# EDELWEISS

## *Report on EDELWEISS-III*

*WIMP masses 4-20 GeV/$c^2$*

## *Perspectives of the low-mass program*

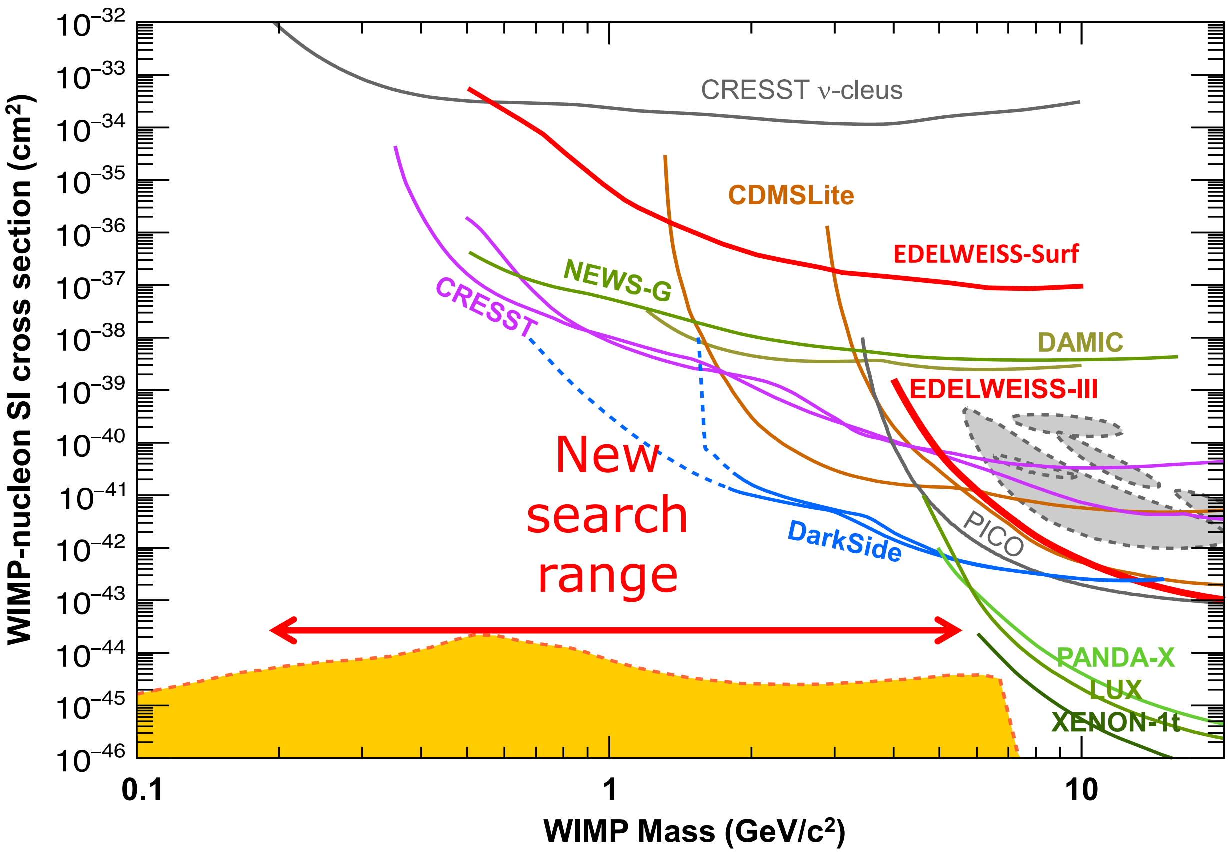
*WIMP masses 0.5-5 GeV/$c^2$ and below*

Jules Gascon
(IPNLyon, Université Lyon 1 + CNRS/IN2P3)

# ~GeV range new hunting ground for WIMPs

- Absence of minimal SUSY signals at LHC
- No signals in 10 GeV/c² – 10 TeV/c² range (LUX, PandaX, XENON)
- Searches extended to generic DM particle interacting with nuclei

*Spin-independent Dark matter interaction with nuclei*



# *Future projects for SubGeV range*

- Cryogenic experiments: SuperCDMS (SNOLAB), CRESST (LNGS)
- Others (limited to ~1 GeV/c²): DarkSide, DAMIC-M

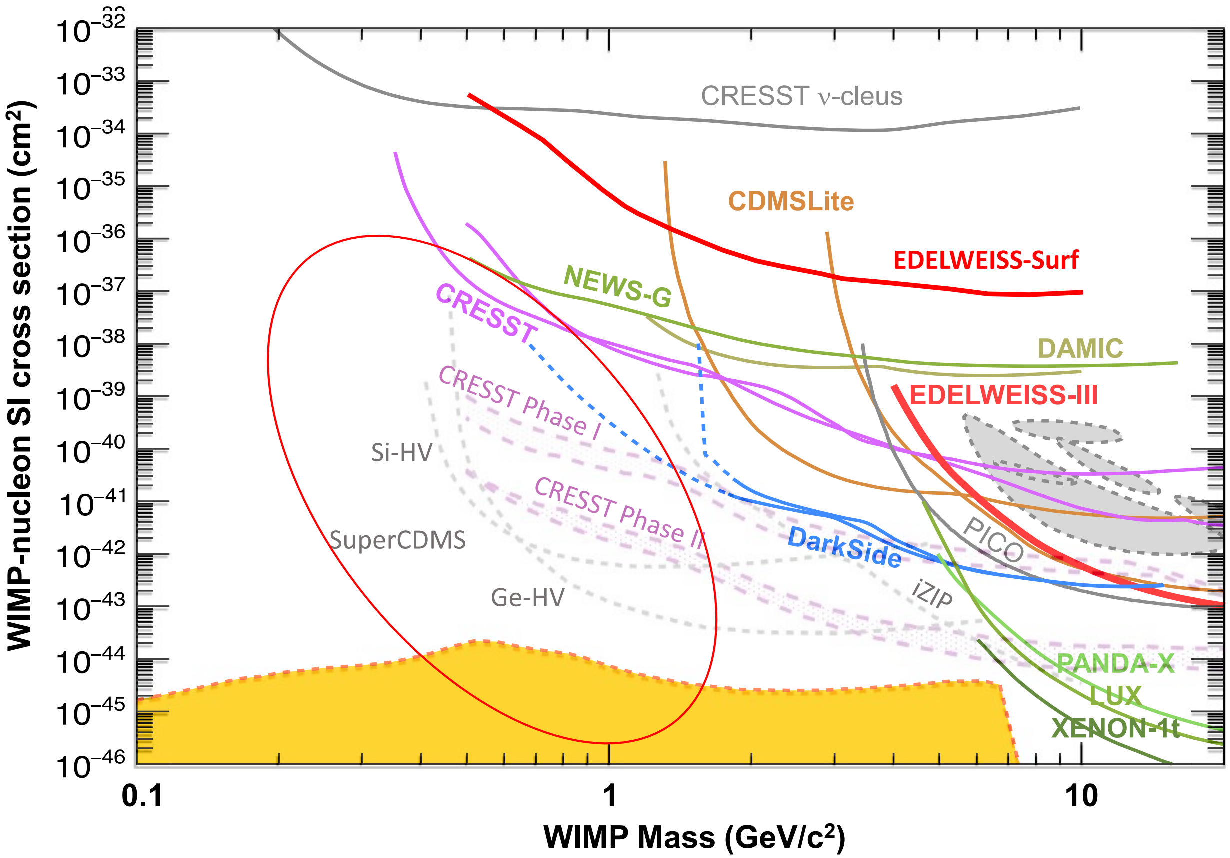
Limitations:

- *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)**

- Original ANR (2010) objective: WIMPs > 10 GeV/$c^2$
- 2012 updated objective (Oct. CSin2p3): 5-20 GeV/$c^2$
- *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

CSNSM CNRS/IN2P3

IPNL CNRS/IN2P3

NÉEL institut CNRS/INP

Laboratoire de Photonique et de Nanostructures CNRS

Irfu CEA/IRFU

IRAMIS CEA/IRAMIS

KIT Karlsruher Institut für Technologie IKP EKP IPE

JINR JINR DUBNA

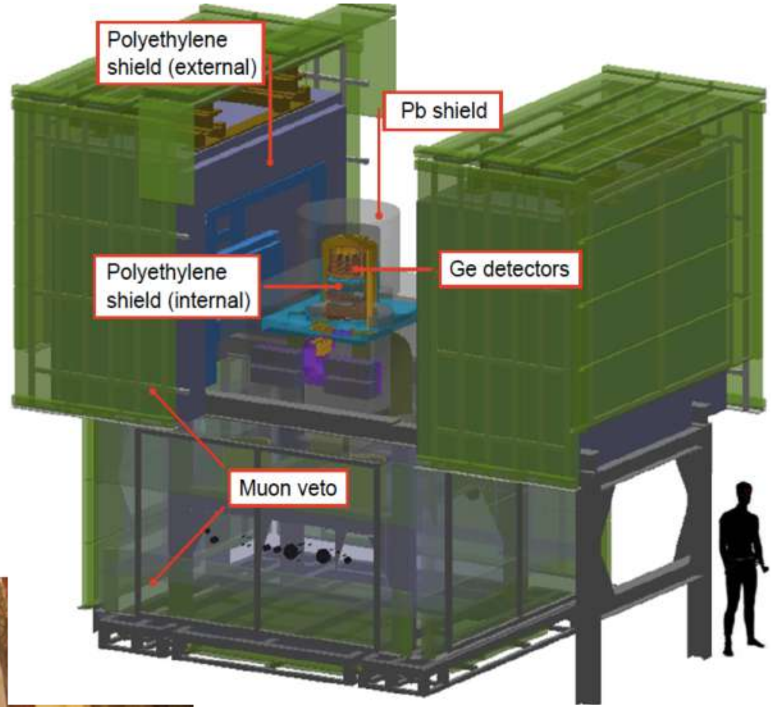
University of Oxford Univ. OXFORD

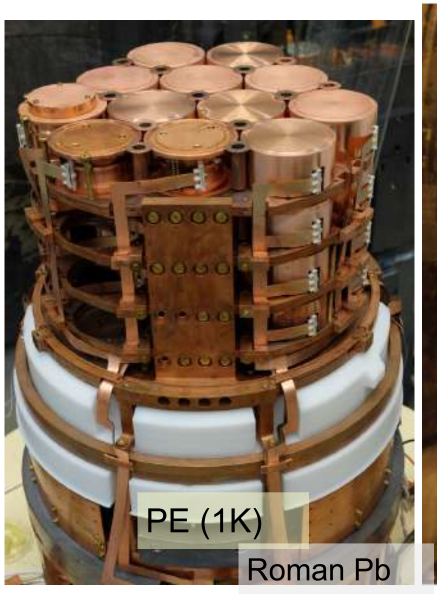
The University Of Sheffield. Univ. SHEFFIELD

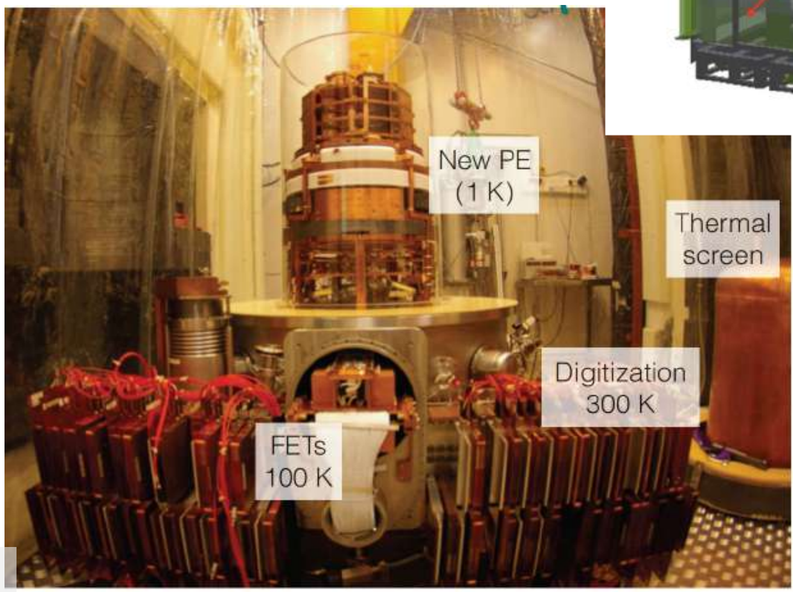
48 people, 46% in2p3

# EDELWEISS Setup

- ***LSM: Deepest site in Europe***
  ***4800 m.w.e., 5 $\mu$/m$^2$/day***
- Clean room + deradonized air
  *Radon 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



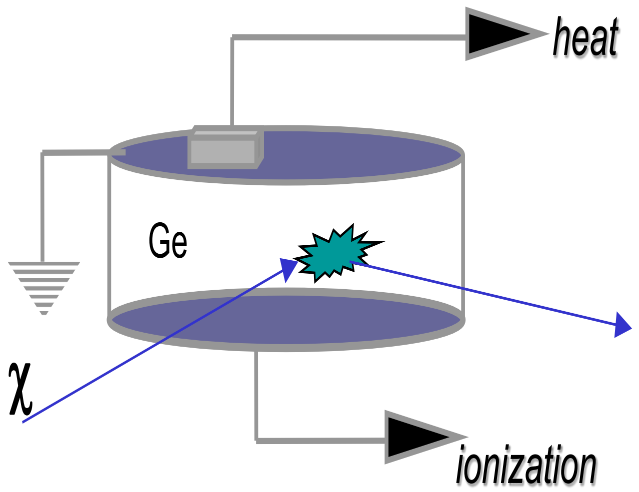

Cryostat can host up to 40 kg detector at 18 mK

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

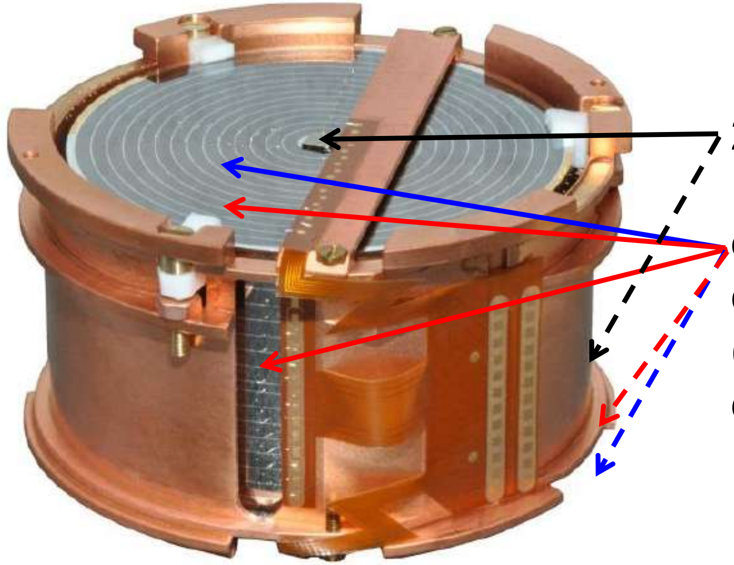
***[JINST 12 (2017) P08010]***

# EDELWEISS-III detectors (CSNSM design)

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




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



**Ø = 70 mm**
**h = 40 mm**

**870 g Ge**

2 GeNTD heat sensors

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

**Operated at**
**T = 18 mK**

J Low Temp Phys (2014)**176**:182
Phys.Lett.B **681** (2009) 305

- Ionization:

  $\varepsilon_\gamma$ = 3 eV/(e-hole pair) for electron recoils ($\gamma,\beta$)

  $\varepsilon_n$ ~ 12 eV /(e-hole pair) for nuclear recoils (neutrons, WIMPs)

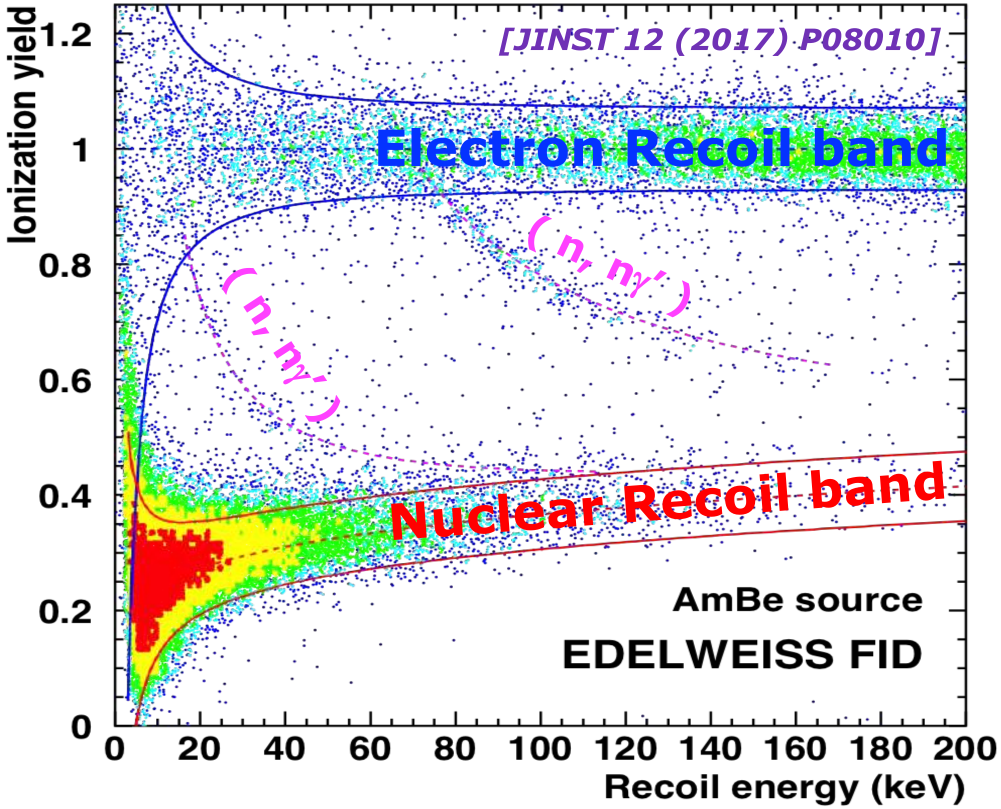
  $\varepsilon_\gamma/\varepsilon_n$ = ionization quenching Q → $E_{ion} = Q\, E_{recoil}$ in $keV_{ee}$

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

# 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:



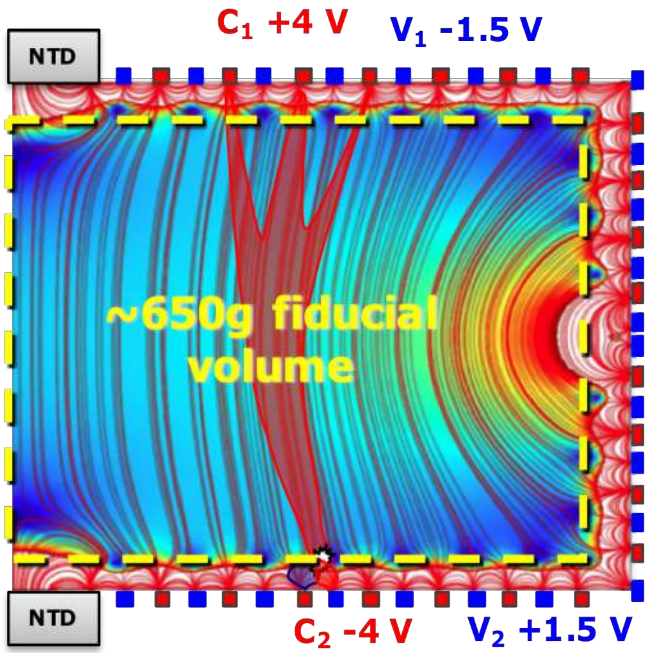

$$E_{phonon} = E_{recoil} + \text{heating due to charge drift in } \vec{E}_{field} \text{ (Luke-Neganov effect)}$$

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

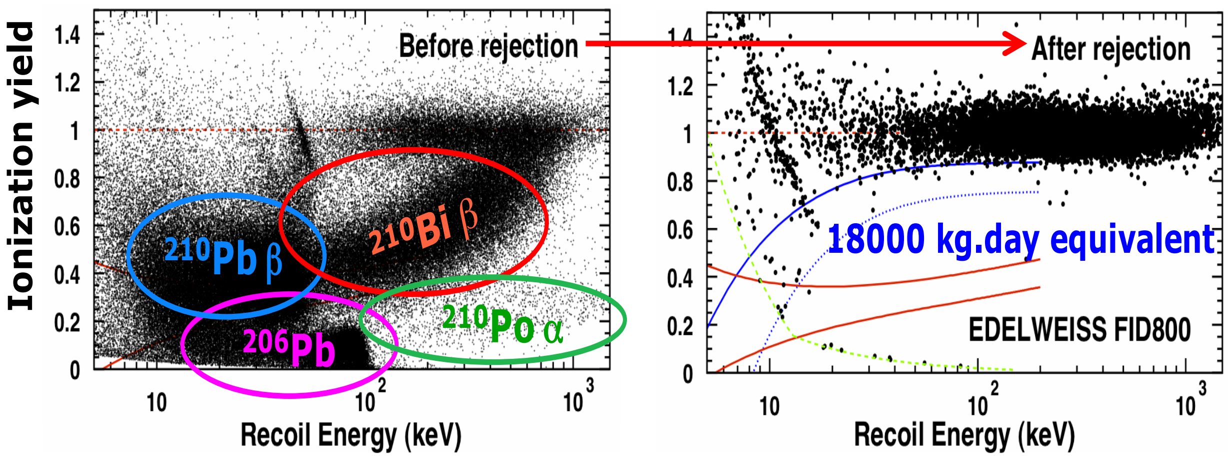
$$E_{recoil} = E_{phonon} - \text{Voltage} * (E_{ion}/\varepsilon_\gamma) \text{ for all types of recoils}$$

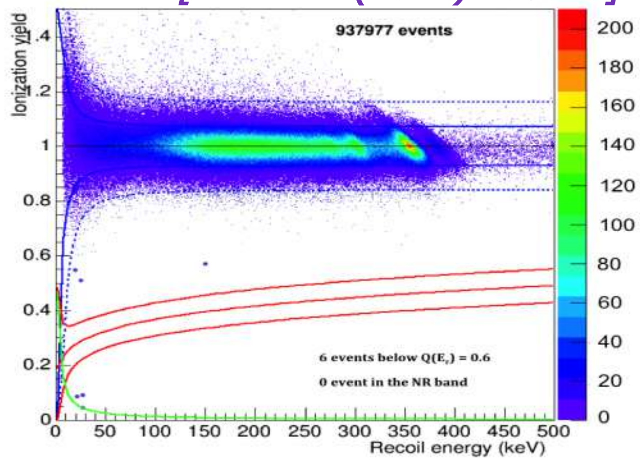
# Surface event discrimination

- 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 $C_2+V_2$
- **$<4\text{x}10^{-5}$ rejection of surface events**
- **$<2.5\text{x}10^{-6}$ rejection of ER in fiducial volume**




*[JINST 12 (2017) P08010]*



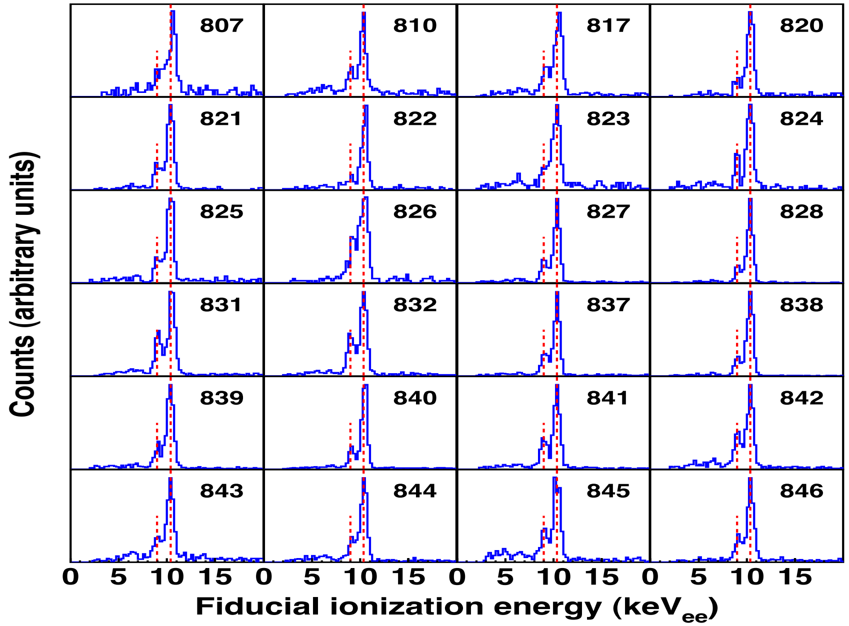
# EDELWEISS-III calendar

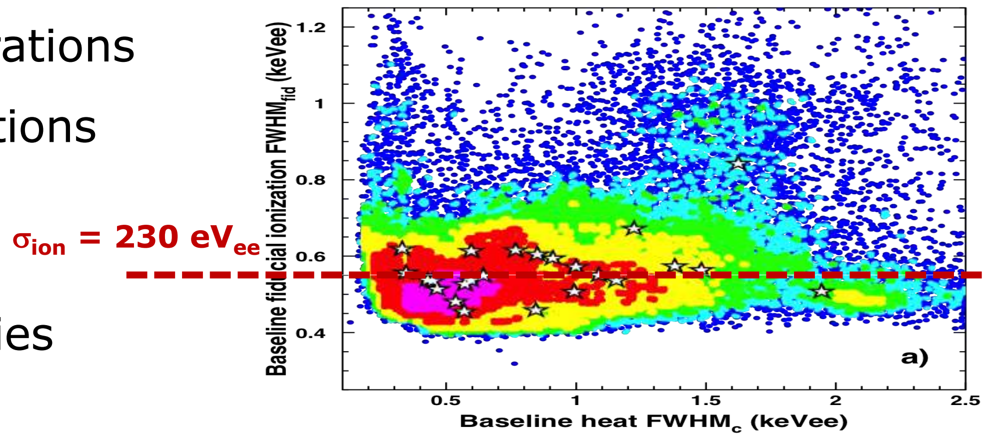
- 2009-2010: prototype tests
- 2011-2013: detector production
  - One year delay to find new technique to solve problem of unexpected leakage currents between electrodes (now: <0.1 fA)
  - Also: electronic + cryogenic upgrades
- 2013-2014: commissioning
  - Problem with Kapton cables between 10 mK and 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: $\sigma_{ion}$ =230 $eV_{ee}$, uniform performance
- 8 detectors with best $\sigma_{phonon}$ used for WIMP search (5-20 GeV/$c^2$)
- Main limitation to $\sigma_{phonon}$: vibrations
- 19 detectors with best resolutions selected for searches of Axion-Like Particle searches & cosmogenic activation studies

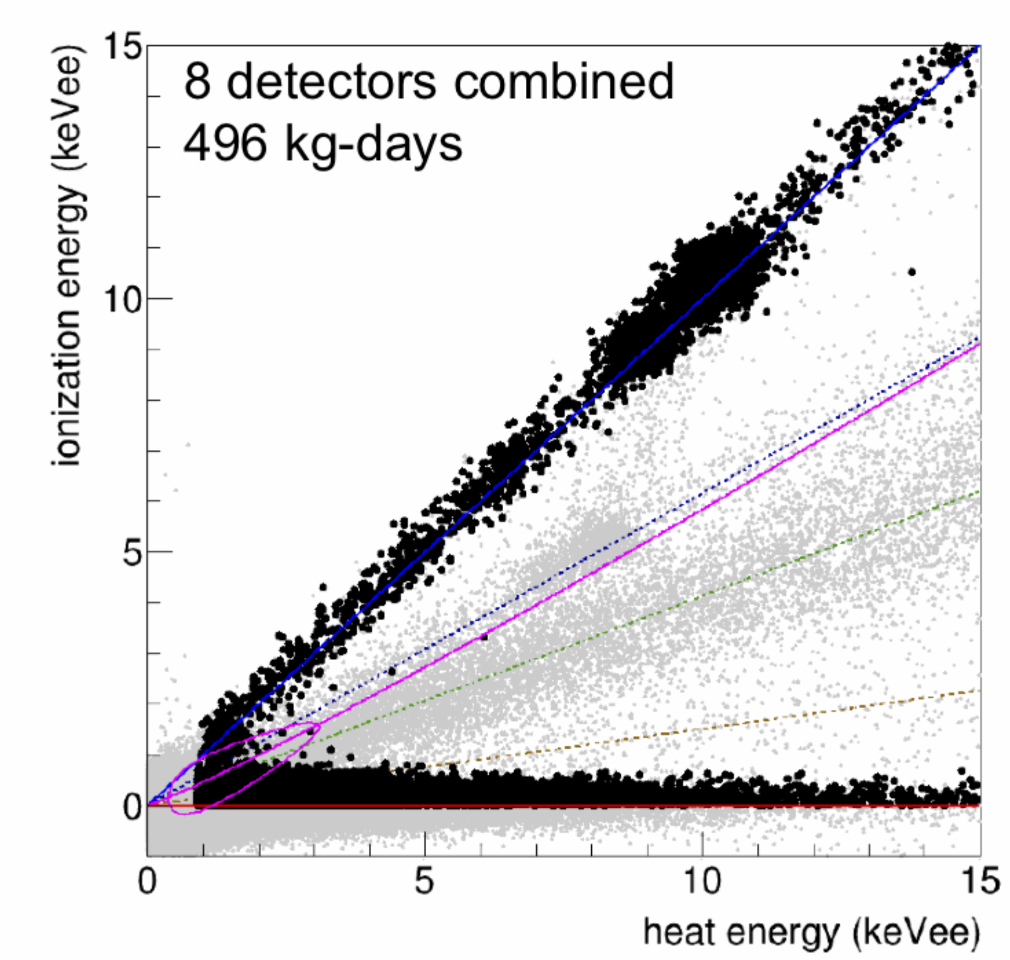
8.98 + 10.37 keV cosmic activation doublet



# WIMP search: identification of backgrounds

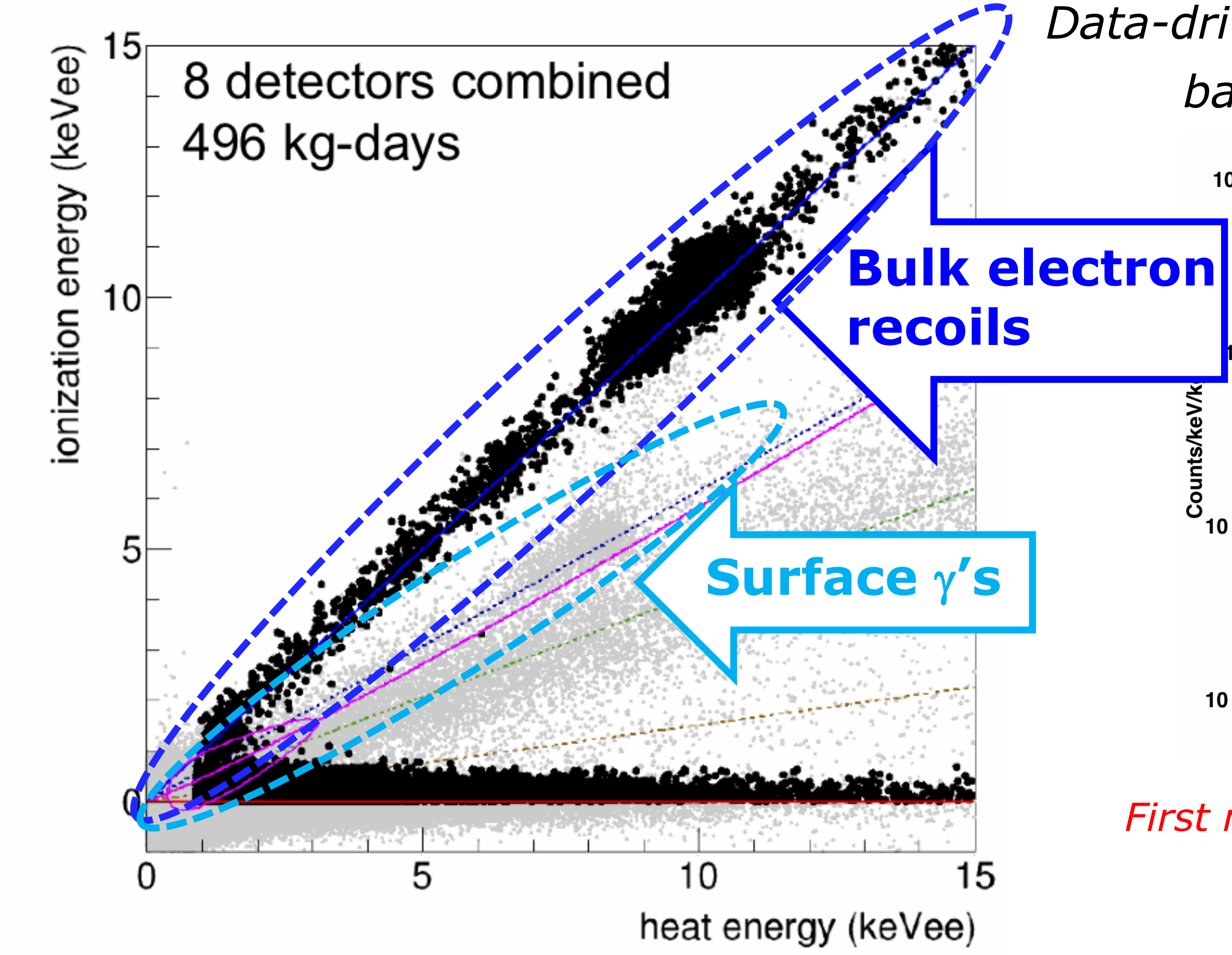
- Analysis with Boosted Decision Tree [JCAP05 (2016) 019]
- Analysis with Profile Likelihood [EPJC 76 (2016) 548]



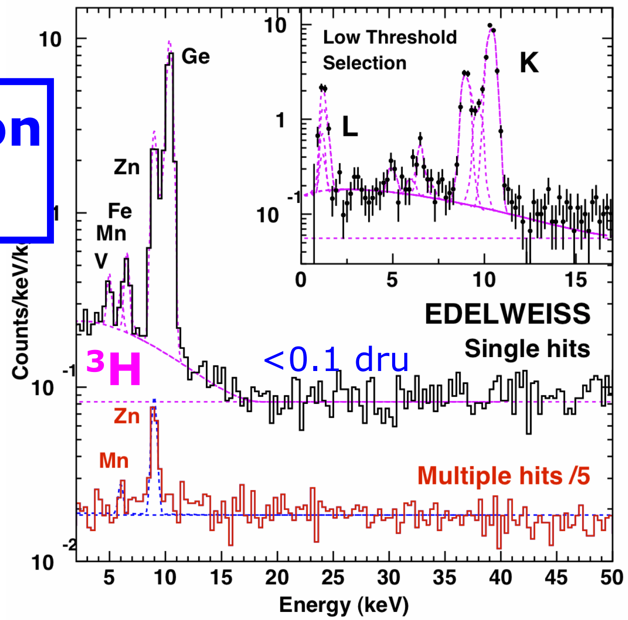

*Data-driven background models based on sidebands*

# Low-Mass analysis & background model

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




*Data-driven background models based on sidebands*




*First measurement of cosmogenic production of $^{3}H$ in Ge [AstroPart. 91 (2017) 51]*

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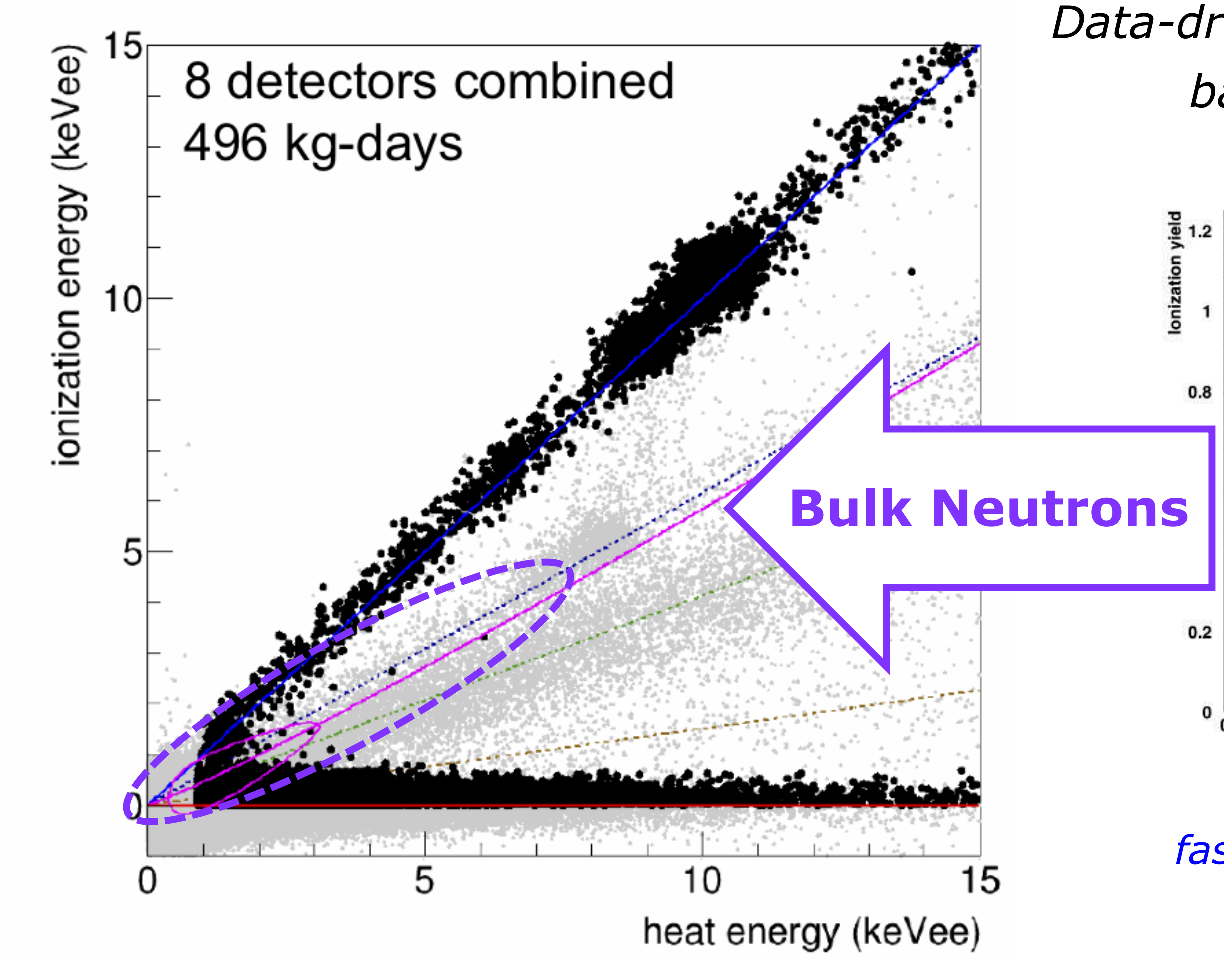
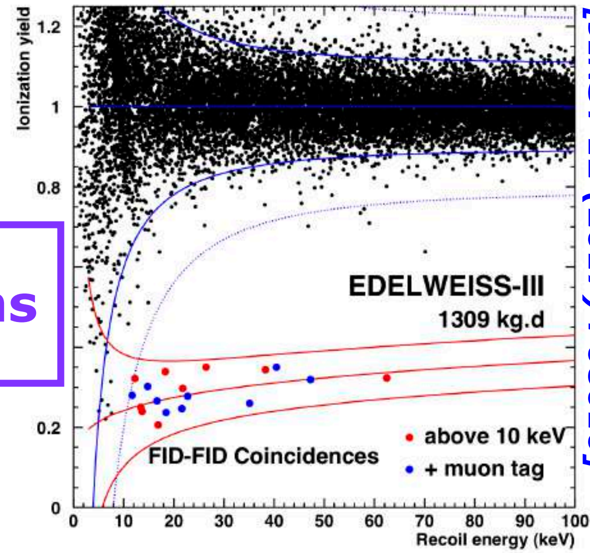



*Data-driven background models based on sidebands*




*[JINST 12 (2017) P08010]*

*Multiple-detector events*
*fast neutron flux measurement*

# Low-Mass analysis & background model

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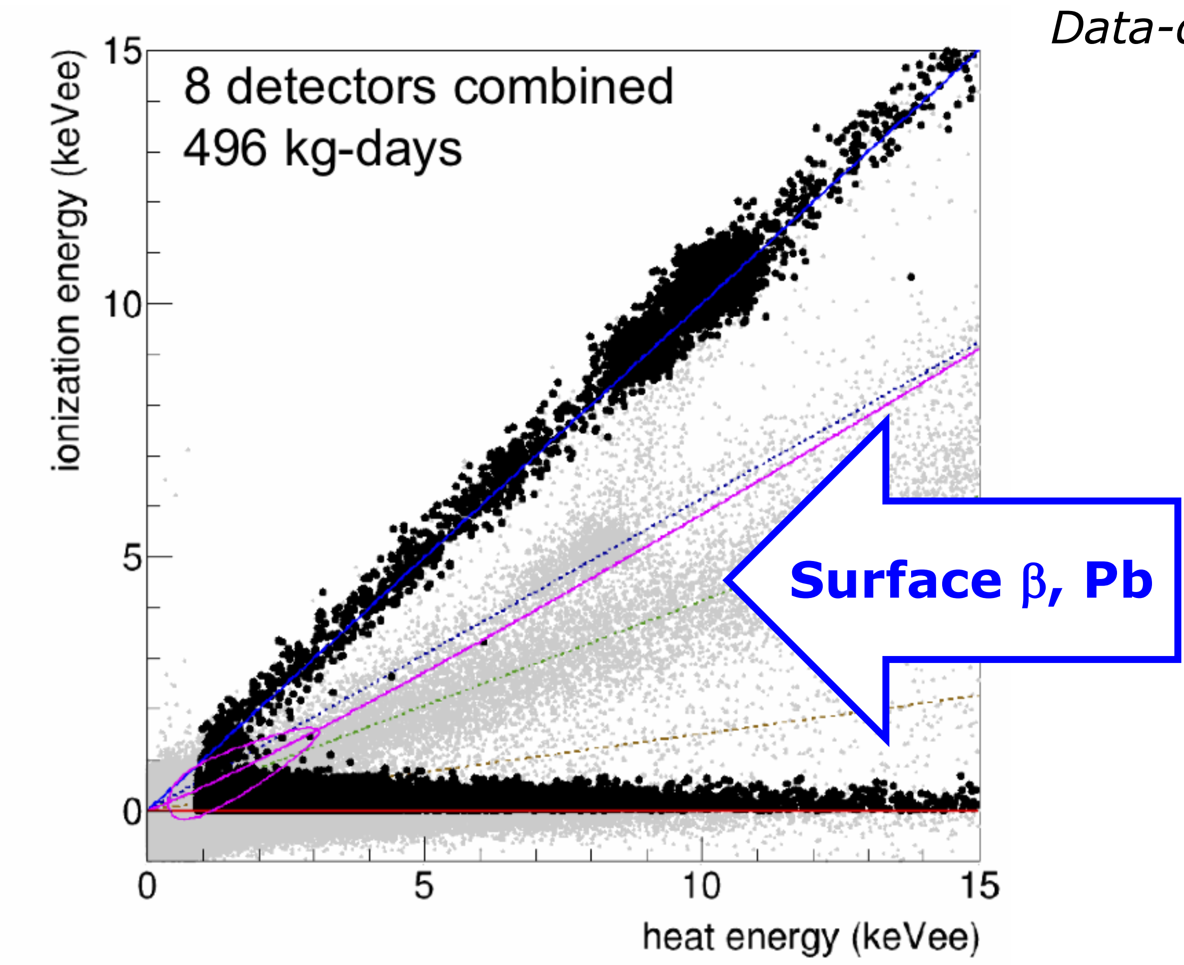


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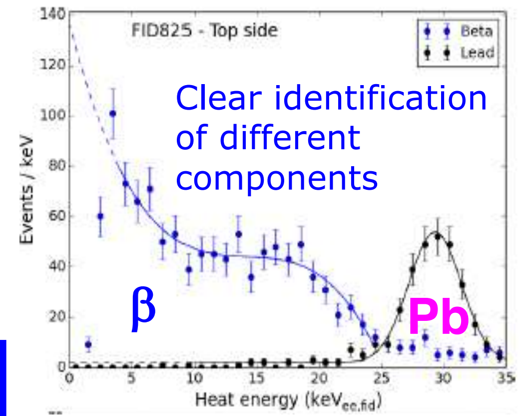


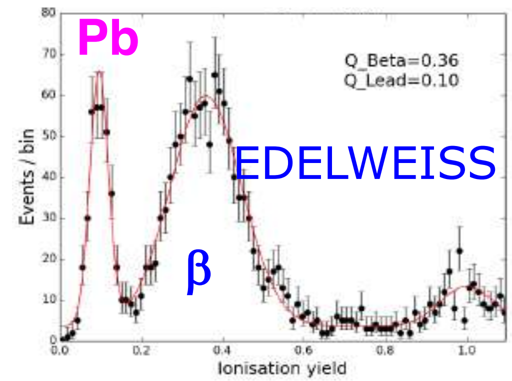

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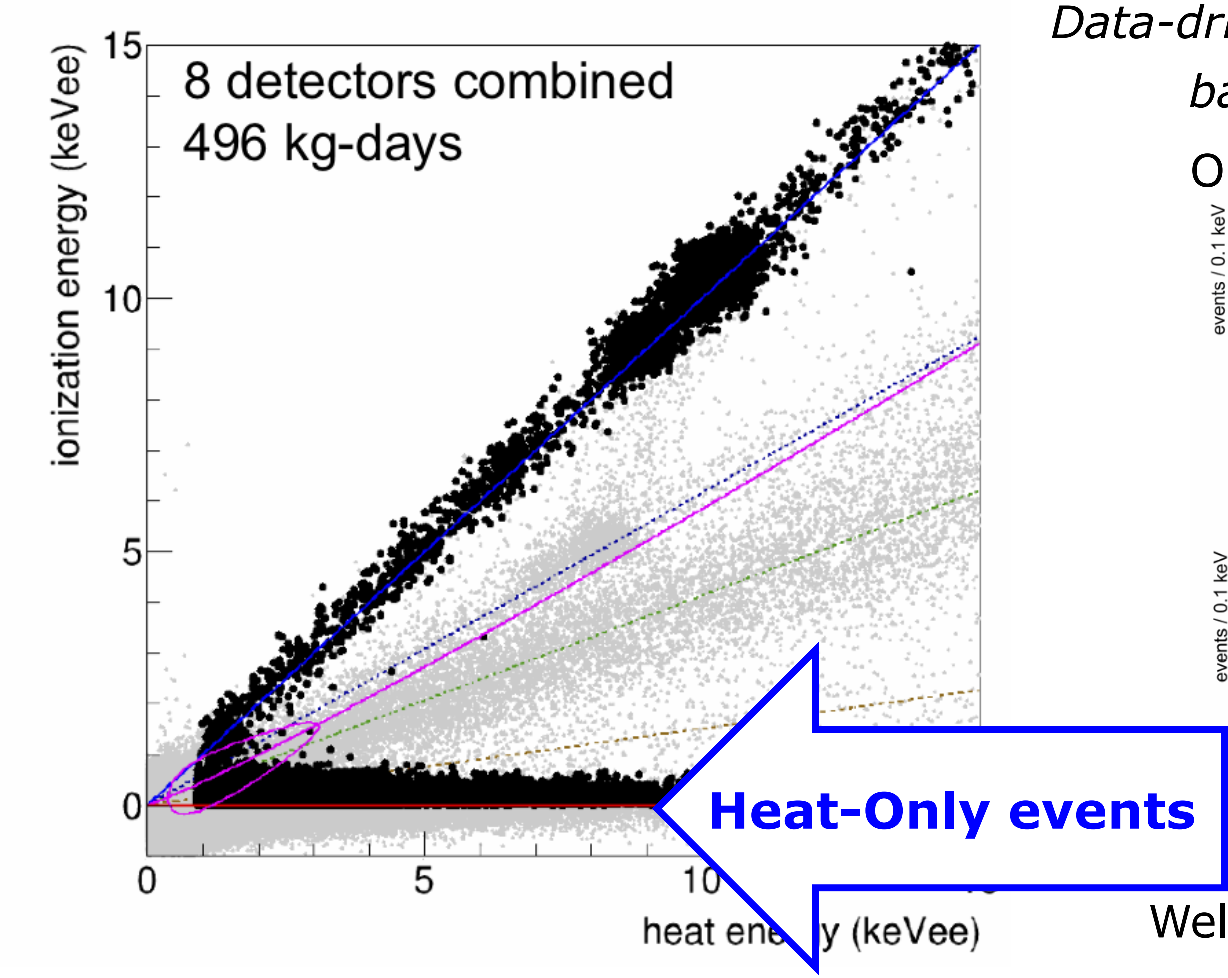
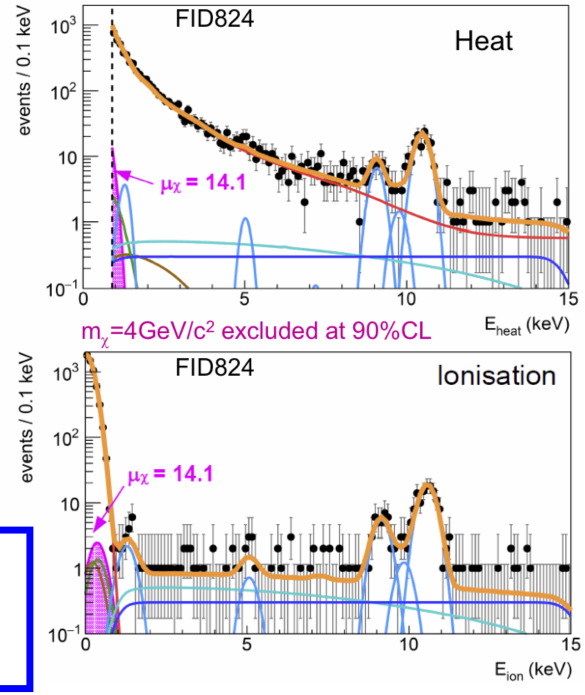



*Data-driven background models based on sidebands*

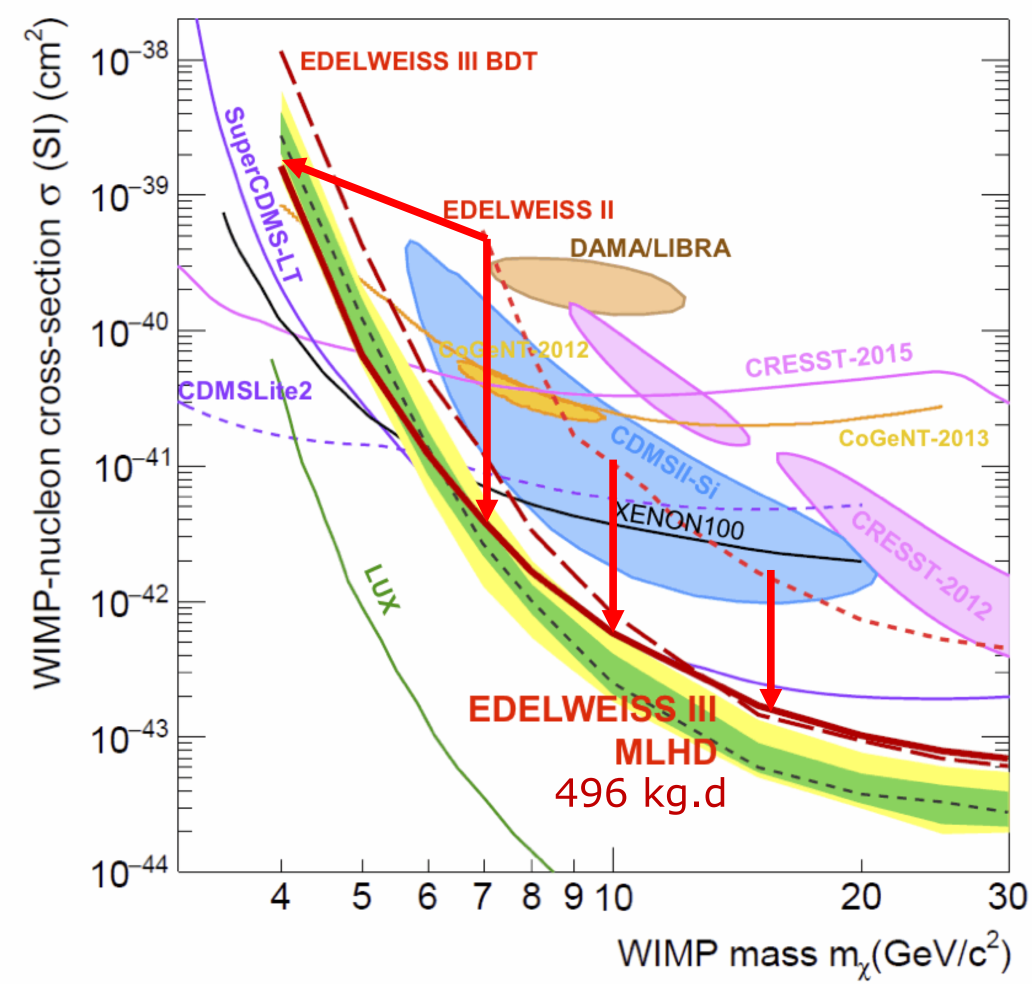
Origin under investigation




Well reproducible over >years

# Low-Mass analysis

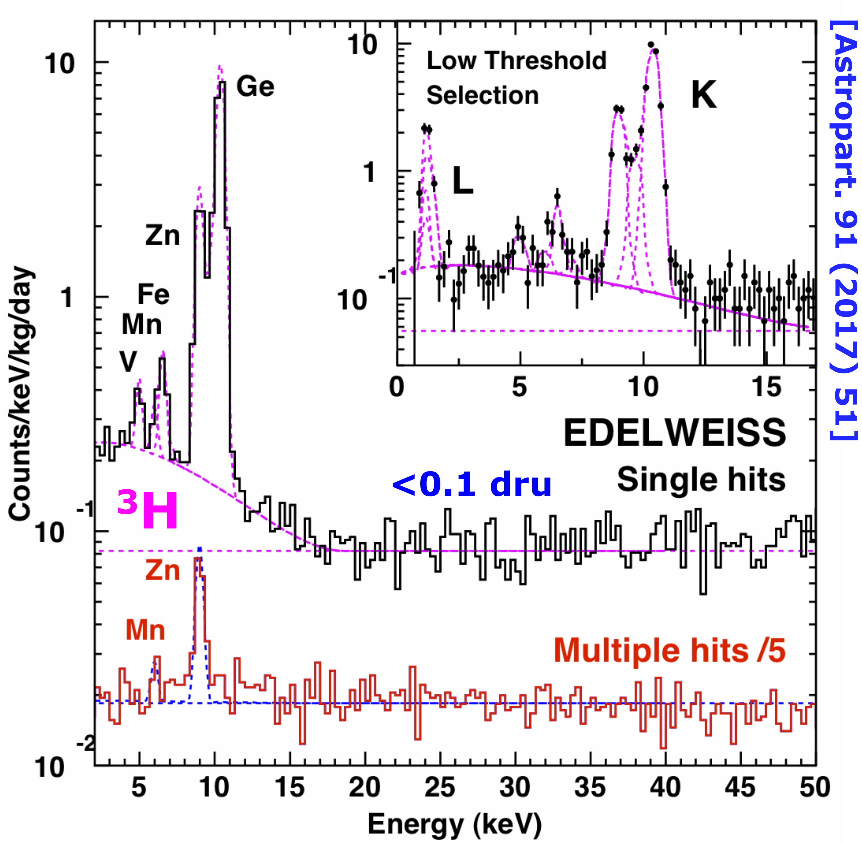
- Analysis with Boosted Decision Tree *[JCAP05 (2016) 019]*
- Analysis with Profile Likelihood *[EPJC 76 (2016) 548]*




- **Improvement by x20 to x150 between 7 and 10 GeV wrt EDW-II**
- Limited by heat-only background: *identification and rejection using the $\sigma_{ion}$ =230 $eV_{ee}$ resolution on ionization*
- Ionization resolution is key for rejection
- Heat resolution is key for low thresholds

# Electron recoil analysis: cosmic activation

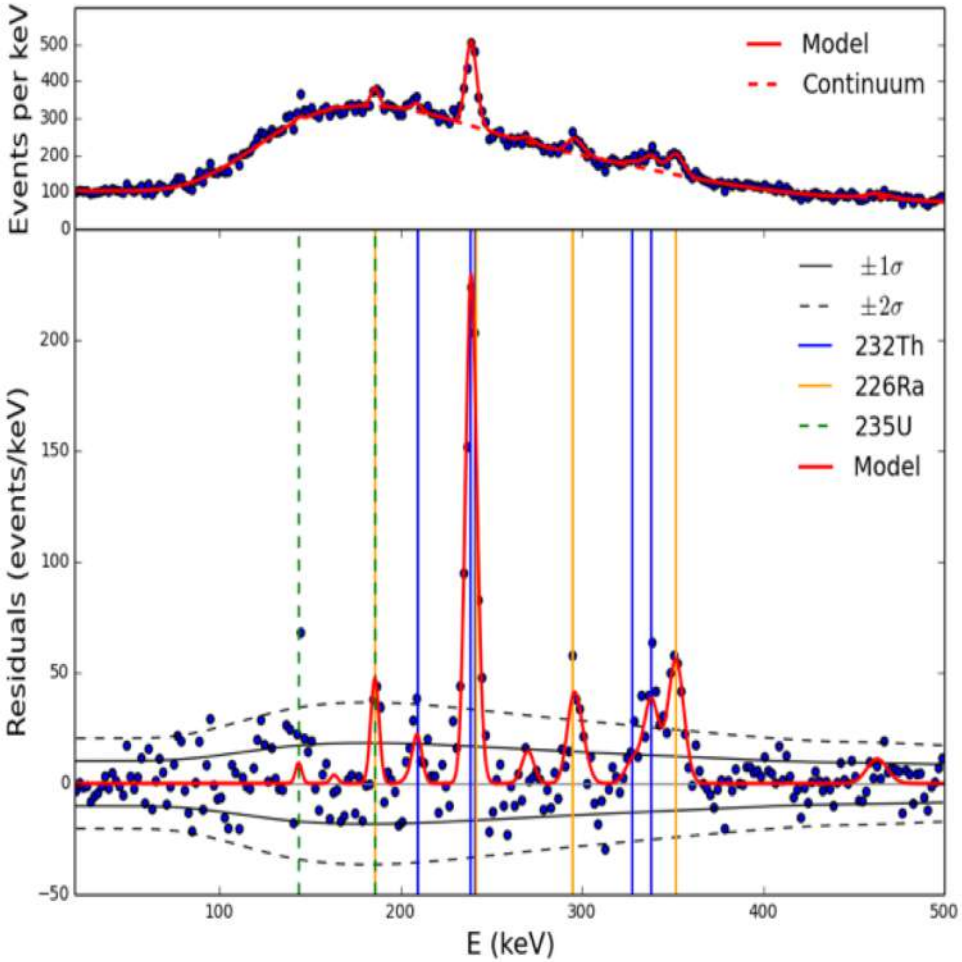
- Lowest electron background levels in cryogenic detector (thanks to surface evt rejection + 650 g fiducial volume)
  - 1149 kg.d with 2 $keV_{ee}$ threshold
  - 287 kg.d with 0.8 $keV_{ee}$ threshold
- Analysis of cosmic activation
- Activation of $^{3}H$ in Ge exposed to hadronic component of cosmic rays is a limiting background for SuperCDMS




- First precise measure of $^{3}H$ production in Ge: 82±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 $keV_{ee}$
- Combine heat+ionization signals for optimal ER energy resolution:
  - Baseline $\sigma$ = 190 $eV_{ee}$
  - Proportional term = 1.2%
- Intensities of observed peaks consistent with known Th/U lines




**[ArXiv:1808.02340, accepted by PRD]**

# *ALP & dark photons results*

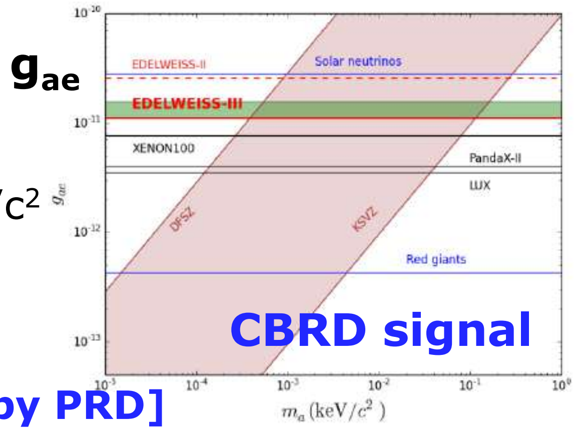
- Emission of axion/ALPs from the sun

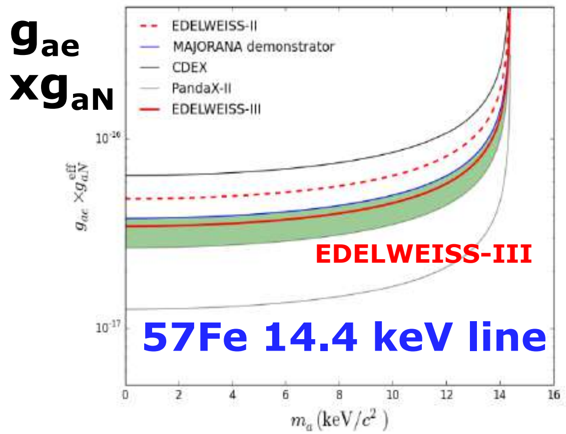
*keV-scale Bosonic DM:*

- Best Ge-based limits <6 keV/c² (thanks to surface rejection)
- Start to explore <1 keV/c²

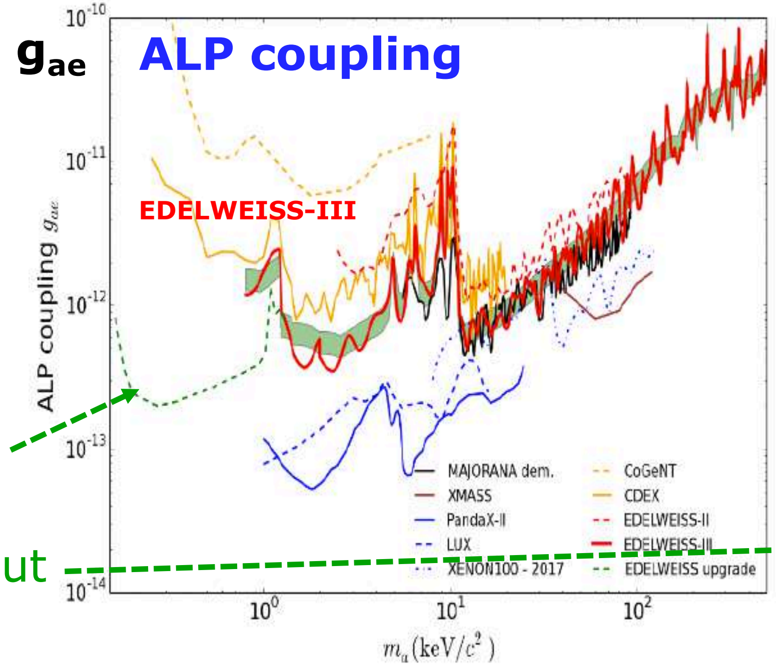
**[ArXiv:1808.02340, accepted by PRD]**

Emission of axions from the sun

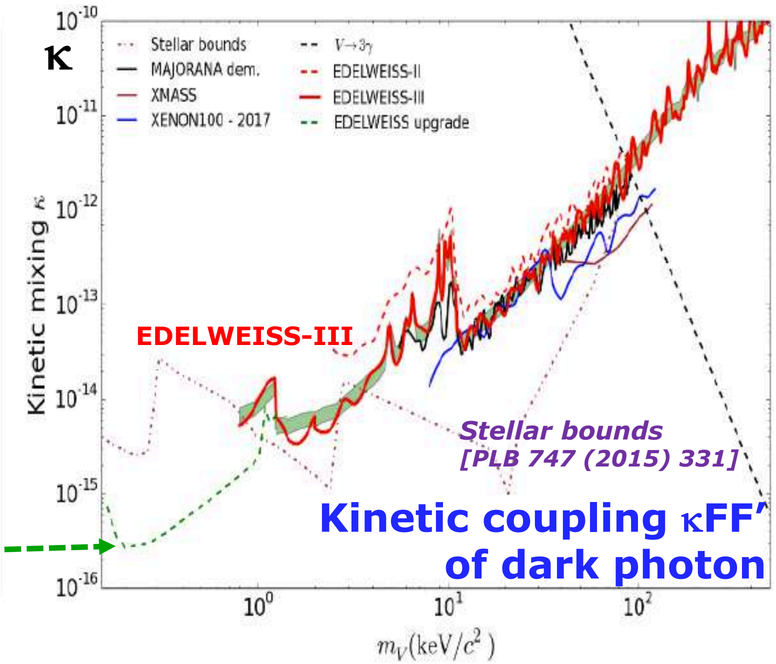



Bosonic DM results




EDELWEISS reach with HEMT readout



# 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 $M_{WIMP} > 10$ GeV/$c^2$, not a problem for lighter masses
- Large Heat-Only event background: studied and parameterized in next phase (EDELWEISS-LT)

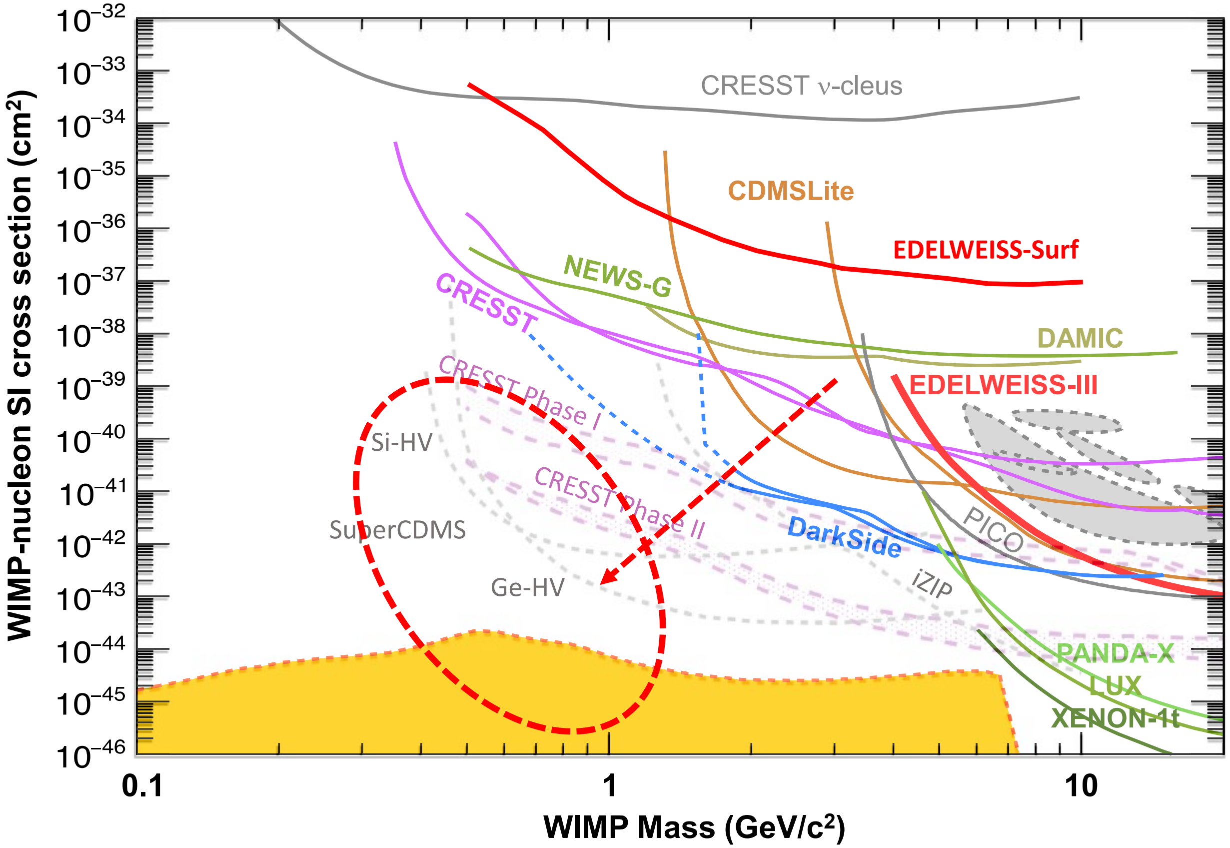
- Study of impact of improvement of resolution on physics reach: x5 on heat, x2 on ion. explored in projection paper ***[PRD 97 (2018) 022003]***

# 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 $\sigma_{phonon}$ = 10 eV and $\sigma_{ion}$ = 20 $eV_{ee}$ (assuming Lindhard Q)*

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

SuperCDMS iZIP goal of $\sigma_{ion}$ = 100 $eV_{ee}$ doesn't offer an attractive coverage



# Objective of low-mass program

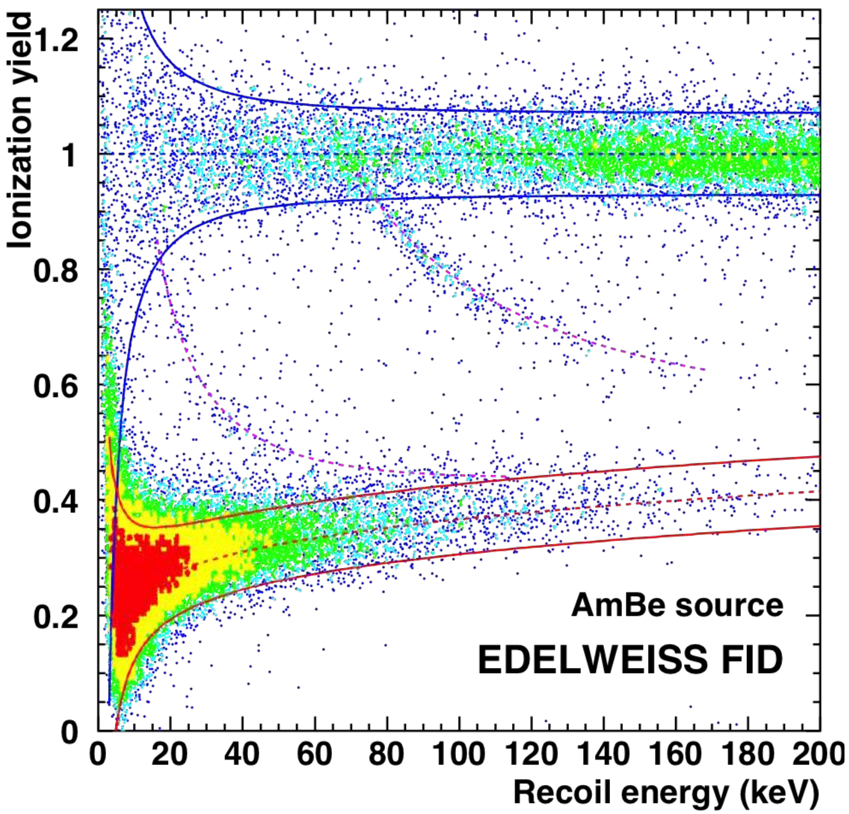
- 3 tasks indentified by the collaboration
  - **Heat resolution: $\sigma_{phonon}$= 10 eV (also: V = 100 Volt)**
  - **Ionization resolution: $\sigma_{ion}$= 20 $eV_{ee}$**
  - **Cryogenics adapted to these performance**

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

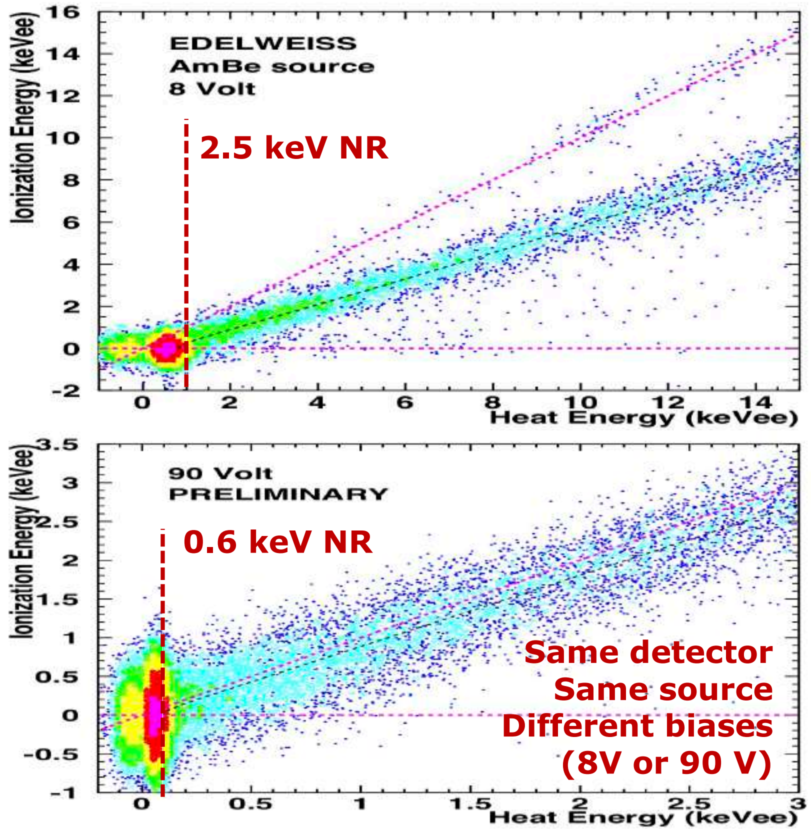
- First application: measure quenching for ~100 eV recoils (directly, not using extrapolation models)

# Nuclear recoil identification in EDELWEISS

- **Event-by-Event:** simultaneous measurement of ionization + heat signals

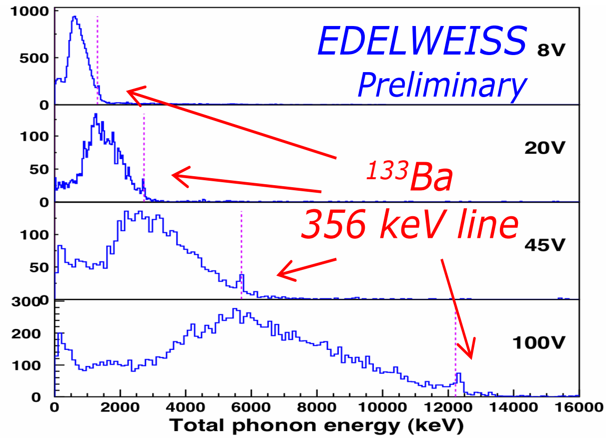


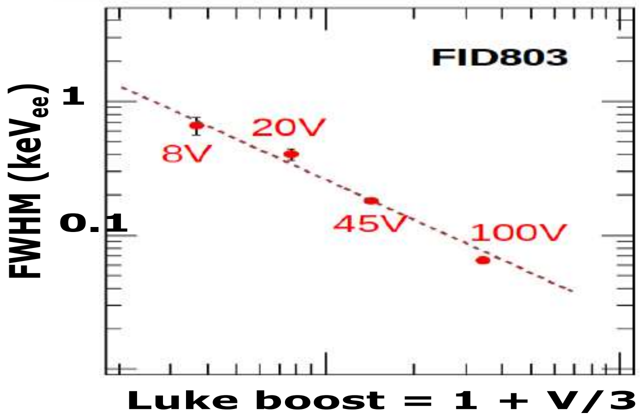

- **Statistical:** compare populations at low & high V bias: "Luke-Neganov" portion of thermal signal proportional to ionization yield quenching



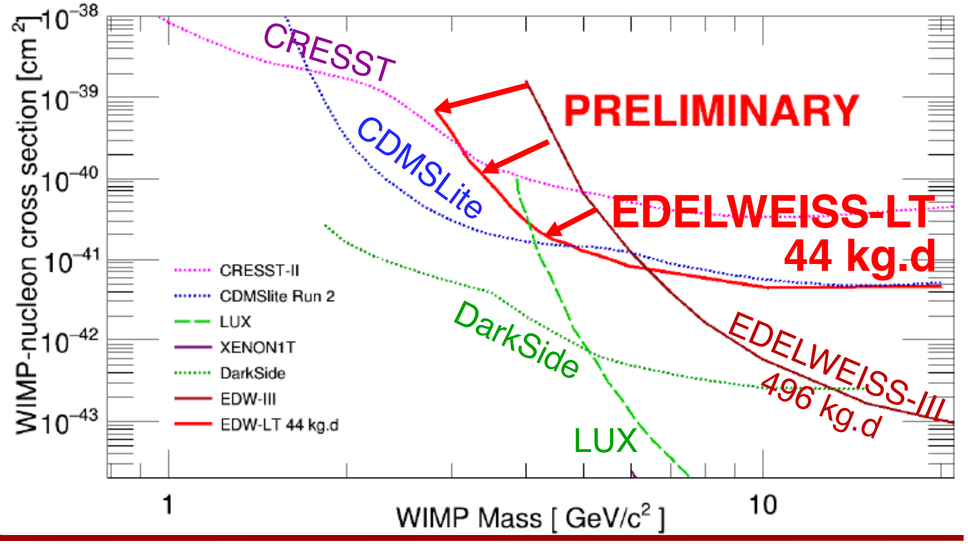
# First study: EDELWEISS-LT

- Luke-Neganov boost to amplify signal (and not noise) on existing FID800 detectors [E. Queguiner PhD thesis, Oct. 23rd 2018]



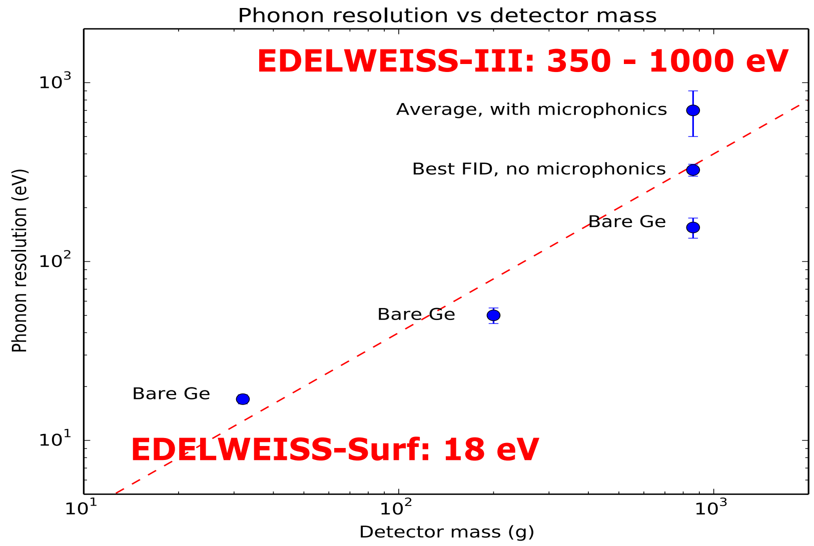

- 2 FIDs, $\sigma_{phonon}$ = 1.0 and 0.35 keV, $V_{bias}$ = 100 V and 30 V
- $\sigma_{ion}$ essential for full characterization of bkgs with 8 V data
- *Does provide the expected statistical discrimination of all bkgs*
- Next step: improve phonon resolution

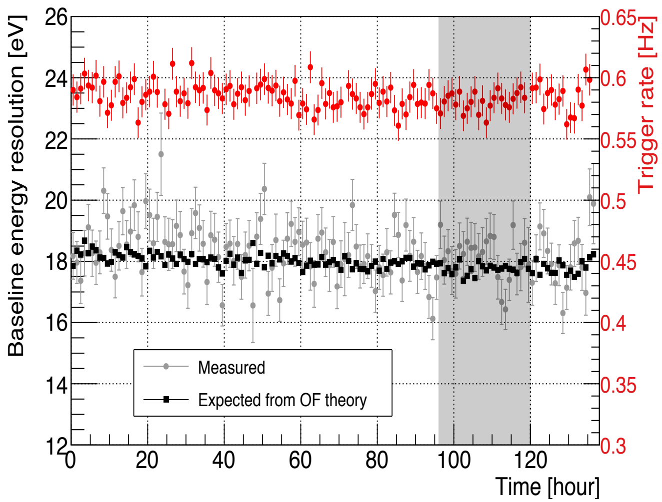


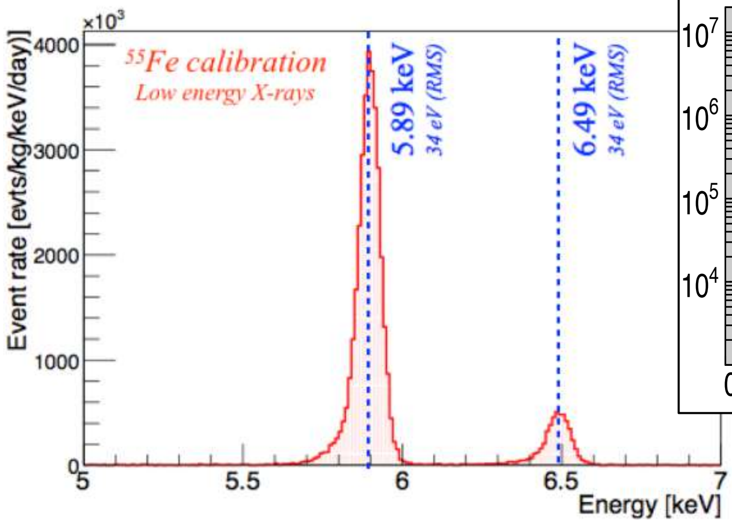
# Heat resolution progress

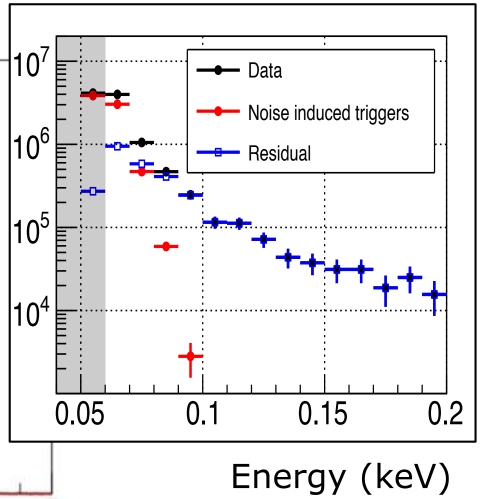
- Better understanding of heat sensor performance + scaling with detector mass
- ***Resolution of $\sigma_{phonon}$ = 18 eV achieved on 32 g detector***
- *Vibration control is the key element to obtain stable resolution vs time*

  *[cf: NIMA 858 (2017) 73 & arXiv:1803.03463]*



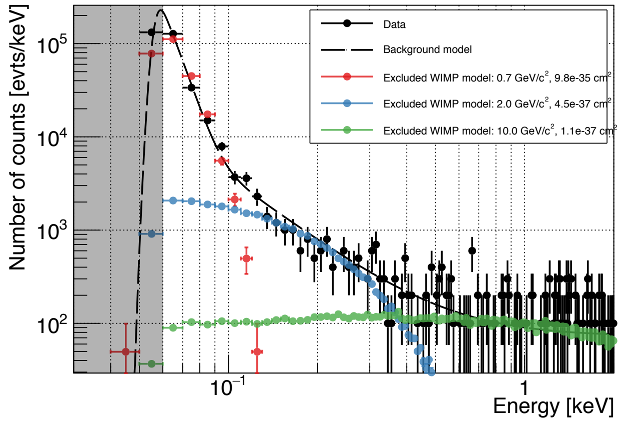



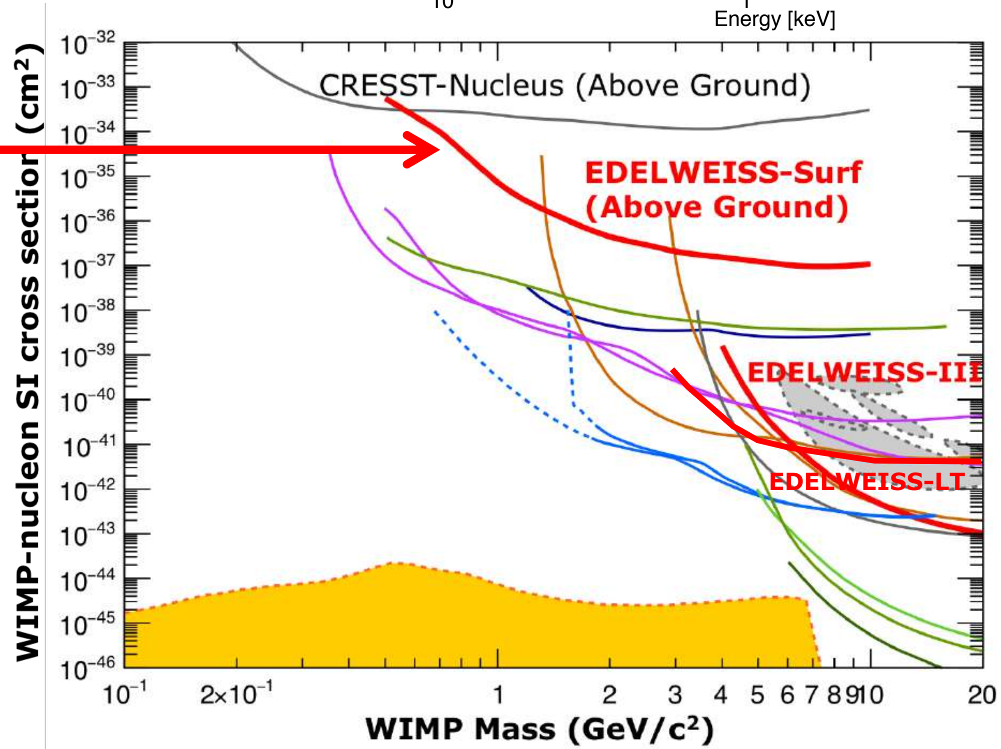



# EDELWEISS-Surf limit

- 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/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 $keV_{ee}$

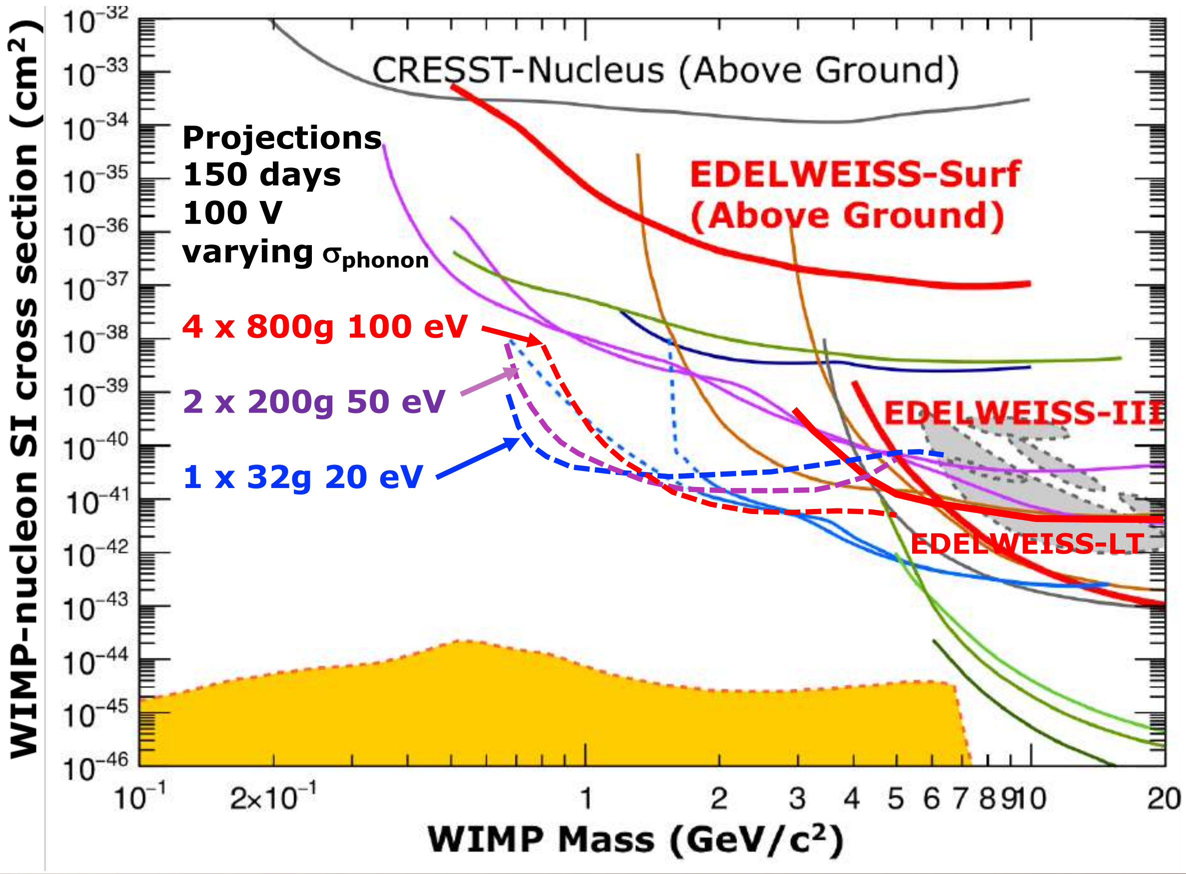
60 eV
threshold



# Comparison of 20-50-100 eV

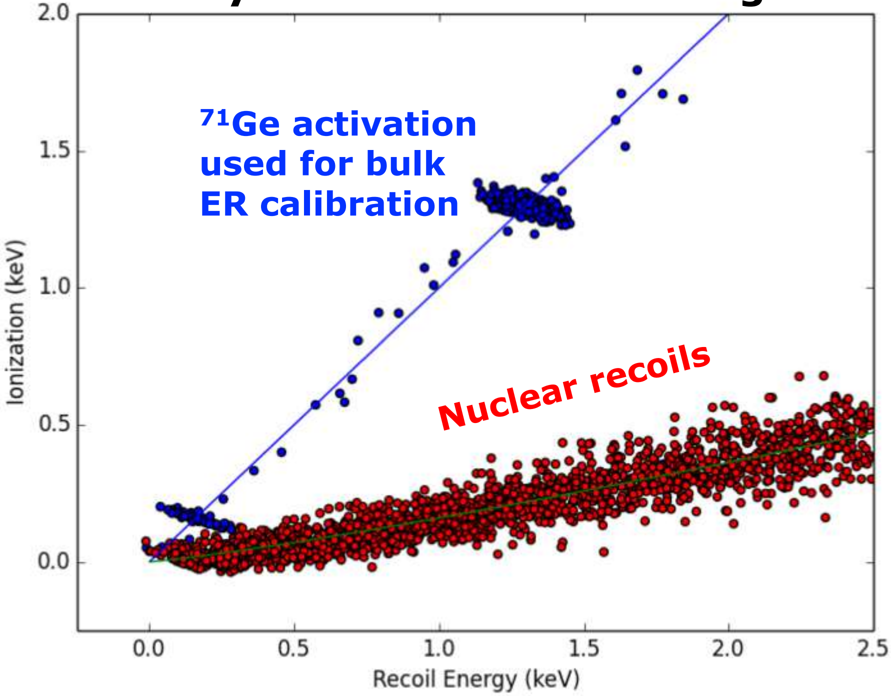
- The use of small detector mass is not an obstacle to low-mass WIMP searches, if it improves the phonon resolution
- For $M_{WIMP}$< 1 GeV/c², the gain in efficiency and threshold from improving $\sigma_{phonon}$ = 100 → 50 → 20 eV largely compensate the loss of exposure



# 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 $eV_{ee}$.

**10 day AmBe calibration - 32g FID**




**2 mm spacing → 4 mm spacing**

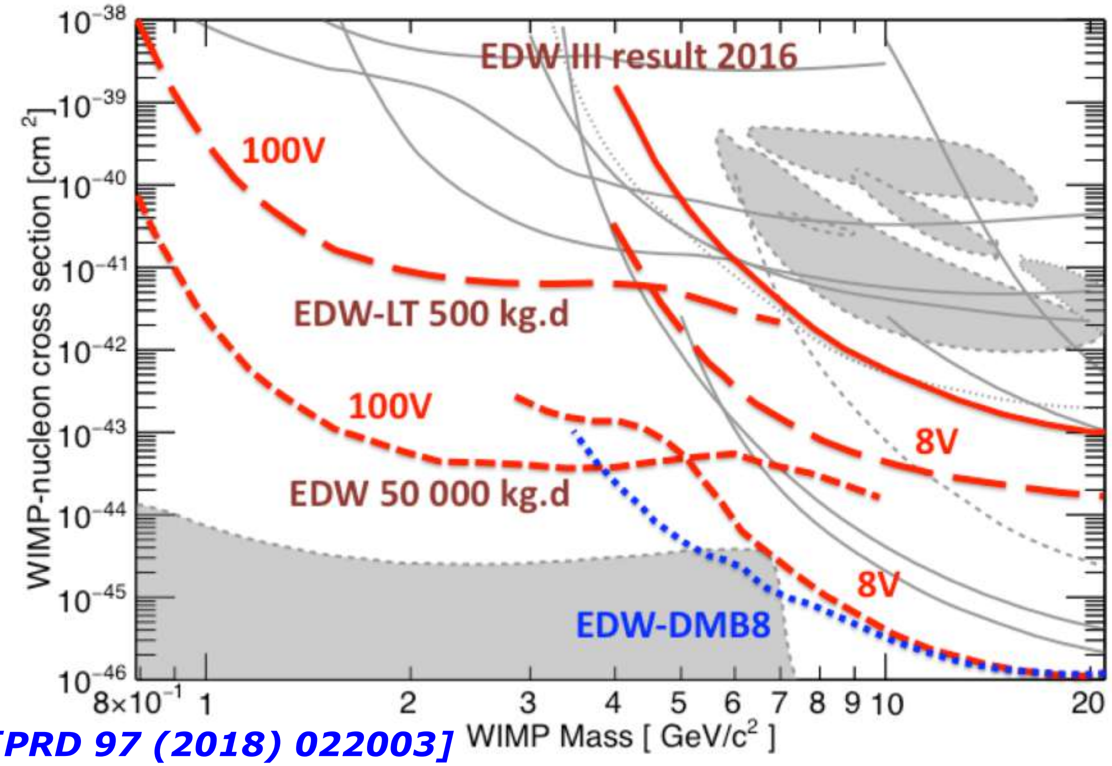

**A 32 g detector with $\sigma_{ion}$ = 20 $eV_{ee}$ and $\sigma_{phonon}$ = 20 eV would be able to measure directly the ionization yield of 100 eV nuclear recoils** with present bkg conditions at LSM

***ANR projet MIYLEN***

# 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 $eV_{ee}$.

**2 mm spacing → 4 mm spacing**


***[PRD 97 (2018) 022003]***

**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 $^8$B solar ν's with resolution and discrimination**

# Low-mass program calendar

2019-2020

- Development of a 32 g FID detector at CSNSM and IPNL. Objective: $\sigma_{phonon}$ = 10 eV and $\sigma_{ion}$ = 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

# People

## EDELWEISS-III

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

### Organigramme Projet 2018

Coordinators

| Spokesperson | Technical |
|---|---|
| J Gascon | C Nones |

Institute Board

| Spokes | IPNL | CSNSM | CEA | KIT | Dubna |
|---|---|---|---|---|---|
| J Gascon | C Augier | S Marnieros | C Nones | K Eitel | E Yakushev |

Publication Board

Coordination Board

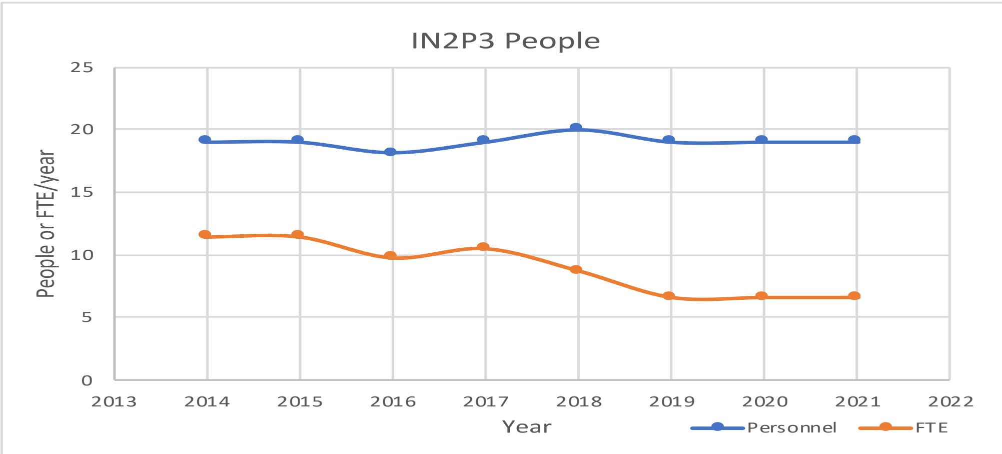
| | | | |
|---|---|---|---|
| J Gascon | M de Jesus | K Eitel | C Nones |

| Spokes | Technical coord. | Background | Detectors | R&D |
|---|---|---|---|---|
| J Gascon | C Nones | M de Jesus | S Marnieros | A Juillard |
| **Cryogenics** | **Electronics+DAQ** | **External systems** | **DataBase+Monit.** | **Analysis** |
| F Charlieux | B Paul | K Eitel | V Sanglard | J Billard |

LSM Link: A Rojas

## 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



# Budget

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 $^{3}H$ cosmic activation rate

## EDELWEISS low-mass R&D program

- Goal: develop detector able to probe sub-GeV WIMPs with $\sigma_{SI} < 10^{-43}$ cm$^2$ with nuclear recoil discrimination capabilities
- Plan to reach objectives of $\sigma_{phonon}$=10 eV, $\sigma_{ion}$=20 eV$_{ee}$, 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: $\sigma_{phonon}$=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