MIMAC

MIcro-tpc MAtrix of Chambers

A Large TPC for Directional non baryonic Dark Matter detection

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(LPSC-Grenoble)

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MIMAC:
(MIcro-tpc MAtrix of Chambers)

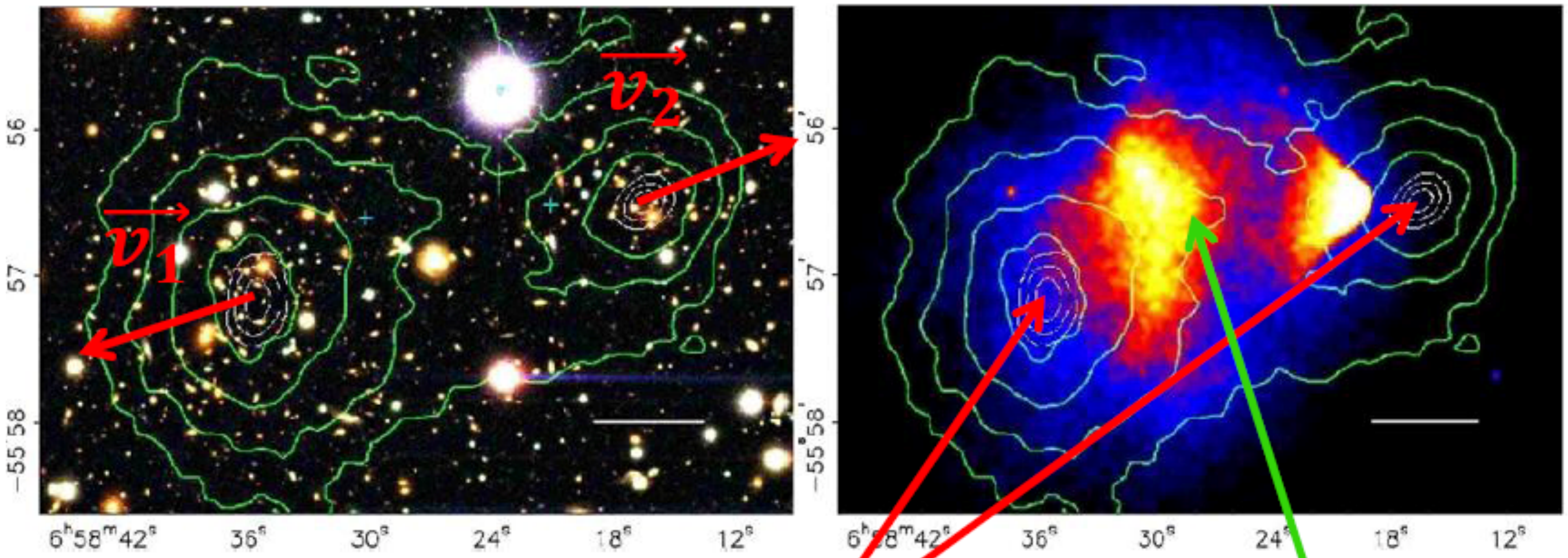
LPSC (Grenoble) : F. Mayet , J. Lamblin (6/2011**-** 9/2013)**, D. Santos**
J. Billard (Ph.D) (left in July 2012)**, Q. Riffard (Ph.D)** (started in October 2012)
Technical Coordination : O. Guillaudin

- Electronics :	**G. Bosson, O.Bourrion, J-P. Richer, J.L. Bouly**
- Gas detector :	**O. Guillaudin, A. Pellisier**
- Data Acquisition:	**O. Bourrion, T. Descombes** (started 10/2013)
- Mechanical Structure :	**Ch. Fourel, J. Giraud, S. Roudier, M. Marton**
- Ion source (quenching) :	**J-F. Muraz**

IRFU (Saclay): (2007-2010, 9/2013): **P. Colas, E. Ferrer-Ribas, I. Giomataris**
Rui de Oliveira (Cern)
CCPM (Marseille): J. Busto, Ch. Tao, D. Fouchez, J. Brunner
Neutron facility (AMANDE) :
IRSN (Cadarache): L. Lebreton, D. Maire (Ph. D.)

At the galaxy cluster scale…

(1E0657-558) Z= 0.296



Collision de l'amas du Boulet
(D. Clowe *et al.* 2006)

Total mass profiles

Baryonic Matter

Non-baryonic matter is 6 times more important than baryonic one…

Matière sombre non-baryonique : halo galactique

Modèle standard de halo galactique : *référence pour comparaisons*

Sphère isotherme et isotrope

$$f(\vec{v}) = \frac{1}{(2\pi\sigma_v^2)^{3/2}} \exp\left(-\frac{(\vec{v}+\vec{v}_\odot)^2}{2\sigma_v^2}\right)$$

avec :
- $\overrightarrow{v}_\odot$: vitesse du Soleil
- $\sigma_v = v_0/\sqrt{2}$: dispersion des vitesses
- v_0 : vitesse asymptotique de rotation

Valeurs de référence :

- $\rho_0 = 0,3\ GeV/c^2/cm^3$ ⇐ *0,2-0,8 GeV/c²/cm³*
- $v_0 = 220\ km/s$ ⇐ *~20-30%*

Alternatives :

- Halo ellipsoïdal (triaxial)
- Anisotrope
- En rotation ?

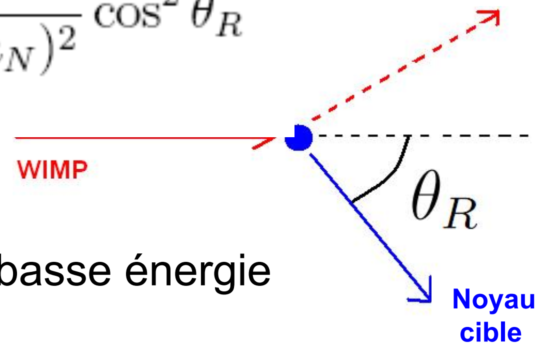
Détection directe : principes

<u>Détection directe :</u>

mesure de l'énergie déposée

lors de la diffusion élastique WIMP-noyau

$$E_R = \frac{2v^2 m_\chi^2 m_N}{(m_\chi + m_N)^2} \cos^2 \theta_R$$



- énergie typique : 1-100 keV ➡ détecteur basse énergie
- Taux d'événements très faible

$$R = \sigma \times \left(\frac{\rho_0}{m_\chi}\right) \times < v > \times \frac{1}{m_N}$$

- ρ_0 : densité locale de WIMP
- σ : section efficace WIMP-noyau
- $< v >$: vitesse relative moyenne des WIMP
- m_N : masse du noyau cible

En tenant compte de la distribution de vitesse f(v), du facteur de forme F(q) :

$$\frac{dR}{dE_r} = \frac{\sigma_0}{2 m_\chi m_r^2} \times F^2(q) \times \rho_0 \int_{v_{min}}^{v_{esc}} \frac{f(\overrightarrow{v})}{v} d^3v$$

nucléaire

Astro

SUSY

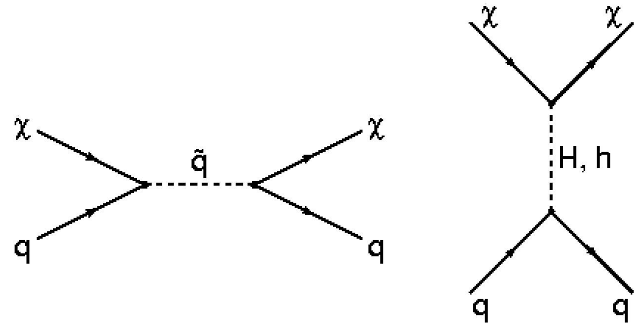
Détection directe : scalaire vs axial

Interaction WIMP-quark :

Interaction scalaire :

$$\sigma_{SI}(^{A}X) \propto \sigma_{SI}(p) \times A^{4}$$

Noyaux lourds : Ge, Xe, …

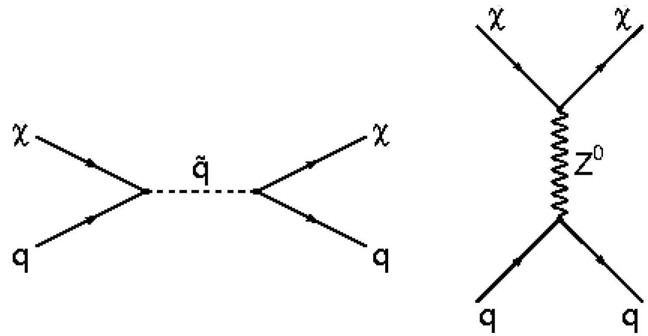


Interaction axiale : (couplage spin)

$$\sigma_{SD}(^{A}X) \propto \sigma_{SD}(p) \times A^{2}$$

Noyaux de spin non-nuls : ^{1}H, ^{3}He, ^{19}F,

Ou fraction isotopique (^{73}Ge, ^{129}Xe)



Interactions faiblement corrélées

→ Stratégies de détection complémentaires

Détection directe : contenus en spin

Noyau	J^π	$< S_p >$	$< S_n >$	Ref.	frac. iso.	Expériences
^{3}He	$1/2^+$	-0,021	**0,462**	[42]	100 %	MIMAC
^{19}F	$1/2^+$	**0,441**	-0,109	[43]	100 %	MIMAC, COUPP [44], Picasso [45]
^{73}Ge	$9/2^+$	0,030	**0,378**	[46]	7,73 %	Edelweiss [47], CDMS [48]
^{127}I	$5/2^+$	**0,309**	0,075	[49]	100 %	KIMS [50]
^{129}Xe	$1/2^+$	0,028	**0,359**	[49]	26,4 %	Xenon [51], Zeplin III [52]
^{131}Xe	$3/2^+$	-0,041	**-0,236**	[53]	21,2 %	Xenon [51], Zeplin III [52]
^{133}Cs	$7/2^+$	**-0,370**	0,003	[54]	100 %	KIMS [50]

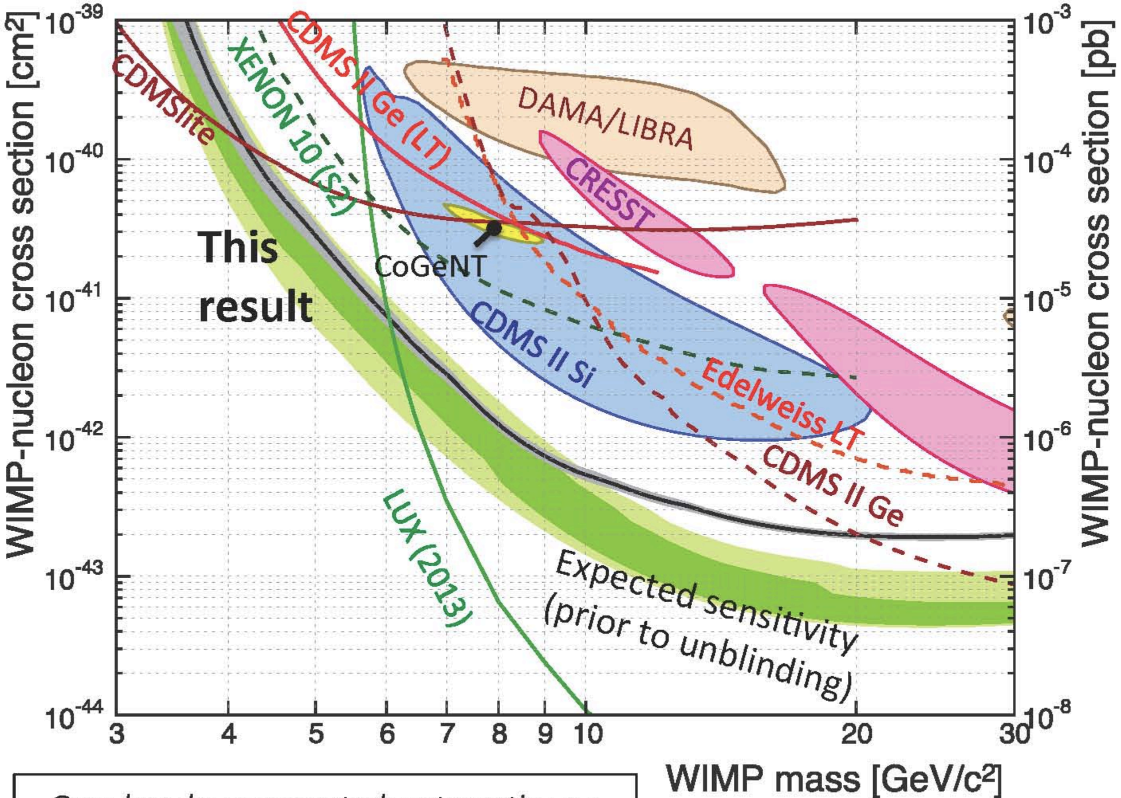
^{19}F : contenu en spin selon les auteurs

Modèle	$< S_p >$	$< S_n >$	Ref.
odd-group	0.5	0.	
Pacheco & Strottman	0.441	-0.109	[43]
Divari *et al.*	0.475	-0.0087	[68]

Last results in Direct Dark Matter Detection (SCDMS-February 2014)

Spin-independent Scattering Constraints

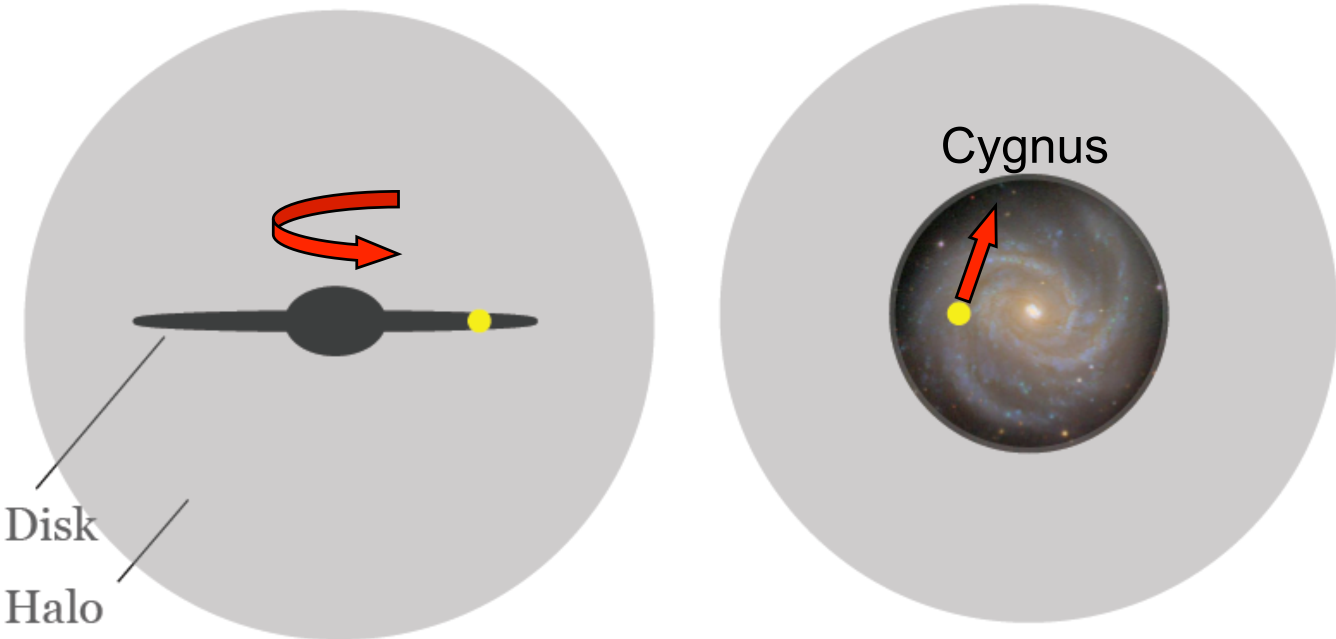
90% C.L. optimal interval upper limit, no background subtraction, treating all observed (eleven) events as WIMP candidates



- CoGeNT strongly disfavored in model-independent scenario
- CDMS II (Si) disfavored under assumption of standard halo model and A^2 coupling
- Explores new parameter space below 6 GeV/c^2
- Competitive constraint for Ge up to 20 GeV/c^2; dedicated HT analysis yet to come
- Disagreement between limit and sensitivity at high WIMP mass due to events on T5Z3.
- For CDMSlite: please see: *PRL 112, 041302 (2014)*

Gray bands: propagated systematic unc. from fiducial volume + nuclear recoil energy scale + trigger efficiency

Directional detection : principle



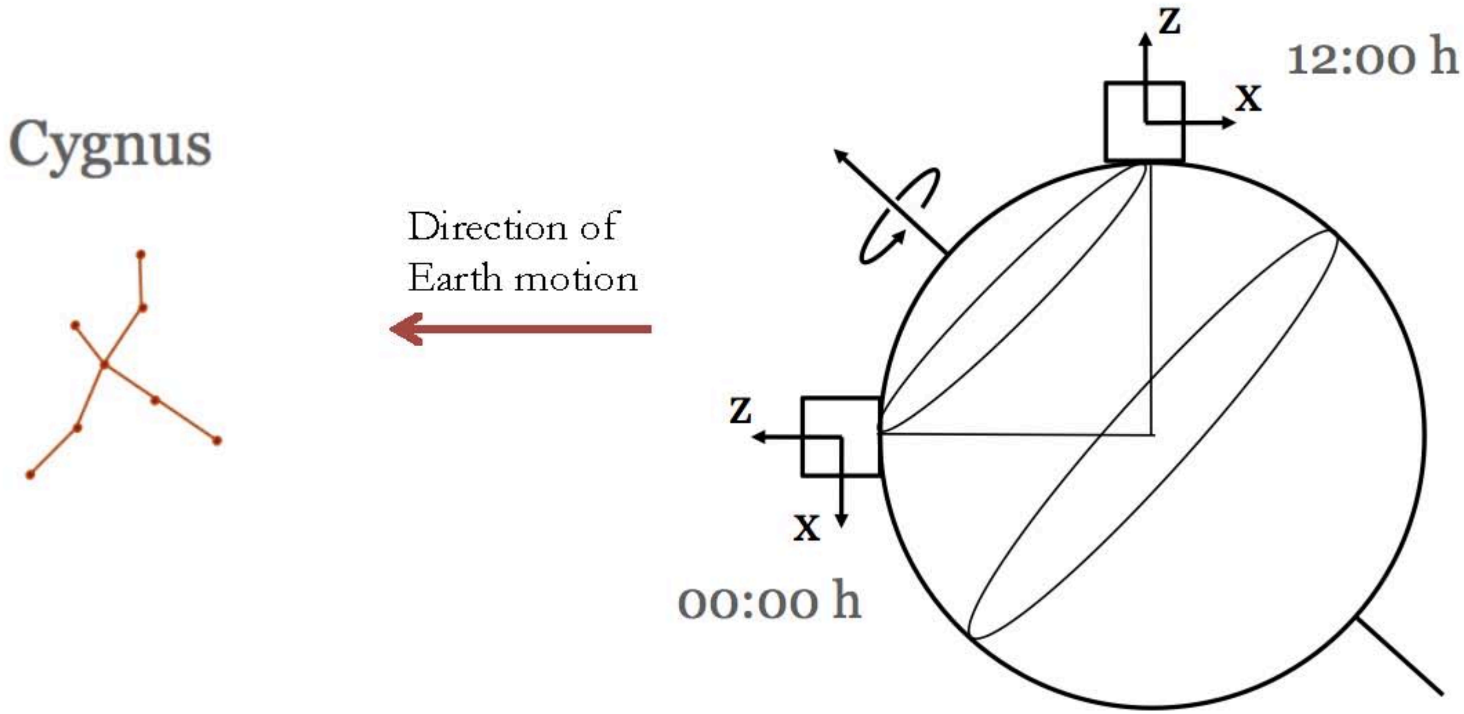
$\langle V_{rot} \rangle \sim 220$ km/s

« A wind of WIMPS coming from the Cygnus constellation »

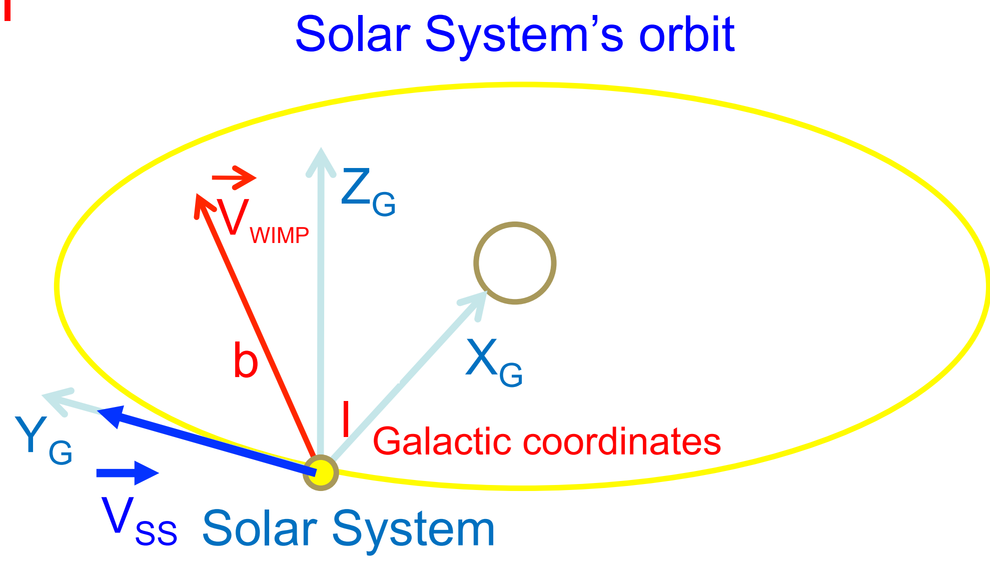
The signature able to correlate the events found to the galactic halo !

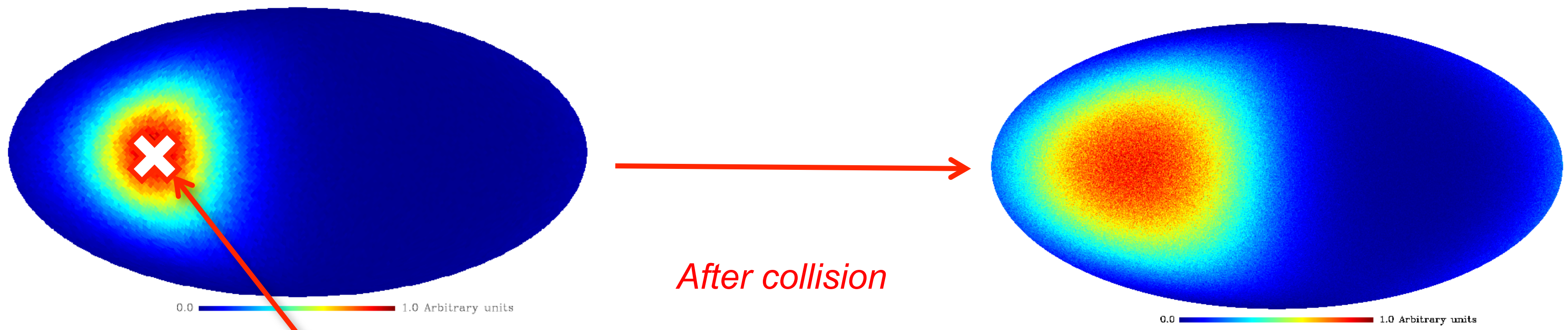
Angular modulation of WIMP flux

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



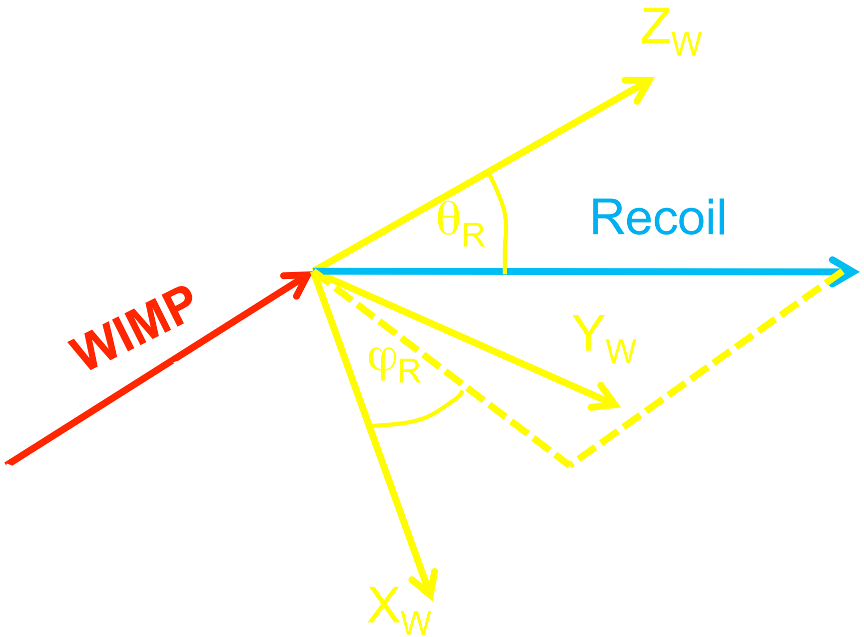
WIMP signal

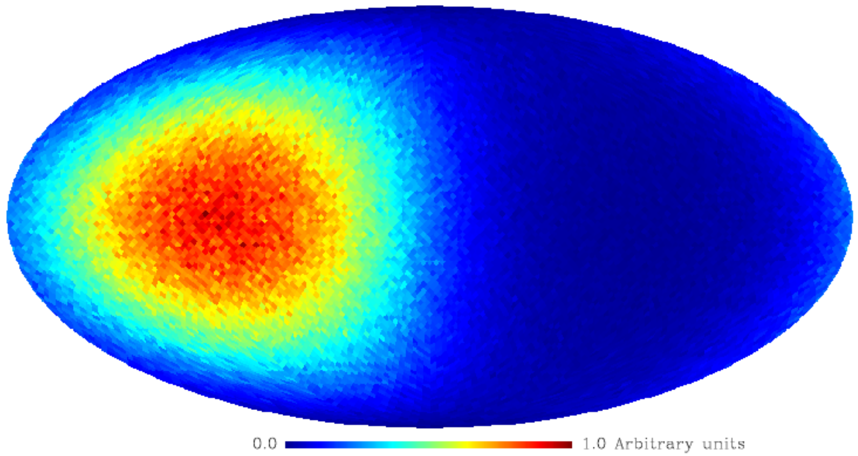




Cygnus Constellation (l = 90°,b = 0°)

WIMP signal expected

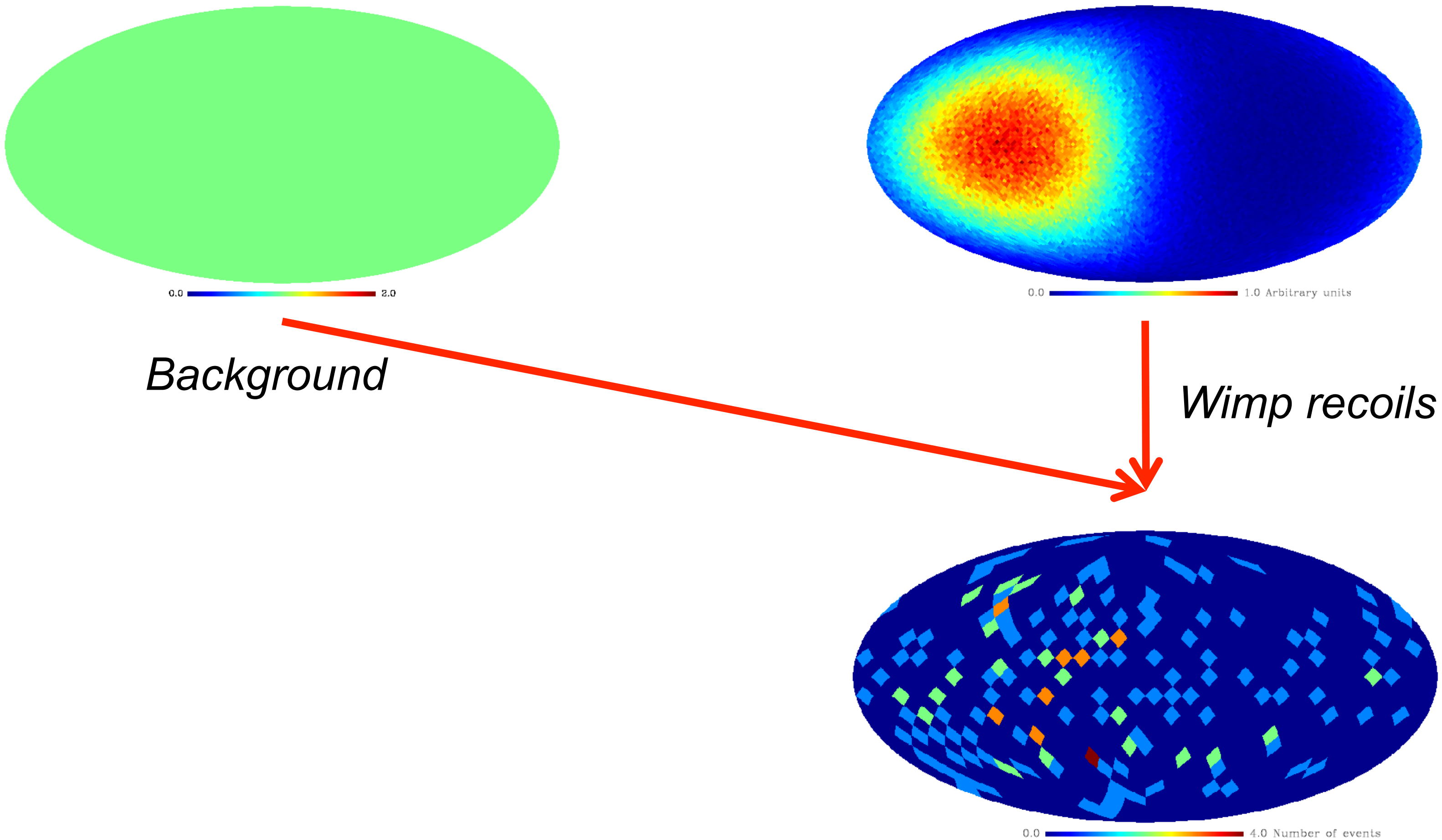




Map of recoils in galactic coordinates (HealPix)

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

100 WIMP evts + 100 Background evts

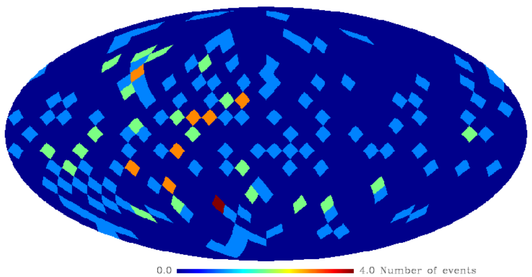


Phenomenology: Discovery

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

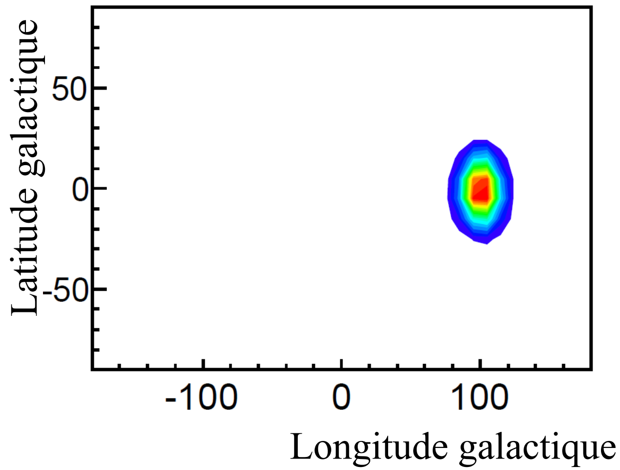
Proof of discovery: **Signal pointing toward the Cygnus constellation**

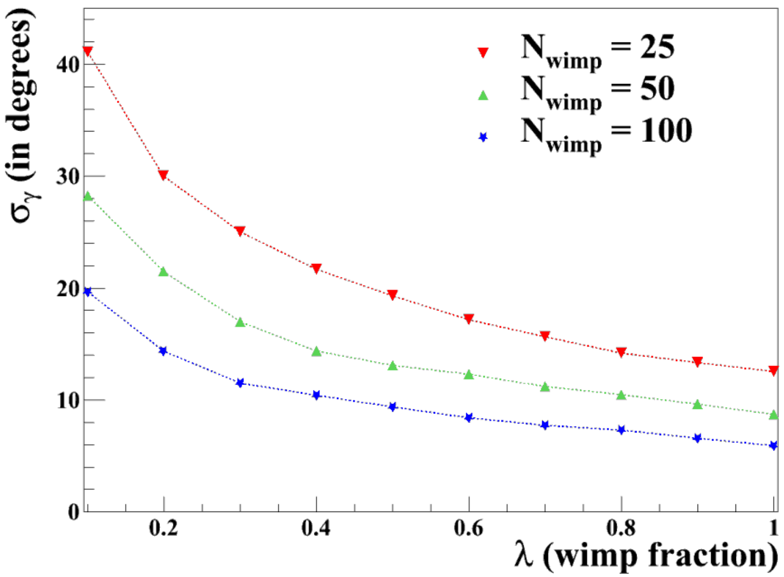
Blind likelihood analysis in order to establish the galactic origin of the signal



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

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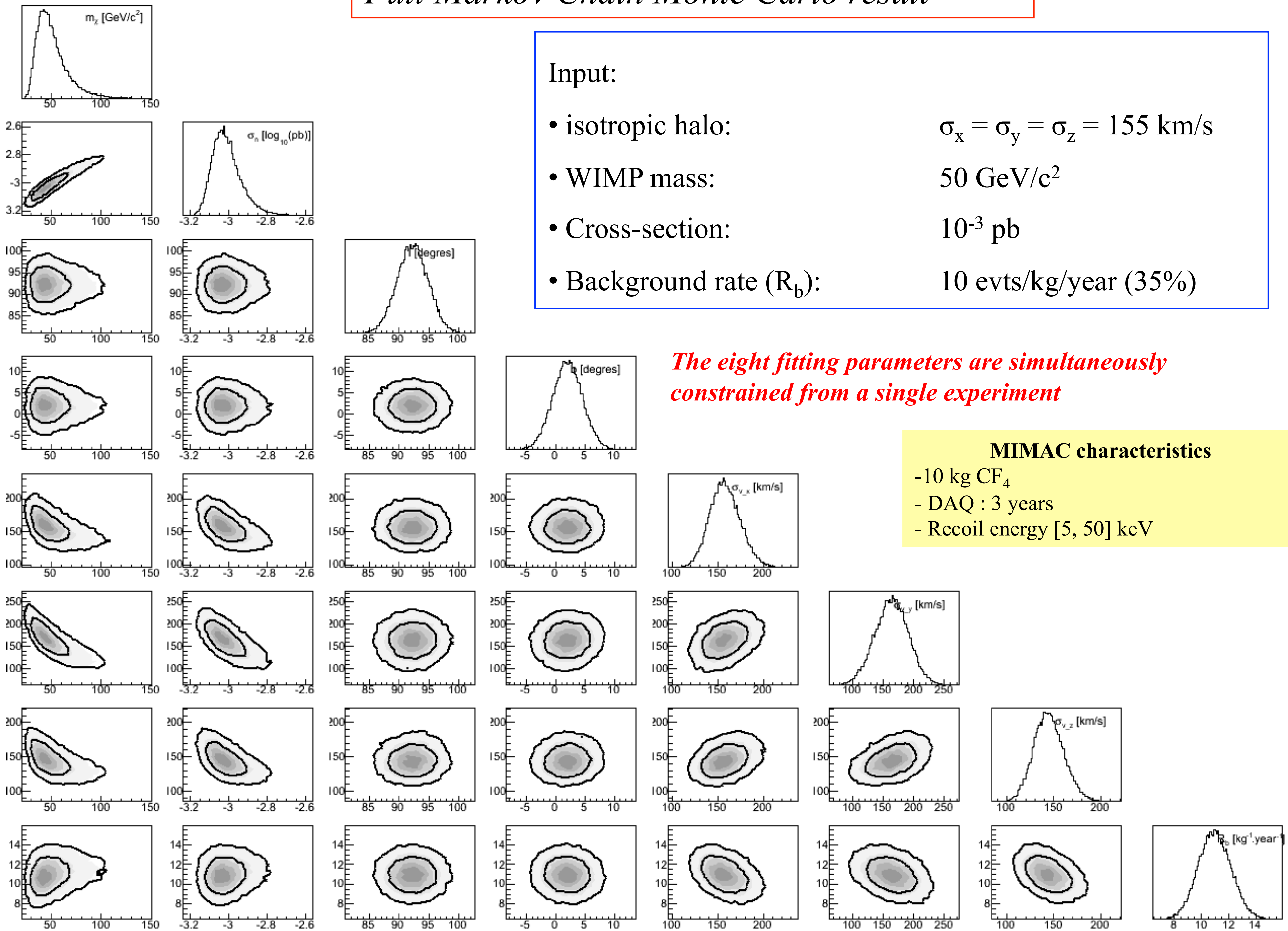
Full Markov Chain Monte Carlo result



Input:

- isotropic halo: $\sigma_x = \sigma_y = \sigma_z = 155$ km/s
- WIMP mass: 50 GeV/c^2
- Cross-section: 10^{-3} pb
- Background rate (R_b): 10 evts/kg/year (35%)

The eight fitting parameters are simultaneously constrained from a single experiment

MIMAC characteristics

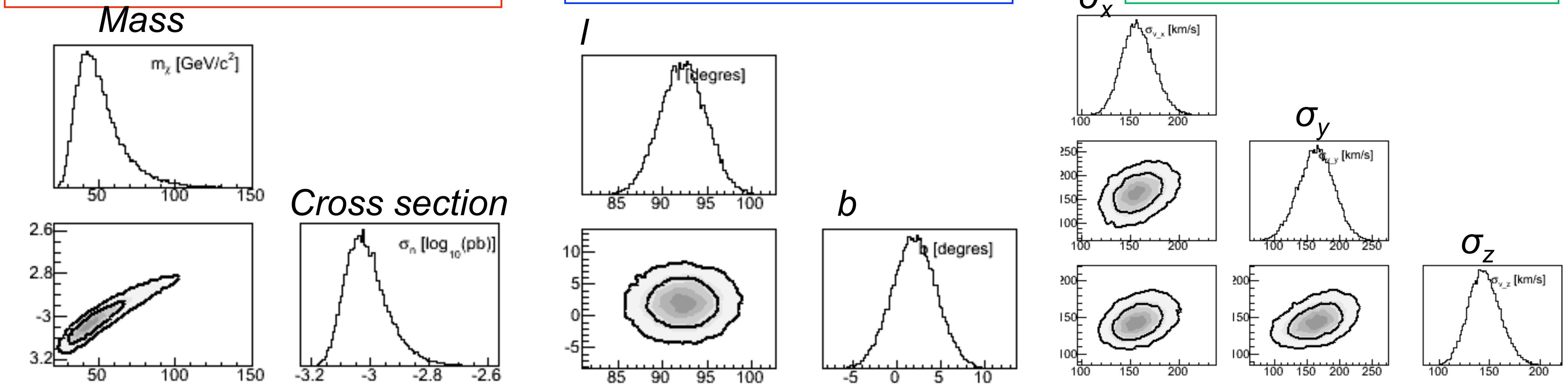
-10 kg CF_4
- DAQ : 3 years
- Recoil energy [5, 50] keV

Directional Detection : identification

J. Billard *et al.*, PRD 2011

8 parameters simultaneouly constrained by only one experiment

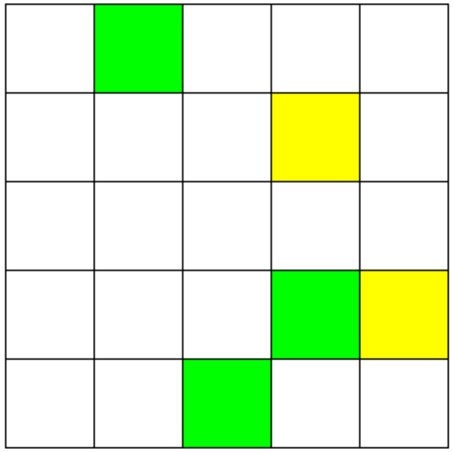
Mass – cross section ***Dark Matter signature*** ***Galactic Halo shape***



	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

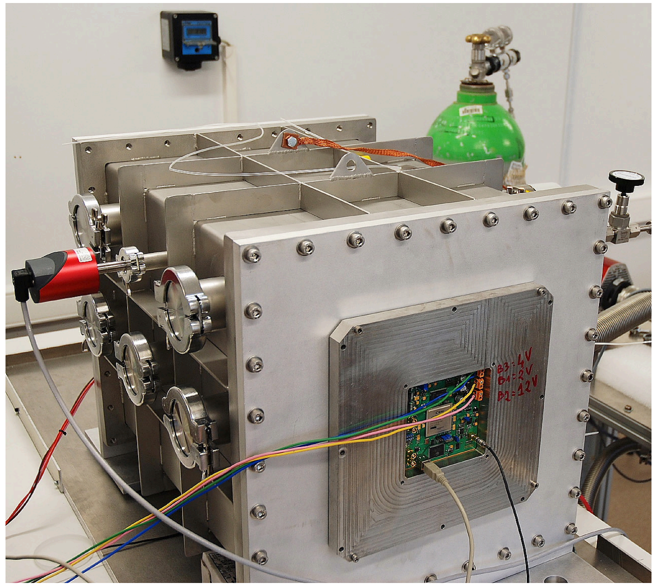
Directional experiments around the world

The MIMAC project



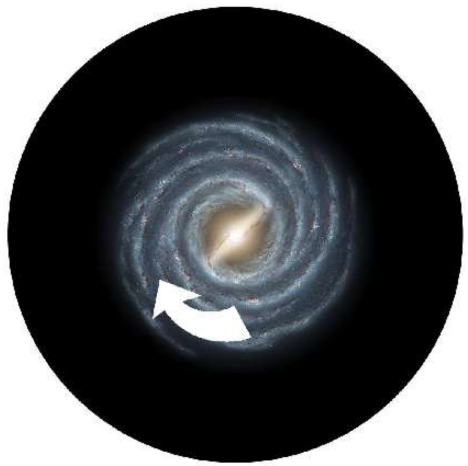
A low pressure multi-chamber detector

- Energy and 3D Track measurements
- Matrix of chambers (correlation)
- µTPC : Micromegas technology
- CF_4, CHF_3, and ^{1}H : 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 "



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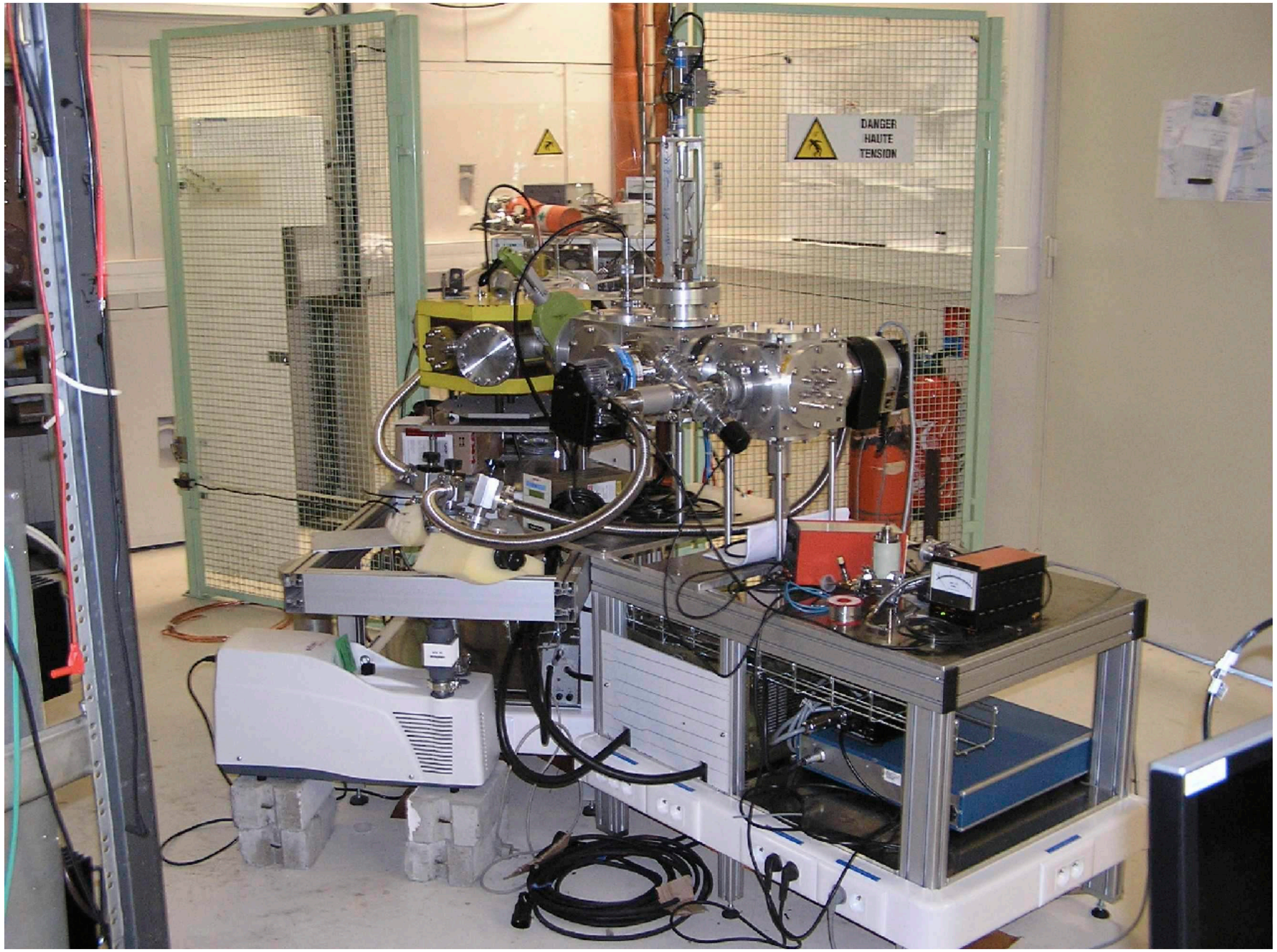
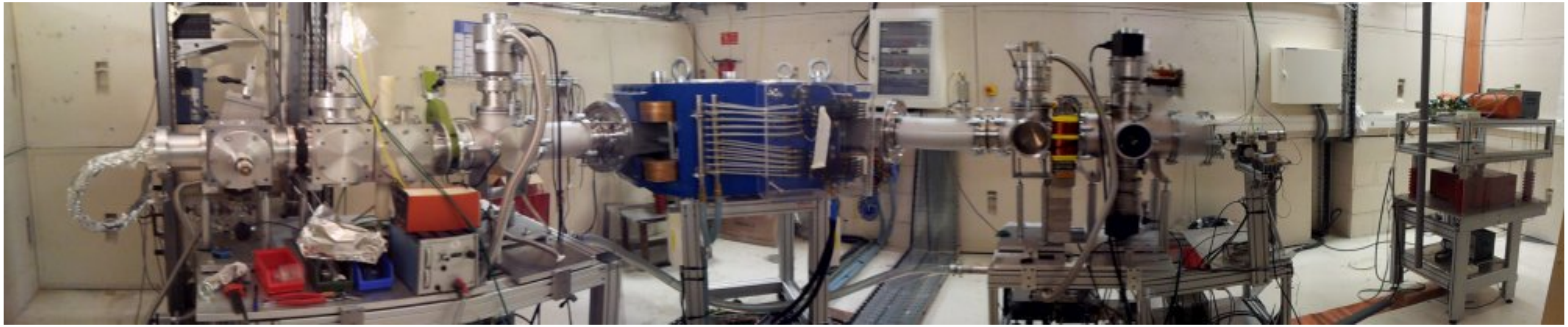
Ionization Quenching Facility at LPSC-Grenoble

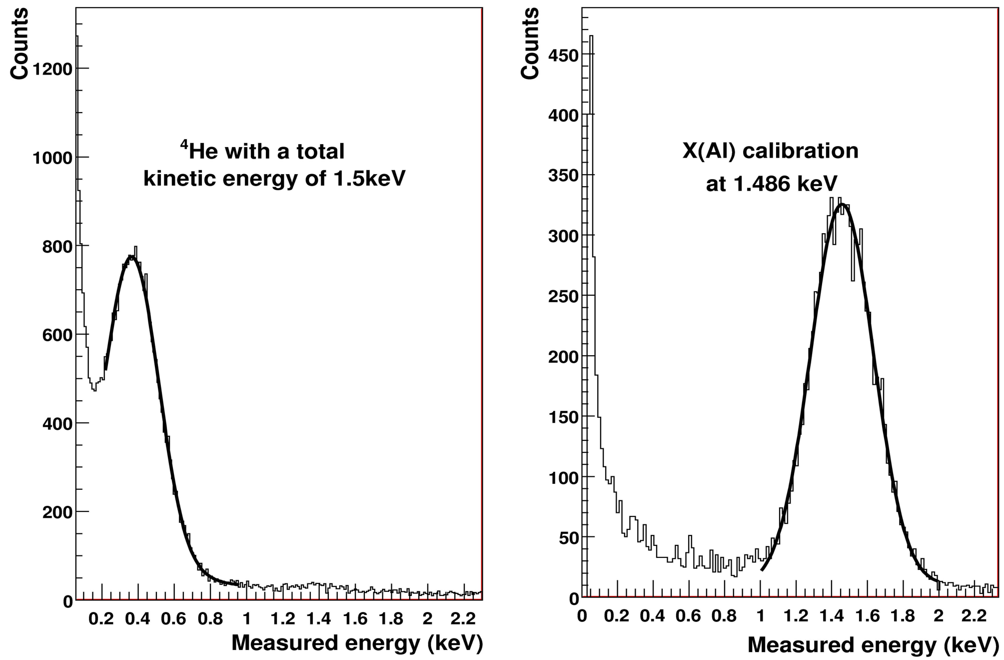


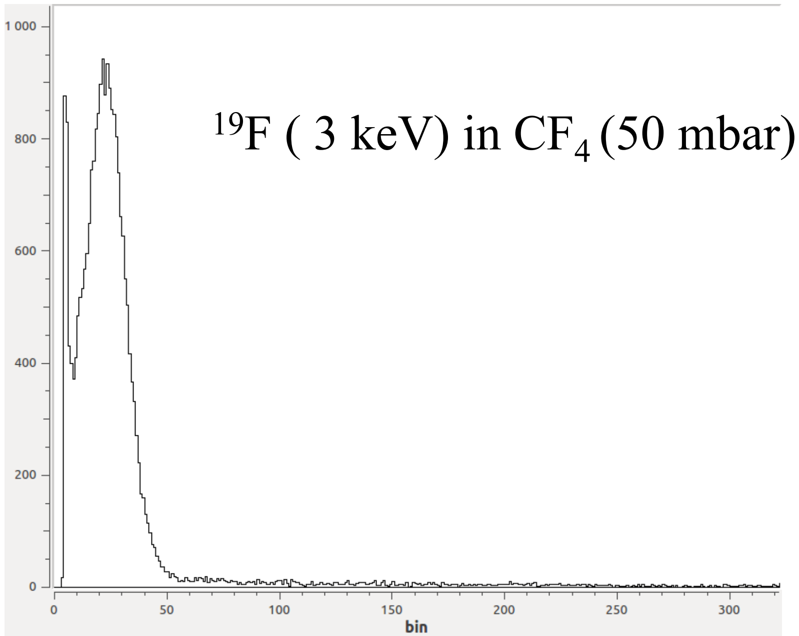
- **Low energy ion source**

  1 to 50 keV
- **Developped @LPSC**

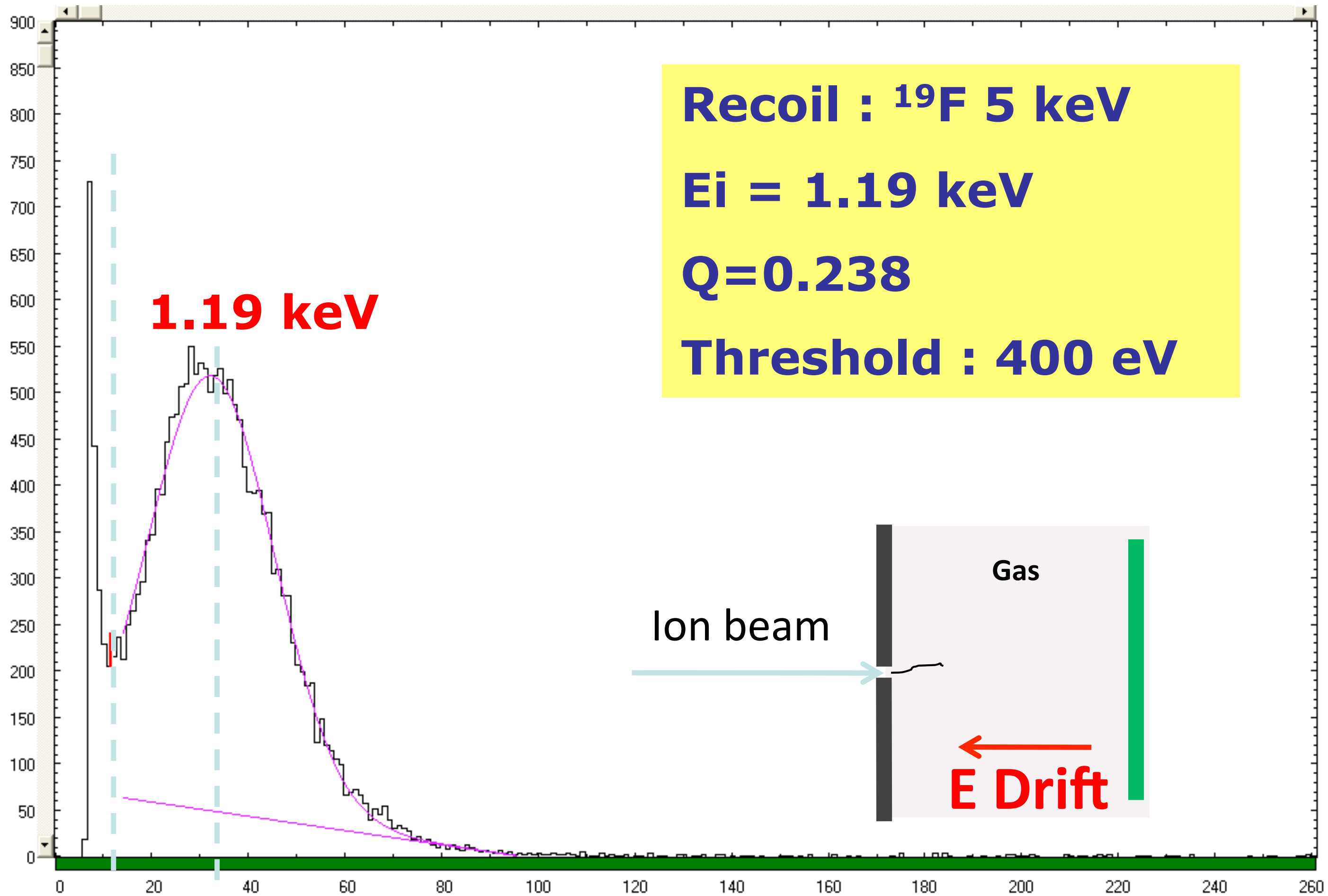
Ionization Quenching Factor Measurements at LPSC-Grenoble

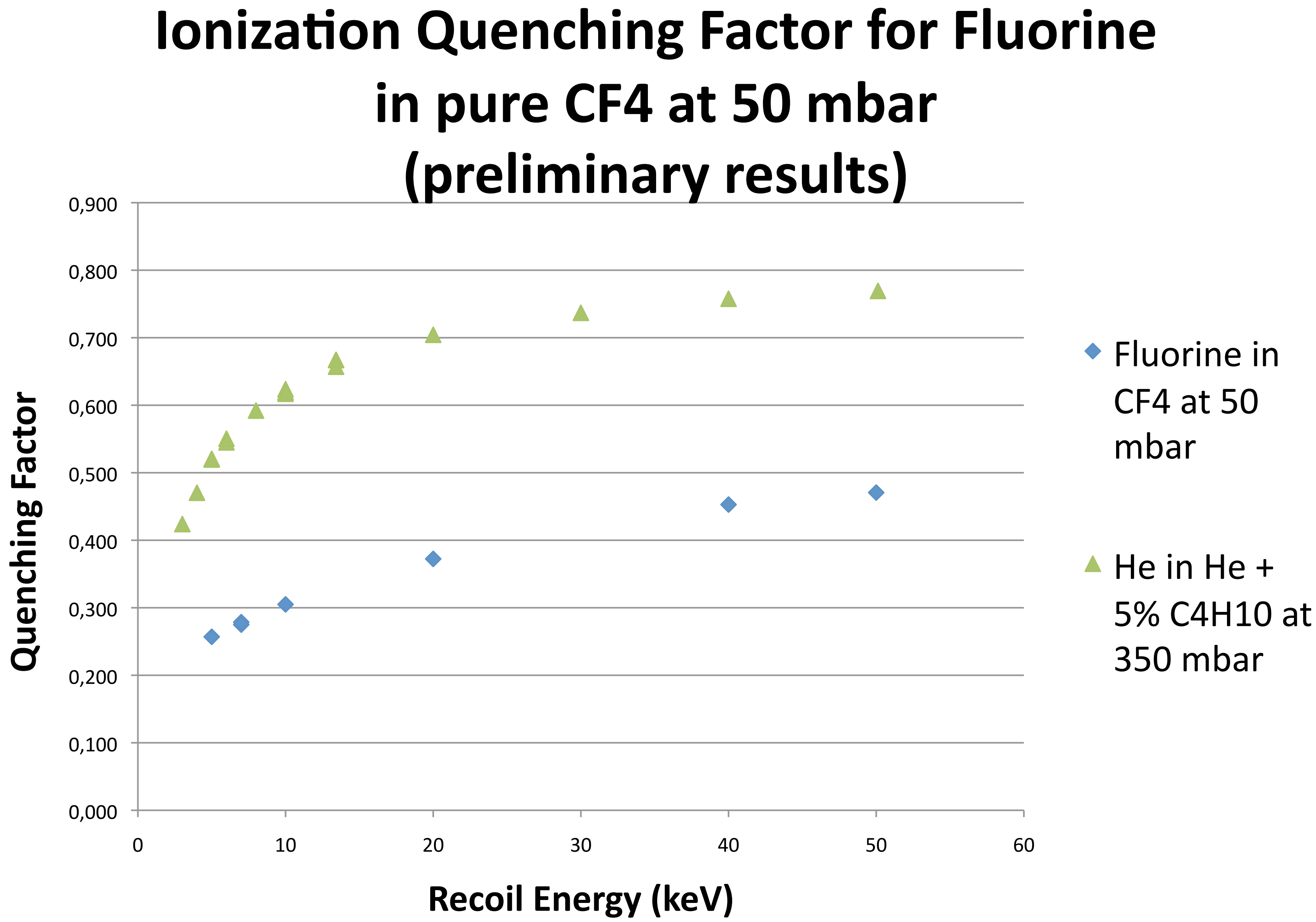






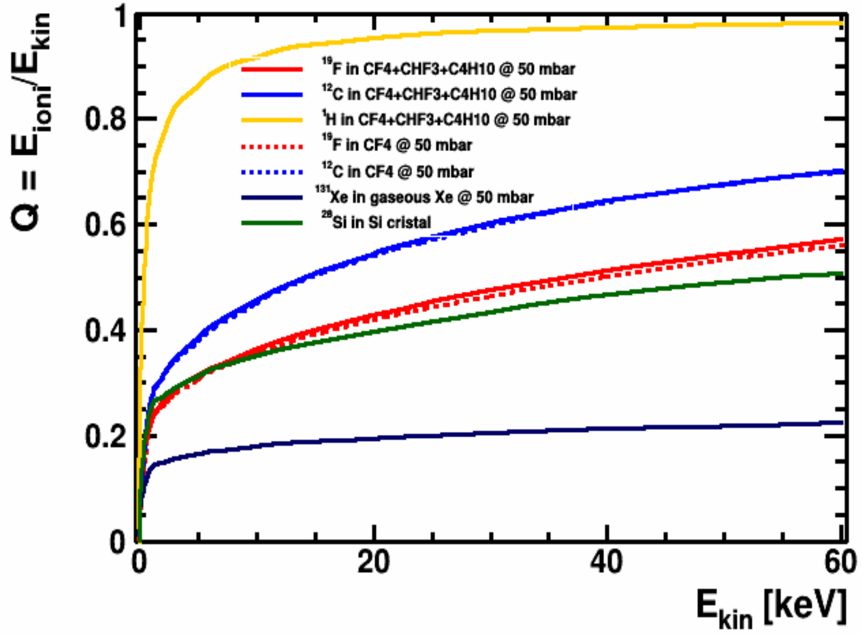
Ionization Quenching Measurements:
5keV ^{19}F « recoil » in 60 mbar
40mbar CF_4+16.8mbar CHF_3+1.2 mbar Isobutane

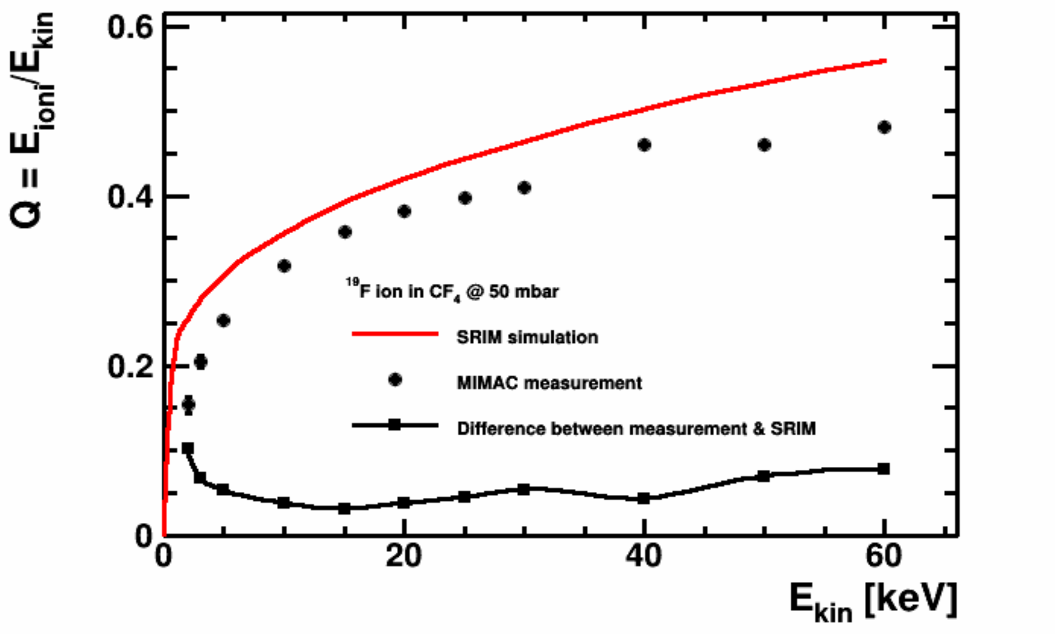



Ionization Quenching Factor for Fluorine
in pure CF4 at 50 mbar
(preliminary results)
Quenching Factor
0,000
0,100
0,200
0,300
0,400
0,500
0,600
0,700
0,800
0,900
0
10
20
30
40
50
60
Recoil Energy (keV)
Fluorine in CF4 at 50 mbar
He in He + 5% C4H10 at 350 mbar

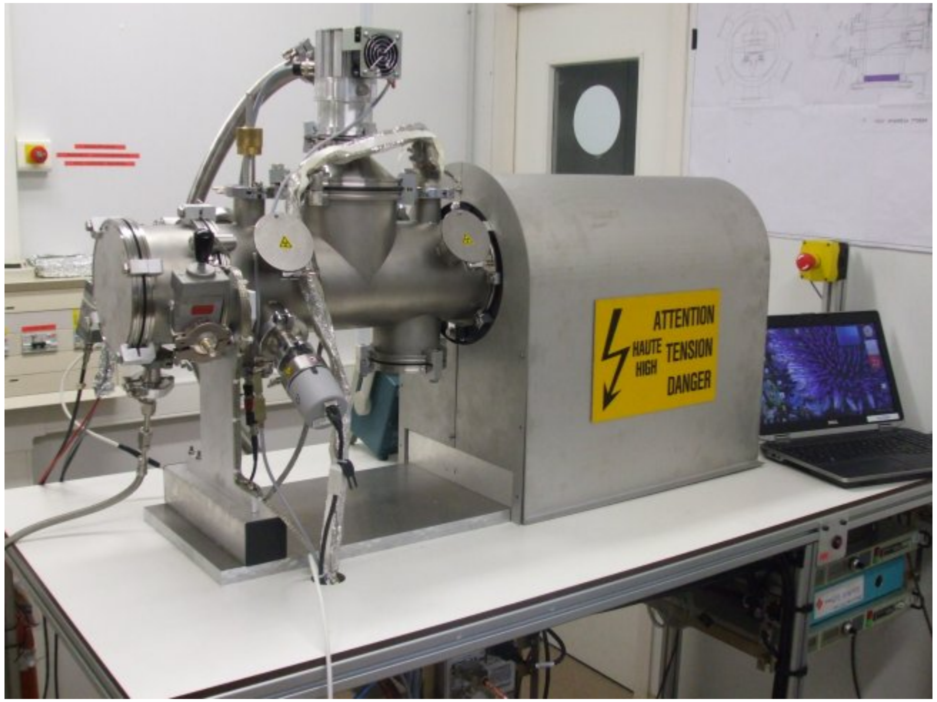
Ionization Quenching Factors

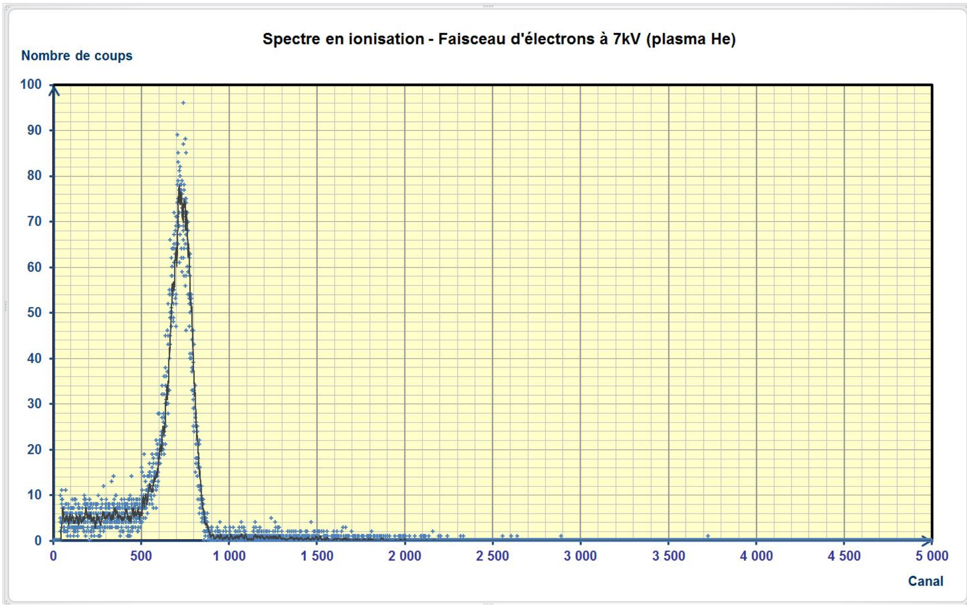
Simulations and Measurements (LPSC)



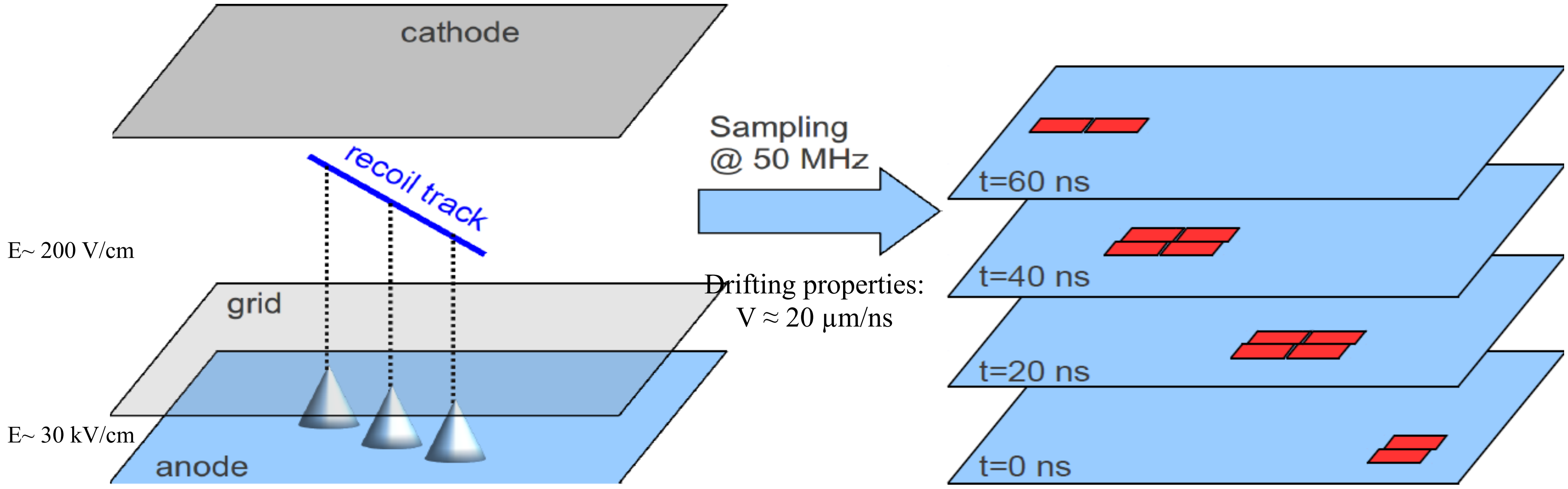


Ligne de quenching portable (COMIMAC)





MIMAC: Detection strategy

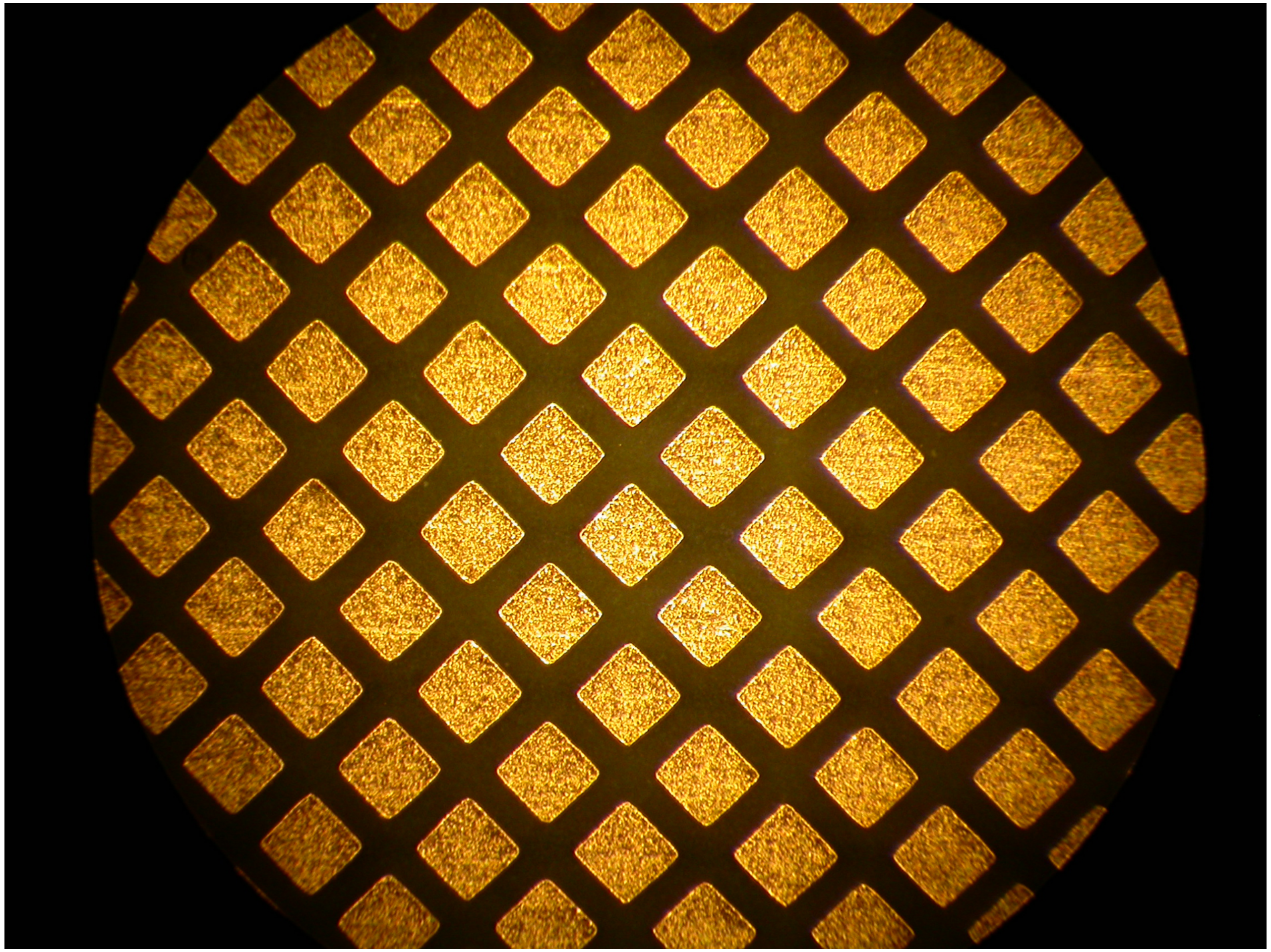


Scheme of a MIMAC µTPC

Evolution of the collected charges on the anode

Measurement of the ionization energy: Charge integrator connected to the grid

MIMAC 100x100 mm^2(v2)
(designed by IRFU- Saclay (France))



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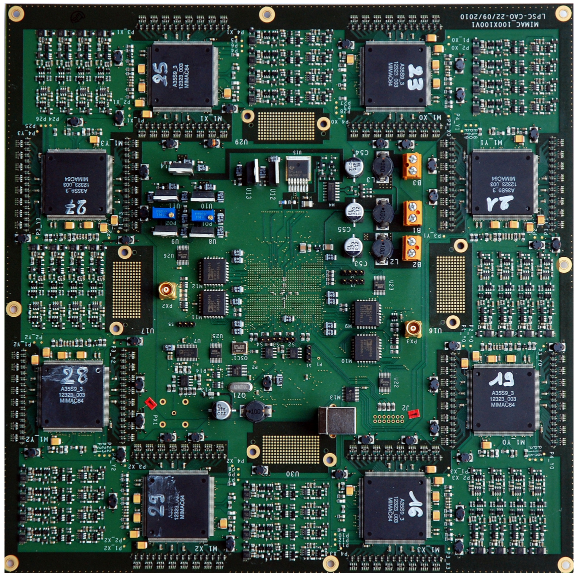
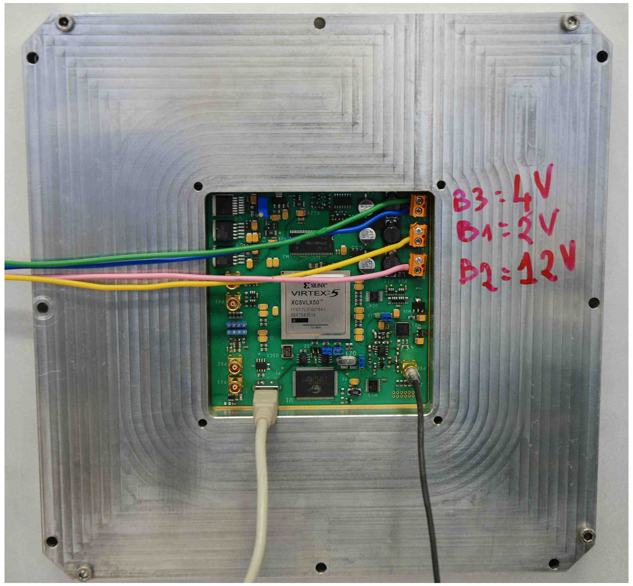
MIMAC electronics (512 channels)





Entirely developed (ASICs included) by the MIMAC team at the LPSC-Grenoble (France)

V1: 2007 (192 channels for the 3cm x3cm)
ASIC-Mimac (16 channels)

V2: 2009 (512 channels for the 10cmx10cm)
ASIC-Mimac (64 channels)

V3: 2011 (upgraged version) 512 channels

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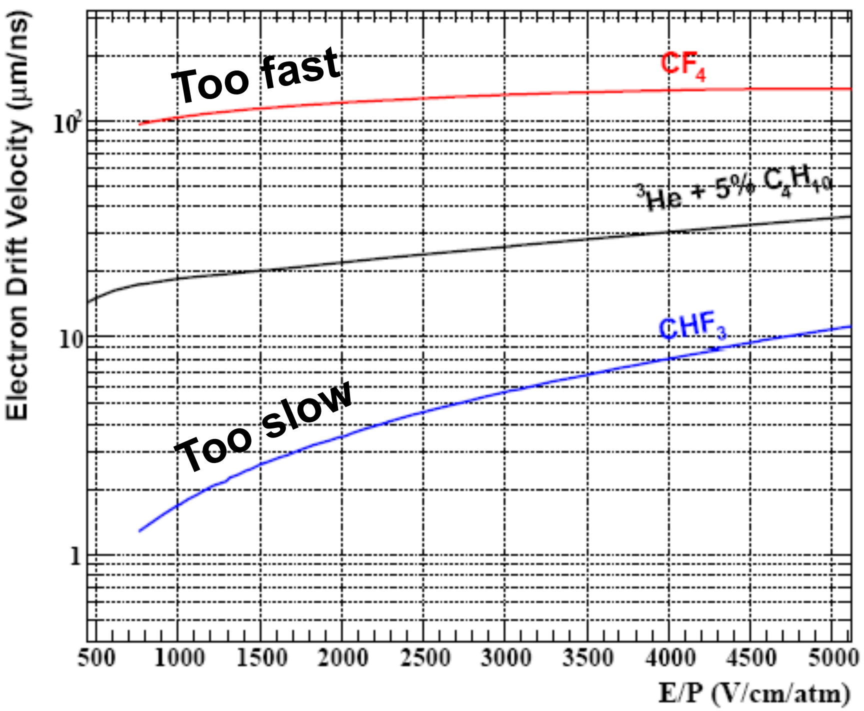
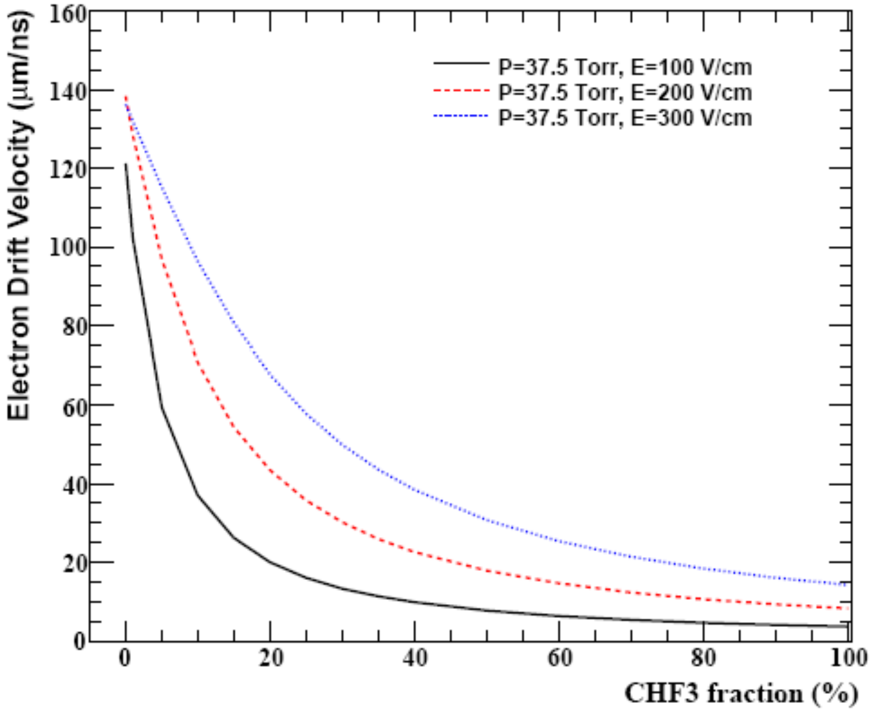
3D Tracks: Drift velocity

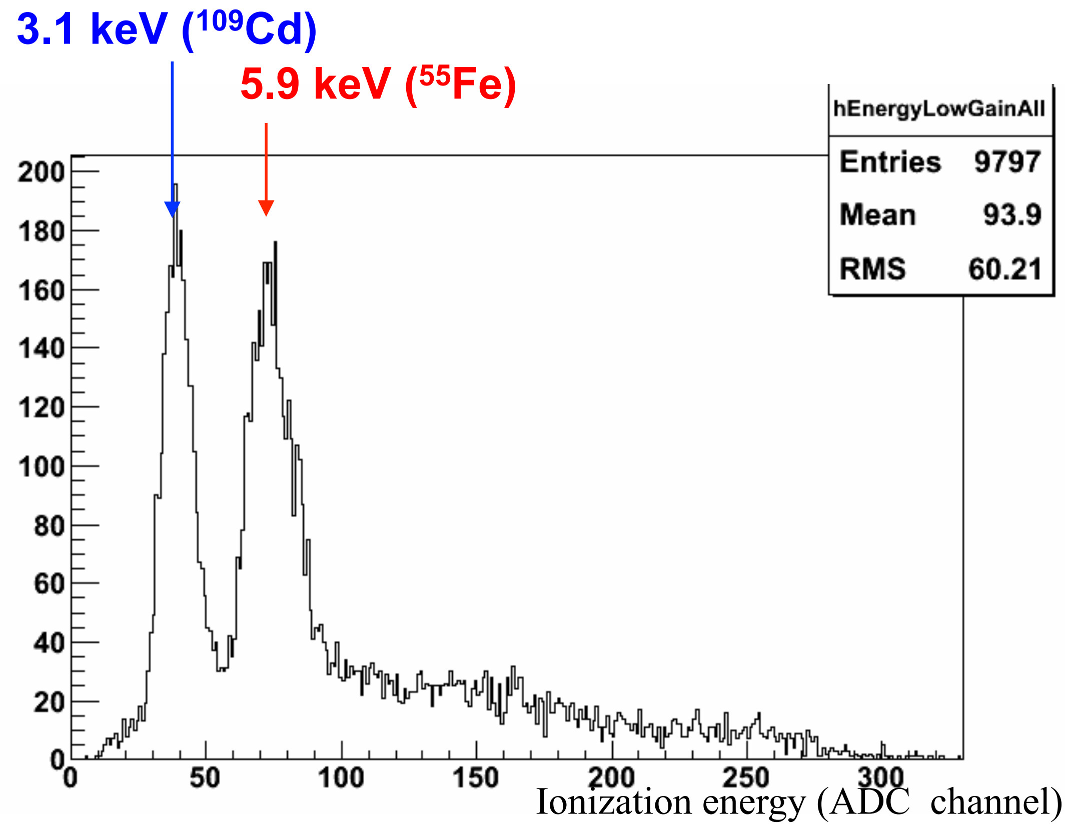
Magboltz Simulation





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

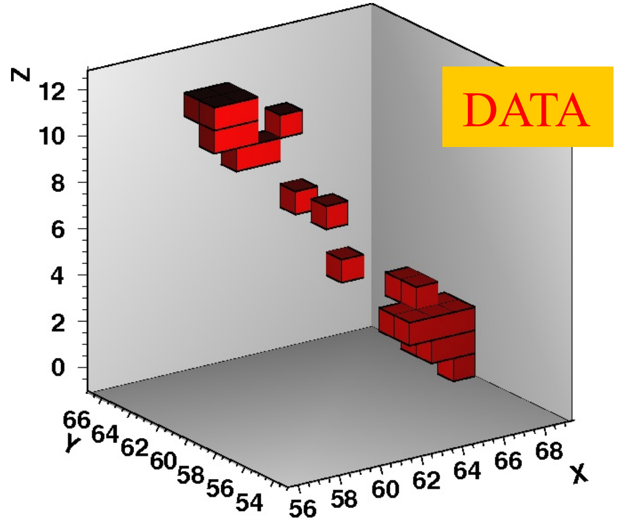
MIMAC: Performance at low energies



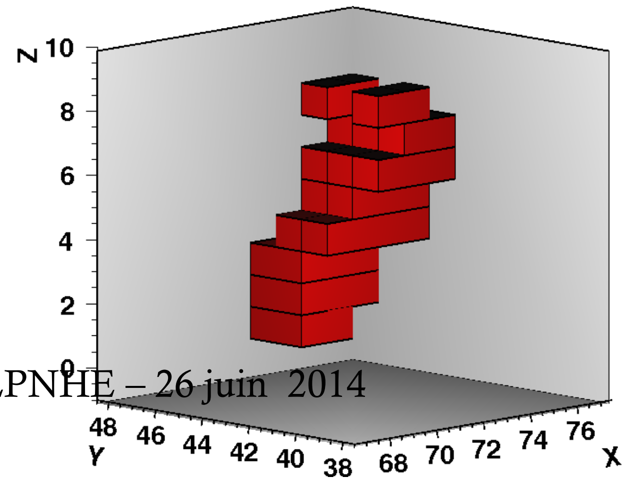
CF_4+ 28%CHF_3

(+2% C_4H_{10})

50 mbar



One electron track (6 keV)



Fluorine candidate
@ 50 keV ionization
Produced with a
monochromatic neutron
field (AMANDE)

MIMAC validation with neutrons

Neutron monochromatic field:

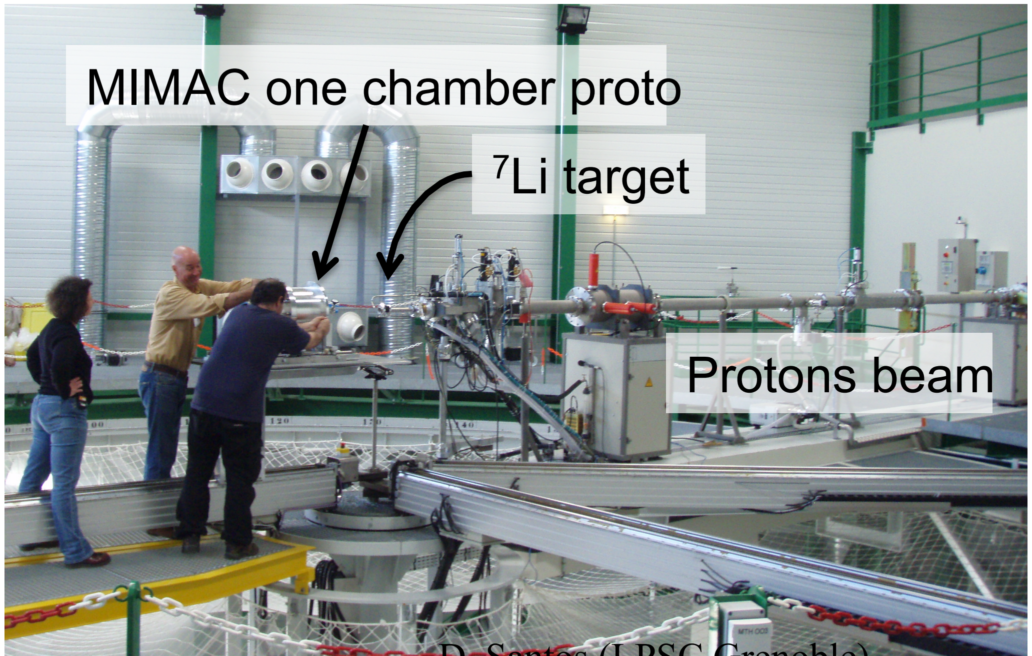
AMANDE facility at IRSN of Cadarache

– 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



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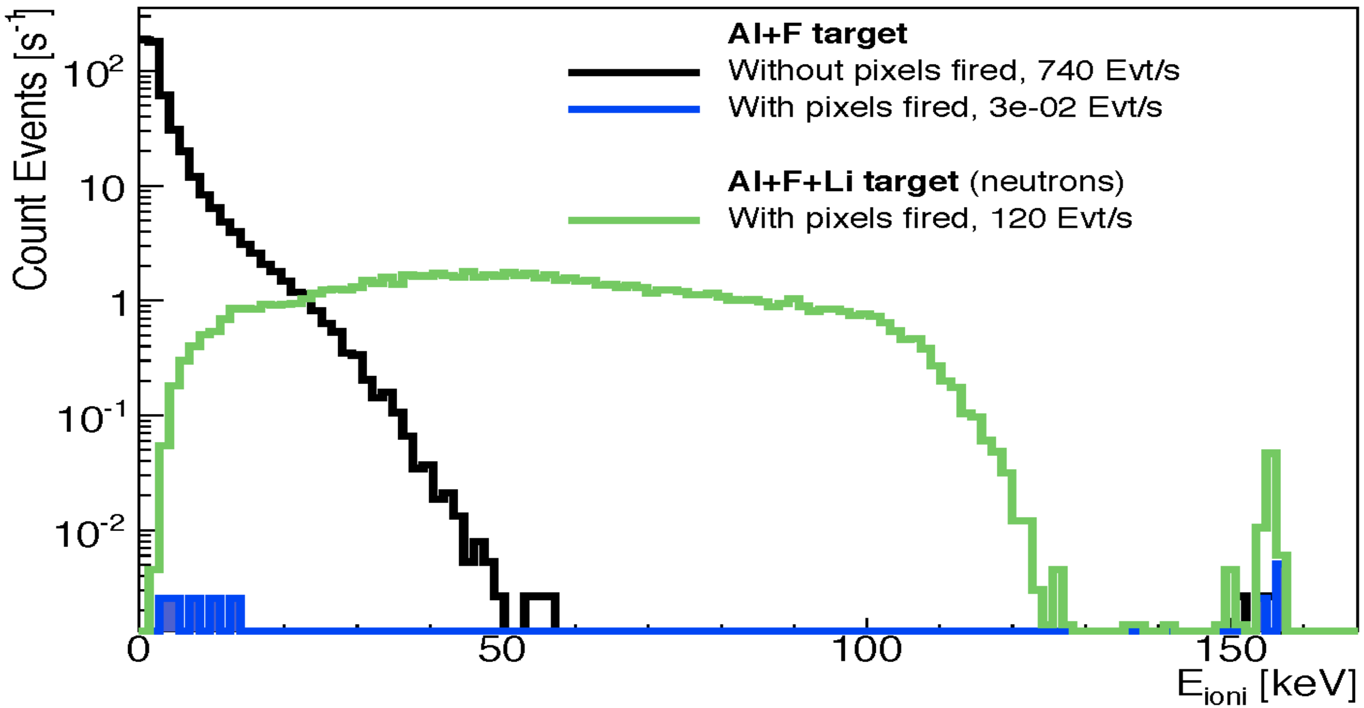
« Gamma rejection »

from the background of an in beam proton reaction (2.5 MeV)

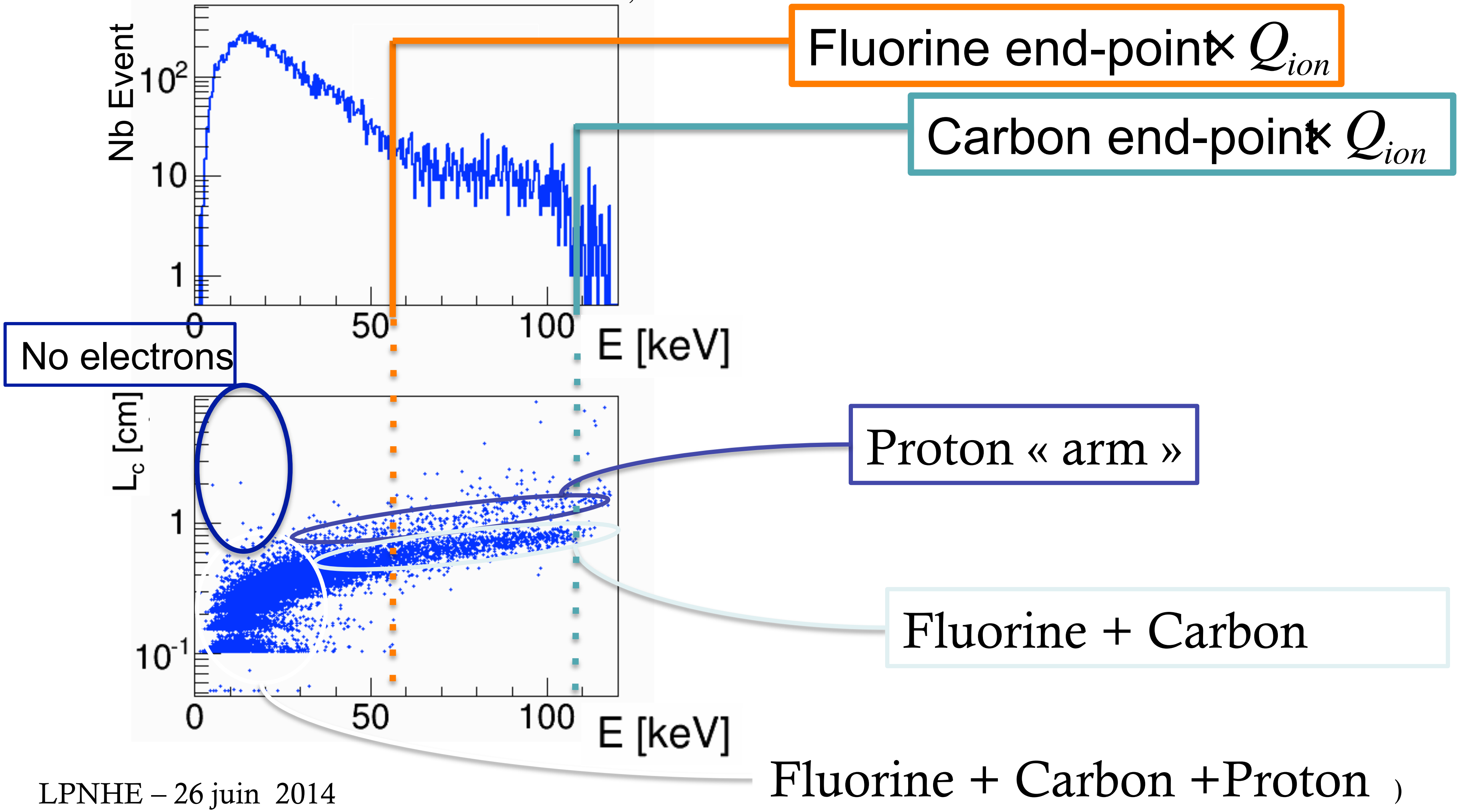
(50 mbar : C_4H_{10} + 30% CHF_3)

E_{max}(neutrons)=127 keV



Measurement of the ionization energy and the 3D track

Max neutrons energy: $E_{n,\max} = 565$ keV



Electron/Recoil discrimination measurement

@ Amande Facility (IRSN Cadarache):

Neutron field production reaction:

$$^{7}\mathrm{Li(p,n)}^{7}\mathrm{Be}$$

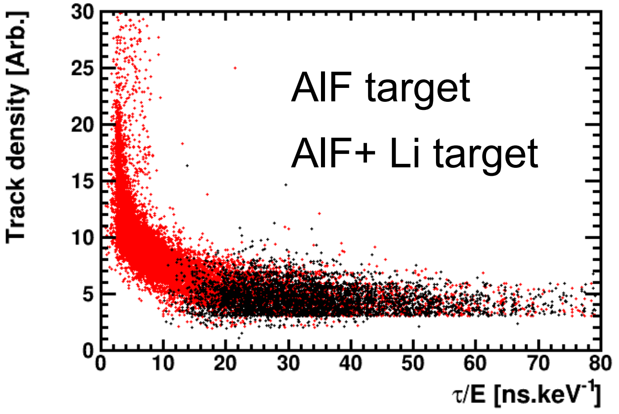
Target : $\mathrm{Al\,F + Li}$

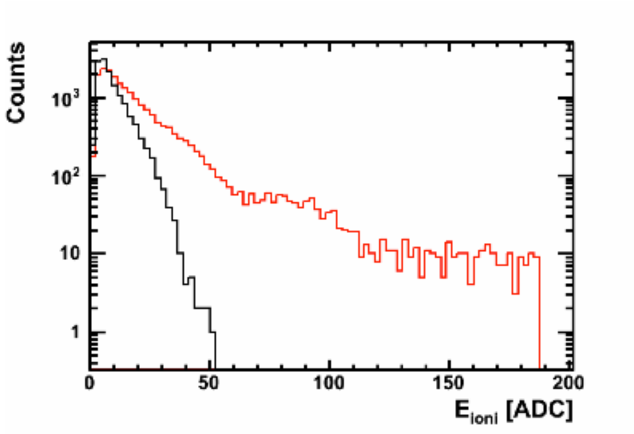
$\gamma - \mathrm{ray}$ → Electrons production by Compton scattering

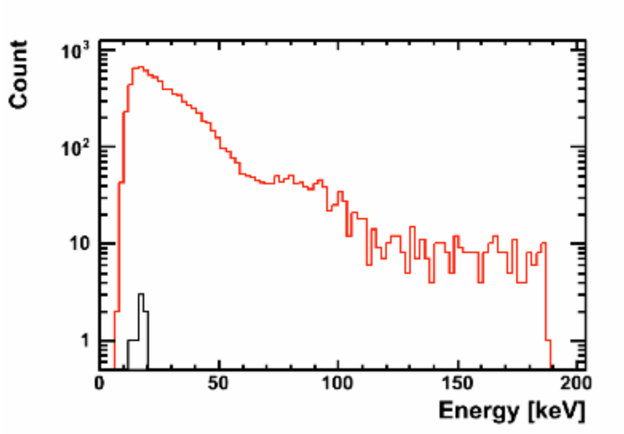
Neutrons → Nuclear recoils production by elastic diffusion

Experiment with and without Li

Electron/Recoil discrimination measurement





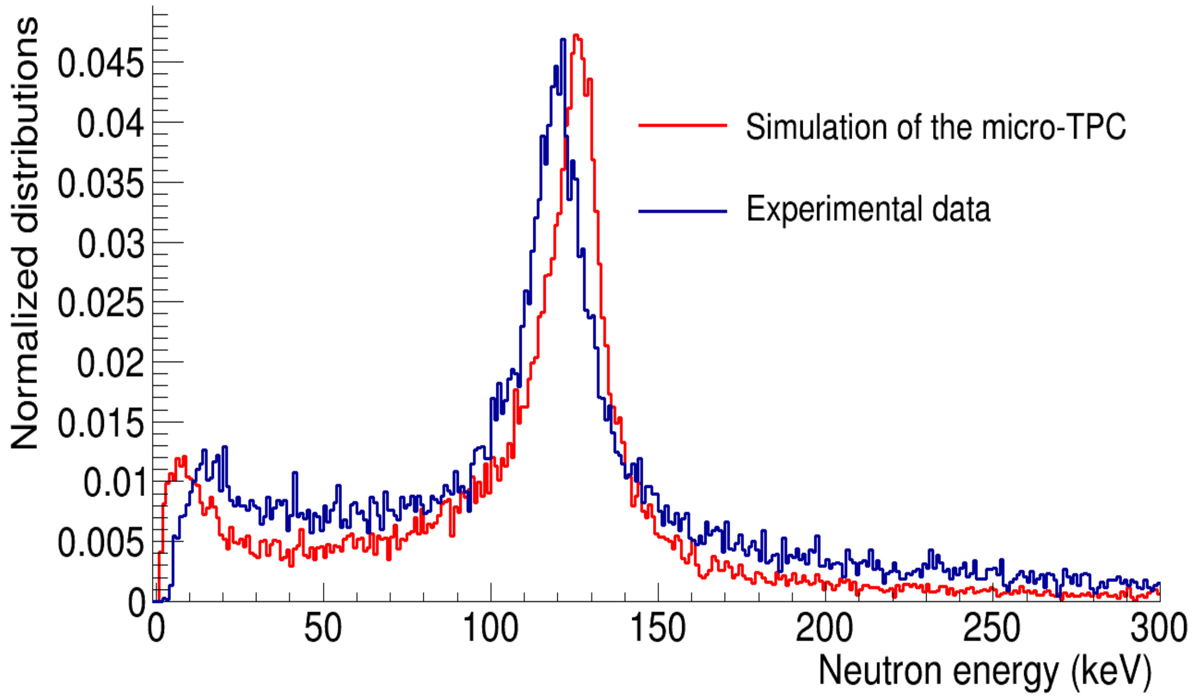


Cut on track density vs normalized rise-time

10^{-5} electron - recoil discrimination

Measurement of 127 keV neutrons at Cadarache

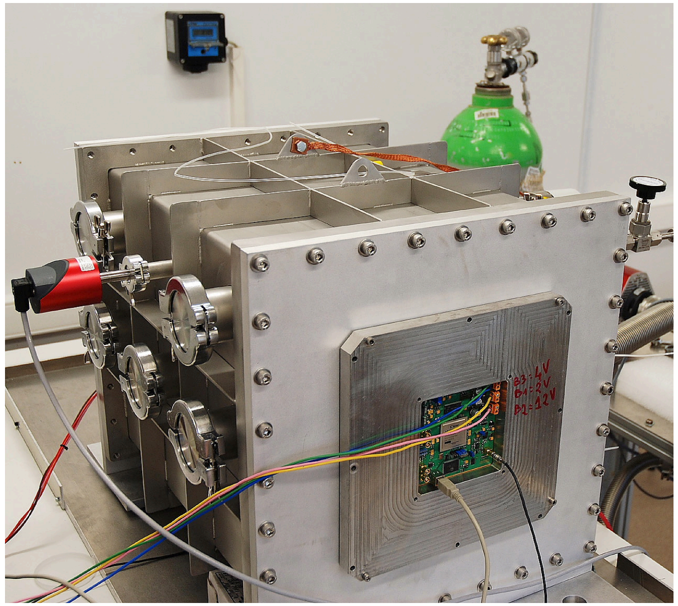
(D.Maire et al. (2014), IEEE)

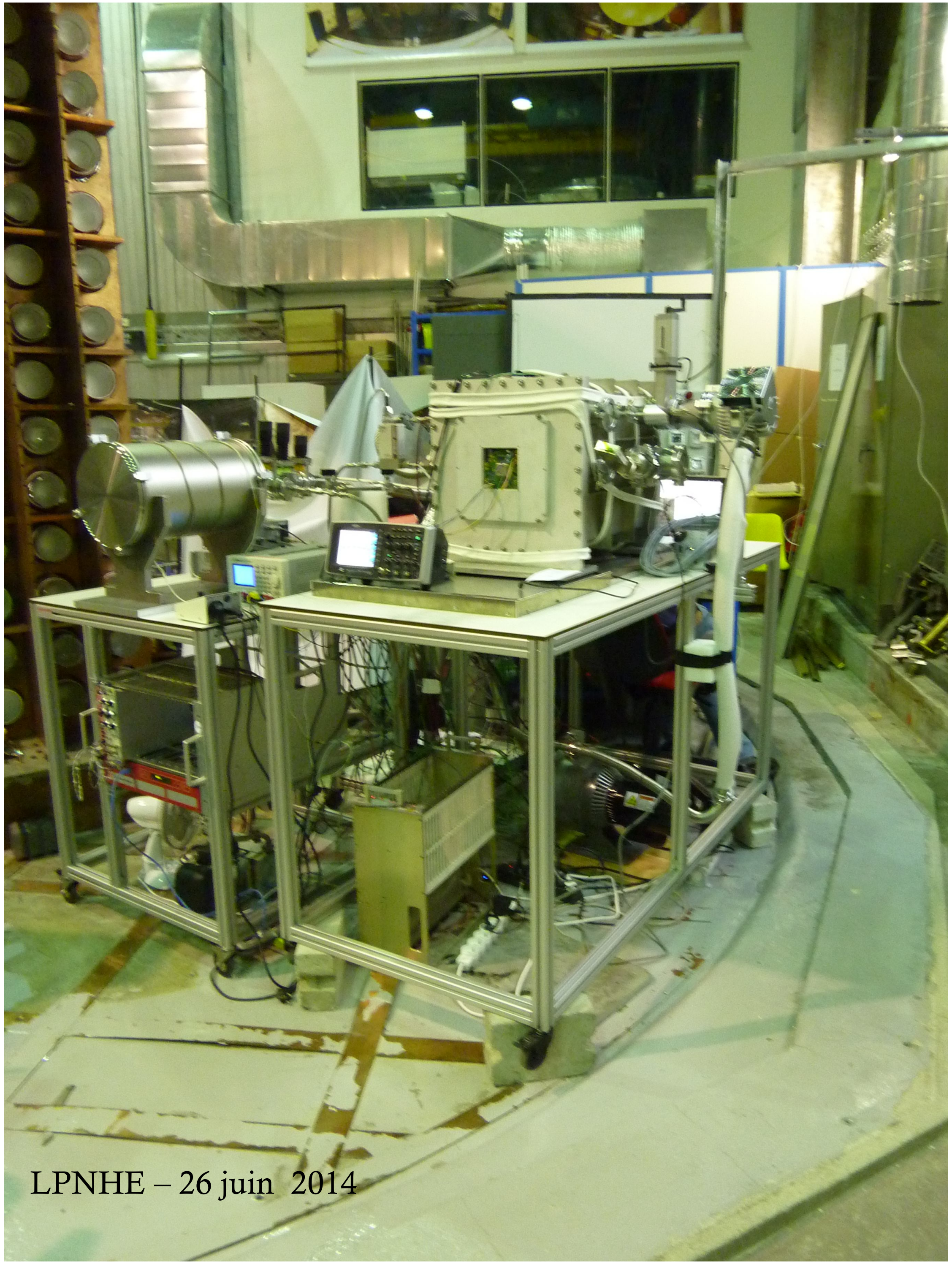


MIMAC bi-chamber module

- Two detectors with a common cathode (mylar 24um (6/2012), 12um (6/2013))
- Active volume = 2x(25x10.8x10.8) cm^3 ~ 5.8 l
- Gas mixture $70\%\ CF_4 + 28\%\ CHF_3 + 2\%\ C_4H_{10}$

  at 50 mbar
- Gas circulation system with a buffer volume, a pressure regulator and a O_2 filter (+ charcoal filter)
- On-line calibration system with a X-ray generator (by fluorescence)





MIMAC (bi-chamber module)at Modane Underground Laboratory (France)
since June 22nd 2012

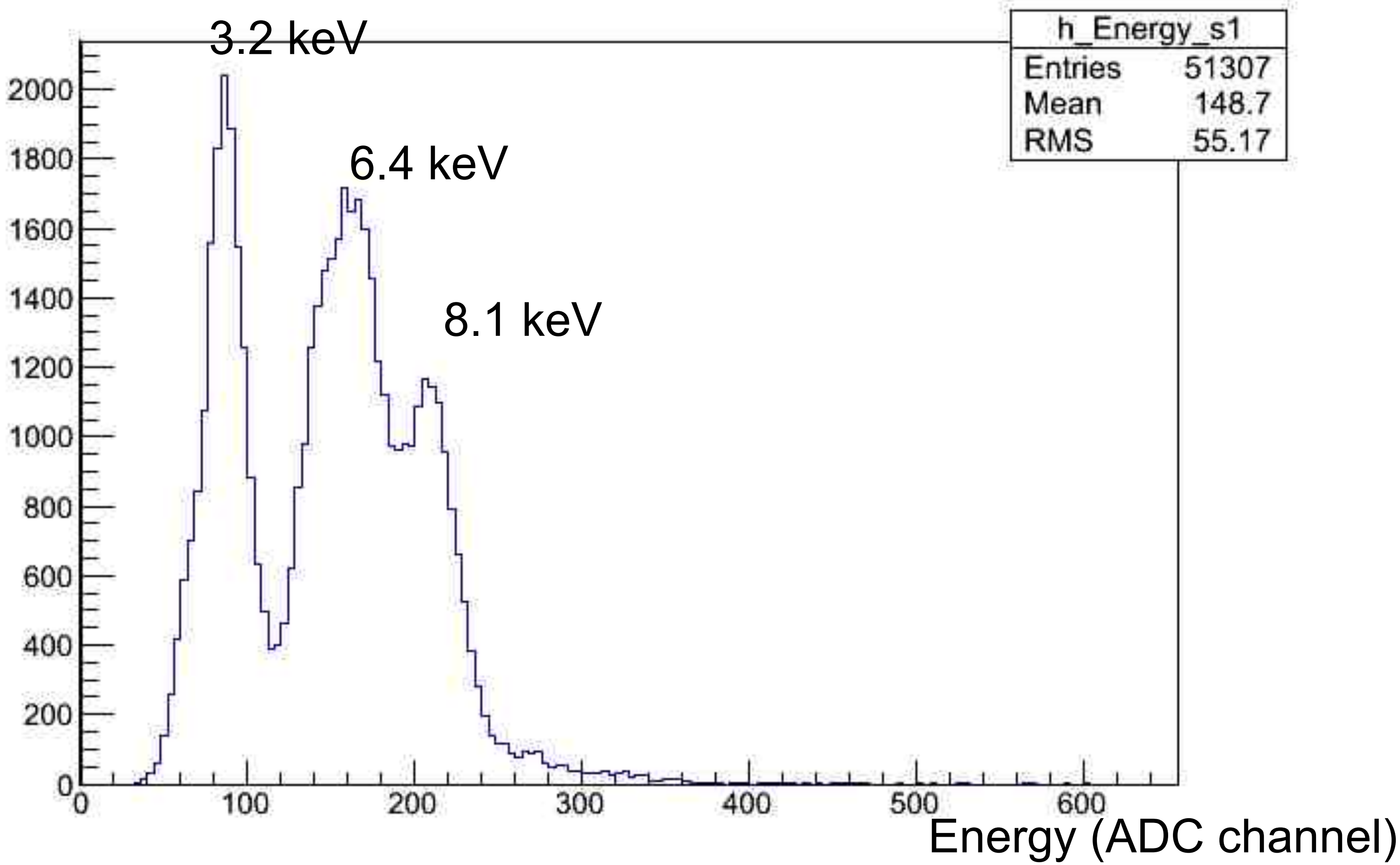
-working at 50 mbar
(CF_4+28% CHF_3 + 2% C_4H_{10})

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

Many thanks to LSM staff

D. Santos (LPSC Grenoble)

Calibration – Chamber2 (at Modane) fluorescence of Cd-(Cr-Fe)-Cu



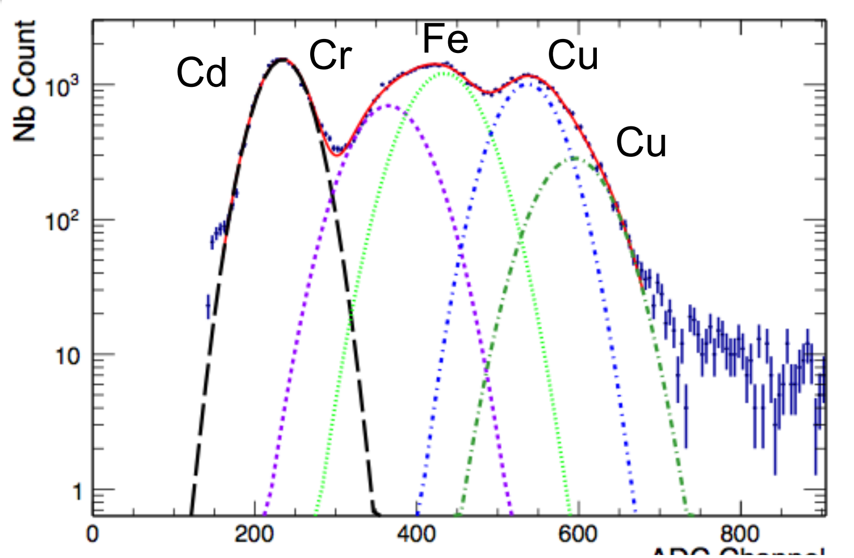
MIMAC Calibration (Modane)

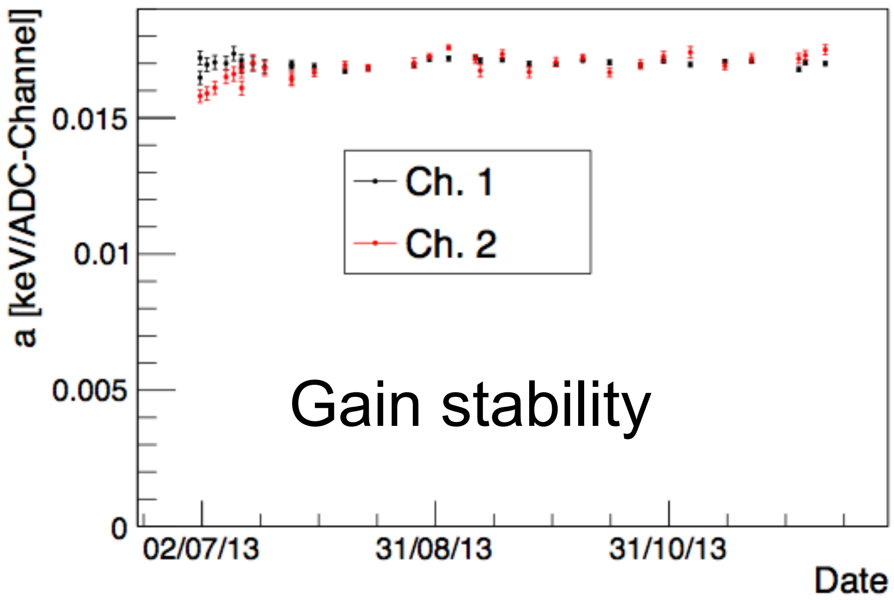
Calibration:

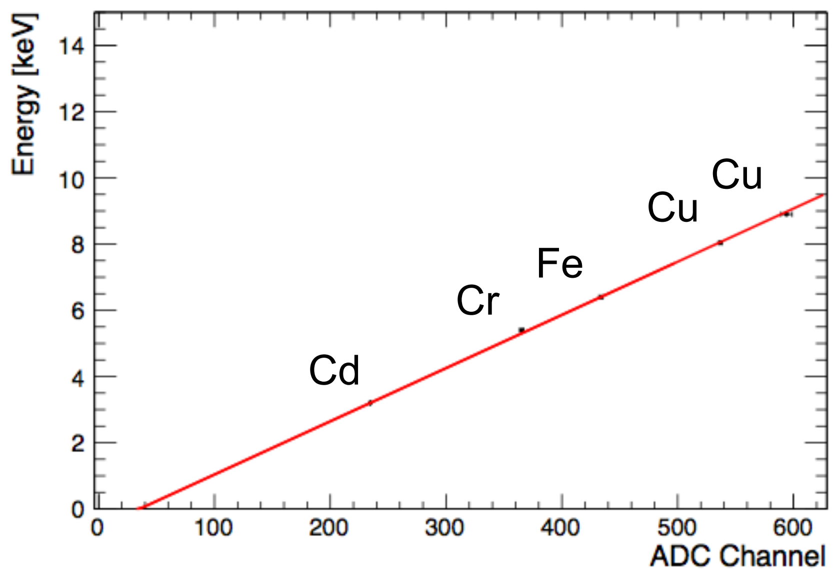
X-ray generator to produce fluorescence photons from metal foils (Cd, Fe, Cu)

Once a week

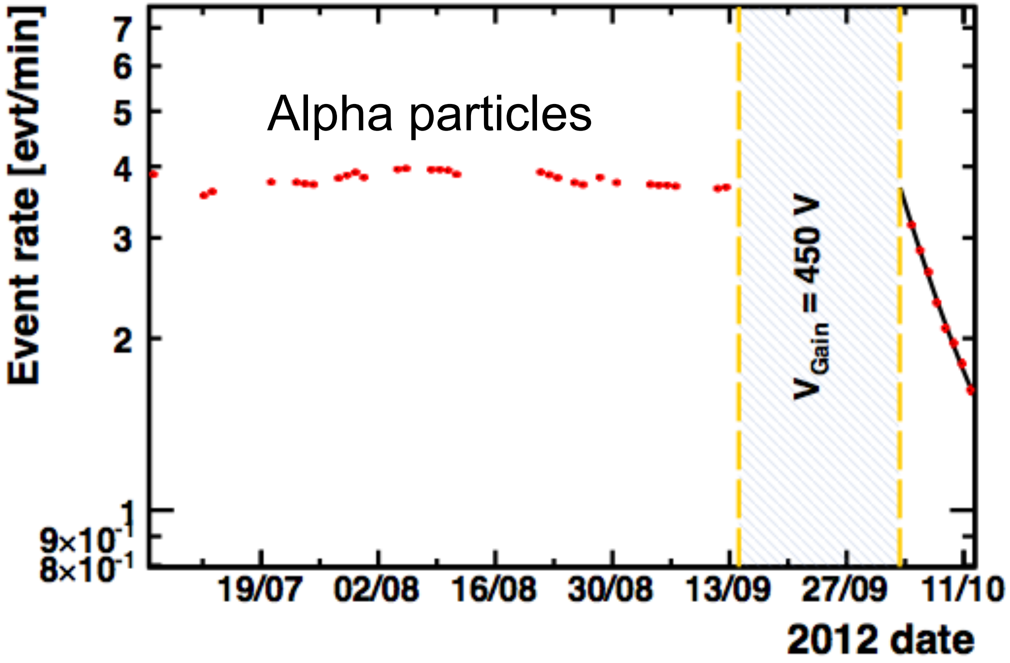
Low energy detector calibration.







Circulation cut



α-particles rate:

$$R_\alpha \approx 4\,\mathrm{evt/min}$$

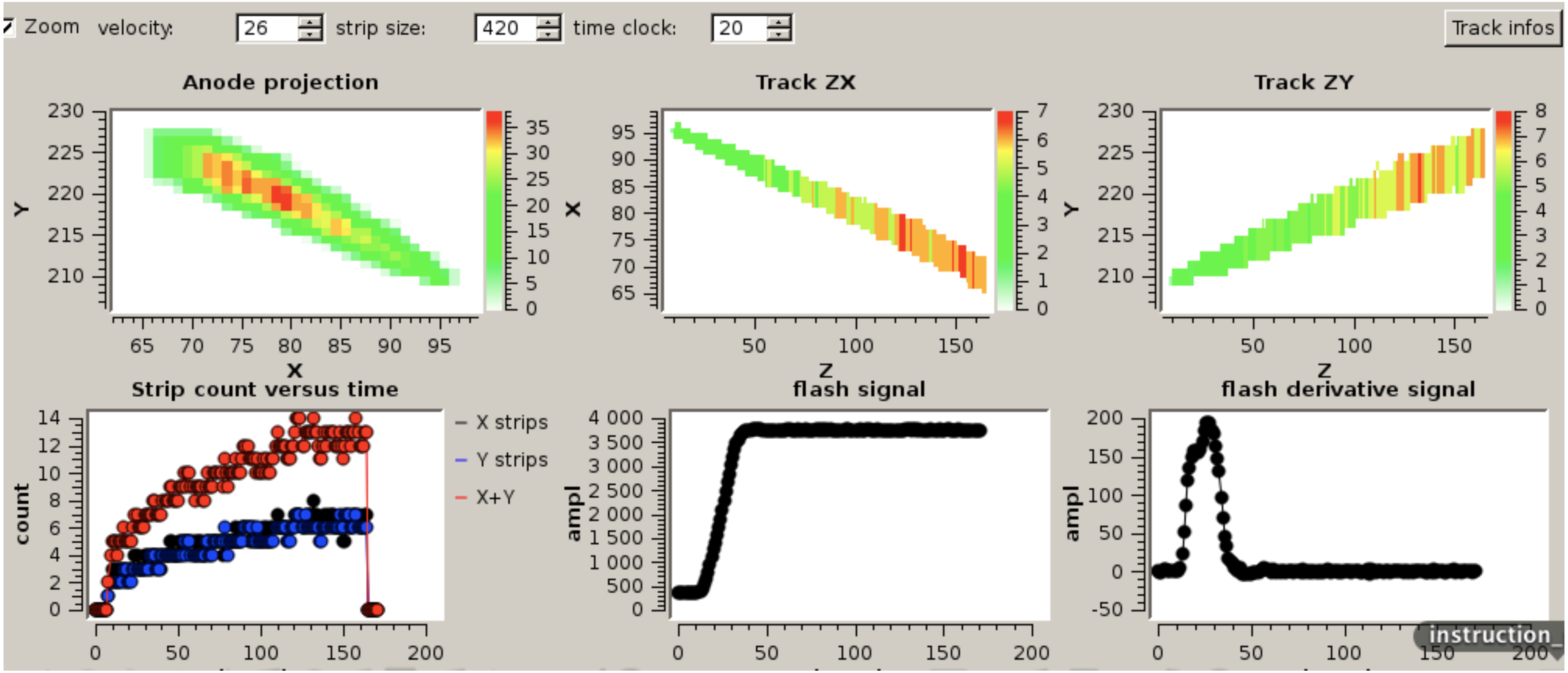
Circulation cut
→ Exponential decreasing

Compatible with the $\alpha-$decay of the $^{222}\mathrm{Rn}$ (3.8 days)

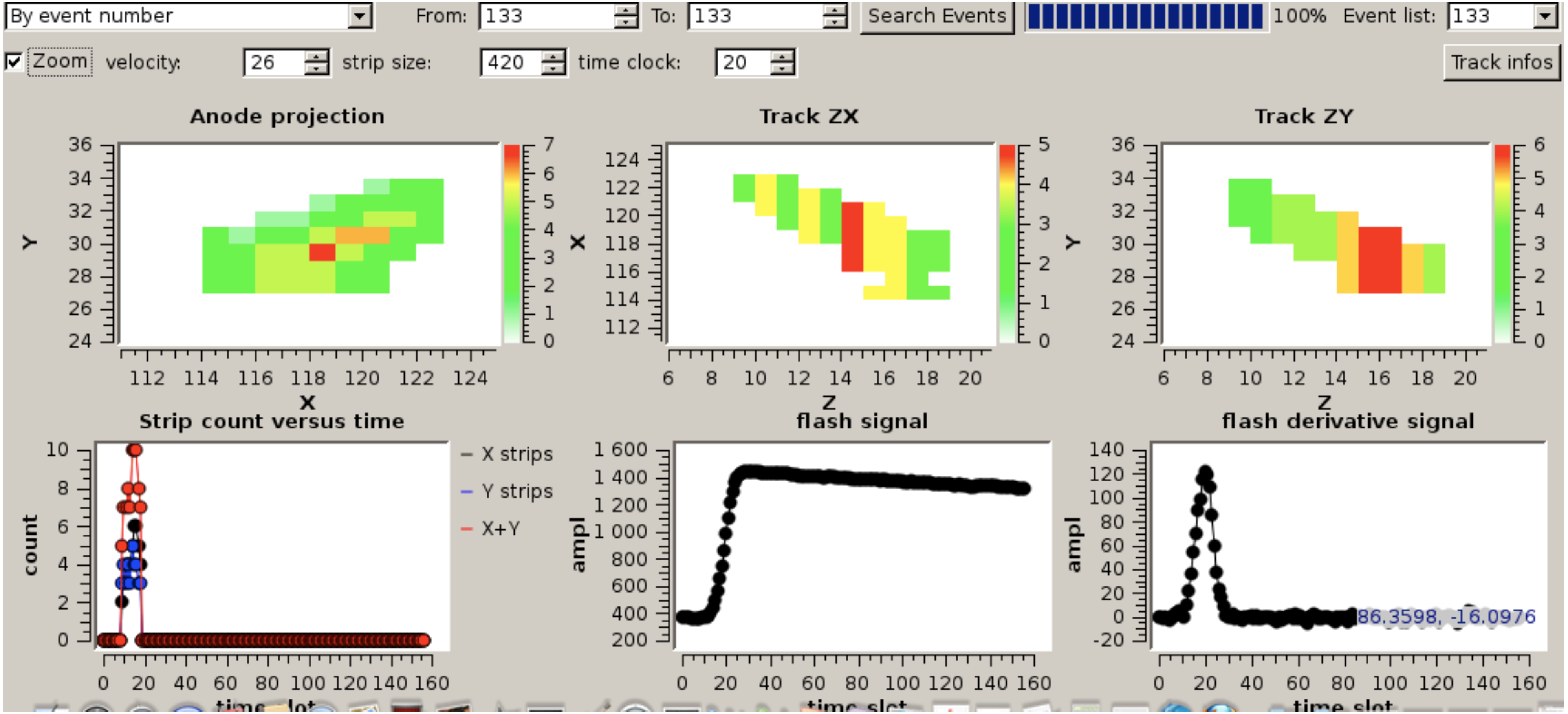
$$(\alpha - \mathrm{decay})$$

An alpha particle crossing the detector
(as an illustration of the MIMAC observables)

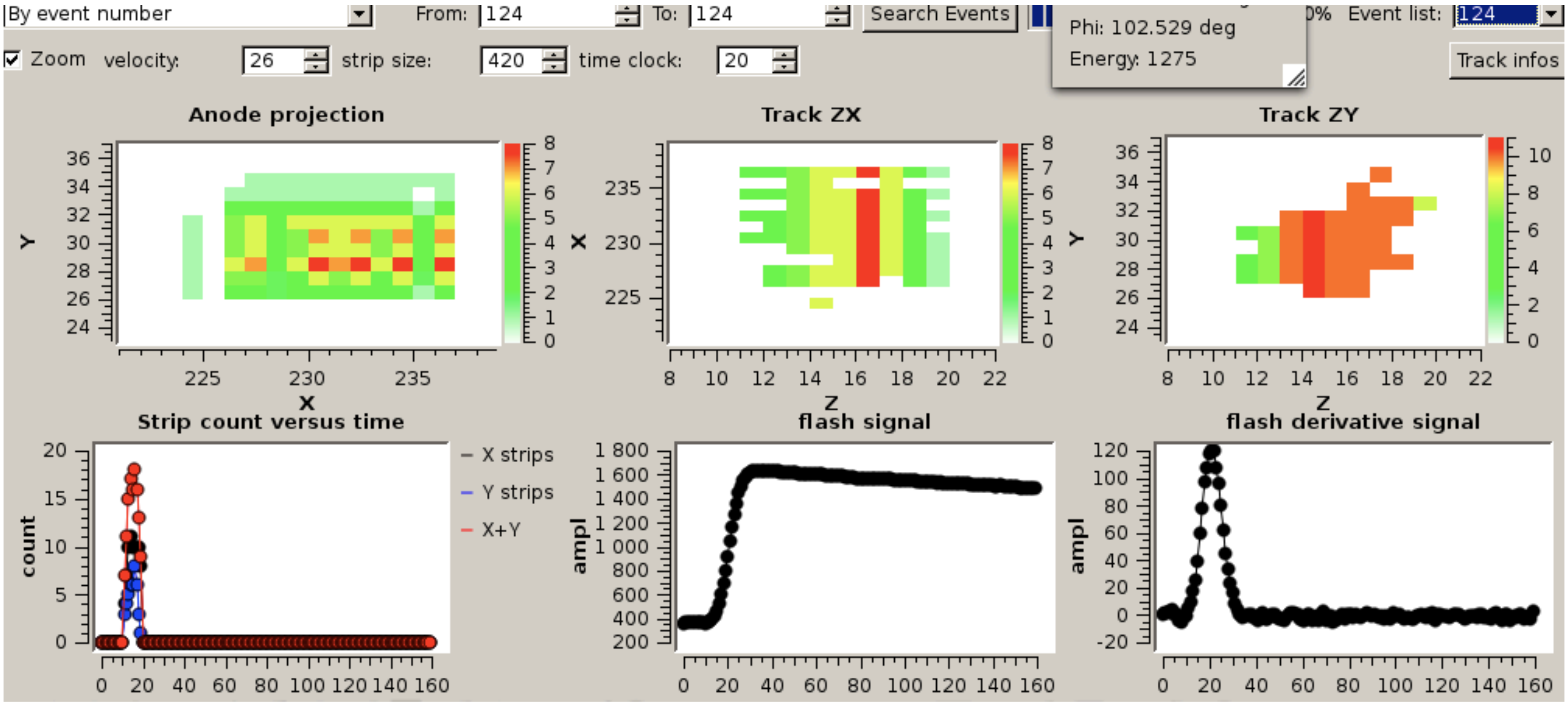
X-Y (anode) X-Z(t) Y-Z(t)



A "recoil event" (~ 34 keVee)



A “recoil” event (~ 40 keVee)



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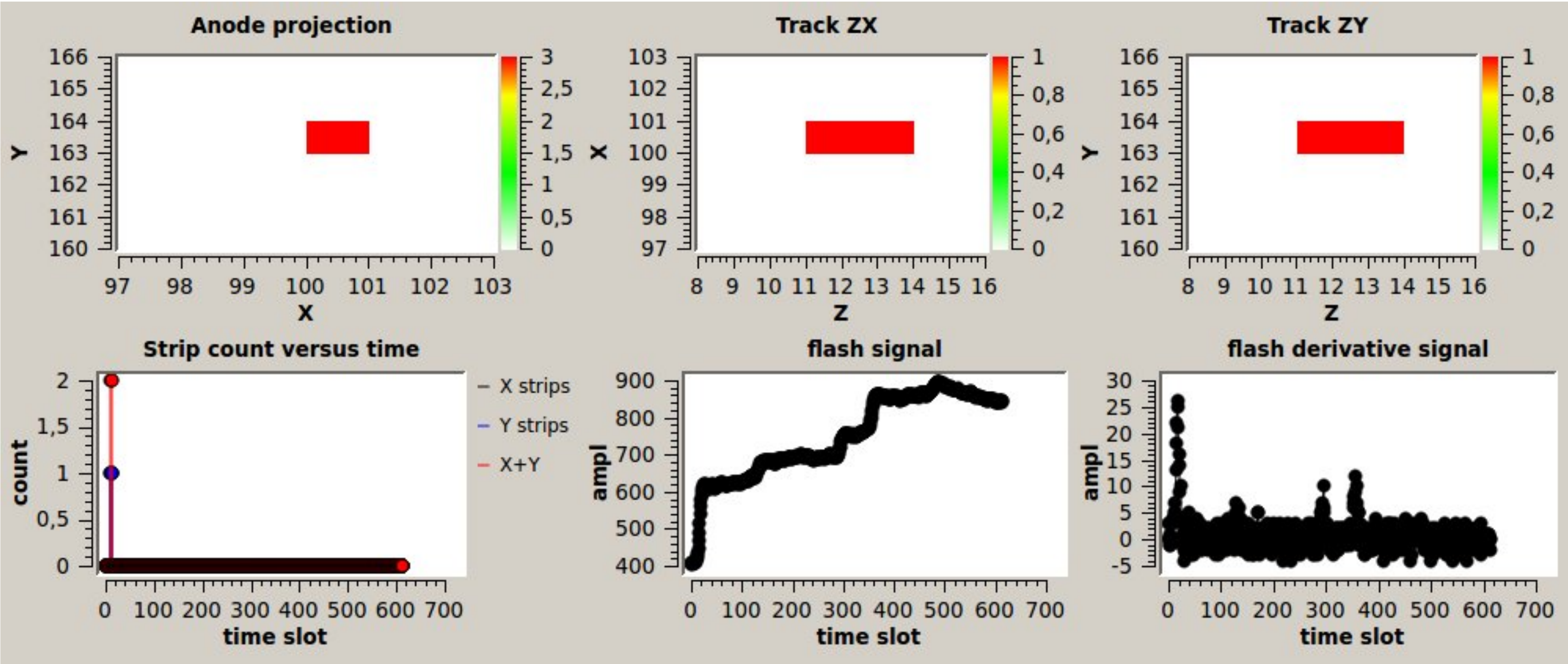
An Electron event (18 keV)



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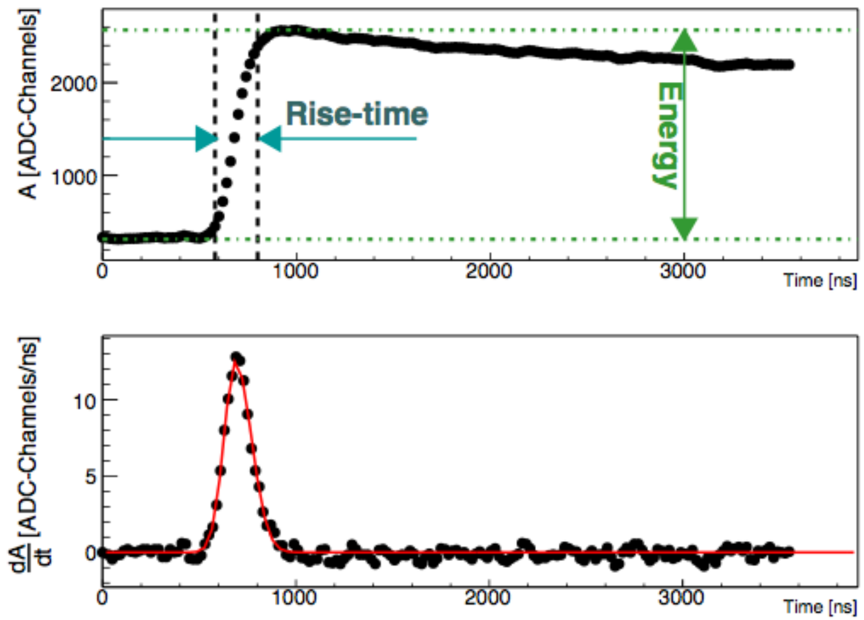
MIMAC - Observables

Flash-ADC observables:

Ionization energy $E_{ioni}^{ADC} = S_{max} - S_{min} \rightarrow E_{ioni}^{keV} = a \times E_{ioni}^{ADC} + b$

Normalized rise-time τ / E_{ioni}



Track observables:

Track density

Slot duration

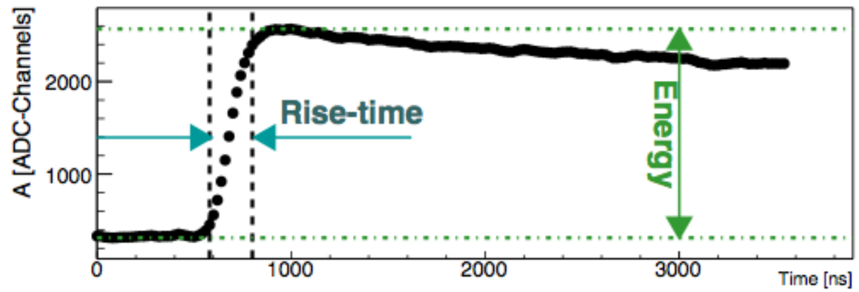
Track projected width

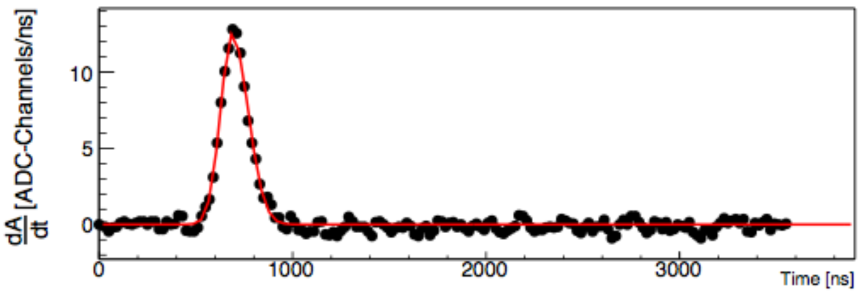
Track mean projected difussion (<deltaX> < deltaY>) (MPD)

MIMAC - Observables

Definitions Flash-ADC:

- Energy: $E = A_{\max} - A_{\min}$
- Rise-time: τ —> τ / E_{ioni}
- Peak number
- Fit results : χ^2
  - Peak position: μ
  - Peak width: $\sigma_1 + \sigma_2$
  - Peak asymmetry: $r = \sigma_1 / \sigma_2$



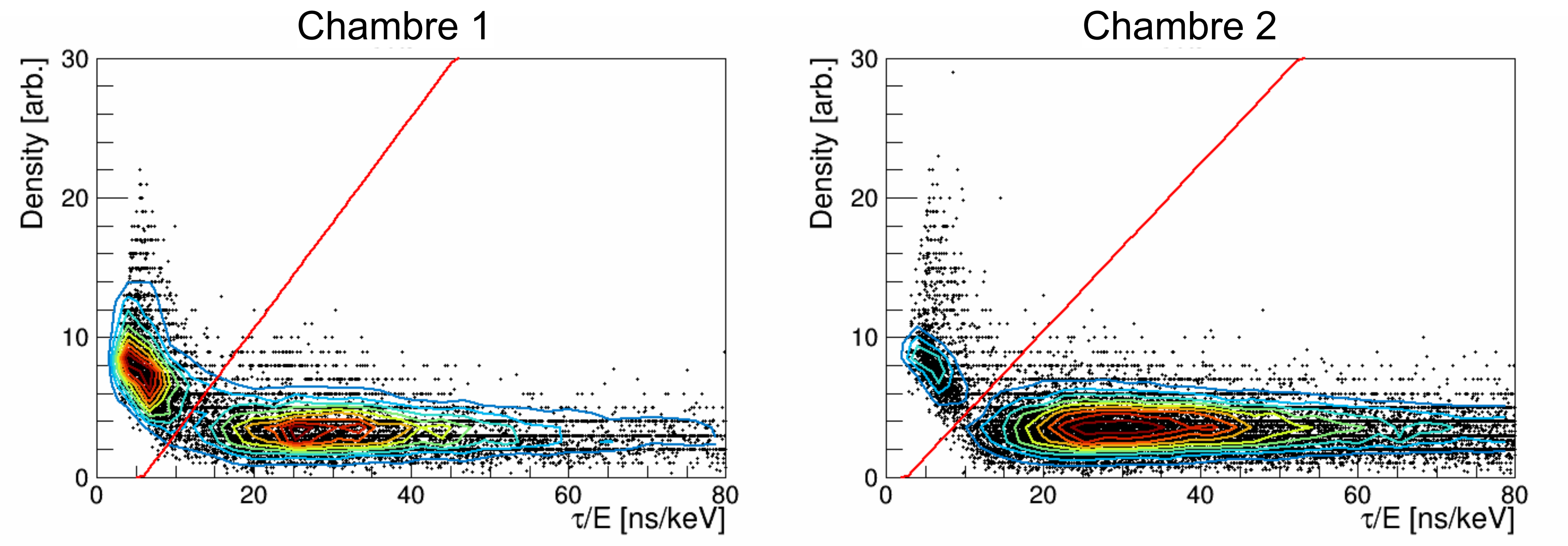


Definitions track:

- Slot duration Δt_{slot}
- (X,Y) Fiducialisation
- Track homogeny (No clusters)
- Track density $\rho_{\mathrm{track}} = \sum N^i_{px} / \Delta X_i \Delta Y_i$
- Mean Projected Diffusion (MPD)

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

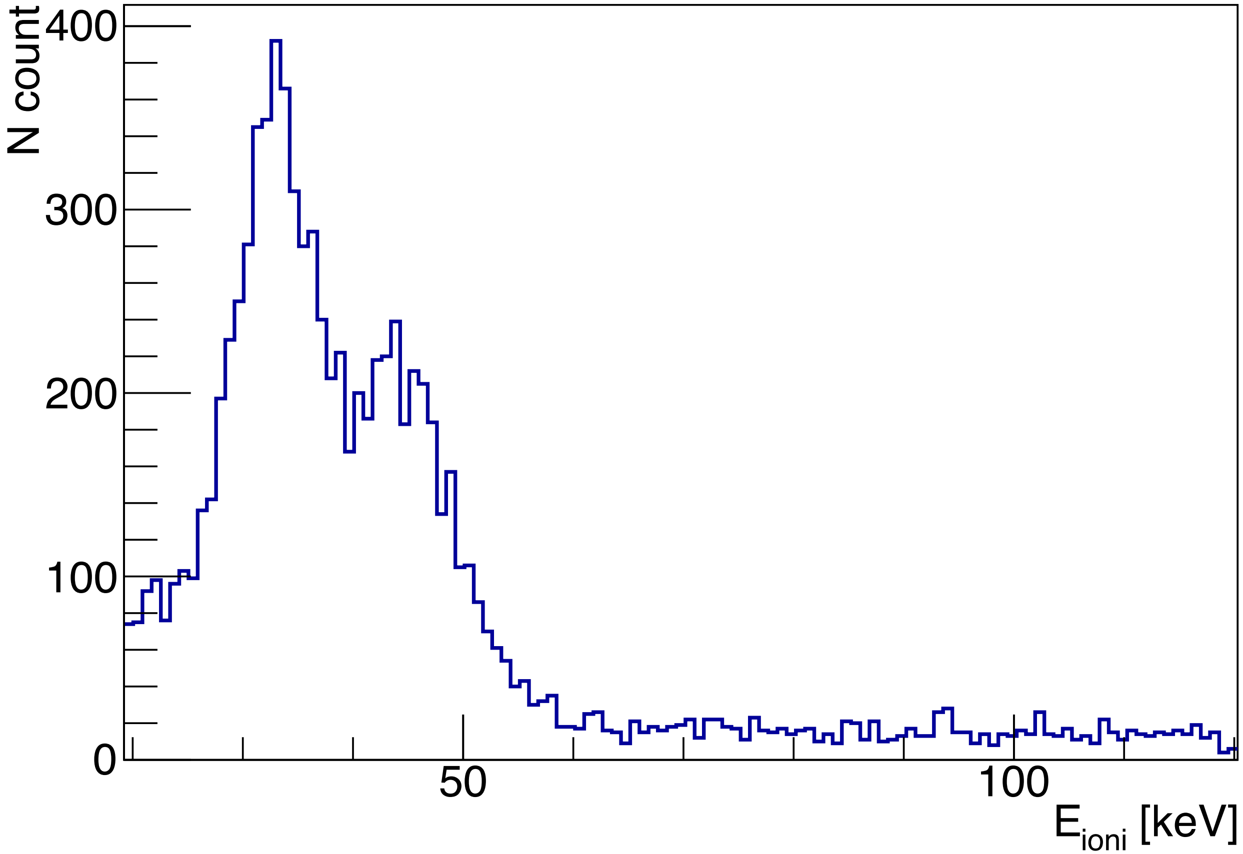
Electron/recoil discrimination



Cut: Optimisation of the separation

$$\begin{cases} \text{Chamber 1:} \quad d > \tau/E \times 0.756 - 4.52 \\ \text{Chamber 2:} \quad d > \tau/E \times 0.6 - 1.6 \end{cases}$$

Spectrum of nuclear recoil tracks detected at Modane (coming from the ^{222}Rn chain decay, surface events) and the alpha particles through the cathode…



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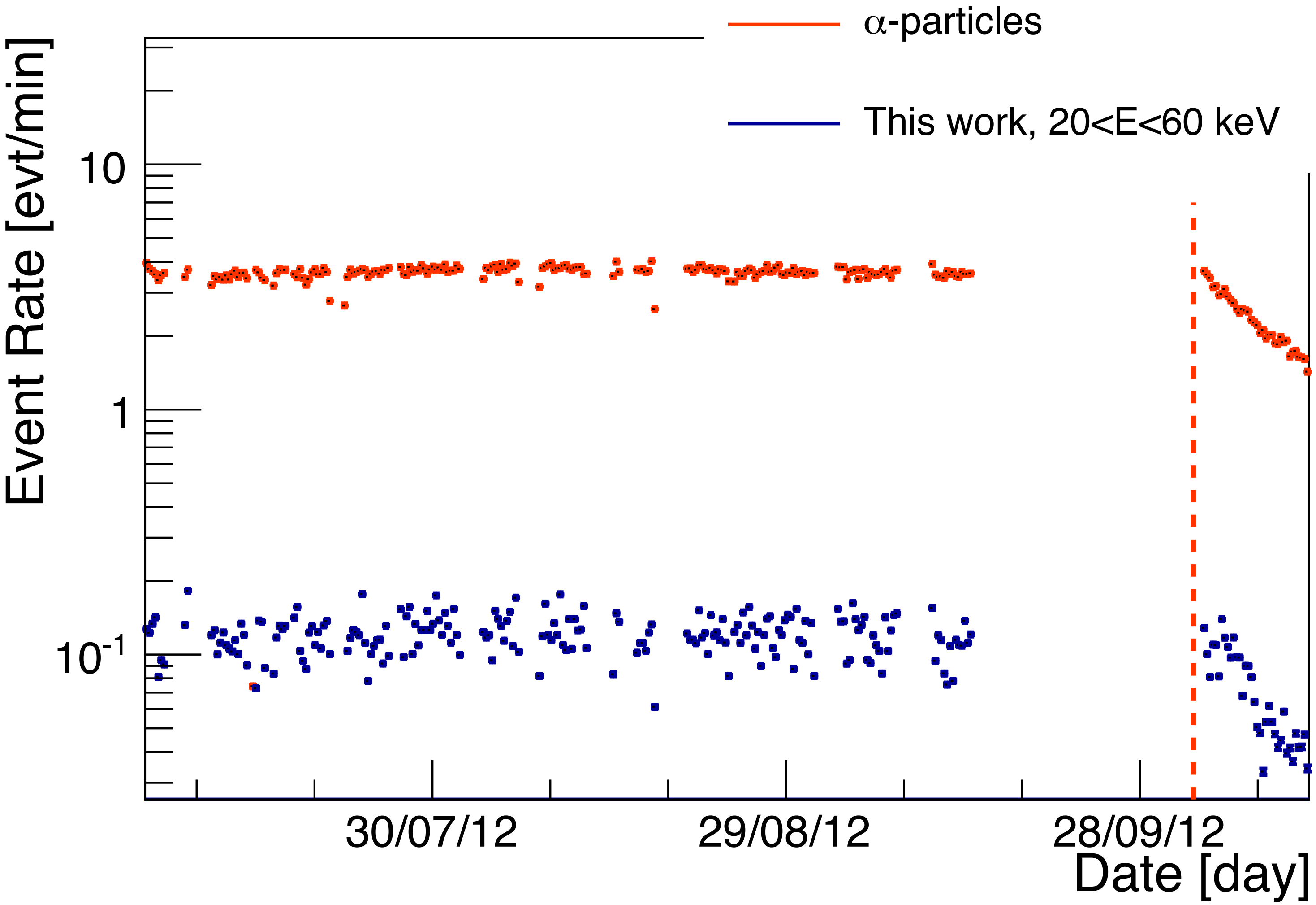
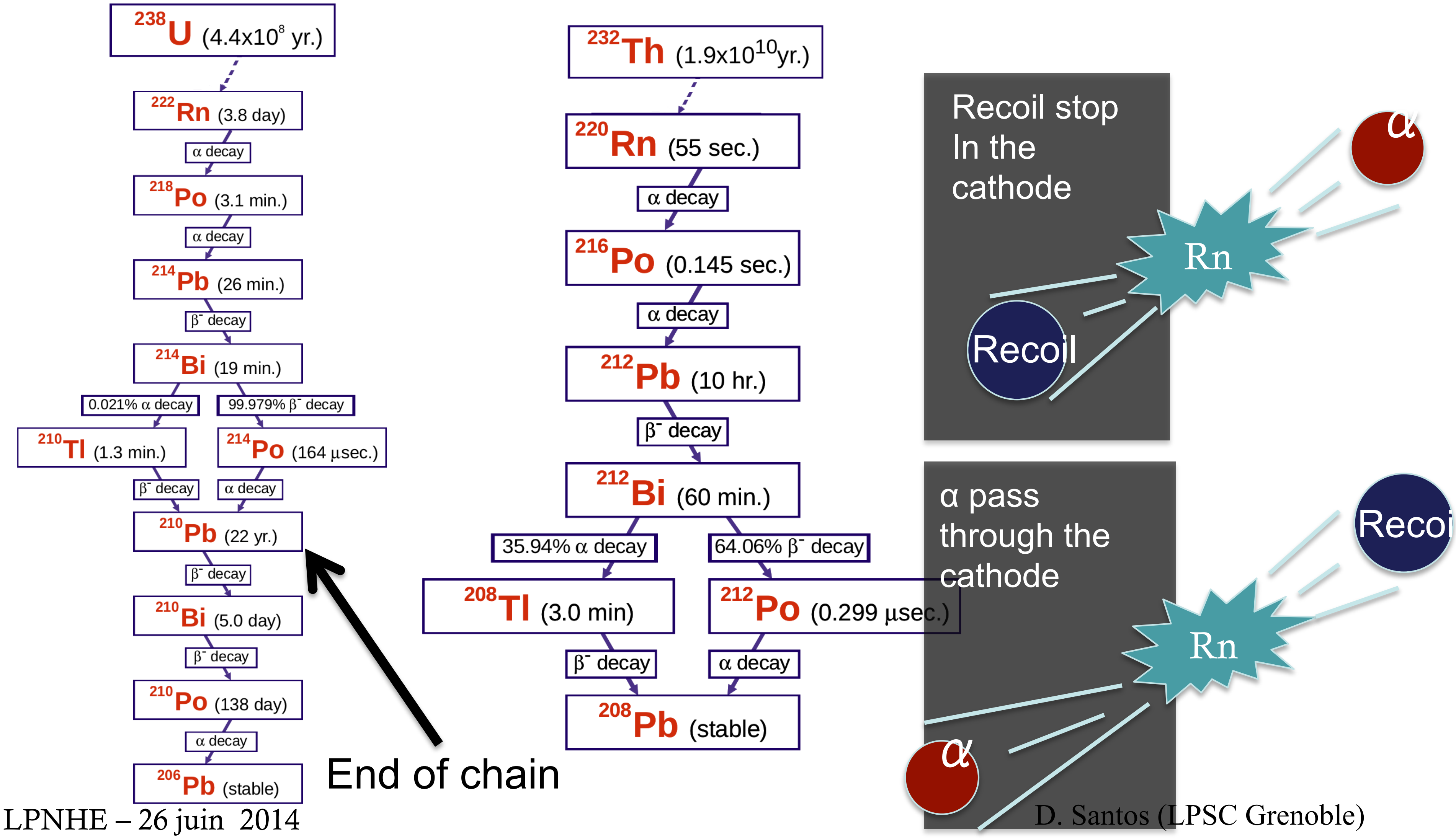
Event rate of alphas at Modane in Ch2
(validation of the source of alphas (^{222}Rn))

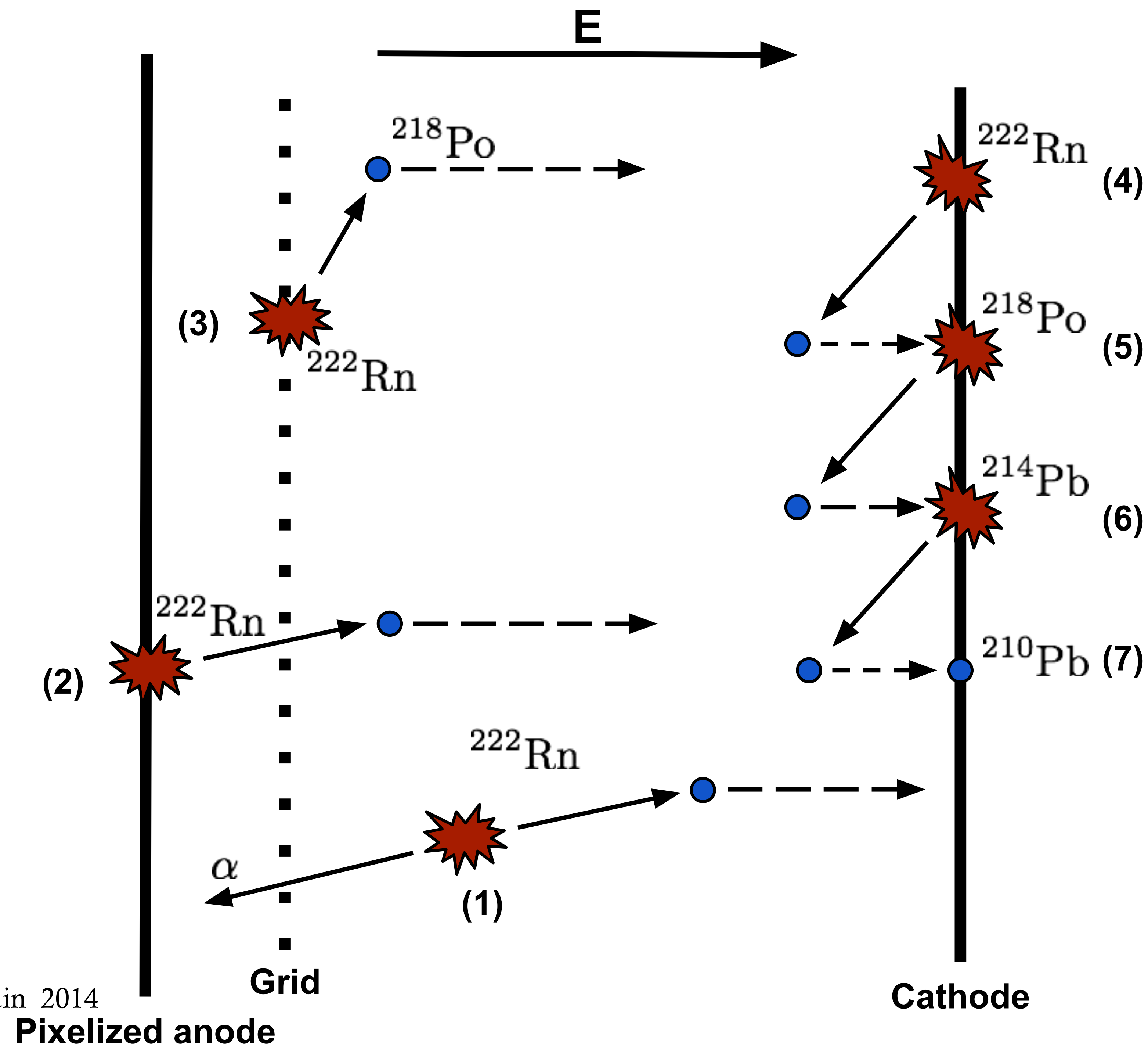


Rn progeny events

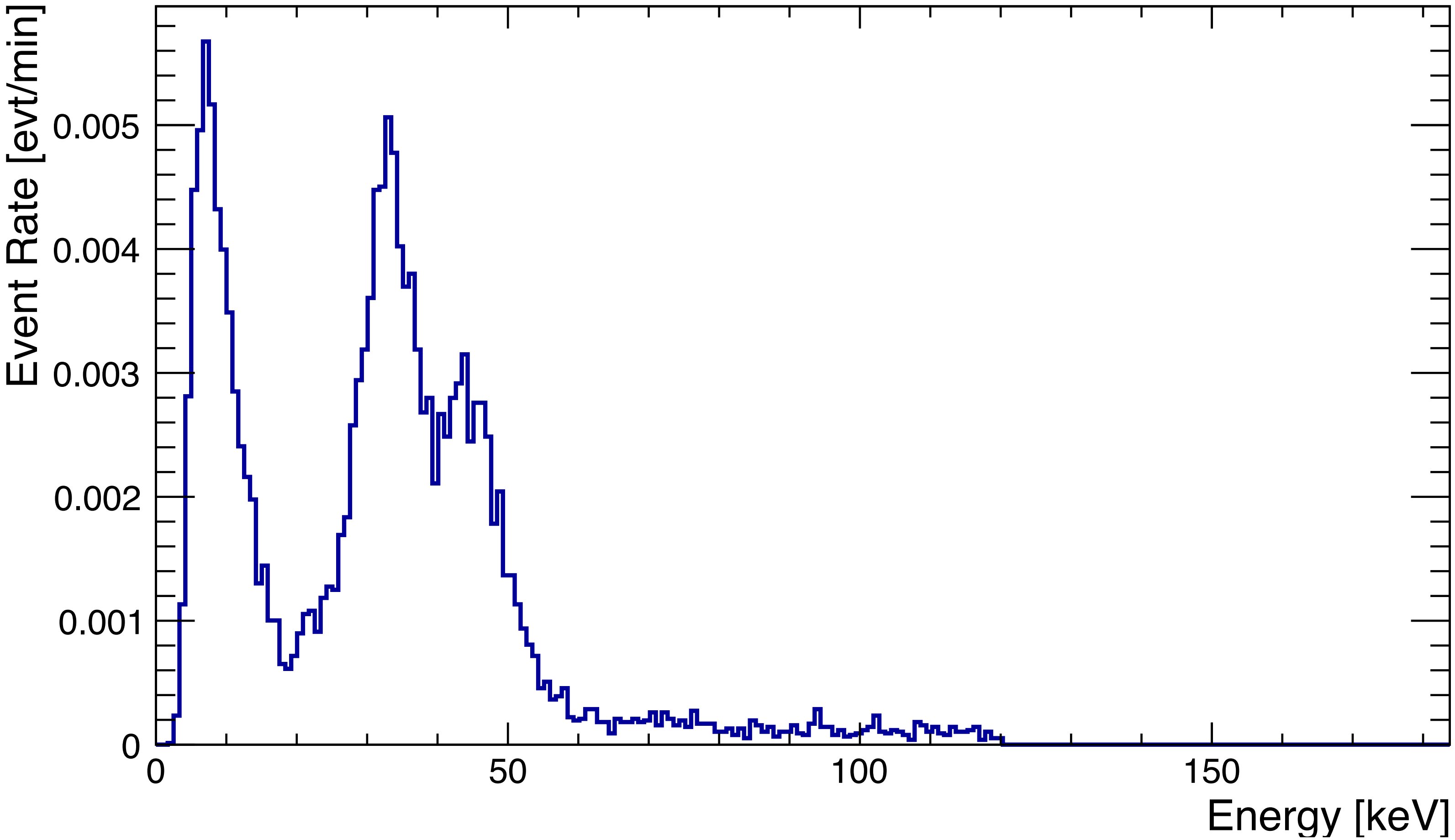


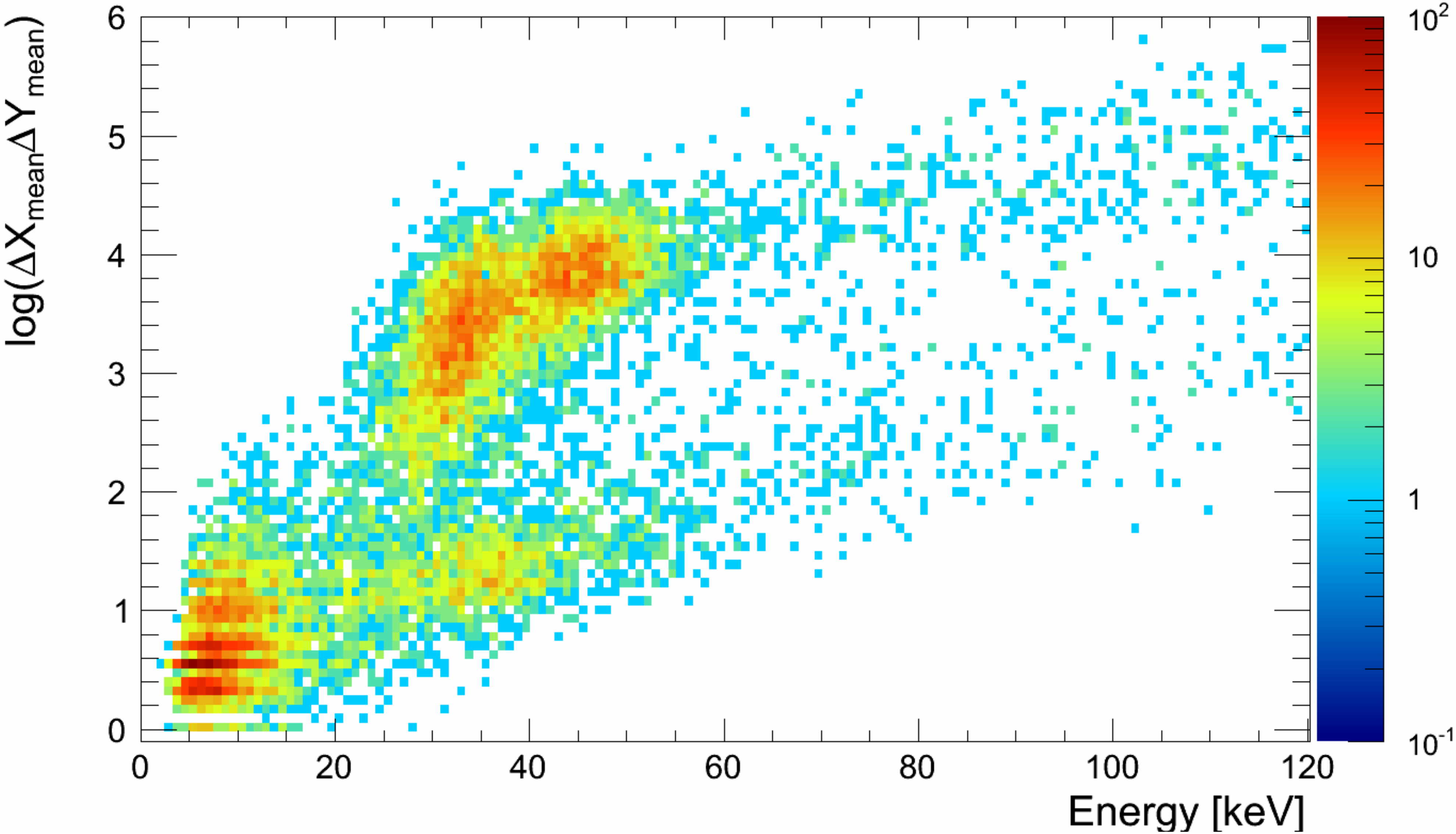
^{222}Rn progeny events in ionization energy (MIMAC)

Recoil	Recoil Energy [keV]	Ionization Quenching factor (SRIM) [%]	Ionization Energy (SRIM) [keV]	Ionization Energy measured [keV]
^{218}Po	100.79	37.93	38.23	32
^{214}Pb	112.27	39.10	43.90	34
^{210}Pb	146.52	40.12	58.78	45


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

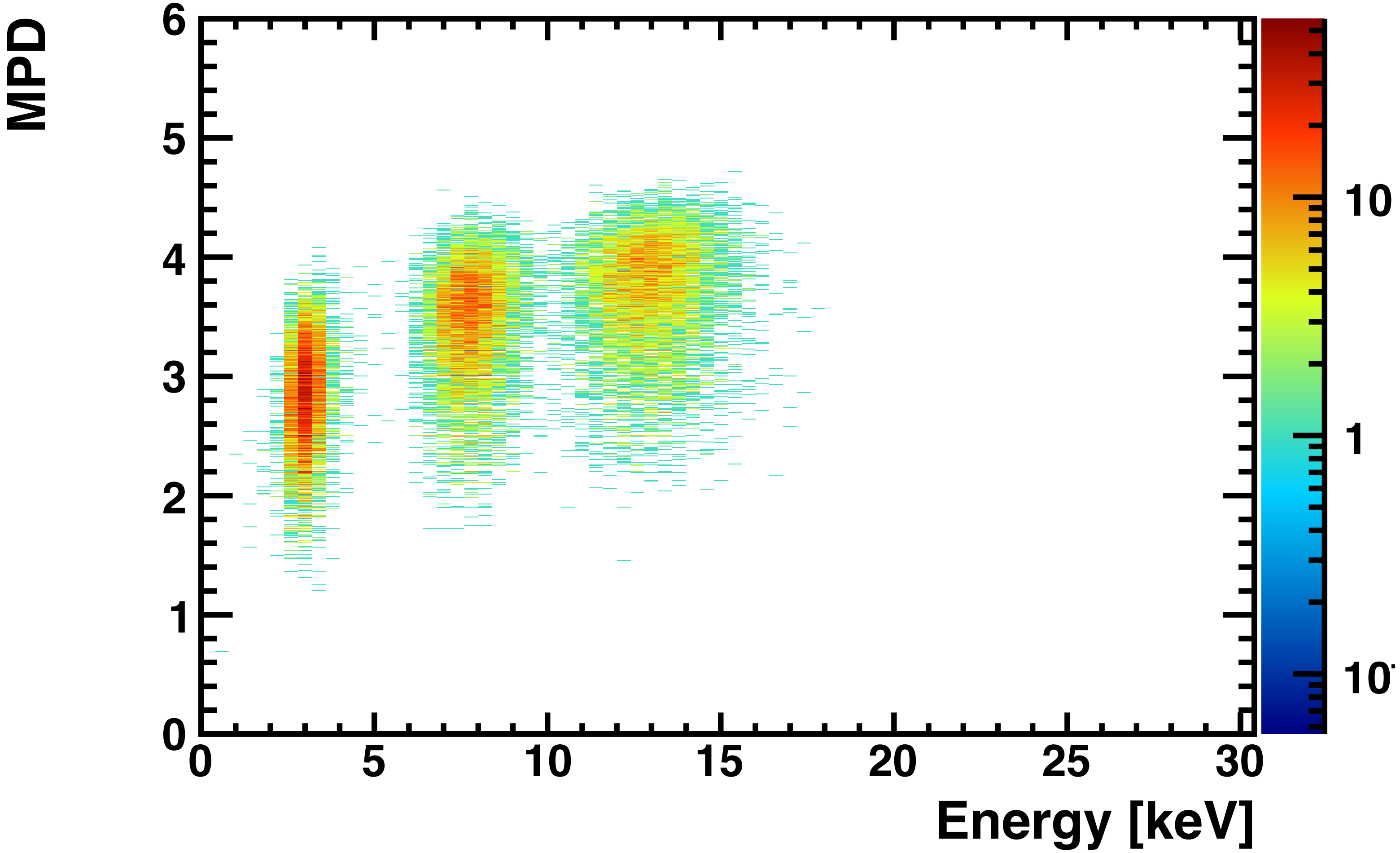
2012 Data (53 days)

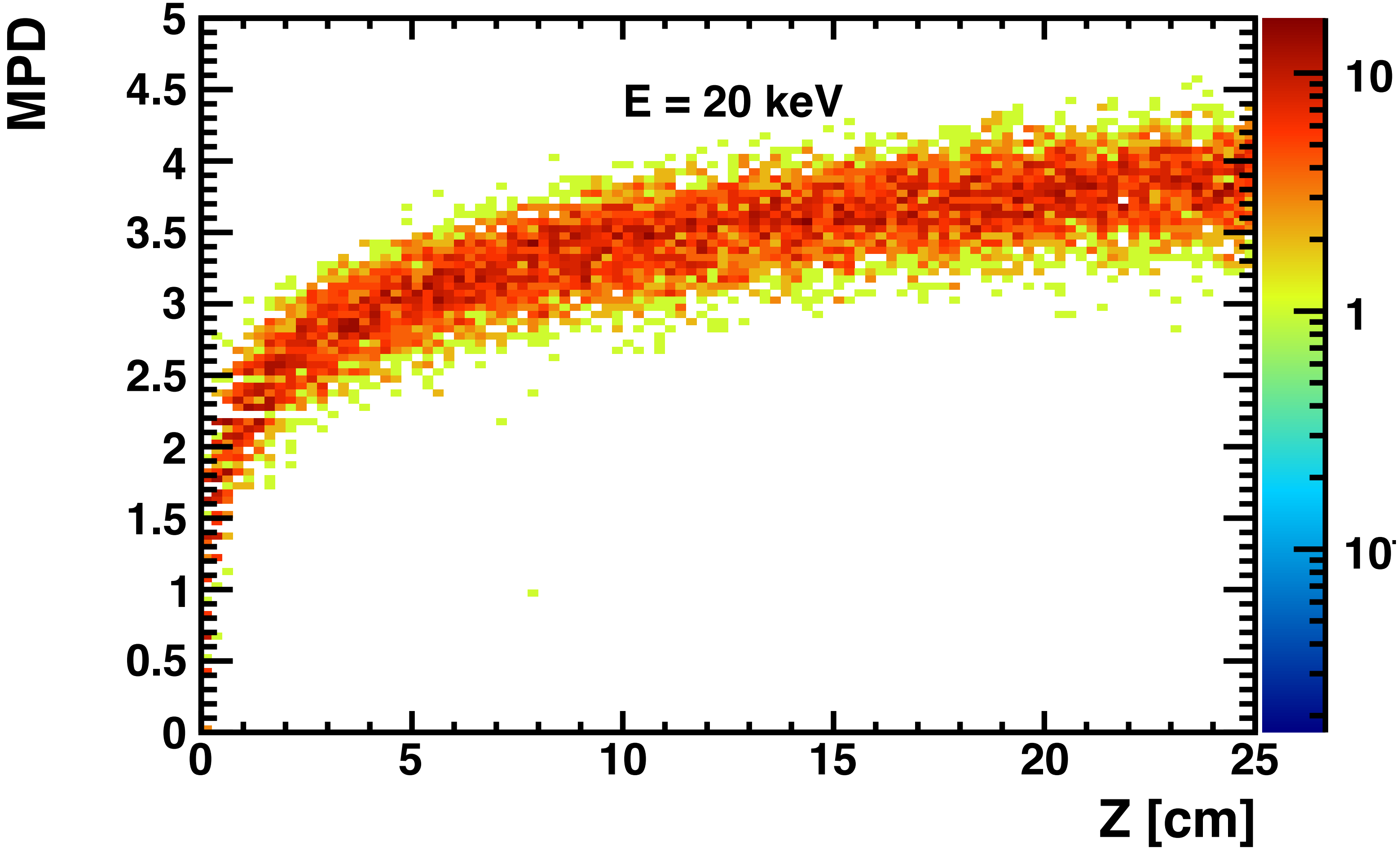




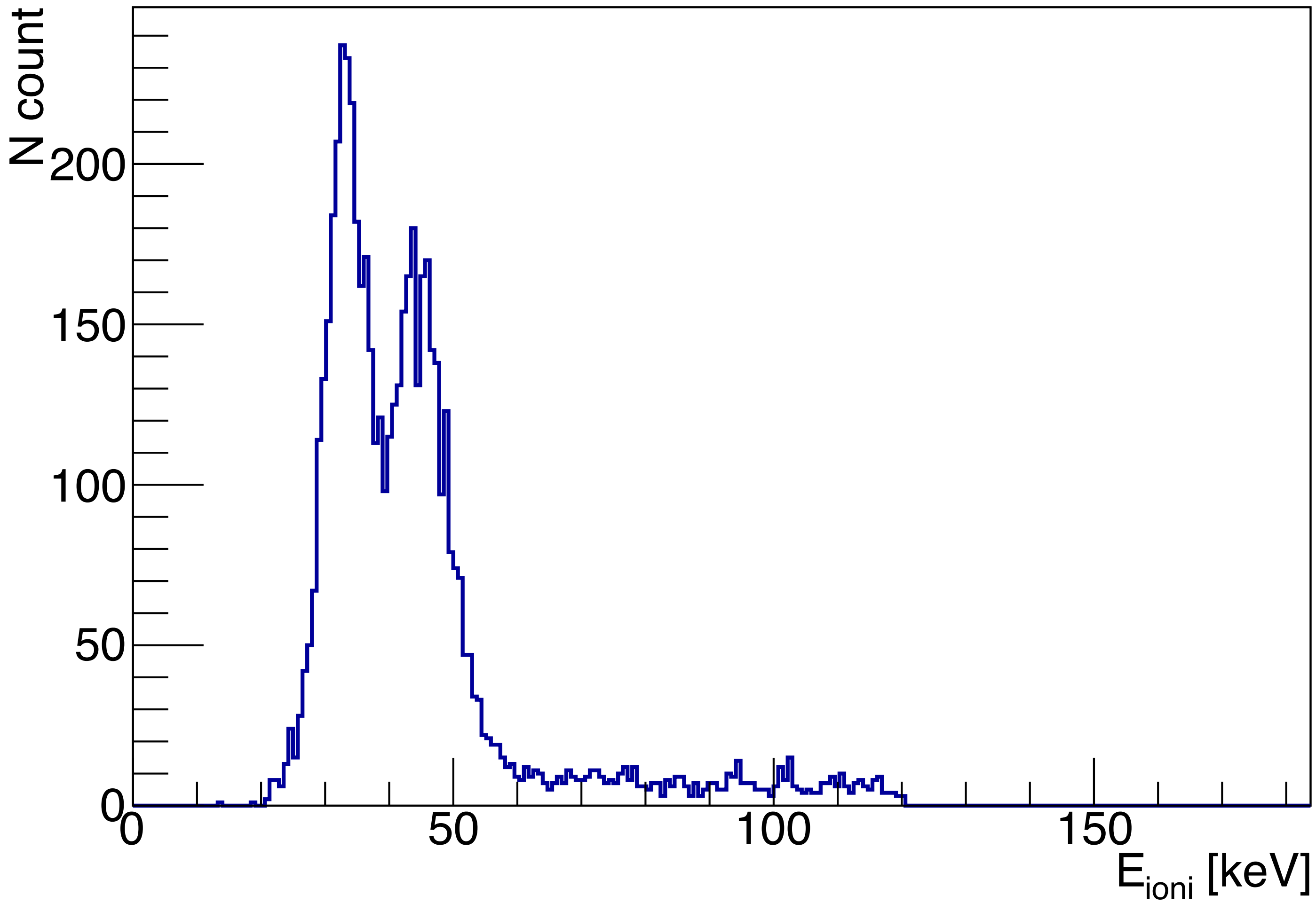
6
5
4
3
2
1
0
log(ΔX_mean ΔY_mean)
0
20
40
60
80
100
120
Energy [keV]
10^2
10
1
10^-1

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

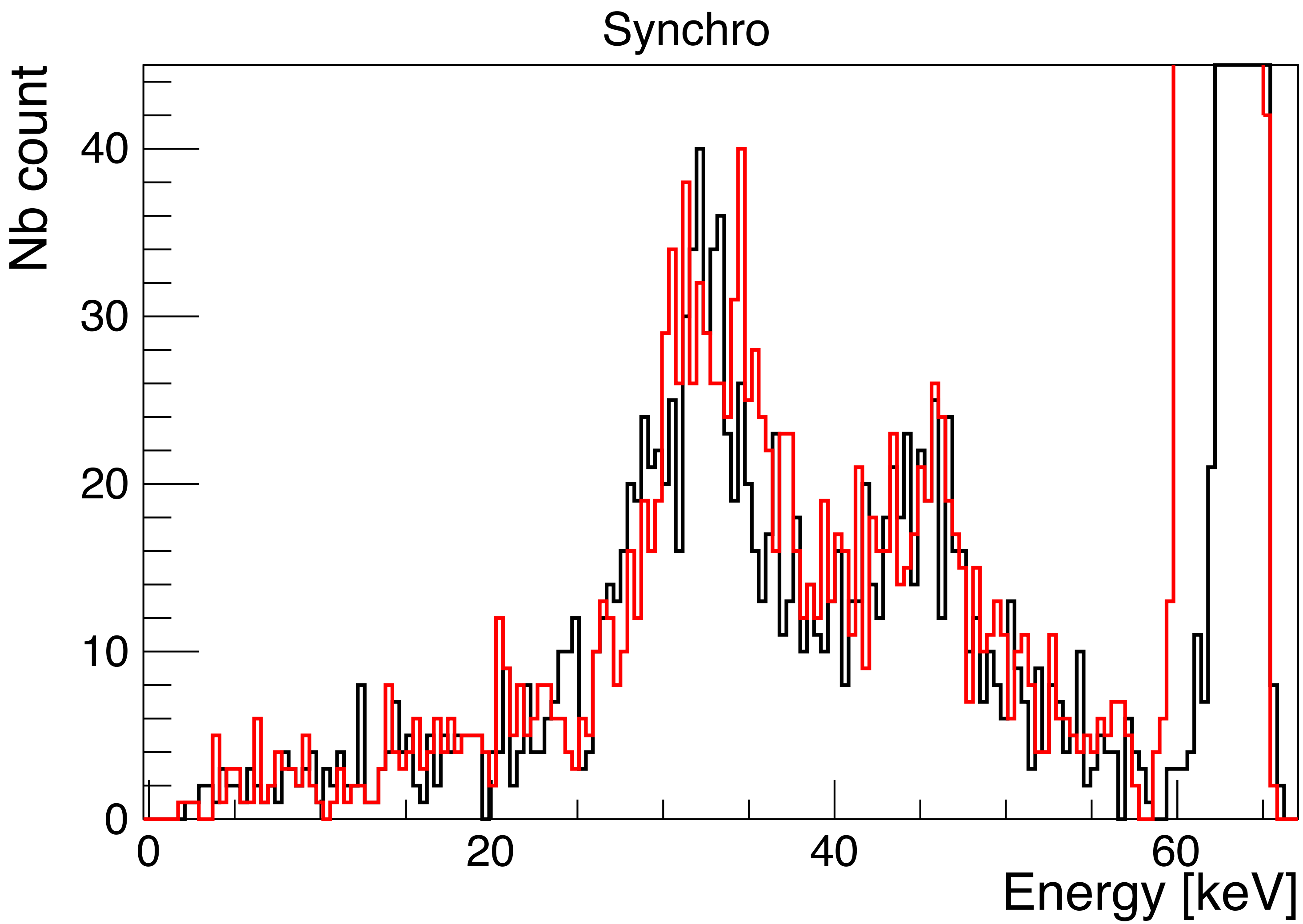



MPD
E = 20 keV
Z [cm]
0
5
10
15
20
25
0.5
1
1.5
2
2.5
3
3.5
4
4.5
10
1

Energy Spectrum with the MPD > 2.5 cut.



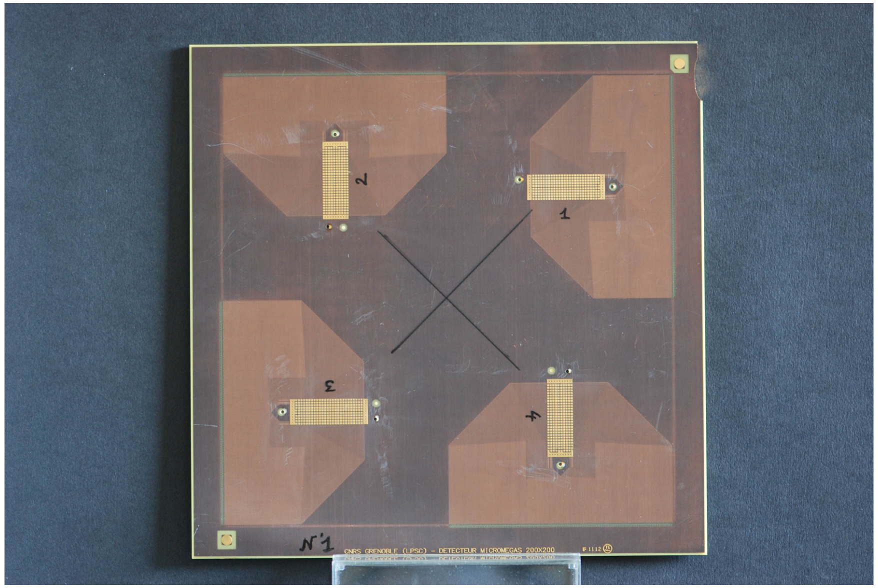
Coincidence spectra (Ch1(black) and Ch2 (red))
(Data: July 1st 2013- September 15th 2013)



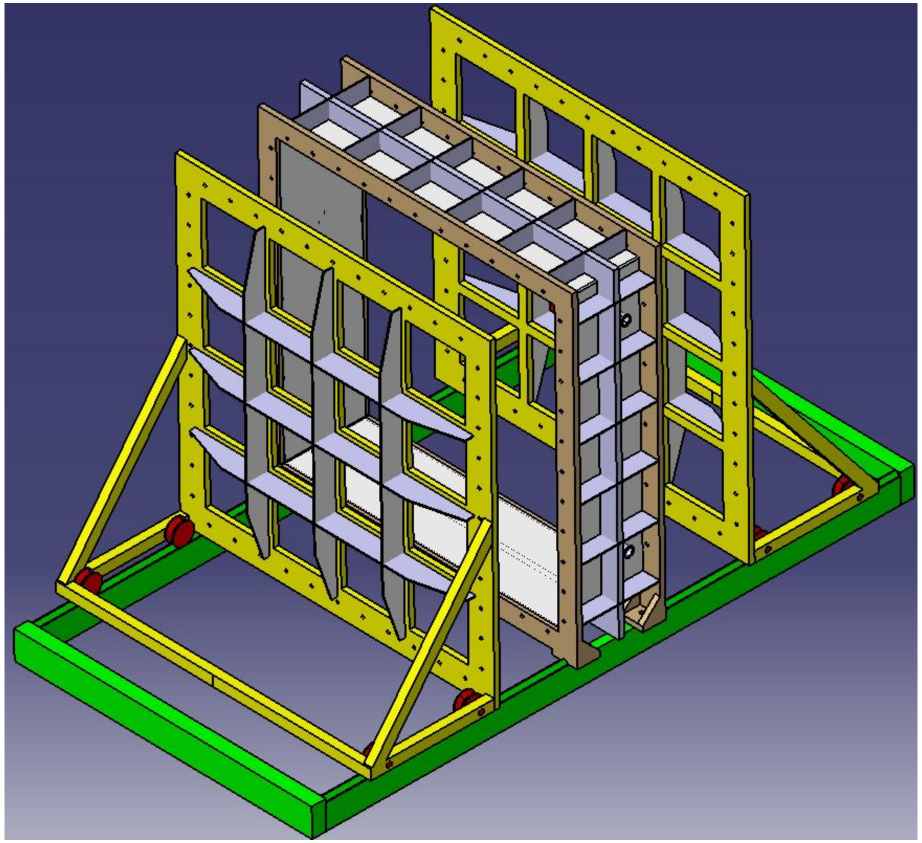
D. Santos (LPSC Grenoble)

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

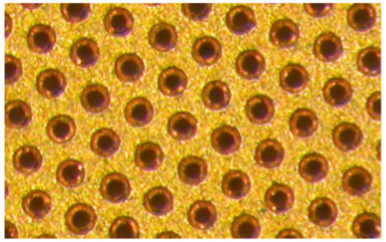


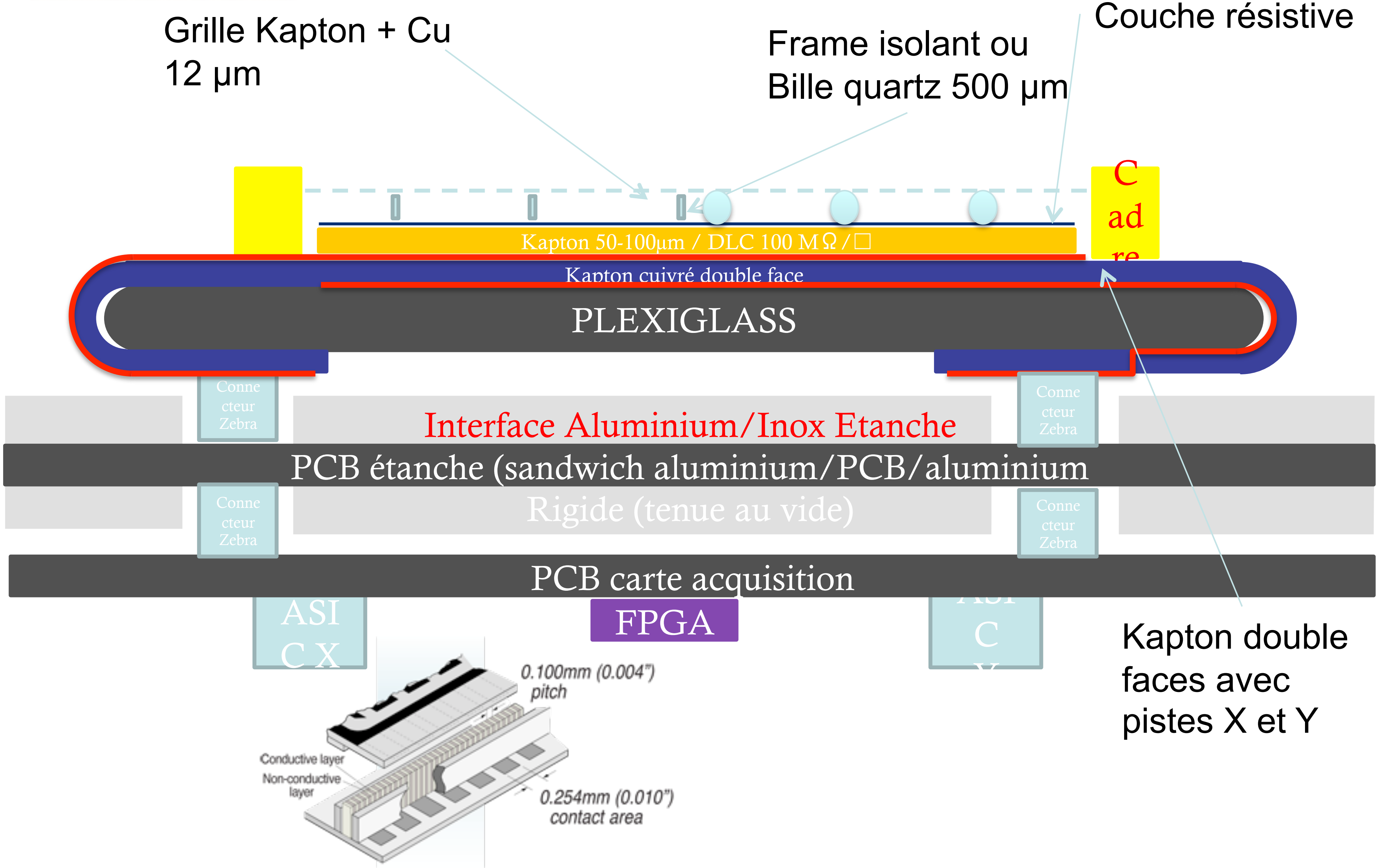
New 20cmx20cm pixellized anode
(1024 channels)



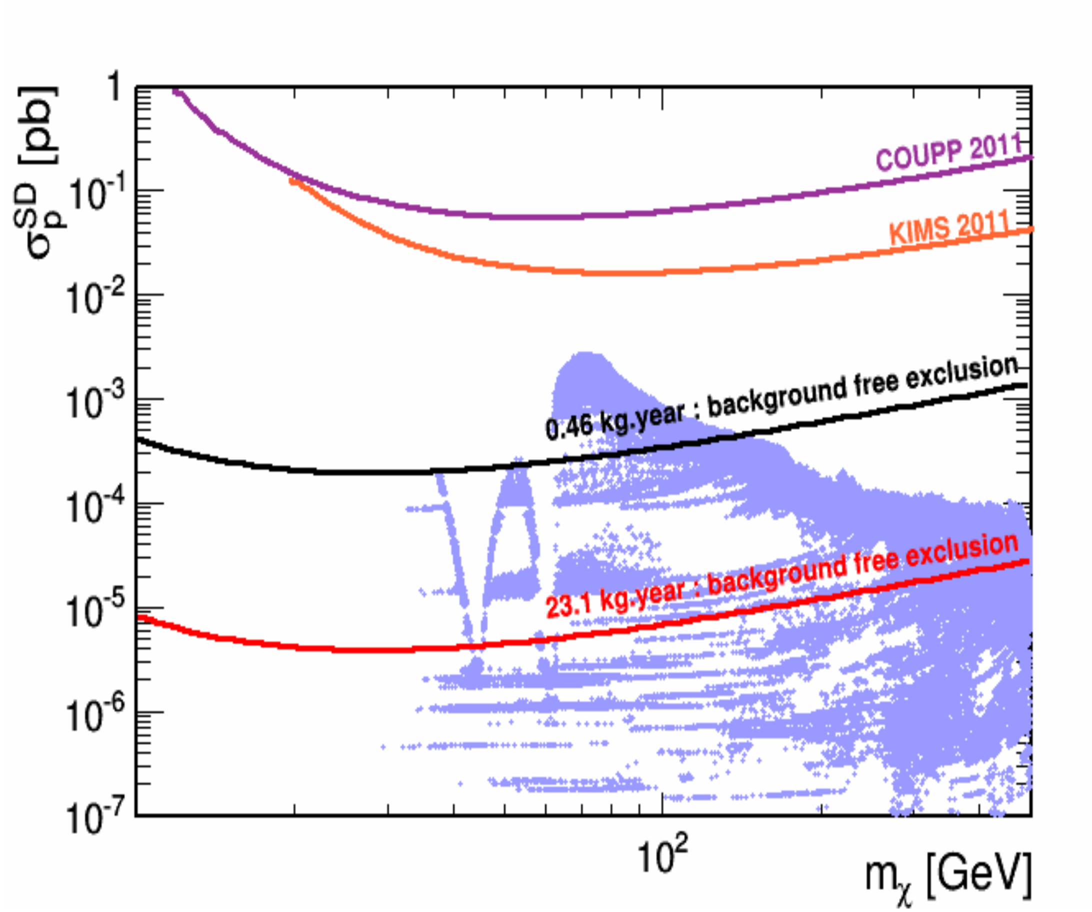
D. Santos (LPSC Grenoble)

Micromegas MIMAC 35x35 cm
Low activity – V3





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



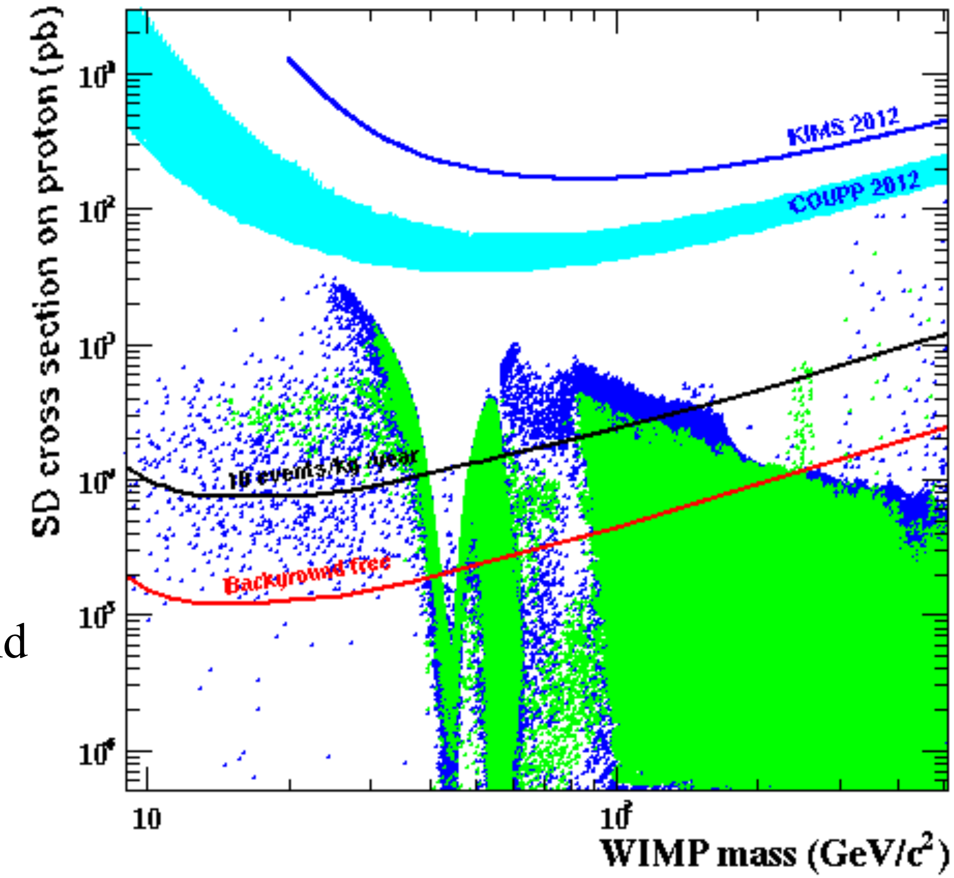
MIMAC Phenomenology: Discovery

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

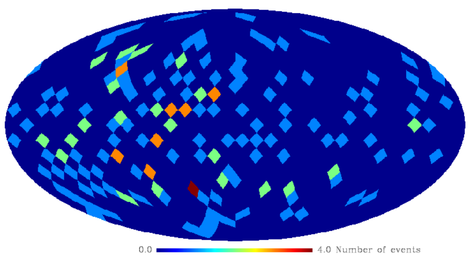
→ Only low number of WIMP events are required at low masses

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

Directional Dark Matter: discovery/exclusion

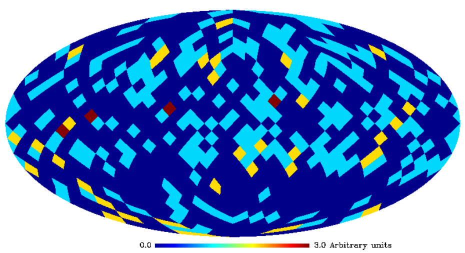
J. Billard *et al.*, PLB 2010
J. Billard *et al.*, PRD 2010

- ***discovery (5σ)***
  Up to 10^{-4} pb

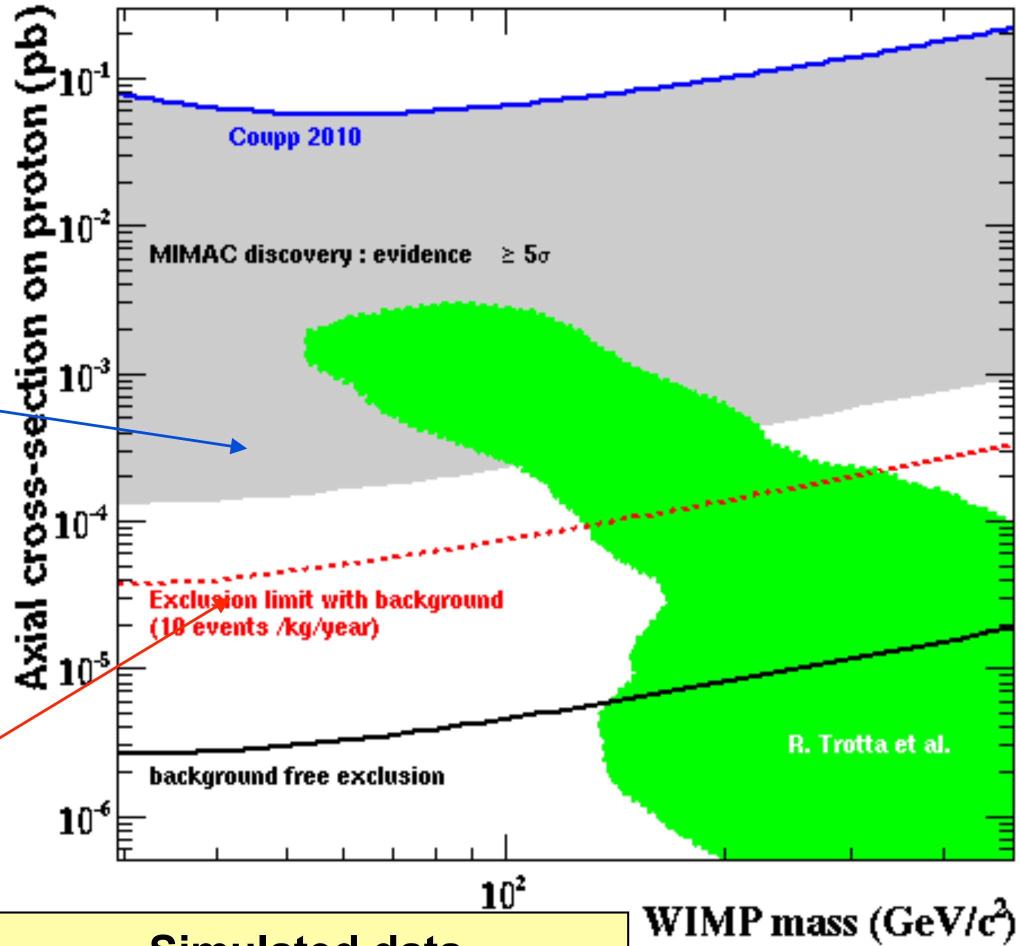


100 WIMP, 100 bkg

- **exclusion**
  Up to 10^{-6} pb



0 WIMP, 300 bkg



Simulated data
- 30 kg.year CF_4
- Recoil energy [5, 50] keV
- Angular resolution : 15°

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.

iii) Phenomenology studies performed by the MIMAC team show the impact of this kind of detector.

iv) MIMAC bi-chamber module has been installed at Modane Underground Laboratory in June 2012. An upgraded version in June 2013.

v) For the first time the 3D nuclear recoil tracks from the 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) The 1 m^3 will be the validation of a new generation of DM detector including directionality (the ultimate signature for DM)

You are all welcome to participate in this challenge