Directional Detection of Dark Matter

WIMPs with MIMAC

Ilias Ourahou - PhD Student

Laboratoire de Physique Subatomique et de Cosmologie (LPSC) – 38000 Grenoble, France

1

Motivation: Why Directional Detection ?

2

MIMAC : MIcro-tpc MAtrix of Chambers

- WIMPs : Weakly interacting massive particles
- Experimental principle : The measurement of nuclear recoils and their 3D-direction
- Analysis and results

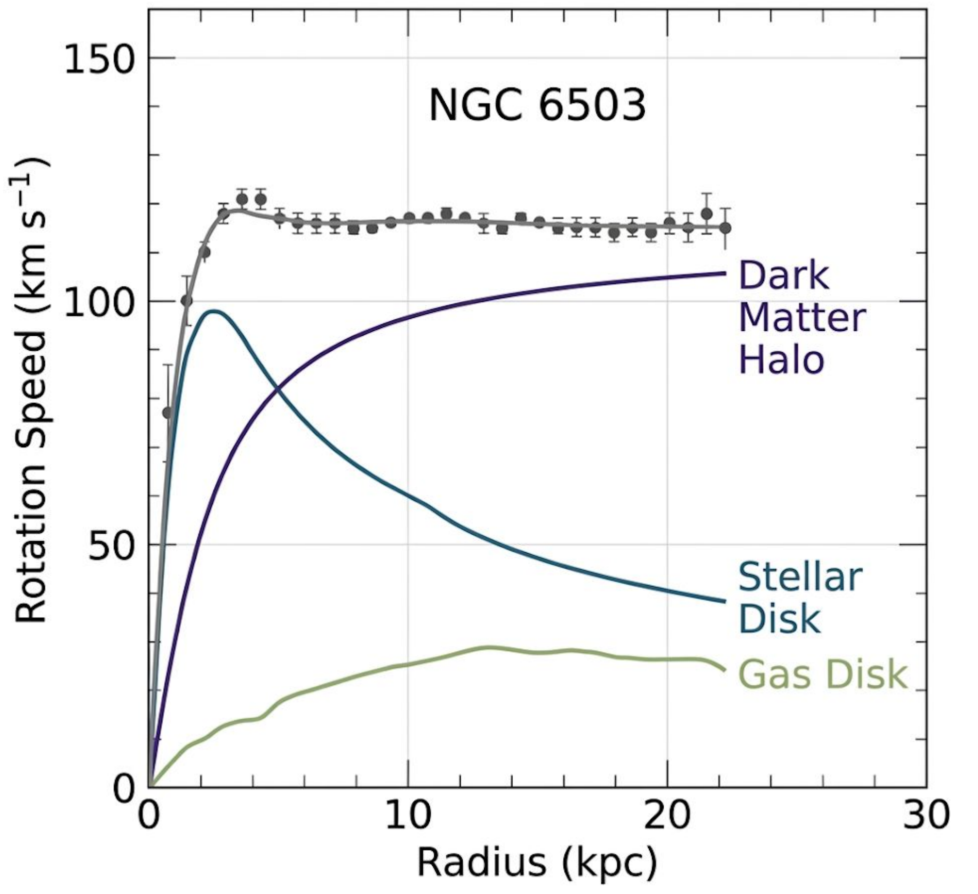
3

Conclusion

Motivation: Dark Matter

Small Scales: galaxy rotation curves

- Flat rotation curves at large radii
- Difference between baryonic-induced velocity and observations



Big Scales :

Precision cosmology (CMB, ...)

Dark energy	$\Omega_\Lambda = 0.686 \pm 0.020$
Non-baryonic matter	$\Omega_{CDM} = 0.2640 \pm 0.0068$
Baryonic matter	$\Omega_b = 0.0487 \pm 0.0007$

Planck (Ade *et al.* 2013)

~ 26% of the Universe's content is non-baryonic dark matter

WIMPs

Weakly Interacting Massive Particles

- Masses: 0.5 GeV - 1 TeV
- Interaction via weak force
- WIMP Miracle
- Stable (relic density)
- Direct Detection: nuclear recoil

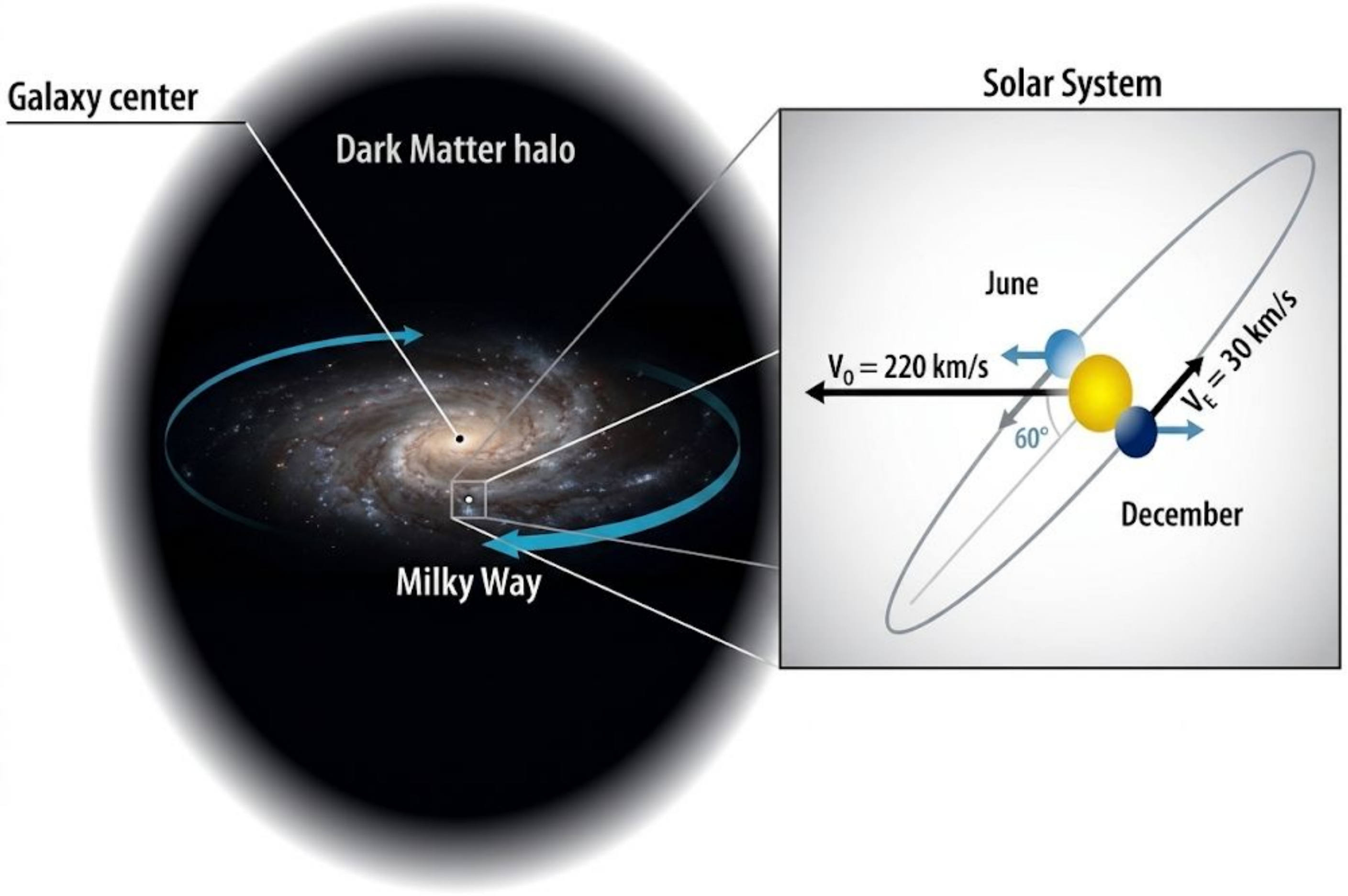
Neutrons produce a similar recoil: directionality discriminates WIMPs from the neutron background.

Motivation: Directional Detection

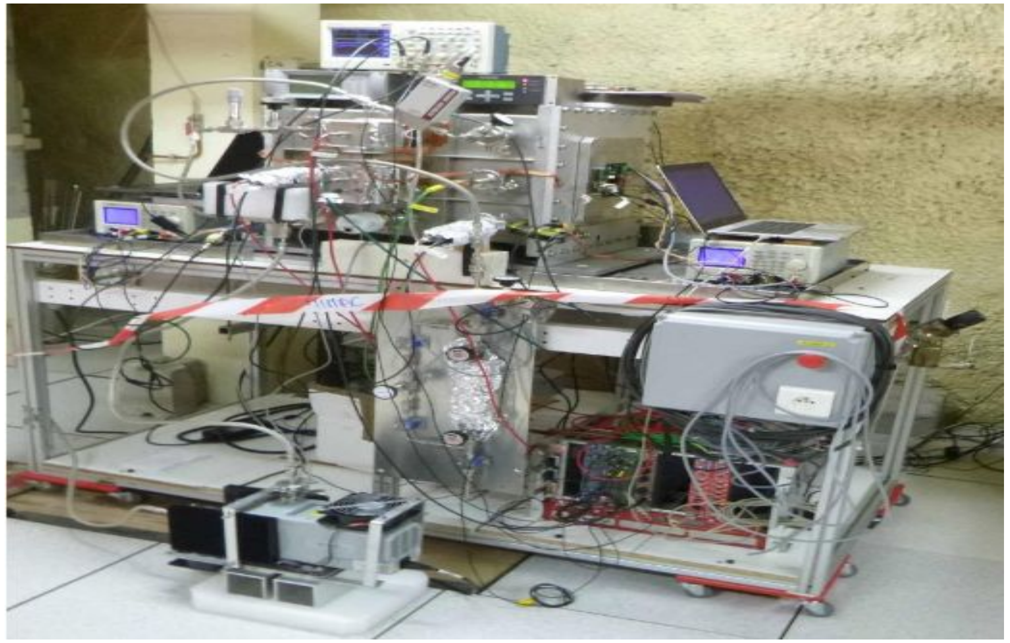
Directional detection seeks a measurable **signature that is distinct from the background .**

The movement of the solar Sun will create a **wind of dark matter** .

WIMP signature (MIMAC) : The signature is the location of the wimp contribution in the galactic map.

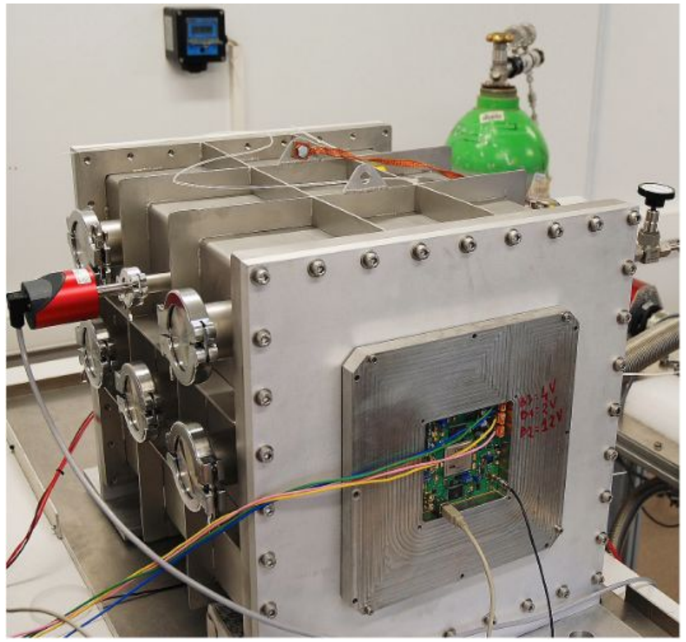


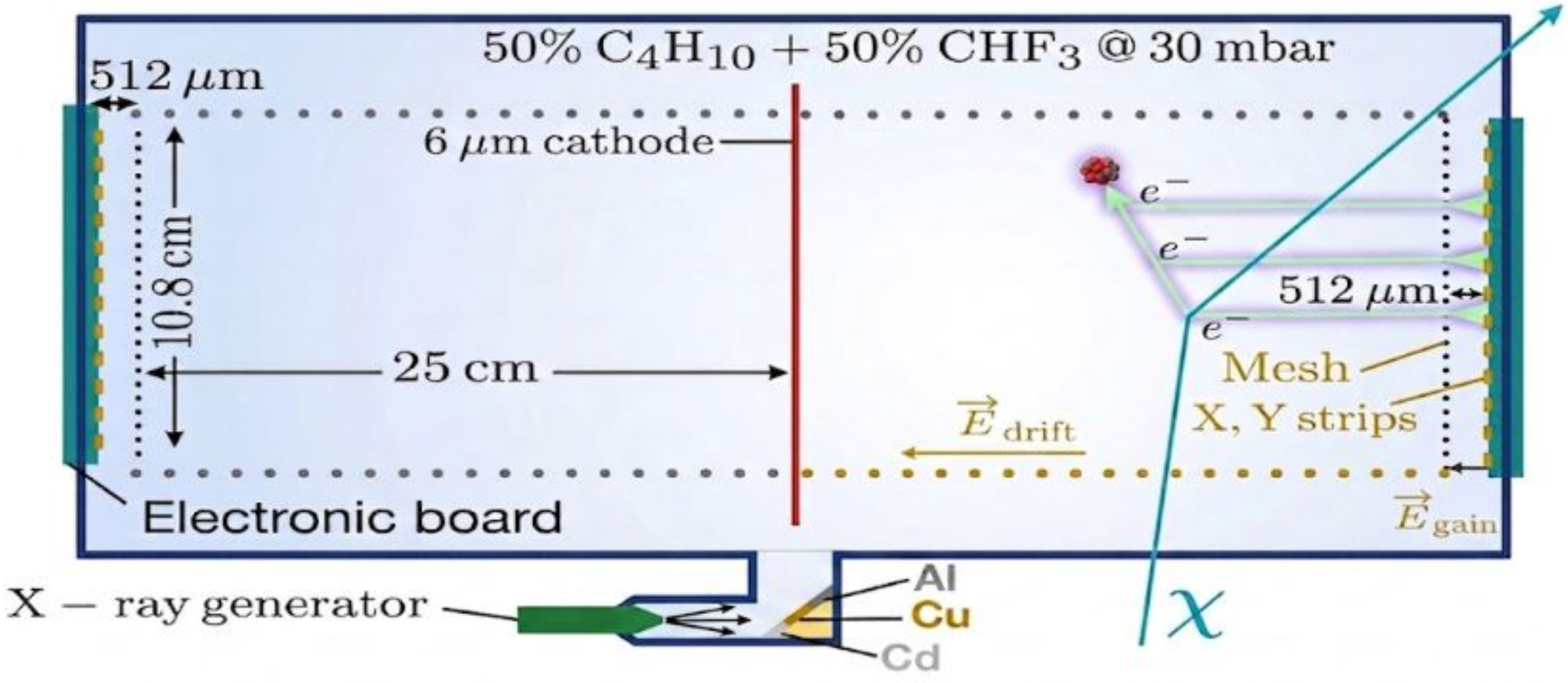
MIMAC Experiment: Setup



TPC Detector

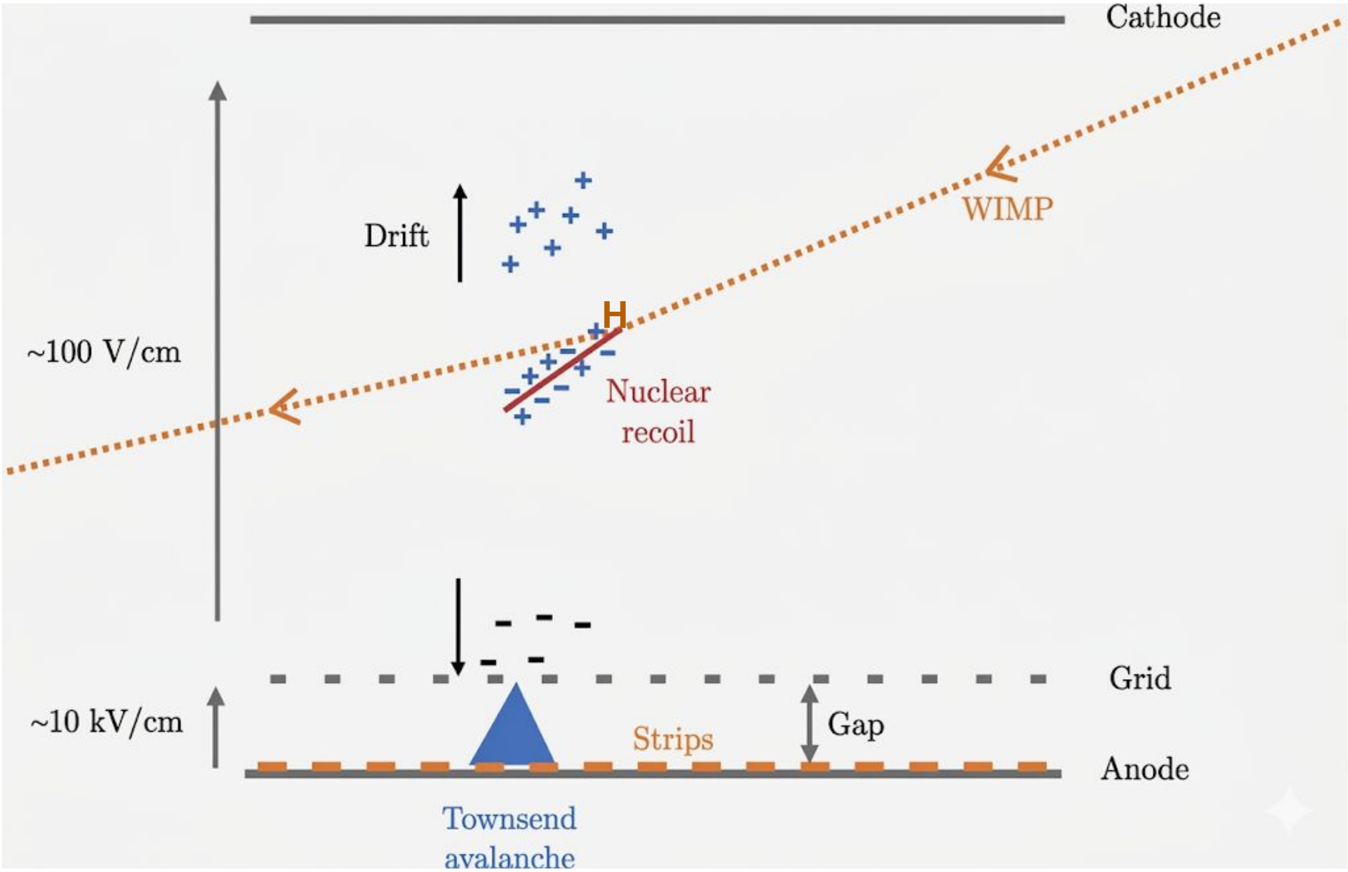
- Low-pressure gaseous TPC (50% i-C_4H_{10} + 50% CHF_3 at 30 mbar).
- Micromegas with pixelated anode (gap: 512 µm).
- Sampling at 50 MHz (20 ns).
- Location: Modane
- Volume : (10.8 x 10.8 x 25 cm^3)
- Duration: 495 days.



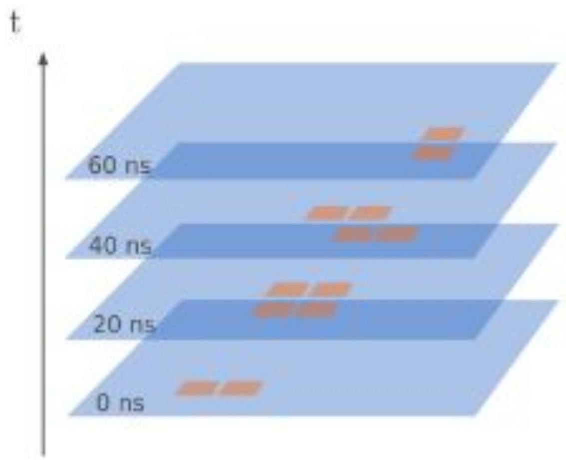


MIMAC Experiment: Setup

- Low-pressure gaseous TPC (50% i-C_4H_{10} + 50% CHF_3 at 30 mbar).
- Micromegas with pixelated anode (gap: 512 μm).
- Sampling at 50 MHz (20 ns).
- Location: Modane
- Volume : (10.8 x 10.8 x 25 cm³)
- Duration: 495 days.

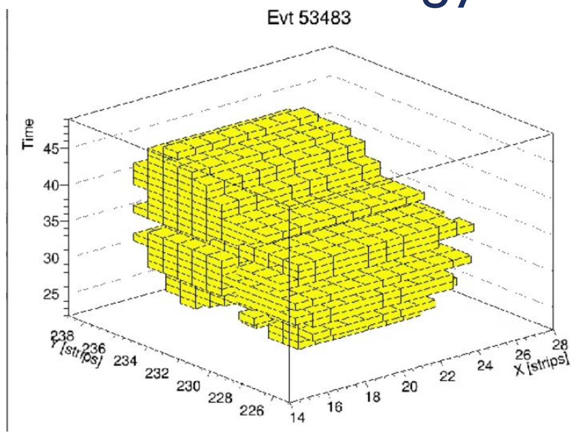


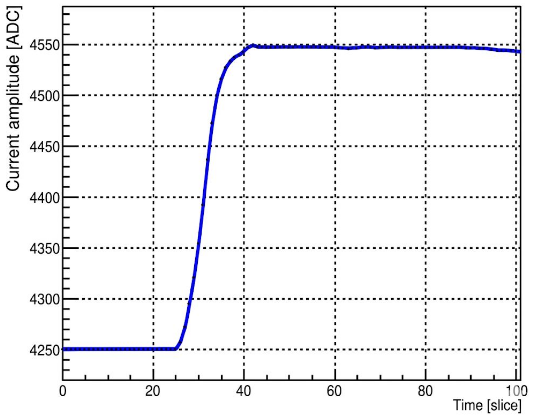
$$z = \Delta t \cdot v_{drift}$$



Two main observables

- 3D-Track
- Ionization energy

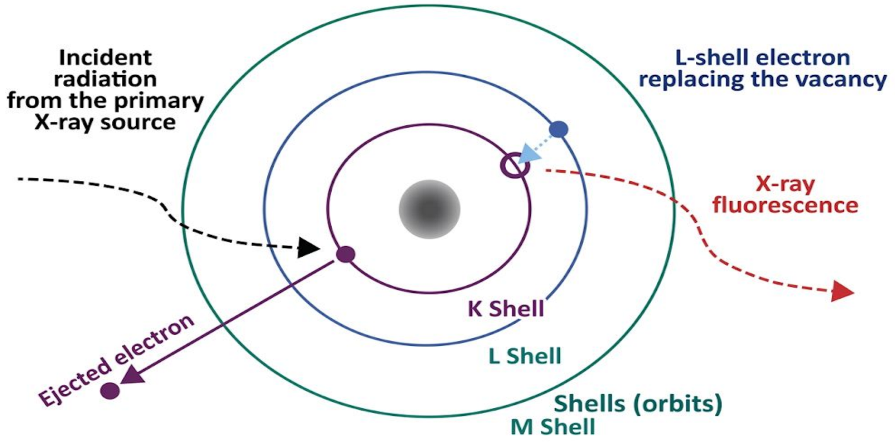


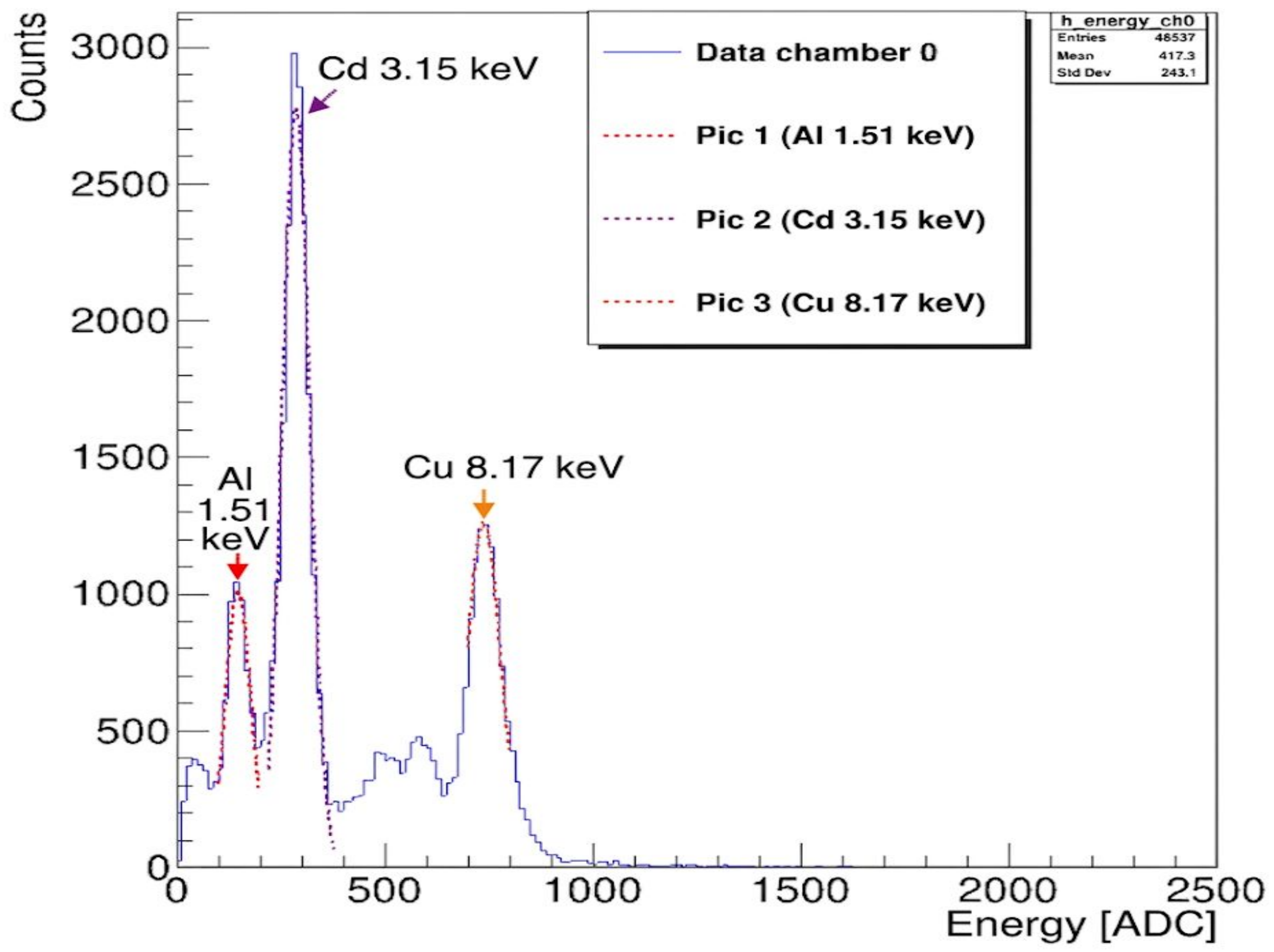


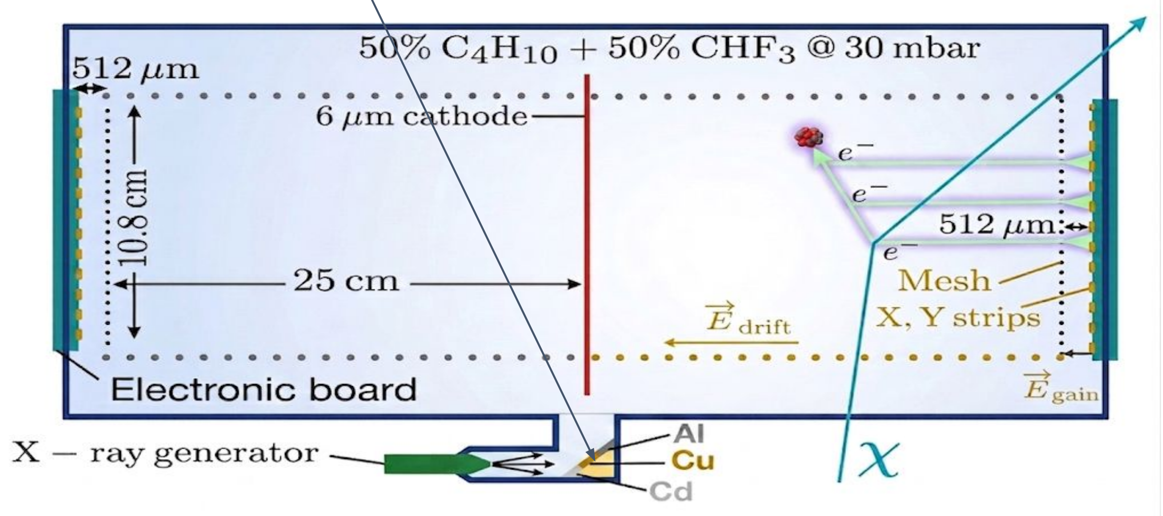
Calibration

Ionization Energy

We hit a (Al, Cd, Cu) target with a primary X-ray beam source.

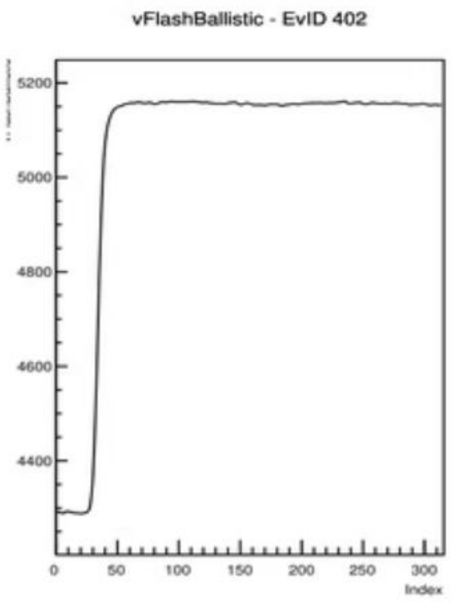


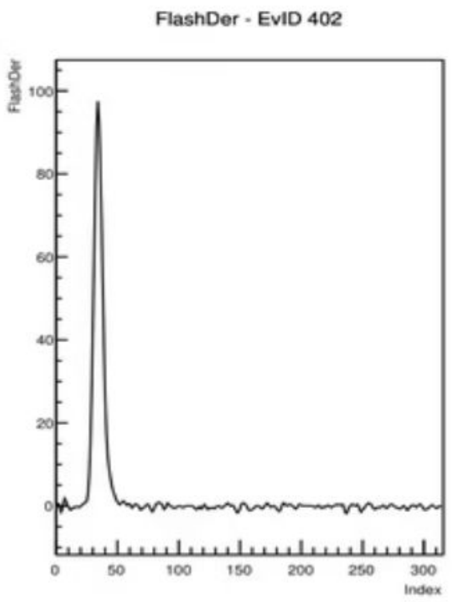


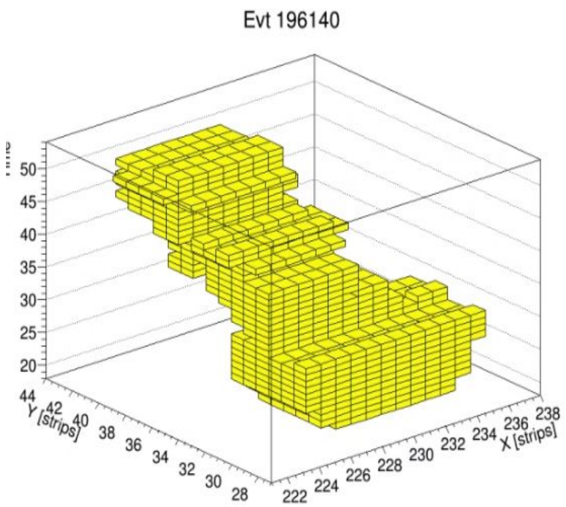


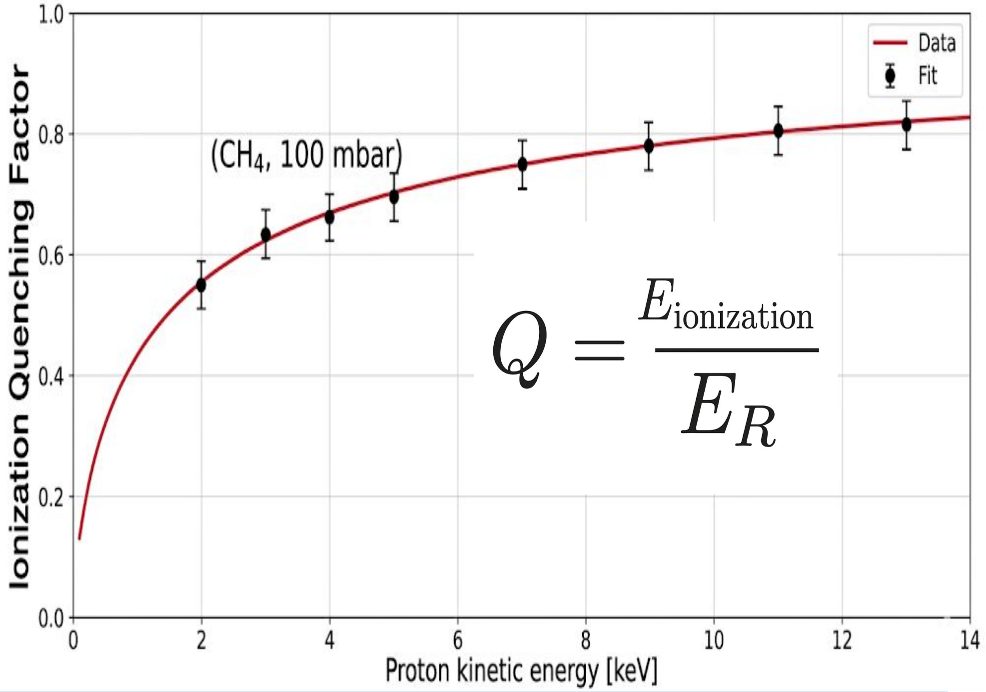
Discrimination: Nuclear recoils and Electronic recoils

Nuclear Recoil



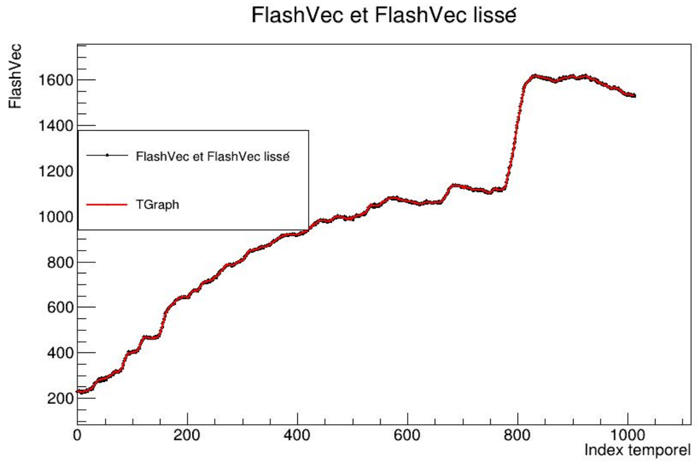


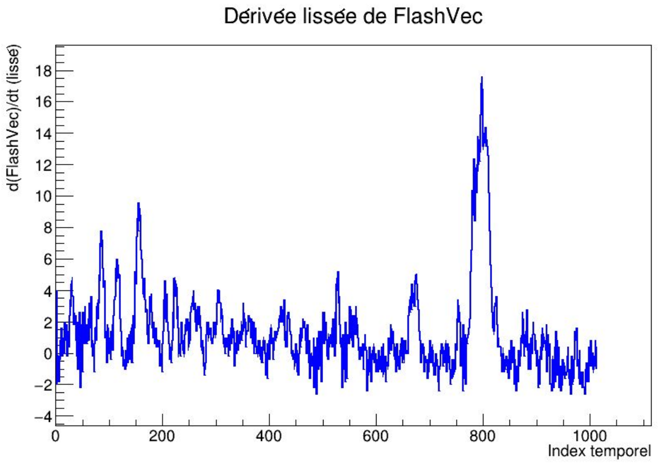


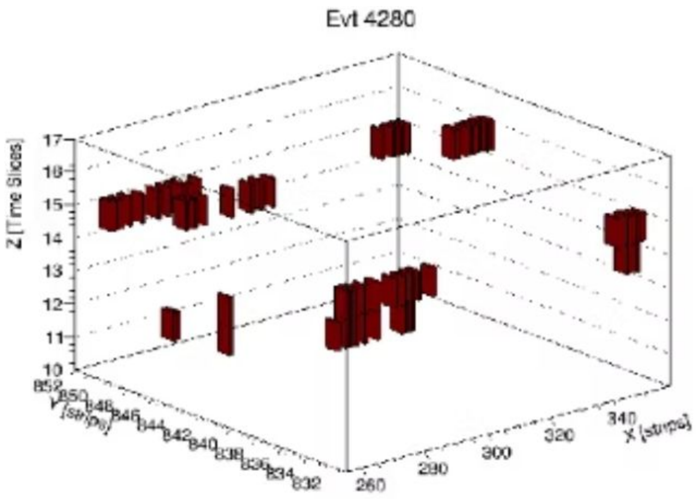


Electronic Recoil

- Beta electrons and Gamma rays

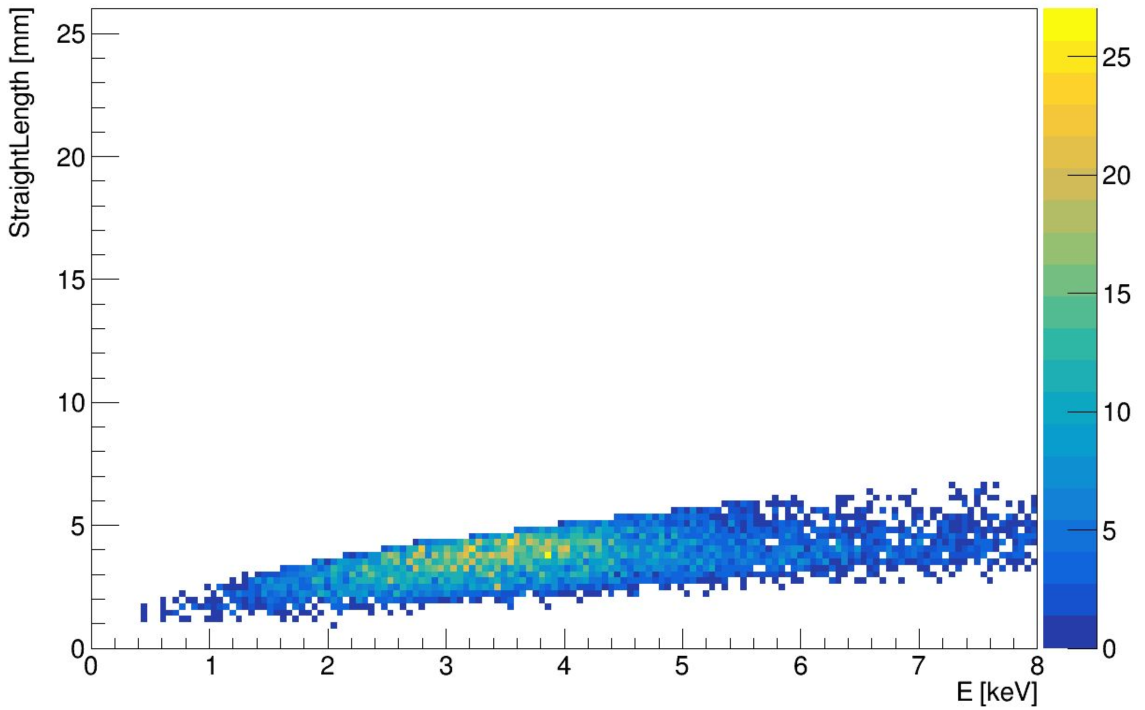






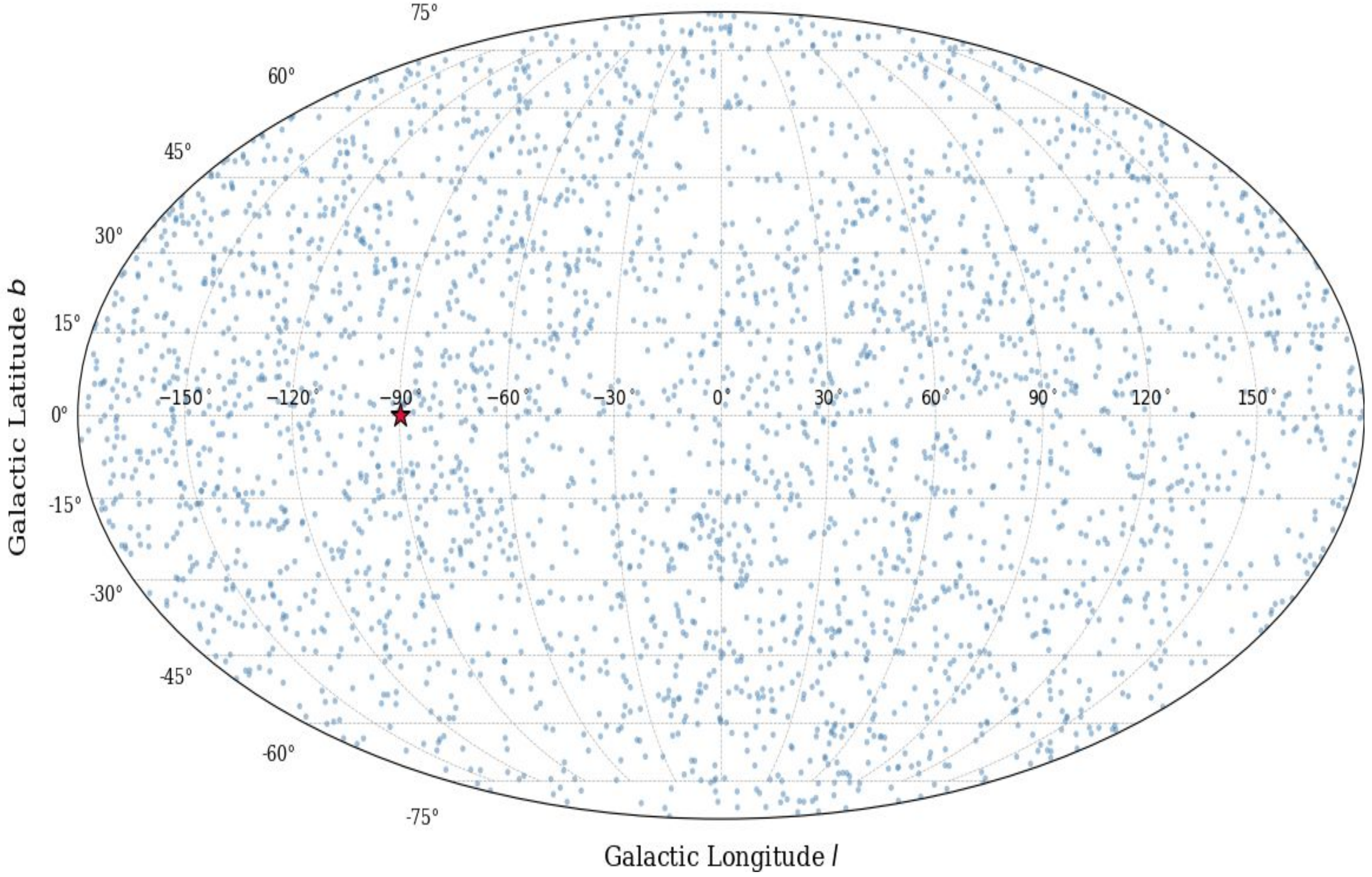
MIMAC Results: Event Analysis

Identification of Nuclear Recoils



The two-dimensional diagram shows that the hydrogen recoil branch dominates. The contributions of the other nuclei (carbon and fluorine) are negligible.

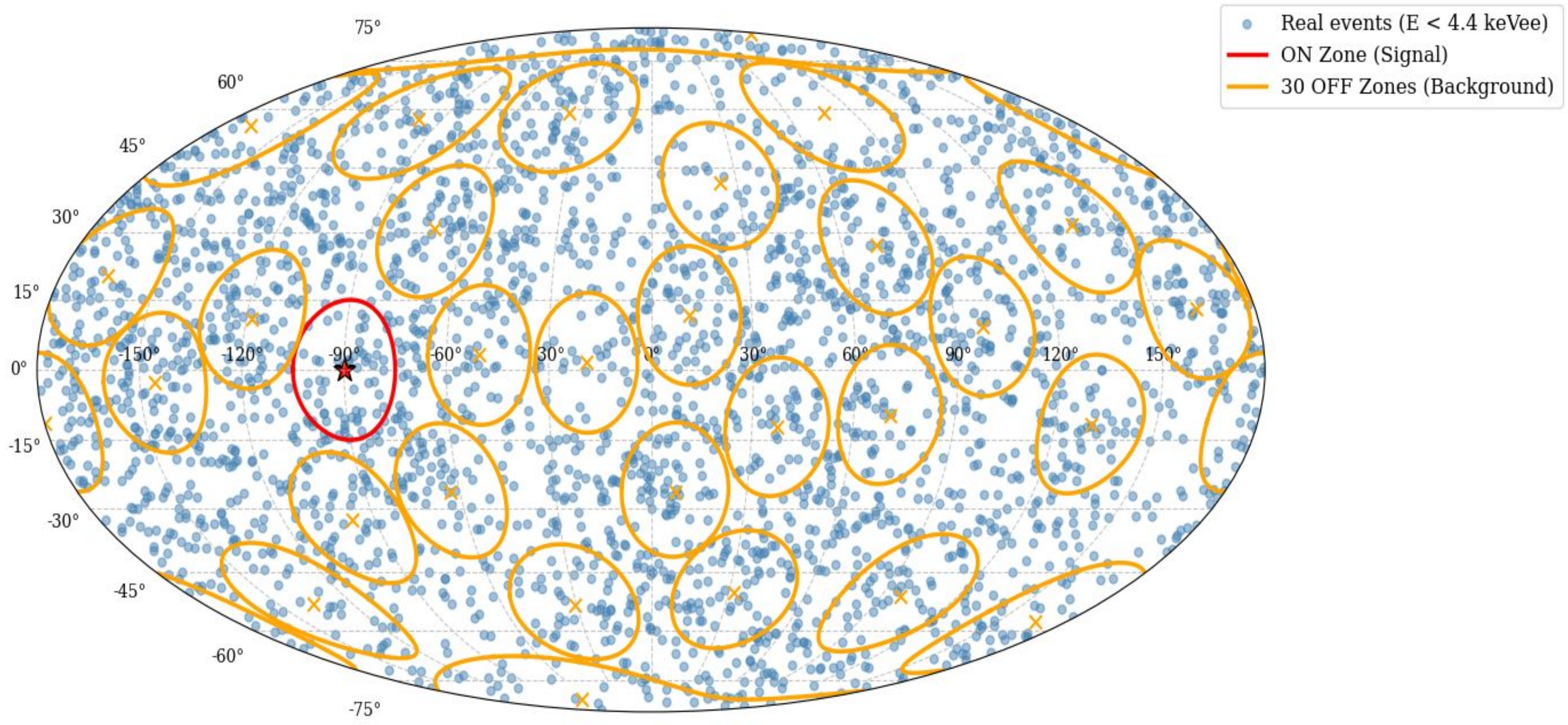
Galactic Projection



Signal/Background Separation: Directionality Analysis

Strategy

- Construction of the background model on events in off region
- N_{on}~Poisson(S+B) & N_{off}~Poisson(B)
- The 30 OFF-zones are randomly re-sampled 300 times.

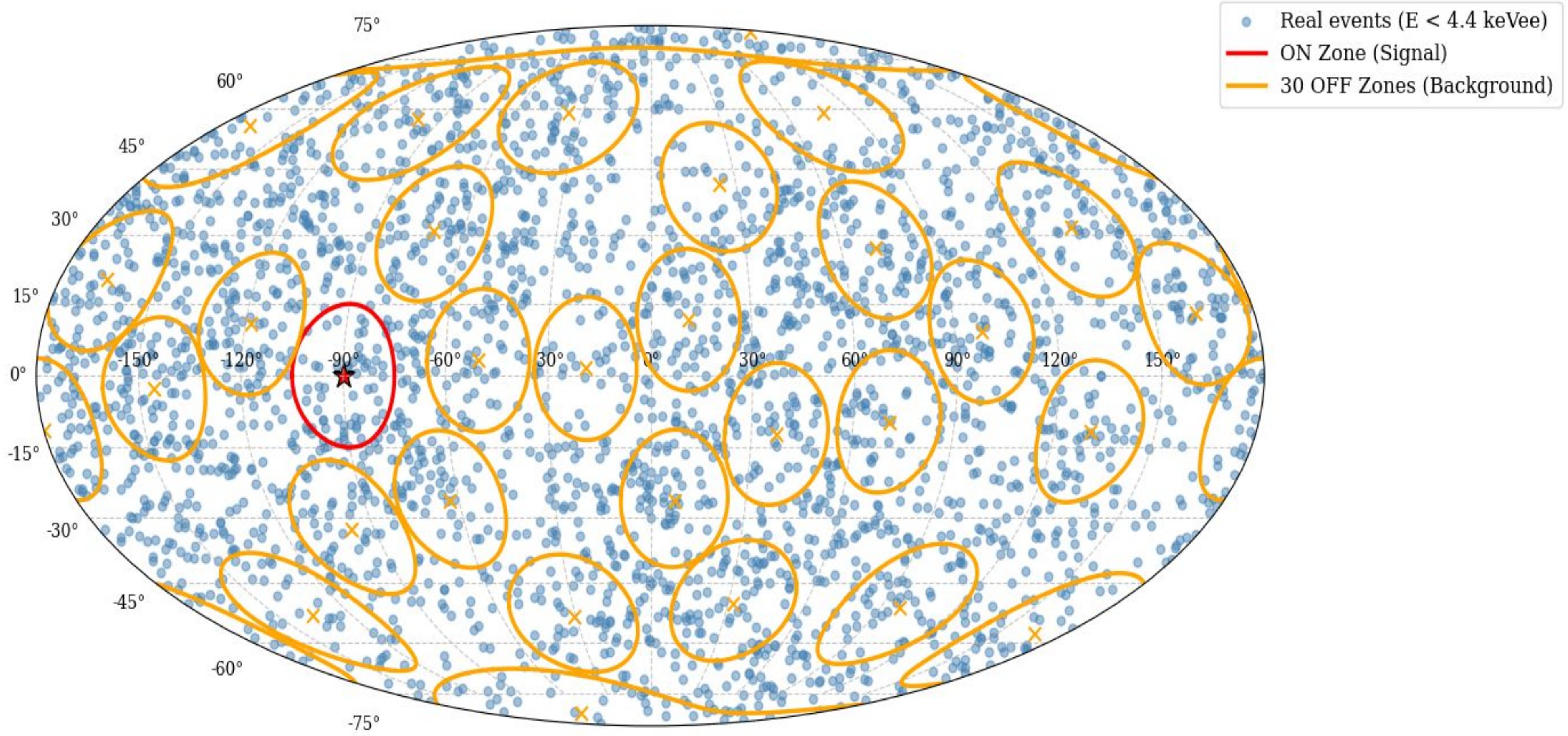


Mass-Dependent Kinematic Cut (The "Moving Cut")

WIMP mass (GeV/c^2)	$E^{\max}_{\text{kinetic,H}}$ (keV)
1	1.65
5	4.12
10	5.19
50	5.99
100	6.08

Results

No signal measured

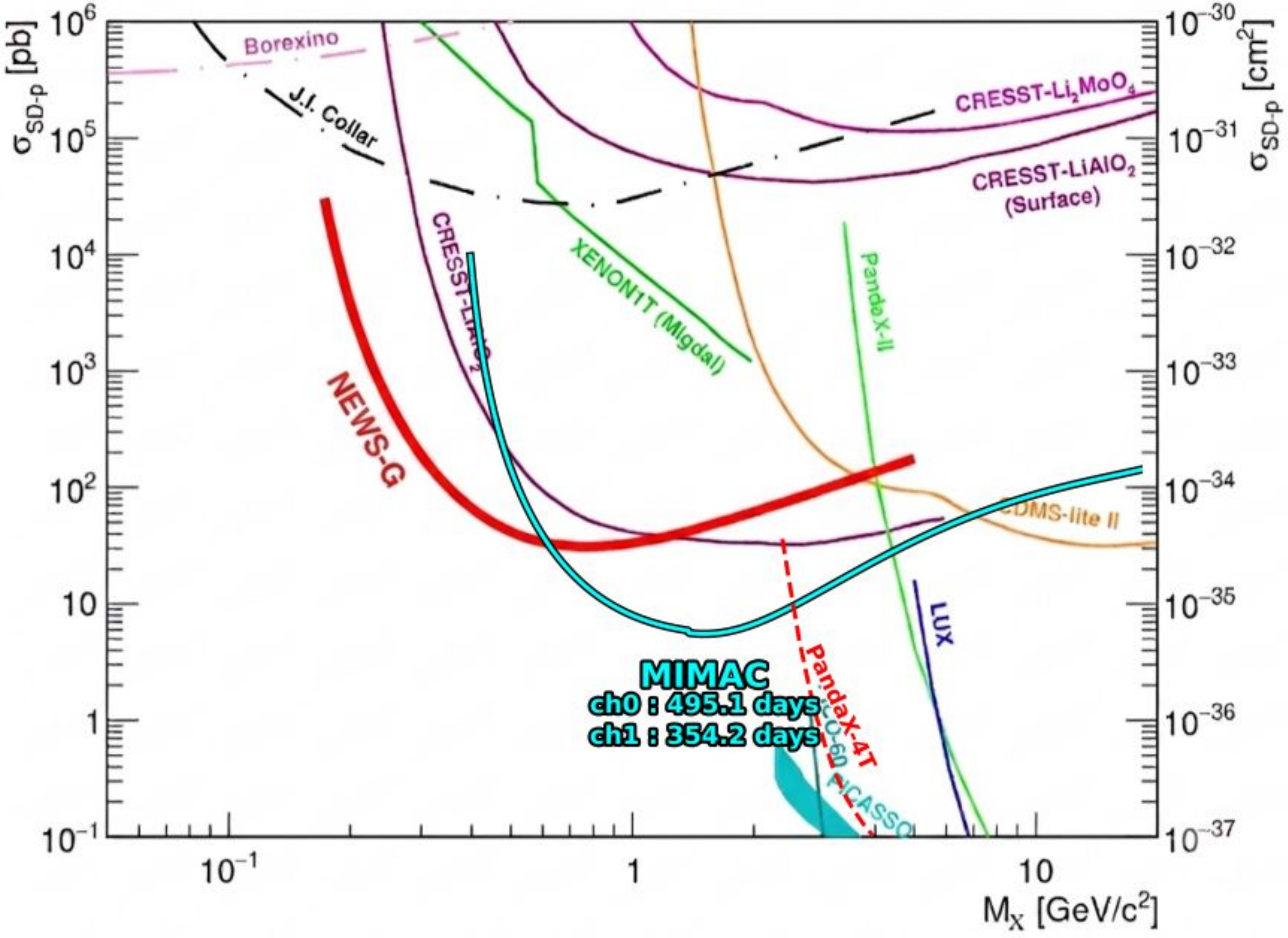


MIMAC Results: Exclusion Curve and Cross Section limit

With a kinetic energy threshold of 0.94 keV, we obtain the following exclusion curve.

Limit reached with no shielding

The limit on the cross section obtained is: $\sigma < 10^{-35}$ cm²

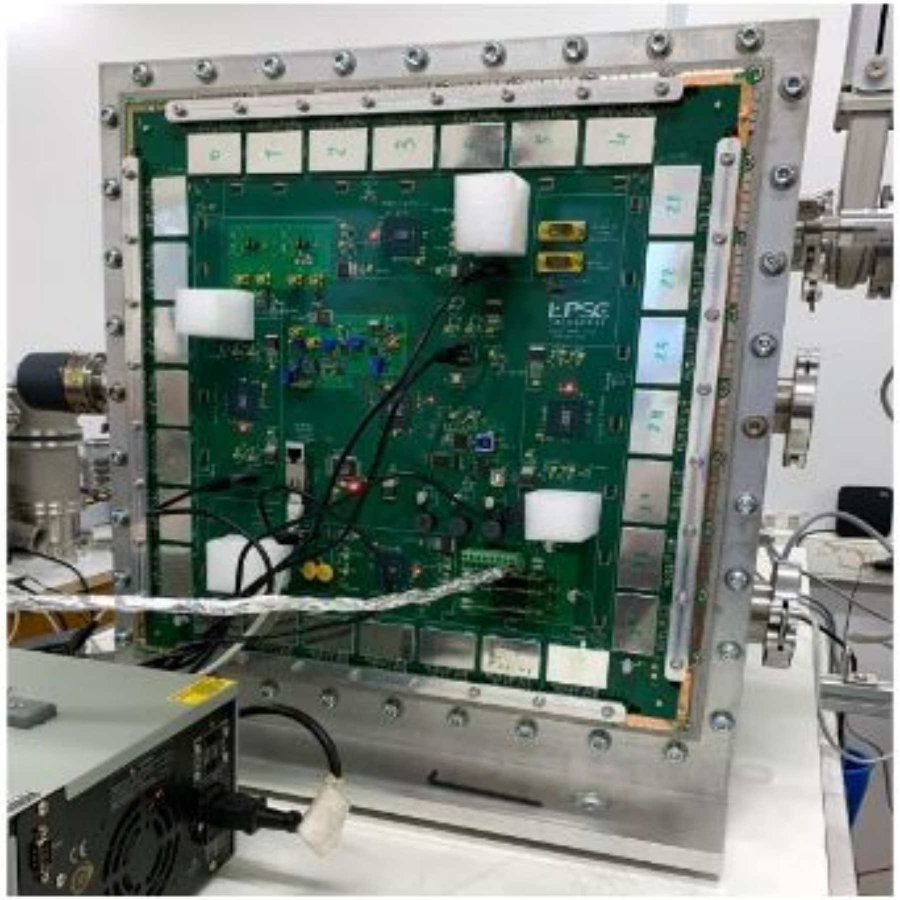


MIMAC-35 cm: Thermal Neutron Capture

Background Analysis : $^{1}\mathrm{H}(n,\gamma)^{2}\mathrm{H}.$

arXiv:2602.17880

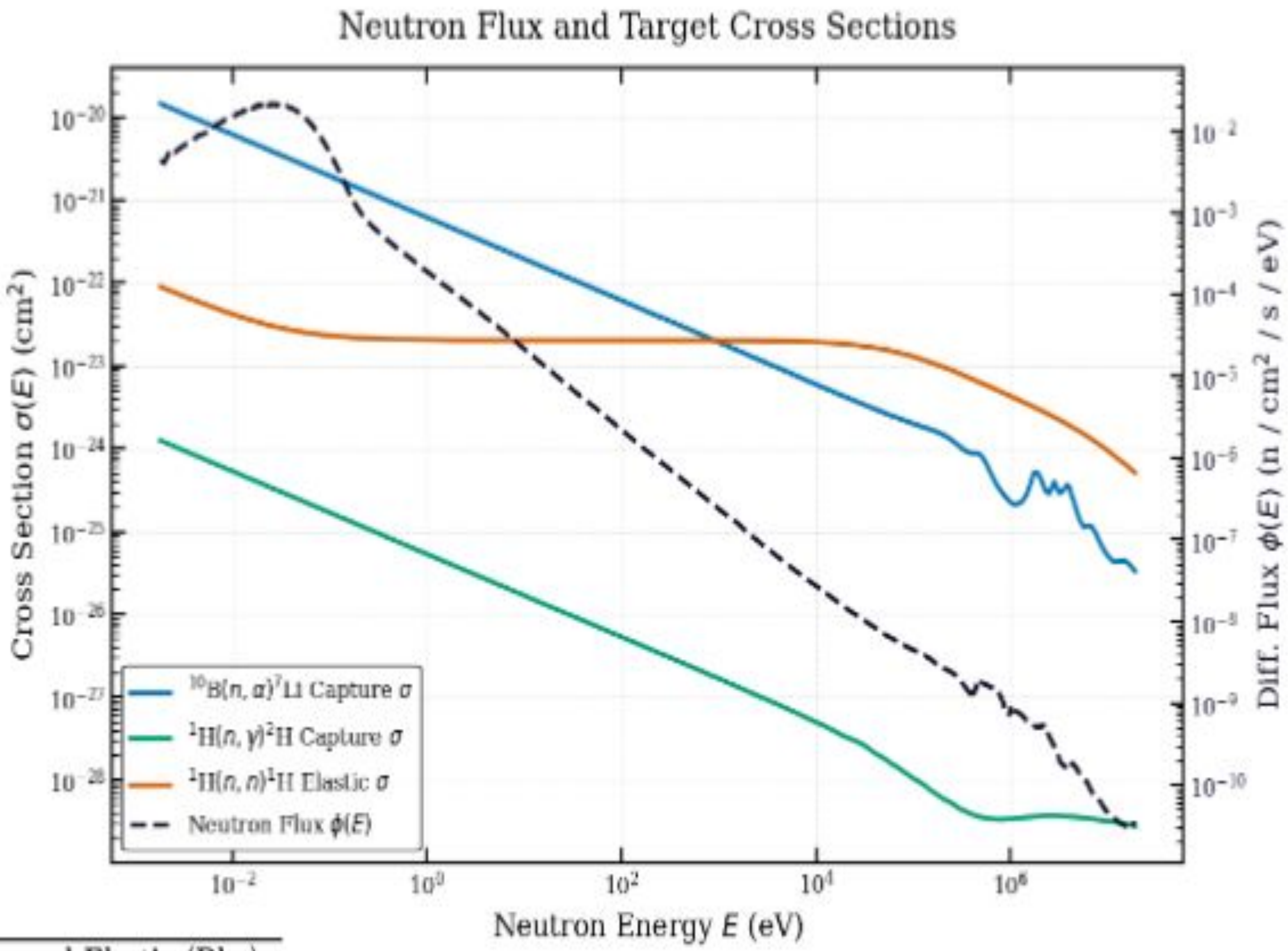
- ^{2}H recoils at 1.3 keV.
- Duration : 5 days
- Location : LPSC
- With a new TPC detector (35x35x29) cm^3
  - 70% i-C_4H_{10} + 30% CHF_3 at 30 mbar



- Same observables for Signal/Background separation
- Energy threshold of 300 eV

Proton Recoil Background

$$\mathcal{R}_{S/B} = \frac{\phi_{\text{thermal}} \cdot \sigma_{\text{cap, thermal}}}{\phi_{\text{2keV}} \cdot \sigma_{\text{ela, 2keV}}} = \frac{7.13 \times 10^{-27}}{2.08 \times 10^{-30}} \approx 3429$$



Parameter	Thermal Capture (Signal)	Epithermal Elastic (Bkg)
Neutron Energy (E_n)	0.025 eV	2.4 keV
Diff. Flux $\phi(E_n)$ [n/cm^2/s/eV]	2.13×10^{-2}	1.04×10^{-7}
Cross-Section $\sigma(E_n)$ [cm^2]	3.34×10^{-25} (capture)	2.01×10^{-23} (elastic collision)
Rate Density ($\phi \cdot \sigma$)	$\mathbf{7.13 \times 10^{-27}}$	$\mathbf{2.08 \times 10^{-30}}$

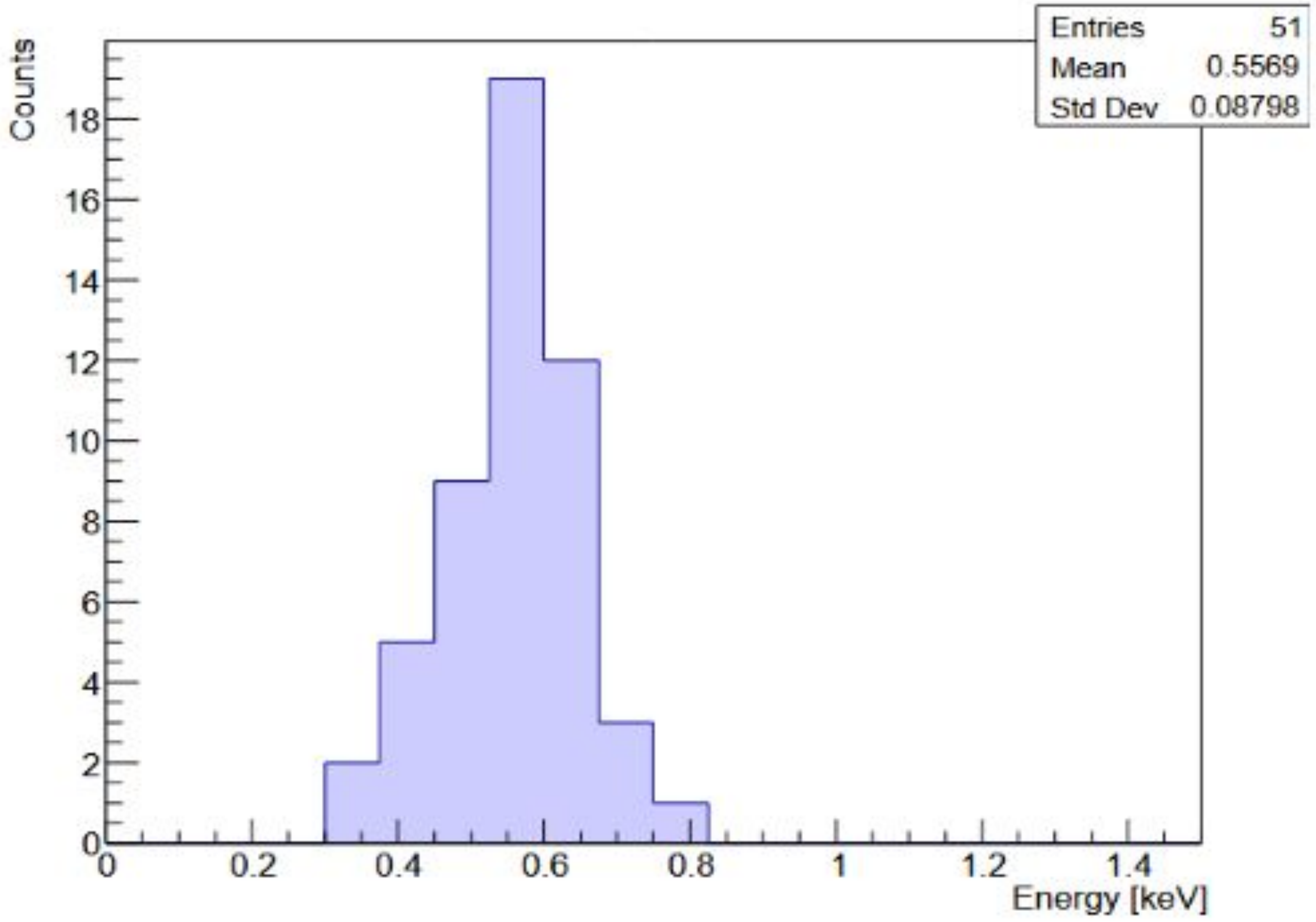
MIMAC-35 cm: Thermal Neutron Capture

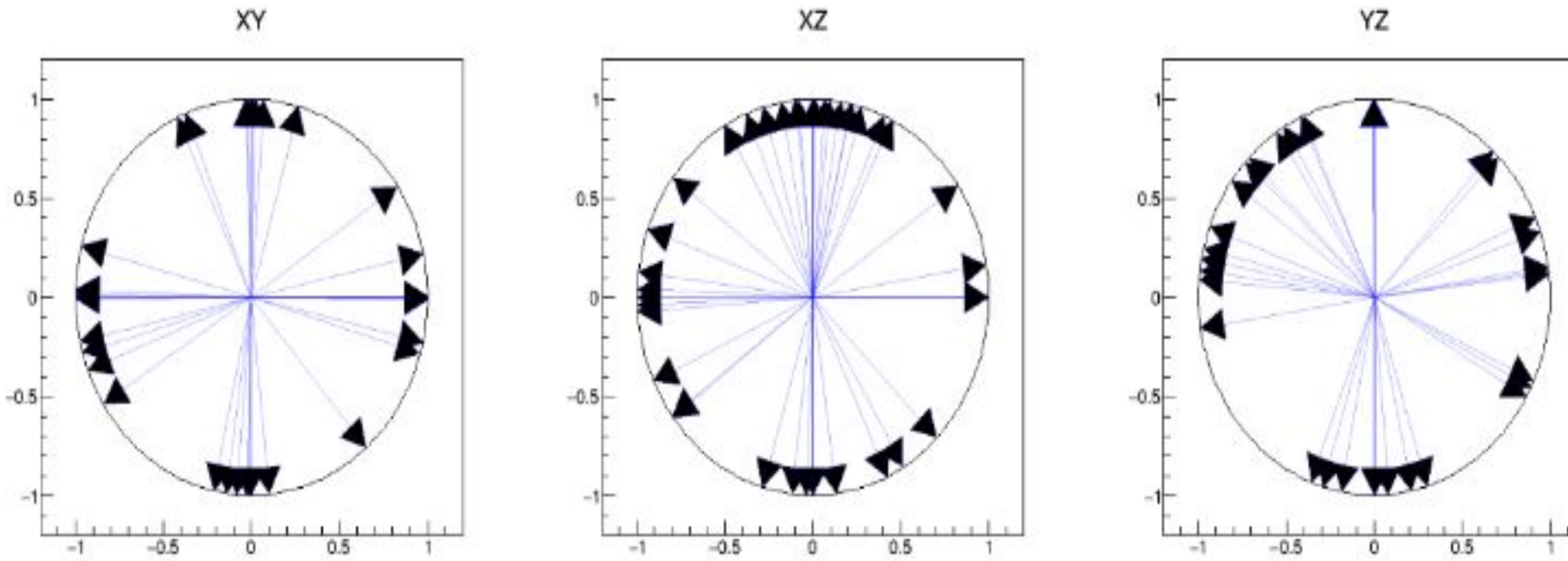
Background Analysis :

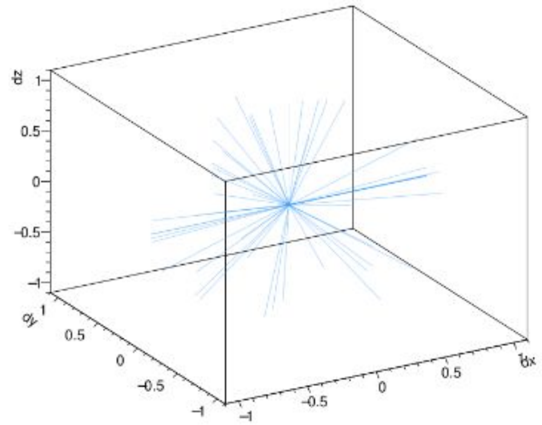
arXiv:2602.17880

$$^{1}\mathrm{H}(n,\gamma)^{2}\mathrm{H}.$$

- Same observables for Signal/Background separation
- Energy threshold of 300 eV







Conclusion and Perspectives

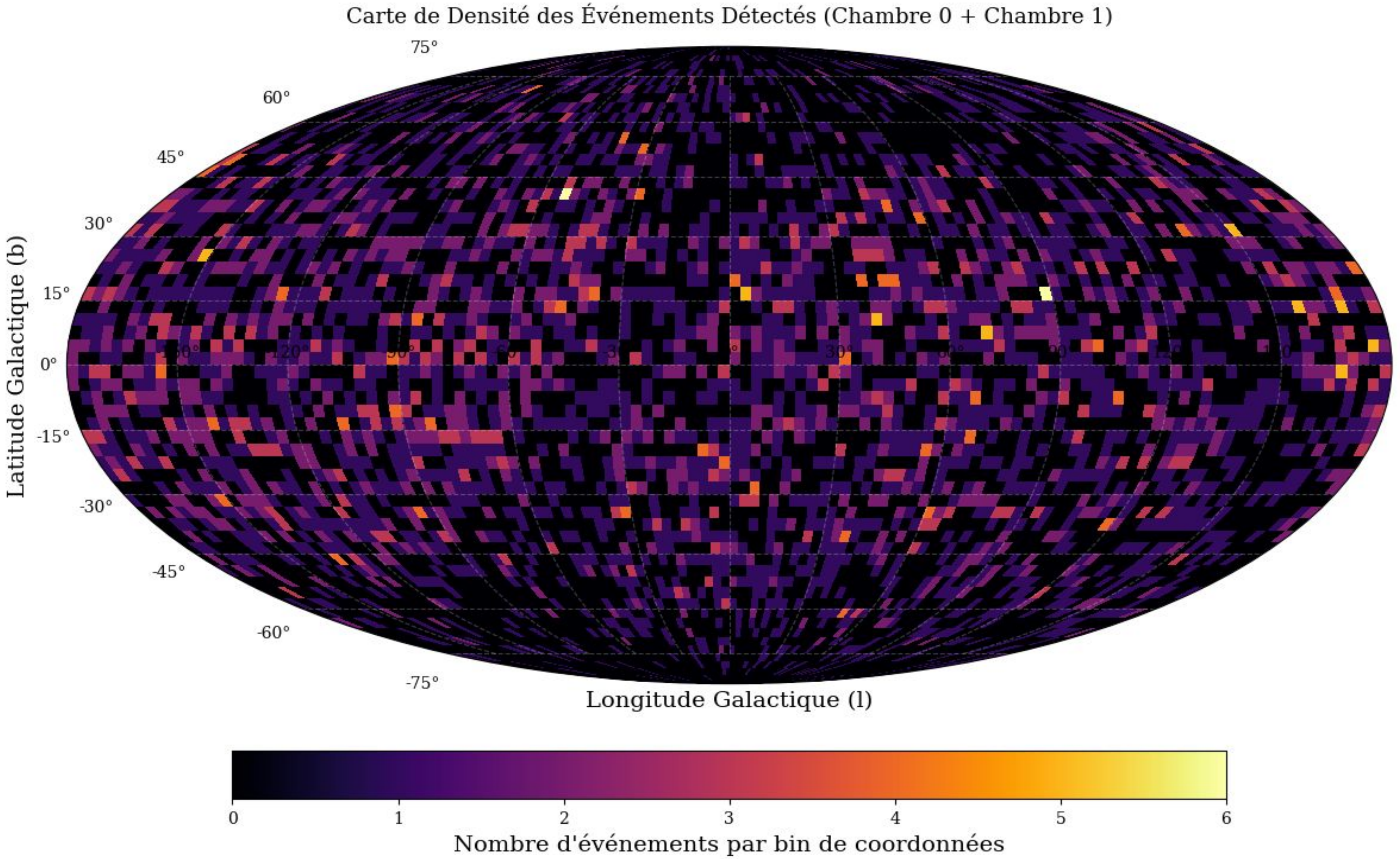
Summary of results

- Demonstrated the power of 3D track reconstruction in a gas TPC to reject background without heavy shielding.
- Established a spin-dependent cross-section limit of $\sigma < 10^{-35}$ cm^2 .

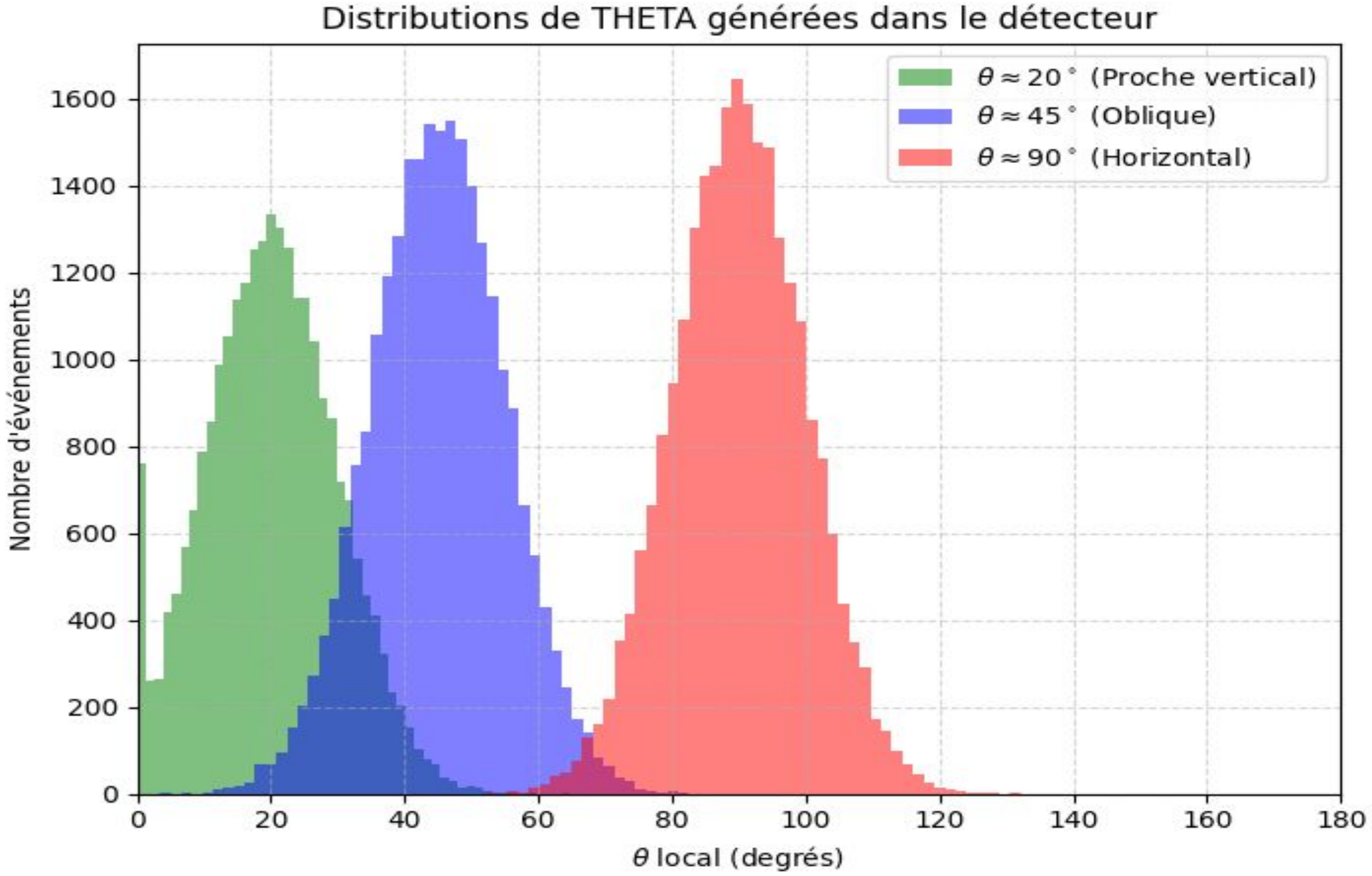
Future prospects

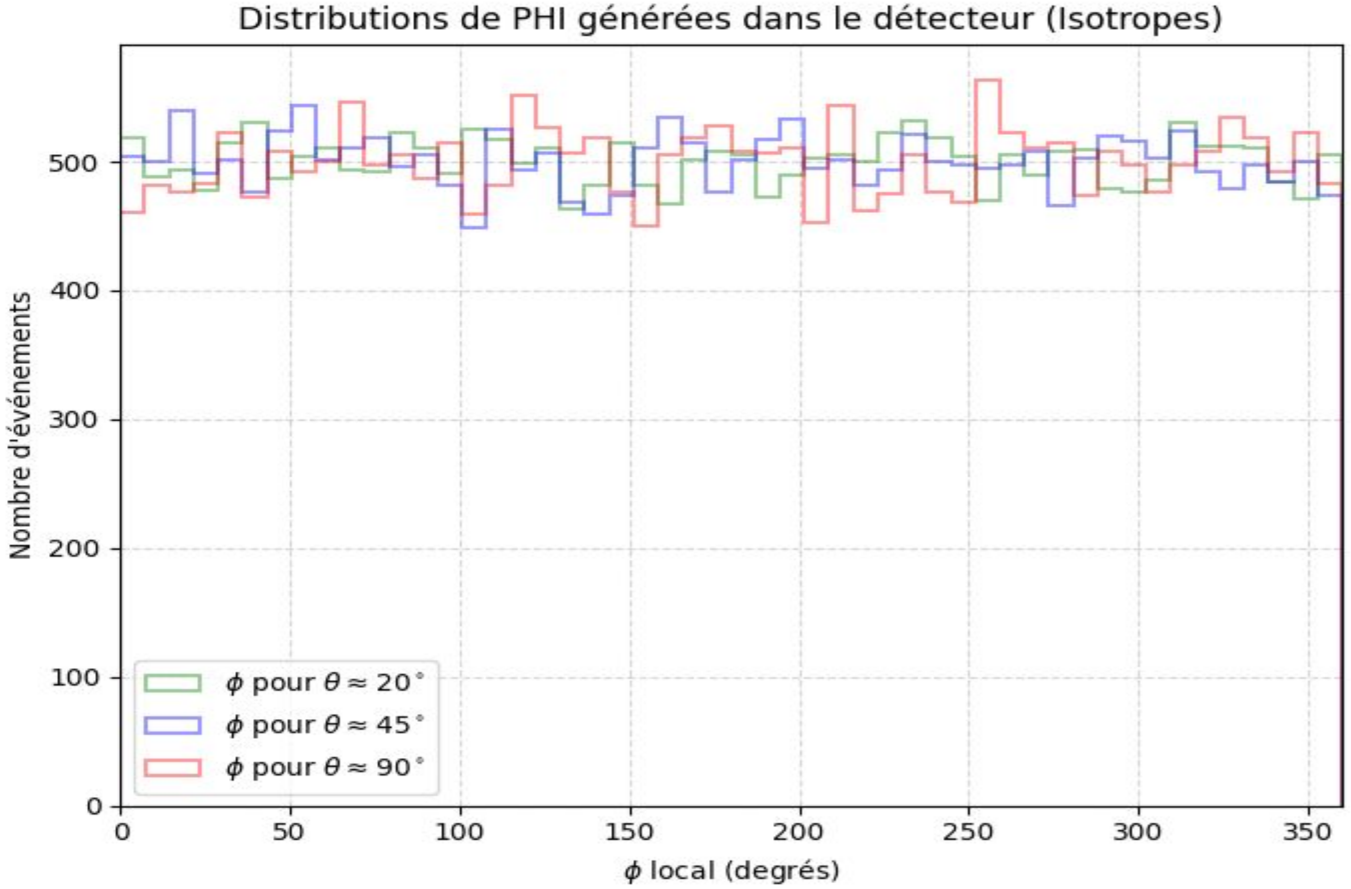
- Scaling up the active volume ($35\times35\times29$ cm^3) and lowering the energy threshold down to 300 eV to probe lighter WIMPs.
- Implementing detailed injection tests to precisely constrain:

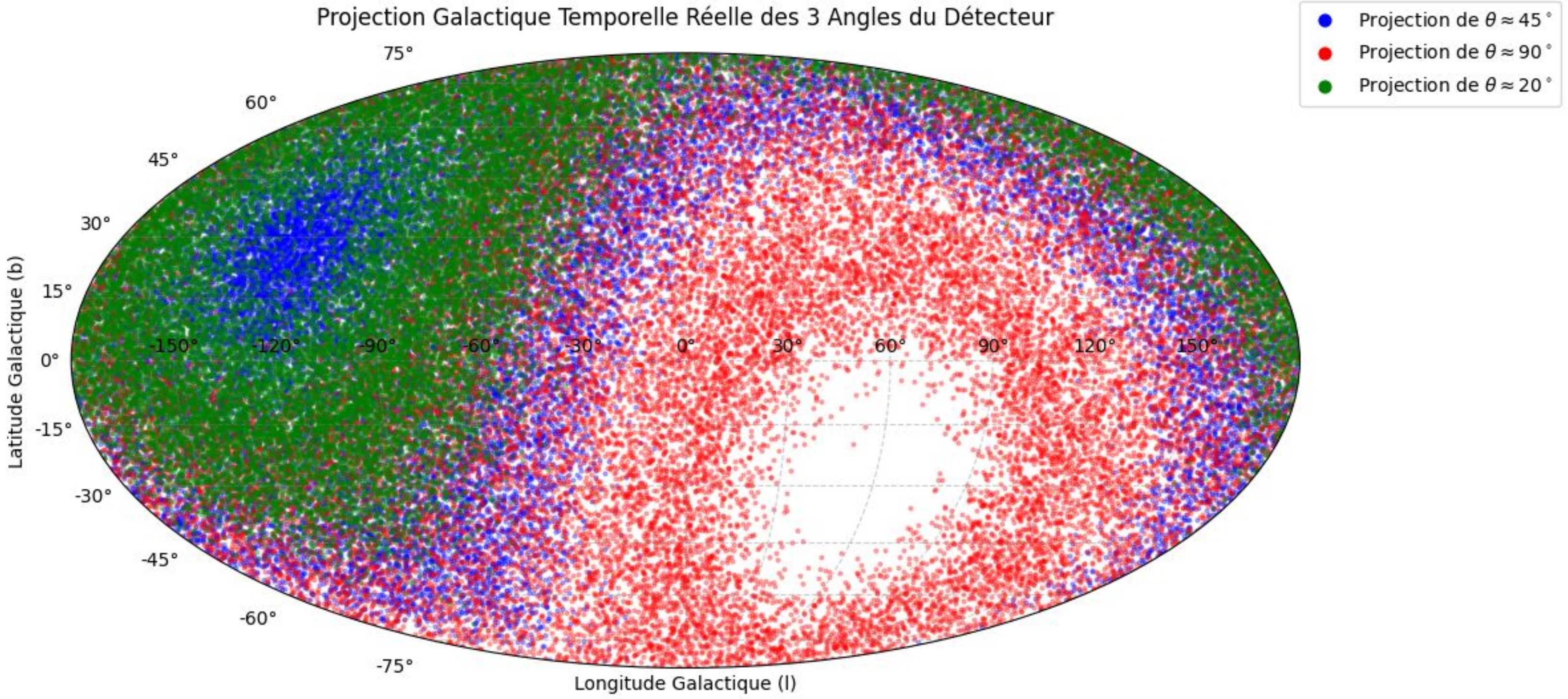
1. Quenching factor uncertainties.
2. Pressure and temperature drift effects.
3. BDT classifier systematic errors.

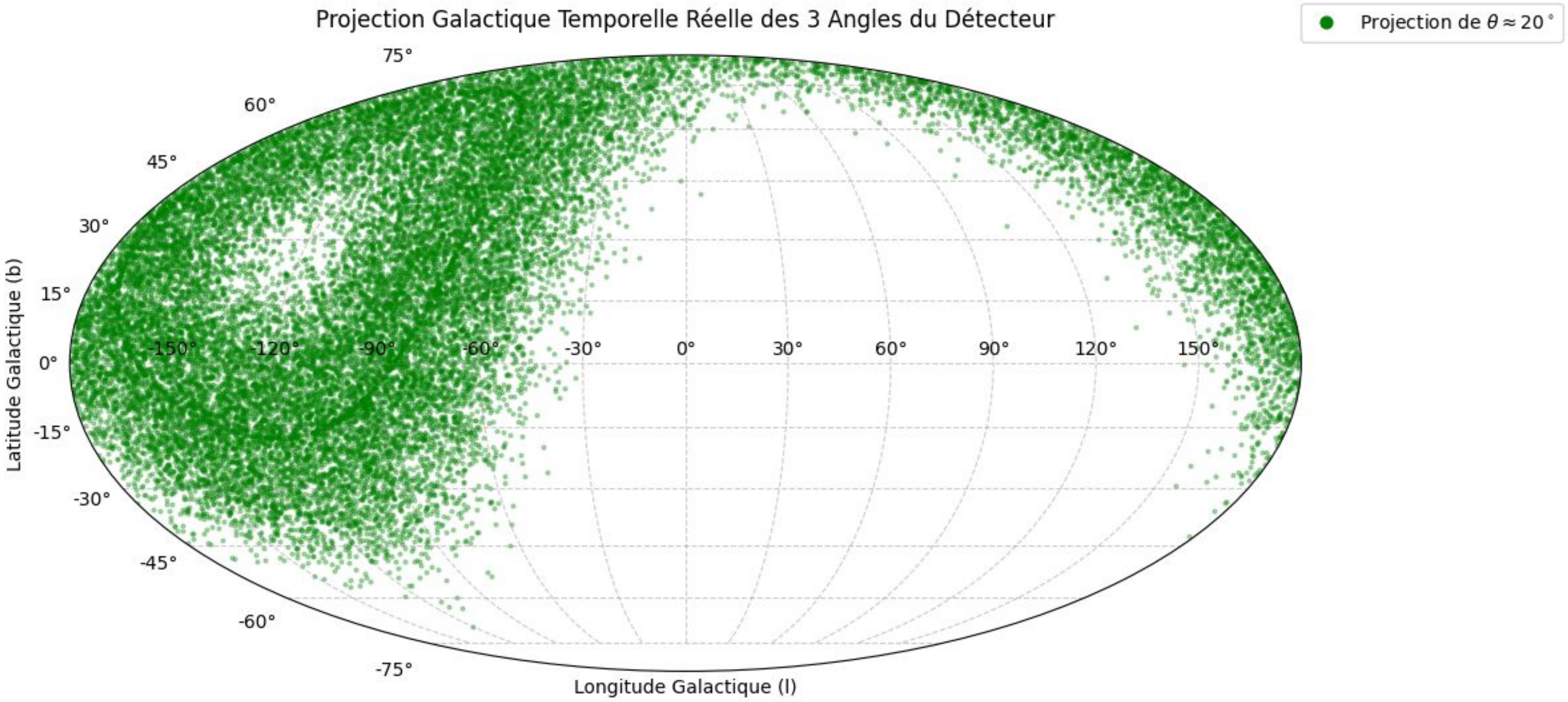


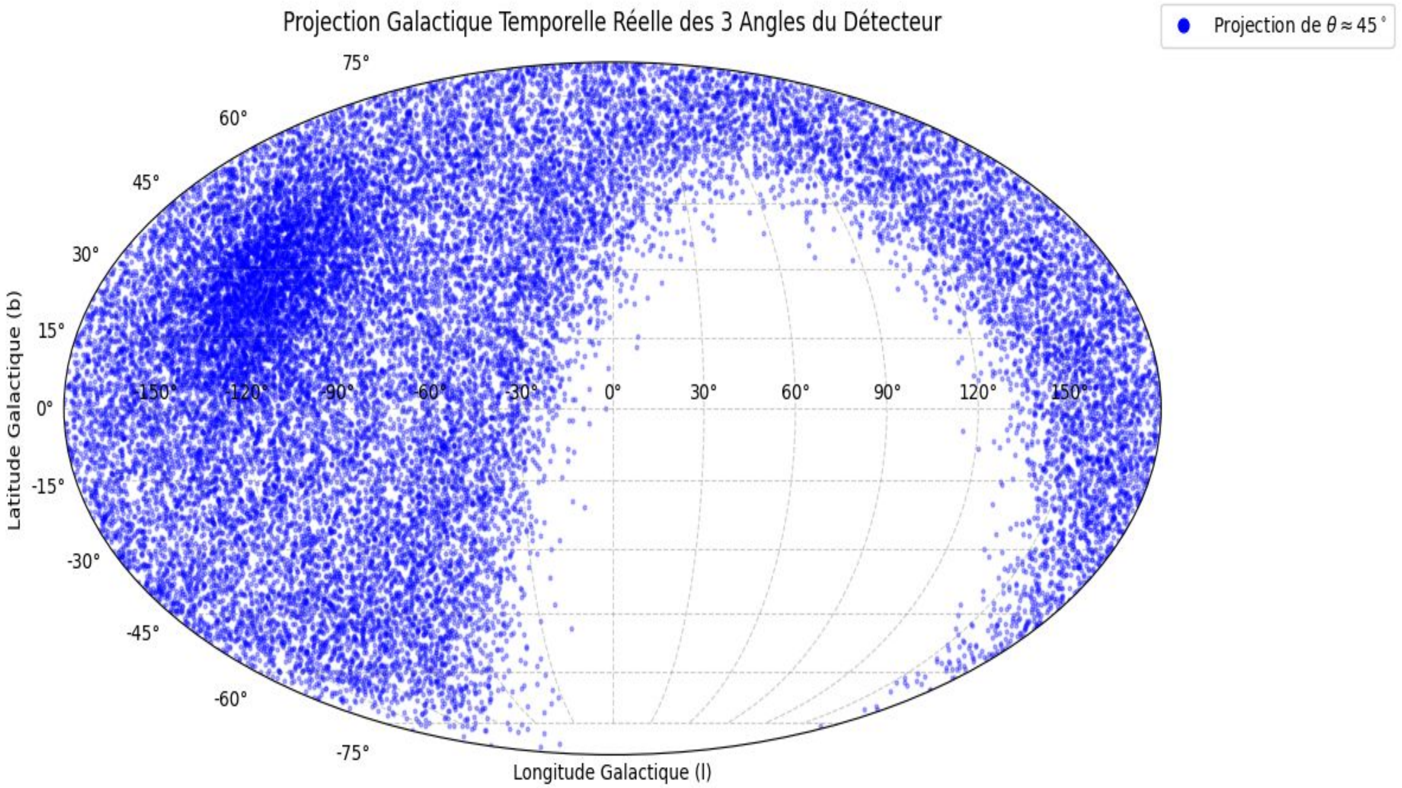
Carte de Densité des Événements Détectés (Chambre 0 + Chambre 1)
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
Latitude Galactique (b)
Longitude Galactique (l)
0
1
2
3
4
5
6
Nombre d'événements par bin de coordonnées

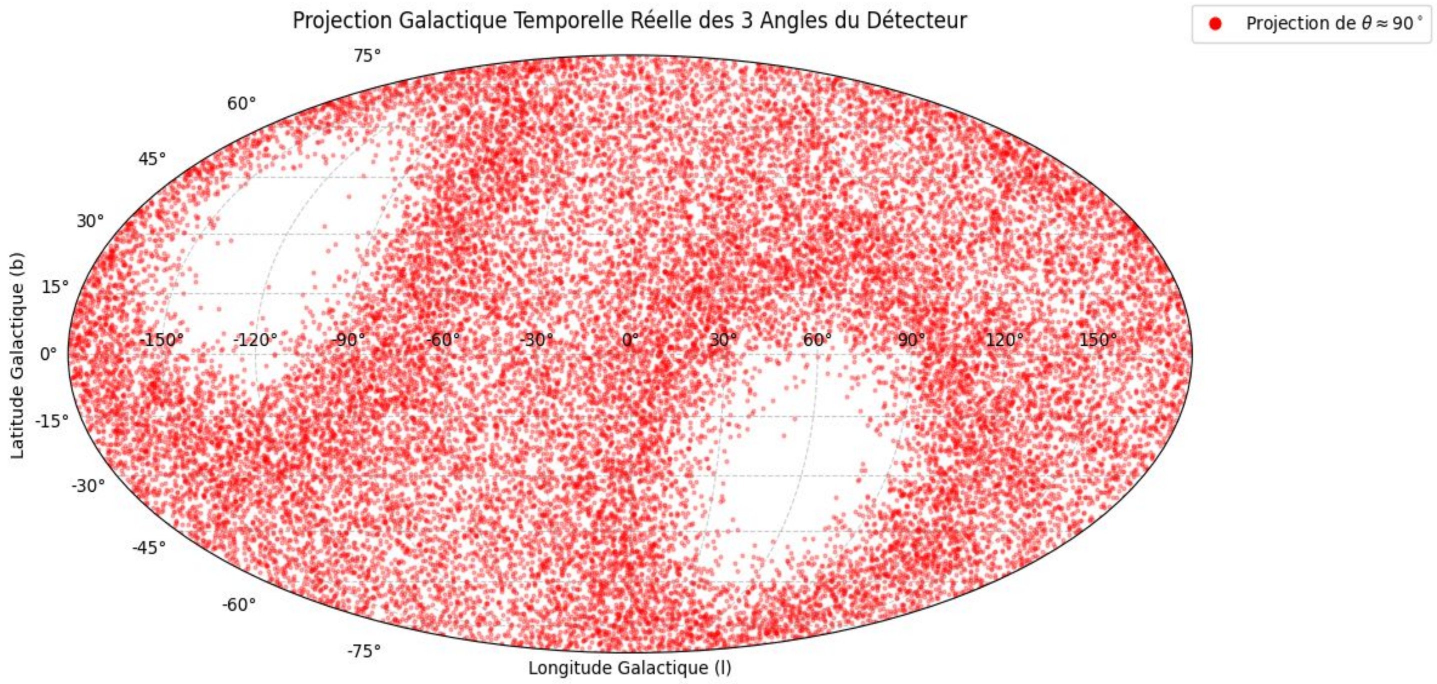

Distributions de THETA générées dans le détecteur
$\theta \approx 20^\circ$ (Proche vertical)
$\theta \approx 45^\circ$ (Oblique)
$\theta \approx 90^\circ$ (Horizontal)
Nombre d'événements
θ local (degrés)


Distributions de PHI générées dans le détecteur (Isotropes)
ϕ pour $\theta \approx 20^\circ$
ϕ pour $\theta \approx 45^\circ$
ϕ pour $\theta \approx 90^\circ$
Nombre d'événements
ϕ local (degrés)


Projection Galactique Temporelle Réelle des 3 Angles du Détecteur
Projection de $\theta \approx 45^\circ$
Projection de $\theta \approx 90^\circ$
Projection de $\theta \approx 20^\circ$
Latitude Galactique (b)
Longitude Galactique (l)


Projection Galactique Temporelle Réelle des 3 Angles du Détecteur
Projection de $\theta \approx 20^\circ$
Latitude Galactique (b)
Longitude Galactique (l)
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
-150° -120° -90° -60° -30° 0° 30° 60° 90° 120° 150°


Projection Galactique Temporelle Réelle des 3 Angles du Détecteur
Projection de $\theta \approx 45^\circ$
Latitude Galactique (b)
Longitude Galactique (l)
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
-150° -120° -90° -60° -30° 0° 30° 60° 90° 120° 150°


Projection Galactique Temporelle Réelle des 3 Angles du Détecteur
Projection de $\theta \approx 90^\circ$
Latitude Galactique (b)
Longitude Galactique (l)
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
-150° -120° -90° -60° -30° 0° 30° 60° 90° 120° 150°

We assume the number of events in the Source (ON) and Background (OFF) regions follow Poisson distributions:

ON Region:

Non~Poisson(S+αB)

OFF Region:

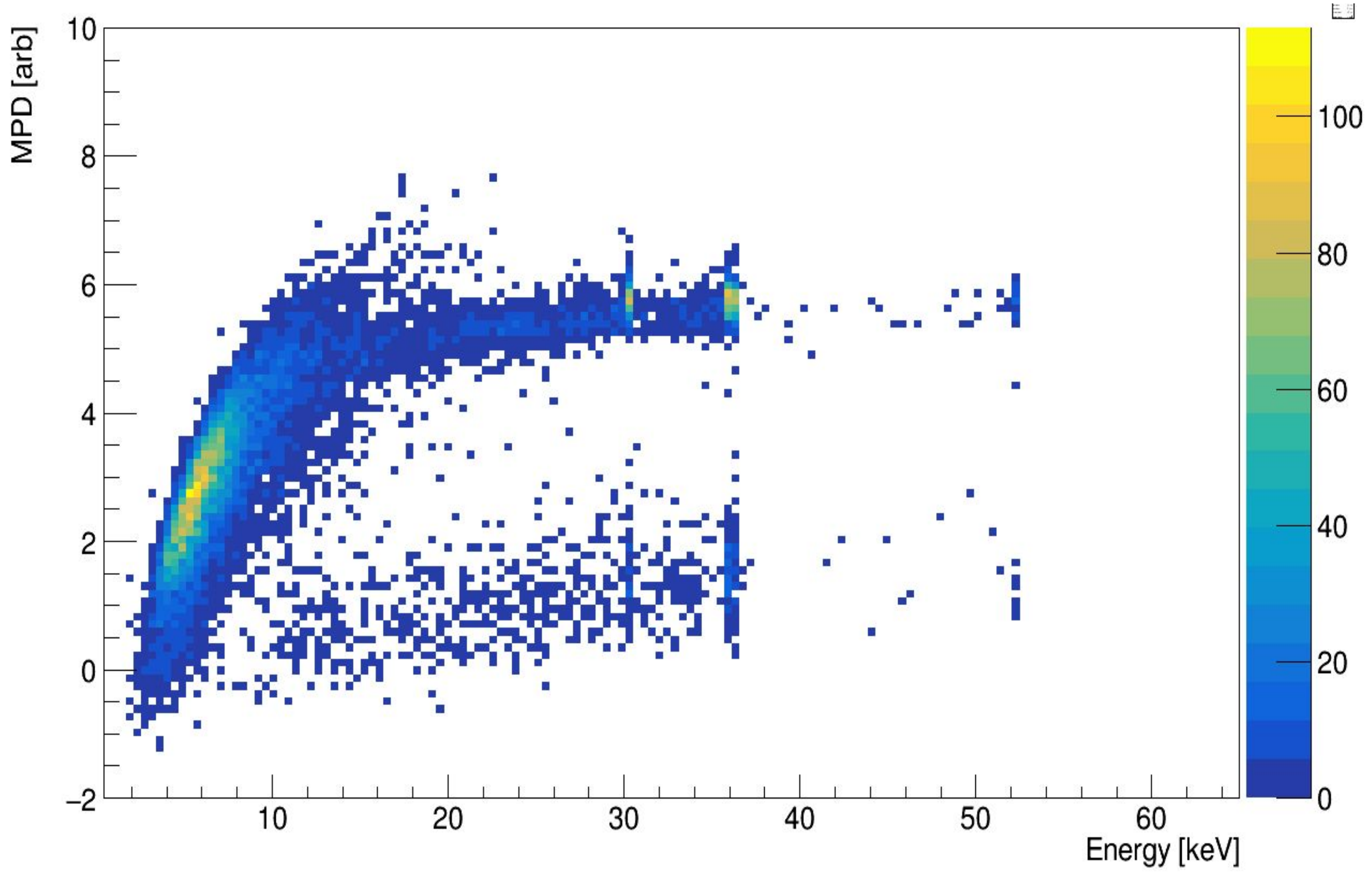
Noff~Poisson(B)

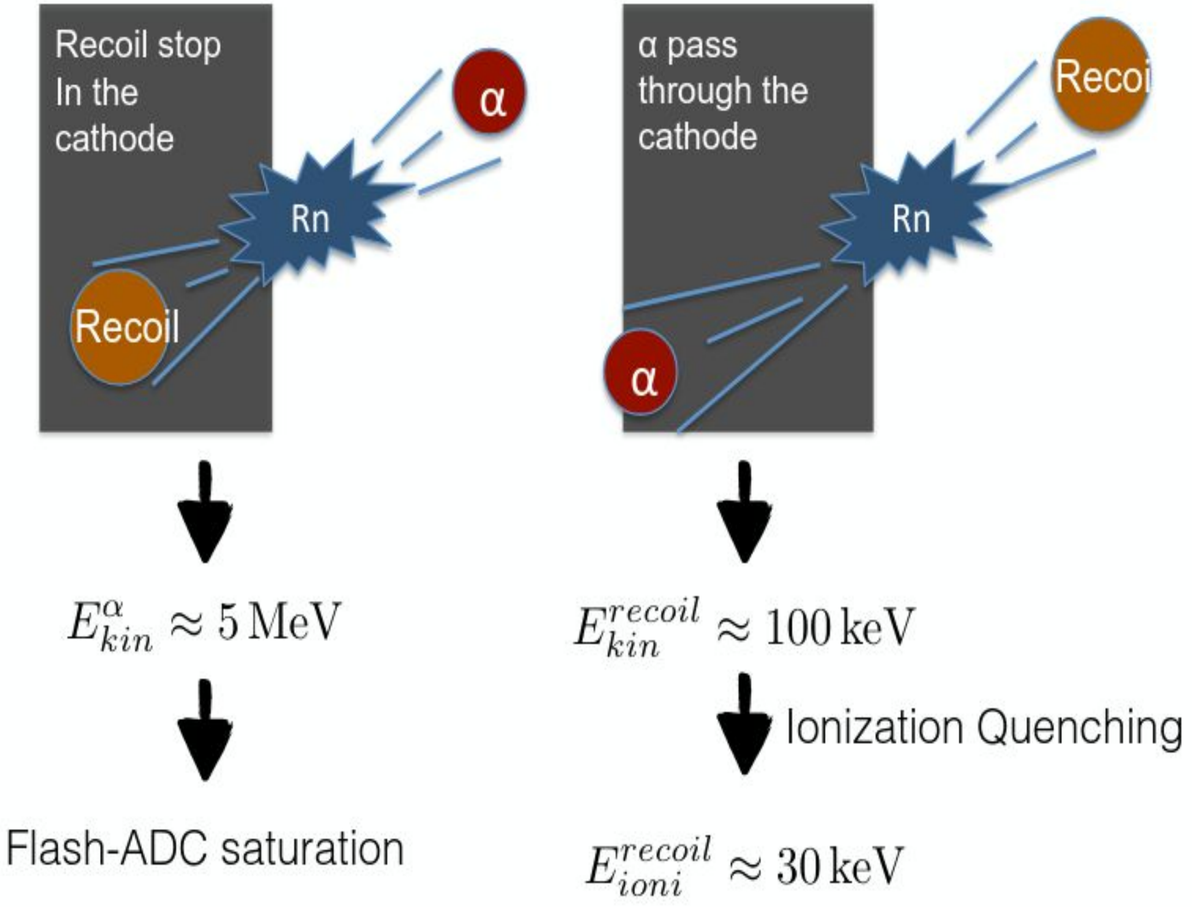
To find the best estimates for S and B, we maximize the joint likelihood:

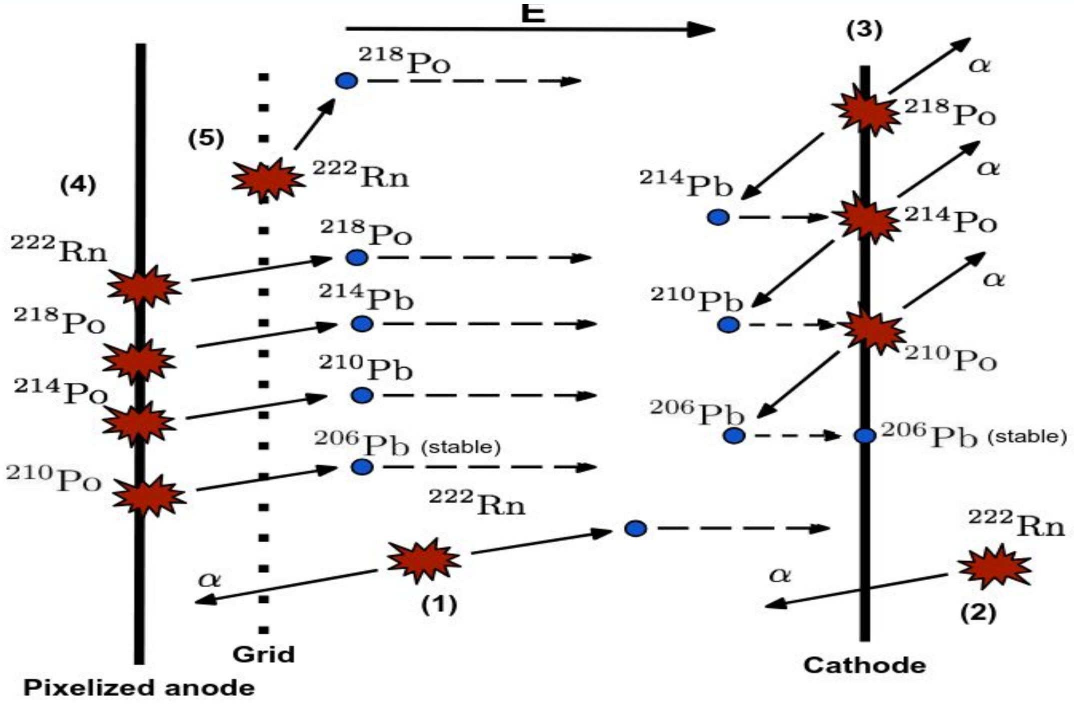
$$\mathcal{L}(S,B) = \frac{(S+\alpha B)^{N_{on}} e^{-(S+\alpha B)}}{N_{on}!} \times \frac{B^{N_{off}} e^{-B}}{N_{off}!}$$

Radon progeny events

$$MPD = \log\left(\overline{\Delta X} \times \overline{\Delta Y}\right)$$







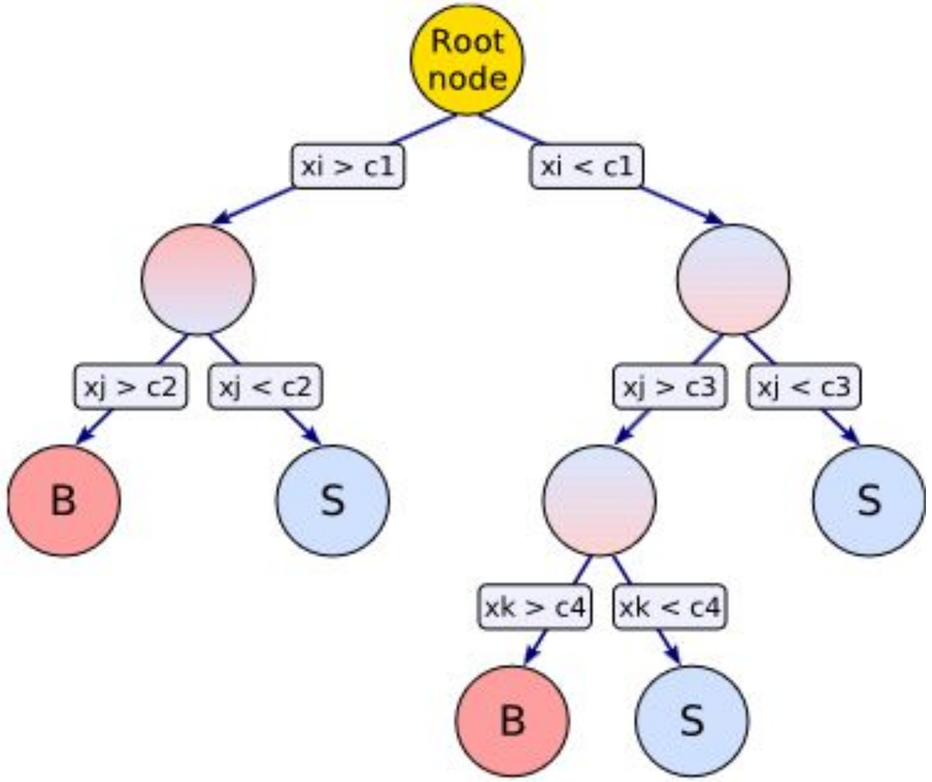
BDT : Boosted decision Tree

What is a decision tree?

It consists of defining cuts on subsets of the data,

applying these cuts sequentially,

and classifying events as signal or background



By combining multiple decision trees statistically, one can compute a weighted average and achieve better classification performance (BDT score).

$$\text{Score\_BDT}(x_{\text{event}}) = \sum (\alpha_m \cdot \text{prediction}_m(x_{\text{event}}))$$

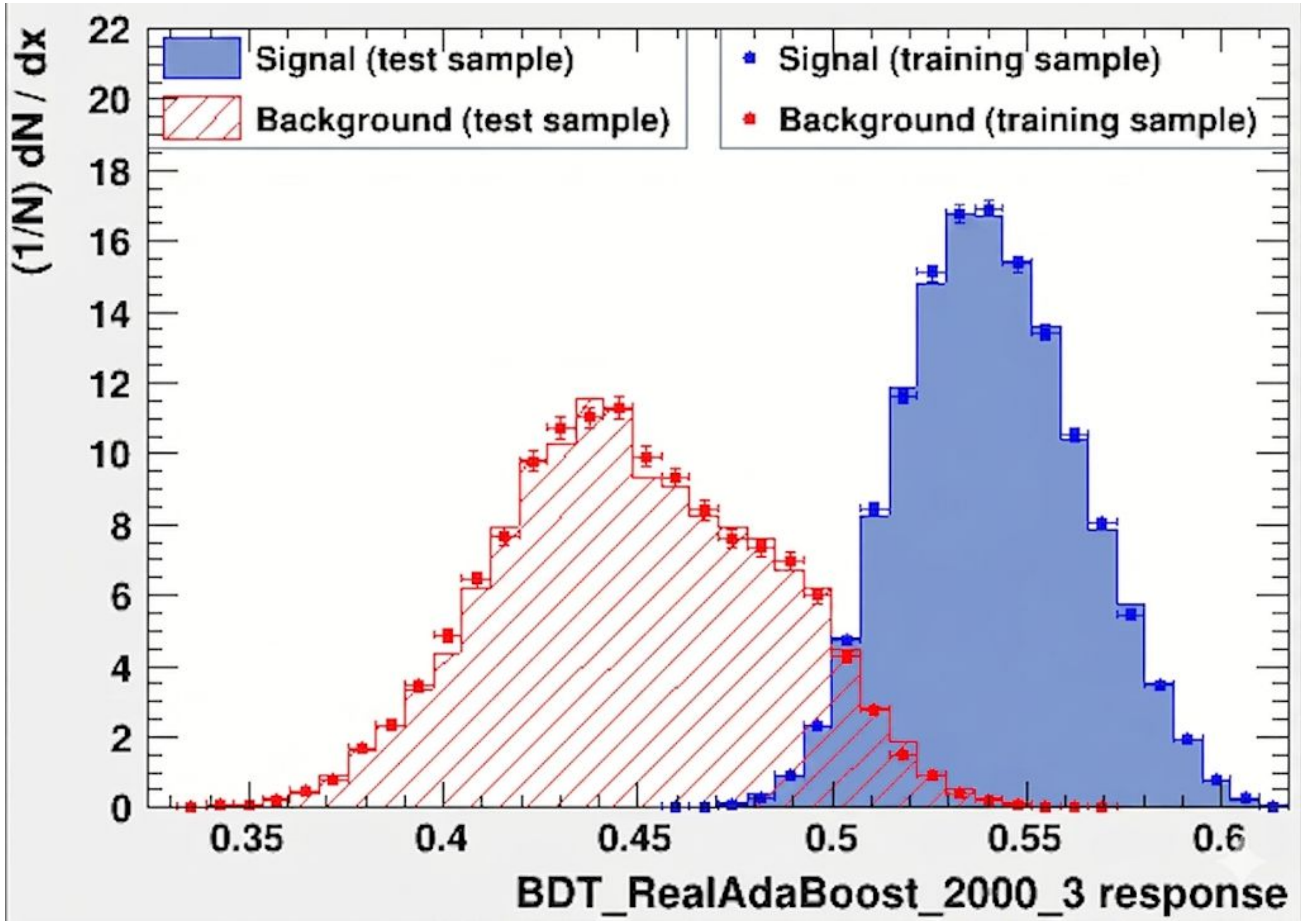
Boosted Decision Tree (BDT)

Method

Statistical combination of several decision trees for improved classification. Sequential application of cuts over 495 days of data.

BDT variables

- Number of TimeSlices > 2
- Track length
- Number of pixels / Energy
- Number of peaks
- Track width



$$Score_{BDT} = \sum(\alpha_m \quad prediction_m)$$