MIMAC

MIcro-tpc MAtrix of Chambers

A Large TPC for Directional Dark Matter detection

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(UJF Grenoble 1 -CNRS/IN2P3-INPG)

MIMAC (MIcro-tpc MAtrix of Chambers)
(France)

LPSC (Grenoble) : D. Santos, F.Naraghi C.Couturier (post-doc), N. Sauzet

-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 : **Ch. Fourel, J. Giraud**
- COMIMAC (quenching) : **J-F. Muraz**

IRFU (Saclay): P. Colas, E. Ferrer-Ribas, I. Giomataris

CCPM (Marseille): J. Busto, D. Fouchez, C. Tao (Tsinghua (China))

Tsinghua (China): C. Tao, N. Zhou

Neutron facility (AMANDE) :

IRSN (Cadarache): T. Vinchon, B. Tampon (Ph. D.)

Some important and common points concerning Directional Dark Matter and Coherent Neutrino Scattering Detection

Low energy recoils detection requires:

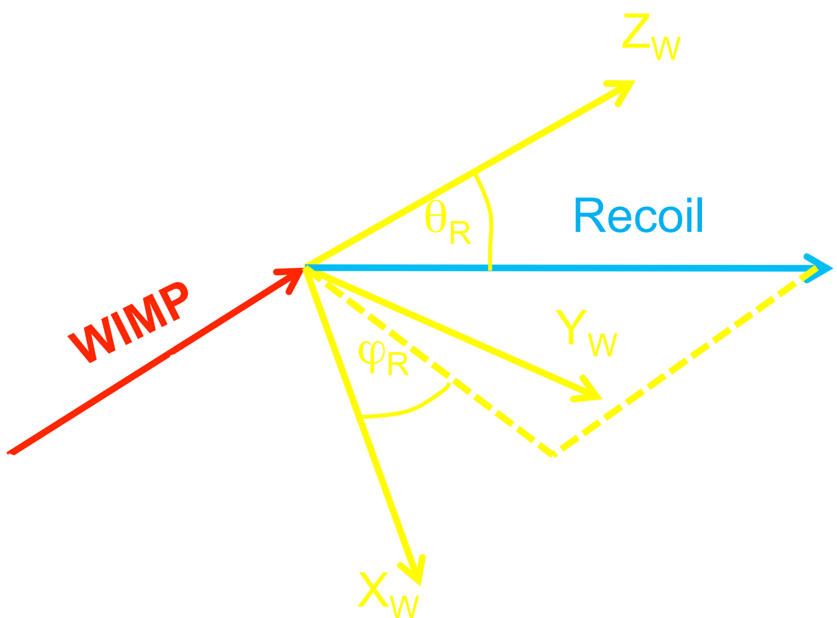
- Low energy thresholds (sub-keV) incompatible with very long strips !!
- Ionization quenching factors very well measured and controlled.
- Excellent (~ 10^5) electron-recoil discrimination.

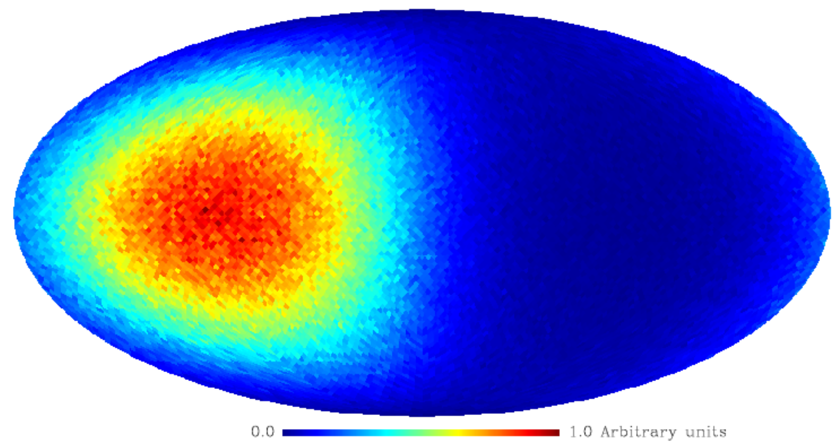
In addition, the directionality requires:

- 3D tracks description (event by event)
- Angular distribution acceptance (there are many angles to detect)
- Good angular resolution

What we can call a High Definition (HD) detector

There are many angles for recoils!!
A lot of information and important events to detect





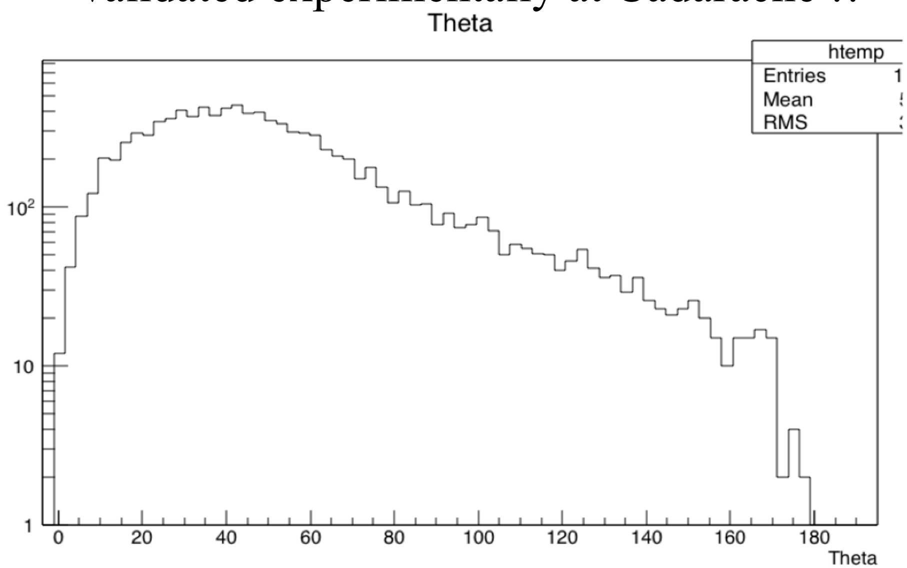
Map of recoils in galactic coordinates (HealPix)

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

There are many angles for recoils!!
A lot of information and important events to detect

^{19}F recoils (E_{kin}= 1-110 keV)
Angular distribution in the laboratory
(with respect to the neutron direction)

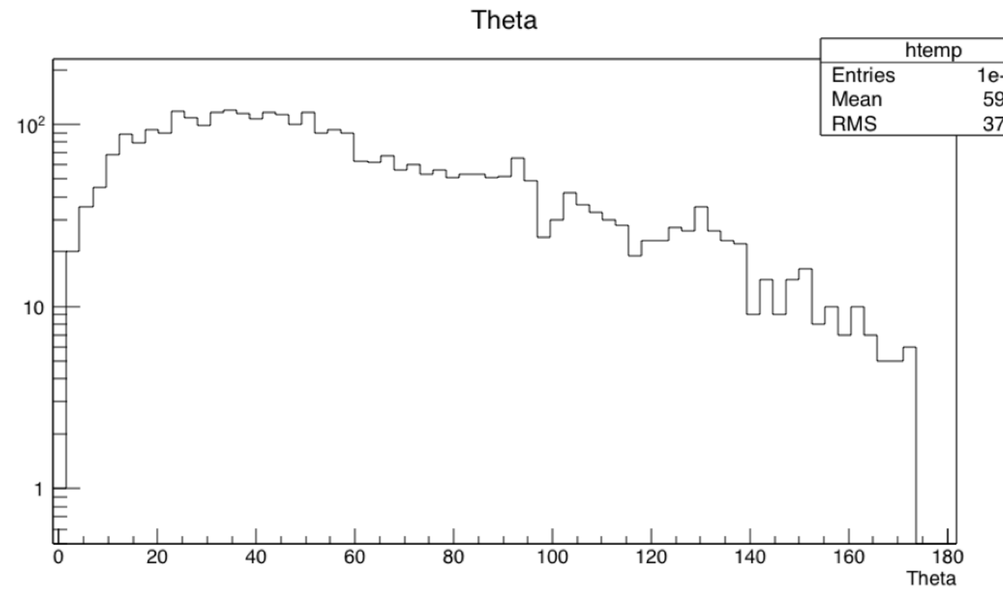
Produced by neutrons of 565 keV
Validated experimentally at Cadarache !!



Geant4 simulations (N. Sauzet, DS. (2016))

^{19}F recoils (E_{kin}= 1- 40 keV)
Angular distribution in the laboratory

Produced by neutrons of 200 keV



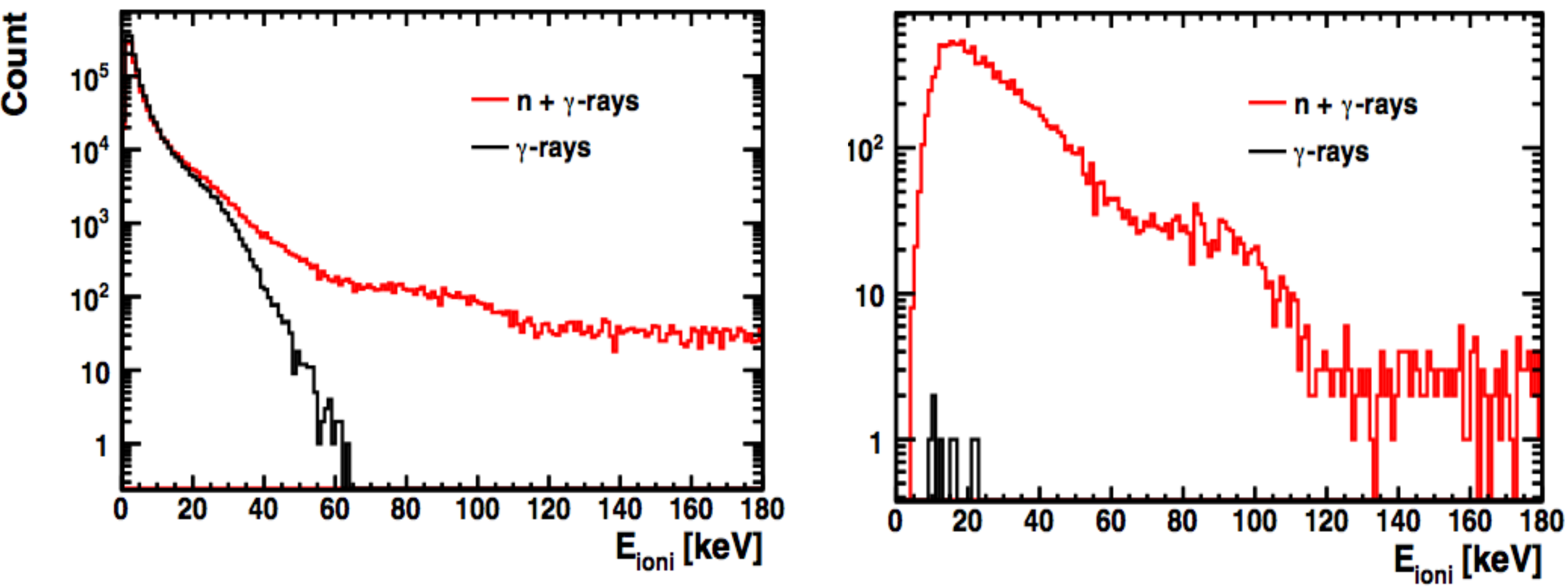
The same kind of distributions for C !!

Electron-recoil Discrimination

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

Neutrons → F , C, H, nuclear recoils

$\gamma - $ rays → Electrons

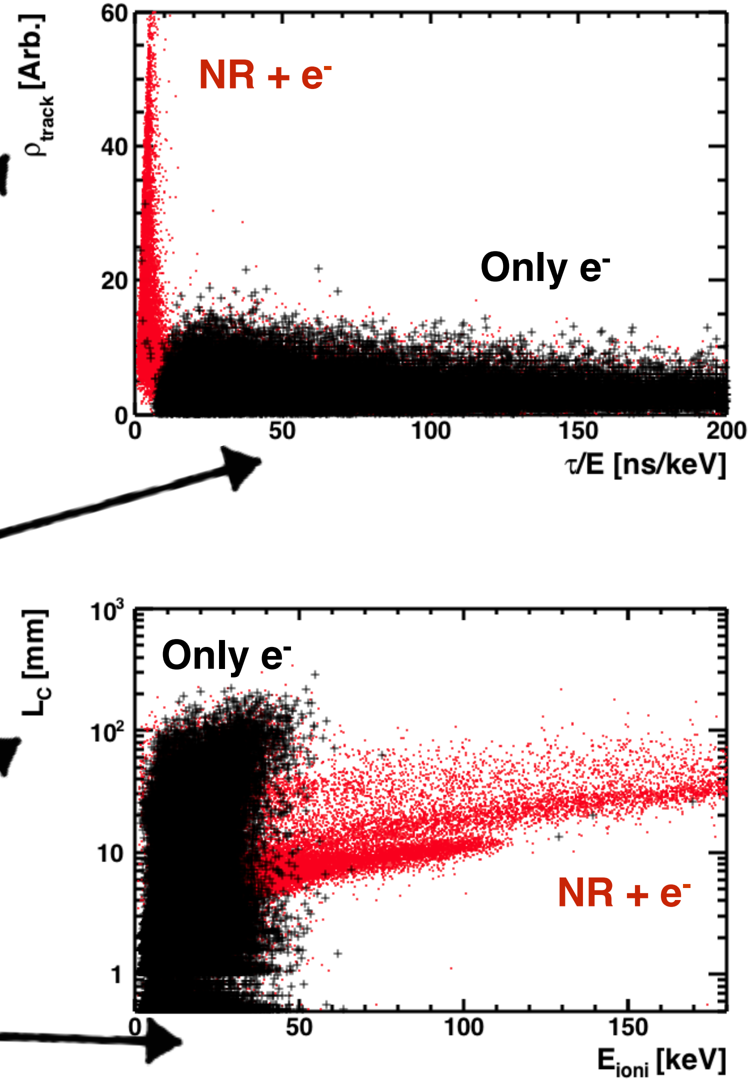


$N_{acpt}/N_{tot} = 1.1 \times 10^{-5}$ electron integrated rejection

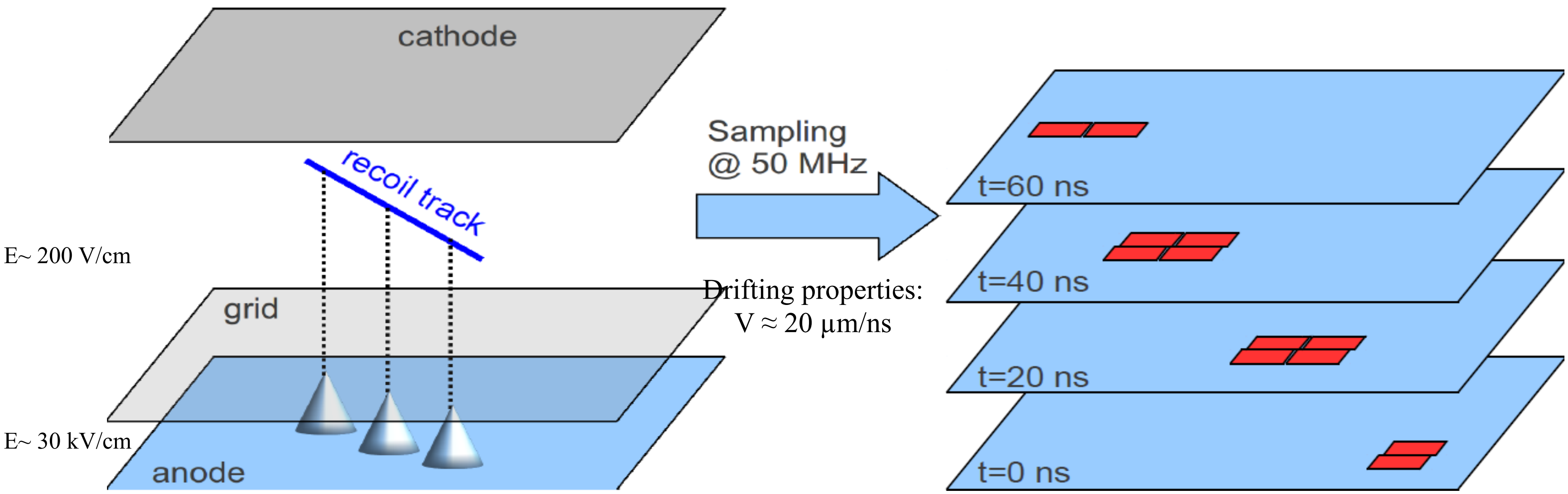
22 observables built using the MIMAC readout…. and more …
(Q. Riffard et al. arXiv: 1602.01738 (2016))

Variable	Type
Minimals	
$S[0]$	Pulse-shape
Track is outside	Track
Clustering	Track
$\Delta X > 1$ or $\Delta Y > 1$	Track
Discriminanting	
N_{Coinc}	Track
$\rho_{track}/\Delta t_{slot}$	Track
N_{Strip}	Track
A_{peak}	Pulse-shape
ρ_{track}	Track
NIS	Track
τ	Pulse-shape
t_{slot}^{start}	Track
Δt_{slot}	Track
$t_{start}^{pulse} - t_{slot}^{start}$	Both
χ^2_{peak}	Pulse-shape
σ_{Long}	Track
μ_{peak}	Pulse-shape
τ/E_{ioni}	Pulse-shape
L_C	Track
$V(\Delta X \Delta Y)$	Track
E_{ioni}	Pulse-shape
$\sigma^{(1)}_{Trans} - \sigma^{(2)}_{Trans}$	Track

With fast neutrons



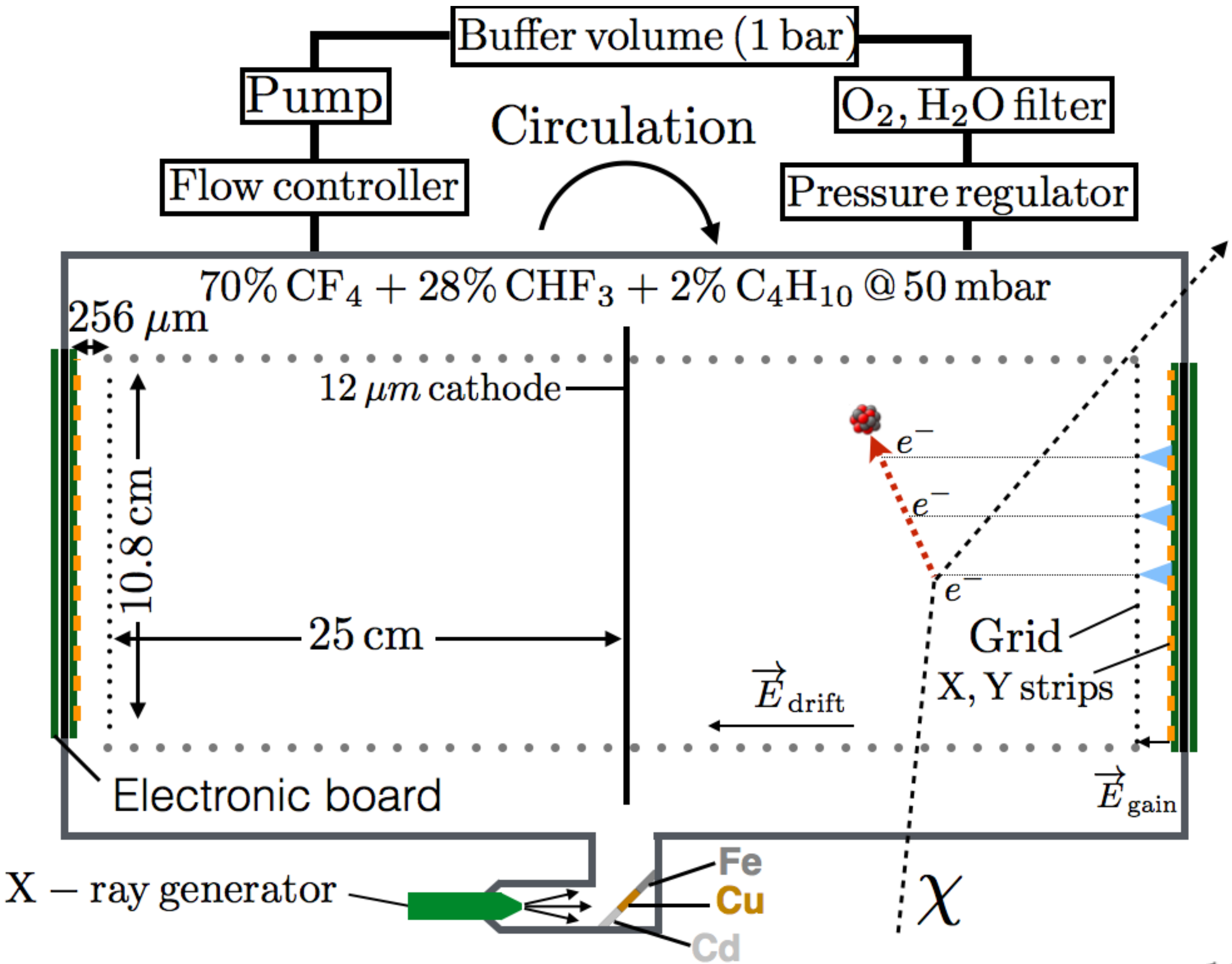
MIMAC: Detection strategy

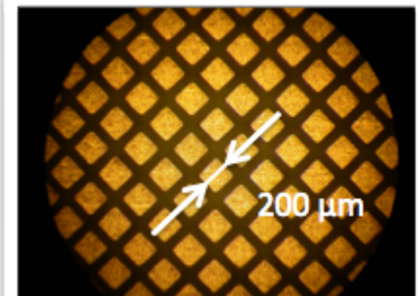


Scheme of a MIMAC µTPC *Evolution of the collected charges on the anode*

Measurement of the ionization energy: Charge integrator connected to the mesh coupled to a FADC sampled at 50 MHz

MIMAC-bi-chamber module prototype



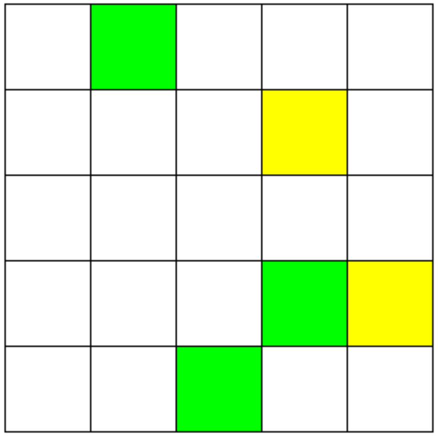


Micromegas 10x10 cm², designed by IRFU- Saclay (France)

MIMAC Target: ^{19}F

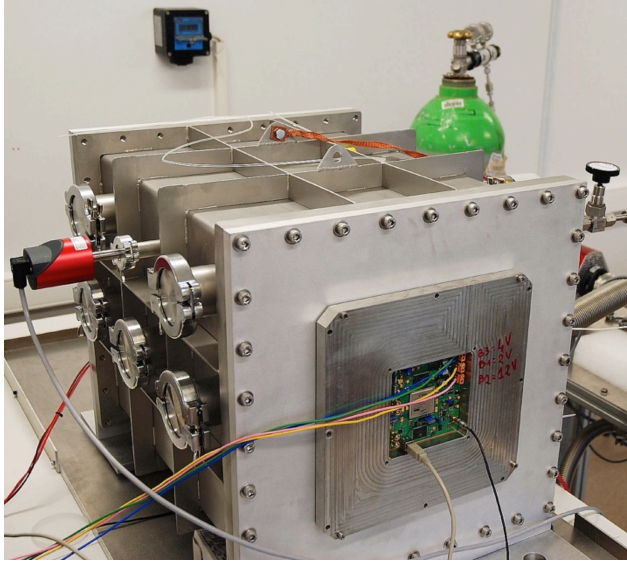
- Light WIMP mass
- Axial coupling

The MIMAC project



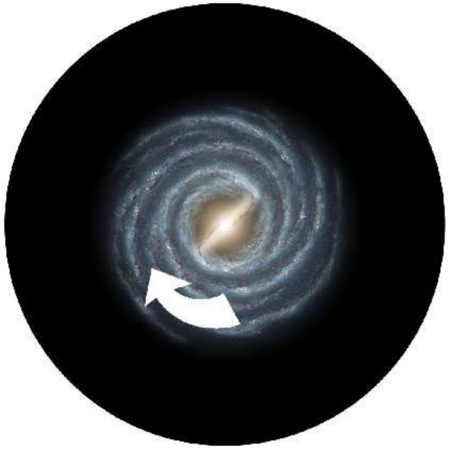
A low pressure multi-chamber detector

- Energy and 3D Track measurements
- Matrix of chambers (correlation)
- μTPC : Micromegas technology
- CF_4, CHF_3, and ^1H : σ(A) dependancy
- Axial and scalar weak interaction
- **Directionnal detector**



Bi-chamber module
2 x (10.8x 10.8x 25 cm³)

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



MIMAC (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

D. Santos (LPSC Grenoble)

Detector calibration (not at the maximum gain!)

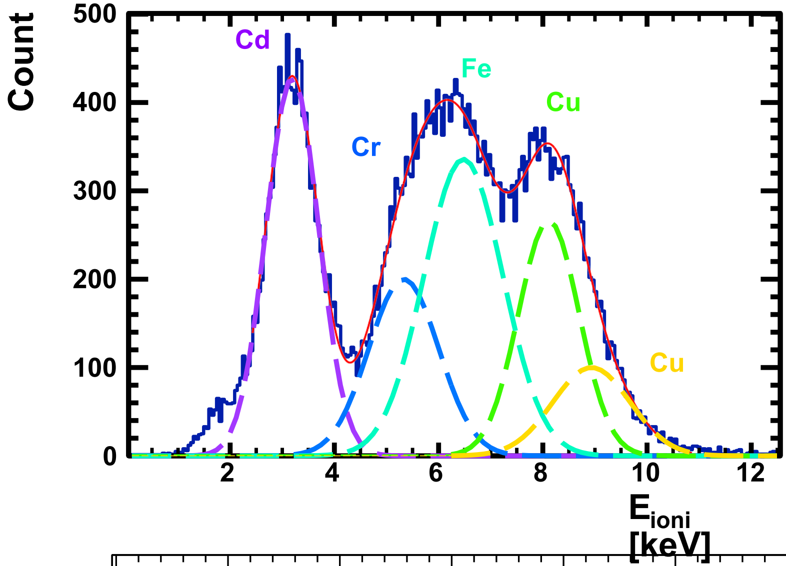
Calibration: (once a week)

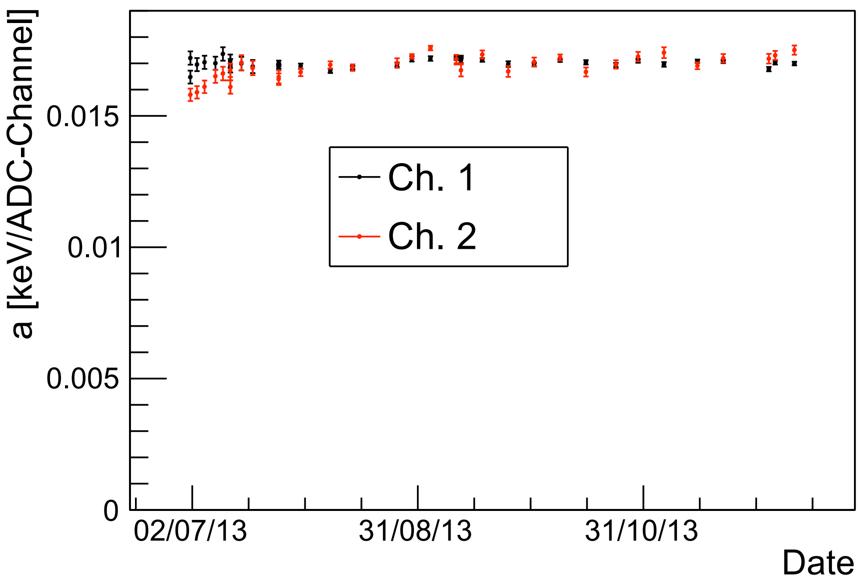
X-ray generator producing fluorescence photons from Cd, Fe, Cu foils.

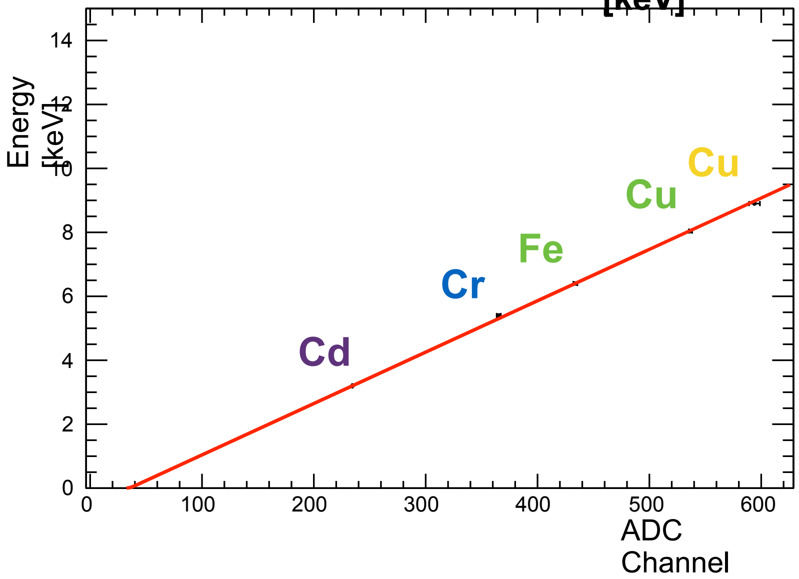
Threshold ~ 1 keV

Circulation system:

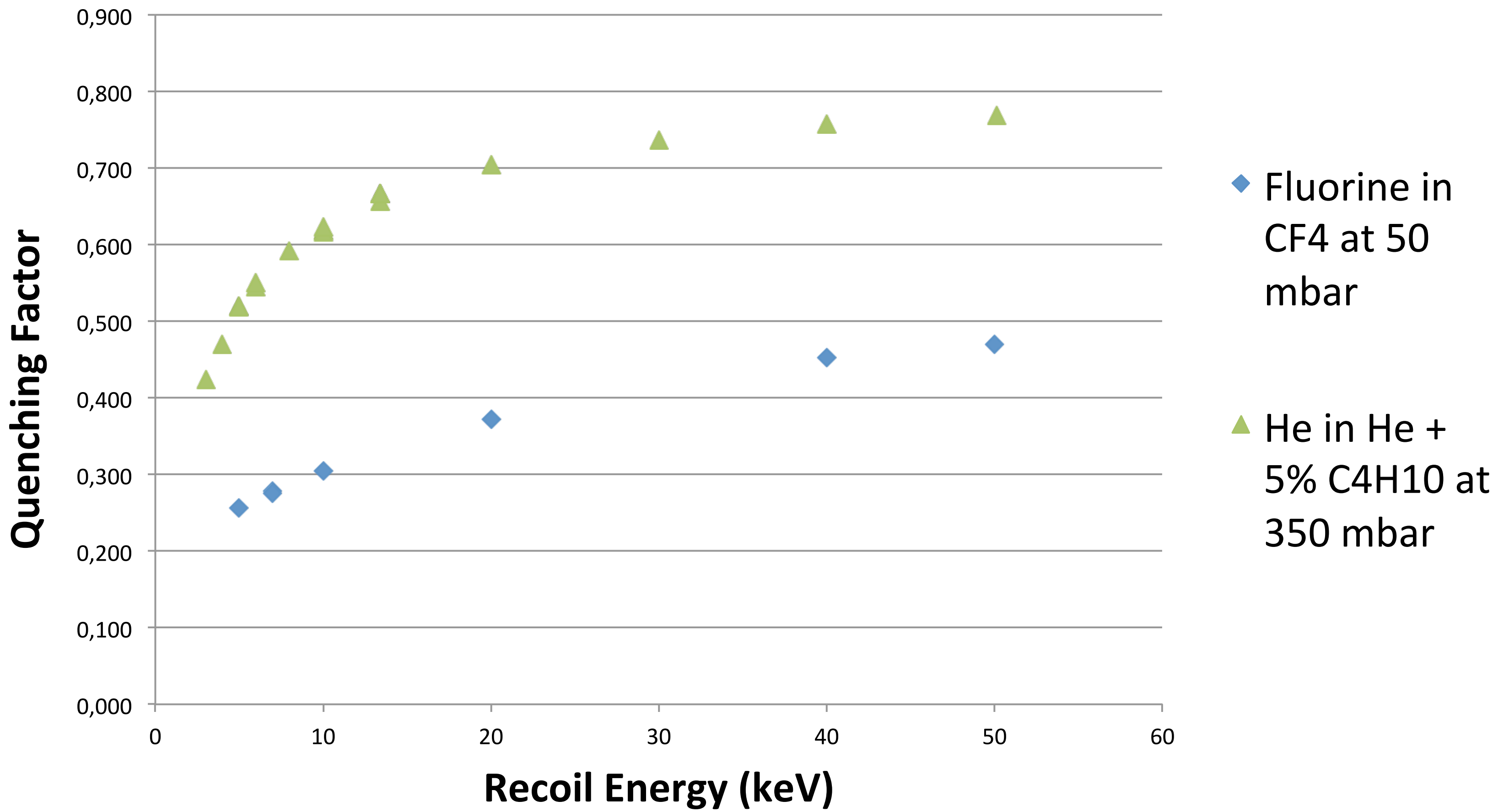
Excelent Gain stability in time





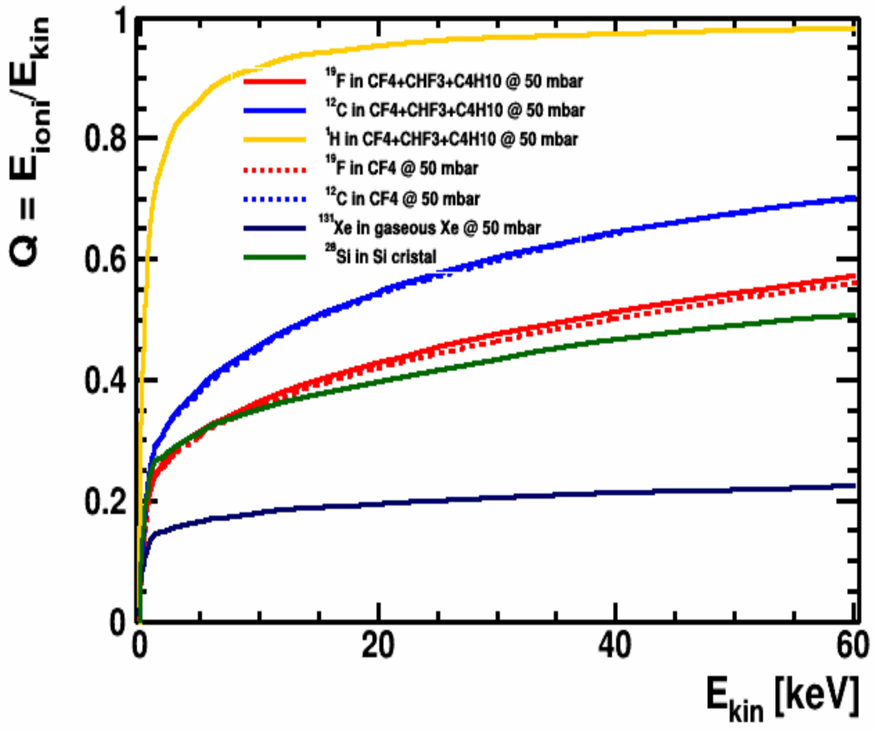


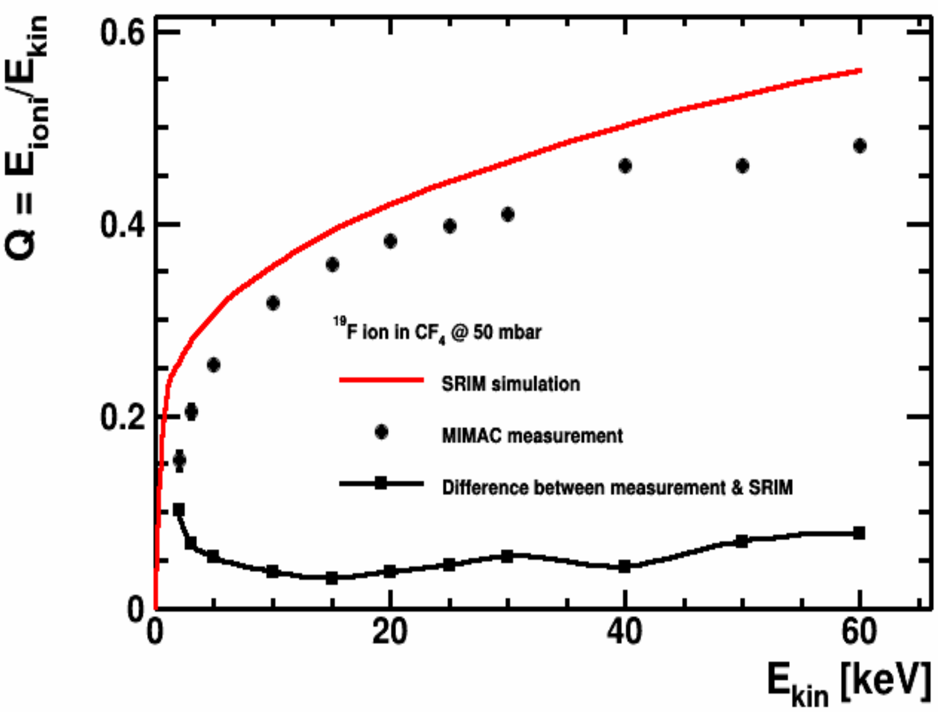
Ionization Quenching Factor for Fluorine in pure CF4 at 50 mbar



Ionization Quenching Factors

Simulations and Measurements (LPSC)

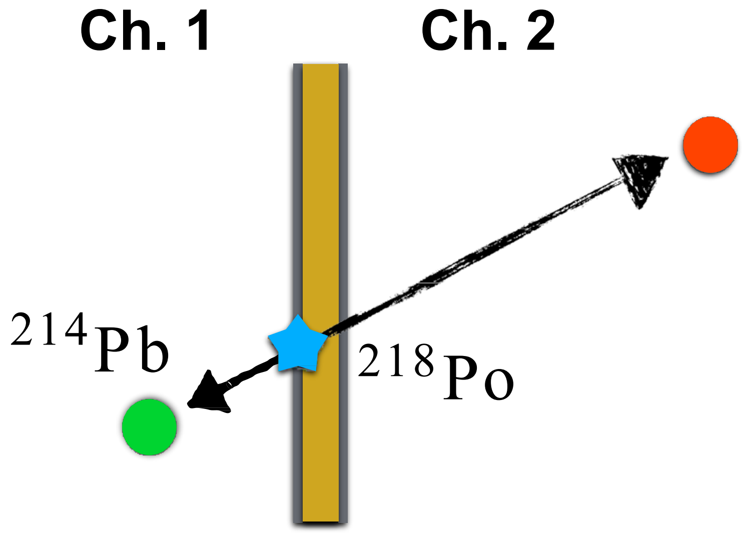




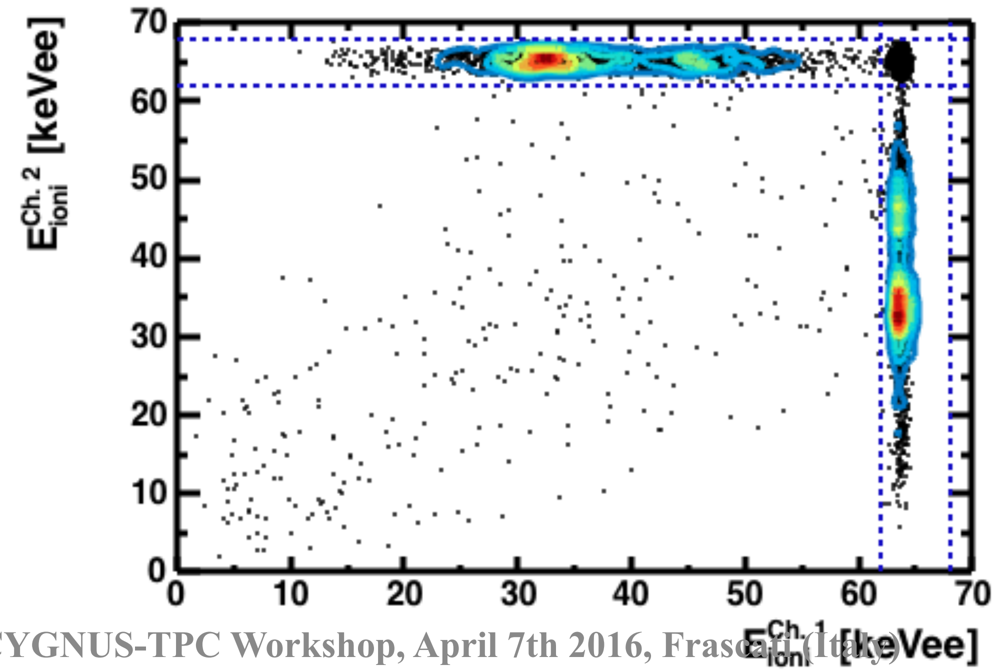
RPR: « In coincidence » events

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)



Chamber coincidences:



3D tracks from nuclear recoil of radon progeny detection

First detection of 3D tracks of Rn progeny

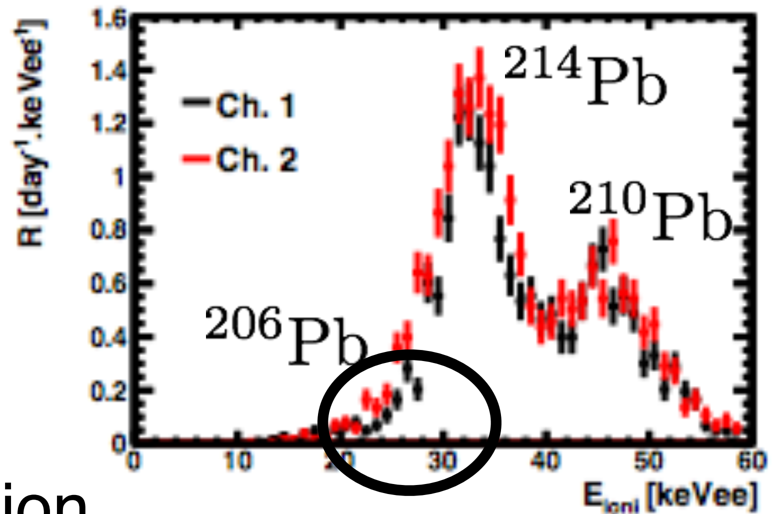
Electron/recoil discrimination

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

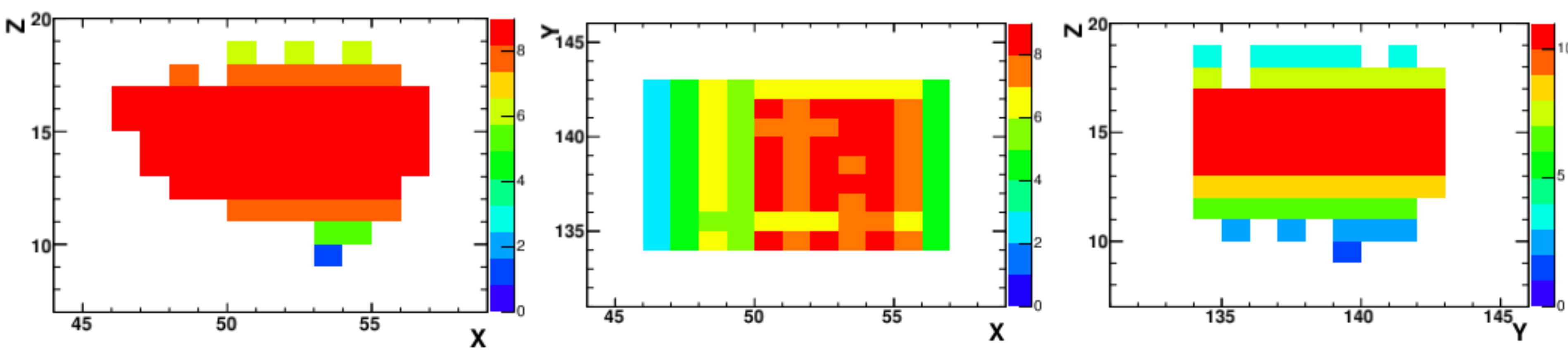
First measurement of 3D nuclear-recoil tracks coming from radon progeny

⟶ MIMAC detection strategy validation

Nuclear recoil spectra



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

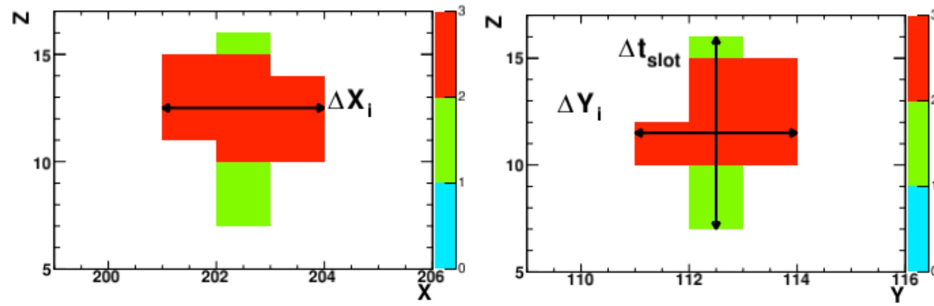


RPR events occur at different positions in the detector…

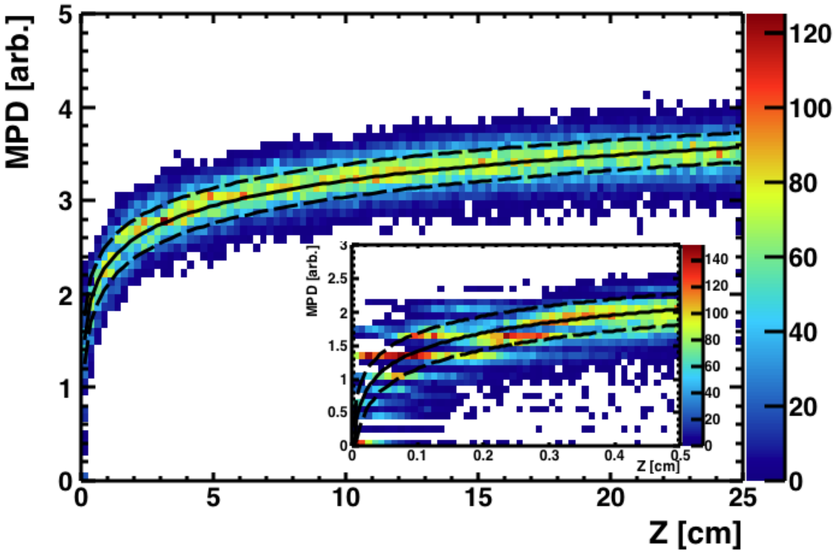
$$z_0 \longleftrightarrow \text{Diffusion}$$

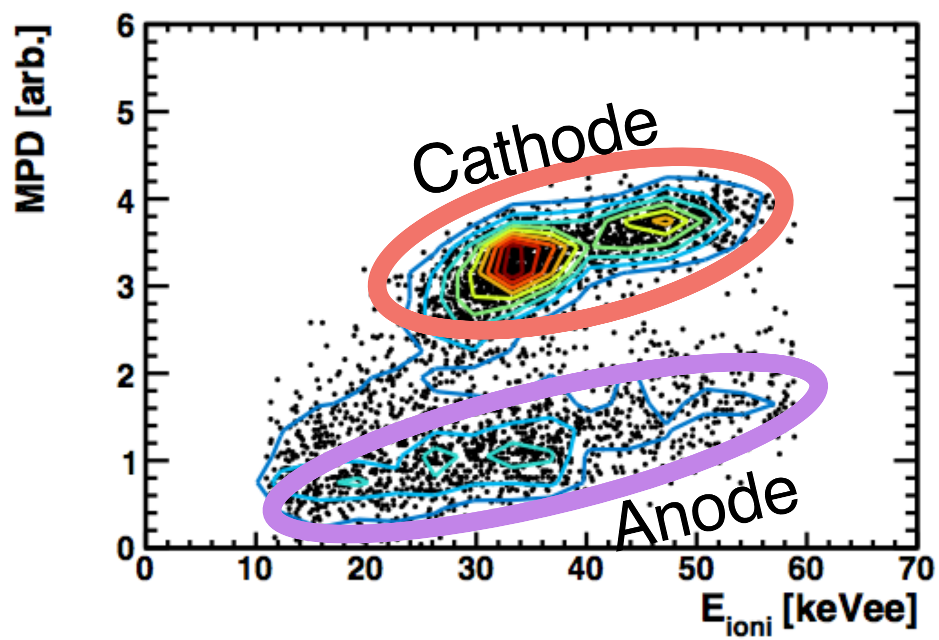
$$\begin{cases} D_T = 237.9\,\mu\text{m}/\sqrt{\text{cm}} \\ D_L = 271.5\,\mu\text{m}/\sqrt{\text{cm}} \end{cases}$$

« Anode » event



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

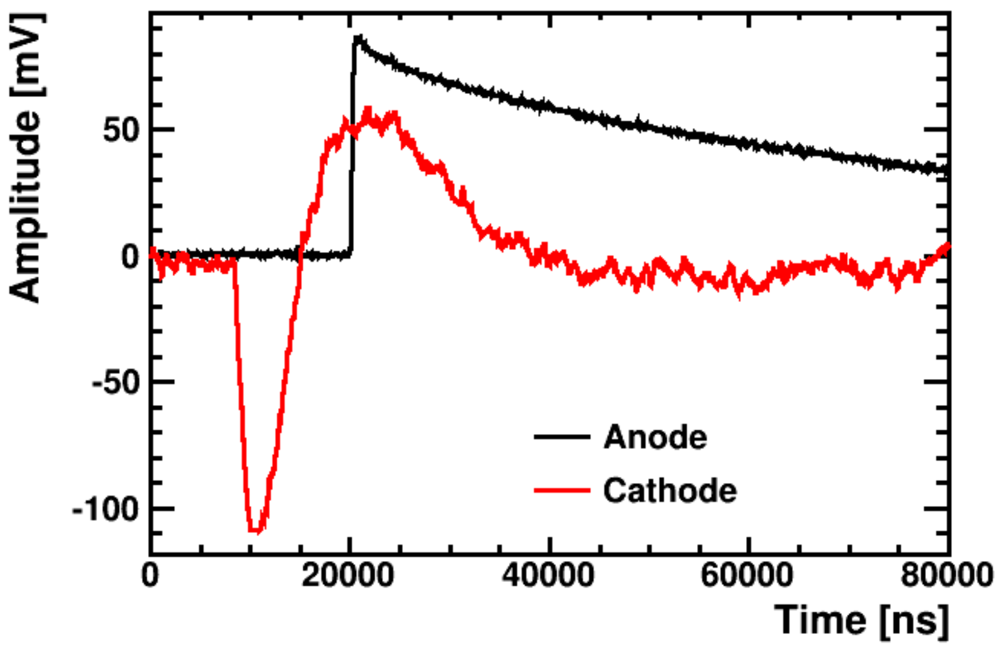




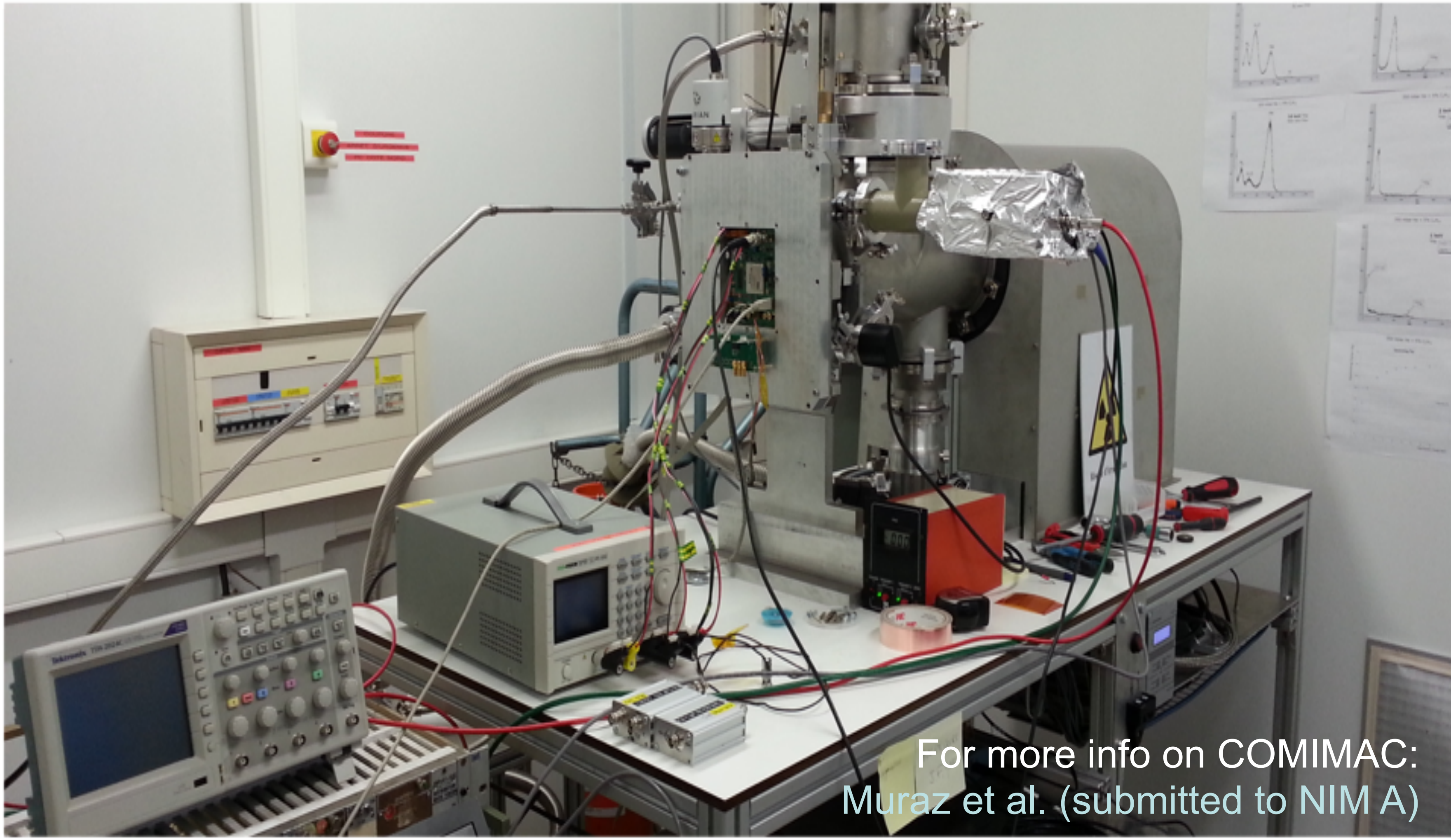
Cathode Signal to place the 3D-track

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

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

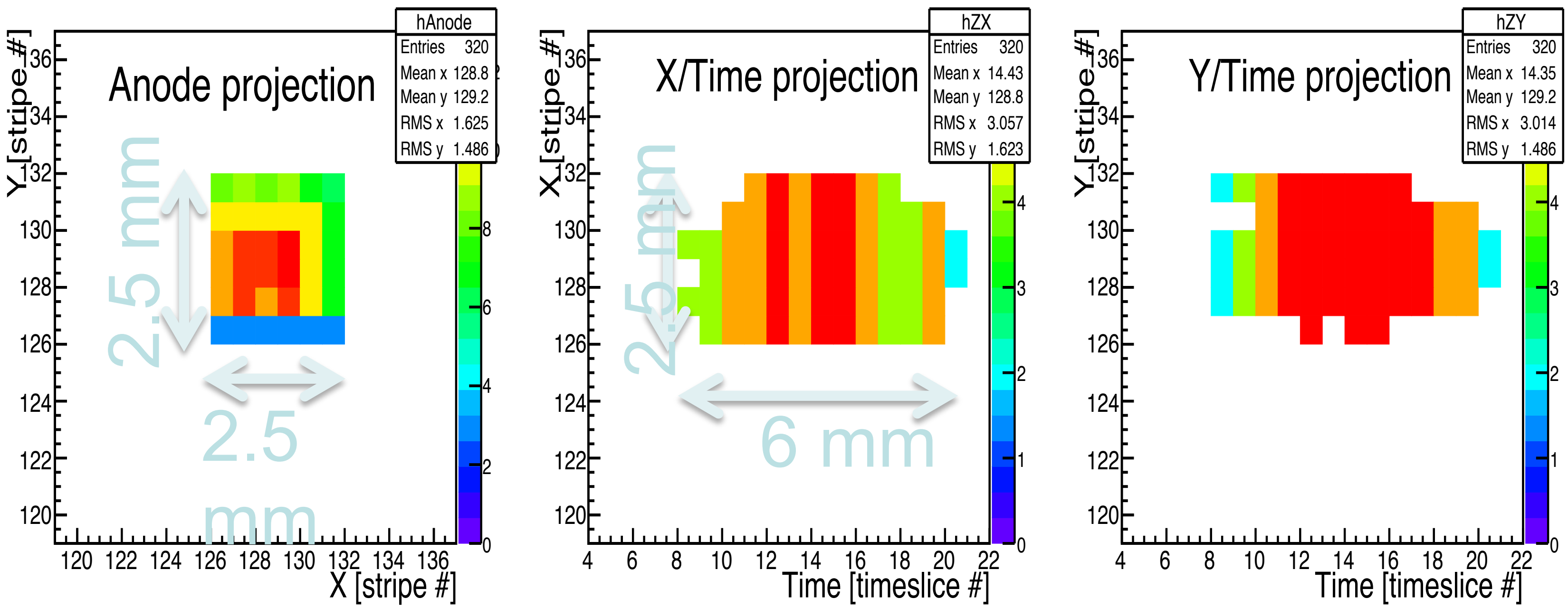


First controlled Fluorine tracks, using COMIMAC



COMIMAC: first measurements on controlled tracks of Fluorine

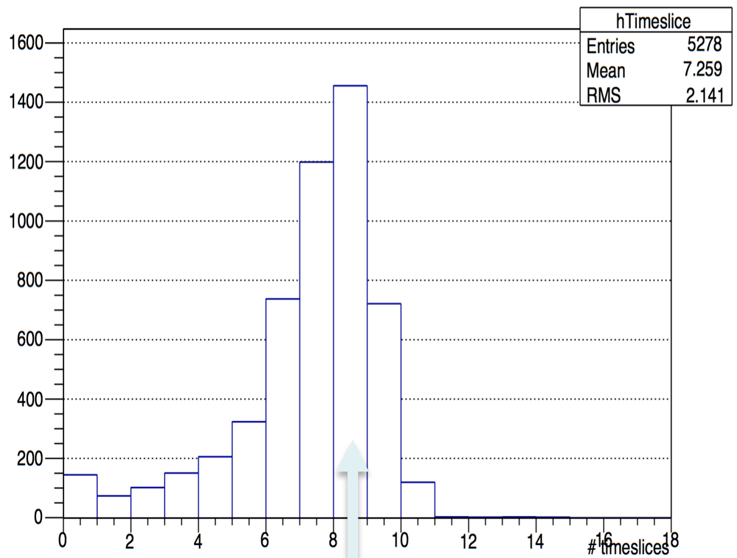
25 keV (kinetic) Fluorine → ~ 9 keVee



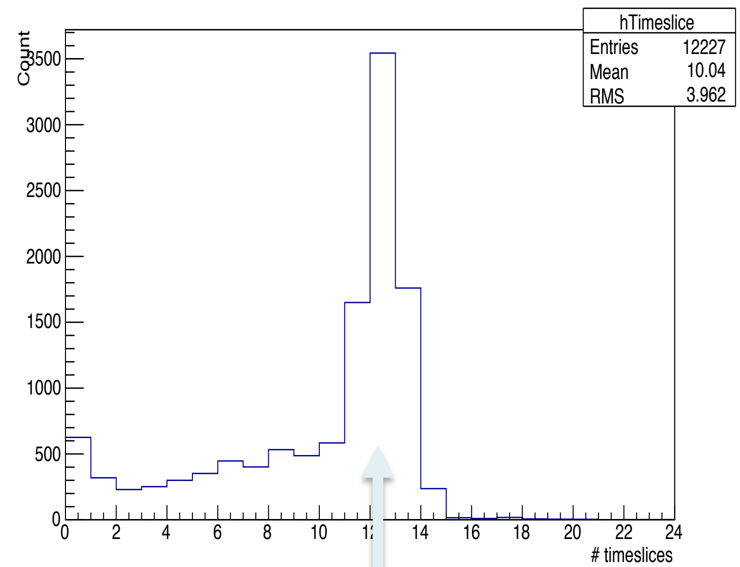
D. Santos (LPSC Grenoble)

COMIMAC: first controlled tracks of ^{19}F

8 keV kinetic → 2 keVee



25 keV kinetic → 9 keVee



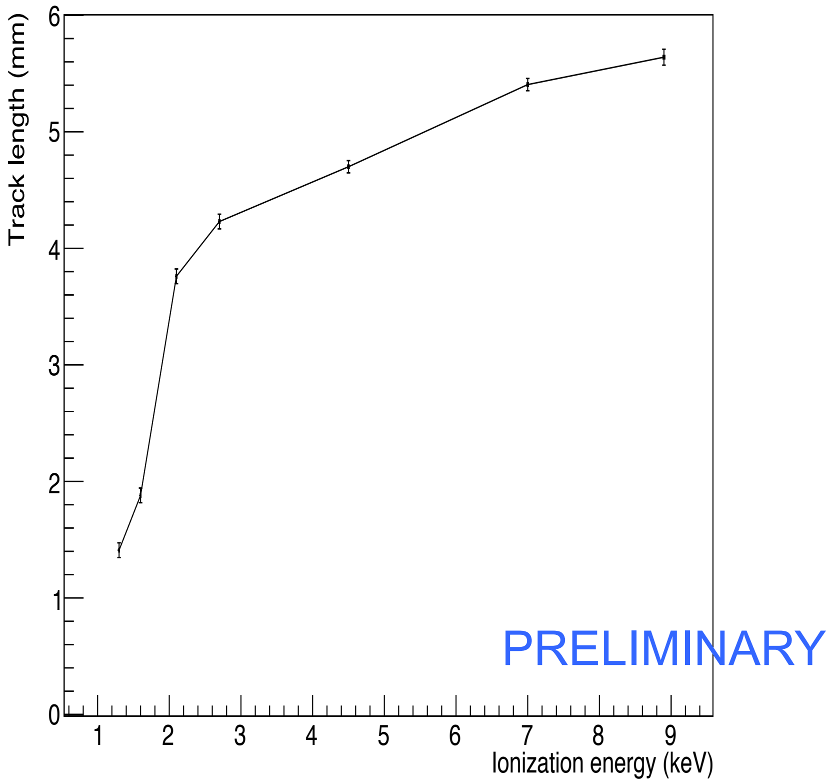
8 timeslices
* 20 ns/timeslices
* 23.5 µm/ns
= 3.8 mm

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

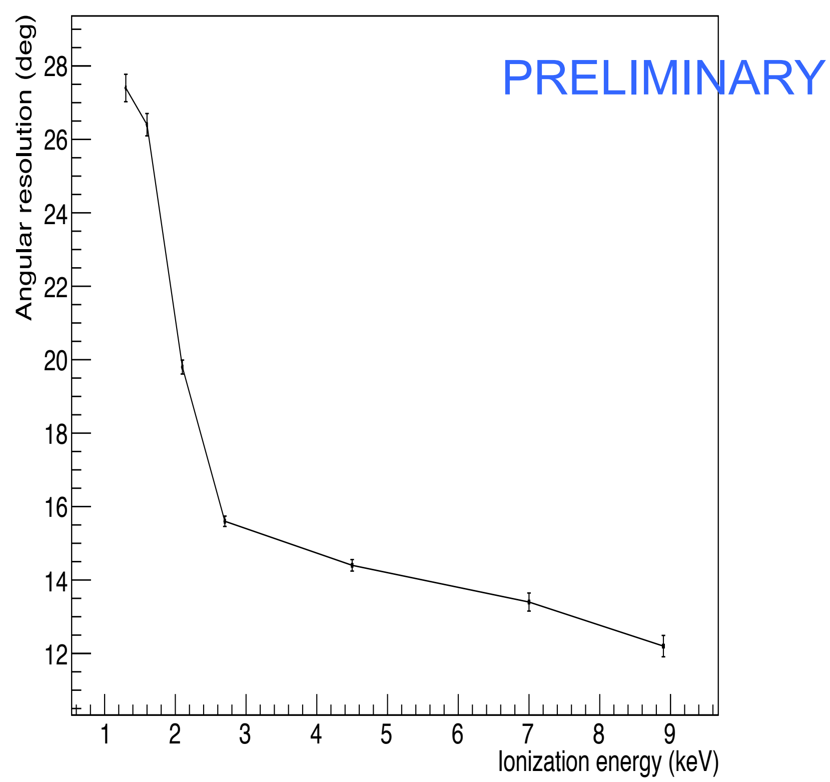
Couturier et al. (in preparation)

COMIMAC: first measurements on controlled tracks of Fluorine

- Track



- Angular resolution

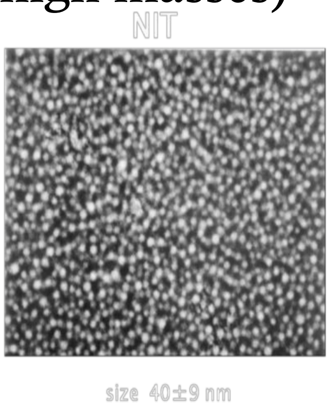


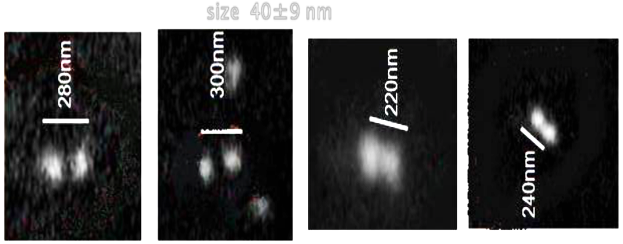
Couturier et al. (in preparation)

Directional detection: comparison of strategies

- Emulsion layers

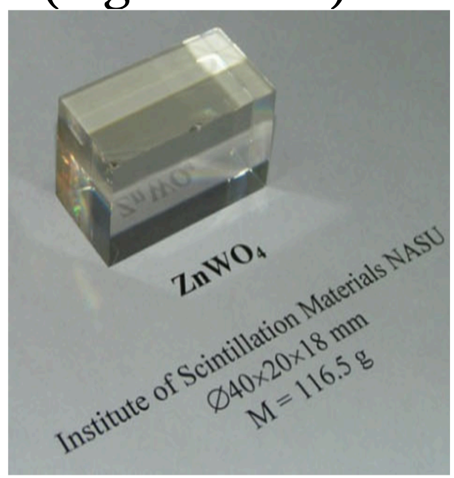
  target = C (low masses), Ar, Br, Kr (high masses)





- Anisotropic crystals

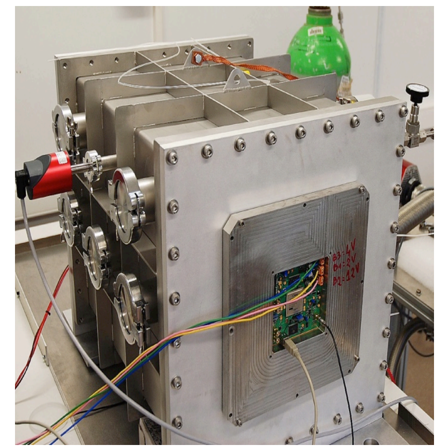
  target = O (low masses), Zn, W (high masses)

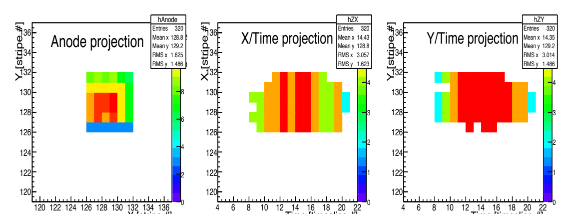


No tracks ; only statistical distributions (!)

- Low pressure TPCs

  target = F



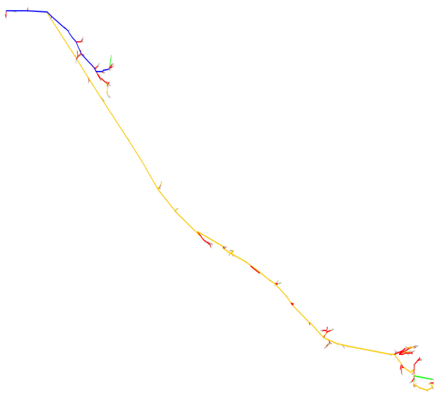


D'Ambrosio et al. 2014

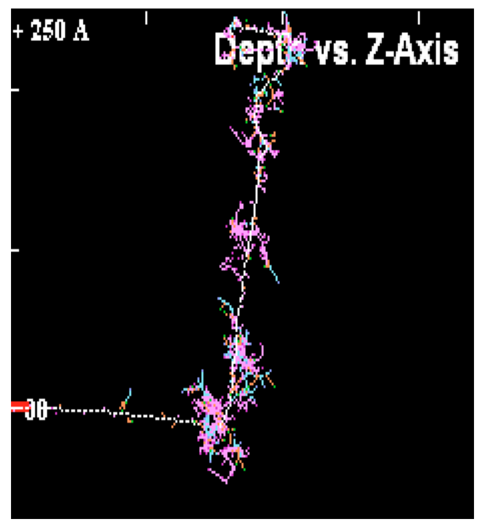
Capella et al. 2013

Directional detection: comparison of strategies

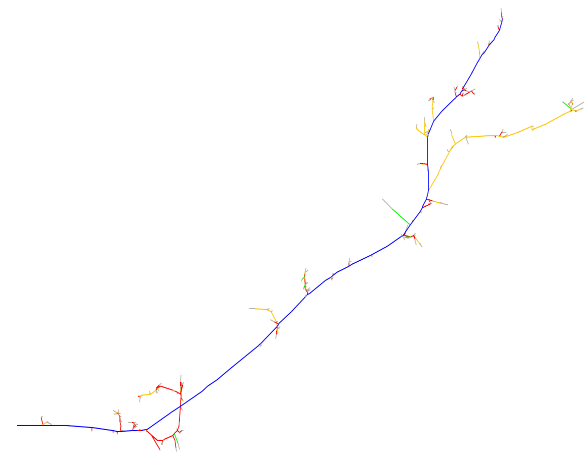
- Emulsion
- Anisotropic crystals
- Low pressure TPCs



~100 nm



~10 nm

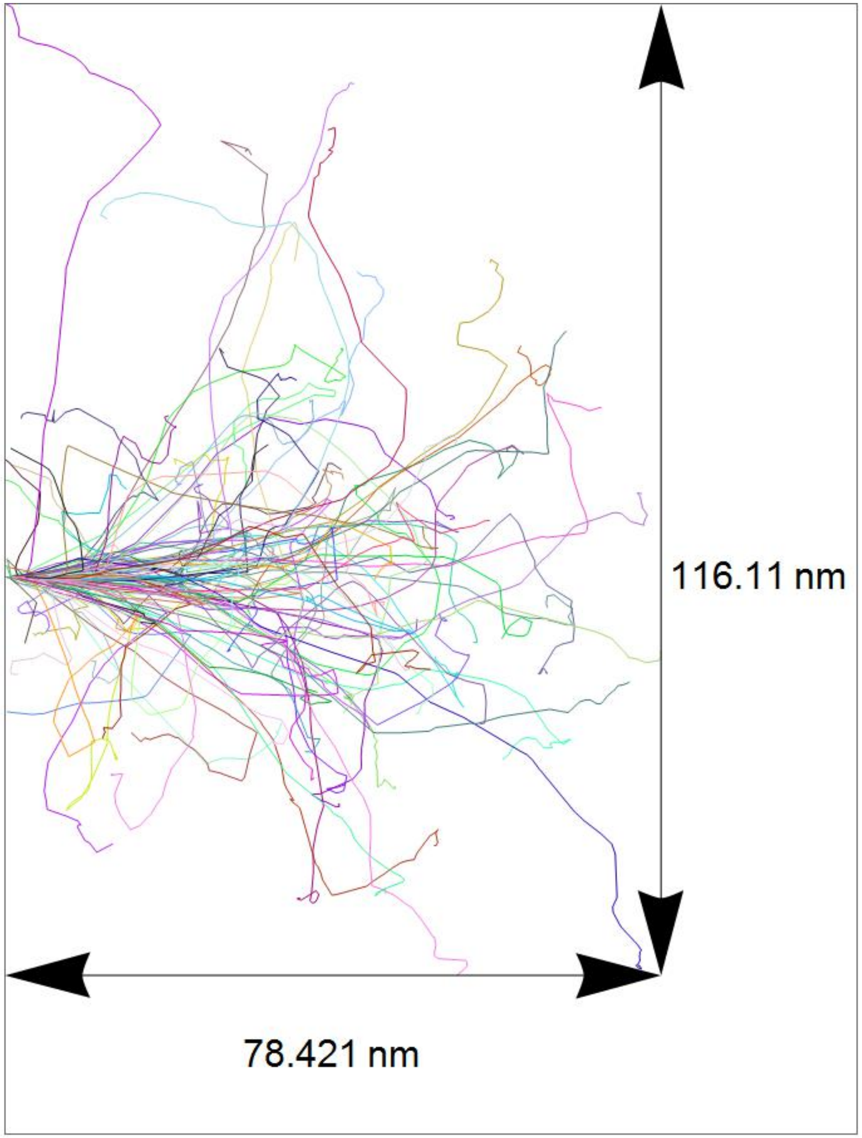


~1 mm

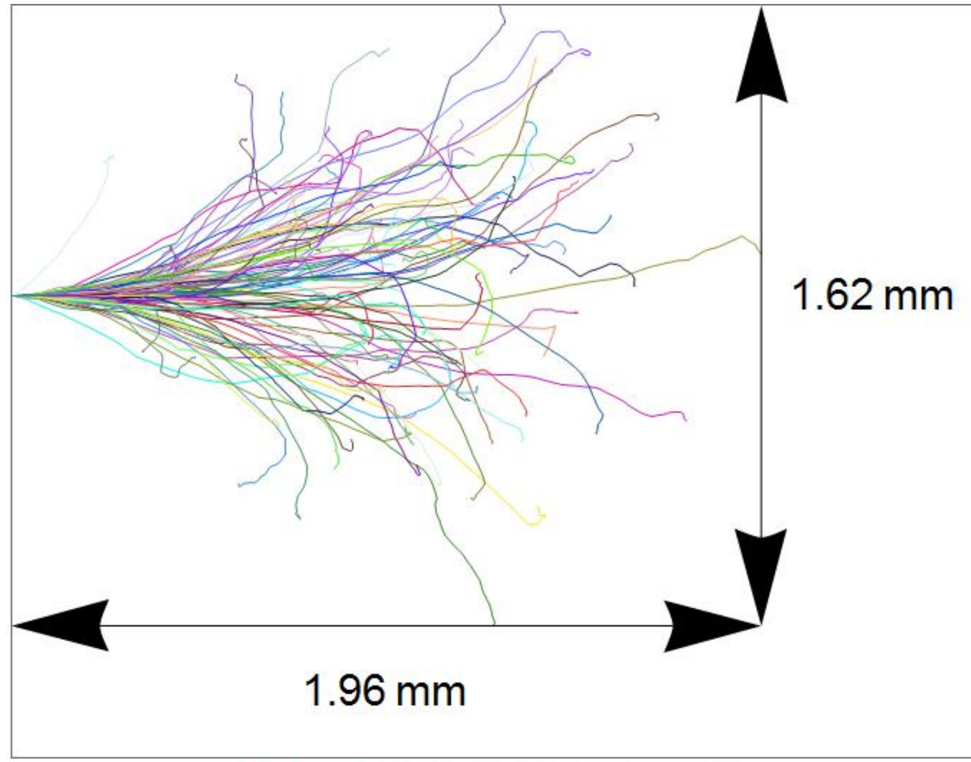
(10^4 - 10^5 times longuer !!)

(SRIM simulations)

SRIM simulations…

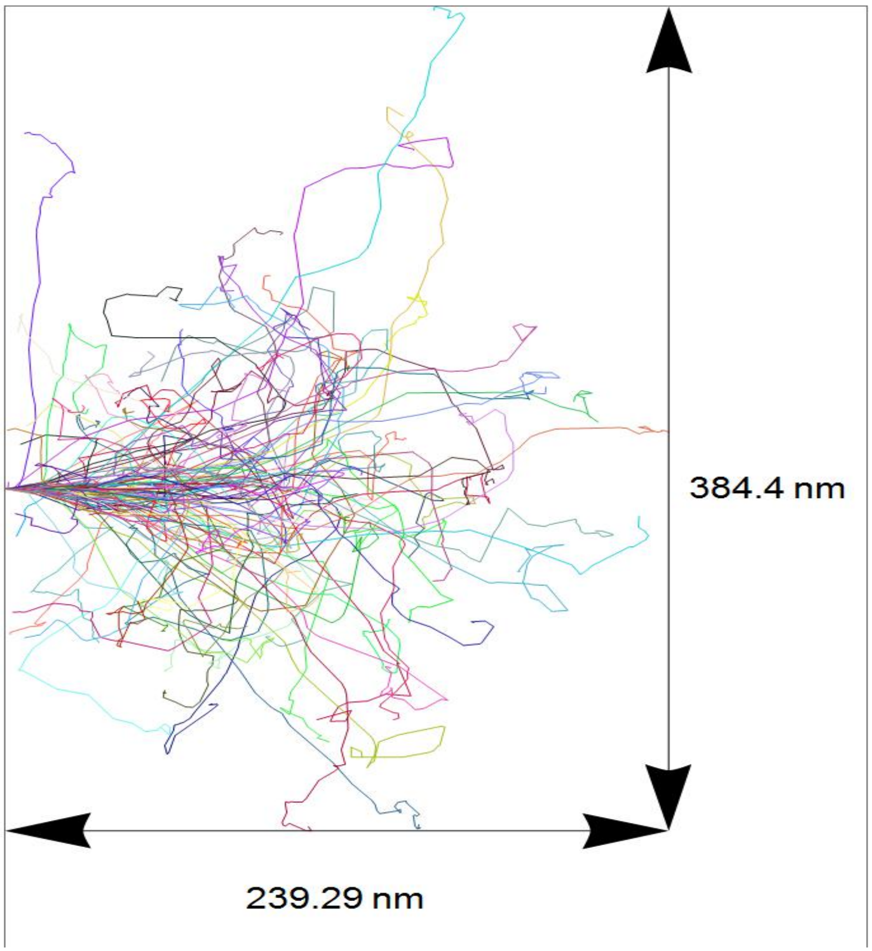


O in Crystal (29keV)



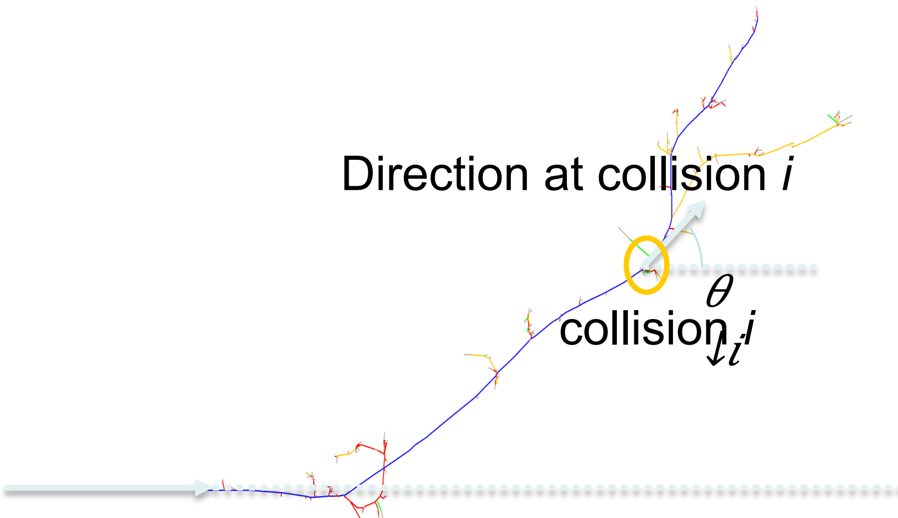
F in MIMAC (34keV)

C (22 keV) in emulsion (SRIM simulation)



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

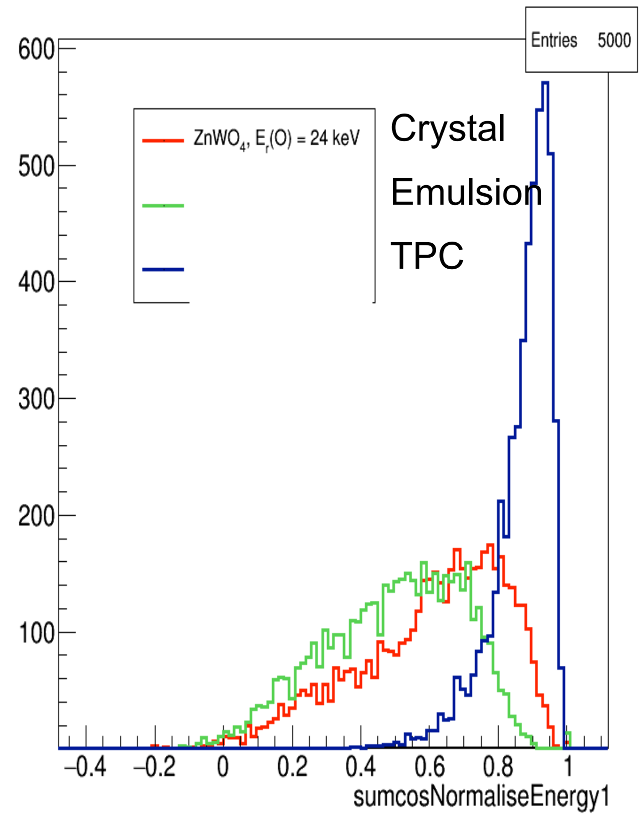
Directional detection:
Directionality observable: ‘D’



Initial direction of the recoil

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

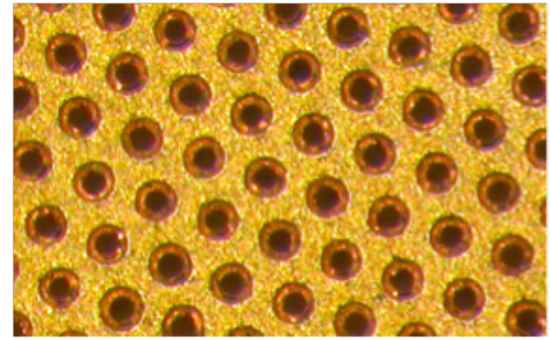
For more information on the comparison:
Couturier et al. (in preparation)

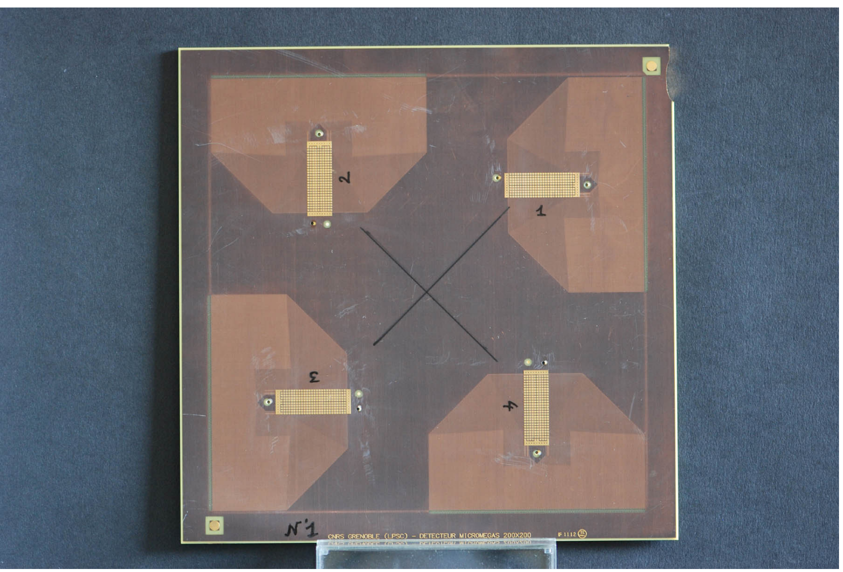


Directionality D (preservation of the direction)

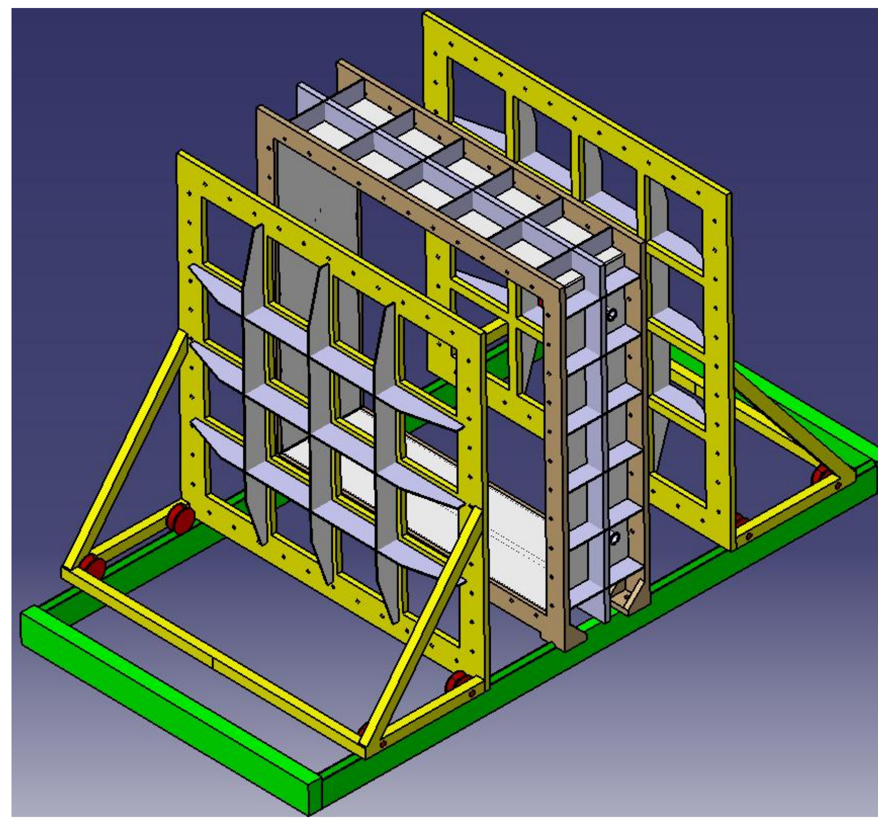
MIMAC – $1m^3$ = 16 bi-chamber modules (2x 35x35x26 cm^3)

i) New technology anode 35cmx35cm (resistive uM adaptation)
ii) Stretched thin grid at 500um.
iii) New electronic board (640 channels)
iv) Only one big chamber





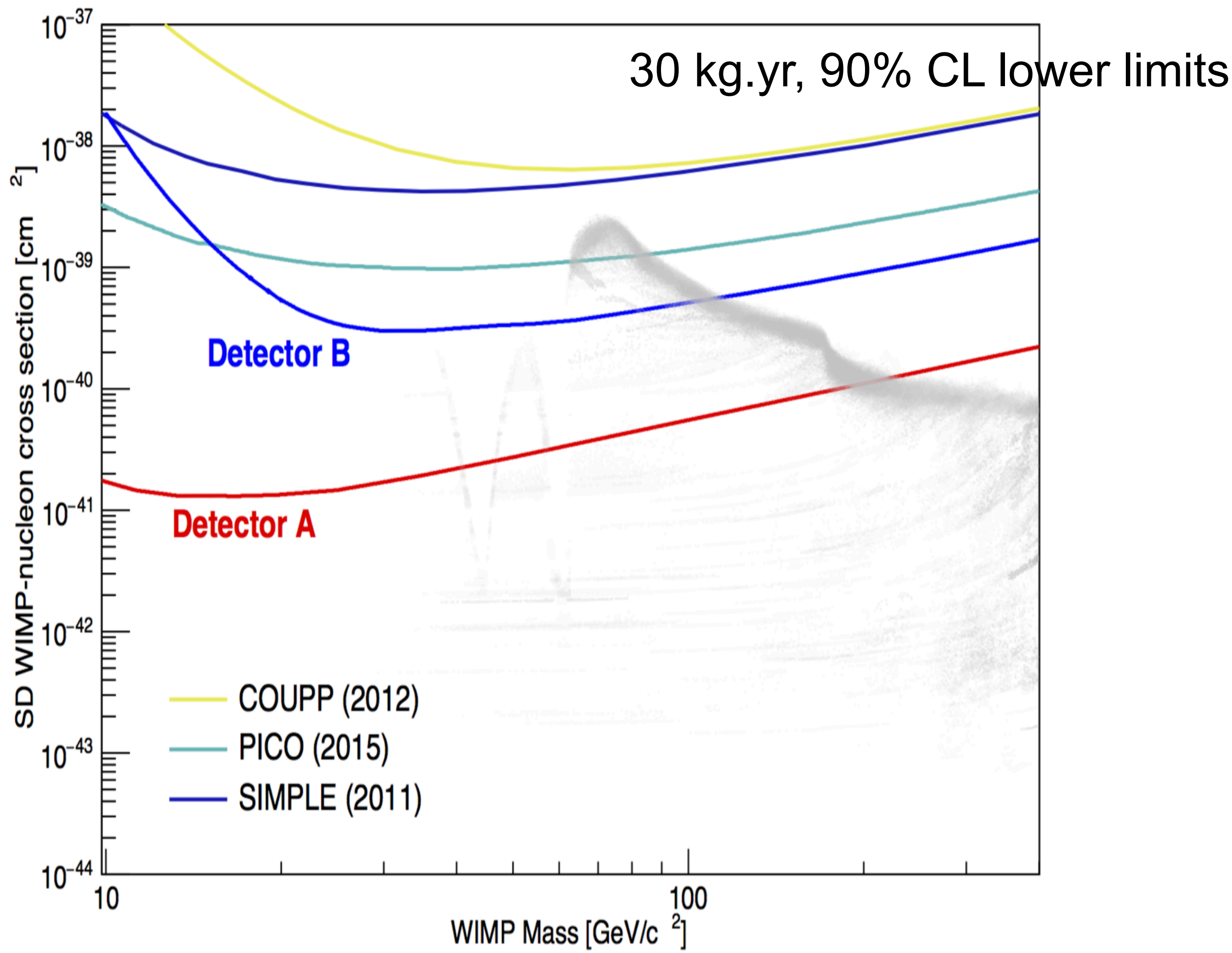
New 20cmx20cm pixellized anode (1024 channels)



Conclusions

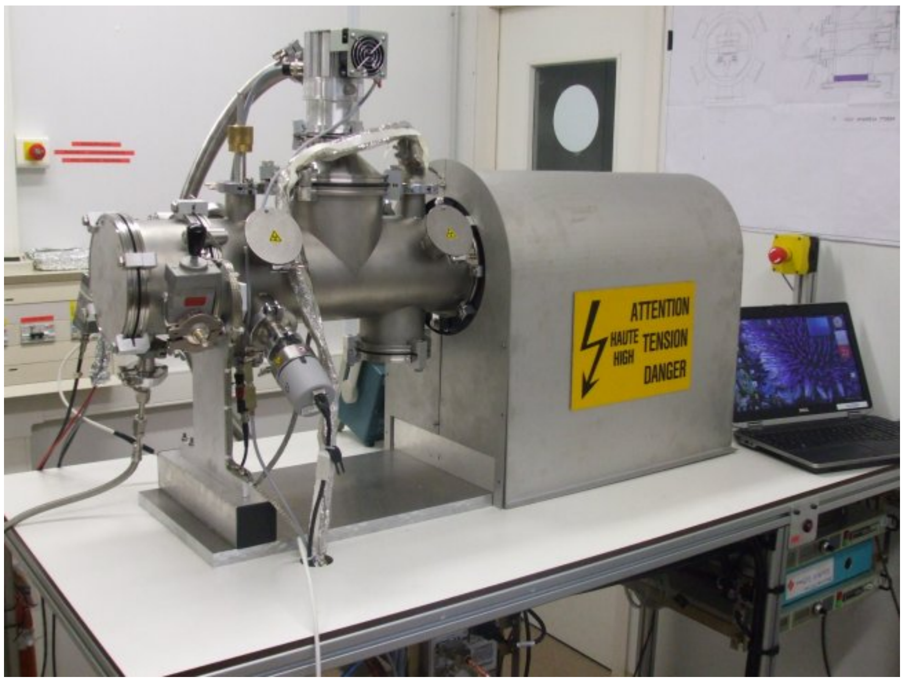
i) A new directional detector of nuclear recoils at low energies has been developed giving a lot of flexibility on targets, pressure, energy range…
ii) Ionization quenching factor measurements have been determined experimentally and they can be checked in-situ.
iii) For the first time the 3D nuclear recoil tracks from Rn progeny have been observed.
vi) New degrees of freedom are available to discriminate electrons from nuclear recoils to improve the DM search for.
vii) Angular resolution and directional studies of 3D tracks are now possible.
vii) The 1 m^3 will be the validation of a new generation (High Definition) of a large DM detector including directionality (a needed signature for neutron discrimation and Halo Galactique correlation)
viii) Before to build large we must show that we have the HD at 1 m^3 scale.
ix) We have to compare the different HD prototypes (not only designs) and make a common decision (all together) about the HD detector to build.

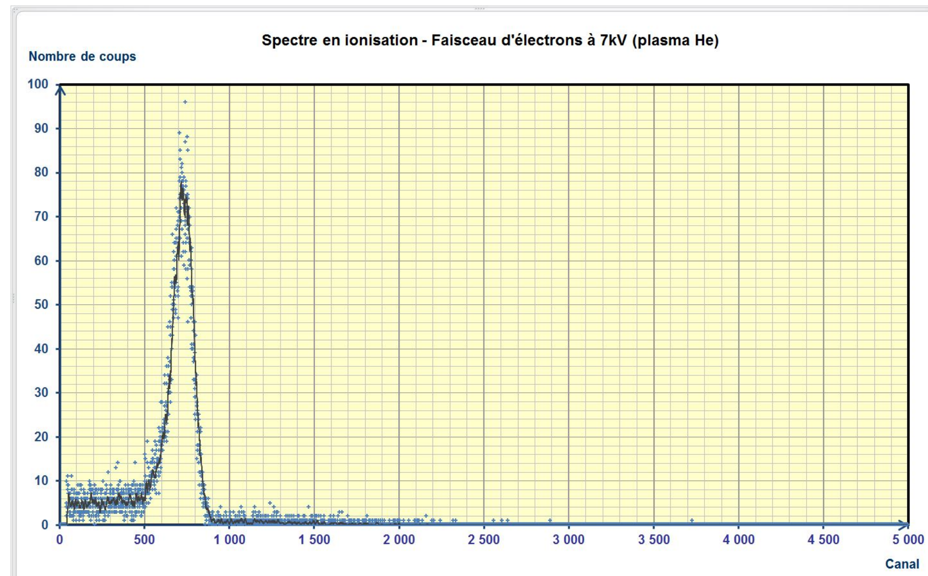
Sensitivity



Portable Quenching Facility (COMIMAC)

(Electrons and Nuclei of known energies)





Electrons of 7 keV

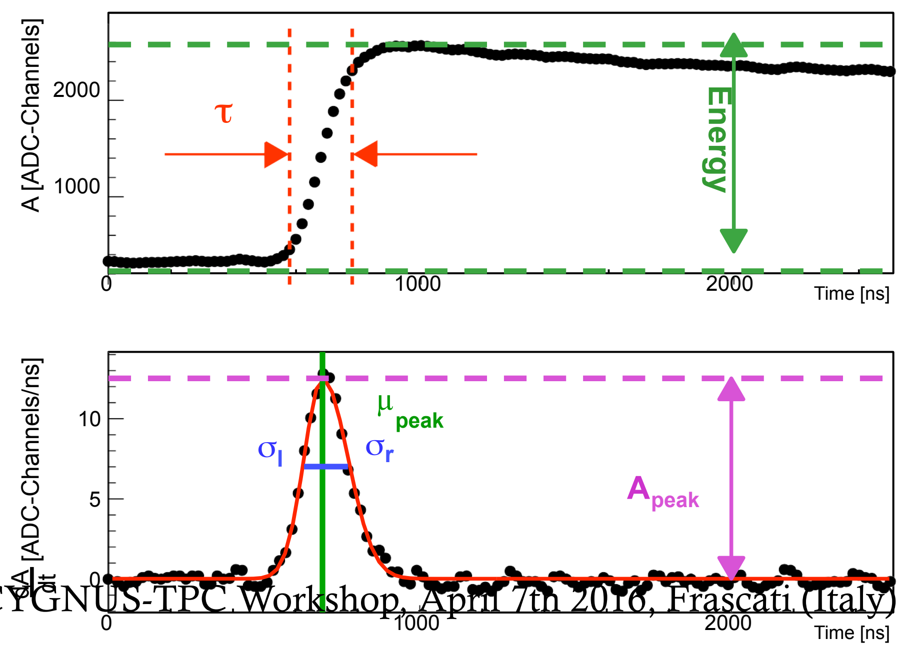
In a gas detector the IQF depends strongly on the quality of the gas.
The IQF needs to be measured periodically (in-situ) in a long term run experiment.

D. Santos (LPSC Grenoble)

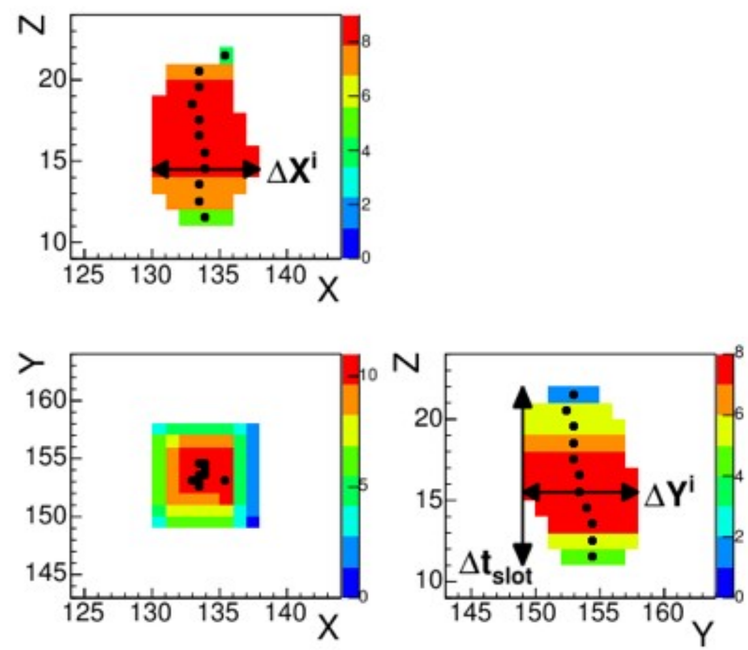
MIMAC readout

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

preamplifier signal + FADC: Energy



3D - track



D. Santos (LPSC Grenoble)

MIMAC validation with neutrons

Neutron monochromatic field:

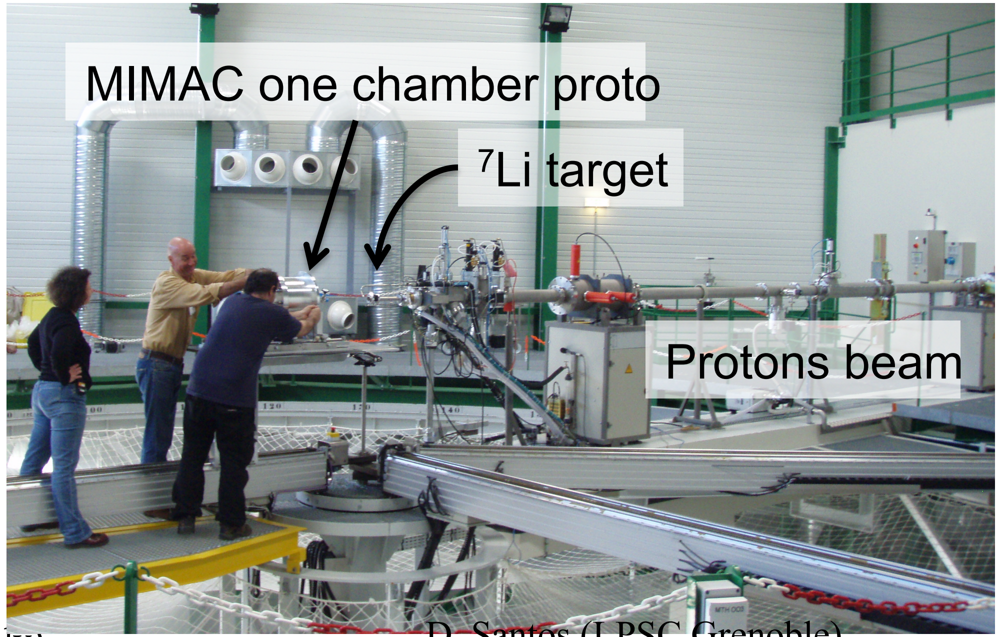
AMANDE facility at IRSN of Cadarache

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

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

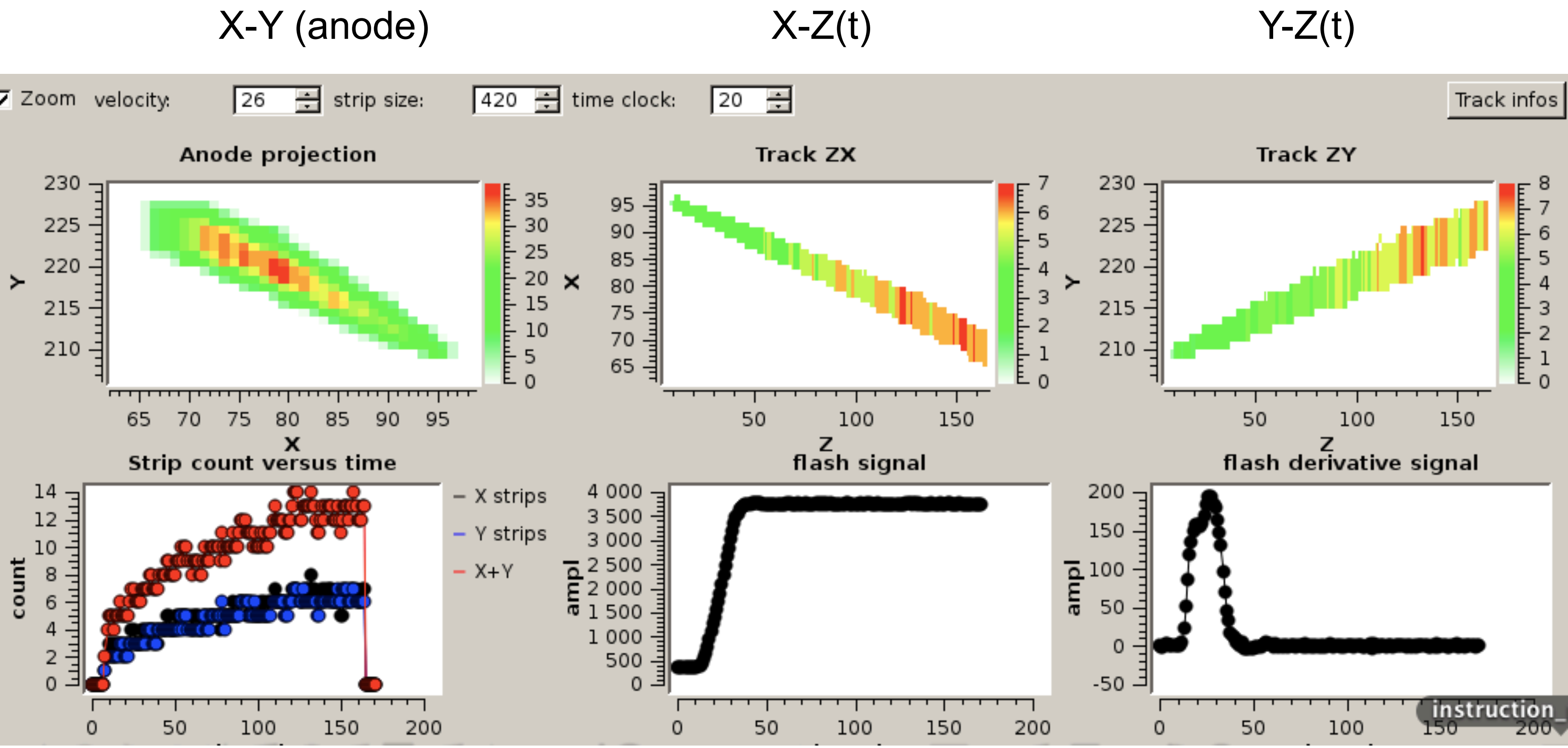
Calibration:

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

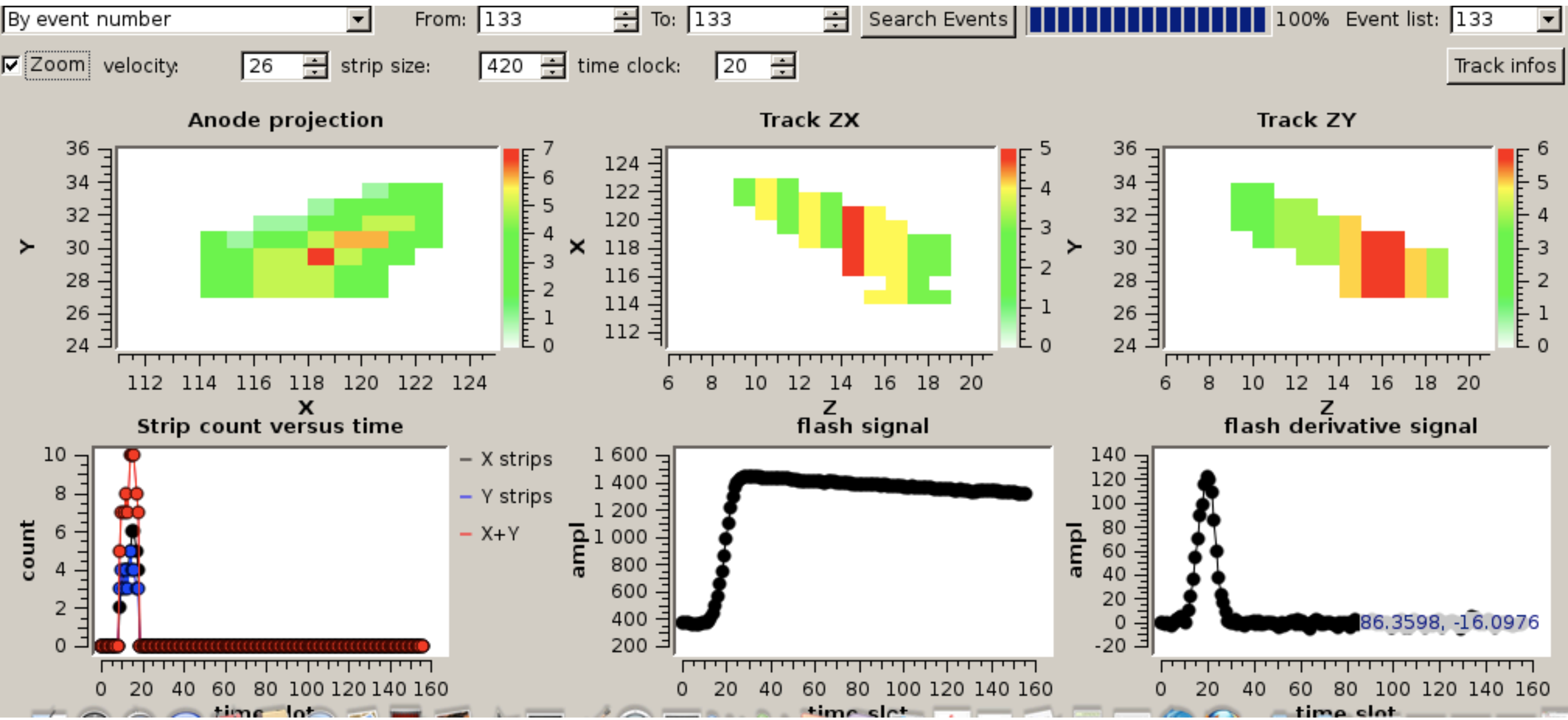


An alpha particle crossing the detector

(as an illustration of the MIMAC observables)

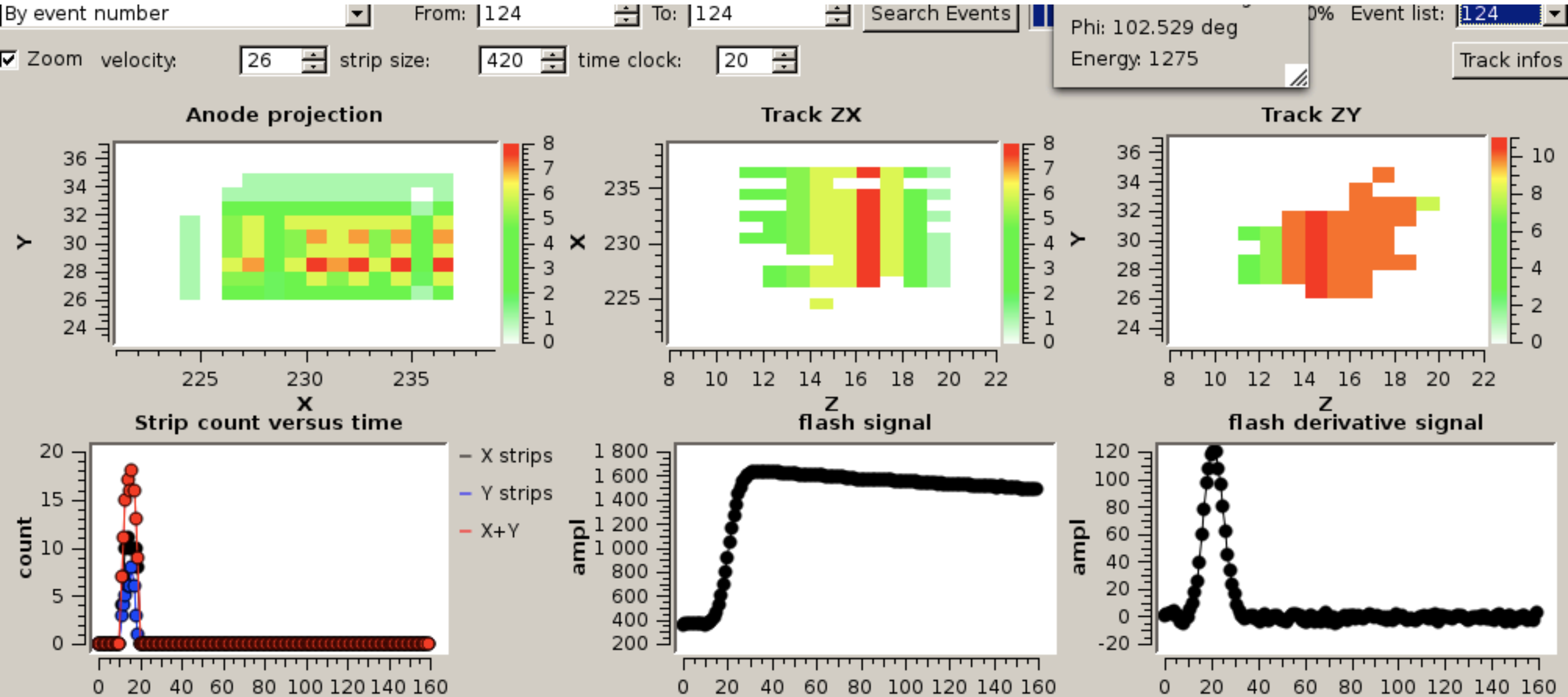


A “recoil event” (~ 34 keVee)



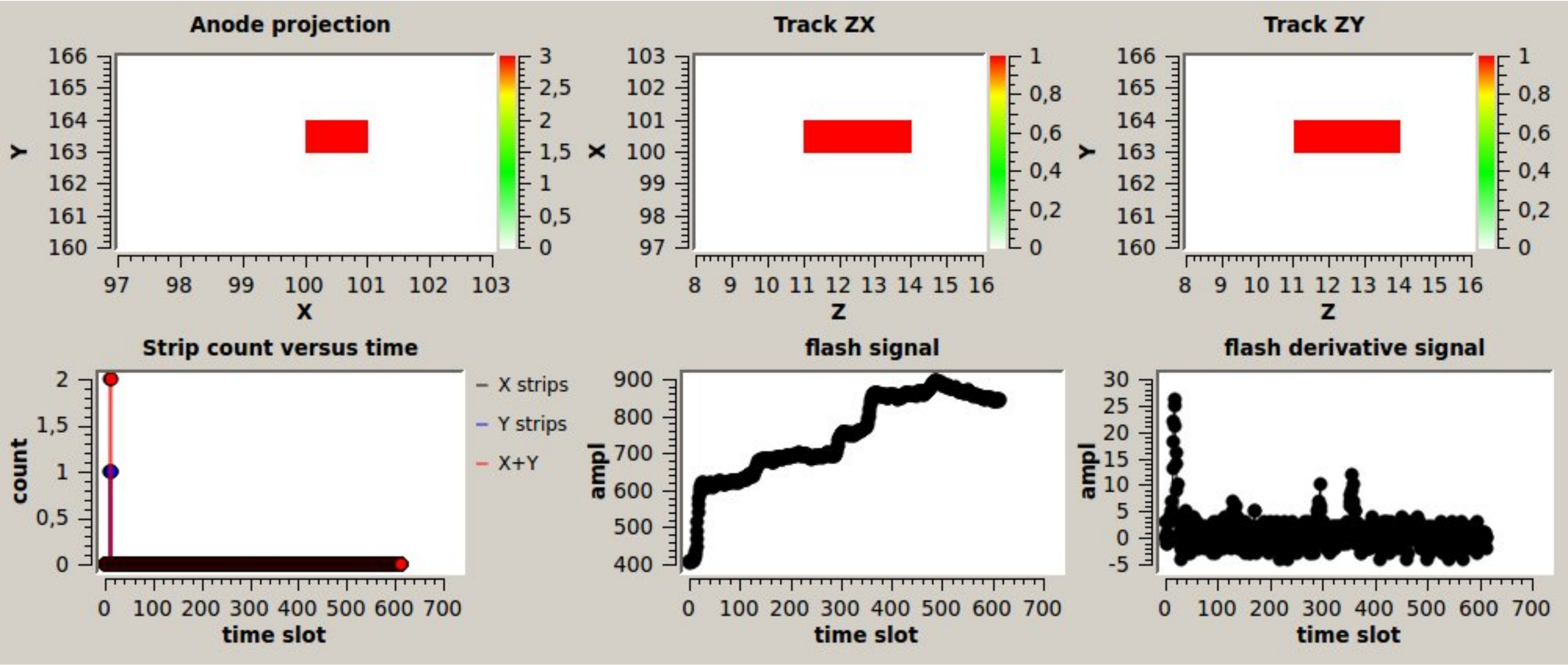
D. Santos (LPSC Grenoble)

A “recoil” event (~ 40 keVee)

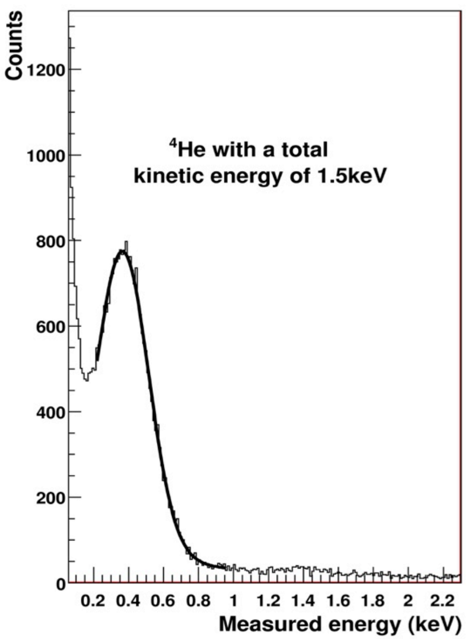


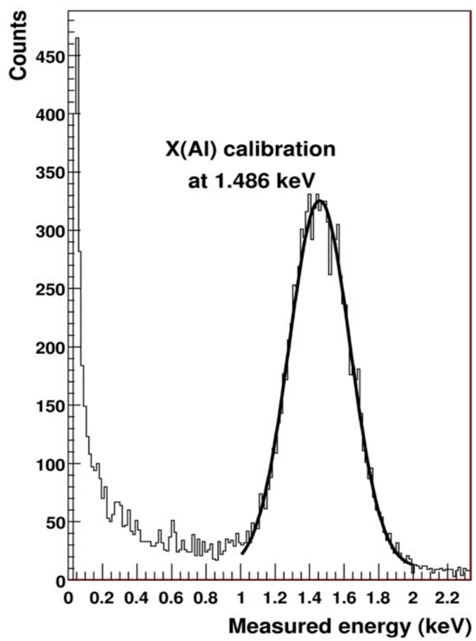
D. Santos (LPSC Grenoble)

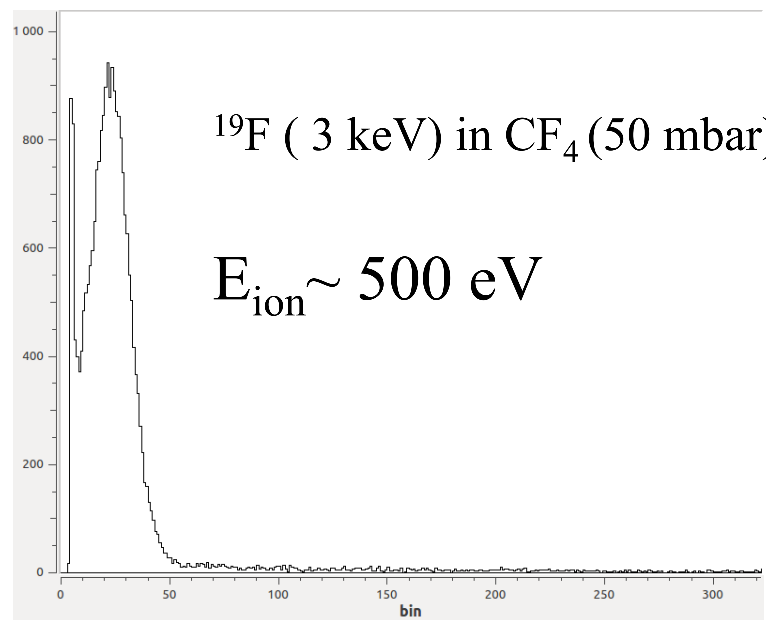
An Electron event (18 keV)



Ionization Quenching Factor Measurements at LPSC-Grenoble





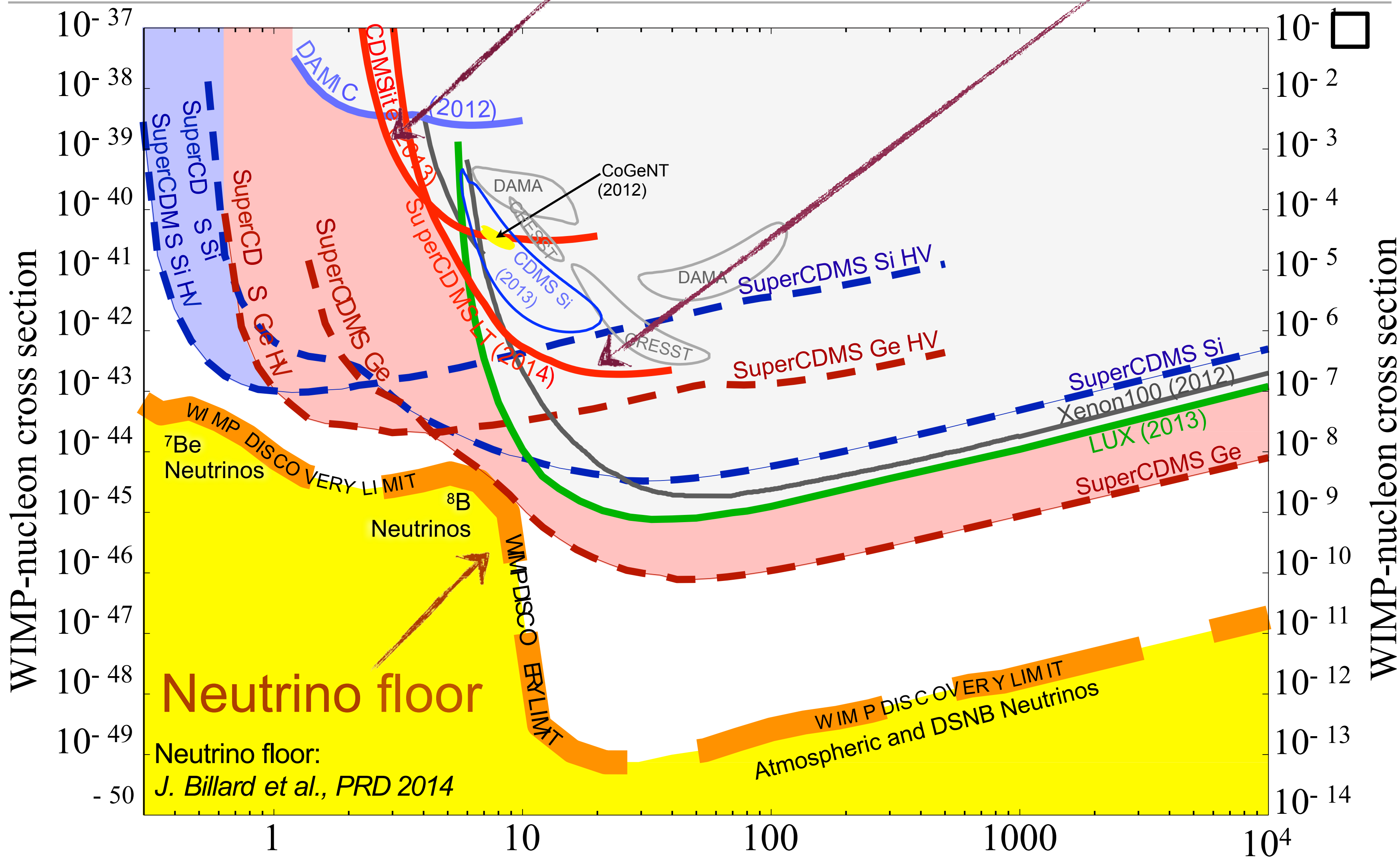


CDMSLite

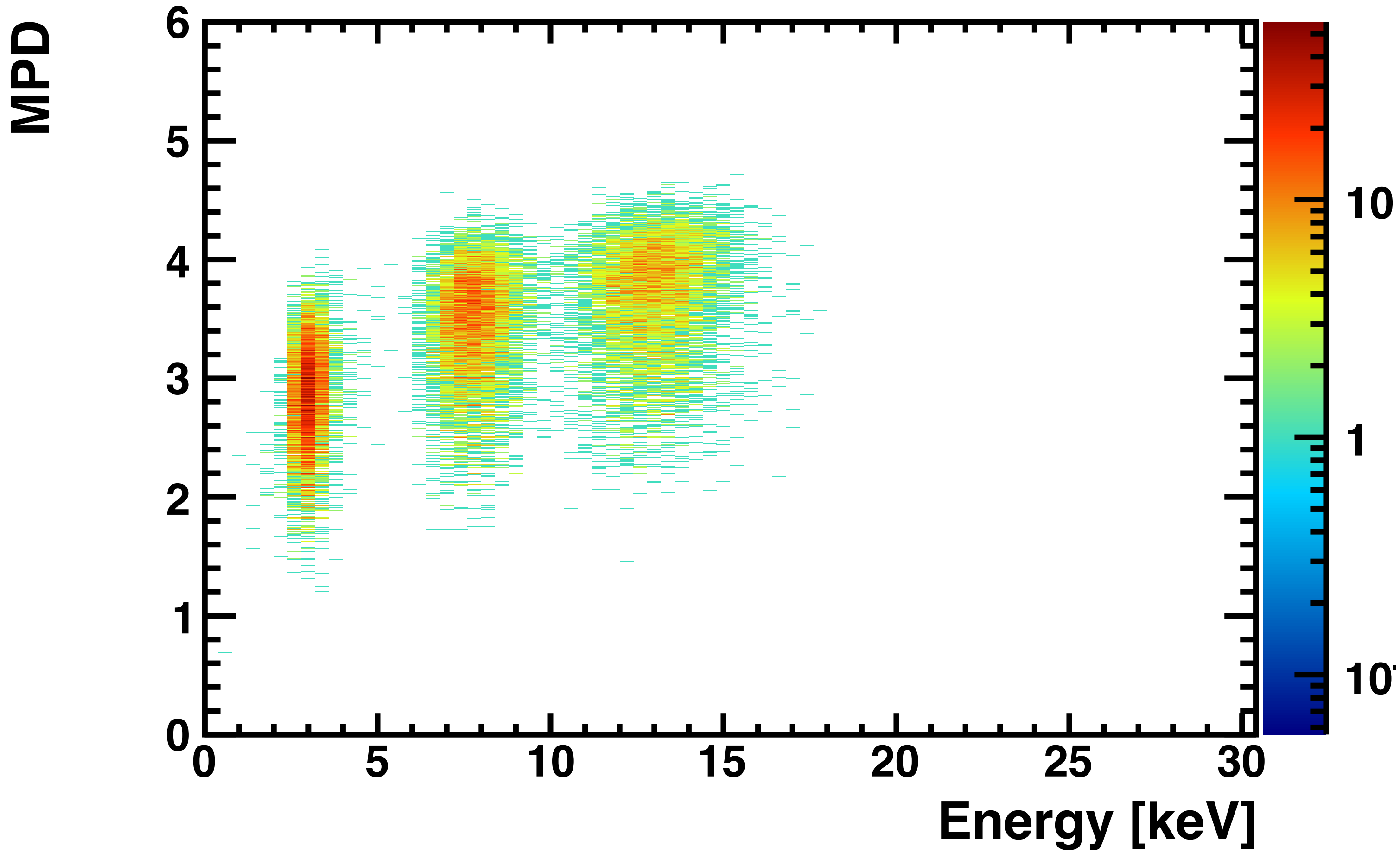
R. Agnese et al., PRL 2014
(1) (See P. Di Stefano's talk)

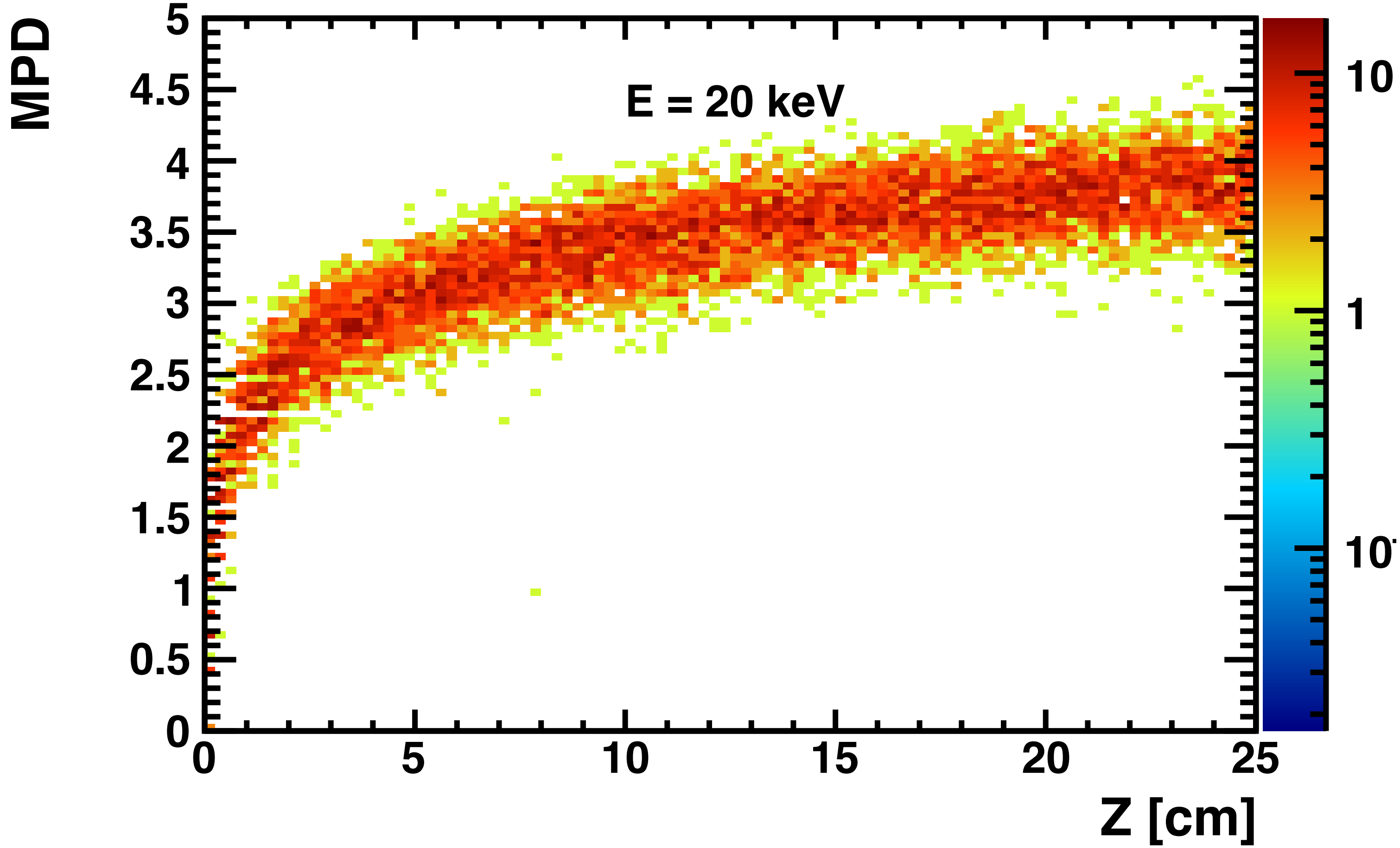
SuperCDMS LT analysis

R. Agnese et al., PRL 2014 (2)



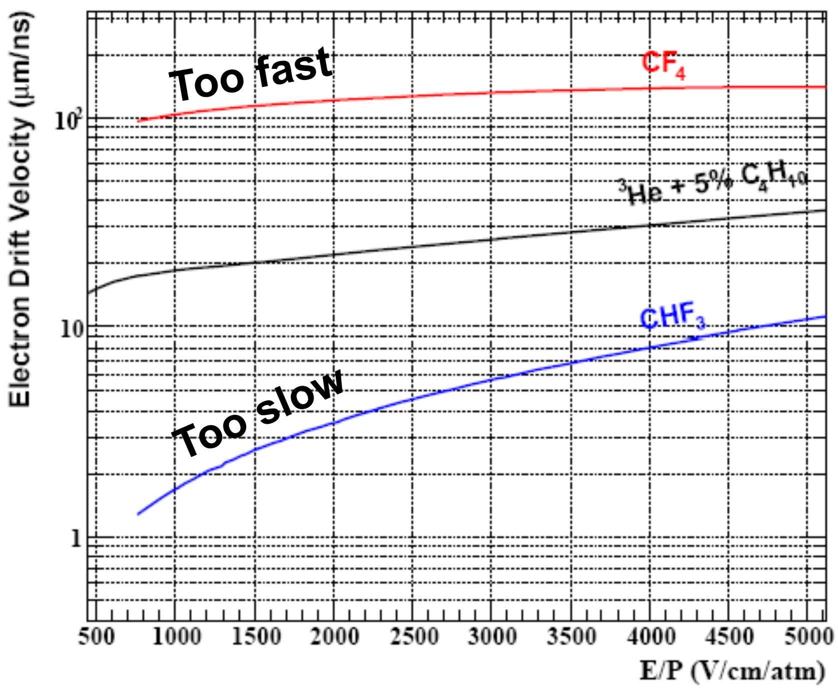
Simulation of ^{19}F recoils diffusion observable (MDP) of 10, 20 and 30 keV kinetic energies in the MIMAC detector

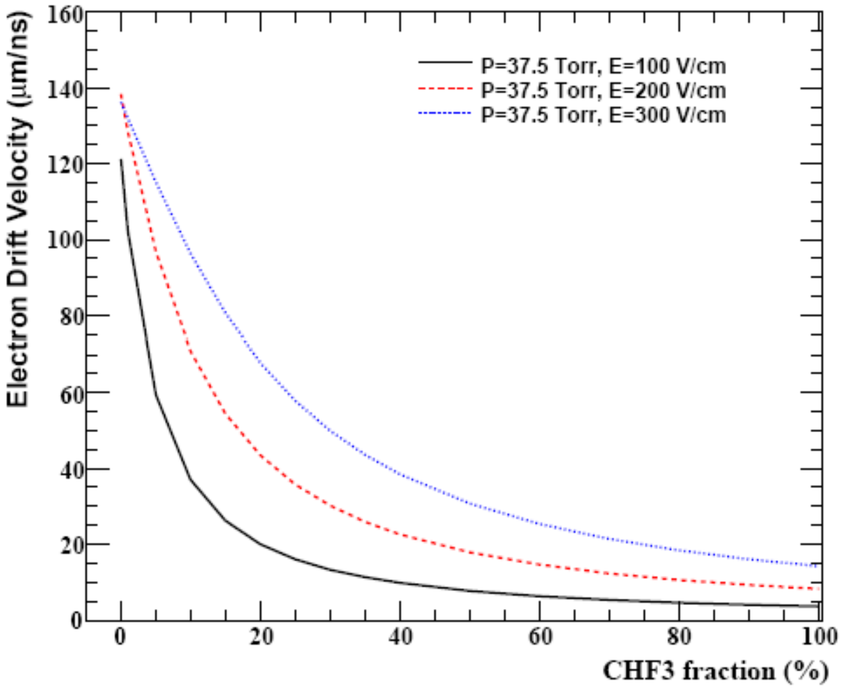



MPD
E = 20 keV
Z [cm]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
5
10
15
20
25
10
1
10

3D Tracks: Drift velocity

Magboltz Simulation





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

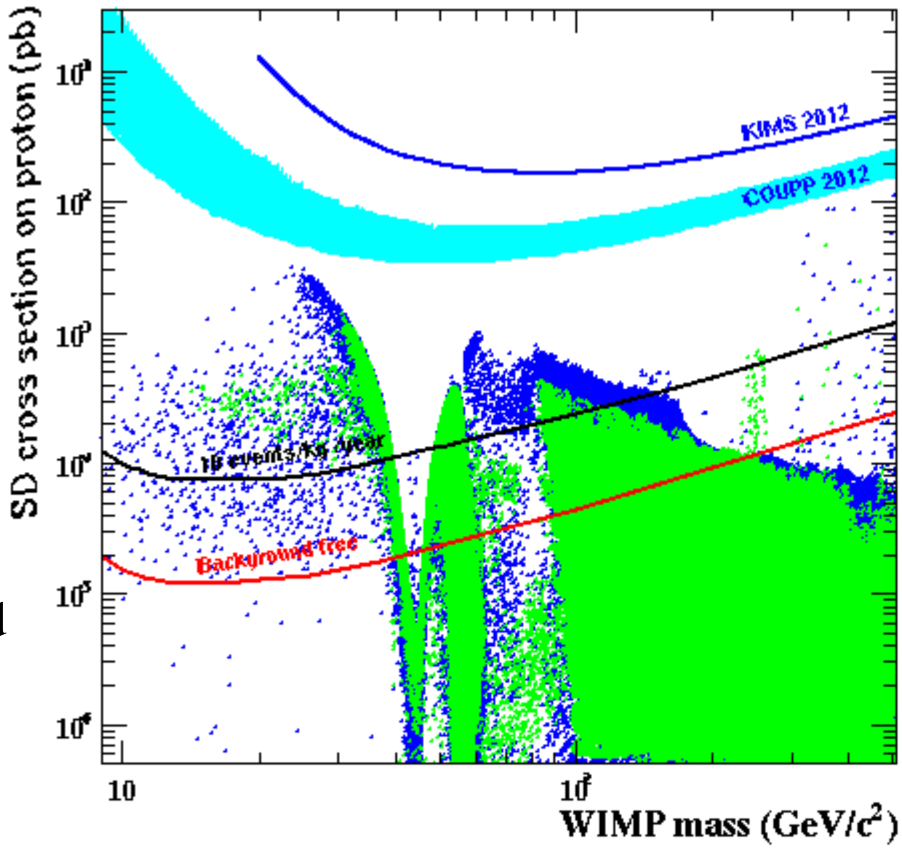
MIMAC Phenomenology: Discovery

Estimation of the discovery potential

MSSM
NMSSM
} *D. Albornoz-Vasquez et al.*, ***PRD 85***

MIMAC characteristics
- -10 kg CF_4
- DAQ : 3 years
- Recoil energy range [5, 50] keV

Discovery at 3σ { With BKG (300) / Without BKG



→ Even with a large number of background events, discovery is still possible

→ Only low number of WIMP events are required at low masses

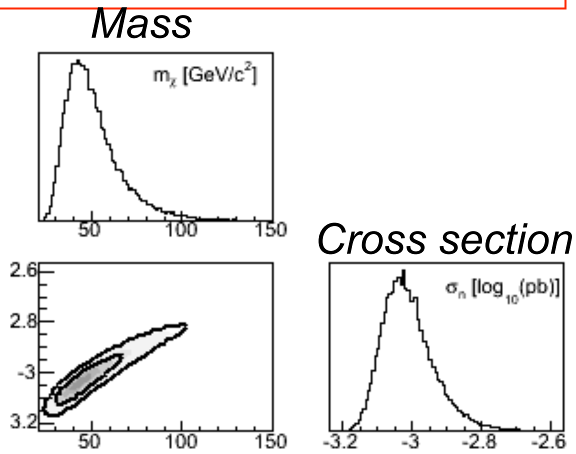
→ ***A discovery (>3σ @90%CL) with BKG*** is possible down to ***10^{-3}-10^{-4} pb***

Directional Detection : identification

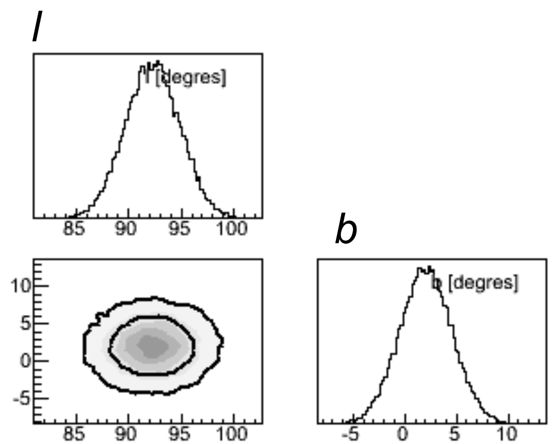
J. Billard *et al.*, PRD 2011

8 parameters simultaneouly constrained by only one 3D experiment

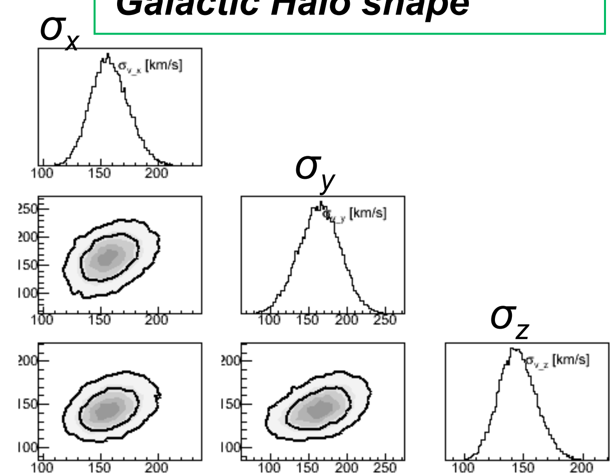
Mass – cross section



Dark Matter signature



Galactic Halo shape



	m_χ (GeV/c^2)	$\log_{10}(\sigma_n$ (pb))	$\ell_\odot$ (°)	$b_\odot$ (°)	σ_x (km.s^{-1})	σ_y (km.s^{-1})	σ_z (km.s^{-1})	β	R_b (kg^{-1}year^{-1})
Input	50	-3	90	0	155	155	155	0	10
Output	$51.8^{+5.6}_{-19.4}$	$-3.01^{+0.05}_{-0.08}$	$92.2^{+2.5}_{-2.5}$	$2.0^{+2.5}_{-2.5}$	158^{+15}_{-17}	164^{+27}_{-26}	145^{+14}_{-17}	$-0.073^{+0.29}_{-0.18}$	10.97 ± 1.2