EDELWEISS: Report on the EDELWEISS-III phase and perspectives for the EDELWEISS low-mass program

Summary

After the completion of its phase-III, the EDELWEISS collaboration has set for goal to search for the coherent nuclear scattering of WIMPs with masses in the 0.1 to 6 GeV/c² range, down to cross-sections where the search will be limited by the irreducible background from the coherent nuclear scattering of solar neutrinos. At 1 GeV/c² and below, the neutrino floor corresponds to a cross-section of 7×10^{-45} cm² (~2×10^{-45} cm² at 0.1 GeV/c²). In the absence of background, the required sensitivity to reach this neutrino floor could be obtained with an exposure of 20 kg.y of a detector with a 10 eV resolution for nuclear recoils (NR). In principle, such an exposure requires an array of cryogenic detectors, each with typical mass between 100 g and 1 kg. ***However, the reach below 1 GeV/c² of all present and future experiments is limited by non-NR backgrounds, and it is therefore crucial to improve the discrimination performance at low energy.***

The EDELWEISS collaboration has completed in 2014 the collection of an exposure of 8 kg.y in its ***EDELWEISS-III LSM*** *setup with the largest mass of cryogenic Ge detectors ever built (20 kg) using 800-g Ge detectors with discrimination.* ***The results confirmed the power of the discrimination based on the double measurement of ionization and phonon signals****, for 10-GeV/c² scale WIMP masses. The electron-recoil events (ER) and the background of surface events that inevitably affects all solid-state detectors were effectively removed down to recoil energies close to 2.5 keV, exceeding the original 5 keV goal presented to the IN2P3 Scientific Council in 2012. The* ***surface rejection performance*** *also resulted in competitive results in the search of alternate dark matter particles producing ER signals, such as* ***axion-like particles, in the 0.8 to 500 keV/c² mass range****.*

The same Council also advised to pursue the R&D to reduce thresholds. ***Since 2015, the collaboration has started a new low-mass program where the target WIMP mass for the detector optimization is the 1-GeV/c^2 scale and below.*** *This requires first the reduction by an order of magnitude of the experimental thresholds before scaling up the detectors to gradually improve the sensitivity, down to the neutrino floor. This program encompasses three tasks to reduce the experimental thresholds. The first one is to obtain a* ***10 eV resolution for NR energy****, by both improving the resolution of the phonon channel and using the Luke-Neganov amplification of this signal. The second task is to enhance the discrimination by improving the ionization resolution with the use of HEMT amplifiers and by reducing the capacitance of the detector electrodes and cabling. The objective is to reach an* ***ionization resolution*** *less than* ***20 eV_{ee}*** *on the largest possible detectors. Understanding how this performance scales with detector mass is crucial to determine the feasibility of an aggressive program to measure precisely the NR recoil spectrum from ^8B neutrinos, an irreducible background for the search of 6 GeV/c^2 WIMPs. Finally, the third task is to upgrade the current* ***cryogenic facility at LSM*** *in collaboration with the French CUPID team. Indeed the ultimate performance of the detectors can only be assessed in an underground facility with a radioactive background as good as that achieved in EDELWEISS-III but with a dilution refrigerator with significantly reduced microphonic backgrounds. In addition of WIMP searches, the targeted thresholds and discrimination performance would also enable the accurate measurement of the* ***ionization response of germanium to NR in the 100 eV range****, essential to resolves the puzzle offered by the apparent inconsistencies in the most recent measurements in Si and Ge, with a major impact in the interpretations of low-mass WIMP searches. They would also improve by an order of magnitude the sensitivity to axion-like particles in the poorly covered mass domain between 0.1 and 1 keV/c^2.*

Important results have already been achieved in this low-mass program. First, ***the experimental thresholds of the existing 800-g detectors were successfully improved using the Luke-Neganov effect****. Starting in 2017, smaller detectors with superior resolution performance were designed and tested.* ***A resolution of 18 eV NR on the phonon channel has already been achieved in 2018 with a 32-g Ge detector, resulting in the first sub-GeV WIMP limit using germanium, and the best above-ground limits for WIMPs above 0.6 GeV/c^2.*** *The development of an HEMT-based ionization charge readout has gained momentum with a collaboration with the Berkeley CDMS group that resulted in an ionization resolution of 90 eV_{ee} on a 300-g detector. It is planned to pursue this development in collaboration with the French RICOCHET team. These developments are essential to define the baseline detector for a possible French contribution to an upgrade of the SuperCDMS SNOLAB experiment in 2023, designed to significantly enhance its physics reach. The success of the low-mass program depends of the operation of a* ***1 kg-size array of detectors at LSM, based on the current R&D on both thresholds and discrimination, able to probe cross-section values of 10^{-43} cm^2 below 1 GeV/c^2****.*

1. Scientific context

1.1 Dark Matter

The case for the existence of Dark Matter is strongly established by cosmological and astrophysical observations. The nature of this new type of particle has been one of the most important questions of particle physics in the recent decades. There is an intense experimental effort to either i) produce Dark Matter particles in accelerators, ii) observe products of its annihilation in cosmic rays, or iii) in an approach called "direct detection", measure the recoils produced in a laboratory target by the scattering of the Dark Matter particles that constitute the halo of our galaxy [1]. A major challenge is that the mass of those particles is unknown and the cross-sections of all processes where it is involved are extremely small. No single experiment can cover by itself the entire search domain, and large part of it may even be out of experimental reach. Up to the start of LHC, the most attractive – and predictive - hypothesis was that the small cross-sections were due to the weak-force interaction of the neutralino, a stable supersymmetric particle thermally produced in the Big Bang. In that context, it was natural for the Dark Matter particle to have a mass near the weak scale (~100 GeV/c^2) and a scattering cross-section on a nucleus in the range from 10^{-46} to 10^{-40} cm^2. The absence of signals from supersymmetric particles at LHC and in the direct searches using large xenon TPCs [2] has made this scenario less likely. In addition, the gamma-ray flux emitted at the core of dwarf galaxy satellites of the Milky Way sets important constraints on thermally-produced Weakly Interacting Massive Particles (WIMPs). In the absence of the predictions of a preferred model, the searches are being extended to wider ranges in mass and interaction cross-section, and the hypotheses of thermal production in the Big Bang and electroweak-force interactions are no longer a prerequisite bias. On the theoretical side, there is a keen interest for models where the WIMP would have so far escaped detection by having a mass below 10 GeV/c^2 (a natural consequence, for instance, in Asymmetric Dark Matter models [3]) and by interacting with nucleons via a light mediator [4].

1.2 Direct Searches

The emphasis has shifted to the development of the new experimental techniques needed to cover this new mass range. Above WIMP mass of 6 GeV/c^2, the best constraints are presently obtained with large xenon TPC experiments (LUX, Panda-X and XENON) and current projects (LZ, Xenon-nT, Darwin, GADMC) are expected to be sensitive to cross-sections as low as 10^{-48} cm^2, and to be limited only by the irreducible background of the coherent nuclear scattering of neutrinos from cosmic rays. The strengths of these detectors is the achievement of a very low radioactive backgrounds in the core of a large fiducial volume and the ability to discriminate electron recoils (ER) from nuclear recoils (NR) by the use of either the scintillation signal or pulse shape discrimination. The rate of progress of these almost background-free searches has been impressive. However, the situation is different if the WIMP mass is below 6 GeV/c^2. In that domain, the large TPC detectors lose their ability to discriminate electron and nuclear recoils and the searches are background-limited. The limits obtained by the DarkSide argon TPC experiment, that could provide the best sensitivity in the 2 to 6 GeV/c^2 mass range [5], depend on the model used to extrapolate their ionization yield below the energy for which direct measurements exist. Xenon and argon experiments are limited by the achieved levels of ER backgrounds, and projections predict a large loss of efficiency for WIMP masses below 1 GeV/c^2. The LUX experiment intends to exploit the bremsstrahlung and Migdal effects [6] to extend its efficiency in the sub-GeV region [7]: this requires a good understanding of this new effect at the edge of the acceptance of the detector, and a good control of the ER background.

1.3 Low-mass WIMP searches with Cryogenic detectors: International context

Cryogenic detectors with double readout, such as those developed by the EDELWEISS [8], SuperCDMS [9] and CRESST [10] collaborations, have the potential to completely cover the WIMP mass region between a few hundred MeV/c^2 and 6 GeV/c^2. To detect the nuclear recoils induced by WIMP-nucleon scattering, the required energy resolution in recoil energy should be 10 eV, a value within the reach of a massive bolometer. For this WIMP mass range, the neutrino floor due to the irreducible background of nuclear recoils from the coherent scattering of solar neutrinos corresponds to a spin-independent WIMP-nucleon cross-section of a few 10^{-45} cm^2. In the absence of backgrounds, probing this region requires an exposure of 20 kg.y with an array of detectors having a NR energy resolution of 10 eV, an objective achievable with cryogenic detectors with typical mass between 100 g and 1 kg. However, the reaches of the current projects [11,12,13] are limited by backgrounds. The double-readout of the cryogenic detectors was originally designed to provide an event-by-event discrimination of ER and NR events, based on the measurement of the distinct ionization (for EDELWEISS and SuperCDMS with Ge detectors) or scintillation yields (for CRESST with $CaWO_4$ detectors) for these two categories of events. The discrimination power depends crucially on the resolution of that channel, and degrades at the lowest energy. Near current achieved thresholds, an additional source of background arises from purely thermal events ("heat-only" events, HO), a particularly important problem for detectors relying on scintillation yield, which is systematically lower than the ionization yield.

However, the radioactive backgrounds surrounding semiconductor detectors could be reduced at levels where it would be possible to probe cross-sections as low as 10^{-43} cm^2 for sub-GeV WIMPs [11,13], using a ~10 kg-size array of detectors with an energy resolution in the 10-100 eV range (Fig. 1). This is because, in semiconductor detectors, the total energy signal is amplified by the heat signal, which is generated by the migration of the charges under the field resulting from the applied bias. With this so-called Luke-Neganov effect, an amplification factor of the order of 30 can be attained for ER by applying a bias of 100 V. The amplification depends on the ionization yield of the recoil, and will be of the order of ~5 for very low-energy NR events, and zero for HO events. With this amplification scheme, the event-by-event discrimination of NR/ER/HO events is no longer possible. It can however be replaced by a *statistical* discrimination, granted that the same detector can be operated either at low or high bias, and, preferably, using the ionization readout at low bias to better constrain the different types of backgrounds.

The Luke-Neganov amplification is at the core of the SuperCDMS strategy to reach a sensitivity of 10^{-43} cm^2 (Fig. 1). This goal is limited by the projected background levels, and their reduction from current levels to those needed is a crucial objective in installing SuperCDMS at SNOLAB [11]. The commissioning of their array of eight 1.4-kg detectors (Ge-HV) is planned for 2021, and the curves shown in Fig. 1 correspond to a five-year operation. The limits are still an order of magnitude above the neutrino floor, but so far SuperCDMS is the only experiment proposing to reach a 10^{-43} cm^2 sensitivity for 1-GeV/c^2 WIMPs. Because of the lack of discrimination capabilities of their HV detectors, it relies heavily on ambitious goals in the reduction of environmental radioactive backgrounds. The CRESST collaboration anticipates that internal radioactive backgrounds will limit their detectors at significantly higher cross-section for masses of 1 GeV/c^2 and below (Fig. 1). Additional backgrounds have since then been reported at the conference IDM2018, and their elimination is required if the CRESST experiment wants to reach its phase-I goal of 10^{-40} cm^2 at 1 GeV/c^2.

SuperCDMS also plans to use, in its first phase at SNOLAB, an array of ten 1.4-kg detectors operated at low bias (iZIP on Fig. 1), and therefore with the event-by-event rejection. However, with a target ionization resolution of 160 eV_{ee} (eV equivalent-electron, i.e. the energy scale for ER), the discrimination becomes ineffective at low energy and for a WIMP of 6 GeV/c^2, the foreseen sensitivity should reach 3×10^{-44} cm^2. This is an order of magnitude over the neutrino floor, and comparable to what is already achieved by current xenon-based experiments.

SuperCDMS is actively preparing an eventual second phase using detectors with improved performance. Recently [14], the collaboration demonstrated the sensitivity to the single-electron signal with a 0.93 g silicium prototype operated at high bias. So far the method has only been applied to set limits on ER-producing dark matter interactions, with results comparable to those of the DAMIC experiment [38]. However, reading out a heat signal instead of a pure charge signal opens the possibility to observe NR signals and discriminate them from ER using the quantized nature of the signal for electron recoils. This endeavor would require a good knowledge of the response of semiconductors to nuclear recoils with kinetic energy well below 1 keV. For this, calibrations with very low-thresholds are sorely needed, especially in view of the contrasting results obtained around 1 keV in Si [15] and Ge [16]. It is yet to be understood why, in the Si case, there are indications of a factor three suppression of the yield relative to the standard Lindhard, but not in the case of Ge. This needs to be clarified with more measurements, preferably with 100 eV-scale nuclear recoils, and it is crucial for the interpretation of all semiconductor experimental searches for sub-GeV WIMPs.

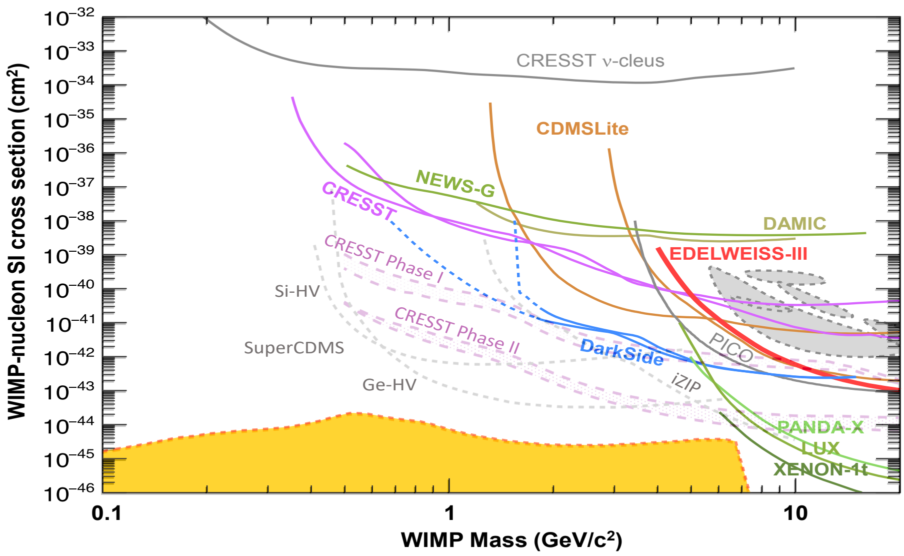

Figure 1: Current experimental limits on SI interaction with nucleus of WIMPs with masses between 0.1 and 20 GeV/c² from Refs. [2,5,9,22,37]. The projections of the cryogenic experiments SuperCDMS and CRESST are from Refs [11-12].

In conclusion, experimental search projects for NR-inducing dark matter particle interactions with masses between a few hundred MeV/c² to 1 GeV/c² are limited by backgrounds, and in particular by the lack of discrimination against them. The most ambitious goals in this mass region are those of SuperCDMS at SNOLAB, with a commissioning starting in 2020-2021. There is a need to further extend the reach of future cryogenic detectors.

1.4 Low-mass WIMP searches with Cryogenic detectors: EDELWEISS positioning

The goal of EDELWEISS is to search for nuclear recoils induced by the coherent scattering of dark matter particles in semiconductor detectors with a simple design and robust performance. An important choice made in 2008, separating EDELWEISS from CDMS, was to base the surface rejection using an interleaved electrode charge readout made of a simple pattern of concentric rings on the top and bottom flat surface of the Ge crystal (ID design), while keeping the heat sensor as close as possible to a simple thermal measurement. The EDELWEISS heat measurement is done with a pair of Ge-NTD (Neutron Transmutation Doped) thermistances (16 mm³) glued on the top and bottom electrodes, resulting in a negligible contribution to the total capacitance of the detector. In contrast, the flat surfaces of the SuperCDMS detector are covered by long strings of TES sensors and Al phonon traps, directly in contact with the detector. The superior rejection performance of the EDELWEISS ID design [17] relative to the athermal-phonon based discrimination of the original CDMS detectors lead them to partially implement the ID electrode scheme on their subsequent detectors. However, in contrast with the SuperCDMS detectors, the simplicity of the thermal readout of the EDELWEISS detector made it possible to extend the interleaved electrode coverage to all surfaces (FID electrode scheme [8]) and thus obtain a rejection of surface events better than 4×10^{-5}. The measured ER rejection, after surface event rejection, is better than 2.5×10^{-6} (Fig. 2).

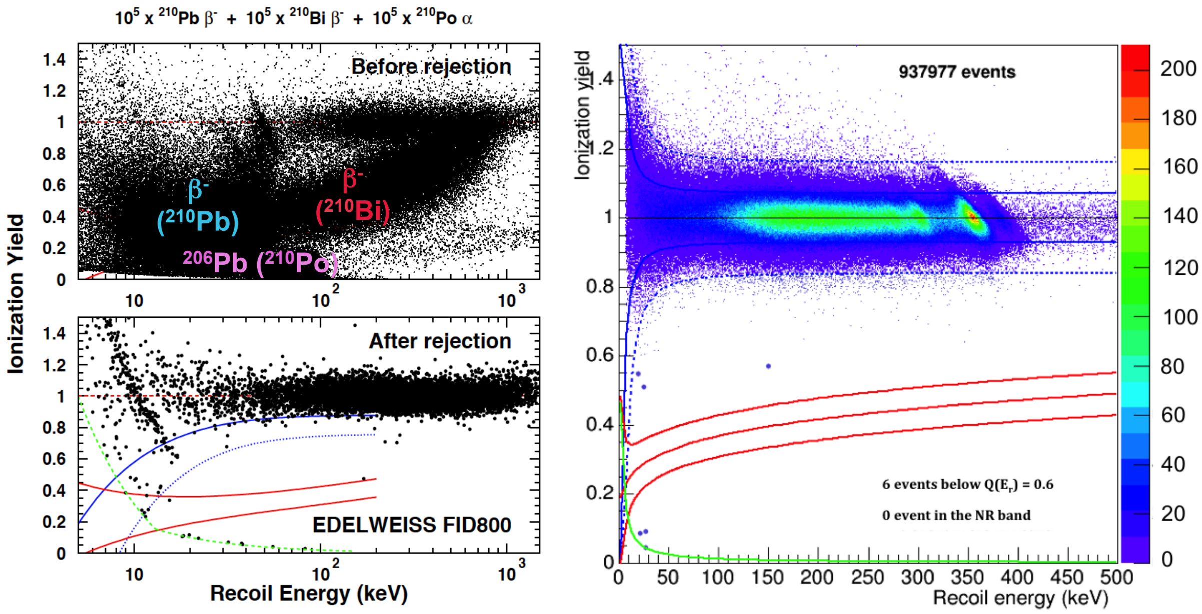

Figure 2. Left: surface rejection of the EDELWEISS FID detectors (from [8]). Right: separation of electron and nuclear recoils in the fiducial volume of the EDELWEISS FID detectors [8].

The simple FID design is easily scalable, and EDELWEISS has been able to produce for its EDELWEISS-III phase more than 36 detectors with an average unit mass of 860 g (FID800 detectors), resulting in a total mass of ~30 kg, equal to the goal for the total detector payload of SuperCDMS experiment for its first phase at SNOLAB in 2020. At the time the SuperCDMS collaboration submitted its CDR for SNOLAB in 2015 [1], it was agreed that the case for the American project would be stronger if its scope was restricted to a smaller payload based on well-defined technologies based on their SuperCDMS results at Soudan, reserving the project for an upgrade with European-made detectors from EDELWEISS and CRESST to a future upgrade (Science Goal 10) that would come after the first phase. An important input for such a contribution was the results of the EDELWEISS-III phase, described in section 2, that had yet to come. The CDMS and EDELWEISS collaborations pursue a similar strategy by exploring different technological choices, and there are frequent exchanges between the two groups. A common physics paper was published in 2011 [19], and the technical modifications needed to operate EDELWEISS detectors in the SuperCDMS towers have been studied in 2015-2016. The emphasis has now shifted to detector developments.

2. EDELWEISS-III objectives

2.1 Original objectives

The EDELWEISS-III project was originally defined in ANR "FIDSUSY" (2010-2012). The goal then was to record an exposure of 3000 kg.d using 36 FID800 detectors with a predicted background of less than one NR above a recoil energy of 15 keV in order to obtain a limit of 5×10^{-45} cm^2 for the spin-independent interaction of a ~100 GeV/c^2 WIMP. This corresponded to the region predicted by Focus-Point Supersymmetric models that were favoured at the time of submission of the project. The ANR provided the funds needed to build an array of 36 FID800 detectors, together with their electronic channels, as well as some modifications to the existing EDELWEISS-II cryostat at LSM.

2.2 Revised objectives

Updated objectives were presented to the IN2P3 Scientific Council in October 2012. The Council supported the target of a 3000 kg.d exposure but now the focus was the mass range between 5 and 20 GeV/c^2. Such a goal was achievable because the preliminary tests on prototype detectors indicated that an event-by-event rejection of ER backgrounds could be achieved down to a threshold of 5 keV NR. In a background-less search near threshold, the performance are dominated by the detectors that have the best performance, and the strategy was to identify these detectors and concentrate the efforts on them. The Scientific Council also recommended to pursue the detector developments toward lower thresholds.

In 2013, EDELWEISS also published the results of its phase II for the search of axion-like dark matter particles and solar axions [20], showing the relevance of its detector for this type of search, granted the ER background could be maintained at a competitive level. The study of alternative models where the dark matter particles interacts with electrons, for example axion-like particles was thus added to the physics program of EDELWEISS-III.

3. The EDELWEISS-III Calendar

After the test of a few prototypes in 2009-2010, the detector production was performed between 2011 and 2013. The production was delayed for a year because the appearance of a systematic problem of leakage current between adjacent electrodes that had not been detected in the first prototypes [21]. The problem was solved with a post-processing XeF_2 pulsed dry etching of the detectors that could be applied even on detectors that had already been produced. In parallel, the electronics and cabling needed for the readout of 36 detectors was being prepared, as well as a modification of the thermal machines to improve the decoupling of their vibration levels to the cryostat. The entire setup was commissioned in 2013-2014. In order to limit the commissioning delays induced by the appearance of a problem with part of the Kapton cables linking the 1 K and 10 mK stages of the cryostat, it was decided to concentrate the repairs on 24 of the 36 channels. In this way, a 3000 kg.d exposure on the best 24 detectors could be attained much quicker. That exposure was acquired between June 2014 and April 2015.

4. EDELWEISS-III results

The EDELWEISS-III data was the object of 6 major collaboration publications [8,23-27] and 6 theses (2 IPNL, 1 IPNL+KIT, 1 CEA and 2 KIT). The data was also used in 2 additional major collaboration publications [13,35] on the subsequent program to extend the sensitivity to lower mass WIMPs.

1) **Detector performance**. The experimental setup and the detector performance were described in detail in Ref. [8]. The rejection performance have already been mentioned in the previous section (Fig. 2). A testimony to the robustness of the technology is that all 24 cabled detectors were operational and could be used in physics analysis. Also, the average ionization resolution of all the detectors was σ = 230 eV_{ee}, with little dispersion. This resolution, better than that achieved by SuperCDMS Soudan detectors (400 eV_{ee}), is obtained by using an original charge readout scheme that only uses capacitance and relays, thus eliminating the noise associated with the use of resistances. That system also makes possible to continuously monitor all leakage currents with a precision <0.1 fA. The average phonon resolution is 1 keV (before the Luke-Neganov associated with the 8 V bias), with one detector reaching 500 eV. The vibration levels that remained despite the cryogenic machine upgrade had an important impact on this performance, notably by inducing a 1/f noise with an

amplitude that varied considerably from day to day. However, no further optimization of the heat resolution were deemed essential for the EDELWEISS-III program, as for most detectors the discrimination was essentially limited by the ionization performance and not the heat resolution.

2) WIMP search. The search for WIMPs in the mass range from 4 to 30 GeV/c^2 was performed first by the use of a Boosted Decision Tree selection [22,T4], and then, a maximum likelihood analysis [23,T5]. The results are shown in Fig.3. These analyses were restricted to the 8 detectors with the best and most reproducible threshold performance. The excellent ionization resolution meant that the discrimination of nuclear recoils was extended down to a recoil energy of 2.5 keV, a factor two below the original 5 keV goal. The ionization resolution was also important to discriminate against a background of HO events that was higher than anticipated. With these results, EDELWEISS was able to extend its reach for lower mass WIMPs down to 4 GeV/c^2. Its sensitivity for 7 GeV/c^2 improved by a factor 150 relative to the EDELWEISS-II ID detectors.

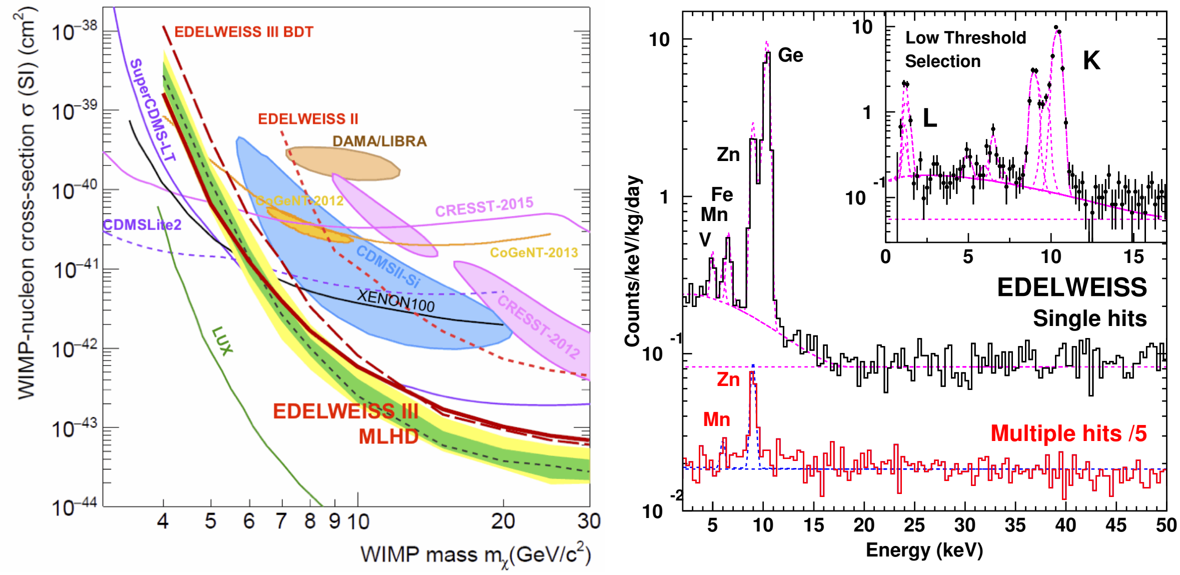

Figure 3. Left: EDELWEISS-III limits obtained with a BDT analysis [22] (dashed red line) and a maximum likelihood analysis [23] (full red line). Right: measurement of the cosmogenic activation of Ge detectors in EDELWEISS-III [24].

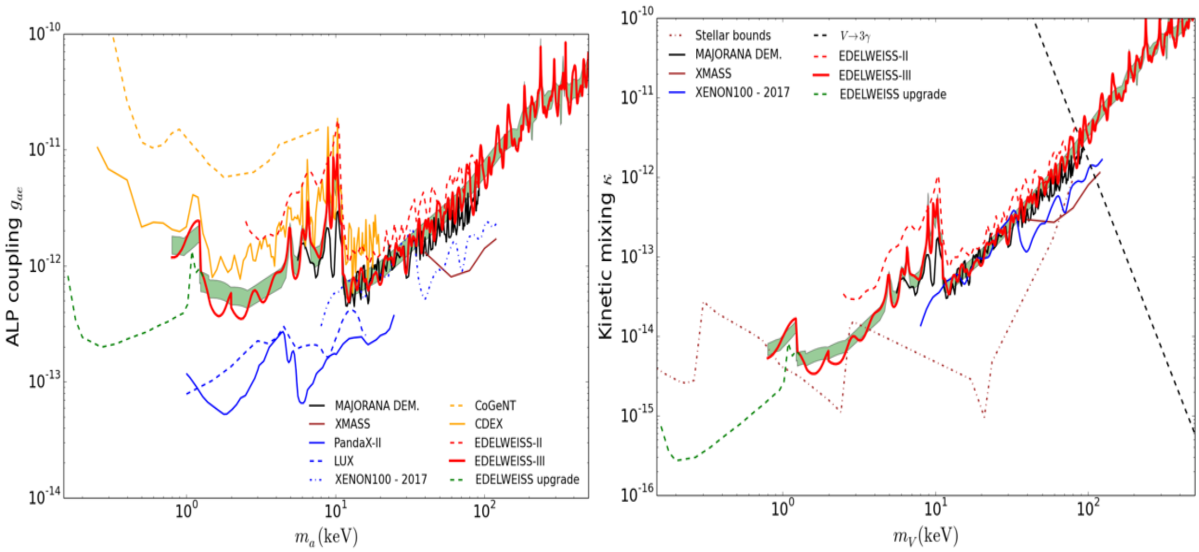

Figure 4. EDELWEISS-III results for ALPS (left) and for dark photons (right) [26].

3) Measurement of tritium and other products of cosmic activation in Ge. Thanks to a background level of ER events of less than 0.1 event/kg/d/keV (0.1 dru), EDELWEISS was the first experiment to measure accurately the activation rate of tritium in bulk germanium while it is exposed to the hadronic component of cosmic rays (Fig. 3) [25]. This activation is expected to be the source of the limiting ER background at low energy for SuperCDMS at SNOLAB. The EDELWEISS results was instrumental in defining the prescription that the above-ground steps in the procedure to build the SuperCDMS detectors (from the growth to the lithography steps) should be restricted to less than 60 days [11]. It can be noted that this goal is readily achievable with the simpler EDELWEISS electrode evaporation procedure. The other activation products ^{49}V, ^{55}Fe and ^{65}Zn were also measured to help constrain the simulation codes calculating cosmic activation in solid-state detectors.

4) Axion-Like particle search. The achieved level of the ER background at low energy as well as the good resolution achieved by most detectors were exploited to search for electron interactions induced by particles beyond the Standard Model that are not NR-inducing WIMPs [26]. The limits for axions or axion-like particles emitted from the sun and for the electron decay in three neutrinos were improved relative to those obtained with EDELWEISS-II. The most significant gain came for the search for the absorption of bosonic keV-scale dark matter from our galactic halo. For masses between 6 and 100 keV/c^2, the bounds are comparable to those recently obtained by the MAJORANA demonstrator. We extended the search up to 500 keV/c^2, and in the 1-6 keV/c^2 range, we obtained the best limits from any Ge experiment. The results from xenon detectors are lower by an order of magnitude in the 1 to 20 keV/c^2 range, but EDELWEISS was able to reach a lowest mass of 0.8 keV/c^2, indicating that improvement in ionization resolution in our detectors would be highly relevant for such searches. The bounds for the kinematic mixing for hidden photons with masses smaller than 0.9 keV/c^2 are at the same level than those derived from energy losses in Horizontal Bar stars.

5) Charge collection. The quality of the charge collection in cryogenic semiconductor detectors operated at low temperature, as the accumulation of space charge with time can degrade the quality of charge collection and produce possible fake WIMP candidates. The effect of trapping on charge collection was thoroughly investigated in the FID detectors [27,T1]. These effects are well under control, and the procedure to ensure the neutralization of the accumulated trapped charges can reliably be limited to a one-hour procedure every two days.

6) Background assessments for future phase of the experiments. The origin of the backgrounds of different origins has been studied in the framework of the above analyses. In addition, this assessment was important to establish realistic background levels in future developments, and to determine the best strategies to reach the optimal sensitivities to low-mass WIMPs [12]. The low-level of ER background has been achieved in large part due to the careful selection of material in the vicinity of the detectors, but a factor of ~2 comes from the rejection of surface events (in majority ER events) and another factor ~2 by rejecting coincidences between the 24 detectors of the array. This stresses the importance of surface rejection and of a close-packed array of detectors. The majority of the remaining fiducial ER background comes from thorium traces in the CuBe alloy used to ensure the elasticity of the connectors close to the detector and in one of the solder in the Cu thermal shield. These backgrounds were however not relevant for the ~8 kg.y EDELWEISS-III search, but would require attention for a larger exposure search. More problematic was the neutron background. It could be studied in details since the ratio of single-to-multiple nuclear recoil events in the 24 detector array is 1:3, and no other signal or background can produce such coincidences. Neutrons from natural radioactivity could be efficiently discriminated from those originating from cosmic-ray muon interactions thanks to a ~100 m^2 plastic scintillator with near 4π coverage [T3]. The background of events with multiplicity 2 or higher and with no muon counterpart was observed to exceed the expected background by a factor 10 [T1]. This is a surprising result considering that this background remained at the same level than what was observed in EDELWEISS-II, despite adding an additional internal polyethylene shield. The observed single NR rate corresponds to what is expected from the single-to-multiple event ratio in Monte Carlo simulations, but nevertheless constitutes a dominant background for WIMP searches above 10 GeV/c^2. Possible sources for this excess are trace contamination of uranium that escaped the material screening procedure and weak spots in the external polyethylene shielding. The remedy would be a more systematic use of ICPMS in the screening procedure, as gamma-ray spectroscopy is not efficient to search for out-of-equilibrium U sources. For example, ICPMS scan of CuBe samples revealed the presence of such out-of-equilibrium ^{238}U contamination, but not enough to explain the observed effect. Weak spots in the polyethylene shield can be probed by systematic scans with a strong neutron source. However, these actions are not required as long as the required sensitivity is for <10 GeV/c^2 WIMPs with cross-sections above 10^{-43} cm^2. Lastly, the dominating background for WIMPs below 10 GeV/c^2 are HO events [T5]. These are still under investigation [T2]. No single source has been clearly identified, and it is probable that different sources are at play simultaneously. However, the study of this population revealed that their rate and energy spectrum are rather predictable. Their existence (as well as the CRESST-III results recently presented at the IDM2018 conference [39]) stresses the importance of discrimination.

5. Objective of the low-mass program

With completion of the above program, the emphasis turned to the optimization of the sensitivity of the detectors to WIMPs at the GeV/c^2 scale and below. The results highlighted the importance of discrimination.

The improvement of event-by-event discrimination can only come from an improvement of the ionization resolution. Alternatively, a statistical discrimination can be achieved using the dependence of the Luke-Neganov amplification on the ionization yield of the relevant population of events. In this case also ionization resolution plays an important role, as it makes possible to measure more precisely the importance of the different background populations in the low-bias data, down to lowest possible energy. Projections indicate that Ge detectors with Luke-Neganov amplification can be sensitive to WIMP masses down to 0.5 GeV/c^2 [11,13]. Reducing this value could be possible once the relative effect of quantization of charge on the response to NR at very low energy are understood in detail, as this information could be used to resolve the ER and NR components in the heat signal spectrum. A thermal measurement with a resolution of 10 eV combined with the Luke-Neganov amplification with a bias of 100 V would result in a resolution of 0.3 eV_{ee}, sufficient to resolve the regular structure of peaks separated by 3 eV_{ee} for ER in germanium. The sensitivity could then be extended to the 0.1 GeV/c^2 scale, depending on the ionization yield values for NR and the associated straggling effects. The first observation of the regular ER structure in a 0.9 g Si detector by the SuperCDMS collaboration is a very encouraging start in this direction, but a lot of work remains in order to understand how to exploit this strategy in more massive detectors. EDELWEISS strongly believes that these developments to improve the heat resolution by the use of the Luke-Neganov amplification should be accompanied by a strong program to radically improve the ionization resolution. This goal is more readily achievable with the EDELWEISS detectors, as the thermal readout scheme and the use of thin circular electrodes on all surfaces is inherently more compatible with a low capacity than in the SuperCDMS design. Extending the ionization-based discrimination to lower energy will be beneficial to the background-free searches in the mass range from 0.5 to 6 GeV/c^2, and indirectly to Luke-Neganov searches by extending the precise measurement of ionization yield and the identification of the different backgrounds down to lower energy.

The EDELWEISS low-mass program consists of three tasks: heat resolution, ionization resolution and cryogenics. Combining the results of the three tasks would result in the operation at LSM of a kg-size array of detectors with resolutions of 10 eV phonon and 20 eV_{ee} ionization with either event-by-event or statistical discrimination, able to probe cross-section values of 10^{-43} cm^2 below 1 GeV/c^2, thus demonstrating the relevance of the EDELWEISS detector performance for the search of low-mass WIMPs.

5.1 Task 1: heat resolution

While discrimination is crucial, it must be achieved with a detector having a phonon signal resolution suitable for the detection of 100 eV nuclear recoils. That resolution can be improved by the use of Luke-Neganov amplification, but the diminishing ionization yield of low-energy nuclear recoils favors **a target of 10 eV for the energy resolution**, before amplification. This is an ambitious factor 50 improvement compared to EDELWEISS-III performance. Published projections [8] were based on a more conservative factor 5 improvement, but recent developments indicate that this limitation can be lifted. Concurrently, it is also imperative to study how the Luke-Neganov amplification can be used to increase the sensitivity to the lowest mass of WIMPs, and in particular to evaluate the effectiveness of the strategy of alternating high- and low-bias run to better control the backgrounds in each detector. EDELWEISS **targets a bias of 100 V on its detectors**. As the NTD sensor is attached to the electrode using insulated glue, the application of a large bias does not perturb its operation. The same readout and field configuration can be applied to both low- and high-bias modes, in contrast with the SuperCDMS design. The goal to achieve a 10 eV heat resolution at 0 V on a detector able to operate at 100 V corresponds to a phase called **EDELWEISS-SubGeV**.

The strategy to progress in this domain is the following. In a preparatory phase called **EDELWEISS-LT** (2015-2017), the collaboration selected its best 800-g detectors (in terms of leakage current and intrinsic heat resolution) to evaluate the performance of the existing FID800 detectors when operated at high bias, and to start the evaluation of the method of varying the bias to determine the different background components [T2]. In 2015, it also performed simulations [T1] to evaluate the possible ultimate performance of the EDELWEISS-LT phase. It calculated the sensitivity of a set of four 800 g detectors with a heat resolution of 100 eV operated at a bias of 100 V assuming current-level backgrounds. It was found that with a 150 day exposure, this array would reach a sensitivity of 10^{-41} cm^2 at 2 GeV/c^2. The 100 eV resolution goal is a factor 5 below the resolution of the best FID800 detectors, and a factor 7 below the more typical resolution values. This goal was motivated by the preliminary results of our R&D to better understand the origin of this resolution performance. In the context of the more ambitious SubGeV phase, the detectors with smaller masses were studied to better understand how performance scaled with detector size. This was performed in cryostats at IPNL and CSNSM. The EDELWEISS-LT phase also included a series of tests at LSM designed to try to understand the origin of the HO population.

5.2 Task 2: ionization resolution

The ultimate discrimination performance requires improving substantially the ionization resolution. In ref [8], it was shown that discrimination becomes relevant for WIMP searches around 6 GeV/c^2 if the ionization resolution reaches 50 eV_{ee}. This study was motivated by the recent development of High Electron Mobility Transistors (HEMTs) [28,29,30] that have the specifications needed to provide low-noise front-end amplifiers adapted to cryogenic temperatures. The 50 eV_{ee} benchmark point is relevant because a new problem arises when probing cross-section below 10^{-44} cm^2 for WIMP masses around 6 GeV/c^2: the so-called neutrino floor, i.e. the background of nuclear recoils induced by the coherent elastic scattering of solar ^{8}B neutrinos (CENNS) in the detector. No current detector can tackle efficiently the specific case of a WIMP with a mass close to 6 GeV/c^2, producing a nuclear recoil spectrum mimicking the one induced by the coherent scattering on nucleus of solar neutrinos from the decay of ^{8}B, with an average nuclear recoil energy of 0.8 keV [31]. As the searches for rare low-energy events extend their reach to lower cross-section, and hence become sensitive to more rare backgrounds, the ability to separate unambiguously nuclear recoils will become important, and even essential to confirm a discovery. However the radioactive background levels required are beyond those achieved in the present LSM cryostat, and an array of ~200 kg of detectors is needed to obtain a background-free sample of many ten's of ^{8}B CENNS events with a phase called **EDELWEISS-DMB8**. Such a phase would be better suited in the context of the upgrade of the SuperCDMS SNOLAB experiment. It should be noted that in such case, the LSM cryostat would still be needed to test massive detectors, and assemble them in towers ready for SNOLAB. Indeed, the operation of SuperCDMS at SNOLAB requires having all detector towers assembled and tested outside SNOLAB before installation.

An ionization resolution of 50 eV_{ee} would not be sufficient to obtaining an event-by-event discrimination for WIMPs with masses below 1 GeV/c^2. **This ultimate goal of the EDELWEISS low-mass program requires an ionization resolution of 20 eV_{ee}.** This is achievable on smaller detectors (32 g – 200 g). Achieving this performance on a few detectors of that type would make possible the study of background-free NR events down to recoil energy of the order of 100 eV. This is an exciting prospect for understanding the ionization process at energy where no ionization yield measurements are available and the apparent difference in behavior between Si and Ge remains to be understood. The first phase of task 2 is called **EDELWEISS-HEMT**. It consists of developing a HEMT-based charge readout for the EDELWEISS detectors. The first step of the EDELWEISS-HEMT phase is to build a 32-g detector, already able to provide valuable information on the ionization yield of low-energy NR. The RICOCHET collaboration has also similar goals [32], and EDELWEISS intends to develop this capability with its cooperation. A MoU between EDELWEISS and the French RICOCHET team is in discussion. The second step is to study the scaling of the ionization performance with detector mass, with a 200-g detector designed for a kg-size experiment at LSM to demonstrate rejection performance below 1 GeV/c^2 and an eventual 800-g prototype that could be better suited for DMB8.

5.3 Task 3: Cryogenics

The success of the SubGeV phase (Sect. 5.1) depends on a dilution refrigerator with significantly reduced microphonic backgrounds. In the context of EDELWEISS-HEMT (Sect. 5.2), the installation of HEMT electronics at LSM requires an adaptation of the cryostat for an increased thermal load on the 1K-4K stage. Also, the present logistics for the constant supply of cryogenic fluids for the cryostat are a drain of resources that can be avoided by upgrading it using the recent development of thermal machines. Since the installation of the cryostat in 2005, much progress has been done in the control of the effect of the vibration of thermal machines on detectors [33,34]. On this aspect, EDELWEISS benefits from the expertise of the Néel Institute (with already a partial upgrade of the cryostat for EDELWEISS-III), the developments in the context of LUMINEU of towers for small detectors in the EDELWEISS detector, and the recent vibration work for the LIO cryostat at IPNL, proving that vibration levels of ~10^{-7} g are achievable with thermal machines. The LSM cryostat upgrade is important as both EDELWEISS and CUPID plan for intensive detector R&D in the coming decade. Moreover a cryogenic platform at LSM is mandatory for the validation of EDELWEISS detector towers destined to be inserted in SuperCDMS-SNOLAB.

A joint EDELWEISS/CUPID working group is currently defining cryogenics upgrade with two hypotheses: (1) a minimal upgrade to ensure a minimal running for EDELWEISS and CUPID in the coming years and (2) a more important upgrade to fully adapt the facility to the EDELWEISS and CUPID requirements for the coming decade. Discussions have started with the LPSC for a full integration of the future cryogenic facility to the LSM platform. A first report of the working group is expected by the end of 2018.

6. Advancement status of the low-mass program

6.1 HV developments

Task 1 requires the operation at LSM of detectors at voltage biases close to 100 V. This was an important objective of the EDELWEISS-LT phase. The original specification for which the EDELWEISS-III detectors were tested was that a bias of 20 V would not induce leakage currents above 1 fA. Above this "breakdown" value, the stray currents start to affect the resolutions of the ionization and heat signals. Also, the original EDELWEISS-III electronic design limited the electrode biases to values between -10 V and +10 V, the normal operating range being ±4 V. In 2016, the KIT and CEA teams provided the necessary adaptation of this range to ±70 V (i.e. a maximum total bias of 140 V). It was tested that the contribution of the cabling in the cryostat to the leakage currents at the highest biases was less than 0.1 fA. Five of the FID800 detectors with the best phonon resolution were then selected for the EDELWEISS-LT phase on the basis of having the highest bias breakdown values. These varied from 30 to 110 V. The surface treatment and electrode evaporation procedure was therefore optimized, and breakdown values above 100 V were obtained more reliably in the production of new detectors.

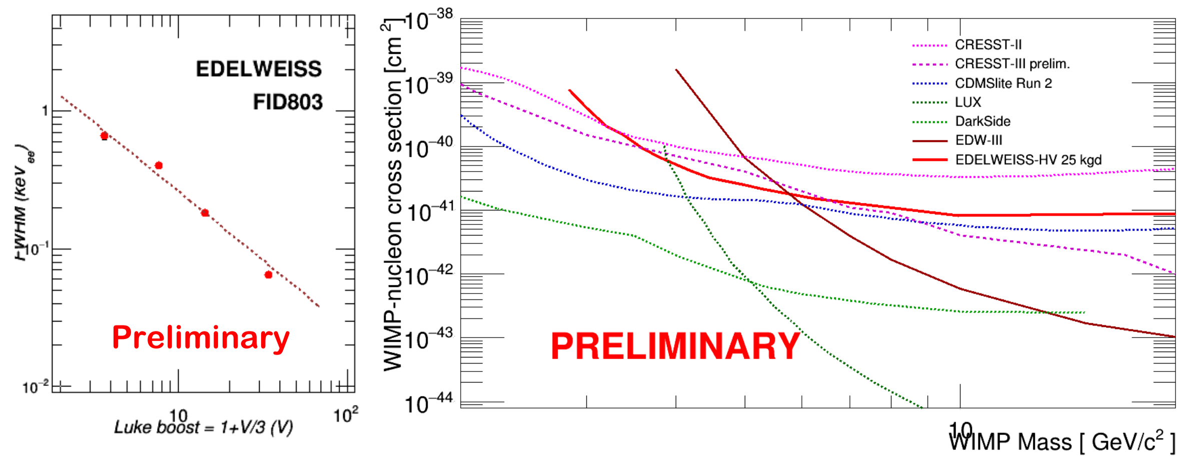

Figure 5. Left: phonon resolution (FWHM = 2.35σ) in keV$_{ee}$ vs amplitude of the Luke-Neganov Boost for a Ge FID detector. Right: limit on the spin-independent WIMP-nucleon cross-section obtained with an exposure of 25 kg.d of the same detector operated at a bias of 100 V. Both figures from [T2].

Before launching a significant production of new detectors able to withstand 100 V, it was necessary to study the behavior and performance of the five original EDELWEISS-LT detectors. In particular, it was observed (fig. 5 left, from [T2]) that the improvement of the resolution with the applied bias did follow expectation up to bias values very close to the breakdown limit. The **Luke-Neganov amplification at 100 V** did provide the expected improvement in the energy threshold in actual WIMP searches, commensurate with the limited performance achievable with the existing EDELWEISS-III detectors. Above 5 GeV/c^2, the limits on the WIMP-nucleon cross-section obtained in this tests (fig. 5 right) are within a factor of two of those obtained by CDMSLite 2 [9], and this despite an order of magnitude in difference in energy resolution. This highlights the advantage of being able to constrain the different backgrounds at high bias using the data with discrimination recorded at low bias with the same detector. This advantage is no longer relevant below 5 GeV/c^2, as the effect of the threshold dominates the performance.

6.2 Heat resolution

The second objective of the EDELWEISS-LT phase was to study the possibility of improving the rms heat resolution σ_{phonon} (with FWHM = 2.35σ) of a few EDELWEISS-III detectors, with an objective of σ_{phonon} = 100 eV before the Luke-Neganov amplification. This target of a factor 5 improvement relative to the performance of the best EDELWEISS-III FID800 detectors was motivated by a detailed characterization and modelling of the amplitude and shape of the pulses delivered by the NTD heat sensors, based on the measured thermal properties of the detectors [35]. The studies identified the presence of stray heat capacitances and of an athermal ballistic component in the signal. A better control of these effects could have led to the desired improvement. It was however realized that the present FID800 detectors could achieve at best a resolution of 300 eV. The best value obtained with a bare 860-g Ge crystal not equipped with any electrodes is 160 eV (Fig. 6).

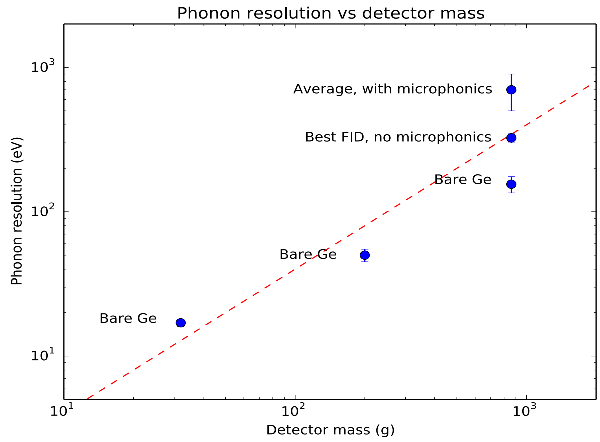

Fig. 6. Phonon baseline resolution (σ_{phonon} in eV), as a function of the mass of the Ge detectors (in g).

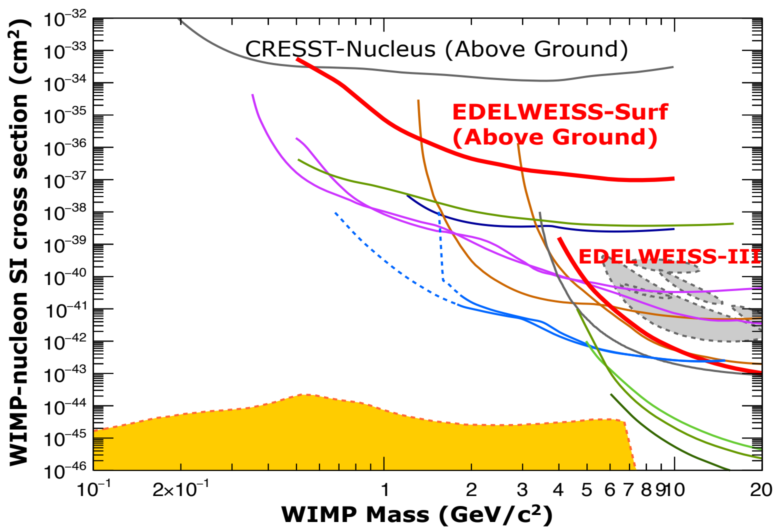

Fig. 7. Surface limit obtained with a 32-g Ge detector having a resolution of 18 eV (60 eV NR threshold) [36].

The thermal model developed in these studies predicted that much would be gained by reducing the mass of the bare Ge crystal [35]. Indeed, resolution of σ_{phonon} = 50 eV has been obtained on a 200-g detector, and **σ_{phonon} = 18 eV with a 32-g detector** (Fig. 6). To illustrate the physics potential opened by the performance achieved on this 32-g detector, it has been operated in the LIO low-vibration cryostat at IPNL in order to perform an above-ground WIMP search, relevant in the discussion of models with Strongly Interacting Massive Particles (SIMPs). An analysis threshold of 60 eV for nuclear recoils has been achieved [36], resulting in the **strongest above-ground constraints for WIMP masses above 600 MeV/c^2 (Fig. 7), and the first sub-GeV limit using germanium**. A version of this detector equipped with electrodes is currently being tested in the same cryostat.

The work to bring the heat resolution of EDELWEISS detectors to its SubGeV target of 10 eV extends to the development of another phonon sensor technology that can be adapted to their design. The CSNSM team has developed thin NbSi films (50 nm) [37] lithographed on the surface of the germanium crystal in a spiral pattern with a 10 mm radius and a 200 μm pitch. The NbSi films are designed to have a sharp transition from the superconducting phase to the normal phase between 25 to 35 mK in order to be used as very sensitive thermistances. A first 32-g Ge detector equipped with such a sensor has achieved a resolution of σ_{phonon} = 55 eV on the phonon signal in tests at the CSNSM. A resolution of σ_{phonon} = 100 eV has recently been achieved on a larger 200-g detector operated in the EDELWEISS cryostat at LSM. That detector is fully equipped with electrodes and tests with Luke-Neganov amplification are in progress.

The performance of both NTD and NbSi sensors show promising progress and the choice of the best solution for the SubGeV phase is planned for 2020. An already established conclusion of this work is that the SubGeV objectives are better served by using less massive detectors. Simulations based on present levels of EDELWEISS backgrounds at LSM show that the sensitivity to 1 GeV/c^2 WIMPs depends more on the recoil energy threshold of the detectors than on the total exposure. A 500 kg.d experiment with a phonon resolution of σ_{phonon} = 100 eV (the original EDELWEISS-LT goal) has the same sensitivity that a 50 kg.d experiment with a resolution of σ_{phonon} = 50 eV, and a 5 kg.d experiment with a resolution of σ_{phonon} = 20 eV. As the WIMP mass decreases below 1 GeV/c^2, the advantage of resolution over mass is inexorable. **Therefore, the priority of the detector development for the low-mass program of EDELWEISS has shifted to lower mass detectors**. This decision has the additional advantage of speeding up the progress of the R&D, as smaller detectors can more readily be tested in the above-ground cryostats available to the collaboration.

Detector tests in the EDELWEISS-III cryostat and in the LIO low-vibration cryostat at IPNL [33,34] have shown that the best resolutions can only be achieved via a very tight control of the effect of vibrations induced by thermal machines. The work of the CUPID team to design suspended towers for their detectors in the EDELWEISS-III cryostat has also provided valuable insights on this very important question. However, the ultimate resolution targets can only be achieved by the simultaneous use of suspended detector towers and aggressive measures to suppress vibrations as close to their sources as possible. New solutions for this purpose have recently emerged (see e.g. [33]) and this question is a central issue in the planned upgrade of the cryostat at LSM (Sect. 5.3).

6.3 Heat only events (HO)

As stated in Sect. 4.6, the possible origin of the large population of HO events observed with the EDELWEISS-III detectors has been thoroughly investigated [T2], and despite some progress (notably with detectors with NbSi sensors), no single dominating source has been formally identified so far. Nevertheless, the work in [T2] has demonstrated that the empirical model developed to describe the behavior of these events is sufficiently precise for its use of a likelihood-based data interpretation. The study of HO events is still ongoing. Meanwhile, all projections of future performance of detectors at LSM are calculated assuming the same HO rate as observed. The presence of this population of events is a strong incentive for considering an **efficient ionization-based discrimination** (preferably event-by-event, or, at the very least, statistical) as a prerequisite.

6.4 Ionization resolution

In 2016, an EDELWEISS member participated in the seminal work [30] that proved for the first time that HEMT-based ionization readout on a massive Ge detector could result in a sizeable gain in resolution. This work resulted in a σ_{ion} = 90 eV_{ee} ionization resolution on a 300-g CDMS detector. The EDELWEISS detectors present the advantage of having an electrode design and, in particular, heat sensors that contribute significantly less to the total capacitance compared to the values of the CDMS detector used in the test. Taking this into account, an 800-g EDELWEISS detector with a HEMT readout should have an ionization resolution below 50 eV_{ee}. The electrode contribution to the detector capacitance can be further reduced, by increasing the pitch between consecutive rings from 2 mm to 4 mm. This increase in pitch has already been tested on a FID800 detector. No reduction of rejection or resolution performance was observed, and indeed this detector was one of the 8 detectors selected for the EDELWEISS-III low-mass WIMP search [23,24]. The smaller detector masses now considered by EDELWEISS also translate to lower capacitance, with ionization resolution as good as σ_{ion} = 20 eV_{ee}. The last year was devoted to the organization of a **strong effort for the development of the HEMT readout**, with new partnerships. The collaboration intends to increase the resources devoted to task 2. Access to HEMT units adapted to this purpose is secured, as its only producer, Y. Jin from CNRS/C2N Marcoussis, is member of the EDELWEISS collaboration.

6.5 Low-mass program calendar

The EDELWEISS collaboration plans to devote the next two years to the SubGeV R&D on 32-g detectors at CSNSM and IPNL, covering the items described in Sect. 5.1, 6.1 and 6.2. In parallel the HEMT readout would be developed in partnership with the Richochet-France team (Sect. 5.2). These developments should lead to rapid breakthroughs on the measurement of NR ionization yields at the 100 eV scale. By 2021, the program would enter the stage of studying the scaling of the HEMT readout to 200-g detectors, and of operating a kg-size array of SubGeV detectors, both requiring the adapted cryostat facility at LSM described in Sect. 5.3. An earlier availability of the improved LSM facility would greatly help in the study of HO events. The goal of the kg-size array of SubGeV detector operation at LSM is to demonstrate a sensitivity of 10^{-43} cm^2 below 1 GeV/c^2, essential to define by 2022 a high-impact contribution to the upgrade of the SuperCDMS-SNOLAB.

7 EDELWEISS resources

The IN2P3 laboratories participating in EDELWEISS are IPNL and CSNSM (Table 1). Other contributions from CNRS come from Néel Institute and C2N. The other participants are CEA, KIT and Dubna. The main EDELWEISS-III publications in 2016 were signed by 48 people (46% from IN2P3). Since the start of the preparation for the SubGeV phase preparation, the number of signatures decreased to 38, with an increase of the IN2P3 share to 55% that reflects the strong involvement of the French teams in the detector developments. The IN2P3 personnel also dominate in number in the organizational structure (Fig. 8). It should be noted that since 2016, the FTE contributions to the running of the cryostat at LSM, shared between most participants, benefits in the same manner both EDELWEISS and CUPID. Fig. 9 illustrates the evolution of IN2P3 personnel and FTE since 2014. The decrease in FTE in 2019 corresponds to the formal appearance of the RICOCHET IN2P3 program, sharing with EDELWEISS common R&D goals.

The initial investment cost of the EDELWEISS-III projects (presented at the Scientific Council of IN2P3 in October 2012) was 1.9 M€ in 2010-2013, with a major contribution from the ANR-FIDSUSY (840 k€), as well as CEA, KIT, Dubna, Oxford and Sheffield contributions. The IN2P3 contribution to this investment stage was 80 k€. The contribution of IN2P3 was more important for the operation costs. In the years 2010 to 2013, the full average cost of operations of the cryogenic facility at LSM was close to 112 k€ per year, rising to 145 k€/y during the height of the data recording period in 2013-2015 (Fig. 10). The average contribution of IN2P3 to these costs was 65 k€/year. These costs are mostly due to the costs of helium (even if a large part is recuperated and sent back to the provider), helium transport, LSM fees, and cryogenic machine maintenance. With the reduction of running days at LSM due to the start of the SubGeV preparation phase, these costs have been reduced to an average of 105 k€ since 2016. The IN2P3 contribution to running has been an average of 50k€/year in the same period. The rest is paid by CEA, KIT and Dubna. Since 2015, the ANR-LUMINEU and more recently the CUPID-Mo project have started to contribute to an increasing share the operating budget of the cryostat at LSM in the context of joint cool-downs.

Lab	Name	Category	FTE 2018	FTE 2019
IPNL	J. Billard	Researcher	0.5	0.1
	M. De Jesus	Researcher	0.6	0.5
	C. Augier	Univ.	0.4	0.2
	A. Cazes	Univ.	0.5	0.3
	J. Gascon	Univ.	0.4	0.5
	V. Sanglard	Univ.	0.5	0.3
	F. Charlieux	IT	0.3	0.1
	D. Ducimetiere	IT-Univ.	0.15	0.15
	A. Juillard	IT	0.8	0.5
	L. Vagneron	IT	0.2	0.2
	R. Maisonobe	PostDoc	0.5	
	E. Elkhoury	PhD		1.0
	D. Misiak	PhD	0.2	0.2
	E. Queguiner	PhD	1.0	
CSNSM	L. Dumoulin	Researcher	0.5	0.5
	A. Giuliani	Researcher	0.1	0.2
	S. Marnieros	Researcher	0.4	0.4
	L. Bergé	IT	0.2	0.3
	E. Olivieri	IT	0.3	0.25
	C. Oriol	IT	0.2	0.4
	M. Chapellier	Associate	1.0	0.5
Total			8,8	6,6

Table 1: EDELWEISS personnel in IN2P3 laboratories, and their corresponding Full-Time-Equivalent involvement in the project in 2018 and projected in 2019.

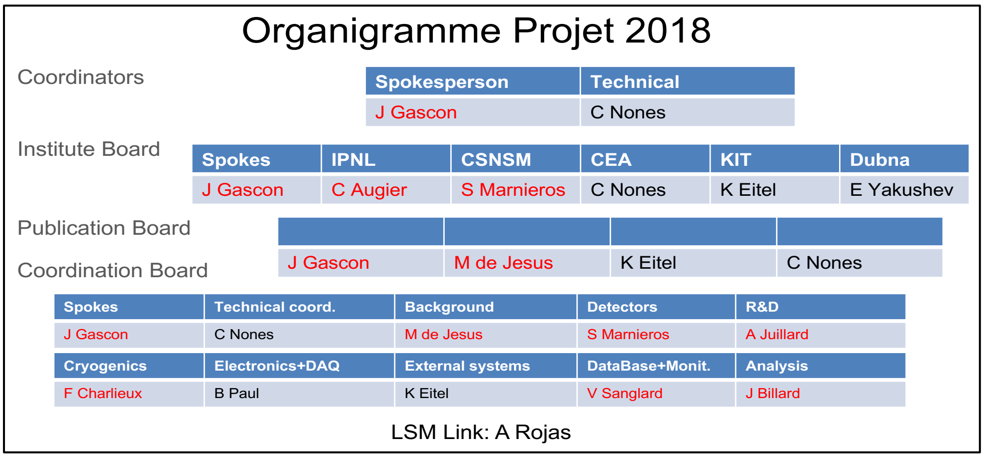

Figure 8. Organization chart of the EDELWEISS collaboration in 2018. IN2P3 personnel are indicated in red.

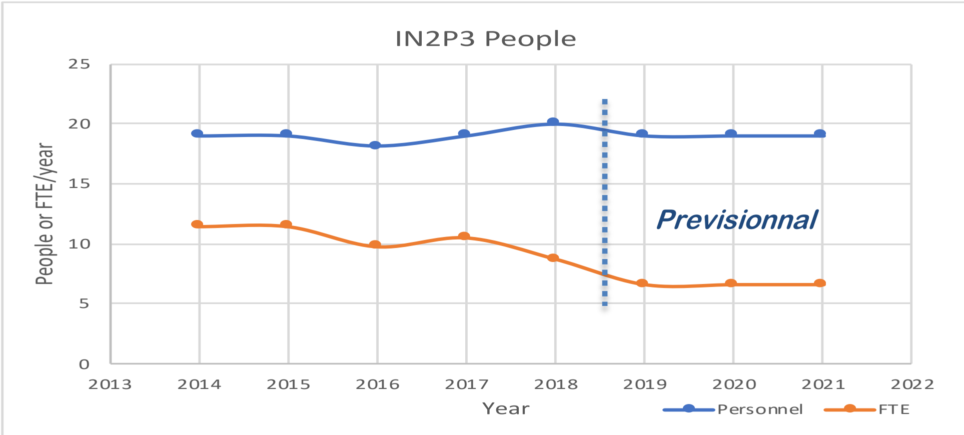

Figure 9. Number of EDELWEISS participants in IN2P3 laboratories as a function of year (blue), as well as the corresponding Full-Time-Equivalent (FTE).

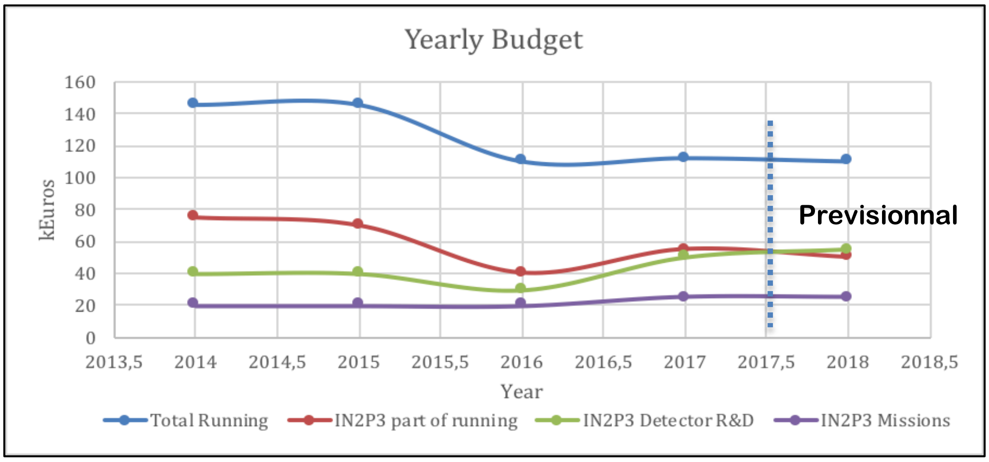

Figure 10. EDELWEISS operation budget as a function of year (blue), together with the IN2P3 contribution (red). Separate IN2P3 contributions to the detector R&D and scientific missions are in green and violet, respectively. The reduction in operation budget after 2015 correspond to the end of the 3000 kg.d physics run and start of EDELWEISS-LT.

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