Directional Detection of Dark Matter

WIMPs with MIMAC and Dark Photons with Dandelion

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GRENOBLE | MODANE

1

Dandelion : DArk photoN DirEctionaL detectION

- Dark photons (1 meV)
- Experimental principle : the conversion of dark photons into ordinary photons
- Analysis and results

2

MIMAC : MIcro-tpc MAtrix of Chambers

- WIMPs : Weakly interacting massive particles (1 GeV)
- Experimental principle : The measurement of nuclear recoils and their direction
- Analysis and results

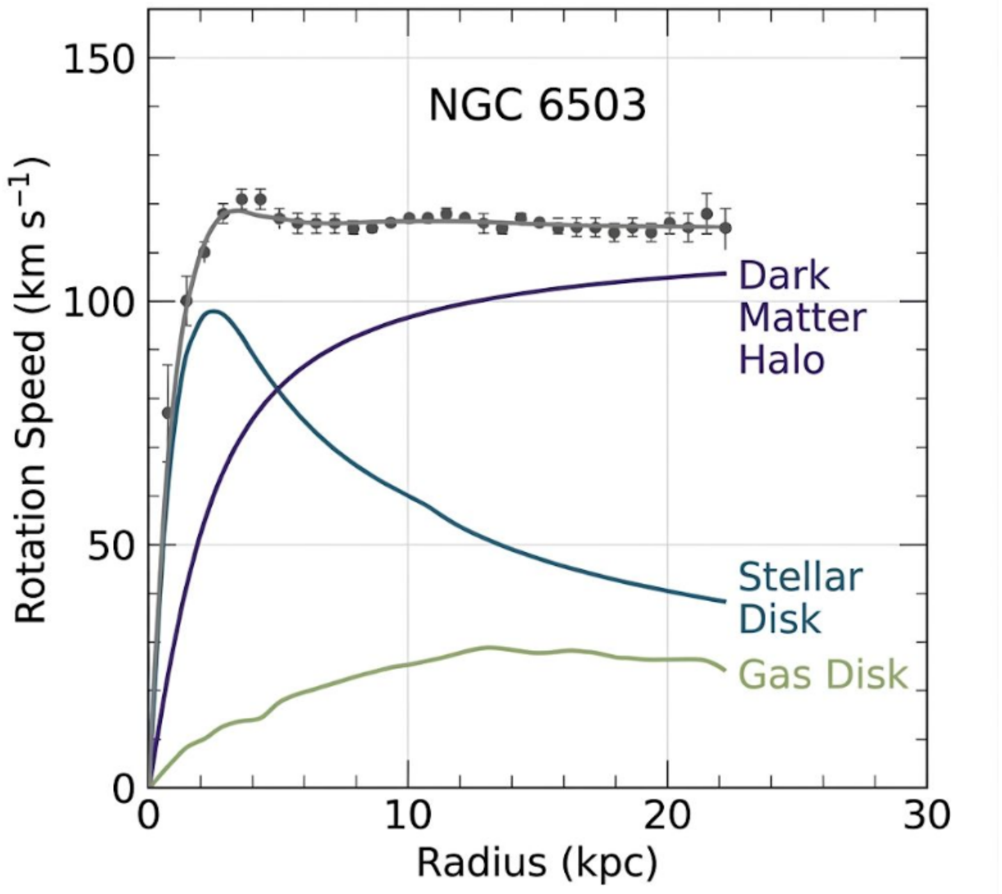
3

Conclusion

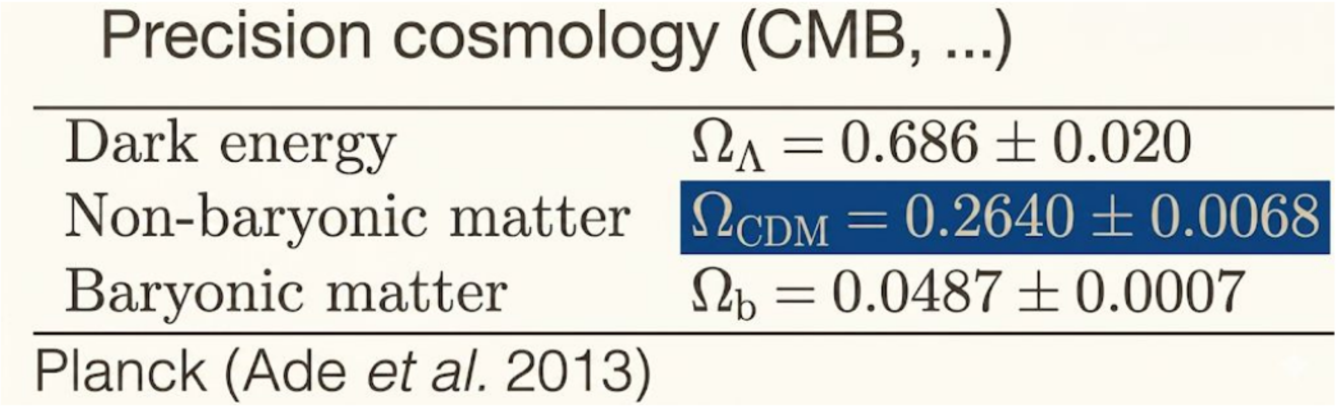
Motivation: Dark Matter

Small Scales: galaxy rotation curves

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



Big Scales :



Precision cosmology (CMB, ...)

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

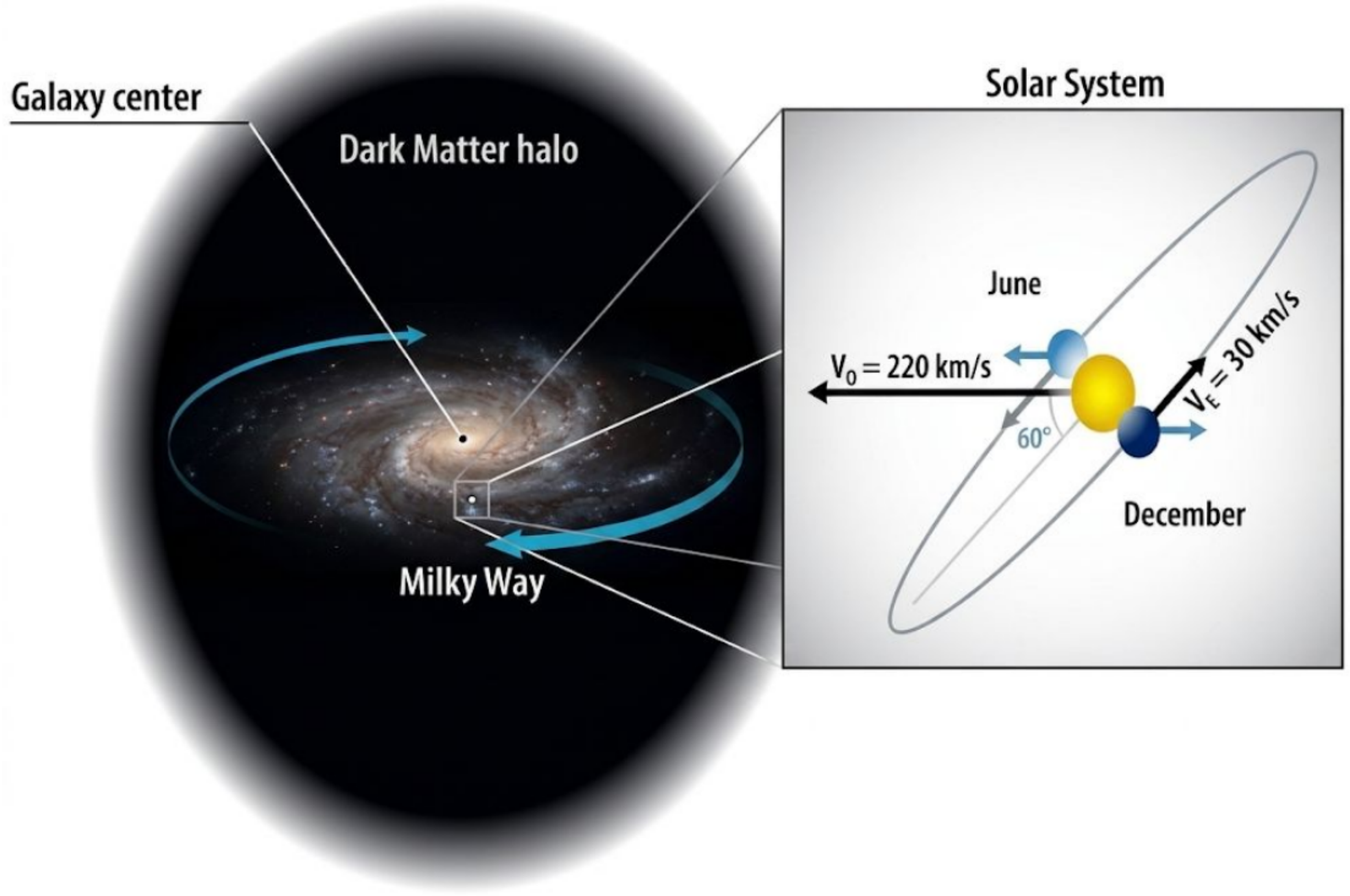
Planck (Ade *et al.* 2013)

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

Motivation: Directional Detection

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

The movement of the Sun creates a **wind of dark matter** .



Dark Photon Signature (Dandelion) : The signature is the trajectory of the signal in the detector's frame of reference.

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

Dandelion: Dark Photons

Dark Photon

- New massive spin-1 gauge boson
- associated with a broken U(1)' symmetry of the dark sector.

Kinetic Mixing

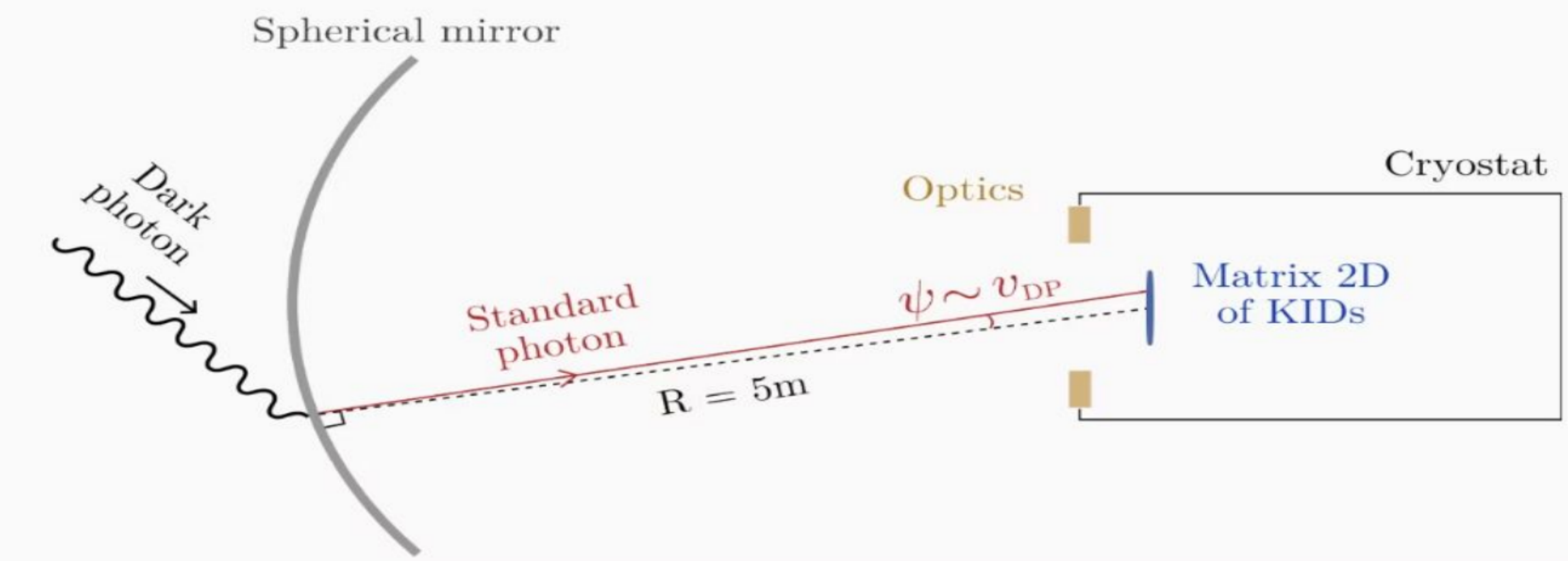
- Vector portal to the dark sector.
- Conversion of dark photons to ordinary photons.

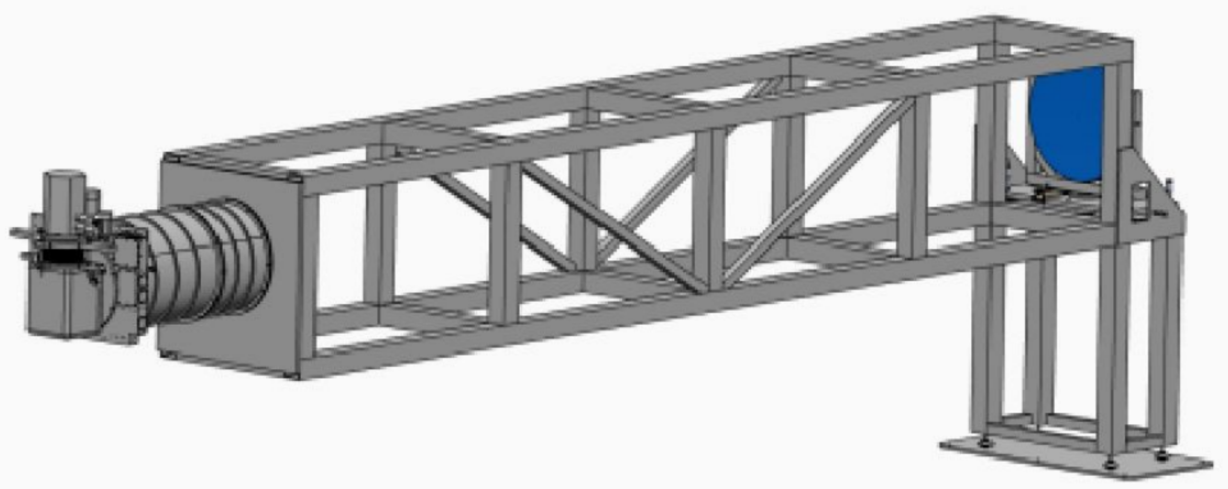
$$\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{\chi}{2}F_{\mu\nu}X^{\mu\nu} + \frac{1}{2}m_X^2 X_\mu X^\mu + eJ_\mu^{em}A^\mu$$

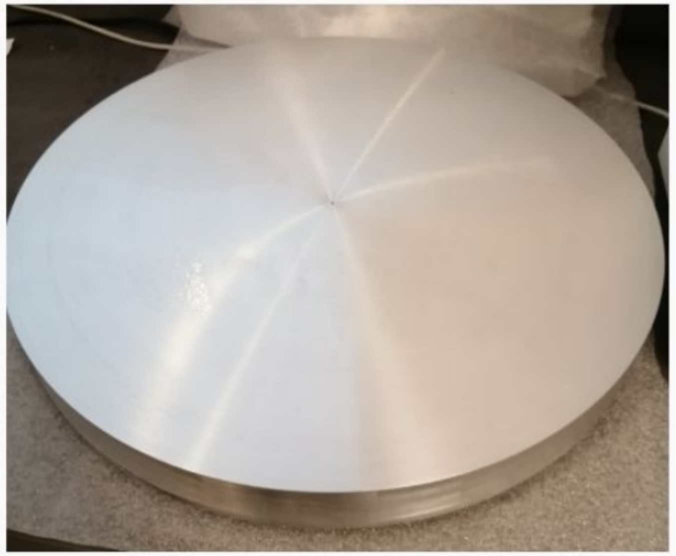
Dandelion Experiment: Setup

Configuration

- Spherical mirror: R = 5 m, aperture 25 cm
- KID Detector (221 pixels)
- 150 mK cryostat
- Duration: 24 hours 50 minutes
- Optical system: 3 lenses
- Location and date: January 11, 2024 , LPSC







Picture of the mirror

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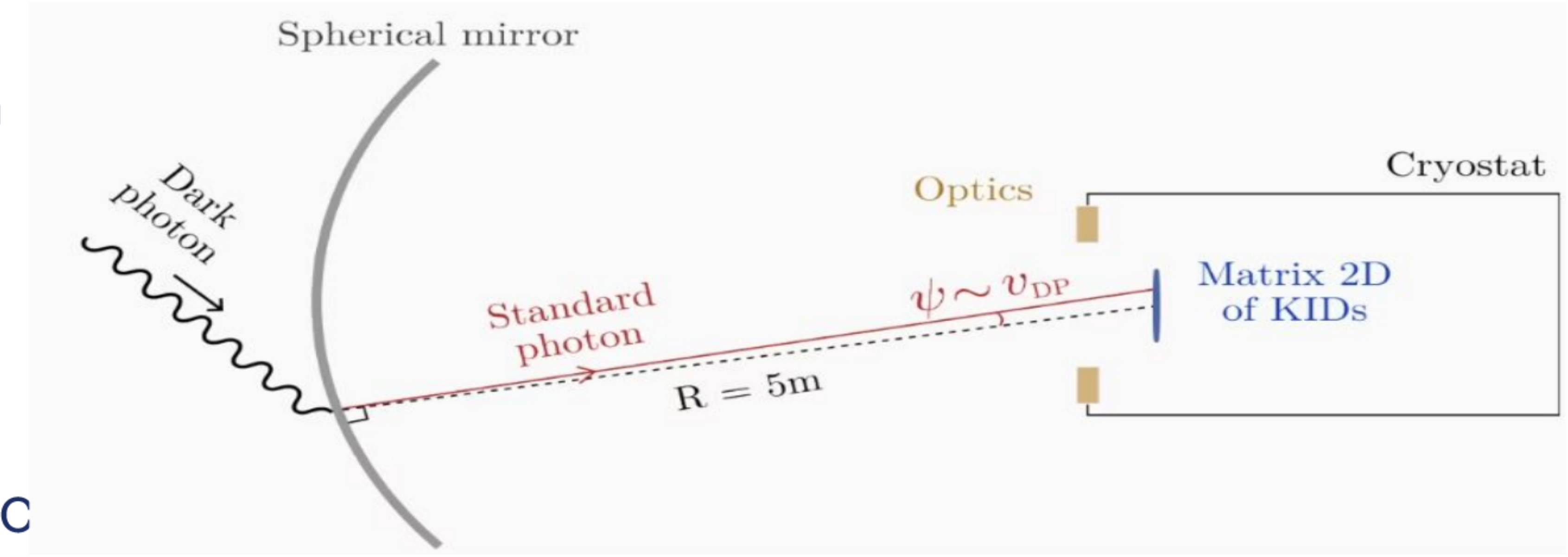
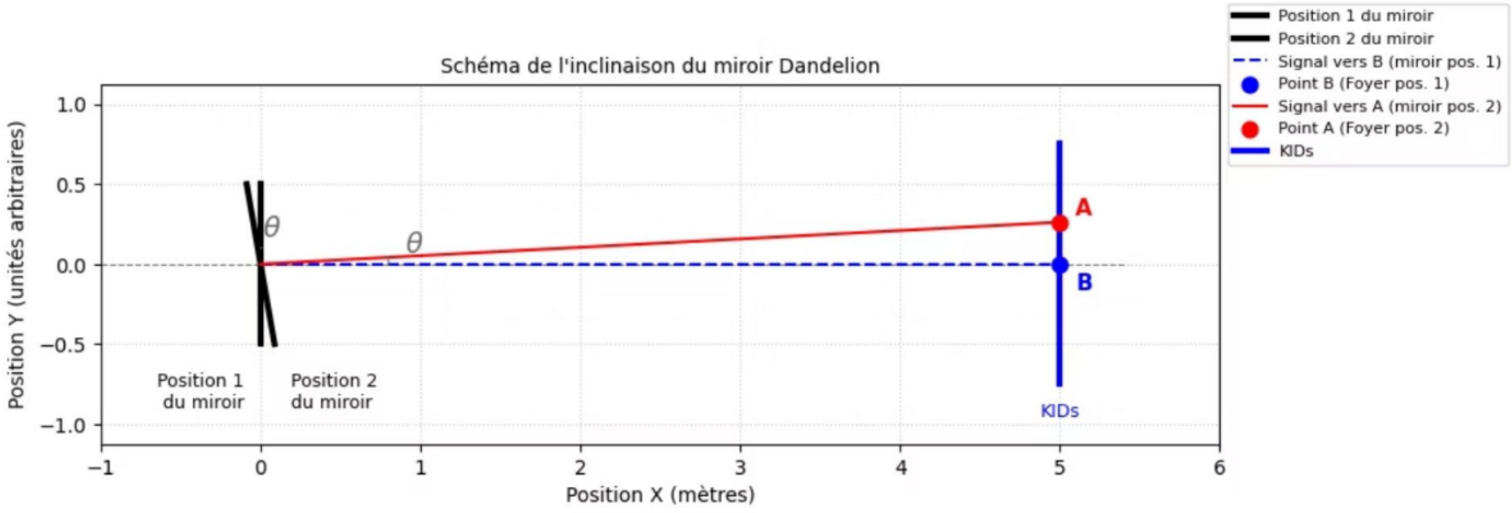
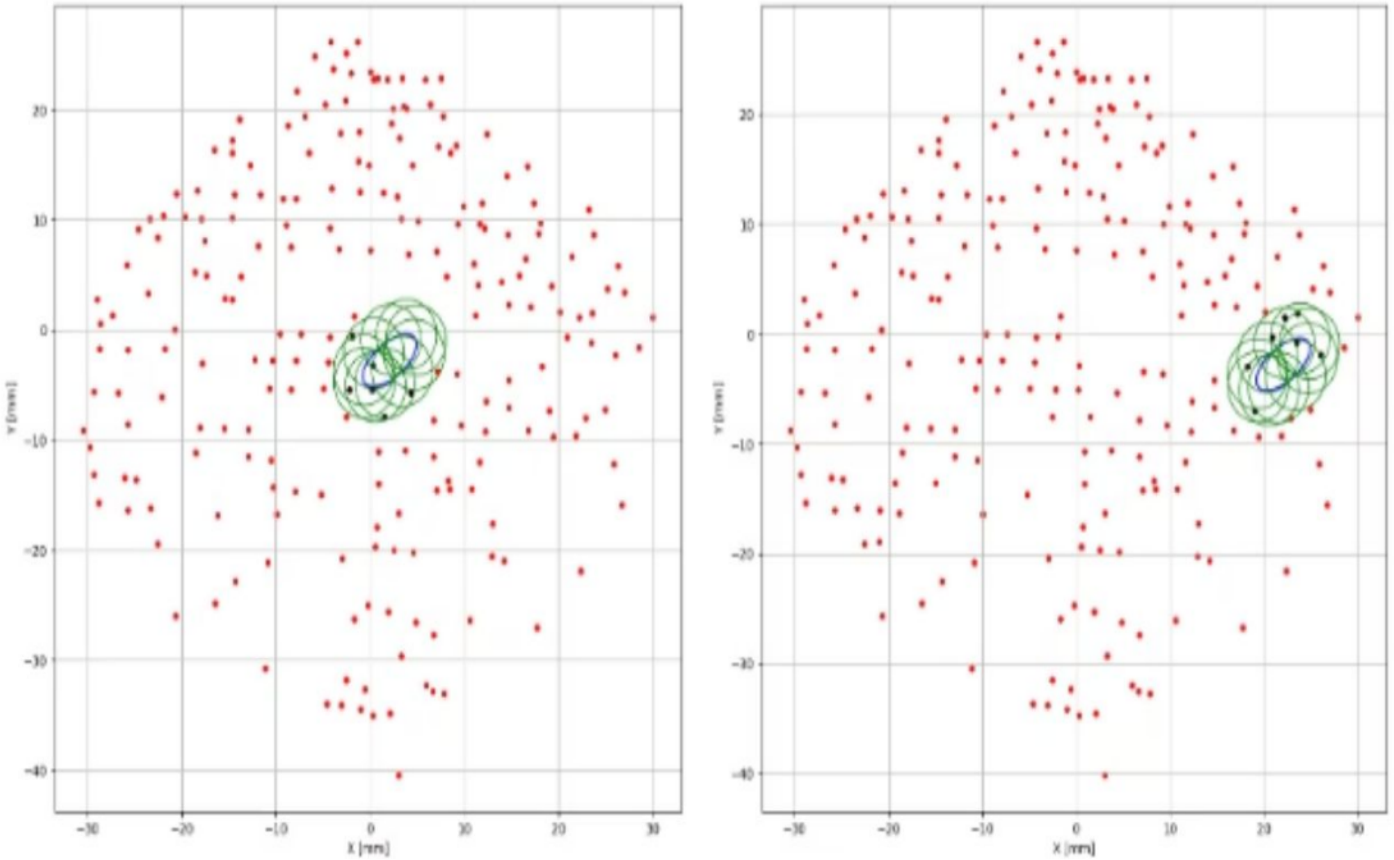


Method

The mirror is tilted at 5 mrad at 1 Hz around its vertical axis. The measured power depends on the kinetic coupling:

$$P = \chi^2 \rho_{CDM}\, \eta A_{mirr}\, I(x,y,t) \cos^2 \alpha(t)$$





Data analysis and exclusion curve

Signal measurement and trajectory

During the measurement, the temperature shift corresponding to the energy absorbed by the pixels during the 24 hours is recorded.

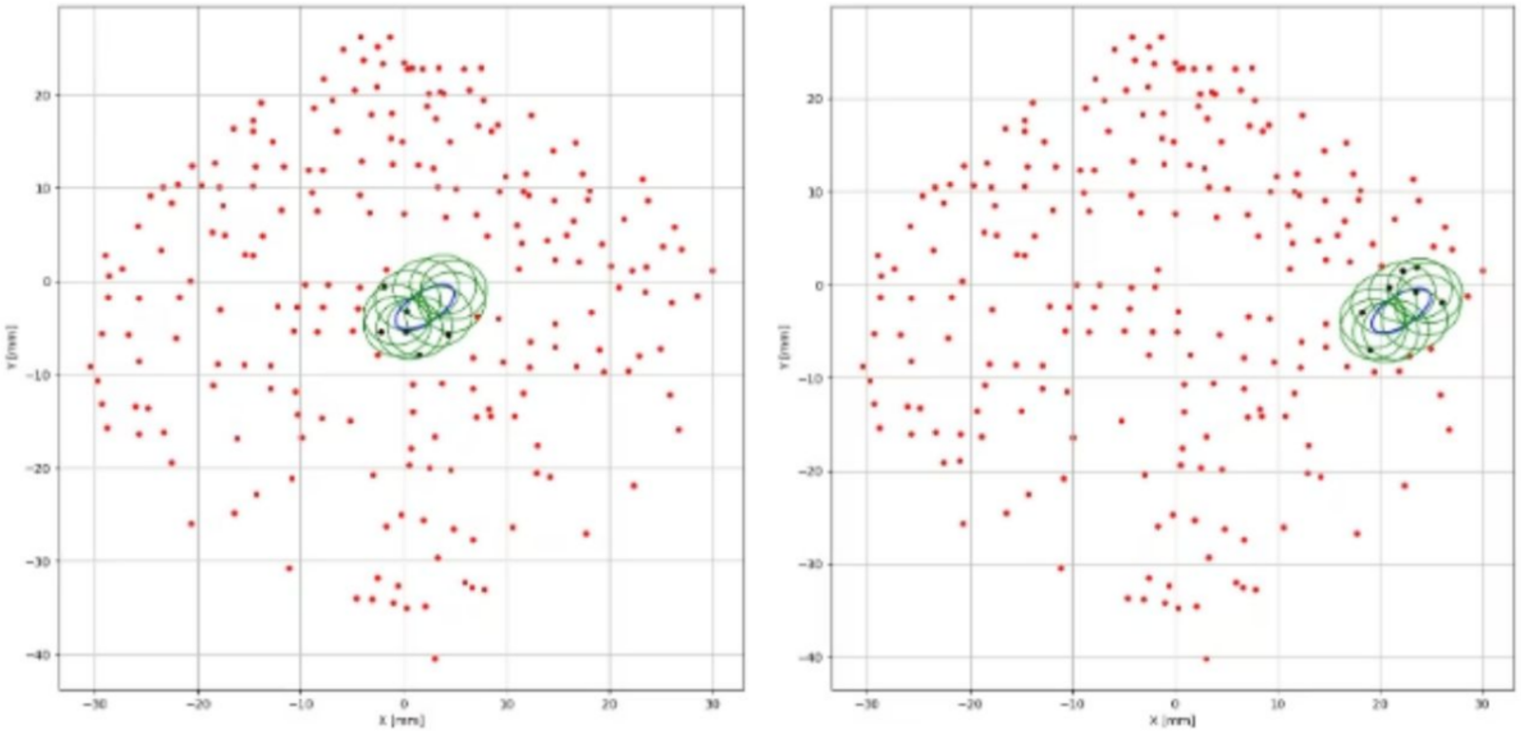
In BLUE : the trajectory in each position

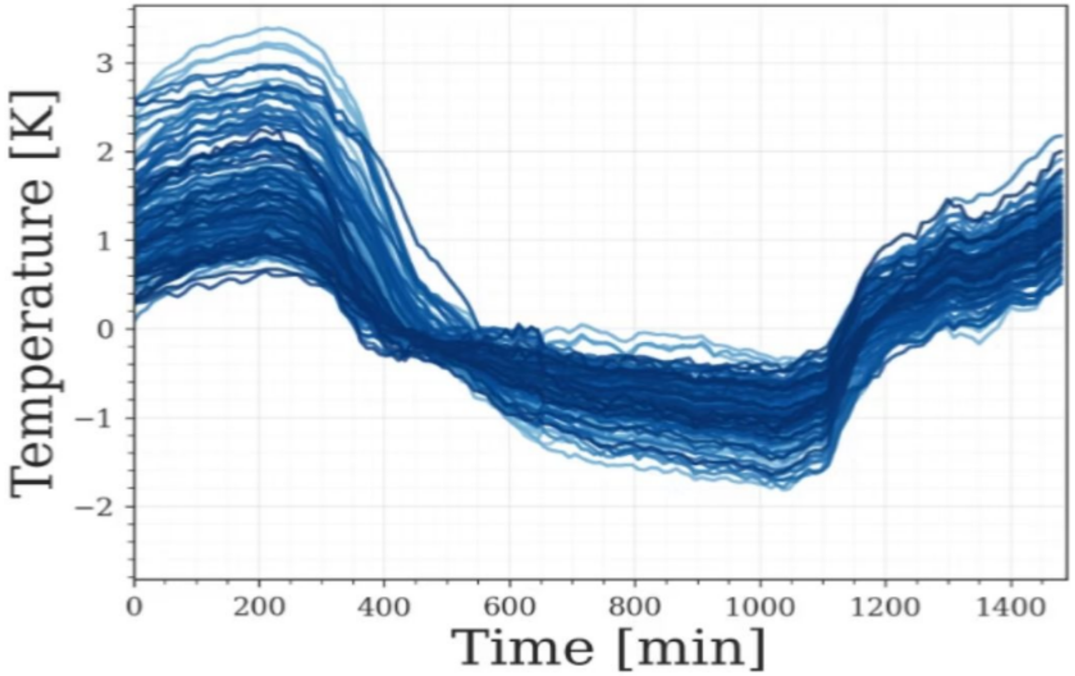
In BLACK : the pixels that see the signal

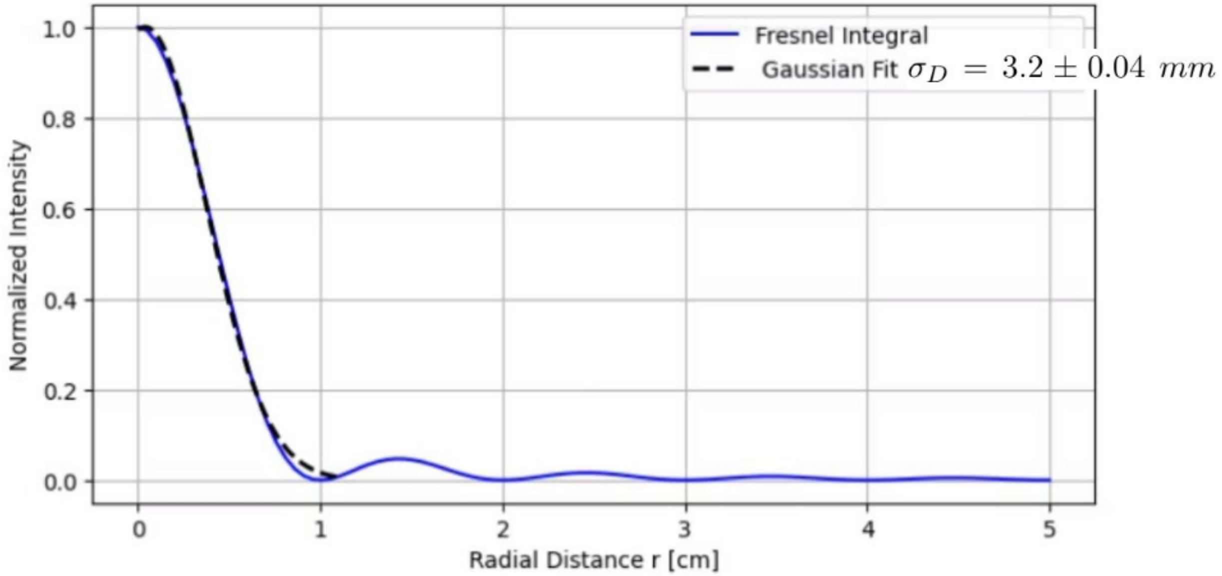
In RED : the pixels that see the background

In GREEN : the diffraction spot ring that travels the entire trajectory over 24 hours

$$I(x(t), y(t)) = \exp\left(-\frac{1}{2\sigma_{\text{tot}}^2}\left(x(t)^2 + y(t)^2\right)\right)$$







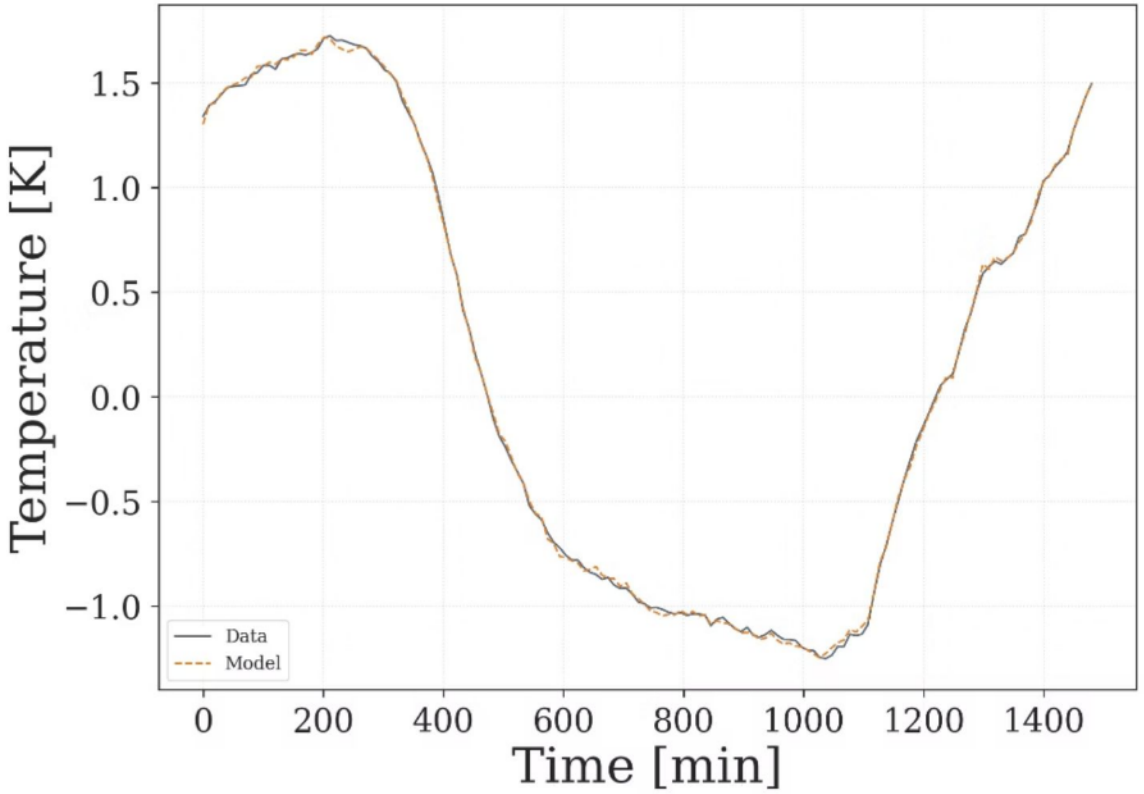
Background Noise Modeling

Background noise

- Uniform background noise across all pixels
- The signal is masked by a dominant background noise

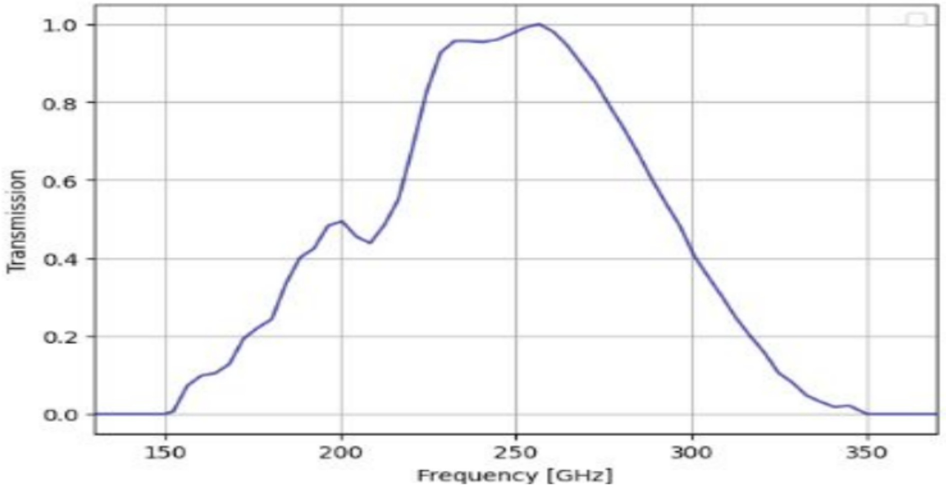
  Contributions to the background:
- Thermal emission of the mirror (300 K),
- Emissivity of the 3 lenses (300 K, 4 K, 150 mK)
- electronic noise and stray light
- Room temperature

$$T_k^{traj}(t) = b_k + \sum_{i=1}^{N_{sys}} a_{k,i} \cdot T_i^{\text{syst}}(t) + T_{\text{S}} \cdot \exp\left(-\frac{(x(t)-x_k)^2 + (y(t)-y_k)^2}{2\sigma_D^2}\right)$$



Final result

We are exploring dark photon masses between 0.6 meV and 1.4 meV.



Final result and summary

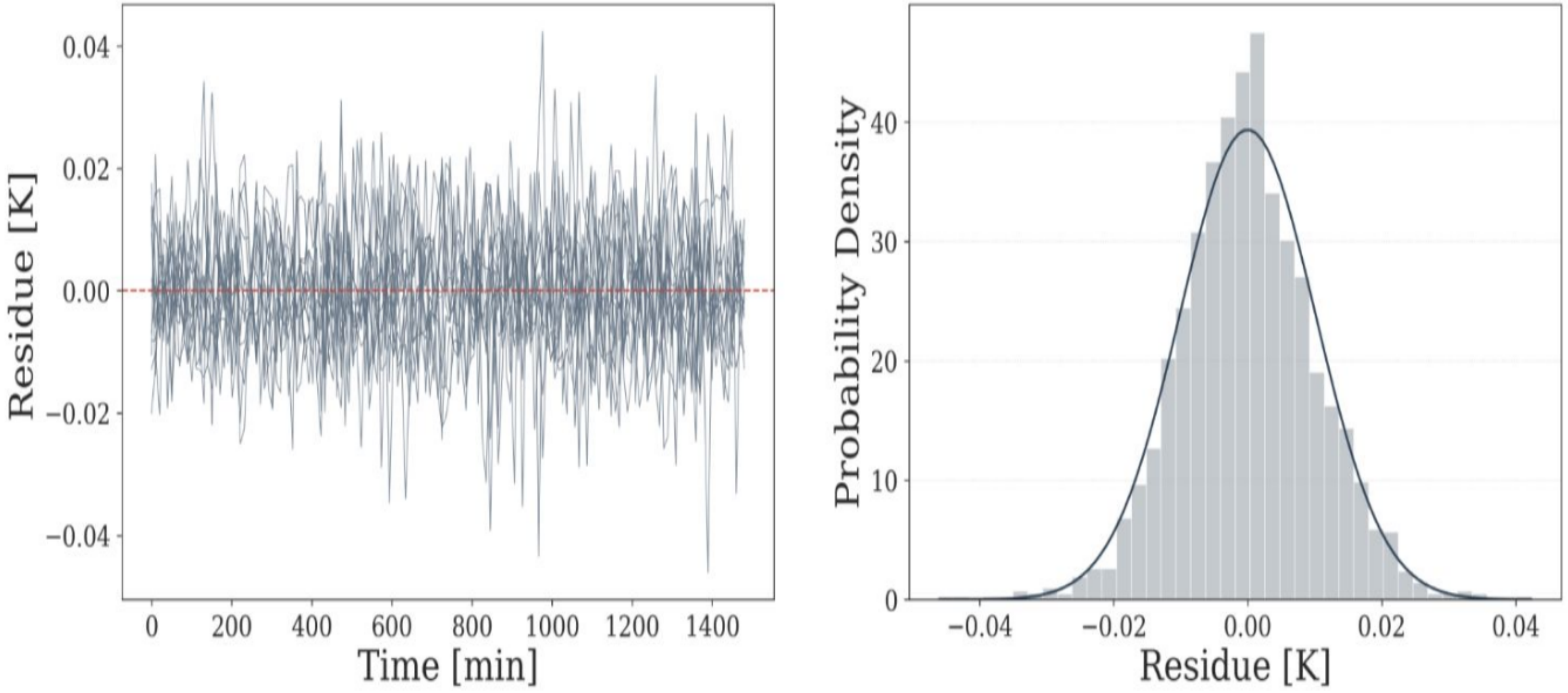
Final result:

$$T_{\text{signal}} = 0 \pm 6 \text{ mK}$$

$$\Delta T_{\text{upper-limit}} = 12 \text{ mK}$$

$$\chi = \sqrt{\frac{A_{\text{power}}}{\rho_{\text{CDM}} \cdot A_{\text{mirror}} \cdot \frac{2}{3} \cdot c \cdot \langle \eta(\nu) \rangle}}$$

$$\chi < 8.7 \times 10^{-10}$$



Final result and exclusion curve

Final result and summary

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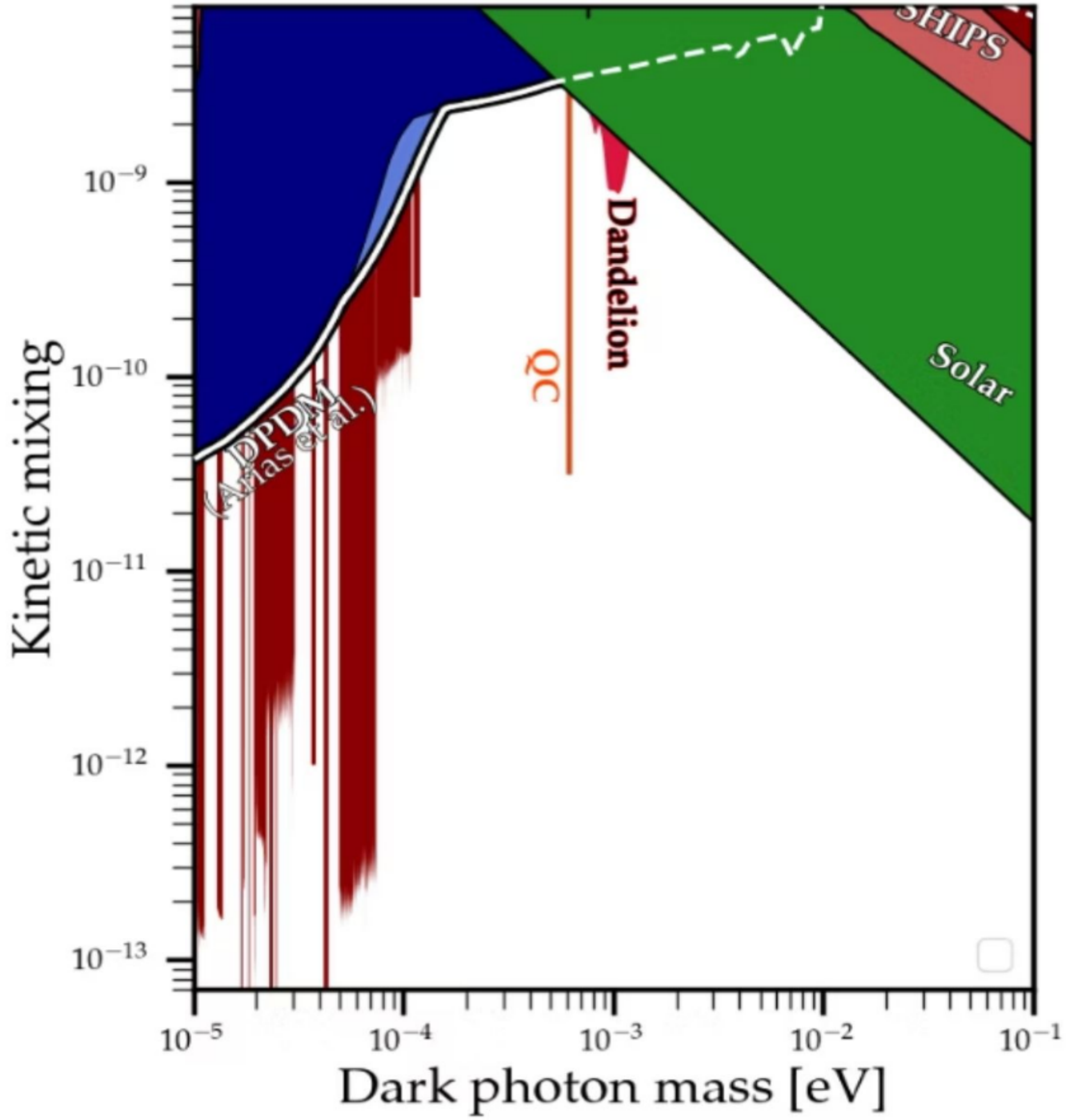


I. Ourahou, S. Savorgnano, C. Beaufort, M. Bastero-Gil, J. Bounmy, A. Catalano, J. Macias-Perez, D. Santos, C. Smith, F. Naraghi, D. Tourres, and F. Vezzu, "*First Dark Photon Search Results from the Dandelion Experiment*", arXiv:2602.18218 [astro-ph.CO] (2026) arXiv preprint arXiv:2602.18218.

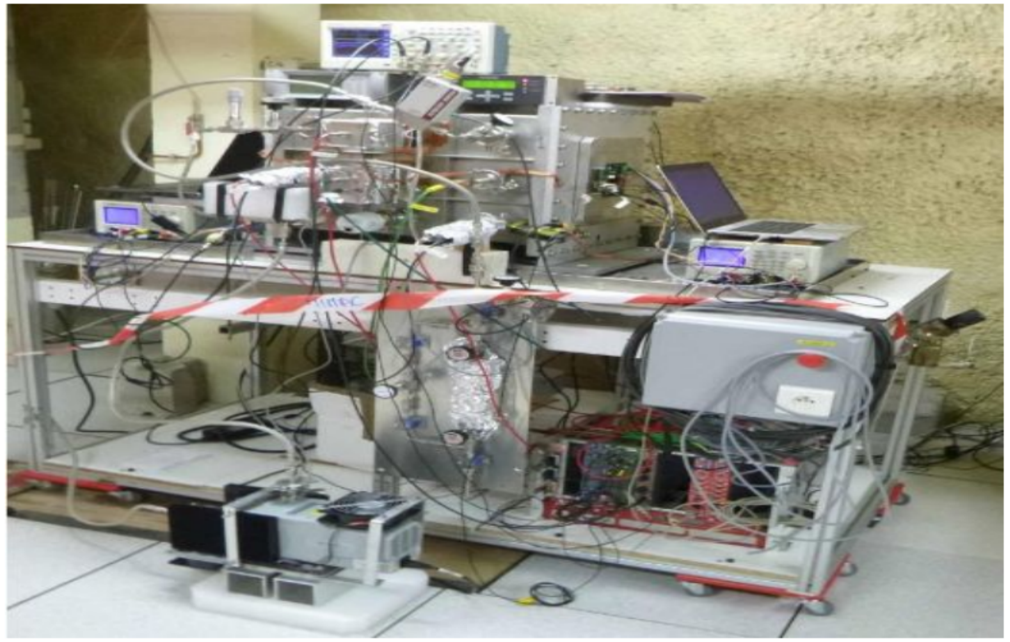
WIMPs

Weakly Interacting Massive Particles

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

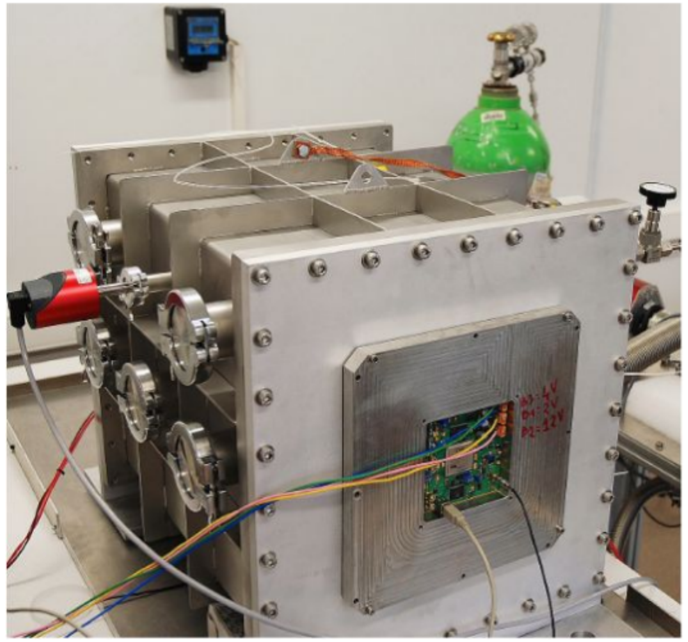
Neutrons produce a similar recoil: directionality discriminates WIMPs from the neutron background.

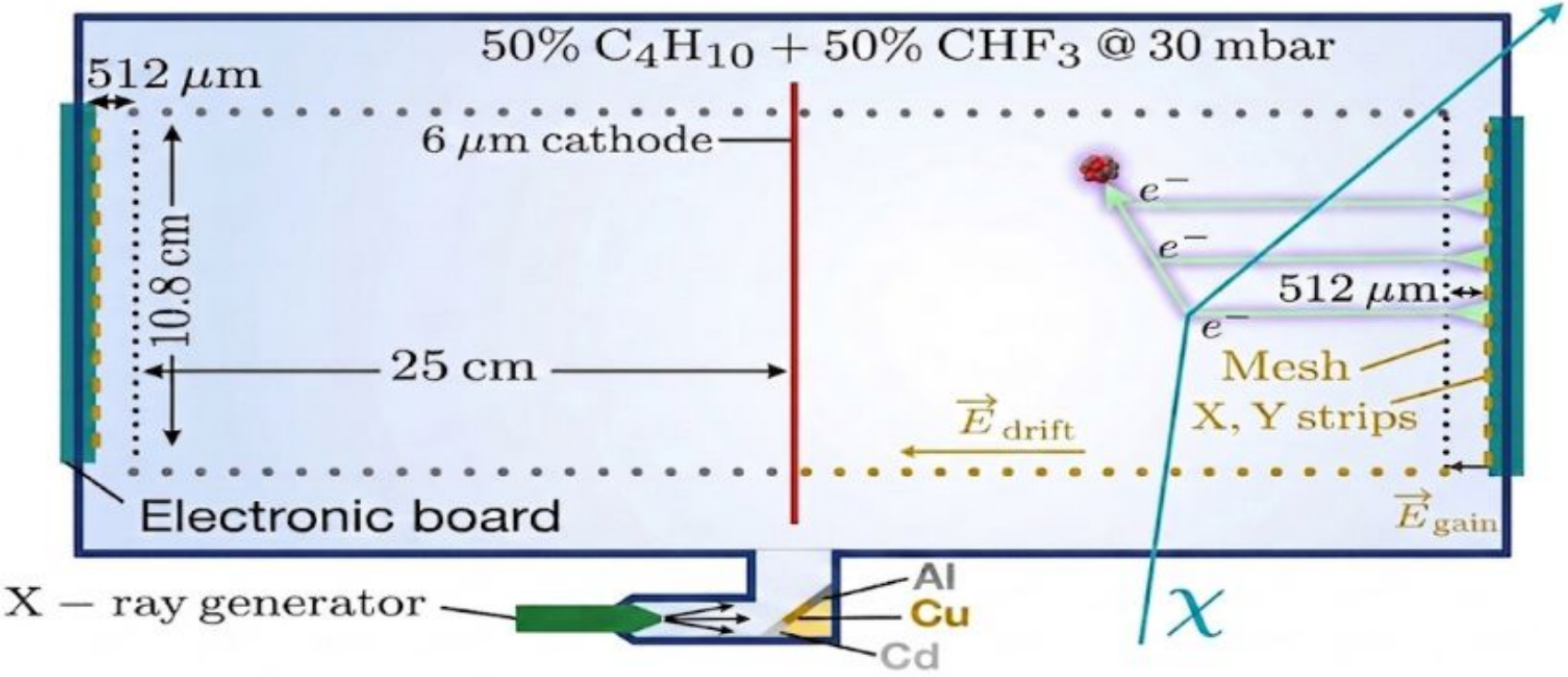
MIMAC Experiment: Setup



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: 371 days.





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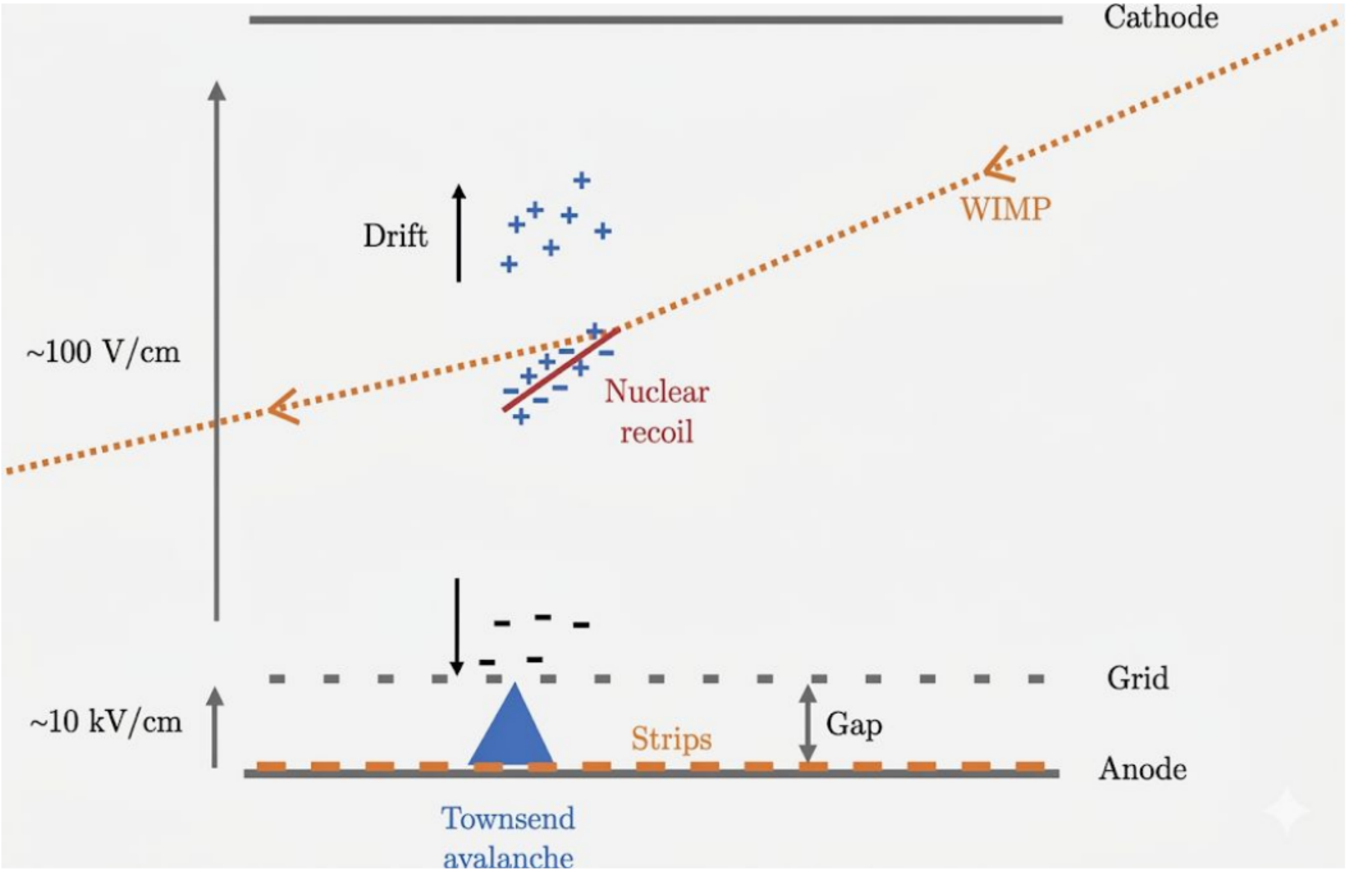
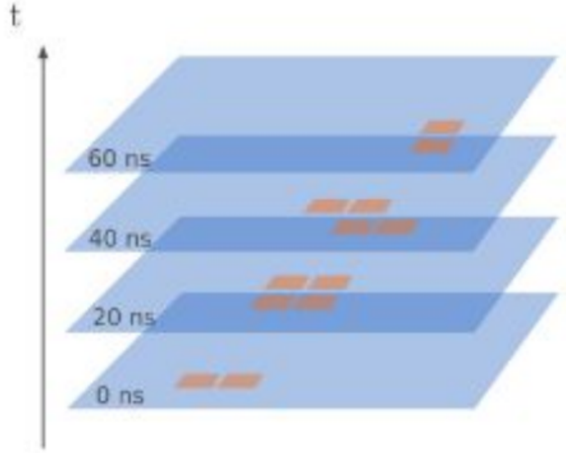
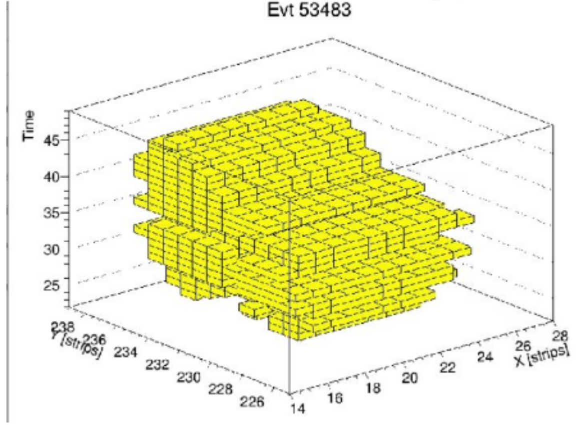


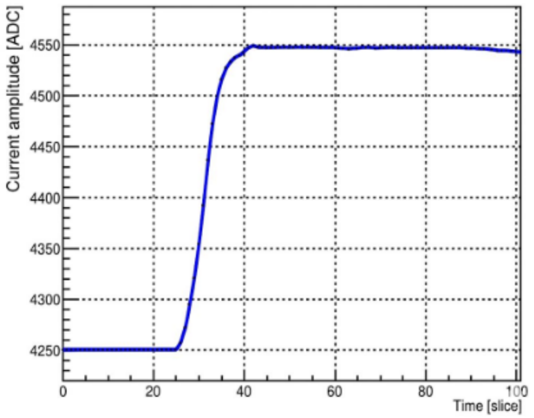
$$z = \Delta t \cdot v_{drift}$$



Two main observables

- 3D-Track
- Ionization energy

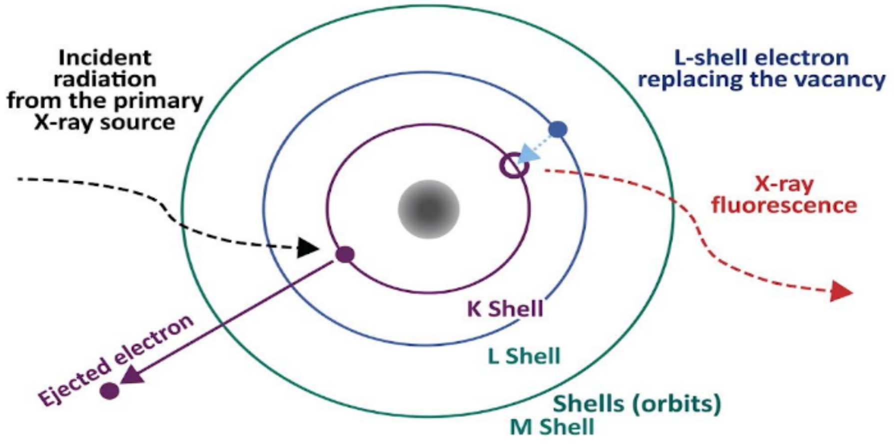


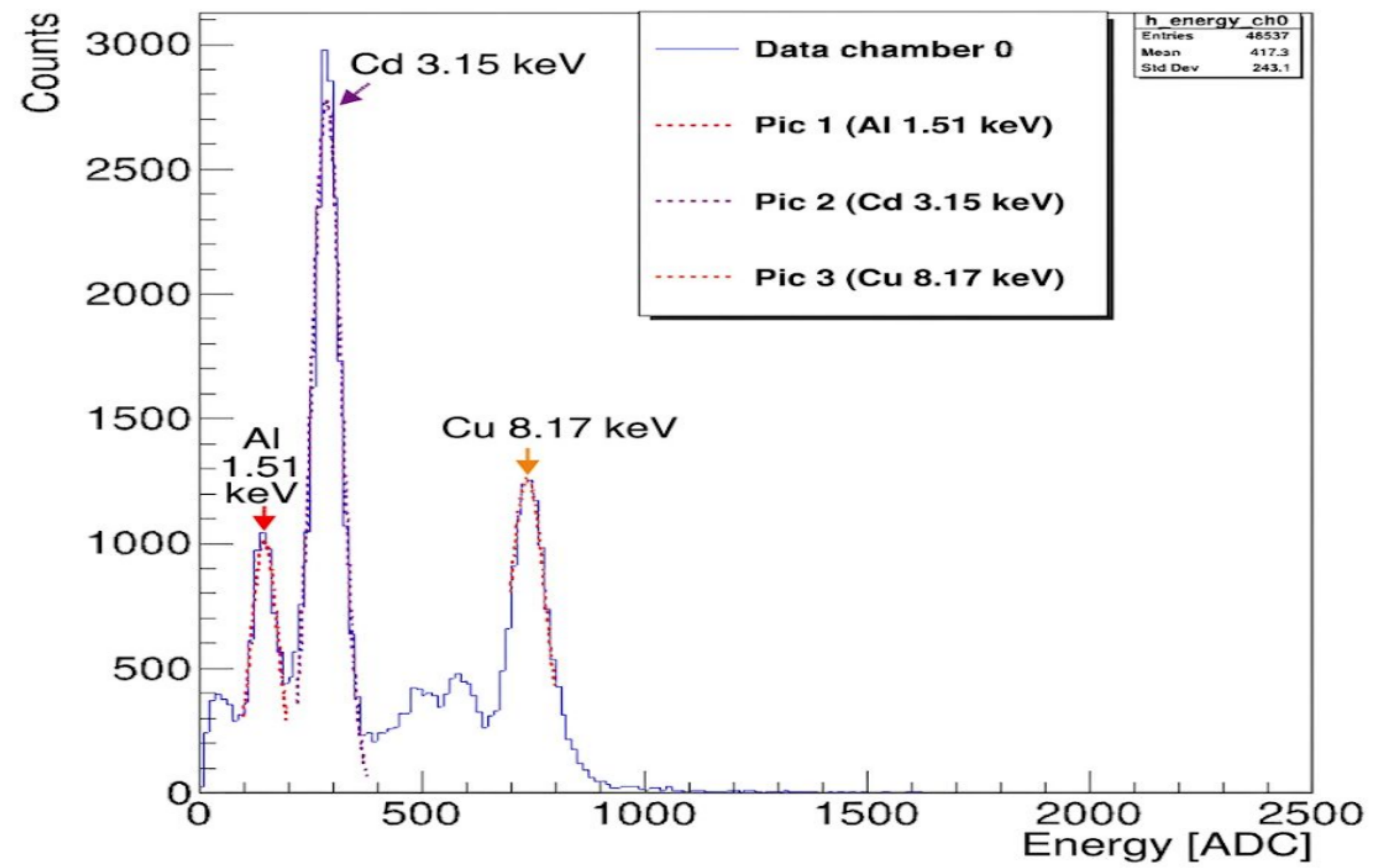


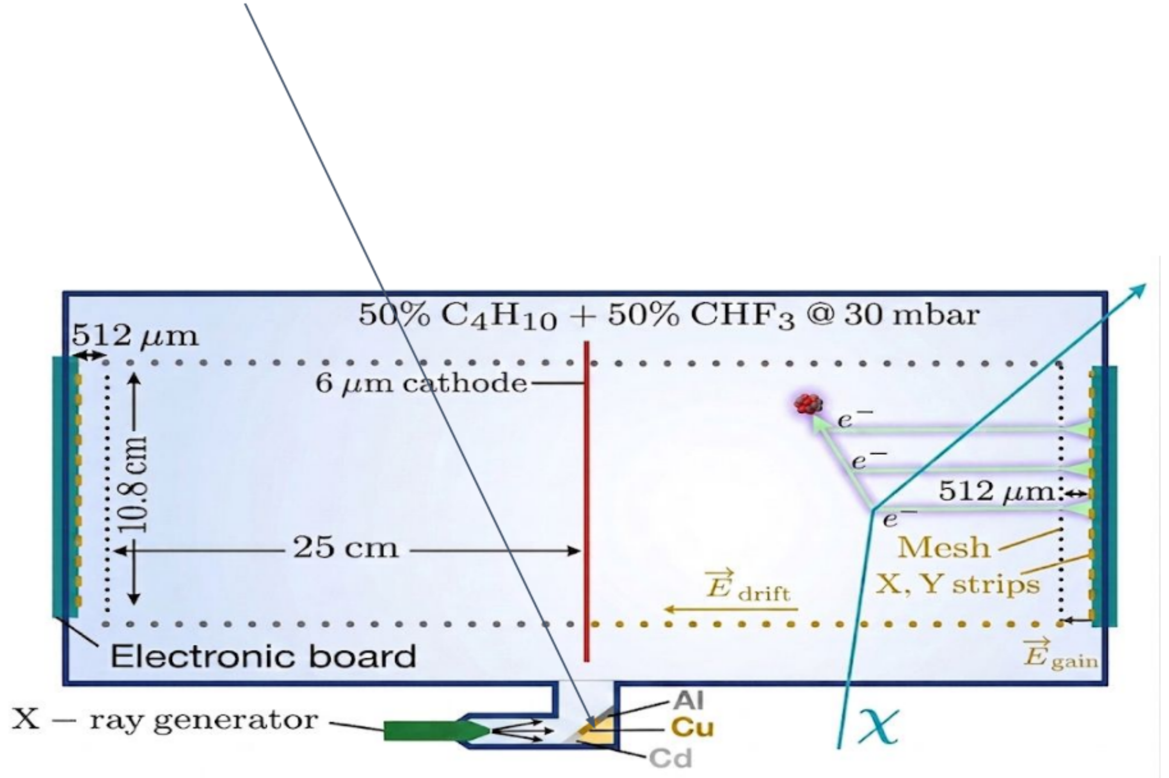
Calibration

Ionization Energy

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

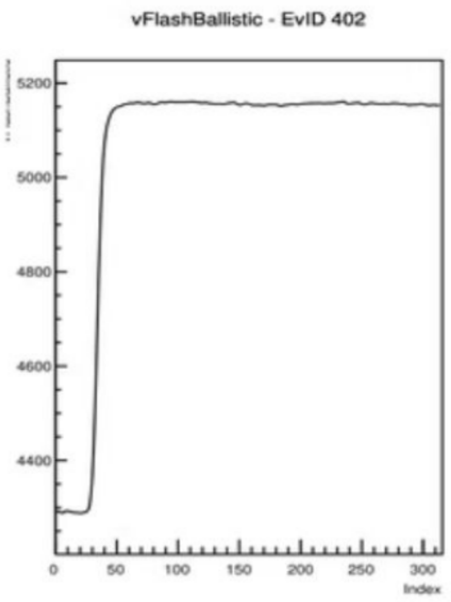


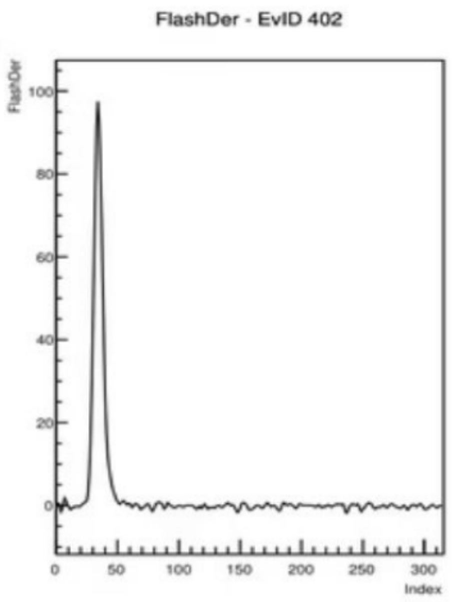


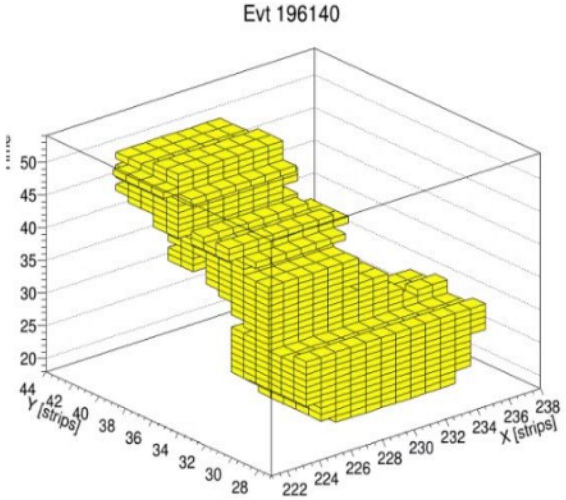


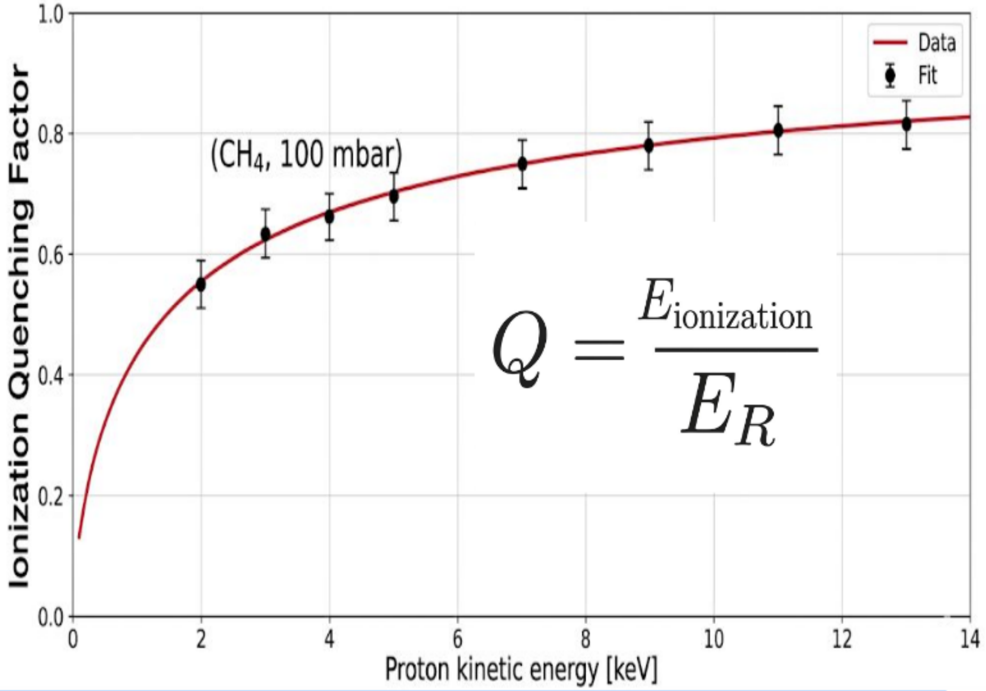
Discrimination: Nuclear recoils and Electronic recoils

Nuclear Recoil





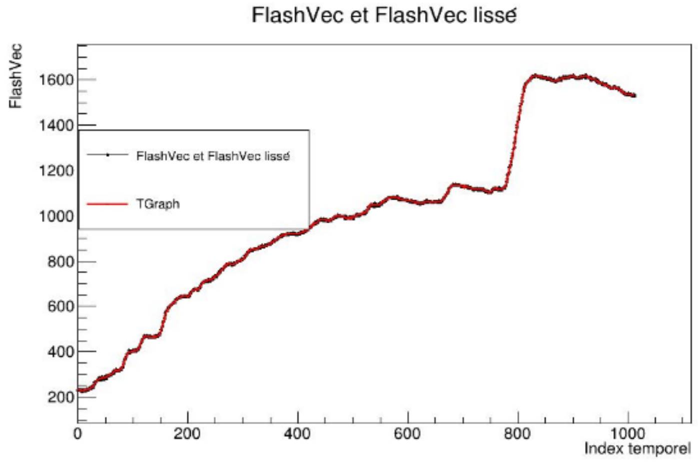


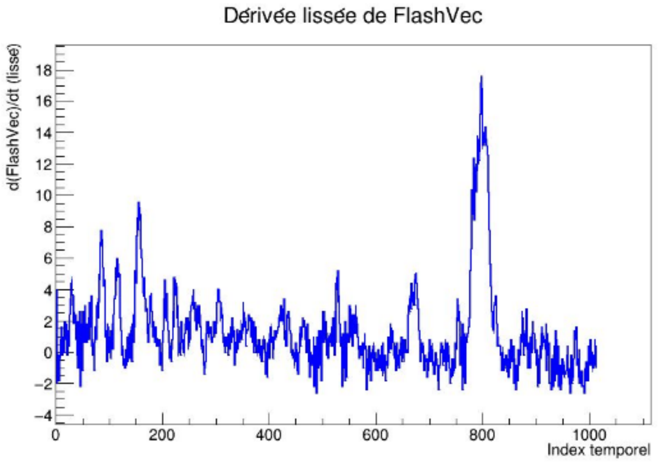


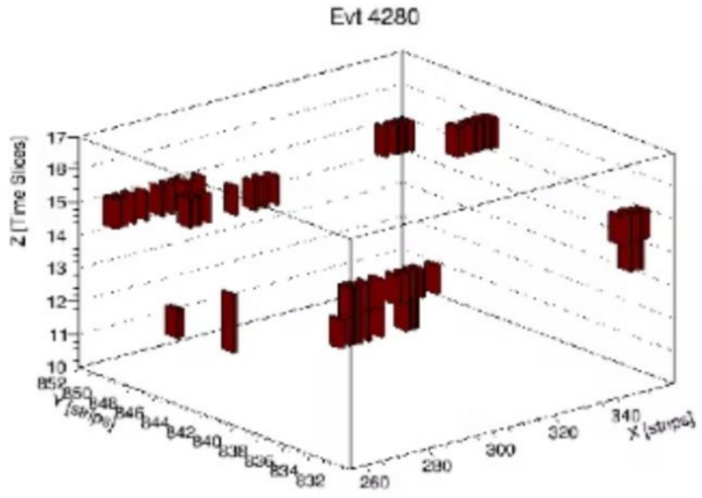
$$Q = \frac{E_{\text{ionization}}}{E_R}$$

Electronic Recoil

- Beta electrons and Gamma rays

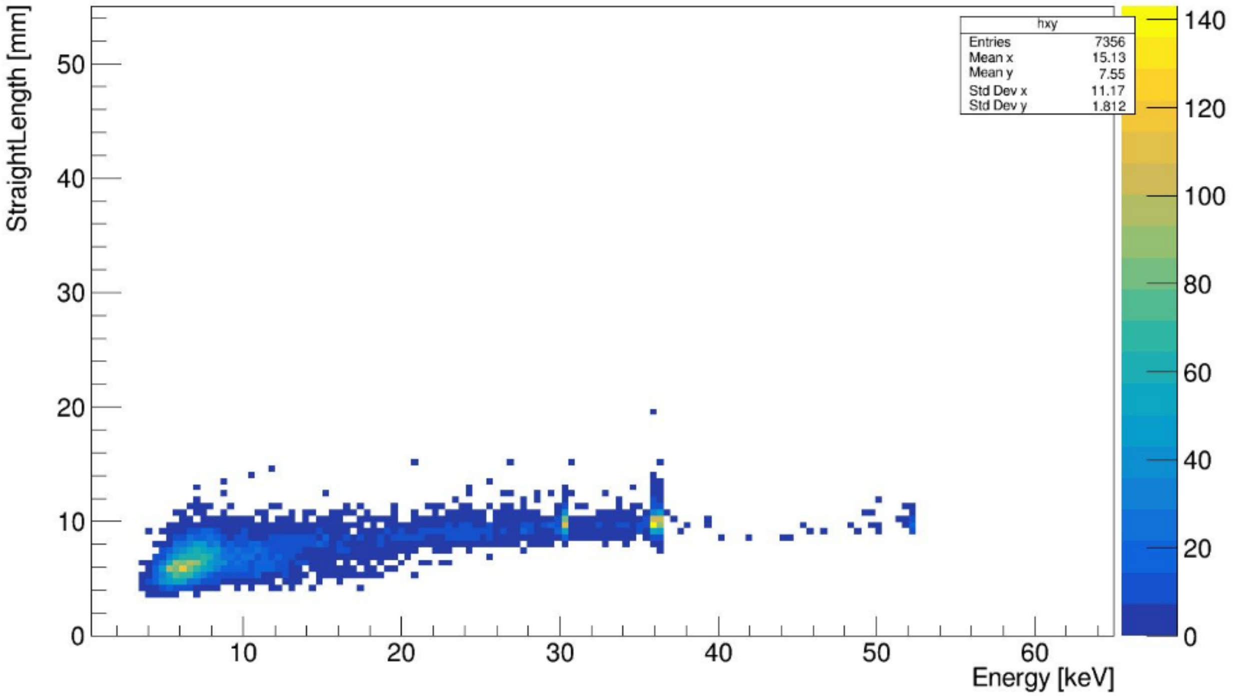






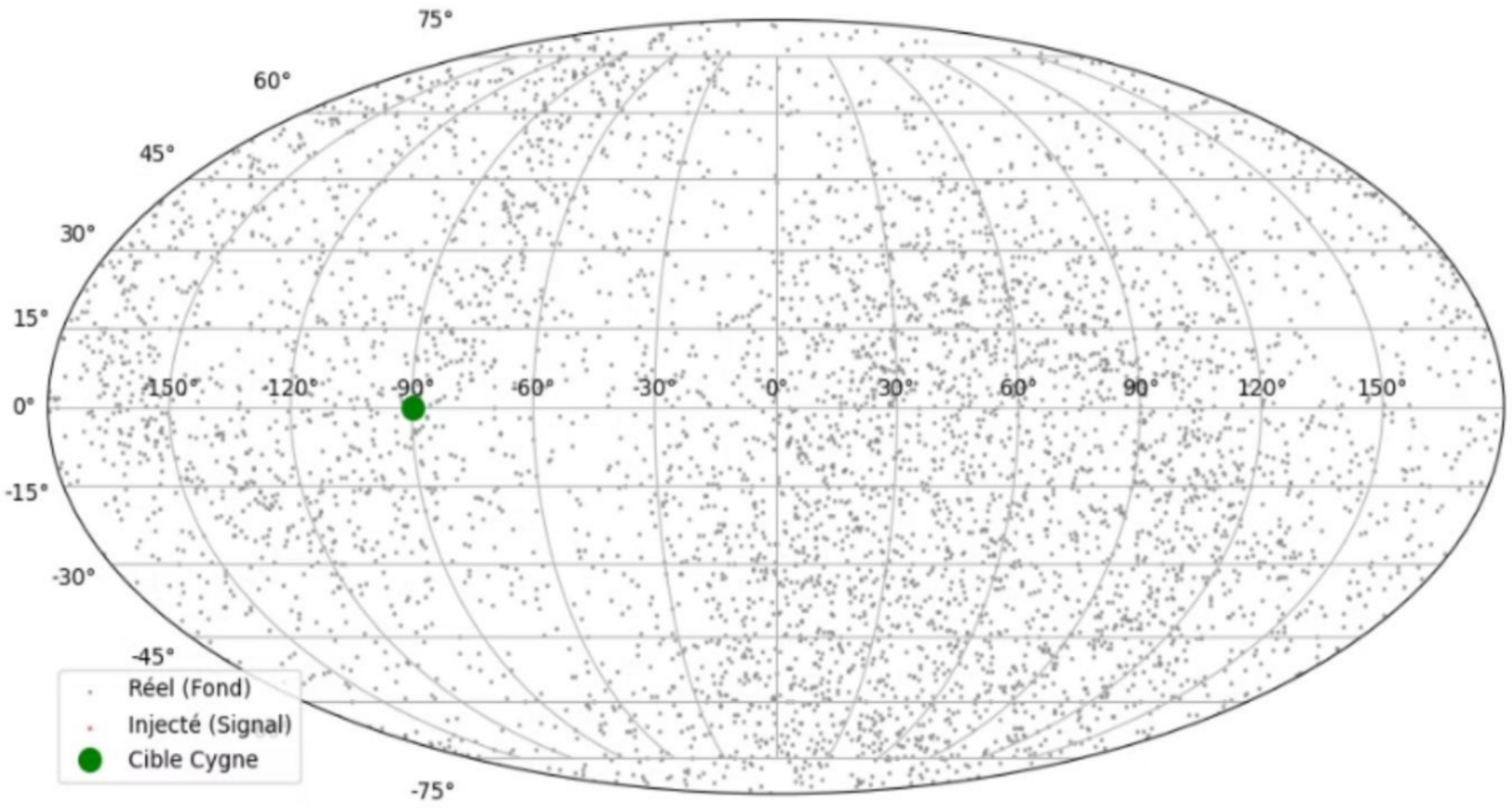
MIMAC Results: Event Analysis

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



Projection of nuclear recoil events onto the galactic plane. Only events with energy E < 10 keV are selected to focus on the search for WIMPs.

Signal/Background Separation: Directionality Analysis

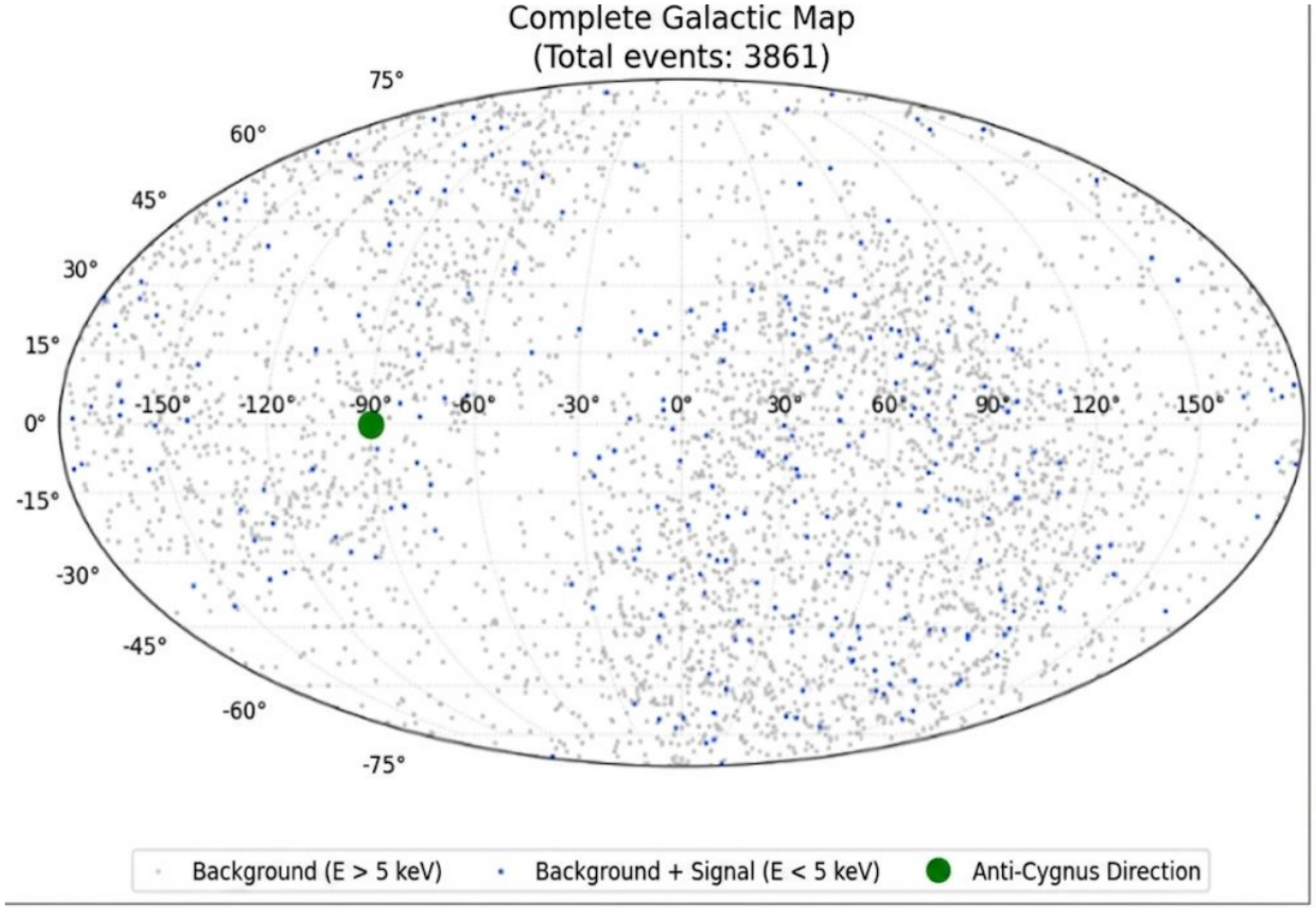
Directionality makes it possible to distinguish nuclear recoil induced by WIMPs from that originating from the background, thanks to a likelihood analysis.

Strategy

- Construction of the background model on events E > 5 keV
- Applying the model to E < 5 keV to deduce an upper limit on the number of events

Results

- Upper limit: 7 events
- No signal measured



MIMAC Results: Exclusion Curve and Cross Section limit

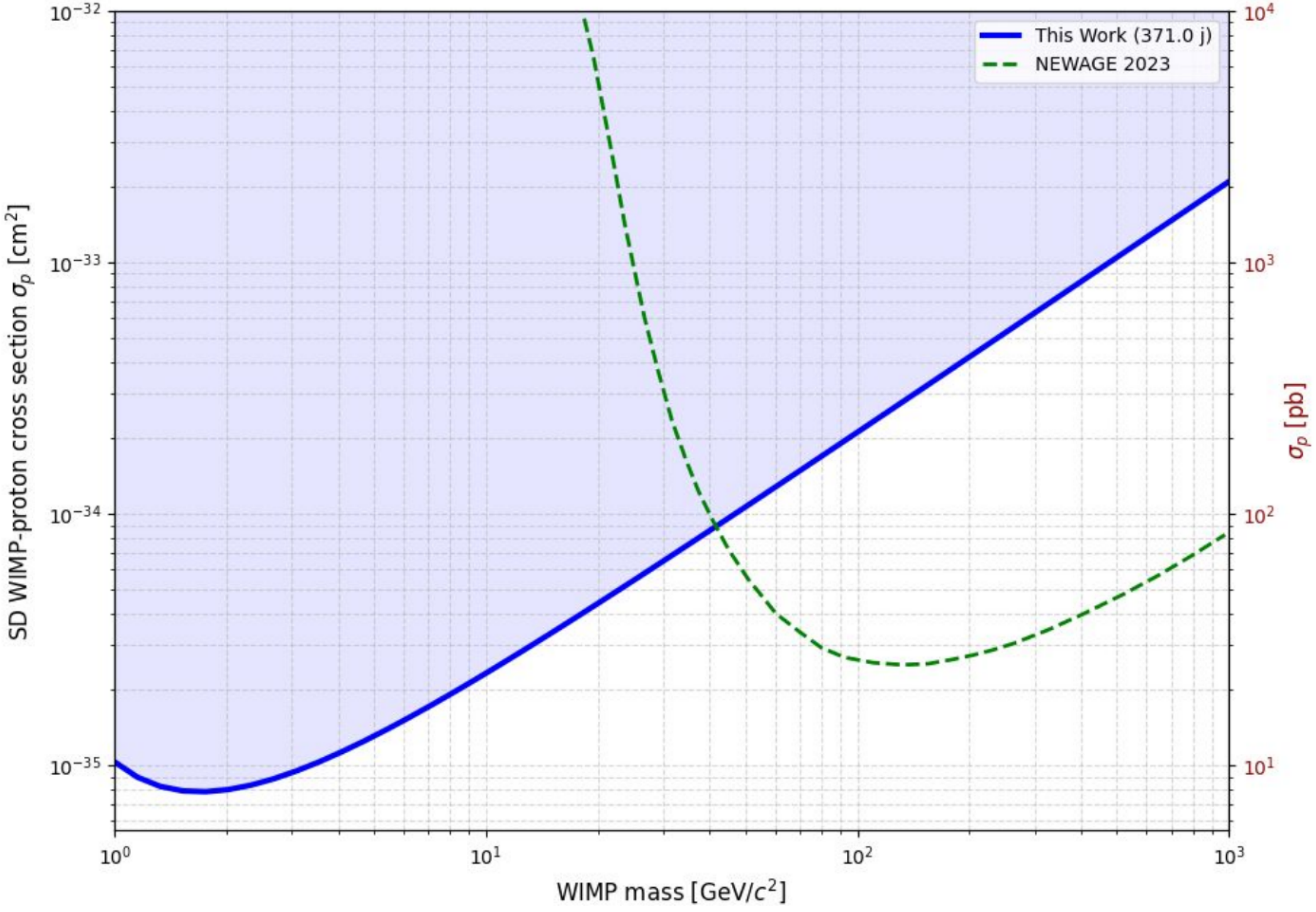
With an energy threshold of 0.94 keV, we obtain the following exclusion curve.

Limit reached

The limit on the cross section obtained is: $\sigma < 10^{-35}\ \text{cm}^2$

$$N = MT\frac{\rho_\chi \sigma_0 m_N}{2m_\chi \mu_{\chi N}^2}\int_{E_{\min}}^{E_{\max}} dE_r\, F^2(E_r)\int_{|\vec{v}|\geq v_{\min}(E_r)} d^3v\, \frac{f(\vec{v})}{v}$$

$$\sigma_{lim} = \sigma_{ref} \times \frac{N_{lim}}{N_{th}(\sigma_{ref})}$$



Conclusion and Perspectives

Summary of results

- Dandelion: limit on kinetic mixing for 24 hours of data
- MIMAC: limit on the cross section $\sigma < 10^{-35}$ cm^2 for 371 days of data
- Using directionality to discriminate the background signal

Key points

- Competitive results in dark matter research
- No signal detected, but competitive limits

Future prospects

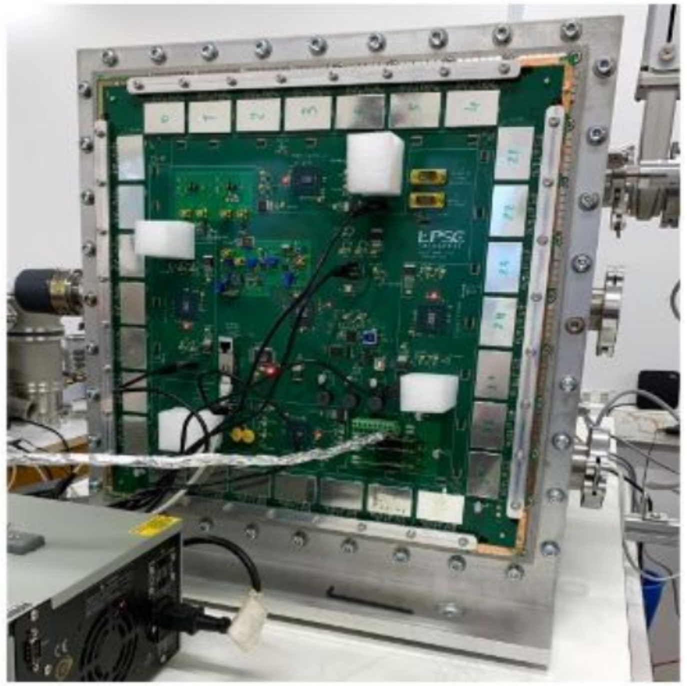
- Increasing exposure time
- Analysis of Fluorine recoils

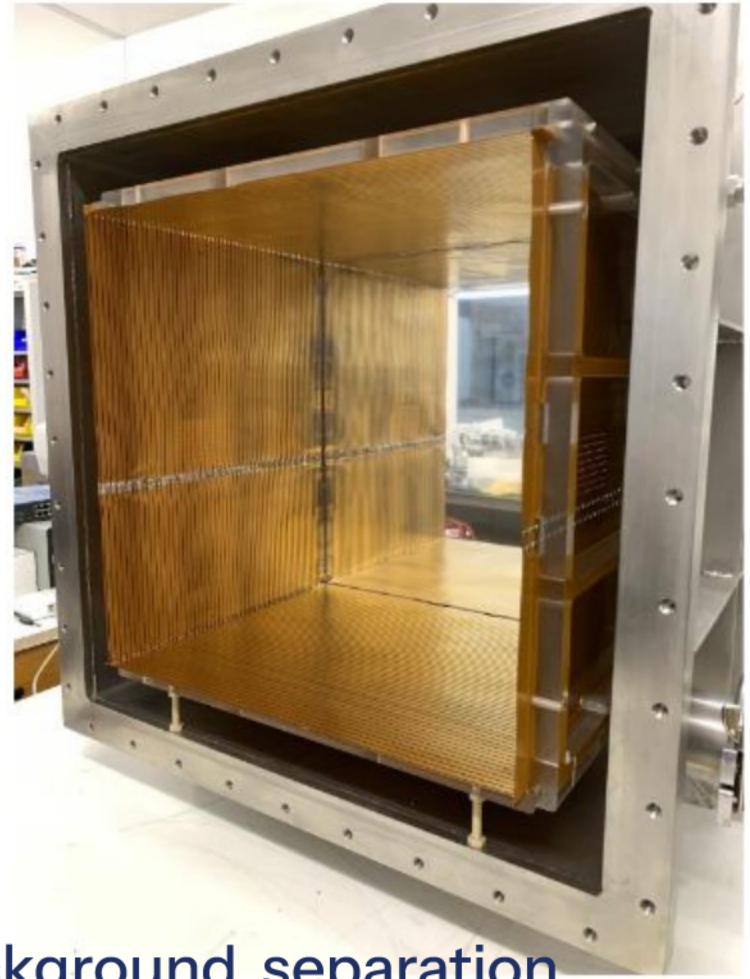
MIMAC-35 cm: Thermal Neutron Capture

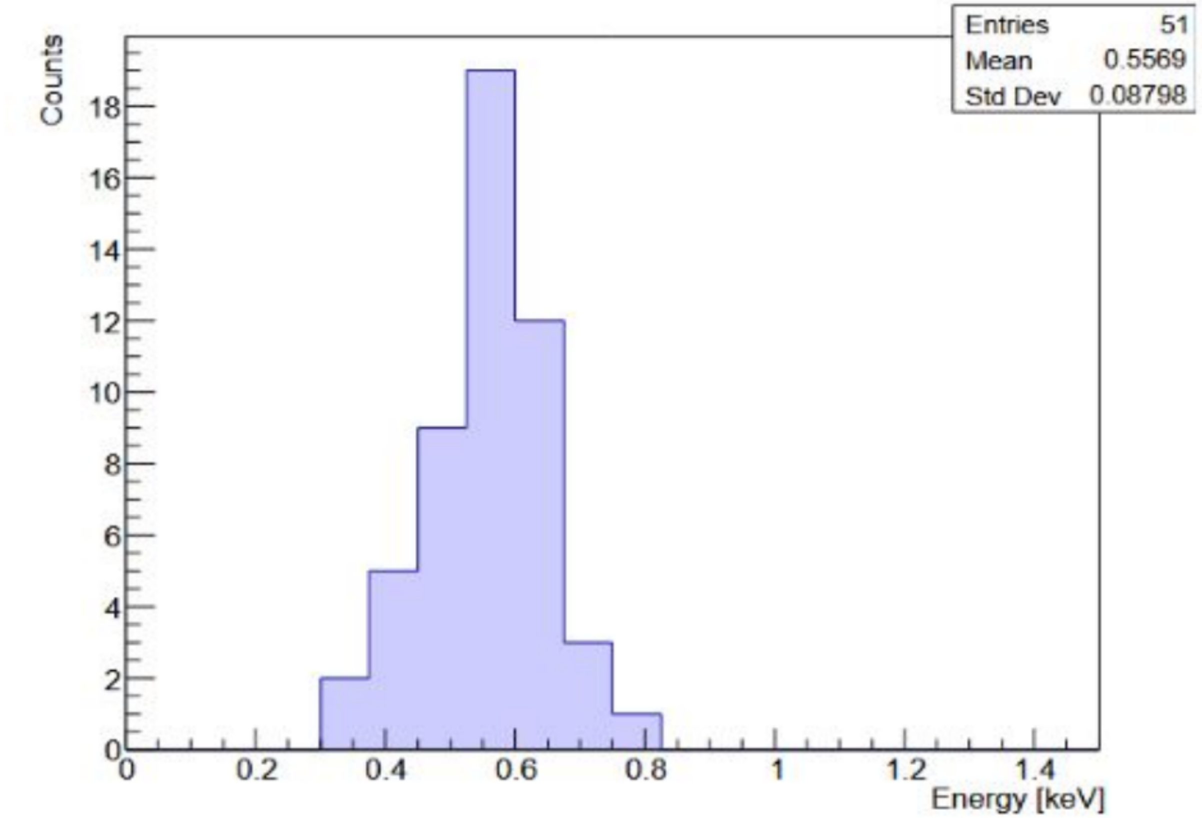
Background Analysis : $^{1}\mathrm{H}(n,\gamma)^{2}\mathrm{H}$

arXiv:2602.17880

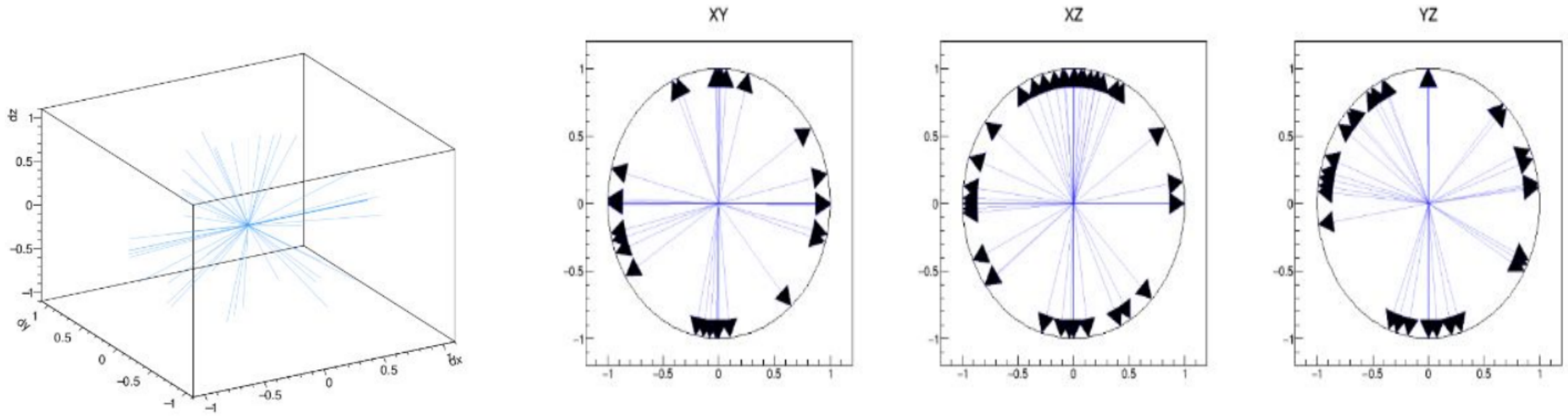
- ^{2}H recoils at 1.3 keV.
- Duration : 5 days
- Location : LPSC
- With a new TPC detector (35x35x29) cm^3







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



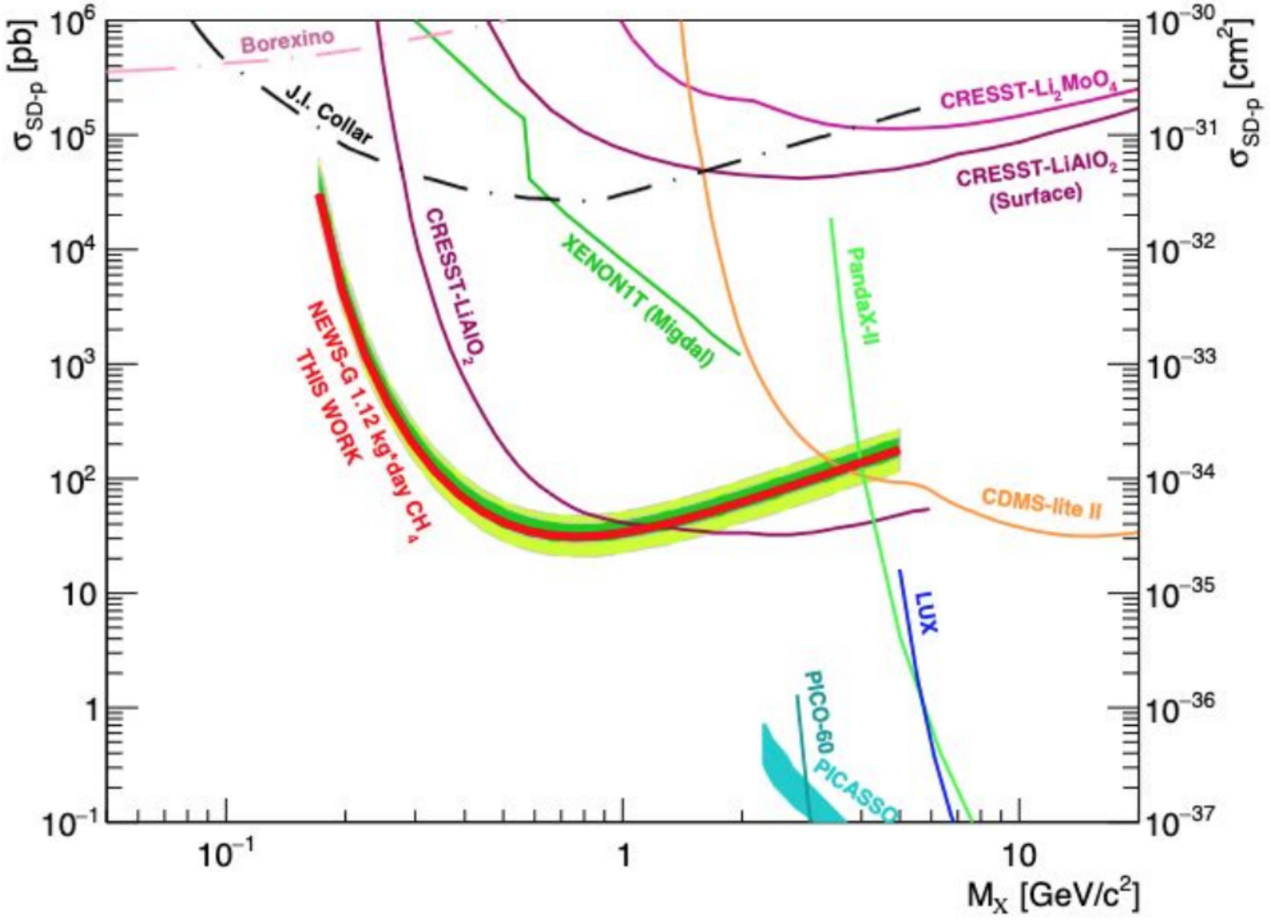
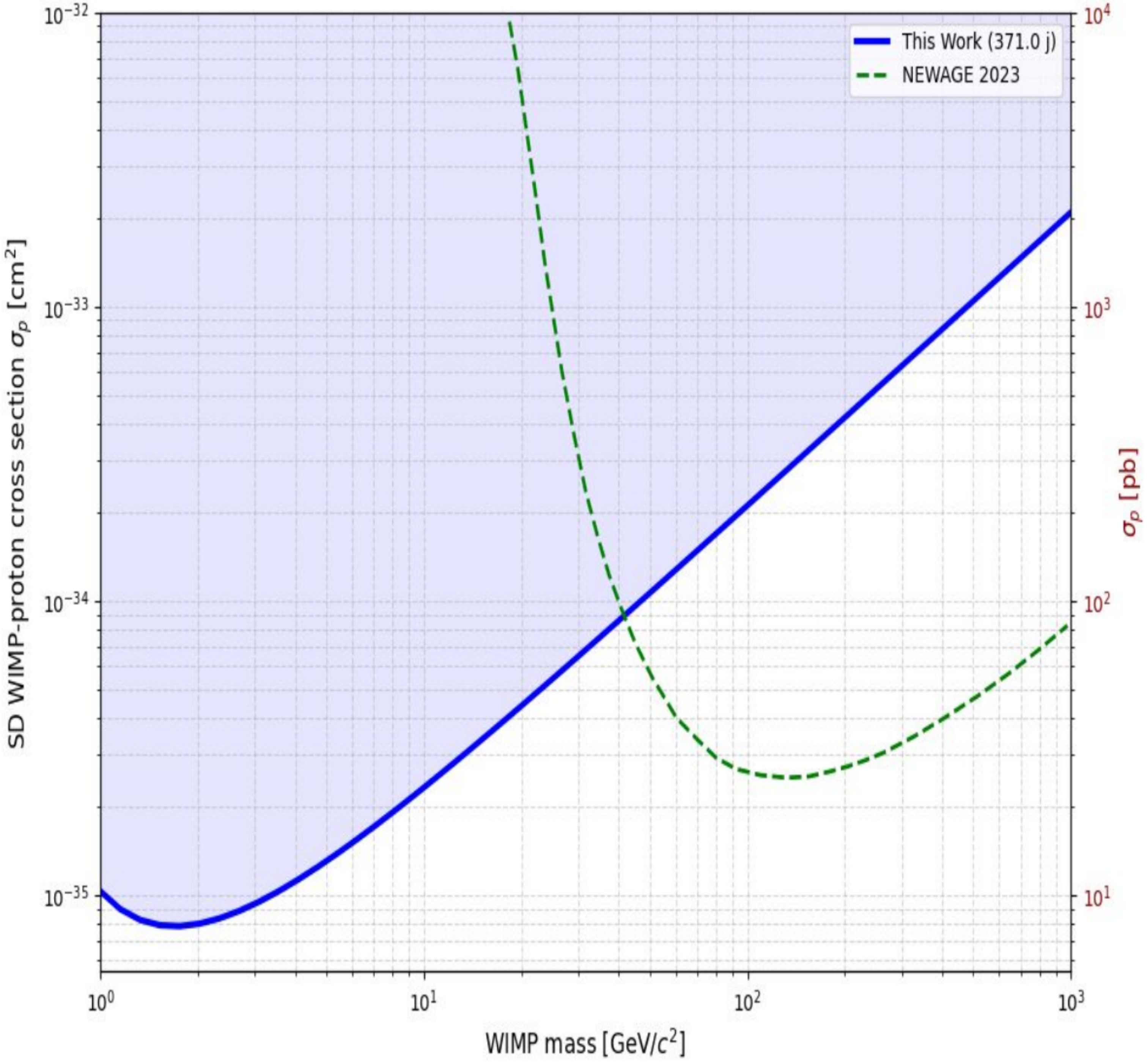
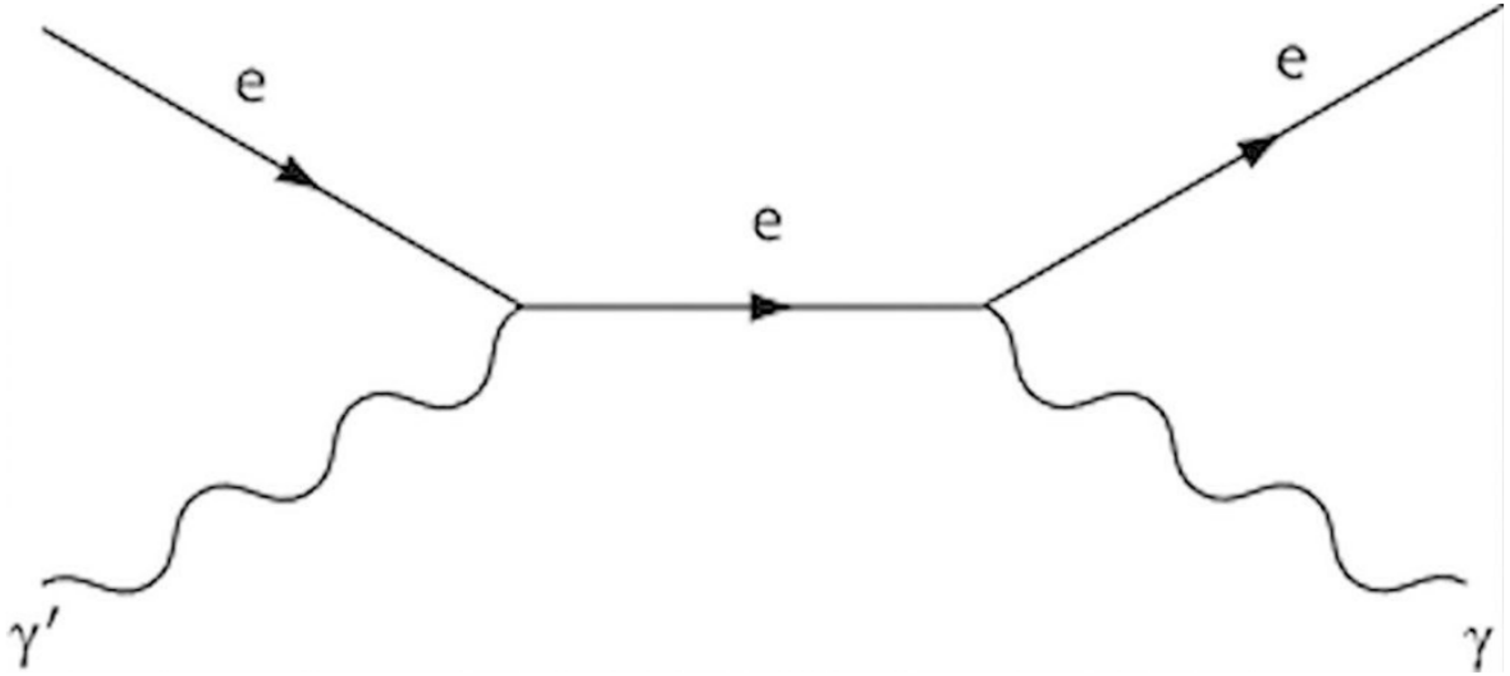


FIG. 3. Exclusion limit on the WIMP-proton spin-dependent cross section from this work (thick red line) and 1σ and 2σ sensitivity bands (dark and light green shaded areas respectively). Upper limits from CDMS-lite [56], CRESST-III [57–59], LUX [60], PANDAX-II [61], XENON-1T (Migdal) [62], PICASSO [63], PICO-60 [64], J.I. Collar [65] and Borexino [66] are also shown.



$$\mathcal{L}_{diag} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m^2_{A'}A'_\mu A'^\mu + eJ^\mu_{EM}A_\mu + \left(\chi e J^\mu_{EM} + g' J'^\mu\right) A'_\mu$$



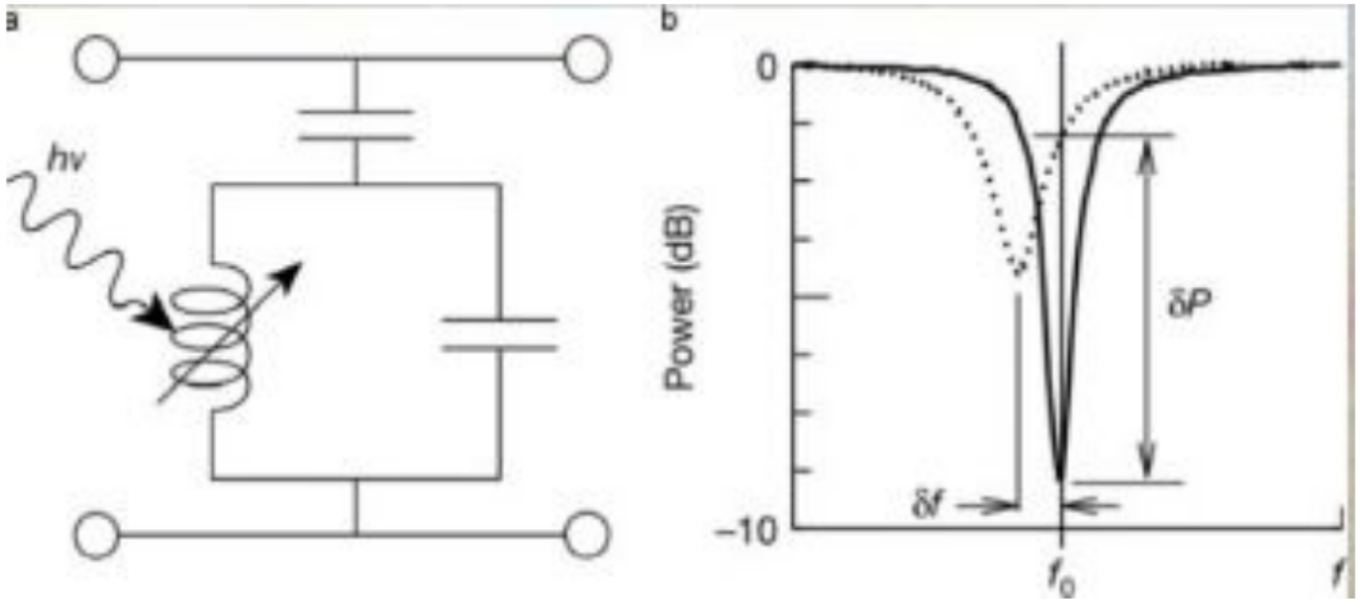
KIDs

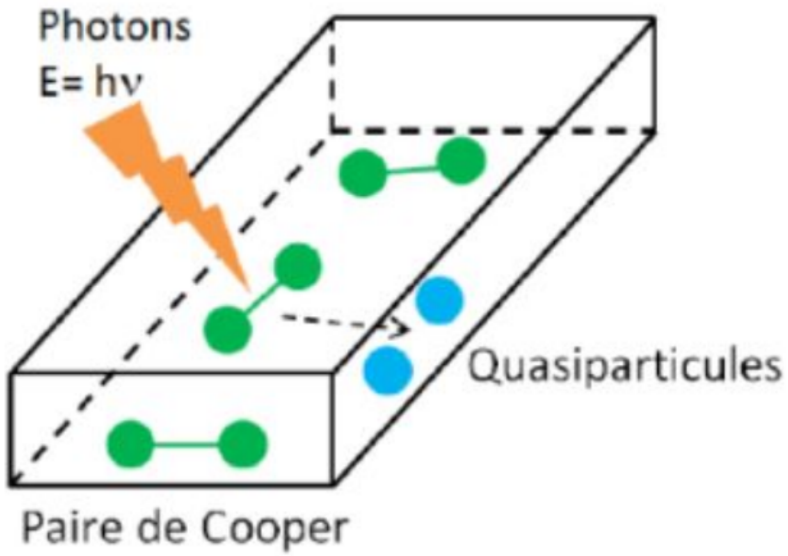
Superconducting photon detector

RLC resonating circuit :

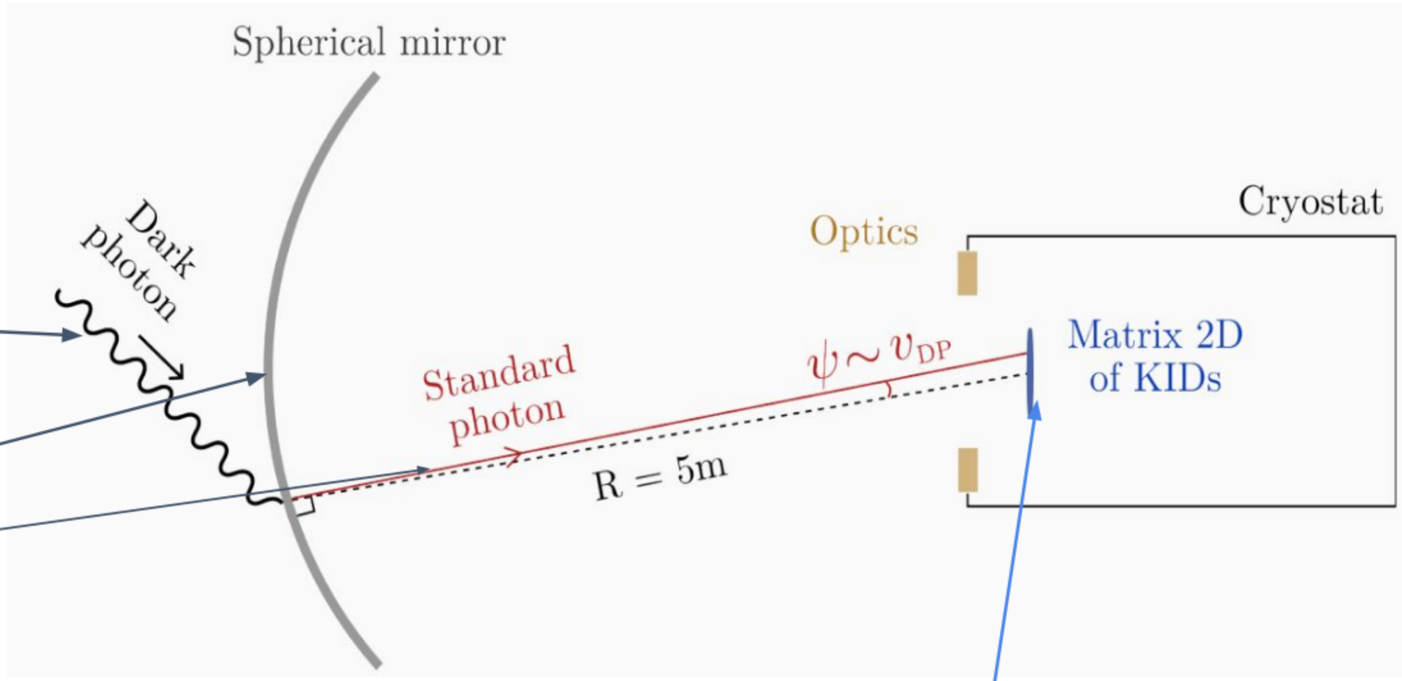
$$L_k \propto \frac{1}{n_{CP}} \qquad f_r \propto \frac{1}{\sqrt{L_k C}}$$

we can detect incident photons by observing a shift in the resonance frequency.





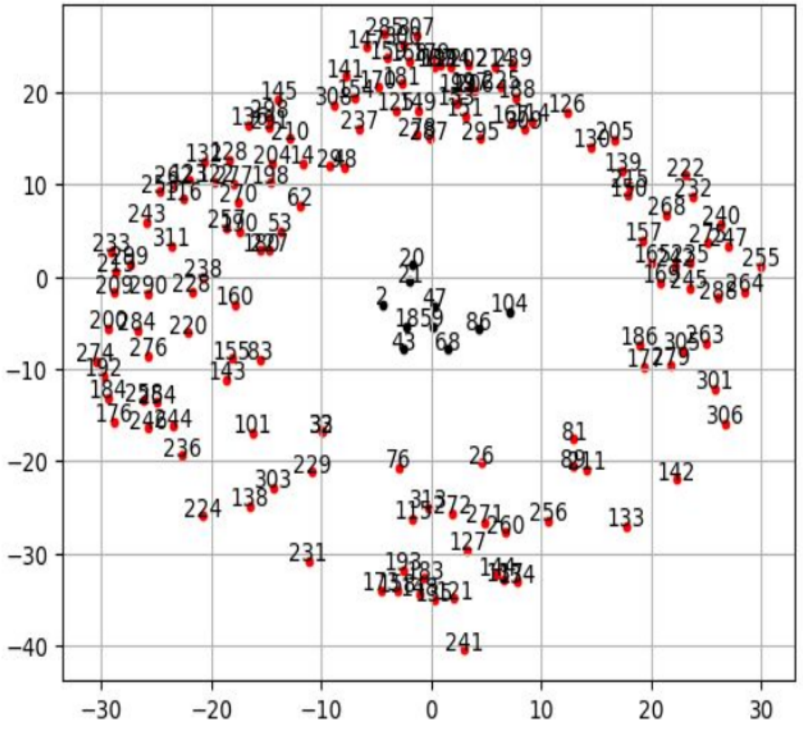
$$\begin{pmatrix}\mathbf{E}\\ \mathbf{E}_{\mathrm{hid}}\end{pmatrix} = \mathbf{E}_{\mathrm{DM}}\begin{pmatrix}-1\\ 1/\chi\end{pmatrix}\exp(-i(\omega t - \mathbf{k}_0\mathbf{x})).$$



$$\mathbf{E}_{||\ \mathrm{surface}} = 0$$

$$\begin{pmatrix}\mathbf{E}\\ \mathbf{E}_{\mathrm{hid}}\end{pmatrix}_{\mathrm{emitted}} = \mathbf{E}_{\mathrm{DM},\|}\begin{pmatrix}1\\ \chi\end{pmatrix}\exp(-i(\omega t - \mathbf{k}_1\mathbf{x}))$$

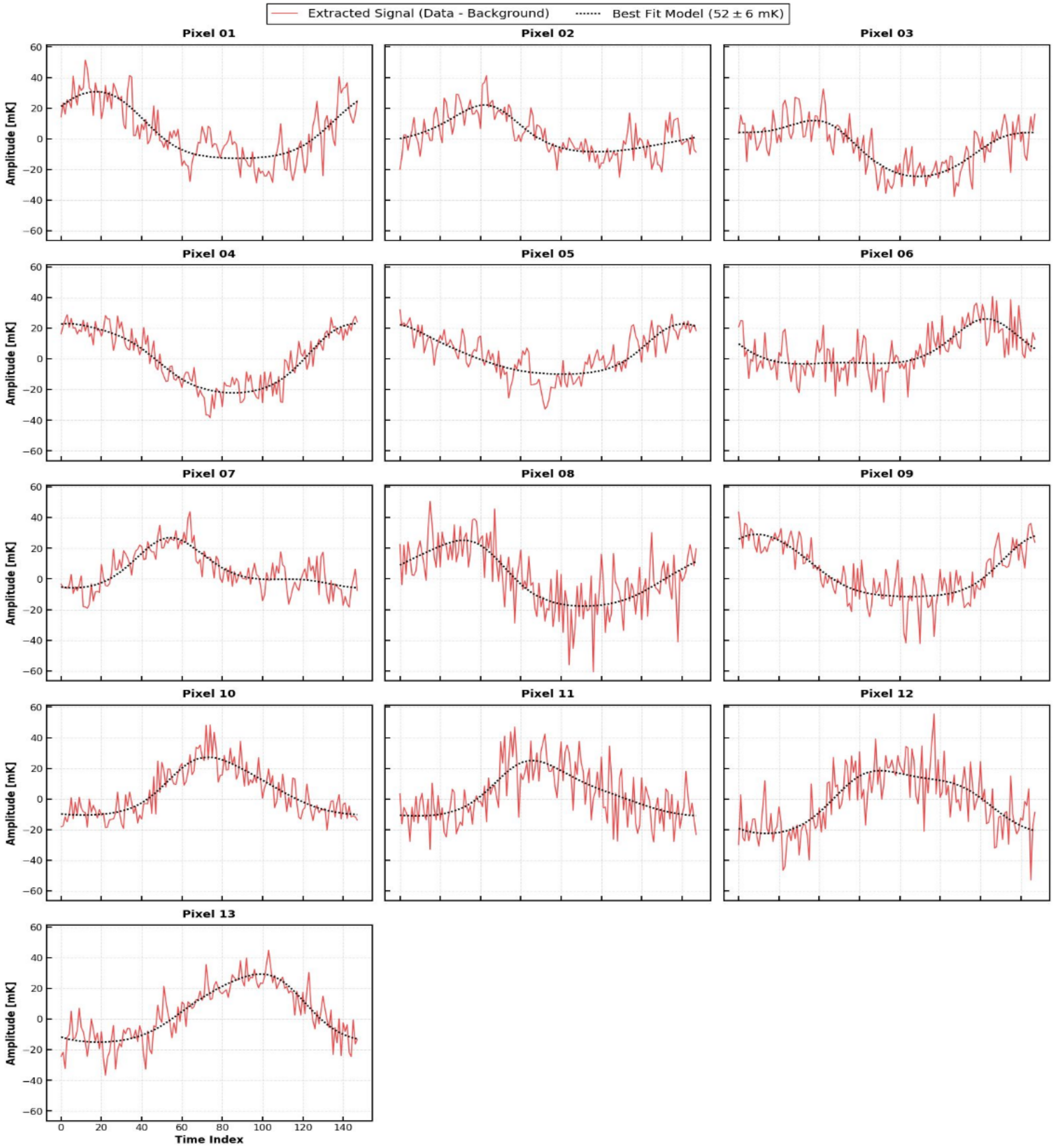
$$k_{0,\|} = k_{1,\|}$$



$$P(x,y,t;E_\gamma) = \chi^2\,\rho_{\mathrm{CDM}}\,\eta(E_\gamma)\,A_{\mathrm{mirr.}}\,I(x,y,t)\,\cos^2\alpha(t)$$

Signal Injection : Dandelion

- Injected a dark photon signal with an amplitude of **50 mK** into the raw timelines.
- The extraction pipeline recovered **52 ± 6** mK, demonstrating:
- The signal is **orthogonal** to PCA components.
- The signal is **fully preserved** during background subtraction.

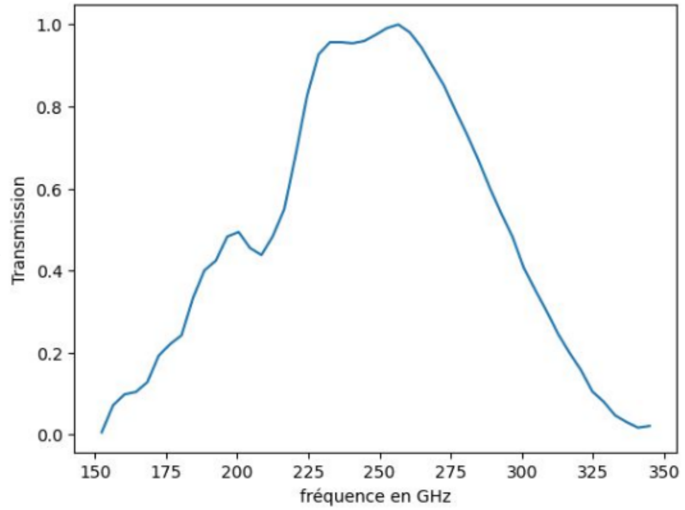


$$P(x,y,t;E_\gamma) = \chi^2 \rho_{\mathrm{CDM}}\, \eta(E_\gamma)\, A_{\mathrm{mirr.}}\, I(x,y,t)\, \cos^2\alpha(t)$$

$$\chi = \sqrt{\frac{\mathrm{P}}{\rho_{\mathrm{CDM}} \cdot A_{\mathrm{mirror}} \cdot \frac{2\cdot c\cdot\eta}{3}}}$$

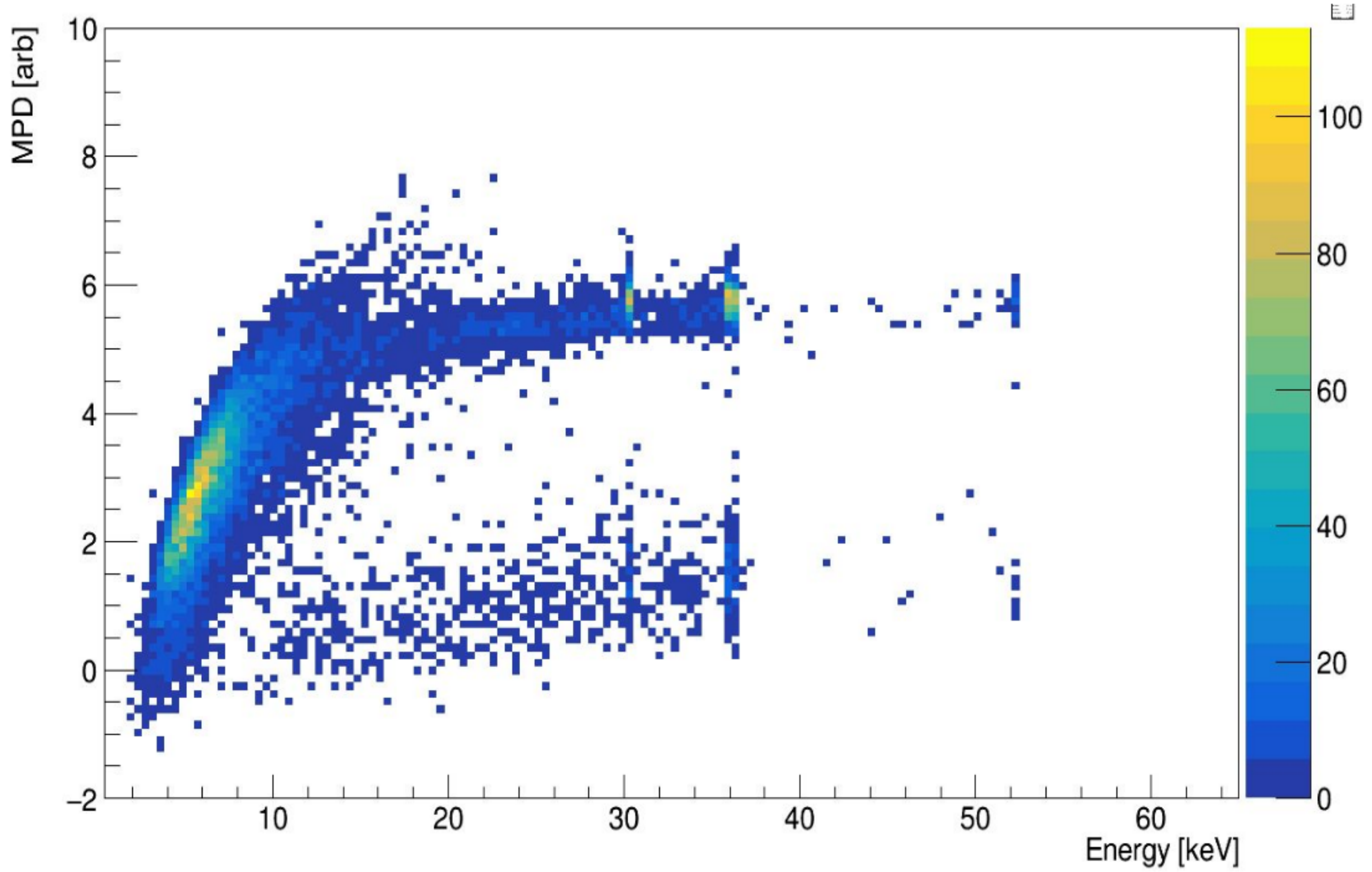
$$P = A\Omega \int_{\nu_{\mathrm{min}}}^{\nu_{\mathrm{max}}} \eta(\nu) H(\nu) B(\Delta T,\nu)\, d\nu$$

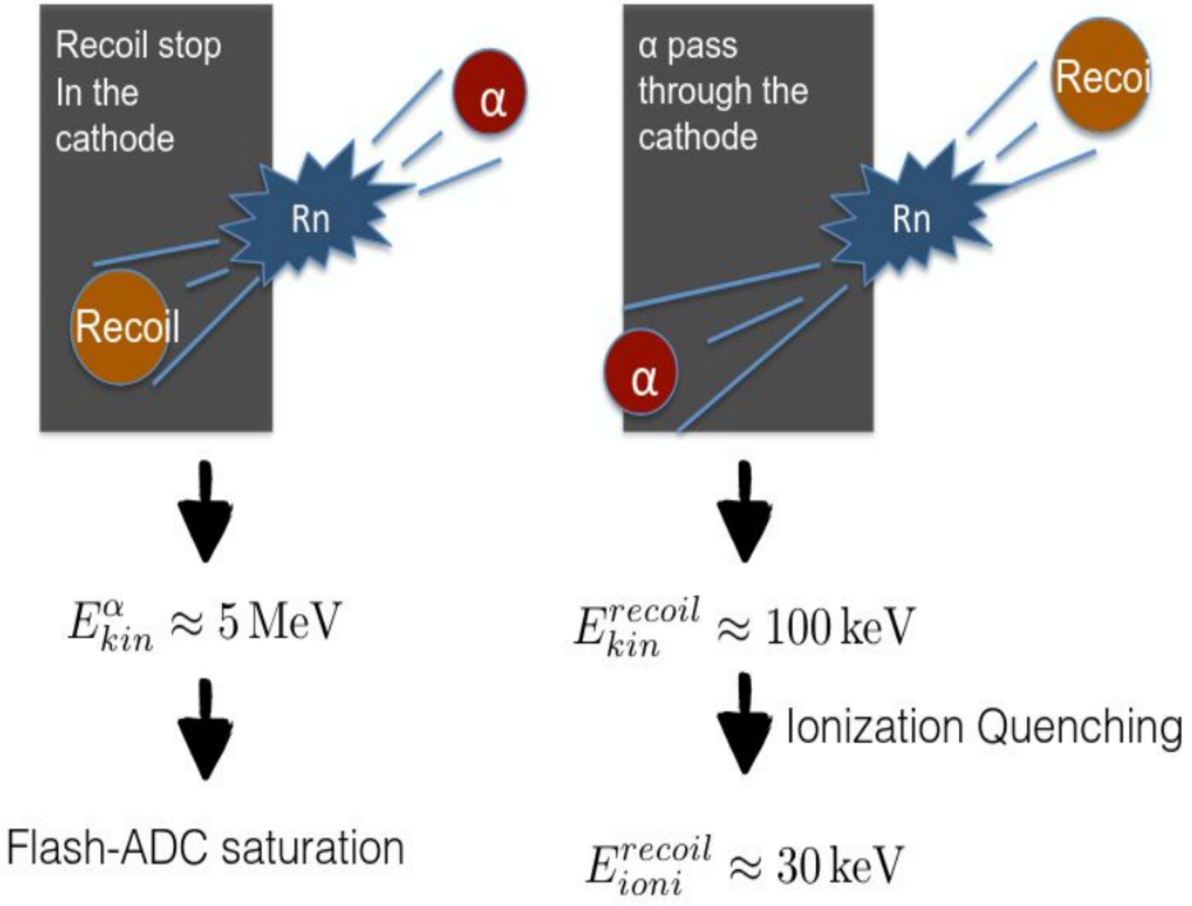
$$\eta(\nu) = \prod_{i=1}^{3} (1-2\epsilon_{\mathrm{HDPE}})\, e^{-\frac{2\pi\nu B p_i n_{\mathrm{HDPE}}}{c}}$$



Radon progeny events

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





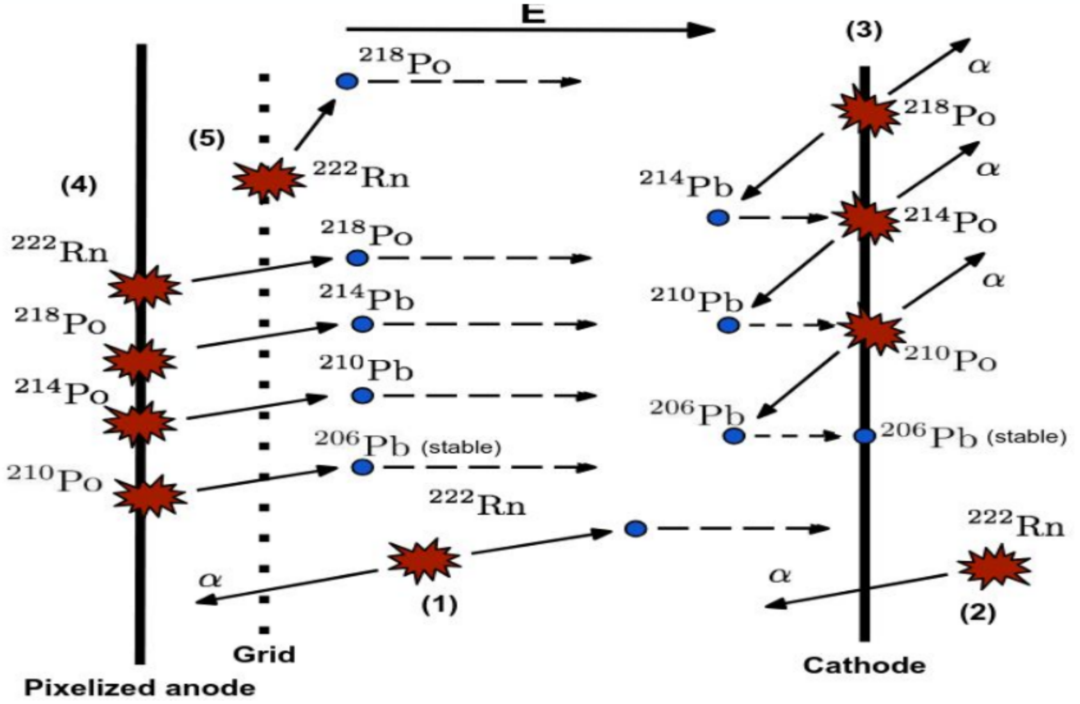
$E_{kin}^{\alpha} \approx 5\,\mathrm{MeV}$

Flash-ADC saturation

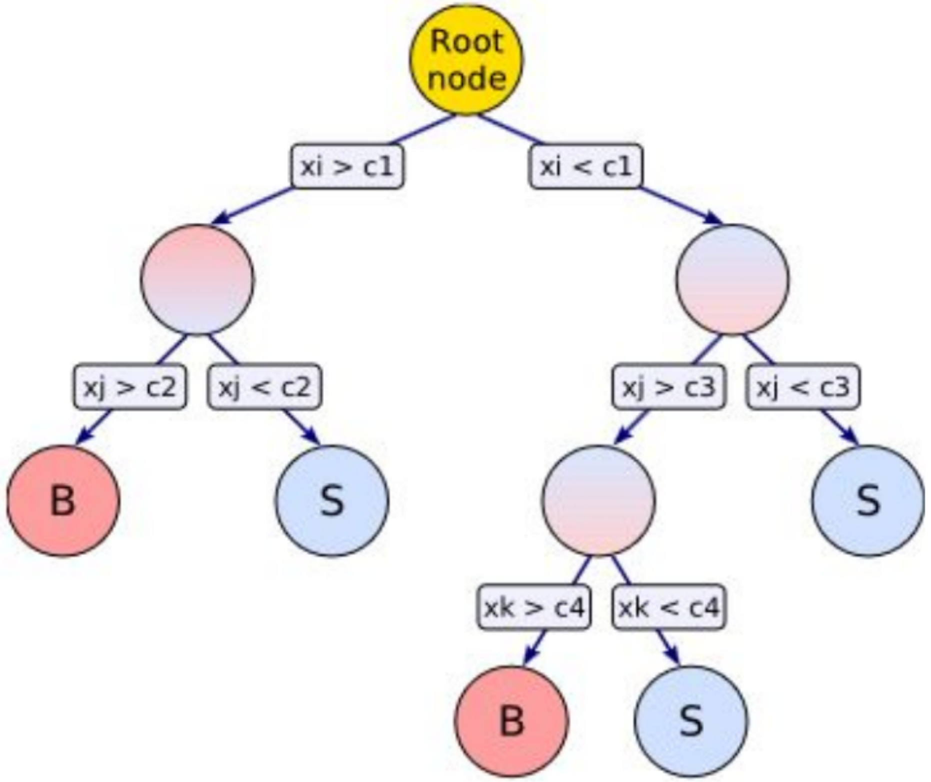
$E_{kin}^{recoil} \approx 100\,\mathrm{keV}$

Ionization Quenching

$E_{ioni}^{recoil} \approx 30\,\mathrm{keV}$



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).

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

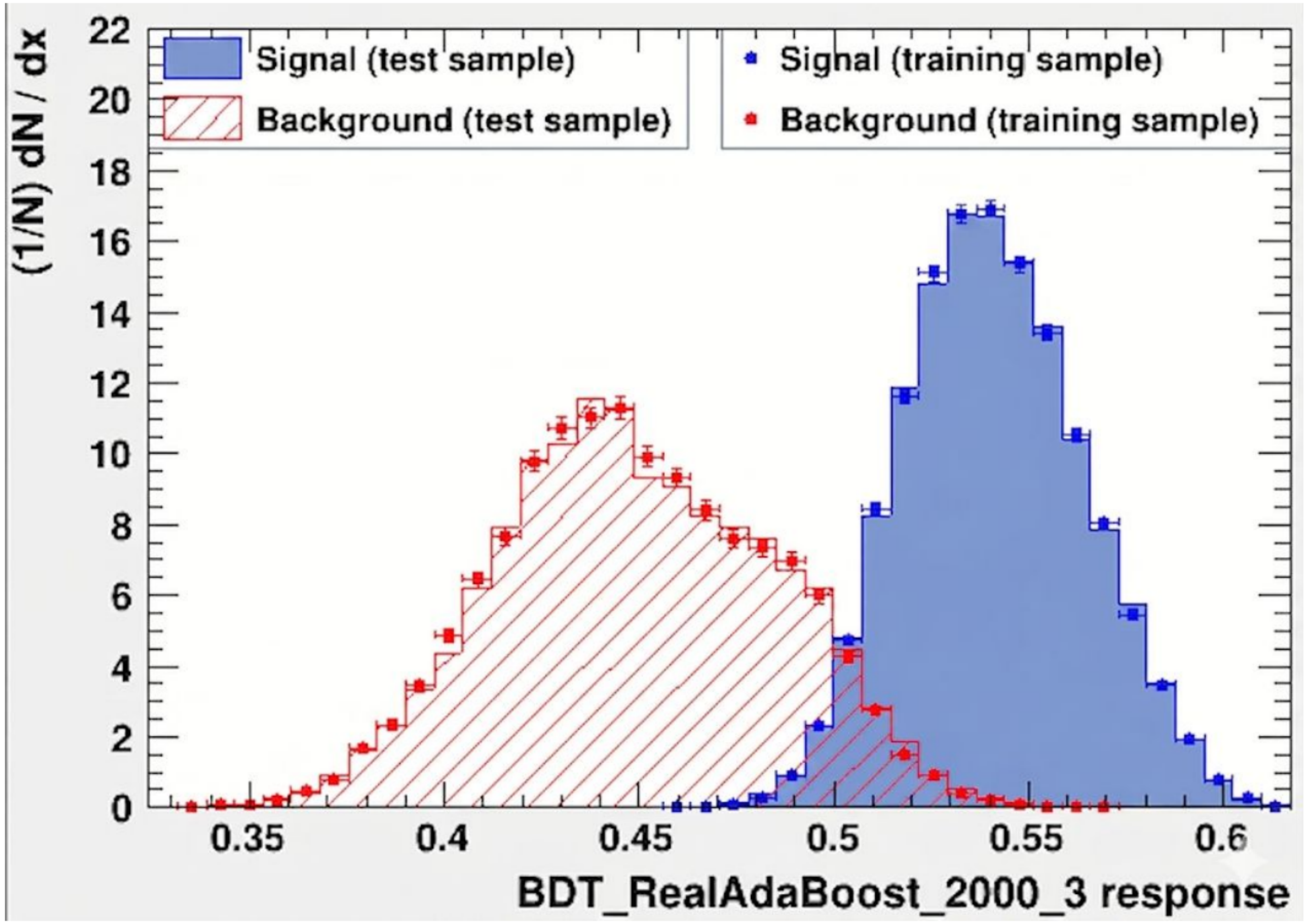
Boosted Decision Tree (BDT)

Method

Statistical combination of several decision trees for improved classification. Sequential application of cuts over 371 days of data.

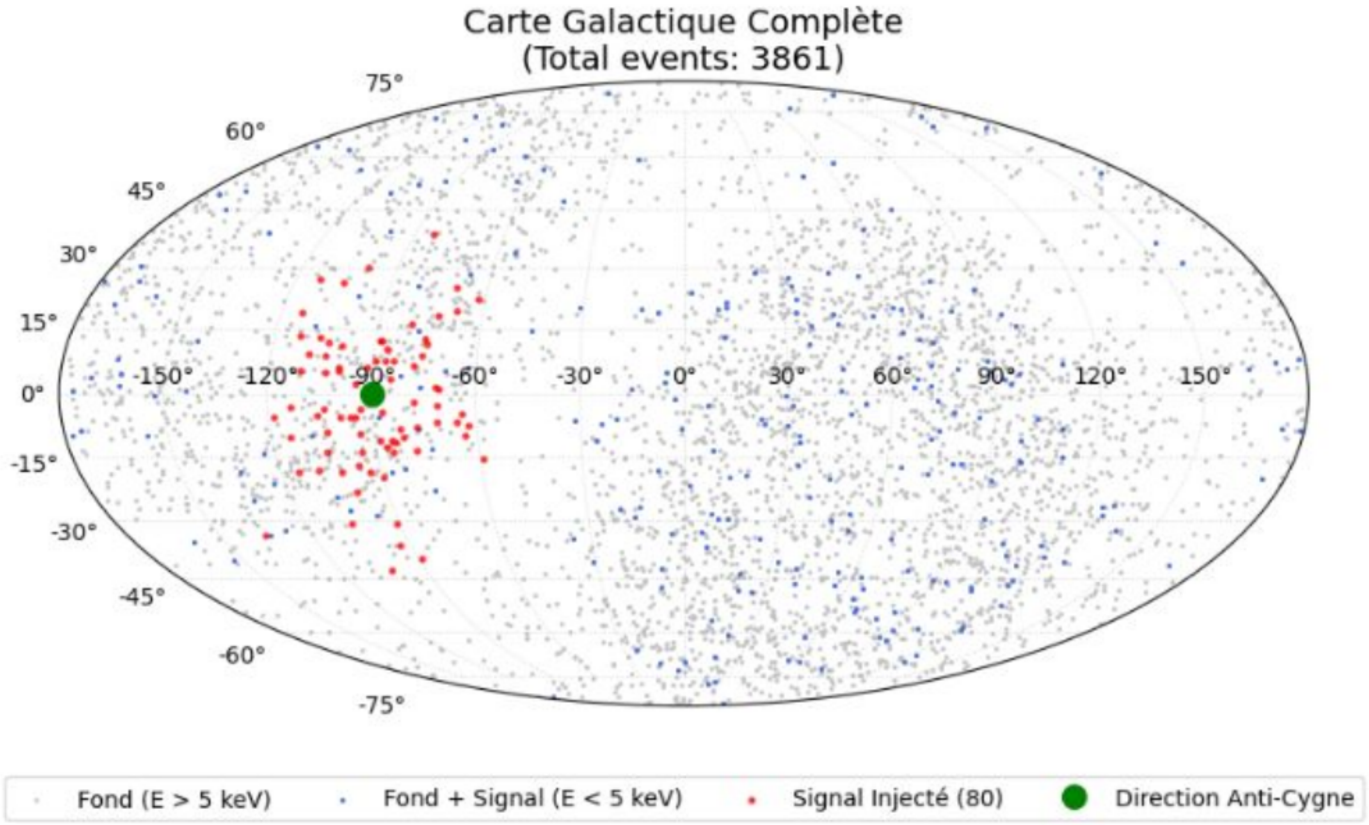
BDT variables

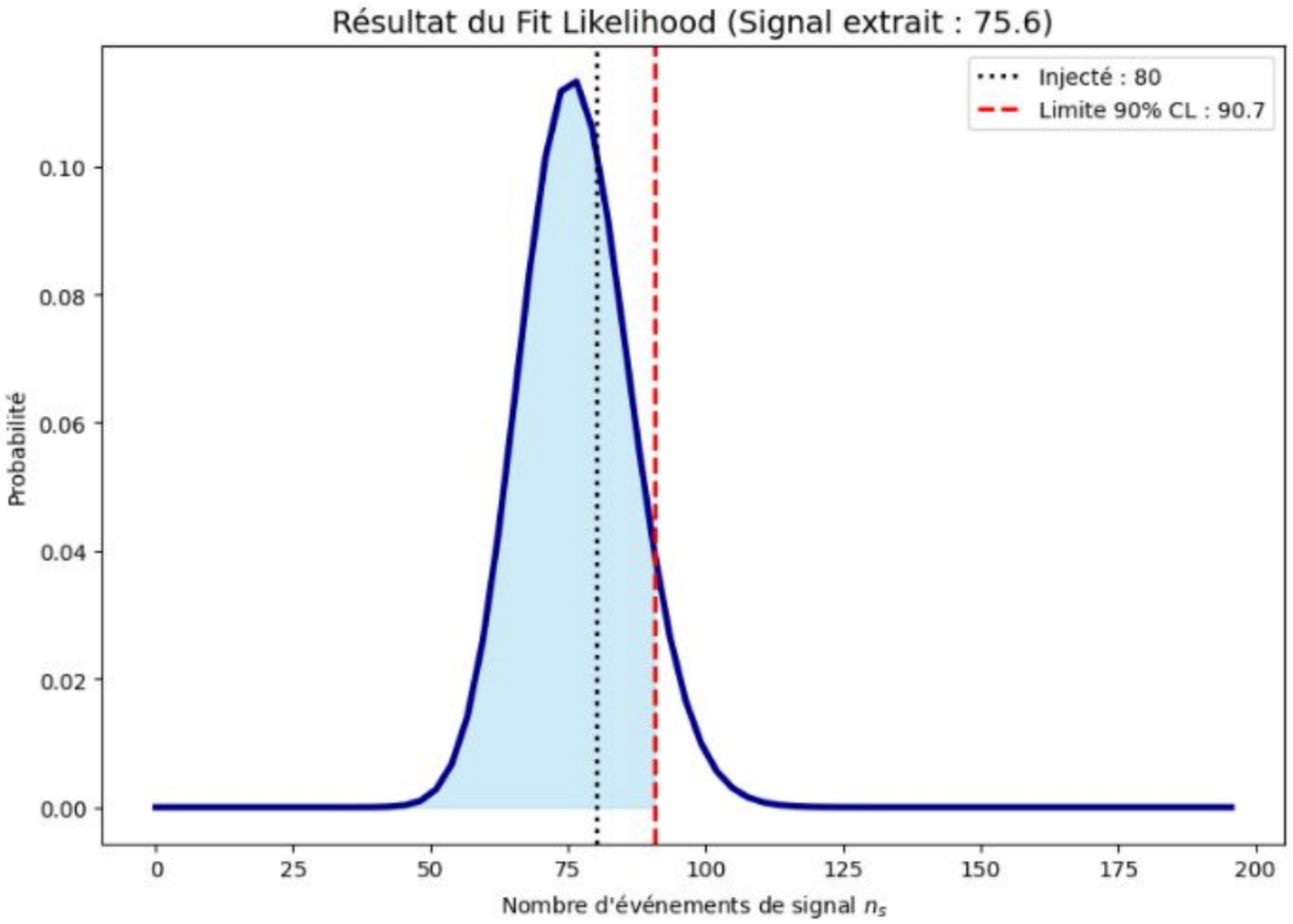
- Number of TimeSlices > 4
- Track length
- Number of pixels / Energy
- Number of peaks
- Track width



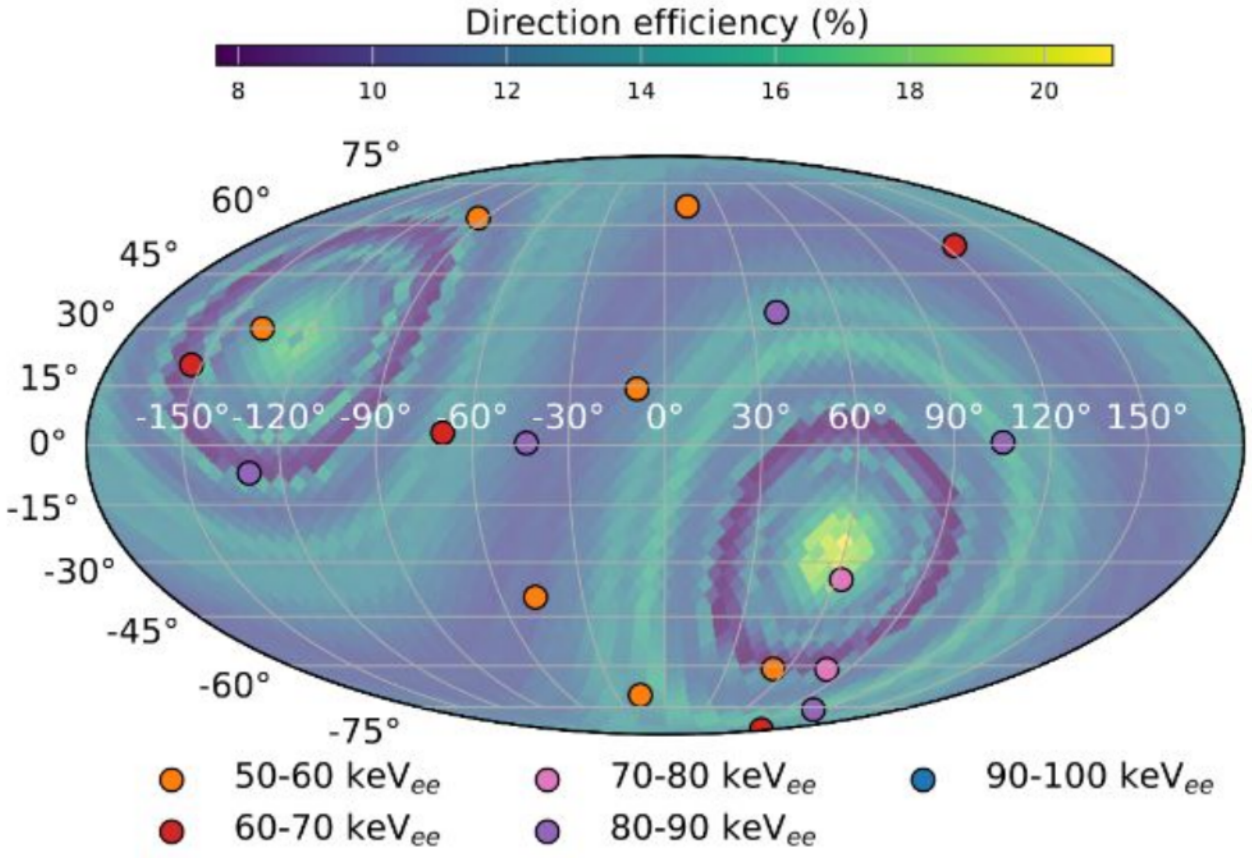
$$\text{Score}_{BDT} = \sum(\alpha_m \quad \text{prediction}_m)$$

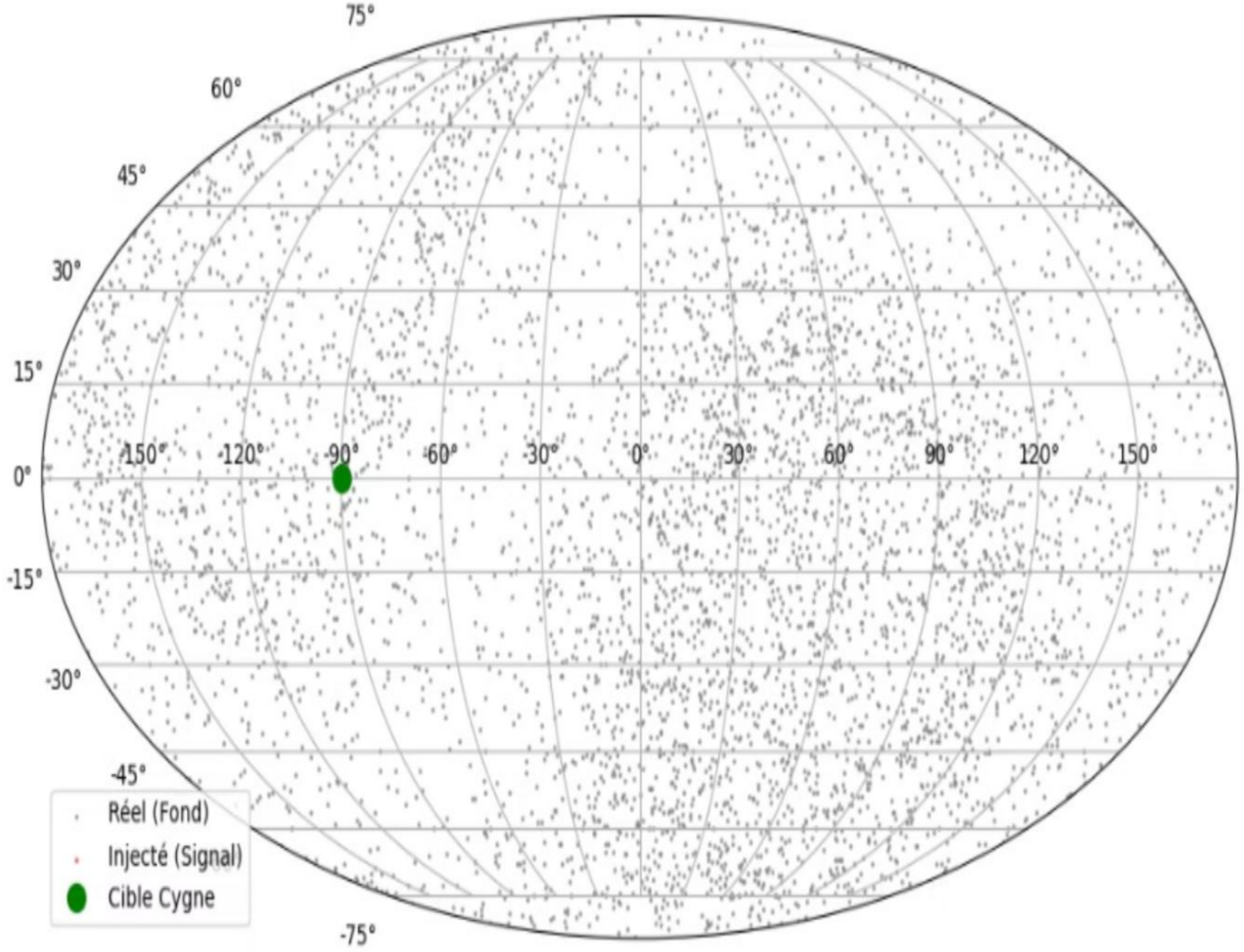
Signal Injection





- Model Band (E > 5.0 keV): 3611 events
- Analysis Band (E < 5.0 keV): 250 events
- Injected Signal: 80
- Extracted Signal (Fit): 75.57
- Upper Limit (90% CL): 90.7


Direction efficiency (%)
8
10
12
14
16
18
20
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
-150°
-120°
-90°
-60°
-30°
0°
30°
60°
90°
120°
150°
● 50-60 keV$_{ee}$
● 60-70 keV$_{ee}$
● 70-80 keV$_{ee}$
● 80-90 keV$_{ee}$
● 90-100 keV$_{ee}$


75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-75°
-150°
-120°
-90°
-60°
-30°
0°
30°
60°
90°
120°
150°
Réel (Fond)
Injecté (Signal)
Cible Cygne