From EDELWEISS to TESSERACT

- New perspective on DM cryogenic detection
@ Laboratoire Souterrain de Modane -

—

EDSU-Tools 2024 conference

Alex Juillard, IP2I Lyon

on behalf of the Tesseract coll.

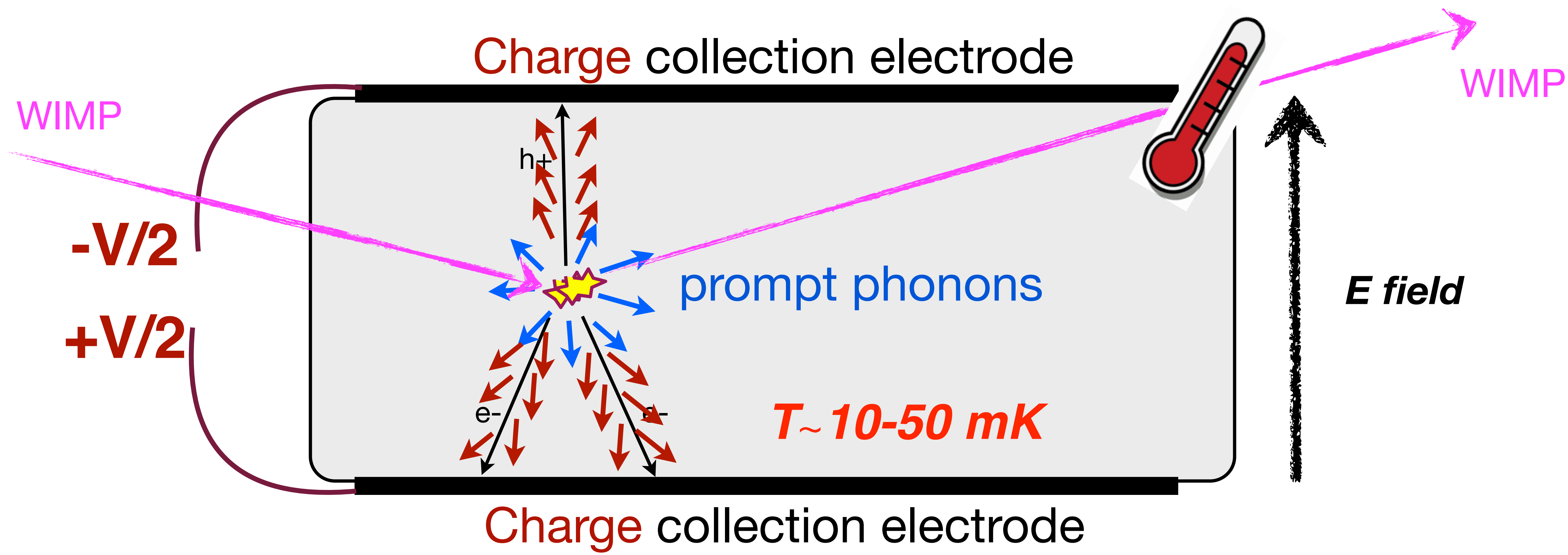
cnrs
dépasser les frontières
IN2P3
Institut national de physique nucléaire
et de physique des particules

iP2i
LES 2 INFINIS
LYON

Outline

- ✦ Cryogenic heat-and-ionization detector
- ✦ EDELWEISS cryogenic Ge detectors legacy
- ✦ Low Energy Excess in cryo detectors
- ✦ Ricochet Ge detector for CEνNS
- ✦ **Tesseract proposal @ LSM**

Cryogenic Ge : Simultaneous Heat & Ionization



$E_{total} = E_{recoil} + E_{luke}$

$= E_{recoil} + E_{recoil}/\varepsilon \cdot V$

ε = 3 eV for Electronic Recoil (X, gamma, beta, …)

ε = 10-**30 eV** Nuclear Recoil (neutron, Wimp, Ceνns)

Low Voltage Mode @ ~V : *Heat from Recoil ~Heat from charge drift*

→ ***Particule ID***

High Voltage Mode @ > 100 V : *Heat = E_{Luke} : huge signal boost*

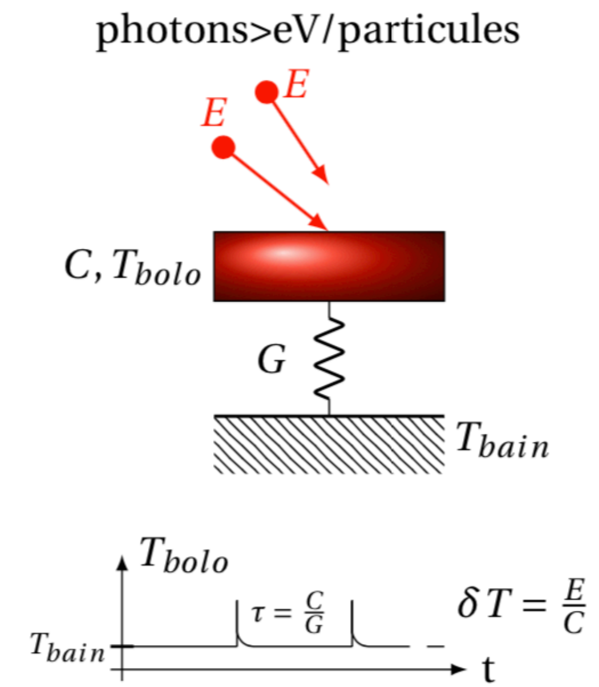
→ ***No PID, single e/h sensitivity***

Cryogenic Ge : EDELWEISS FID Cryogenic Detector

Heat and Ionization on Ge/Si detector :

- ➡ Elec. Recoil / **Nuclear Recoil discrimination**
- ➡ **Heat only** event **rejection**
- ➡ **surface event rejection**

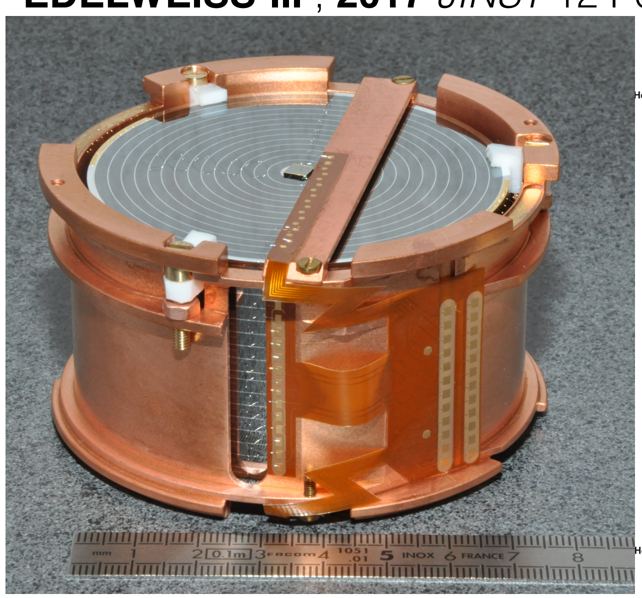
Initially developed by the EDW & CDMS collab. in the 00s' for the old « standard » 100 GeV SUSY Wimps…

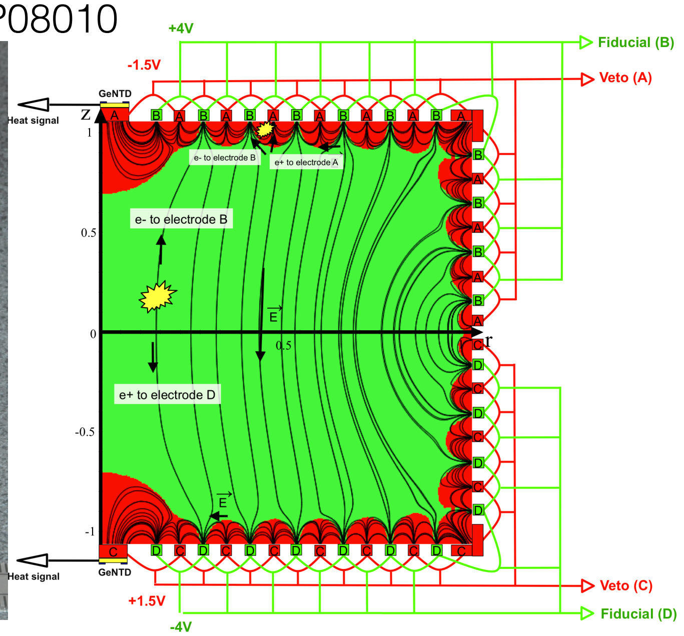


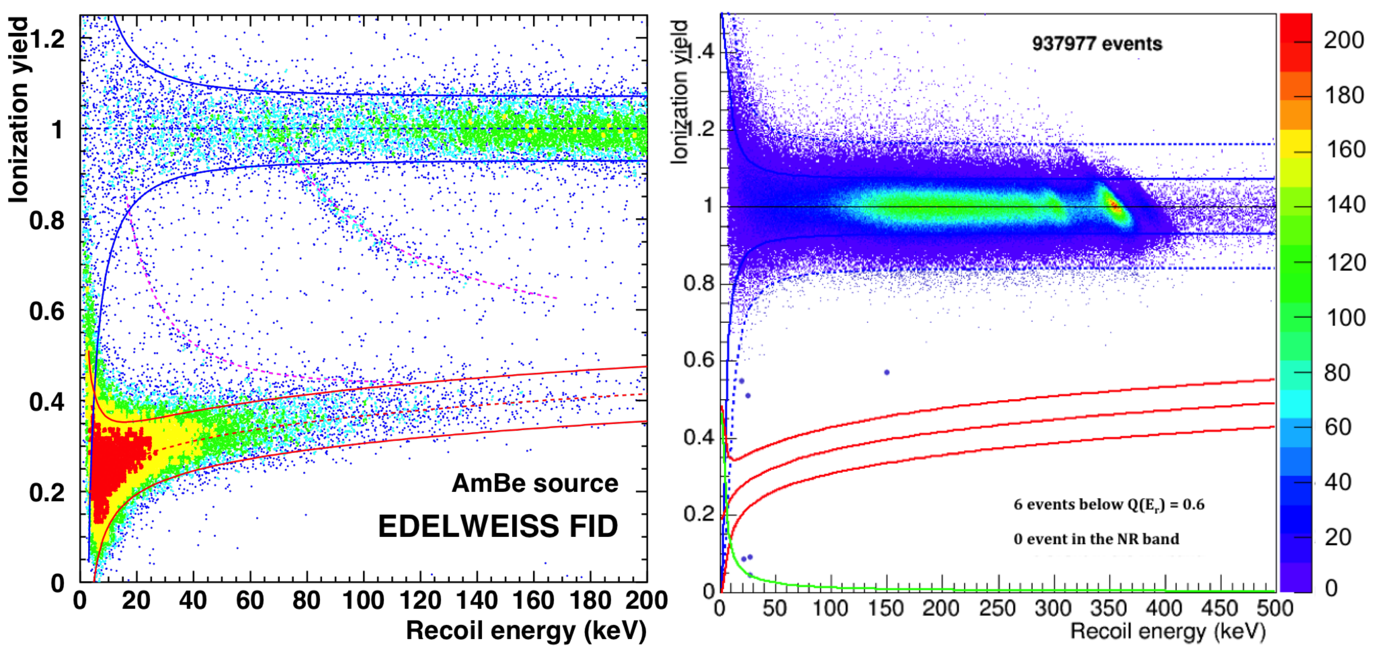
Low Temperature ➙ Sensitivity ↗ & Noise ↘

T_{bath} ~10 mK - 300 mK

EDELWEISS-III ; **2017** *JINST* 12 P08010

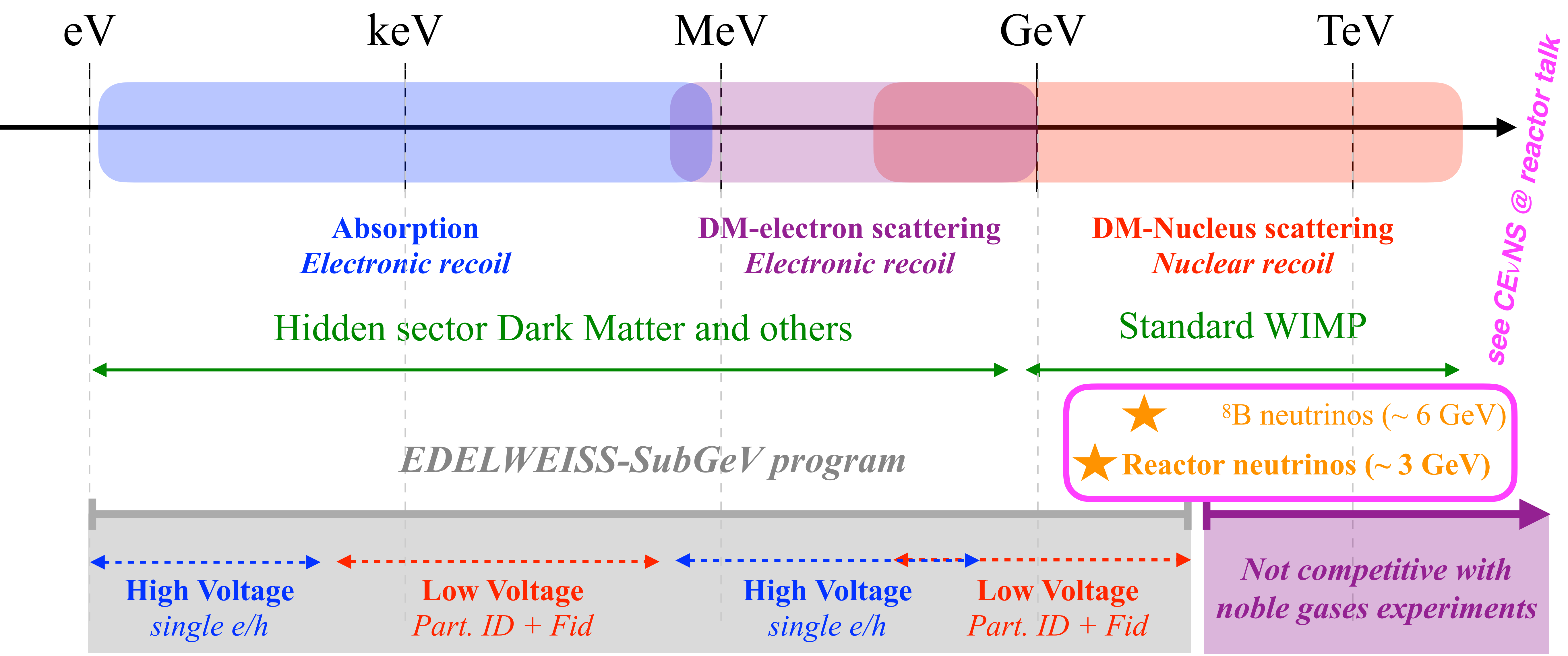






800g Ge EDW-III Ge detector in LV mode operation

EDELWEISS : DM search objectives

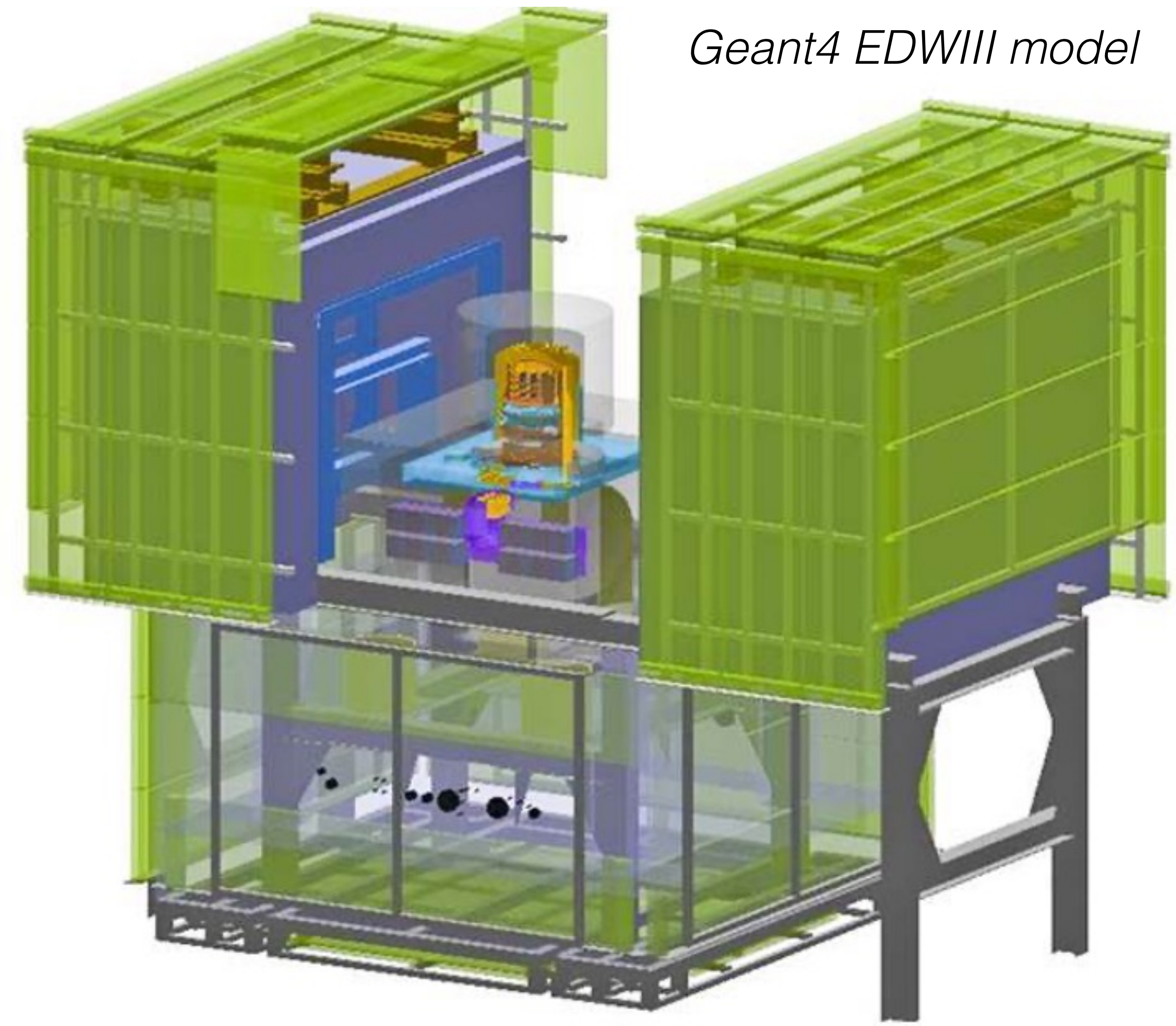


EDELWEISS-SubGeV: was aiming for a kg-scale payload of few-g to 30g Ge detectors running in two modes:

- **High Voltage:** single-e/h sensitivity by operating in a NTL mode
- **Low Voltage:** Particle ID - ER/NR/'unknown backgrounds' - and fiducialization

Both operating modes require sub-100 eV heat energy thresholds

Dark Matter search : EDELWEISS -II / -III setup



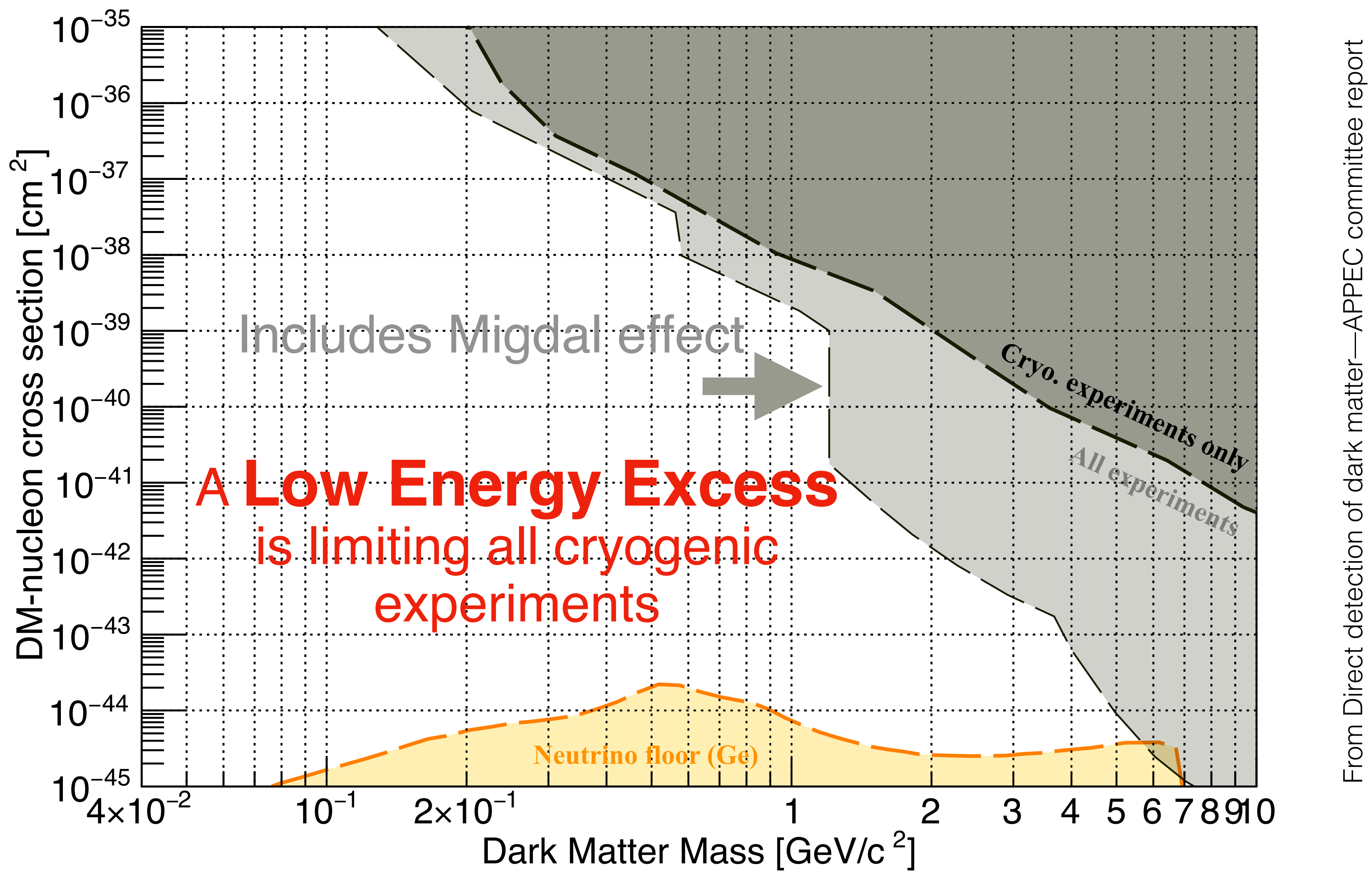
- **located in LSM in the French Alps**
- **started in 1994** (w/ Al2O3, Ge in 1996)
- **EDW-II (2002-2011)**
  - 10 * 400 g Ge
- **EDW-III (2012-2022)**
  - 36 * FID 800 g Ge
  - R&D on 200g and 33g detector for low mass DM **(EDW-SubGeV)**
  - 3000 coax. cables (6 km)
  - 350 Si-JFET transistors@ 120K
  - 36*2 « Bolometers Boxes » @ 300K

- 35 tons **PE** + 40 tons **Pb shielding**
- 100 m^2 active **muon veto**
- **Low radioactivity** material in the detector vicinity

Low Mass Dark Matter search : state of the art

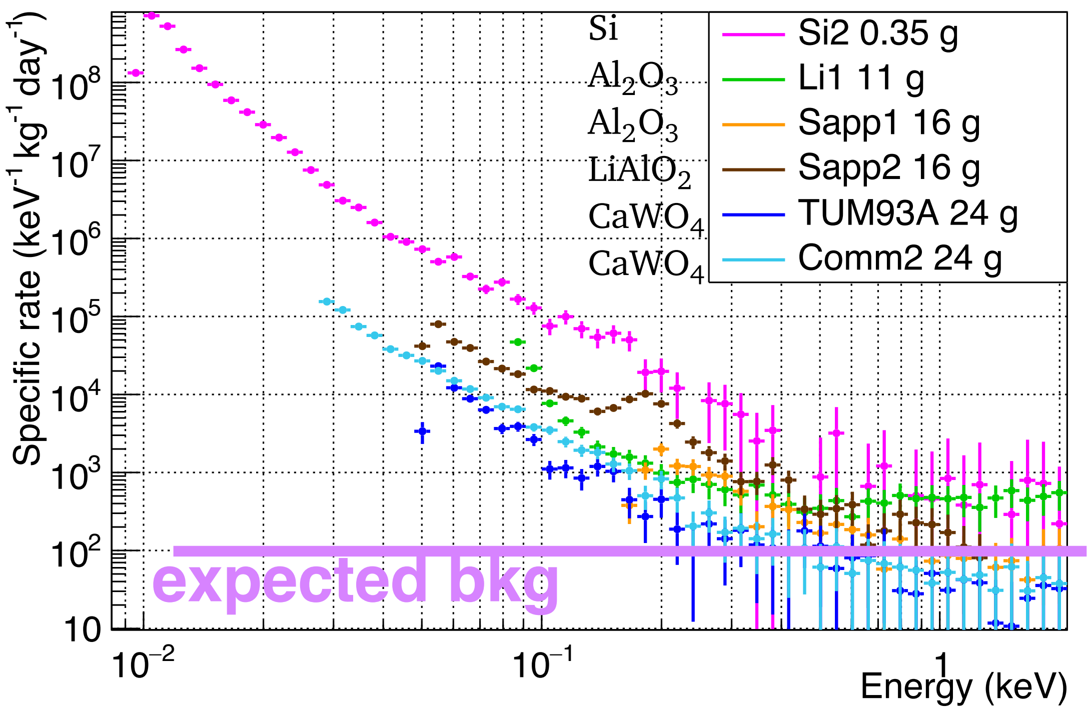
(Nuclear Recoil DM)

Why 100 eV-scale cryogenic DM experiments aren't leading the sub-GeV search region ?

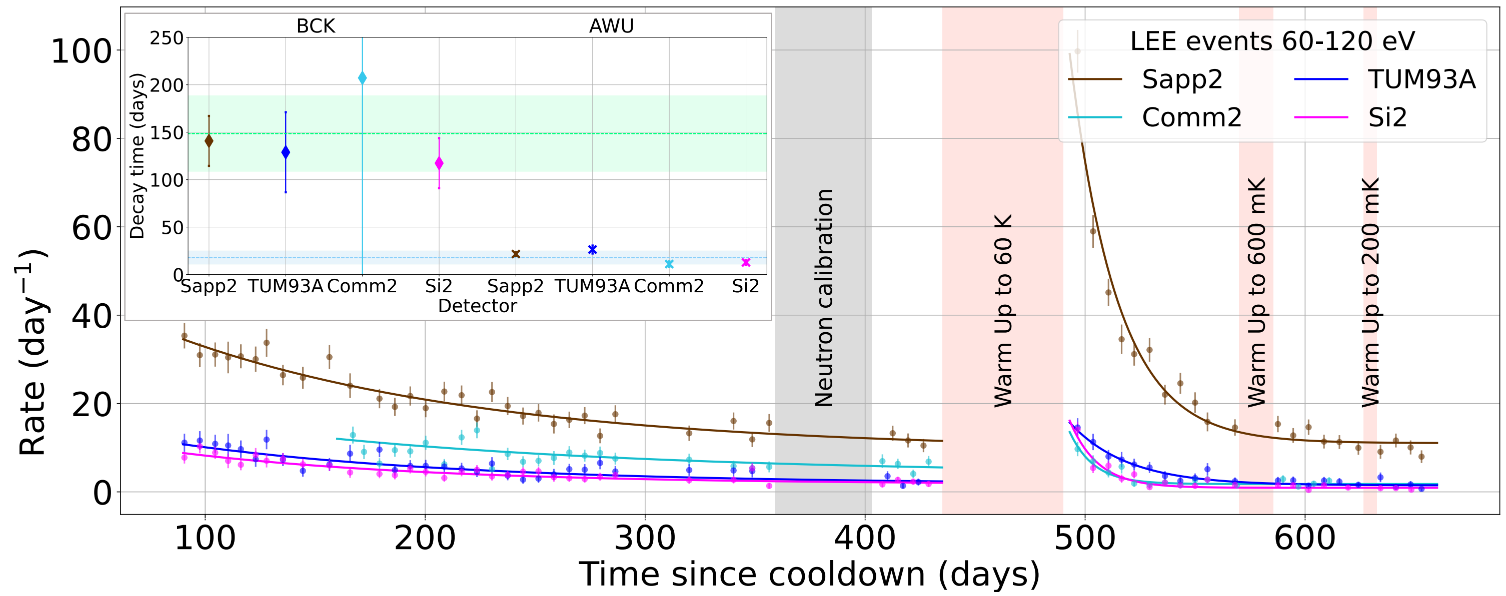


- Currently, **all cryogenic experiments** which have reached sub-100 eV thresholds **are seeing such an excess** limiting their DM reach
- **LEE characteristics**: time dependent, **non-ionizing**, mostly independent of sites, dependence with holders/vibrations (?)
- Possible connection to anomalously short coherence time in Q-bits partially

Cryo detector : Low Energy Excess evts

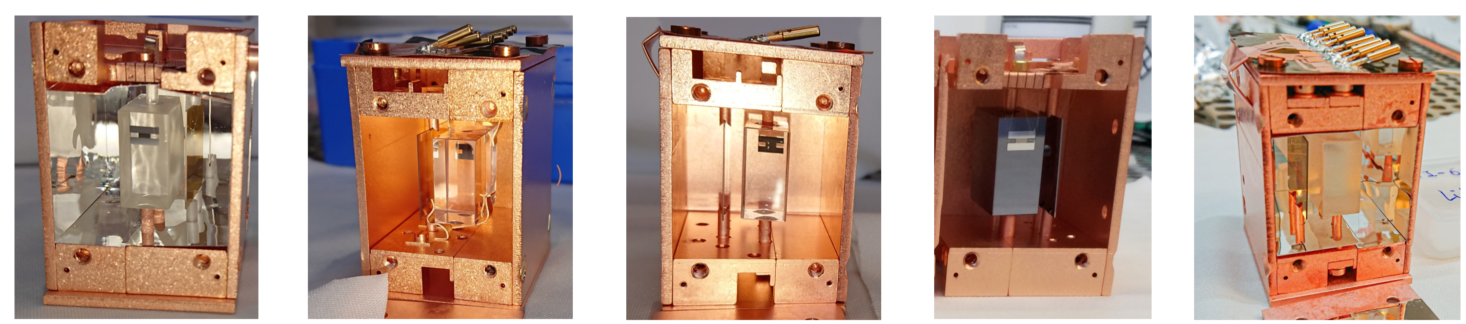


arXiv:2207.09375



Ex of CRESST work to fix the LEE issue

Multiple design modifications were applied in the current data-taking campaign to test ideas about the LEE origin.



$CaWO_4$ grown at TUM | Commercially grown $CaWO_4$ | Al_2O_3 | Si | $LiAlO_2$

Current measurement campaign started in November 2020 and is now at the last stage.

- Various target materials: $CaWO_4$, Al_2O_3, $LiAlO_2$, Si
- Different holding structures (sticks, clamps)
- Remove scintillating parts (foil, sticks, scintillating crystals)

All thresholds are at O(10 eV)

LEE is observed in all detectors

CRESST

TAUP 2023 | 30.08.2023 | Margarita Kaznacheeva

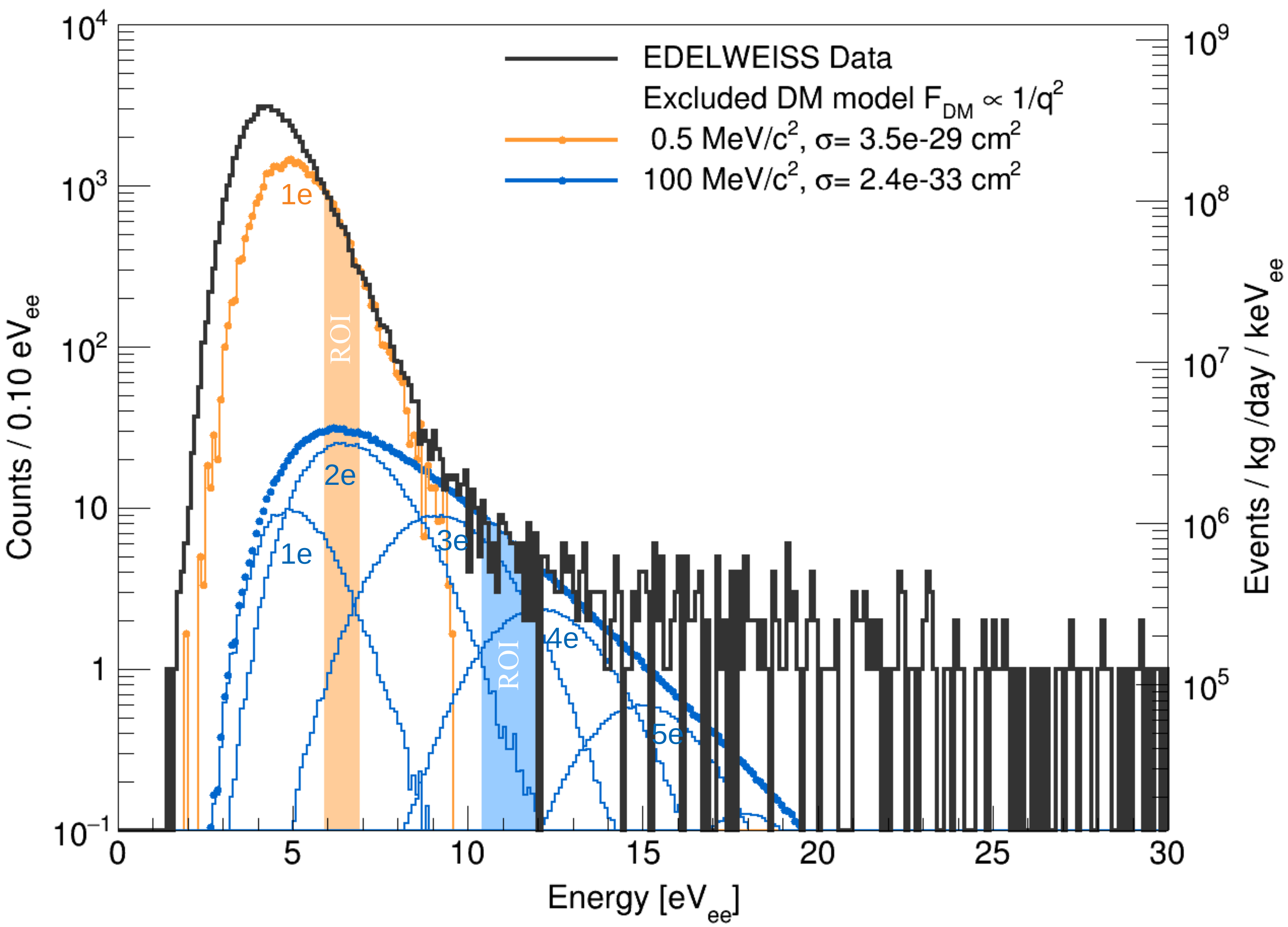
- *Low Energy Excess seen by ALL cryogenic detectors !!*
  - Radiogenic bkg more expected to be flat and at the 1-100 dru level :
  - ***LEE orders of magnitude higher !***
- **Origins under investigation:**
  - Sensor related events
  - Relaxation of holding-induced stress
  - Intrinsic crystal effects

Major issue today.

Will limit most of the science cases if not solved/mitigated

TAUP 2023 | 30.08.2023 | Margarita Kaznacheeva

EDELWEISS : Dark Matter search in HV mode @ LSM



https://doi.org/10.1103/PhysRevLett.125.141301

33 g Ge @ 78V

σ∼1.5 eV$_{ee}$ (0.53 eh pair)

2020 World leading results
(DM scattering on e, DM absorption)
with only 58 hours of DM search at LSM!

200 g Ge @ 66V

σ∼4.45 eV$_{ee}$ (1.5 eh pair)

2022 World leading results
(DM scattering on e, DM absorption)
with only 28 days of DM search at LSM!

https://doi.org/10.1103/PhysRevD.106.062004

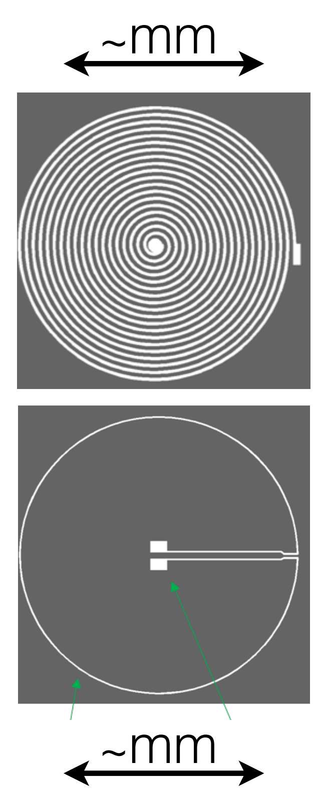
Spectra <25eV$_{ee}$ =680 eV phonon) ***dominated by Low Energy Excess (heat only event)***

- **HV mode is not sufficient** by itself **to probe low mass DM**, must be combined w/ **heat only event identification**
- Similar results on a 200g detector with NbSi thermometer

EDELWEISS : Identification of Low Energy Excess (« heat only »)

- **Low Energy Excess are non ionizing** (« heat only » event)
  - ***Ionization can be used to reject LEE***
  - Huge effort over the past 7 years :
    - from **EDWIII σ = 200 eV to σ = 30 eV** (reached for RICOCHET)
  - **σ = 20 eV in hand** but hard to do better than 10

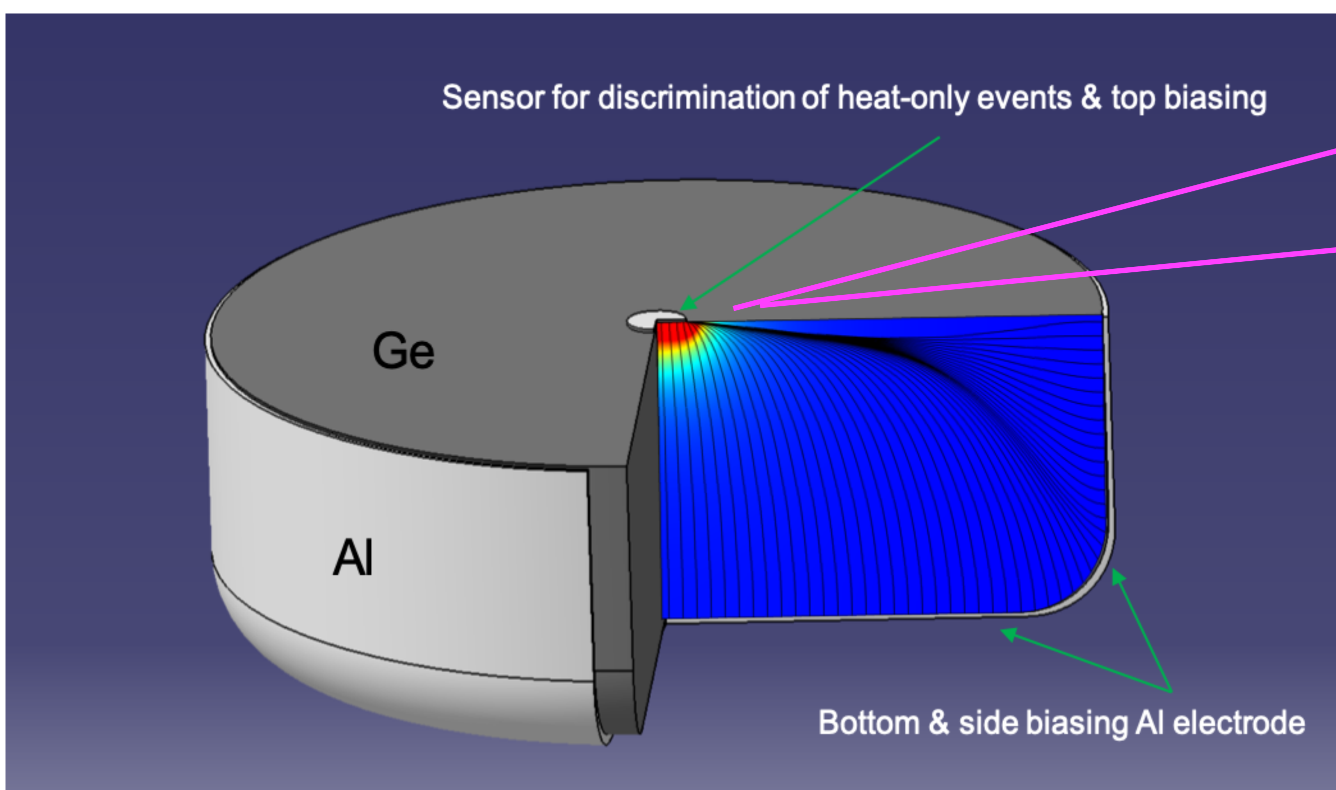
- **Tricks = use the Luke effect**
  - ***Concentrate it***
  - ***trigger a « LEE » veto thermometer***
  - single e-h sensitivity possible



~mm^2 ultra sensitive **NbSi TES**

~mm*µm innovative **NbSi SSED**

Superconducting Single Electron Device



EDELWEISS : Future

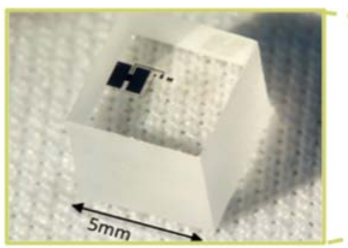
- **EDELWEISS-III setup dismantled in 2023**
- EDELWEISS collaboration is not existing anymore
- ….But ***EDW Ge detector technology still alive :***
    - 38g Ge cryo detector development for CEνNS : **Ricochet experiment installed and taking data on a 60 MW reactor @ ILL** (Grenoble).
    - Ongoing participation of some of the EDW members + new French groups to the ***TESSERACT @ LSM Project***

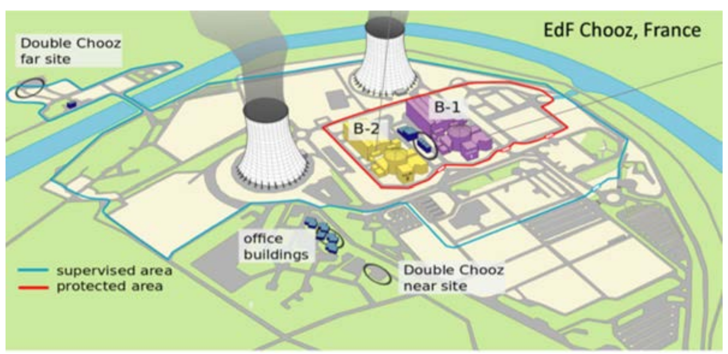
Empty EDW space @ LSM (feb 2024)

The CEνNS connexion

CRESST→ NUCLEUS

Two 3x3 arrays of
6g $CaWO_4$ + 4g Al_2O_3
read out by W TES

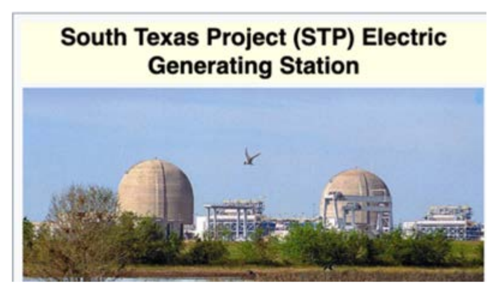




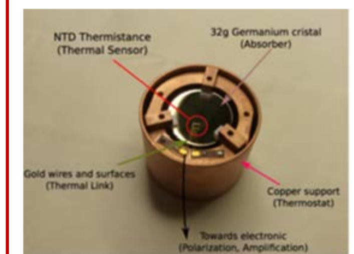
SuperCDMS→ MIνER

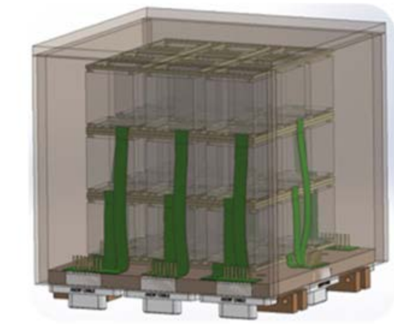
HV, iZIP
Al_2O_3 + QET

TRIGA research nuclear reactor at TAMU with moveable core

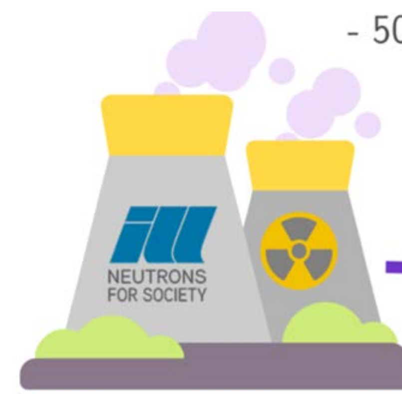


EDELWEISS→ Ricochet





Array of 27x32g detectors:
- 8x8x8 cm^3
- 50% Ge semiconductors
- 50% Zn superconductors



Institut Laue-Langevin
(Grenoble, France)

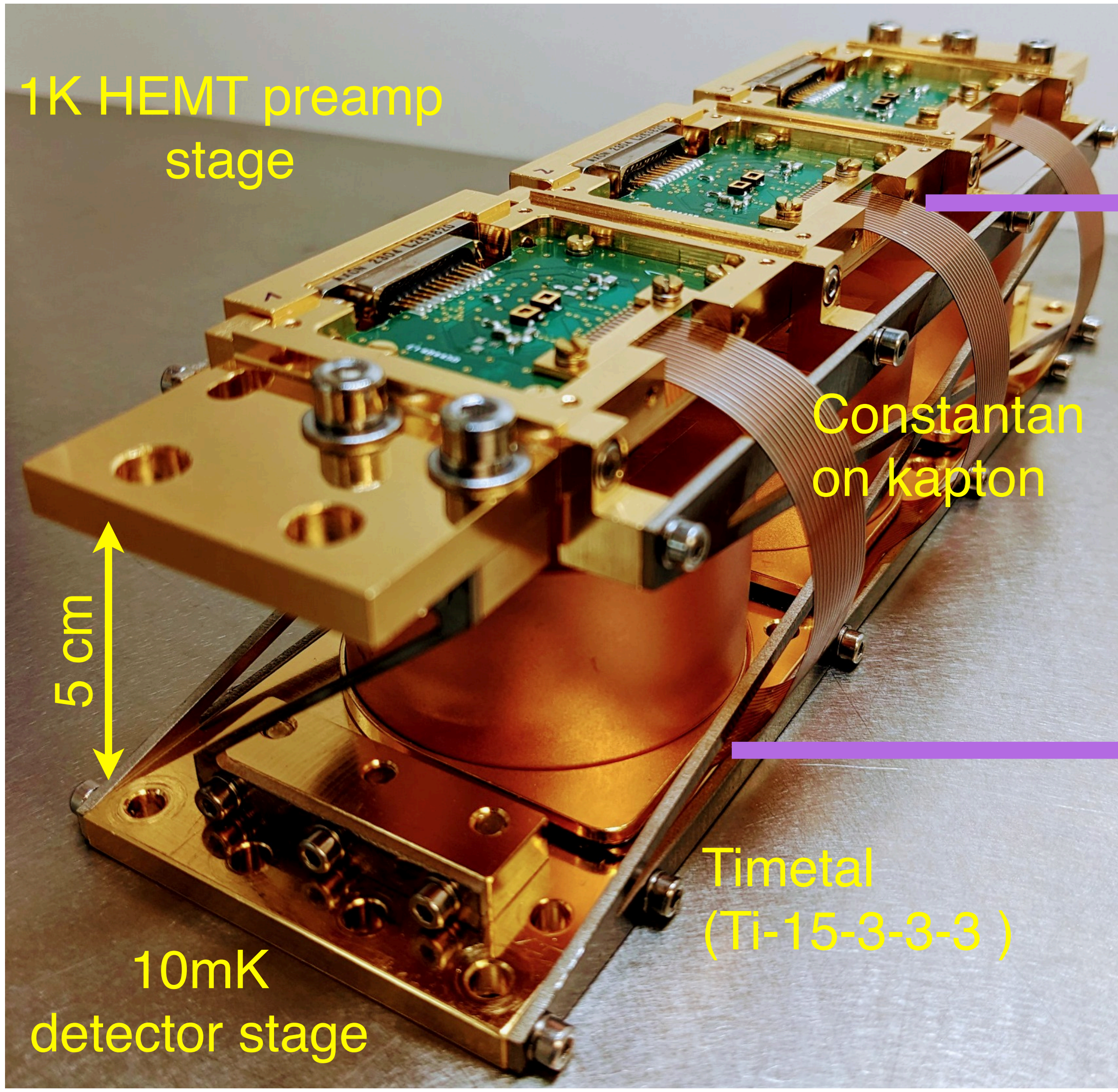
Prisca Cushman NDMNP 2022

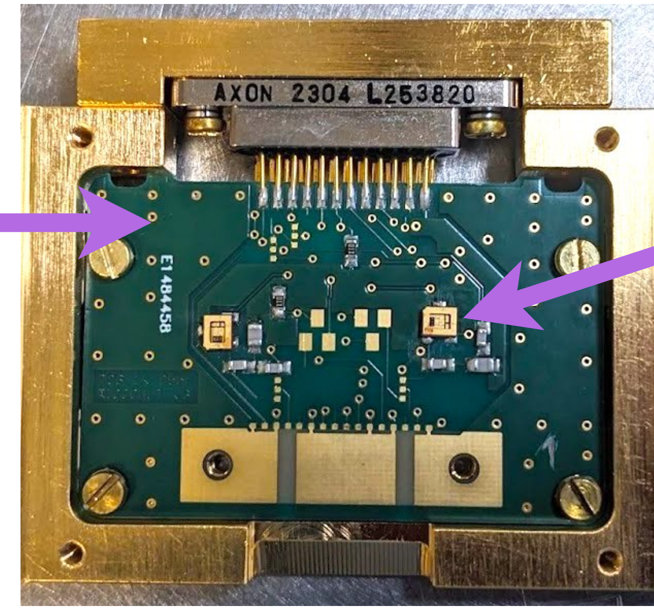
see CEνNS @ reactor talk

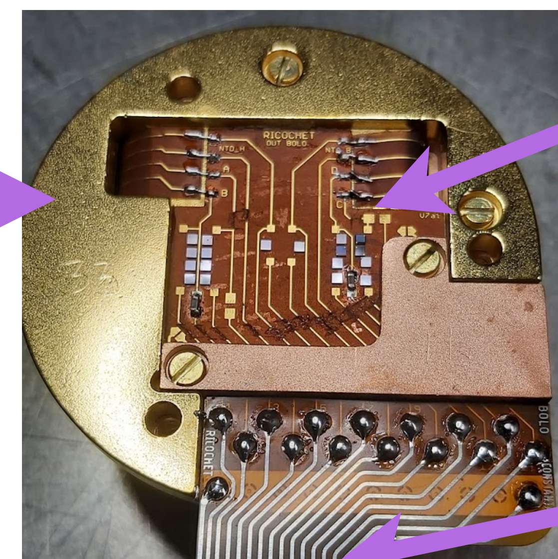
Main cryogenic det. **DM search experiments have a CEνNS side project**:

- ***Coherent elastic neutrino nucleus scattering***
- If you are ***sensitive to low mass DM you are sensitive to CEνNS***
- You know precisely what you want to measure and **you want to measure it precisely**
- Depending on the site **you can design your experiment** accordingly

CEνNS : RICOCHET - MiniCryoCube







✦ **HEMT** (High electron Mobility Transistor) **@ 1K** to replace the standard Si-JFET working at 100K

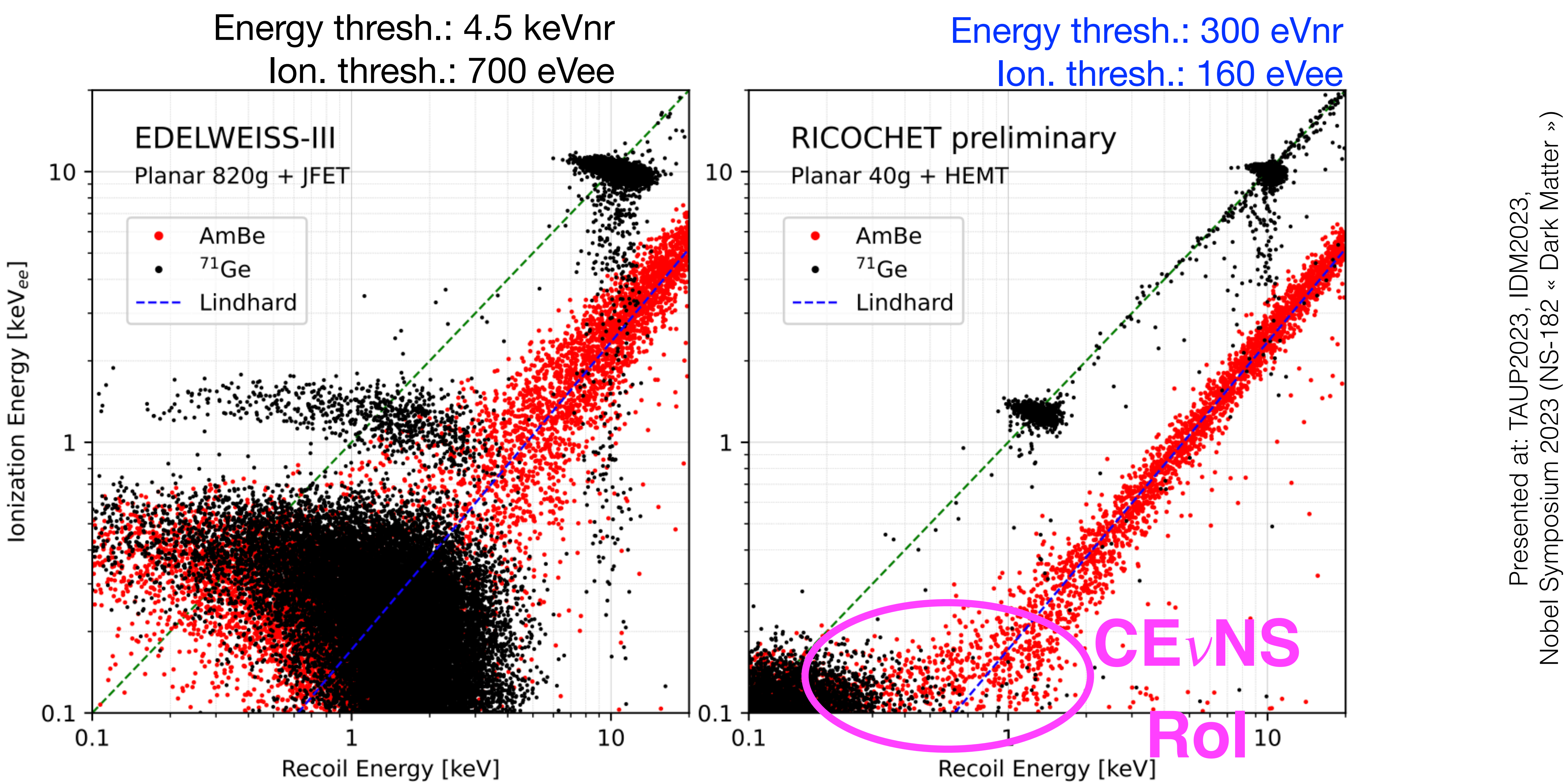
✦ Bias and feedback resistor **placed at 10mK** to minimize the thermal noise

✦ 35 µm contantan tracks on 100 µm kapton foil for the 10mK-1K path

✦ Intense work on the 1K HEMT based cold elec and 1K-10mK interface :

- **Mitigate stray capacitance** (ionization reso)
- **Mitigate heat load** on 10mK stage
  - ➡ low HEMT bias dissipation (~15uW/HEMT)
  - ➡ Use of special material for the 1K-10mK mechanics
- **Mitigate Johnson noise** of FB and and bias resistor

Ricochet R&D : MiniCryoCube demonstrator @ IP2I Lyon

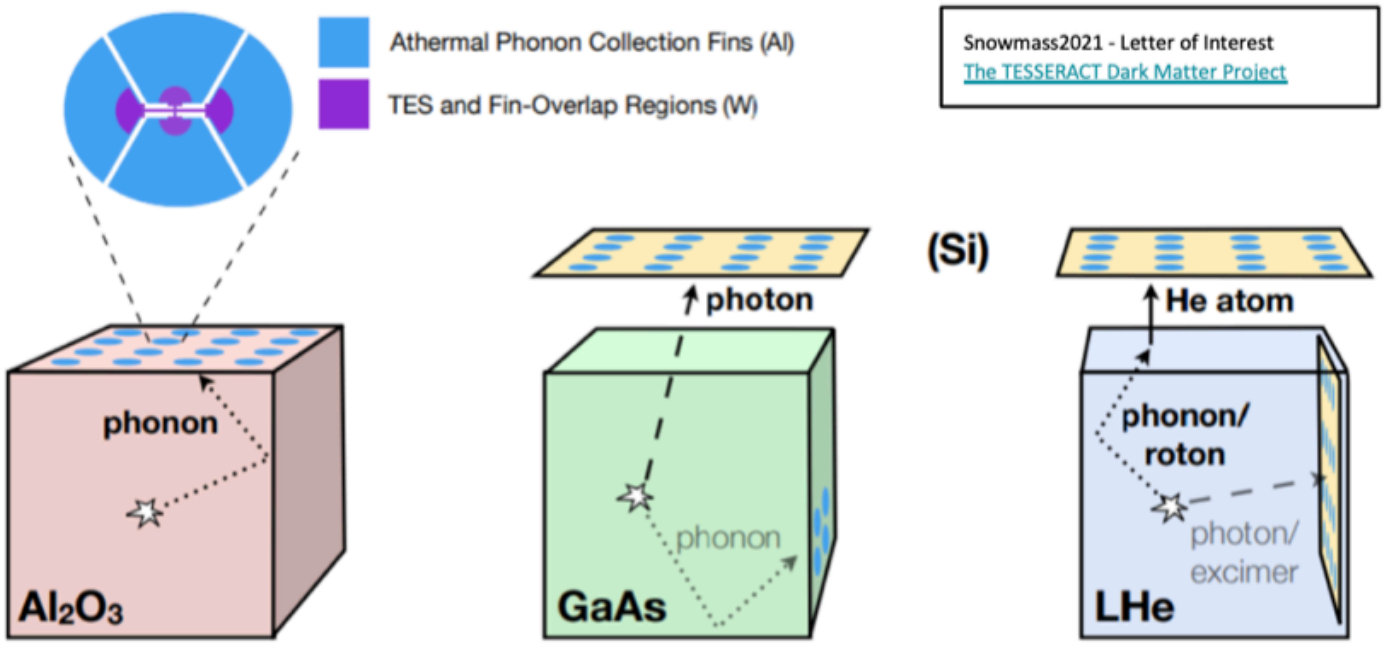


- ER/NR discrimination **threshold** has been improved **by about one order of magnitude w.r.t EDW** and SuperCDMS
- **Ricochet can** now **probe reactor neutrinos (CEvNS)** (and equiv. 3 GeV WIMP with highly efficient LEE and ER rejection)
  - ➡ **Ricochet resolution goals: 10 eV (heat) + 20 eVee (ionisation)**
  - ➡ *factor of ~2 still missing*

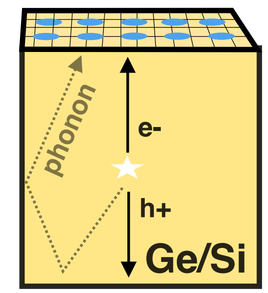
TESSERACT : Proposal experiment @ LSM

Transition Edge Sensors with Sub-Ev Resolution And Cryogenic Targets

Snowmass2021 - Letter of Interest
The TESSERACT Dark Matter Project



- DOE Funding for R&D and project development began in June 2020 (Dark Matter New Initiative)
- One experimental design, and different target materials with complementary DM sensitivity, all using TES
- Includes **SPICE** (**Al_2O_3** and **GaAs**) and **HeRALD** (**LHe**)
- ~ 40 people from 8 institutions
- ~~Actively searching for an underground lab~~
- **found an underground Lab and new partners**

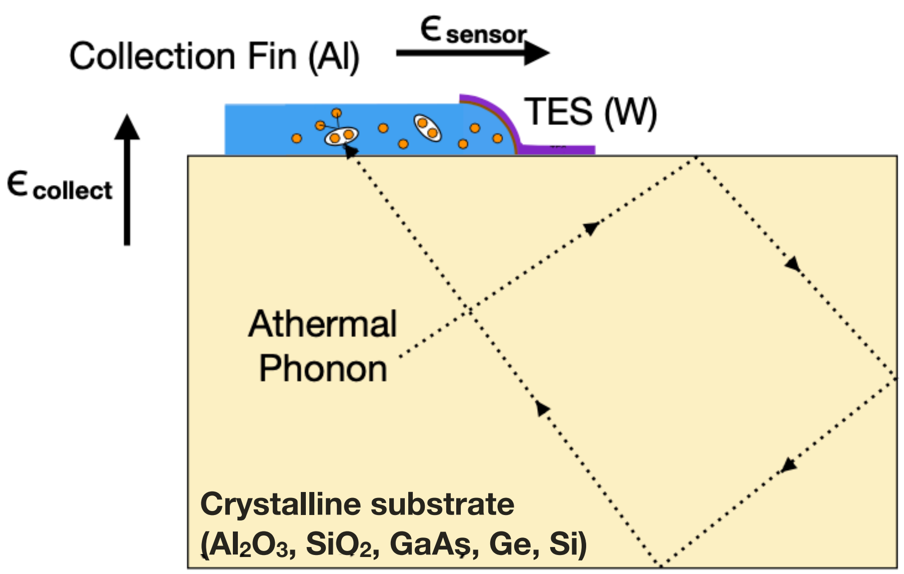


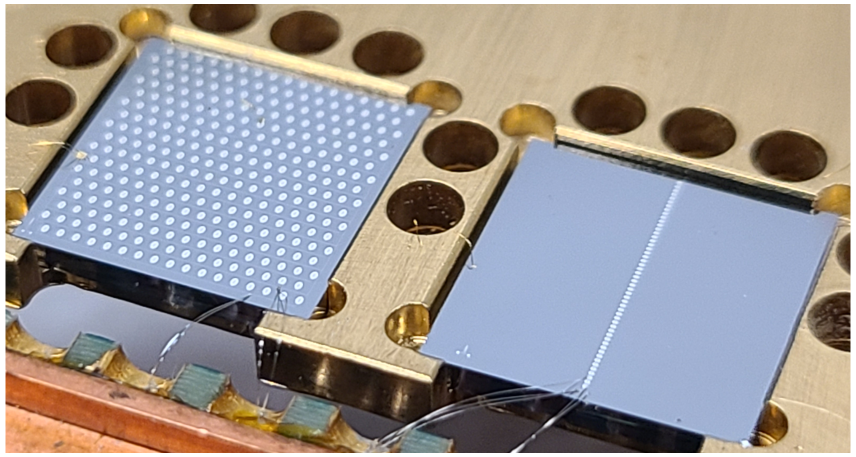
TESSERACT @ LSM proposal:

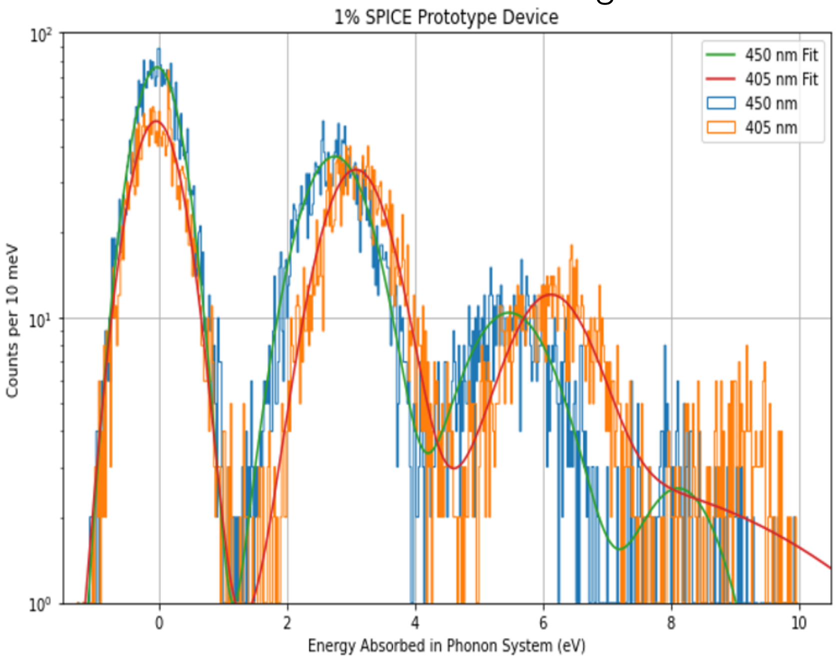
- Benefit from EDW+Ricochet+CUPID Ge bolometer expertise and low-background cryogenic experience to:
  1. **Add the French** semiconductor **Ge bolometer** technology (**both LV and HV mode**) to the TESSERACT science program
  2. **Deploy** the future TESSERACT **experiment at LSM**
- Achieve leading light DM sensitivities on short time scales
- Benefit from exchange of technologies with US partners

TESSERACT : New generation TES sensors

Roger Morani. LTD20







$$\sigma_E \sim \frac{\sqrt{4k_b T_c^2 G(\tau_{collect} + \tau_{sensor})}}{\epsilon_{collect}\epsilon_{sensor}}$$

$$\sigma_E \propto V_{det}^{1/2} T_c^3$$

Energy threshold **decreases w/ detector mass**

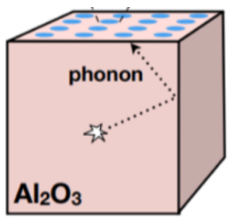
Energy threshold **decreases very quickly w/ Tc**

- SuperCDMS TES technology optimized for small volume crystal.
- **273 meV (RMS) leading to eV-scale threshold already achieved** with a 0.2g Si detector and Tc = 50 mK
- Targeted Tc around 15-20 mK recently achieved

  ~100 meV threshold achievable on 1 cm^3 crystals

- **Next challenge:** parasitic power (vibrations, EMI, IR photons) needs to be <aW to fully reach TES sensitivity

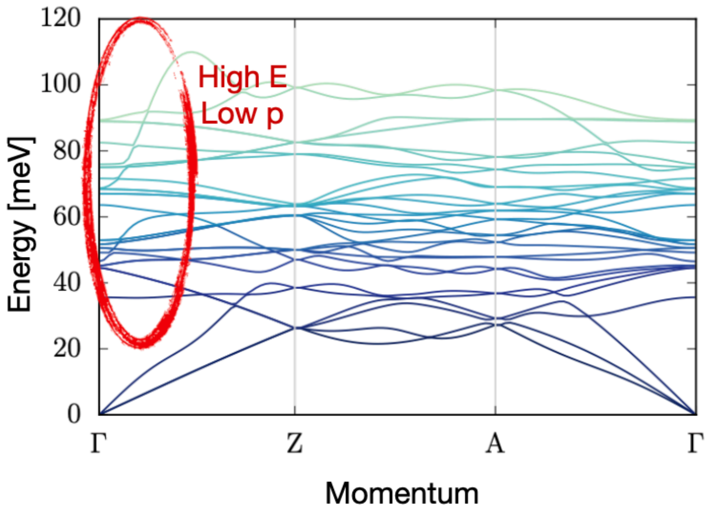
TESSERACT @ LSM : SPICE



Sub-eV Polar Interactions Cryogenic Experiment: Al_2O_3

1. **Sapphire** supports many **optical phonon modes**.
   (phonons with a high energy:momentum ratio)

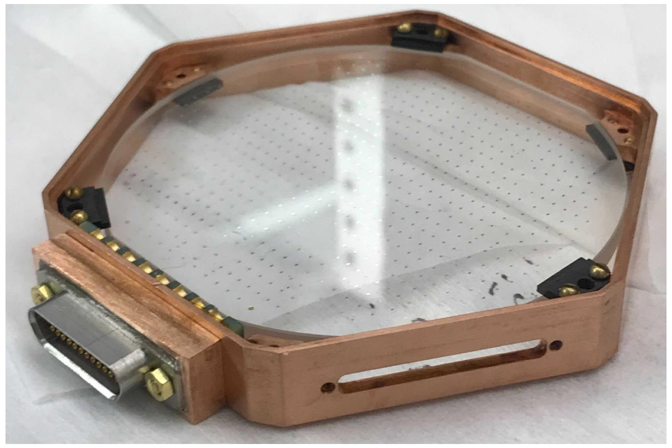
   Instead thinking about 'kicking an atom' we now think about recoiling off the lattice, and 'exciting a phonon'. **Optical phonons** are kinematically **well-matched to low-mass dark matter** (similar effective mass)



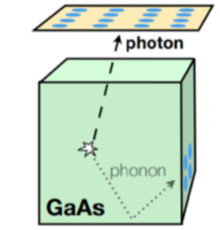
2. **Sapphire** is a **polar crystal**
   (couples well to E&M-like inputs)

   Allows to **extend DM scattering searches** via light dark photon down to keV masses not accessible to any other target materials
   Possibility to extend further down to 100-meV (eV) DM masses thanks to absorption on phonon (electron)

   LEE mitigation: Use of > 2 TES channels with various bandwidth response

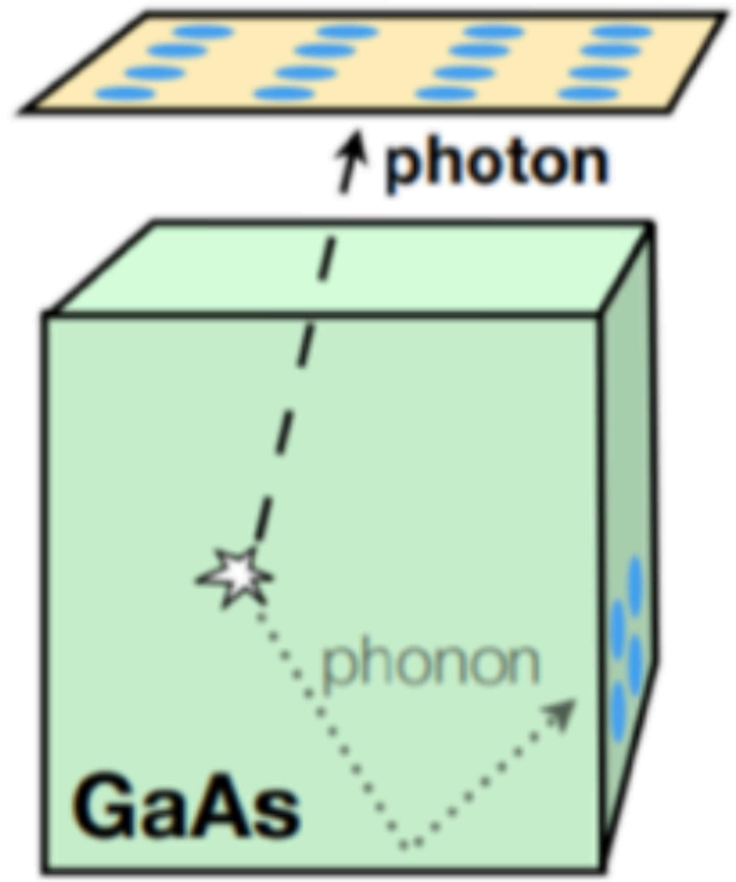


TESSERACT @ LSM : SPICE

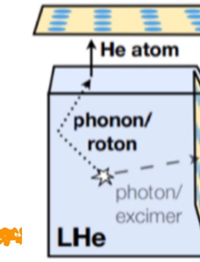


Sub-eV Polar Interactions Cryogenic Experiment: GaAs

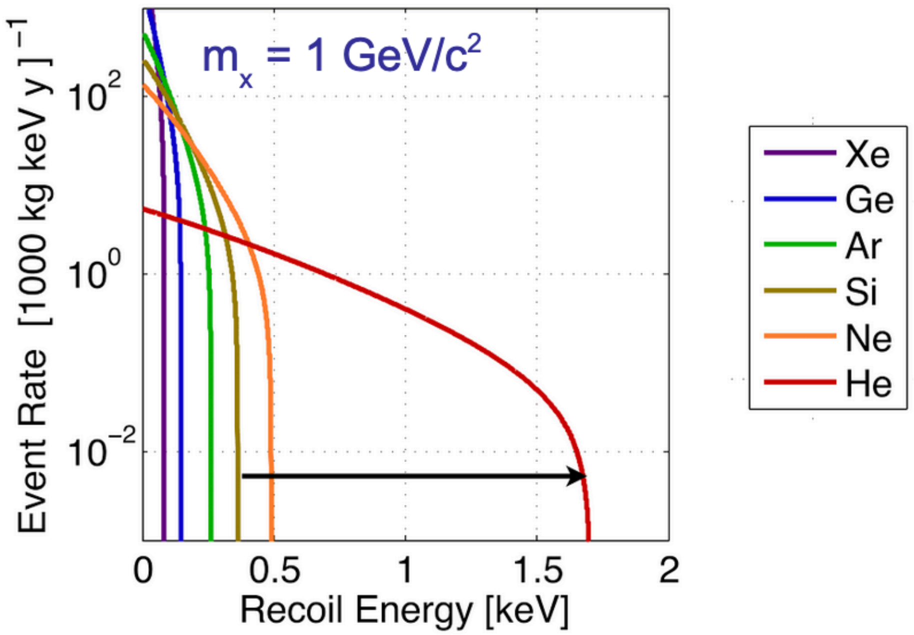
- **GaAs** has **very high scintillation** yield (125 ph/keV, arxiv:1904.09362)
- **GaAs** has a similar DM sensitivity than Ge/Si and similarly allows for control of the backgrounds:
  - **photon:phonon ratio** depends on the recoiling particle type:
    - **NR/ER discrimination** (~10 eV scale)
  - **photon/phonon coïncidence** in two separate sensors:
    - **Low Energy Event rejection** (~eV scale)

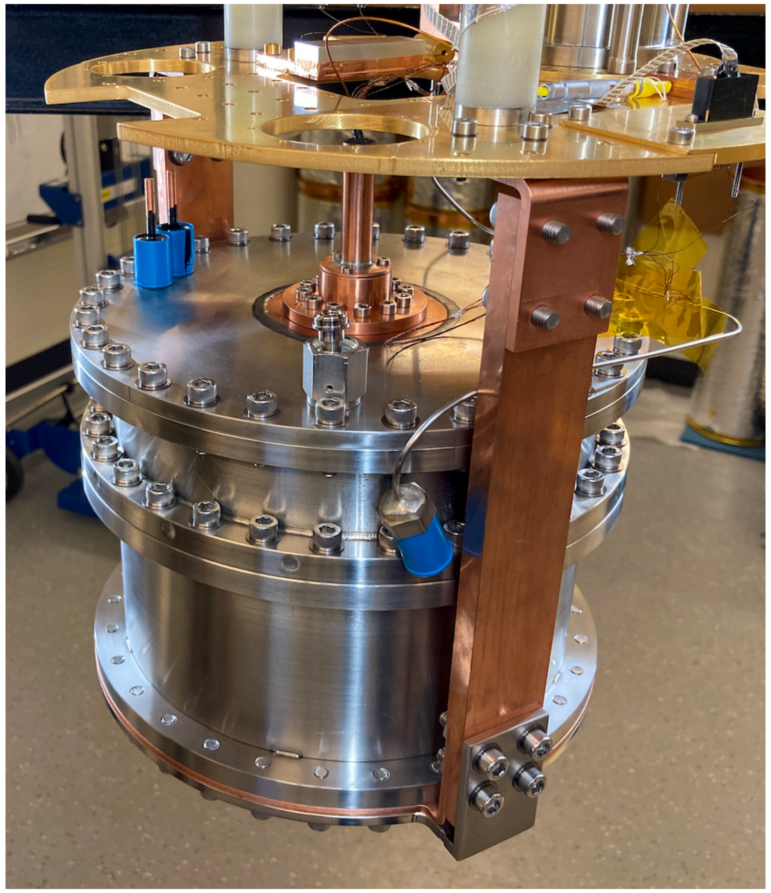


TESSERACT @ LSM : HeRALD

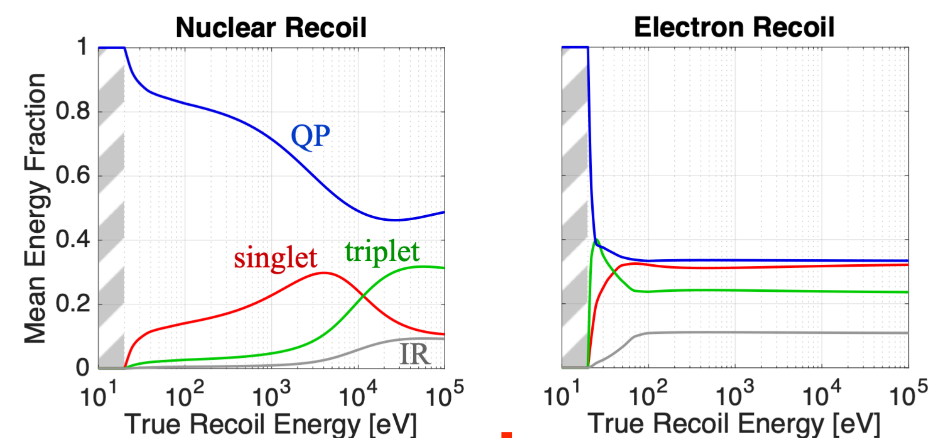


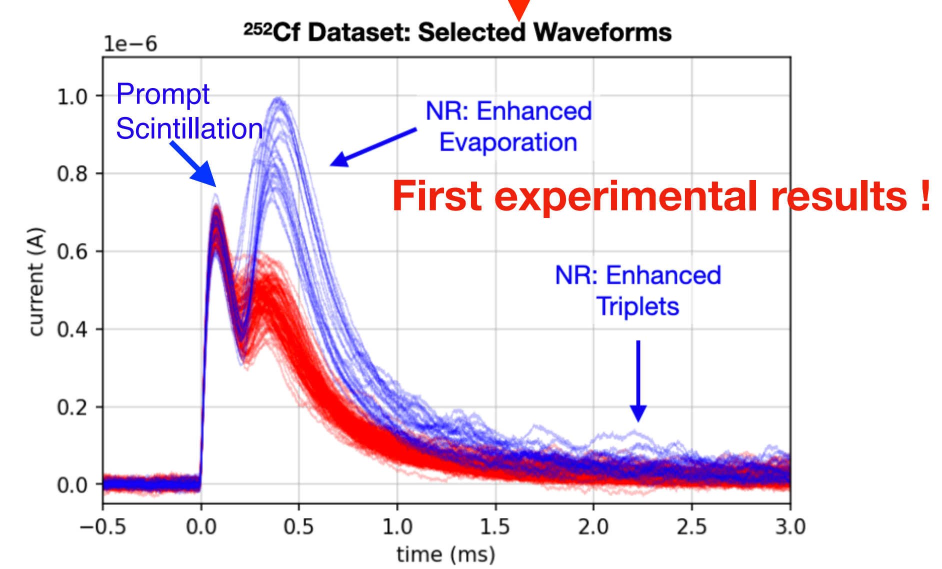
Helium Roton Apparatus for Light Dark matter



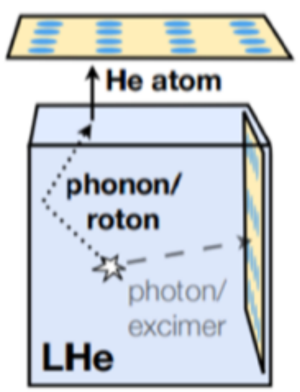


R. Anthony-Petersen et al., arXiv:2307.11877

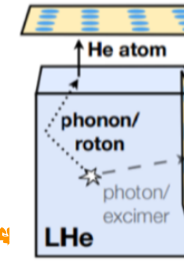




- Well **kinetically matched to GeV-scale DM**
- Easy to purify, intrinsically radio pure
- Monolithic and scalable
- LHe cell operated at 20-50 mK with wafer-like cryogenic detectors with TES suspended in vacuum
  - UV/IR photons and He atoms from qp induced evaporation
- **First evidence of ER/NR discrimination** @10 keV
- Already **achieved ~170 eV threshold on He recoils** (300 MeV DM)



TESSERACT @ LSM : HeRALD



Helium Roton Apparatus for Light Dark matter

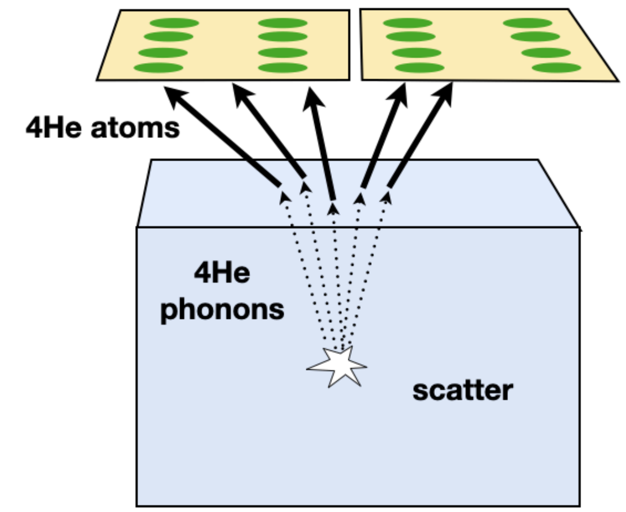
^{4}He is unique in two ways:

- Target material (4He) close to a macroscopic quantum ground state, with **no defects/stress/etc.**

  Superfluid 4He is nearly unique among bulk target materials in this regard : **No Low Energy Excess ??**
- **Quantum evaporation** allows for robust coincidence-based selection of target events at sub-eV scales

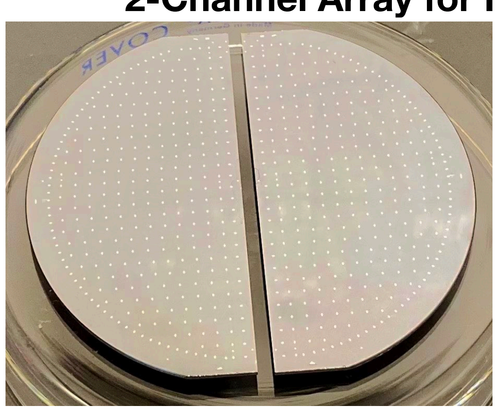
  Events in calorimetry: single-channel (vacuum gaps mean no shared phonons)

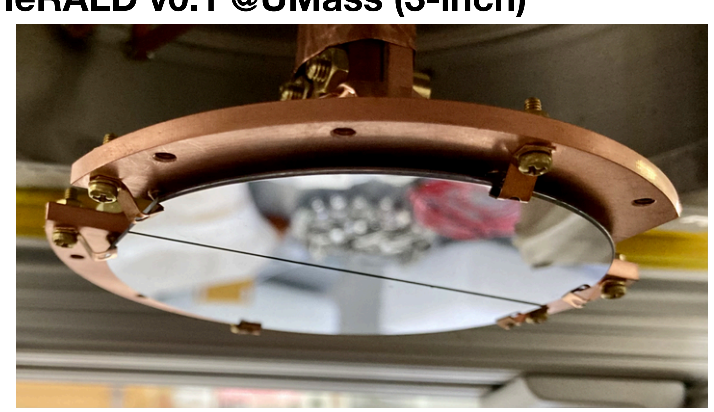
  Events in 4He: always multiple channel (evaporated atoms have large angular spread)



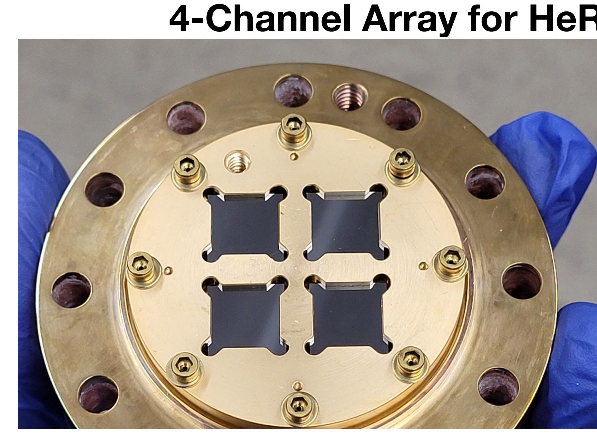
→ Near-term HeRALD plans all **involve multi-channel evaporation readout** and testing the above strategy

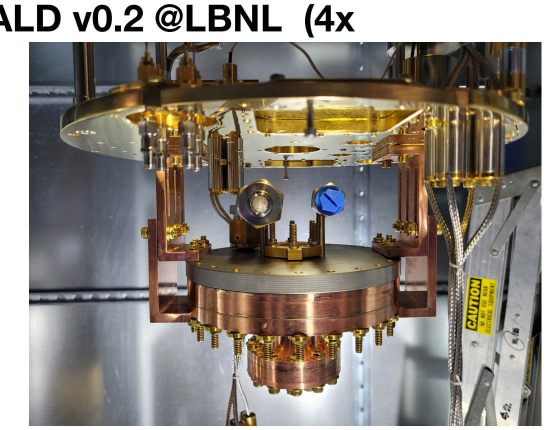
2-Channel Array for HeRALD v0.1 @UMass (3-inch)



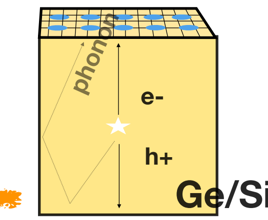


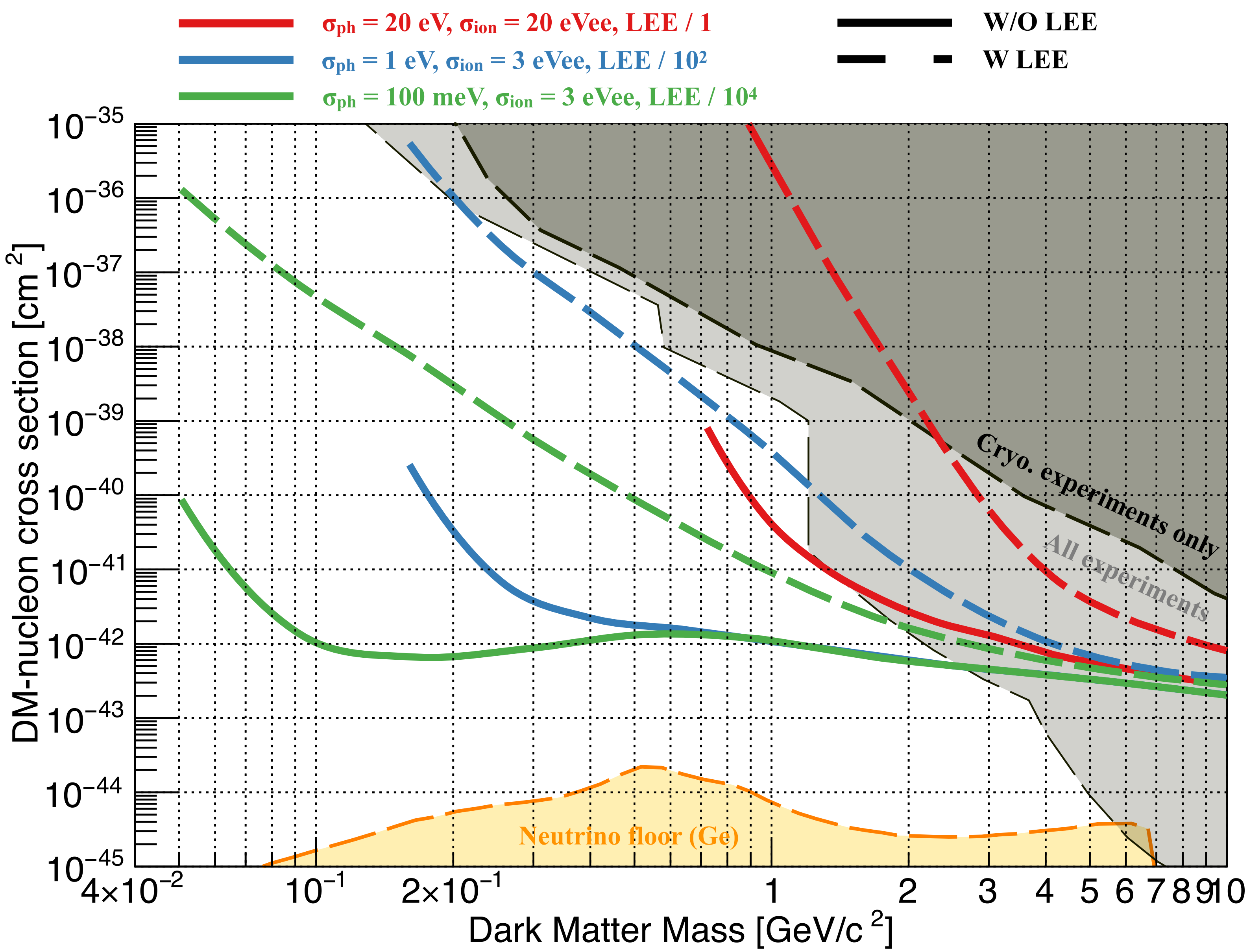
4-Channel Array for HeRALD v0.2 @LBNL (4x





TESSERACT @ LSM : Ge/Si Cryo detector





The EDW/Ricochet cryogenic Ge LV technology in TESSERACT **will allow to extend the NRDM searches down to 100 MeV** with **particle ID and LEE rejection** in a region of the parameter space inaccessible to non-cryogenic experiments

TESSERACT back. model = 10 DRU gamma + other backgrounds from EDW-III

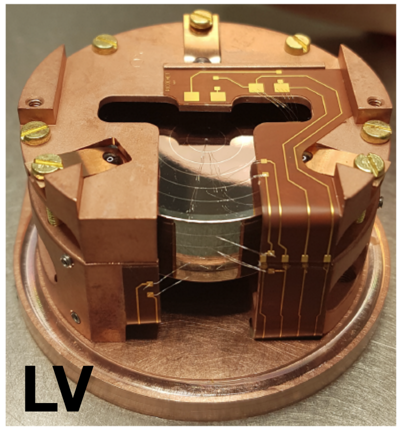
TESSERACT @ LSM: summary

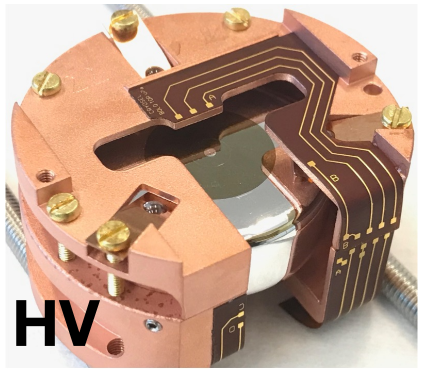
All detector technologies will be using:

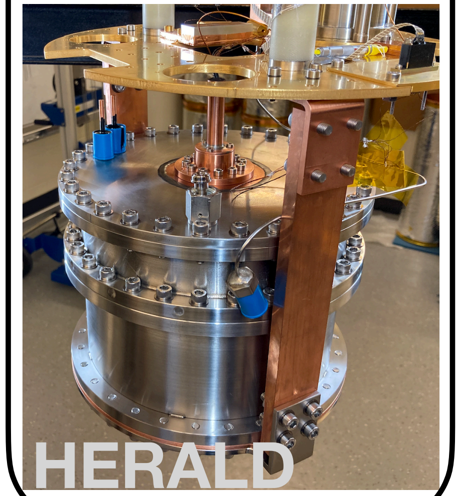
1. athermal phonon TES with sub-eV energy thresholds,
2. drastically mitigated Low Energy Excess
3. and payloads between 10g to 100g

	Target	Search type	Mass range	LEE rejection	Particle ID
SPICE *Polar crystals*	Al_2O_3, SiO_2	ERDM	100 meV - MeV	multi TES channel	None
SPICE *Scintillator*	GaAs	NRDM/ ERDM	eV - MeV MeV - GeV	Phonon/ photon coïncidence	Dual Phonon-photon readout
HERALD	He	NRDM	MeV - GeV	Multiple He4/ photon detector	Pulse shape discrimination
Semicon. *High V*	**Ge, Si**	**ERDM**	**eV - MeV**	**SSED**	**None**
Semicon. *Low V*	**Ge, Si, C**	**NRDM**	**MeV - GeV**	**Phonon/ Ionization coincidence**	**Dual phonon-ionisation readout**

IN2P3





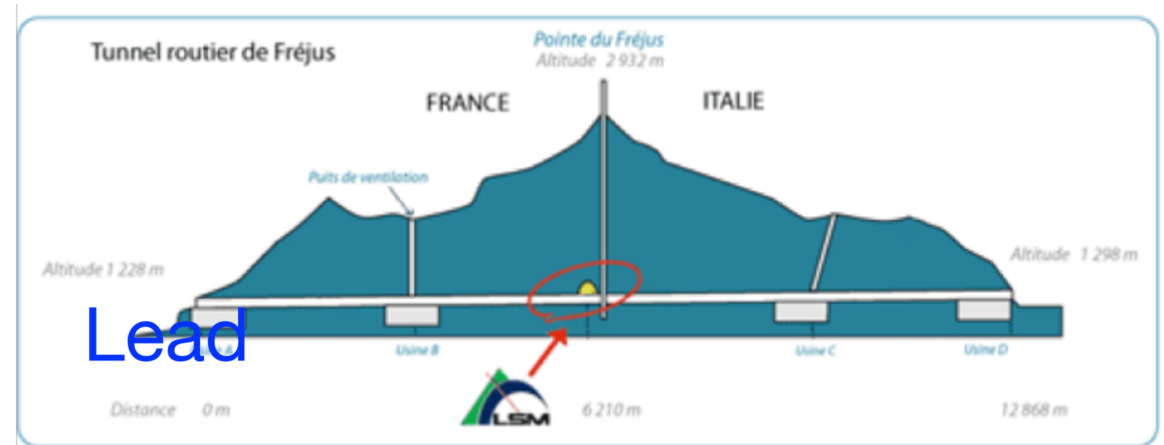


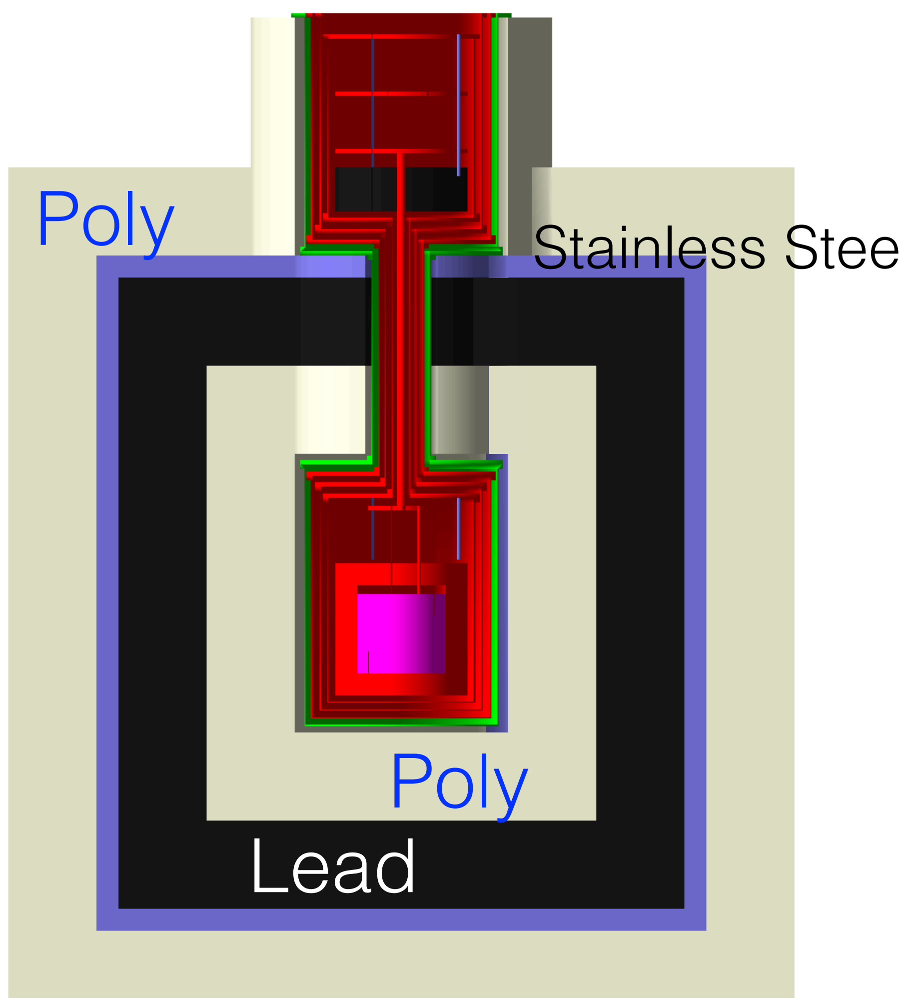
TESSERACT @ LSM: Conclusion

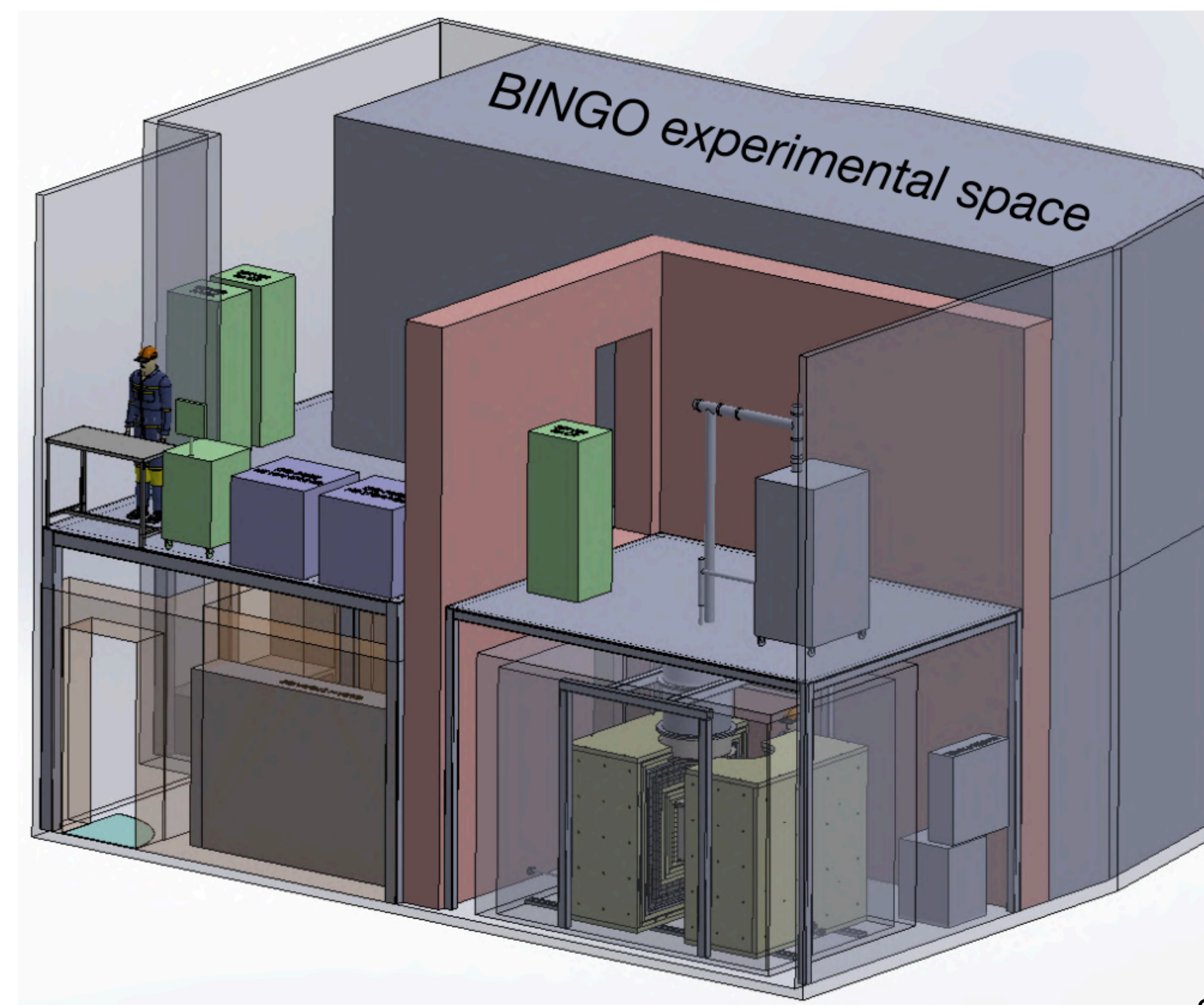
- Tesseract will be **installed at LSM**
- Installation of a **1st cryostat in the next 3 years funded** by CNRS
- extra DoE funding available

Neck like structure will prevent line of sight backgrounds

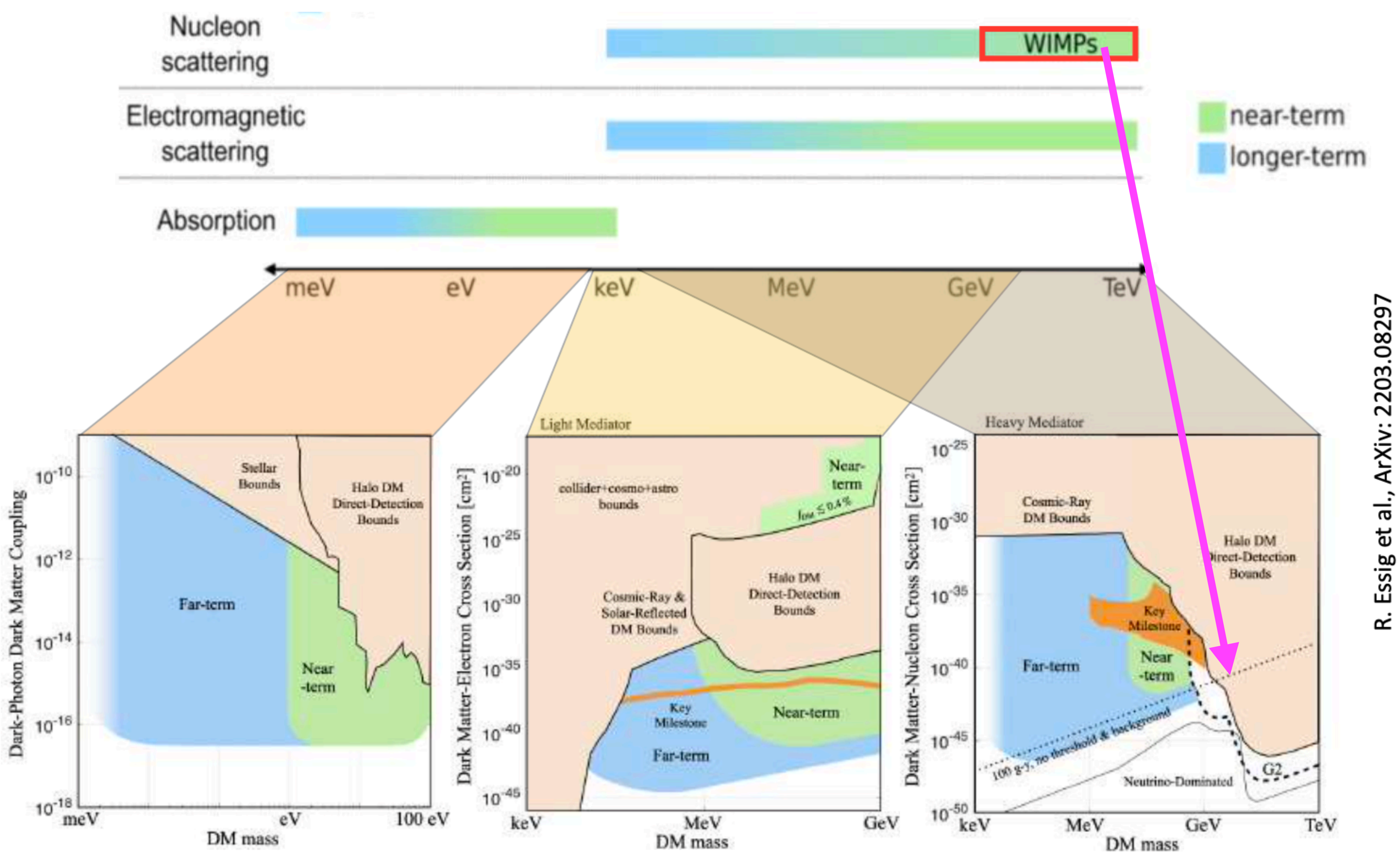
~1 DRU ER / <1e-3 DRU NR







TESSERACT @ LSM: Conclusion



R. Essig et al., ArXiv: 2203.08297

Key of success :

- **Low Threshold** detector
- **Control and identification of the Low Energy Excess** (Heat Only Event)
- Ultra **low background**
- Limit dark count on Ge HV detector (IR induced **leakage**, shallow site impurities etc)

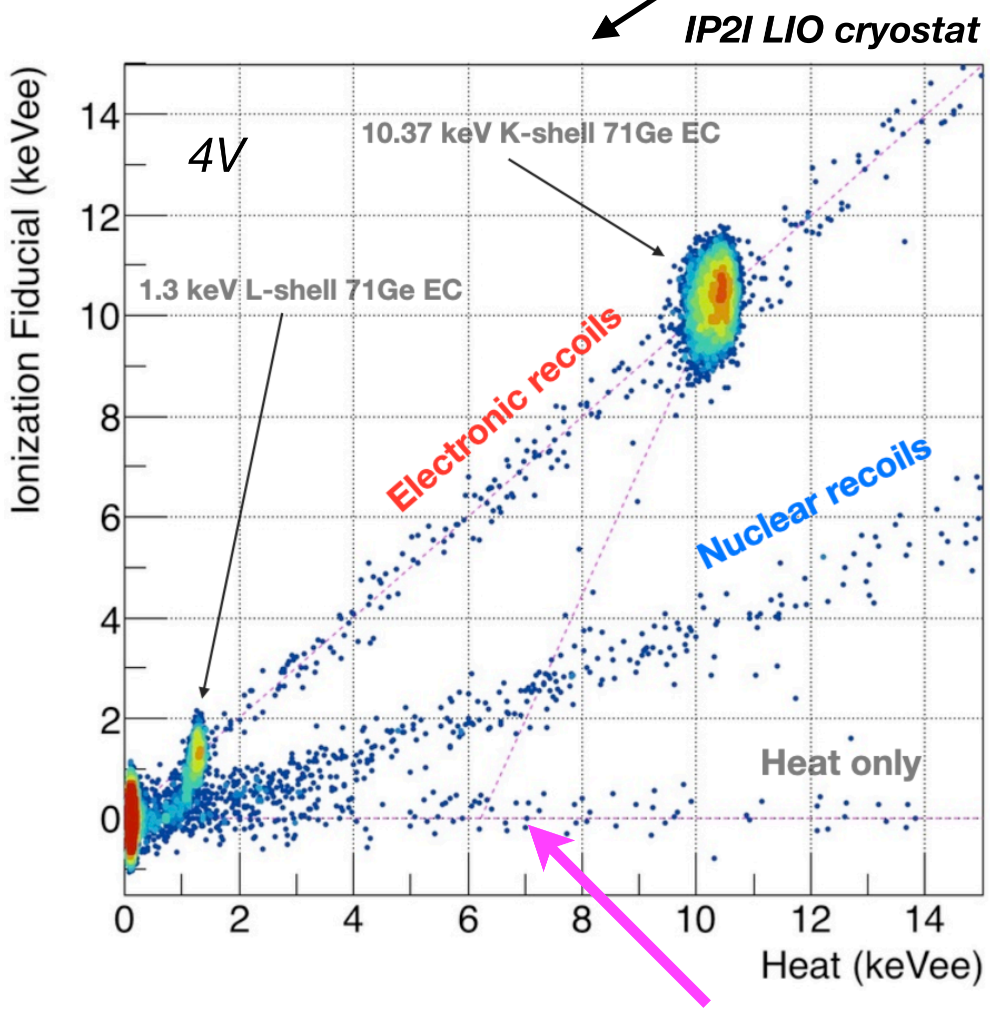
Back-up

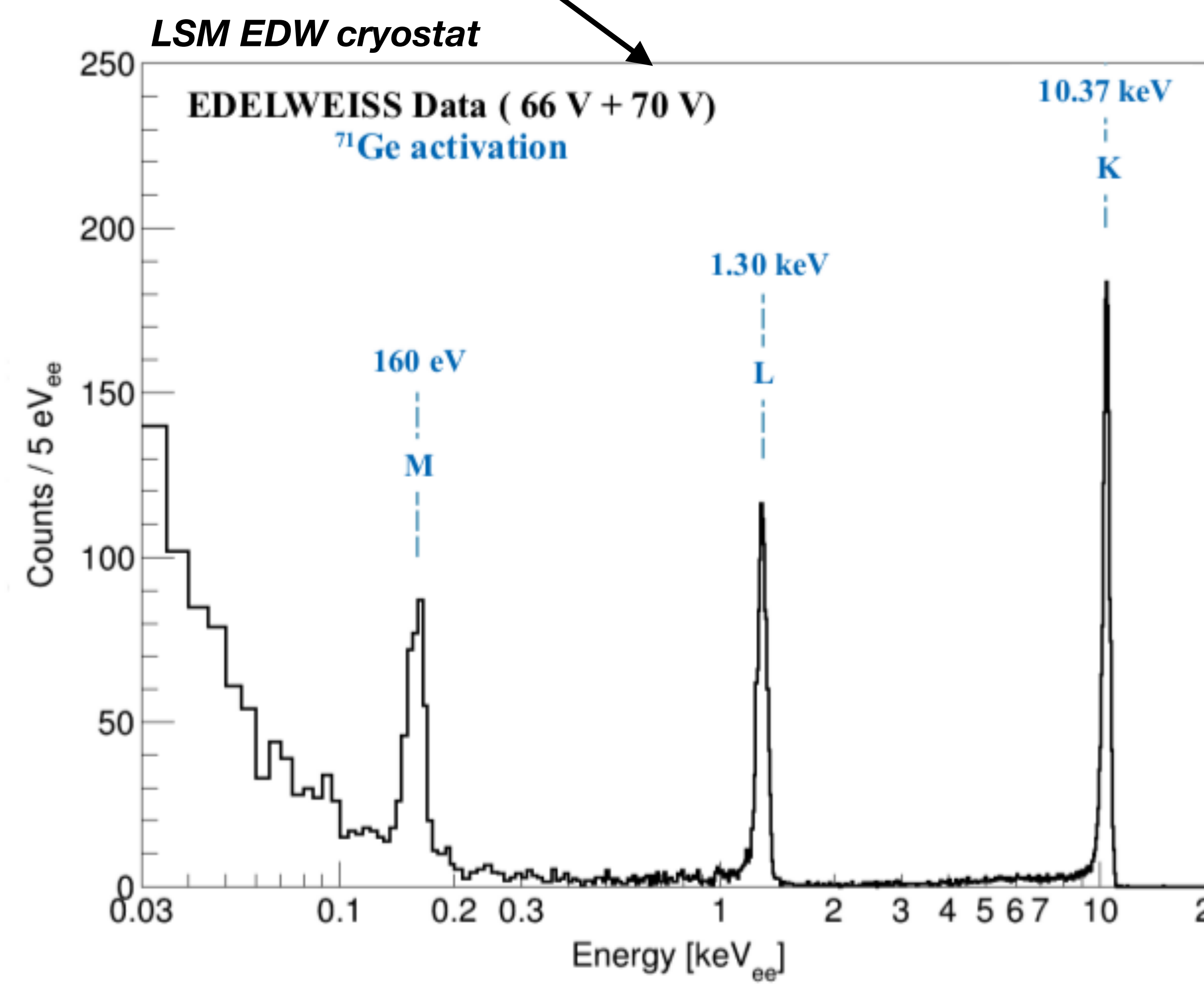
EDELWEISS : 2 modes of operation

$$E_{total} = E_{recoil} + E_{luke}$$
$$= E_{recoil} + E_{recoil}/\varepsilon \cdot V$$

Low Voltage mode
Part. ID + Fid

High Voltage mode
single e/h - No PID



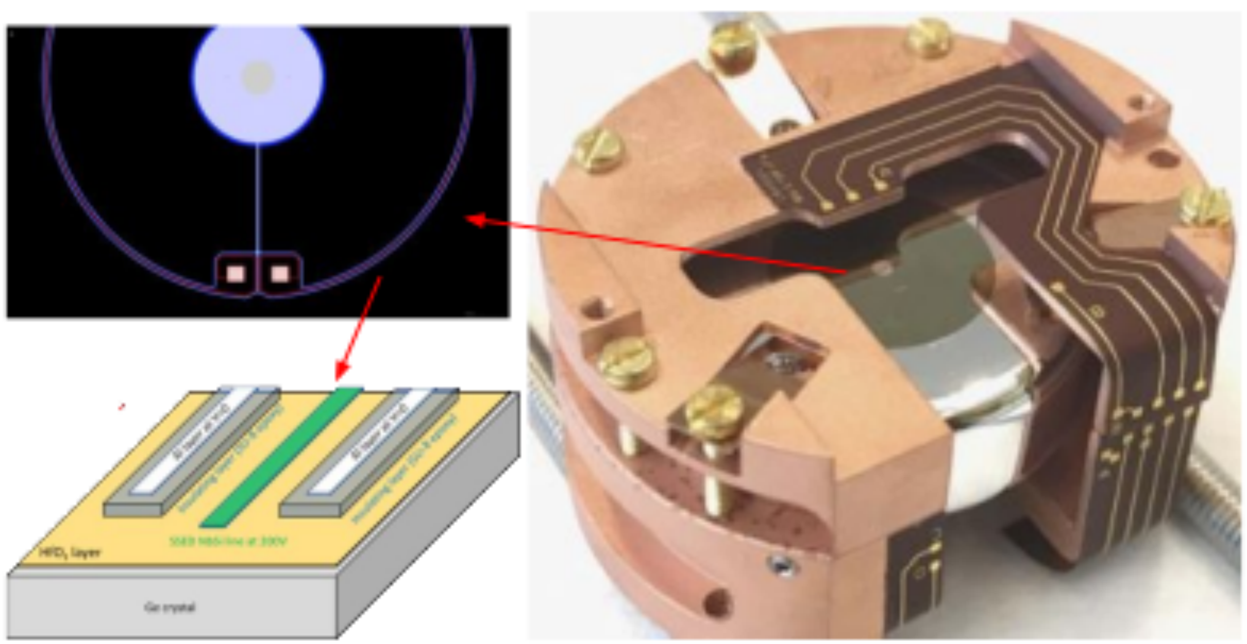


Low Energy Excess (Heat Only)

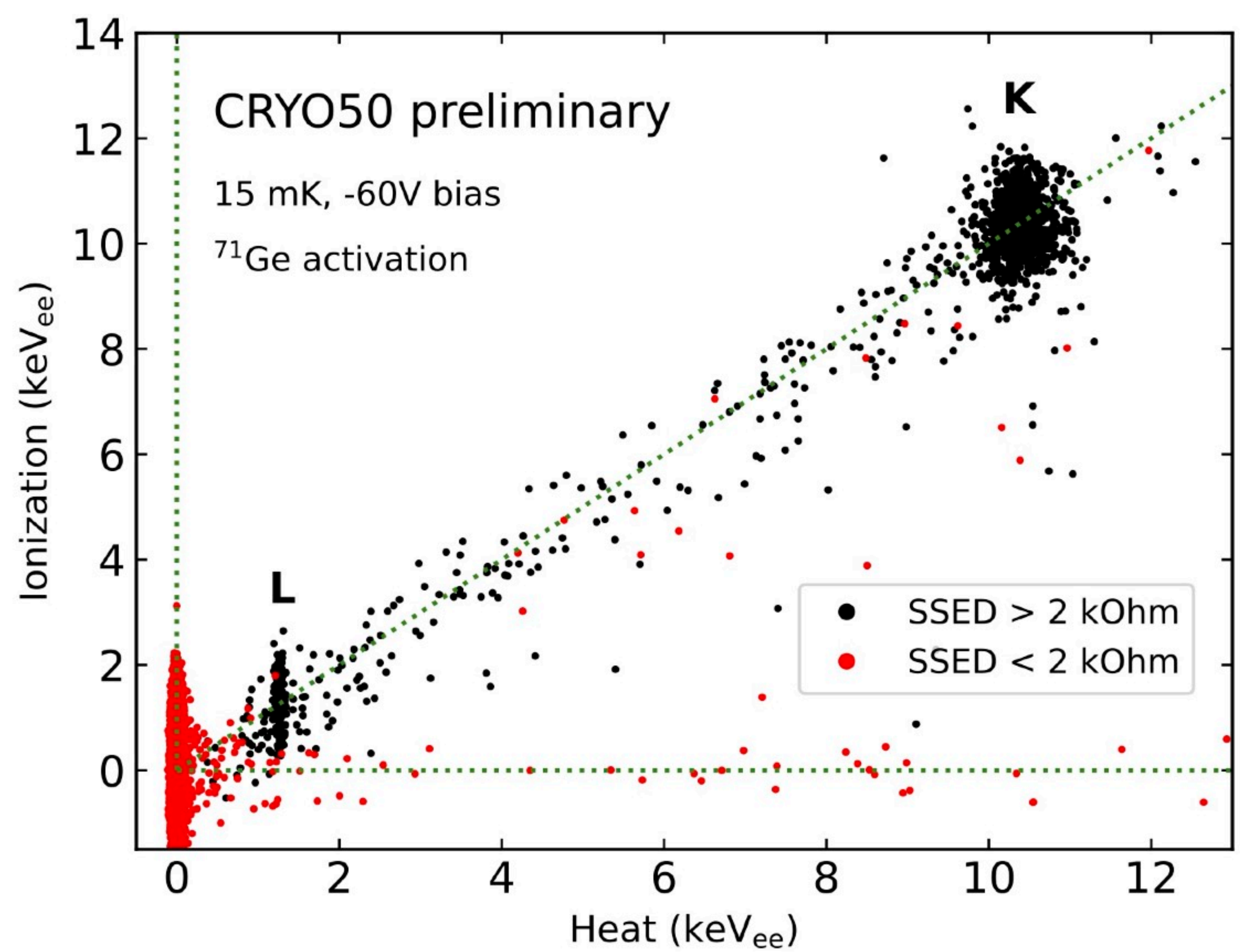
EDELWEISS : Identification of Low Energy Excess (« heat only »)

- **Tricks = use the Luke effect**
  - ***Concentrate it***
  - ***trigger a « LEE » veto thermometer***
  - single e-h sensitivity possible

Proof of concept in 2023 !
SSED is working…but threshold still high as of today

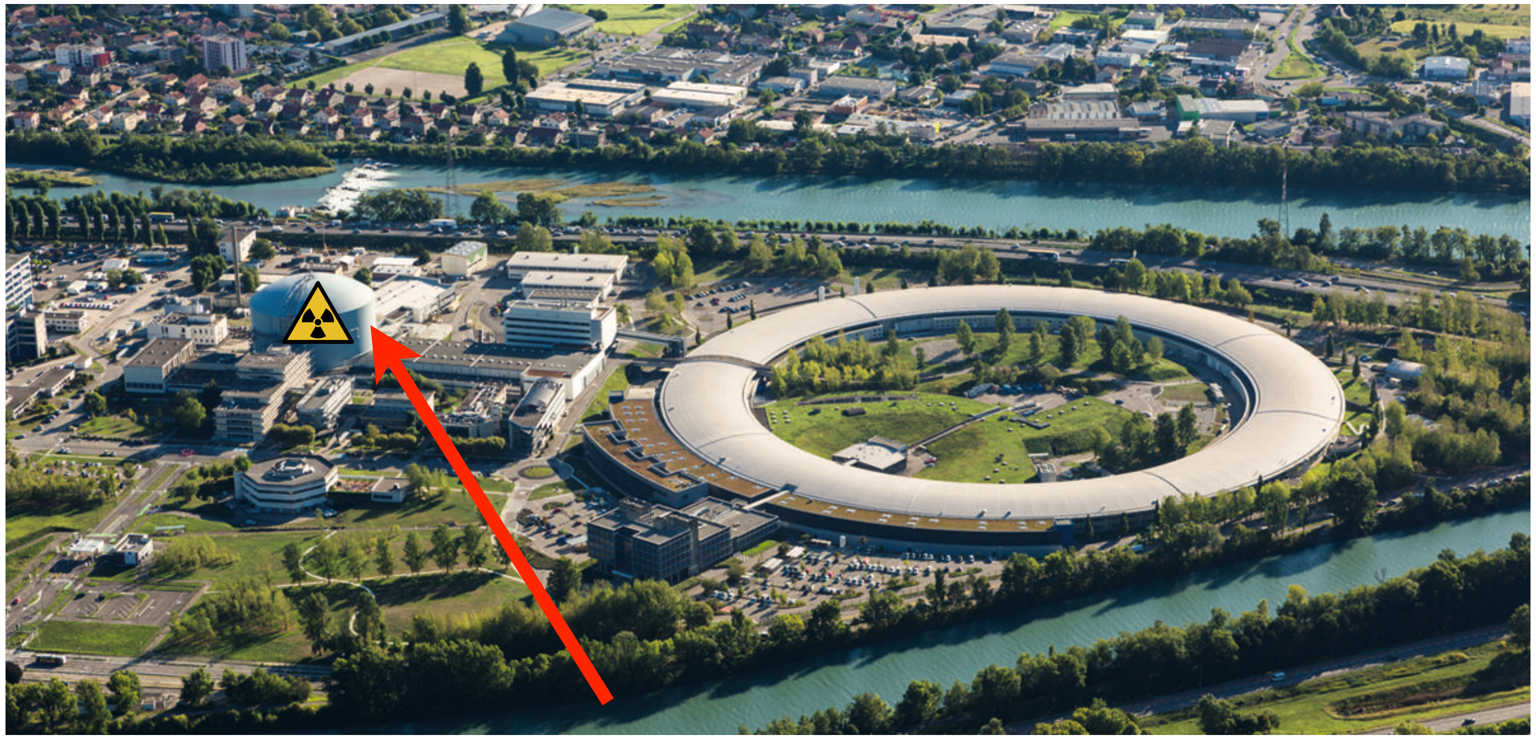


40g Ge



CEνNS : RICOCHET @ ILL

https://fr.wikipedia.org/wiki/Institut_Laue-Langevin

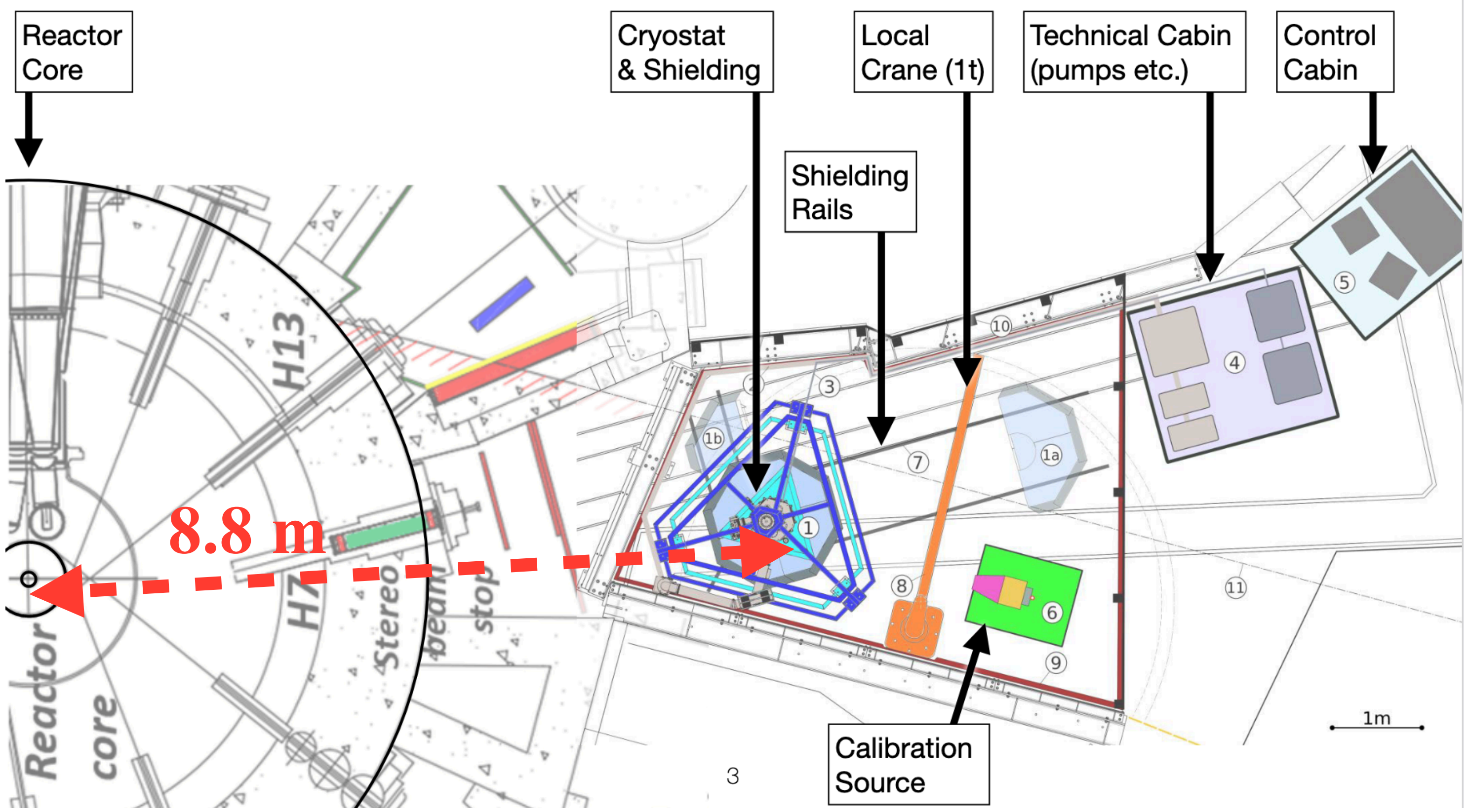


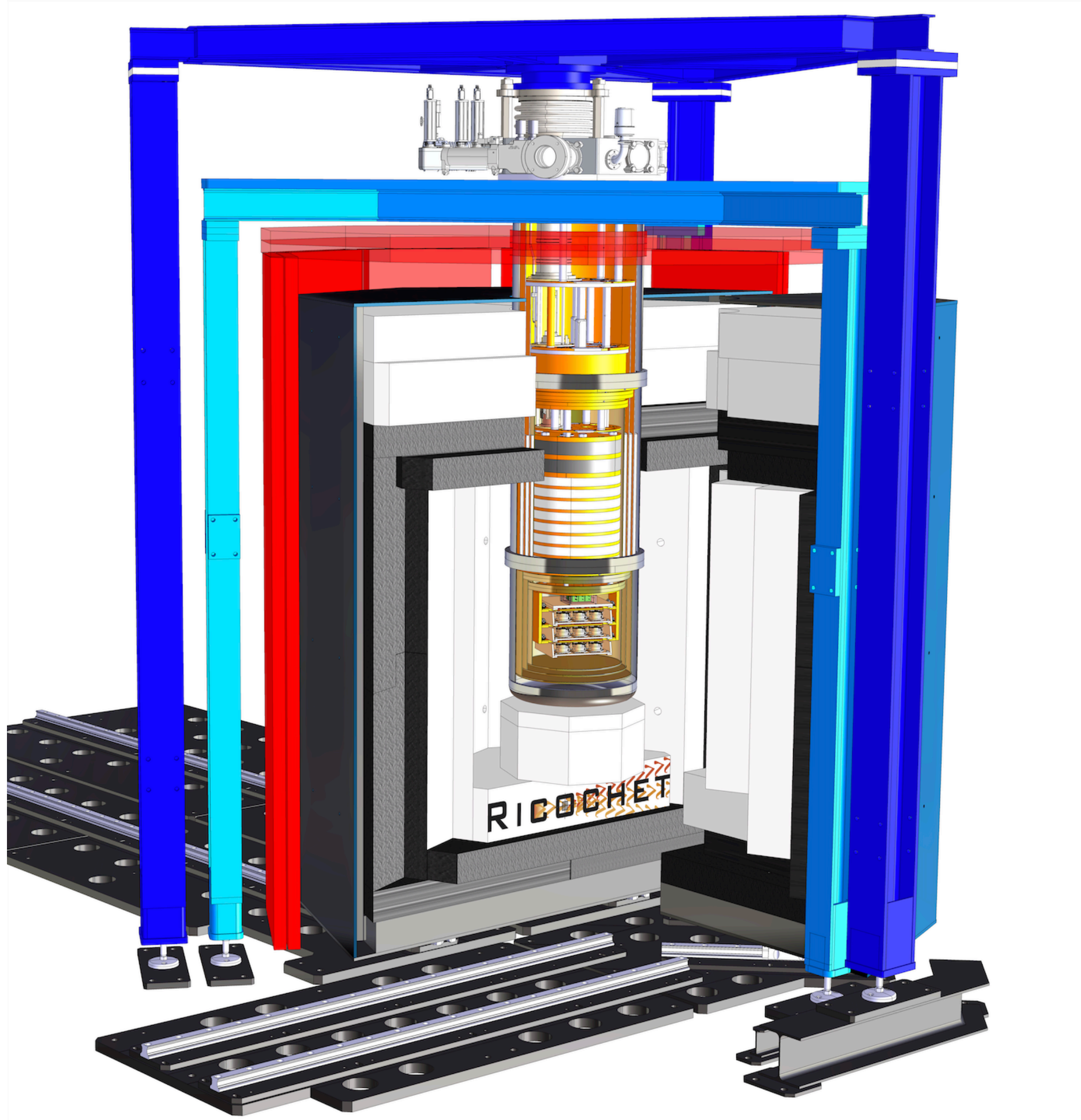
60 MW reactor @ ILL / Grenoble

- ✦ Ricochet installation **started in 2022**
- ✦ **5-10 years program**

- ✦ US-France-Russia collab.
- ✦ Specifications goals for french cryogenic Ge techno.
  - **~0.75 kg Ge (18*40g)**
  - **20 eV ioni + 10eV chal (10* better than EDWIII)**
- ✦ ***Low Energy Excess (heat only) Identification above the ionization threshold***

CEνNS : Ricochet @ ILL



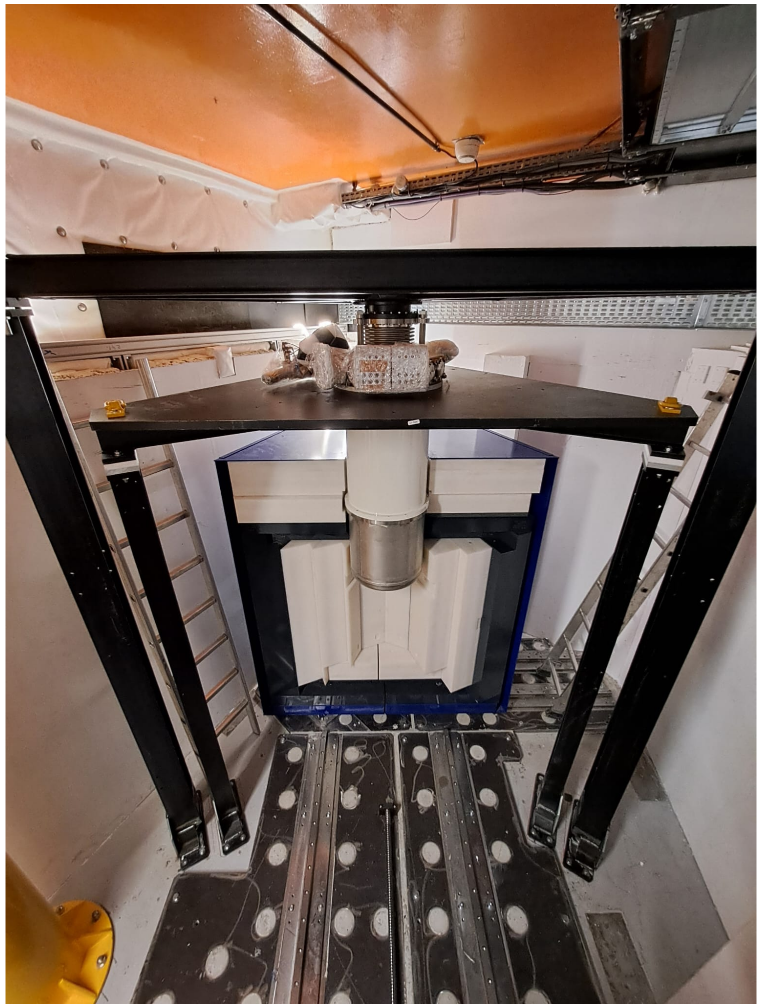


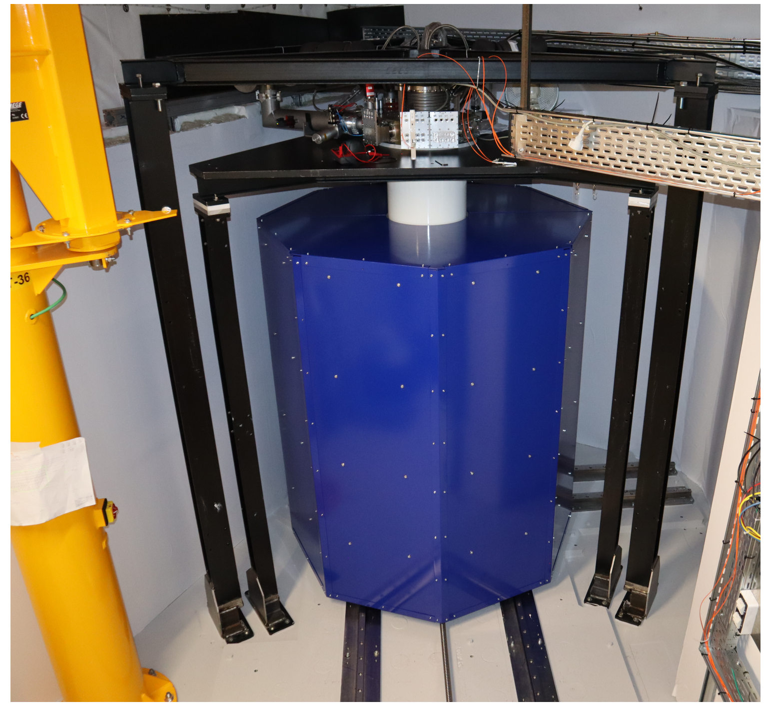
- **58 MW** nominal thermal power
  - **8.8 m away from the core**
  - ***~7 evts/day*** w/ 50 eV threshold (much less if 20 eV not reached on ionization)
- 3 to 4 cycles per year: ON/OFF modulation to subtract uncorrelated backgrounds
- **Significant overburden** (~15 m.w.e) to reduce cosmics
- ***Ricochet integration finalized***
  - ***First reactor data early-2024***

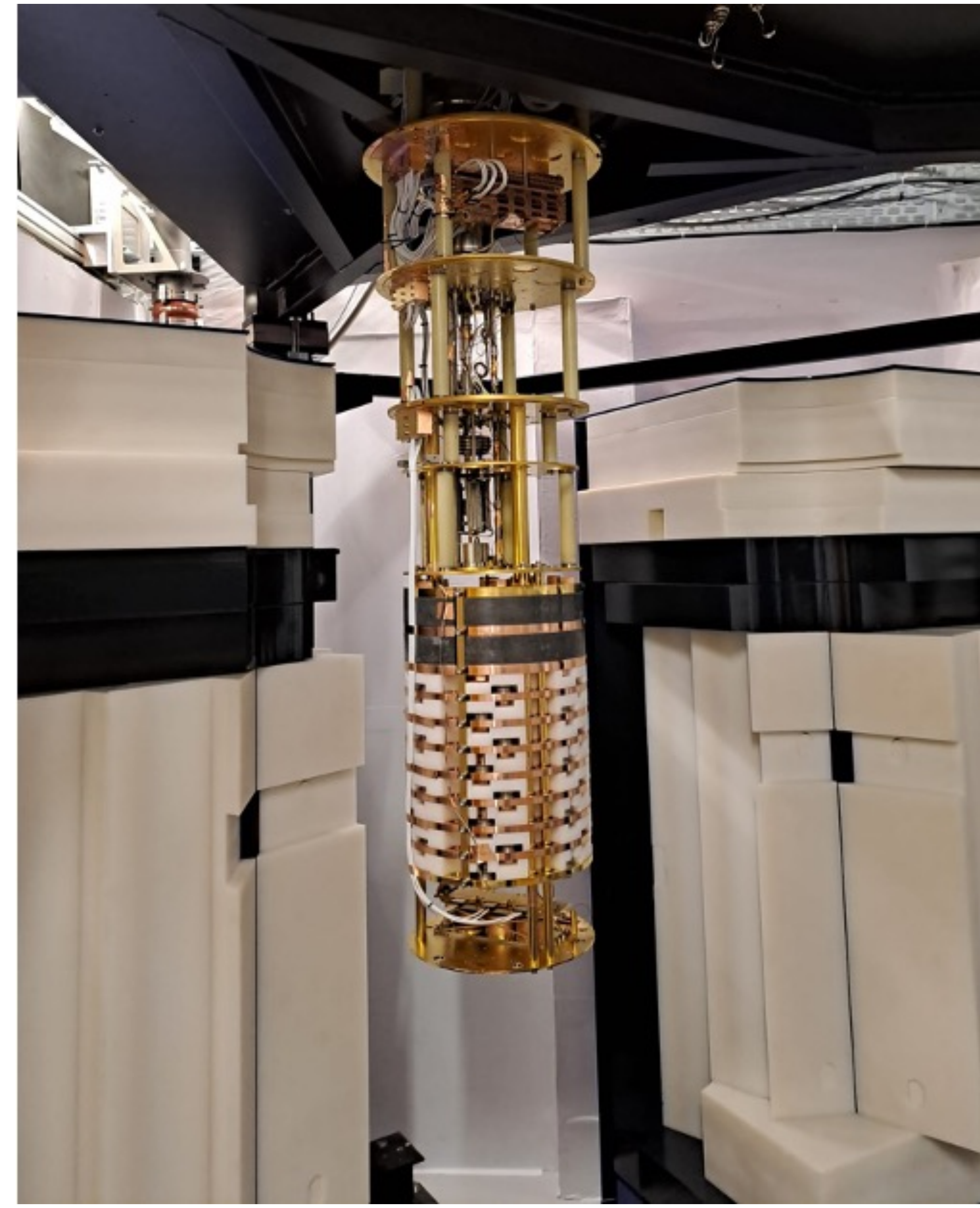
Outer shielding:
- PE: 35 cm
- Pb: 20 cm
- Muon veto
- Soft iron

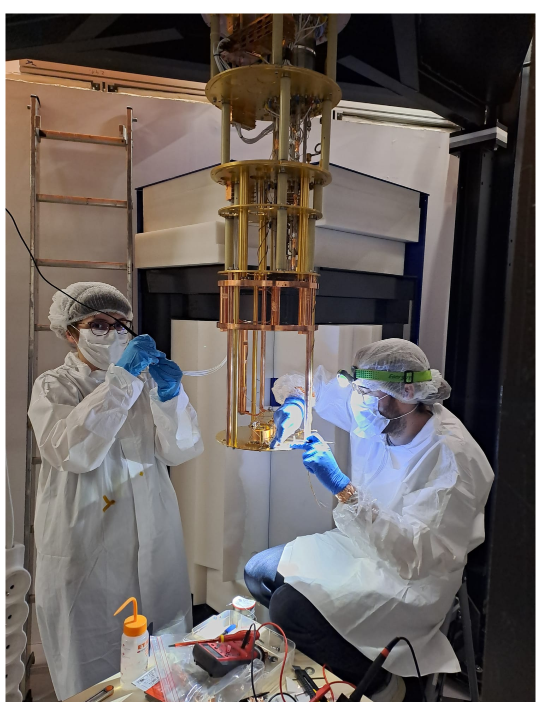
Inner shielding:
- PE/Cu: 30 cm
- Pb/Cu: 15 cm
- Cryogenic Muon Veto
- Mu-Metal

CEνNS : RICOCHET @ ILL









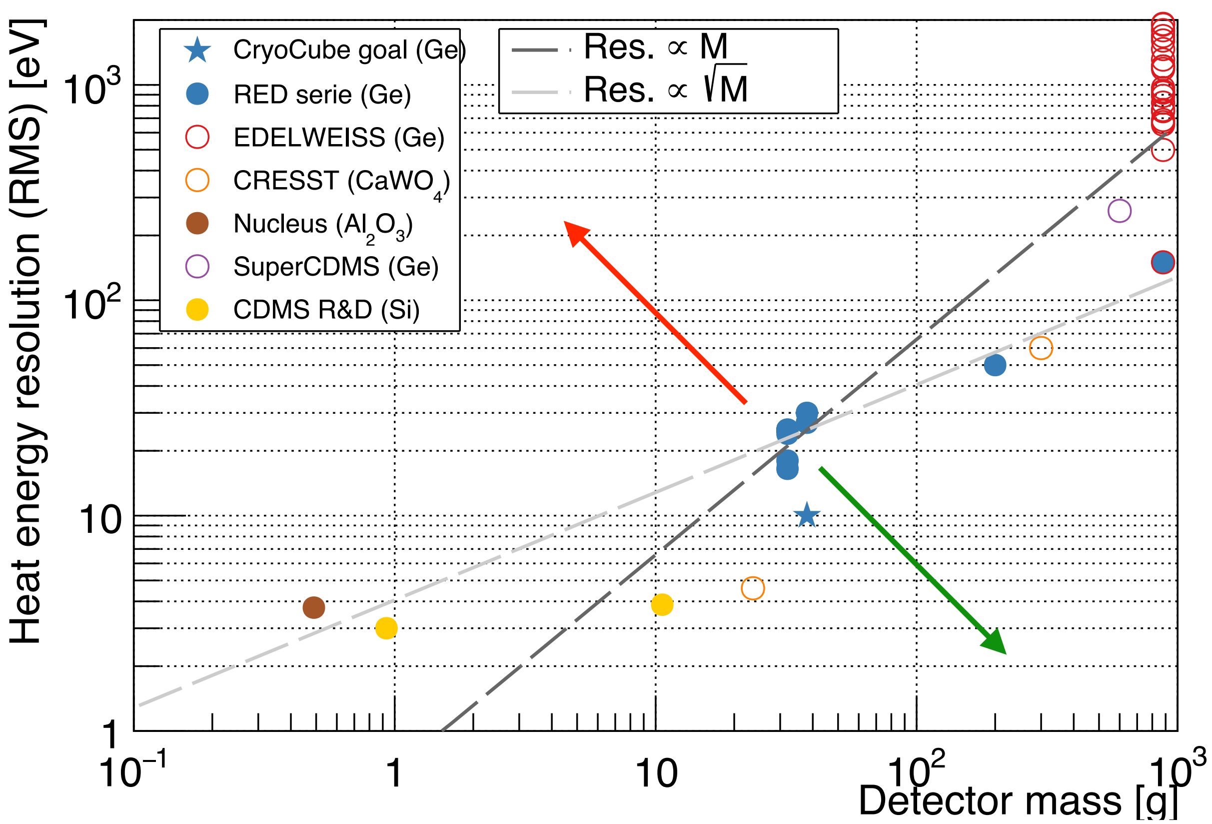
- ***Reaching 8.7 mK on the 6th of February 2024*** on the first cryogenic (Run012)
- 1 miniCryoCube installed (Run013), full 1K PE/Pb shielding installed (Run014) started mid-Feb

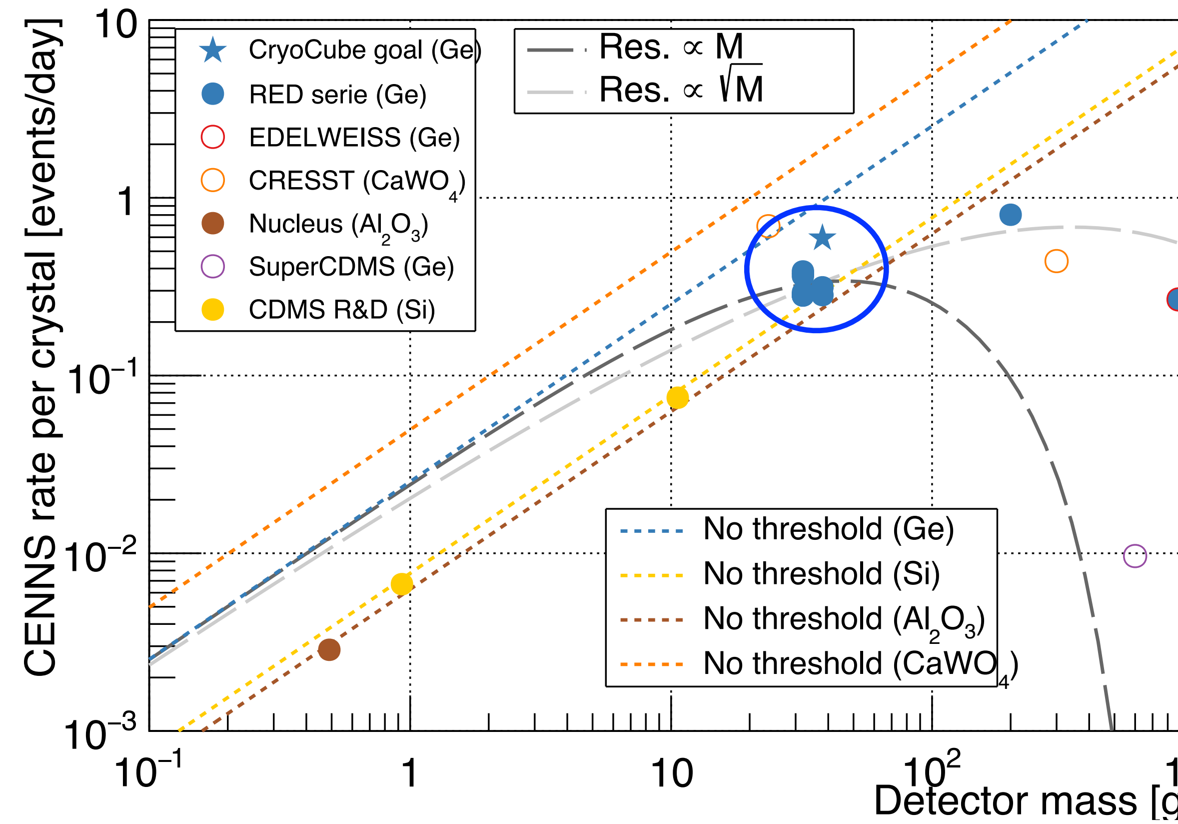
  ➡ ***Commissioning ongoing*** (Reactor OFF and ON)

CEνNS : RICOCHET - detector optimization

Salagnac & al: **arXiv:2111.12438**

Threshold defined for all experiments as 5σ





- **Individual detector size optimisation :**
  - ***Balance between :***
    - heat threshold
    - ionization (capacitance)
    - event rate
- ***30-50 g is a good compromise for Ge***

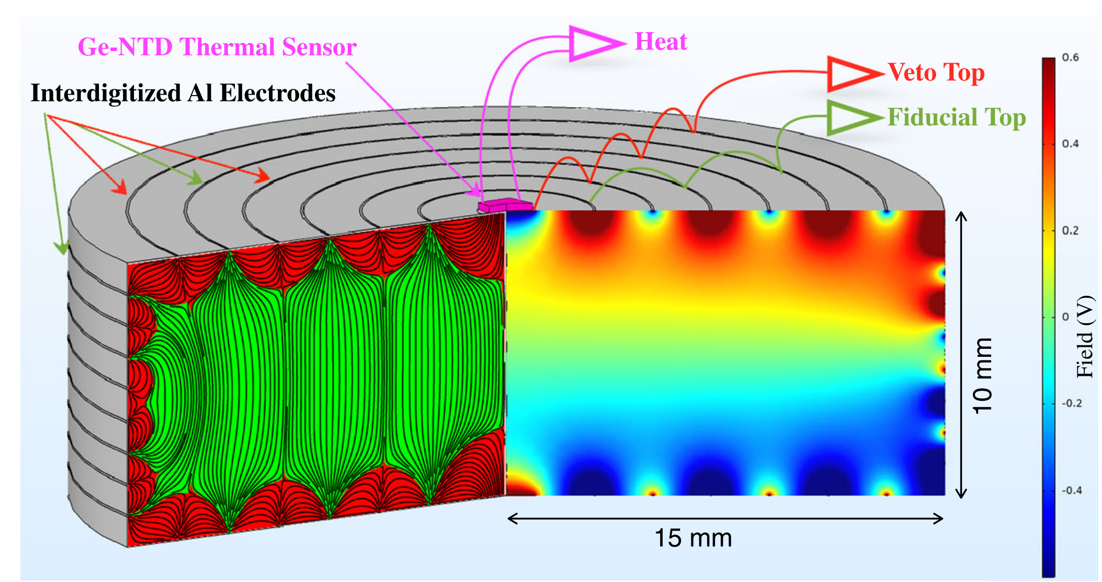


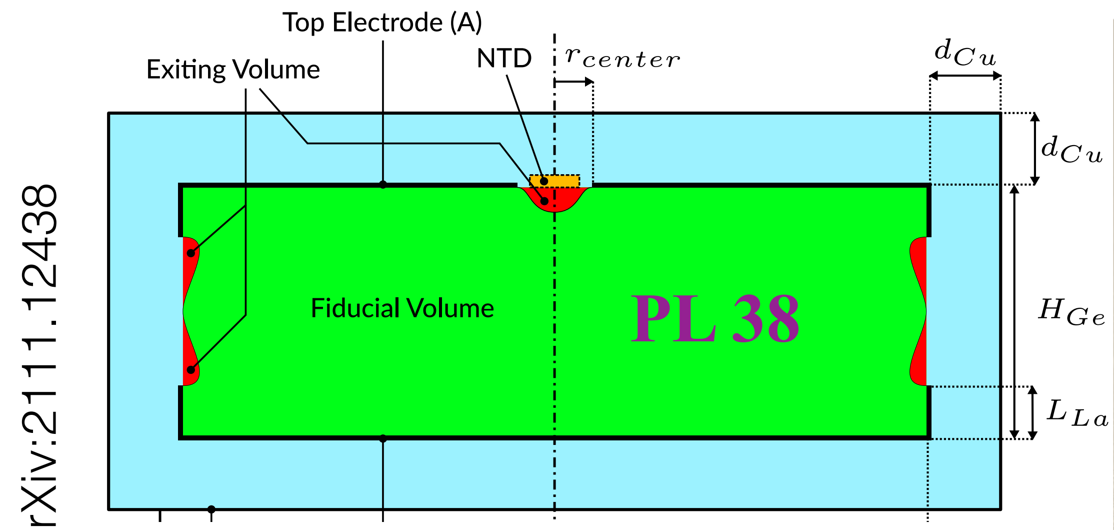
Fig. 6 Electrostatic simulation of a Full Inter-Digitized electrodes scheme on a 38 g germanium crystal (Φ = 30 g, h = 10 mm). The crystal is surrounded at 2 mm distance by a chassis connected to the ground (not shown). The capacitance of the 4 electrodes with respect to the ground is about 20 pF (Color figure online.)

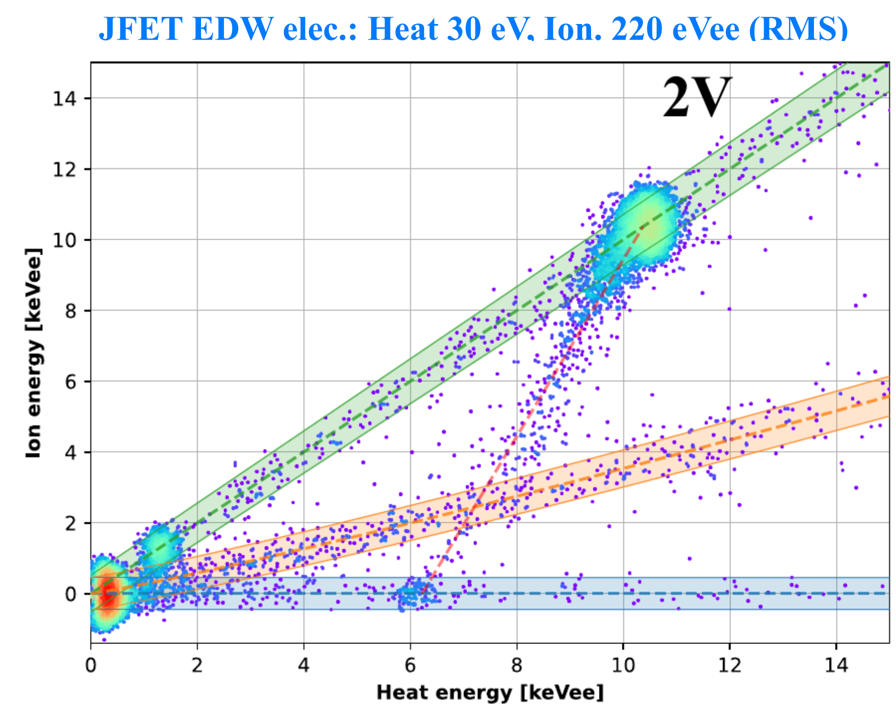
ArXiv 1909.02879

CEνNS : RICOCHET - detector optimization

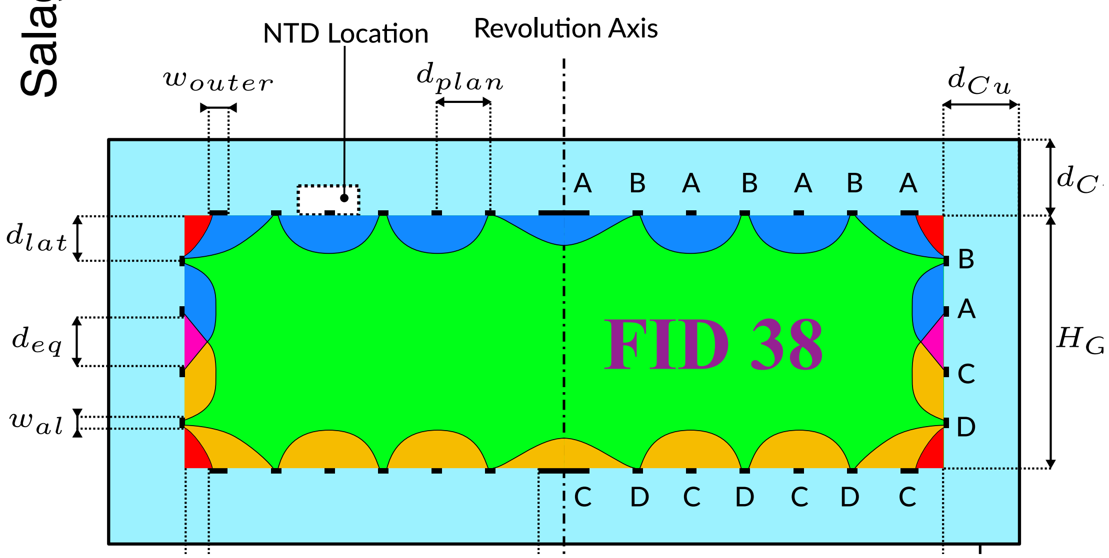
Low-Voltage approach for optimal particle identification

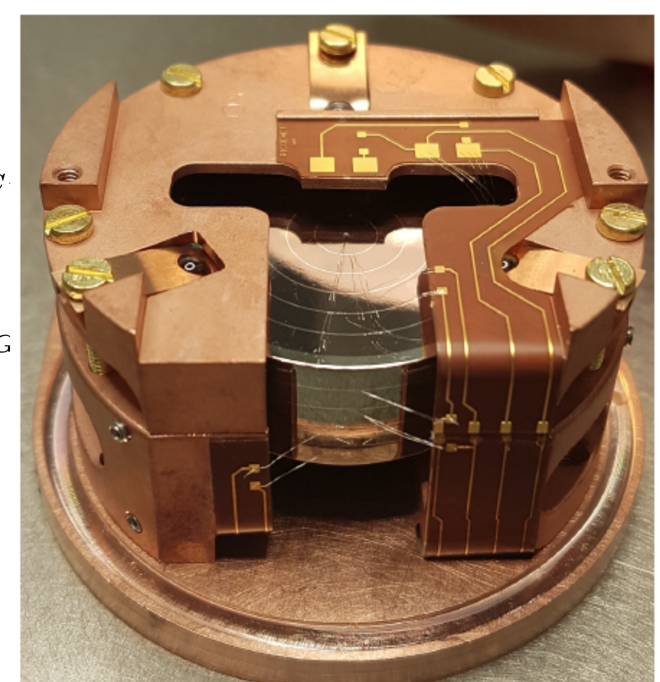
Salagnac & al: arXiv:2111.12438

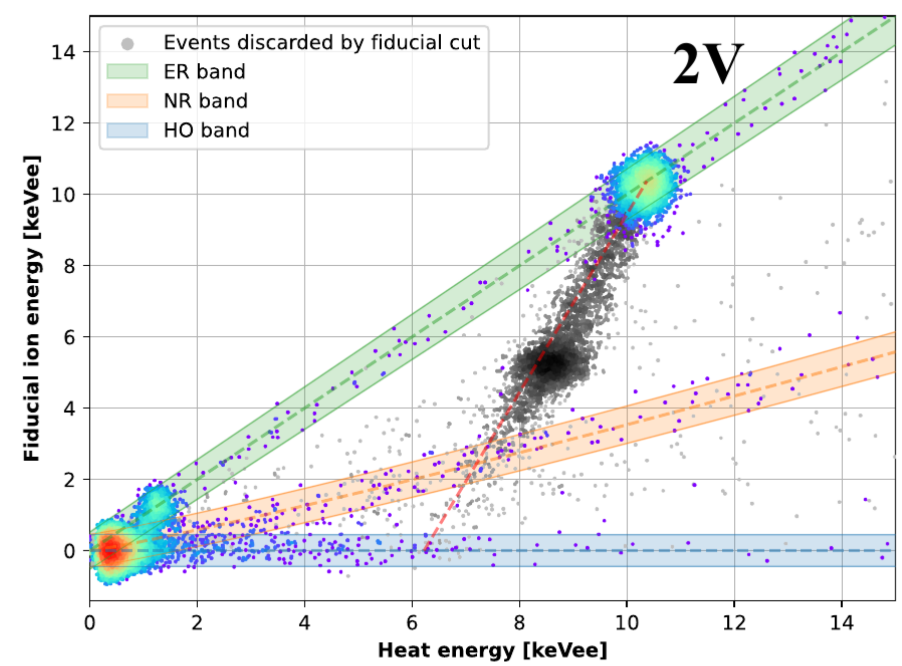




- Incomplete charge coll. **< 10%**
- Fiducial volume: **98.6 %**
- Surface event rejection: **NO**
- Total capacitance: **15 pF**







- Incomplete charge coll. **< 1%**
- Fiducial volume: **62 %**
- Surface event rejection: **YES**
- Total capacitance: **18 pF**