MIMAC

MIcro-tpc MAtrix of Chambers

A Large TPC for Directional Dark Matter detection

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(LPSC-Grenoble)

(Université Grenoble-Alpes -CNRS/IN2P3)

MIMAC (MIcro-tpc MAtrix of Chambers)

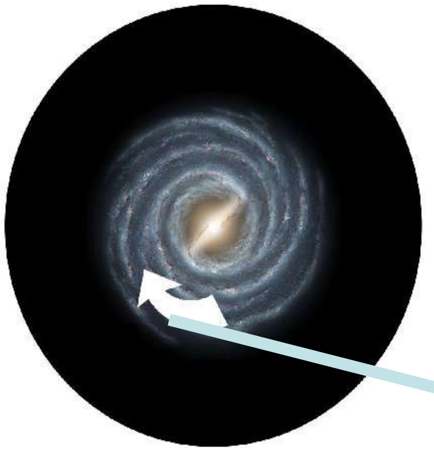
LPSC (Grenoble) : D. Santos, F.Naraghi C.Couturier (post-doc), N. Sauzet
-Technical Coordination, Gas circulation and detectors : **O. Guillaudin**
- Electronics : **G. Bosson, J. Bouvier, J.L. Bouly, L.Gallin-Martel, F. Rarbi**
- Data Acquisition: **T. Descombes**
- Mechanical Structure : **Ch. Fourel, J. Giraud**
- COMIMAC (quenching) **:** **J-F. Muraz**

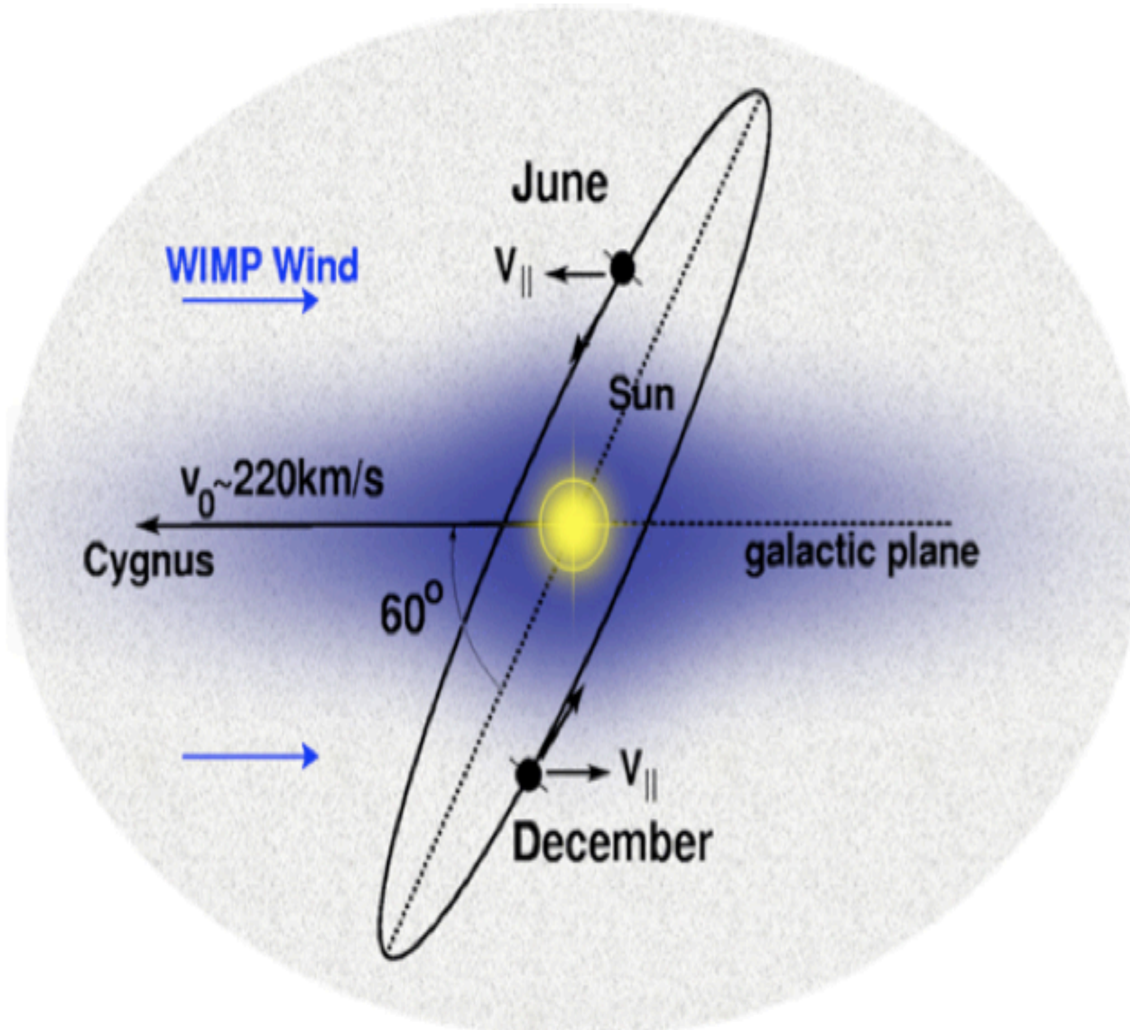
IRFU (Saclay): P. Colas, E. Ferrer-Ribas, I. Giomataris

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

Tsinghua University (Beijing-China): C. Tao, I. Moric, Y. Tao
XAO (Xinjiang-China): Chung-Lin Shan
Neutron facility (AMANDE) :
IRSN (Cadarache): T. Vinchon, B. Tampon (Ph. D.)

Directional detection: principle





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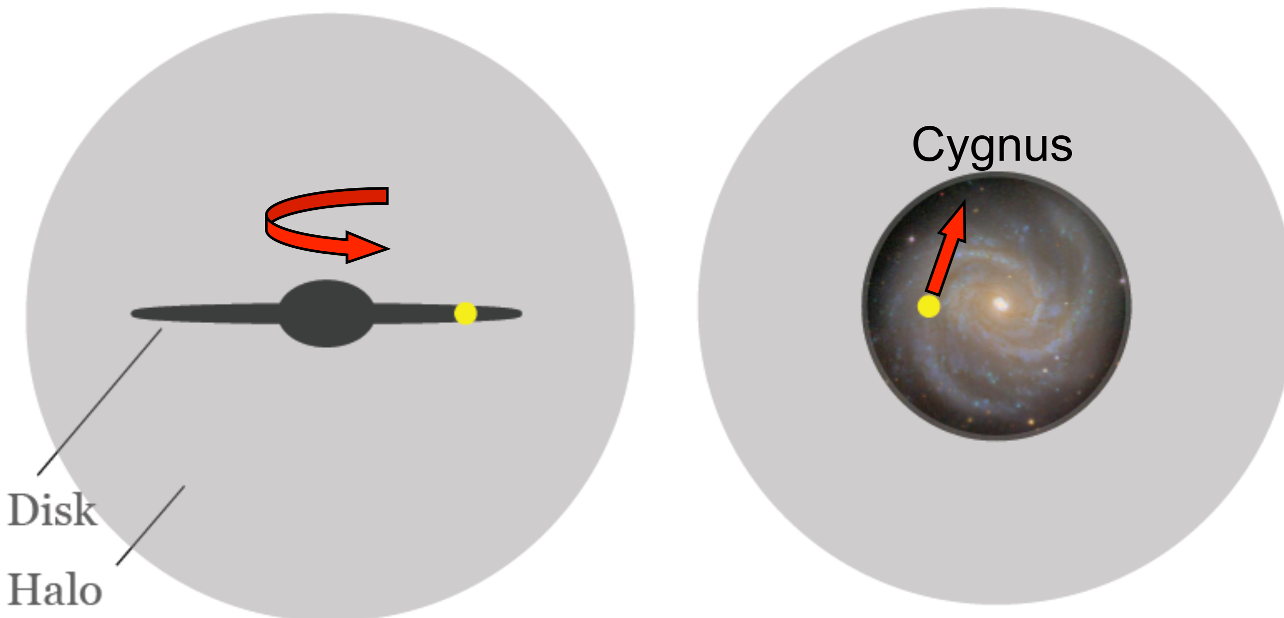
Directional detection : principle



$<V_{rot}> \sim 220$ km/s

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

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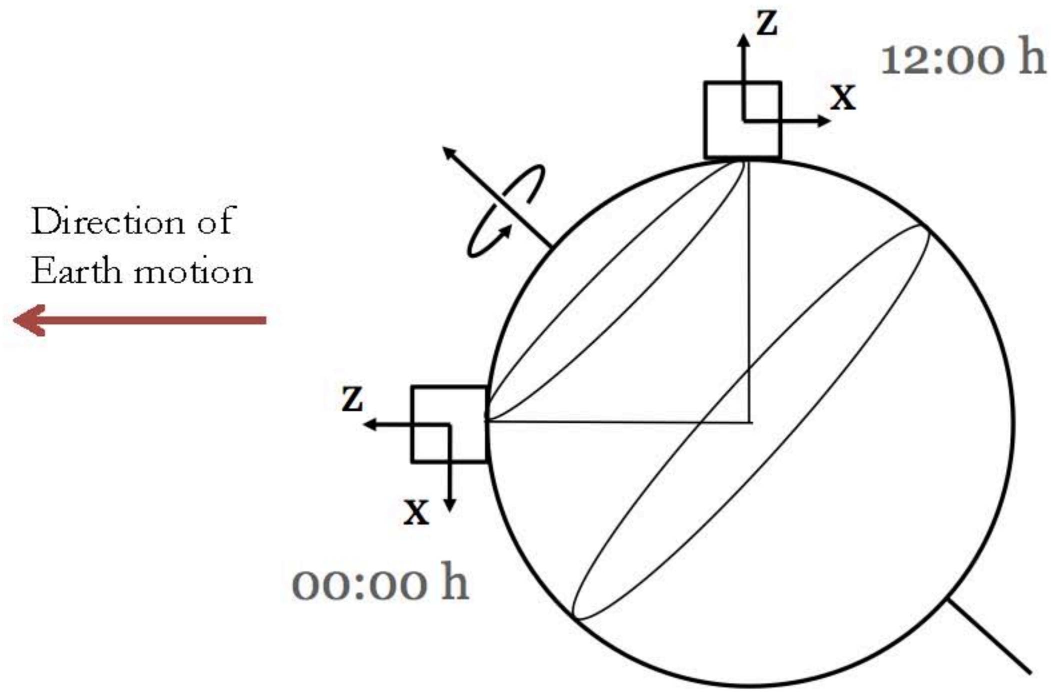
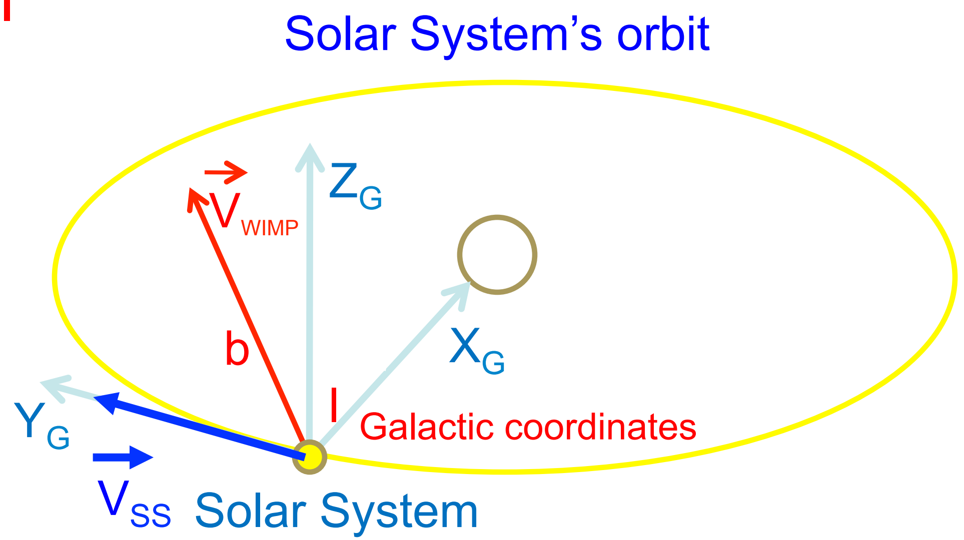
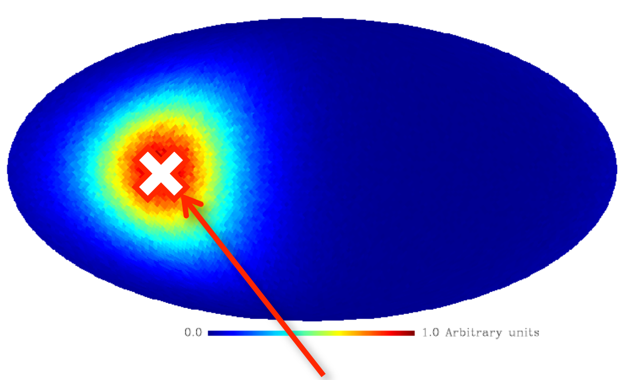
Angular modulation of WIMP flux

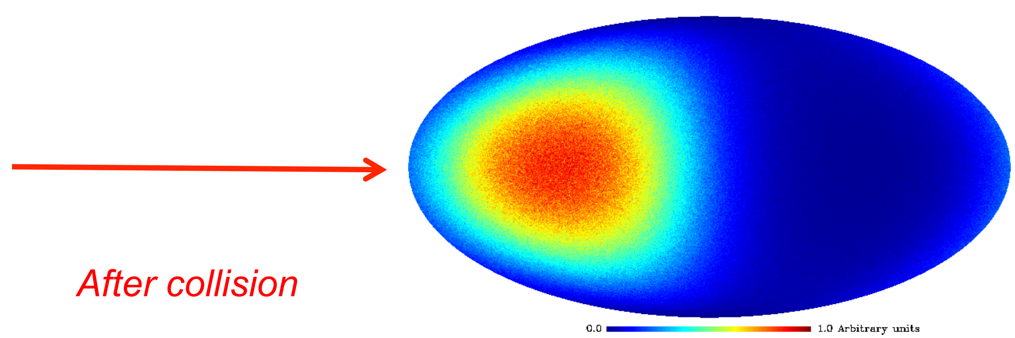
Modulation is sidereal (tied to stars) not diurnal (tied to Sun)



WIMP signal



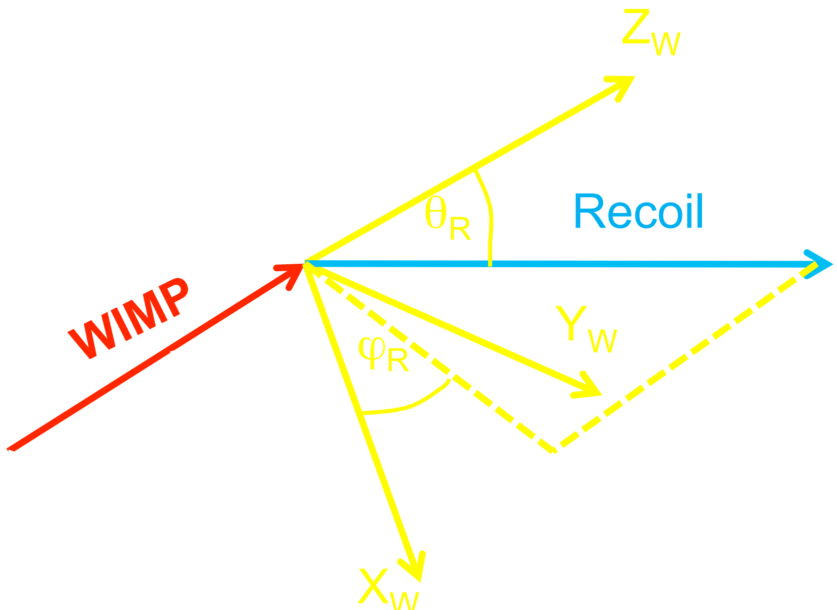


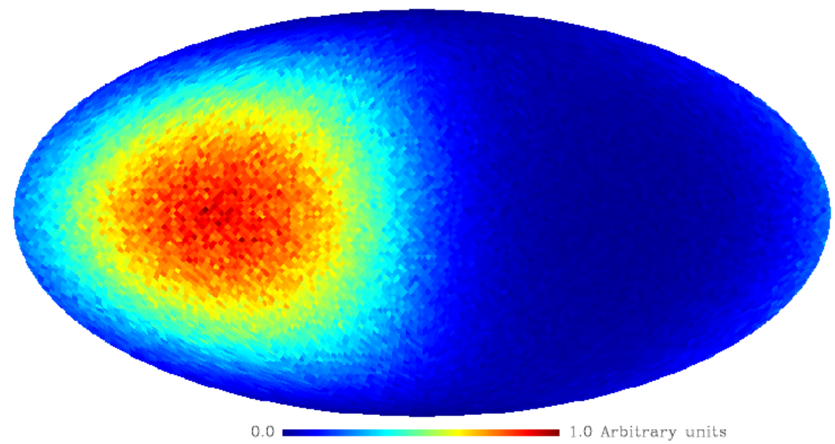


Cygnus Constellation (l = 90°,b = 0°)

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

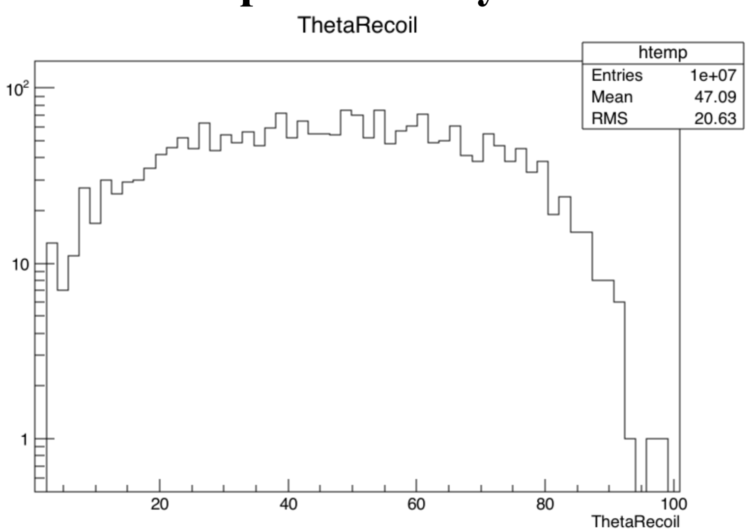
There are many angles to measure… A lot of information and important events to detect

^{19}F recoils (E_{kin}= 1-110 keV)

Angular distribution in the laboratory (with respect to the neutron direction)

Produced by neutrons of 565 keV

Validated experimentally at Cadarache !!

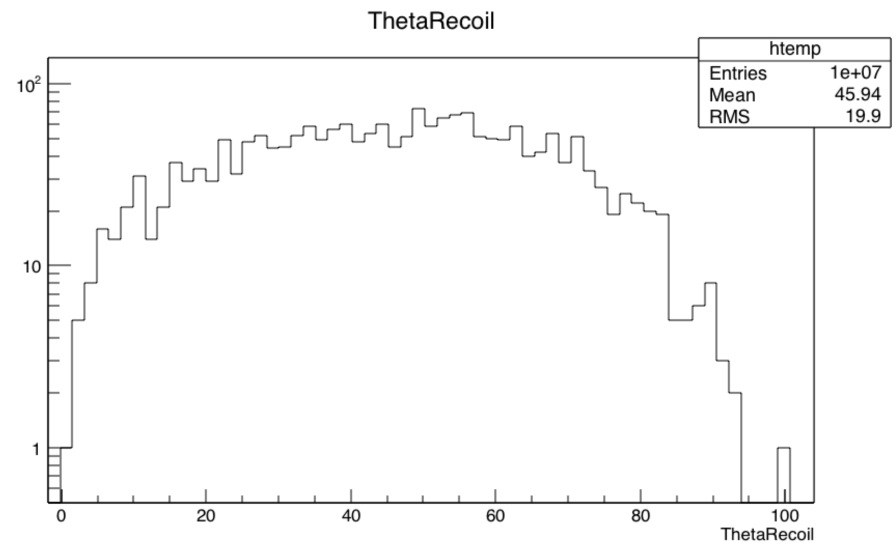


Geant4 simulations (N. Sauzet, DS. (2016))

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

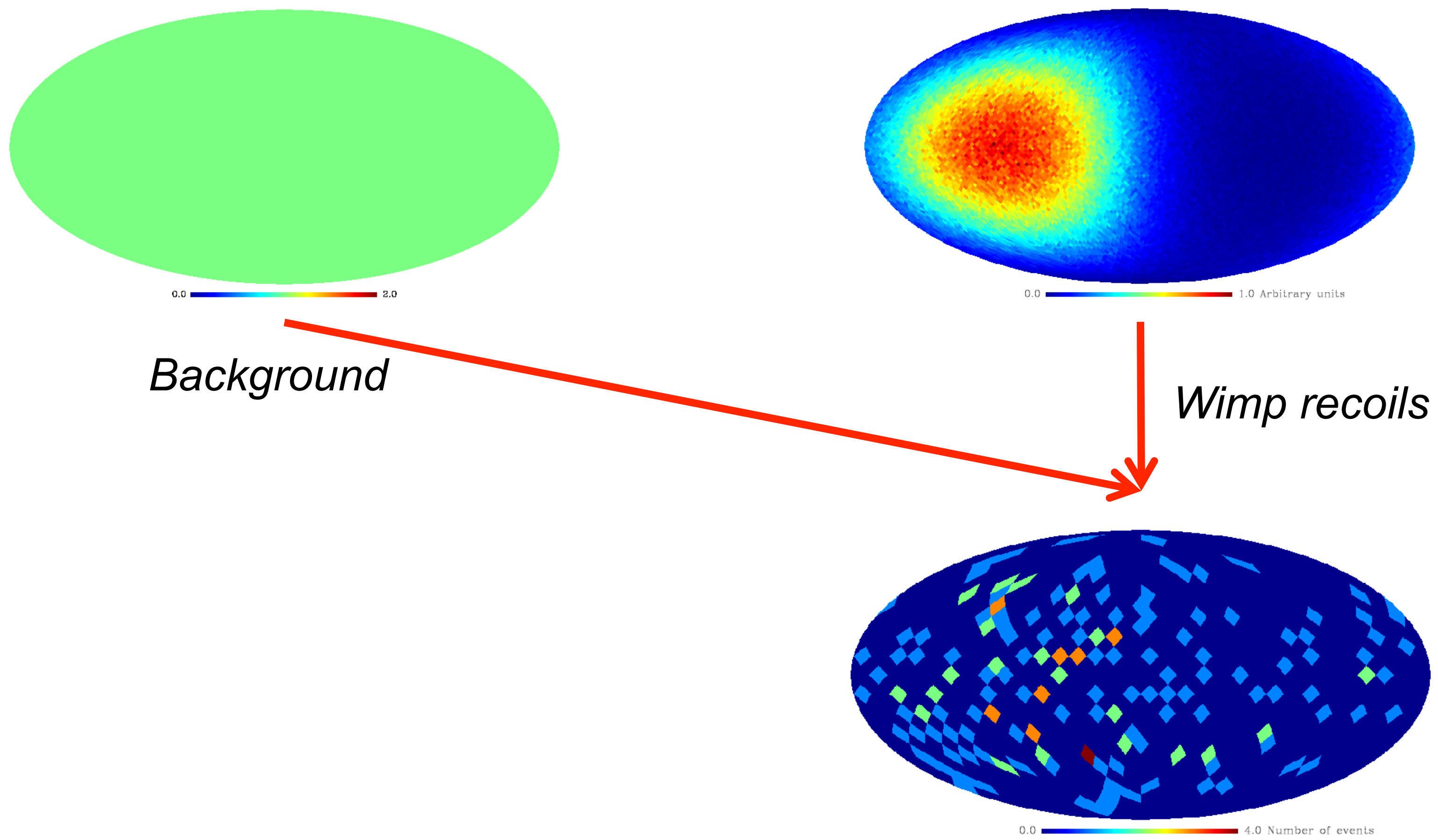
Angular distribution in the laboratory

Produced by neutrons of 200 keV



The same kind of distributions for C !!

100 WIMP evts + 100 Background evts

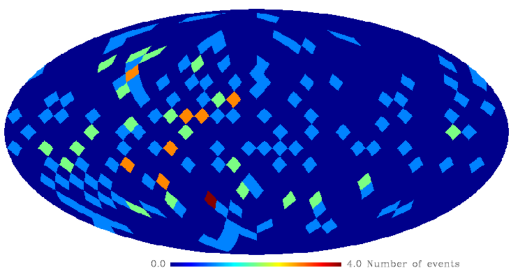


Phenomenology: Discovery

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

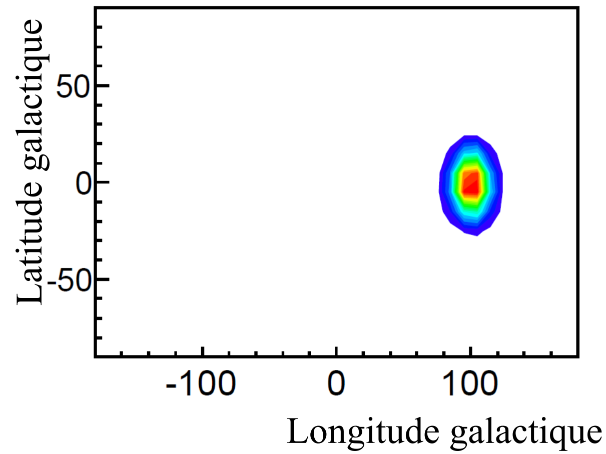
Proof of discovery: **Signal pointing toward the Cygnus constellation**

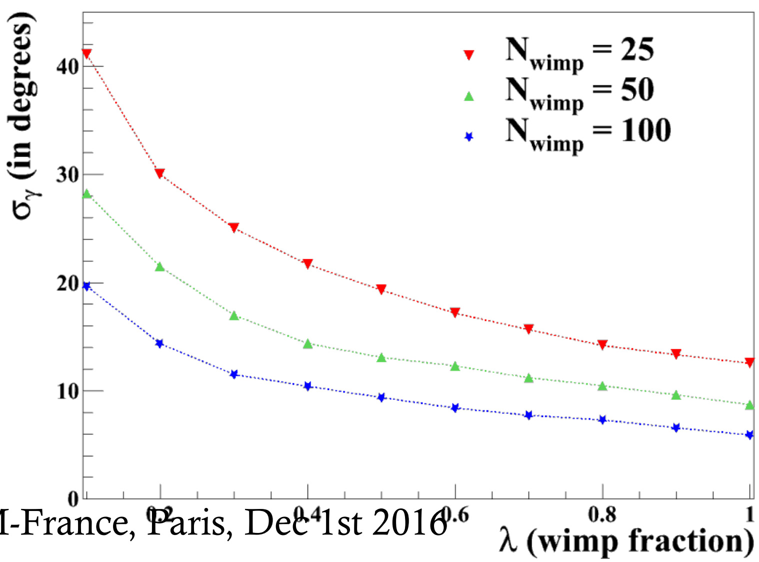
Blind likelihood analysis in order to establish the galactic origin of the signal



100 WIMP + 100 BKG

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



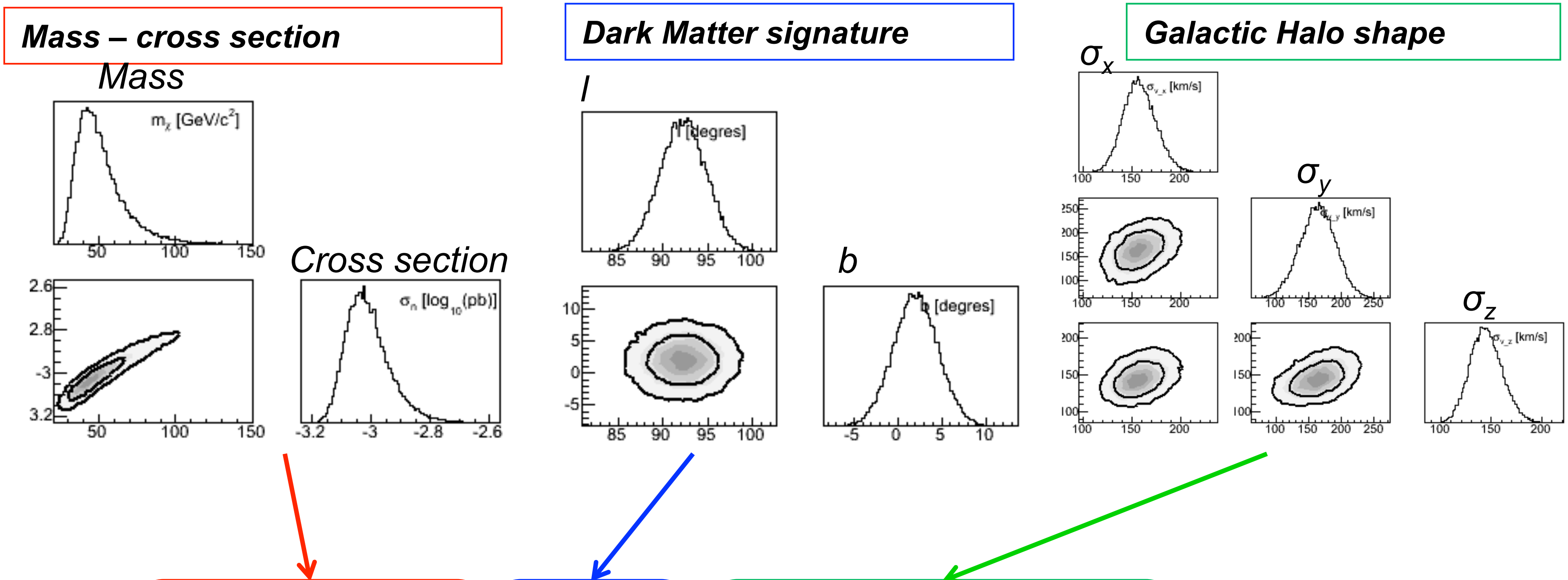


Strong correlation with the direction of the Constellation Cygnus **even with a large background contamination**

Directional Detection : identification

J. Billard *et al.*, PRD 2011

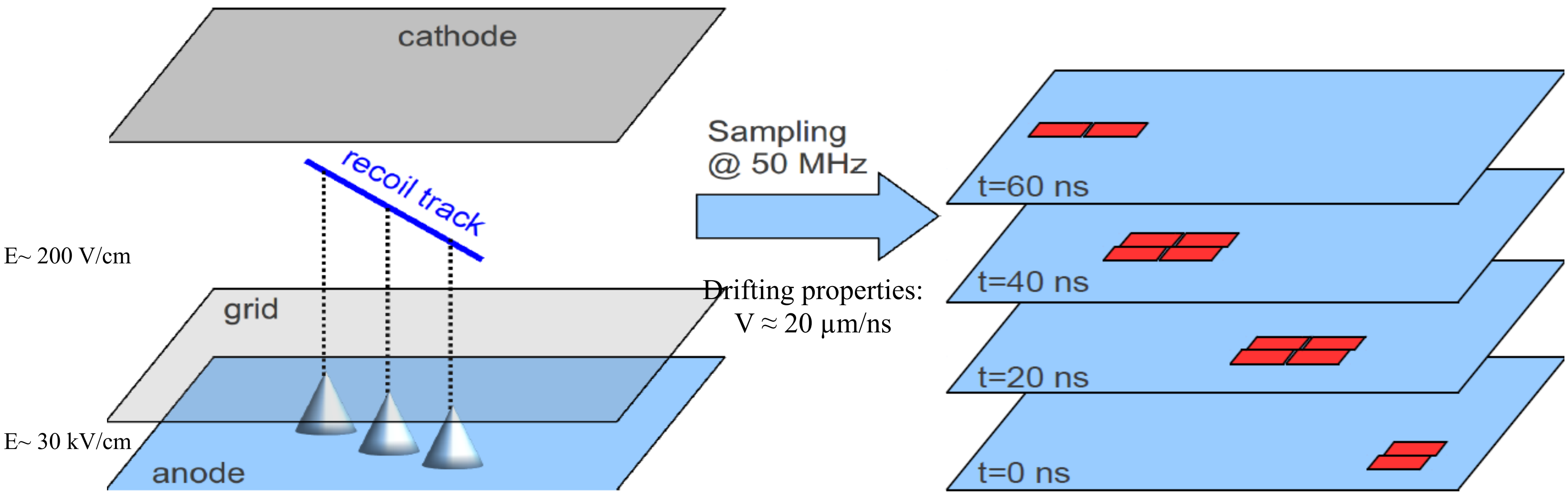
8 parameters simultaneouly constrained by only one 3D experiment



	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

MIMAC: Detection strategy

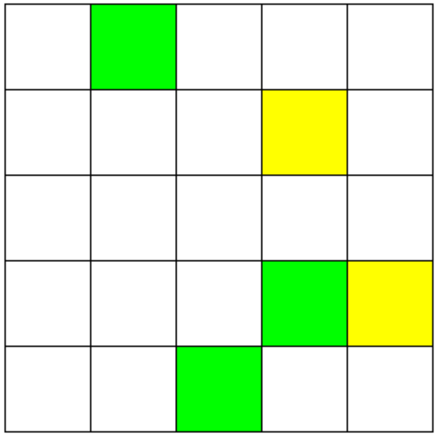


Scheme of a MIMAC µTPC

Evolution of the collected charges on the anode

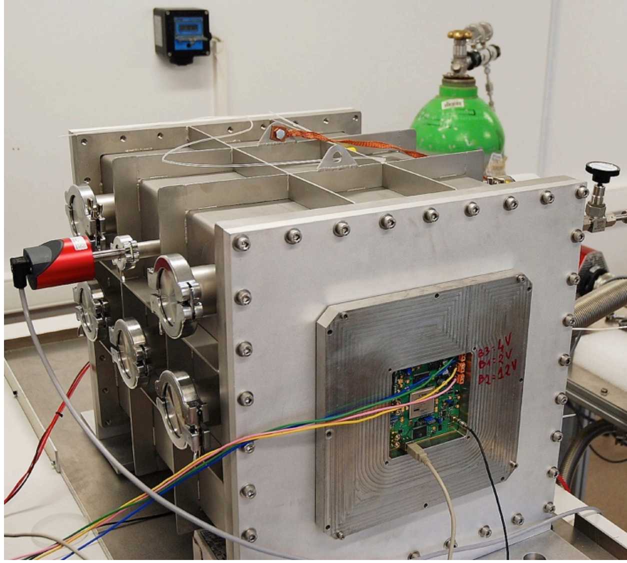
Measurement of the ionization energy: Charge integrator connected to the mesh coupled to a FADC sampled at 50 MHz

The MIMAC project



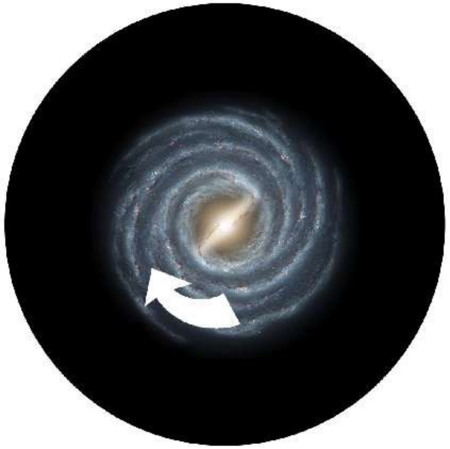
A low pressure multi-chamber detector

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

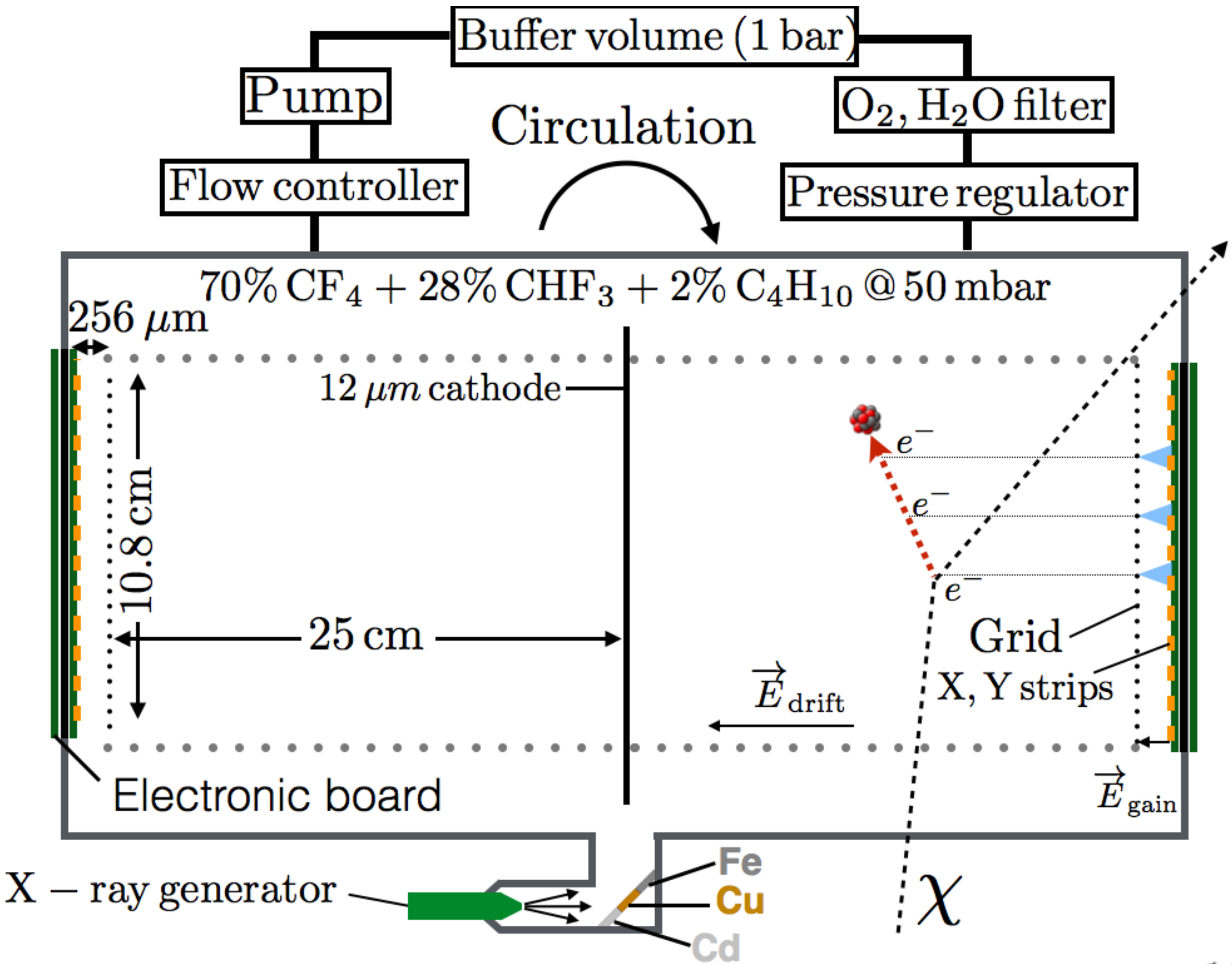


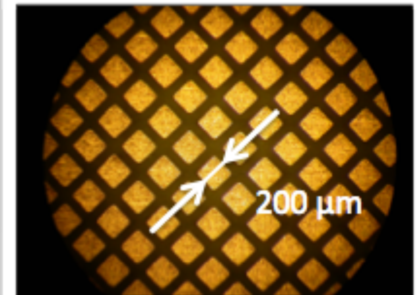
Bi-chamber module
2 x (10.8x 10.8x 25 cm^3)

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



MIMAC-bi-chamber module prototype





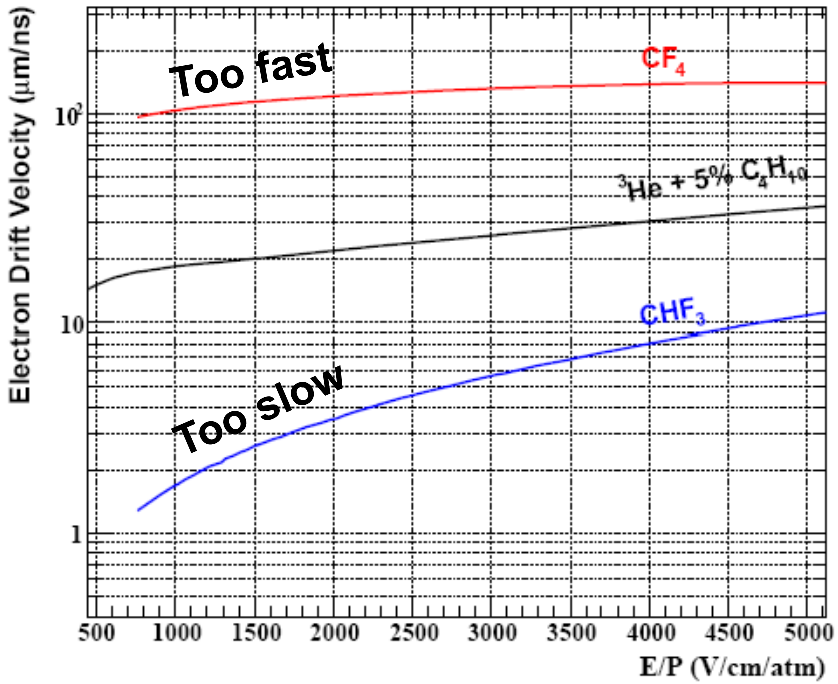
Micromegas 10x10 cm², designed by IRFU- Saclay (France)

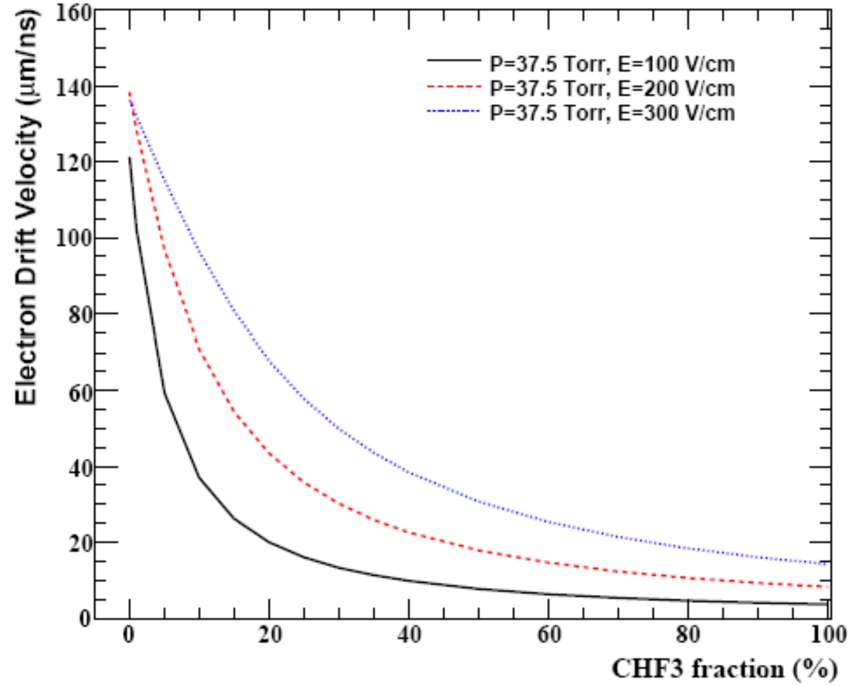
MIMAC Target: ^{19}F

- Light WIMP mass
- Axial coupling

3D Tracks: Drift velocity

Magboltz Simulation



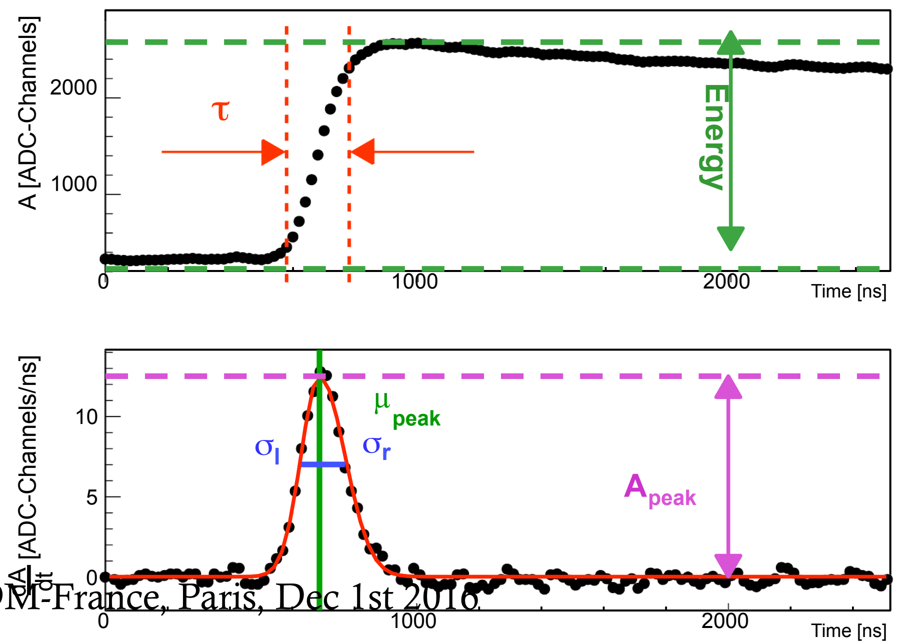


- New mixed gas MIMAC target : CF_4 + x% CHF_3 (x=30)

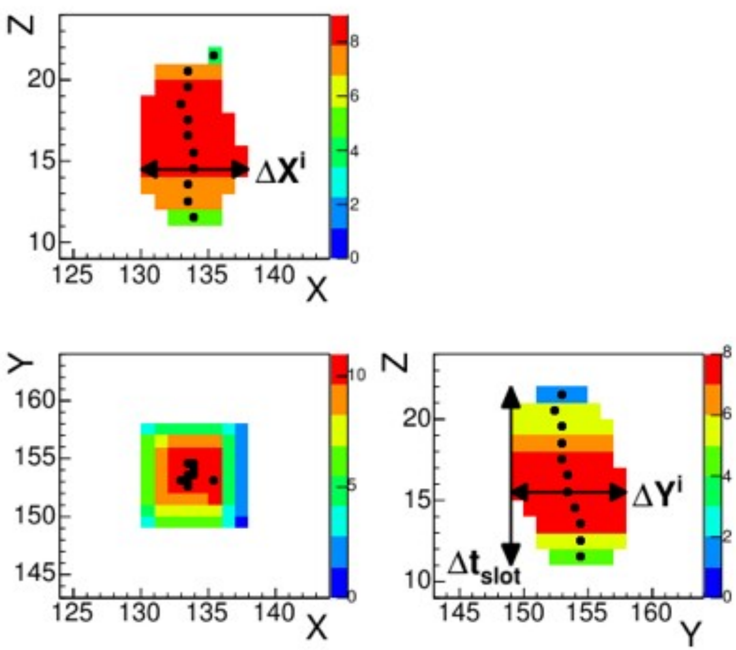
MIMAC readout

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

preamplifier signal + FADC: Energy



3D - track



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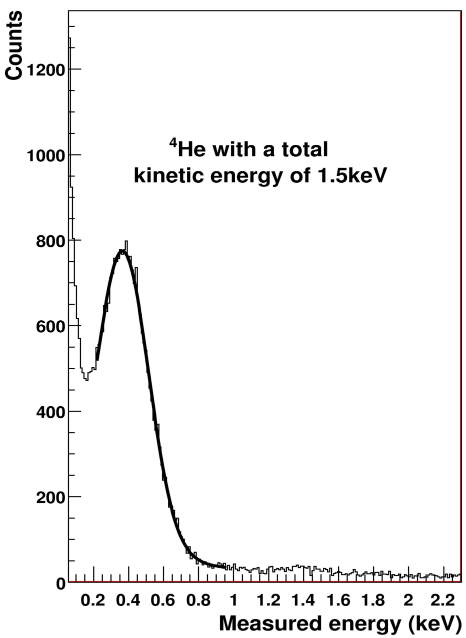
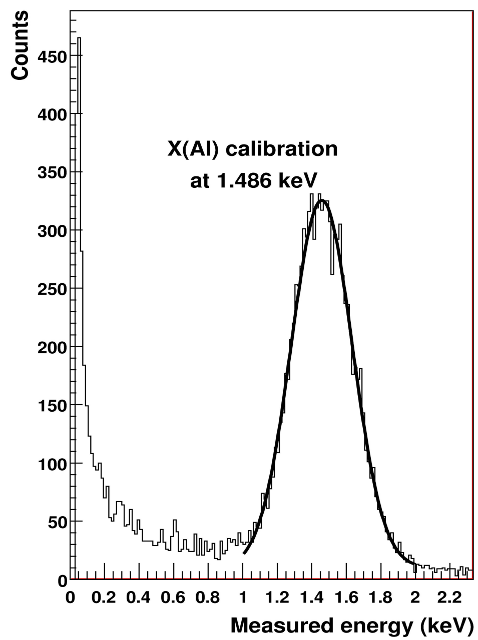
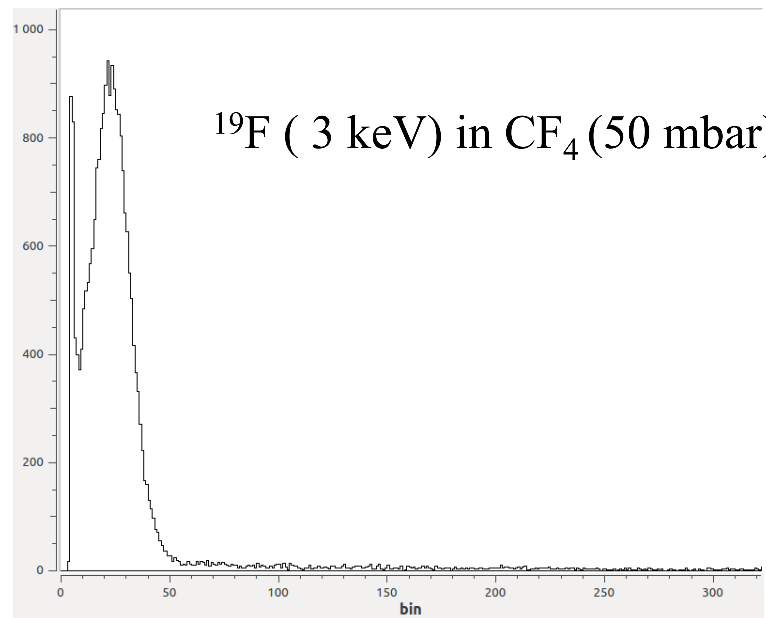
Ionization Quenching Factor Measurements at LPSC-Grenoble

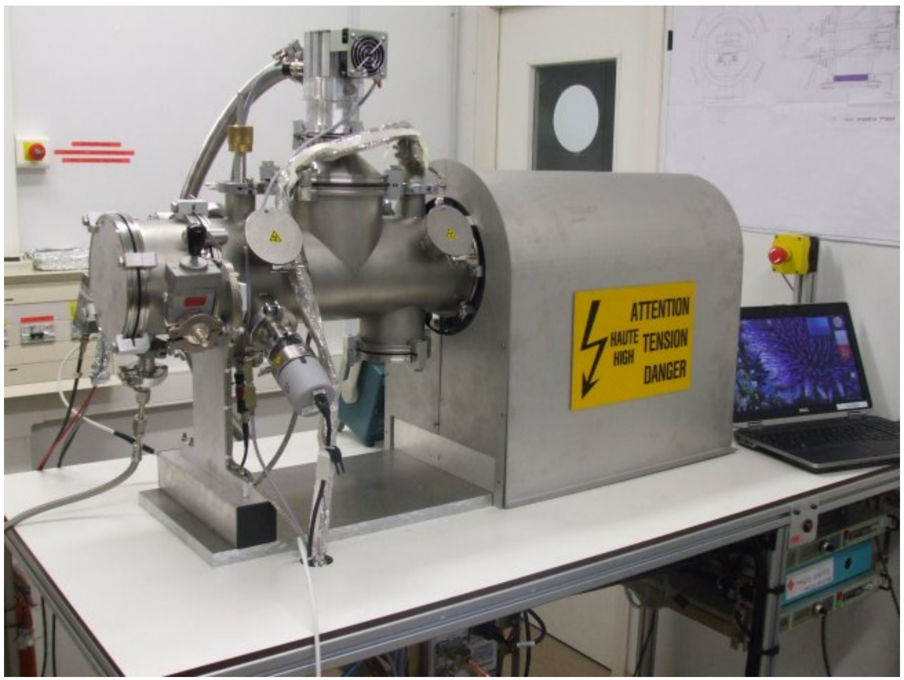


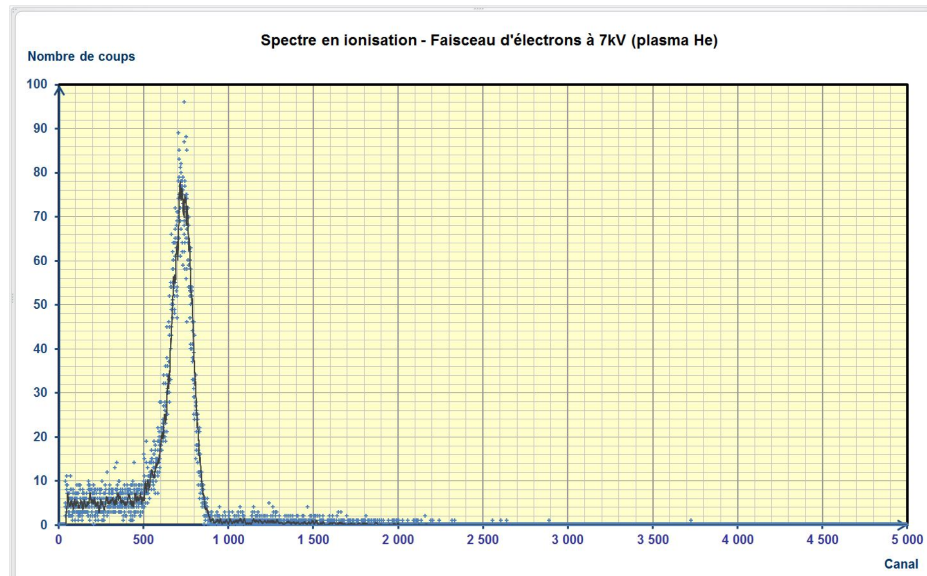




Portable Quenching Facility (COMIMAC)

(Electrons and Nuclei of known energies)



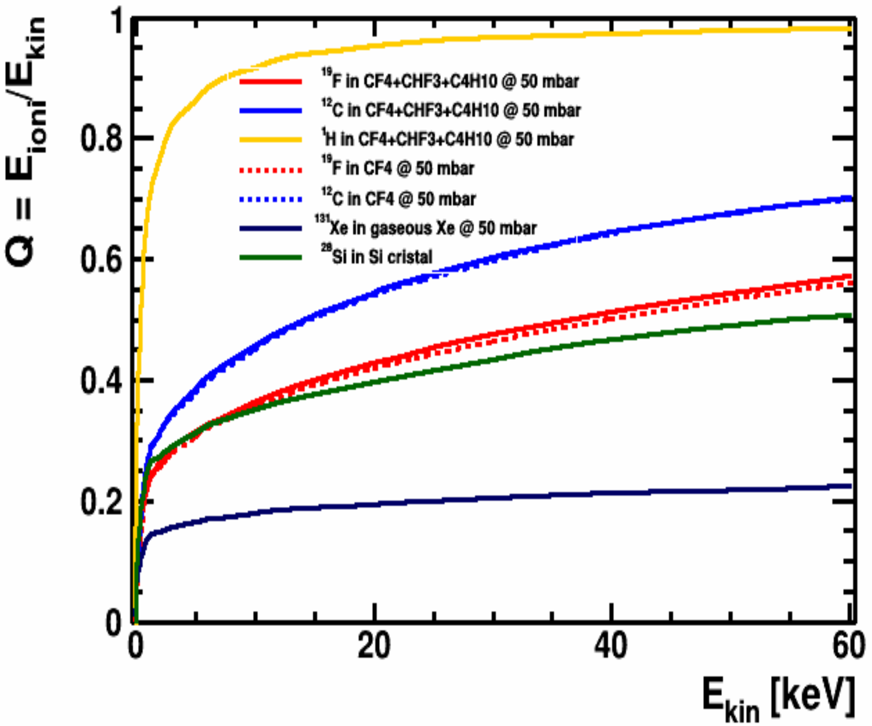


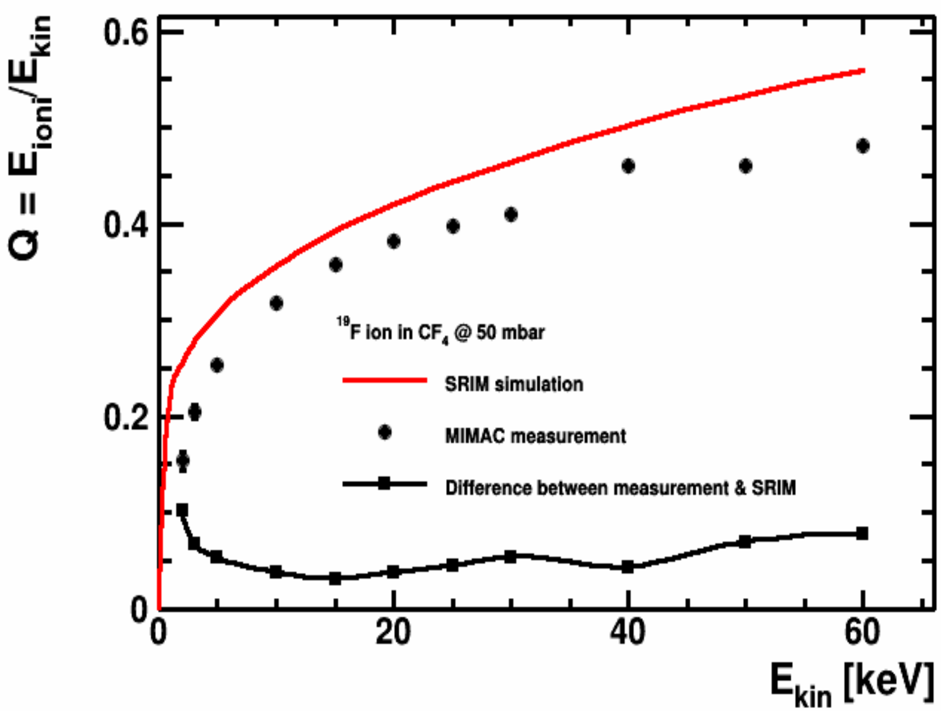
Electrons of 7 keV

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.

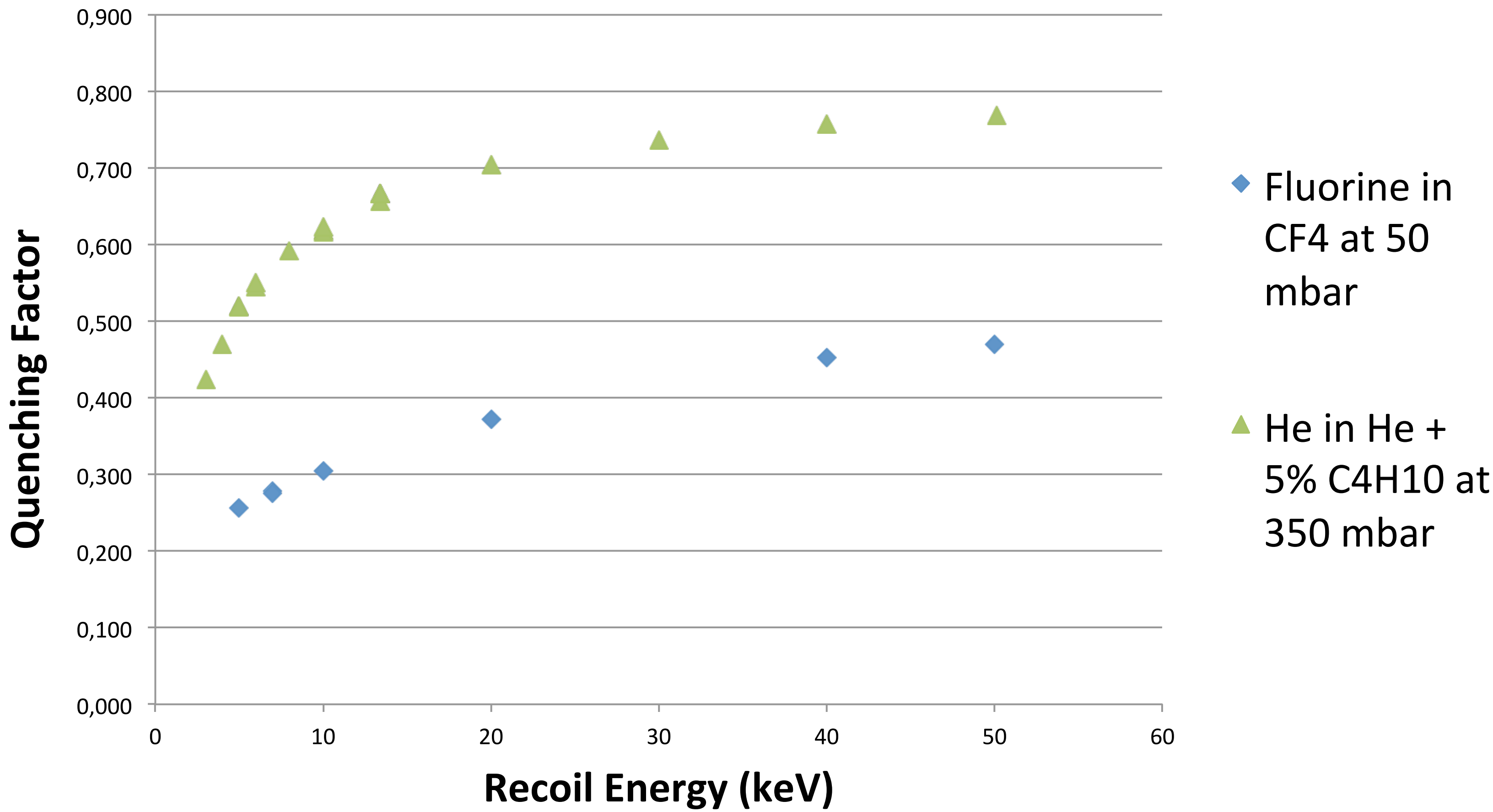
Ionization Quenching Factors

Simulations and Measurements (LPSC)

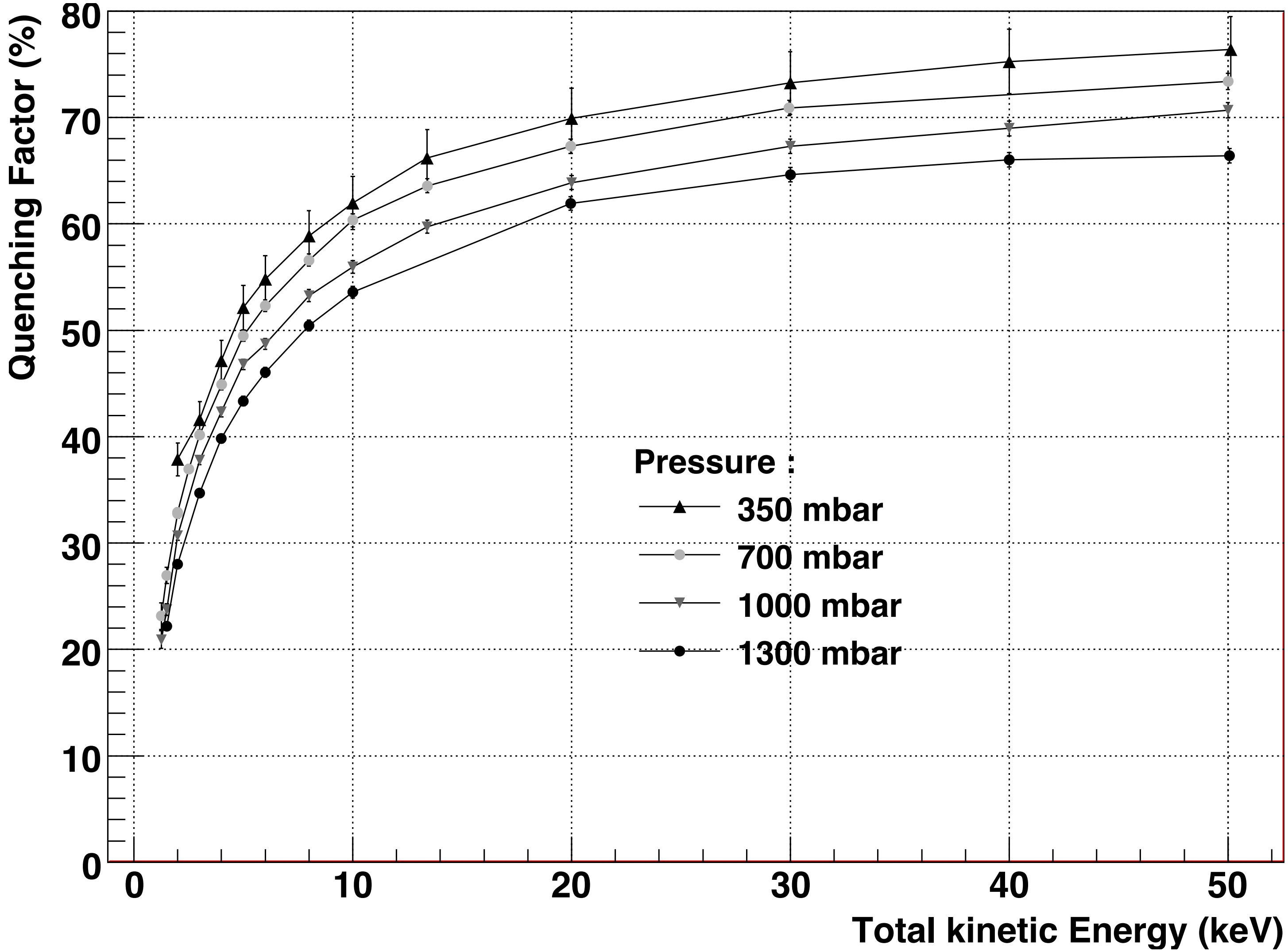




Ionization Quenching Factor for Fluorine in pure CF4 at 50 mbar



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



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MIMAC validation with neutrons

Neutron monochromatic field:

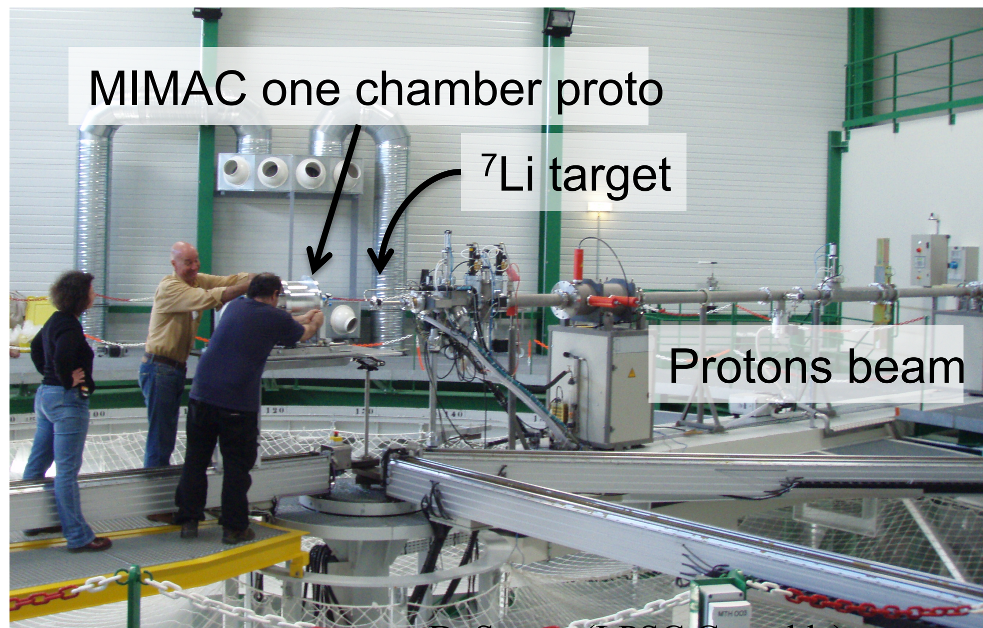
AMANDE facility at IRSN of Cadarache

- 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

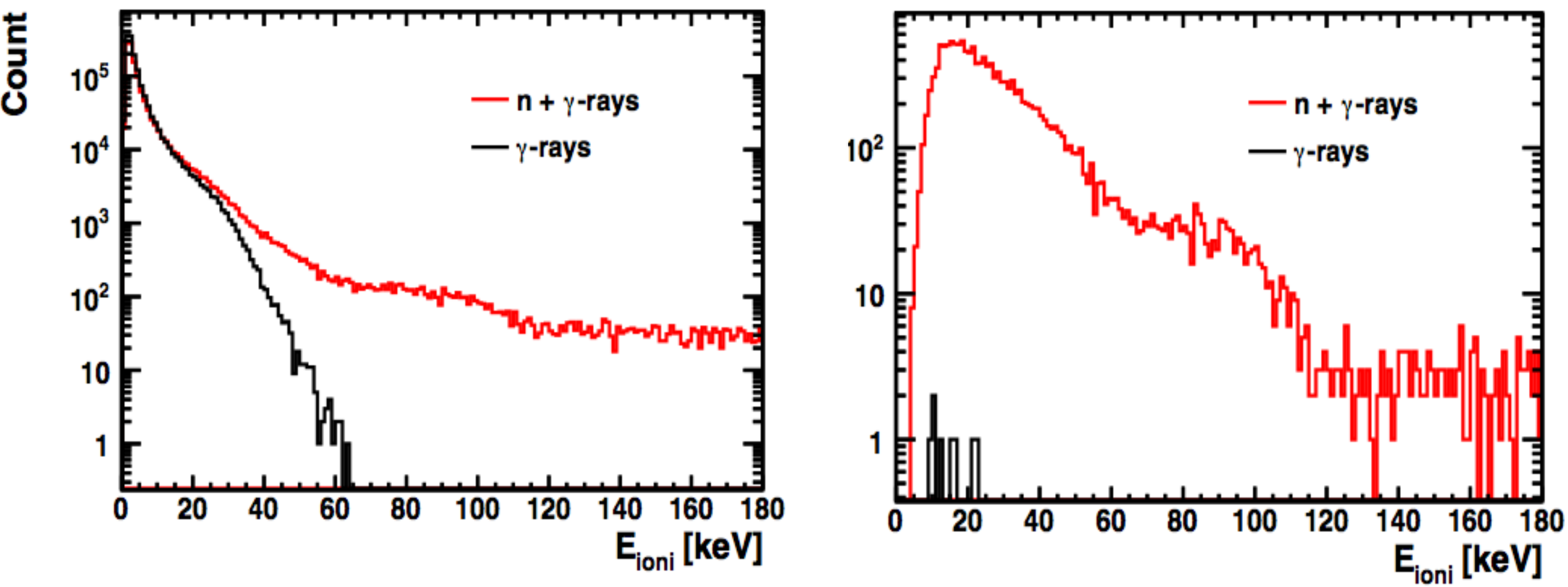


Electron-recoil Discrimination

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

Neutrons ⟶ F , C, H, nuclear recoils

$\gamma - \text{rays}$ ⟶ Electrons

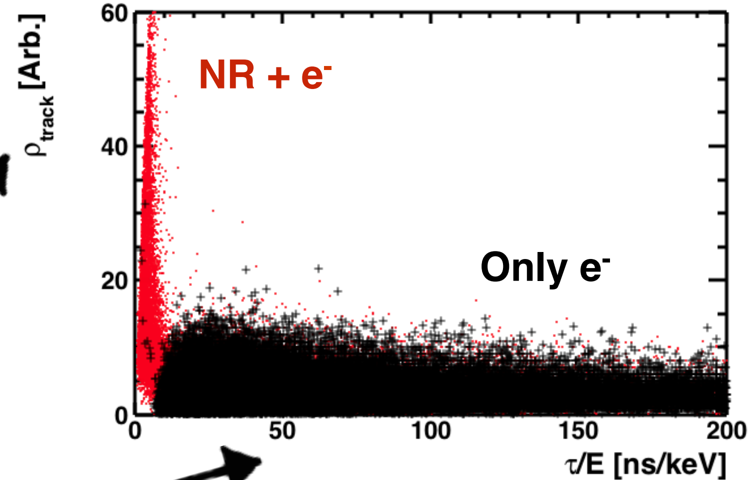


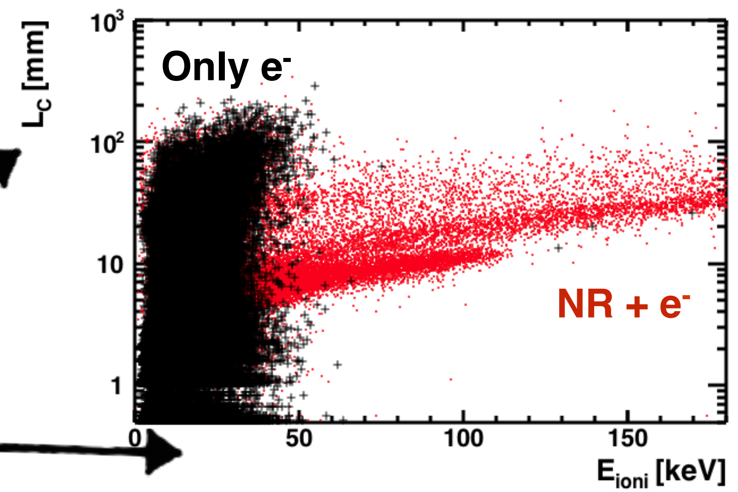
$N_{acpt}/N_{tot} = 1.1 \times 10^{-5}$ electron integrated rejection

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

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

With fast neutrons



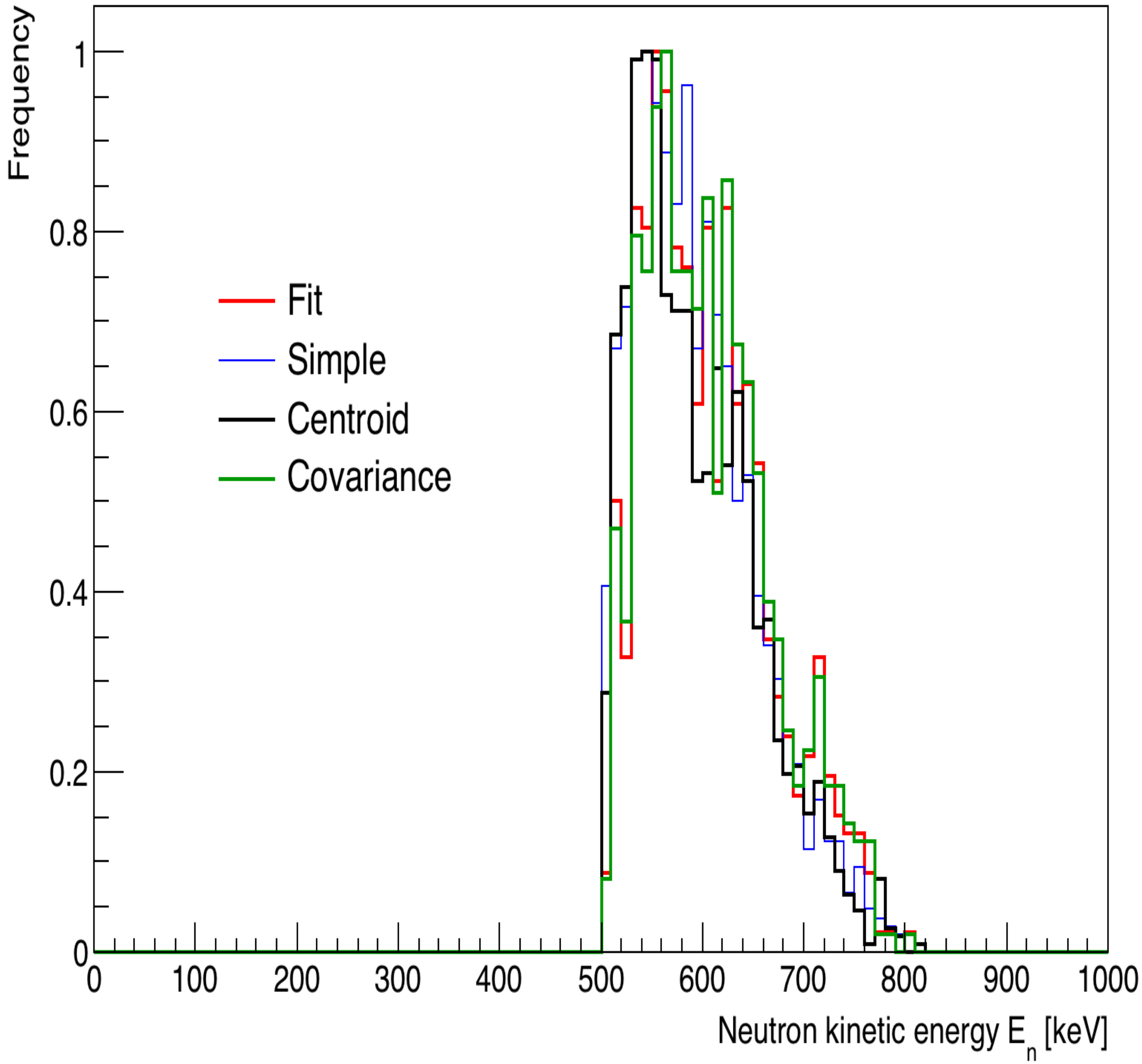


Neutron kinetic energy distribution

Focusing on the "Fluorine Endpoint":

- ionization energies above 50 keV
- theta < 0.5 rad

max ~ 550 keV

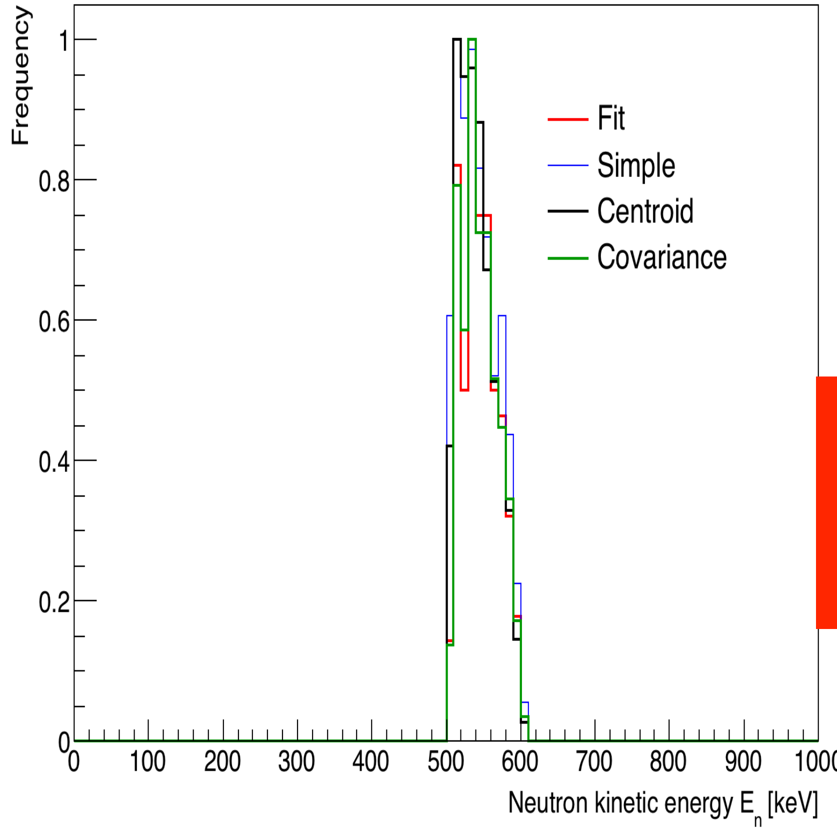


Neutron kinetic energy distribution

Focusing on the "Fluorine Endpoint":

- ionization energies above 50 keV
- theta < 0.2 rad

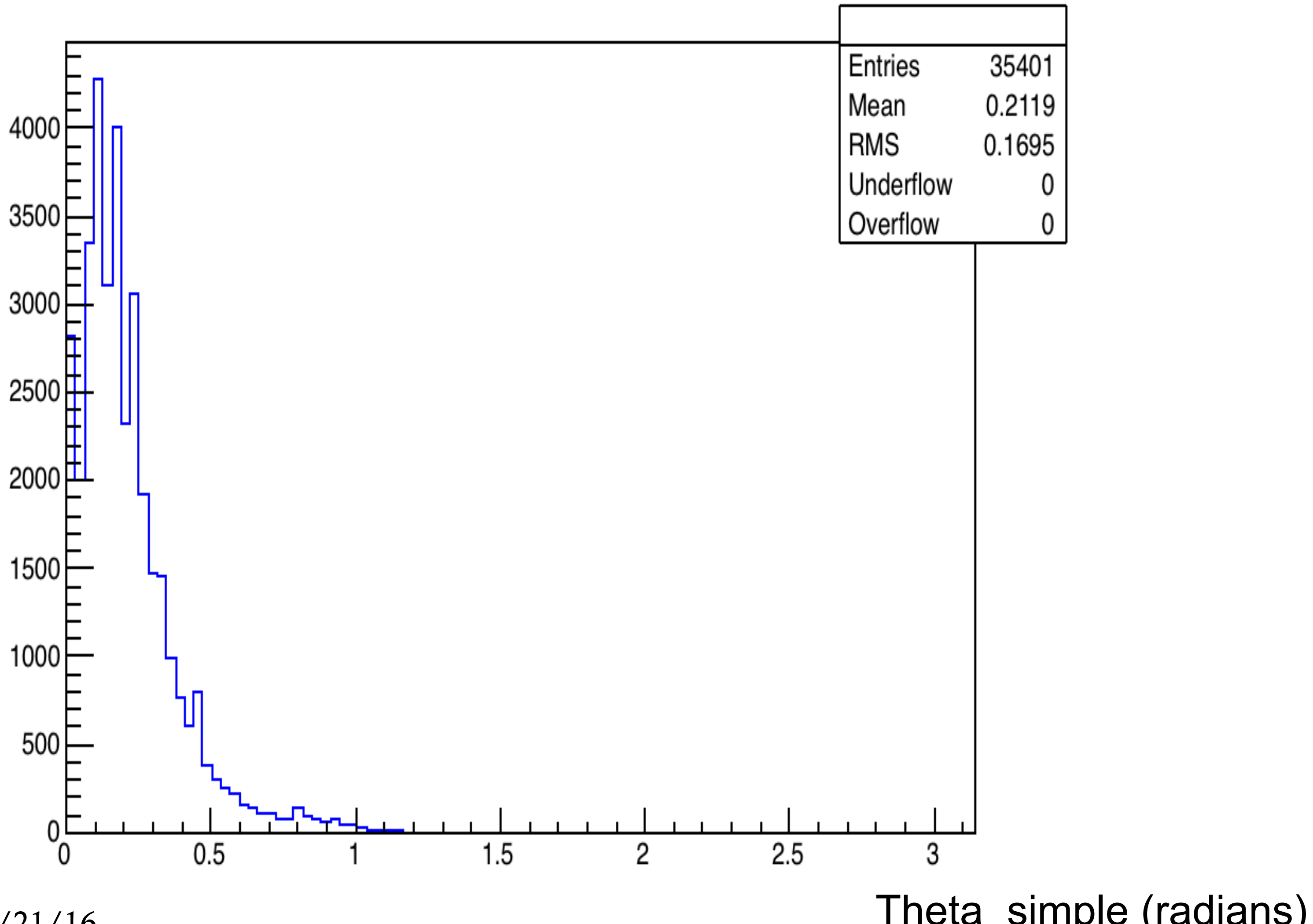
max ~ 545 keV



/!\ Extrapolating the quenching factor above the measured range

Method	Neutron kinetic energy (mean ± 1 σ) [keV]
"Simple" = Joining barycenters of the extreme timeslices	542.8 ± 25.6
Fit of the centroids	541.3 ± 23.8
Fit of every (x,y,z) coincidence	545.8 ± 23.4
Principal Component Analysis	545.7 ± 23.5

Theta distribution



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

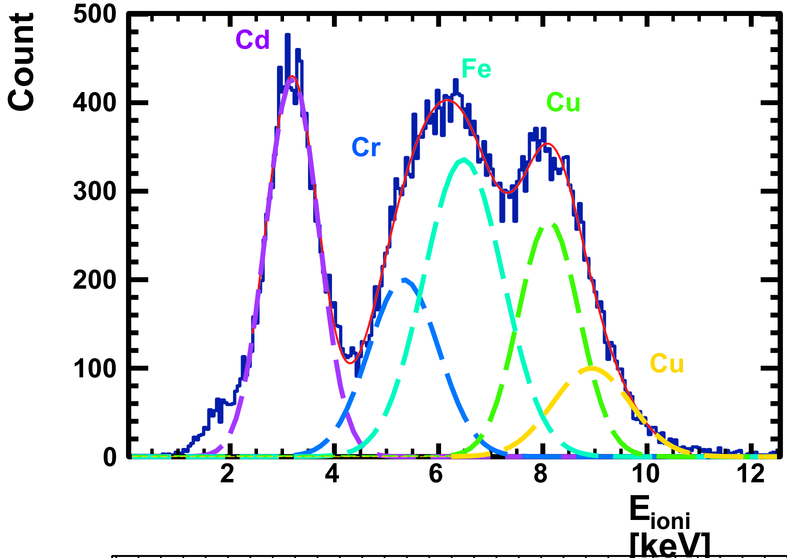
Many thanks to LSM staff

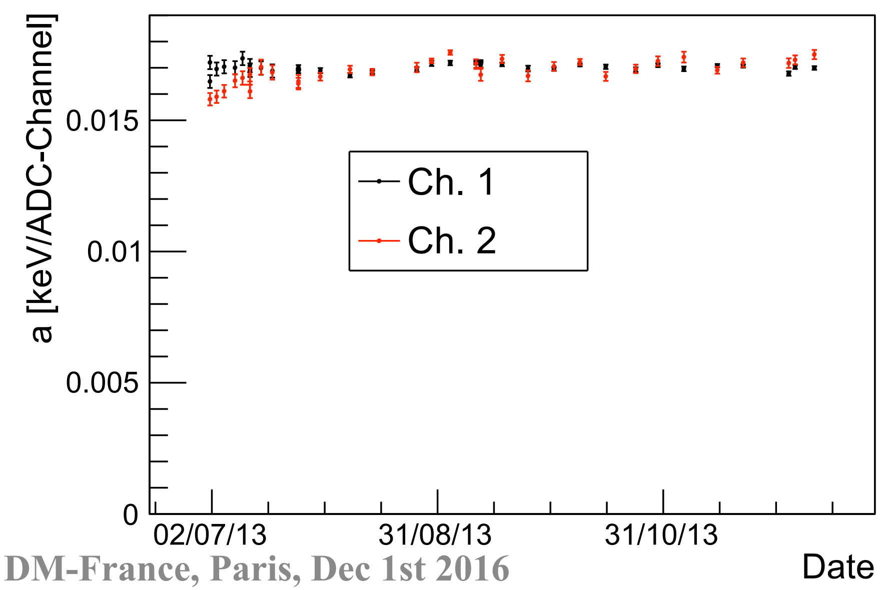
Detector calibration (not at the maximum gain!)

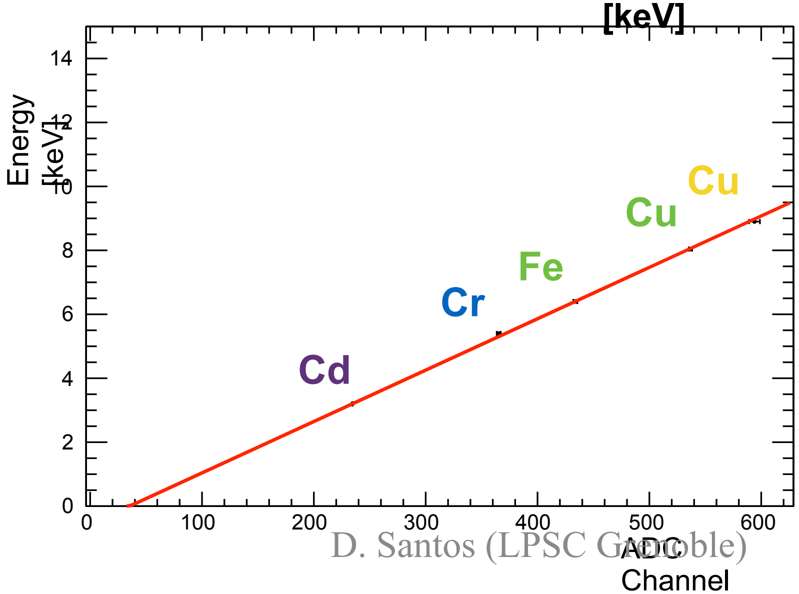
Calibration: (once a week)

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

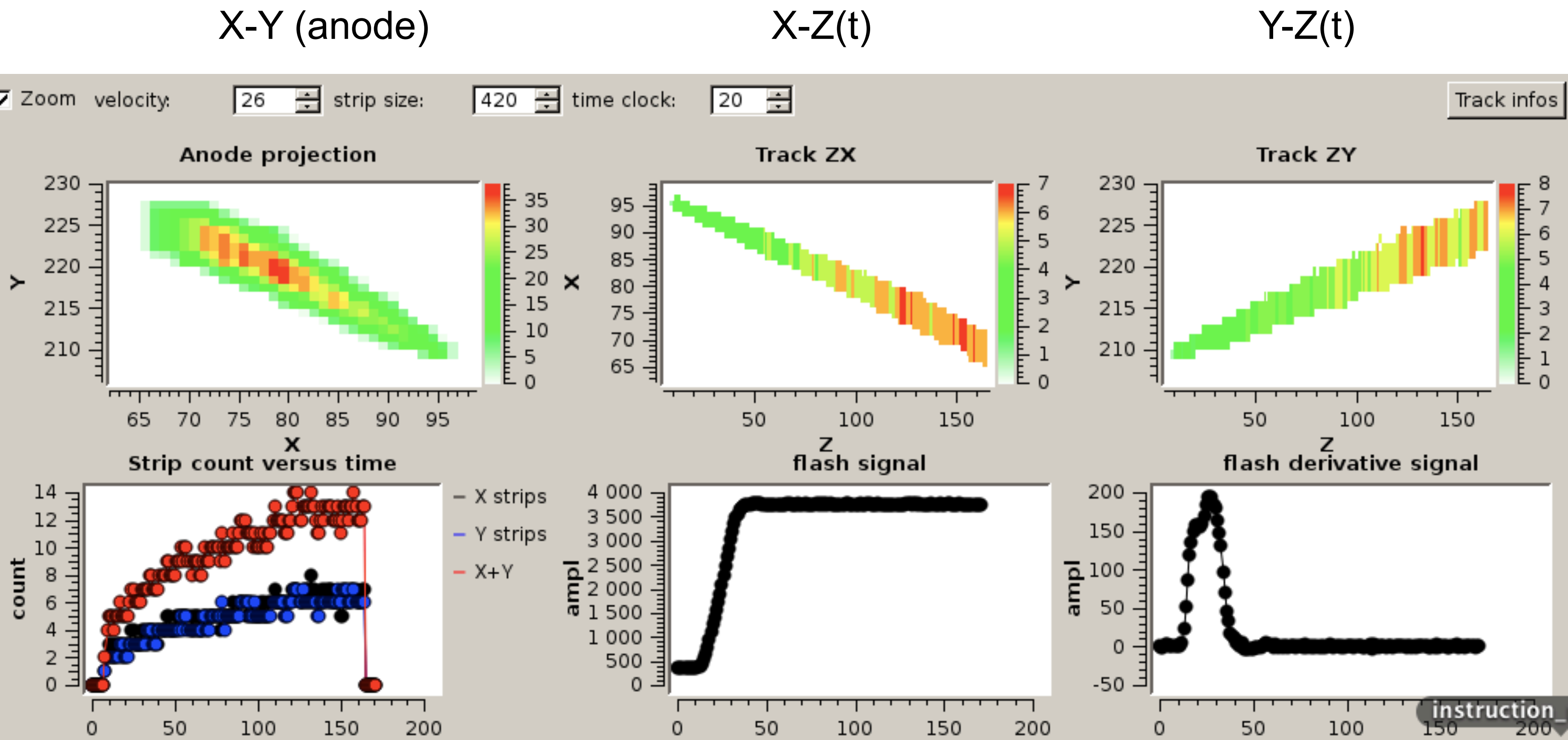
Circulation system:
Excelent Gain stability in time



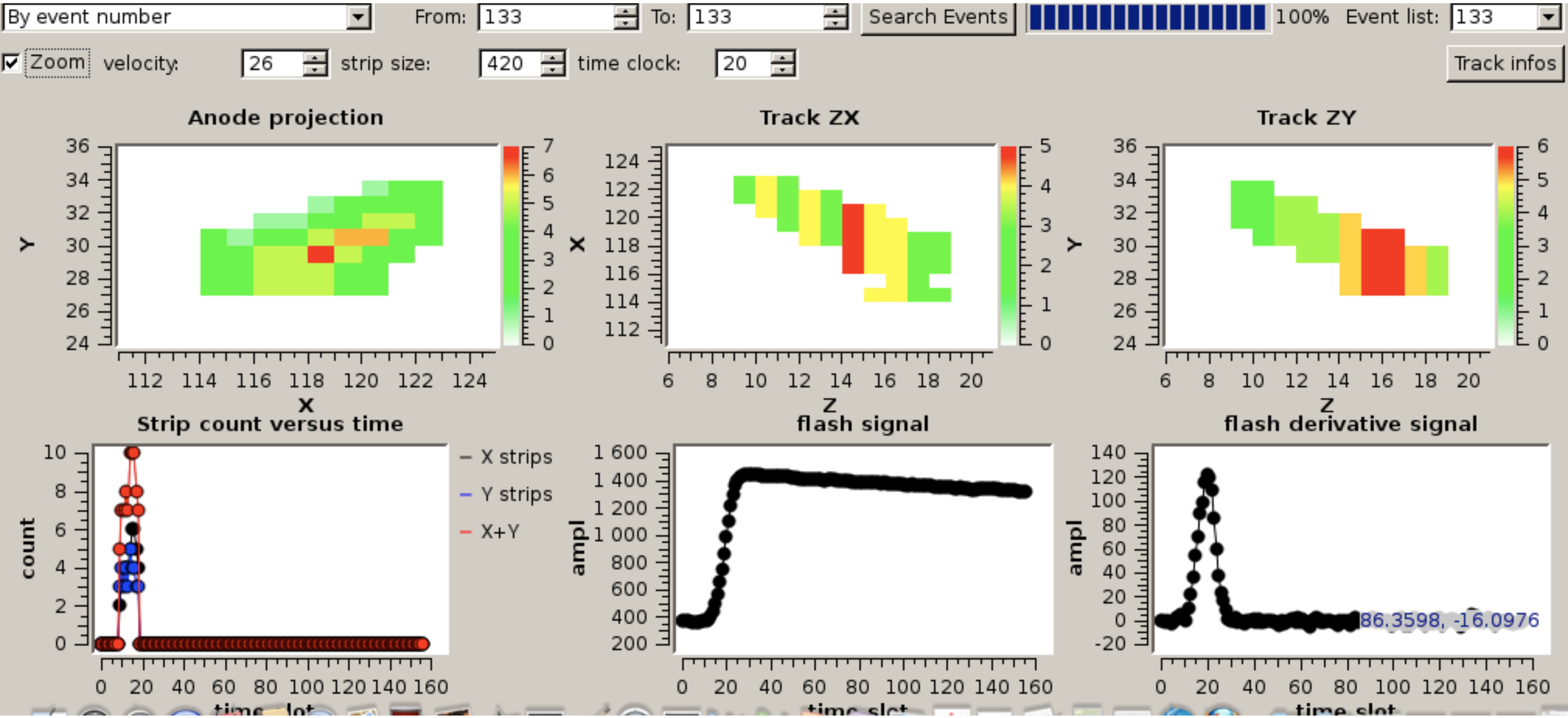




An alpha particle crossing the detector
(as an illustration of the MIMAC observables)



A "recoil event" (~ 34 keVee)



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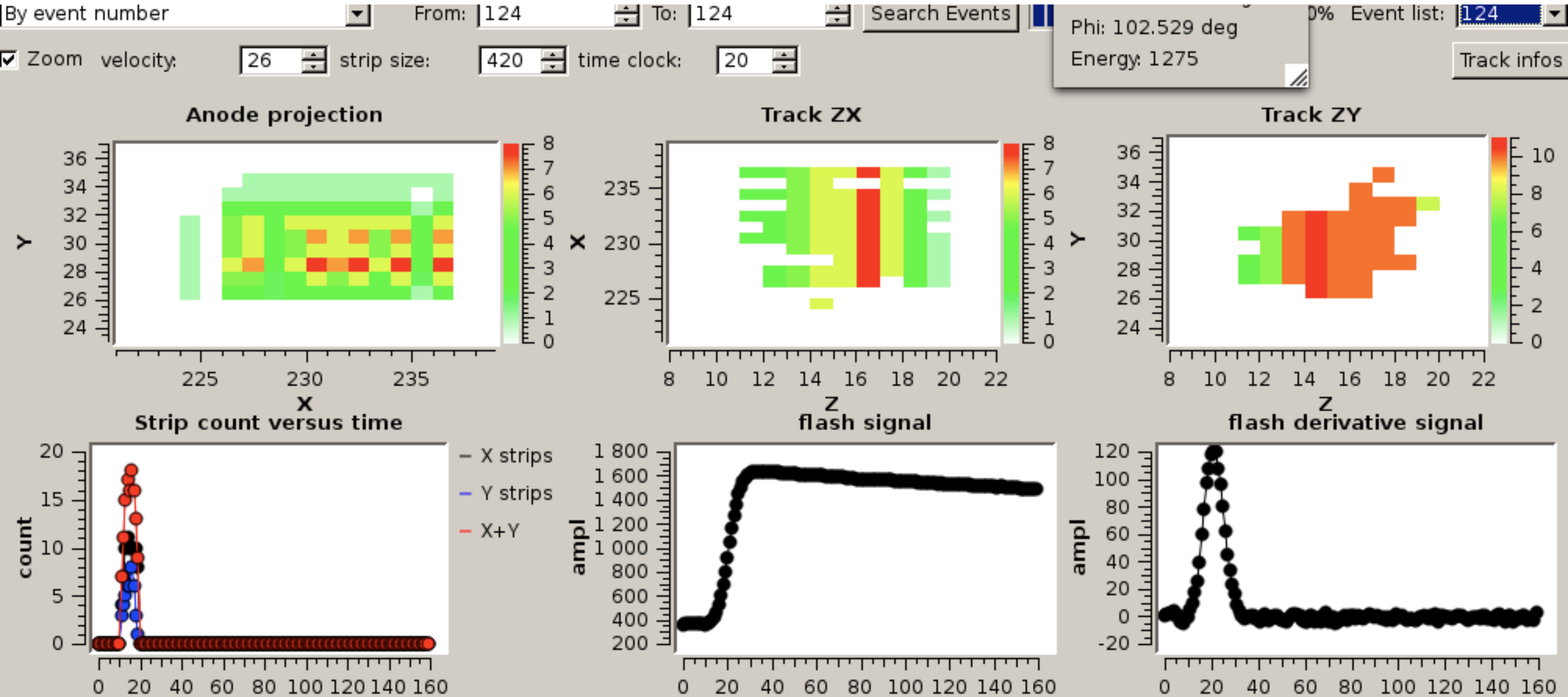
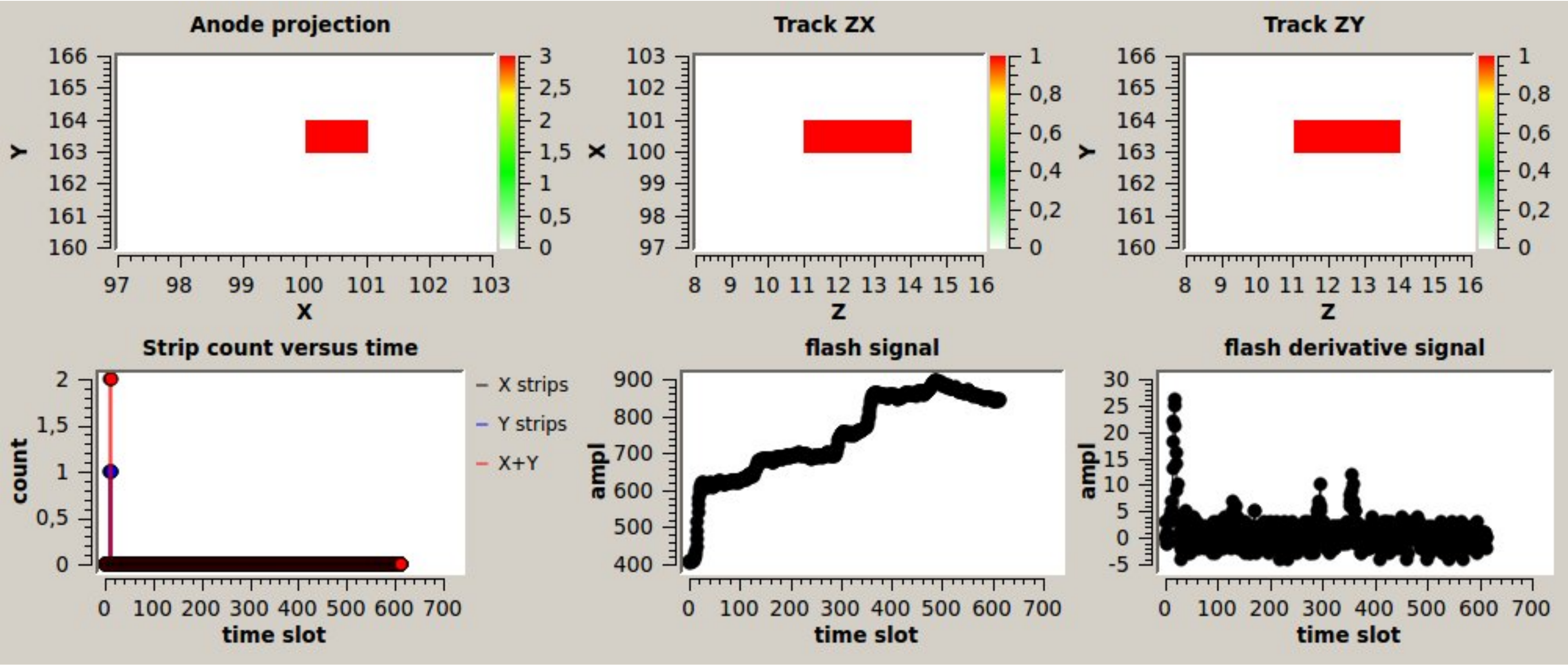
A “recoil” event (~ 40 keVee)



An Electron event (18 keV)



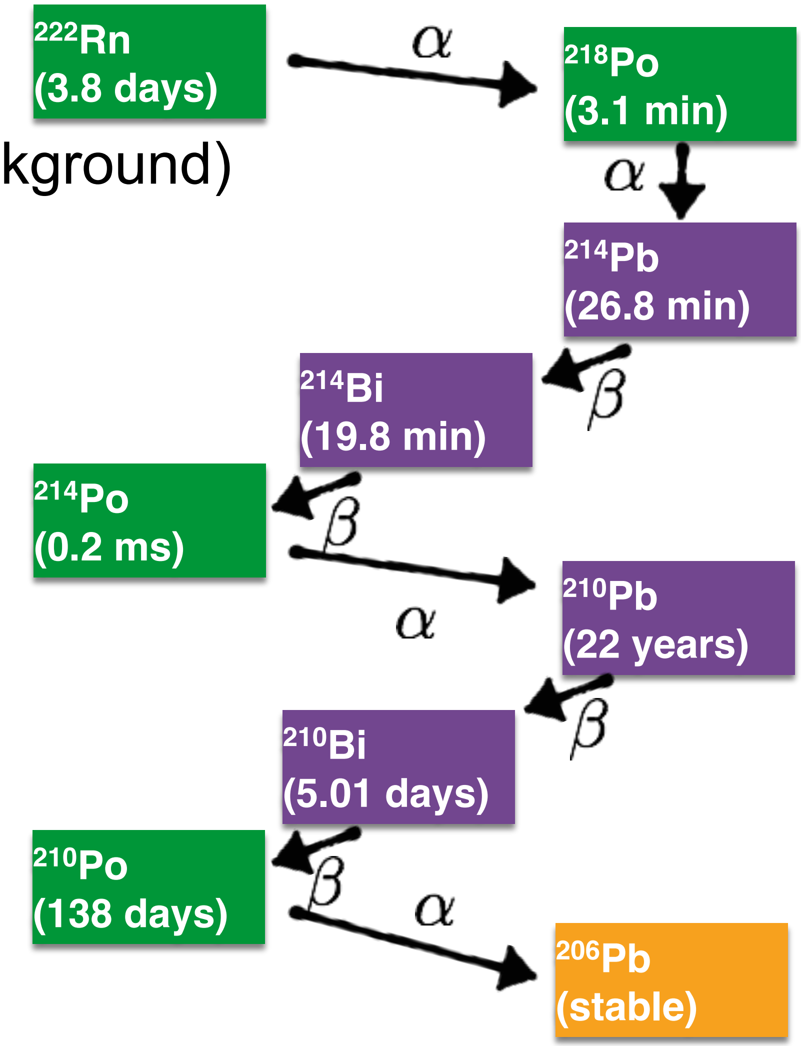
Radon Progeny

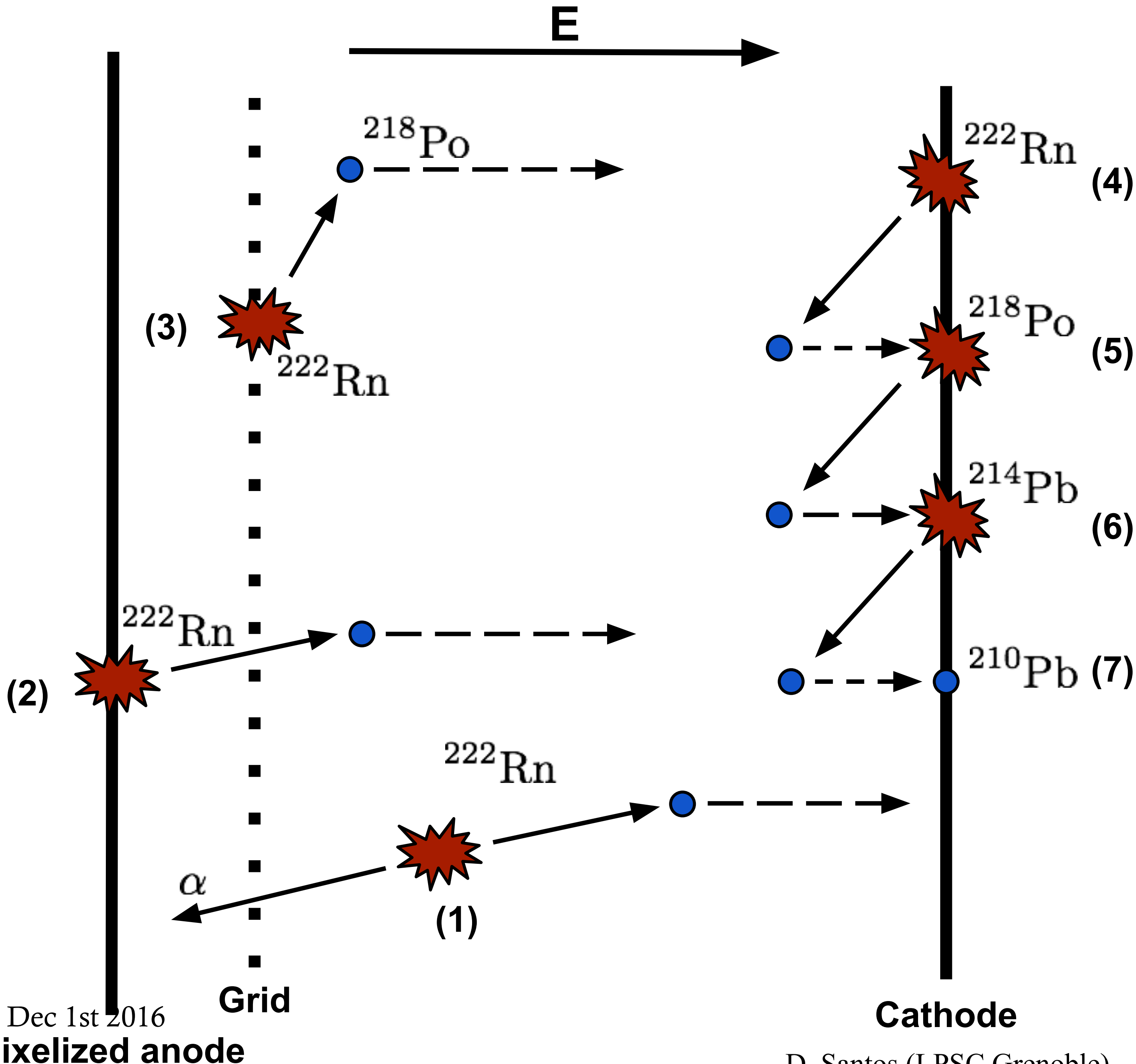
^{222}Rn chain:

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

Simulation (SRIM)





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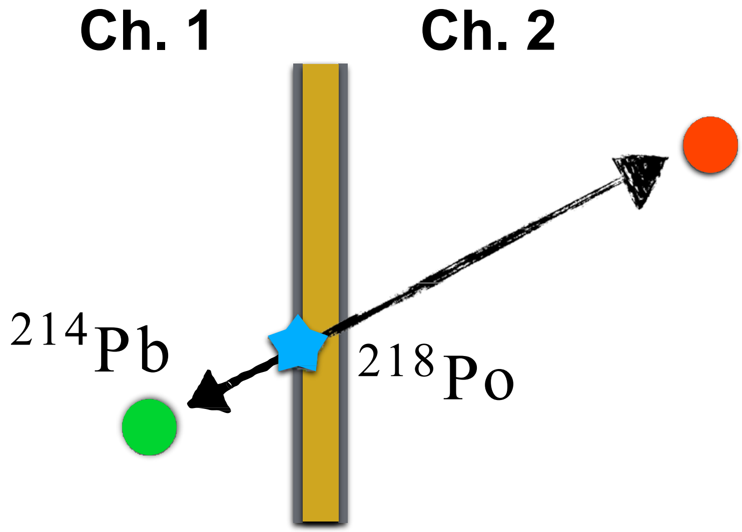
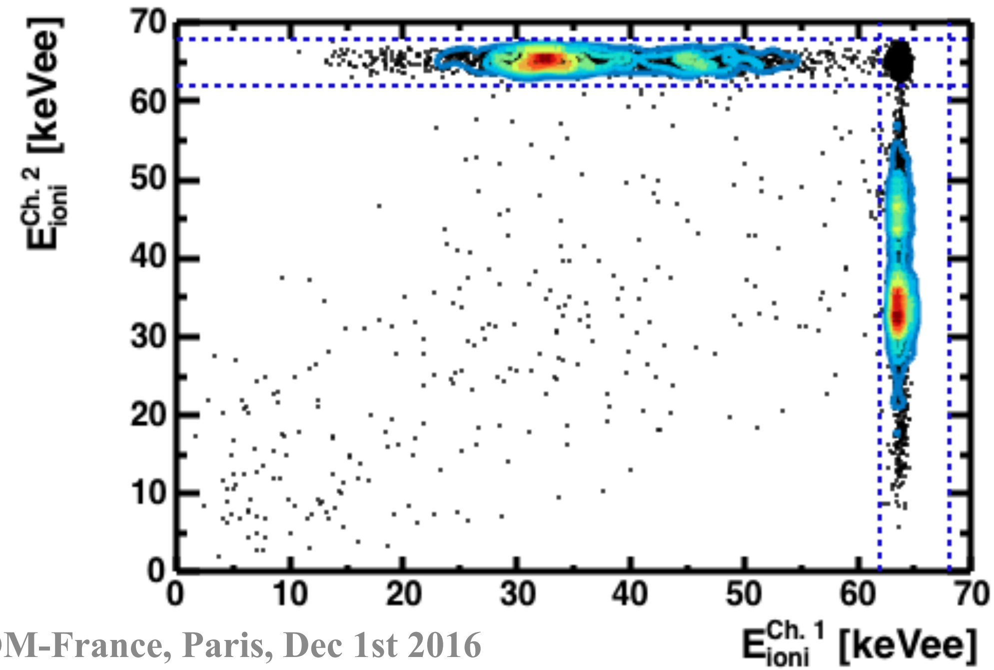
RPR: « In coincidence » events

Chamber coincidences:





3D tracks from nuclear recoil of radon progeny detection

First detection of 3D tracks of Rn progeny

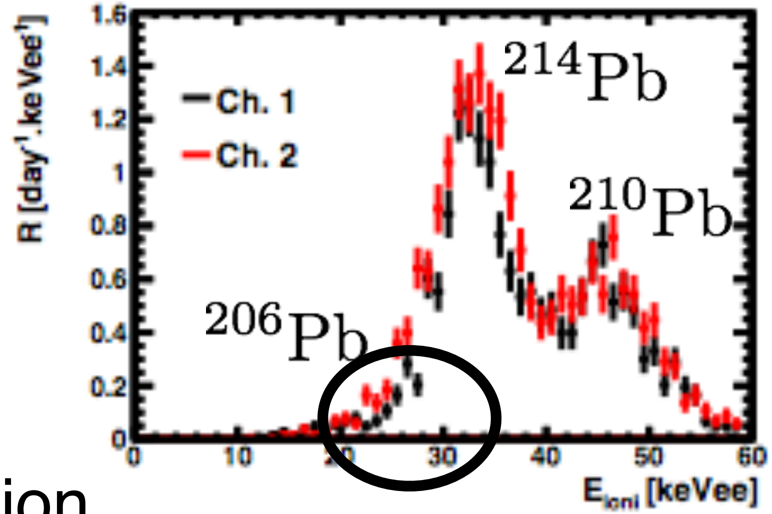
Electron/recoil discrimination

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

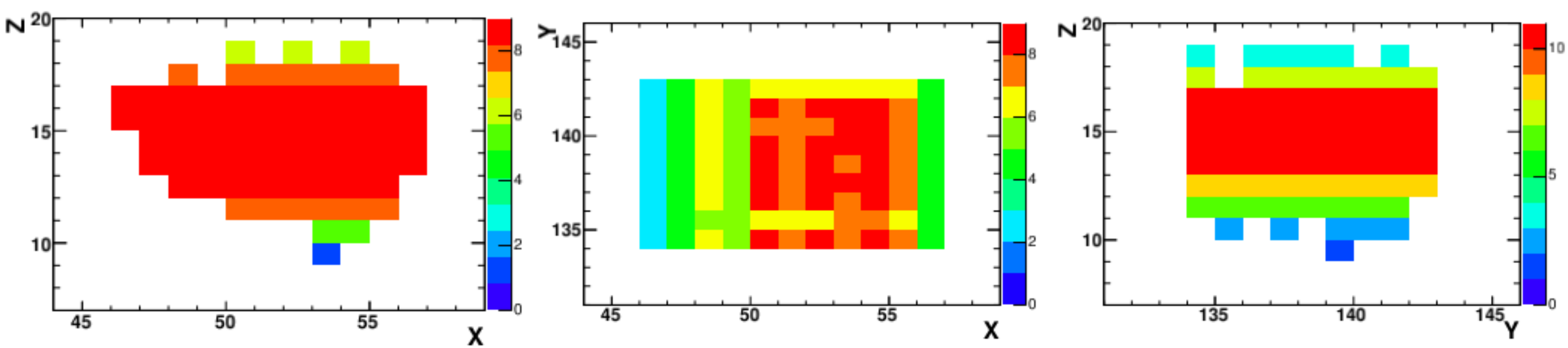
First measurement of 3D nuclear-recoil tracks coming from radon progeny

→ MIMAC detection strategy validation

Nuclear recoil spectra



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

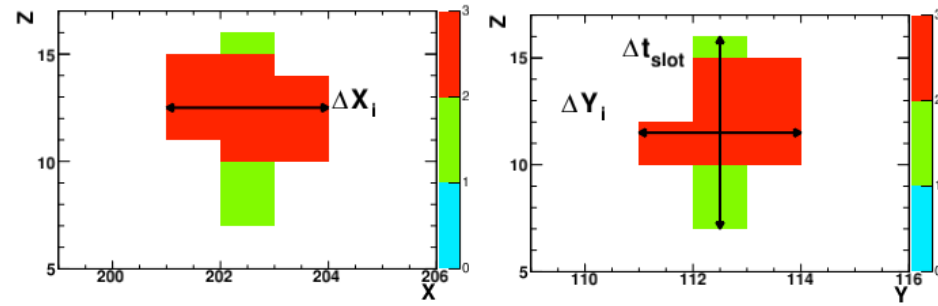


RPR events occur at different positions in the detector…

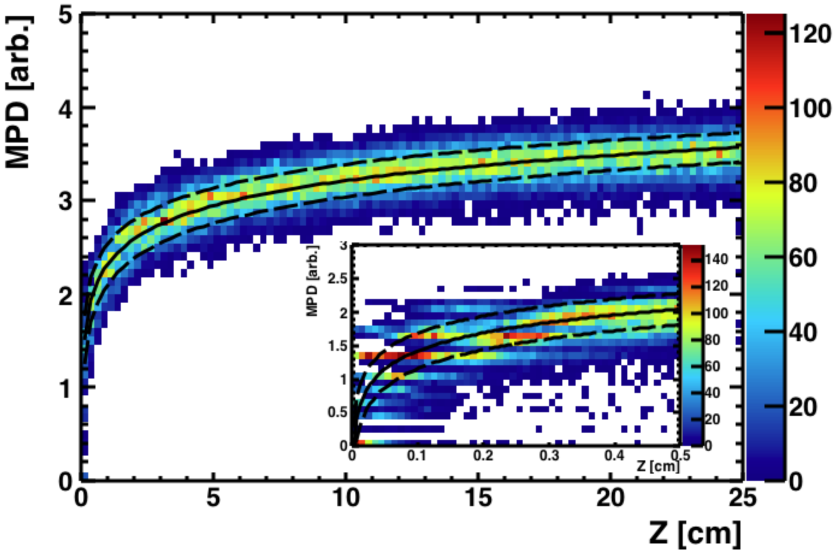
$$z_0 \longleftrightarrow \text{Diffusion}$$

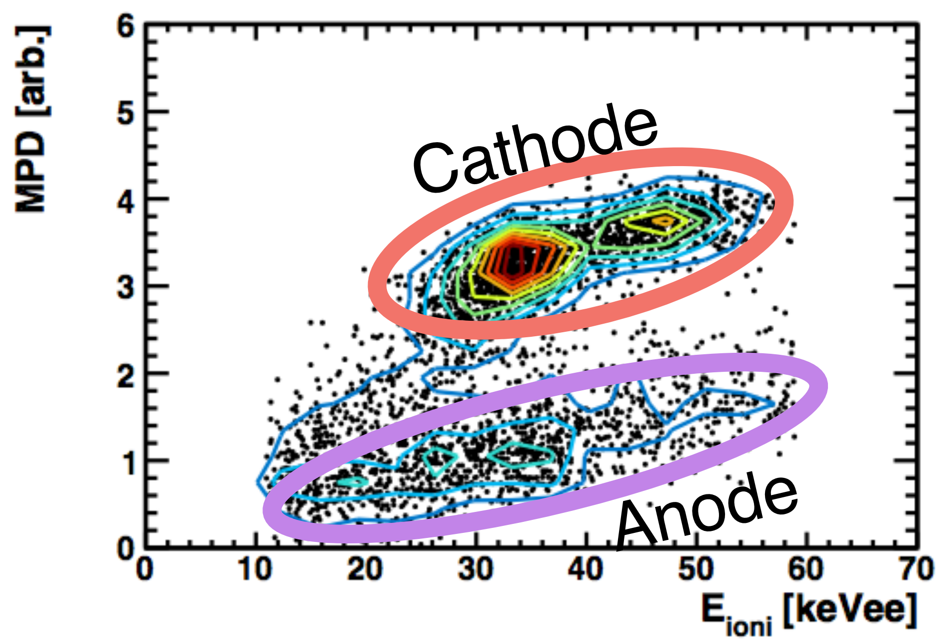
$$\begin{cases} D_T = 237.9\,\mu\text{m}/\sqrt{\text{cm}} \\ D_L = 271.5\,\mu\text{m}/\sqrt{\text{cm}} \end{cases}$$

« Anode » event

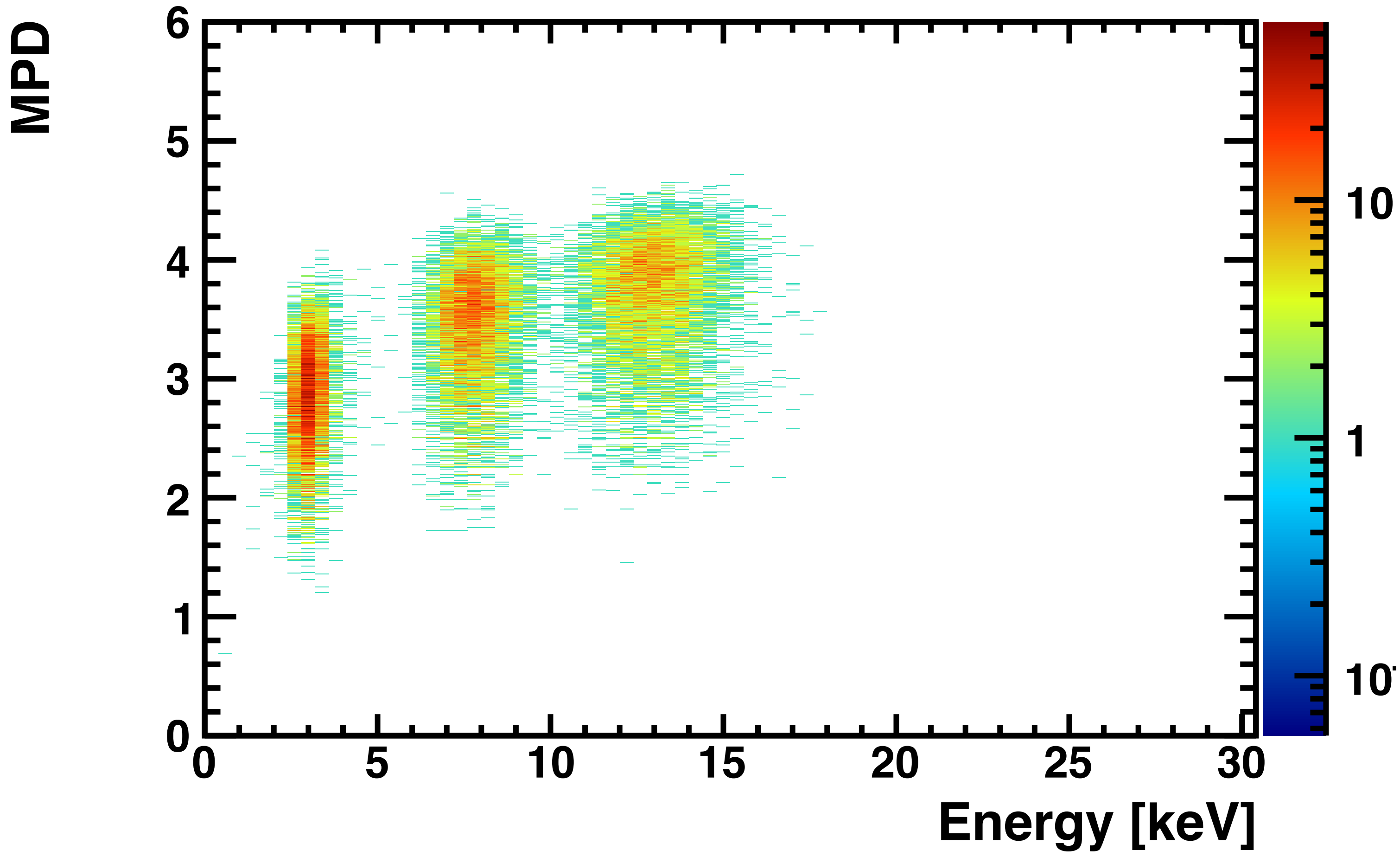


Mean Projected Diffusion: $\overline{\mathcal{D}} = \ln\left(\overline{\Delta X} \times \overline{\Delta Y}\right)$





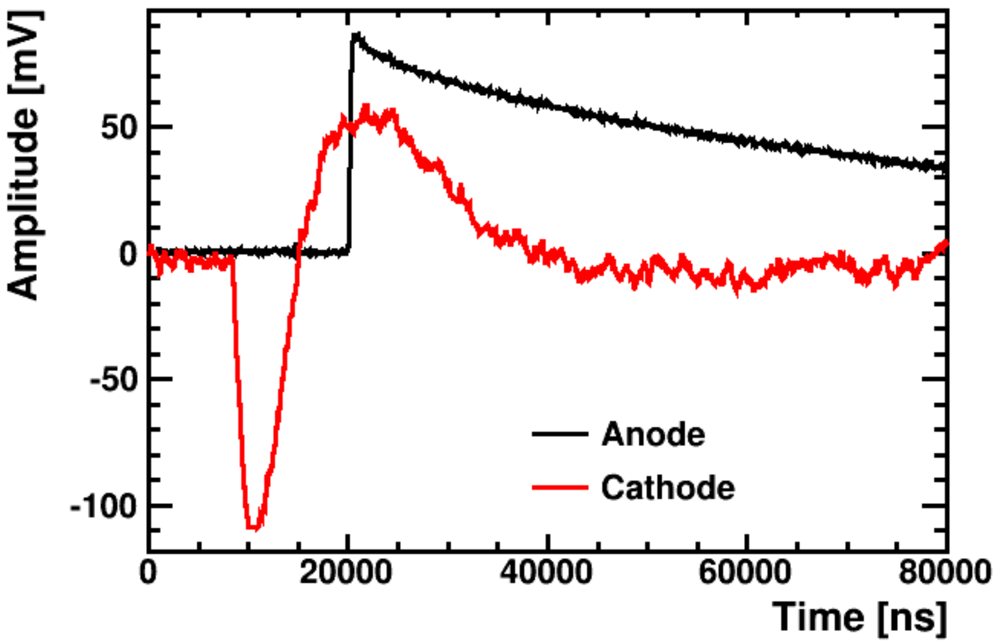
Simulation of ^{19}F recoils diffusion observable (MDP) of 10, 20 and 30 keV kinetic energies in the MIMAC detector



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)

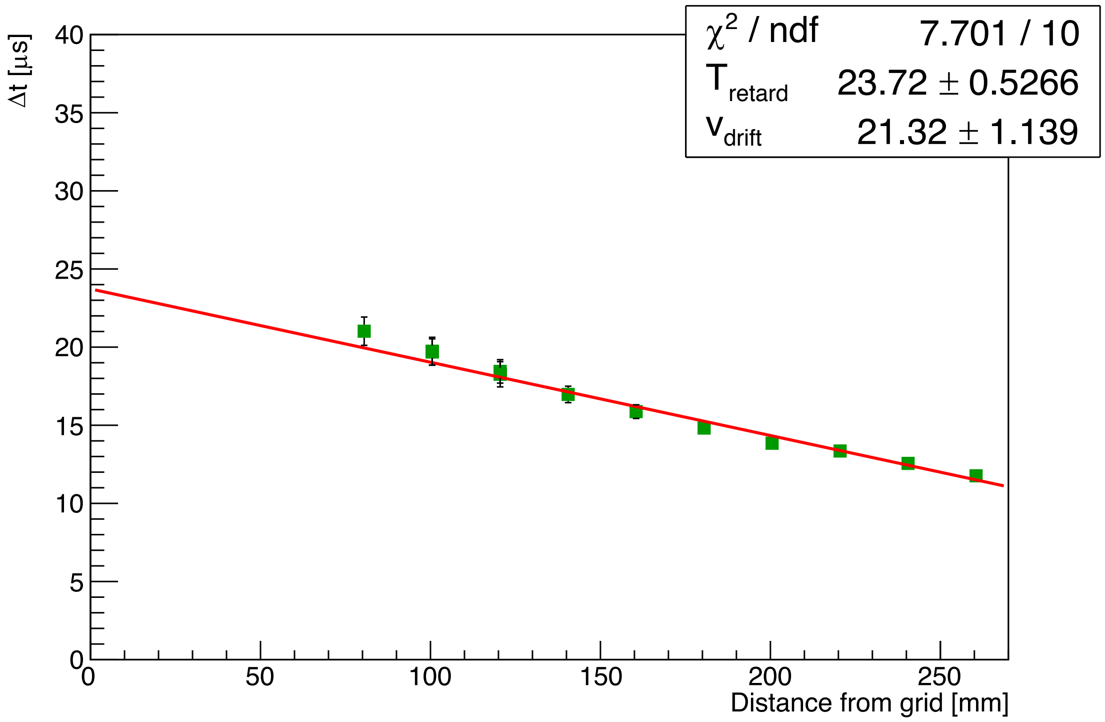
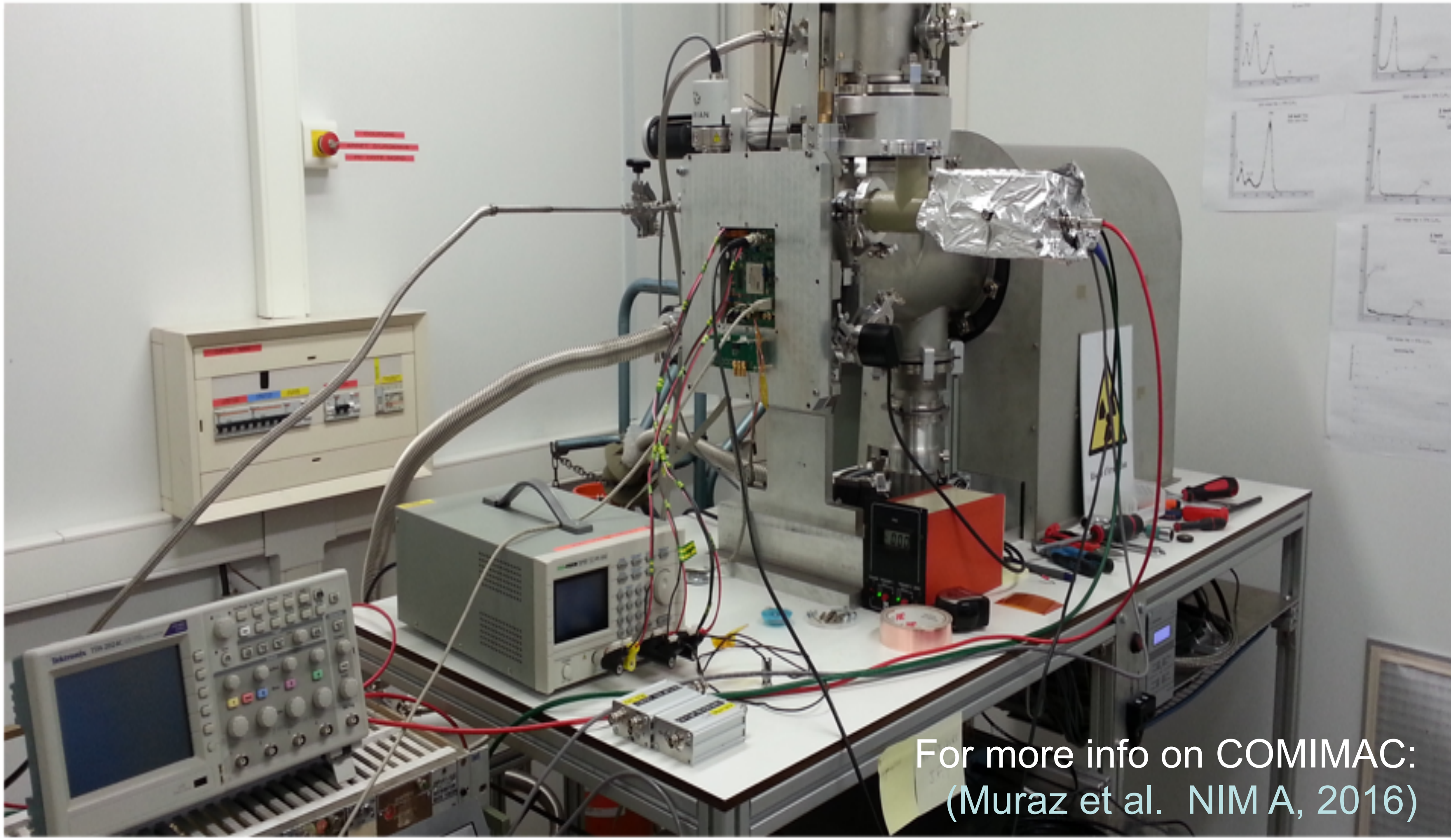


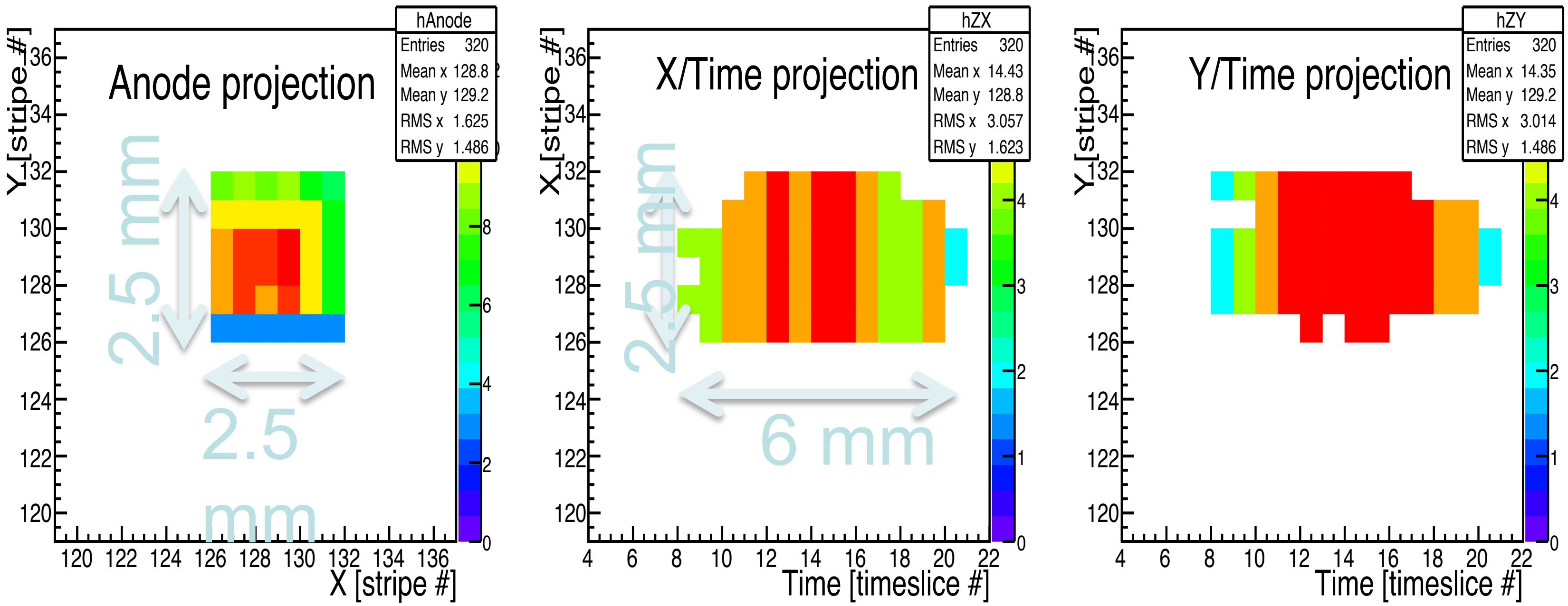
Figure 4. Measure of the time differences (TAC) between the grid signal and the delayed cathode signal in the "START Grid" configuration, as a function of the distance of the α source from the anode (green points) ; error bars correspond to the standard deviation of the mean. A linear fit of these points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

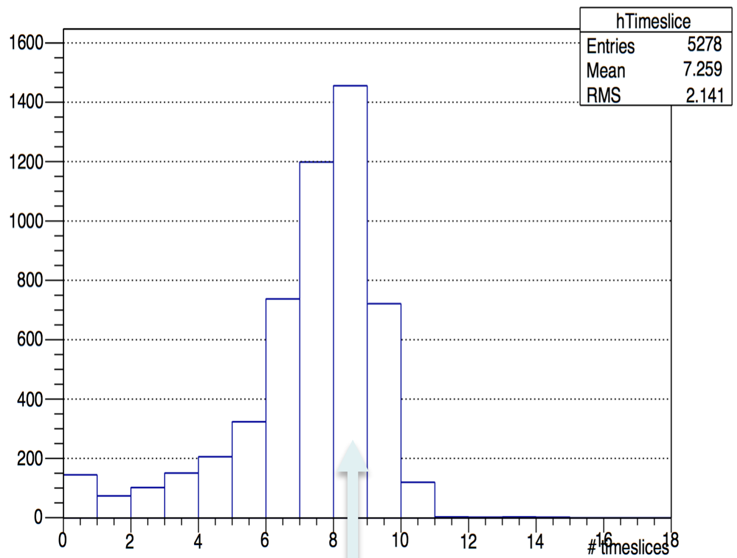
25 keV (kinetic) Fluorine → ~ 9 keVee



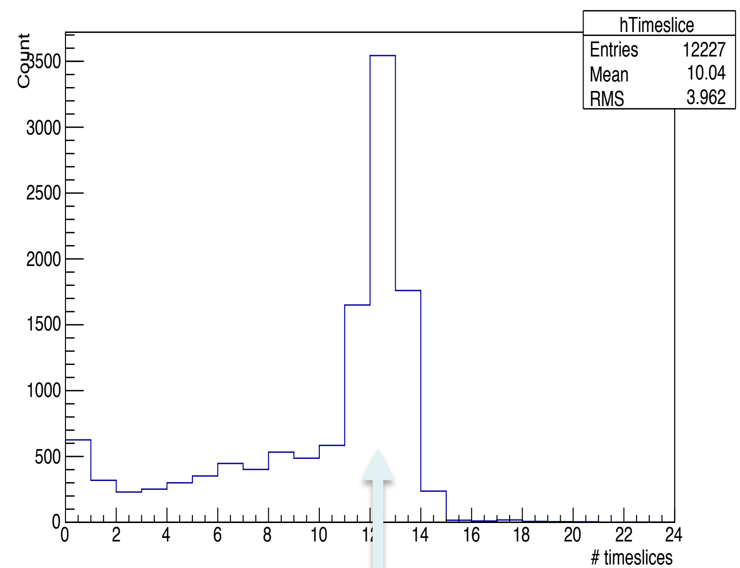
D. Santos (LPSC Grenoble)

COMIMAC: first controlled tracks of ^{19}F

8 keV kinetic → 2 keVee



25 keV kinetic → 9 keVee



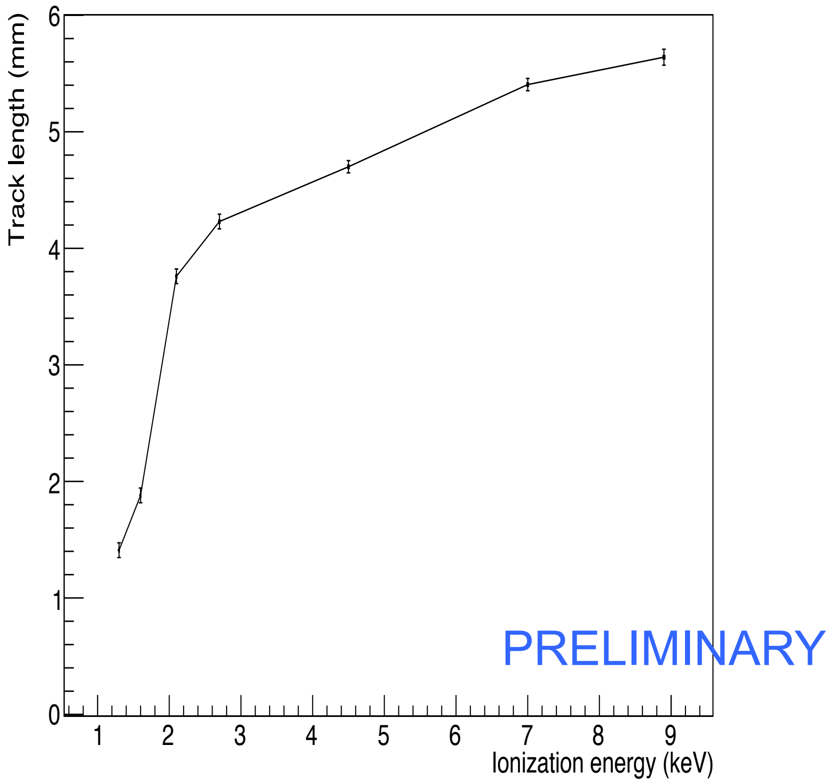
8 timeslices
* 20 ns/timeslices
* 23.5 μm/ns
= 3.8 mm

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

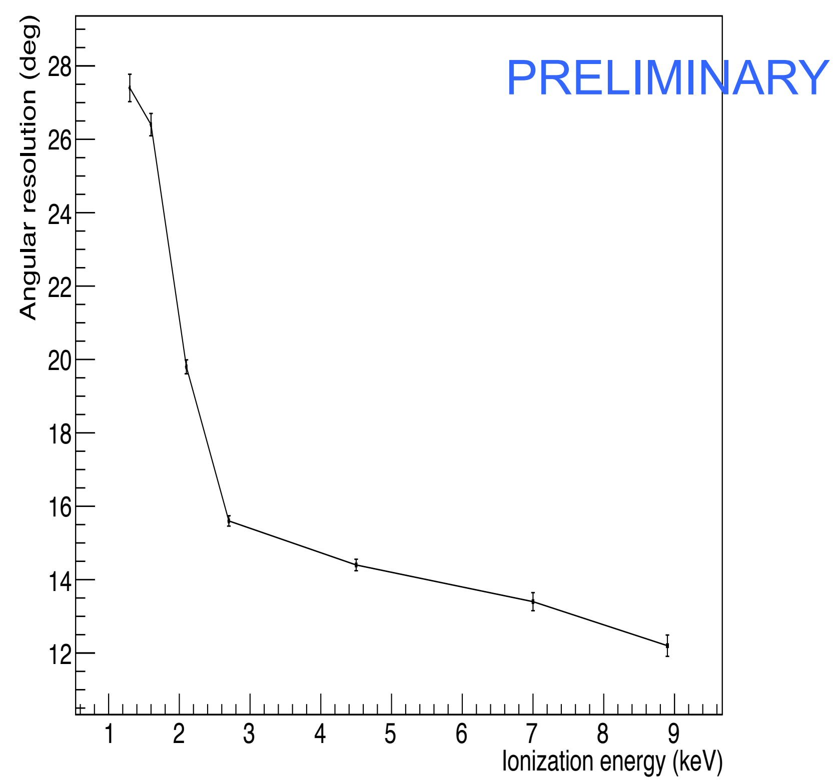
C. Couturier, I. Moric, Y. Tao et al. (in preparation)

COMIMAC: first measurements on controlled tracks of Fluorine

- Track



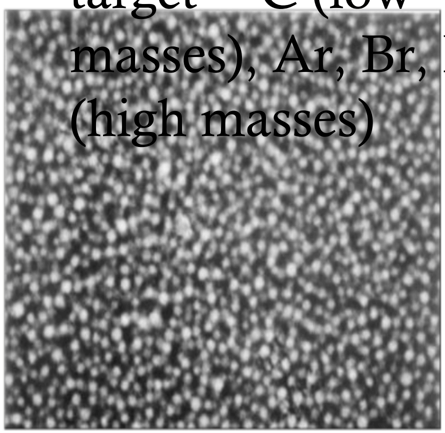
- Angular resolution



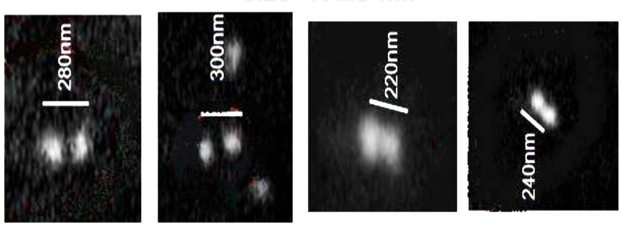
Couturier et al. (in preparation)

Directional detection: comparison of strategies

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

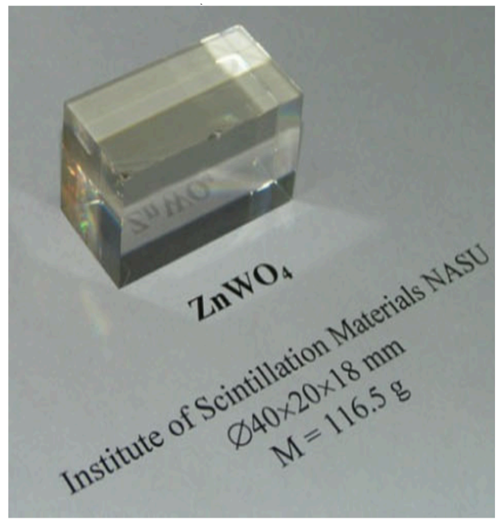


size 40±9 nm



D'Ambrosio et al. 2014

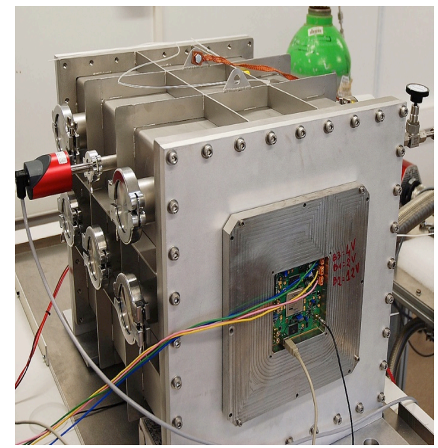
- Anisotropic crystals
target = O (low

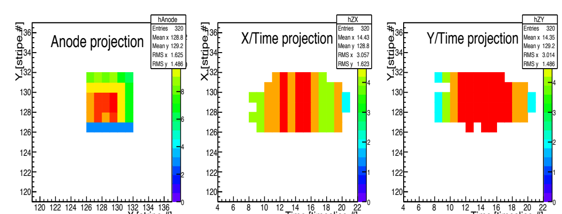


No tracks ; only statistical distributions (!)

Capella et al. 2013

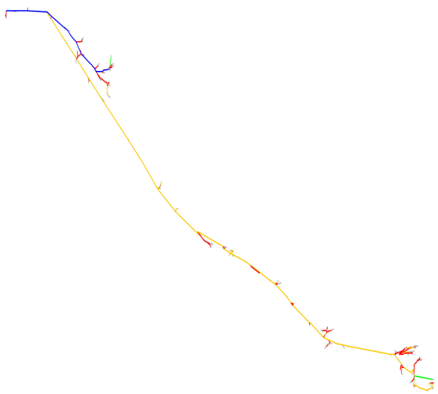
- Low pressure TPCs
target = F



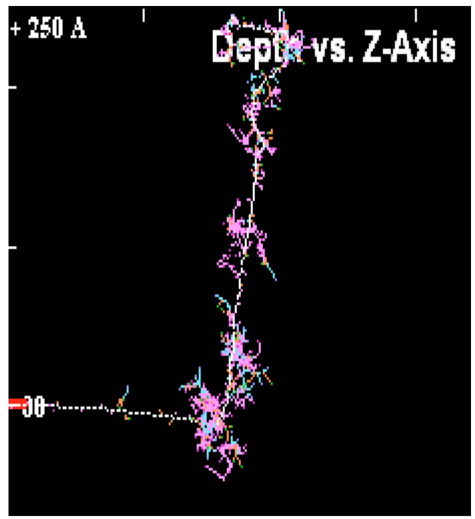


Directional detection: comparison of strategies

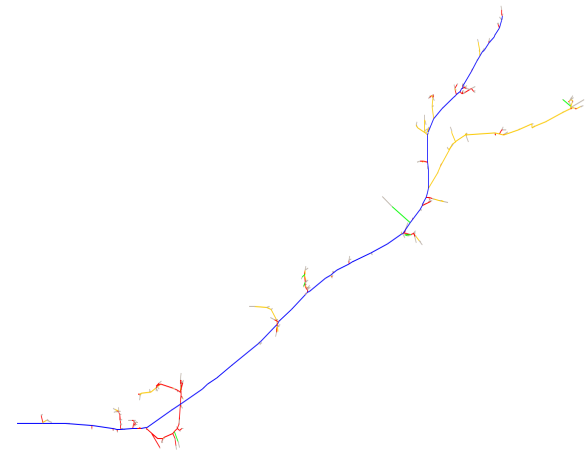
- Emulsion
- Anisotropic crystals
- Low pressure TPCs



~100 nm



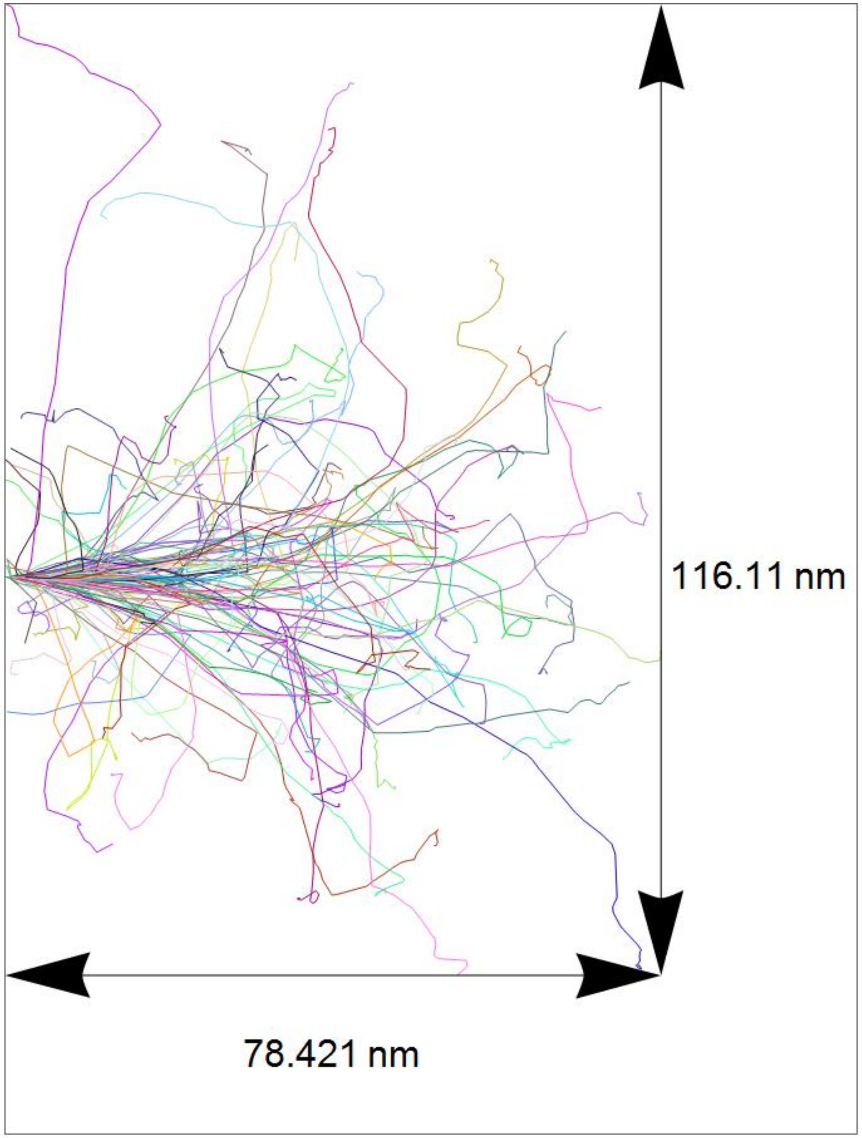
~10 nm



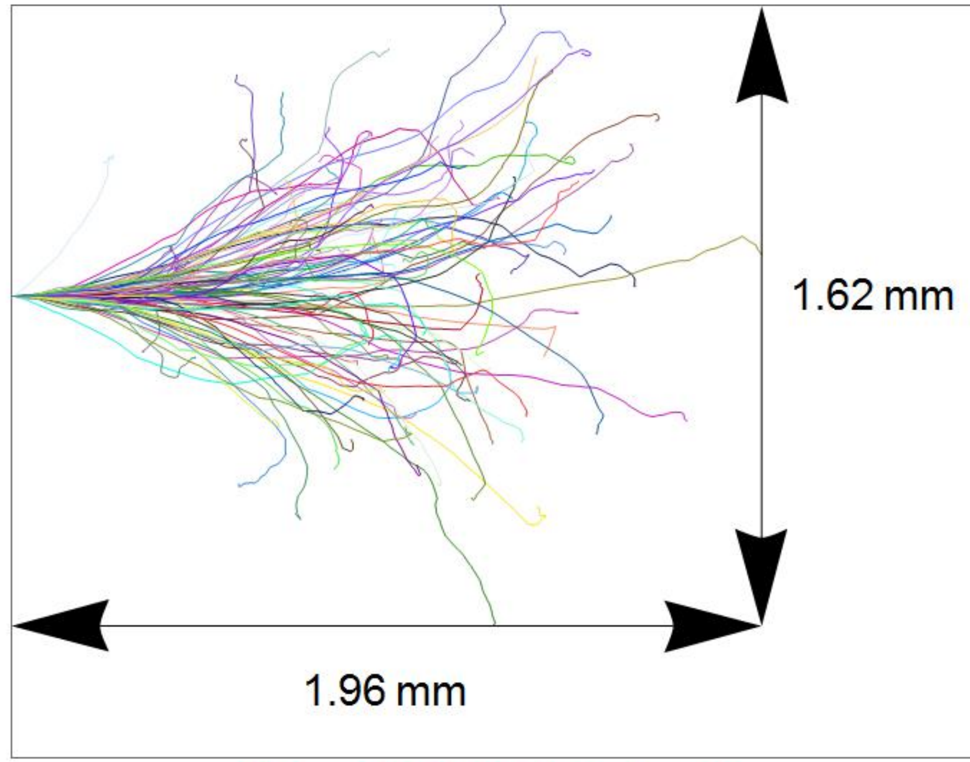
~1 mm
(10^5 times longuer !!)

(SRIM simulations)

SRIM simulations…



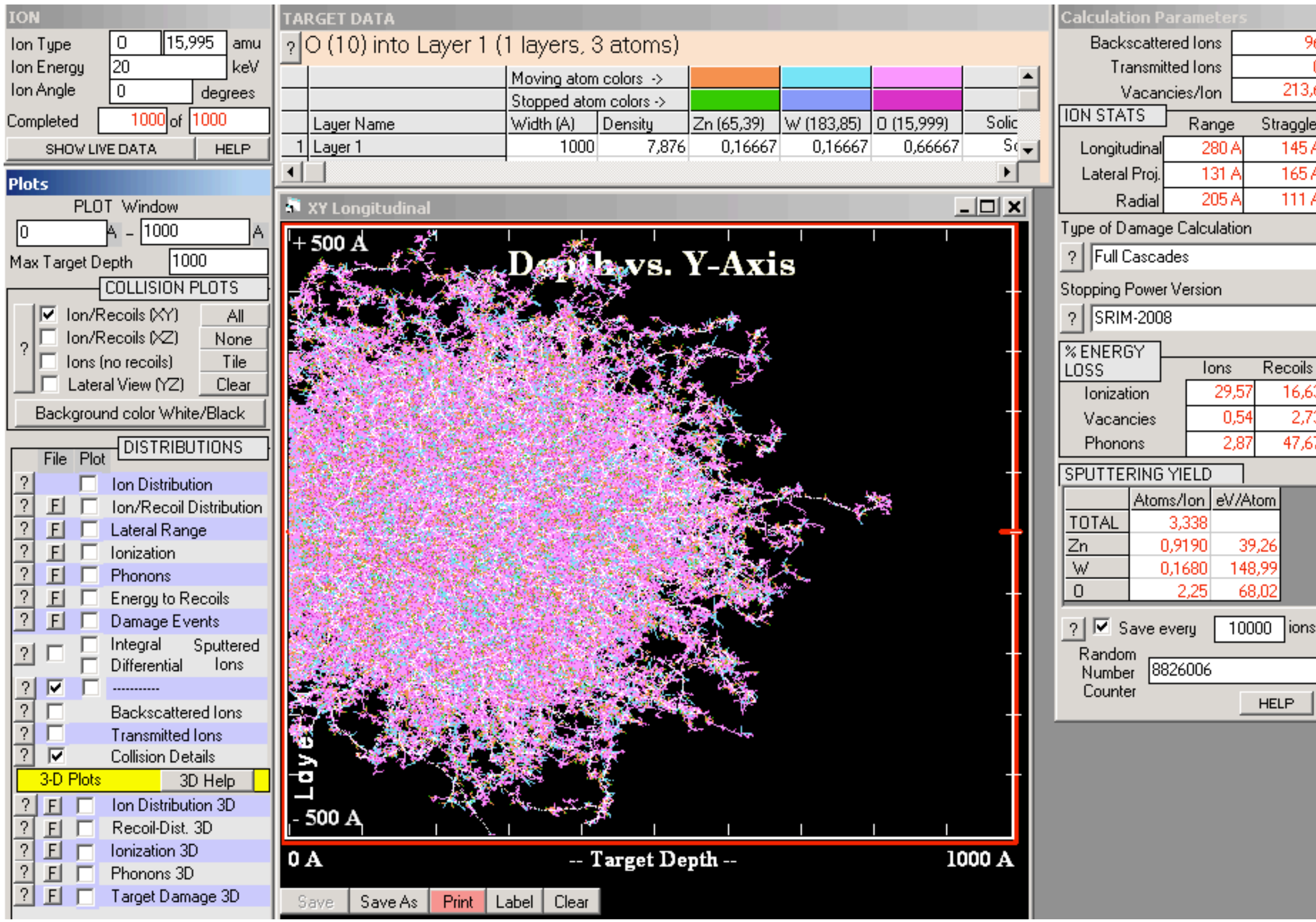
O in Crystal (29keV)



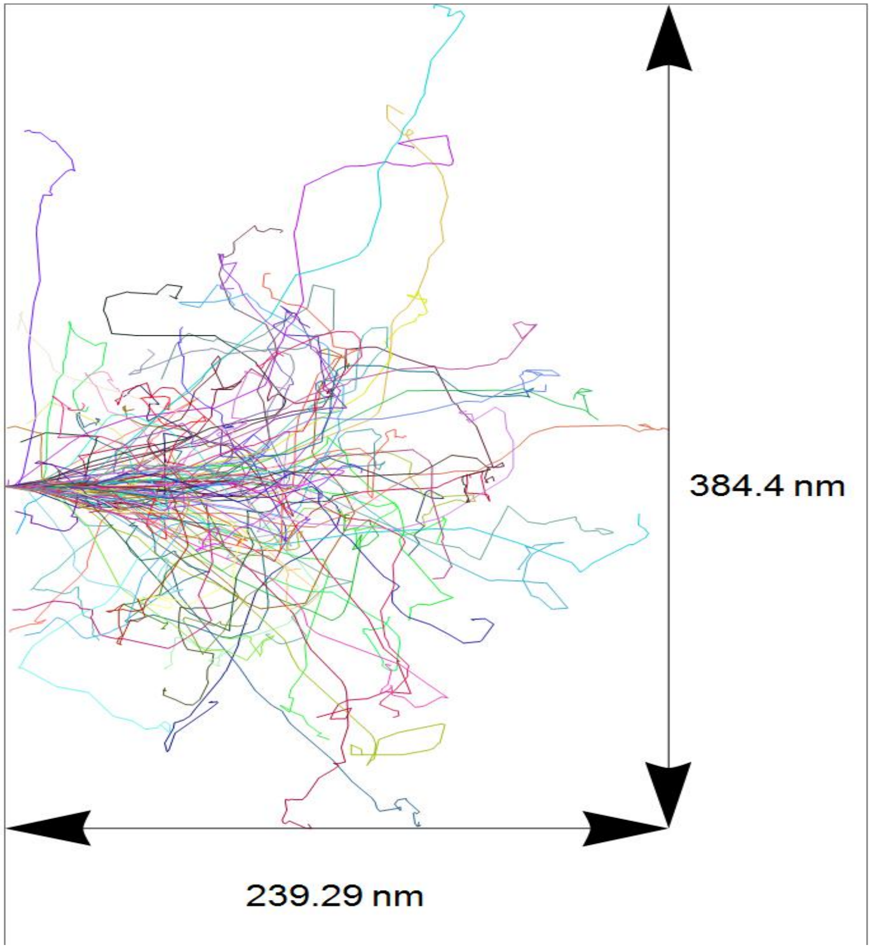
F in MIMAC (34keV)

SRIM simulation of O (20 keV) in ZnO_4W

showing the secondary recoils

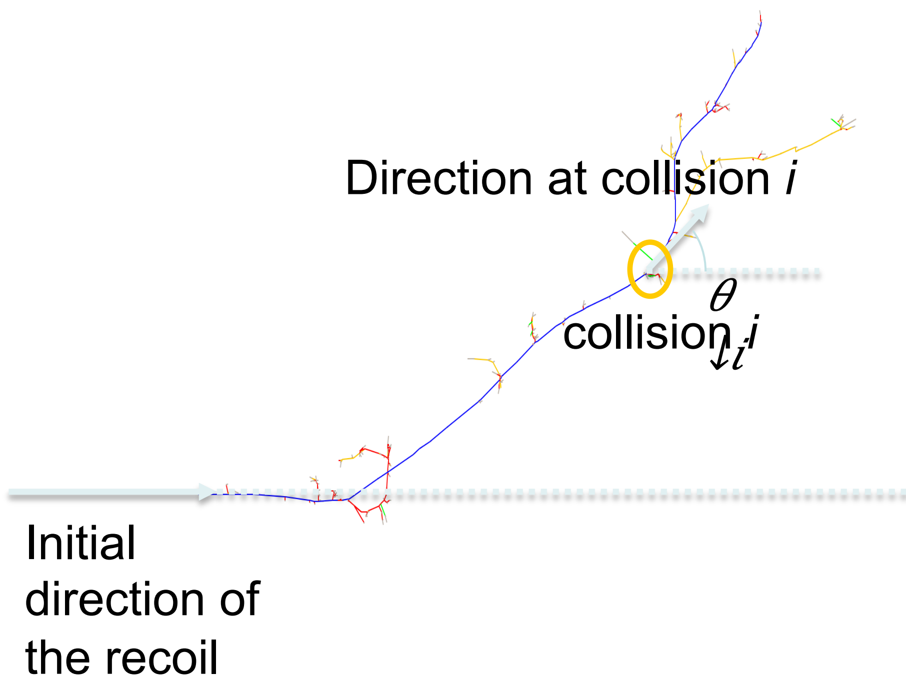


C (22 keV) in emulsion (SRIM simulation)

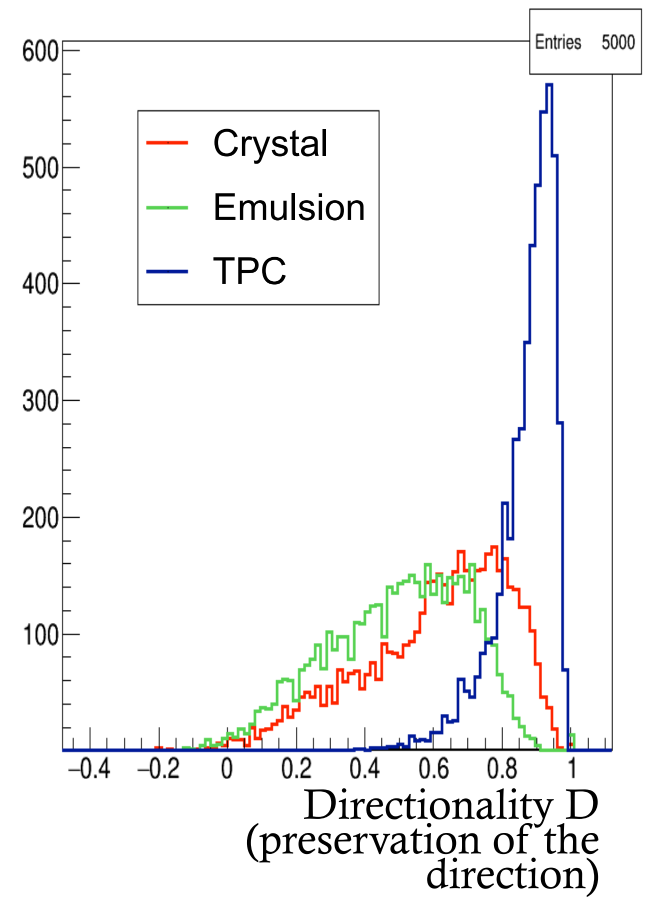


In emulsions and solids the transverse development is in general greater than the longitudinal !!

Directional detection: Directionality 'D'



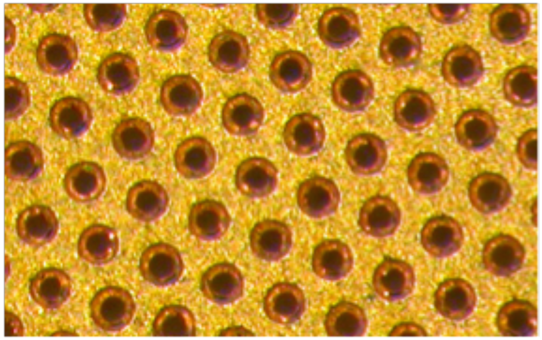
$$D = \frac{<\cos(\theta)\cdot E>_{track}}{<E>_{track}} = \frac{\sum_{i=0}^{N_{collisions}} \cos(\theta_i)\cdot E_i}{\sum_{i=0}^{N_{collisions}} E_i} = \frac{\sum_i \cos(\theta_i)\cdot E_i}{N_{collisions}\cdot <E>_{track}}$$

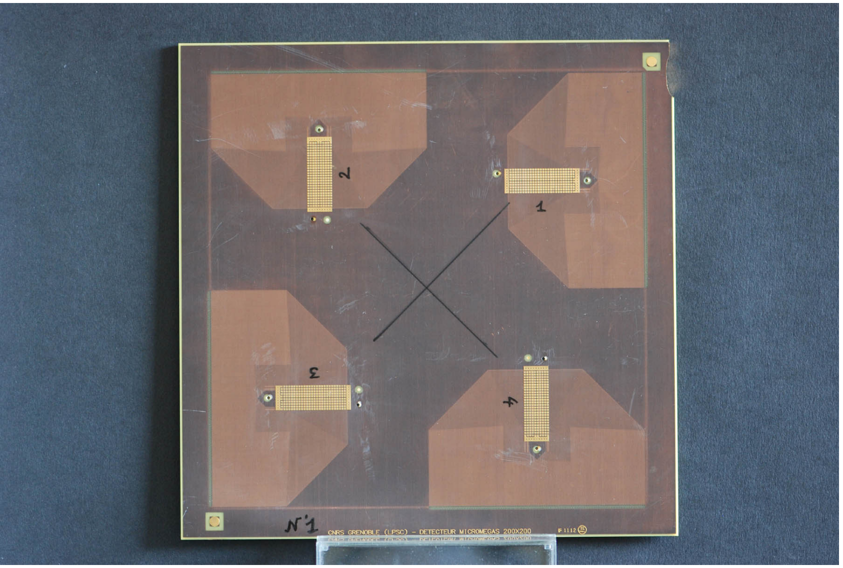


For more information on the comparison:
Couturier et al. (JCAP 2016)

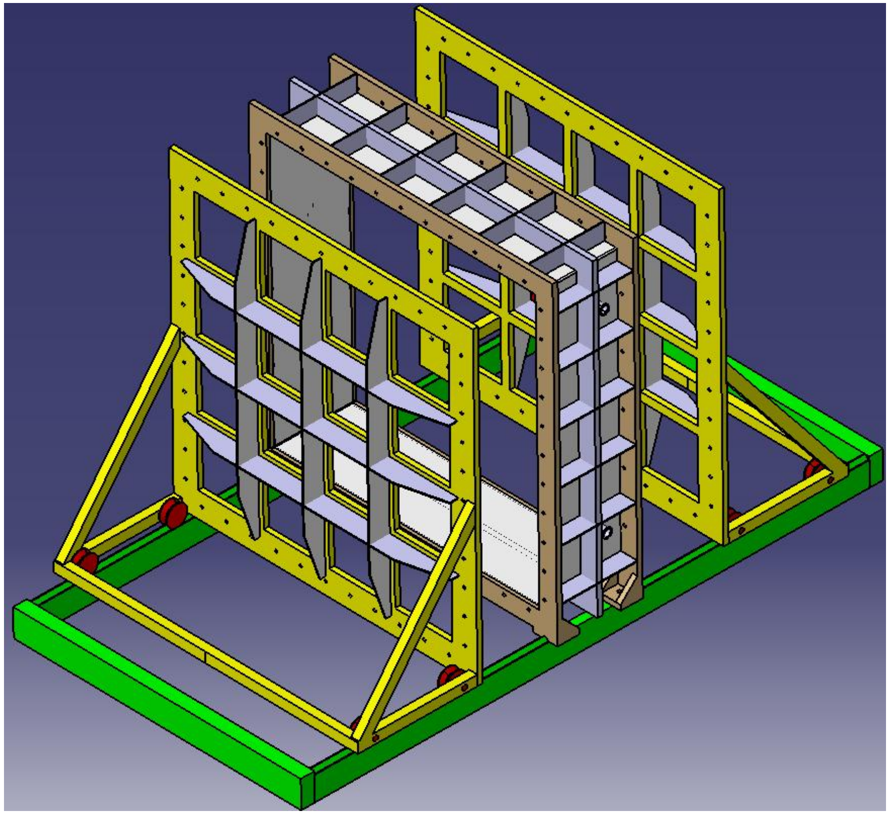
MIMAC – $1m^3$ = 16 bi-chamber modules (2x $35x35x26\ cm^3$)

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

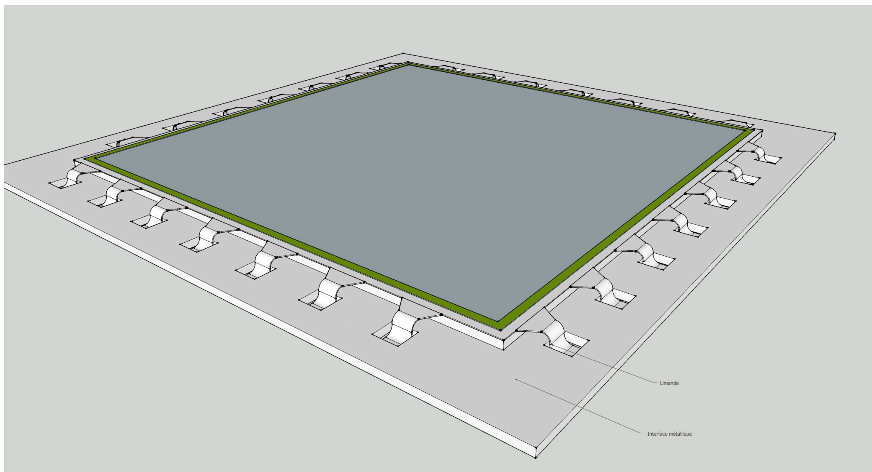


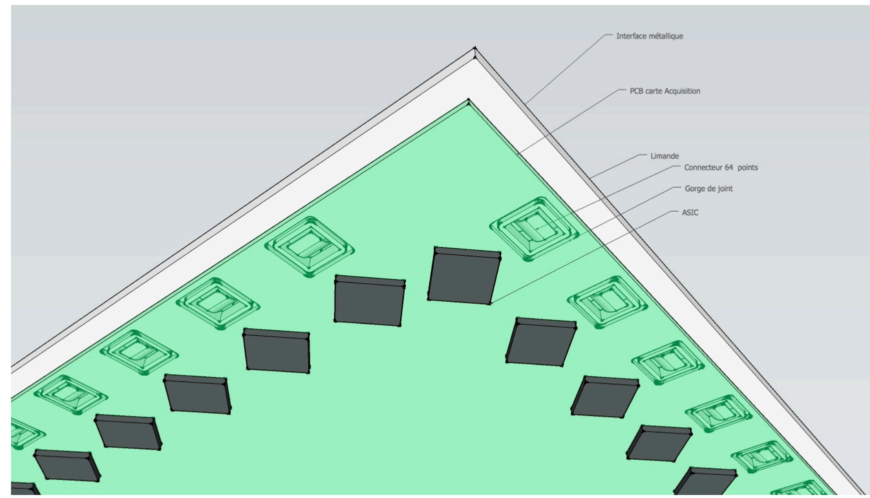


New 20cmx20cm pixellized anode (1024 channels)



New 35 x 35 cm^2 low background detector design
(1920 channels) (O. Guillaudin et al. 2016)



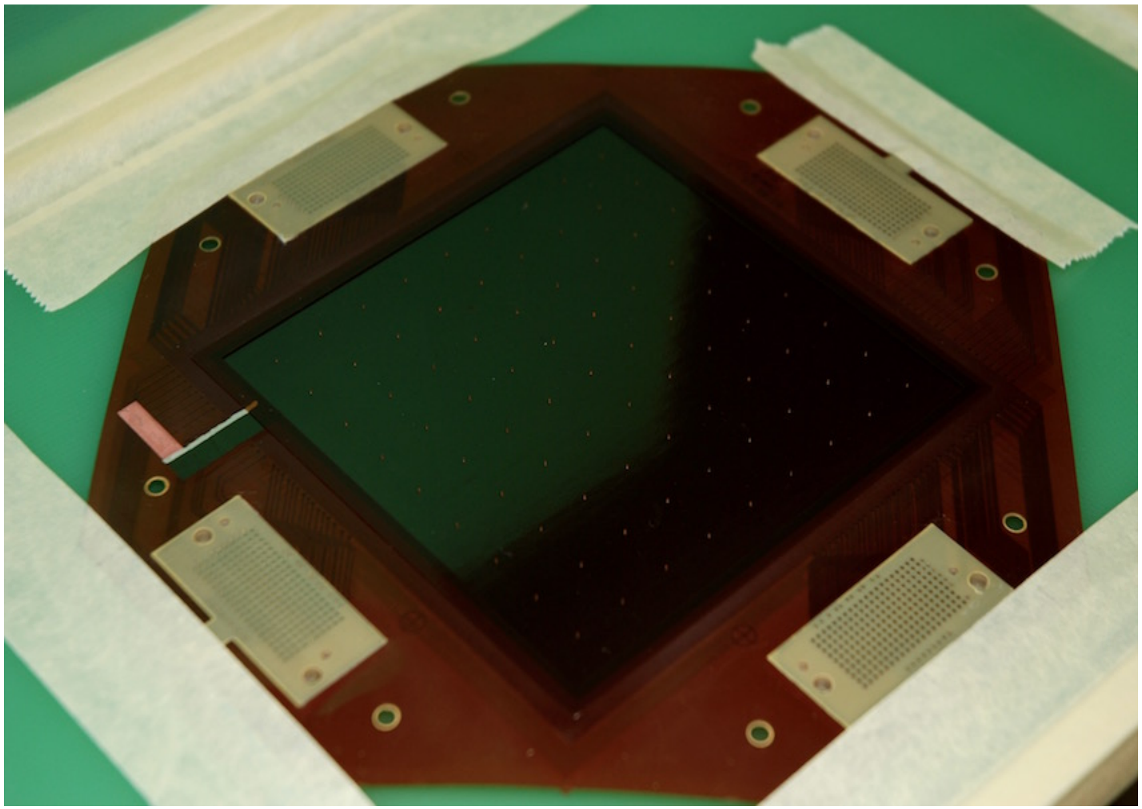


Left: Top view of the new detector design using kapton and plexiglass instead of PCB.

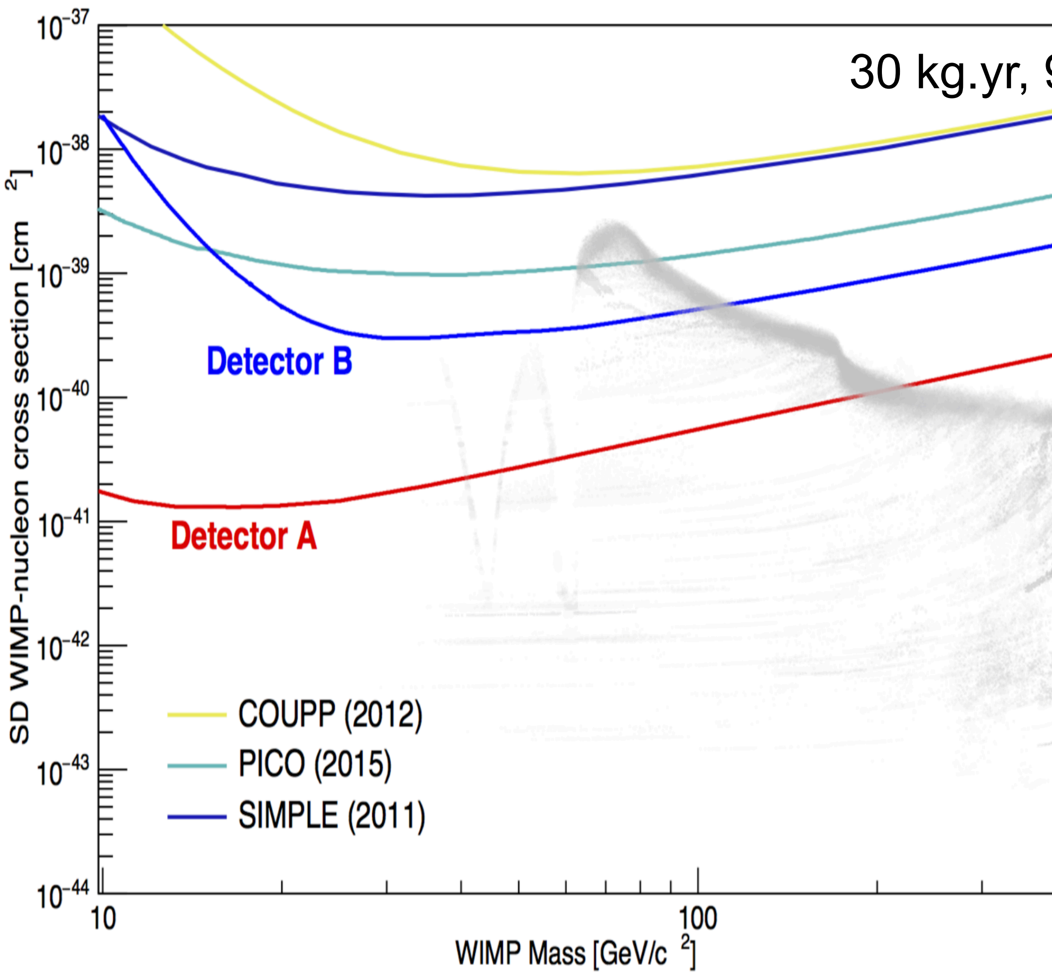
Right: Bottom view, showing the ASICs distribution to minimize the length of the connections.

New low background MIMAC detector prototype (10cmx10cm, 512 channels)(11/2016)

(O.Guillaudin et al. (2016))



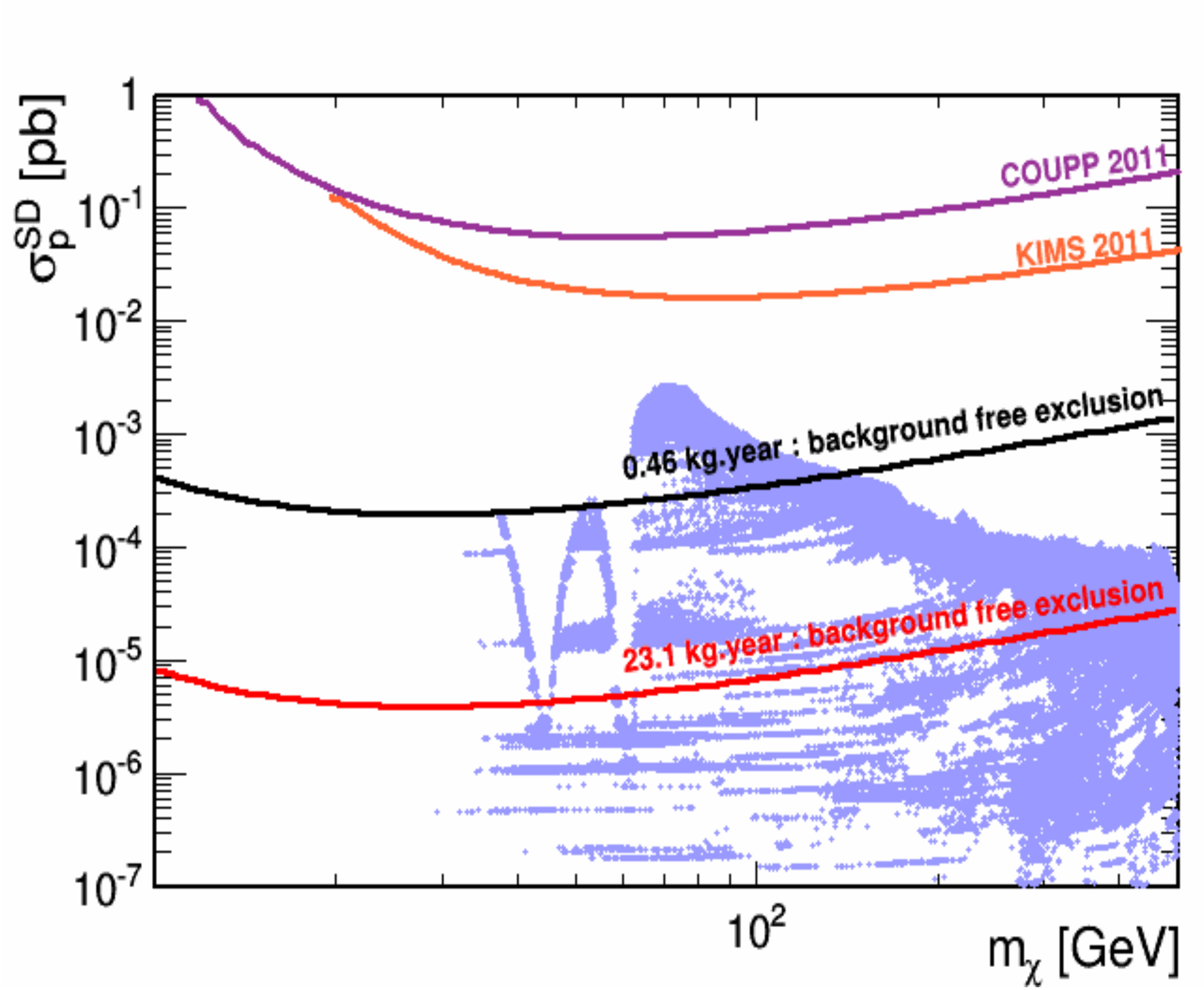
Exclusion limits



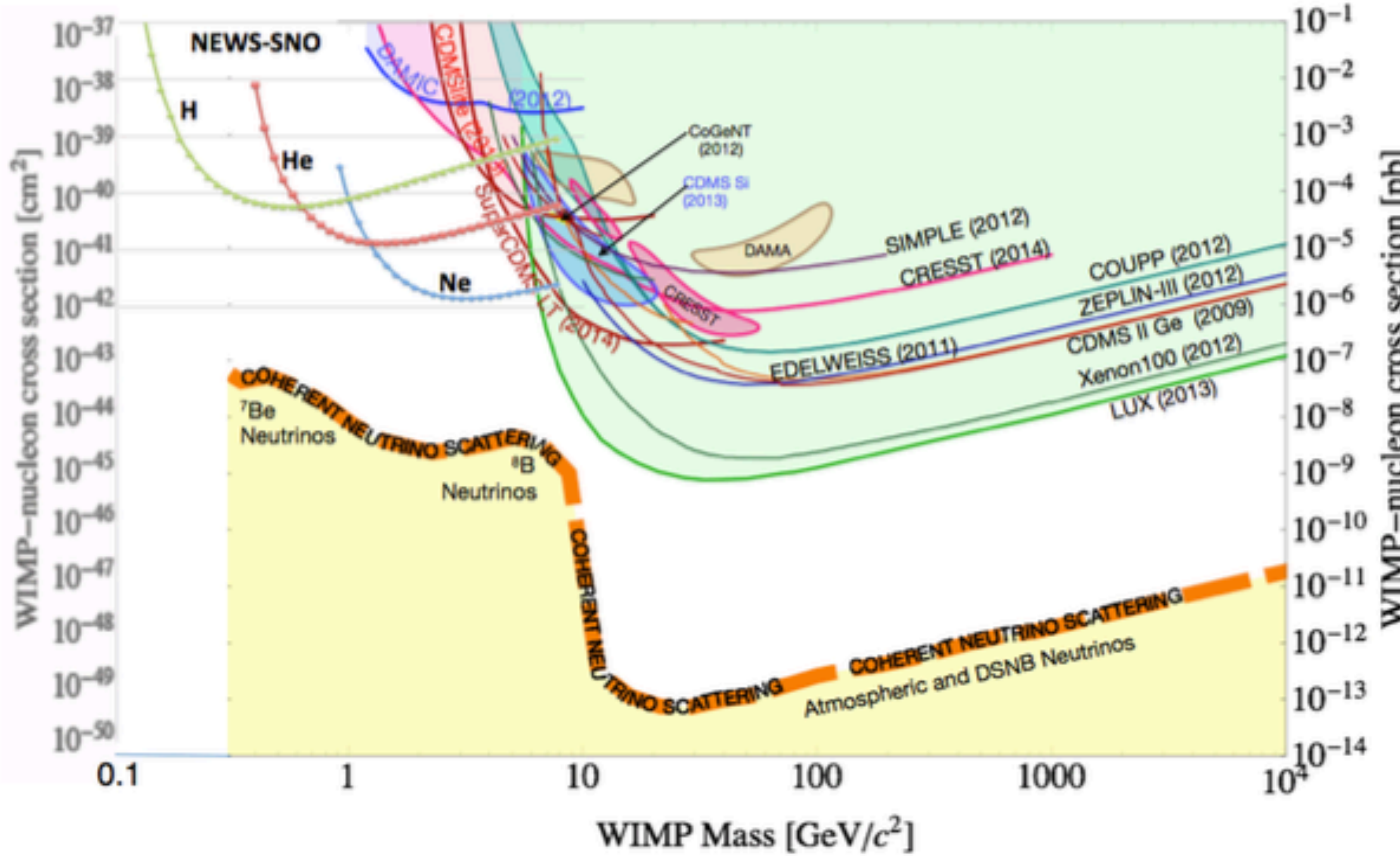
A: 5 keV (threshold)
no background
3D track with head-tail
angular resolution 20°

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

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



WIMP Light Mass window
MIMAC- NEWS complementarity



Conclusions

i) A new directional detector of nuclear recoils at low energies has been developed giving a lot of flexibility on targets, pressure, energy range…

ii) Ionization quenching factor measurements have been determined experimentally and they can be checked in-situ.

iii) 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 versions in June 2013 and June 2014 and it shows an excellent gain stability.

v) For the first time the 3D nuclear recoil tracks from Rn progeny have been observed.

vi) New degrees of freedom are available to discriminate electrons from nuclear recoils to improve the DM search for.

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

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


CYGNUS 2017- International Workshop
Jinping (CHINA) – June 13th- 15th 2017

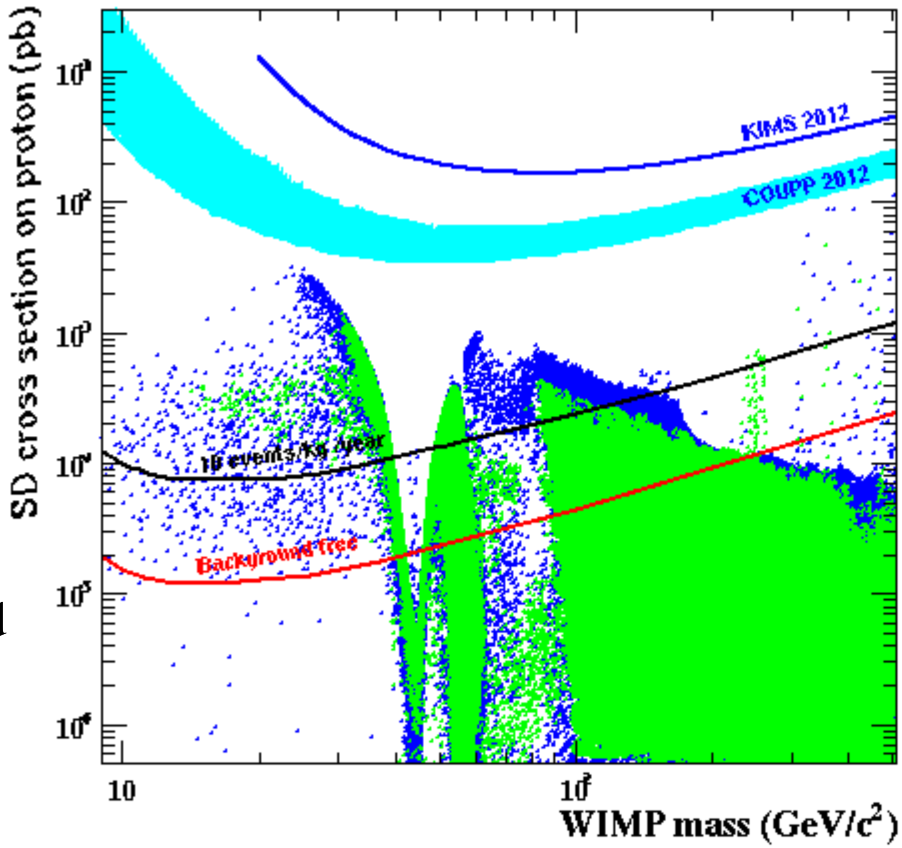
MIMAC Phenomenology: Discovery

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***

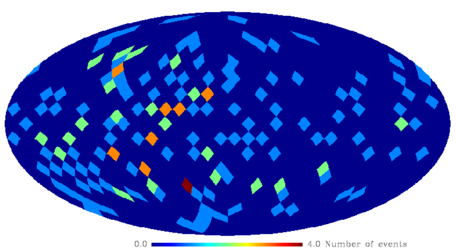
Directional Dark Matter: discovery/exclusion

J. Billard *et al.*, PLB 2010

J. Billard *et al.*, PRD 2010

- ***discovery*** (5σ)

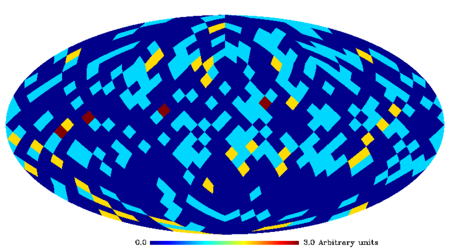
Up to 10^{-4} ***pb***



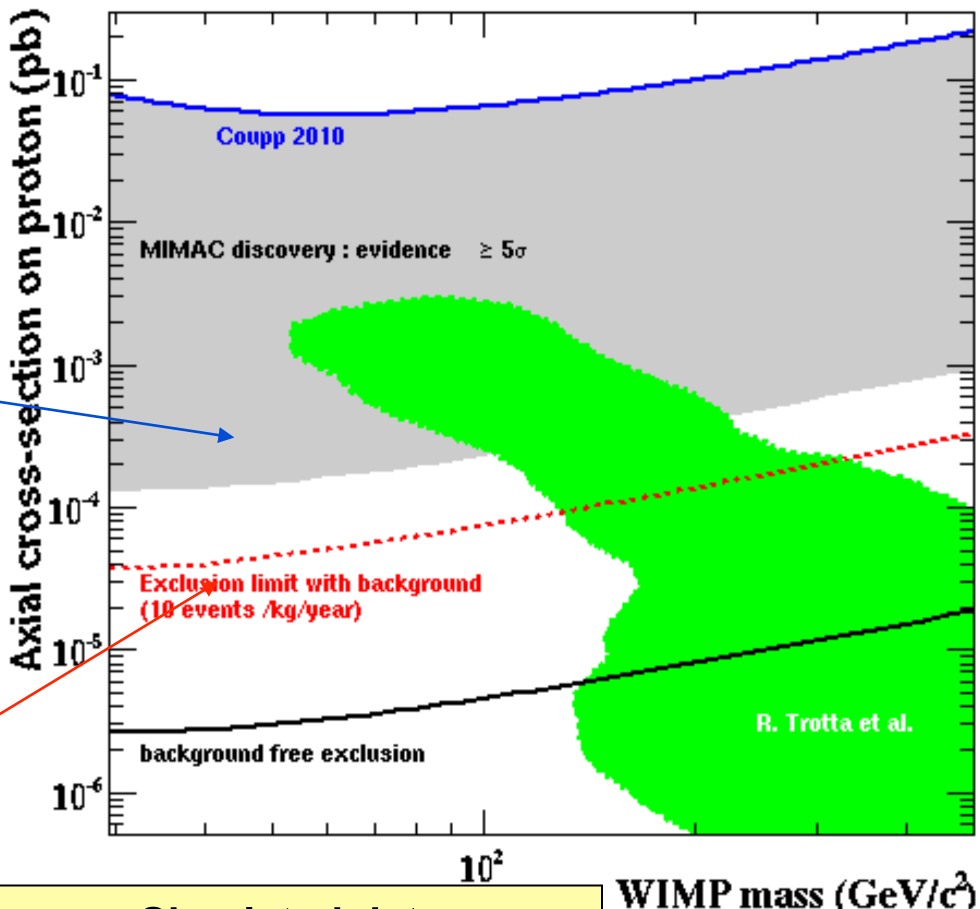
100 WIMP, 100 bkg

- **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°

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]

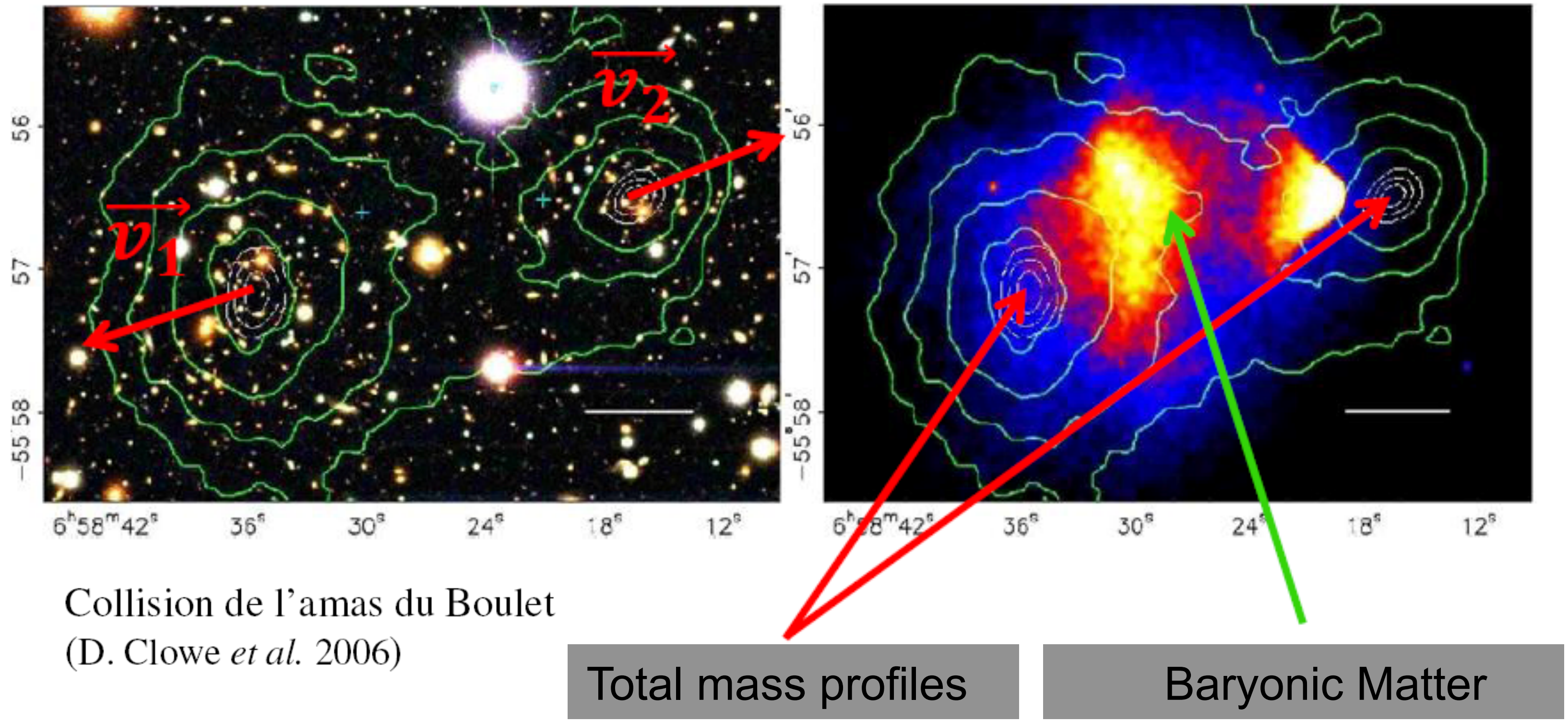
TPC directional detectors

	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]

At the galaxy cluster scale…

(1E0657-558) Z= 0.296



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

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

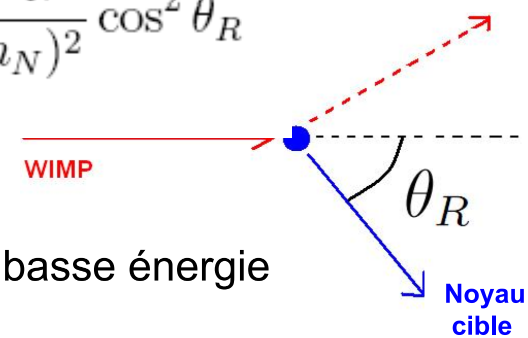
Détection directe : principes

<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) :

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

nucléaire

Astro

SUSY ou Autres…