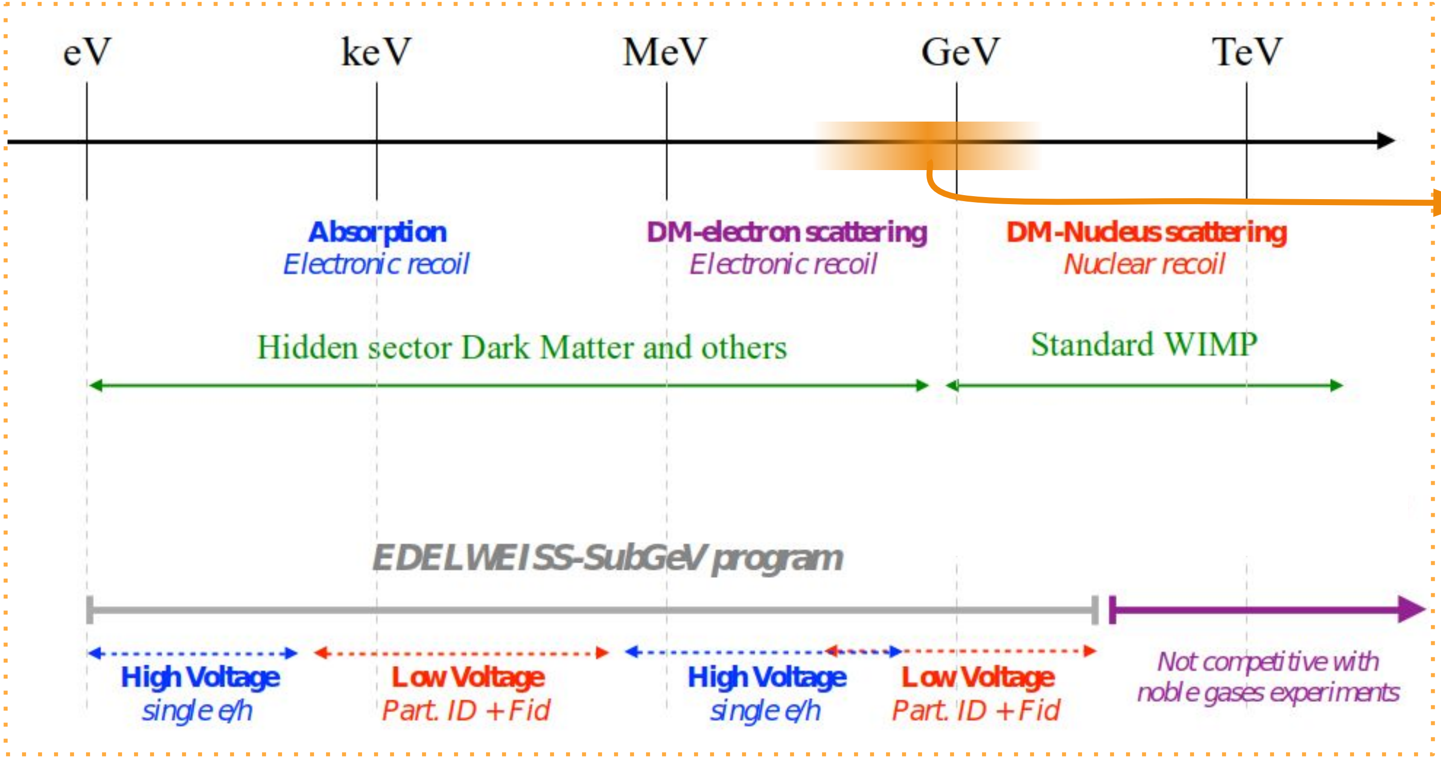
Sub-GeV Dark Matter Searches with EDELWEISS:

New results

[arXiv:220303993]

Hugues Lattaud on behalf of the EDELWEISS collaboration

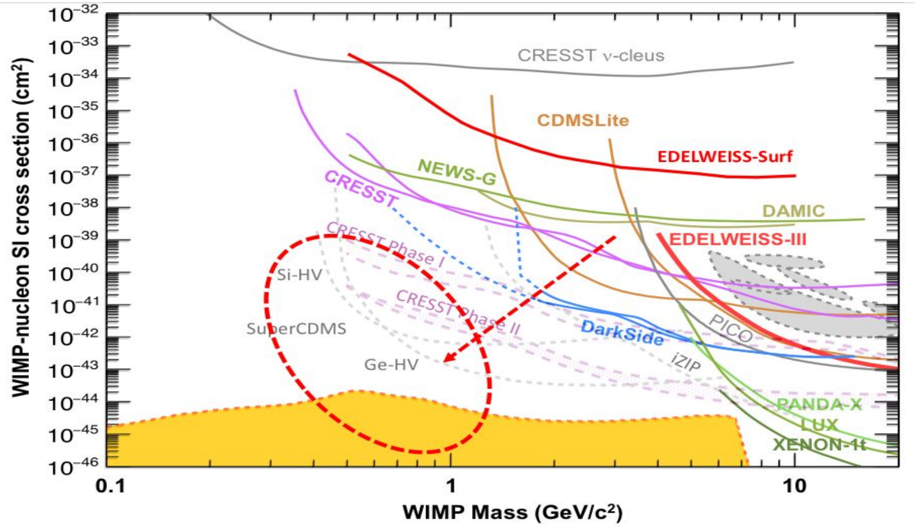
Direct DM detection with EDELWEISS



→Challenging search area
→ Many new techniques being proposed
→ Need low threshold (down to single electron)
→ ER/NR discrimination

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

Edelweiss sub-GeV program



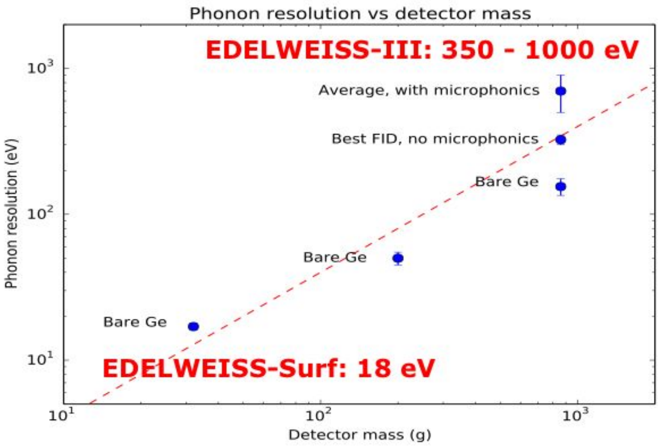
Goals :

→ particle ID down to 1 GeV/c² and below,

→ improvement of resolutions down to **σ_{phonon} = 10 eV** (for thresholds) **and σ_{ion} = 20 eV** (for discrimination at LV),

→ reach cross sections down to 10^{-43} cm²,

→ reduce background.



How ?

→ Reduce detector mass

EDELWEISS-Surf [PRD 99 082013 (2019)]

33 g Ge bolometer.

→ Apply HV to amplify signals

Electron-DM results [PRL 125, 141401 (2020)]

78 V applied onto 33 g Ge bolometer.

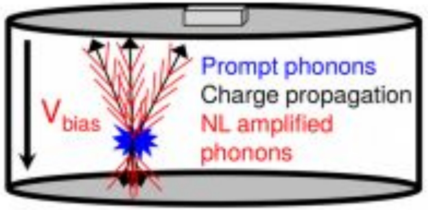
→ Probing bkg using TES

Migdal with NbSi TES [arXiv:2203.03993 (2022)]

200g Ge bolometer operated at 66V

Neganov-Luke-Trofimov (NTL) amplification

What is NTL ?

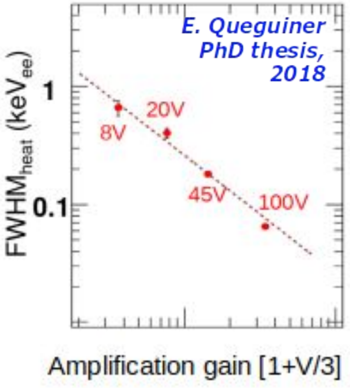


$$E_{heat} = E_{recoil} + E_{Luke} = E_{recoil} + N_p \, \Delta V$$

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

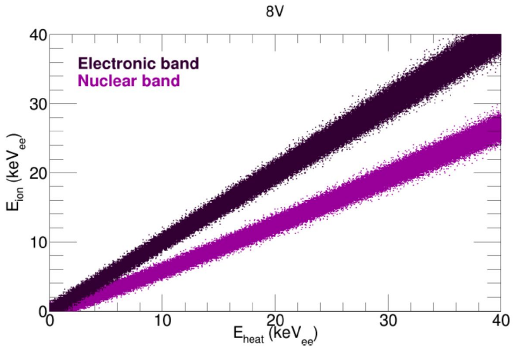
Why use it ?

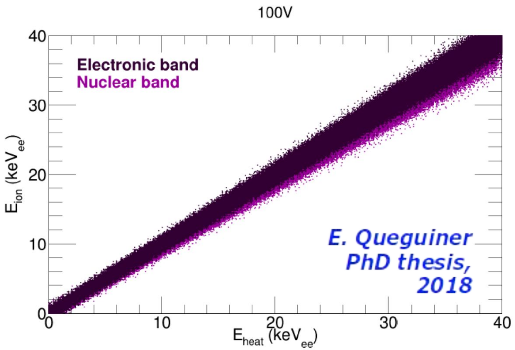
→ Heat resolution gain by a factor (1+V/3) for e⁻ signals



Limits of HV :

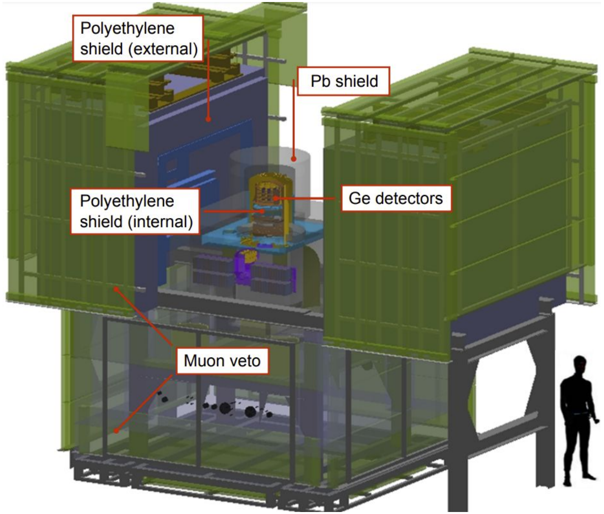
→Loss of discrimination between ER and NR bands



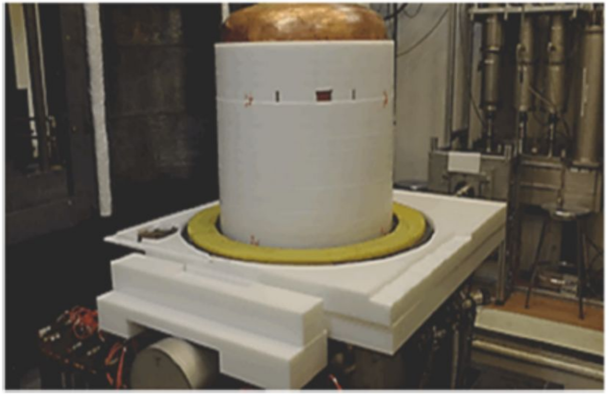


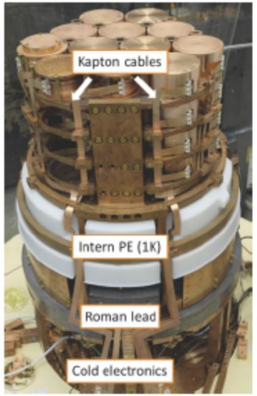
EDELWEISS experiment

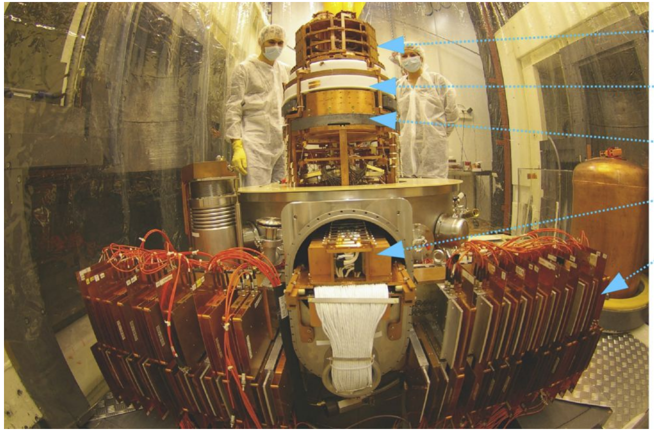
EDELWEISS-III setup at LSM



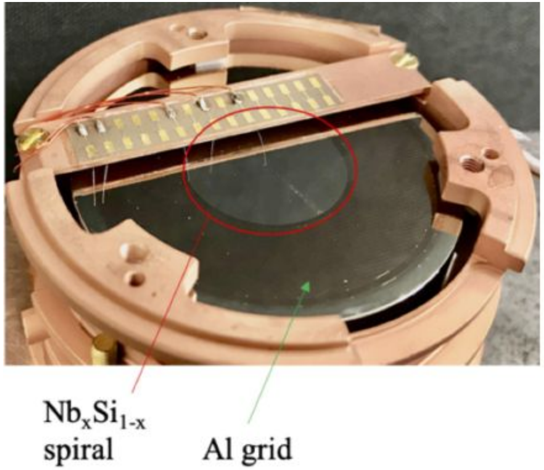
→ LSM : deepest site in Europe, 4800 m.w.e, 5 μ/m²/day
→ Active μ-veto (>98% coverage)
→ Clean room + deradonized air
→ PE and lead shielding
→ Selection of radiopure materials
→ Operated ~ 20mK
→ [arXiv:1706.01070]

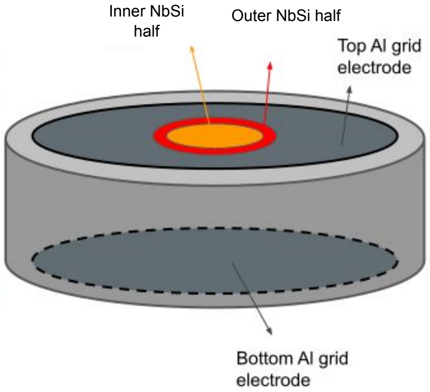


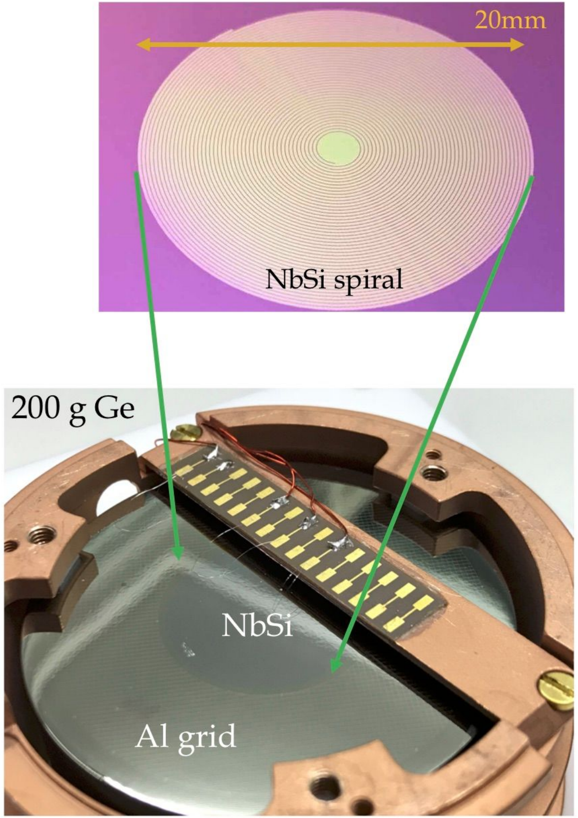




EDELWEISS NbSi TES (NbSi209)





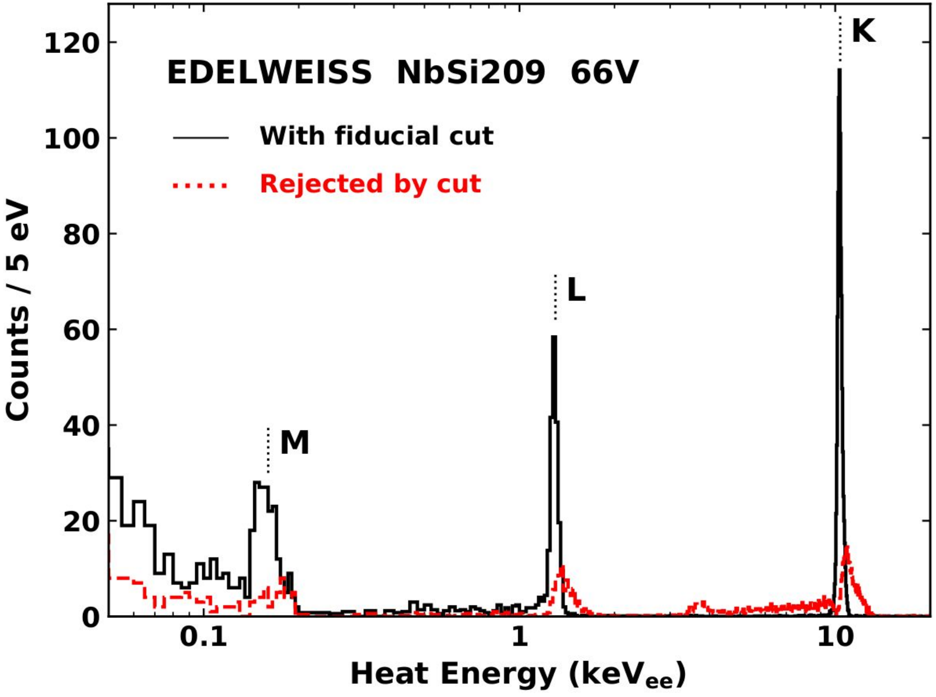


→ 200g Ge bolometer
→ **heat signal:** NbSi Transistor Edge Sensor (TES) lithographed on top surface, read as two channels
→ **ionization signal:** Al electrodes lithographed on top and bottom surfaces

Analysis

Data calibration

→ **Calibration from K, L, M, ^{71}Ge decay line,**
→ **Heat baseline resolution 100 eV** on total energy, i.e. **4 eVee** for ER at 66V,
→ Ideal resolution for Migdal DM search !
→Low energy background, appears not to have ionization !

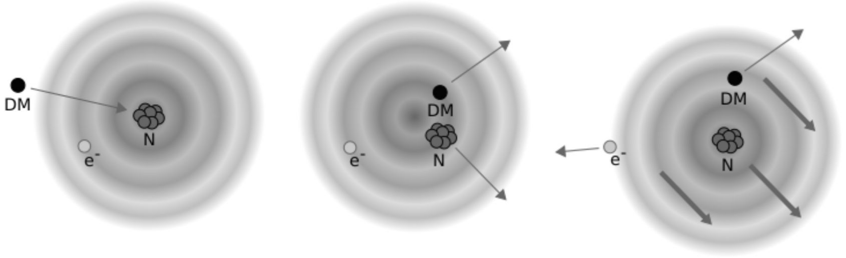


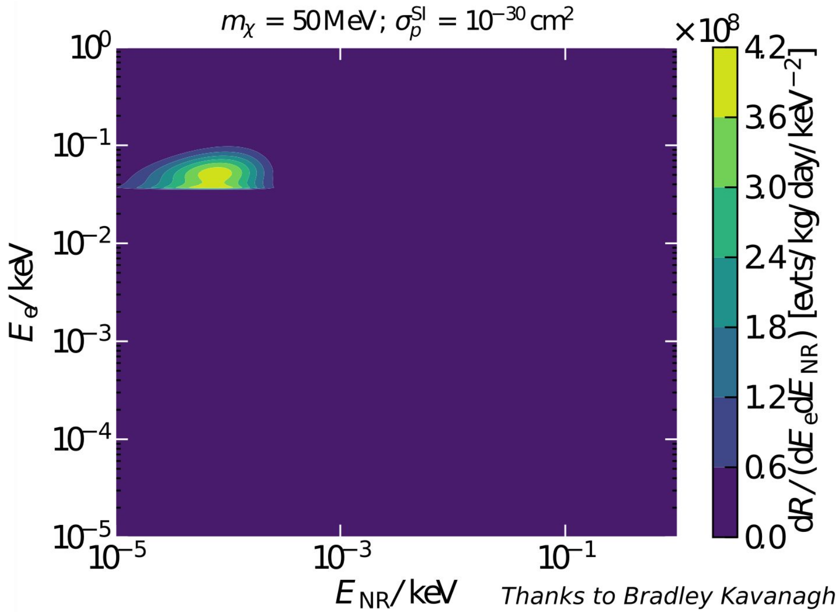
Migdal effect

What is the Migdal effect ?
→interaction DM-nucleus which induces both a NR *and* the ionization of a Ge atom
→ **electronic** signal with NR

Why use it ?
→ for low-mass DM particles, NR induced energy ~1 eV against ~100 eV for Migdal e⁻ yield

In Germanium :
→Ideal target of search for NbSi209 with σ_{heat} = 4 eVee
→Calculations (Ibe et al arxiv:1707.07258) reliable for n = 3 shell-e⁻ (only shell considered here)
→ Migdal electron energy > 35 eV for n=3

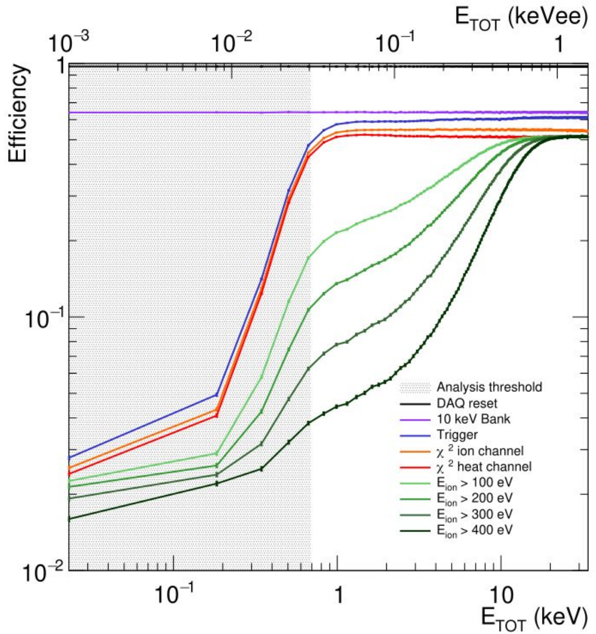




Thanks to Bradley Kavanagh

Efficiency and selection

→ **Inject** actual **10.37 keV events, scaled** to desired energy, at **random times** in the entire search datastream at a **0.02 Hz rate**,
→ **Process** the new datastream as real data



→ Conservatively only consider efficiency for **events with full charge collection** and **no athermal phonons (64%) – cyan** "Bank cut"
→ **Trigger** on **heat channel** using optimal filter (**blue**)
→ **Loose cuts** on **chi2 pulse fit** (ionization and **heat**) + **equal signal** on **both NbSi film halves:** small effect on efficiency.
→require **E_{ion}> 400 eV_{ee}** signal on electrodes (**green**) to **reduce** amount of **HO,** Aggressive, but well-understood cut.

Limit extraction

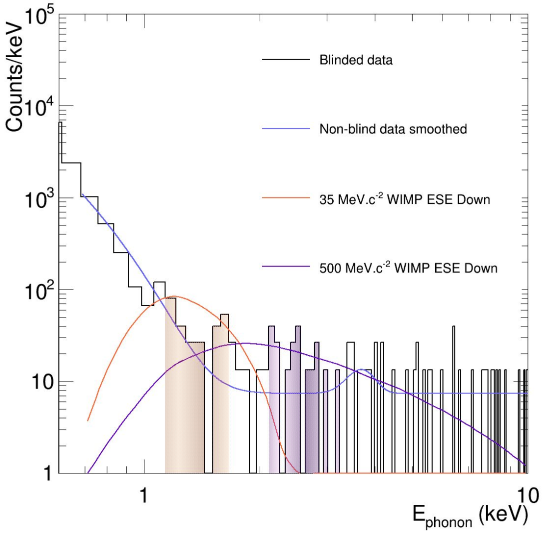
→ All calculations of Migdal are corrected for **Earth shielding effect** (ESE)

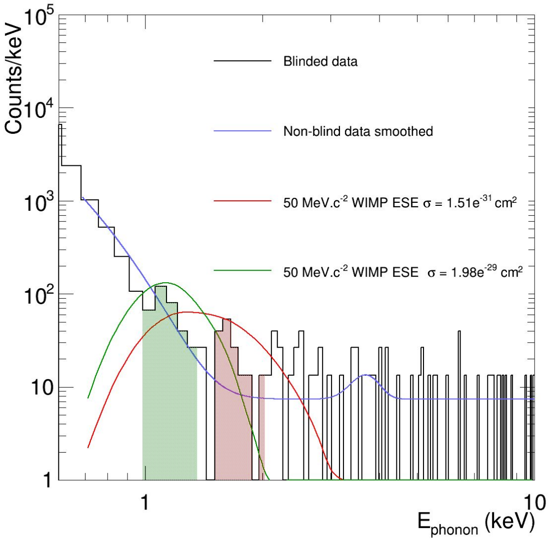
→ **Choice of regions of interest** (RoIs) to maximize S/N ratio **on non-blinded sample**,

→ Use chosen RoIs, 90% C.L. Poisson upper limit **on blinded sample**,

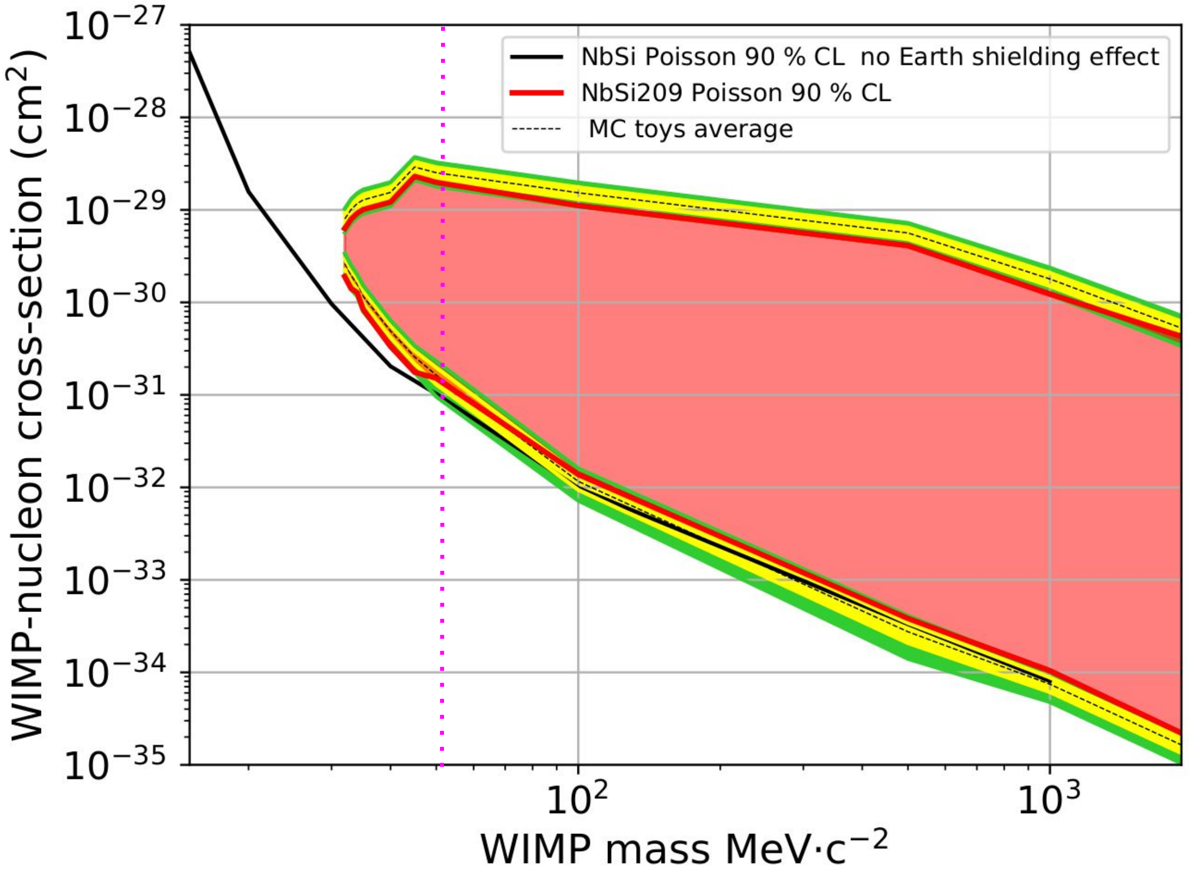
→ *Left* : **Signal** drifts towards **high energies** with DM mass,

→ *Right* : **Signal** shifts down for high cross-section due to attenuation of DM flux through rock.



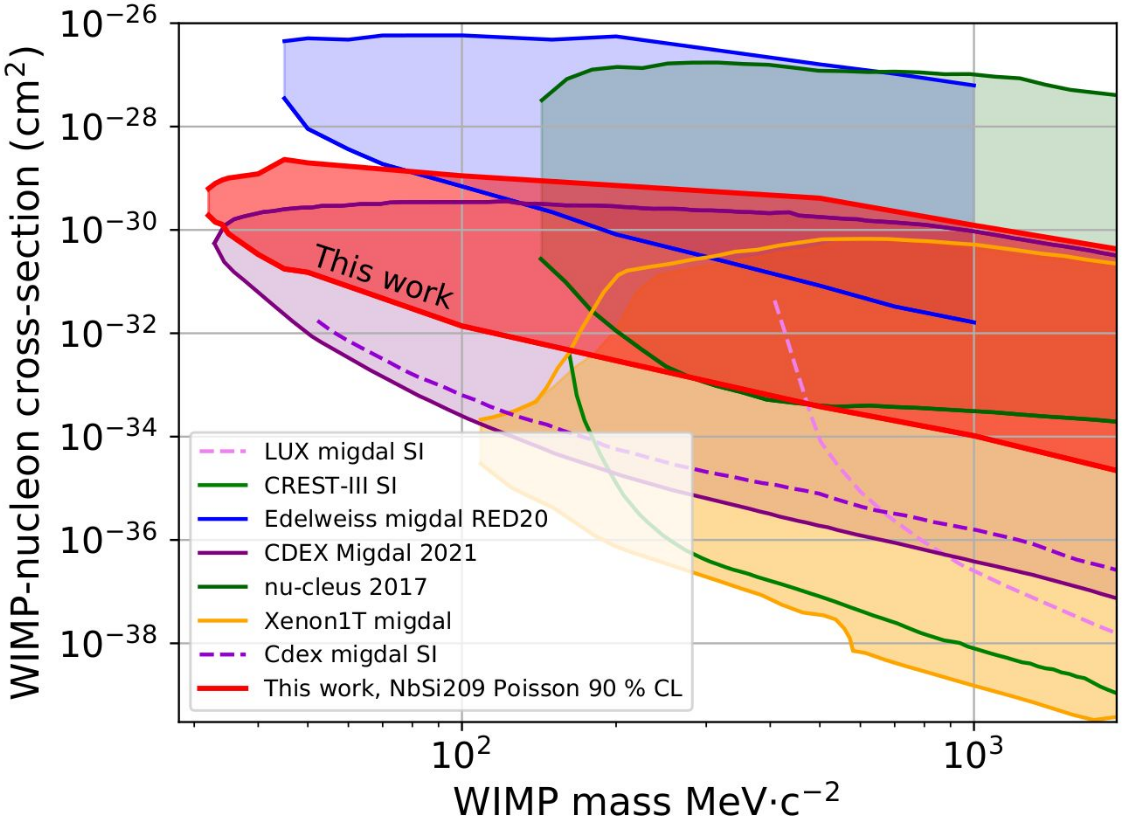


New limit



→ 90% C.L. upper limit on cross-section for Spin-Independent interaction through Migdal effect,
→ limited in mass sensitivity because of ESE,
→ Strong ESE effects for M<50 MeV/c^2,
→ MC toys used to probe statistical stability of the results.

New limit

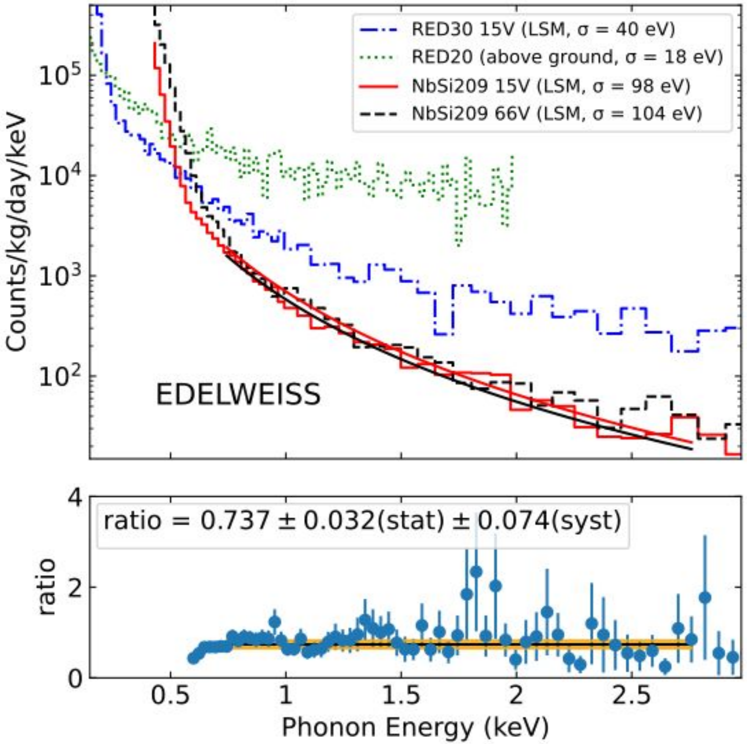


→ Same red contour as previously,
→ New tiny region of parameter space constrained : $\sigma \simeq 10^{-29}$ cm² and M ∈ [32 ; 2000] MeV/c²,
→ Several orders of magnitude of improvement compared to EDW-Surf Migdal search (blue contour)
- reduction of bkg
- 4 eVee resolution with TES sensor design

→ Limited by HO background

Note: SuperCMDS new results in this mass domain: arXiv:2203.02594

Rate and shape of HO spectrum with NbSi sensor

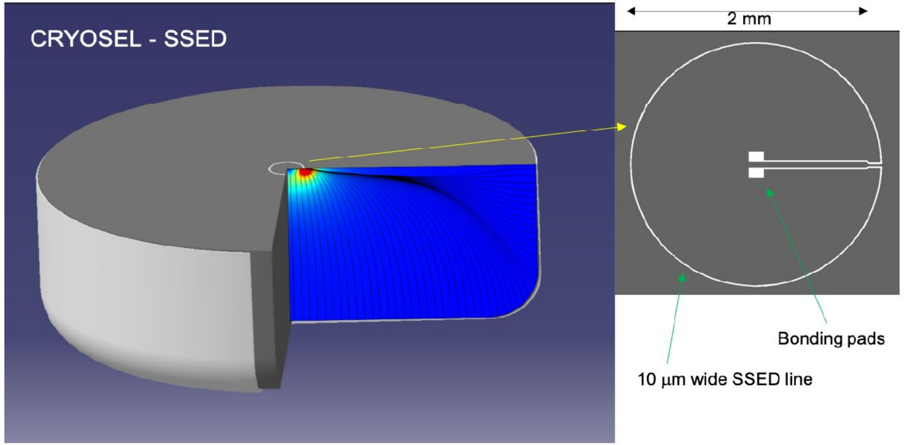


→ **Heat-Only** (HO) background : events not associated with charge creation.

→ **Top** : NbSi209 LV and HV data
→ Compatibility of HV/LV spectra for E_{ph} > 0.8 keV
→ Mostly HO events !

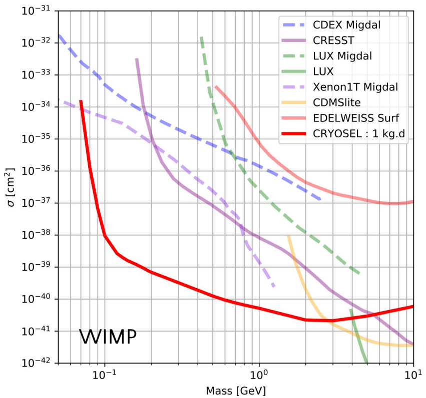
→ **Bottom** : LV/HV ratio of histograms
→ limit on events associated with charges < 0.04%.

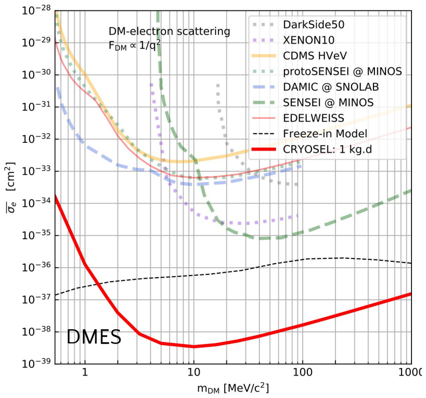
Prospects : CRYOSEL

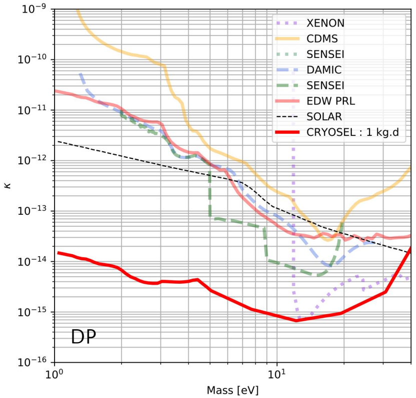


CRYOSEL

→ 40g Ge detector, σ_{phonon} = 20 eV, 200 V bias,
→ SSED "*Superconducting Single Electron Device*", detection of **athermal phonons** from **individual charges** → **discrimination** of HO events,
→ Expect many orders of magnitude **improvement** compared to present-day sensitivity.



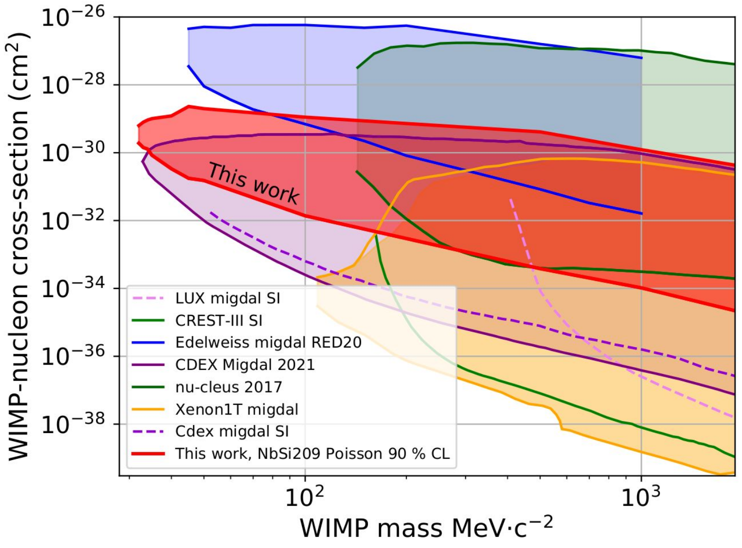




Conclusion

Takeaway messages

→ EDELWEISS collaboration developed new **NbSi TES**-equipped detectors as part of its Sub-GeV program,
→ It allowed to constrain a **new region** of parameter space : $\sigma \simeq 10^{-29}$ cm² and M ∈ [32 ; 100] MeV/c²,
→ Several orders of magnitude of **improvement** compared to EDW-Surf Migdal search (blue contour),
→ Established an **upper limit** on number of events producing charges of 0.04% in data at low energies,
→ Exciting prospects with new **CRYOSEL** detectors.



Thank you!

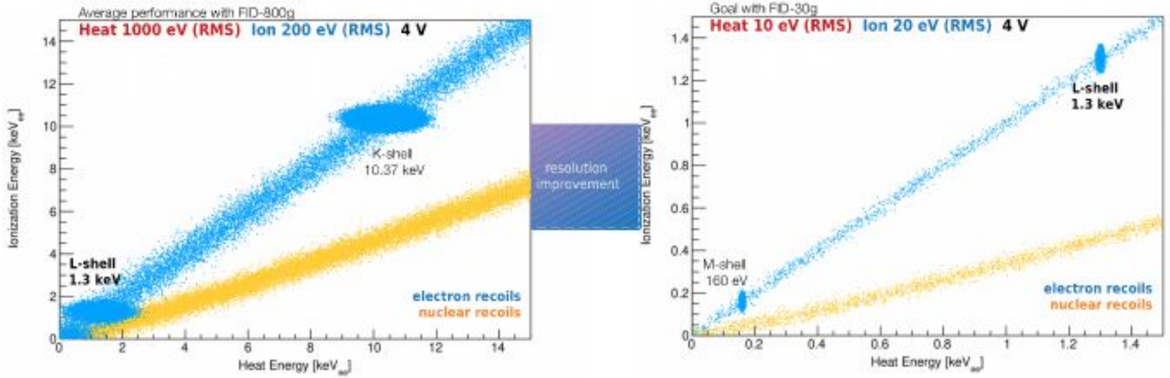
Back up

EDW 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



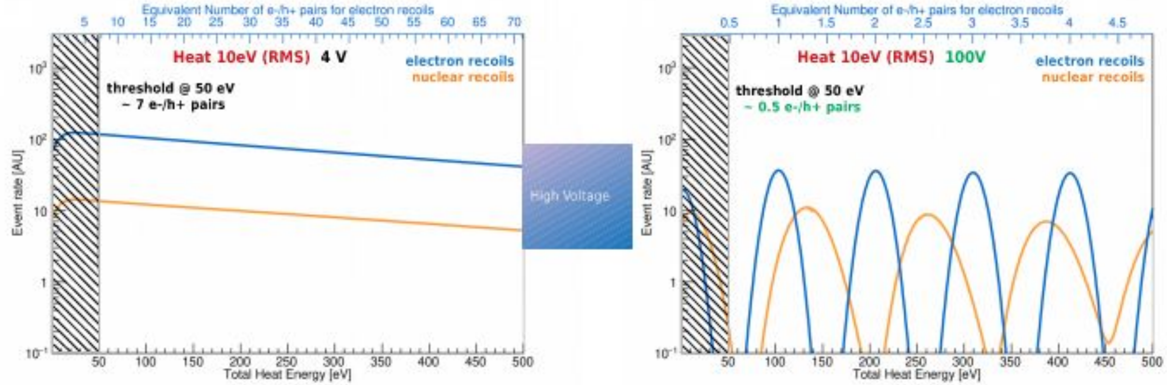
Low-voltage objectives are part of a common effort with the Ricochet collaboration, dedicated to studying CENNS at reactors supported by the ERC-CENNS Starting Grant (2019-2024)

High Voltage Objectives

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

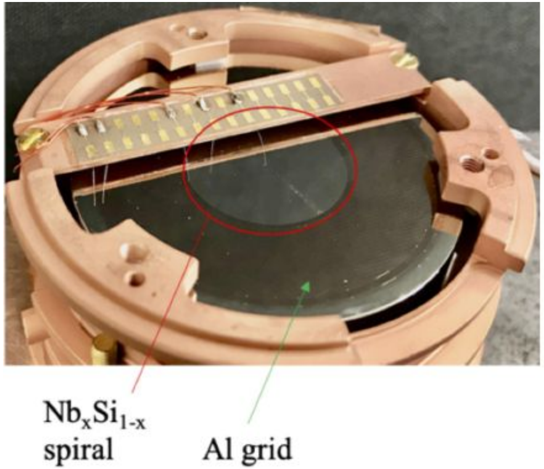
Single-e/h pair sensitivity with massive (~30g) bolometers

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

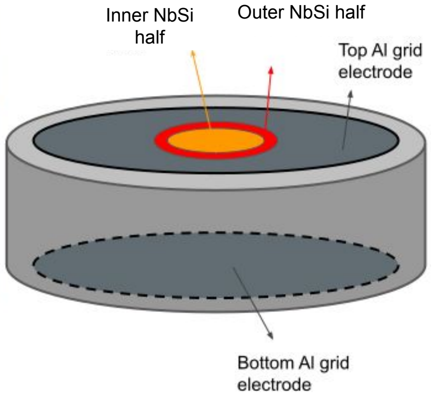


SELENDIS project has received funding from the European Union's Horizon 2020 research and innovation program under the Marie Sklodowska-Curie grant agreement No 838537

EDELWEISS NbSi TES (NbSi209)



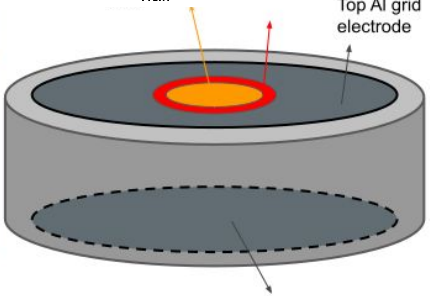
→ 200g Ge bolometer :
48 mm diameter,
20 mm height.

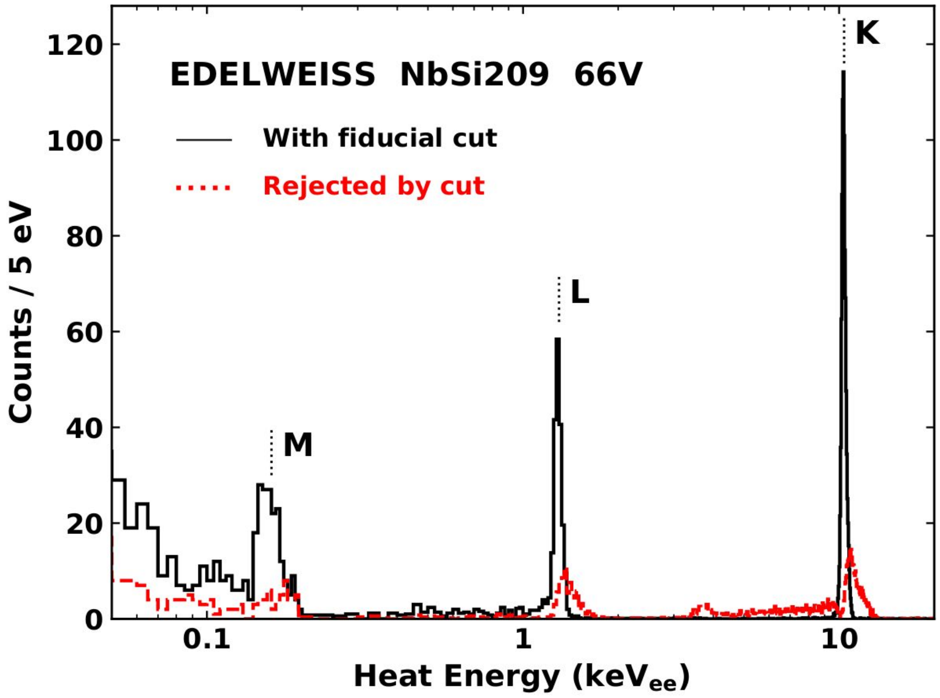


→ heat signal: NbSi Transistor Edge Sensor (TES) lithographed on top surface,
→ 100 nm-thick NbSi spiral,
→ 160 µm track width,
→ Film maintained at constant 44 mK,
→ Spiral split into two halves of equal resistance,
→ readout using cold-FET electronics at 100K,
→ heat link via gold wires btwn detector and copper holder,
→ combined TES resolution of ~90-100 eV = 4eVee at 66V.

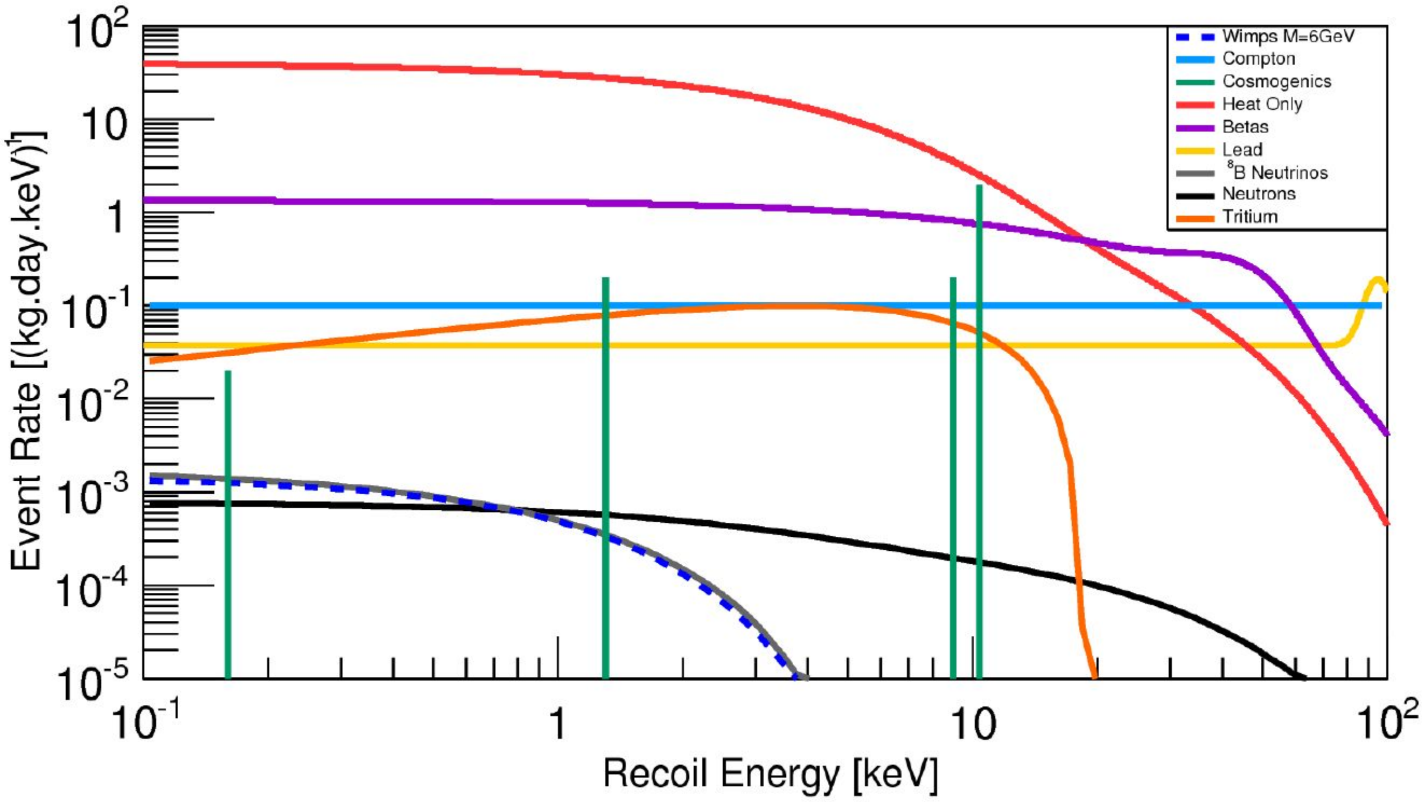
Calibration

Apply **fiducial cut** to remove "abnormal" events :
→ **incomplete** charge collection (NbSi film or trapped charges),
→ **extra-amplitude** due to sensitivity to out-of-equilibrium phonons,
→ cut 36% of events in the 10.37 keV peak.





EDW backgrounds



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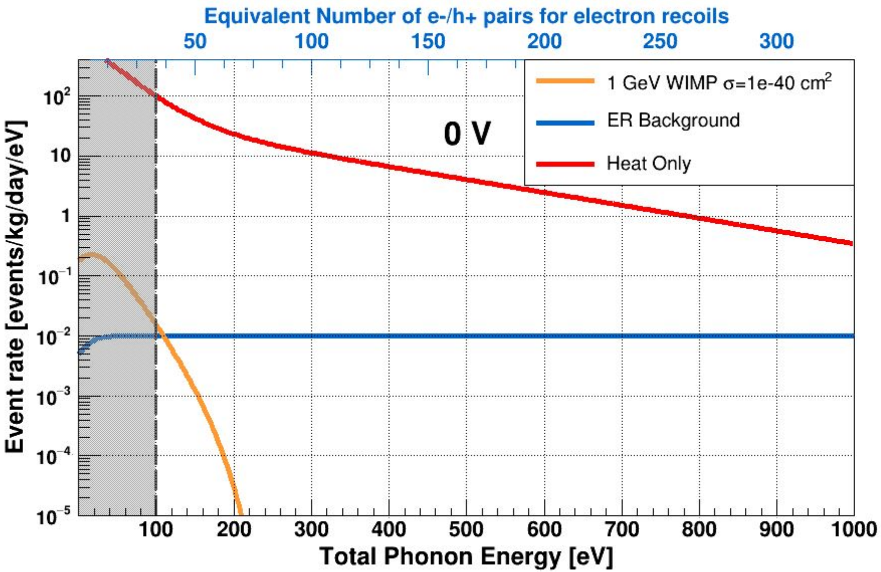
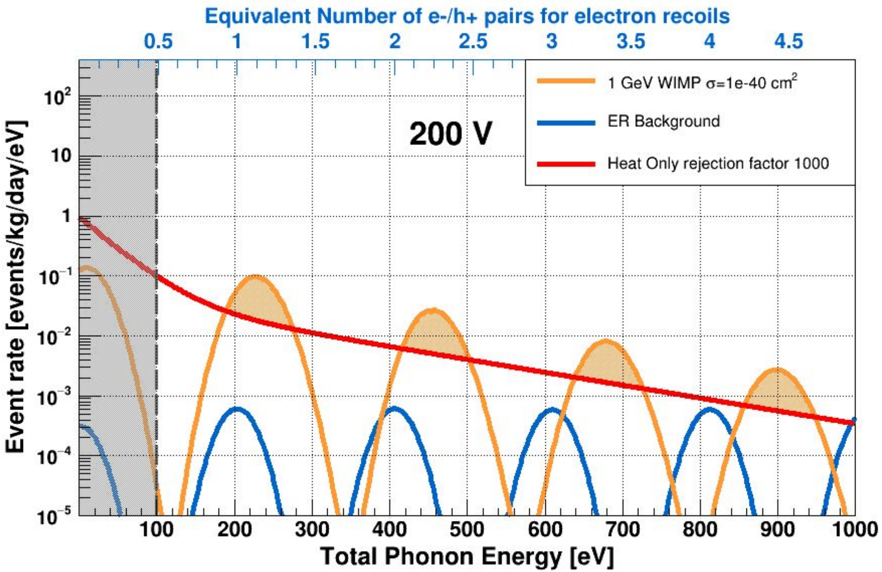
Neganov-Luke-Trofimov (NTL) amplification





$E_{heat} = E_R + E_{NL}$

$E_{heat} = E_R + (N_{pairs} \times V)$

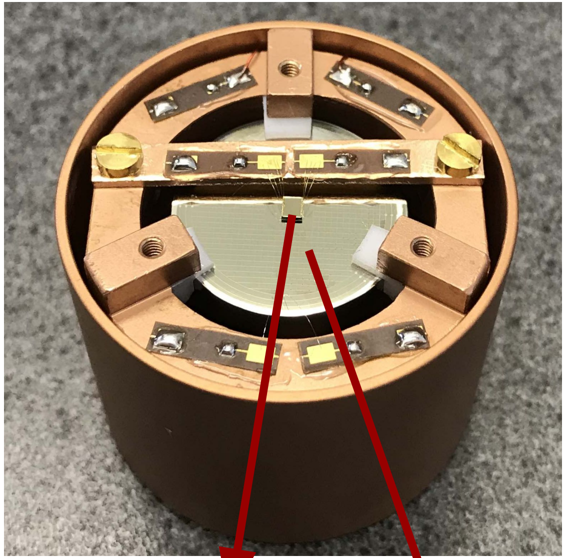
À haute tension :

$E_{heat} \approx (N_{pairs} \times V)$ pour les reculs électroniques.

D'où $E_{ion} \propto E_{heat}$

Other detectors performances

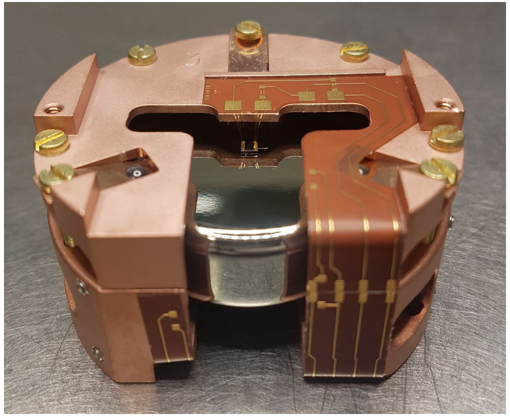
RED30 : 33g Ge detector operated at 78V
σ= 1.6 eV$_{ee}$ (0.54 pair)
($\rightarrow$ 43 eV)

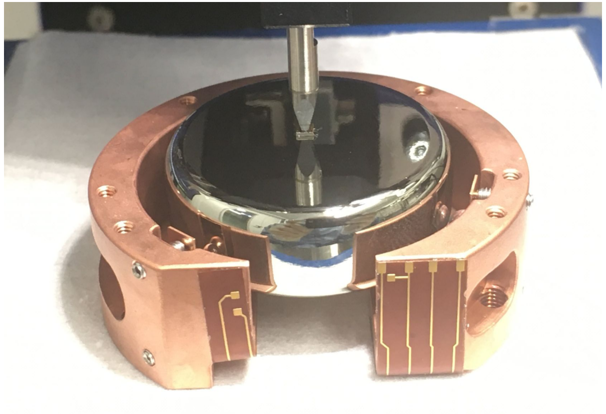


NTD Heat Sensor

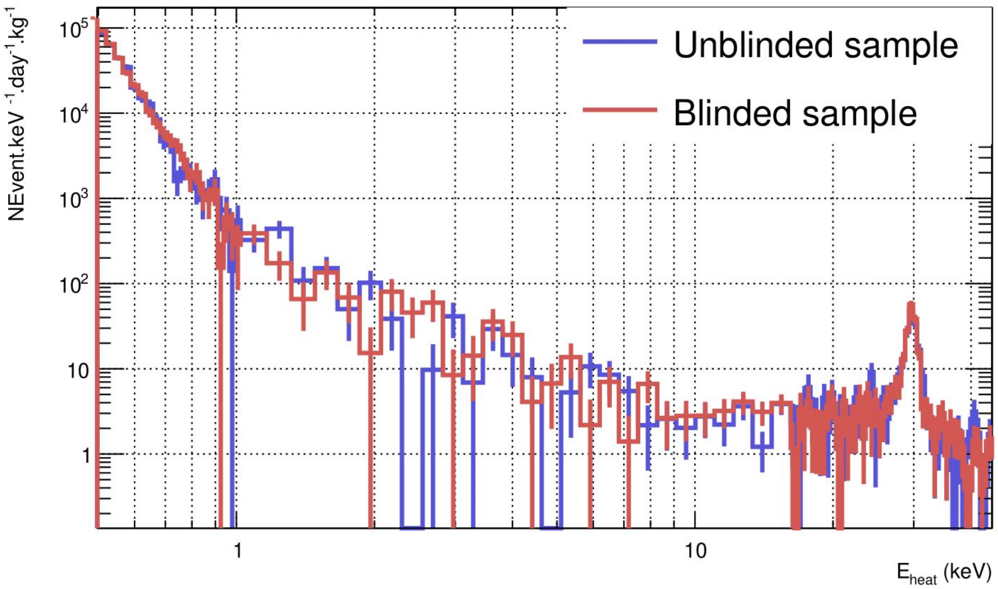
Al electrode

CRY30 & 20: 40g Ge detector operated at 0V
σ= ~50-70 eV





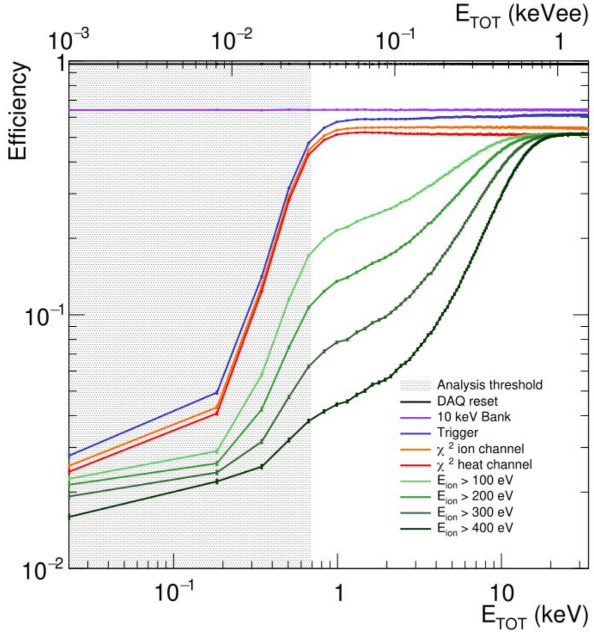
Blinded/non-blinded data



- Poisson upper limit assuming all events are DM candidates, no background subtraction
- Dataset divided in half, 1 over 2 hours blinded → two sets of 28 days
- Non-blinded data to set analysis cut and regions of interest

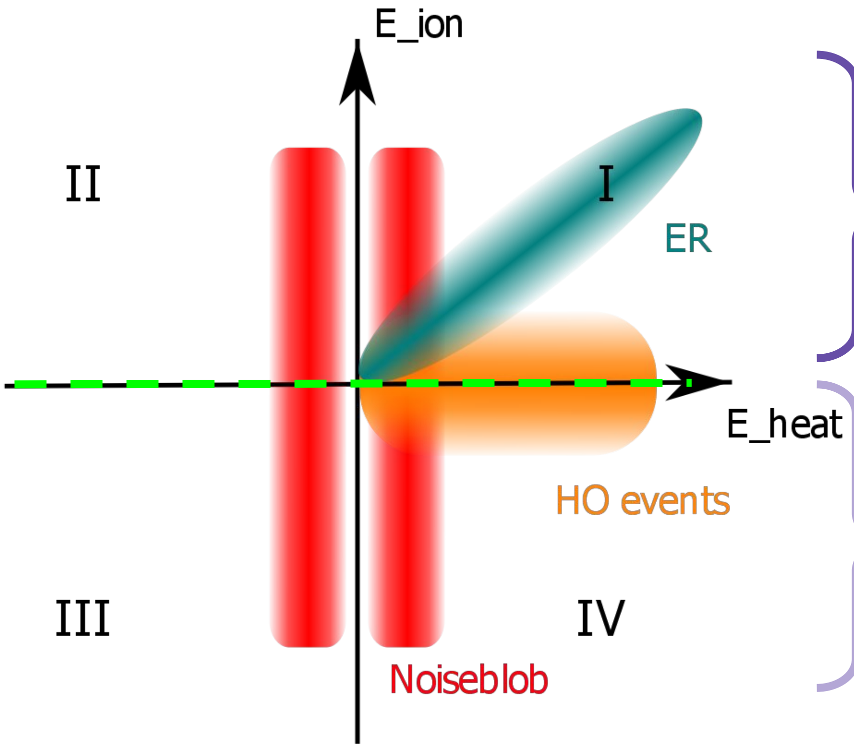
Efficiency and selection

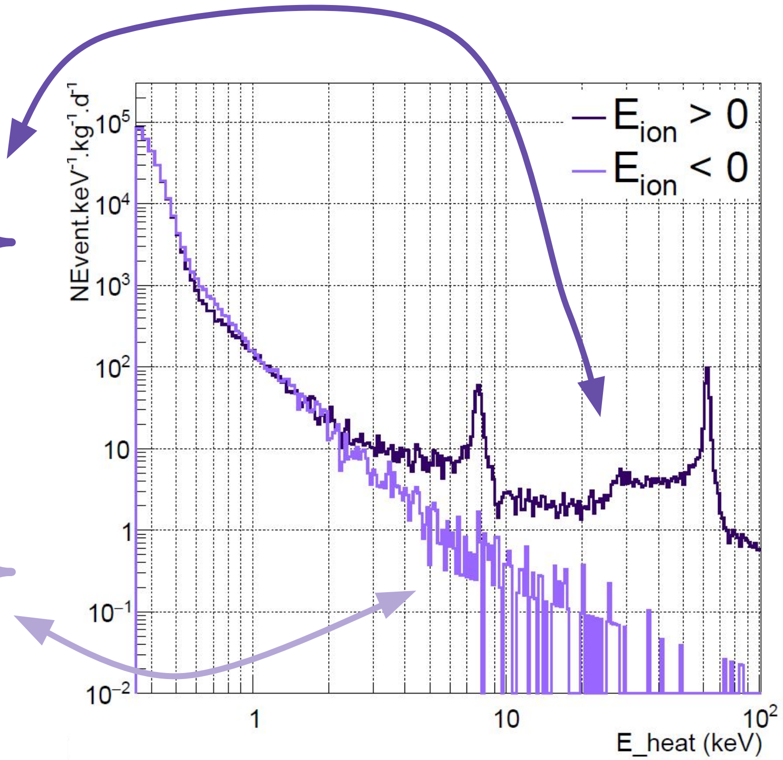
→ **Inject** actual **10.37 keV events, scaled** to desired energy, at **random times** in entire search datastream at a **0.02 Hz rate**,
→ **Process** the new datastream as real data



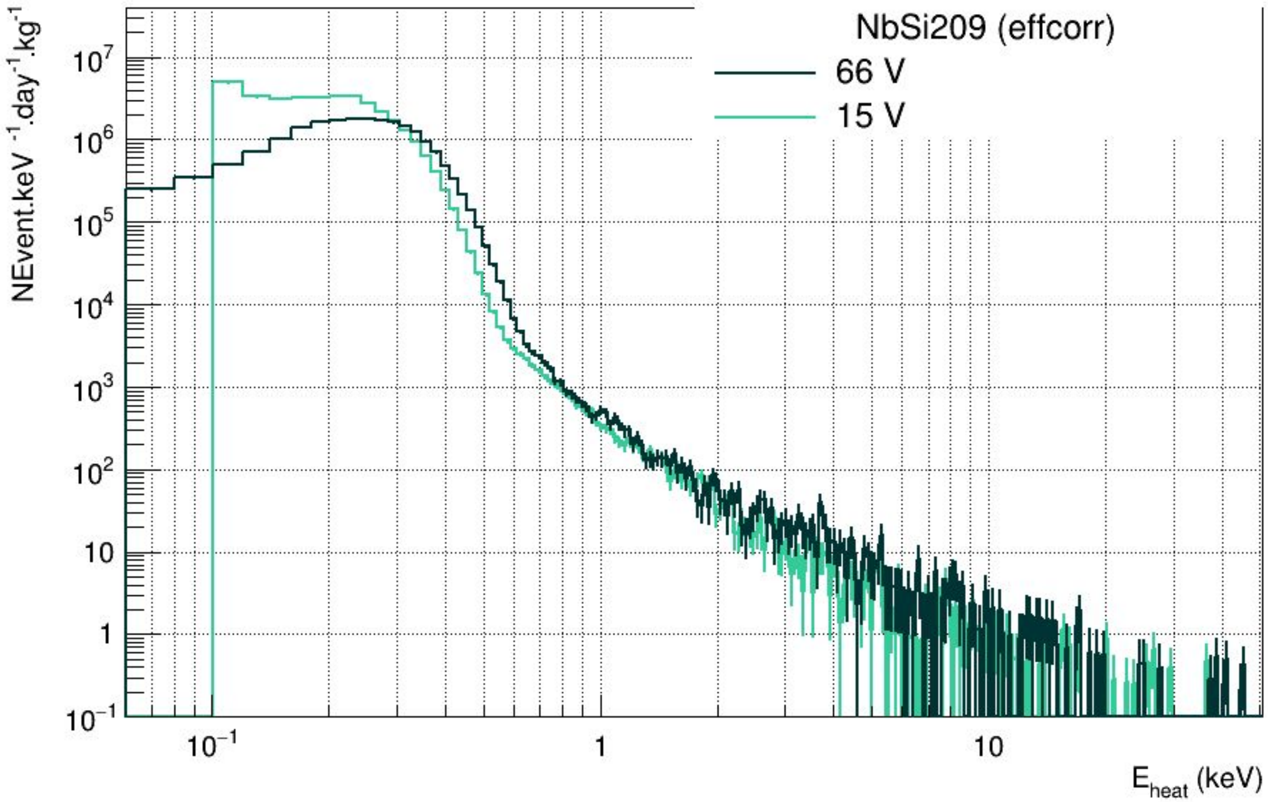
→ Conservatively only consider efficiency for **events with full charge collection** and **no athermal phonons (64%) – cyan** "Bank cut"
→ **Trigger** on **heat channel** using optimal filter (**blue**)
→ **Loose cuts** on **chi2 pulse fit** (**ionization** and **heat**) + **equal signal** on **both NbSi film halves:** small effect on efficiency.
→require **E_{ion}> 400 eV$_{ee}$** signal on electrodes (**green**) to **reduce** amount of **HO,** compared to **σ = 210 eV**. Aggressive, but well-understood cut.

HO study → cut on ionization

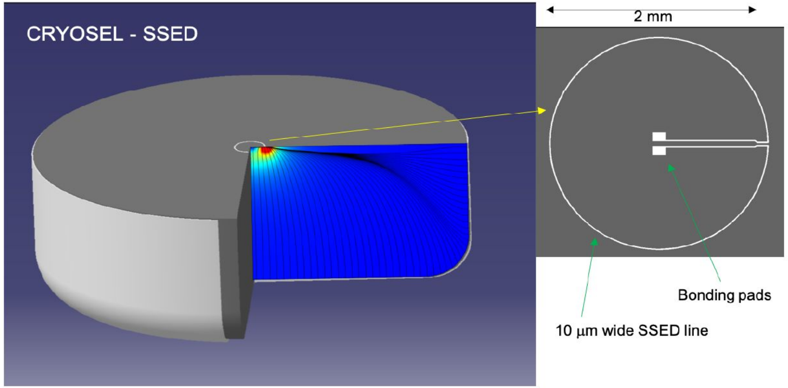




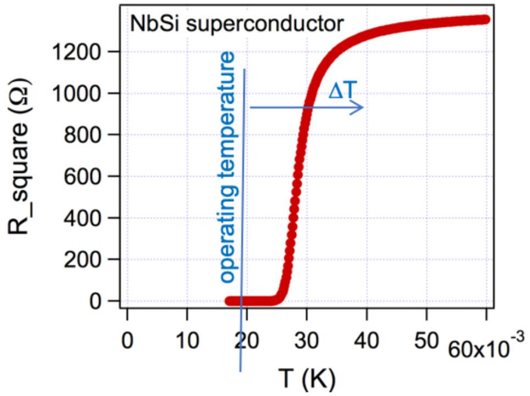
NbSi209 HV vs. LV



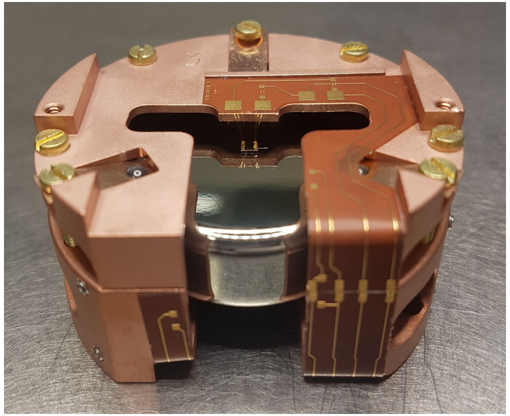
CRYOSEL

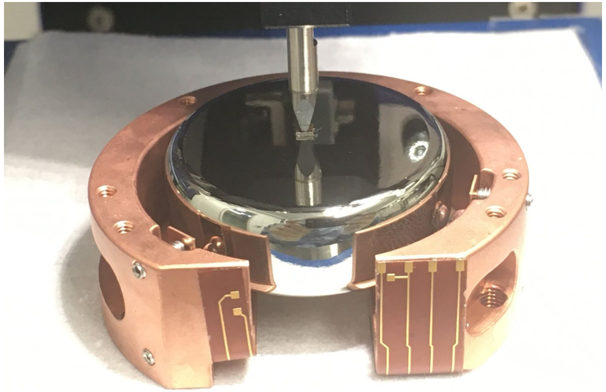


CRYOSEL - SSED
2 mm
Bonding pads
10 µm wide SSED line

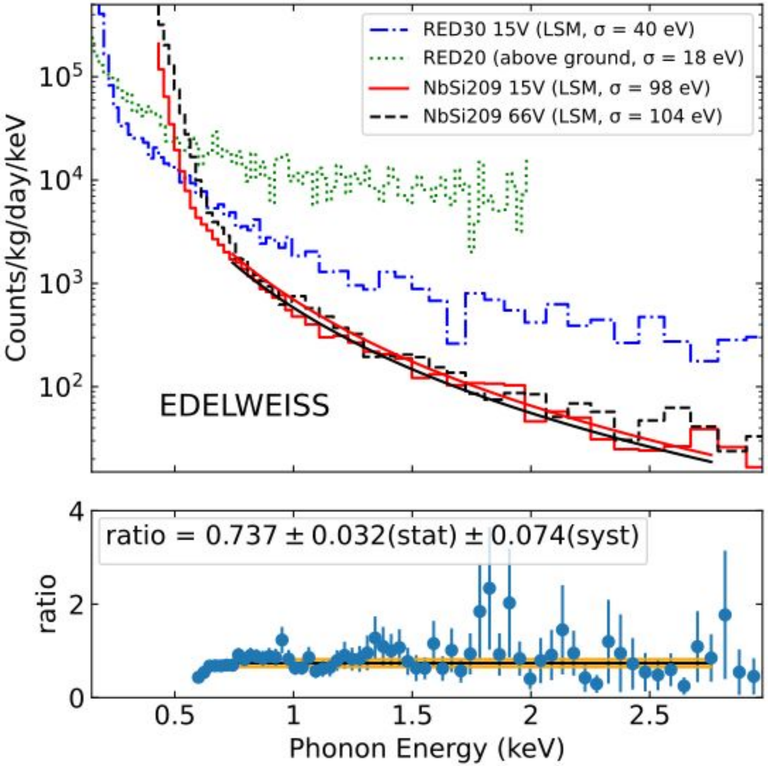


NbSi superconductor
R_square (Ω)
operating temperature
ΔT
T (K)
0
200
400
600
800
1000
1200
0
10
20
30
40
50
60x10^-3





Upper limit on events producing charges



→ **Top** : NbSi209 LV and HV data

→ Histograms fitted with **power law** αE^{β} in the 0.8 to 2.8 keV range

→ **identical slopes** within uncertainties : $\beta = 3.40 \pm 0.07$

Bottom : LV/HV ratio of histograms

→ **Flat ratio** at value 0.74 ± 0.03 (*stat*) ± 0.07 (*syst*)

→ ratio depends on fraction x of events producing charges (ratio = 1 if $x = 0$)

→ deviation from 1 taken as conservative syst uncertainty

→ Assuming case where HO and ER follow the same power spectrum : extract upper limit for x : $\boldsymbol{x}$ **< 0.04%** at 90% C.L.