# SubGeV Dark Matter Searches with EDELWEISS

*The EDELWEISS SubGeV program*

*SIMPs search results*

[PRD 99 082013 (2019)]

*New: search results for light DM interacting with electrons*

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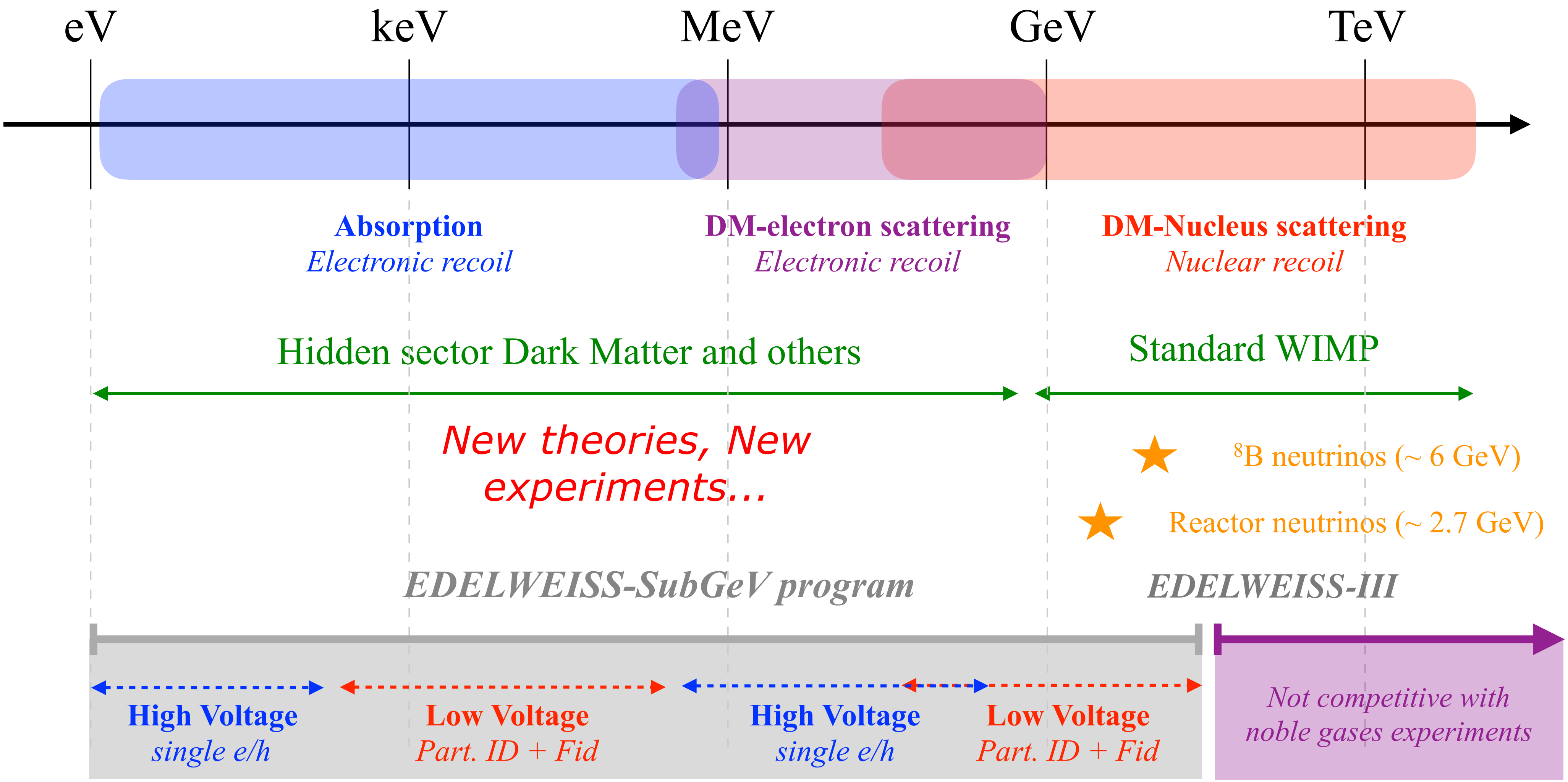
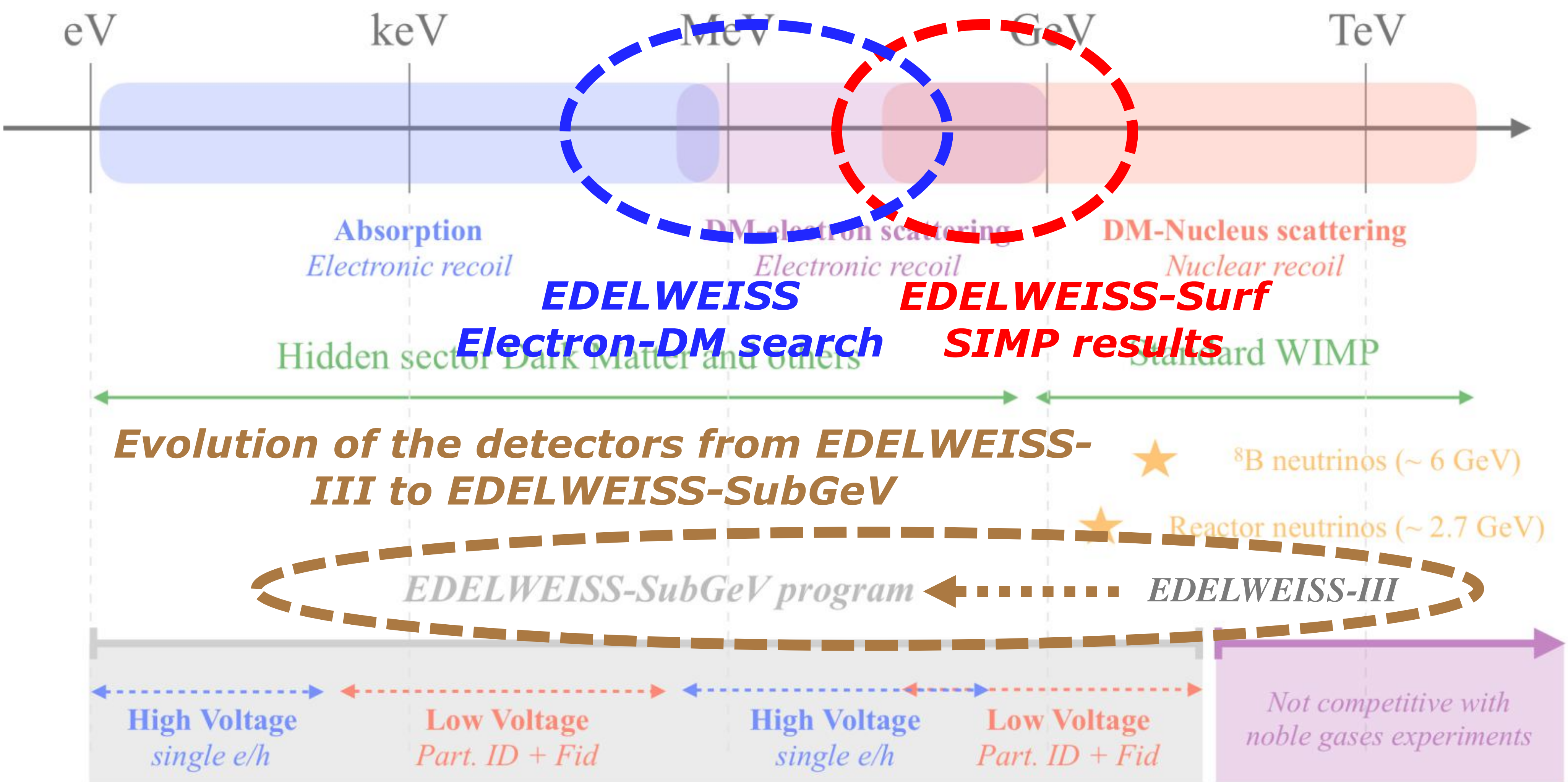
# A widening search domain



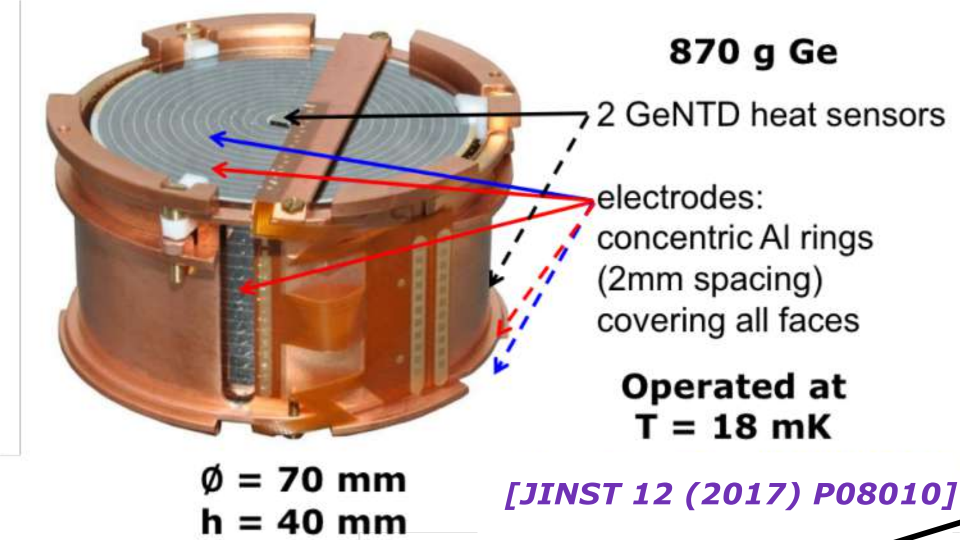

*J. Billard, New Directions in the Search for Light Dark Matter Particles, Fermilab 2019*

# This talk

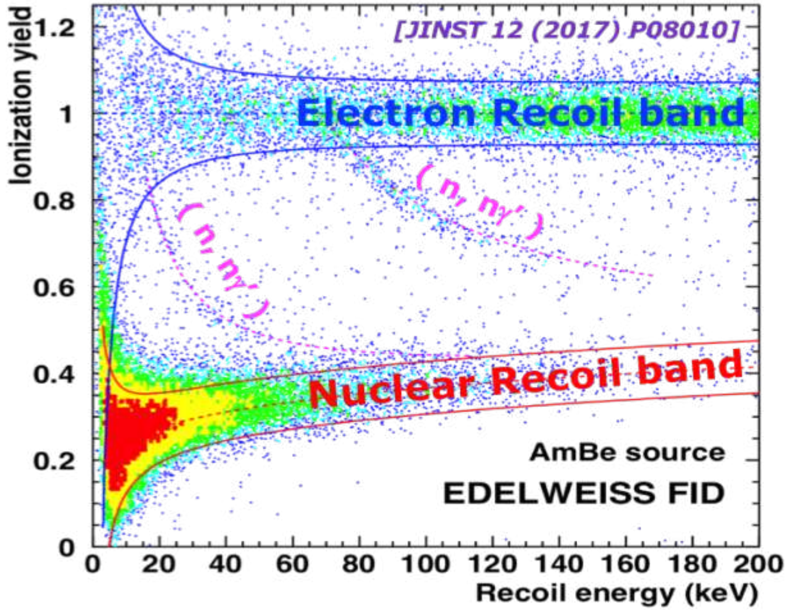



*J. Billard, New Directions in the Search for Light Dark Matter Particles, Fermilab 2019*

# EDELWEISS-III detectors



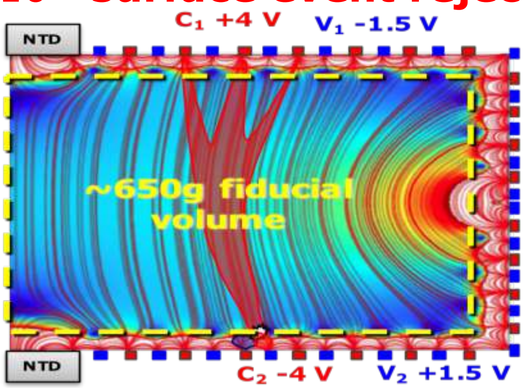

[JINST 12 (2017) P08010]

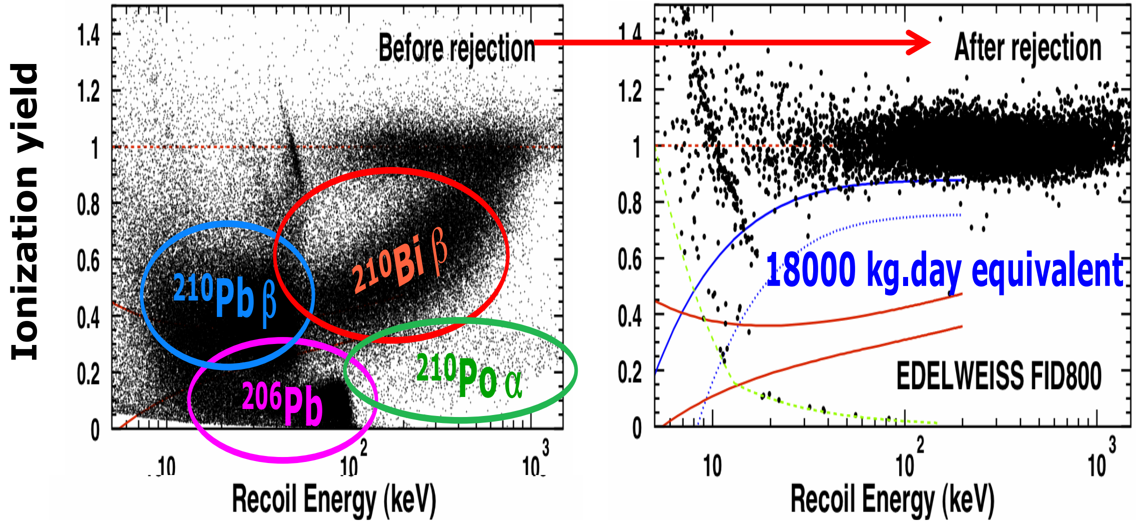



**Heat: $\Delta T = E/C_{cal}$ + Ionization: $N_{pairs} = E/\varepsilon_\gamma$ or $\varepsilon_n$**

**$<2\times10^{-5}$ rejection of electron/nuclear recoils**

Readout of *all* electrodes provides a $<4\times10^{-5}$ **surface event rejection**.

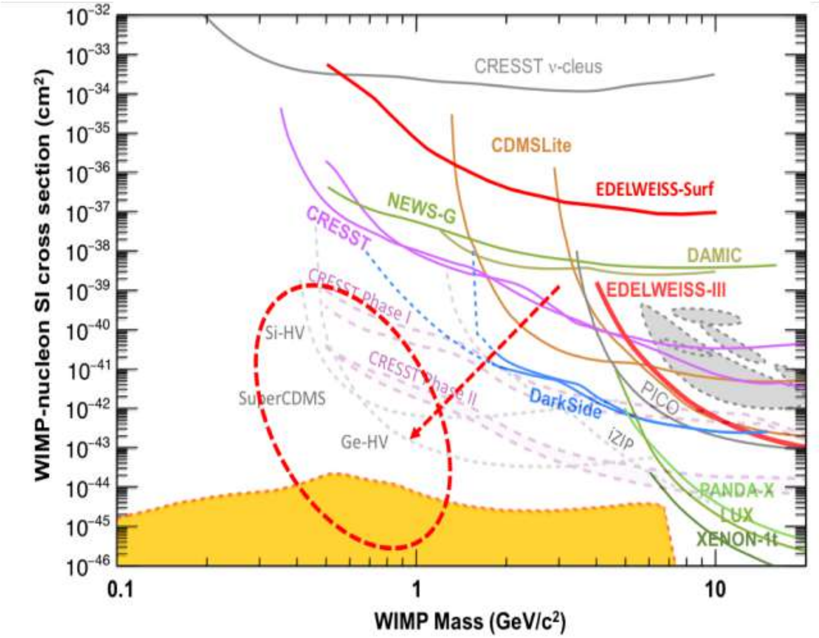


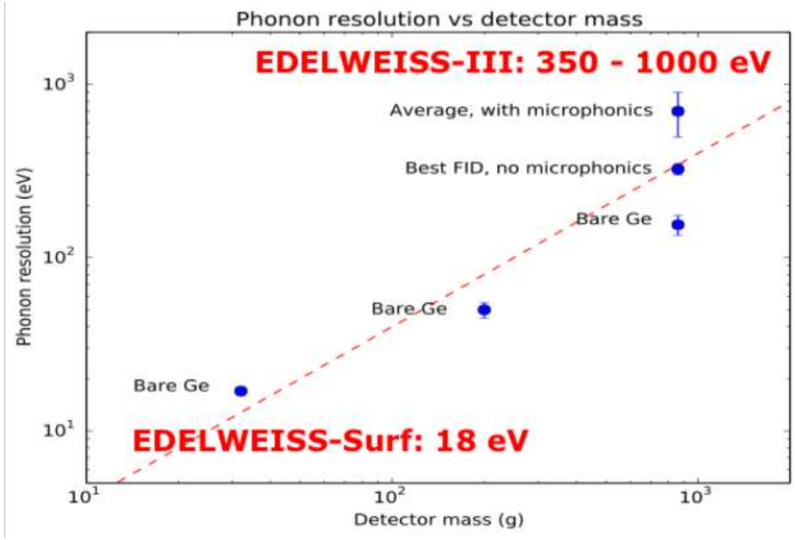



# EDELWEISS SubGeV program

- Current+future projects: background limited
- Event-by-event identification of nuclear recoils down to 1 GeV/$c^2$ ( and reach $10^{-43}$ cm$^2$ with kg-size array) requires

  $\sigma_{phonon}$ ***= 10 eV and*** $\sigma_{ion}$ ***= 20 eV***$_{ee}$
- Ionization resolution is key to particle identification + surface rejection :
  **Cold HEMT preamp + low capacitance (joint development with Ricochet)**



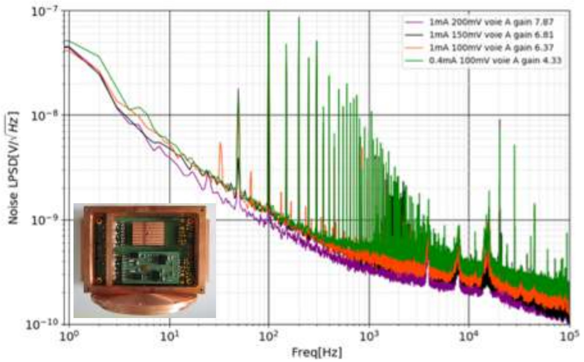

- Reducing the **detector mass** from 860 to 33 g is key to meet these resolution goals

  ***1st milestone: EDELWEISS-Surf***
- Keeping the ability to **apply HV** to amplify heat signal: low thresholds in ER searches & statistical NR/ER separation

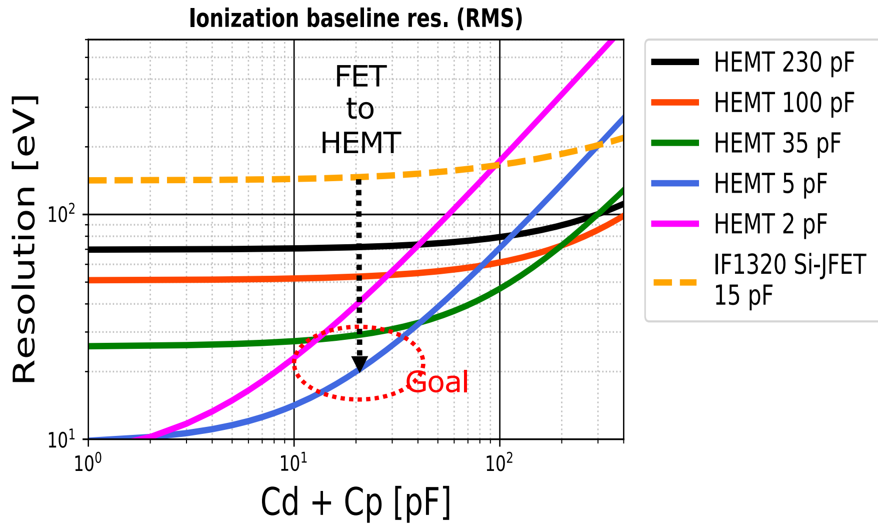
  ***1st milestone: Electron-DM results***

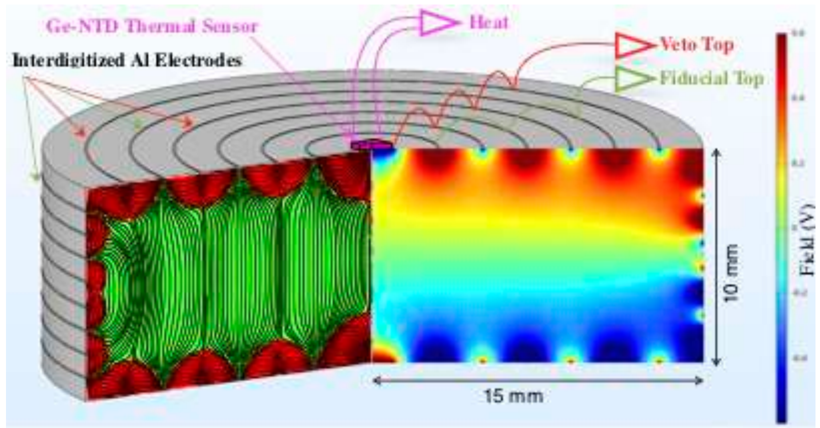
# *Toward 20 $eV_{ee}$ ionization resolution*

- 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**

*Searching for low-mass dark matter particles with a massive Ge bolometer operated above-ground*, Phys. Rev. D 99 (2019) 082003

# ABOVE-GROUND SEARCHES WITH A 33G DETECTOR

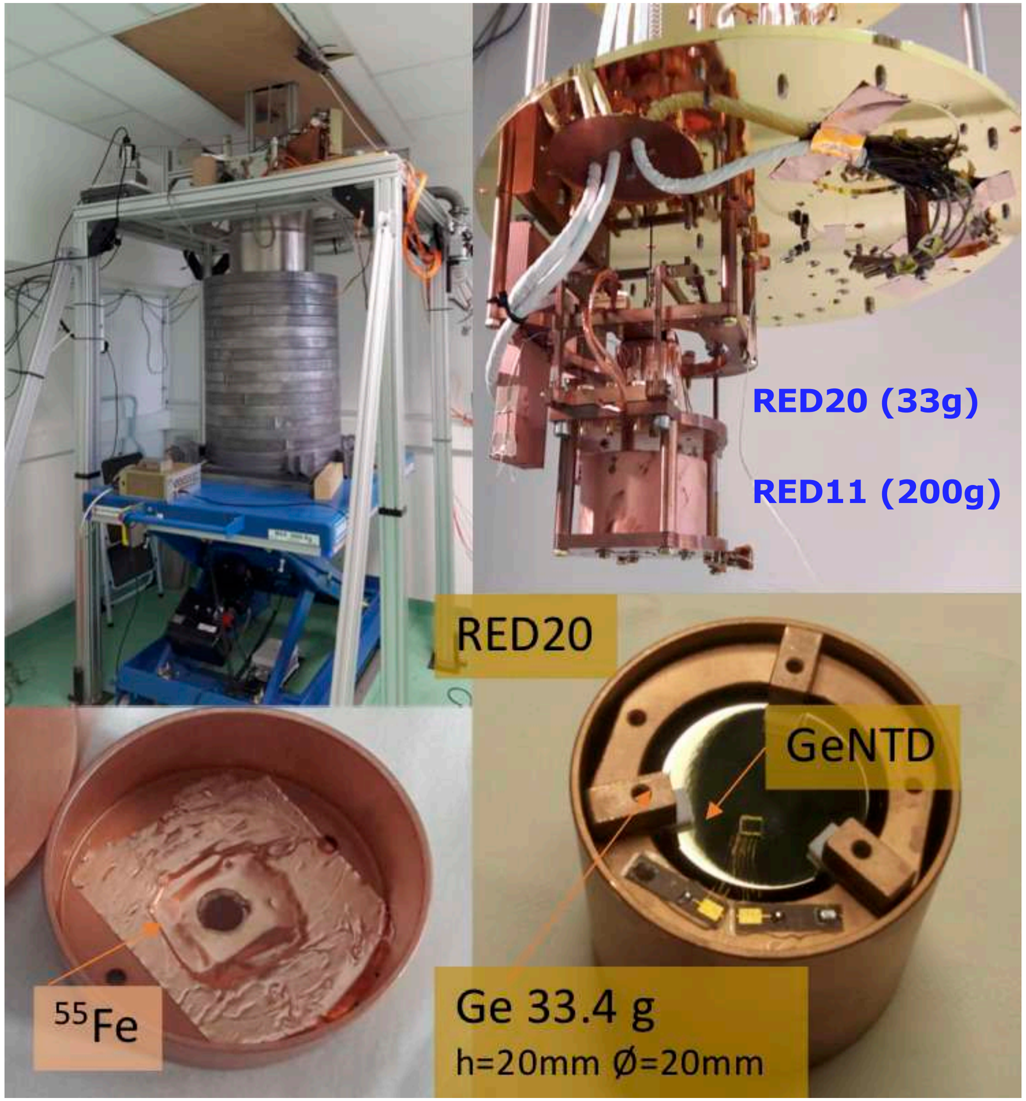
# Theory & experiment motivations for DM surface searches

- Relevance of strong interactions of ~GeV DM particles
  - Main focus of direct DM searches so far: DM-nucleon cross sections below $10^{-31}$ cm$^2$ → Shielding from Earth + atmosphere can be neglected, i.e. experiments are located in deep underground sites, to reduce cosmic-ray induced backgrounds
  - O($10^{-24}$) cm$^2$ **DM-DM** cross-section of ~GeV DM particles could actually help CDM problems at small-scale (DM halo, satellites...) *[Spergel+Steinhardt PRL 84 3760 (2000)]*
  - Natural extension: test for O($10^{-24}$) cm$^2$ **DM-nucleon** interactions *[e.g. Chen et al, PRD 65 123515 (2002)]*

- Technological:
  - *First physics with prototype low-threshold 33g Ge detectors*
  - Detector development program based in surface laboratory
  - Proof that relatively massive EDELWEISS-like detectors can be used in surface experiment, i.e. relevant for the study of the coherent elastic scattering of reactor neutrinos on nucleons (like Ricochet)

# EDELWEISS-Surf Above-ground DM search

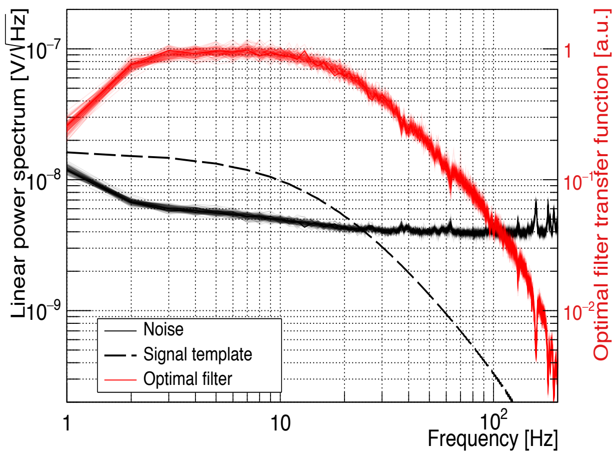
- Context: EDELWEISS and Ricochet common R&D for low-threshold detectors performed in easy-access surface lab @ IPN-Lyon
- **<1 m overburden**: ideal for SIMP search (strongly interacting DM)
- Dry cryostat (CryoConcept) with <30h cool-down (fast turnover ideal for detector R&D) [NIM A858 (2017) 73]
- **< $\mu$g/$\sqrt{}$Hz vibration levels** (spring-suspended tower). [JINST 13 (2018) No.8 T08009]
- RED20: **33g Ge** with NTD sensor, with no electrodes
  - No ER/NR discrimination, but no uncertainty due to ionization yield or charge trapping)
- 55Fe source for calibration

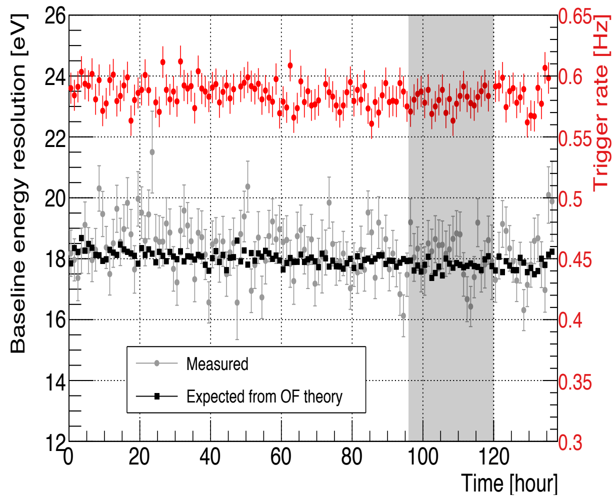


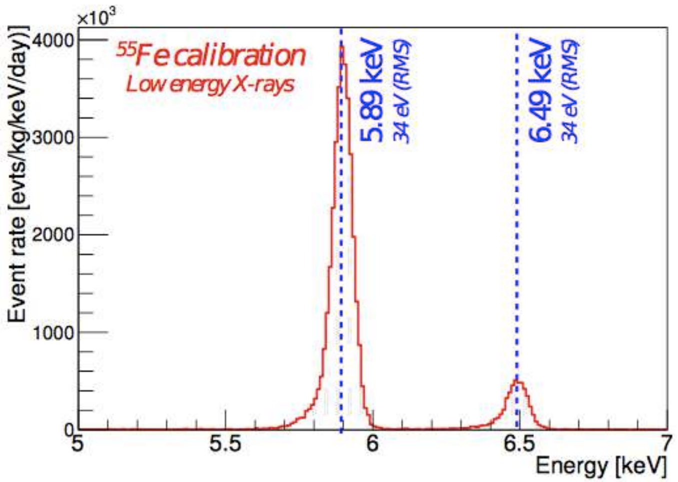
# EDELWEISS-Surf data

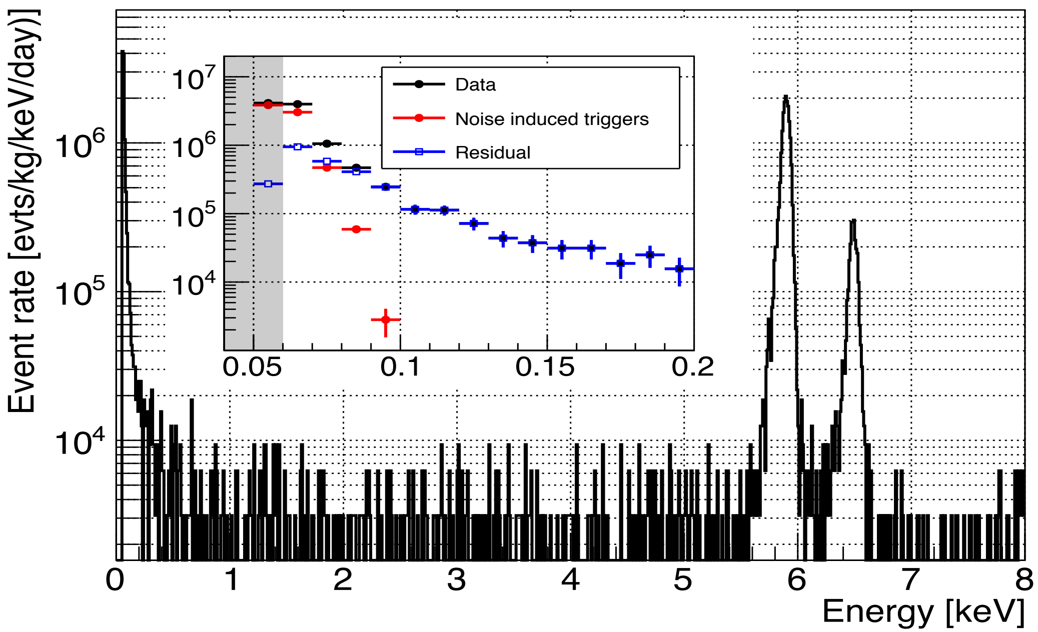
- Streamed data processed with optimum filter
- **Stability** of noise & resolution over 137h (6 days) of data taking
- 1 day set aside a priori for blind search
- **Baseline: σ = 17.8 eV**
- **@5.9 keV: σ = 36 eV**

*PSD from 137 h displayed*



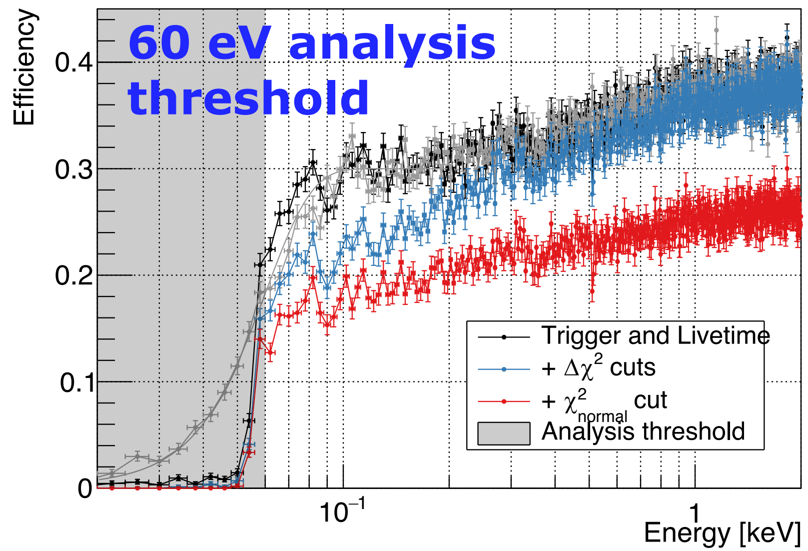



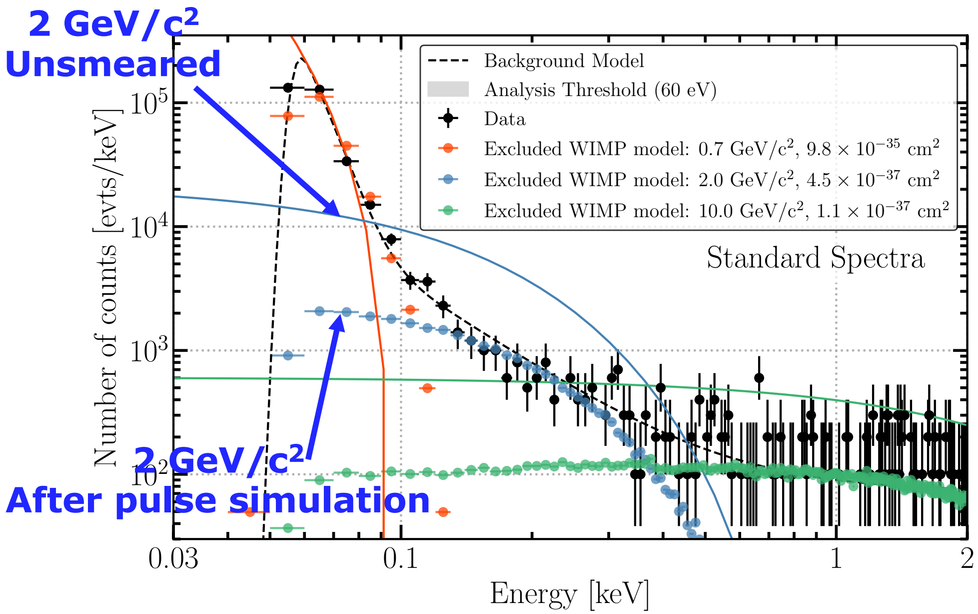



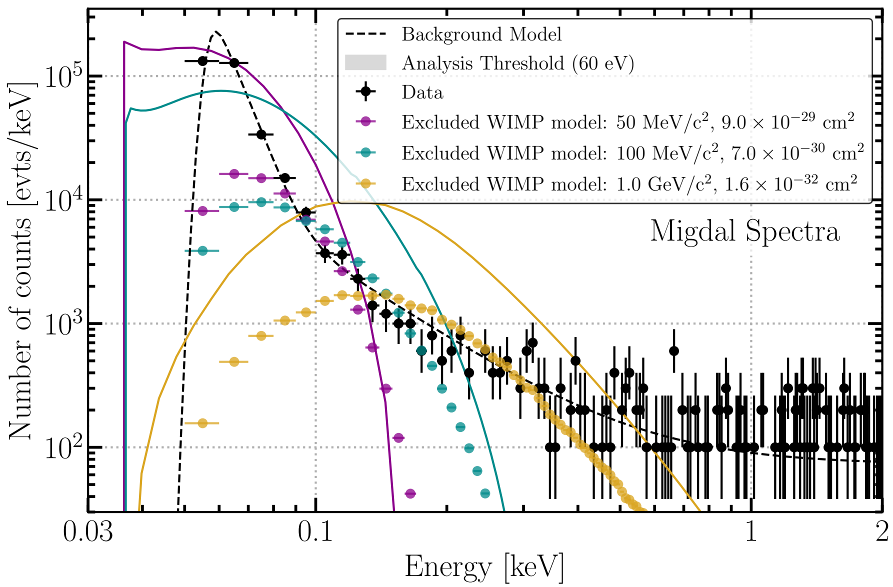

**[PRD 99 082013 (2019)]**

# *Efficiency, signal prediction: pulse simulation*

- Efficiency (including deadtime, pileups and $\chi^2$ cuts) obtained by inserting pulses at random times in actual data stream
- Same technique used to evaluate response to WIMPs of given masses
  - **Case 1: NR from standard WIMPs**
  - **Case 2: ER+NR including Migdal effect (ejection of *n*=3-shell e$^-$ in WIMP-atom collision** *[cf Ibe et al, JHEP 03 (2018) 194]* **)**



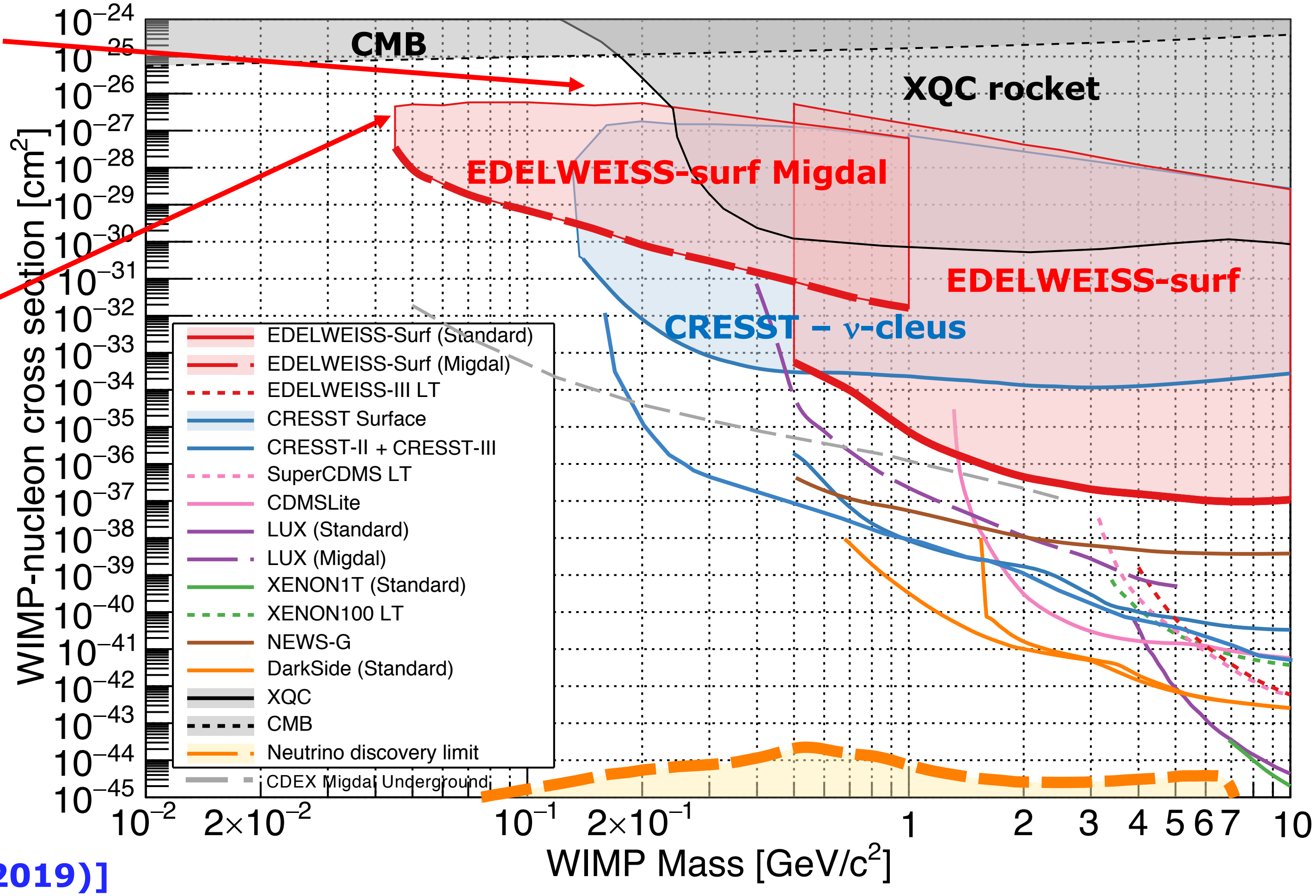



# Filling the gap between ground & space searches

- Shaded regions: with full Earth-Shielding (ES) calculation
- Lines: underground limits (w/o ES calculation, ~ok for <$10^{-31}$ $cm^2$)

Stronger upper cutoff for Migdal (subleading component)

Sharp 45 MeV/$c^2$ cutoff due to ES effect on velocity




*** Also: spin-dependent limits**

**[PRD 99 082013 (2019)]**

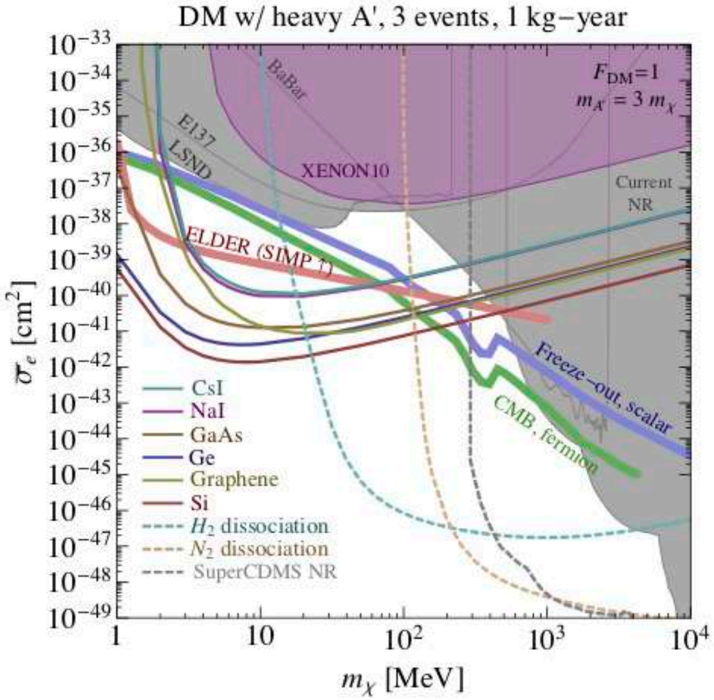
Next step: going deep underground to reduce backgrounds

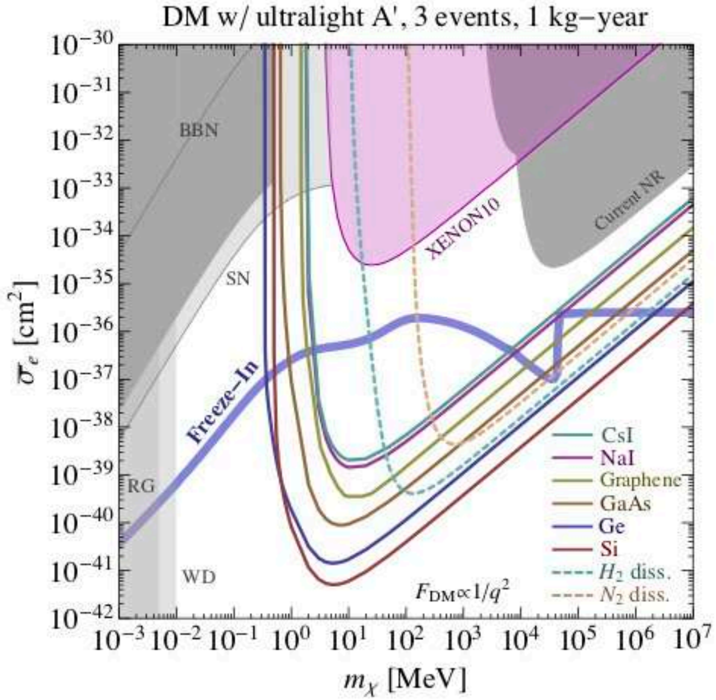
New results:

# *UNDERGROUND SEARCH FOR ELECTRON-DM INTERACTIONS WITH A 33G GE DETECTOR*

## *Theory + experiment motivation: searches for electron-DM interactions*

- New class of light DM models where the interaction with normal matter comes from the coupling of a Dark Sector photon with the normal photon
- Preferred detection mode: DM-electron scattering
- ***Benchmark model predictions:*** *complete coverage ($10^{-40}$ cm$^2$) possible with ~1 kg.year exposure of a detector sensitive to the single-electron in the absence of any background*




Dark Sectors 2016 Workshop: Community Report (arXiv:1608.08632):

# Searching with semiconductors: Ge

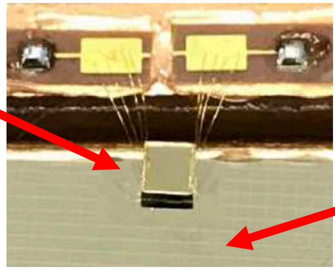
- Semiconductors: small gap energy + small leakage current
- Challenges: leakage current (1 e-/kg/y ~ $10^{-27}$ A/kg) and electrons from radioactivity (1 e-/kg/y ~ $10^{-8}$ Bq/kg)
- Interesting improvements in bkg levels already obtained in Si with ~g pixel CCD arrays (DAMIC, SENSEI) and <1g cryogenic detector (CDMS)
- *Ge interesting alternative for a massive detectors : need to assess performance in terms of currents & backgrounds*

- ***HV mode of EDELWEISS-SubGeV program:***
  - A 33g EDELWEISS-surf detector (equipped with electrodes) operated at ~100 V should reach sub-electron resolution (<<3 eV)
  - EDELWEISS has been able to obtain at LSM the lowest radioactive background levels below 10 keV in massive Ge detectors (~0.1 evt/kg/day/keV)

# RED30 Detector

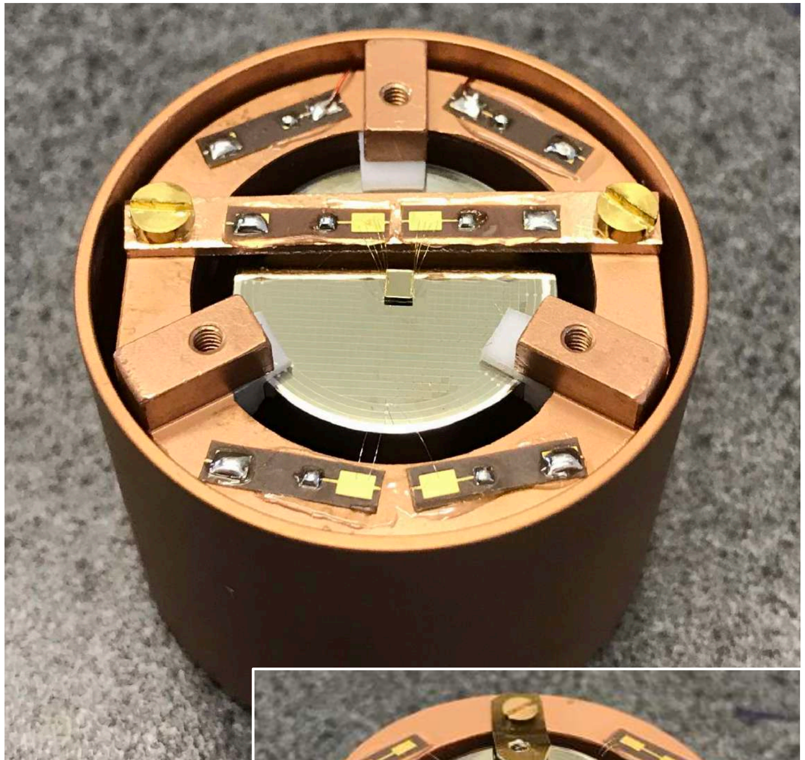
- Essentially: EDELWEISS-surf detector + with electrodes added
- Ge ϕ 20 x H 20 mm² (33.6 g)
- 1 Ge-NTD sensor (1.6 mm³) glued directly on bottom Ge surface

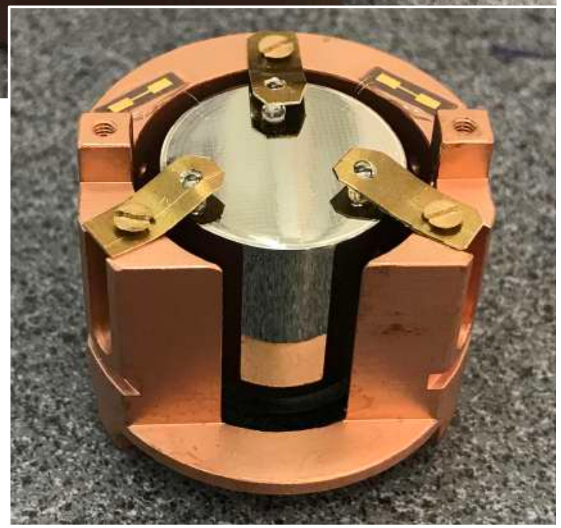
NTD sensor



Al grid electrode

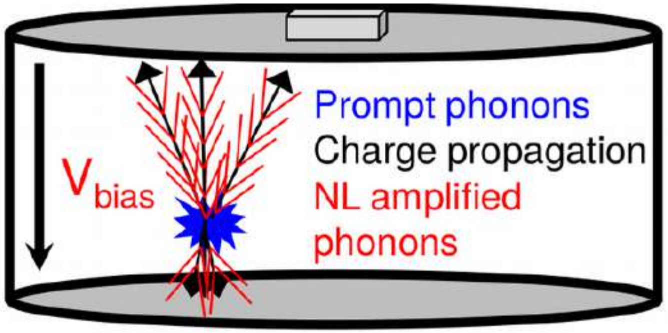
- Electrodes on flat surface: lithographed Al grid (500 μm pitch, 4% coverage to reduce phonon trapping)
- Outer rings of the grid acts as separate guard electrodes (outer ~2 mm)
- No side electrodes on this prototype (mitigation of risk of leakage at HV)





# Luke-Neganov amplification

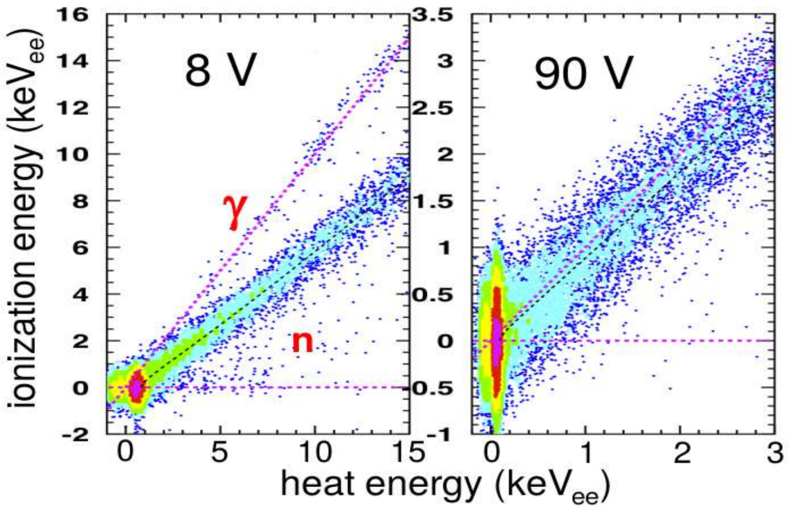
- Addition to heat signal due to drift of charges in applied electric field

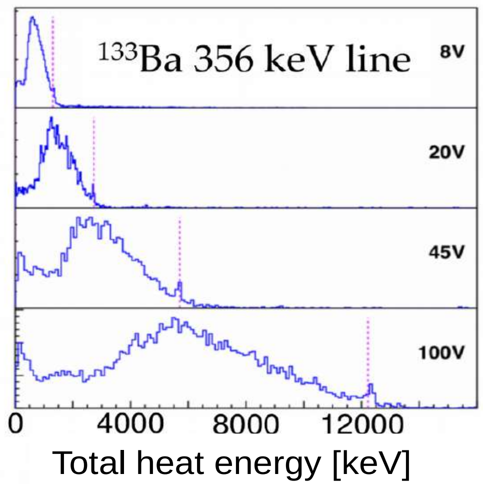


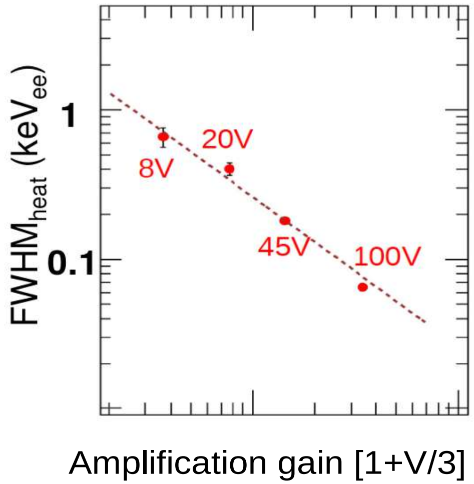

$$E_{heat} = E_{recoil} + E_{Luke} = E_{recoil} + N_p \Delta V$$

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

- Amplification proportional to ionization signal and to bias :
  - Loss of discrimination as heat signal becomes a copy of the ionization signal
  - ***Gain in resolution by a factor (1+ΔV/3) for electron signals***

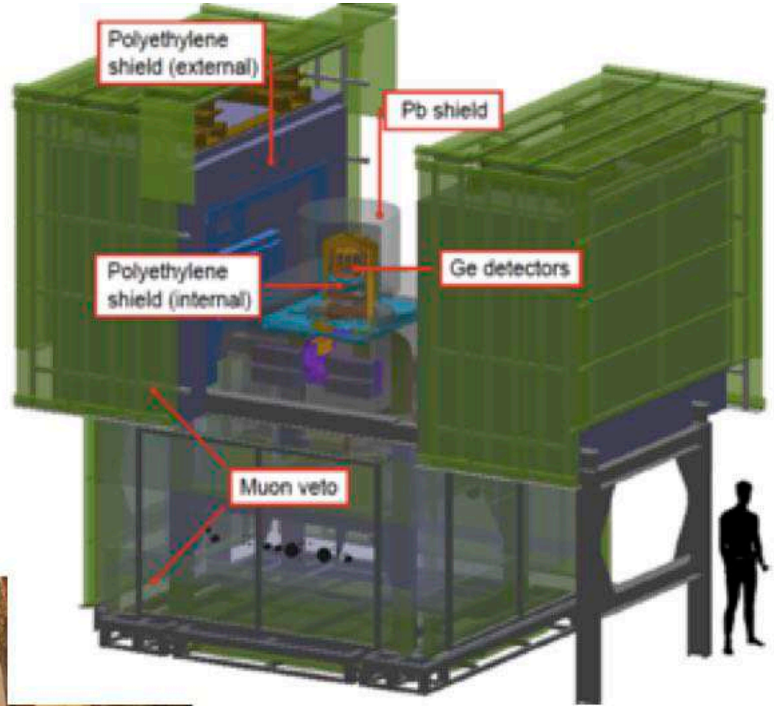


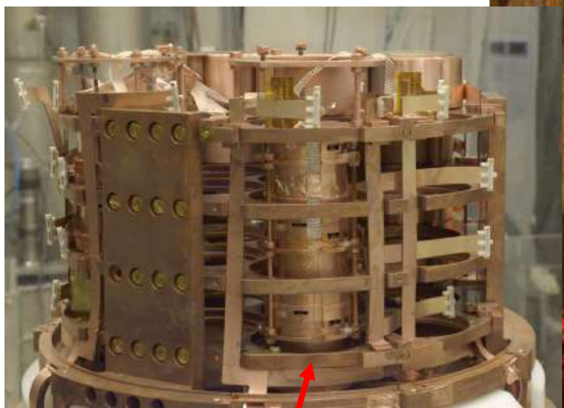



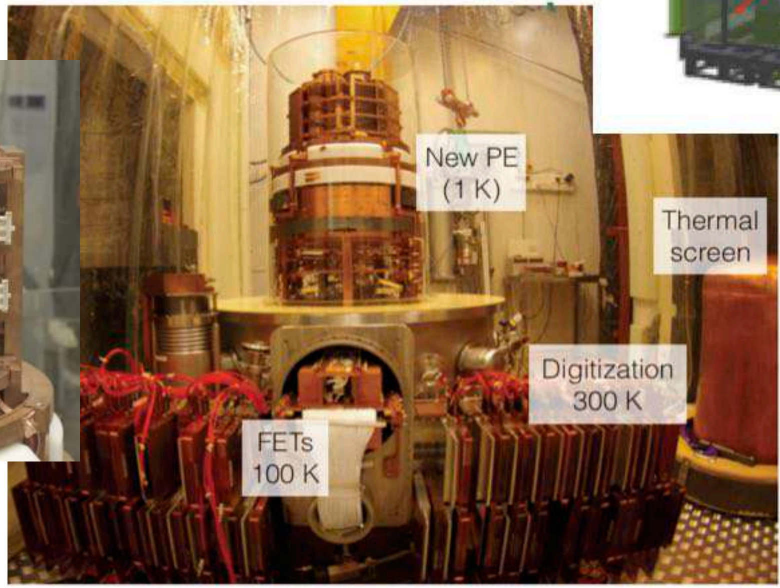
# EDELWEISS setup at LSM

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



RED30 tower



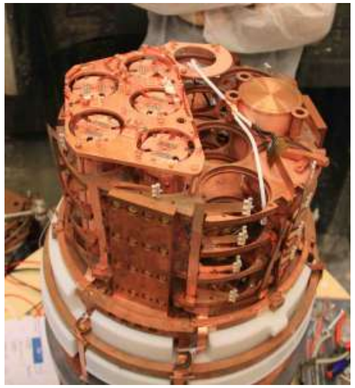

Cryostat can host up to 40 kg detector at 18 mK

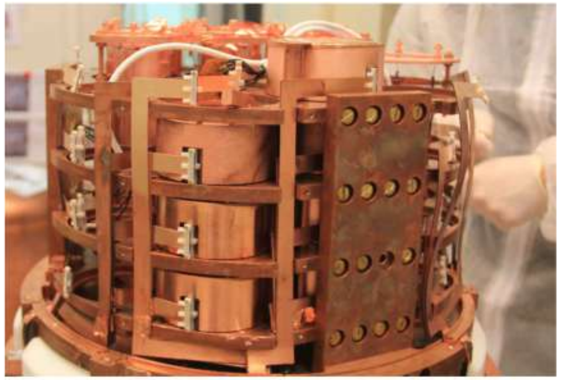
*Performance of the EDELWEISS-III experiment for direct dark matter searches*

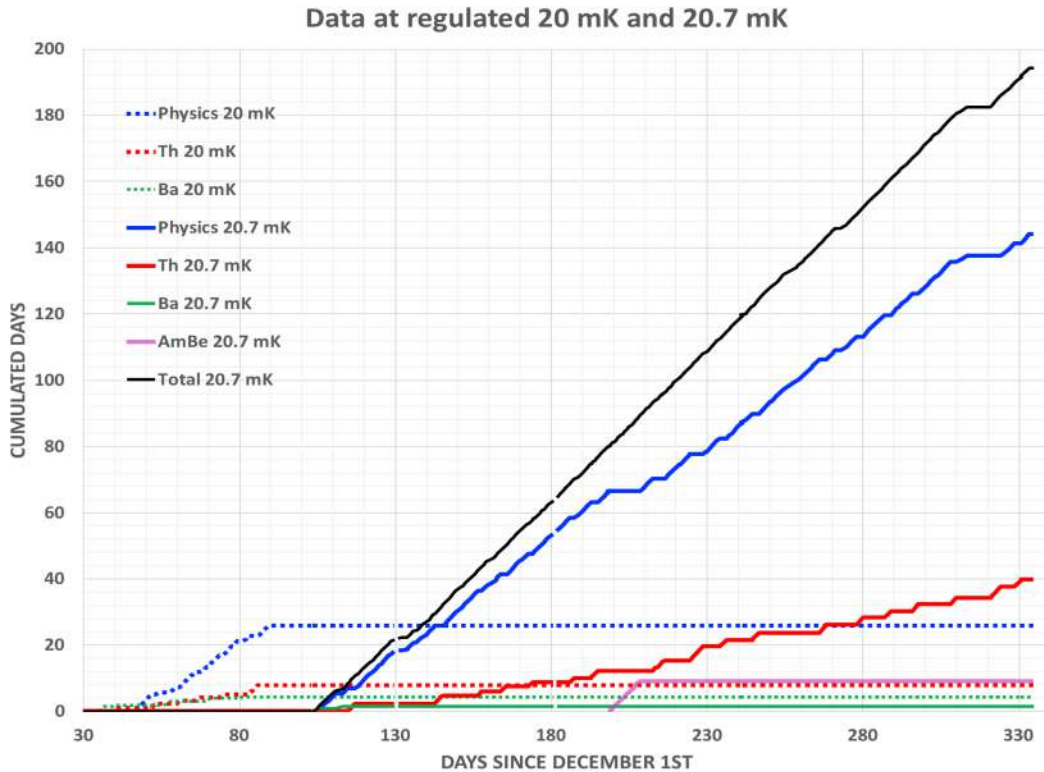
***[JINST 12 (2017) P08010]***

# Current EDELWEISS run at LSM

- **Continuous running at ≤22 mK Jan-Dec 2019**
- Eleven Ge detectors
  - Rest of cryostat used for joint physics run with CUPID-Mo
- Compare detector physics in 33g, 200g and 800g detectors
- Compare performance of NTD and NbSi-TES heat sensors
- Study of low-energy backgrounds in Ge detectors operated with large Luke-Neganov amplification
- **Limits on Dark Matter using ER and NR spectra of detectors with large Luke-Neganov amplification**
- Data taking to continue in 2020

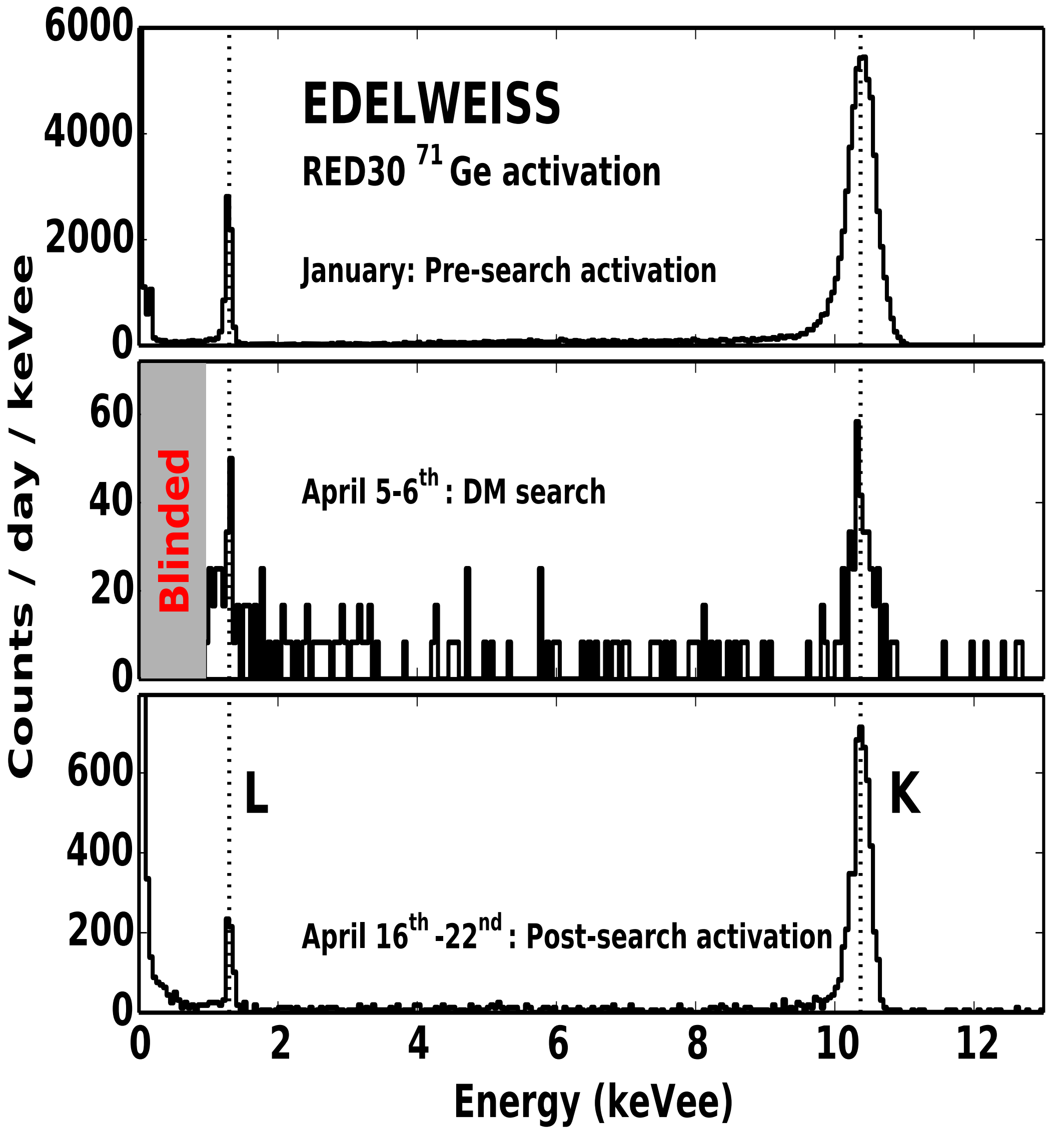






# Detector response measurement with $^{71}$Ge

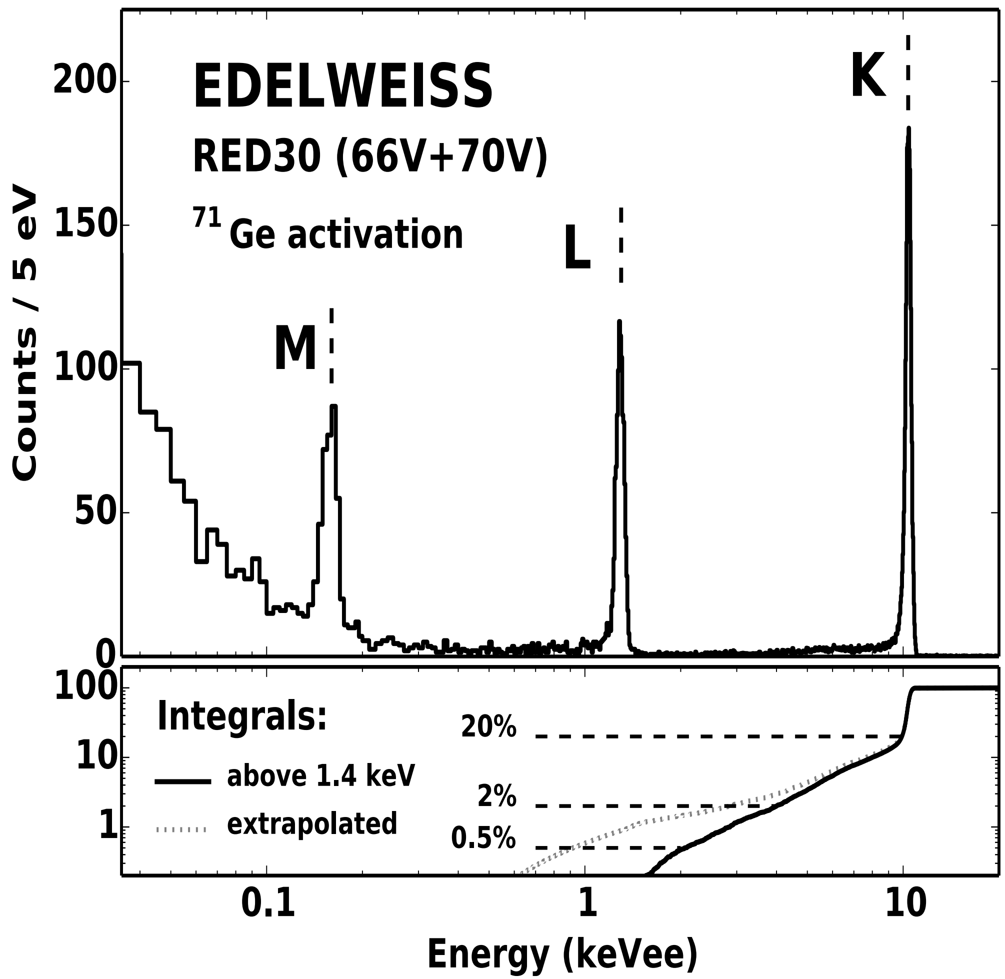
- Extensive detector studies (calib., fid. volume, charge collection) using **$^{71}$Ge 10.37 keV line from exposure to a AmBe neutron source** prior to LSM installation
- April 1st-7th: **DM search at highest stable bias (78V) with reduced (but still visible) $^{71}$Ge activation**
- April 10th : in-situ re-activation to confirm the stability of the detector response and obtain **reference sample of 10.37 keV events** to be used in the data analysis of the DM search data
- May-December: AmBe calibration + further studies of properties of backgrounds at low energy, behavior at high bias, leakage currents, charge collection, etc..



# Detector response

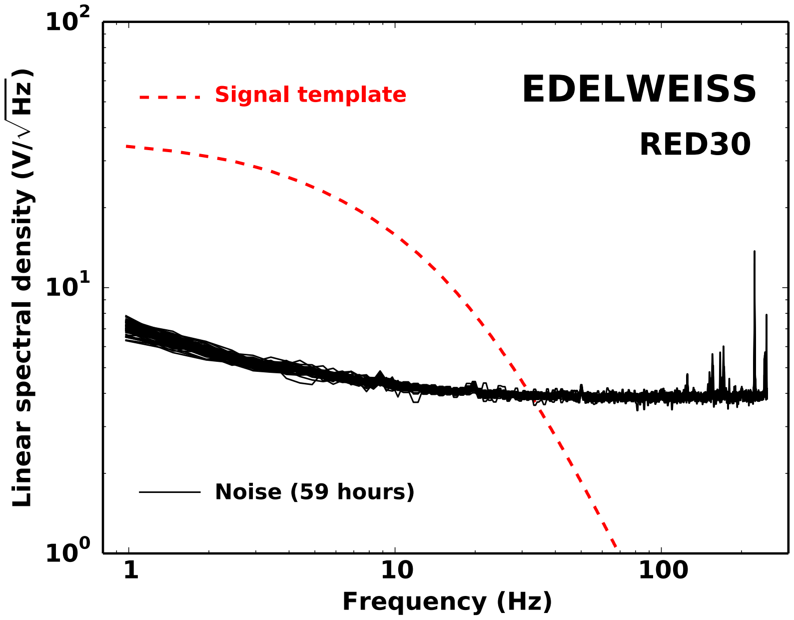
- Ionization channel only used for detector studies, not for DM search
- Heat channel calibrated using $^{71}$Ge KLM lines (0.16, 1.30 and 10.37 keV) at different biases (0V to 81V)

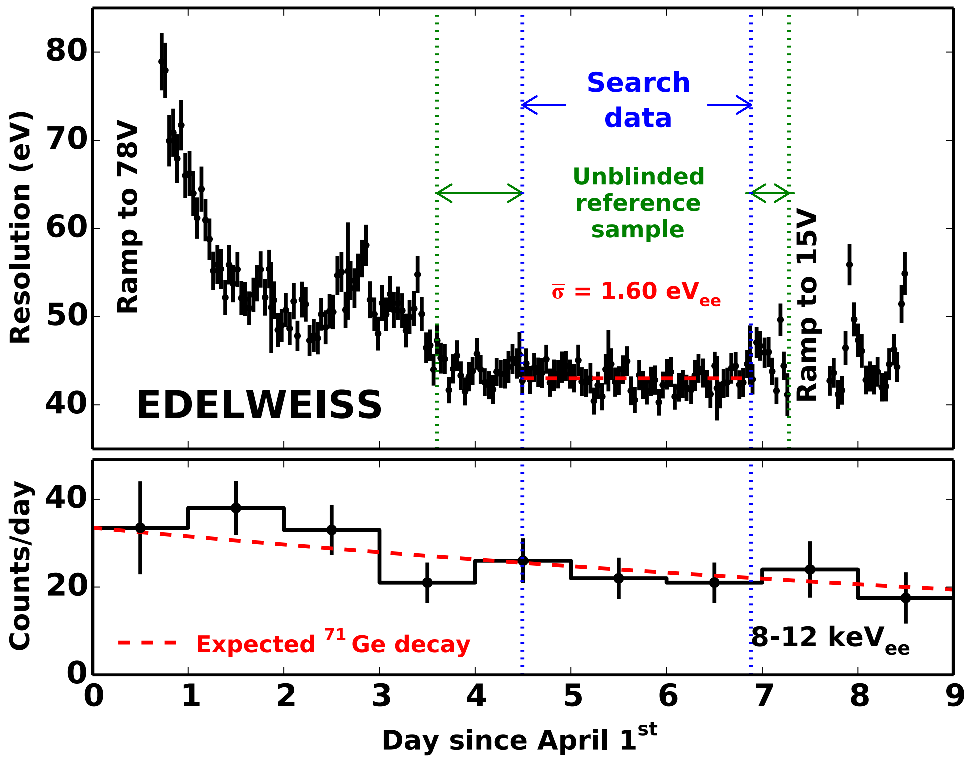
- Tail due to incomplete charge collection on side surface (confirmed by ring guard signal analysis) is <25%: conservatively taken as a 25% loss of efficiency in the following analysis.



# Detector resolution

- Search data: 2.44 day (at 78V) blinded below 1 keV
  - Baseline resolution stabilizes around $\sigma$= 42 eV (1.60 $eV_{ee}$) 4 days after the ramp to 78V
  - Constant resolution (from random trigger data) during these 2.44 days
- Reference sample: 1.3 days before/after search data

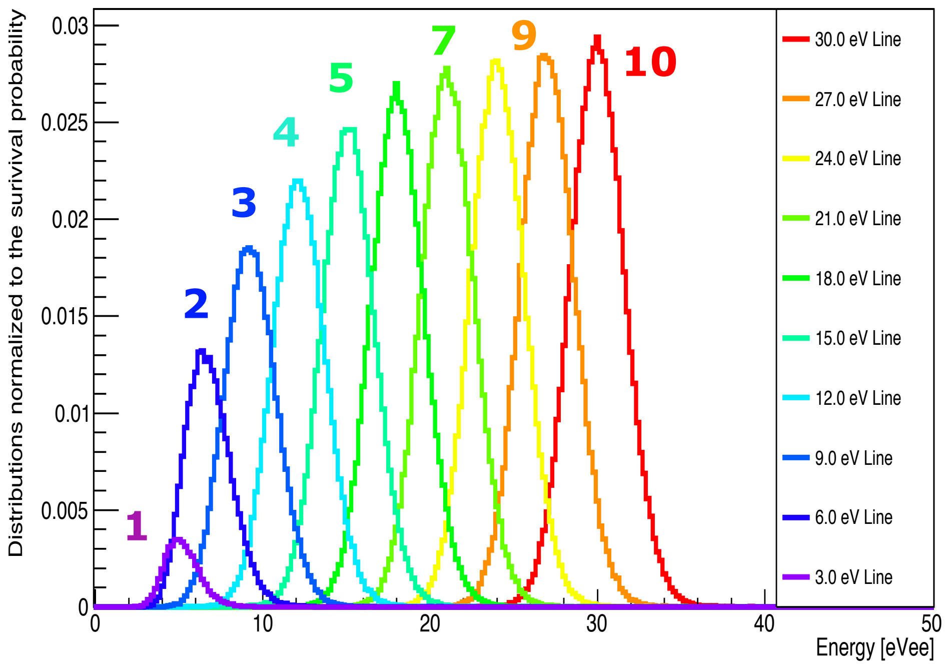


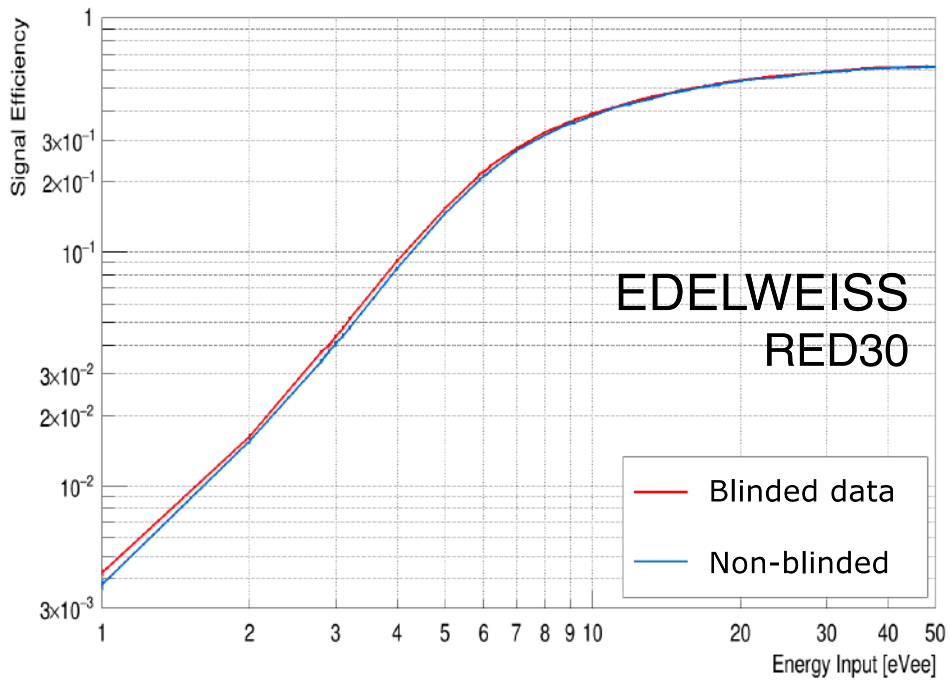



# Efficiency

- Efficiency determined by injecting pulses at random time in the recorded data streams
- The injected pulses are actual $^{71}$Ge K-line events (from the activation that immediately followed the search), rescaled to the desired energy
- Some sensitivity to 1 electron-hole pair signal

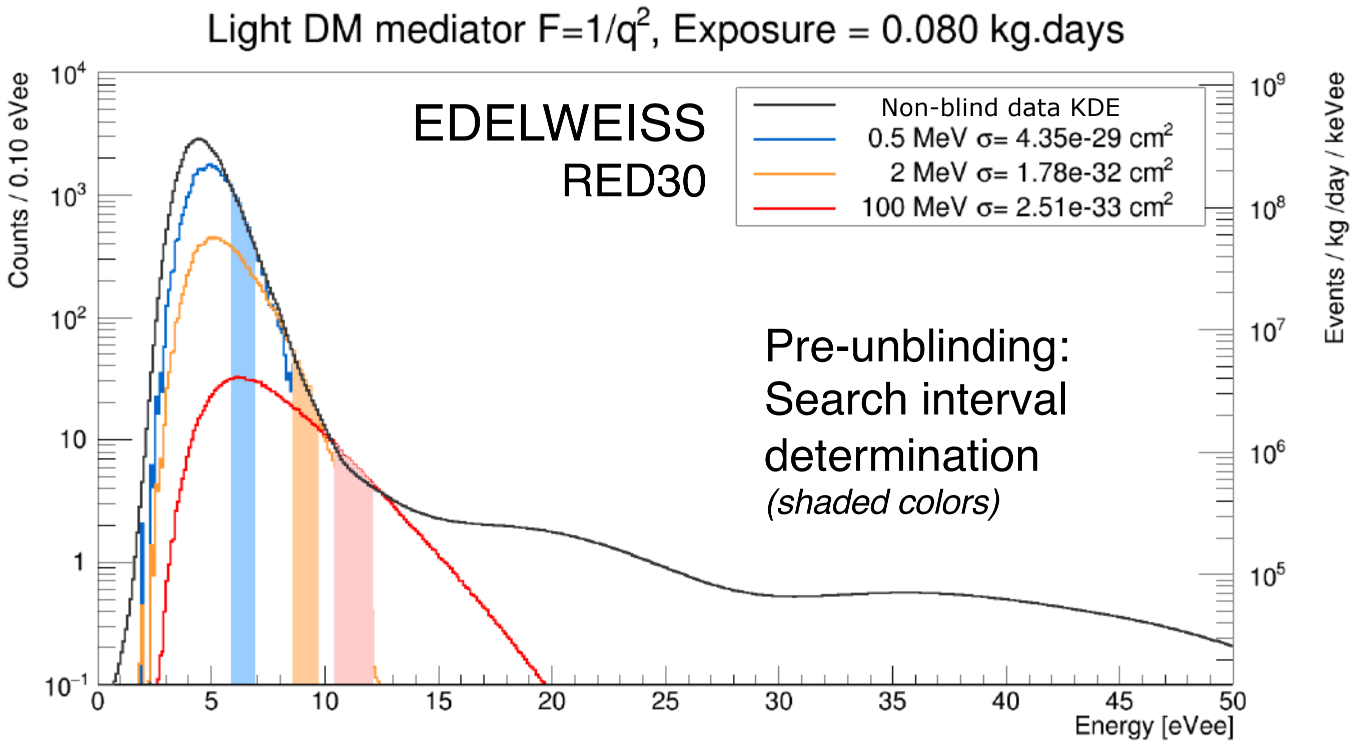
**Simulated number of electron-hole pairs**



# Limit setting strategy

- No bkg subtraction: 90%CL Poisson upper limit on rate in fixed energy range
- Determine most sensitive range using 1.3 day sample non-blinded data (smoothed with KDE) recorded just before/after the search
- Signal calculation: QEdark [R. Essig et al., JHEP05 (2016) 046]
  + charge quantization [as in SuperCDMS, PRL 121 (2018) 051301]
  + pulse simulation



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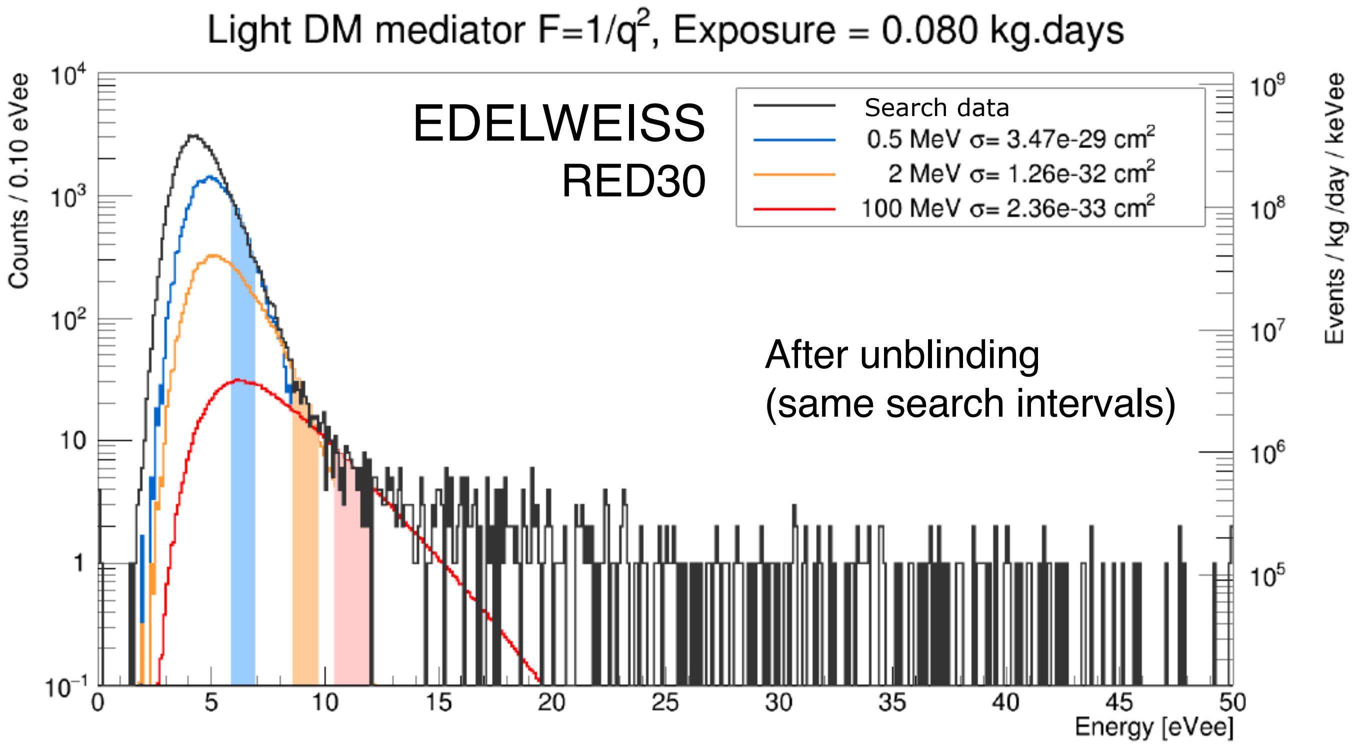
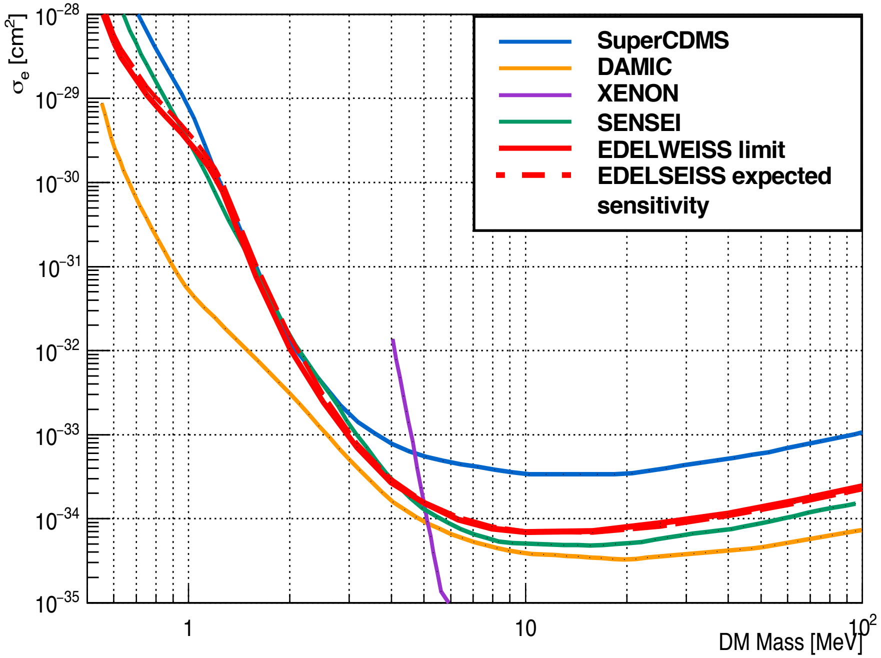


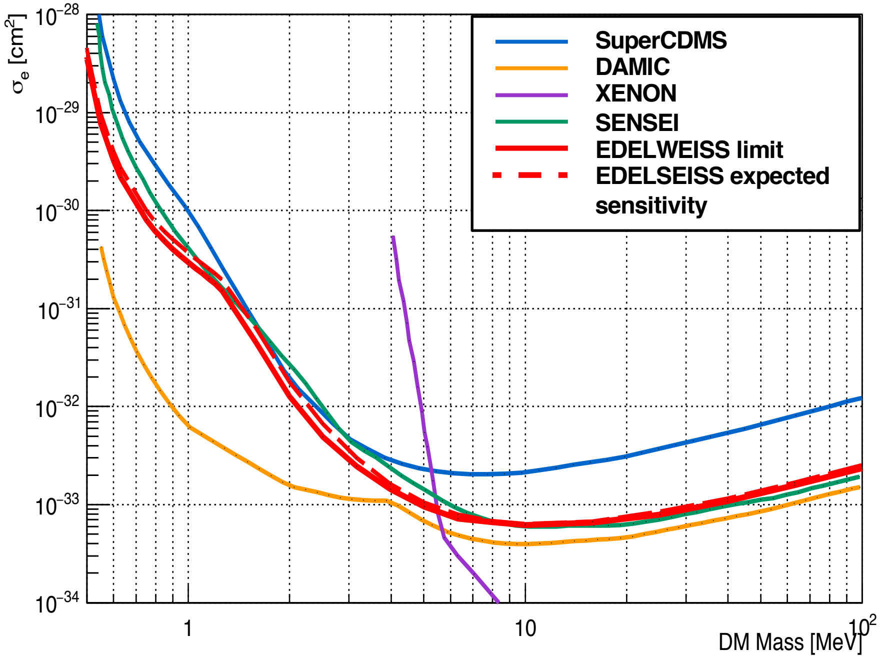
# Results

- Limits slightly better than the expectation from the nonblind sample, because of a slightly better resolution ($\sigma$ = 1.60 vs 1.63 $eV_{ee}$)
- Sensitivity extends into the domain of **sub-MeV DM particles:** with **$\sigma$ = 0.53 $e^-$-h pairs** there is some sensitivity to **single-$e^-$ events**
- Competitive with Si expts (that use smaller detectors: few g vs 33 g)

**Heavy Dark Sector mediator case (F=1)**




**Light Dark Sector mediator case (F=1/q²)**

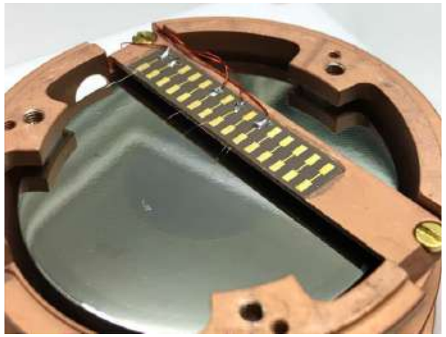


# *Next steps*

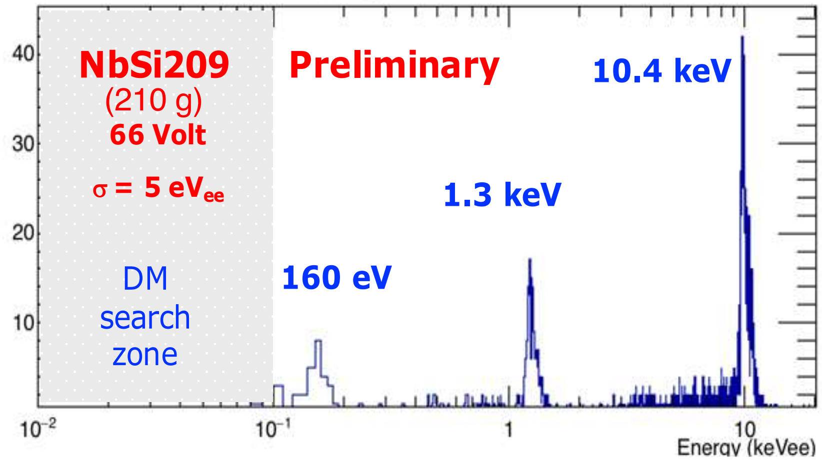
*Pursuing the study of the noise (& detector performance) that currently limits the sensitivity*

- Gain in baseline resolution: x2 on NTD sensor sensitivity and x2 on bias had been obtained on other prototype detectors
- Study of leakage currents & release of trapped charges (using also the presently available ionization signals) + electrode design
- If events are not associated to charge: stress release in crystal?
- Noise related to similar rise at low energy in the spectra observed by other cryogenic detectors?

***Alternative heat sensor under investigation: high-impedance NbSi TES***



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



# Conclusions

The EDELWEISS-SubGeV program aims at probing MeV-GeV particles via Electron Recoil and Nuclear Recoil signals, with a ~kg-size array

- Low-voltage objectives : $\sigma$ = 10 eV (phonon), 20 eV$_{ee}$ (ion.)
  - *Particle identification and surface event rejection down to 50 eV*
- High-voltage objectives : $\sigma$ = 10 eV (phonon) + 100 V bias
  - *Single e-/h+ pair sensitivity on massive (~30 g) bolometers*

*First results with 33g prototypes:*

- *EDELWEISS-Surf: above-ground search with 18 eV phonon resolution*
  - *First Ge-based limit below 1.2 GeV, best above-ground limits down to 600 MeV, Migdal effect used to probe down to 45 MeV*
- *First results with 33g Ge detector with $\sigma$ = 0.6 electron resolution*
  - *First use of Ge: currents + background competitive with Si*
  - *Limits below 1 MeV competitive with best results*