MIMAC

(MIcro-tpc MAtrix of Chambers)

searching for Axion-Like Particles (ALPs) and opening the possibility for directional DM

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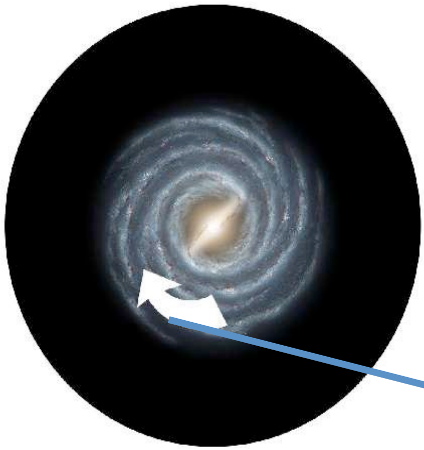
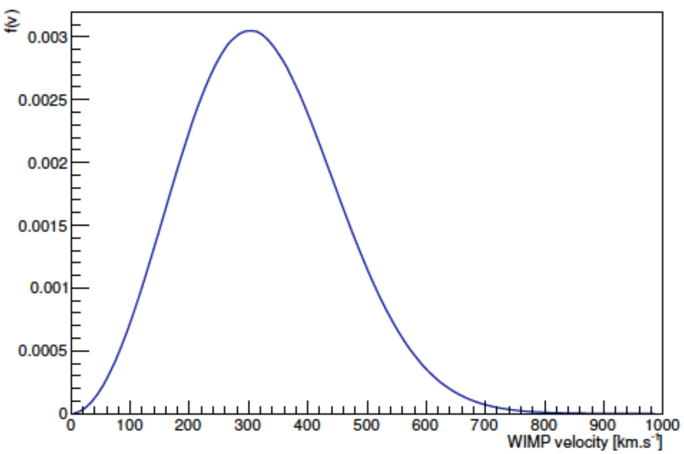
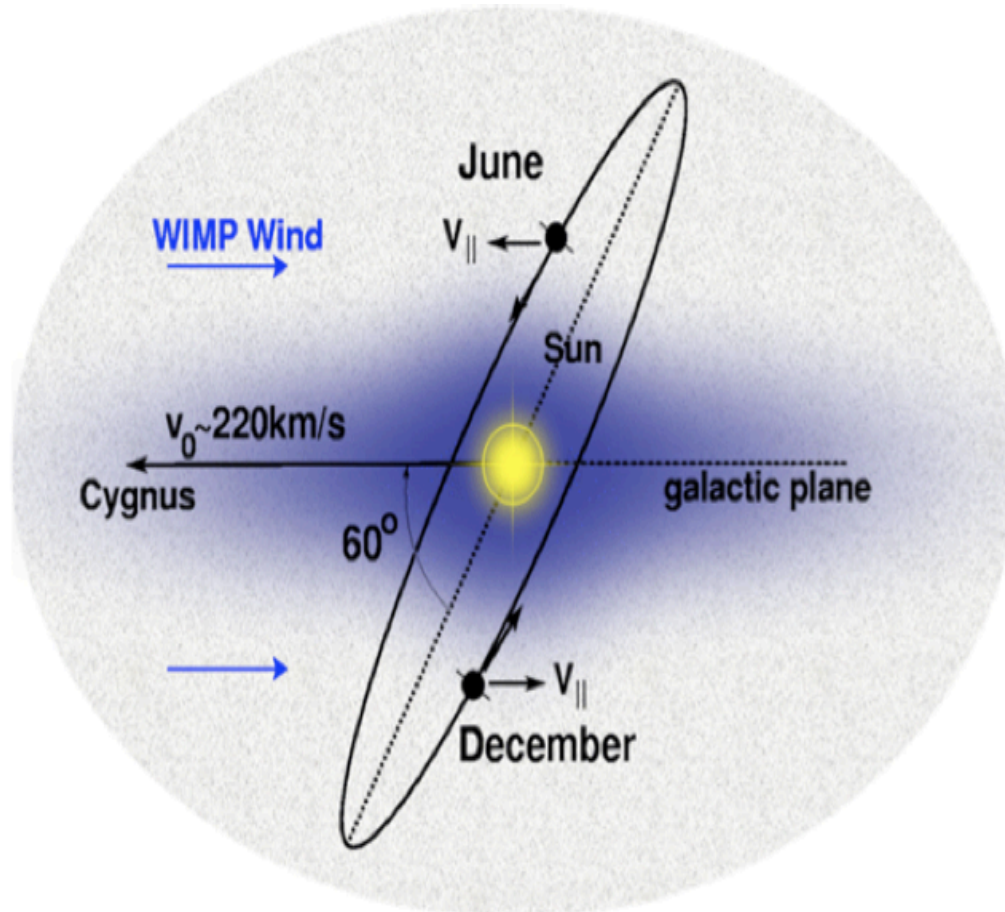
Directional detection: principle

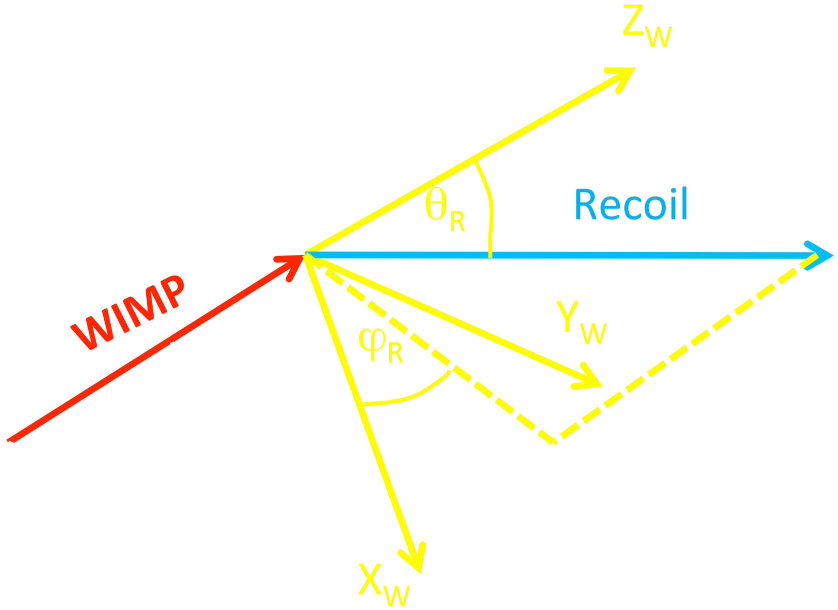


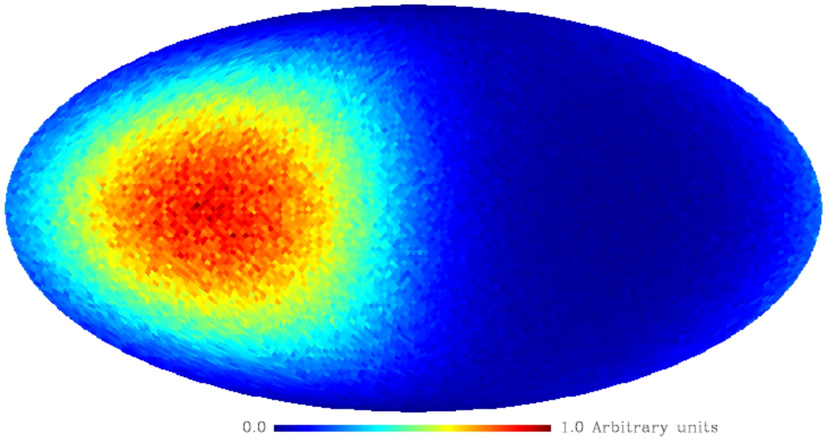




The signature able to correlate the rare events in a detector to the galactic halo !!

There are many possible "angles" for nuclear recoils… it's an angular distribution 3D tracks are needed…



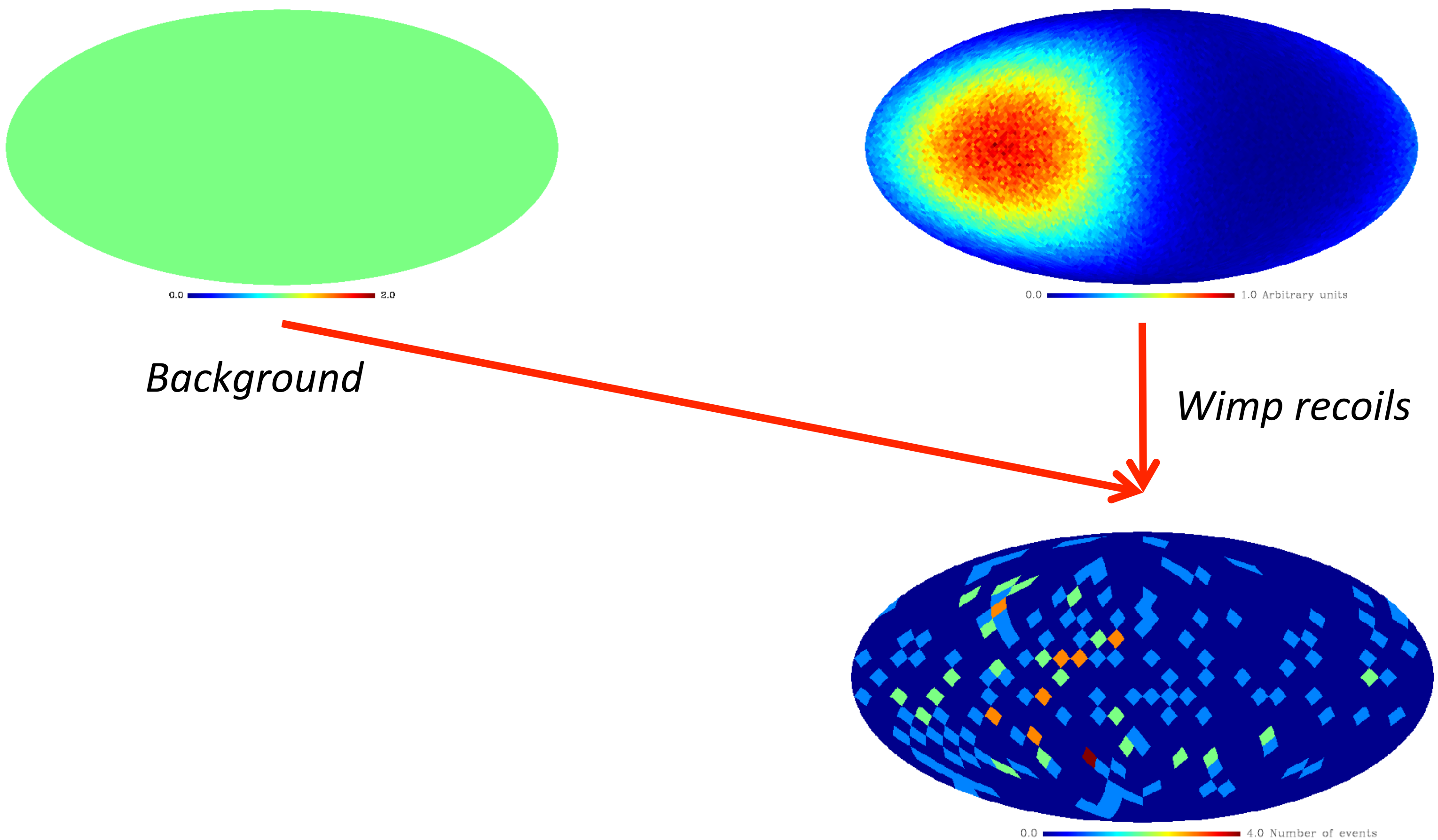


Map of recoils in galactic coordinates (HealPix)

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

Robust with respect to Background events

100 WIMP evts + 100 Background evts

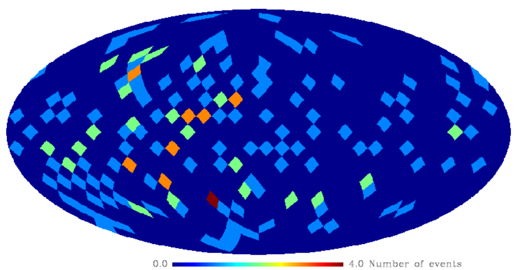


Phenomenology: Discovery

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

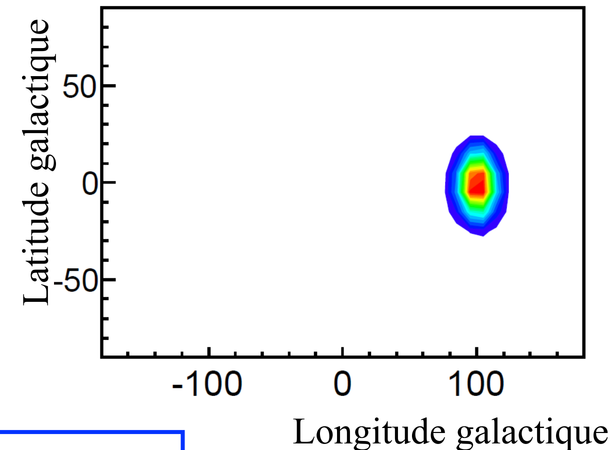
Proof of discovery: **Signal pointing toward the Cygnus constellation**

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



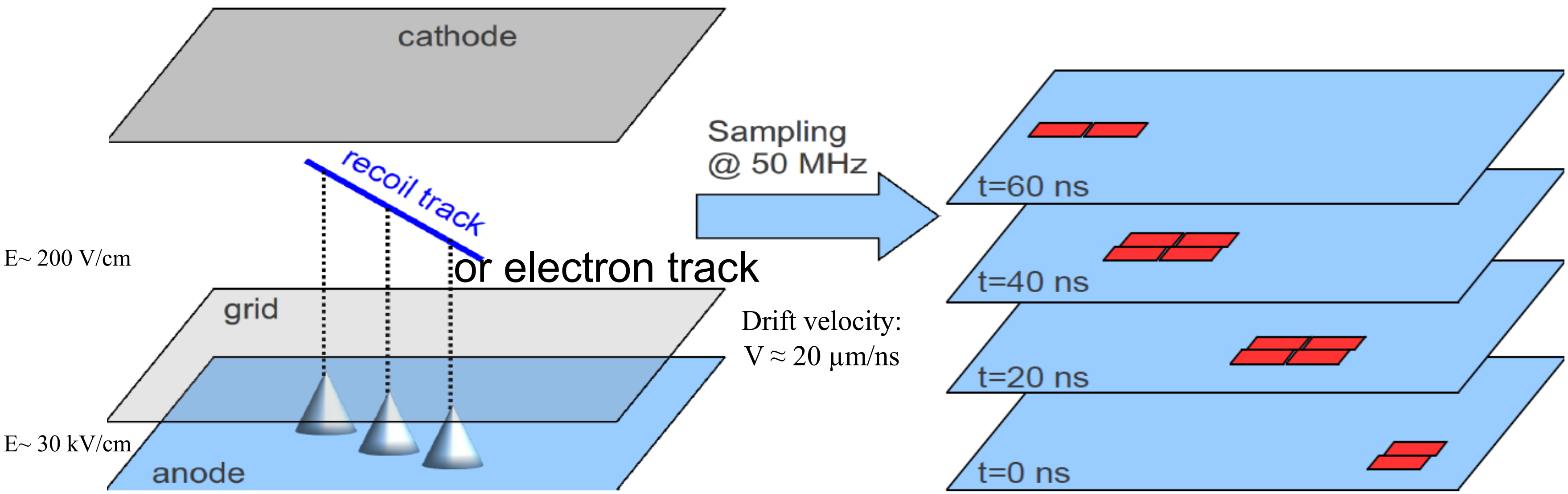
100 WIMP + 100 BKG

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



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

MIMAC: Detection strategy

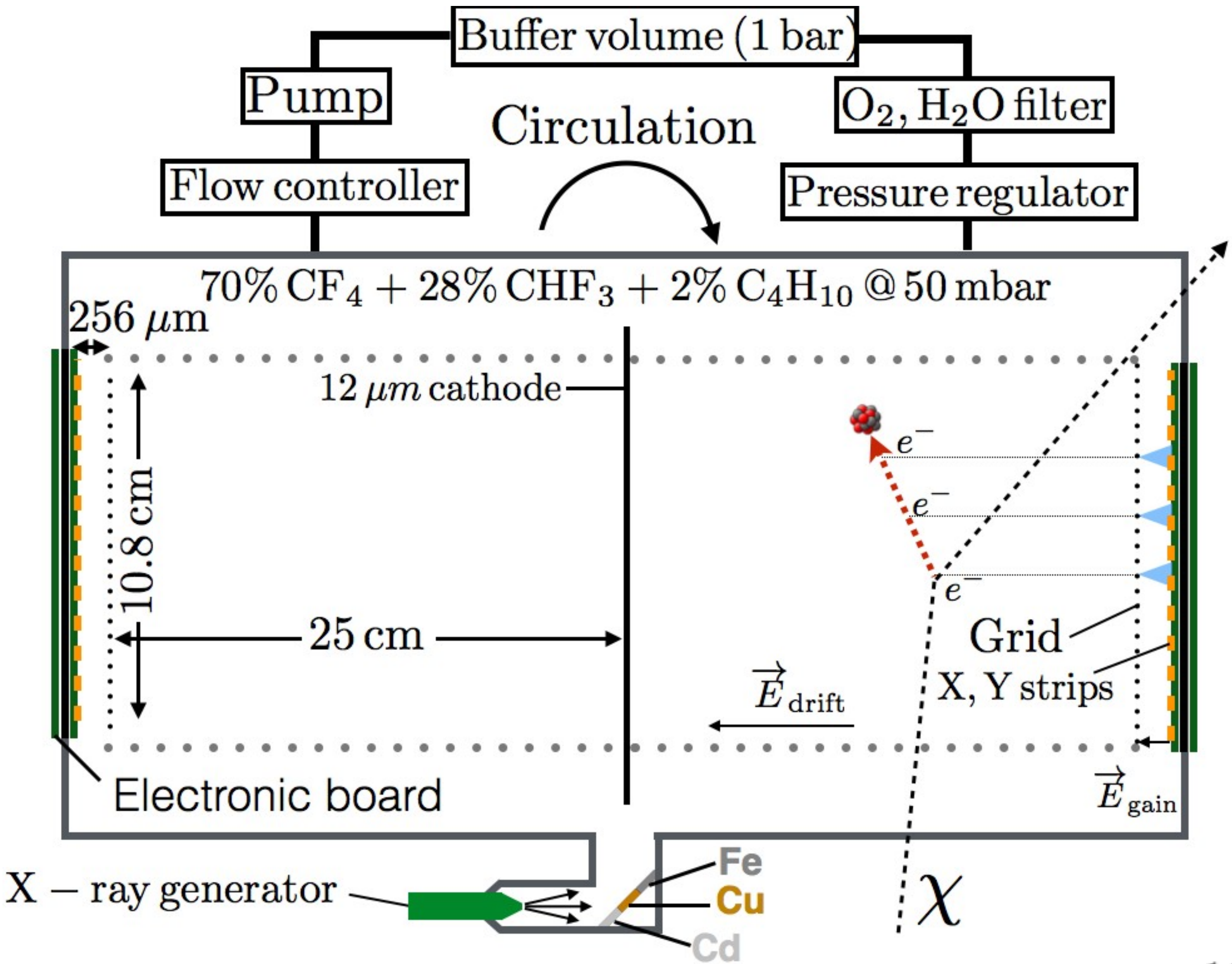


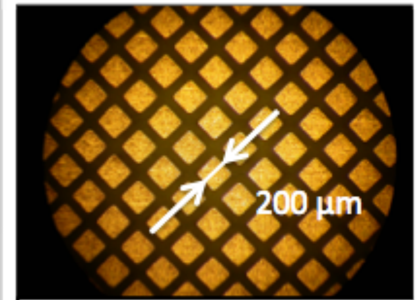
Scheme of a MIMAC µTPC *Evolution of the collected charges on the anode*

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)

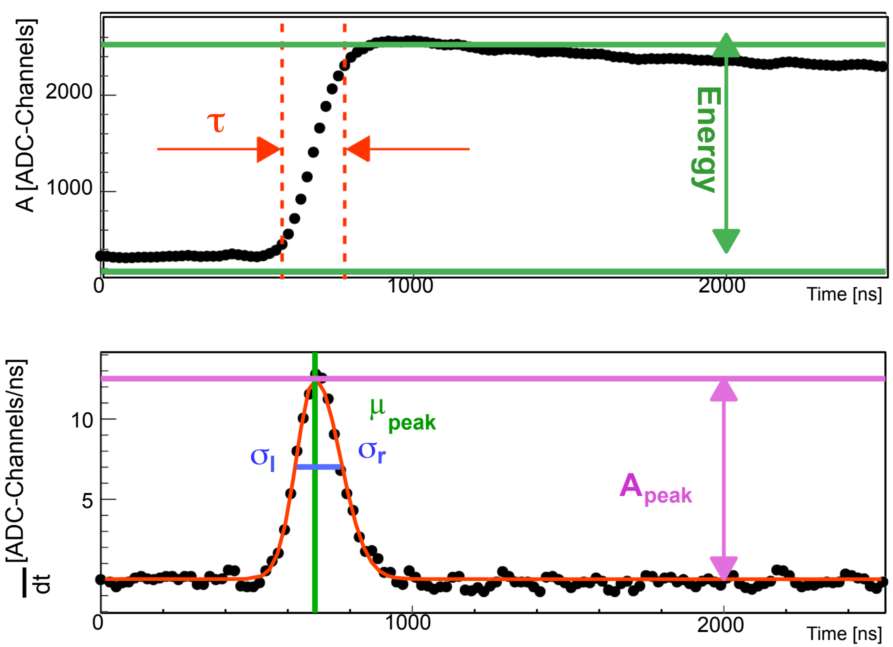
MIMAC Target: ^{19}F

- Light WIMP mass
- Axial coupling

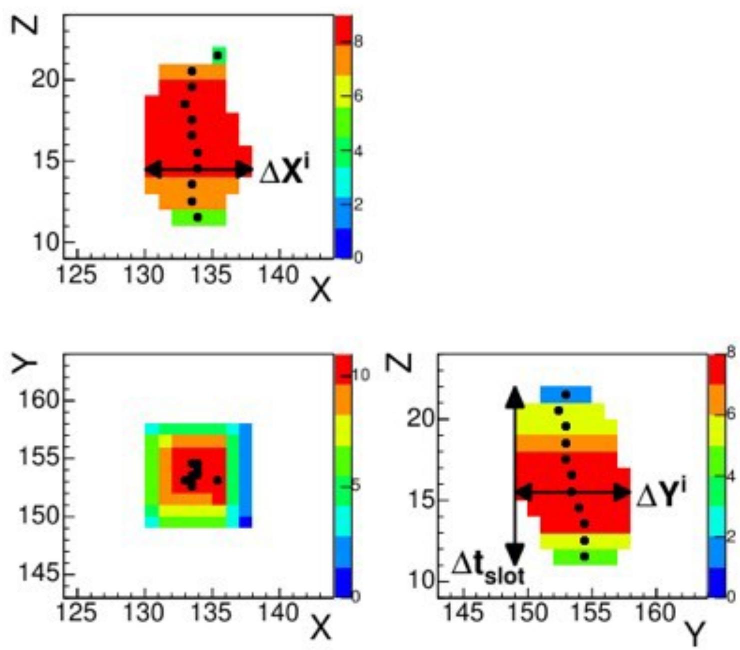
MIMAC readout

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

preamplifier signal + FADC: Energy



3D - track



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MIMAC (bi-chamber module)at Modane Underground Laboratory (France)

-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

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

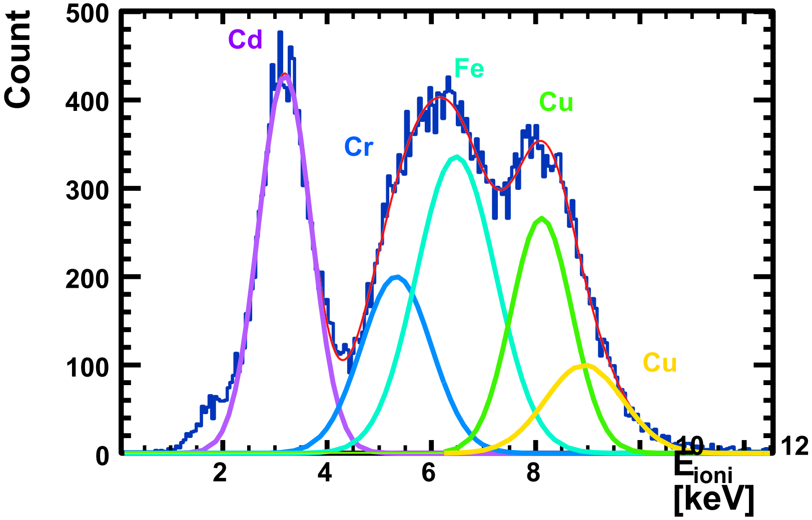
Example of calibration (MIMAC)

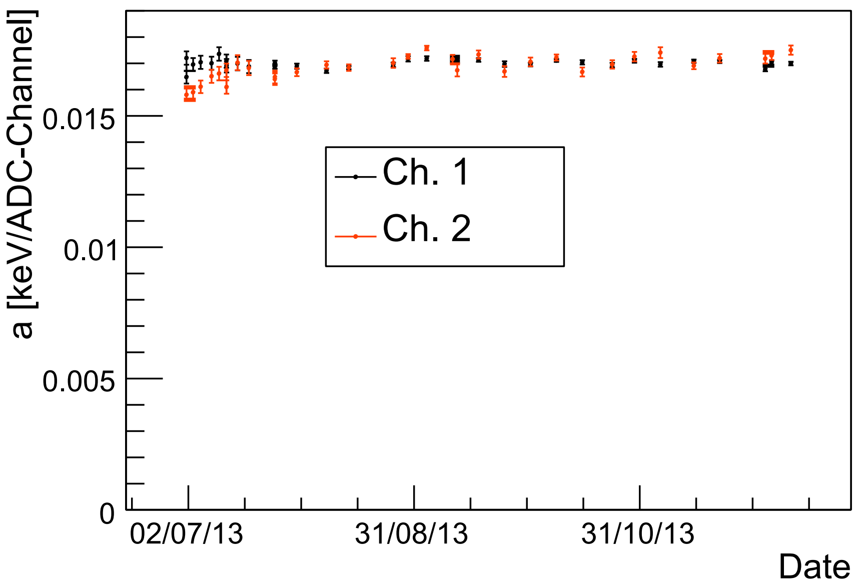
X-ray generator producing fluorescence photons from Cd, Fe, Cu foils.

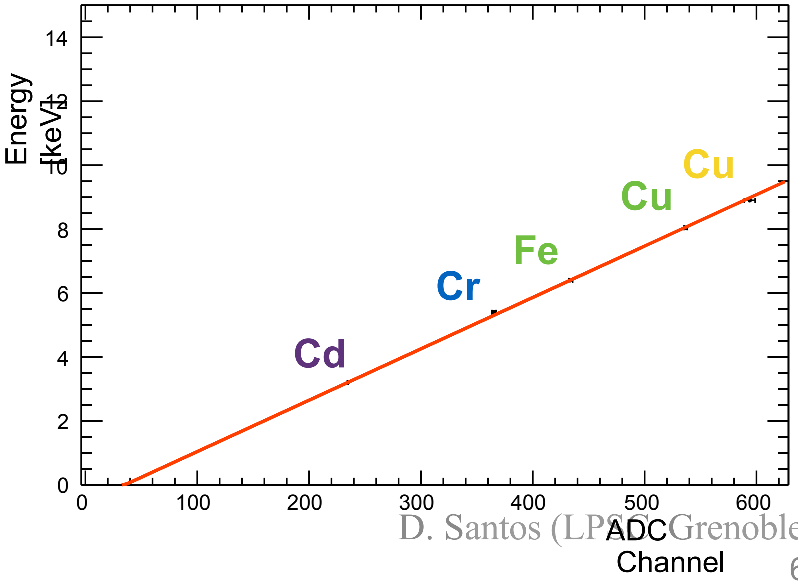
Threshold ~ 1 keV (but not a max. gain !)

Circulation system:

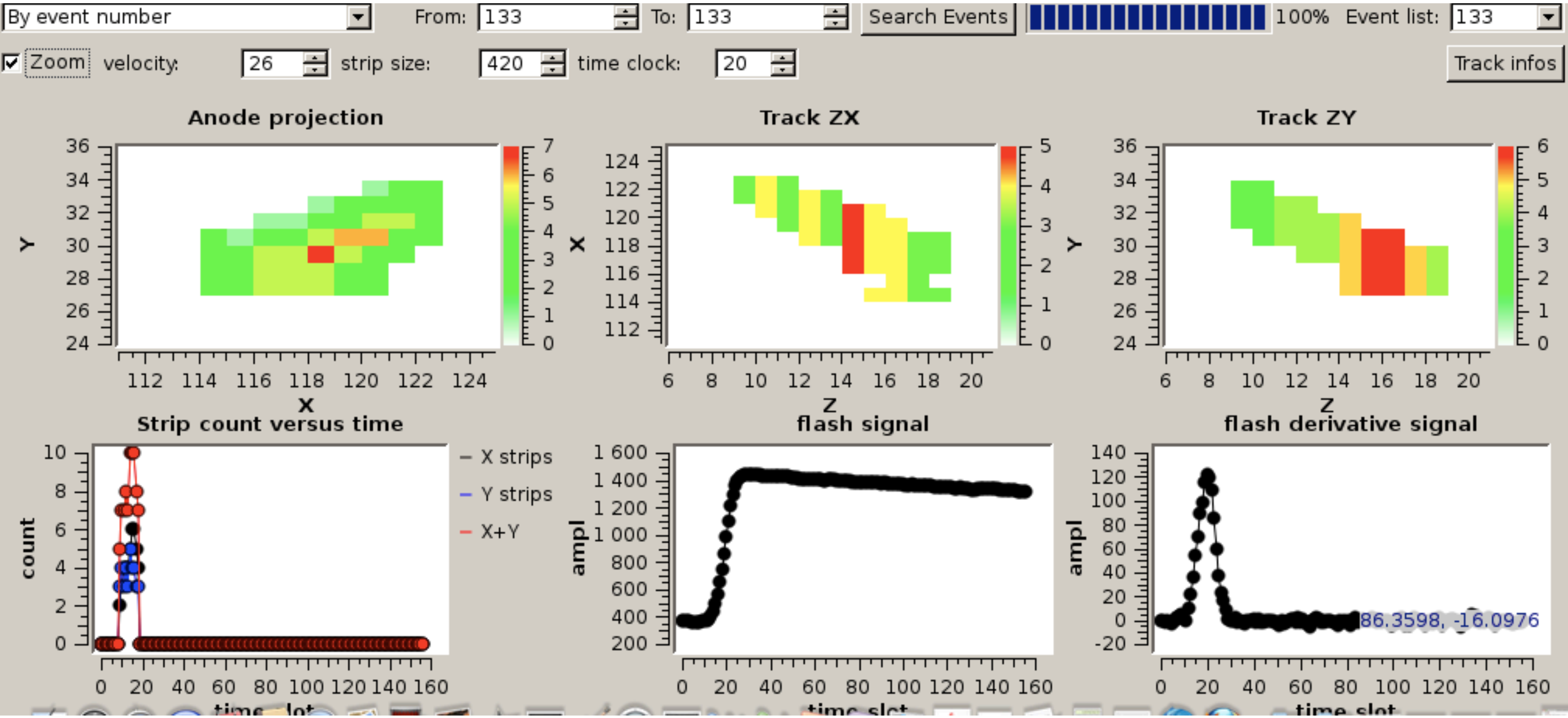
Excelent Gain stability in time







A “recoil event” (~ 34 keVee)



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

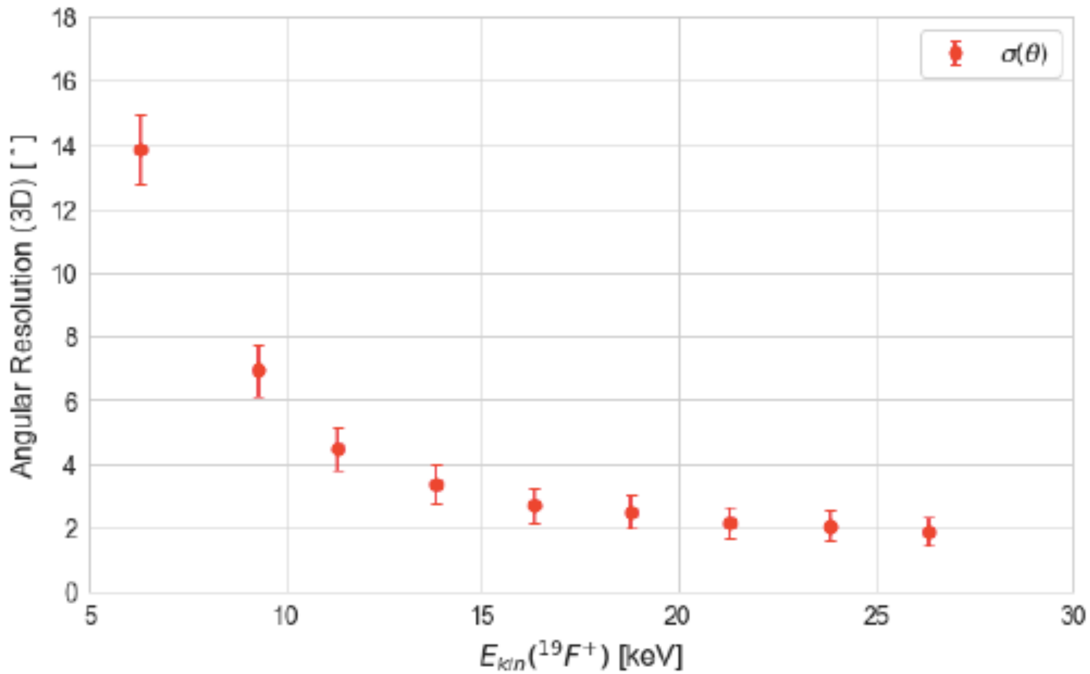


Figure 8. MIMAC angular resolution as a function of ^{19}F ion kinetic energy. At lower energies, the ion tracks are shorter and have more straggling resulting in worse angular resolution and bigger error bars. The angular resolution is better than 20° down to a kinetic energy of 6.3 keV, and is below 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.

Standard Axion (QCD axion)

Strong CP problem and AXION :

→ QCD has a CP violation term, ——

→*but this violation is not at all observed !*

→ Global Symmetry Broken $U(1)_{PQ}$ ⇒ axion

Effectif Lagrangian after broken symmetry $U(1)_{PQ}$:

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

Standard Axion

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

Parameters :

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

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

Standard Axion

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Constrains :

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

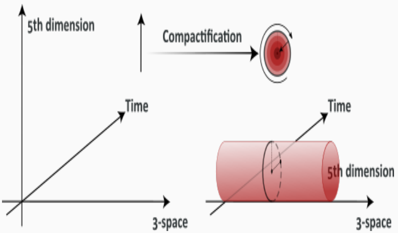
$\Rightarrow$ Dark Matter candidate but $a \to \gamma\gamma$

needs an external magnetic field to force the decay...

Axions in compactified extra-dimensions

Compactified Spatial Extra-dimensions :

- SM particles confined in $(1+3)$D
- Singlet gage bosons (axion, graviton, ...) can propagate in $(1+3+\delta)$D space-time with $\delta \leq n$ extra dimensions
- Extra-dimensions with a compactification radius $R < 30\,\mu$m

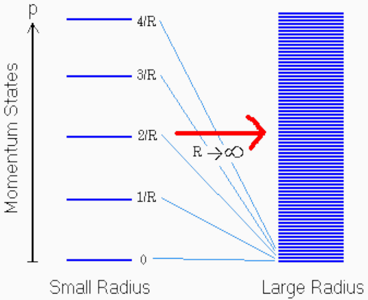


- $M_P = (2\pi R M_S)^{n/2} M_S$ with $M_S \sim \mathcal{O}(\text{TeV})$
- $\hat{f}_{PQ} \equiv (2\pi R M_S)^{\delta/2} f_{PQ}$
- $\hat{f}_{PQ} \gg f_{PQ}$

Axions in extra-dimensions

Kaluza-Klein decomposition:

- $a(x^\mu, \mathbf{y}) = \sum_{\mathbf{n}=0}^{\infty} a_{\mathbf{n}}(x^\mu) \; \cos\left(\frac{\mathbf{ny}}{R}\right)$
- In observable space, the axion would be a superposition of KK continuum states



$$\mathcal{L}^{eff}_{\delta=1} \supset \frac{\xi}{\hat{f}_{PQ}} \frac{g_S^2}{32\pi^2} \left(\sum_{n=0}^{\infty} r_n a_n \right) G_a^{\mu\nu} \tilde{G}_{a\mu\nu}$$

Axions in extra-dimensions

Decay $a_n \rightarrow \gamma\ \gamma$:

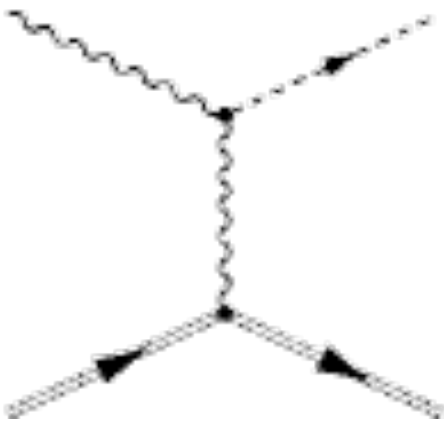
$$\tau(a_n \to \gamma\gamma) \sim \left(\frac{m_{PQ}}{m_{a_n}}\right)^3 \tau(a_0 \to \gamma\gamma)$$

- Each KK-axion decay $\Rightarrow$ continuum
- In the Sun, $m_{a_n} \sim \mathcal{O}(10\,\mathrm{keV})$

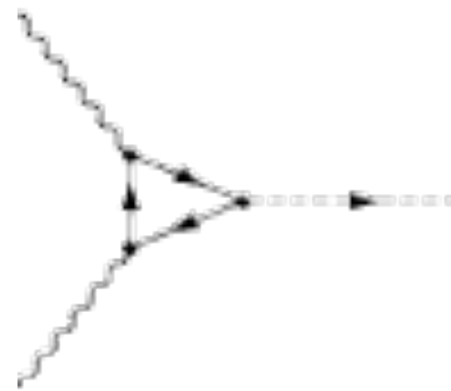
$\Longrightarrow 10^{11} \lesssim \tau_{a_n \to \gamma\gamma} \lesssim 10^{17}$ days

$a_n \rightarrow \gamma\ \gamma$ is detectable

Solar Kaluza-Klein Axions production



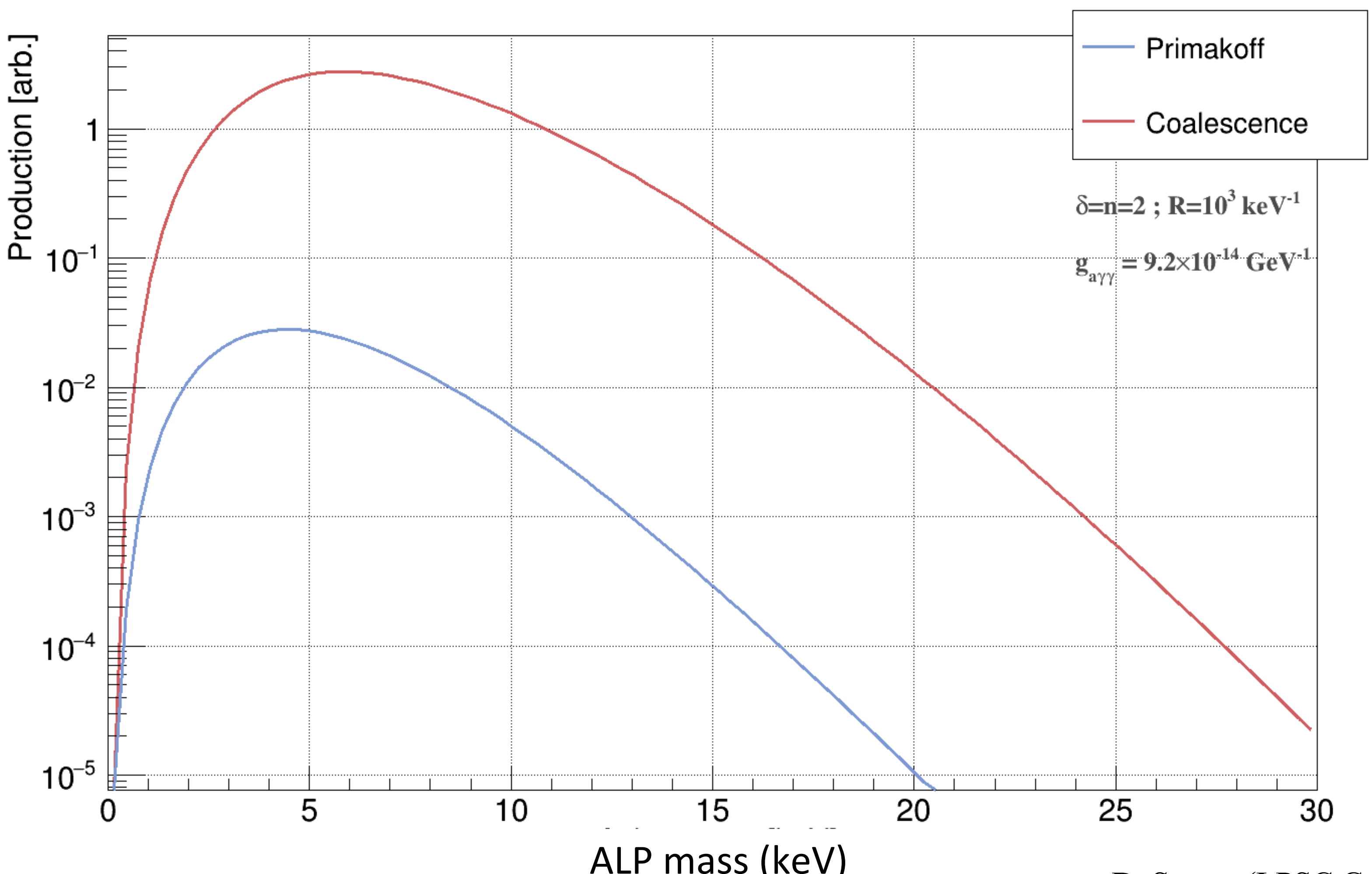
Primakoff effect



Photon Coalescence

Kaluza-Klein Axions with masses between $(1 - 30)$ keV

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



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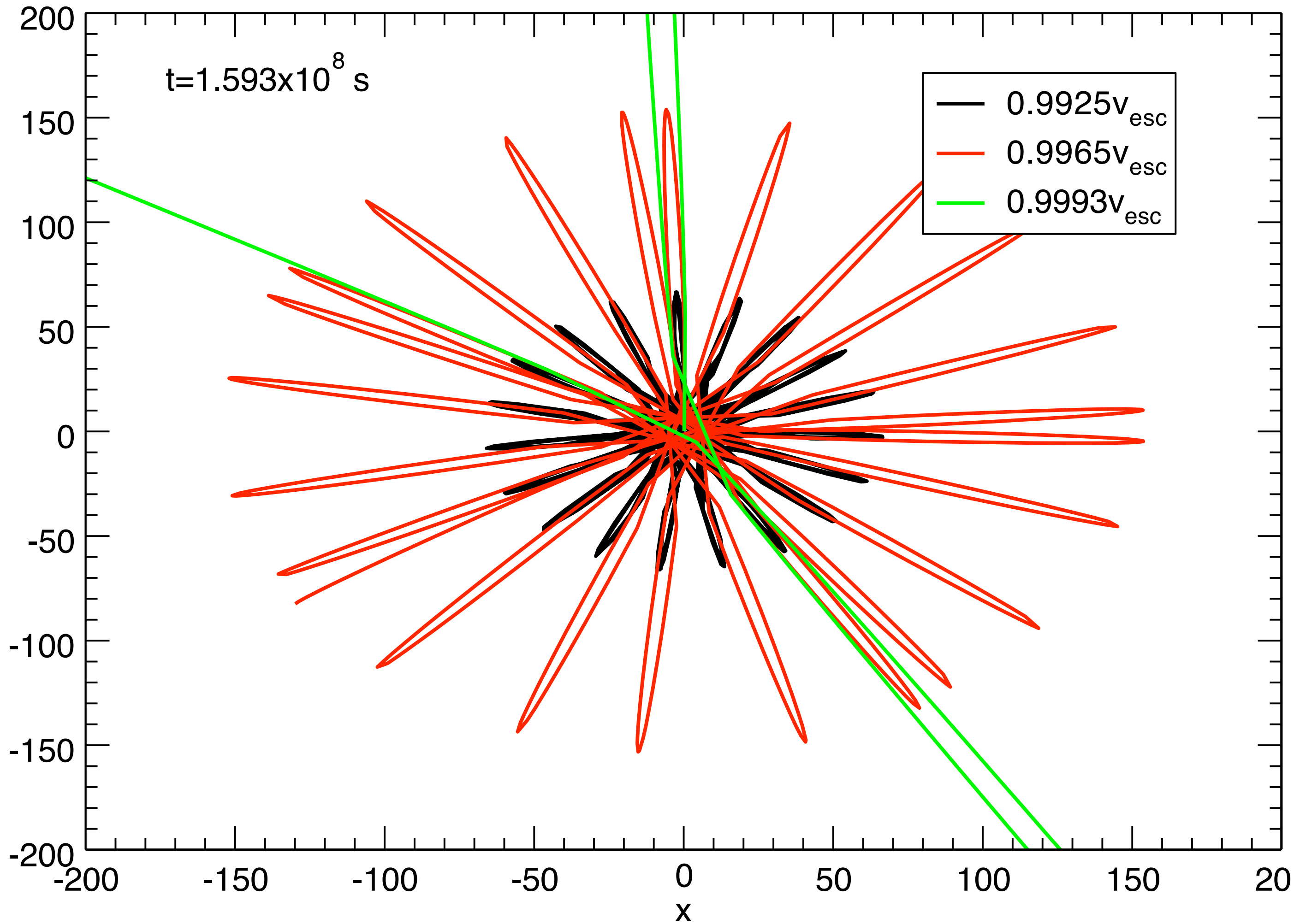
KK- axion Orbits for different velocities

$V_{esc} = 617$ km/s



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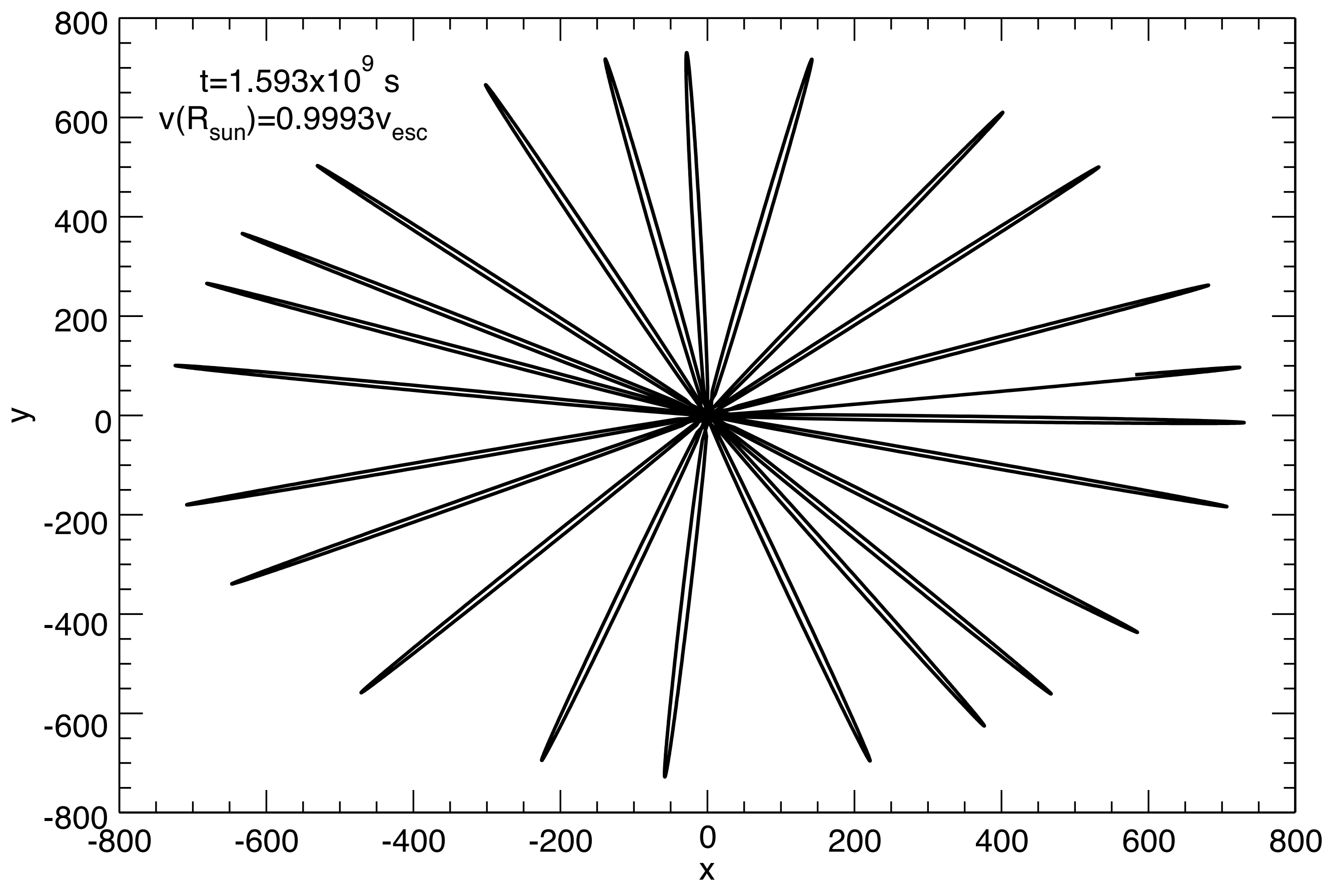
KK-axion orbits



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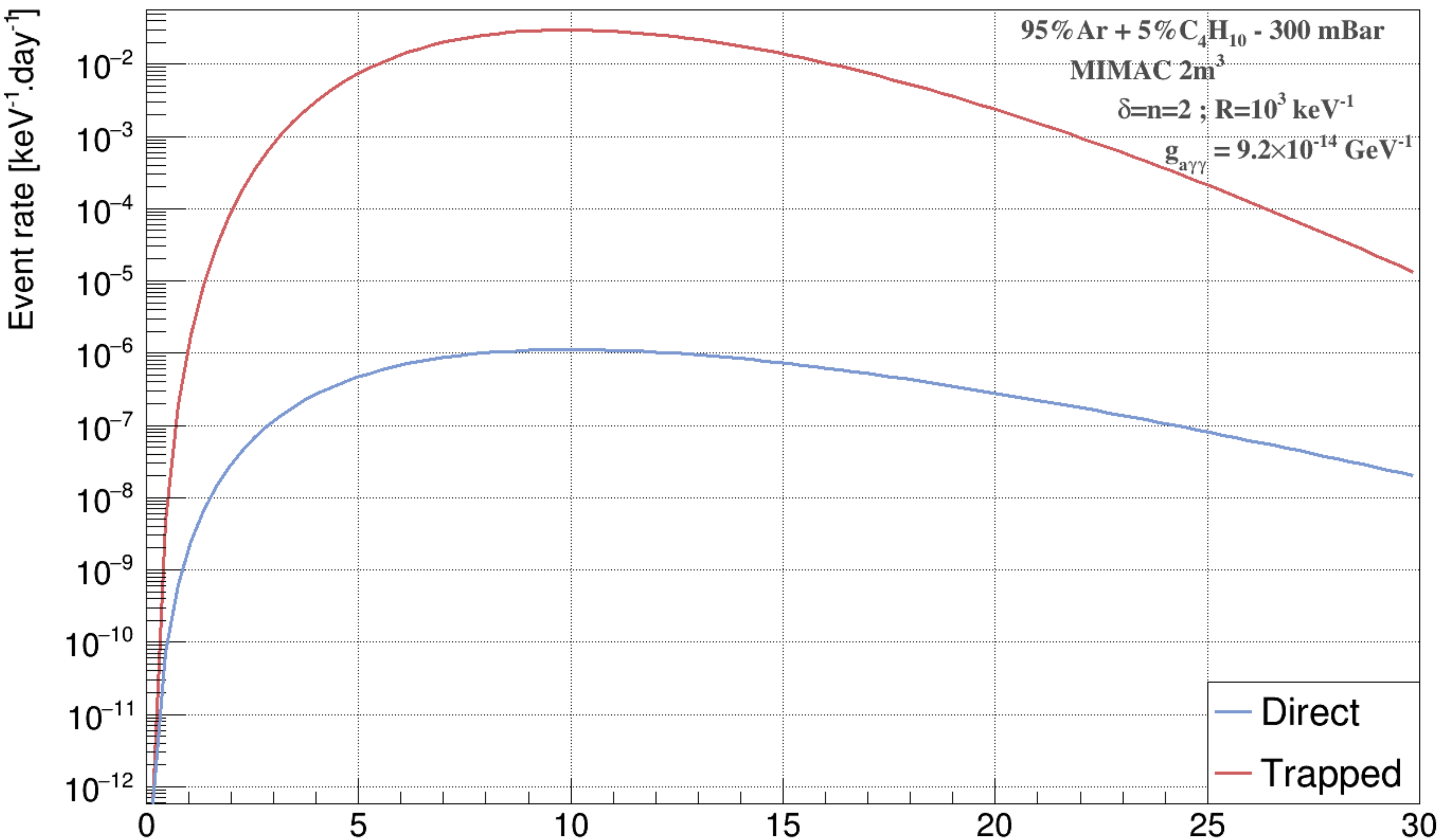
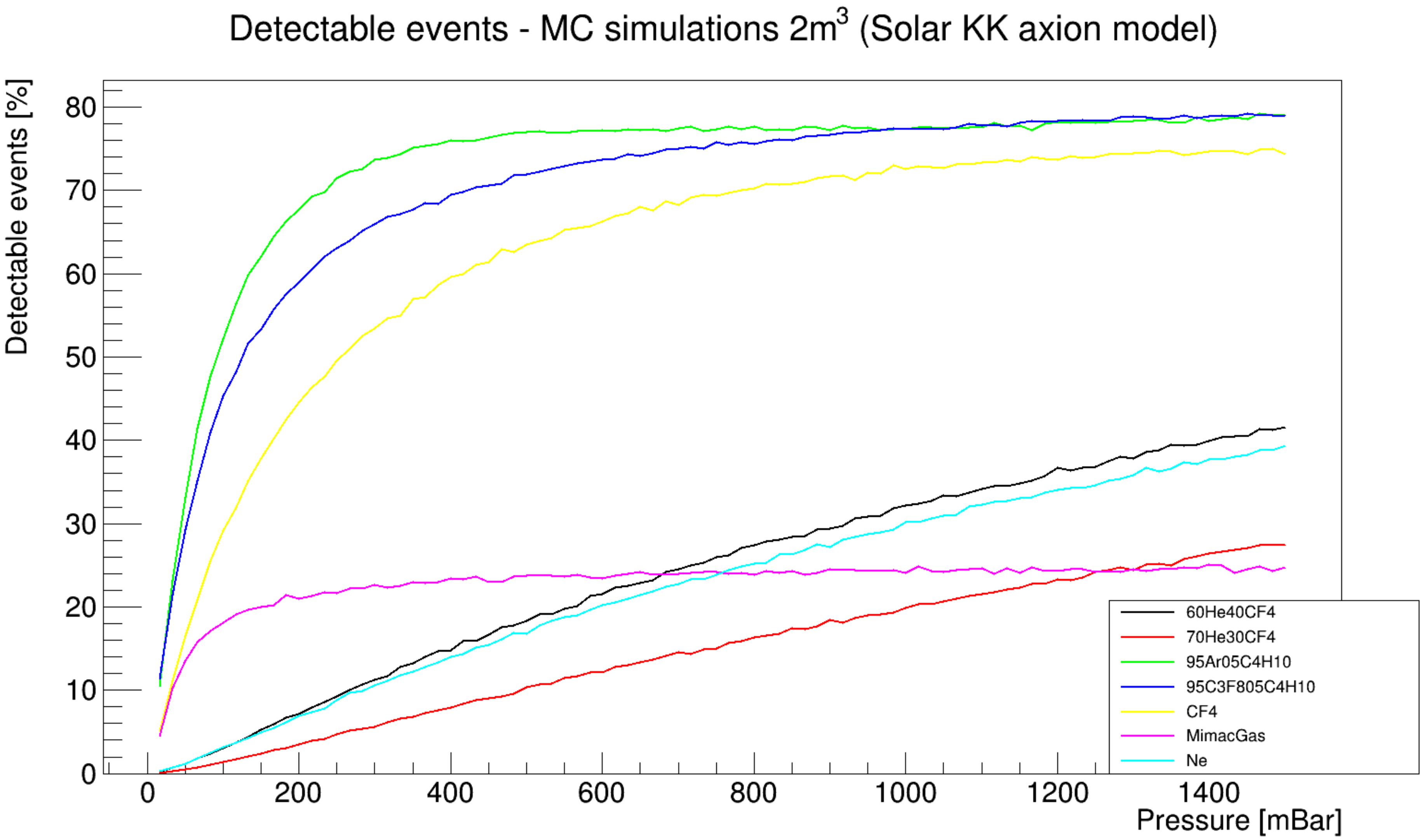
Event rate expected from the direct flux and gravitationally trapped



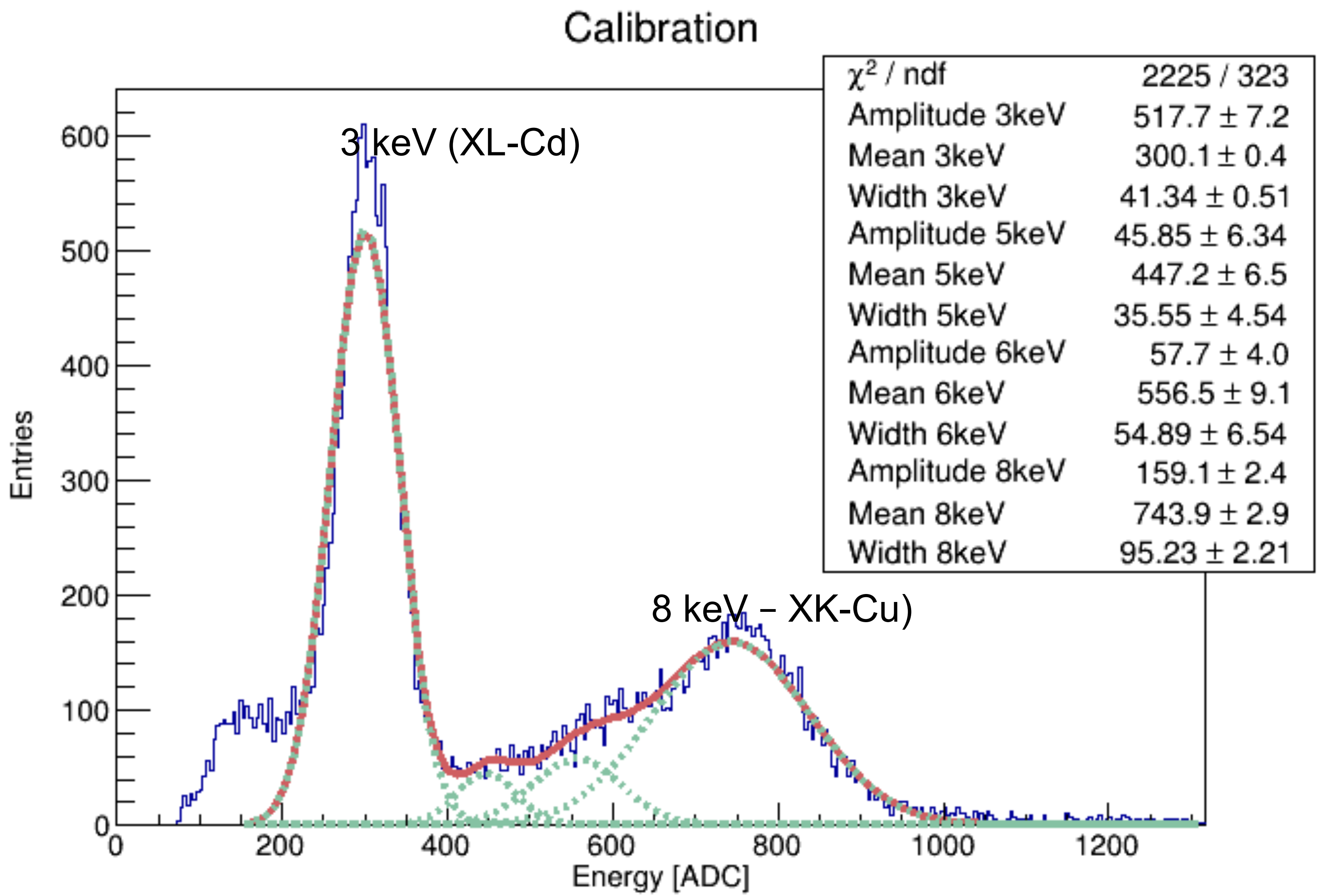
ALP's mass (keV)

Efficiency as a function of the Gas and pressure



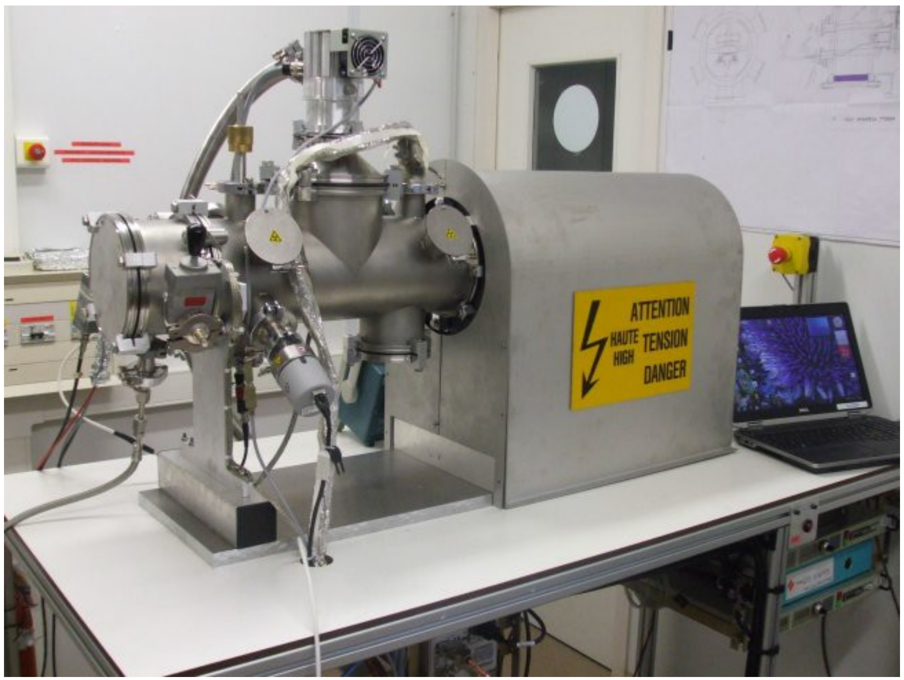
X-rays calibration in $^{40}Ar + 5\% \ C_4H_{10}$

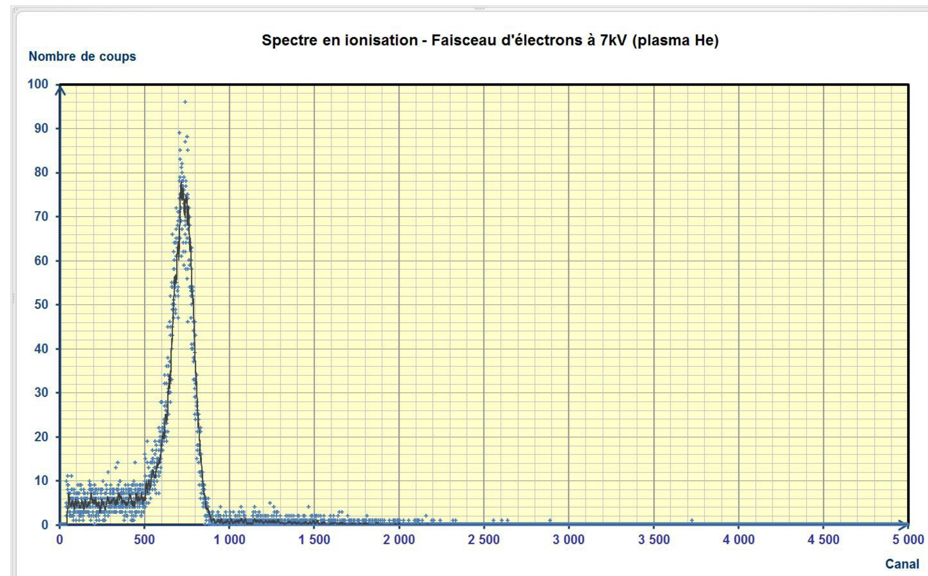
(300 mbar)



COMIMAC

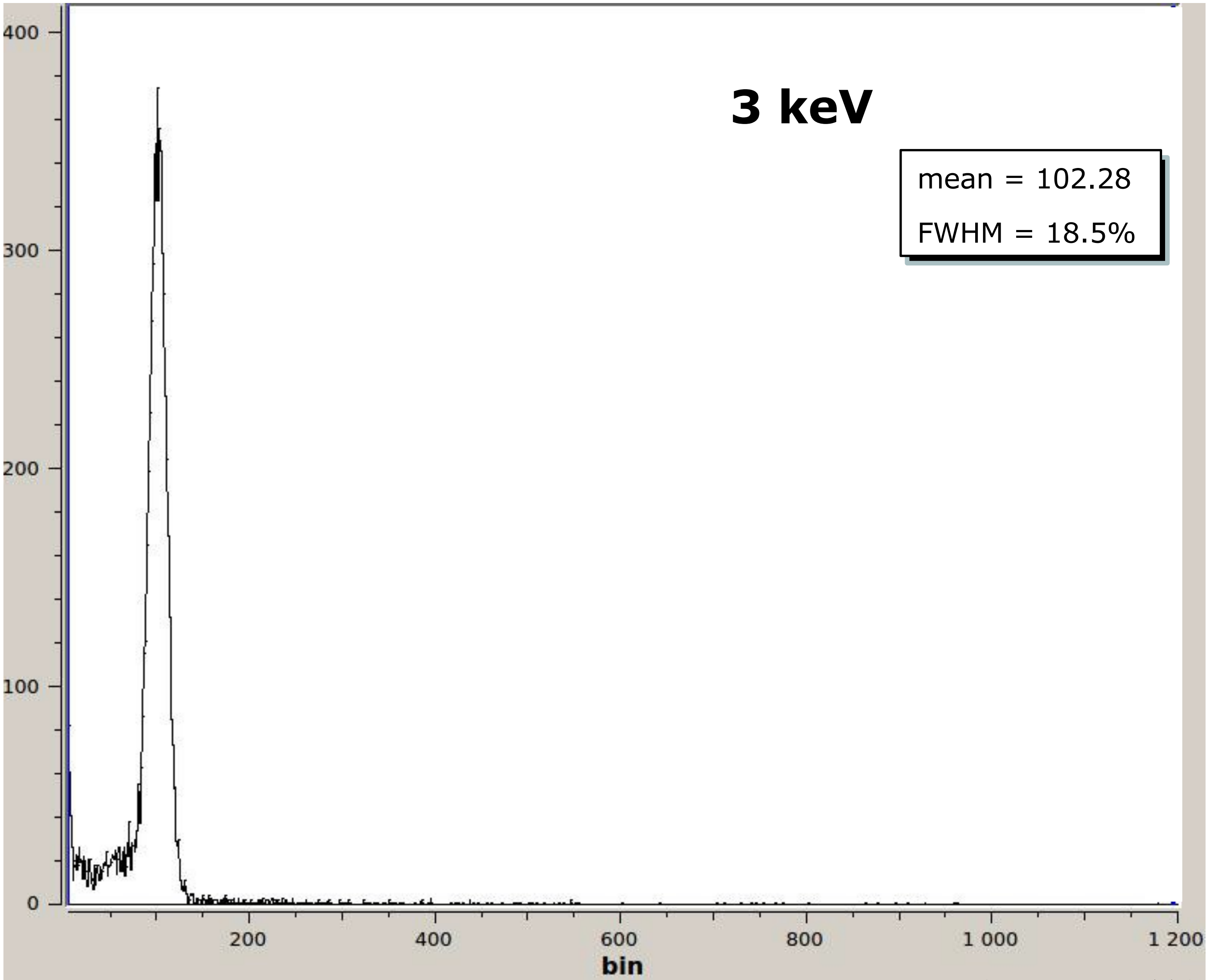
A calibration tool for gas detectors
(Electrons and Nuclei of known kinetic energies)





Electrons of 7 keV

Electrons Performance



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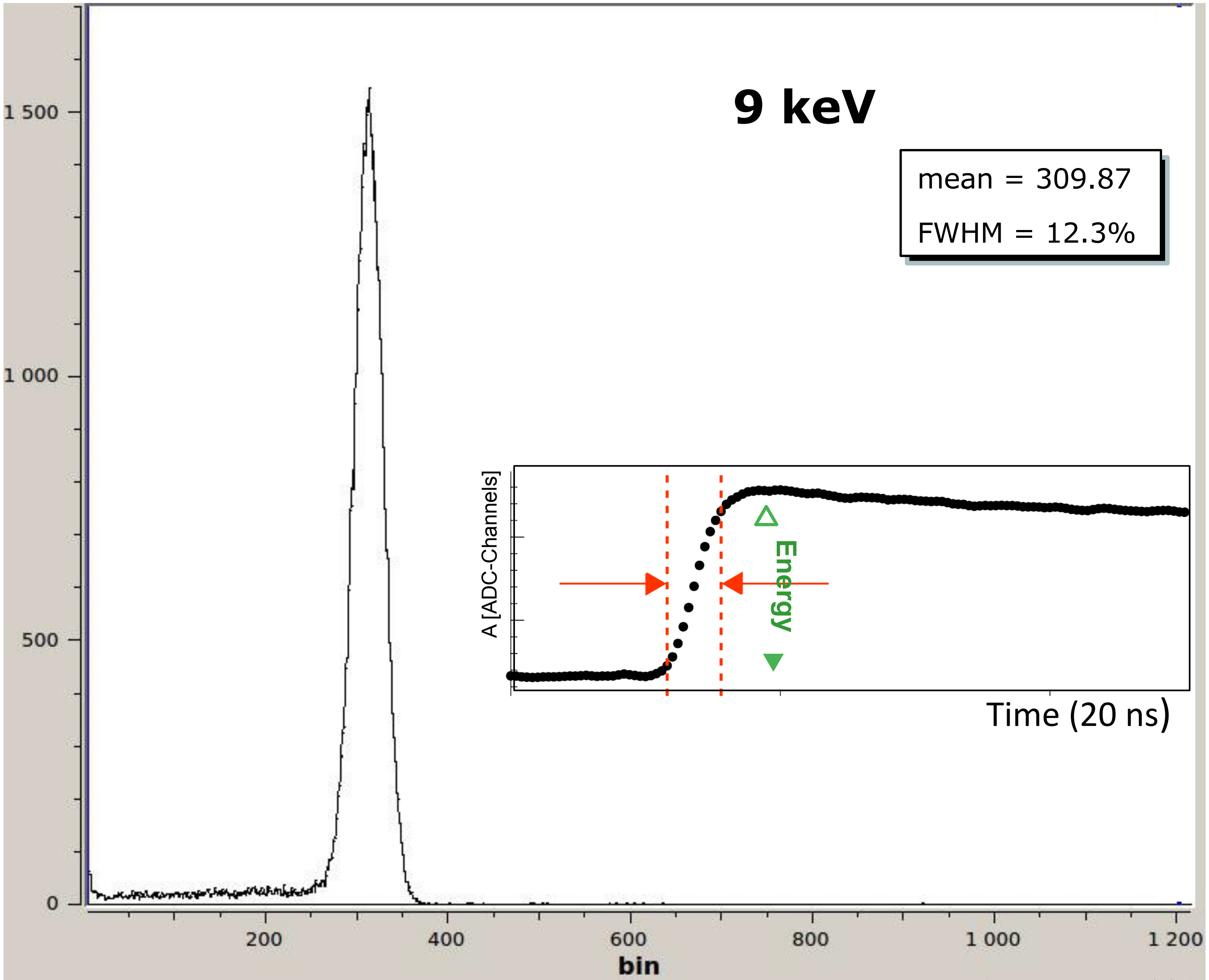
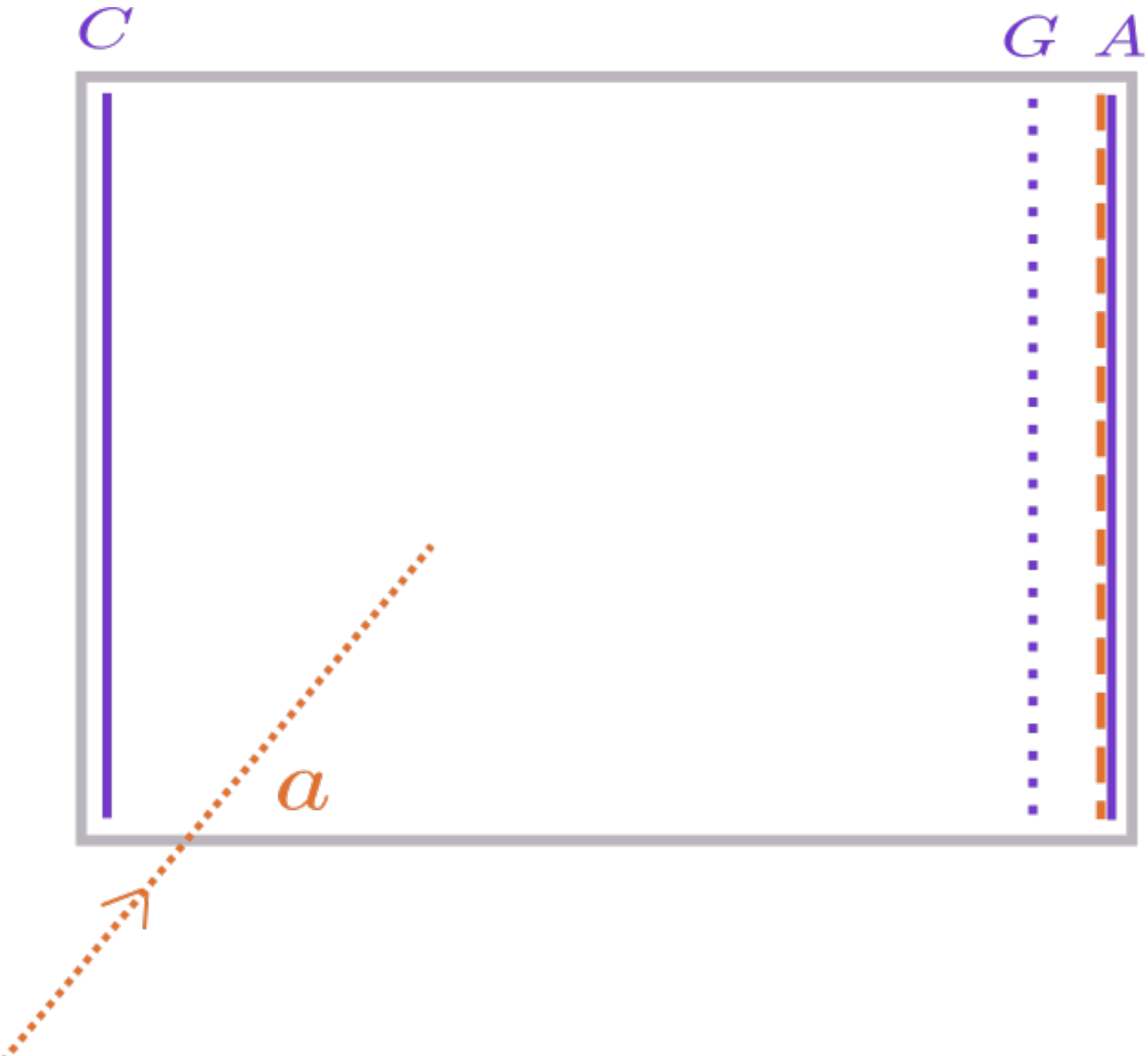
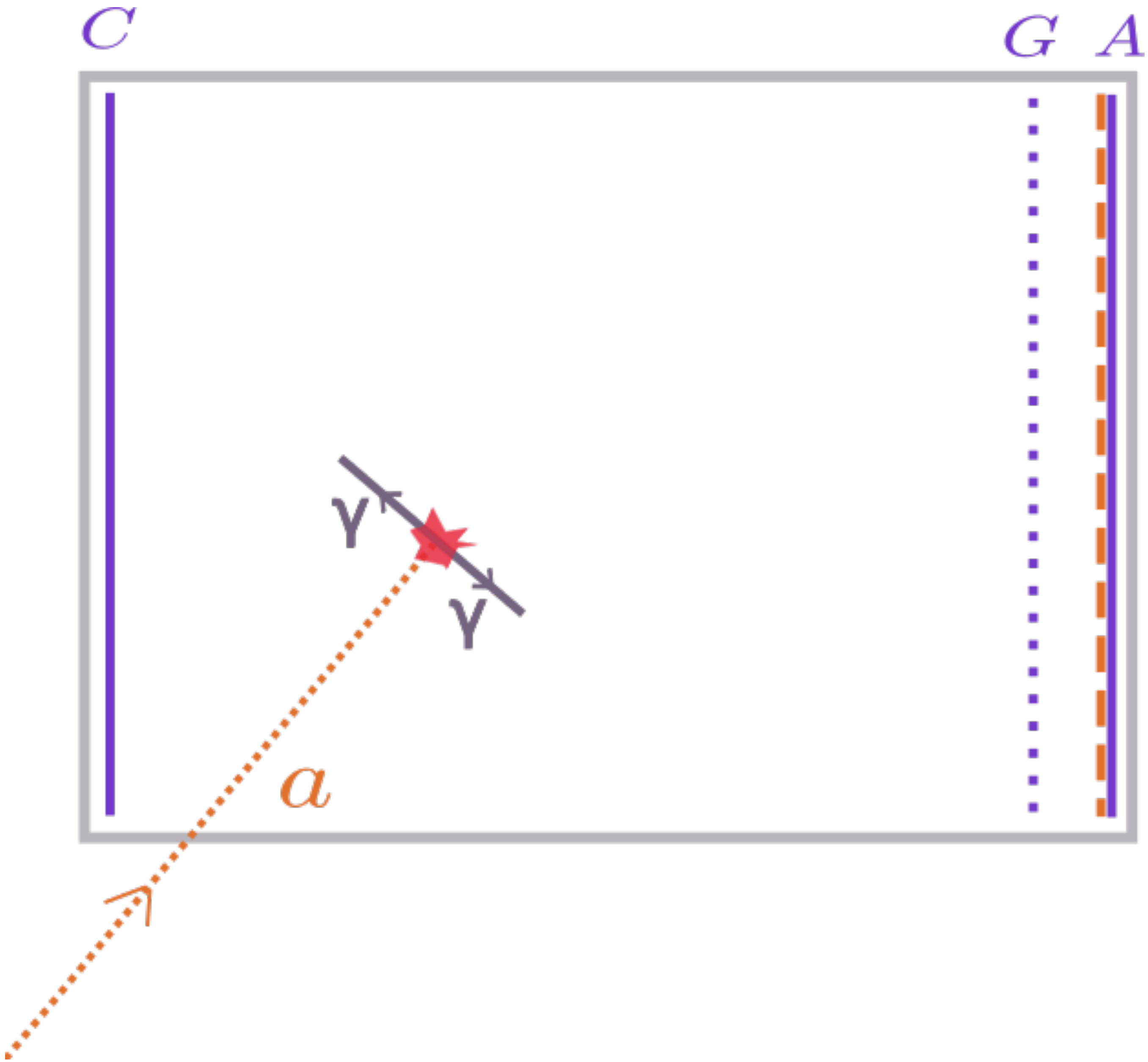
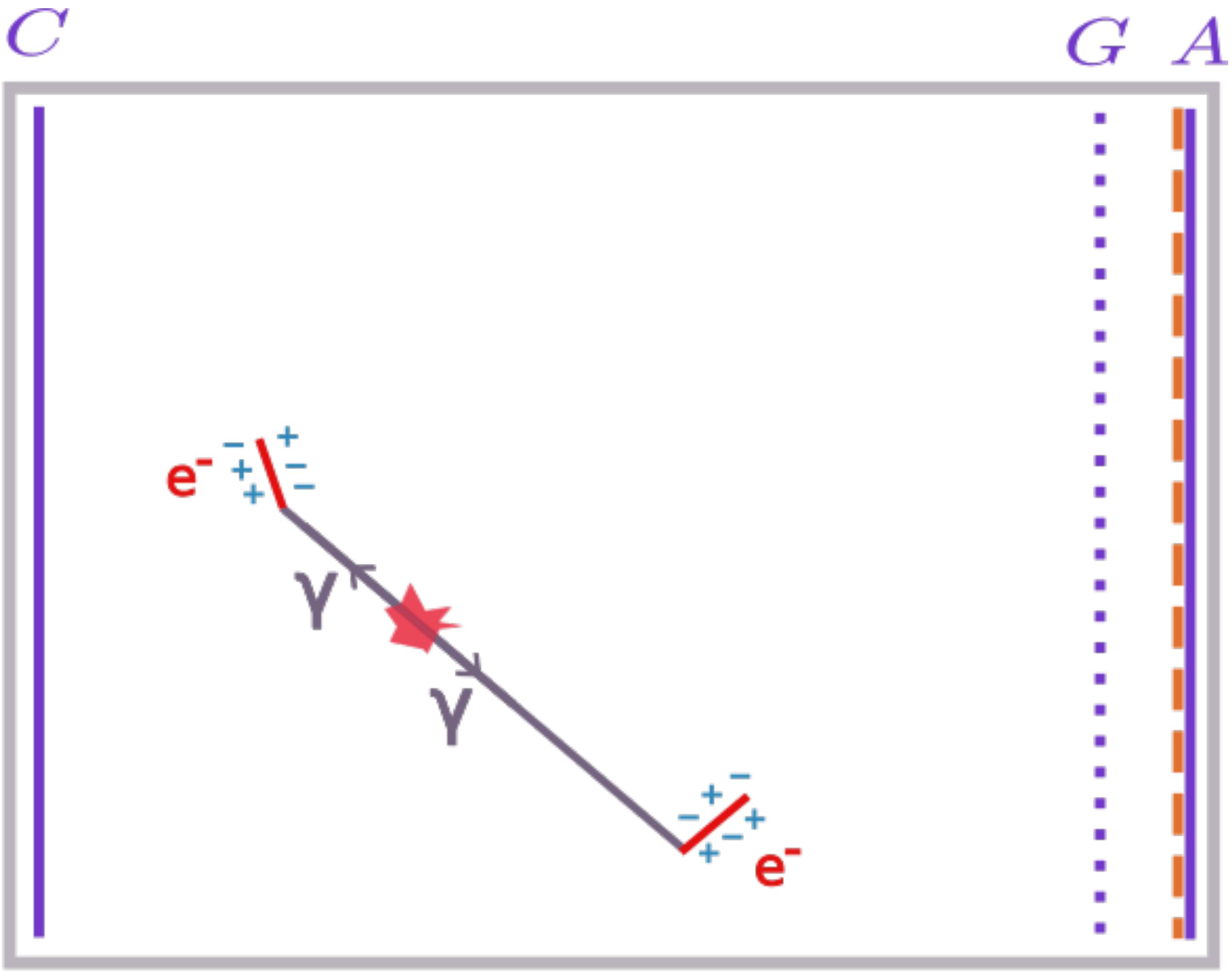
Electrons

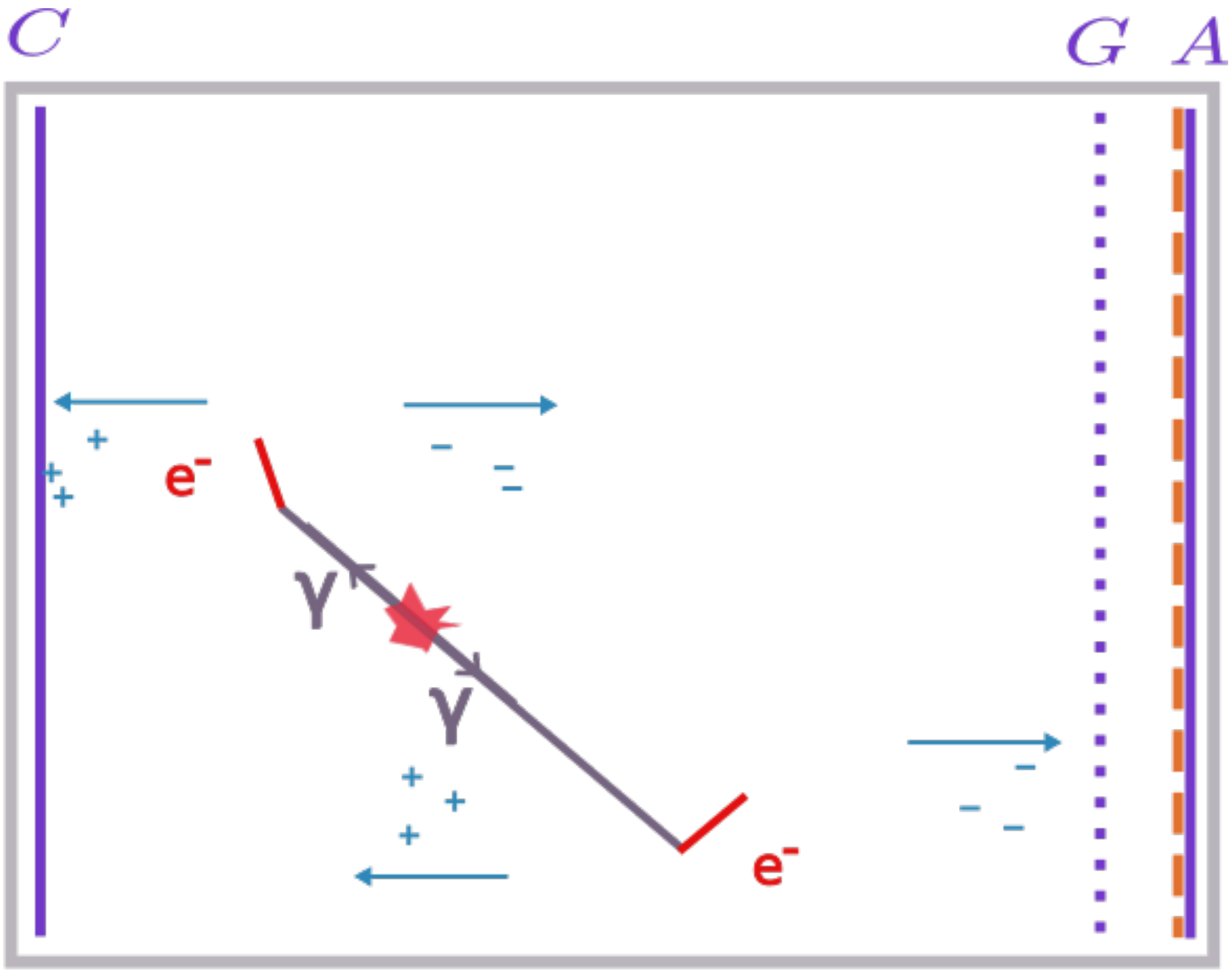


9 keV
mean = 309.87
FWHM = 12.3%
A [ADC-Channels]
Energy
Time (20 ns)
1 500
1 000
500
0
200
400
600
800
1 000
1 200
bin


C
G
A
a


C
G
A
γ
γ
a


C
G
A
e-
γ
γ
e-


C
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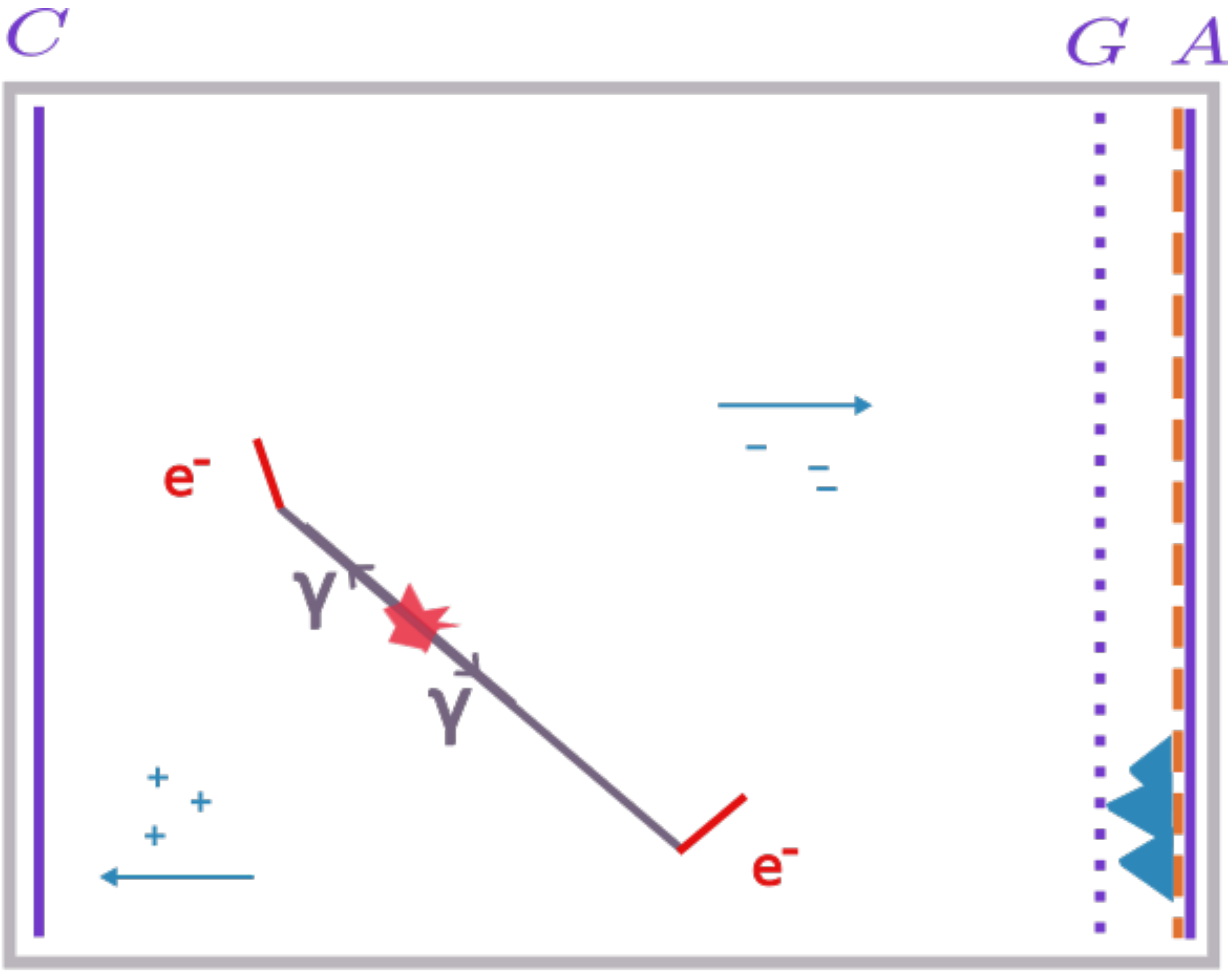
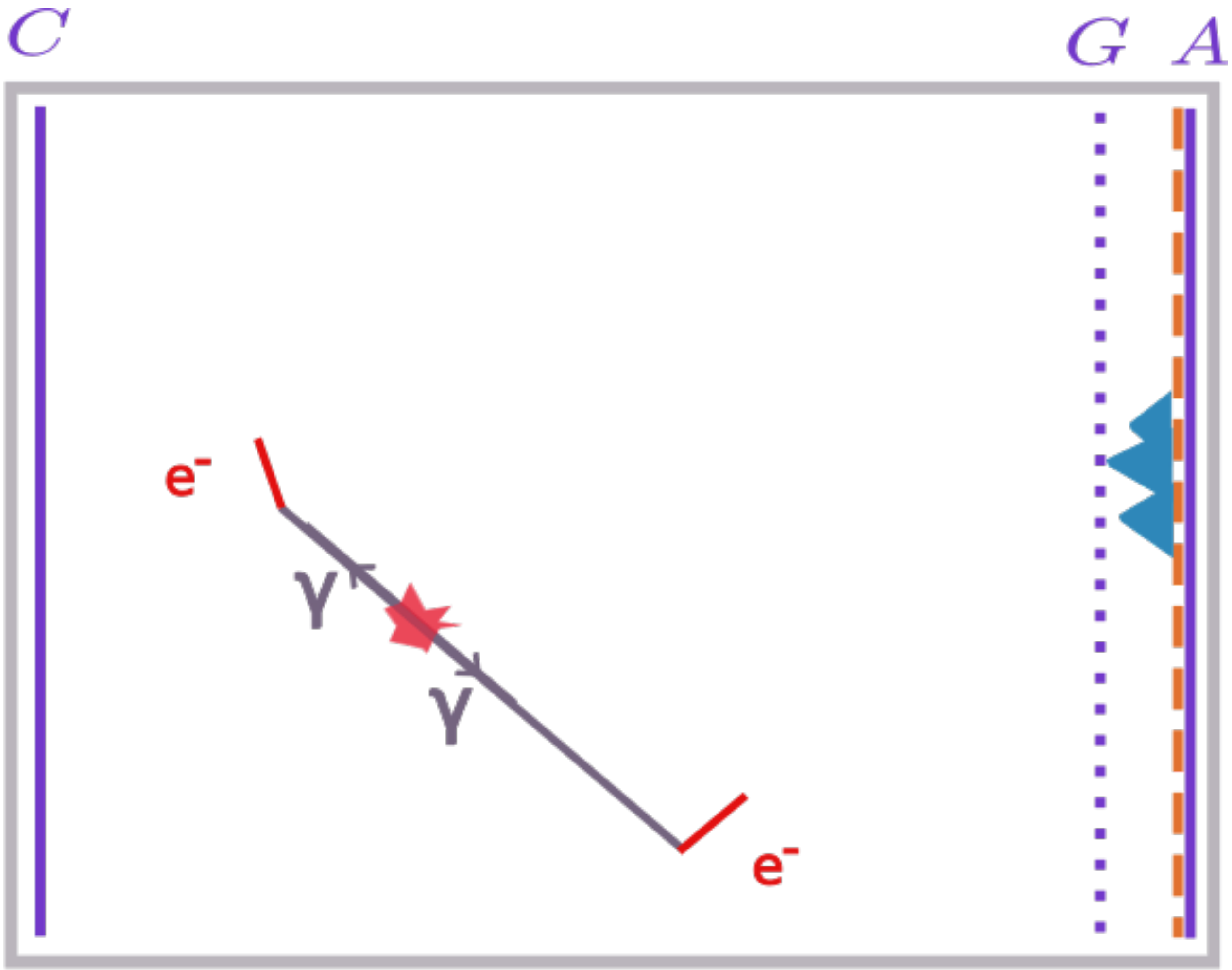
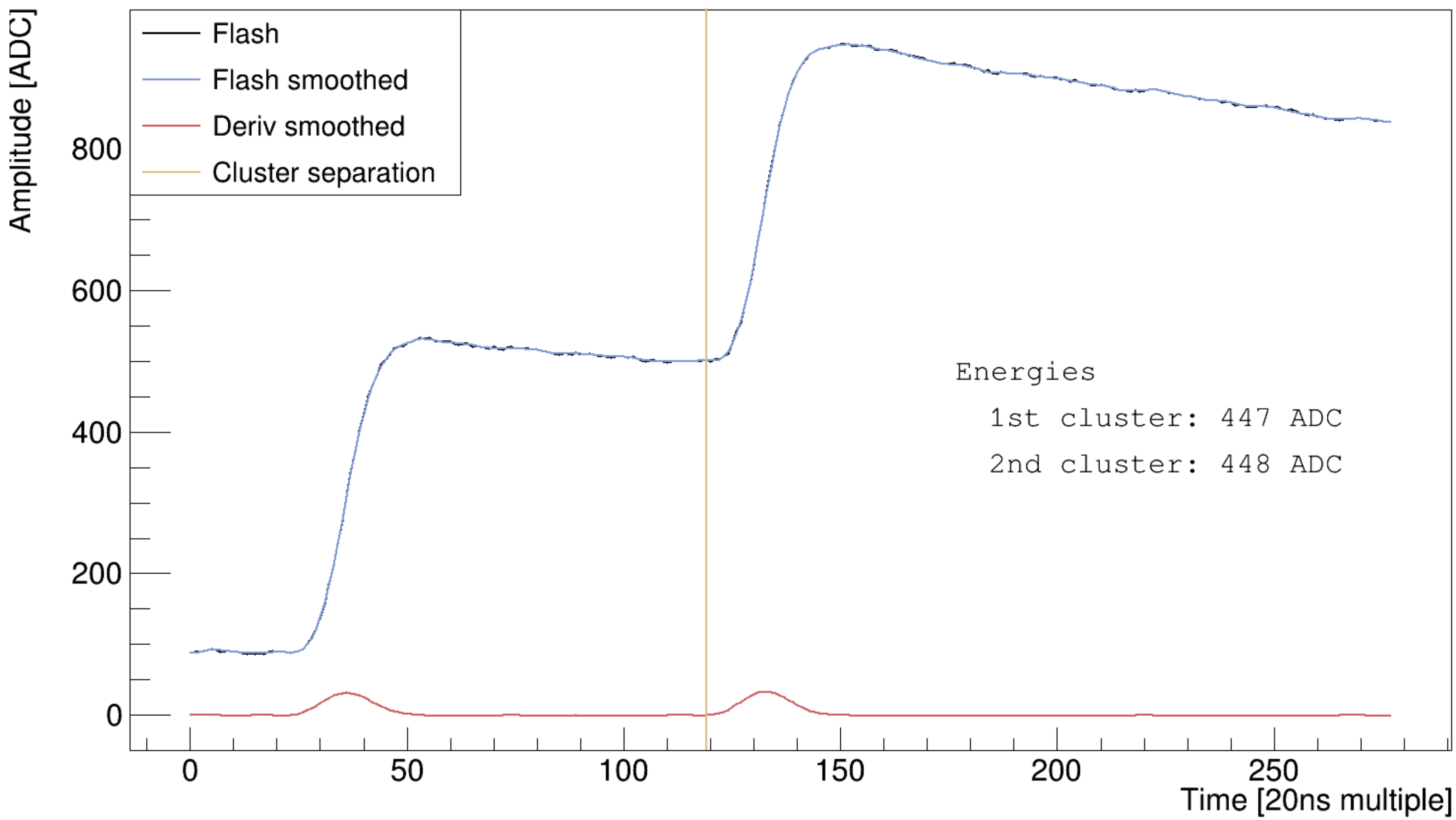
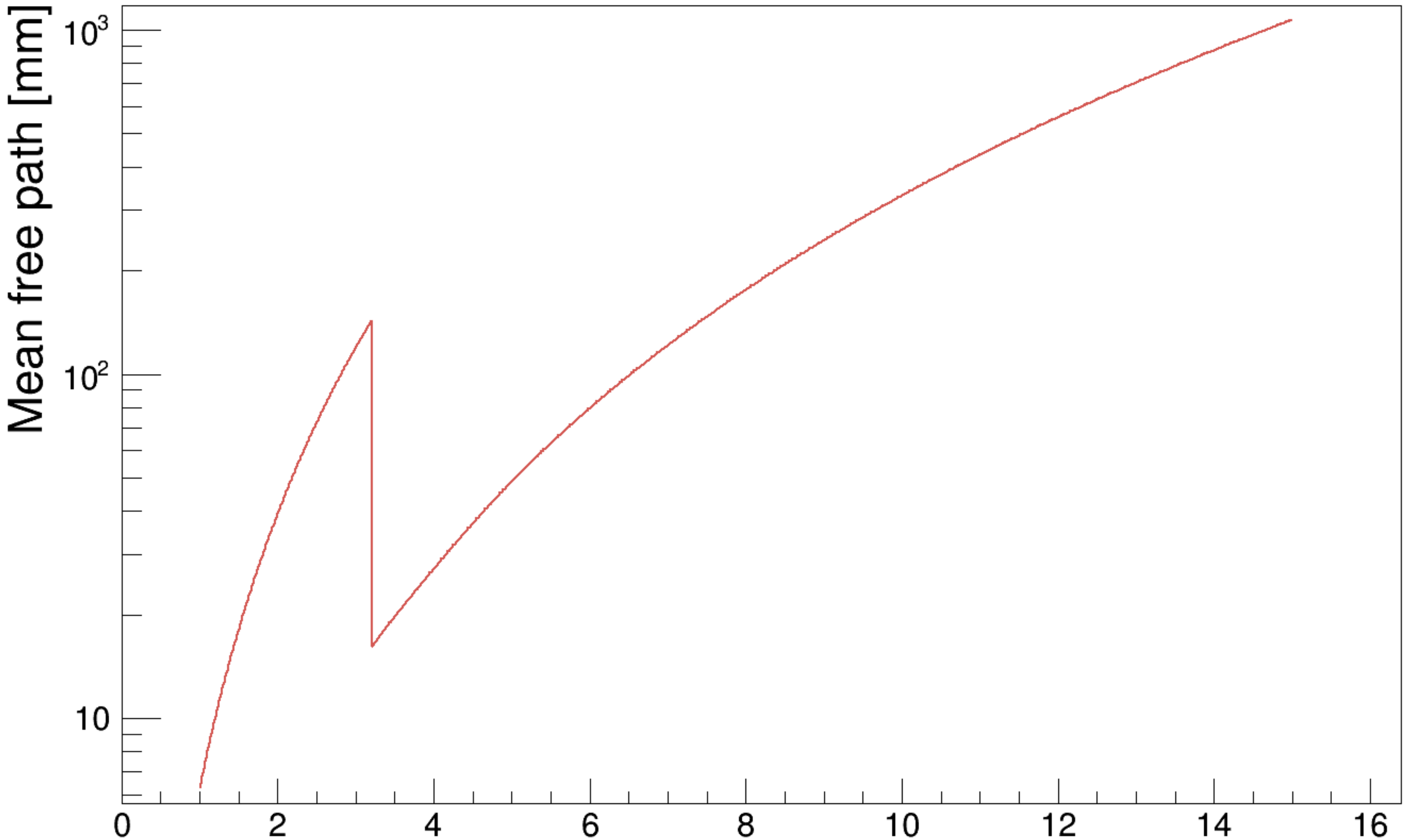

C
G
A
e-
γ
γ
e-
-
-
-
+
+
+


C
G
A
e-
γ
γ
e-

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



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



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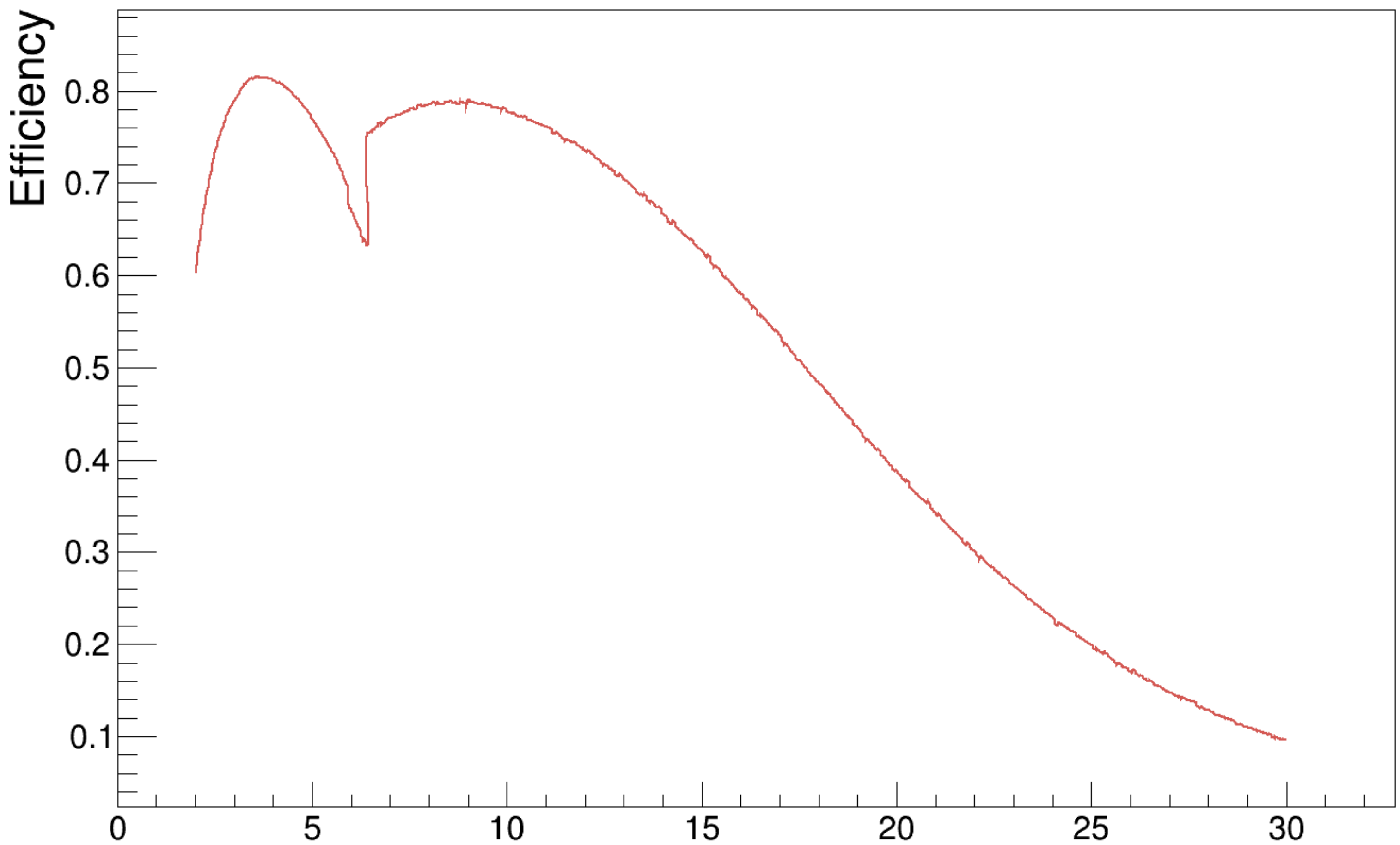
Efficiency in the Argon mixture at 300 mbar vs. KK-axion mass



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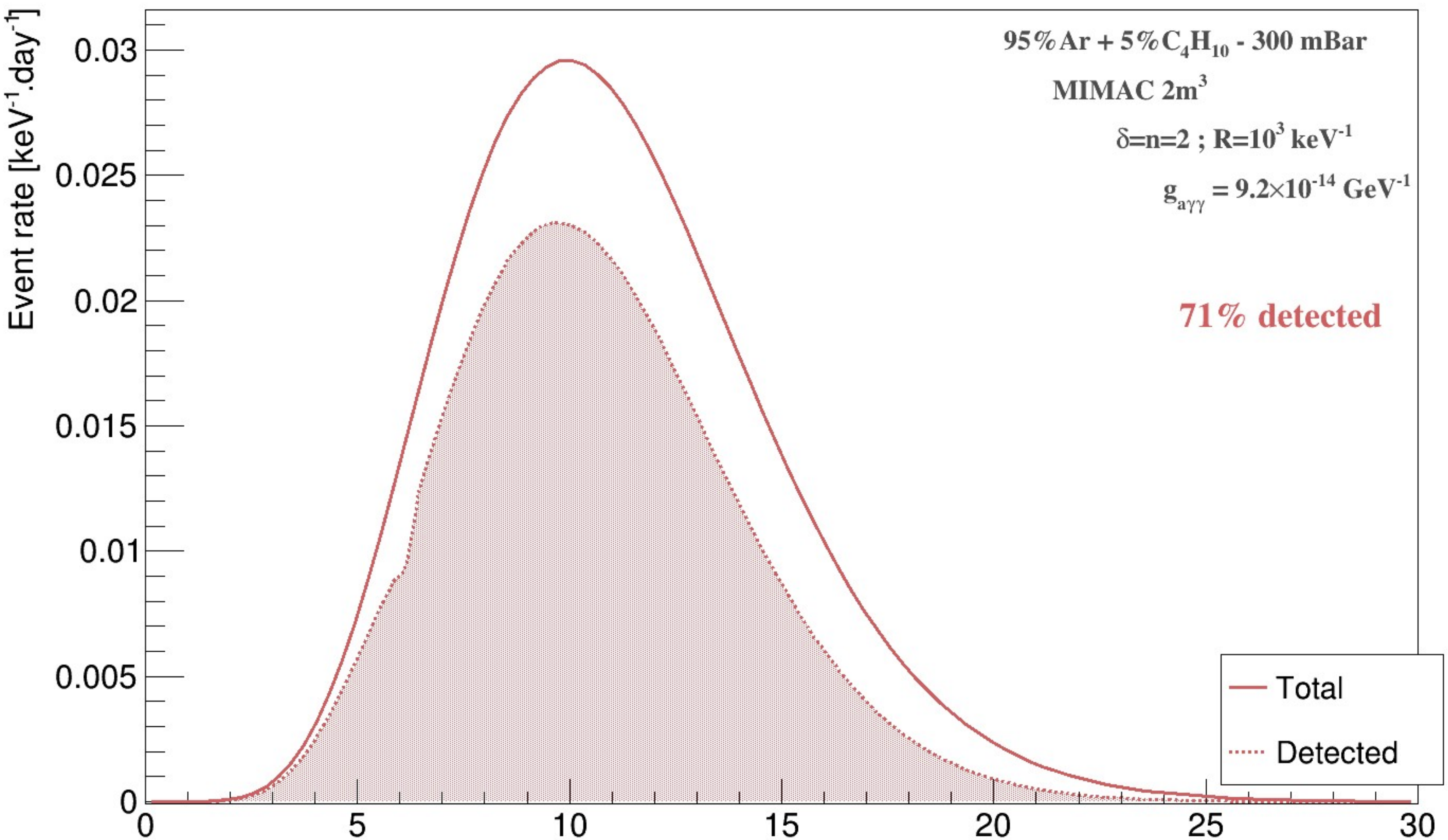
Event rate vs. KK-axion energy



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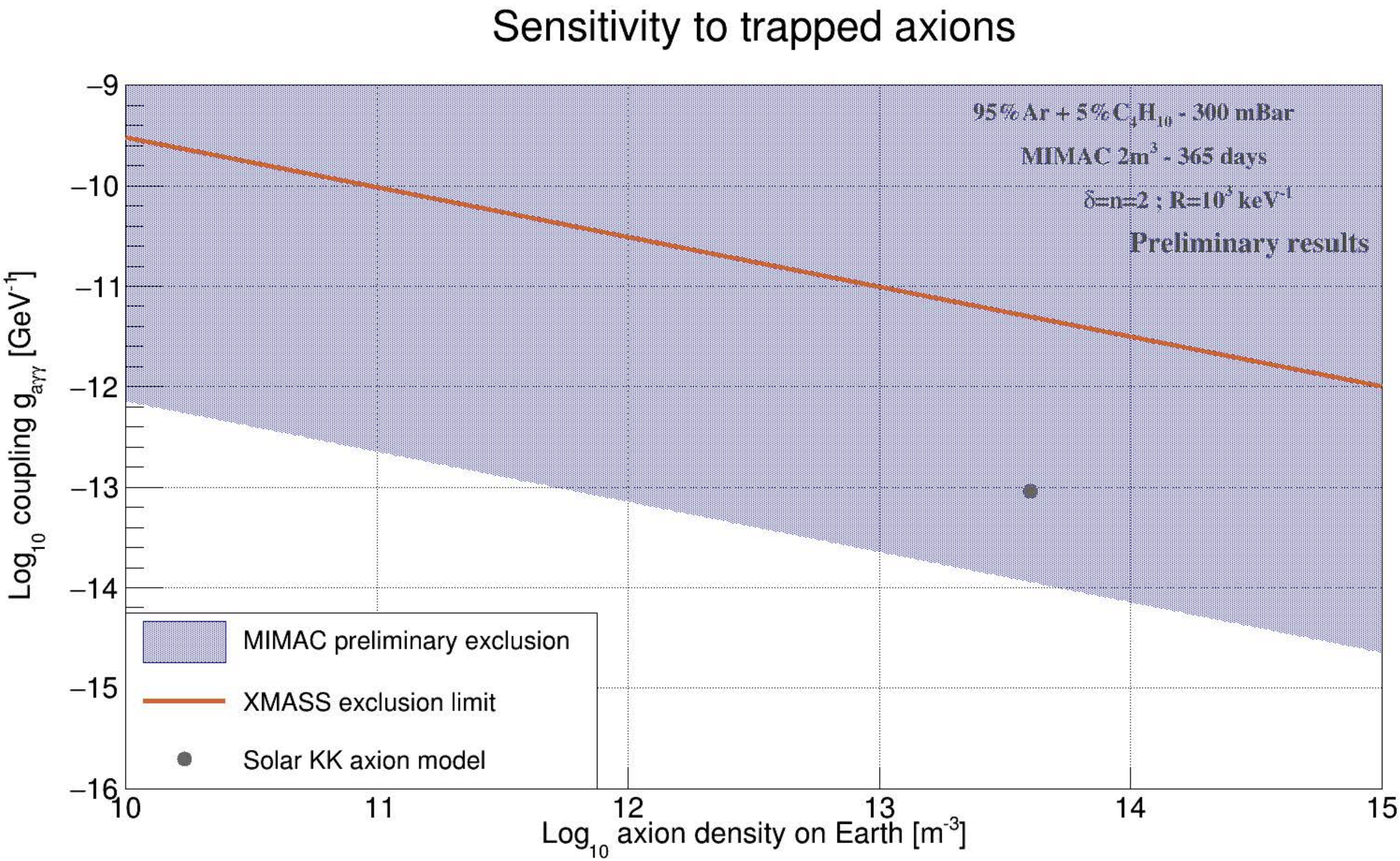
Exclusion curves



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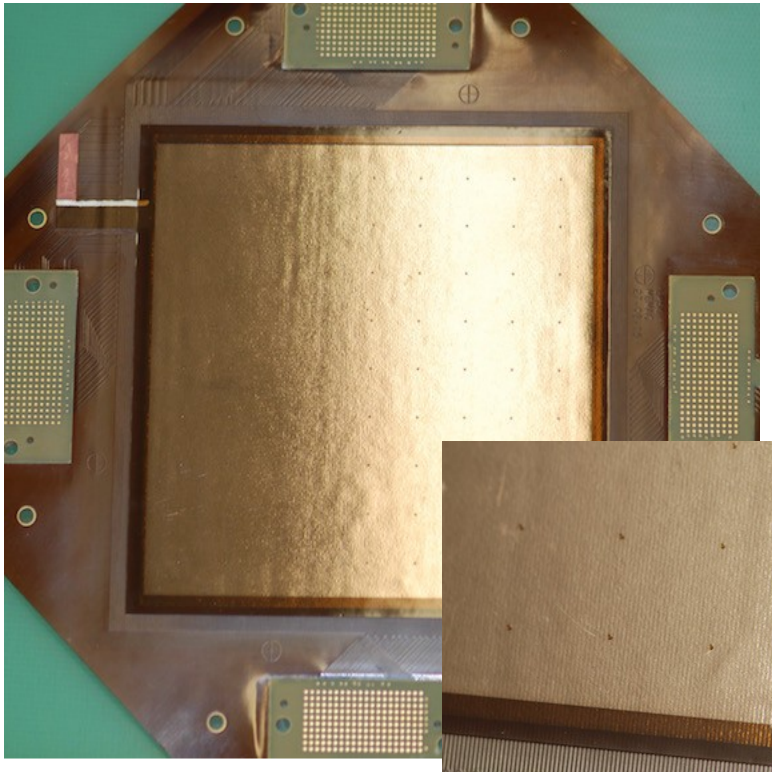
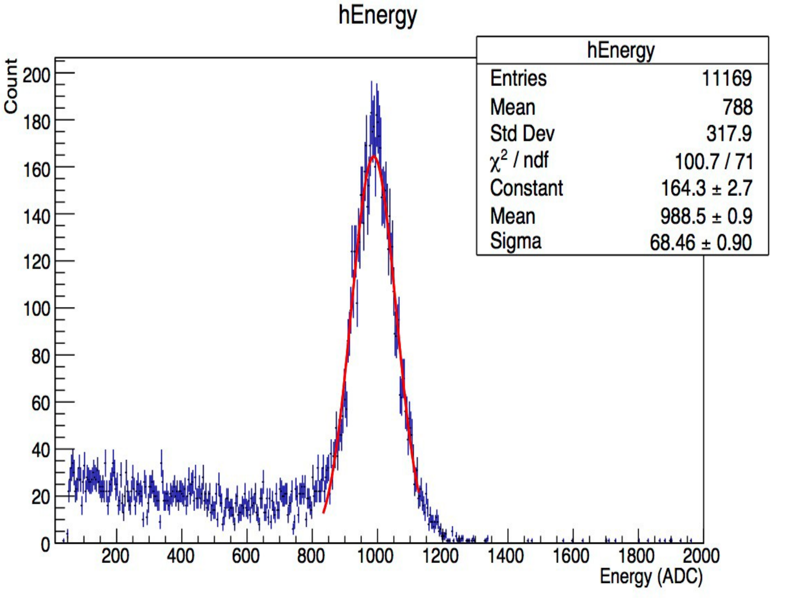
New MIMAC low background detector





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

Kapton micromegas readout
Piralux Pilar

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

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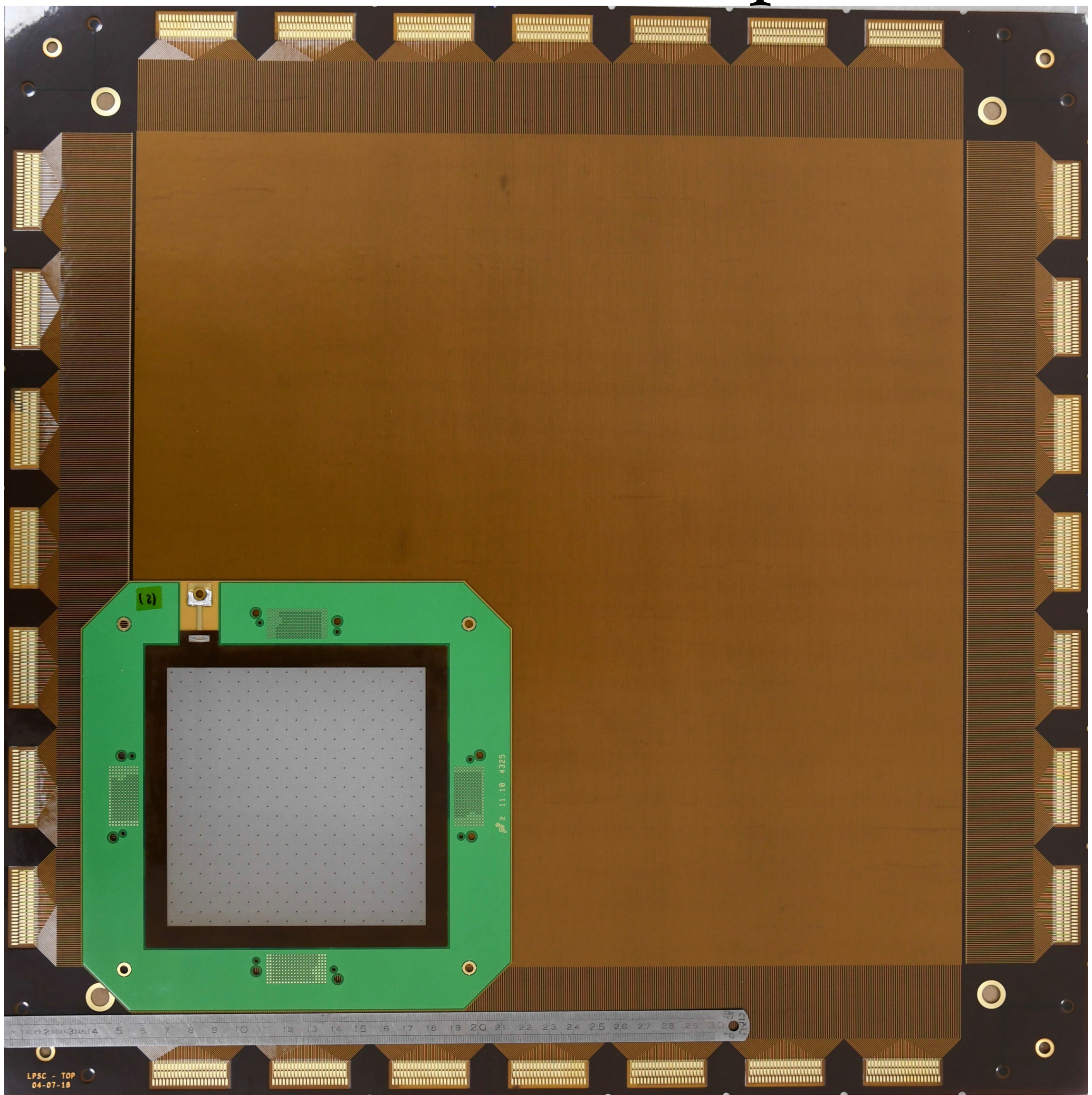
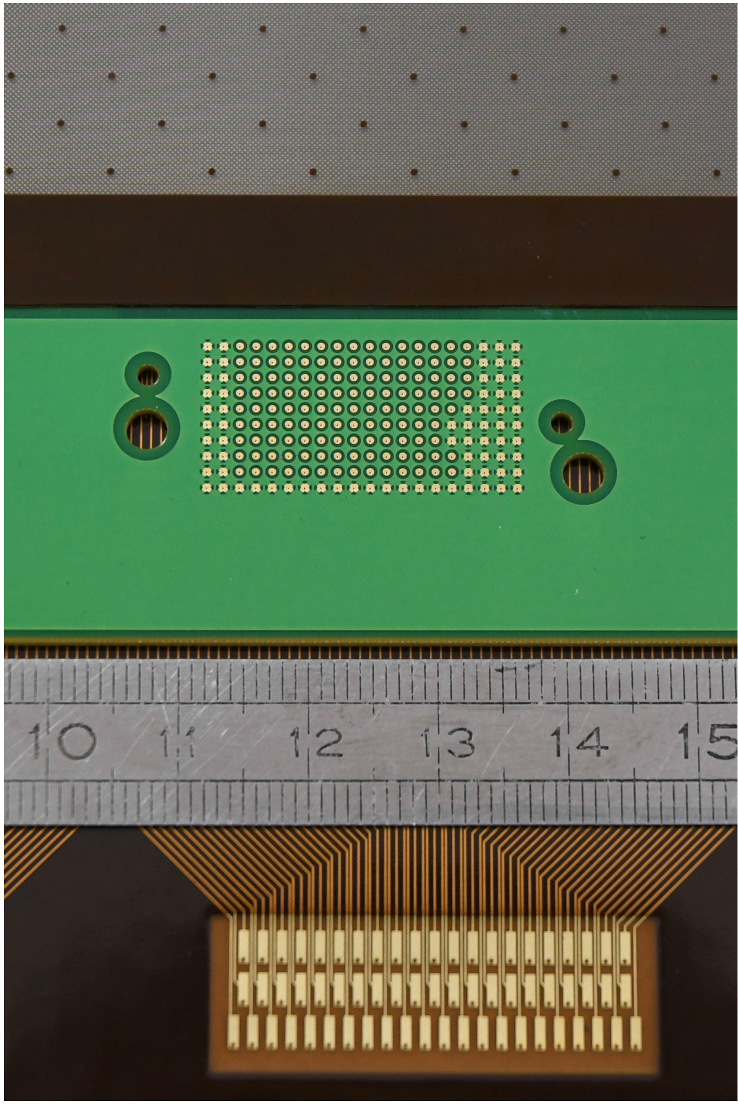
The 35 cm “new technology” MIMAC detector compared to the old one





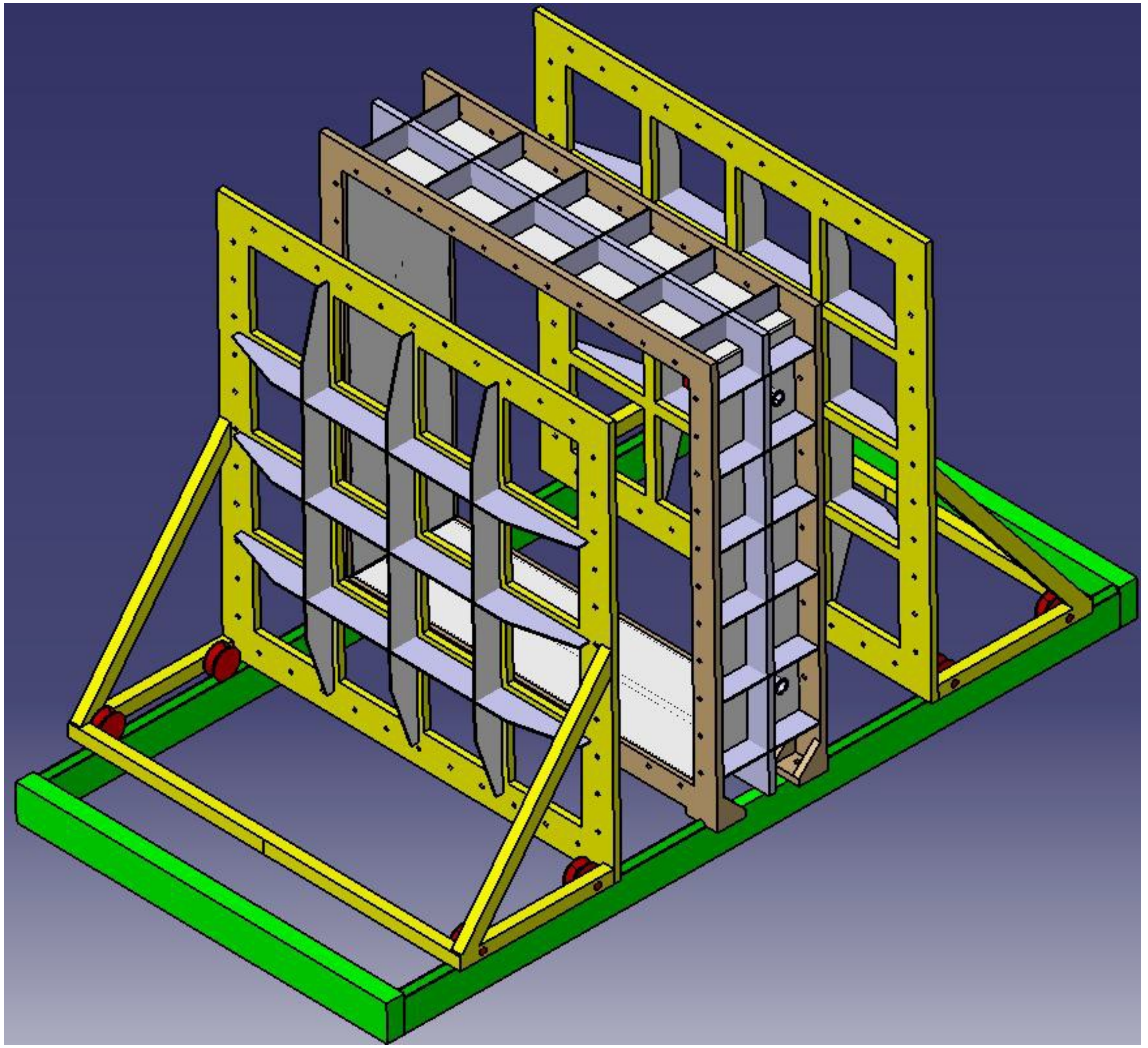
MIMAC – $2m^3$ = 16 bi-chamber modules (2x 35x35x52 cm^3)

New technology anode 35cmx35cm

Stretched thin (12 um) grid at 512um.

New electronic board (1792 channels)

Only one big chamber



Conclusions

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

- MIMAC with its 3D tracks at high spatial resolution opens a new window in the exploration of rare events !

- MIMAC-2m3 will explore ALPs and compactified dimensions

- At the same time the low energy H "recoils" from the C_4H_{10} will be "3D tracked" exploring the low mass directional WIMP detection.