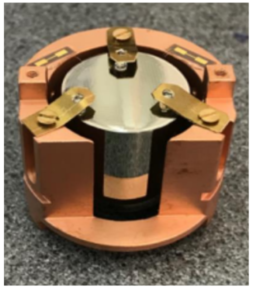
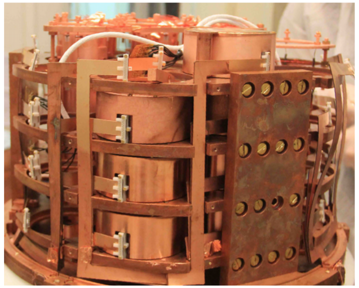
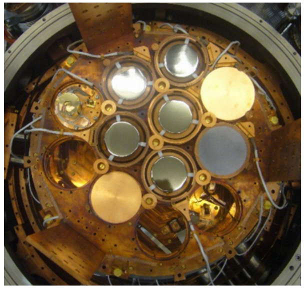
Quentin Arnaud, *on behalf of the* EDELWEISS collaboration
IP2I, Université Lyon 1, CNRS/IN2P3

Sub-GeV Dark Matter searches with the EDELWEISS experiment

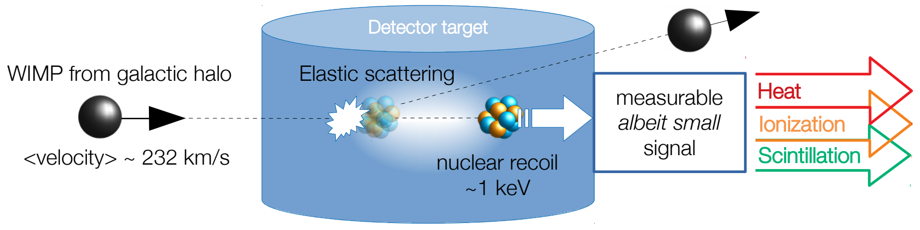



IRN Terascale, Bruxelles, October 16 -18, 2019

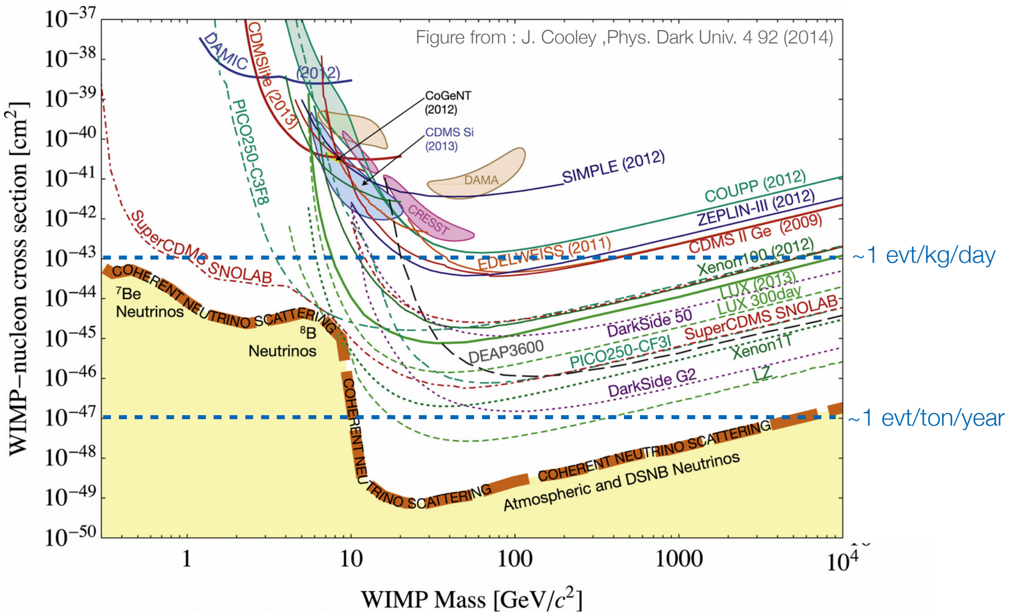
Experience pour DEtecter Les WIMPs En Site Souterrain

DM Direct detection

'Standard Weakly Interacting Massive Particle (WIMP)' searches



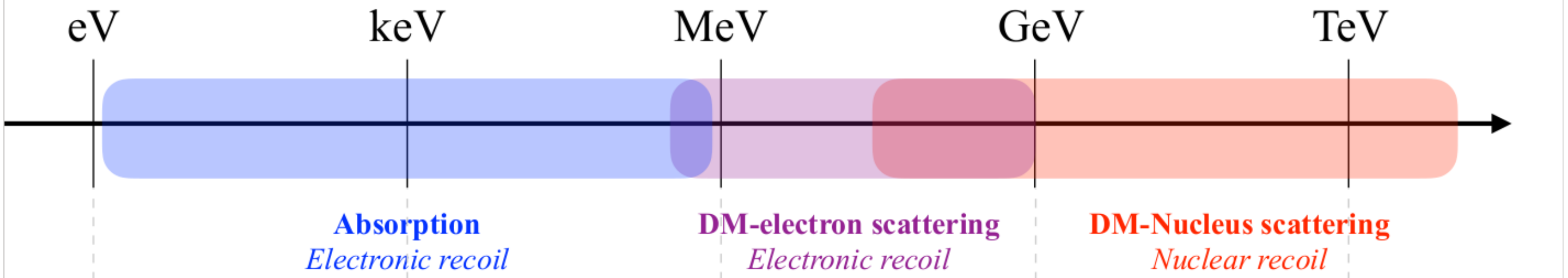
	Cryogenic experiments	Large Dual-phase TPCs
Detector masses	**kg-scale**	**ton-scale**
Background levels 1 dru = 1 evt/kg/day/keV	**~1 dru**	**~1 mdru**
Detection Thresholds	**sub-100 eV**	**sub-keV**
Discrimination Thresholds	**sub-keV**	**~1 keV**
WIMP sensitivity optimum	***O*(1 - 10) GeV**	***O*(10 - 1000) GeV**



Extending the search to low-mass WIMPs and other sub-GeV DM particles

Variety of DM candidates

- ALPs
- Dark photons
- DM-electron scattering
- low-mass SIMPs
- ...



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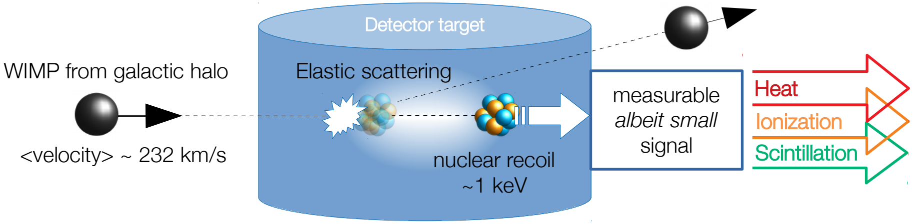

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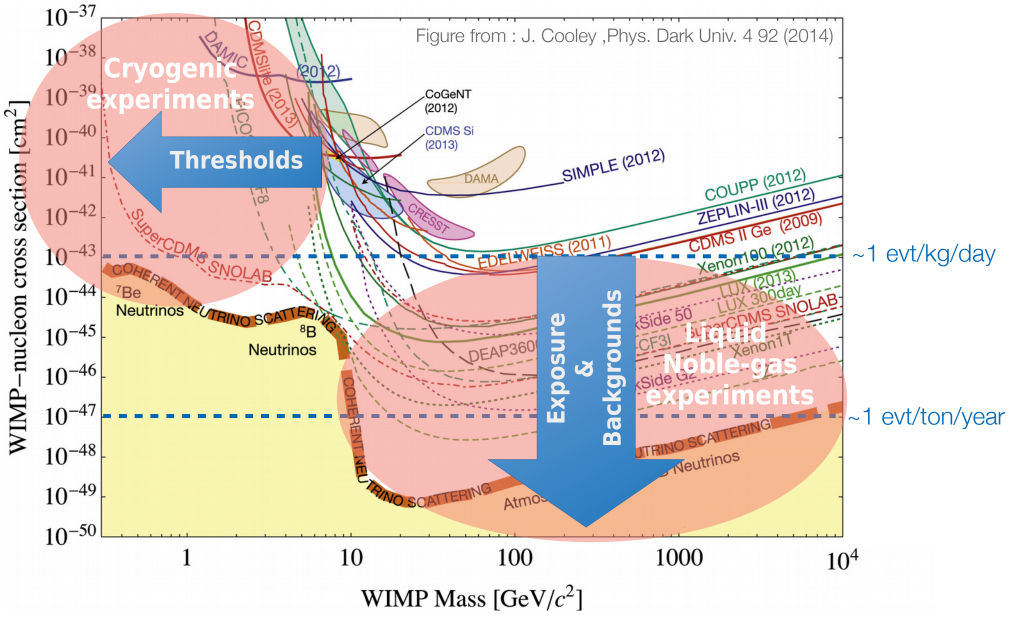

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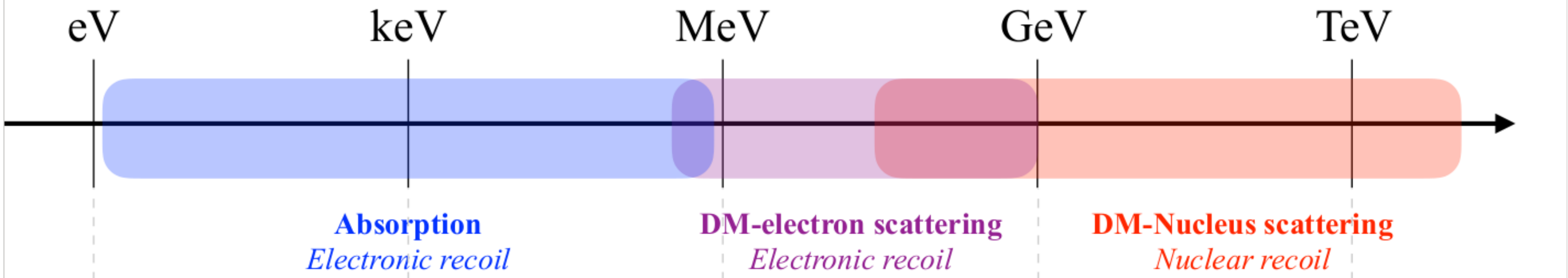
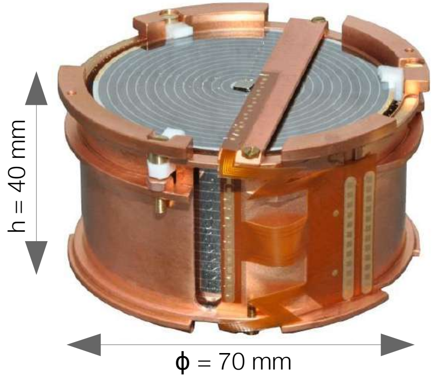


EDELWEISS detectors — Low voltage (~ 4 V) operation mode

Fully Inter-Digitized (FID)



870 g High-Purity Ge detectors operated at ~ 18mK

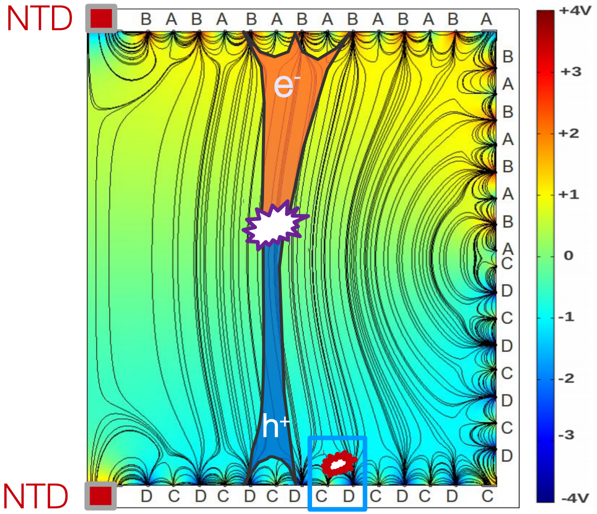
Heat measurement
2 NTDs (thermal sensors)

Ionization measurement
4 sets of electrodes
concentric Al rings (2mm spacing)

Simultaneous measurement of heat and ionization signals

$E_{heat} \sim E_{recoil}$ *irrespective of particle-ID*

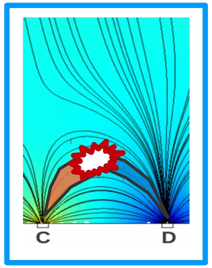
$E_{ion} \propto N_p = \frac{E_{recoil}}{\epsilon}$ *particle-ID dependent*



Surface event rejection

Bulk event:
Signal on fiducial electrodes only

Surface event:
Signal on fiducial + veto electrodes



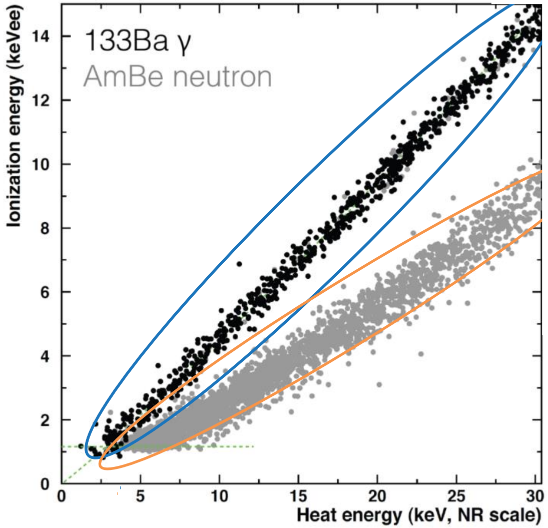
Particle-type identification

Electron recoils (ɣ,β)
ϵ~ 3 eV / electron hole pair

Nuclear recoils (n,WIMPs)
ϵ~12 eV / electron hole pair

Typical performance with FID-800g detectors

Electron Recoil rejection factor < 2.5×10^{-6}
Surface Event rejection factor < 4×10^{-5}



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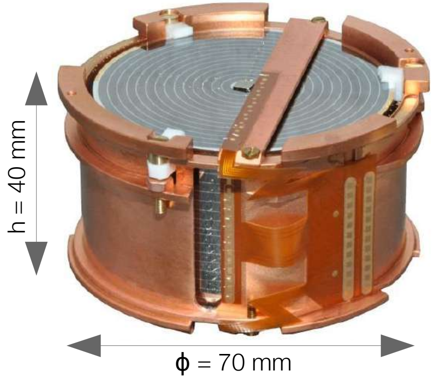

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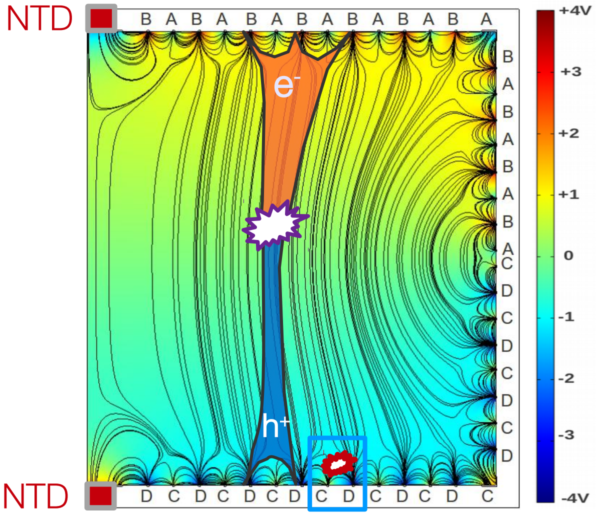
$$E_{heat} = E_{recoil} + E_{Luke} = E_{recoil} + N_p \Delta V$$

$$E_{heat} = E_{recoil}\left(1 + \frac{\Delta V}{\epsilon}\right)$$ *particle-ID dependent*

Amplification of the Heat signal due to Neganov-Luke effect

$$E_{ion} \propto N_p = \frac{E_{recoil}}{\epsilon}$$ *particle-ID dependent*



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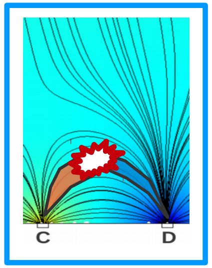

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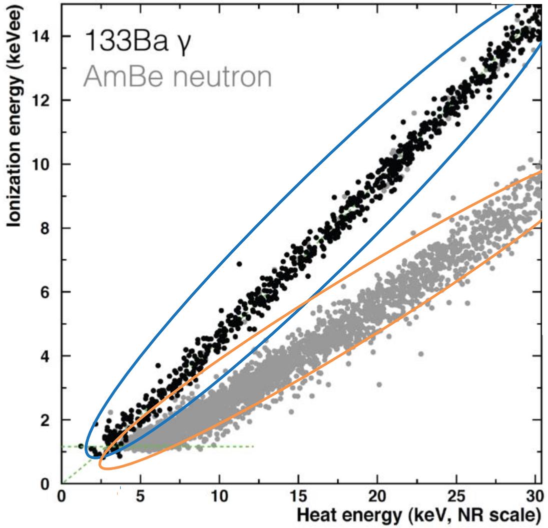
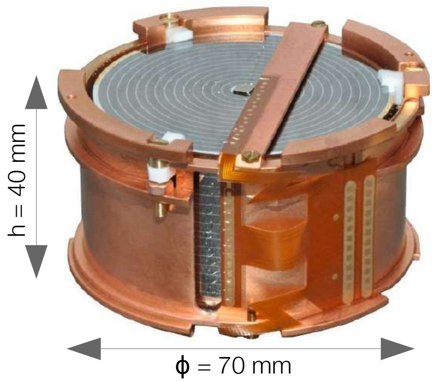


High voltage (~100 V) operation mode

Fully Inter-Digitized (FID)



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Amplification of the Heat signal due to Neganov-Luke effect

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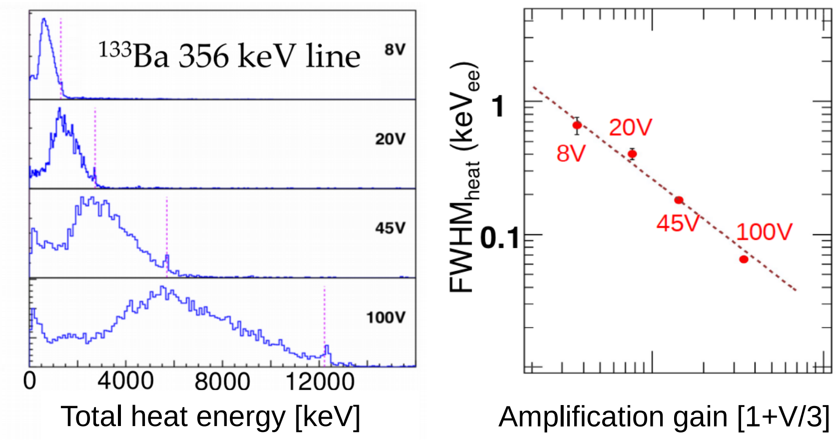
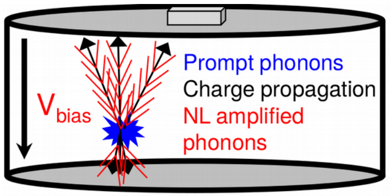
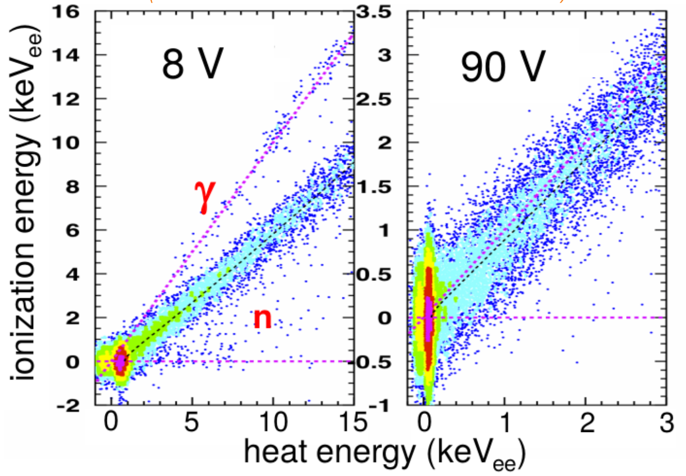
Huge Amplification of the signal only (not noise)
lower thresholds + improved resolution



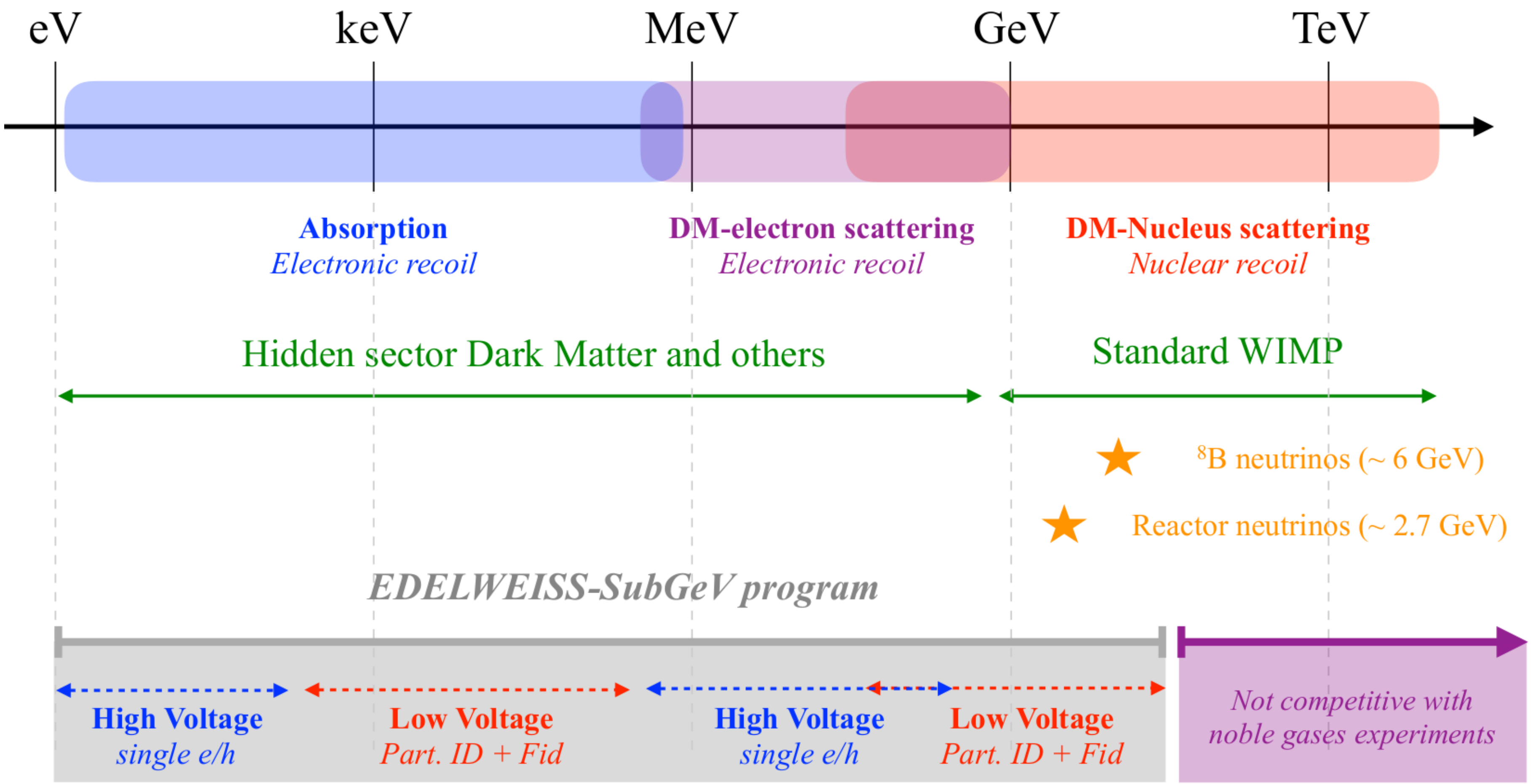
~~Surface event rejection~~
(planar mode, no veto electrodes)



~~Particle-type identificaiton~~
(thermal sensor measures ionization!)



Scientific context of the EDELWEISS Sub-GeV program

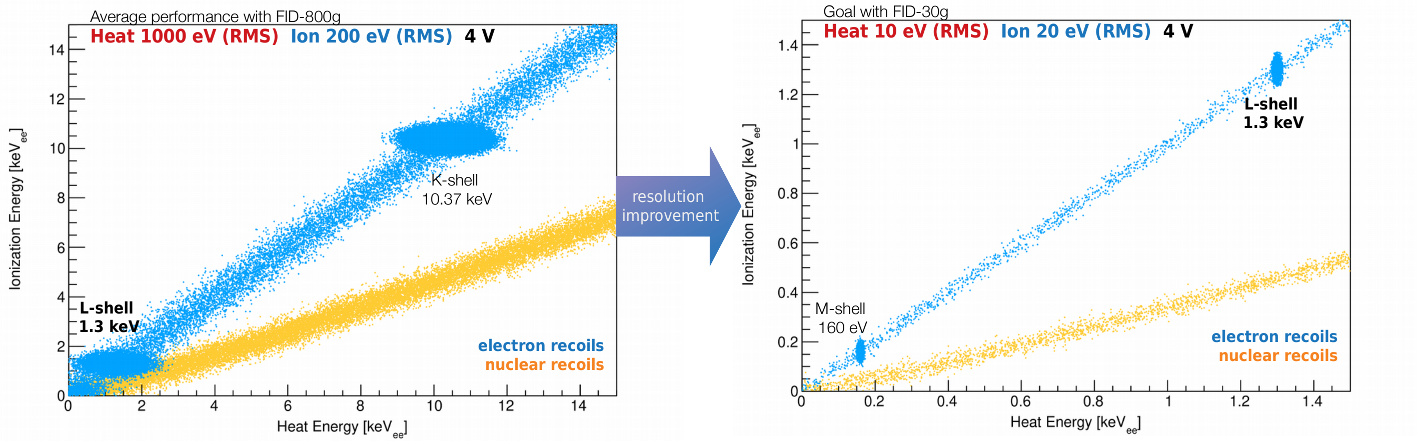


EDELWEISS Sub-GeV program

Low Voltage Objectives

- **10 eV (RMS) Heat energy resolution**
- **20 eV (RMS) Ionization energy resolution**

Particle identification & surface event rejection down to 50 eV



Low-voltage objectives are part of a common effort with the Ricochet collaboration, dedicated to studying CENNS at reactors supported by the ERC-CENNS Starting Grant (2019-2024)

EDELWEISS Sub-GeV program

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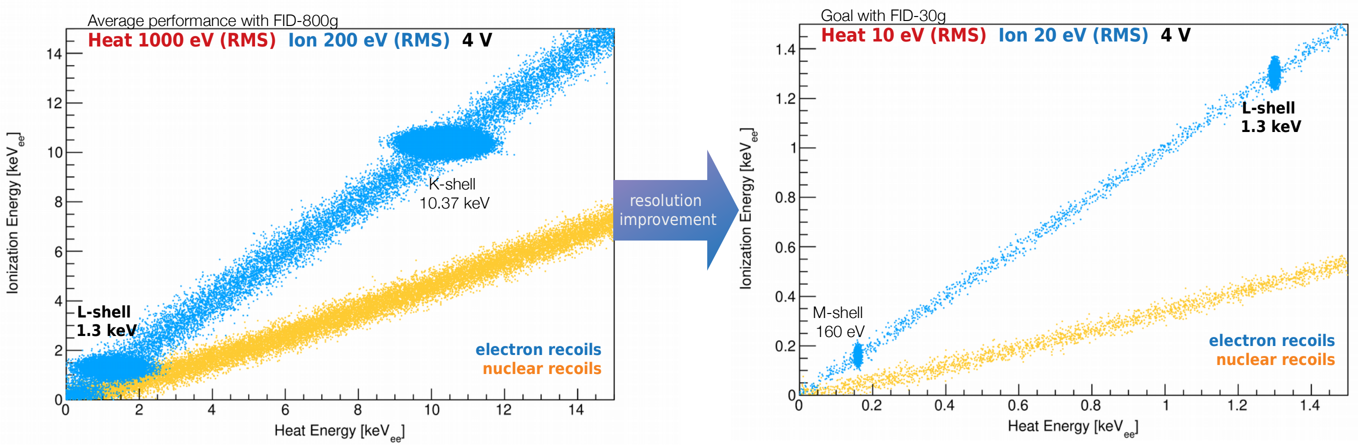

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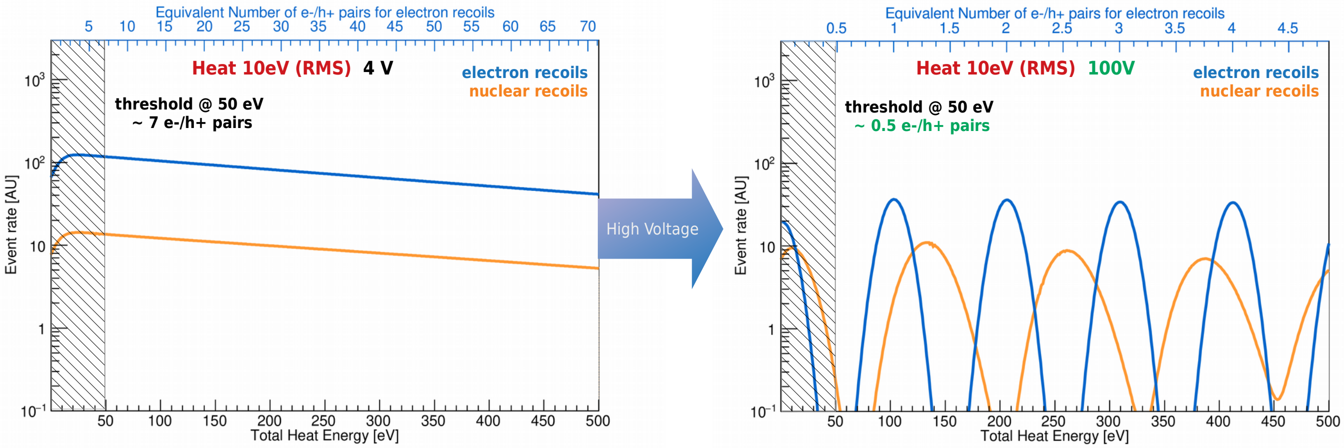
High Voltage Objectives

- **10 eV (RMS) Heat energy resolution**
- **100 V with signal amplification only**

Single-e/h pair sensitivity with massive (~30g) bolometers

Single **ELE**ctron **N**uclear recoil **DIS**crimination
SELENDIS



SELENDIS project has received funding from the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement No 838537

EDELWEISS R&D @ IP2I above-ground laboratory

dry cryostat (Cryoconcept)
cool down < 30 h (fast turnover ideal for R&D)
[NIM A858 (2017) 73]

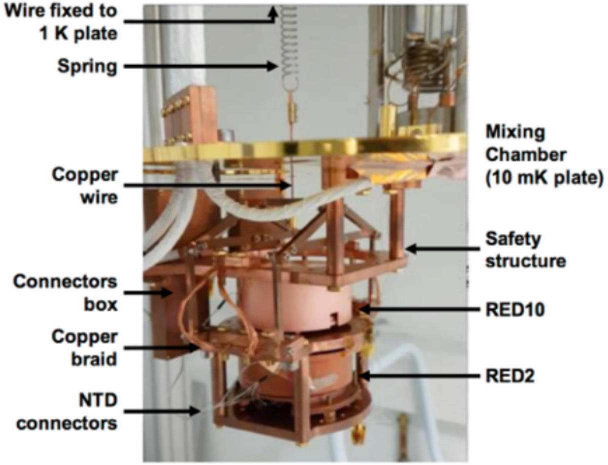
Vibrations mitigation with cryogenic suspension system
< µg/√Hz vibration levels with spring-suspended detector tower
[JINST 13 (2018) No.8 T08009]

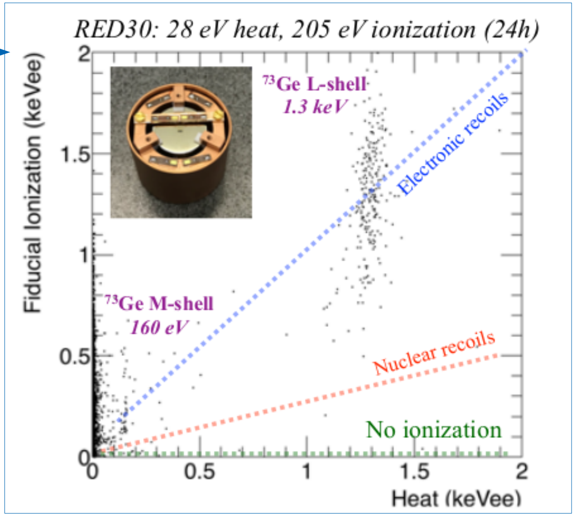
Large improvement of heat baseline resolutions :

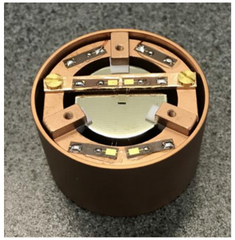
- 28 eV (RMS) on a 33.4 g detector with electrodes
- 20 eV (RMS) on four 33.4 g Ge crystals → *reproducibility*
- 50 eV (RMS) on a 200 g Ge crystal

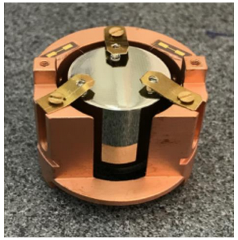
Thanks to :

- *vibrations mitigation*
- *enhanced thermal response sensitivity*
- *down-scaling of crystal masses*









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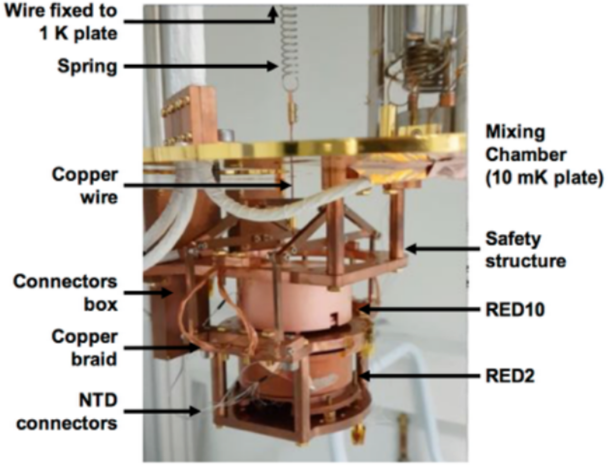
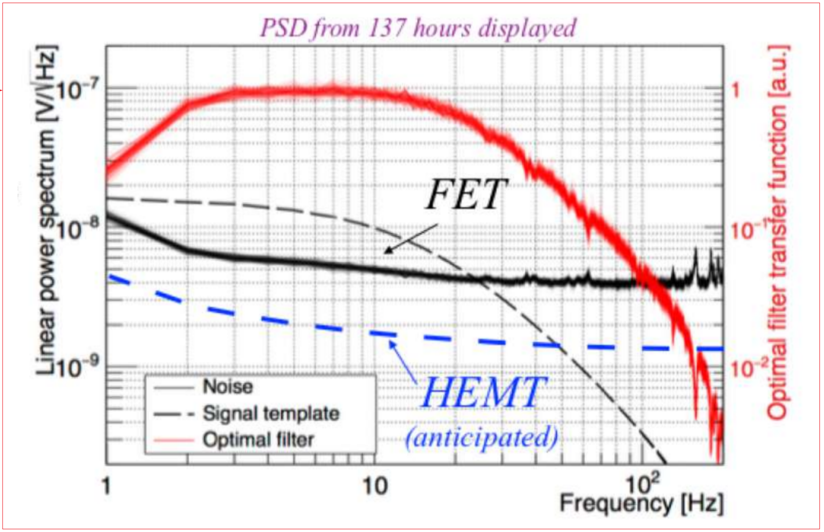
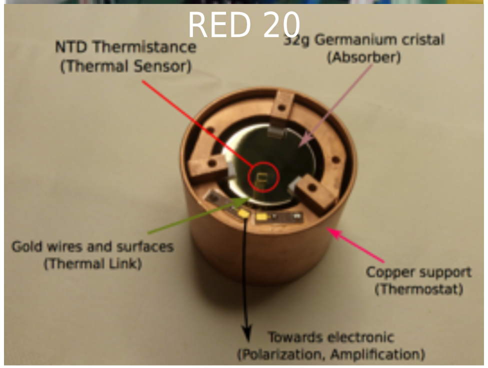


Major accomplishment with RED20
33.4 g detector (Ge)

- 18 eV (RMS) heat resolution
- 55 eV energy threshold
- near perfect stability (~%)





Now limited by FET current noise
- switch to HEMT to reach 10 eV (RMS)
  arXiv:1909.02879

Also investigating TES thermal sensors (vs. NTDs)

EDELWEISS-surf DM searches with RED20

Continous data-taking for 137 hours with one day blinded in [0-2] keV region for DM searches

RED20 : 33.4 g detector (Ge) operated as a true calorimeter (no electrodes) : 1 eV = 1 eVnr = 1 eVee

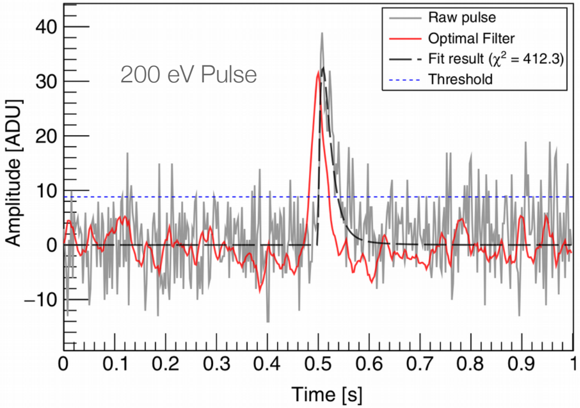
Energy resolution : 18 eV (RMS)
Trigger threshold : 55 eV

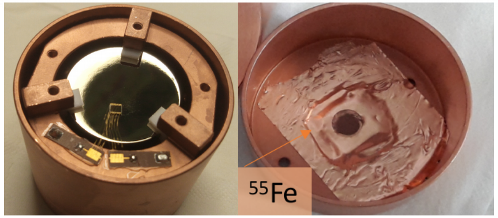
Data taking in so-called stream mode (offline trigger)

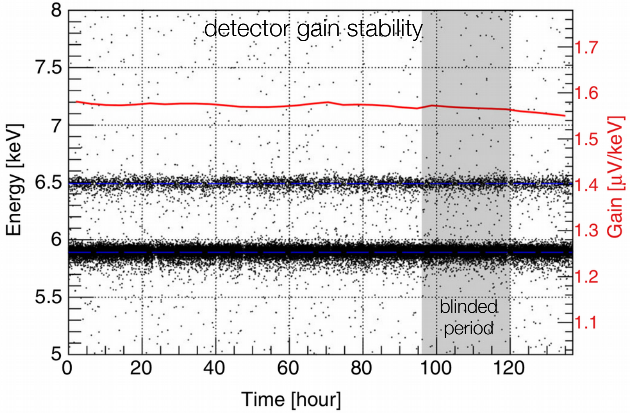
Signal Processing using an optimum filter approach

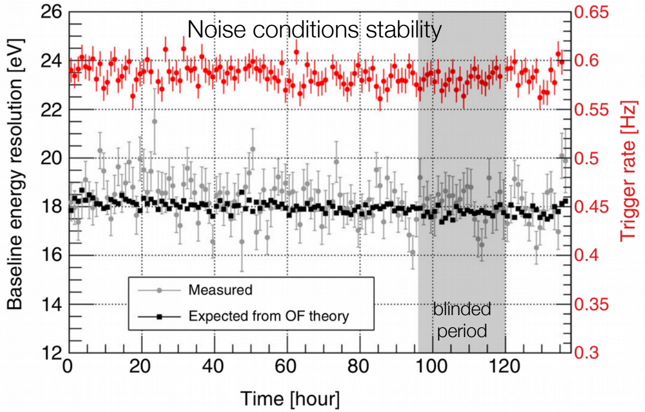
Calibration with ^{55}Fe source ~ 0.3 Hz of 5.89 keV and 6.49 keV X-rays

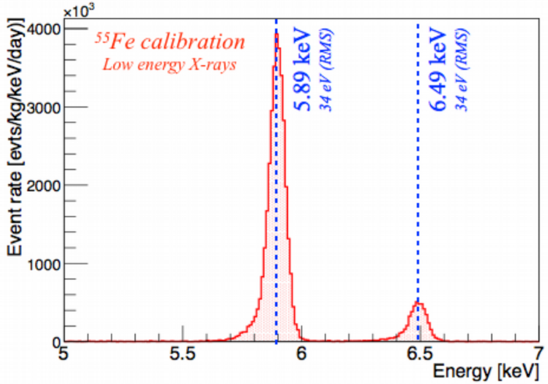
Monitoring of the stability of the detector gain and noise conditions over time (near perfect stability)











Unblinding the data

No surprises

Blinded day = carbon copy of preceding + following days

Between 500 eV and 8 keV

Flat background 8000 dru

expected from ɣ-ray bkg in a non-low-radioactivity environment

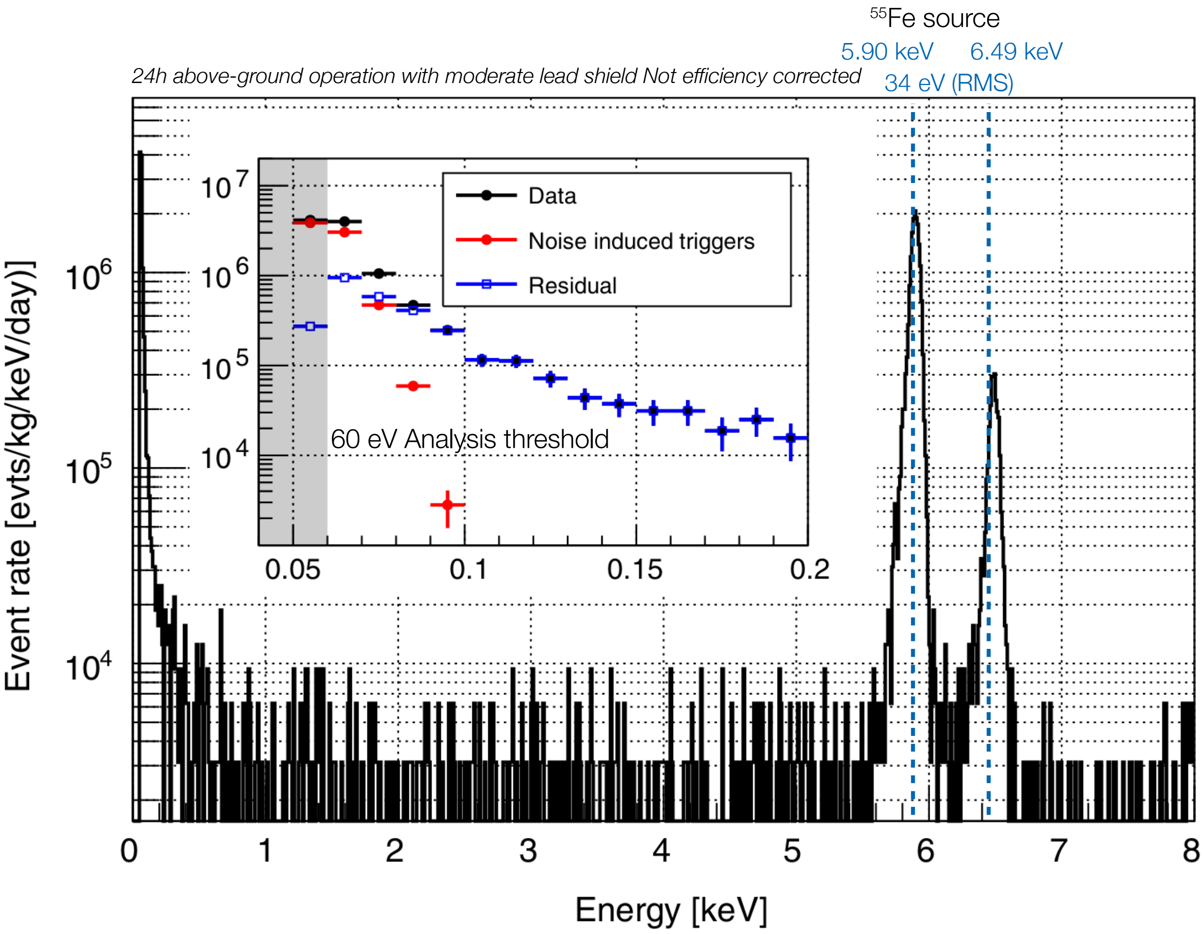
Below 500 eV

Exponential with ~25 eV slope

10^5 dru at 200 eV and 2×10^7 dru at 60 eV

In the [60-80] eV range

Significant contribution from noise-induced triggers



WIMP sensitivity calculation

Pulse simulation procedure

DM-induced events simulated for each WIMP mass considered

Pulse amplitudes drawn from theoretical WIMP-induced nuclear recoil energy spectrum
with standard halo parameters (v_0=220 km/s, v_{esc}=544 km/s, v_{lab}=232 km/s, ρ=0.3 GeV/cm^3)

Simulated pulses injected at random times throughout the entire data stream

Same processing/analysis pipeline for (Data + Simu) stream than actual Data stream

Pulse simulation output

Simulated DM energy spectra including all possible sources of efficiency losses :

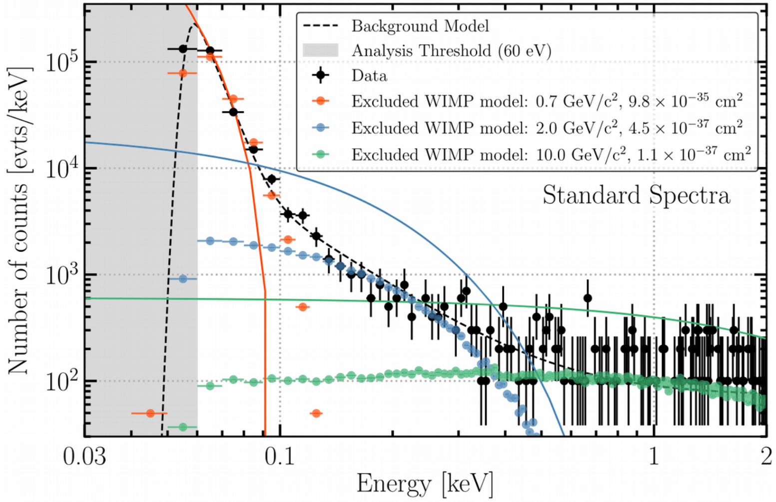
- *Trigger efficiency*
- *Live-time losses (physical event rate, quality cuts)*
- *Signal efficiency of cuts (e.g. chi2 cuts)*
- *Any systematic uncertainty/bias related to the processing pipeline*

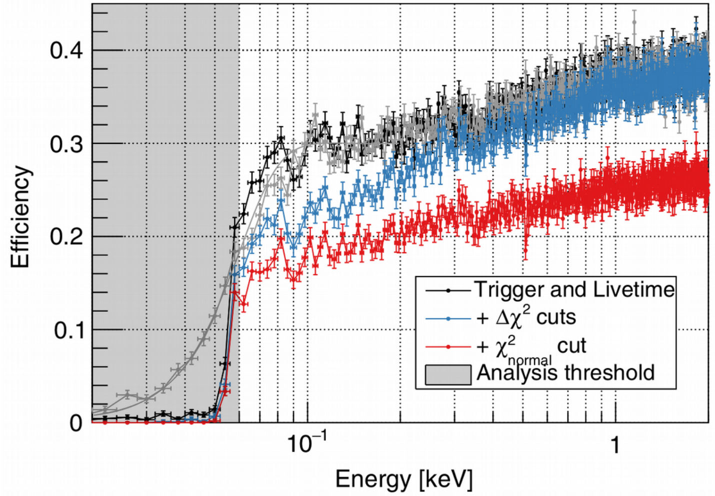
Optimization of the ROI prior to unblinding

- Background-model extracted from non-blinded data
- optimal ROI = ROI maximizing expected signal/bkg for each WIMP mass

Setting upper limits

- all events observed in ROI considered as WIMP candidates
- No background subtraction (Poisson Limit @ 90%CL)



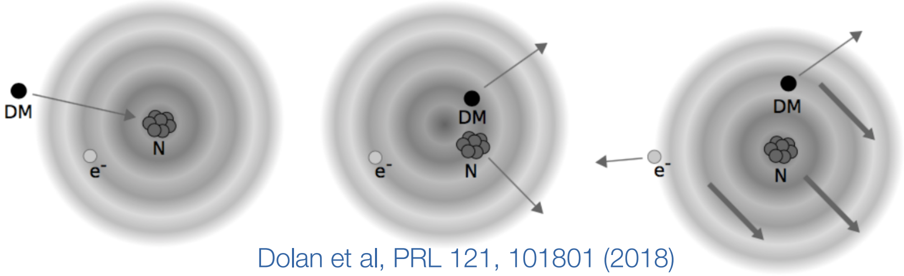


EDELWEISS-surf DM searches with RED20

Migdal Effect

(inelastic scattering)

Consider ionization effects of e⁻ cloud due to sudden boost of nucleus in DM collision



Dolan et al, PRL 121, 101801 (2018)

Not yet observed but calculable (*Ibe et al, JHEP 03 (2018) 194*)

0.01 % - 1 % probability of ionizing electrons from outer shells

We only consider the M shell (n=3) in Ge ([30-160] eV)

K, L electrons too tightly bound ([1-10] keV)

n=4 affected by band structure

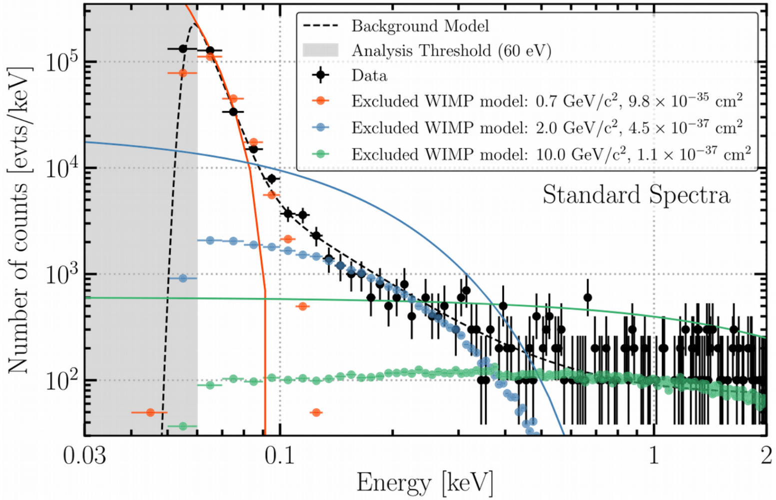
Detectability enhancement of light dark matter in the sub-GeV mass range

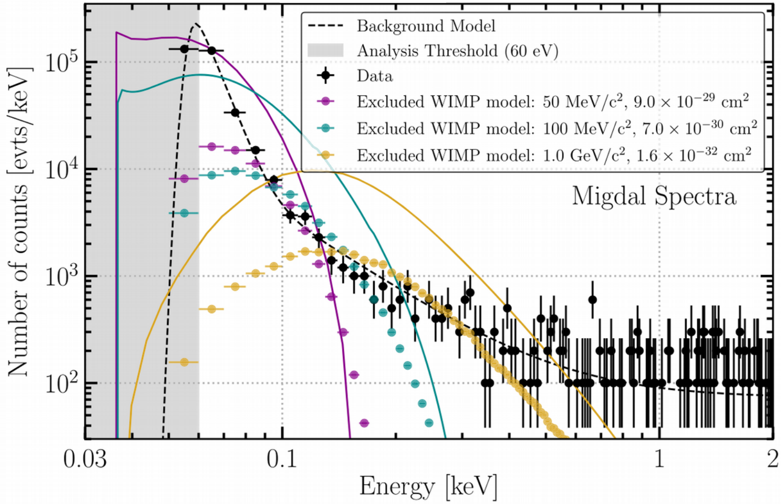
Injection of ER energy in the sub-keV to keV range

RED20 true calorimeter : ER energy adds up to the NR energy

Robust signal > 100 eV even for WIMP masses < 100 MeV/c²

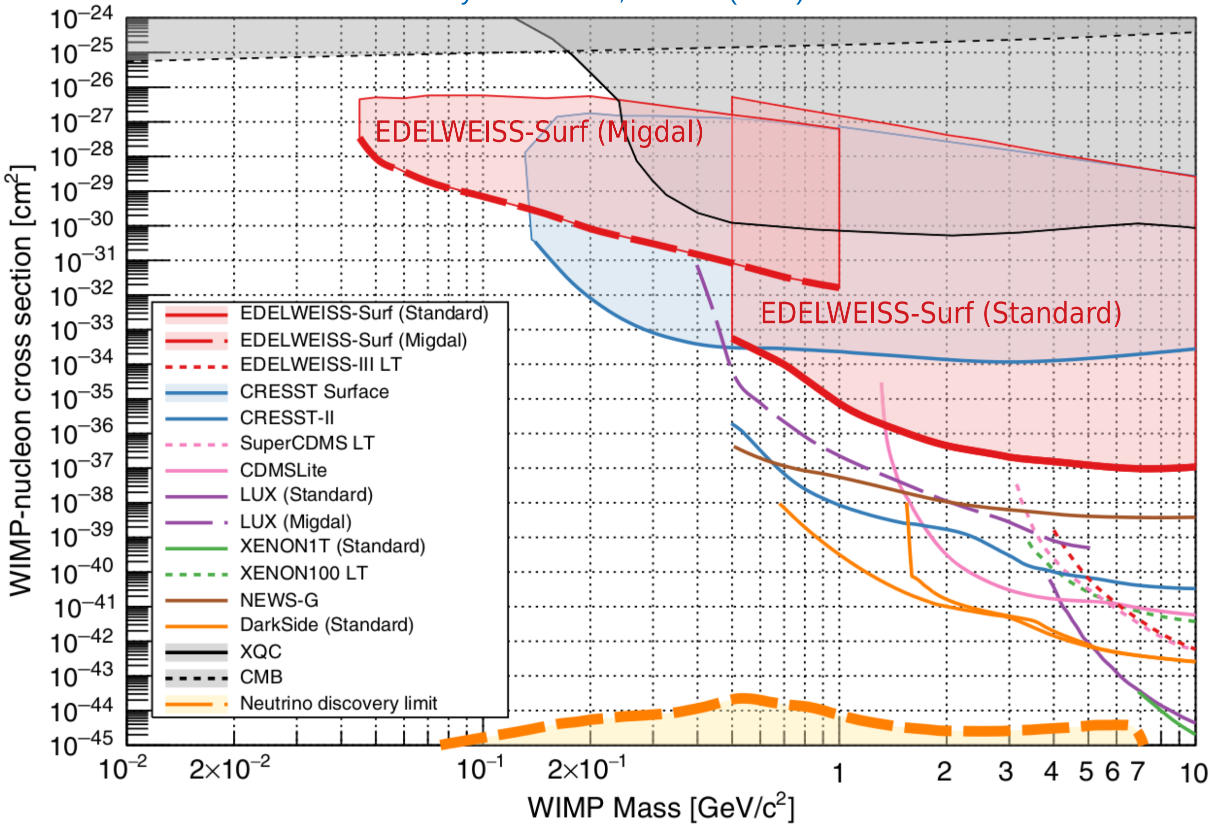
Negligible for WIMP masses >10 GeV/c² s

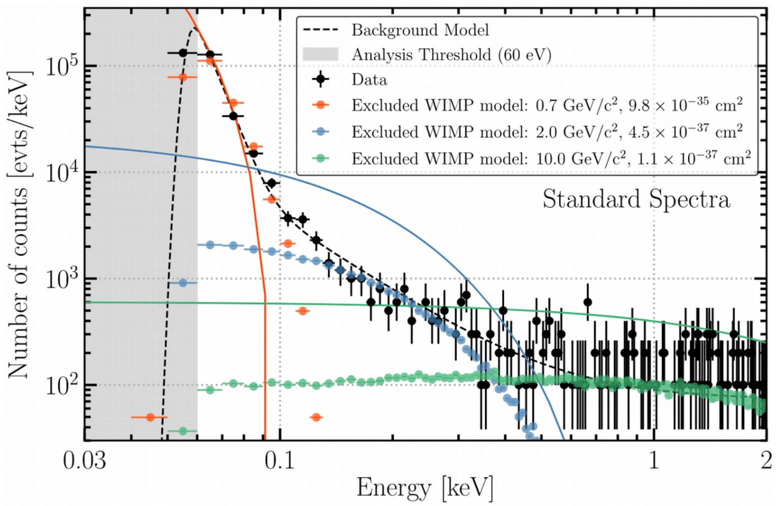


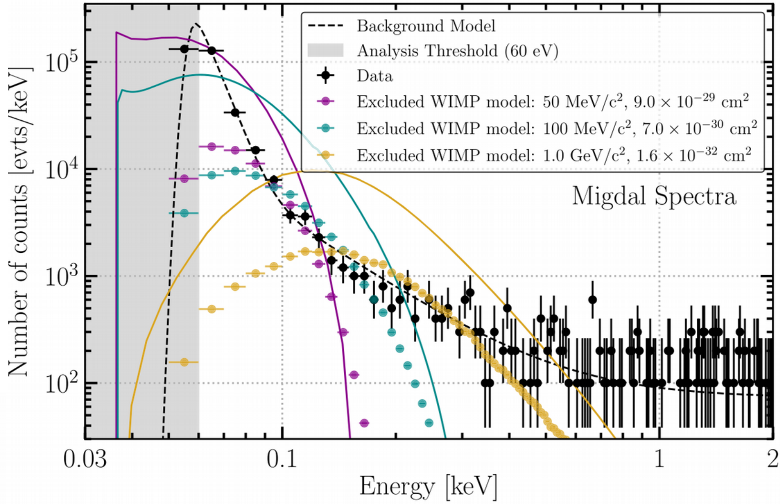


EDW-Surface Results : Spin-Independent

Phys. Rev. D 99, 082003 (2019)







EDELWEISS-surf (Standard): best above ground limit down to 600 MeV

EDELWEISS-surf (Migdal) : first DM limit down to 45 MeV

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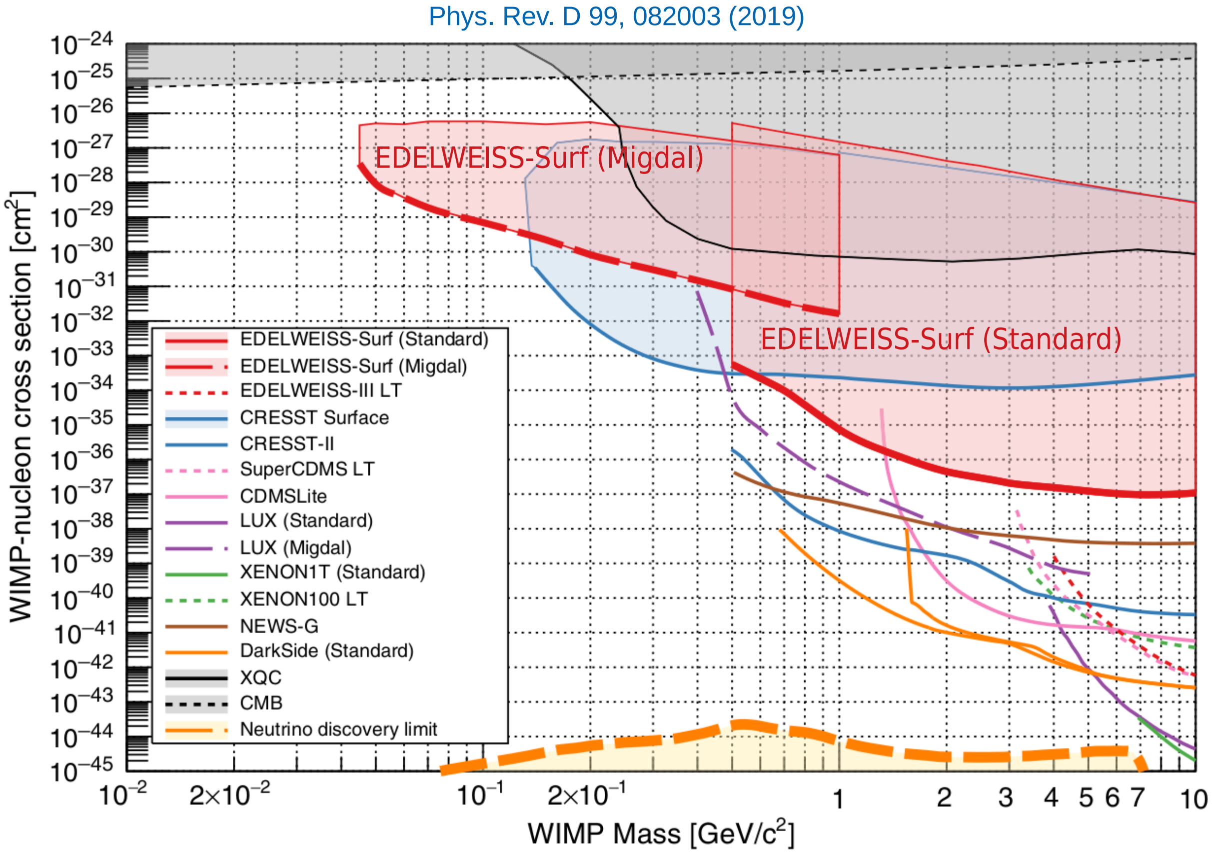
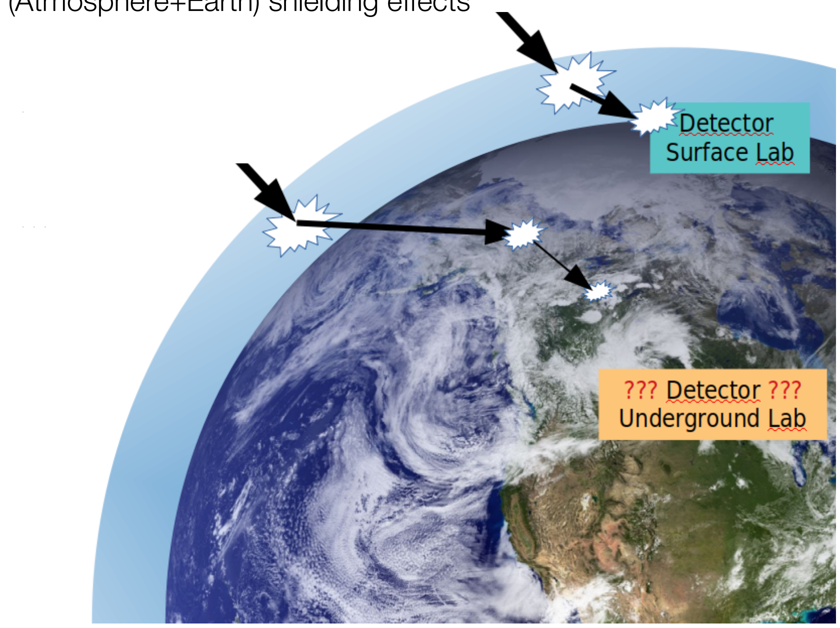


Strongly Interacting Massive Particless (SIMPs)
undetectable in deep-undergound sites

(Atmosphere+Earth) shielding effects

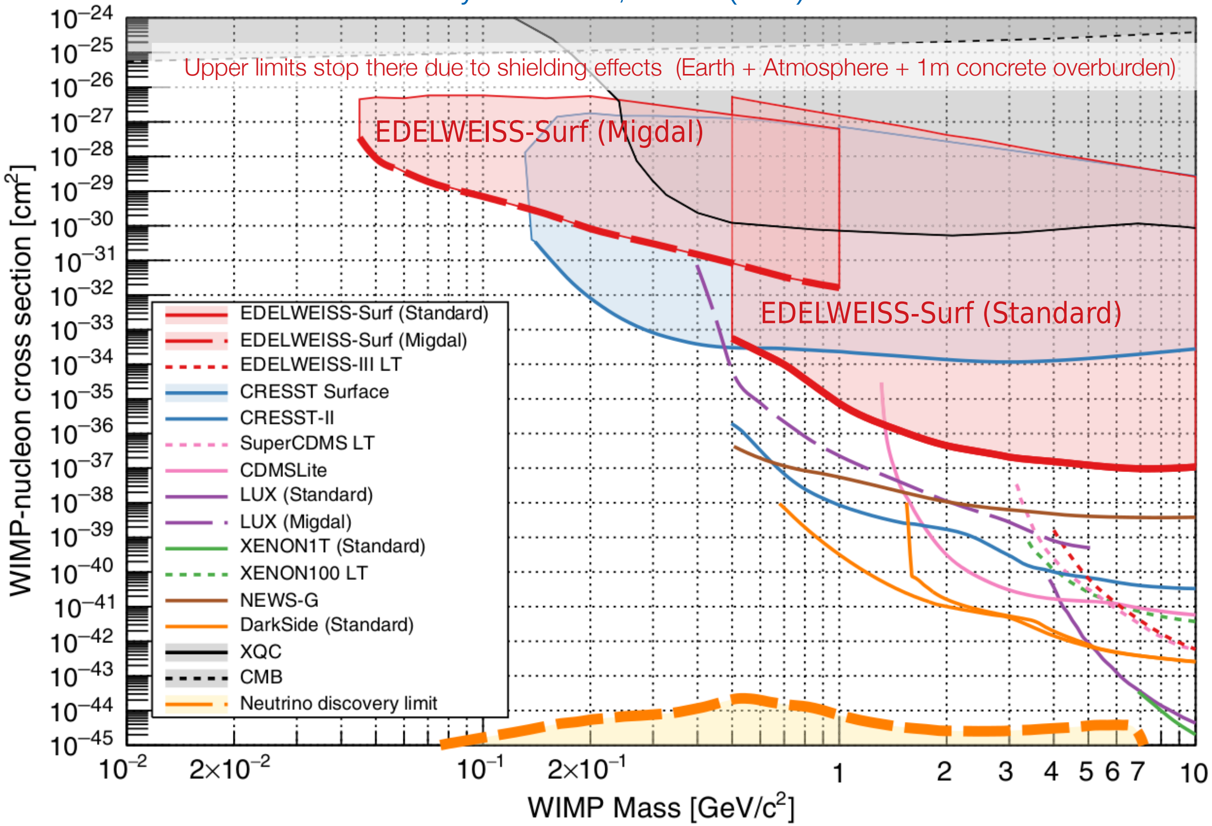


EDELWEISS-surf (Standard): best above ground limit down to 600 MeV

EDELWEISS-surf (Migdal) : first DM limit down to 45 MeV limited by Earth-Shielding effect *(B. Kavanagh, 2017)*, which becomes significant > 10^{-31} cm²

EDW-Surface Results : Spin-Independent

Phys. Rev. D 99, 082003 (2019)



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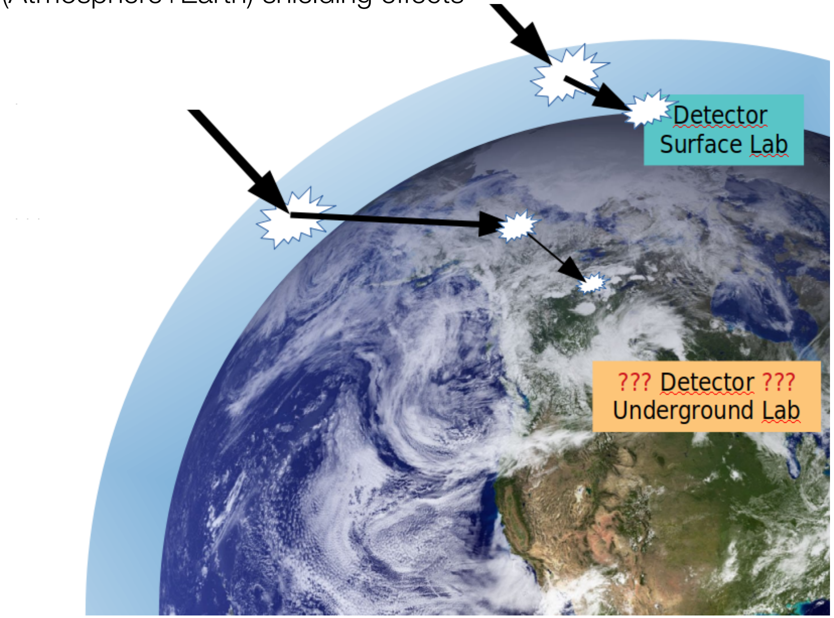
undetectable in deep-undergound sites

(Atmosphere+Earth) shielding effects



EDELWEISS-surf (Standard): best above ground limit down to 600 MeV

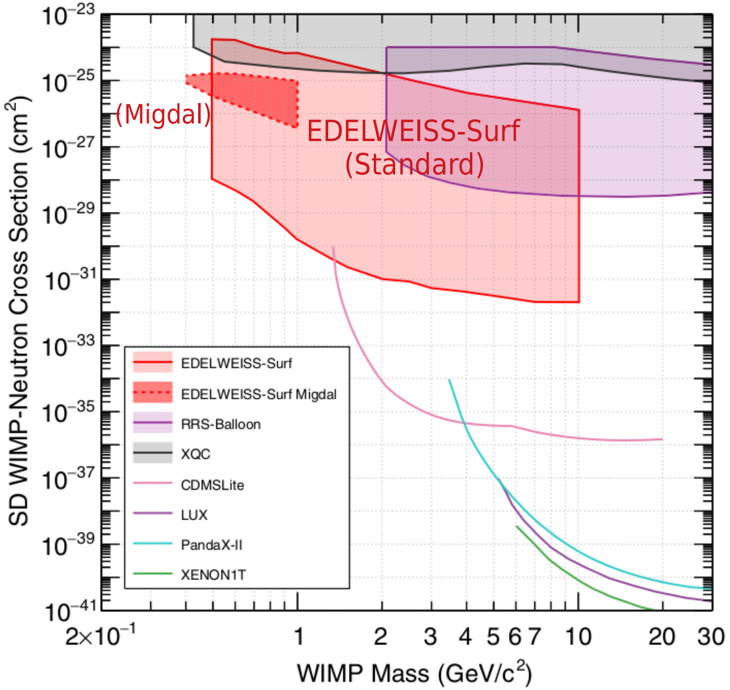
EDELWEISS-surf (Migdal) : first DM limit down to 45 MeV limited by Earth-Shielding effect *(B. Kavanagh, 2017)*, which becomes significant > 10^{-31} cm^2

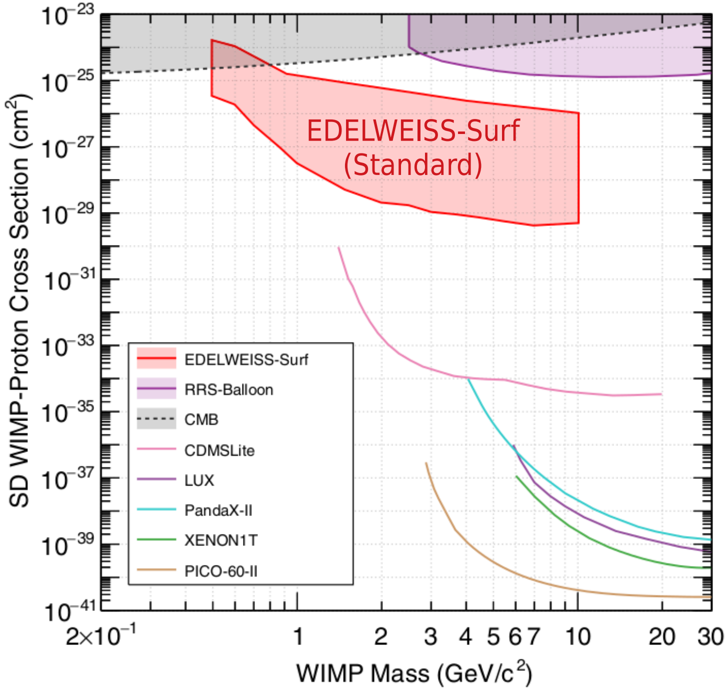
EDW-Surface Results : Spin-Dependent

^{73}Ge is the only stable germanium isotope with nonzero nuclear spin (J=9/2)

- *natural abundance of 7.73%*
- *single unpaired neutron*

Most Spin Dependent stopping comes from Nitrogen in the atmosphere : ^{14}N has both p and n spin





EDELWEISS-surf (Standard): best above ground limit in the [500 MeV – 1.3 GeV] mass range for both SD couplings on protons and neutrons
EDELWEISS-surf (Migdal) : only in the SD-neutron case : extends our lower DM mass bound down to 400 MeV

LSM underground laboratory

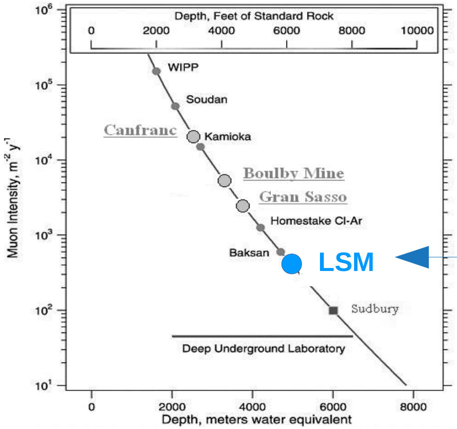
LSM : deepest site in europe
4800 m.w.e. rock overburden ~5 μ/m²/day

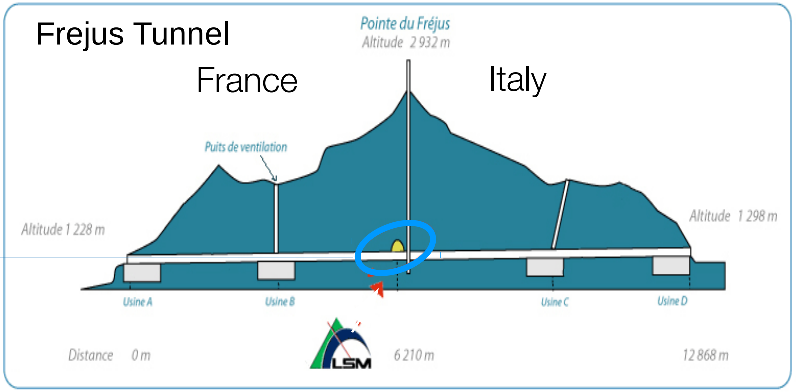
Clean room, de-radonised air ~10-20 mBq/m³

External (50 cm) + internal polyethylene shielding

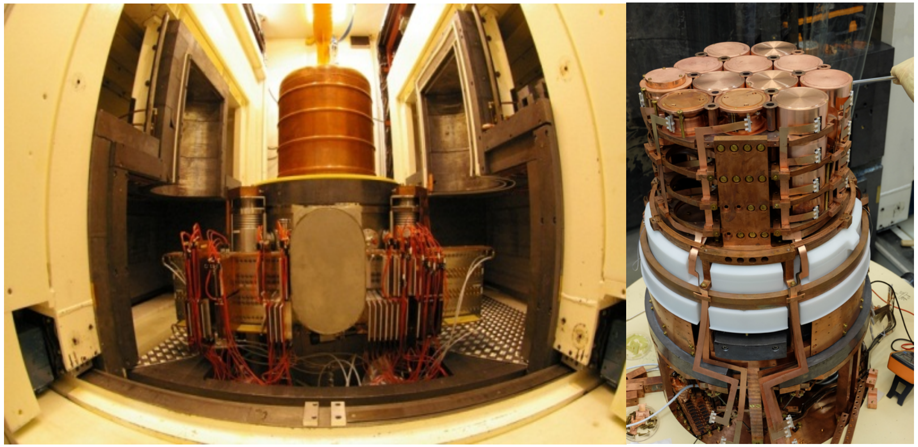
Lead shielding (20 cm, including 2 cm Roman lead)

Selection of radiopure materials

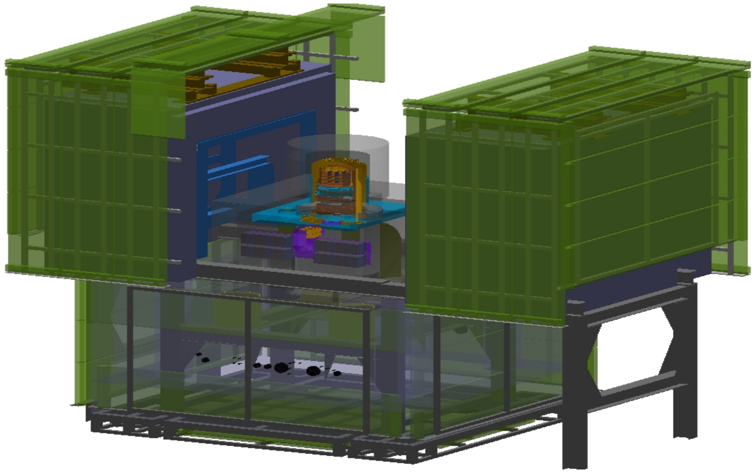




Cryostat hosting up to 40 kg of detectors at 18 mK

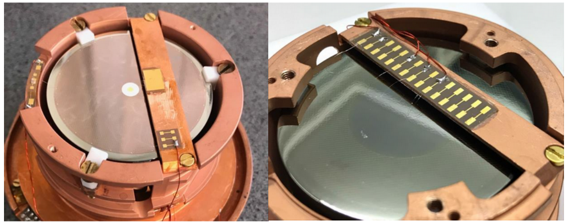


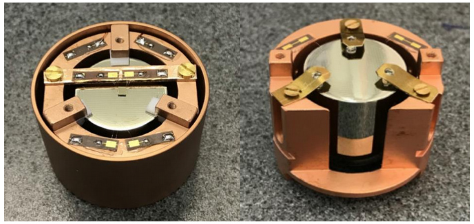
Active muon veto (>98% coverage) on mobile shield



DM-electron scattering searches at LSM

Near single-electron sensitivity with massive bolometers operated at the LSM

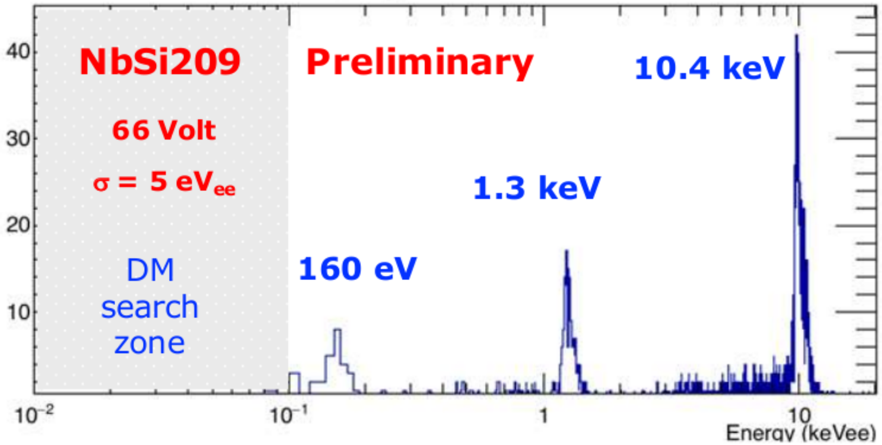


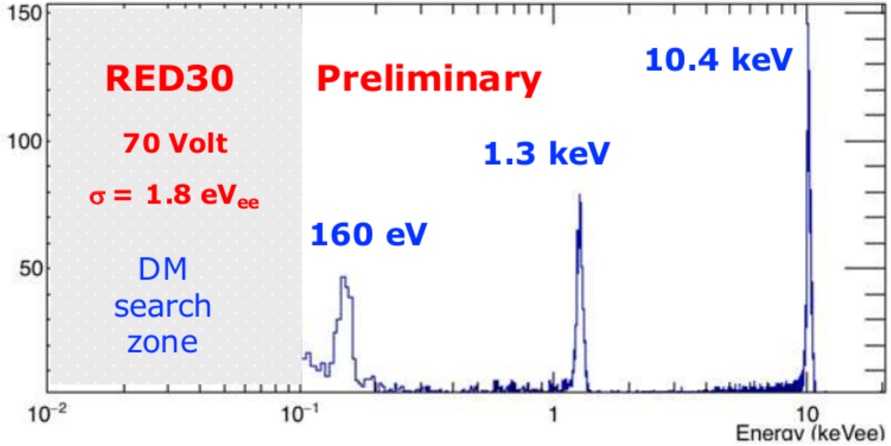


NbSi209
200 g Ge crystal with TES thermal sensor

RED30
33 g Ge crystal with NTD thermal sensor

Calibration : KLM ^{71}Ge from neutron activation 3.7 GBq AmBe source (~2x10^5 neutrons)





First EDELWEISS DM-electron scattering and absorption results expected by the end of the year

Conclusions

The **EDELWEISS-SubGeV** program aims at probing **MeV-GeV particles** via **ER** and **NR** interactions

Low-voltage program objectives : baseline resolutions (RMS) of 10 eV (heat) and 20 eV_{ee} (ionization)

- ***Particle identification and surface event rejection down to 50 eV***

High-voltage program objectives : baseline resolutions (RMS) of 10 eV (heat) and 100 V with amplification of signal only

- ***Single e^-/h^+ pair sensitivity on massive (~30 g) bolometers***
- ***Single ELEctron Nuclear recoil DIScrimination (SELENDIS)***

Huge improvement of heat baseline resolutions beneficial both to low- and high-voltage programs

✓ 20 eV heat energy resolution on multiple detectors ***(reproducibility)***
✓ 18 eV heat energy resolution on RED20 ***(EDW-surf competitive constraints)***
✓ Near single e^-/h^+ sensitivity on 33.4 g and 200 g detectors operated at the LSM ***(Science results by the end of the year)***

CSNSM CNRS/IN2P3
iP2i CNRS/IN2P3
NÉEL institut CNRS/INP
Laboratoire de Photonique et de Nanostructures CNRS
Irfu
IRAMIS CEA/IRAMIS
KIT Karlsruher Institut für Technologie IKP EKP IPE
JINR JINR DUBNA

Back-up Slides

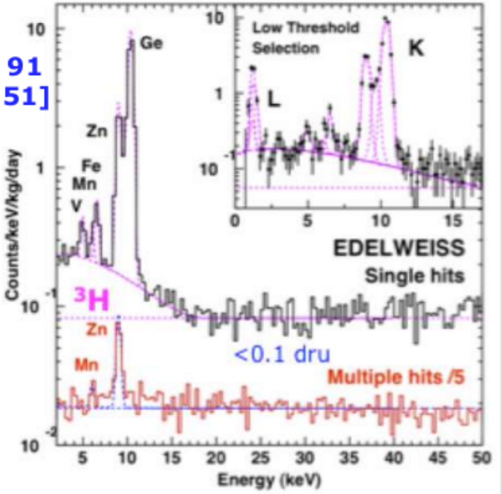
Axion-Like Particle searches

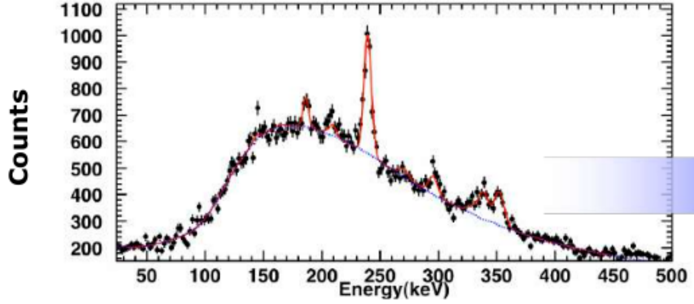
- Starting point: ER spectrum of tritium paper
  - ***Fiducial selection*** (~/2 ER background)
  - ***Singles only*** (~/2 ER background)
  - **1149 kgd** with 2.0 keV_{ee} threshold
  - **287 kgd** with 0.8 keV_{ee} threshold
- **Line search extended up to 500 keV_{ee}**
  - Observed peak intensities consistent with known ^{232}Th, ^{226}Ra, ^{235}U lines from chains in equilibrium
- Resolution (19 detectors @8V):
  - Ion σ ~ 230 eV_{ee}, heat σ ~ 140-500 eV_{ee}
  - **Combined: baseline σ = 190 eV_{ee}**
  - **Proportional term = 1.2%**

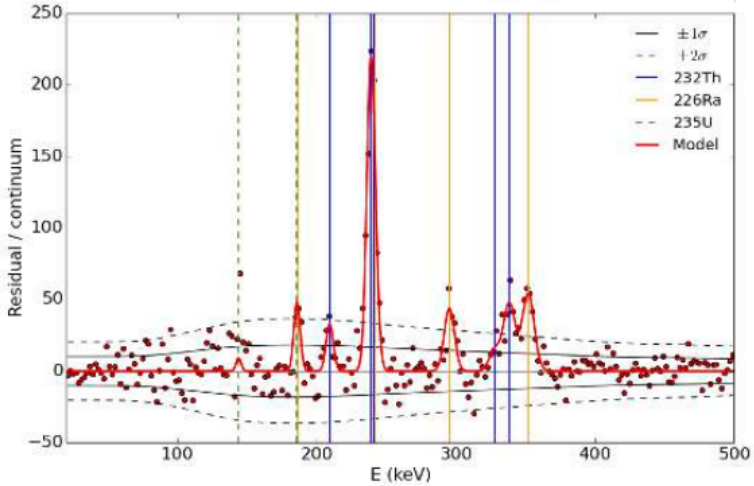
  (V_1 V_2 used to correct for bulk trapping)

[Astropart. 91 (2017) 51]

Compton <0.1 DRU



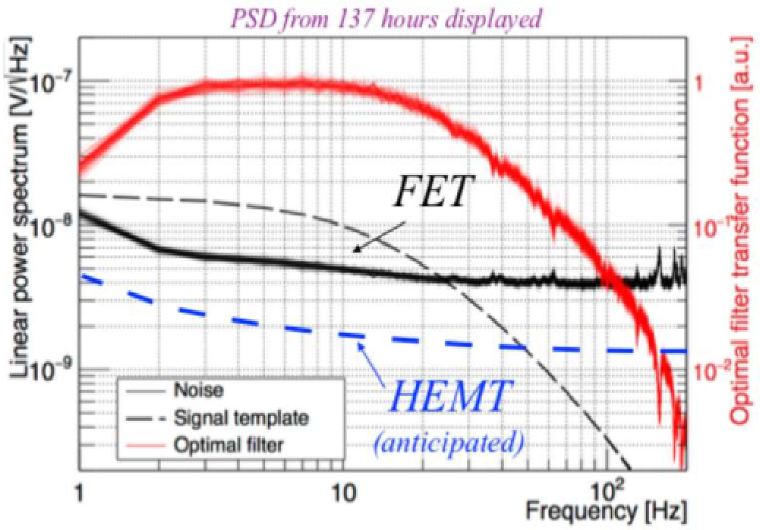




[J. Gascon presentation given @ TAUP2019]

Goal 1: 10 eV phonon resolution

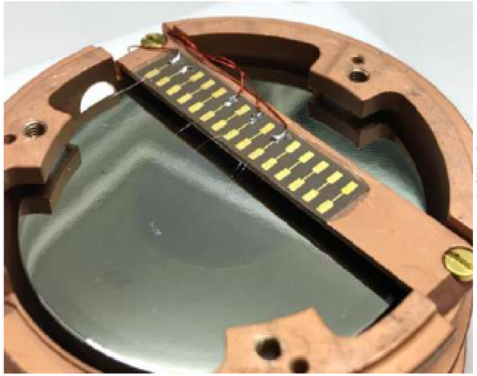
- Results with 33g + Ge-NTD detectors confirm that these sensors are a reliable choice to reproducibly reach σ=20 eV

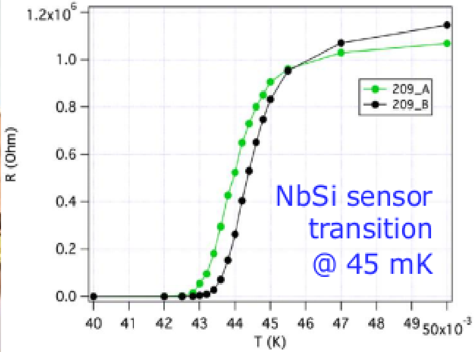


- Replacing JFETs @ 100K with HEMTs @ 1K should provide additional x2 needed in resolution

- Also being investigated: NbSi transition edge sensors

100 nm thick,
20mm diameter spiral NbSi
sensor lithographied
on a 200 g Ge

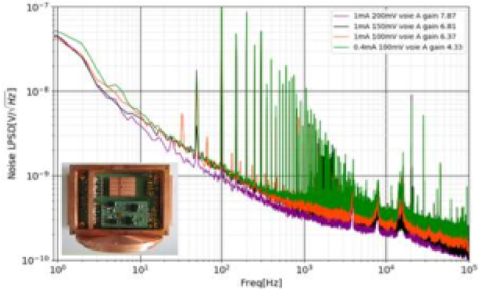




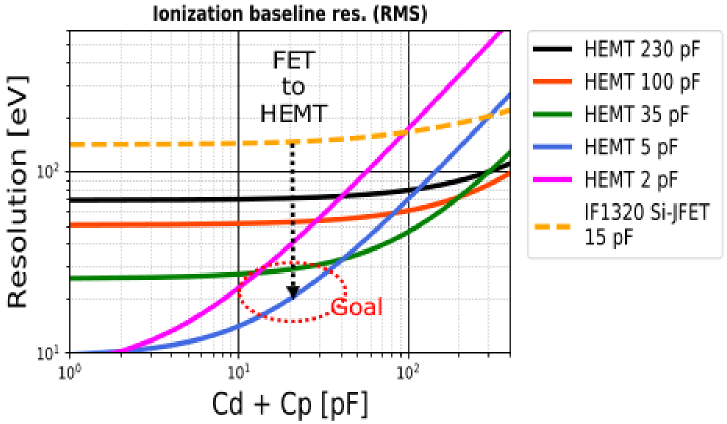
[J. Gascon presentation given @ TAUP2019]

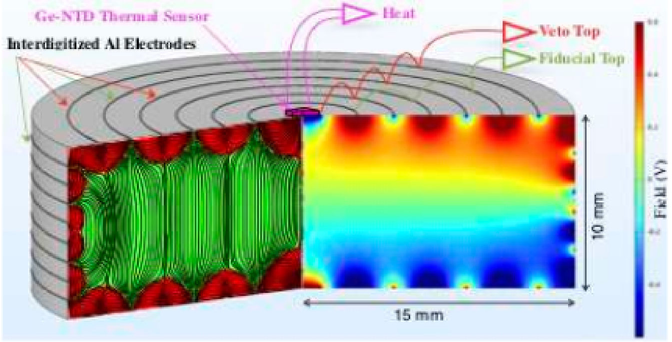
Goal 2: 20 eV_{ee} ionization resolution

- Transition from JFET to HEMT
  [new **arXiv:1909.02879**]
- Lower intrinsic noise + reduce cabling capacitance by working at 1K or 4K
- Data driven HEMT models show that the goal of 20 eV_{ee} is reachable with ~20 pF total input impedance
- Ongoing HEMT characterizations



- HEMT-based preamp tests end of 2019
- Cryogenics + cabling challenges ahead
- **Work done in synergy with the Ricochet-CryoCube collaboration**





Optimization of 33g FID design: large fiducial volume & low capacitance

[J. Gascon presentation given @ TAUP2019]