Report on EDELWEISS-III

WIMP masses 4-20 GeV/c²

Perspectives of the low-mass program

WIMP masses 0.5-5 GeV/c² and below

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**~GeV range new hunting ground for WIMPs**

- Absence of minimal SUSY signals at LHC
- No signals in 10 GeV/c^2 – 10 TeV/c^2 range (LUX, PandaX, XENON)
- Searches extended to generic DM particle interacting with nuclei

**Spin-independent Dark matter interaction with nuclei**

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**Graphical representation**

*WIMP-nucleon SI cross section (cm^2)*

- CRESST nucleus
- CDMSLite
- NEWS-G
- EDELWEISS-Surf
- DAMIC
- EDELWEISS-III
- PICO
- DarkSide
- PANDA-X
- LUX
- XENON-4L

*New search range*
Future projects for SubGeV range

- Cryogenic experiments: SuperCDMS (SNOLAB), CRESST (LNGS)
- Others (limited to ~1 GeV/c^2): DarkSide, DAMIC-M

Limitations:

- **Thresholds**
- **Backgrounds**
  (internal bkgs in CRESST)
- **Ion. quenching uncertainties**
  Ge/Si/Ar

**Serious issue:**
Lack of nuclear recoil discrimination at low energy
**EDELWEISS : phase III vs low-mass program**

**EDELWEISS-III (2010-2015)**

- *Largest mass of cryogenic Ge (30 kg) for DM search*
- Difference from CDMS:
  - Emphasis on ionization signal for surface discrimination
  - Simpler heat signal readout, for scalability & optimal ionization readout (... and detector operation & calibration)
- Data taking ended in 2015 with 3000 kg.d (8 kg.y)

**EDELWEISS Low-mass program (since 2016)**

- R&D program for GeV/c^2 -> subGeV/c^2 WIMP mass range
- Second part of presentation
EDELWEISS-III collaboration

48 people, 46% in2p3
**EDELWEISS Setup**

- **LSM: Deepest site in Europe**
  4800 m.w.e., 5 μ/m²/day
- Clean room + deradonized air
  Radon monitoring down to few mBq/m³
- Active muon veto (>98% coverage)
- External (50 cm) + internal polyethylene shielding
  *Thermal neutron monitoring with $^3$He detector*
- Lead shielding (20 cm, incl. 2 cm Roman lead)
- Selection of radiopure material

Cryostat can host up to 40 kg detector at 18 mK

*Performance of the EDELWEISS-III experiment for direct dark matter searches*

*[JINST 12 (2017) P08010]*
**EDELWEISS-III detectors (CSNSM design)**

**Heat:** $\Delta T = E/C_{\text{cal}}$

**Ionization:** $N_{\text{charge}} = E/\varepsilon_\gamma$ or $\varepsilon_n$

- Ionization:
  
  $\varepsilon_\gamma = 3$ eV/(e-hole pair) for electron recoils ($\gamma, \beta$)
  
  $\varepsilon_n \sim 12$ eV/(e-hole pair) for nuclear recoils (neutrons, WIMPs)

  $\varepsilon_\gamma/\varepsilon_n = \text{ionization quenching } Q$

  $E_{\text{ion}} = Q \cdot E_{\text{recoil}}$ in keV$_{\text{ee}}$

- Heat: direct measurement of ALL the energy, irrespective of particle ID

**EDELWEISS III**

- Measuring heat & ionisation
- Fully digitized: ~870 g HPGe detectors
- Top $= 18 \text{ mK}$

**870 g Ge**

2 GeNTD heat sensors

- Electrodes: concentric Al rings (2mm spacing) covering all faces

**Operated at**

$T = 18 \text{ mK}$


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**Update on the EDELWEISS DM Search**

- New result: ALP limits
- New result: Sub-GeV WIMP limit at surface

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Nuclear recoil identification in EDELWEISS

- Event-by-Event discrimination of Nuclear Recoils (NR) vs Electron Recoils (ER): simultaneous measurement of ionization + heat signals

- True recoil energy can be obtained from heat and ionization signals irrespective of quenching $Q$

$$E_{\text{phonon}} = E_{\text{recoil}} + \text{heating due to charge drift in } E_{\text{field}} \text{ (Luke-Neganov effect)}$$

$$= E_{\text{recoil}} + N_{\text{charge}} \times \text{(Voltage)} = E_{\text{recoil}} + E_{\text{ion}} \times \text{(Voltage)} / \varepsilon_\gamma$$

$$E_{\text{recoil}} = E_{\text{phonon}} - \text{Voltage} \times (E_{\text{ion}} / \varepsilon_\gamma) \text{ for all types of recoils}$$
Surface event discrimination

- Main limitation of technique: poor charge collection of charge for surface events can mimic the reduced quenching of a nuclear recoil
- **EDELWEISS solution**: cover entire surface with interleaved ring electrodes (FID800 design)
- Lateral surface also covered (not in CDMS)
- Bulk: collection by $C_1 + C_2$; $V_1 + V_2$ act as veto
- Surface: charges collected by $C_1 + V_1$ or $C_2 + V_2$
- $<4 \times 10^{-5}$ rejection of surface events
- $<2.5 \times 10^{-6}$ rejection of ER in fiducial volume

October 25th, 2018
EDELWEISS - CS in2p3
EDELWEISS-III calendar

- 2009-2010: prototype tests
- 2011-2013: detector production
  - One year delay to find new technique to solve problem of unexpected leakage currents between electrodes (now: <0.1 fA)
  - Also: electronic + cryogenic upgrades
- 2013-2014: commissioning
  - Problem with Kapton cables between 10 mK and 1 K: decision to concentrate the repairs for the readout of the 24 detectors with the best performance
- 2014-2015: 3000 kg.d for physics
Detector performance

- 24 detectors used for physics

- Best ionization resolution achieved for cryogenic Ge detector: $\sigma_{\text{ion}} = 230$ eV$_{ee}$, uniform performance

- 8 detectors with best $\sigma_{\text{phonon}}$ used for WIMP search (5-20 GeV/c$^2$)

- Main limitation to $\sigma_{\text{phonon}}$: vibrations

- 19 detectors with best resolutions selected for searches of Axion-Like Particle searches & cosmogenic activation studies
WIMP search: identification of backgrounds

- Analysis with Boosted Decision Tree [JCAP05 (2016) 019]
- Analysis with Profile Likelihood [EPJC 76 (2016) 548]

Data-driven background models based on sidebands
Low-Mass analysis & background model

- Analysis with Boosted Decision Tree [JCAP05 (2016) 019]
- Analysis with Profile Likelihood [EPJC 76 (2016) 548]

8 detectors combined
496 kg-days

Data-driven background models
based on sidebands

First measurement of cosmogenic production of $^3$H in Ge
[AstroPart. 91 (2017) 51]
Low-Mass analysis & background model

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Data-driven background models based on sidebands

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Bulk Neutrons

Multiple-detector events fast neutron flux measurement
Low-Mass analysis & background model

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- Analysis with Profile Likelihood [EPJC 76 (2016) 548]

Data-driven background models based on sidebands

8 detectors combined 496 kg-days

Clear identification of different components

Surface $\beta$, Pb

Pb

$\beta$

EDELWEISS

October 25th, 2018
EDELWEISS - CS in2p3
Low-Mass analysis & background model

- Analysis with Boosted Decision Tree [JCAP05 (2016) 019]
- Analysis with Profile Likelihood [EPJC 76 (2016) 548]

Data-driven background models based on sidebands

Origin under investigation

8 detectors combined 496 kg-days

Heat-Only events

Well reproducible over >years
Low-Mass analysis

- Analysis with Boosted Decision Tree [JCAP05 (2016) 019]
- Analysis with Profile Likelihood [EPJC 76 (2016) 548]

- Improvement by x20 to x150 between 7 and 10 GeV wrt EDW-II

- Limited by heat-only background: identification and rejection using the $\sigma_{\text{ion}} = 230$ eV$_{ee}$ resolution on ionization

- Ionization resolution is key for rejection

- Heat resolution is key for low thresholds

Image: Low-mass WIMP detection plot with various experiments and data points.
Electron recoil analysis: cosmic activation

- Lowest electron background levels in cryogenic detector (thanks to surface evt rejection + 650 g fiducial volume)
  - 1149 kg.d with 2 keV<sub>ee</sub> threshold
  - 287 kg.d with 0.8 keV<sub>ee</sub> threshold

- Analysis of cosmic activation
- Activation of $^3$H in Ge exposed to hadronic component of cosmic rays is a limiting background for SuperCDMS

- First precise measure of $^3$H production in Ge: $82 \pm 21$ atom/kg/d
- Input to SuperCDMS 2016 DOE review
- Measurement of $^{49}$V, $^{55}$Fe and $^{65}$Zn to constrain models
Axion-Like Particle searches

- Extend analysis of electron recoil to higher energy for line search up to 500 keV\textsubscript{ee}

- Combine heat+ionization signals for optimal ER energy resolution:
  - Baseline $\sigma = 190$ eV\textsubscript{ee}
  - Proportional term = 1.2%

- Intensities of observed peaks consistent with known Th/U lines

[ArXiv:1808.02340, accepted by PRD]
**ALP & dark photons results**

- Emission of axion/ALPs from the sun
  - *keV-scale Bosonic DM:*
  - Best Ge-based limits <6 keV/c² (thanks to surface rejection)
  - Start to explore <1 keV/c²

[ArXiv:1808.02340, accepted by PRD]

**Bosonic DM results**

- EDELWEISS reach with HEMT readout

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October 25th, 2018

EDELWEISS - CS in2p3
Conclusions on EDW-III + evolution

- Excellent performance of surface + ER rejection via ionization
- Ionization resolution is essential for rejection of ER backgrounds (either event-by-event or statistically, via likelihood)

- Heat resolution (and exposure) limited by cryogenic noise
- NR backgrounds: too large for searches with $M_{\text{WIMP}} > 10 \text{ GeV/c}^2$, not a problem for lighter masses
- Large Heat-Only event background: studied and parameterized in next phase (EDELWEISS-LT)

- Study of impact of improvement of resolution on physics reach: $x5$ on heat, $x2$ on ion. explored in projection paper [PRD 97 (2018) 022003]
**EDELWEISS Low-Mass program**

- Progressing below 1 GeV/c$^2$ and $10^{-43}$ cm$^2$ requires a new generation of detectors with event-by-event rejection – not yet available

- *Reaching* $10^{-43}$ cm$^2$ *at* 1 GeV/c$^2$ *requires an exposure of 1 kg.y with a detector with* $\sigma_{\text{phonon}} = 10$ eV and $\sigma_{\text{ion}} = 20$ eV$_{\text{ee}}$ *(assuming Lindhard Q)*

SuperCDMS-HV (commissioning 2020) will be limited by this absence of rejection

SuperCDMS iZIP goal of $\sigma_{\text{ion}} = 100$ eV$_{\text{ee}}$ doesn’t offer an attractive coverage
Objective of low-mass program

- 3 tasks identified by the collaboration
  - **Heat resolution:** $\sigma_{\text{phonon}} = 10$ eV (also: $V = 100$ Volt)
  - **Ionization resolution:** $\sigma_{\text{ion}} = 20$ eV$_{\text{ee}}$
  - Cryogenics adapted to these performance

- **Demonstrator:** operation at LSM of a kg-size array of detectors with $\sigma_{\text{phonon}} = 10$ eV and $\sigma_{\text{ion}} = 20$ eV$_{\text{ee}}$ with either event-by-event or statistical discrimination, with the objective to probe cross-section values of $10^{-43}$ cm$^2$ below 1 GeV/c$^2$

- First application: measure quenching for $\sim 100$ eV recoils (directly, not using extrapolation models)
Nuclear recoil identification in EDELWEISS

- **Event-by-Event:** simultaneous measurement of ionization + heat signals
- **Statistical:** compare populations at low & high V bias: “Luke-Neganov” portion of thermal signal proportional to ionization yield quenching

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**Figure 11.** Ionization yield versus recoil energy for a large statistics (>3×10^4) of events from a neutron calibration using an AmBe source. The two red (blue) solid lines delimit the 90% C.L. nuclear (electron) recoil band. Purple dashed lines correspond to inelastic scattering of neutrons on the first (13.28 keV) or the third (68.75 keV) excited state of ^{73}Ge.

The AmBe source also emits high energy ~-rays of 4.4 MeV which lose energy via Compton scattering, leading to the population of events distributed around \( \langle Q(E_r) \rangle = 1 \). Events between \(-2.5\) keV and \(-0.6\) keV are indicated.

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First study: EDELWEISS-LT


2 FIDs, $\sigma_{\text{phonon}} = 1.0$ and $0.35$ keV, $V_{\text{bias}} = 100$ V and 30 V

- $\sigma_{\text{ion}}$ essential for full characterization of bkgs with 8 V data

- Does provide the expected statistical discrimination of all bkgs

- Next step: improve phonon resolution
Heat resolution progress

- Better understanding of heat sensor performance + scaling with detector mass
- Resolution of $\sigma_{\text{phonon}} = 18$ eV achieved on 32 g detector
- Vibration control is the key element to obtain stable resolution vs time
  
- Achieved resolution on a smaller detector exceeds by x5 the original LT goal with 800 g detectors

- Best above-ground limit down to 600 MeV/c²:

- First sub-GeV limit with Ge, down to 500 MeV/c²

- Opens the way for the 0.1 – 1 GeV/c² range

- Small detectors with lower thresholds to be combined with expertise acquired on HV: threshold reduction by factor \((1+V/3)\) in keV_{ee}
The use of small detector mass is not an obstacle to low-mass WIMP searches, if it improves the phonon resolution.

For $M_{\text{WIMP}}<1$ GeV/$c^2$, the gain in efficiency and threshold from improving $\sigma_{\text{phonon}} = 100 \rightarrow 50 \rightarrow 20$ eV largely compensate the loss of exposure.

![Graph showing projections for different detector masses and exposures.](graph.png)
Ionization improvements

- Cold front-end: replace JFET @100K with HEMT (High Electron Mobility Transistor) @4K
- Can be operated at 4K: shorter cabling -> reduced capacitance -> better signal/noise
- Successful HEMT amplifier with sub-100 eV resolution operated on a CDMS-II detector
  [A. Phipps et al., arXiv:1611.09712]
- EDELWEISS electrode design with lower capacitance: 2 → 4 mm spacing already achieved. Goal: reach 50 eV_{ee}.

A 32 g detector with $\sigma_{\text{ion}} = 20$ eV_{ee} and $\sigma_{\text{phonon}} = 20$ eV would be able to measure directly the ionization yield of 100 eV nuclear recoils with present bkg conditions at LSM

ANR projet MIYLEN
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EDELWEISS-DMB8:
Operation of a 200 kg array @8V (with nuclear recoil discrimination) in the improved background environment of SuperCDMS @ SNOLAB

Probing the region of the coherent scattering of $^8\text{B}$ solar $\nu$'s with resolution and discrimination

[PRD 97 (2018) 022003]
Low-mass program calendar

2019-2020

- Development of a 32 g FID detector at CSNSM and IPNL.
  Objective: $\sigma_{\text{phonon}} = 10$ eV and $\sigma_{\text{ion}} = 20$ eV$_{ee}$.
  → Collaboration with RICOCHET-France

- Upgrade of cryogenics at LSM
  → Collaboration with CUPID-France and LSM platform

- ANR MIYLEN: Measure ionization yield @ LSM with 32 g FID + HEMTs

2021-2022

- Study of scaling to 200 g FIDs (or 800 g for DMB8 option)

- Operation of a 1 kg demonstrator of sub-GeV detectors at LSM,
  with goal $10^{-43}$ cm$^2$ below 1 GeV/c$^2$.

- Definition of a high-impact contribution to the upgrade of SuperCDMS-SNOLAB
**EDELWEISS-III**

- 48 people, 46% in2p3
- Very strong presence of in2p3 in organigram

**SubGeV R&D (LT + beyond)**

- 38 people, 55% in2p3
- Reduction of FTE wrt to people involved reflects increased work shared in synergy with RICOCHET and CUPID
EDELWEIS-III

- 1.5 M€ investment in 2010-2013
  - 840 k€ from ANR FIDSUSY
  - 80 k€ from IN2P3

- Running costs during physics: 112 k€ /year
  - Average IN2P3 contribution to running costs: 65 k€ /year

EDELWEISS-LT

- Running costs during physics: 105 k€ /year
  - Average IN2P3 contribution to running costs: 50 k€ /year
  - Rising contribution from LUMINEU and CUPID (sharing of cryostat)
  - Similar IN2P3 contribution to detector R&D
Conclusion

**EDELWEISS-III**
- 8 collaboration papers since 2016 (121 spires citations) and 6 PhDs (incl. 3 IN2P3)
- Successful demonstration of ionization-based rejection of backgrounds
- WIMP and Axion-like particle limits improved wrt EDW-II, first precise measure of $^3\text{H}$ cosmic activation rate

**EDELWEISS low-mass R&D program**
- Goal: develop detector able to probe sub-GeV WIMPs with $\sigma_{\text{SI}} < 10^{-43}$ cm$^2$ with nuclear recoil discrimination capabilities
- Plan to reach objectives of $\sigma_{\text{phonon}}=10$ eV, $\sigma_{\text{ion}}=20$ eV$_{\text{ee}}$, and Luke-Neganov amplification to further reduce experimental thresholds
- EDELWEISS-LT: 100V on detector achieved, competitive limits achieved compared to other cryogenic experiments
- EDELWEISS-Surf: $\sigma_{\text{phonon}}=18$ eV, best surface limit for WIMPs > 0.6 GeV/c$^2$, first Ge limit below 1 GeV.
- kg-size demonstrator @ LSM for 2021-2022