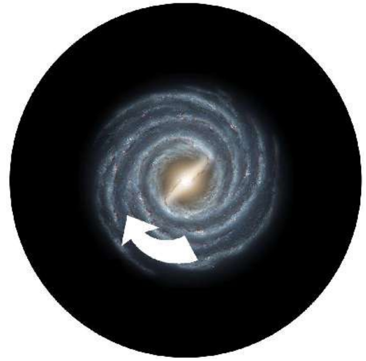


Directional Dark Matter Detection

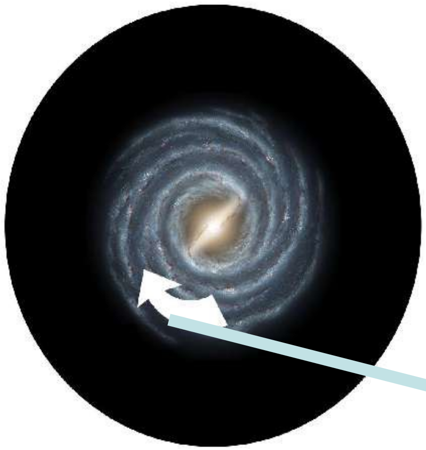
Daniel Santos

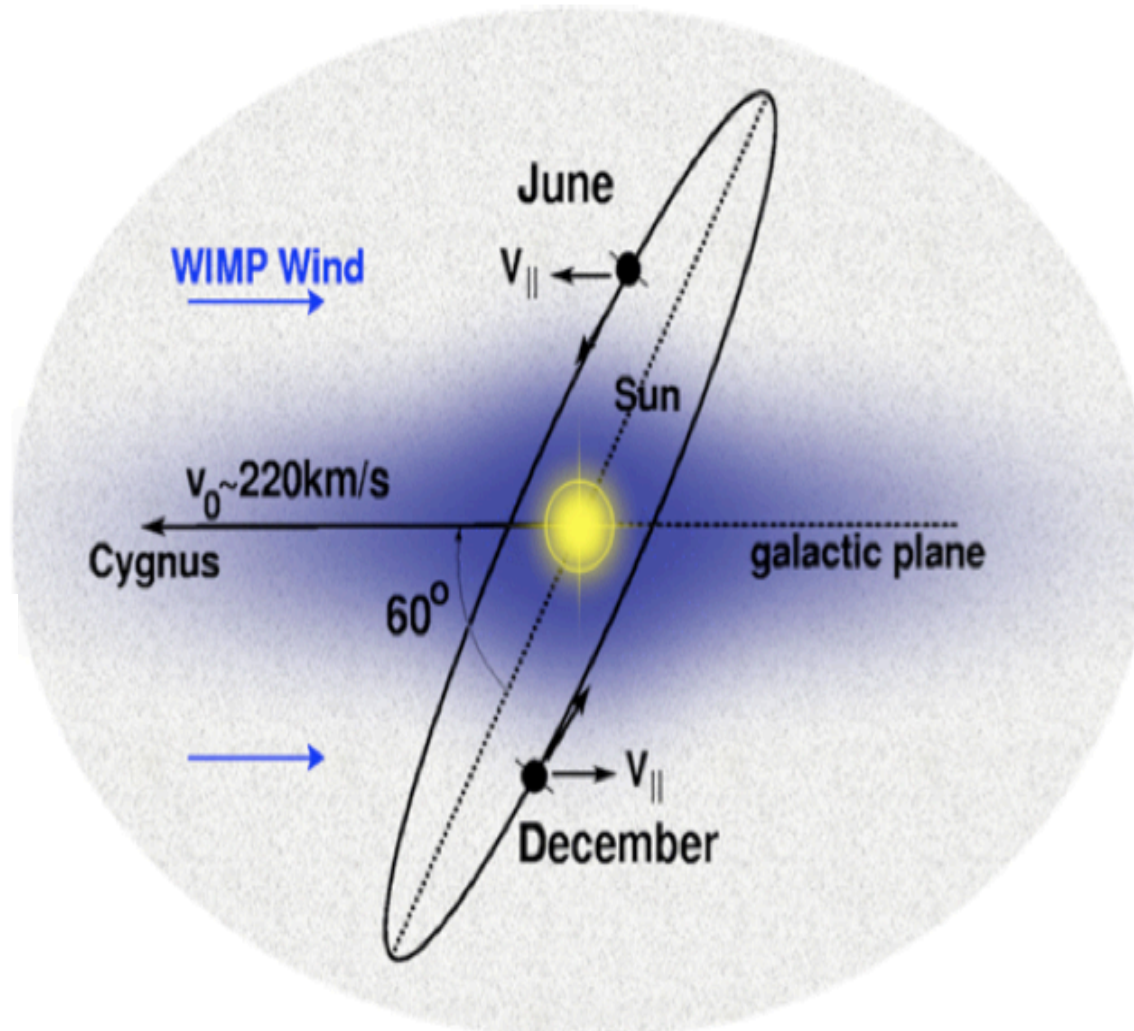
Laboratoire de Physique Subatomique et de Cosmologie

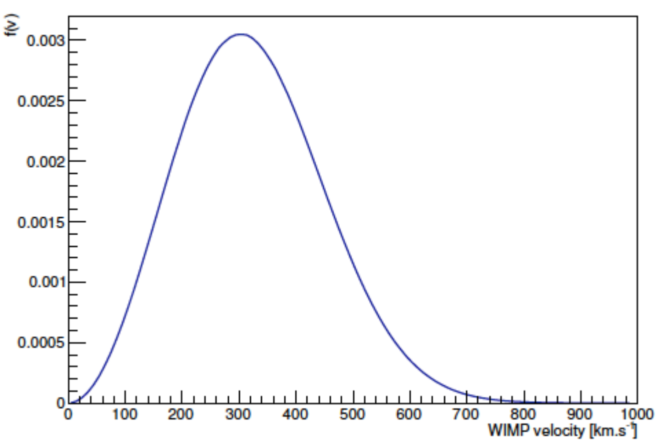
(LPSC-Grenoble)

(Université Grenoble-Alpes -CNRS/IN2P3)

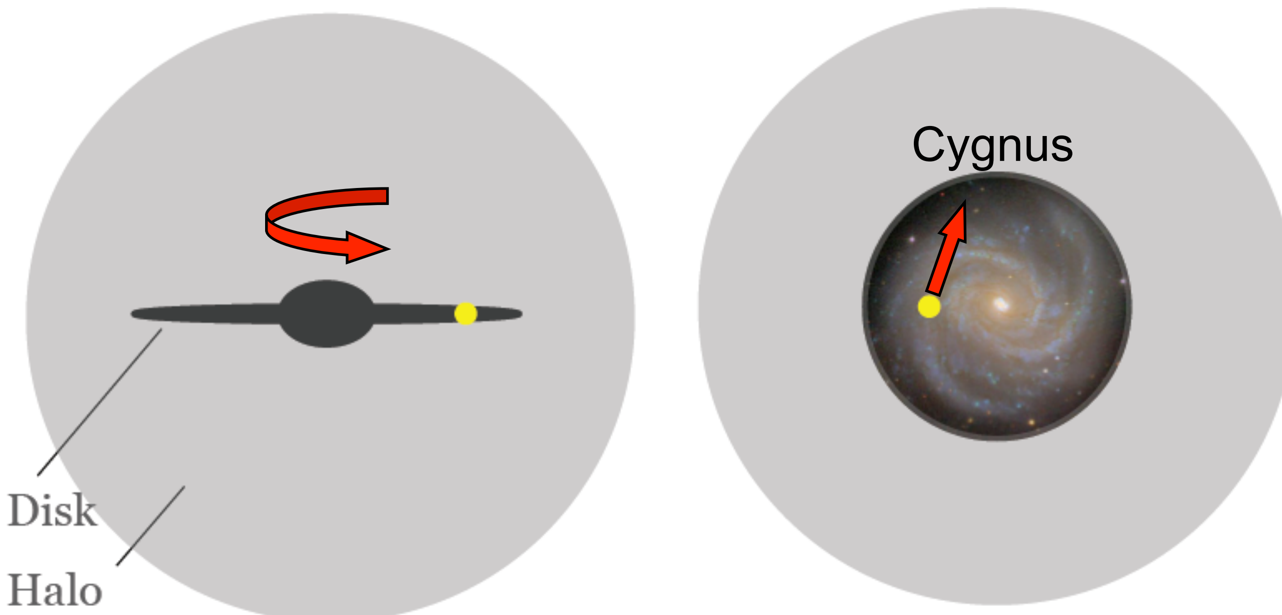
Directional detection: principle







Directional detection

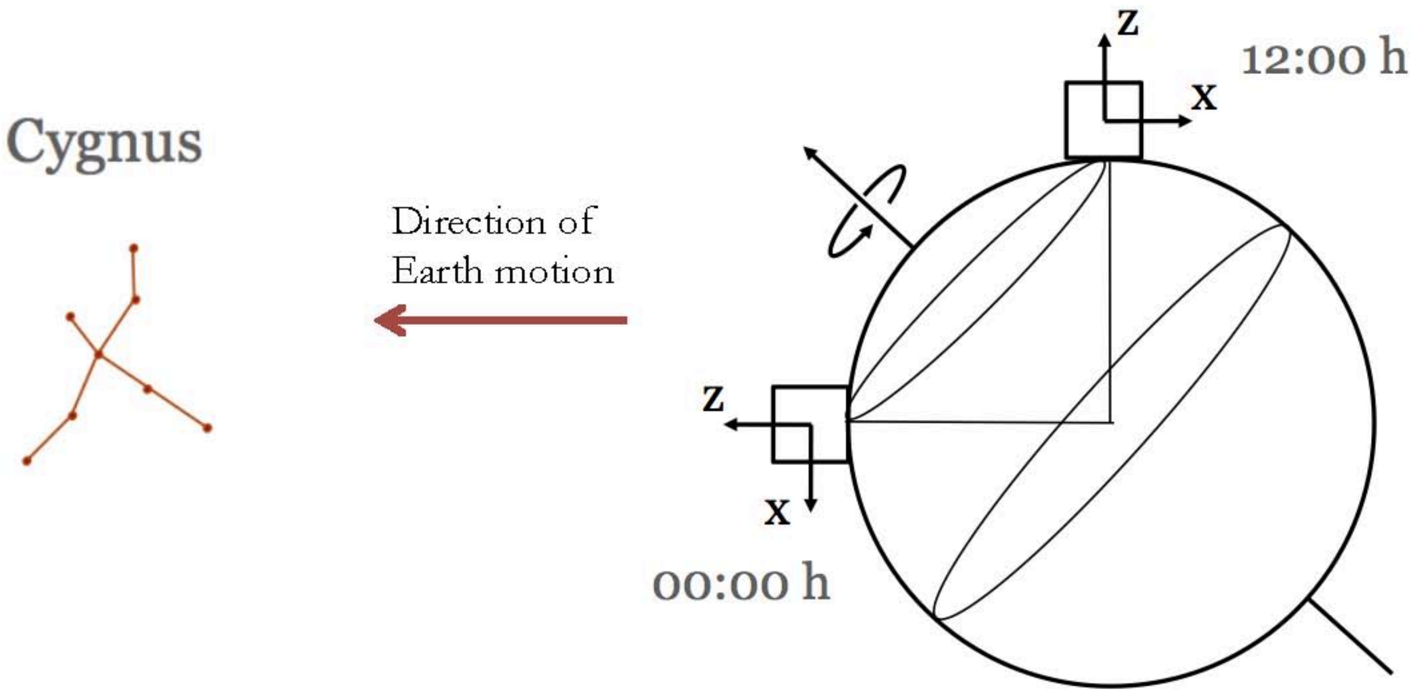


$\langle V_{rot} \rangle \sim 220$ km/s

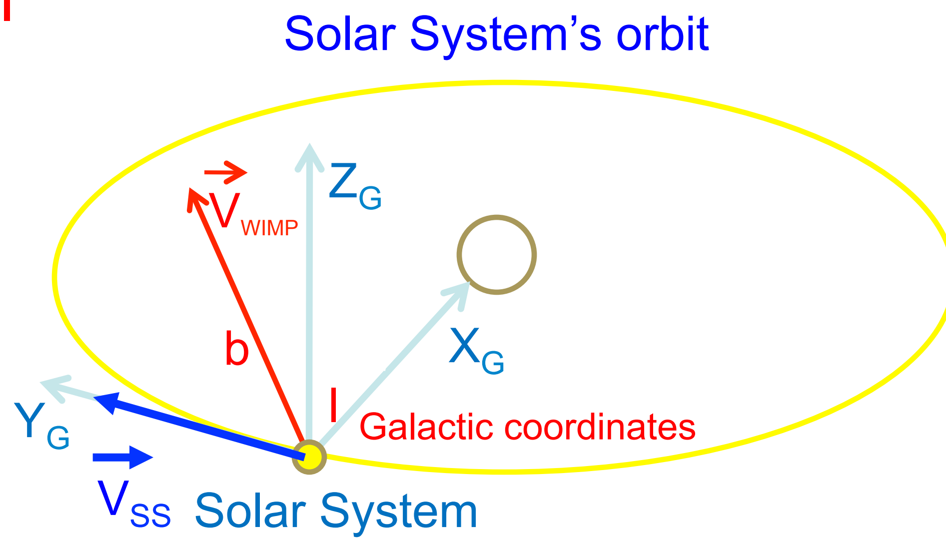
The signature, the only one (!), able to correlate the events in a detector to the galactic halo !!

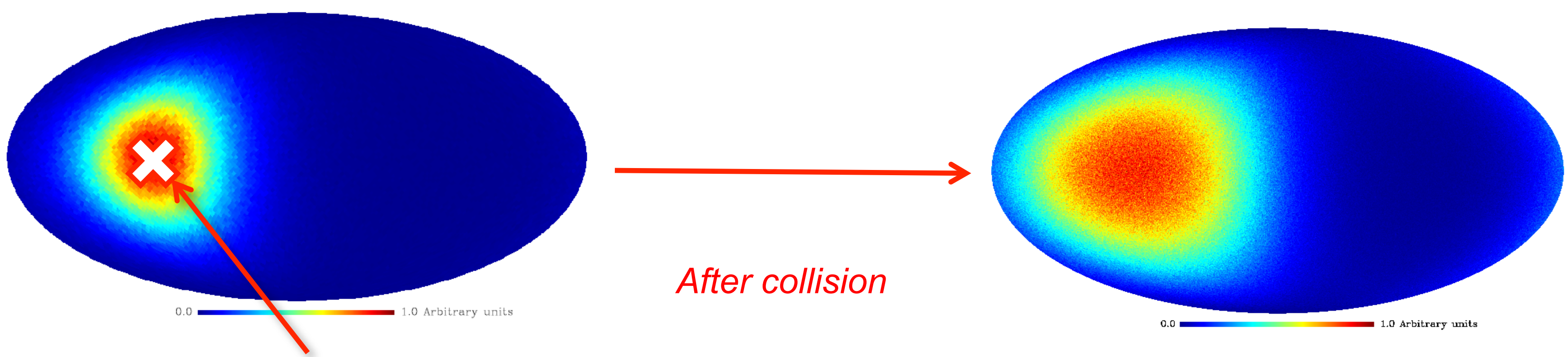
Angular modulation of WIMP flux

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



WIMP signal

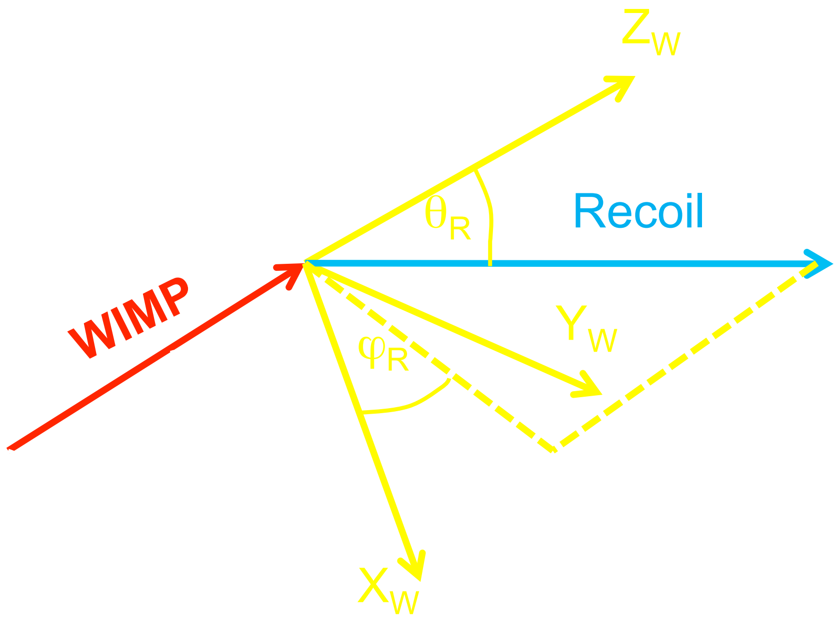


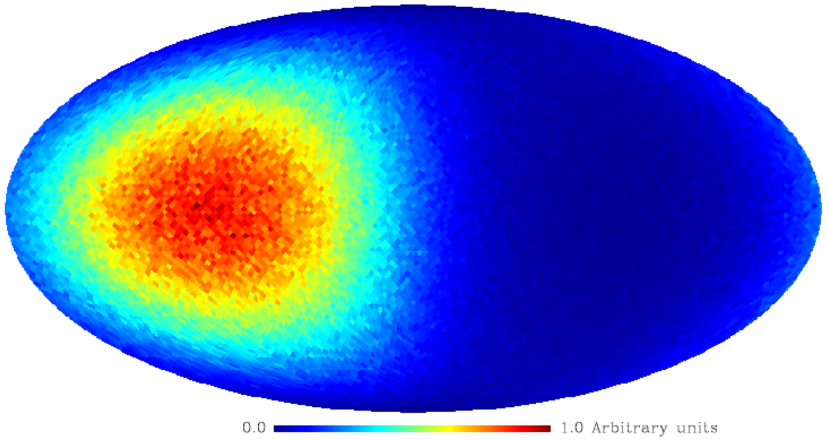


Cygnus Constellation (l = 90°,b = 0°)

WIMP signal expected

There are many "angles" for nuclear recoils…

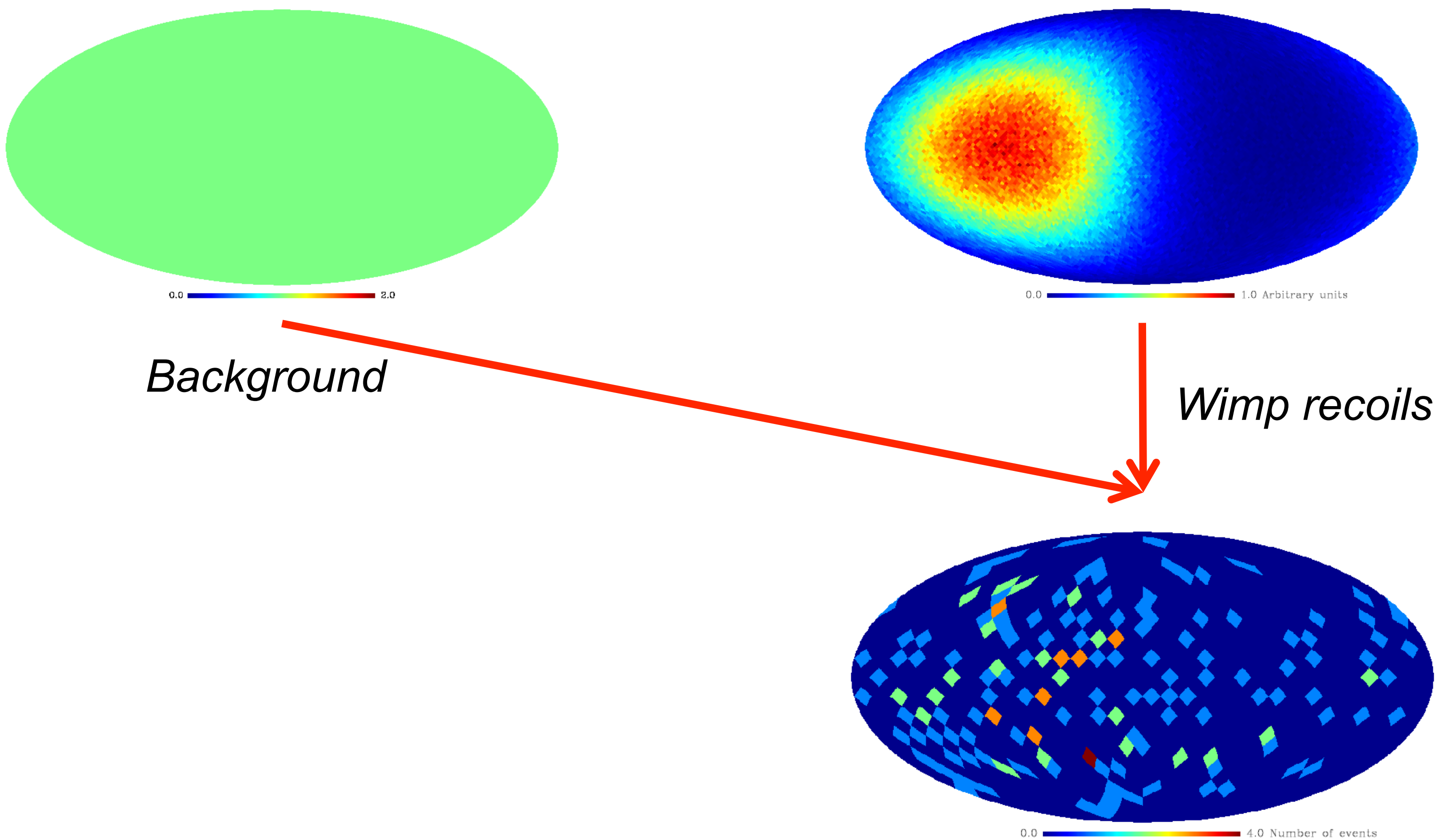




Map of recoils in galactic coordinates (HealPix)

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

100 WIMP evts + 100 Background evts

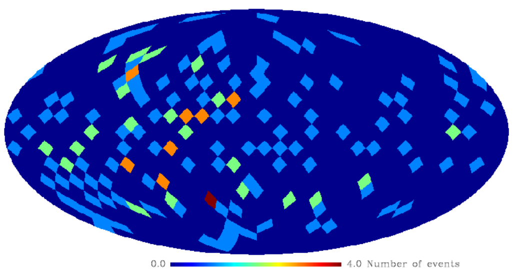


Phenomenology: Discovery

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

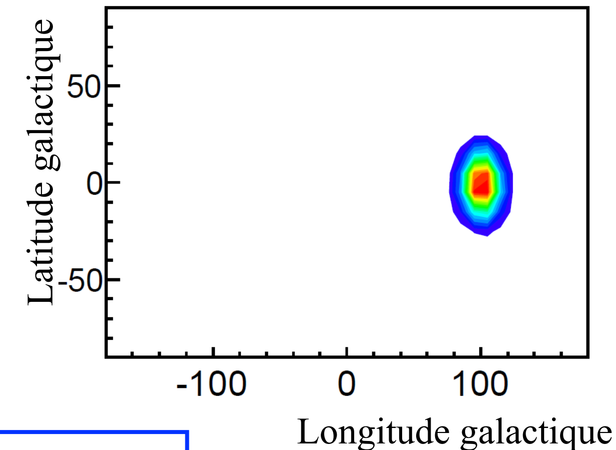
Proof of discovery: **Signal pointing toward the Cygnus constellation**

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



100 WIMP + 100 BKG

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



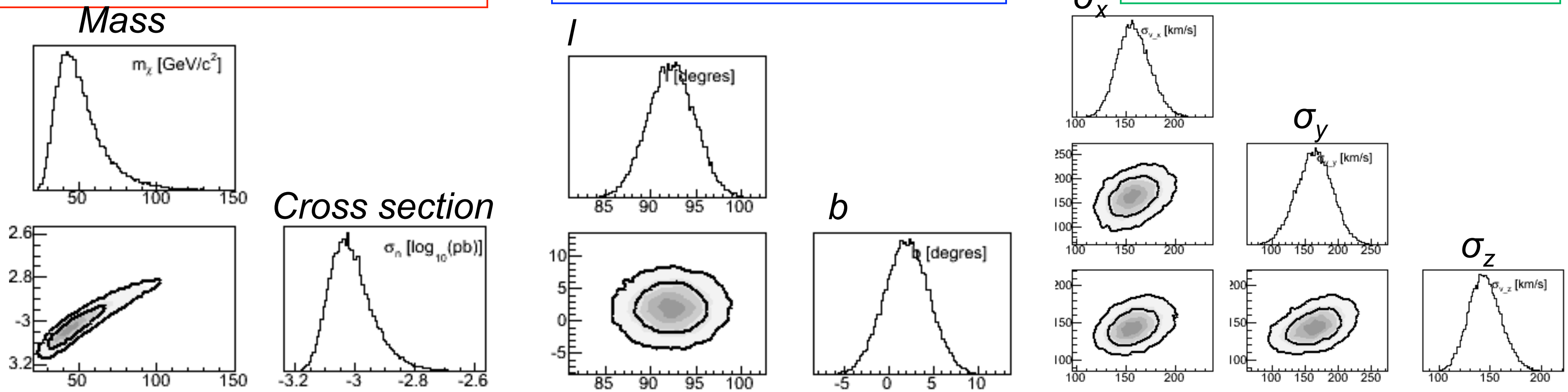
Strong correlation with the direction of the Constellation Cygnus **even with a large background contamination**

Directional 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

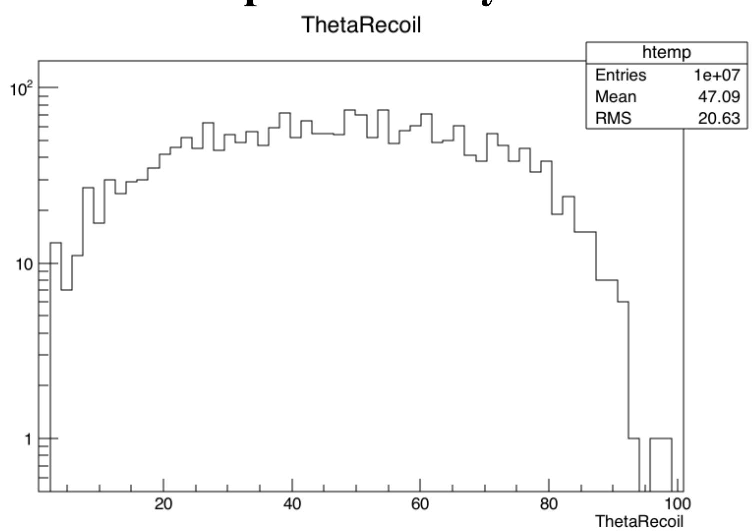
There are many angles to measure in 3D! 1D and 2D are not enough !

^{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

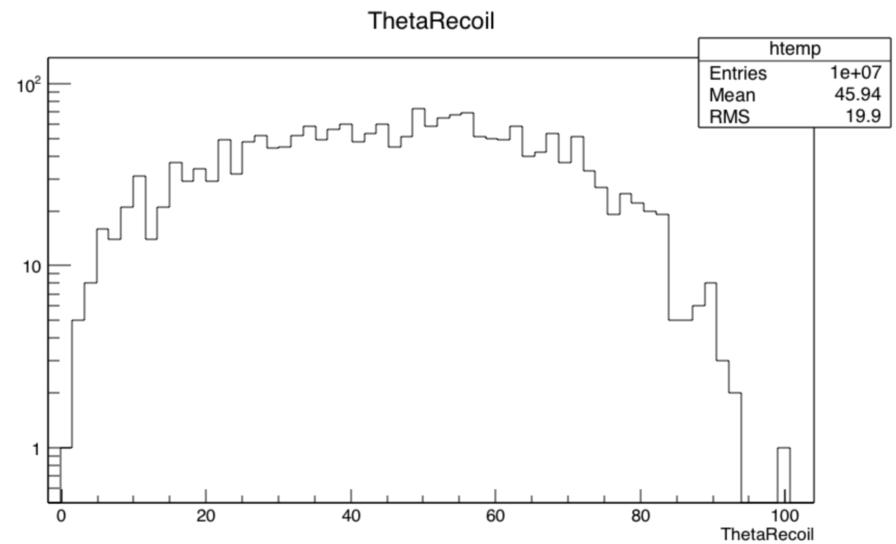
Validated experimentally at Cadarache !!



^{19}F recoils (E_{kin}= 1- 40 keV)

Angular distribution in the laboratory

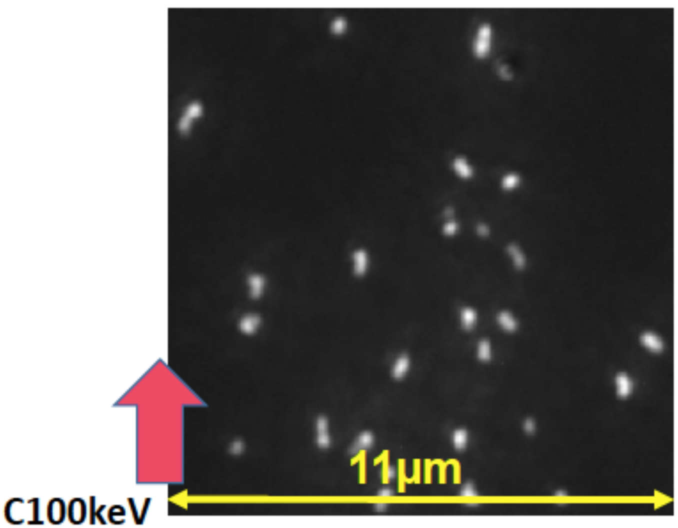
Produced by neutrons of 200 keV



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

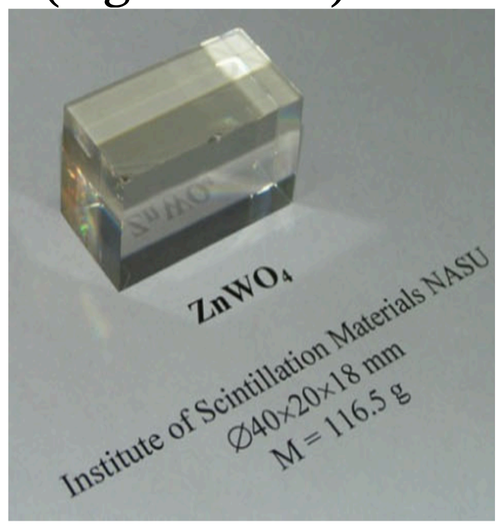
Directional detection: comparison of strategies

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



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

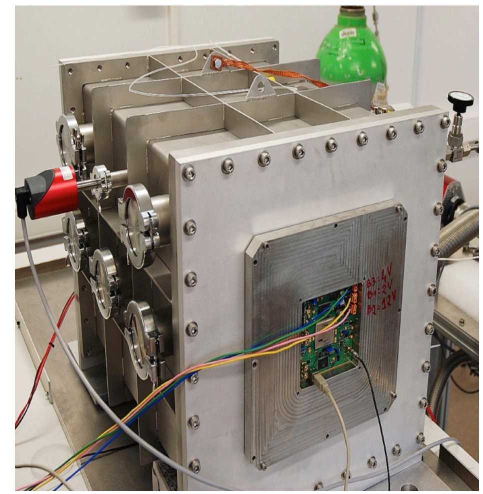
- **Anisotropic crystals**
  target = O (lowmasses), Zn, W (high masses)

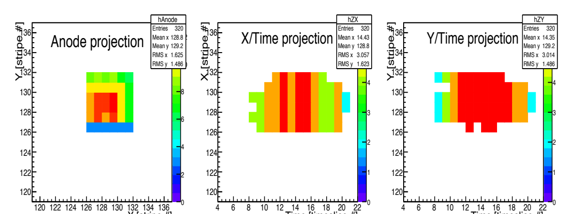


No tracks ; only statistical distributions (!)

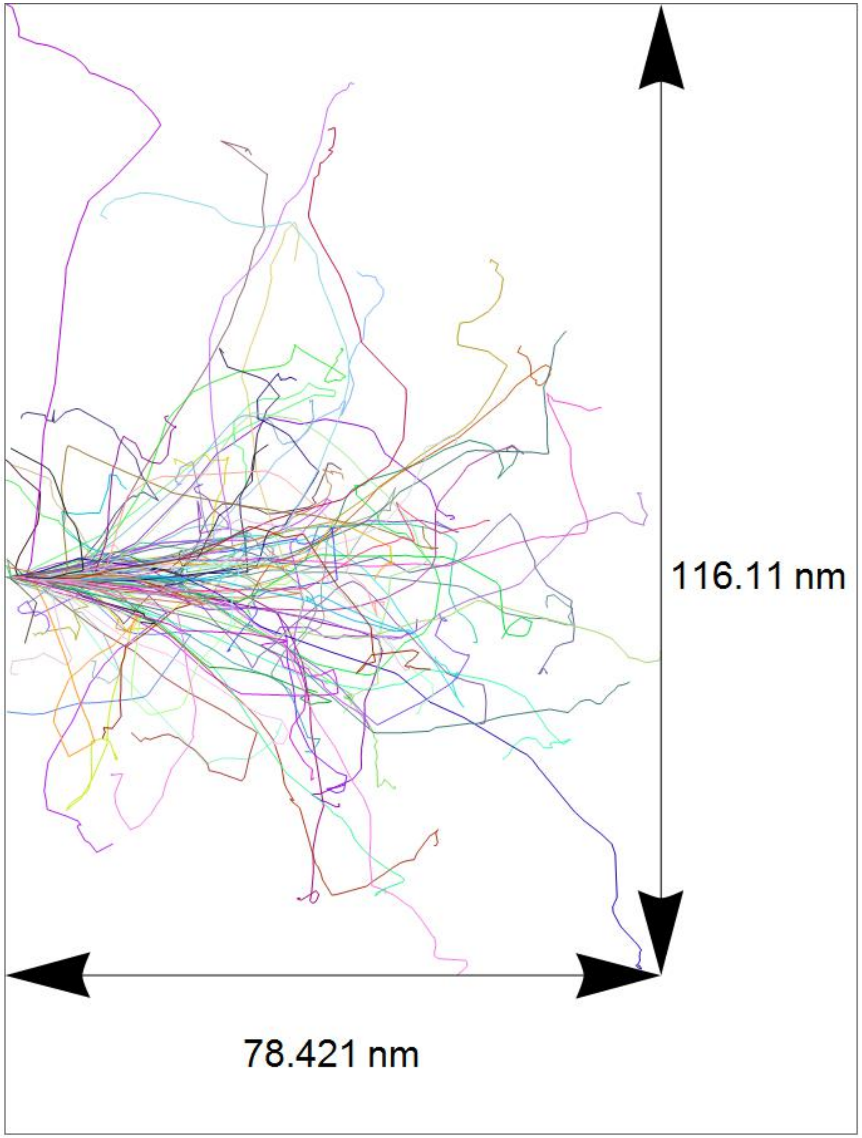
Capella et al. 2013

- **Low pressure TPCs**
  target = F

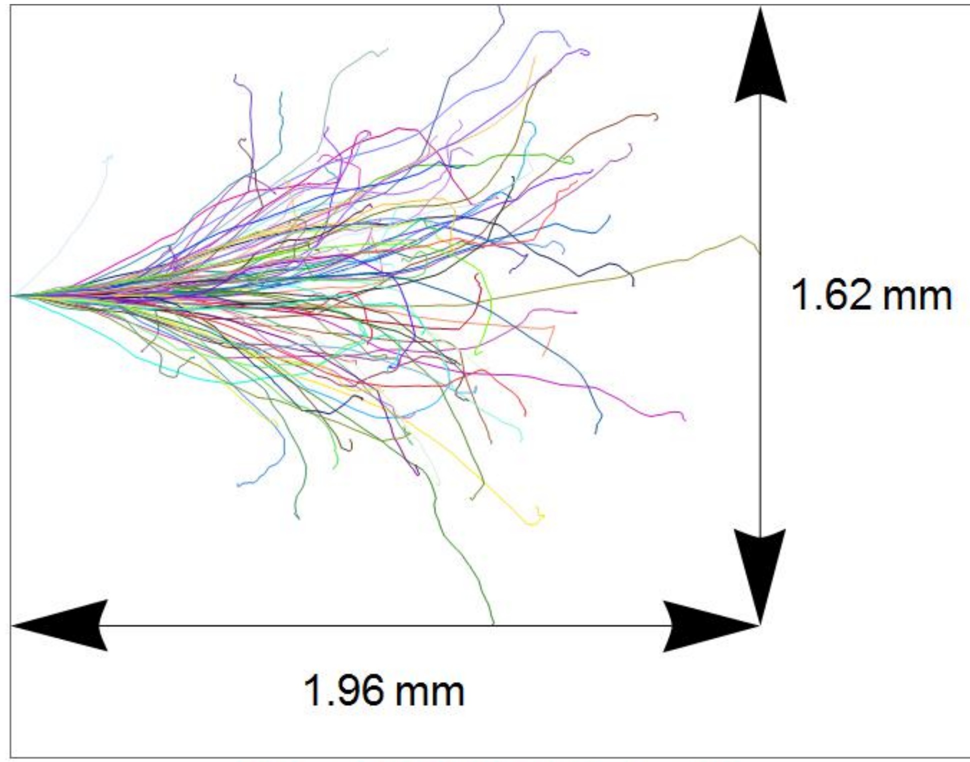




SRIM simulations…

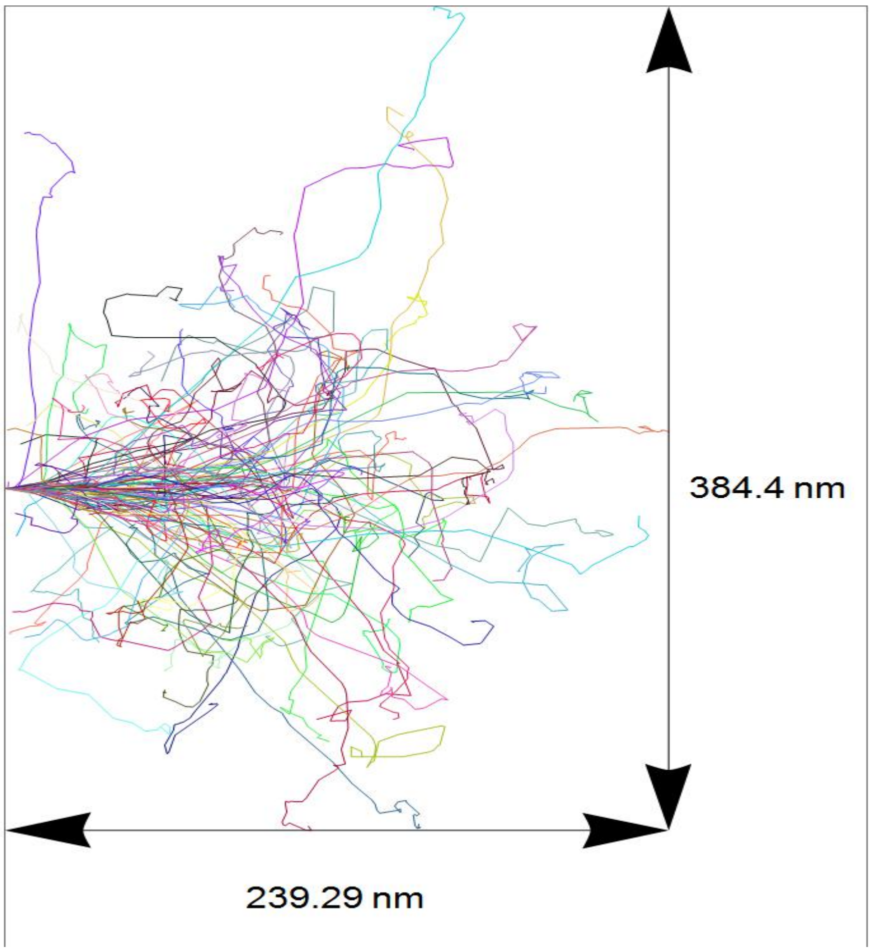


O in Crystal (29keV)



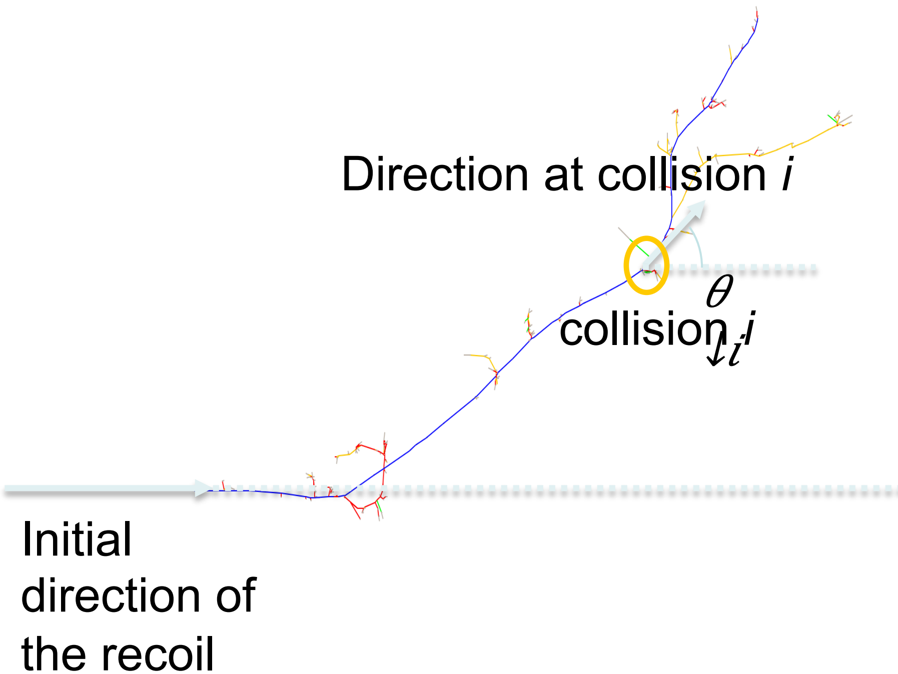
F in MIMAC (34keV)

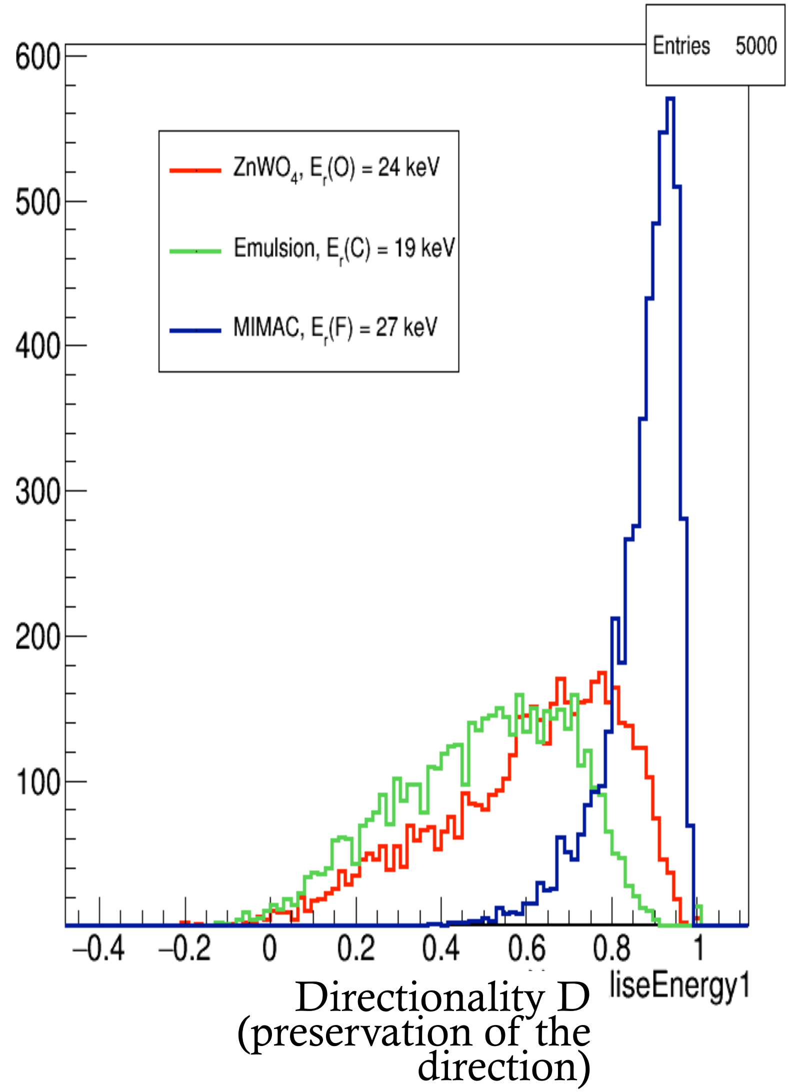
C (22 keV) in emulsion (SRIM simulation)



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

Directional detection: Directionality ‘D’





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

For more information on the comparison:
Couturier et al. (JCAP 01/2017)

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** ($N_{evts} \sim N_{nuclei}$)

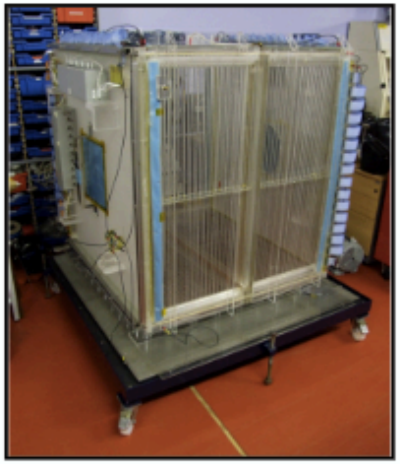
iv) Opening the **directional** signature (1D, 2D and 3D **tracks**)

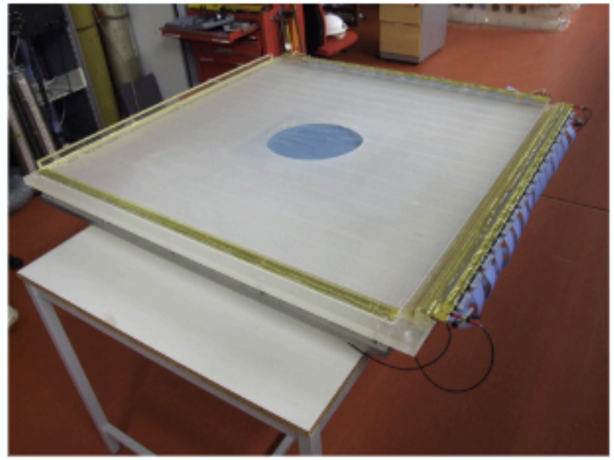
v) Allowing to cope with **neutron background** events

Directional experiments around the world

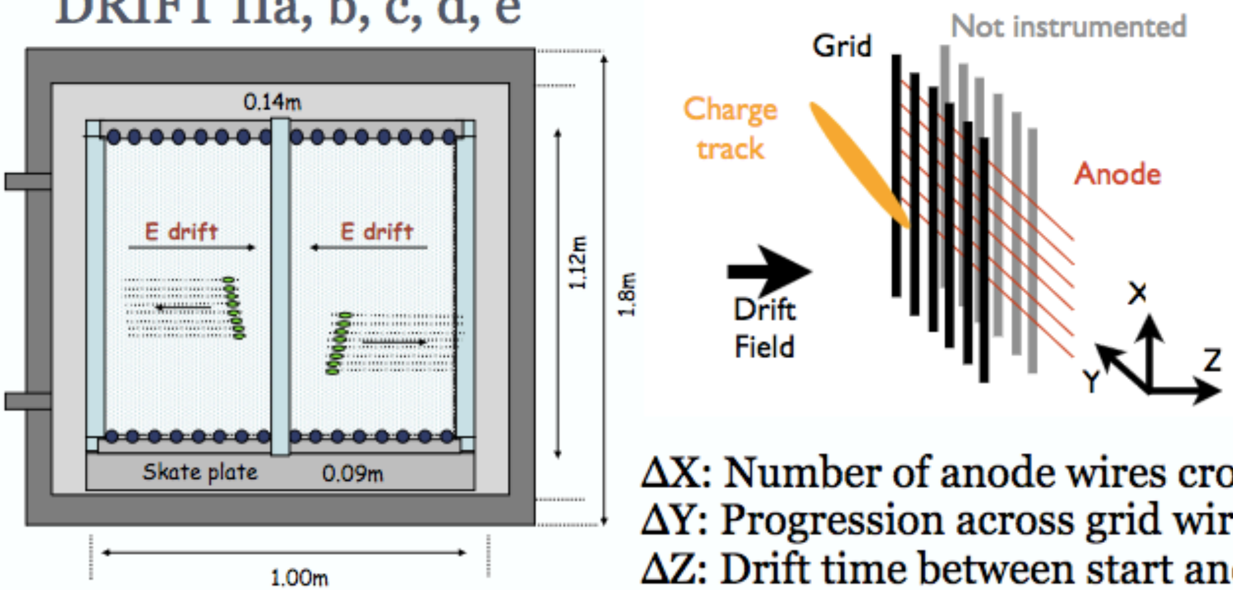
DRIFT Basics

Negative Ions drift !!

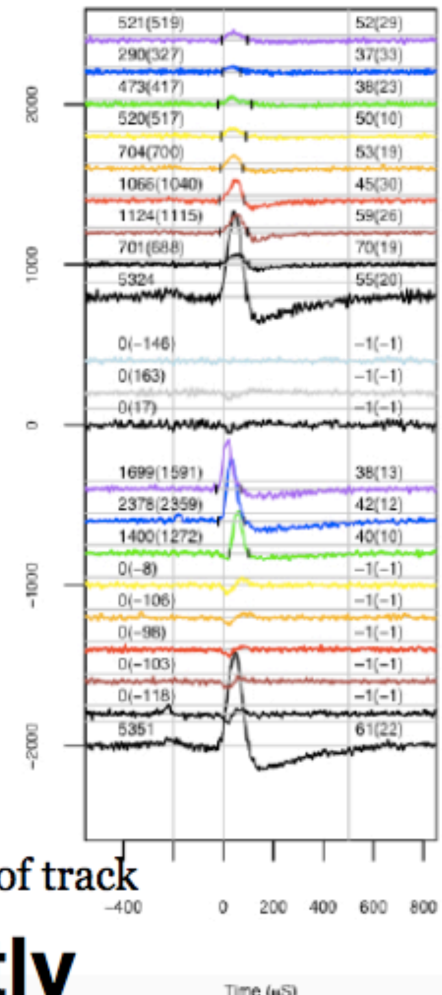




DRIFT IIa, b, c, d, e



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

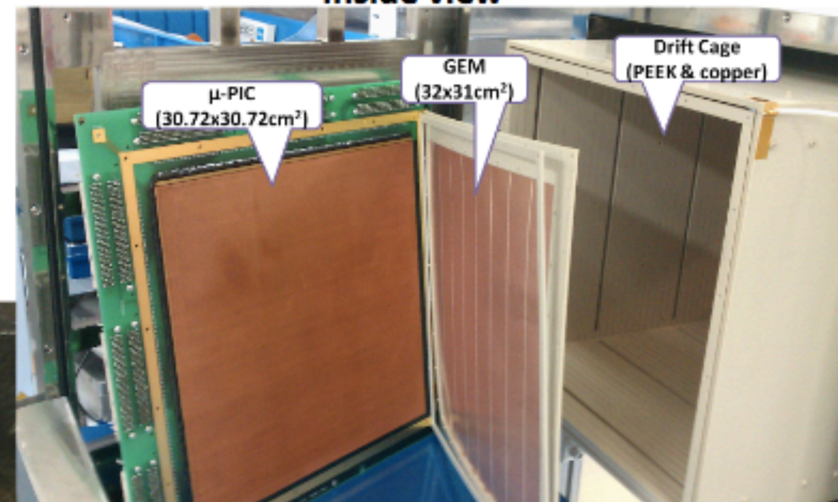


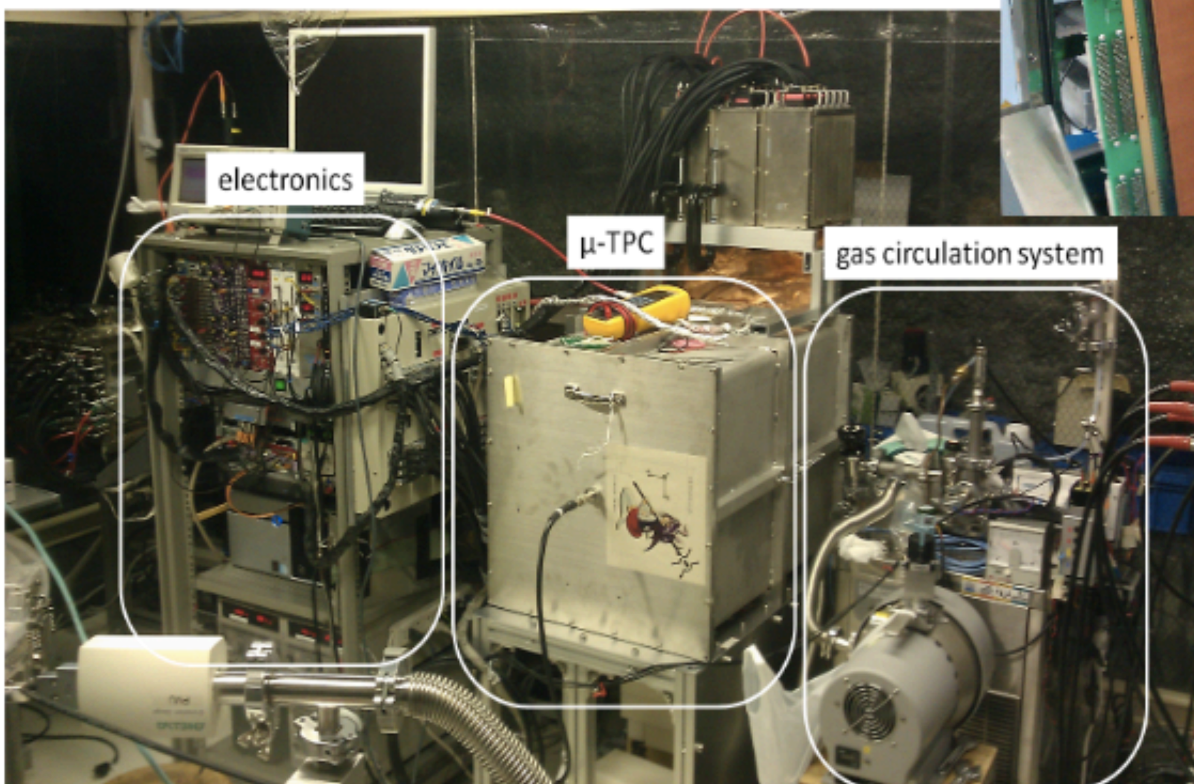
Significant advances recently

NEWAGE-0.3b' Detector

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

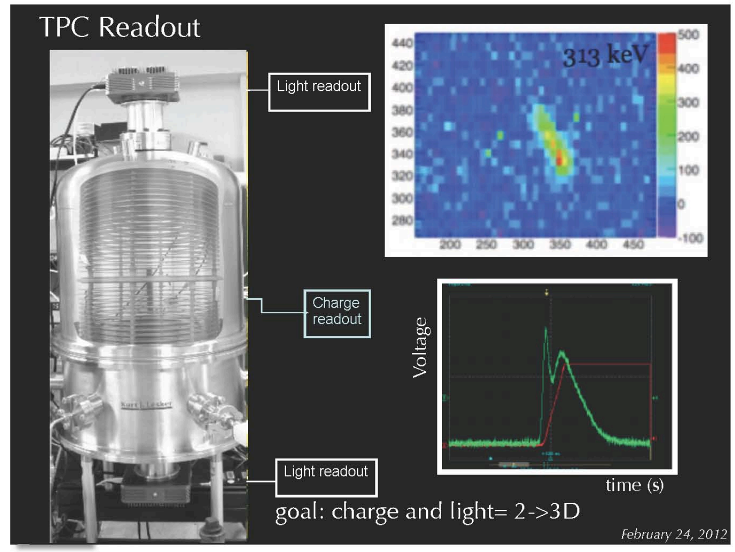
Inside view

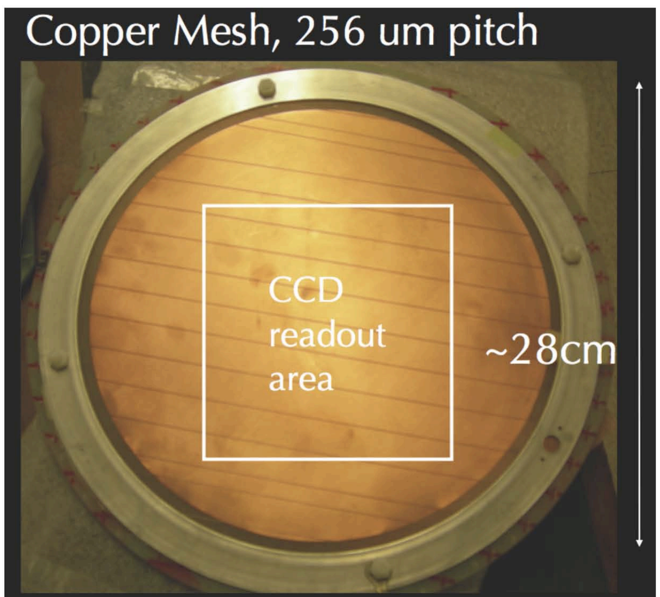




DM-TPC – Dark Matter TPC

Started = 2007, US
Underground in WIPP, USA in 2011
Current operating detector = DMTPC 10 liter
Technology = TPC with micromegas + light and charge readout

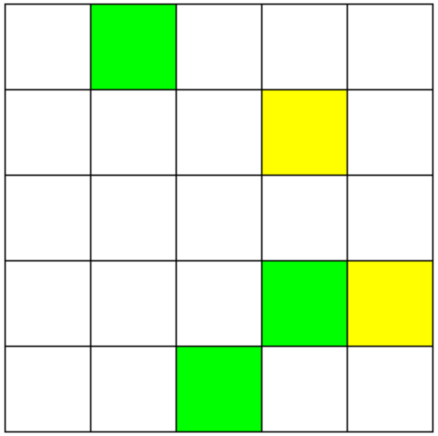




xyz resolution = 0.256 mm & absolute in xy, Δz coming
Target = CF_4 @ 75 Torr
Fiducial volume = 9.18 liters
F mass = 2.85 g
Limit setting threshold = 80 keVr

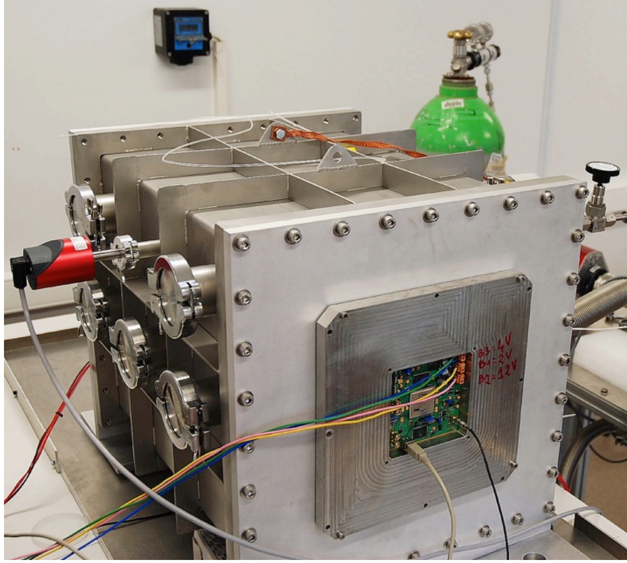
These values are probably out of date
See more on DMTPC website

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**

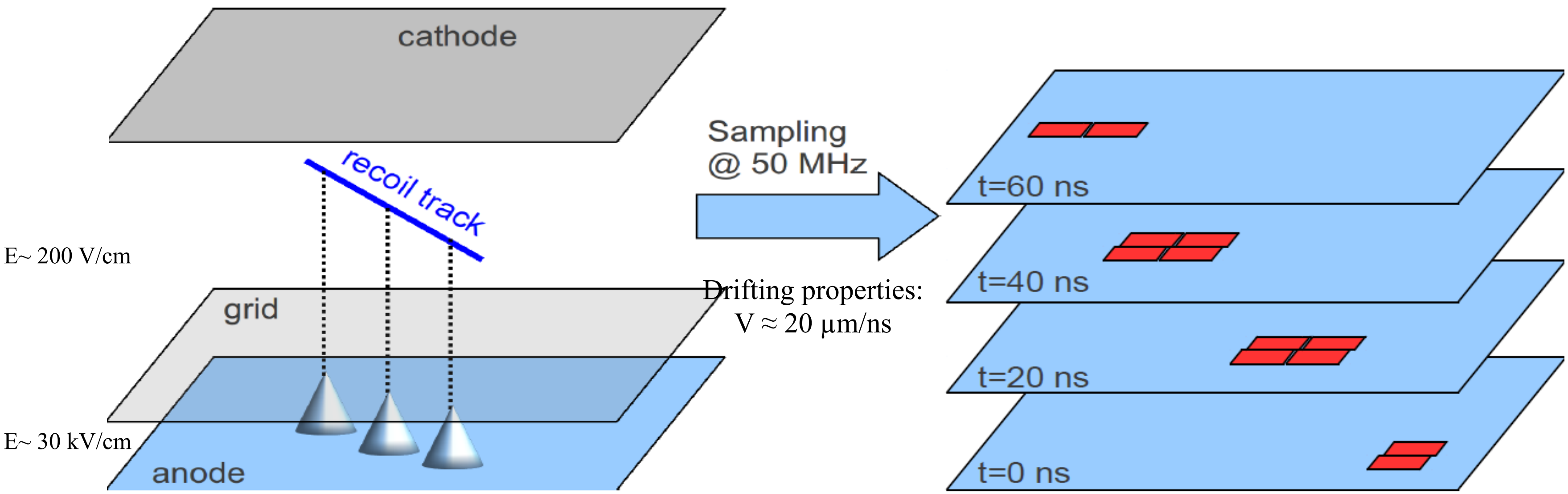


Bi-chamber module
2 x (10.8x 10.8x 25 cm^3)

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, ^{4}He, ^{20}Ne, ^{40}Ar, ^{129,130}Xe

MIMAC: Detection strategy

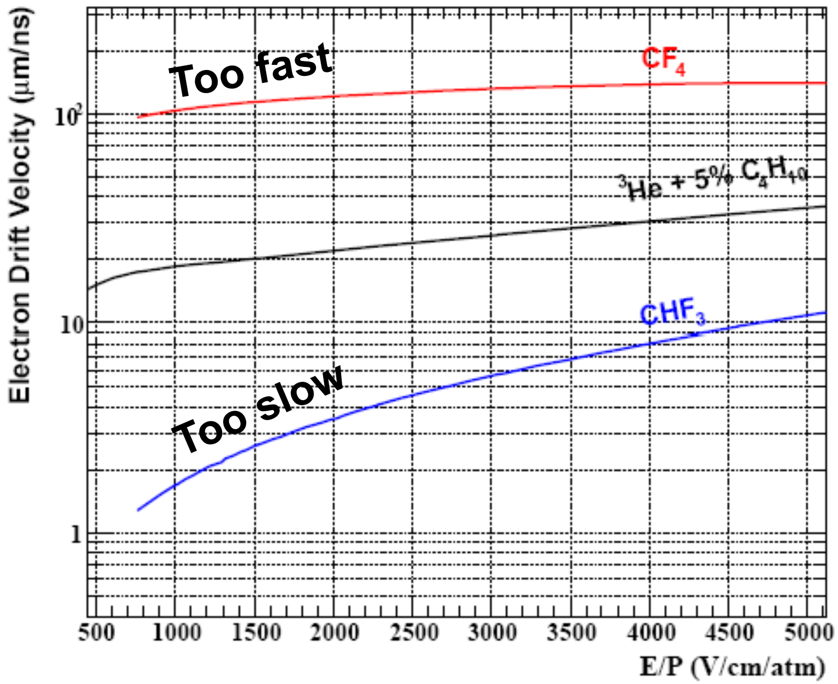


Scheme of a MIMAC μTPC

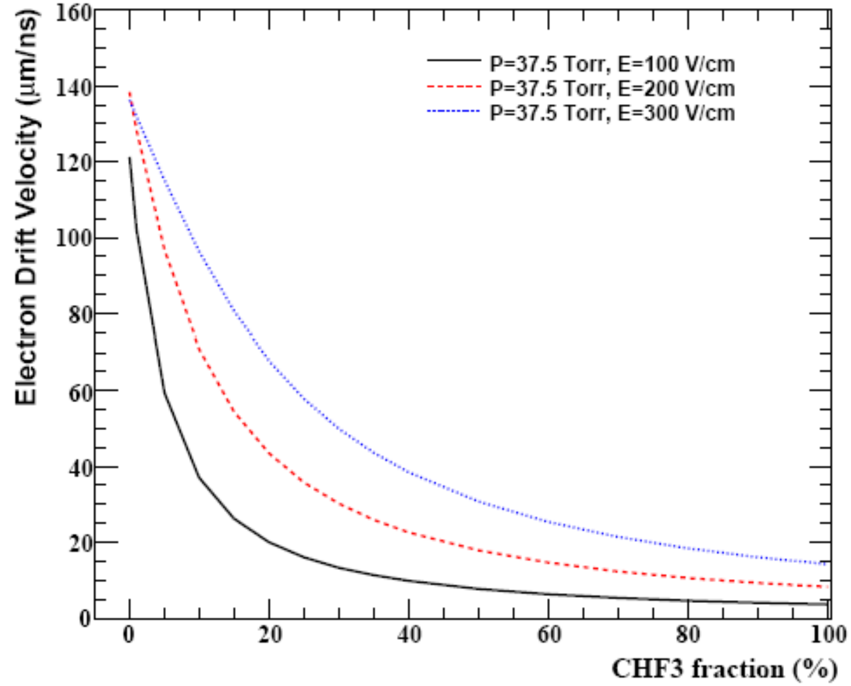
Evolution of the collected charges on the anode

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

3D Tracks: Drift velocity



Magboltz Simulation



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

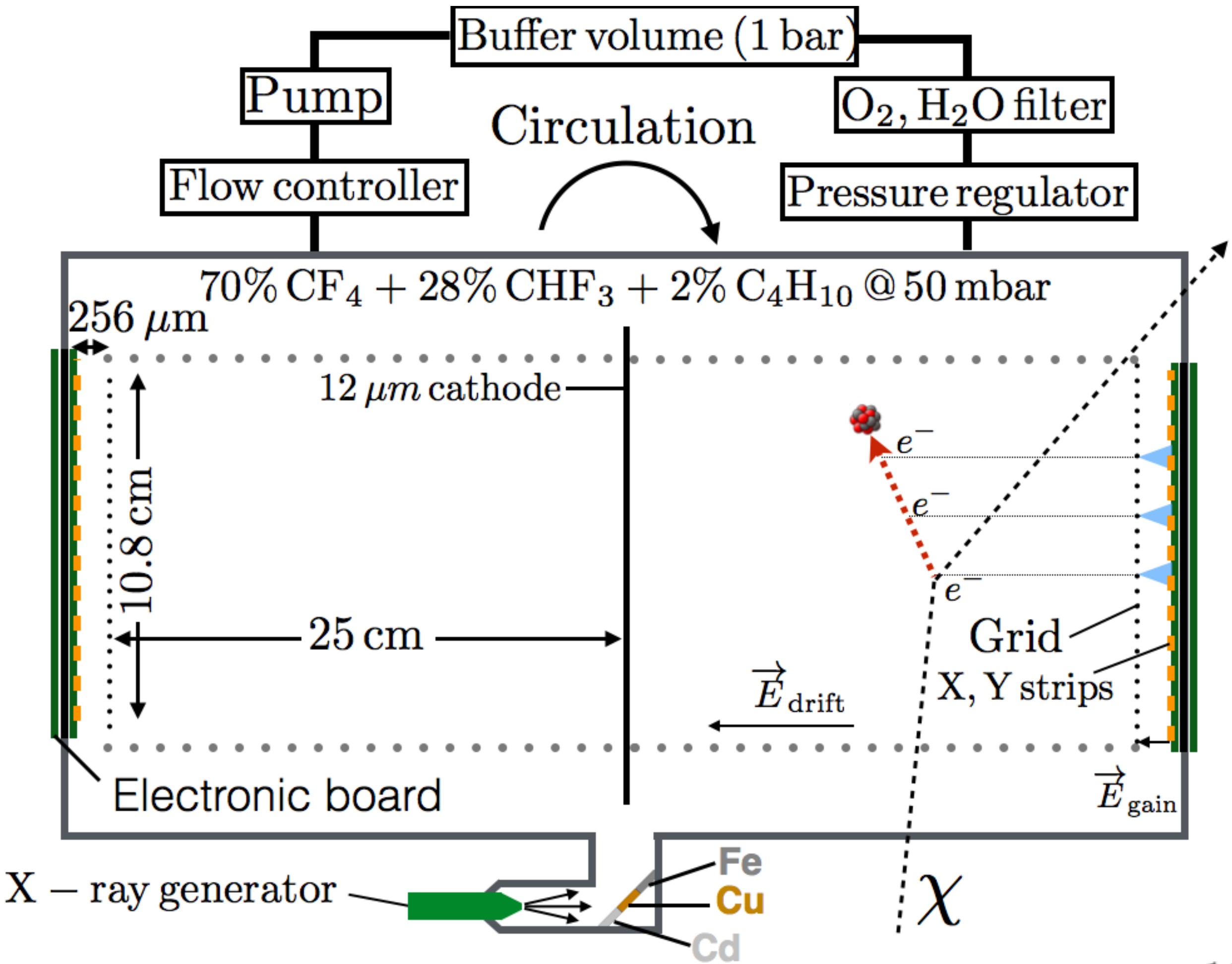
MIMAC (bi-chamber module)at Modane Underground Laboratory (France)
since June 22nd 2012.
Upgraded in June 2013, and
in June 2014.

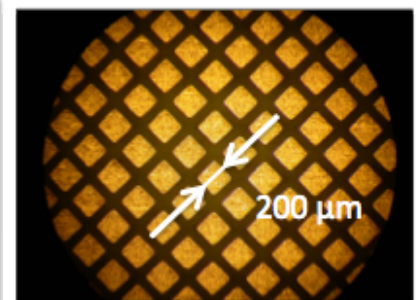
-working at 50 mbar
(CF_4+28% CHF_3 + 2% C_4H_{10})

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

Many thanks to LSM staff

MIMAC-bi-chamber module prototype





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

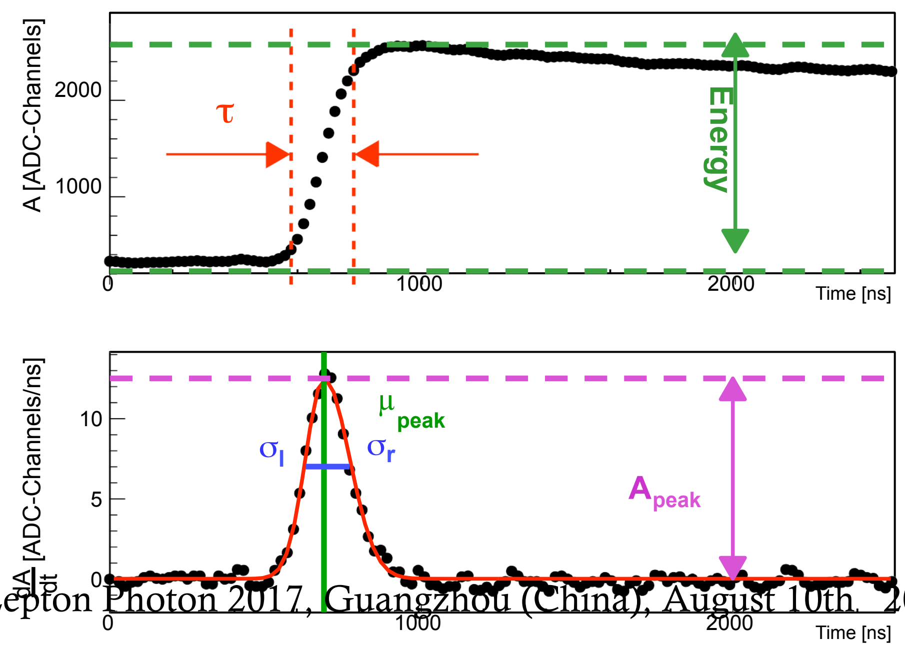
MIMAC Target: ^{19}F

- Light WIMP mass
- Axial coupling

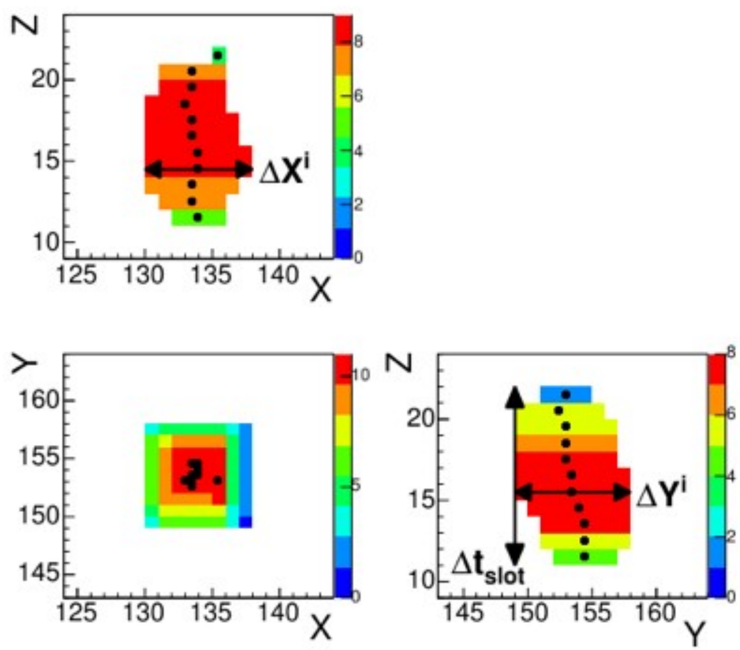
MIMAC readout

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!)

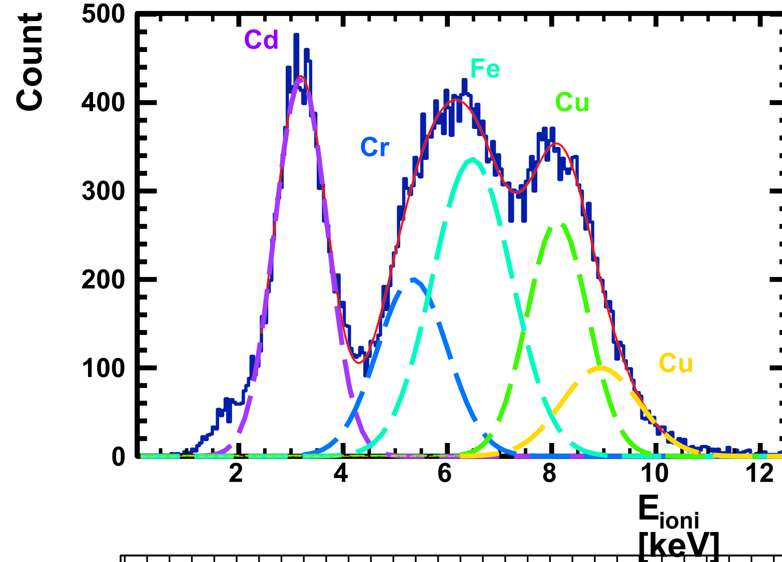
Calibration: (once a week)

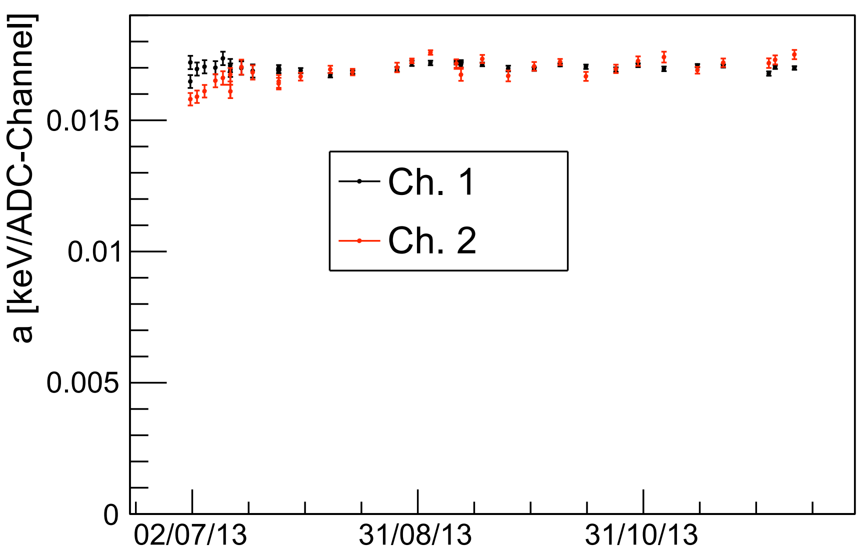
X-ray generator producing fluorescence photons from Cd, Fe, Cu foils.

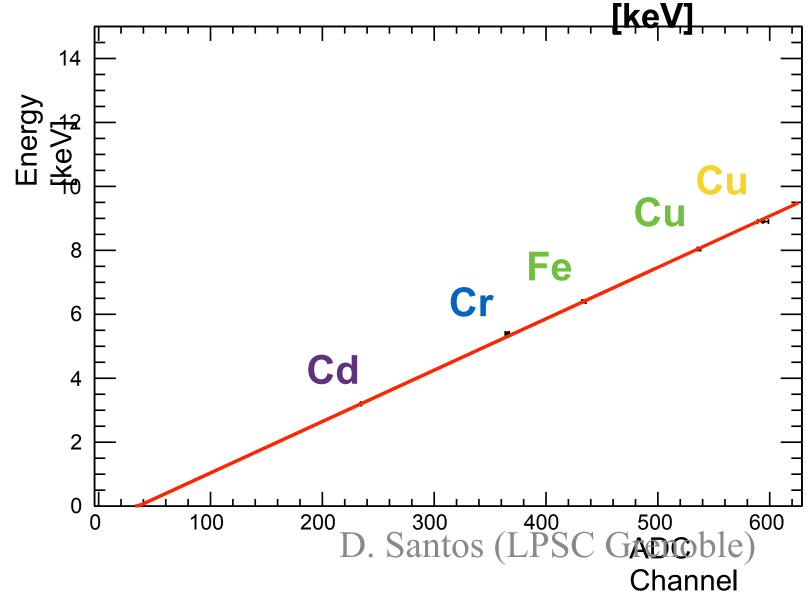
Threshold ~ 1 keV

Circulation system:

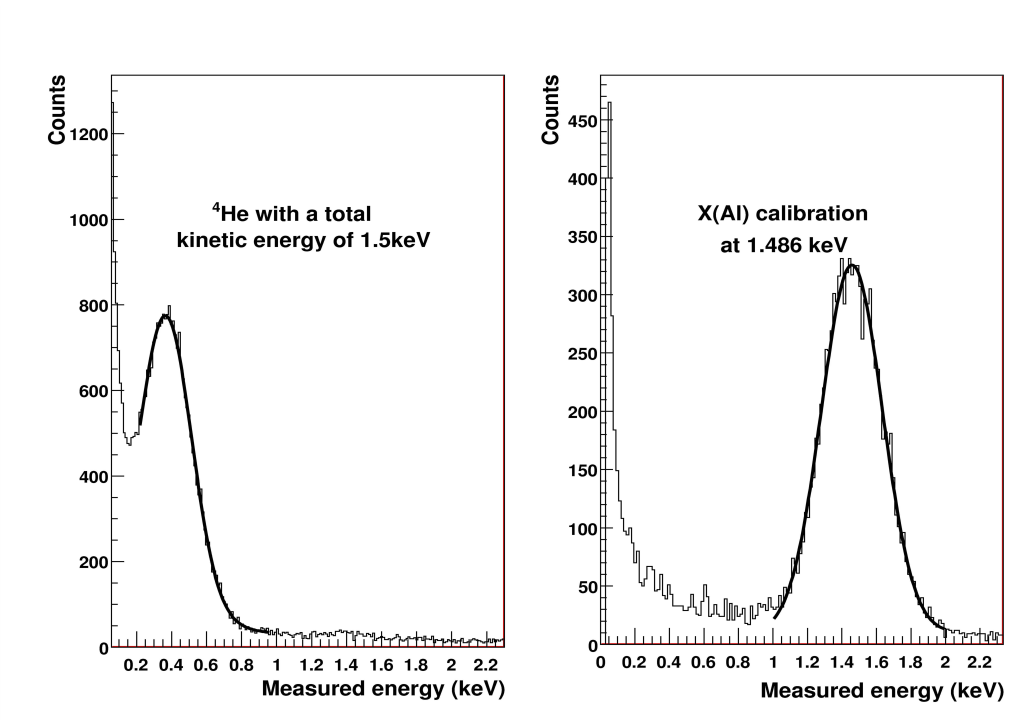
Excelent Gain stability in time

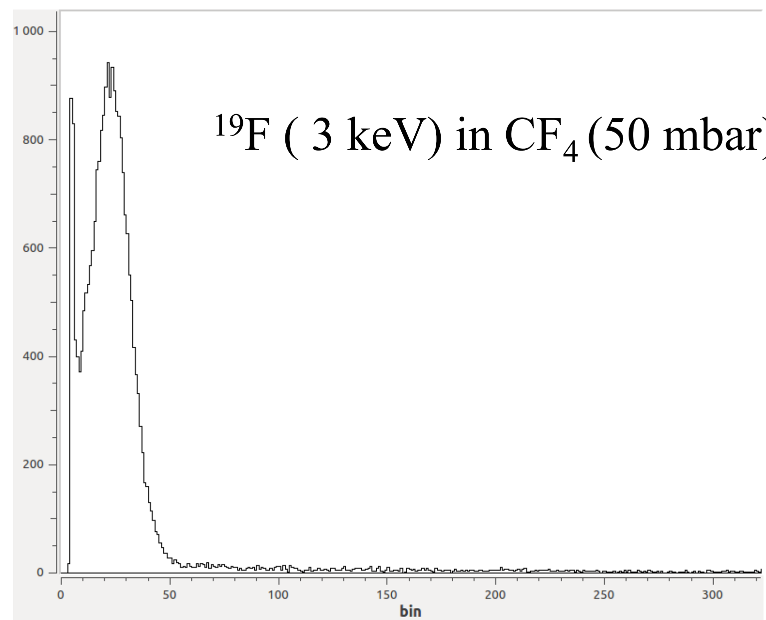




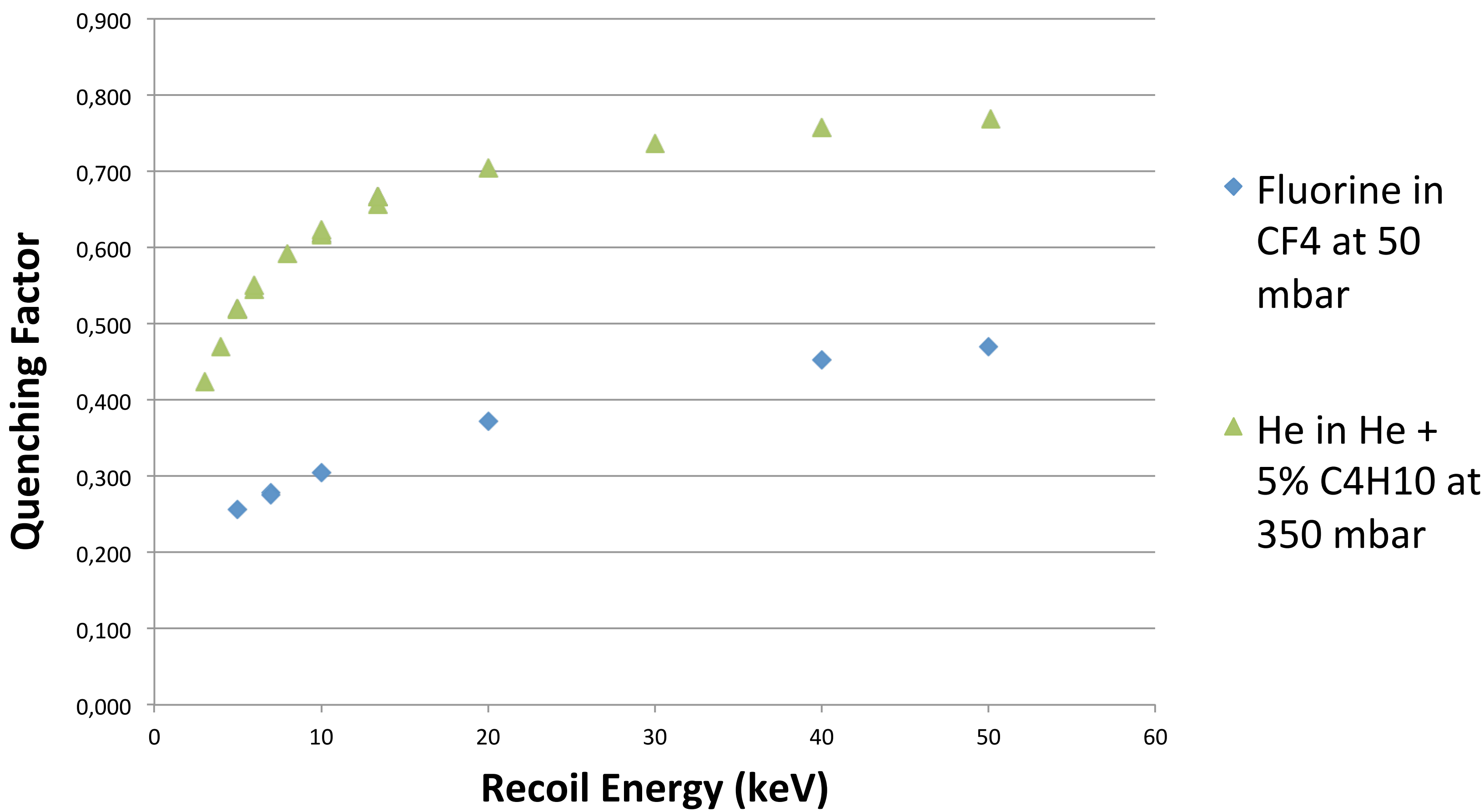


Ionization Quenching Factor Measurements at LPSC-Grenoble

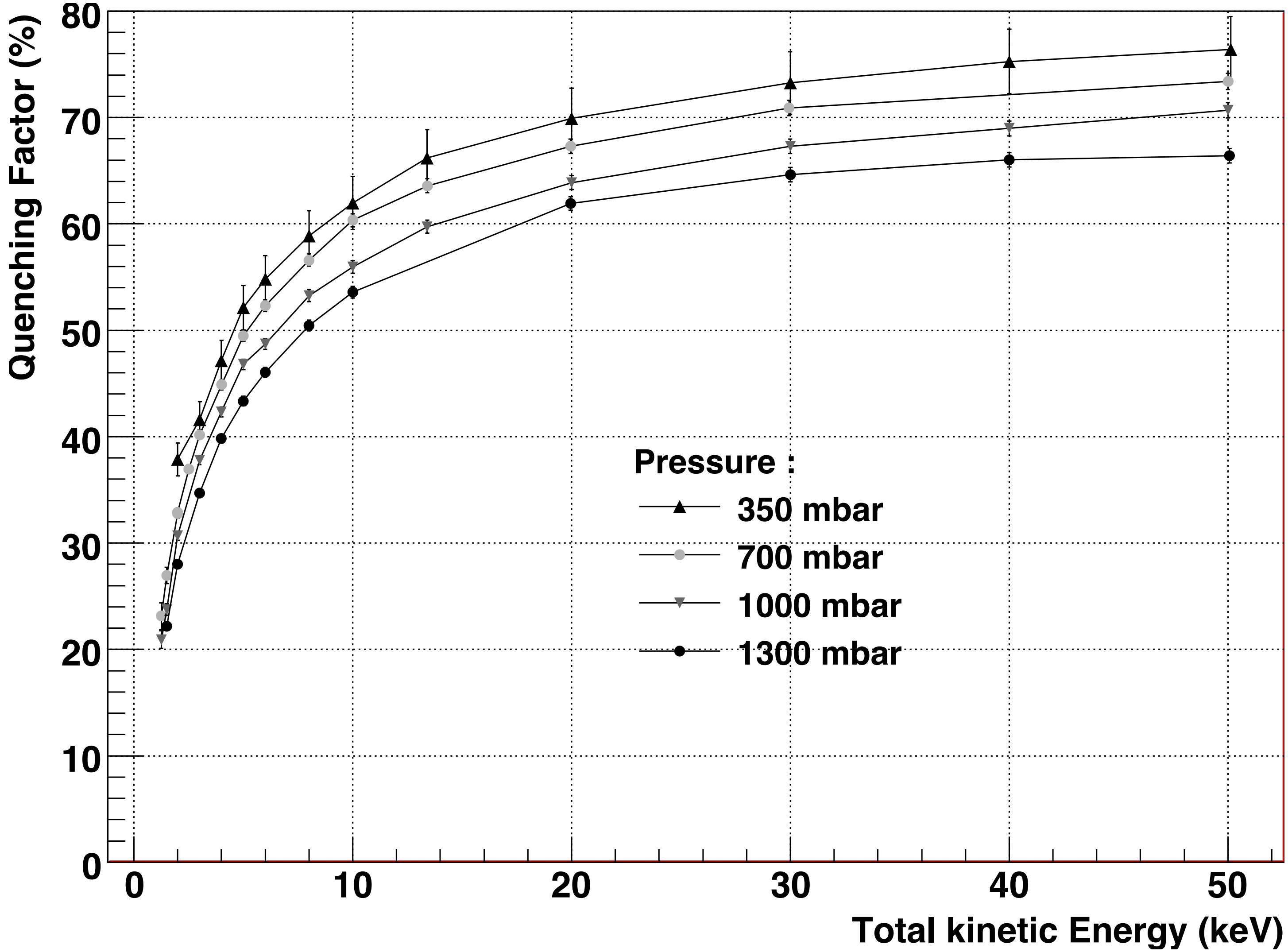




Ionization Quenching Factor for Fluorine in pure CF4 at 50 mbar



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



MIMAC validation with neutrons

Neutron monochromatic field:

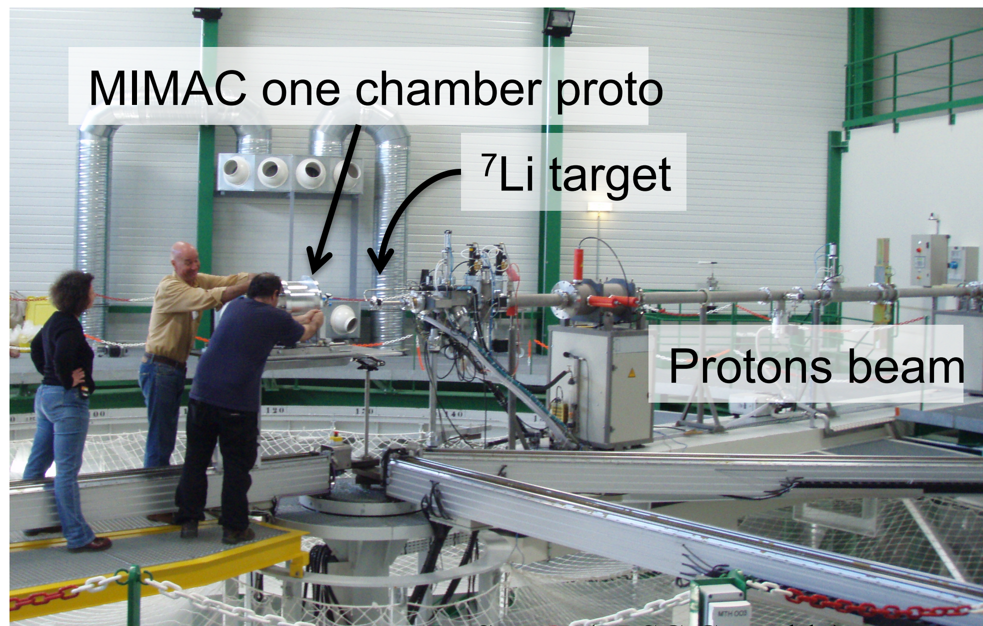
AMANDE facility at IRSN of Cadarache

– 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

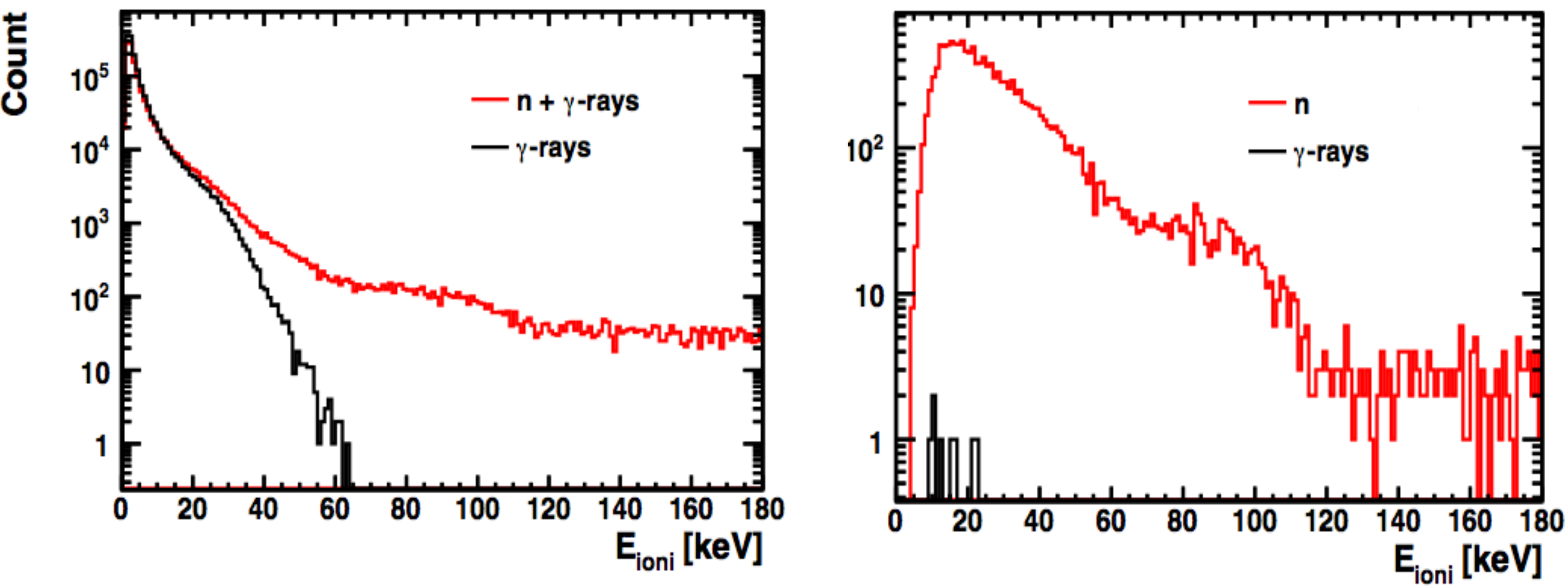


Electron-recoil Discrimination

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

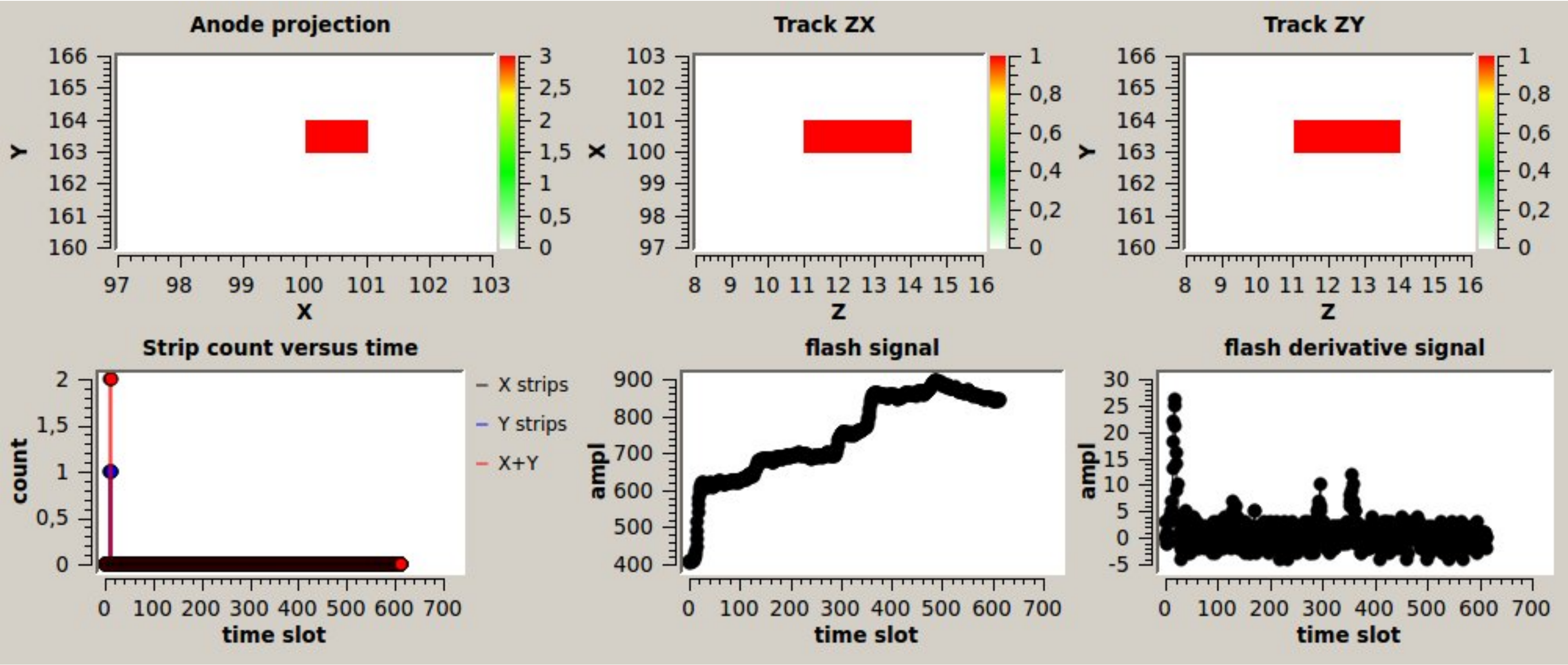
Neutrons → F , C, H, nuclear recoils

γ − rays → Electrons

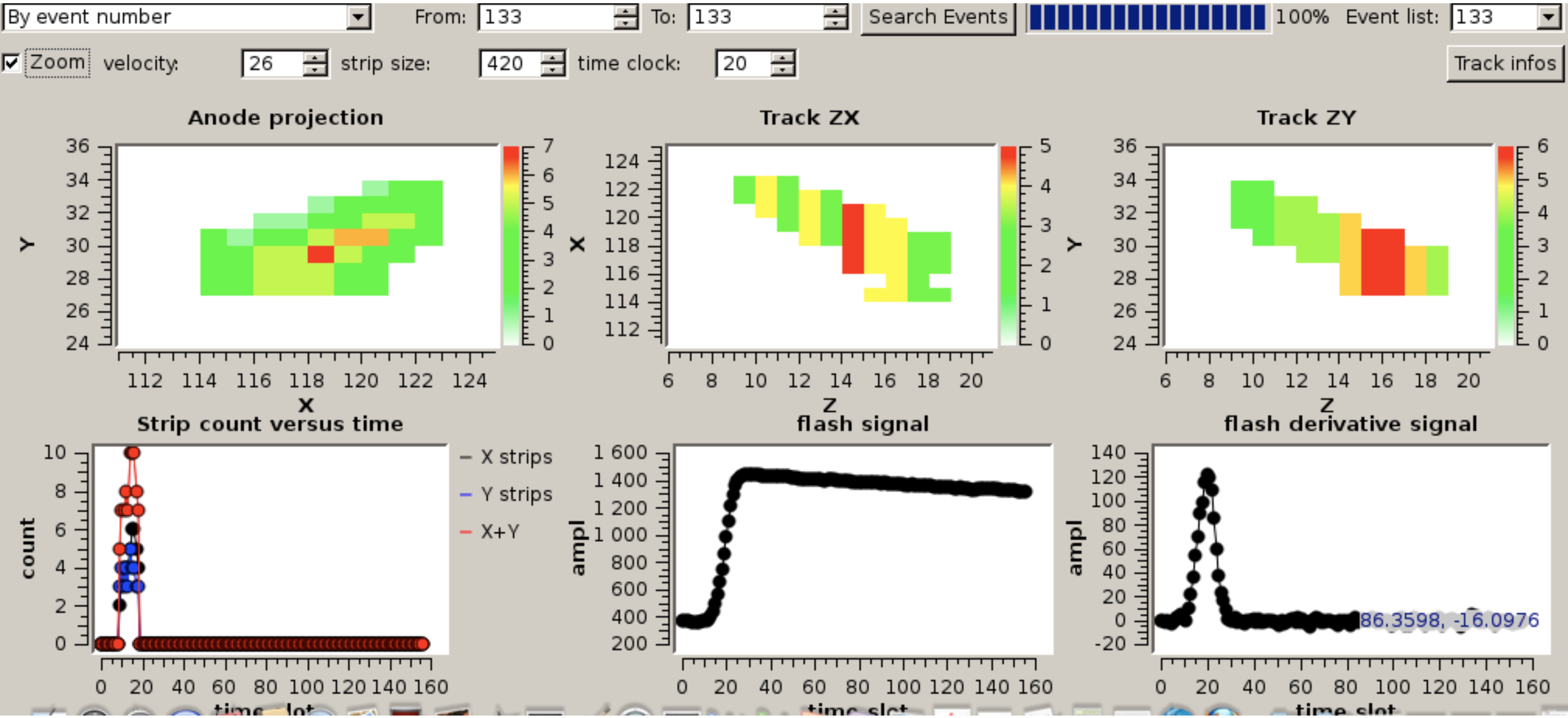


$N_{acpt}/N_{tot} = 1.1 \times 10^{-5}$ electron integrated rejection

An Electron event (18 keV)



A “recoil event” (~ 34 keVee)



Radon Progeny

^{222}Rn chain:

- 4 β-decays

→ Electron event (background)

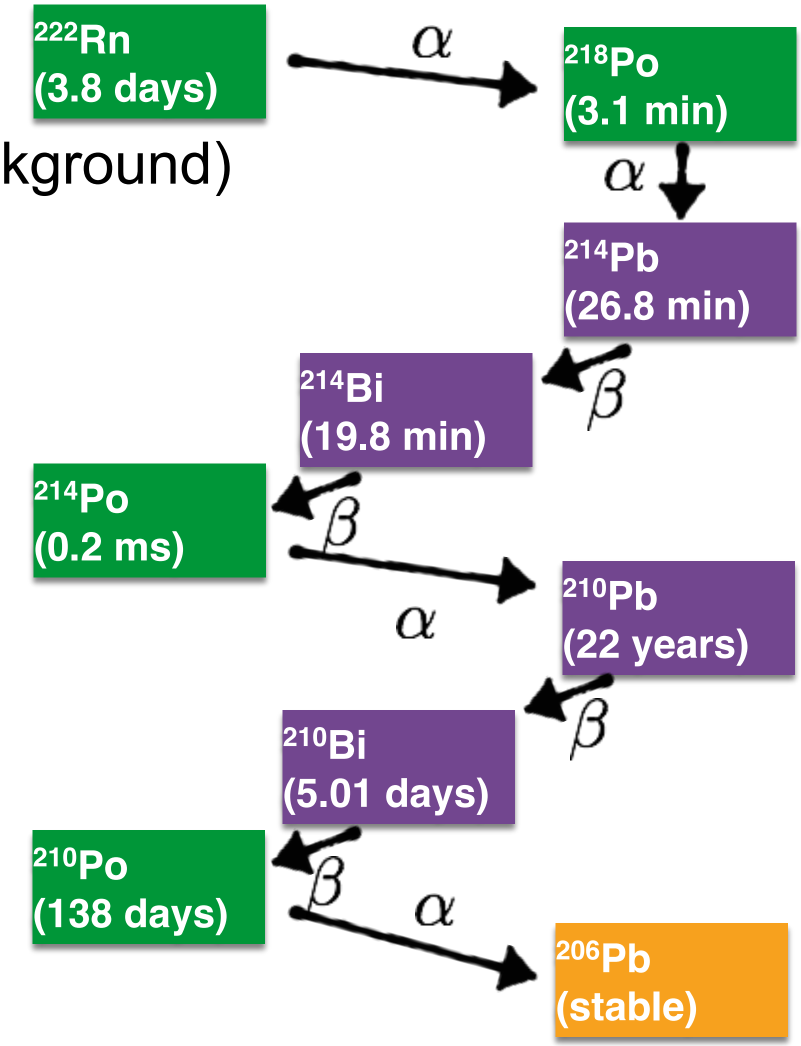
- 4 α-decays

→ 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)



First detection of 3D tracks of Rn progeny

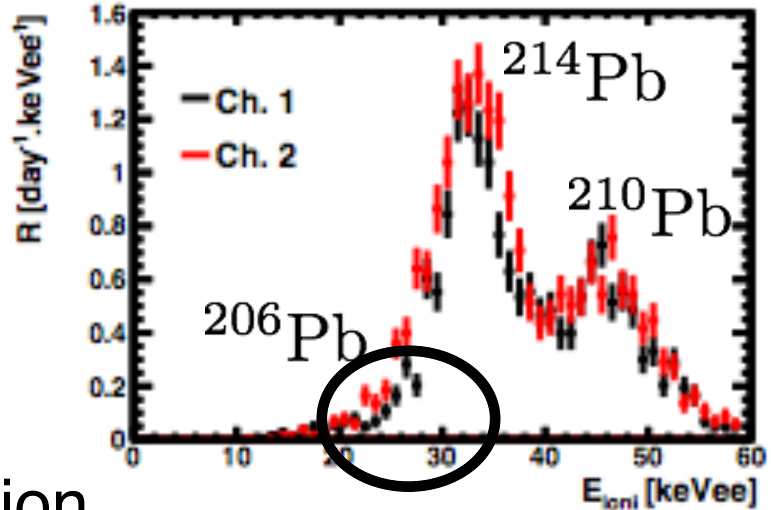
Electron/recoil discrimination

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

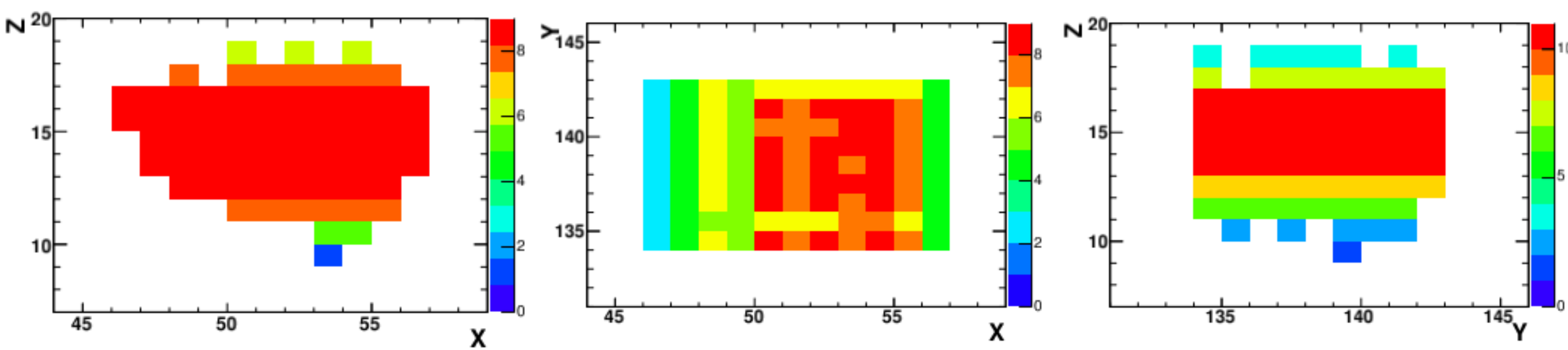
First measurement of 3D nuclear-recoil tracks coming from radon progeny

⟶ MIMAC detection strategy validation

Nuclear recoil spectra



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

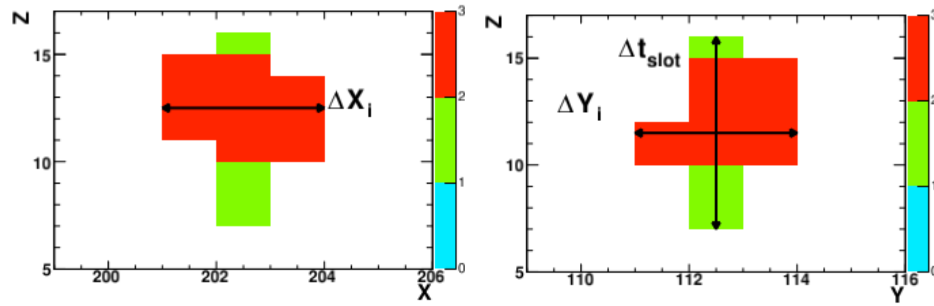


RPR events occur at different positions in the detector…

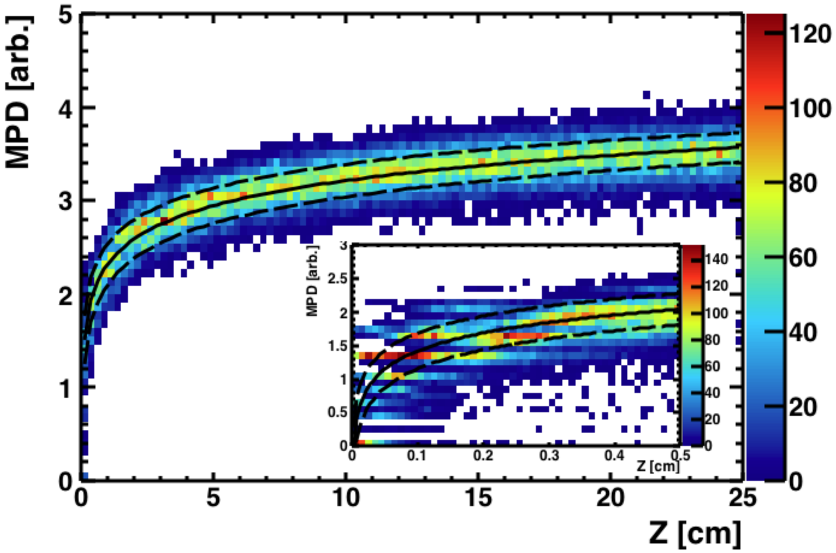
$$z_0 \longleftrightarrow \text{Diffusion}$$

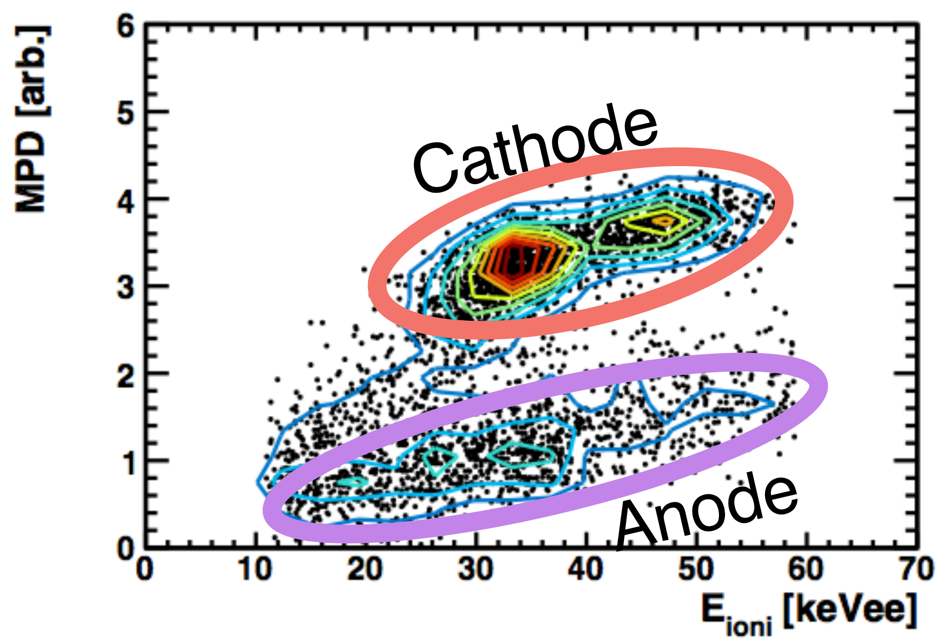
$$\begin{cases} D_T = 237.9\,\mu\text{m}/\sqrt{\text{cm}} \\ D_L = 271.5\,\mu\text{m}/\sqrt{\text{cm}} \end{cases}$$

« Anode » event



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

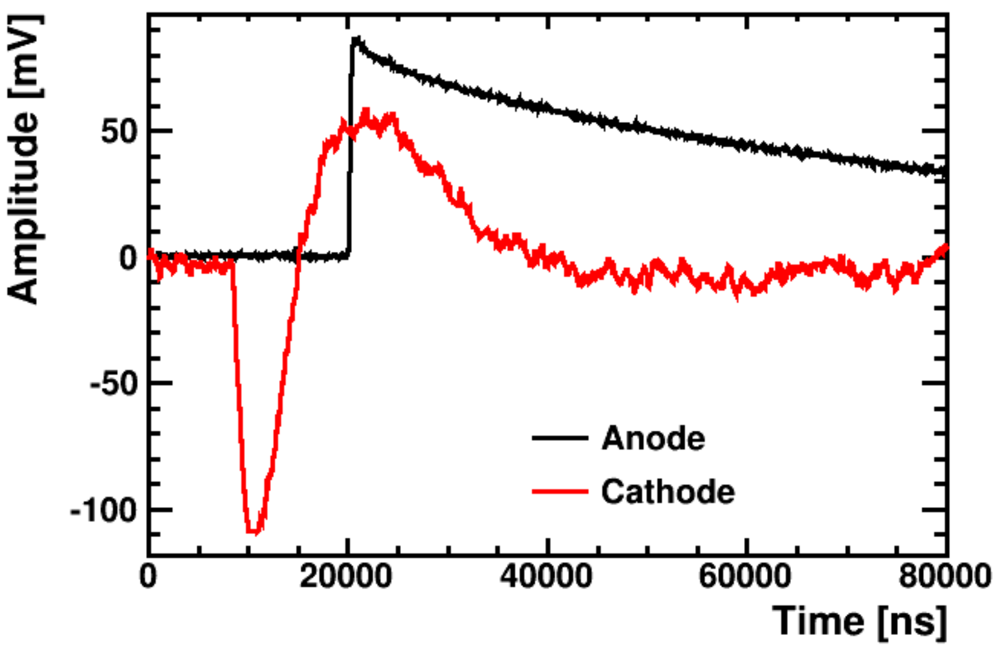




Cathode Signal to place the 3D-track

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

(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)

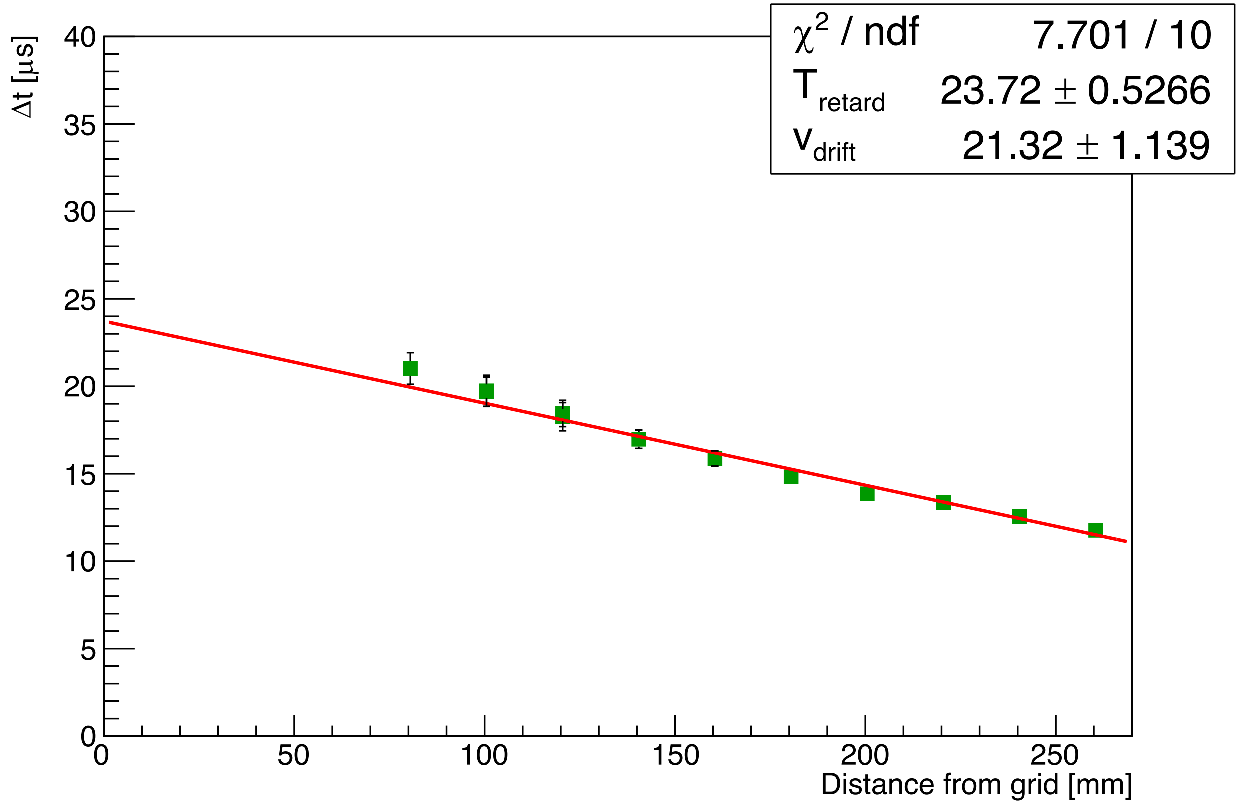
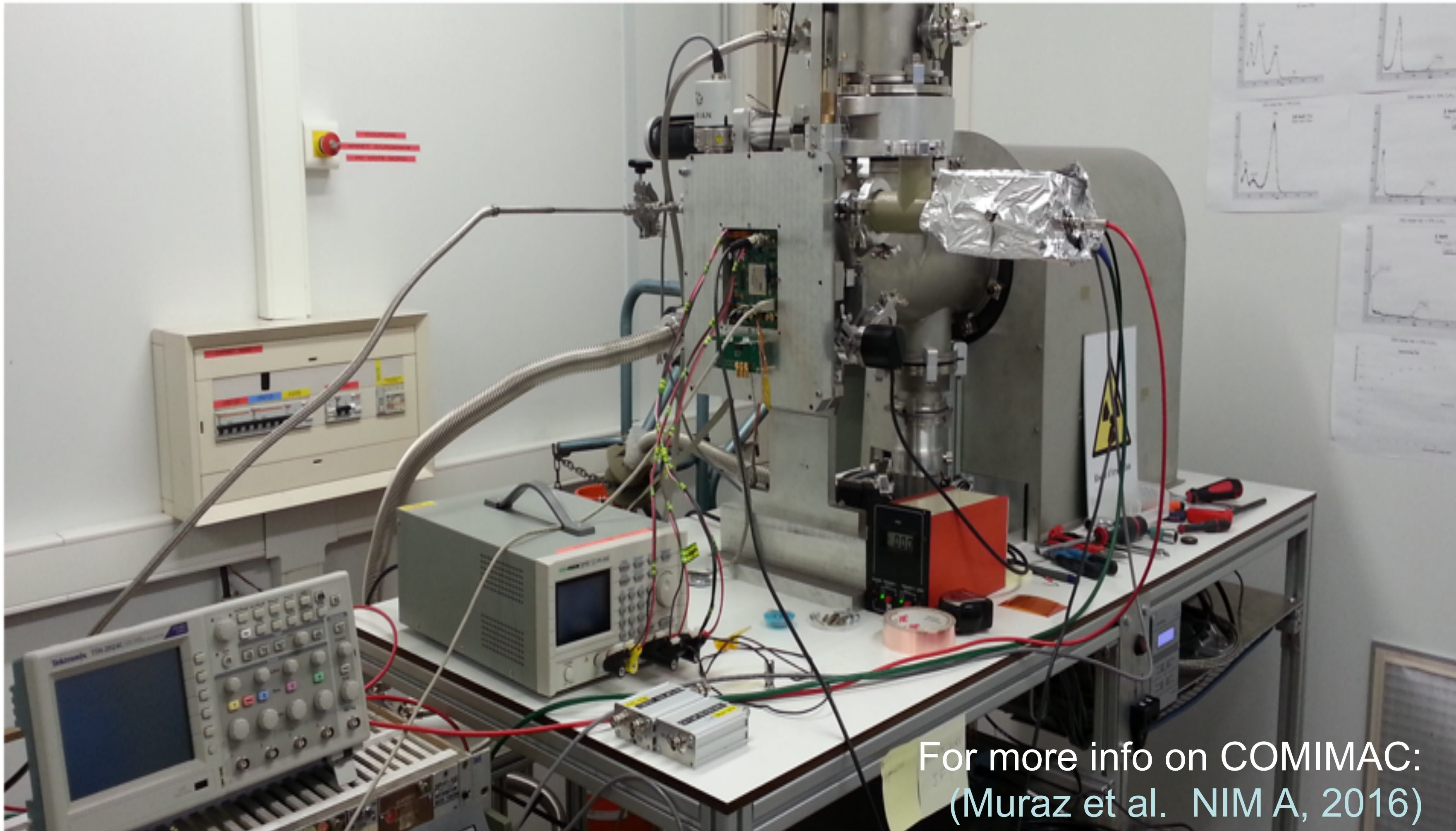


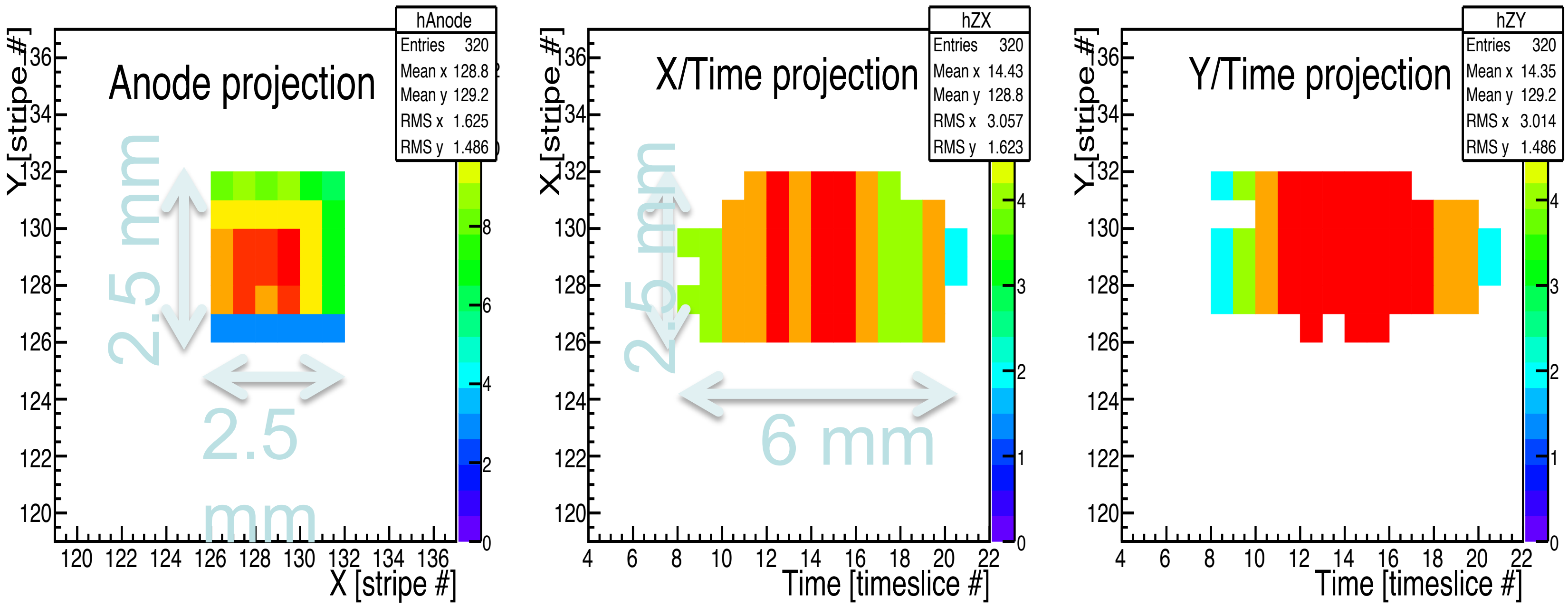
Figure 4. Measure of the time differences (TAC) between the grid signal and the delayed cathode signal in the "START Grid" configuration, as a function of the distance of the α source from the anode (green points) ; error bars correspond to the standard deviation of the mean. A linear fit of these points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

First controlled Fluorine tracks, using COMIMAC



COMIMAC: first measurements on controlled tracks of Fluorine

25 keV (kinetic) Fluorine → ~ 9 keVee



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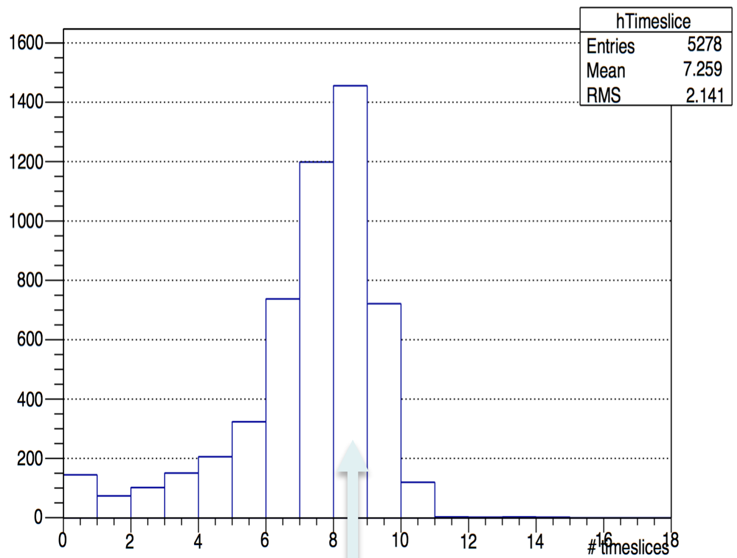
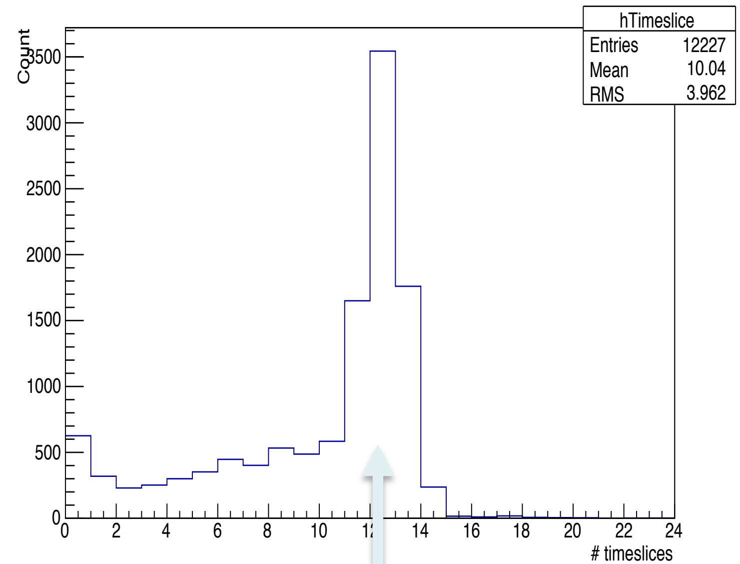
COMIMAC: first controlled tracks of ^{19}F

8 keV kinetic → 2 keVee



25 keV kinetic → 9 keVee



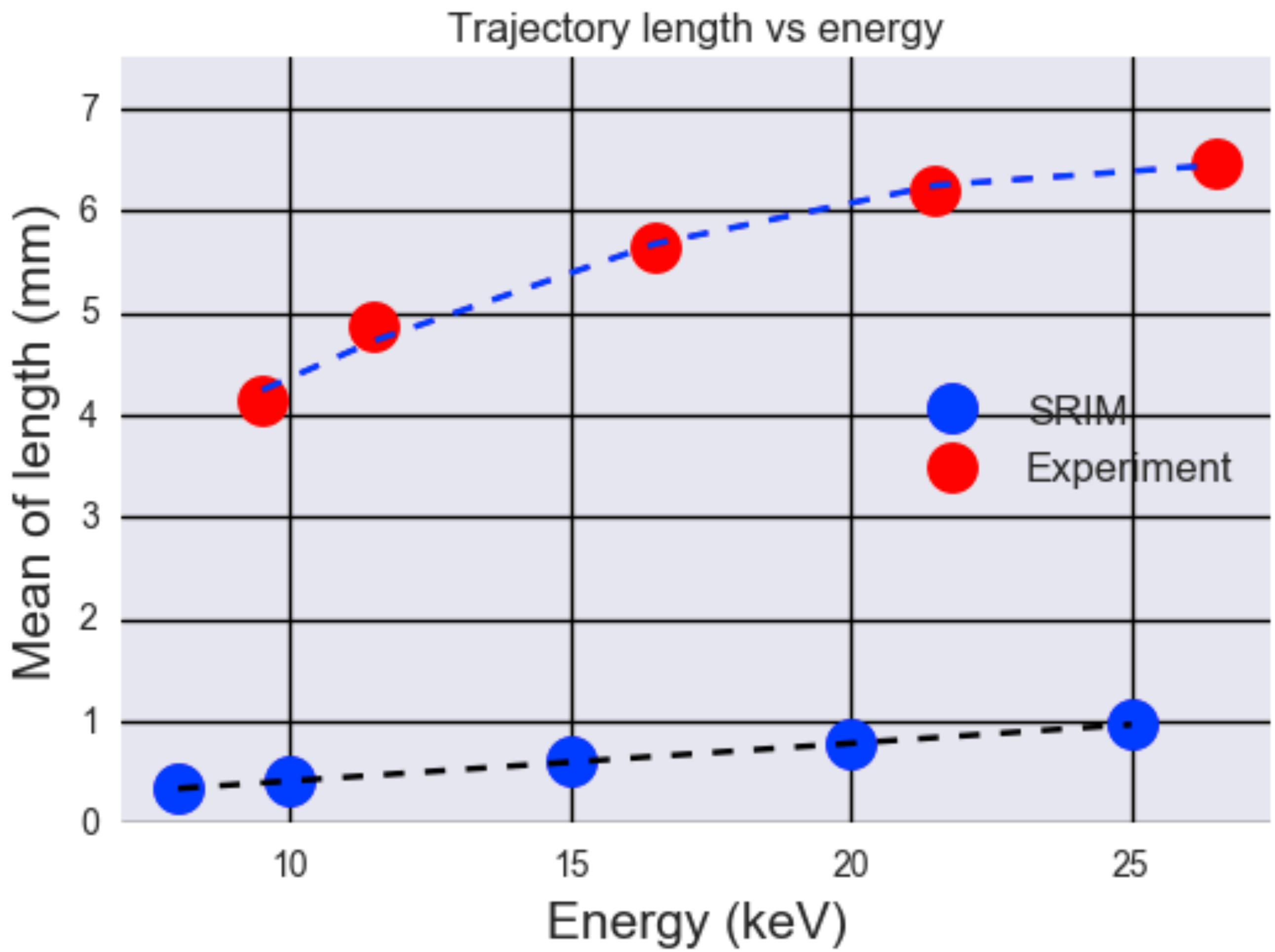
8 timeslices
* 20 ns/timeslices
* 23.5 µm/ns
= 3.8 mm

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

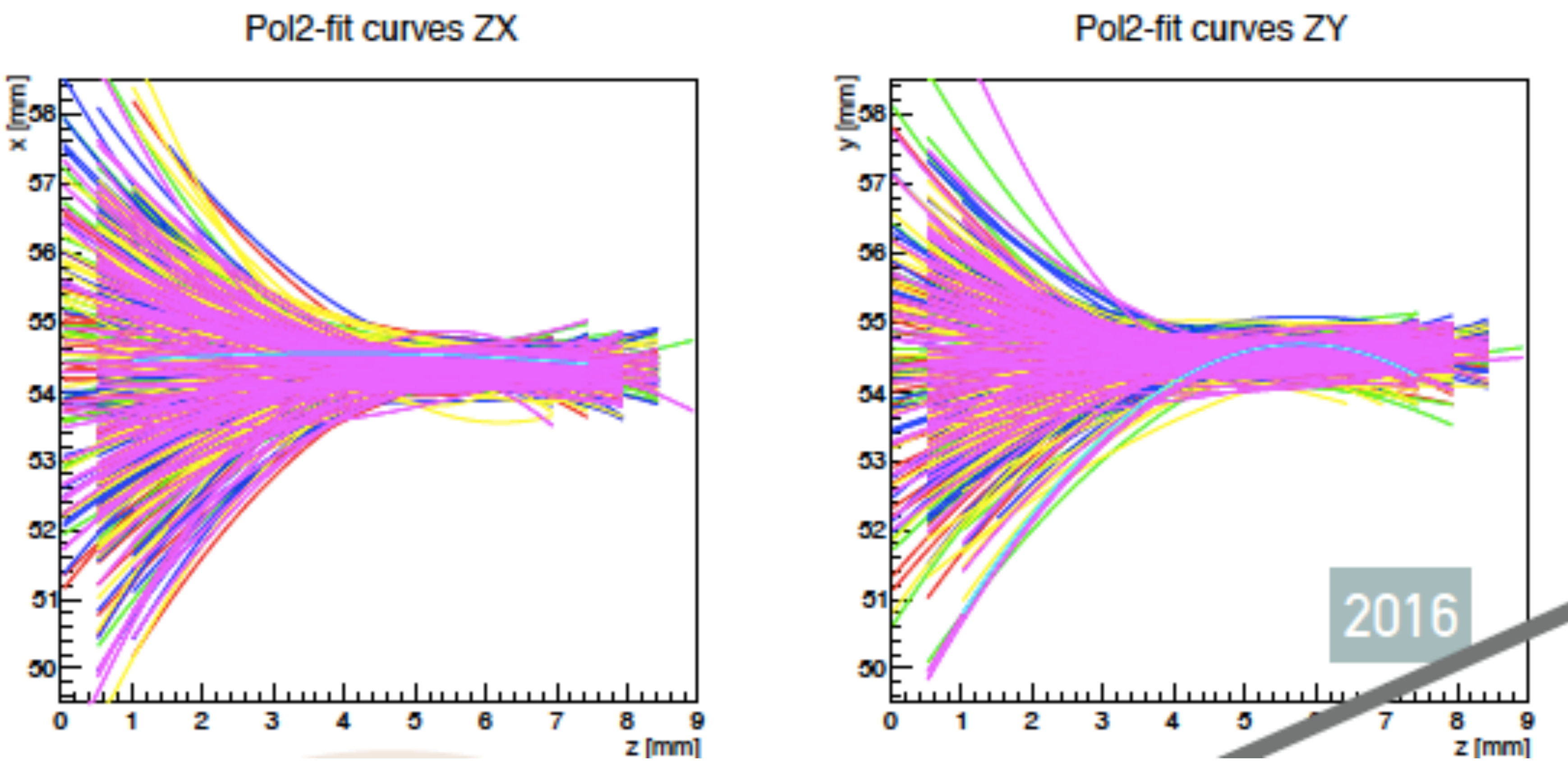
C. Couturier, I. Moric, Y. Tao et al. (in preparation)

Track "Lengths" measured with COMIMAC

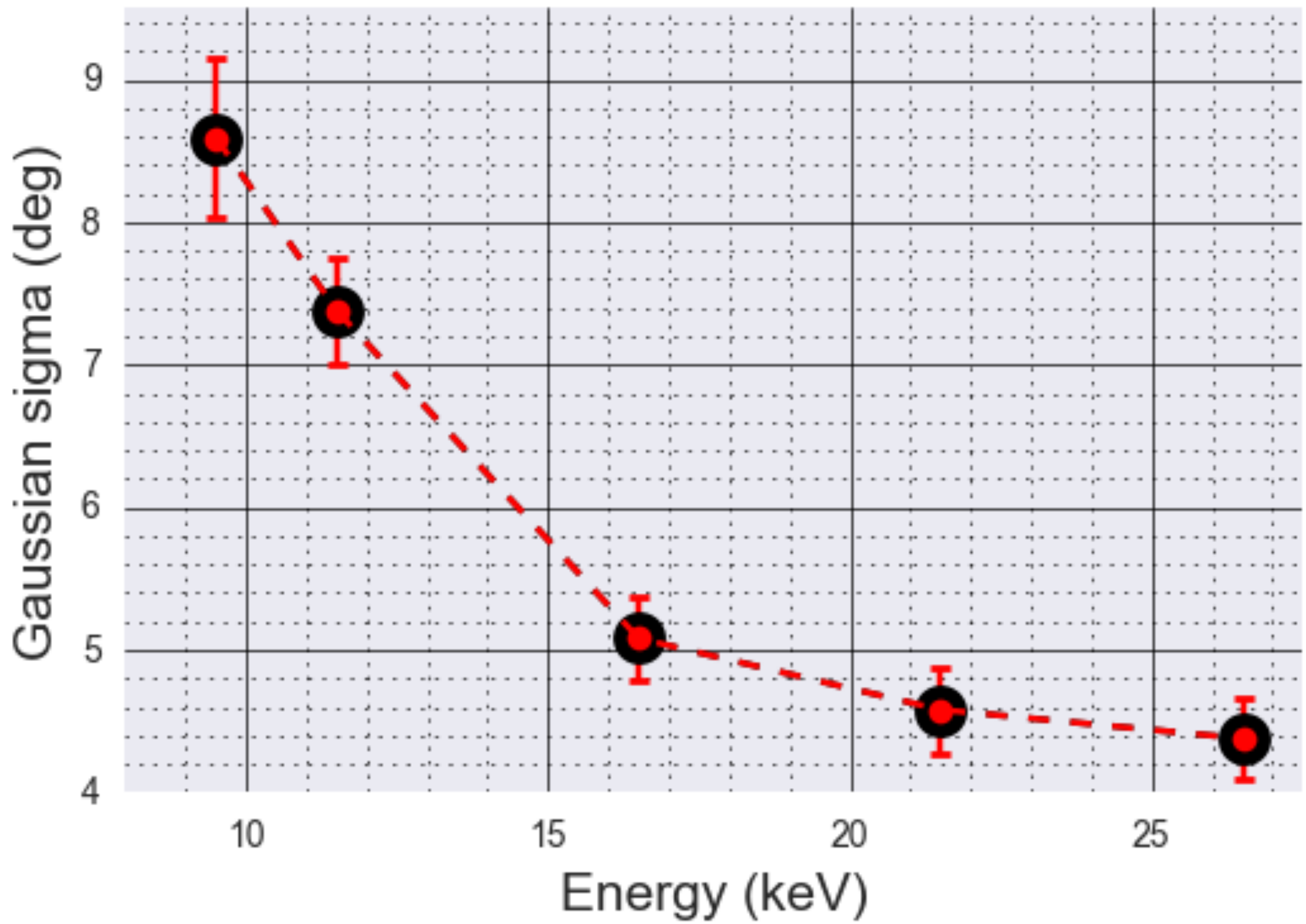
(I. Moric, Y. Tao, C. Couturier, et al. 2016 data, preliminary)
(important differences with respect to the SRIM simulations !)



3D ^{19}F tracks from COMIMAC measurements (Yi Tao et al. preliminary (2017))

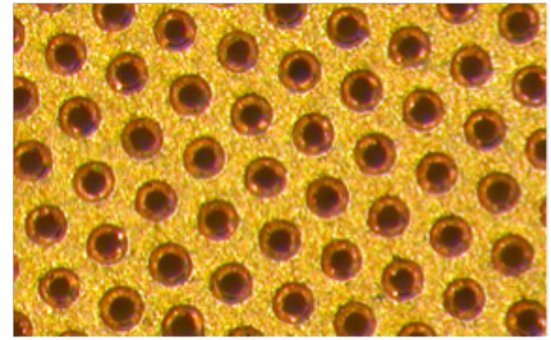


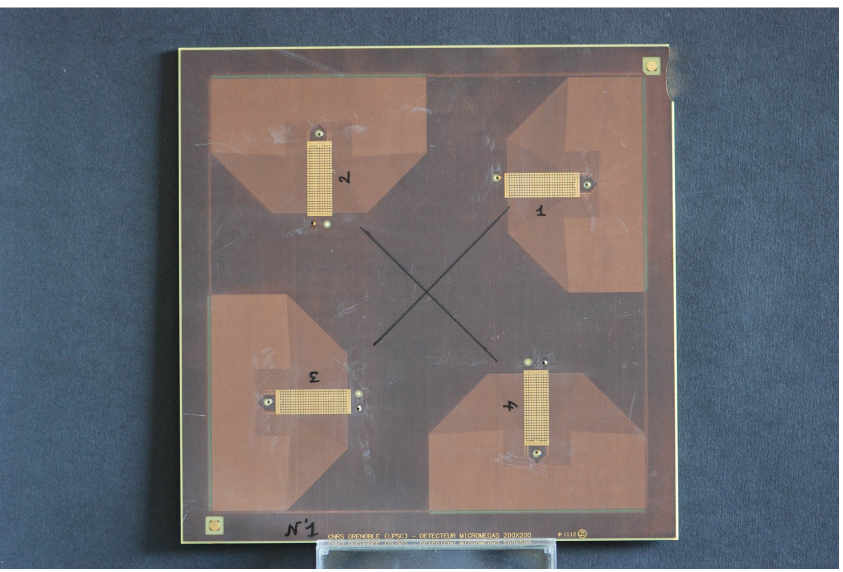
Angular resolution measured with COMIMAC (^{19}F ions at known kinetic energies) (I. Moric, Y. Tao, C. Couturier et al. (2016 data, preliminary)



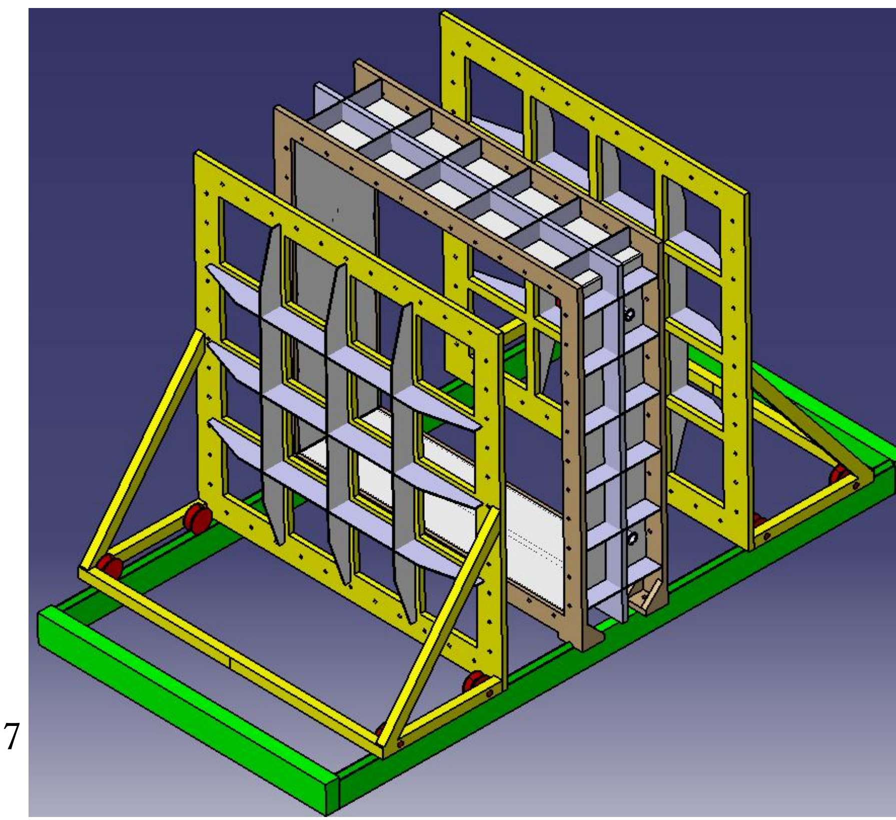
MIMAC – 1m^3 = 16 bi-chamber modules (2x 35x35x26 cm^3)

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



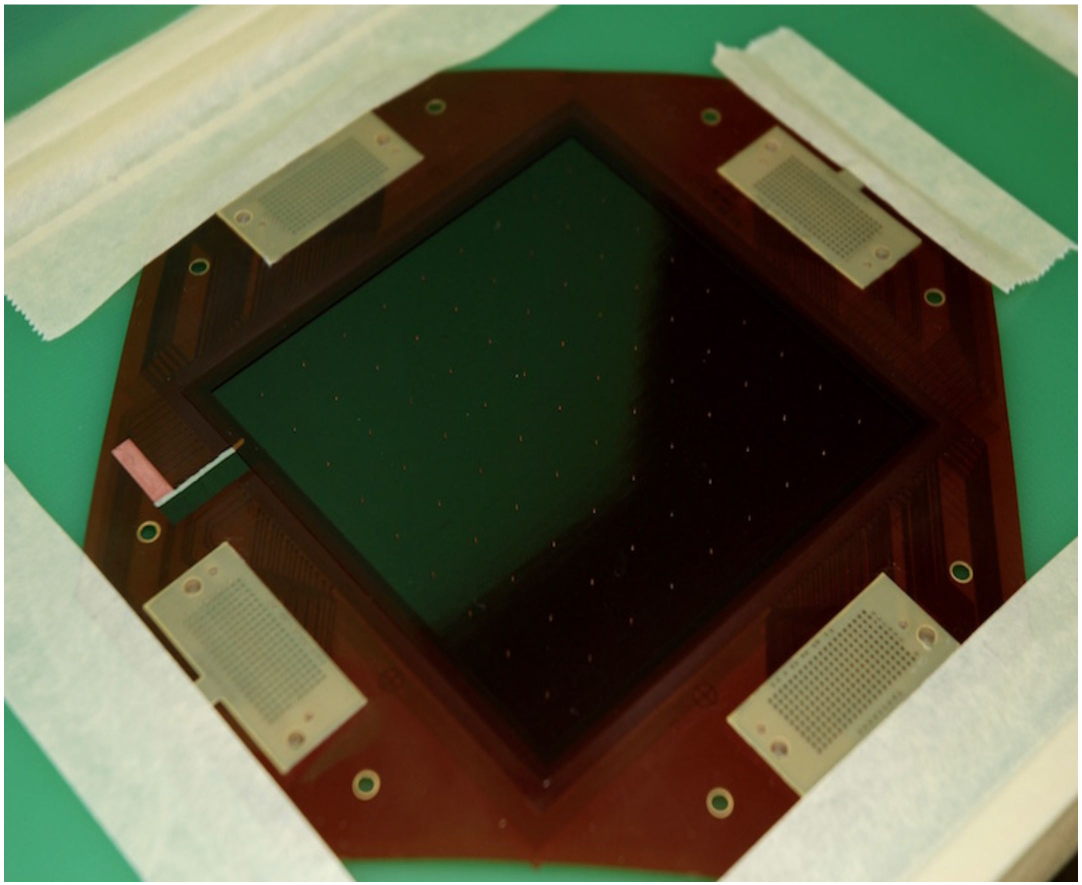


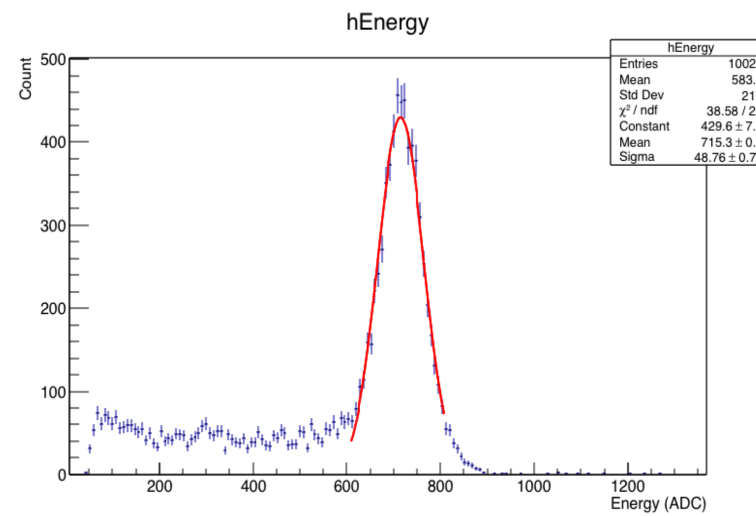
New 20cmx20cm pixellized anode
(1024 channels)



New low background MIMAC detector (10cmx10cm, 512 channels)(1/2017)

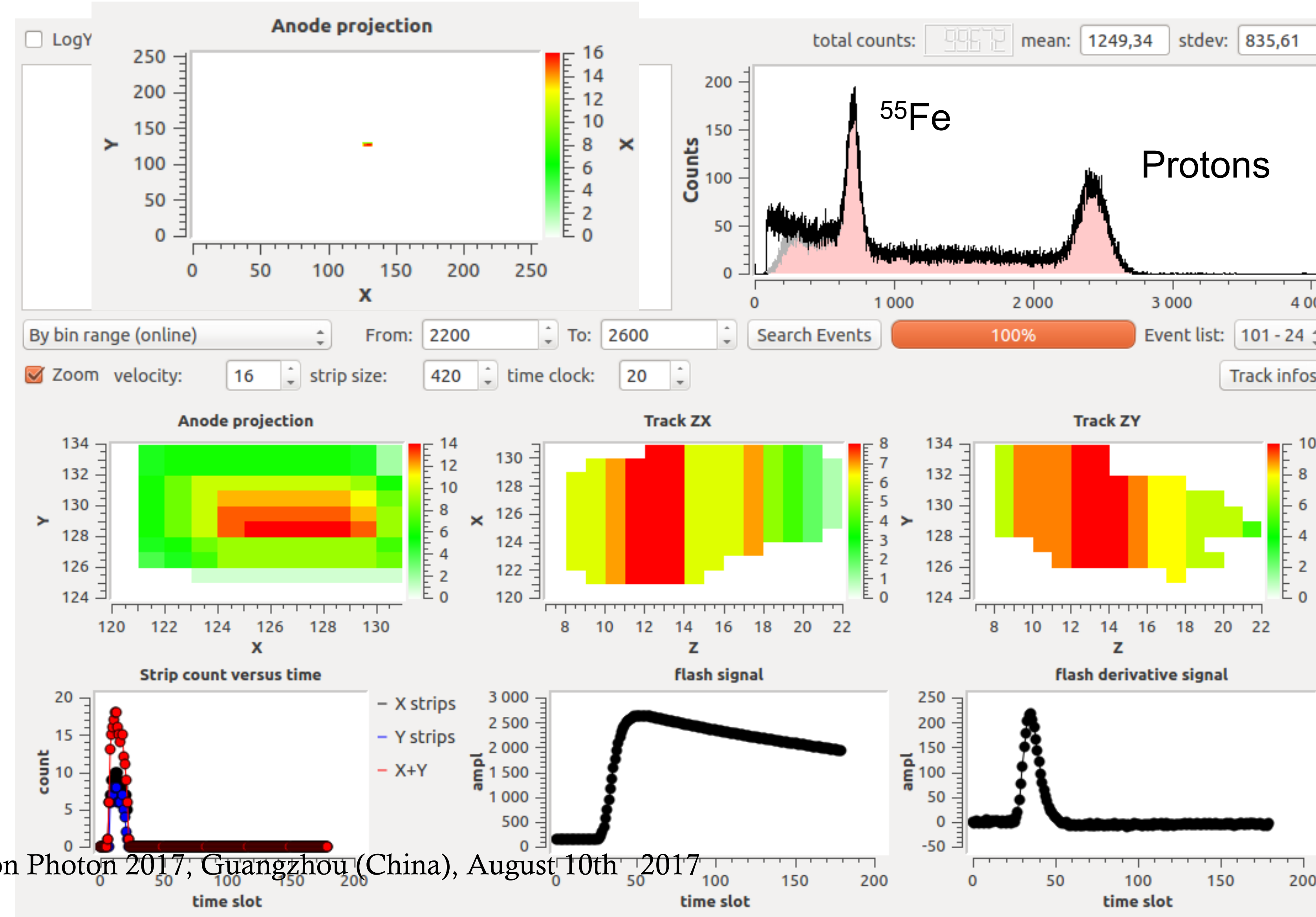
(O.Guillaudin et al. (2016))



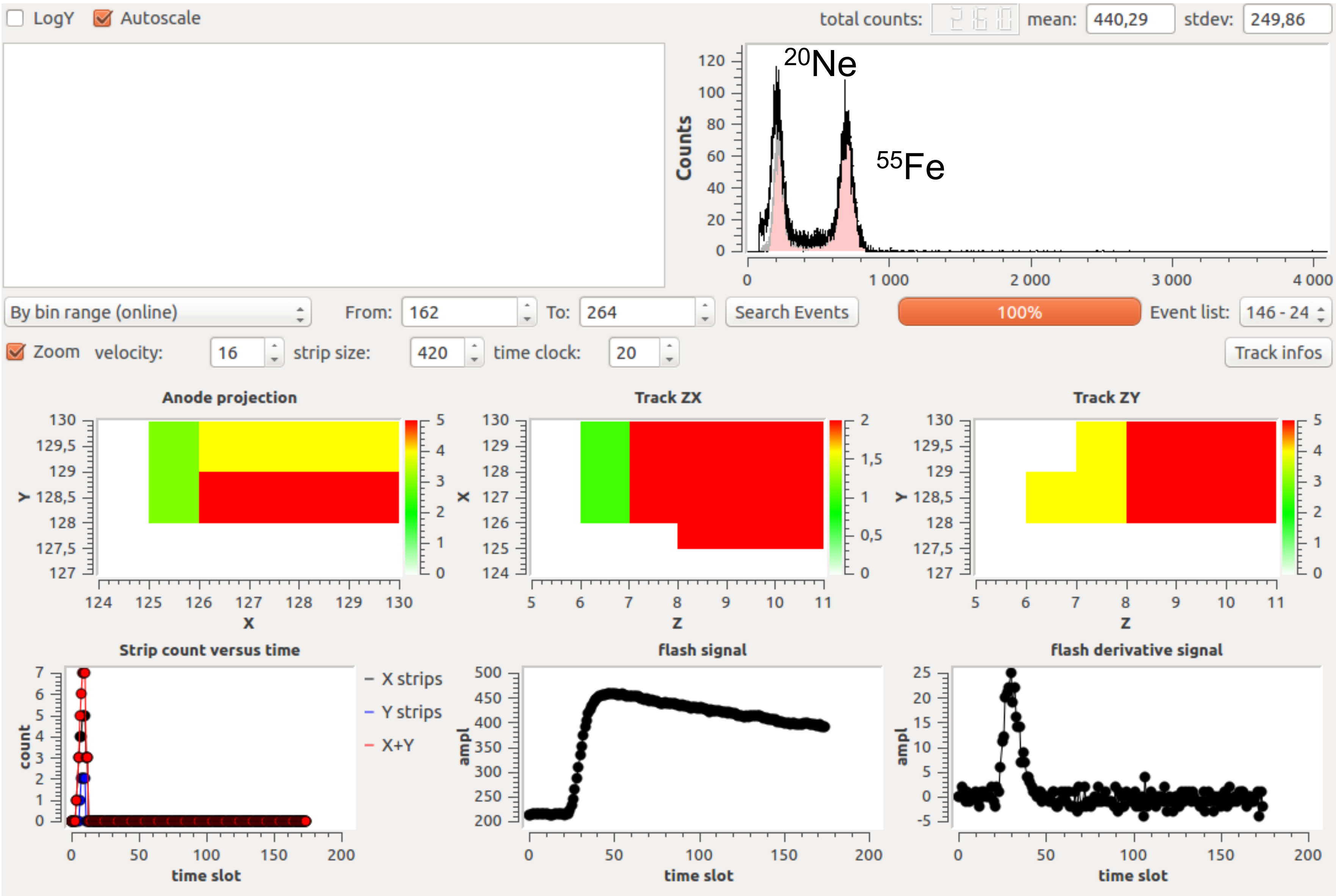


^{55}F source,
16 % of resolution !!

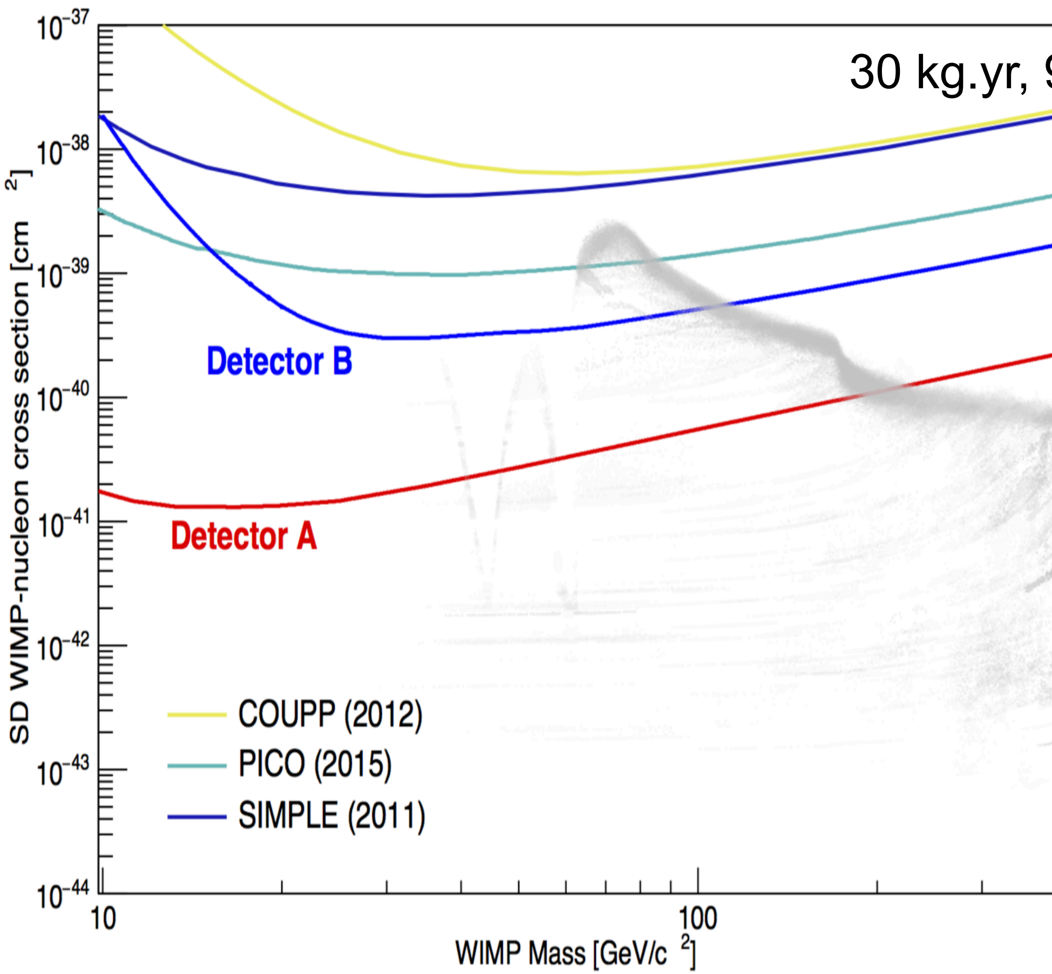
Proton (E_{kin}= 25 keV) in MIMAC gas with the new low-background detector (05/2017)



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



Exclusion limits



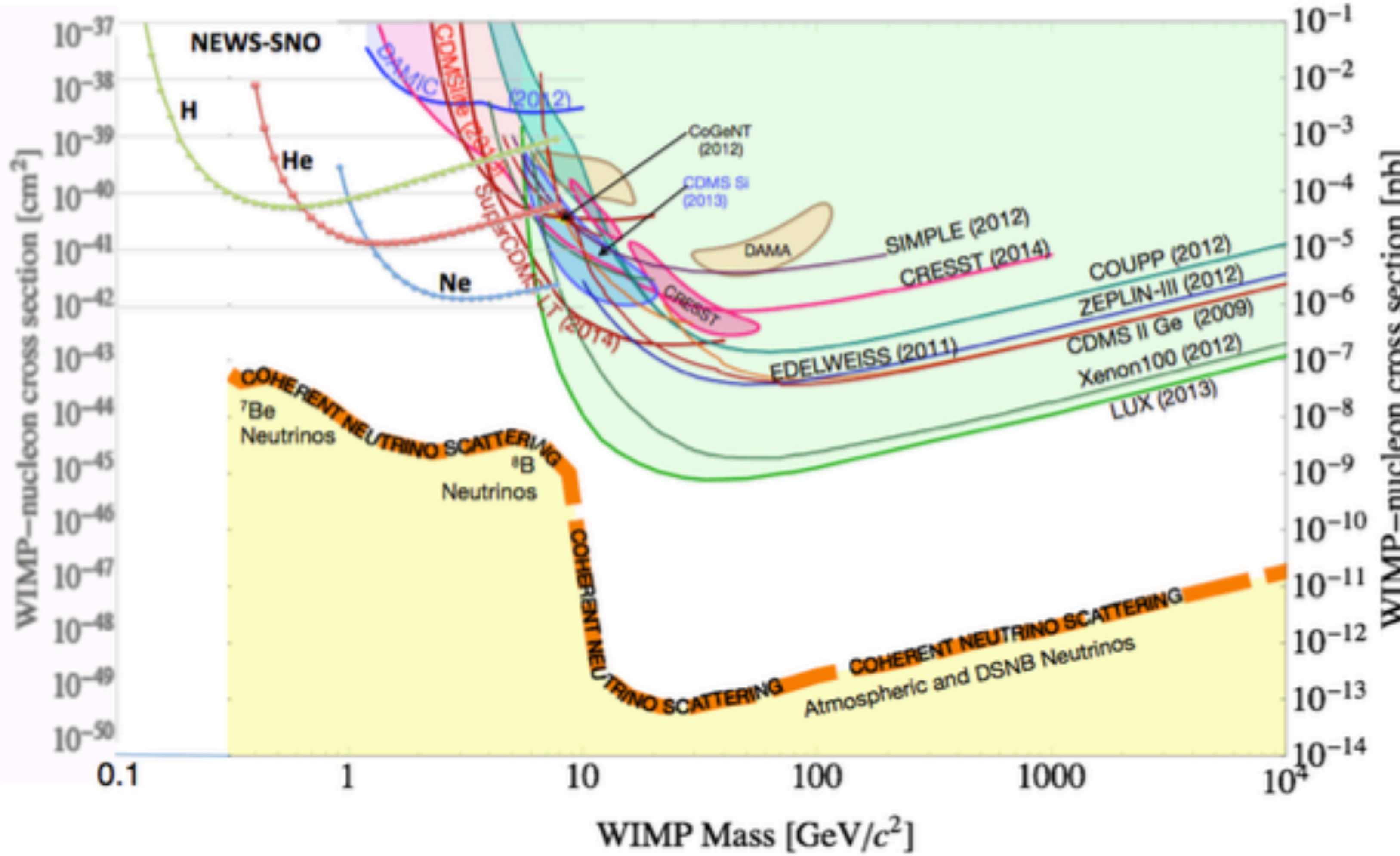
30 kg.yr, 90% CL lower limits

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)

WIMP Light Mass window
MIMAC- NEWS complementarity

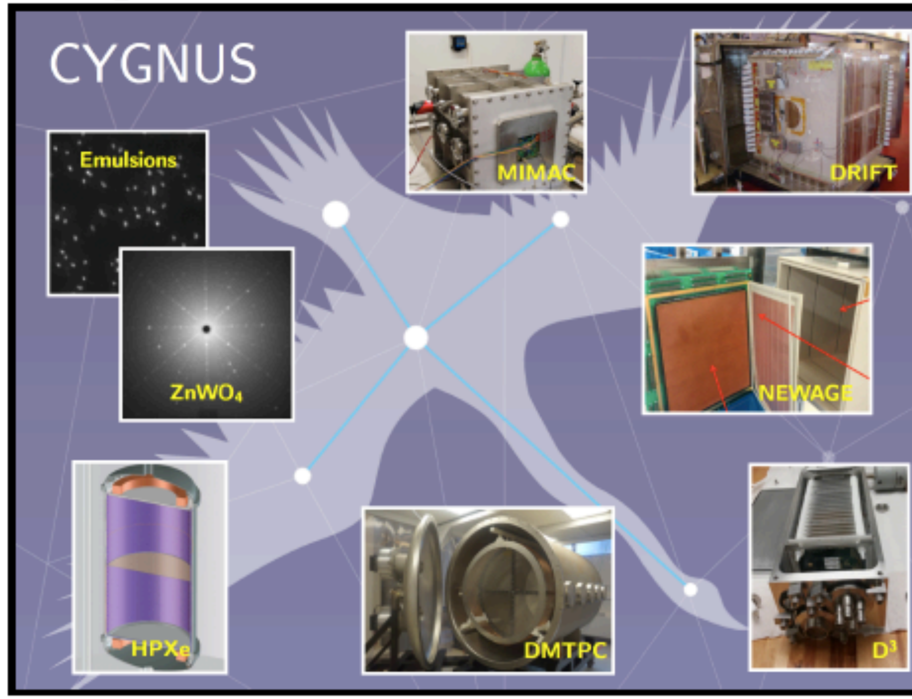


Conclusions

- 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.
- MIMAC bi-chamber module has been installed at Modane Underground Laboratory in June 2012. An upgraded versions in June 2013 and June 2014 and it shows an excellent gain stability.
- For the first time the 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 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**

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

MIMAC (MIcro-tpc MAtrix of Chambers)

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 : **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)

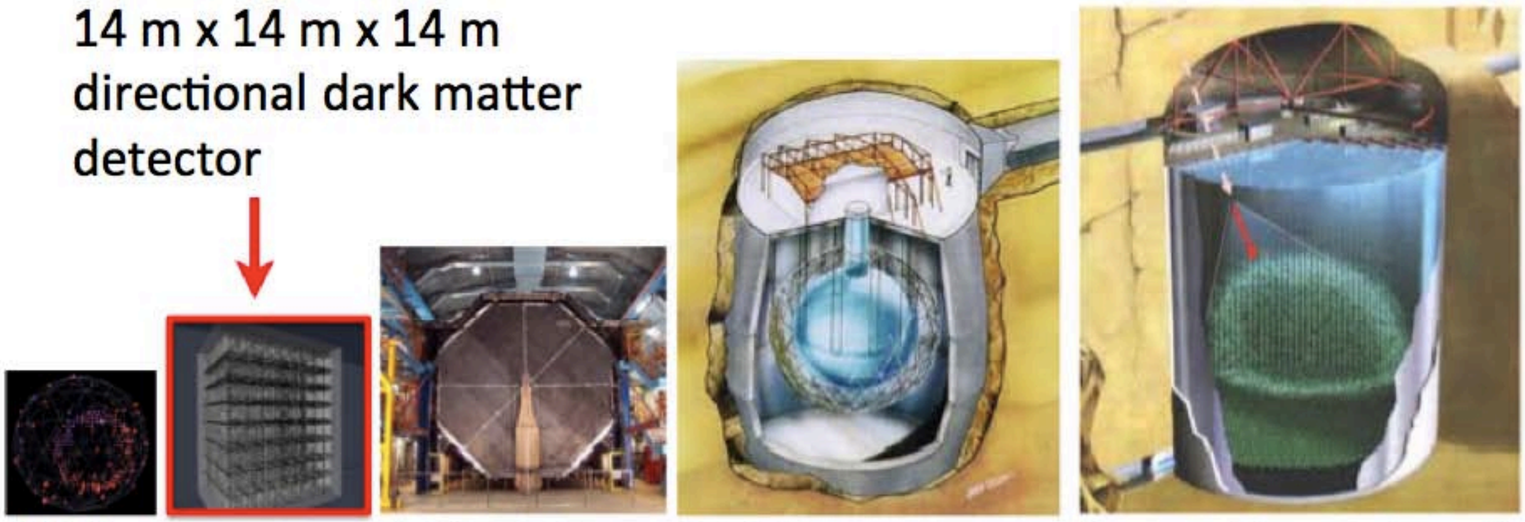
XAO (Xinjiang-China): Chung-Lin Shan

Neutron facility (AMANDE) :

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

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

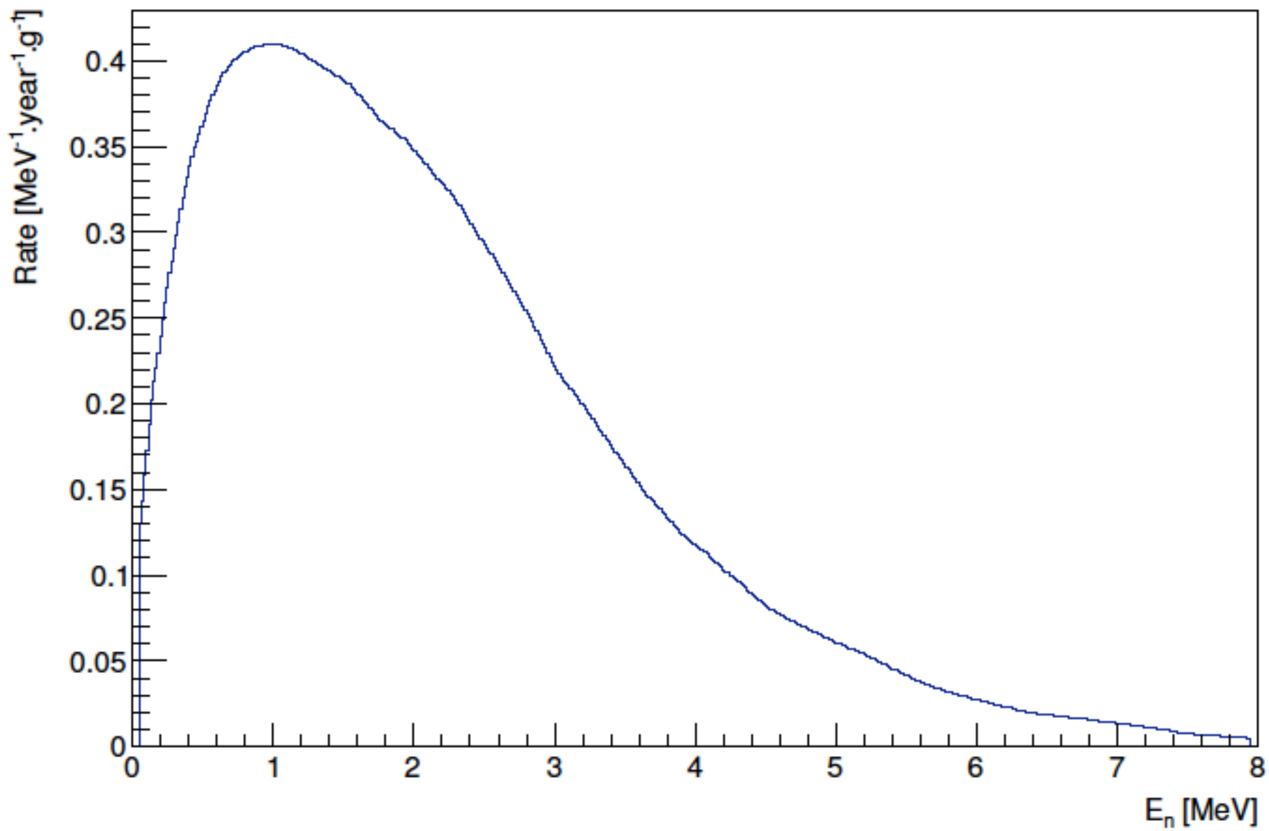
	DRIFT	MIMAC	NEWAGE	DMTPC
	Boulby	Modane	Kamioka	SNOLAB
Gas mix	73%CS2 +25%CF4 +2%O2	70%CF4 +28%CHF3 +2%C4H10	CF4	CF4
Current volume	800 L	6 L	37 L	1000 L
Drift	ion, 50 cm	e–, 25 cm	e–, 41 cm	e–, 27 cm
Threshold (keVee)	20	1	50	20
Readout	Multi-Wire Proportional Counters	Micromegas	micro-pixel chamber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

Adapted from Mayet et al. [arXiv:1602.03781]

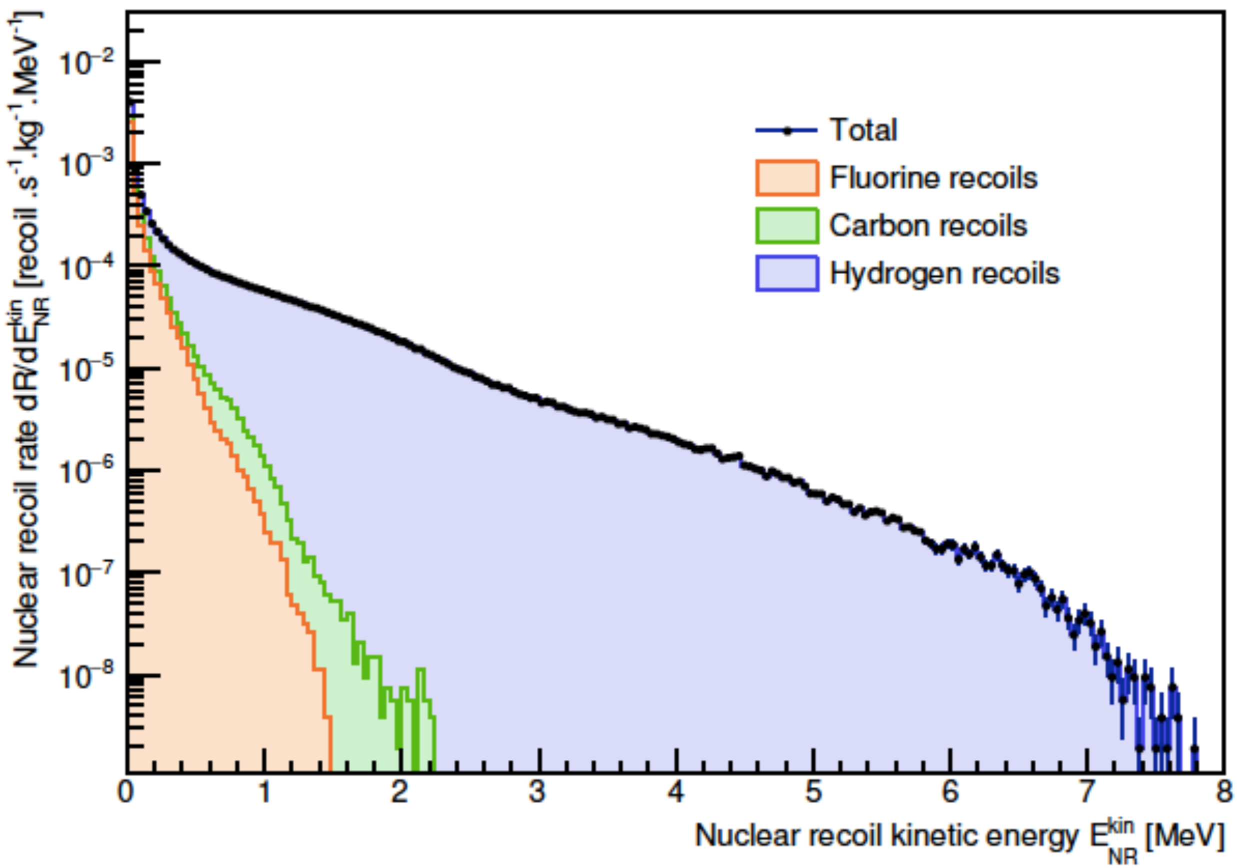
Neutron spectrum from the rock at Modane laboratory (SOURCES simulation)

77% (α,n)

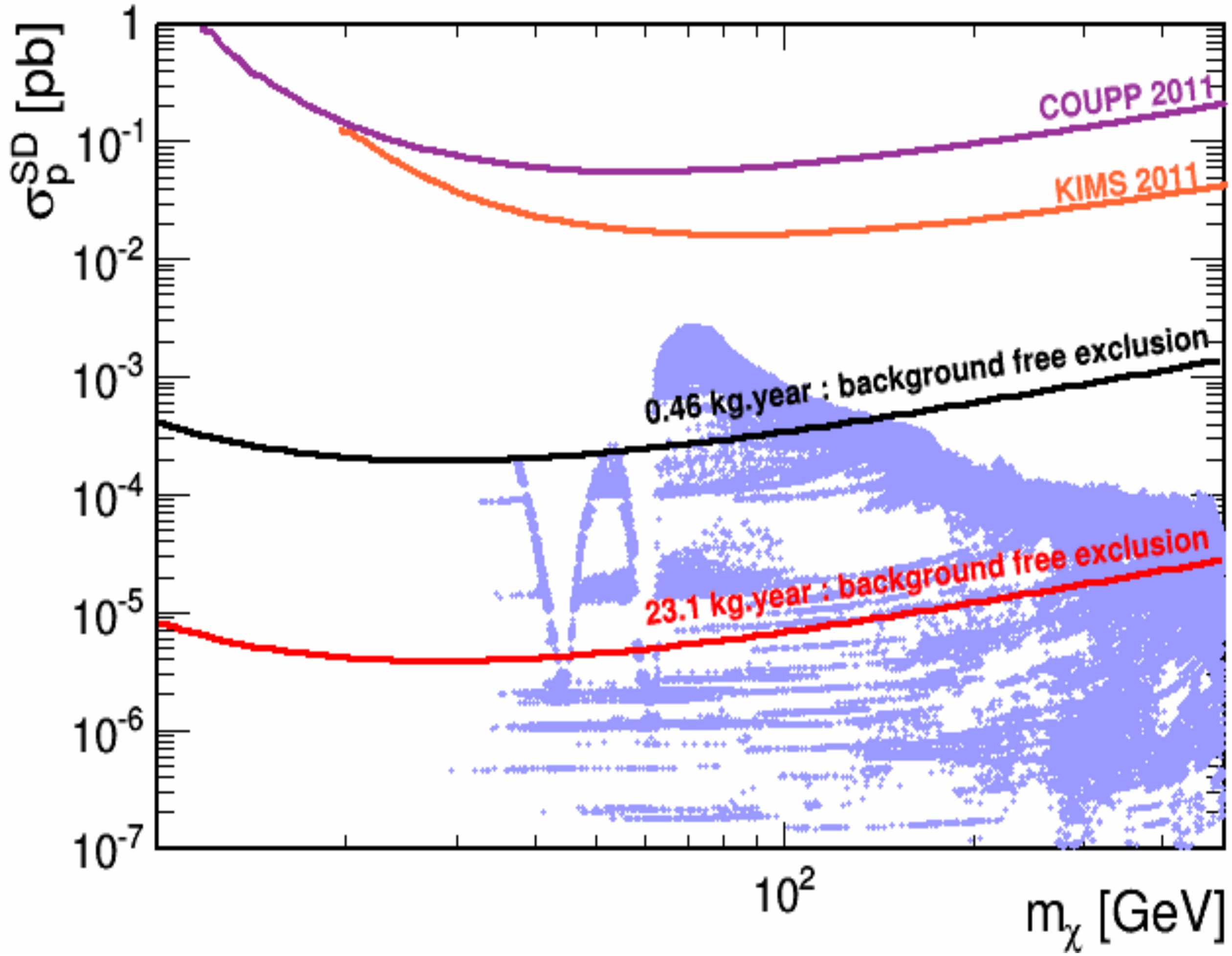
23% spontaneous fissions (^{238}U (0.84 ppm, ^{232}Th (2.45 ppm))



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)



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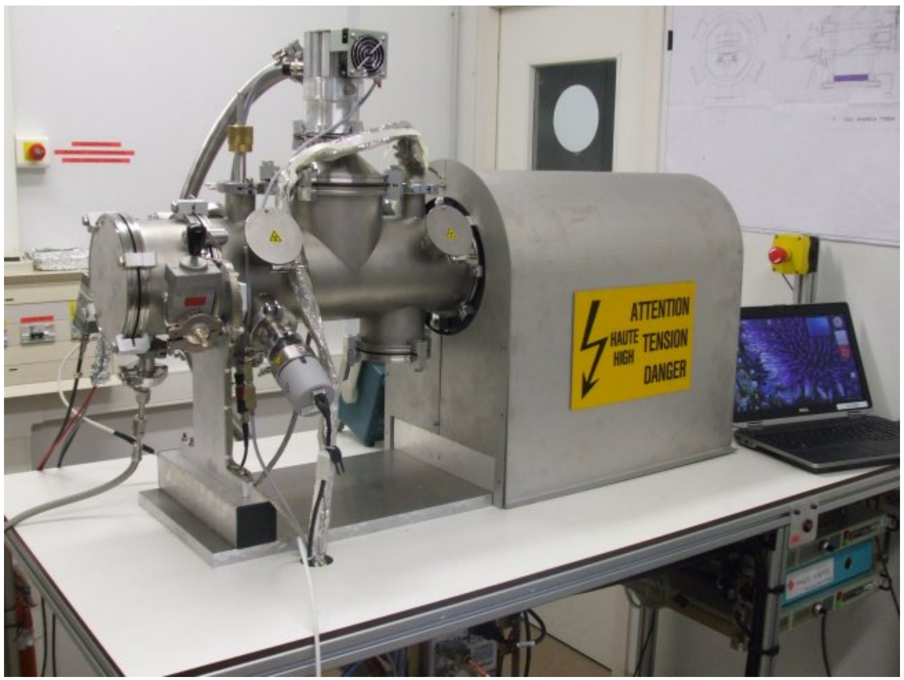
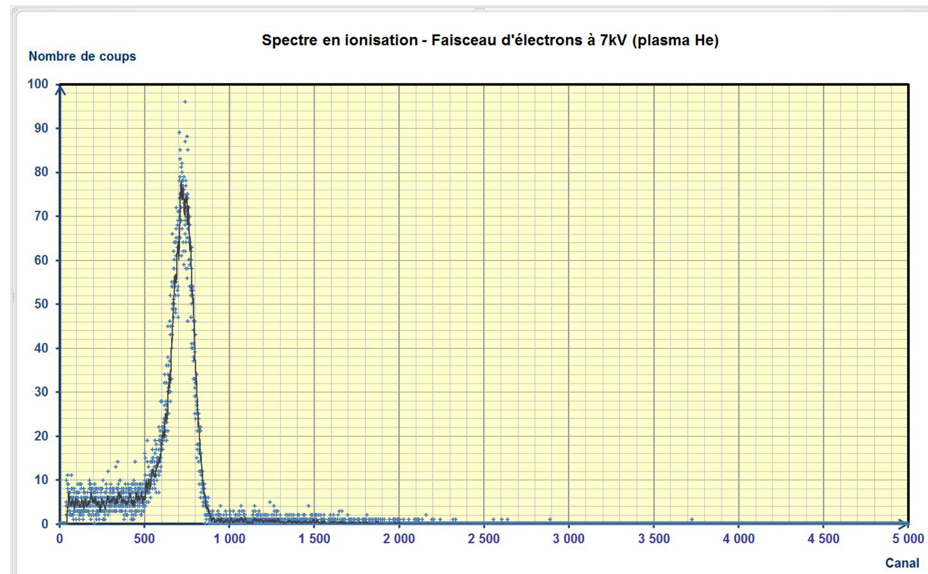
Portable Quenching Facility (COMIMAC)

(Electrons and Nuclei of known energies)





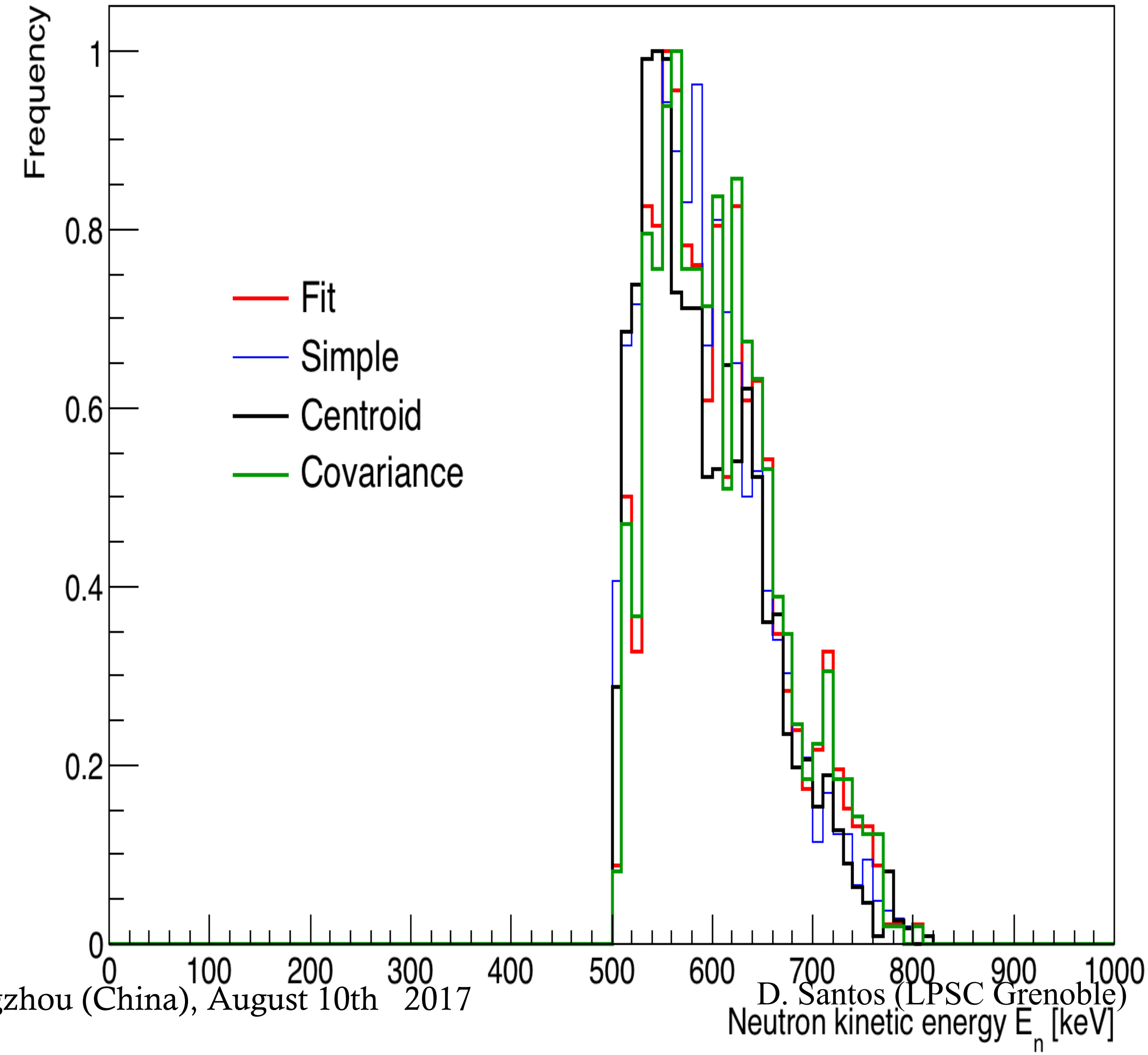
Electrons of 7 keV

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))