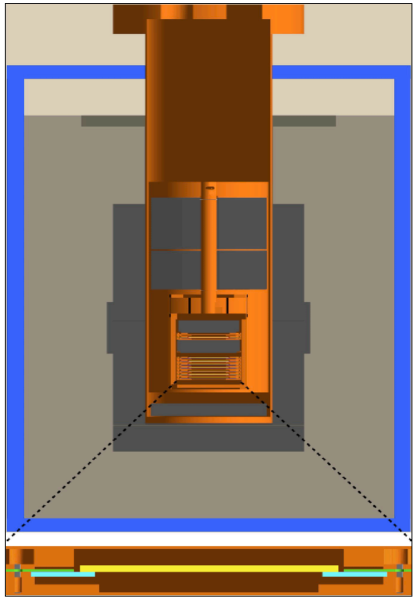
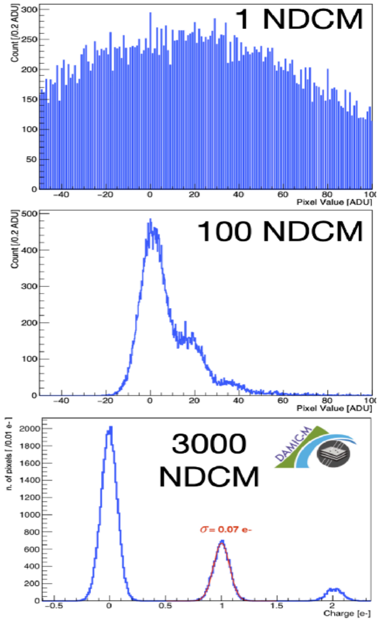
DAMIC (-M) Project @ IN2P3

Report to scientific council 23/10/2023

For the team : Antoine Letessier Selvon - 11 September 2023



GEANT4 geometry of the DAMIC@SNOLAB set up



Evolution of energy resolution thanks to multiple measurements (NDCM, Non Destructive Charge Measurement) of skipper CCDs (LPNHE and University of Chicago)

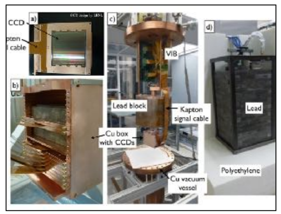
Introduction

It is in 2014 that a group at LPNHE proposed to participate in the DAMIC experiment at SNOLAB an experiment aiming at detecting dark matter particles using low background CCDs. We joined this collaboration in 2015 and have been collaborating with them since then. This experiment uses as target and detection system the silicon mass of 8 thick CCDs (0.7 mm) for a total of approximately 50g of active mass.

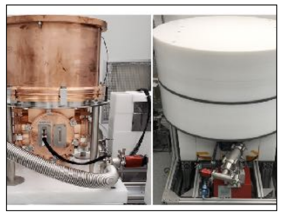
In 2017, with Paolo Privitera from the University of Chicago also a member of the DAMIC@SNOLAB experiment, we prepared an ERC proposal to extend the DAMIC experiment. With an objective of 1 kg of active mass and using a new CCD reading technique (skipper), the DAMIC-M project (DAMIC in Modane) makes it possible to lower the detection threshold from 70 eV used at SNOLAB to less than 10 eV (only 2 or 3 electrons detected in s single pixel). Such a low threshold allows to very significantly extends the domain of parameters (mass vs. cross section) accessible to the experiment for WIMPs and leptophilic dark matter.

The ERC DAMIC-M project was approved by the European Research Council in April 2018 (3.5 M€) and we obtained additional funding from the NSF for an additional amount of 4 MUSD.

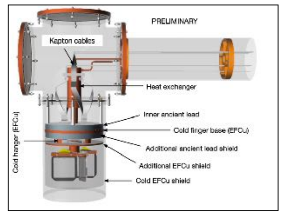
DAMIC-M has become since 2019 and for 5 (+1) years an important project in the direct search for dark matter at IN2P3. The installation of a prototype detector (the Low Background Chamber or LBC) was carried out at the end of 2021. At the beginning of 2022 a first data collection campaign has taken place and has been analysed leading to two publications in PRL. The final DAMIC-M detector will be installed in 2024 for approximately two years of data collection followed by two or three years of scientific exploitation.



DAMIC @ SNOLAB



La LBC à Modane.



Conception de DAMIC-M

Scientific Program

Our understanding of the laws governing the universe has progressed enormously in recent decades, moving from a fuzzy picture to the realm of precision cosmology. Observations of the sky with large telescopes have unequivocally established that dark matter and dark energy are major components of the universe. Dark matter is five times more abundant than ordinary matter, and has a considerable influence on its evolution: it accelerates the movement of stars around their galaxy, binds clusters, drives the distribution of large-scale structures that we observe, and left an unequivocal imprint in the power spectrum of the cosmic microwave background. Despite these effects its nature remains elusive. Elucidating the nature of dark matter is one of the most fundamental questions of modern cosmology.

The WIMP paradigm.

The experimental search for dark matter has been guided for several decades by the paradigm of weakly interacting massive particles (WIMP): a new class of particles, with masses around 100 GeV, interacting via the electroweak force. The prediction of such particles by supersymmetric extensions of the standard model of particle physics reinforced this hypothesis. A WIMP bound by gravity to our galaxy has a kinetic energy of a few tens of keV; its elastic scattering on a nucleus of ordinary matter produces recoil leaving a tiny energy deposit in the detector. Various techniques based on this detection principle have been developed to search for WIMPs, including scintillating crystals, noble liquids (Xenon, Argon), bubble chambers and cryogenic calorimeters. To protect the detectors from the considerable flux of cosmic rays, the experiments are located in underground laboratories under several kilometres of rock.

The hidden sector.

The most sensitive experiments using multi-ton liquid xenon detectors have produced strict limits on the existence of WIMPs [1]. Moreover, super-symmetry has not been demonstrated in the LHC experiments at CERN [2]. Thus the scientific community is looking more broadly at the WIMP paradigm and exploring alternative scenarios. In particular, several experiments are searching for low mass WIMPs (<10 GeV, [3]), with specifically developed detectors. Another approach goes beyond the WIMP paradigm, recognising that DM particles may be lighter and have different interaction properties than previously thought. In particular, a hidden sector (also called a dark sector) may exist where particles have their own set of interaction forces and therefore do not directly couple with (are "hidden" from) ordinary matter. Interaction with standard model particles can still occur, for example by mixing a dark photon (A’) with an ordinary photon. In addition to acting as a mediator, the dark photon could itself be a dark matter particle. The phenomenology of hidden sector particles results in a much larger

unexplored parameter space than that of WIMPs, especially for masses m_χ << GeV. Experimentally, the nuclear recoil induced by such light particles will be difficult to measure. However, the energy transfer in elastic diffusion with electrons is much more efficient, moreover, the absorption of a dark photon results in ionisation even for $m_{A'}$ masses of the order of eV.

[1] For example “First Dark Matter Search with Nuclear Recoils from the XENONnT Experiment”, E. Aprile et al, arXiv:2303.14729

[2] “Search for R-parity-violating supersymmetry in a final state containing leptons and many jets with the ATLAS experiment,...”, G. Aad et al, Eur. Phys. J.C 81, 1023 (2021).

[3] For example “Low-Mass Dark Matter Search with the DarkSide-50 Experiment”, P. Agnes et al, Phys. Rev. Lett. 121, 081307 (2018)

Project Positioning

1. Ambitions

DAMIC-M aims to accumulate an exposure of approximately 1kg-year with a background noise of a few tenths of DRU (Differential Rate Units corresponding to 1 event per keV, per kilogram and per day). An improvement of almost 2 orders of magnitude compared to the DAMIC@SNOLAB experiment.

These ambitious objectives presuppose on the one hand an excellent control of the production of CCDs with a high satisfactory manufacturing rate and an increased control of the sources of contamination at each stage of manufacturing and transport. On the other hand, they involve extreme care in the choice of materials that will surround the detector (by choosing for example to use electro-formed copper both for the CCD support module and also for the cryostat).

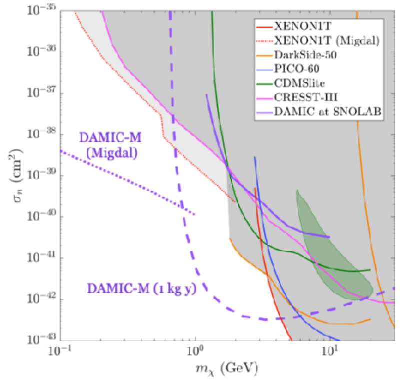
The DAMIC-M project obtained European funding (ERC) of €3.35 million in September 2018 for 5 years. This deadline was extended by one year following the pandemic and we can benefit from funding until September 2024.

The budget was essentially distributed as follows (in €k):

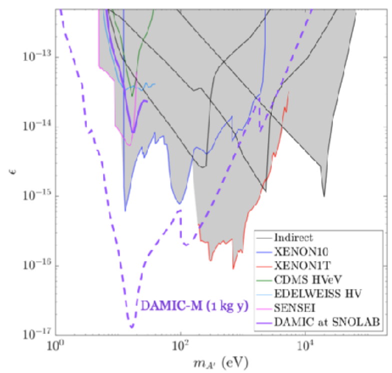
- €1.1 million for the manufacturing of CCDs, shields, electro-formed cooper cryostat elements
- €600k overhead (Sorbonne University and Regional Delegation 2)
- 700 k€ of temporary staff (theses x3 post-docs x2)
- 450 k€ electronics (conception, design, manufacturing)
- €500k of equipment (test benches x3, clean rooms x2, shielding x2, cryostat x2)

Following ERC funding, the project was approved by the scientific councils of the 4 French laboratories involved (SUBATECH Nantes, IJCLAB Orsay, LPNHE Paris, LPSC Grenoble) and by that of IN2P3 in October 2018.

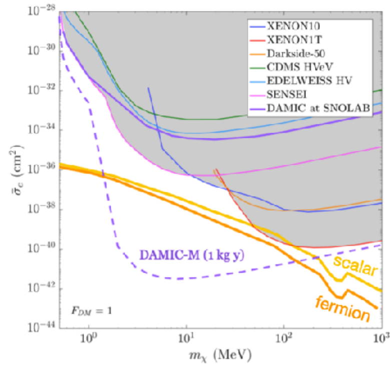
The quantitative scientific objectives of DAMIC-M are summarised in the figures below. They concern on the one hand the detection of low mass WIMPs (between 1 and 10 GeV) by interaction with silicon nuclei and the detection of dark sector particles by interaction with electrons. These sensitivity forecasts are given for an exposure of one kilogram.year and a residual background noise of 0.1 dru.



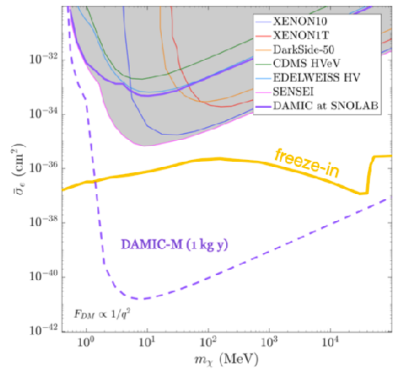
Sensibilité aux Wimps de basse masse (tirets reculs nucléaires seuls, pointillés avec électrons Migdal).



Sensibilité au paramètre de mélange d'un photon du secteur sombre avec les photons ordinaires.



Sensibilité à la matière noire leptophilique (reculs d'électrons) pour une interaction avec un médiateur lourd.

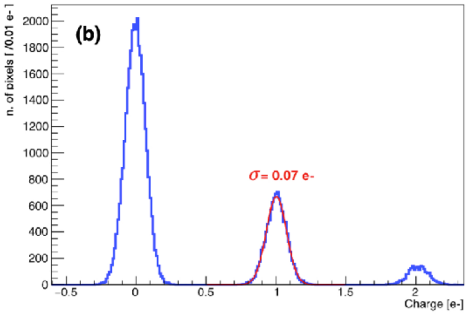


Sensibilité à la matière noire leptophilique (reculs d'électrons) pour une interaction avec un médiateur léger.

2. Technological context

Regardless of theoretical motivations, it is important to recognise that current WIMP experiments have limited sensitivity to dark matter-electron interactions, and that a light dark matter particle may have escaped detection. An ideal detector should be able to resolve the energy deposited by ionisation at the individual electron level. Furthermore, the dark current (coming from thermal excitation, from a charge released by traps on the surface or in the mass of the detector material or produced by ionising background particles) must be extremely low so that a signal is recognisable. These constraints are very strict and difficult to respect.

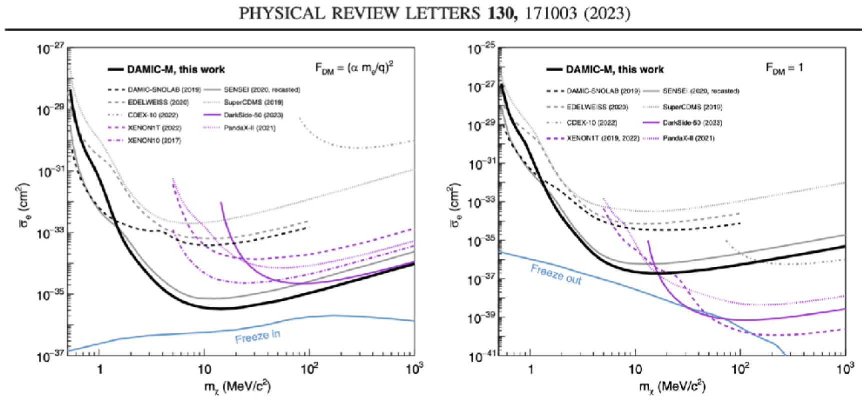
In this context, DAMIC-M (Dark Matter in CCDs at Modane) uses an innovative detection technology, capable of detecting a single electron at high resolution, which offers unprecedented sensitivity to the hidden sector. Charge-coupled scientific devices (CCDs) are commonly used in the focal plane of astronomical telescopes for digital imaging of faint astrophysical objects. The unconventional use of CCDs for the detection of dark matter has been successfully demonstrated at the SNOLAB laboratory (located in a mine 2 km below Sudbury, Canada) in a project where our team was involved and the detection potential was validated by a search for low-mass WIMPs and dark sector dark matter [4]. DAMIC-M capitalised on this experience and, at the same time, took a giant step in sensitivity through radical innovations: its CCD sensors are the most massive ever built and use a new concept of signal reading (based on a non-destructive and repetitive readings of the pixel charge) which offers unequaled resolution (figure opposite) [5].



Record resolution obtained by the DAMIC-M team with a multiple reading CCD (skipper CCD) [5].

Additionally the experience accumulated during the study of the DAMIC@SNOLAB detector and in particular the complete GEANT4 simulation developed by Joao Da Rocha then Michelangelo Traina, thesis students in the LPNHE team, allows us to monitor the key points. In particular the control of the exposure of bare wafers to radon (which causes Lead210 deposits on surfaces) and to cosmic rays (which induces tritium contamination by spallation). Or even during the manufacturing process itself, the implementation of a reduction in the impurity absorption layer (gettering layer which is contaminated with tritium) which once its action has taken place can be partially removed. Overall we expect a factor of 10 reduction in background noise through the choice of materials, control of manufacturing and handling. A further reduction is expected from the design of the detector itself (geometry and positioning of potentially contaminating elements), from fiducial cut-offs and from the rejection of background noise during the analysis.

A DAMIC-M prototype called Low Background Chamber (LBC), developed with ERC funds, is currently in operation at LSM (Modane Underground Laboratory). This prototype only has 2 CCD modules while DAMIC-M will have a total of 50. Despite this small size (and therefore a sensitive mass of only a few tens of grams) the chosen resolution of 0.2 electrons allows a detection threshold of less than 10 eV offering very high sensitivity to electron scattering. Thus we recently (April 2023) published in PRL [6] the best global limits on electron scattering for masses mχ around 10 MeV. See the figure below.



Mass-effective cross-section limit for the diffusion of dark dark matter on electrons (left light mediator, right heavy mediator) [6].

DAMIC-M will have a detection threshold of 2 to 3 electrons (corresponding to energy transfers as low as ≈ 3 eV considering the silicon band energy gap of 1.2 eV). There is no other experience with such ability. DAMIC-M will include 50 CCD modules (in production) for a sensitive mass of nearly 1Kg. The sensitivity of DAMIC-M to the hidden sector for an integrated exposure of 1 kg per year and a background level of 0.1 event/keV/kg/day will be 3 to 4 orders of magnitude higher than that of LBC. DAMIC-M therefore takes a considerable leap forward in the exploration of the hidden sector and can discover the dark matter in this sector even if it constitutes only a small fraction of all the dark matter in the universe.

[4] "Results on Low-Mass Weakly Interacting Massive Particles from an 11 kg-day Target Exposure of DAMIC at SNOLAB", A. Aguilar-Arevalo et al, Phys. Rev. Lett. 125, 241803 (2020)

[5] "The DAMIC-M Experiment: Status and First Results", I. Arnquist et al, 14th International Conference on Identification of Dark Matter Vienna, Austria, 18-22 July 2022

[6] "First Constraints from DAMIC-M on Sub-GeV Dark-Matter Particles Interacting with Electrons", I. Arnquist et al, Phys. Rev. Lett. 130, 171003 (2023)

Organisation

1. National and International Collaboration

IN2P3 laboratories involved in DAMIC-M, their staff and responsibilities are as follows :

- SUBATECH Nantes, Mariangela Settimo CR, cryostat studies, CC-IN2P3 correspondent, simulation manager
- LPNHE Paris, Antoine Letessier Selvon DR, Paolo Privitera PR, Romain Gaior IR, respectively scientific manager, ERC leader, technical manager. Lounes Iddir (ERC/In2p3, end of September 2025) doctoral engineer thesis on CCD reading electronics, Claudia de Dominicis post-doc (ERC, end of September 2024), Jean-Philippe Zopounidis (ERC, end of December 2024), Marc Dhello AI, electronics.
- IJCLab Orsay, Olivier Deligny DR, acquisition system, Olivier Pochon AI, shielding mechanics
- LPSC Grenoble, Ali Dastgheibi-Fard CR, Guillaume Warot CR, LSM liaison, commissioning, radioactivity,

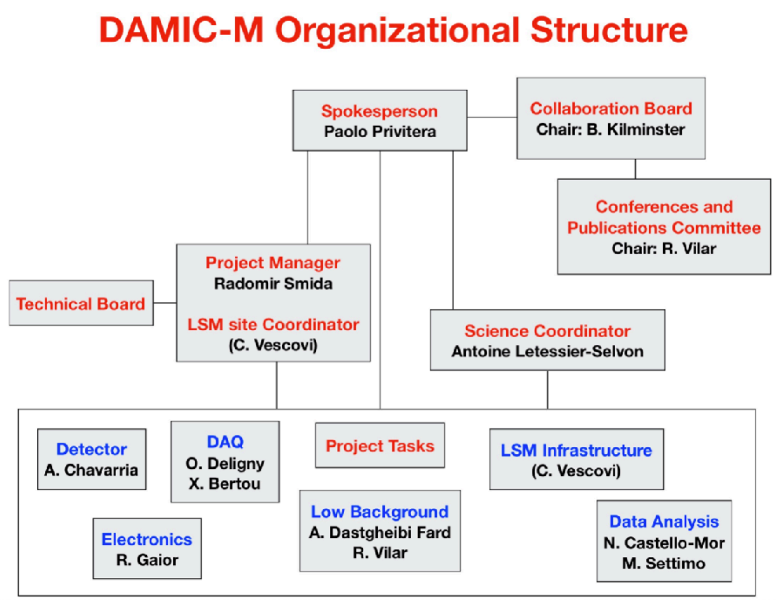
Given the ERC funding of DAMIC-M, there is no direct financial support from in2p3 to the laboratories and their involvement is by nature limited to in kind contributions. For the LPNHE which is the project leader the situation is different as it benefits directly from the ERC funding. Between 2017 and 2023 we supervised 7 theses, 5 on DAMIC-M (4 at LPNHE with ERC funding) and one at SUBATECH (Chicago-IN2P3 funding), and 2 on DAMIC@SNOLAB (at LPNHE, 2 Sorbonne University grants). All those thesis but one at LPNHE have already been defended.

From an international point of view DAMIC-M has 40 researchers from 11 institutes:

1. Pacific Northwest National Laboratory (PNNL), Richland, WA, United States
2. Centro Atomico Bariloche and Instituto Balseiro, San Carlos de Bariloche, Argentina
3. Kavli Institute for Cosmological Physics and The Enrico Fermi Institute,The University of Chicago, Chicago, IL, United States
4. Instituto de Fısica de Cantabria (IFCA), CSIC - Universidad de Cantabria, Santander, Spain
5. Center for Experimental Nuclear Physics and Astrophysics, University of Washington, Seattle, WA, United States
6. LPSC LSM, CNRS/IN2P3, Université Grenoble-Alpes, Grenoble, France CNRS/IN2P3,
7. IJCLab, Université Paris-Saclay, Orsay, France

8. Laboratoire de physique nucléaire et des hautes energies (LPNHE), CNRS/IN2P3, Paris, France
9. SUBATECH, Nantes Université, IMT Atlantique, CNRS-IN2P3, Nantes, France
10. Universitat Zurich Physik Institut, Zurich, Switzerland
11. SNOLAB, Lively, ON, Canada

2. Project organisation



The international project organisation has a very strong contribution from the french collaborator. In the structure depicted above most task are headed by an IN2P3 researcher, these includes for the project management Spokesperson, LSM site coordinator and Science Coordinator, and for the project tasks DAQ, LSM infrastructure, Electronics, Low Background and Data Analysis.

3. Project manpower (France)

The current (2023) scientific manpower on the project is 4,15 FTE including postdocs and students. The table below gives the individual contributions. In 2024 this will be reduced to 3,15 and further reduced to 1,9 in 2025 if nothing changes.

Nom	Statut	2023	2024
SUBATECH			
Mariangela Settimo	CR	15 %	15 %
LPNHE			
Antoine Letessier Selvon	DR	80 %	80 %
Paolo Privitera	PR	50 %	50 %
Romain Gaior	IR chercheur	50 %	50 %
Claudia De Dominicis	Post Doc (ERC)	100 %	75 %
Jean-Philippe Zopounidis	Post Doc (ERC)	75 %	-
LPSC			
Ali Dastgheibi Fard	IR Chercheur	15 %	15 %
Guillaume Warot	IR Chercheur	10 %	10 %
IJCLab			
Olivier Deligny	DR	20 %	20 %

Table 1: IN2P3 researchers and teacher-researchers involved in the project

Similarly the project technical manpower is depicted in table 2 below. It amounts to about 2 FTE in 2023 and 2024 and will be reduced to 1 when Lounes Iddir will finish his PhD in 2025.

Nom	Statut	2023	2024
LPNHE			
Romain Gaior	IR chercheur	20 %	20 %
Marc Dhellot	AI	50 %	50 %
Lounes Idir	These ingénieur (ERC et IN2P3)	100 %	100 %
LPSC			
Ali Dastgheibi Fard	IR Chercheur	15 %	15 %
Guillaume Warot	IR Chercheur	10 %	10 %
IJCLab			
Olivier Pochon	AI	20 %	-

Table 2: IN2P3 engineers and technicians involved in the project

4. List of people in the collaboration

I. Arnquist,[1] N. Avalos,[2] D. Baxter,[3,*] X. Bertou,[2] N. Castelló-Mor,[4] A.E. Chavarria,[5] J. Cuevas-Zepeda,[3] J. Duarte-Campderros,[4] A. Dastgheibi-Fard,[6] O. Deligny,[7] C. De Dominicis,[8,9] E. Estrada,[2] N. Gadola,[10] R. Gaïor,[8] T. Hossbach,[1] L. Iddir,[8] B. J. Kavanagh,[4] B. Kilminster,[10] A. Lantero-Barreda,[4] I. Lawson,[11] S. Lee,[10] A. Letessier-Selvon,[8] P. Loaiza,[7] A. Lopez-Virto,[4] A. Matalon,[3,8] S. Munagavalasa,[3] K. J. McGuire,[5] P. Mitra,[5] D. Norcini,[3] G. Papadopoulos,[8] S. Paul,[3] A. Piers,[5] P. Privitera,[3,8] P. Robmann,[10] M. Settimo,[9] R. Smida,[3] M. Traina,[5,8] R. Vilar,[4] G. Warot,[6] R. Yajur,[3] and J-P. Zopounidis[8]

(DAMIC-M Collaboration)

[1] *Pacific Northwest National Laboratory (PNNL), Richland, WA, United States*
[2] *Centro Atómico Bariloche and Instituto Balseiro, Comisión Nacional de Energía Atómica (CNEA), Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Universidad Nacional de Cuyo (UNCUYO), San Carlos de Bariloche, Argentina*
[3] *Kavli Institute for Cosmological Physics and The Enrico Fermi Institute, The University of Chicago, Chicago, IL, United States*
[4] *Instituto de Física de Cantabria (IFCA), CSIC - Universidad de Cantabria, Santander, Spain*
[5] *Center for Experimental Nuclear Physics and Astrophysics, University of Washington, Seattle, WA, United States*
[6] *LPSC LSM, CNRS/IN2P3, Université Grenoble-Alpes, Grenoble, France*
[7] *CNRS/IN2P3, IJCLab, Université Paris-Saclay, Orsay, France*
[8] *Laboratoire de physique nucléaire et des hautes énergies (LPNHE), Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris, France*
[9] *SUBATECH, Nantes Université, IMT Atlantique, CNRS-IN2P3, Nantes, France*
[10] *Universität Zürich Physik Institut, Zürich, Switzerland*
[11] *SNOLAB, Lively, ON, Canada*

Table 3: Full staff from laboratories involved in the project

Technical realisations

The ERC funding is allocated only to LPNHE and transfer between laboratories is not allowed, so most of the technical commitments have been undertaken at LPNHE and will be described in some details below. However, several technical contributions have been made by SUBATECH and IJCLab they include :

- Studies of the design of the cooling system for the DAMIC-M cryostat, done at SUBATECH and now terminated.
- Design and construction at IJCLab of a shield opening mechanism for the LBC, now operational at LSM.
- Design and construction at IJCLab of a transport shield for the DAMIC-M wafers and fabricated CCDs. The shield has already been used to transport the raw wafers sliced in the UK to the CCD fabrication plant in Canada. It will be used again to transport the fabricated CCDs to Europe.
- Contribution by IJCLab to the DAQ software together with LPNHE and CAB-Bariloche, now in the final integration phase. Note that this DAQ software is designed and produced by the physicists involved in the project.

Funds for those developments have been provided by LPNHE buying from the ERC funds and delivering equipment at LPNHE to then redistribute it to the relevant places. This is a complication and cannot be done on a large scale as it is in principle not allowed by the ERC grant funding rules.

1. *Electronic design at LPNHE :*

The technical commitments of the LPNHE team on DAMIC-M mainly concern the front-end electronics, control and reading of the CCDs and the acquisition system:

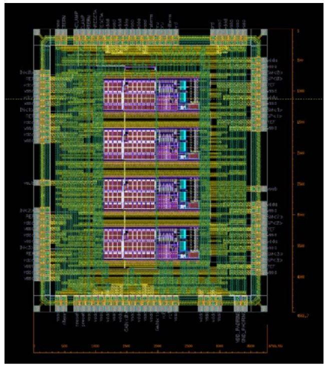
- The front-end amplifier intended to amplify the video signal as close as possible to the CCD. Based on the ASIC ASPIC developed at LPNHE for LSST, this amplifier must have an adjustable gain between 5 and 100, a noise of less than 2 electrons and a bandwidth of around 10 MHz.
- The clock and bias generation card for polarisation and sequencing for CCD reading and measurement. Based on the CABAC ASIC also developed at LPNHE for LSST.
- The digitisation card carrying 4 ADCs of which several versions were studied and for which the collaboration chose the LPNHE proposal with an 18-bit ADC of 15 MHz sampling frequency rather than 20-bit ADCs having a lower frequency, of the order of MHz.

- The motherboard (ODILE. Online Digital Interface for Low noise Electronics) comprising a control and timing FPGA for acquisition, a Gbits ethernet interface and connections to the front-end cards above initially on the mezzanine.

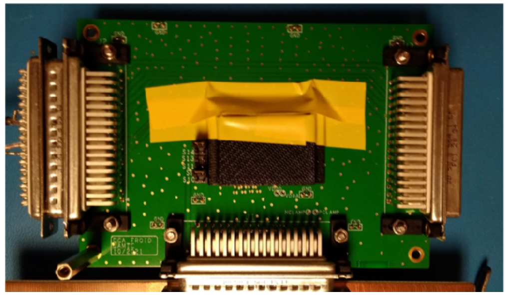
We quickly abandoned point 4 because our resources were not sufficient to produce the motherboard, the design and production of which was transferred to the University of Chicago.

CROC: CCD Read-Out Chip

The CROC ASIC is an evolution of the ASPIC front-end ASIC that LPNHE designed and produced for LSST (Large Synoptic Survey Telescope today the Vera C. Rubin Observatory). An adaptation was necessary for DAMIC-M both to increase the range of programmable gains but also the bandwidth. Several modifications have been made in this direction with the addition of a switch to a differential amplifier with inverted inputs to achieve CDS (Correlated Double Sampling). The CDS makes it possible to effectively eliminate the "reset" noise of the CCD output amp and consists of integrating the pedestal then the signal with the pedestal by inverting the gain of the amp at each measurement.



DCA layout

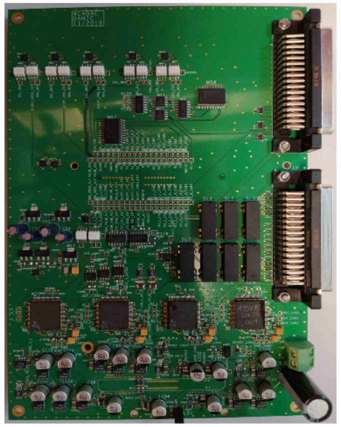


DCA wire bonded directly on its test card then protected (artisanally).

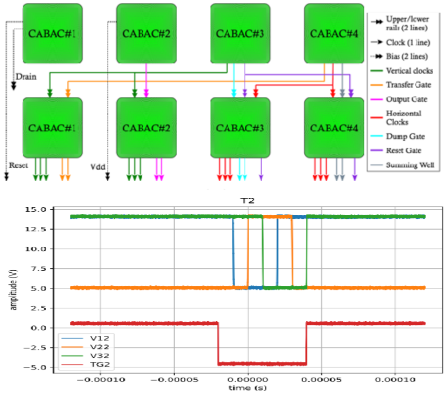
These modifications unfortunately did not have the expected effect and despite two successive foundry versions we had linearity and stability problems, only part of which could be resolved. As a result, we have drastically simplified the ASIC and produced a version called DCA (Differential CCD Amplifier) which has 4 channels with programmable gain, a unipolar input, a differential output and no CDS. This chip was received at the end of 2021 and evaluated in 2022. Several problems where identified in particular that the chips packaged by the manufacturer did not work. Only chips "wire bonded" by us directly on our test cards could be tested. The origin of this problem is still unresolved. The characteristics of the DCA are satisfactory (input noise of around 5μV, the equivalent of a little less than two electrons) but the stability is insufficient. Given the retirement of its main developing engineer we have decided to revert to a commercial solution.

CABAC: Clock And Biases ASIC for CCD

The CABAC ASIC was also developed by the laboratory for the LSST program. This chip makes it possible to generate the biases and clocks necessary for the operation and reading of a CCD. Both clock rails and biases are programmable through an SPI interface. The card generates the clocks by following the logic signals produced by the motherboard FPGA on which the sequencing firmware itself runs. One of the advantages of CABAC apart from its compactness is that it offers the possibility of controlling the slope of the clocks which can reduce the noise induced by them when reading the CCD.



The 4-CABAC card (the 4 black square modules).



Vertical clocks and transfer clock generated by CABACs.

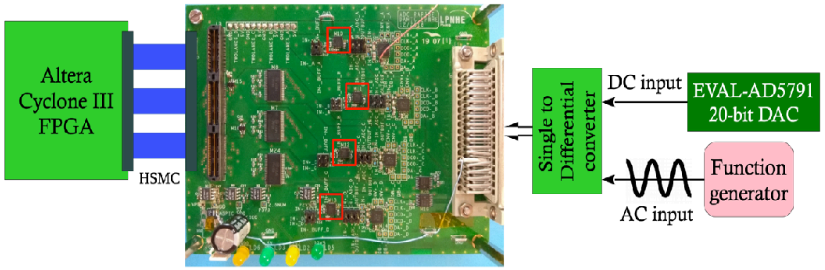
Given the number of clocks and biases to be generated to control a DAMIC-M CCD, we had to couple 4 CABAC chips on the same card. Unfortunately this configuration proved to be very unstable and caused numerous breakdowns and component breakages. Despite these instabilities, we still managed to read and control a CCD in 2021. We then spent many months trying to resolve these reliability problems but ultimately without success. We then developed a simpler model where the CABACs are decoupled and where the rail heights and biases are given by DACs.

A prototype version of this new scheme with a single CABAC has been produced and tested. It works correctly but another characteristic of CABAC chips needed to be modified. In fact, these cannot generate clocks whose amplitude is less than approximately 4V; However, we needed for DAMIC-M CCDs to be able to go down to around 2V. The modification planned to reduce the amplitude of the clocks at the output, although functioning, induces a coupling (cross talk) between the different clocks generated by the card. Crippling coupling in terms of noise for optimal operation of CCDs. The collaboration therefore chose at the beginning of this year to integrate into the

DAMIC-M electronics (in fact directly on the ODILE card which becomes the ODILE-ACM card for Acquisition Control Module) a clock and biases generating card using DAC, switches and digital potentiometers. In the process we lost the ability to control the clock slopes.

ADC card

The LPNHE proposed using ADCs that are shallower (18 bits instead of 20) but faster (15 Ms rather than 1.5 Ms) to digitise the video signals output from the front-end amplifier. We studied and characterised the LTC2387-18 from Linear Technology. We designed and produced a test card with 4 fast ADCs whose performance we then measured. We showed that these ADCs displayed superior performance to the two 20-bit ADCs offered by the University of Zurich and the University of Chicago. These ADCs, although deeper, have a lower resolution given their intrinsic noise and their lower sampling speed.



Test bench and evaluation diagram of the card carrying the 4 fast ADCs (in the red squares).

The production of the card was entrusted to the University of Zurich and the control firmware developed partly in Paris and Zurich was finalised in Paris.

With this fast ADC, online processing, i.e. on the front-end electronics, of data is essential. We have therefore developed a specific firmware module which calculates in the FPGA of the motherboard (ODILE-ACM) the averages and variances of the signals on the N-skip (N non-destructive measurements of the load) available for each pixel. This module also inserts information on the state of the sequencer into the data flow, making it possible to follow and reconstruct the organisation in pixels of the images collected.

2. Firmware and DAQ software :

In parallel with these hardware developments, commitments on contributions to the firmware and the acquisition system concern:

- The sequencing firmware, based on that of LSST, the ADC control firmware, the online data processing firmware.
- The interface middleware with ODILE for configuring the sequencing firmware, bias voltages and ADC configurations.
- The acquisition system itself with the control of the 50 CCD modules, image recovery, monitoring, etc.

These latter contributions are supported by the physicists and students of the team.

CCD sequencing : Firmware

The sequencer of the CCD acquisition electronics consists of three parts, the sequencing card (described above) which generates the signals from logic signals, the firmware synthesized in the FPGA which adjusts the timing of the logic signals and middleware which allows the firmware to be configured from a series of timing and sequencing instructions given in the form of understandable text in ASCII format.

```
Vtransfer12:    # One pixel vertical transfer towards both sides 1 and 2
    clocks:     V11, V21, V31, TG1,   V12, V22, V32, TG2
    slices:
        100 ns =  1,   0,   1,   0,     1,   0,   1,   0    # side_1: V2 to V1 to V3 to V2 to V1
        TVpart =  0,   0,   1,   0,     1,   0,   0,   0    # side_2: V2 to V3 to V1 to V2 to V3
        TVpart =  0,   1,   1,   0,     1,   1,   0,   0
        TVpart =  0,   1,   0,   0,     0,   1,   0,   0
        TVpart =  1,   1,   0,   0,     0,   1,   1,   0
        TVpart =  1,   0,   0,   0,     0,   0,   1,   0
        TVpart =  1,   0,   1,   1,     1,   0,   1,   1
    constants: H1L=1, H2L=0, H3L=1, SW1=0, OG1=1, RG1=1, DG1=1,   H1U=1, H2U=0, H3U=1, SW2=0,
    OG2=1, RG2=1, DG2=1
```

Sequencing rule as written in an ASCII file. These rules are "compiled" then transmitted to the ODILE firmware register by the middleware.

The firmware was originally designed for the LSST project and we adapted it to our FPGA which is of a different nature from that used by the telescope. It offers a very wide variety of configurations. A total of 32 clocks can be defined and their status programmed into functions. Each function allows the definition of a sequence (continuation) of change of state of clocks of length 16 maximum. Up to 16 distinct functions are programmable and can be called by subroutines which will carry out a particular task (for example shift a row of pixels downwards).

DAQ : Middleware and software

As mentioned previously, all cards (4-CABAC, ADC, CROC, this is also true for the ACM) as well as the sequencing firmware need to be configured. The user communicates with these elements using LDAQ middleware written in Python. Developing this code required a deep understanding of programming the different chips. This Python software allows the user to program the ACM card, to reread what is written in the register of each

chip or the memories linked to the clock and biases generation in the FPGA. It also allows you to load the sequencer file and more generally the firmware configuration file itself as well as the operating mode of the digital CDS filter that we have written.

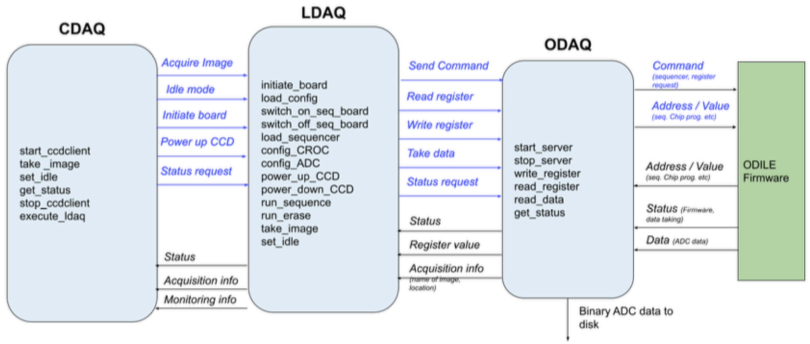


Diagramme d'échange des messages entre les différentes composantes du système d'acquisition de données et de contrôle du détecteur.

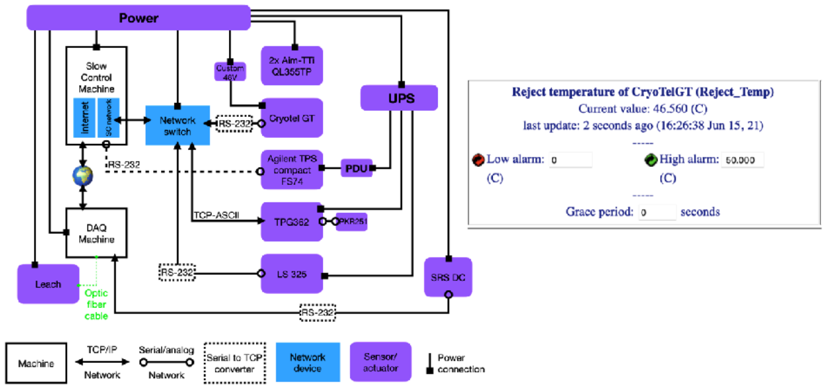
The CDAQ central acquisition system will control a set of LDAQ middleware, one for each of the 50 DAMIC-M CCD modules. It also integrates monitoring and synchronisation functions. At the other end of the chain, an ODAQ server manages communications with the ODILE-ACMs via the Ethernet protocol. This server receives messages from LDAQs and directs them to the appropriate IP addresses and ports of each recipient ODILE. In return, it receives the information transmitted by the ODILEs cards and in particular the ADC data streams which are then distributed to consumer clients (for archiving of course but also for example for online evaluation of data quality).

This client-server architecture is very flexible. It allows to add as many CCD modules as necessary. The central CDAQ part is independent of the hardware details which are hidden in the middleware.

We are currently in the final process of integration of those various firmware/ software components and we plan to install a fully functional system at LSM for the LBC at the end of 2023. Additionally LPNHE has developed a synchronisation firmware and fan out board that allows, if needed, to synchronise all CDD readout clock in order to prevent cross talk noises during the ADC sampling time intervals.

Monitoring

A slow control and monitoring system has been developed with the Universities of Chicago and Zurich. This system set up on the blue cryostat (see below) at the LPNHE was then put into service on the LBC at the Modane underground laboratory. It allows on the one hand to record at regular intervals the operating parameters of the detector as well as the environmental parameters and on the other hand to trigger alarms indicating a malfunction of an element of the system.



On the left, the private network of the slow control and monitoring system developed and installed at LPNHE for the blue cryostat. "Power" refers to the LPNHE electrical network. UPS is the APC SMC1000 uninterruptible power supply. PDU is the power distribution unit used to control the pump switch. The TPS compact vacuum pump is connected to the SlowControl machine using an RS-232 serial port, allowing pump parameters (e.g. rotation speed) and the pump-side pressure gauge to be monitored. TPG362 is the Pfeiffer pressure controller managing the PKR251 pressure gauge.
On the right is an example of an alarm with its trigger parameters.

Alarms are sent by email and SMS to the personnel in charge of acquisition. Some alarms are intended to cause a complete automatic shutdown of the detector. This automatic system requires very precise focusing at the risk of irreparably damaging the CCDs. It is still under development.

Detectors and detector testing

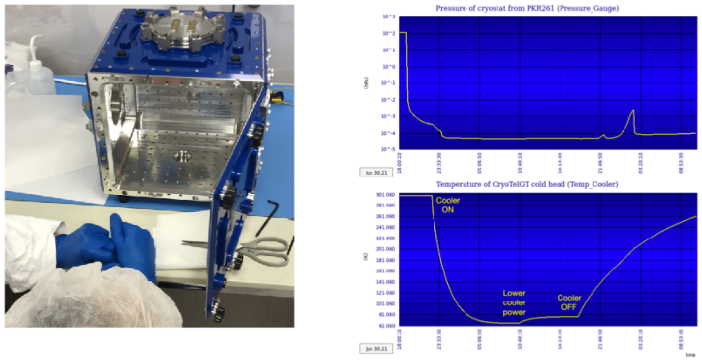
To test and qualify all of the above components but also for the implementation of CCDs and the collection of images, between 2019 and today we have equipped, thanks to ERC funds, a test laboratory with a clean room, 3 cryogenic benches, and all the equipment (PC, temperature and pressure probes, oscilloscopes, power supplies, etc.) necessary for the operation of the detectors.

Our laboratory with its clean room. Our three cryostats are visible (Orange for the implementation of LEACH and the reading noise reference in the background on the left, blue in the background on the right, silver in the foreground for testing electronic cards).

One of our cryostats allowed us to familiarise ourselves with the acquisition of CCDs using a commercial system (Leach from Astronomical Research Camera Inc.) then to qualify CCDs and obtain an energy resolution such as that which is shown on the cover of this document. This test bench then served as a reference for noise measurements of the reading electronics.

A second cryostat was used for the sequencing test with the 4-CABAC card and for the CROC then DCA front-end amplifiers.

The third was used to test CCDs and to develop (with Zurich and Chicago) a monitoring and alarm system now installed in Modane for the Low Background Chamber (see below).



On the left the cryostat (blue) used for the qualification of CCDs and the monitoring system. On the right example of monitoring data (pressure and temperature).

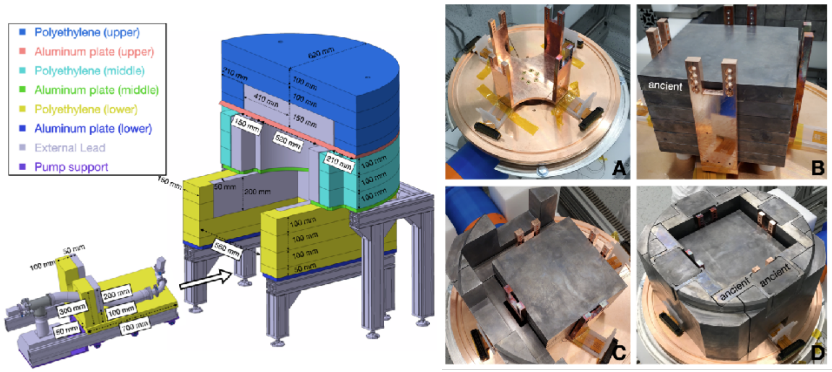
The Low Background Chamber at Modane

The Low Background Chamber (LBC) is a prototype of DAMIC-M. which serves as both a demonstrator and a test bench. Its configuration is frequently updated to accommodate and test the parts and technologies to be deployed in the final experience. Installation and commissioning took place between October 2021 and March 2022, with extensive CCD characterisation activities in January and February. Scientific data acquisition campaigns have been underway for several months.

The low background Chamber being installed. On the left the pump, on the right the cryostat with its internal shielding before closing.

The detector is equipped with two scientific-grade Skipper 6144 × 4128 CCDs, for an overall sensitive mass of 17.8 g. Its characteristics and its low background noise rate (10 DRU) make it a competitive experiment on dark matter. The LBC is housed in the clean room where the DAMIC-M experiment will itself be installed. This was built by ADS Laminaire under our direction and finalised in spring 2021. Earlier this year (2023) we installed to new CCD modules with the final DAMIC-M design. Each module consist of 4 independent CCDs of 1.6kx6k pixels for a total of 36 Mega pixels per module. Those modules are currently used for a new science data taking run.

Most of the design of the cryostat was done in the USA; Our direct contributions in addition to the clean room concern lead shielding, installation, the slow control system mentioned above, data collection and today analysis including the calculation of sensitivity and measurement of an upper limit to leptophilic interactions

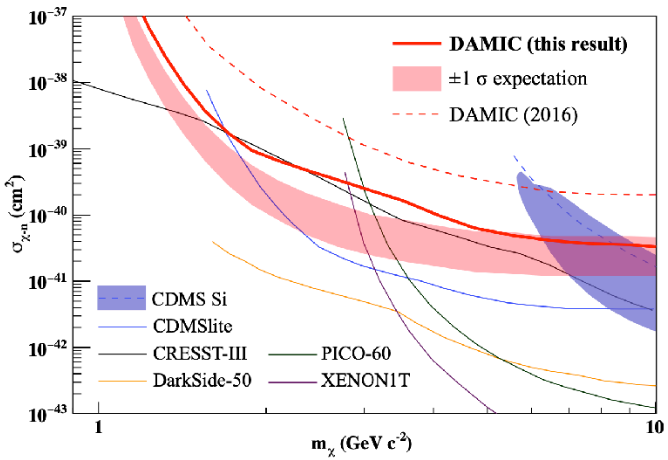


Low Background Chamber: On the left model of the shielding and the opening system. On the right mounting of the internal shielding.

Scientific Publications

Here is a list of the main scientific publications to which the IN2P3 team has particularly contributed. I reproduce here the summaries of these articles as well as some of the main figures.

1. **Results on Low-Mass Weakly Interacting Massive Particles from an 11 kg-day Target Exposure of DAMIC at SNOLAB (arXiv:2007.15622, 2020)**. We present constraints on the existence of weakly interacting massive particles (WIMPs) from an 11 kg-day target exposure of the DAMIC experiment at the SNOLAB underground laboratory. The observed energy spectrum and spatial distribution of ionization events with electron-equivalent energies > 200 eV_{ee} in the DAMIC CCDs are consistent with backgrounds from natural radioactivity. An excess of ionization events is observed above the analysis threshold of 50 eV_{ee}. While the origin of this low-energy excess requires further investigation, our data exclude spin-independent WIMP-nucleon scattering cross sections σ_χ–n as low as 3×10^{-41} cm^2 for WIMPs with masses m_χ from 7 to 10 $GeVc^{-2}$. These results are the strongest constraints from a silicon target on the existence of WIMPs with m_χ < 9 $GeVc^{-2}$and are directly relevant to any dark matter interpretation of the excess of nuclear-recoil events observed by the CDMS silicon experiment in 2013.



Upper limit (90% C.L.) on σχ–n obtained from this analysis (solid red line). The expectation ±1σ band if only known backgrounds are present in our data set is shown by the red band. For comparison, we also include 90% C.L. exclusion limits from our previous result with a 0.6 kg d exposure, other experiments, and the 90% C.L. contours for the WIMP-signal interpretation of the CDMS silicon result

2. **Characterization of the background spectrum in DAMIC at SNOLAB (arXiv:2110.13133).** We construct the first comprehensive radioactive background model for a dark matter search with charge-coupled devices (CCDs). We leverage the well-characterized depth and energy resolution of the DAMIC at SNOLAB detector and a detailed GEANT4-based particle-transport simulation to model both bulk and surface backgrounds from natural radioactivity down to 50 eV_{ee}. We fit to the energy and depth distributions of the observed ionization events to differentiate and constrain possible background sources, for example, bulk ^3H from silicon cosmogenic activation and surface ^{210}Pb from radon plate-out. We observe the bulk background rate of the DAMIC at SNOLAB CCDs to be as low as 3.1±0.6 counts $kg^{-1}day^{-1}keV^{-1}{}_{ee}$, making it the most sensitive silicon dark matter detector. Finally, we discuss the properties of a

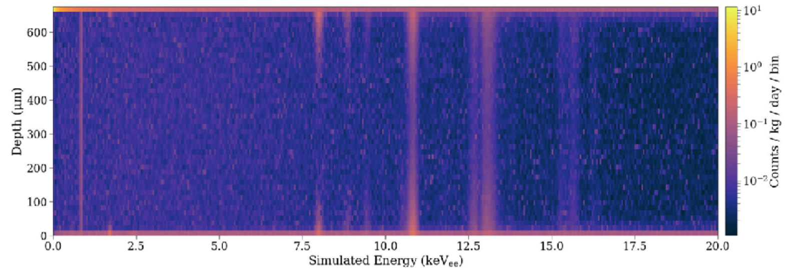


FIG. 10. The background model template (for CCDs 2–7) in raw simulated energy E_{sim} and depth ($z = 0$ corresponds to the front of the CCD) according to the best-fit combination of the 49 templates used in the binned likelihood fit above 6 keV_{ee}. The color bar indicates the rate of events expected per kg-day per 50 eV_{ee} × 15 μm bin.

statistically significant excess of events over the background model with energies below 200 eV_{ee}.

3. **Measurement of the bulk radioactive contamination of detector-grade silicon with DAMIC at SNOLAB (arXiv:2011.12922).** We present measurements of bulk radiocontaminants in the high-resistivity silicon CCDs from the DAMIC at SNOLAB experiment. We utilise the exquisite spatial resolution of CCDs to discriminate between α and β decays, and to search with high efficiency for the spatially-correlated decays of various radioisotope sequences. Using spatially-correlated β decays, we measure a bulk radioactive contamination of ^{32}Si in the CCDs of 140±30 μBq/kg, and place an upper limit on bulk ^{210}Pb of <160 μBq/kg. Using similar analyses of spatially-correlated bulk α decays, we set limits of <11 μBq/kg (0.9 ppt) on ^{238}U and of <7.3 μBq/kg (1.8 ppt) on ^{232}Th. The ability of DAMIC CCDs to identify and reject spatially-coincident backgrounds, particularly from ^{32}Si, has significant implications for the next generation of silicon-based dark matter experiments, where β's from ^{32}Si decay will likely be a dominant background. This capability demonstrates the readiness of the CCD technology to achieve kg-scale dark matter sensitivity.

4. **Precision measurement of Compton scattering in silicon with a skipper CCD for dark matter detection (arXiv:2207.00809).** Experiments aiming to directly detect dark matter through particle recoils can achieve energy thresholds of (1eV). In this regime, ionization signals from small-angle Compton scatters of environmental γ-rays constitute a significant background. Monte Carlo simulations used to build background models have not been experimentally validated at these low energies. We report a precision measurement of Compton scattering on silicon atomic shell electrons down to 23 eV. A skipper charge-coupled device (CCD) with single-electron resolution, developed for the DAMIC-M experiment, was exposed to a ^{241}Am γ-ray source over several months. Features associated with the silicon K, L_1, and $L_{2,3}$-shells are clearly identified, and scattering on valence electrons is detected for the first time below 100 eV. We find that the relativistic impulse approximation for Compton scattering, which is implemented in Monte Carlo simulations commonly used by direct detection experiments, does not reproduce the measured spectrum below 0.5 keV. The data are in better agreement with *ab initio* calculations originally developed for X-ray absorption spectroscopy.

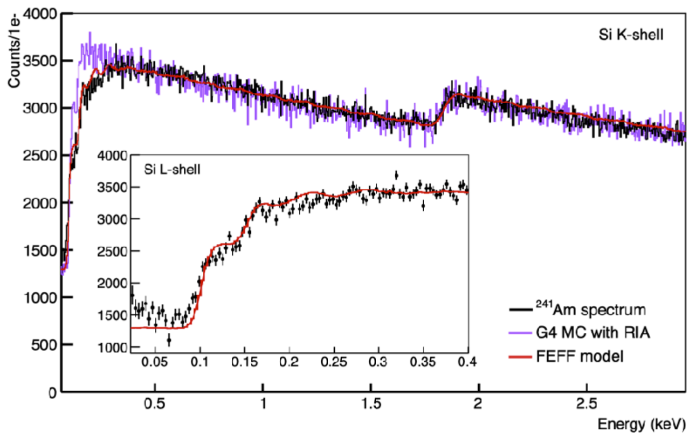


FIG. 10. The measured ^{241}Am Compton spectrum (black) from the 23 eV detection threshold to 2.1 keV. The K-step is observed at 1.8 keV. The GEANT4 simulated spectrum (purple) that is based on the relativistic impulse approximation is also shown. In red is the *ab initio* calculation from the FEFF code, with detector response taken into account. The inset shows the data comparison to the FEFF prediction in the L-shell energy range.

5. **First Constraints from DAMIC-M on Sub-GeV Dark-Matter Particles Interacting with Electrons.** We report constraints on sub-GeV dark matter particles interacting with electrons from the first underground operation of DAMIC-M detectors. The search is performed with an integrated exposure of 85.23gdays, and exploits the sub-electron charge resolution and low level of dark current of DAMIC-M Charge-Coupled Devices (CCDs). Dark-matter-induced ionization signals above the detector dark current are searched for in CCD pixels with charge up to 7e−. With this data set we place limits on dark matter particles of mass between 0.53 and 1000MeV/c2, excluding

unexplored regions of parameter space in the mass ranges [1.6,1000] MeV/c2 and [1.5,15.1] MeV/c2 for ultra-light and heavy mediator interactions, respectively.

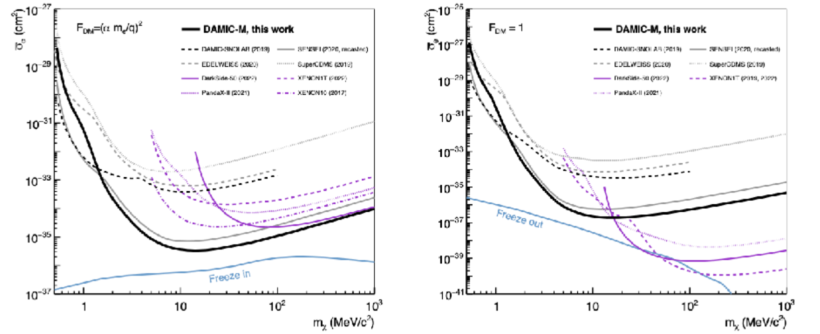


FIG. 3. DAMIC-M 90% C.L. upper limits (solid black) on DM-electron interactions through a ultra-light mediator (left) and heavy mediator (right). Also shown are current best direct-detection limits from other experiments, DAMIC-SNOLAB [35] (dashed black), SENSEI [20] (solid gray), EDELWEISS [36] (dashed gray), SuperCDMS [37] (dotted gray), DarkSide-50 [38] (solid violet), XENON1T combined result from [39, 40] (dashed violet), PandaX-II [41] (dotted violet), and a limit obtained from XENON10 data in Ref. [42] (dash-dotted violet). Theoretical expectations assuming a DM relic abundance from freeze-in and freeze-out mechanisms are also shown in light blue [11].

6. **Search for Daily Modulation of MeV Dark Matter Signals with DAMIC-M.** Dark Matter (DM) particles with sufficiently large cross sections may scatter as they travel through Earth's bulk. The corresponding changes in the DM flux give rise to a characteristic daily modulation signal in detectors sensitive to DM-electron interactions. Here, we report results obtained from the first underground operation of the DAMIC-M prototype detector searching for such a signal from DM with MeV-scale mass. A model-independent analysis finds no modulation in the rate of 1e− events

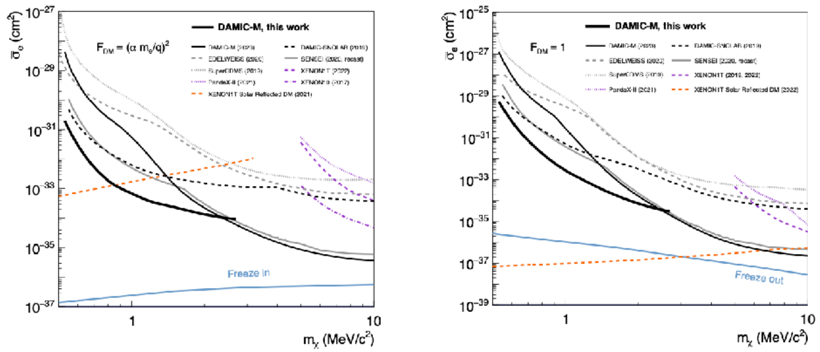


FIG. 4. DAMIC-M 90% C.L. upper limits (solid thick black) on DM-electron interactions through an ultralight (left) and heavy (right) dark photon mediator obtained from the daily modulation analysis. Also shown are previous limits from DAMIC-M [16] (solid black) and other experiments: DAMIC-SNOLAB [13] (dashed black); SENSEI [14] (solid gray); EDELWEISS [15] (dashed gray); SuperCDMS [12] (dotted gray); XENON1T combined result from [66, 67] (dashed violet); PandaX-II [68] (dotted violet); a limit obtained from XENON10 data in Ref. [69] (dash-dotted violet); and a limit obtained from XENON1T data considering "solar reflected DM" (dashed orange) from Ref. [70] (left) and Ref. [71] (right). Theoretical expectations assuming a DM relic abundance from freeze-in and freeze-out mechanisms are also shown in light blue [72].

with periods in the range 1-48 h. We then use these data to place exclusion limits on DM in the mass range [0.53, 2.7] MeV/c2 interacting with electrons via a dark photon mediator. Taking advantage of the time-dependent signal we improve by ~2 orders of magnitude on our previous limit obtained from the total rate of 1e− events, using the same data set. This daily modulation search represents the current strongest limit on DM-electron scattering via ultralight mediators for DM masses around 1 MeV/c2.

7. **Confirmation of the spectral excess in DAMIC at SNOLAB with skipper CCDs.** We present results from a 3.1 kg-day target exposure of two charge-coupled devices (CCDs), each with 24 megapixels and skipper readout, deployed in the DAMIC (DArk Matter In CCDs) setup at SNOLAB. With a reduction in pixel readout noise of a factor of 10 relative to the previous detector, we investigate the excess population of low-energy bulk events previously observed above expected backgrounds. We address the dominant systematic uncertainty of the previous analysis through a depth fiducialisation designed to reject surface backgrounds on the CCDs. The measured bulk ionisation spectrum confirms with higher significance the presence of an excess population of low-energy events in the CCD target with characteristic rate of ~7 events per kg-day and electron- equivalent energies of ~80 eV, whose origin remains unknown.

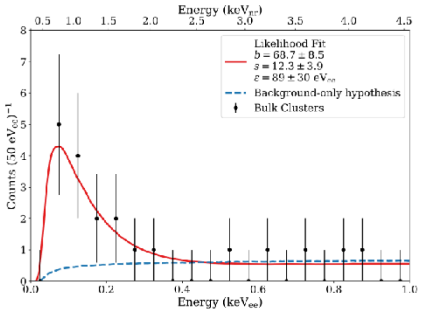


FIG. 3. Result of the fit to bulk events with the exponential excess + background (red) and the background-only (blue dashed) hypotheses. The fit prefers a low-energy exponential component. The top axis shows the nuclear recoil energy scale from CCD calibrations [14].

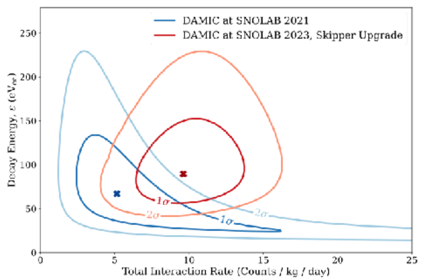


FIG. 4. Comparison of the allowed parameter space of the bulk excess measured in this work and the previous 11 kg-day analysis [2].

Perspectives

The installation of DAMIC-M will take place in 2024 for approximately two years of data collection. The sensitivity projections, particularly in the dark sector (leptophilic dark matter, dark sector photon coupled to the ordinary photon) are excellent with an improvement of the existing limits by several orders of magnitude. A prototype of the DAMIC-M detector (the LBC) was installed in Modane.

IN2P3 teams were very much involved in starting up the prototype detector and taking data during the spring and summer-fall of 2022. The analysis of the latter was very conclusive and lead to two PRL publication in 2023 (one published, one submitted). The next two years will be devoted to electronics integration tests and CCD tests thanks to the three cryogenic test benches that we have carried out in the laboratory, as well as to the installation of the detector and its commissioning. in Modane. The first scientific publications based on around 1kg.year of exposure should take place in 2026.

The installation and commissioning of DAMIC-M represents a significant workload. Tests of the electronics (front-end amplifier) and its integration will largely be carried out at LPNHE while DAQ test will take place at IJCLab, LPNHE and LSM. The packaging of the CCDs must be done in an underground laboratory (either in Modane or at Gran Sasso) and involves meticulous work in a clean room. This will also be a significant work load. Finally, the start-up in Modane will require a strong presence of physicists and technicians on site. The French, American, Spanish and Swiss teams are all very involved in these stages.

In parallel with DAMIC-M, we are following the development of the American DOE's OSCURA project. Based on the same CCDs as DAMIC-M but smaller (1kx1k instead of 1.5kx6k for DAMIC-M) and in much larger numbers (around 30,000 CCDs) this pre-financed project aims to bring together 10kg of target mass, i.e. ten times more than DAMIC-M. Several avenues of participation are possible, ranging from purely scientific contribution to participation in CCD tests making use of the DAMIC-M installations at the LSM or the establishment of a skipper technology transfer partnership with a European foundry.

The Americans intend to finance almost entirety this project. However, they wish to form an international collaboration and our participation would be very much welcome.