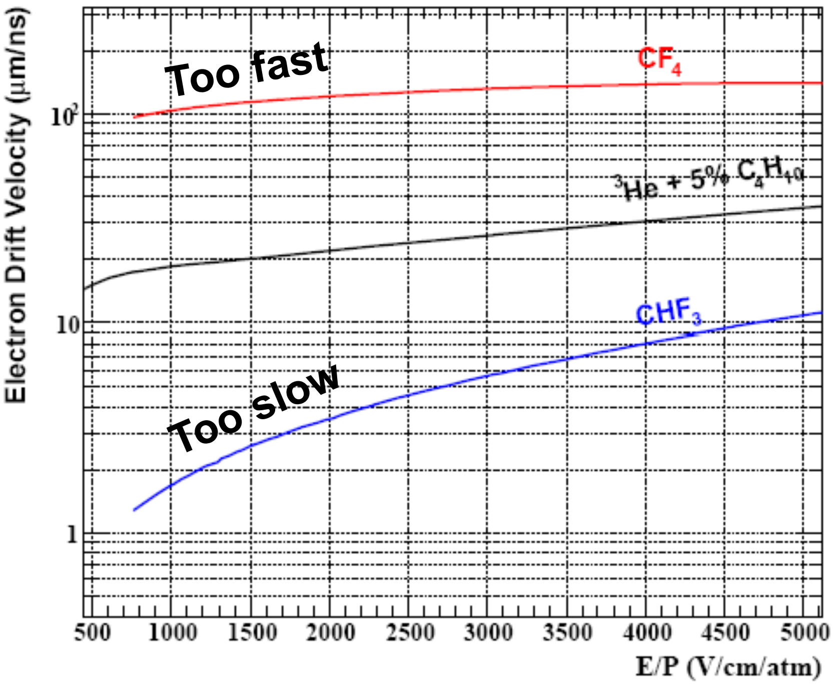
-working at 50 mbar
(CF_4+28% CHF_3 + 2% C_4H_{10})

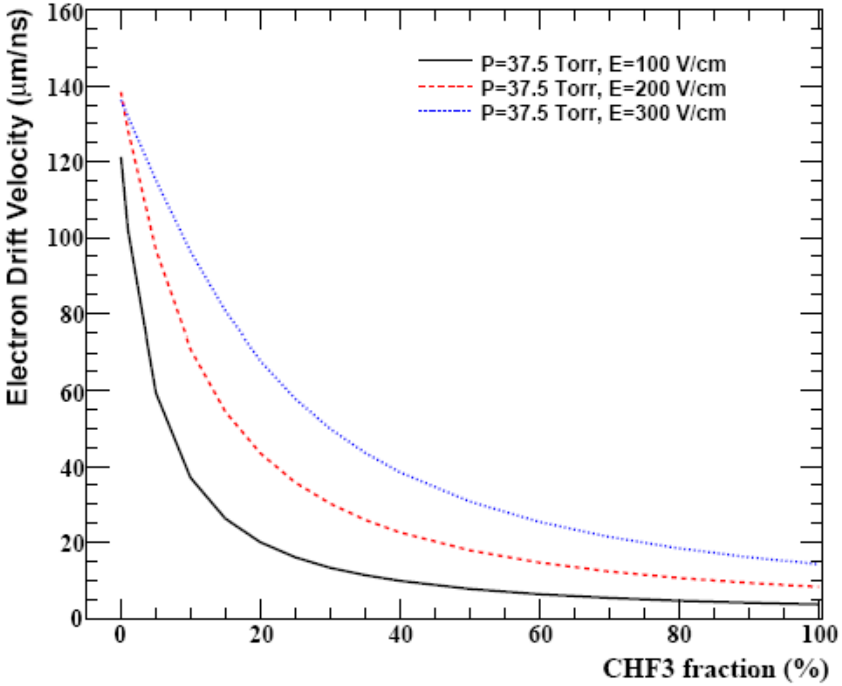
-in a permanent circulating mode
-Remote controlled
and commanded
-Calibration control twice per week

Many thanks to LSM staff

3D Tracks: Drift velocity

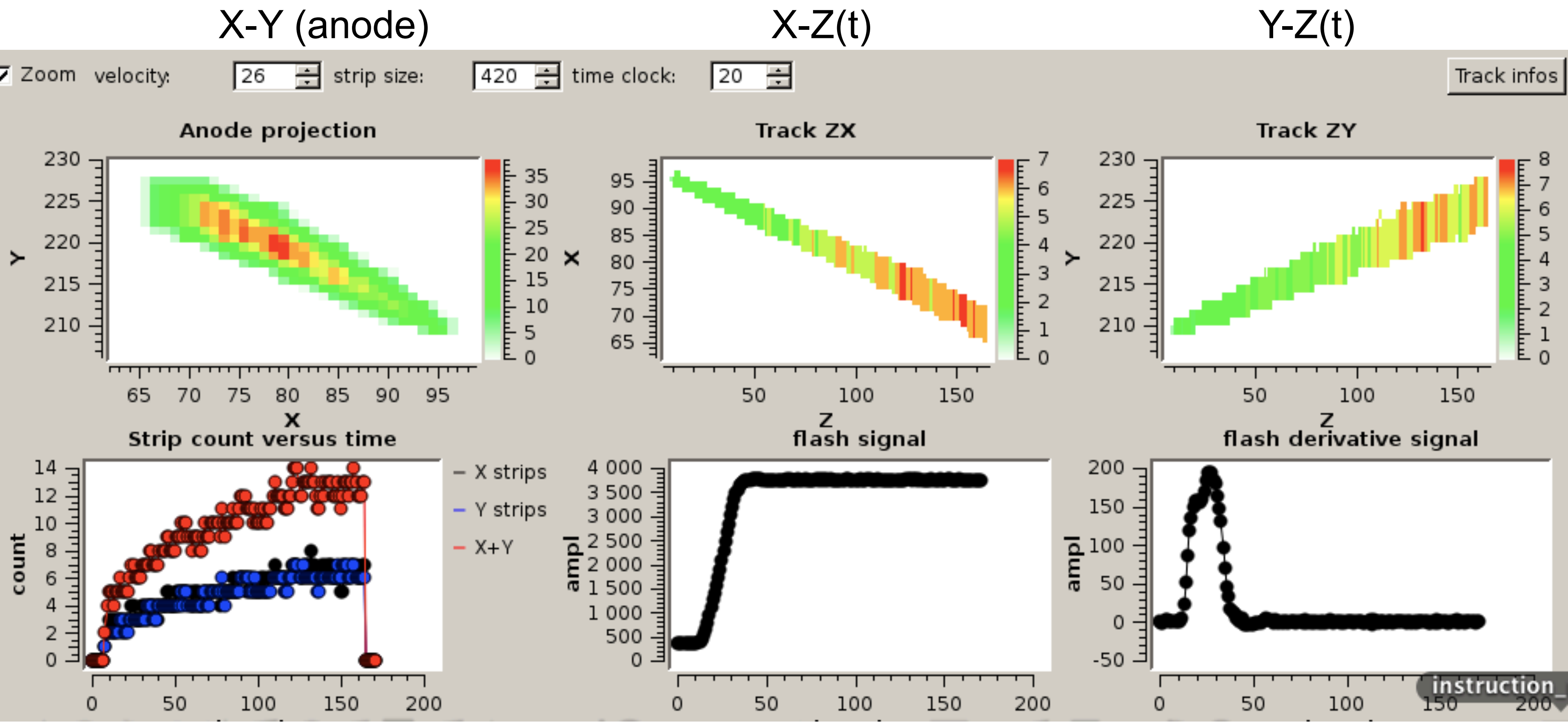
Magboltz Simulation





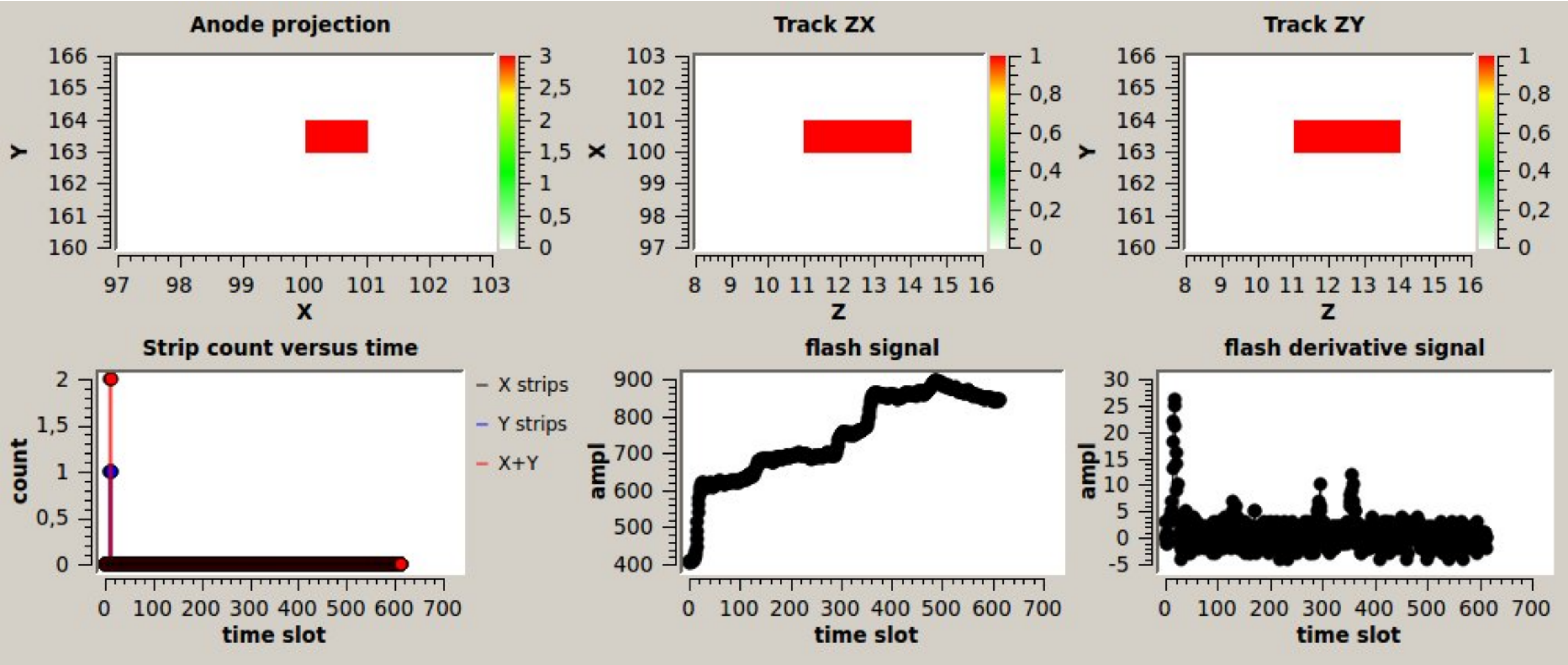
- mixed gas MIMAC target : CF_4 + x% CHF_3 (x=30)

An alpha particle crossing the detector

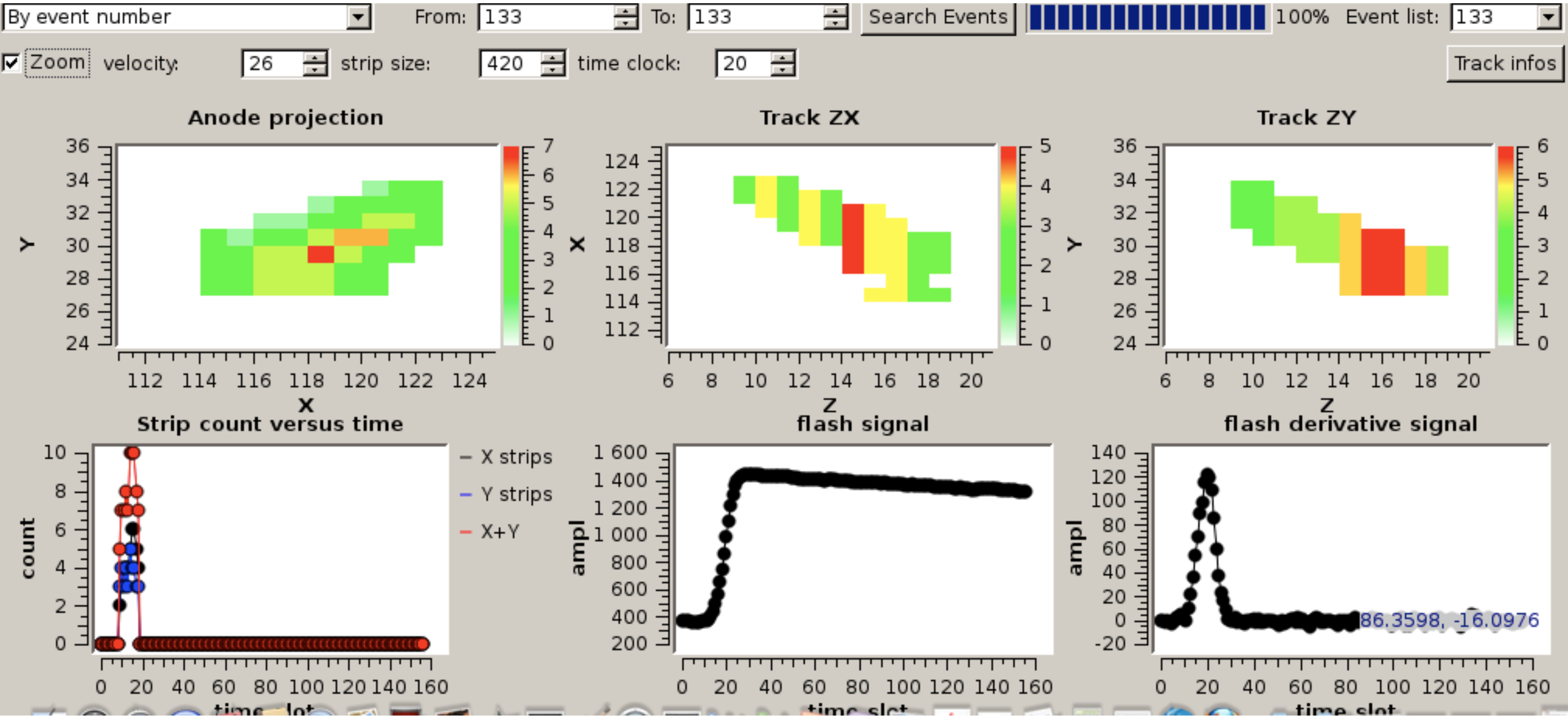


an illustration of the MIMAC observables

An electron event (18 keV)



A “recoil event” (~ 34 keVee)



Radon Progeny

^{222}Rn chain:

- 4 β-decays

→ Electron event (background)

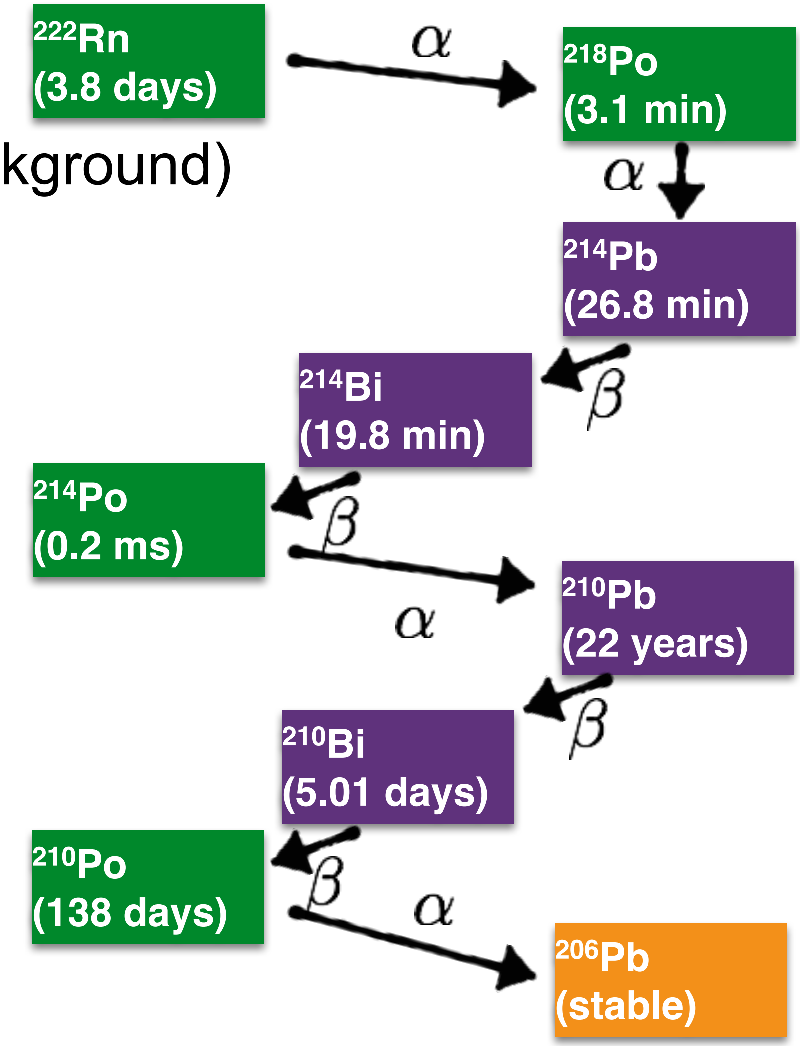
- 4 α-decays

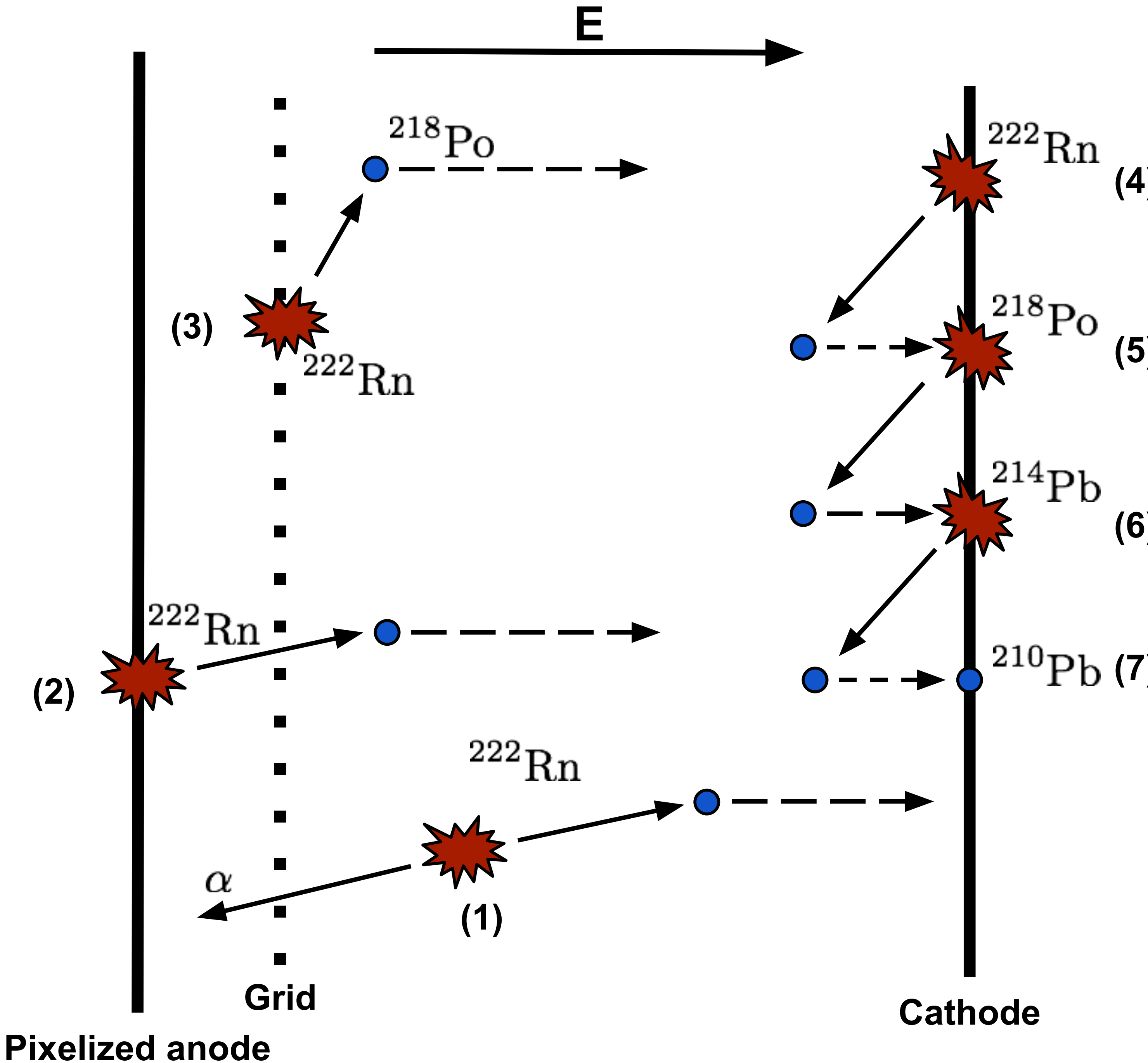
→ α-particle emission: $E_\alpha \sim 5\,\mathrm{MeV}$ → Saturation

→ Daughter nucleus recoil (surface event):

Parent	Daughter	E^{kin}_{recoil} [keV]	E^{ioni}_{recoil} [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)

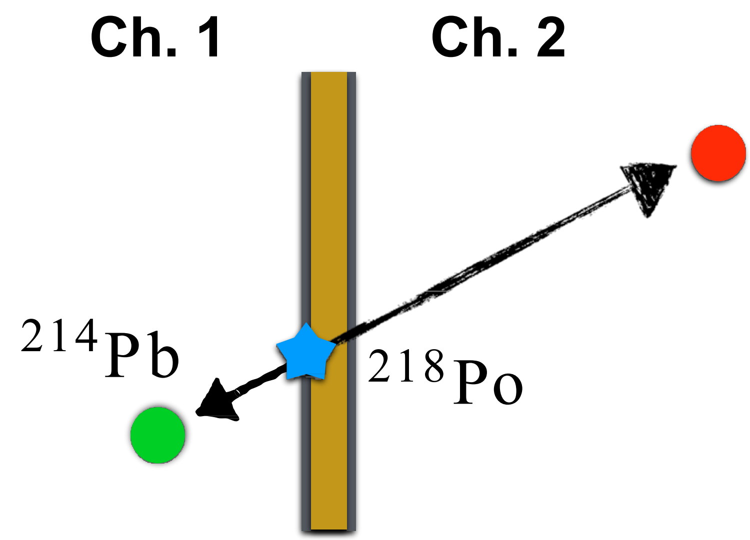


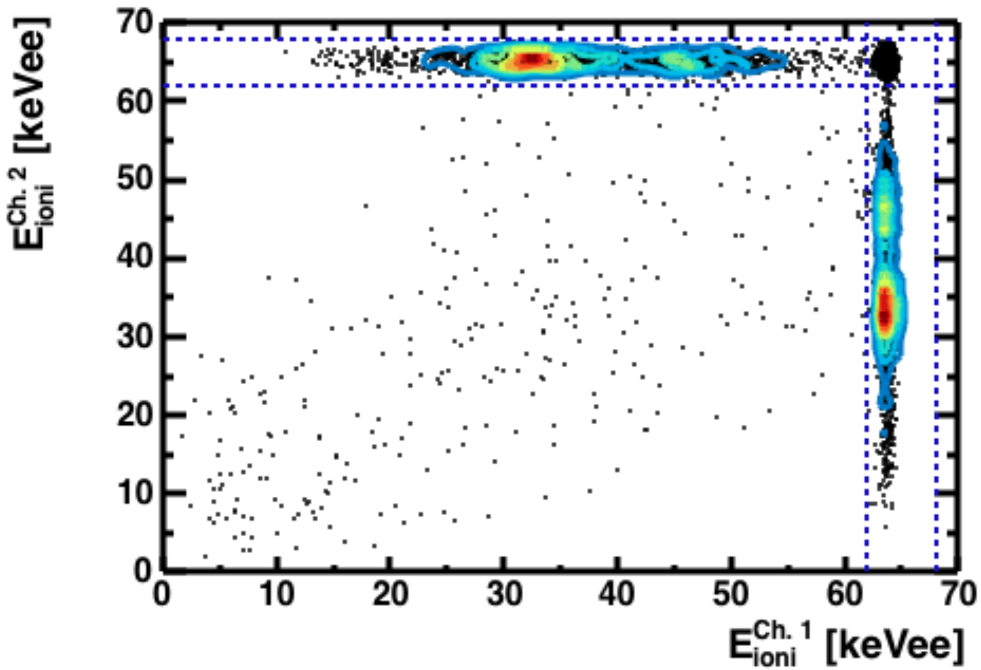


E
^{218}Po
^{222}Rn
(4)
(3)
^{222}Rn
^{218}Po
(5)
^{214}Pb
(6)
^{222}Rn
^{210}Pb
(7)
(2)
^{222}Rn
α
(1)
Grid
Cathode
Pixelized anode

RPR: « In coincidence » events

Chamber coincidences:





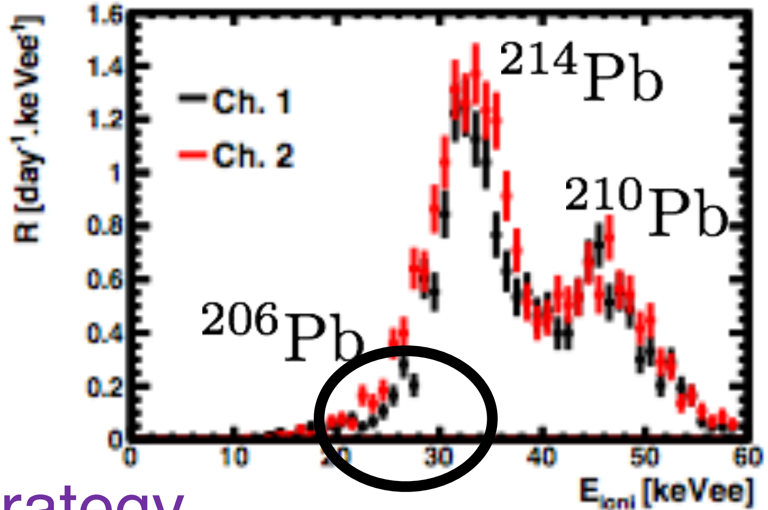
3D tracks from nuclear recoil of radon progeny detection

First detection of 3D tracks of Rn progeny

Electron/recoil discrimination

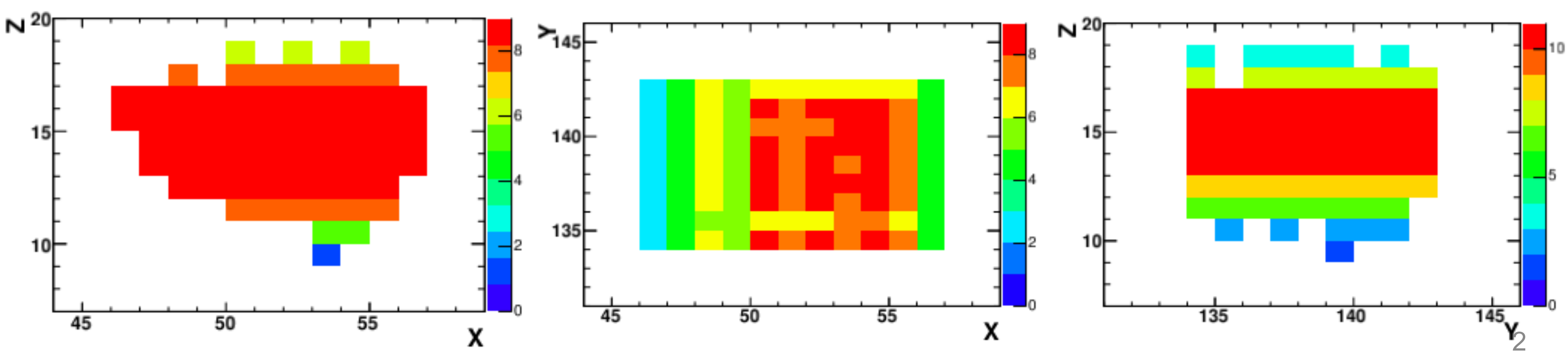
Measure $\begin{cases} E_{ioni}(^{214}\mathrm{Pb}) = 32.90 \pm 0.16\,\mathrm{keVee} \\ E_{ioni}(^{210}\mathrm{Pb}) = 45.60 \pm 0.29\,\mathrm{keVee} \end{cases}$

Nuclear recoil spectra



→ Validation of MIMAC detection strategy

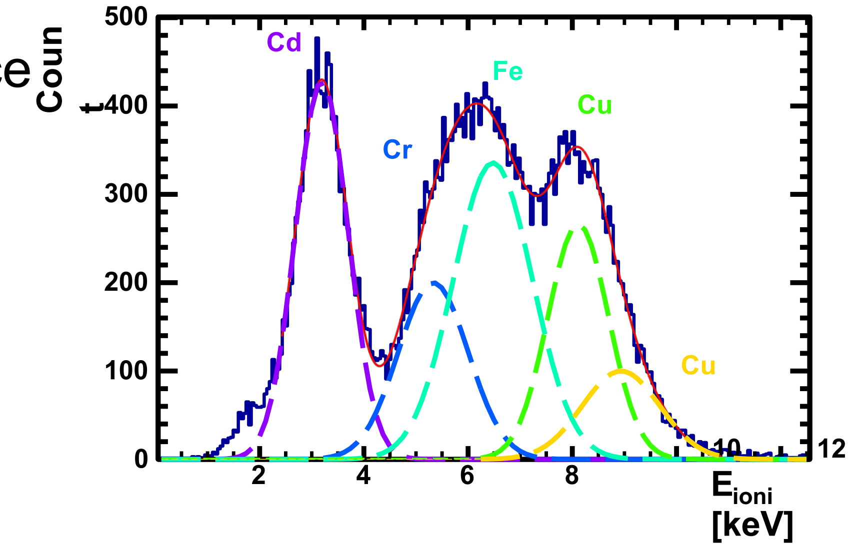
$R_{^{206}\mathrm{Pb}} \sim 0.25\,\mathrm{day}^{-1}.\mathrm{keVee}^{-1}$

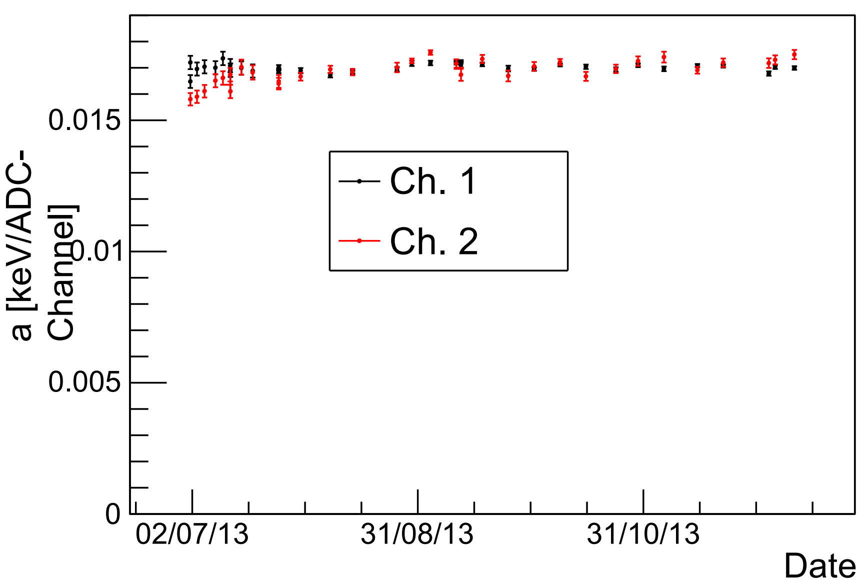


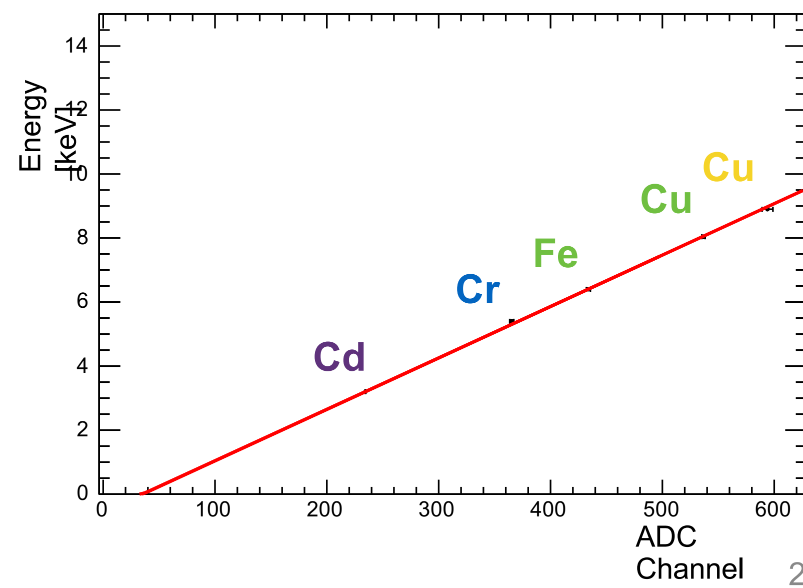
MIMAC calibration with X-rays stable in LSM

X-ray generator producing fluorescence photons from Cd, Fe, Cu foils.
Threshold ~ 1 keV

Circulation system:
Excellent Gain stability in time

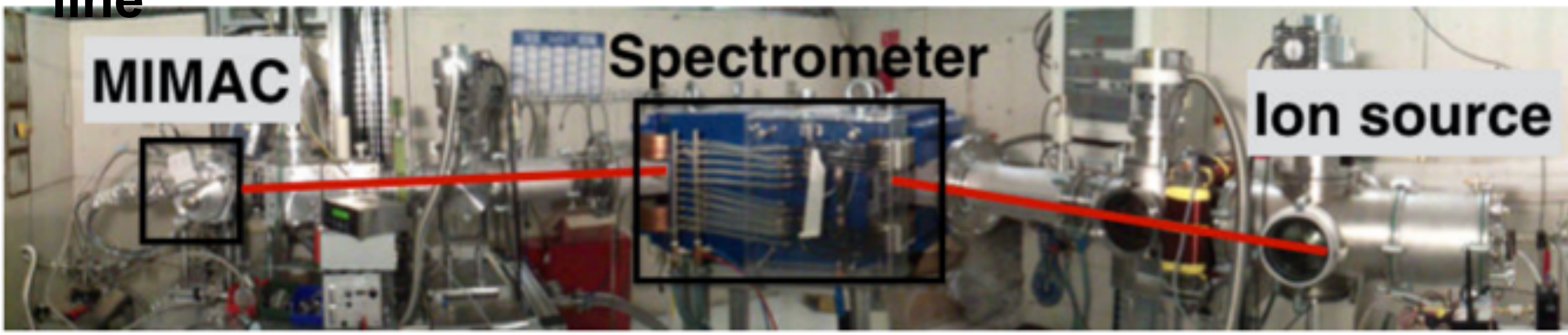






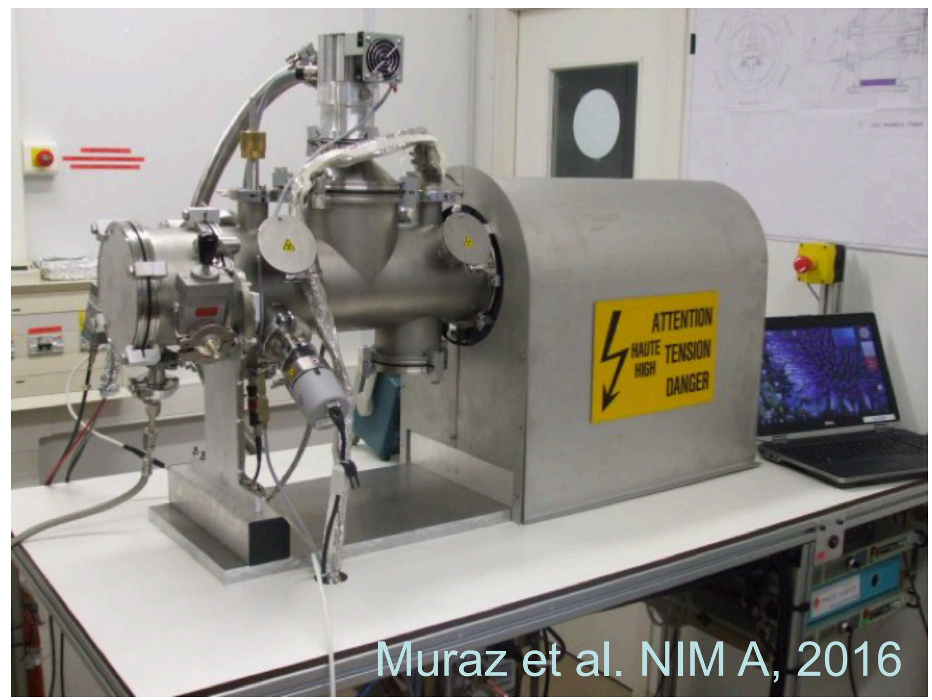
Ion Beams

LHI beam line



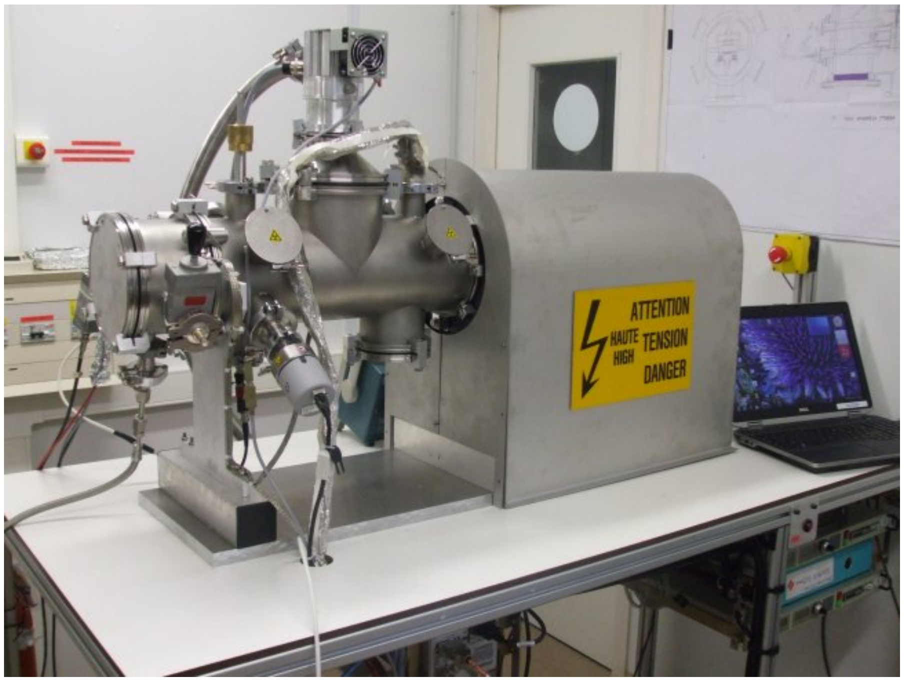
COMIMAC – A Portable Quenching Facility

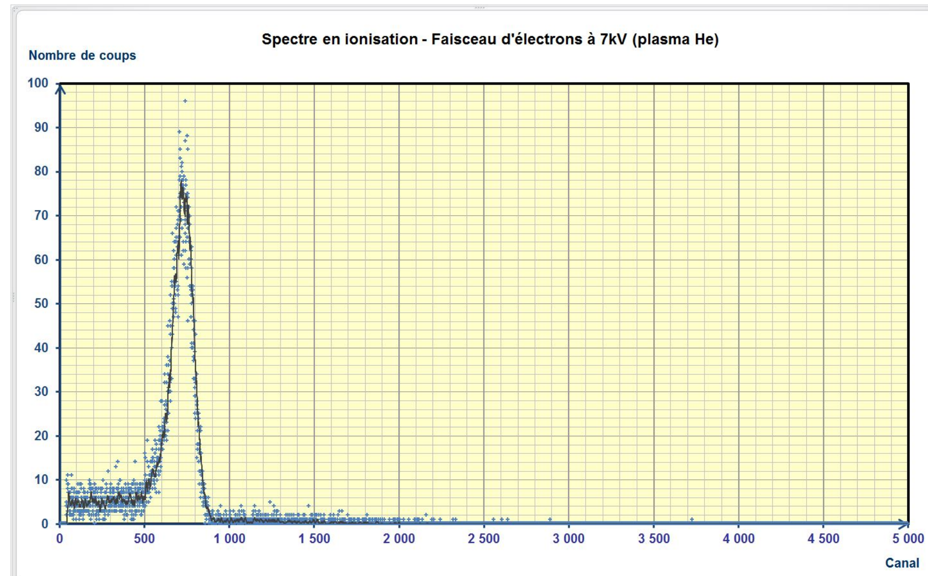
Target: ^{19}F (but flexible to change)



Portable Quenching Facility COMIMAC

Electrons and IONS of known energies

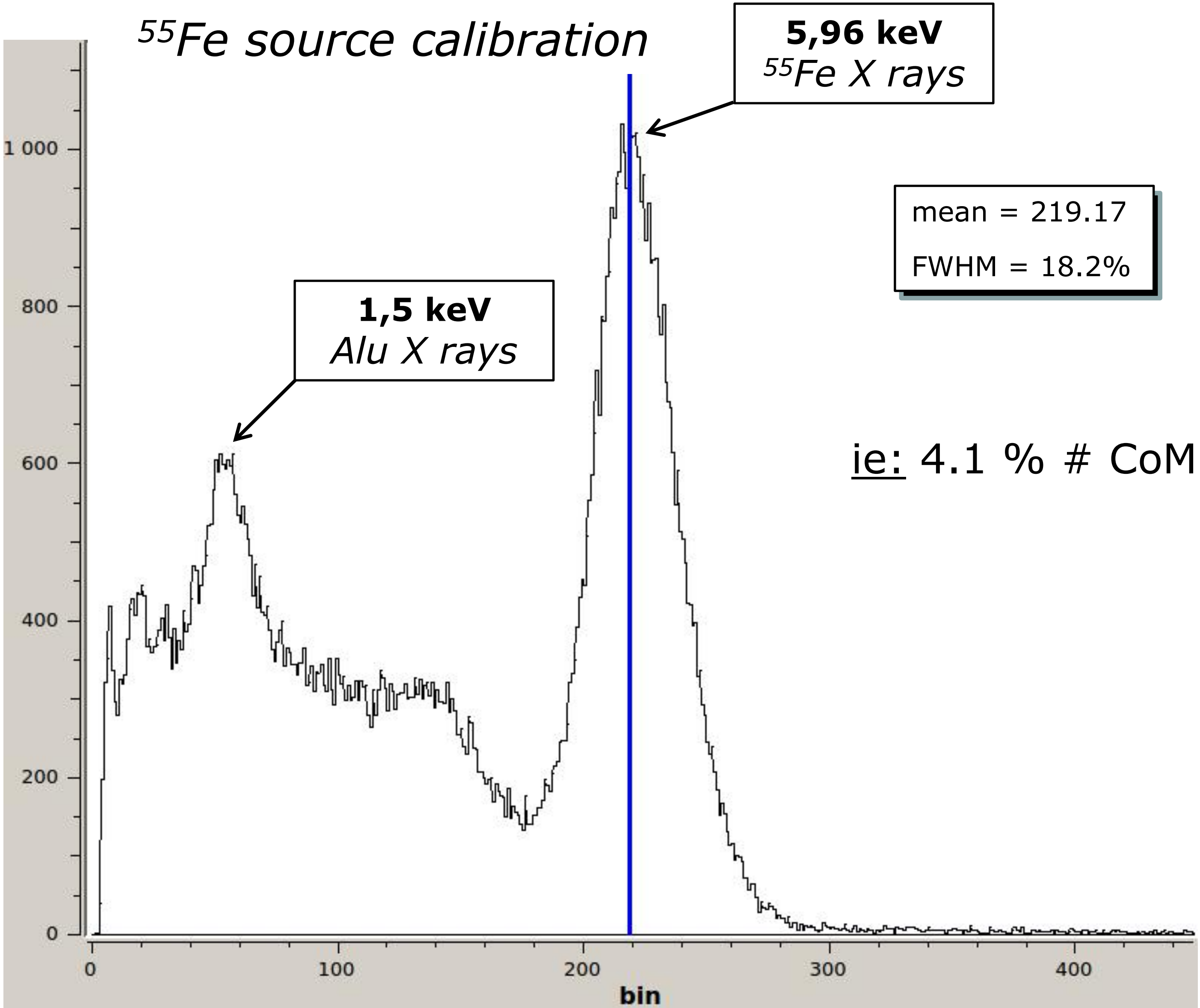




Electrons of 7 keV

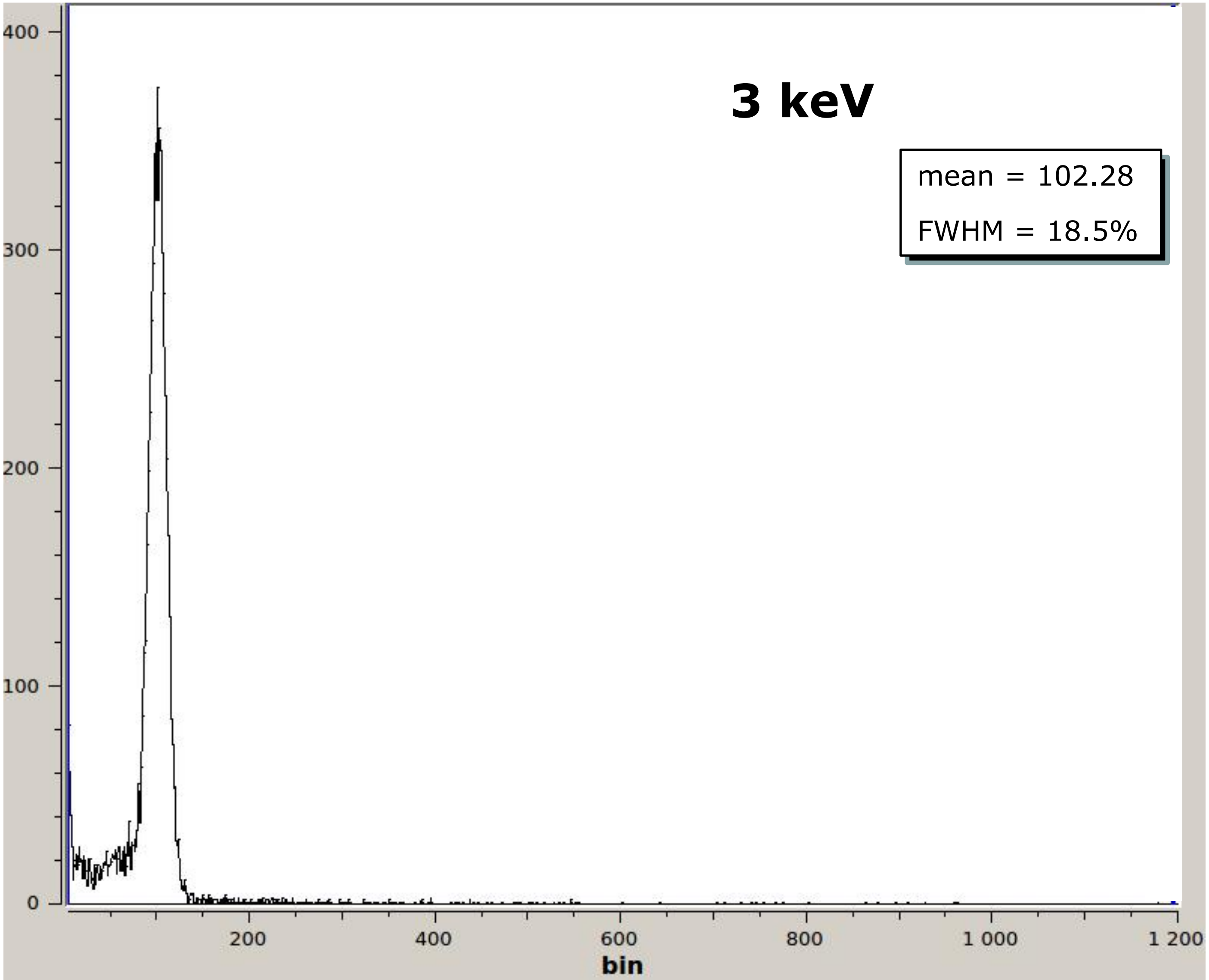
In a gas detector the IQF depends strongly on the quality of the gas.
The IQF needs to be measured periodically (in-situ) in a long term run experiment.

Electrons Performance

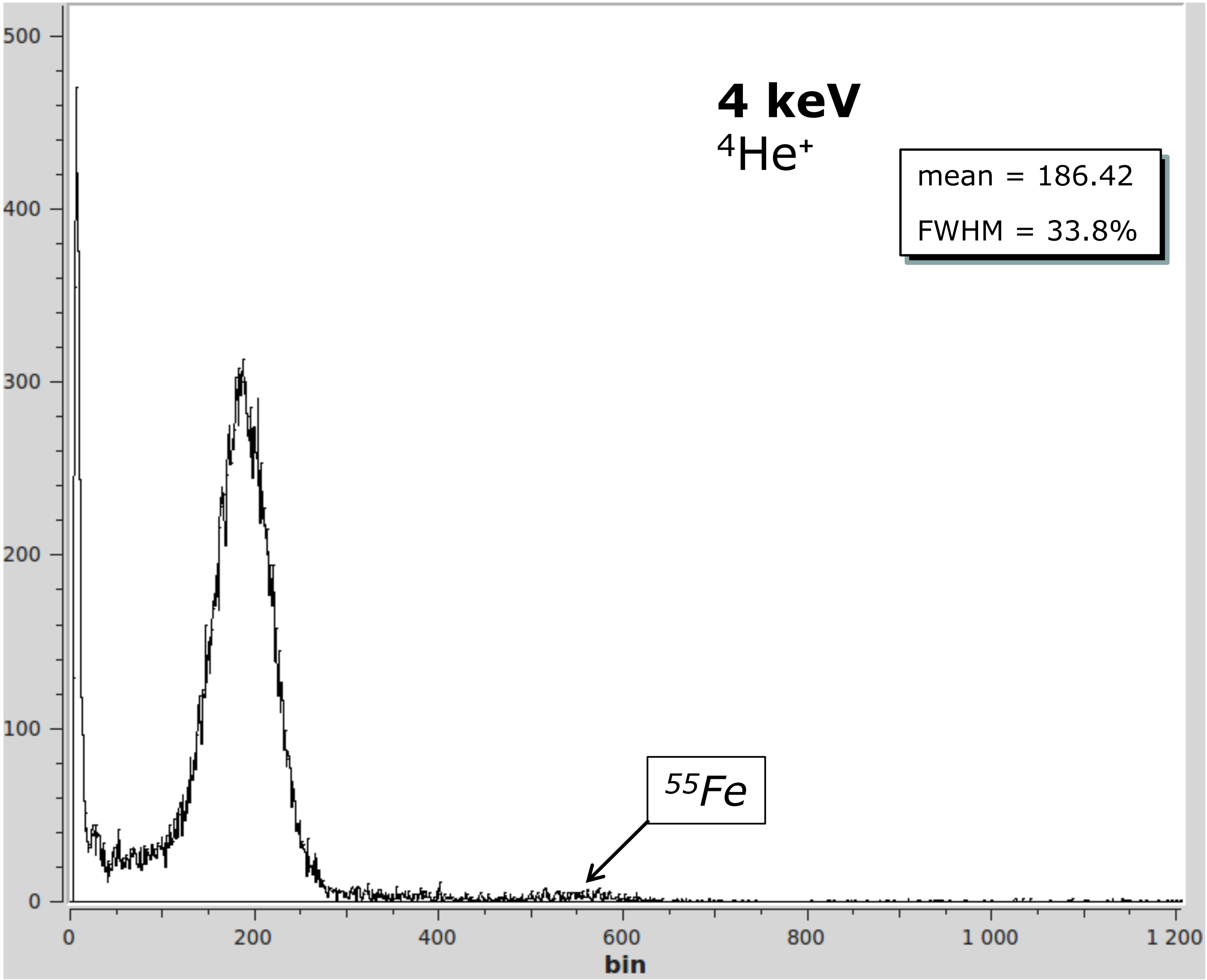


ie: 4.1 % # CoMimac

Electrons Performance

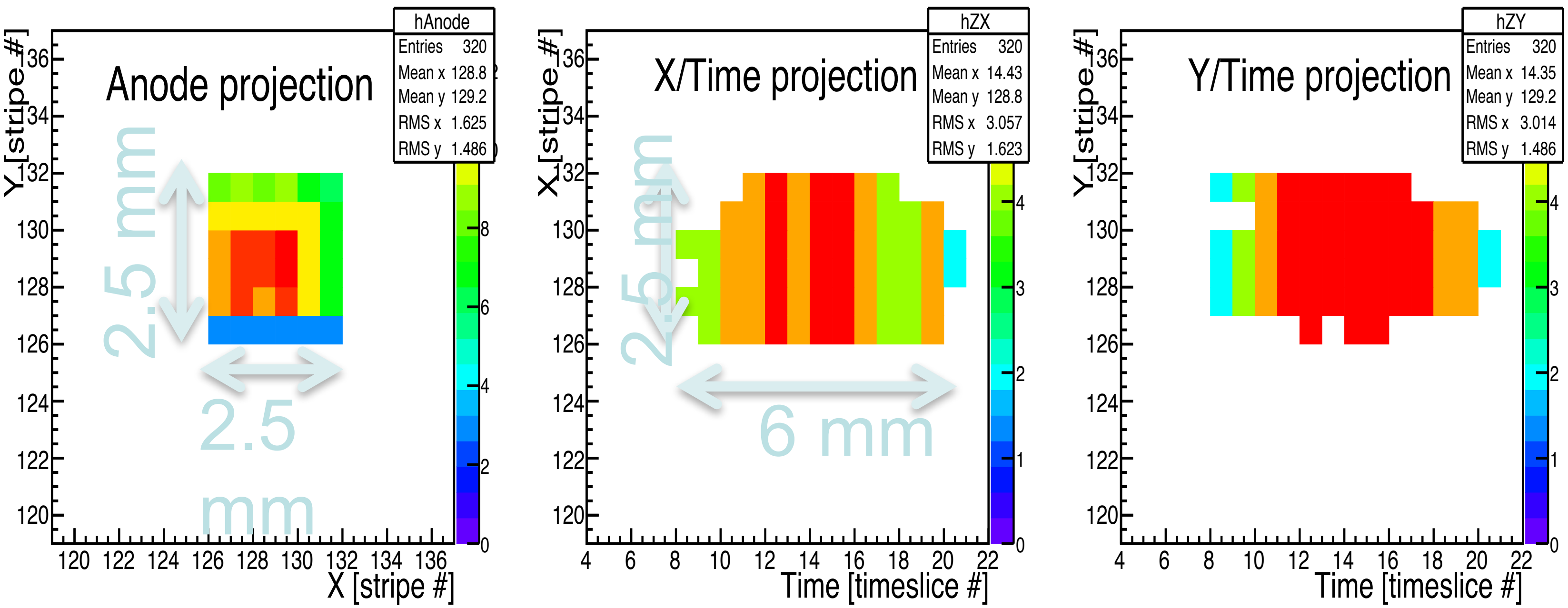


Ions Performance



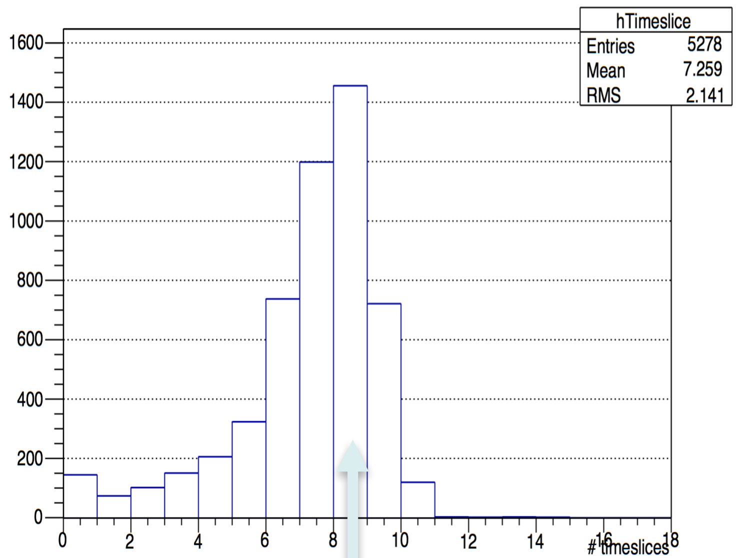
COMIMAC: first measurements on controlled tracks of Fluorine

25 keV (kinetic) Fluorine → ~ 9 keVee ionization



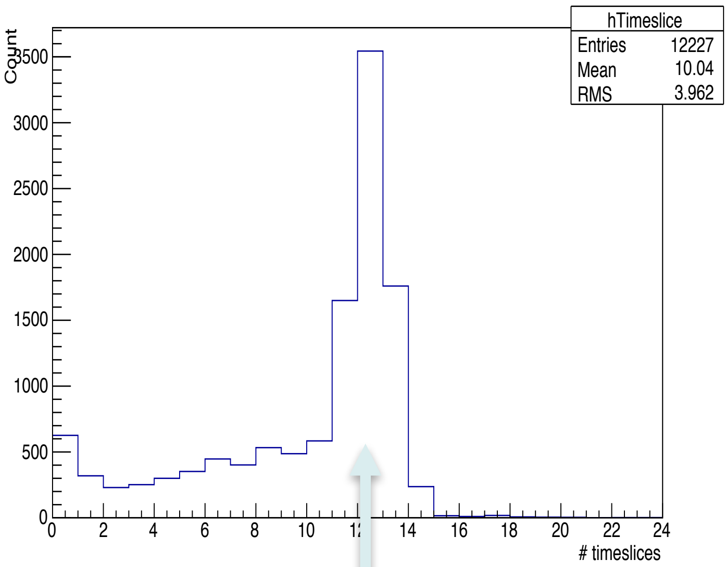
COMIMAC: first controlled tracks of ^{19}F

8 keV kinetic → 2 keVee



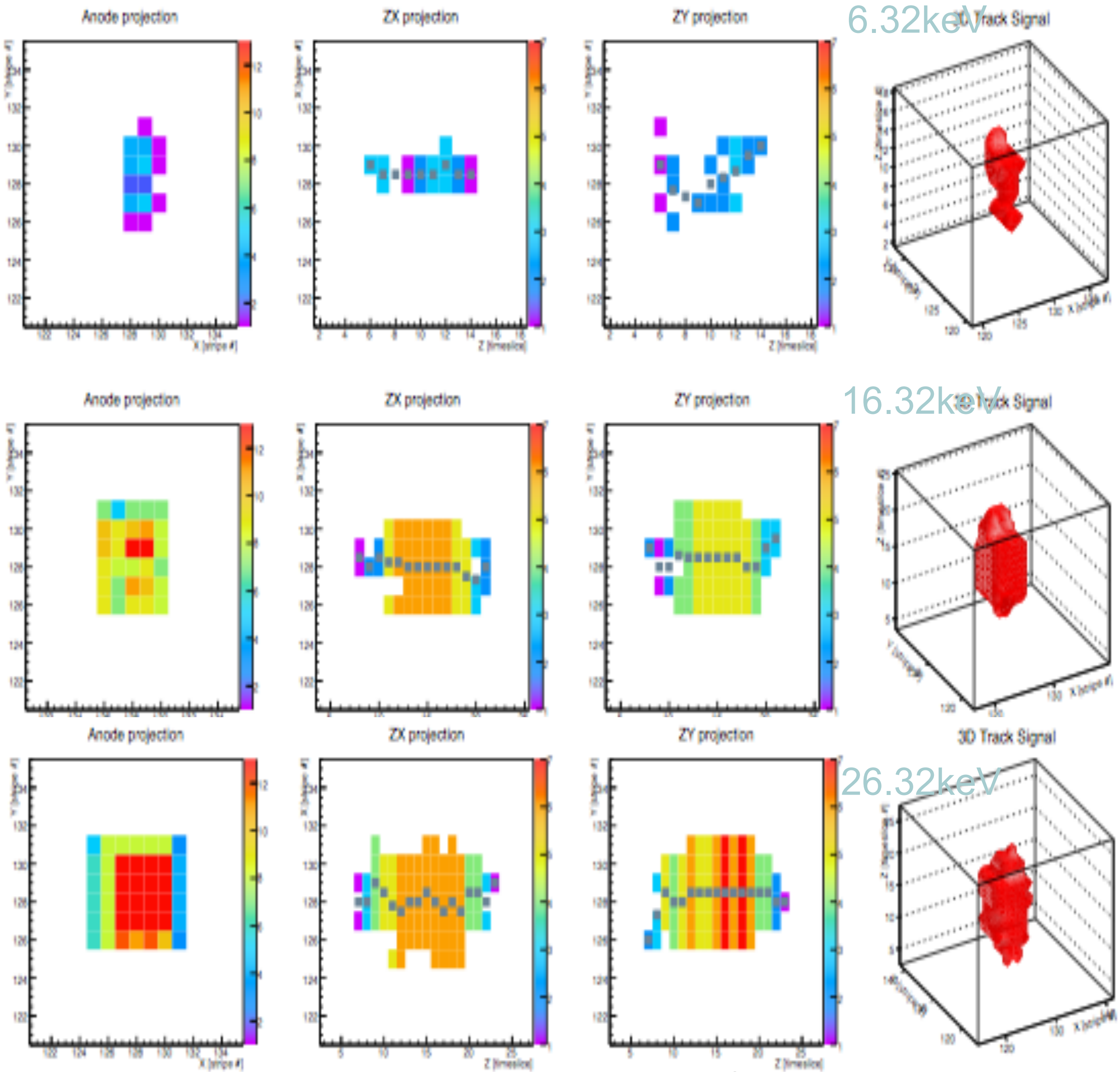
8 timeslices
* 20 ns/timeslices
* 23.5 μm/ns
= 3.8 mm

25 keV kinetic → 9 keVee

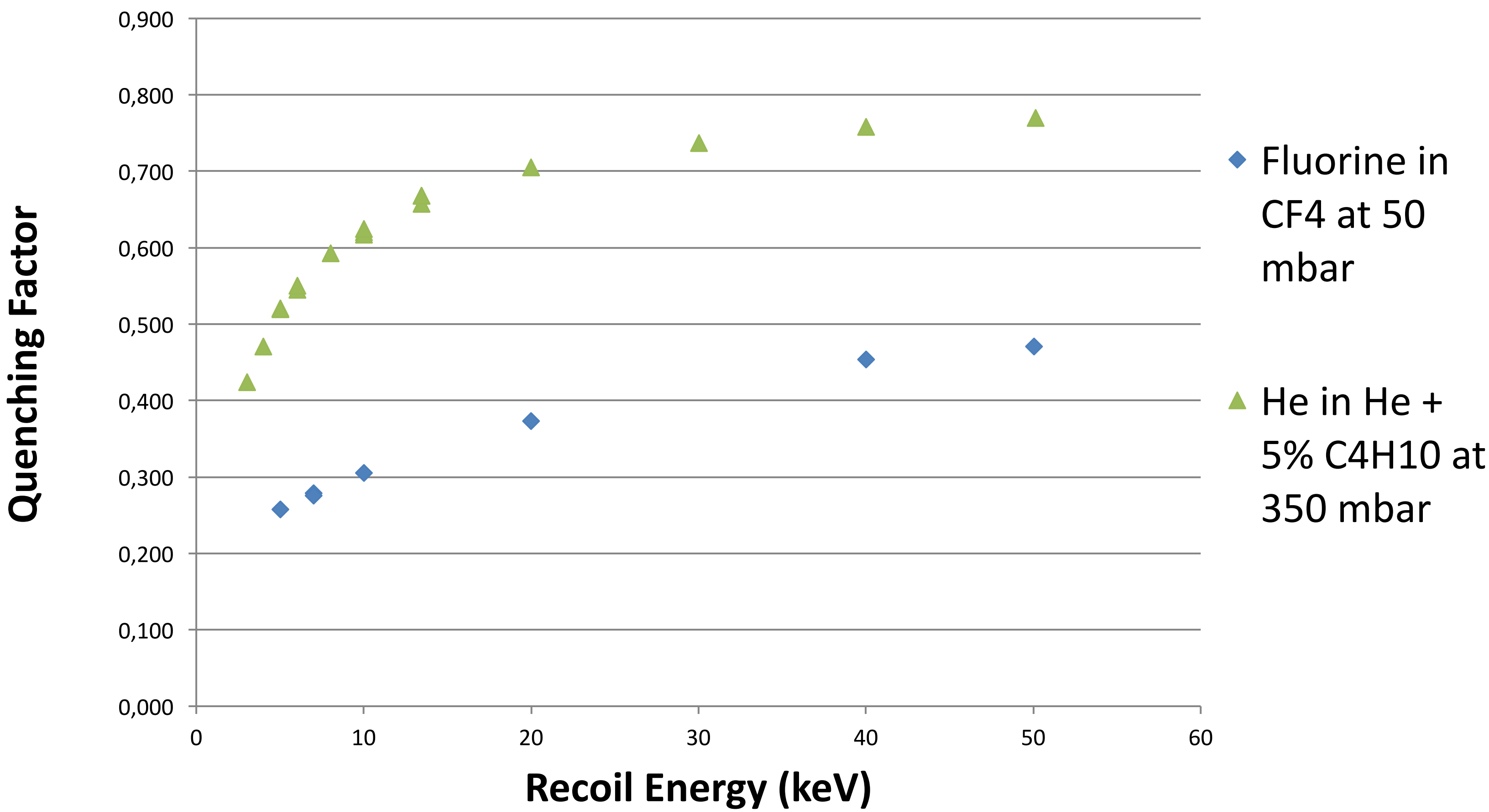


12 timeslices
* 20 ns/timeslice
* 23.5 μm/ns
= 5.8 mm

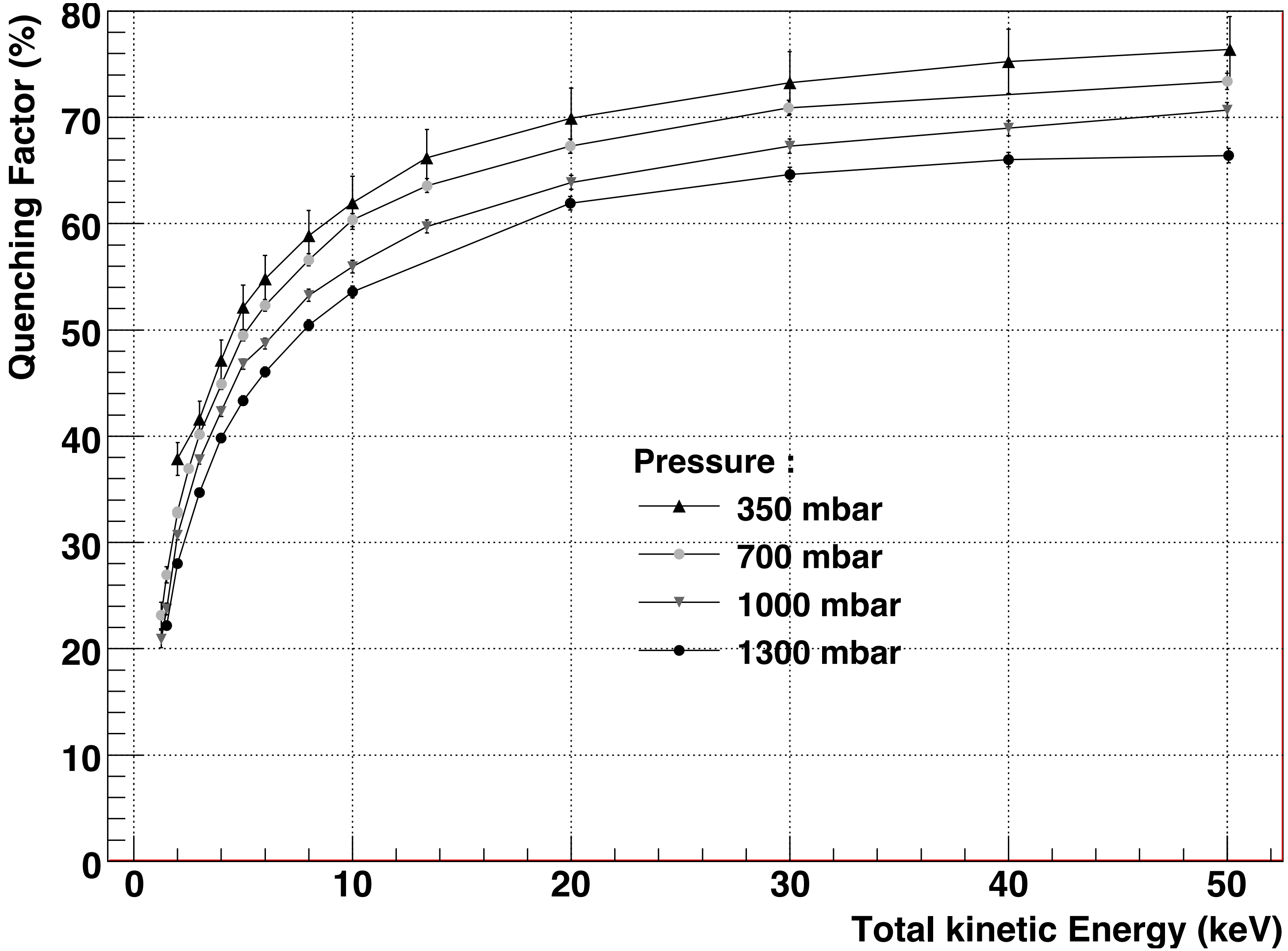
Reconstructing Track Projections



Ionization Quenching Factor for Fluorine in pure CF4 at 50 mbar

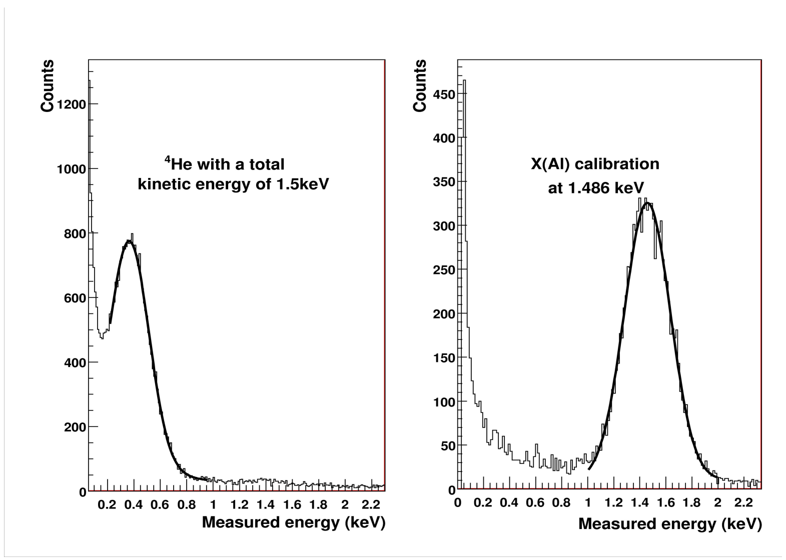


IQF in ^{4}He + 5% isobutane for different pressures!!

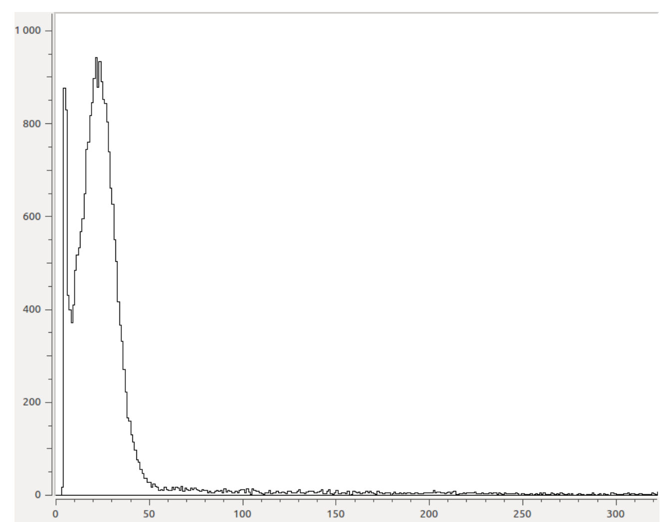


Ionization Quenching Factor Measurements with LHI at LPSC-Grenoble

8.5 GHz ECR ion source;
high resolution magnetic spectrometer separates the ion masses based on q/m f
trajectory : arc of circle r= 0.7 m with B = 0.23 T/m.
Energy resolution 1%

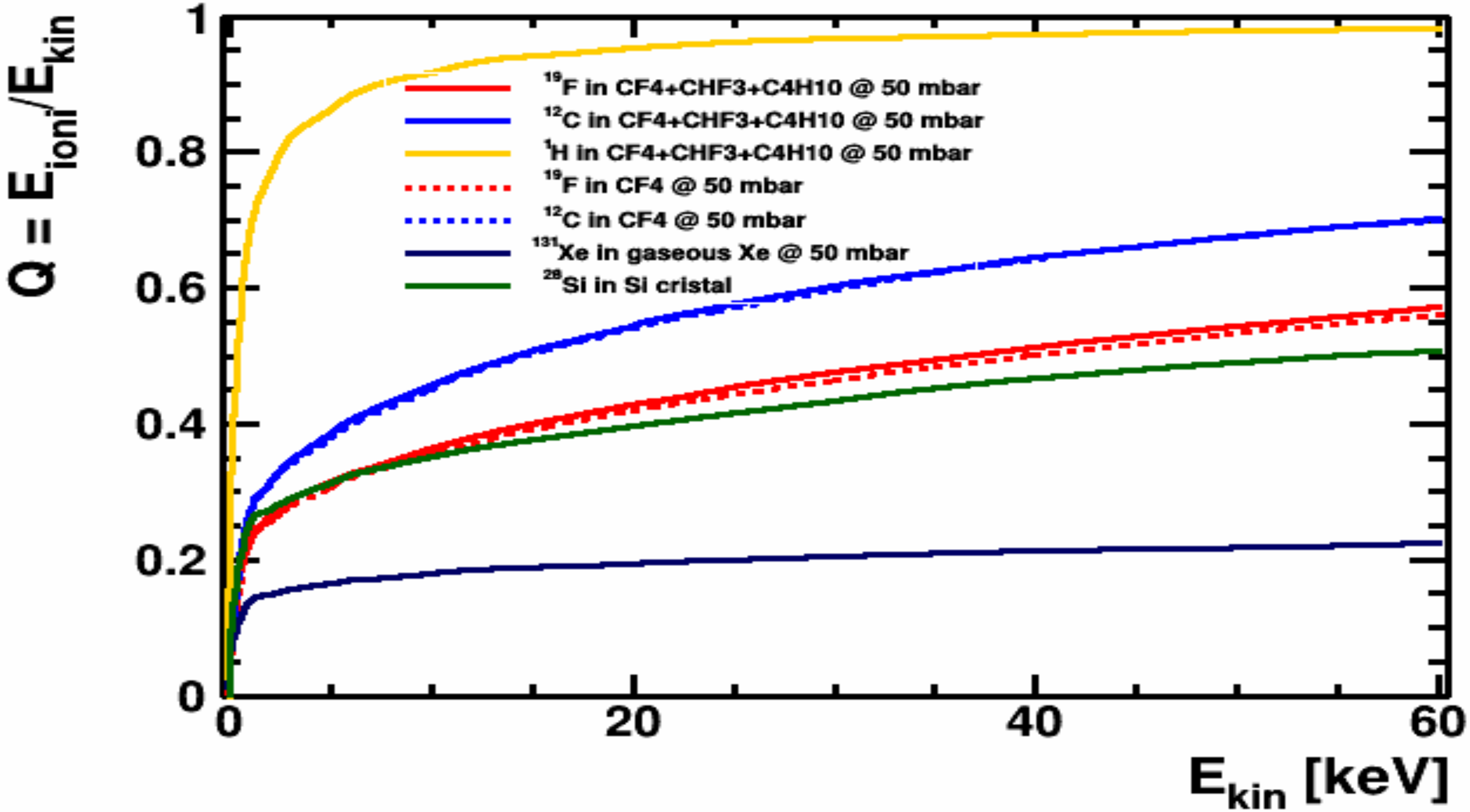


^{19}F (3 keV) in CF_4 (50 mbar)

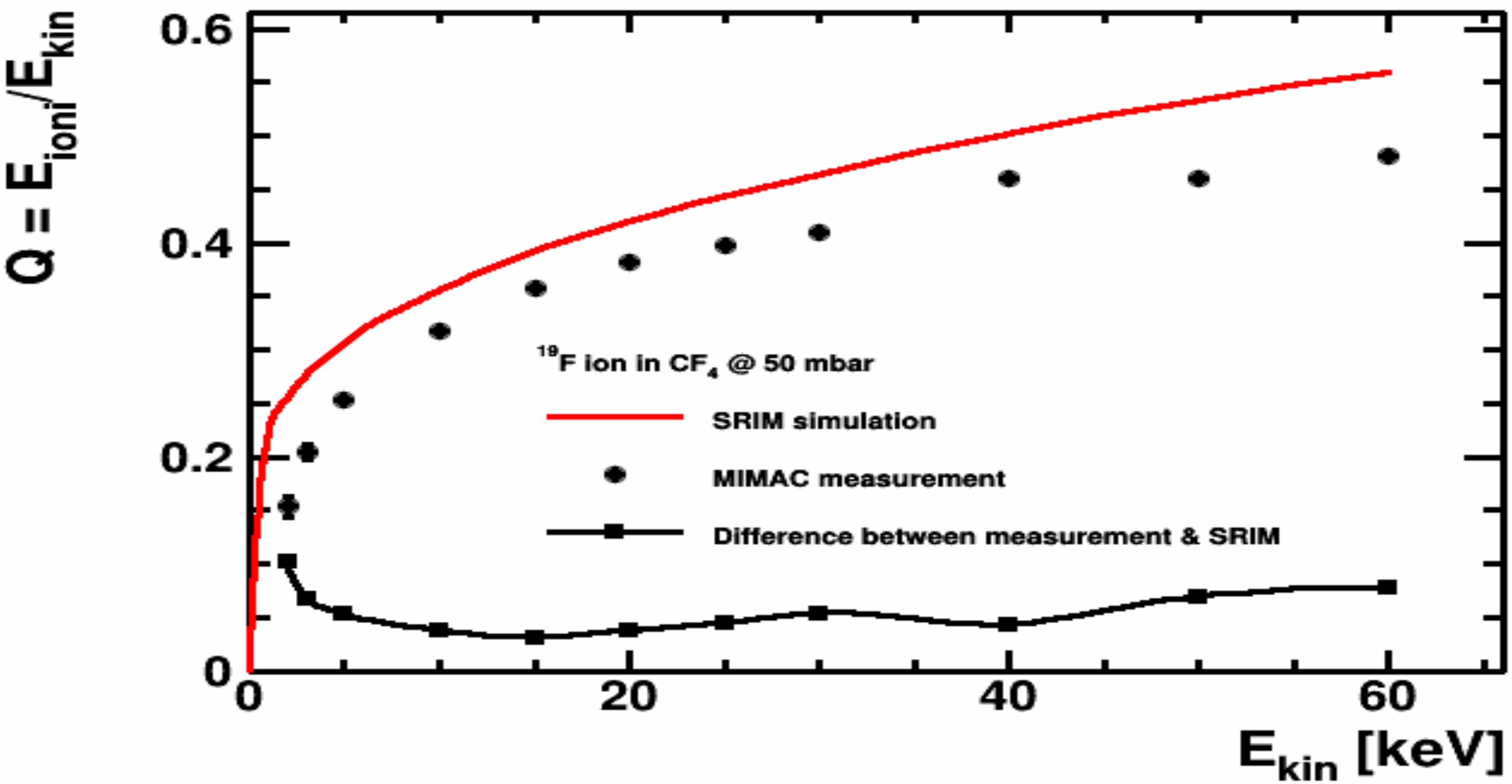


Ionization Quenching Factors

SRIM-Simulations (LPSC)

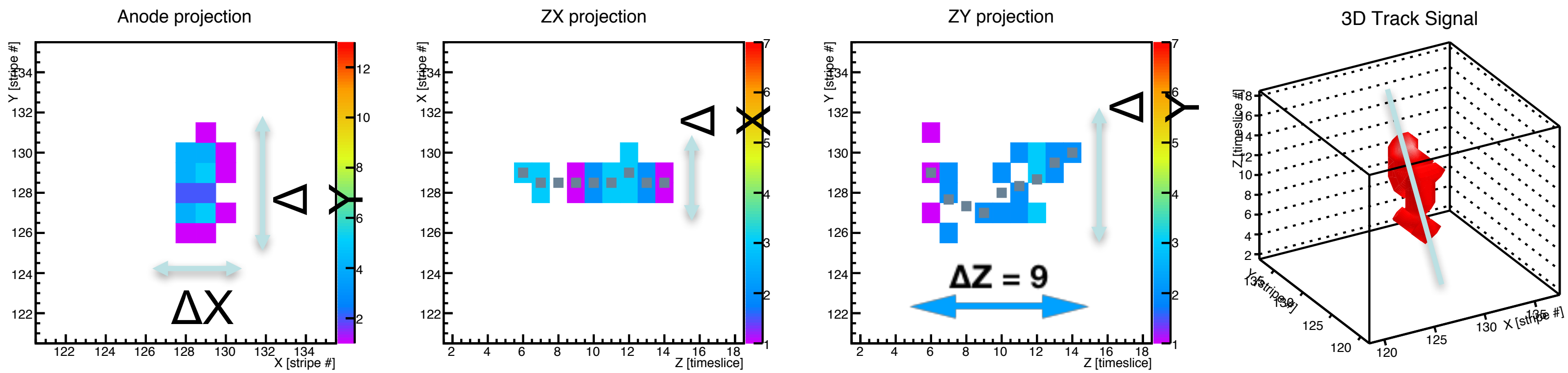


^{19}F - IQF Measurements vs SRIM

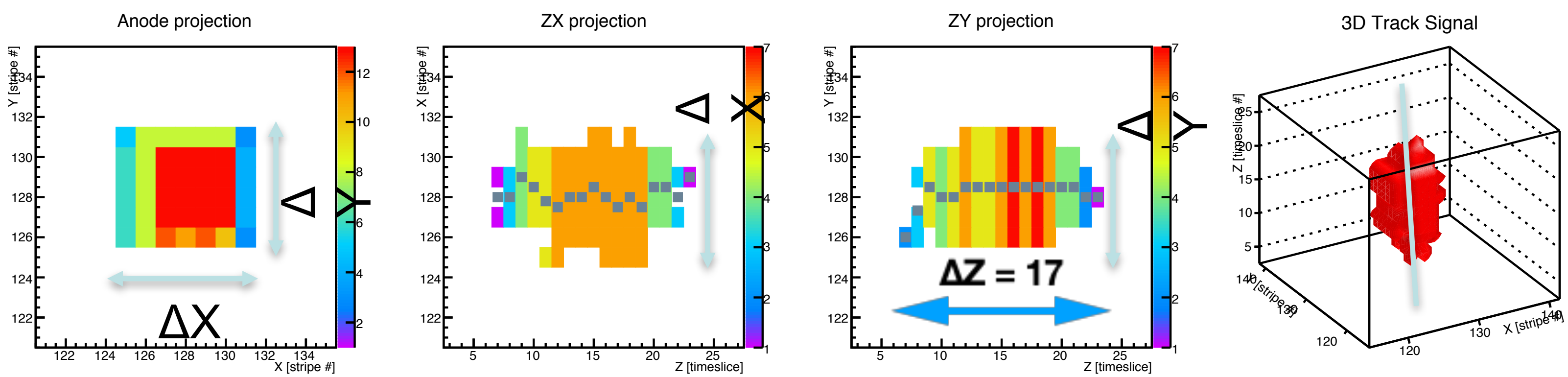


MIMAC: has 3D-reconstructed keV tracks.

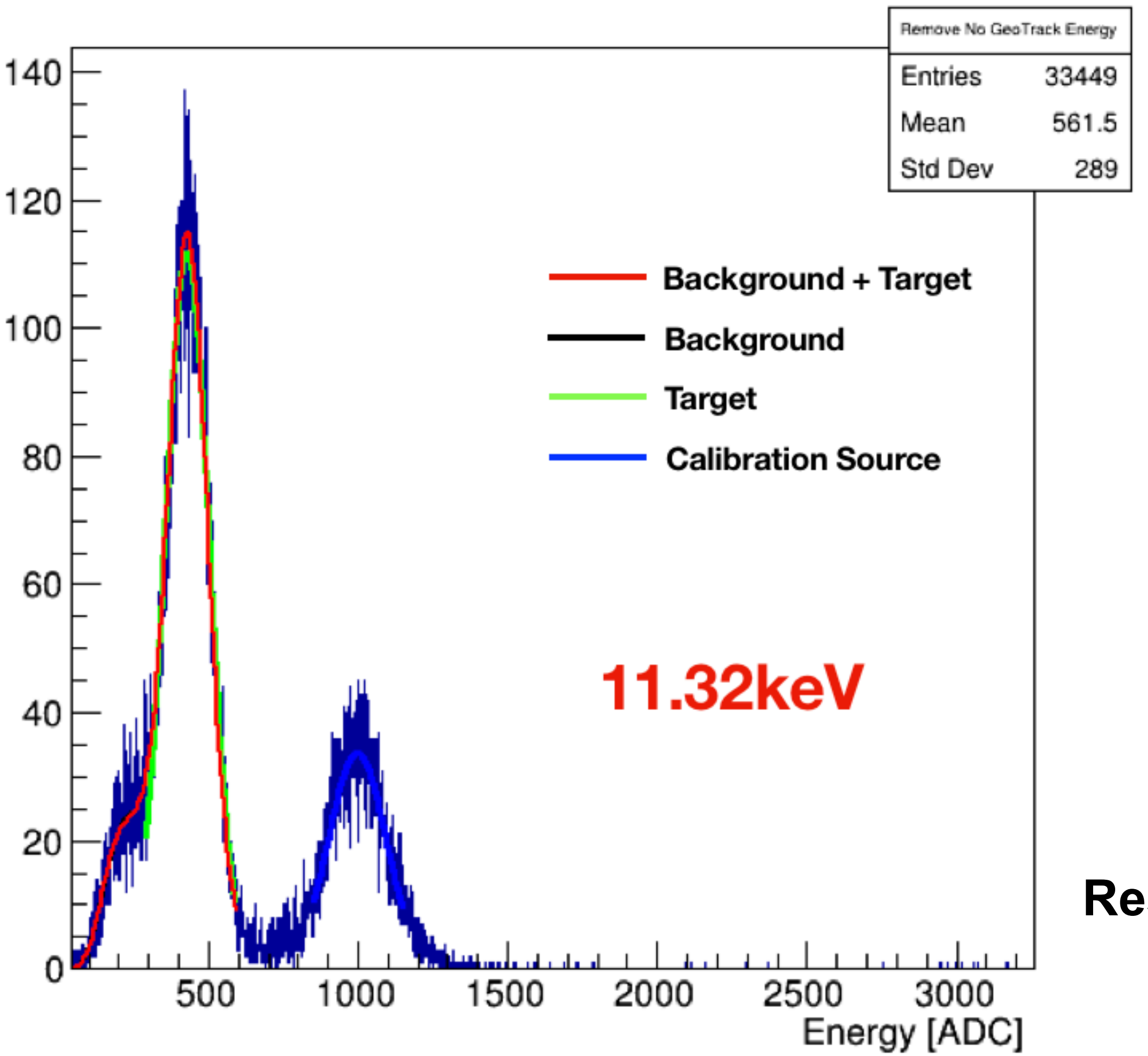
Fluorine 6.3 keV (~2 keVee)



Fluorine 26.3 keV (~9 keVee)



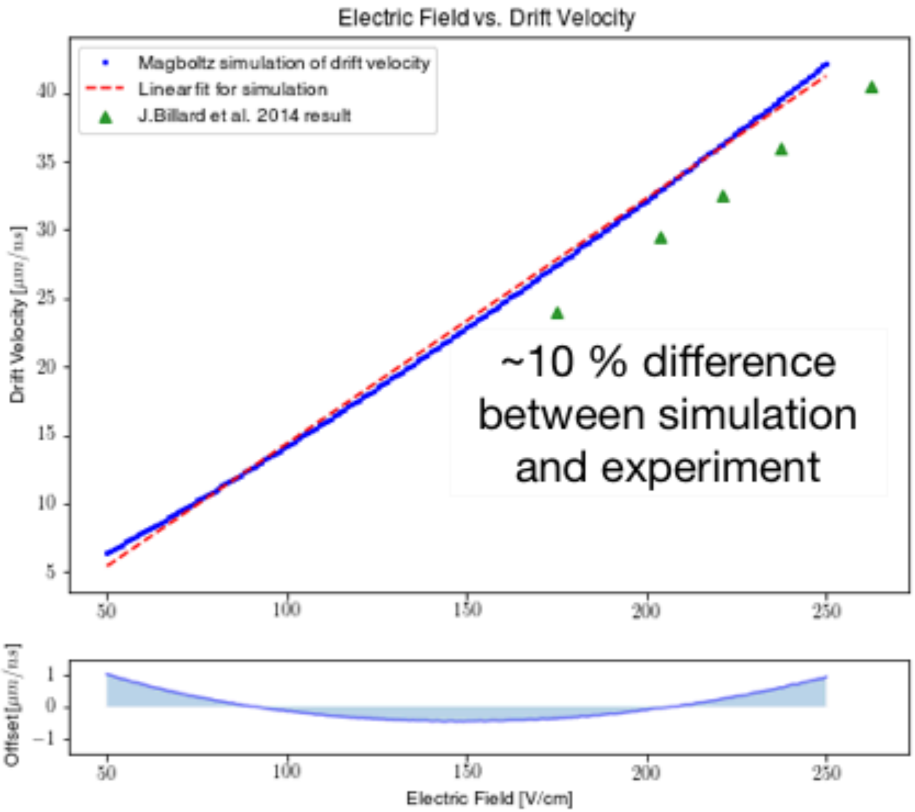
Energy Resolution < 15% (FWHM)

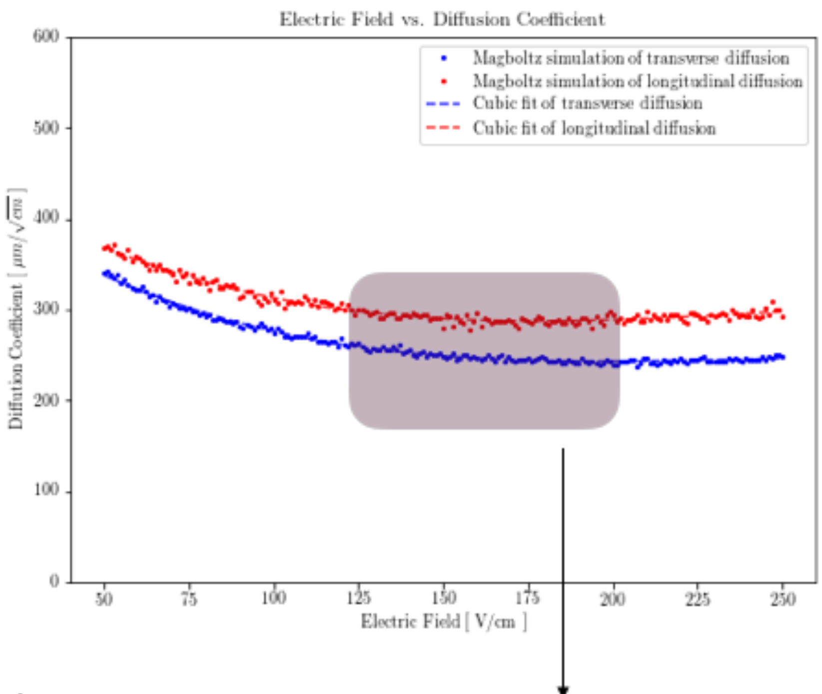


Energy Spectrum of a 11.32 keV F ion run as an example

Resolution: < 15% (FWHM)

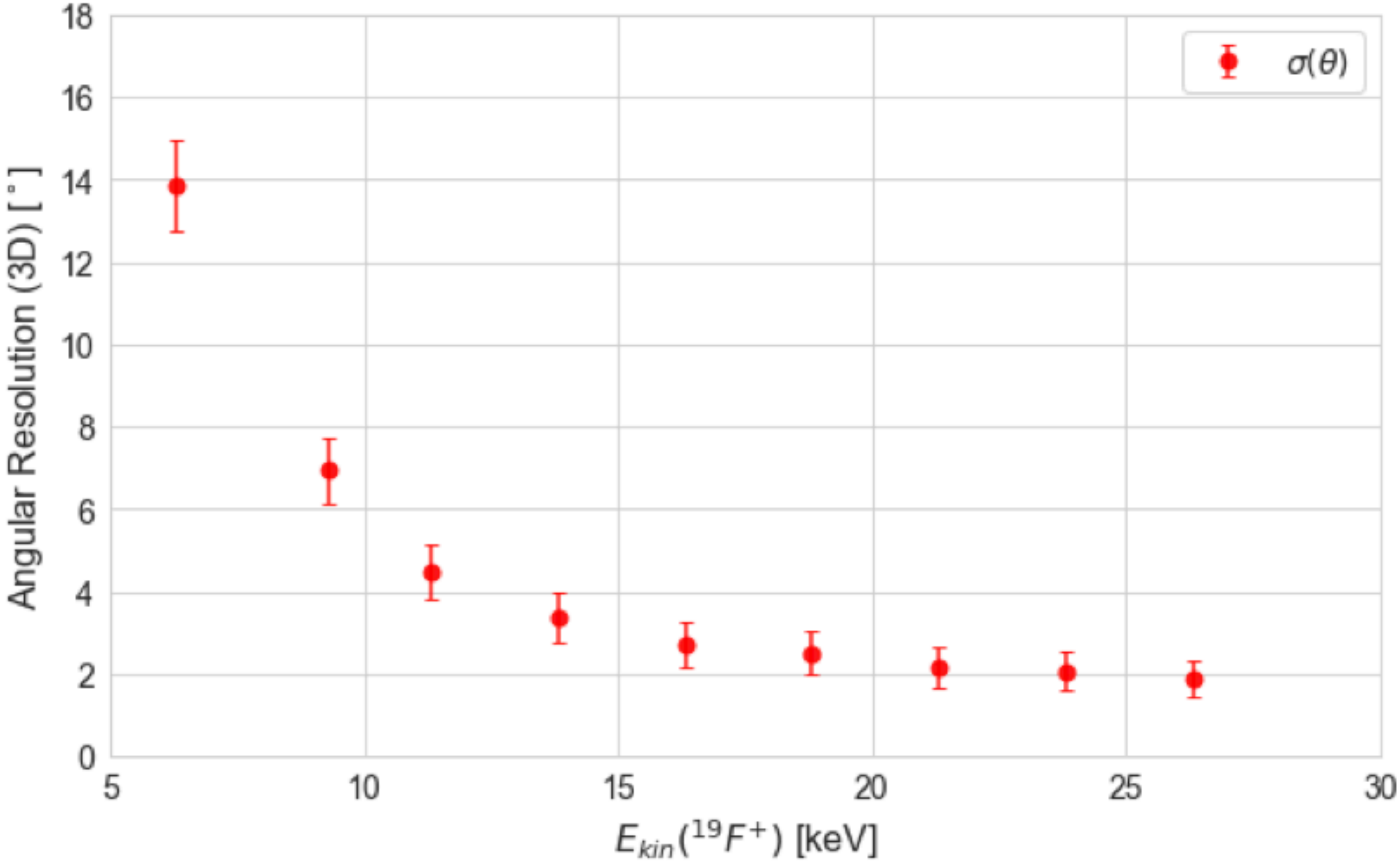
Drift Velocity and Diffusion Coefficient Results from MAGBOLTZ Simulation





Conclusion: In the experimental range, simulation only give a few difference between transversal and longitudinal diffusion impact (But this difference will be enhanced if the drift distance is large enough)

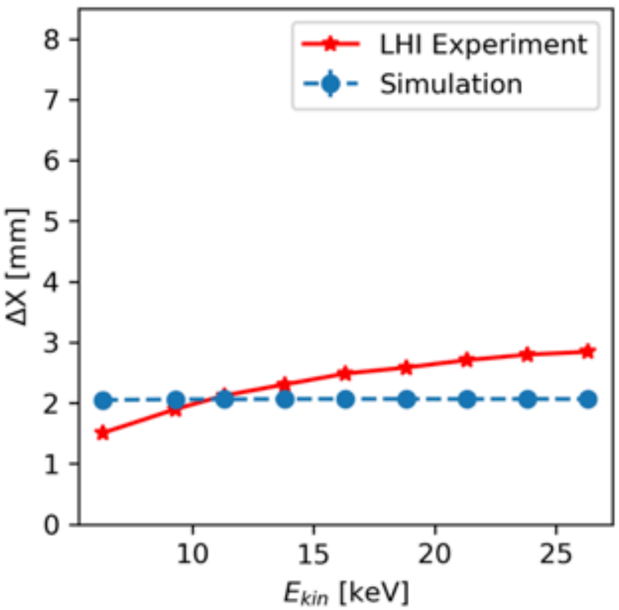
Angular Resolution: better than required 20deg



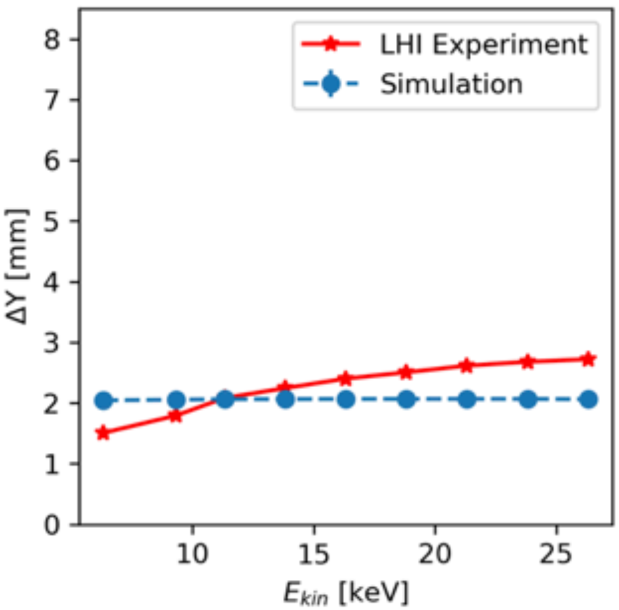
Y. Tao *et al.*, arXiv: 1903.0215

Comparison with Simulation (SRIM + MAGBOLTZ)

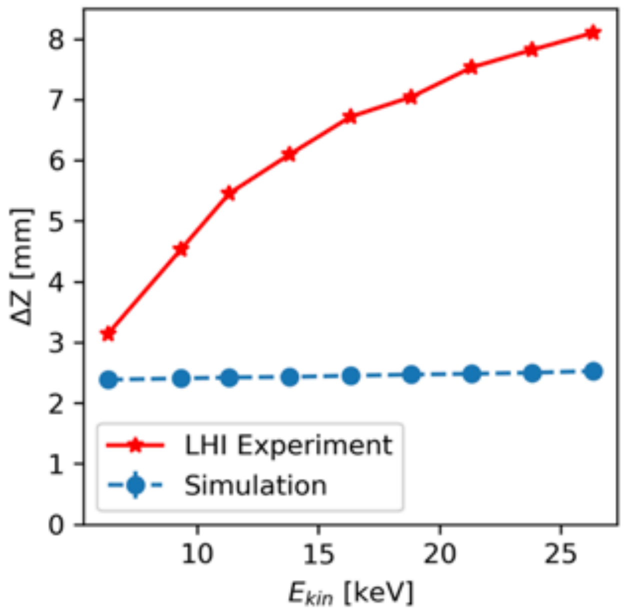
Width X



Width Y



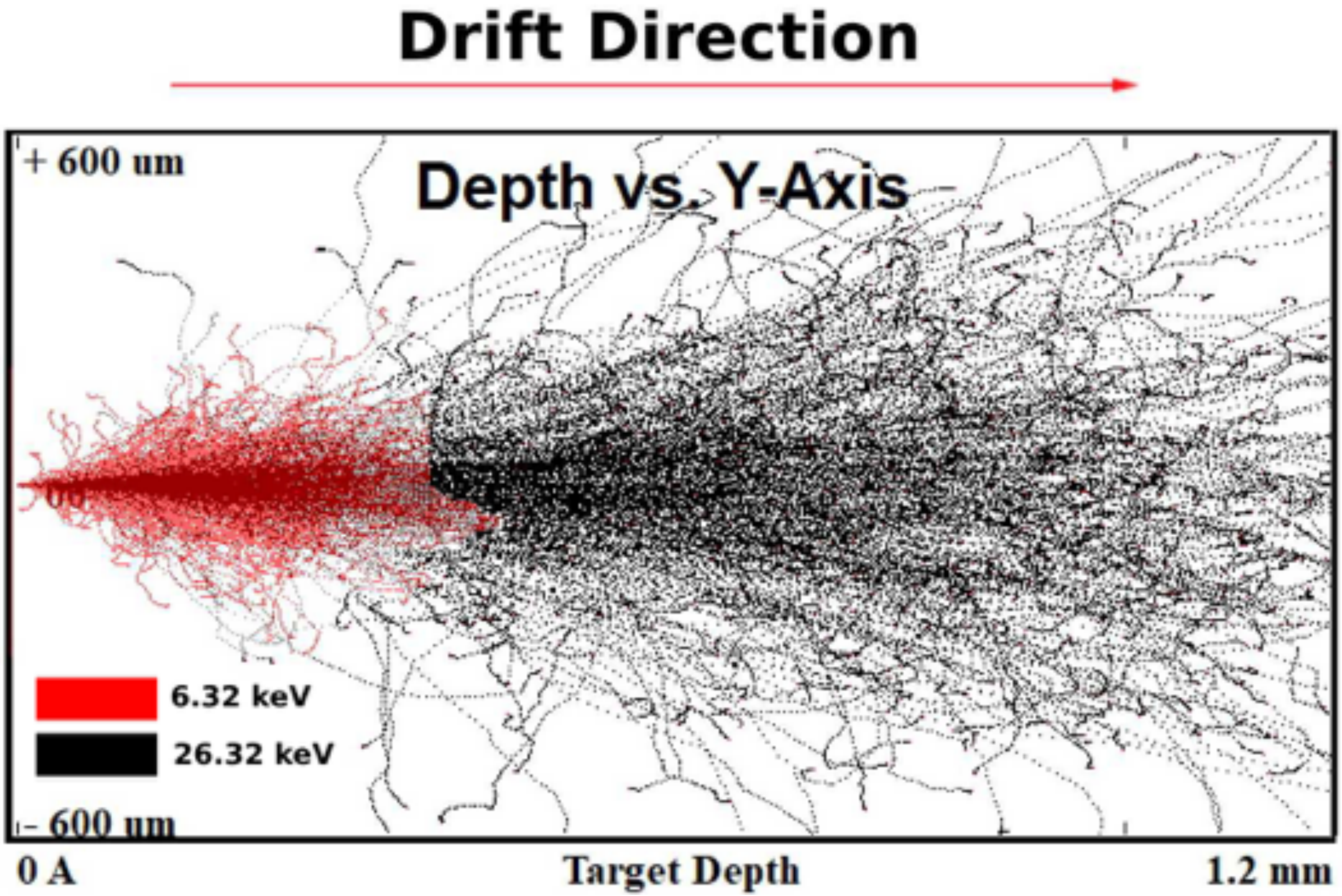
Depth Z



Large discrepancy !!

Molecular effect ?

SRIM Simulation Results



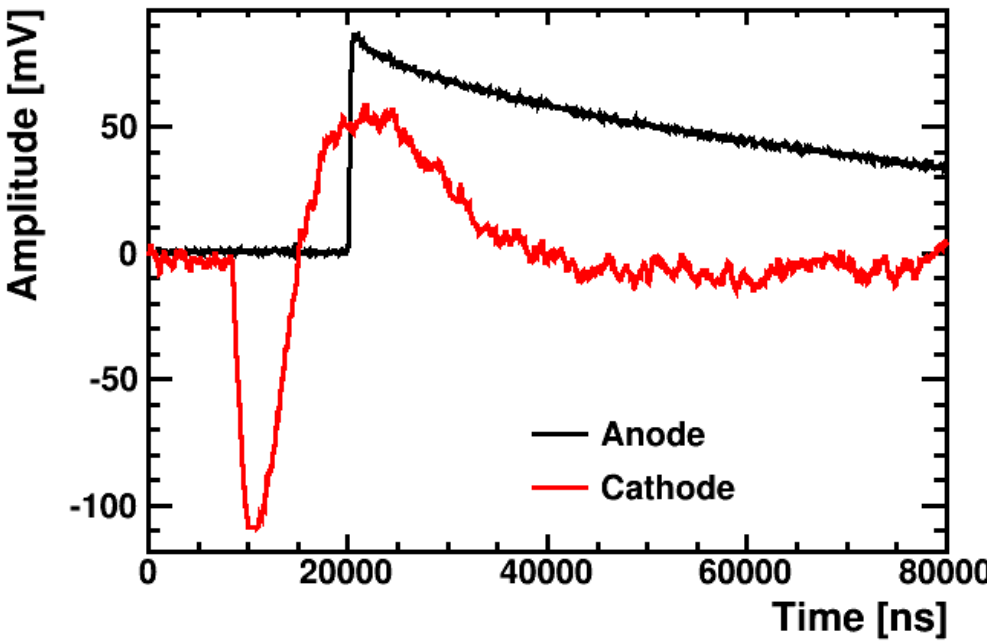
SRIM (Stopping and Range of Ions in Matter)

- Key Points: No external fields applied

Cathode Signal to place the 3D-track

- The cathode signal is produced by the primary electrons. It is produced before the anode signal produced by the avalanche.

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



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

C. Couturier, Q. Riffard, N. Sauzet et al. 2016

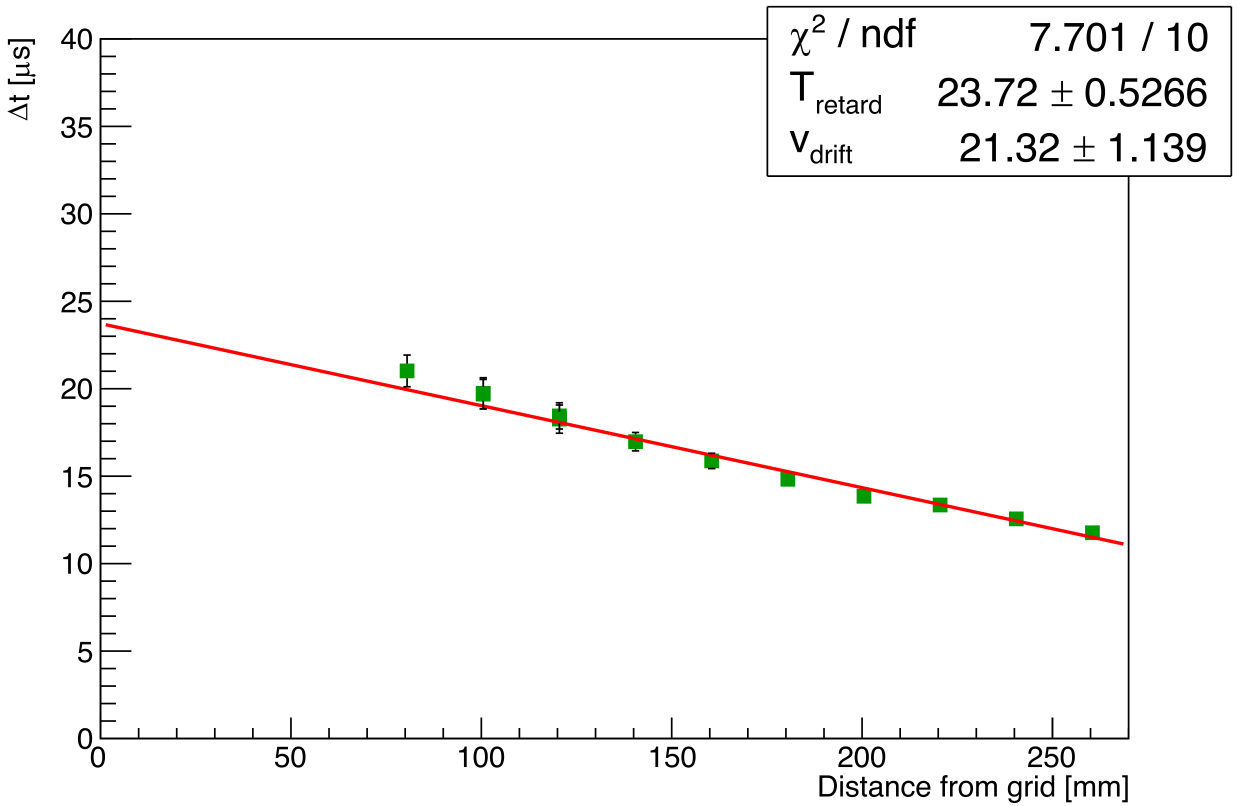
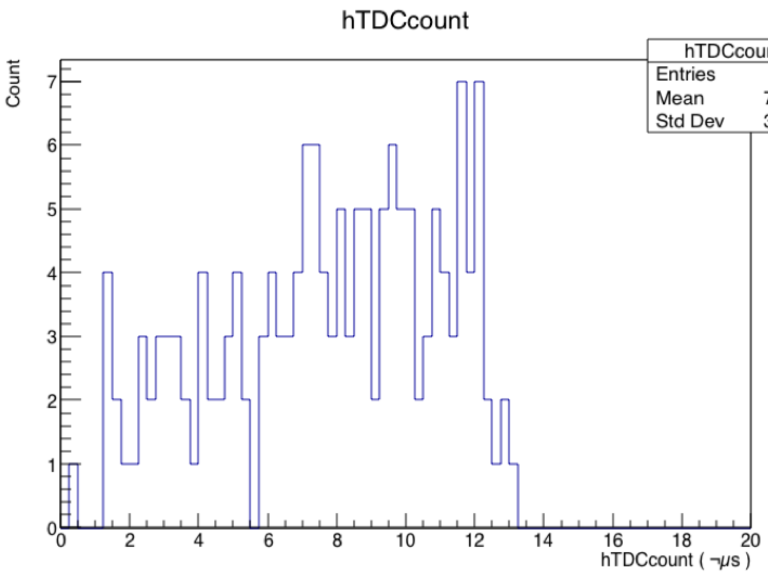


Figure 4. Measure of the time differences (TAC) between the grid signal and the delayed cathode signal in the "START Grid" configuration, as a function of the distance of the α source from the anode (green points) ; error bars correspond to the standard deviation of the mean. A linear fit of these points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

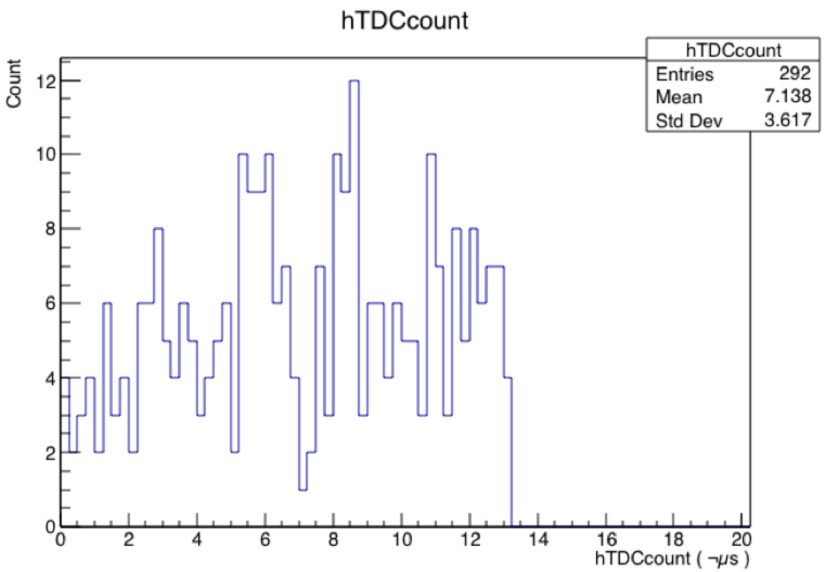
First Cathode Signals from the MIMAC bichamber background

(O. Guillaudin, D.S. et al. October 2018)

Chamber 1

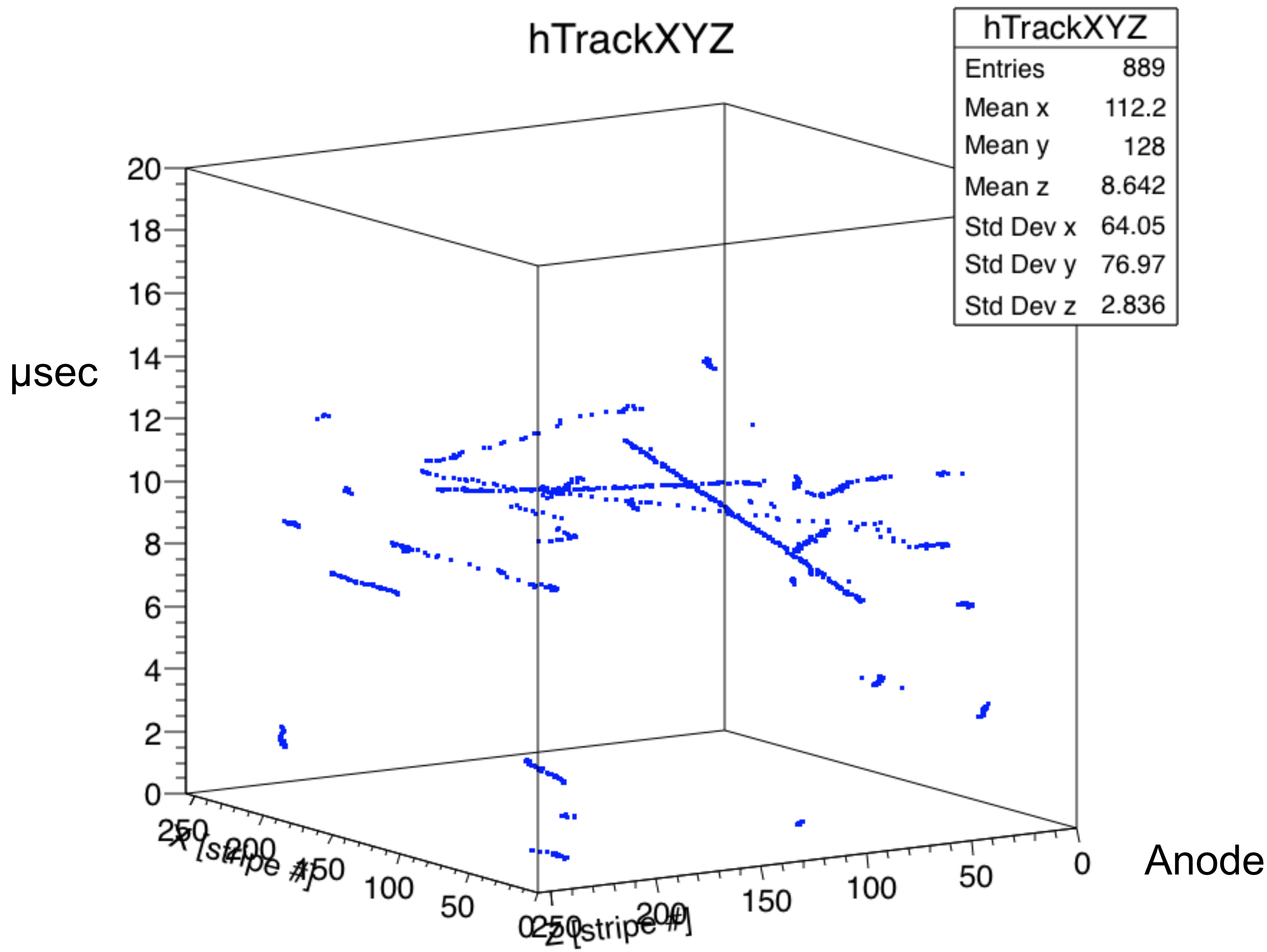


Chamber 2



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



MIMAC validation with neutrons

Neutron monochromatic field:

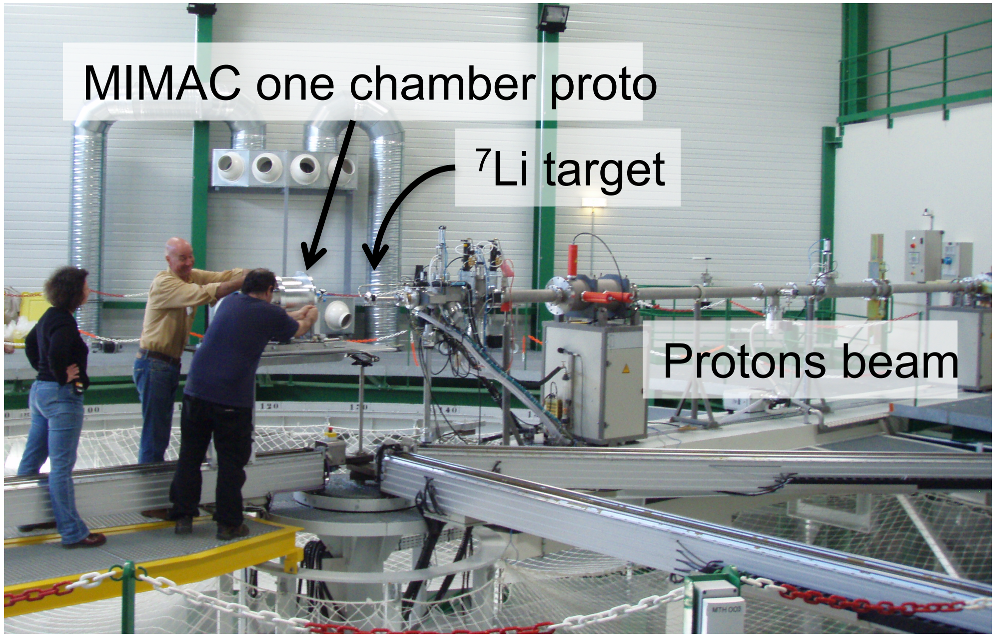
AMANDE facility at IRSN of Cadarache

– Neutrons with a well defined energy from resonances of ^{7}Li by a (p,n) reaction

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

Calibration:

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

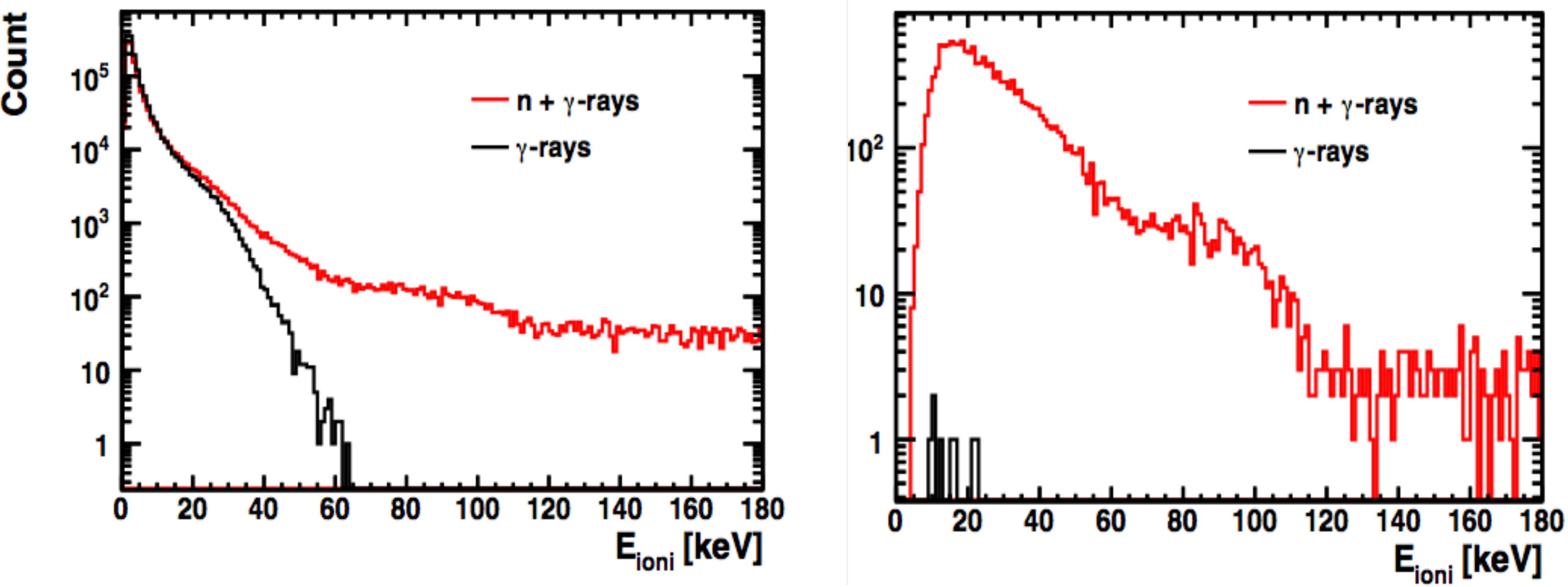


Electron-recoil Discrimination

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

Neutrons → F , C, H, nuclear recoils

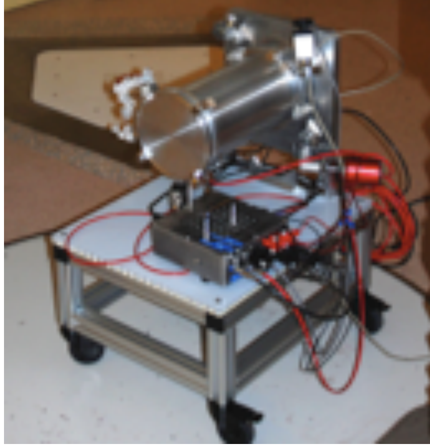
$\gamma - \text{rays}$ → Electrons

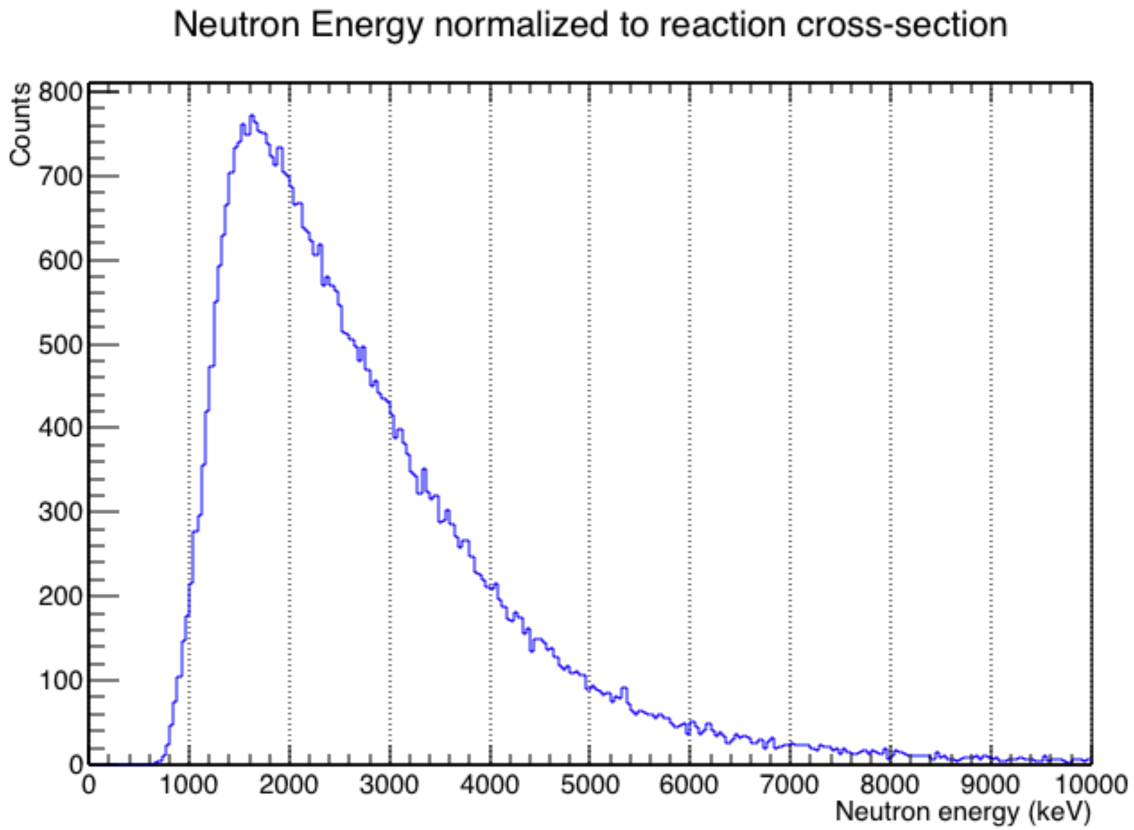


$N_{acpt}/N_{tot} = 1.1 \times 10^{-5}$ electron integrated rejection

Fast neutron detection from a ^{252}Cf source ! measured with MIMAC-FastN

N. Sauzet et al. (2017)





MIMAC 1m^3 in preparation

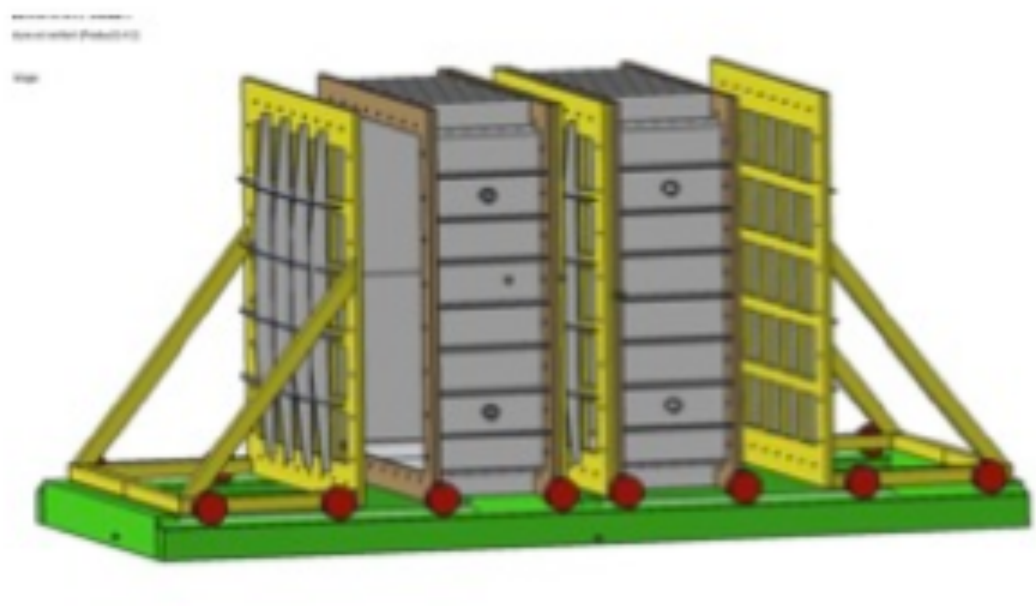
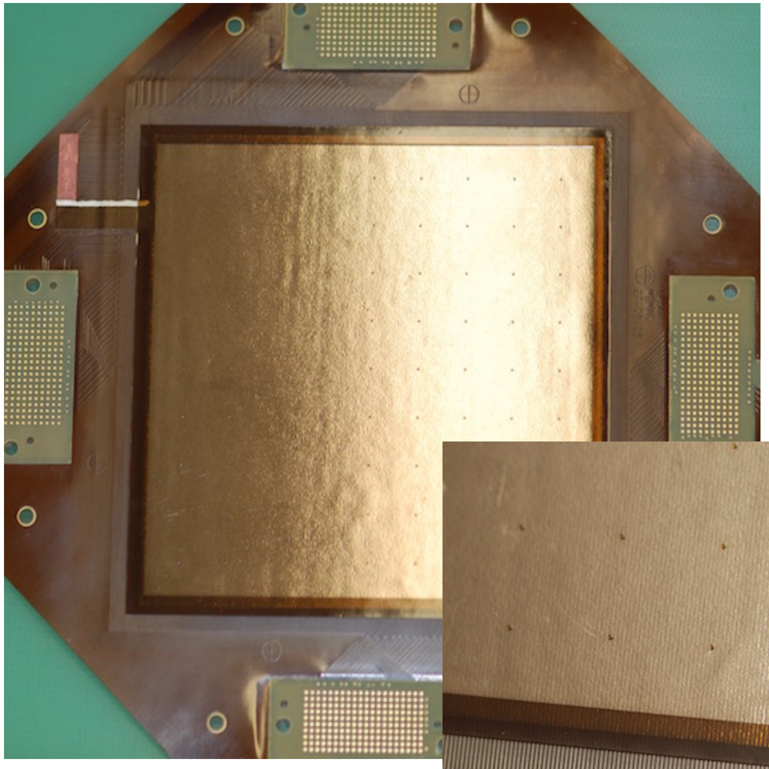
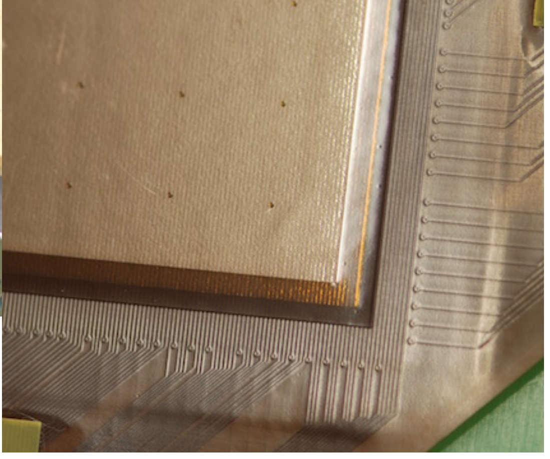


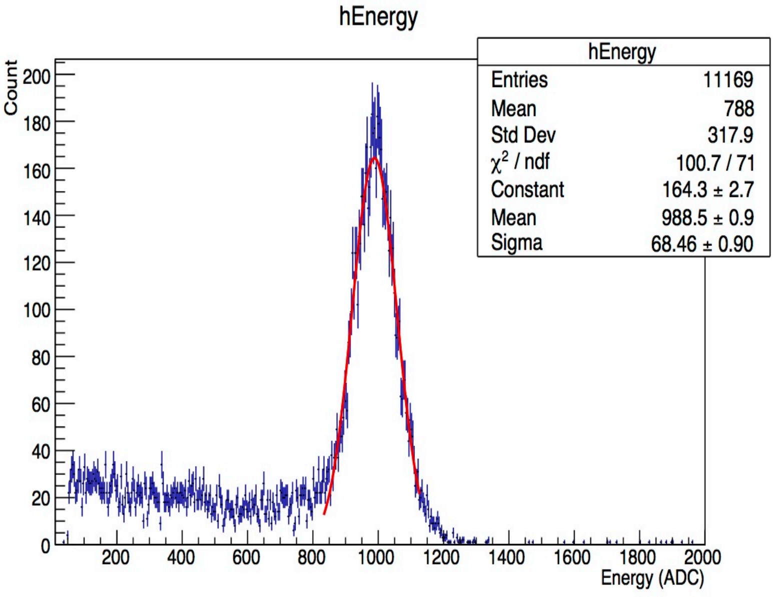
Figure 5. The preliminary mechanical design of the demonstrator of MIMAC -1 m^3 .

Installation in 2020 in LSM ?

New MIMAC low background detector





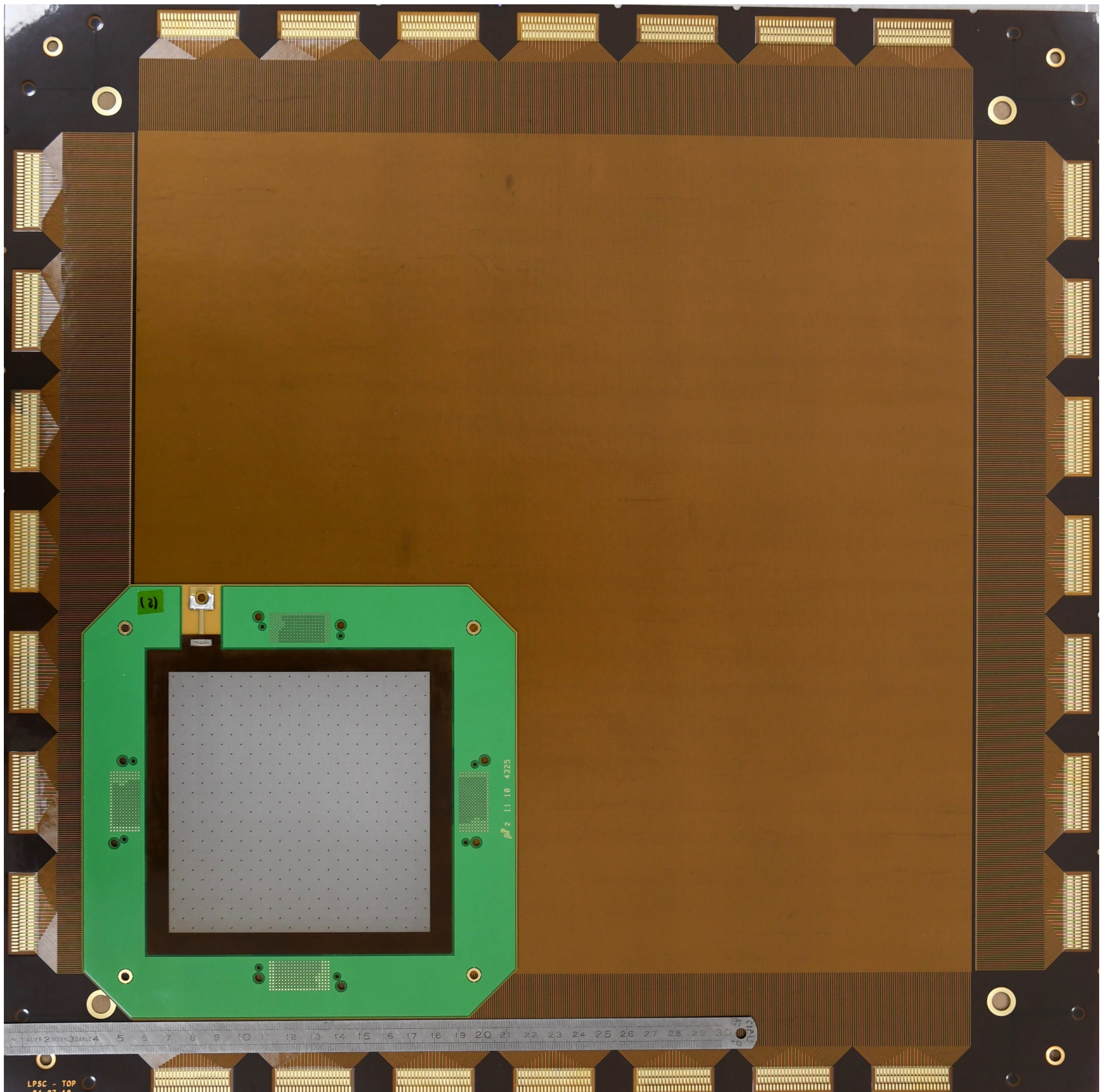


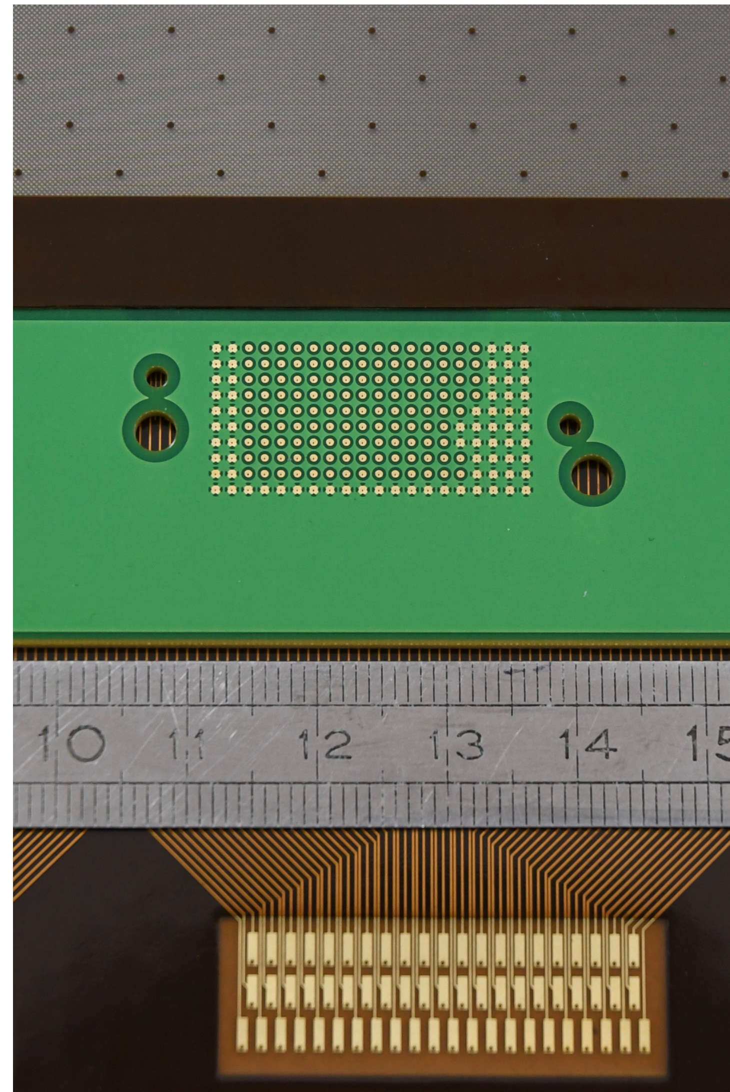
Kapton micromegas readout
Piralux Pilar

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

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

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

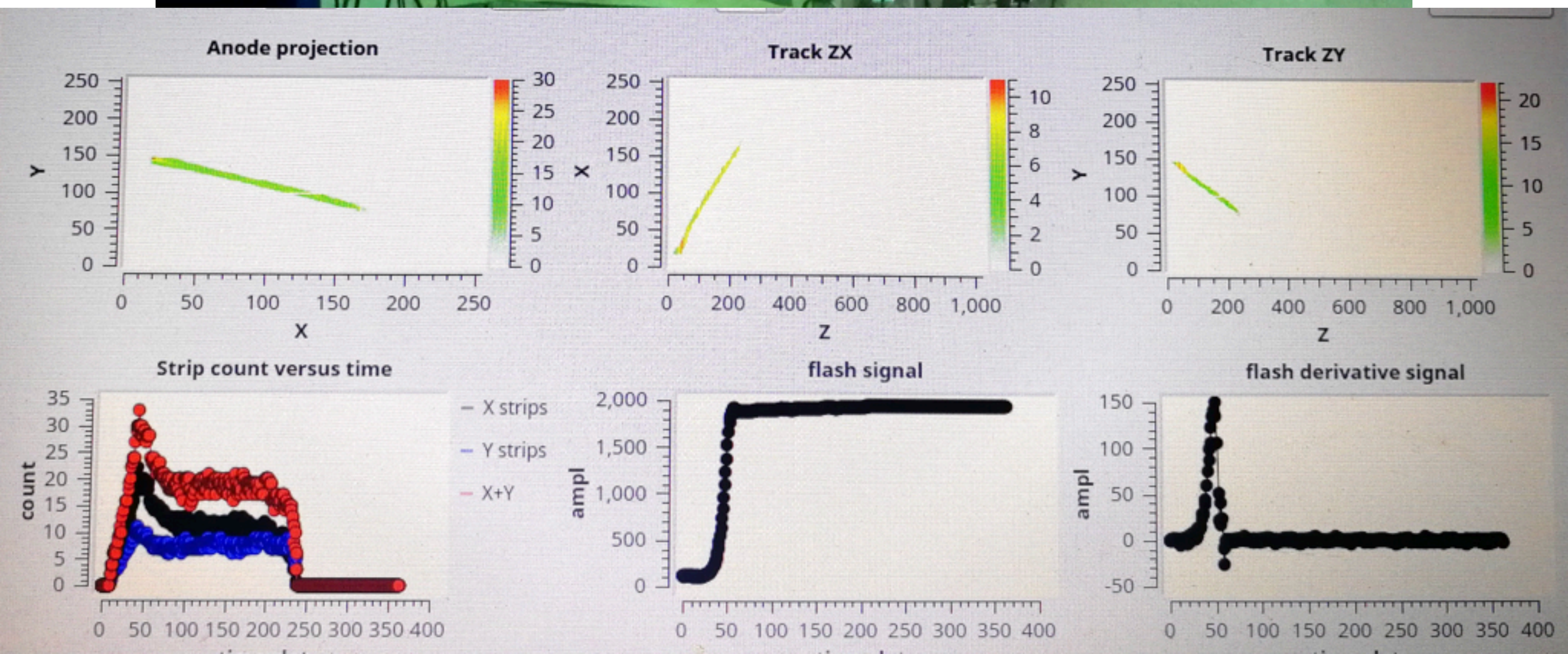




Future

- $1m^3$ with larger surfaces and low background in LSM
- prototypes in ion beams and neutrons
  - Angular resolution at all angles
  - Head tail
  - …
- **International Collaboration :**
  - China, Argentina, Japan (K.Miuchi),
  - USA, India…
  - Cygnus/Cygno collaborators,…

MIMAC Bi Chamber in Beijing (IHEP)



Conclusions

- A new directional detector of nuclear recoils at low energies has been developed 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.
  - New degrees of freedom are available to discriminate electrons from nuclear recoils to improve the DM search for.
  - Angular resolution and directional studies of 3D tracks have been performed with COMIMAC and LHI.
- Neutron Spectroscopy with MIMAC is possible and opens a large energy range.
- MIMAC with its 3D tracks at high spatial resolution opens a new window in the exploration of rare events !

- **The 1 m^3 MIMAC will be the validation of a new generation of a large DM high definition detector including directionality (a needed signature for DM discovery)**

How to convince the scientific community to invest in DDDMD ?

1) A prototype that
   - is low radioactivity,
   - has angular resolution <10deg at 10keV
   - Head-tail
   - Excellent electron rejection

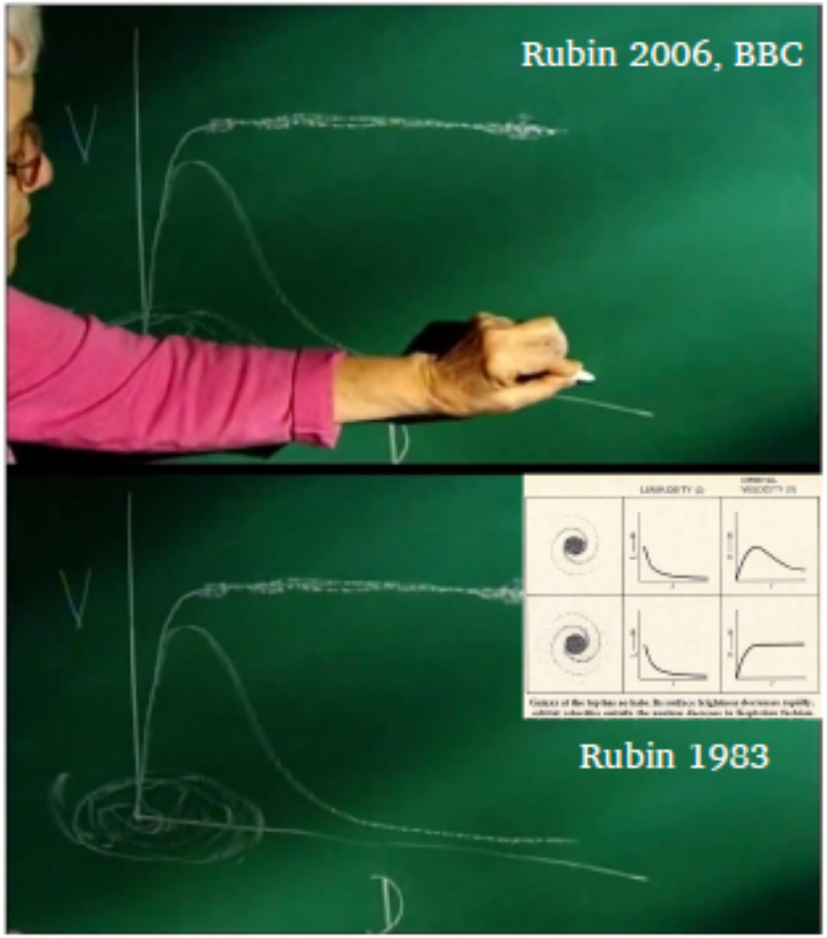
2) A signal in non-directional DM detectors or LHC LSP-like!

Wealth of evidence for DM is astrophysical !

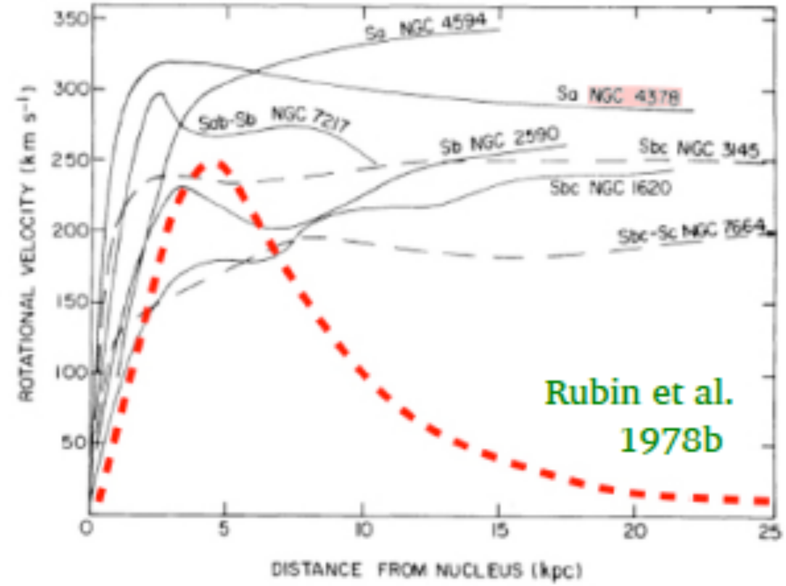
More complex than presented usually!

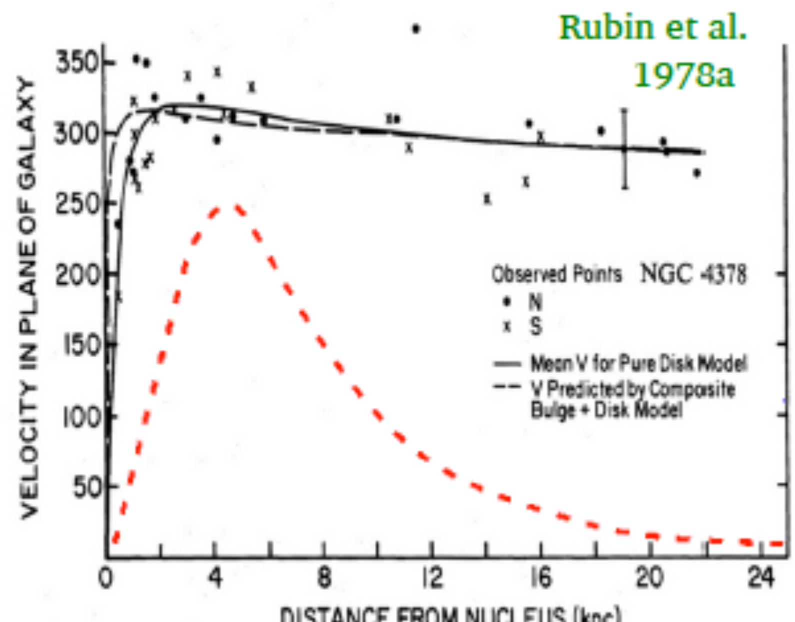
DM: some revisits

Rotation curves : what is often said [incorrectly] to be expected



Galaxy at the top has no halo. Its surface brightness decreases rapidly, orbital velocities outside the nucleus decrease in Keplerian fashion.





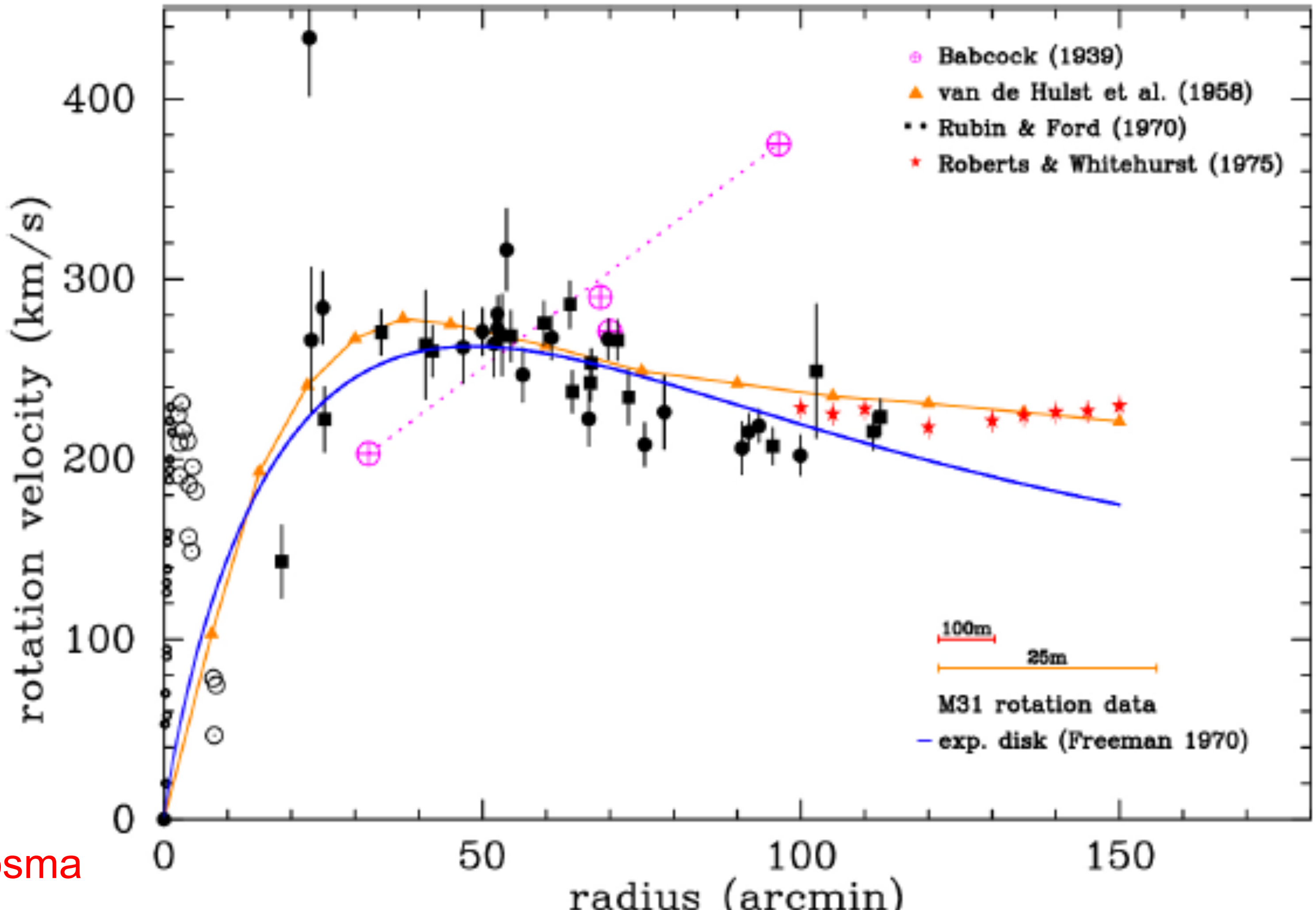
Keplerian behaviour just outside the nucleus can NOT be expected

A. Bosma

Freeman 1970, appendix

For NGC 300 and M33, the 21-cm data give turnover points near the photometric outer edges of these systems. These data have relatively low spatial resolution; if they are correct, then there must be in these galaxies additional matter which is undetected, either optically or at 21 cm. Its mass must be at least as large as the mass of the detected galaxy, and its distribution must be quite different.

M31 – Need for dark matter based on radio data



A. Bosma

Rotation curve analysis

From data to mass models

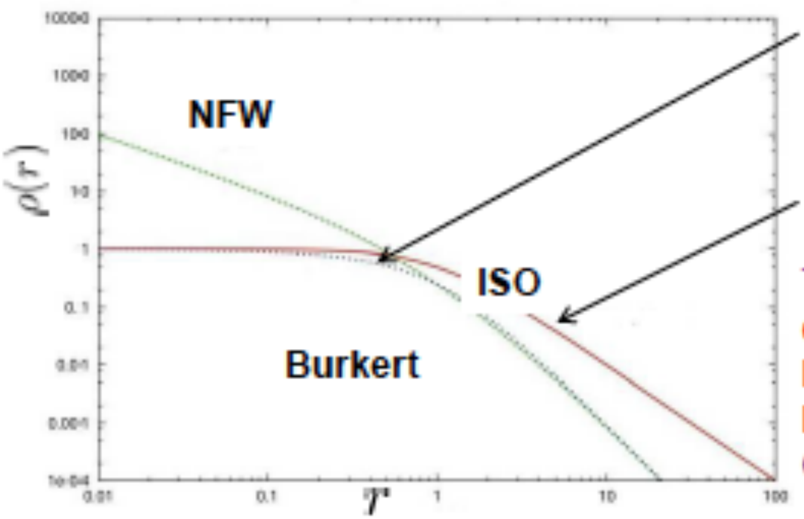
$$V^2(R) = V^2_{halo}(R) + V^2_{HI}(R) + V^2_{disk}(R)$$

observations = model

- V^2_{disk} from I-band photometry
- V^2_{HI} from HI observations
- V^2_{halo} different choices for the DM halo density

Dark halos with central constant density (Burkert, Isothermal)

Dark halos with central cusps (NFW, Einasto)



$$\rho(r) = \frac{\rho_0}{(1 + r/r_0)(1 + (r/r_0)^2)}$$

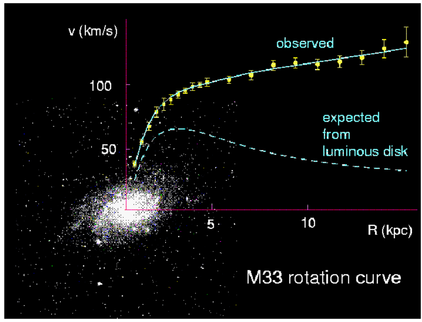
$$\rho(r) = \frac{\rho_0}{1 + (r/r_0)^2}$$

The mass model has 3 free parameters:
disk mass
halo central density
Halo core radius (length-scale)
Obtained by best fitting method

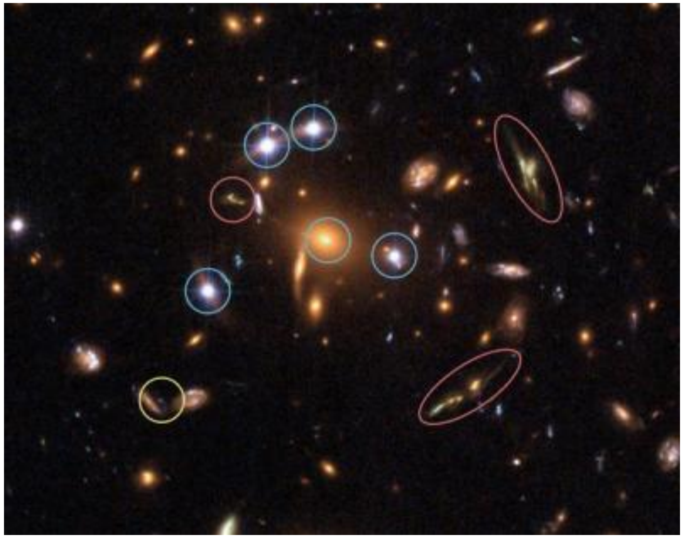
P. Salucci, NAOC 2014

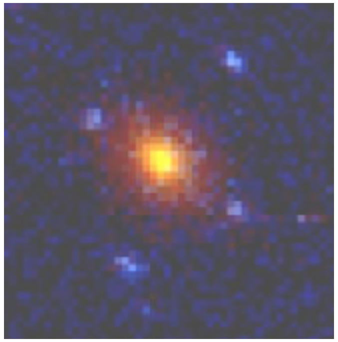
Wealth of Evidence for DM

- Galaxy rotation curves (V. Rubin) Bosma (HI)



- Dynamics of galaxy clusters (Zwicky)
- Gravitational lensing mass reconstruction



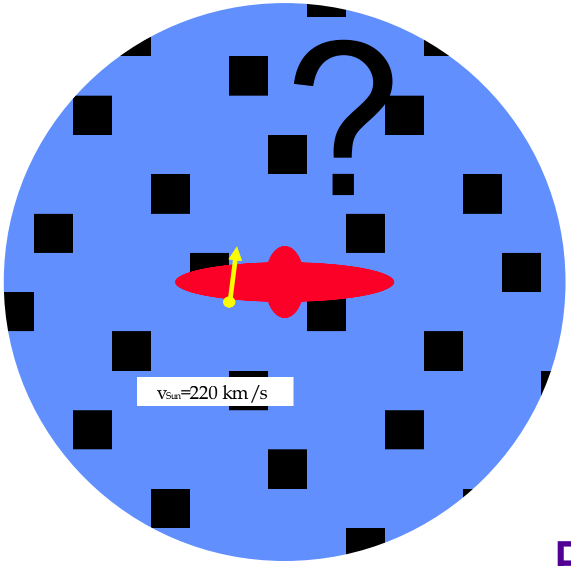


- Bullet cluster (Clowe+,2006)

DM distribution in our Galaxy

Usual assumptions:

ρ_{DM}= 0.3 GeV/cm^3, β=10^{-3}, Maxwellian distribution of velocities, v_{rms}=270 km/s



« Simplified Model »of Matter in our Galaxy: SMMG

Used for most comparisons…

But is it the reality? Clumps? Corotation?

Galactic scale N-body simulations with Baryons

- Ling+ 2009 Dark Matter Direct Detection Signals inferred from a Cosmological N-body Simulation with Baryons

➔2 DM populations : halo+disk DM

➔ only measurements can tell

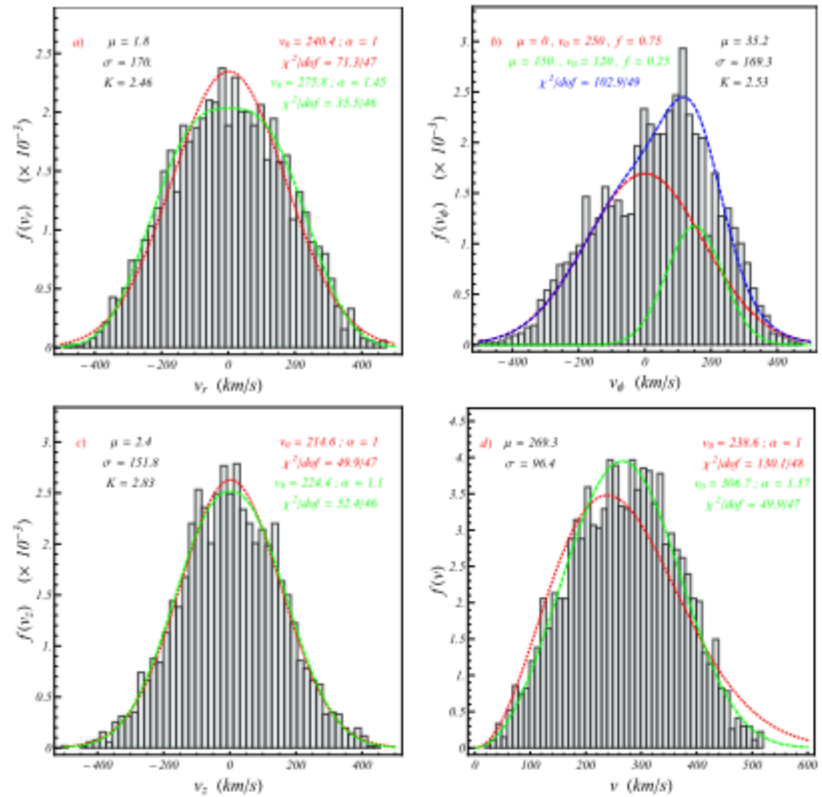


Figure 5: *Velocity distributions of dark matter particles ($N_{ring} = 2,662$) in a ring $7 < R < 9$ kpc, $|z| < 1$ kpc around the galactic plane.*
a) Radial velocity v_r, with Gaussian (red) and generalized Gaussian (green) fits (cfr. Eq. (2.1)).
b) Tangential velocity v_ϕ, with a double Gaussian fit. f indicates the fraction of each component.
c) Velocity across the galactic plane v_z, with Gaussian (red) and generalized Gaussian (green) fits (cfr. Eq. (2.1)).
d) Velocity module, with Maxwellian (red) and a generalized Maxwellian (green) fit (cfr. Eq. (2.2)). μ, σ (both in km/s) and K stand for the mean, the standard deviation and the Kurtosis parameter of the distribution. The goodness of fit is indicated by the value of the χ^2 vs. the number of degrees of freedom (dof).

Analysis of Gaia results

- second release april 2018: high-precision positions, velocities, and distances for **1.3 billion stars**

1) GD-1 stream from Gaia ➔a new level of precision in simulating a stream-dark-matter encounter (A. Bonaca et al., 2019).

Need a clump of 10^7Mo!

2) Lisanti et al 2019: 2 non disk populations of stars :

i) Old, isotropic velocity distributions

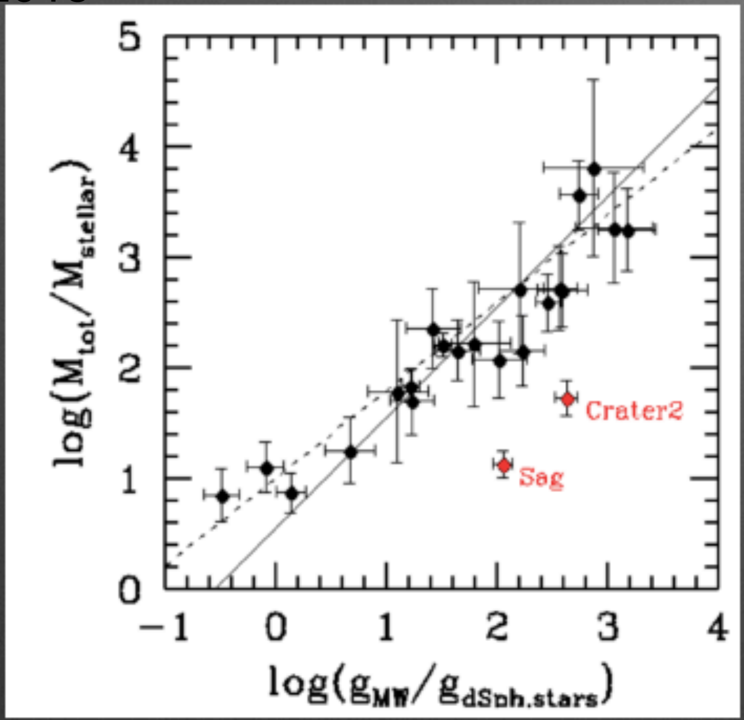
ii) Young, large radial velocities from merger 7 billion years ago!

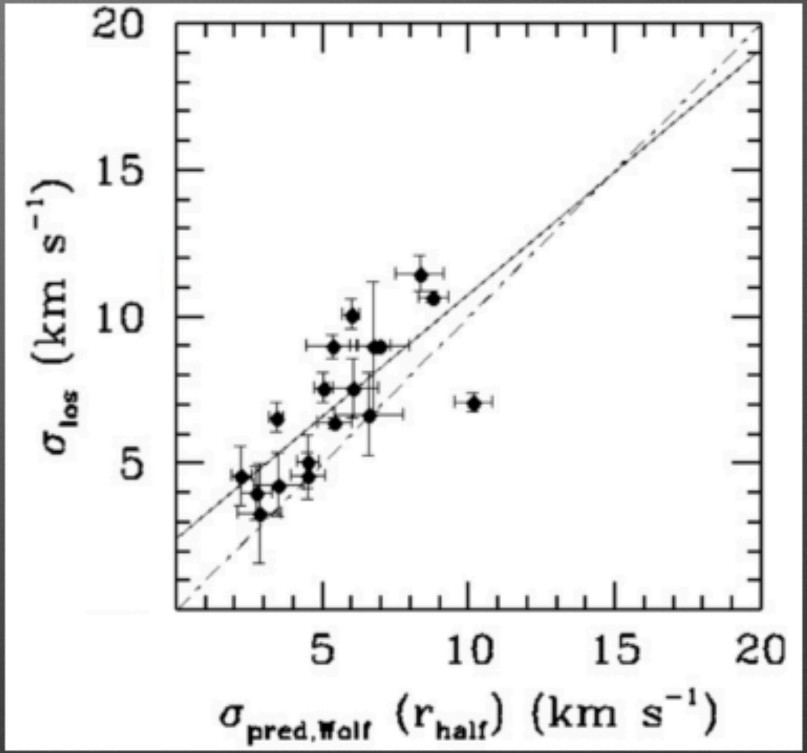
Each should have its own DM population!!!

Galactic forces rule dynamics Milky Way dwarf galaxies

Yang Yanbin in Yunnan Sino french meeting Nov 2018

Hammer et al. 2018, ApJ





$$\sigma^2_{los,MW} = \sqrt{2}\, g_{MW}\, r_{half}$$

MW tidal shock predicts

This correlation falsifies the hypothesis of neglecting the MW impact!

Van Dokkum et al. 2018

NGC1052-DF2 : a Galaxy without DM?

➔ Evidence « for » DM! (against modified gravity)

Thank you
for your attention!

MIMAC validation with neutrons

Neutron monochromatic field:

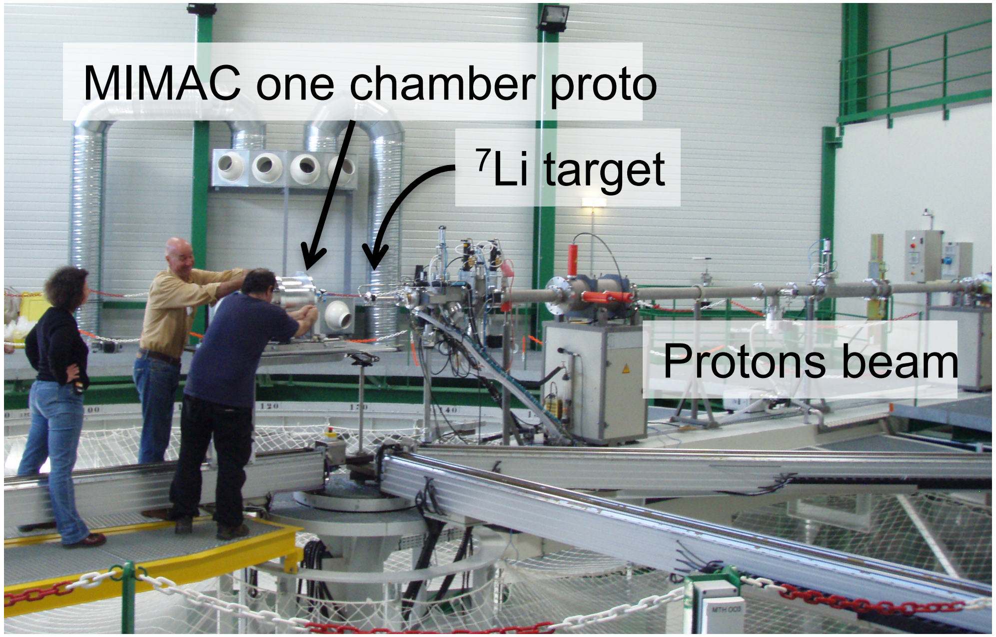
AMANDE facility at IRSN of Cadarache

– Neutrons with a well defined energy from resonances of ^{7}Li by a (p,n) reaction

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

Calibration:

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

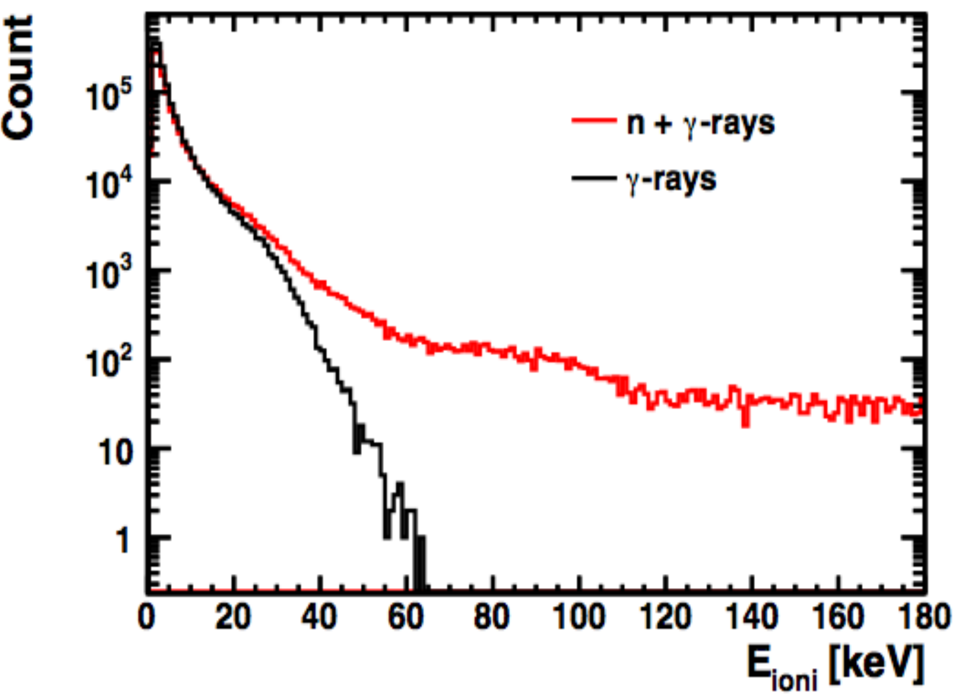


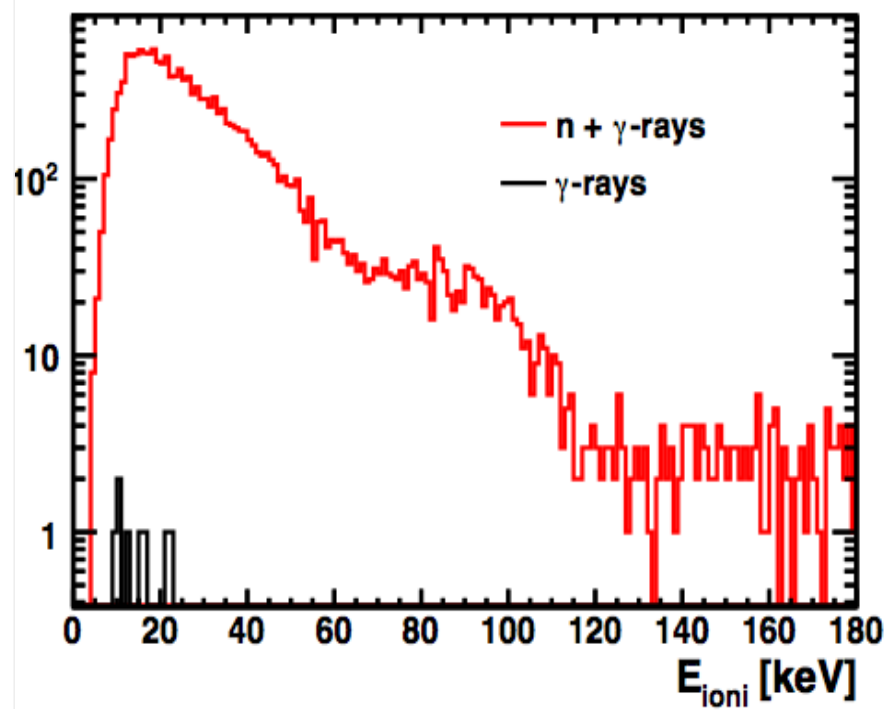
Electron-recoil Discrimination

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

Neutrons → F , C, H, nuclear recoils

$\gamma - \text{rays}$ → Electrons

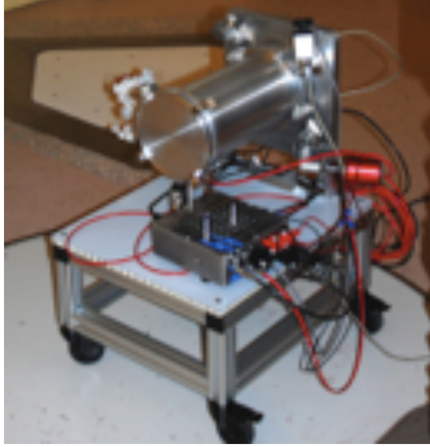


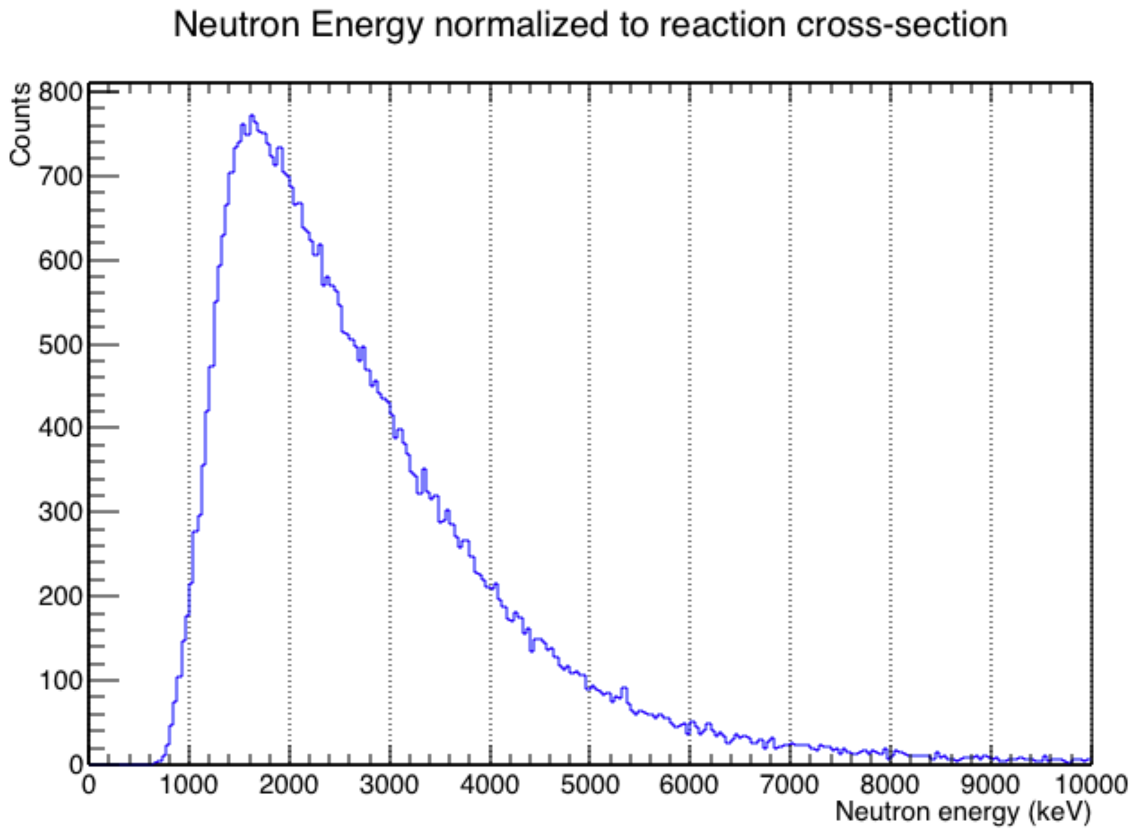


$N_{acpt}/N_{tot} = 1.1 \times 10^{-5}$ electron integrated rejection

Fast neutron detection from a ^{252}Cf source ! measured with MIMAC-FastN

N. Sauzet et al. (2017)





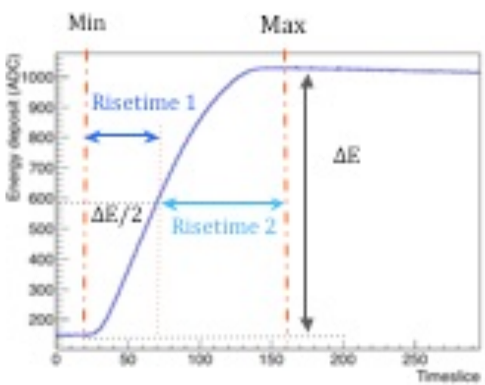
Direction of ^{4}He recoil tracks : head-tail signature

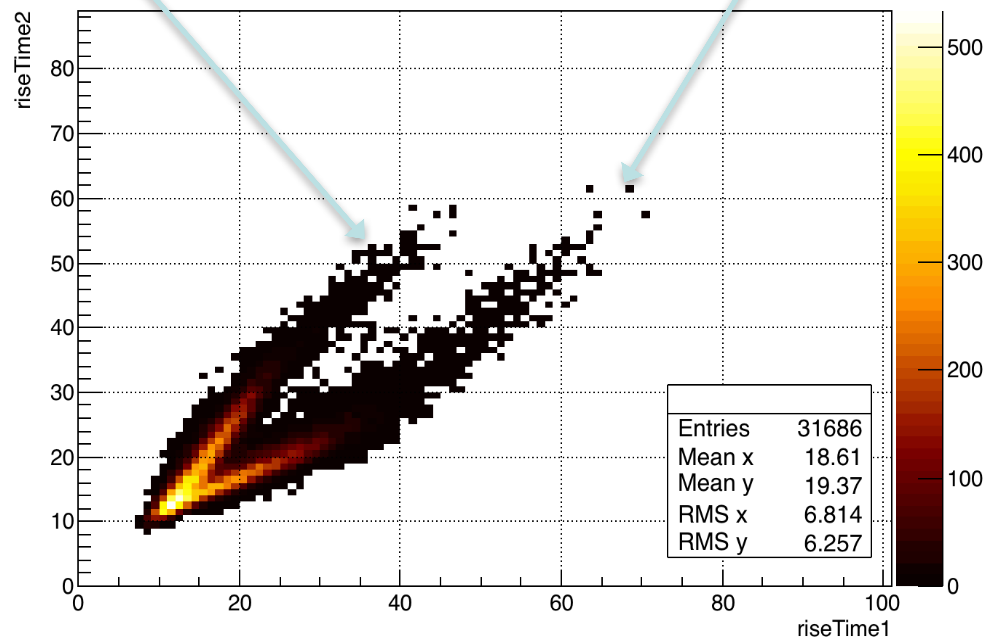
Detector perpendicular to the beam direction

1 Cathode direction

2 Anode direction

Analysis from the charge deposit profile on the grid :





The track direction is essential for the definition of the interaction point

IRSN /AMANDE (Cadarache)

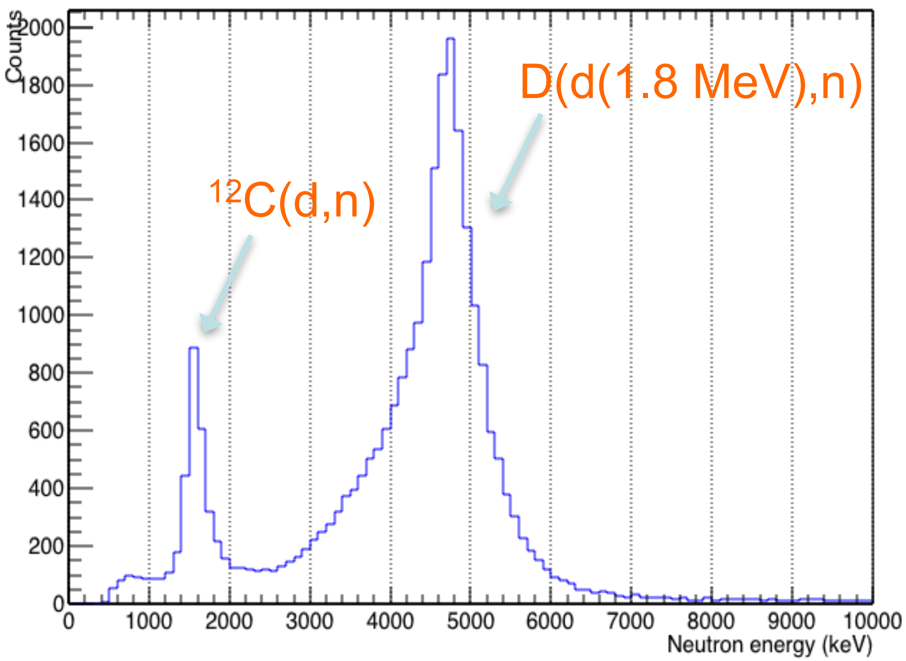
^{3}H(p(3357 keV),n)

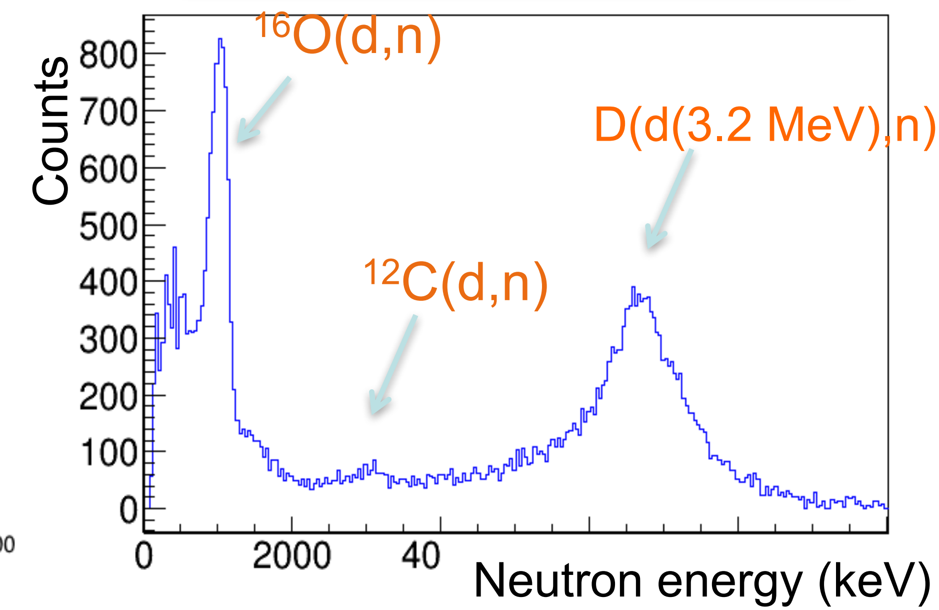
Monoenergetic neutrons of 2.5 MeV

MIMAC-FastN: Neutron Spectroscopy 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





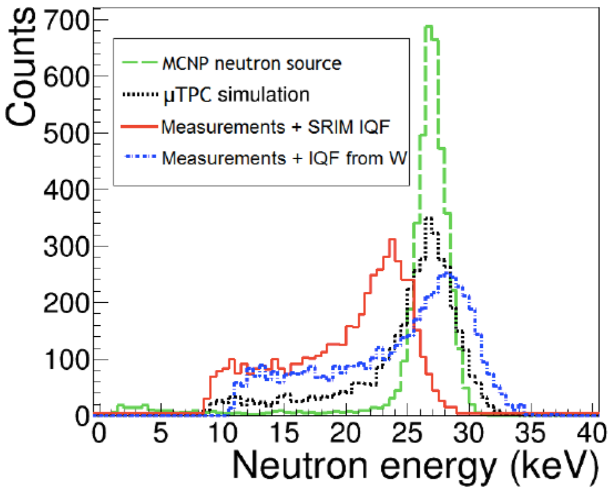
NPL /(UK)

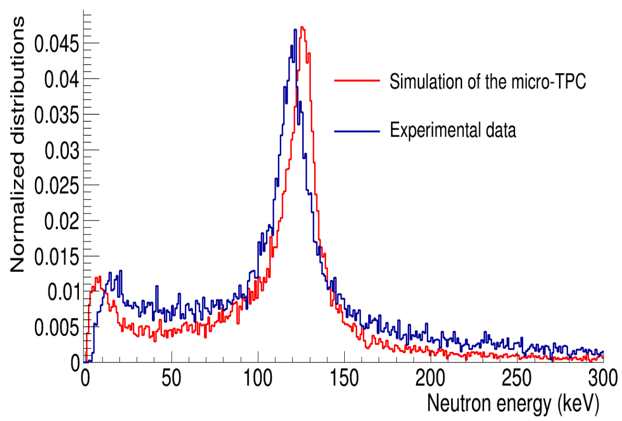
IRSN / AMANDE (Cadarache)

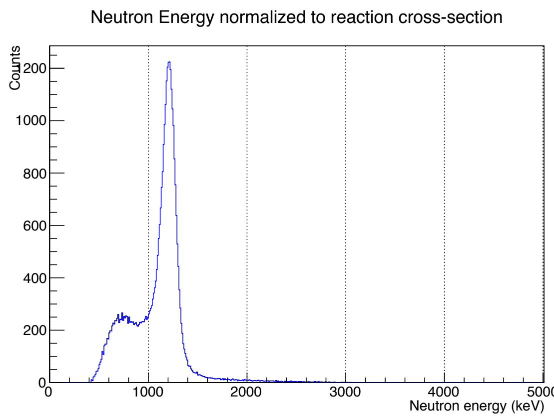
700 mbar He/CO_2 (5%)

A large energy 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***





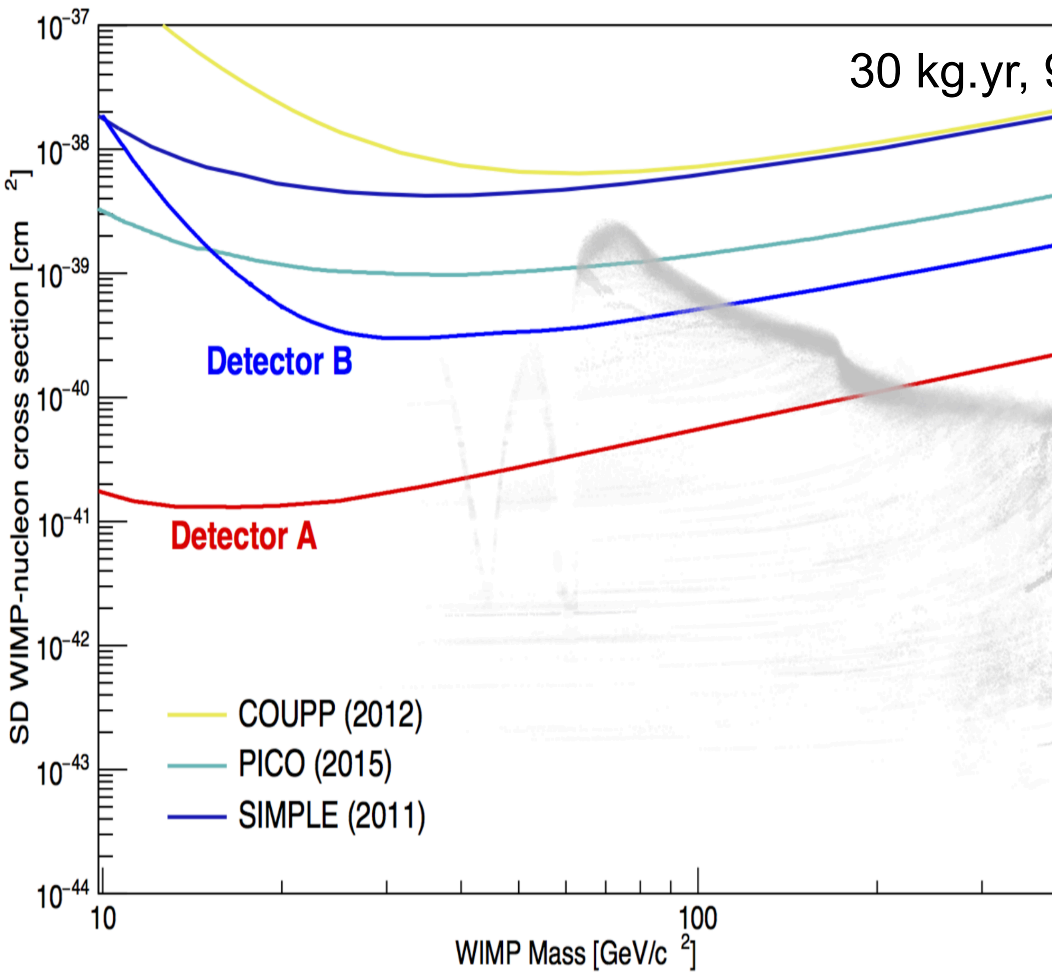


D. Maire *et al.*
« Neutron energy reconstruction and fluence determination at 27 keV with the LNE-IRSN-MIMAC µ-TPC recoil detector »
IEEE Transactions on Nuclear Science, 63(3) : 1934-1941, June 2016

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

Paper to be submitted

MIMAC-Exclusion limits



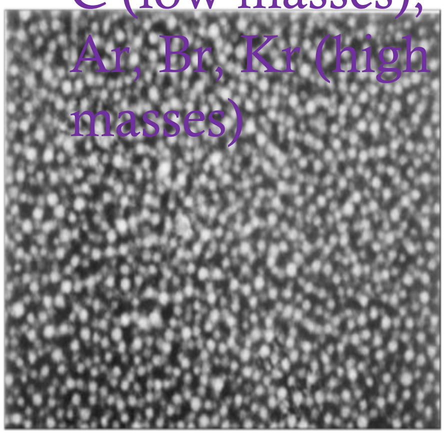
A: 5 keV (threshold)
no background
3D track with head-tail
angular resolution 20^o

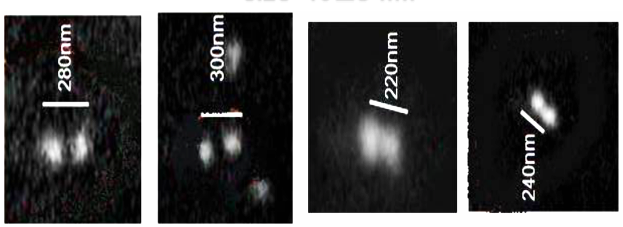
B: 20 keV
background= 10evt/kg yr
angular resolution 50^o
3D with no head-tail

D. Santos (LPSC Grenoble)

Directional detection: comparison of strategies

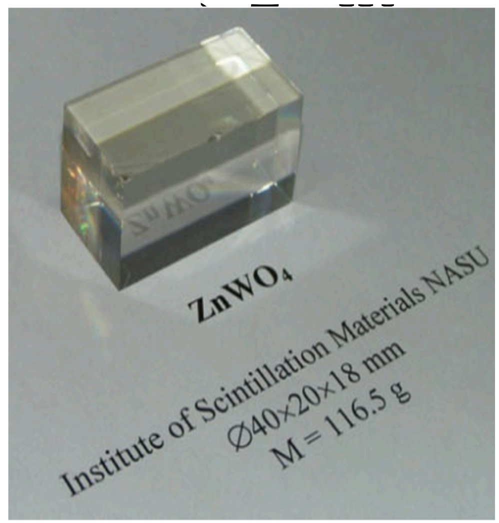
- Emulsion layers target = C (low masses), Ar, Br, Kr (high masses)





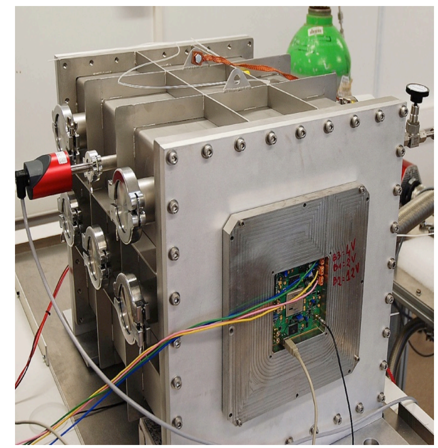
D'Ambrosio et al. 2014

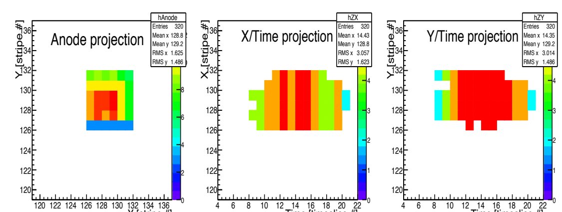
- Anisotropic crystals
target = O (low



No tracks ; only statistical distributions (!)

- Low pressure TPCs
target = F

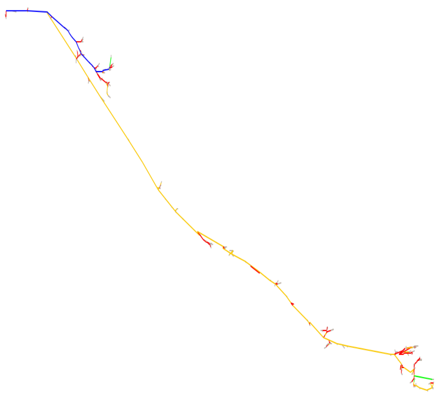




Capella et al. 2013

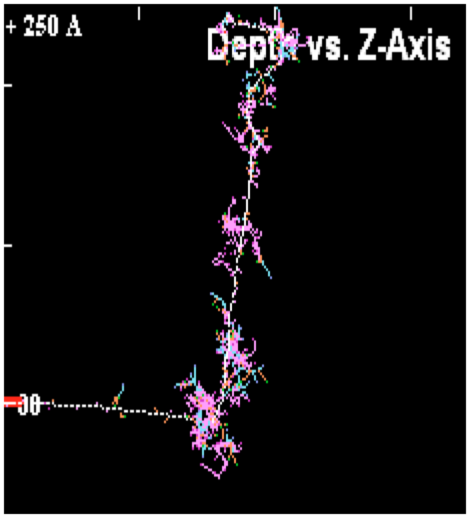
Directional detection: comparison of strategies

- Emulsion



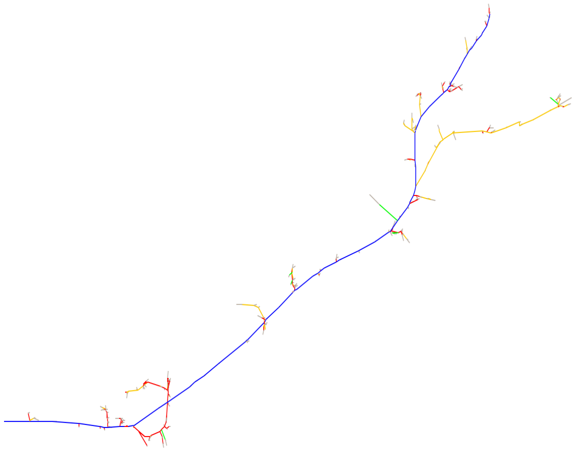
~100 nm

- Anisotropic crystals



~10 nm

- Low pressure TPCs

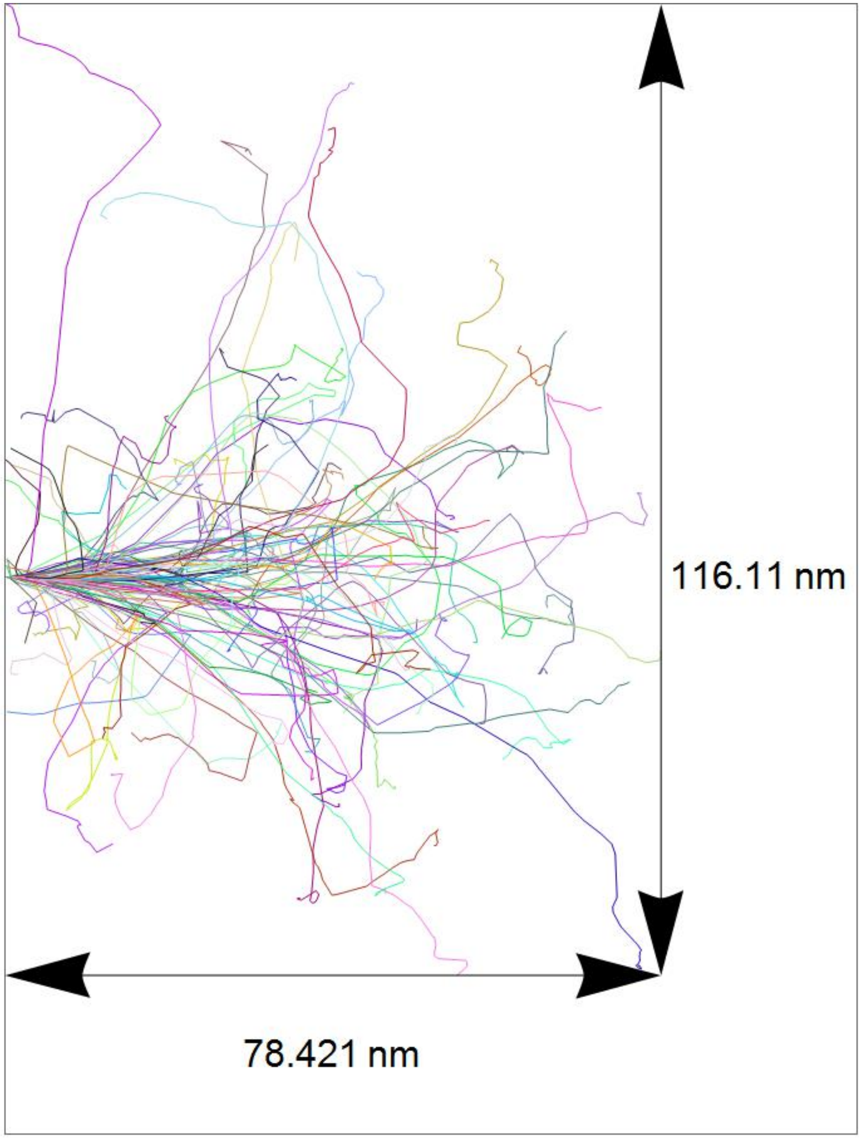


~1 mm

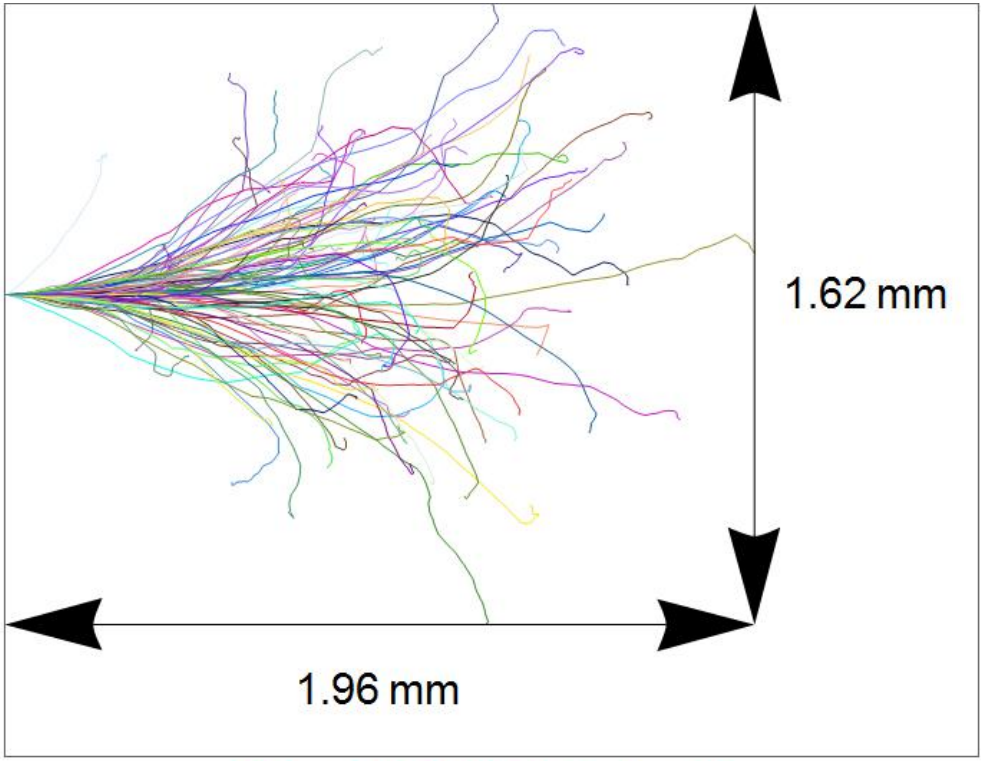
(10^5 times longer !!)

(SRIM simulations)

SRIM simulations…



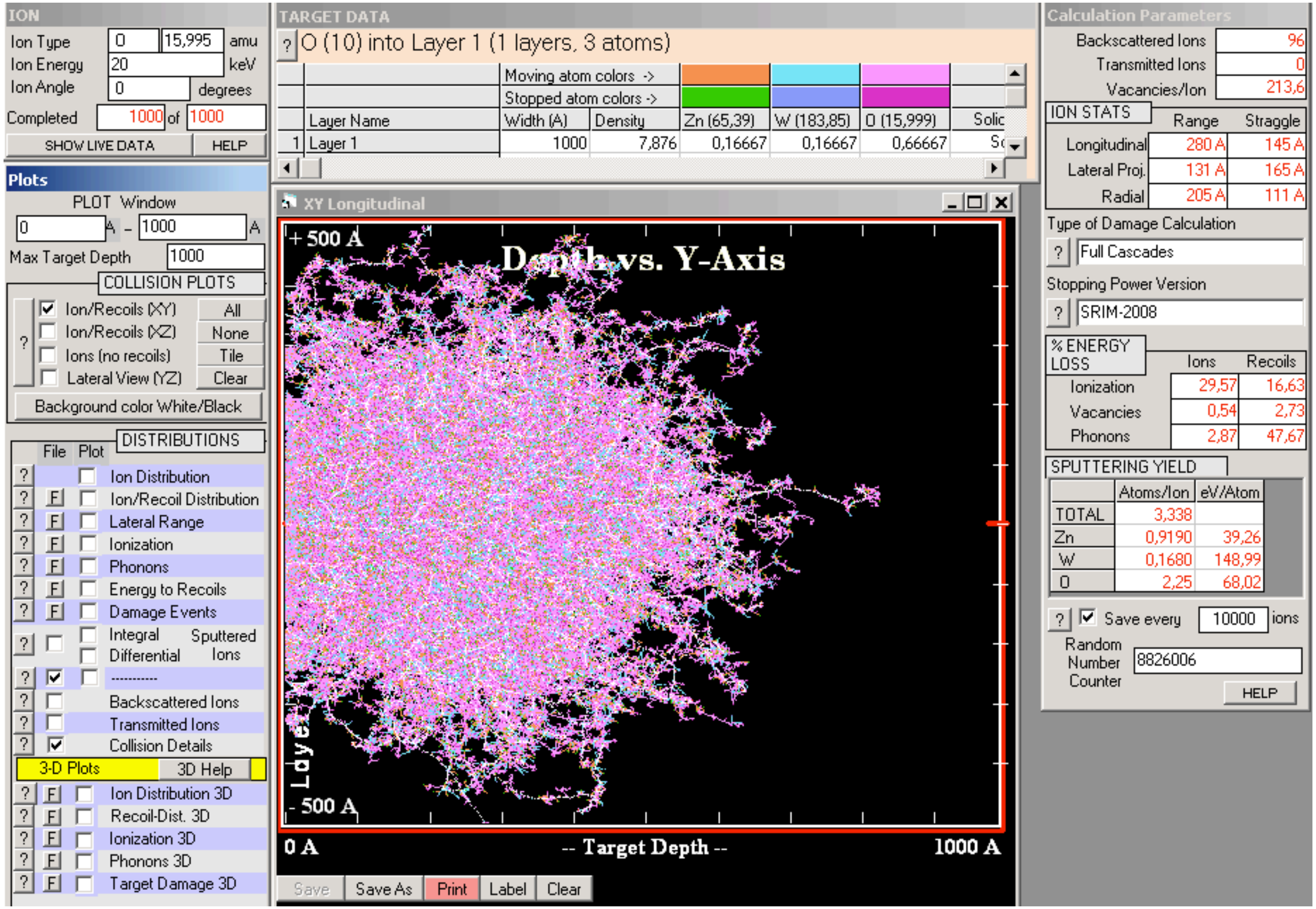
O in Crystal (29keV)



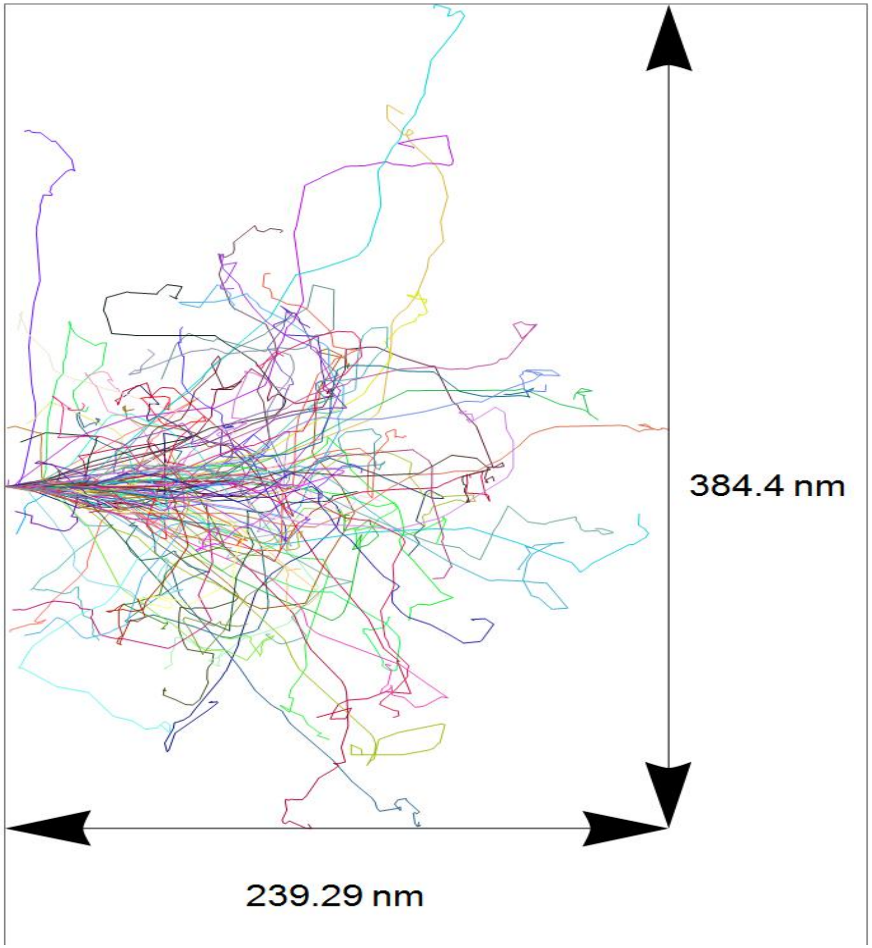
F in MIMAC (34keV)

SRIM simulation of O (20 keV) in ZnO_4W

showing the secondary recoils

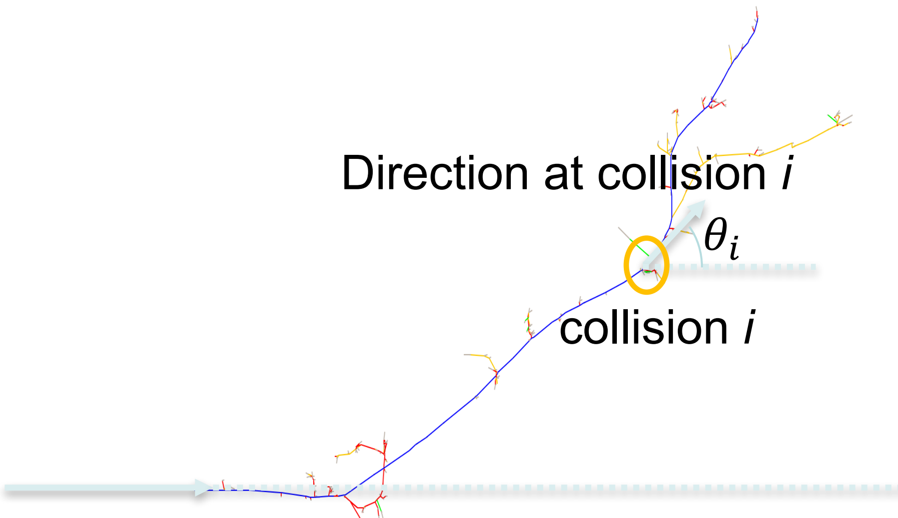


C (22 keV) in emulsion (SRIM simulation)



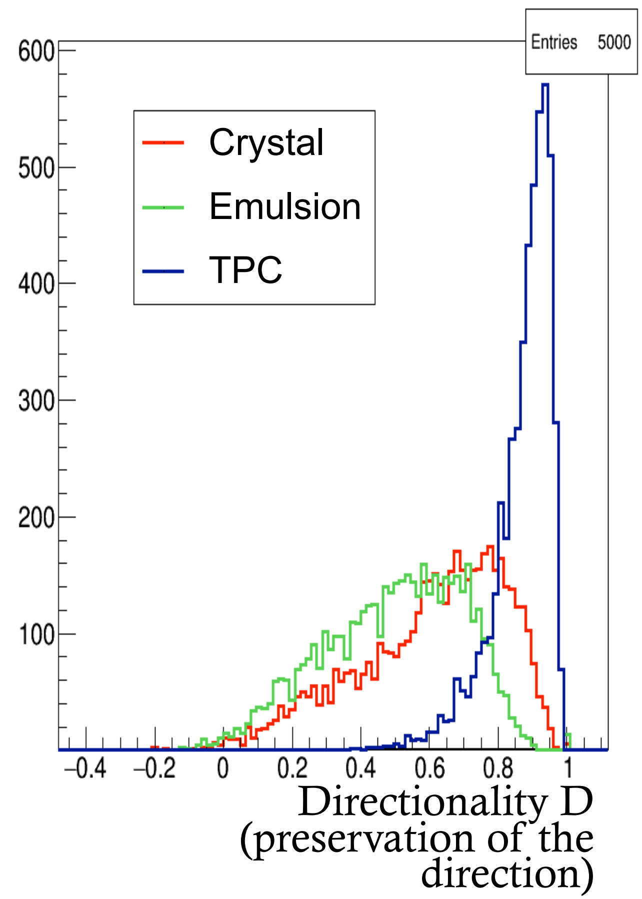
In emulsions and solids the transverse development is in general greater than the longitudinal !!

Directional detection: Directionality 'D'



Initial direction of the recoil

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

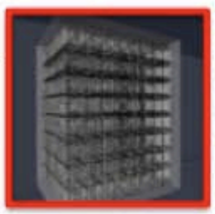


For more information on the comparison:
Couturier et al. (in preparation)

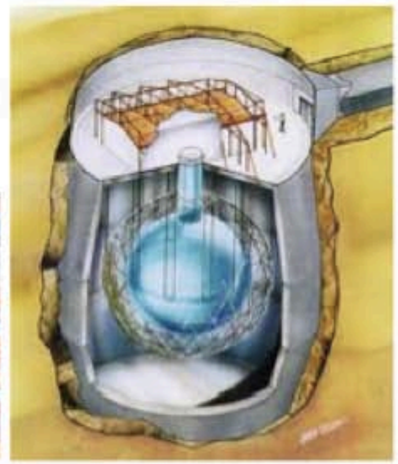
How big is a 1 tonne directional detector?

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]