Contribution Prospective 2020
GT06 – Physique des neutrinos et matière noire

# The direct search for Dark Matter in the keV/c$^2$ to GeV/c$^2$ range through its interaction with nucleons or electrons using solid-state cryogenic detectors

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*Abstract:*

*The search for Dark Matter (DM) particles with masses between 1 keV/c$^2$ and 1 GeV/c$^2$ is particularly attractive. In particular, the range from 1 MeV/c$^2$ to 1 GeV/c$^2$ covers models where the DM particle masses are related to those of the Standard Model that have gained interest in the context of the absence of signal for new physics at LHC. This range poses the challenge of having to face signals that are either nuclear recoils (NR) or electron recoils (ER) at energies spread over a daunting energy range. It should however be readily accessible with new generation of small (<1 kg) cryogenic semiconductor detector arrays. To face efficiently the challenge of backgrounds, it is possible to use detectors that can be operated in two modes. In the first one, nuclear and electron recoils can be differentiated event-by-event down to 50 eV using the difference between the phonon and ionization yield of the two populations. In the second mode, the experimental threshold is reduced to the single-electron sensitivity by amplifying the ionization-induced heat signal with a strong electric field, resulting in a statistical separation of the two populations. Both modes are used to completely characterize the NR and ER signals and backgrounds, allowing to broaden the search to models that predict DM interaction with either nucleons or electrons. Nuclear recoils inducing a Migdal effect could be unambiguously tagged by the double ionization and phonon measurement. The objective would be to test light DM models with electron scattering compatible with the freeze-in constraints down to 1 MeV/c$^2$, and extend the reach for WIMPs with masses between 0.1 and 1 GeV/c$^2$. A kg-size array would be sensitive to cross-sections close to 10$^{-43}$ cm$^2$ and provide the information needed to build a larger array able to reach the solar neutrino floor. These detectors would also be well suited to search for conversion electron from interactions by bosonic or axion-like particles with masses as low as a few eV/c$^2$. The extension of the search for DM particles to masses as low as 1 keV/c$^2$, requires the development of detectors with meV range thresholds, such as cryogenic detectors with superconducting metal absorbers.*

## Direct Dark Matter Searches

Our current understanding on the nature of the Universe implies that we should be immersed in an intense flux of particles that are beyond those comprising the Standard Model of particle physics. There is ample evidence supporting the presence of this large mass of so-called Dark Matter (DM) at astronomical and cosmological scale. However, despite an intensive search in the last decades, there has been no conclusive observation of collisions between a DM particle and ordinary matter. Experiments looking for such collisions with target detectors in laboratories are called Direct Dark Matter searches. There is still the possibility that these particles will always escape direct detection because of negligibly small interaction rates with ordinary matter. However, such non-observation would already be a fundamental information that is required in order to formulate a viable theory for DM.

The astronomical and cosmological observations give very limited information on the possible mass of the DM particles [1]. Constraints from the Heisenberg uncertainty principle and searches for massive compact objects indicate that it can be anywhere from $10^{-22}$ to $10^{+54}$ eV/$c^2$, respectively. For fermion DM particles, the Pauli exclusion principle applied to our Galactic halo moves up the lower bound to 1 eV/$c^2$. No detection technique can tackle such wide mass ranges. It had been hoped that the observation of new physics at LHC would help to orient the searches towards a preferred mass scale, assuming that the DM particles were related to this new sector. The absence of SUSY signal has revived the interest to broaden the search and consider models with a wider variety of DM particle mass ranges.

## Direct Dark Matter Searches in the keV/$c^2$ to GeV/$c^2$ mass range

Experimentally, the search strategy for a direct DM search depends on the considered mass range, since the maximum energy transfer in a collision occurs when the projectile and target mass are similar. Considering that readily available target materials are made of nuclei and electrons, the mass range that is the most accessible for experiments is in the keV/$c^2$ to TeV/$c^2$ range. This range is of particular interest for models where the DM mass is not too far from those of Standard Model particles. In addition to models where the DM particle is a weakly-interacting massive particle produced thermally in the Big Bang (WIMP), there has been a growing interest for Asymmetric Dark Matter (ADM) models [2], where the DM mass is of the order of the GeV/$c^2$. Other models concern Strongly Interacting Massive Particles (SIMPs [3]) inspired by the possibility to solve the cusp/core and halo satellite problems with DM particles having strong-force size interactions and of masses in the sub-GeV/$c^2$ domain. DM particles could also be part of a Dark Sector, i.e. new particles that can only interact with Standard Model via a mediator that has a small coupling to either photons, Higgs or neutrinos and has yet escaped accelerator searches. In this context, a wider mass range and the possibility of DM interactions with electrons has to be explored. It thus makes sense that this is the first domain that direct searches should turn to. At lower masses, direct searches can look for the monoenergetic peak due to the absorption of bosonic DM particle (such as an Axion-Like Particle (ALP) searches) or a Dark Photon [4], but cannot compete below the eV/$c^2$ range with dedicated searches for the interaction of the axion field with an electromagnetic field.

Figure 1 (top part) shows what type of signal can be observed in a collision of a DM particle with matter, as a function of its mass. Above ~0.5 GeV/$c^2$, the most efficient process is the coherent scattering of the DM particle with the entire nucleus, producing a nuclear recoil (NR). Taking into account typical velocities for objects bound to our Galaxy, the kinetic energy of this recoil can vary from 0.1 to 10 keV for DM masses between 1 and 100 GeV/$c^2$. As the mass of the DM increases, it becomes increasingly attractive to use a target nucleus with a large atomic mass. First, it maximizes the energy transfer in the collision, and secondly, in the case of coherent scattering, the event rate scales as the square of the atomic mass. The region above 10 GeV/$c^2$ is particularly well covered by large xenon and argon detectors. Historically, this region corresponded to the type of SUSY particles in models that would have also been observed at LHC. There already exists detector plans to fill the remaining SUSY phase space above the neutrino floor in the coming years. Below 1 GeV/$c^2$, the efficiency of the energy transfer to a nucleus decreases rapidly. The efficiency of large detectors also decreases, partly because of this, but also by the fact that the average recoil energy is less than 1 keV and is not sufficient to produce a significant scintillation signal. Large xenon or argon detectors are then limited by the loss of their ER background rejection capabilities. Cryogenic detectors have shown their capabilities to explore the 0.1 to 1 GeV/c$^2$ domain (bottom part of figure 1), but in a mode where they also lose their ER background rejection. All current projects in that mass range are limited by backgrounds, and there is a clear need for an experiment with discrimination capabilities extended to the lowest energy possible.

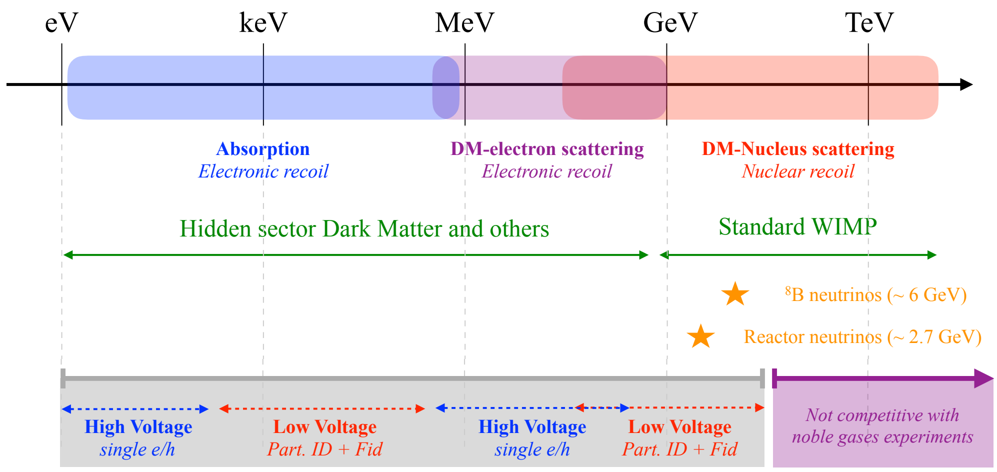


Figure 1: The DM particle mass range accessible by present and future generations of solid-state cryogenic detectors

In the MeV/c$^2$ domain, the electron becomes the ideal target. The signal is then an electron recoil (ER), with a kinetic energy well below 1 keV. The efficiency vanishes as the average ER energy becomes comparable to the electron binding energy, for DM masses close to 1 MeV/c$^2$. In such searches, the limiting background is not the usually sub-dominant NR background, but the external or surface ER backgrounds. Current projects in this domain are expected to be background limited.

In a target made of electrons and nuclei, the two are bound by an intense electric field. An unknown particle that has electromagnetic interaction could interact with this field, creating a conversion photon or electron. That photoelectric-like effect can be used to search for bosonic or axion-like DM particles that have interactions with the electromagnetic field. In both cases, the signal is also an ER: either the conversion electron, or the recoil produced by the reabsorption of the photon.

Recently, it has been shown that searches with cryogenic [8] or noble-gas detectors [9] can improve their reach by using the Migdal effect [10], whereby the collision of a DM particle with an atom emits a high-energy (~100 eV) electron. Future detectors should obviously use this effect, but also ideally be able to validate by direct observation (not yet achieved in any detector) the assumptions on which are based its calculation.

## *Prospectives 2021-2025:* Searches of DM particles in the MeV/c$^2$ to GeV/c$^2$ range with a 1-kg cryogenic detector array with discrimination

The APPEC strategy for European Astroparticle Physics in 2017-2026 had identified solid-state cryogenic detectors as the best technology to explore WIMP masses below 10 GeV/c$^2$. Since that report, the physics case to probe this region has strengthen, with an increased interest for light DM interactions with electrons, and the consideration of the Migdal effect as a powerful tool to extend searches to much lower masses than previously anticipated. Current projects in this mass range, down to 0.1 GeV/c$^2$, are currently limited by backgrounds that are particularly difficult to control and eliminate. The strong physics case and the need to develop techniques that can better tackle the problem of background in this uncharted domain call for the development of detectors able to discriminate event-by-event ER, NR and surface backgrounds down to 50 eV. Once these are understood, the experimental thresholds can be reduced to a value below the single electron energy (3 eV in germanium), with statistical tools to separate the signal and the background. This can be achieved by a detector similar to the CryoCube in development for the Ricochet experiment [11], combined with the possibility to operate this type of detectors at high bias [12] in the EDELWEISS environment [5]. With its phonon resolution of $\sigma_{phonon}$ = 10 eV and ionization resolution of $\sigma_{charge}$ = 20 $eV_{ee}$, a 1-kg CryoCube would be able to explore cross-section values of a few $10^{-43}$ $cm^2$ with an event-by-event discrimination of NR and ER. With this unique capability to completely separate signal from background at such low rates, this array could be in turn used in a high-bias mode, first to extend the search to even lower mass, and secondly to complete the physics program with searches of DM-electron interactions. The achievement of this program, called EDELWEISS-SubGeV, would be an important milestone in the design of a larger array adapted to the extension of the searches down to the solar neutrino floor. This detector would be also ideally suited to exploit the Migdal effect to extend the search for DM particles interacting with nucleons, down to DM masses of a few 10's of MeV/$c^2$ (as shown in Ref.[8]), since the ER and NR components can be separated statistically by comparing the data recorded at low and high bias values. In addition, the ionization resolution is small compared to the typical ~100 eV energy of Midgal electrons, making it possible to design a high-statistics neutron source experiment able to observe for the first time this effect, and better constrain the assumption used in the calculation of the response to DM particle interactions.

This program has already been presented [6] and the proposed development has been reviewed favorably by the IN2P3 Scientific Council in October 2018 [7]. The aim would be to complete the 1-kg stage at LSM before 2025. The extension to a larger array could follow, in the context of a high-visibility IN2P3 contribution to the upgrade of the SuperCDMS experiment at SNOLAB. Progress in achieving the phonon and ionization resolutions as well as the high-bias goals are well underway [12]. A phonon resolution of 18 eV has already been achieved with a 33 g detector [8], and a further factor two can be obtained by replacing the front-end FET pre-amplifier by a High Electron Mobility Transistor (HEMT) [13]. This HEMT readout development (IP2I, CSNSM, C2N, CEA/IRFU) is done in synergy with the French Ricochet teams. The study from Ref [13] describes how a 38-g germanium detector fully equipped with electrodes, heat sensor and cabling, can have the low capacitance (<20 pF) needed on the input of a cold HEMT preamplifier to obtained a single-electrode resolution of 20 $eV_{ee}$. Finally, the work done by EDELWEISS on high-bias operations of its large detector will be extended to smaller devices in the context of the SELENDIS Marie-Curie Fellowship. A resolution of 1.8 eV (i.e. below the single-electron value of 3 eV) has already been obtained with a 33 g Ge detector [12], the best result obtained so far on a cryogenic detector with a mass well above 1 g.

The physics program would include the search for Axion-Like and Bosonic Dark matter particles in the mass range from 0.1 to 1 keV/$c^2$. As shown in Ref. [14], the ionization resolution is the key to reject the important background of surface electron recoil events that is of concern in all such searches using semiconductor detectors. Moreover, the voltage-assisted amplification of the phonon signal improves the line resolution that is essential in these line-search based experiments. The Sub-GeV array performance is better than that assumed in Ref. [14]. The improved threshold and rejection would put EDELWEISS back in the leadership for sensitivity for these searches below 1 keV/$c^2$.

Another extension of the physics program would be to address SIMP models where the cross sections are so large that detectors in underground laboratories are completely shielded from their flux. The challenging mass region below 50 MeV/$c^2$ is yet to be covered properly [8]. In that respect, the Ricochet-EDELWEISS synergy is highly relevant, since the CryoCube detector units are developed for above-ground operations, and Ricochet could plan special low-shielding runs for this type of searches.

Finally, with the growing interest to the sub-GeV/$c^2$ range for DM particles searches, there is an acute need to further improve our understanding of the physics related to the slowing-down of ions with kinetic energy between 10 eV and 10 keV. More precise measurements are needed in order to ensure a correct interpretation of the data. These measurements should not be limited to the average ionization yield as a function of energy, but also get information on the dispersion around this average. In addition to the Midgal effect already mentioned earlier, another expected and more important source of dispersion is that due to the stochastic nature of the slowing-down process for ions, giving rise to the quenching effects. Anisotropy effects also need to be investigated. The high-resolution data that could provide a sub-GeV detector would enable significant progress in that respect, and is an input urgently needed for the interpretation of the data from experiments searching for interaction of low-mass DM particles with nucleons.

In the domain of DM particle searches, the choices of mass range and of detector technology are closely linked. Recent technological advances have been made so that the MeV/$c^2$ to GeV/$c^2$ range will be ripe for exploration in the next 5 years. The proposed program should maximize the coverage of this domain both by its mass reach and its possibility to exploit both ER and NR signals. More information on these recent technological advances and those expected in the near future are presented in separate contributions to the GT08 (*Détecteurs et instrumentation associée*). This explains some overlap between parts of these contributions and the present one.

### *Prospectives 2025-2030:* Extending the sensitivity below 1 MeV/$c^2$

The current focus on semiconductor detectors as a tool to extend direct DM searches well below the GeV/$c^2$ domain is dictated by the unique opportunity to reap, in the coming years, an important scientific return from the maturation of the program of technological innovations described above. The longer term plan for the concerned collaborations is to develop radically new technique of cryogenic detectors with significantly lower threshold.

Further improvement to reduce the threshold for the discrimination of ER and NR (and also all type of events that would not produce significant charge signals) in a massive Ge or Si requires the development of new type of sensors, able to detect single-charge events and independently measure precisely the associated total energy deposited in the crystal. An interesting possibility is to develop massive semiconductor detectors equipped with superconducting thin film sensors inspired by the so-called Superconducting Single Photon Detectors (SSPD), but designed to measure single charges at very low temperature. These developments, and those mentioned below, will be described in an associated detector contribution to the GT08 (*Détecteurs et instrumentation associée*).

The mass range that can be covered with this technology will be limited by the threshold imposed by the semiconductor gap energy (0.7 eV in Ge). To avoid this, a superconducting material can be used as absorber in a cryogenic detector. The scattering of the DM particle on an electron with an energy as low as a fraction of meV produces quasiparticles that can be detected by either an athermal phonon or a quasiparticle sensor [16]. Detectors based on the interaction of Dark Sector DM particles in superfluid helium [17] or with optical phonons in AsGa [18] have also been proposed. Beyond 2024, the French teams will be in good position to extend their expertise to investigate the use of cryogenic detectors with superconducting metal absorbers able to reach few meV energy thresholds and study their electromagnetic background suppression capabilities. This technology would significantly extend the range of searches for light DM particle candidates from Dark Sector theories.

## Advantages of the French cryogenic detector teams

The French IN2P3 teams involved in EDELWEISS have unique advantages to carry out this program.

- World-renowned expertise in the design, production and operation of cryogenic germanium detectors
- Very strong synergy with two other major projects using solid-state cryogenic detectors: Ricochet-CENNS for the CryoCube array, and CUPID-Mo/CROSS double beta decay experiments [15] for the know-how on phonon sensors. Both CENNS and CROSS are supported by ERC grants. An important milestone for the EDELWEISS-SubGeV program will be the successful demonstration of the performance of the Ricochet CryoCube.
- Close relationship with the French company CryoConcept, best designer of ultra-low vibration dry dilution refrigerators (used by Ricochet and CROSS, as well as the EDELWEISS-SubGeV detector R&D).
- Long standing experience and investment in the operation of very-low background experiments at the LSM. The LSM is the deepest underground laboratory in the EU.
- Dominant position in the international collaboration EDELWEISS-III.
- Collaboration with US and Canadian members of SuperCDMS collaboration.

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