MIMAC

MIcro-tpc MAtrix of Chambers

for Directional Dark Matter detection and Axion-Like-Particle Exploration

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MIMAC (MIcro-tpc MAtrix of Chambers)

LPSC (Grenoble) : D. Santos, F.Naraghi , N. Sauzet, C. Beaufort (Ph.D)

-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**

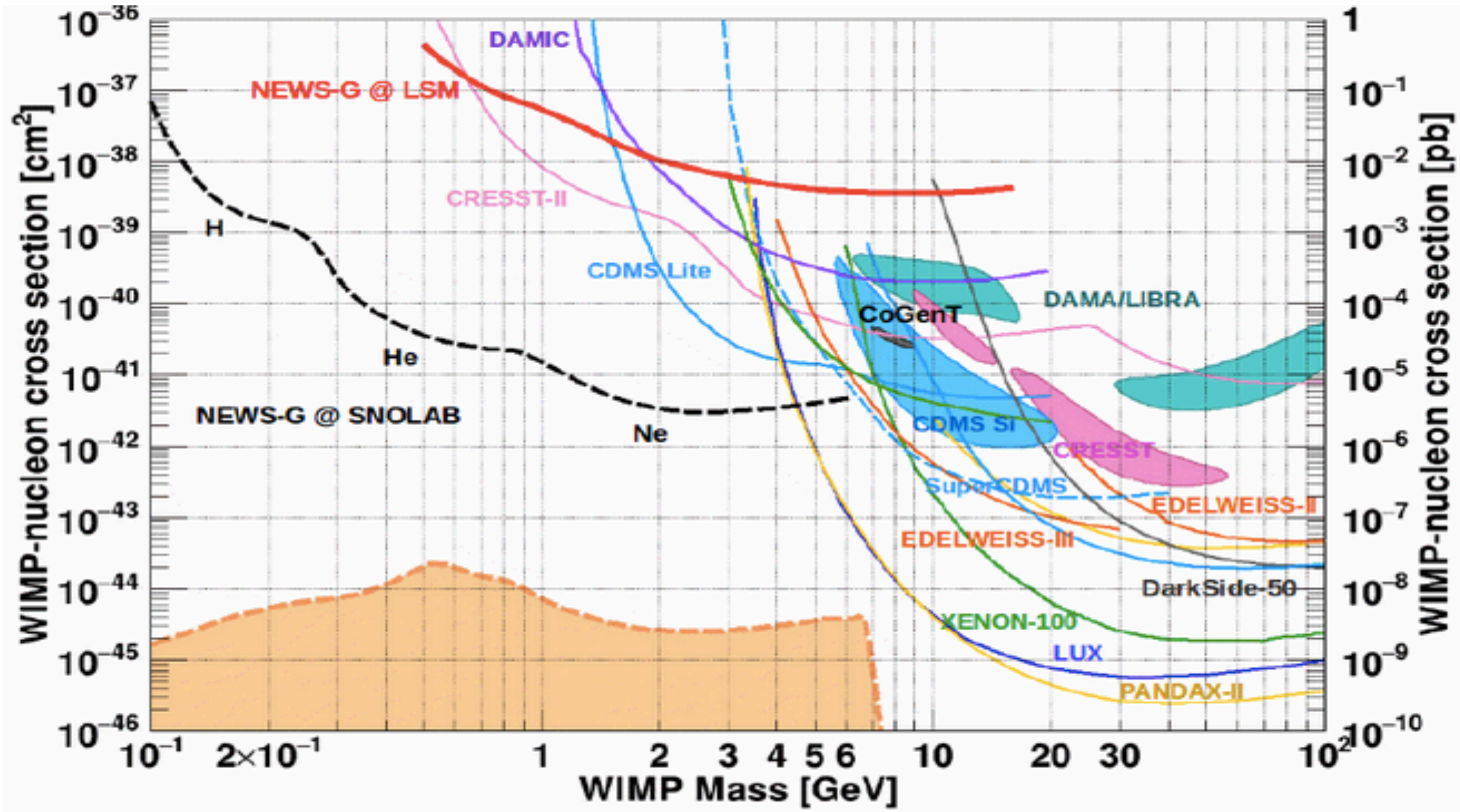
IRFU (Saclay): P. Colas, I. Giomataris

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

Tsinghua University (Beijing-China): Y. Tao (Ph.D)

Prototype hosted in **IHEP (Beijing-China)**: **ZhiminWang , Changgen Yang**

WIMP Light Mass window
MIMAC- NEWS-G complementarity



WIMP Light Mass window
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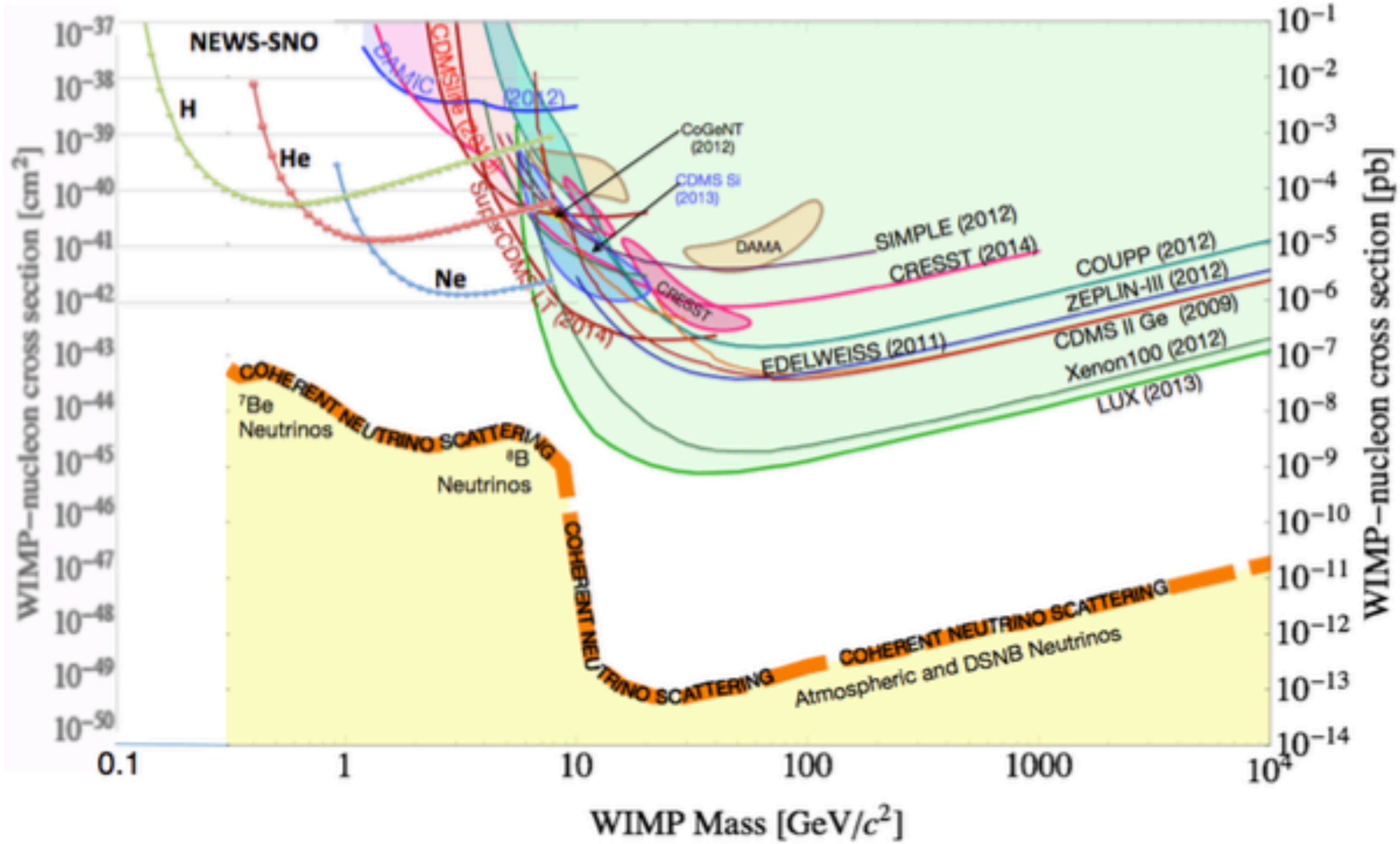

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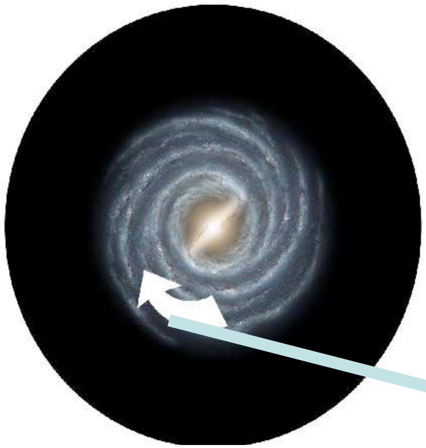
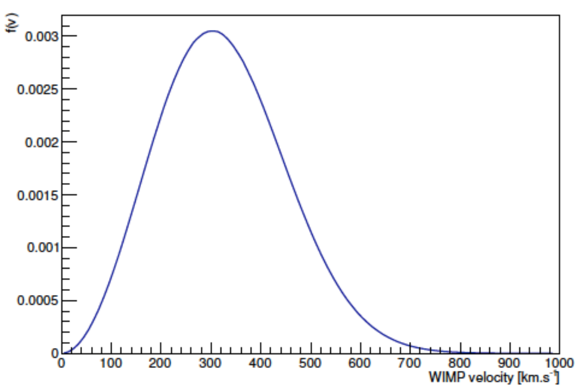
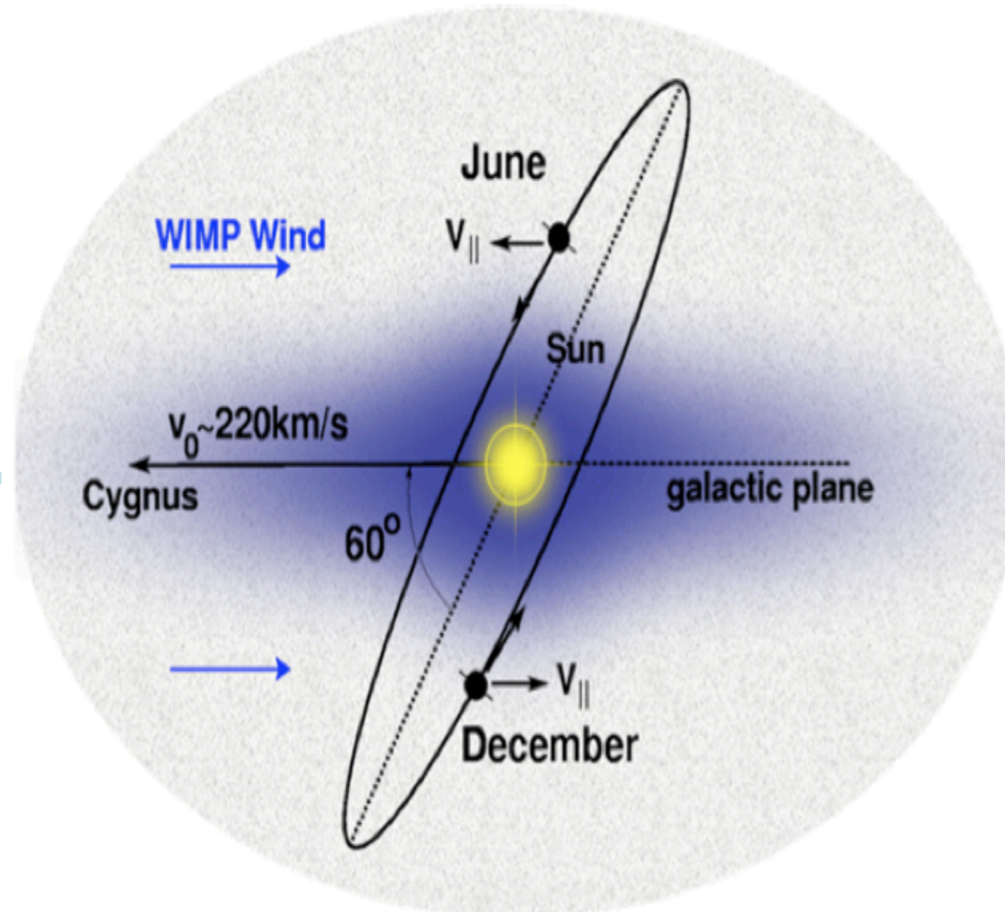
Directional detection: principle



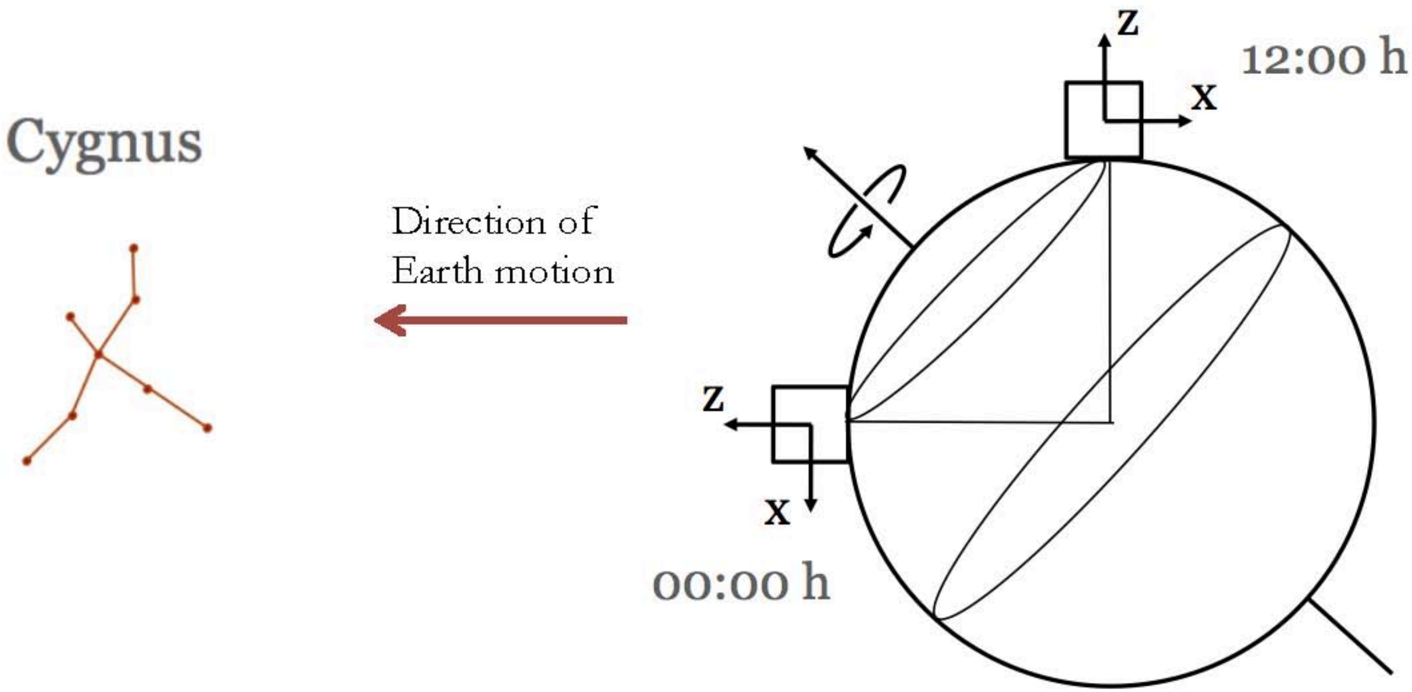




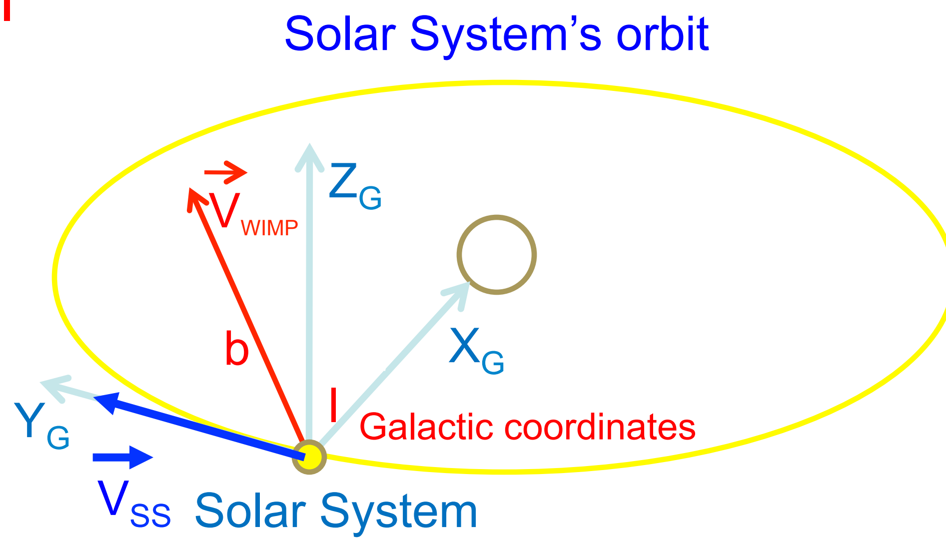
The signature able to correlate the rare events in a detector to the galactic halo !!

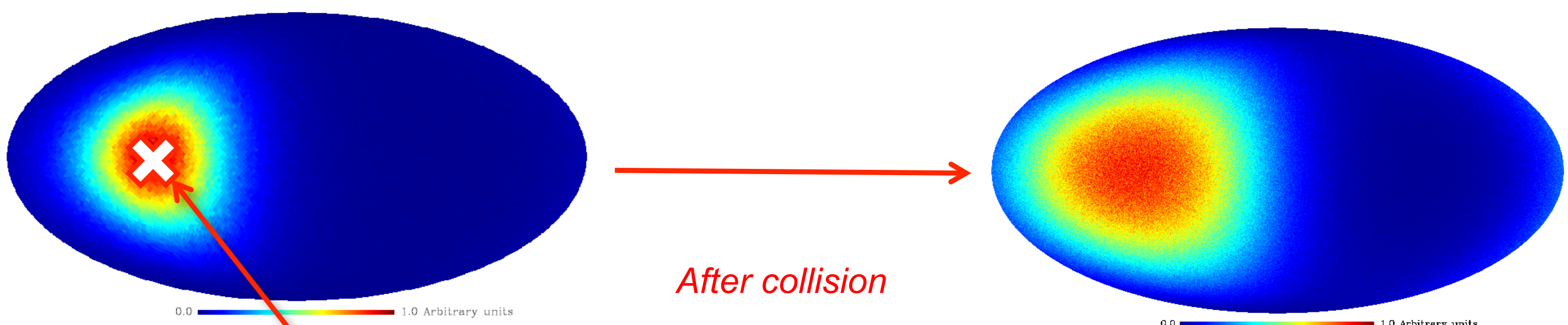
Angular modulation of WIMP flux

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



WIMP signal

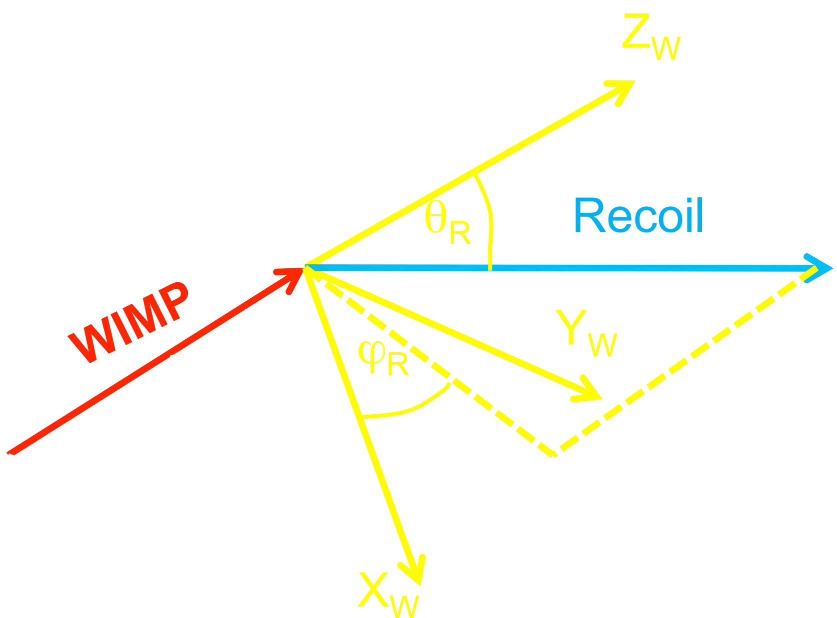


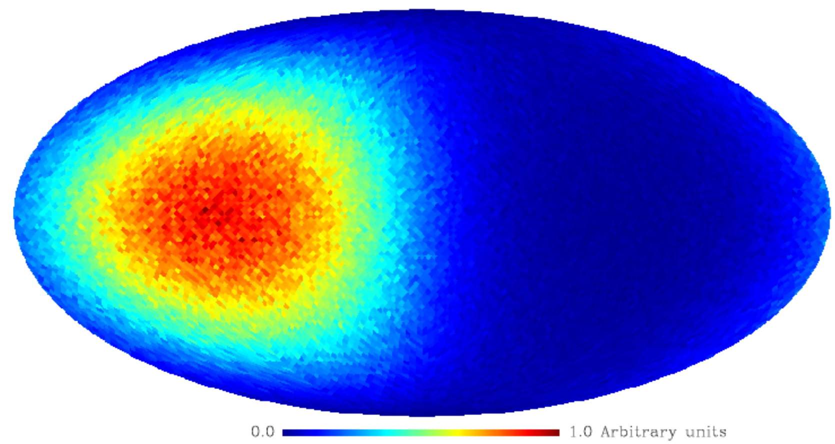


Cygnus Constellation (l = 90°,b = 0°)

WIMP signal expected

There are many "angles" for nuclear recoils…
3D tracks are needed…



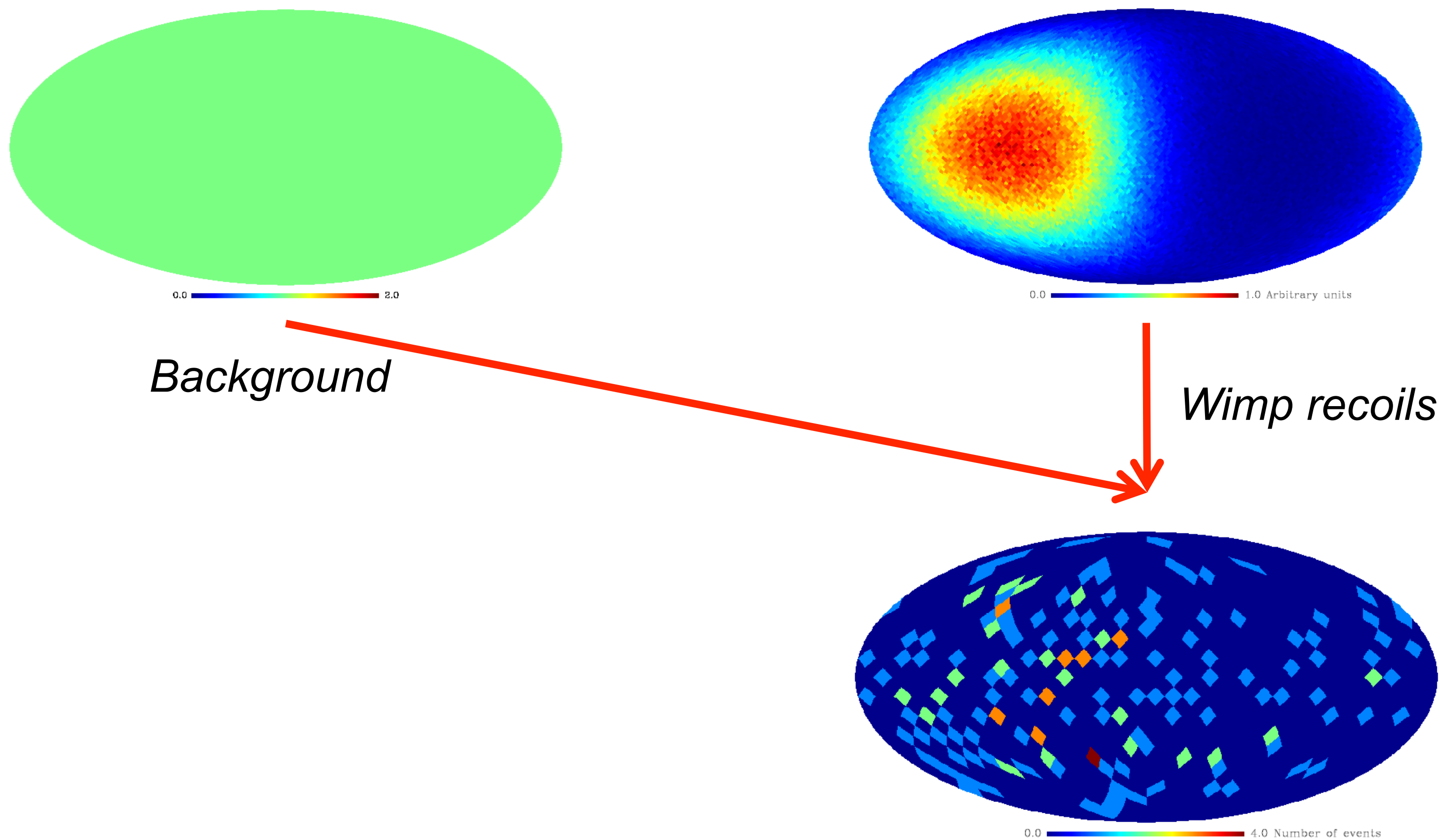


Map of recoils in galactic coordinates (HealPix)

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

Robust with respect to Background events

100 WIMP evts + 100 Background evts

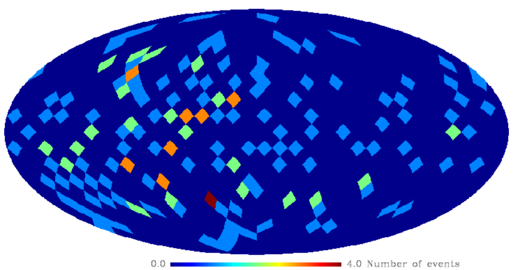


Phenomenology: Discovery

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

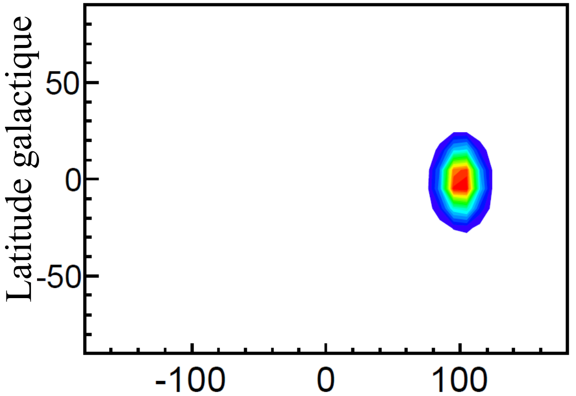
Proof of discovery: **Signal pointing toward the Cygnus constellation**

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



100 WIMP + 100 BKG

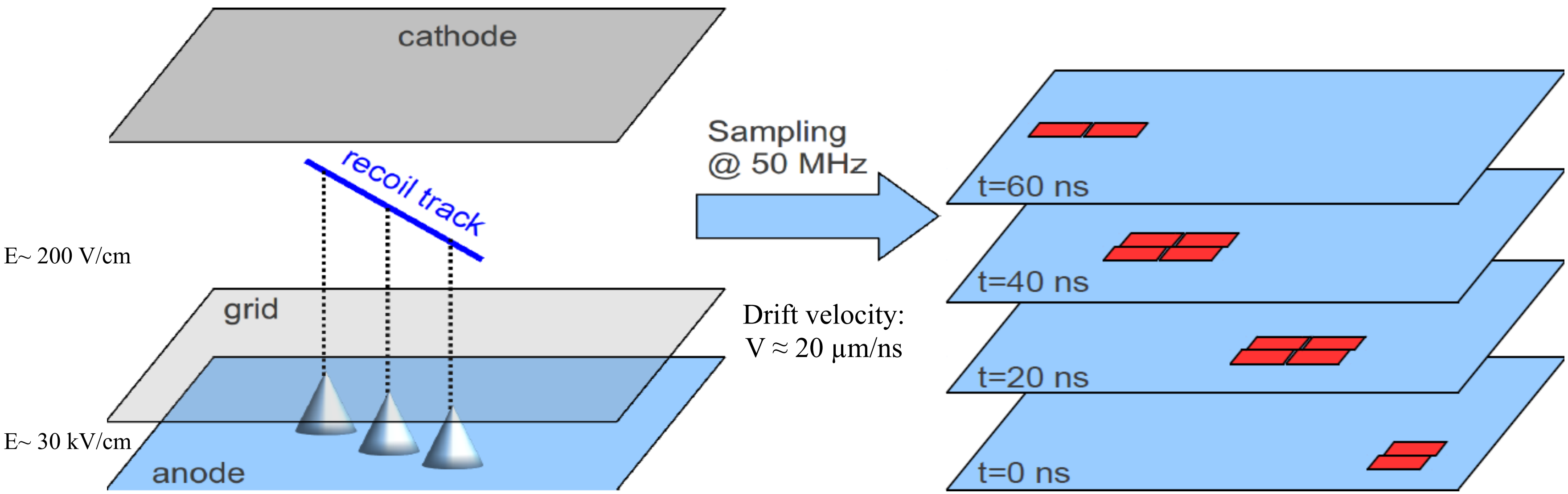
$$\mathscr{L}(\ell, b, m_\chi, \lambda)$$



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

Directional experiments around the world

MIMAC: Detection strategy



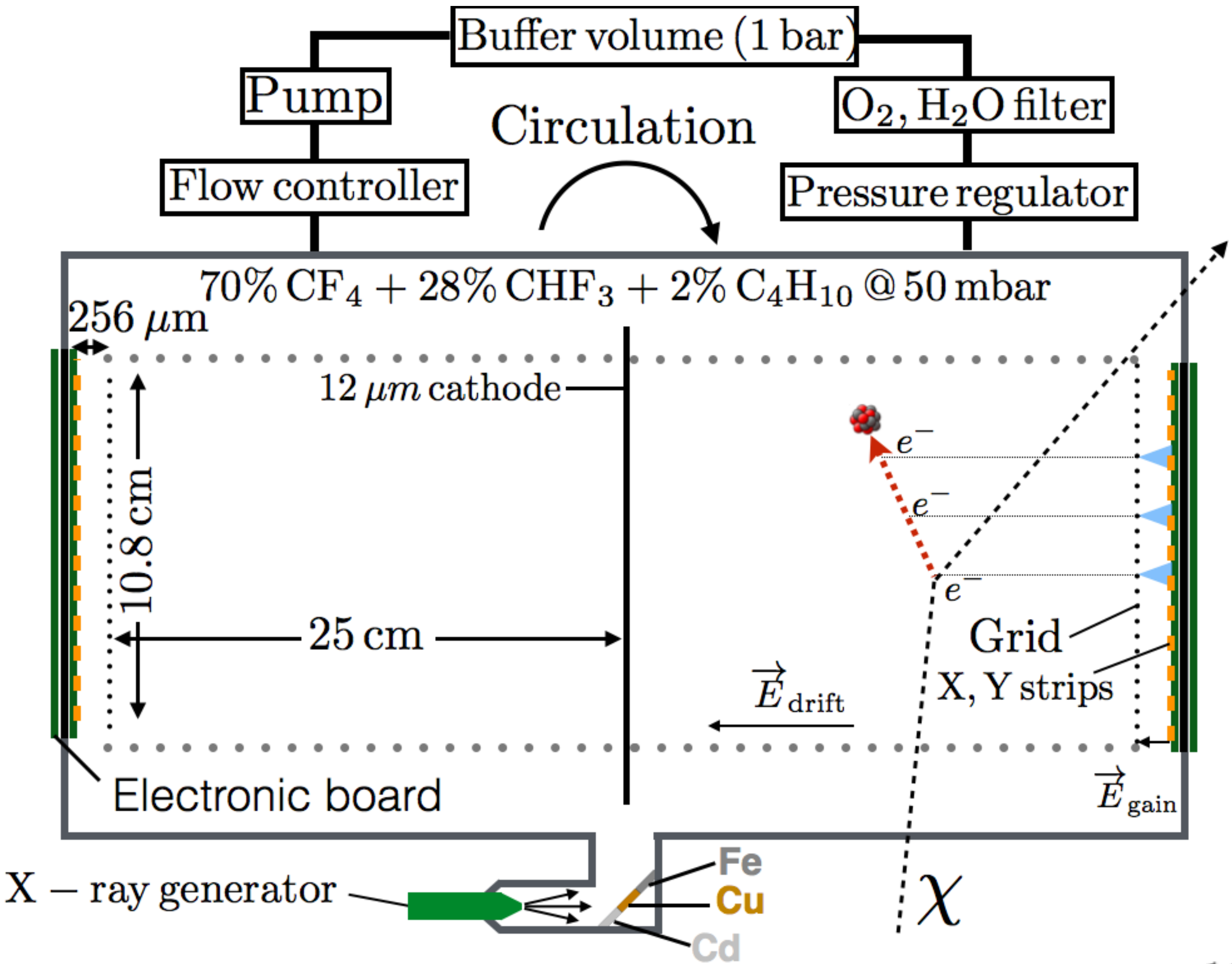
Scheme of a MIMAC µTPC

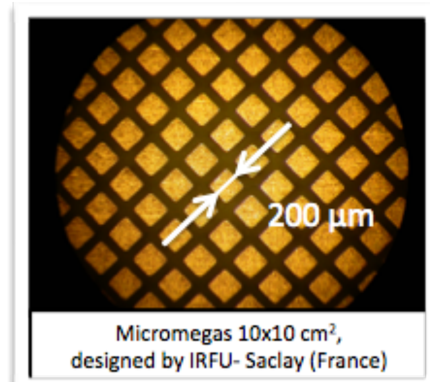
Evolution of the collected charges on the anode

Measurement of the ionization energy:

Charge integrator connected to the mesh coupled to a FADC sampled at 50 MHz

MIMAC-bi-chamber module prototype





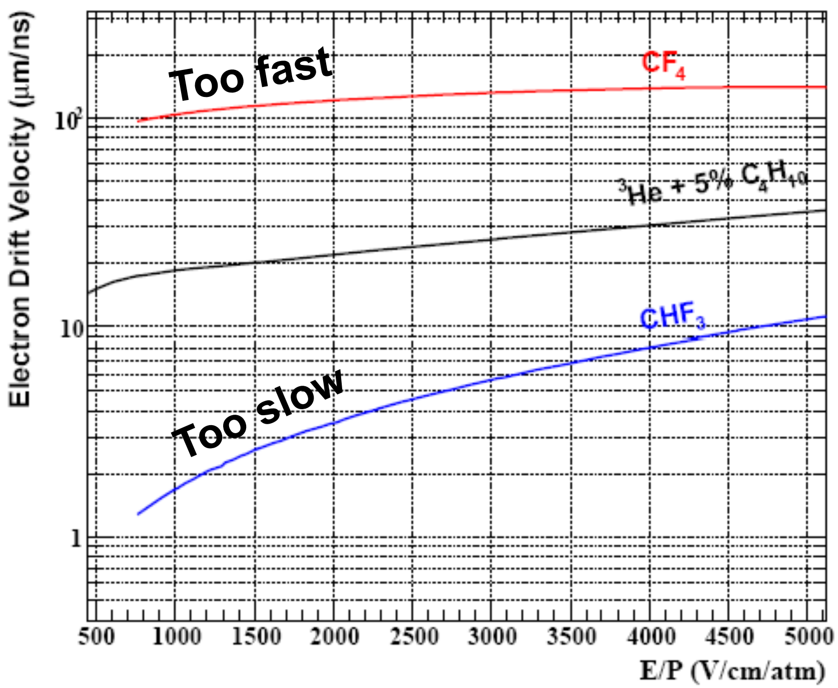
Micromegas 10x10 cm², designed by IRFU- Saclay (France)

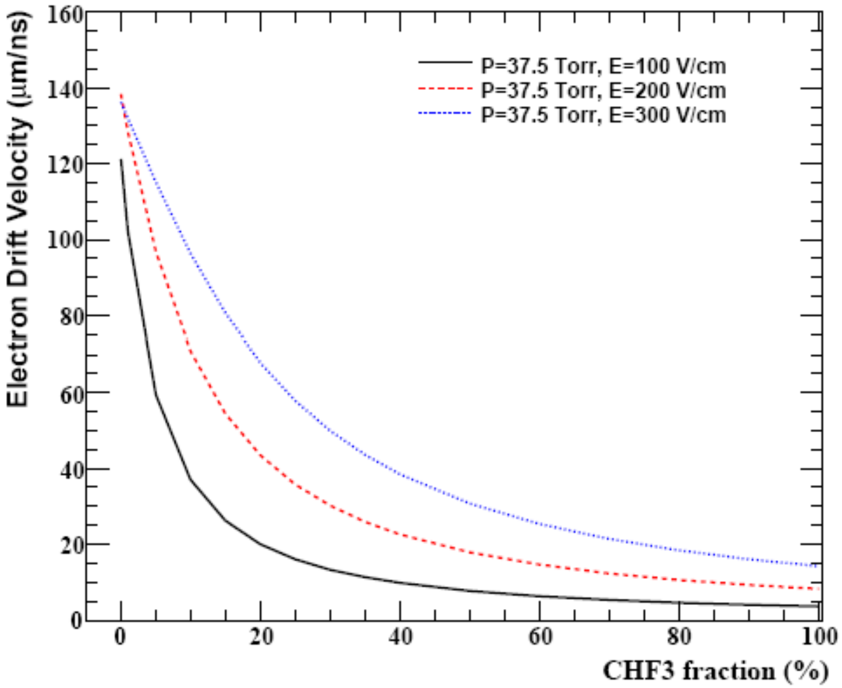
MIMAC Target: ^{19}F

- Light WIMP mass
- Axial coupling

3D Tracks: Drift velocity

Magboltz Simulation





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

MIMAC (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

In any case one needs to measure the ionization released by the particles in the active volume

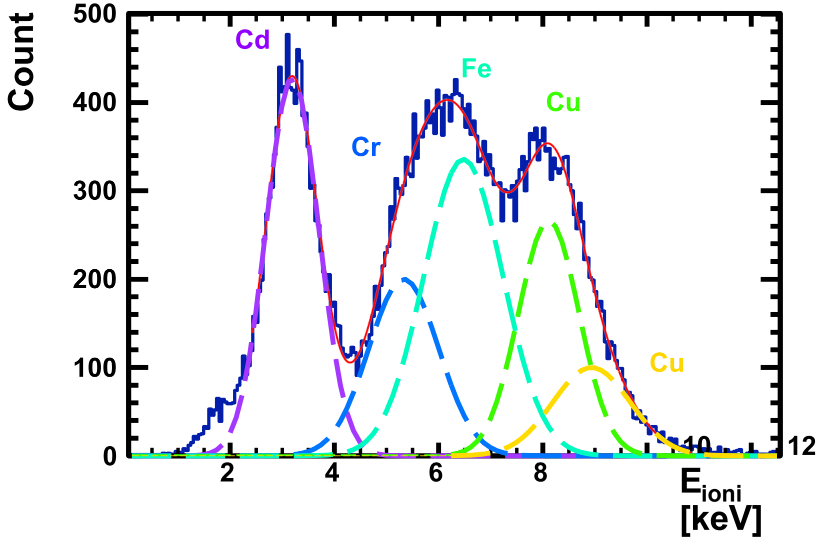
Example of calibration (MIMAC)

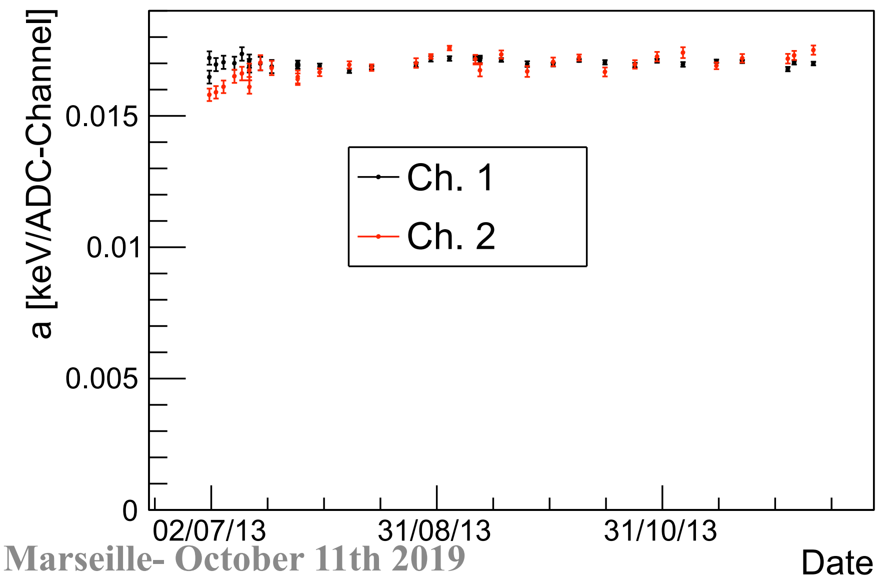
X-ray generator producing fluorescence photons from Cd, Fe, Cu foils.

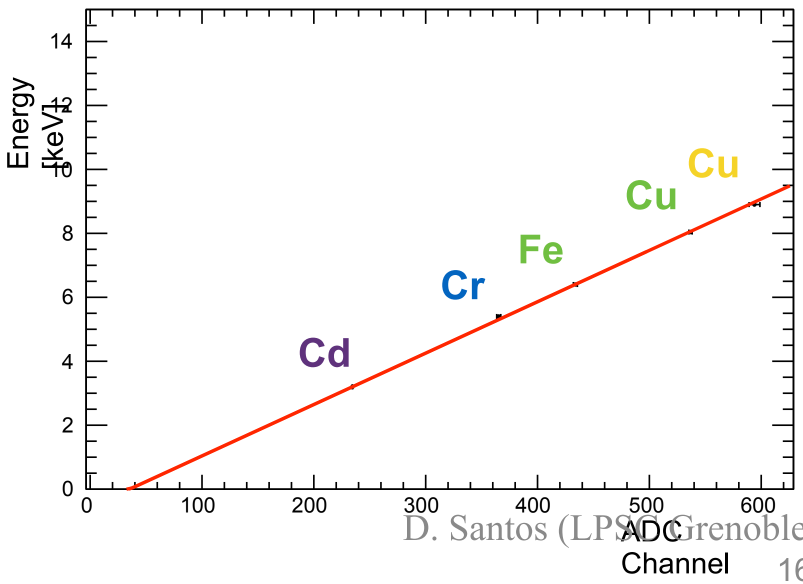
Threshold ~ 1 keV

Circulation system:

Excelent Gain stability in time



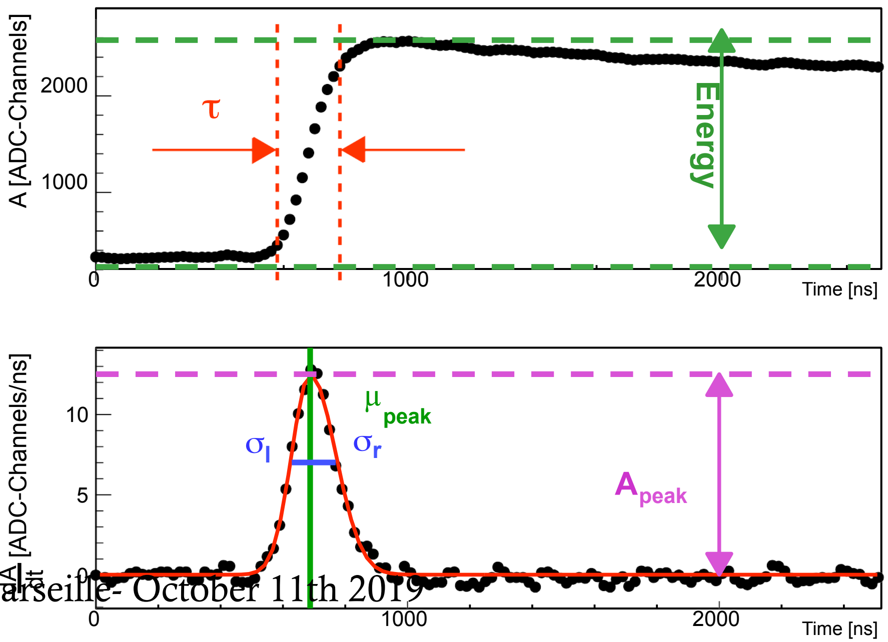




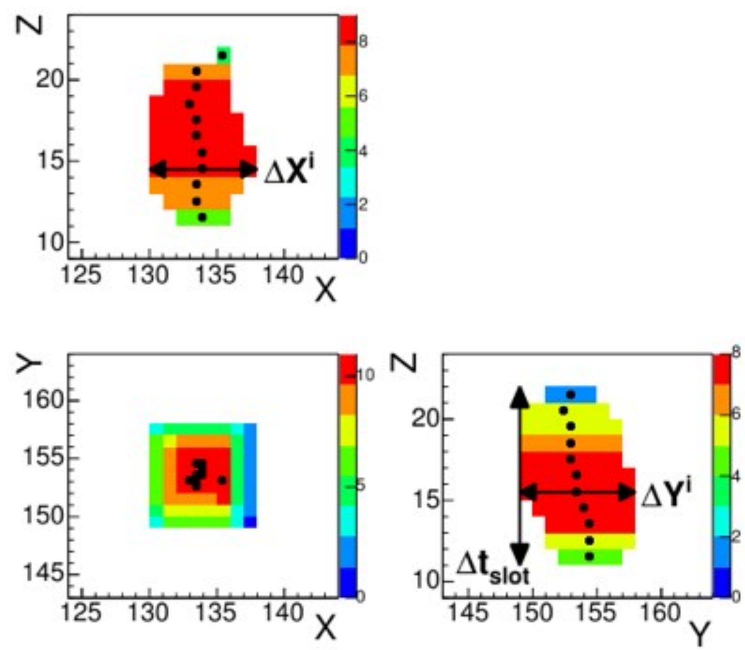
MIMAC readout

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

preamplifier signal + FADC: Energy



3D - track



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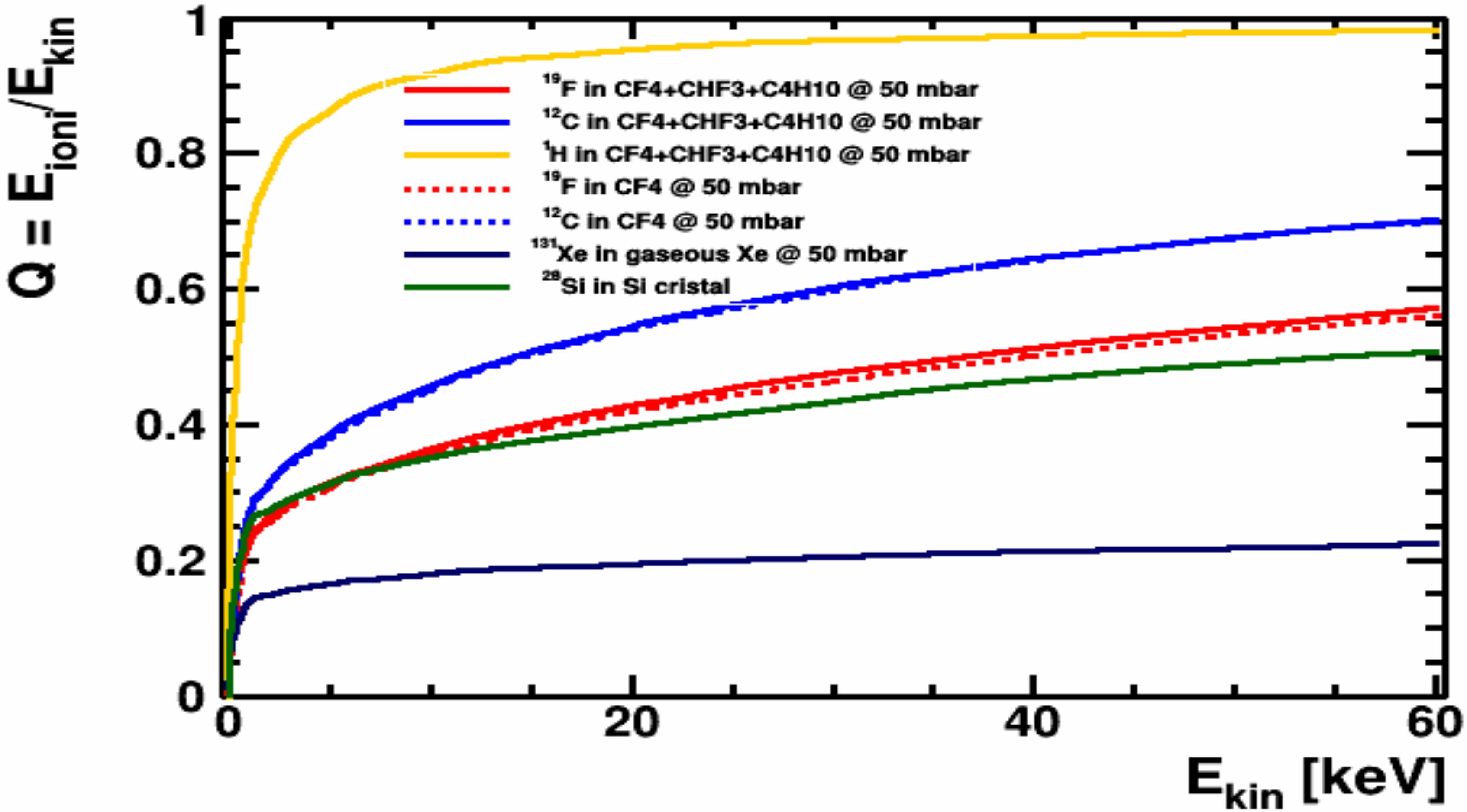
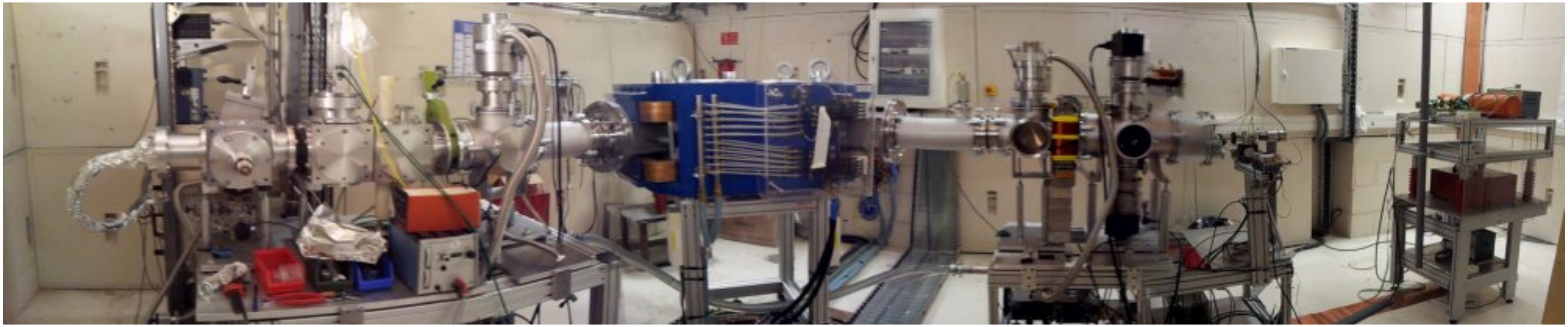
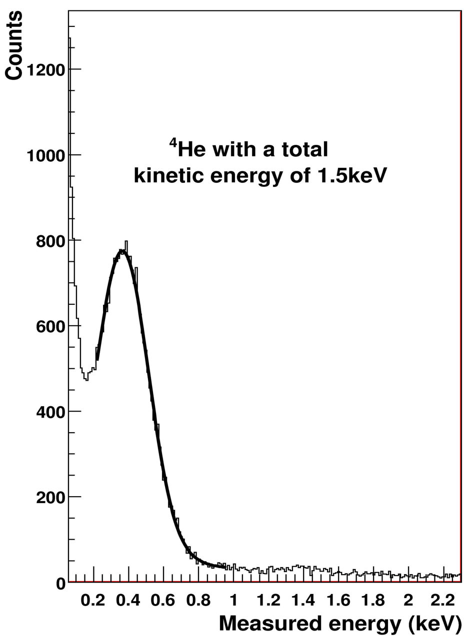
Ionization Quenching Factors

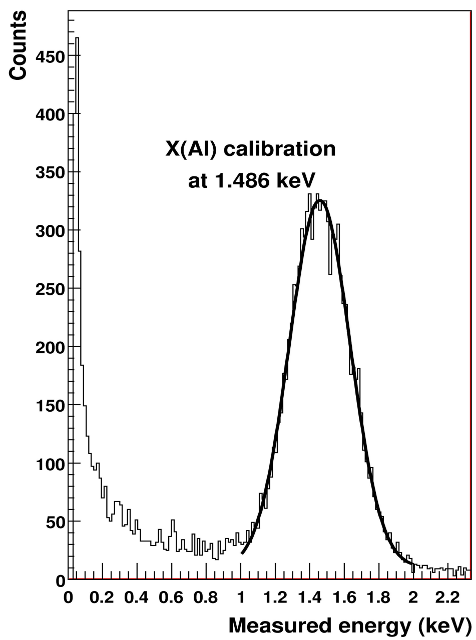
SRIM-Simulations (LPSC)

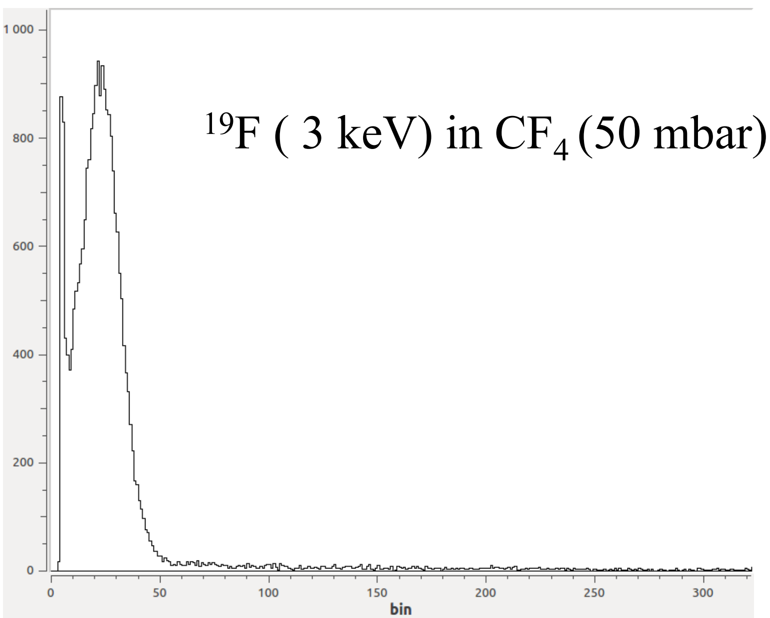


Ionization Quenching Factor Measurements at LPSC-Grenoble





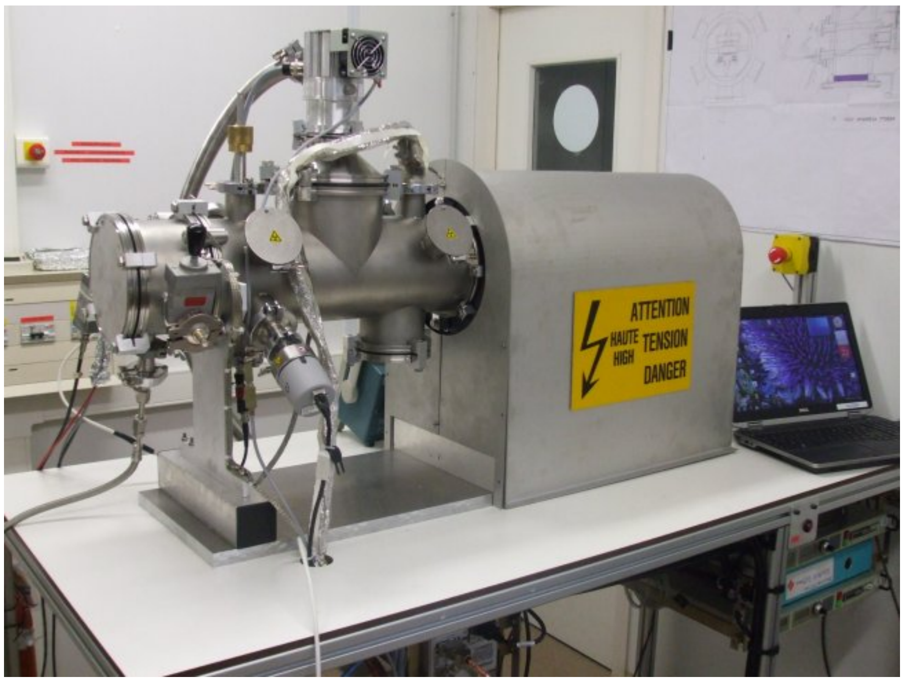


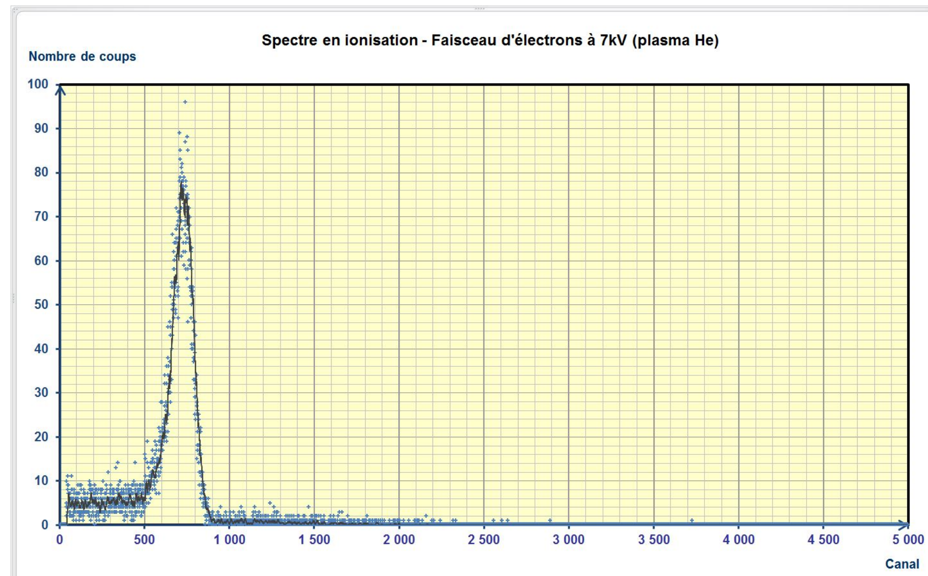


^{19}F (3 keV) in CF_4 (50 mbar)

Portable Quenching Facility (COMIMAC)

(Electrons and Nuclei of known energies)

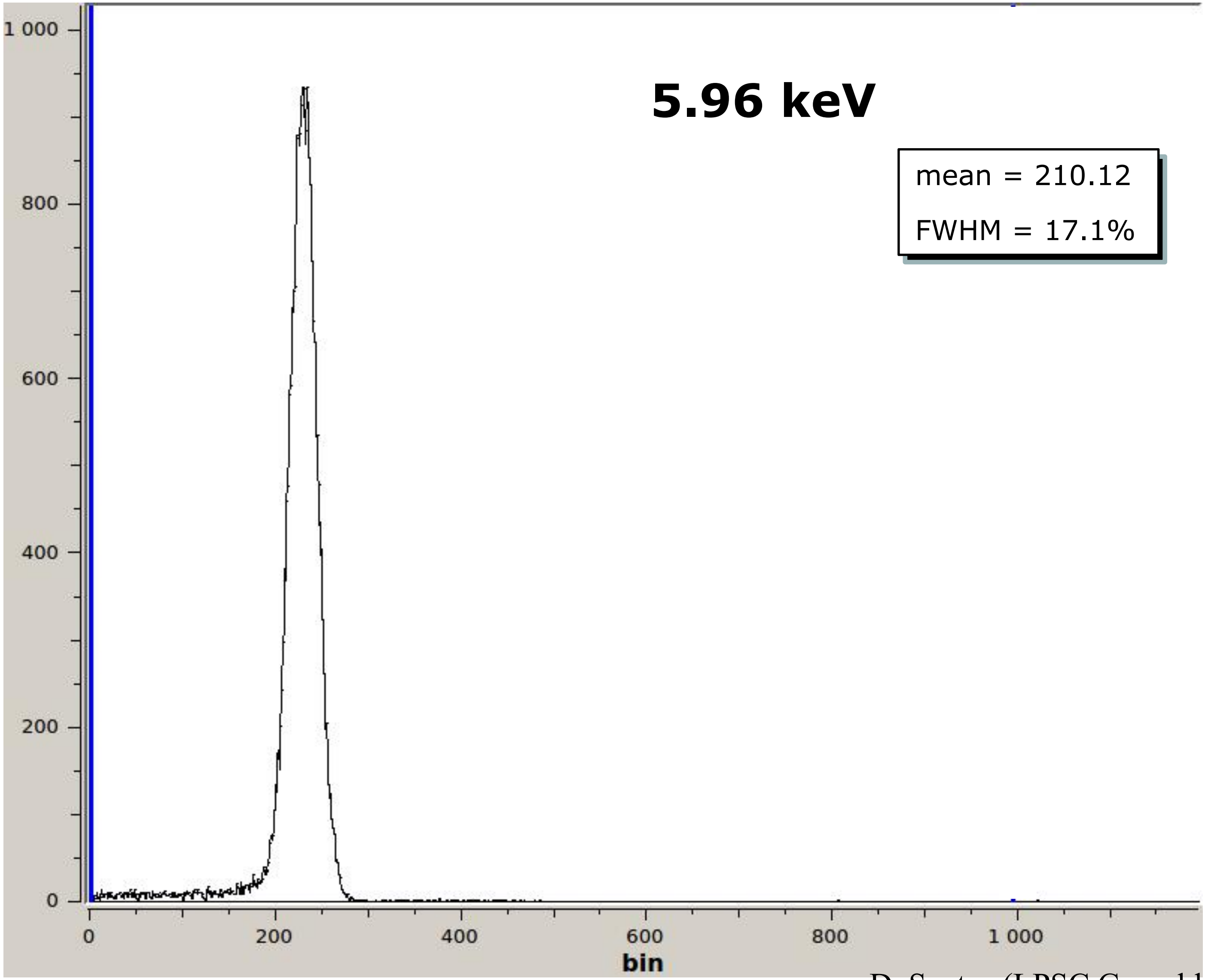




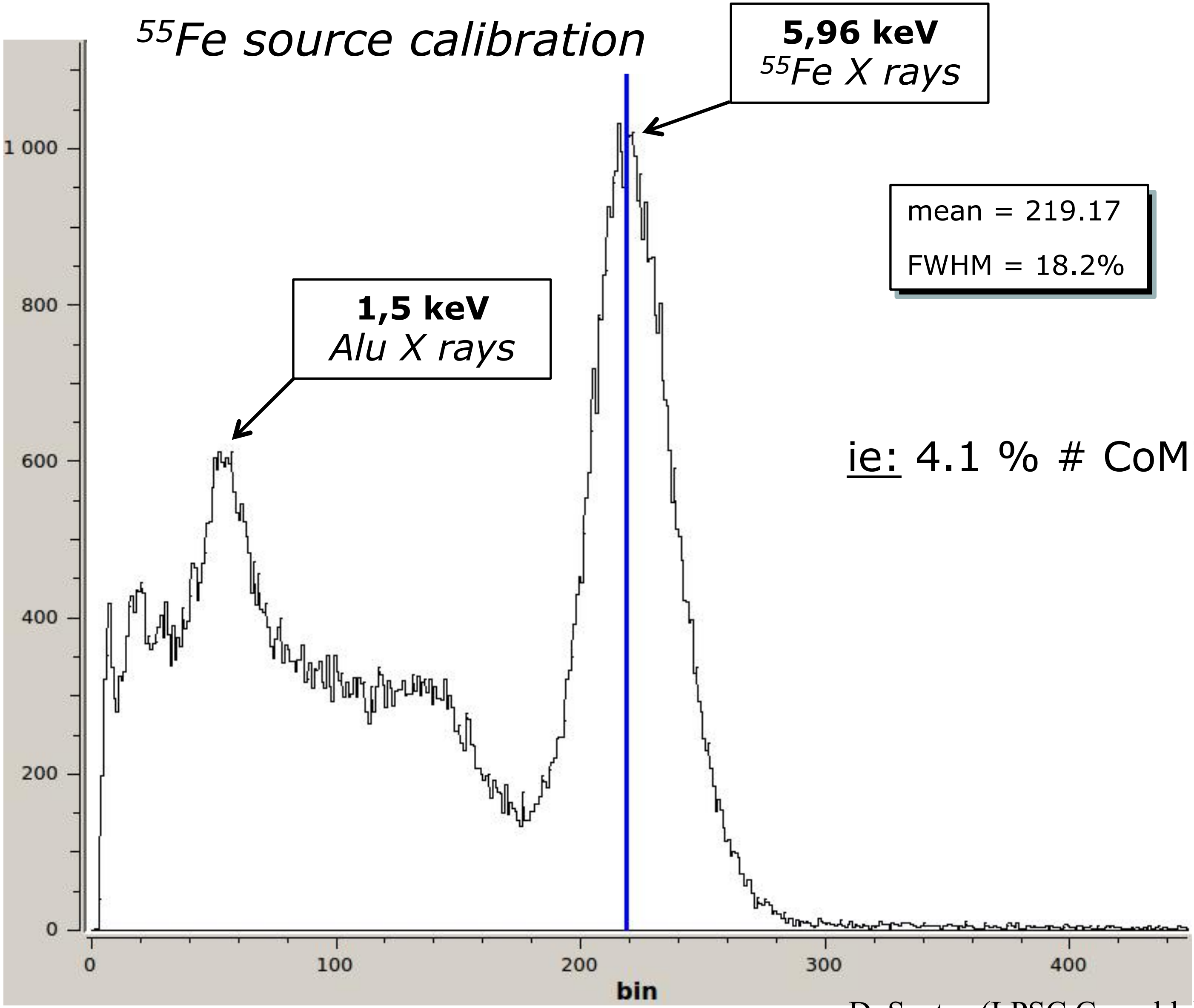
Electrons of 7 keV

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.

Electrons Performance

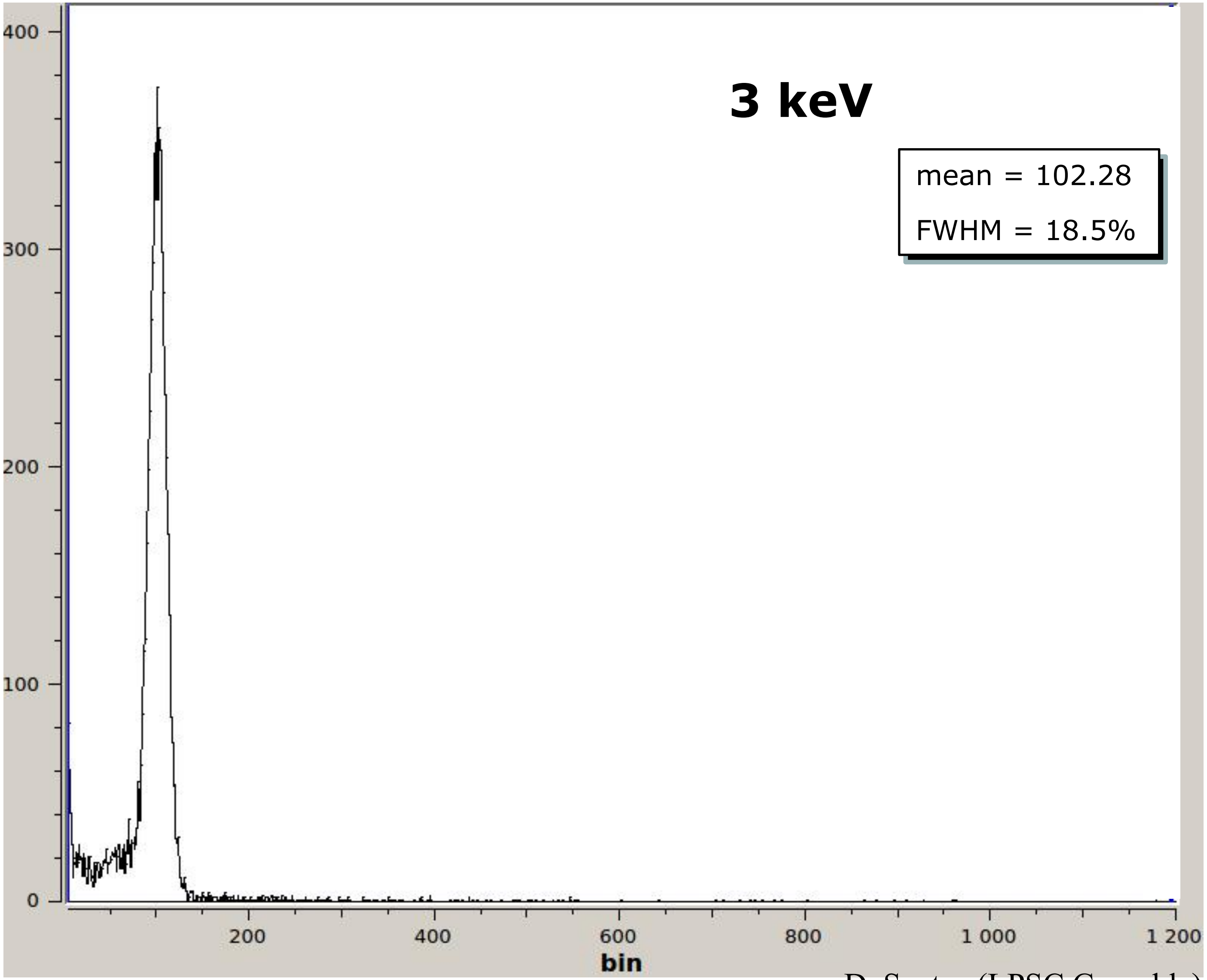


Electrons Performance

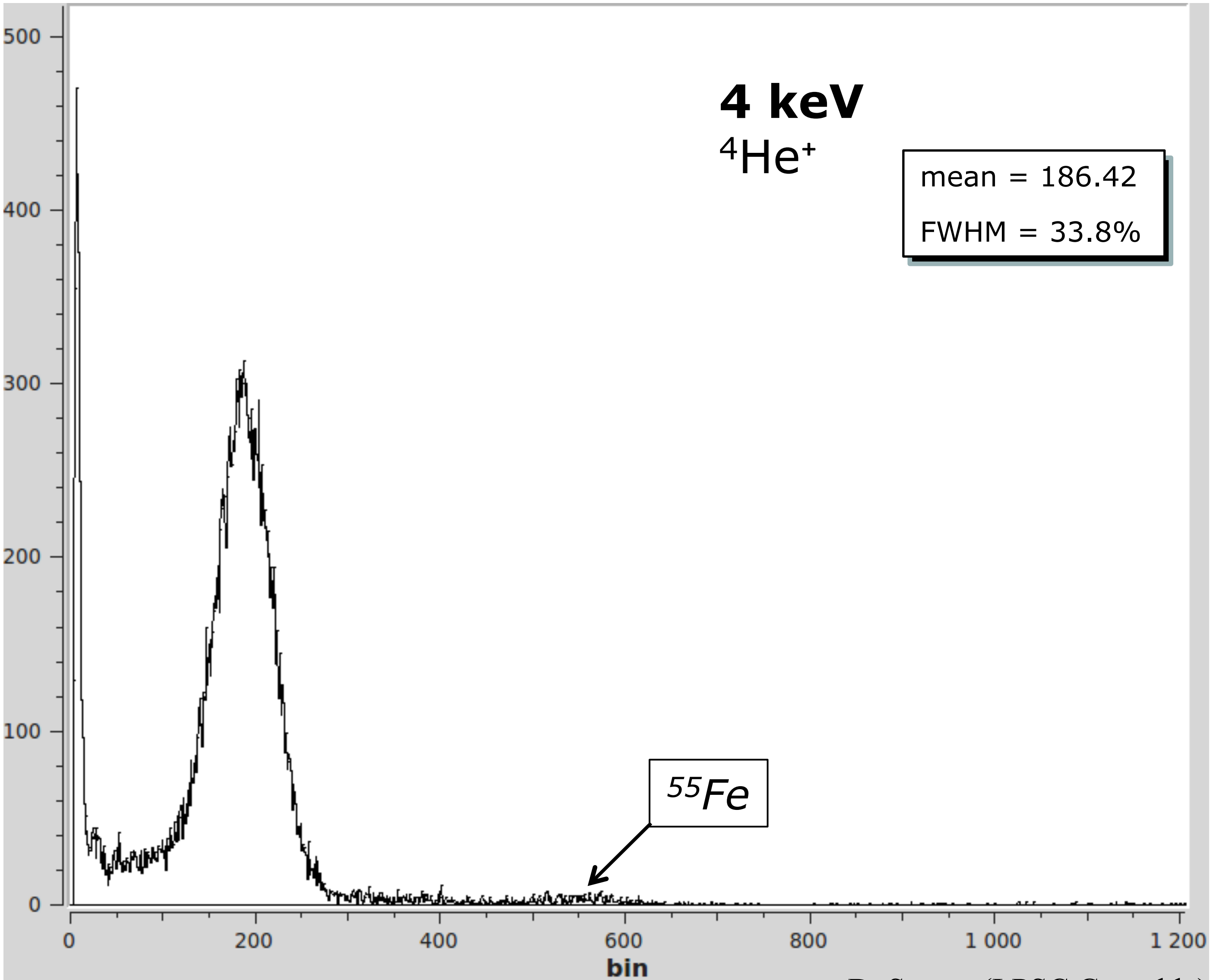


ie: 4.1 % # CoMimac

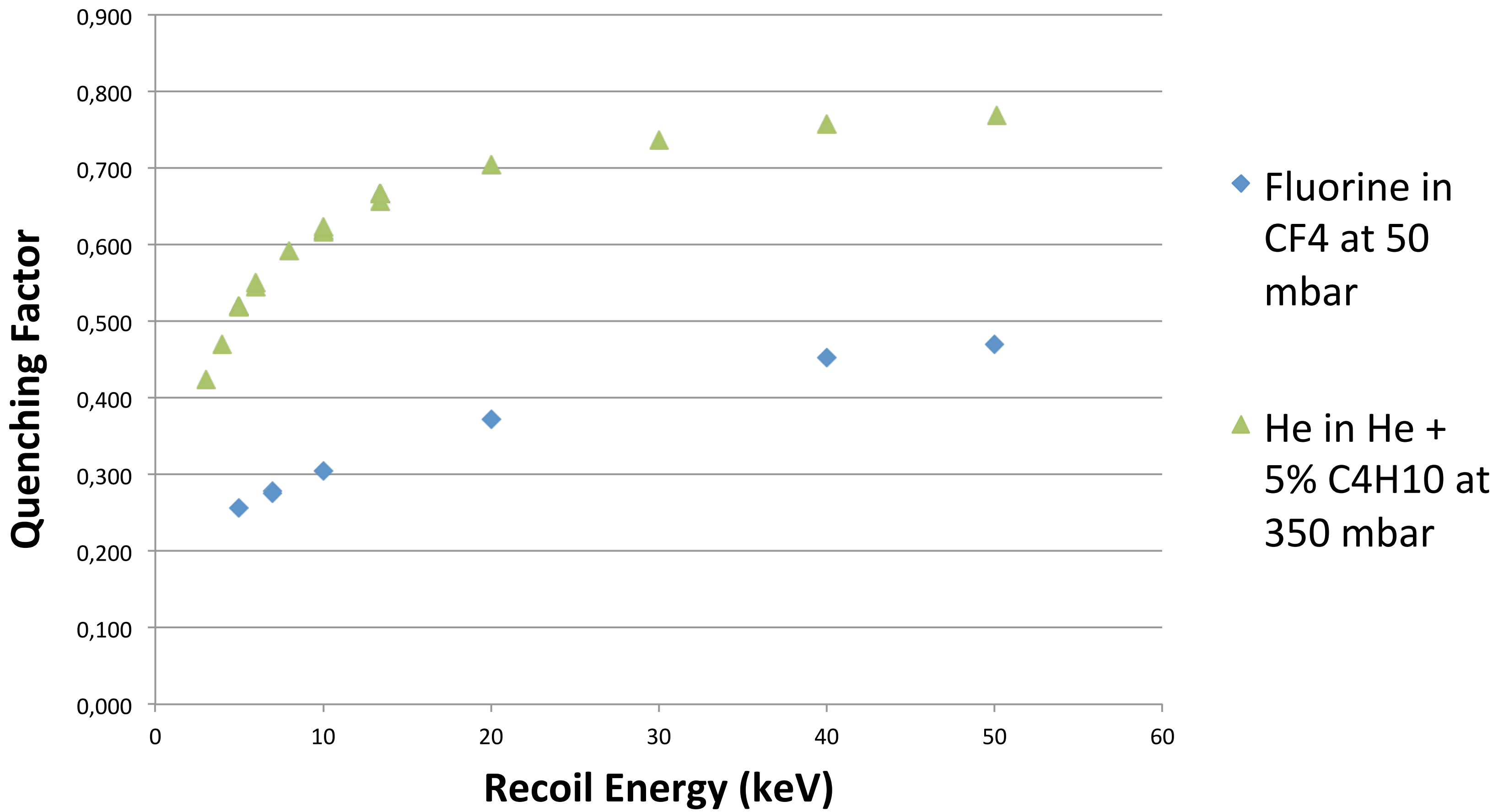
Electrons Performance



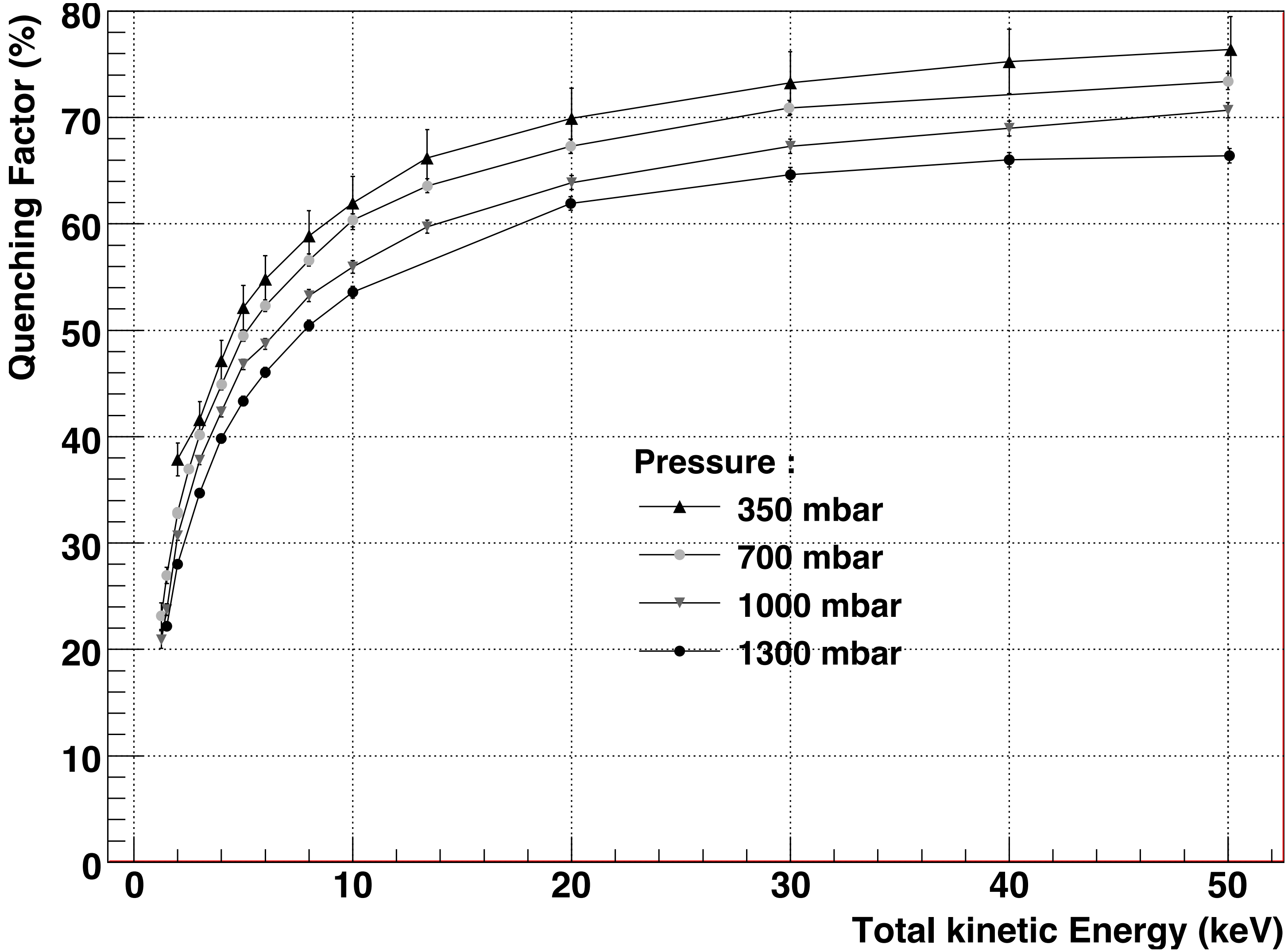
Ions Performance



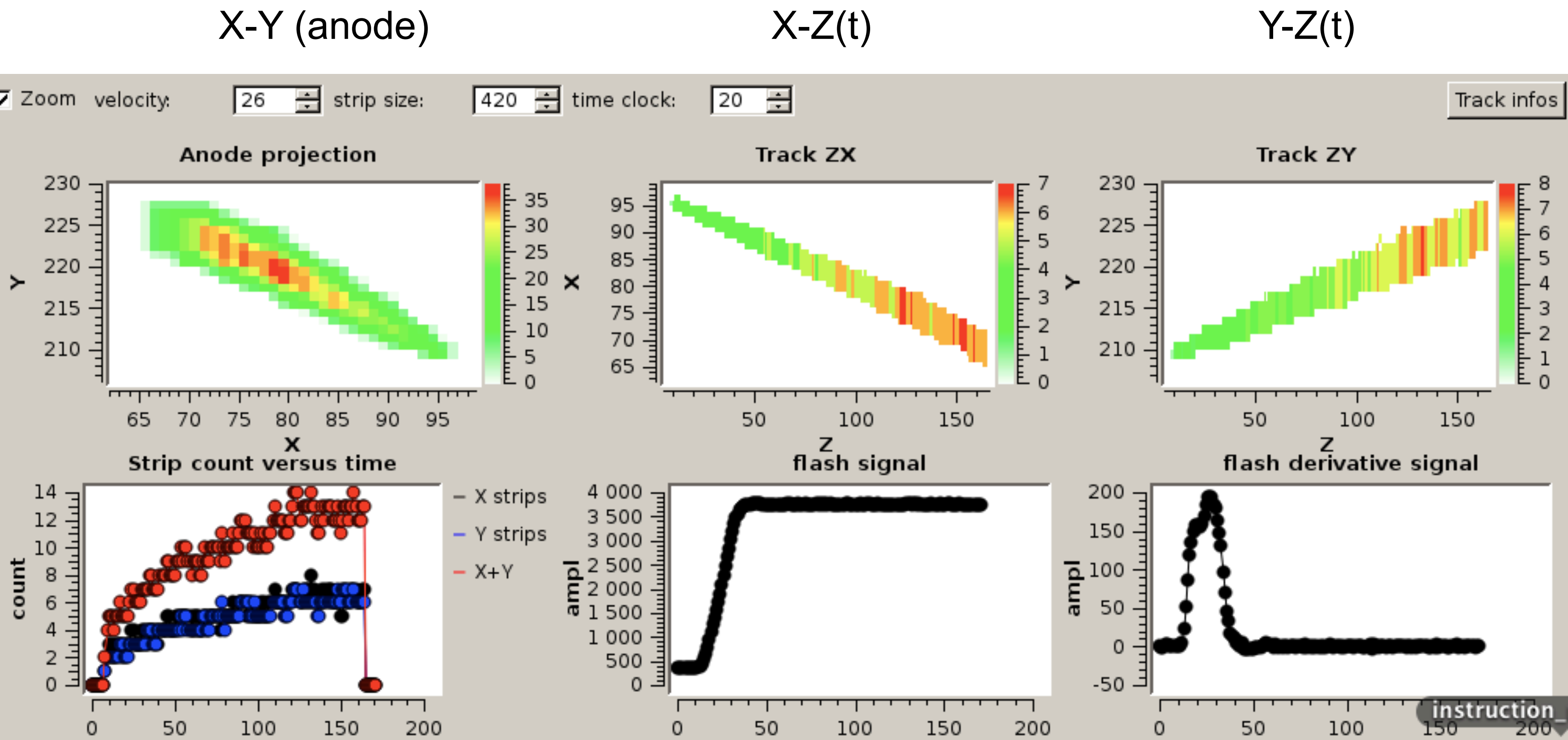
Ionization Quenching Factor for Fluorine in pure CF4 at 50 mbar



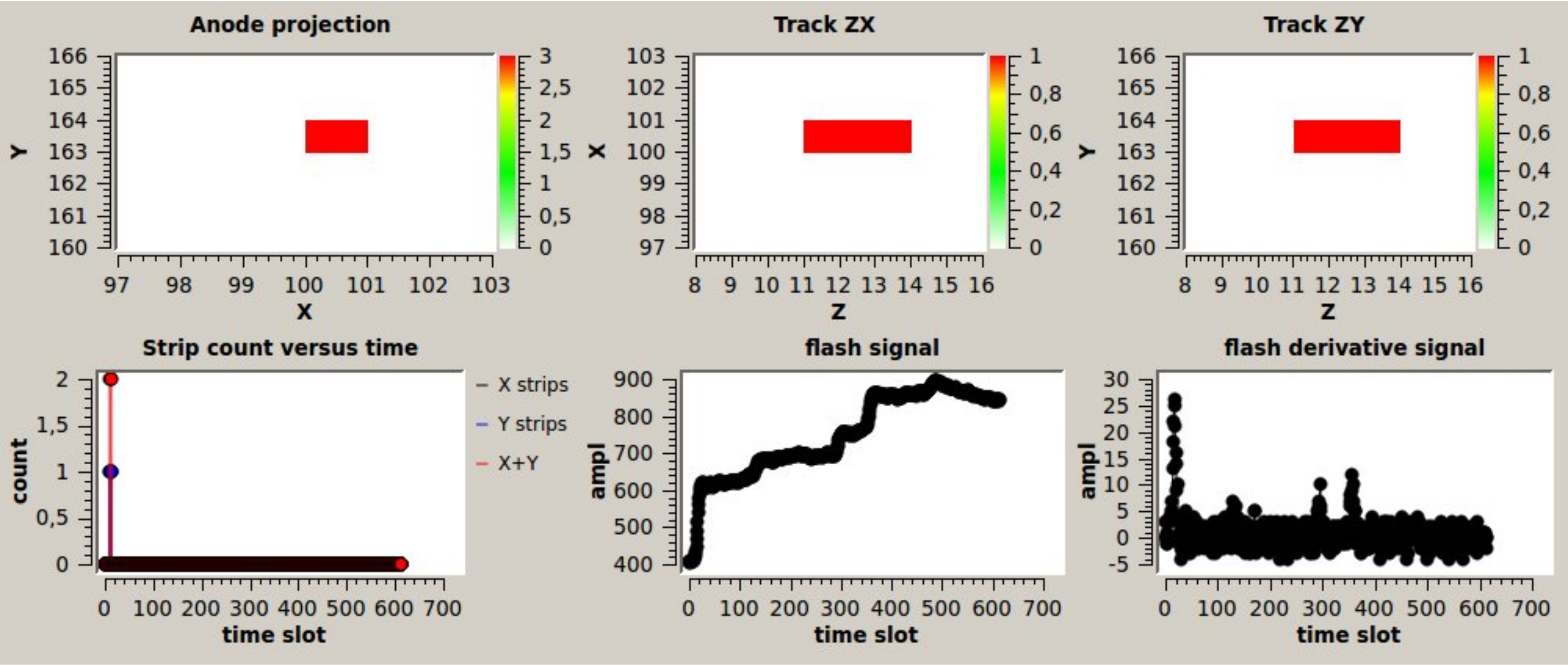
IQF in ^{4}He + 5% isobutane for different pressures!!



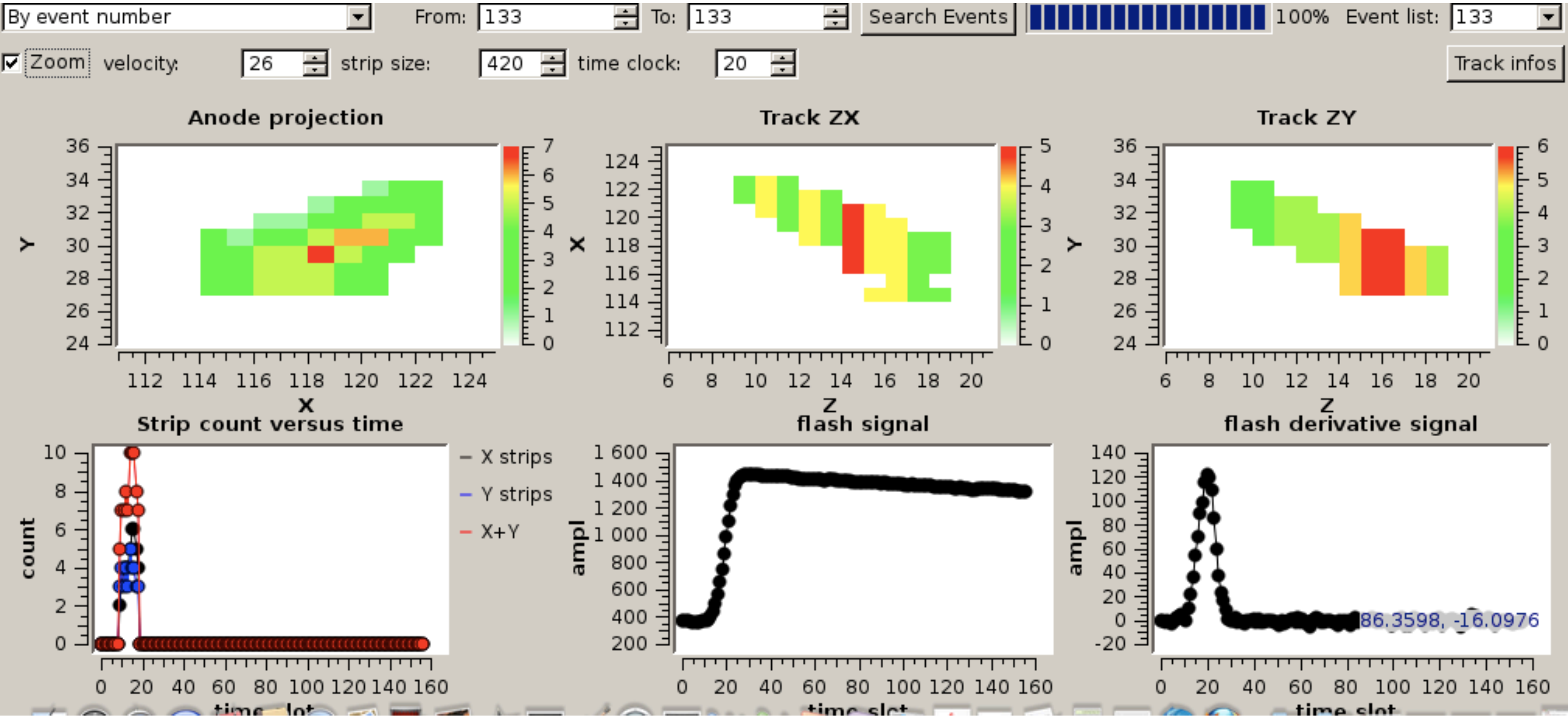
An alpha particle crossing the detector
(as an illustration of the MIMAC observables)



An Electron event (18 keV)



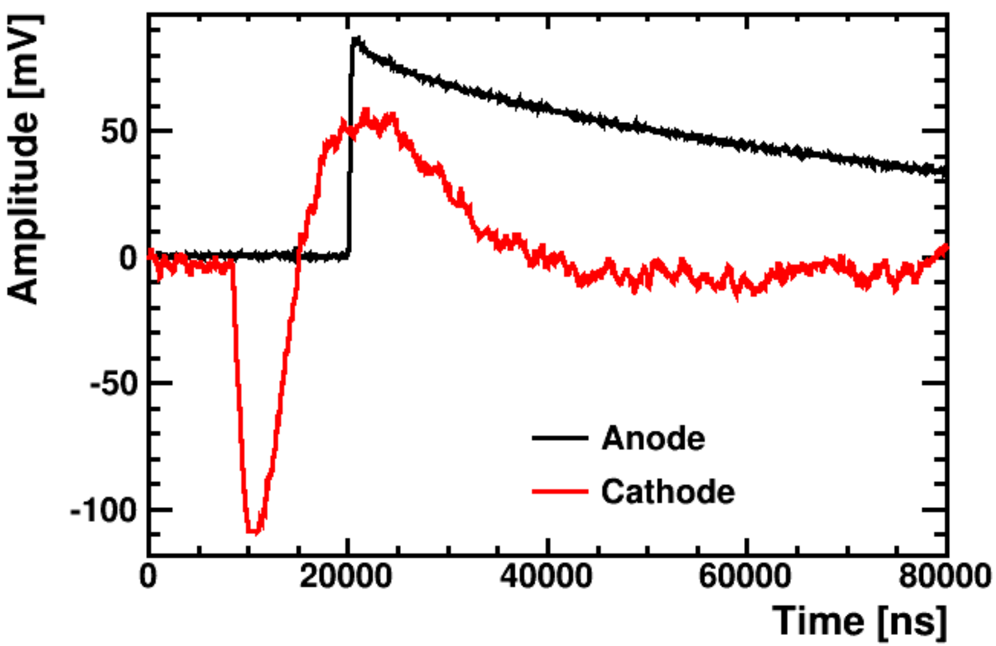
A “recoil event” (~ 34 keVee)



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. JINS 12 (11)P11020,2017)



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. JINS 12 (11)P11020,2017)

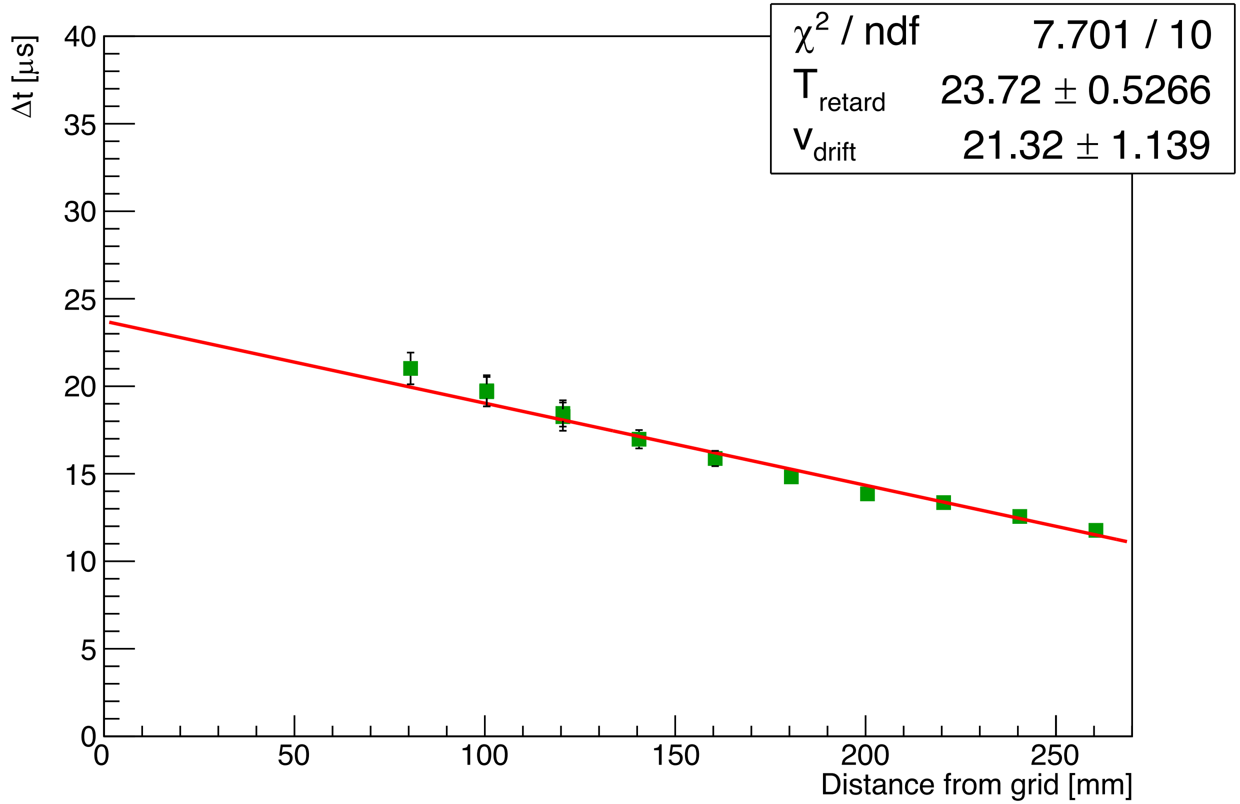
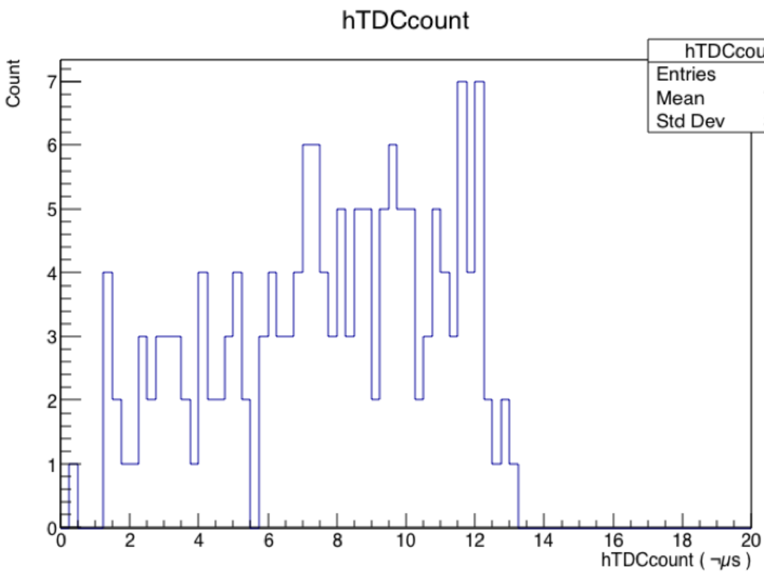


Figure 4. Measure of the time differences (TAC) between the grid signal and the delayed cathode signal in the "START Grid" configuration, as a function of the distance of the α source from the anode (green points) ; error bars correspond to the standard deviation of the mean. A linear fit of these points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

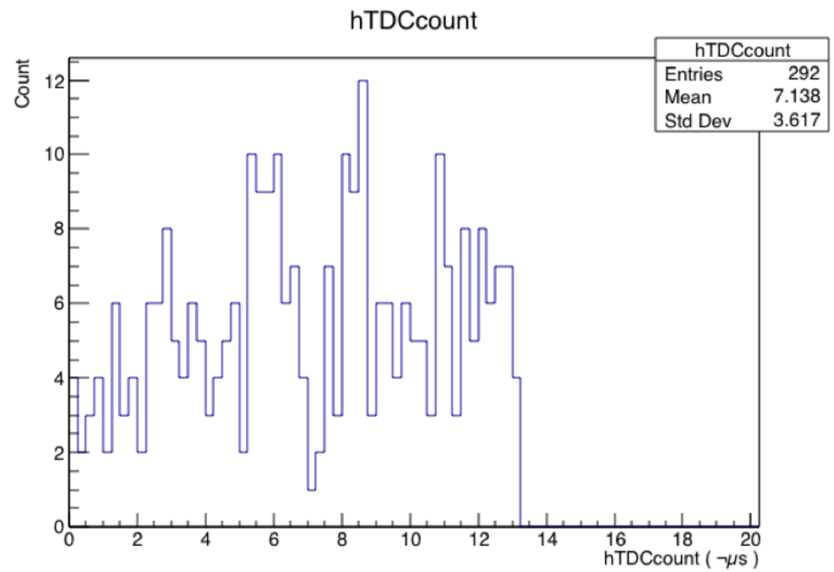
First Cathode Signals from the MIMAC bichamber background

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

Chamber 1

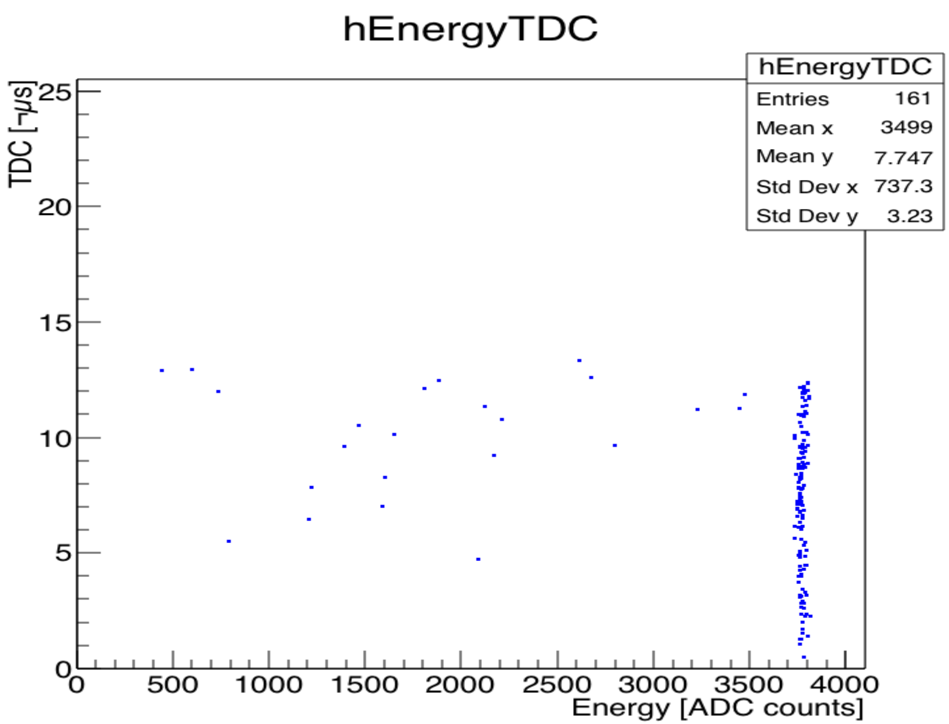


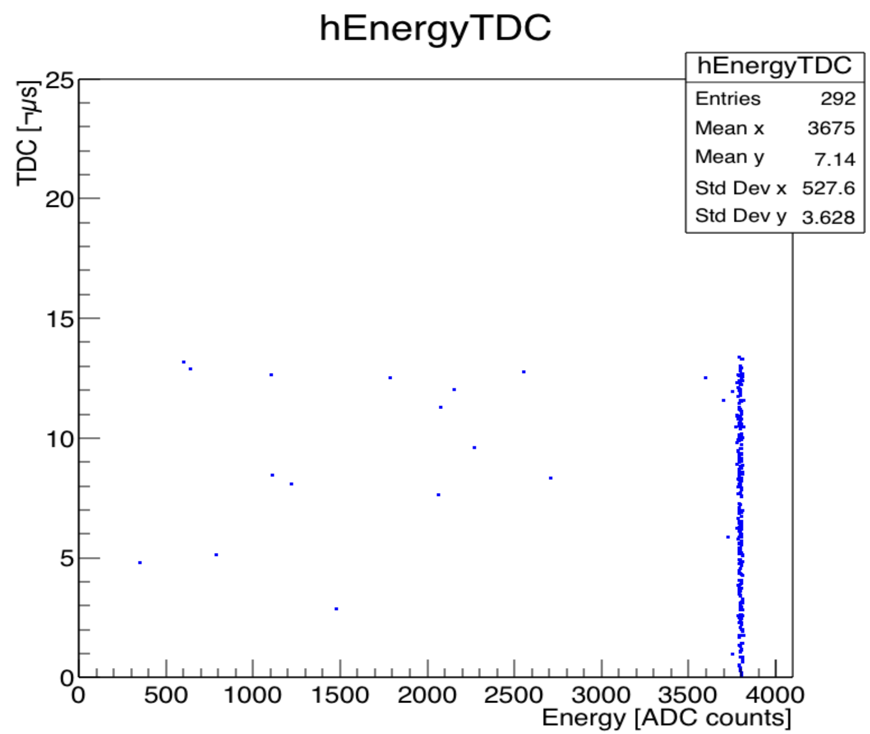
Chamber 2



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

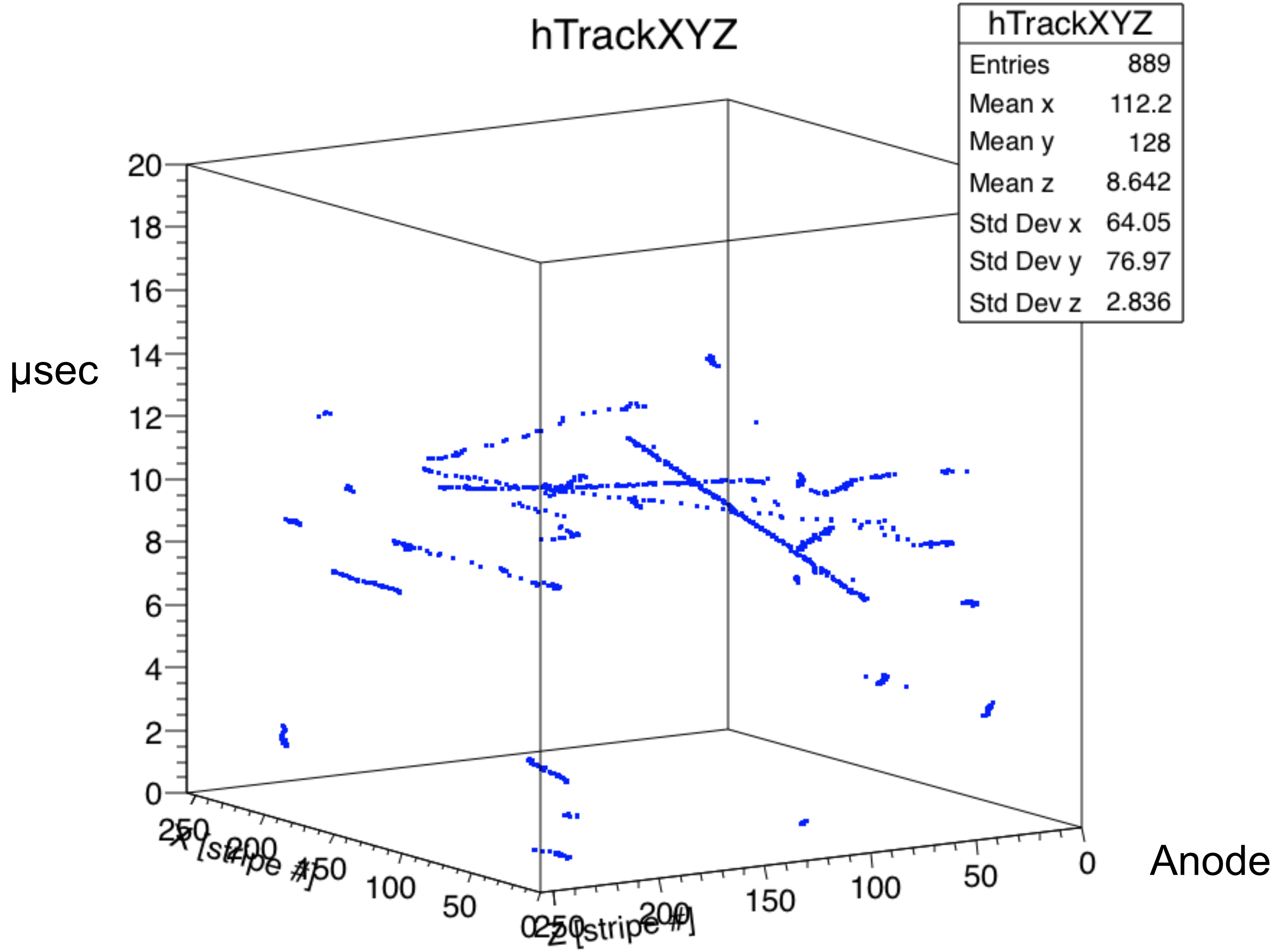
Ionization Energy distribution of the events recorded with the Cathode Signal





Energy range: 1-60 keV

3D event-localization in MIMAC



Angular resolution measured with COMIMAC (^{19}F ions at known kinetic energies) (Y. Tao, I. Moric, et al. (arXiv1903.02159)

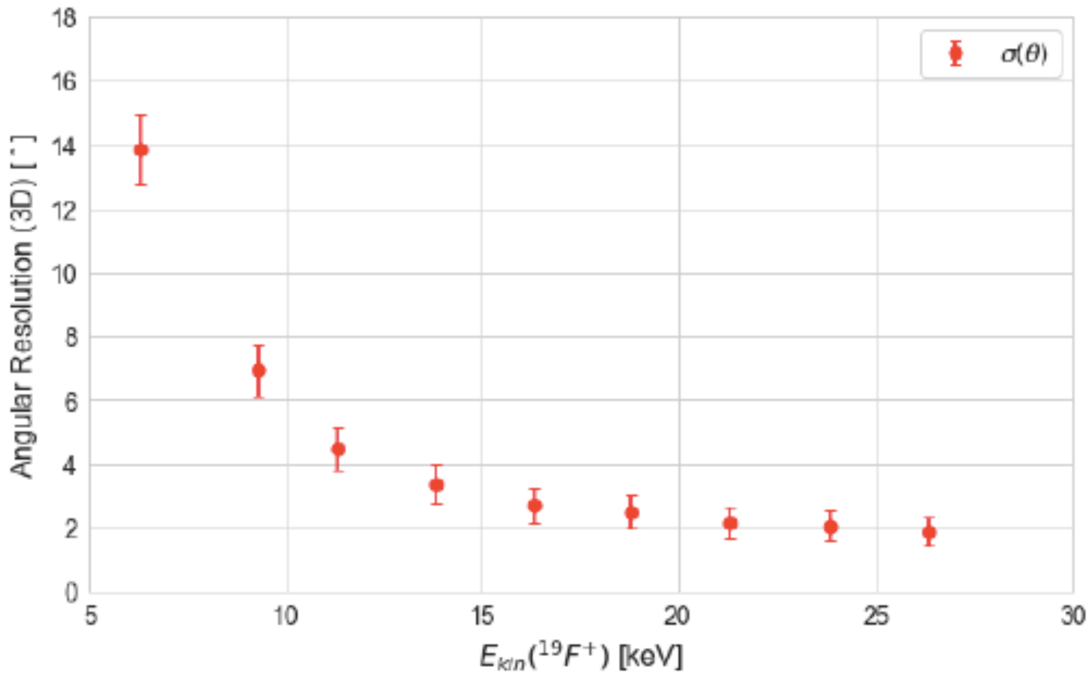
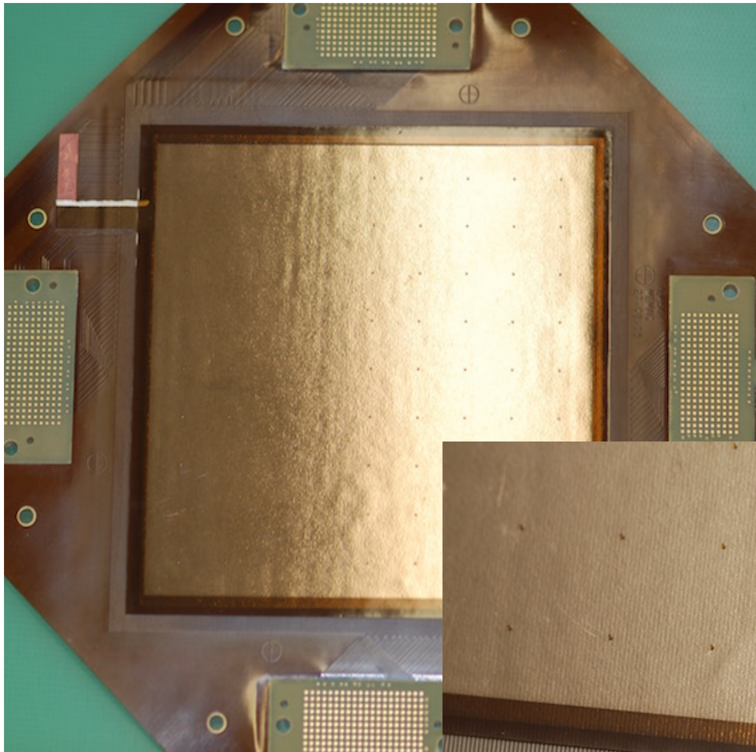
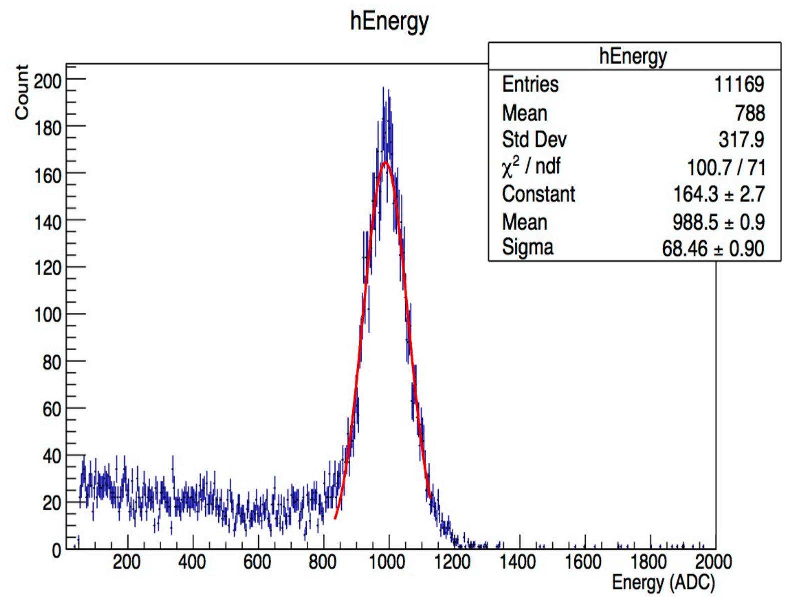


Figure 8. MIMAC angular resolution as a function of ^{19}F ion kinetic energy. At lower energies, the ion tracks are shorter and have more straggling resulting in worse angular resolution and bigger error bars. The angular resolution is better than 20° down to a kinetic energy of 6.3 keV, and is below 10° for a kinetic energy of 9.3 keV. Error bars are derived from the pixel strips pitch and reconstructed track length as described in the text.

New MIMAC low background detector



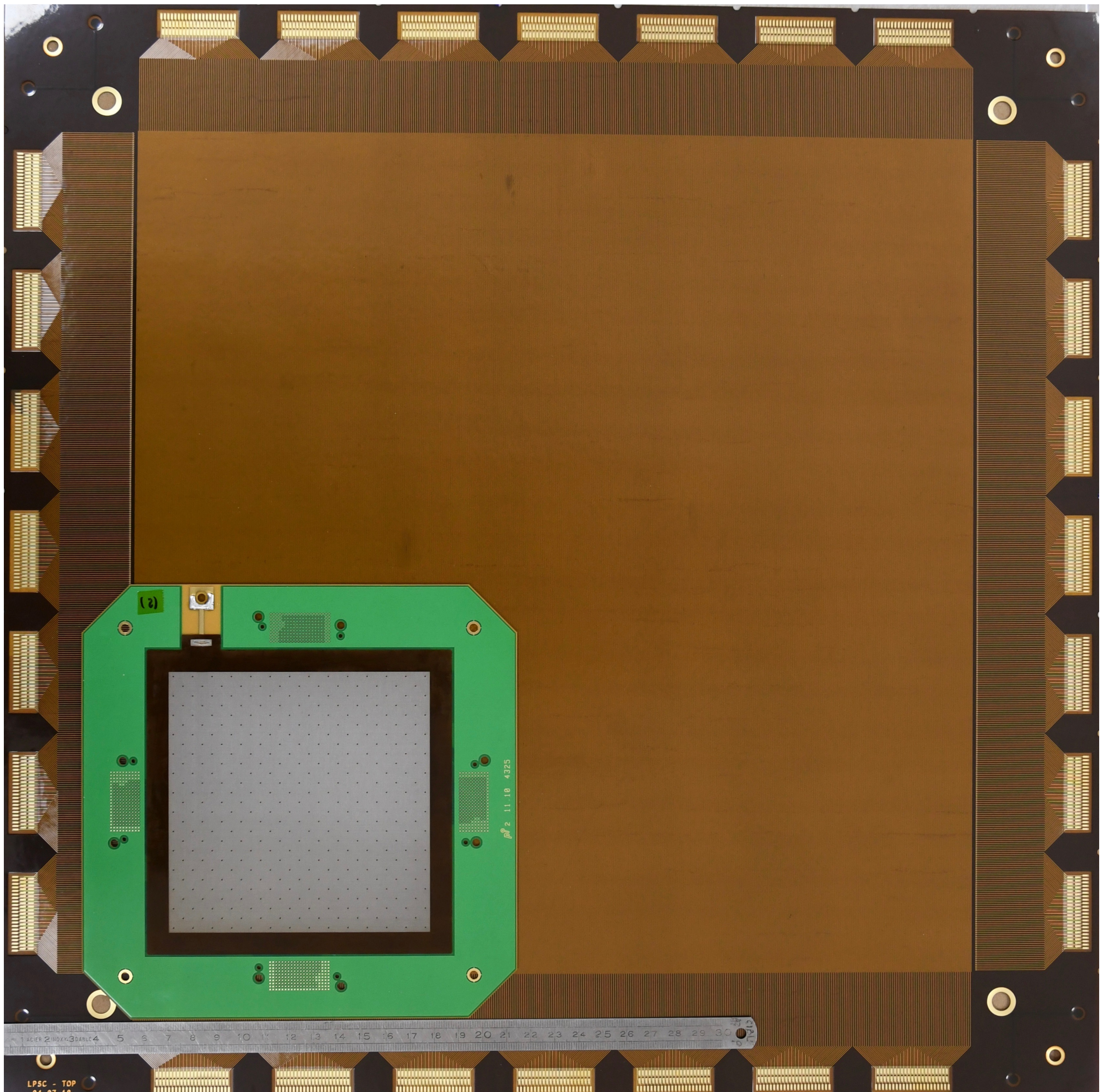


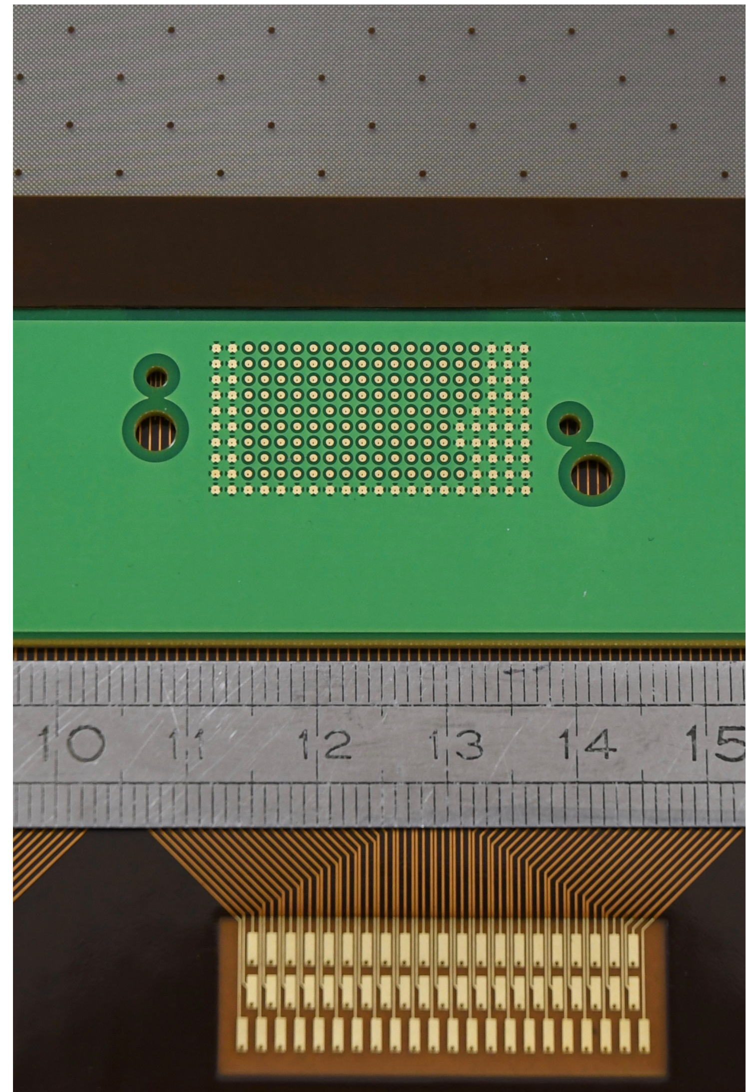
Gaz : MIMAC 50 mbar
HT grille : -560 V
Drift field : -150 V/cm

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

Kapton micromegas readout
Piralux Pilar

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





MIMAC – $2m^3$ = 16 bi-chamber modules (2x 35x35x52 cm^3)

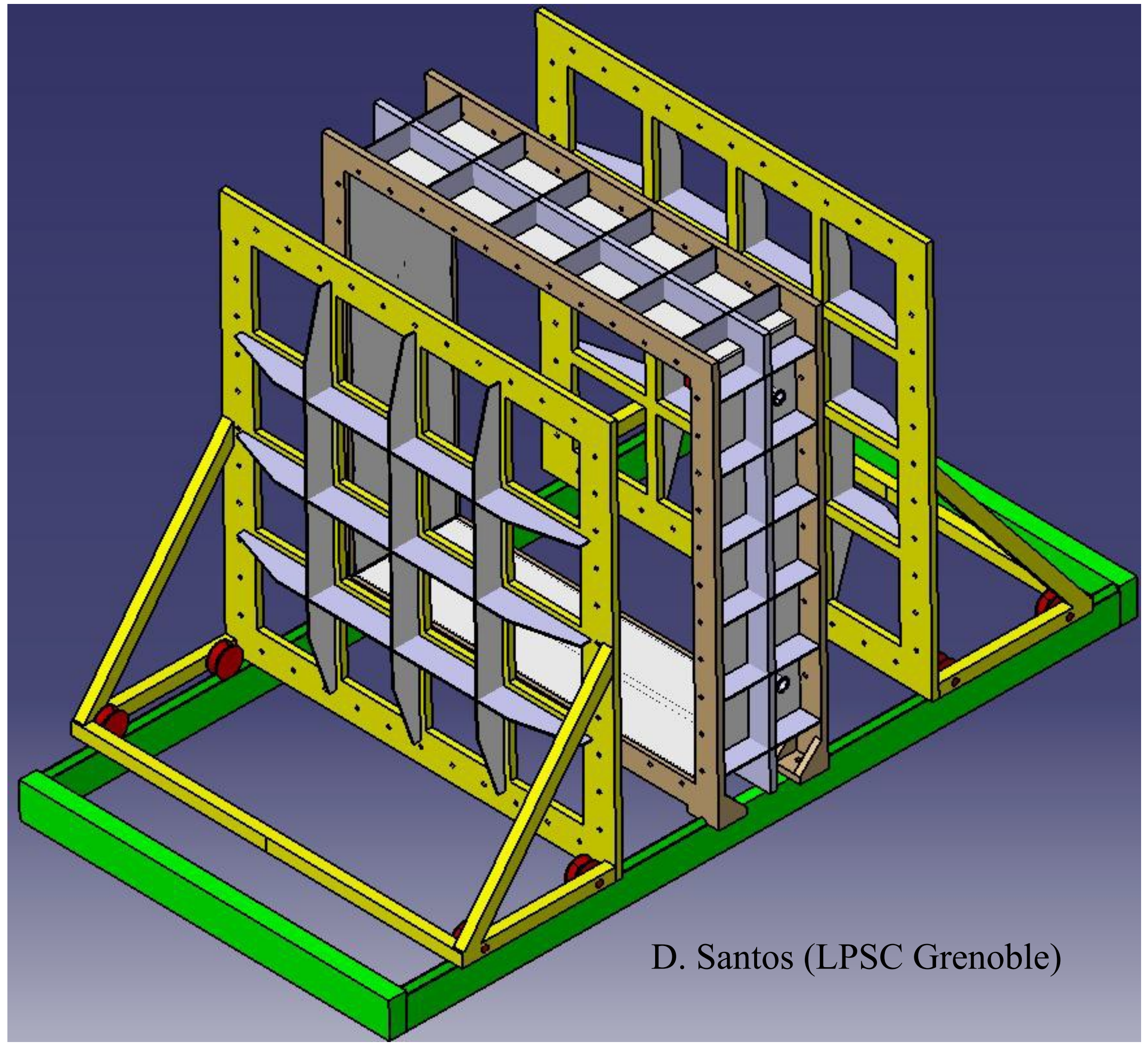
New technology anode 35cmx35cm

Stretched thin (12 um) grid at 512um.

New electronic board (1792 channels)

Only one big chamber

To explore the New Physics…



D. Santos (LPSC Grenoble)

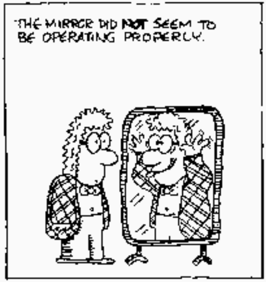
Standard axion (1/2)

Strong CP problem:

→ QCD contains a CP-violating term, $\mathcal{L}_{QCD} \supset \bar{\theta}\, \frac{g_s^2}{32\pi^2}\, G_a^{\mu\nu} \tilde{G}_{a\mu\nu}$

→ From theory $|\bar{\theta}| \in [0, \pi]$; but experimentally $|\bar{\theta}| < 10^{-10}$

Why is CP conserved in QCD?



Peccei-Quinn solution:

→ New global symmetry $U(1)_{PQ}$

→ $U(1)_{PQ}$ breaking ⇒ axion

→ The QCD vacuum structure is modified by the *vev* $\langle a \rangle \propto \bar{\theta}$

The axion dynamically compensates the CP-violating term

Standard axion (2/2)

$\rightarrow$The axion can couple to photons through a coupling $g_{a\gamma\gamma}$ which depends on the scale of the symmetry breaking f_{PQ}:

$$\mathcal{L}_{QCD}^{eff} \supset \frac{g_{a\gamma\gamma}}{4} a\, F^{\mu\nu} \tilde{F}_{\mu\nu}$$

$\rightarrow$ f_{PQ} is constrained from astrophysical and cosmological concerns

Axion properties:

- $10^{-5} \lesssim m_{PQ} \lesssim 10^{-2}\,\mathrm{eV}$
- $10^{30} \lesssim \tau_{a\rightarrow\gamma\gamma} \lesssim 10^{45}\,\mathrm{days}$

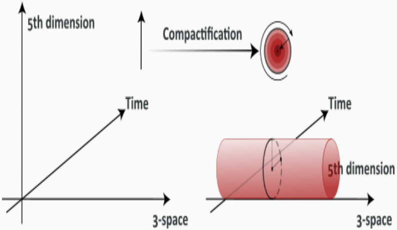
$\Longrightarrow$ Dark matter candidate...

...but decay $a \rightarrow \gamma\gamma$ undetectable

Axion in extra dimensions (1/3)

FRAMEWORK:

- SM particles are confined into the observable $(1+3)D$ space
- Singlets under SM gauge group (axion, graviton, ...) can propagate into a $(1+3+\delta)D$ space
- Extra dimensions δ are compactified with $R < 30\,\mu\mathrm{m}$

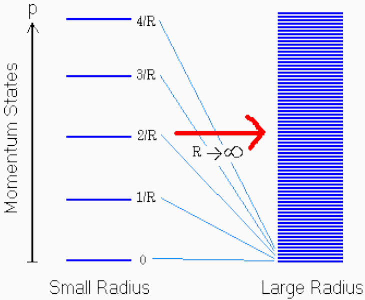


- $f_{PQ}^{4D} \gg f_{PQ}^{(4+\delta)D}$
  - f_{PQ}^{4D} is constrained experimentally
  - $f_{PQ}^{(4+\delta)D}$ sets the scale of the symmetry breaking

Axion in extra dimensions (2/3)

Kaluza-Klein decomposition:

- In the observable space, the axion is seen as an infinite tower of KK excitations
- $\mathcal{L}_{4D}^{eff} \supset \frac{g_{a\gamma\gamma}}{4} \left(\sum_{\mathbf{n}=0}^{\infty} r_{\mathbf{n}} a_{\mathbf{n}} \right) F^{\mu\nu} \tilde{F}_{\mu\nu}$



Axion-Like Particle (ALP):

- The standard axion is identified to the fundamental mode a_0
- Non-diagonal mass matrix

  $\Rightarrow$ the KK excitations pull m_{a_0} away from m_{PQ}

  $\Rightarrow$ m_{a_0} decouples from f_{PQ}

Axion in extra dimensions (3/3)

DECAY $a_{\mathbf{n}} \to \gamma\gamma$:

$$\tau(a_{\mathbf{n}} \to \gamma\gamma) \sim \left(\frac{m_{PQ}}{m_{a_{\mathbf{n}}}}\right)^3 \tau(a_0 \to \gamma\gamma)$$

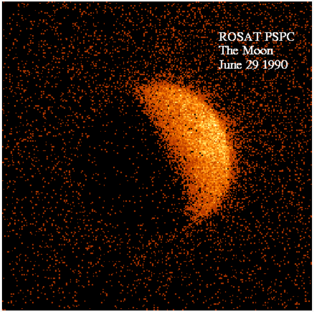
- Decay of every single KK excitation $\Rightarrow$ continuum
- In the Sun, KK axions are produced in the range $m_{a_{\mathbf{n}}} \sim (1-25)\,\mathrm{keV}$

$\Longrightarrow 10^{11} \lesssim \tau_{a_{\mathbf{n}}\to\gamma\gamma} \lesssim 10^{17}\,\mathrm{days}$

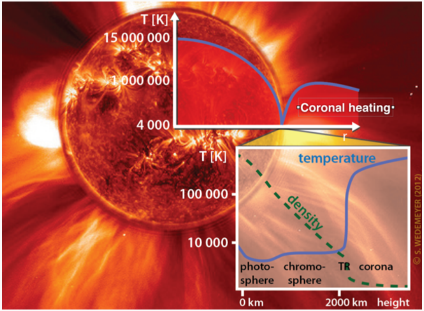
$a_{\mathbf{n}} \to \gamma\gamma$ is detectable with $a_{\mathbf{n}}$ produced in the Sun

Event rate (1/2)

THE SOLAR KK AXION MODEL:



- X-rays dark side of the Moon -

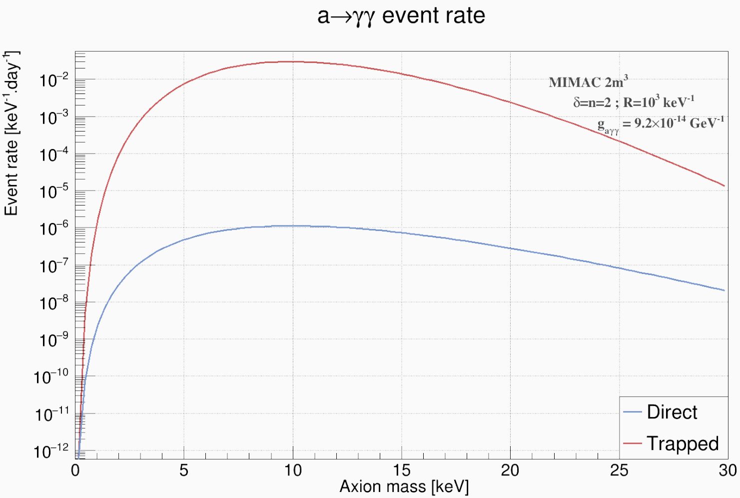


- Heating of the solar corona -

→ Each parameter of the model is constrained according to observations (test of Newton's law, helioseismology, coronal heating, *etc.*)

Di Lella *et al.*, **2003**, Astroparticle Physics

Event rate (2/2)



Only depends on the detection volume

$\sim$ 1 event per day in a $2m^3$ terrestrial detector

Motivation for KK axion searches

Axion in extra dimensions:

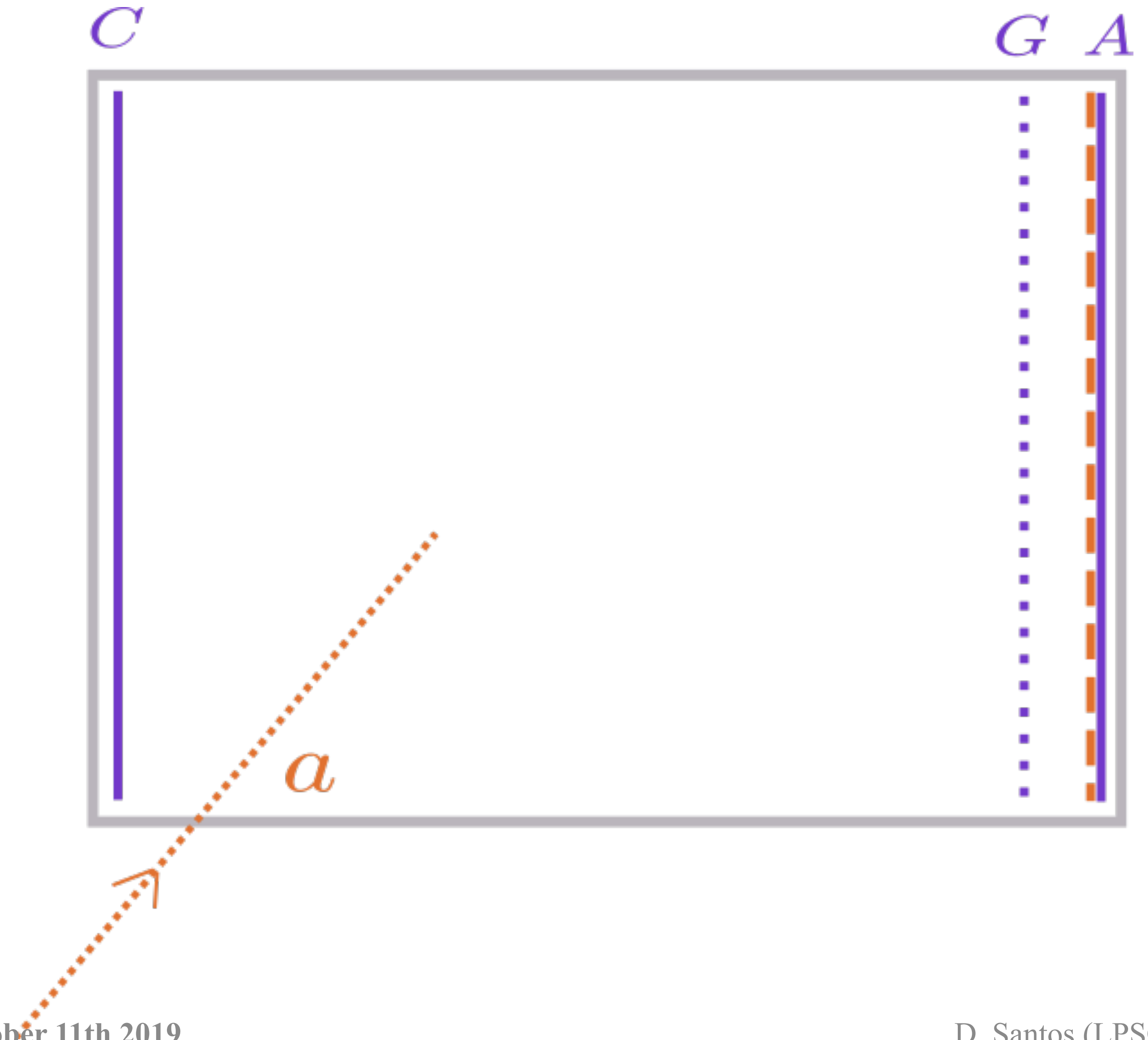
- Increases its mass of ~ 7 orders of magnitude: $\mathcal{O}(10\,\mathrm{keV})$
- Decreases its lifetime of ~ 19 orders of magnitude : $\tau_a \sim \mathrm{age\,of\,the\,universe}$
- Explains some observations (dark matter, coronal heating, *etc.*)

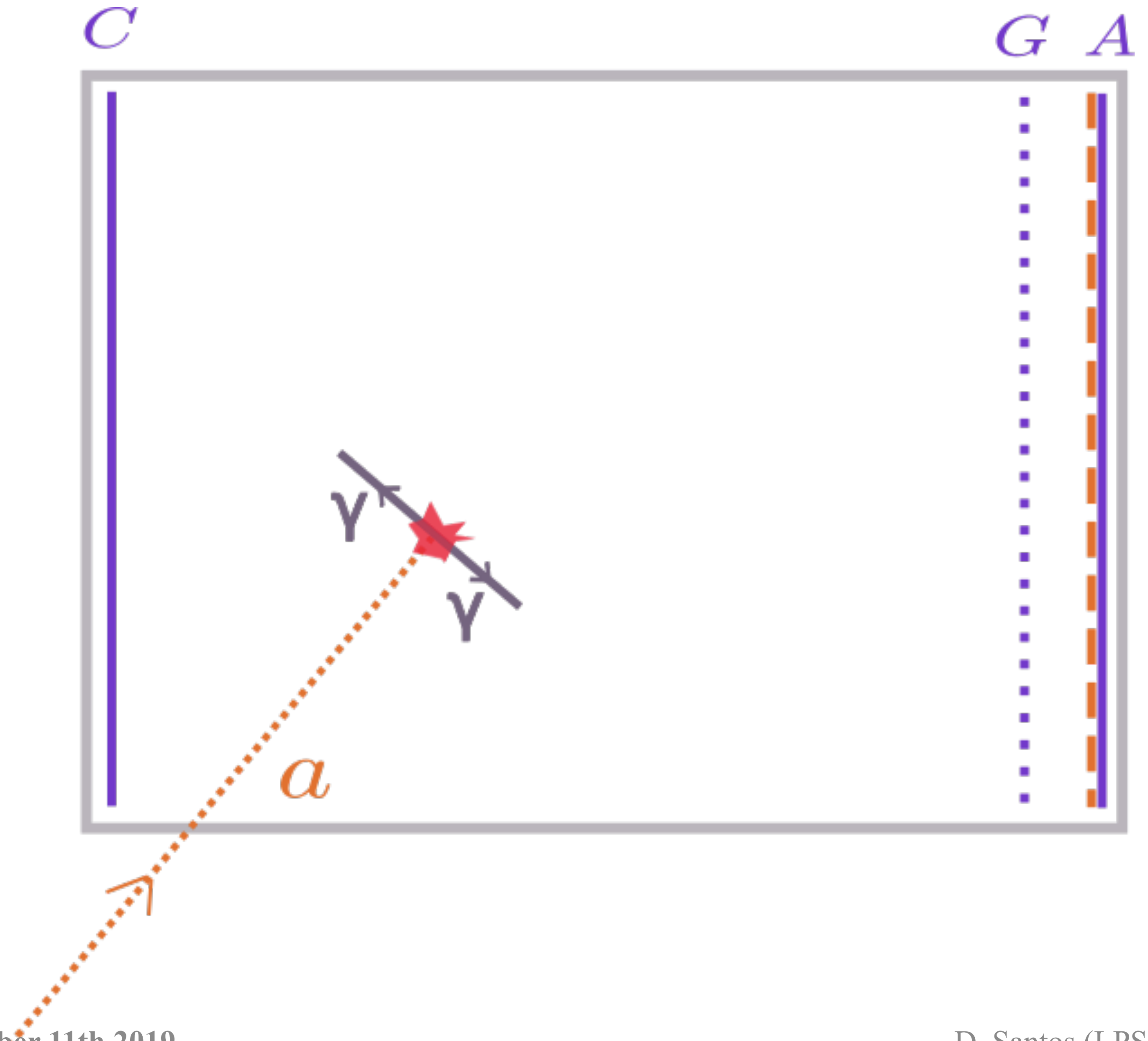
The event rate:

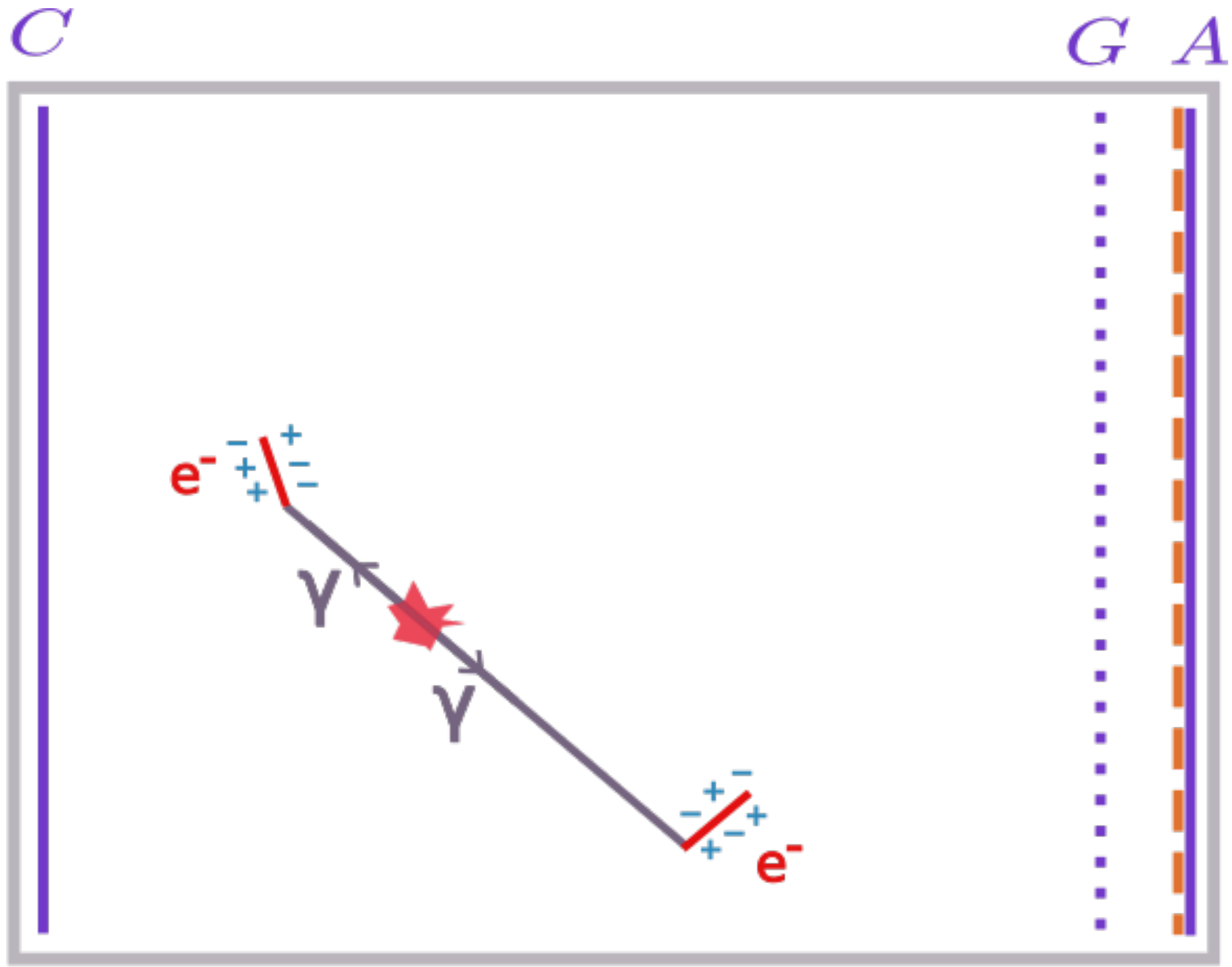
- Only depends on the detection volume
- Is a continuum in range $(1 - 25)\,\mathrm{keV}$
- Shows a peak around $9\,\mathrm{keV}$

Search for KK axion:

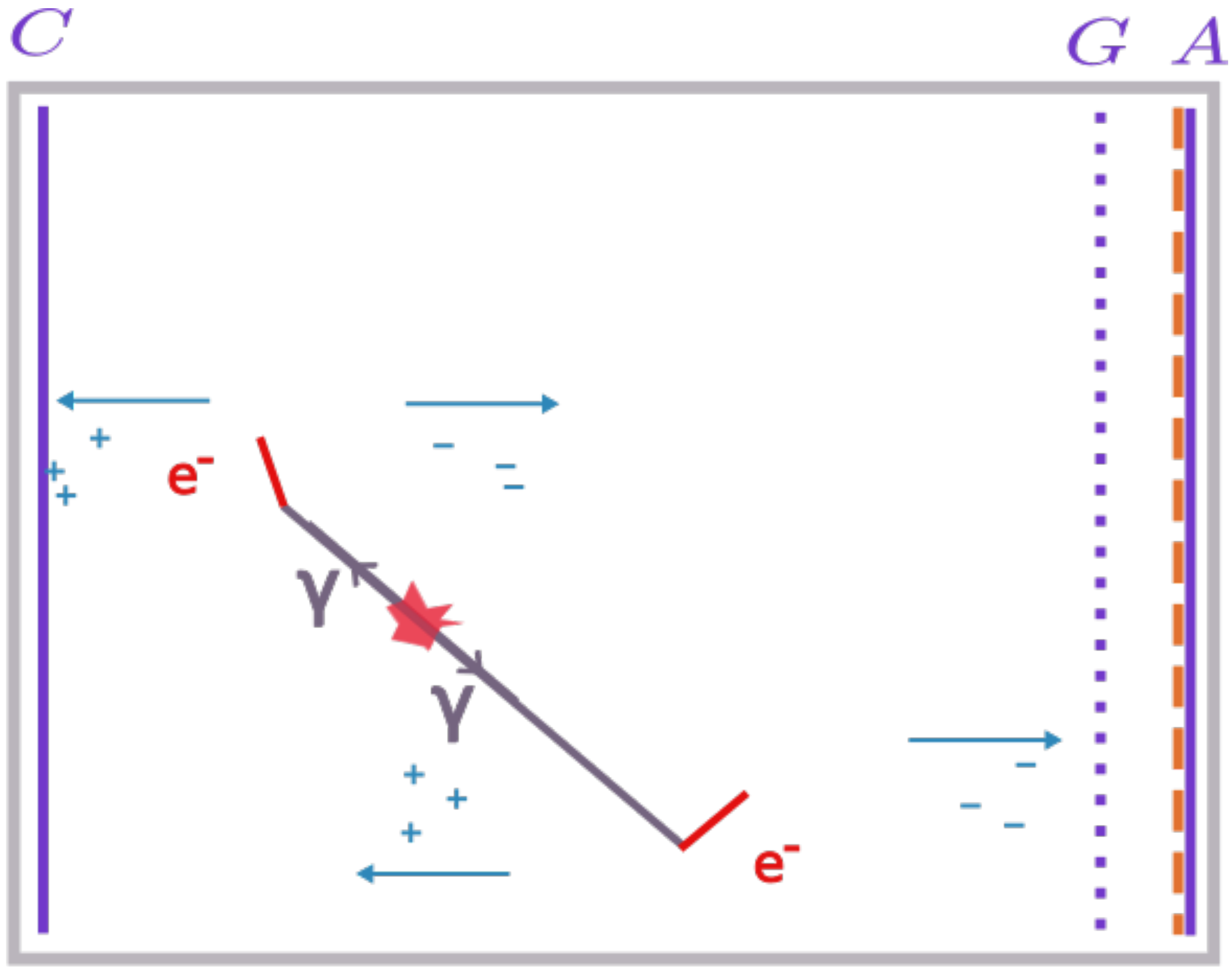
- For dark matter studies
- Can probe extra dimensions

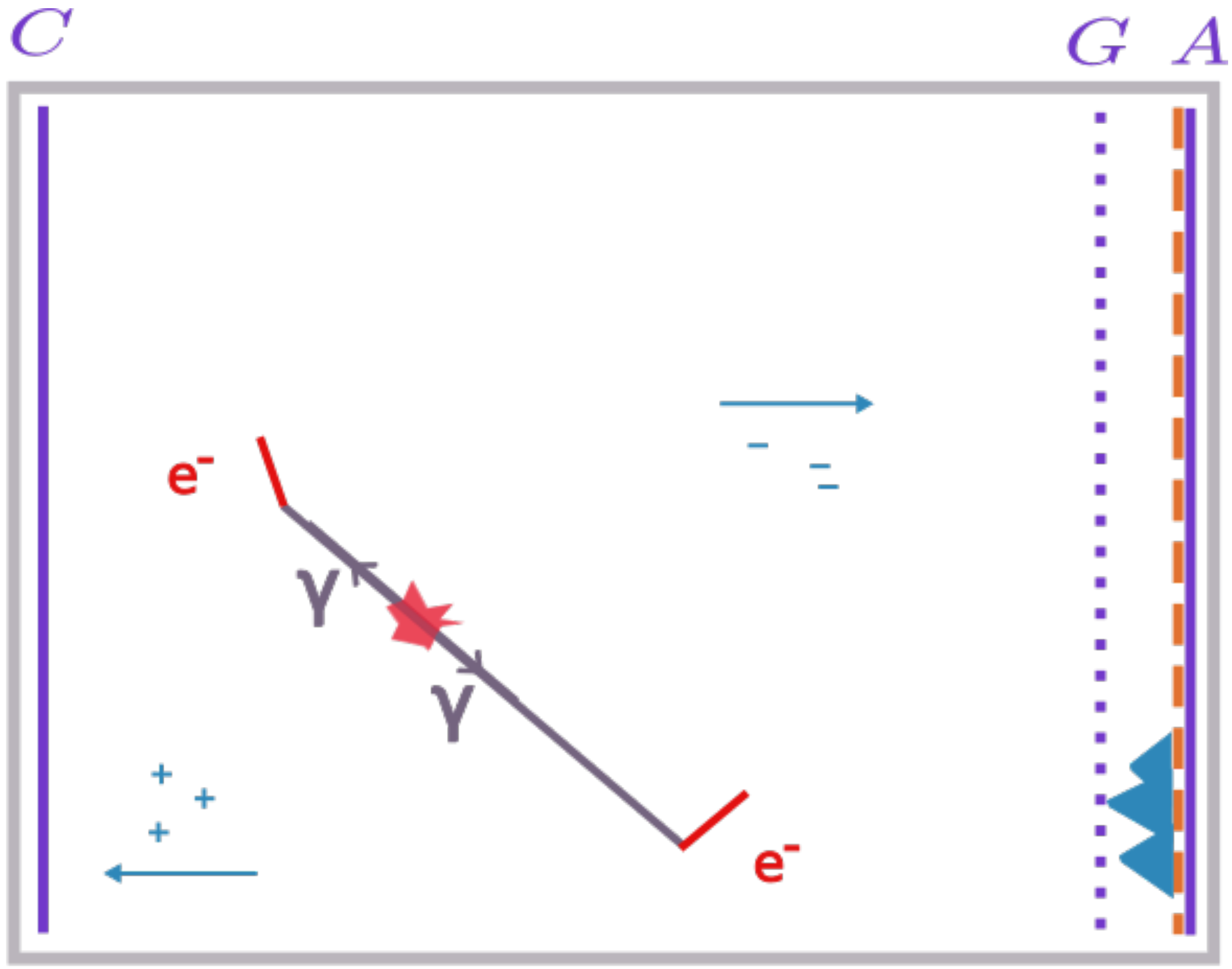

C
G
A
a

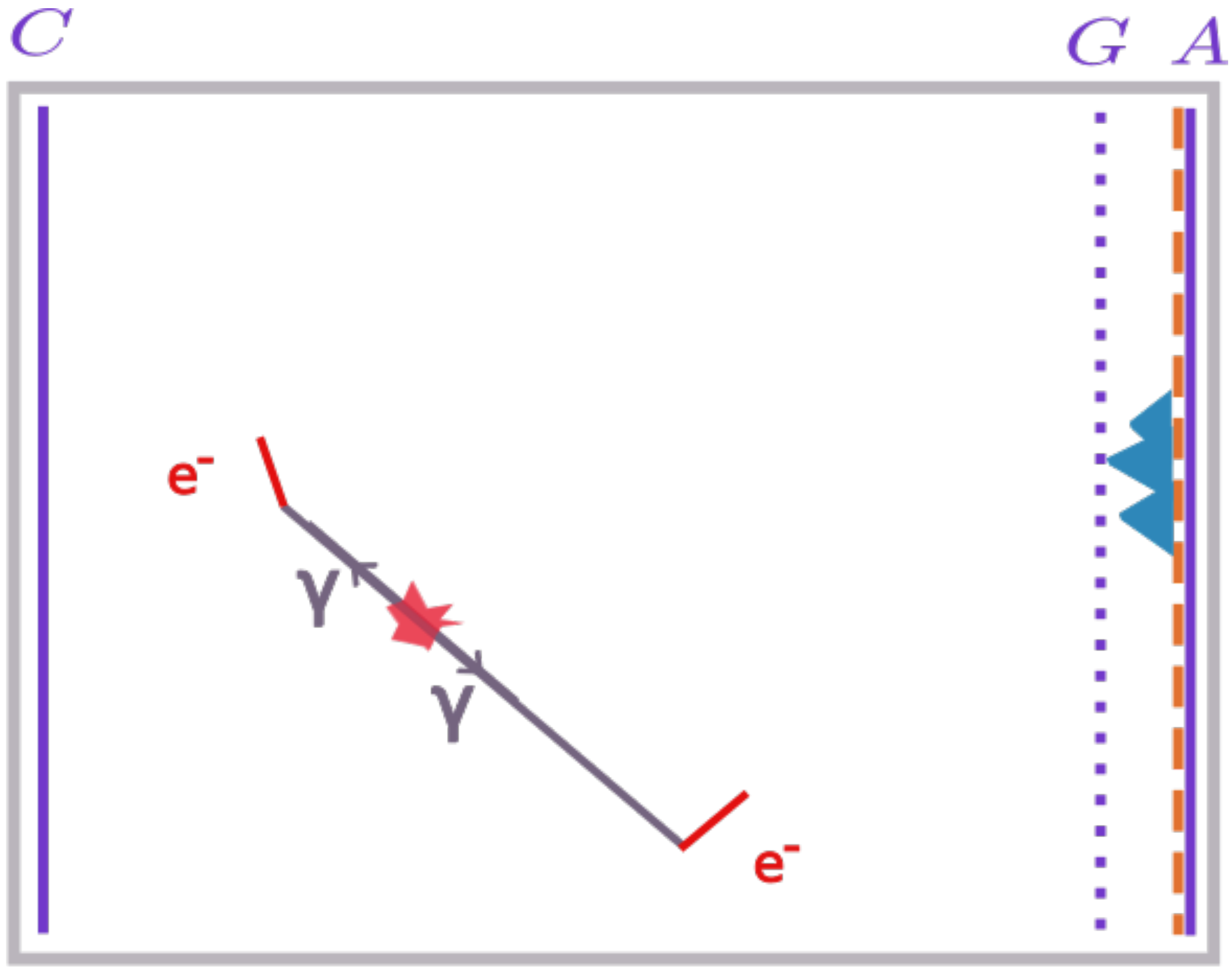

C
G
A
γ
γ
a



C
G
A
e-
γ
γ
e-

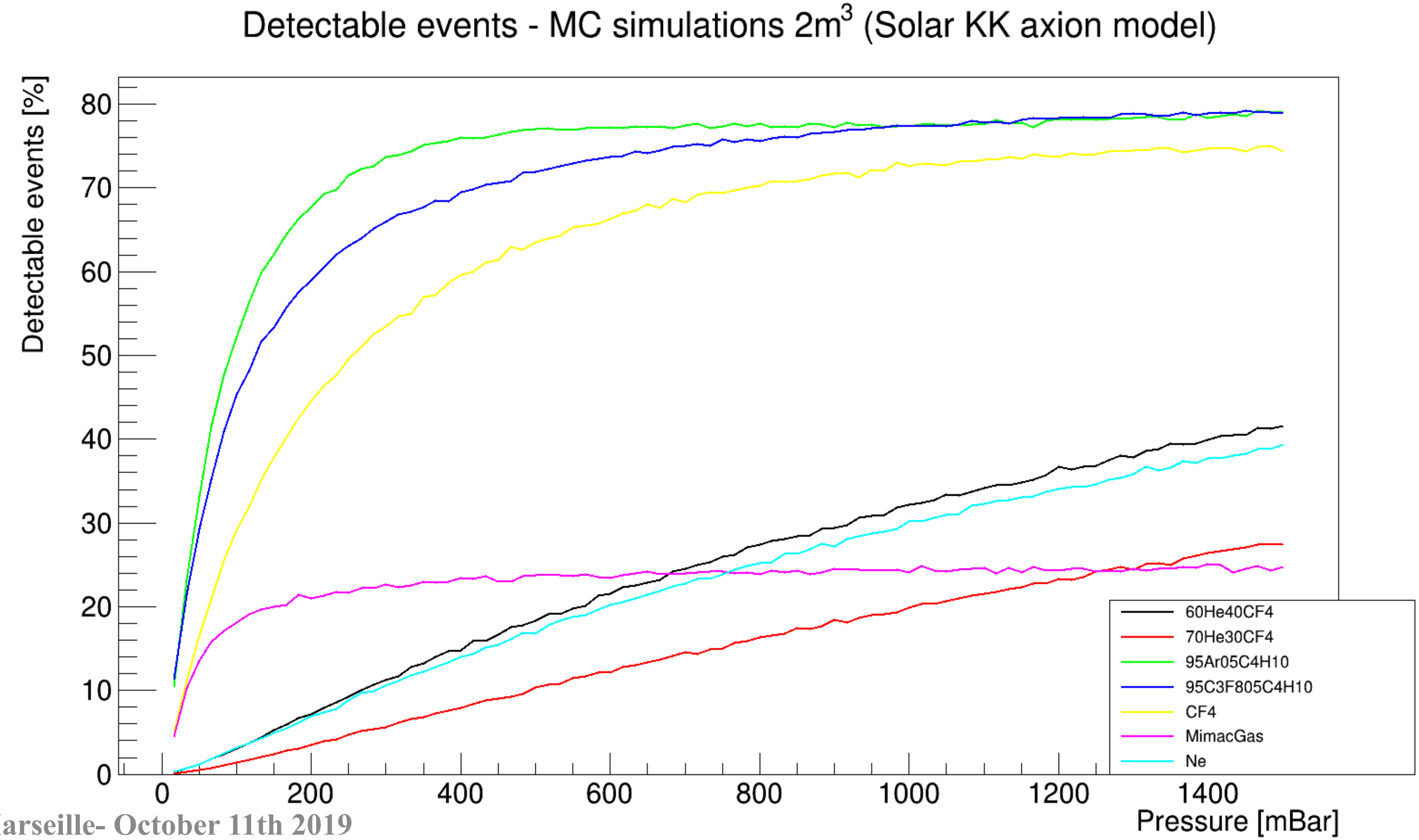

C
G
A
e-
γ
γ
e-


C
G
A
e-
γ
γ
e-

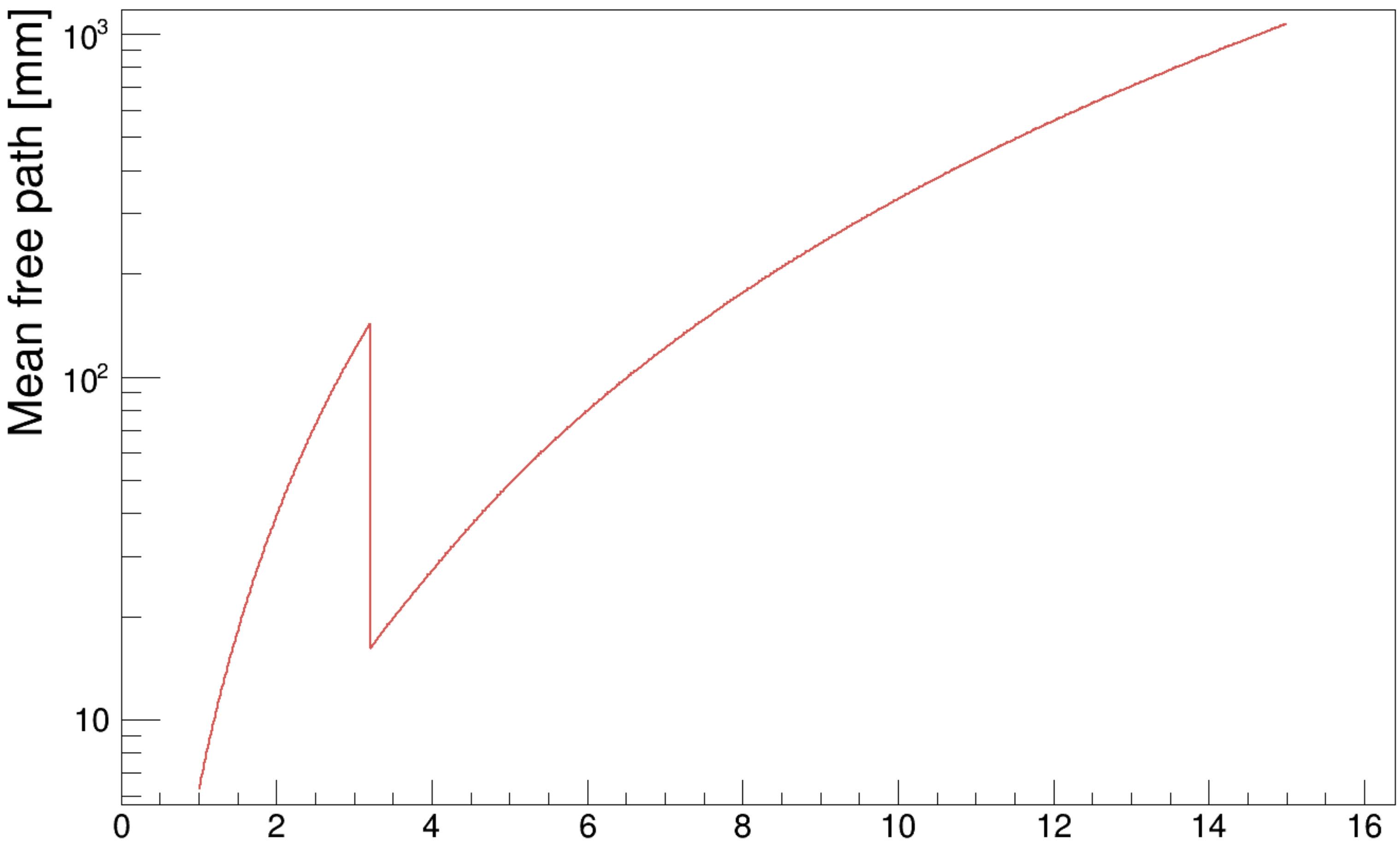


C
G
A
e-
γ
γ
e-

Efficiency as a function of the Gas and pressure

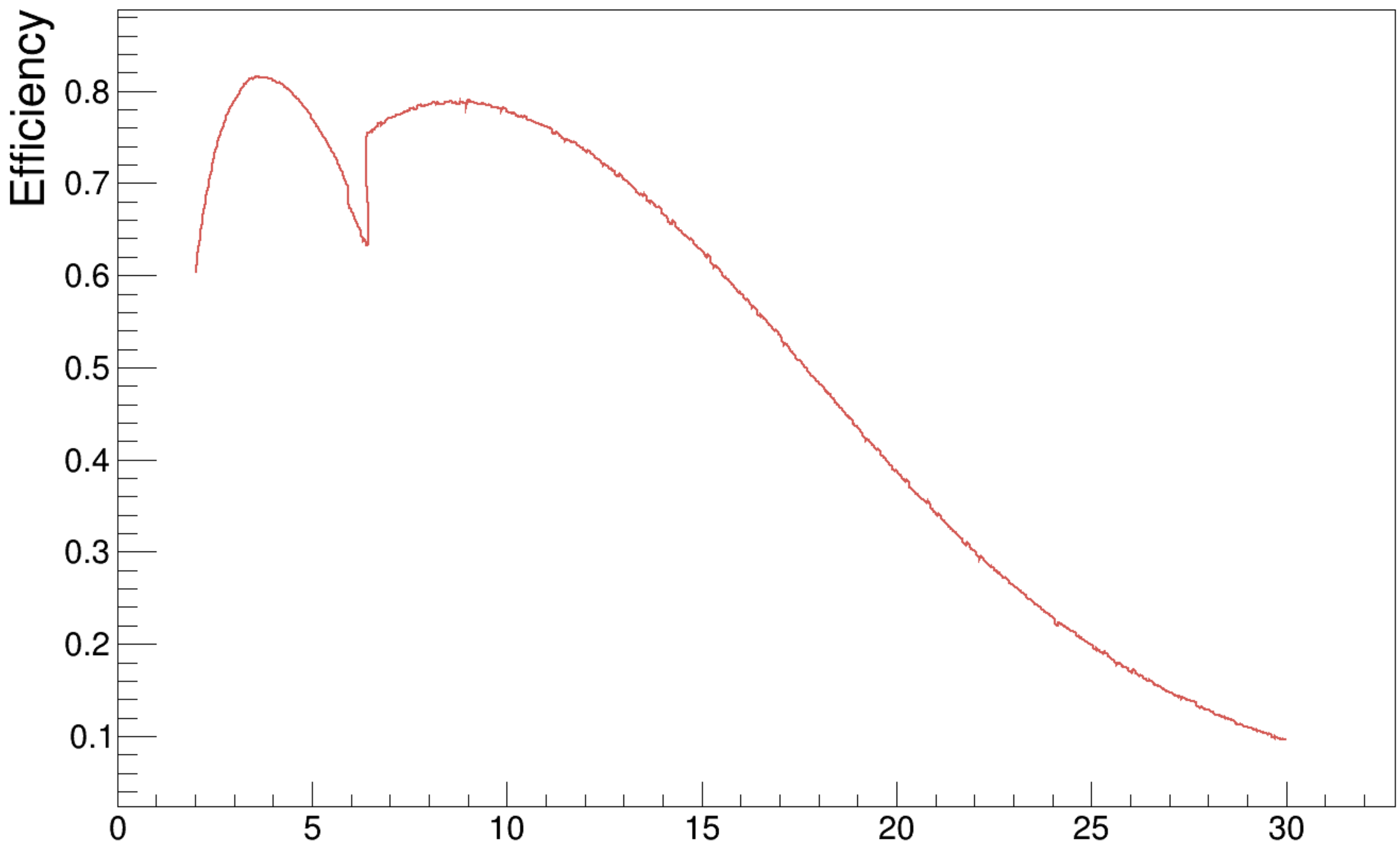


Mean free path of photons in Ar +5% isobutane (300 mbar) as a function of their energy (keV)



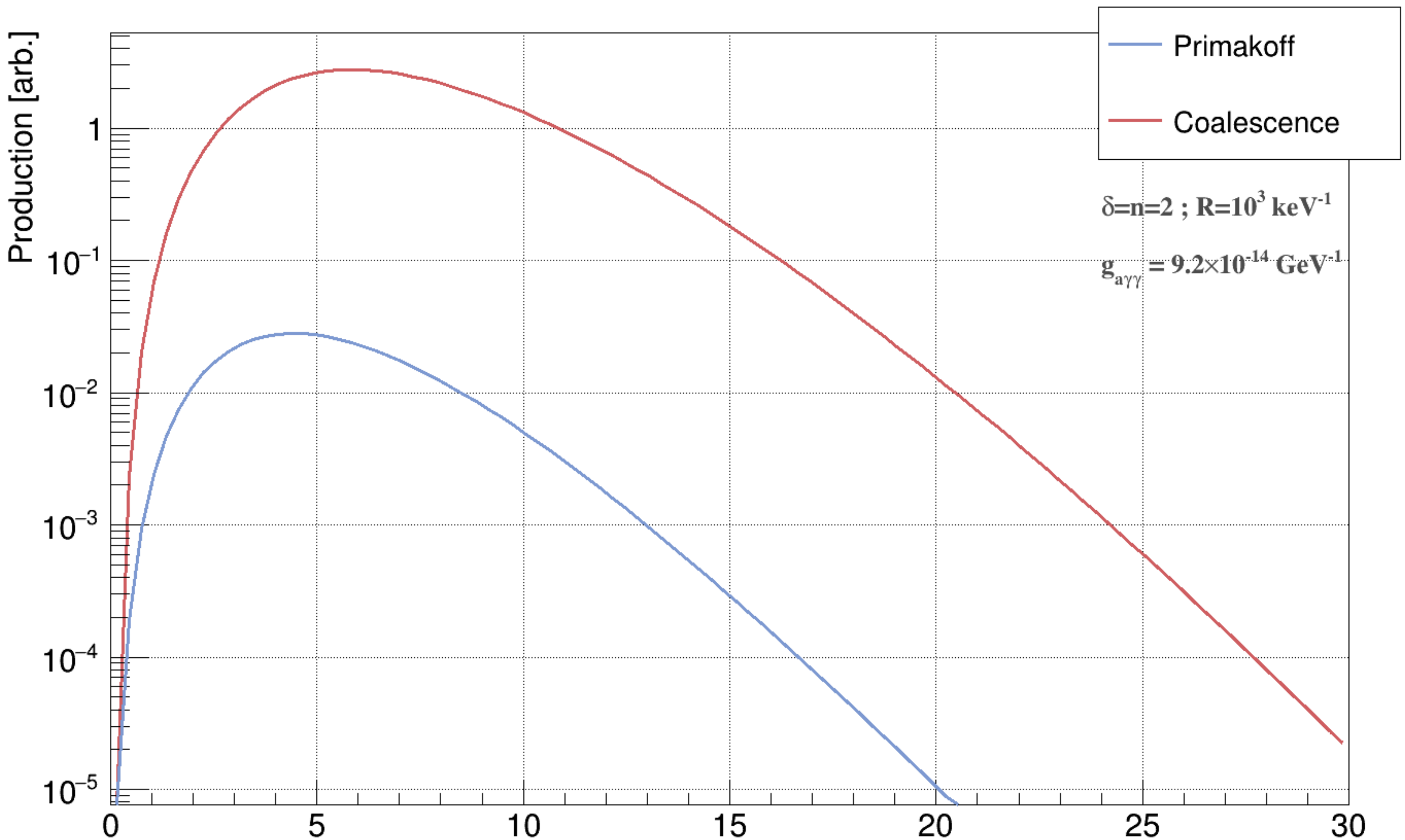
D. Santos (LPSC Grenoble)

Efficiency in the Argon mixture at 300 mbar vs. KK-axion energy



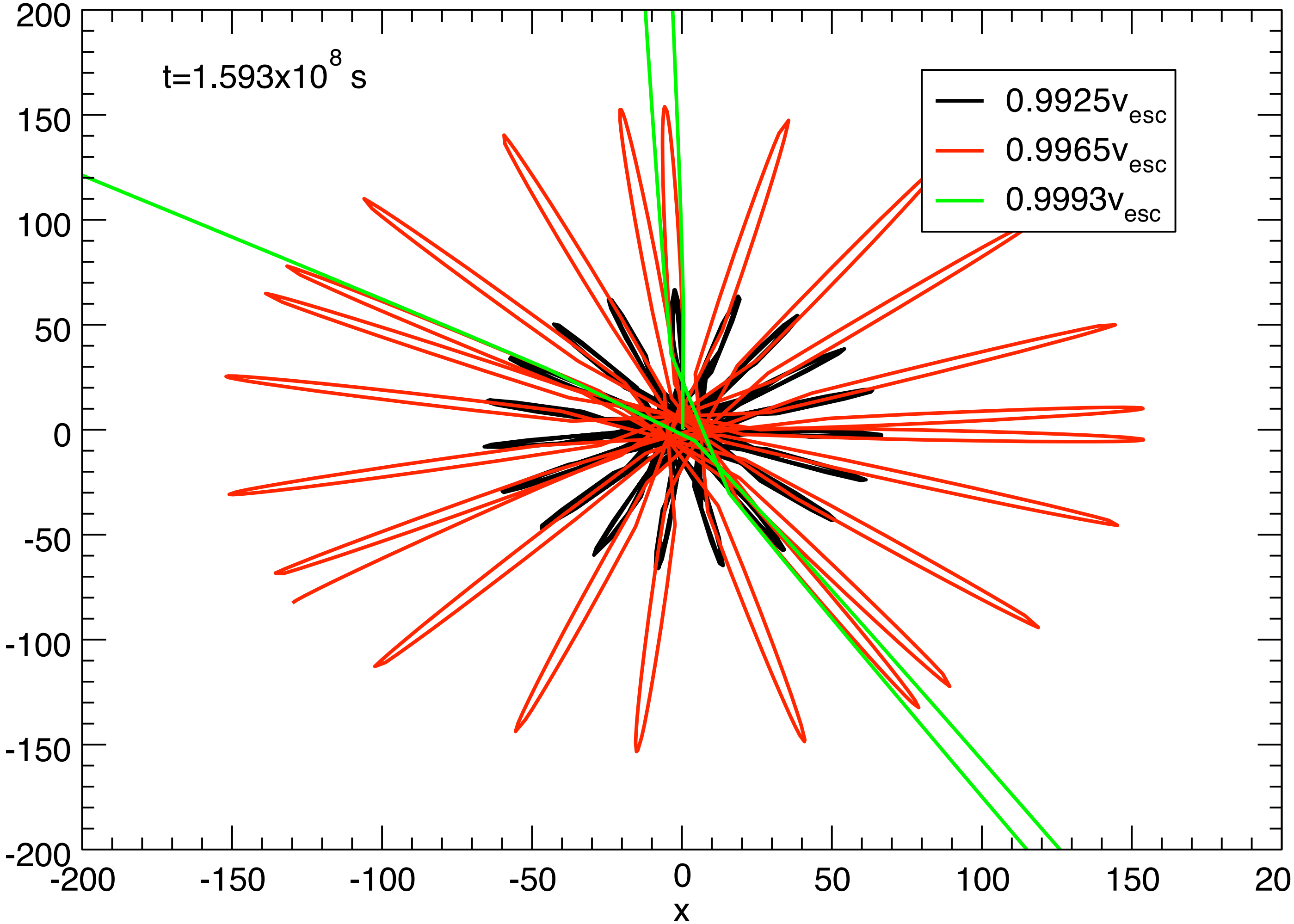
D. Santos (LPSC Grenoble)

Two sources of production in the Sun (Primakoff effect + photon Coalescence)

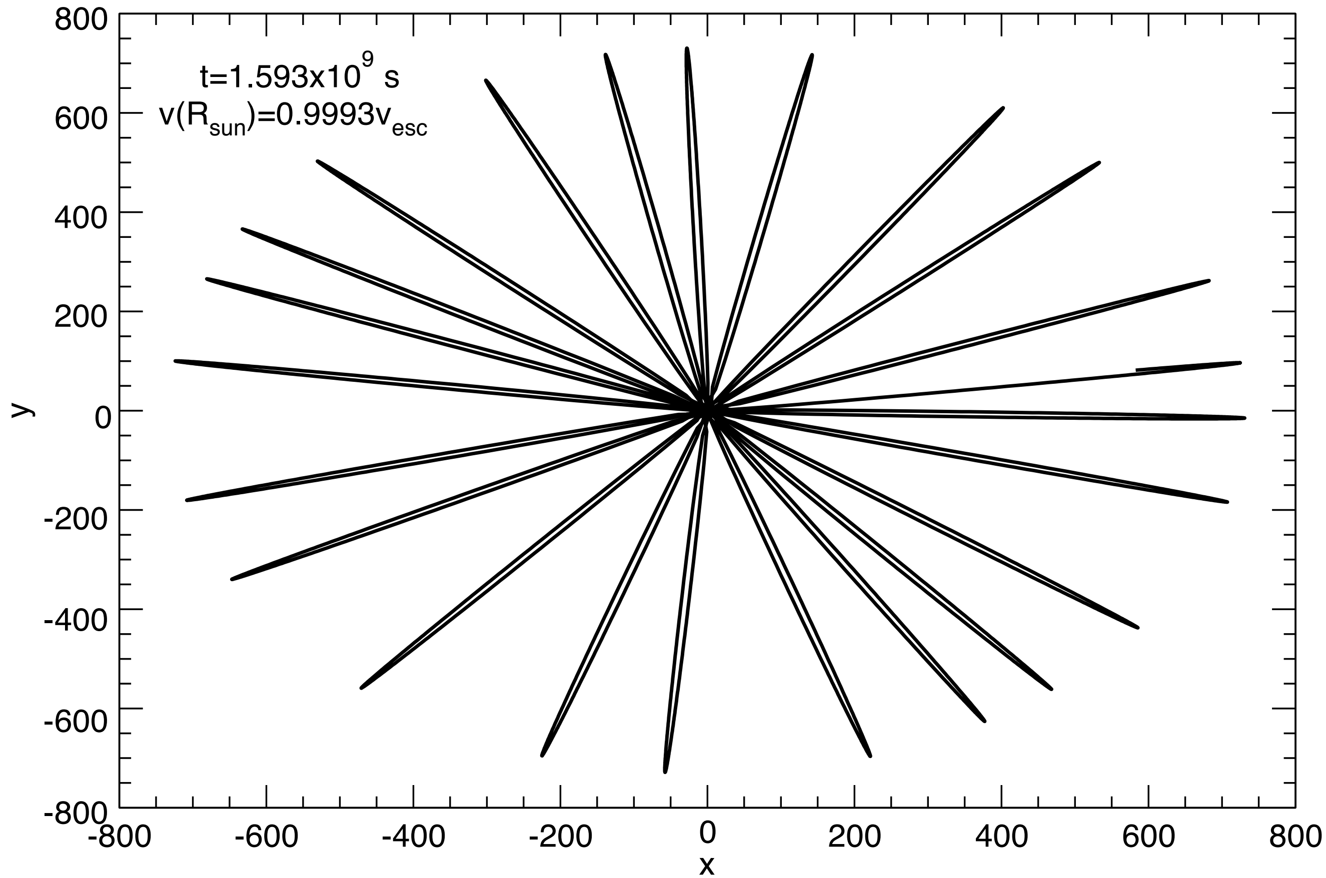


KK- axion Orbits for different velocities

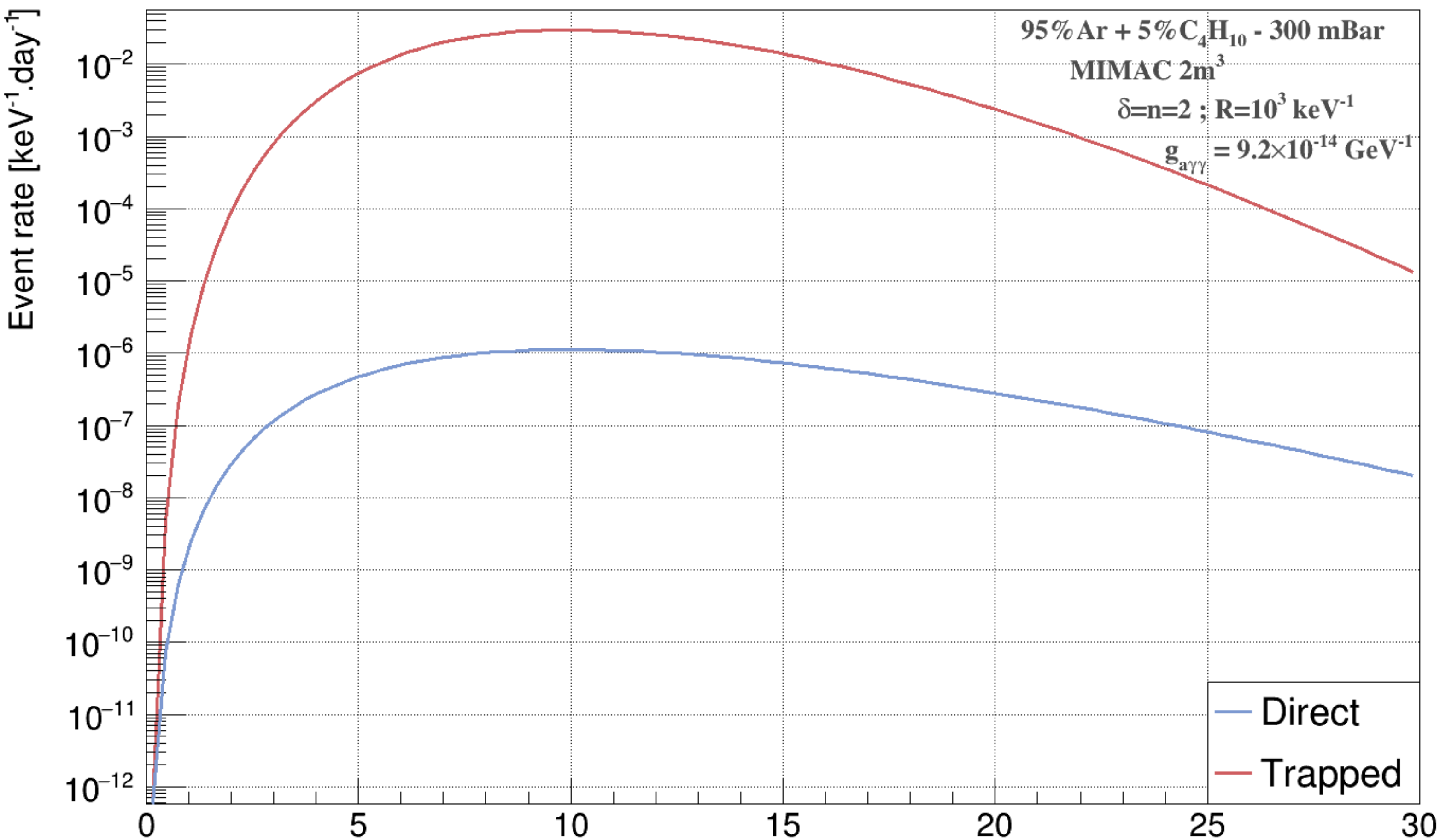
M. Bastero-Gil (2019)



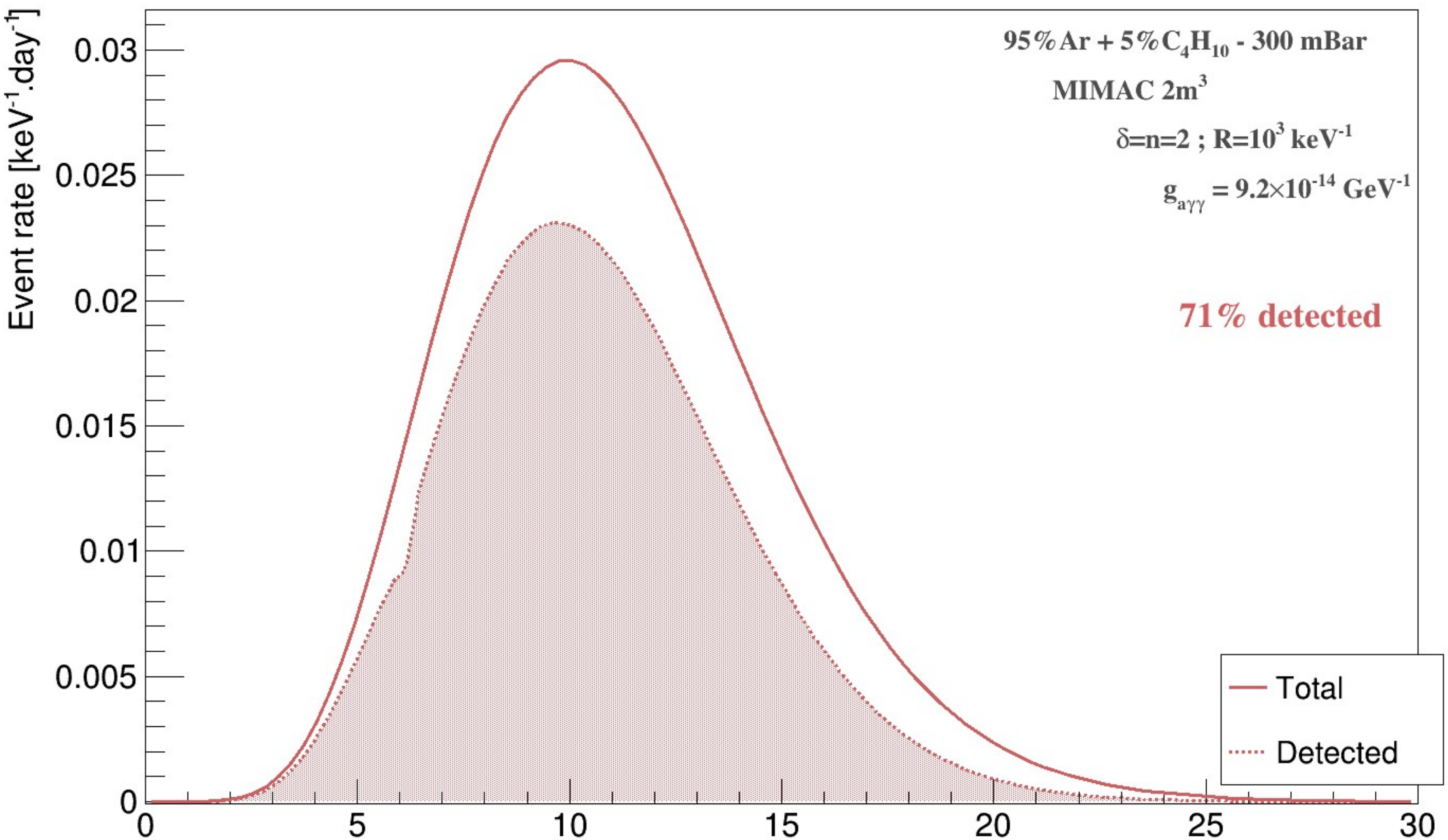
KK-axion orbits



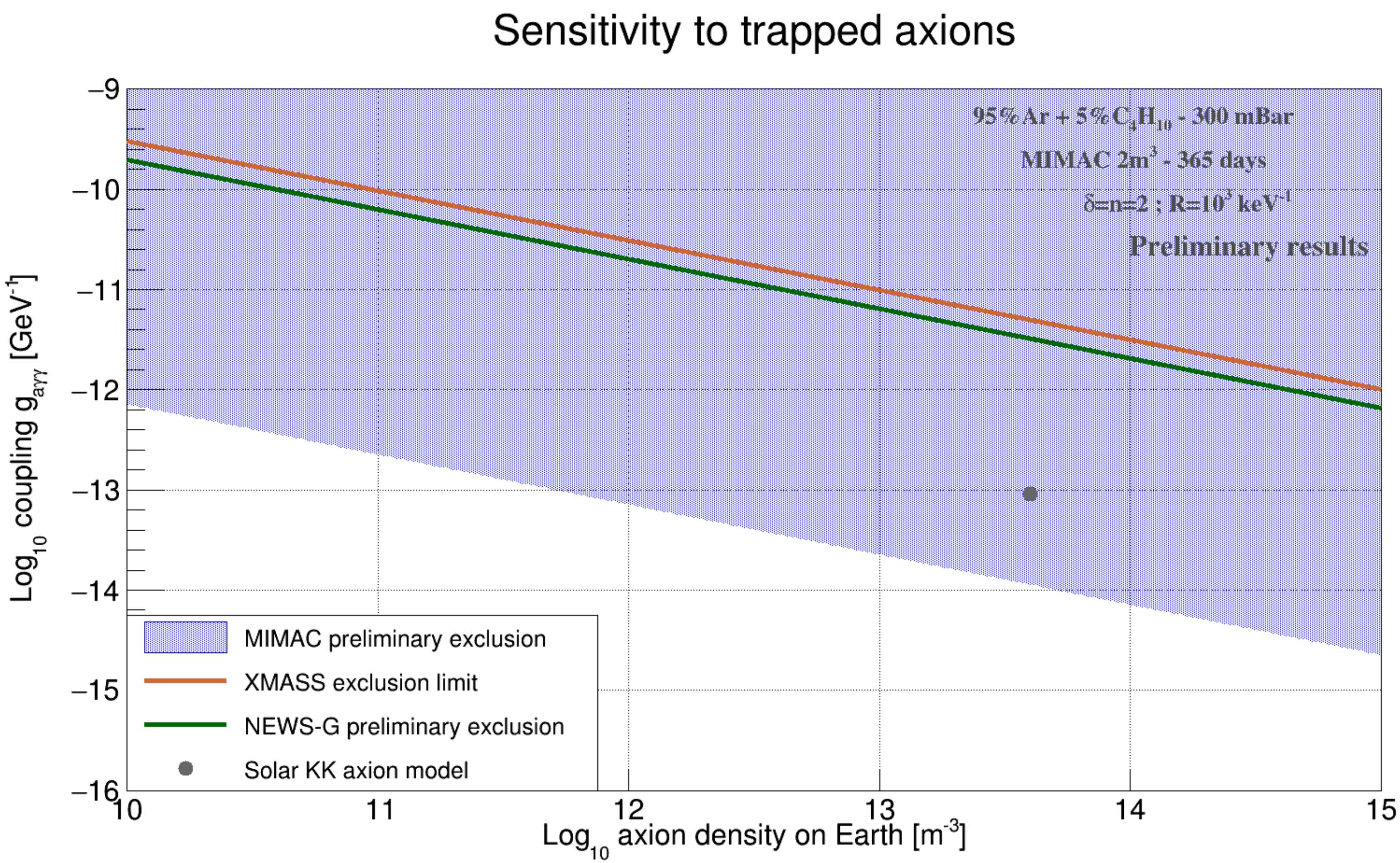
Event rate expected from the direct flux and gravitationally trapped



Event rate vs. KK-axion energy



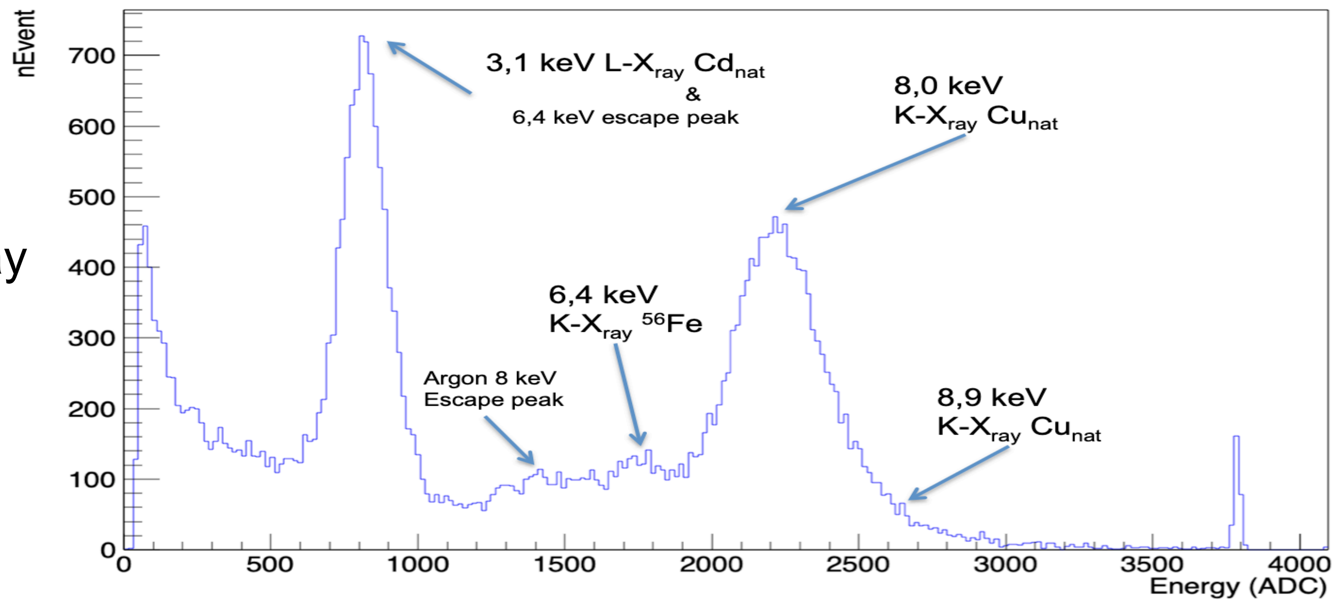
Exclusion curves

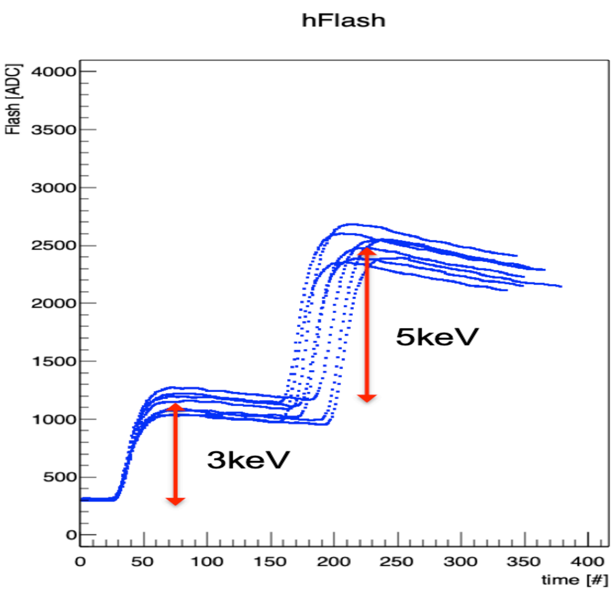


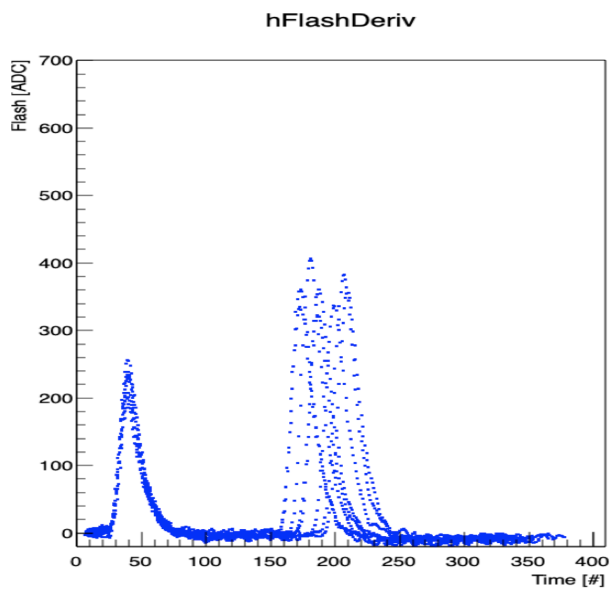
Calibration

Fluorescence X-ray

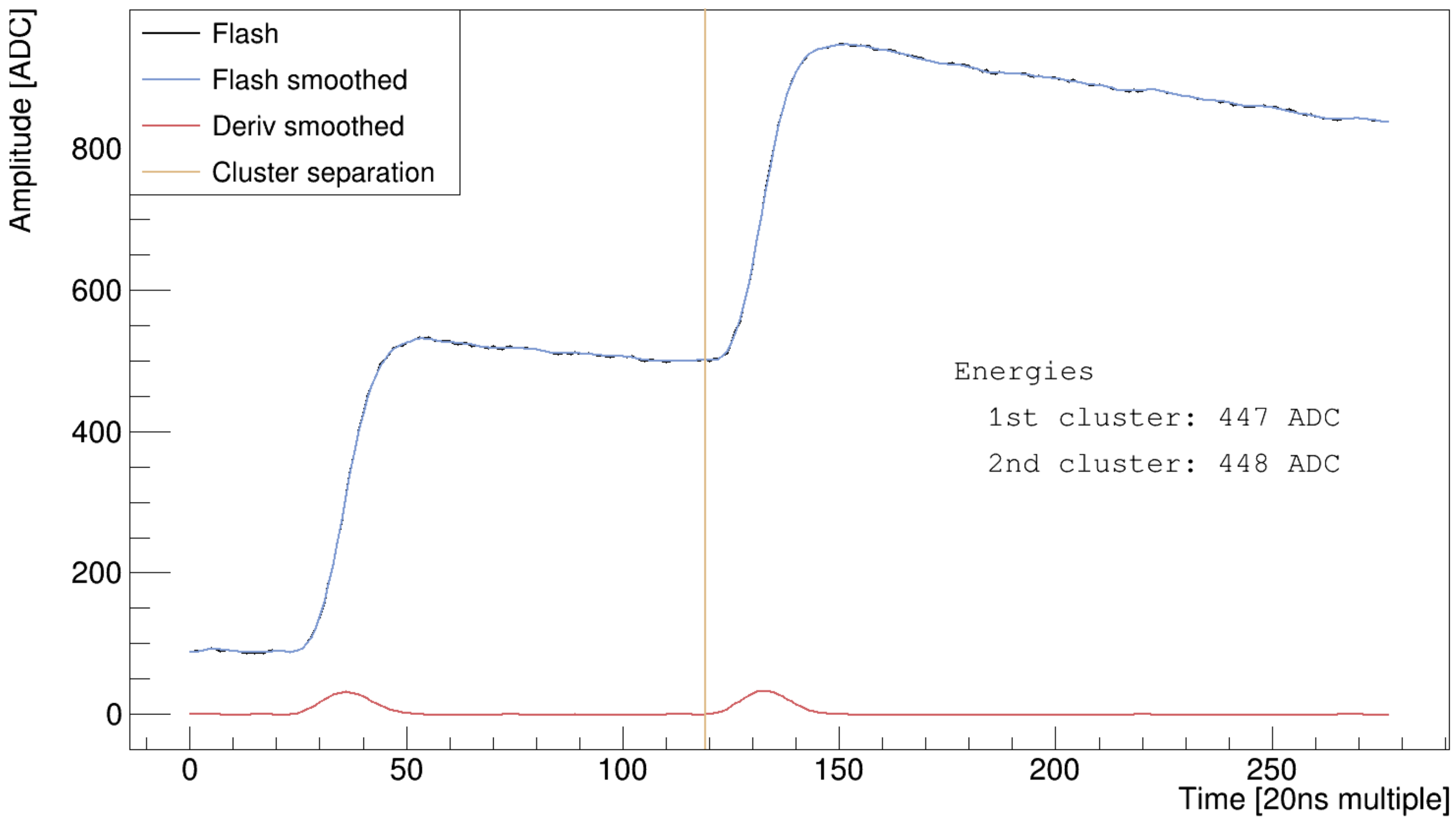
$^{40}Ar + 5\% \ C_4H_{10}$

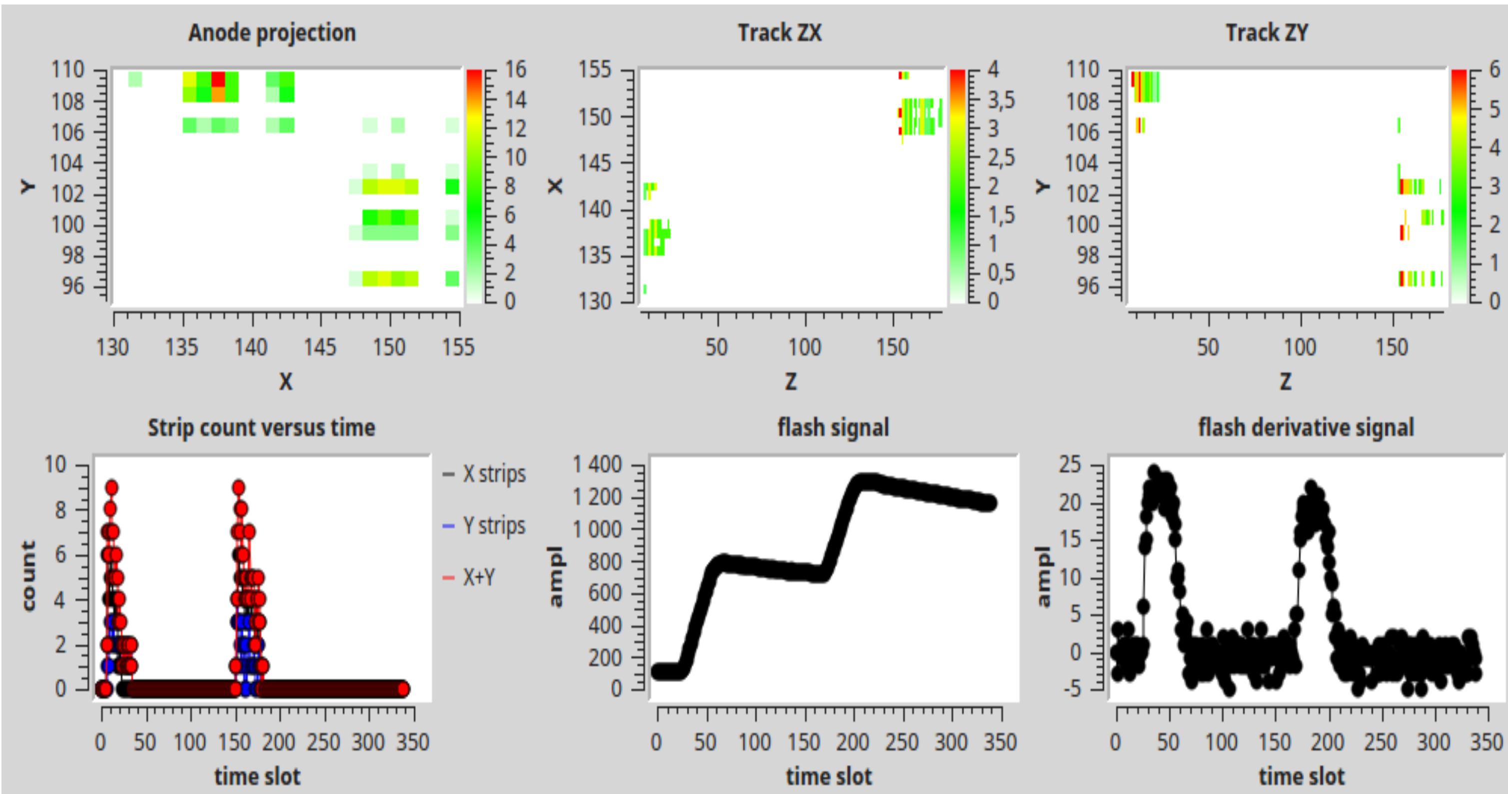






Two e$^-$ (4 keV) sent by COMIMAC (in less than 2 us)




Anode projection
Track ZX
Track ZY
Strip count versus time
flash signal
flash derivative signal
X strips
Y strips
X+Y
time slot
count
ampl

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.
- 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 have been performed with COMIMAC.
- MIMAC with its 3D tracks at high spatial resolution opens a new window in the exploration of rare events !
- **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)**
- **An efficient ALP exploration can be performed with the same detector !**

Standard axion properties

$$\mathcal{L}^{eff} = \mathcal{L}_{QCD} + \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}{m_{PQ}}^2 a^2 + \frac{a}{f_{PQ}} \xi \frac{g_s^2}{32\pi^2} G_a^{\mu\nu} \tilde{G}_{a\mu\nu} + \frac{g_{a\gamma\gamma}}{4} a F^{\mu\nu} \tilde{F}_{\mu\nu}$$

PARAMETERS:

- f_{PQ} : scale of the symmetry breaking
- $g_{a\gamma\gamma} = \frac{\alpha_{em}}{2\pi f_{PQ}} \left(\frac{E}{N} - 1.92(4) \right)$

  $\frac{E}{N} = \begin{cases} 0 & \text{for KSVZ} \\ \frac{8}{3} & \text{for DFSZ} \end{cases}$
- $m_{PQ} = 5.70(7) \left(\frac{10^{12}\,\mathrm{GeV}}{f_{PQ}} \right) \mu\mathrm{eV}$
- $\tau_{a\to\gamma\gamma} = \frac{64\pi}{{g_{a\gamma\gamma}}^2\, {m_{PQ}}^3}$

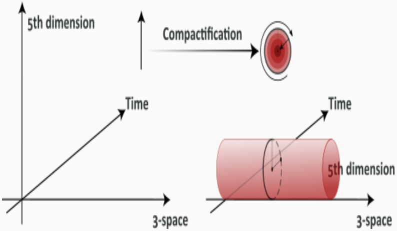
CONSTRAINTS:

- $10^9 \lesssim f_{PQ} \lesssim 10^{12}\,\mathrm{GeV}$
- $10^{-5} \lesssim m_{PQ} \lesssim 10^{-2}\,\mathrm{eV}$
- $10^{30} \lesssim \tau_{a\to\gamma\gamma} \lesssim 10^{45}\,\mathrm{days}$

$\Longrightarrow$ Dark matter candidate...
...but $a \to \gamma\gamma$ is undetectable

Axion in extra dimensions

Extra dimensions (ADD theory):



- $M_P = (2\pi R M_S)^{n/2} M_S$
  avec $M_S \sim \mathcal{O}(\text{TeV})$
- $\hat{f}_{PQ} \equiv (2\pi R M_S)^{\delta/2}\, f_{PQ}$
- $\hat{f}_{PQ} \gg f_{PQ}$
  - $\hat{f}_{PQ}$ experimentally constrained
  - f_{PQ} scale of the $U(1)_{PQ}$ breakdown

Kaluza-Klein decompisition:

- $a(x^\mu, \mathbf{y}) = \sum_{\mathbf{n}=0}^{\infty} a_{\mathbf{n}}(x^\mu)\ \cos\left(\frac{\mathbf{ny}}{R}\right)$
- $\mathcal{L}_{4D}^{eff} \supset \frac{g_{a\gamma\gamma}}{4}\left(\sum_{\mathbf{n}=0}^{\infty} r_{\mathbf{n}} a_{\mathbf{n}}\right) F^{\mu\nu}\tilde{F}_{\mu\nu}$

The SM gauge fields couple to a linear combination of KK excitations

PQ mechanism in extra dimensions

Peccei-Quinn mechanism:

$$\begin{cases} \langle a_0 \rangle \;=\; \frac{\hat{f}_{PQ}}{\xi}\big(-\bar{\theta}+\ell\pi\big)\;, & \ell \in 2\mathbb{Z} \\ \langle a_k \rangle \;=\; 0\;, & \forall k>0 \end{cases} \quad \text{and} \quad \begin{cases} a_0 \xrightarrow[U(1)_{PQ}]{} a_0+\alpha f_{PQ} \\ a_k \xrightarrow[U(1)_{PQ}]{} a_k\;,\;\; \forall k>0 \end{cases}$$

The standard axion is identified to the fundamental mode a_0

KK mass eigenstates

Mass matrix:

$$\mathcal{M}^2 = m_{\rm PQ}^2 \begin{pmatrix} 1 & \sqrt{2} & \sqrt{2} & \sqrt{2} & \dots \\ \sqrt{2} & 2+y^2 & 2 & 2 & \dots \\ \sqrt{2} & 2 & 2+4y^2 & 2 & \dots \\ \sqrt{2} & 2 & 2 & 2+9y^2 & \dots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

with:

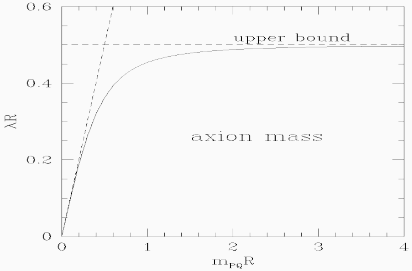
$$m_{PQ}^2 = \xi^2 \frac{g_S^2}{32\pi^2} \frac{\Lambda_{QCD}^4}{\hat{f}_{PQ}^2}$$

$$y \equiv \frac{1}{m_{PQ} R}$$

Mass eigenstates:

$$\begin{cases} m_{a_0} \sim m_{PQ} \\ m_{a_{n\neq 0}} \sim \frac{n}{R} \end{cases} \quad \text{if } m_{PQ} R \ll 1$$

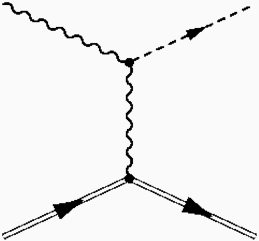
$$m_{a_n} \sim \frac{2n+1}{2R} \quad \text{if } m_{PQ} R \gg 1$$



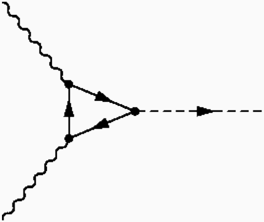
$$m_{a_{QCD}} = \min\left(m_{PQ}\,,\, \tfrac{1}{2R}\right) \implies f_{PQ} \text{ decouples from } m_{a_{QCD}}$$

KK axion production

KK axion production in the Sun:



- Primakoff effect -



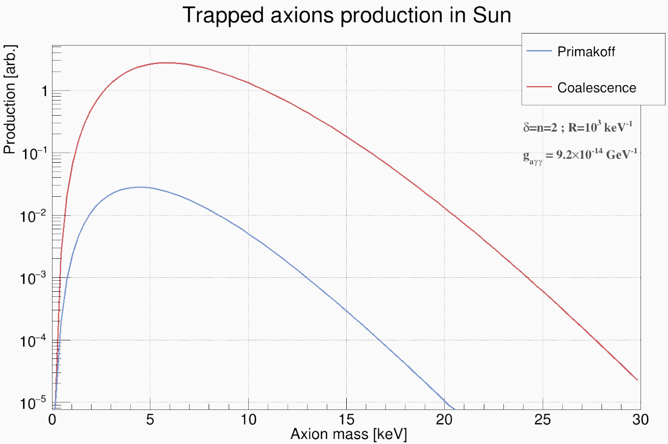
- Photons coalescence -

KK axions production with mass in range $\sim (1-25)\,\mathrm{keV}$

Trapped axions

Axions gravitationnally trapped:

- Axions with $v_a < v_{esc} \sim 617\,\mathrm{km.s^{-1}}$ are trapped into the Sun's gravitational field $\Rightarrow$ orbit
- Their number increases all along the Sun life



Solar KK axion model

Observations and parameters:

- Test of Newton's law: $R < 30\,\mu\mathrm{m}$
- Hierarchy problem solving: $M_S \sim \mathcal{O}(\mathrm{TeV})$
- Astrophysical/cosmological constraints: $10^9 \lesssim \hat{f}_{PQ} \lesssim 10^{12}\,\mathrm{GeV}$
- Limit energy loss in the Sun: $L_a^{max} \lesssim 0.2 L_\odot$
- Heating of the solar corona
- X-rays from the dark side of the Moon

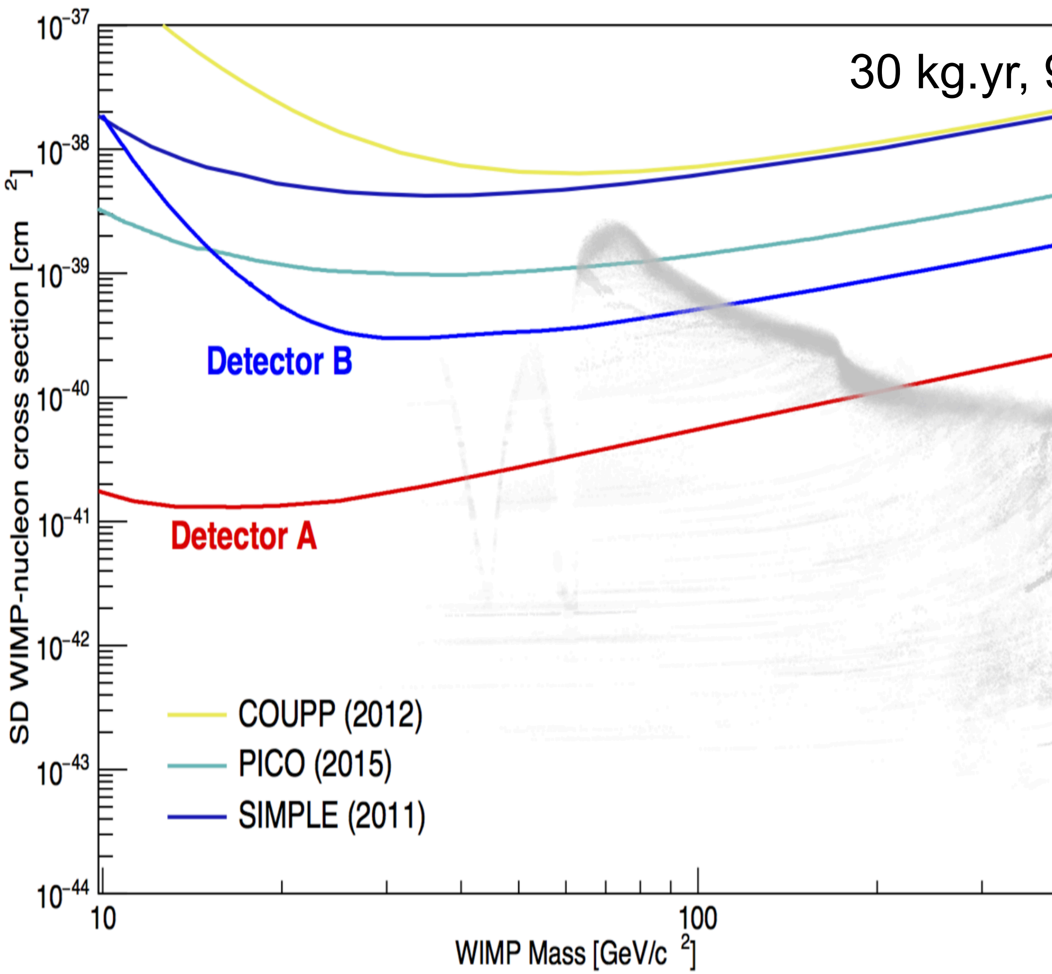
Solar KK axion model:

$\delta = n = 2 \quad ; \quad R = 10^3\,\mathrm{keV}^{-1}$

$g_{a\gamma\gamma} = 9.2 \times 10^{-14}\,\mathrm{GeV}^{-1} \quad ; \quad n_a = 4.07 \times 10^{13}\,\mathrm{m}^{-3}$

Di Lella *et al.*, **2003**, Astroparticle Physics

MIMAC-Exclusion limits

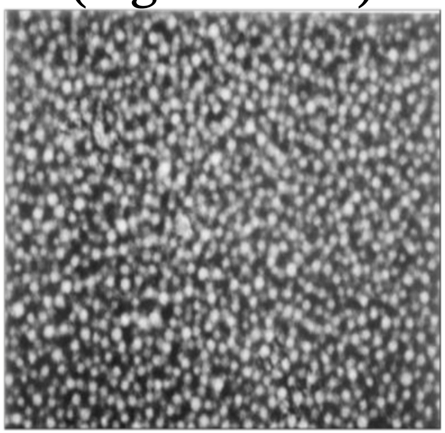


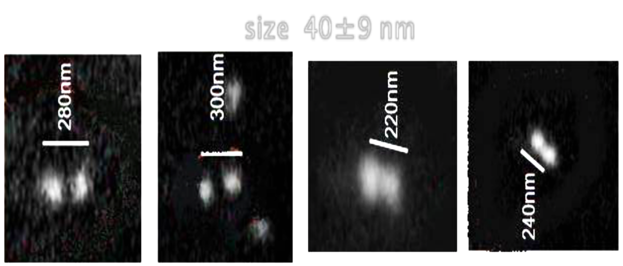
A: 5 keV (threshold)
no background
3D track with head-tail
angular resolution 20º

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

Directional detection: comparison of strategies

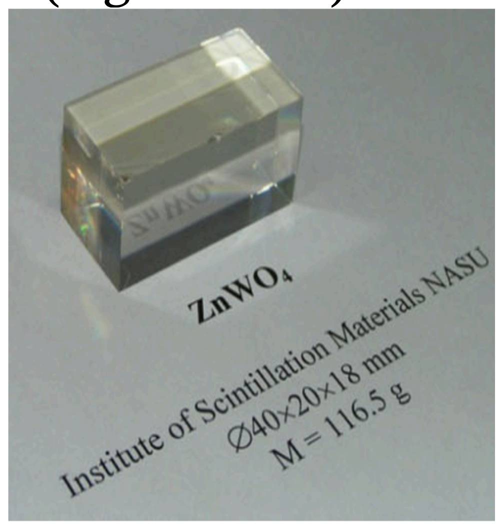
- Emulsion layers target = C (low masses), Ar, Br, Kr (high masses)





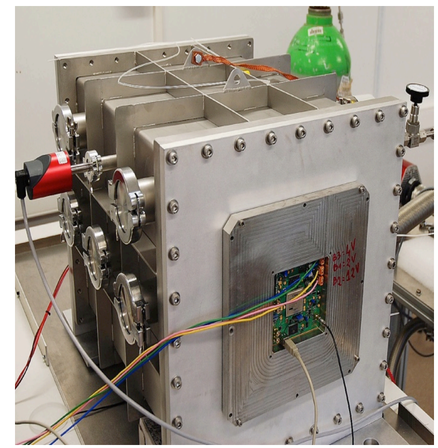
D'Ambrosio et al. 2014

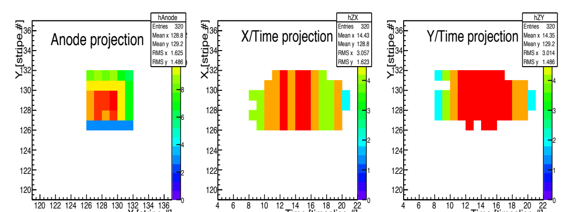
- Anisotropic crystals target = O (low masses), Zn, W (high masses)



No tracks ; only statistical distributions (!)

- Low pressure TPCs target = F

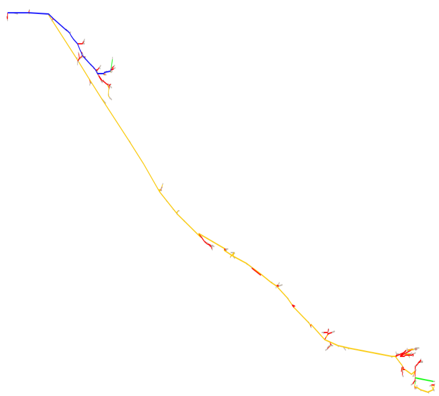




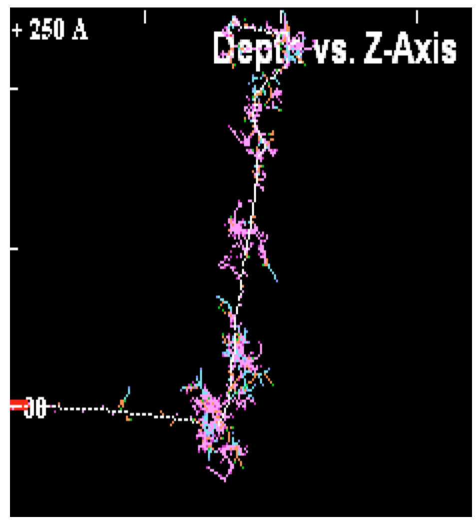
Capella et al. 2013

Directional detection: comparison of strategies

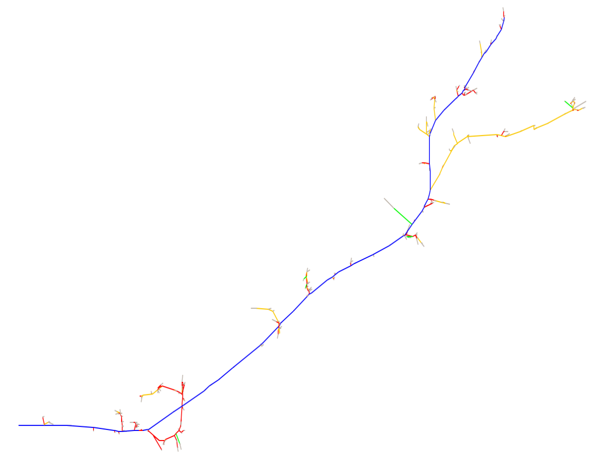
- Emulsion
- Anisotropic crystals
- Low pressure TPCs



~100 nm



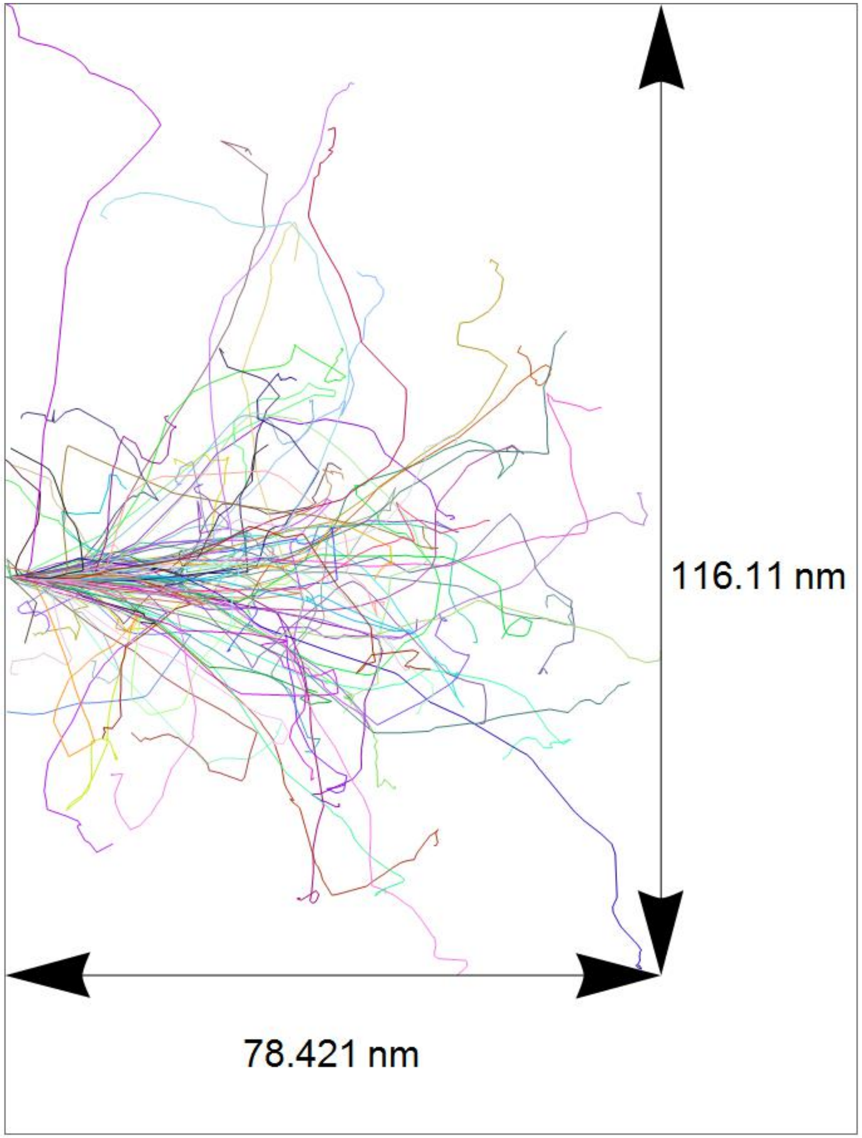
~10 nm



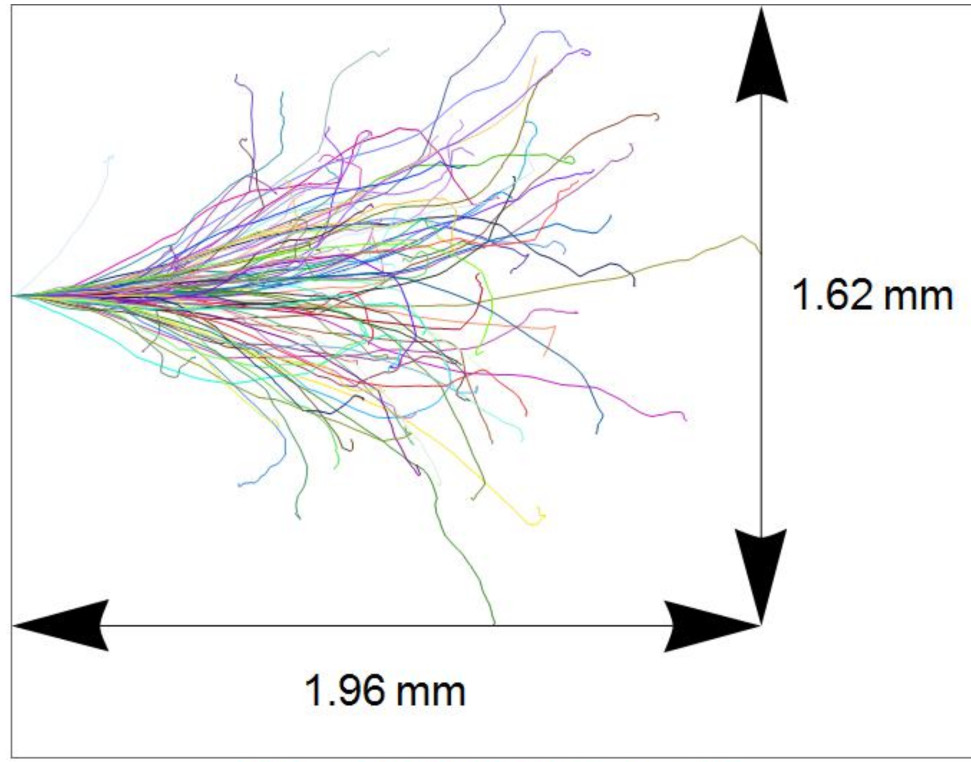
~1 mm
(10^5 times longuer !!)

(SRIM simulations)

SRIM simulations…



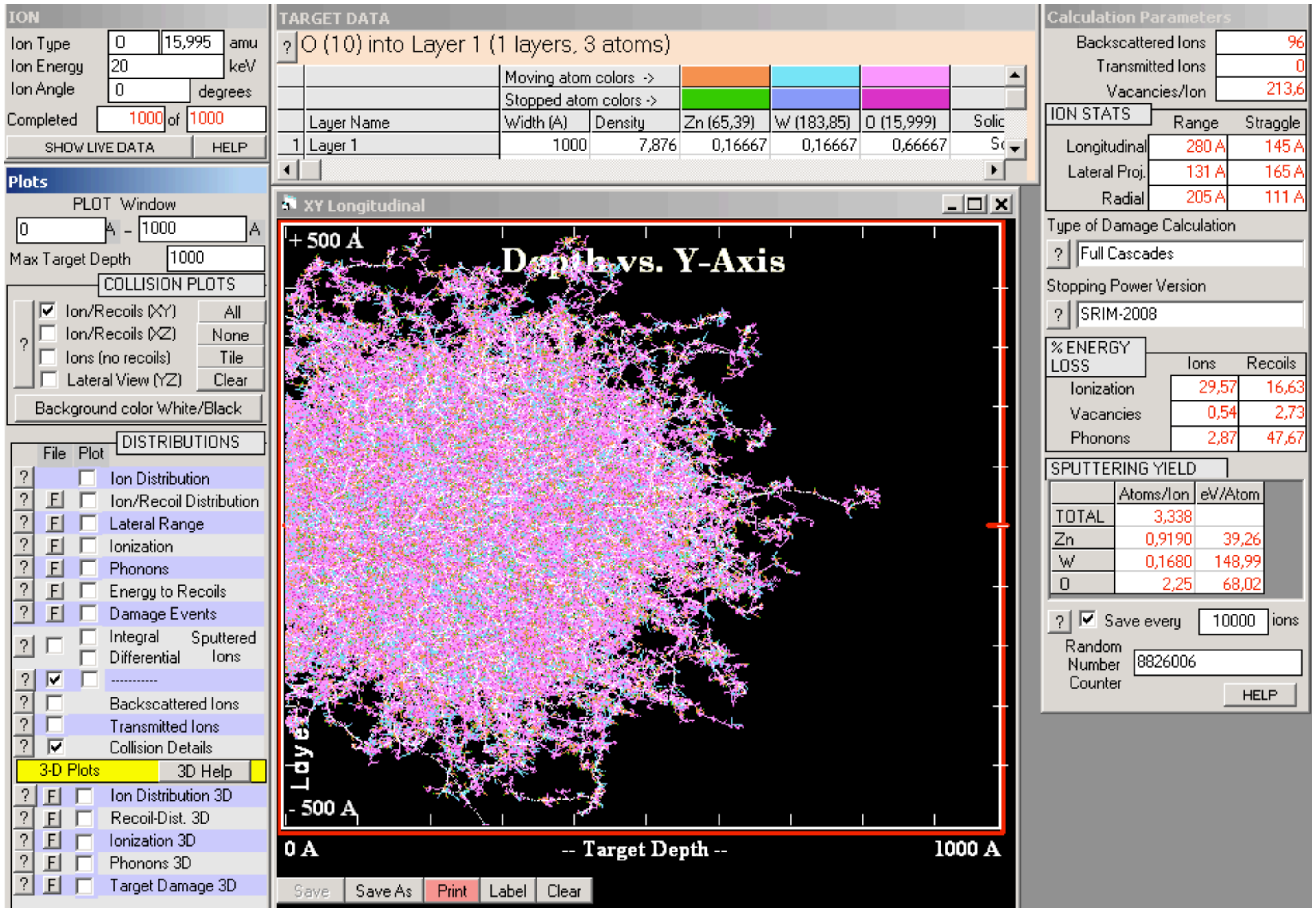
O in Crystal (29keV)



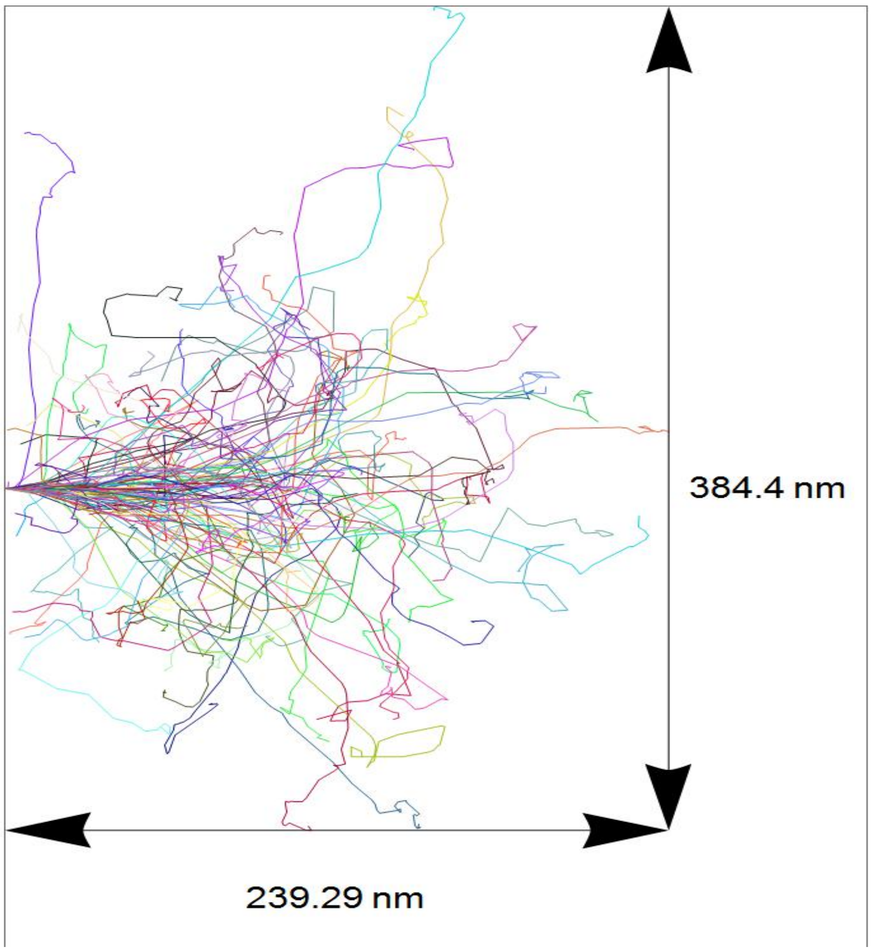
F in MIMAC (34keV)

SRIM simulation of O (20 keV) in ZnO_4W

showing the secondary recoils

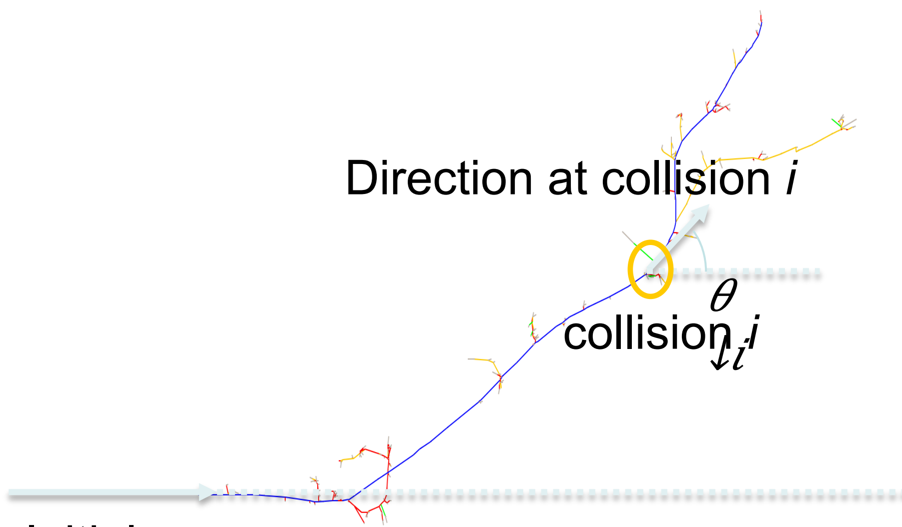


C (22 keV) in emulsion (SRIM simulation)

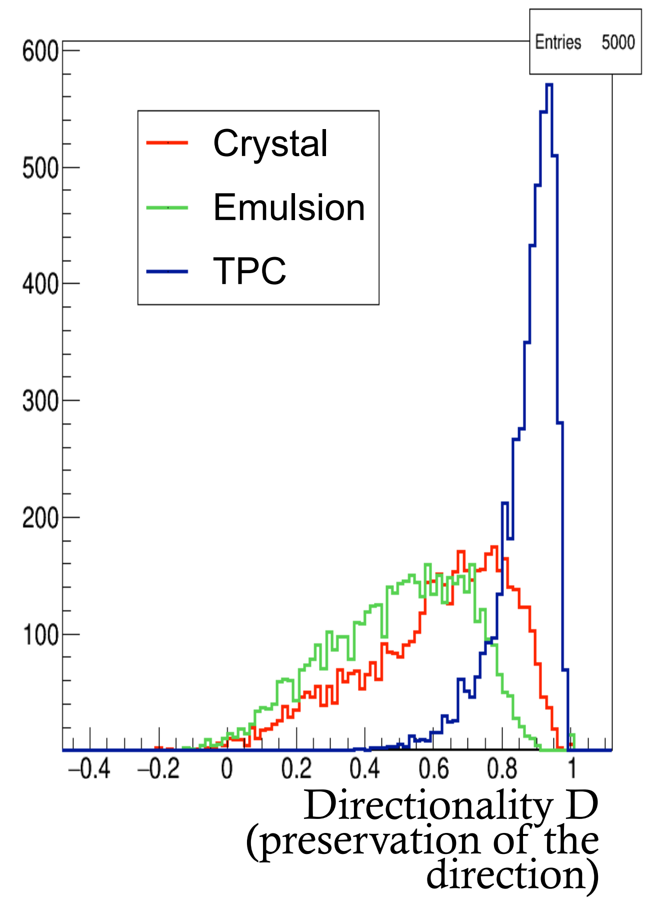


In emulsions and solids the transverse development is in general greater than the longitudinal !!

Directional detection: Directionality 'D'



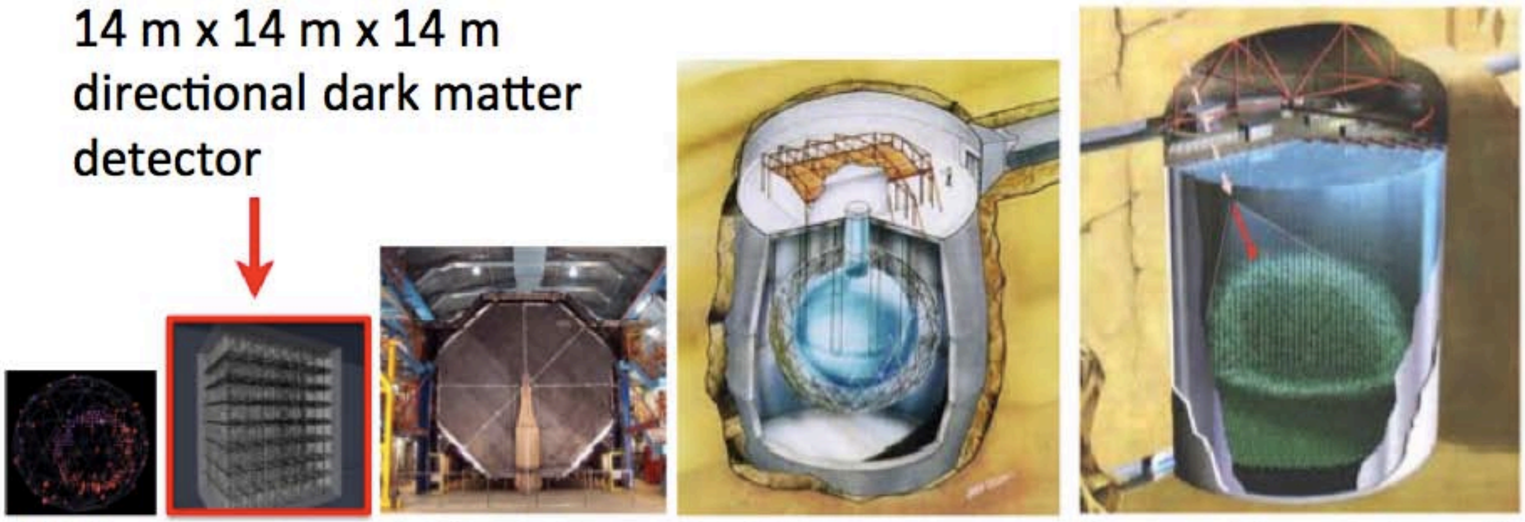
$$D = \frac{<\cos(\theta)\cdot E>_{track}}{<E>_{track}} = \frac{\sum_{i=0}^{N_{collisions}} \cos(\theta_i)\cdot E_i}{\sum_{i=0}^{N_{collisions}} E_i} = \frac{\sum_i \cos(\theta_i)\cdot E_i}{N_{collisions}\cdot <E>_{track}}$$



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

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%CS_2 +25%CF_4 +2%O_2	70%CF_4 +28%CHF_3 +2%C_4H_{10}	CF_4	CF_4
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]

Radon Progeny

^{222}Rn chain:

- 4 β-decays

→ Electron event (background)

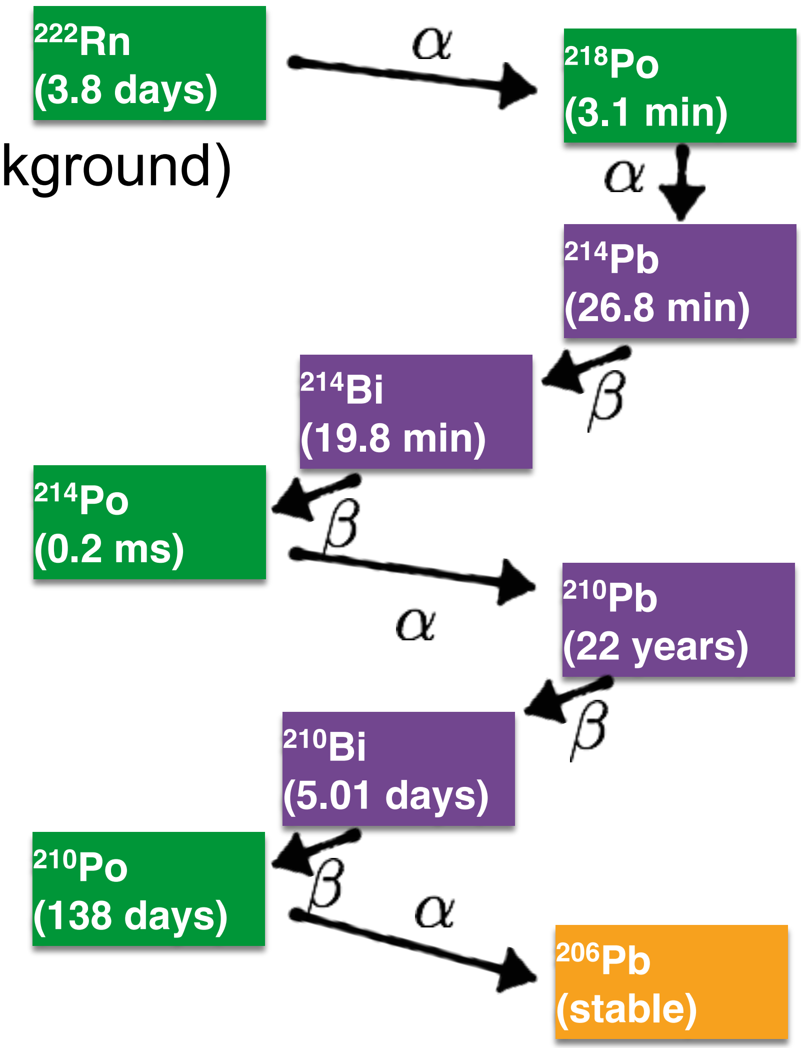
- 4 α-decays

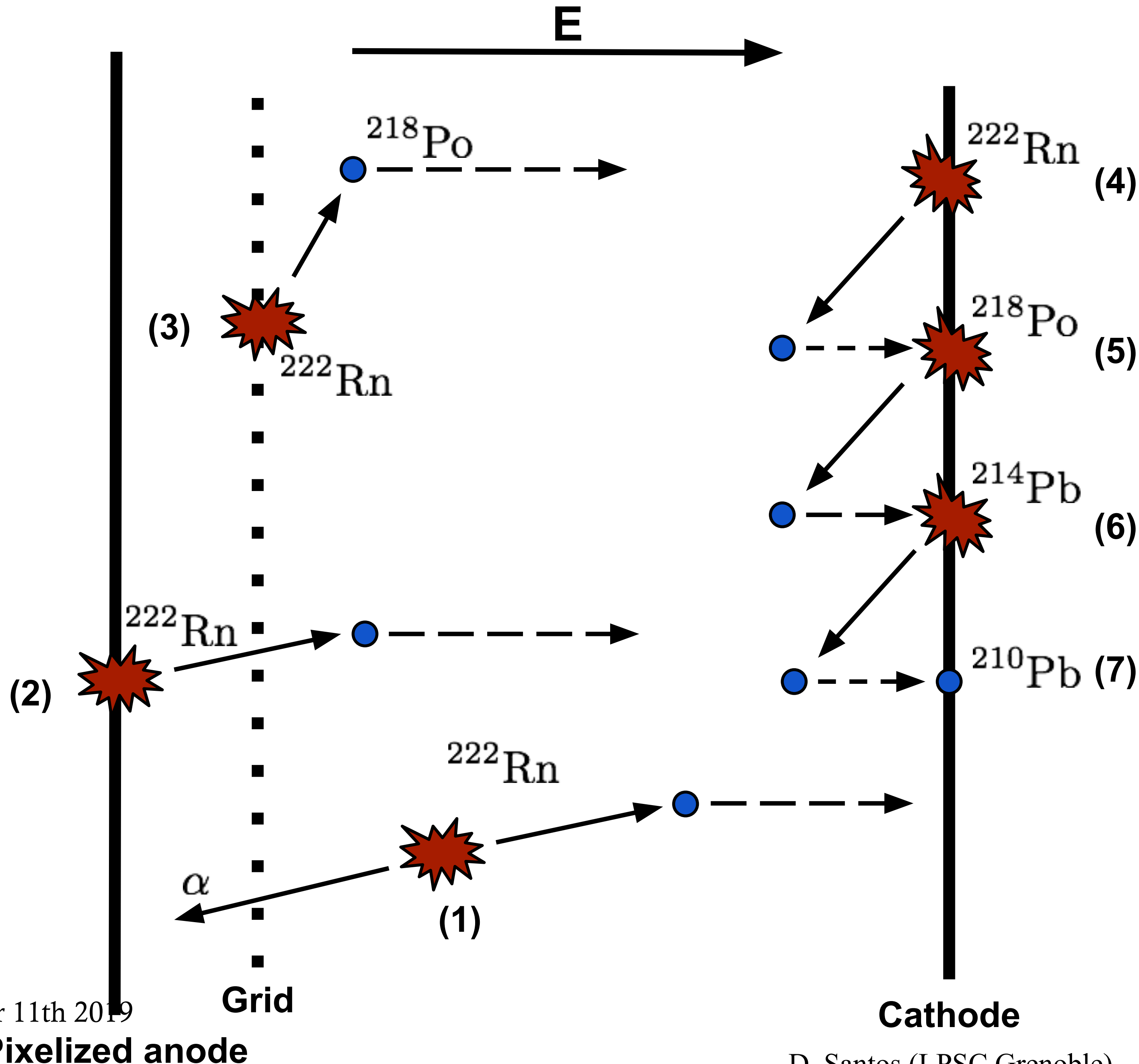
→ α-particle emission: $E_\alpha \sim 5\,\mathrm{MeV}$ → Saturation

→ 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)

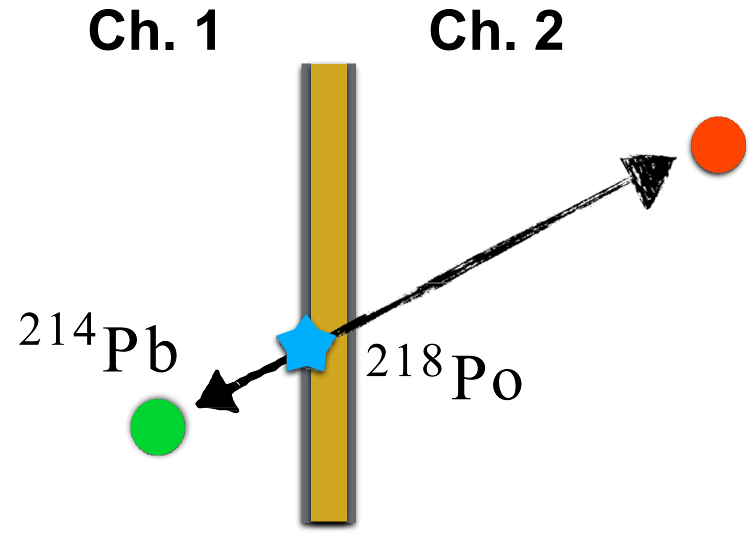


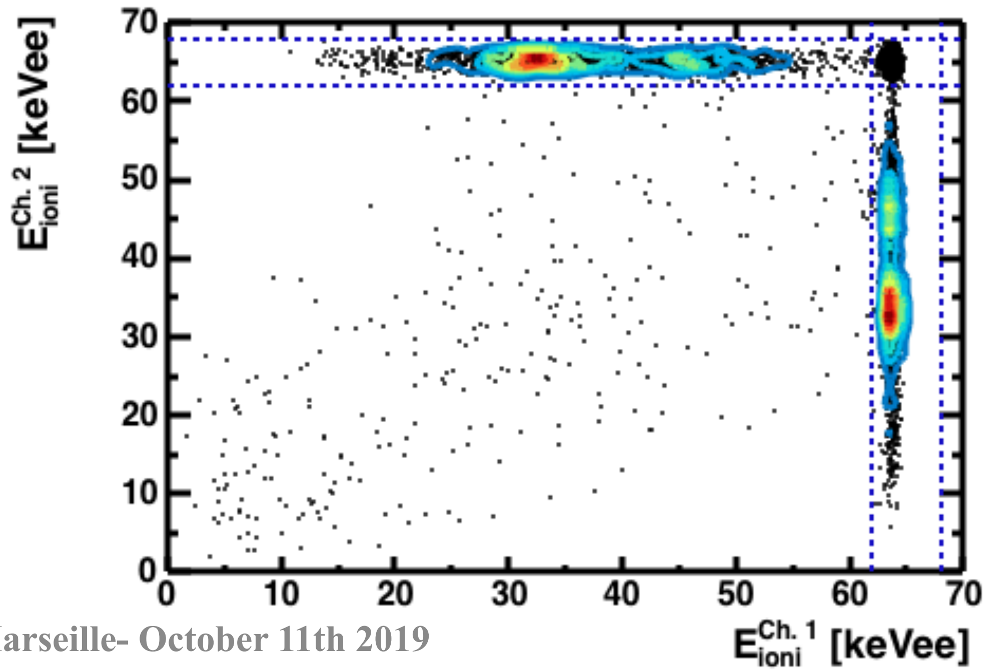


E
^{218}Po
^{222}Rn
(4)
(3)
^{222}Rn
^{218}Po
(5)
^{214}Pb
(6)
^{222}Rn
^{210}Pb (7)
(2)
^{222}Rn
α
(1)
Grid
Cathode
Pixelized anode

RPR: « In coincidence » events

Chamber coincidences:





3D tracks from nuclear recoil of radon progeny detection

First detection of 3D tracks of Rn progeny

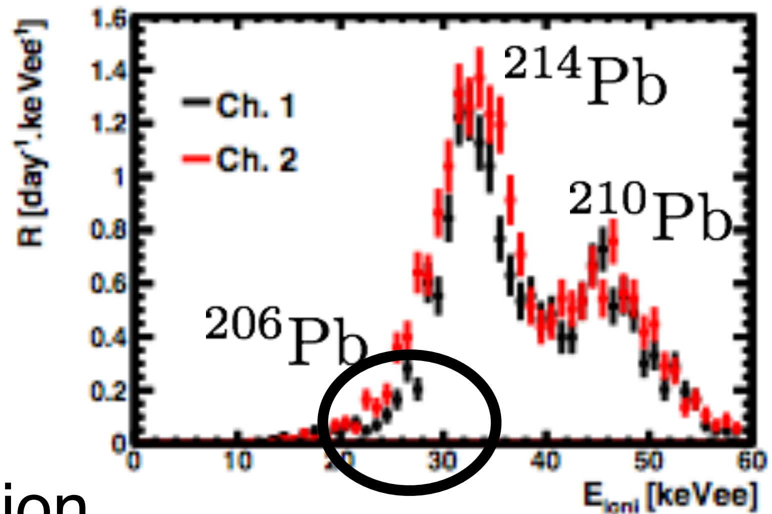
Electron/recoil discrimination

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

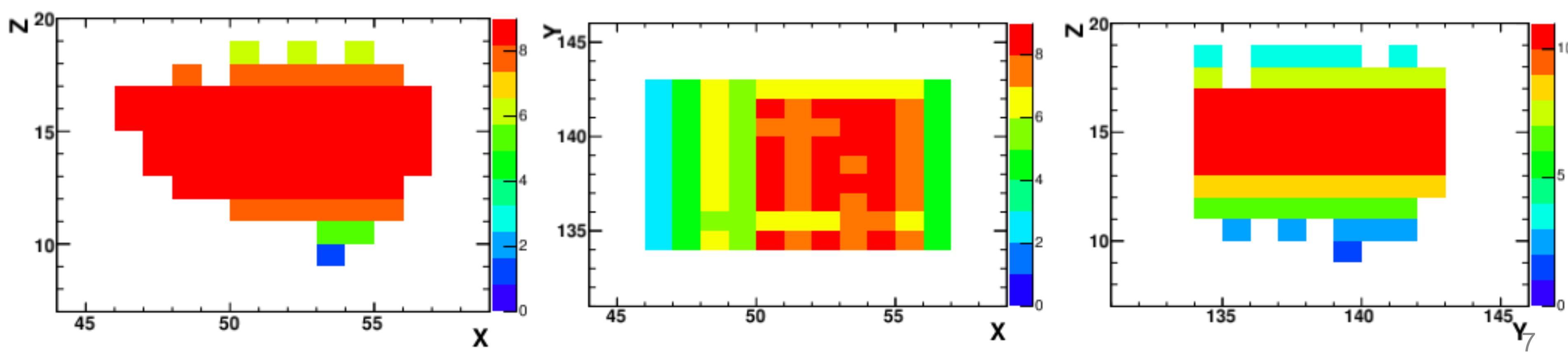
First measurement of 3D nuclear-recoil tracks coming from radon progeny

→ MIMAC detection strategy validation

Nuclear recoil spectra



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

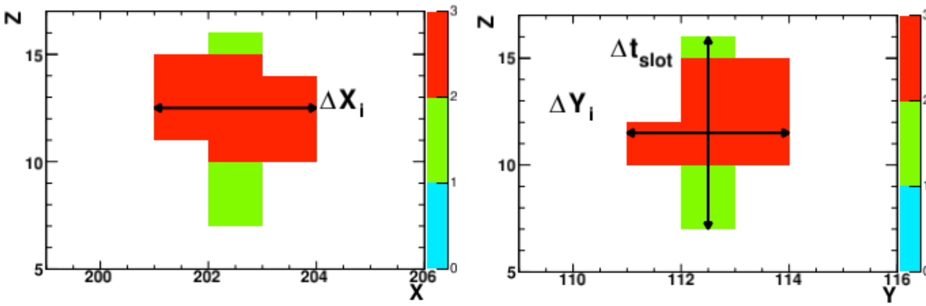


RPR events occur at different positions in the detector…

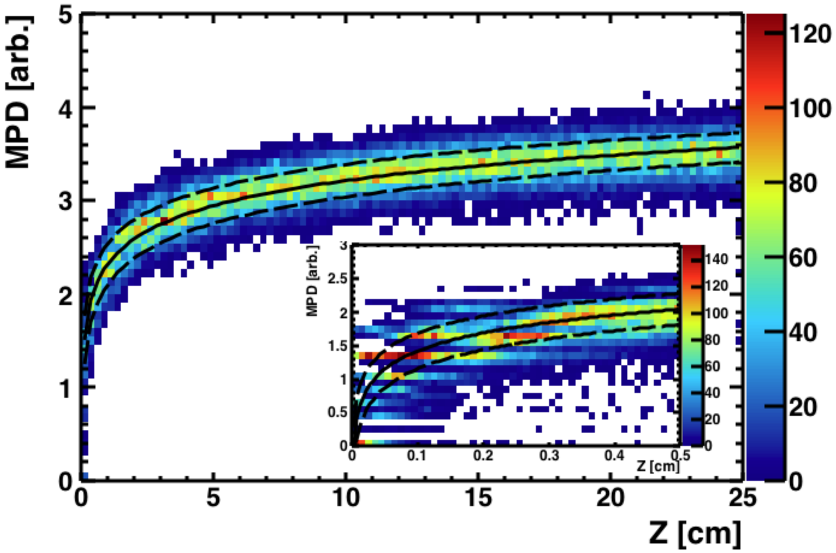
$$z_0 \longleftrightarrow \text{Diffusion}$$

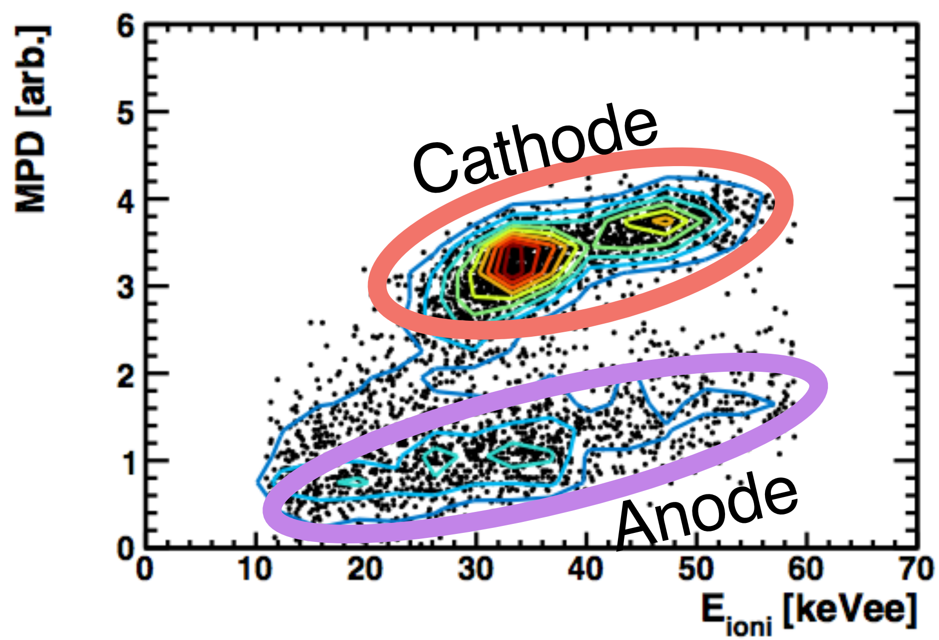
$$\begin{cases} D_T = 237.9\,\mu\text{m}/\sqrt{\text{cm}} \\ D_L = 271.5\,\mu\text{m}/\sqrt{\text{cm}} \end{cases}$$

« Anode » event



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





Standard axion properties

$$\mathcal{L}^{eff} = \mathcal{L}_{QCD} + \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}{m_{PQ}}^2 a^2 + \frac{a}{f_{PQ}}\xi \frac{g_s^2}{32\pi^2} G_a^{\mu\nu}\tilde{G}_{a\mu\nu} + \frac{g_{a\gamma\gamma}}{4} a F^{\mu\nu}\tilde{F}_{\mu\nu}$$

Parameters:

- f_{PQ} : scale of the symmetry breaking
- $g_{a\gamma\gamma} = \frac{\alpha_{em}}{2\pi f_{PQ}}\left(\frac{E}{N} - 1.92(4)\right)$

  $$\frac{E}{N} = \begin{cases} 0 & \text{for KSVZ} \\ \frac{8}{3} & \text{for DFSZ} \end{cases}$$
- $m_{PQ} = 5.70(7)\left(\frac{10^{12}\,\mathrm{GeV}}{f_{PQ}}\right)\mu\mathrm{eV}$
- $\tau_{a\to\gamma\gamma} = \frac{64\pi}{{g_{a\gamma\gamma}}^2\,{m_{PQ}}^3}$

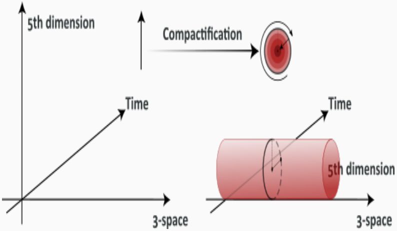
Constraints:

- $10^9 \lesssim f_{PQ} \lesssim 10^{12}\,\mathrm{GeV}$
- $10^{-5} \lesssim m_{PQ} \lesssim 10^{-2}\,\mathrm{eV}$
- $10^{30} \lesssim \tau_{a\to\gamma\gamma} \lesssim 10^{45}$ days

$\Longrightarrow$ Dark matter candidate...
...but $a \to \gamma\gamma$ is undetectable

Axion in extra dimensions

Extra dimensions (ADD theory):



- $M_P = (2\pi R M_S)^{n/2} M_S$
  avec $M_S \sim \mathcal{O}(\text{TeV})$
- $\hat{f}_{PQ} \equiv (2\pi R M_S)^{\delta/2}\, f_{PQ}$
- $\hat{f}_{PQ} \gg f_{PQ}$
  - $\hat{f}_{PQ}$ experimentally constrained
  - f_{PQ} scale of the $U(1)_{PQ}$ breakdown

Kaluza-Klein decompisition:

- $a(x^\mu, \mathbf{y}) = \sum_{\mathbf{n}=0}^{\infty} a_{\mathbf{n}}(x^\mu)\ \cos\left(\frac{\mathbf{ny}}{R}\right)$
- $\mathcal{L}_{4D}^{eff} \supset \frac{g_{a\gamma\gamma}}{4} \left(\sum_{\mathbf{n}=0}^{\infty} r_{\mathbf{n}} a_{\mathbf{n}}\right) F^{\mu\nu}\tilde{F}_{\mu\nu}$

The SM gauge fields couple to a linear combination of KK excitations

PQ mechanism in extra dimensions

Peccei-Quinn mechanism:

$$\begin{cases} \langle a_0 \rangle \;=\; \frac{\hat{f}_{PQ}}{\xi}\big(-\bar{\theta}+\ell\pi\big)\;, & \ell \in 2\mathbb{Z} \\ \langle a_k \rangle \;=\; 0\;, & \forall k>0 \end{cases}$$

and

$$\begin{cases} a_0 \xrightarrow[U(1)_{PQ}]{} a_0 + \alpha f_{PQ} \\ a_k \xrightarrow[U(1)_{PQ}]{} a_k\;,\;\; \forall k>0 \end{cases}$$

The standard axion is identified to the fundamental mode a_0

KK mass eigenstates

Mass matrix:

$$\mathcal{M}^2 = m_{\rm PQ}^2 \begin{pmatrix} 1 & \sqrt{2} & \sqrt{2} & \sqrt{2} & \dots \\ \sqrt{2} & 2+y^2 & 2 & 2 & \dots \\ \sqrt{2} & 2 & 2+4y^2 & 2 & \dots \\ \sqrt{2} & 2 & 2 & 2+9y^2 & \dots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

with:

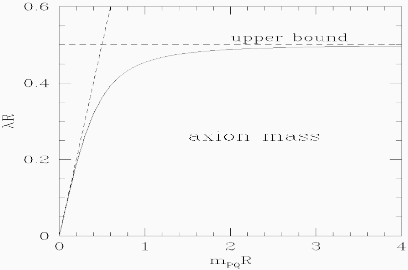
$$m_{PQ}^2 = \xi^2 \frac{g_S^2}{32\pi^2} \frac{\Lambda_{QCD}^4}{\hat{f}_{PQ}^2}$$

$$y \equiv \frac{1}{m_{PQ} R}$$

Mass eigenstates:

$$\begin{cases} m_{a_0} \sim m_{PQ} \\ m_{a_{n \neq 0}} \sim \frac{n}{R} \end{cases} \quad \text{if } m_{PQ} R \ll 1$$

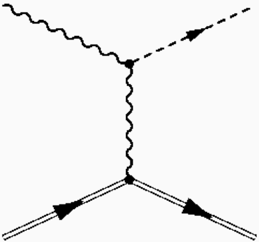
$$m_{a_n} \sim \frac{2n+1}{2R} \quad \text{if } m_{PQ} R \gg 1$$



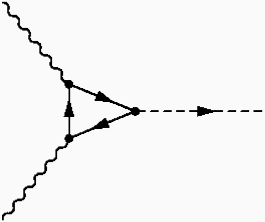
$m_{a_{QCD}} = \min\left(m_{PQ}\,,\ \frac{1}{2R}\right) \implies f_{PQ}$ decouples from $m_{a_{QCD}}$

KK axion production

KK axion production in the Sun:



- Primakoff effect -



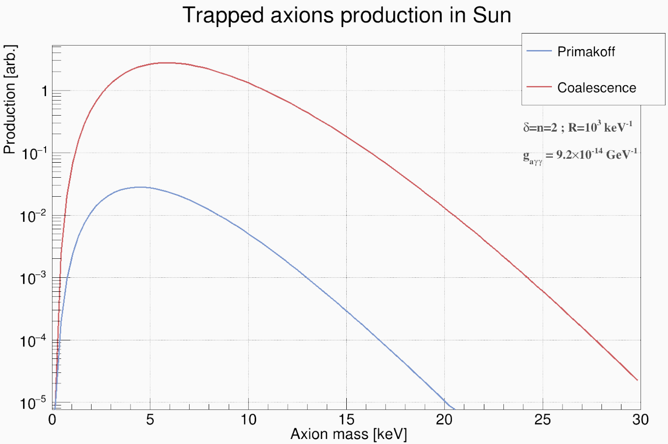
- Photons coalescence -

KK axions production with mass in range $\sim (1 - 25)\,\mathrm{keV}$

Trapped axions

AXIONS GRAVITATIONNALLY TRAPPED:

- Axions with $v_a < v_{esc} \sim 617\,\mathrm{km.s}^{-1}$ are trapped into the Sun's gravitational field $\Rightarrow$ orbit
- Their number increases all along the Sun life



Solar KK axion model

Observations and parameters:

- Test of Newton's law: $R < 30\,\mu\mathrm{m}$
- Hierarchy problem solving: $M_S \sim \mathcal{O}(\mathrm{TeV})$
- Astrophysical/cosmological constraints: $10^9 \lesssim \hat{f}_{PQ} \lesssim 10^{12}\,\mathrm{GeV}$
- Limit energy loss in the Sun: $L_a^{max} \lesssim 0.2 L_\odot$
- Heating of the solar corona
- X-rays from the dark side of the Moon

Solar KK axion model:

$\delta = n = 2 \quad ; \quad R = 10^3\,\mathrm{keV}^{-1}$

$g_{a\gamma\gamma} = 9.2 \times 10^{-14}\,\mathrm{GeV}^{-1} \quad ; \quad n_a = 4.07 \times 10^{13}\,\mathrm{m}^{-3}$

Di Lella *et al.*, **2003**, Astroparticle Physics