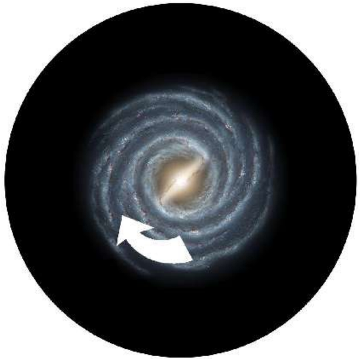
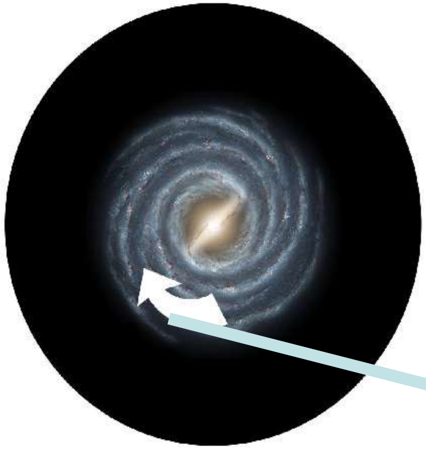
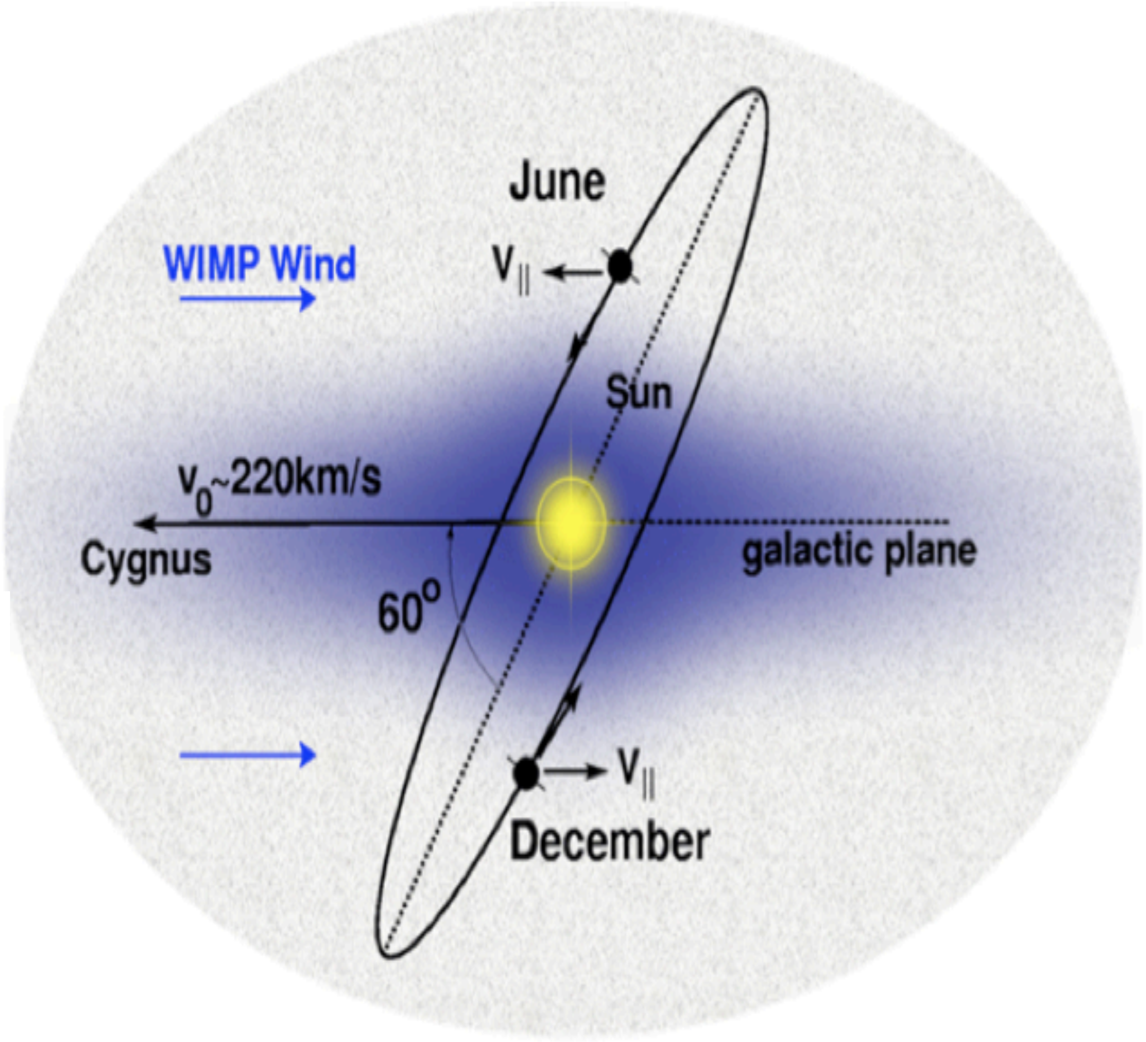


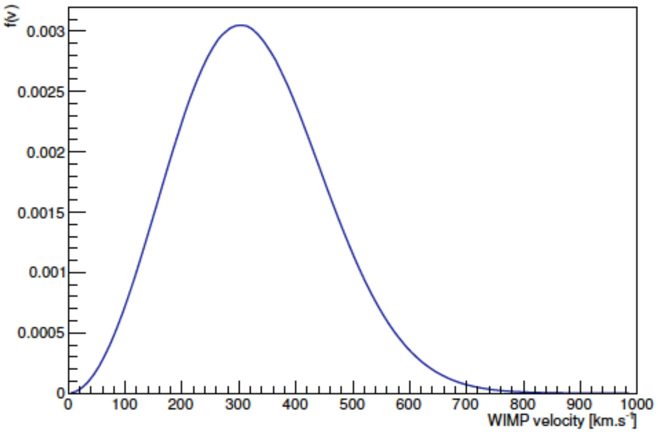
Directional Dark Matter Detection

Daniel Santos
Laboratoire de Physique Subatomique et de Cosmologie
(LPSC-Grenoble)
(Université Grenoble-Alpes -CNRS/IN2P3)

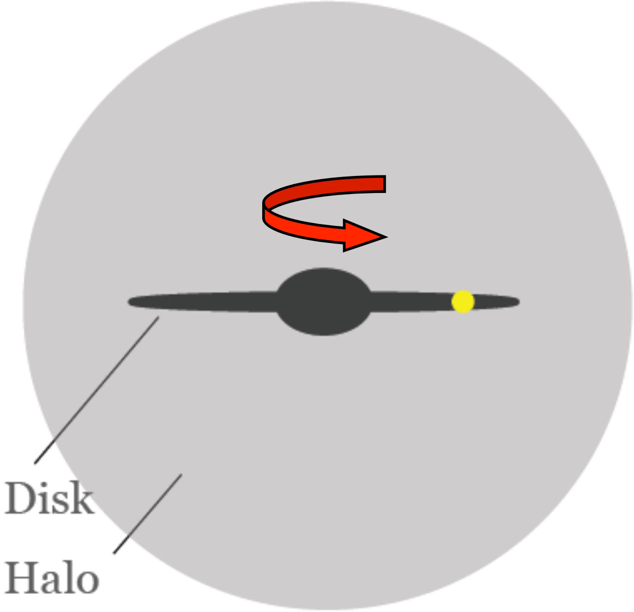
Directional detection: principle

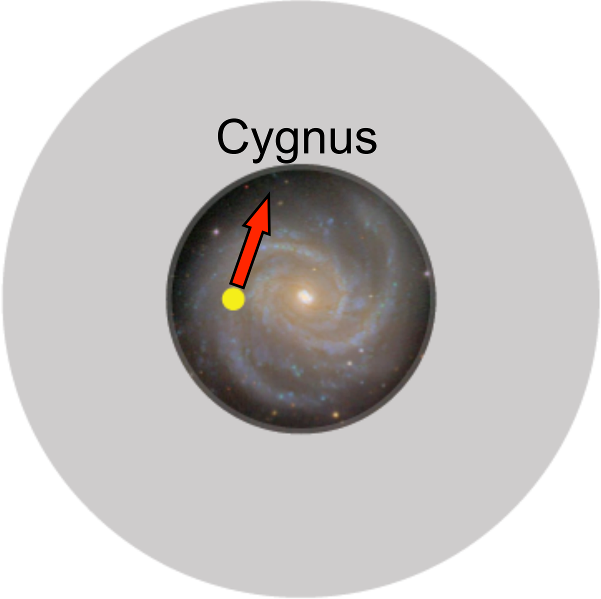






Directional detection



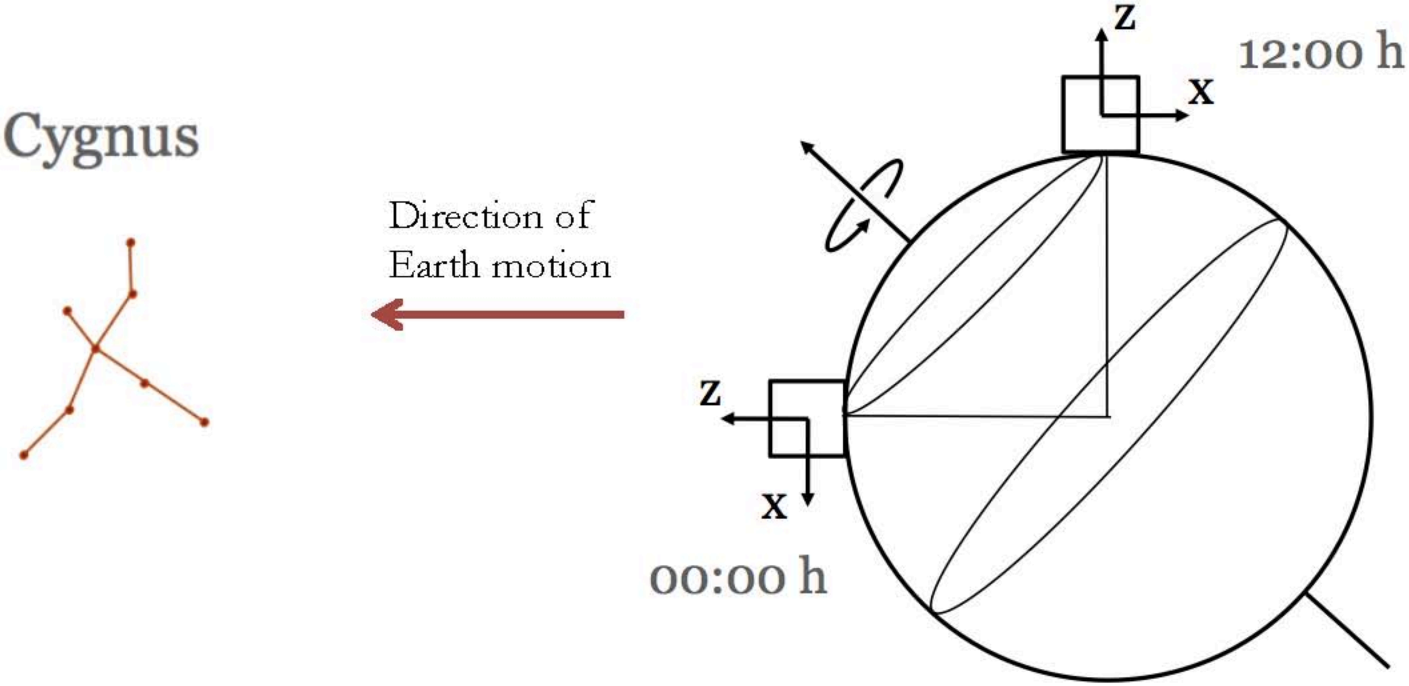


$\langle V_{rot} \rangle \sim 220$ km/s

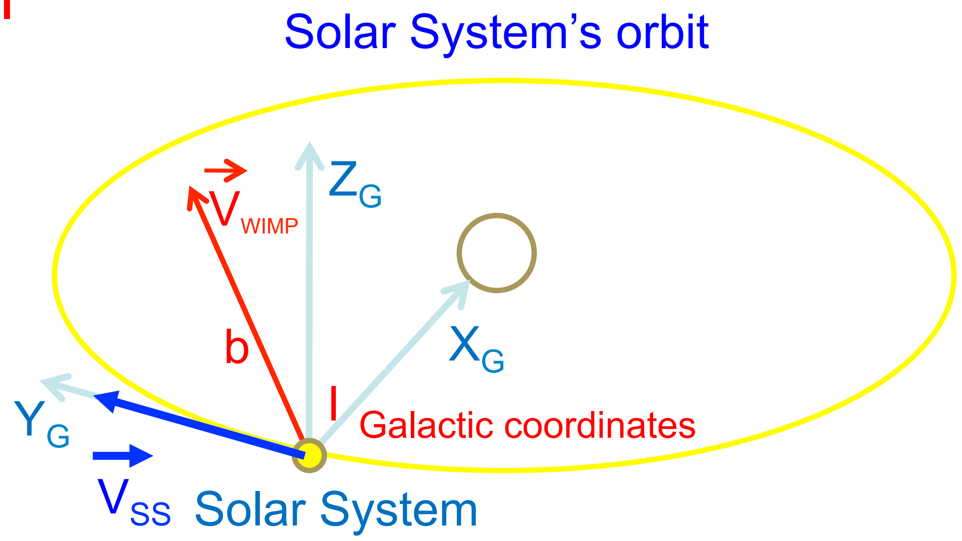
The signature, the only one (!), able to correlate the events in a detector to the galactic halo !!

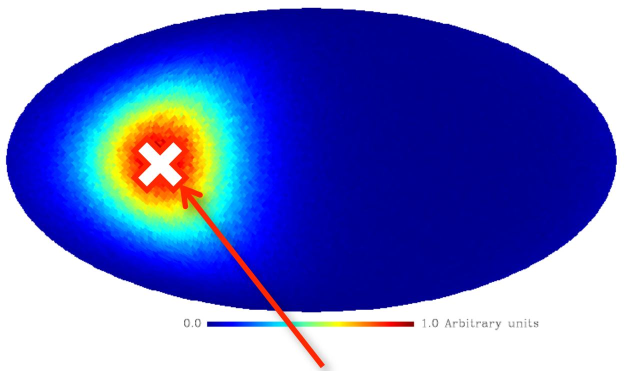
Angular modulation of WIMP flux

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



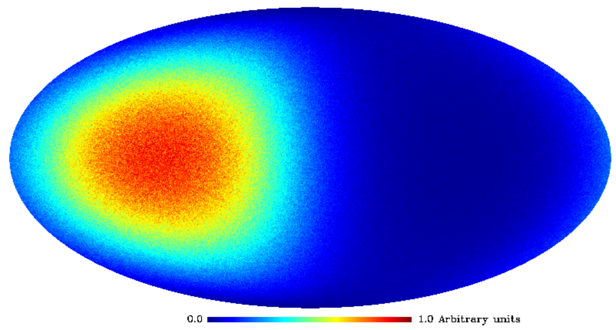
WIMP signal





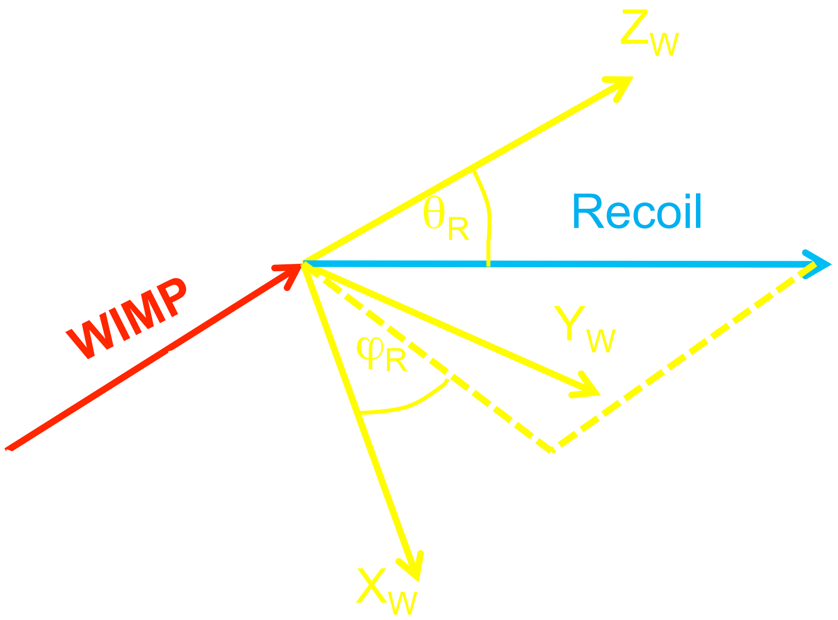
Cygnus Constellation (l = 90°,b = 0°)

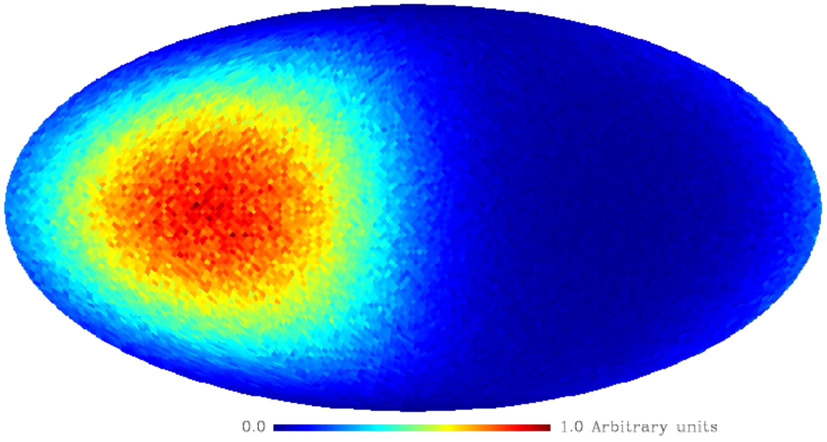
After collision



WIMP signal expected

There are many “angles” for nuclear recoils…

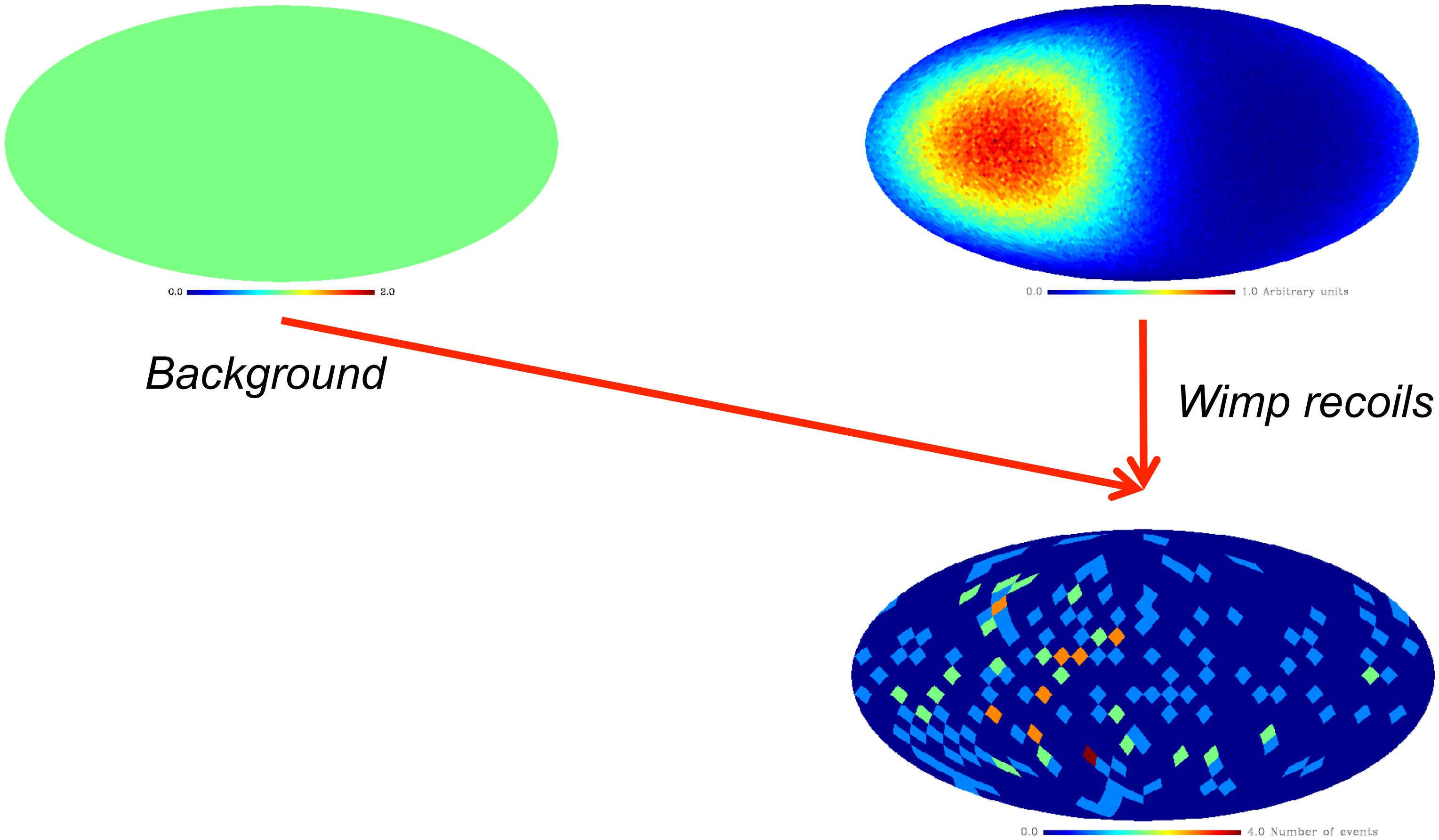




Map of recoils in galactic coordinates (HealPix)

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

100 WIMP evts + 100 Background evts



Background

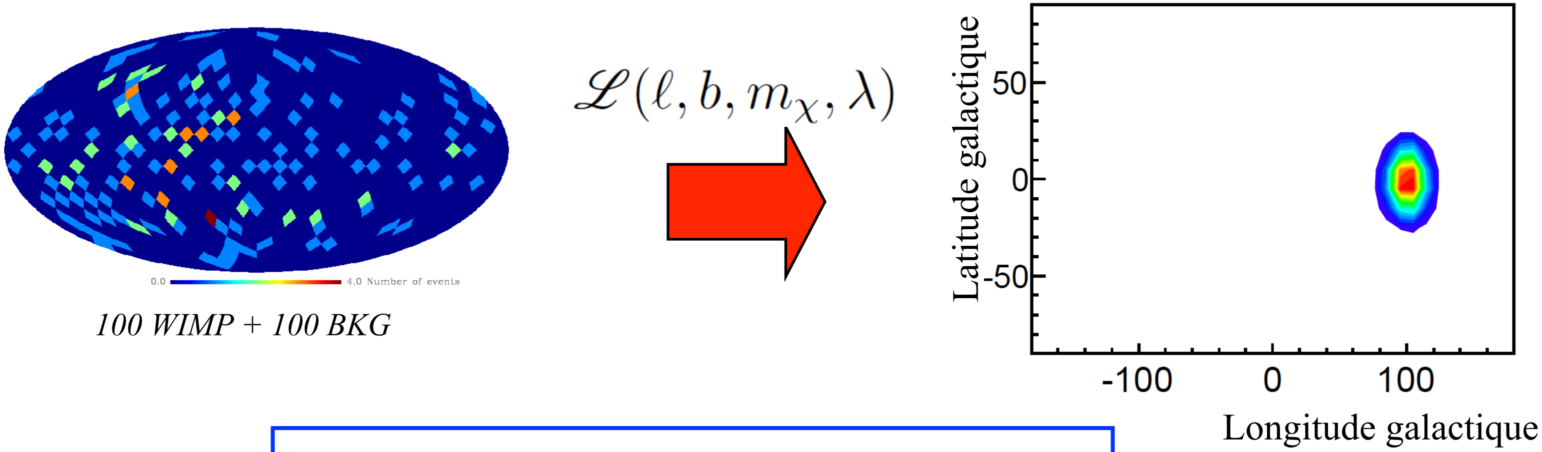
Wimp recoils

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



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

100 WIMP + 100 BKG

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

LTPC – Conference, Paris- December 13th 2018

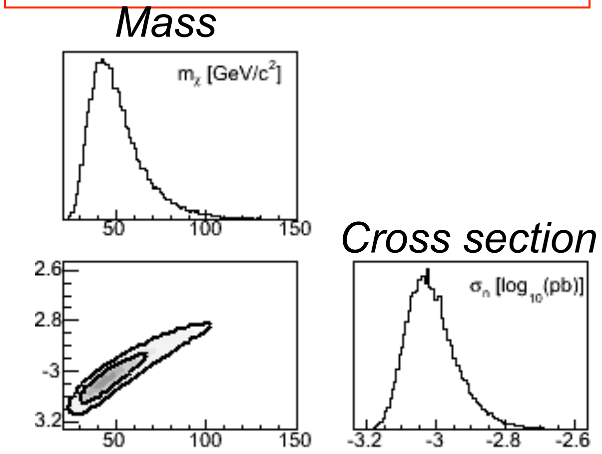
D. Santos (LPSC Grenoble)

Directional Detection : identification

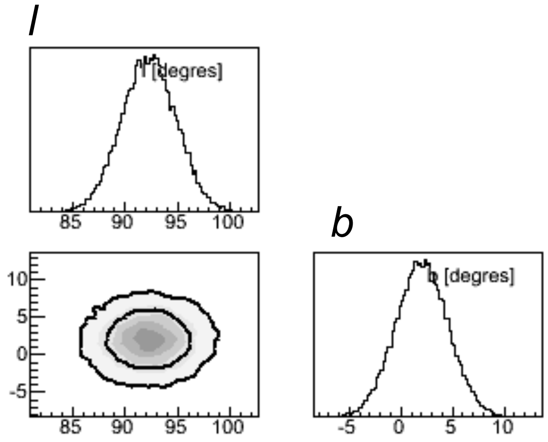
J. Billard *et al.*, PRD 2011

8 parameters simultaneouly constrained by only one 3D experiment

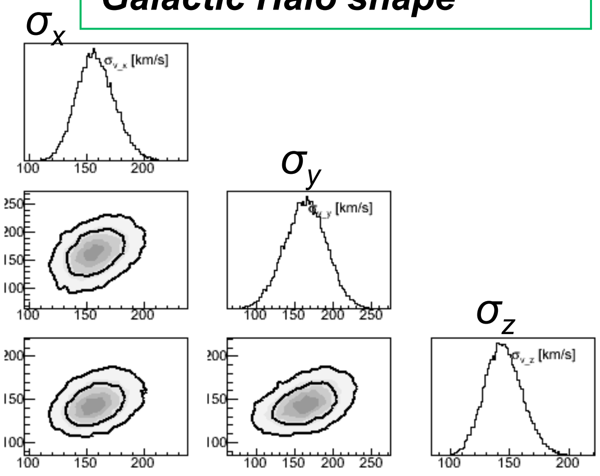
Mass – cross section



Dark Matter signature



Galactic Halo shape

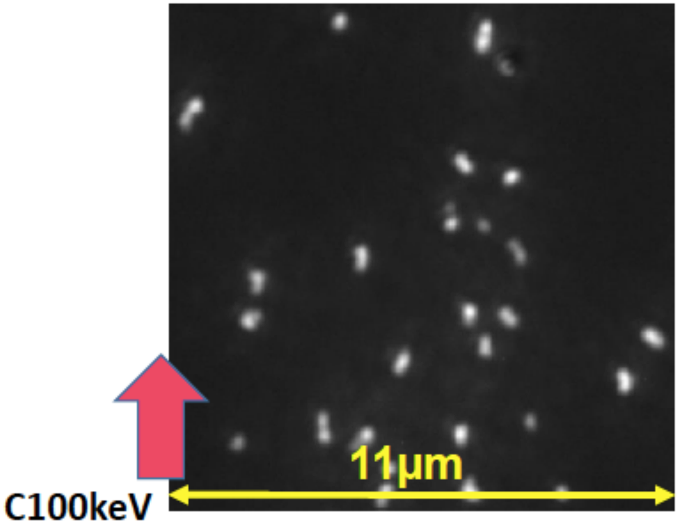


	m_χ (GeV/c^2)	$\log_{10}(\sigma_n$ (pb))	$\ell_\odot$ (°)	$b_\odot$ (°)	σ_x (km.s^{-1})	σ_y (km.s^{-1})	σ_z (km.s^{-1})	β	R_b (kg^{-1}year^{-1})
Input	50	-3	90	0	155	155	155	0	10
Output	$51.8^{+5.6}_{-19.4}$	$-3.01^{+0.05}_{-0.08}$	$92.2^{+2.5}_{-2.5}$	$2.0^{+2.5}_{-2.5}$	158^{+15}_{-17}	164^{+27}_{-26}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

Directional detection in different materials

Couturier et al. (JCAP 01/2017)

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



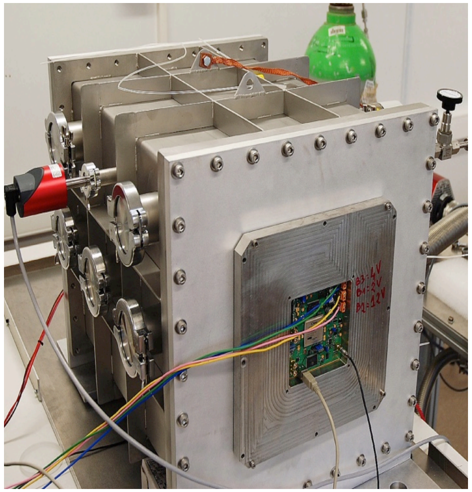
NEWS-DM collaboration
(Atsuhiro-Umemoto et al.(2017)

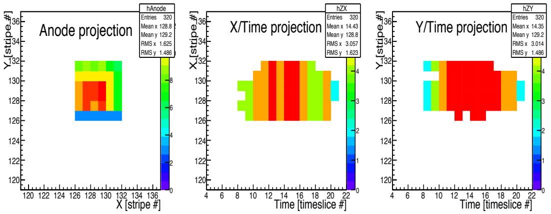
- Anisotropic crystals
  target = O (lowmasses), Zn, W (high masses)

No tracks ; only statistical distributions (!)

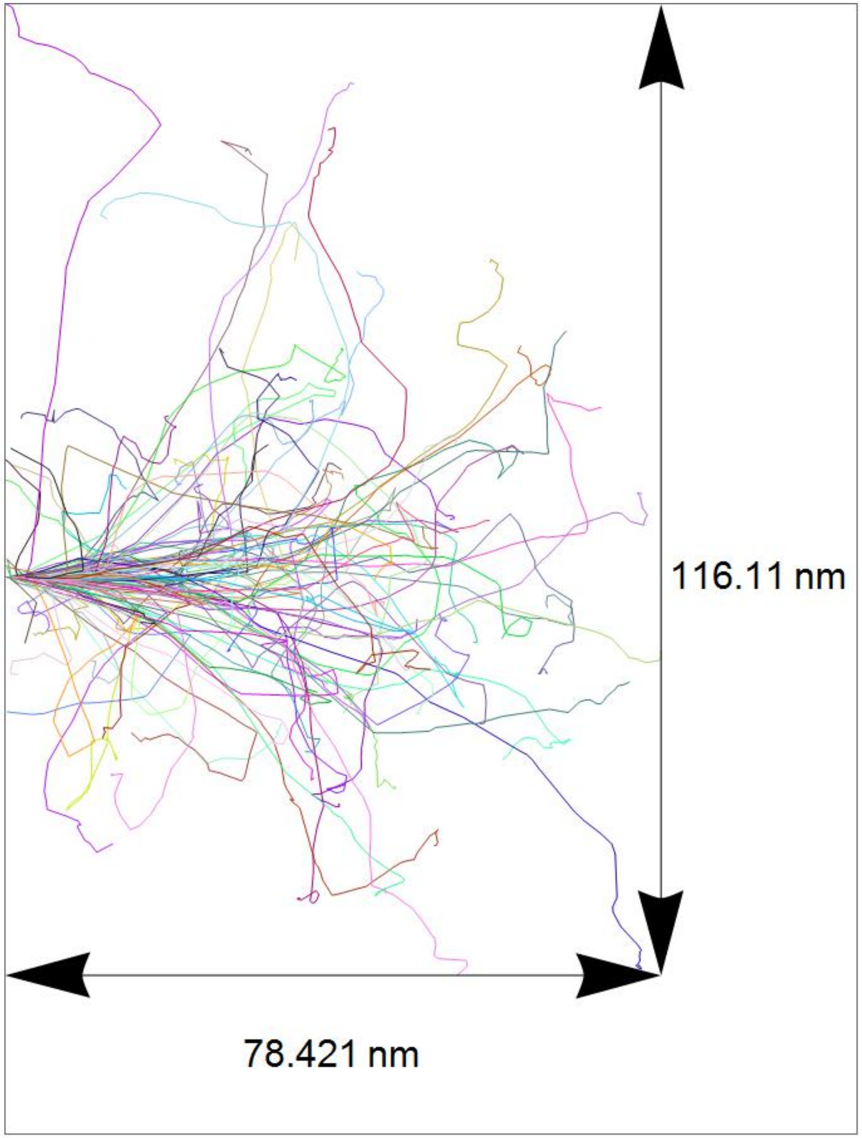
Capella et al. 2013

- Low pressure TPCs
  target = F

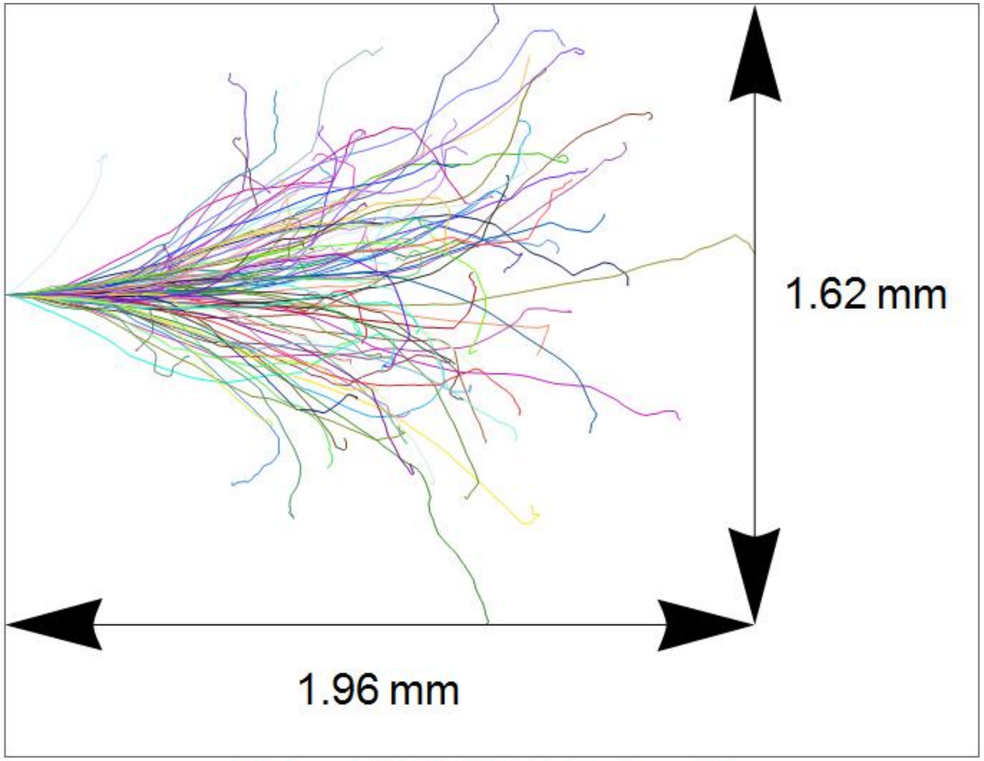




SRIM simulations…

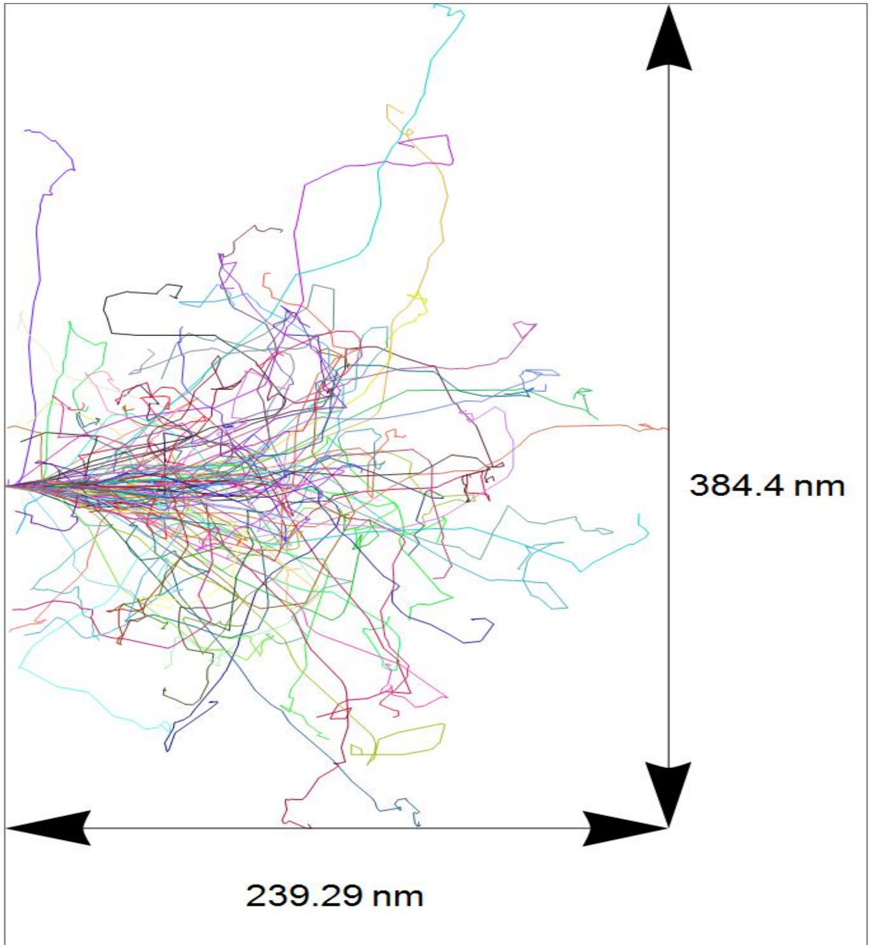


O in Crystal (29keV)



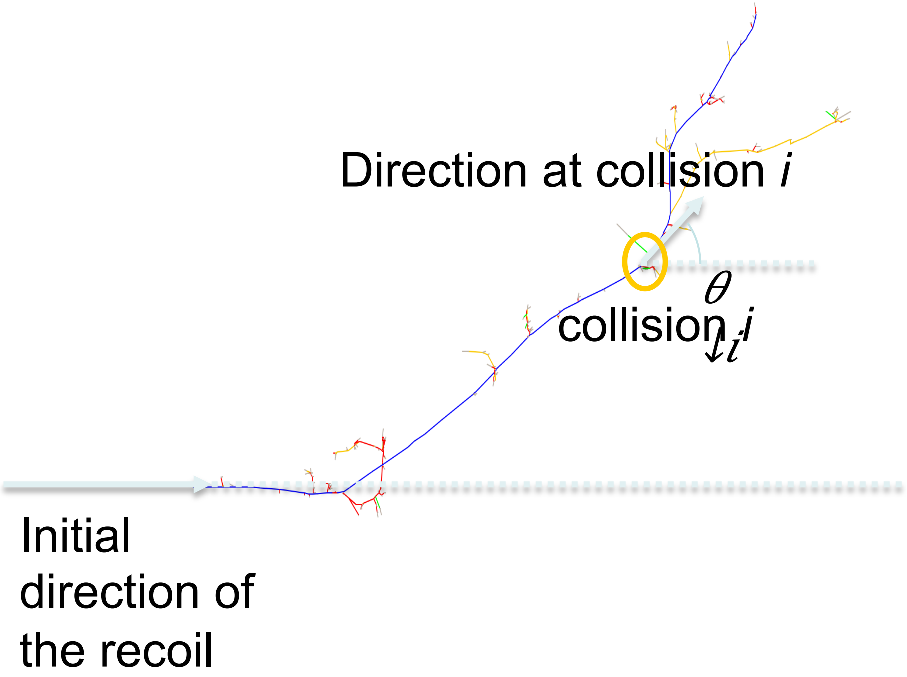
F in MIMAC (34keV)

C (22 keV) in emulsion (SRIM simulation)



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

Directional detection: Directionality ‘D’



Direction at collision *i*

collision *i*

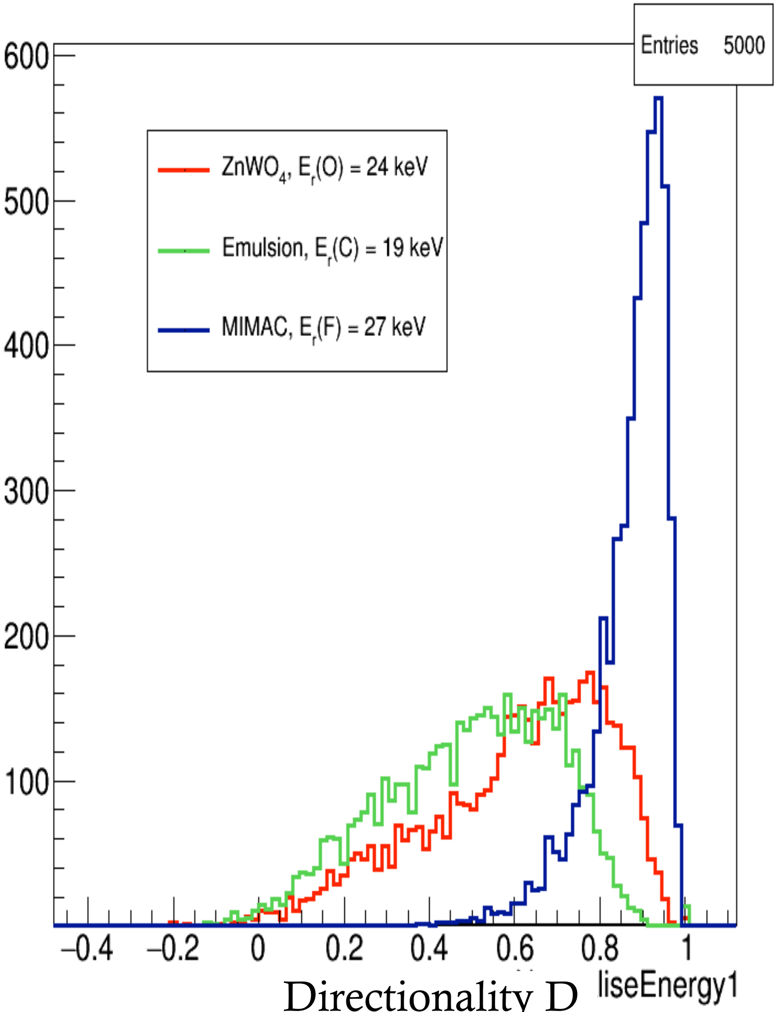
θ

θ_i

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. (JCAP 01/2017)



Directionality D
(preservation of the
direction)

Why Gas Detectors for DM detection
(ionization, scintillation and tracks)

i) Flexibility to change the nucleus **target**:

^{1}H, ^{3}He, ^{4}He, ^{19}F, ^{20}Ne, ^{40}Ar, ^{129,130}Xe

Optimizing the momentum transfer !!

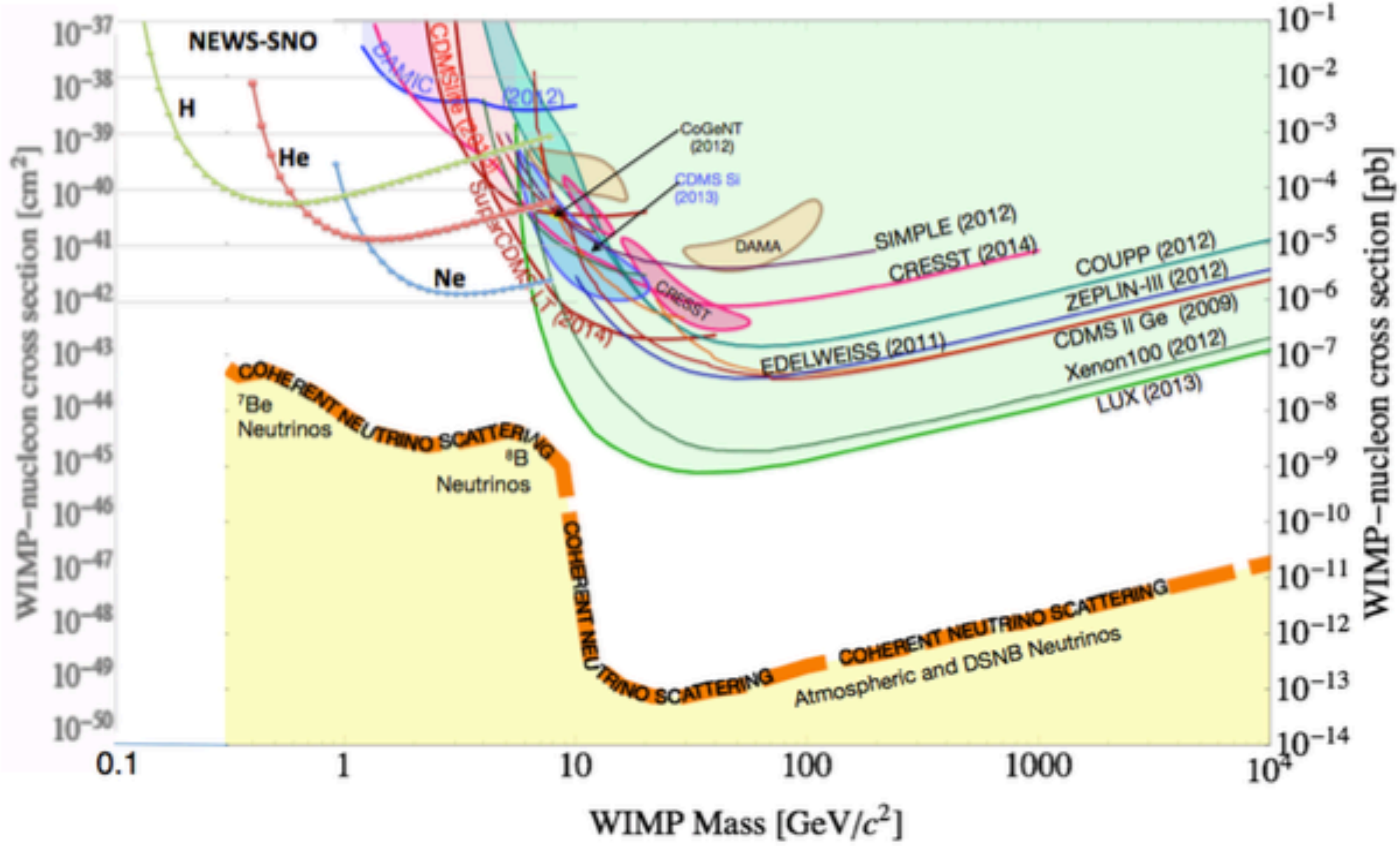
ii) Access to very low threshold in **ionization energy** (sub-keV) by low capacitance and high gains

iii) Flexibility to change **pressure** ($N_{evts} \sim N_{nuclei}$)

iv) Opening the **directional** signature (1D, 2D and 3D **tracks**)

v) Allowing to cope with **neutron and neutrino background** events

WIMP Light Mass window
MIMAC- NEWS-G complementarity



Directional experiments around the world

DMTPC
(WIPP)

DRIFT
(Boulby)

Emulsions
(Gran Sasso)

NEWAGE
(Kamioka)

MIMAC
(Modane)

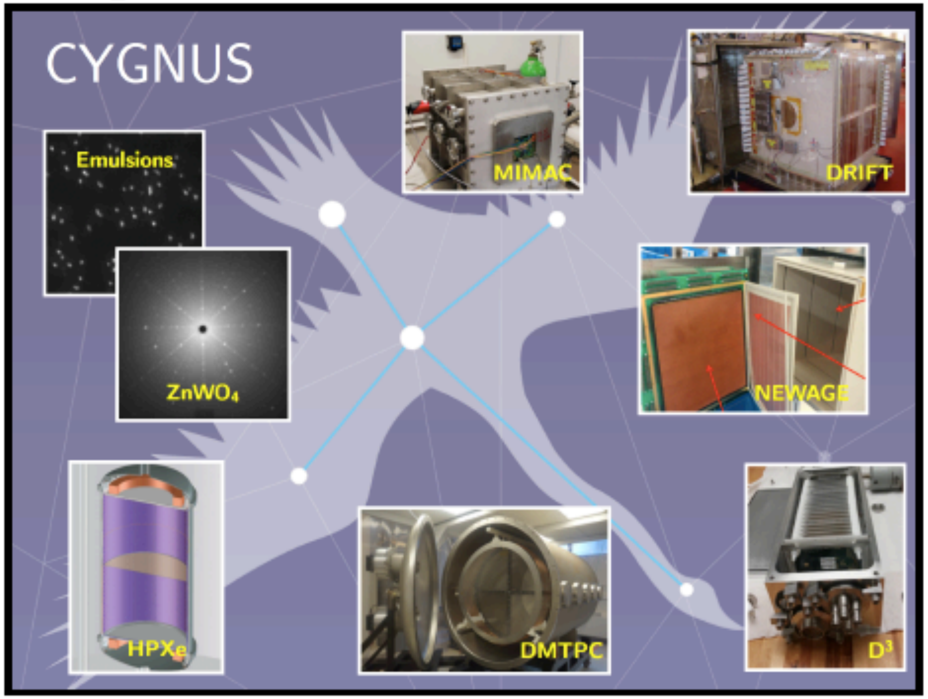
Running in an Underground Laboratory

CYGNUS Workshops & Collaboration

2007	Boulby, UK
2009	MIT, US
2011	Modane, France
2013	Toyama, Japan
2015	Los Angeles, USA
2017	JinPing, China

- From Workshops to Collaboration

Australia, China, France, Italy, Japan, UK, US…



- Meet challenge of scale-up
- Optimise techniques


CYGNUS 2017

Sixth International Workshop on Directional Detection of Dark Matter

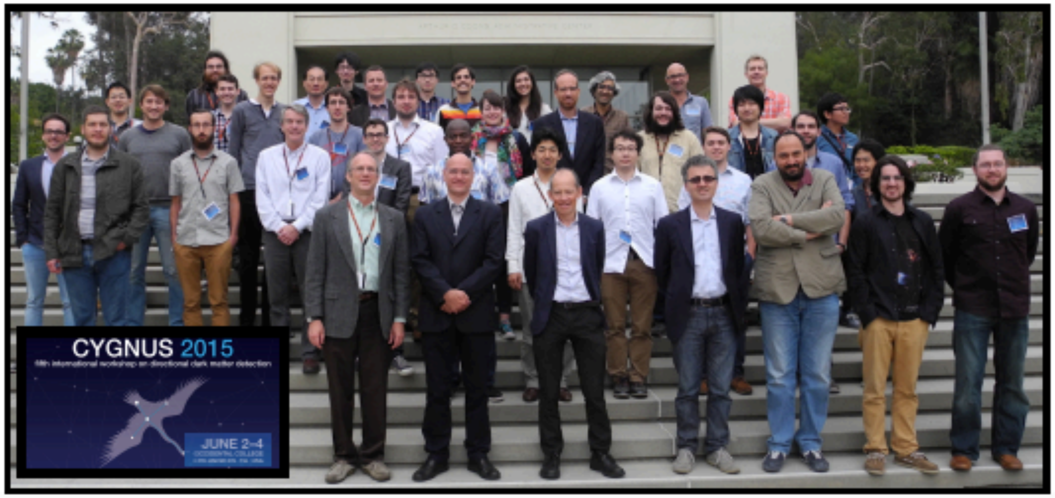
Registration

Topics

International Advisory Committee

Local Organizing Committee

Sponsors

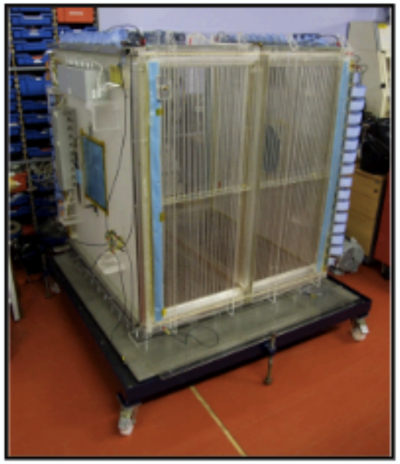


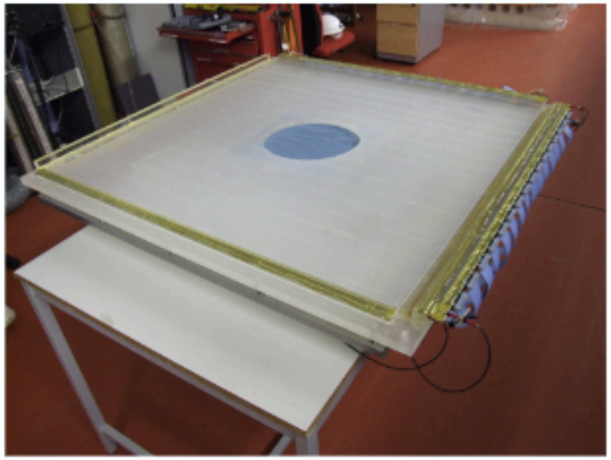
CYGNUS 2017- International Workshop
Xichang, Sichuan (CHINA) – June 13th- 15th 2017

DRIFT Basics

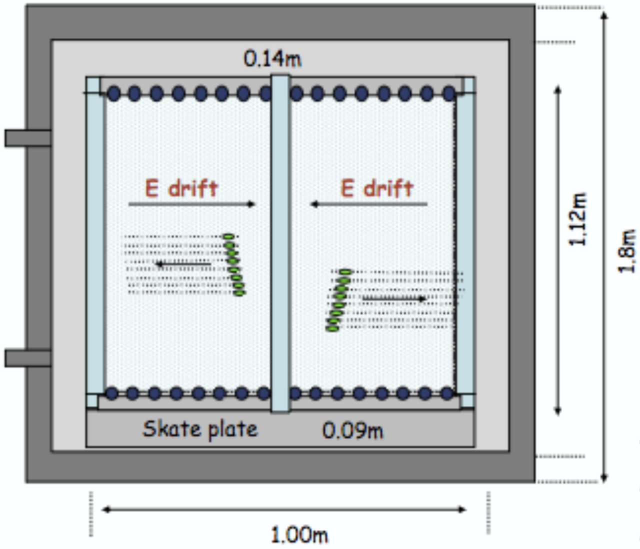
Negative Ions drift !!
CS_2 and SF_6

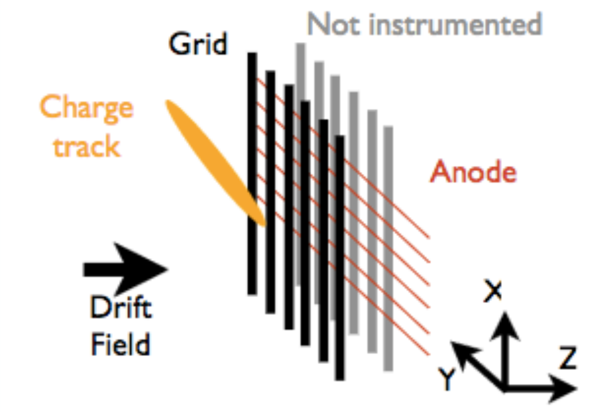
Directional Recoil Identification From Tracks (DRIFT)



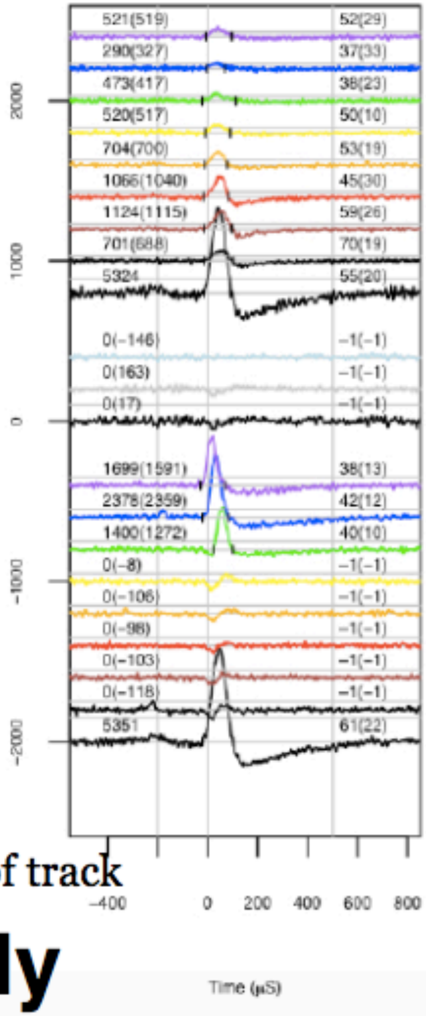


DRIFT IIa, b, c, d, e





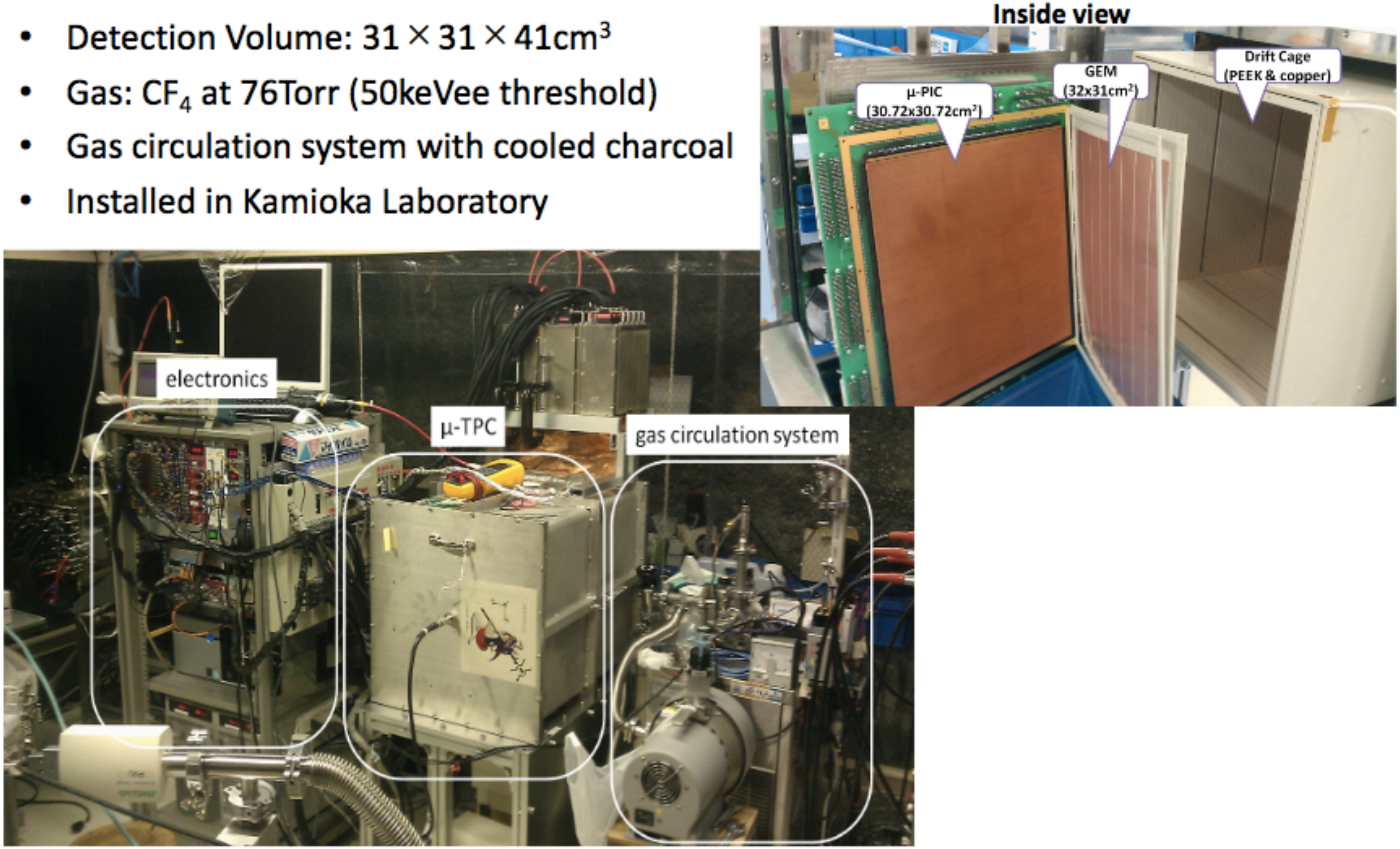
ΔX: Number of anode wires crossed
ΔY: Progression across grid wires
ΔZ: Drift time between start and end of track



Significant advances recently

NEWAGE-0.3b’ Detector

- Detection Volume: 31 × 31 × 41cm^3
- Gas: CF_4 at 76Torr (50keVee threshold)
- Gas circulation system with cooled charcoal
- Installed in Kamioka Laboratory



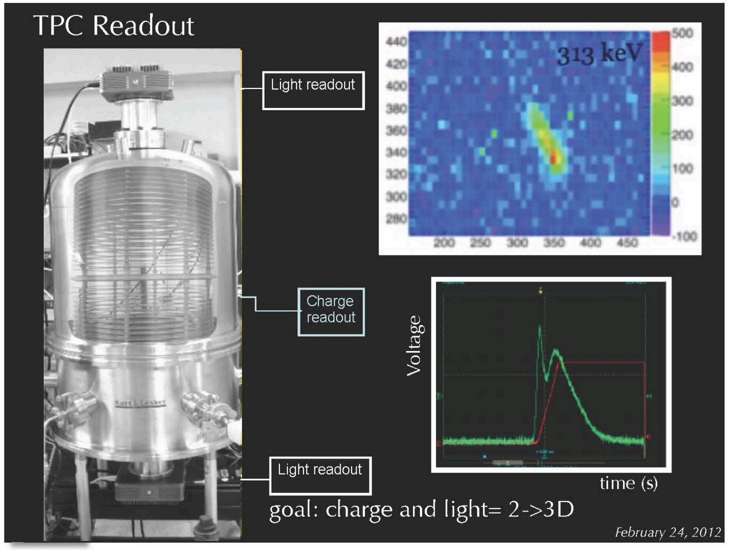
DM-TPC – Dark Matter TPC

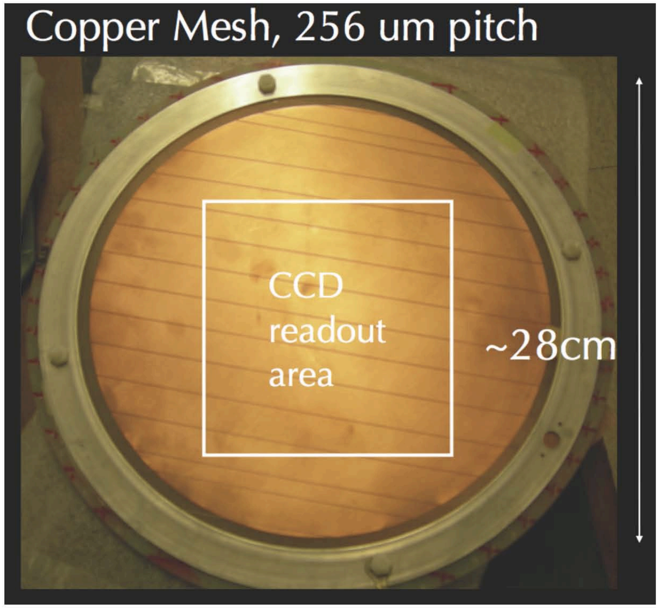
Started = 2007, US

Underground in WIPP, USA in 2011

Current operating detector = DMTPC 10 liter

Technology = TPC with micromegas + light and charge readout





xyz resolution = 0.256 mm & absolute in xy, Δz coming

Target = CF_4 @ 75 Torr

Fiducial volume = 9.18 liters

F mass = 2.85 g

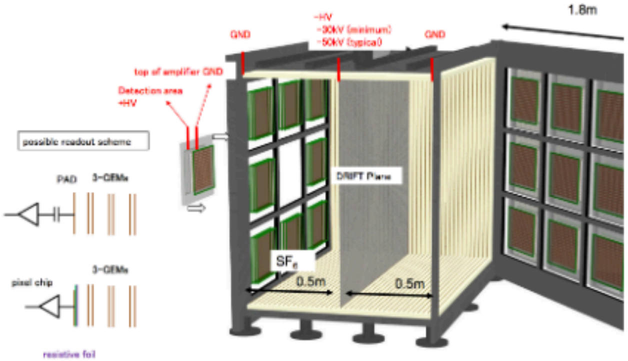
Limit setting threshold = 80 keVr

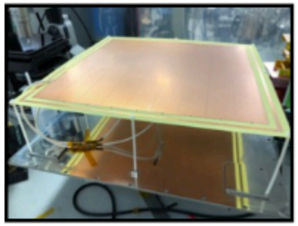
These values are probably out of date
See more on DMTPC website

Example new activity towards goal

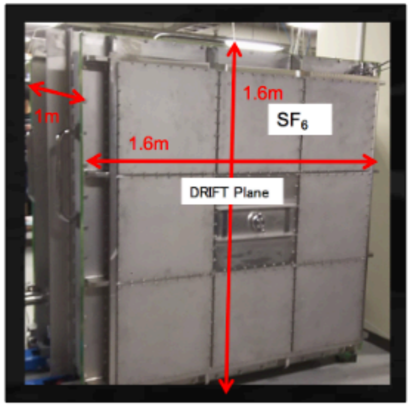
• CYGNUS-Kamioka, Japan, $1m^3$

- New $1m^3$ test facility built to compare readouts (K. Miuchi et al. Kobe)



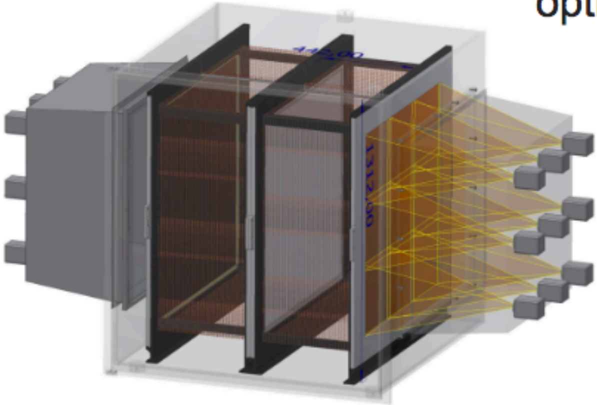


ThGEM prototype
(Sheffield group)

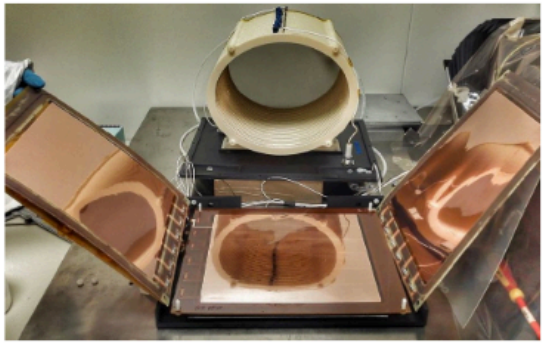


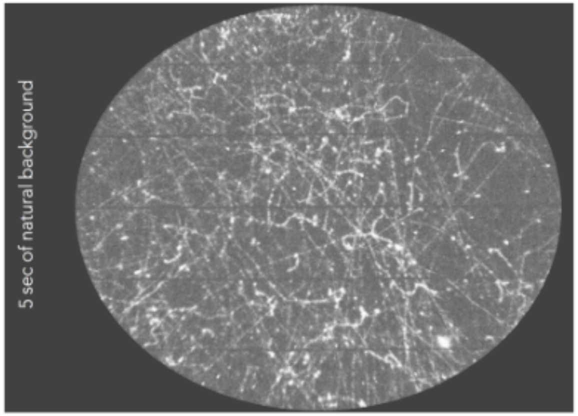
• CYGNO-LNGS, Italy, $1m^3$

- Funded R&D and proposed $1m^3$ test facility at LNGS (E. Baracchini et al., GSSI)
- Improved optical readout (CMOS + GEM), measure LNGS neutron background

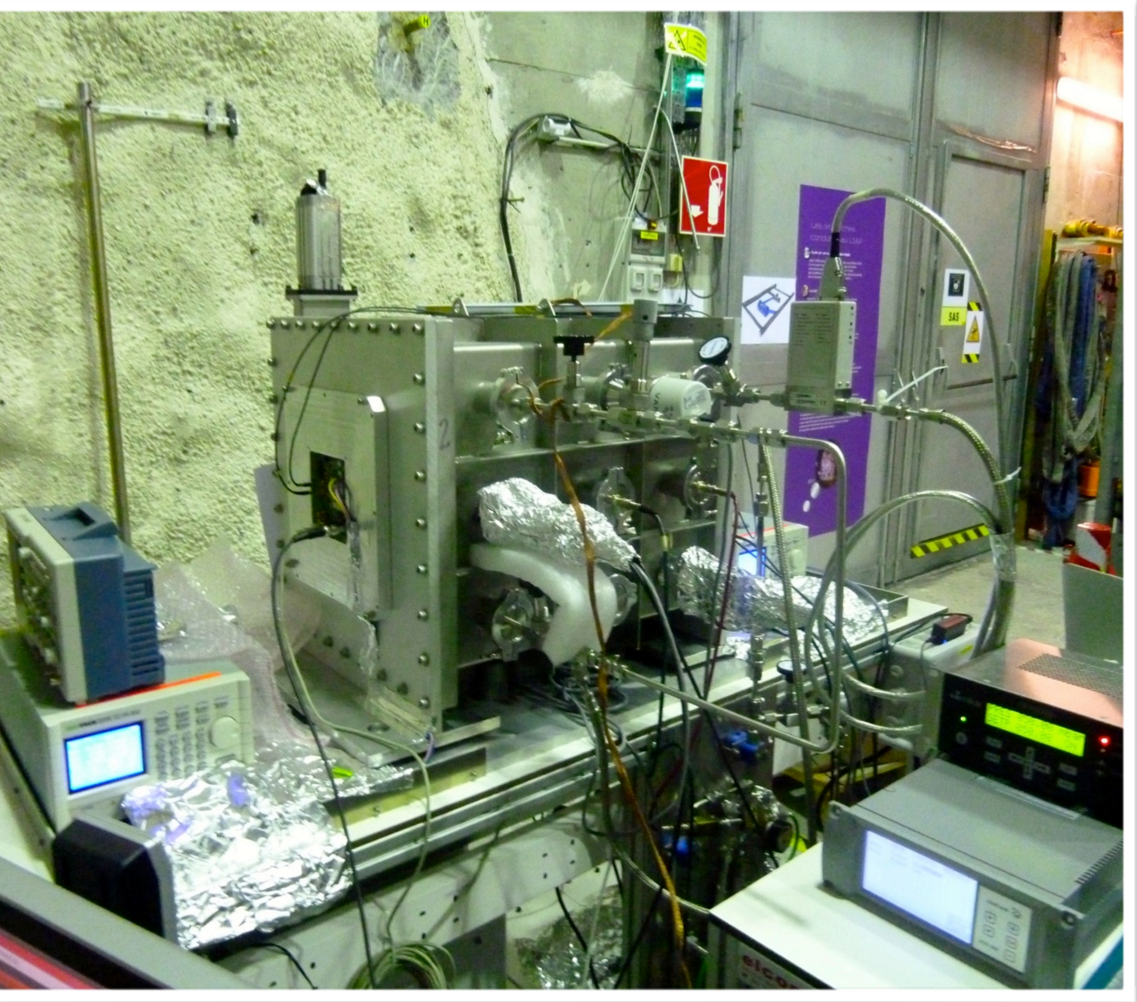


optical prototype (GSSI/Frascati)





Neil Spooner, IDM 2018



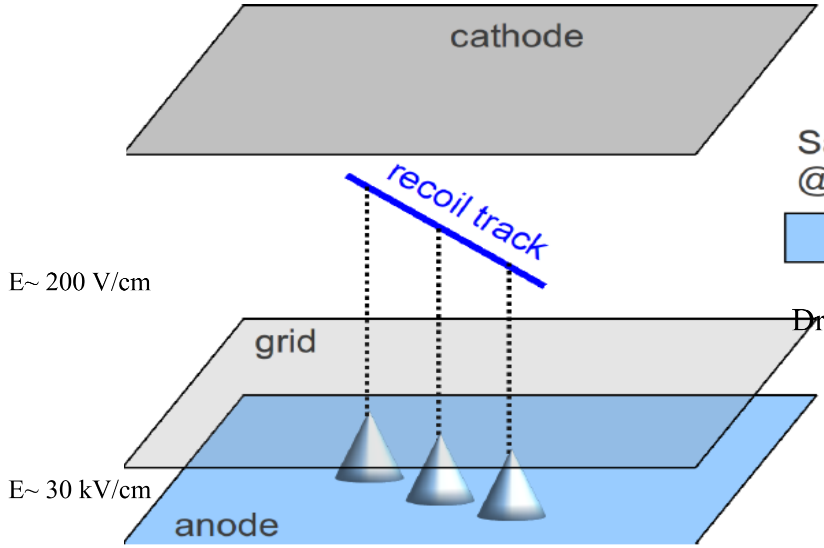
MIMAC (bi-chamber module)at
Modane Underground Laboratory
(France)
since June 22nd 2012.
Upgraded in June 2013, and
in June 2014.

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

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

Many thanks to LSM staff

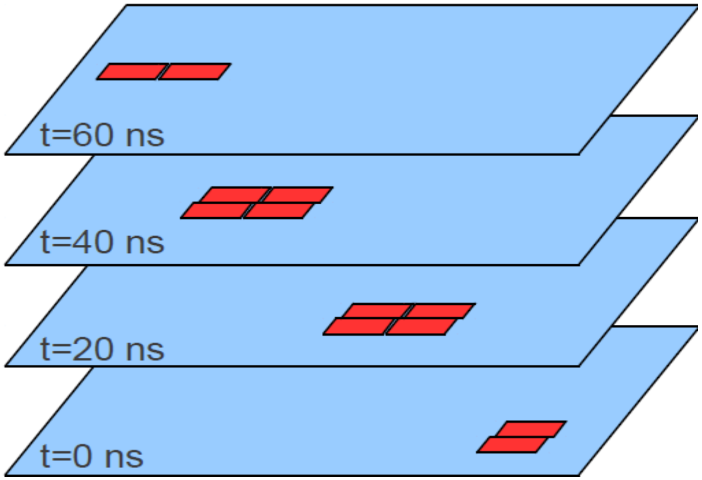
MIMAC: Detection strategy



Scheme of a MIMAC µTPC

Sampling
@ 50 MHz

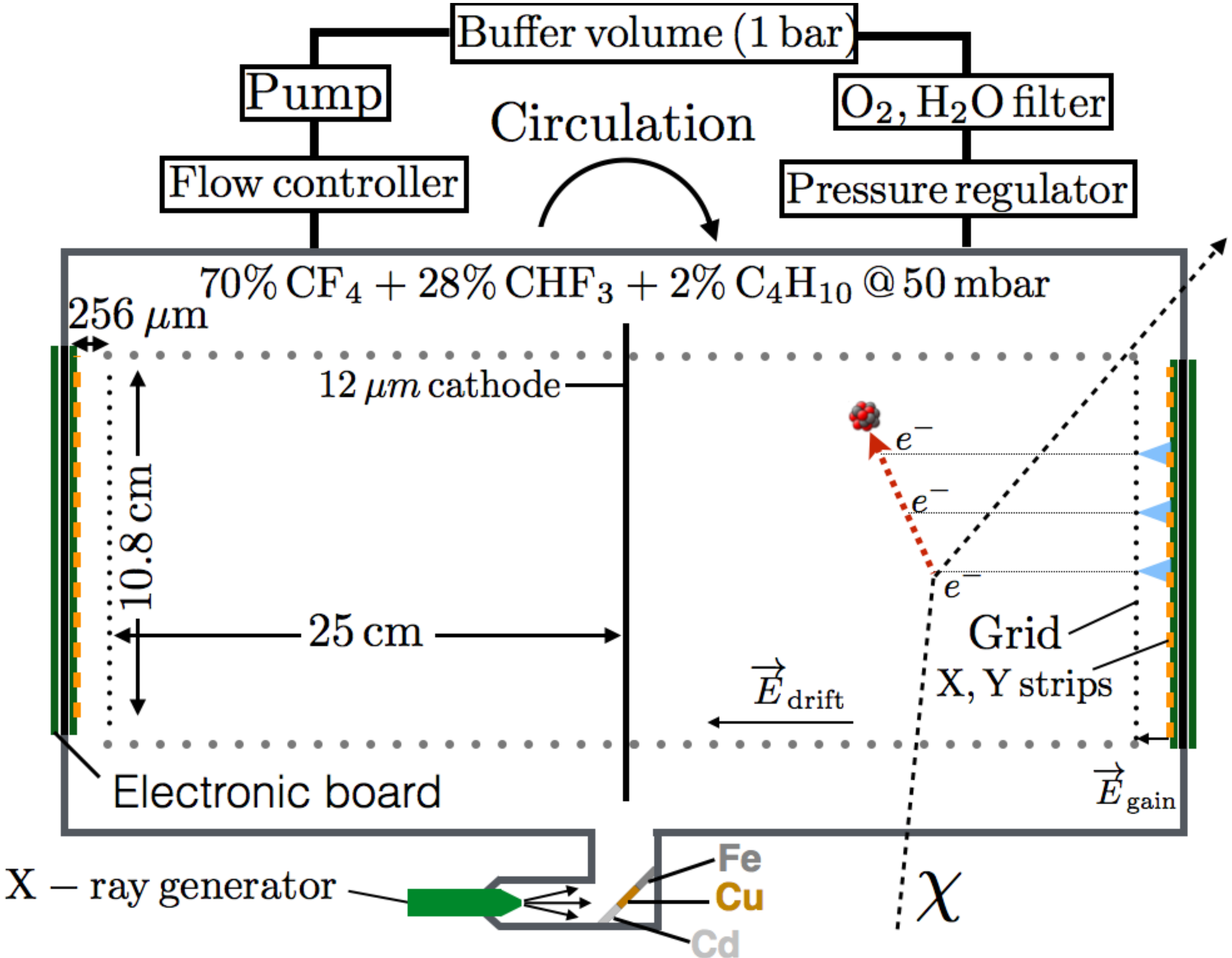
Drifting properties:
V ≈ 20 µm/ns



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



Buffer volume (1 bar)

Pump

Circulation

O_2, H_2O filter

Flow controller

Pressure regulator

70% CF_4 + 28% CHF_3 + 2% C_4H_{10} @ 50 mbar

256 μm

12 μm cathode

10.8 cm

25 cm

e^-

e^-

e^-

Grid

X, Y strips

$\vec{E}_{drift}$

$\vec{E}_{gain}$

Electronic board

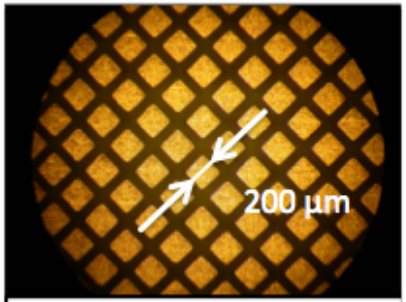
X – ray generator

Fe

Cu

Cd

χ



Micromegas 10x10 cm^2,
designed by IRFU- Saclay (France)

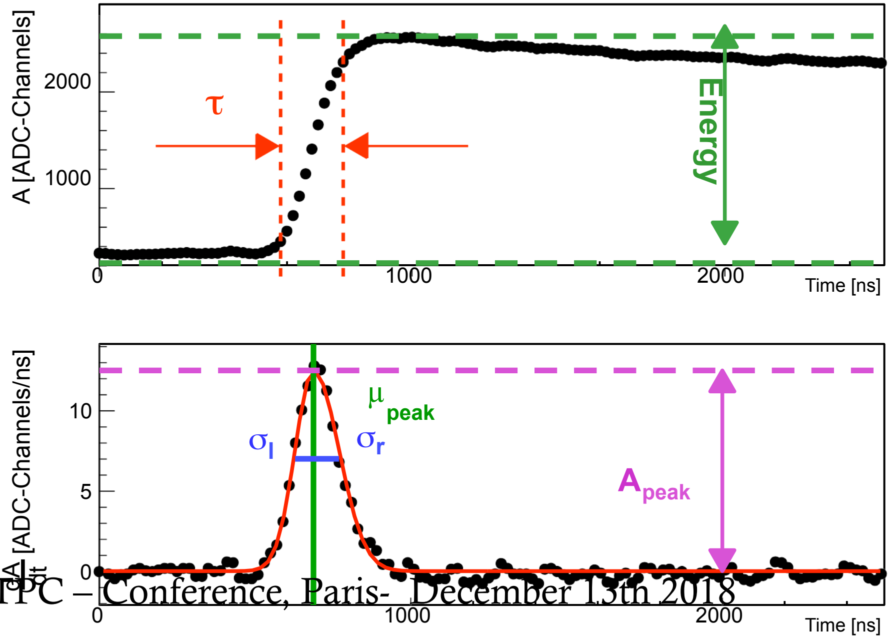
MIMAC Target: ^{19}F

- Light WIMP mass
- Axial coupling

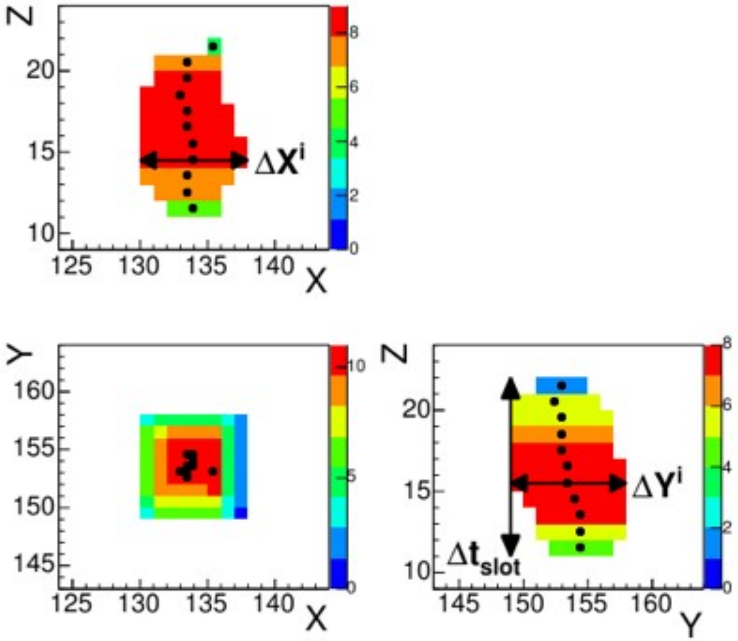
MIMAC readout

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

preamplifier signal + FADC: Energy



3D - track



D. Santos (LPSC Grenoble)

Detector calibration
(not at the maximum gain!)

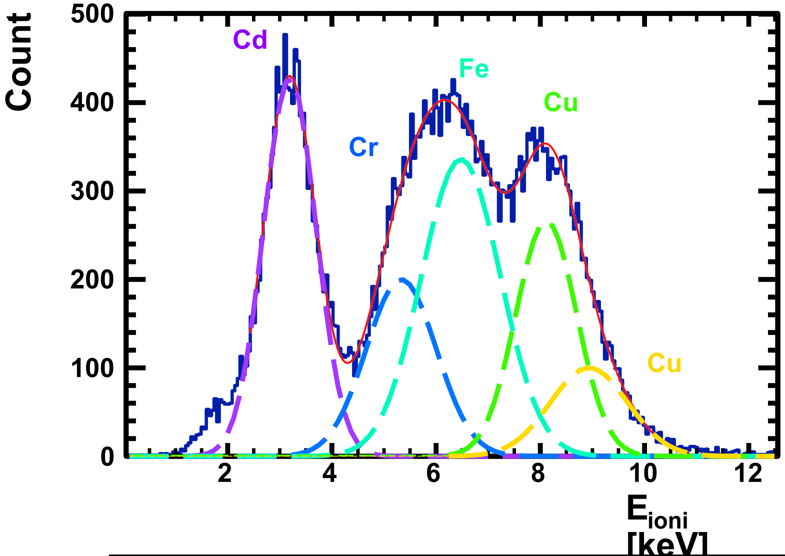
Calibration: (once a week)

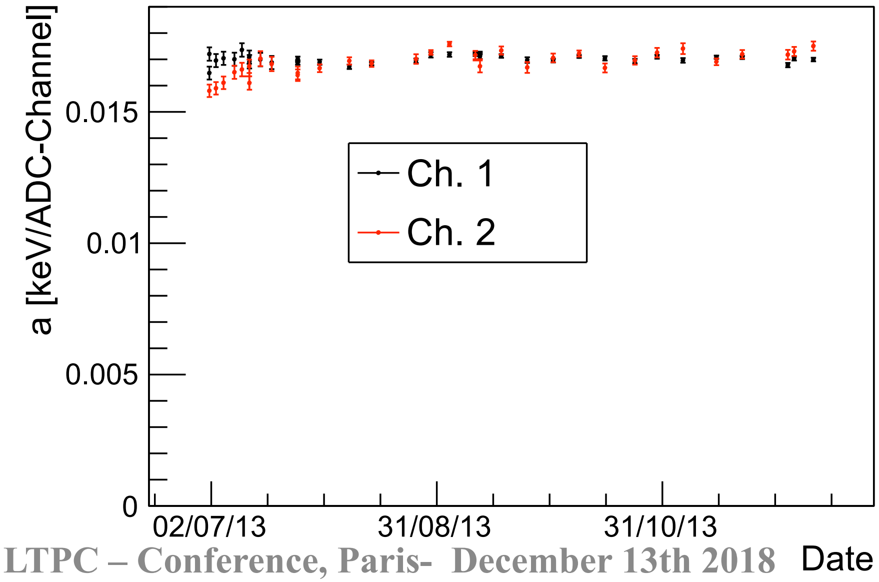
X-ray generator producing fluorescence photons from Cd, Fe, Cu foils.

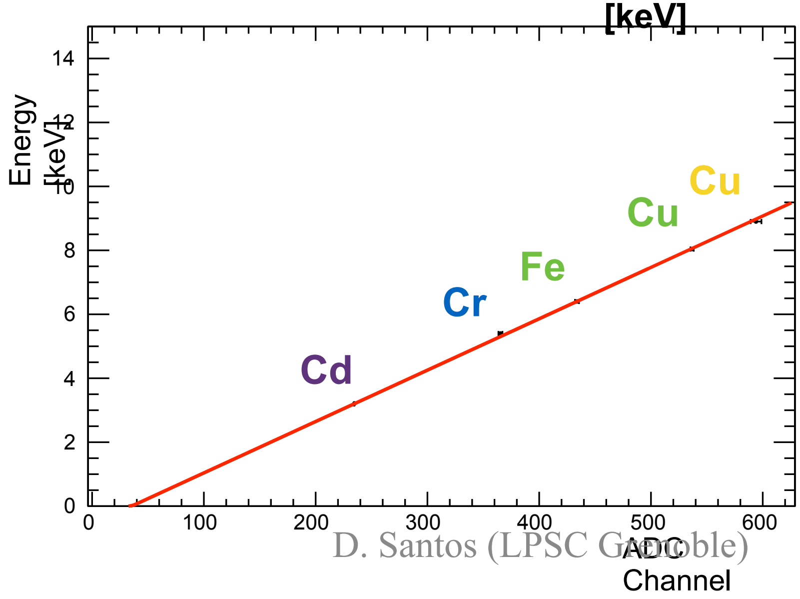
Threshold ~ 1 keV

Circulation system:

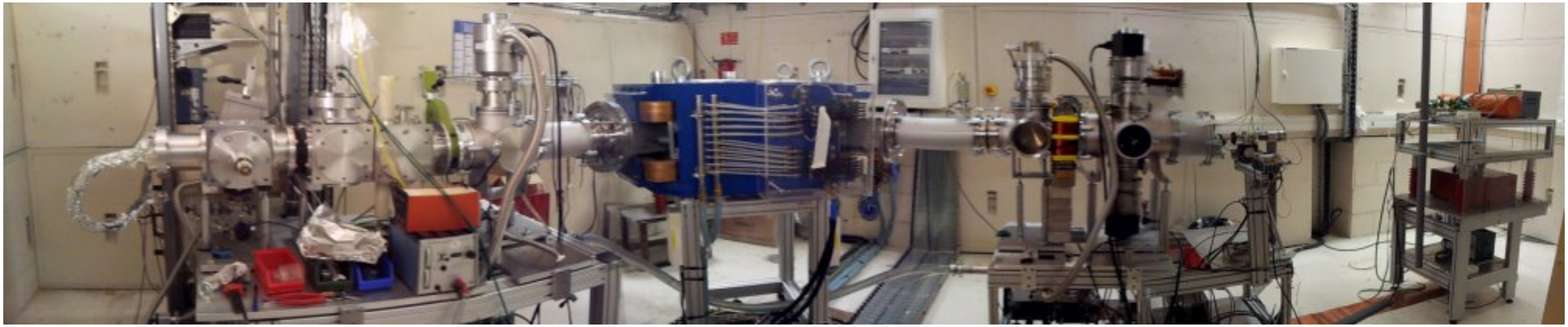
Excelent Gain stability in time

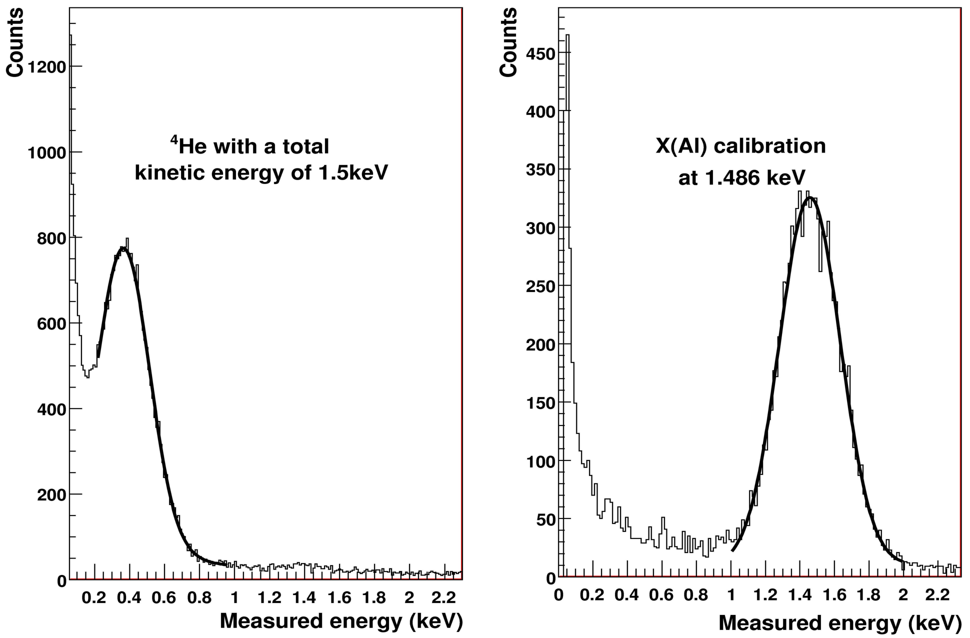


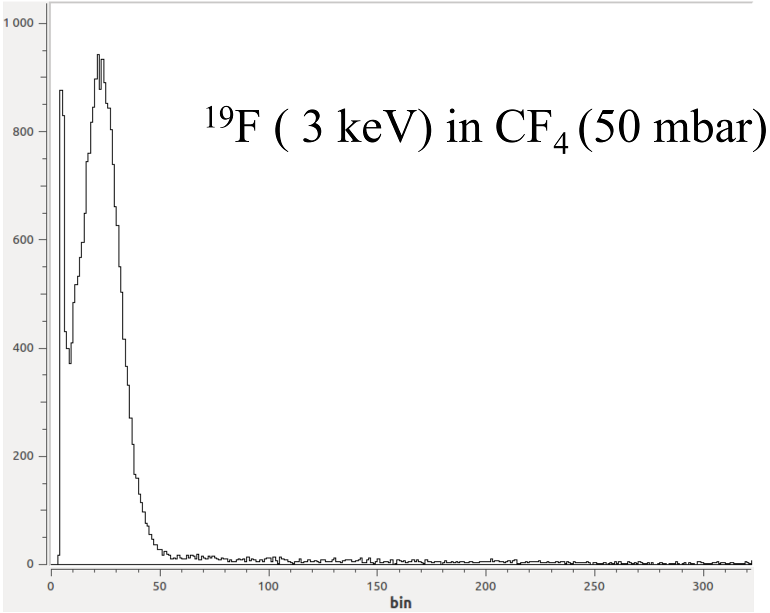




Ionization Quenching Factor Measurements at LPSC-Grenoble

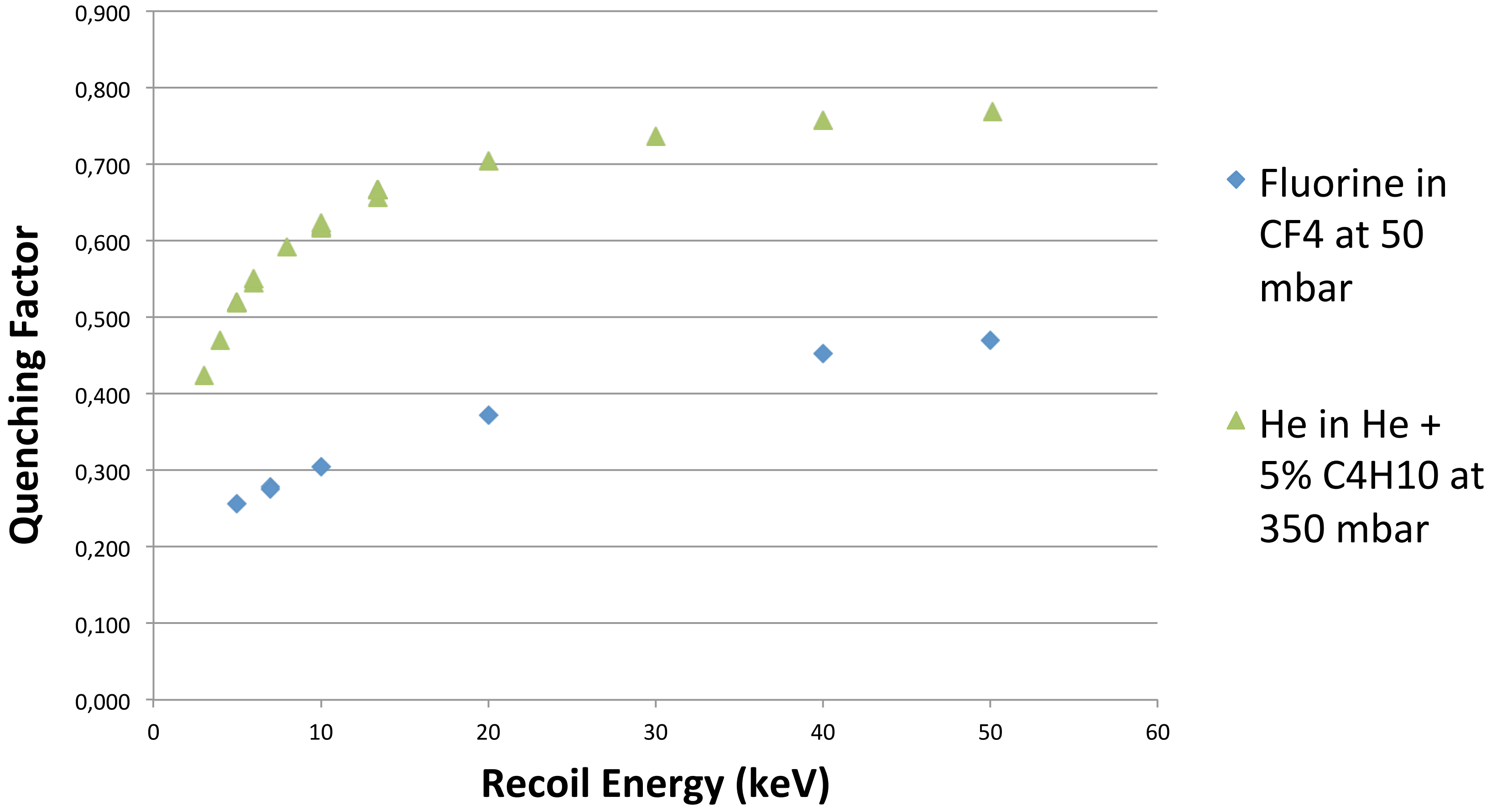




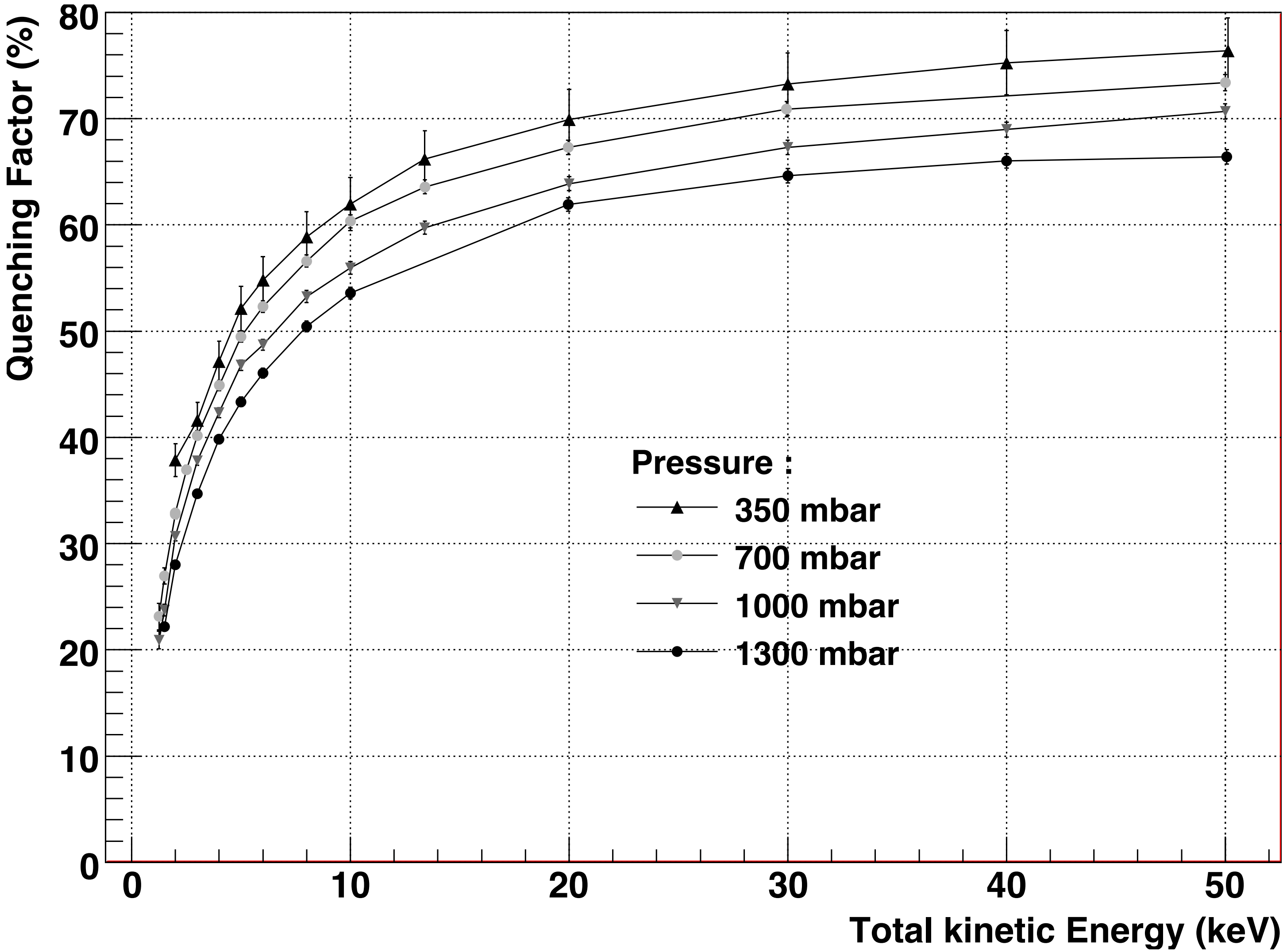


^{19}F (3 keV) in CF$_4$ (50 mbar)

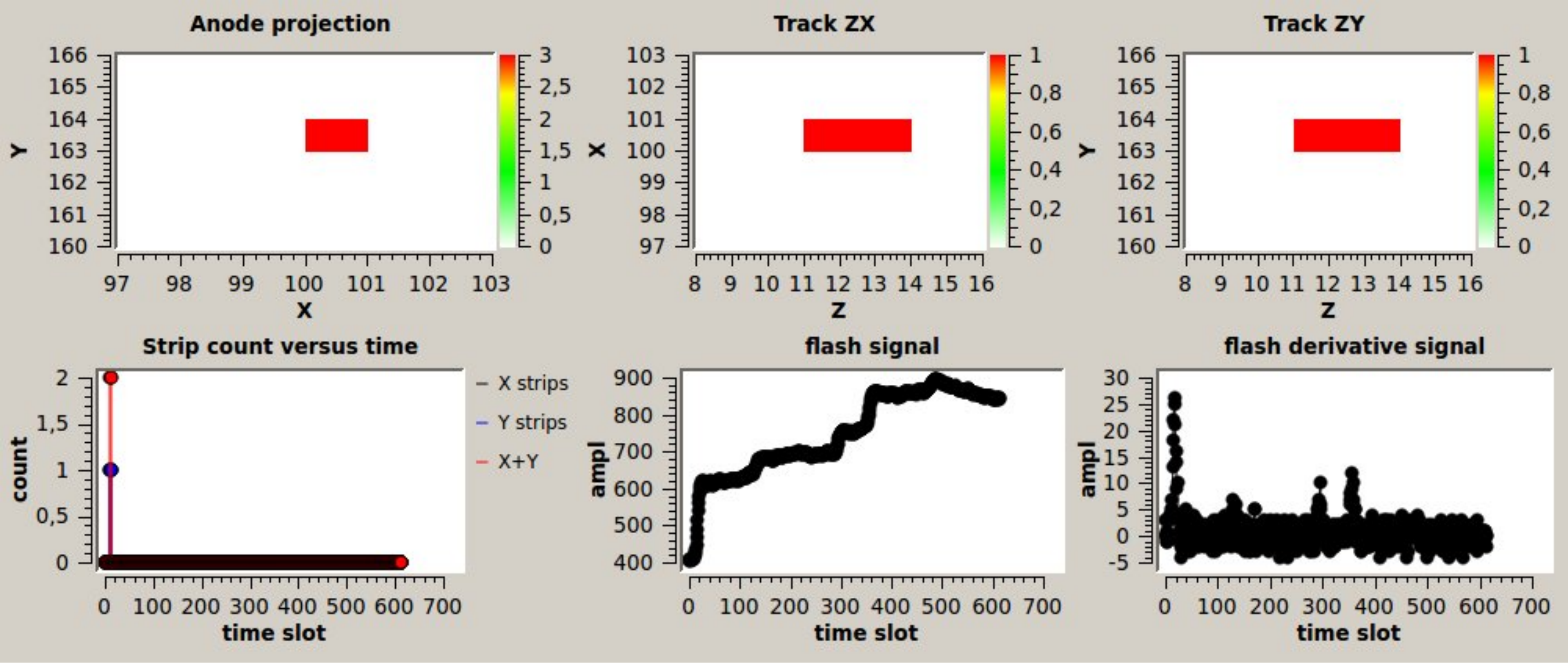
Ionization Quenching Factor for Fluorine in pure CF4 at 50 mbar



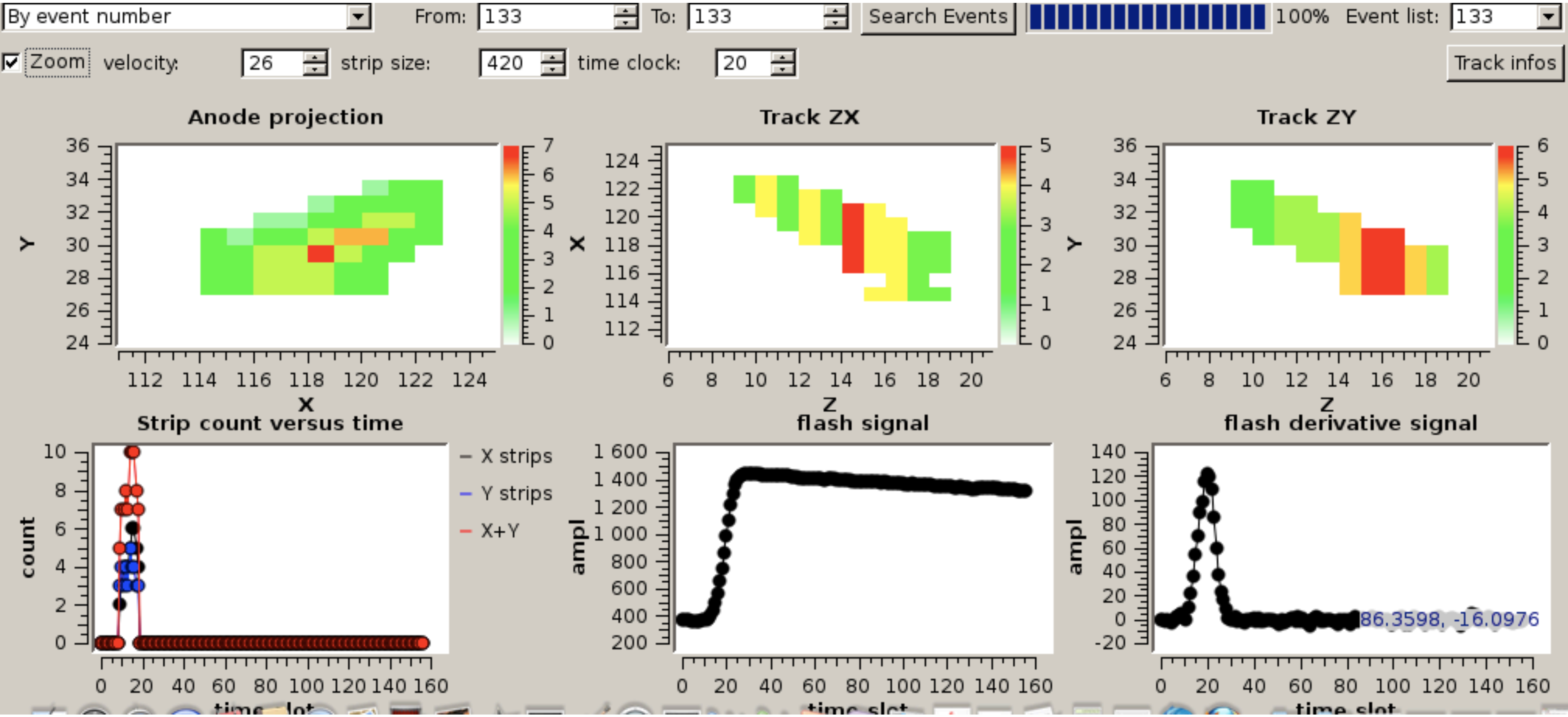
IQF in ^{4}He + 5% isobutane for different pressures!!



An Electron event (18 keV)



A “recoil event” (~ 34 keVee)



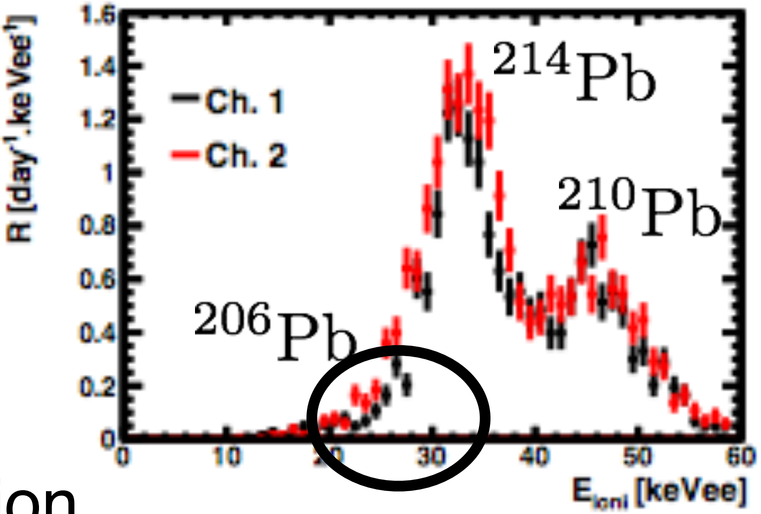
By event number
From: 133
To: 133
Search Events
100%
Event list: 133
☑ Zoom
velocity: 26
strip size: 420
time clock: 20
Track infos

First detection of 3D tracks of Rn progeny

Electron/recoil discrimination

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

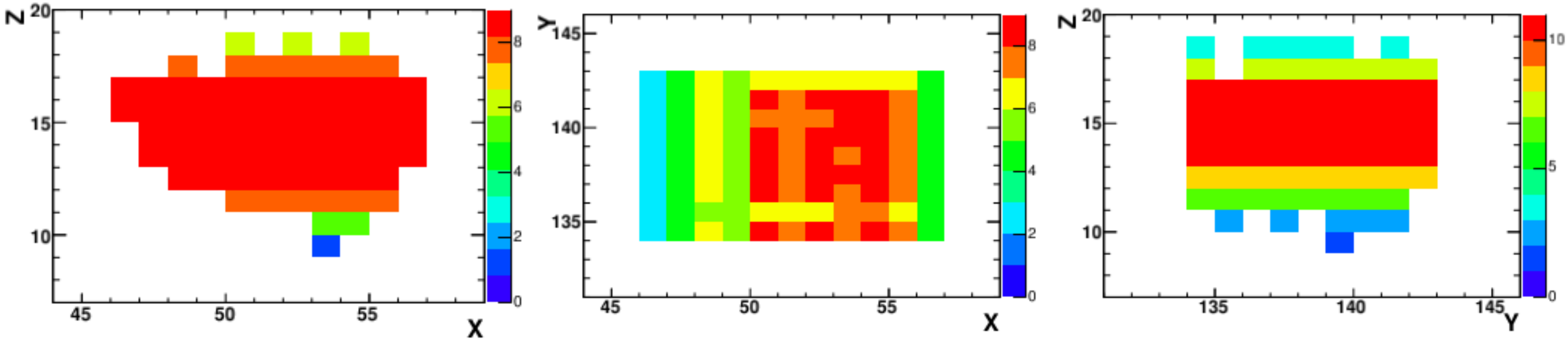
Nuclear recoil spectra



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

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

→ MIMAC detection strategy validation

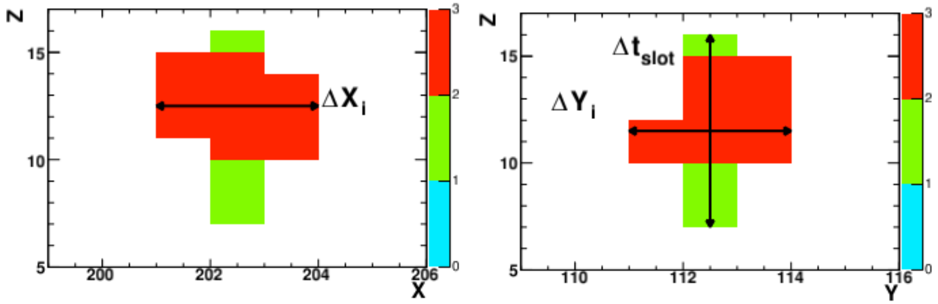


RPR events occur at different positions in the detector…

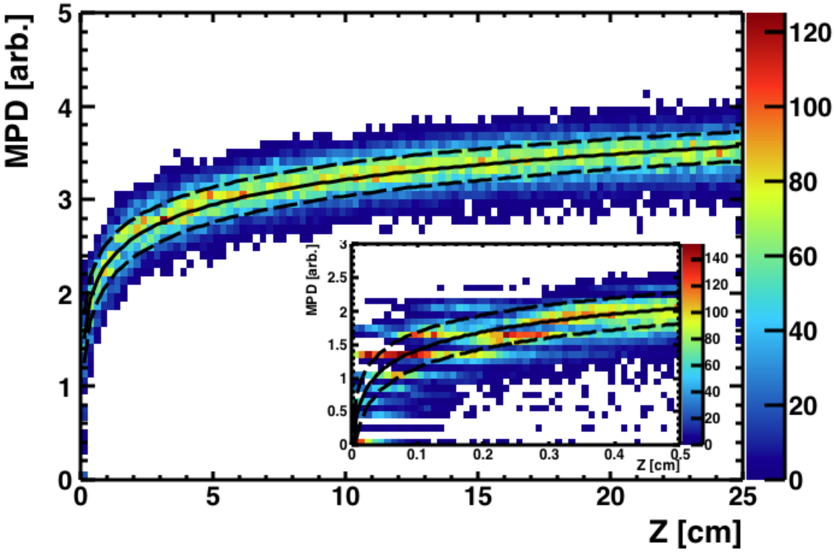
$$z_0 \longleftrightarrow \text{Diffusion}$$

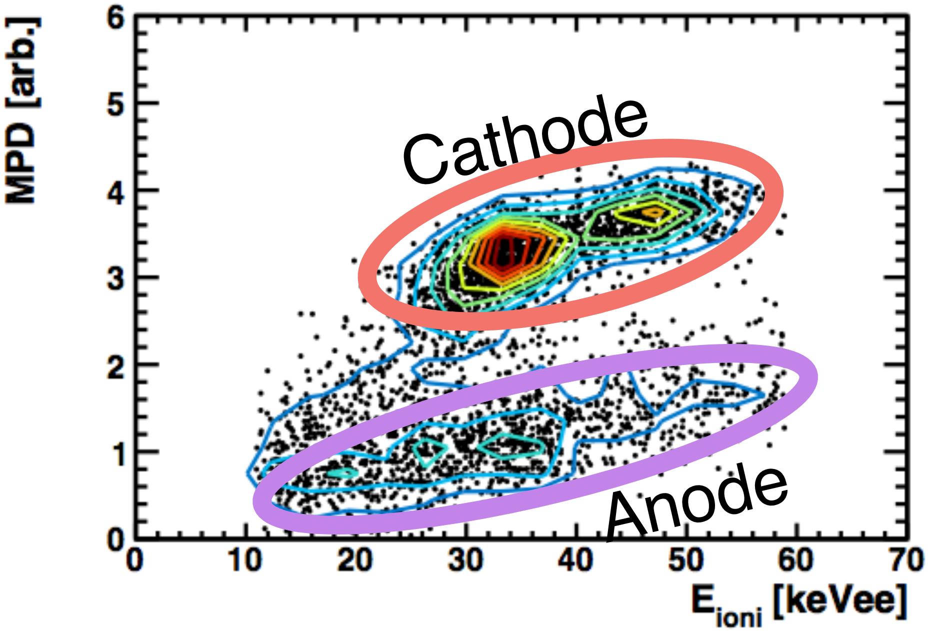
$$\begin{cases} D_T = 237.9\,\mu\text{m}/\sqrt{\text{cm}} \\ D_L = 271.5\,\mu\text{m}/\sqrt{\text{cm}} \end{cases}$$

« Anode » event



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





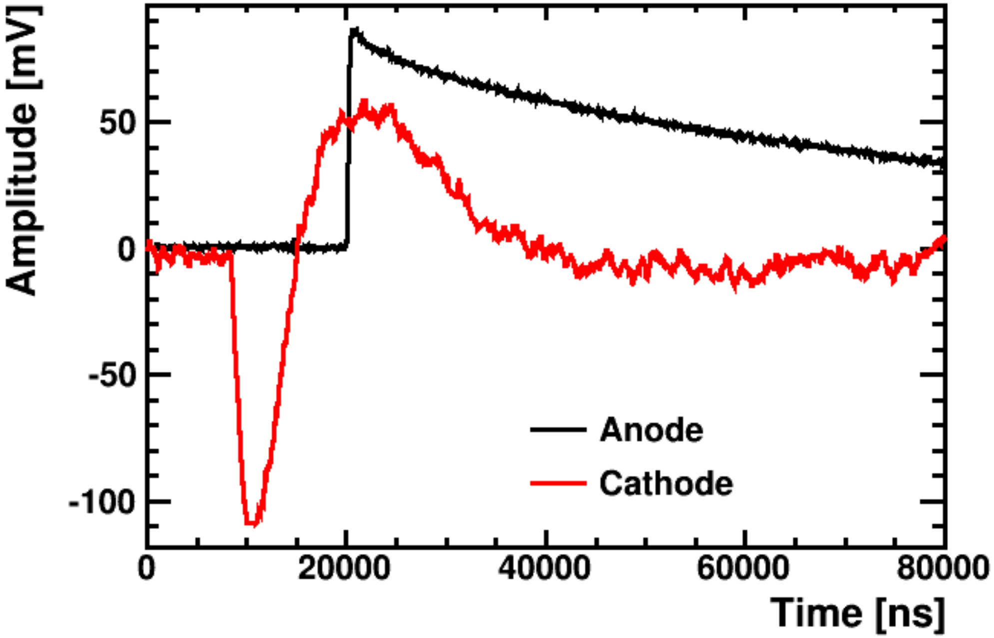
Cathode Signal to place the 3D-track

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

C. Couturier, Q. Riffard, N. Sauzet, O. Guillaudin, F. Naraghi, and D. Santos. Journal of Instrumentation, 12(11):P11020, 2017b.

-

)



Measurement in a MIMAC chamber of an alpha passing through the active volume parallel to the cathode at 10 cm distance.

MIMAC-Cathode Signal Drift velocity measurements

C. Couturier, Q. Riffard, N. Sauzet, O. Guillaudin, F. Naraghi, and D. Santos.
Journal of Instrumentation, 12(11):P11020, 2017b.

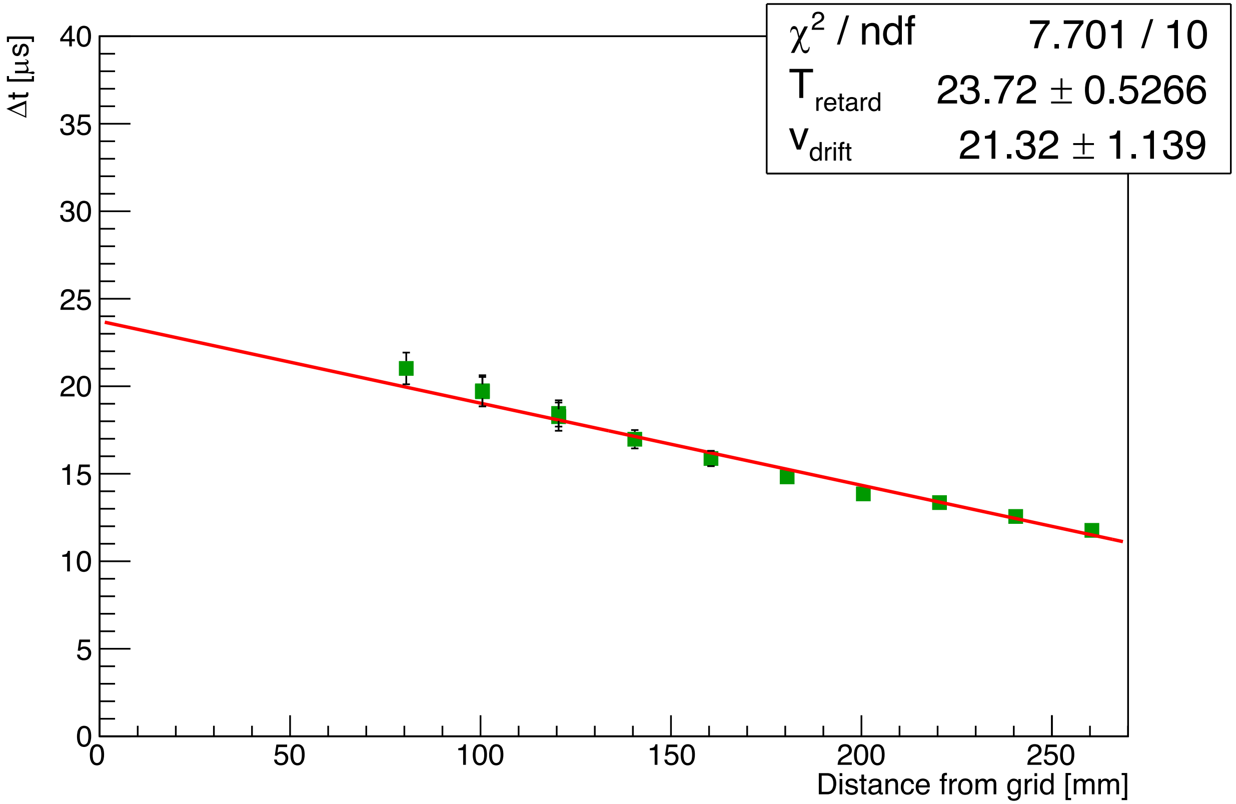
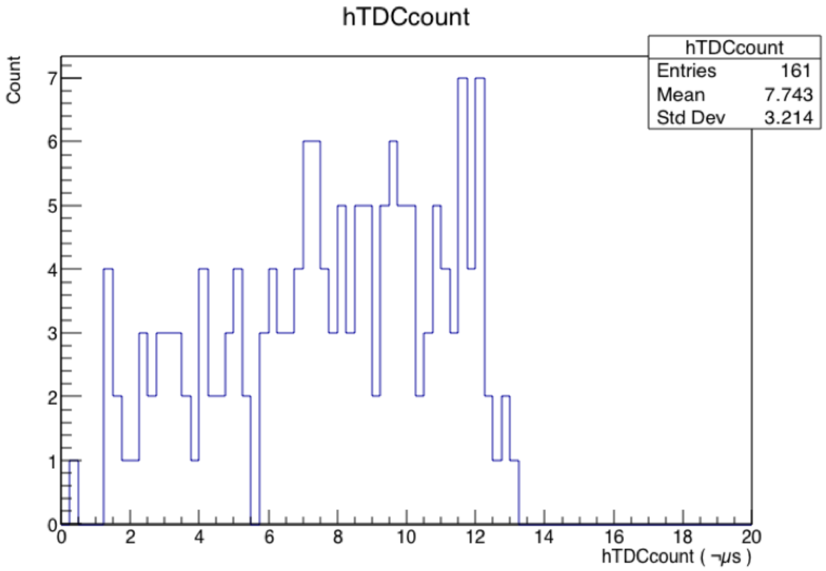


Figure 4. Measure of the time differences (TAC) between the grid signal and the delayed cathode signal in the "START Grid" configuration, as a function of the distance of the α source from the anode (green points) ; error bars correspond to the standard deviation of the mean. A linear fit of these points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

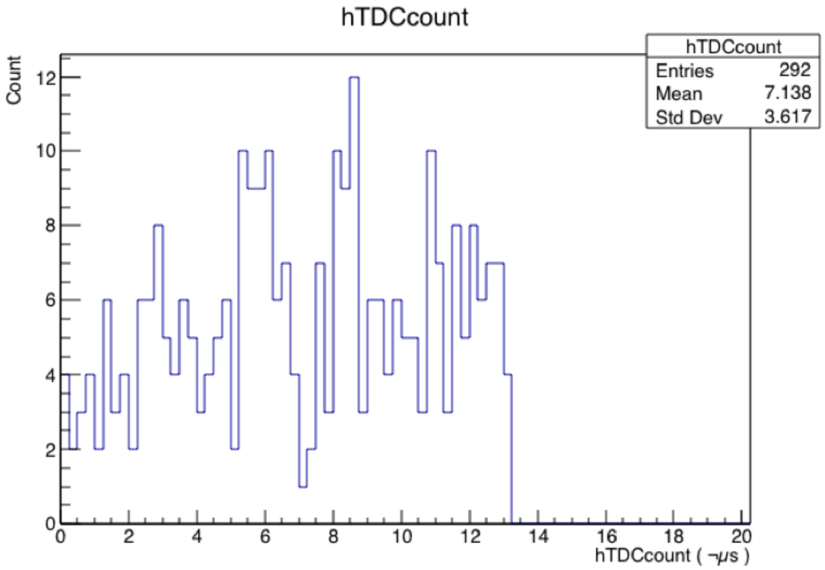
First Cathode Signals from the MIMAC bichamber background

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

Chamber 1

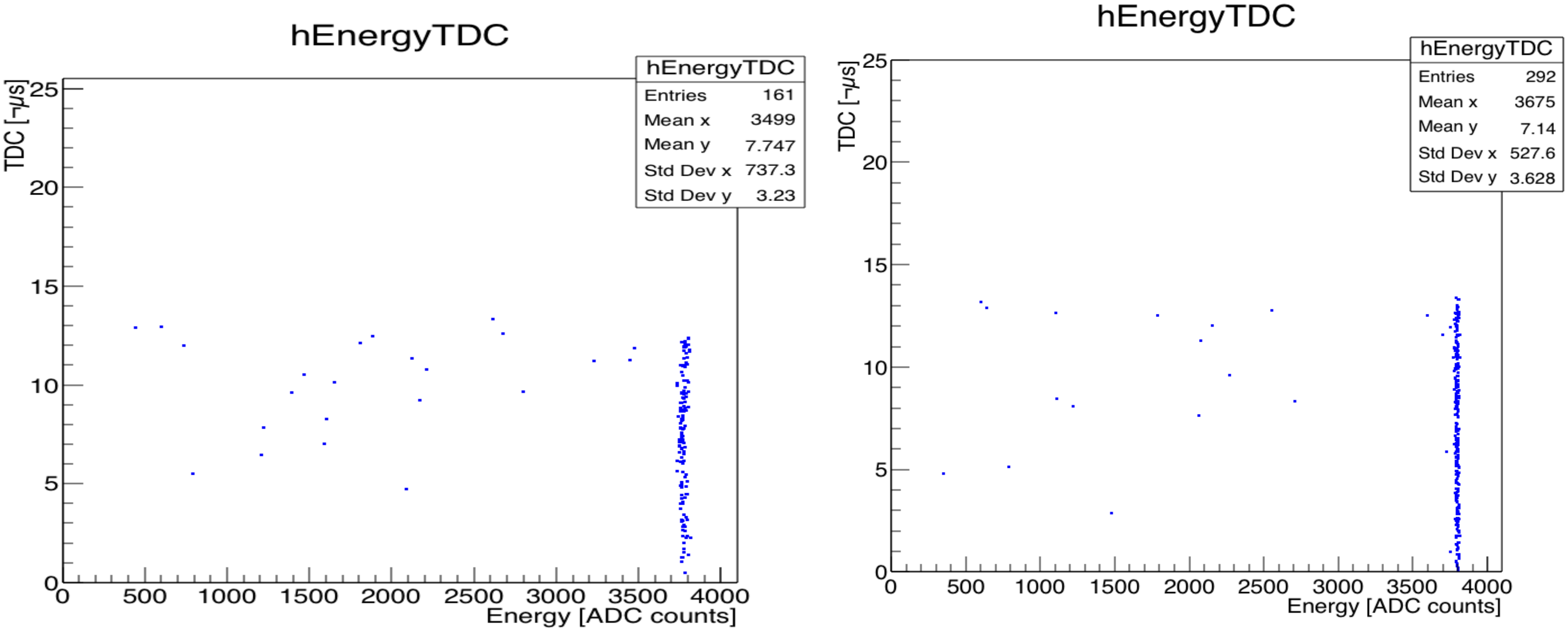


Chamber 2



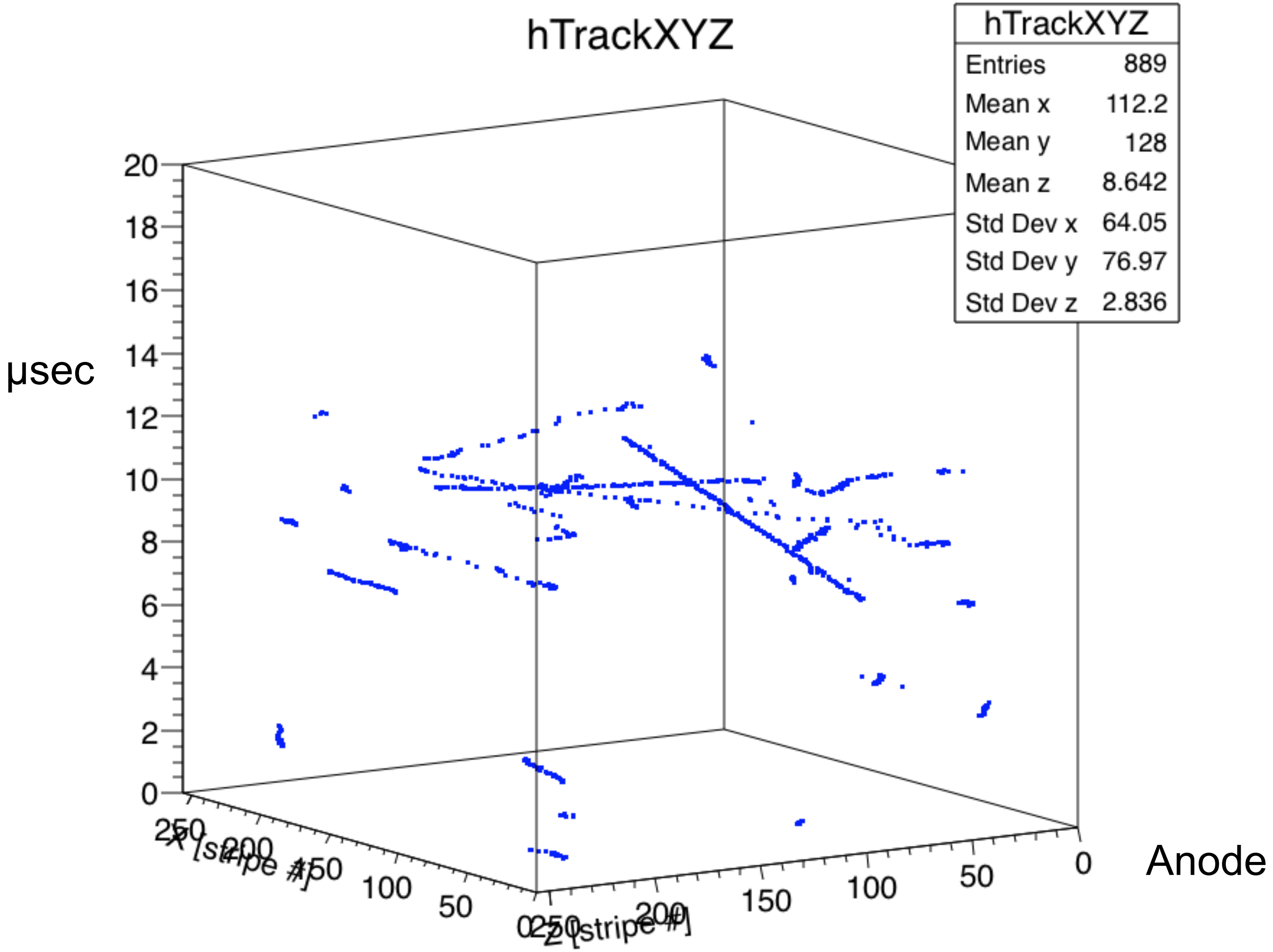
Measuring the time between the “event production” and the avalanche signal !!
Covering the 26 cm drift distance (13 us x 20 um/ns) !!

Ionization Energy distribution of the events recorded with the Cathode Signal

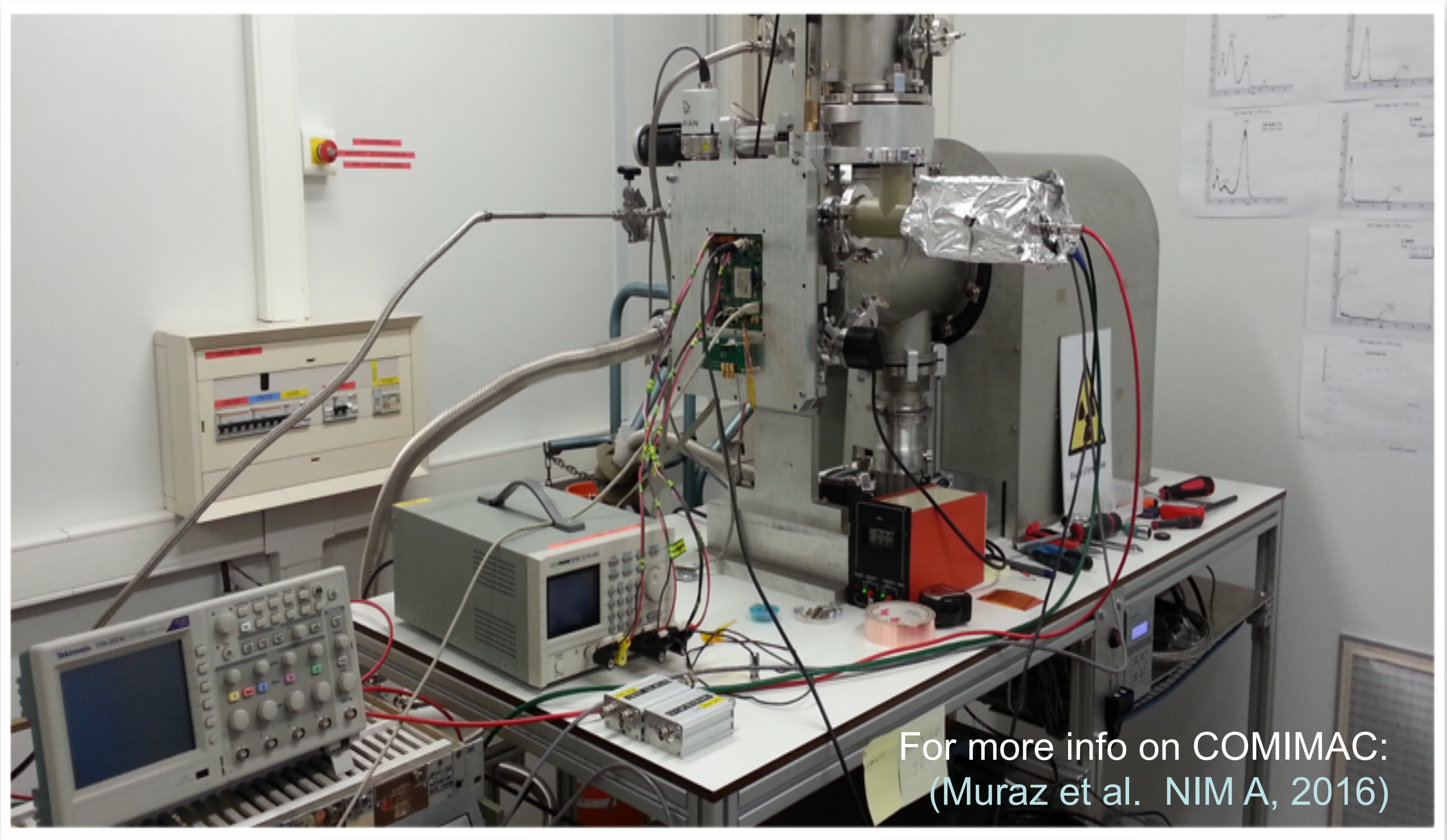


Energy range: 1-60 keV

3D event-localization in MIMAC



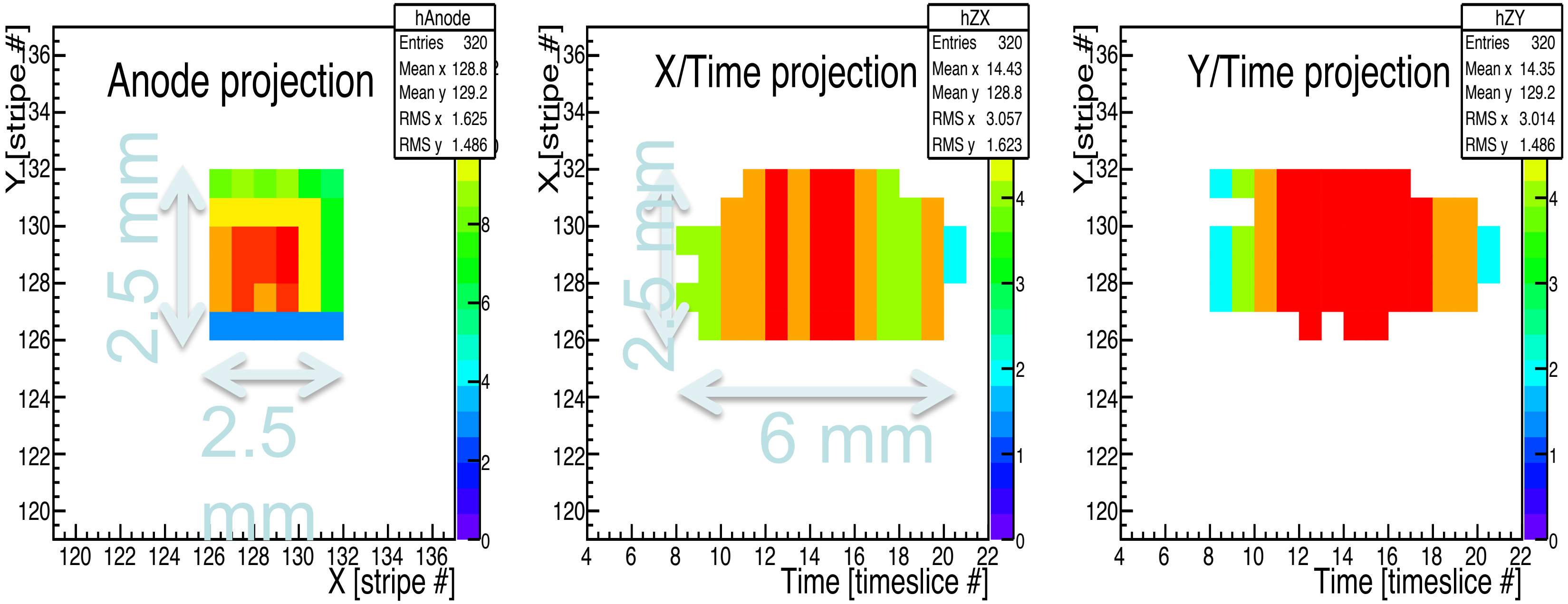
First controlled Fluorine tracks, using COMIMAC



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

COMIMAC: first measurements on controlled tracks of Fluorine

25 keV (kinetic) Fluorine → ~ 9 keVee

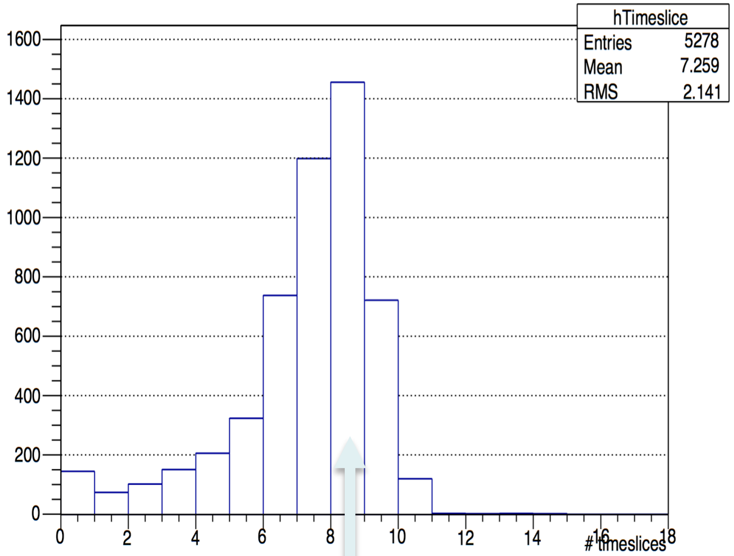


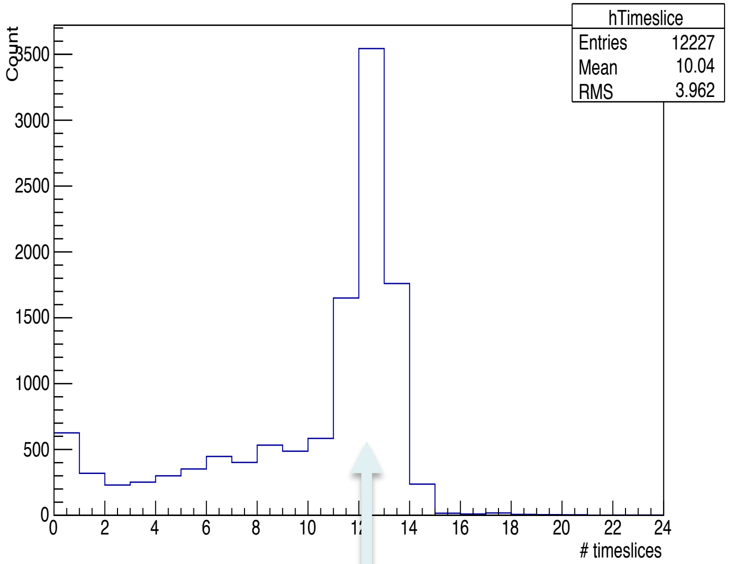
D. Santos (LPSC Grenoble)

COMIMAC: first controlled tracks of ^{19}F

8 keV kinetic → 2 keVee

25 keV kinetic → 9 keVee





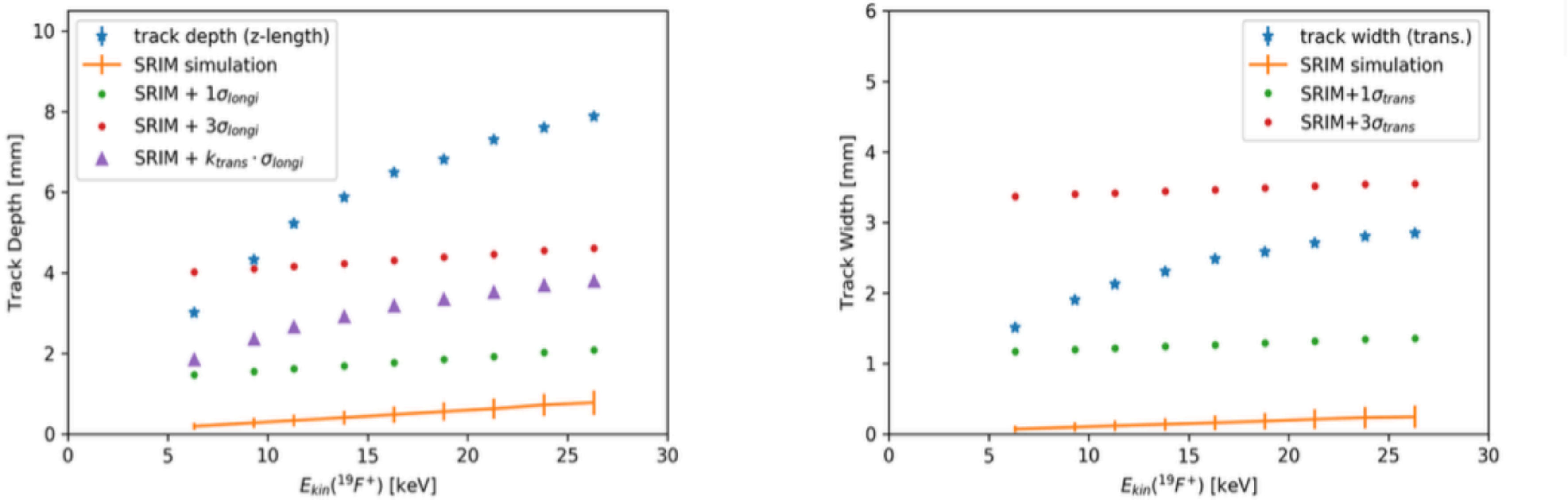
8 timeslices
* 20 ns/timeslices
* 23.5 μm/ns
= 3.8 mm

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

C. Couturier, I. Moric, Y. Tao et al. (in preparation)

Track “Lengths” measured with COMIMAC

(Y. Tao, I. Moric et al. 2018 to be published)

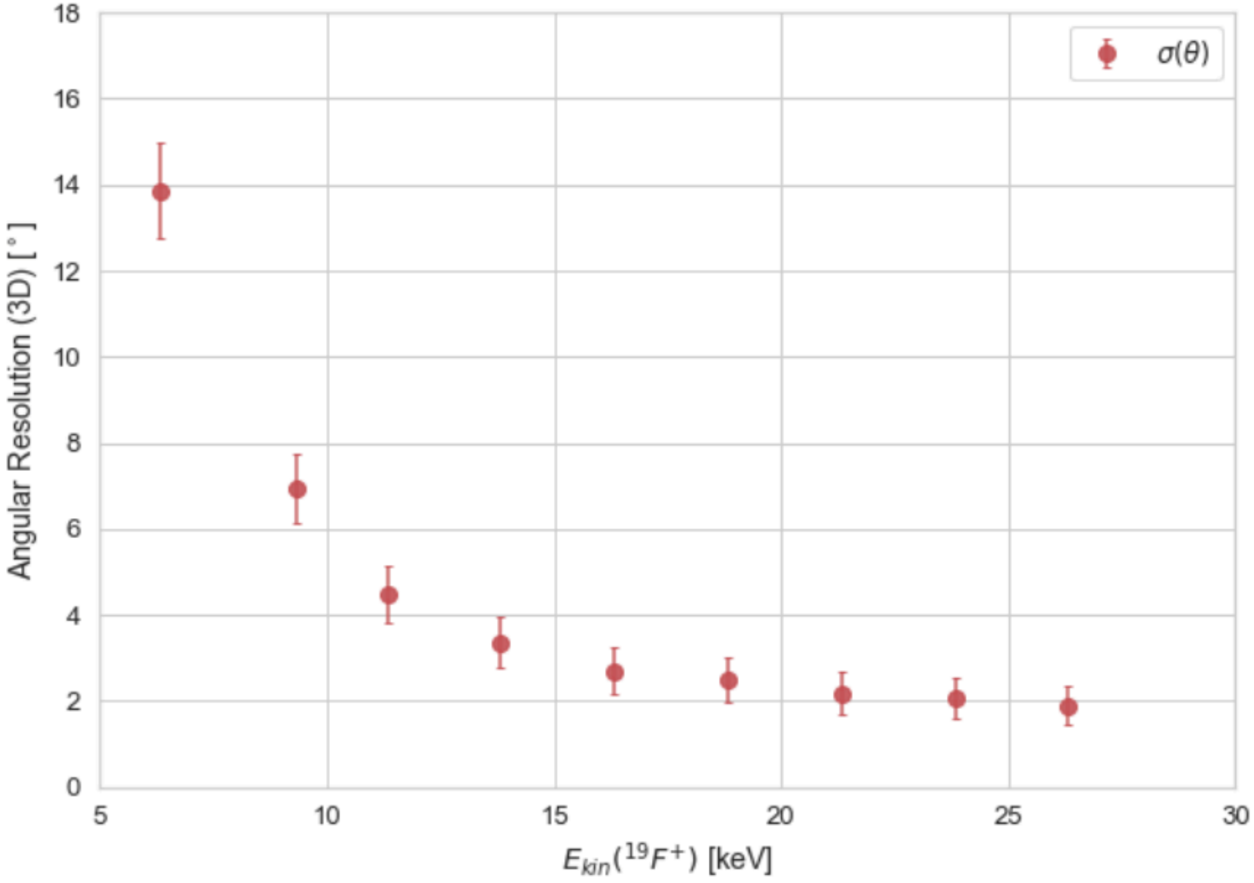


(a) Track depth comparison

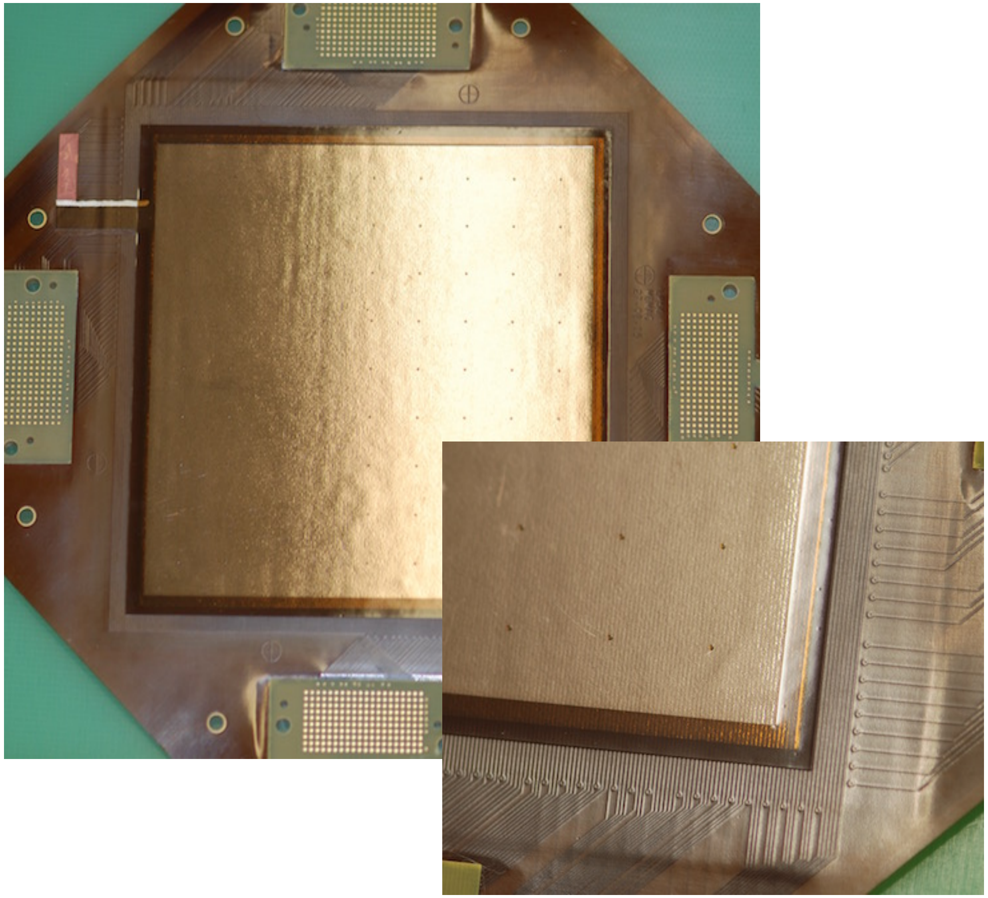
(b) Track width comparison

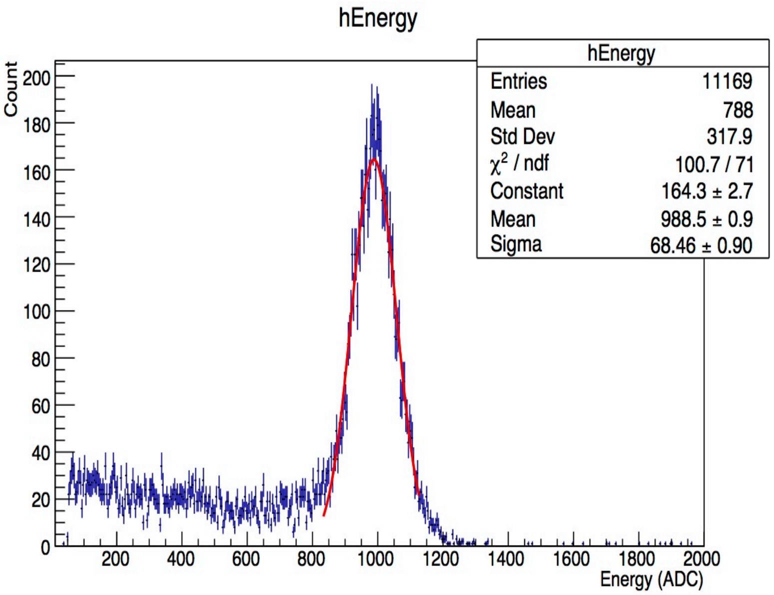
Figure 9. Comparison of ion track depths and widths at different energies between experiment (blue stars) and simulation using SRIM and MAGBOLTZ (orange curve for SRIM-only, green and red dots for adding extra 1σ and 3σ MAGBOLTZ diffusion contributions). Left: Track depth comparison. We also show ”SRIM + $k_{trans} \cdot \sigma$ of MAGBOLTZ” in this subplot, where k_{trans} depends on energy and derived from the width result, showing the experimental contribution of diffusion. Right: Track widths comparison.

Angular resolution measured with COMIMAC
(^{19}F ions at known kinetic energies)
(Y. Tao, I. Moric et al. (2018) to be published)



New MIMAC low background detector
10 cm x 10 cm



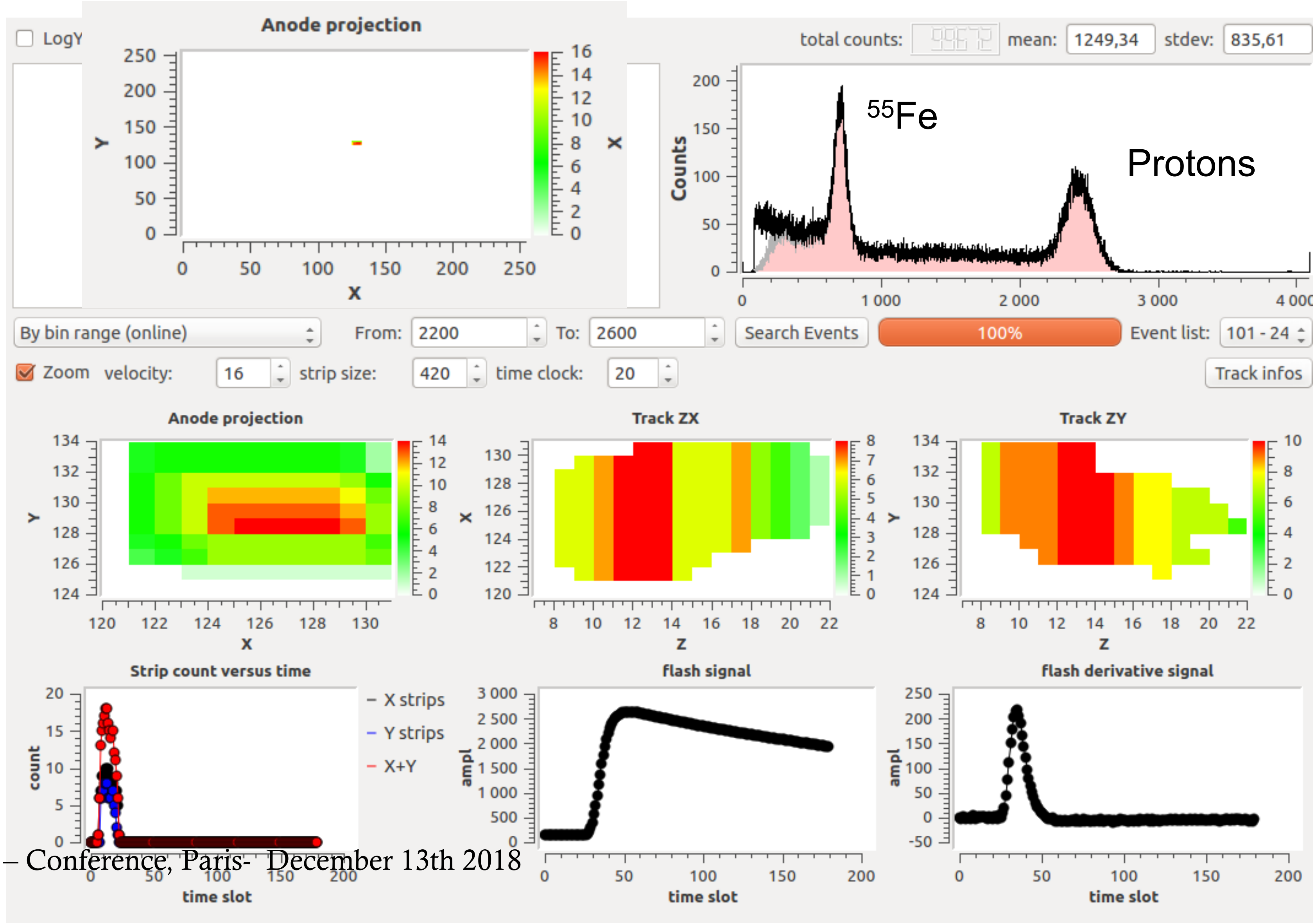


Gaz : MIMAC 50 mbar
HT grille : -560 V
Drift field : -150 V/cm

Kapton micromegas readout
Piralux Pilar

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

Proton (E_{kin}= 25 keV) in MIMAC gas with the new low-background detector (05/2017)



☐ LogY

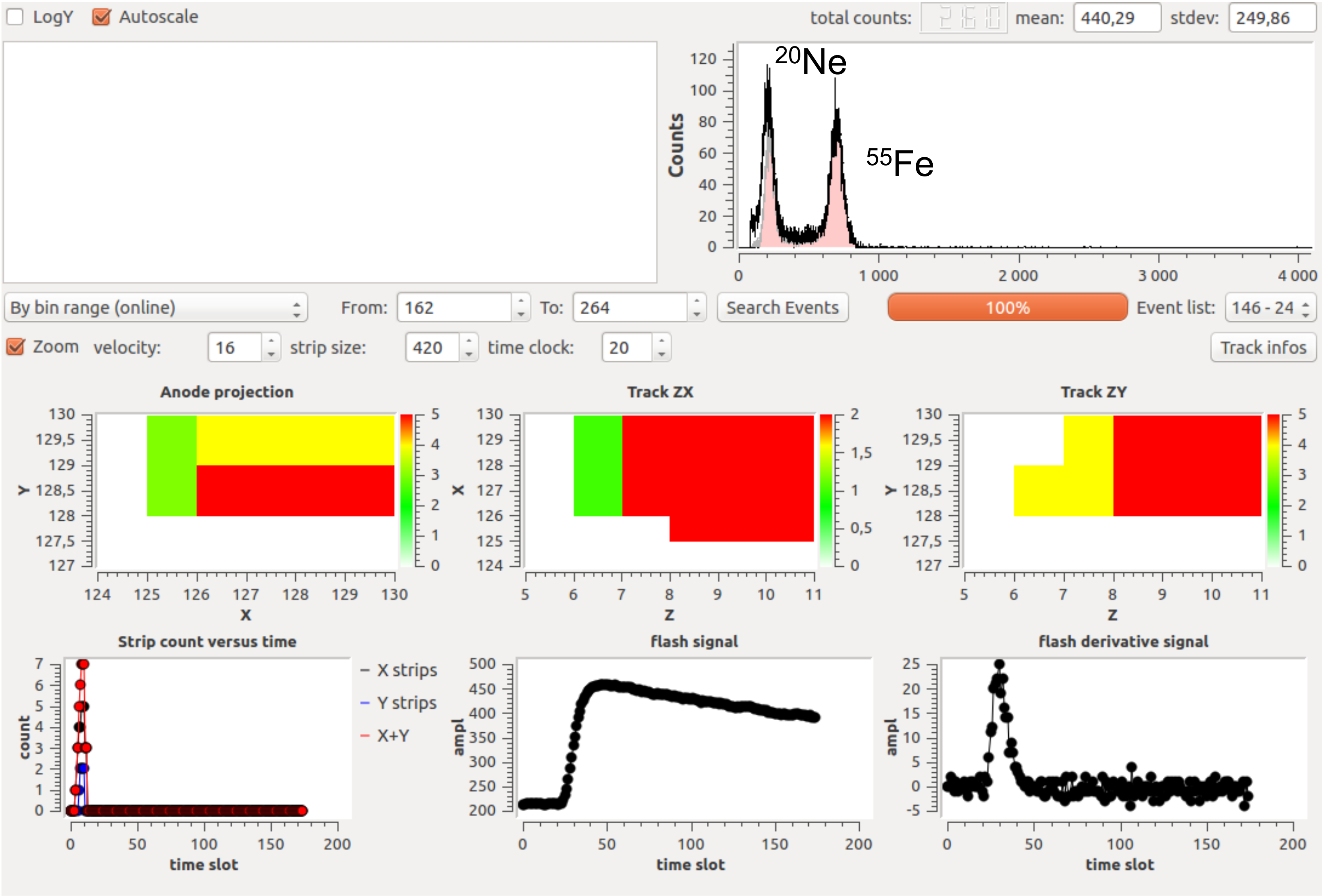
total counts: 99672 mean: 1249,34 stdev: 835,61

By bin range (online) From: 2200 To: 2600

Event list: 101 - 24

☑ Zoom velocity: 16 strip size: 420 time clock: 20

^{20}Ne (E_{kin}= 7.3 keV !!)



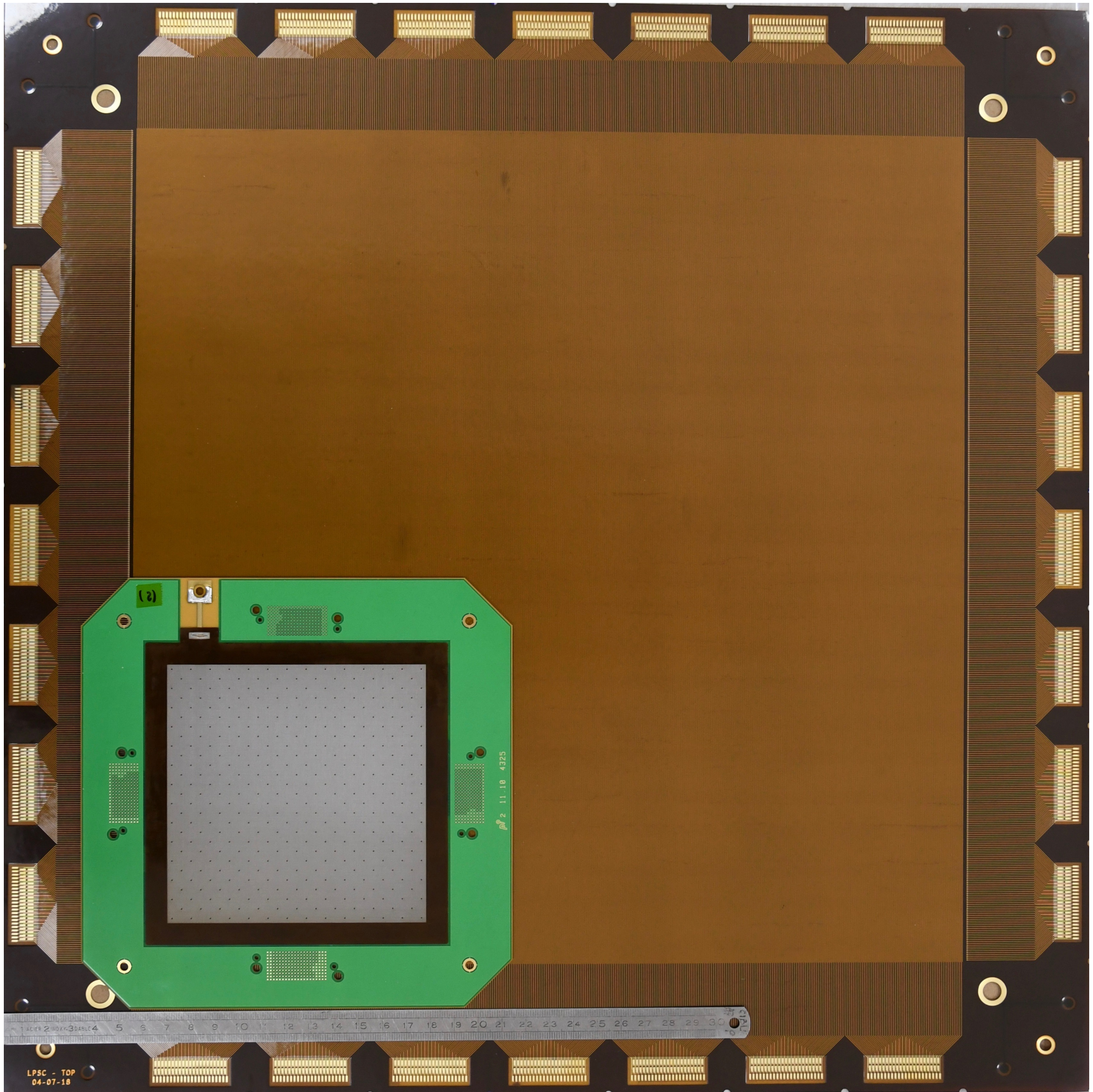
☐ LogY ☑ Autoscale

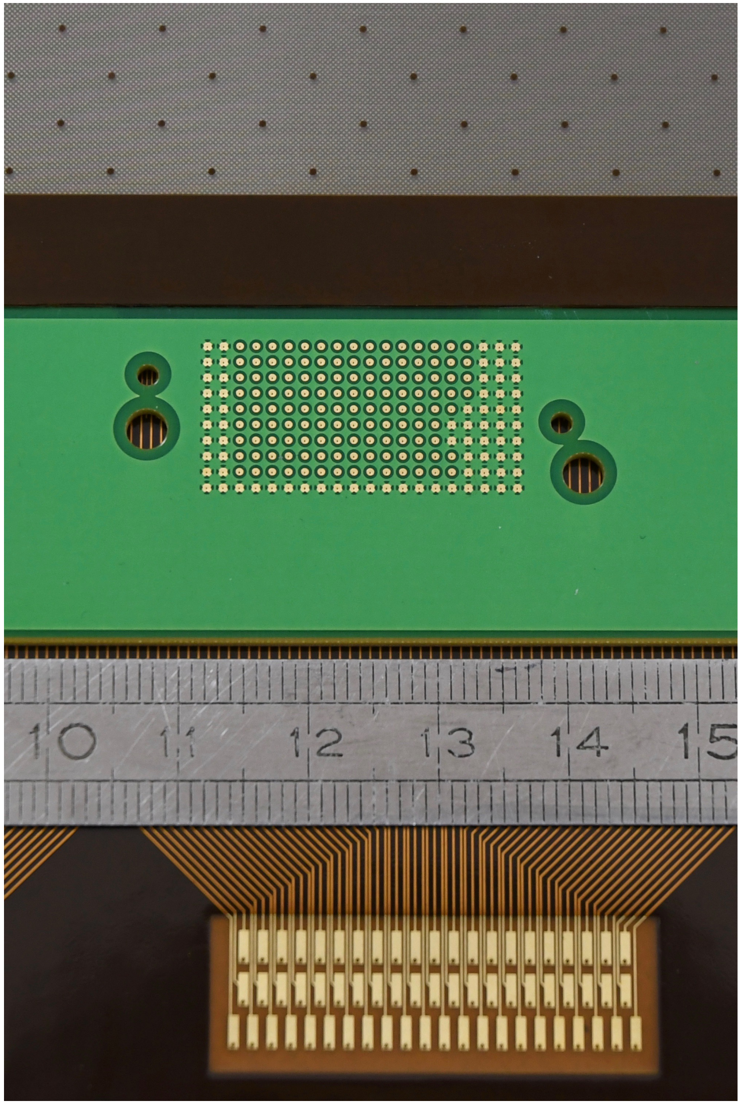
total counts: 260 mean: 440,29 stdev: 249,86

By bin range (online) From: 162 To: 264 Search Events 100% Event list: 146 - 24

☑ Zoom velocity: 16 strip size: 420 time clock: 20 Track infos

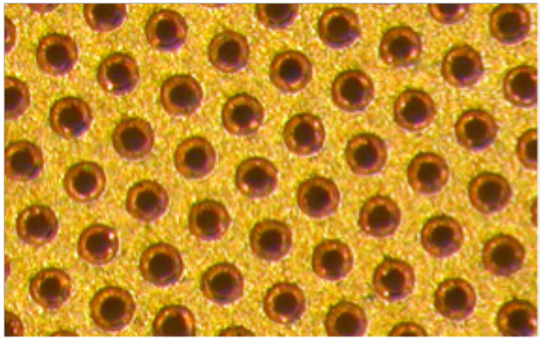
The new 35 cm "new technology" MIMAC detector compared to the old one

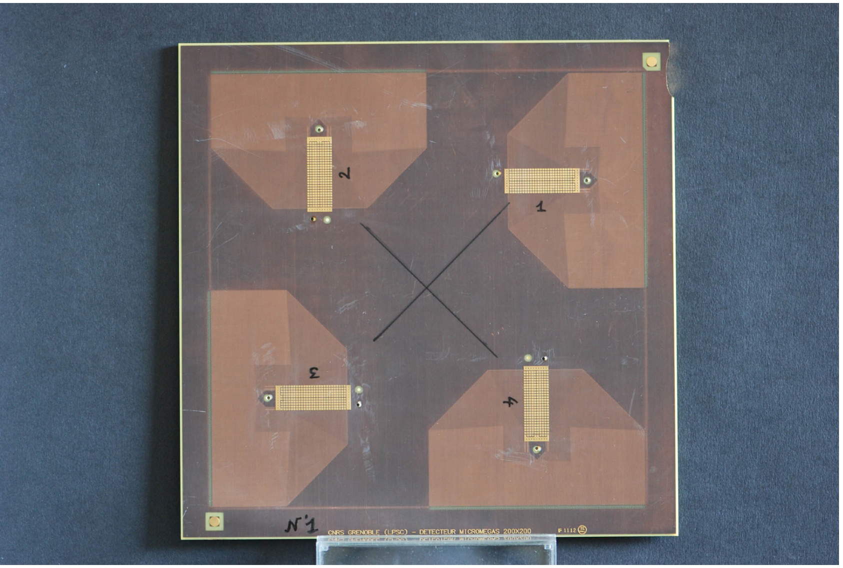




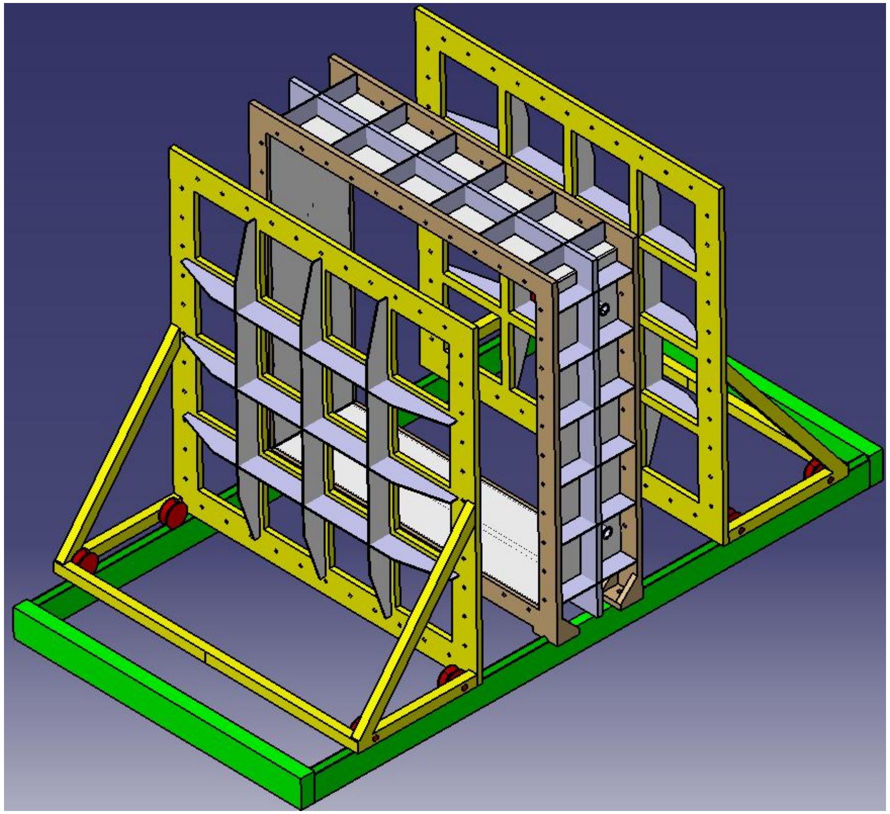
MIMAC – 1m^3 = 16 bi-chamber modules (2x 35x35x26 cm^3)

i) New technology anode 35cmx35cm
ii) Stretched thin (12 um) grid at 512um.
iii) New electronic board (1920 channels)
iv) Only one big chamber

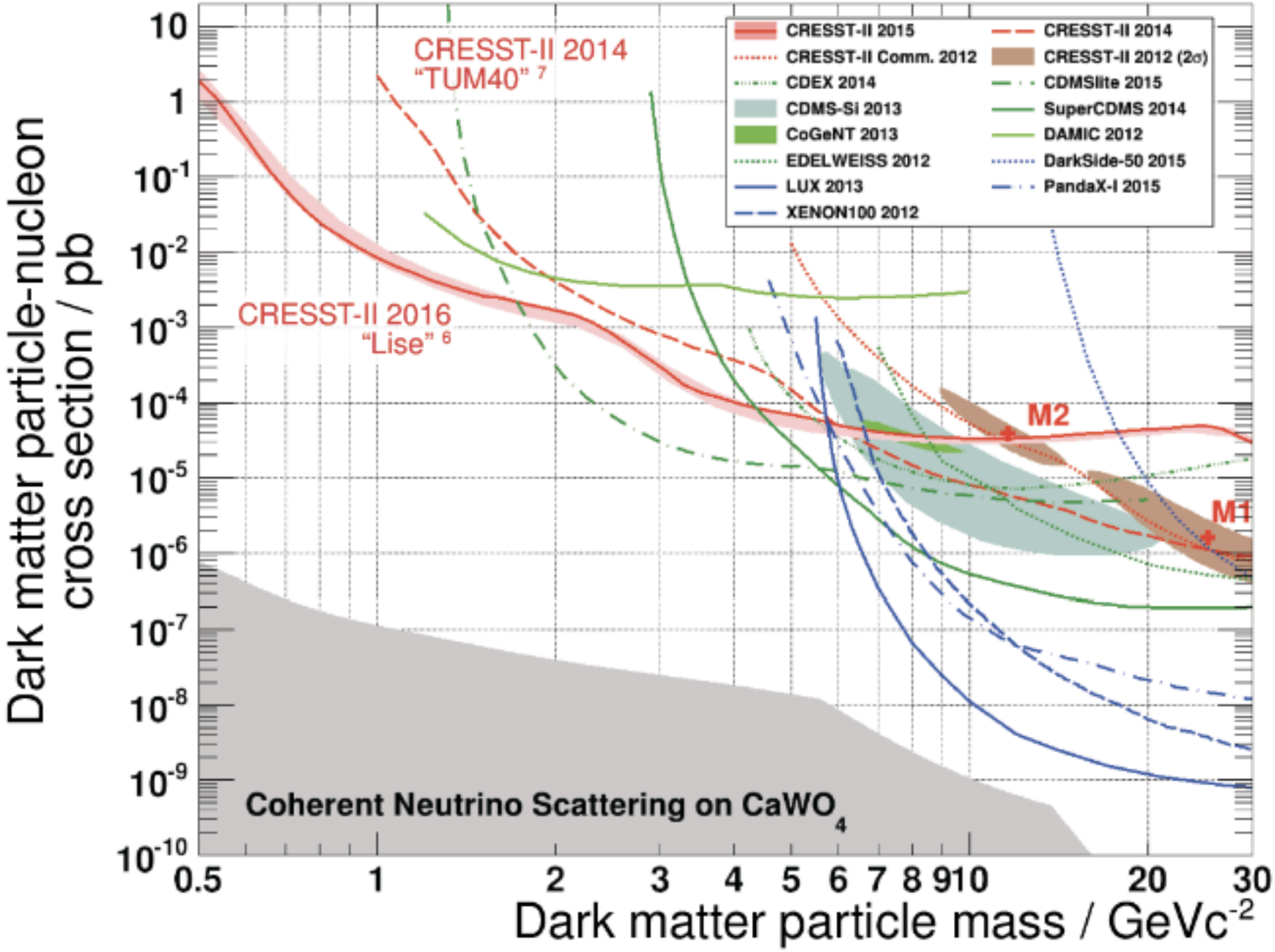




New 20cmx20cm pixellized anode (1024 channels)



Exclusion curves at low mass WIMP… **without directionality**



Conclusions

- A directional detector of nuclear recoils at low energies is needed to cope with the neutron and neutrino background

- The 3D nuclear recoil tracks from Rn progeny can be used as a benchmark to compare the directional detectors.

- New degrees of freedom are available to discriminate electrons from nuclear recoils and to place the 3D tracks in the active volume.

- Angular resolution and directional studies of 3D tracks are now possible with COMIMAC.

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

- **The CYGNUS collaboration is an international effort to define the large TPC (> 10 m^3) for Dark Matter Directional Detection**

MIMAC (MIcro-tpc MAtrix of Chambers)

LPSC (Grenoble) : D. Santos, F.Naraghi , 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 : **J. Giraud**
- COMIMAC (quenching) : **J-F. Muraz**

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

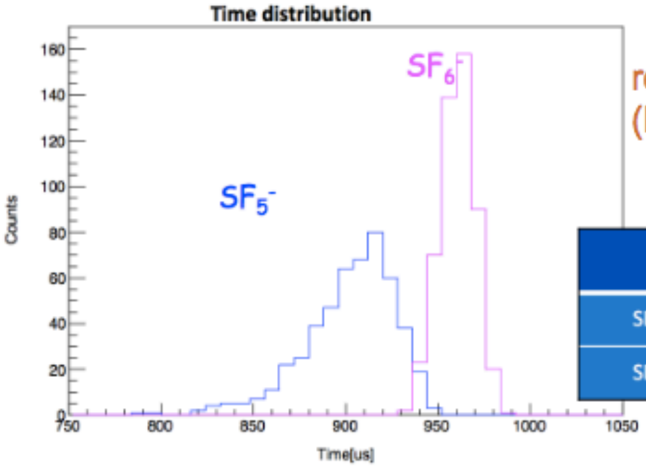
CCPM (Marseille): J. Busto, D. Fouchez, C. Tao

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

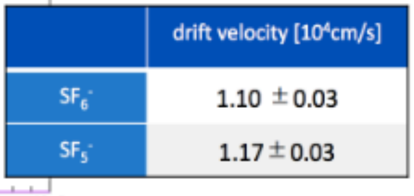
Neutron facility (AMANDE) :
IRSN (Cadarache): V. Lacoste, B. Tampon (Ph. D.)

Key Experimental Breakthroughs

- **SF_6 with negative ion drift, fiducialization and He**
  - Pure SF_6 with minority carriers
  - Also CF_4 + small amount of SF_6
  - Low diffusion maintained



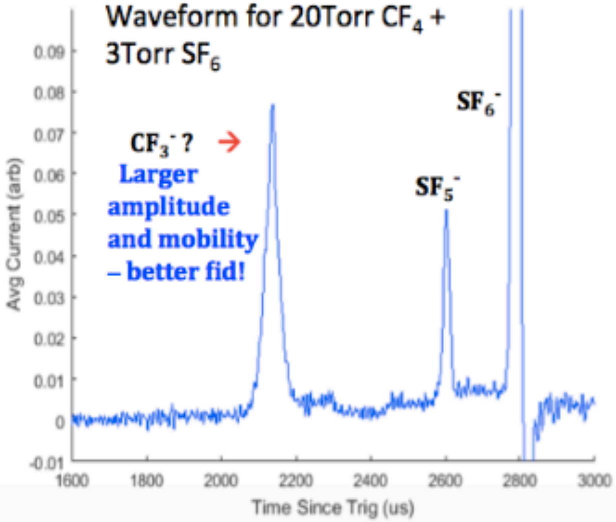
results from Kobe (K. Miuchi et al.)



	drift velocity [10^4cm/s]
SF_6^-	1.10 ± 0.03
SF_5^-	1.17 ± 0.03

- SF_5^- is 6% faster than SF_6^-
- For SF_5^-, the extent is large

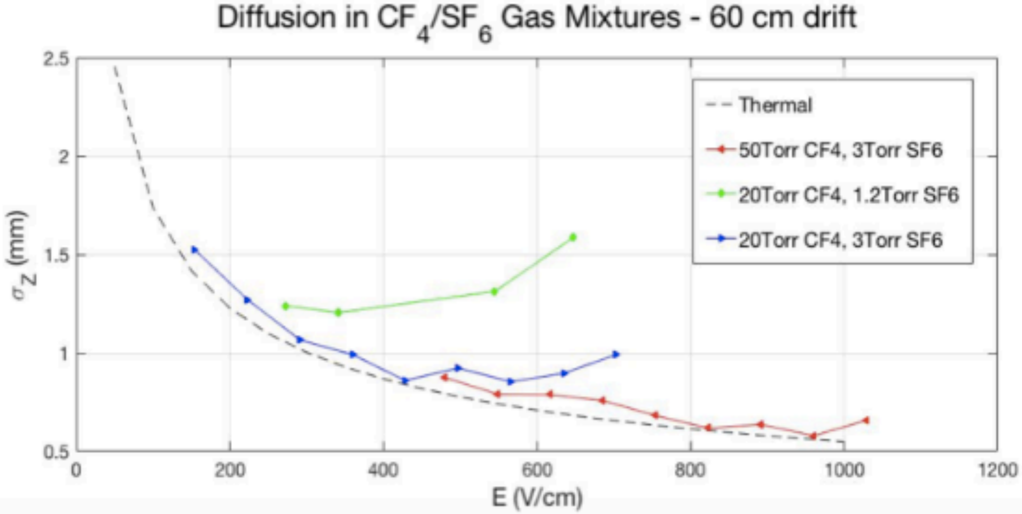
results from UNM (D. Loomba et al.)



Waveform for 20Torr CF_4 + 3Torr SF_6

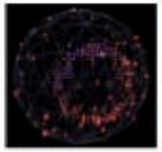
CF_3^- ? →

Larger amplitude and mobility – better fid!



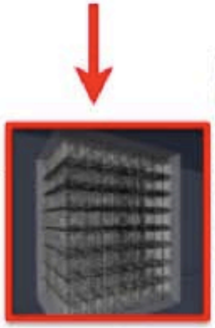
Diffusion in CF_4/SF_6 Gas Mixtures - 60 cm drift

How big is a 1 tonne directional detector?

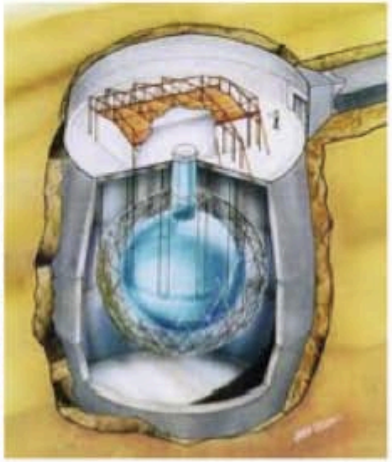


Mini-BooNE

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



MINOS



SNO

Super-Kamiokande

TPC directional detectors

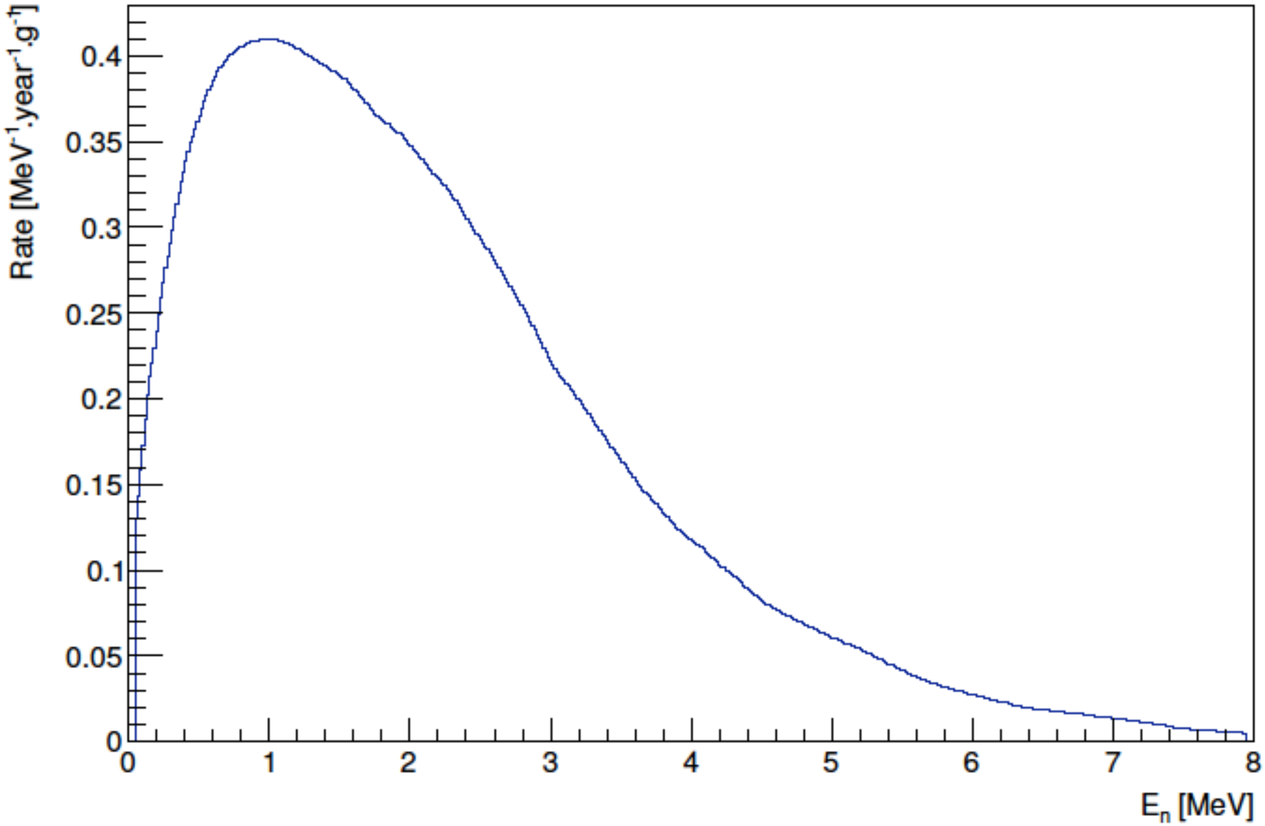
	DRIFT	**MIMAC**	**NEWAGE**	**DMTPC**
	Boulby	Modane	Kamioka	SNOLAB
Gas mix	73%CS2 +25%CF4 +2%O2	70%CF4 +28%CHF3 +2%C4H10	CF4	CF4
Current volume	800 L	6 L	37 L	1000 L
Drift	ion, 50 cm	e–, 25 cm	e–, 41 cm	e–, 27 cm
Threshold (keVee)	20	1	50	20
Readout	Multi-Wire Proportional Counters	Micromegas	micro-pixel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

Adapted from Mayet et al. [arXiv:1602.03781]

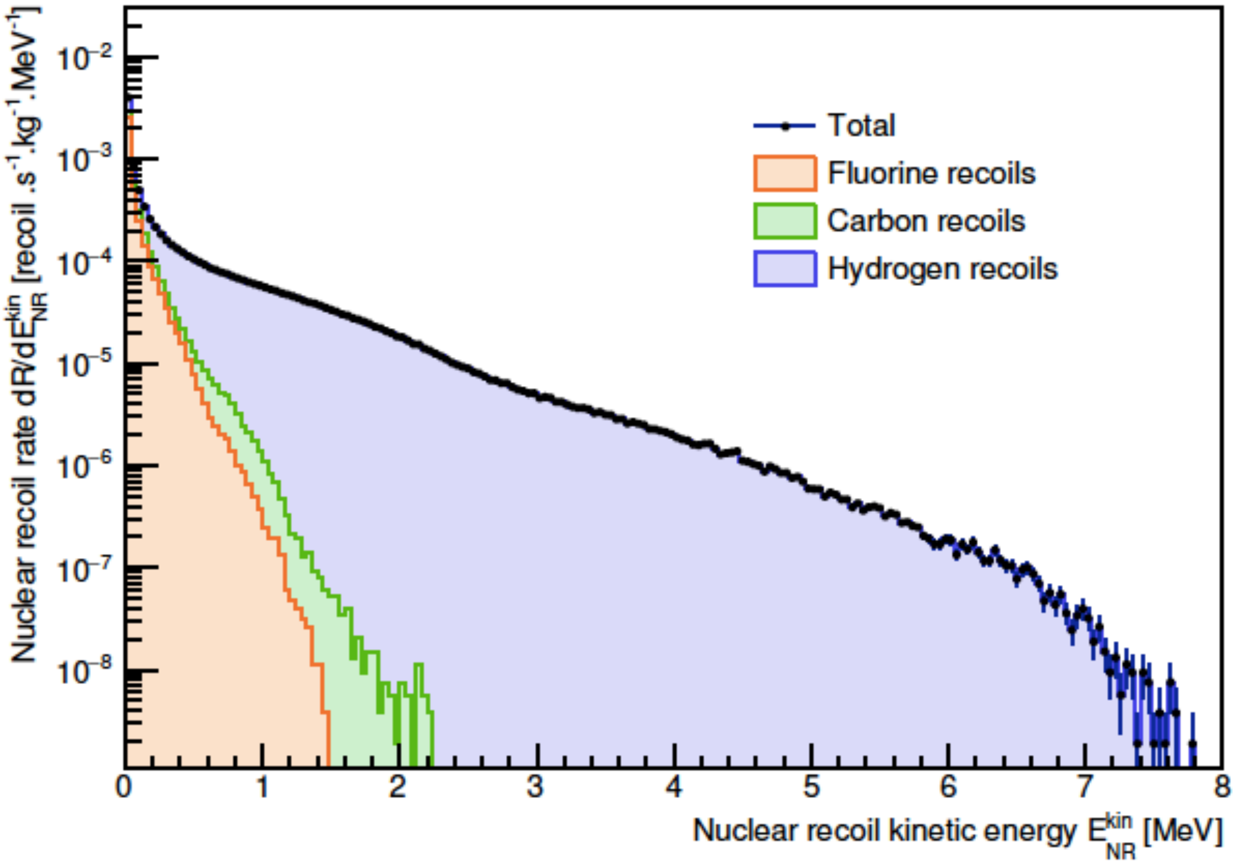
Neutron spectrum from the rock at Modane laboratory (SOURCES simulation)

77% (α,n)

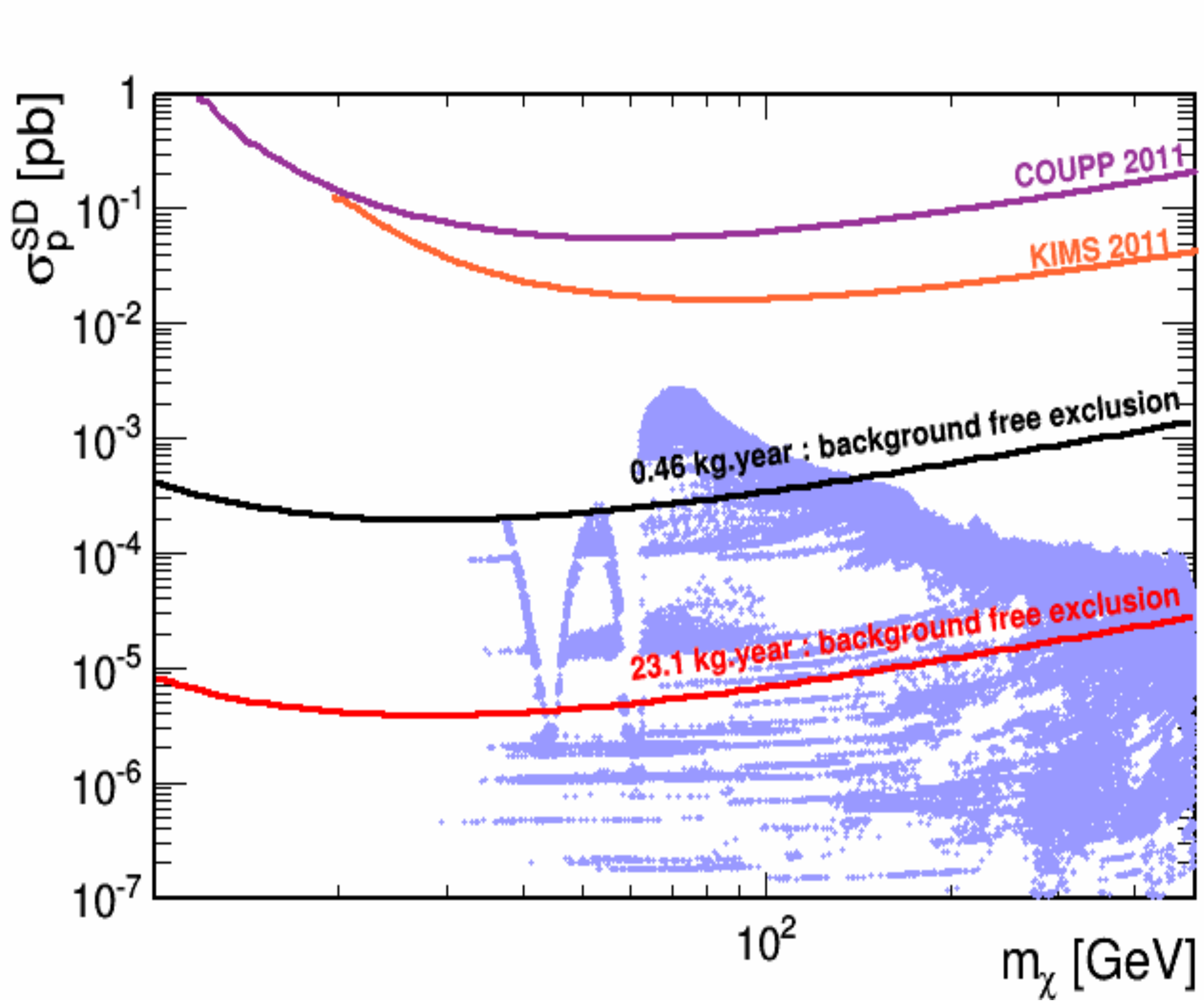
23% spontaneous fissions (^{238}U (0.84 ppm, ^{232}Th (2.45 ppm))



Nuclear recoils energy distribution in MIMAC (without any shielding) produced by neutrons coming from the LSM (Modane) rock cavern (Q. Riffard , Ph.D thesis (2015))

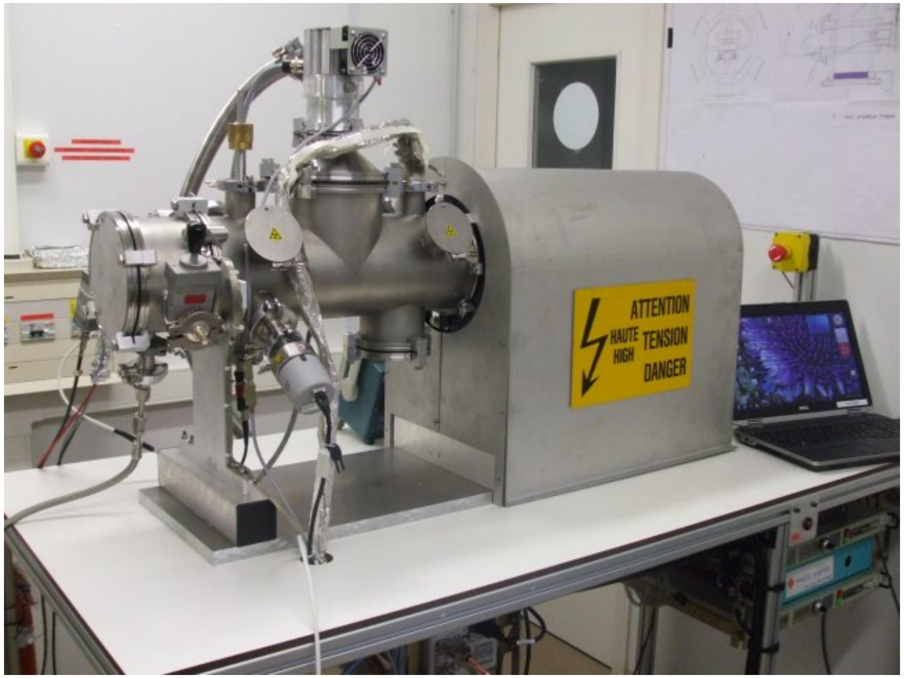


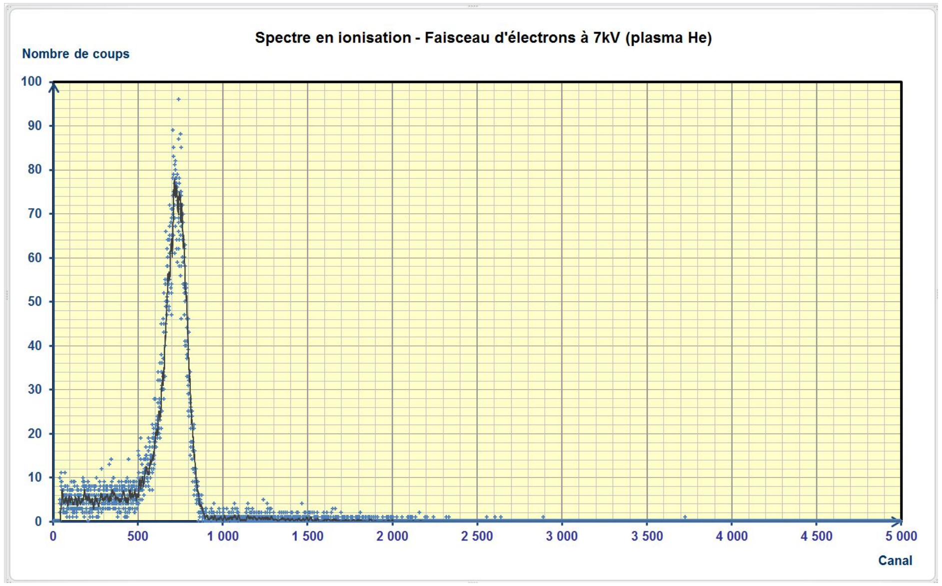
Exclusion curves for MIMAC (1 and 50 m^3)



Portable Quenching Facility (COMIMAC)

(Electrons and Nuclei of known energies)





Electrons of 7 keV

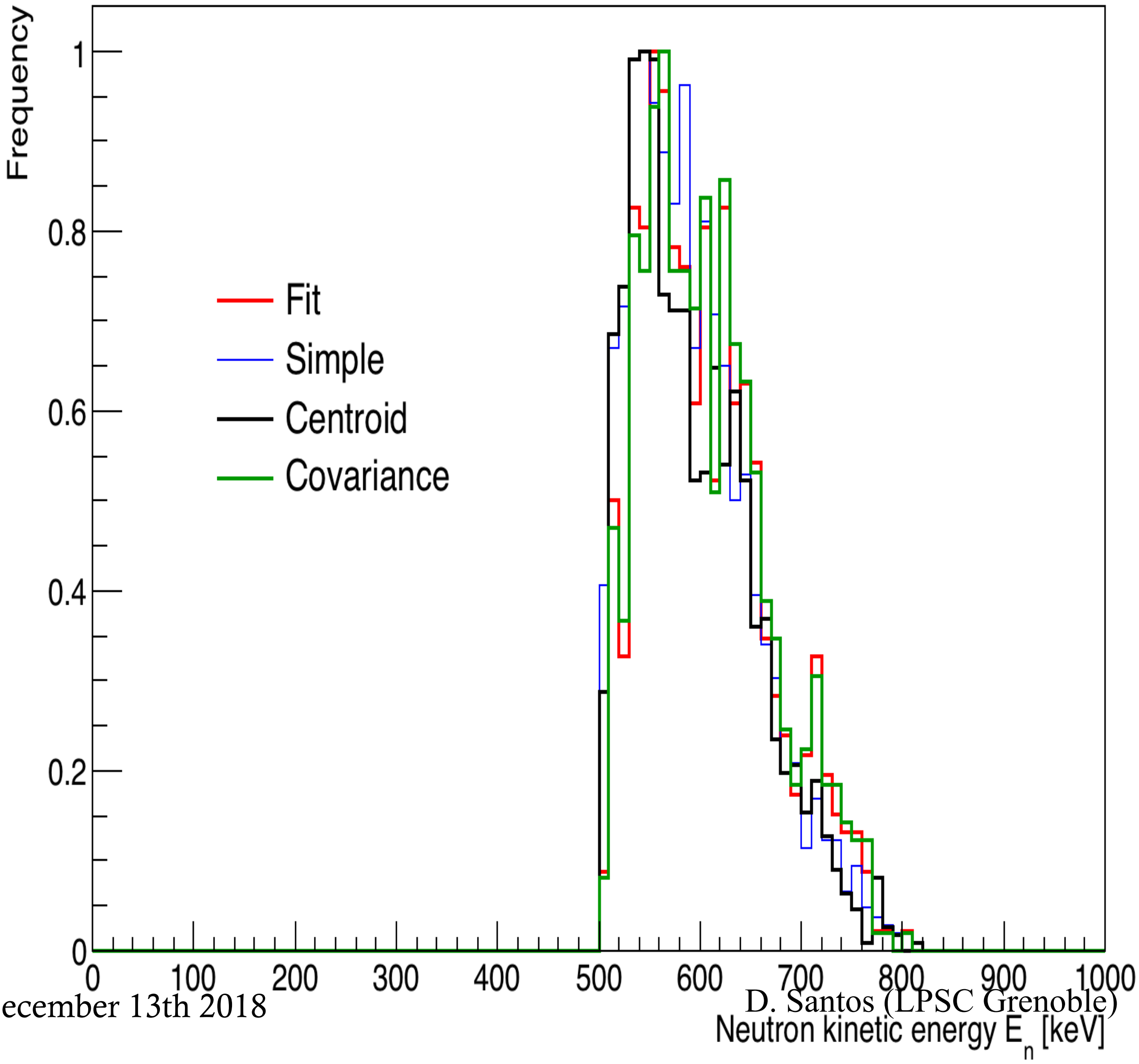
In a gas detector the IQF depends strongly on the quality of the gas.
The IQF needs to be measured periodically (in-situ) in a long term run experiment.

Neutron kinetic energy distribution

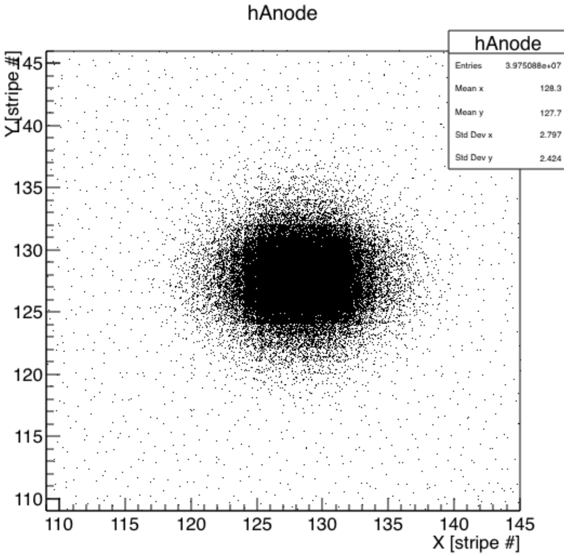
Focusing on the "Fluorine Endpoint":

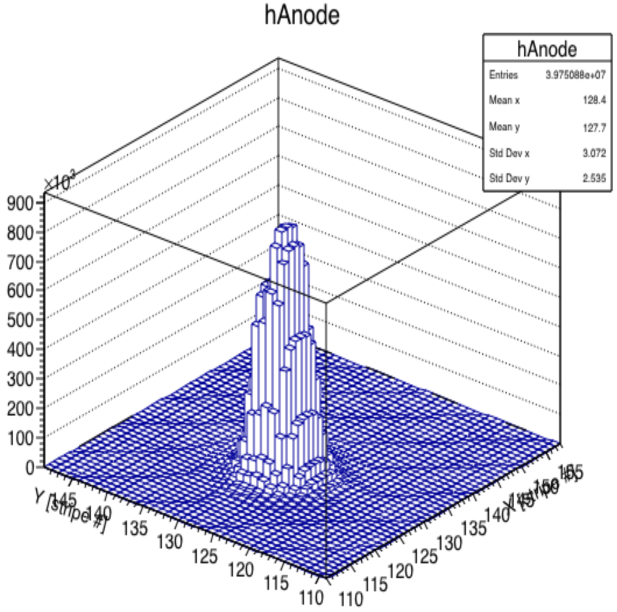
- ionization energies above 50 keV
- theta < 0.5 rad

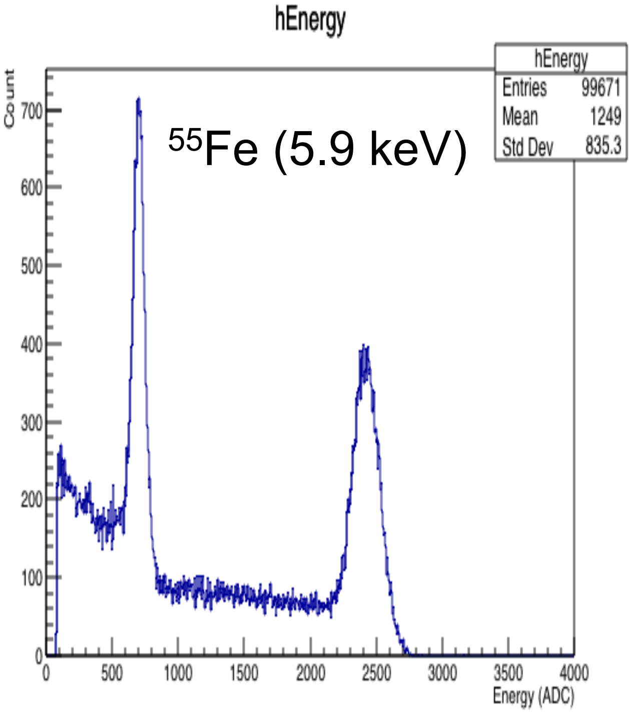
max ~ 550 keV



Protons (25 keV (kinetic))

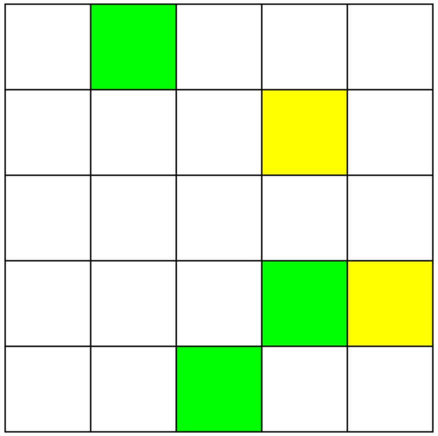






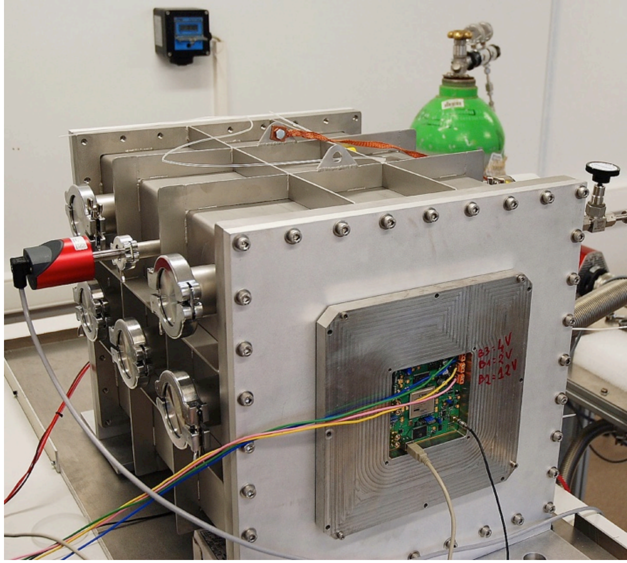
^{55}Fe (5.9 keV)

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 cm^3)

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

The target (gas) can be changed to explore other mass response
H, ^4He, ^{20}Ne, ^{40}Ar, $^{129,130}Xe$

MIMAC validation with neutrons

Neutron monochromatic field:

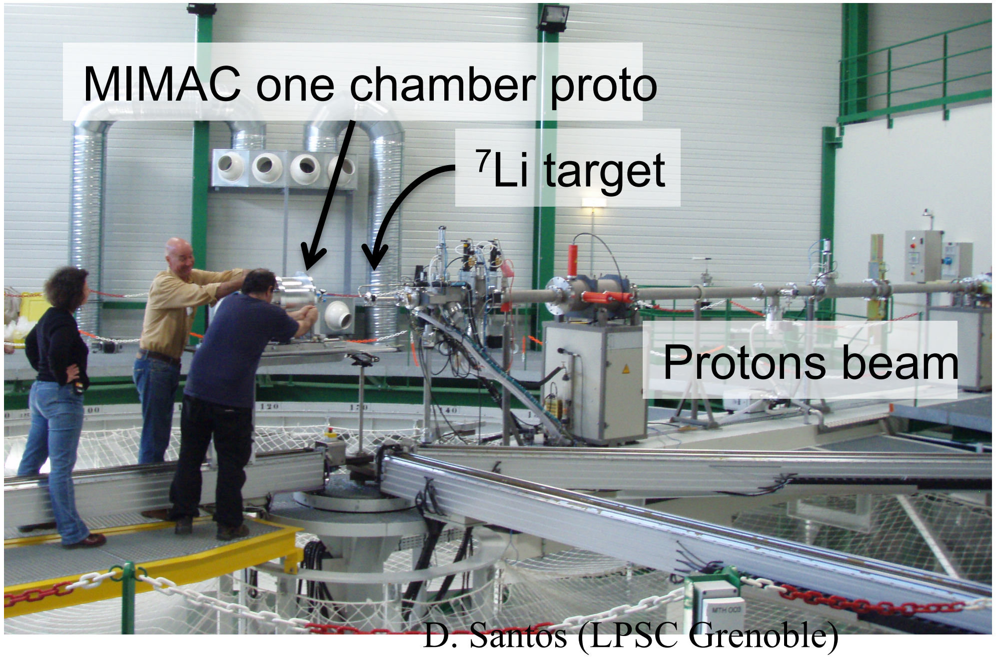
AMANDE facility at IRSN of Cadarache

- 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

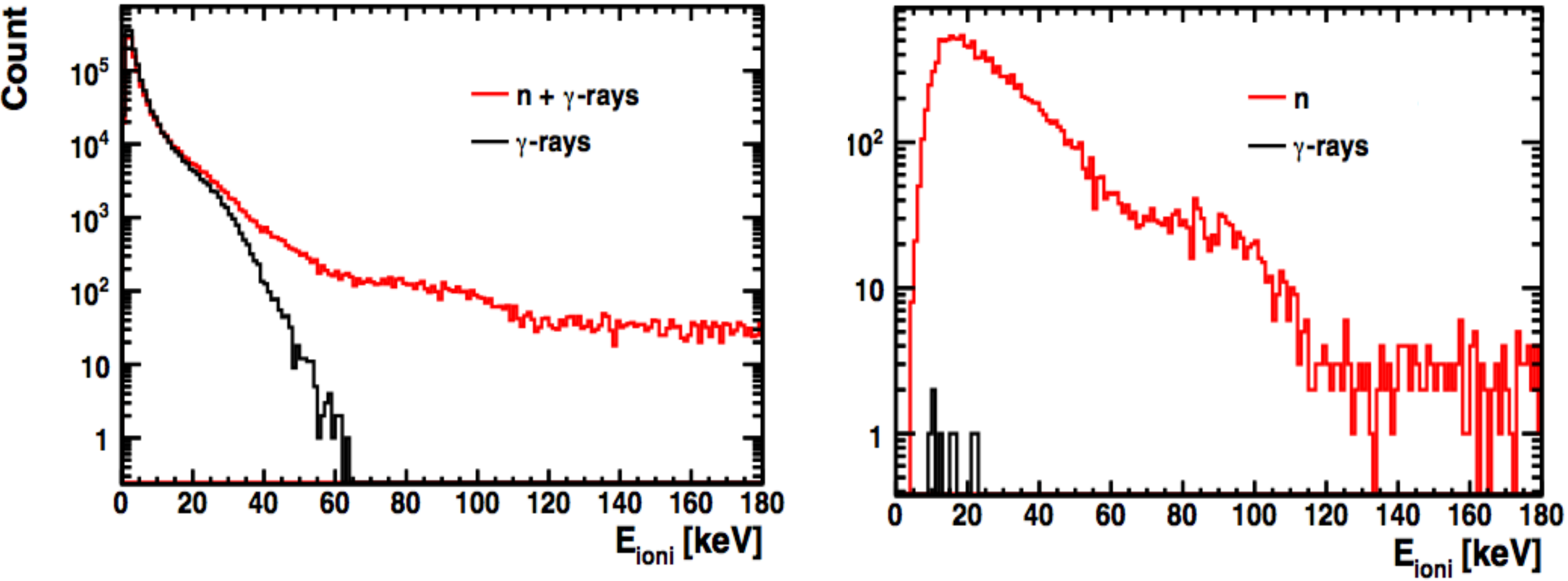


Electron-recoil Discrimination

^{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

Radon Progeny

^{222}Rn chain:

- 4 β-decays

→ Electron event (background)

- 4 α-decays

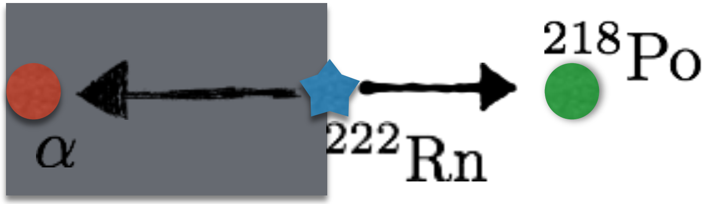
→ α-particle emission:

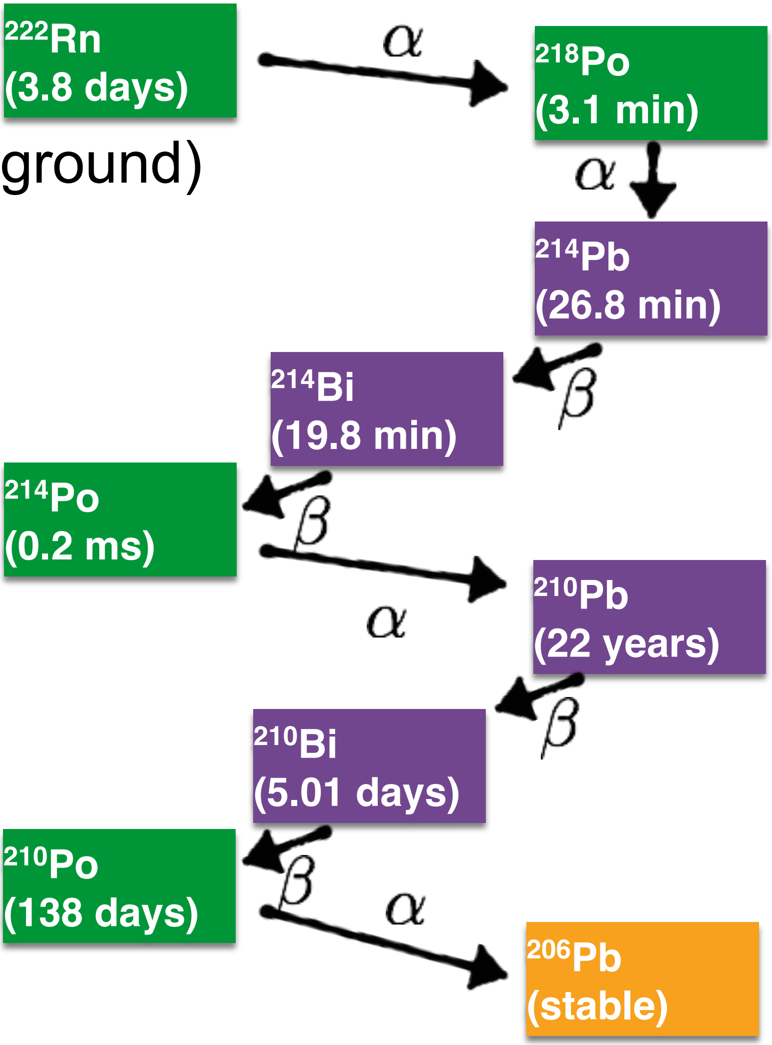
$E_\alpha \sim 5\,\mathrm{MeV}$ → Saturation

→ Daughter nucleus recoil (surface event):

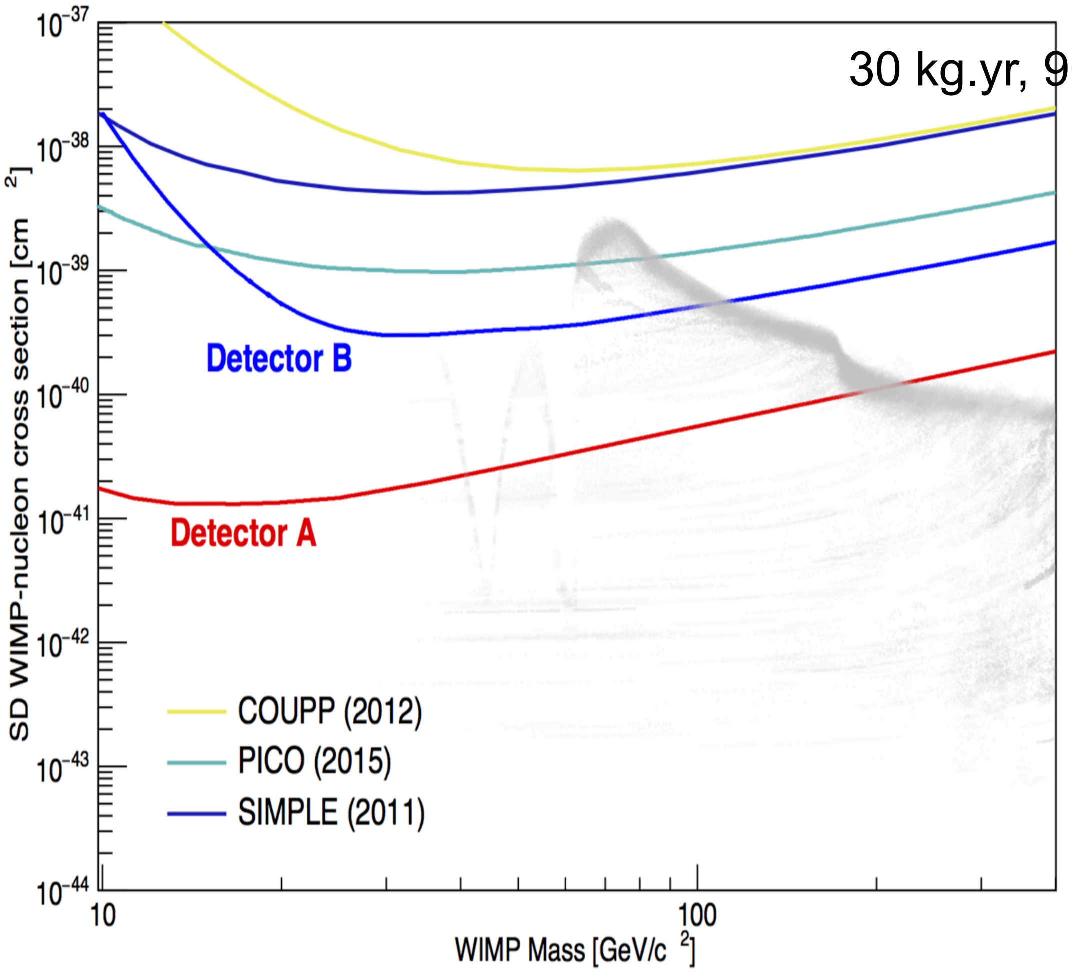
Parent	Daughter	E^{kin}_{recoil} [keV]	E^{ioni}_{recoil} [keV]
^{222}Rn	^{218}Po	100.8	38.23
^{218}Po	^{214}Pb	112.3	43.90
^{214}Po	^{210}Pb	146.5	58.78
^{210}Po	^{206}Pb	103.1	39.95

Simulation (SRIM)





Exclusion limits



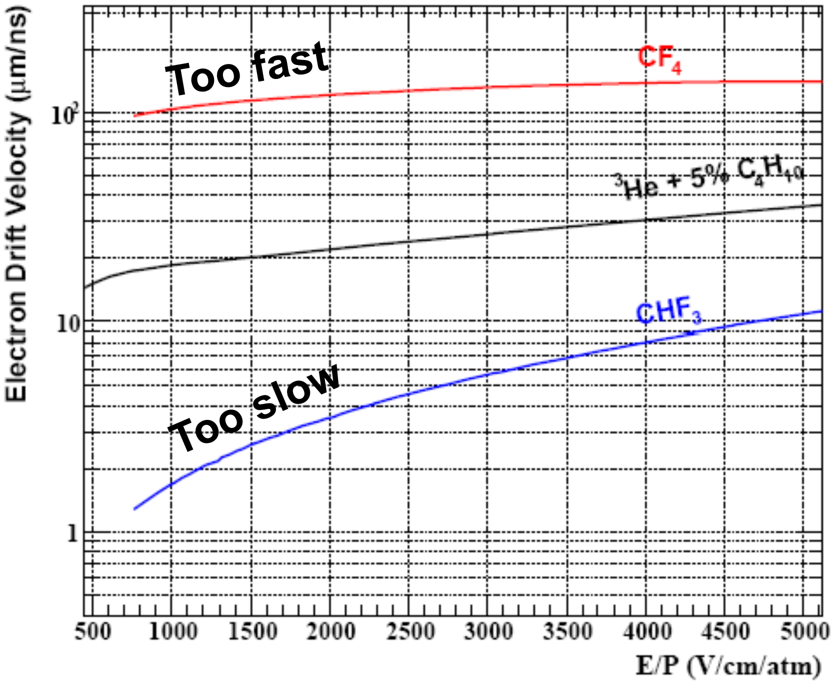
30 kg.yr, 90% CL lower limits

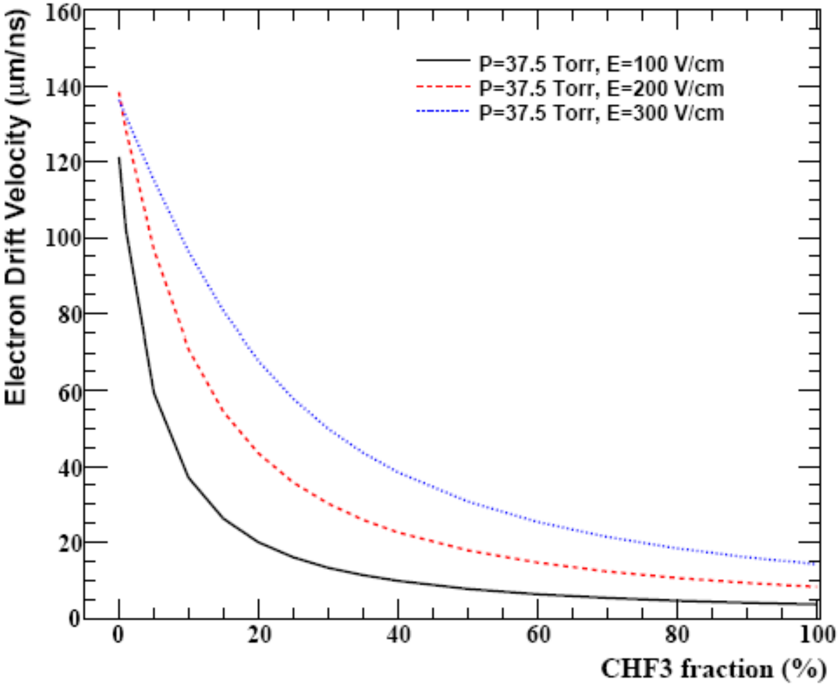
A: 5 keV (threshold)
no background
3D track with head-tail
angular resolution 20°

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

3D Tracks: Drift velocity

Magboltz Simulation





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