Cryogenic Detectors
- Application to rare events searches -

—

DRTBT 2024 Aussois 24-29 Mars 2024 *https://drtbt.neel.cnrs.fr/*

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contributions from Julien Billard, Denys Poda, A. Armatol & others

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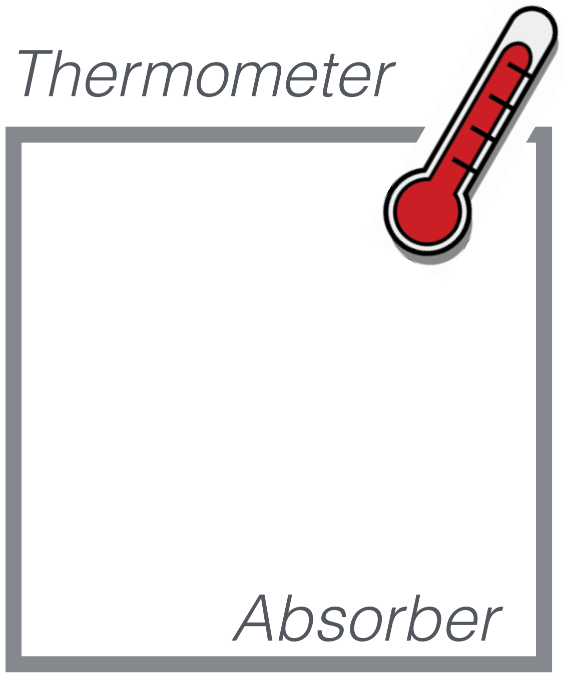
2024 TBT

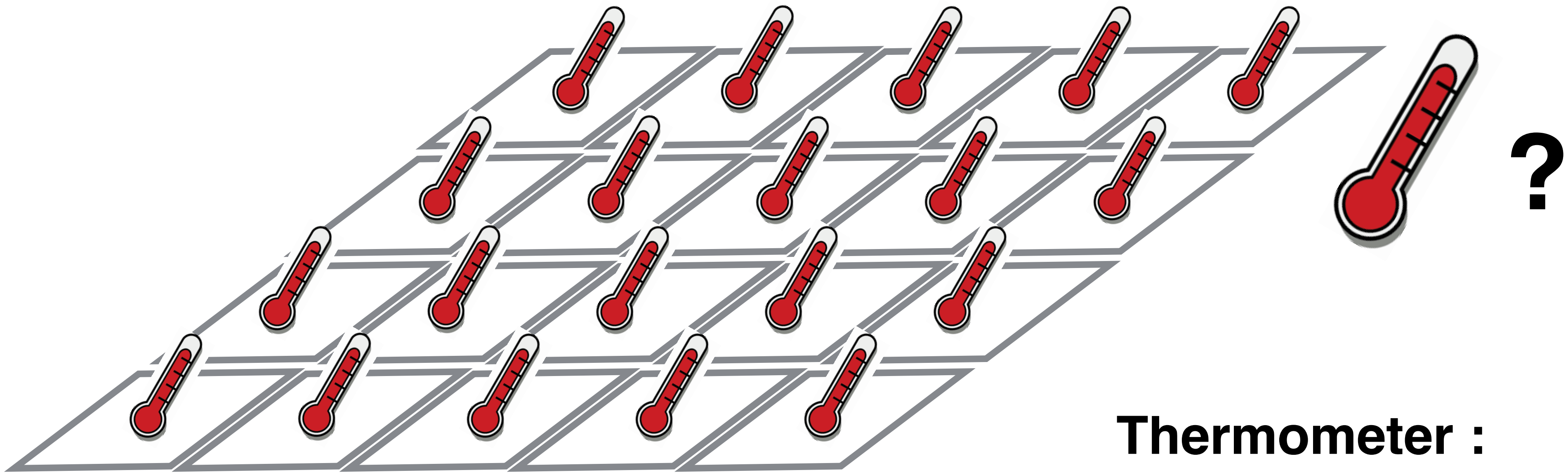
IP2I LES 2 INFINIS LYON

Outline

- Brief recap of bolometer vs calorimeter
- **Science application w/ massive detector for rare event searches**
  - Dark Matter
  - CEνNS
  - $0\nu\beta\beta$
- **Conclusion**

Cryogenic Detector ??





« massive » detector:

- ~ g ➙ ~ kg
- Some of the fabrication step done *«by hand»*
- Particle detection « one by one »
- Main application :
  Rare event detection
  - Dark Matter
  - $0\nu\beta\beta$
  - CEνNS

Matrix of detector :

- 1 ➙ 100k « pixels »
- Some of the fabrication step done *«collectively»*
- Particle detection « one by one » or by flux
- Main application :
  Astro
  - Sub-mm (50-600 Ghz)
  - X

see M. Gonzales for Astro application

Thermometer :

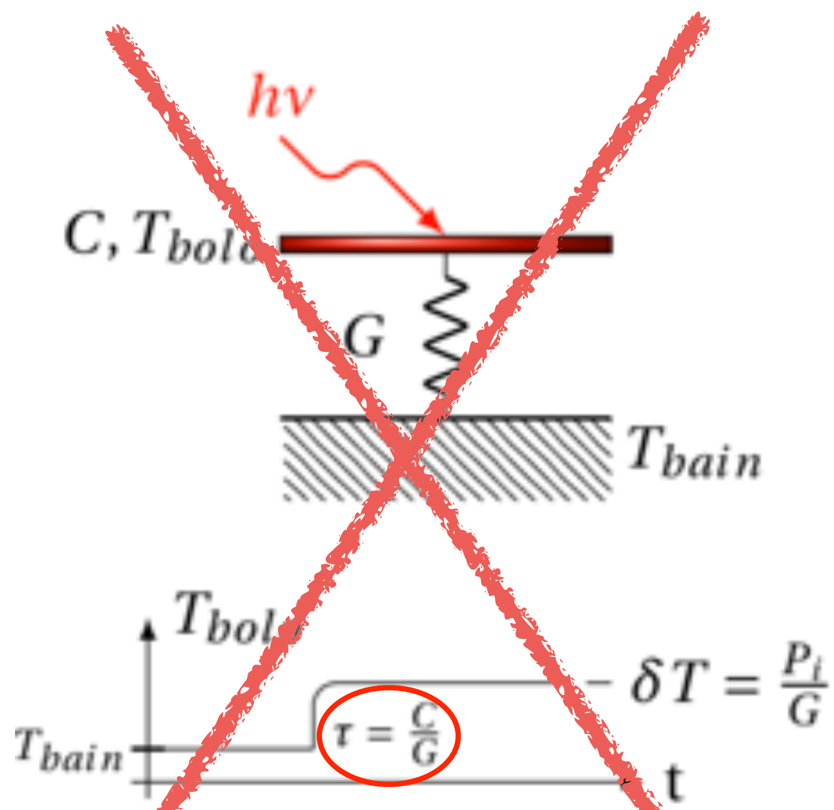
- T ➙ measurable value
- Resistive
  - superconductor
  - Metal InsulatorTransition
- Magnetic
- w/ out of equilibrium mediator
  - Copper pairs in SC material :
  - Kinetic Inductance vs dN_{qp}
  - Out of equilibrium phonon can brake Cooper Pairs

Link with Quantum sensor

Cryogenic Detector ??

D. Prêle DRTBT 2018

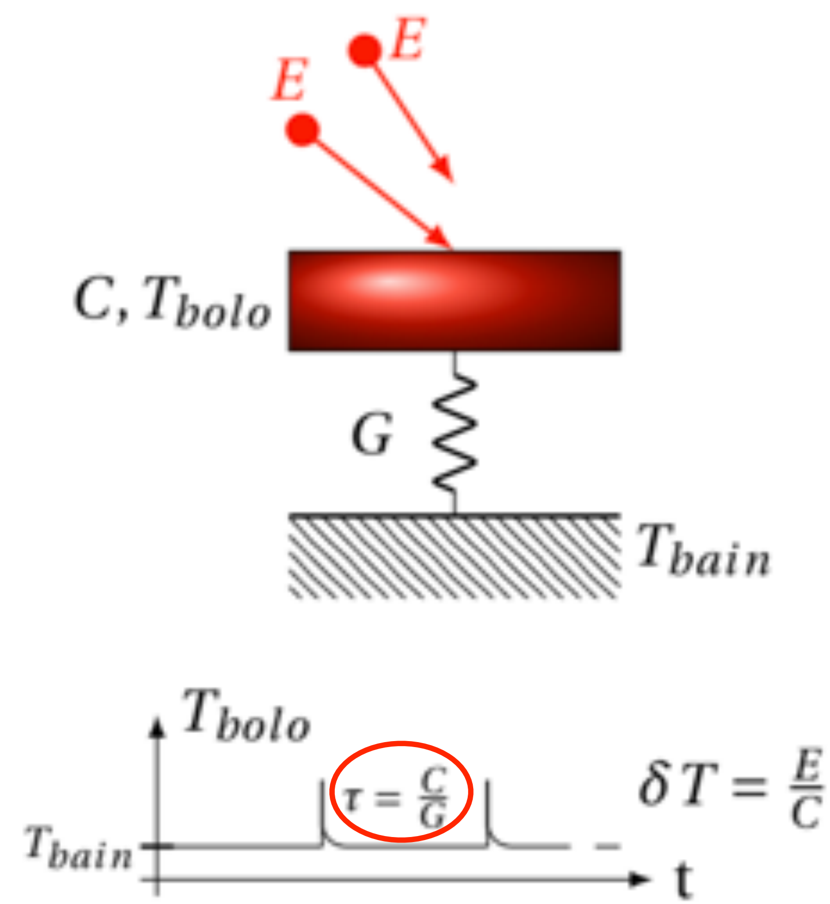
"background"/flux de photon



« Bolometer » Mode

- Response ~ C/G
- NEP = $\sqrt{4k_BT^2G}$ [W/√Hz]

photons>eV/particules



« Calorimeter » Mode

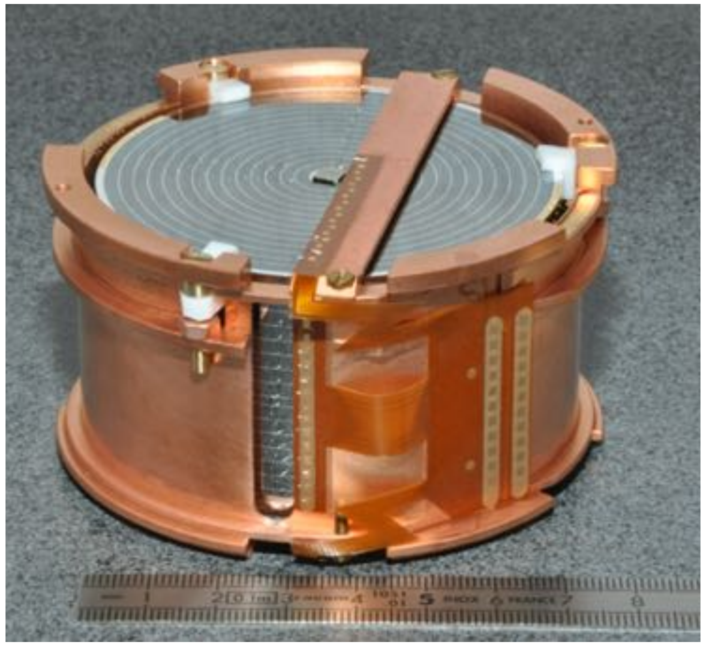
- Decay ~ C/G
- δE = $\sqrt{4k_BT^2C}$ [J]

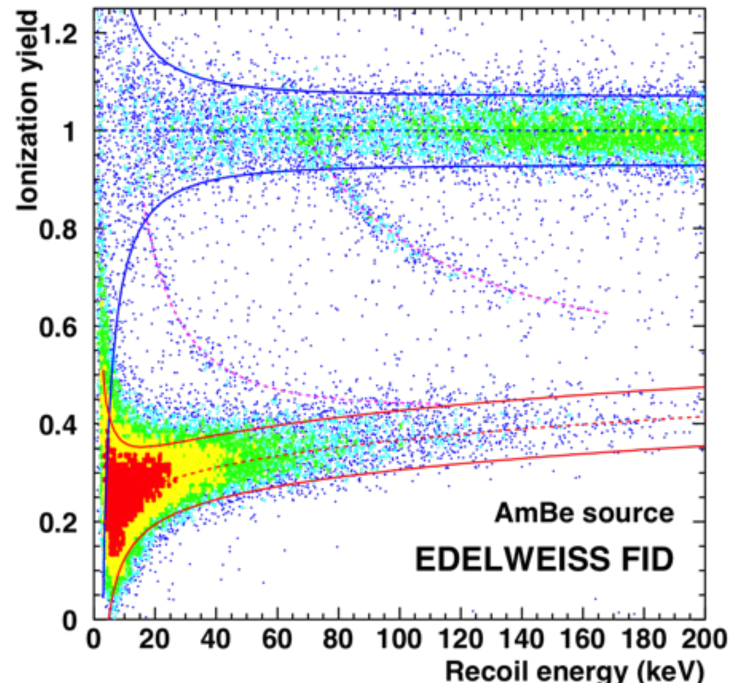
Low Temperature → Sensitivity ↗ & Noise ↘

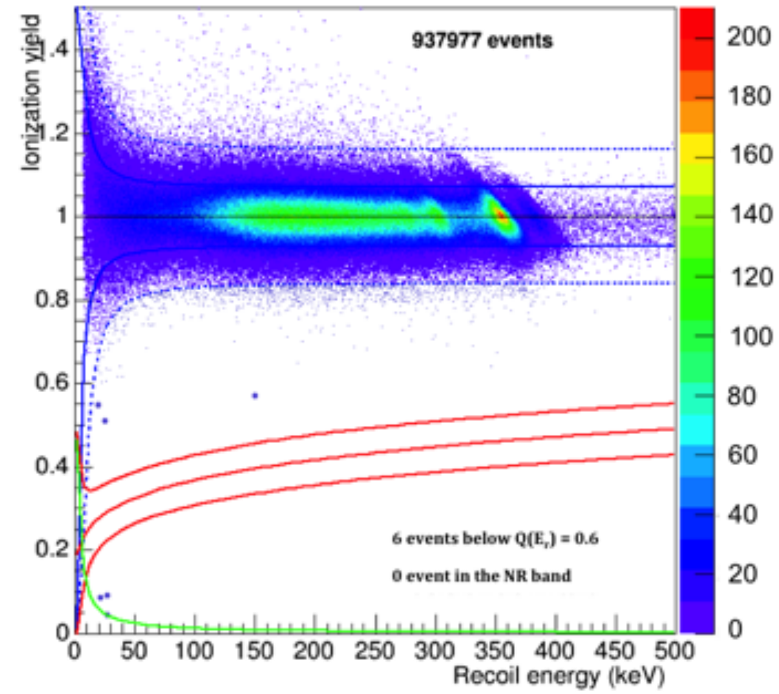
T_{bath} ~10 mK - 300 mK

R&D = absorber + thermometer + electronics (Z adaptation, gain, readout) + cryo environment

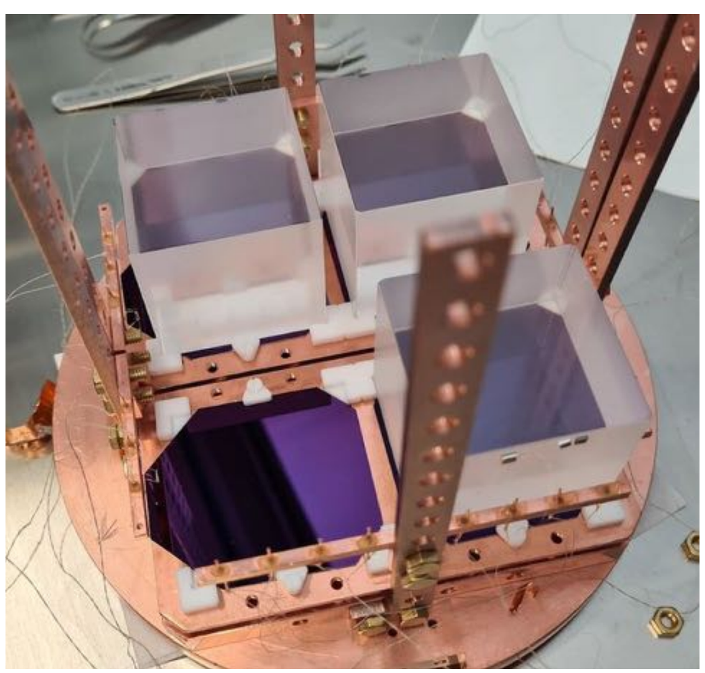
Cryogenic Detector ??

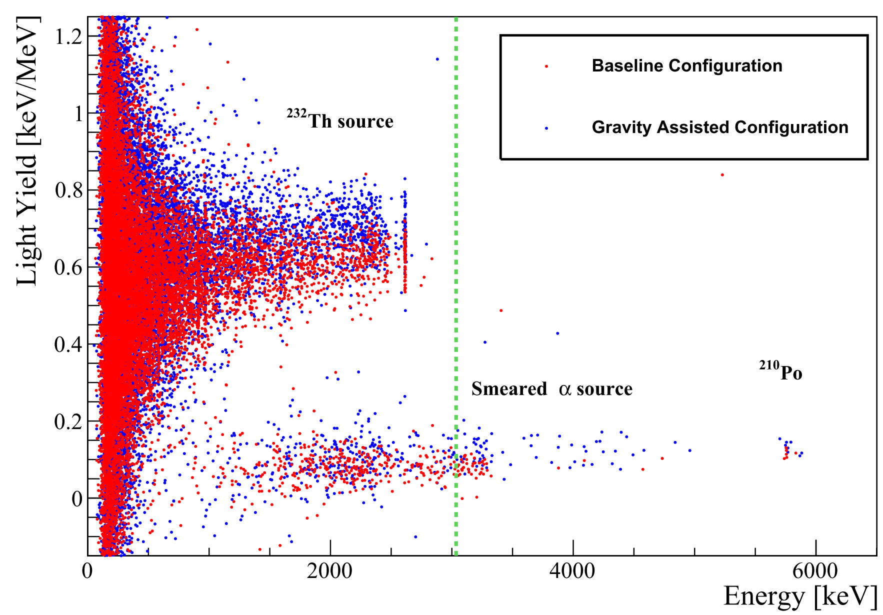






EDELWEISS-III ; **2017** *JINST* 12 P08010



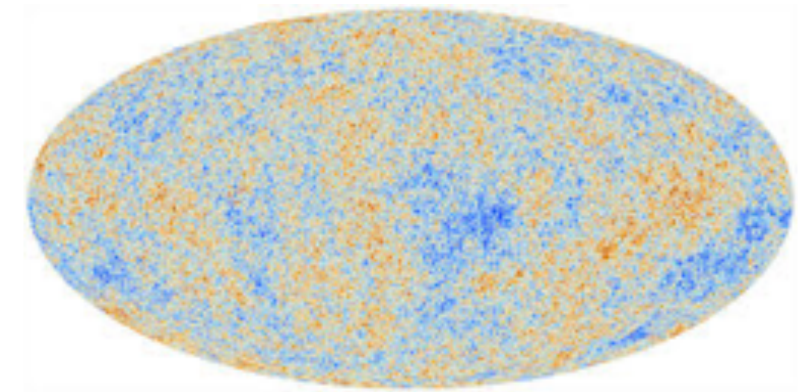


CUPID ; Eur. Phys. J. C (**2022**) 82:810

Double readout cryogenic detectors allows for an ***evt-by-evt background rejection*** *:*

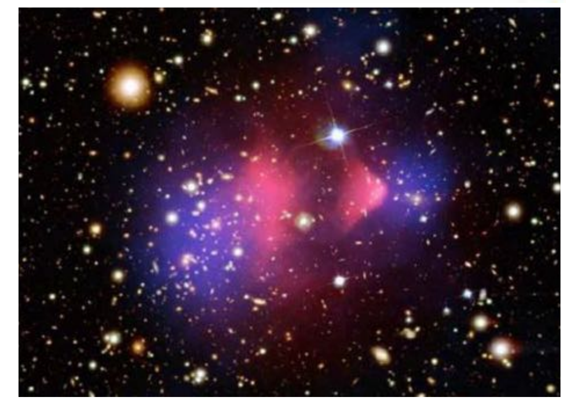
- ✦ **Heat and Ionization on Ge** detector :
  - ➡ Elec. Recoil / **Nuclear Recoil discrimination**
  - ➡ **Heat only** event **rejection**
  - ➡ **surface event rejection**
- ✦ **Heat and Light** on different crystal
  - ➡ Elec. Recoil / **Nuclear Recoil discrimination**
  - ➡ **α background rejection**

Dark Matter : evidence



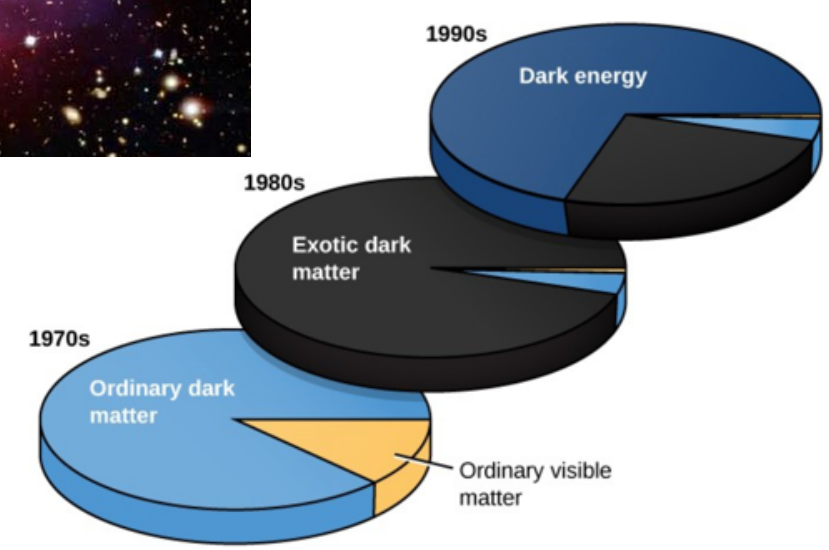
From precision cosmology (CMB, BAO, SN, …):

- **~26% of the matter/energy content** of the universe is **made of non baryonic Dark Matter**



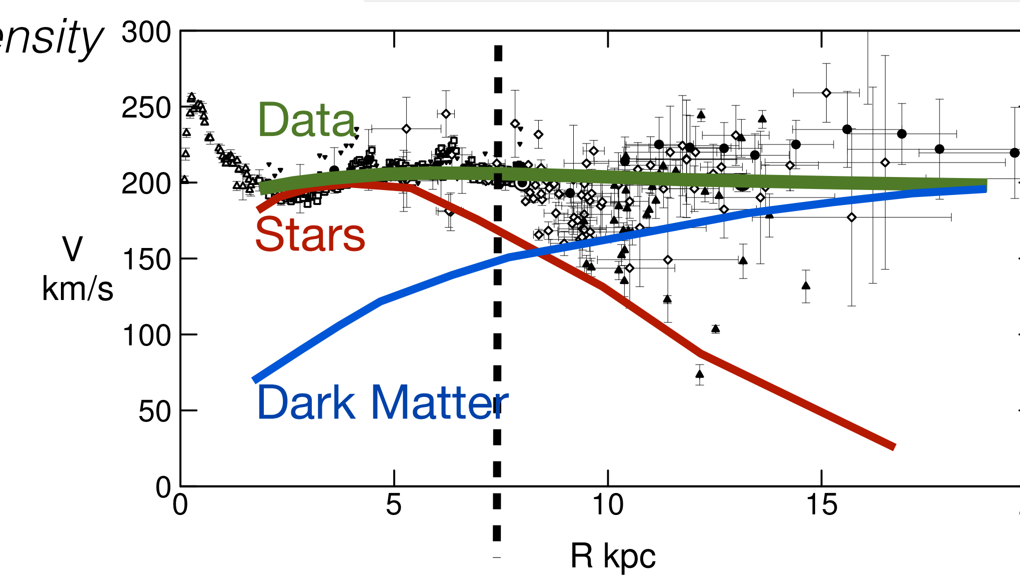
Large scale structure:

- bullet cluster
- lensing



From rotation velocity measurement of galaxies:

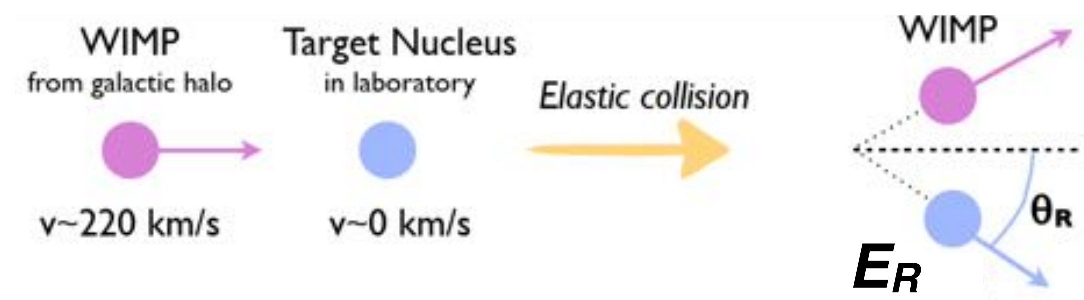
- Spiral galaxies are embedded in **Dark Matter halo** that outweights the luminous part by a factor ~10
- **Milky Way local Dark Matter density: 0.3±0.1 GeV/cm^3** *(note that average dark Matter density in the universe ~1.2 GeV/m^3 !!)*



Issues:

- Density is « known » ***but the mass of the dark matter candidate(s) remains unknown as well as its cross section with matter…***
- Not easy to design the experiment !!!

Dark Matter : WIMP candidate

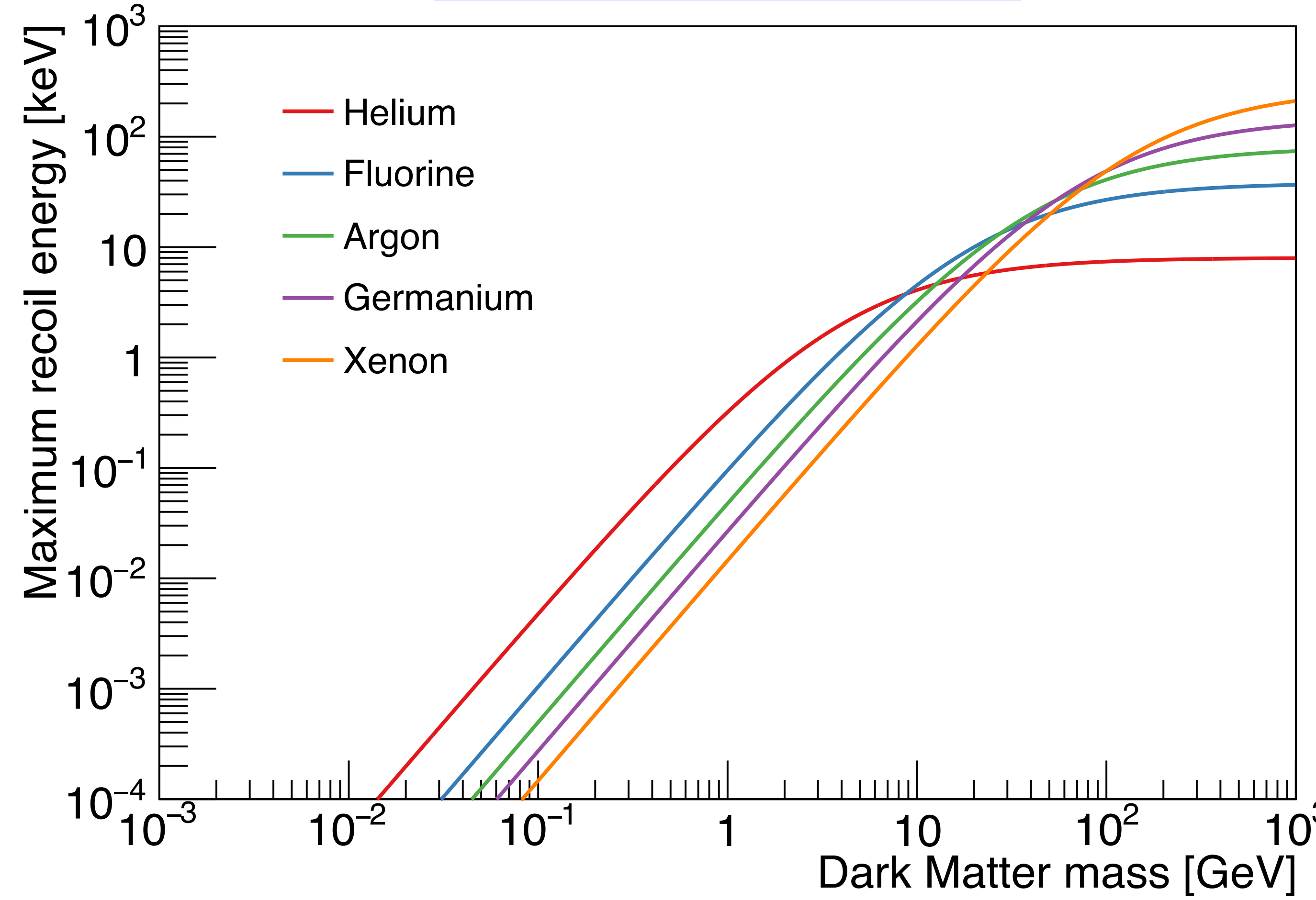


$$E_r = E\frac{4m_\chi m_N}{(m_\chi + m_N)^2}\cos^2\theta_r$$

J. Coley
10.21468/SciPostPhysLectNotes.55

WIMP Candidate:
Weakly Interacting Massive Particle

- Stable
- Neutral from charge and color
- Massive GeV - TeV (« standard » WIMP)
- Weak interaction
- Ω_{wimp} ~1 (Wimp Miracle) for some model



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Differential event rate as a function of the recoil energy:

$$\frac{dR}{dE_r} = \frac{\rho_0}{2m_\chi m_r^2}\left(\sigma_0^{\rm SI}F_{\rm SI}^2(E_r) + \sigma_0^{\rm SD}F_{\rm SD}^2(E_r)\right)\int_{v_{\rm min}}\frac{f(\vec{v})}{v}d^3v$$

Astrophysics / Nuclear physics / Particle physics

Dark Matter : WIMP candidate

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High WIMP flux !

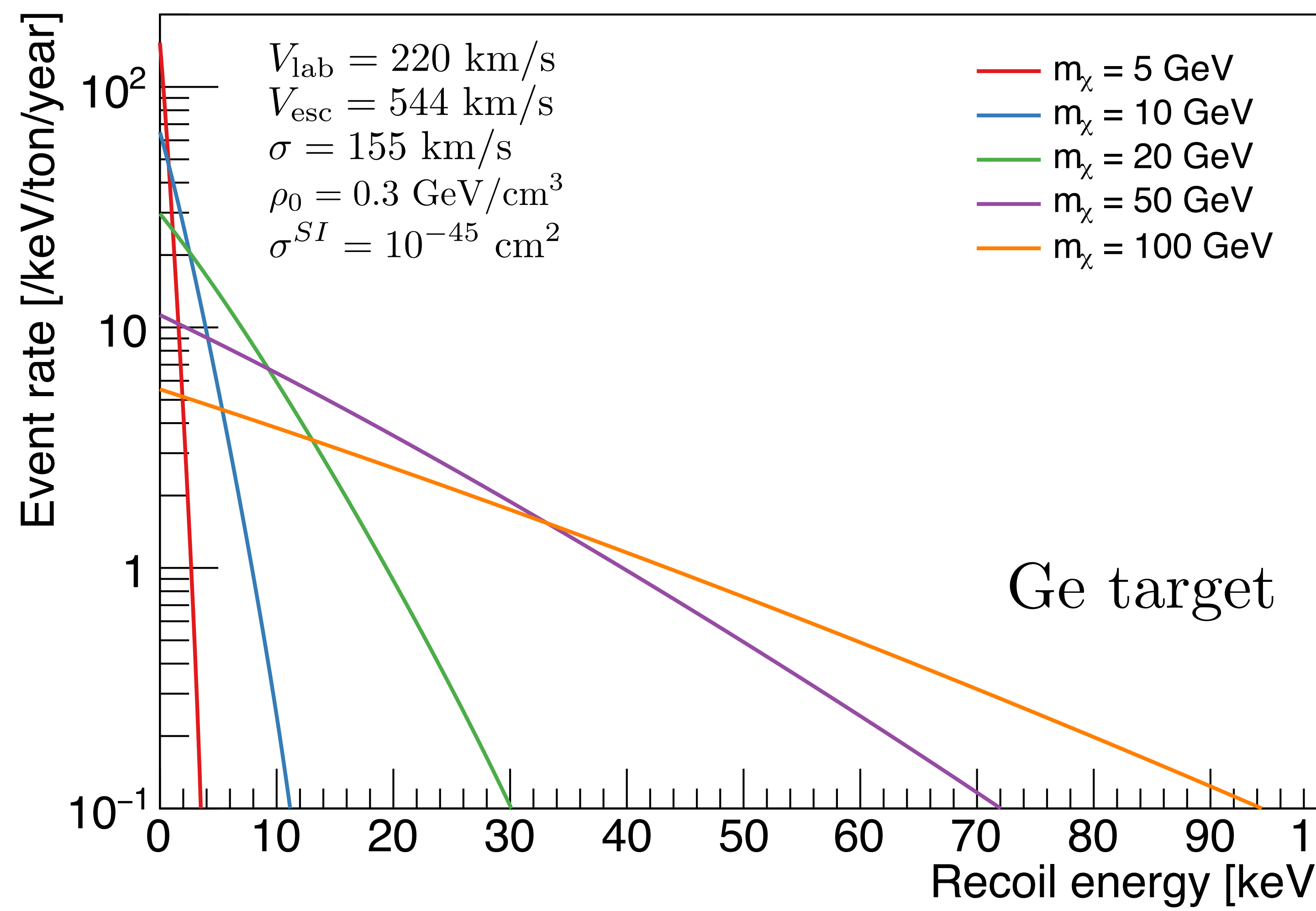
- **~ 100 000 particles/cm²/s** !! for 100 GeV WIMP

But very low event rate (for standard Wimps) **:**

- R < O(10) ***evts/ton/year***

Mean recoil energy:

- ~ O(1) keV (for standard Wimps)



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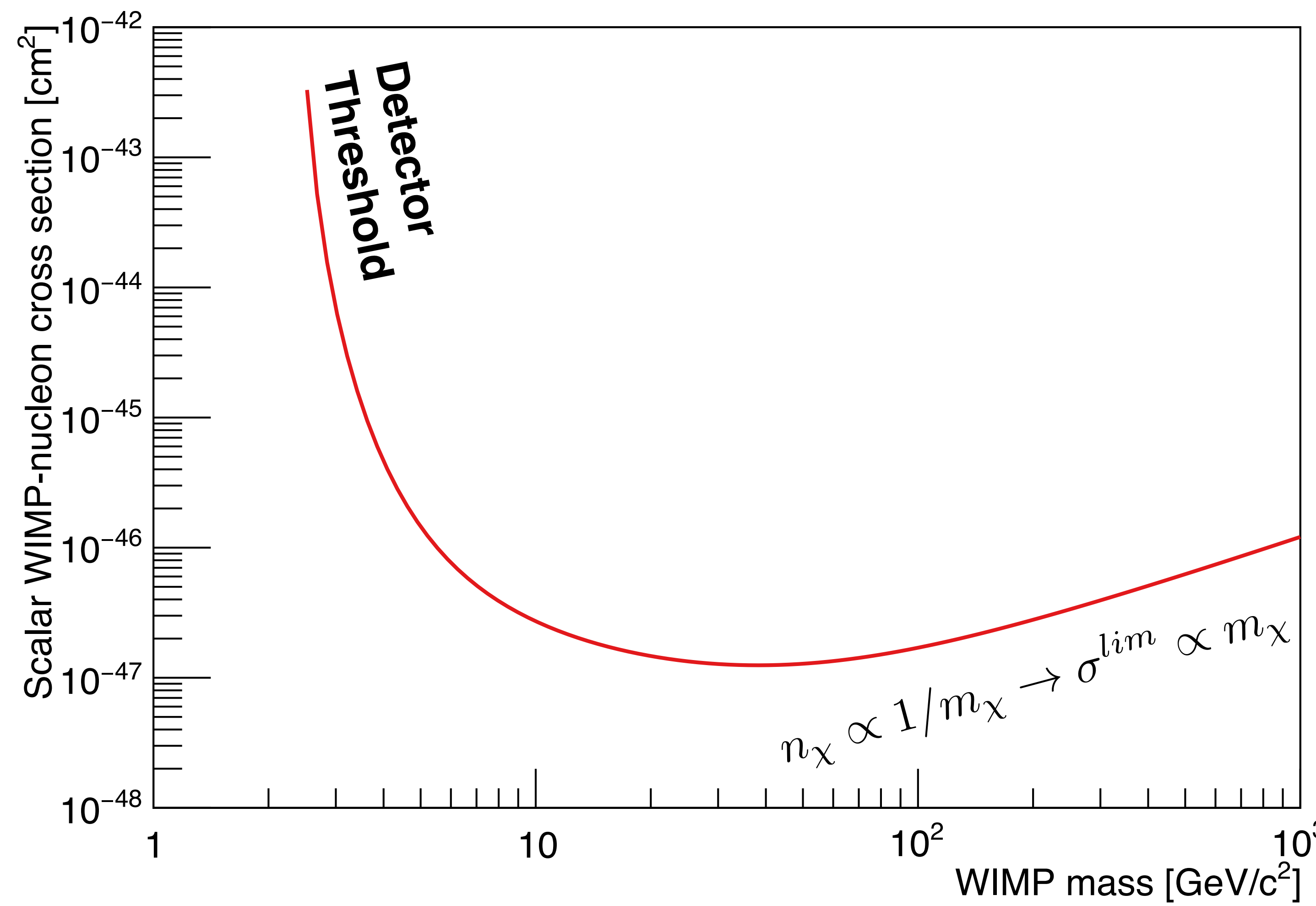
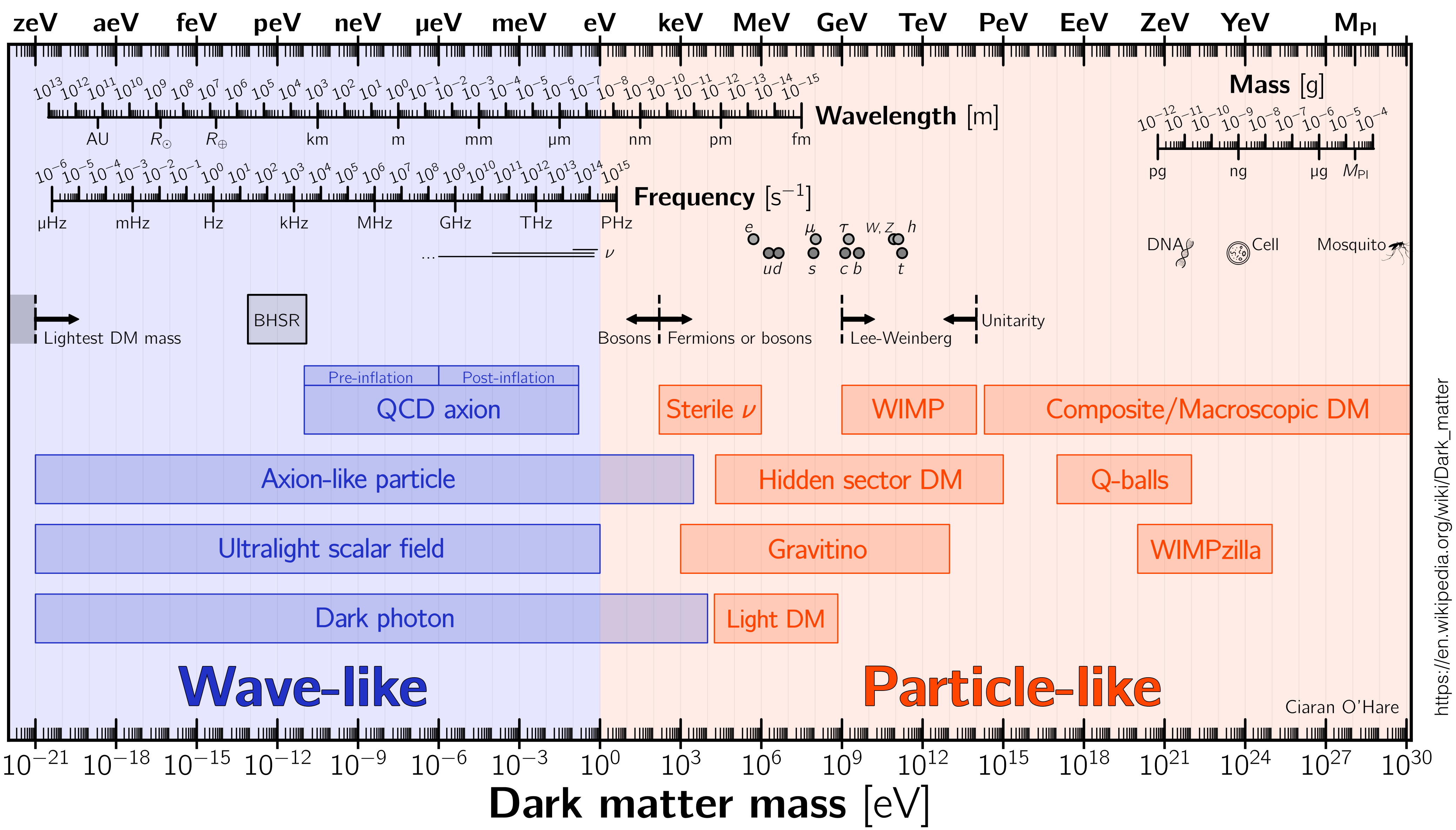


Example of a 90% C.L. sensitivity limit (background free) from a 1 ton-year Ge experiment with a 1 keV energy threshold

J. Billard DRTBT2018

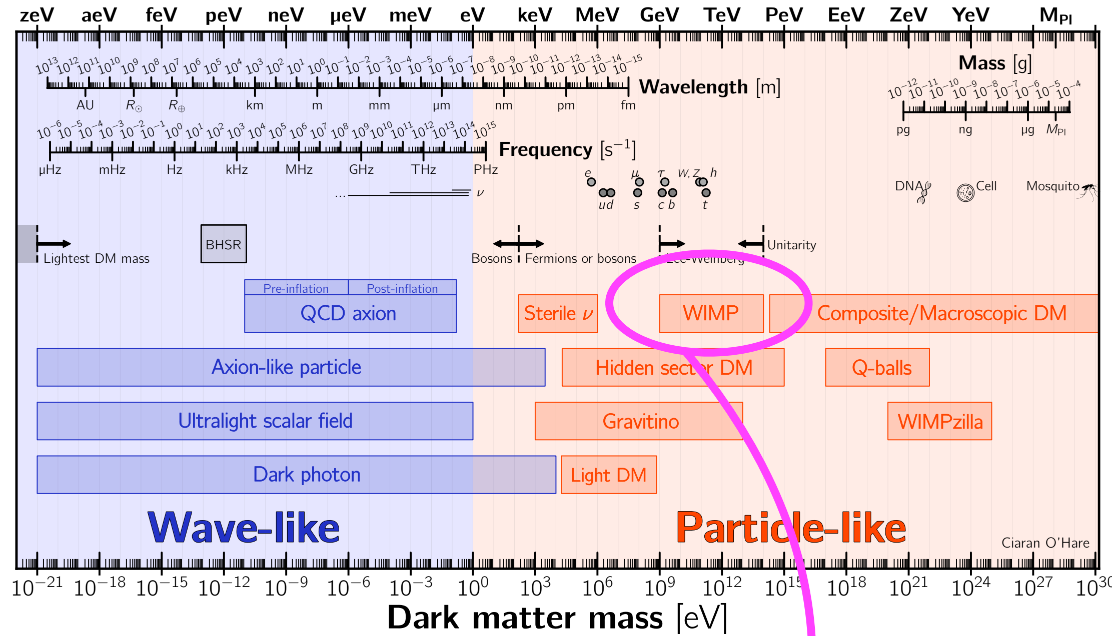
Dark Matter : Much more candidates !!

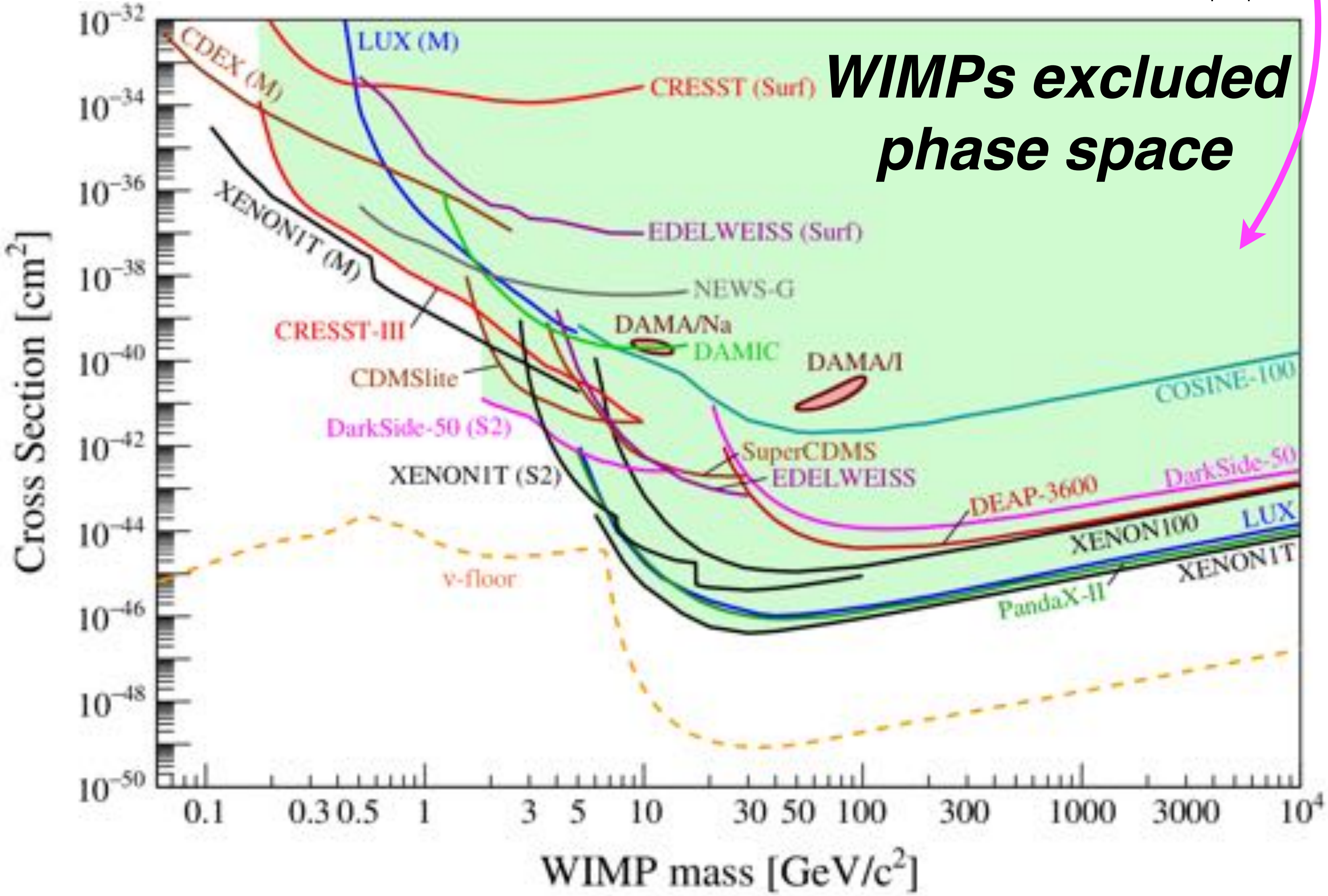


Dark Matter candidate :

- Many candidates **over *50 order of magnitude* in mass** !
- **WIMP still motivated**
- …but we should **enlarge the focus** with new R&Ds (US P5 report & Dark Matter Small Projects New Initiatives)

Dark Matter : Direct Wimp search status





Direct detection of dark matter—APPEC committee report

Xenon 1T sensitivity:

~2 bkg evts in about 1ton.year of exposure !!

Dark Matter search: detectors

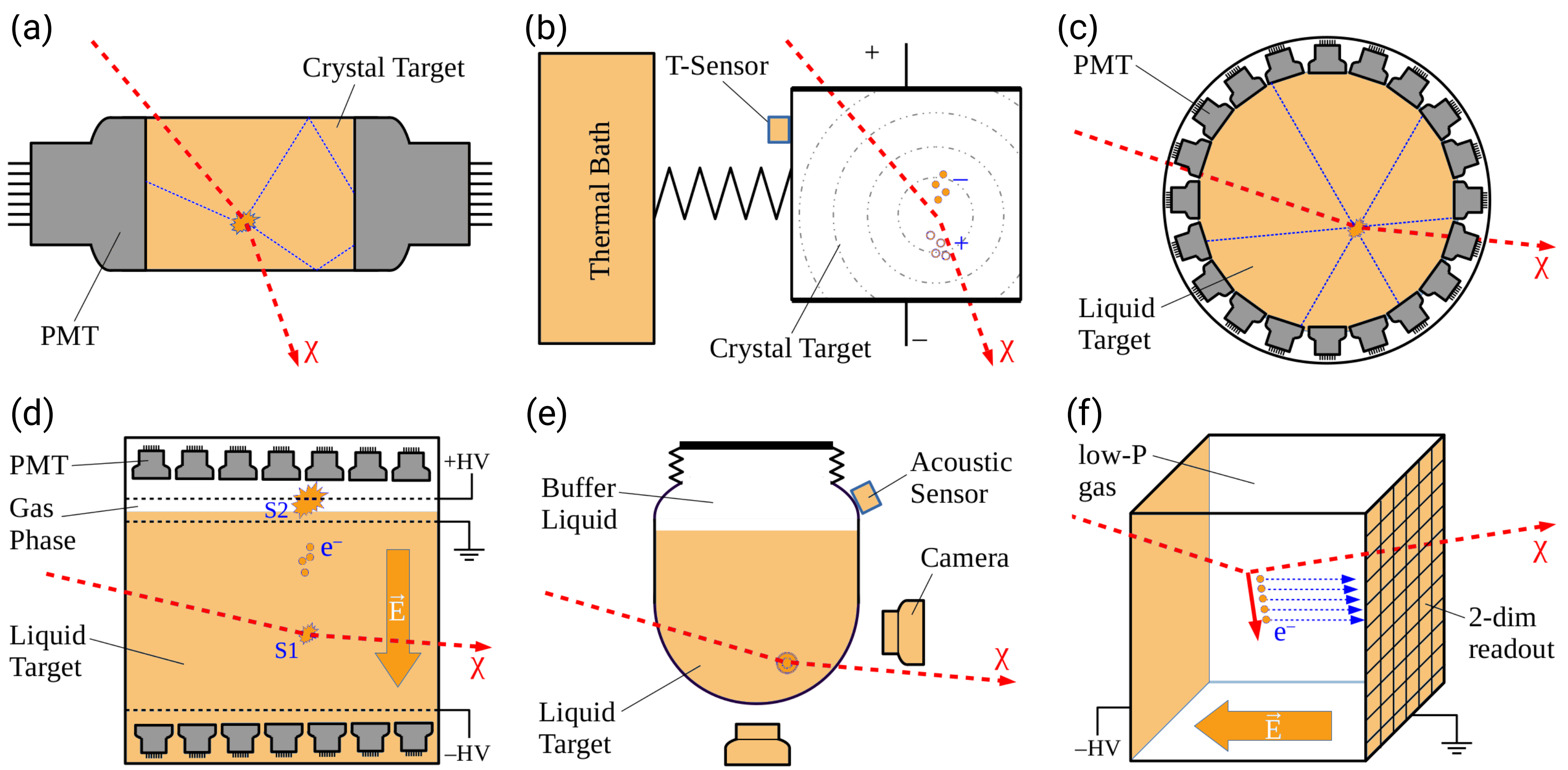


Figure 2: Working principle of common detector types for the direct WIMP search: (a) scintillating crystal, (b) bolometer (here with additional charge-readout), (c) single-phase and (d) dual-phase liquid noble gas detectors, (e) bubble chamber, (e) directional detector. Images adapted from [113].

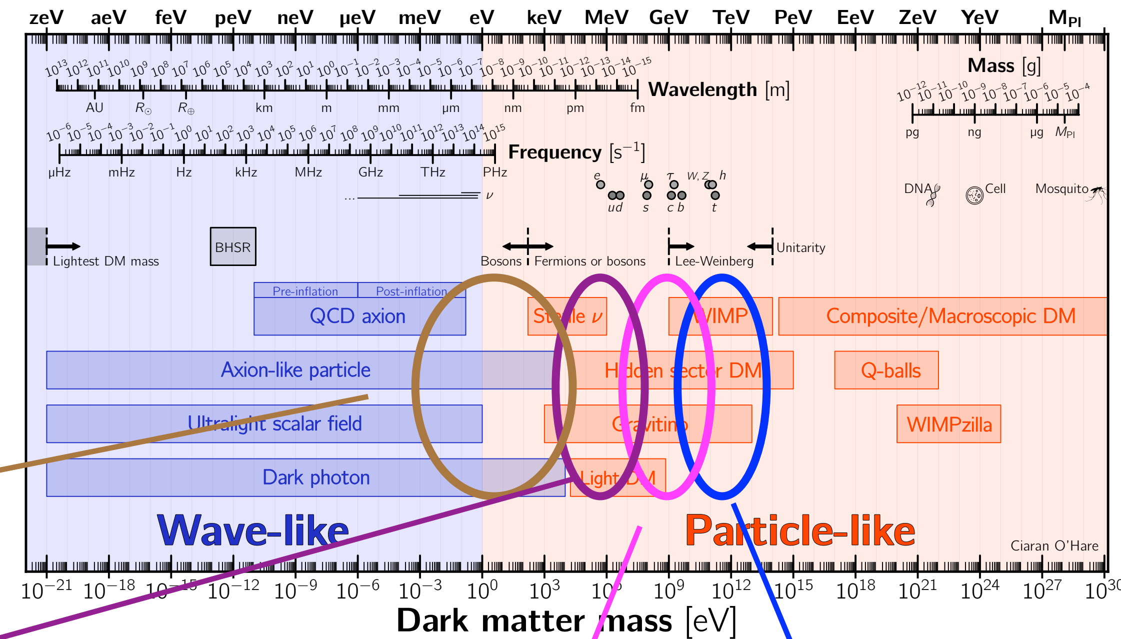
Direct detection of dark matter—APPEC committee report

+ CCD, Haloscope, …

The « wish list » for a direct detection experiment :

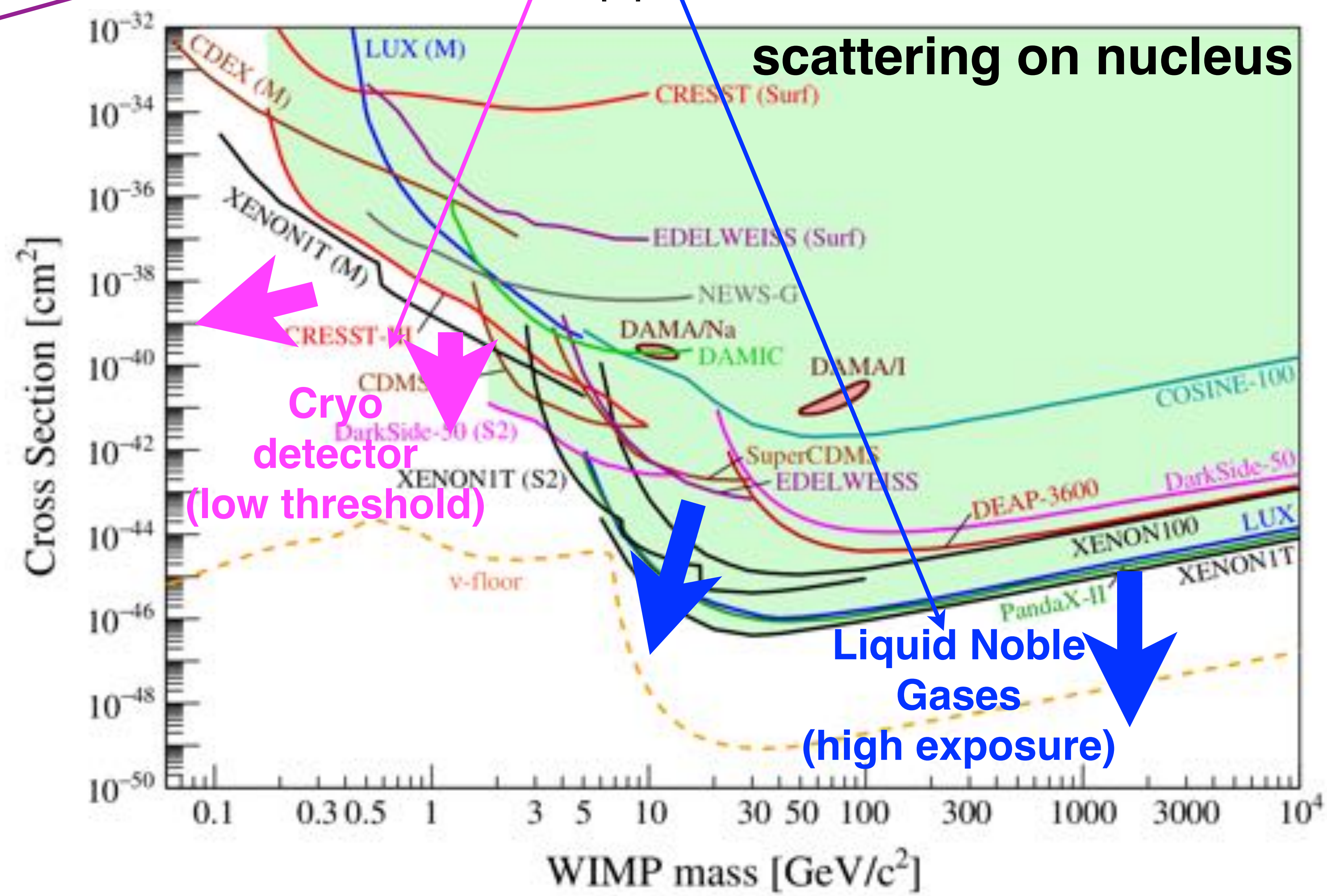
- **Low energy threshold** *if low mass search*
- **Large exposure** (few events per ton-year) *if standard wimp search*
- **Low and controlled backgrounds** (underground labs and passive shielding)
- **Discrimination** between signal and backgroundS

Dark Matter search: detectors



Absorption

scattering on electron

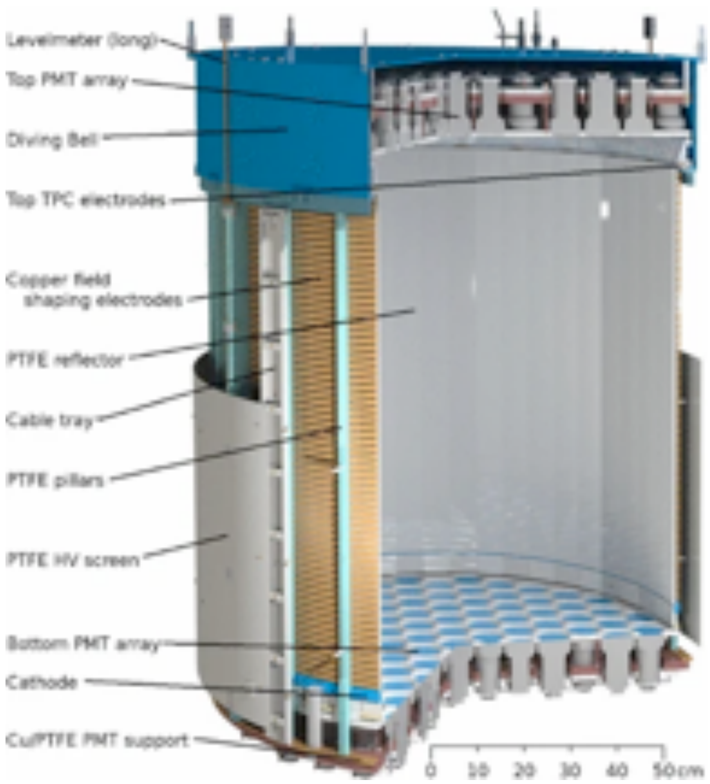


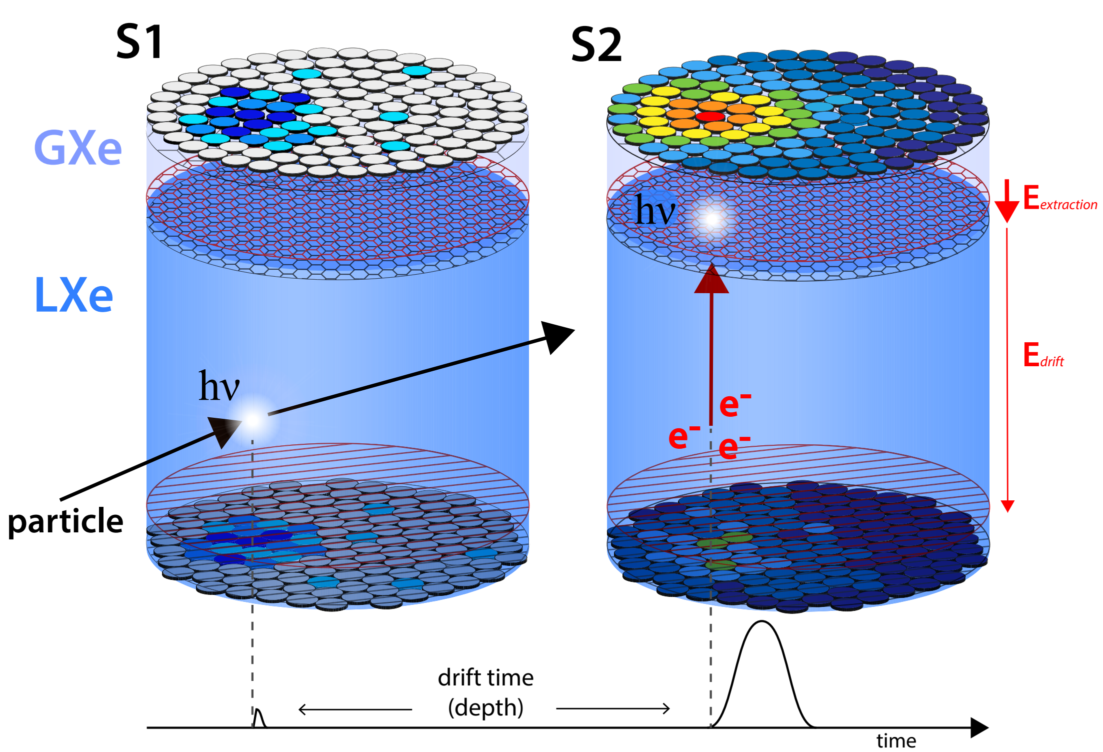
Different metrics and different plots to represent the detector sensitivity.

- Intense competition between various detector technology
- **Main advantage of cryo detector : low threshold**

Direct detection of dark matter—APPEC committee report

Dark Matter search: LXe detector





Xenon1T @ Gran Sasso

https://xenonexperiment.org/

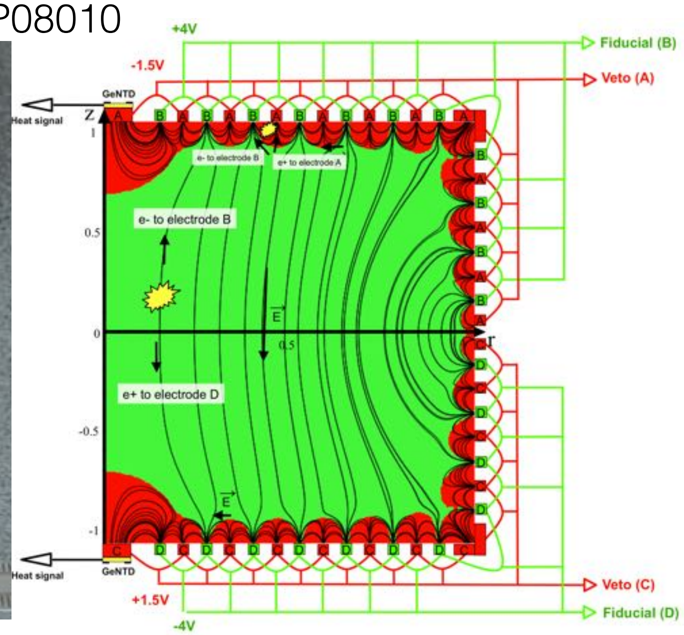
Dark Matter search : Cryogenic Detector

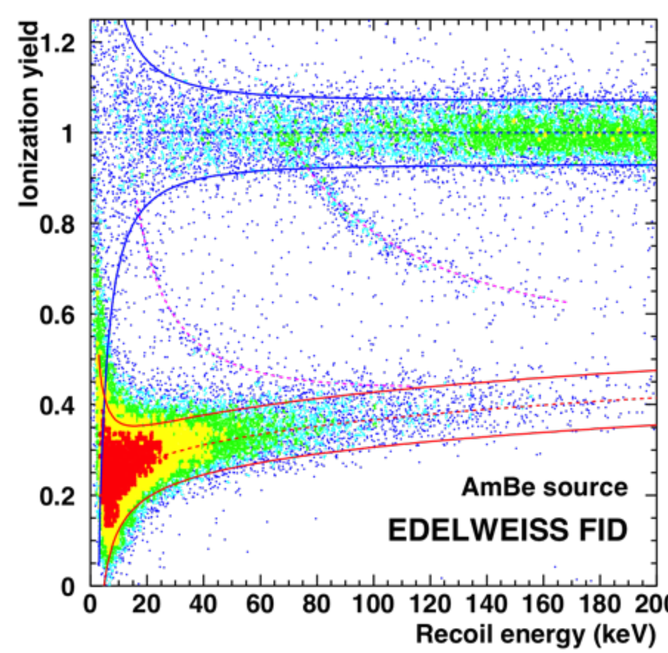
Double readout cryogenic detectors allows for an **evt-by-evt background rejection** :

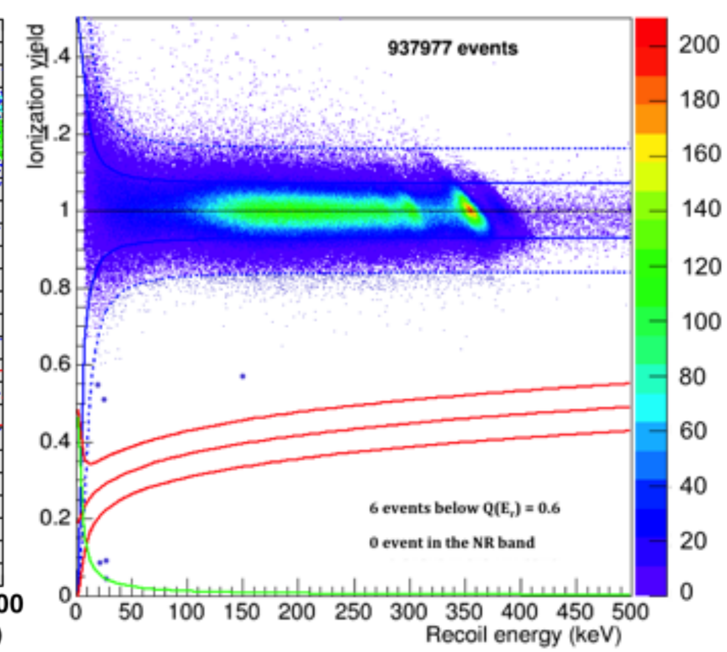
- ✦ **Heat and Ionization on Ge/Si** detector :
  - ➡ Elec. Recoil / **Nuclear Recoil discrimination**
  - ➡ **Heat only** event **rejection**
  - ➡ **surface event rejection**

EDELWEISS
CDMS-SuperCDMS

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







800g Ge EDW-III Ge detector

Dark Matter search : Cryogenic Detector

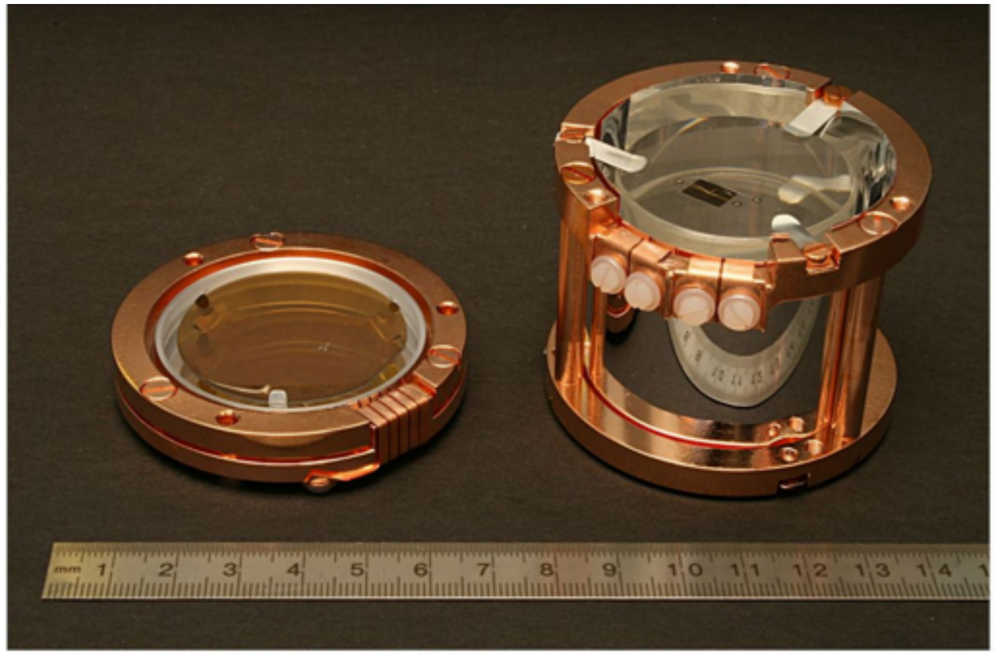
Double readout cryogenic detectors allows for an **evt-by-evt background rejection** :

- ✦ **Heat and Light** on different crystal
  - ➡ **α background rejection**

CRESST

Developed initially for standard WIMPs search :

- ✦ **head of the competition early 2000's**
- ✦ **Far behind noble gas detector since**
- ✦ **New development to go to low mass Dark Matter since 2010**



Eur. Phys. J. C (2012) 72:1971

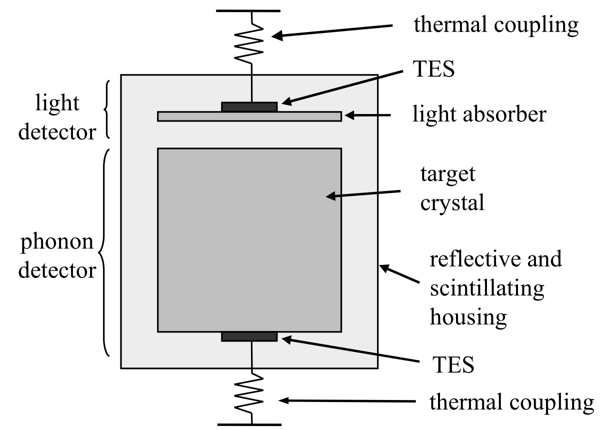
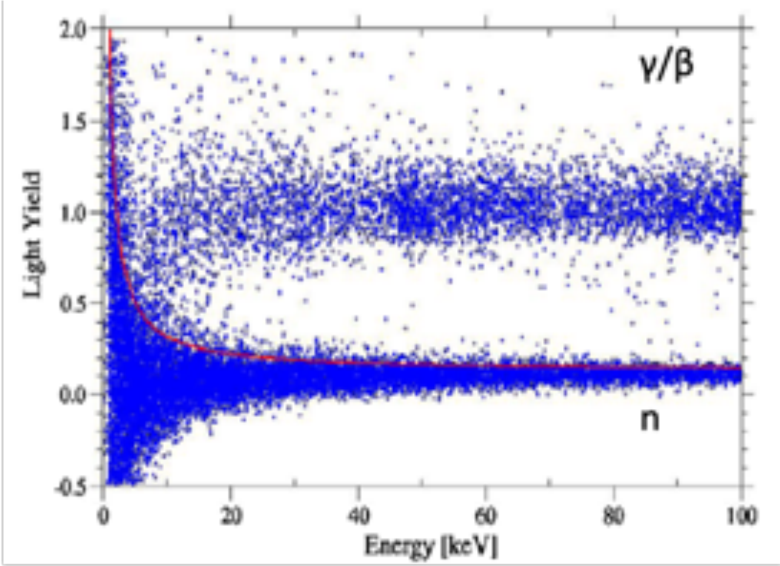


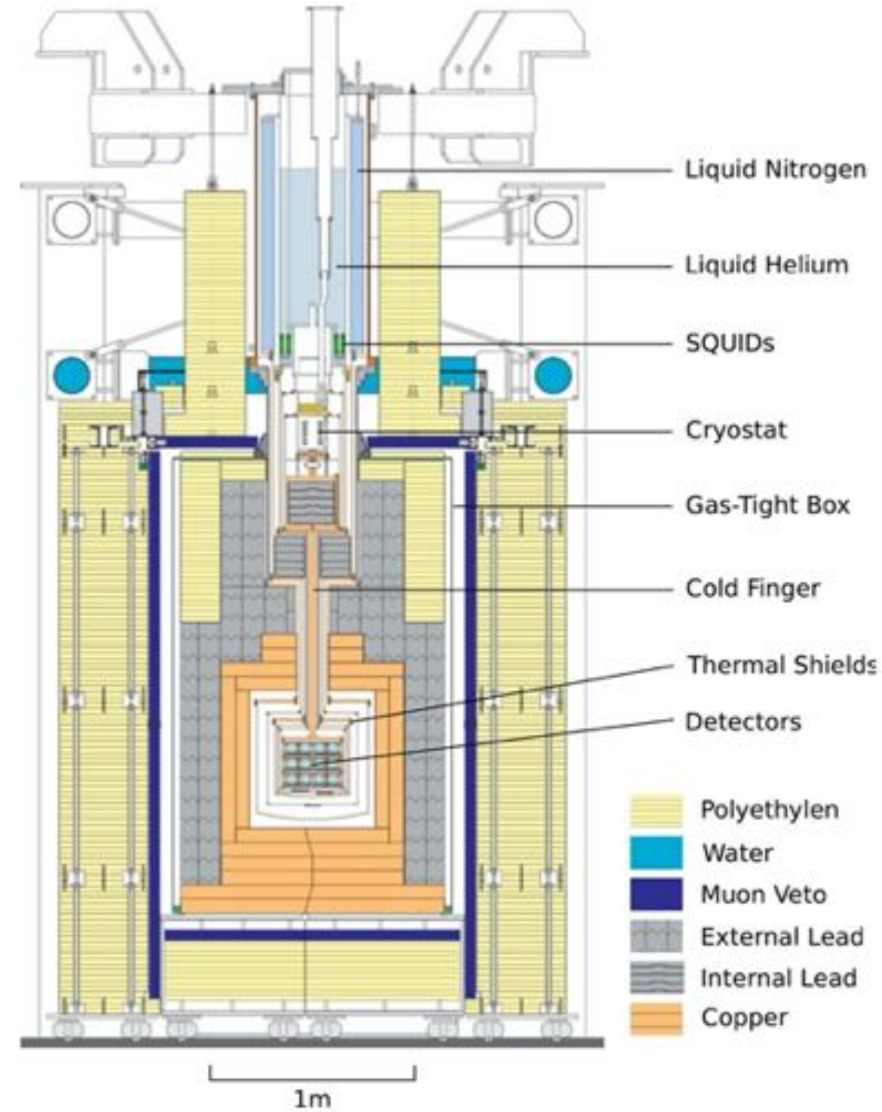
Fig. 2 Schematic drawing of a CRESST detector module, consisting of the target crystal and an independent light detector. Both are read out by transition edge sensors (TES) and are enclosed in a common reflective and scintillating housing



G. Angloher, et al, Astroparticle Physics, 31, 270, 2009

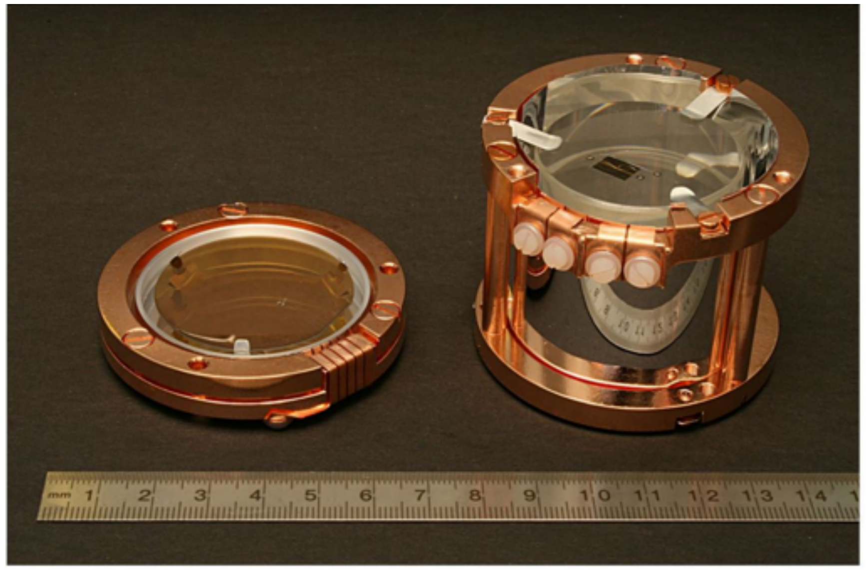
300g CRESST-II $CaWO_4$ detector

Dark Matter search : CRESST



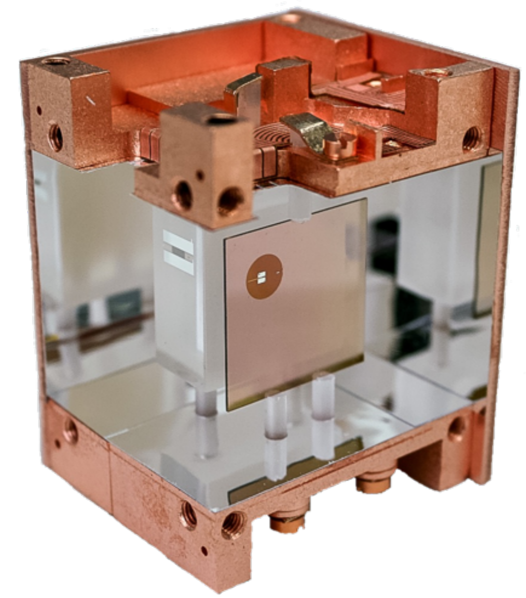
- **located in LNGS in Italy**
- **started in 1996**
- **CRESST-II (2006-2015)**
  - 33 * 300 g $CaWO_4$
- **CRESST-III (2017-)**
  - up to 33 * module of different target & size
  - Major upgrade ongoing (600 readout channels)

CRESST : from 300g detectors to sub-g one !



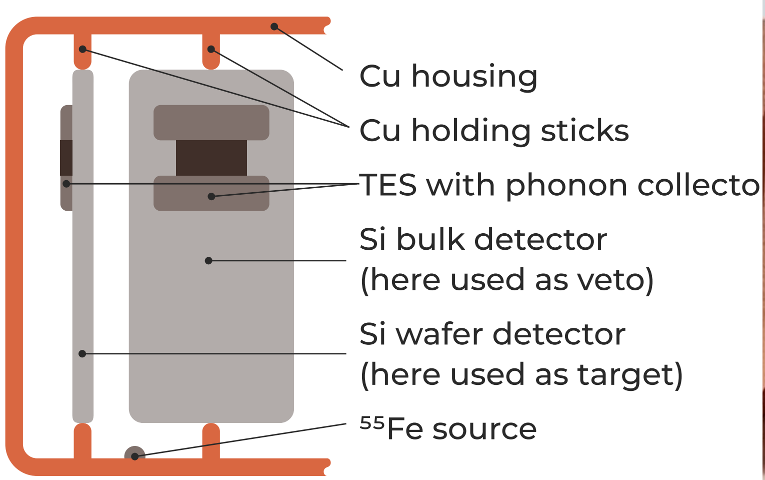
300 g CaWO4
σ~ 80eV (best)

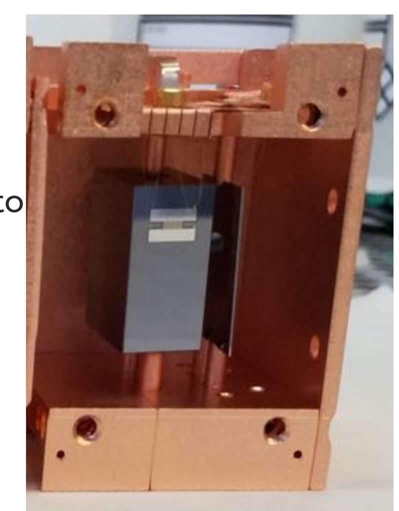
730 kg.day published 2012



24g CaWO4
σ~10 eV (best)

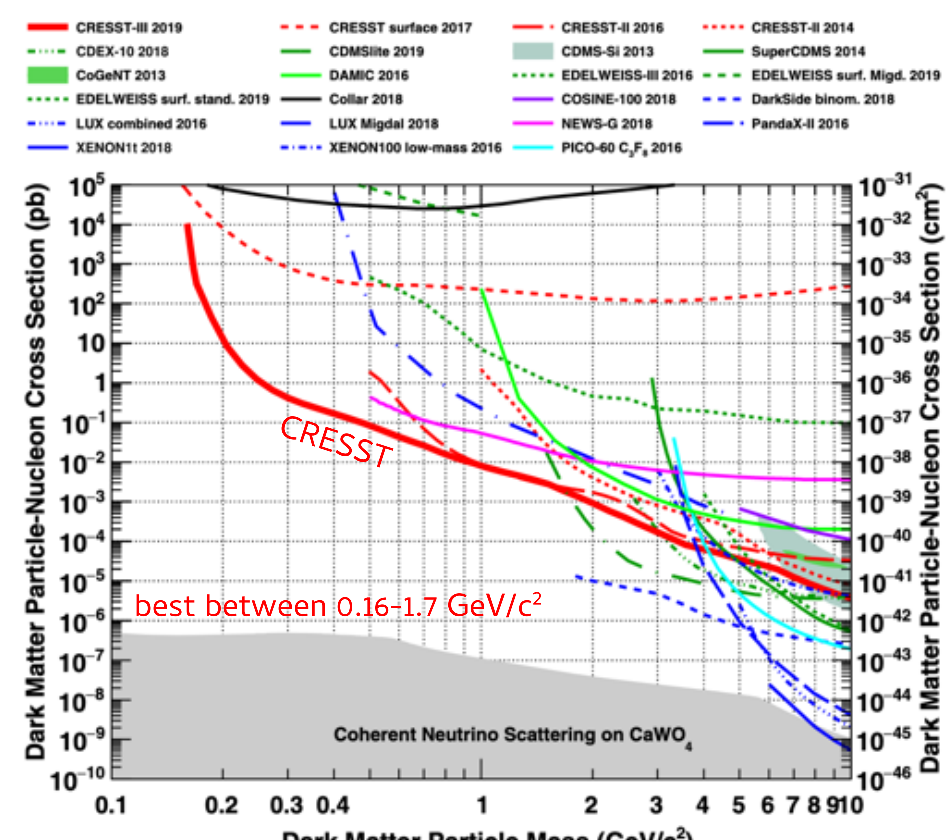
2019 World leading result with only 5.7 kg.day !





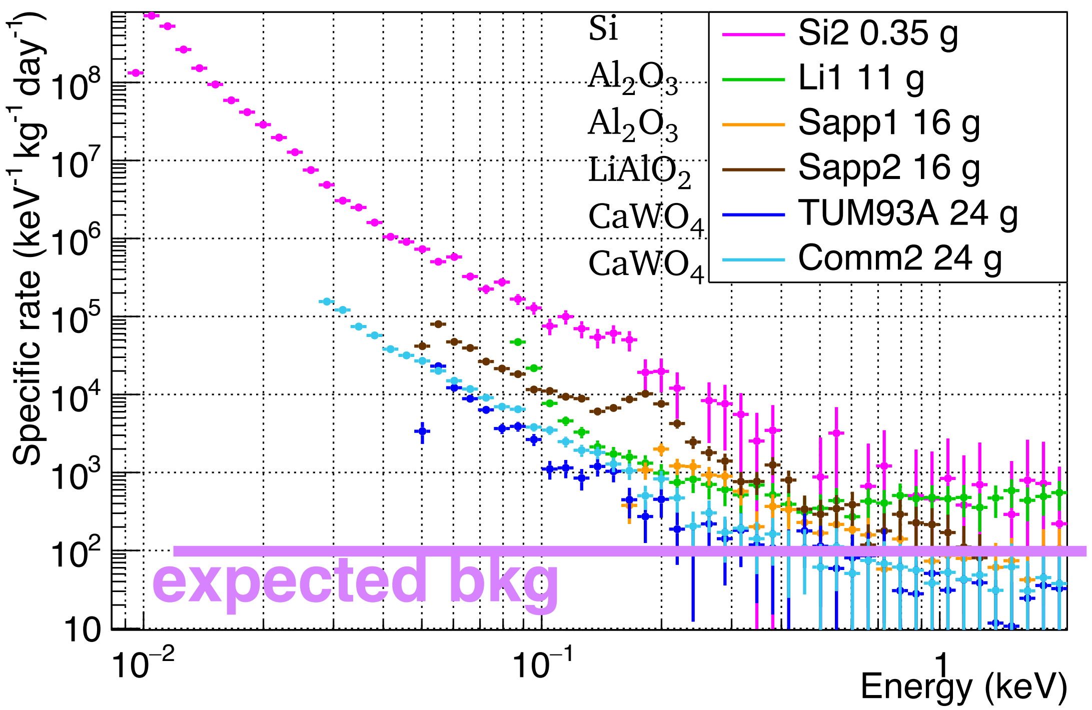
0.35 g Si
σ~1.3 eV

2022 World leading result with only 55 g.day !

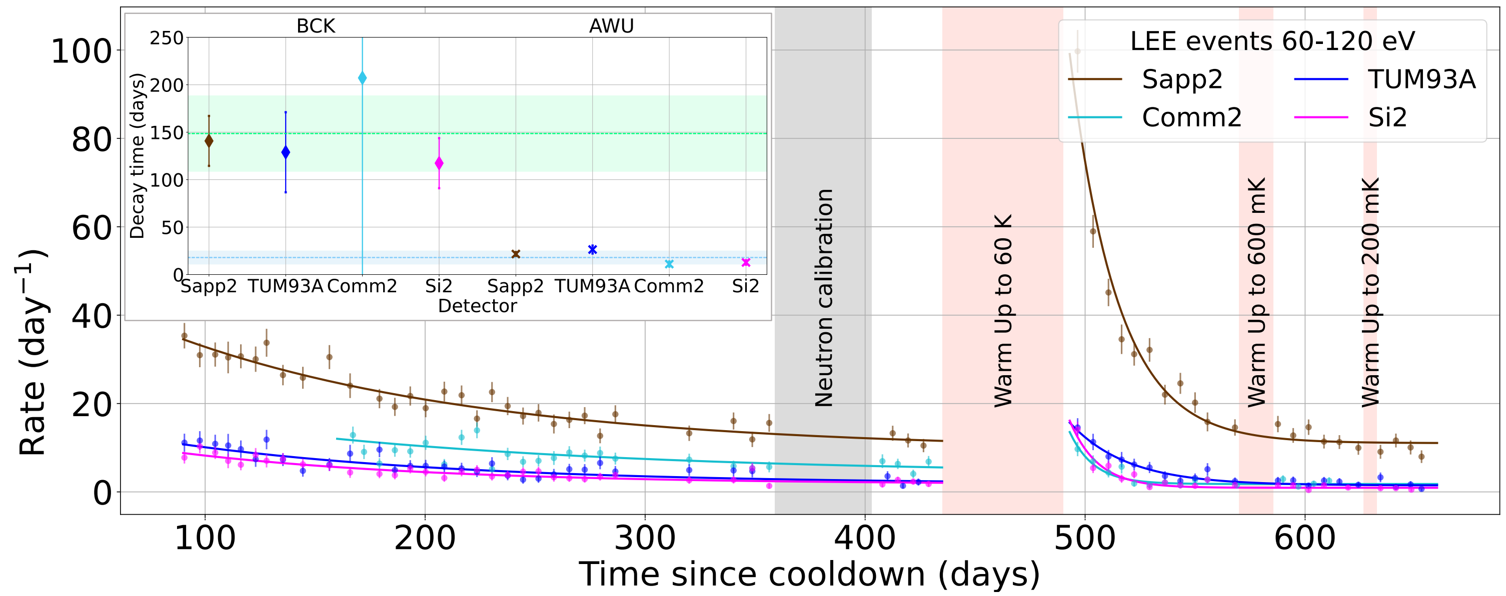


Phys. Rev. D 100, 102002 (2019) / arXiv:1904.00498

CRESST : Low Energy Excess evts



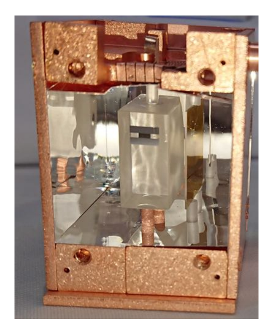
arXiv:2207.09375

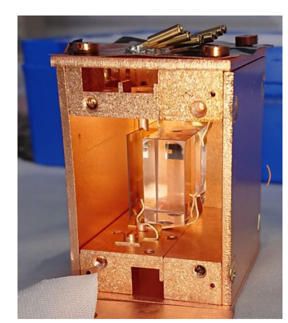


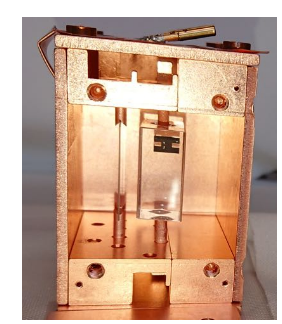
- ***Low Energy Excess also seen by ALL cryogenic detectors !!***
  - Radiogenic bkg more expected to be flat and at the 1-100 dru level :
  - ***LEE orders of magnitude higher !***
- **Origins under investigation:**
  - Sensor related events
  - Relaxation of holding-induced stress
  - Intrinsic crystal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

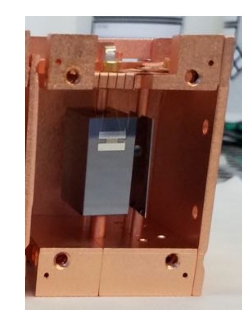
Major issue today.
Will limit most of the science cases if not solved/mitigated

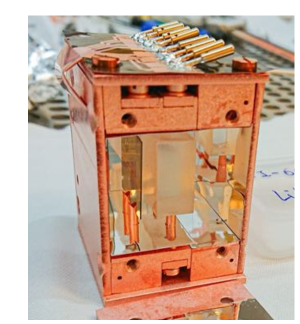
Multiple design modifications were applied in the current data-taking campaign to test ideas about the LEE origin.


$CaWO_4$ 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)

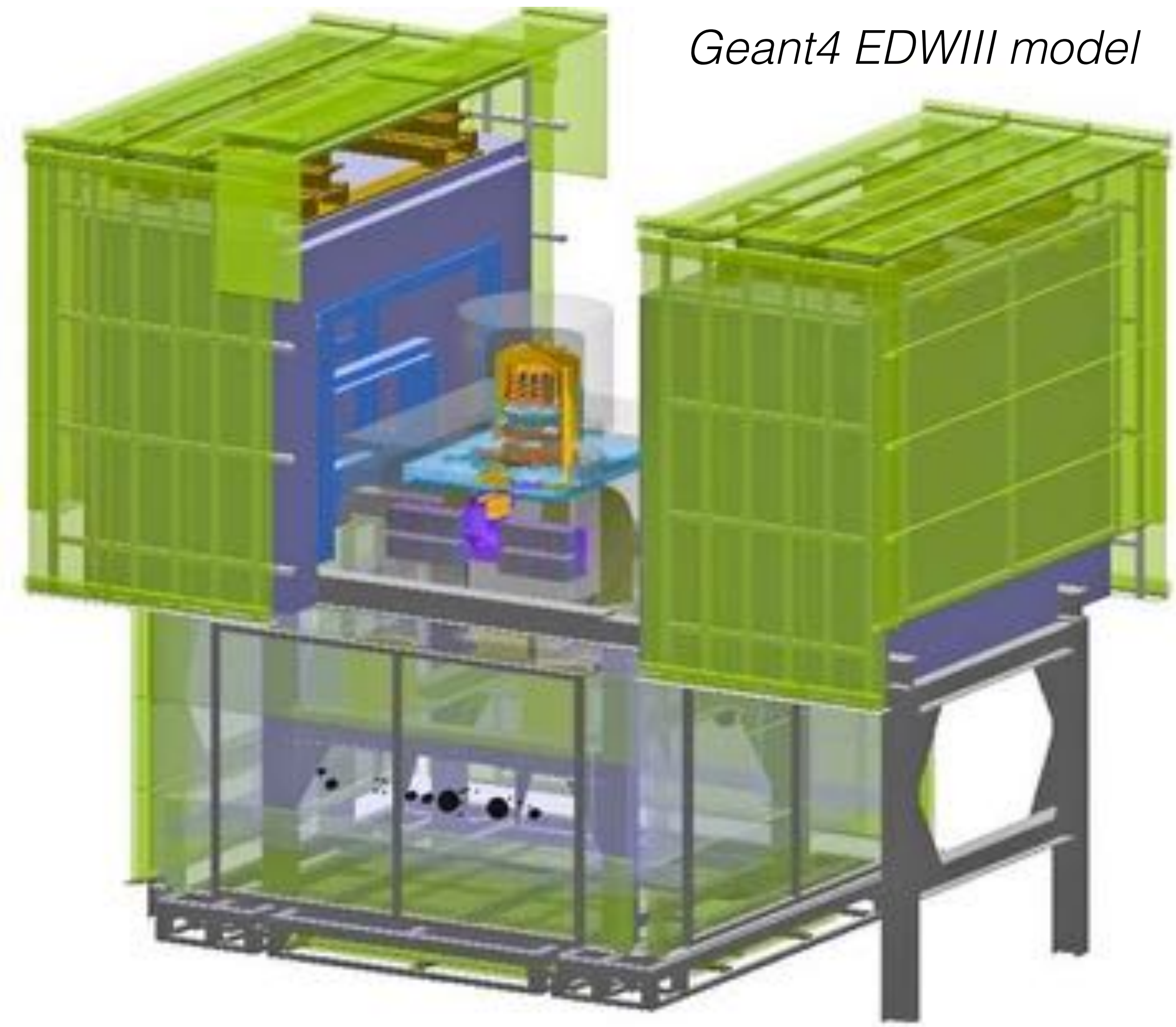
All thresholds are at O(10 eV)

LEE is observed in all detectors

CRESST

TAUP 2023 | 30.08.2023 | Margarita Kaznacheeva

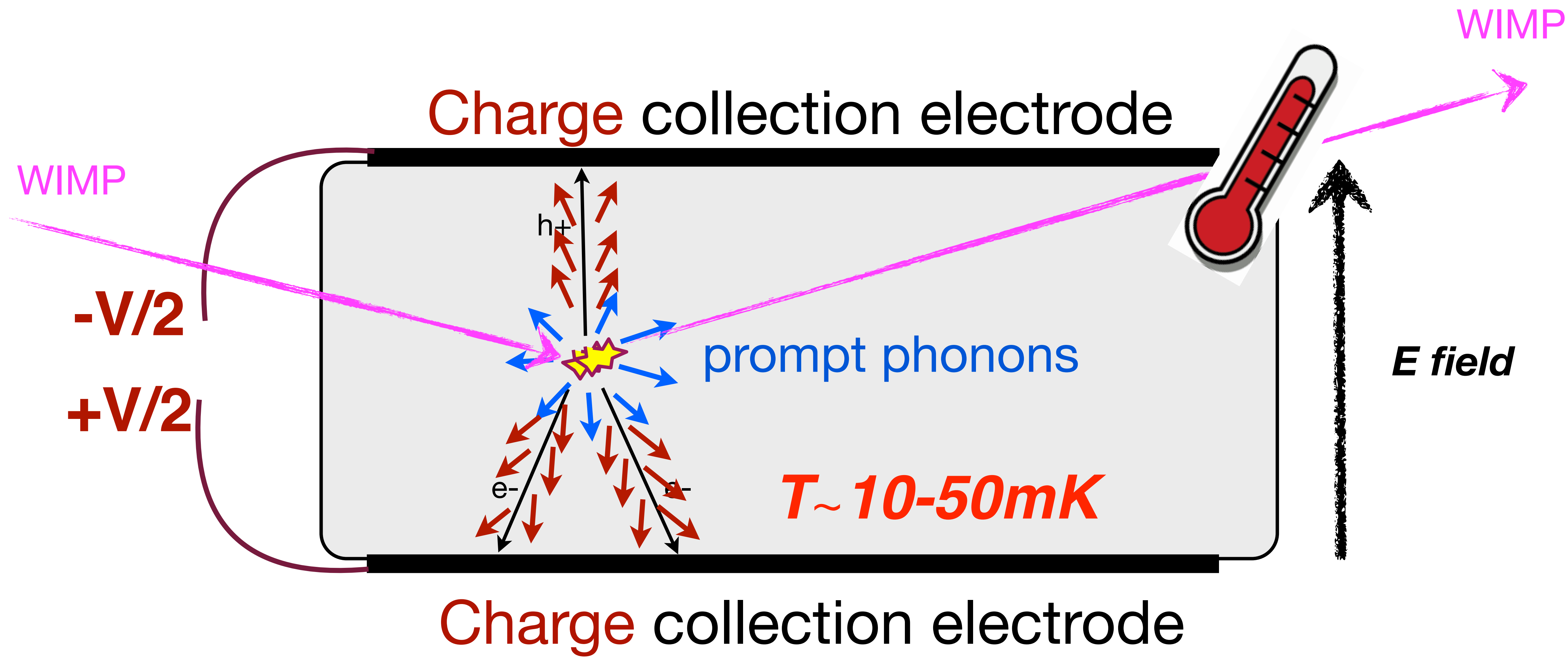
Dark Matter search : EDELWEISS -II / -III setup



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

- **35 tons PE + 40 tons Pb shielding**
- **100 m² active muon veto**
- **Low radioactivity material in the detector vicinity**

EDW Cryogenic Ge : Simultaneous Heat & Ionization



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

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

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

@ 3V : ***Heat from Recoil = Heat from charge drift* 2*** (for ER)

@ > 100V : ***Heat = E_{Luke} : signal boost, no ID***

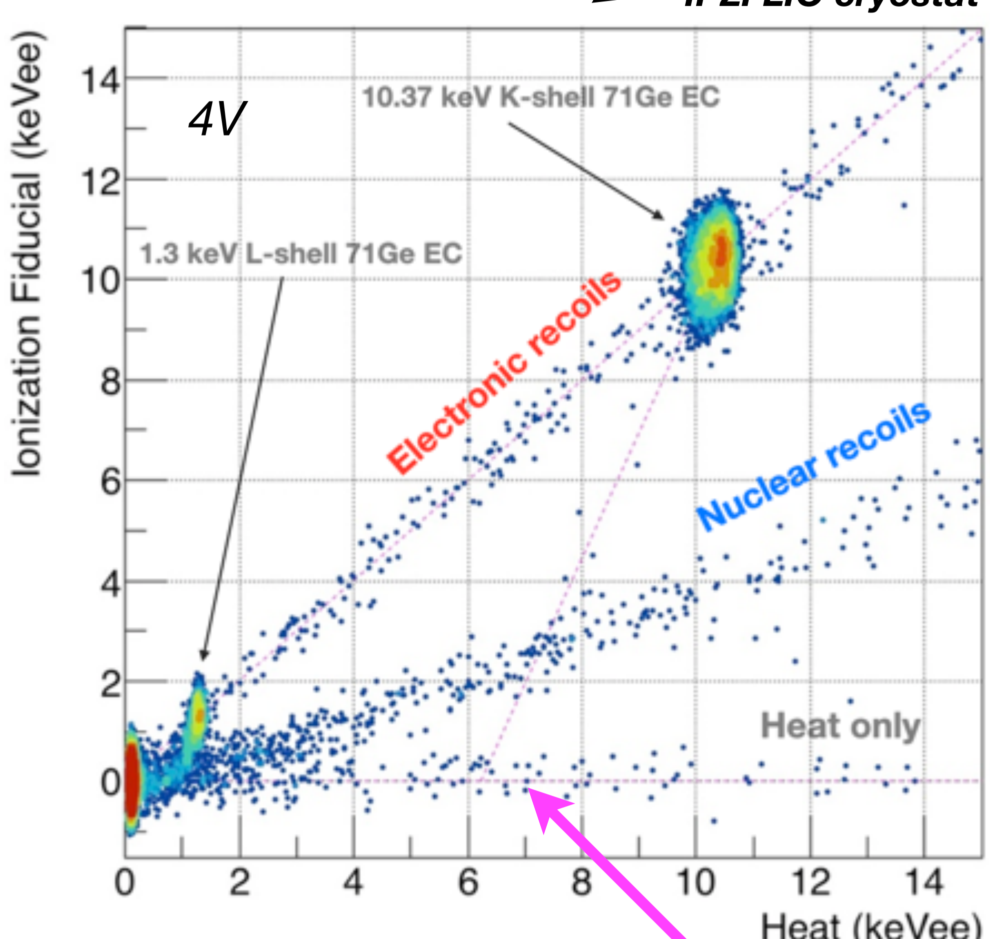
EDELWEISS : 2 modes of operation

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

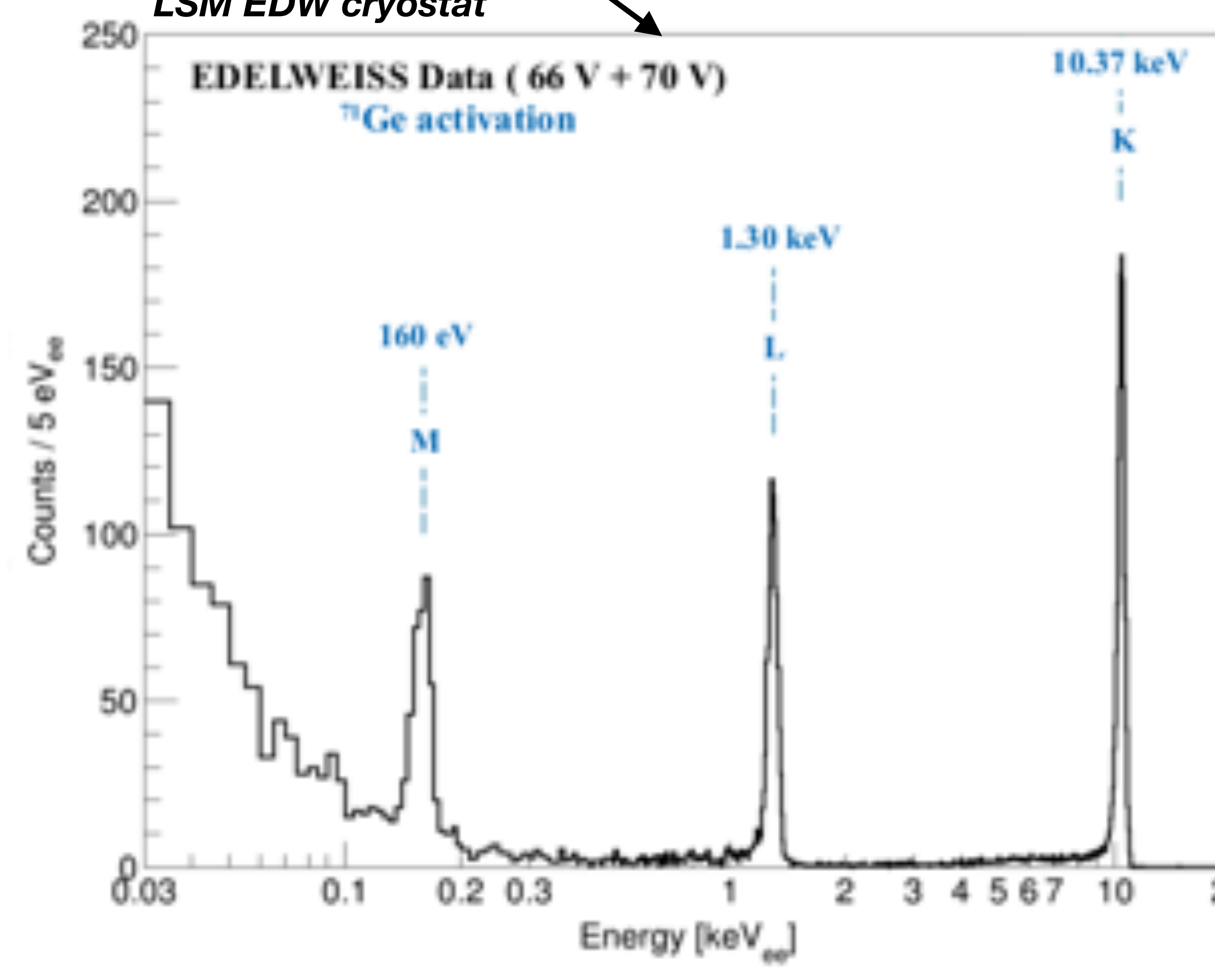
Low Voltage mode
Part. ID + Fid

High Voltage mode
single e/h - No PID

IP2I LIO cryostat

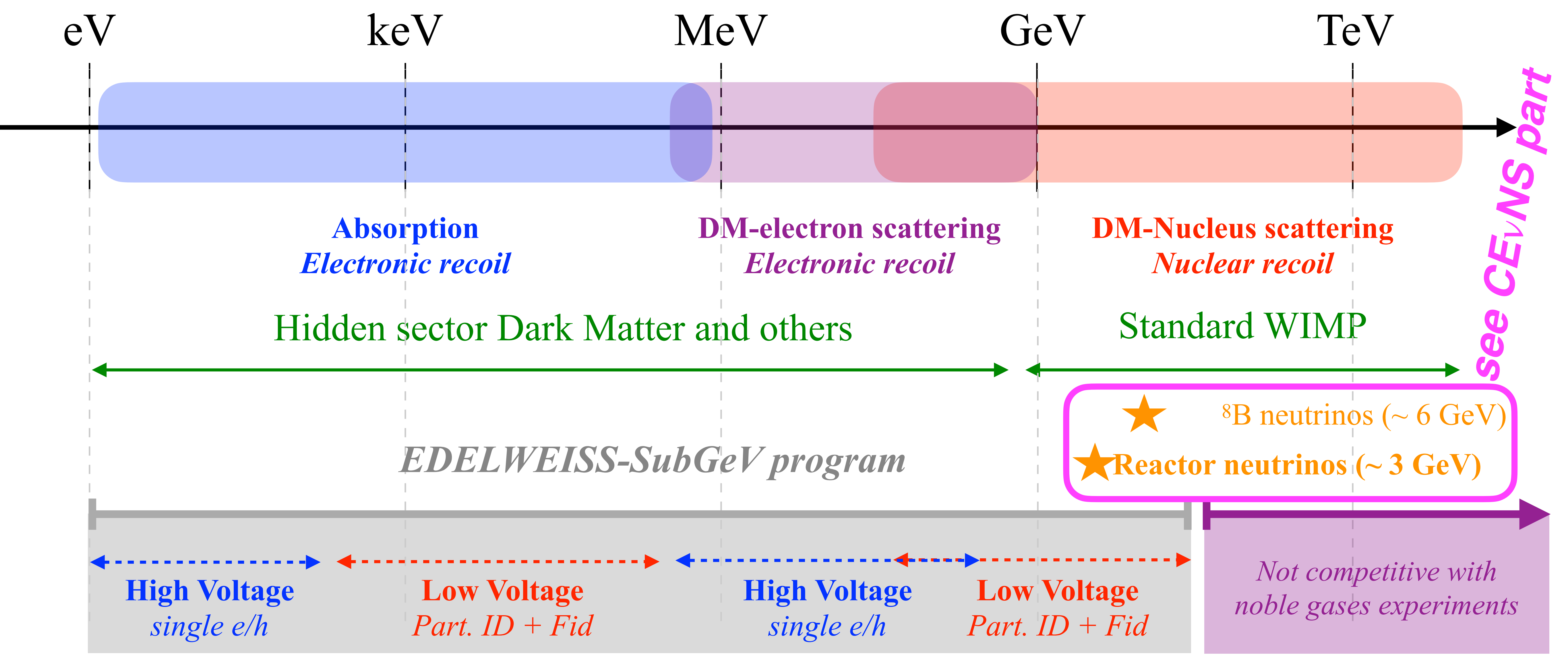


LSM EDW cryostat



Low Energy Excess (Heat Only)

EDELWEISS : DM search objectives

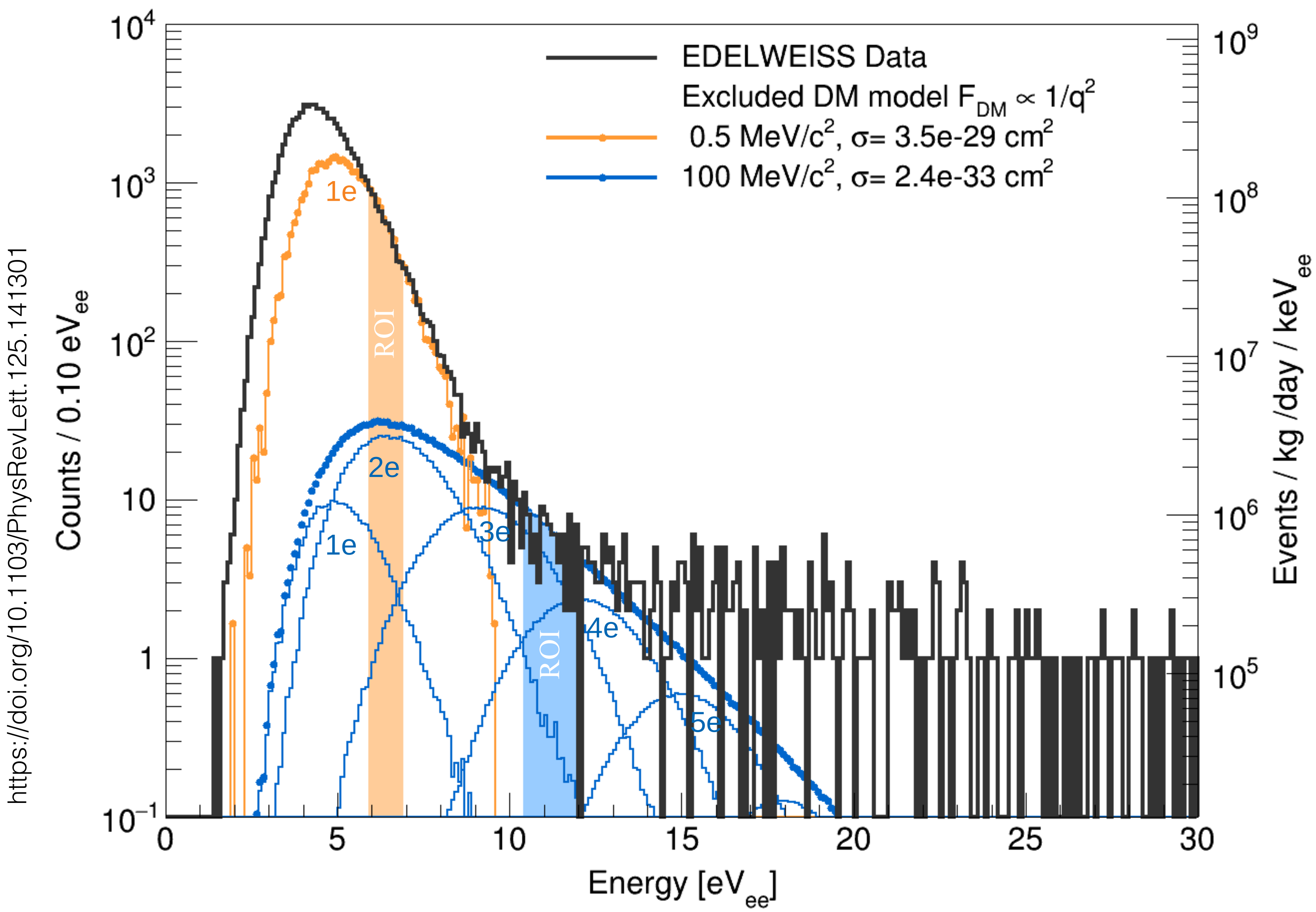


EDELWEISS-SubGeV: aiming for a kg-scale payload of few-g to 30g Ge detectors running in two modes:

- **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

EDELWEISS : Dark Matter search in HV mode @ LSM



33 g Ge @ 78V

$\sigma \sim 1.5$ 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!

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**

200 g Ge @ 66V

$\sigma \sim 4.45$ eV$_{ee}$ (1.5 eh pair)

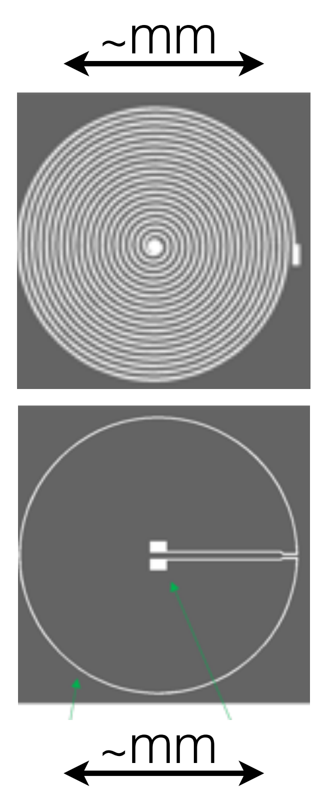
2022 World leading results
(DM scattering on e, DM absorption)
with only 28 days of DM search at LSM!

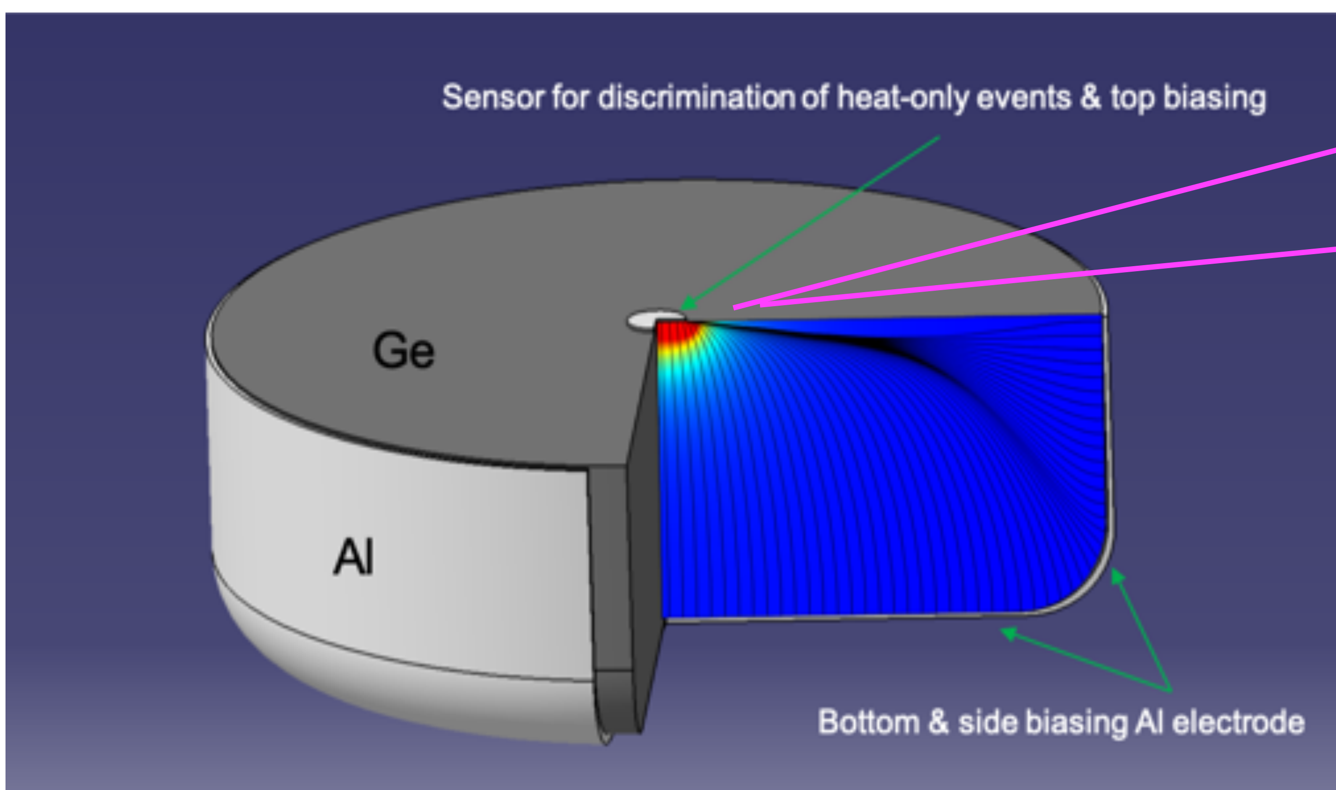
https://doi.org/10.1103/PhysRevD.106.062004

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

- **Low Energy are non ionizing** (« heat only » event
  - *Ionization can be used to reject LEE*
  - but limited by the ionization energy
  - Huge effort over the past 7 years :
    - from **EDWIII σ = 200 eV to σ = 30 eV** (reached for RICOCHET, see Cenns)
  - **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

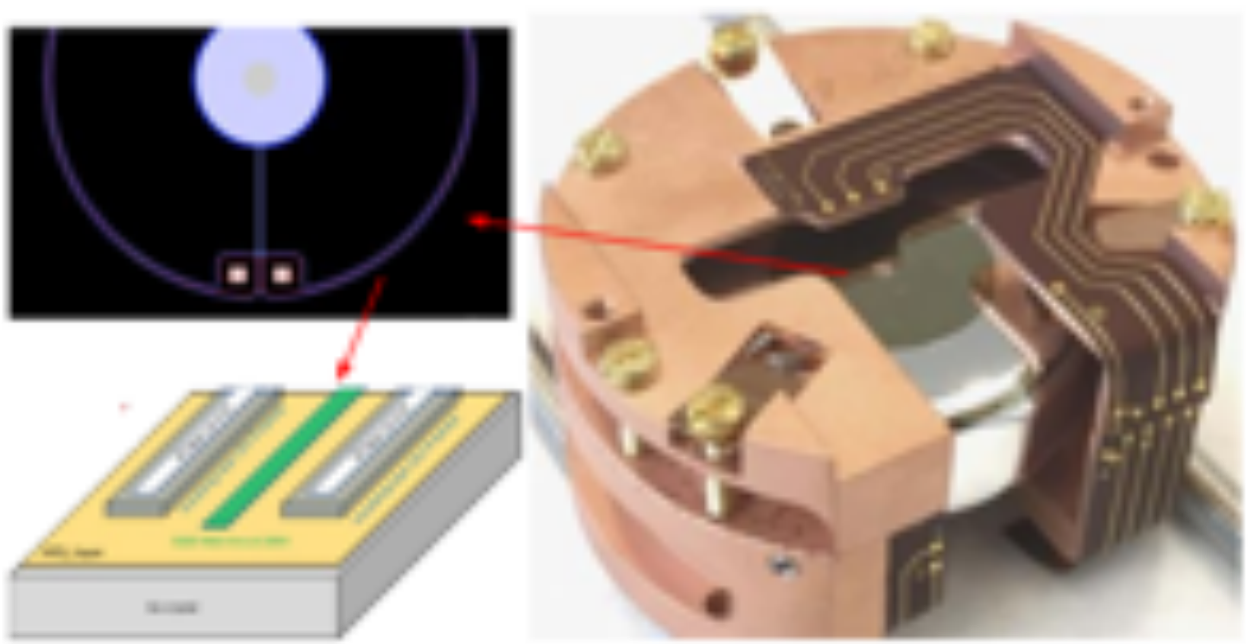




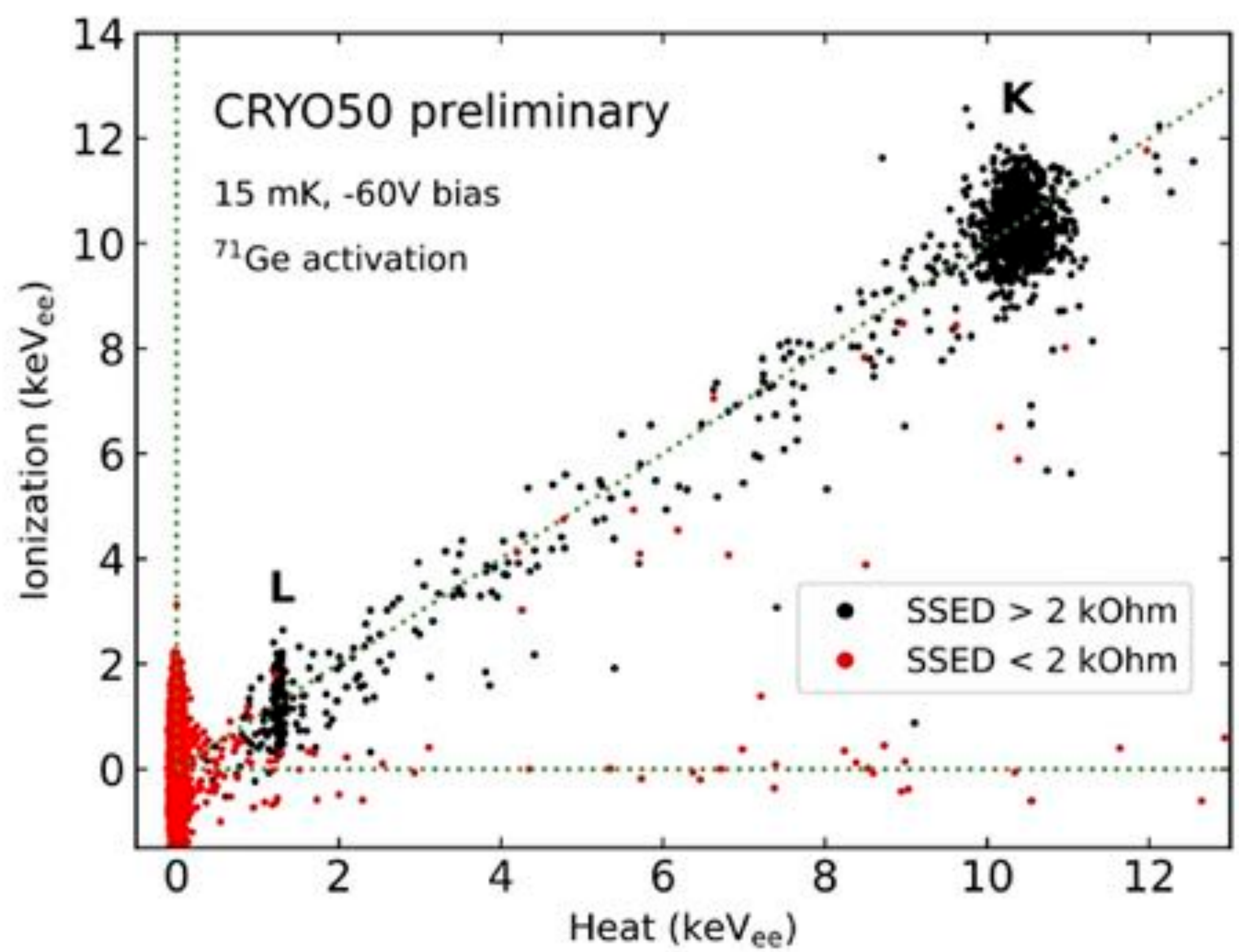
EDELWEISS : Identification of Low Energy Excess (« heat only »)

- **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



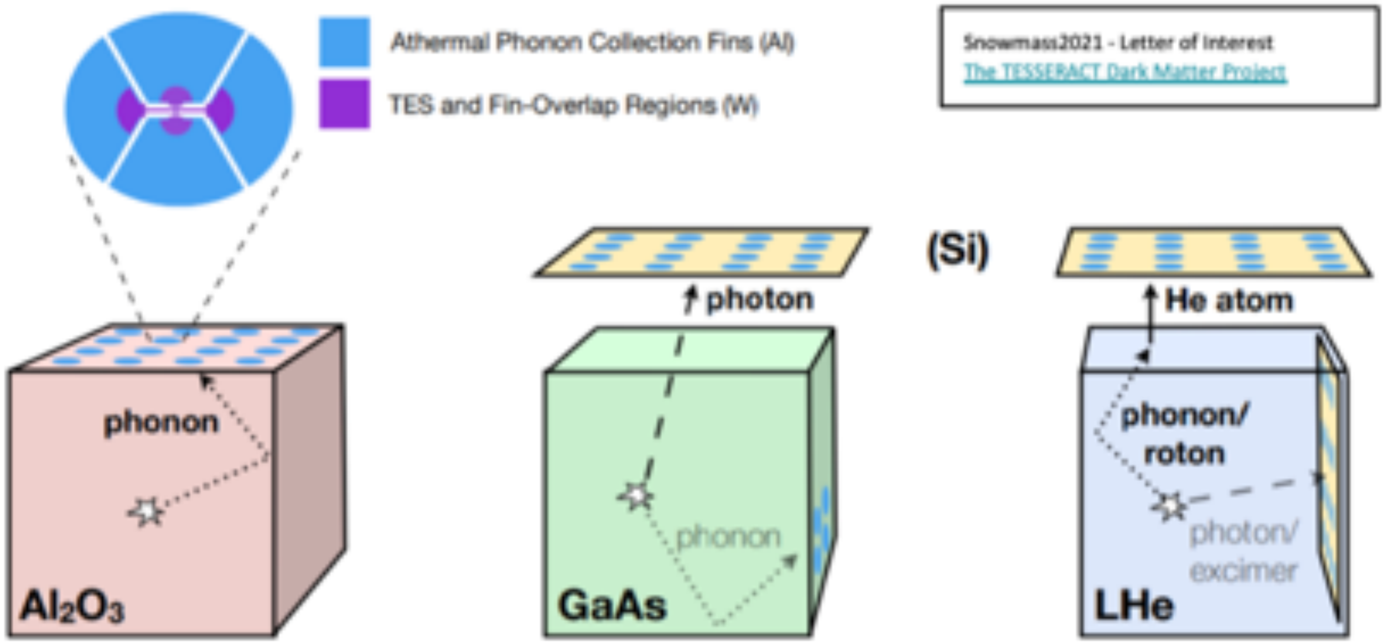
EDELWEISS : Future

- **EDELWEISS-III setup dismantled in 2023**
- EDELWEISS collaboration is not existing anymore
- ….But ***french Ge detector technology still alive !***
- ***RICOCHET*** 38g Ge detector started from EDW legacy
- ANR ***CryoSEL*** ongoing (all EDW partner)
- Participation of most of the previous EDW members to the ***TESSERACT Project under discussion***

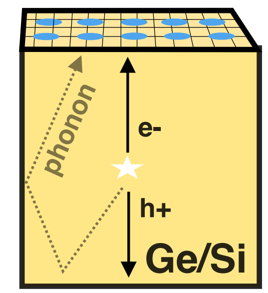
Empty EDW space @ LSM (feb 2024)

TESSERACT : Proposal experiment @ LSM

Transition Edge Sensors with Sub-Ev Resolution And Cryogenic Targets



- 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



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 @ LSM: summary

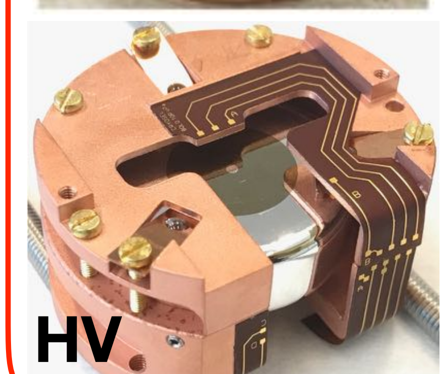
TESSERACT

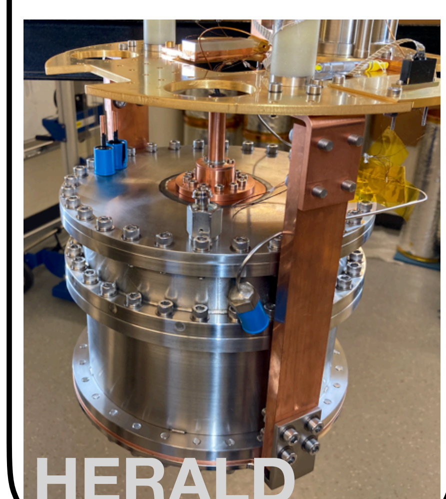
All detector technologies will be using:

1. athermal phonon TES with sub-eV energy thresholds,
2. drastically mitigated LEE (under intense investigation),
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	Dual 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**

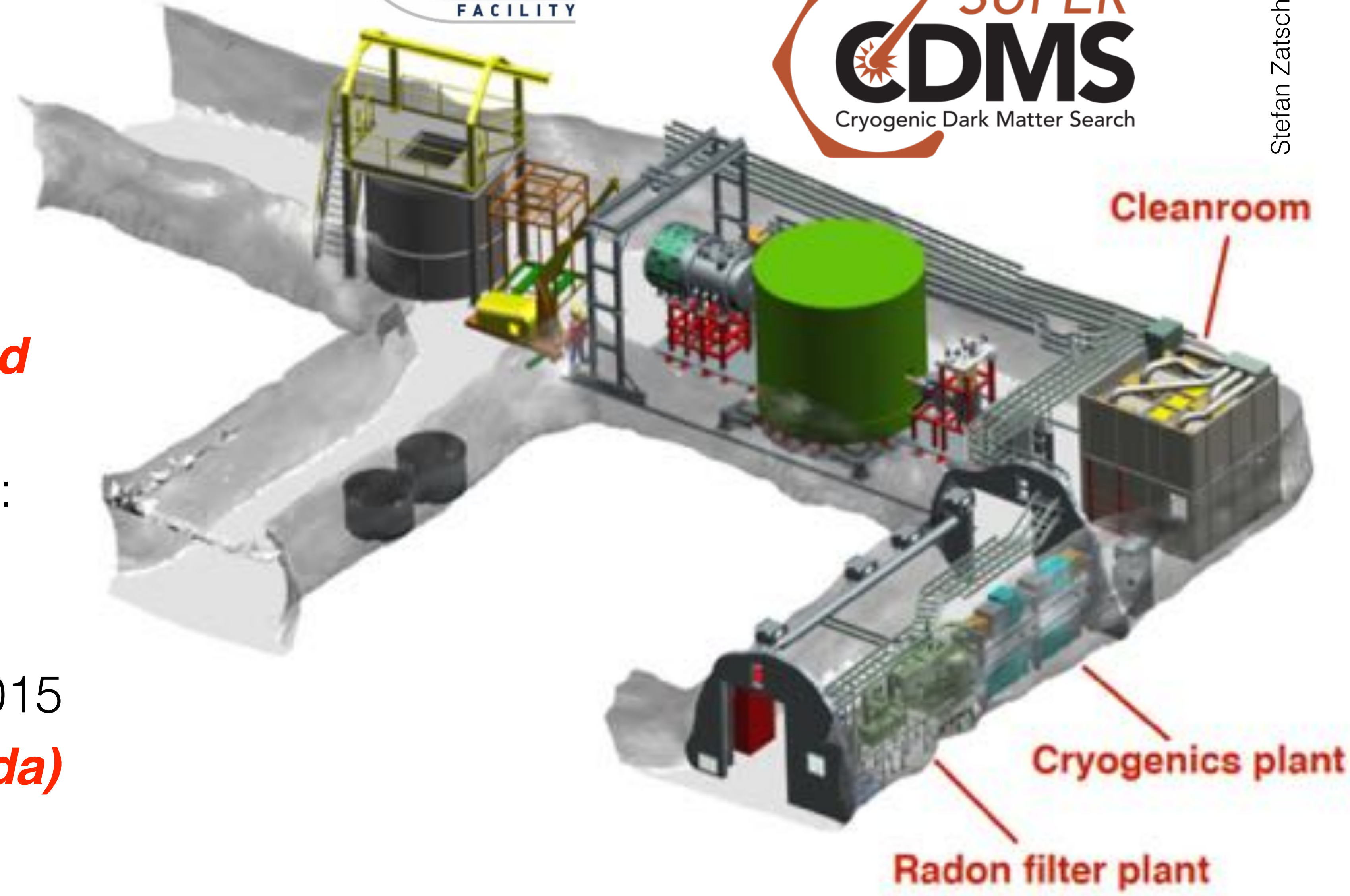
cnrs
IN2P3





Dark Matter search : CDMS-SuperCDMS

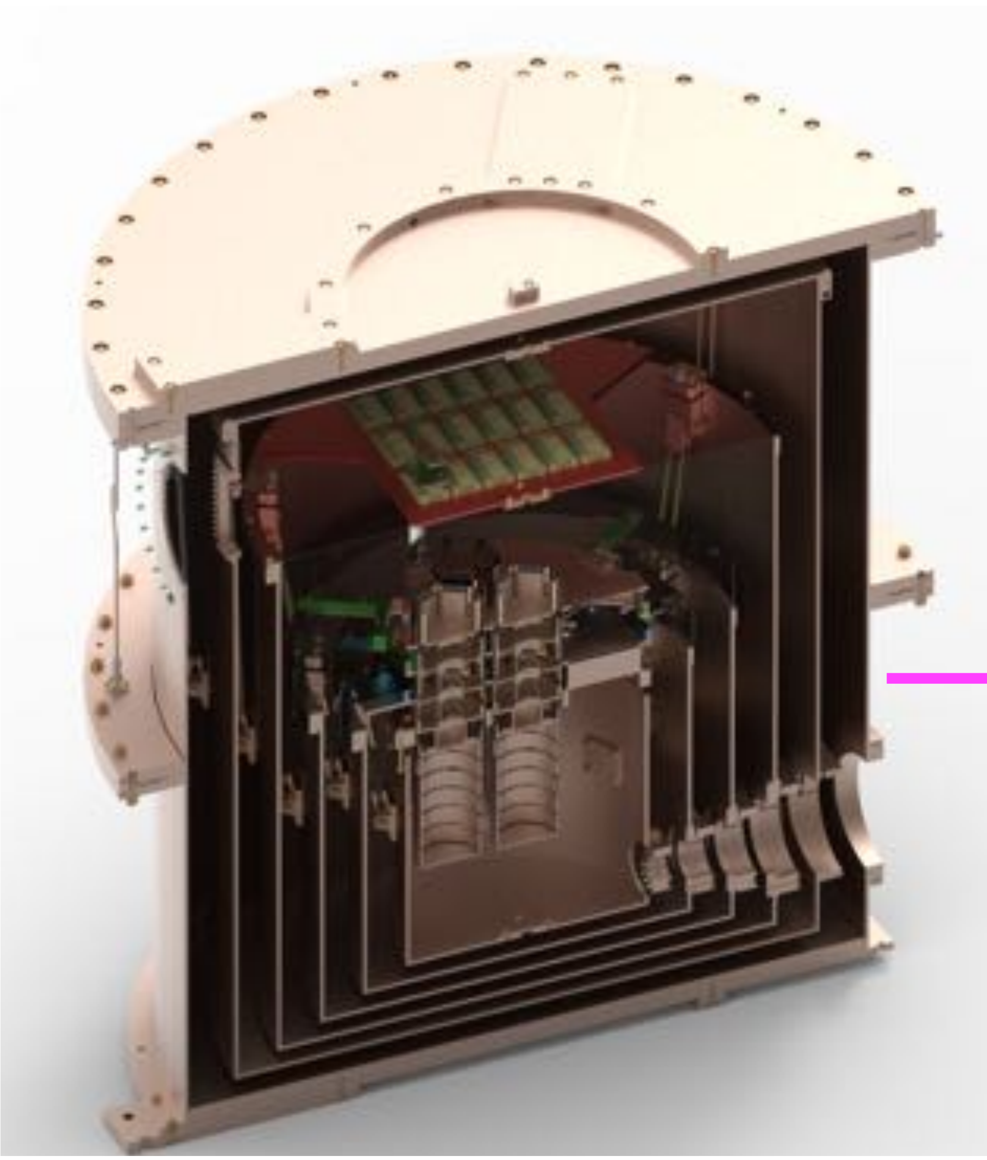
SuperCDMS facility in construction at SNOLAB

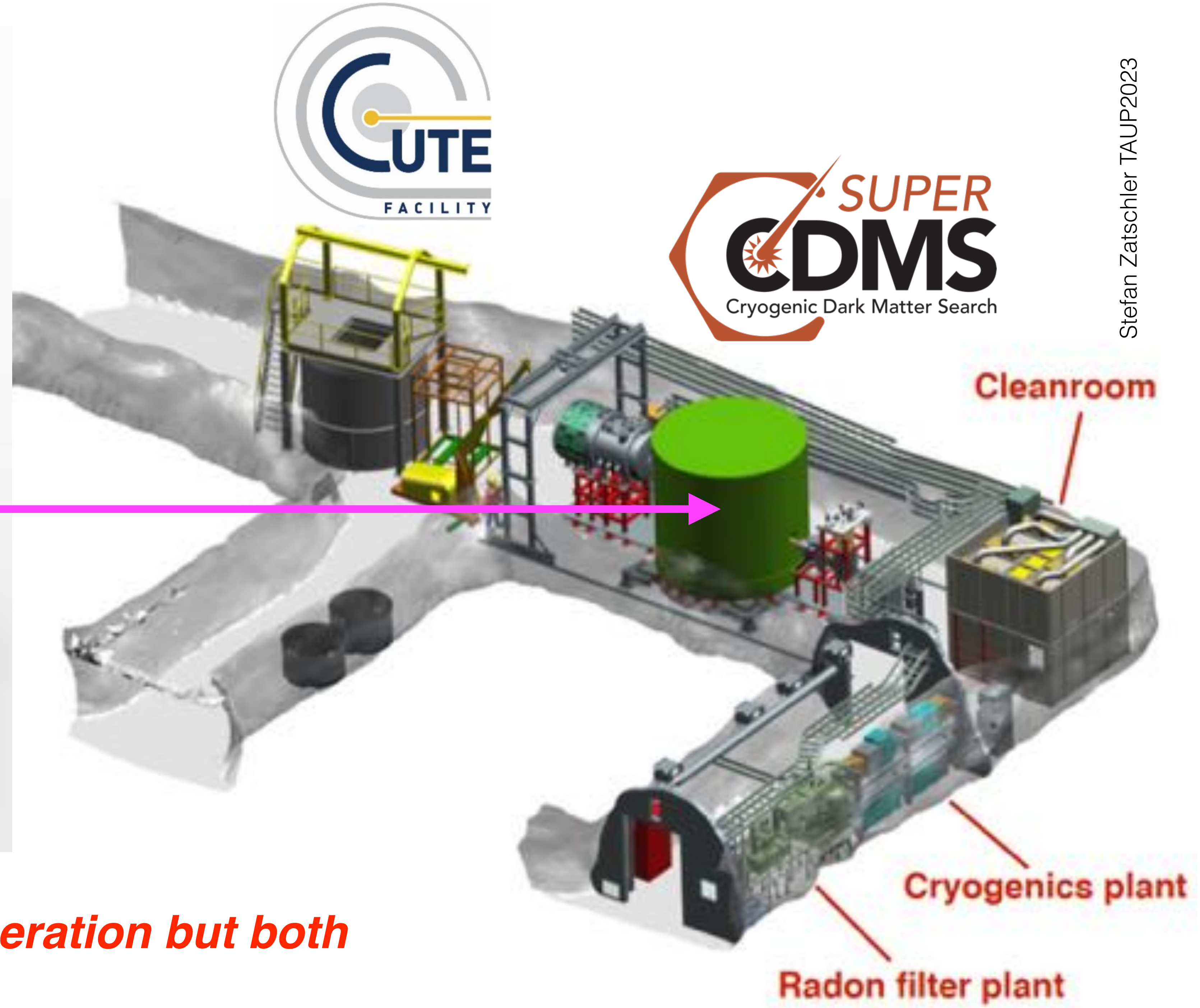


Stefan Zatschler TAUP2023

- ***started in 1990 (R&D heat and ionisation)***
- CDMS I : SUF (Stanford Univ.) : 1996-2002
- CDMS-II Soudan : 2003-2009
- SuperCDMS Soudan : 2010-2015
- ***SuperCDMS SNOLAB (Canada)***
  - construction **started 2018**
  - ***data taking 2024-25*** ?

Dark Matter search : SuperCDMS

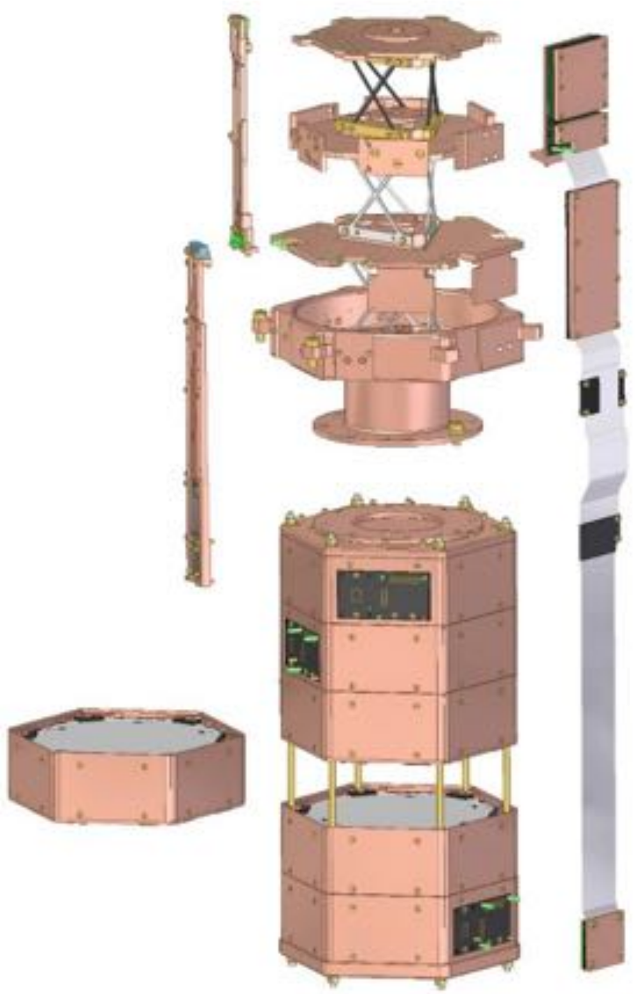


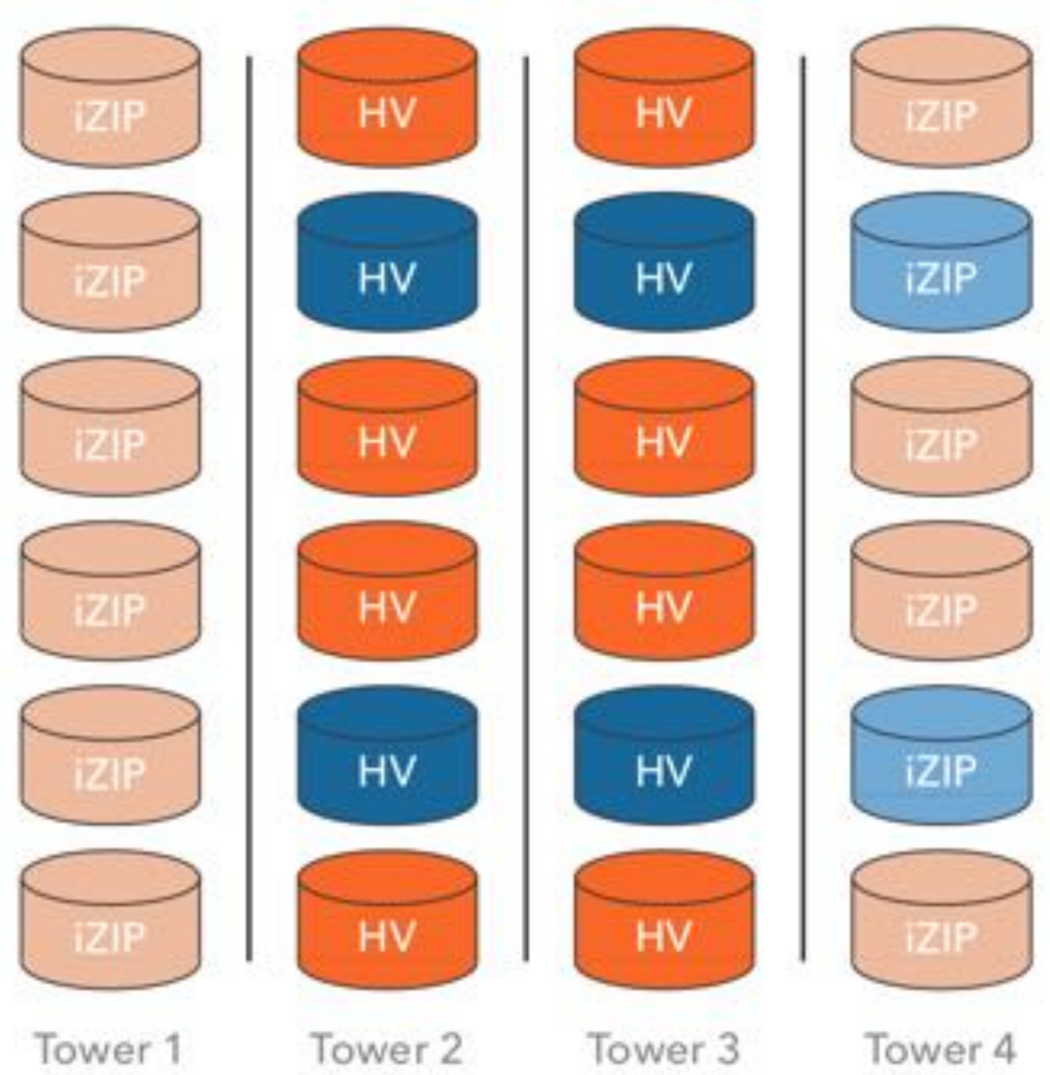


Stefan Zatschler TAUP2023

- As EDW ***2 possible mode of operation but both on Si and Ge crystals***
- ***LV : iZIP*** detector towers 10 Ge+2 Si
- ***HV*** towers 8 Ge + 4Si
- ***Tower can be tested in CUTE facility***

Dark Matter search : SuperCDMS





- As EDW ***2 possible mode of operation but both on Si and Ge crystals***
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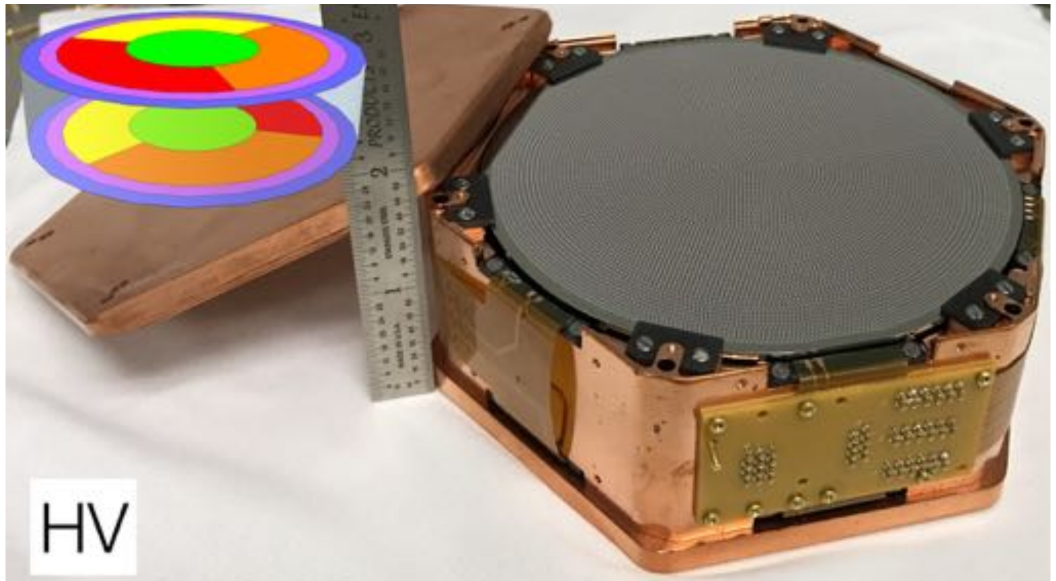
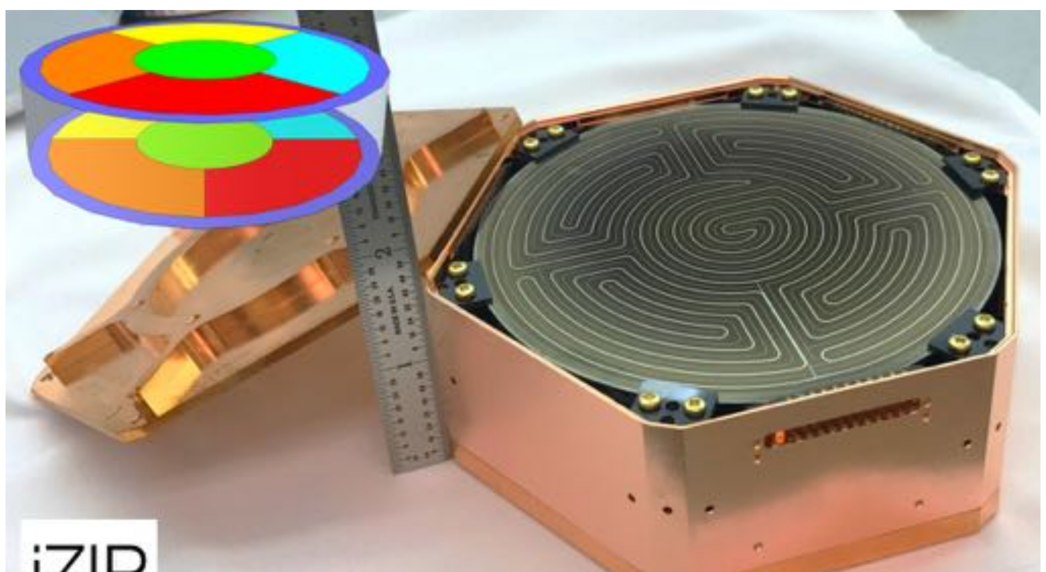
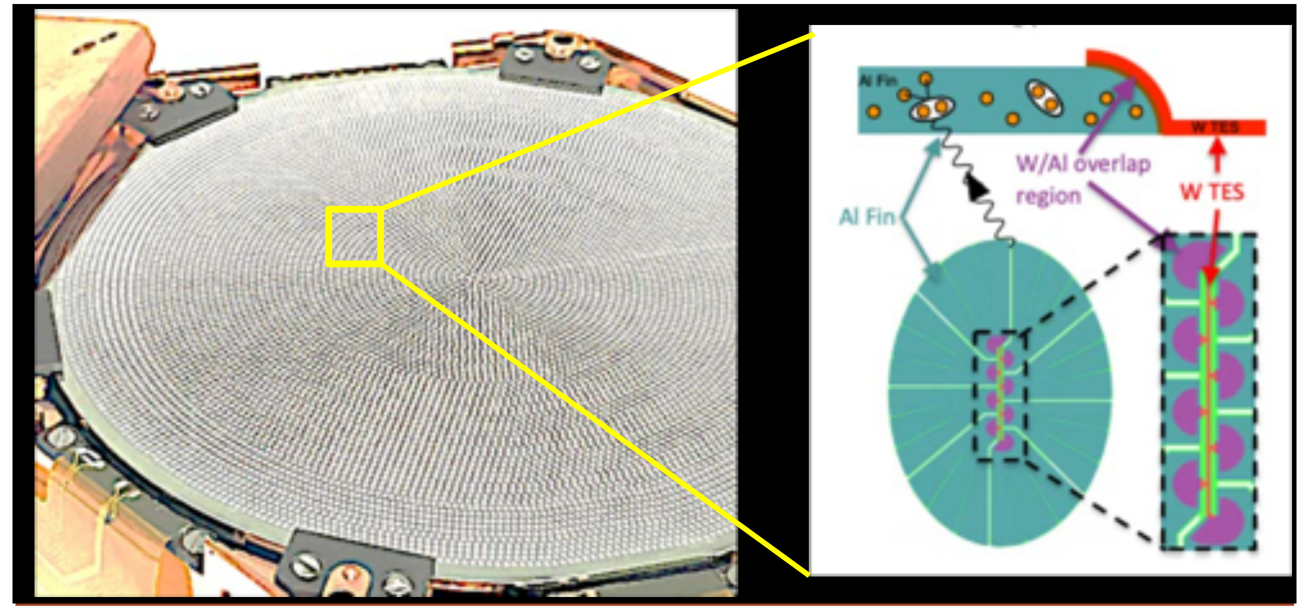
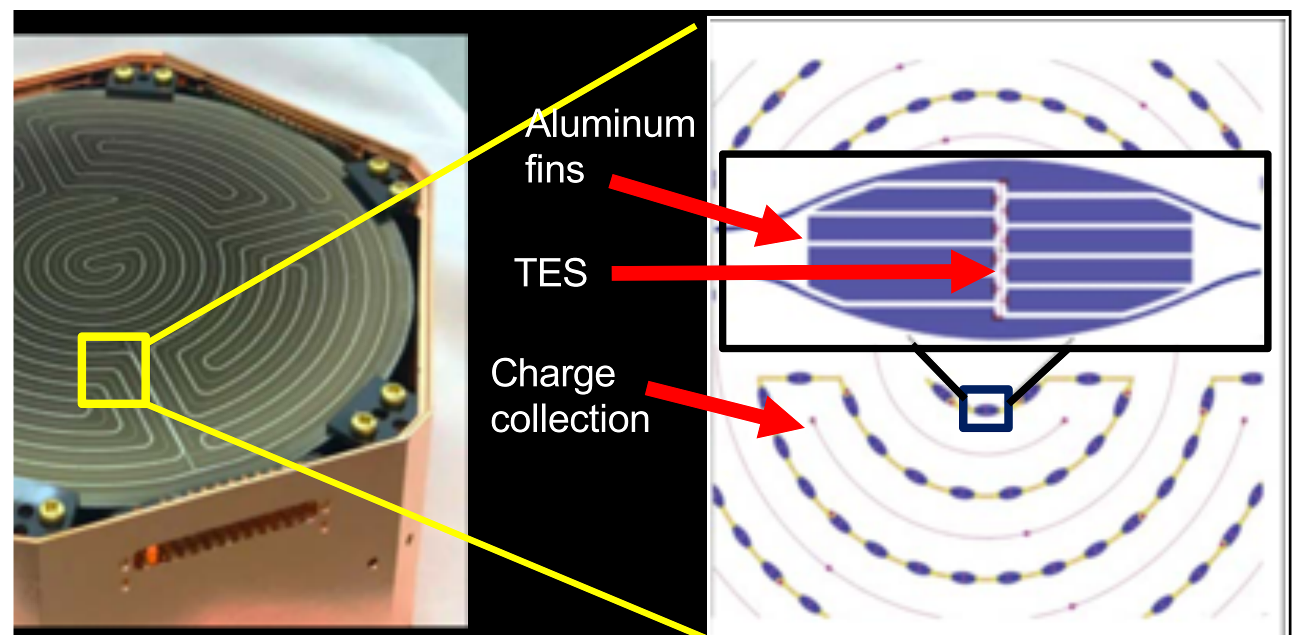
Dark Matter search : SuperCDMS





PRD 95, 082002, 2017





Prisca Cushman NDMNP 2022

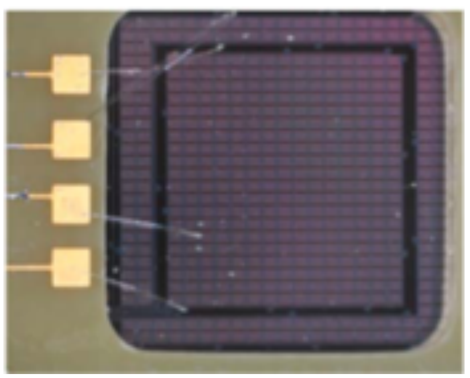
- HV : ***6 phonon channels on each side***
- iZIP : ***6 phonons channel + 2 ionization on each side !***
- **Φ**100mm, h 33.3mm : **1.4kg Ge, 0.6 kg Si**

- **20-30 eV phonon, 180 eV ionisation**
  ➙ ***Ionisation will limit a lot the mass range due to Low Energy Excess (Heat-Only)***

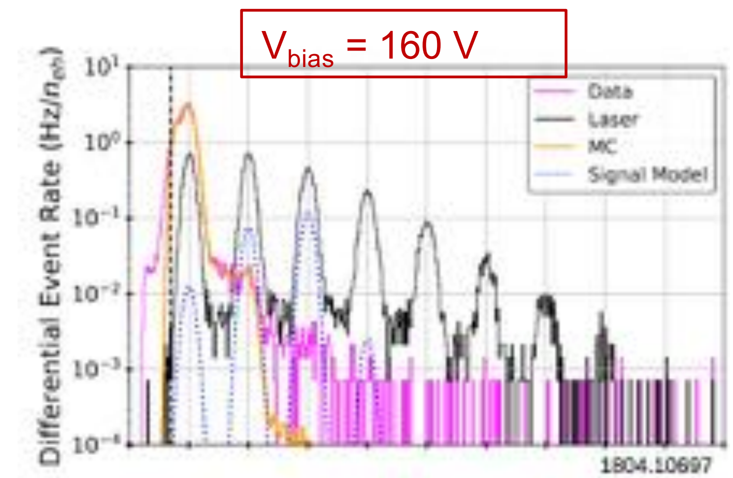
Dark Matter search : SuperCDMS

SuperCDMS is already using small 0 V and single eh-sensitive HV detectors

HVeV (Si or Ge, 1 cm^2 x 4 mm). Like a small HV detector with single e-h resolution.

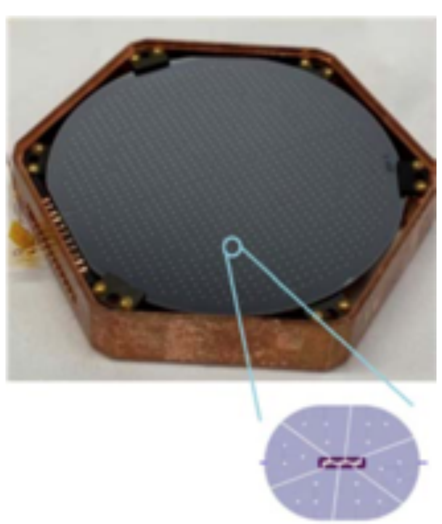


ER events are in the peaks, NR fills in gaps
A mosaic of these on 2 SuperCDMS towers can get to the ν-fog in 0.5 – 5 GeV range

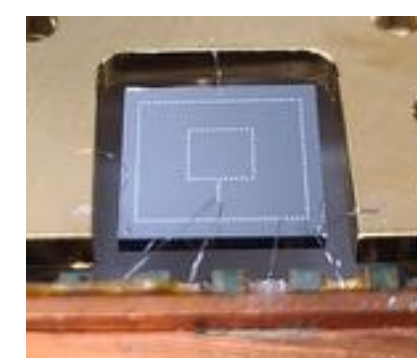


Prisca Cushman NDMNP 2022

0V (aka CPD). A thin, phonon-only device with SuperCDMS TES readout

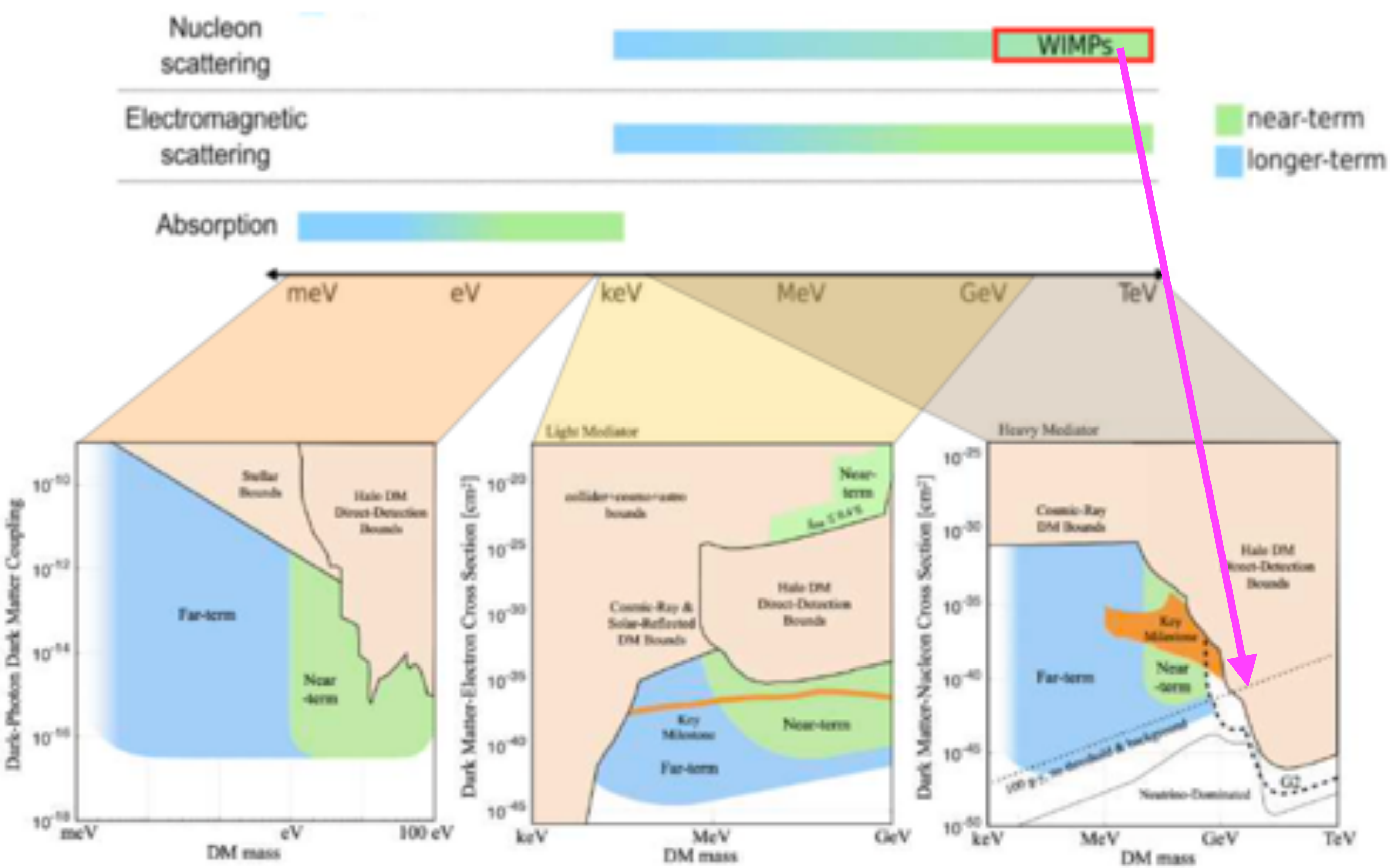


Improving *"environmental"* phonon-only backgrounds
Phonon resolution in the σ_{pt} ~ 1 eV range now.
New prototype with hanging support (M. Pyle-Berkeley) is approaching σ_{pt} ~ 50 - 100 meV



A mosaic of sub-eV σ_{pt} CPDs on 2 towers can get to masses of 50 MeV

Dark Matter search : Conclusion



R. Essig et al., ArXiv: 2203.08297

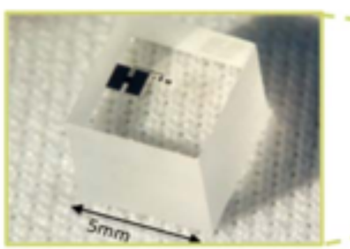
Key of success :

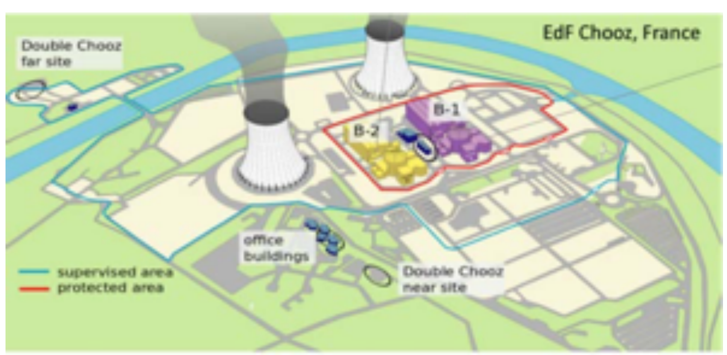
- **Low Threshold** detector
- **Control and identification of the Low Energy Excess** (Heat Only Event)
- Ultra **low background**
- Limit dark count on HV detector (IR induced **leakage**, shallow site impurities etc)

The CEνNS connexion

CRESST➔ NUCLEUS

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

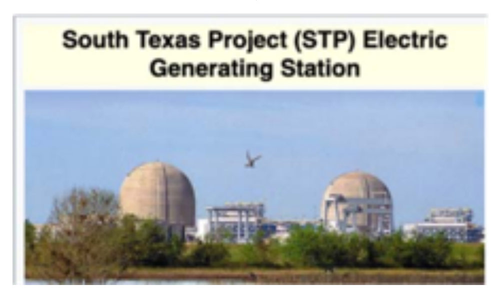




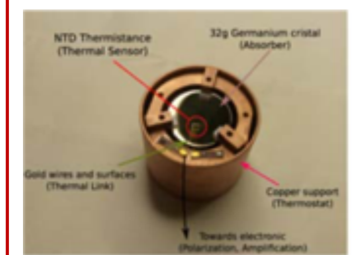
SuperCDMS➔ MIνER

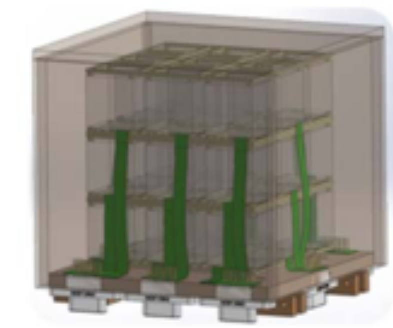
HV, iZIP
Al_2O_3 + QET

TRIGA research nuclear reactor
at TAMU with moveable core

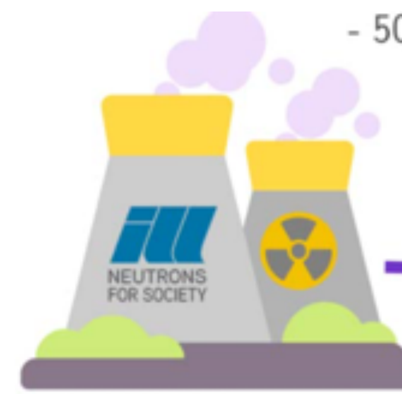


EDELWEISS➔ Ricochet





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



Institut Laue-Langevin
(Grenoble, France)

Prisca Cushman NDMNP 2022

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

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

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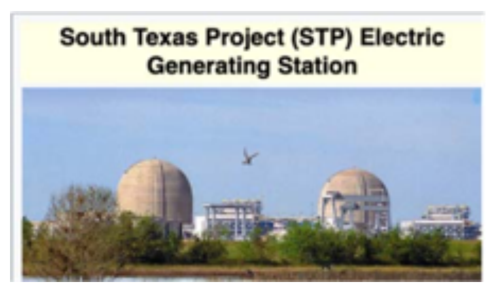
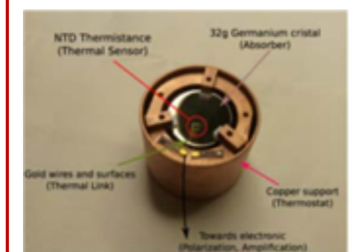
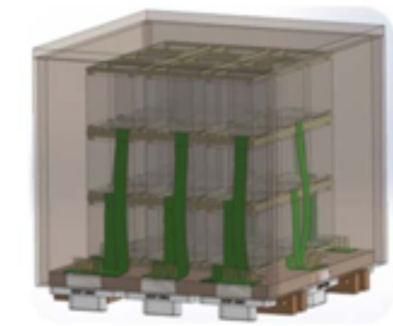


EDELWEISS➔ Ricochet





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- 8x8x8 cm^3
- 50% Ge semiconductors
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Prisca Cushman NDMNP 2022

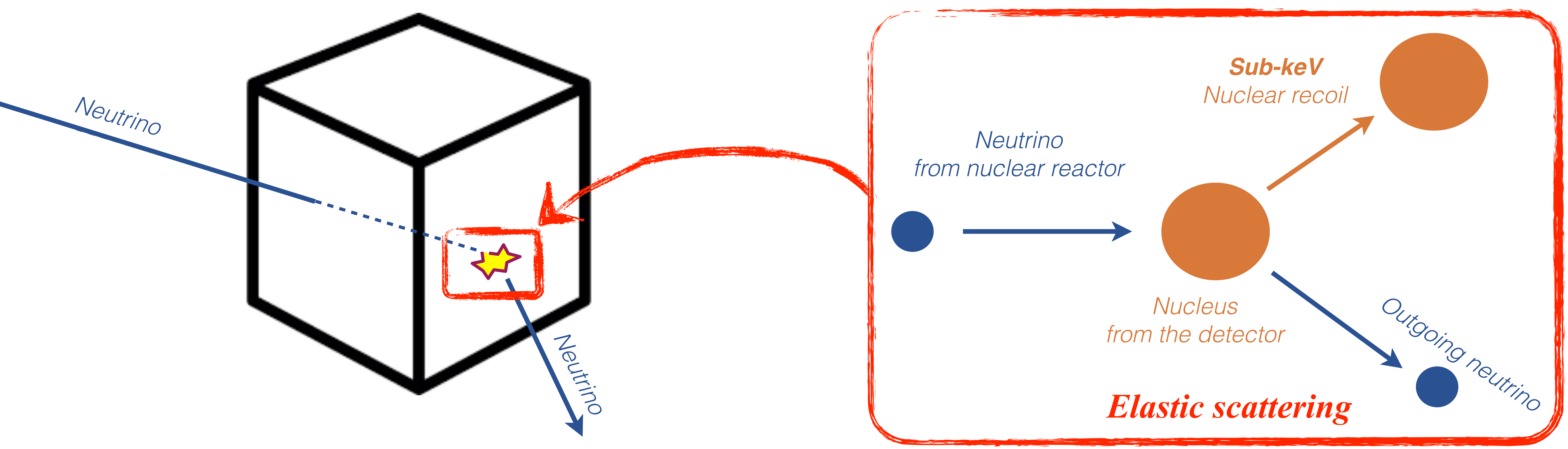
Philosophical change w.r.t DM search !

Main cryogenic det. **DM search e**... ...**ject**:

- ***Coherent elastic n***...
- If you are ***sensiti***... ...***sensitive to CEνNS***
- You know precisel... ...measure and **you want to measure it precisely**
- Depending on the s... ...**an design your experiment** accordingly

The CEνNS process

Coherent **E**lastic **N**eutrino-**N**ucleus **S**cattering (CEνNS)



at the detector level same as a neutron or WIMP interaction

For a recent and detailed review:
M. Abdhulla et al., « Coherent elastic neutrino-nucleus scattering: Terrestrial and astrophysical applications », arXiv:2203.07361

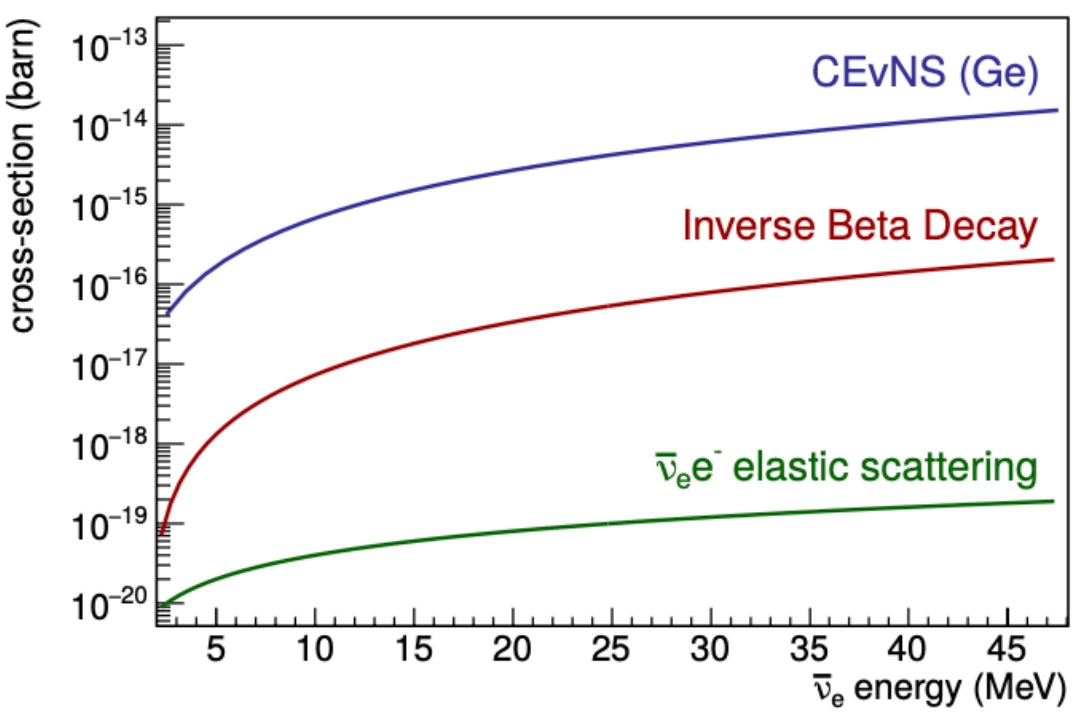
The CEνNS process

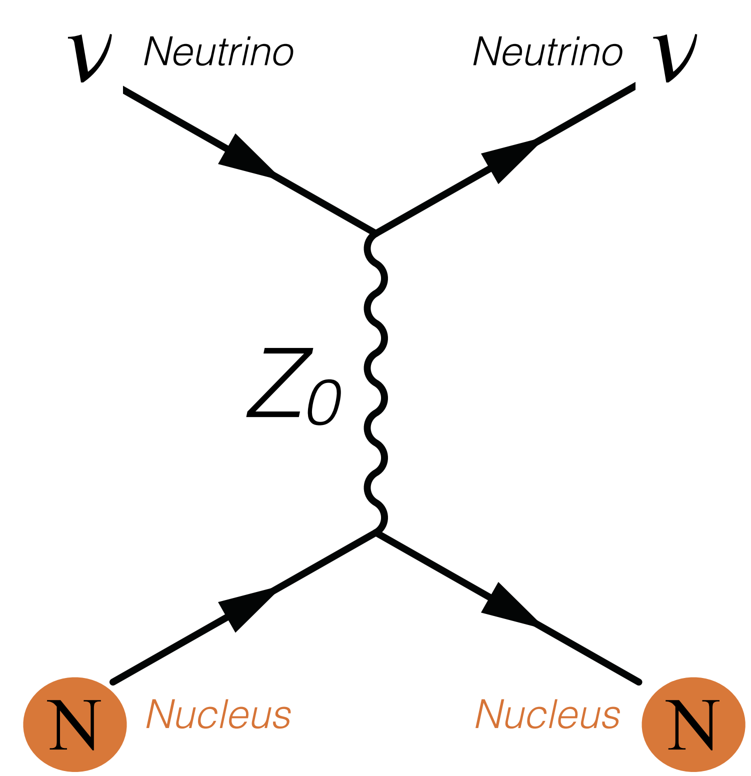
D. Z. Freedman, PRD 9 (5) 1974

Coherent Elastic Neutrino-Nucleus Scattering (CEνNS)

$$\frac{d\sigma(E_\nu, E_r)}{dE_r} = \frac{G_f^2}{4\pi} Q_w^2 m_N \left(1 - \frac{m_N E_r}{2E_\nu^2}\right) F^2(E_r)$$

$$Q_w = N - Z(1 - 4\sin^2\theta_w)$$





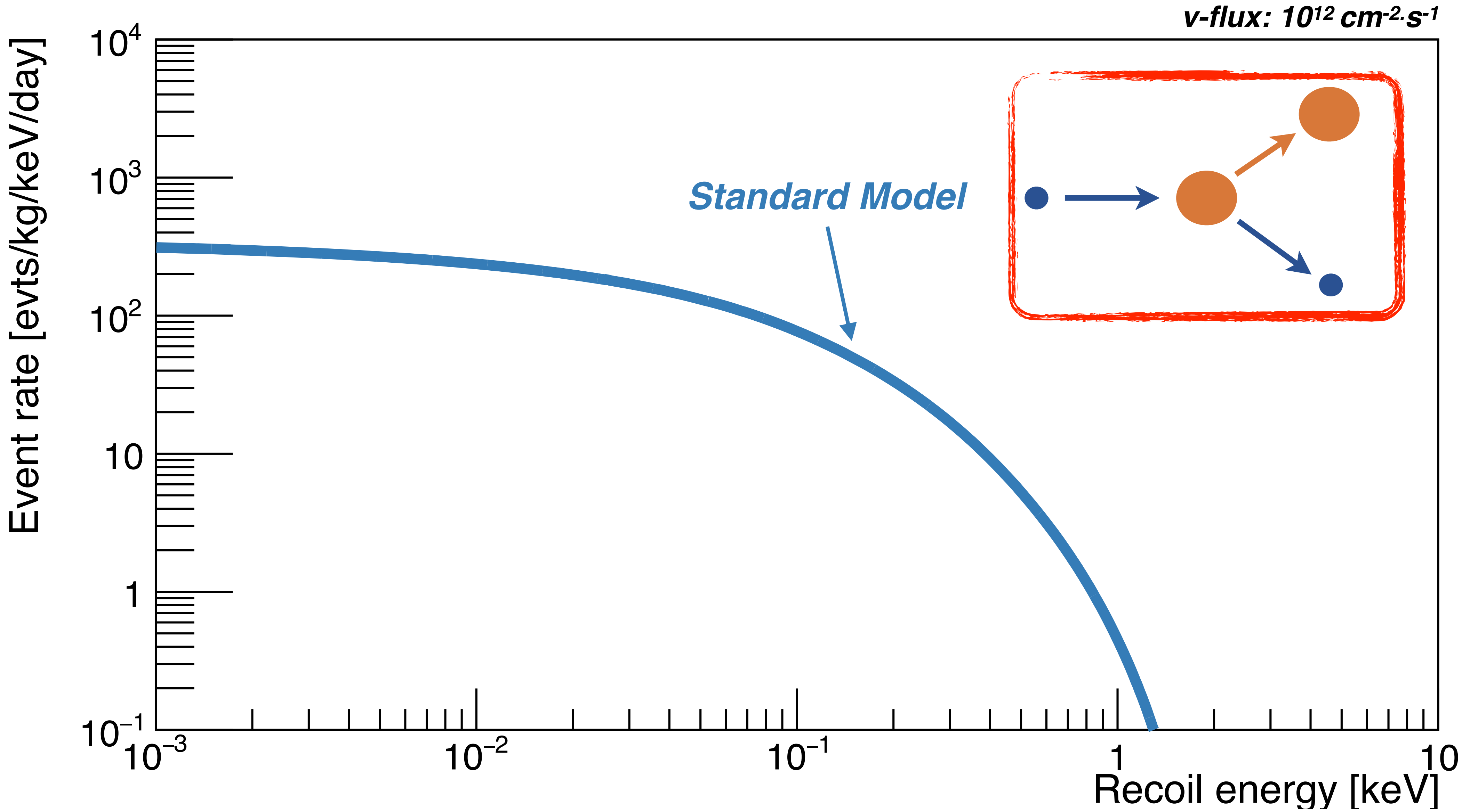
- CENNS cross-section : **1000 times larger** than IBD cross-section
- No energy threshold - Elastic Scattering
- ***From ton-scale to kg-scale neutrino detector payloads***

A gateway to new physics:

- Non-Standard Interaction
- Existence of new massive bosons
- Neutrino Magnetic Moment
- …

The CEνNS signal

Recoil energy distribution

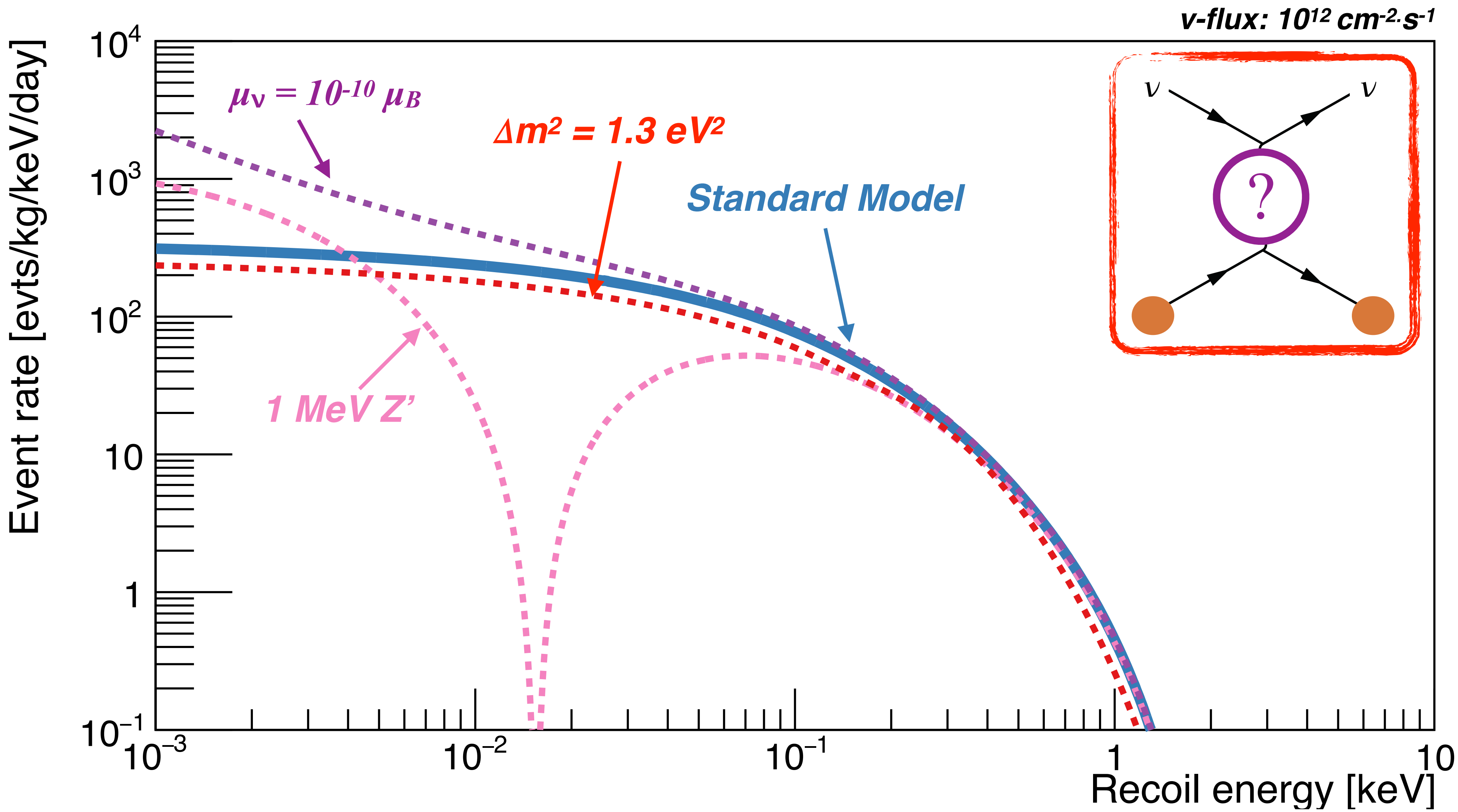


J. Billard, J. Johnston and B. Kavanagh, JCAP (2018)

- For v-flux: 10^{12} cm^{-2}·s^{-1} , we expect a ***few tens of events per day and per kg of detector material*** (➙ rare event search !)
- Calls for **small total detector mass** to reach high-precision:
  kg-scale with sub-100 eV threshold

CEνNS : gateway to new physics

Recoil energy distribution

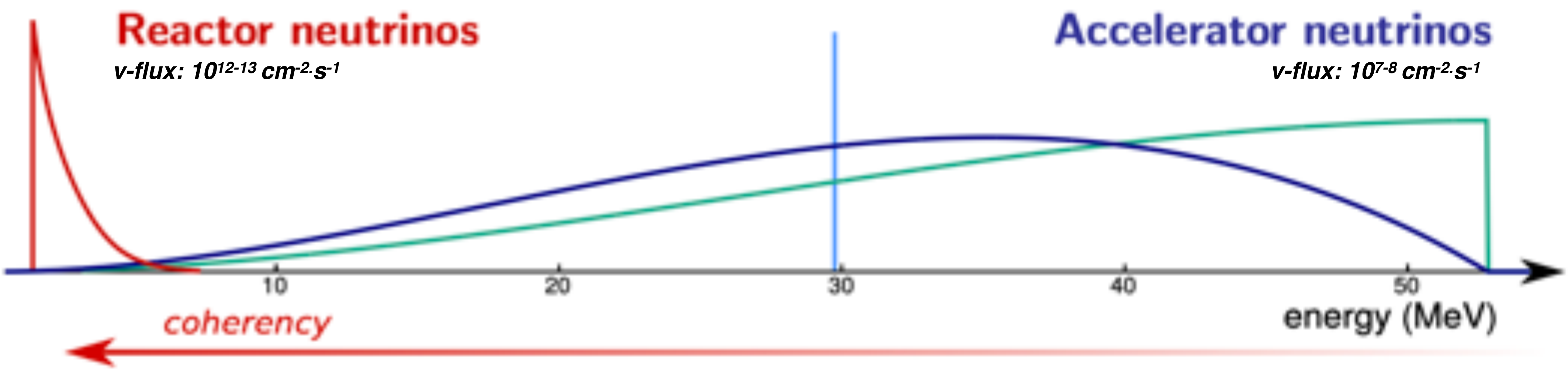


J. Billard, J. Johnston and B. Kavanagh, JCAP (2018)

New physics signatures will arise at the lowest energies :

➙ *Calls for very low-energy thresholds: O(10) eV*

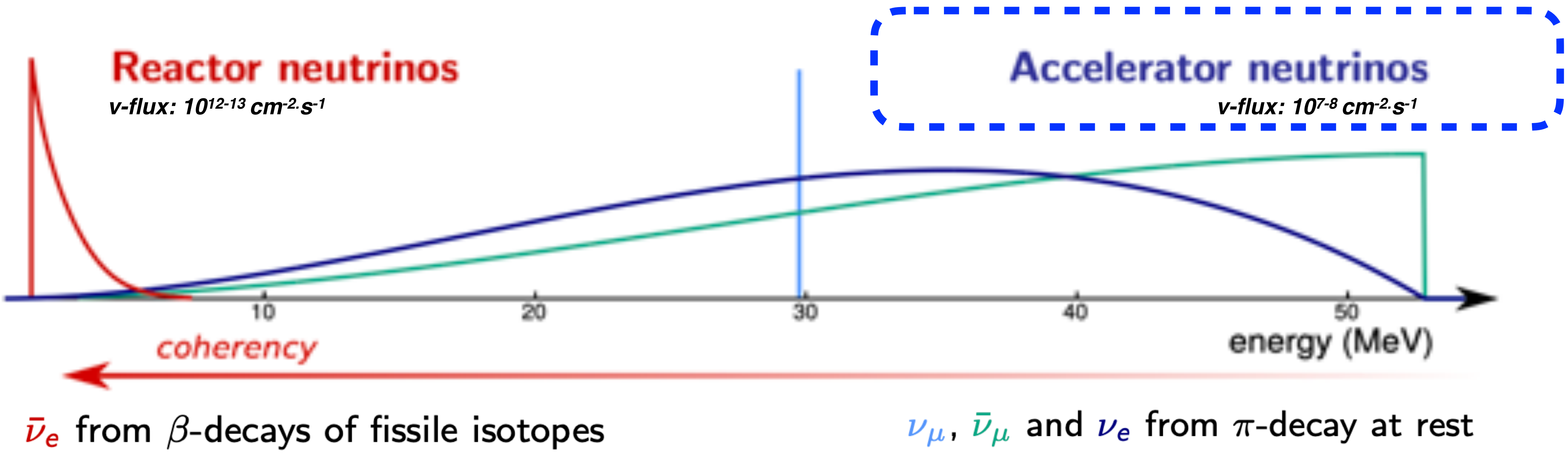
State of the art of CEνNS measurment



$\bar{\nu}_e$ from β-decays of fissile isotopes

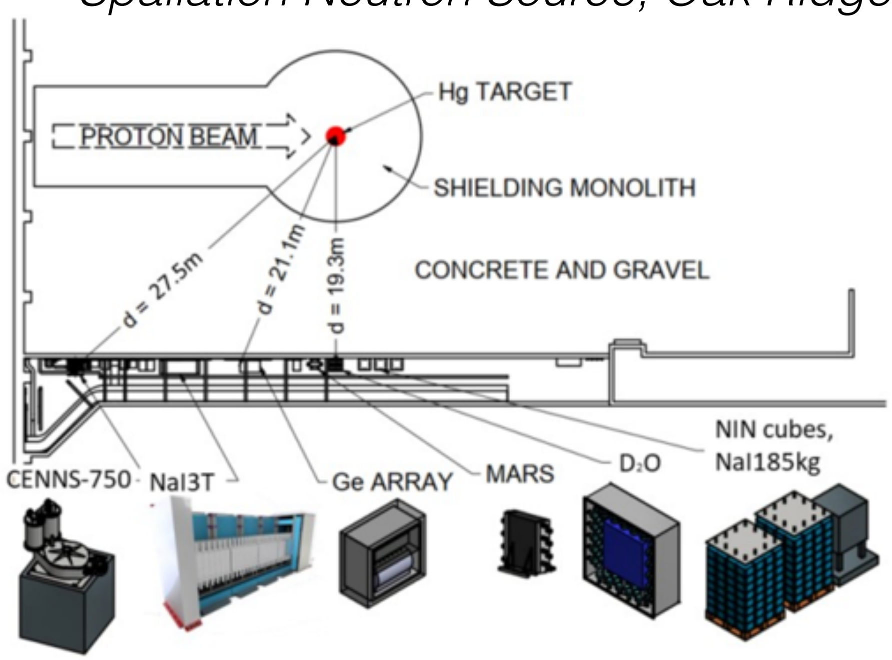
ν_μ, $\bar{\nu}_\mu$ and ν_e from π-decay at rest

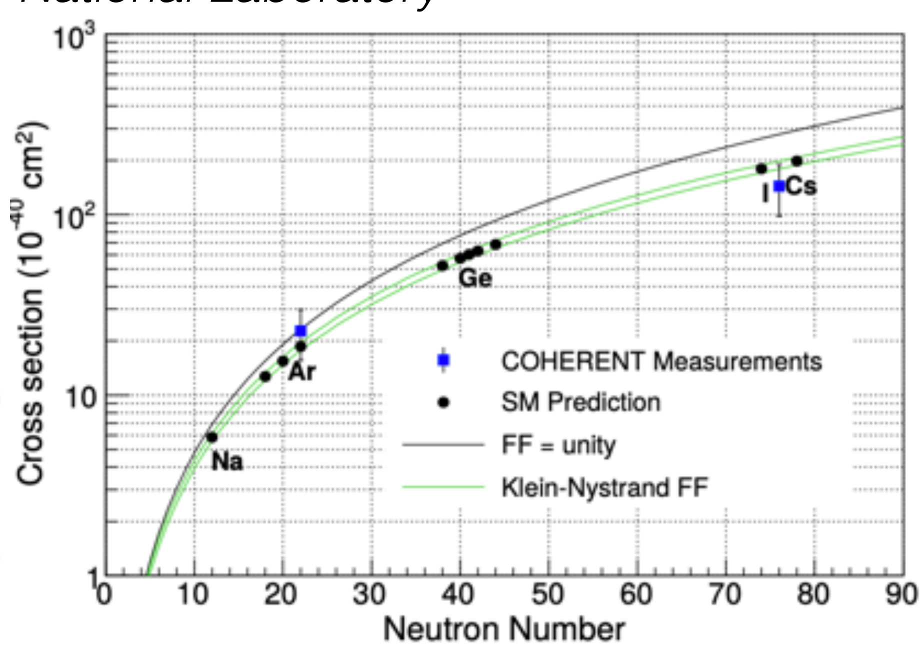
State of the art of CEνNS measurement



The COHERENT experiment at SNS : ***The first (two) detections !***

Spallation Neutron Source, Oak Ridge National Laboratory





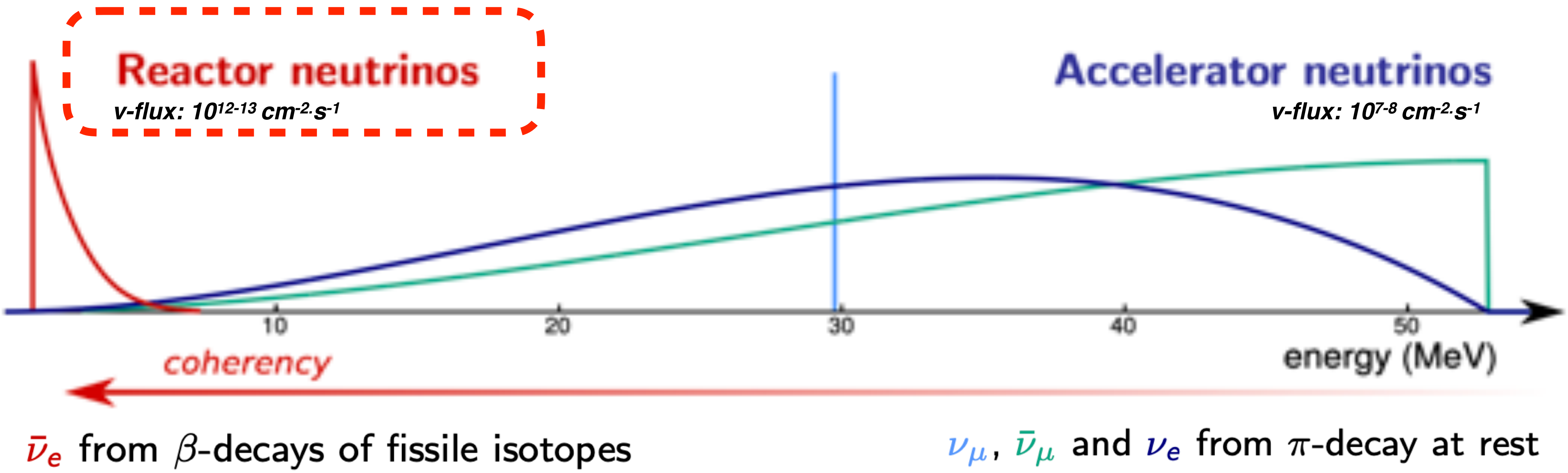
COHERENT at the spallation Neutron Source first observation ! **CsI (2017) [1], Ar (2020) [2]**

- Combine different targets and technology
  - Measure the N^2 dependence
- Sensitive to nuclear physics (form factor)
- Some BSM physics sensitivity: NSI, light mediators, …

Ongoing proposals for CENNS @ ESS [3]

[1] D.Akimov et al., Science (2017), arXiv:1708.01294
[2] D.Akimov et al., PRL (2021), arXiv:2003.10630
[3] D. Baxter et al., JHEP (2020), arXiv:1911.00762

State of the art of CEνNS measurement



Reactor neutrino experiments

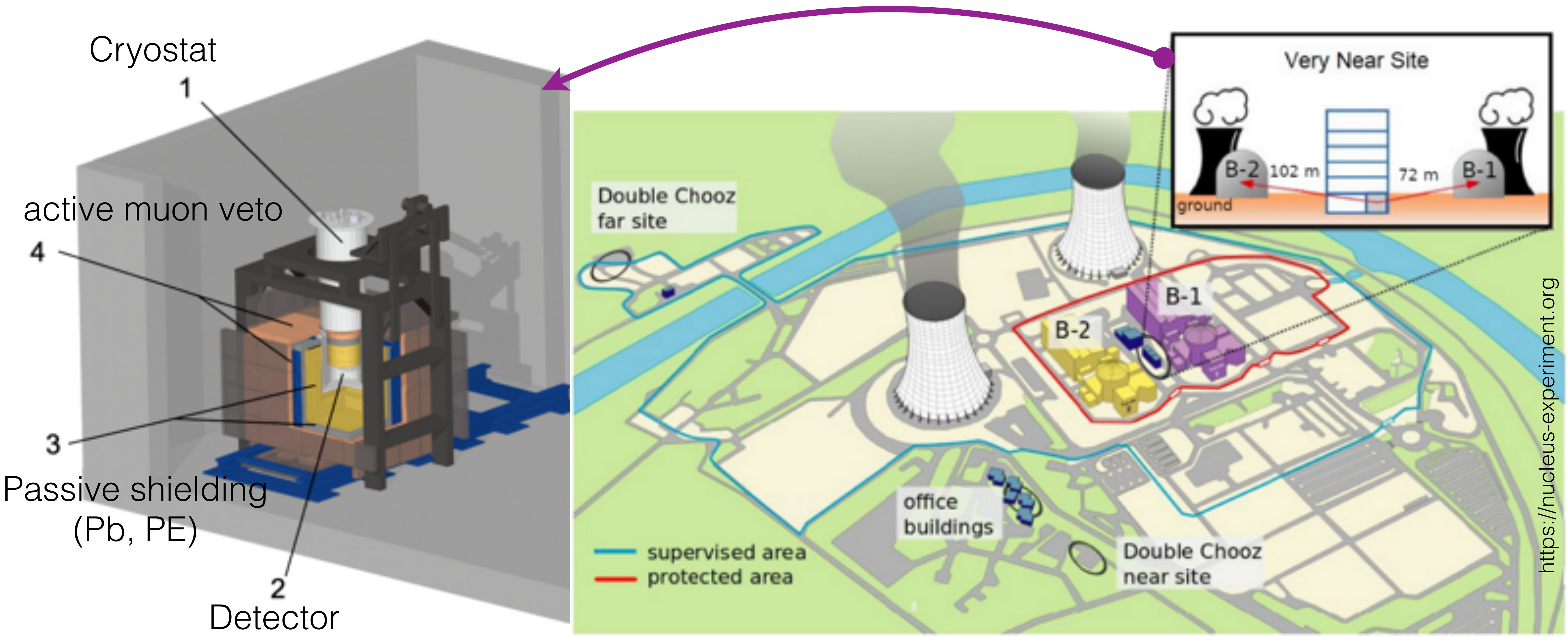
Running: CONUS, TEXONO, CONNIE, Nu-GEN, …

Future: Ricochet, NuCLEUS, MINER, …

- Higher neutrino flux for high-precision measurement
- Fully coherent regime
- Optimized sensitivity to neutrino magnetic properties and BSM physics: new light mediator, NSI, NMM, …
- Reactor spectrum investigations (and monitoring)

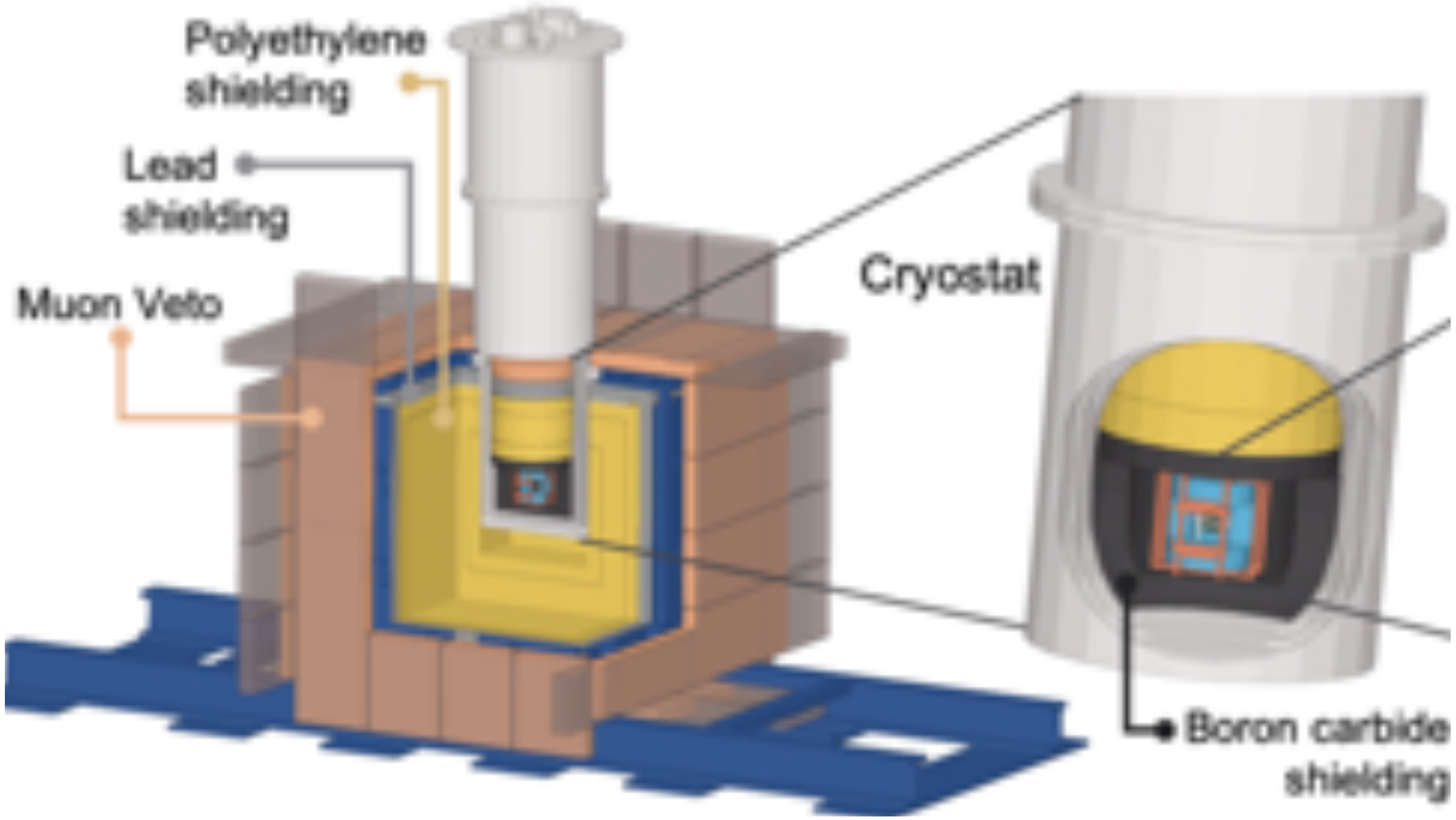
No CENNS detection at reactor up to now

CEνNS : Nucleus @ Chooz



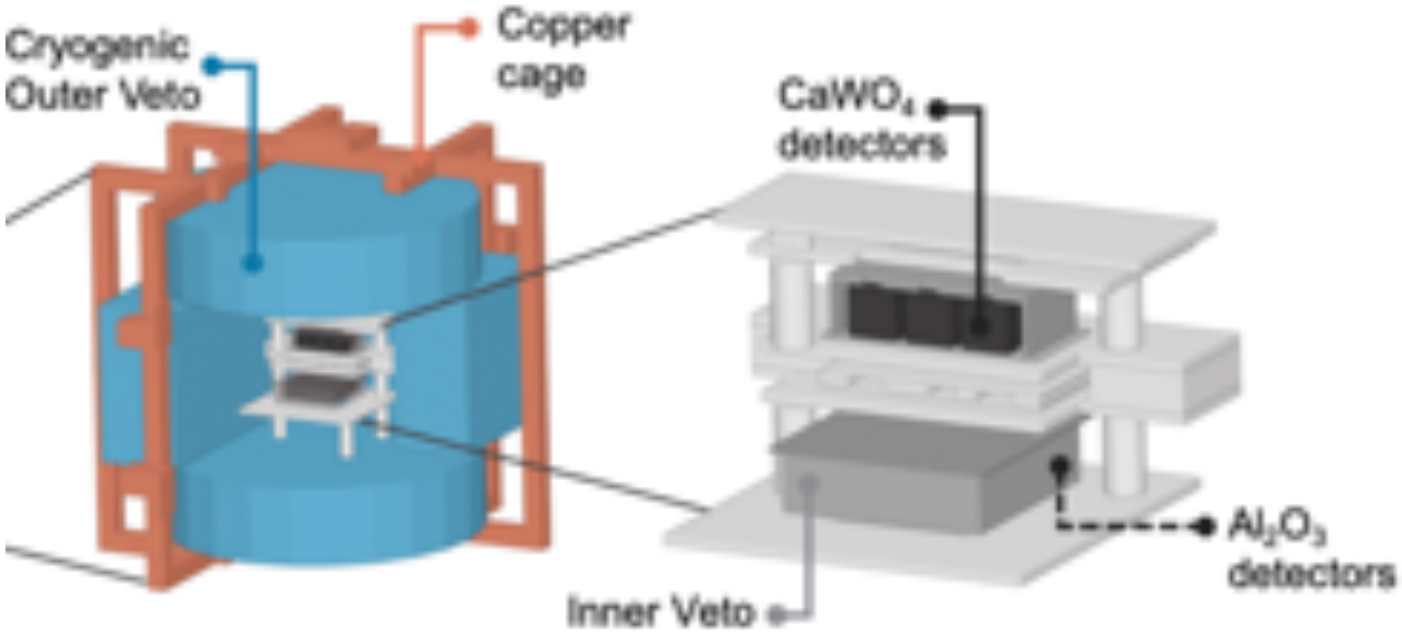
- @ Chooz nuclear power plant
- 2 * 4.25 GWth
- **NUCLEUS will be installed** at the VNS (very near site) ***@ 72 & 102 m from the reactors***
- precise planning not defined
- ***$1.7*10^{12}$ cm^{-2}·s^{-1} ν-flux expected @ the VNS***
  (* 2 wrt Ricochet@ILL)

CEνNS : Nucleus @ Chooz

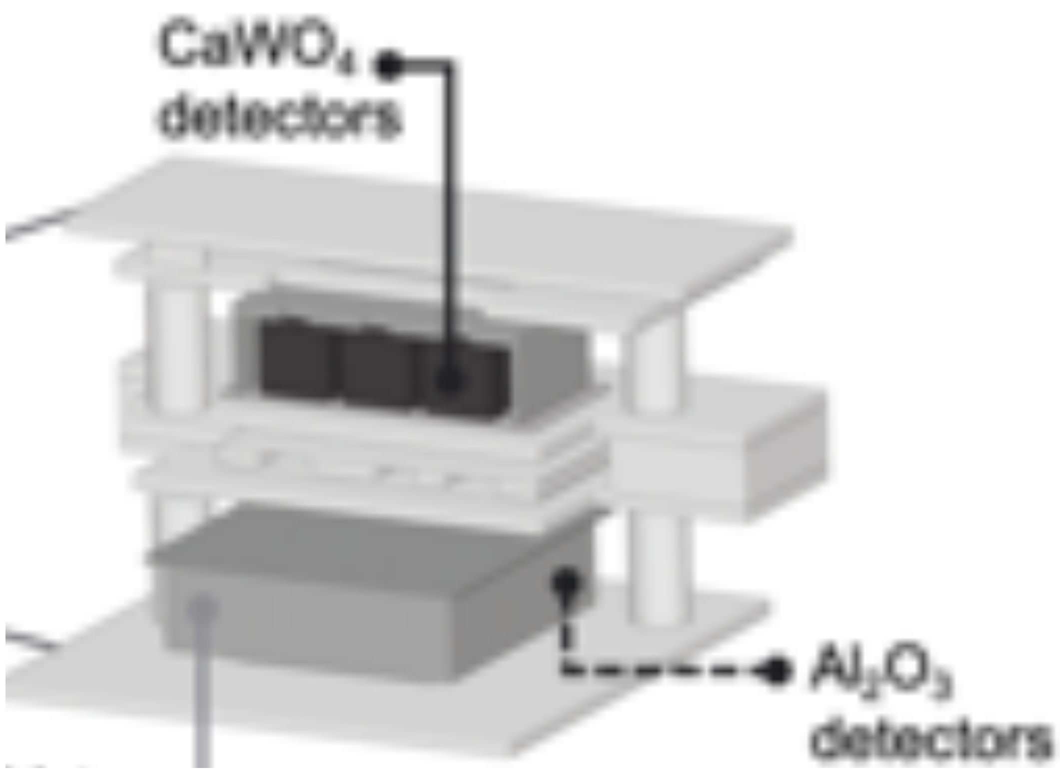


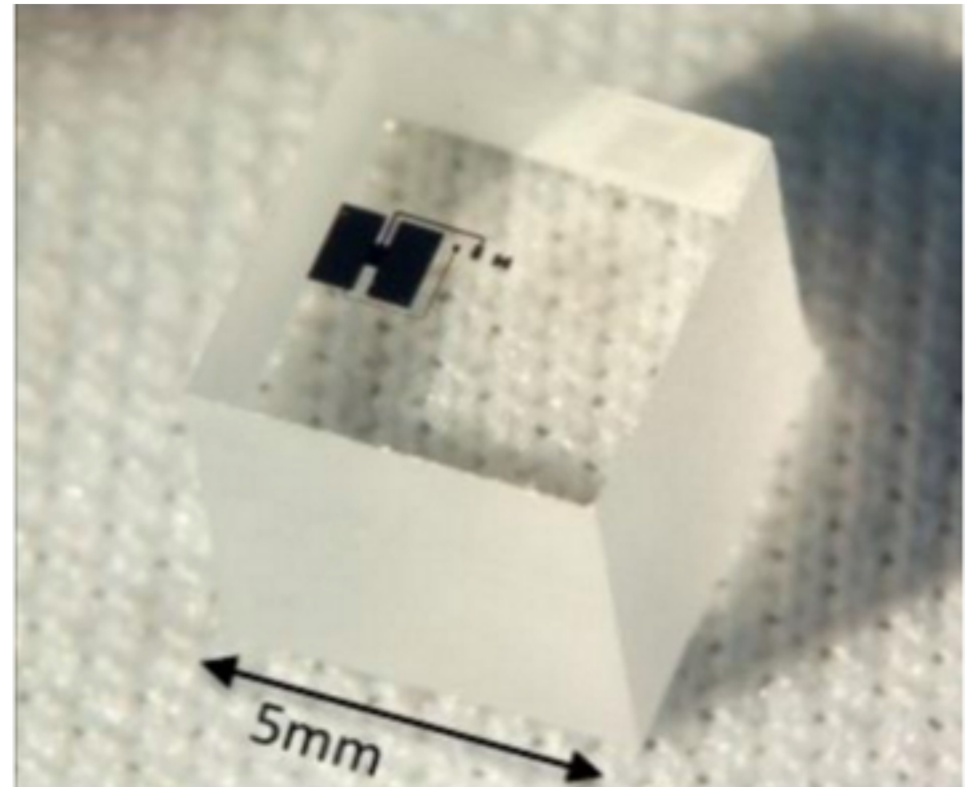
https://nucleus-experiment.org

- ***Shielding*** to protect against fast neutron & gammas
  - PE & Pb (mass ?)
- ***Active muon veto for cosmic***-induced neutrons
- **6 cryogenic Ge** ionization detector as an ***Outer Veto***
- detectors array are encapsulated in Si holders configured in cryo detectors (fitted with TESs) : ***Inner Veto***

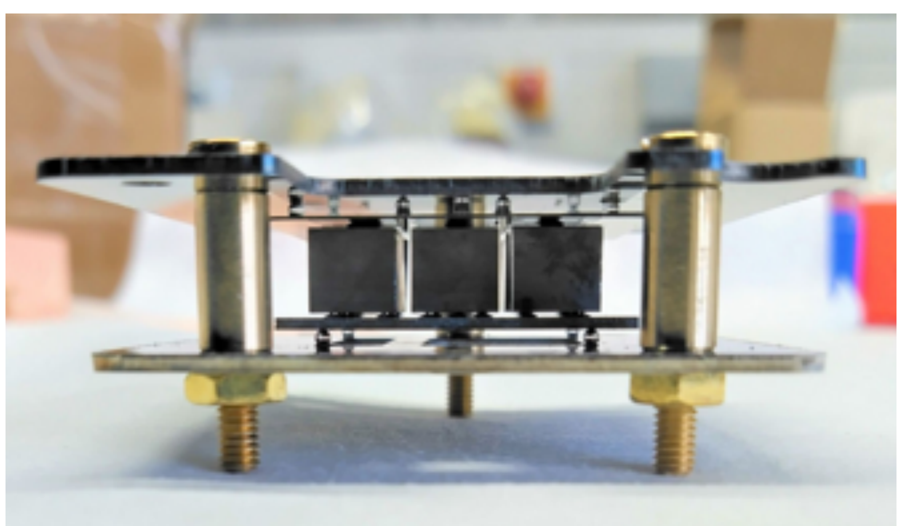


CEνNS : Nucleus @ Chooz





0.45g Al_2O_3 prototype



Silicon inner veto mock-up

- Detector design **focus on low threshold (~10eV)** with very small individual detector
  - 3×3 array of $CaWO_4$ (6 g total)
  - 3×3 array of Al_2O_3 (4 g total)
  - **10 g in total only !**
- 2 target will help to distinguish neutron vs CEνNS…but ***less than 0.1 evt/day expected in the whole detector array***
- ***Upgrade to 1kg planned in the future***
- ***RISK : No Low Energy Excess (heat only) Identification***

https://nucleus-experiment.org

CEνNS : RICOCHET @ ILL

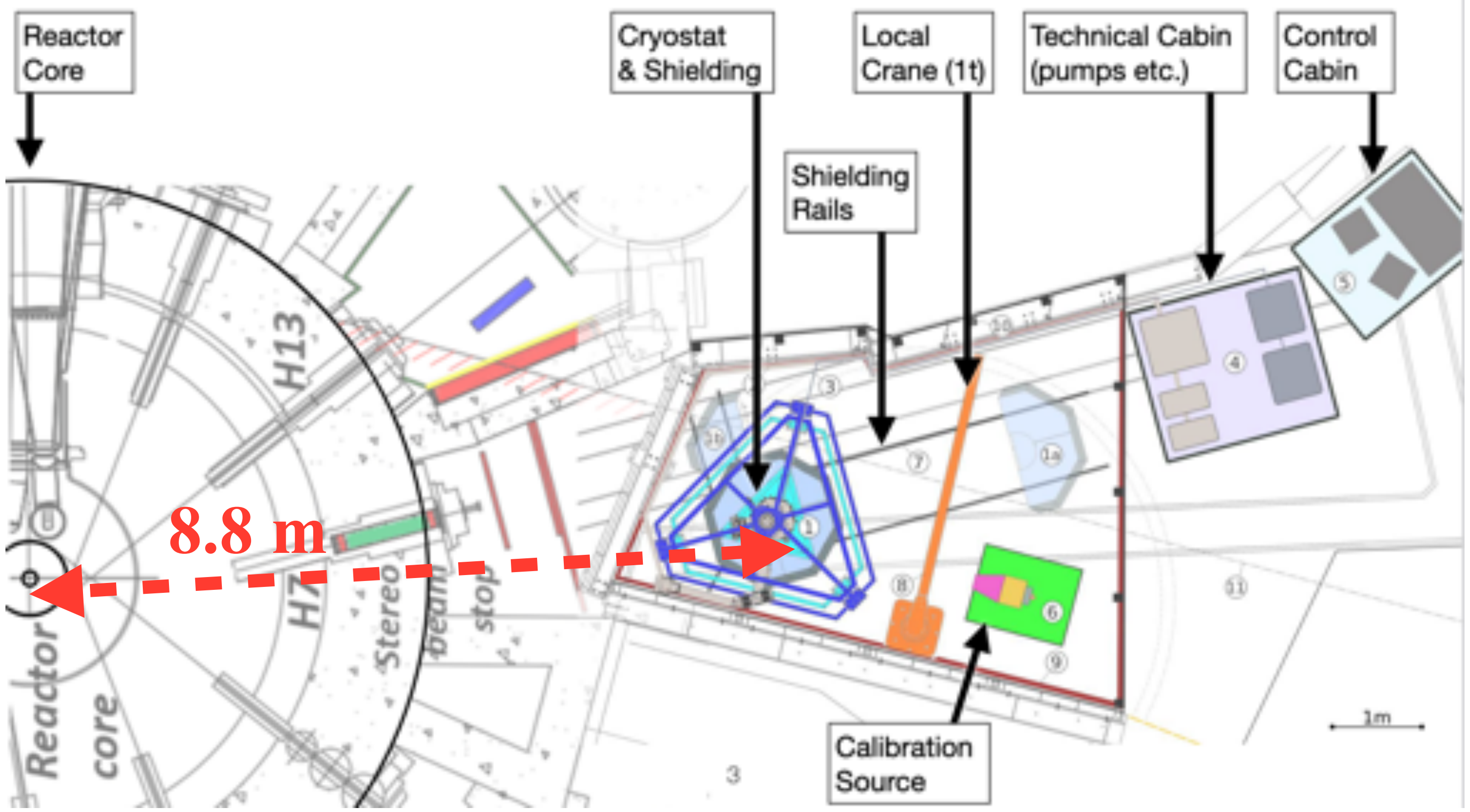
https://fr.wikipedia.org/wiki/Institut_Laue-Langevin

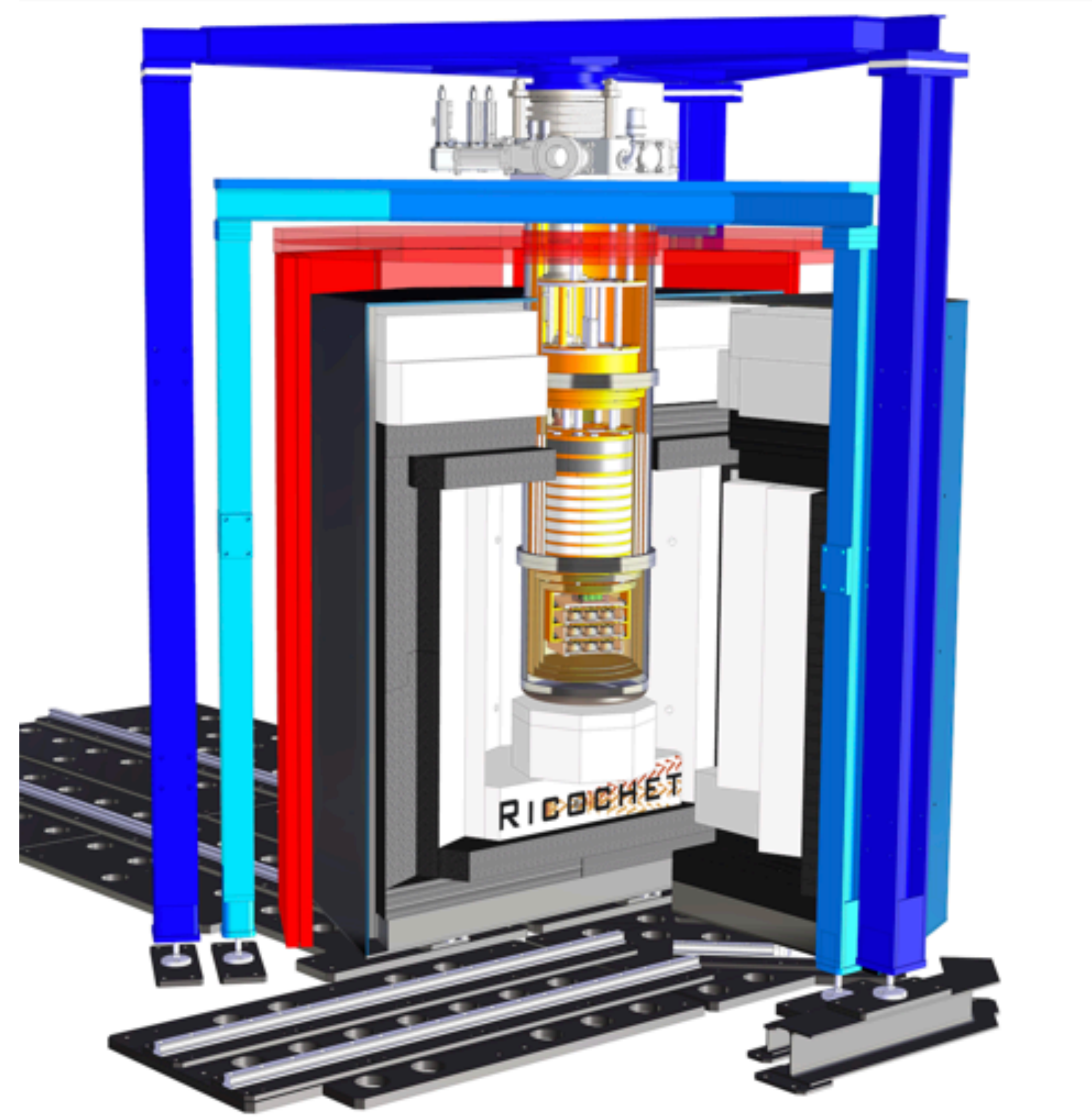
60 MW reactor @ ILL / Grenoble

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

- ✦ US-France-Russia collab.
  - ➡ 2 detectors technology
- ✦ Specifications goals for french 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***
- ***RISK : huge pressure on the ionization. decreased sensitivity if 20 eV not reach*** (35eV already reached @ IP2I)

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 !***

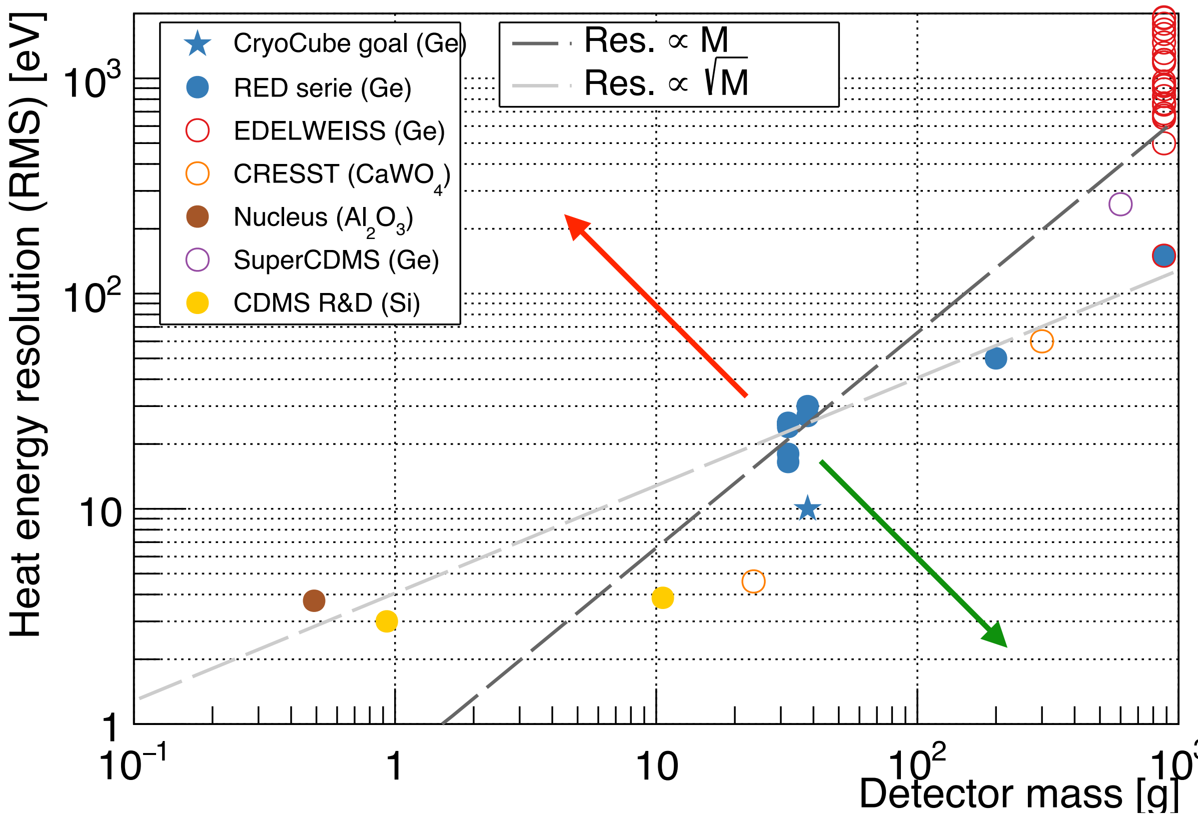
Outer shielding:
- PE: 35 cm
- Pb: 20 cm
- Muon veto
- Soft iron

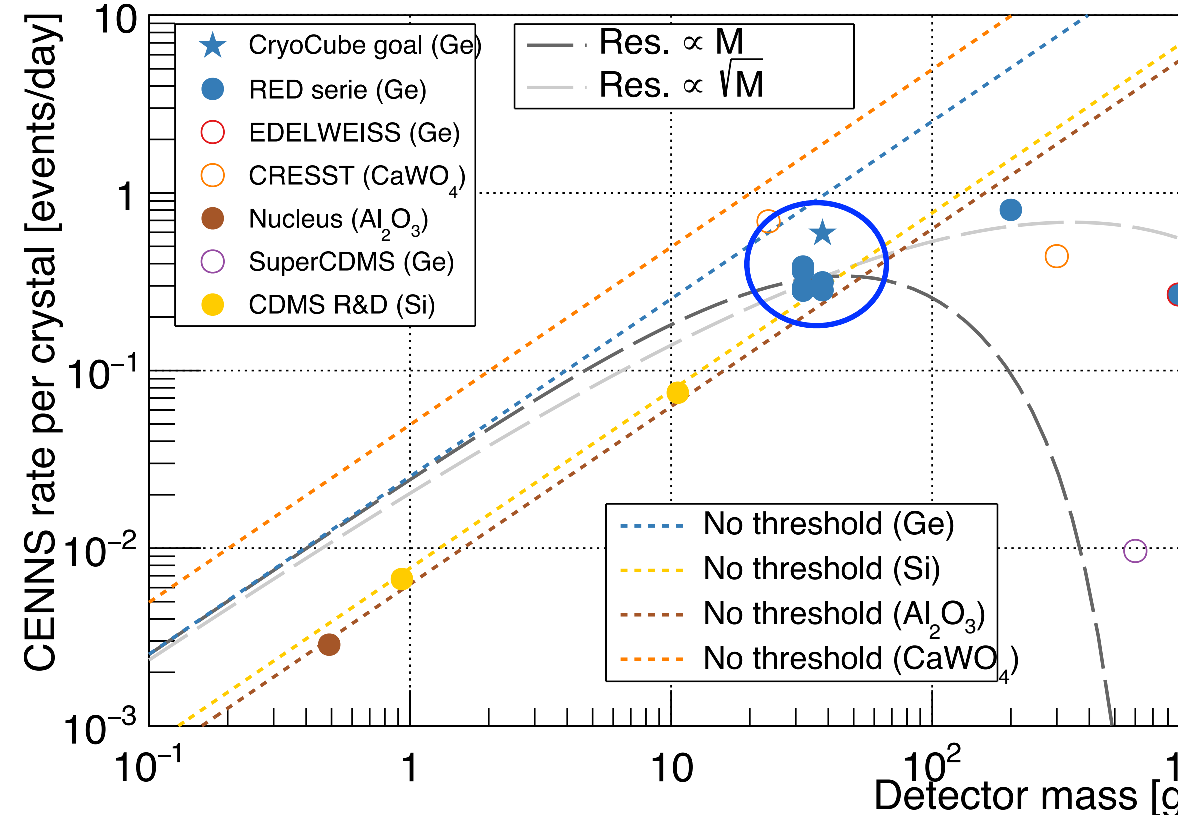
Inner shielding:
- PE/Cu: 30 cm
- Pb/Cu: 15 cm
- Cryogenic Muon Veto
- Mu-Metal

CEνNS : RICOCHET - 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***

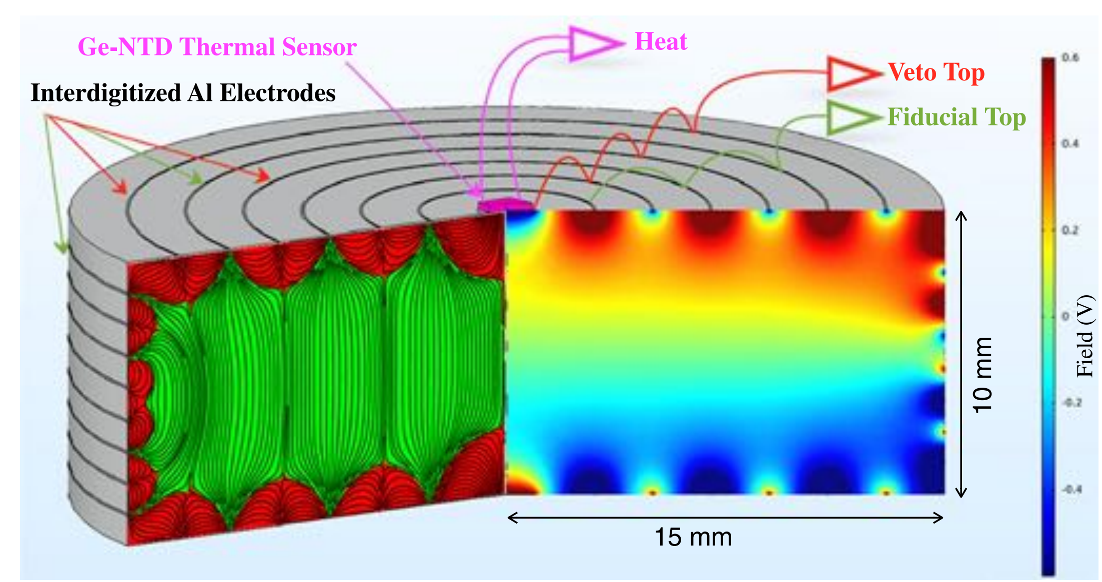


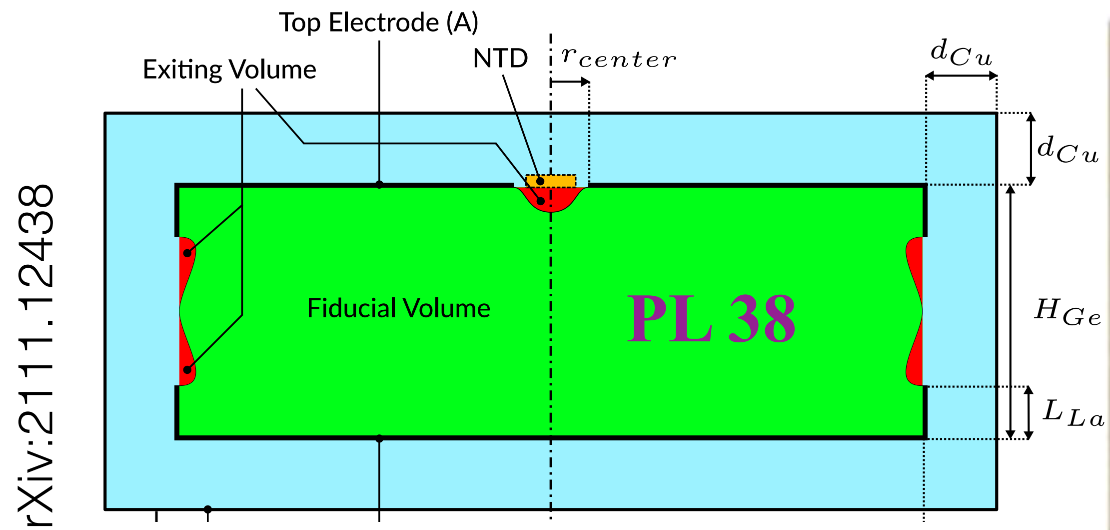
Fig. 6 Electrostatic simulation of a Full Inter-Digitized electrodes scheme on a 38 g germanium crystal ($\Phi = 30$ g, h = 10 mm). The crystal is surrounded at 2 mm distance by a chassis connected to the ground (not shown). The capacitance of the 4 electrodes with respect to the ground is about 20 pF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

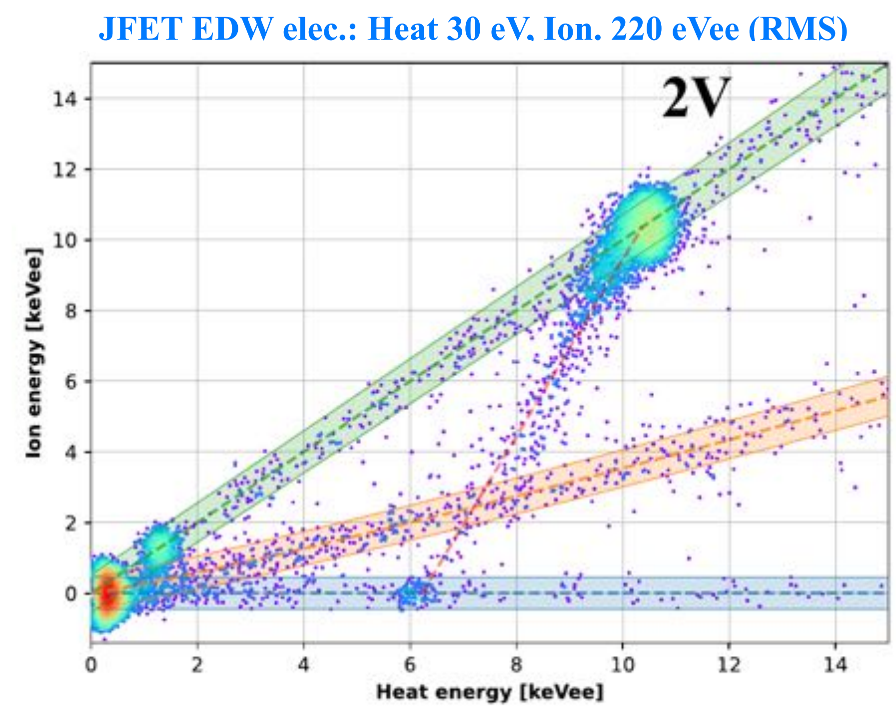
ArXiv 1909.02879

CEνNS : RICOCHET - detector optimization

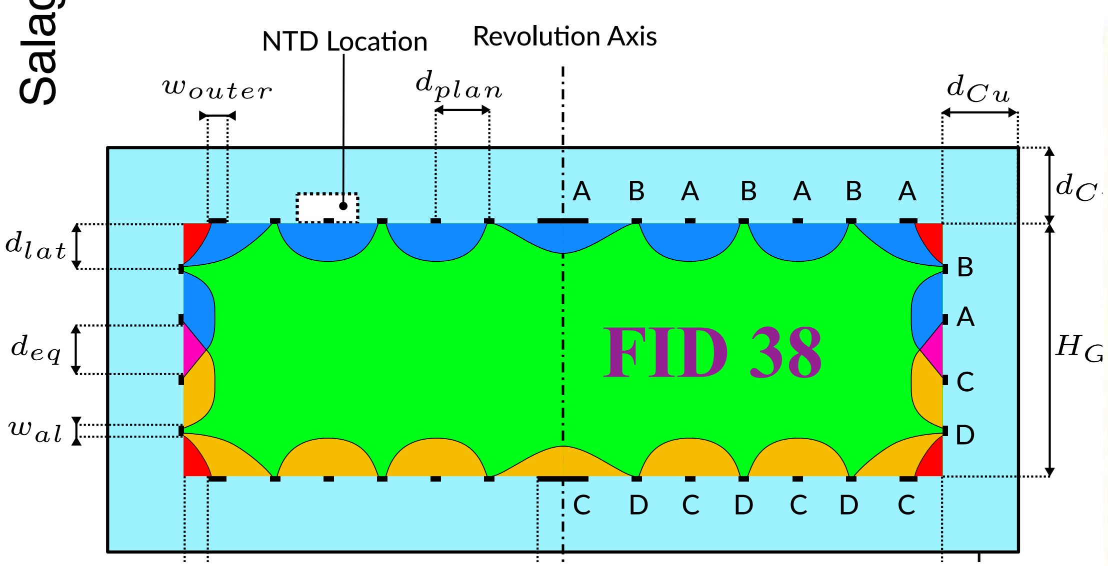
Low-Voltage approach for optimal particle identification

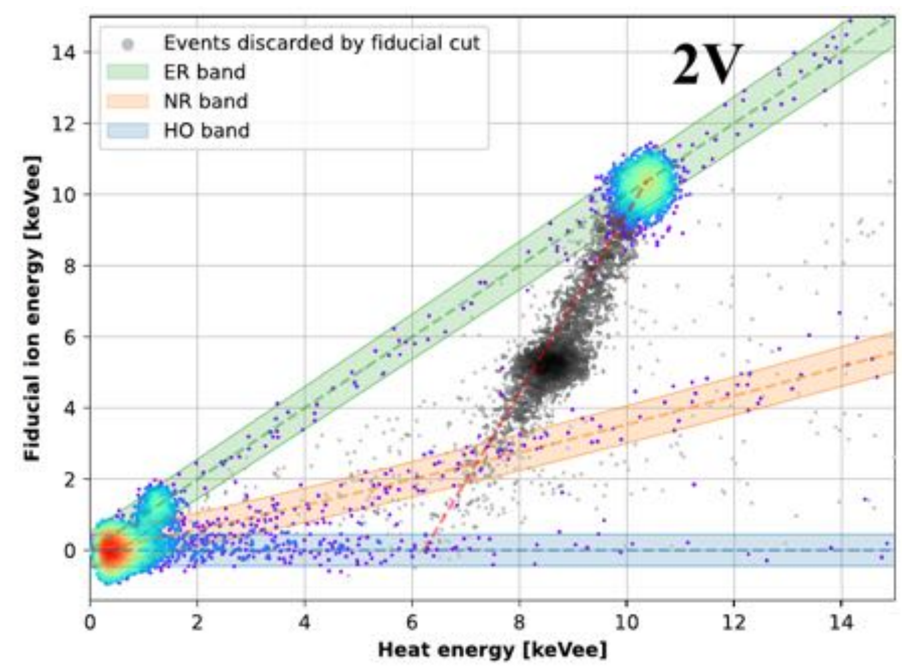
Salagnac & al: arXiv:2111.12438





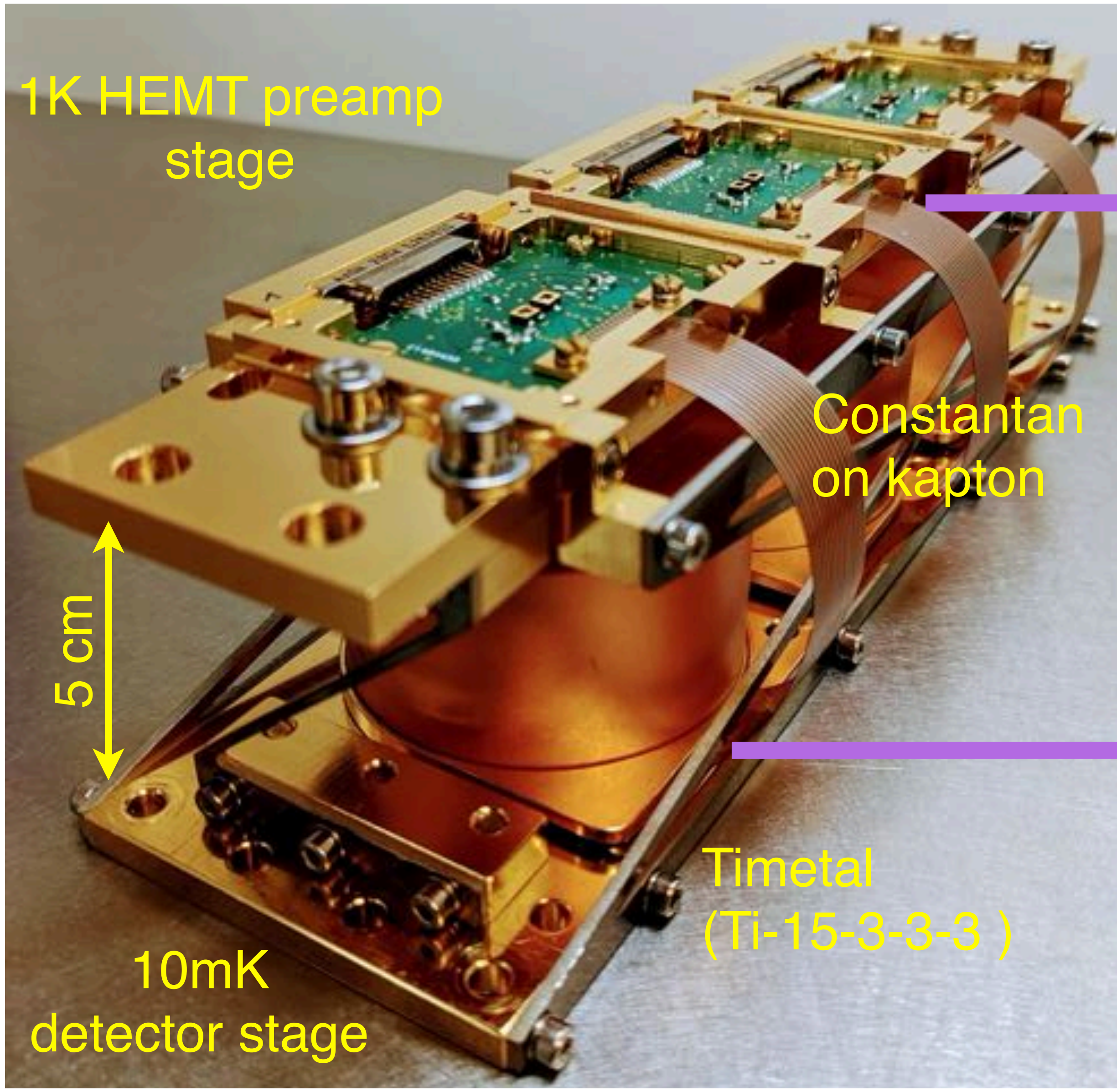
- Incomplete charge coll. **< 10%**
- Fiducial volume: **98.6 %**
- Surface event rejection: **NO**
- Total capacitance: **15 pF**

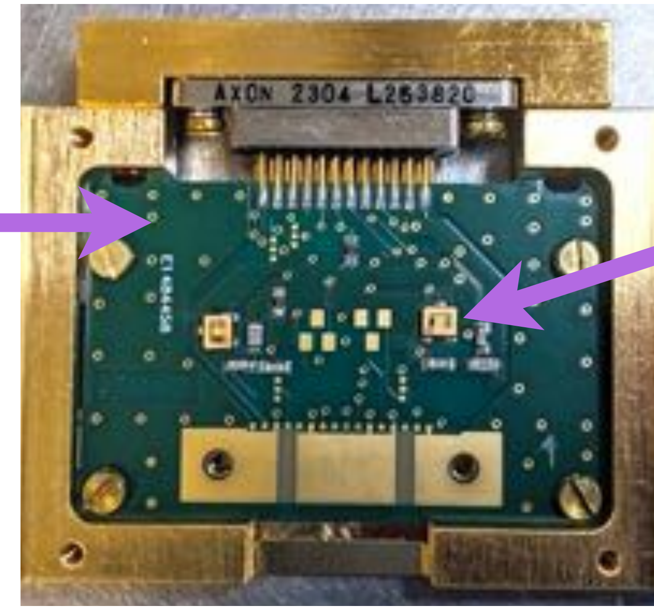




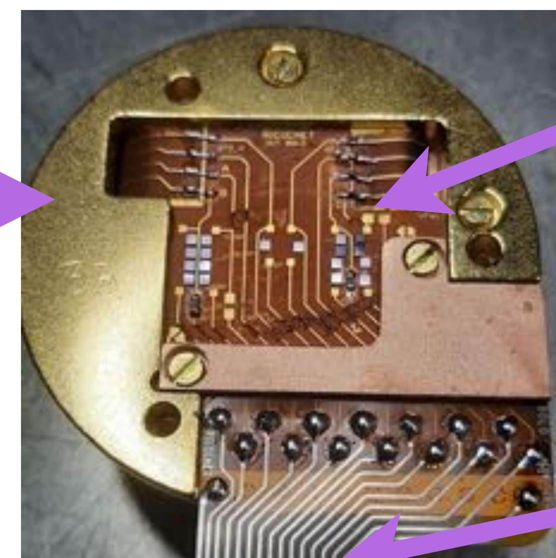
- Incomplete charge coll. **< 1%**
- Fiducial volume: **62 %**
- Surface event rejection: **YES**
- Total capacitance: **18 pF**

CEνNS : RICOCHET - MiniCryoCube





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

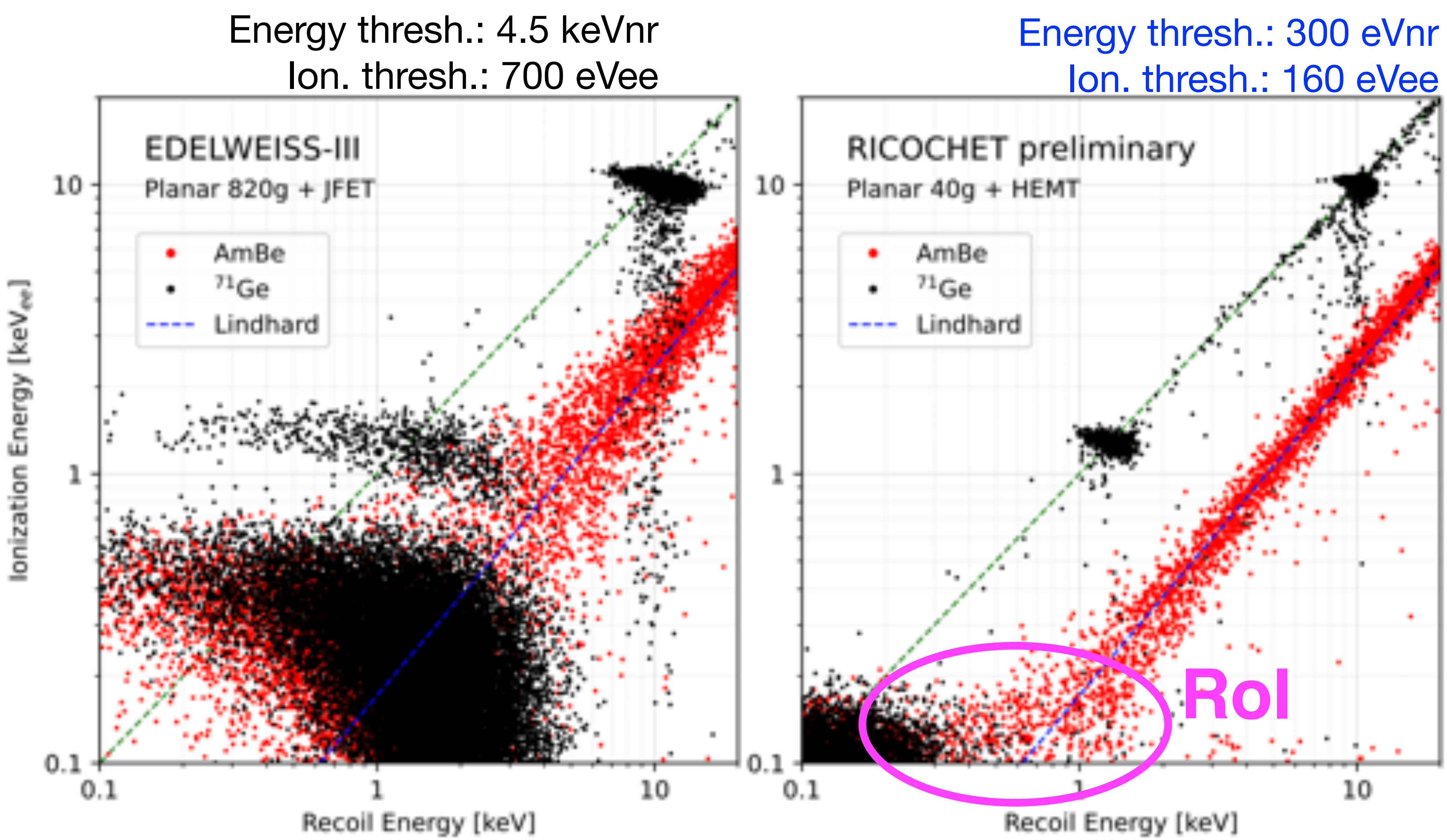


- ✦ Bias and feedback resistor **placed at 10mK** to minimize the thermal noise
- ✦ 35 µm contantan tracks on 100 µm kapton foil for the 10mK-1K path

✦ 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

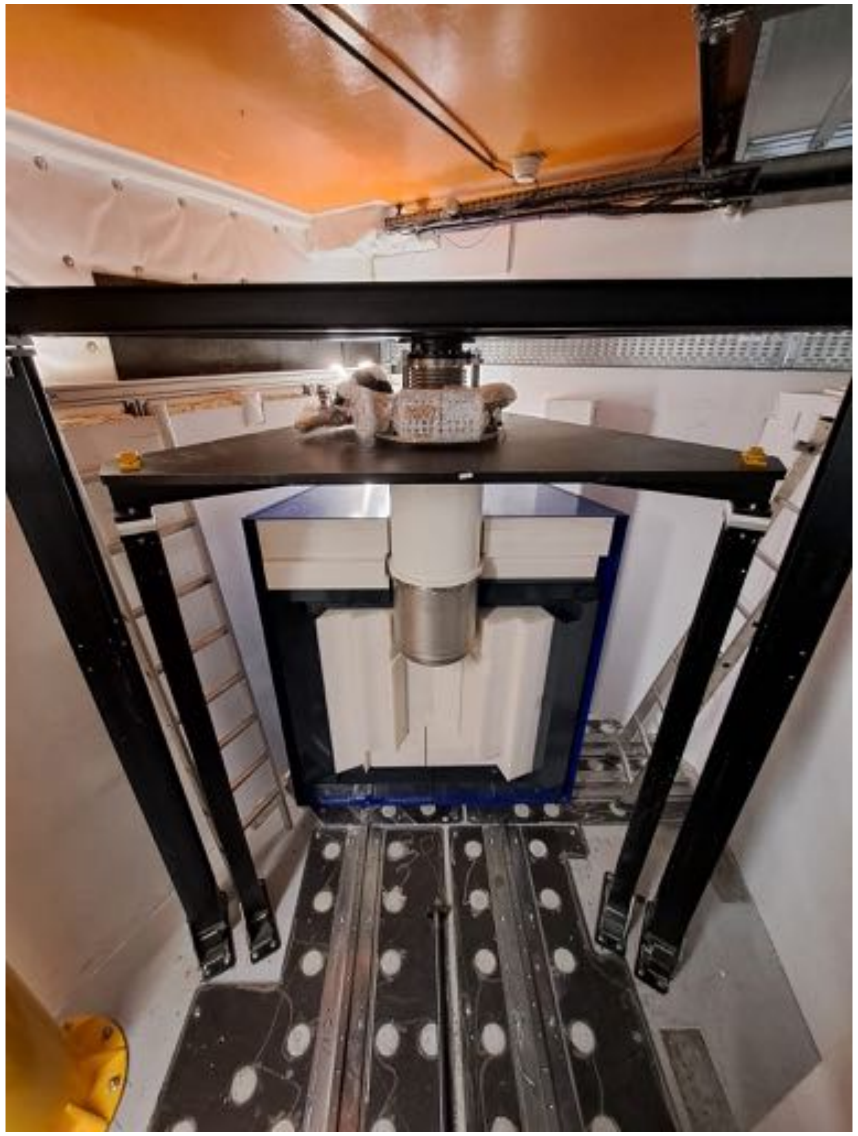
Ricochet R&D : MiniCryoCube demonstrator @ IP2I



Presented at: TAUP2023, IDM2023, Nobel Symposium 2023 (NS-182 « Dark Matter »)

- 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***

CEνNS : RICOCHET @ ILL



- ***Reaching 8.7 mK on the 6th of February 2024*** on the first cryogenic (Run12)
- 1 miniCryoCube installed and Run 13 started mid-Feb
  ➡ ***Commissioning ongoing*** (Reactor OFF first, then ON)

0νββ ??

Two neutrino double beta decay
(2ν2β)

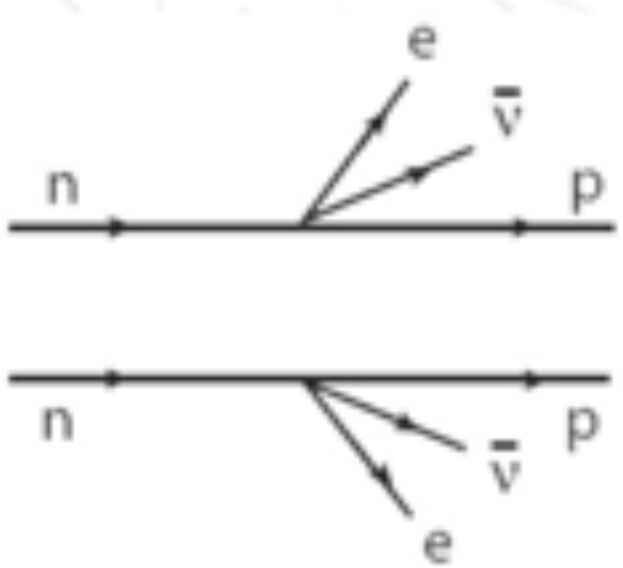
$$2\nu\beta^-\beta^- : (A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$$

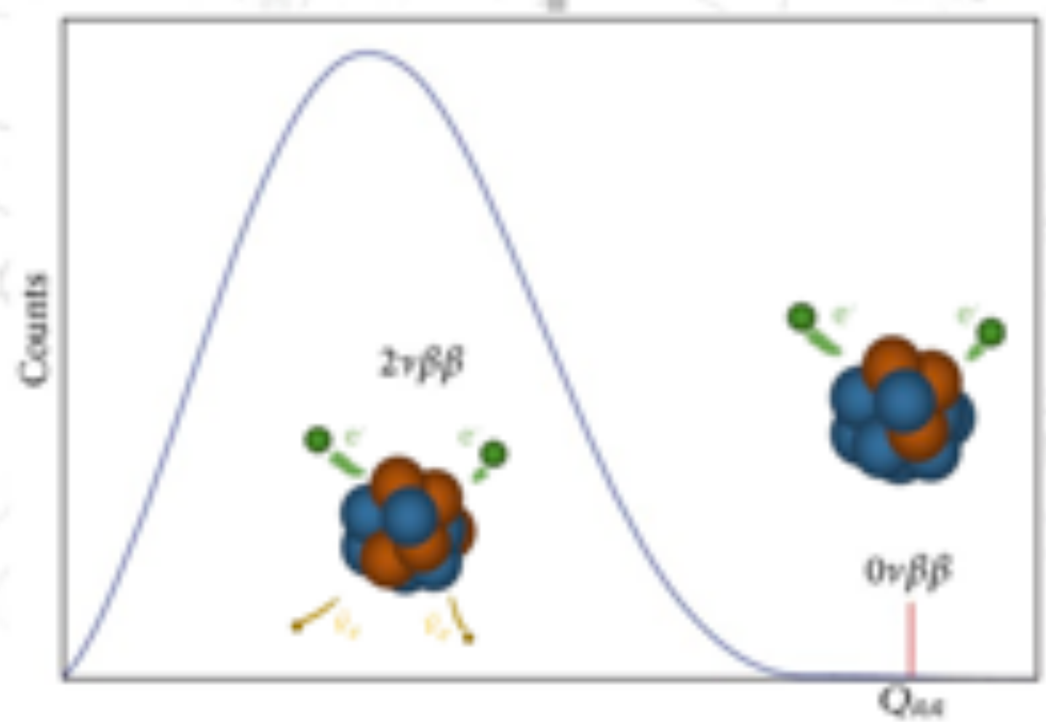
- **Allowed by the SM**
- 2nd order weak process → Extremely rare
- Energetically allowed for 35 nuclei.
- Observed for 12 with $T_{1/2}^{2\nu} \sim 10^{18} - 10^{22}$ years

Neutrinoless double beta decay
(0ν2β)

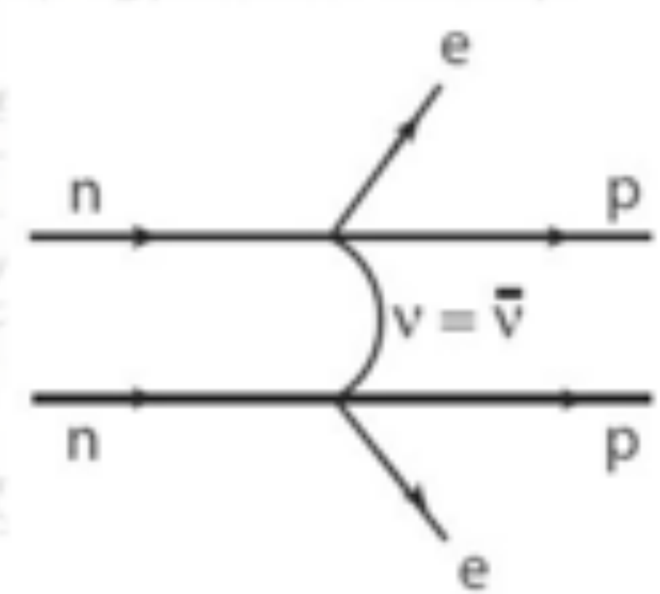
$$0\nu\beta^-\beta^- : (A,Z) \rightarrow (A,Z+2) + 2e^-$$

- **Forbidden by the SM**
- Violates lepton number conservation ΔL=2
- **Requires a Majorana neutrino**
- Not observed yet: $T_{1/2}^{0\nu} > 10^{24} - 10^{26}$ years





Summed energies of the two emitted e⁻



$Q_{\beta\beta}$ at few MeV !

$0\nu\beta\beta$??

Experimental observable: **$0\nu\beta\beta$ half-life**

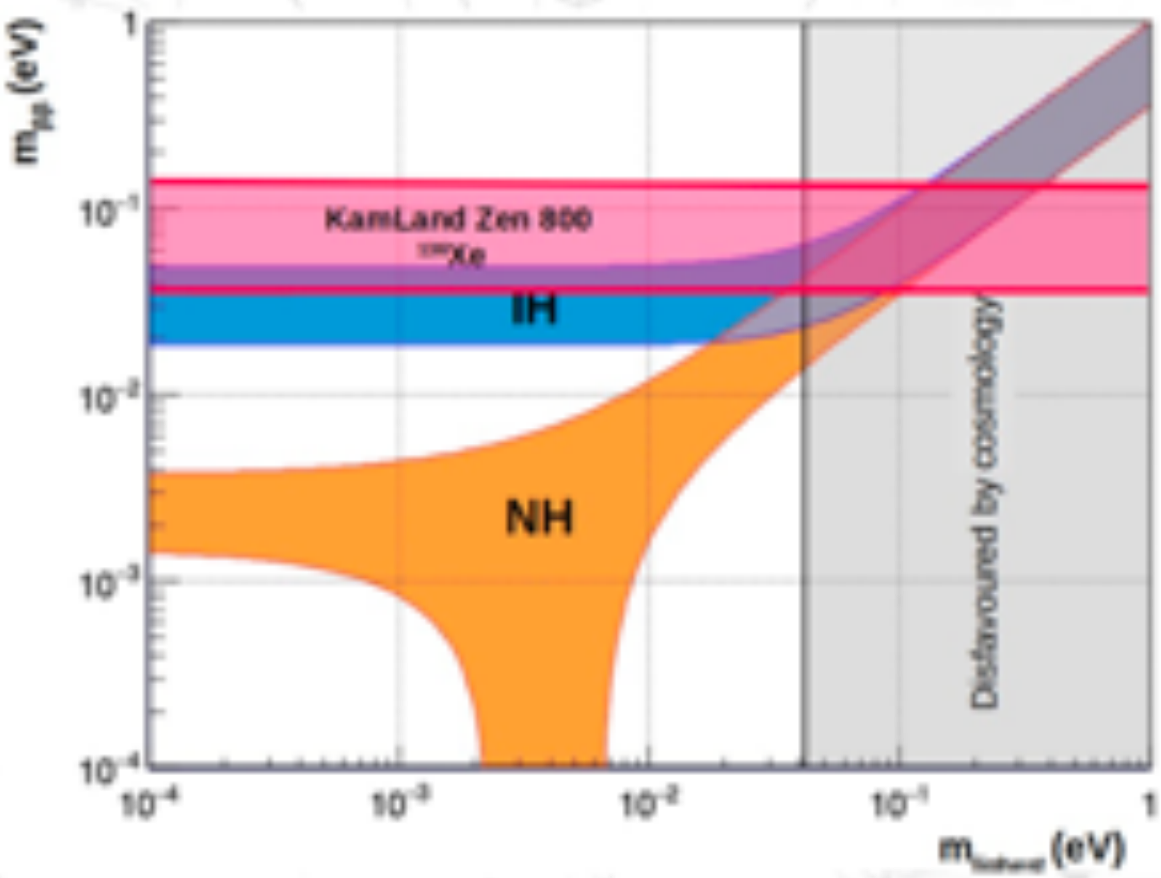
Kinematic

Nuclear physics

$$\frac{1}{T^{0\nu}_{1/2}} = G(Q,Z)\, g_A^4 \left|M^{0\nu}\right|^2 \frac{m_{\beta\beta}^2}{m_e^2}$$

Parameter related to neutrino physics : the **Majorana effective mass**

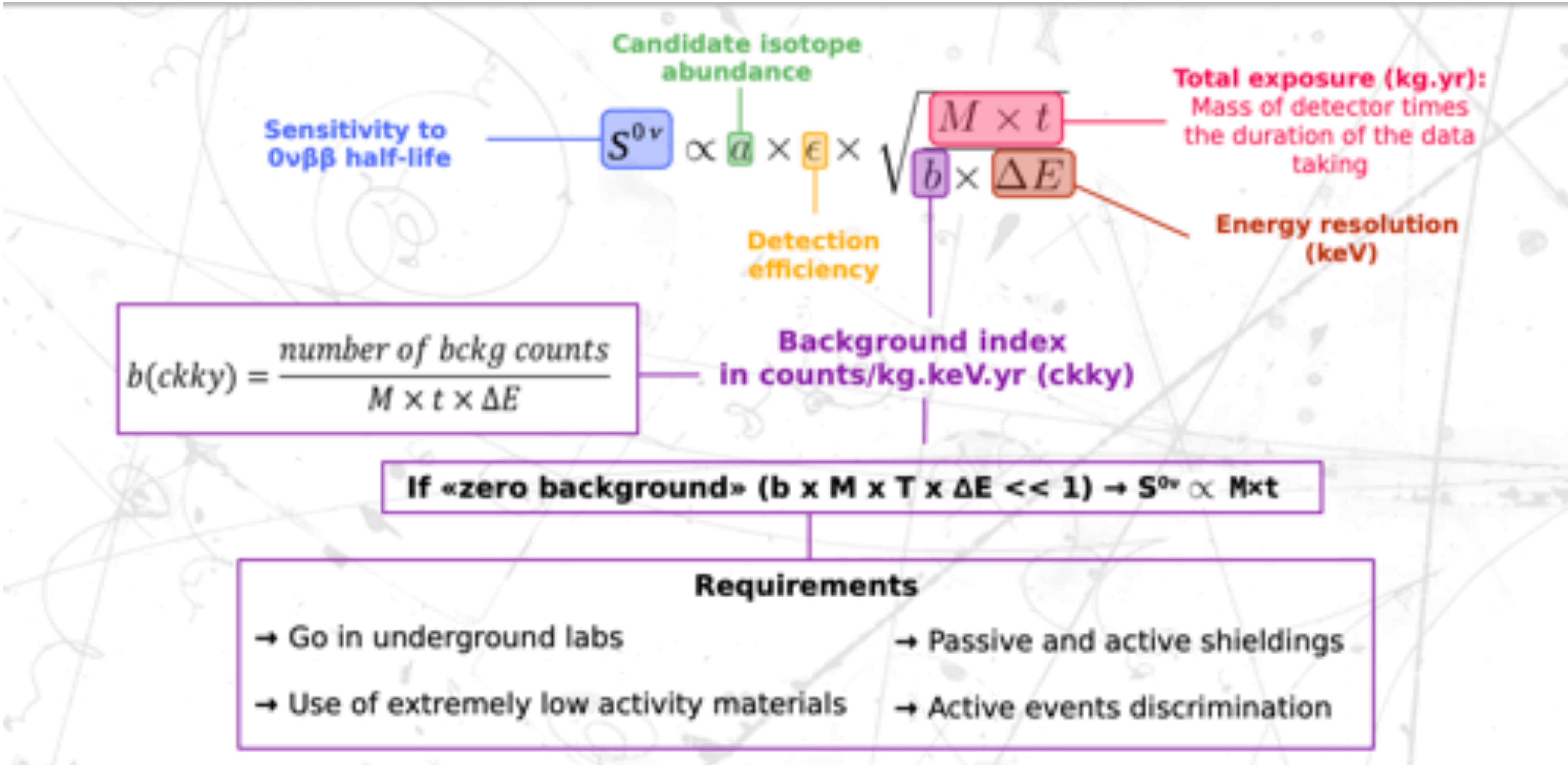
$$m_{\beta\beta} = \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$$



- Experiments are then exploring this plot by **putting limits on $m_{\beta\beta}$**
- **Cosmology can constrain the plot from the right**
- **Give info on the mass hierarchy and neutrino mass scale**

A.Armatol Thesis defense. 21 sept 2023

$0\nu\beta\beta$??



Some contrains **similar to Dark Matter** (Wimps) search

- …but ***signal expected at HE (few MeV)***
- ***No Low Energy Excess issue !!***
- main issue : large mass, low background, alpha bkg rejection
  ➡ ***double readout cryo detector can fit*** *(if ton scale)*

$0\nu\beta\beta$: state of the art & future goals

.KamLAND-Zen 800

.^{136}**Xe** – 970 kg.yr

.Liquid scintillator

.$T_{1/2}^{0\nu} > 2.3\times10^{26}$ yr

.$m_{\beta\beta}$<36-156 meV

.*Phys. Rev. Lett., 130:051801, Jan 2023*

.CUORE (ongoing)

.^{130}**Te** – 561.6 kg.yr

.Bolometers

.$T_{1/2}^{0\nu} > 3.3\times10^{25}$ yr

.$m_{\beta\beta}$<75-255 meV

.*«Latest results from the CUORE experiment», TAUP 2023*

.GERDA (finished)

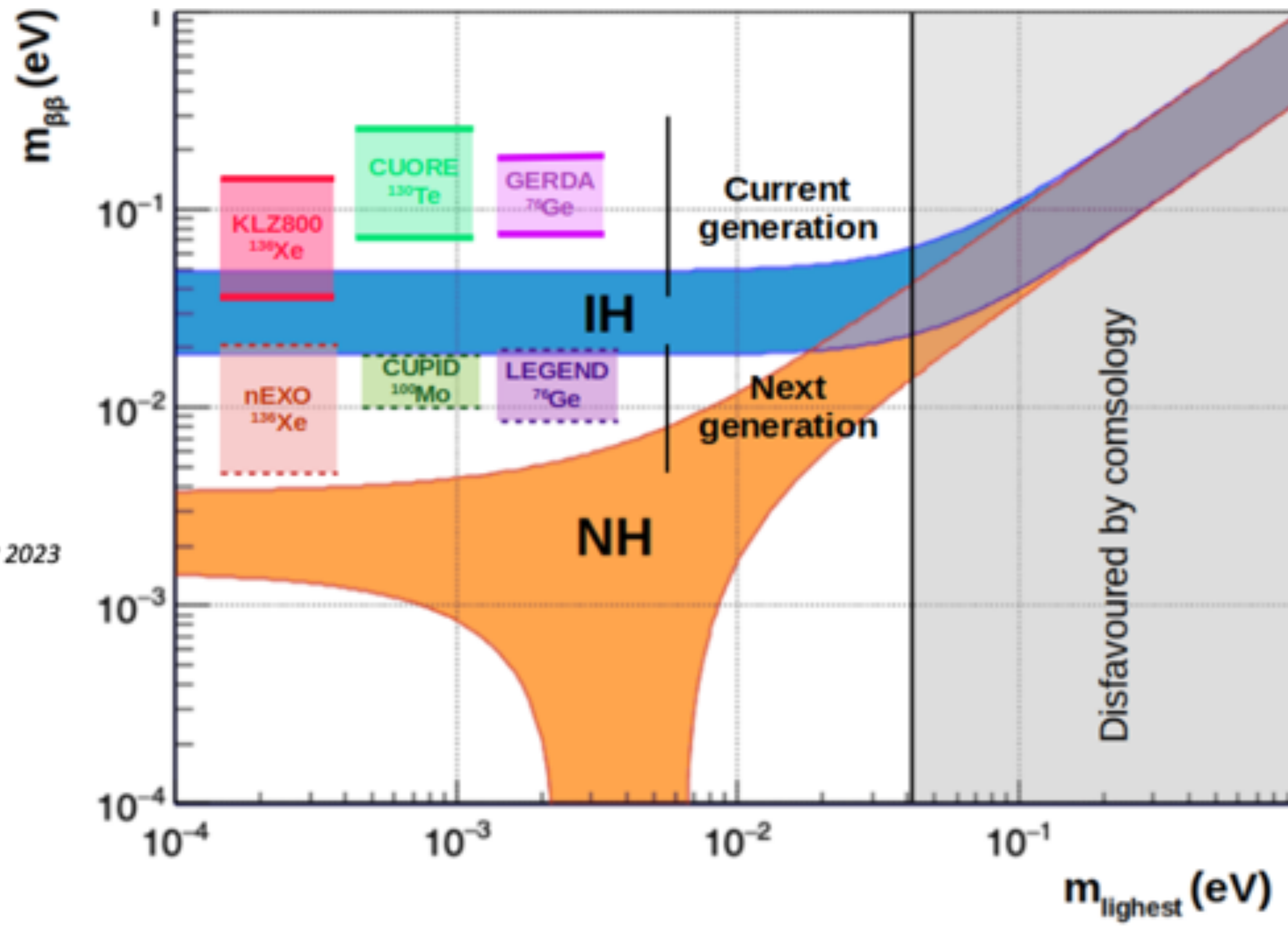
.^{76}**Ge** – 127.2 kg.yr

.Semiconductor detectors

.$T_{1/2}^{0\nu} > 1.8\times10^{26}$ yr

.$m_{\beta\beta}$<79-180 meV

.*Phys. Rev. Lett., 125:252502, Dec 2020*



.nEXO

.^{136}**Xe** – 5000 kg

.TPC

.$m_{\beta\beta}$<4.7-20.3 meV

.*Journal of Physics G: Nuclear and Particle Physics, 49(1):015104, dec 2021.*

.CUPID

.^{100}**Mo** – 253 kg

.Bolometers

.$m_{\beta\beta}$<10-17 meV

.*The CUPID Interest Group. Cupid pre-cdr, 2019.*

.LEGEND-1000

.^{76}**Ge** – 1000 kg

.Semiconductor detectors

.$m_{\beta\beta}$<8.5-19.4 meV

.*LEGEND-1000 Preconceptual Design Report. 7 2021.*

$0\nu\beta\beta$: towards CUPID

CUPID

CUORE Upgrade with Particle Identification

- ✦ 30 institut., 100s of people
- ✦ Long **process of R&D selection**
  - *https://arxiv.org/abs/1504.03612*
- ✦ French R&D (**CUPID-Mo**, IJCLab-IP2I + CEA) **selected as the CUPID baseline**
  - *https://arxiv.org/abs/1907.09376*
  - *Luke Neganov Ge **Light detectors will be produced by IJCLab***
- ✦ dedicated « small » underground R&D project : CROSS, BINGO ERC project
- ✦ **lots to be done over the next 3 decades**

https://arxiv.org/abs/1712.07995

Parameter	CUPID	CUPID-reach	CUPID-1T
Crystal	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$
Detector mass (kg)	472	472	1871
^{100}Mo mass (kg)	253	253	1000
Energy resolution FWHM (keV)	5	5	5
Background index (counts/(keV kg y))	10^{-4}	2×10^{-5}	5×10^{-6}
Containment efficiency	79%	79%	79%
Selection efficiency	90%	90%	90%
Livetime (years)	10	10	10
Half-life exclusion sensitivity (90% C.L.)	1.5×10^{27} y	2.3×10^{27} y	9.2×10^{27} y
Half-life discovery sensitivity (3σ)	1.1×10^{27} y	2×10^{27} y	8×10^{27} y
exclusion sensitivity (90% C.L.)	10–17 meV	8.2–14 meV	4.1–6.8 meV
discovery sensitivity (3σ)	12–20 meV	8.8–15 meV	4.4–7.3 meV

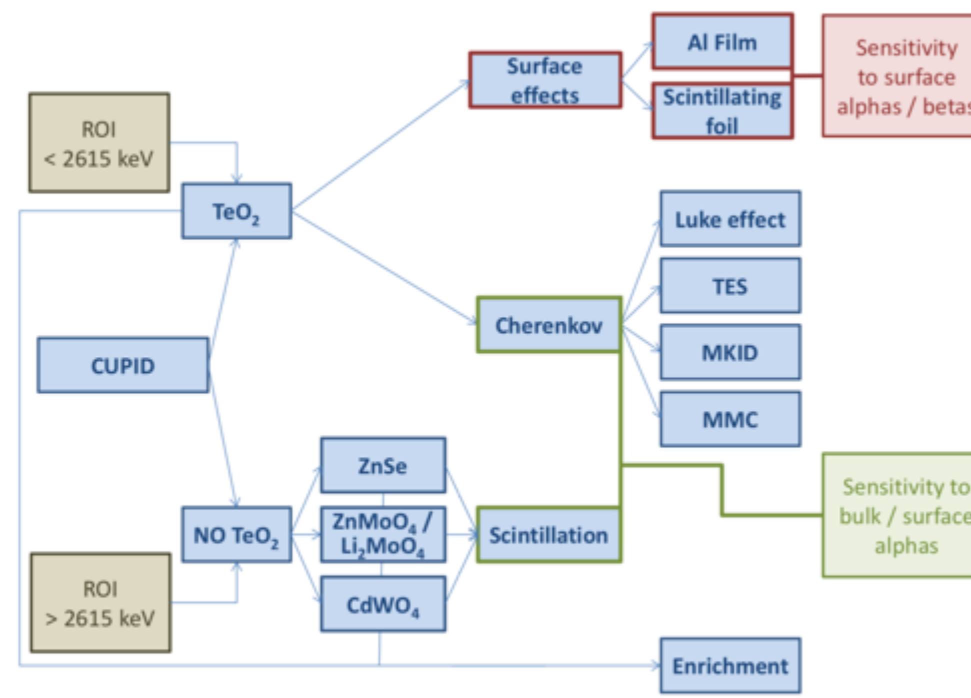


FIG. 1: Scheme of the R&D detector activities for CUPID

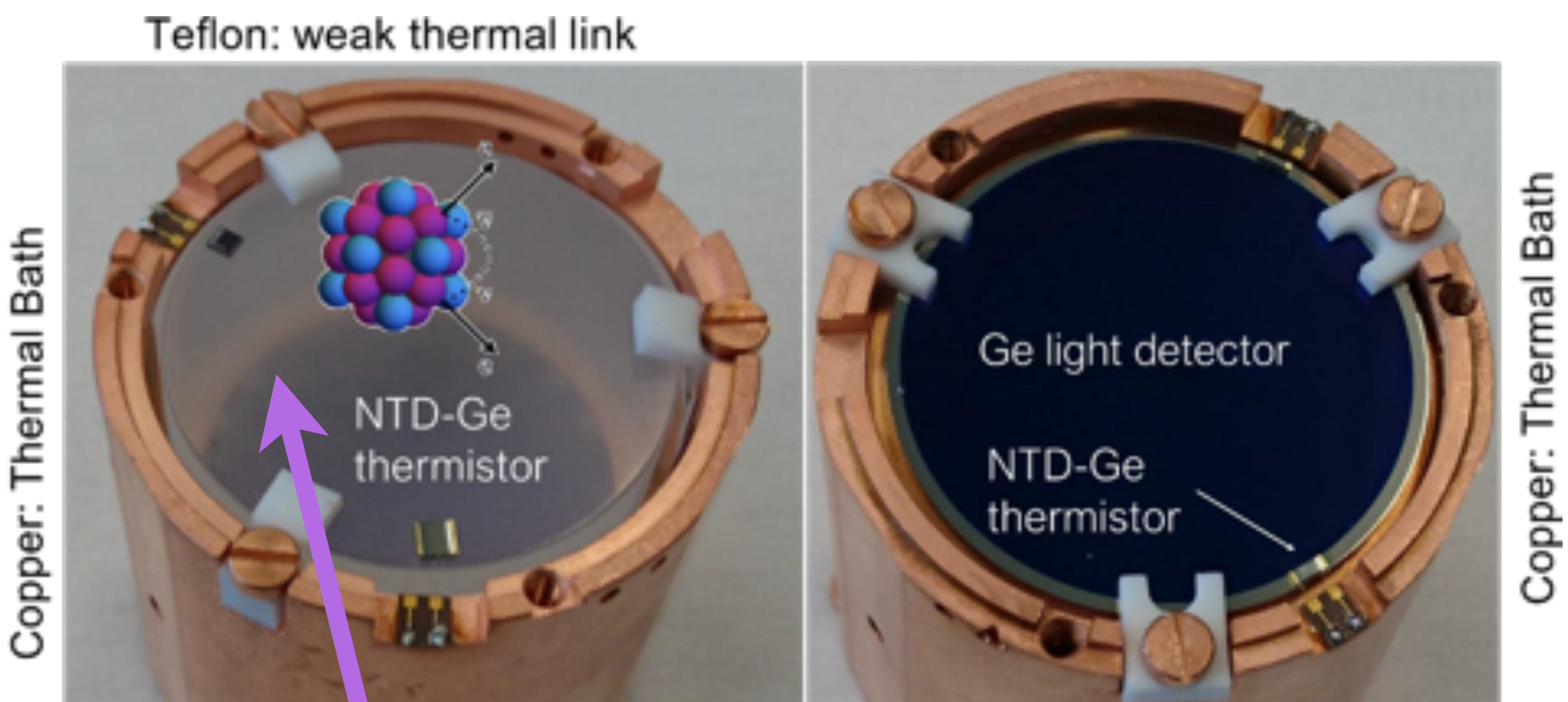
https://arxiv.org/abs/1504.03612

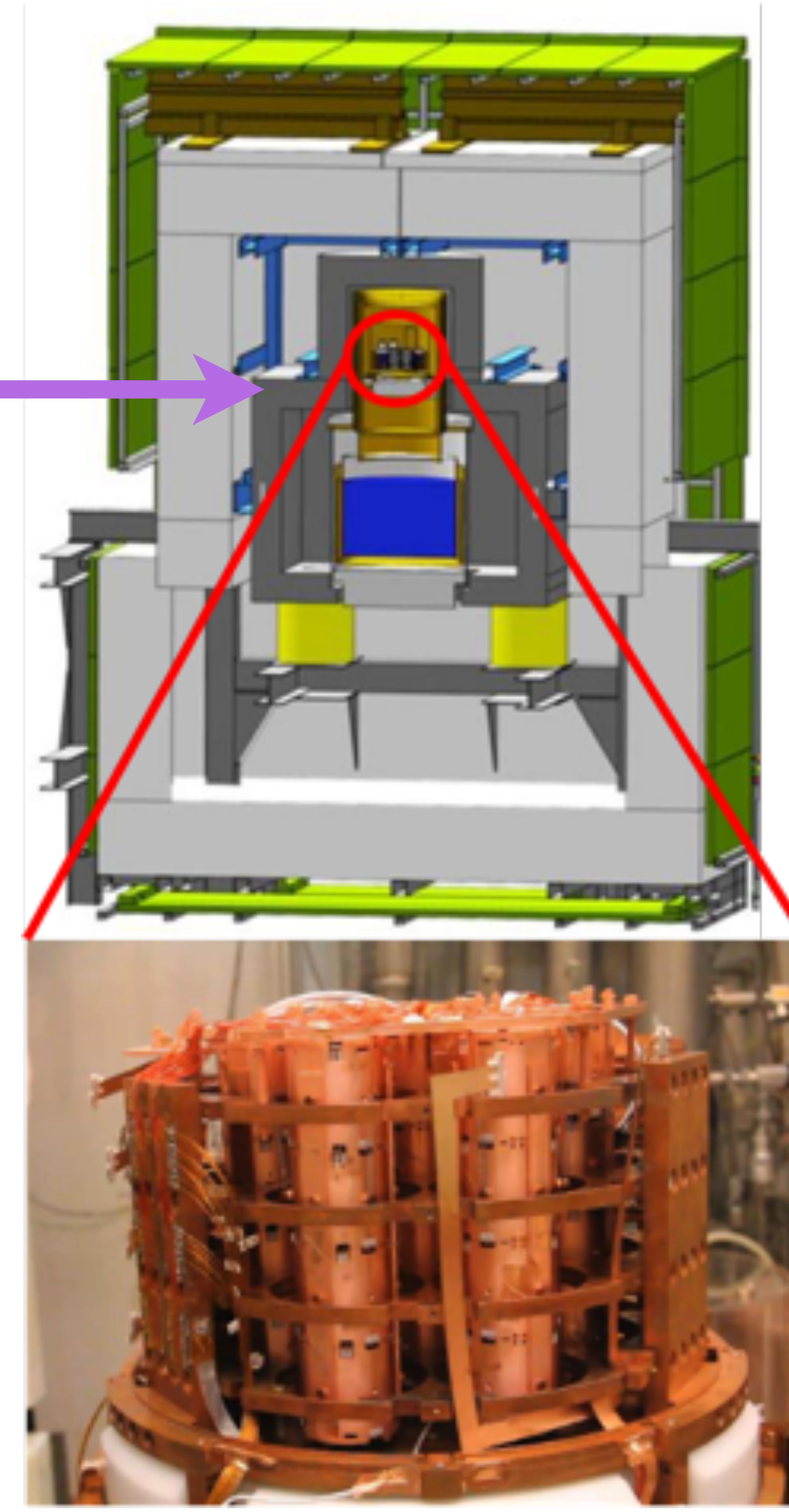
CUPID-Mo @ LSM [EPJC 83, 675 (2023), PRL162501 (2023)]

✦ IJCLab, IP2I + CEA

✦ **Pilot ββ experiment** based on scintillating bolometers with NTD readout

- **20x Li_2MoO_4** crystals coupled to Ge light detectors
- Data taking at **LSM in EDELWEISS cryostat (2018-20)**
- **Best worldwide results** on ββ decay of ^{100}Mo
- Demonstrator of the **CUPID technology (see next slide)**



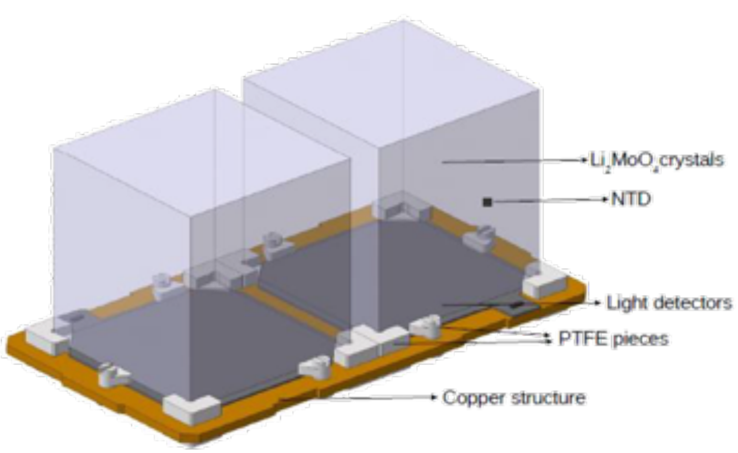


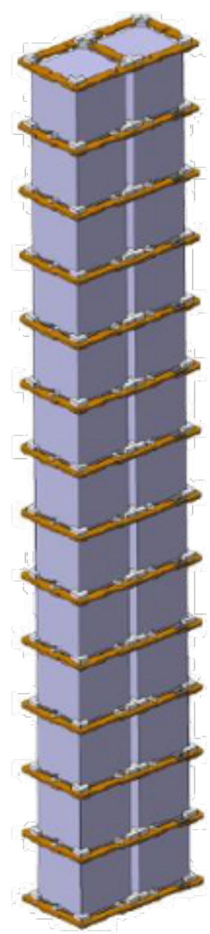
Li_2Mo_4 crystal enriched in ^{100}Mo (99%)
210 g – cylinders ø44 mm x 45mm
2.1 kg of ^{100}Mo

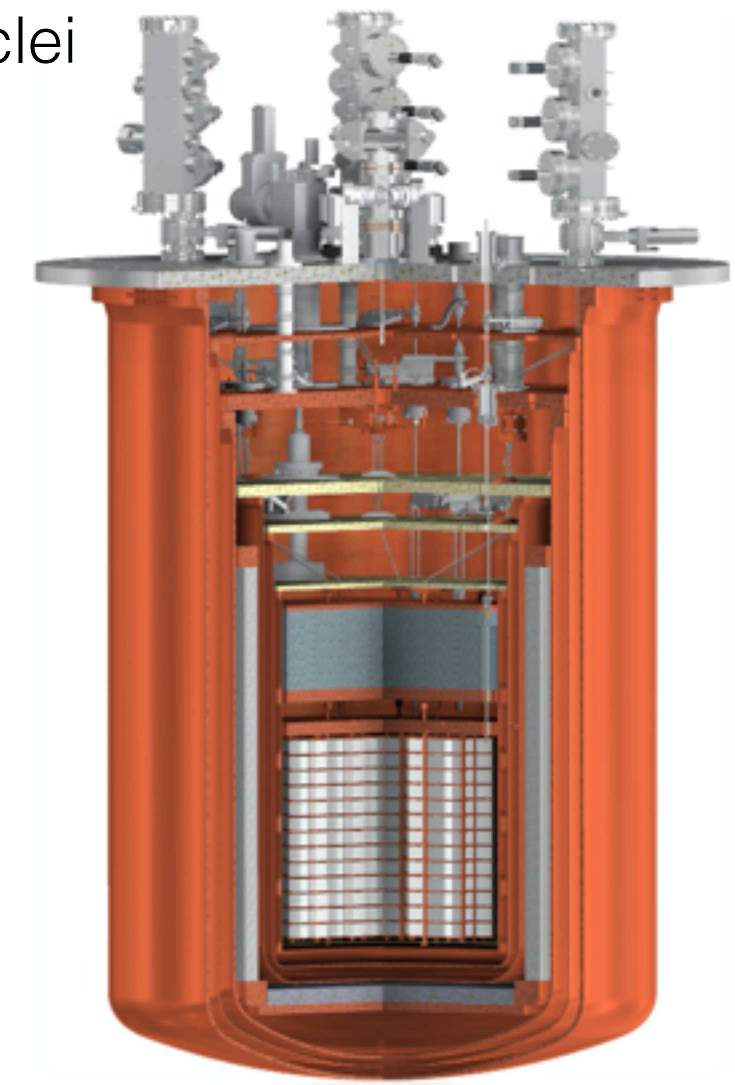
CUPID (CUORE Upgrade with Particle Identification)

[EPJC 82, 810 (2022), JINST 18, P06033 (2023)]

- ✦ IJCLab, IP2I + CEA
- ✦ **One of the 3 next-generation ββ experiments** selected by the US and EU funding agencies (CUPID, LEGEND, nEXO)
  - **170 people & 33 institutions**
  - Exploit **CUORE infrastructure** (Gran Sasso) with **CUPID-Mo technology**
  - **Single module**: $Li_2{}^{100}MoO_4$ 45×45x45 mm **~ 280 g**
  - 57 towers of 14 floors with 2 crystals each - **1596 crystals**
  - **~240 kg of ^{100}Mo** with >95% enrichment ~1.6×10^{27} ^{100}Mo nuclei
  - **Bolometric Ge light detectors as in CUPID-Mo**
- ✦ **Data taking > 2030**







2 X 14 x 57 = 1596

R&D : CUPID (CUORE Upgrade with Particle Identification)

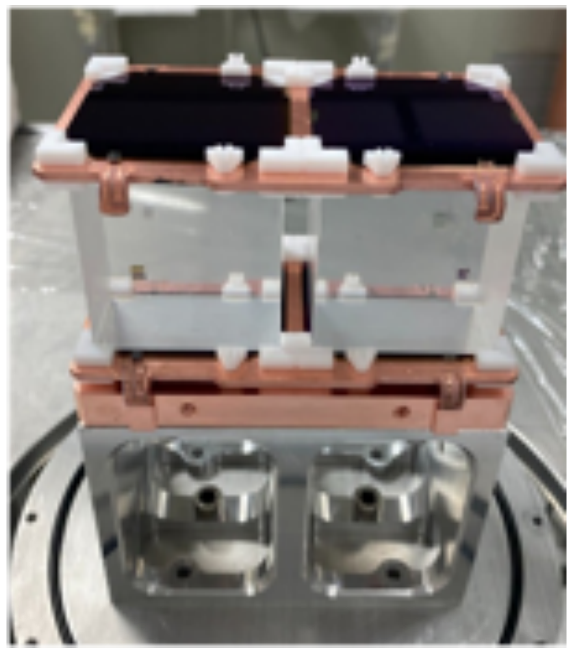
CUPID Prototype Tower : ANR CUPID1 2022-25 + R&T IN2P3

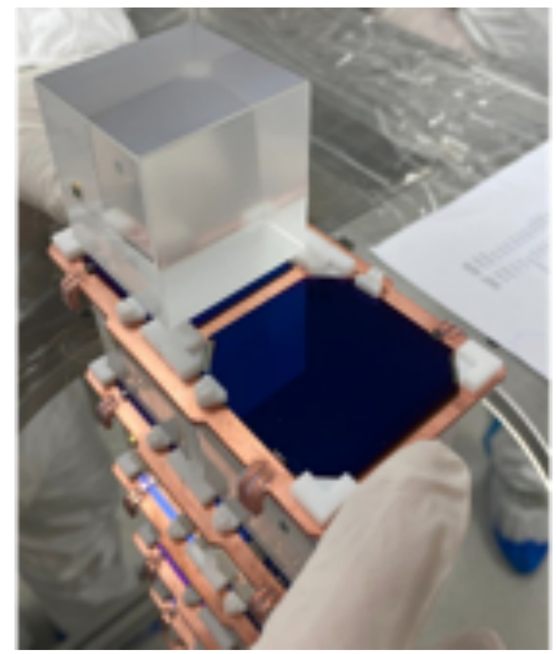
✦ **Assembly in IJCLab and Gran Sasso**

- **To be tested Mid-2024** in Cuoricino Cryostat @ Gran Sasso

Light Detector

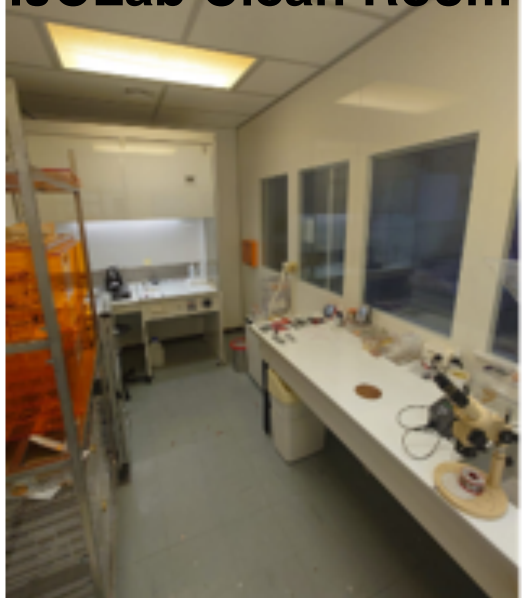
Tower Construction

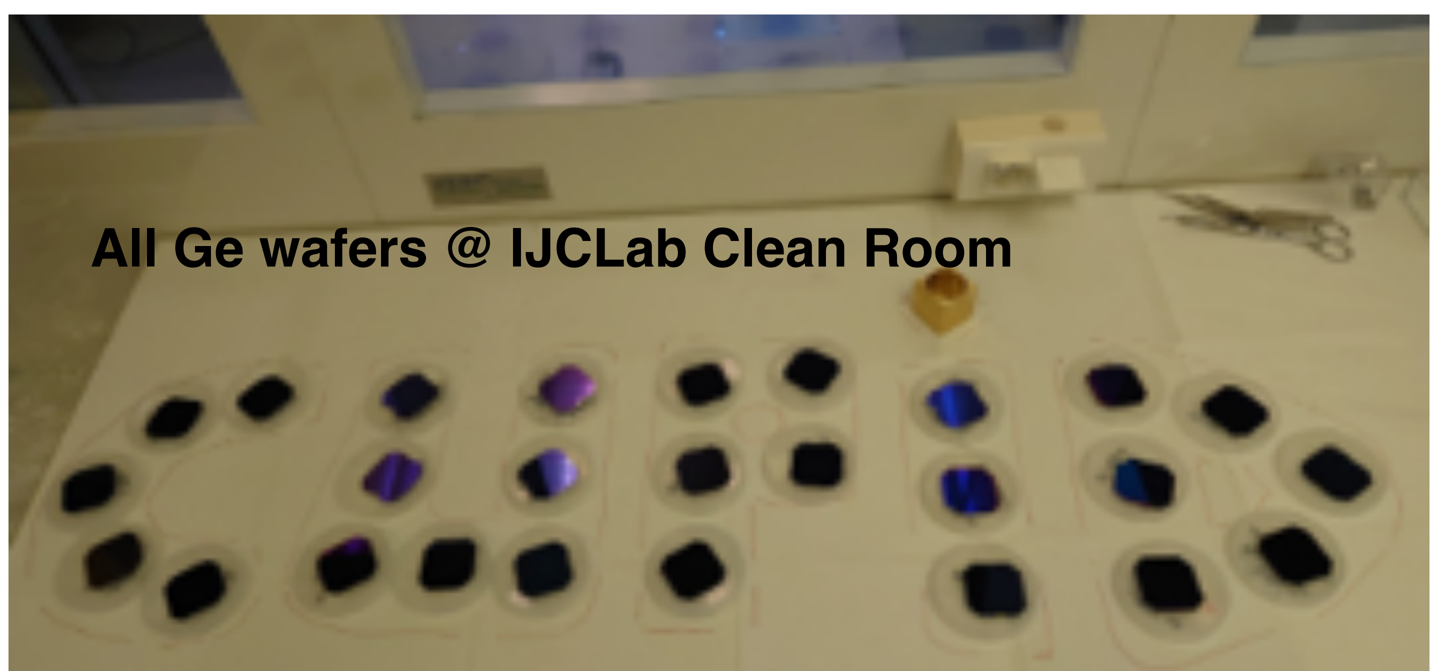




CUPID Tower @ GS (2022)

IJCLab Clean Room





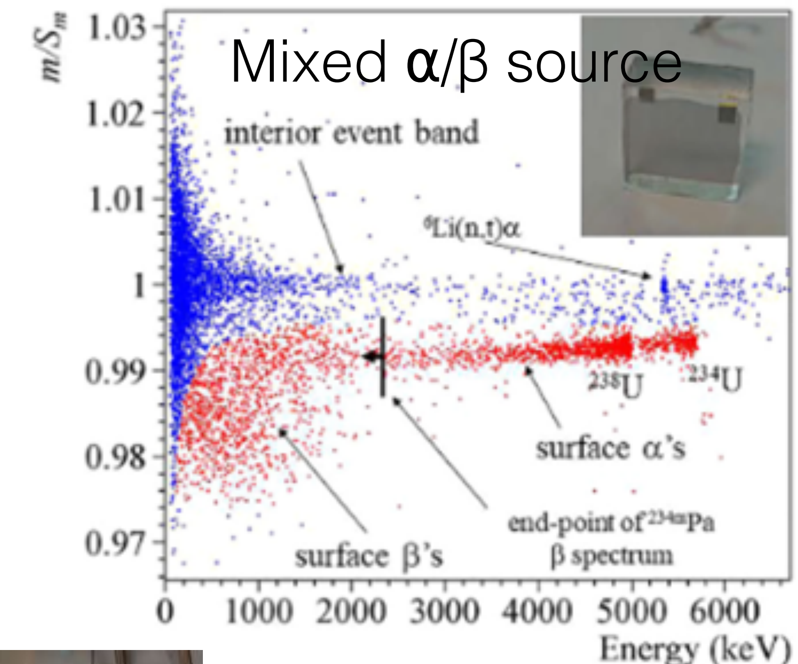
All Ge wafers @ IJCLab Clean Room

CUPID related R&D : CROSS (2018-24)

[Appl. Phys. Lett. 118, 184105 (2021), Appl. Phys. Lett. 118, 184105 (2021)]

✦ **Reject surface events by PSD assisted by metal film coating**

- Proof of concept achieved with small prototypes
- Both **surface α's and β's** are **separated from bulk events**

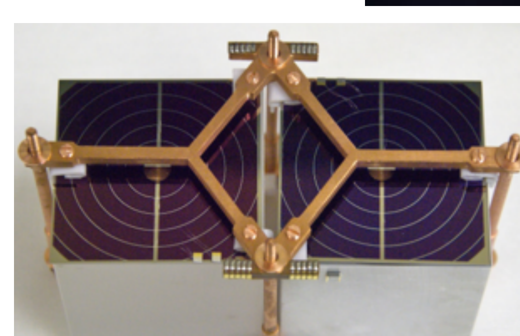


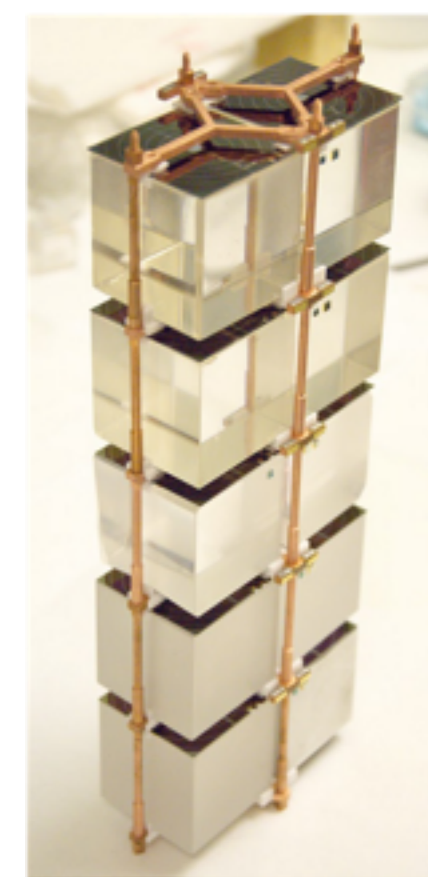
✦ **Technology demonstrator**

- ~ 5 kg of ^{100}Mo shared in ~36 x Li_2MoO_4 crystals (+ 6x $^{130}TeO_2$ crystals)
- **Dedicated cryostat** @ Canfranc underground laboratory

✦ **Redundancy**

- surface sensitivity
- scintillation light detection
- Improved Light detectors
  - ➡ enhanced by Neganov-Trofimov-Luke technology : **demonstrated**
  - ➡ Now **CUPID baseline**





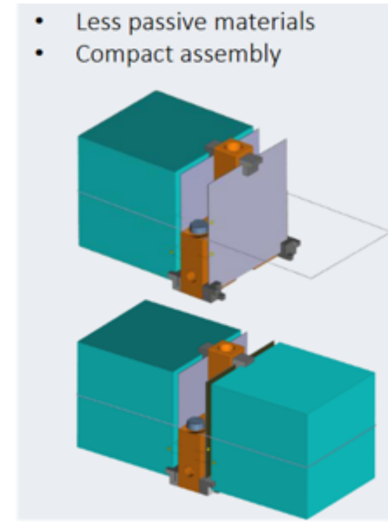
Prototype CROSS Tower

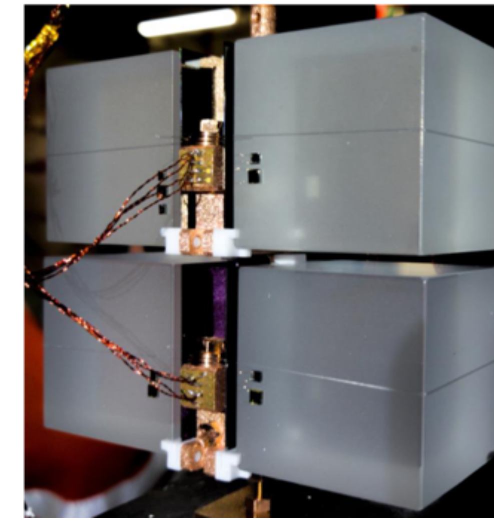
CUPID related R&D : BINGO (2020-26)

[arXiv.2301.06946, arxiv.2204.14161]

✦ Three innovations to reject background in **ββ** decay experiments based on Li_2MoO_4 and TeO_2

- **Revolutionary assembly** to reject surface background
  ➡ The light detector shields the passive materials





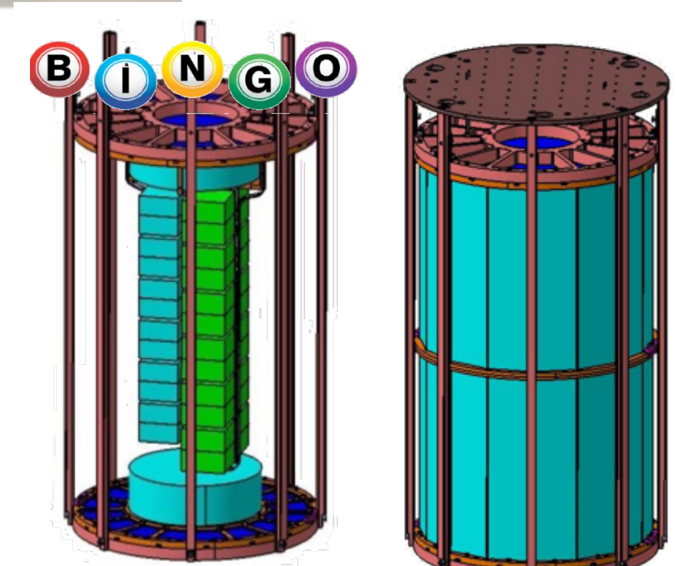
- **Enhanced-sensitivity** light detectors (Neganov-Trofimov-Luke) **(see next slide)**

- **Internal veto** (ultrapure BGO/$ZnWO_4$ scintillators)
  ➡ mitigate **γ** background in TeO_2

VETO prototype BGO scintillators

✦ BINGO demonstrator at LSM

- **Dedicated cryostat :** installation in 2024 in part of the EDELWEISS space (now dismantled) @ LSM

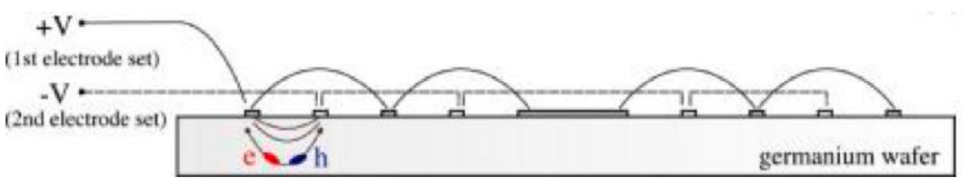


CUPID related R&D : BINGO (2020-26)

[arXiv.2301.06946, arxiv.2204.14161]

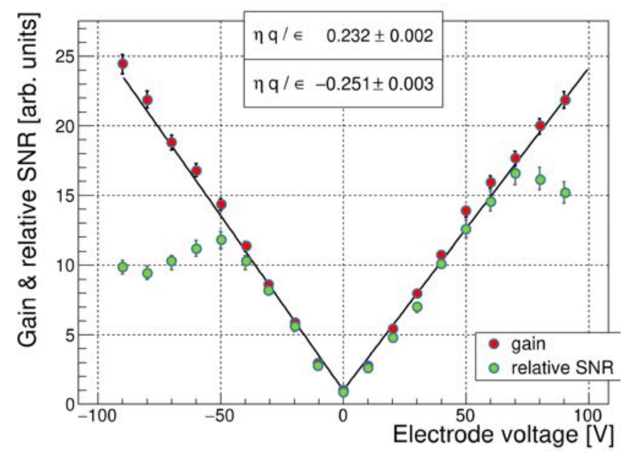
BINGO - Technology demonstration NTL

NTL assisted light detectors
Original design: 1 sided Electrode deposition, circular, typical operation voltage 50 to 100V

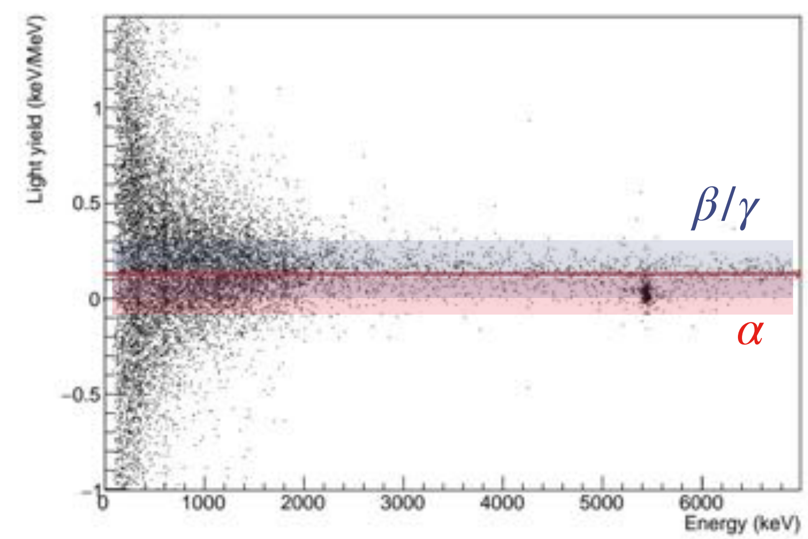


$$E_{tot} = E_0 \left(1 + \frac{q \cdot V_{el} \cdot \eta}{\epsilon}\right)$$

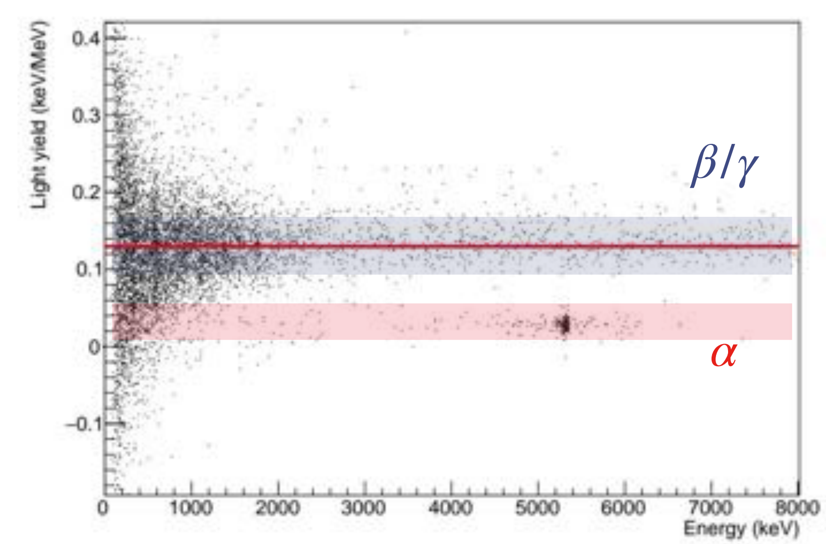
NIM A 940 (2019) 320

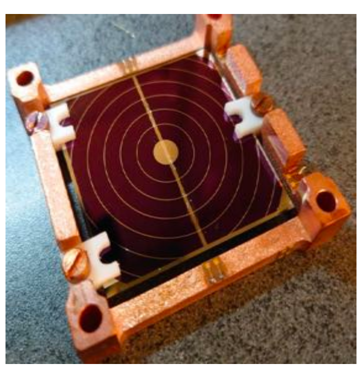


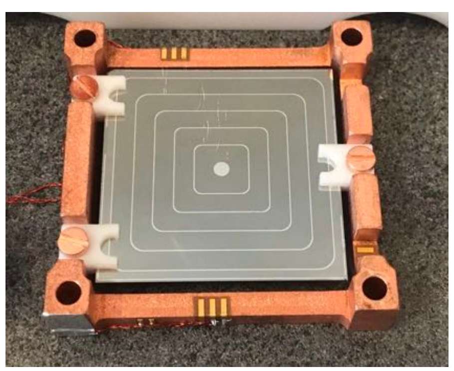
Concentric1 - 0V

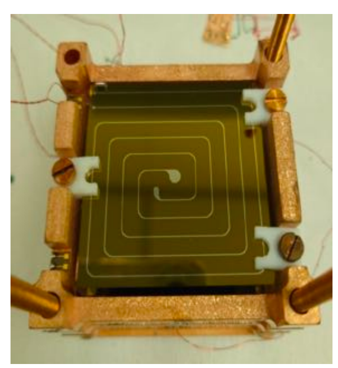


Concentric1 - 35 V





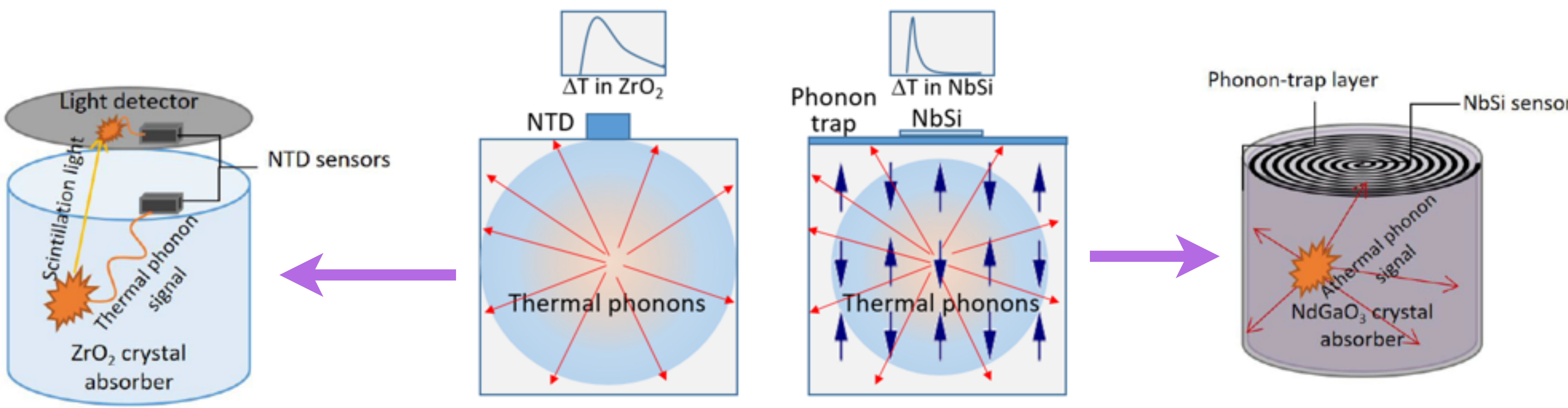




Ongoing work:
Optimisations for CUPID/BINGO: Square and trapezoidal geometries, two-sided LDs, optimised voltage & operation, minimize loss from charge trapping η

CUPID related R&D : TINY (2023-29)

- ✦ Development of bolometric detectors containing **the most promising ββ isotopes** ^{96}Zr and ^{150}Nd
  - Main challenge in Nd-based compounds: high specific heat from magnetism
  - detect phonons before thermalization
- ✦ **TINY objective**: develop a demonstrator with a 2 kg mass detector distributed in a few elements for each isotope
  - New **dedicated cryostat** @ Saclay **(**installation in 2025) for R&D
  - demonstrator tested in CROSS or BINGO Cryostat



Classical scintillating **bolometers** with **thermal signals**

ZrO_2

Dielectric diamagnetic

Athermal phonons

$NdGaO_3$

Antiferromagnetic order

R&D : Rare events search CONCLUSION

- Standard WIMPs dead ?
  - Still motivated but ALPs more and more in the game
- ***Low Energy Excess*** (heat only) is the ***main issue for DM & CEνNS***
  - ***LEE Identification or excellent ionization needed***
- Proposal for a ***new DM experiment at LSM (TESSERACT)***
- ***Radiopurity & alpha rejection is the main issue for 0νββ*** + scaling to very large mass
  - Ton scale experiment already exist (CUORE)
  - ***French technology selected for CUPID***

→ ***Enough work for the 2 next decades !***