MIMAC: MIcro-tpc MAtrix of Chambers

I- Directional Dark Matter Direct Detection

1- Introduction

Astrophysical observations have been converging for several decades towards a standard model cosmological and justify the hypothesis of the existence of Dark Matter (DM) both on a large scale and on the local scale of our galaxy. Direct detection of particles constituting this DM has been a major challenge in physics for several decades [1]. The Weakly Interacting Massive Particle (WIMP) acts as a leading non-baryonic DM candidate. While the main direct detection projects keep improving their sensitivity [2], they will soon reach the neutrino floor beyond which a WIMP signal cannot be distinguished from the background [3]. Neutrons produced in the rock and the atmosphere and neutrinos by their coherent dispersion on the nuclei constitute the ultimate background for this type of detection. A DM-nucleus scattering will induce a nuclear recoil with an anisotropic angular distribution correlated with the Earth's motion [5, 6]. The directional detection strategy relies on the simultaneous measurements of the energy and the direction of a DM-induced nuclear recoil for the identification of a DM particle without ambiguity [4, 7]. This directional information is generally measured in gaseous detectors, from the ionization signal [8, 9] or via the optical readout [10], or by exploiting nuclear emulsions in solid detectors [11]. The complete reconstruction of the direction of a nuclear recoil also requires discrimination between the head and the tail of the track, usually established through measurements of a charge asymmetry [12].
The project MIMAC (MIcro-tpc MAtrix of Chambers) is developing a directional DM detector, thus allowing us to count on a new, unique, and necessary signature, the directionality, in order to correlate the relative movement of our solar system around the galactic center with the rare event detected in the detector. The current state of the direct search for non-baryonic dark matter shows efforts considerable in order to detect nuclear recoils that would come from elastic collisions with WIMPs (Weakly Interacting Massive Particles) by discriminating them from the background. These events will be "candidates" to be validated by other direct detection experiments but the only convincing signature of the provenance of a collision with a WIMP of the galactic halo is the directionality. At the same time, the search for low-energy nuclear recoils (E< 10 keV) presents an additional difficulty arising from the quenching in ionization and scintillation which limit the signal accessible to the detection and in general are estimated or measured with significant uncertainties.
The "discovery" parameter is the nuclear recoil track direction which would be correlated to the direction defined by the tangent to the orbit of our solar system around the galactic center which is identified by the direction towards the Constellation Cygnus. The directions of the nuclear recoils allow the construction of a map in galactic coordinates of the events [13]. We have also shown that directionality opens the way to the characterization of the DM-particle's mass and the galactic halo's shape [14].

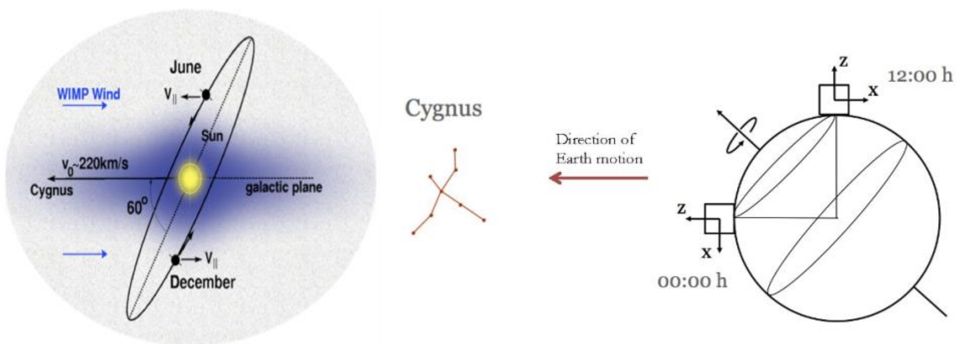

Figure 1: (Left) Scheme showing our solar system movement with respect to the galactic center and the elliptical orbit of the Earth around the Sun. The WIMP wind direction produced by the relative motion is indicated. (Right) A drawing showing how the Earth's rotation changes the orientation of the WIMP direction.

The directional search for dark matter is an international effort developing different types of detectors (DRIFT, DMTPC, Newage, MIMAC, Emulsions). This community proposes an international workshop every two years (CYGNUS).

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2. State of the art

In the international context, several projects aim to carry out the directional detection of dark matter in an ionization chamber being the most important: DRIFT (USA, UK) [EA1], DM-TPC (USA) [EA2], Newage (Japan) [EA3], CYGNO and MIMAC (France) [EA4]. The different projects were summarized in a collective work [EA5].
The different types of gas detectors are:
i) Wire chambers, with a pitch of 2 mm, using the negative ion collection (CS2) in Drift [EA1]
ii) Ionization chamber with a mesh plus a CCD camera (2D) in DM-TPC[EA2]
iii) Micro-dots associated with an ADC flash in Newage [EA3]
iv) GEMs with an optical readout [EA9]
iv) Pixelated Micromegas coupled with fast, self-triggered electronics in MIMAC[EA4].

The specificity of MIMAC is to be able to reconstruct tracks in 3D at energies of the order of keV and to be able to extrapolate this detection strategy to large detection volumes thanks to the repetition of the same two-chamber module. The fact that the number of expected events increases exponentially at low energy shows the importance of relying on a detection threshold of around 100 eV and also being able to count on the measurement of the ionization quenching factor.

Another development path is emulsion detectors [EA6] and certain R&D projects on liquids [EA7] and crystals [EA8]. We published an article comparing different directional search strategies [10]. In any case, all these projects on directionality show the difficulty of such detection, and international competition is both tough and varied.

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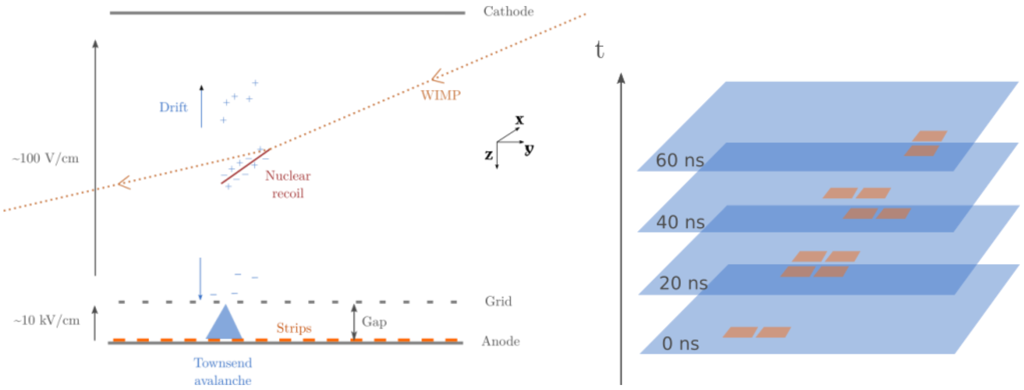
3. Project

The MIMAC (Micro-tpc Matrix of Chambers) project proposes to construct a large matrix of micro-TPC at low pressure (30-50 mbar) in order to detect 3D nuclear recoil tracks by ionization. The target nuclei can be adapted in mass and/or spin in order to optimize the transfer of kinetic energy and the interaction cross-section. The preferred target nuclei for the moment have been: 1H, 19F, 4He, 12C,. The matrix is designed from identical bi-chamber modules (two chambers with a common cathode) which will allow us to better control the intrinsic background and be able to make the coincidence between the different chambers. The detector of each chamber is a micro-TPC, pixelated Micromegas type coupled with fast self-triggered electronics specially developed by LPSC-Grenoble.



(a) A MIMAC chamber: a TPC coupled with a pixelated Micromegas

(b) 3D track reconstruction

Figure 2: Schematic of the MIMAC detection principle. A WIMP induces a nuclear recoil that ionizes the gas. The primary charges drift along the electric field lines direction, i.e. along the Z-axis, towards the grid. They enter the amplification area where they produce avalanches. The signals induced on the grid and on the pixelated anode are measured every 20 ns.

The purpose of the next 2 years is to complete the new bi-chamber module with the new 35x35 cm^2 low-noise detectors. This module will be the base of a future MIMAC matrix to be built when the directional detection of rare events will be required by an international collaboration, for the moment in progress.

4. Genesis and Developments

The MIMAC project began in 2005 with the development of an experimental line for the measurement of the ionization quenching factors at the LPSC by an original method. In 2007, we obtained an ANR-Blanc (400 k€) with the IRFU-Saclay and the Laboratory of Metrology and Neutron Dosimetry (LMDN) of the IRSN (Institute of Radioprotection and Nuclear Safety) as partners with the purpose to build the first MIMAC chamber prototype. The contribution of the I. Giomataris and the IRFU-Saclay team has helped to define and design the first 10x10 cm^2 pixelated micromegas bulk. The collaboration with the LMDN has opened access to monoenergetic neutron fields of metrological quality produced by the AMANDE accelerator (Cadarache) which allowed us to validate our first single-chamber prototype of the MIMAC detector. Since then, some of the most important developments have been the following:

I. Installation and operation of the two-chamber module prototype at LSM

In July 2012, we installed the first two-chamber module at the Modane Underground Laboratory (LSM). We observed excellent gain stability over time thanks to a gas circulation system specially developed for our project. Calibration is carried out by fluorescence, produced on Cd, Fe and Cu sheets, using an X-ray generator, and this with a weekly frequency. We improved the installation in January 2013, correcting a leak in the gas circulation system. Since then, the two-chamber prototype has worked continuously with a weekly calibration up to February 2018. The data gave rise to an article showing for the first time the 3D tracks of the Rn progeny (see point IV) and it is a source of permanent exploration and interesting data still to be explored. Yi Tao and Charling Tao will work on these data in the next months.
From 2/2018 up to 2/2023, we have performed many different measurements at LPSC and profit to upgrade the first version integrating the cathode signal and mounting the new 10x10 cm^2 low-noise detector, see figure. A new X-ray generator has been installed for calibration purposes.

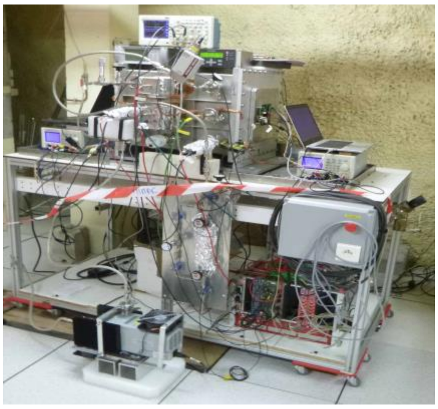


Figure 3: (Left) The present installation at the LSM since 02/2023 and (Right) the former installation up to 2/2018

II. Development of a table-top ion and electron beam facility for ionization quenching factor measurements: COMIMAC

The measurement of the quenching factor in ionization is fundamental in the field of direct detection of dark matter since the nuclear recoil produced by an elastic collision with a WIMP leave an ionization energy different from its kinetic energy. The ratio between the ionization energy left in the detector and the initial kinetic energy of the particle is defined as the quenching factor in ionization. In particular, in a gas, this quenching factor depends on the state of purity of gas and pressure. We have developed a table-top quenching line in order to be able to measure the in-situ quenching factors to control the quenching factors of the gas from a detector installed in an underground laboratory. An article has been published describing the COMIMAC experimental line, see figure 4 and the original method of measurement described in [16].

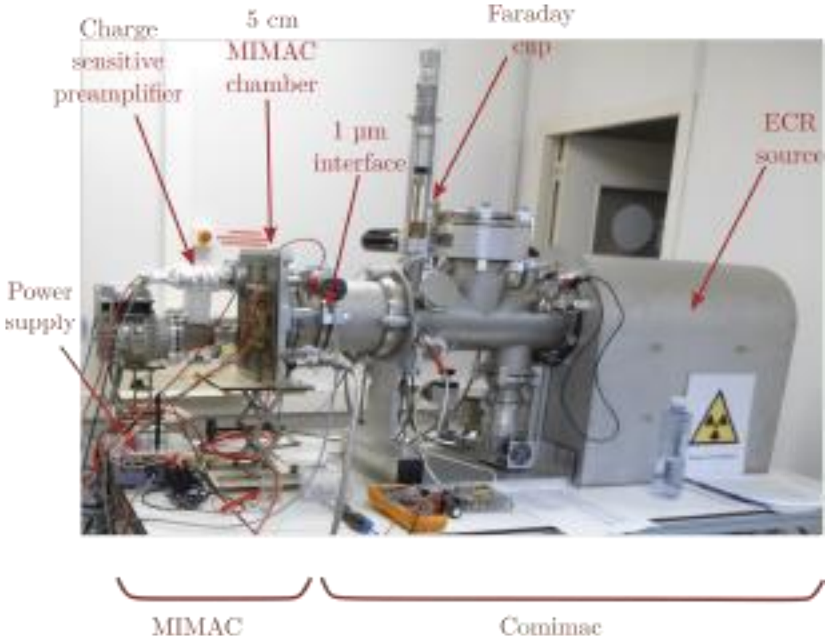


Figure 4: Picture of the experimental setup coupling a MIMAC chamber to the Comimac beamline. The ions and electrons produced by Comimac enter a MIMAC chamber at the cathode level. They are sent parallel to the electric field lines, i.e. along the Z-axis of the detector.

III. Electron-recoil discrimination

One of the major keys to the direct detection of dark matter was measured in the MIMAC gas mixture with monochromatic fast neutrons at Amande (IRSN), see figure 5 and the data analysis using the many MIMAC observables in [12]. The electrons have been produced by the same backing used on the FLi target for neutron production.

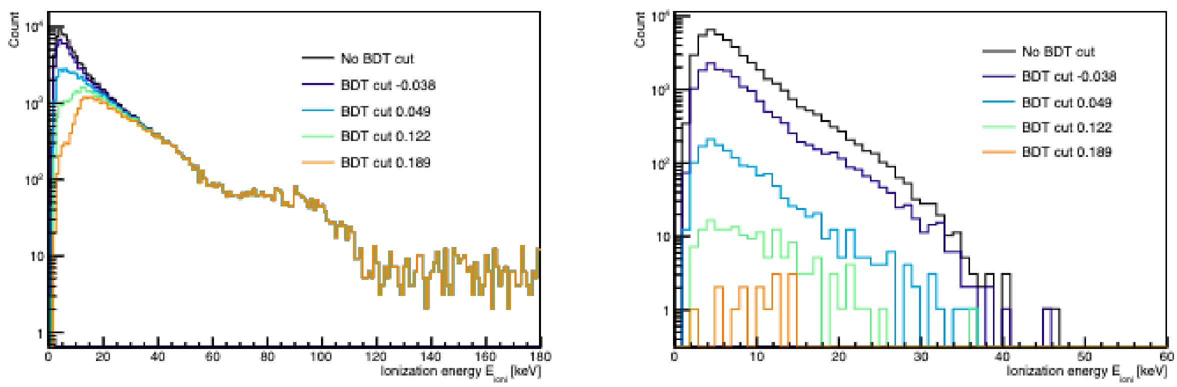


Figure 5: Energy spectra (left panel: with 7Li (electron and nuclear recoil), right panel: without 7Li (electrons only) obtained after the application of cuts on the XBDT value. Black lines represent energy spectra obtained without XBDT cut.

IV. First measurement of 3D tracks of nuclear recoils from Rn progeny.

This measure is truly unique since it constitutes validation of the ability to measure the lengths of low-energy 3D traces, as well as their ionization energy. These events, shown in figure 6, whose kinetic energy is in the range between 100 and 146 keV, only leave ionization between ~30 and ~45 keV in our gas mixture and constitute a background that is found in all detectors, thus being able to serve as a "benchmark" allowing to compare performances among the different detectors [13].

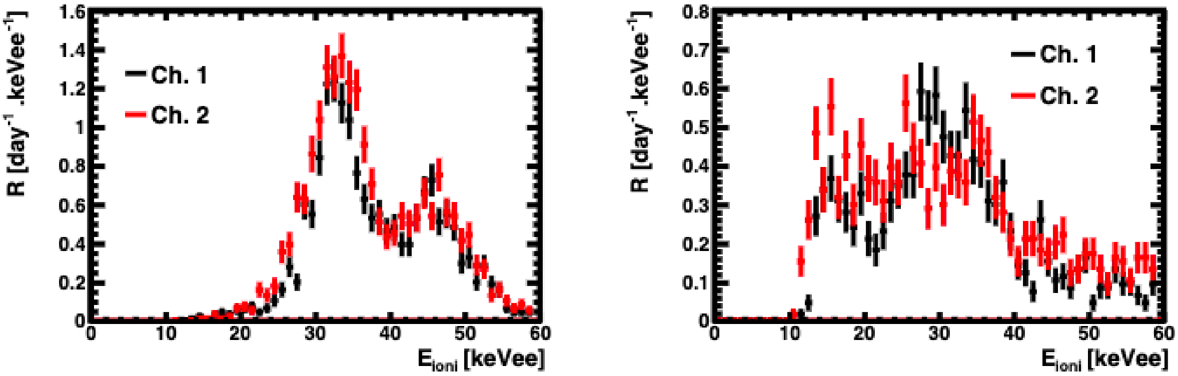


Figure 6: The energy spectra measured in 2013 by chamber 1 (black line) and 2(red line) after ER/NR discrimination with a cut on the event MPD (Mean Projection Diffusion) value. The left panel represents the energy spectra of volume event and cathode events (above the MPD cut) and the right panel the energy spectra of anode and mesh events (below the MPD cut).

V. The cathode signal

The signal induced by the movement of primary electrons during their collection towards the grid, visible before the avalanche, see figure 7 left, was validated and used for measuring the speed of charge collection in a MIMAC chamber [14].

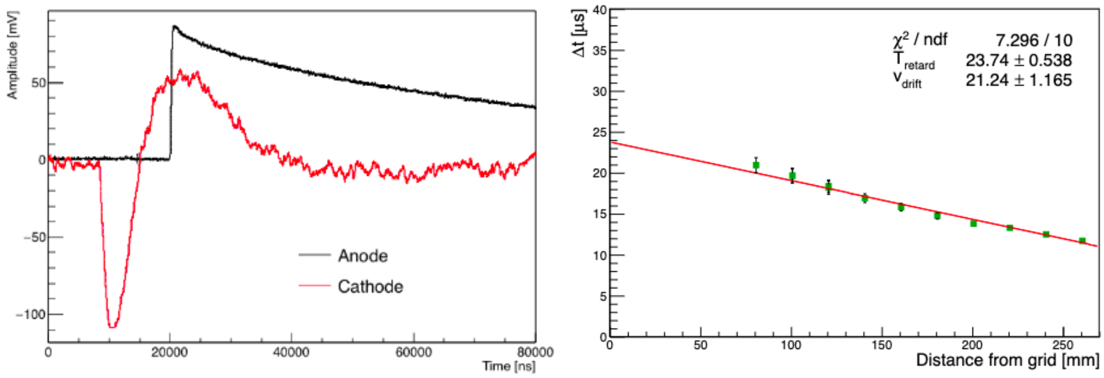


Figure 7:Left: amplitudes of the signals from the cathode preamplifier and from the grid preamplifier as shown on the oscilloscope. Note that here, the cathode signal is not delayed, and is detected before the anode signal. Right: Measure of the time differences (ΔTAC) between the grid signal and the delayed cathode signal as a function of the distance of the α source from the anode (green points) . A linear fit of these points is superimposed in red and provides the values of the drift velocity and the additional delay.

VI. Comparative simulation of different directional techniques (crystals, emulsions, and TPCs).

We published an article clearly showing that the directional information of the nuclear recoil is "preserved" only in the case of low-pressure TPCs [15]. Defining a directional figure of merit D, we have succeeded in showing the differences among the different directional strategies, see figure 8.

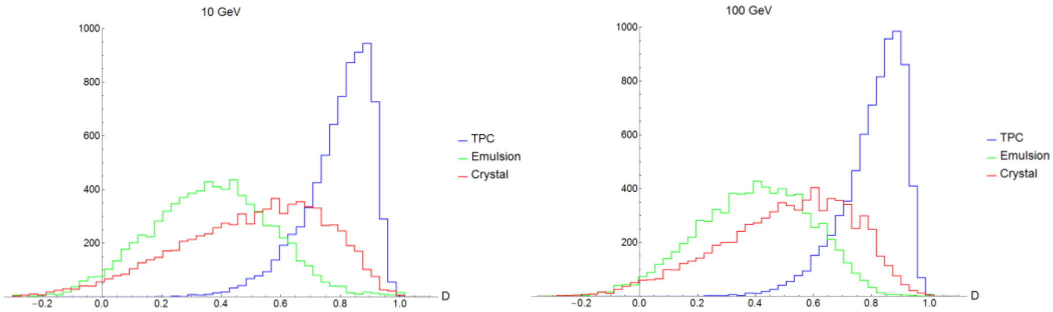


Figure 8: Comparison of the directionality D for the three strategies – gaseous TPC in blue, crystal in red, emulsion in green – for 4 different WIMP masses: 10 and 100 GeV/c2. For all WIMP masses, the simulations of the recoils in the different detector materials lead to higher D values for a gaseous TPC (direction is better preserved); emulsion and crystal show similar, lower distributions of D.

VII. A new low-noise detector (Bas Bruit (BB))

A new low-noise detector has been developed thanks to funding from Labex Enigmass. A new Micromegas type detector was developed for MIMAC by O. Guillaudin (LPSC) using Plexiglass and Kapton instead of PCB. The validation of the 3D- track quality was made in January 2017 for the 10 cm x 10 cm prototype, see figure 9. The first design of the 35 cm detector was finalized in November 2017.

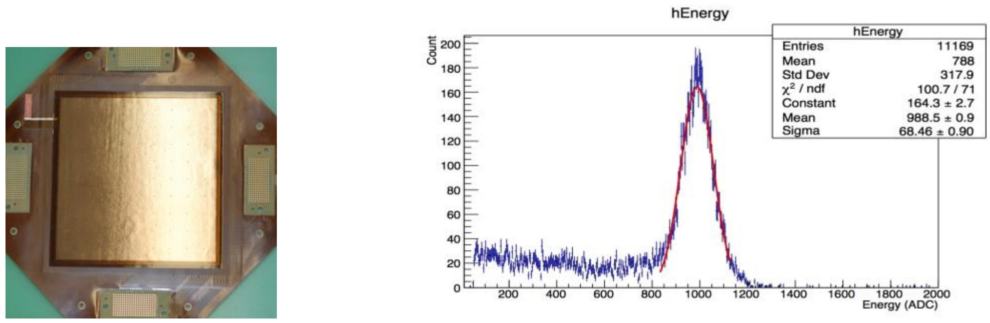


Figure 9: Left: Picture of the new low-noise micromegas bulk 10x10 cm^2. Right: The ^{55}Fe- X-ray at 5,96 keV spectrum of the new detector in our MIMAC gas mixture.

The new 35x35 cm^2 detector represents a real challenge with 1792 electronic channels, see figure 10. A lot of work has been done by O. Guillaudin on the detector design and mechanical aspects and J-L. Bouly, G. Bosson and J. Bouvier on the electronics to develop it. The last two retired in 8/2020. Delays have been managed and absorbed but a huge total delay with respect to the first engagements forced us to still working on the final validation.

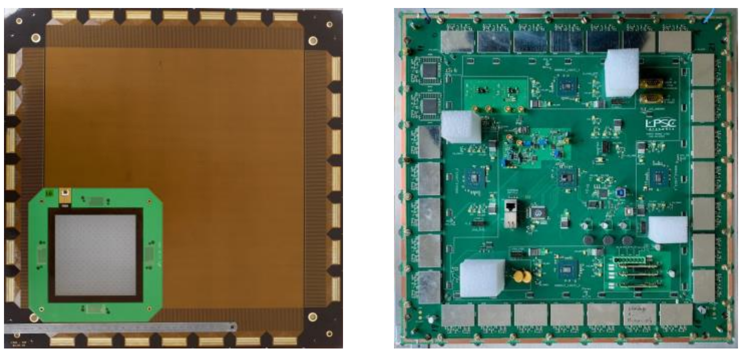


Figure 10: (Left) The new 35x35 cm^2 detector compared with the 10x10 cm^2.
(Right) The 1792 channel-electronic board.

VIII. Collaboration with Tsinghua University and the IHEP (Beijing, China). The presence of Charling Tao in Beijing as a professor at Tsinghua University in 2017 allowed us to establish a very rich collaboration between the two teams. A three-year post-doc as well as a thesis are funded by Tsinghua to work on MIMAC (respectively Dr. Igor Moric and Mr. Yi Tao). These two collaborators came twice for 6 months and 3 months respectively to the LPSC of Grenoble to participate in data analysis and experiments performed on LHI and COMIMAC, on 3D-track measurements, and reconstruction and angular resolution of our directional strategy. They have published their work [22,23]. The IHEP hosts a MIMAC chamber bought by Tsinghua University. We have installed the data acquisition and we performed with the IHEP team and Yi and Igor, neutron and X-ray source measurements at the IHEP in April 2018.

IX. In June 2017, the Chinese teams working on MIMAC organized the workshop international CYGNUS-2017 on directional dark matter detection. The workshop took place in Xichang near the Jinping underground laboratory, with more than 40 participants, see pictures in figure 11and more details about it in (http://www.tir.tw/conf/cygnus2017/).

Figure 11: Pictures taken during the Cygnus-2017 workshop in China. The right picture has been taken at Jinping underground laboratory.

X. 3D-Directionality on nuclear recoils in the keV-range

The deconvolution of the ionic signal produced during the avalanche can lead to additional observables for directionality. Cyprien Beaufort has worked on these new degrees of freedom in the frame of his PhD thesis developing new methods, based on 3D track reconstruction involved in directional detection.
The directional performances of the MIMAC detector have been evaluated experimentally in mono-energetic neutron fields, at 27 and 8 keV at the Amande facility (IRSN-Cadarache) see the set-up in figure 12.
The elastic scattering of neutrons on the nuclei of our gas mixture will produce nuclear recoils. These nuclear recoils will ionize our gas and most of them will be stopped in the active volume. The amount of energy released in ionization compared with the kinetic energy defines the ionization quenching factor (IQF). **Without an IQF measurement of the recoils is not possible to get the kinetic energy of the neutrons.**

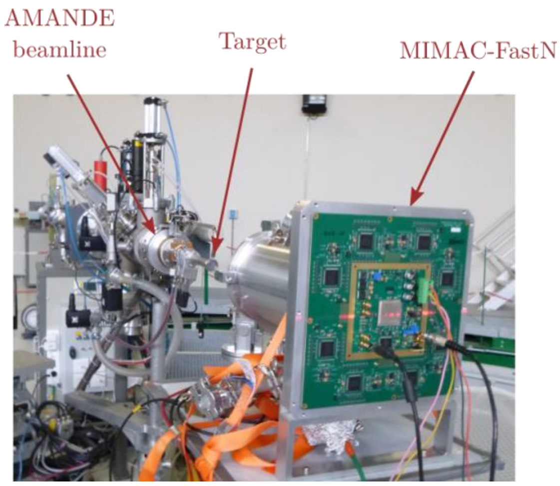


Figure 12: The MIMAC-FastN detector in front of the [45]Sc target for low energy (8 and 27 keV) neutron fields. The chamber was filled with a low-pressure gas mixture (50% i-C4H10 + 50% CHF3 at 30mbar). The beam was protons at 2.912 and 2.925 MeV.

Considering only proton recoils, since in our gas mixture of 50% i-C4H10 + 50% CHF3 they represent 87% of the total nuclear recoils, according to stoichiometry and cross-sections from the ENDF database, the angular distribution of such proton recoils and the neutron spectra are shown in the figure 13 left and right for 27 and 8 keV at the top and bottom respectively.

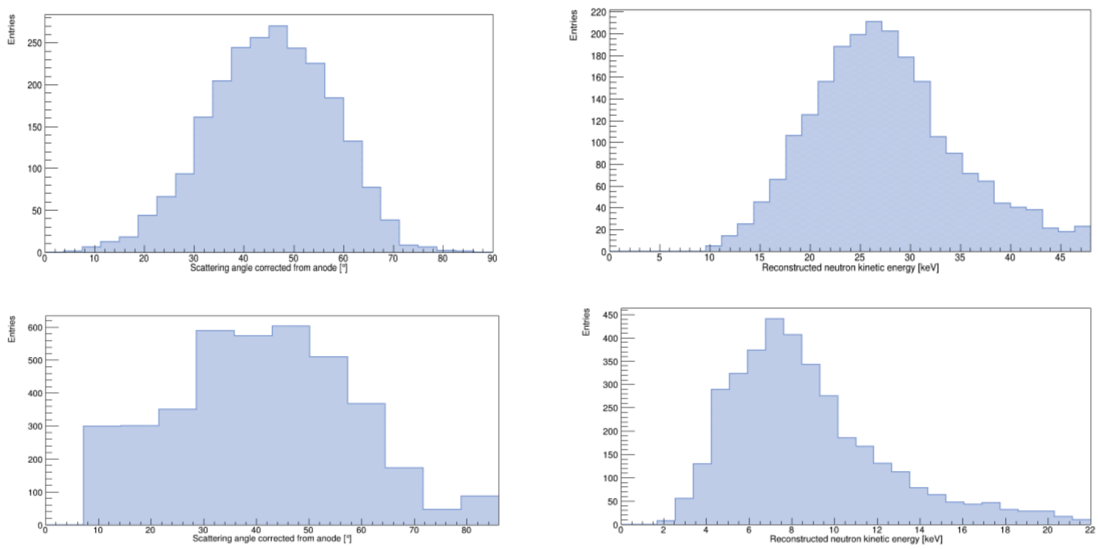


Figure 13: Reconstruction of the neutron scattering angle distribution and the kinetic energy spectrum of a mono-energetic neutron field at 27 and 8 keV at the top and bottom respectively.

The 8 keV spectrum is the first neutron spectroscopy of an epi-thermal neutron field (0.5 eV<E<10 keV). The spectrum is the result of one hour of beam at the Amande facility (IRSN-Cadarache). In order to get the same kind of neutron spectroscopy, we have to perform time of flight measurements with a pulsed beam being quite difficult at such low energies.
At high gain, the influence of the ions blurs and distorts the track measurements that constitute the backbone of the directional detection strategy based on 3D track reconstruction.
In this paper, we focused on the deconvolution of the ionic signal to demonstrate its importance at high gain in a Micromegas detector. This work, developed for the MIMAC detector, could be adapted to other directional detectors, see more details in [24].

XI. Participation to NEWS-G: Ionization Quenching Factor Measurements with COMIMAC

NEWS-G is a DM direct detection project, without directionality but very complementary of MIMAC proposing a very simple spherical gas detector with only one electronic channel.
We used the Comimac facility in order to produce the motion of nuclei and electrons of controlled kinetic energy in the active volume, and a NEWS-G Spherical Proportional Counter to measure the ionization released energy, see figure 14 (left). The Comimac electrons are used as a reference to calibrate the detector with 7 energy points, see figure 14 (right).

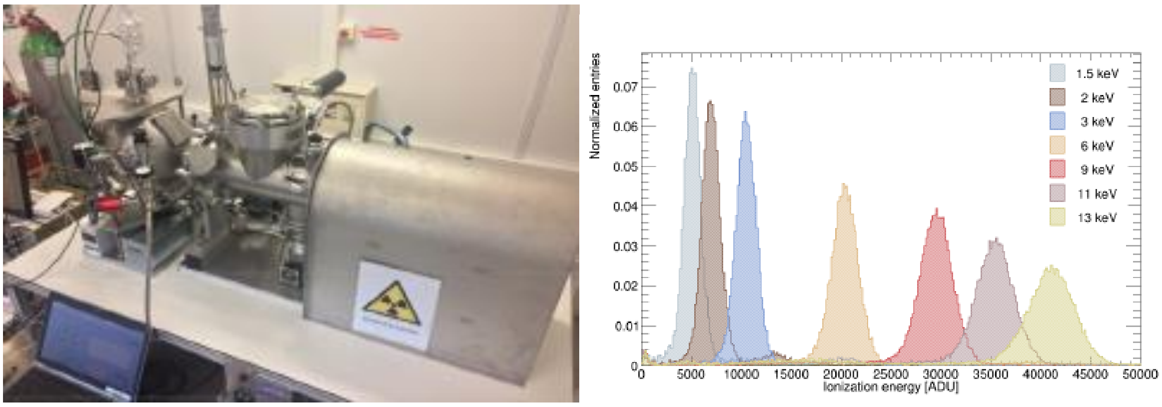


Figure 14 : Left: A picture of the experiment with Comimac on the right and the SPC on the left . Right: Complete set of energy spectra used for the calibration of the detector response. The kinetic energy is determined by the Comimac facility. The cosmic background has been subtracted but no cut is applied.

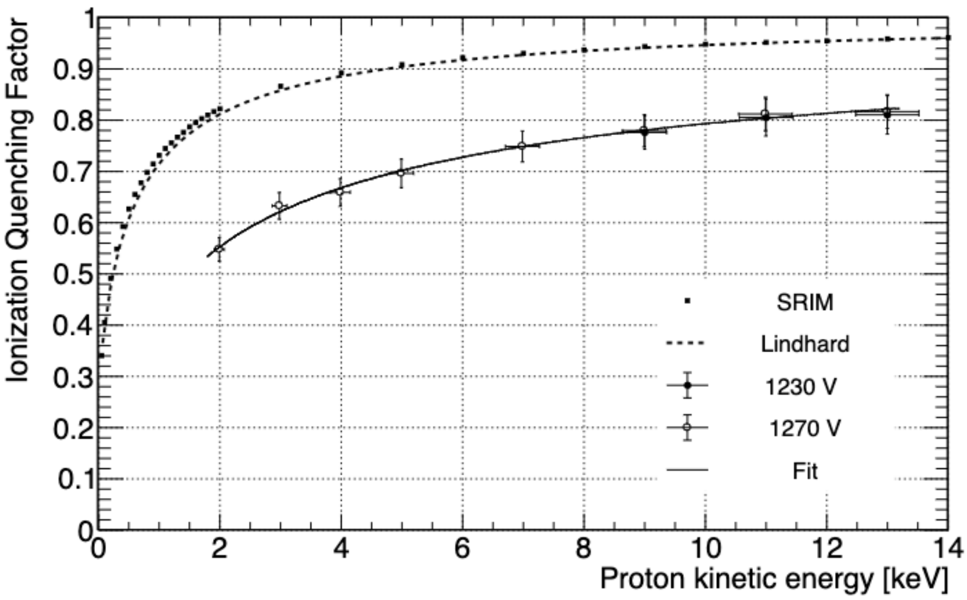


Figure 15: Ionization Quenching Factor for protons in 100 mbar of methane. The measurements at 1230 V and 1270 V are respectively presented with black dots and white dots. Comparisons with SRIM and with the Lindhard theory are also shown.

This work represents the first measurement of the IQF of protons in methane published in 2022 [25]

XII. Valorization of MIMAC and COMIMAC:

A collaboration contract was signed between the IRSN metrology laboratory (LMDN) and the LPSC in 2010 for 5 years in order to demonstrate that our MIMAC prototype detector can become a primary standard for the characterization of fast neutron fields. Two PhD-thesis on this subject under the direction of D. Santos were funded. The demonstration of the measurement of fast neutrons in the low energy range (27 keV - 565 keV) was done by Donovan Maire's thesis and by Benjamin Tampon PhD thesis in the (1.2 - 6.5 MeV) range. The valorization of MIMAC was an important activity in the 3-year period described previously.

The points to highlight on the MIMAC valorization are mainly the following:

i- Collaboration with the IRSN Metrology and Neutron Dosimetry Laboratory.
The contract signed in 2010 running until December 2015 which allowed the Laboratory of Metrology and Neutron Dosimetry (LMDN) of the IRSN to count on a prototype of MIMAC-FastN and a COMIMAC table-top quenching facility were extended in 2016 for 5 years. The LNE (National Metrology and Testing Laboratory) and LMDN (Laboratory of Metrology and Neutron Dosimetry of IRSN) financed Donovan Maire's thesis defended in December 2015 and Benjamin Tampon's thesis defended in December 2018.
The LMDN has evaluated their different projects on new neutron detectors in 2021 and decided to keep our MIMAC-FastN detector as an eventual primary neutron detector in the range below 6.5 MeV, mainly at 565 keV where there are not yet primary neutron detectors.
The LMDN has funded a PhD thesis under D. Santos supervision on metrological epithermal ($E < 10$ keV) neutron field production and characterization, started in October 2021.

ii- Labex Enigmass financed in August 2014, for a period of 2 and a half years, a valorization engineer (Nadine Sauzet) to help us valorize the MIMAC-FastN chamber as a fast neutron detector.

iii. Our MIMAC-FastN project was selected as a Pre-maturation project by the DIRE (CNRS) in July 2015, for a period of 18 months.

iv. Our directional and portable fast neutron detector project (MIMAC-FastN) was retained by SATT (Linksium) in April 2017 for a maturation period of 15 months from September 2017.

v. A CNRS innovation letter was published on our MIMAC-FastN detector in July 2017.
http://www.cnrs.fr/cnrsinnovation-lalettre/actus.php?numero=488

vi. The publication of the paper in 2020: Fast neutron spectroscopy from 1 MeV up to 15 MeV with Mimac-FastN, a mobile and directional fast neutron spectrometer, N. Sauzet , D. Santos, O. Guillaudin, G. Bosson, J. Bouvier, T. Descombes, M. Marton, J.F. Muraz, NIM A 965 (2020) 163799, describing the validation of our method to get the kinetic energy spectrum of a fast neutron field.

vii. A IN2P3 letter was published on our MIMAC-FastN detector in March 2023.
https://www.in2p3.cnrs.fr/fr/cnrsinfo/premier-test-reussi-basse-energie-pour-le-detecteur-de-neutrons-mimac-512

viii. The technical developments carried out as part of the MIMAC master project have made it possible to develop strong expertise within the LPSC in the field of gas detectors and materials as well as in the management and purification of gases. The project also has made it possible to create a team of experts making contributions to the Gas Detectors network of the IN2P3. This team notably organized the IN2P3-IRFU Gas Detectors Network Days, which took place in Grenoble in the spring 2022. Continuing its proximity to the RD51-MGPD network, this team is currently involved in the future DRD1 collaboration at CERN. Nadine Sauzet was recently required as an expert for hiring a person as part of an IN2P3 project.

II- Axion-like particles (ALPs) in large extra-dimensions exploration with MIMAC

In 2019, we started an exploration of the eventual detection of ALPs in large extra-dimensions with MIMAC helped by Prof. Mar Bastero-Gil from the Granada University (Spain). In theories with large extra dimensions, the fundamental scale of quantum gravity can be lowered near the TeV-scale without violating experimental constraints [A1, A2]. Such a framework naturally solves the mass hierarchy problem and it can be embedded in string theory [A3–A5] while preserving gauge coupling unification [A6, A7].
Previously our work, the paper published in 2000 [A8] had shown possible detection in a 1 m^3 gas detector and had motivated many papers [A9-A12] in different detectors. With MIMAC we had many more observables to discriminate the background and a nice opportunity to open the physical case of our detector. Cyprien B. had started his M2 internship on this interesting physics using a new gas mixture to detect the two identical photon decay of a Kaluza-Klein (KK) axion in the 1-10 keV mass range. Di Lella's work did not show all the theoretical details to be confident enough about our projections. We wanted to have all the details and parameters to perform simulations and estimate our eventual contribution. After a huge work performed mainly by Mar and Cyprien a completely revisited model was published in 2021 [A13] and an improved calculation including solar absorption in 2023 [A14]. Very interesting physical implications could be shown concerning the X-ray solar spectrum and the solar corona problem but the detection of the searched decay has been seriously constrained.

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5. Publications of the MIMAC team

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J. Billard, F. Mayet, J.F. Macias-Perez, D. Santos,
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J. P. Richer, G. Bosson, O. Bourrion, C. Grignon, et al.,
Nuclear Instruments and Methods in Physics Research A620 (2010) 470 , arXiv:0912.0186
[3] Exclusion limits from data of directional Dark Matter detectors,
J. Billard, F. Mayet and D. Santos,Phys. Rev. D 82 (2010) 055011 , arXiv:1006.3513
[4] Data acquisition electronics and reconstruction software for directional detection of Dark Matter with MIMAC, O. Bourrion, G. Bosson, C. Grignon, J.L. Bouly, J.P. Richer, O. Guillaudin, F. Mayet, D. Santos,Nuclear Instruments and Methods in Physics Research A662 (2010) 207 , arXiv:1006.1335
[5]Assessing the discovery potential of directional detection of dark matter
J. Billard, F. Mayet, and D. Santos Phys. Rev. D 85, 035006
[6] Three-dimensional track reconstruction for directional Dark Matter detection,
J. Billard, F. Mayet and D. Santos
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[7] Low energy electron/recoil discrimination for directional Dark Matter detection
J. Billard, F. Mayet and D. Santos
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[8] Is a co-rotating Dark Disk a threat to Dark Matter Directional Detection ?
J. Billard, Q. Riffard, F. Mayet, D. Santos, . arXiv:1207.1050
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[9] In situ measurement of the electron drift velocity for upcoming directional Dark Matter detectors
J. Billard, F. Mayet , G. Bosson, O. Bourrion, O. Guillaudin, J. Lamblin, J. P. Richer, Q. Riffard, D. Santos, F. J. Iguaz, L. Lebreton, D. Maire , . arXiv:1305.2360JINST 9 (2014) P01013
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Q. Riffard, D. Santos et al. 2017_JINST_12_P06021
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F. Mayet, A. M. Green, J. B. R. Battat, J. Billard, N. Bozorgnia, G. B. Gelmini, P. Gondolo, B. J. Kavanagh,S. K. Lee, D. Loomba, J. Monroe, B. Morgan, C. A. J. O'Hare, A. H. G. Peter, N. S. Phan, S. E. Vahsen. Physics Reports 627 (2016) 1
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[26] Fast neutron spectroscopy from 1 MeV up to 15 MeV with Mimac-FastN, a mobile and directional fast neutron spectrometer, N. Sauzet , D. Santos, O. Guillaudin, G. Bosson, J. Bouvier, T. Descombes, M. Marton, J.F. Muraz, NIM A 965 (2020) 163799

6. Resources and means

MIMAC is an international Franco-Chinese collaboration.
In France:
LPSC-Grenoble: D. Santos (DR, 50%), C. Beaufort (IR, 50% up to end of 2023), O. Guillaudin (IR, 70%), J-F. Muraz (IR, 10%), M. Marton (AI, 20%), G. Bosson (IE, 30% up to 8/2020 (retired)), J. Bouvier (IR, 30%, up to 7/2020 (retired)), T. Descombes (IE, 40%), N. Sauzet (IR, 70%), J.L. Bouly (IE, 15% up to 7/2023 (retired)), F. Naraghi (MdC, 50%), E. Lagorio (IE, 25%), O. Bourrion (IR, 5%), L. Gallin-Marter (IR, 5%)

CPPM-Marseille: C. Tao (DR, 50%, emerita since 2022), J. Busto (PR, 10%), D. Fouchez (DR, 2010-2017)

IRFU-Saclay: P. Colas (5% up to 2019), I. Giomataris (5% up to 2019), E. Ferrer-Ribas (2007-2012)

In China : Tsinghua University: Y. Tao (PhD. 100%2015-2019), I. Moric (Post-doc 100%, 2015-2018)
IHEP: C. Dai (Emeritus, 50%), Z. Wang (Researcher, 20%)

The MIMAC project will cost € 80,000 not including technical staff (see figure) The two-chamber low-noise module (35cm x 35cm) was financed by Labex Enigmass (74 keuros). The available budget of € 50,000 comes mainly from the valorization of MIMAC as a directional fast neutron spectrometer and from the sale of a MIMAC chamber to Tsinghua University (Beijing).

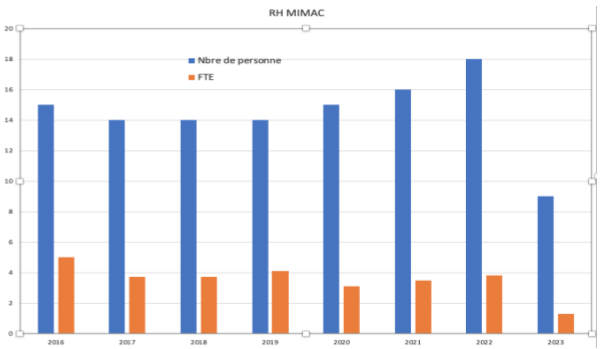

Figure 16: People(all) involved in the MIMAC project since 2016 with the total FTE per year.

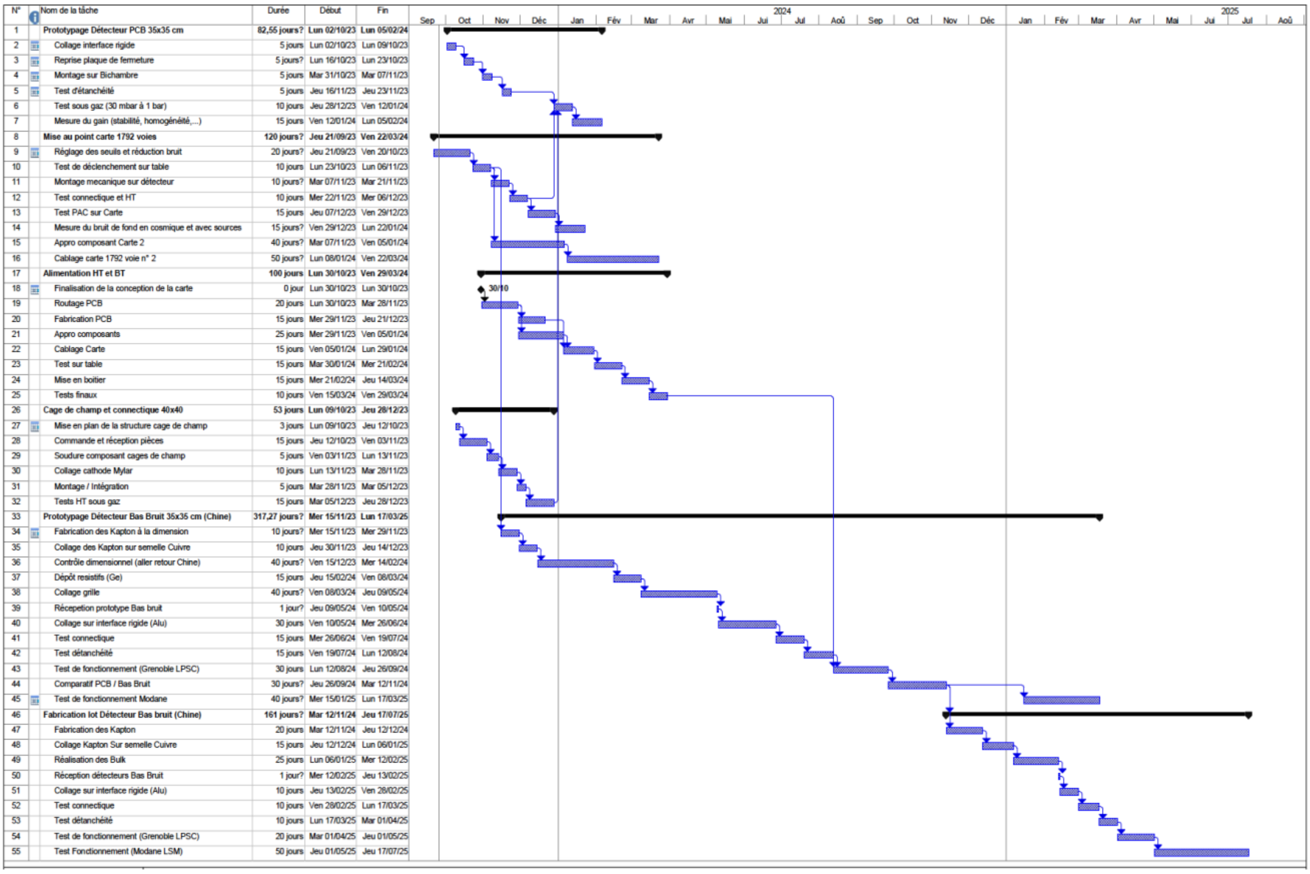

Figure 17: The different tasks foreseen in the next two years between the LPSC and the Chinese partners.

7. Self-analysis SWOT

Strengths :

- MIMAC benefited from an "in-house" development (IN2P3) by taking advantage of the know-how in microelectronics, analog electronics, and high-rate acquisition .
- The ability to measure very low ionization energies and to reconstruct tracks of sub-millimeter length.
- The possibility of developing low-noise MPGD detectors.
- We master the know-how: detector, electronics, and mechanics.
- The COMIMAC facility for ionization quenching factor measurements.
- The simulation package developed by C. Beaufort describing the impact of the ionic signal at high gain.
- Access and proximity to the LSM (Modane Underground Laboratory).
- China's interest in installing a directional detector in the Jinping laboratory (the deepest at the moment).
- Valorization in the fast neutron spectroscopy

Weaknesses:

- The LPSC and CPPM physicist teams are undersized.
- The LPSC electronics team is undersized and very important in the next two years for the project.

Opportunities :

- Our detection strategy and MIMAC technology are currently those that allow the lowest threshold with 3D track measurement.
- We are ahead of the international competition.
- Development of technology in the field of neutron measurement.

Threat :

- Dark matter particles could have a mass of less than 500 MeV/c2.