JINR

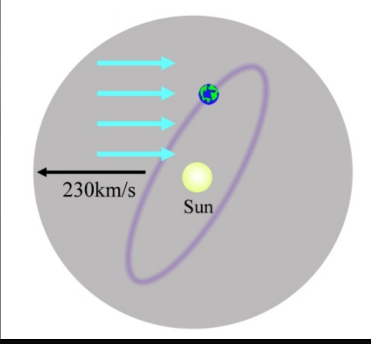
Direct low-mass WIMP searches with HPGe Semiconductor Bolometers

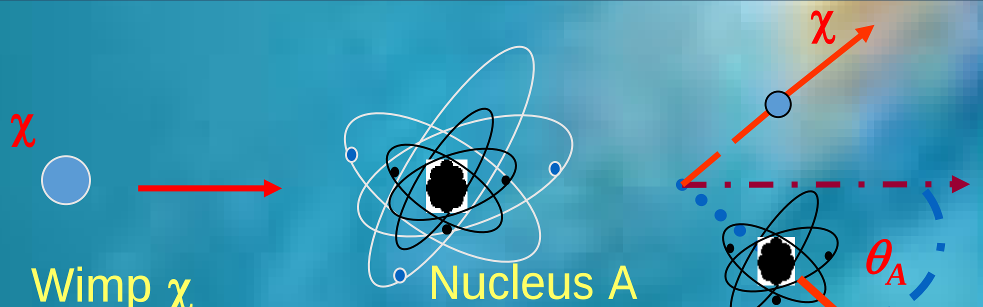
S. Rozov on behalf of the EDELWEISS collaboration

NTIHEP 2018

How to detect

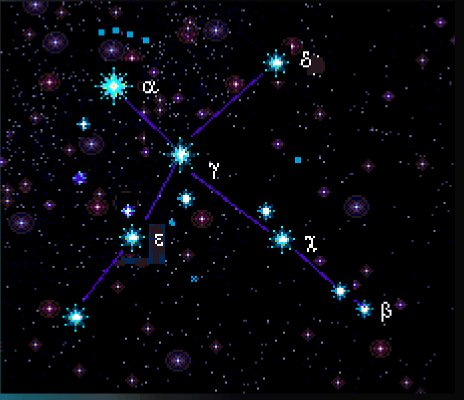
According to models of cosmological structure formation, the luminous matter of galaxies is gravitationally bound to a more massive halo of Dark Matter. It local density is 0.3 GeV/cm^3. If Dark Matter indeed consist from WIMPs, its expect to recoil on the ordinary matter moving through Dark Matter halo (Solar System around Galactic Centre). A process that can be used for WIMP detection is the elastic scattering of WIMP off nuclei. The energy deposited in the detector during the WIMP elastic scattering can be measured.





Wimp χ
from the galactic halo
V ~ 230 km/s

Nucleus A
at rest in the lab
v=0 km/s

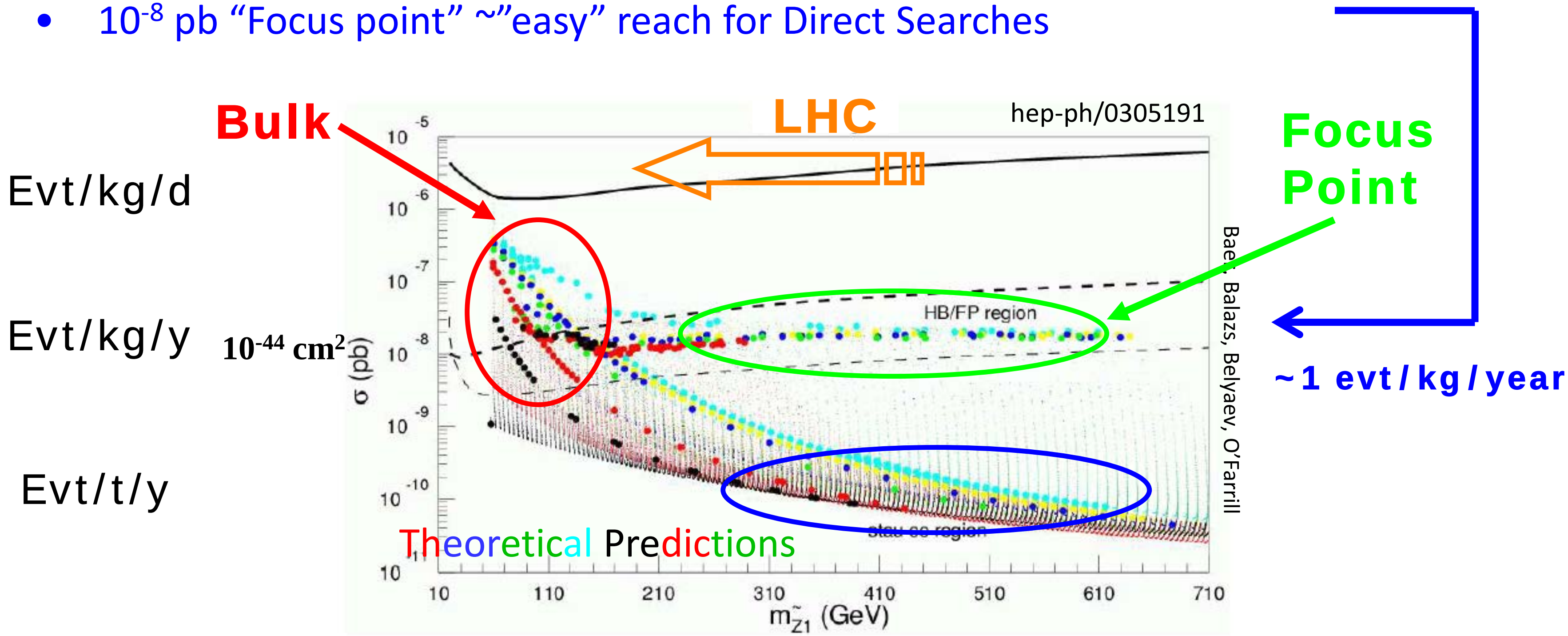


$$\boxed{E_R = E_\chi \frac{4\, M_A M_\chi}{(M_A + M_\chi)^2} \cos^2\theta_A}$$

$\boxed{E_R < 100 \text{ keV !!!}}$

What about cross section and WIMP's mass?

- Most general SUSY not very predictive
- CMSSM (M_{GUT}~10^{16} GeV, "benchmark" for LHC): more predictive
- 10^{-8} pb "Focus point" ~"easy" reach for Direct Searches



- *Focus search on this region, but keep eyes open for alternative models*
- Complementarity: LHC probes M_{WIMP}, direct searches probe $\sigma_{WIMP\text{-}nucleon}$

In anyway the expected signal rate for direct search is small !!!

- **Main experimental challenges are:**
  event rate is ultra small (below of 1 per 100 kg of matter per day);
  energy deposition is tiny (below of 100 keV)

Thus main tasks for experiments are:

- **<u>Detector mass + long stable data taking + stable predictable detector response</u>**
- **<u>Detectors' performance (low energy thresholds, good resolutions)</u>**
- **<u>Background reduction</u>**

E_R < ~100 keV → Very performant detector
Low threshold, good resolution

R_0 < ~0.01 evt/kg/d → Large volume
10 kg – 1 ton

Background → 0 → Efficient shielding,
Underground lab,
material selection, ...

Edelweiss: direct DM search @ LSM (France)

Collaboration

EDELWEISS 2016 @ Karlsruhe (De)

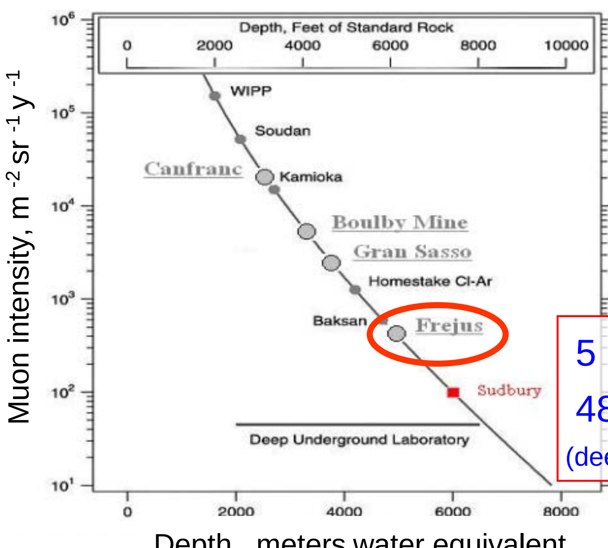
CEA / Irfu / Iramis (Saclay)
CSNSM (Orsay)
Institut Neel (Grenoble)
IPNL (Lyon)
LPN (Marcoussis)

KIT (Karlsruhe)

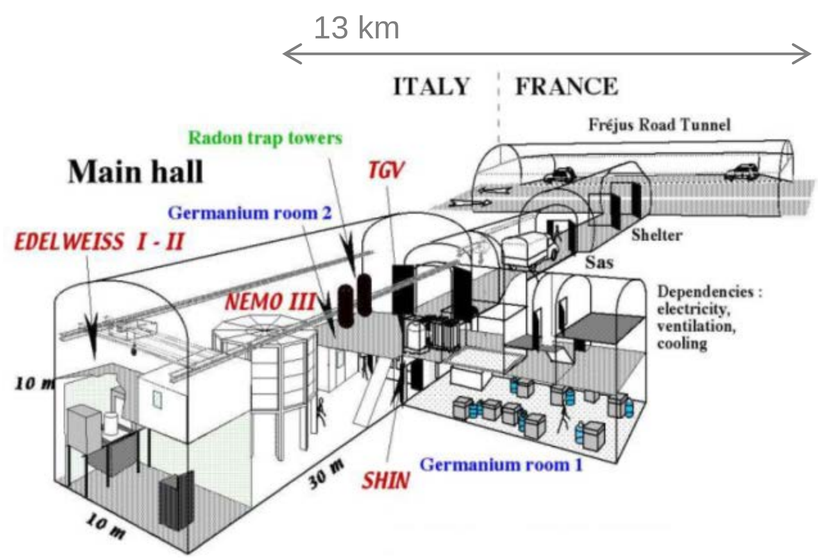
JINR (Dubna)

University of Oxford
University of Sheffield

LSM



$5\ \mu/m^2/day$
4800 mwe
(deepest in Europe)



Edelweiss-III: experimental set-up

Cryogenic installation (18 mK) :

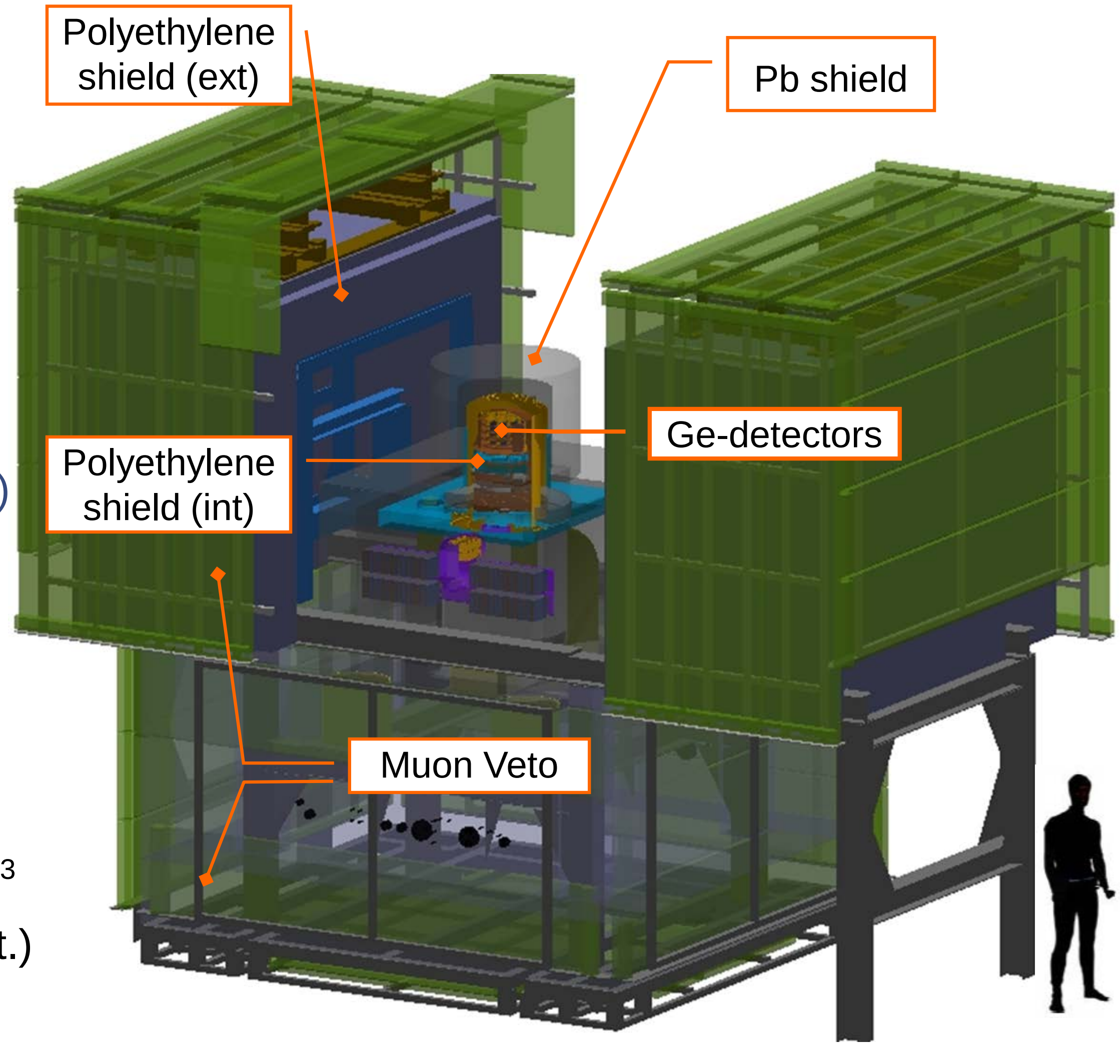
- Reversed geometry cryostat
- **Can host up to 40kg of detectors**

Shielding :

- Clean room + deradonized air: $10 Bq/m^3 \rightarrow 30 mBq/m^3$
- Active muon veto (>98% coverage)
- **PE** shield internal + external (50cm)
- **Lead** shield **20 cm** (18cm + 2cm ancient lead)

(Many) others :

- Remotely controlled sources for calibrations + regenerations
- Radon detector down to few mBq/m^3
- thermal neutron monitoring (3He det.)



Upgrades for EDW-III:

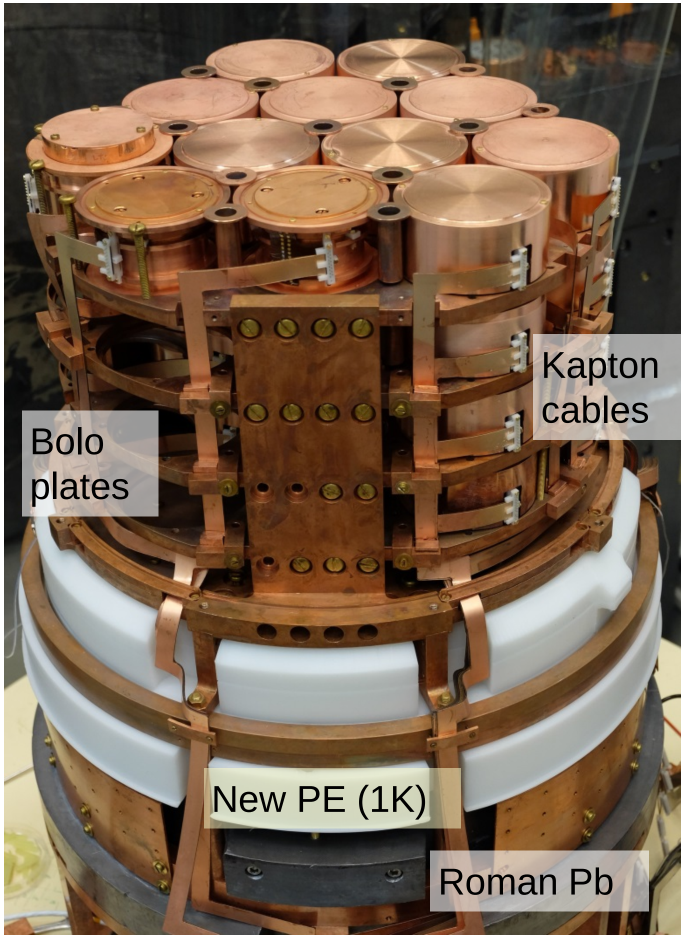
New cryogenics (microphonics), Additional PE shield, new Cu thermal screens, Kapton cables and connectors (α-n reduction), ALL cold electronics at 100K, digitization at 300K, New event-based scalable IPE-DAQ, …

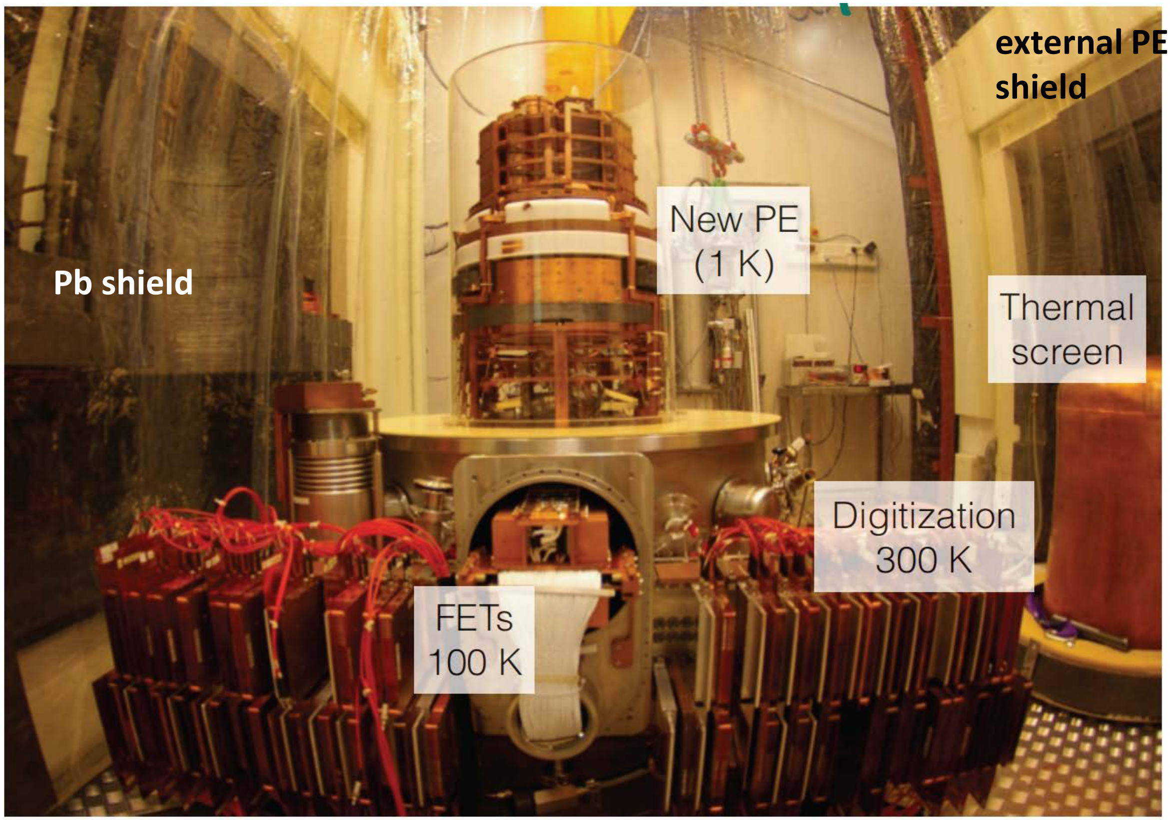
EDELWEISS-III: experimental setup

Performance of the EDELWEISS-III experiment for direct dark matter searches
arXiv:1706.01070

Cryogenic installation (18 mK):

- Reversed geometry cryostat
- Towers of 24 cryogenic detectors
- **Can host up to 40 kg of detectors**

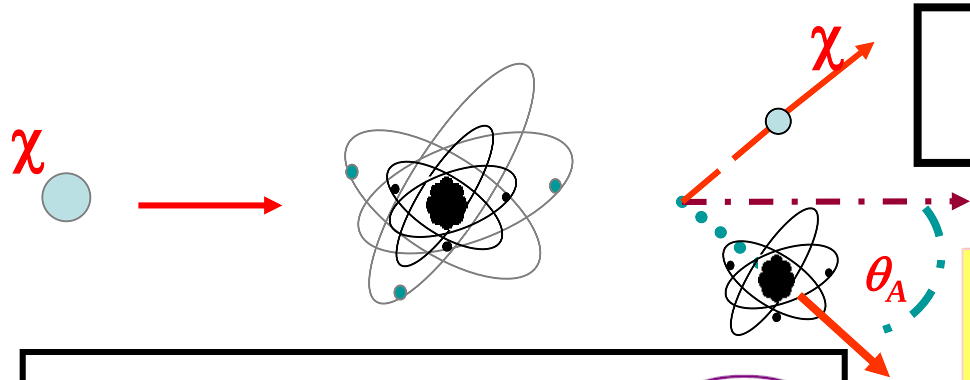




Shieldings:

- Clean room + deradonized air (30 mBq/m^3)
- Active muon veto (> 98% coverage)
- **PE** shielding internal + external (50cm)
- **Pb** shielding **20 cm** (18 cm + 2 cm Roman lead)

Basis for EDELWEISS experiment is Heat and Ionization Ge detectors



Ionization measurements

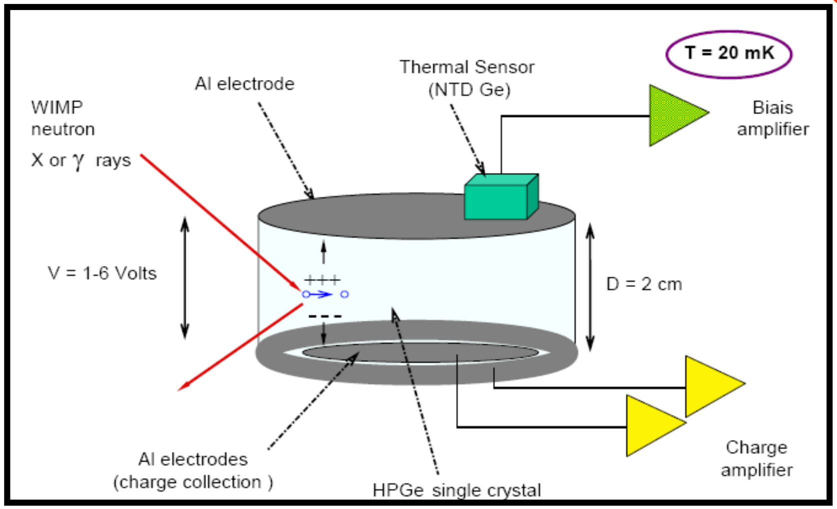
Heat measurements

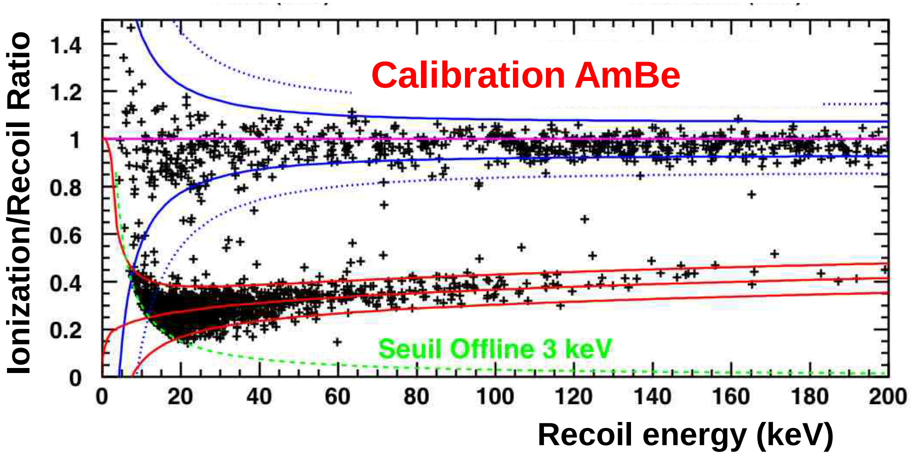
$Q = E_{ionization}/E_{recoil}$

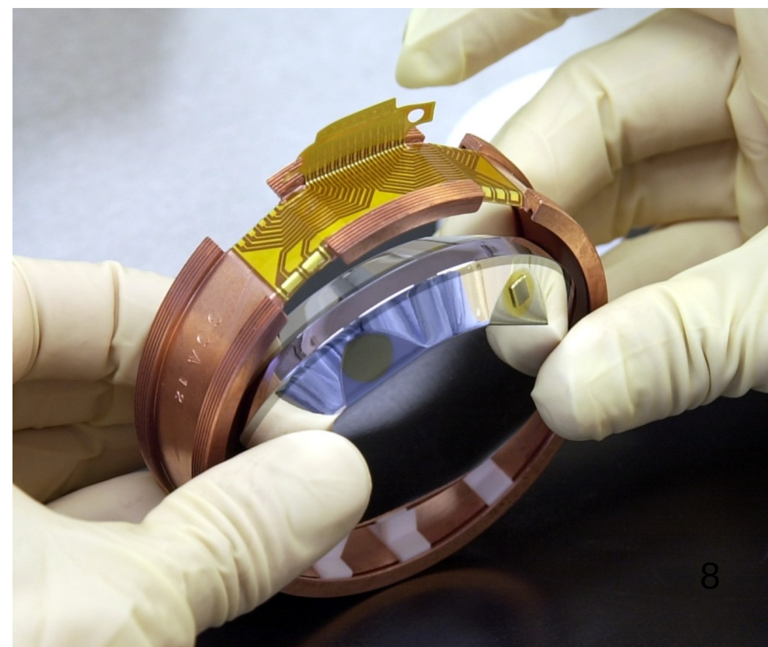
- **Q=1 for electronic recoil**
- **Q≈0.3 nuclear recoil**

⇒Event by event identification of the recoil

⇒<u>Discrimination γ/n > 99.99%</u>

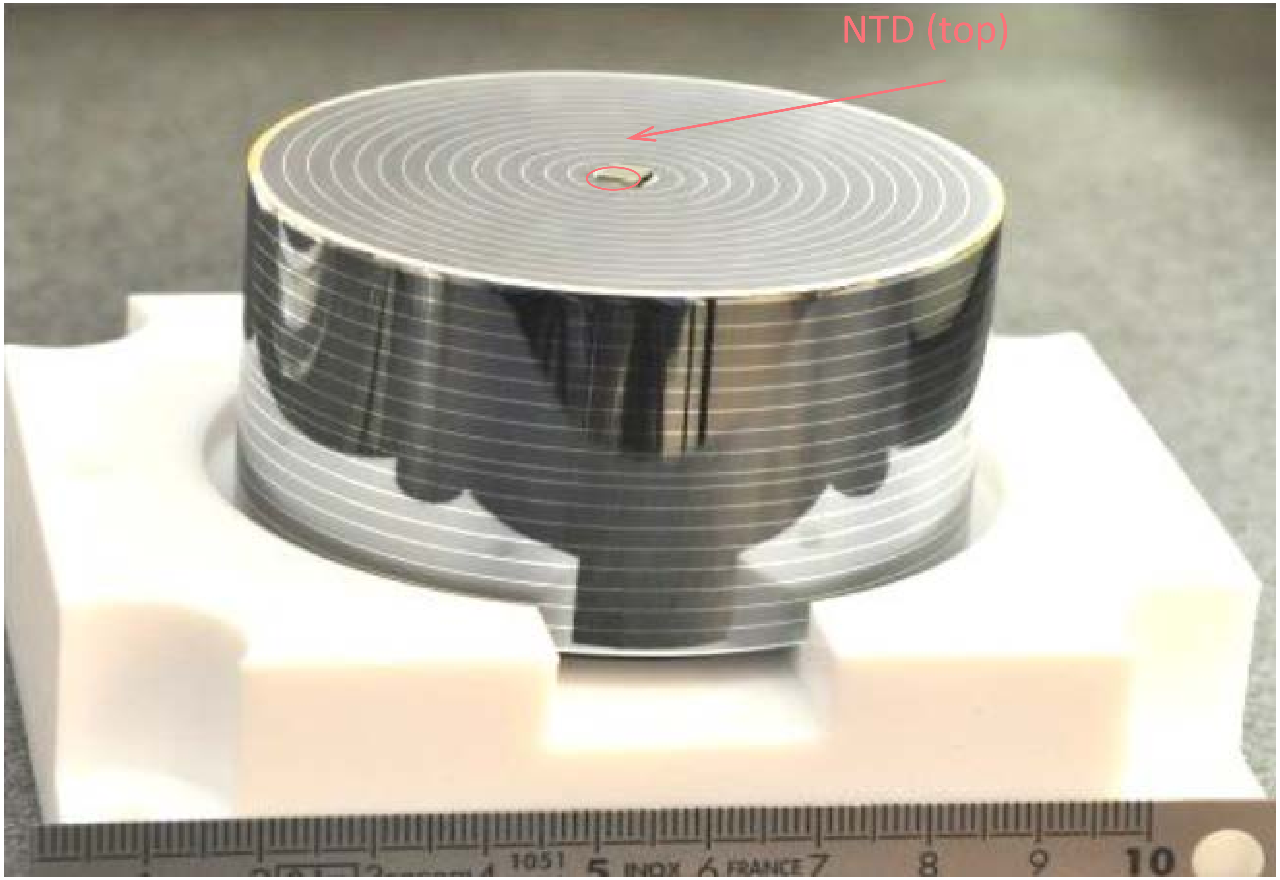






EDELWEISS-III: FID Ge-bolometers

Full InterDigitized (FID) detectors: 820-890 g, h = 40 mm, ∅ = 70 mm

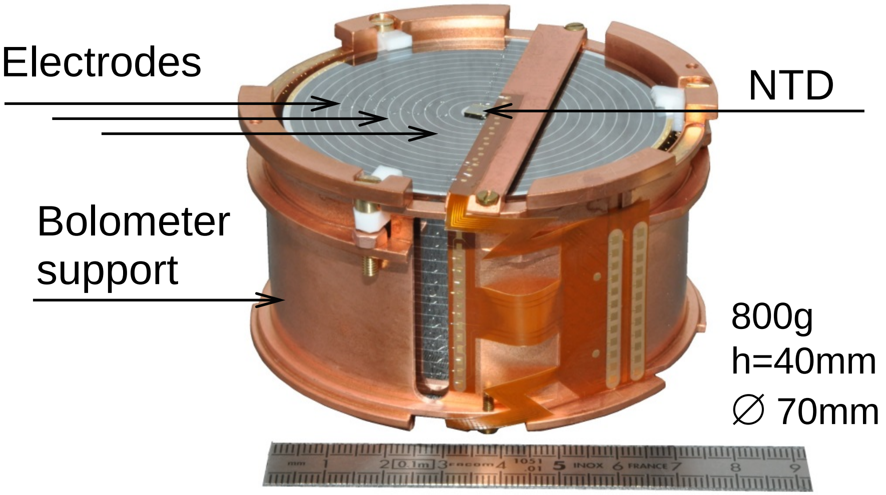


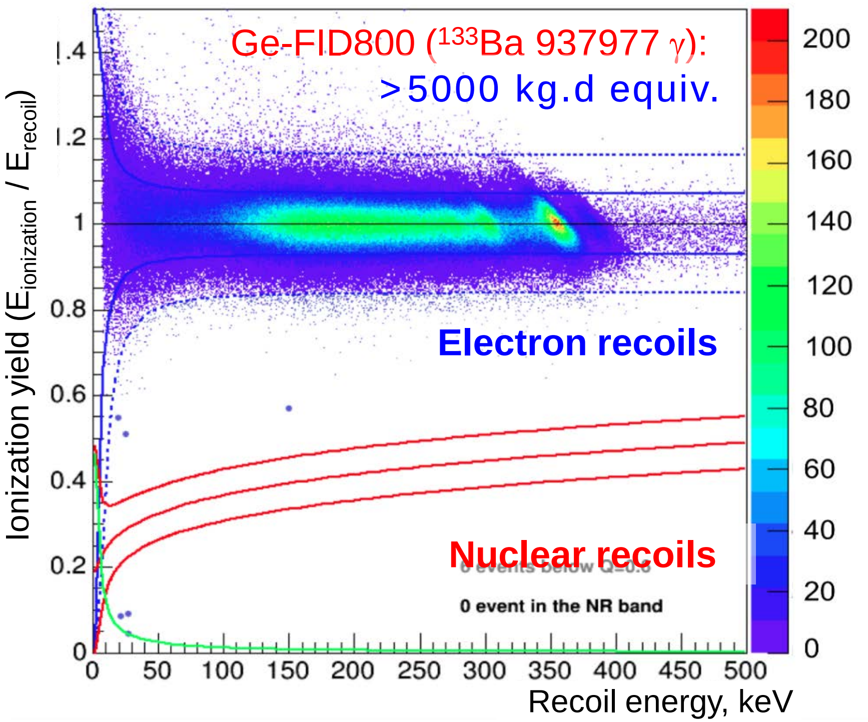
Simultaneous measurement of heat and ionization signals

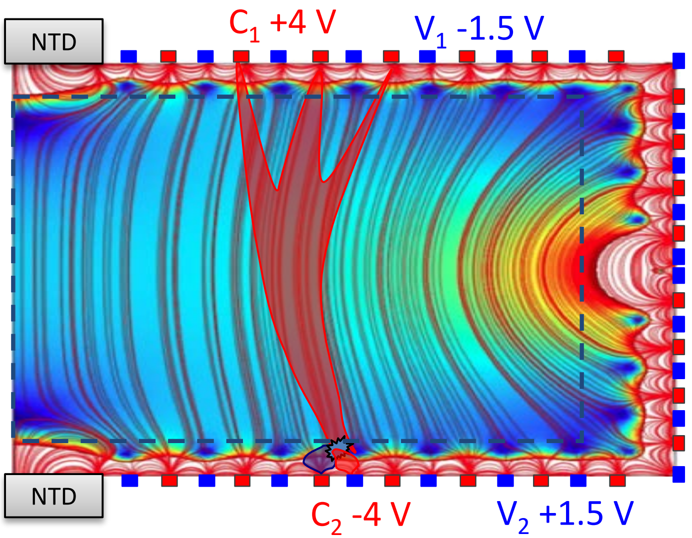
EDELWEISS-III: FID Ge-bolometers

Full InterDigitized (FID) detectors: 820-890 g, h = 40 mm, ∅ = 70 mm

- **Simultaneous measurement**
  - Heat @18 mK, 2 Ge/NTD thermometers
  - Ionization @ few V/cm
- **Evt by evt identification** by ratio $Q = E_{ioniz}/E_{recoil}$
  → **γ-rejection factor <2.5×10⁻⁶**





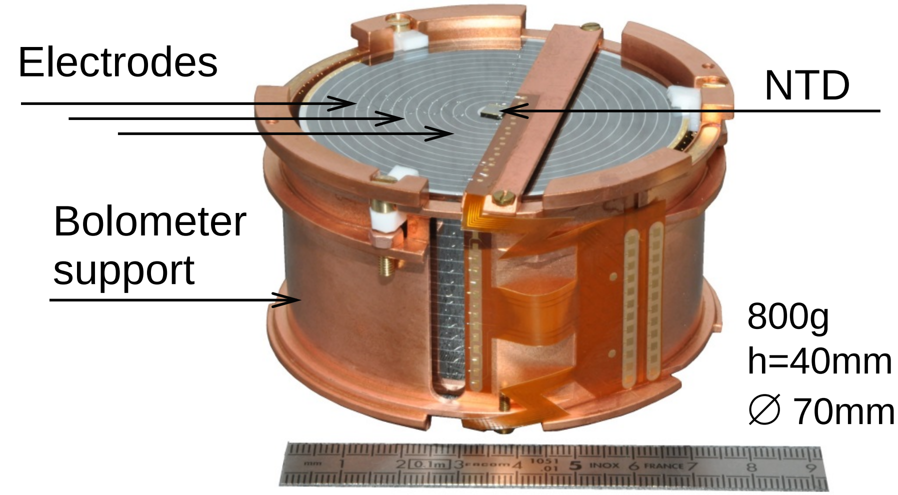


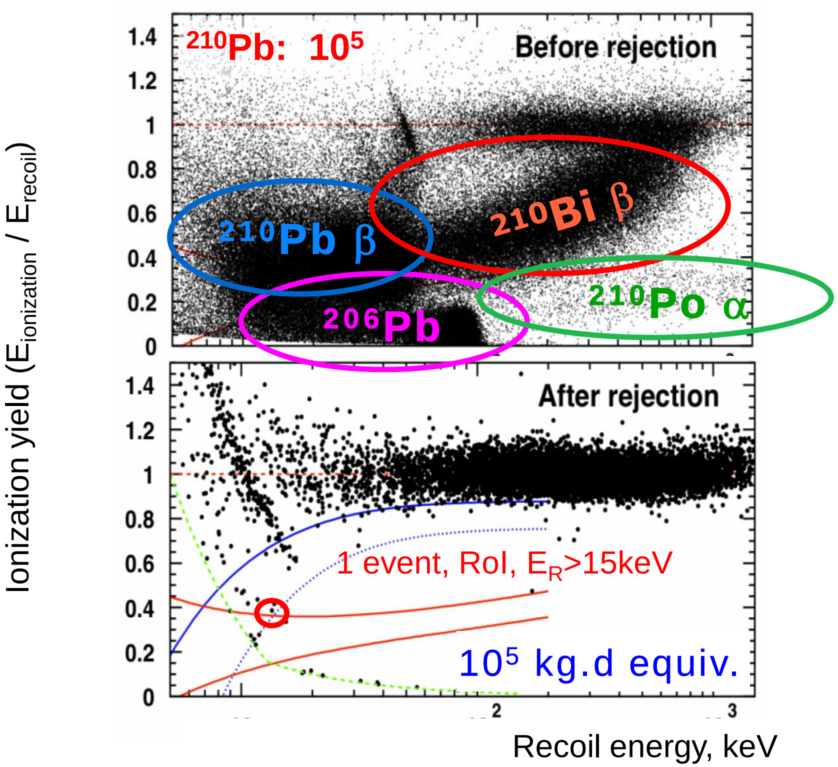
PLB 681 (2009) 305; JLTP (2014) 176:870

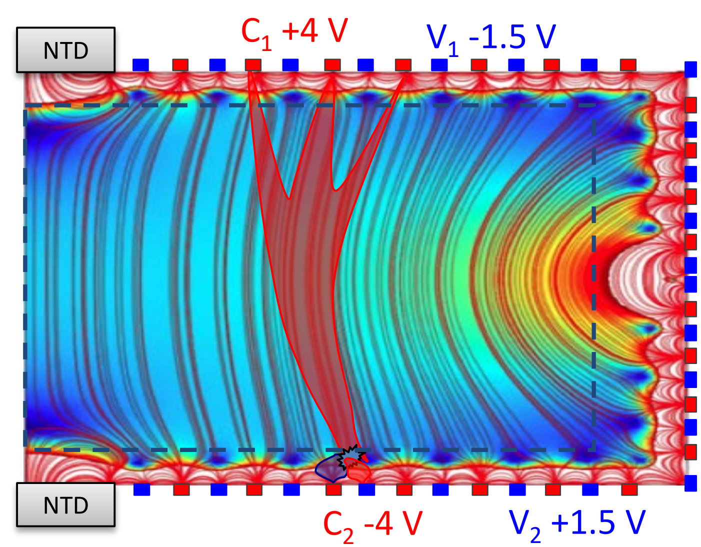
EDELWEISS-III: FID Ge-bolometers

Full InterDigitized (FID) detectors: 820-890 g, h = 40 mm, ∅ = 70 mm

- **Simultaneous measurement**
  - Heat @18 mK, 2 Ge/NTD thermometers
  - Ionization @ few V/cm
- **Evt by evt identification** by ratio $Q = E_{ioniz}/E_{recoil}$
  → **γ-rejection factor $<2.5\times10^{-6}$**
- **Vetoing surface events (ID electrodes)**
  → **surface-rejection factor 4×10^{-5}**



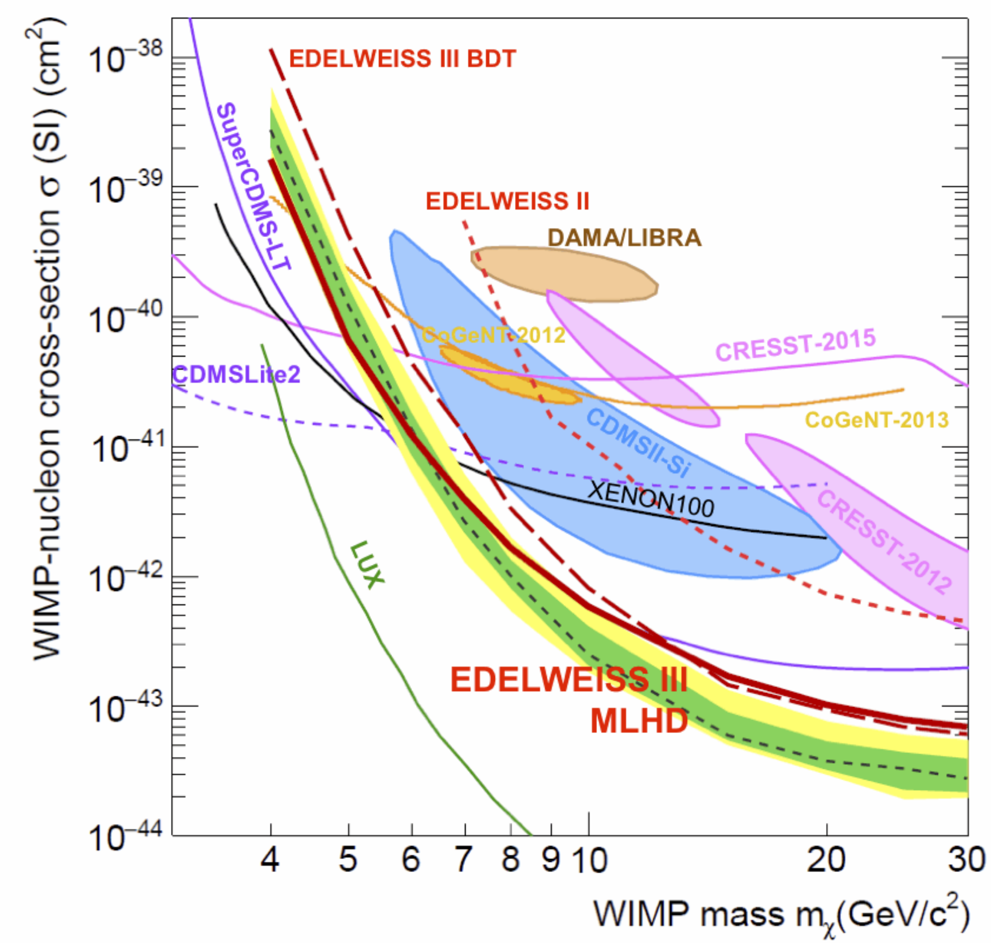




PLB 681 (2009) 305; JLTP (2014) 176:870

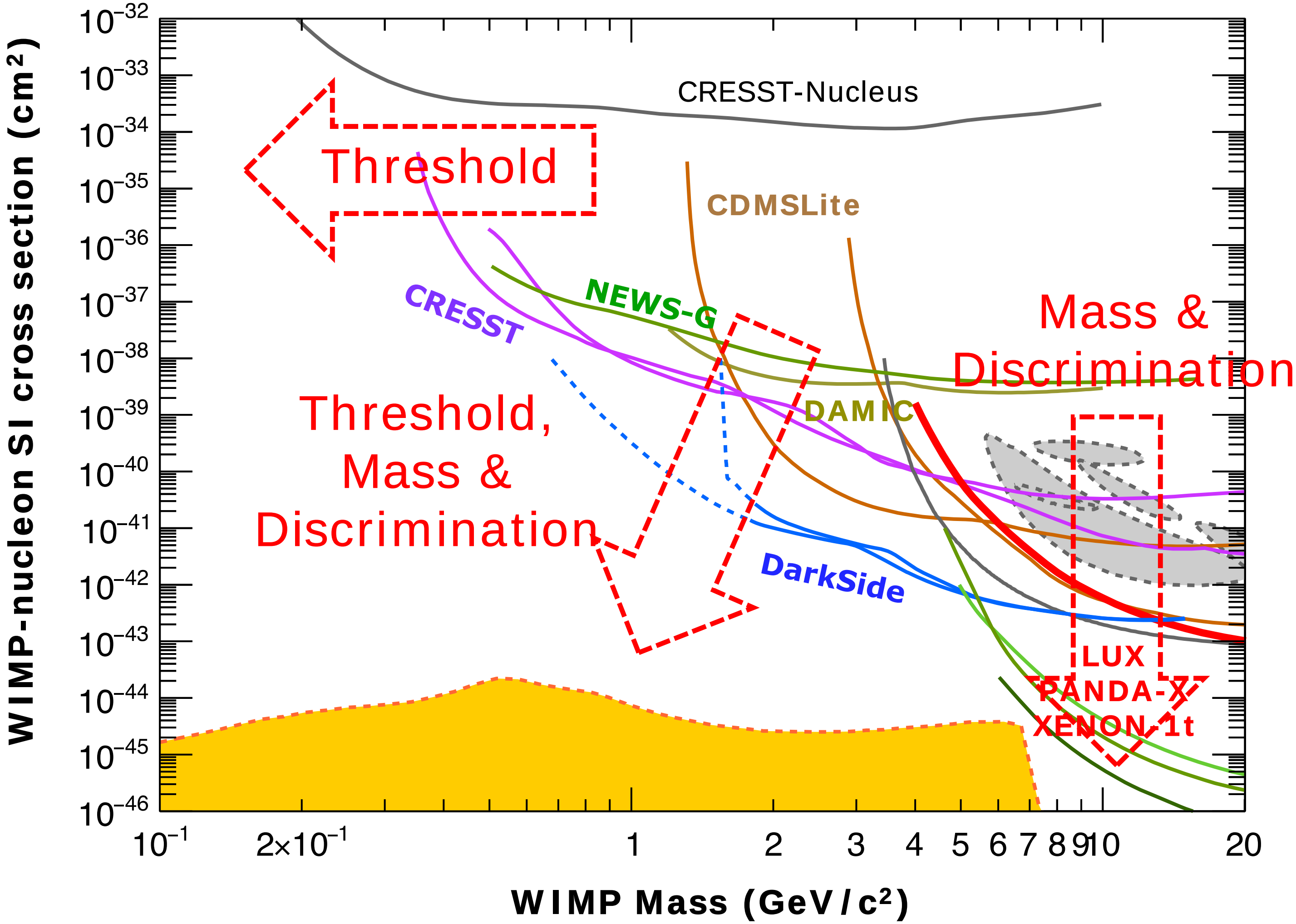
Low-Mass reach of EDELWEISS-III

- 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 EDELWEISS-II
- Limited by heat-only background: *identification and rejection using the σ=230 eV resolution on ionization*
- Ionization resolution is key for rejection
- Heat resolution is key for low thresholds

Low-mass WIMP searches



EDELWEISS Low-mass WIMP searches

EDELWEISS-III

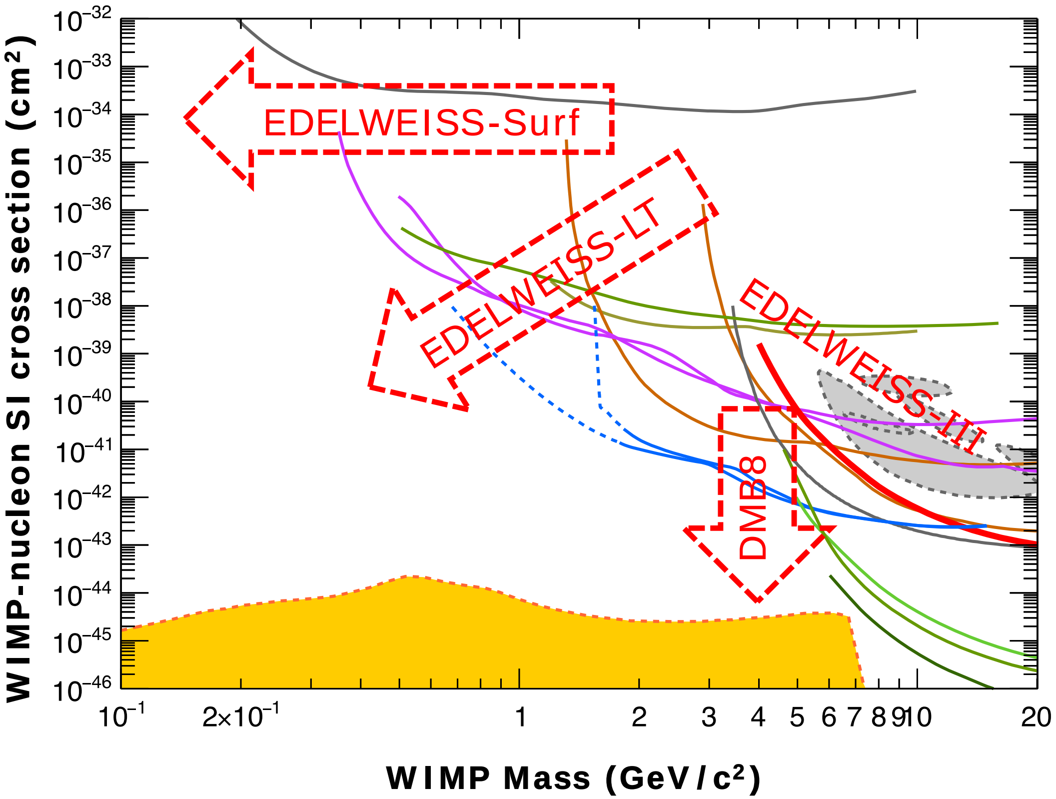
- Exploitation of results with 20 kg array

Ionization R&D

- Improving discrimination to explore the ^{8}B region with resolution (DMB8)
- Exploring non-WIMP DM with smaller array (MELODI)

Heat channel R&D

- Improving the heat channel resolution to reach lower WIMP masses
- Above-ground R&D (Surf) and deployment at LSM (LT)

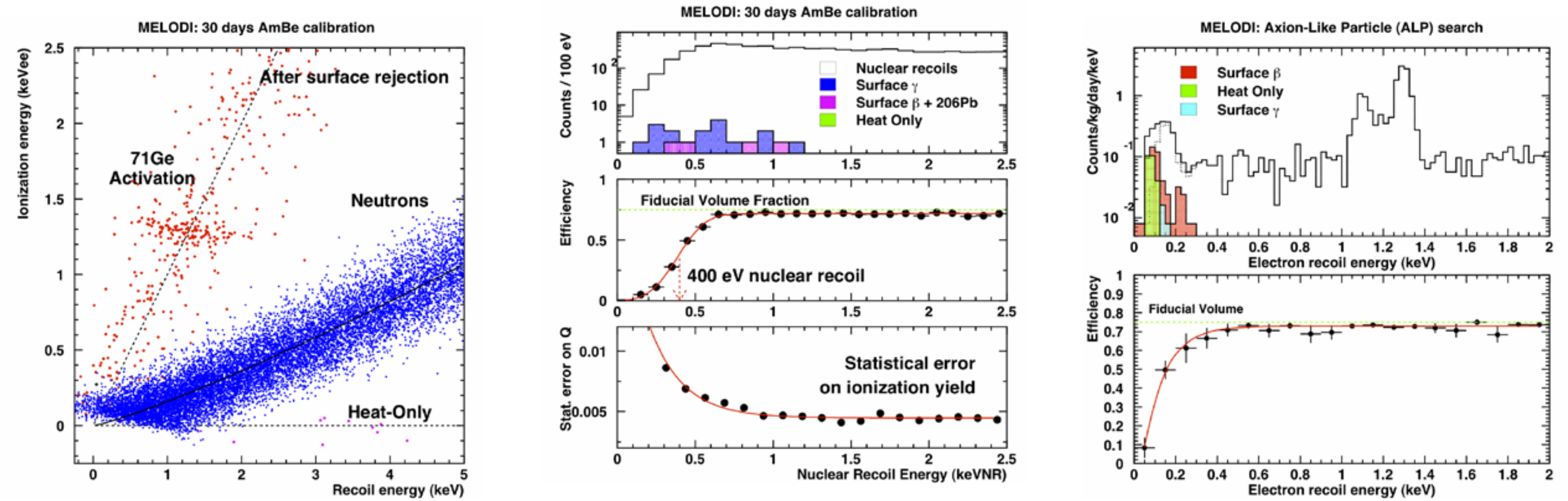


Prospective with improved ionization

- 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}.

First applications with prototype detector: MELODI

- FID detector with <40 pF + <50 eV_{ee} ion. resolution
- **Precision nuclear recoil ionization yield measurement**



EDELWEISS-LT: Luke-Neganov boost

Heat thresholds can be improved by applying larger bias voltages

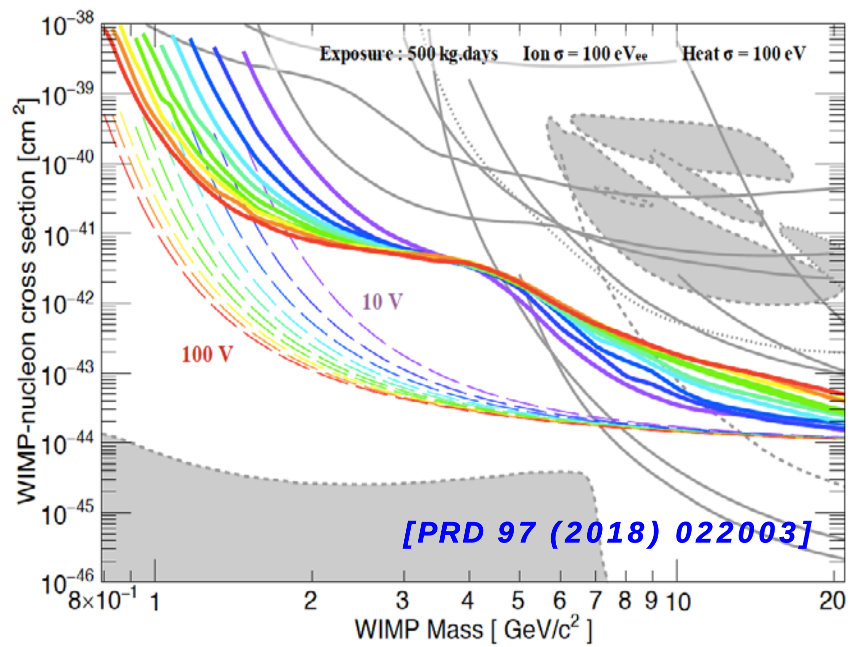
- Heat signal boosted by Neganov-Luke effect (~Joule heating, factor $[1+V_{bias}/3]$)
- Loss of ionization-based bkg discrimination: method benefits low-mass searches only
  → *10^{-41} cm² with 500 kgd and current bkgs*

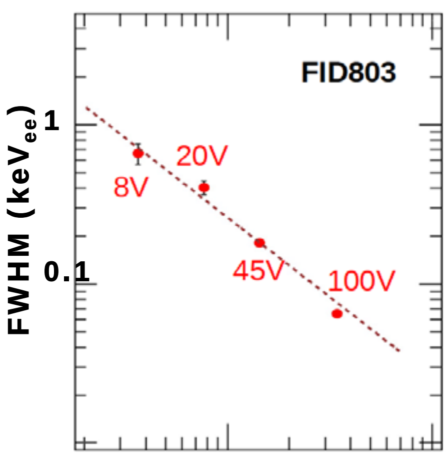
✓ **100V bias already achieved**

✓ **Observe nucl. recoils down to ~0.1 keV$_{ee}$**

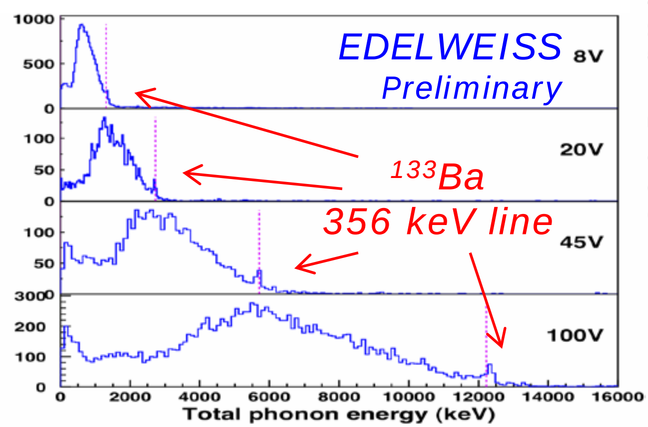
✓ **Full ion.+heat readout possible at any V**

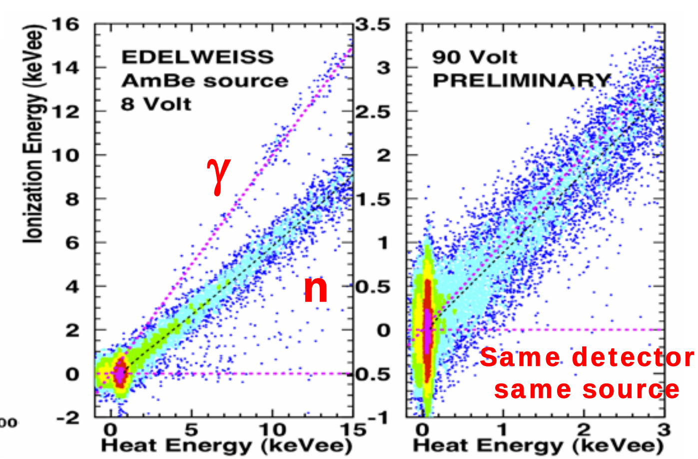
✓ ***First WIMP Data@100V analysis underway***





Luke boost = 1 + V / 3

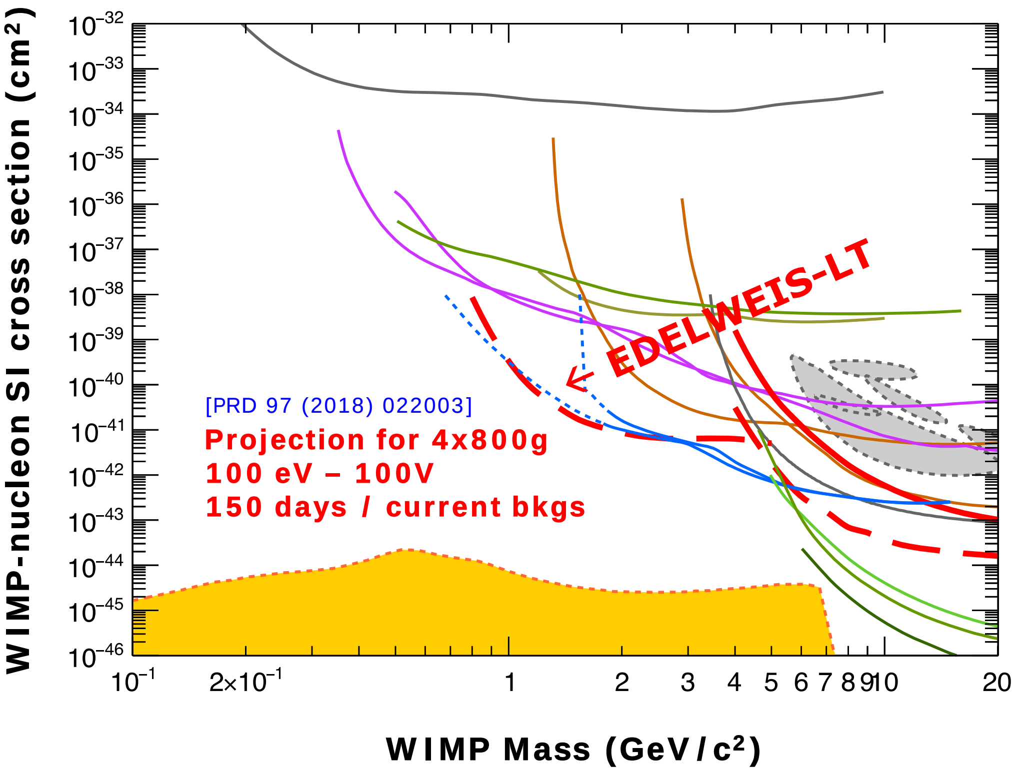




Prospects for GeV-range masses

- Complete study based on present measured backgrounds and resolutions *vs* possible improvements **[PRD 97 (2018) 022003]**

Lower thresholds



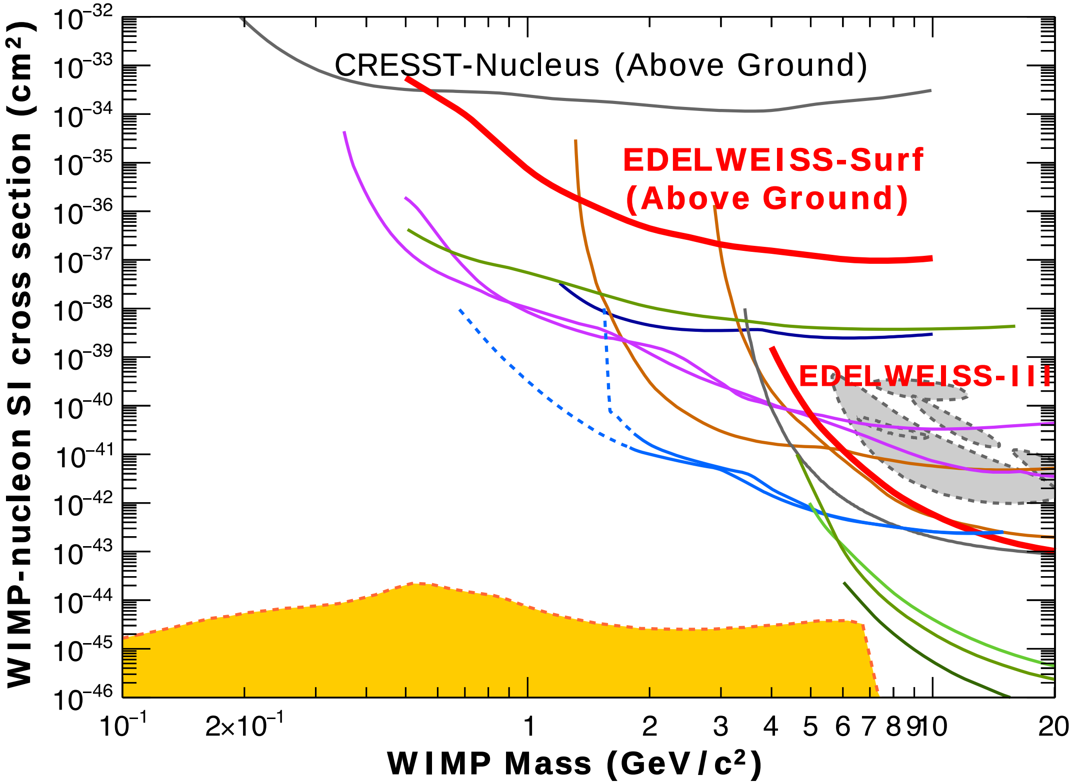
1. Use of Luke-Neganov boost to lower thresholds (up to 100V bias)
2. Improve heat resolution, objective of 800g detectors: σ_{phonon} = 500 eV → **100 eV**
   (50 eV resolution already achieved on 200 g detector)
3. Reduction x100 of heat-only background

Surface limit

- 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/c^2: SIMP
- First sub-GeV limit with Ge, down to 500 MeV/c^2
- Opens the way for the 0.1 – 1 GeV/c^2 range

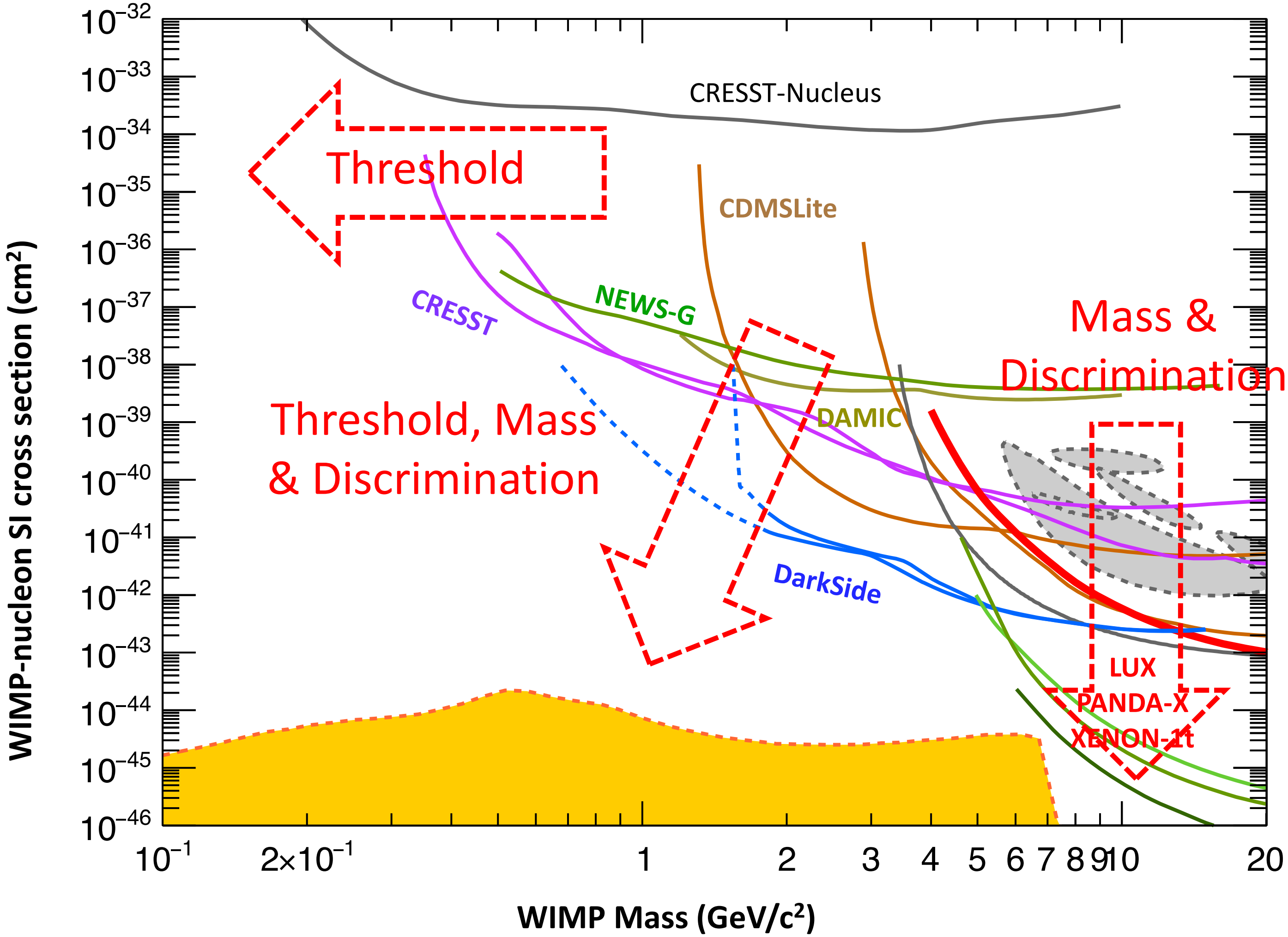
- Small detectors with lower thresholds to be combined with expertise acquired on HV: threshold reduction by factor (1+V_{bias}/3) in keV_{ee}



Conclusions

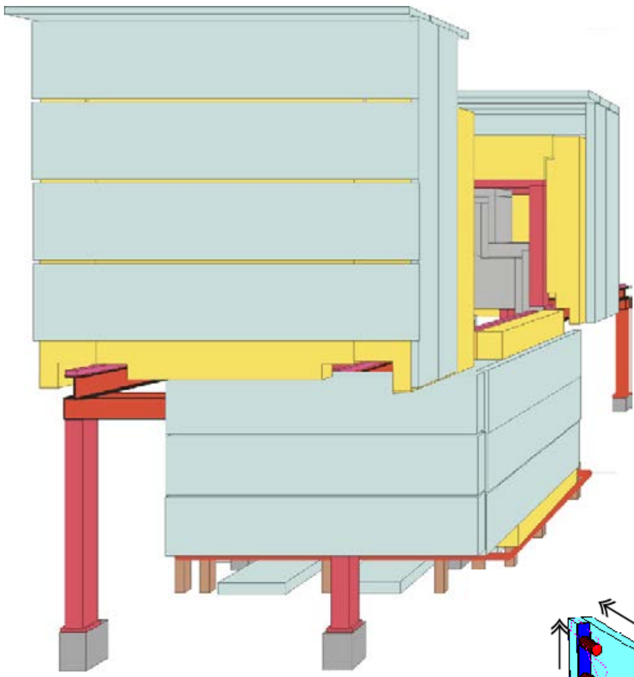
- EDELWEISS-III
  - Robust design, good reproducibility of performances *[arXiv:1706.01070]* *[JINST 11 (2016) P10008]*
  - Detailed description of backgrounds *[AstroPart. 91 (2017) 51]*
  - Excellent rejection performance, but not competitive with large Ar/Xe detectors above 6 GeV *[JCAP05 (2016) 019]* *[EPJC 76 (2016) 548]*
- Prospects in the GeV-WIMP range: EDELWEISS-LT *[arXiv:1707.04308]*
  - Improve thresholds x10 using boost from 8 to 100V (achieved)
  - 10^{-41} cm^2 achievable at LSM with 4 detectors with present levels of backgrounds
- Prospects for WIMPs in the ^{8}B region: EDELWEISS-DMB8
  - 50 eV ionization resolution to obtain pure nuclear recoil sample + 10% resolution on recoil energy: clear spectral identification of ^{8}B ν *[arXiv:1707.04308]*
  - ~200 kg FIDs at SNOLAB to complement nicely the SuperCDMS-SNOLAB reach
  - Use HEMT preamplifier + reduce electrode capacitance (reduction by a factor of 2 of number of electrodes achieved) → MELODI @LSM

Low-mass WIMP searches

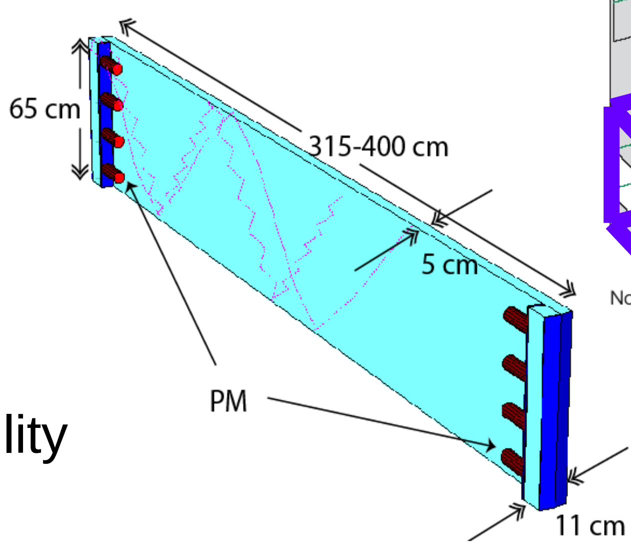


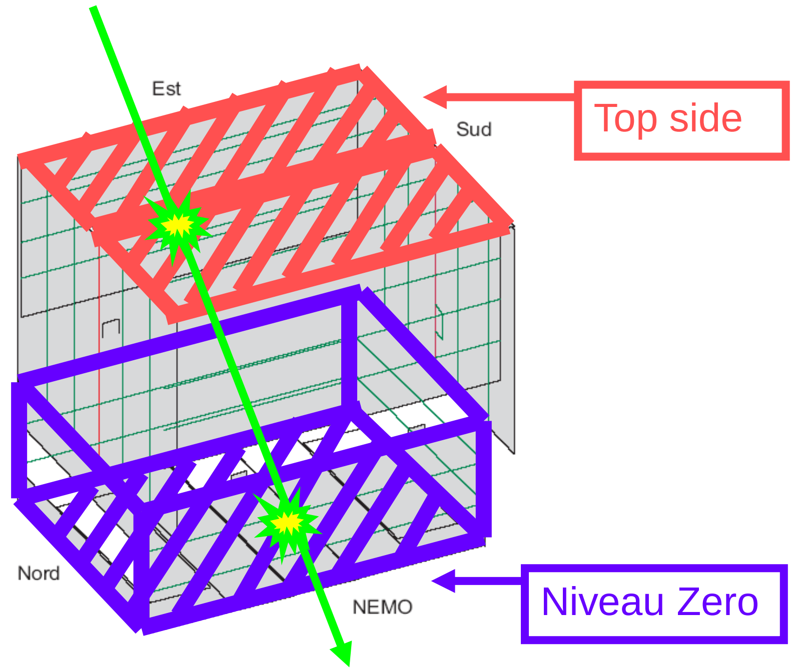
Shield / Neutrons / Active muon veto system

Without muon veto 0.04 events/kg.d -> 6.4 events/160 kg.d
After muon veto -> below 0.06 events/160 kg.d



42 modules
covering 100 m^2
~99% coverage
energy, timing →
μ tracking capability



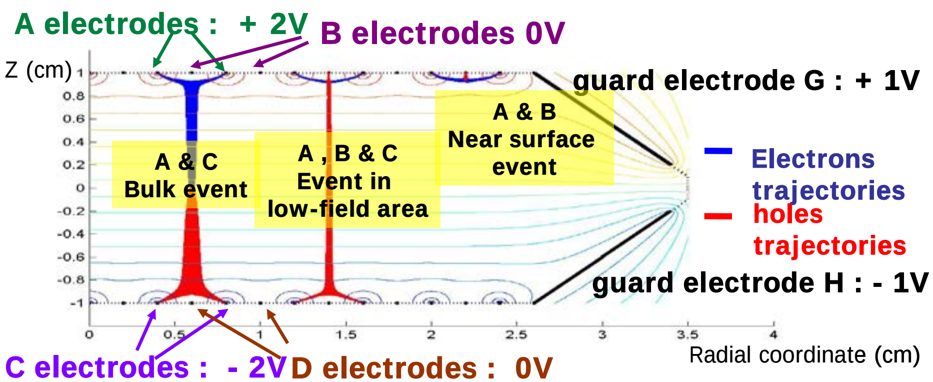


EDELWEISS (Heat and ionization Ge bolometers)

Using of *Heat* and *Ionization* HPGe detectors, running in ^3He-^4He dilution cryostat (<20 mK)

Ratio $E_{ionization}/E_{recoil}$ is
=1 for electronic recoil
≈0.3 for nuclear recoil
⇒Event by event identification of the recoil
⇒Discrimination γ/n > 99.99%

Detectors with special concentric planar electrodes for active rejection of surface events (miss-collected charge)



EDELWEISS

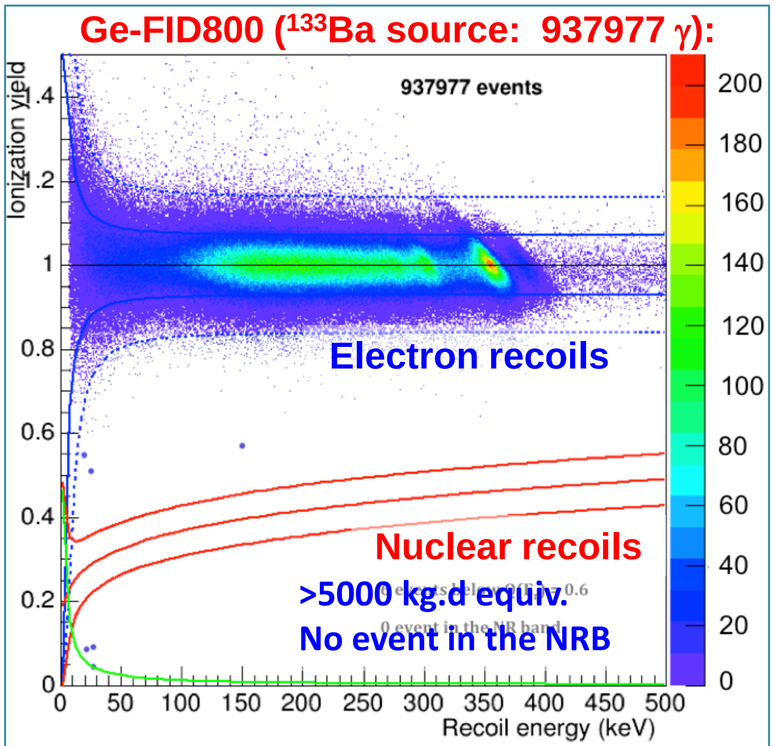
- 36 x 800 g detectors
- 2 charge + 2 charge
- 2 phonon (NTD)

Active rejection performance of FID detectors

Performance of the EDELWEISS-III experiment for direct dark matter searches
arXiv:1706.01070

Rejection tested with more than 5000 kg.d equivalent samples

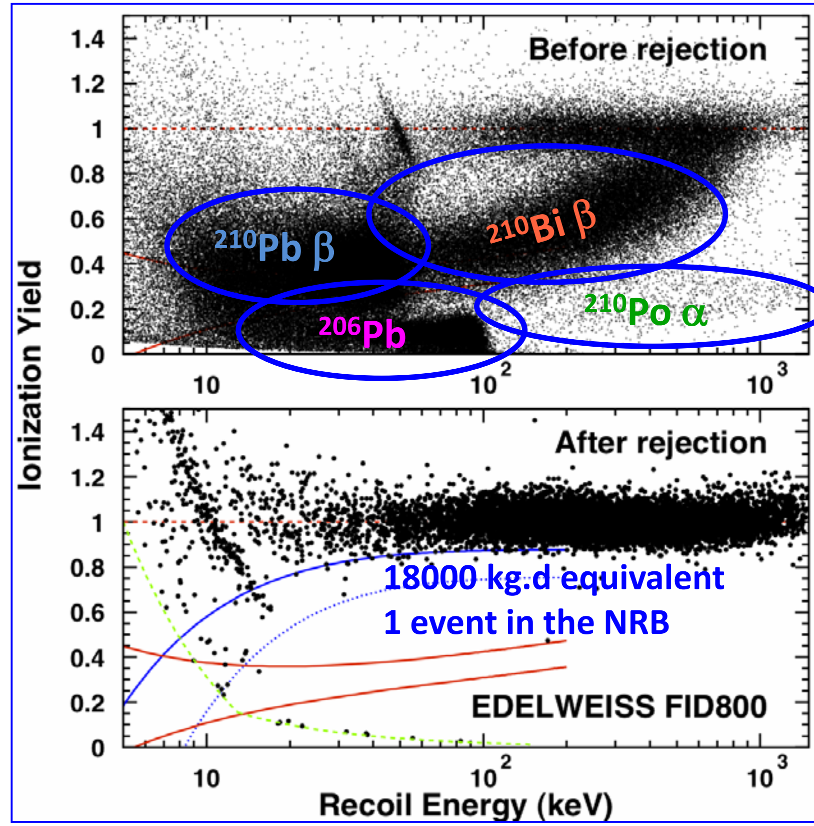
Gamma rejection



$R_{\gamma\text{-mis-FID}} < 2.5 \times 10^{-6}$ (90% C.L.)

$\rightarrow$ at least 12 x better than EDW-II

Surface-event rejection



$R_{surf\text{-FID}} < 4 \times 10^{-5}$ (90% C.L.)

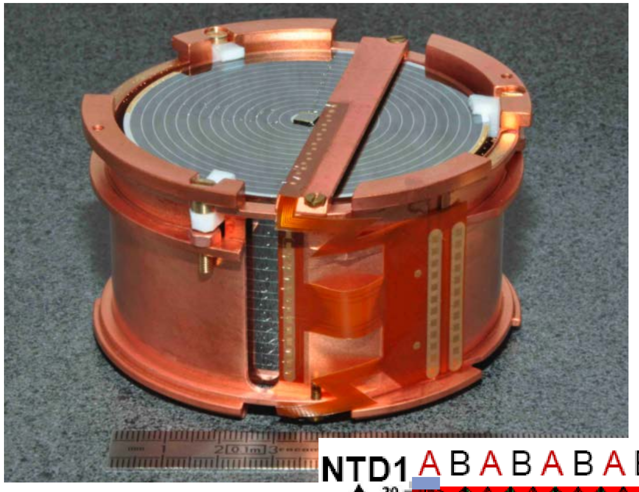
for ^{210}Pb+^{210}Bi β, ^{210}Po α and ^{206}Pb recoils

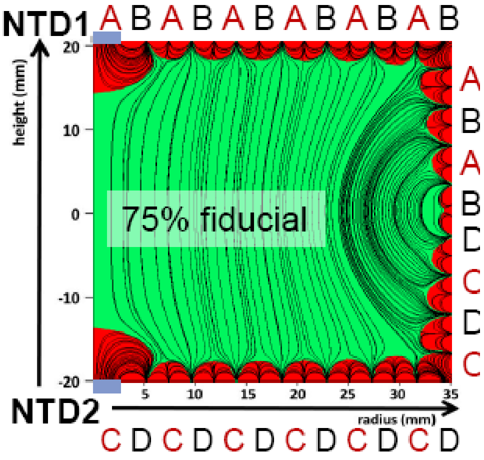
$\rightarrow$ < 1 surface event / 3400 kg.d fiducial exposure in the NRB band for a recoil energy threshold of 15 keV

Conclusions

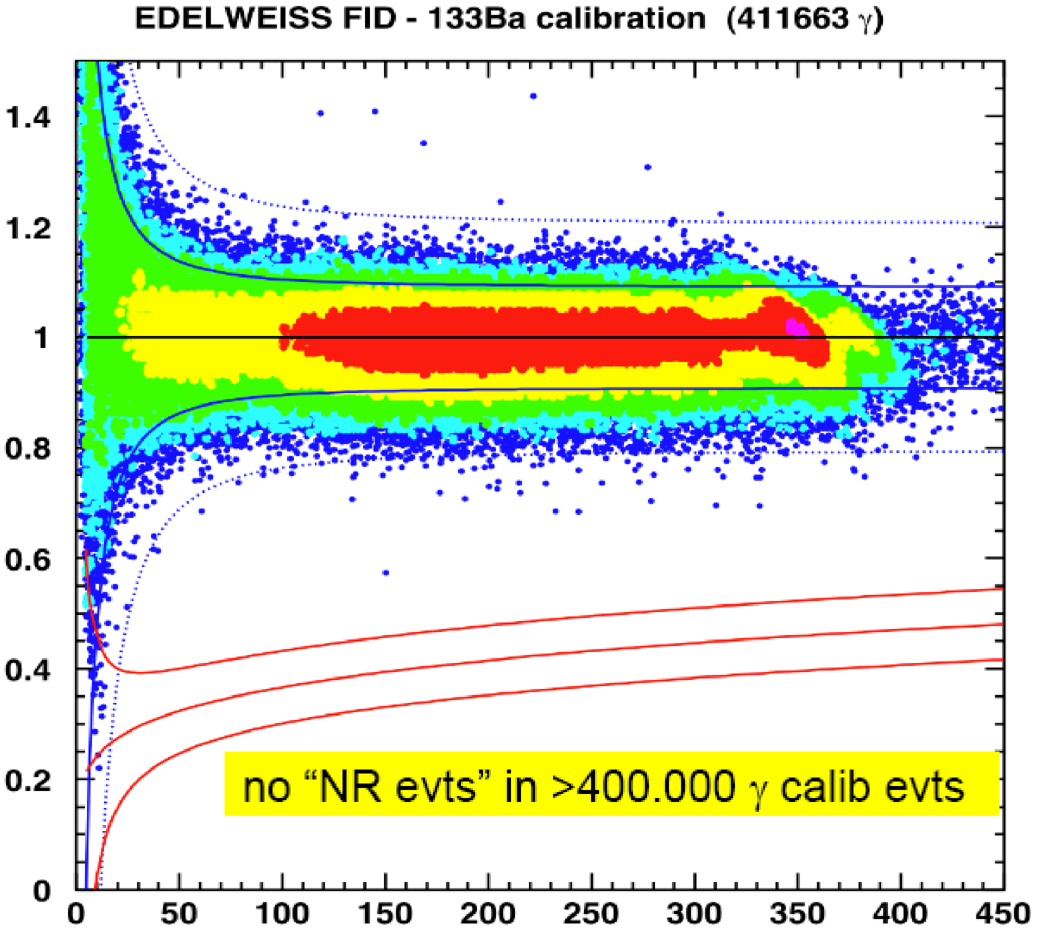
- EDELWEISS-III : large detectors with rejection
  - Excellent rejection performance, but not competitive with large Ar/Xe detectors above 6 GeV
  - Exploitation of excellent surface event rejections from FID to get best Ge ALPs limits, and enter the sub-keV range
- EDELWEISS-MELODI : develop large detector with FID design
  - Exploring non-WIMP DM with prototype: ALPs in the 0.1-1 keV range, and direct sensitivity to quenching at ~0.4 keV_{NR}
  - Building block for a much larger search experiment (DMB8, suited for future SNOLAB program) addressing specifically the region where the DM signal needs to be spectrally resolved from a solar ^{8}B neutrino signal
- Prospects in the sub-GeV-WIMP range: beyond EDELWEISS-LT
  - **Going beyond original [PRD] goal: 100 eV → 18 eV (wrt ~500 eV edw3)**
  - **Best surface limit for WIMPs above 0.6 GeV/c^2**
  - **Resolutions achieved on 32g detectors + expertise acquired in HV runs open the way for the 0.1-1 GeV range**

FID800 detectors





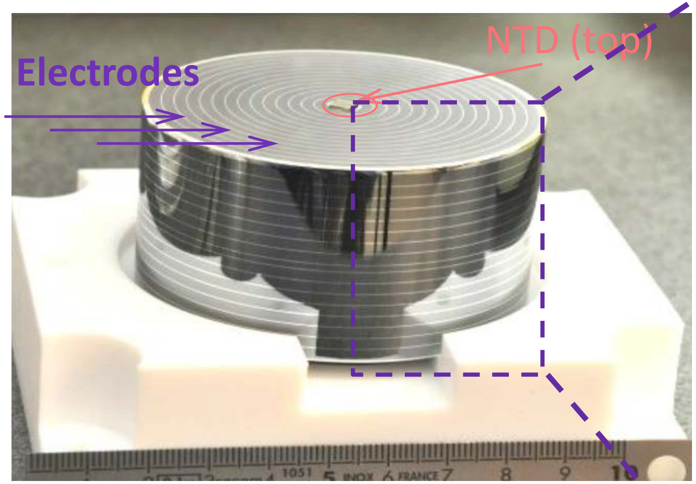
- FID800: 800-850 g / detector
- Two NTD termistors
- All surfaces have special electrodes scheme, fiducial volume ~ 75%

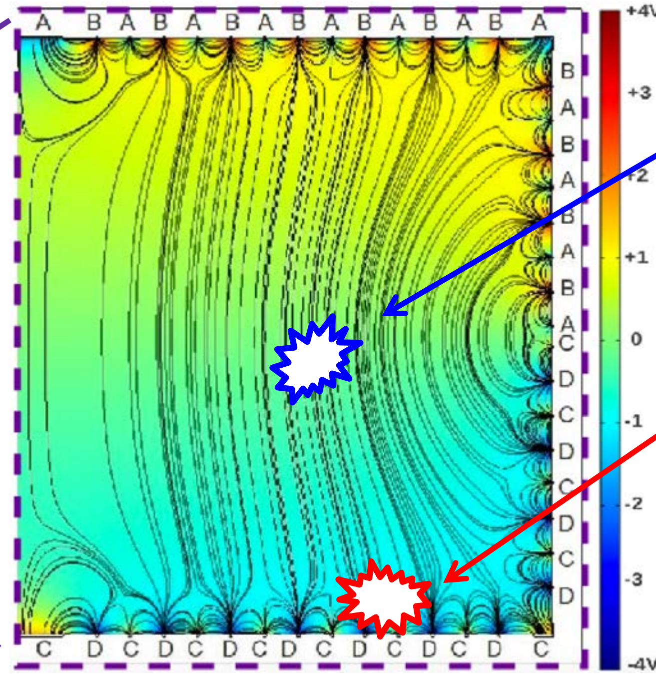


No events in the WIMP search region, less events in the intermediate region

EDELWEISS-III: FID Ge-bolometers

Full InterDigitized (FID) detectors: 820-890 g, h = 40 mm, ∅ = 70 mm





Fiducial events: collected by fiducial electrodes (B & D).

Surface events: collected by one veto electrode (A or C) and its neighbour fiducial one (B or D).

Simultaneous measurement of heat and ionization signals

- Heat @18 mK: measurement of phonon thermalization by 2 Ge/NTD (Neutron transmutation doped) thermal sensors (top and bottom) – $\Delta T = 0.1\ \mu K/keV$
- Ionization @few V/cm: charges collected by Al concentric electrodes (width = 150 μm, gap = 2 mm) ; XeF_2 surface treatment to ensure low leakage current (<1 fA) between adjacent electrodes ; 2 fiducial electrodes B/D ($V_B = +4$ V, $V_D = -4$ V) and 2 veto electrodes A/C ($V_A = -1.5$ V, $V_C = +1.5$ V)

+ Neganov-Luke effect: proportional to the number of charges and to the bias V

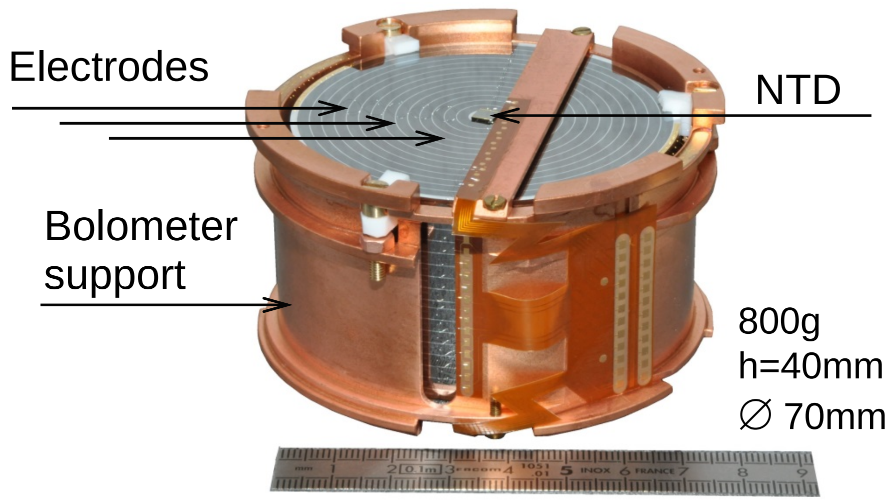
$$E_{Luke} = N_p eV = Q(E_r)\frac{E_r}{\epsilon_\gamma}\, eV$$

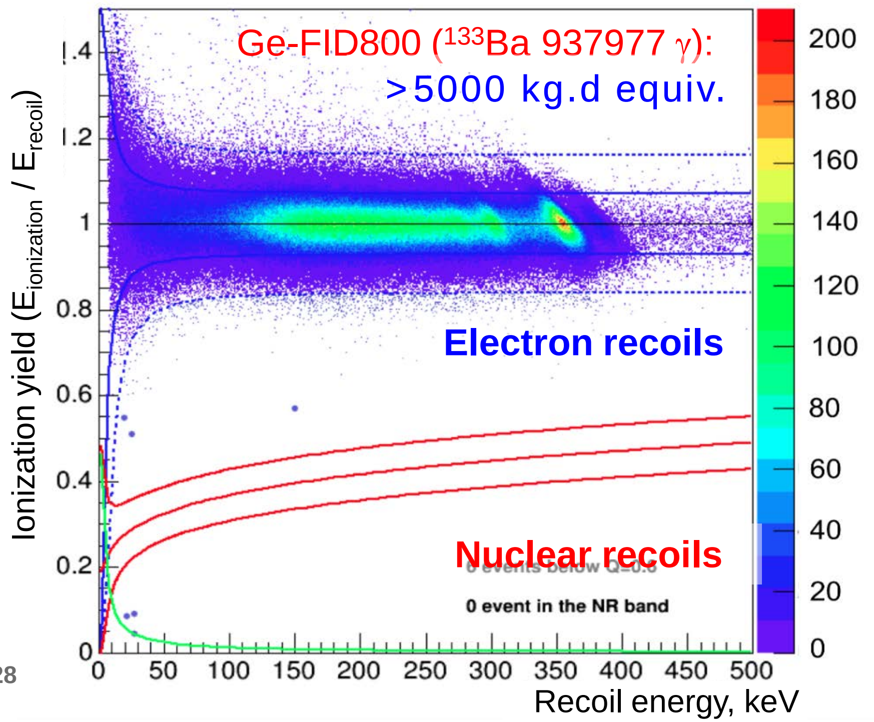
$$Q(E_r) = \frac{E_{ion}}{E_r}$$

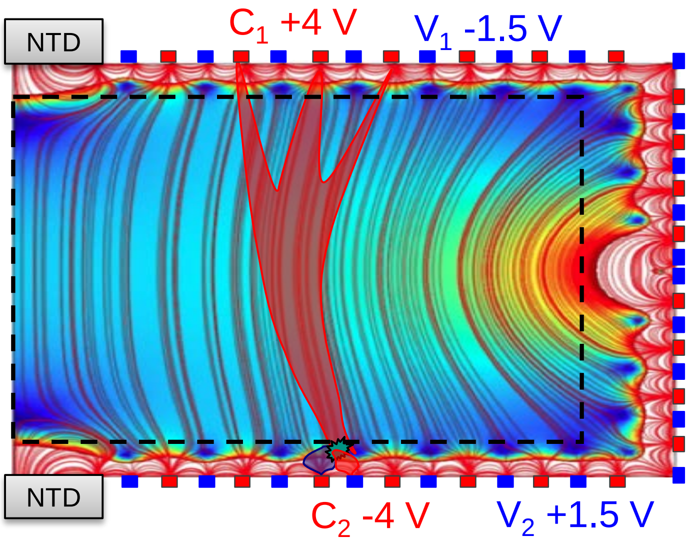
$Q(E_r)$ = ionization yield associated to recoil energy E_r normalized to 1 for electron recoils

Edelweiss-III: FID Ge-bolometers

- **Simultaneous measurement**
  - Heat @18 mK, 2 Ge/NTD thermometers
  - Ionization @ few V/cm
- **Evt by evt identification** by ratio $Q = E_{ioniz}/E_{recoil}$
  → **γ-rejection factor <2.5×10^{-6}**

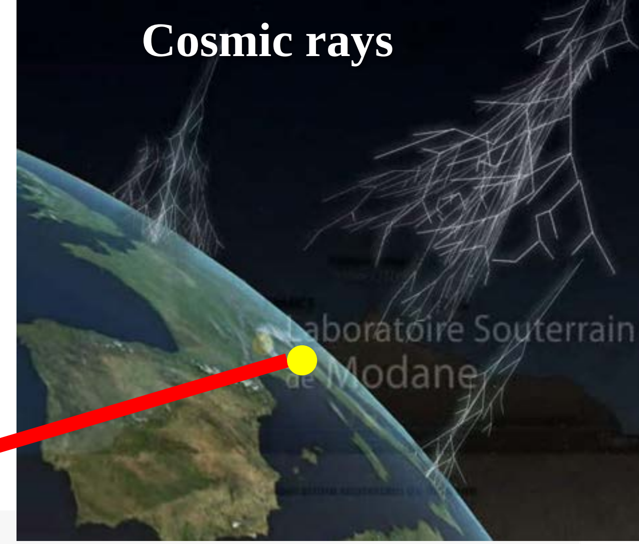




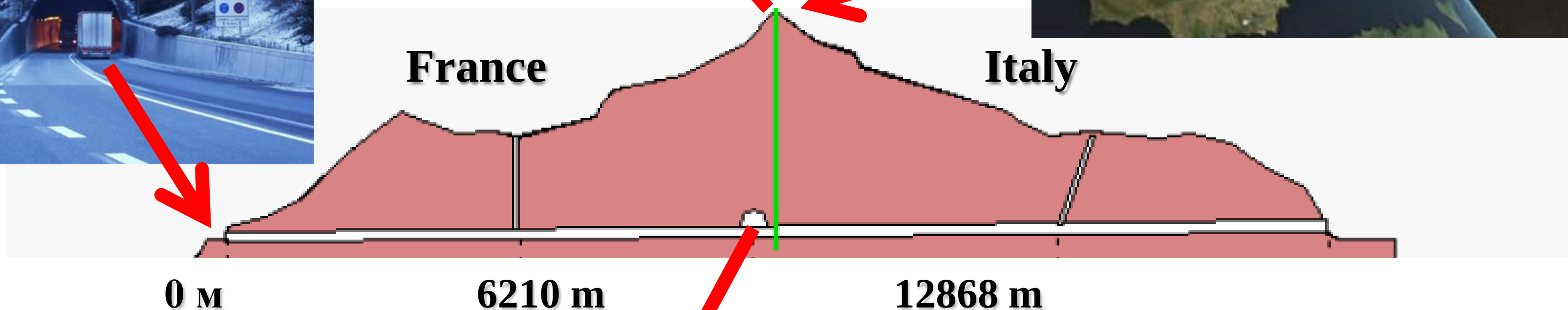


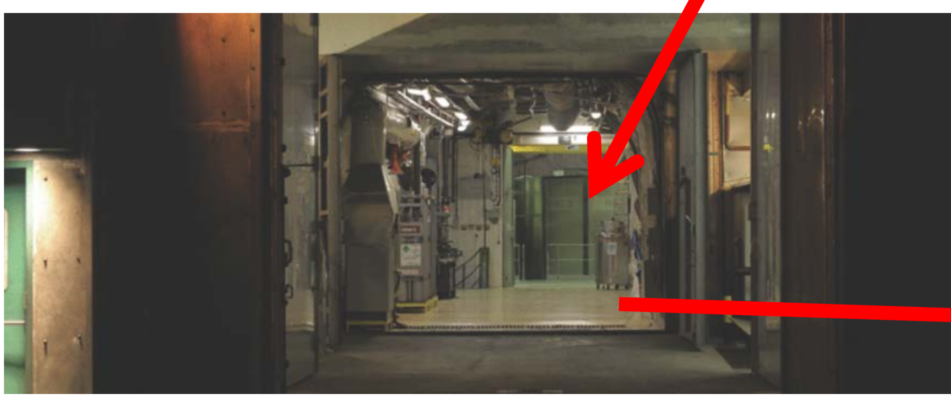
PLB 681 (2009) 305; JLTP (2014) 176:870

Modane Underground Laboratory (LSM)



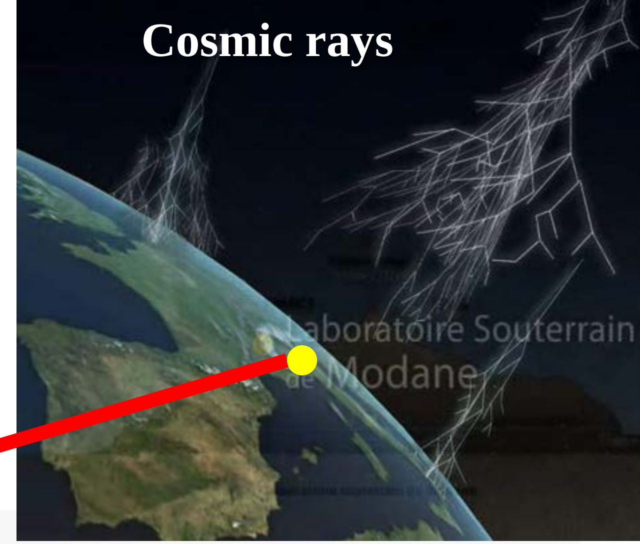
Frejus, height ~3000 m



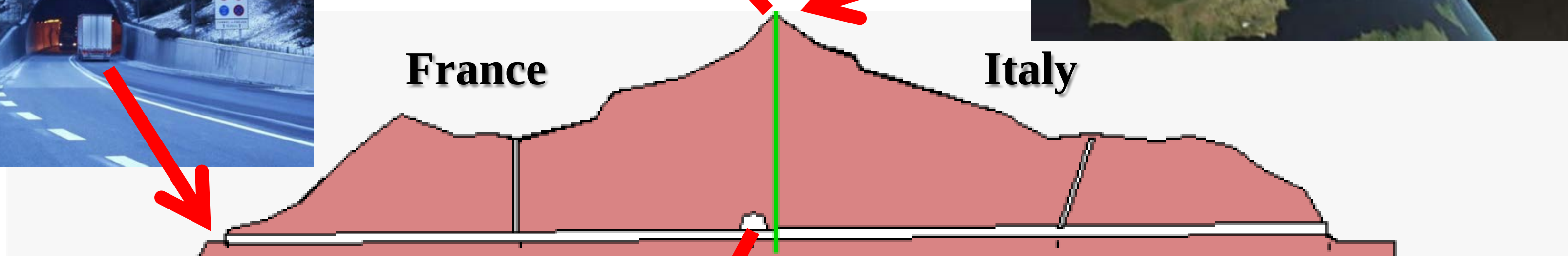


Go deep underground to search for most interesting part of the Universe

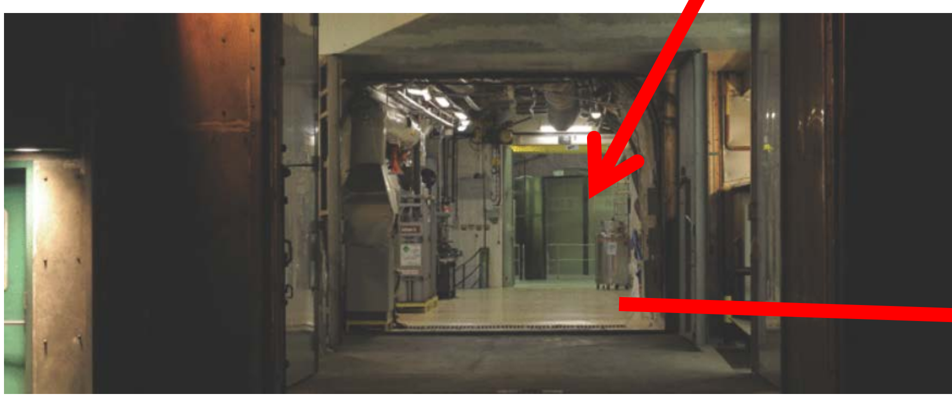
Modane Underground Laboratory (LSM)



Frejus, height ~3000 m



0 м
6210 m
12868 m

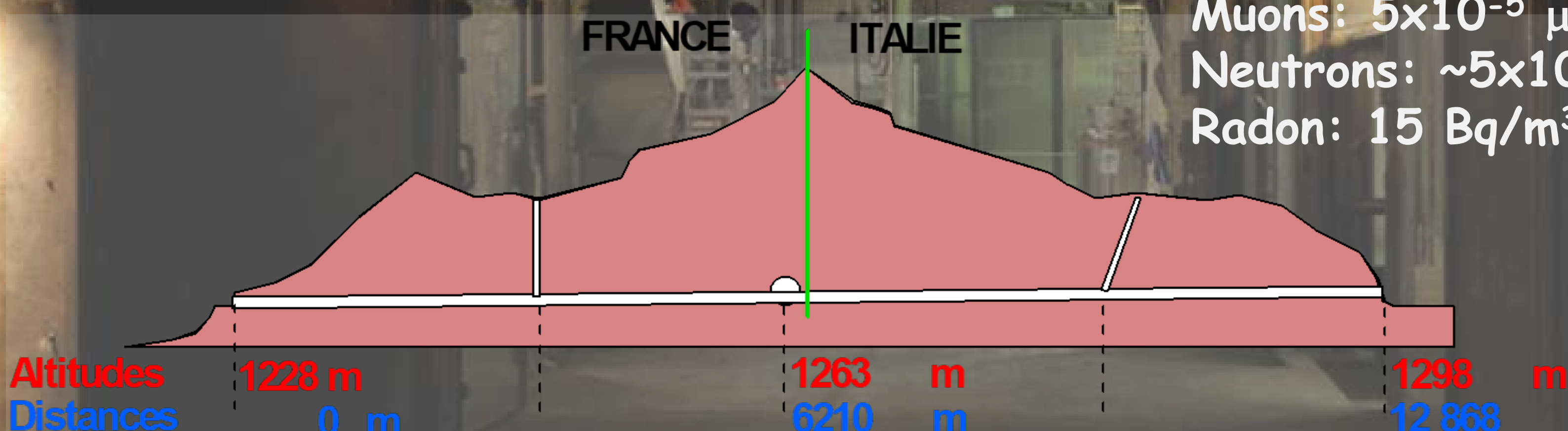


Go deep underground to search for most interesting part of the Universe

Modane Underground Laboratory (LSM)

Depth: 4800 m.w.e
Surface: 400 m^2
Volume: 3500 m^3
Access: horizontal

Muons: 5×10^{-5} $\mu.m^{-2}.s^{-1}$
Neutrons: $\sim5\times10^{-2}$ $n.m^{-2}.s$
Radon: 15 Bq/m^3



EDELWEISS-III likelihood analysis

Results from likelihood analysis

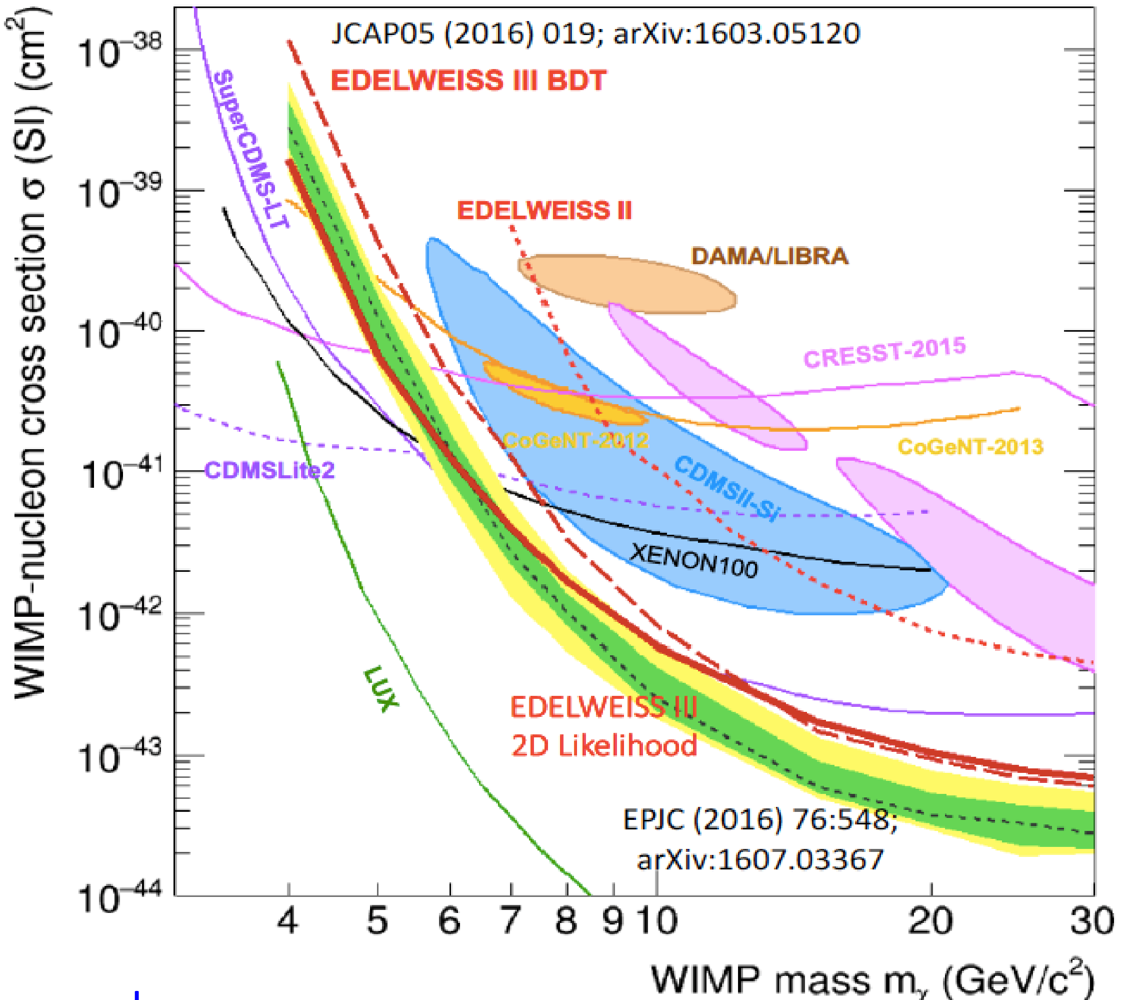
1.6×10^{-39} cm^2 at 4 GeV/c^2 to 6.9×10^{-44} cm^2 at 30 GeV/c^2

Improvement by x20 to x150 between 7 and 10 GeV wrt EDW-II results due to higher signal efficiency and background subtraction

Improvement from **BDT to likelihood**:

1.1×10^{-38} cm^2 $\rightarrow$ 1.6×10^{-39} cm^2 at 4 GeV/c^2

3.34×10^{-42} cm^2 $\rightarrow$ 1.66×10^{-42} cm^2 at 8 GeV/c^2



Limitation due to heat-only event background:

identification and rejection using the σ_{ion} = 230 eV$_{ee}$

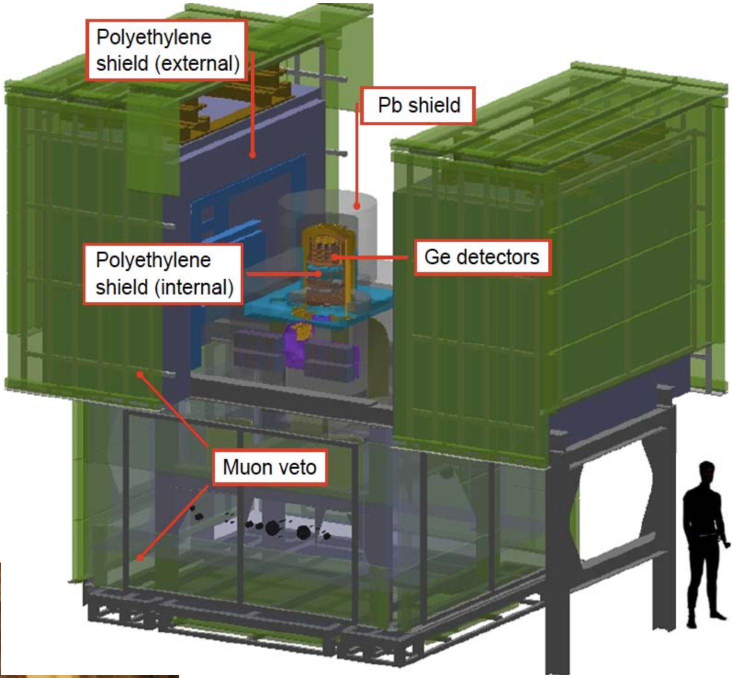
- need to improve ionization resolution for rejection
- need to improve heat resolution to lower thresholds

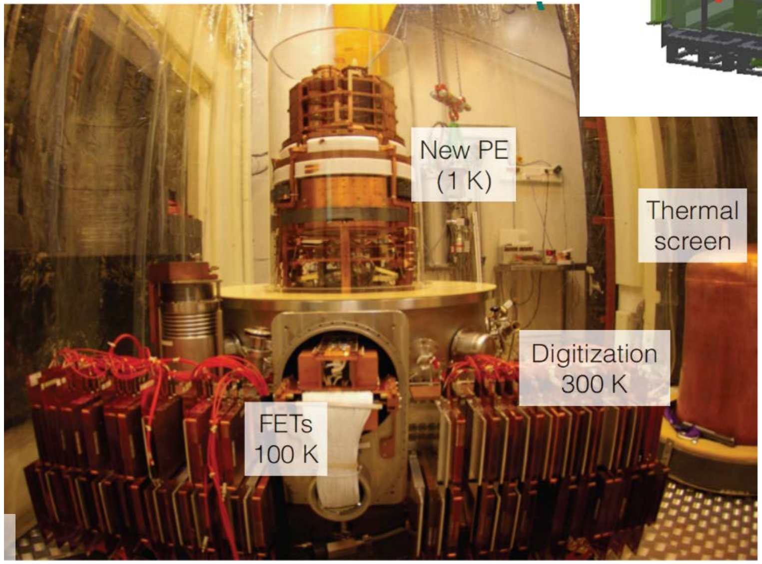
EDELWEISS Setup

- Clean room + deradonized air

  Rn monitoring down to few mBq/m^3
- 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]

90%CL limit on WIMP signals

- Find maximal WIMP rate compatible with total number of counts observed in the pre-defined windows