IRN Terascale @ LPSC

Directional detection of WIMPs with MIMAC

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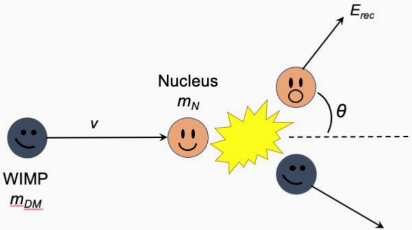
Presentation based on CB et al., JCAP 08 (2022) 057, arXiv 2112.12469

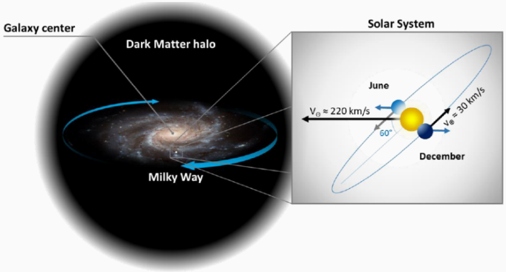
Directional detection of WIMPs

DIRECT DETECTION = measuring the energy of a WIMP-induced nuclear recoil

$$E_{\mathrm{rec}} = 2v^2 \frac{m_N\, m_{\mathrm{DM}}^2}{(m_{\mathrm{DM}} + m_N)^2} \cos^2\theta$$



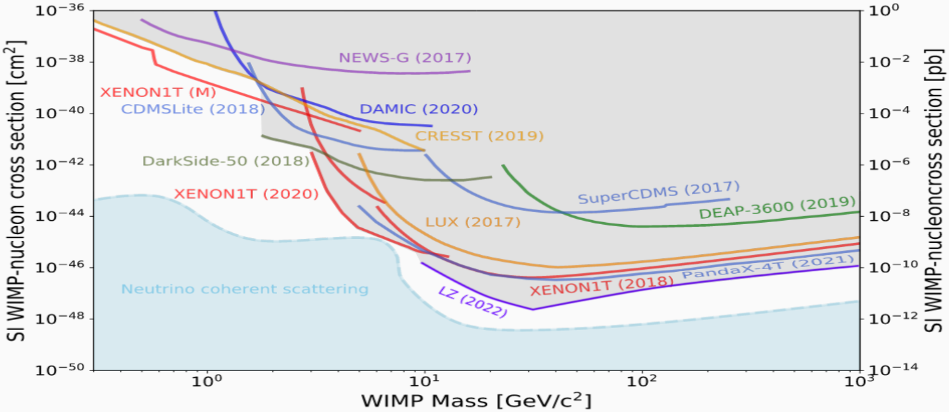
Credit: A. Monte



Credit: A. Zani

The motion of the solar system in the WIMP halo surrounding the galaxy induces a **"wind" of WIMP** on Earth

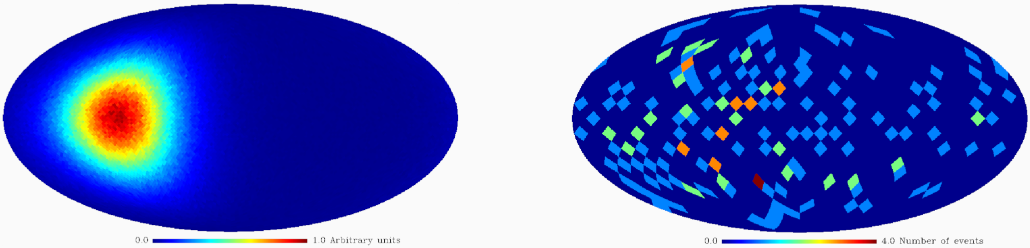
$\Longrightarrow$ **The favoured incoming WIMP direction is known**



Adapted from P.A. Zyla et al., PDG 2020

$\Longrightarrow$ Direct detection is approaching the neutrino fog

$\Longrightarrow$ If a WIMP-like signal is measured, **direct detection cannot prove its galactic origin**



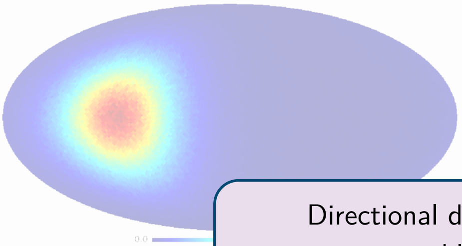
Left: WIMP flux. Right: simulation of 100 WIMP-induced recoils and 100 background events.
J. Billard et al., 0911.4086

DIRECTIONAL DETECTION = **measuring the energy AND the direction**of a nuclear recoil

Unique signature due to the anisotropy of the WIMP flux

$\Longrightarrow$ Can go inside the neutrino fog

$\Longrightarrow$ Enable WIMP discovery



Directional detection is the only strategy enabling WIMP discovery

Left: W... flux. Right: simulation of 100 WIMP-induced recoils and 100 background events.
J. Billard et al., 0911.4086

DIRECTIONAL DETECTION = **measuring the energy AND the direction**of a nuclear recoil

Unique signature due to the anisotropy of the WIMP flux

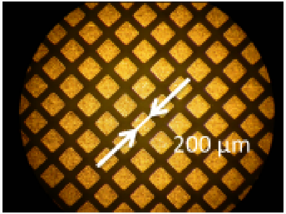
⟹ Can go inside the neutrino fog

⟹ Enable WIMP discovery

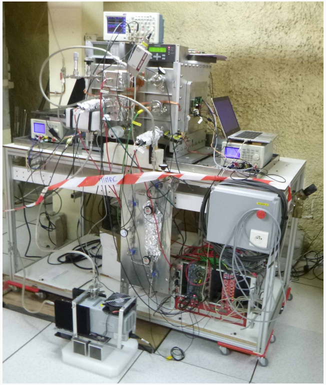
The MIMAC detector

MIMAC

- **Gaseous detector** (i-C_4H_{10} + 50% CHF_3 at 30 mbar)
- **Measure the ionization energy and reconstruct the 3D track**
- $E_K \in [50\,\mathrm{eV}, 15\,\mathrm{keV}]$
- Volume of 62 L that can be duplicated

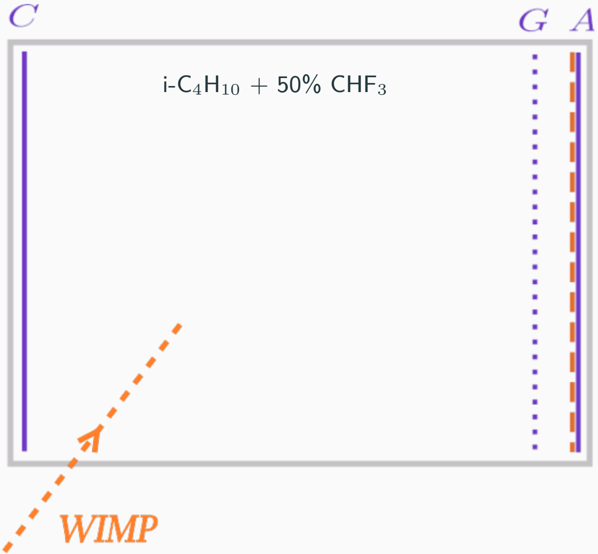


The pixelated anode

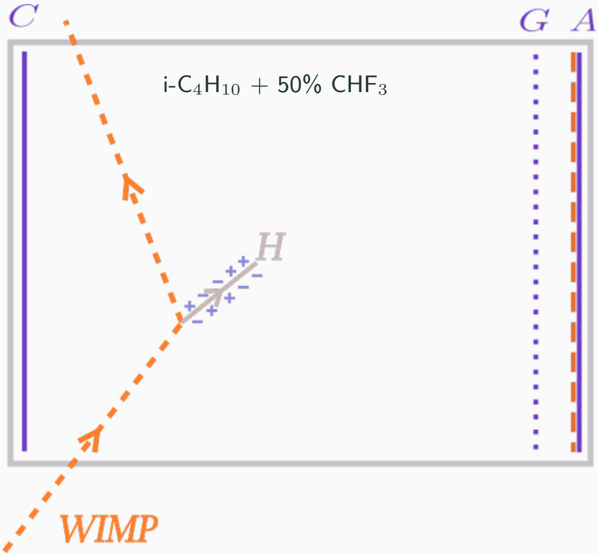


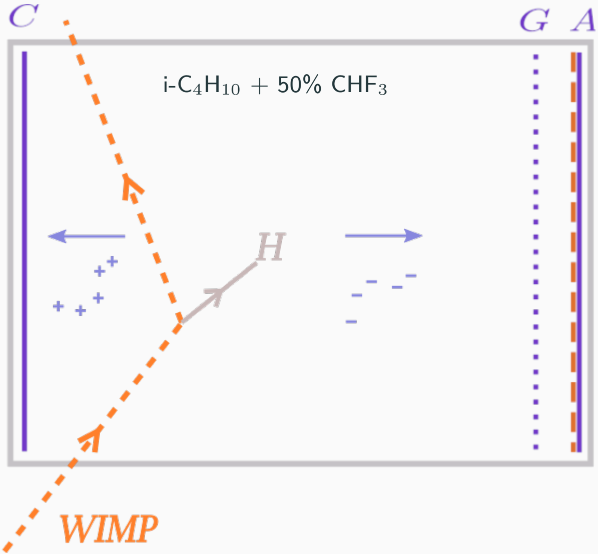
Bi-chamber module

- Pixelated anode (pitch of 424 μm)
- **Sampling at 50 MHz (20 ns)**



C
G
A
i-C_4H_{10} + 50% CHF_3
WIMP


C
G
A
i-C_4H_{10} + 50% CHF_3
H
WIMP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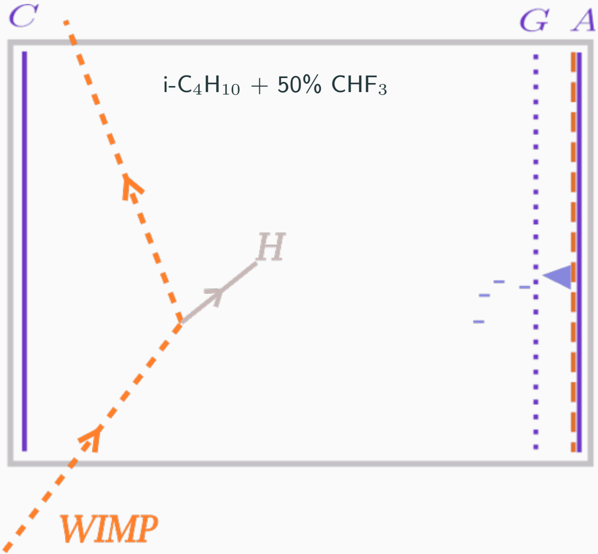

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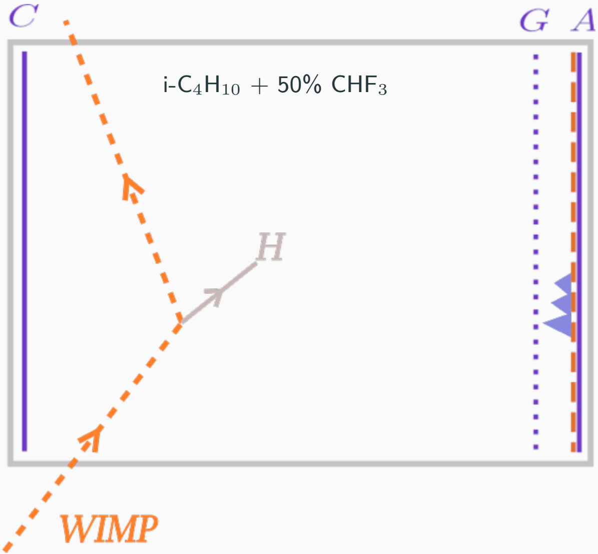
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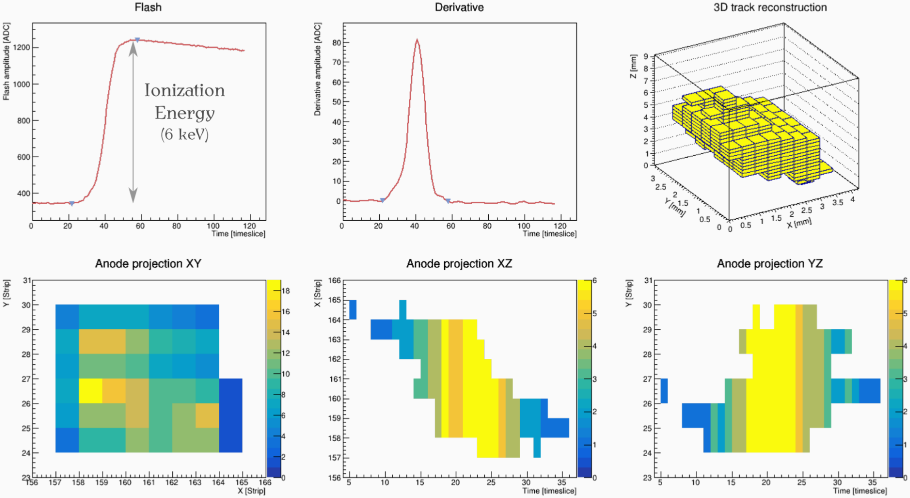


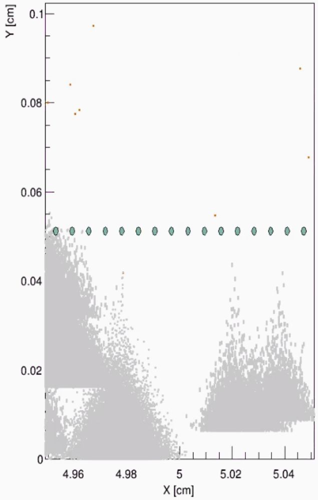
Measurement of a neutron-induced proton recoil with $E_K = 8.6$ keV

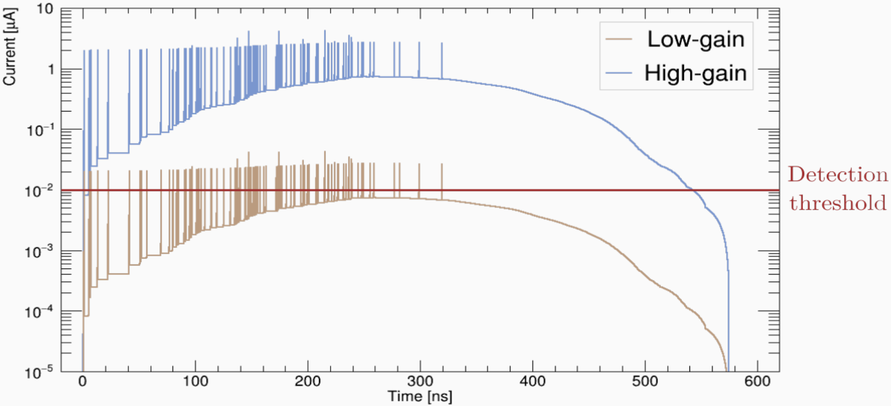
The 3D track distortions at high-gain

The WIMP would induce nuclear recoils in the keV-range

$\Longrightarrow$ MIMAC must operate at high gain ($> 10^4$)

$\Longrightarrow$ **A large number of ions** ($> 10^6$) produced in the avalanches **accumulate in the detector**



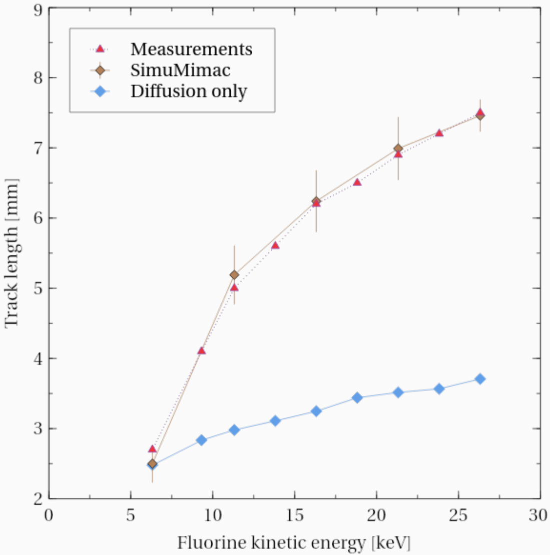


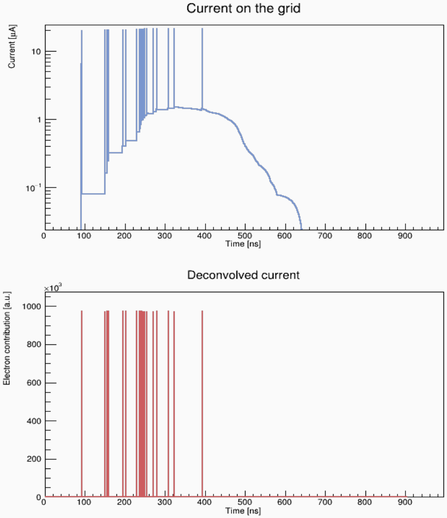
Signal induced by electrons (peaks) and ions (baseline) with different kinematics

$\Longrightarrow$ **Distorts the 3D track reconstruction** but **improves the detector sensitivity**

SimuMimac

- Simulation that models MIMAC at high gain
- **Reproduce the high-gain measurements**
- Demonstrate that the 3D track distortions are due to the ions accumulated near the readout plane





Deconvolution example on simulated data

DECONVOLUTION:

We developed a procedure to extract the electronic current from the measured charge

⟹ No parameter required

⟹ **Can be applied to any measurements**

Head-tail recognition:

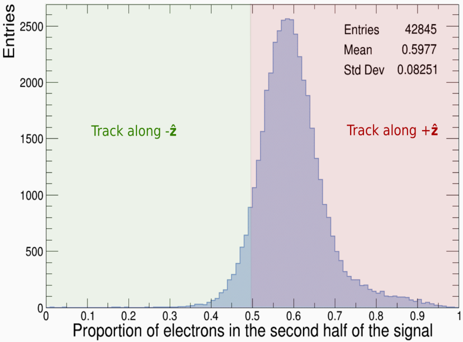
Measuring the direction

AND the sense of the nuclear recoil

$\Longrightarrow$ Improves the directional performance

Asymmetry in the charge deposition:

For a nuclear recoil, most of the charges are produced at the beginning of the track



Measurement of 13 keV protons

The deconvolution of the ionic signal reveals the fine-structure of the primary electrons cloud

$\Longrightarrow$ Gives access to head-tail recognition for tracks along the Z-axis

Head-tail recognition:

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AND the sense of the nuclear recoil

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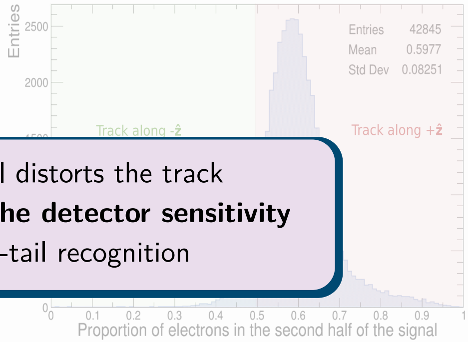


Measurement of 13 keV protons

Asymmetry in

For a nuclear rec

produced at the

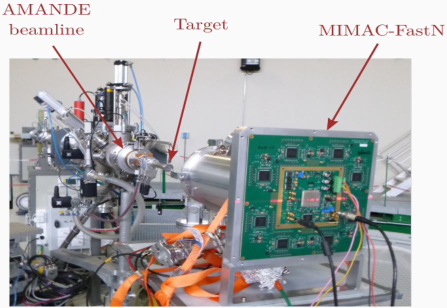
At high gain, the ionic signal distorts the track reconstruction **while improving the detector sensitivity** and giving access to head-tail recognition

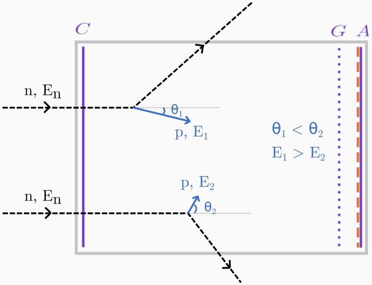
The deconvolution of the ionic signal reveals the fine-structure of the primary electrons cloud

$\Longrightarrow$ Gives access to head-tail recognition for tracks along the Z-axis

Directional performance of MIMAC

Measurement of the directional performance of MIMAC

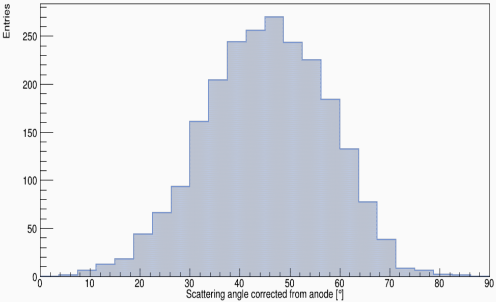




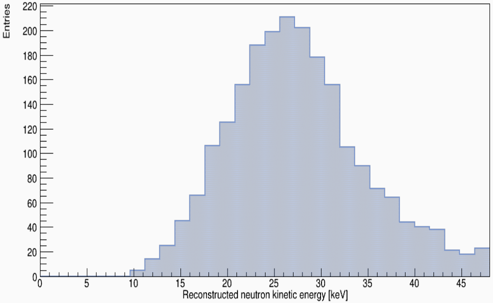
⟹ The AMANDE facility produces mono-energetic neutron fields at $27\,\mathrm{keV}$ and $8\,\mathrm{keV}$

⟹ **The neutrons produce proton recoils at different angles** in the detector with kinetic energies given by

$$E_p = E_n \cos^2 \theta$$



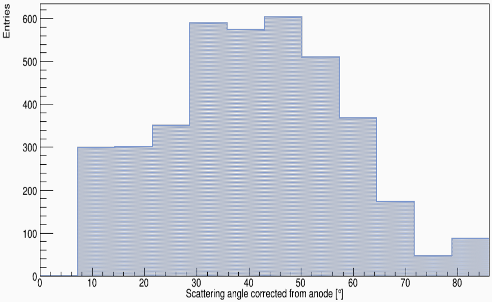
Angular distribution



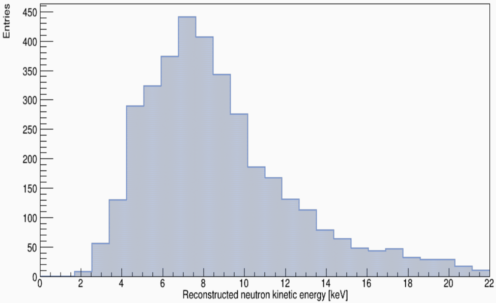
Reconstructed spectrum

Directional performance at 27 keV:

- $\Longrightarrow$ Energy reconstructed agrees within 4% with the energy of the neutron source
- $\Longrightarrow$ Directional threshold at 4 keV kinetic
- $\Longrightarrow$ **Angular resolution better than 12°**
- $\Longrightarrow$ **Embeds all systematics!**(calibration, IQF, energy resolution, angle reconstruction, background discrimination)



Angular distribution



Reconstructed spectrum

DIRECTIONAL PERFORMANCE AT 8 keV:

$\Longrightarrow$ Energy reconstructed agrees within 9.0%

$\Longrightarrow$ Directional threshold at 2 keV kinetic

$\Longrightarrow$ **Angular resolution better than 15°**

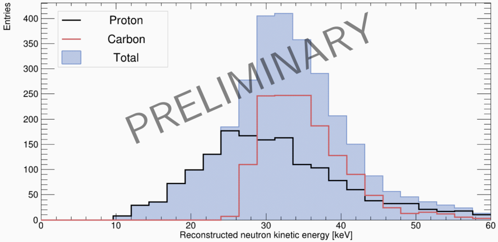
$\Longrightarrow$ **World-leading directional performance**

Summary and outlook

Summary

- **Directional detection is the only admitted strategy to discover WIMPs** even in the presence of a background
  $\Longrightarrow$ Requires to measure the direction of WIMP-induced nuclear recoils in the keV-range
- At high-gain ($> 10^4$), the large number of accumulated ions in MIMAC has two main consequences:
  $\Longrightarrow$ **Distorts the reconstructed 3D tracks**
  $\Longrightarrow$ **Improves the detector sensibility**
- From simulations and experiments, **we exploited the information contained in the 3D track distortions** to improve the directional performance of MIMAC
  $\Longrightarrow$ Access to **head-tail recognition** for protons with $E > 13$ keV along the electric field lines
  $\Longrightarrow$ **15° angular resolution to proton recoils in the keV-range**
  $\Longrightarrow$ Demonstrate that directional detection is now able to search for WIMPs with masses above few GeVs

Outlook



Application to AMANDE 27 keV data

A new method:

Development of a new method that would **exploit the entire measured information**

- Would relate the measured charge to the reconstructed 3D track

Preliminary analysis:

- Provides similar angular resolution than the deconvolution method
- Handles poly-energetic neutron field
- **Gives access to directionality on carbon recoils**

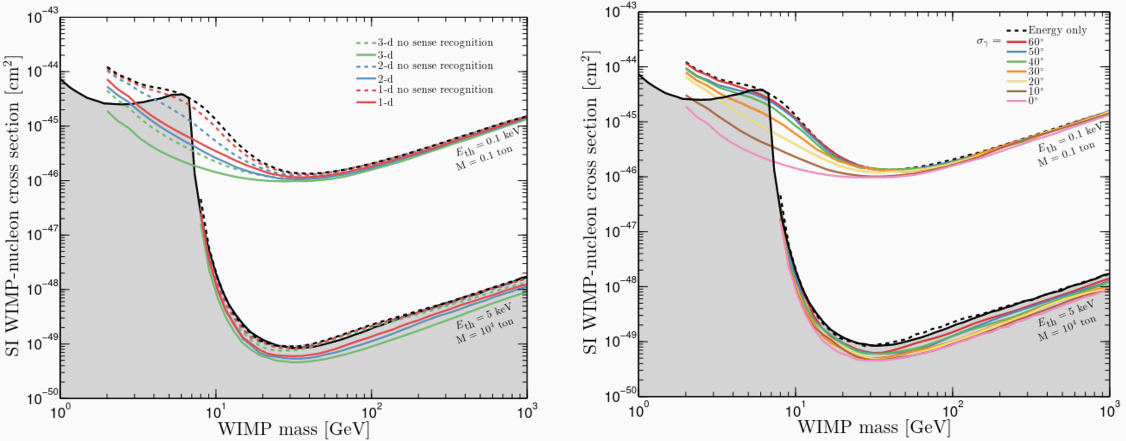
Next steps:

New AMANDE measurements have been performed (March 2023). Goals of the analysis:

- Validate the new method
- Quantify the head-tail recognition efficiency
- Quantify the angular resolution on carbon recoils

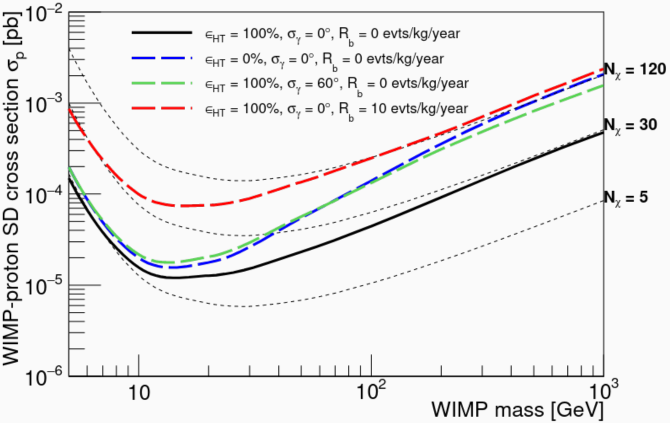
Backup

Neutrino fog



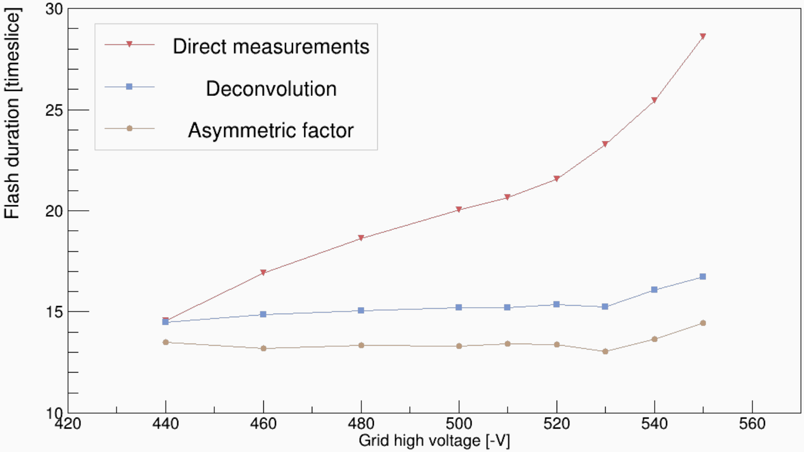
Entering the neutrino fog. Detector using Xe target and an exposure time of one year.
C.A.J. O'Hare et al., 1505.08061

Discovery potential



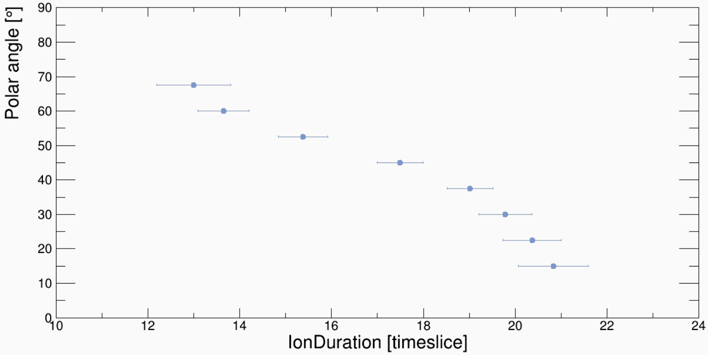
3σ discovery potential of directional detection at 90% confidence level. Estimations for a 30 kg·year CF_4 directional detector with an energy range of [5, 50 keV].

F. Mayet et al., 1602.03781



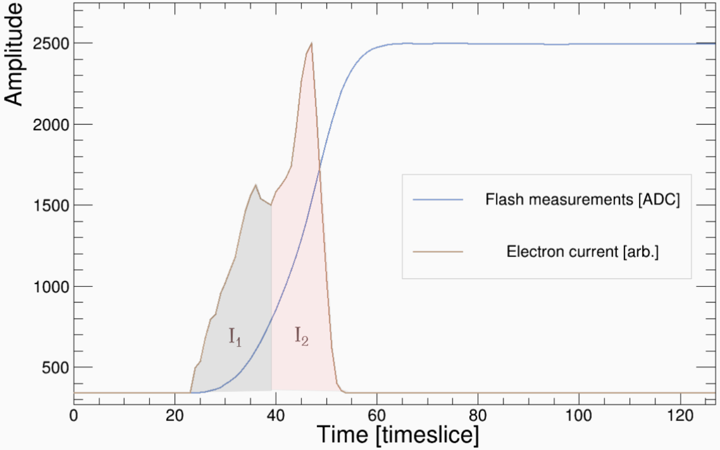
5 keV electrons in i-C_4H_{10} + 50% CHF_3 at 30 mbar

Angle reconstruction

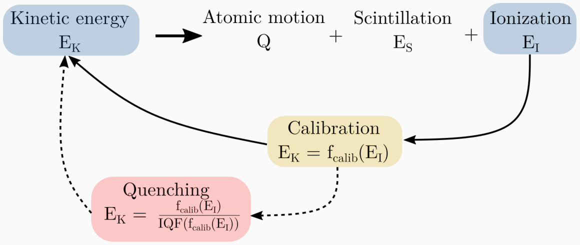


Simulation of the correlation between the polar angle and IonDuration

Head-tail



Flash and deconvolution of a 13 keV proton. Head-tail ratio $= I_2/(I_1 + I_2)$.



For nuclear recoils or ions

IQF = conversion function from E_I to E_K after calibration

Since the electrons are used as energy reference (calibration), $\mathrm{IQF(E_K)} = \left.\frac{E_I^{ion}}{E_I^{elec.}}\right|_{E_K}$

The IQF is a crucial quantity for ionization detectors