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The EDELWEISS DM search: Recent results and outlook for 2013

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Summary. — The EDELWEISS experiment uses massive cryogenic Ge-bolometers to detect the scattering of Weakly Interacting Massive Particles (WIMPs) on the target crystals in the underground laboratory of Modane. For enhanced background suppression both heat and ionization signals are read out via NTD-thermistors and interleaved Al-ring electrodes, respectively. The search of "low mass" WIMPs, focusing on WIMP masses in the range of $(5 \leq m_\chi \leq 30)$ GeV, aims at signals of a few keV close to the threshold of the detectors. After applying strict selection cuts at most 3 events survive with a background expectation of 2 events PRD86,(2012),051701(R). These results exclude the DAMA and CRESST signal regions at 90% CL, but are still marginally compatible with the CoGeNT results. The EDELWEISS results will be reviewed and an outlook on the sensitivity reach of the improved EDELWEISS-III setup will be given.

PACS `95.35.+d` – Dark matter.
PACS `14.80.Ly` – Supersymmetric partners of known particles.
PACS `29.40.Wk` – Solid-state detectors.

1. – Introduction

An essential ingredient of the current cosmological concordance model is the existence of a dark and at most very weakly interacting matter component that accounts for roughly one fourth of the total energy content of the Universe. This component is supposed to be the driving force of structure formation, which means it needs to be non relativistic already at early times. A viable set of extensions of the standard model of particle physics exists that introduce a new heavy particle (typically $O(100\,\text{GeV})$) that can be produced in thermal equilibrium in the very early Universe. With interaction cross sections of the order of the weak scale such particles freeze out during the expansion of the universe as non-relativistic particles. Furthermore, they have about the right abundance for the

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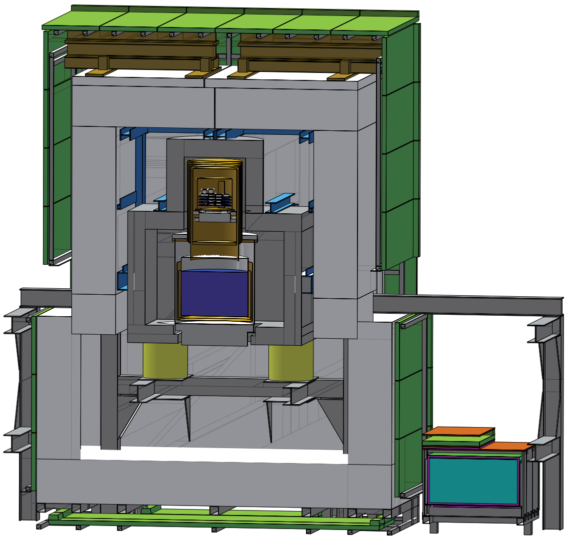

Fig. 1. – Cross section through the EDELWEISS setup. The cryostat housing the Ge-bolometers is surrounded by a 20 cm lead shield, 50 cm PE shield and an active muon veto system. All shields are mounted on rails to allow easy access and maintenance on detectors and cryostat.

dark matter density observed today. Among the models that propose such candidates, Supersymmetry, which was intended to solve the naturalness problem and Kaluza-Klein extra dimension models that can cope with the CP problem, are the most popular ones. However, many more exist. Direct dark matter searches probe the scattering cross section of DM candidates of the local DM population. To detect the scattering of such Weakly Interacting Massive Particles (WIMPs) in a detector one has to be able to identify very rare events. Currently, strong efforts are made with different detector technologies and rates down to a few 10^{-3} evts/kg/day are being probed. The EDELWEISS collaboration has designed germanium bolometers with a dual heat-and-ionization readout to reach this goal. In the following, we will briefly present the EDELWEISS-II infrastructure and detectors whose novelty was the ability to reject surface interactions with an interleaved electrode design. We summarize the results of the final EDELWEISS-II WIMP search [1] and review the latest results of a low mass WIMP analysis [2]. Finally, we present the upgrades to EDELWEISS-III and the current status of the program.

2. – Experimental setup

2˙1. *General setup in the underground laboratory of Modane.* – The EDELWEISS-II setup shown in fig. 1 consists of a cryostat capable of housing up to 40 kilograms of target material, and a set of active and passive shields surrounding this cryostat. The cryostat is cooled by a dilution refrigerator which very accurately maintains the bolometers at an operation temperature of 18 mK. The reversed geometry of the cryostat enables easy access and installation of detectors. The whole system has already been run very stable for more than a year with full remote control. The only intervention still needed in the underground laboratory of Modane (LSM) is the weekly helium refilling. The laboratory lies below a mountain ridge with 1800 m of rock above the laboratory. This rock overburden, which is equivalent to a flat water shield of 4800 m height reduces the cosmic muon flux by more than 6 orders of magnitude down to $5\,\mu/\mathrm{m}^2/\mathrm{day}$ [3]. However, even with such low rates, muon-induced neutrons can be a dominant source of background, since neutrons can not be discriminated from WIMPs. Thus, muon-induced events are tagged with a $100\,\mathrm{m}^2$ plastic scintillator muon-veto system. To reduce environmental backgrounds, all materials used in the vicinity of the detectors were analyzed for their radiopurity with dedicated HPGe detectors. A clean room surrounds the whole setup, and the cryostat environment is under a permanent flow of de-radonized air with a reduced activity of $20\,\mathrm{mBq/m}^3$. To protect the detectors against ambient neutrons, a 50 cm thick polyethylene shield attenuates this background by three orders of magnitude. A 20 cm thick lead shield around the cryostat shields against the external gamma background. Still the gamma background remains the dominant component and needs to be discriminated on an event-by-event basis in the detectors.

2·2. *The InterDigit detector principle.* – EDELWEISS-II detectors were germanium bolometers of a typical mass of 400 g, with Al electrodes on their surfaces. At an operating temperature of 18 mK, low energy interactions are detected in a bolometric approach with neutron transmutation doped (NTD) Ge heat sensors used as thermoresistors. An additional measurement of the ionization yield is provided by the electrode signals for each interaction and allows the discrimination between nuclear (NR) and electron recoils (ER). With ER producing a typically 3 times larger ionization signal than NR this event-by-event discrimination against gamma background was measured with dedicated calibrations to be $3 \cdot 10^{-5}$ [1].

However, this rejection requires reliable charge collection, which cannot be guaranteed for events at the surface or close to the electrodes. At the crystal surface, charges are trapped by impurities and in low field regions which can significantly worsen this rejection. Since the surface is exposed to additional low-energy beta background, this can be a serious issue. A solution to this challenge is found by the definition of an inner fiducial volume, which gives the advantage of being able to use the self-shielding effect of the bolometers and select an extremely clean and sensitive region of the detectors. For the InterDigit (ID) detectors a fiducial volume is defined via the electrode design of interleaved concentric rings polarized at alternate voltages, as shown on fig. 2 (left). Thereby the electrodes are divided into collectrodes with higher voltages of the order of $\pm 4\,\mathrm{V}$ that collect charges from the bulk of the crystals and into veto electrodes with smaller voltages ($\pm 1.5\,\mathrm{V}$). For surface interactions the electric field connects same side collecting and veto electrodes and a cut on veto electrode signals is able to reject surface events. Additionally the charge imbalance on the top and bottom collecting electrodes is used for discrimination. The resulting discrimination against near-surface interactions is remarkably efficient and the rejection efficiency was measured to be of the order of 10^{-5} [4]. While the cylindrical side of the EDELWEISS-II crystals were still equipped with plain guard electrodes, they have been redesigned and are fabricated with interleaved Al electrodes on the sides for 800 g EDELWEISS-III crystals (fig. 2, right). By doubling of the height and the removal of planar electrodes the fiducial volume can be enlarged by a factor 4 per crystal, while simplifying the readout from 6 to 4 ionization channels. Furthermore, for this Full InterDigit (FID) design gamma event discrimination is enhanced significantly by the reduction of the previous large non-fiducial volume and in a first high statistics gamma calibration, no misidentified event was observed among 411663 gamma events.

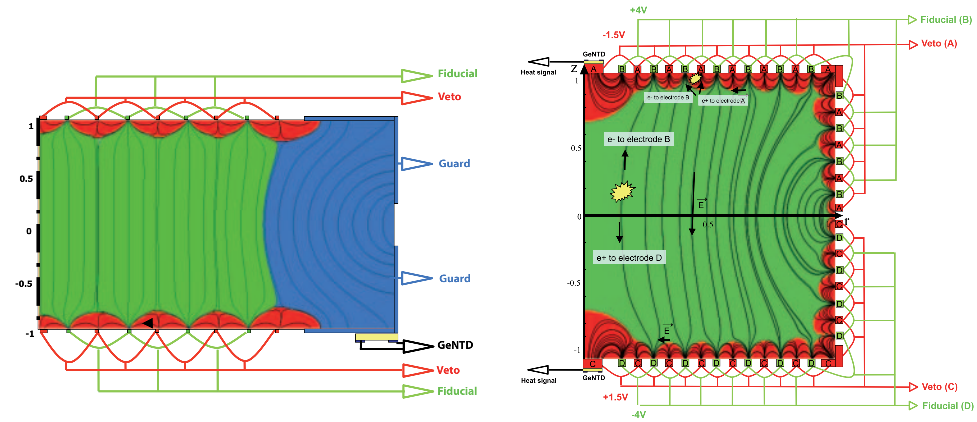

Fig. 2. – Interdigitized electrode scheme of EDELWEISS-II (left) and EDELWEISS-III (right) detectors. The interleaved electrode rings allow the classification of events from different volumes. This design enables a fiducialization, where the inner (green) volume with best charge collection properties and lowest radioactive backgrounds is used for WIMP search.

3. – Recent results

3˙1. *Review of EDELWEISS-II results*. – The EDELWEISS collaboration successfully operated ten 400 g detectors in a single long cool-down over a period of 14 months from April 2009 to May 2010 and in addition two detectors during an initial data taking period between July and November 2008. The full analysis of the WIMP search for $M_\chi > 50\,\text{GeV}$ based on this data set is described in detail in ref. [1], here we summarize the main results: A total effective exposure of 384 kg d has been achieved after all cuts. First a period selection based on noise level was applied, which reduced the amount of data by 17%. This cut was performed on the baseline energy resolutions on an hourly basis requiring the FWHM of fiducial ionization to be below 2 keV and the FWHM of heat and guard ionization channels to be below 2.5 keV. Further cuts are fiducial event selection, coincidence rejection (coincidences between multiple bolometers as well as with the muon-veto system) and energy range (20–200 keV) and Q-value inside the 90% NR region (see fig. 3). The energy threshold of $E_{rec} > 20\,\text{keV}$ was defined a priori for a WIMP search for $M_\chi > 50\,\text{GeV}$, above which the efficiency is independent of energy and in order to ensure a maximum exposure in recoil energy range. Five NR candidates were observed above this threshold (see fig. 3), while the estimated background is three events. This result was interpreted in terms of limits on the cross section of SI interactions of WIMPs and nucleons and $\sigma > 4.4 \cdot 10^{-8}\,\text{pb}$ was excluded at 90% CL for a $M_\chi = 85\,\text{GeV}$. Both the EDELWEISS and CDMS collaborations reached similar sensitivities in 2011 with Ge detectors and consequently combined their results. This allowed to increase the total data set to 614 kg·d equivalent exposure and improve the upper limit on the WIMP-nucleon SI cross section for heavy WIMPs by roughly a factor 1.6 to a minimum value of $3.3 \cdot 10^{-8}\,\text{pb}$ at 90% CL for a WIMP mass of 90 GeV. The results of a simple combination quoted here as well as further details of the work can be found in ref. [5]. At low energies four events observed in EDELWEISS-II prevented any gain from the merger of the two data sets. For further progress these events need to be understood and from extensive MC simulations the dominant sources of background could be traced

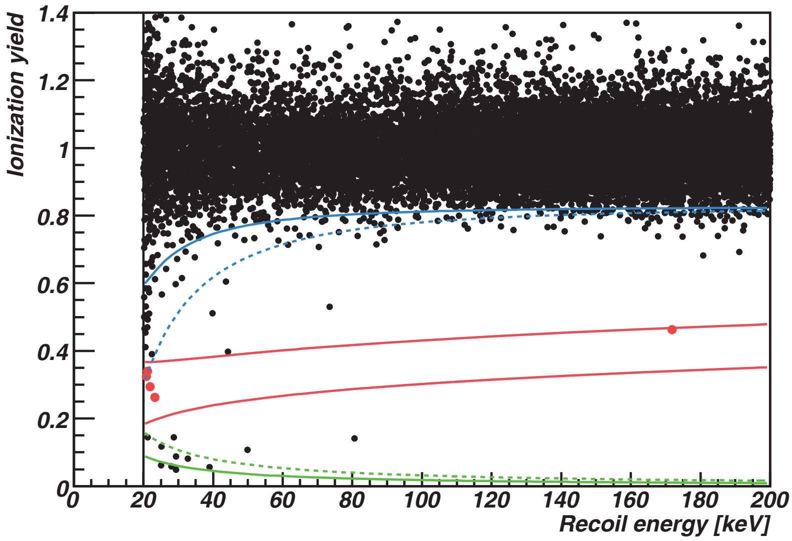

Fig. 3. – Scatter plot of the ionization yield *vs.* recoil energy for the final analysis of the full EDELWEISS-II dataset (384 kg d). For guidance the average 90% acceptance band for nuclear recoils is shown in red, whereas average (solid) and worst (dashed) 99.99% gamma rejection lines are drawn in blue. Furthermore average (solid) and worst (dashed) ionization thresholds are drawn in green. Five WIMP candidate events where observed in the predefined region of interest (20–200 keV, ionization yield in nuclear recoil band) with an expected background of three events. Allowing all of these events to be WIMPs a 90% CL limit was calculated according to the optimum interval method [6].

to neutrons from the electronics and cabling with 1.1 events, followed by the expected background from misidentified gammas with 0.9 events. Further background components include muon-induced neutrons as well as ambient neutrons from the rock and beta events from surfaces. For the misidentified gamma population we have indications that they were caused by double scattering in the guard and fiducial region.

3˙2. *Analysis for low-mass WIMPs.* – In order to test the potential of the EDELWEISS detector design for the detection of low mass WIMPs of the order of 10 GeV an independent analysis was performed on the EDELWEISS-II data below 20 keV [2]. To achieve discrimination of NR and ER, only the 4 best detectors were selected for which a low-background sensitivity to NR down to 5 keV could be achieved. Among the six rejected detectors, four had non-functioning electrodes and/or poor resolutions for one or several channels. One detector was rejected due to a relatively intense source of ^{210}Pb in its vicinity, and one had a low-energy γ-ray background four times larger than that observed on other detectors. The event-based quality cuts and rejection of multiple scatter events applied for event reconstruction are identical to those for the main analysis described in ref. [1]. However, the estimate of the recoil energy $E_r^{(h)}$, is determined solely from the heat channel signal. It is corrected for the Neganov-Luke heating of the crystal caused by charge propagation, assuming that all events have the ionization yield of NR. This implies that all gamma events appear scaled by a factor ~ 2 on this energy scale. However, the advantage of this estimator is a significantly better energy resolution on $E_r^{(h)}$, which is correct for NR.

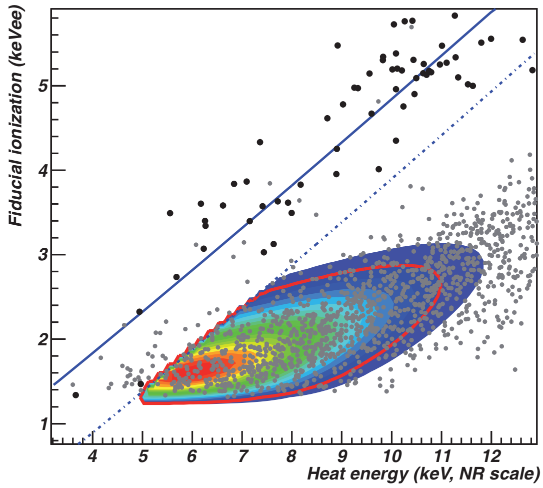

Fig. 4. – Scatter plot of the ionization energy *vs.* recoil energy (nuclear recoil scale) for the EDELWEISS-II detector with the best resolutions during EDELWEISS-II data taking. For illustration purposes the efficiency corrected signal probability density function of a 10 GeV WIMP has been drawn in color. The calculated region falls perfectly into the expected band observed in extensive neutron calibrations (gray dots). In solid black WIMP search data of the EDELWEISS-II experiment is shown. Since no event was observed in the 90% WIMP signal region a limit on the elastic WIMP-nucleon scattering cross section was calculated according to Poisson statistics.

In this analysis very close to the threshold of the bolometers one has to take into account varying efficiency and noise conditions over time. The efficiency of the online DAQ trigger over time as a function of $E_r^{(h)}$ is estimated from the resolution of the heat channel and the adaptive trigger threshold on an hourly basis. It was validated using the flat, low-energy Compton plateau in γ-ray calibration data. The rejection of non-fiducial interactions and ionizationless events is based on the fiducial event selection which is mainly a cut on veto signals and charge balance with a cutoff based on respective baseline resolutions. The efficiency dependence of this cut was extracted from neutron calibration data.

The efficiencies of all offline analysis cuts based on the measured resolutions of fiducial ionization energy E_i, and heat energy $E_r^{(h)}$, are used to construct the observable WIMP signal density for each WIMP mass in the $(E_r^{(h)}, E_i)$-plane (fig. 4). The final WIMP search region is defined as the region containing 90% of the calculated WIMP signal density below the γ-rejection cut. The sensitivity to the WIMP scattering signal is demonstrated by neutron calibration data.

With the observation of 1 to 3 events for different signal regions corresponding to different WIMP masses and together with a background expectation of two events an upper limit is calculated on the spin independent scattering cross section according to Poisson statistics. For each WIMP mass, the number of events allowed at 90% CL are transferred into a cross section by integrating the WIMP signal density $(E_r^{(h)}, E_i)$ over the WIMP search region and scaling the result accordingly. The obtained limit significantly improves the EDELWEISS sensitivity below $M_\chi = 20\,\text{GeV}$ and excludes

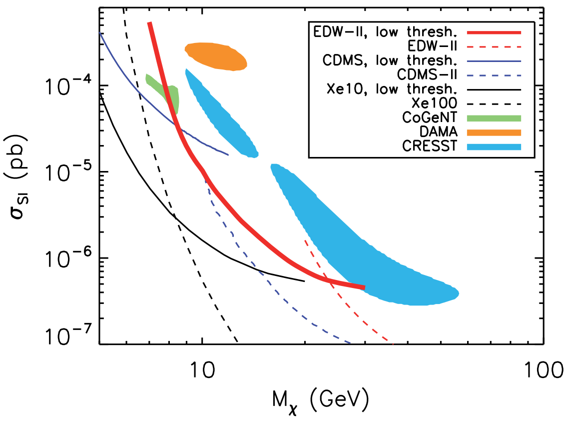

Fig. 5. – WIMP-nucleon scattering cross section *versus* WIMP mass with latest EDELWEISS results and selected results from competing experiments. Signal claims from DAMA/LIBRA [7] and CoGeNT [8] as well as the best fit region from the CRESST experiment [9] are in serious tension to results from XENON, EDELWEISS and CDMS [2, 10, 11]. An extensive discussion of the compatibility of the annual modulation signal observed with very high significance with the exclusion limits can be found in [12].

the regions favored by DAMA/LIBRA [7], CRESST [9] and part of the CoGeNT [8] space above $M_\chi = 8\,\text{GeV}$ (fig. 5) [2]. Furthermore the analysis demonstrates very good discrimination and allows an almost background free analysis down to 5 keV. Together with improvements in resolution and threshold these detectors should allow to produce leading results on low mass WIMPs for present day cryogenic detectors.

4. – Outlook EDELWEISS-III and EURECA

As seen in the EDELWEISS-II analysis, background events started to appear and appropriate improvements of the setup were required to go beyond the achieved sensitivity. The first improvement already discussed in sect. **2**˙2 consists in the development of a new generation of detectors, called fully interdigitized detectors (FID) with ring electrodes on the lateral sides and twice the height. These detectors feature a much increased fiducial volume of 600 g *versus* 160 g and more importantly a much better gamma rejection without anomalous event populations. Hence they will allow the definition of a signal region with a negligible amount of gamma leakage. Forty of these detectors are planned for installation in the upgraded EDELWEISS setup. Since the energy resolution of the ionization channels is the current bottleneck in the low WIMP mass analysis, a redesign of the front-end electronics has been performed. In addition the overall noise level should be reduced by the identification of external noise sources from the cryogenic setup and consequent replacement of several parts. An additional polyethylene shield will be placed between the lead layer and the cryostat. Together with the installation of new cabling and connectors which were designed and fabricated in-house from low radioactivity materials this will reduce the flux of ambient neutrons by an order of magnitude. Better characterization of the muon veto together with supplementary muon veto modules and stricter cuts can improve the rejection of muon induced neutrons by an order of magnitude. Modifications of the DAQ go towards better scalability and integration of various

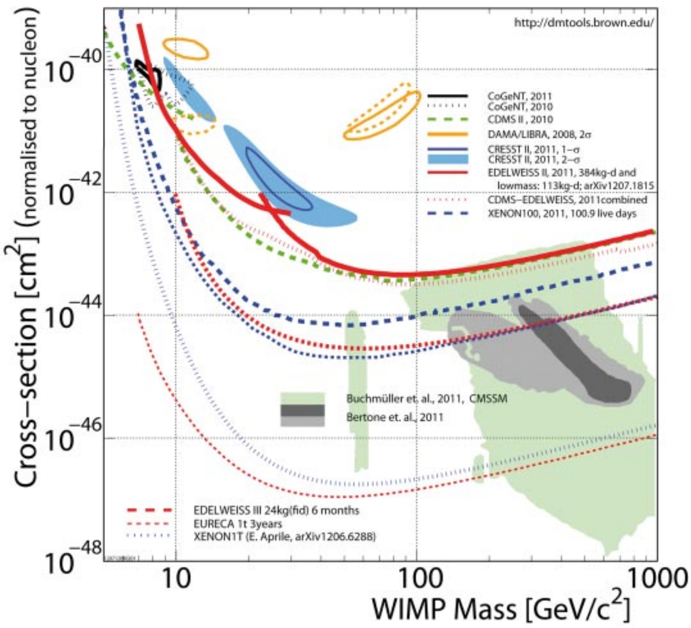

Fig. 6. – WIMP-nucleon scattering cross section *versus* WIMP mass with latest EDELWEISS results and selected results from competing experiments [1, 2, 5, 7-9, 11, 13, 14]. In addition to present limits expected sensitivities for future experiments are shown under he assumption of background free data taking.

readouts. Also new analysis tools [15] are being developed to facilitate the monitoring and analysis of significantly larger data sets. The initial goal of the funded EDELWEISS-III project is to acquire an exposure of 3000 kg d within half a year of operation starting in 2013. The final reach of the WIMP search with EDELWEISS-III could extend up to 10000 kg d of data without background, which should correspond to a WIMP-nucleon scattering cross section sensitivity of $2 \cdot 10^{-9}$ pb or better.

The ongoing research in EDELWEISS-III together with detector R&D and the detailed studies of background conditions in LSM are understood as an essential part of the work on the way to a European (CRESST, EDELWEISS) dark matter experiment of the next generation, EURECA [16], a 1-ton cryogenic detector array. A CDR is finalized featuring a large Water-Cerenkov tank, which is used both as active and passive shield surrounding a Cu cryostat designed to provide the stability and flexibility of housing different kinds of detectors. The intended physics reach shown in fig. 6 extends to spin-independent DM scattering cross sections of the order of 10^{-11} pb.

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