Low Radioactivity Techniques
2024
Workshop IX

INFN
LNGS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Gran Sasso

GSSI
GRAN SASSO SCIENCE INSTITUTE

MARIE CURIE ACTIONS

Rare event search with cryogenic calorimeters

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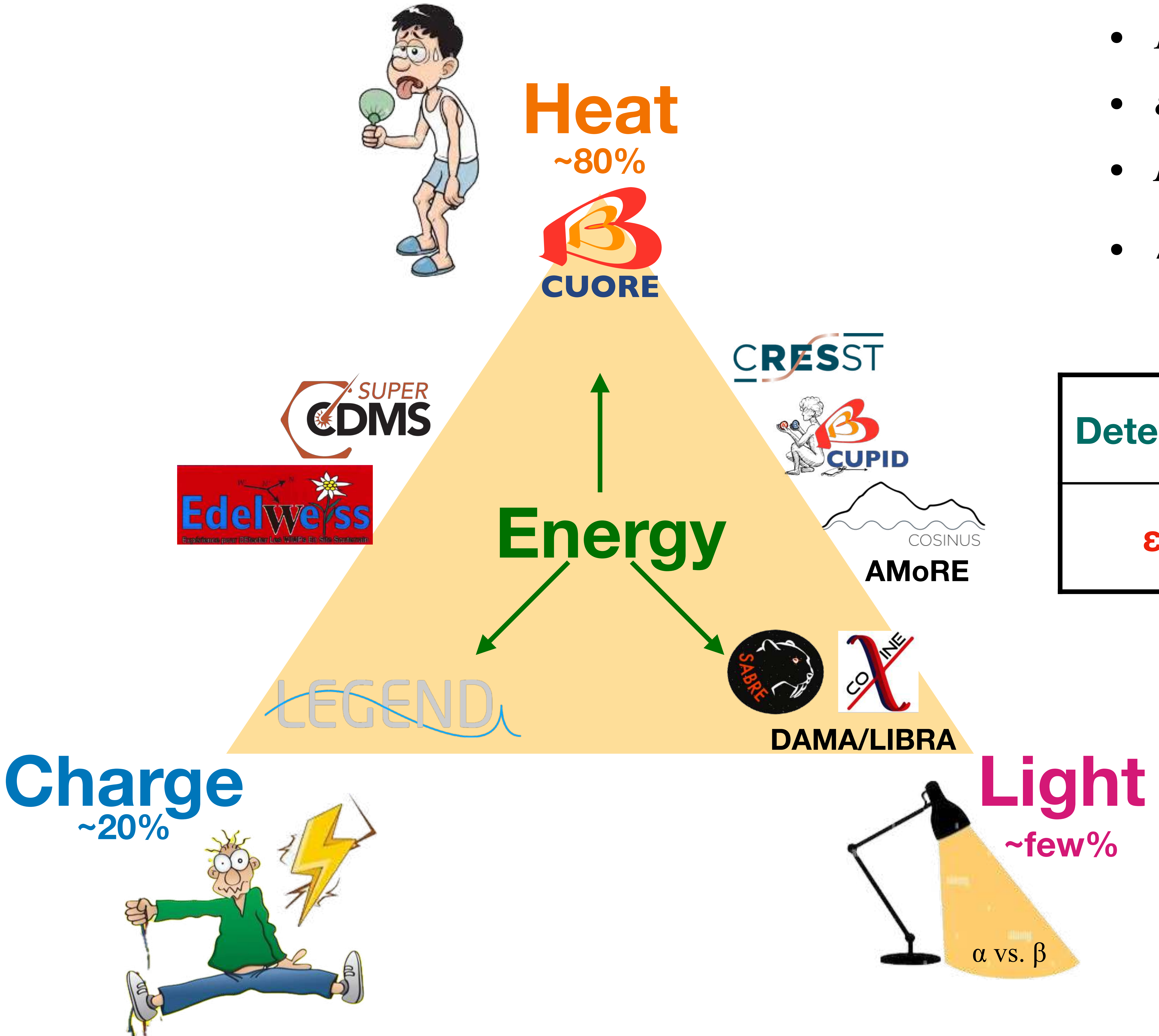
Outline

- **Working principles**
- **Specific backgrounds of cryogenic calorimeters**
  - Surface contaminations
  - 2νββ pileup
  - Low-energy excess
- **Direct Dark Matter Search**
  - CRESST / COSINUS
  - SuperCDMS / EDELWEISS
- **Search for Neutrinoless Double Beta Decay**
  - AMoRE
  - CUORE ➡ CUPID

Detection channels



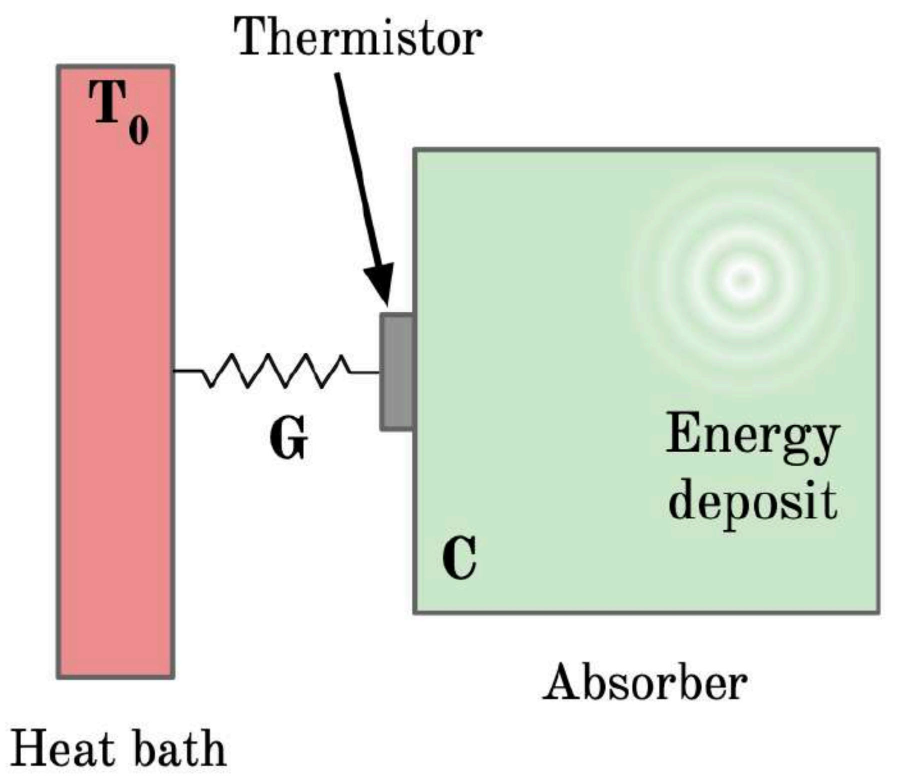
- E ➡ energy release in the detector
- ε ➡ energy to produce an excitation in a detector
- $N = E/\varepsilon$ ➡ number of elementary excitations
- $\Delta E = \varepsilon \Delta N = \varepsilon\sqrt{N} = \sqrt{\varepsilon E}$ ➡ energy resolution

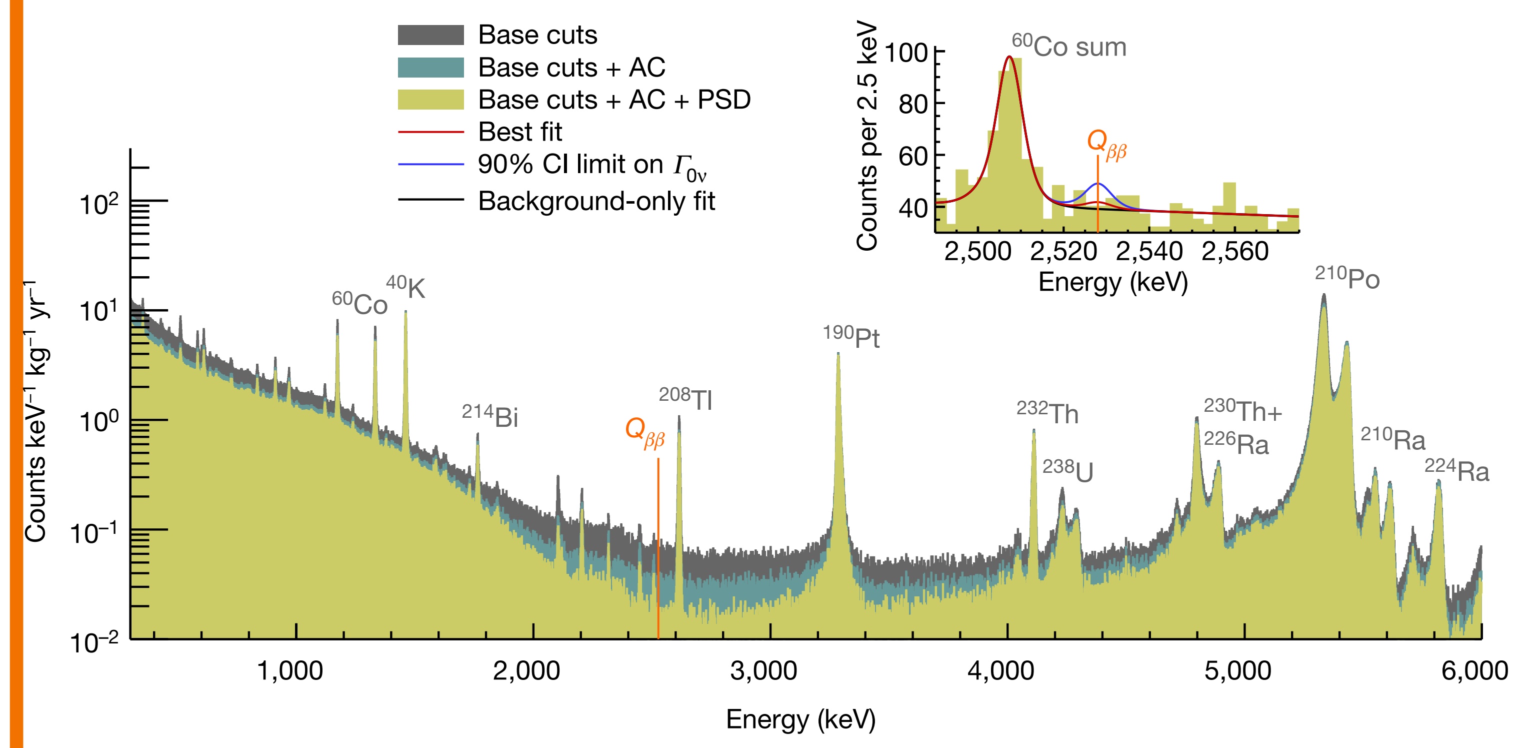
Detector	Scintillators	Gas detectors	Semi-conductors	Cryogenic calorimeters
ε	100 eV	30 eV	3 eV	< 0.01 eV

Heat channel provides a high-resolution estimator for **energy releases** but a **second channel** is needed **background rejection**.

General working principle(s)

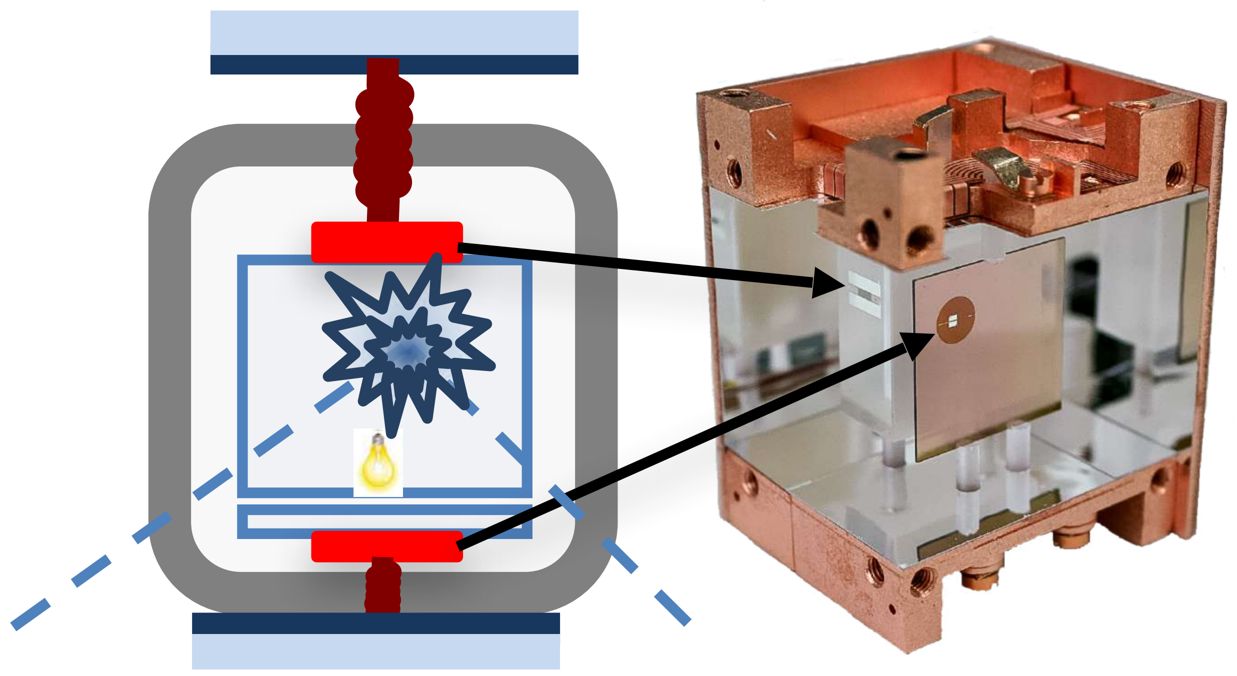
Heat only

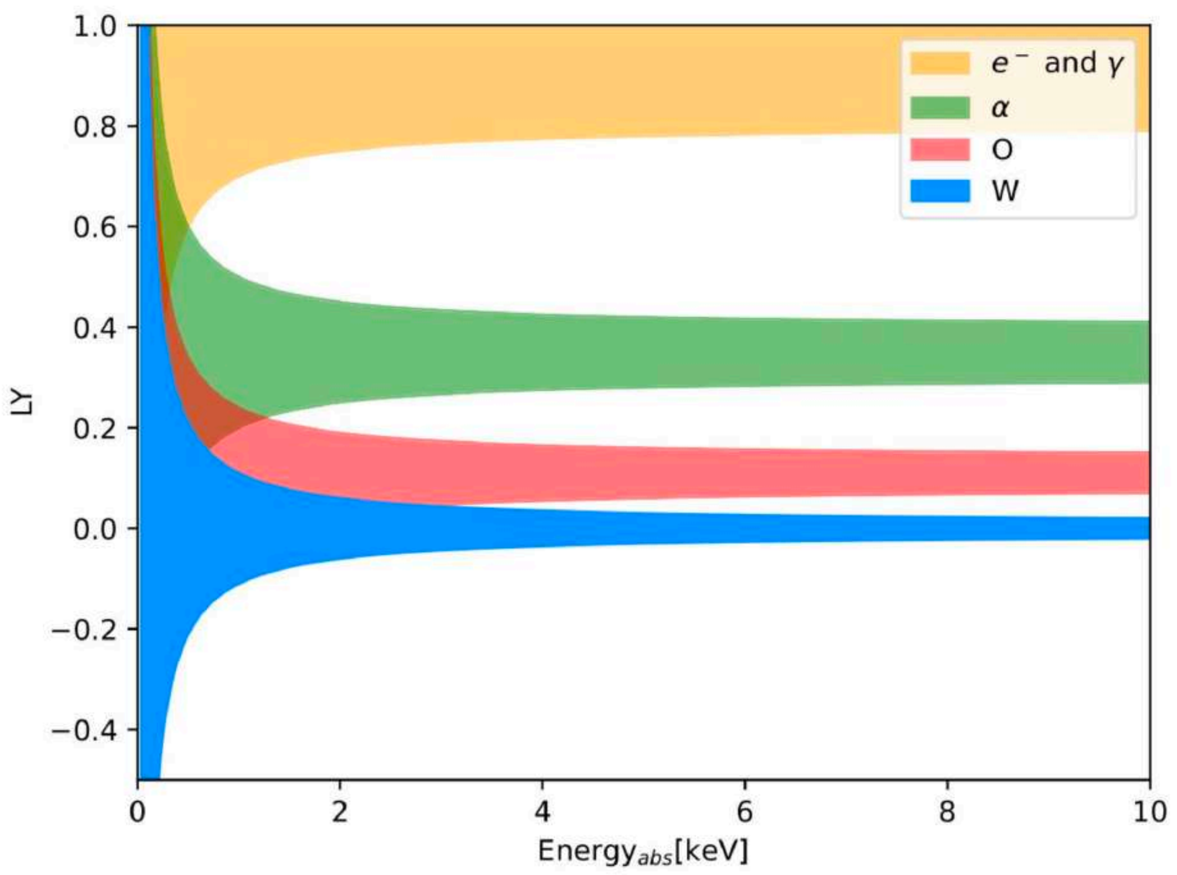




- ✓ Excellent energy resolution < 0.5%
- ✓ Very good energy threshold ~ few keV
- ✘ Poor PSD
- ✘ No Particle ID

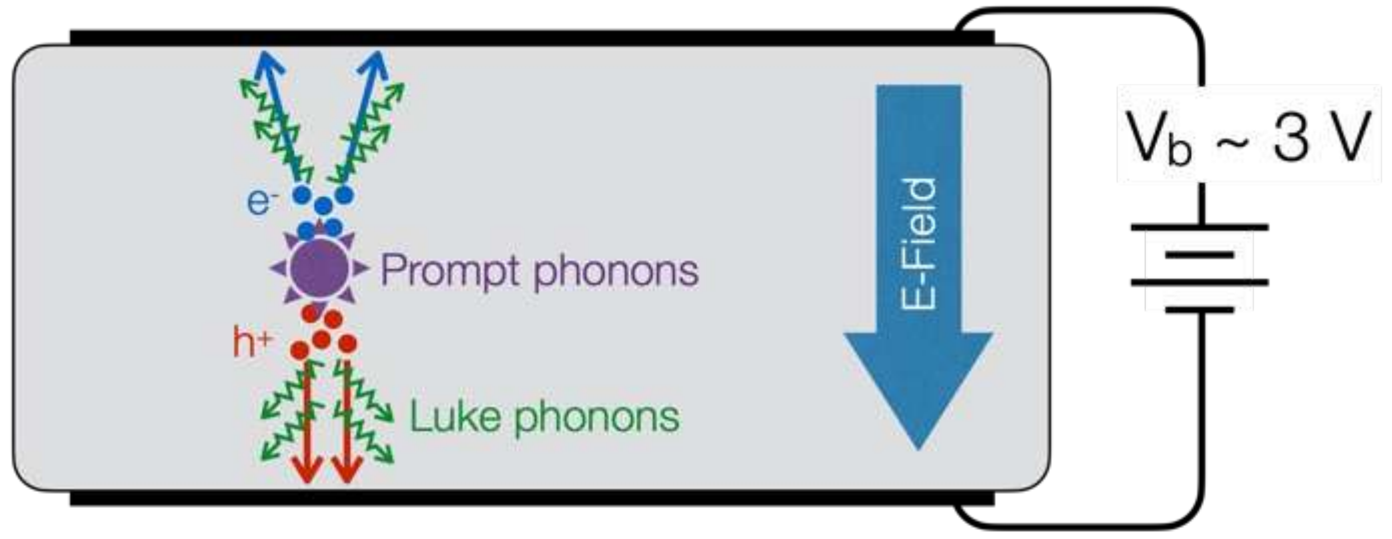
Heat + Light

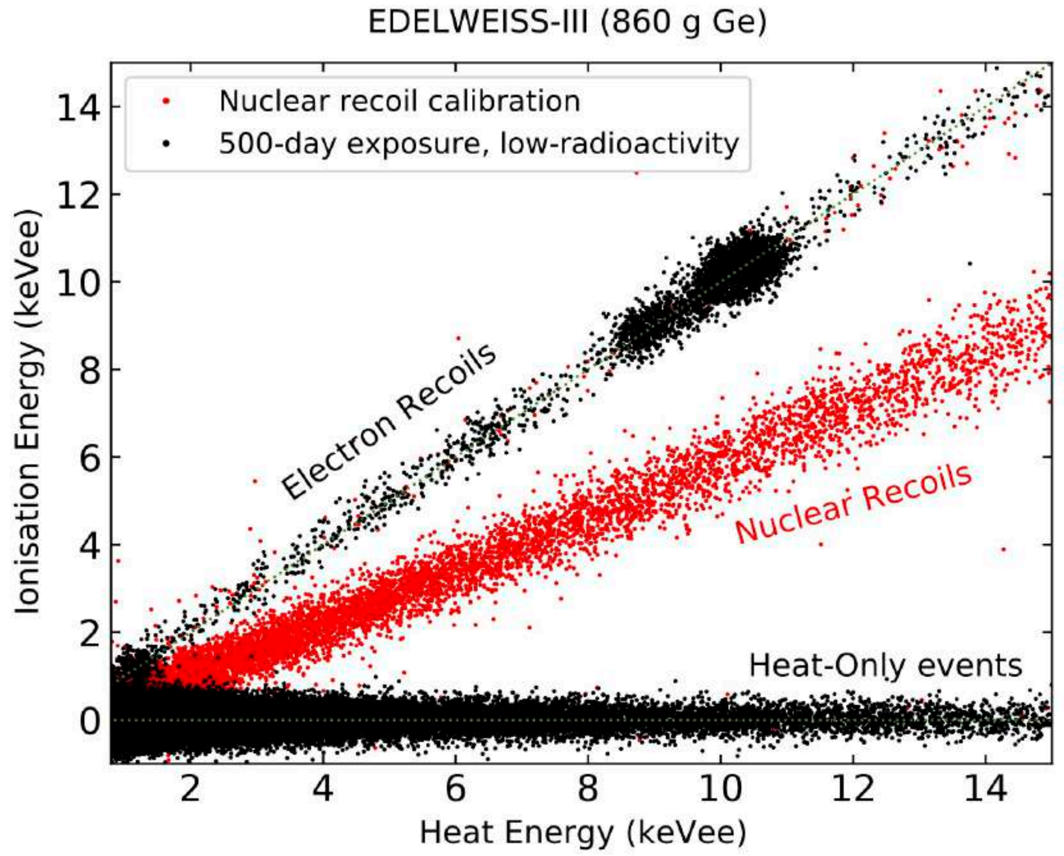




- ✓ Excellent energy resolution 1-5 eV
- ✓ Excellent energy threshold 10-30 eV
- ✓ Excellent Particle ID
- ✘ Mass Scalability

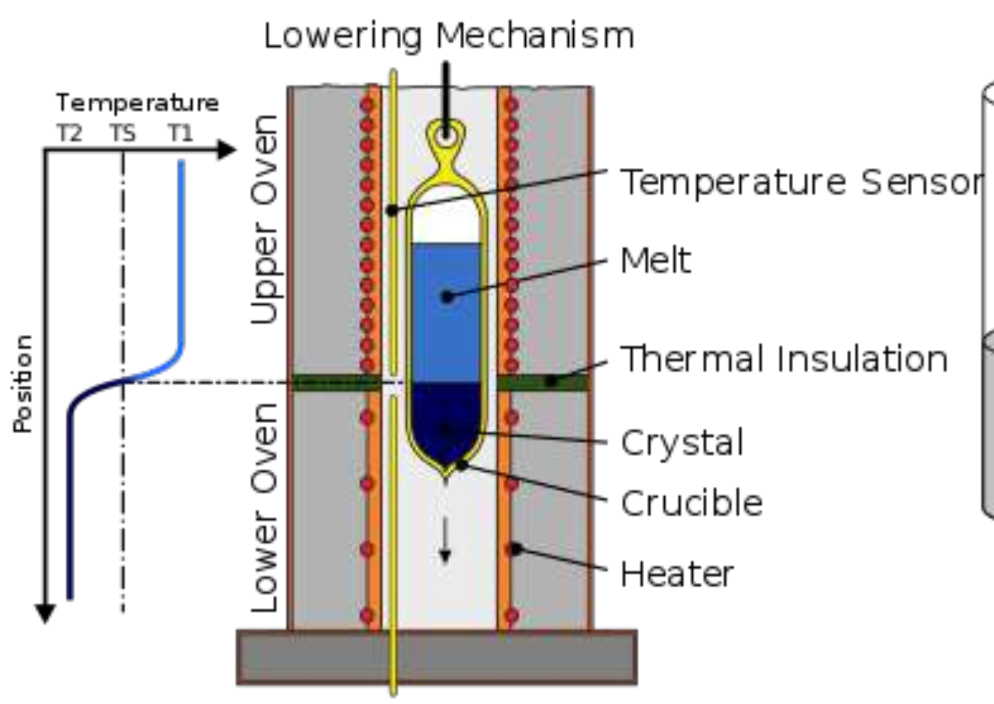
Heat + Charge



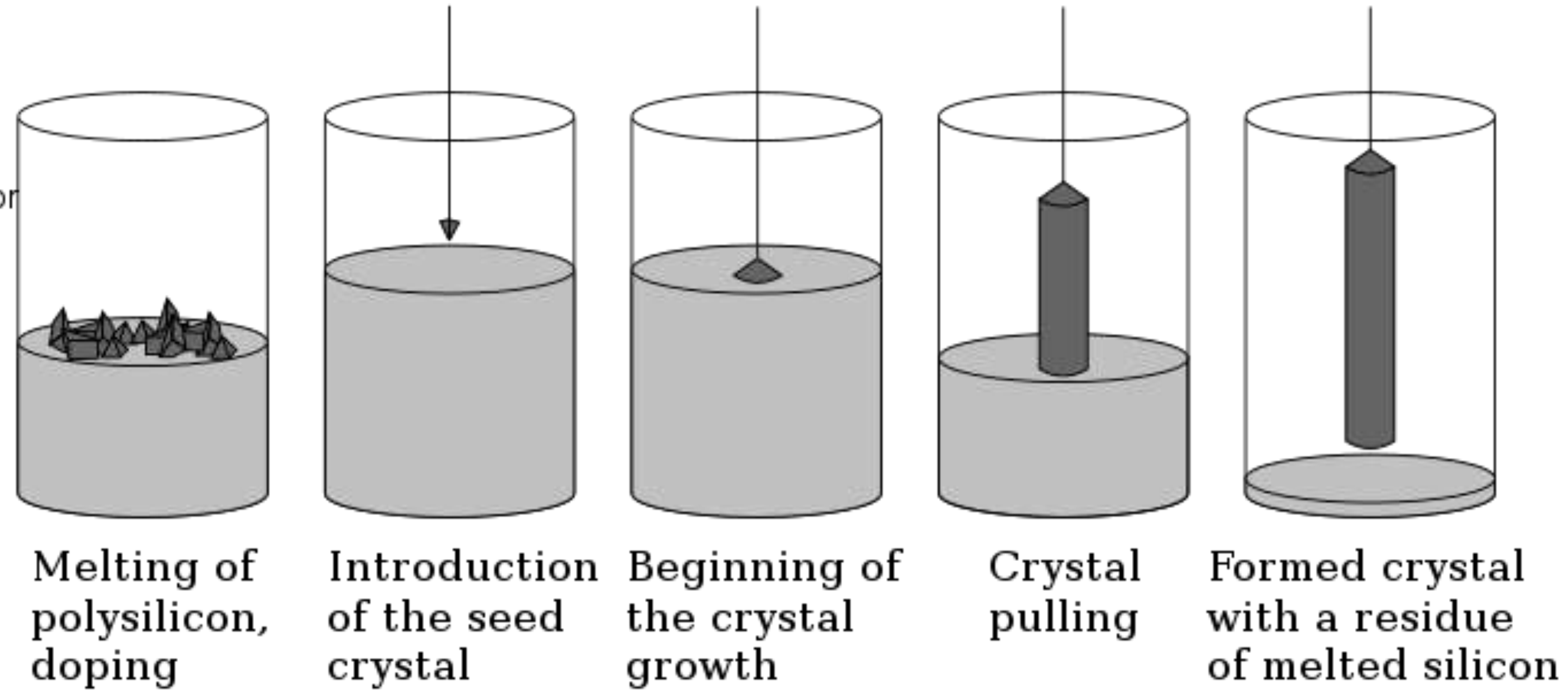


- ✓ Excellent energy resolution ~ 20 eV
- ✓ Excellent energy threshold (~100 eV)
- ✓ Excellent PSD (with iZIP)
- ✘ Mass Scalability

Surface contaminations



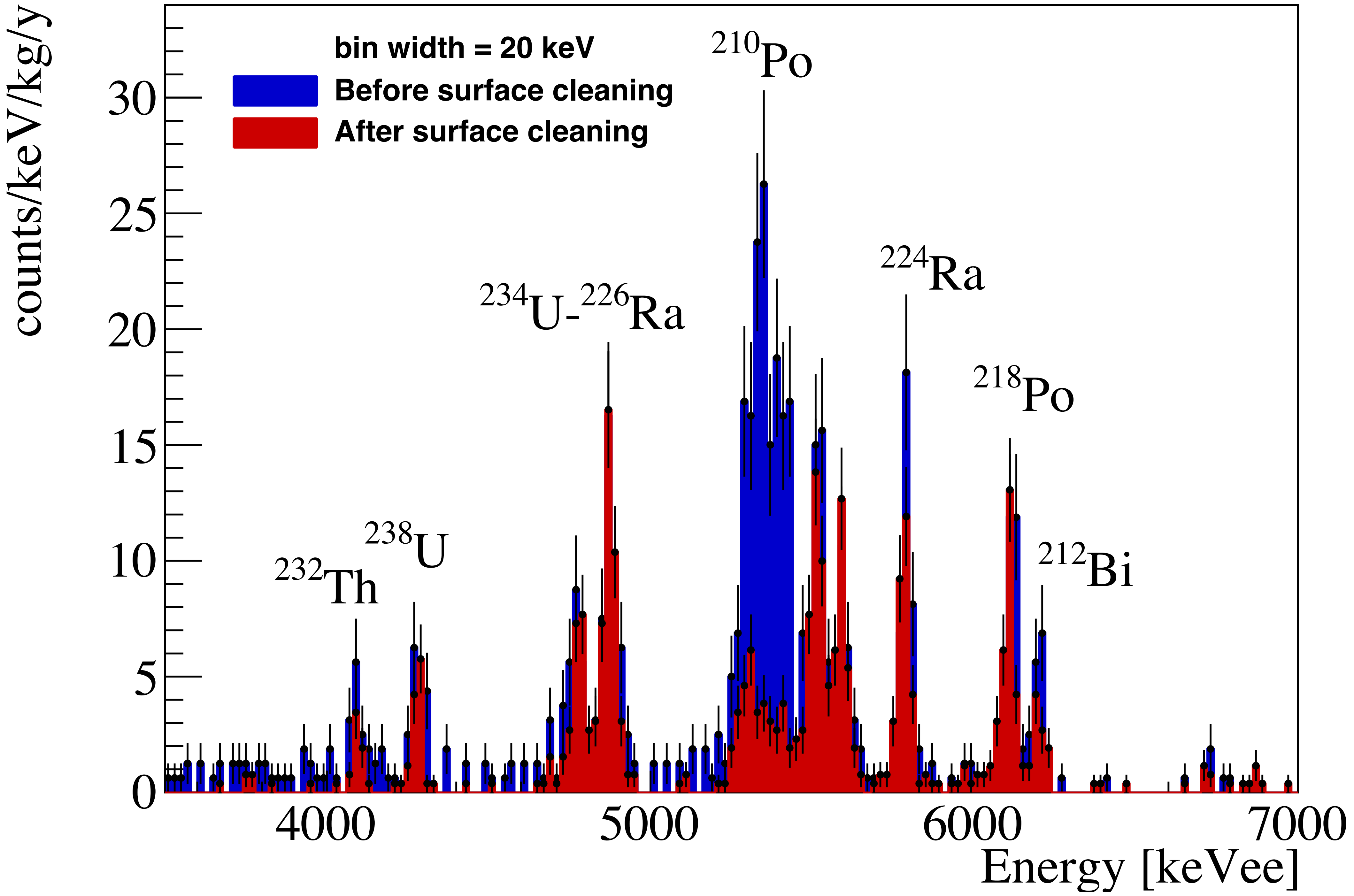
Bridgman



Czochralski

As-grown ingot

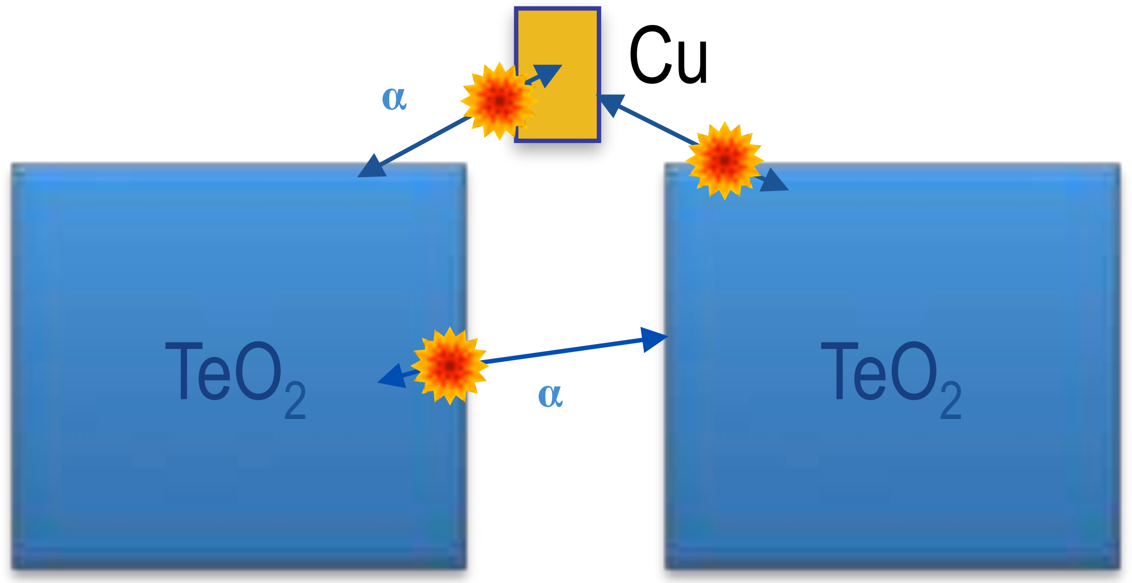
Final crystal



Origins

- Contact with crucible and machining tools
- Radon ➡ diffusion in air
  - glove-box
- Radium ➡ soluble in water
  - ultra-pure water

From CUPID-0 materials

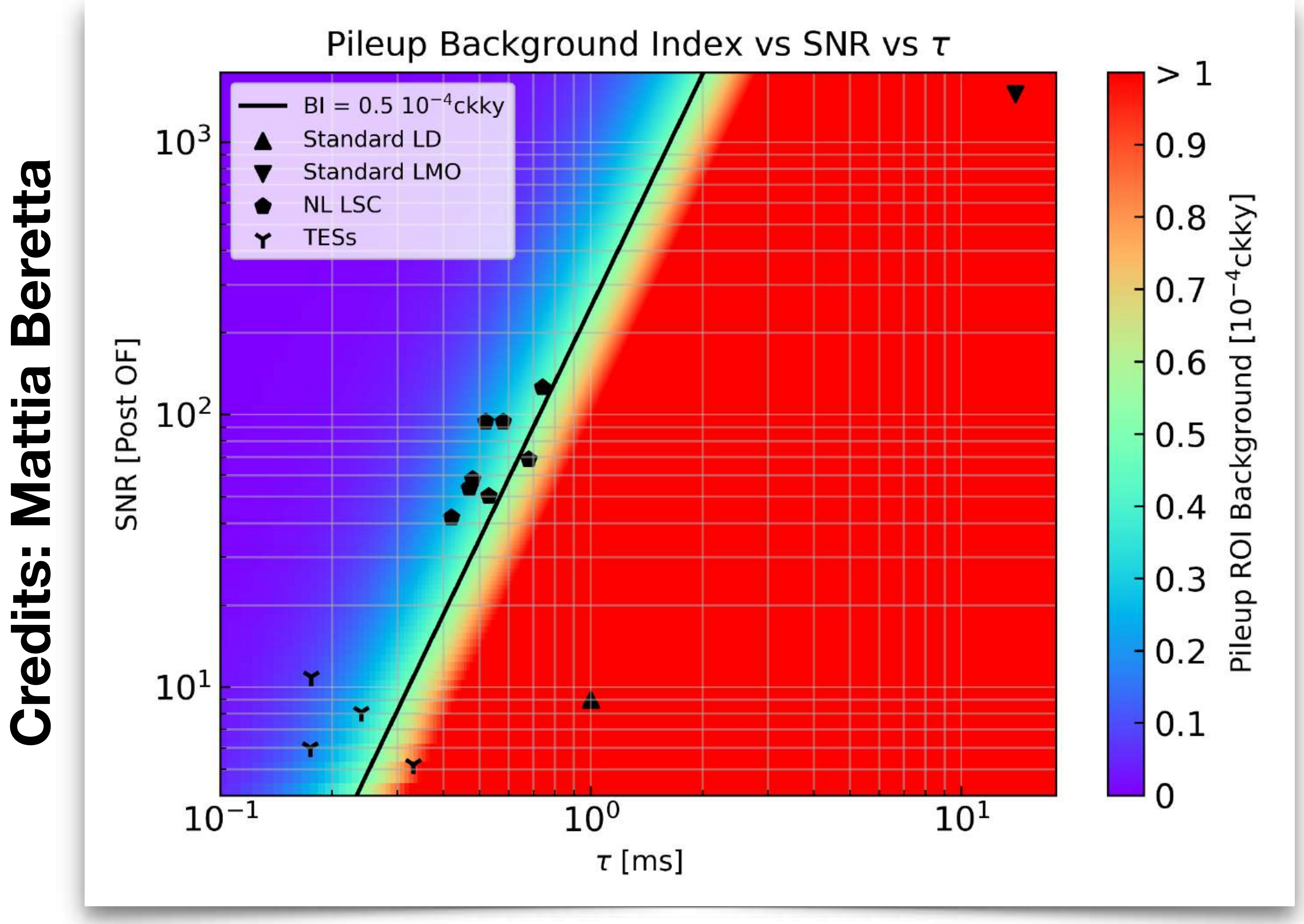


2νββ pileup

- Cryogenic calorimeters are **intrinsically slower** wrt other detectors
- Typical signal rise time for massive calorimeters [O(100) g] are

	NTD	TES	KID	MMC
Heat	~10 ms	~500 us	~ 35 us	~3 ms
Light	830 us (best)	~25 us	85 us	~500 us
Reference	Barucci et al.	G. Bratrud et al.	Casali, Cardani et al	AMoRe Exp.

- **Mo-100: golden candidate** for next-generation experiment
  - Light faster than heat but with smaller S/N ratio
  - **Fastest half-life** $T_{1/2}^{2\nu} = 7.7 \times 10^{18}$ yr
- Combination of solutions:
  - **heat + light** discrimination
  - **faster sensors** (smaller NTD, TES, KID, MMC)
  - light signal **enhancement** (NTL amp)



Low-Energy Excess & Heat-only events

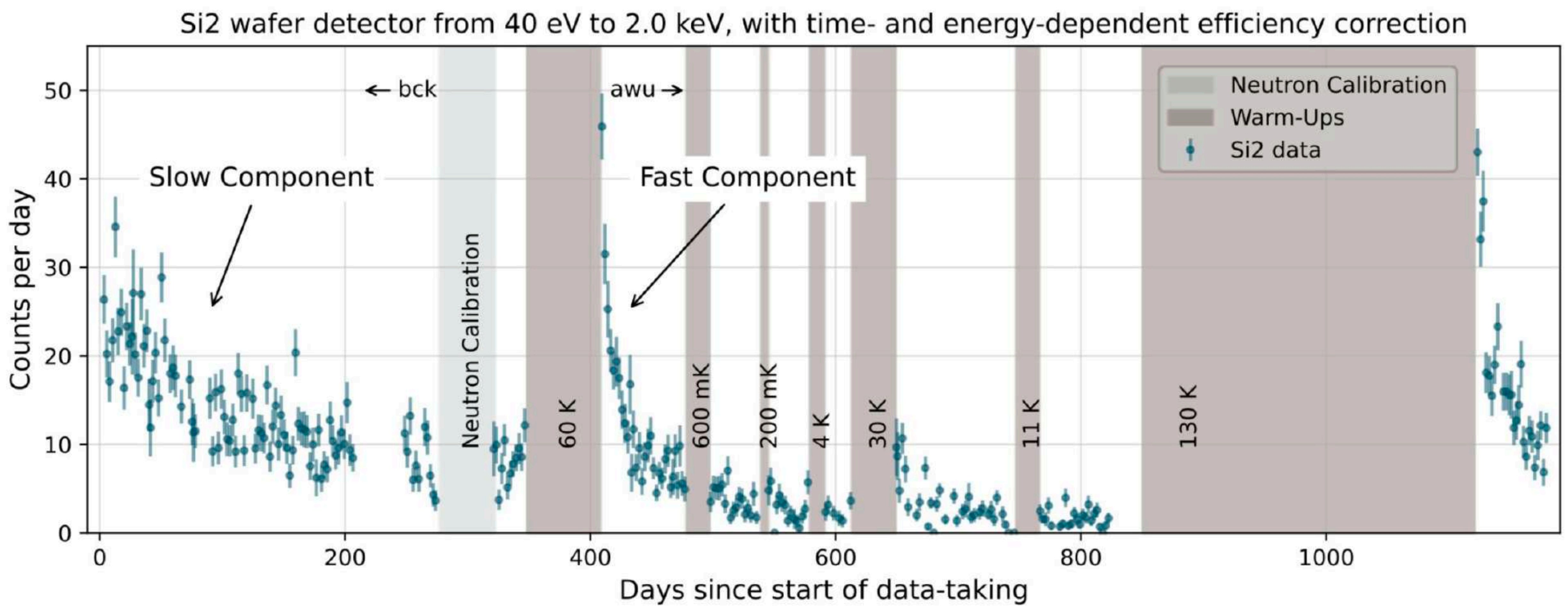
Several experiments based on cryo-calorimeters/bolometers observe an event excess at low-energy < 200 eV

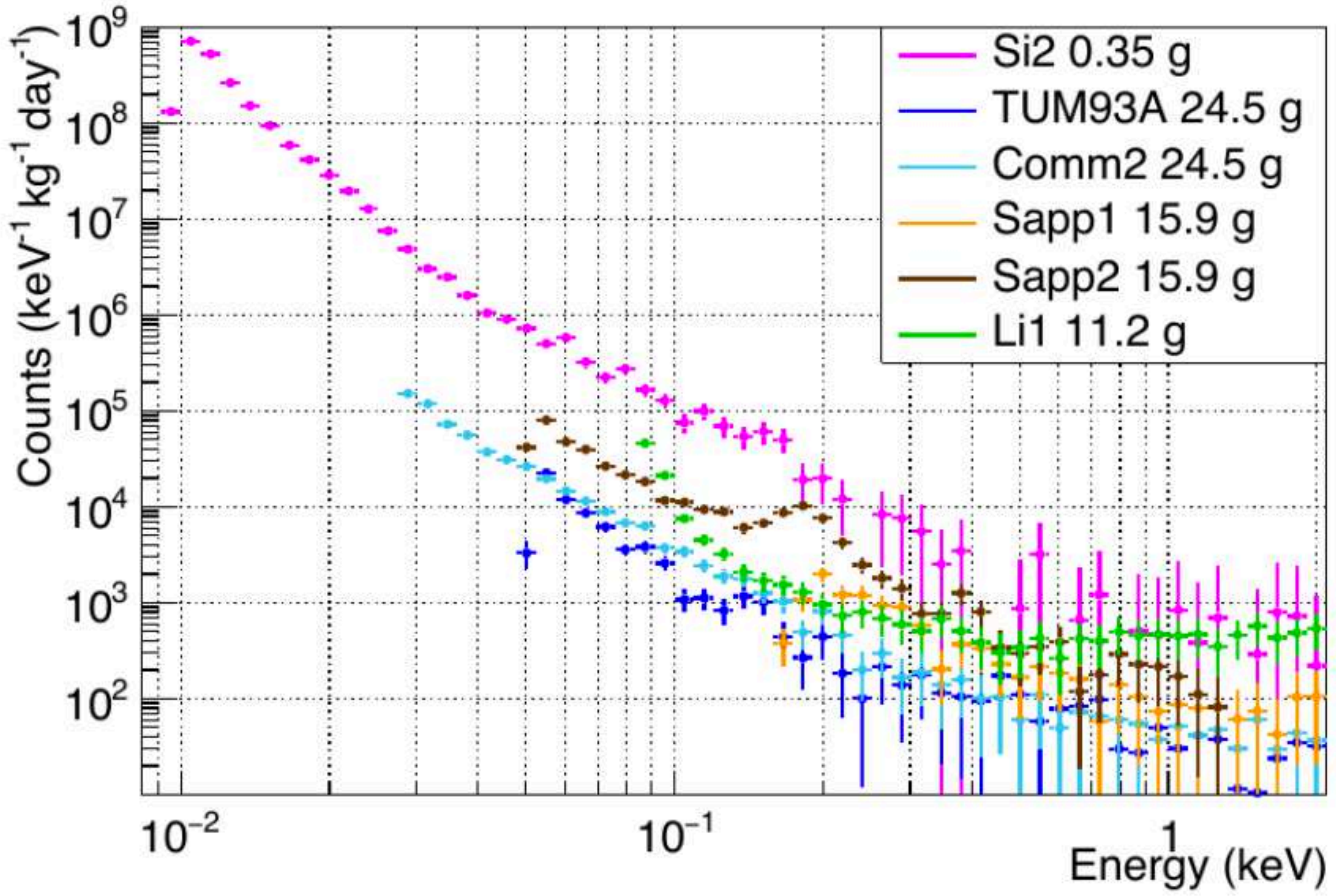
- **Mis-calibration**, **trigger effects**, and **passive scintillating** excluded
- Non compatible with **external radioactivity/common source**

- **Spectral shape** described by a single power-low

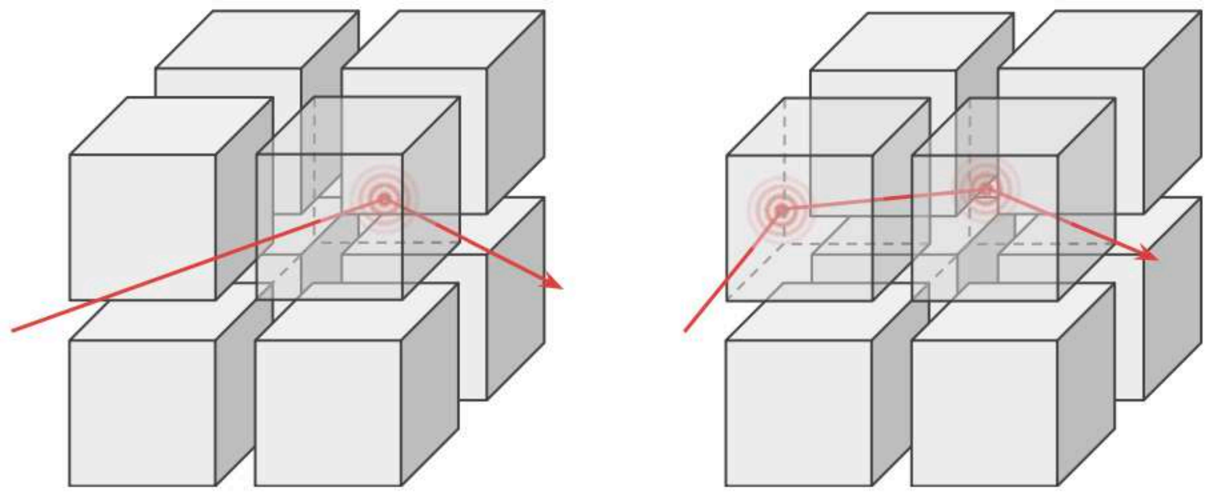
- Event Rate **decays exponentially** in time
- Event rate **rests after warm-up cycles**
- Similar rate regardless difference in **mass, surface, material, TES dimensions**

origin at the **interface between crystal and TES** caused by the mismatch in the Thermal Expansion Coefficient (test ongoing…)

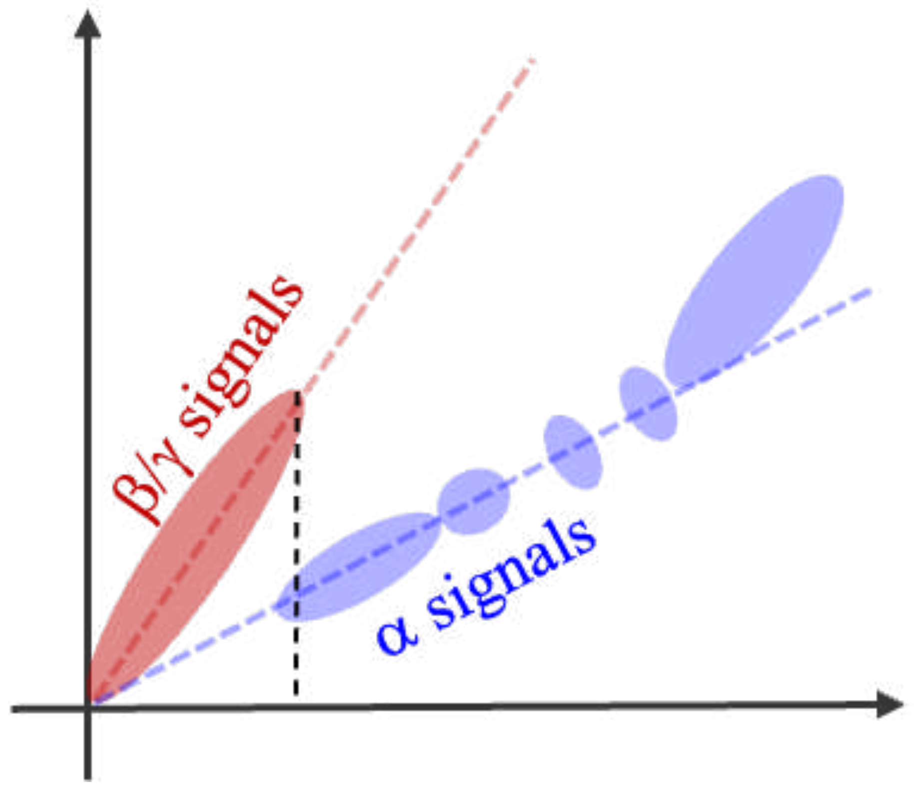




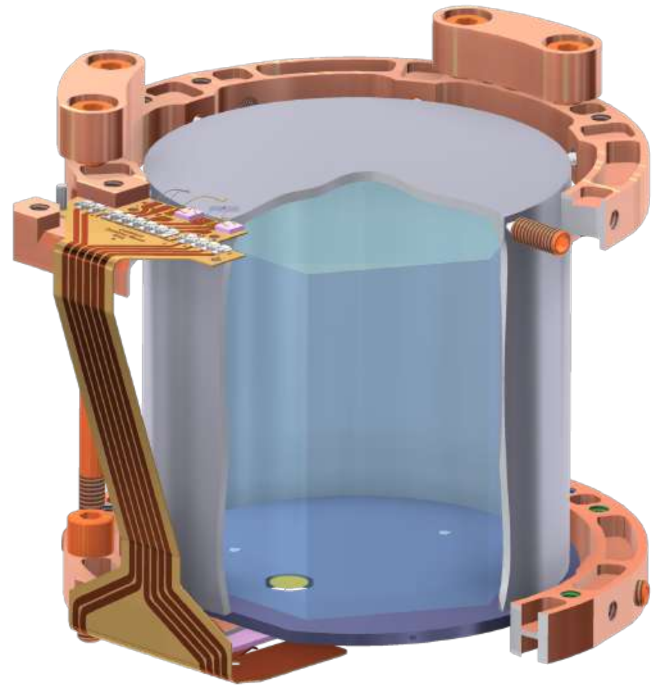
Major Rejection Techniques



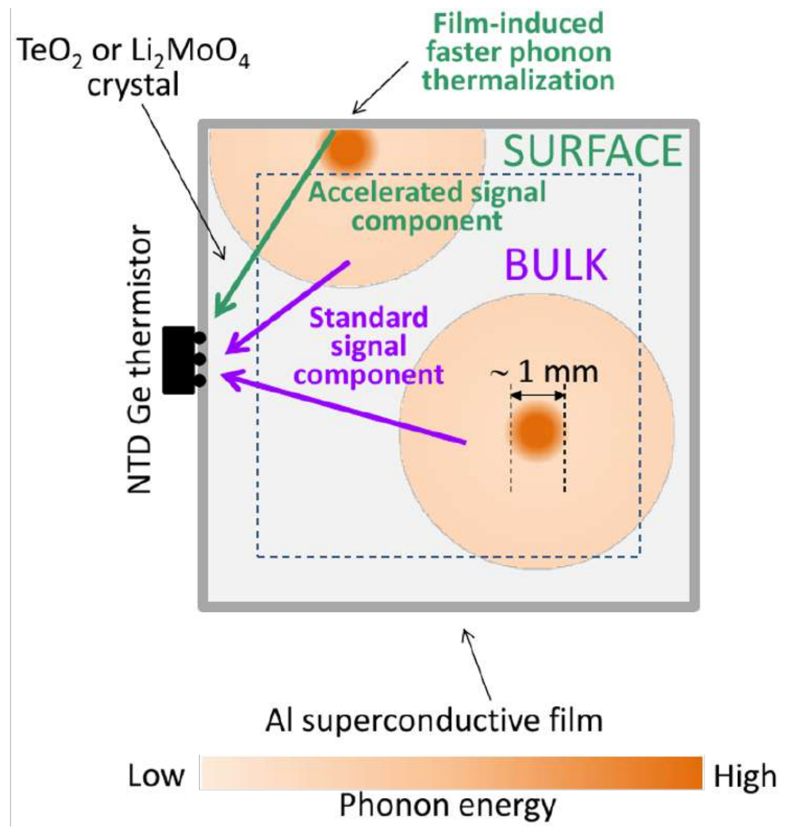
Detector Modularity (surface events / multi-Compton γ-rays)



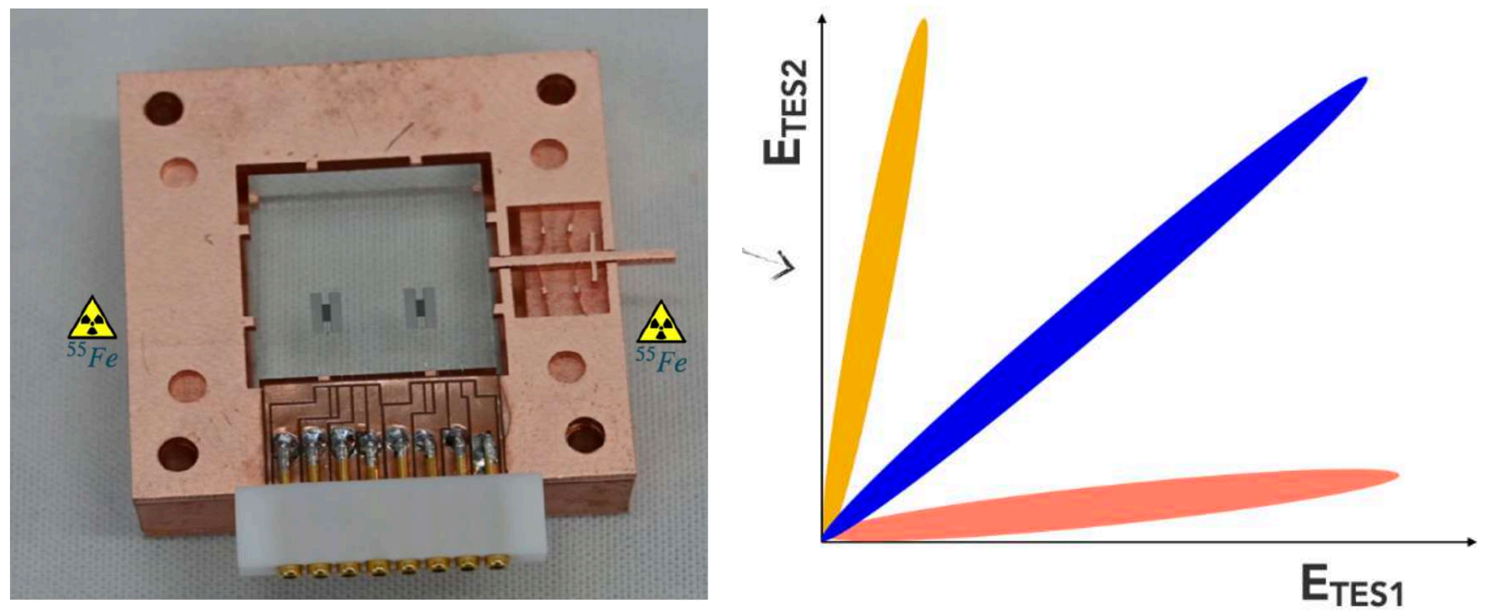
Light/Charge assisted Particle ID (α-particles / e-recoil)



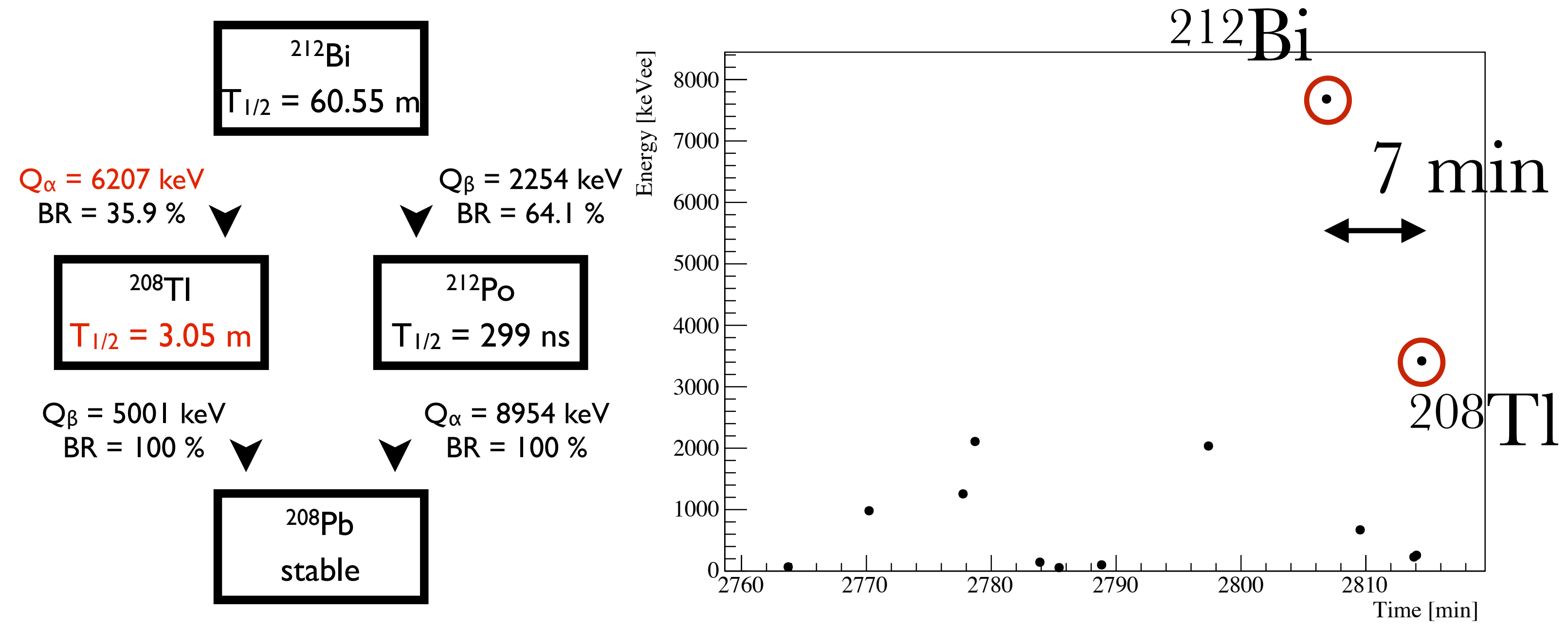
Light Detector as 4π Active Veto (surface events)



Surface sensitivity



Multi-sensor approach (Low Energy Excess ?)



Delayed Coincidences (Radioactive chains)

SWOT table for cryogenic calorimeters

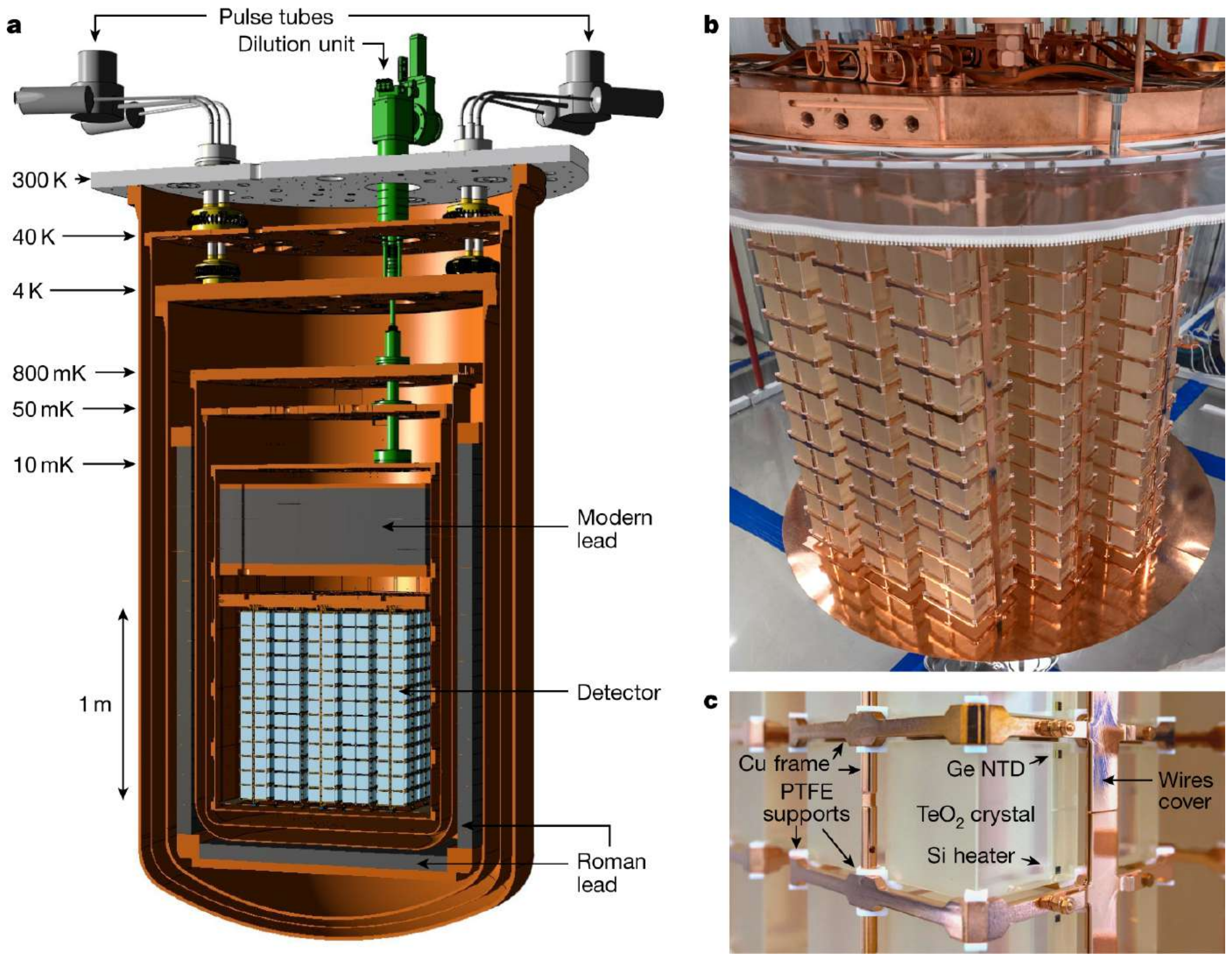
STRENGTHS	WEAKNESSES

○ Excellent energy resolution (~0.5 %)
○ High containment efficiency
○ Low-energy threshold
○ **Versatility in the material choice**
  ○ **Se-82, Mo-100, Te-130, Cd-116**
  ○ **Ge, Si, $CdWO_4$, $CaWO_4$, CsI, NaI**
○ High Q-value
  ○ lower intrinsic background
  ○ higher $\mathcal{G}^{2\nu}(Q_{\beta\beta}, Z) \propto Q_{\beta\beta}^{11}$
○ Modularity
  ○ Scalability without performance spoiling
  ○ Muti-isotope approach
	○ No tracking
	○ Short $2\nu\beta\beta$ half-life (Mo-100)
	○ **Surface events sensitivity**
	  ○ no “protective” dead layer of fiducial volume
	○ Technological effort in cryogenics for mass scalability
	  ○ More difficult with respect to loaded LS
	○ **Intrinsically slow detector response**
	○ No $\beta\beta$-daughter tag
	○ No Liquid Argon active veto (as Ge Diodes)

OPPORTUNITIES	**THREATS**
○ More experiments in the same infrastructure ○ Multipurpose experiment ($0\nu\beta\beta$ - DM - SNν)	○ Isotopic enrichment

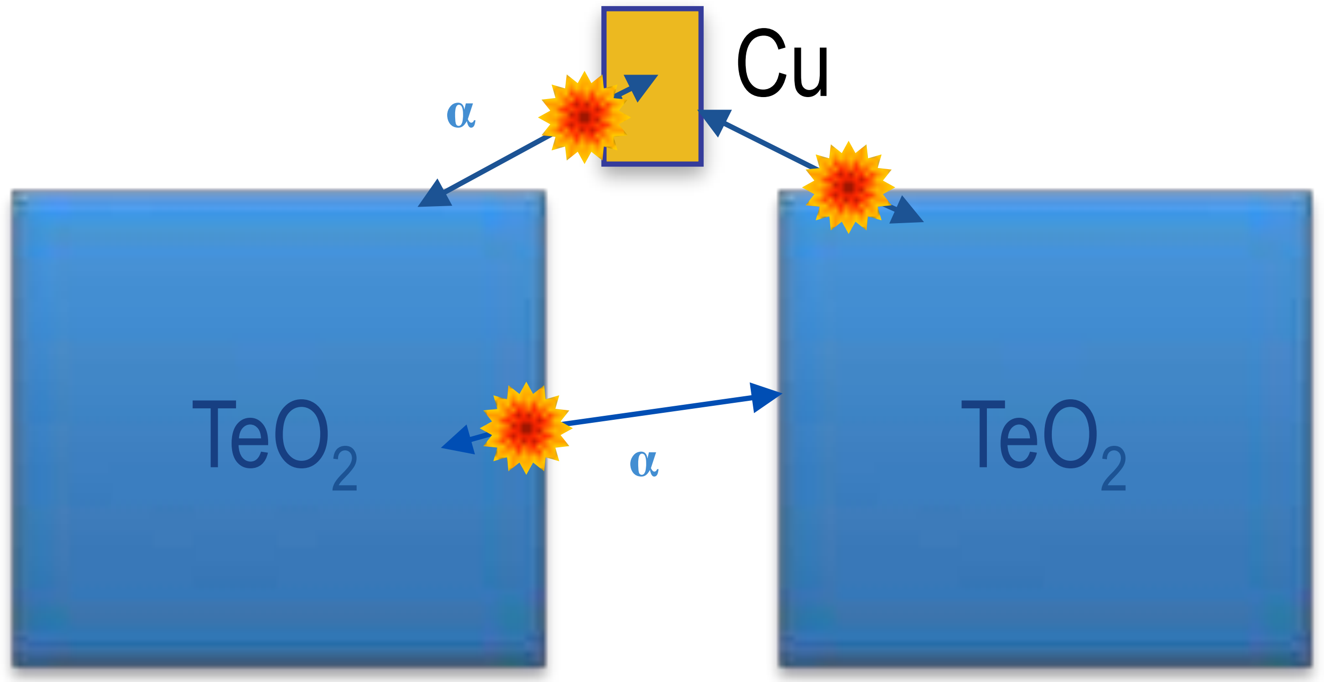
Neutrinoless Double Beta Decay Search with Cryogenic Calorimeters

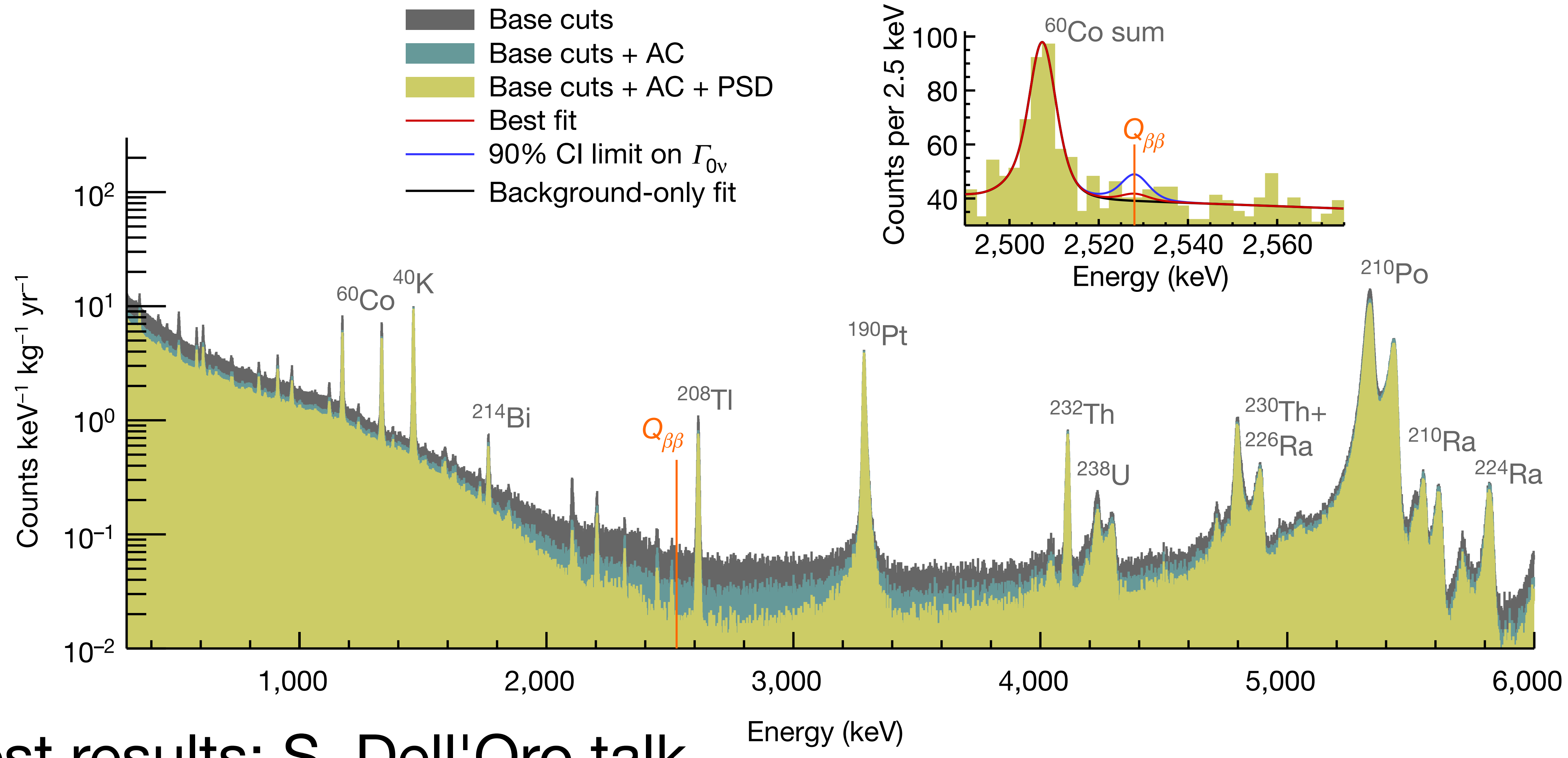
The CUORE Experiment



One of the most advanced application of LTD

- 988 natural TeO_2 crystals @ ~ 15 mK
- NTD readout
- Total mass : 742 kg of TeO_2 (~206 kg ^{130}Te)
- Current exposure: 2 ton x yr
- FWFM ~ 7.3 keV
- **Background index ~ 1.4 x 10^{-2} counts/keV/kg/yr**





Nature 604, 53–58 (2022)

Latest results: S. Dell'Oro talk
Low-energy: A. Ressa talk
Background model: S. Ghislandi poster

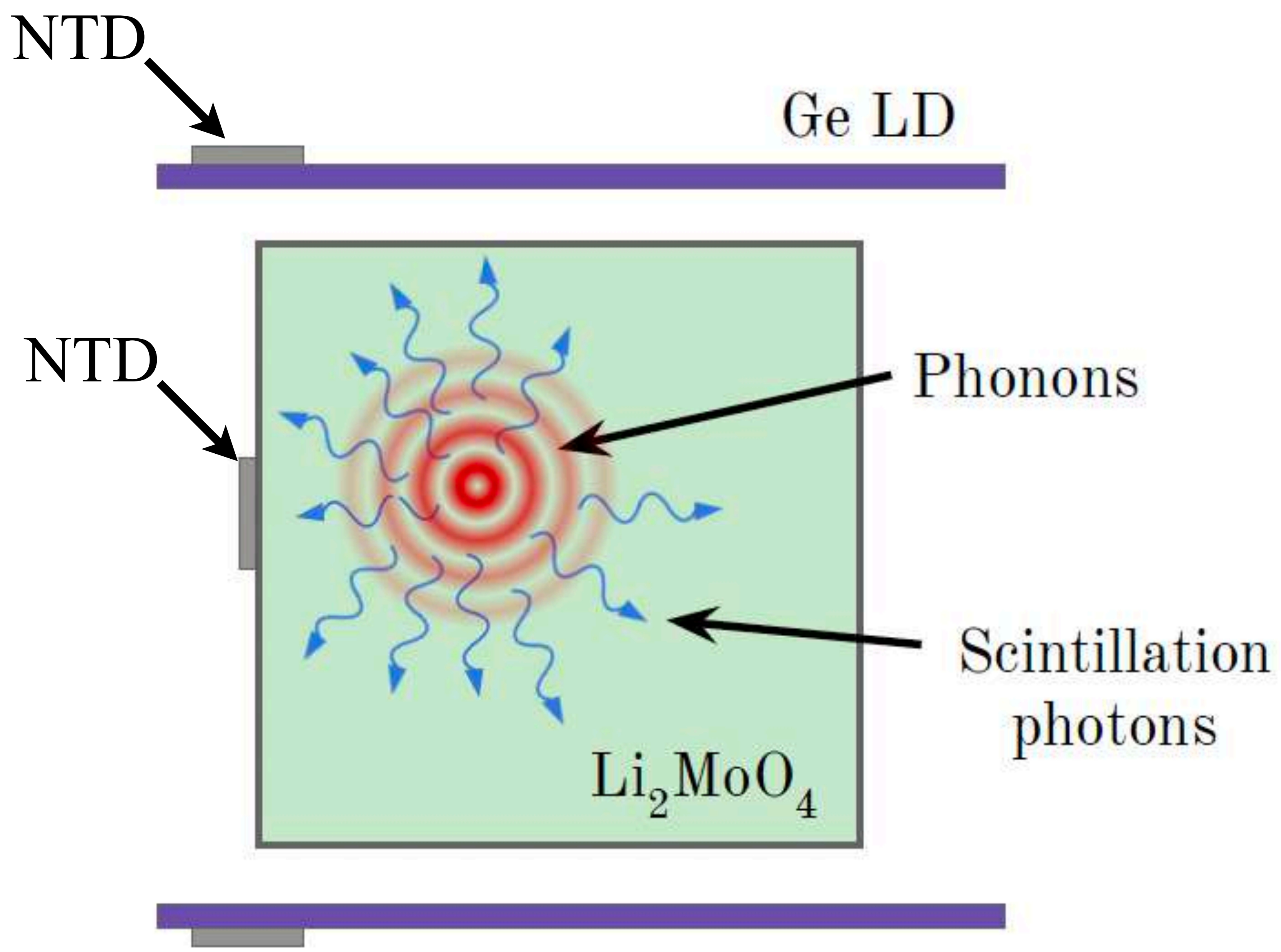
CUPID - CUORE Upgrade with Particle ID

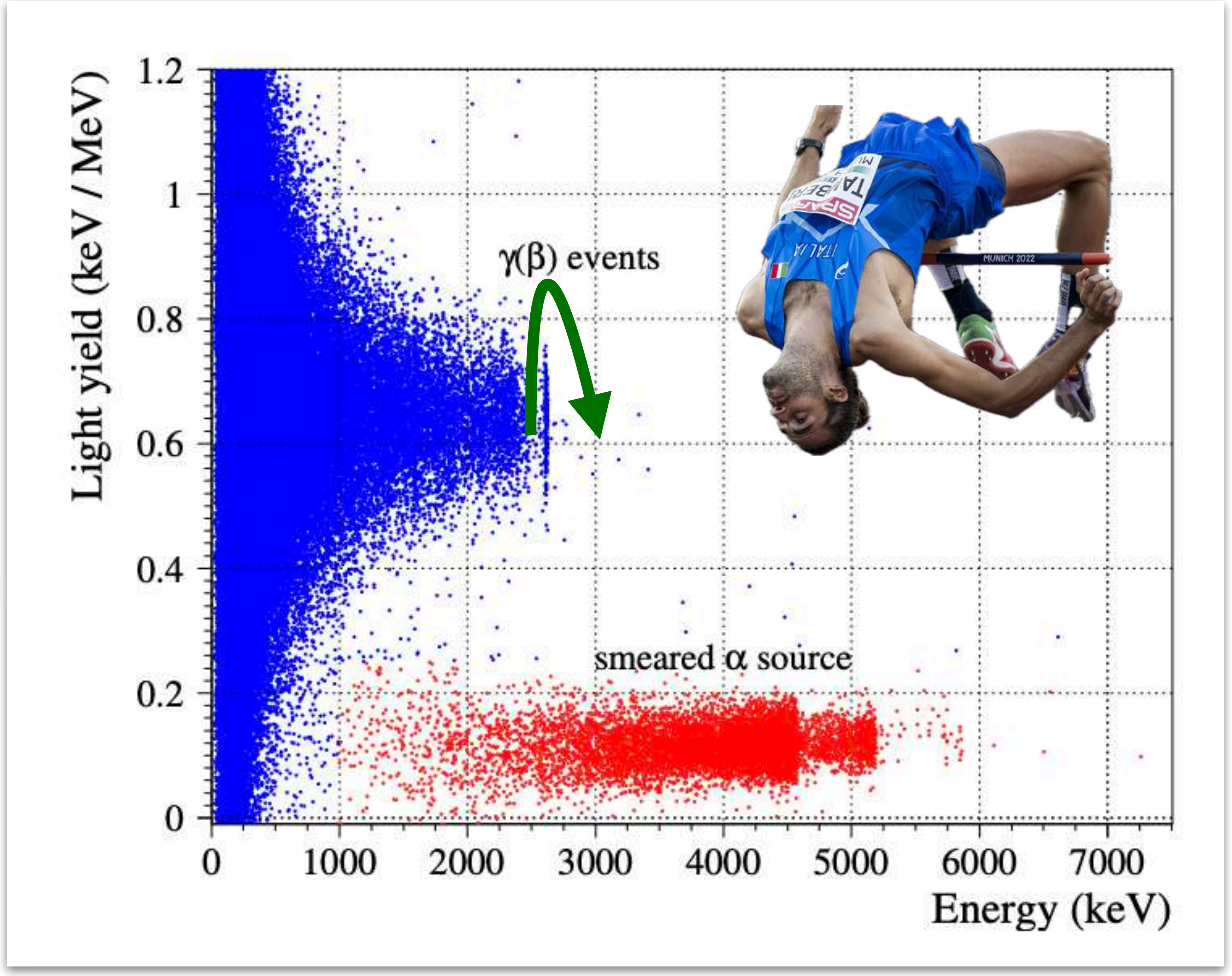
Main Features

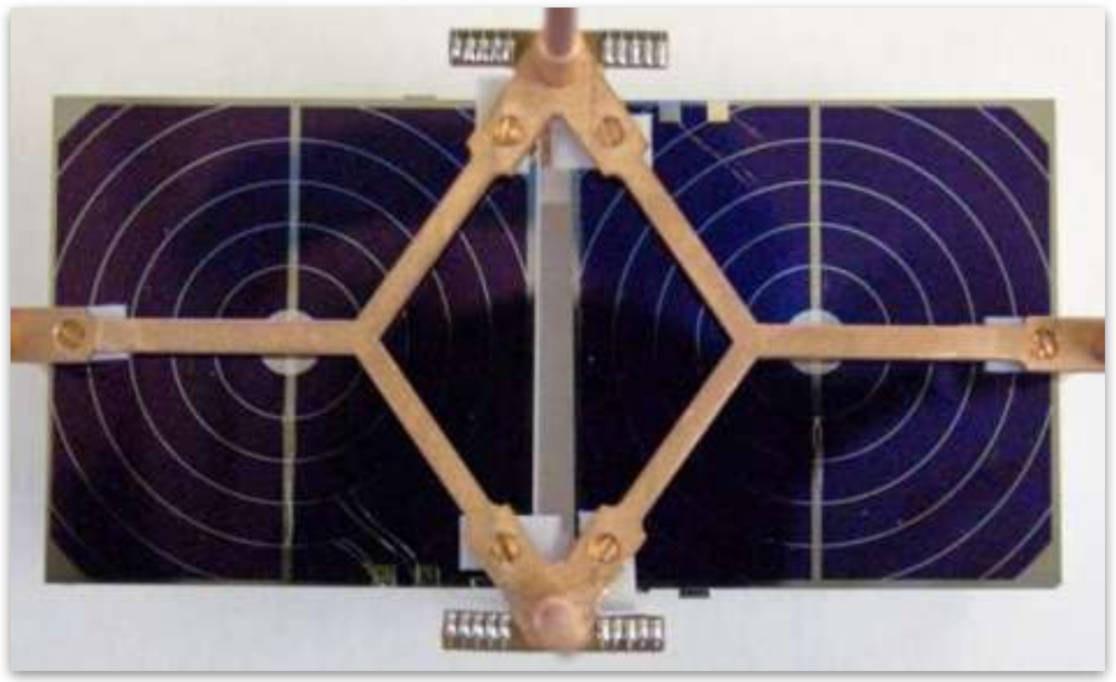
- ~1600 **enriched Li_2MoO_4** crystals @ ~ 15 mK
- CUORE infrastructure + CUPID-0/CUPID-Mo
- Total mass : 450 kg of LMO (~240 kg ^{100}Mo)
- FWFM (Goal) ~ 5 keV
- **Background index ~ 1 x 10^{-4} counts/keV/kg/yr**

Background improvements wrt CUORE

- Light Assisted PID ➡ α rejection
- From ^{130}Te to ^{100}Mo ➡ β/γ reduction
- NTL amplification of light signal ➡ pileup rejection
- Muon Veto (test ongoing in CUORE)
- New neutron Veto (design ongoing)



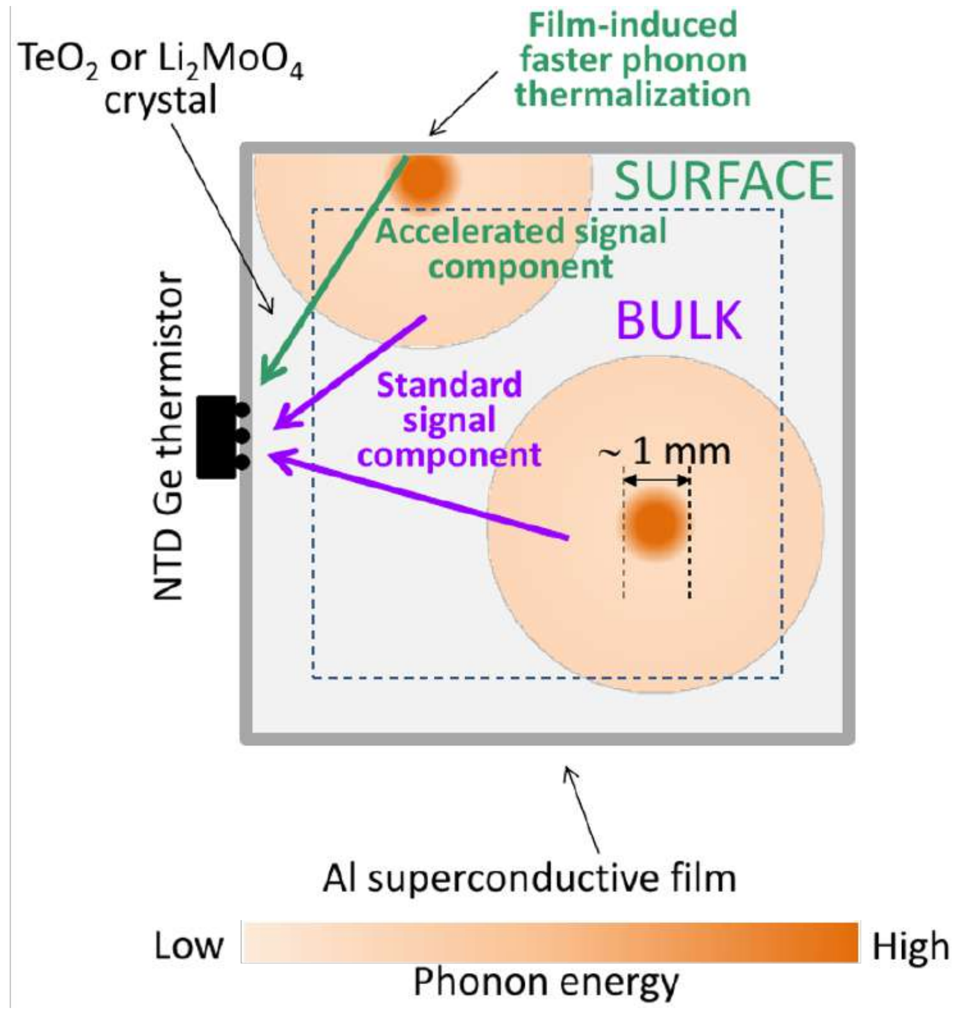




Background budget: P. Loiza talk

CUPID's family and friends

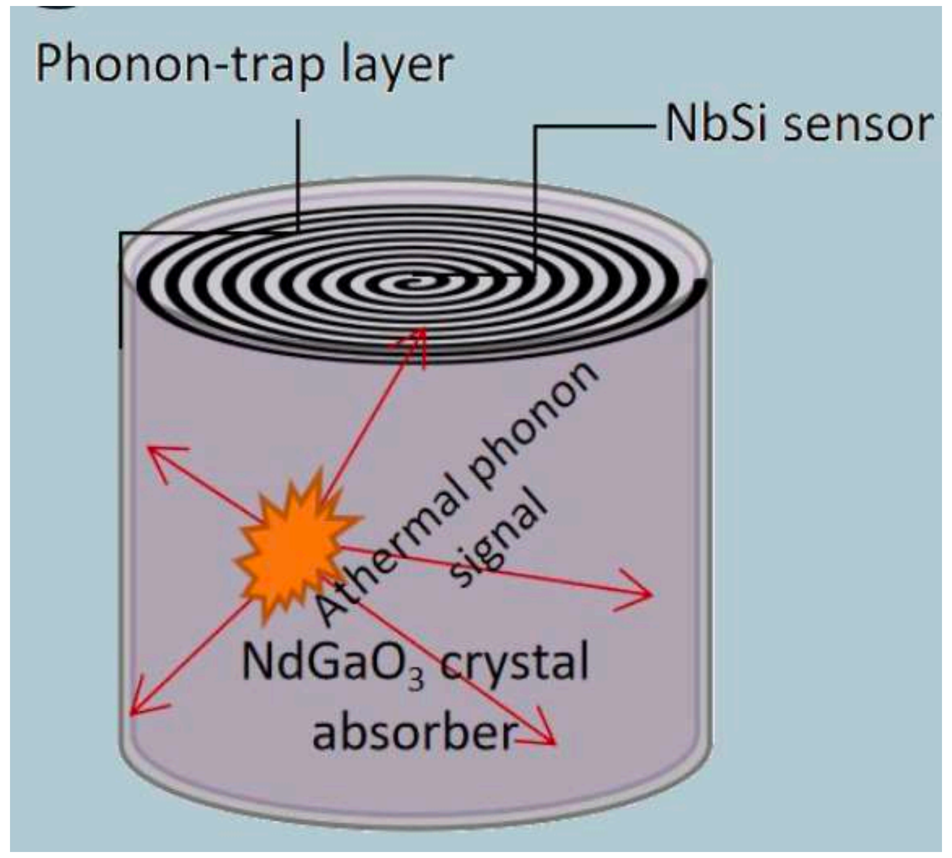
Surface sensitivity
+
NTL amplification of light signal

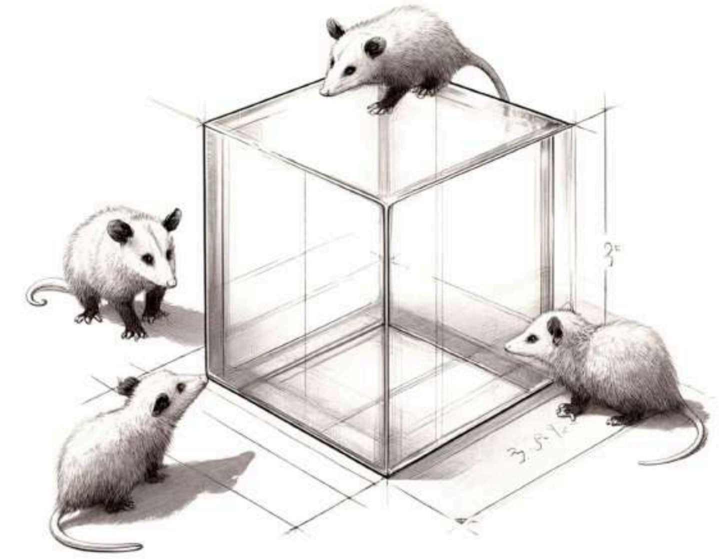


Multi-isotope approach
+
Active inner veto
+
NTL amplification of light signal

See D. Poda talk

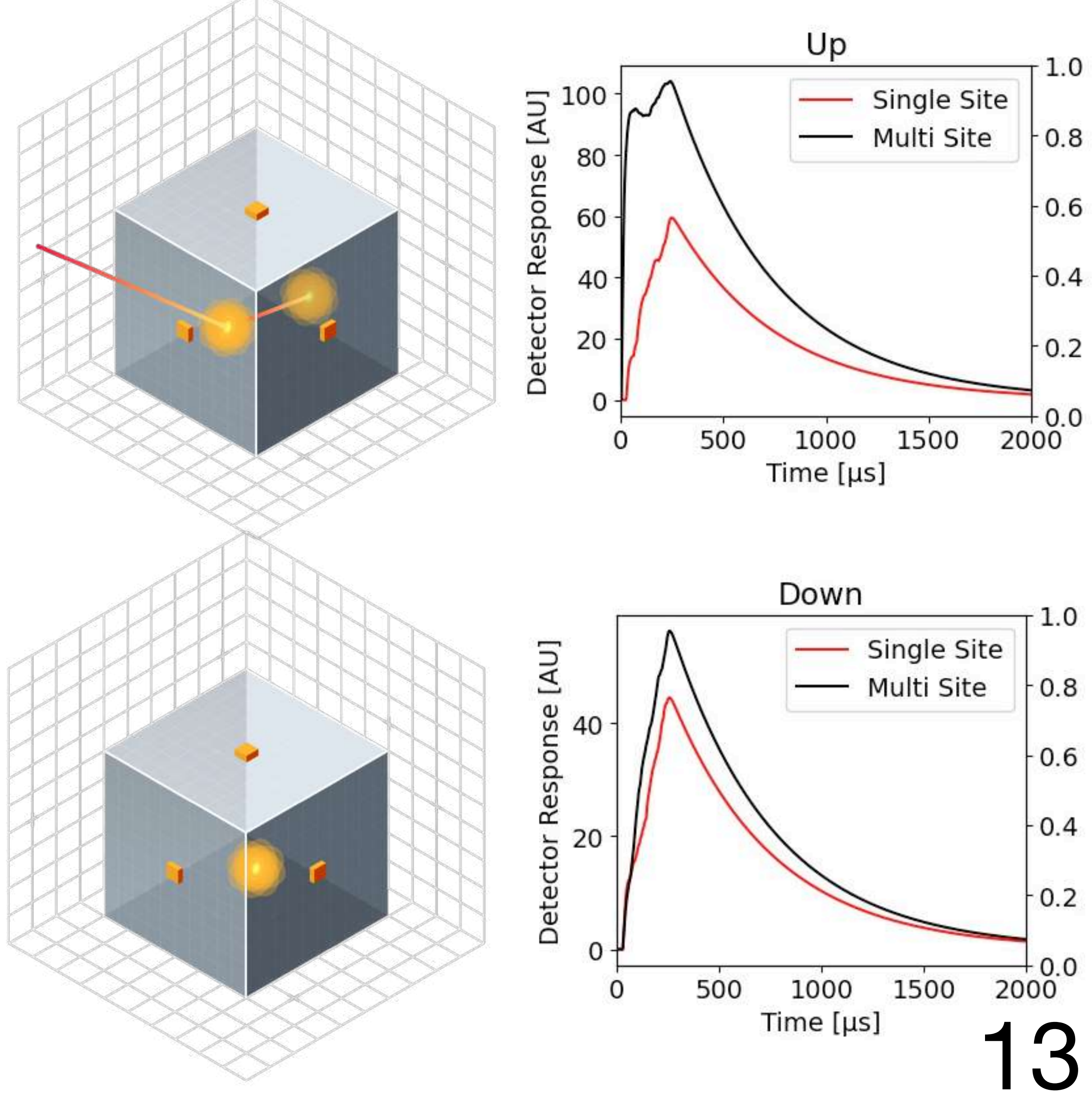
New isotopes with higher Q-values (Nd-150 and Zr-96)



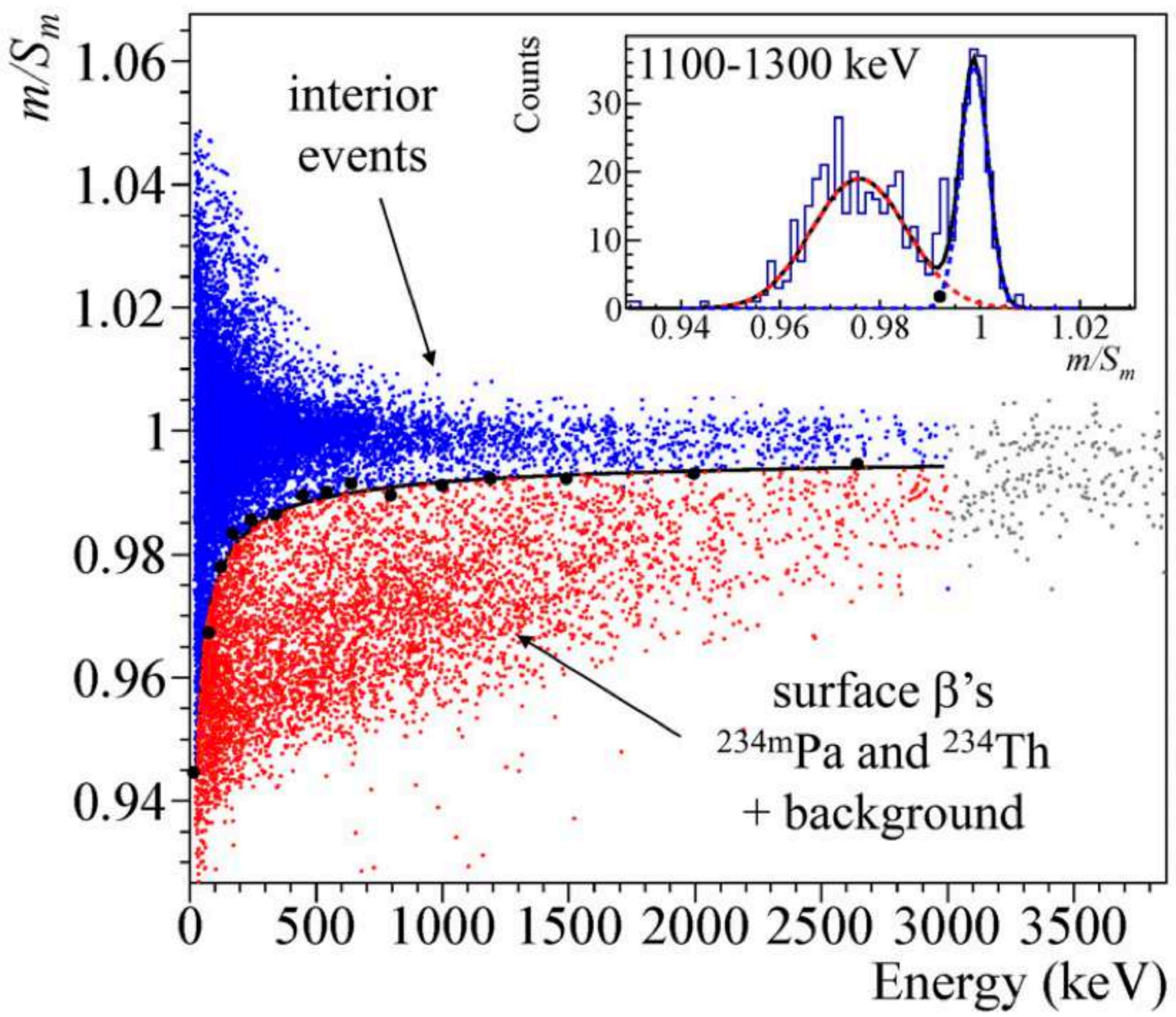


OPOSSUM

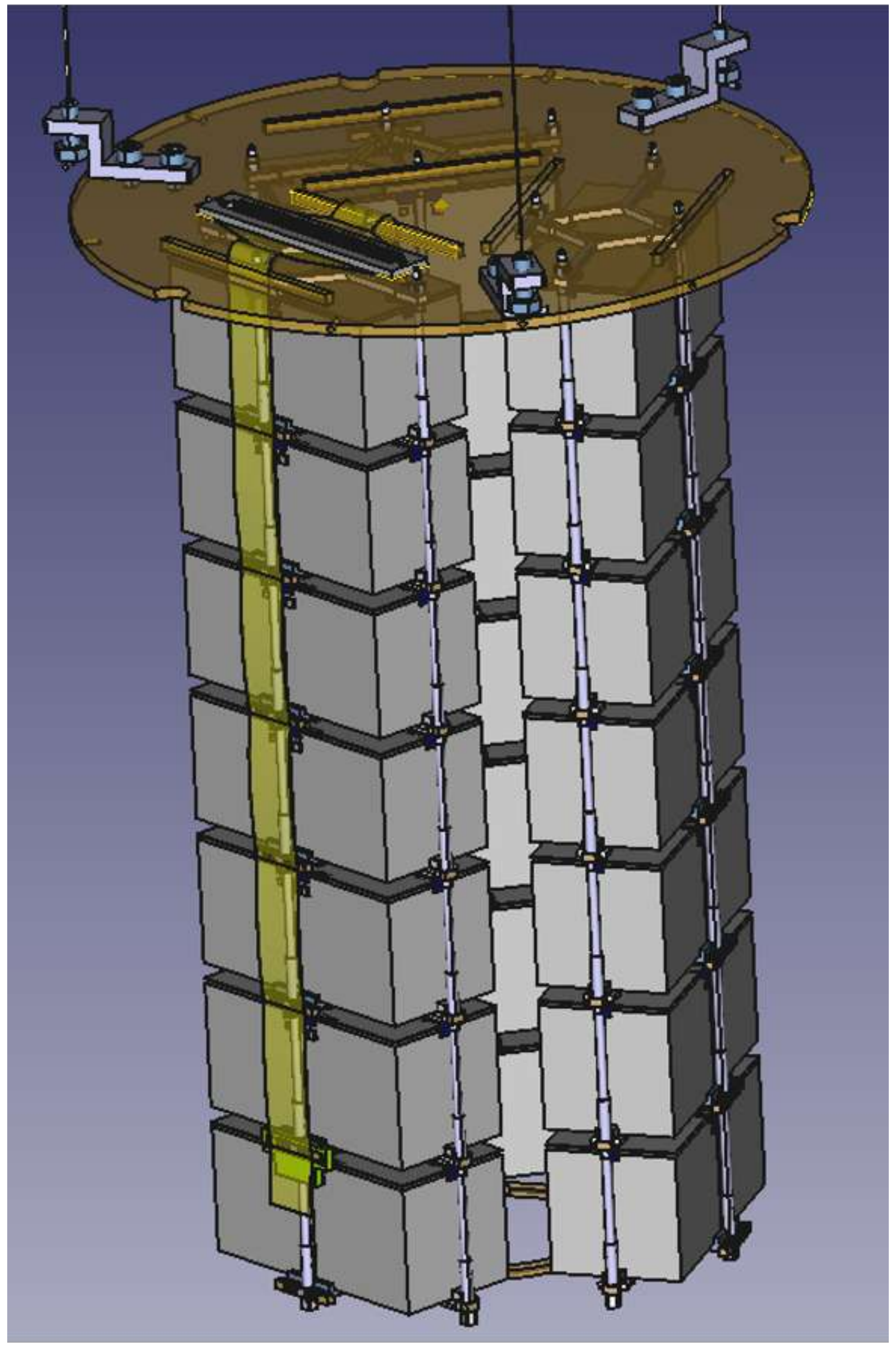
Single Side vs Multi Side discrimination with fast MKID sensors



CUPID's family and friends

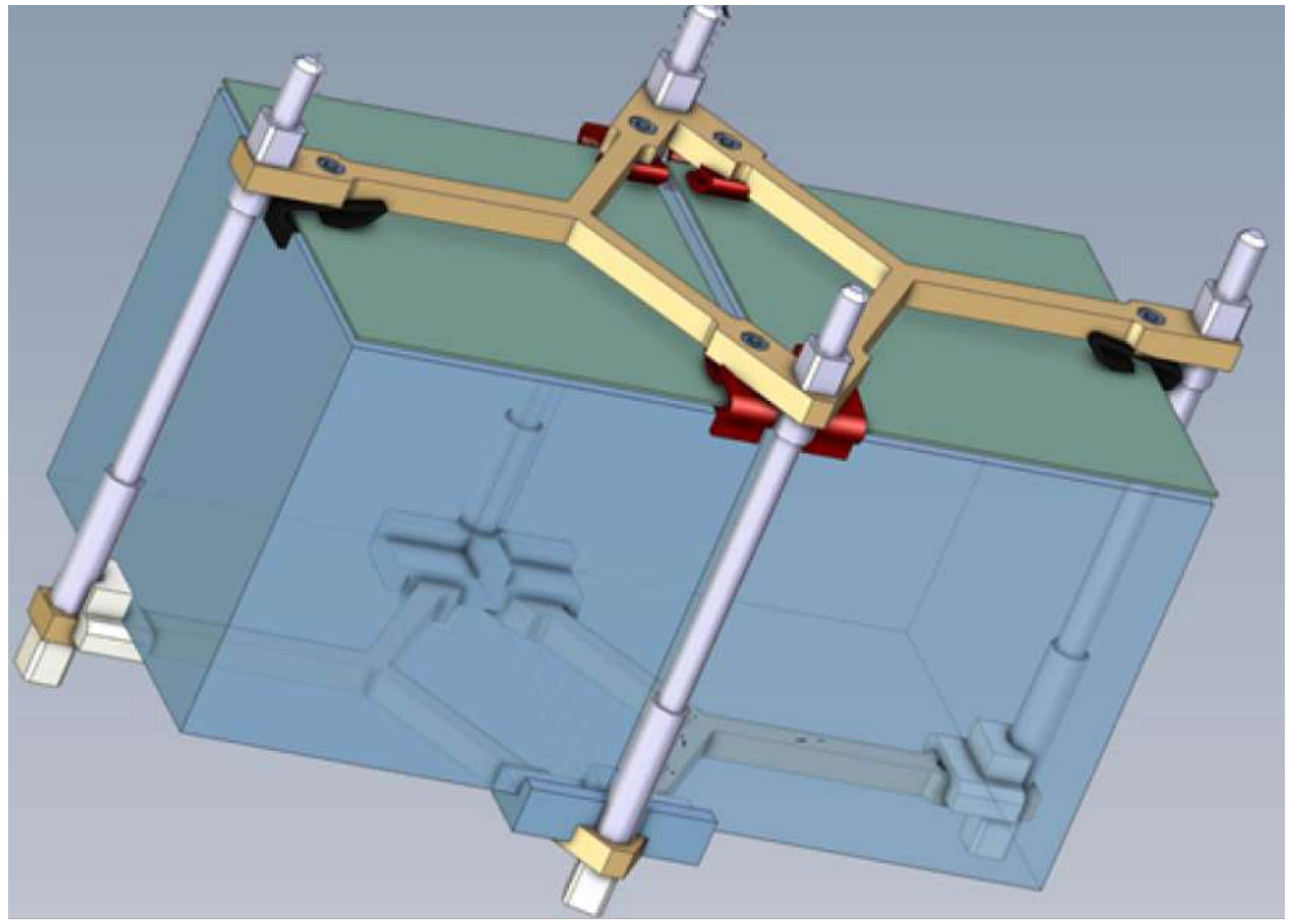


Li$_2$MoO$_4$ detector with an Al–Pd coating exposed to a uranium source



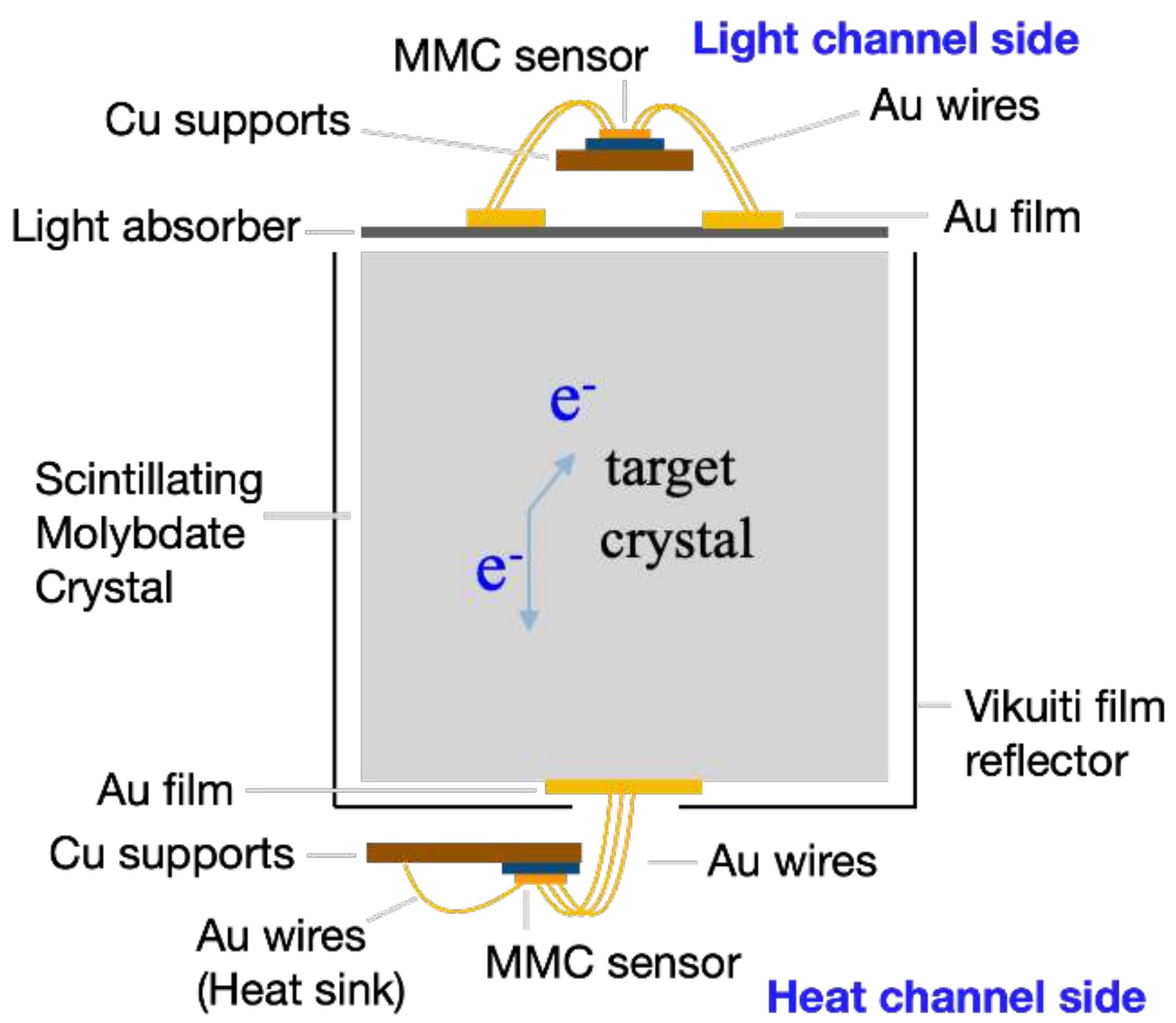
CROSS demonstrator

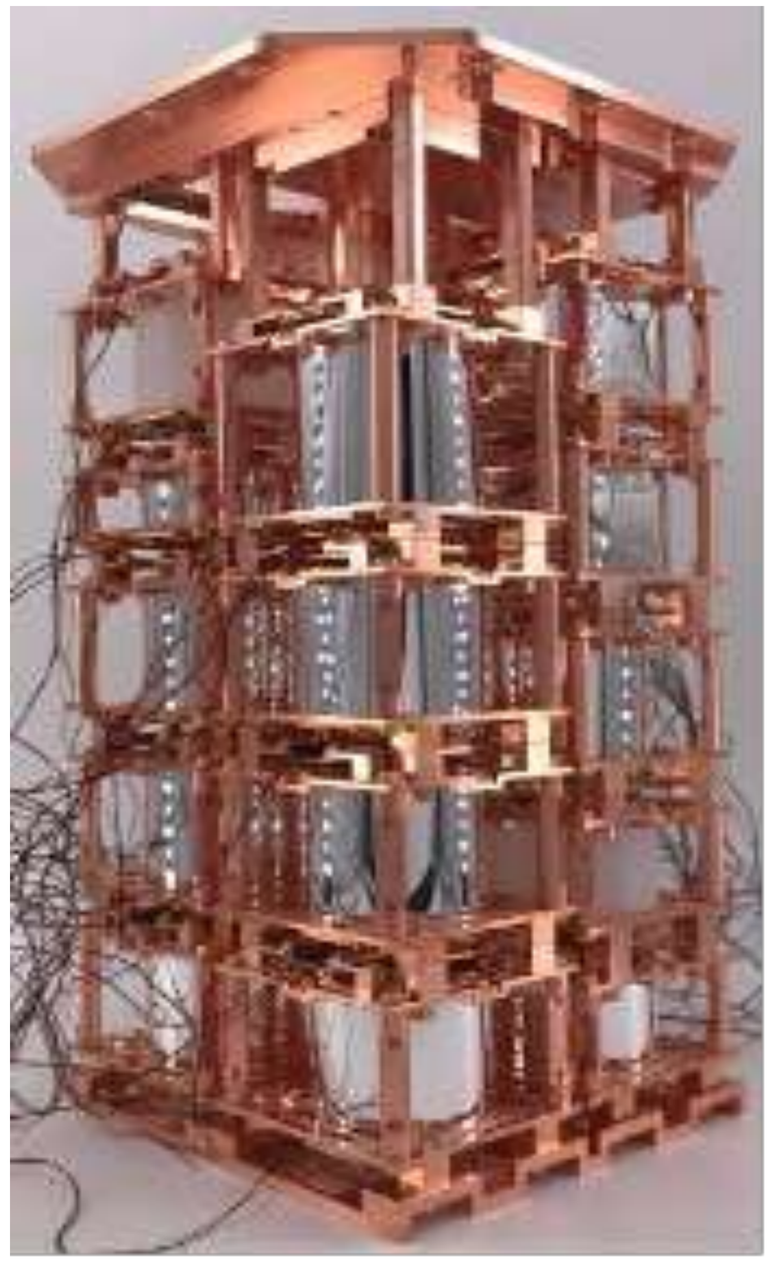
- 36 LMO + 6 TeO crystals (enriched)
- Operation early 2025 in Canfranc
- Mass : 4.7 kg of ^{100}Mo
- **Background index ~ 10^{-3} counts/keV/kg/yr**



Lighter assembly to reduce the amount of close inert material

AMoRE-I (2020.12 - 2023.5 ~ 900 days)

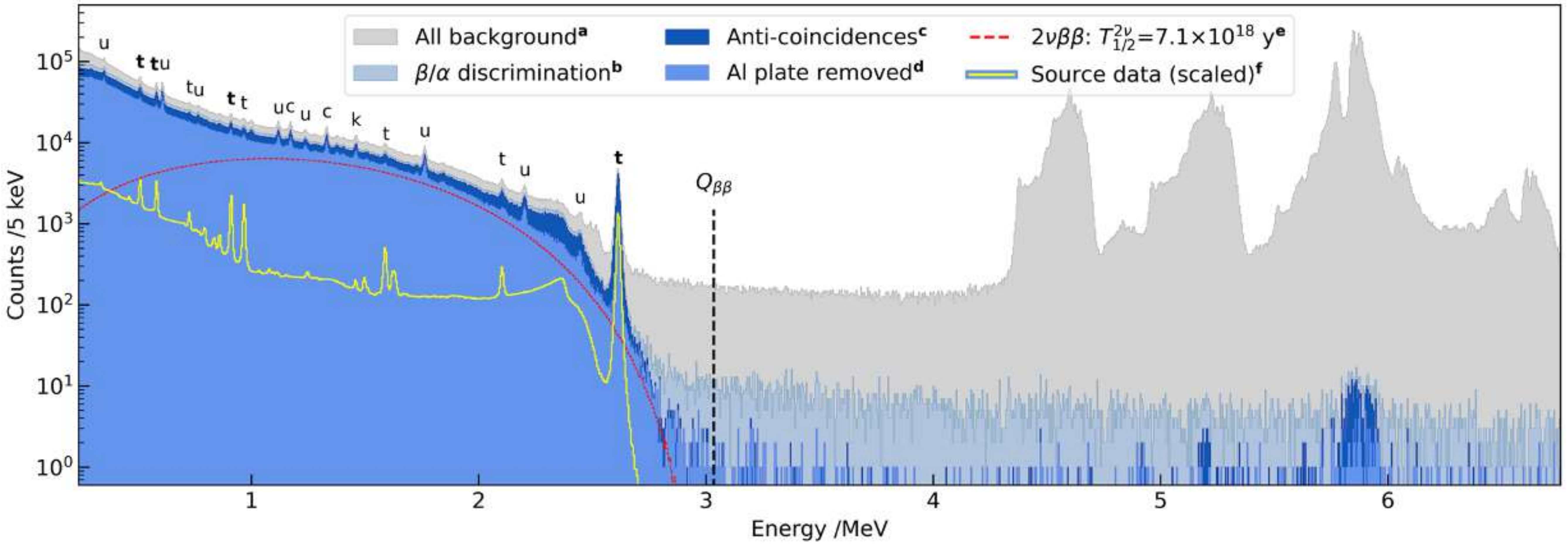


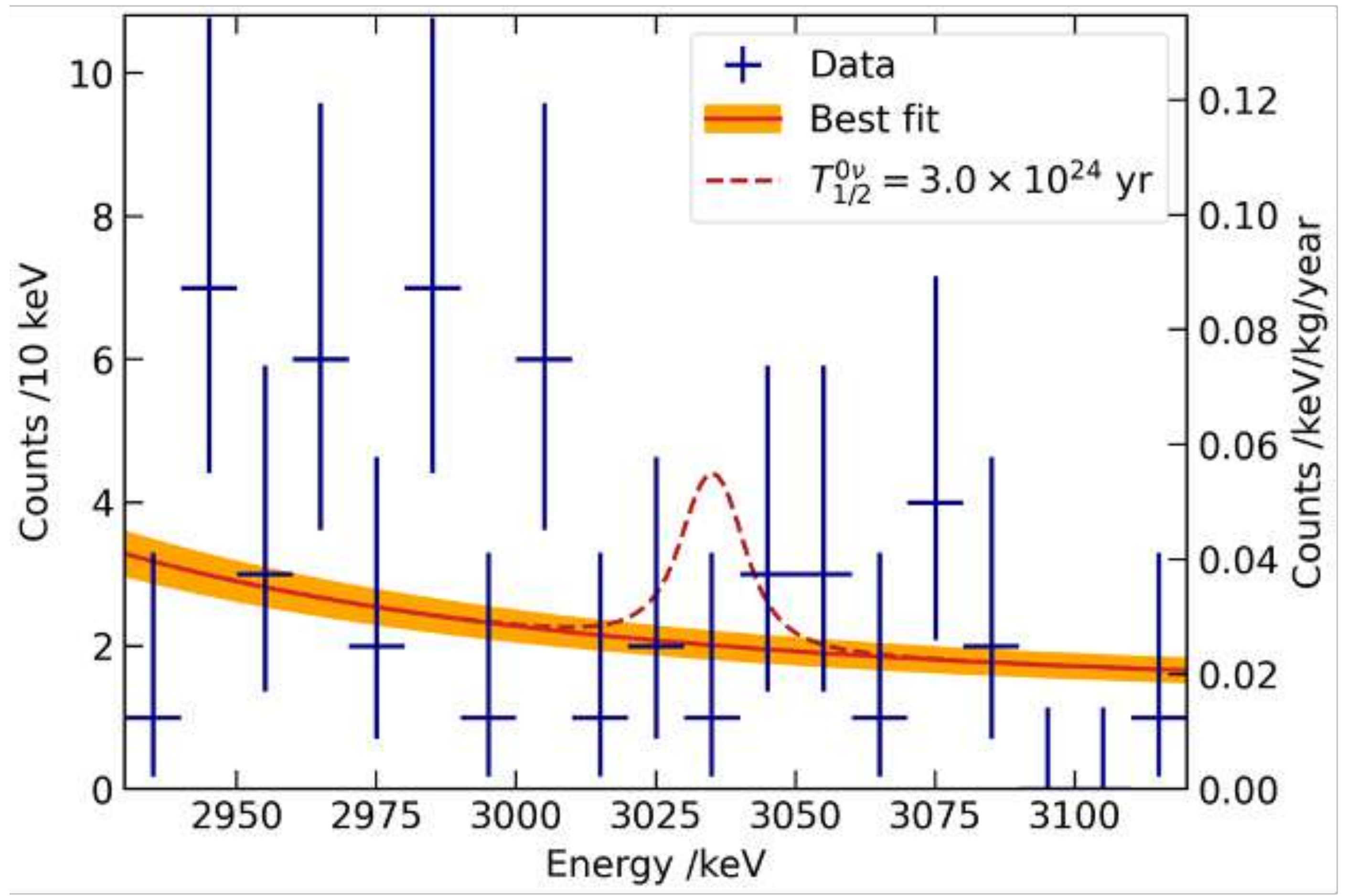


- Run @ Yangyang Underground Laboratory (Y2L)
- **13 CMO crystals (4.6 kg)** and 5 LMO **(1.6 kg) crystals**
- Confirmed stable operation of MMC+SQUID system @12 mK
- Total exposure: 8.02 kg•yr (3.89 kg•yr of Mo-100)

- Backgrounds : 0.025(2) ckky
  - CMO: 0.026(3) ckky
  - LMO: 0.021(5) ckky

- $T^{0\nu}_{1/2} > 3.0 \times 10^{24} yr$ years
- Agrawal et al., arXiv:2407.05618, submitted to PRL





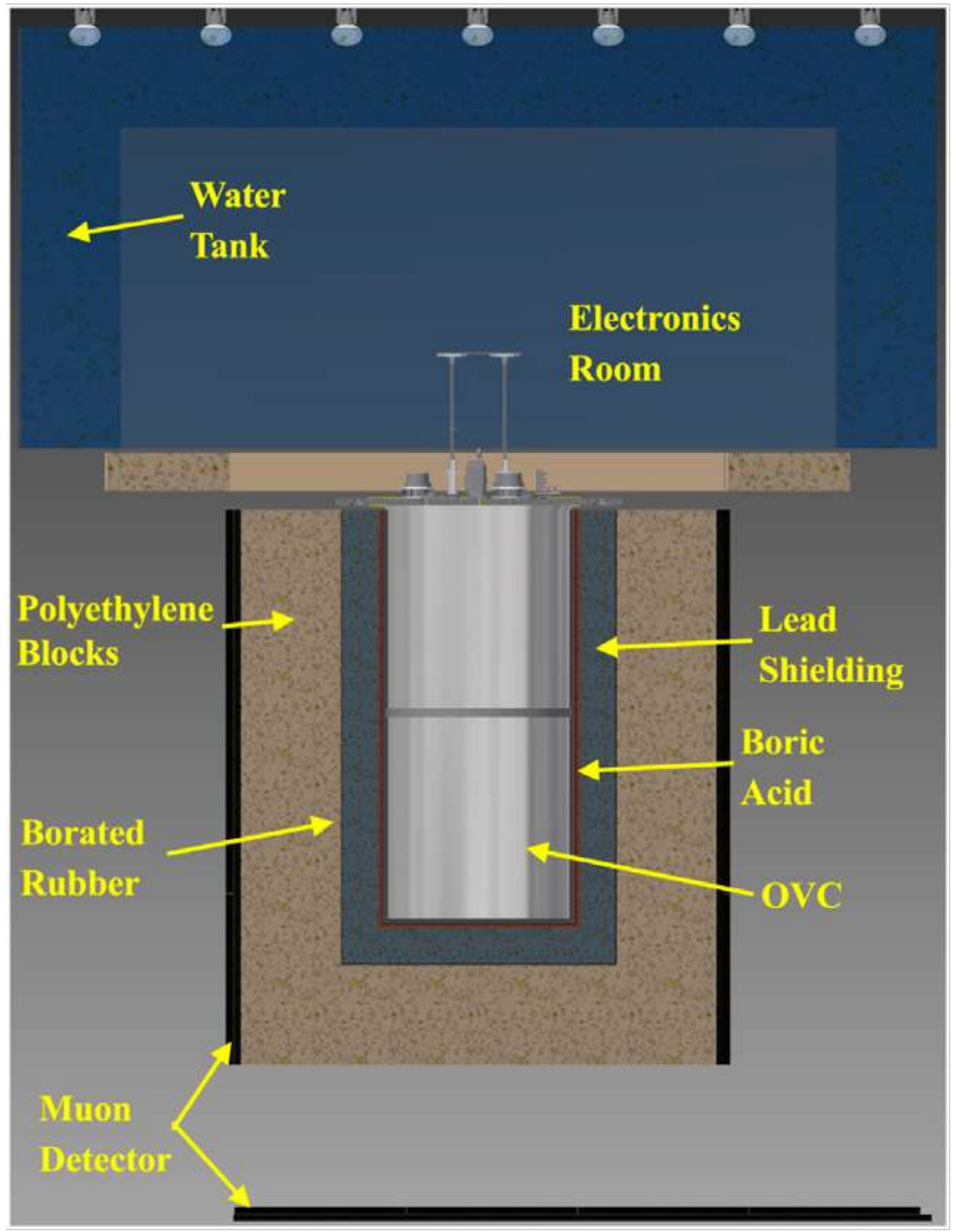
AMoRE-II (2024 - 2030)

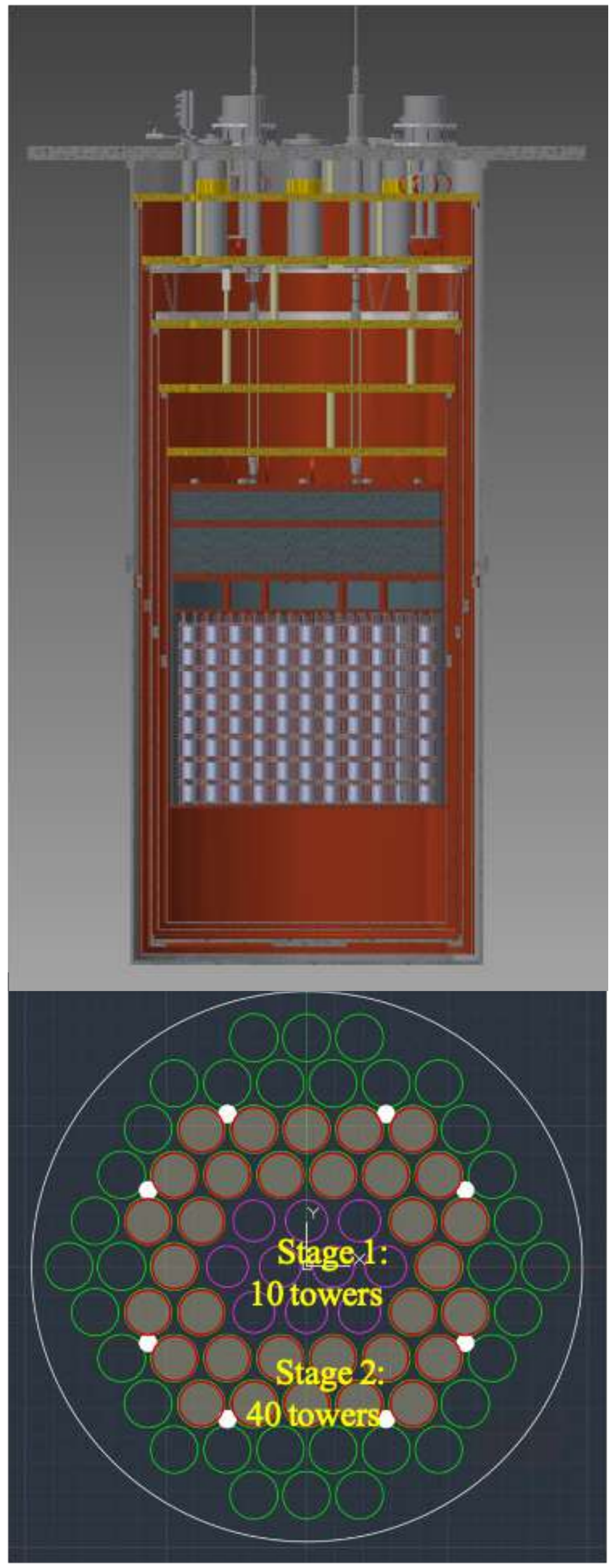
- To be Installed at Yemilab, 1000 meter deep
- 360 crystals LMO (+13 CMO)
  - MMC + SQUID for both heat & light signals
  - Si wafer for light detector w/ Vikuiti reflector
- DR from Leiden installed @ Yemilab.
- Shielding with Pb and PE, Water
  - Lower part : Pb (25cm) + PE(70cm) + PSMD
  - Upper part : Inner Pb (25cm) + WCMD (70cm)

- Backgrounds
  - Goal < 10-4 ckky
  - Main backgrounds are Outer Pb, Pileup

- Sensitivity : 4.6×10^{26} years 90% CL
- Schedule
  - 90 crystals : 2024-2025 (Stage 1)
  - 360 crystals : 2026-2030 (Stage 2)

See O. Gileva poster





AMoRE-II (2024 - 2030)

Improvements to be done before full scale:

Outer Pb shield ➡ Replace with 5cm of purer Pb or Cu

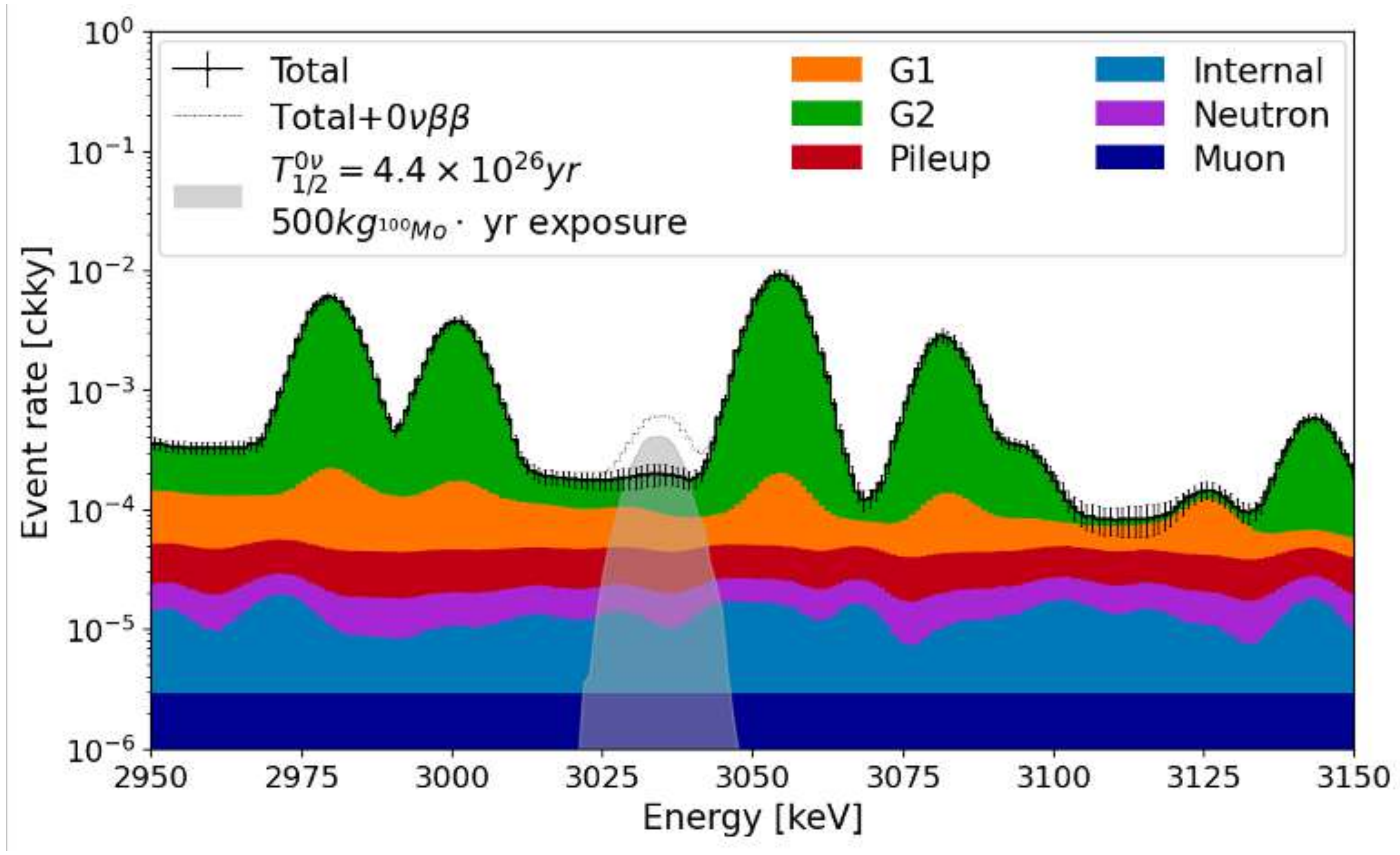
Detector holder ➡ Confirm cleaning works

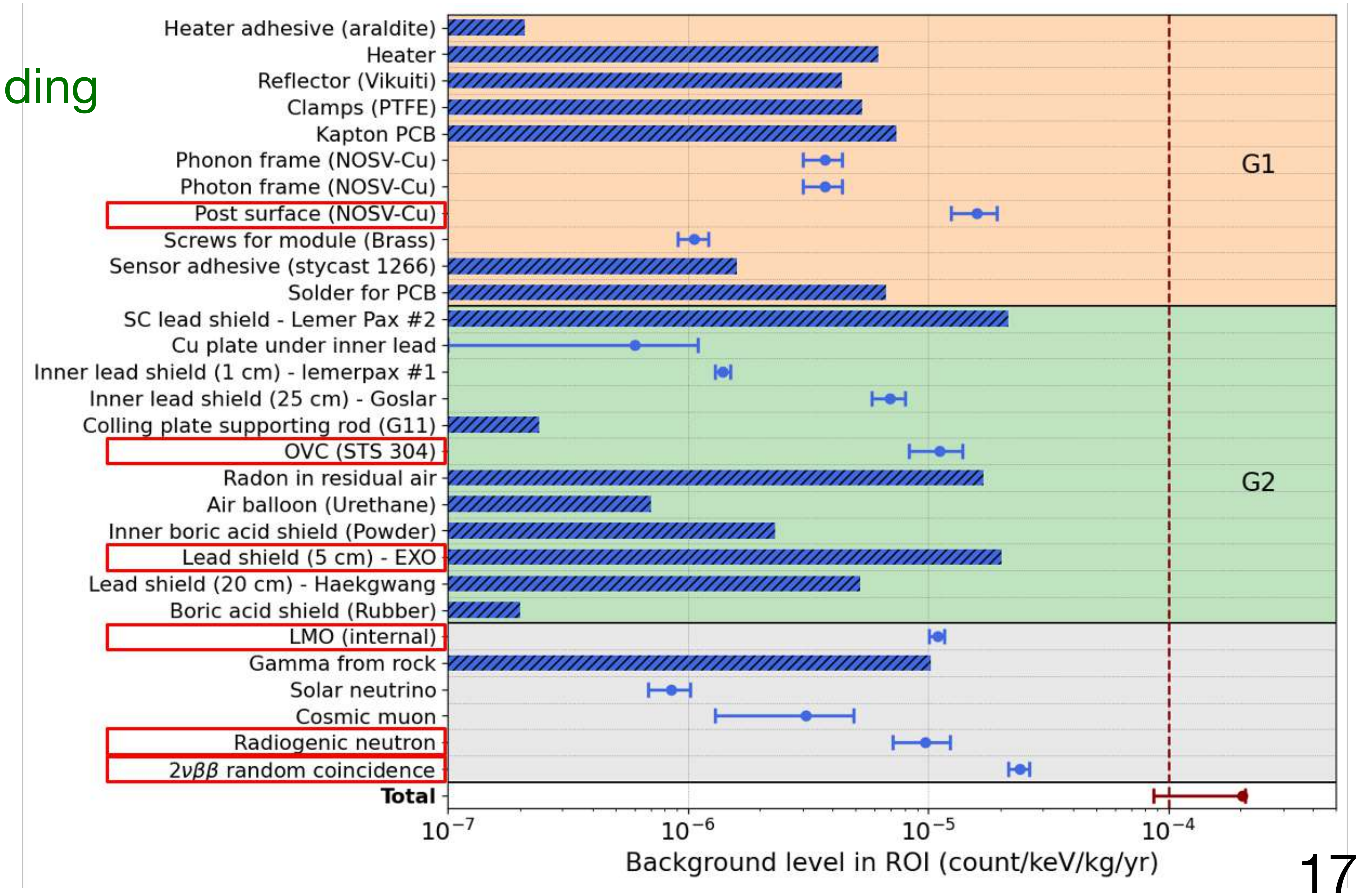
OVC ➡ Replace with purer STS

LMO internal ➡ Confirm with 90 crystal run

Radiogenic neutrons ➡ Improve the Boric acid shielding

Pileup ➡ Improve rejection with machine learning

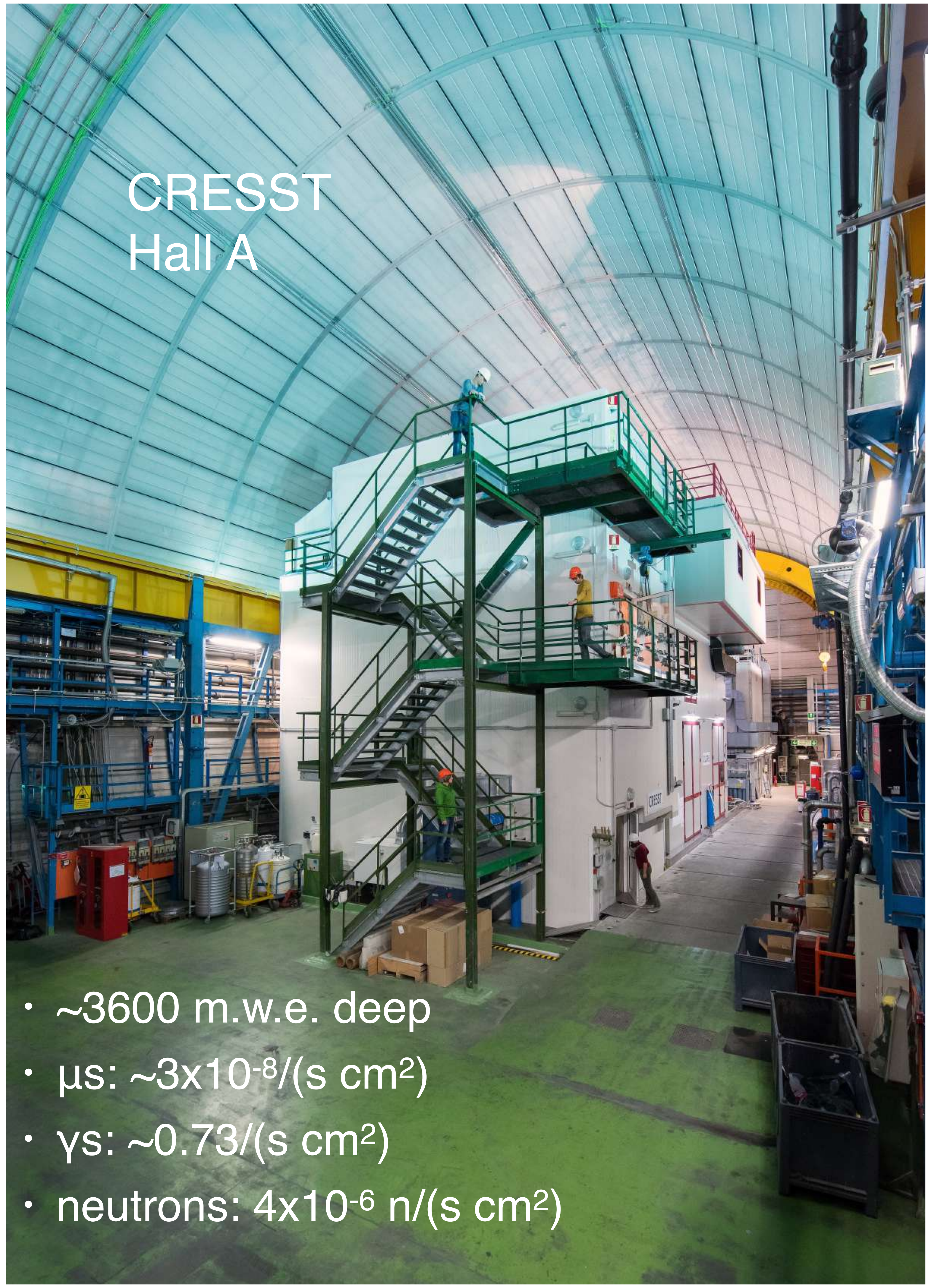




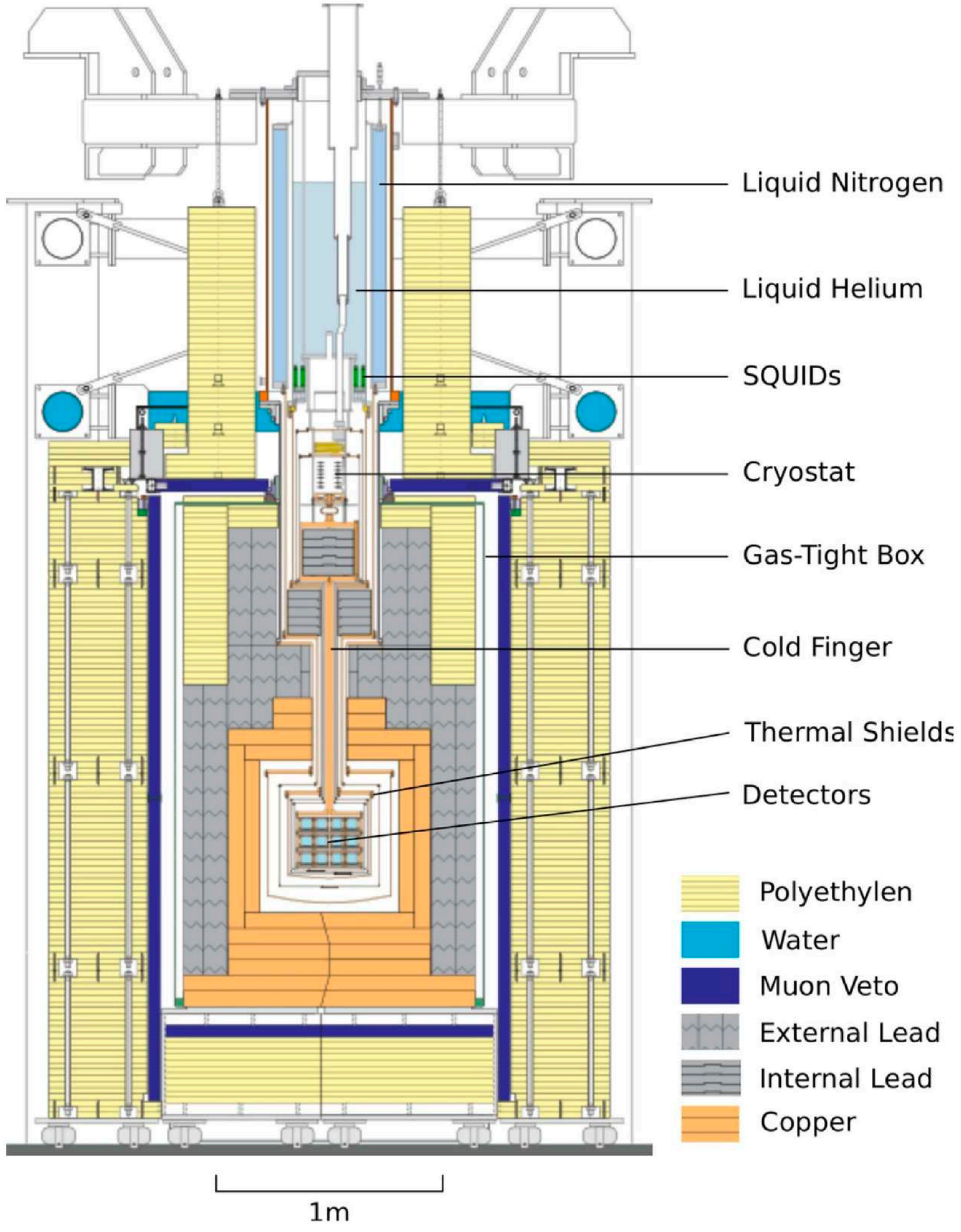
Direct Dark Matter Search with Bolometers

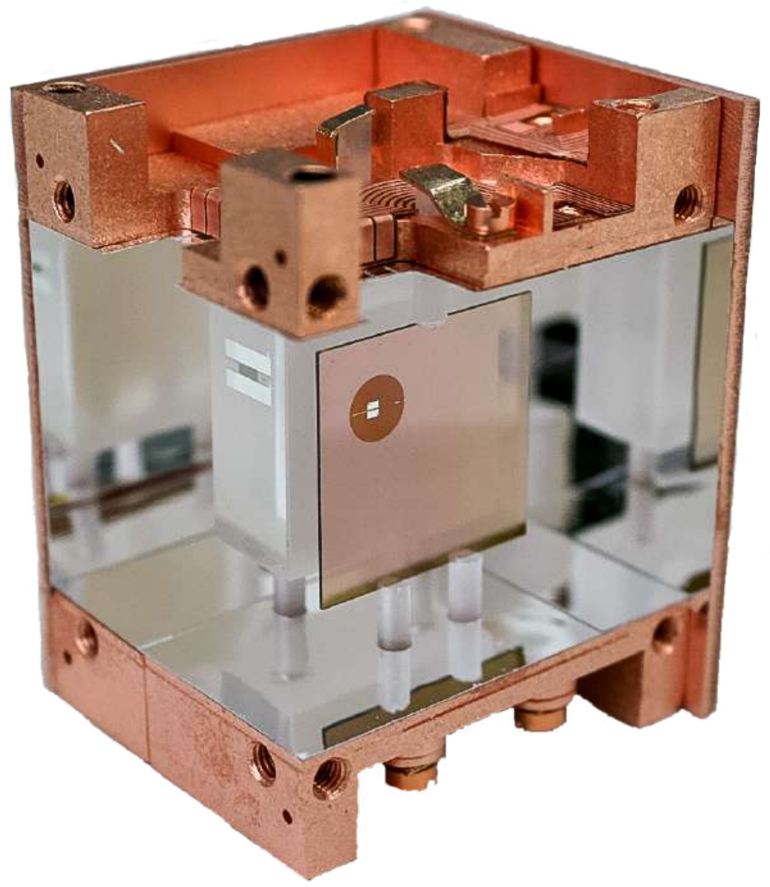
The CRESST Experiment

Cryogenic Rare Event Search with Superconducting Thermometers



- ~3600 m.w.e. deep
- μs: ~3x10^{-8}/(s cm^2)
- γs: ~0.73/(s cm^2)
- neutrons: 4x10^{-6} n/(s cm^2)



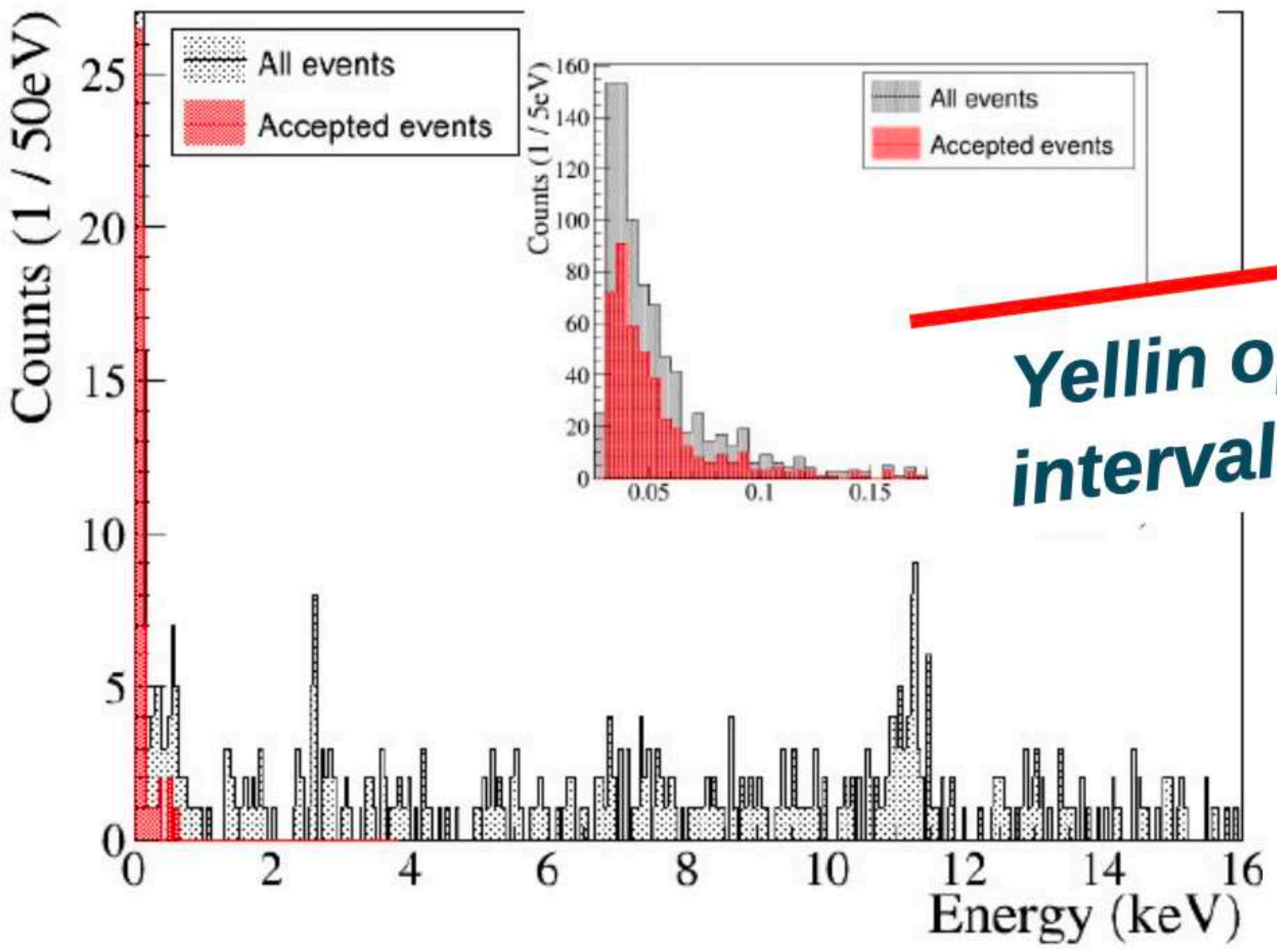


CRESST goal: direct detection of dark matter particles via their scattering off target nuclei in cryogenic detectors, operated at ~15 mK using **Scintillating $CaWO_4$ crystals** as target and **Silicon on Sapphire (SOS)** crystals as cryogenic light detector. Both with TES readout!

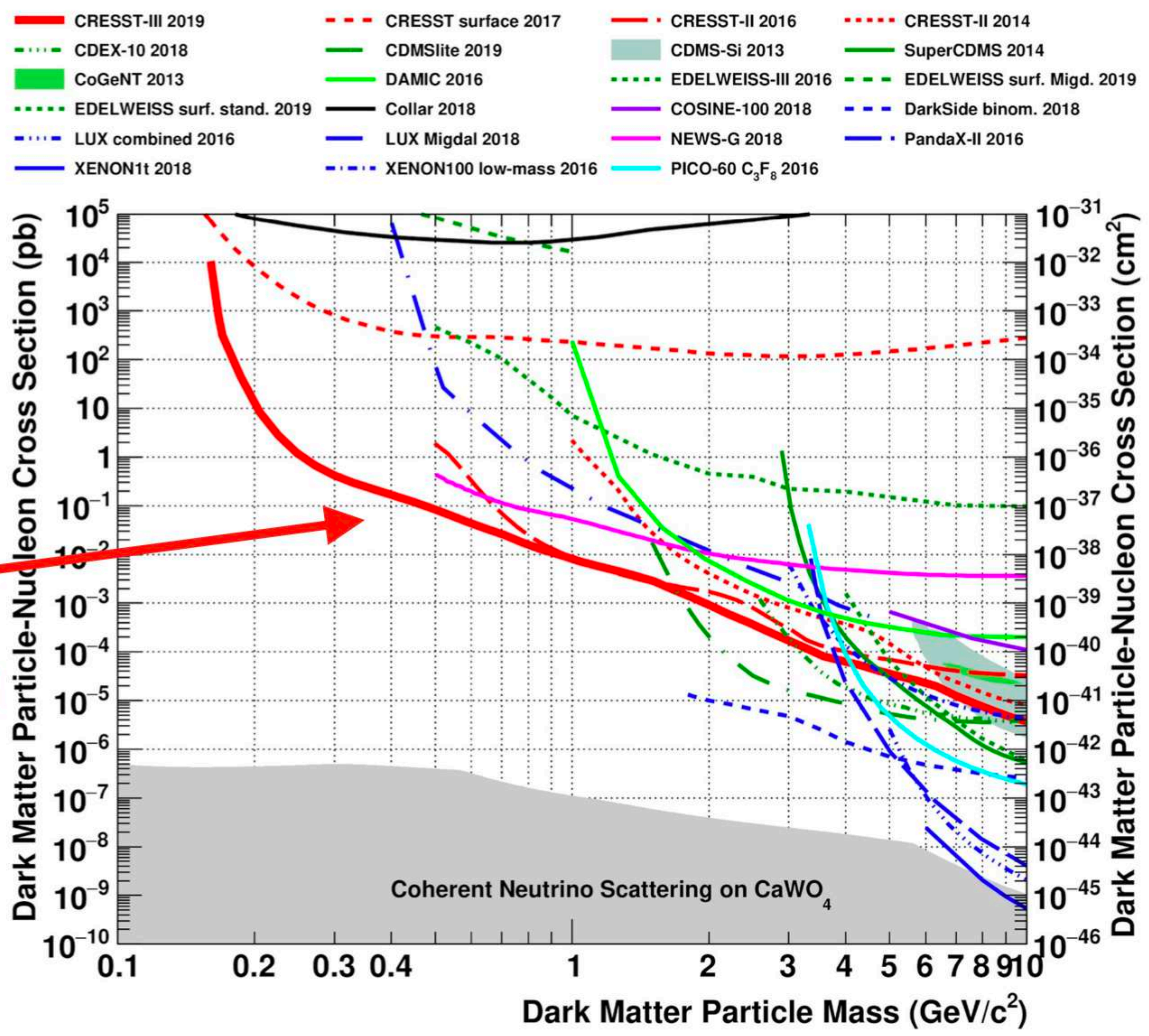
CRESST Results (I)

Detector 1 - 23.6 g $CaWO_4$

- Data taking Oct. 2016 - Jan. 2018
- Exposure 5.7 kg days
- Baseline Resolution 4.6 eV
- Nuclear Recoil Threshold 30 eV



Yellin optimum interval method

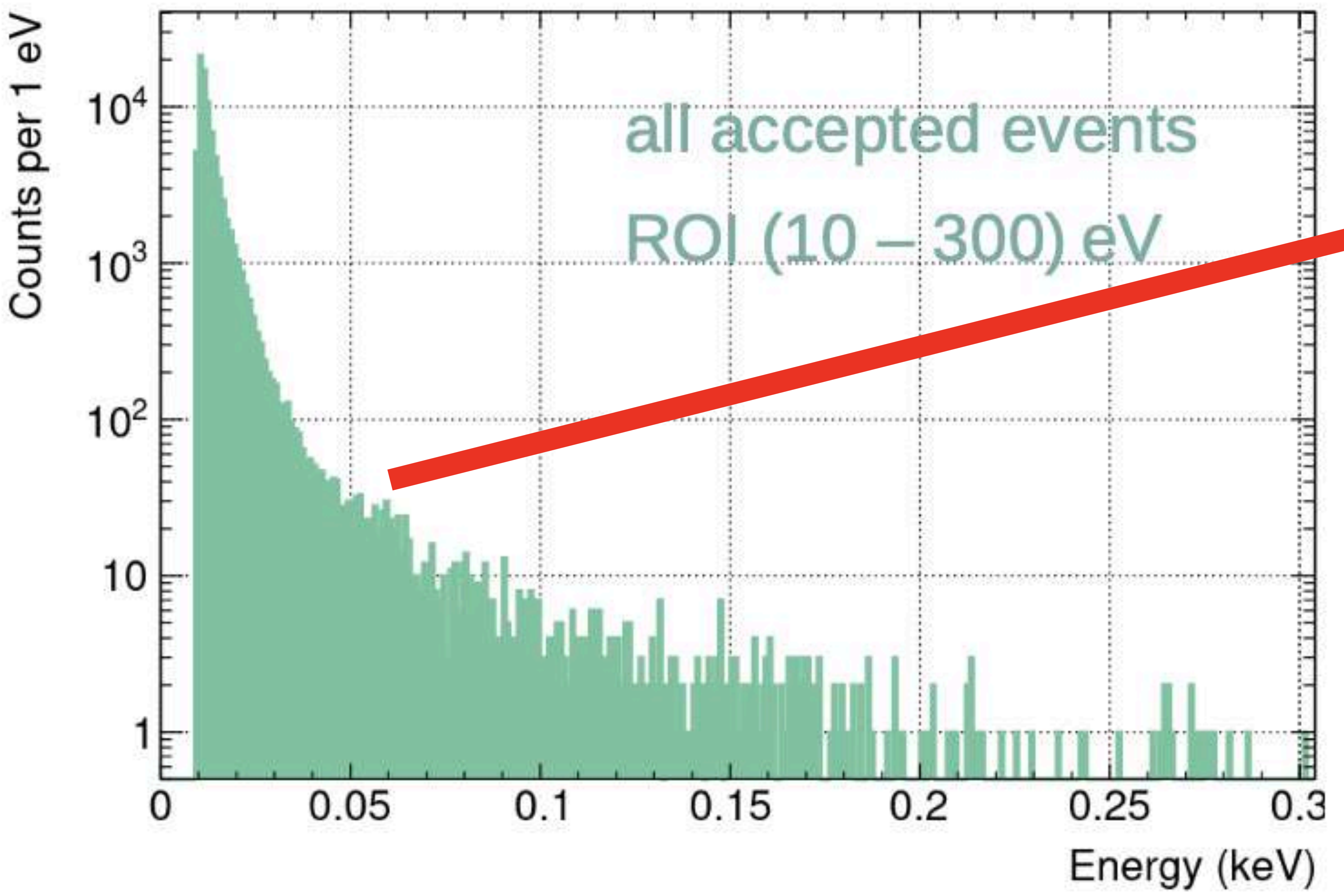


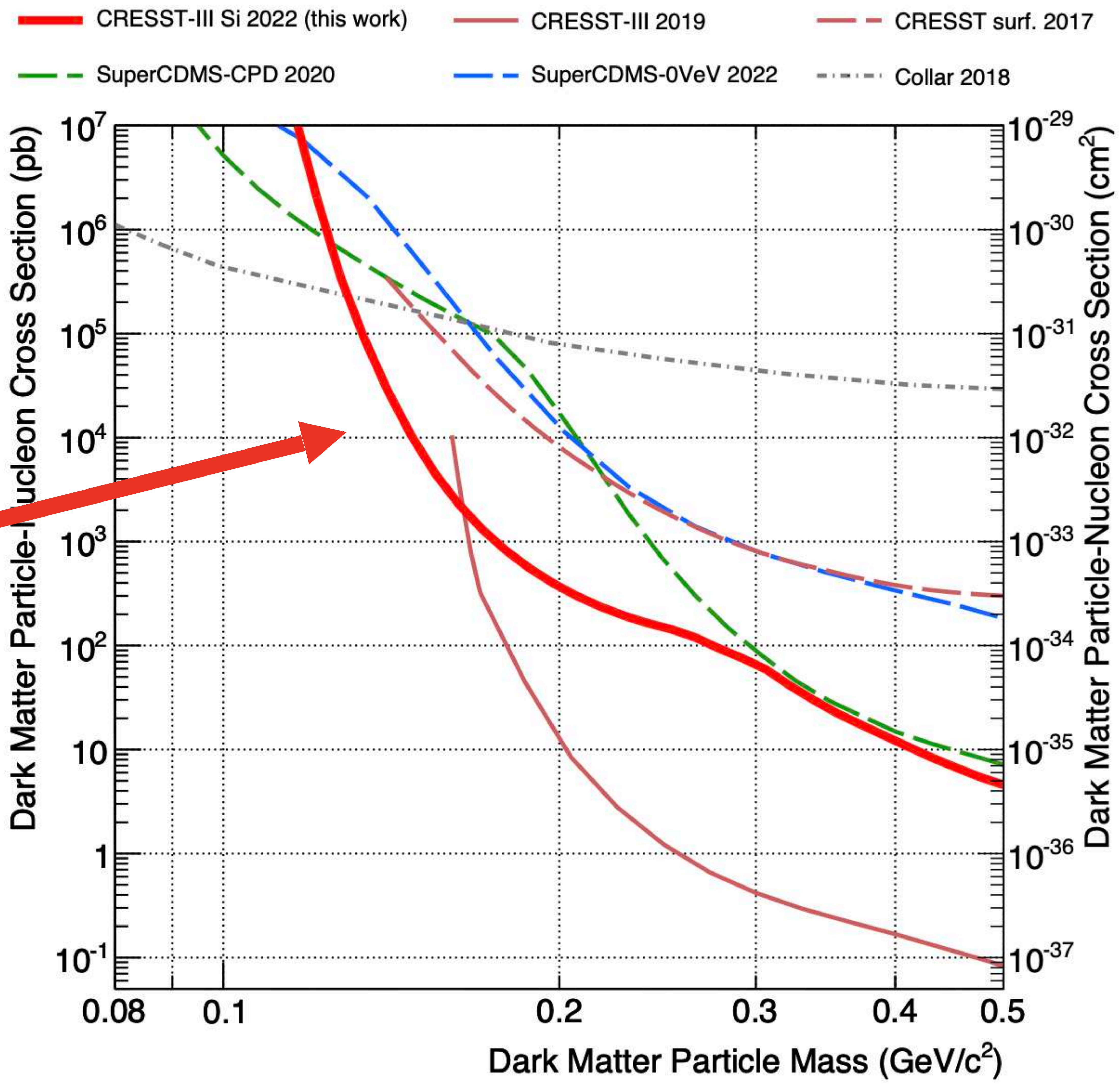
Phys. Rev. D 100, 102002 / arXiv:1904.00498

CRESST Results (II)

Detector 2 - 0.35 g Si wafer

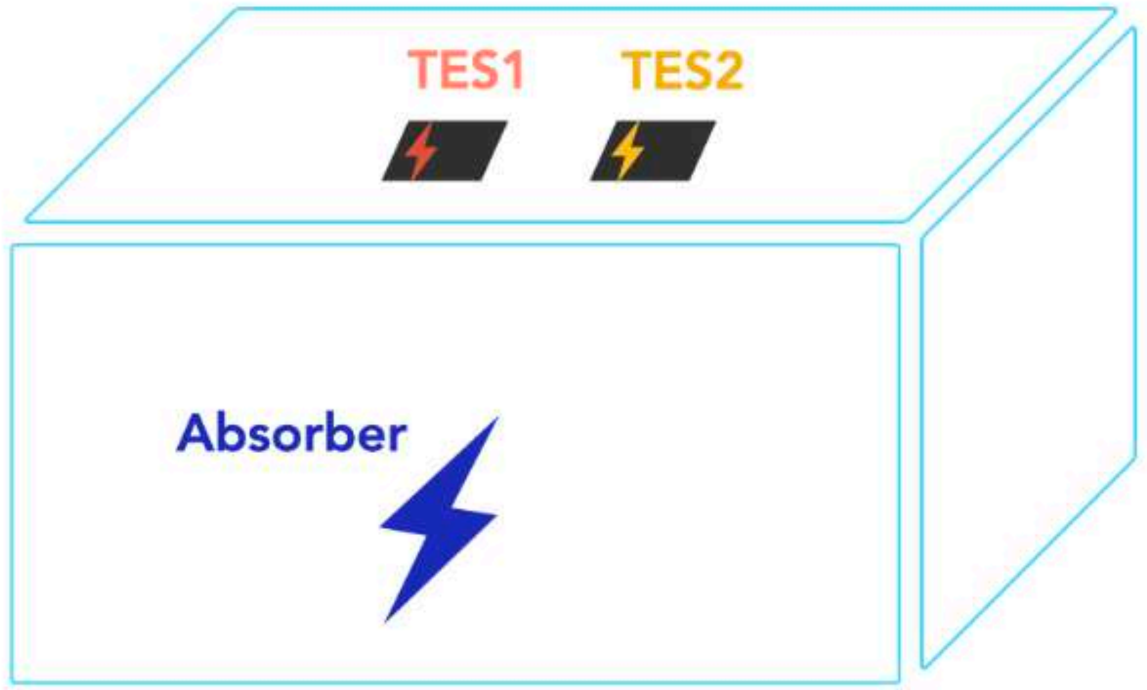
- Data taking Nov.2020 - Aug. 2021
- Exposure 55.1 g·days
- Baseline Resolution 1.36 eV
- Nuclear Recoil Threshold 10 eV

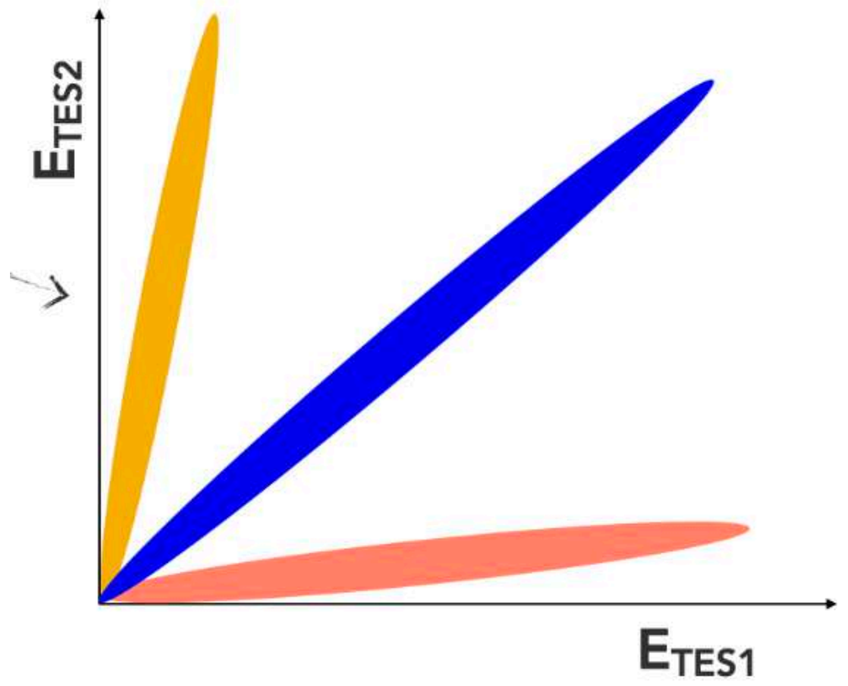


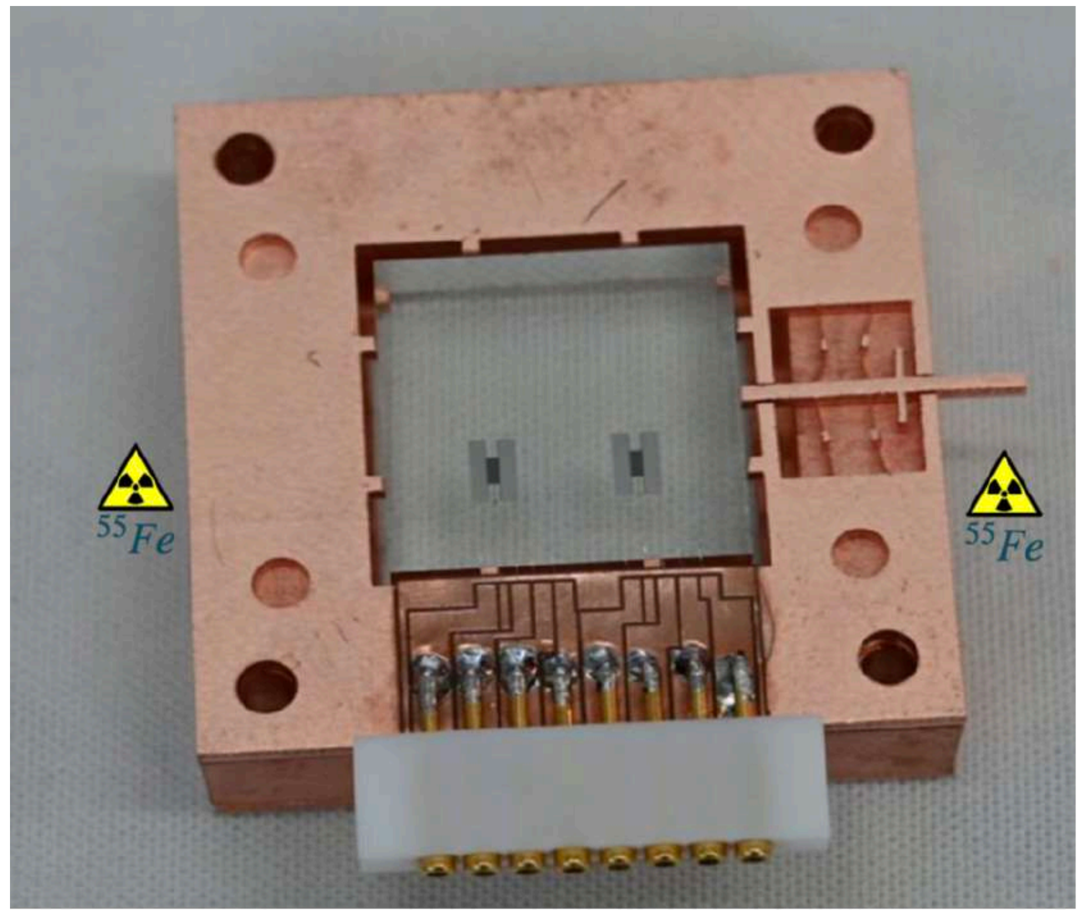


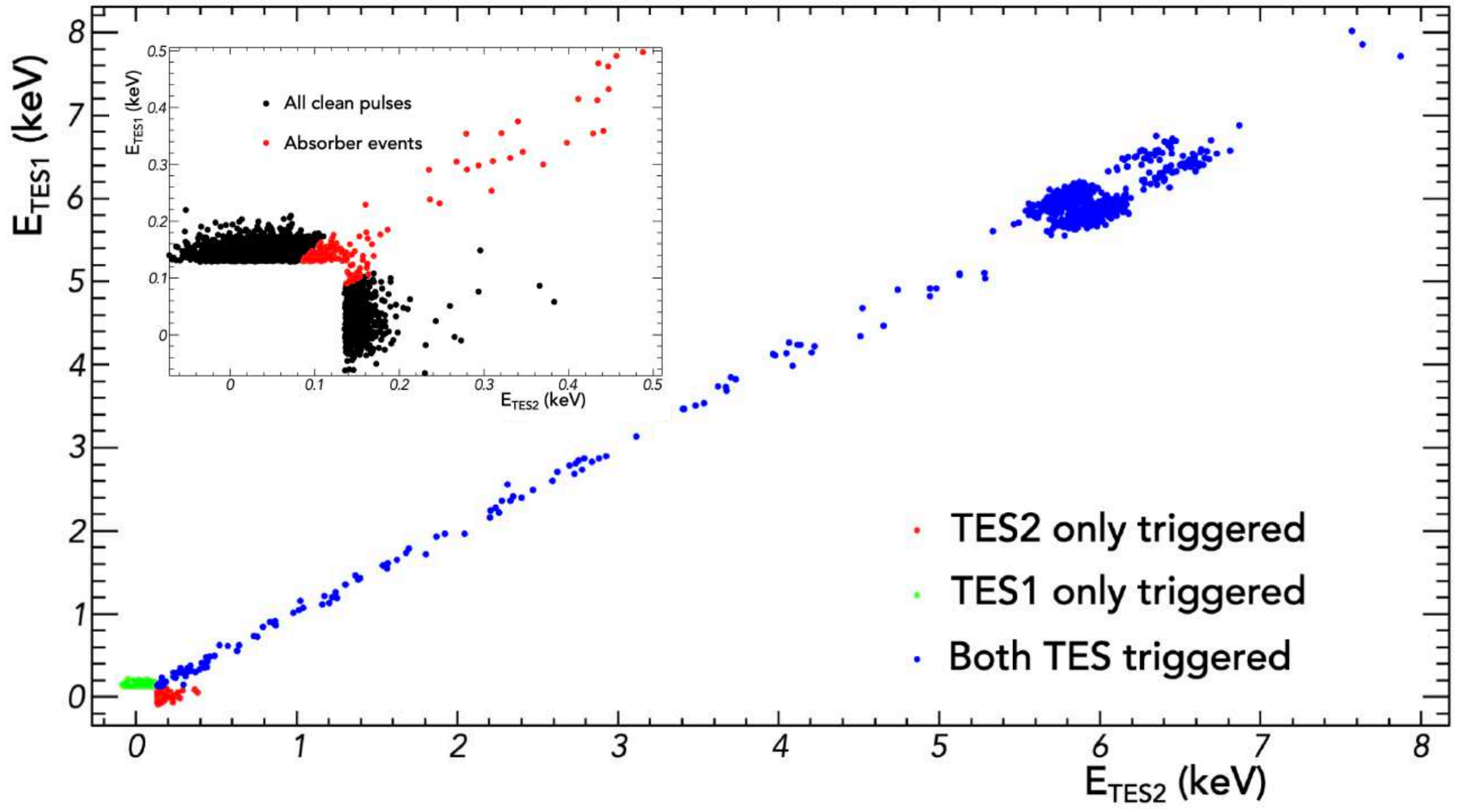
CRESST - Low Energy Excess Study

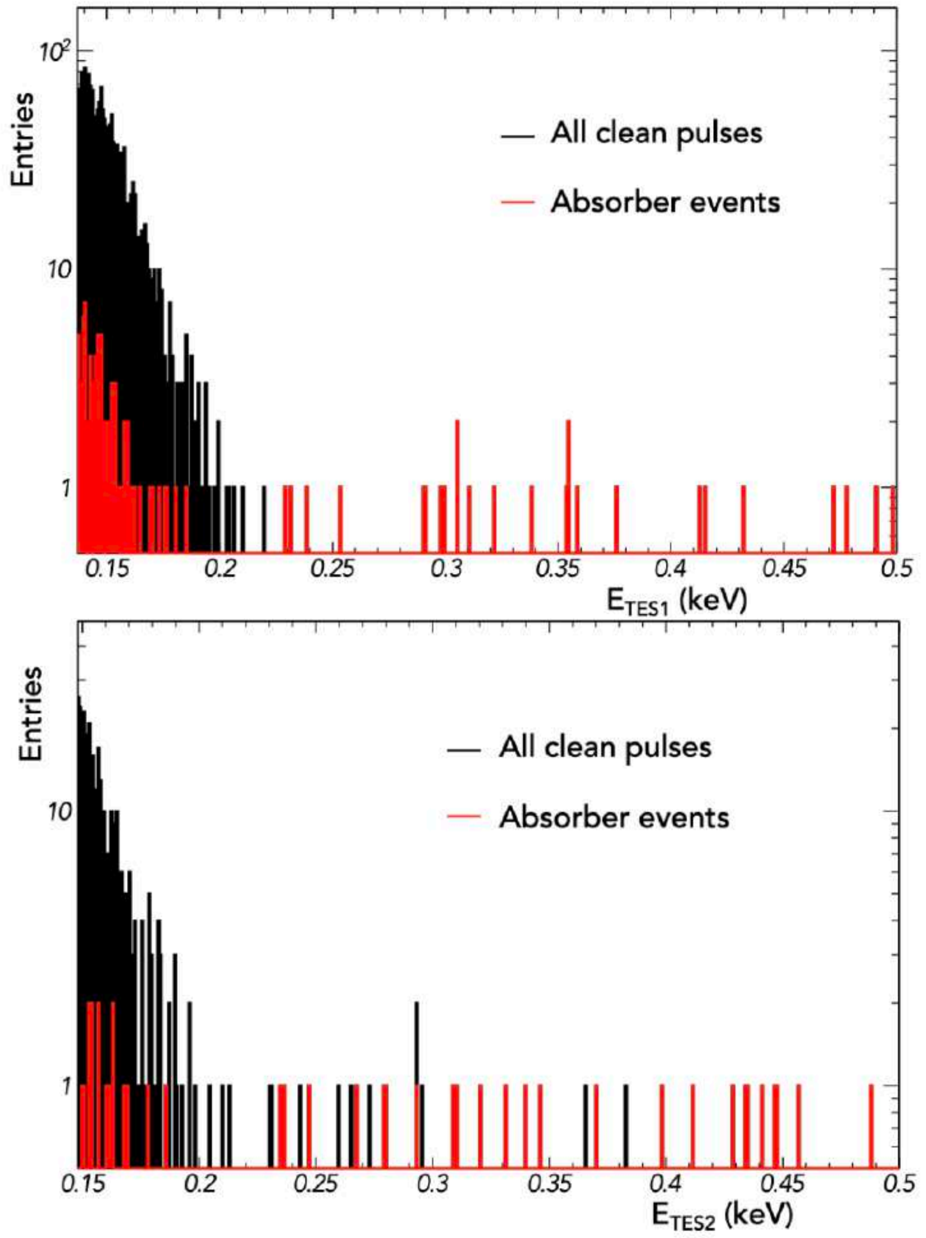
- **Basic idea: instrument the absorber with 2 TES**
- If the signal originates in the absorber the two TES are expected to show the same response.
- If the signal originates in or very close to one TES, the two response signals are expected to be different.







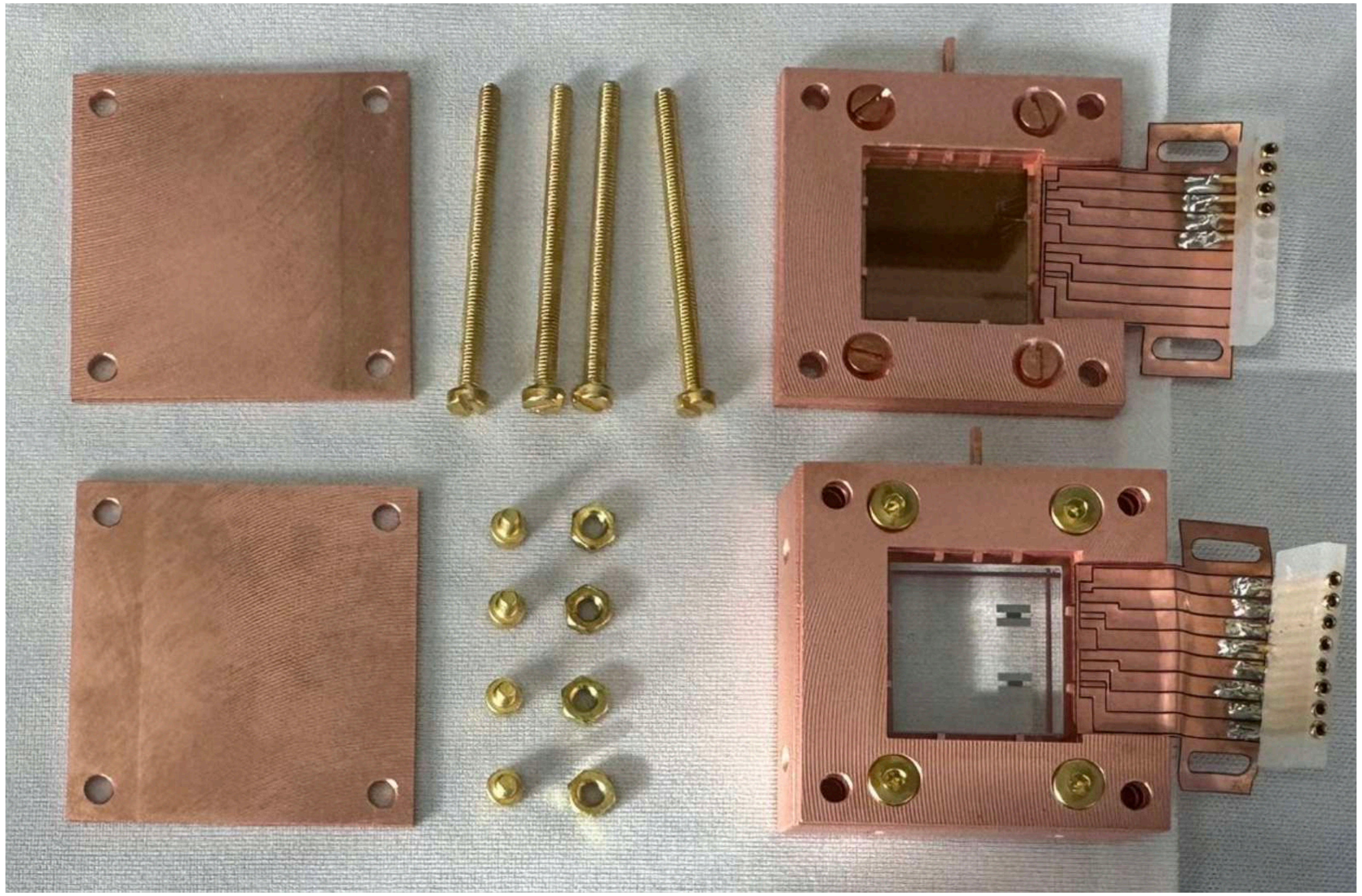




CRESST - Low Energy Excess Study

To explore the full potential of Double TES technology a Run in the CRESST cryostat was mandatory (low background + low noise).

- 5 Double TES $CaWO_4$ modules
- A stack of 4 Double TES Al_2O_3 LD with double TES (with ^{55}Fe source)
- 1 Mini-Beaker module
- TUM93A $CaWO_4$ from Run36

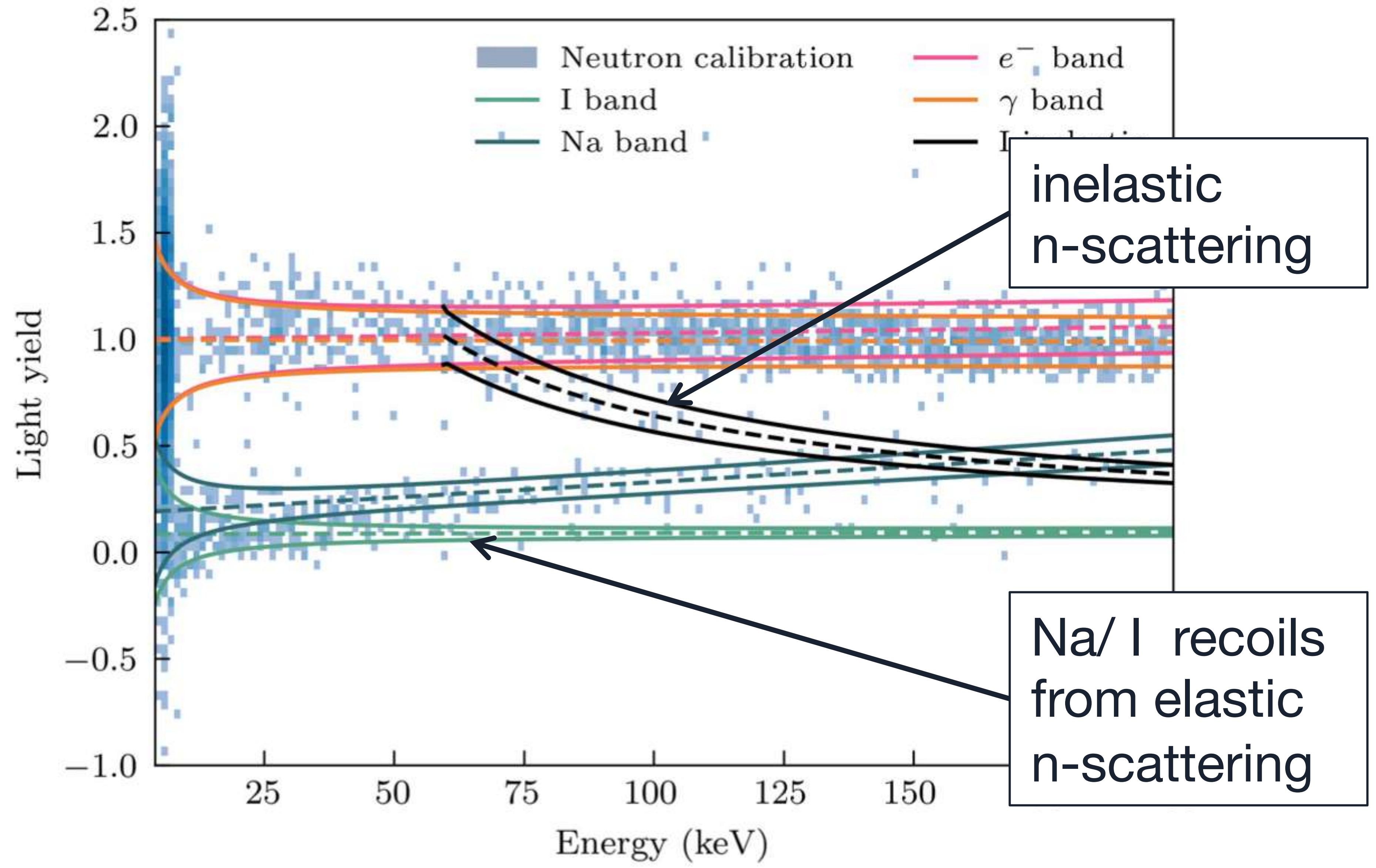


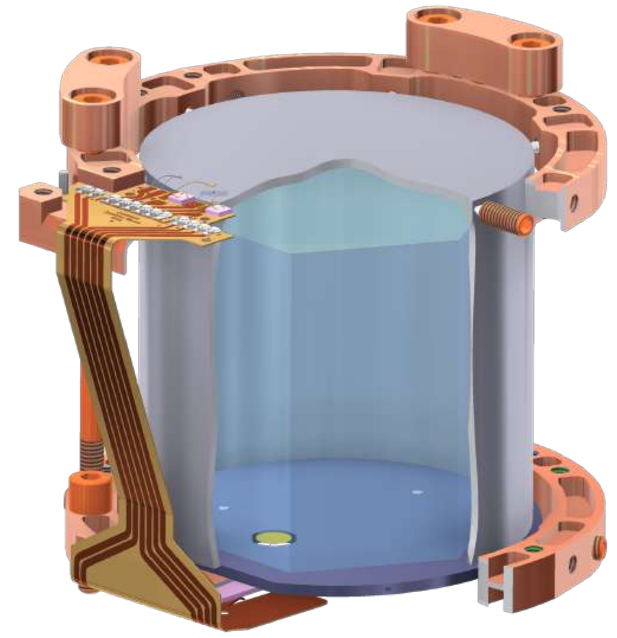
The COSINUS Experiment

Testing the DAMA/LIBRA signal with dual-readout NaI cryogenic calorimeters

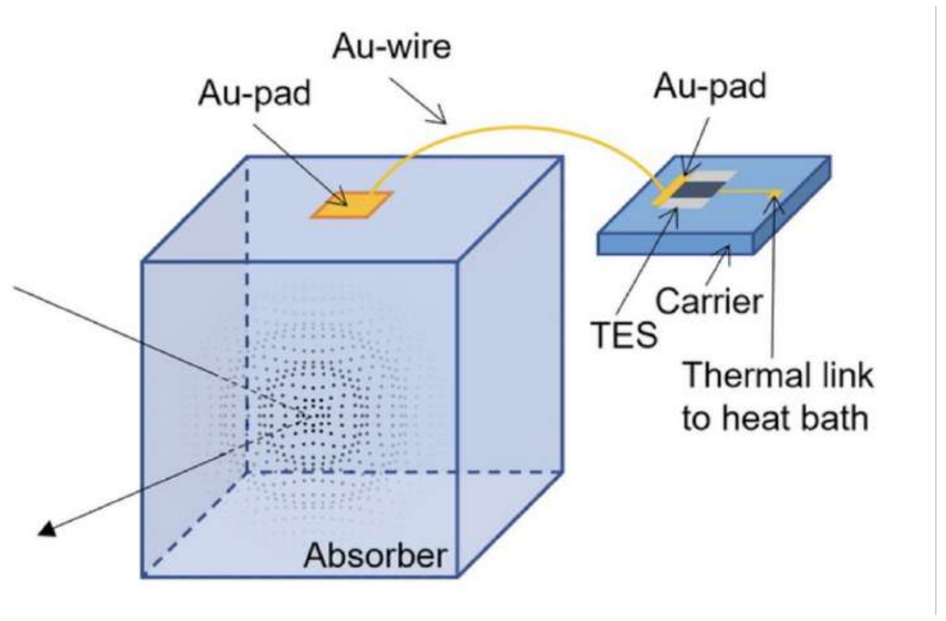
Current Status:

- Fist successful measurement of NaI as cryogenic calorimeter
  - JINST 12 (2017) 11, P11007
- Particle ID in NaI
  - Phys.Rev.D 109 (2024) 8, 082003
- Development of remoTES
  - Nucl.Instrum.Meth.A 1045 (2023) 167532
- First Dark Matter Result
  - Phys.Rev.D 110 (2024) 4, 043010



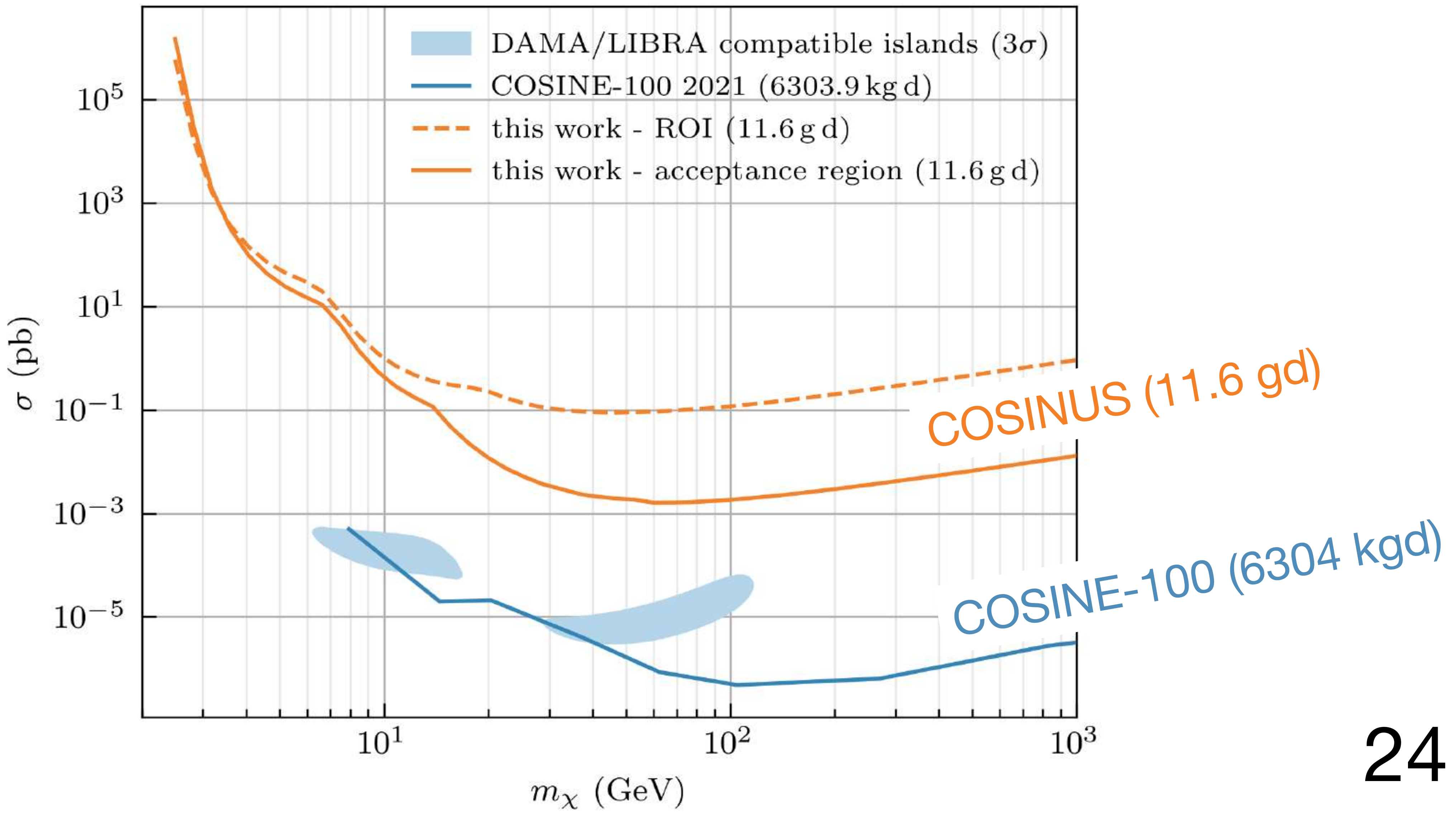


Si-beaker for 4π active surrounding of the crystal



NaI → Au-wire/pad → TES
Phonons couple directly to electron system of Au-pad

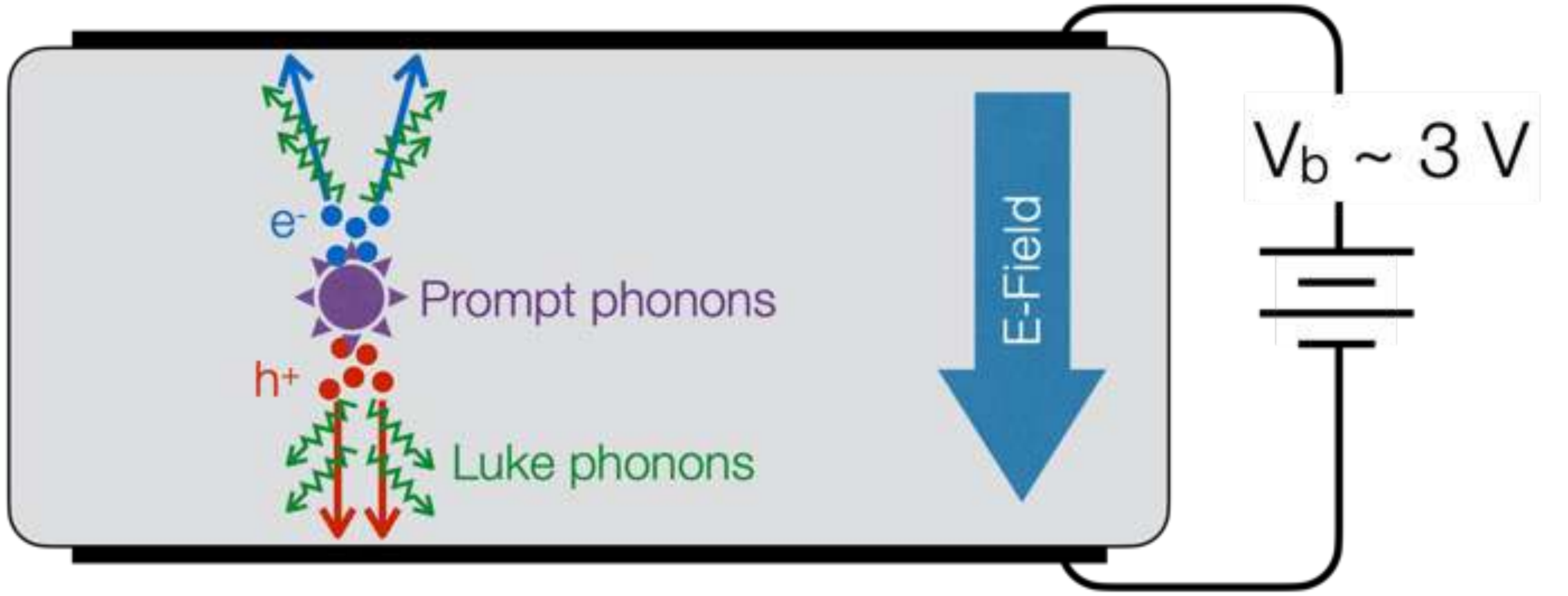
14



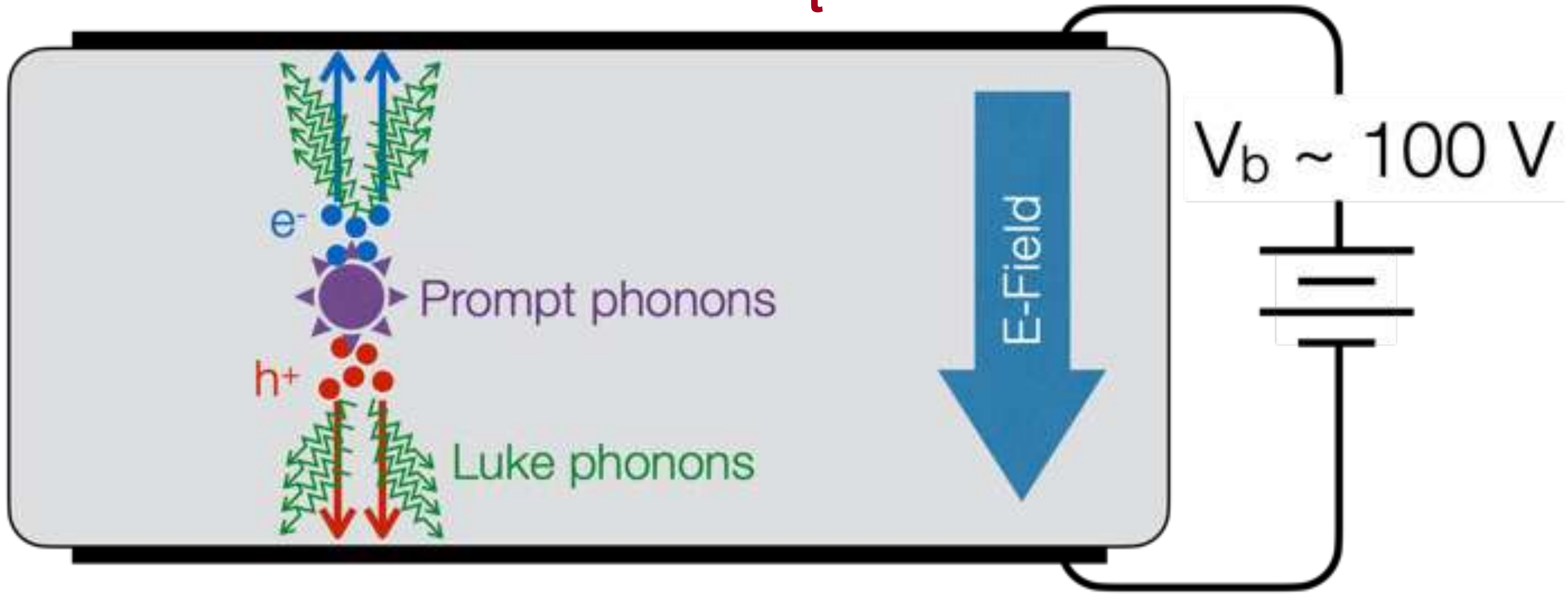
The SuperCDMS Experiment

- iZIP Detector
  - Prompt phonon & ionization signals allow discrimination between nuclear and electron recoil events
  - Event discrimination → low background
  - Trade-off:
    - ✓ Higher energy analysis threshold
- HV Detector
  - Drifting electrons and holes across a potential (V_b) generates many Luke phonons
  - Enables very low energy thresholds
  - Trade-off:
    - ✓ No event-by-event nuclear vs electron recoil discrimination

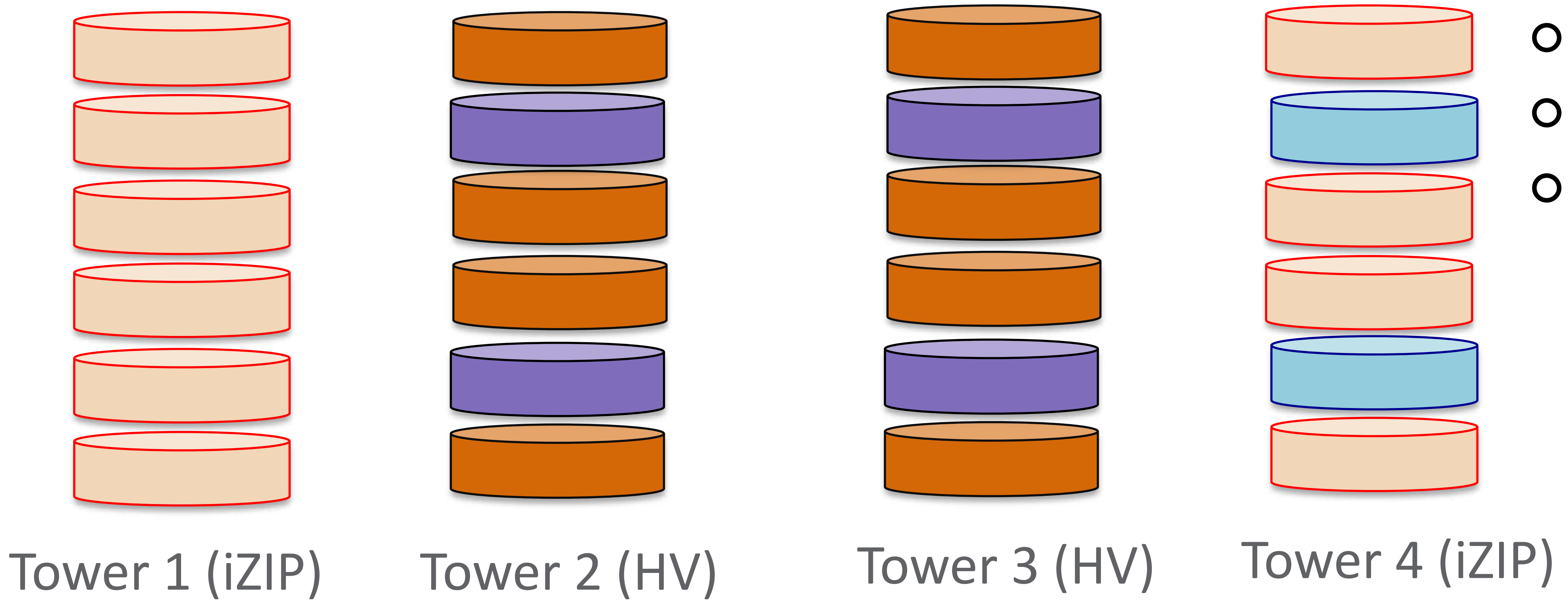
iZIP sensors measure E_t, and n_{eh}



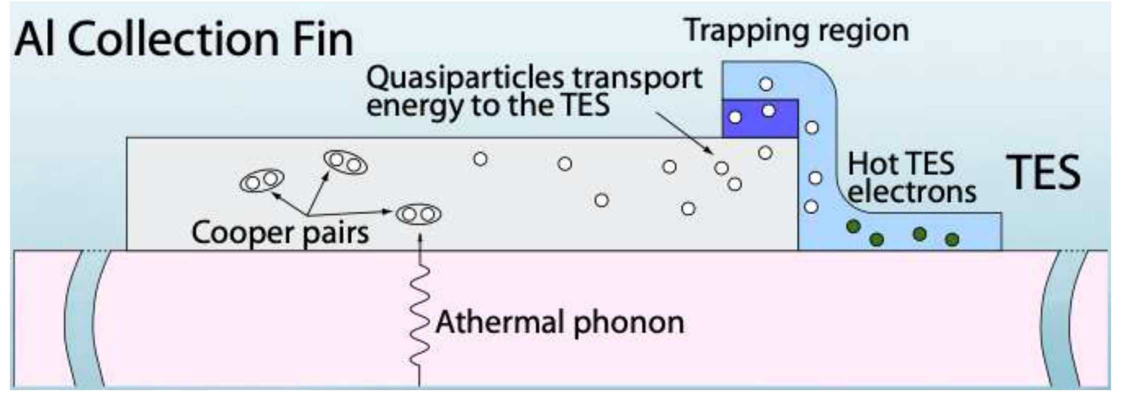
HV sensors measure E_t

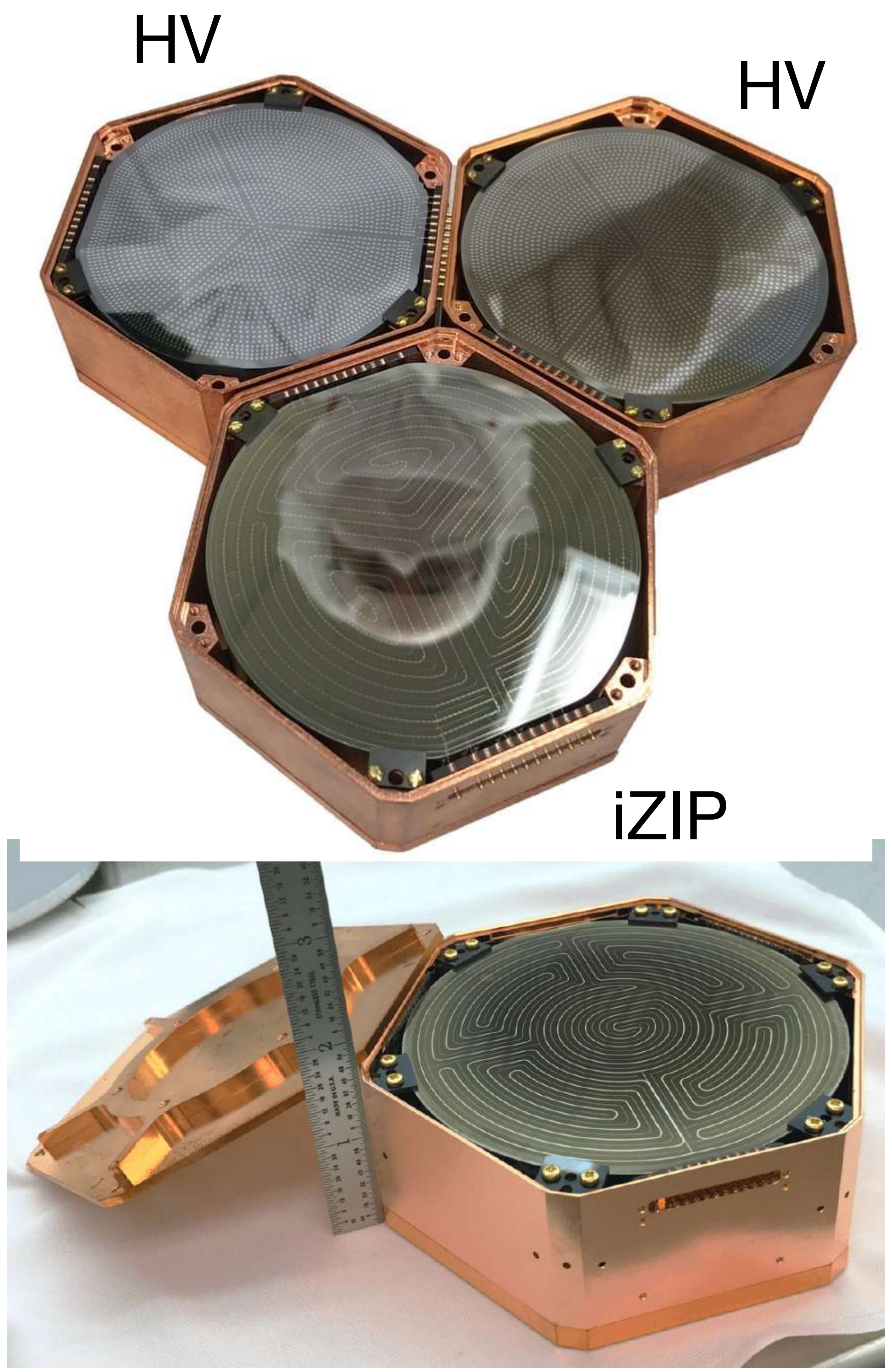


The SuperCDMS Experiment



- Mass: 30 kg Ge + 5 kg Si
- Exposure: 140 kg yr
- Heat channel: TES readout

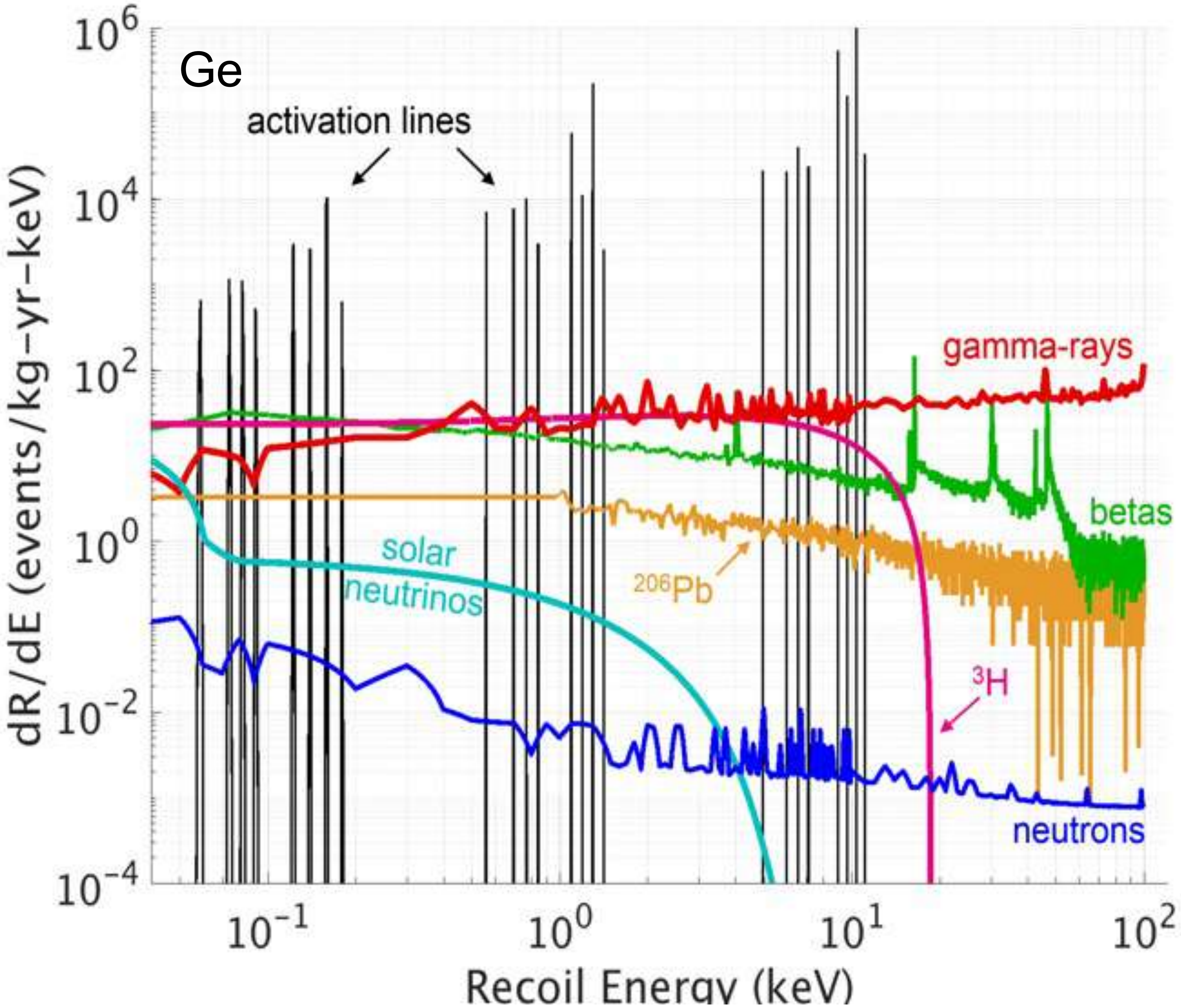


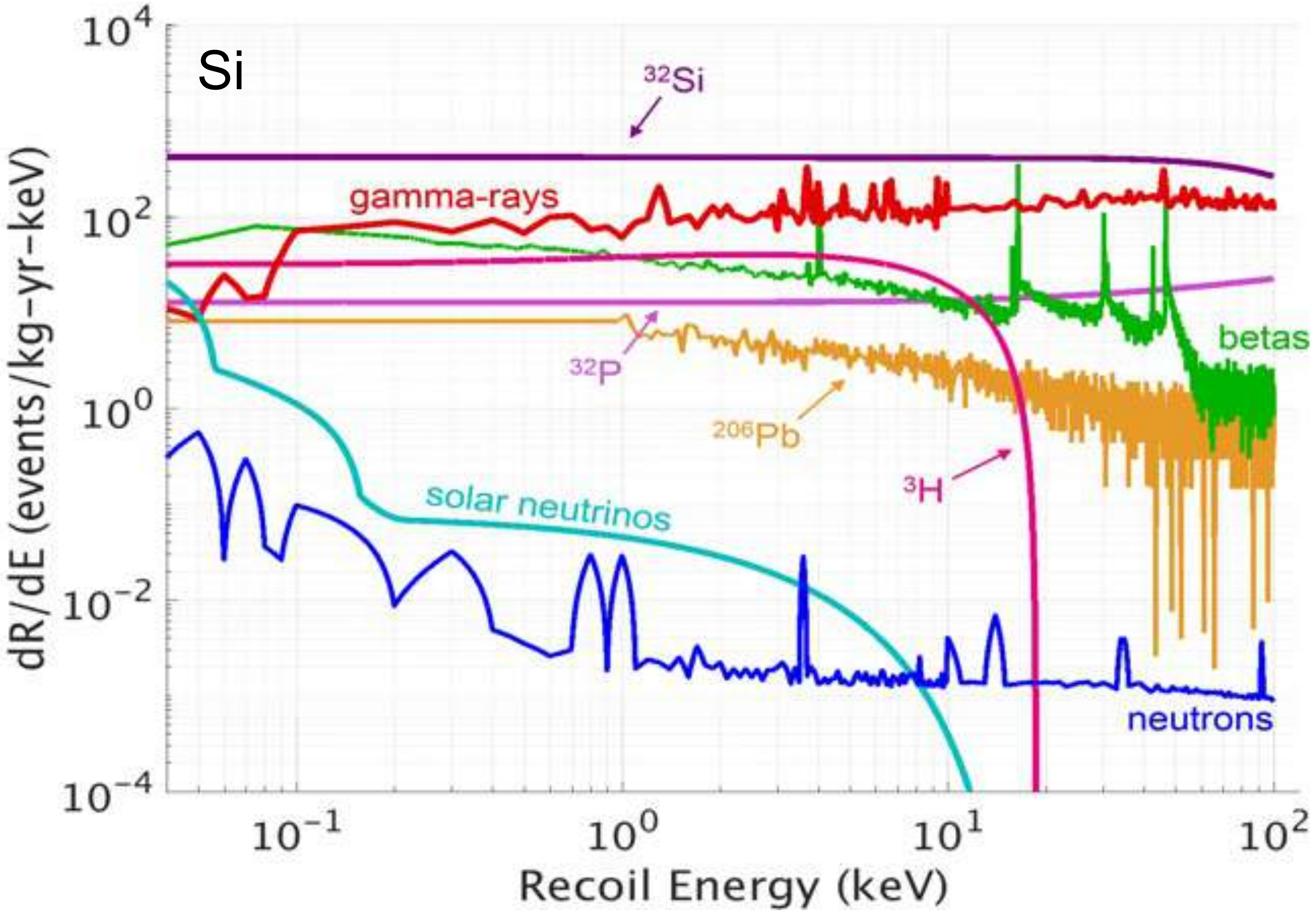


	Germanium	Silicon
HV	Lowest threshold for low mass DM *Larger exposure, no ^{32}Si background*	Lowest threshold for low mass DM *Sensitive to lowest DM masses*
iZIP	Nuclear Recoil Discrimination *Understand Ge backgrounds*	Nuclear Recoil Discrimination *Understand Si backgrounds*

SuperCDMS - Background Overview

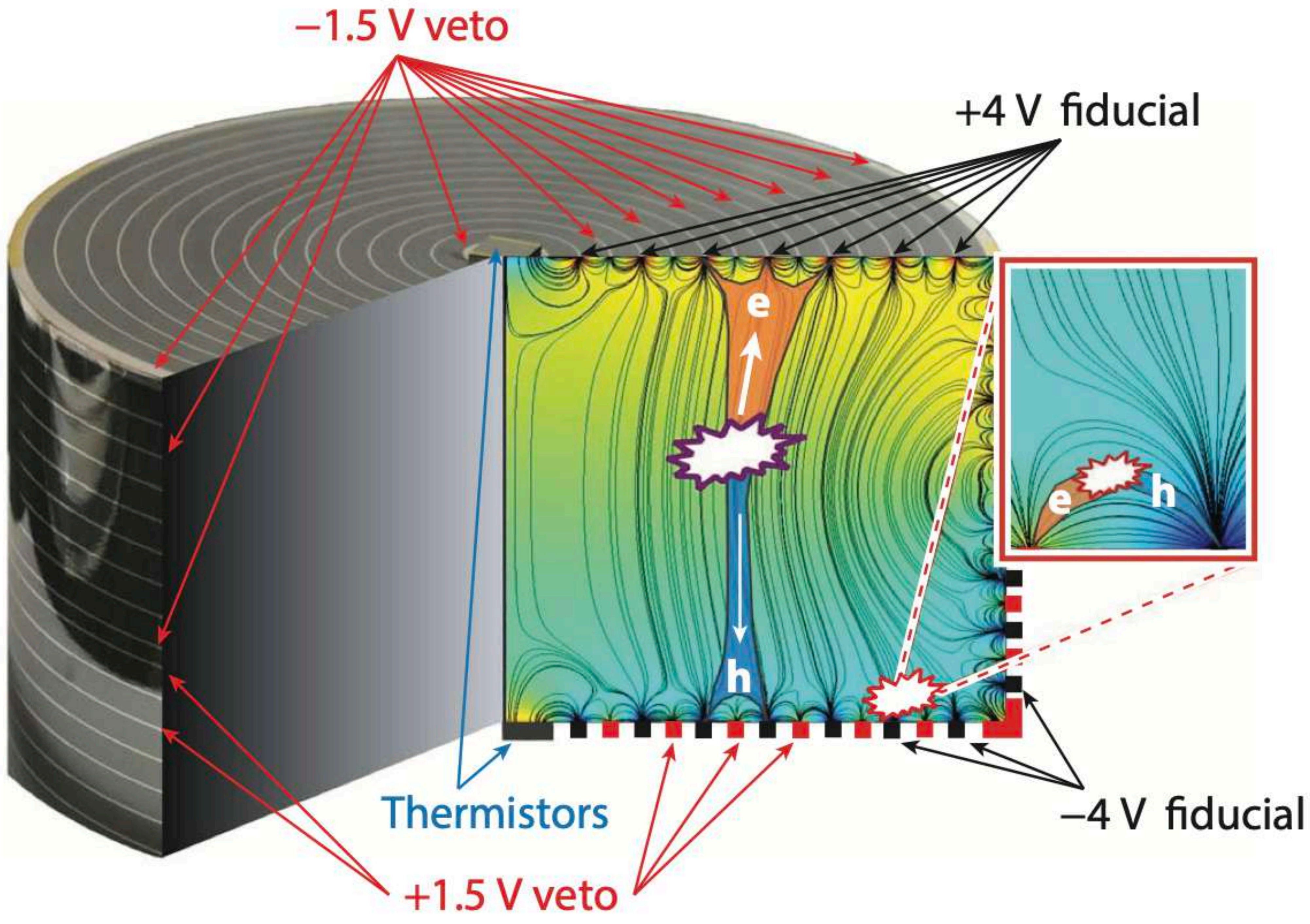
- Tritium, ^{32}Si (in Si), activated copper, surface Rn progeny, material impurities





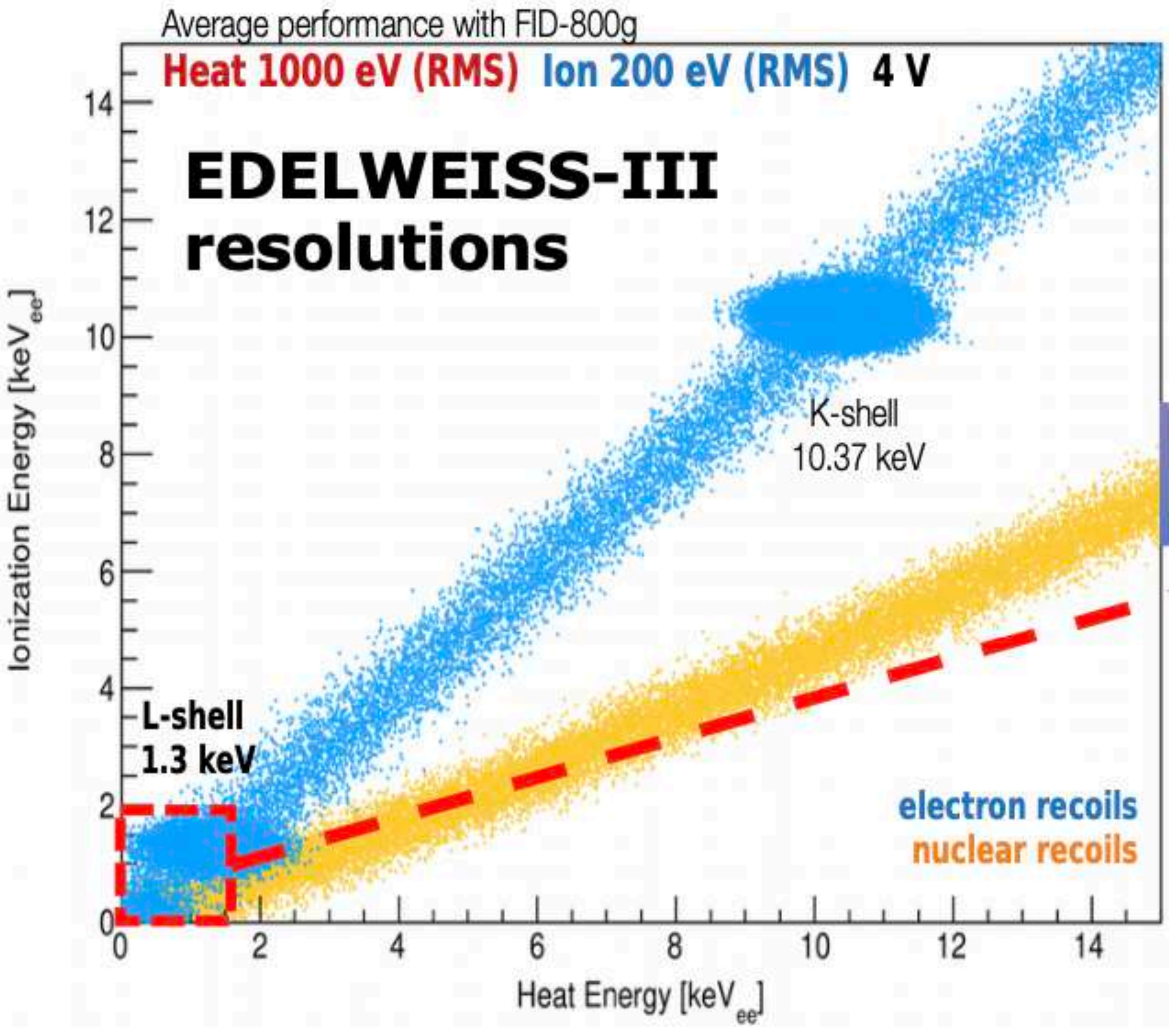
See Sagar Sharma Poudel Talk

The EDELWEISS experiment



Main features:

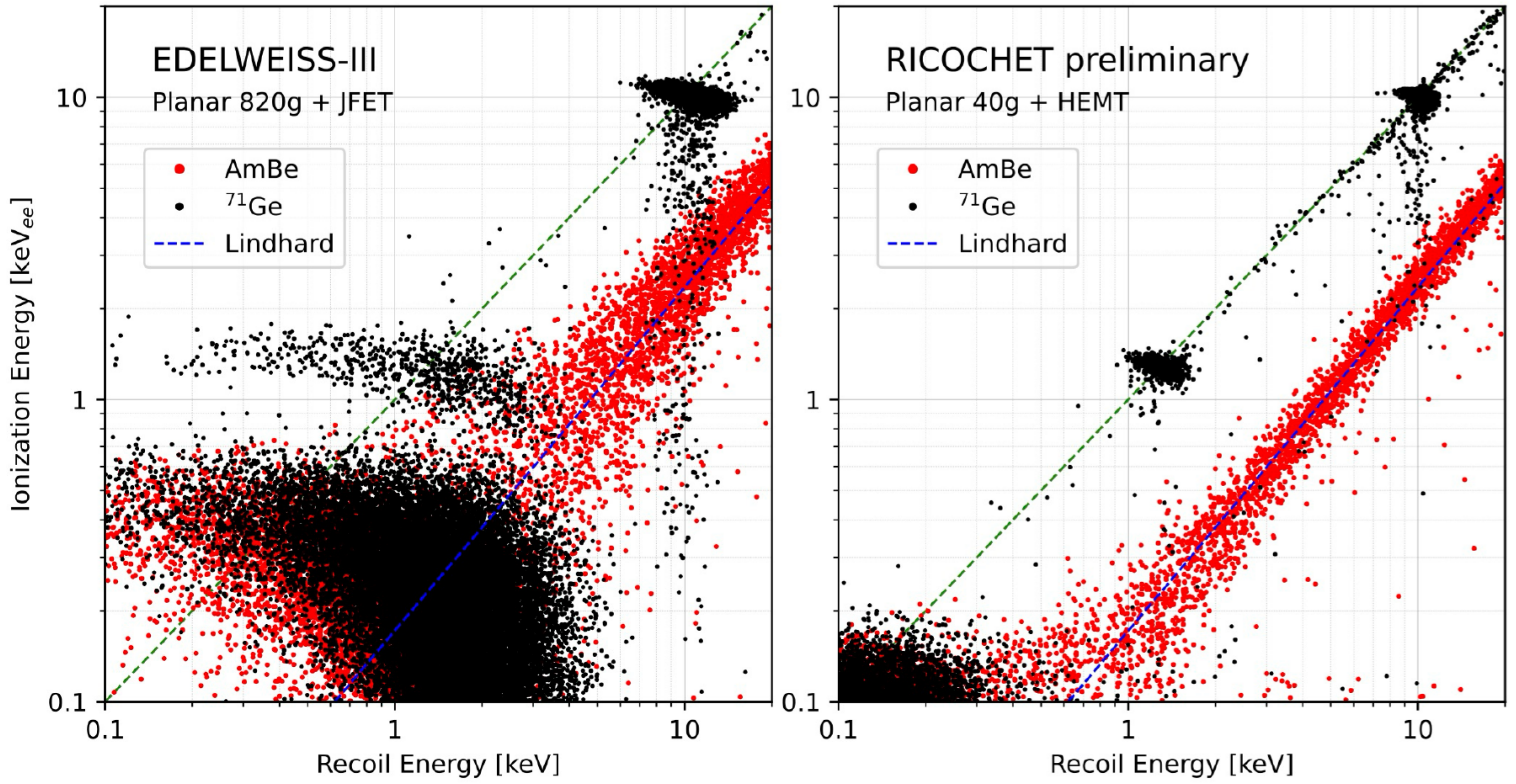
- Ge cylindrical crystals m ~ 800 g
- 2 NTD thermistors (TOP + BOTTOM)
- 2 Charge readout electrodes at ±4 V
- 2 Veto rings ±1.5 V (surface events rejection)

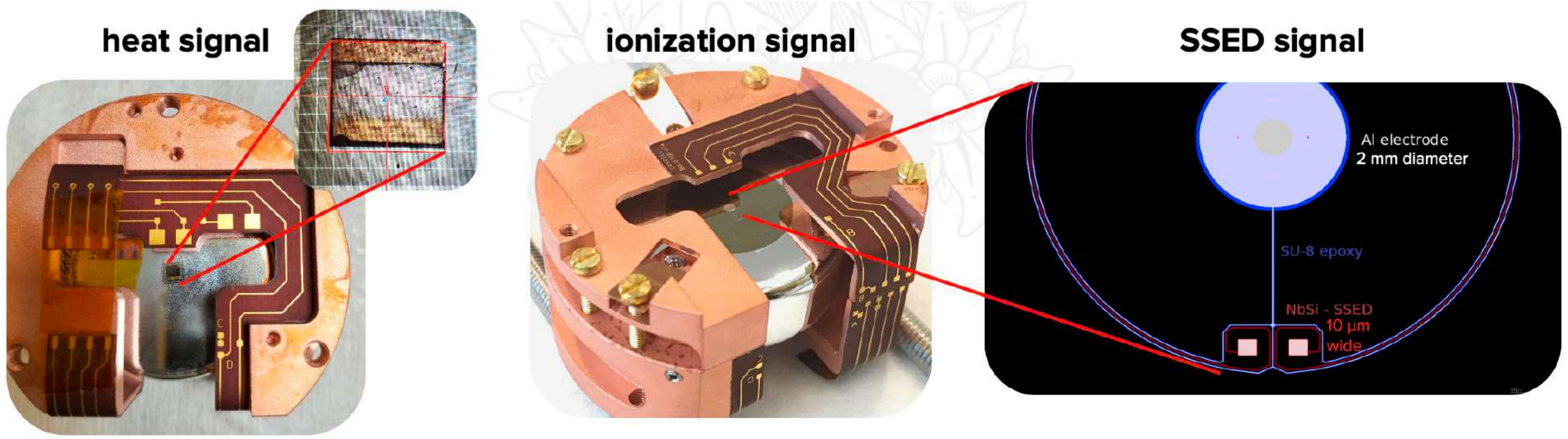


New challenge: transposing rejection performance of EDELWEISS-III 860 g heat-and-ionization Ge detectors from keV to eV scales!

New Objective: ~1kg array in new cryostat @LSM *(collab. with TESSERACT*)

EDELWEISS: future program





Current sensitivity limited by Heat Only Events!

Discrimination at Low Voltage:

High–electron mobility transistor (HEMT) amplifiers instead of the standard junction gate field effect transistor (JFET)

Joint effort with RICOCHET

+

Discrimination at High - Voltage:

development of NbSi **Superconductive Single-Electron Detector (SSED)** to tag charge and reject HO background → CRYOSEL.

JTLP 215 (2024) 268

Naganov–Trofimov–Luke amplification with higher Voltage (180 V) to lower the threshold on heat channel

Summary

Neutrinoless Double Beta Decay

Background are known! We need:

- faster sensor / higher SNR for pileup rejection
- active tool for surface event tagging
- more sensitive screening technique

Once the background has been fixed, the focus will be on the **signal** ➡ mass scale-up!

Mass scalability requires:

- funds (enriched material)
- improved cryogenic infrastructures

Dark Matter (low-energy processes)

Background not fully known! We need:

- mitigation of low-energy excess
- understand what lies beneath it

Once the background has been fixed, the focus will be on the **signal**:

- mass scale-up ➡ reproducible performance
- lower energy threshold
- new techniques for *new paradigms* (quantum sensing)

References

- S. Pirro, P. Mauskopf, Annual Review of Nuclear and Particle Science, 67, 161-181
- M. Kaznacheeva, K. Schäffner, Scintillating low-temperature calorimeters for direct dark matter search, e-Print: 2406.12887

- CUORE Collab., Data-driven background model for the CUORE experiment, Phys.Rev.D 110 (2024) 5, 052003
- AMoRe Collab., Projected background and sensitivity of AMoRE-II, e-Print: 2406.09698

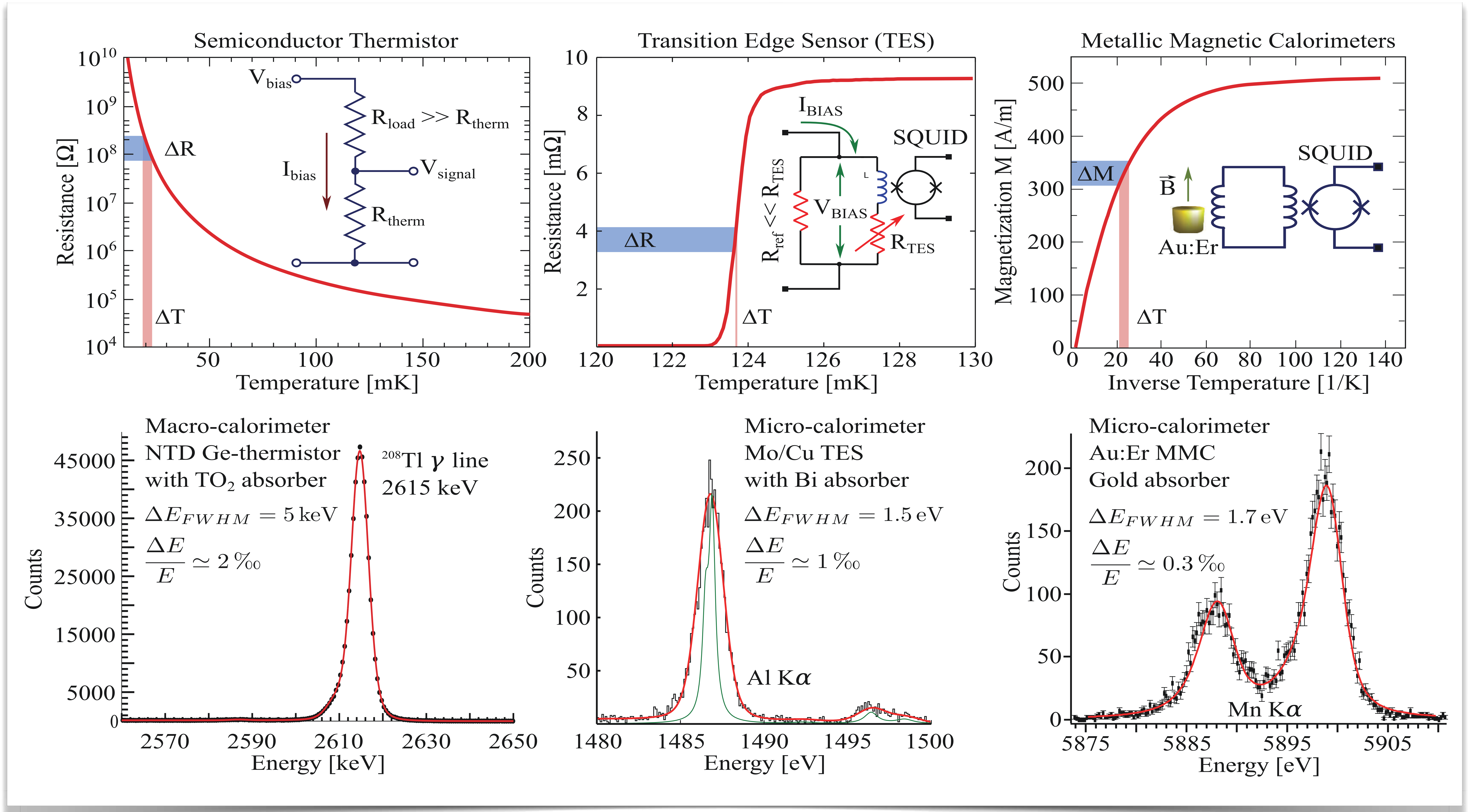
- EDELWEISS and RICOCHET and CRYOSEL Collaborations, Sub-GeV Dark Matter Searches with EDELWEISS and CRYOSEL, PoS TAUP2023 (2024) 031
- CRESST Collab., DoubleTES detectors to investigate the CRESST low energy background: results from above-ground prototypes, e-Print: 2404.02607
- SuperCDMS, First measurement of the nuclear-recoil ionization yield in silicon at 100 eV, Phys. Rev. Lett. 131, 091801

- https://cuore.lngs.infn.it/
- https://cupid.lngs.infn.it/
- https://amore.ibs.re.kr/
- https://cresst-experiment.org/
- https://supercdms.slac.stanford.edu/
- http://edelweiss.in2p3.fr/

Backup slides

General working principle(s)

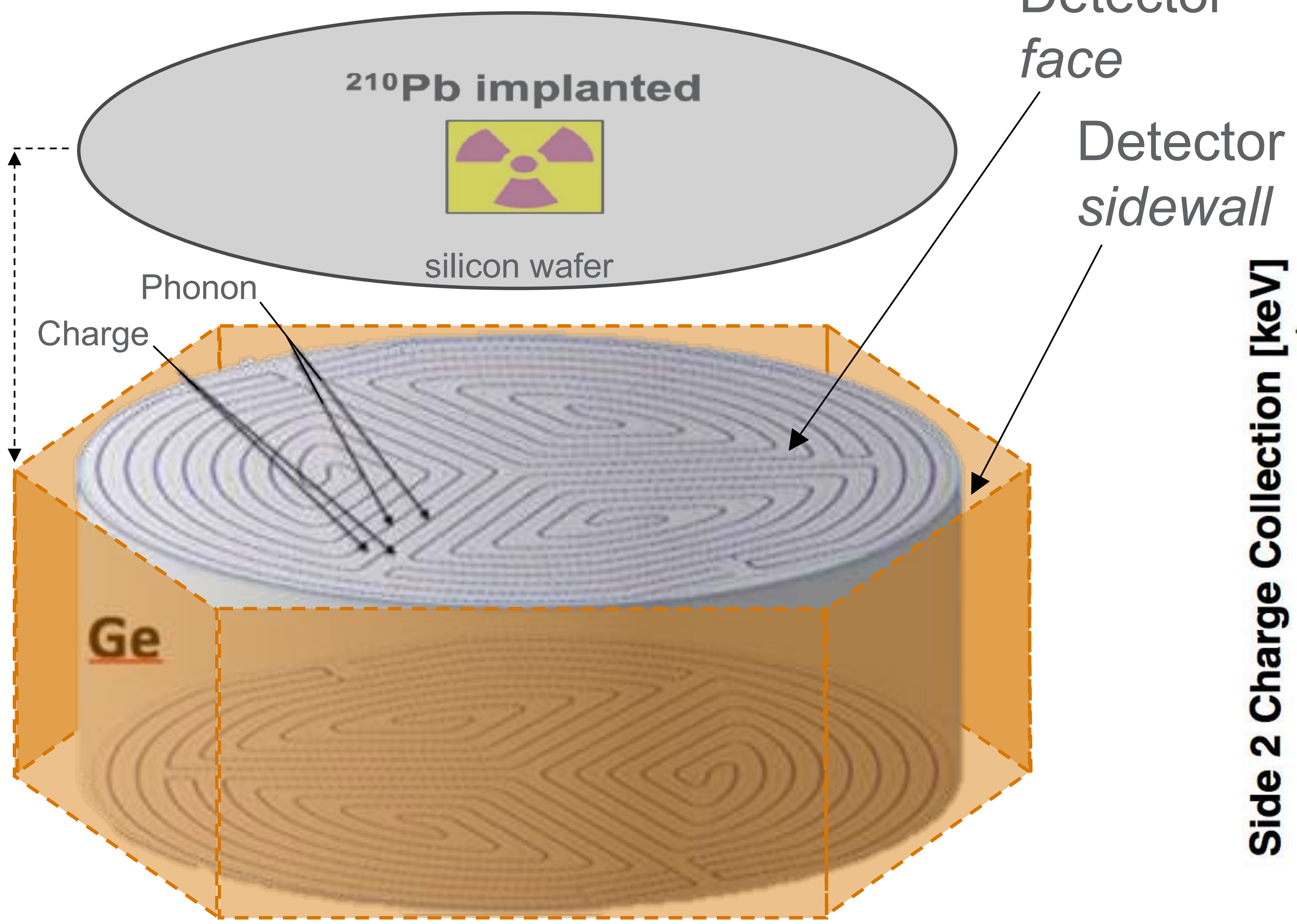
Credits: Andrea Giachero

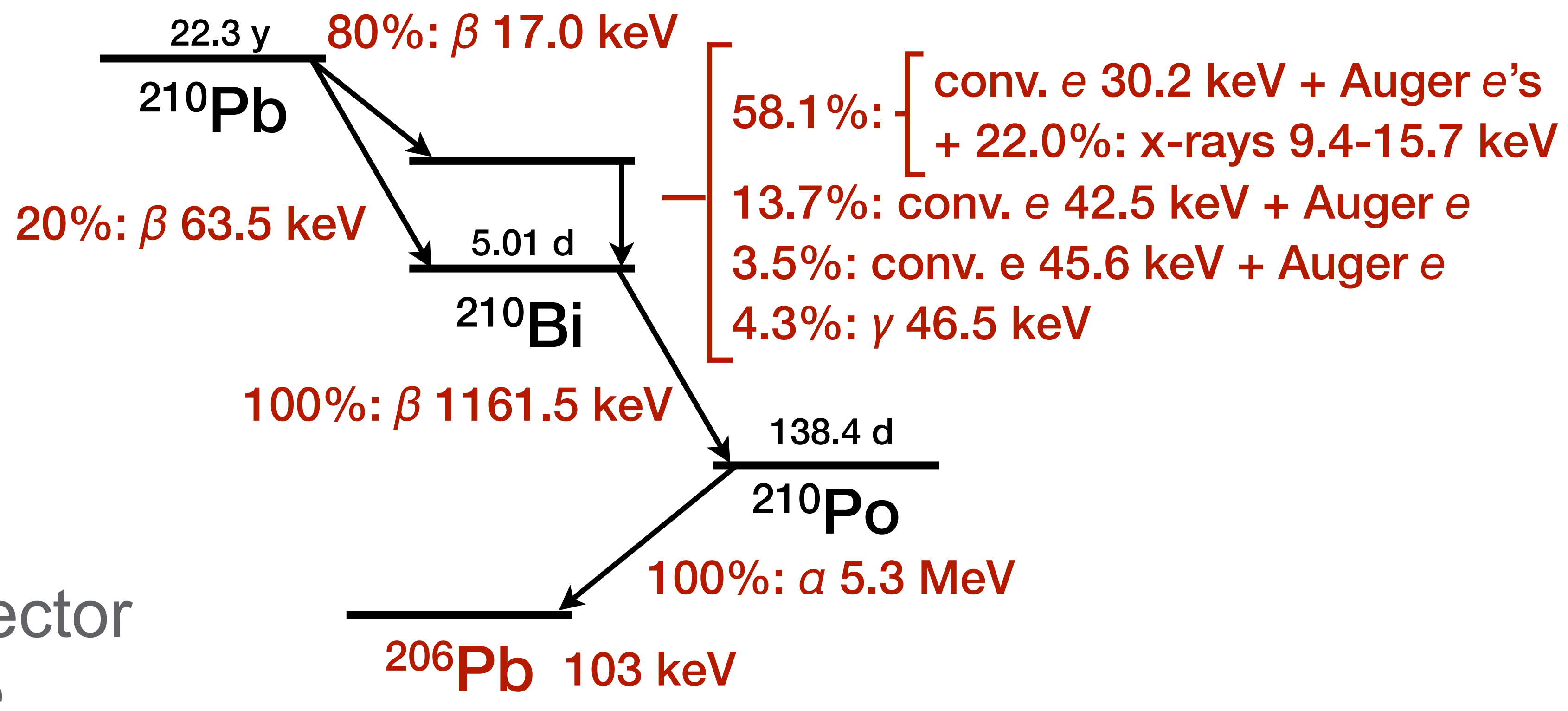


SuperCDMS - Surface Background Study

- Radon progeny (long-lived ^{210}Pb) are potential surface background sources

Soudan iZIP



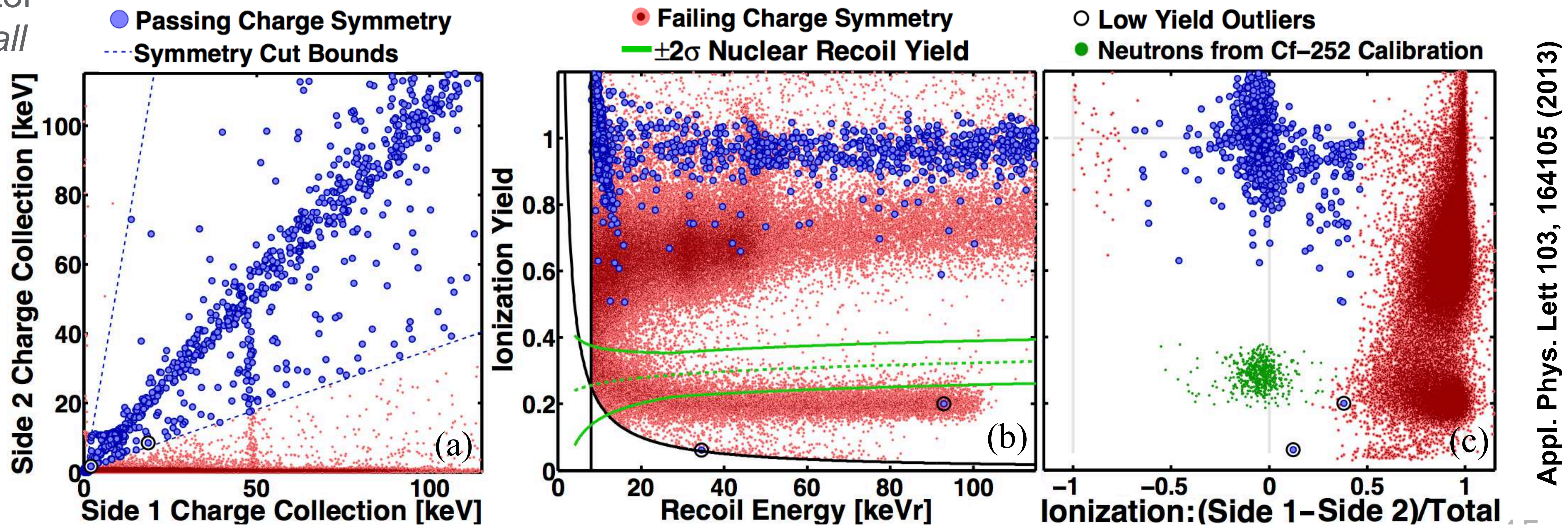


Demonstration of surface electron rejection with interleaved germanium detectors for dark matter searches

R. Agnese *et al.*,
Appl. Phys. Lett. 103 (2013) 164105

Caveats

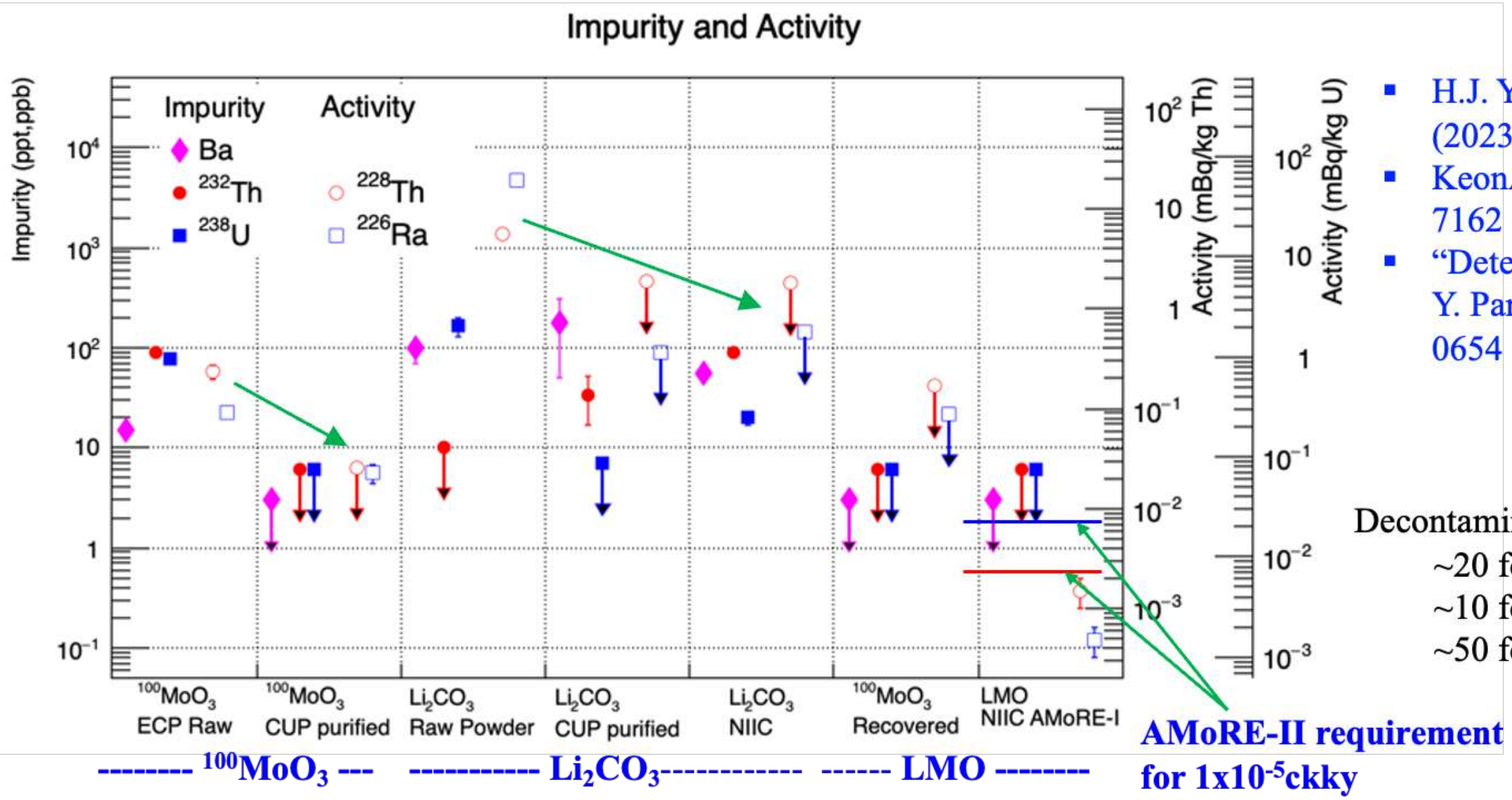
Performed with iZIP, not HV detector
Surface source only irradiated detector *face*



Growing pure enriched LMO crystals

Purification of raw material (for last ~ 5 years work)

- Purification of both powders, $^{100}MoO_3$ and Li_2CO_3.
- 180 kg of enriched MoO_3 powder is purified in wet chemistry: 150 kg at CUP and 30 kg at NIIC.
- Repurification of crystal melts and wastes is going on.



- H.J. Yeon et al., Front. Phys. 11:1142136 (2023)
- KeonAh Shin et al., Front. Phys. 12:134 7162 (2024)
- "Detection efficiency calibration …" S. Y. Park et al., Appl. Radiat. Isot. 193, 11 0654 (2023).

Decontamination factor for Li_2CO_3 powder :

~20 for K
~10 for Th
~50 for ^{226}Ra

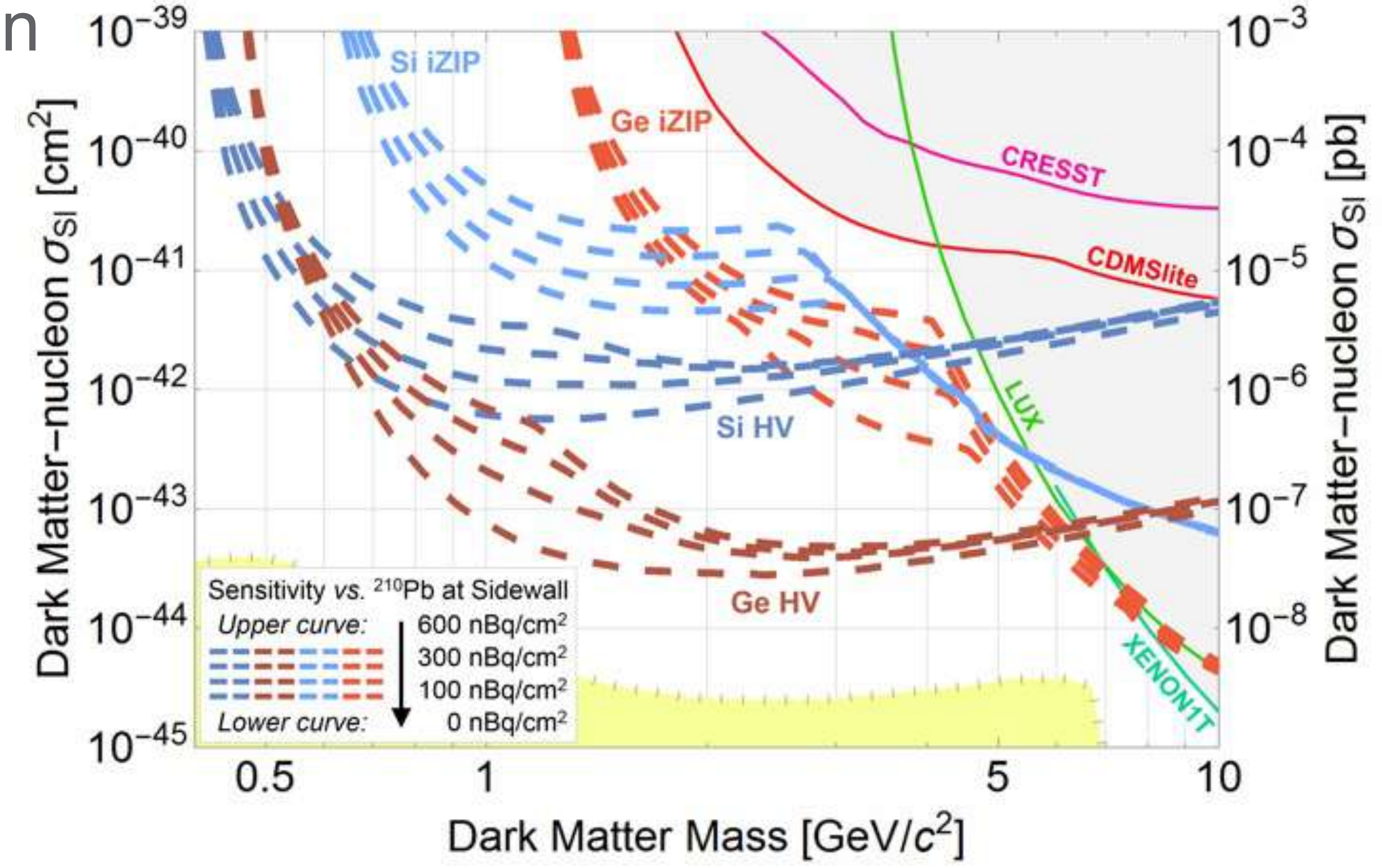
Cu surface background at detector sidewall

- SuperCDMS progressing from Soudan

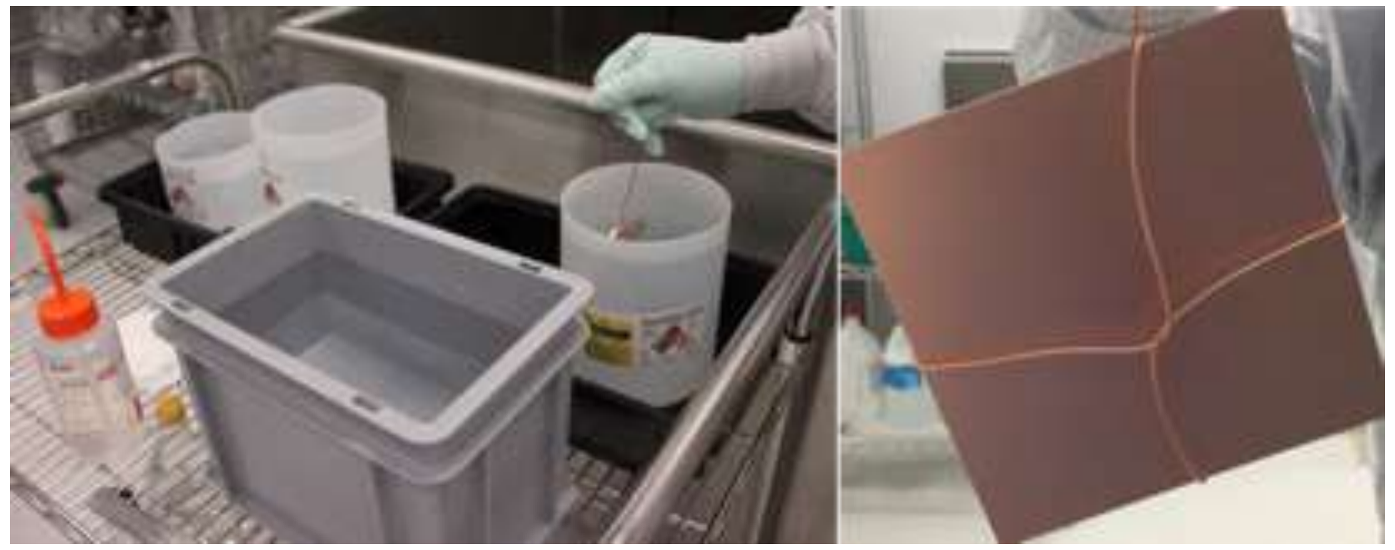
  At Soudan: (based on T2Z1)
  - Bottom face: 20 nBq/cm^2
  - Sidewall total: 1000 nBq/cm^2

  SNOLAB Goals:
  - Detector faces: 25 nBq/cm^2
  - Sidewalls: 50 nBq/cm^2

Sensitivity study vs. sidewall activity



- Summary concern → Cu cleanliness
  - Using acidified-peroxide etching followed by citric acid passivation



  - Tested on McMaster and Aurubis copper

Cleanliness tested with
XIA Ultra-Lo1800 alpha counter
by measuring polonium (^{210}Po), not lead (^{210}Pb) !!!

PNNL efforts on clean Kapton

Sponsors

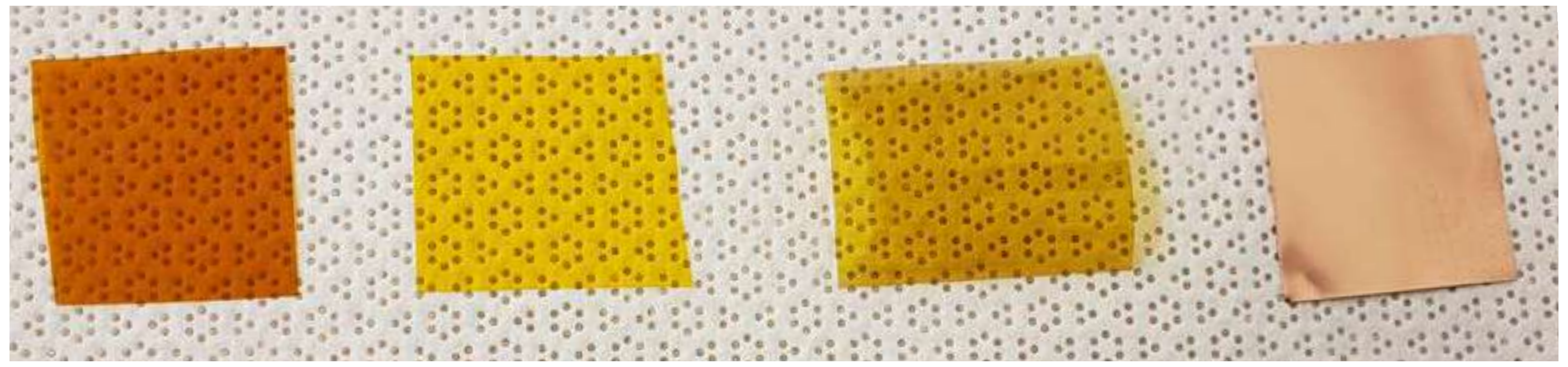
SBIR·STTR America's Seed Fund

Partners

DUPONT

Q-FLEX INC.

- Ultra-low radioactivity Kapton and copper-Kapton laminates
  - IJ Arnquist *et al*., **Nucl. Instrum. Meth. in Phys. Res. Sec. A** 959 (2020) 163573



Kapton	^{238}U [pg/g]	^{232}Th [pg/g]	^{nat}K [ng/g]
Commercial HN	1080 +/- 40	250 +/- 8	44 +/- 18
Radiopure R&D	12.3 +/- 1.9	19 +/- 2	34 +/- 14

Kapton-Cu Laminates	^{238}U [pg/g]	^{232}Th [pg/g]	^{nat}K [ng/g]
Commercial	158 +/- 6	24.1 +/- 0.9	< 210
Radiopure	9 +/- 4	20 +/- 14	160 +/- 80

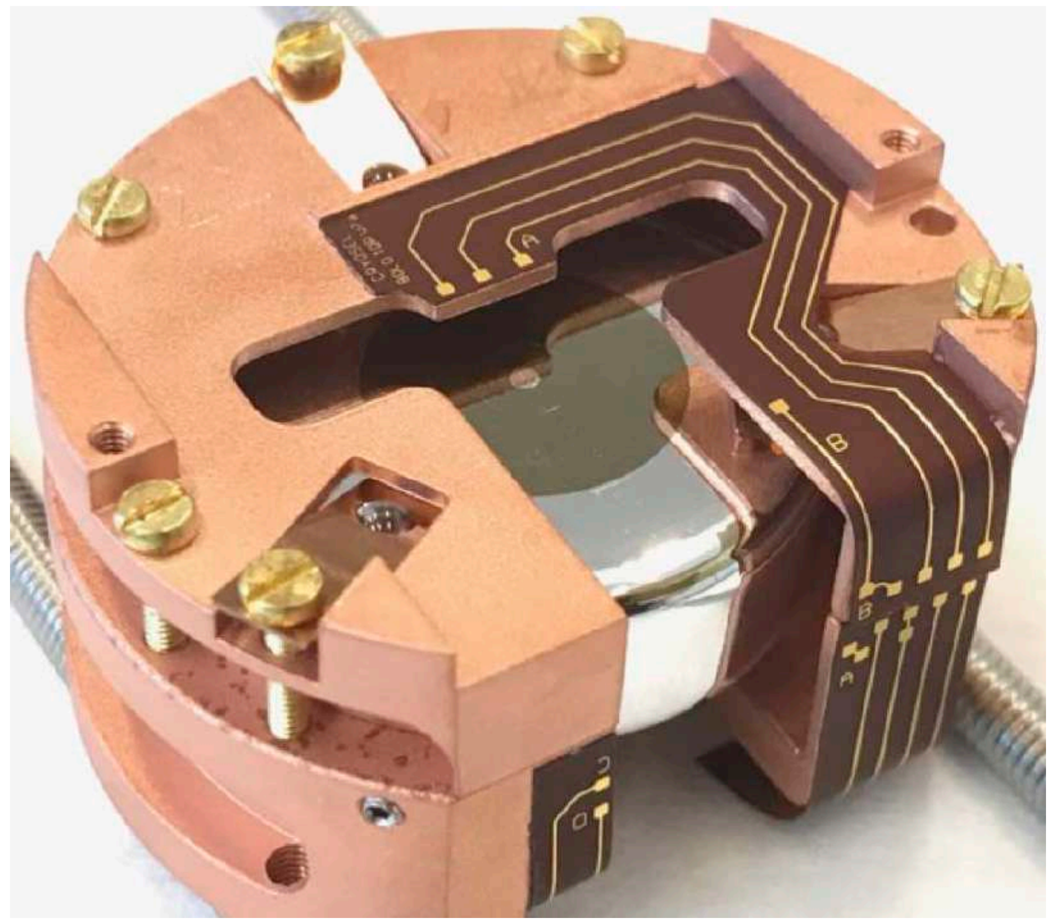
- Ultra-low radioactivity flexible printed cables
  - IJ Arnquist *et al*., **EPJ Techniques and Instrumentation** 10 (2023) 17

Blue: Standard Step
Orange Outline: Modified Step
Orange: New Step
Green: Step done at PNNL

Cables	^{238}U [ppt]	^{232}Th [ppt]	^{nat}K [ppb]
Commercial	2670 +/- 30	260 +/- 10	170 +/- 50
Clean	31 +/- 2	13 +/- 3	550 +/- 20

CRYOSEL concept

- 40 g Ge crystal
- Phonon sensor = single NbSi strip (10 μm wide) forming a 5 mm-wide circle
- Use this small film as Point-Contact-like electrode of HV detector
- NTD glued on large enveloping electrode (high-resolution NTL-amplified heat measurement)
- NbSi operated as SSED (Superconducting Single-Electron Detector)
- *Detector kept well below T_c so that SSED is only triggered by large bursts of primary NTL phonons from* *high-field region* *just in front of it*
- *Most HO will not trigger SSED*



CRYO50