SubGeV Dark Matter searches with EDELWEISS

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on behalf of the EDELWEISS collaboration
Outline

• The scientific context
• EDELWEISS-III: setup & FID detectors
• From EDW-III to EDW-SubGeV
  – Axion-like limits
  – Above-ground activities: EDW-Surf
  – LSM results: EDW R&D
• Conclusions and Prospectives
The scientific context

- **Absorption**
  - Electronic recoil

- **DM-electron scattering**
  - Electronic recoil

- **DM-Nucleus scattering**
  - Nuclear recoil

**EDELWEISS-SubGeV program**

- High Voltage single e/h
- Low Voltage Part. ID + Fid
- High Voltage single e/h
- Low Voltage Part. ID + Fid

**Not competitive with noble gases experiments**

- **8B neutrinos (~ 6 GeV)**
- **Reactor neutrinos (~ 2.7 GeV)**

**Hidden sector Dark Matter and others**
The 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) on mobile shield
- External (50 cm) + internal polyethylene shielding
  
  *Thermal neutron monitoring with $^3$He detector*
- Lead shielding (20 cm, including 2 cm Roman lead)
- Selection of radiopure material

*Performance of the EDELWEISS-III experiment for direct dark matter searches [JINST 12 (2017) P08010]*
The EDELWEISS-III detectors

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

Ionization: $N_{\text{pairs}} = E/\epsilon_{\gamma}$ or $\epsilon_n$

- $\epsilon_{\gamma} = 3 \text{ eV/(e-hole pair)}$ for electron recoils ($\gamma, \beta$)
- $\epsilon_n \sim 12 \text{ eV/(e-hole pair)}$ for nuclear recoils (neutrons, WIMPs)
- $\epsilon_{\gamma}/\epsilon_n = \text{ionization quenching } Q \rightarrow E_{\text{ion}} = Q E_{\text{recoil}} \text{ in keV}_{ee}$

Operated at $T = 18 \text{ mK}$

- $870 \text{ g Ge}$
- 2 GeNTD heat sensors
- Electrodes: concentric Al rings (2mm spacing) covering all faces

- $\varnothing = 70 \text{ mm, } h = 40 \text{ mm}$

- Direct measurement of ALL the energy, irrespective of particle ID
The EDELWEISS SubGeV programme

| Energy | Process | Detection
<table>
<thead>
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<tbody>
<tr>
<td>eV</td>
<td>Absorption</td>
<td>Electronic recoil</td>
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<tr>
<td>keV</td>
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- Absorption: Electronic recoil
- DM-electron scattering: Electronic recoil
- DM-Nucleus scattering: Nuclear recoil
- Standard WIMP
- Not competitive with noble gases experiments

**EDELWEISS-SubGeV program**

**High Voltage**
- single e/h
- Part. ID + Fid

**Low Voltage**
- Part. ID + Fid

**8B neutrinos (~ 6 GeV)**
**Reactor neutrinos (~ 2.7 GeV)**

*Courtesy of J. Billard*
Electron recoil analysis: axion-like limits

Absorption of keV-scale Bosonic DM
- Best Ge-based limit < 6 keV (thanks to surface rejection)
- Start to explore < 1 keV

- Surface rejection (i.e. ionization resolution) very important to reduce low-energy ER backgrounds
- Improvements foreseen in the 100 eV – 1 keV region with improved ionization (here: $\sigma = 35$ eV$_{ee}$ with HEMT readout)
EDELWEISS SubGeV program

- Current+future projects: background limited
- Event-by-event rejection even at 1 GeV/c^2 and 10^{-43} cm^2 requires a new generation of detectors
- An event-by-event rejection with ~1 kg.y requires \( \sigma_{\text{phonon}} = 10 \text{ eV} \) and \( \sigma_{\text{ion}} = 20 \text{ eV}_{ee} \)

- Keeping the ability to apply HV to EDELWEISS detectors is important to reduce thresholds in ER searches
  - For NR: depends a lot on quenching
- Reducing the detector from 860 to 33 g is worth it if the resolution goals are met
EDELWEISS SubGeV program

- Current+future projects:
- Event-by-event rejection even at 1 GeV/c
- A resolution goal for phonon: \(\sigma_{\text{phonon}} = 10\) eV
  and ion: \(\sigma_{\text{ion}} = 20\) eV

3 main pillars to be reached by the EDELWEISS detectors

- Heat energy resolution: 10 eV (RMS)
- EM background rejection (LV mode): \(10^3 \geq 20\) eV
- Operation at high voltages (HV mode): 100V

Two running modes

Low Voltage: Particle ID – ER/NR/unknown backgrounds + fiducialization

High Voltage: single e/h sensitivity thanks to the Neganov-Luke mode

- For NR: depends a lot on quenching

Reducing the detector from 860 to 33 g is worth it if the resolution goals are met
How to reach 10 eV phonon resolution

- Intense above ground R&D on NTD sensor

- Development of a detailed thermal model for the heat channel to optimise the choice of the best configuration

- Test of different glues

- Investigation of alternative sensors: NbSi TES

- Limited by FET current noise: replacing JFETs @ 100K with HEMTs @ 1K should provide additional x2 needed in resolution
EDELWEISS-Surf: an above-ground DM search

- Easy-access surface lab @ IPN-Lyon
- <1 m overburden: ideal for SIMP search (strongly interacting DM)
- Dry cryostat (CryoConcept) with <30h cool-down (fast turnover ideal for detector R&D)
- Vibration mitigation: < $\mu$g/$\sqrt{\text{Hz}}$ vibration levels obtained in spring-suspended tower
- RED20: 33.4 g Ge with NTD sensor, with no electrode
  - No ER/NR discrimination, but no uncertainty due to ionization yield or charge trapping
- Low energy calibration:
  - $^{55}$Fe x-ray source for calibration
  - Ge neutron activation
- Small 0.03 kg.day exposure
Pulses, calibration, resolution and energy spectrum

- Optimal filter fit to pulses
- Stability of noise & resolution over 137h of data taking
- 1 day set aside a priori for blind search
- Baseline: $\sigma = 17.8$ eV
**DM – nucleus interaction**

- First Ge-based limit below 1.2 GeV and best above-ground limit down to 600 MeV (SIMPs)
- Considering Migdal effect: first DM limit down to 45 MeV limited by Earth-Shielding effect

**Sharp 45 MeV/c² cutoff due to ES effect on velocity**

**Stronger upper cutoff for Migdal (subleading component)**
10 eV with high impedance NbSi TES sensor

NbSi209 @ LSM

100mm thick, 20mm diameter spiral NbSi sensor
Lithography
On a 200 g HP-Ge crystal (48 x 20 mm)

NbSi TES: alternative sensor for the heat channel

$\text{Nb}_x\text{Si}_{1-x}$: amorphous compound

$x > 13\% \rightarrow$ superconductor

Directly done by lithography on the crystal or on sapphire/germanium chip

High impedance – compatible with standard JFET

Goal: 10 eV RMS

330 nV/keV on A, 658 nV/keV on B
Phonon: $\sigma_A = 183$ eV, $\sigma_B = 125$ eV
Combined:

$\sigma = 113$ eV or $5 eV_{ee} @ 66$V
How to reach 20 eV ionization resolution

- Transition from JFET to HEMT (as initiated by the CDMS-Berkeley group, arXiv:1611.09712)
- Lower intrinsic noise than JFET
- Reduction of the stray capacitance by working at 1K or 4K
- Thanks to a data driven HEMT model, the goal of 20 eV_{ee} is reachable with ~20 pF total input impedance
- Ongoing HEMT characterizations
- HEMT-based preamp tests foreseen by end of 2019
- Cryogenics + cabling challenges ahead

See A. Juillard – poster #373
How to reach 100V with Neganov-Luke boost

\[ E_{NL} = \frac{E_{\text{ion}}}{e} \cdot V_{\text{bias}} \]

- 100 V on detector already achieved
- observe nuclear recoils down to \( \sim 0.1 \text{ keV}_{ee} \)
- full ion.+heat readout possible at any V

\( ^{133}\text{Ba} \ 356 \text{ keV line} \)

\( \gamma \)

\[ \text{FWHM}_{heat} (\text{keV}_{ee}) \]

\[ \text{Luke boost} = 1 + V/3 \]

\( 8 \text{ V} \)

\( 90 \text{ V} \)

2.5 keV NR

0.6 keV NR
High voltage operation @ LSM

Exploring DM-electron/nucleus interactions with near single-electron sensitivity achieved in massive bolometers operated underground @LSM

**Nbsi209: 200g Ge with TES thermal sensor**
- NbSi209
- 66 Volt
- $\sigma = 5 \text{ eV}_{ee}$
- 160 eV
- DM search zone
- Preliminary
- 1.3 keV
- 10.4 keV

**RED30: 33 g Ge Al electrodes, NTD thermal sensor**
- RED30
- 70 Volt
- $\sigma = 1.8 \text{ eV}_{ee}$
- 160 eV
- DM search zone
- Preliminary
- 1.3 keV
- 10.4 keV

KLM $^{71}$Ge from neutron activation
- 3.7 GBq AmBe source (2x10$^5$ neutrons)
Conclusions

• There is an increasing interest in the low-mass dark matter region motivated by lack of evidence of new physics at LHC (e.g. SUSY):
  -> *Beyond the standard WIMP Dark Matter scenario*

• **EDELWEISS-SubGeV** program aims at probing **MeV-GeV particles** via ER and NR interactions with new detectors:
  – Reduce detector mass to improve resolutions & thresholds -> **confirmed by EDELWEISS-Surf**
  – Particle ID and surface event rejection down to 50 eV$_{NR}$ (**Low Voltage**)
  – Single-e/h sensitivity on massive bolometers (**High Voltage**)

• **Low-voltage R&D program** focusing on front-end HEMT preamplifier and low-capacitance electrode design
  -> objective: $\sigma = 10$ eV (phonon) + 20 eV$_{ee}$ (ionization)
  -> *Goal is to reach to reach $O(10^{-43})$ cm$^2$ with background rejection at 1 GeV, with 1 kg payload in one year at Modane*

• **High-voltage R&D program**, advancing well with near single-e/h sensitivity achieved on 33.4 g and 200 g Ge crystals operated at Modane.

• **New EDELWEISS science results expected in fall 2019 – STAY TUNED**
• BACKUP SLIDES
Spin-dependent cases

- Unfortunately, $^{14}$N has both p and n spin: *shielding from atmosphere*
- Large cross-section $\rightarrow$ dramatic ES effects (especially on Migdal limits)
Consider instead **inelastic scattering**. In particular, look for the possible ionisation of an electron after a DM-nucleus interaction - “**Migdal Effect**”

- Consider ionization effects of e⁻ cloud due to sudden boost of nucleus in DM collision
  
  _Calculated in Ibe et al, JHEP 03 (2018) 194_

- Use M shell (n=3) only in Ge
  - K, L electrons too tightly bound
  - n=4 affected by band structure

- Injection of electronic energy in the sub-keV to keV range
  - <1% probability
  - Negligible for >10 GeV/c² WIMPs
  - In RED20 (only heat): add energy from both NR and ER
  - **Robust signal >100 eV even for DM masses <100 MeV/c²**

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Dolan et al, PRL 121, 101801 (2018)

**Not yet observed, but calculable**
Limit on Low-Mass WIMPs

- 8 selected detectors: low trigger thresholds and good noise conditions
- Resolution: $\sigma_{ph} = 200$ eV, $\sigma_{ion} = 220$ eV$_{ee}$
- A total fiducial exposure of 496 kg.days after quality cuts
- Analysis with BDT/Profile Likelihood
- EDW-III Improvement by $\times 20$ to $\times 150$ between 7 and 10 GeV w.r.t EDW-II
- Limited by heat-only background → identification and rejection using ionization channel