DUPhy GDR Kickoff meeting

Directionality and 3D tracks in the (sub)keV range with the MIMAC detector

In the framework of searches for **WIMP** and **ALP**

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- 31 May 2021 -

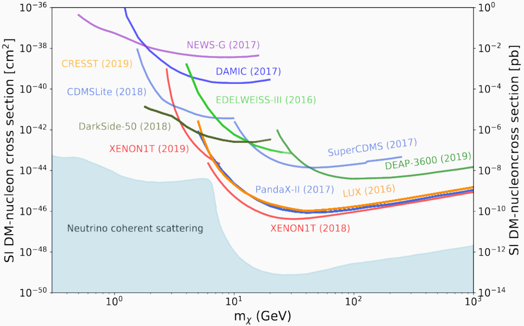
In collaboration with CPPM and CEA-Saclay

Plan

THE MIMAC DETECTOR	– Principle of directional detection – The detector
DIRECTIONALITY ON NUCLEAR RECOILS AT HIGH GAIN	– Diffusion and angular resolution – SimuMimac
LOW-ENERGY ELECTRONS	– 3D tracks – Number of primary electrons

The MIMAC detector

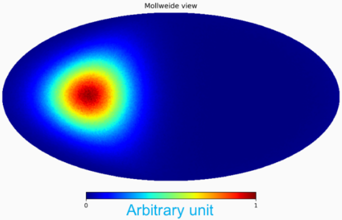
MIMAC - Principle of directional detection



Particle Data Group, **2020**

The main projects searching for WIMPs are approaching the **neutrino floor**

$\Longleftrightarrow$ Irreducible background



Galactic map of the WIMP angular distribution

Tao *et al.*, 2003.11812

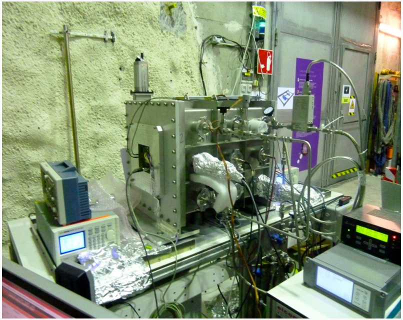
- Anisotropy of the WIMP flux
- **Measuring the direction of the nuclear recoil**
  - $\Longrightarrow$ Enable to overpass the neutrino floor
  - $\Longrightarrow$ **Unambiguous detection**

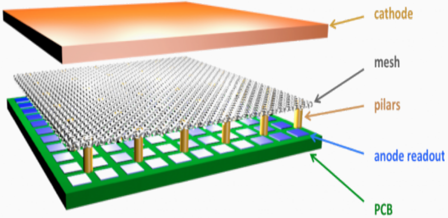
$\Longleftrightarrow$ Principle of directional detection

MIMAC - The detector (1/3)

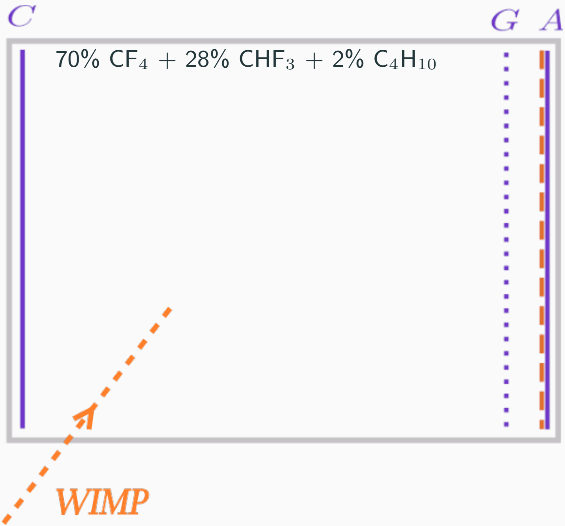
MIMAC = MIcro-TPC MAtrix of Chambers

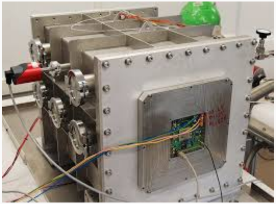
- Directional detector
- Gaseous detector → adapt the properties (target mass, spin, pressure)
- Low pressure ($\sim 30\,\mathrm{mbar}$)
- **Measure simultaneously the energy and the 3D track**
- $E_K \in [50\,\mathrm{eV}, 30\,\mathrm{MeV}]$
- Based on a Micromegas with a **pixelated anode**



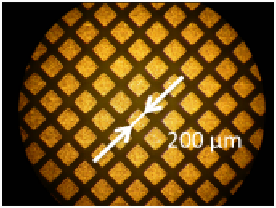


- Micromegas concept -

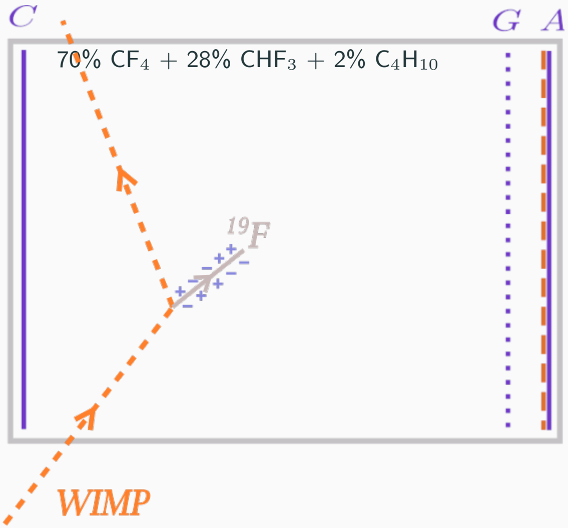


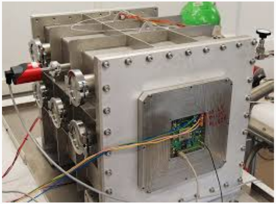


MIMAC bi-chamber



Anode





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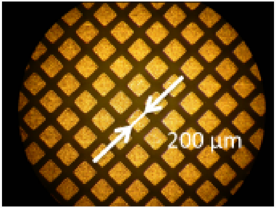

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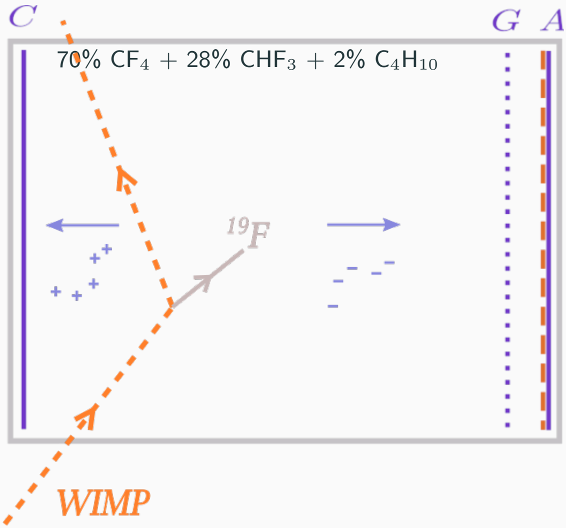

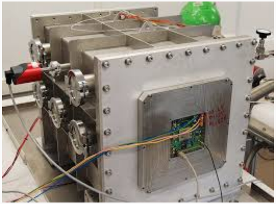

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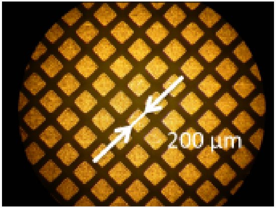

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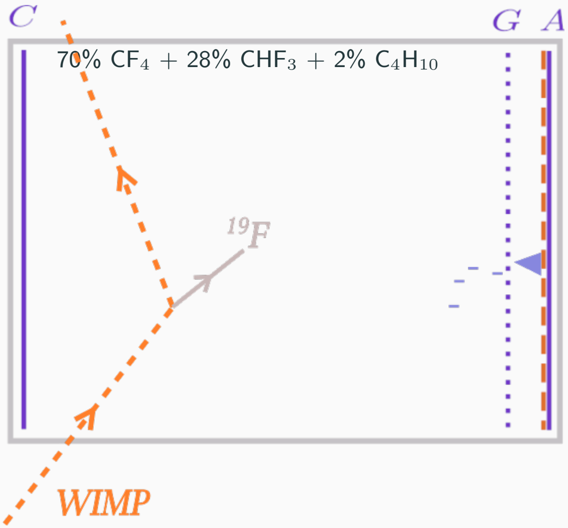

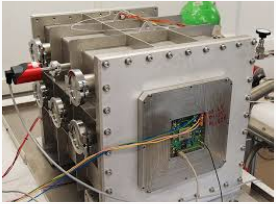

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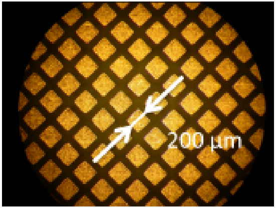

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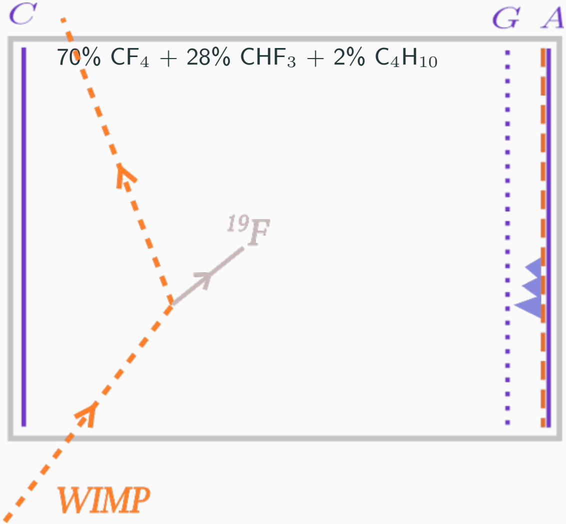

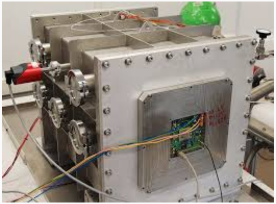

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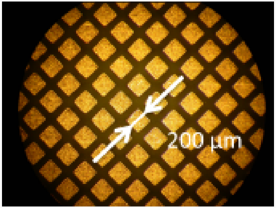

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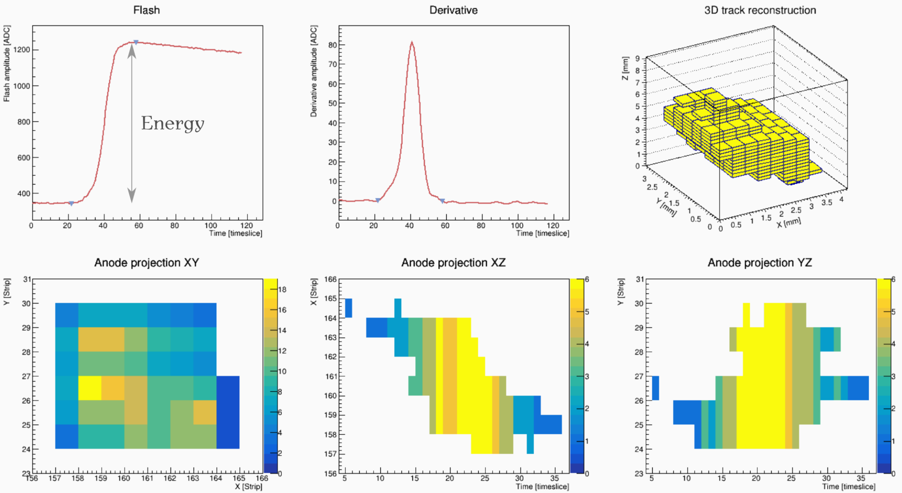
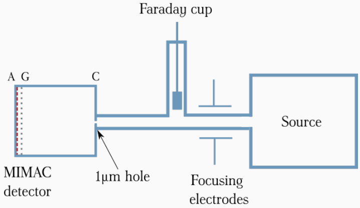
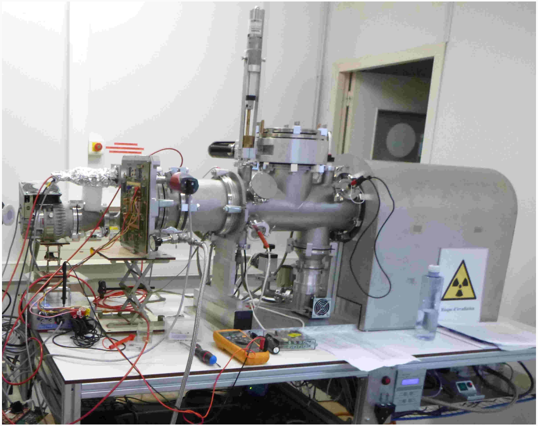


Example of a proton recoil of $6\,\mathrm{keV_{ee}}$ $(8.6\,\mathrm{keV_{nr}})$

$\longrightarrow$ Sampling at $50\,\mathrm{MHz}\,(20\,\mathrm{ns})$

Comimac = source of ions and electrons of controlled kinetic energy coupled to a MIMAC chamber





Directionality on nuclear recoils at high gain

Low-mass WIMP ⇒ Low-energy recoils ($E_R \lesssim 20\,\mathrm{keV}$) ⇒ Few directional information

⟺ **High-gain** to detect all the charges

⟺ **Challenging!**

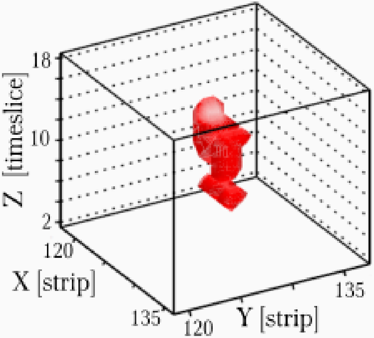
Examples of track lengths before diffusion (SRIM):

- $10\,\mathrm{keV}$ ^{19}F $\longrightarrow$ $320\,\mu\mathrm{m}$
- $10\,\mathrm{keV}$ proton $\longrightarrow$ $2.7\,\mathrm{mm}$

The **diffusion** enlarges the size of the primary cloud by about one order of magnitude

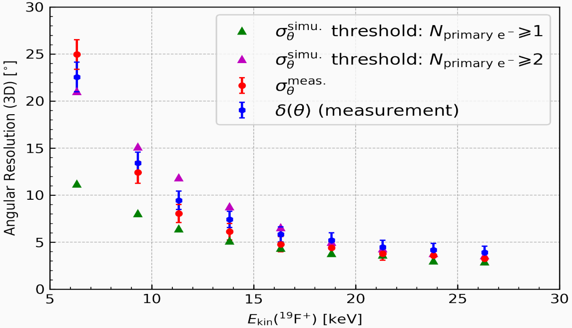
⟹ Distorts the cloud...

⟹ ... but **opens the window for detection of sub-mm tracks**



3D track reconstruction of a $6.32\,\mathrm{keV}$ fluorine

Tao *et al.*, 1903.02159



Measured and simulated angular resolution at 0°

Tao *et al.*, 2003.11812

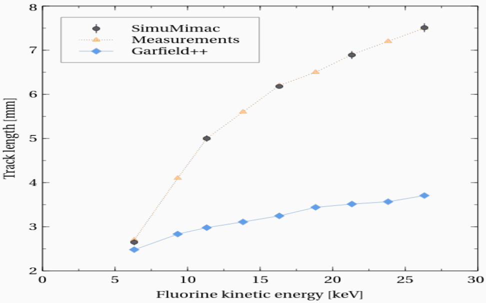
For fluorine ions, we measured an angular resolution below 10° for $E_K > 10\,\mathrm{keV}$

$\Longrightarrow$ **Twice better than requirements** for a directional detector (Billard *et al.*, 1110.6079)

$\Longrightarrow$ 0° is the optimal configuration, the resolution must now be determined at any angle

Directionality at high gain - SimuMimac (1/2)

At high-gain, **measurements and simulations used to strongly disagree**



Measured and simulated fluorine track lengths

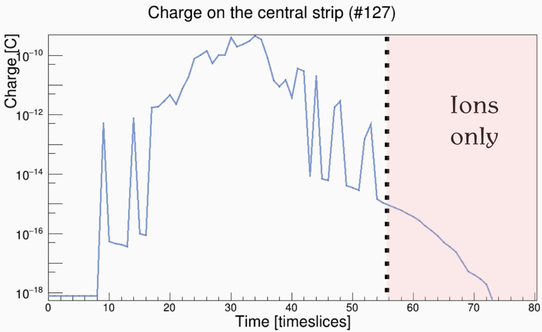
We developed `SimuMimac` (C.Beaufort 2021), a simulation tool based on `SRIM` and `Garfield++` to model the physics of the detector from the primary electron cloud to the signal formation

- `SimuMimac` agrees with the measurements
- Main difference with standard simulation code = **takes into account the current induced by the motion of the ions**

Directionality at high gain - SimuMimac (2/2)

- Current induced by the charges (*Ramo theorem*):

  $$i(t) = \sum_{k=i,e} q_k \, \mathbf{E}_{w,k} \cdot \mathbf{v}_k \quad \text{with } \mathbf{v}_e \sim 10^3 \, \mathbf{v}_i$$
- Ions induce smaller currents than electrons but they remain longer in the gap
- At large gain, the ionic contribution
  - is non-negligible
  - **elongates the signal**



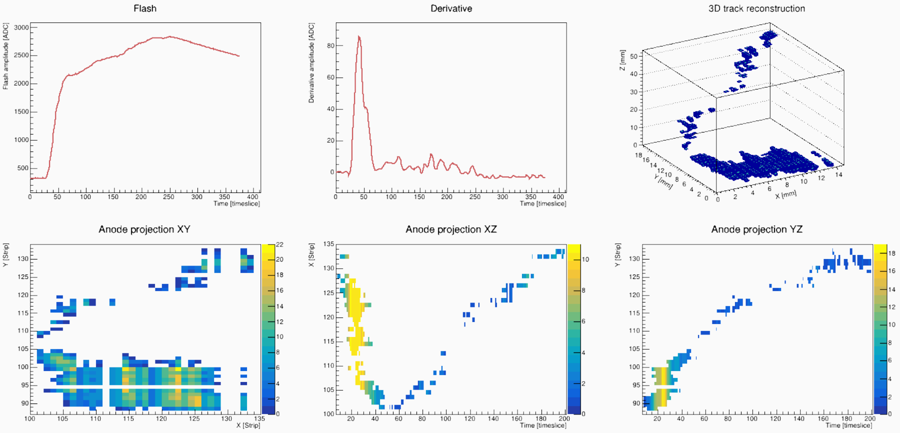
Next step: **to deconvolve the ionic signal**

$\Longrightarrow$ should improve the directional performances

Low energy electrons

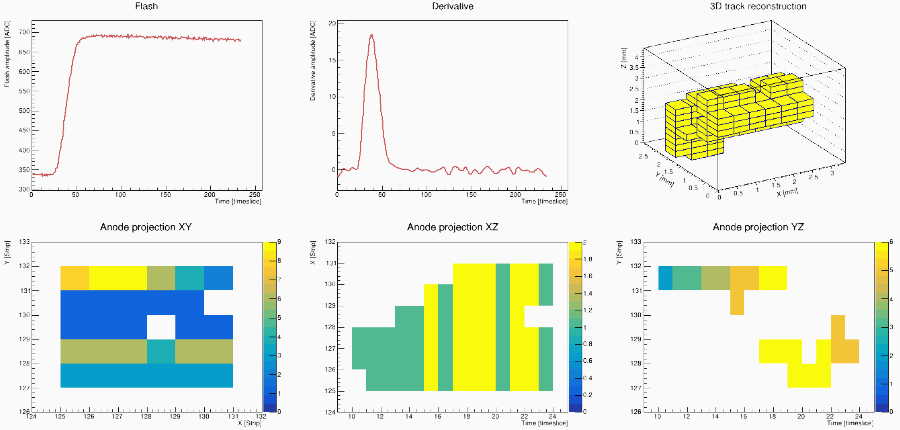
Electrons - 3D tracks (1/2)

MIMAC can measure 3D electrons tracks and study the complexity of the low-energy background



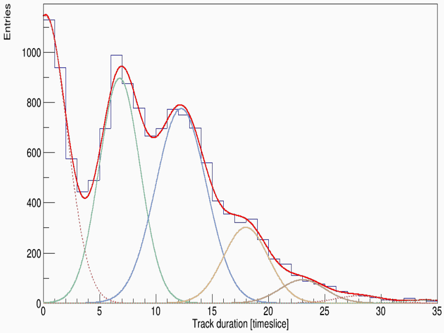
Example of a $12\,\mathrm{keV}$ electron track

Electrons - 3D tracks (2/2)

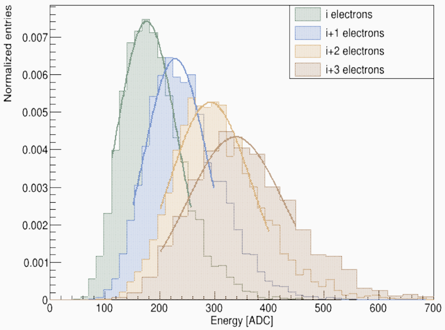


Example of a $150\,\mathrm{eV}$ (!) electron track

For low energy electrons (here $250\,\mathrm{eV}$) we observe several populations with Gaussian energy distributions



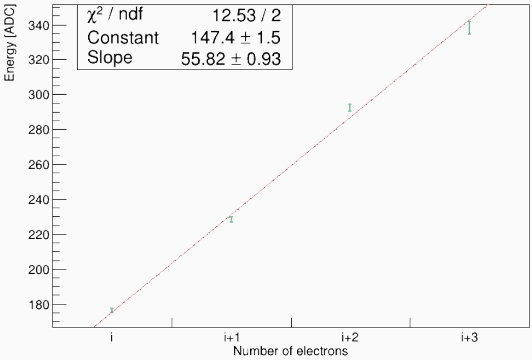
Duration of the signal on the anode



Corresponding energies of the populations

The number of primary electrons, μ, follows a Conway-Maxwell-Poisson distribution
$\Longrightarrow$ we observe one population for each value of μ

The gain per primary electron is linear



Gain per primary electron

⟹ MIMAC is sensitive to each primary electrons when operating at high-gain

Conclusion

Conclusion

- MIMAC searches for low-mass WIMPs **using the directional information to discriminate the background**
- The directional information is difficult to access for fluorine recoils with energies below $10\,\mathrm{keV_{nr}}$
  $\Longrightarrow$ Diffusion seems to improve the resolution for short tracks
- At high gain, **the large number of ions accumulated in the gap distorts the signal**
  $\Longrightarrow$ We developed `SimuMimac` that correctly describes the physics of the detector
  $\Longrightarrow$ We must find a way to deconvolve the ionic contribution to improve the angular resolution
- MIMAC can study low energy electrons
  - **sensitive to the fluctuation of the number of primary electrons**
  - the 3D tracks down to $150\,\mathrm{eV}$ can help in understanding the background

Backup

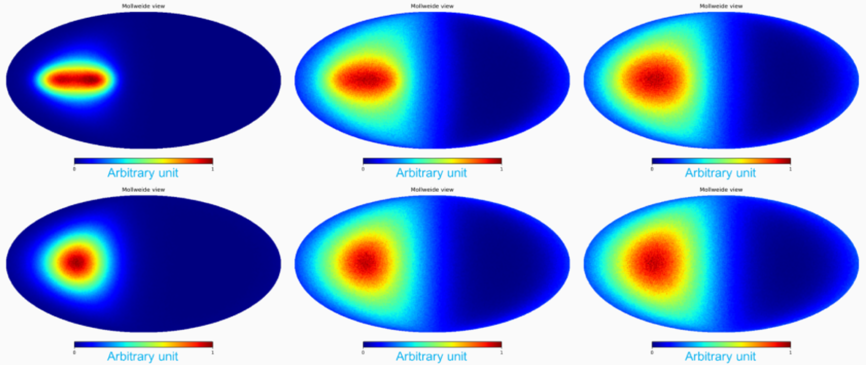
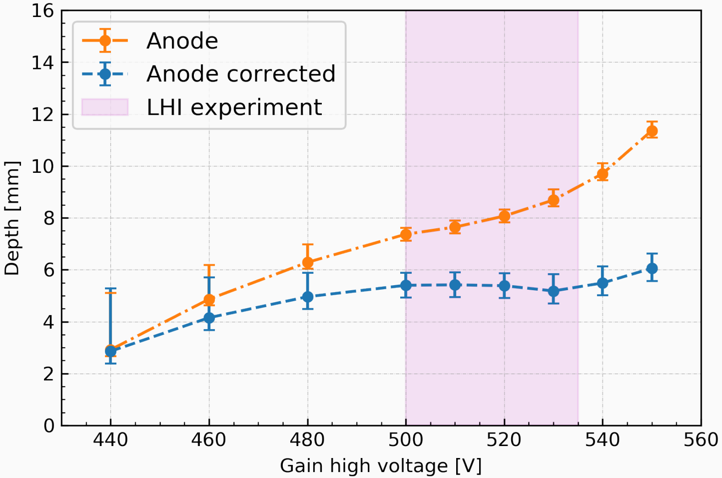


Figure 12. From left to right : WIMP angular distribution, WIMP-induced recoil angular distribution with perfect resolution and with finite resolution (15°). Top: Pure halo component model with $r = 0.0$. Bottom: Two-component model with $r = 0.5$.

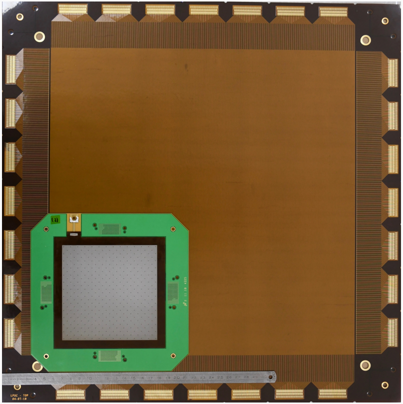
Tao, Beaufort *et al.*, 2003.11812

Gain curve

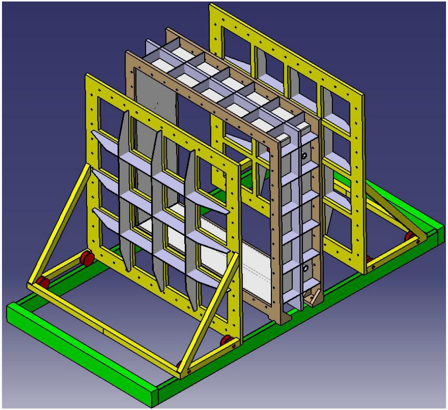


Tao, Beaufort *et al.*, 1903.02159

Mimac $2m^3$



35 cm Micromegas



Module for a $2m^3$ detector

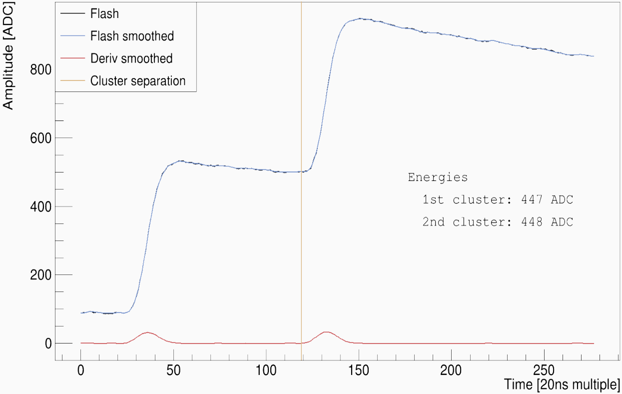
MIMAC $2m^3$ = 16 bi-chamber modules of $2 * 35 * 35 * 52\,\mathrm{cm}^3$

New anode technology

Kaluza-Klein axions

$a \rightarrow \gamma\gamma$ SIGNATURE:

- 2 photons of same energy emitted back-to-back $\Longrightarrow$ photoelectric effect
- Search for 2 electrons of same energy ($\sim 4\,\mathrm{keV}$) close to each other



We use Comimac at high-rate to generate a pile-up of two electrons of same energy ($4\,\mathrm{keV}$) in one time window

$\Longrightarrow$ **Unambiguous signature**, almost no background event can reproduce such signal

$\Longrightarrow$ From Monte Carlo simulations, we estimate 70% of efficiency of detection

Comimac and Ionization Quenching Factor

COMIMAC = source of ions and electrons of known kinetic energy

- $E_K \in [150\,\text{eV}\,,\,30\,\text{keV}]$
- Accurate tool: $\delta E_K \sim 1\%$
- Developed at LPSC

USED FOR:

- Calibration
- Physical measurements (track length, straggling, diffusion)
- Ions/electrons comparison

QUENCHING FACTOR:

- $Q = E_{ioni}/E_K = f(E_K,\ Z,\ p,\ \text{gas})$
- Crucial measurements to determine the kinetic energy of a recoil from the measured ionization energy