Probing light Dark Matter with the CRESST-III experiment

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UCLA Dark Matter 2023

The CRESST collaboration

CRESST

TU WIEN

UNIVERSITAS COMENIANA BRATISLAVENSIS MCMXIX

UNIVERSITY OF OXFORD

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INSTITUTE OF HIGH ENERGY PHYSICS

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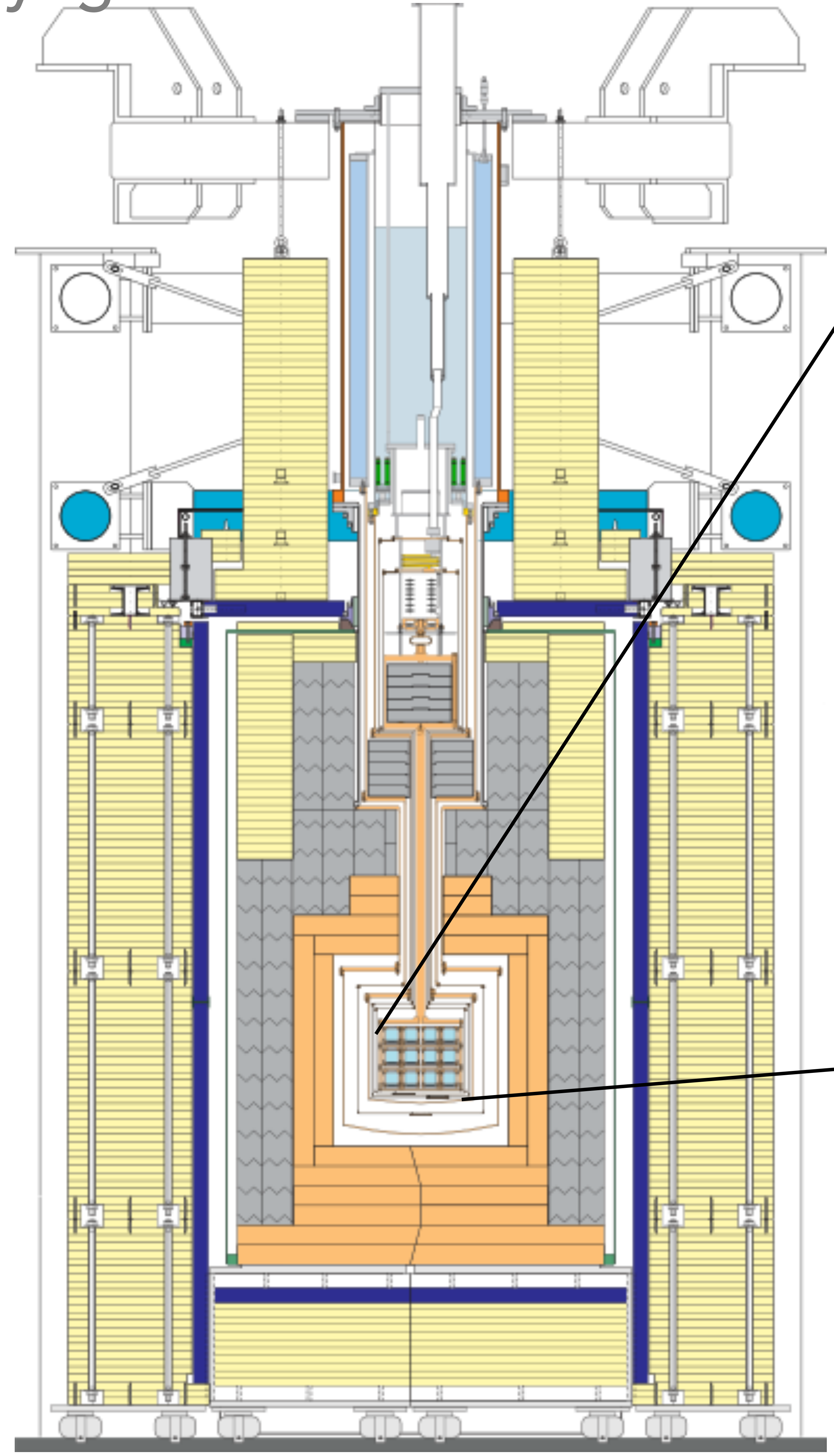
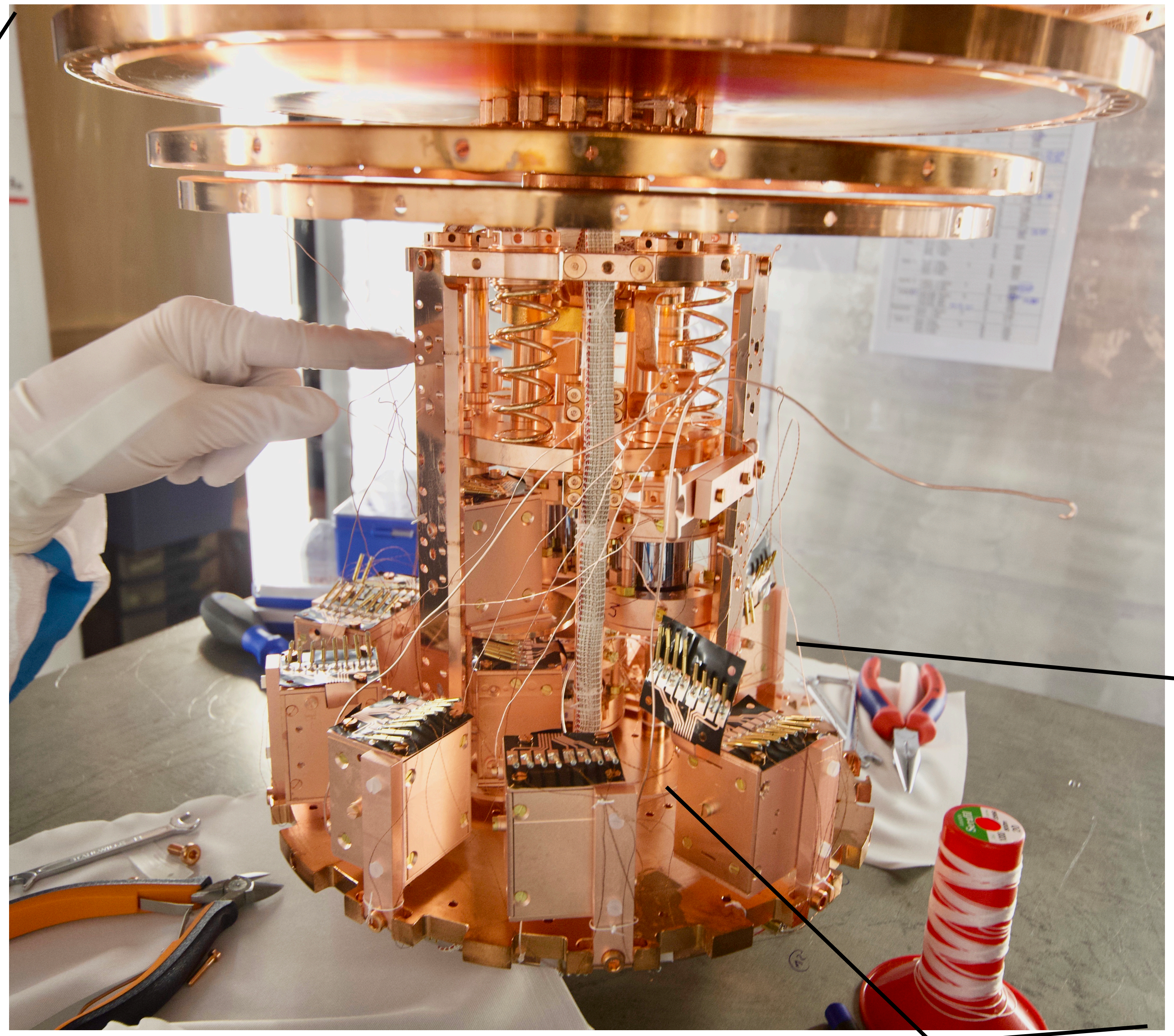
The CRESST experiment

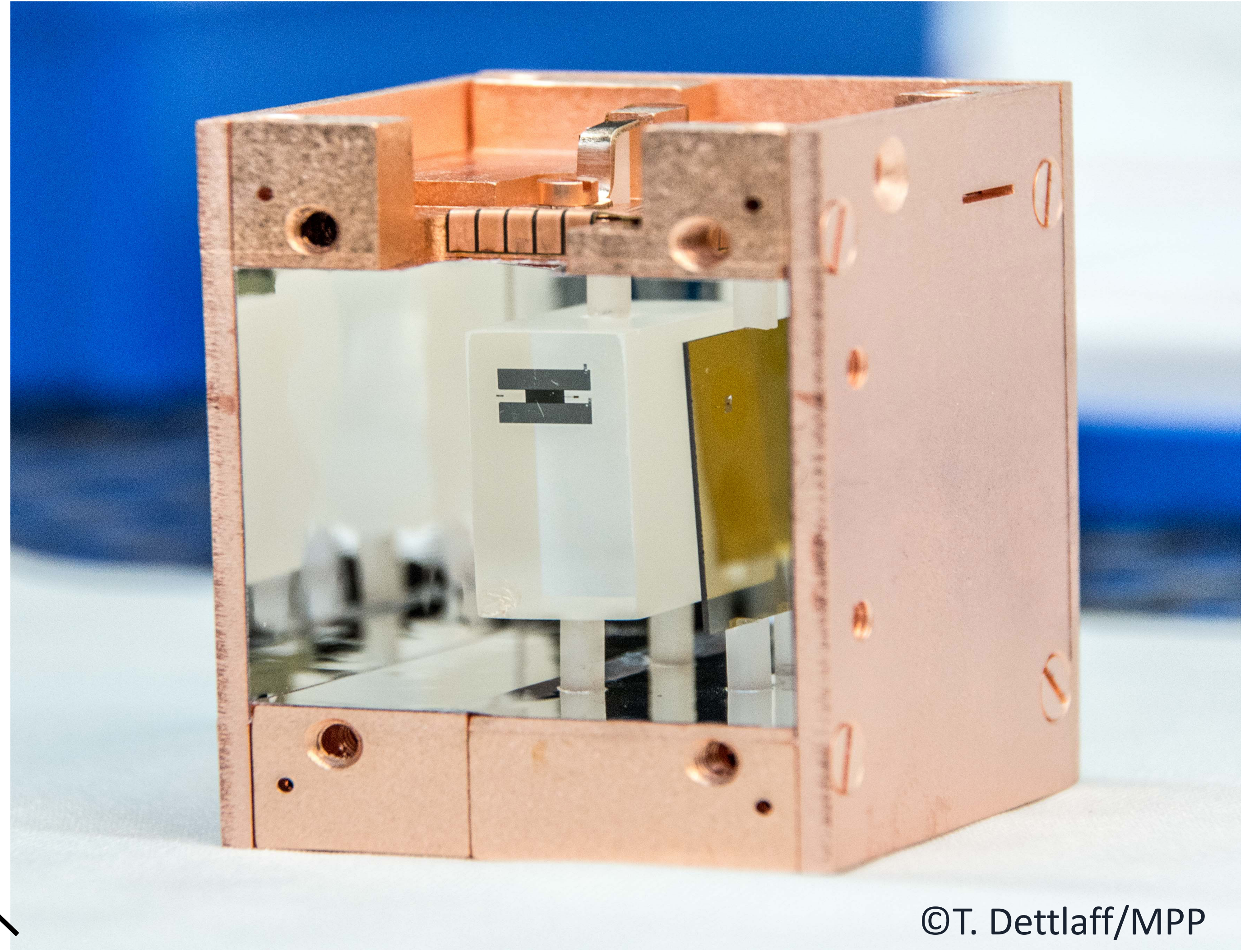
Cryogenic Rare Event Search with Superconducting Thermometers


Dilution Refrigerator



Scintillating ($CaWO_4$)
crystals as target

Separate **cryogenic**
light detector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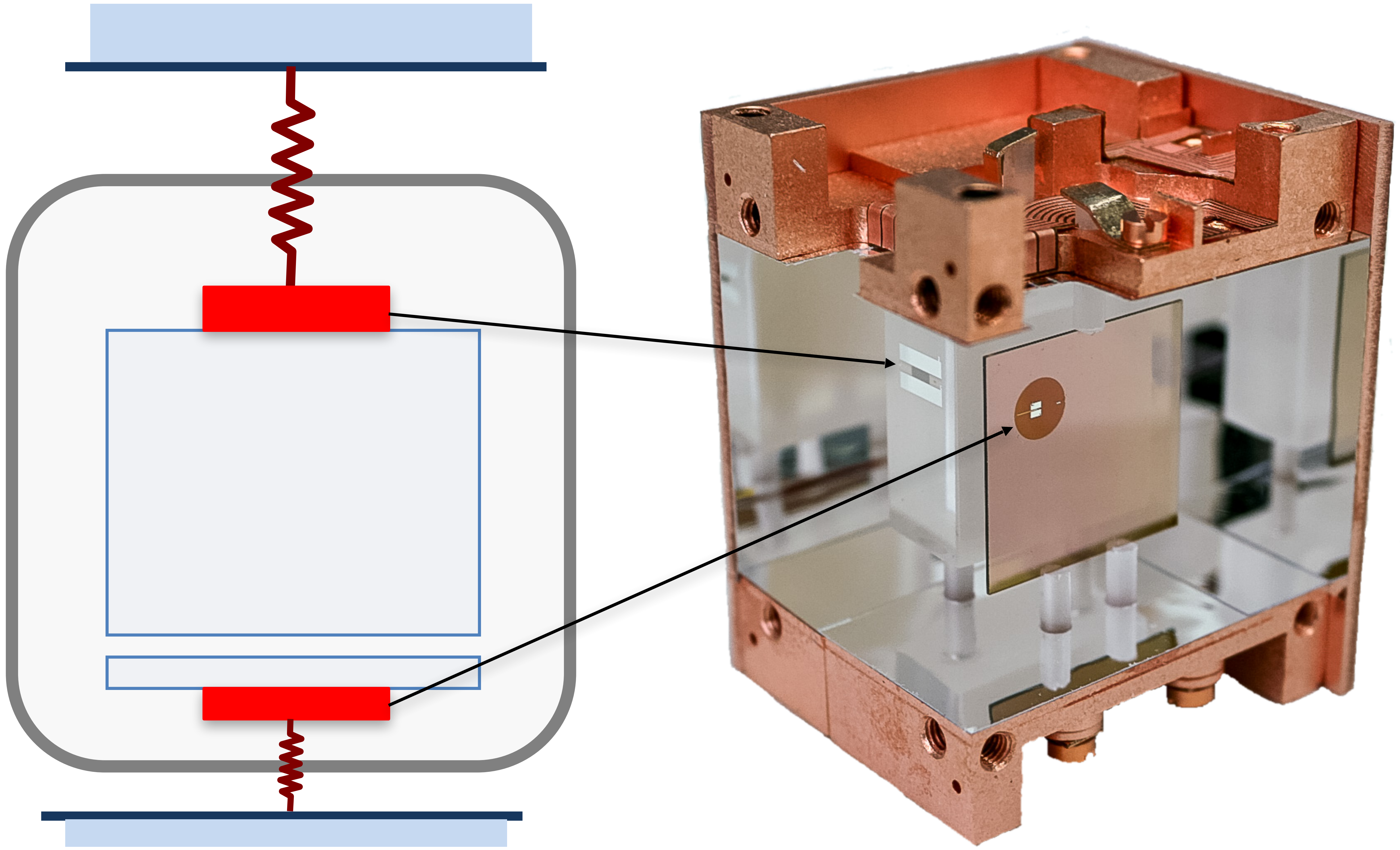
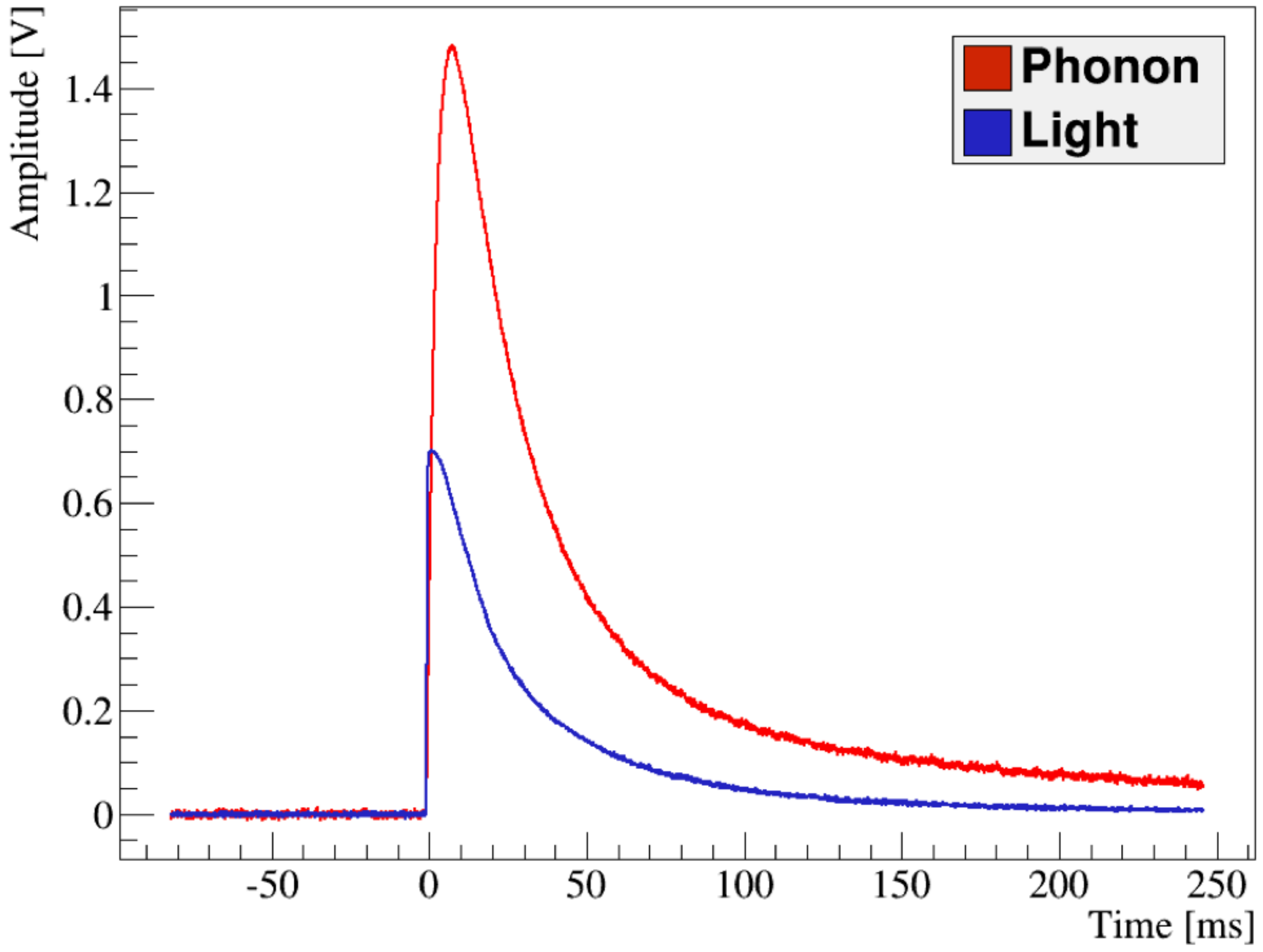
CRESST goal: direct detection of dark matter particles via their scattering off target nuclei in cryogenic detectors, operated at ~15 mK

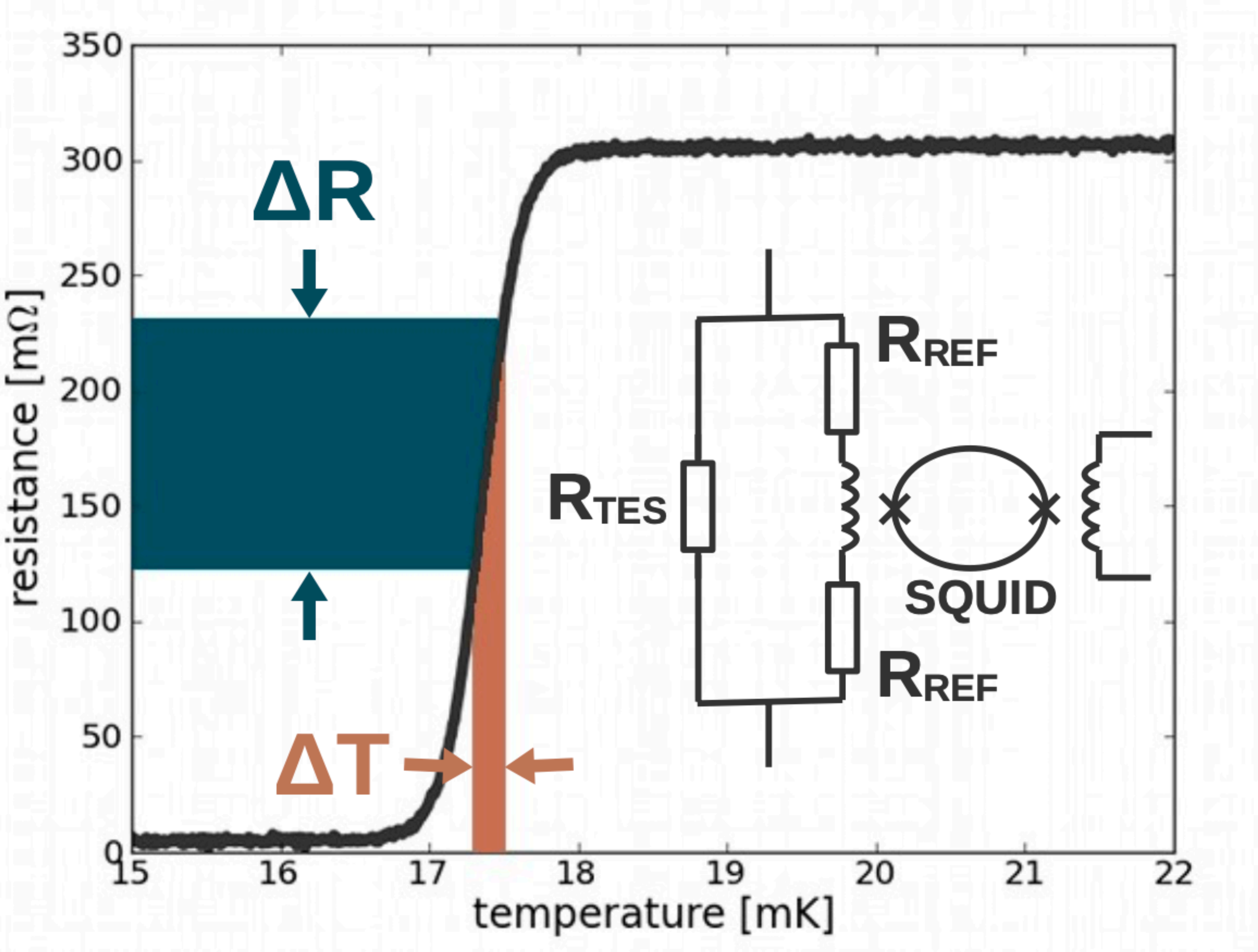
DETECTOR MODULE

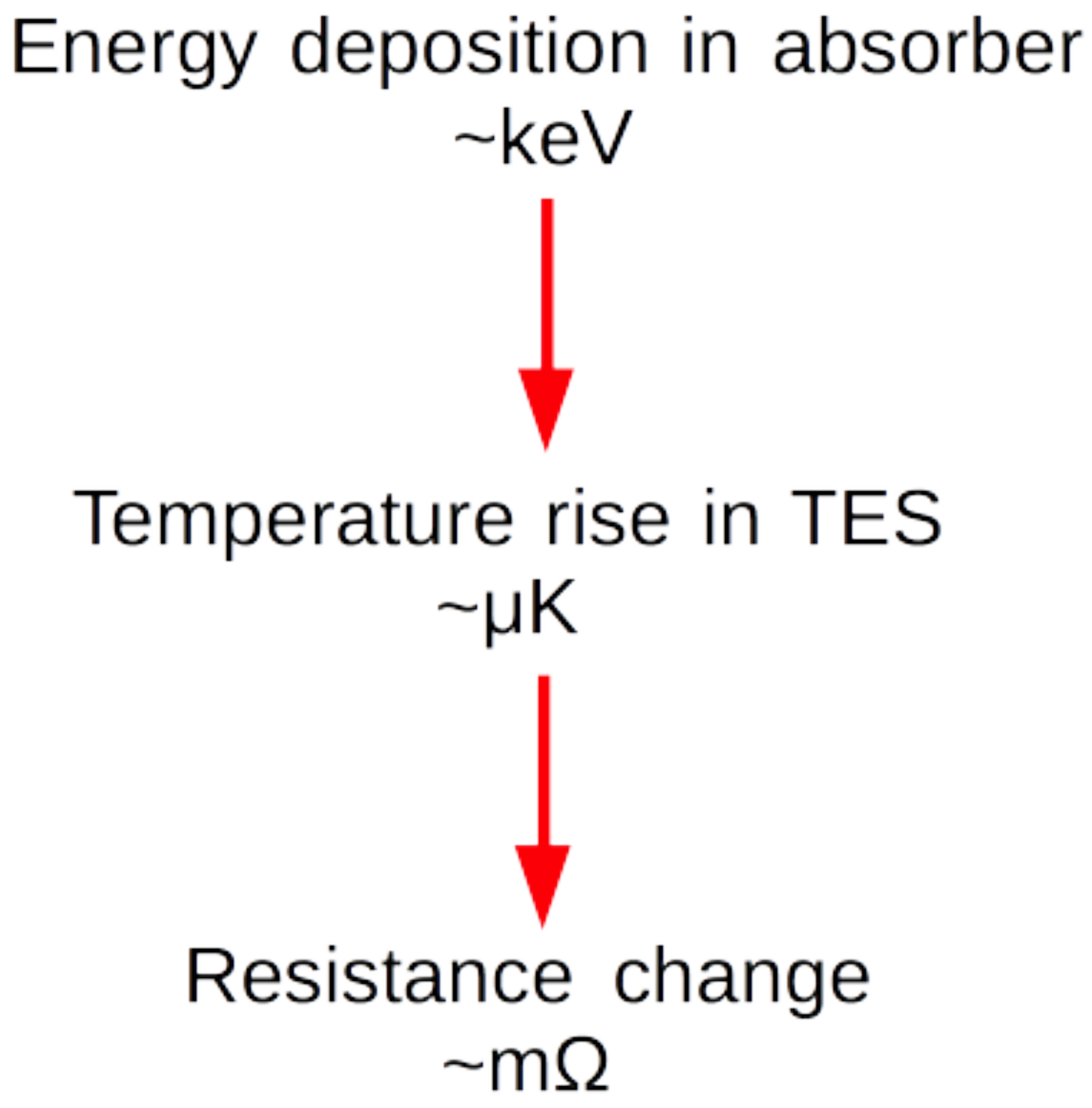




Simultaneous signals from the transition edge sensors (TESs)

TRANSITION EDGE SENSOR





Energy deposition in absorber
~keV

Temperature rise in TES
~μK

Resistance change
~mΩ

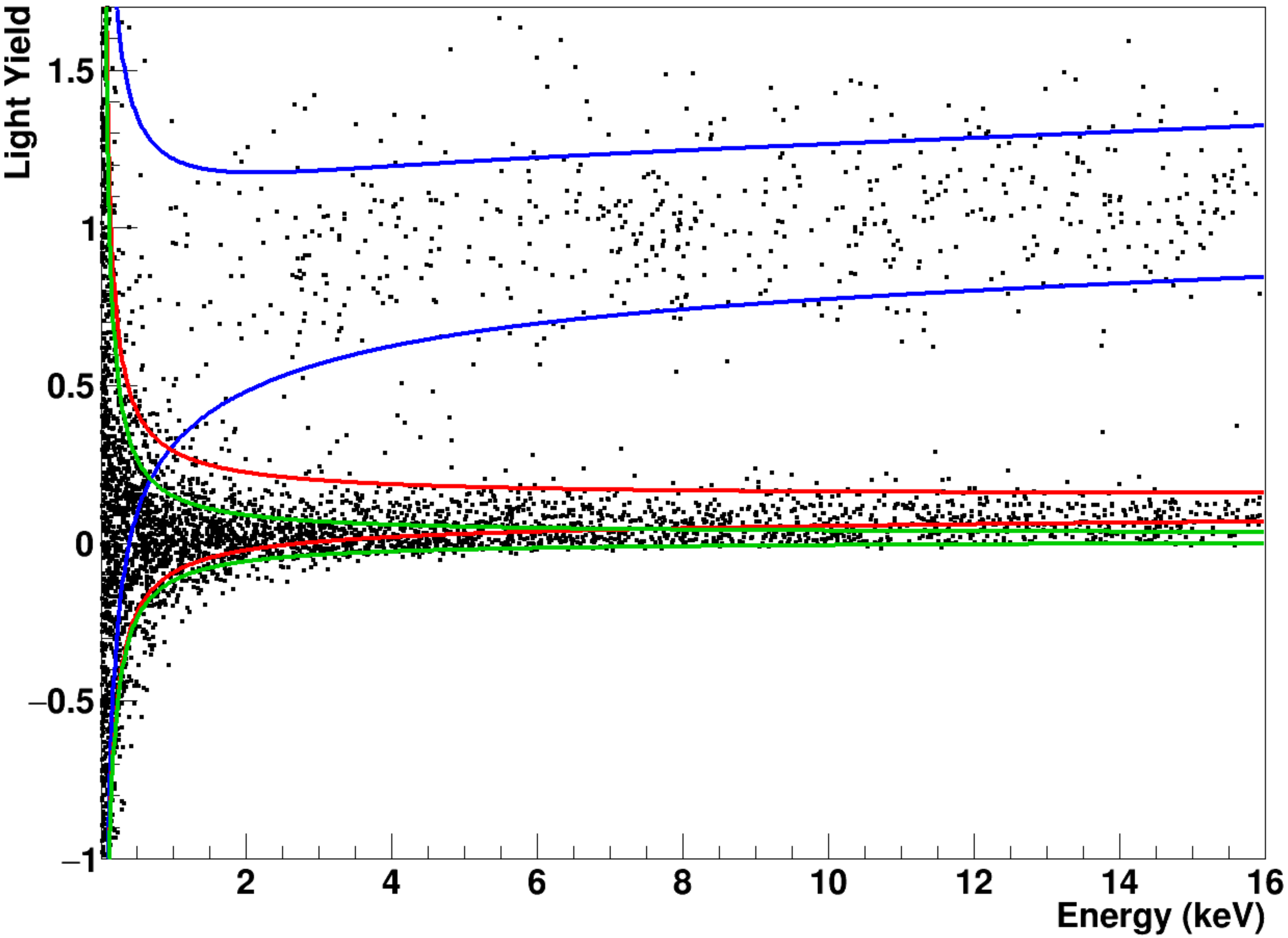
EVENT DISCRIMINATION

CRESST

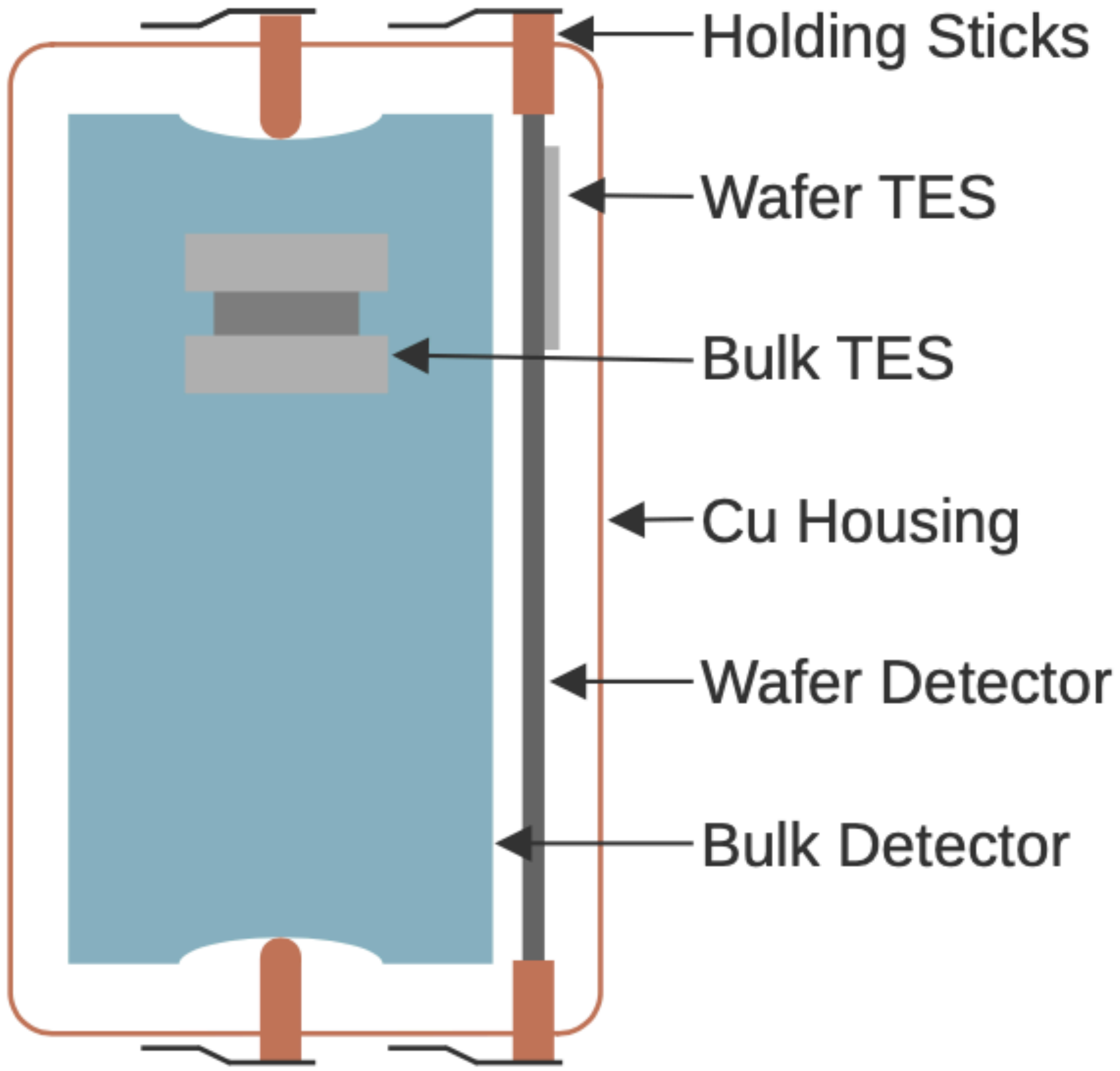
$$\text{Light Yield} = \frac{\text{Light signal}}{\text{Phonon signal}}$$

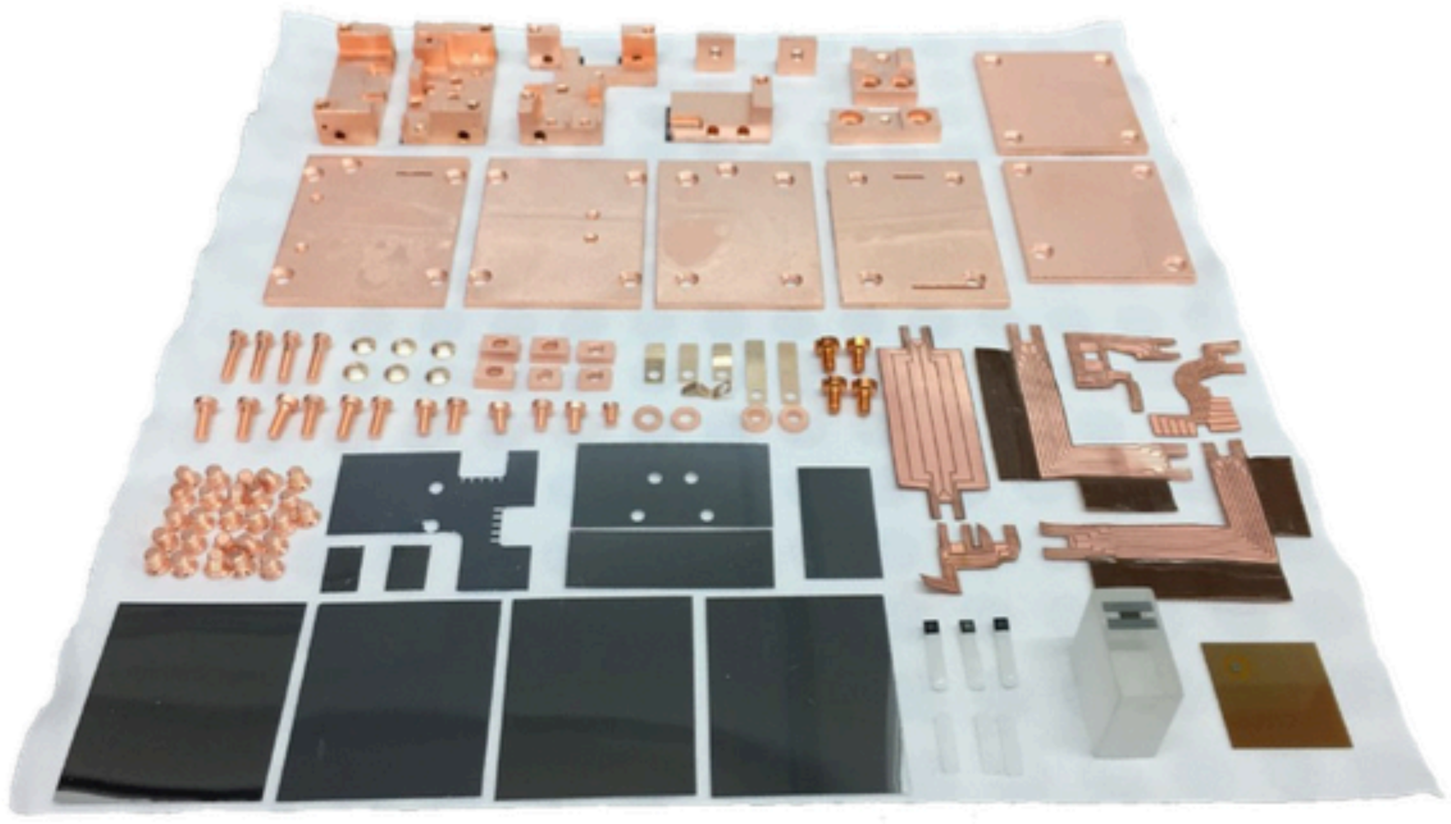
Characteristic of the event type

Excellent discrimination between potential signal events (**nuclear recoils**) and dominant radioactive background (**electron recoils**)



CRESST-III Detectors





Main absorber: (2x2x1) cm^3, broad choice of materials e.g. $CaWO_4$ (24 g), Al_2O_3 - sapphire (16 g), $LiAlO_2$ (10 g), Si (9 g)

Thin wafer detector: (2x2x0.04) cm^3, Si or silicon-on-sapphire (SOS) serves as light detector for scintillating absorbers

Holding structure: light-tight copper housing, scintillating reflector foil, detectors held by sticks from $CaWO_4$ or copper

Sensors: W-TES directly evaporated on the crystals

DARK MATTER Results

Det A: 23.6 g, E_{th} = 30.1 eV

Analysis optimized for very low energies: 30.1eV → 16keV

Acceptance region fixed before unblinding

50 % O recoils below

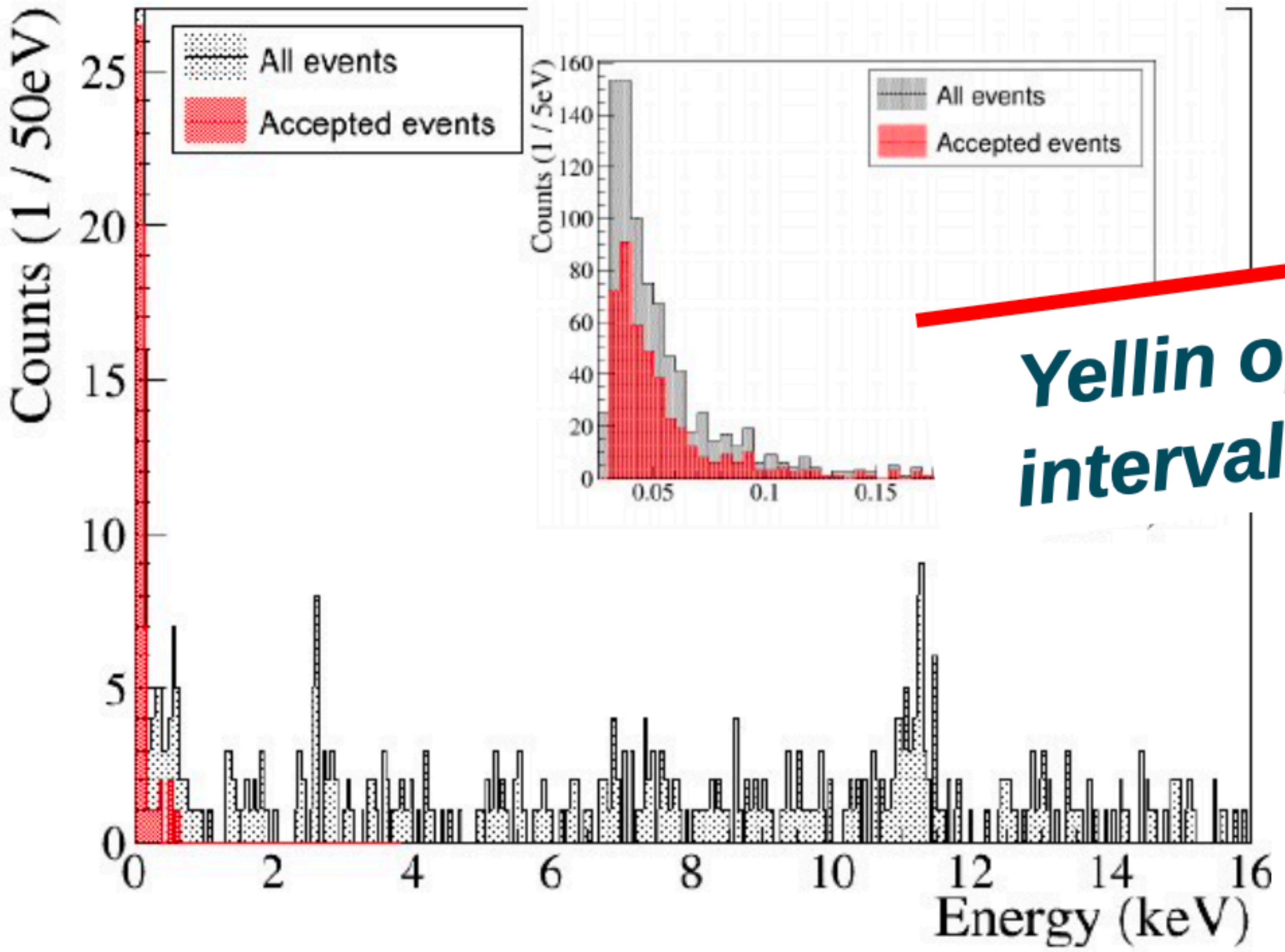
99.5 % W recoils above

DARK MATTER Results

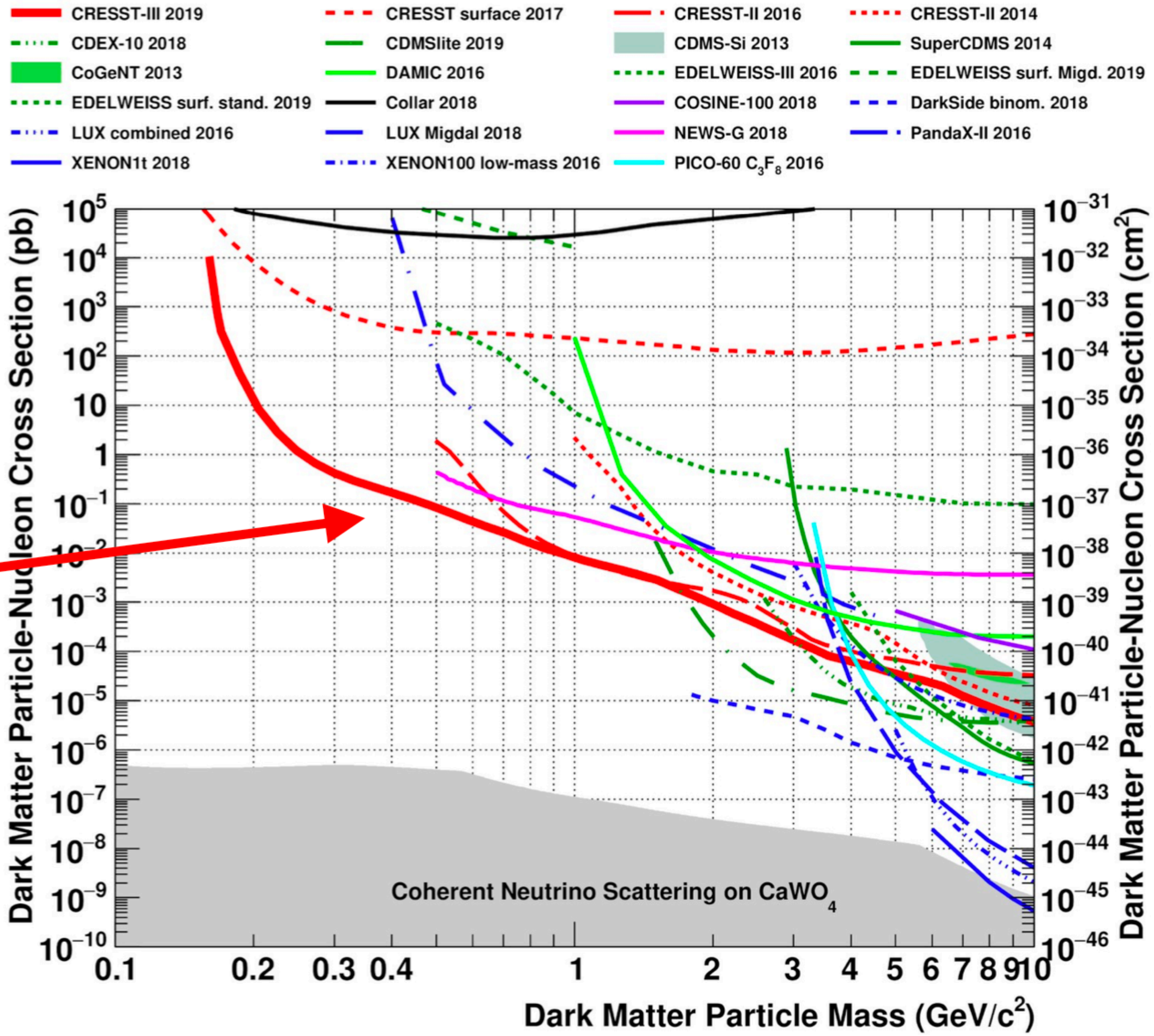
CRESST

Detector A – 23.6 g $CaWO_4$

data taking period	Oct 2016 – Jan 2018
exposure	5.698 kg · days
baseline resolution	4.6 eV
nuclear recoil threshold	30.1 eV



Yellin optimum interval method

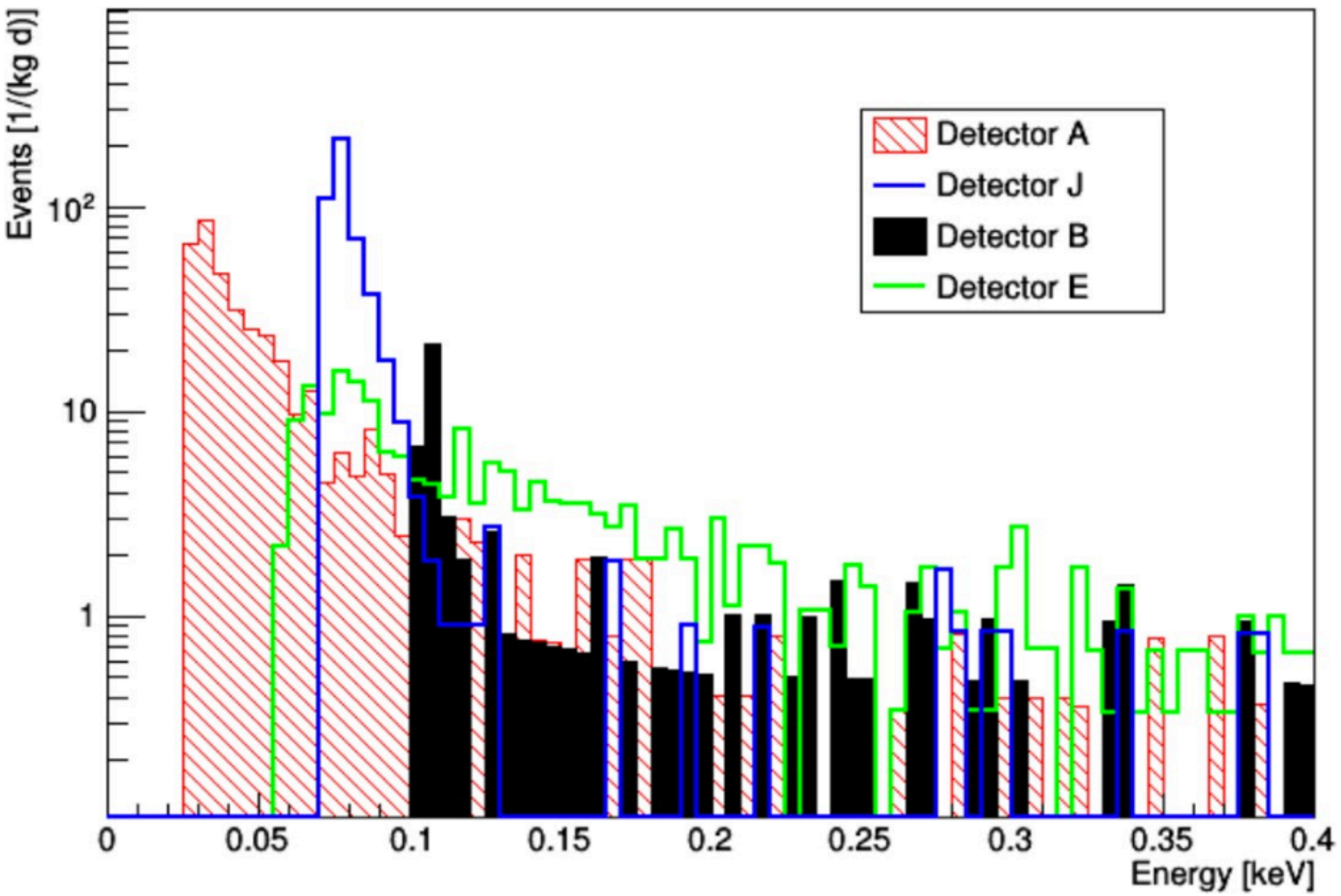


Phys. Rev. D 100, 102002 / arXiv:1904.00498

The Low Energy Excess (LEE)

First observations: 2016 – 2018

Overview of CaWO₄ Detectors



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

Unexplained event population at low energies

- high count rate
- steep rise in energy below ~200 eV
- different shape in different detectors

Detector	Threshold
Det-A	30.1 eV
Det-B	120 eV
Det-E	64.8 eV
Det-J	83.4 eV

- time dependency of LEE (exponentially decreasing with T~150d)

LEE: international scenario

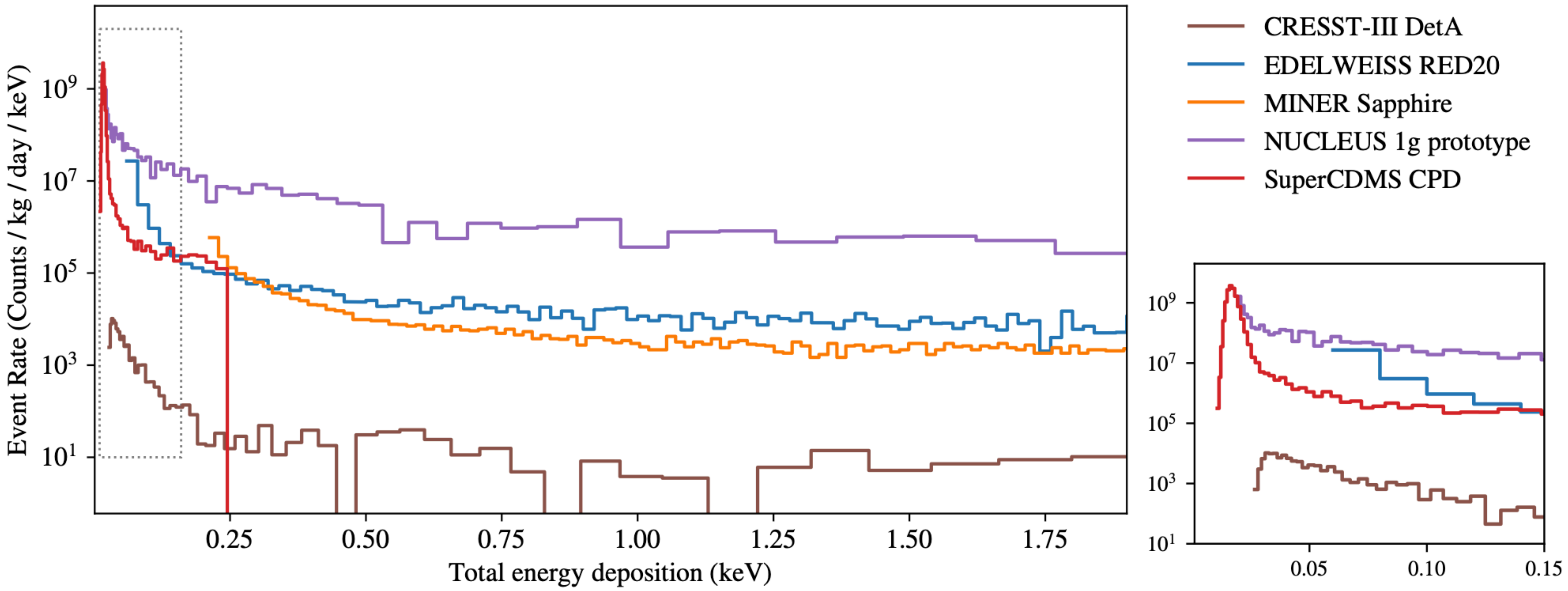
- After the early observation by CRESST, many low energy experiments observed LEE in their data.

See Talk from F.Reindl at the end of this session

- The EXCESS workshop series (promoted by CRESST collaborators) reached in 2022 the 3rd edition and produced a joint publication on LEE (https://arxiv.org/abs/2202.05097)

- LEE in CRESST is at least 10 times lower than in any other experiment so far.

- EDELWEISS collaboration first observed a reset of the counting rate after a thermal cycle at ~50K

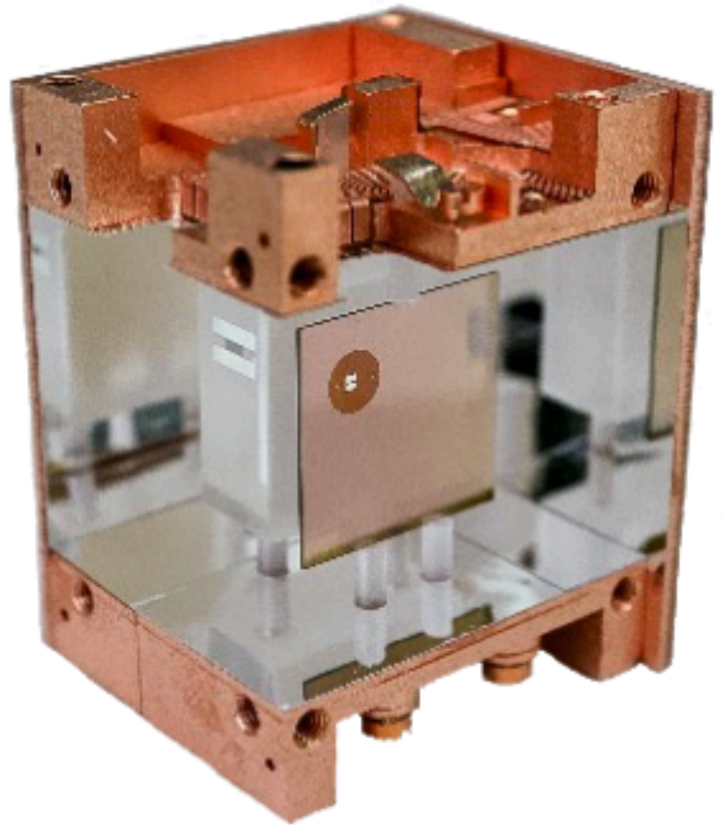


Current Measurement Campaign

Managed to cool-down the detectors in summer 2020 – despite the pandemic

Took data for DM search from Nov 2020 until Aug 2021

Followed by neutron calibration and measurements of the LEE



Dedicated modifications to probe LEE:

- different target materials
- change how crystals are held
- remove scintillating components

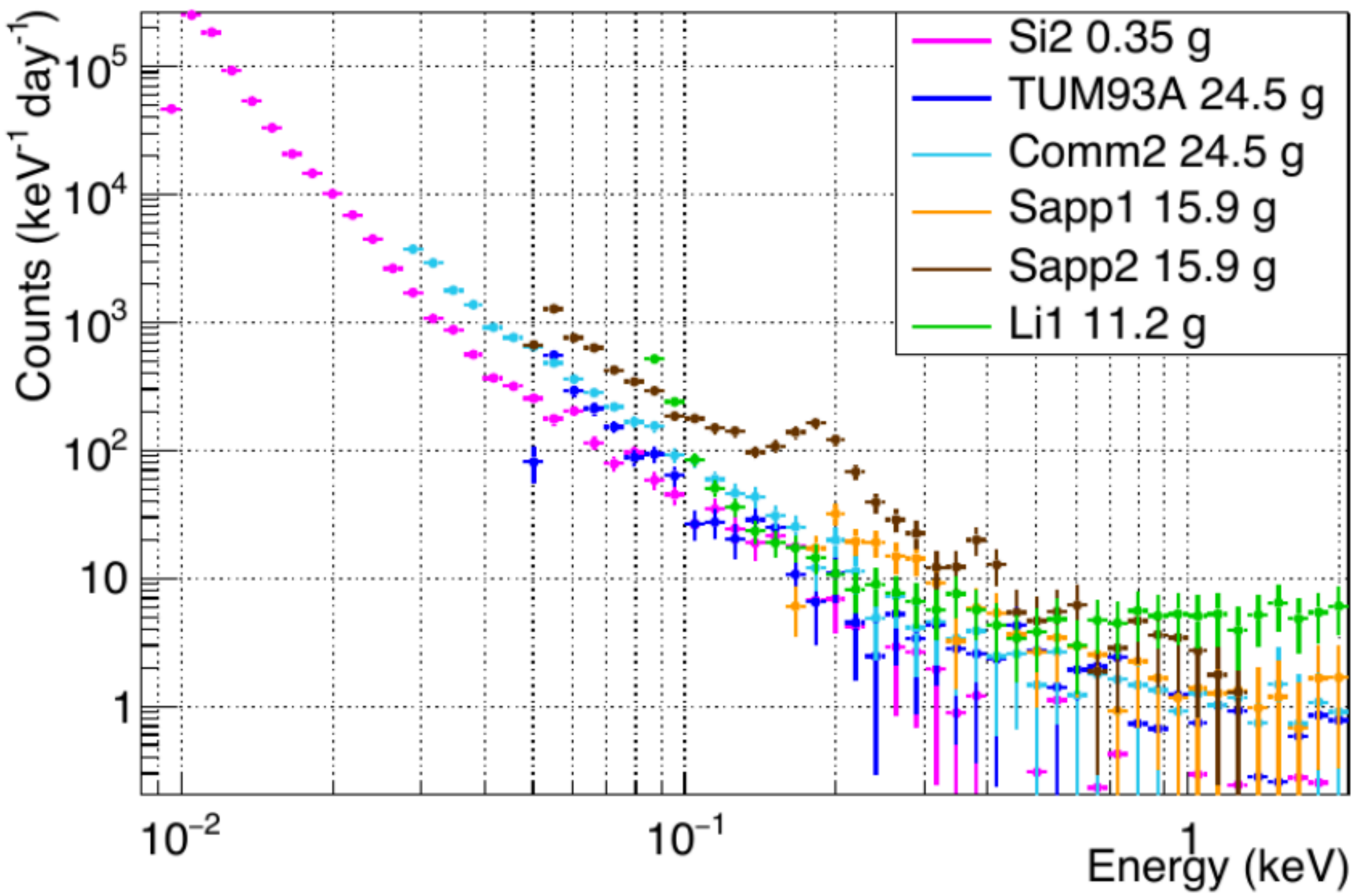
Routinely achieved thresholds < 100 eV

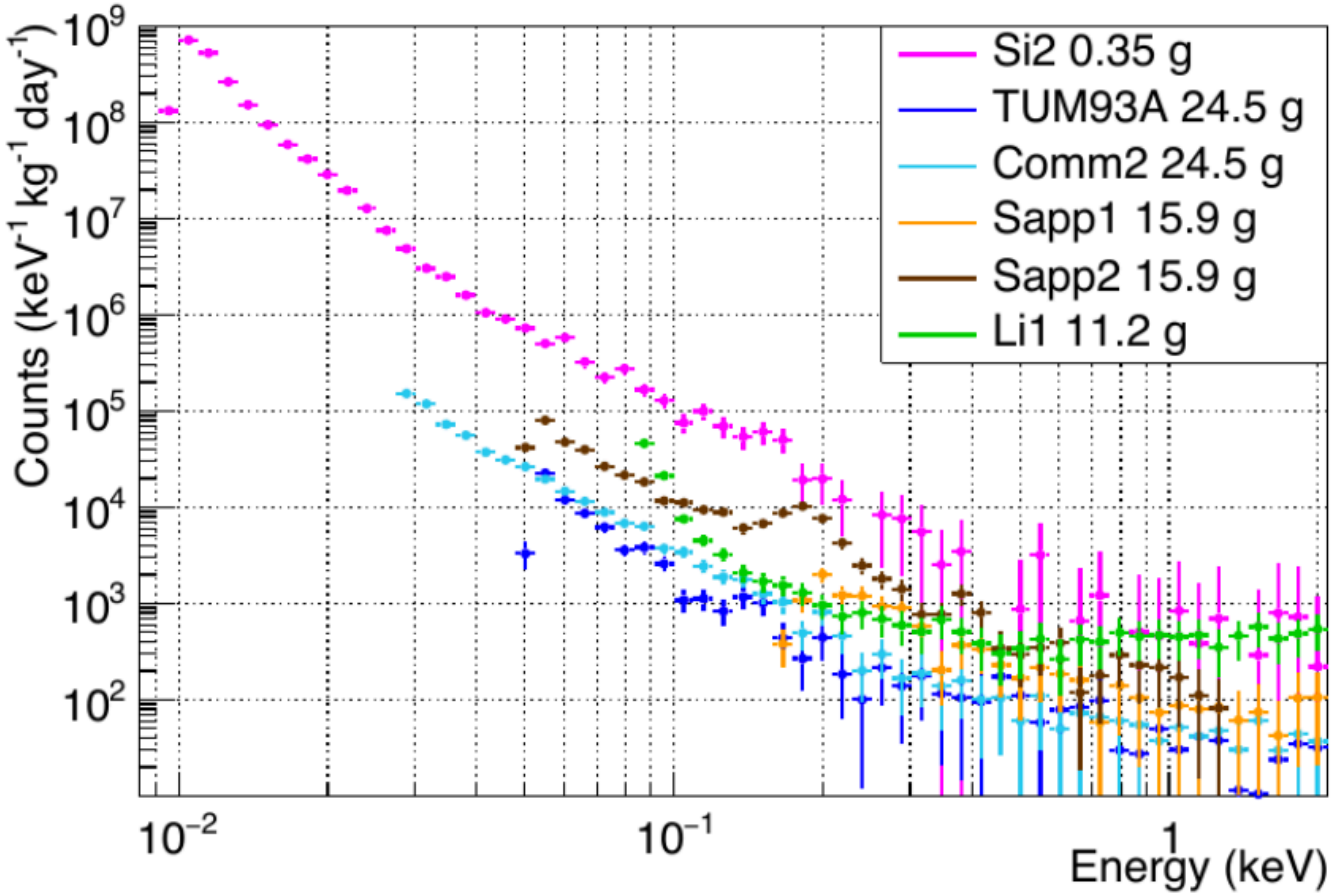
Name	Material	Holding	Foil	Mass	Threshold
Comm2	$CaWO_4$	bronze clamps	no	24.5 g	29 eV
TUM93A	$CaWO_4$	2 Cu + 1 $CaWO_4$	yes	24.5 g	54 eV
Sapp1	Al_2O_3	Cu sticks	no	15.9 g	157 eV
Sapp2	Al_2O_3	Cu sticks	yes	15.9 g	52 eV
Li1	$LiAlO_2$	Cu sticks	yes	11.2 g	84 eV
Si2	Si	Cu sticks	no	0.35 g	10 eV

Observations on LEE

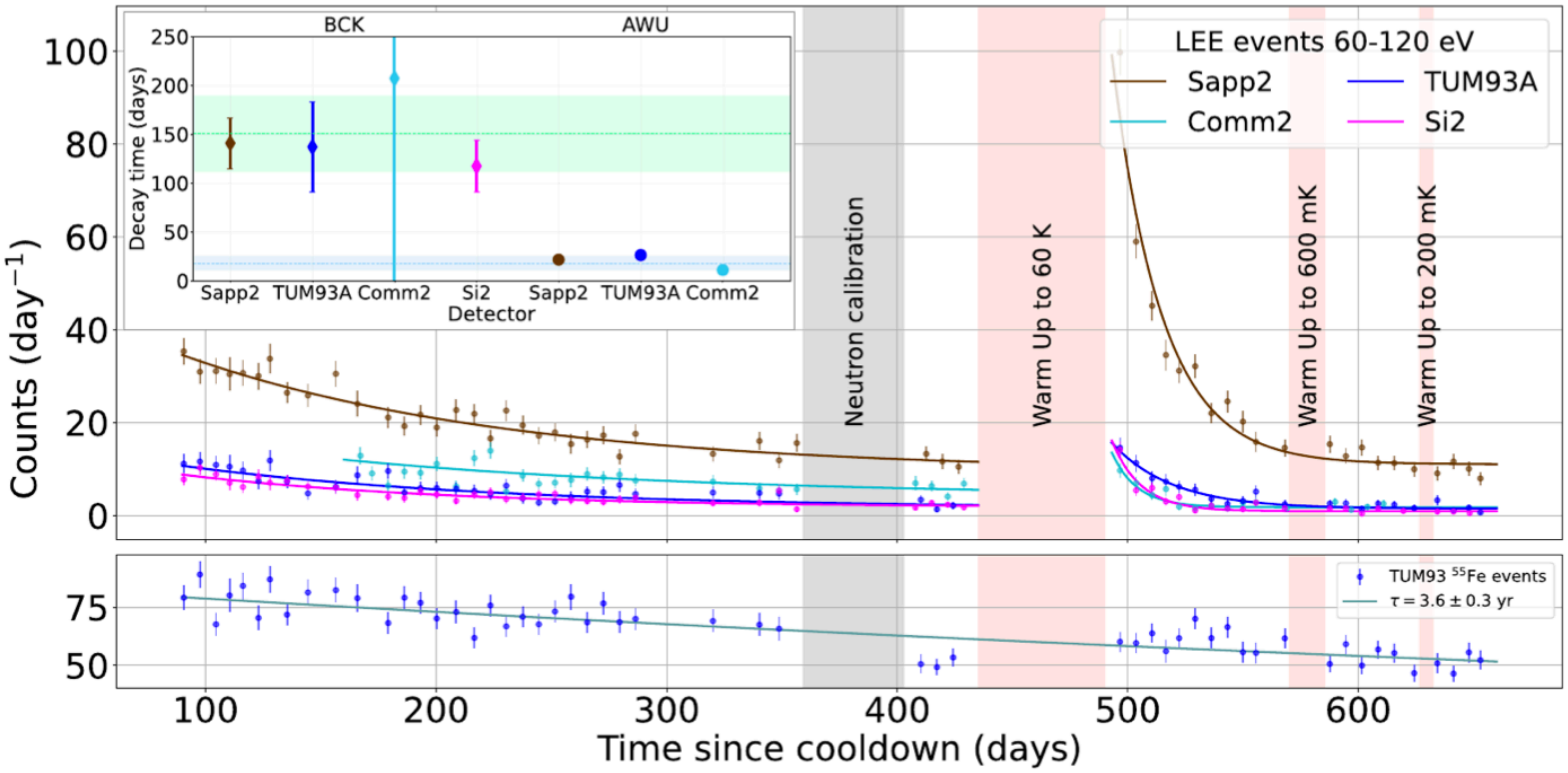
The LEE is observed in all these detectors (different materials and geometries).

Scaling the count rate by the absorber mass (right plot) does not improve the agreement between the count rates in different detectors.





Time-evolution of LEE



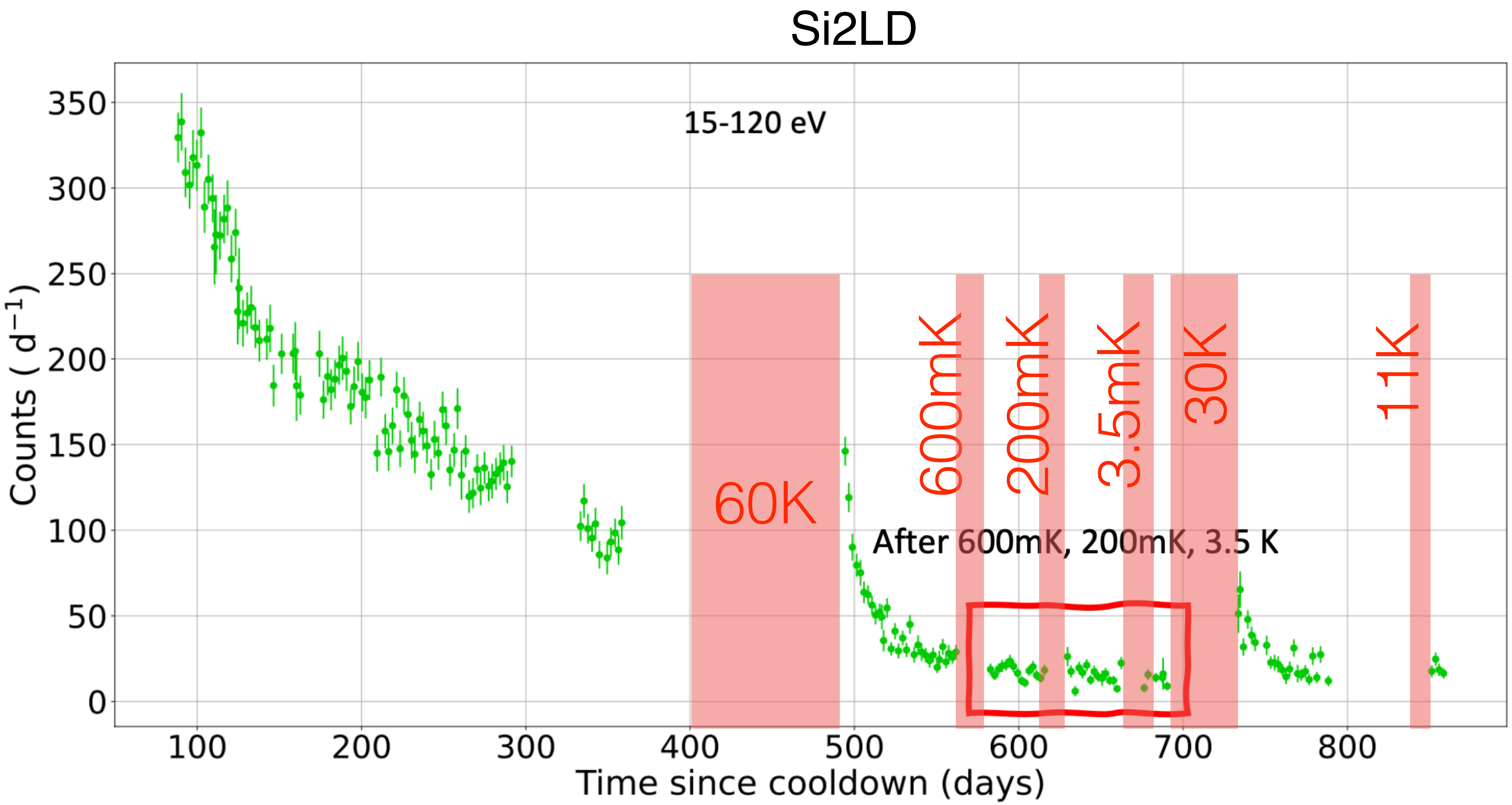
LEE count rate decreases over time in the DM data set (τ ≈ 150 d)

Subsequent neutron calibration has no effect on the LEE rate

Warm-ups 60K and 30K lead to a sudden increase of the LEE rate, which then decrease again relatively fast (τ ~ 15d)

Warm-up 200mK, 600mK, 3.5K, and 11K have no effect on the LEE rate

Time-evolution of LEE



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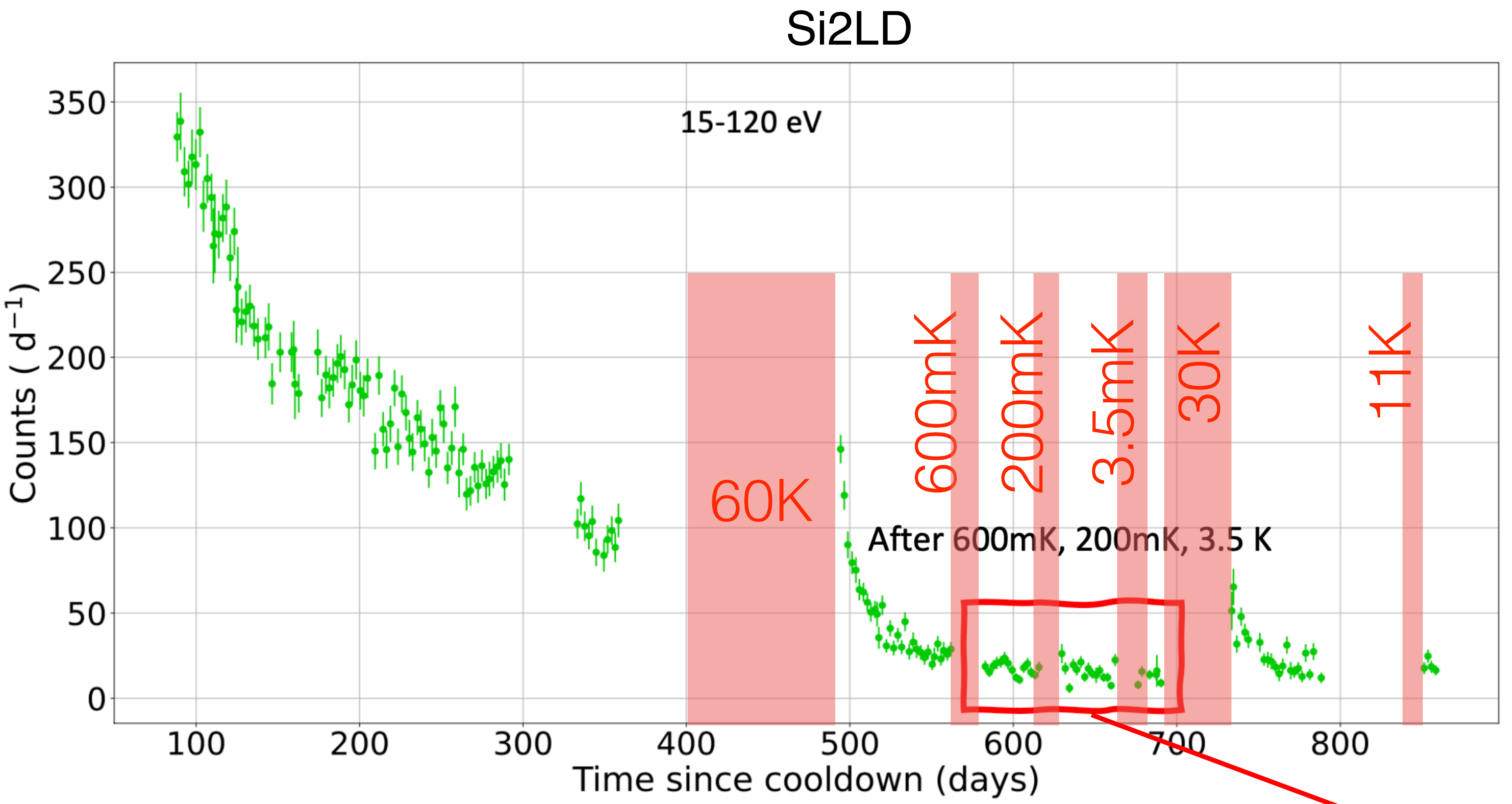


LEE count rate decreases over time in the DM data set ($\tau \approx 150$ d)

Subsequent neutron calibration has no effect on the LEE rate

Warm-ups 60K and 30K lead to a sudden increase of the LEE rate, which then decrease again relatively fast ($\tau \sim 15$d)

Warm-up 200mK, 600mK, 3.5K, and 11K have no effect on the LEE rate

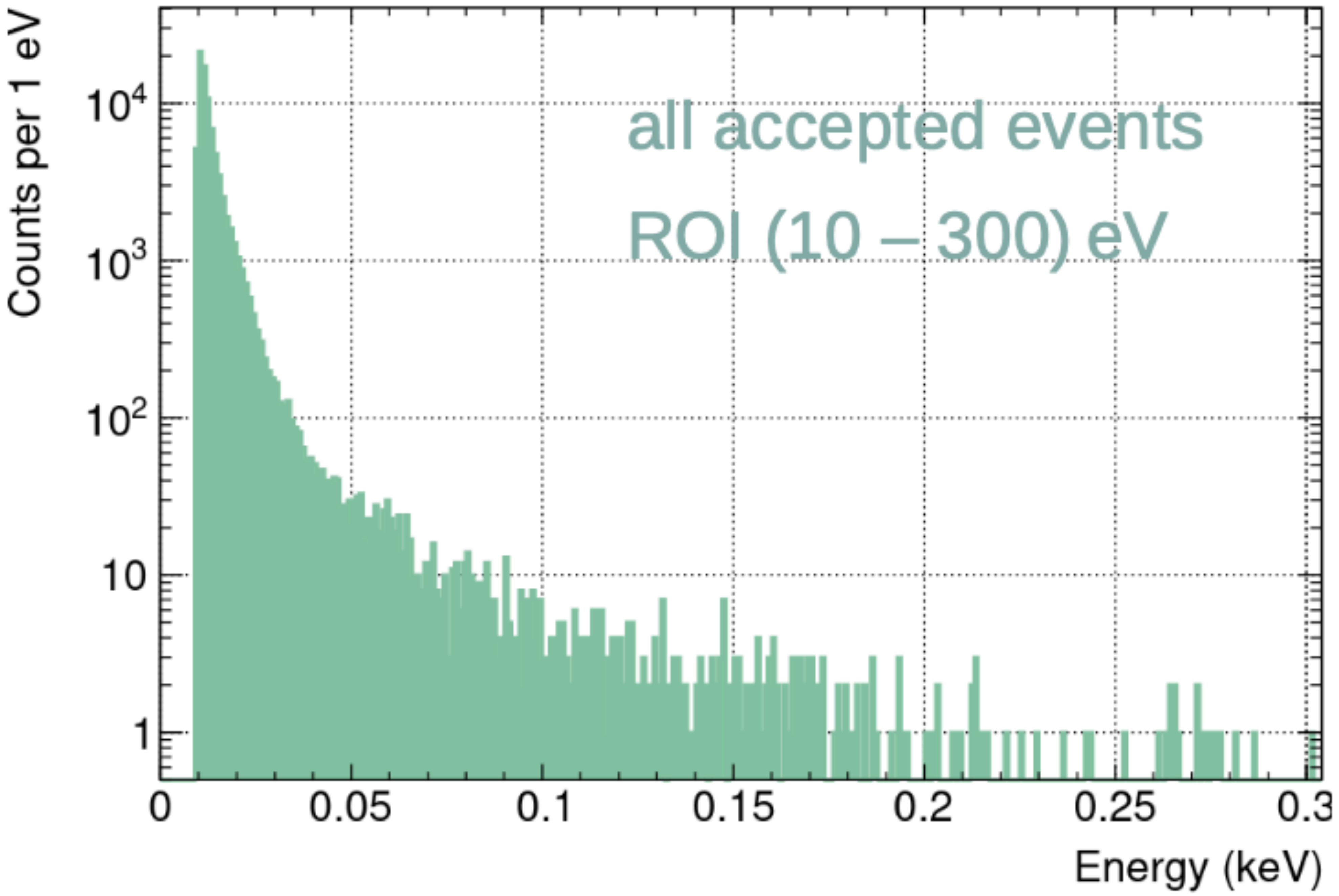
Background improvement a factor ~10 from the beginning of the run.

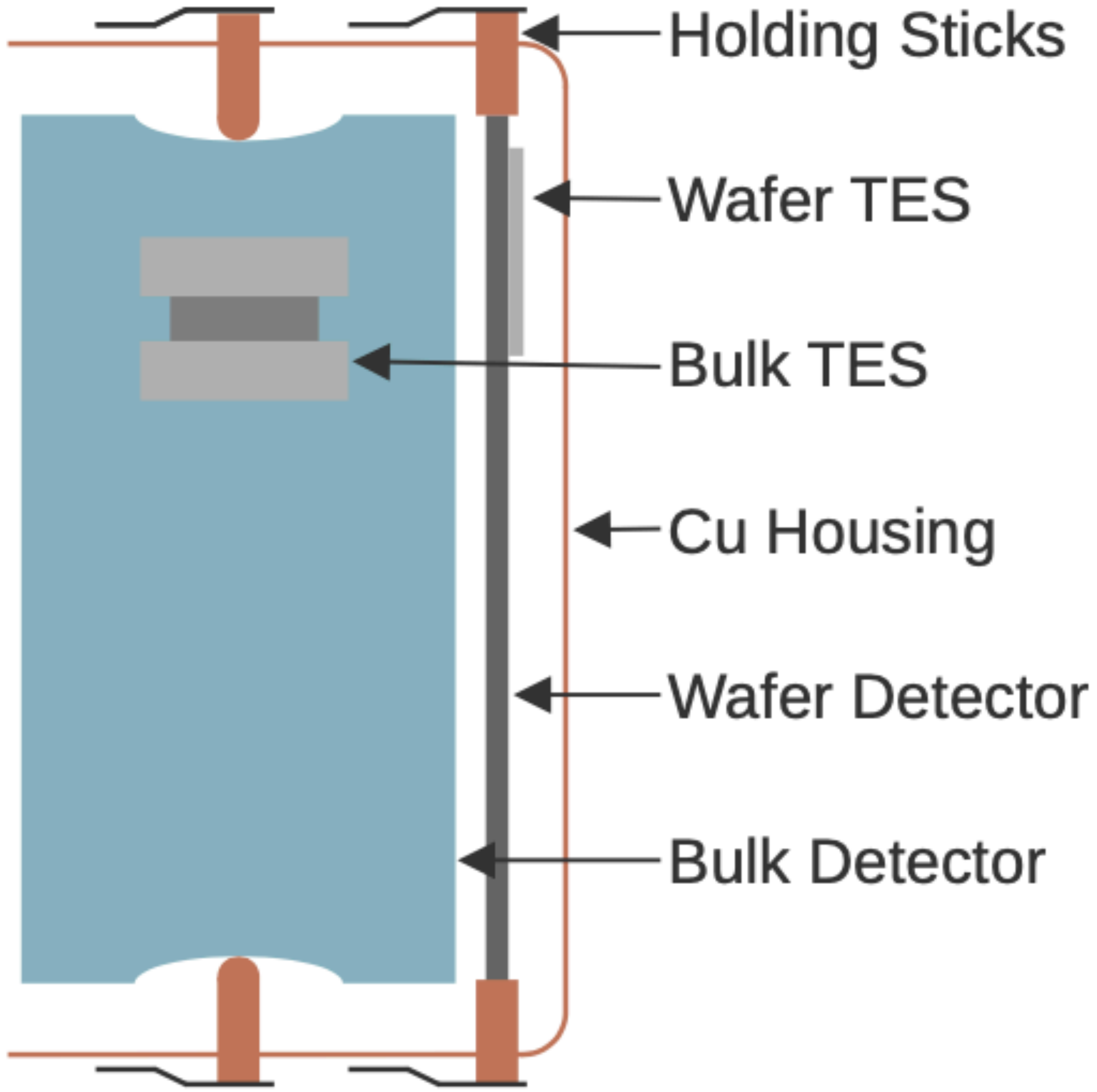
Results from a Si Wafer Detector

CRESST

Si2 wafer detector – 0.35 g Si

data taking period	Nov 2020 – Aug 2021
exposure	55.06 g days
baseline resolution	1.36 eV
nuclear recoil threshold	10.0 eV





Using thin wafer detector as target and bulky detector as veto detector.

https://arxiv.org/abs/2212.12513

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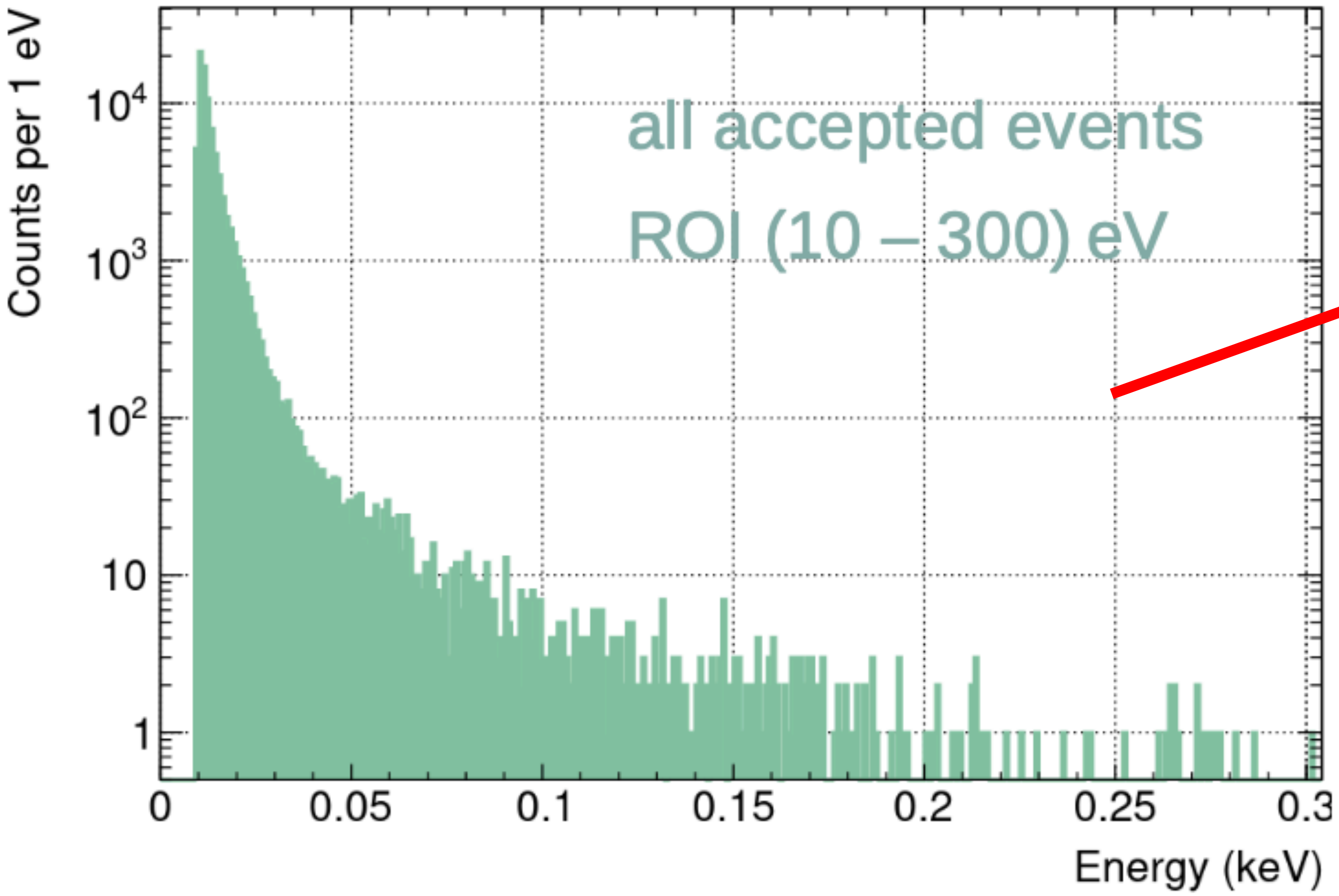
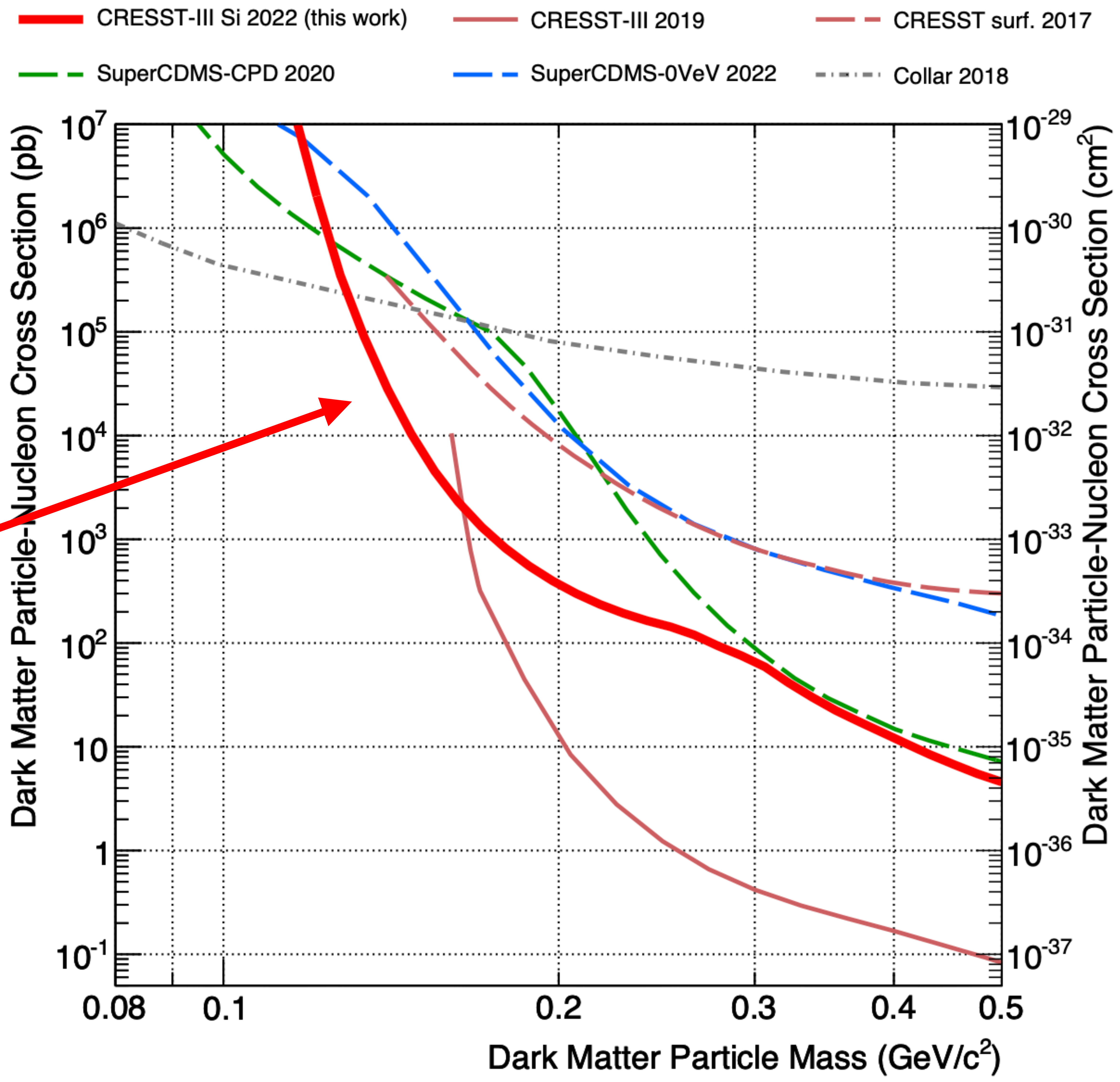


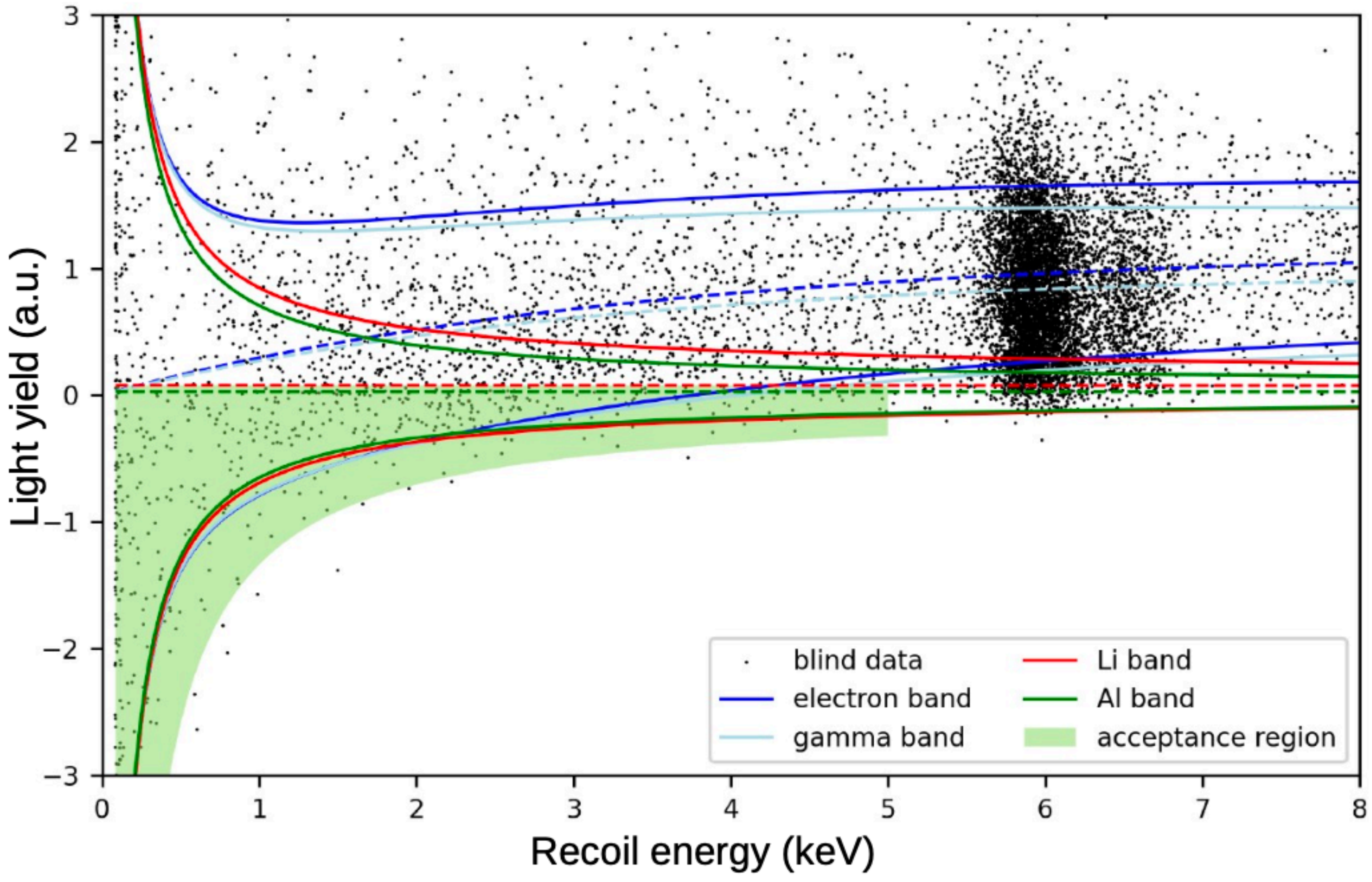


https://arxiv.org/abs/2212.12513

SD Limits with $LiAlO_2$ Detectors

Li1 detector – 11.2 g $LiAlO_2$

data taking period	Nov 2020 – Aug 2021
exposure	1.161 kg days
baseline resolution	12.8 eV
nuclear recoil threshold	83.6 eV



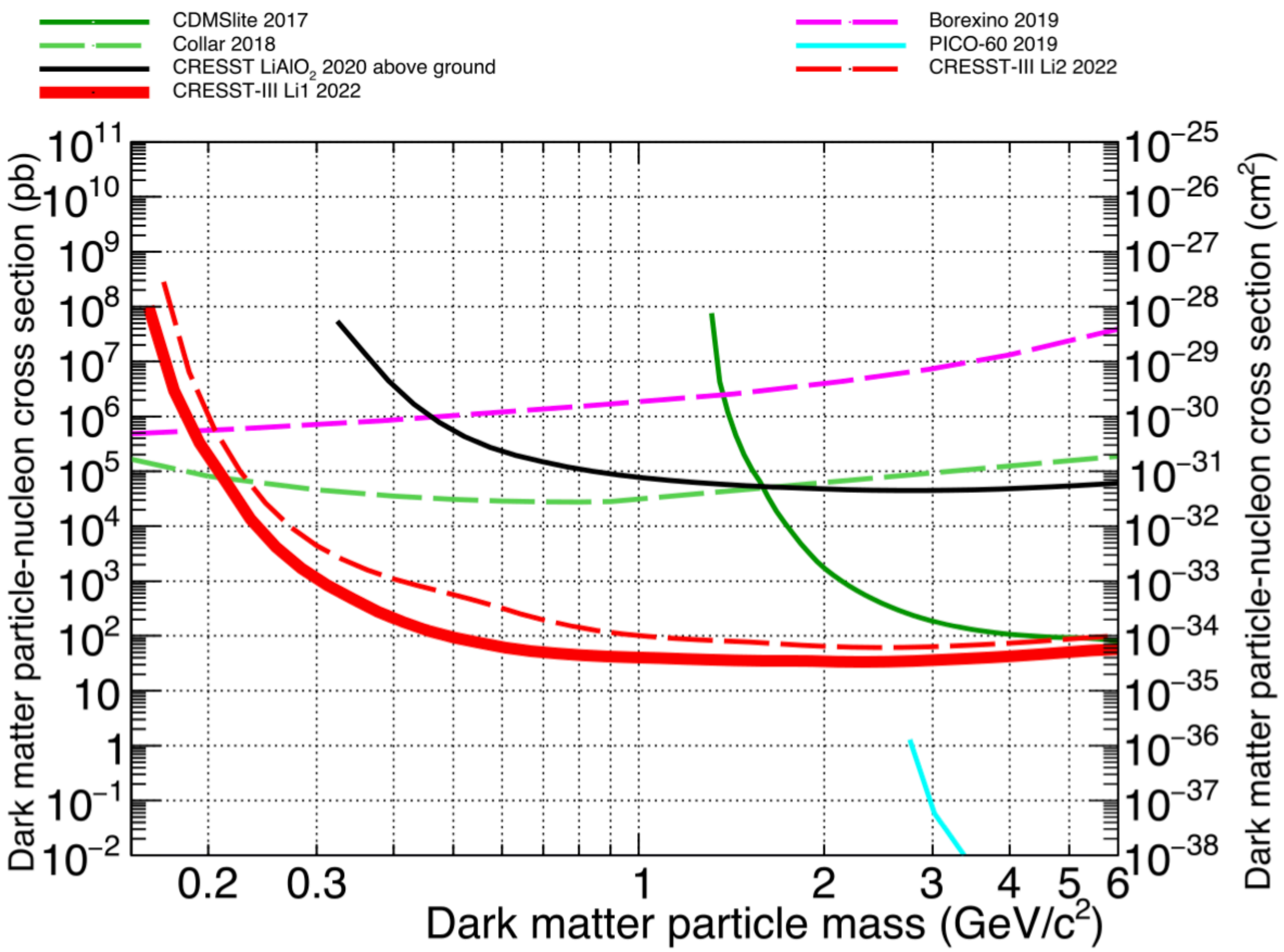
Phys. Rev. D 106, 092008 / arXiv:2207.07640

Isotopes sensitive to SD interactions:

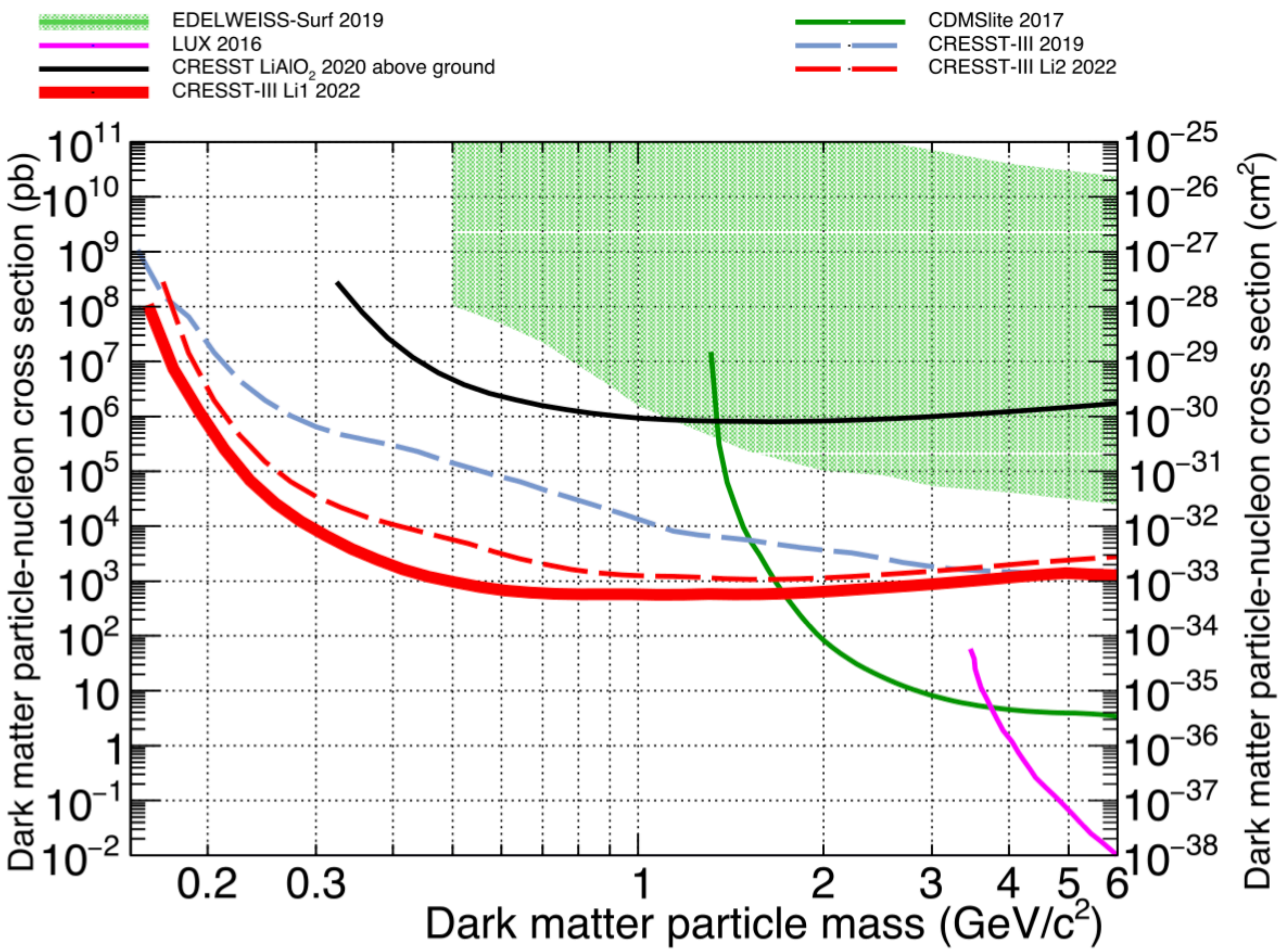
Isotope	$\langle S_p \rangle$	$\langle S_n \rangle$
^6Li	0.472	0.472
^7Li	0.497	---
^{27}Al	0.343	0.0296

SD Limits with LiAlO$_2$ Detectors

Proton-only



Neutron-only



Phys. Rev. D 106, 092008 / arXiv:2207.07640

CRESST calibration with W recoil

- Sub-keV calibrating is challenge for many projects in low energy particle physics (difficult to identify a low energy x-ray source, need to place the source inside the setup generating background,…).

- The proposal to use the nuclear recoil caused by radiative capture of thermal neutrons offers a novel way to calibrate detectors in the ~100 eV range.

Thulliez, et. al. JINST 16 P07032

- In CaWO4 crystals W isotopes should be suitable for this application generating a 112 eV peak.

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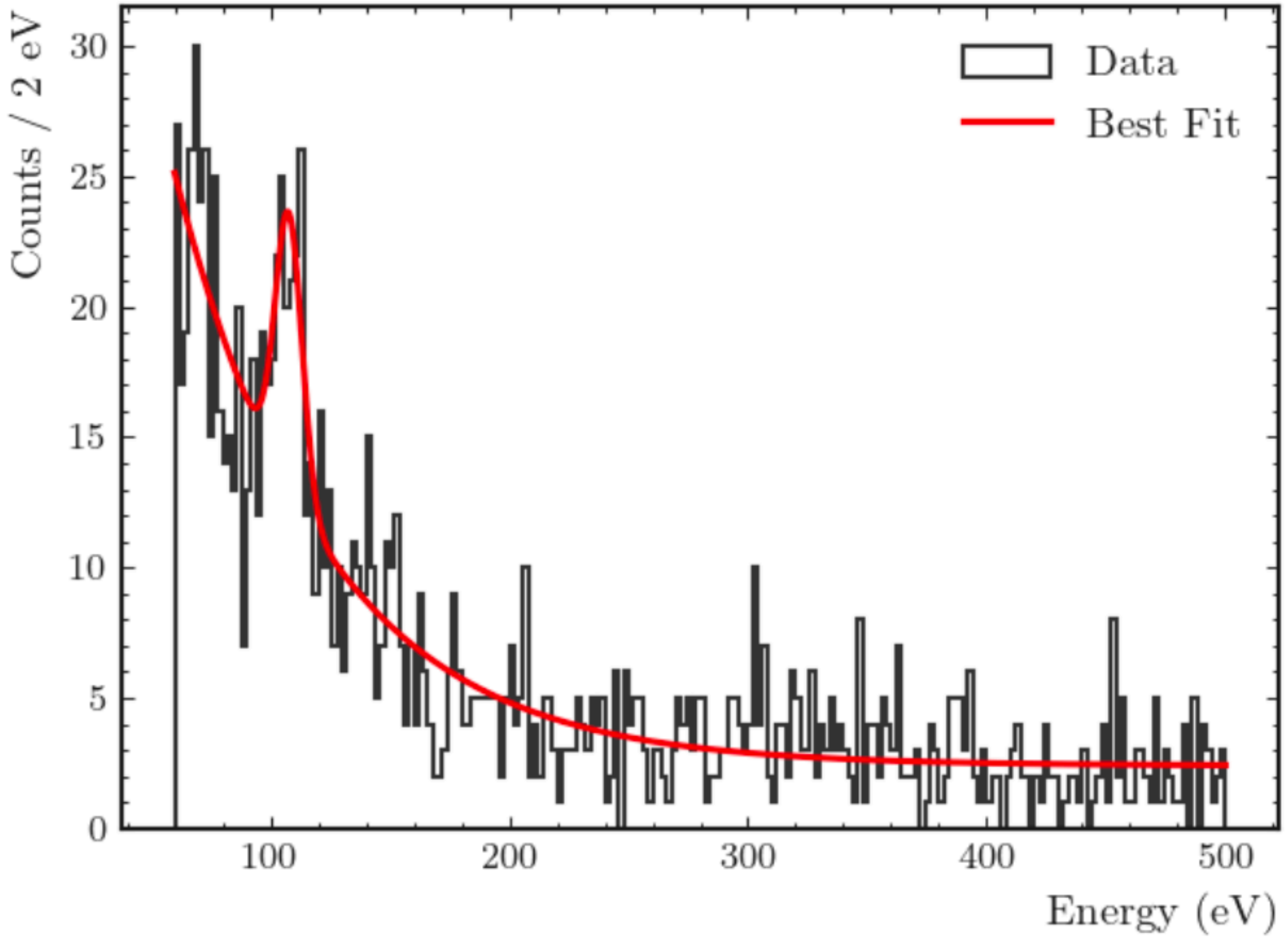


(d) *Comm2*: energy spectrum and fit result

https://arxiv.org/abs/2303.15315

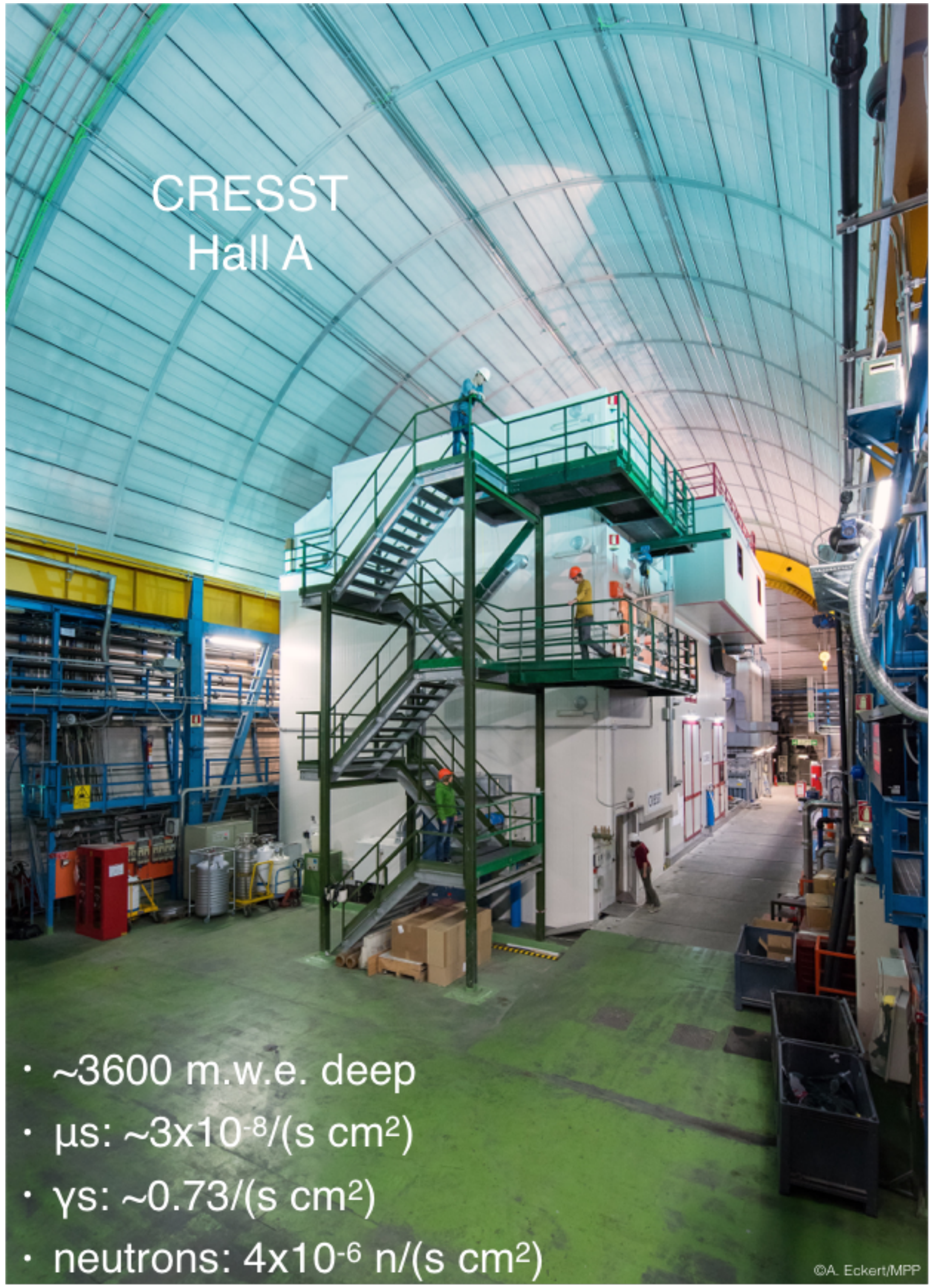
CRESST n-cal data show a peak at ~110eV consistent with simulation (observed in multiple detectors).

Conclusion

- CRESST energy thresholds O(10eV) represent the state of the art in the exploration of the light DM mass region
- Recent results in terms of E threshold are very promising for extending sensitivity in the ~100 MeV range for the DM mass and for both SI (Si, $CaWO_4$) and SD ($LiAlO_2$) interactions
- Calibration from recoils induced by radiative capture of thermal neutrons allow calibration of $CaWO_4$ detectors without introducing contaminants in the CRESST setup
- LEE comprehension and reduction represent a crucial step for the light DM community and for the CRESST science program. Recent achievements are promising to finally solve this puzzle
- CRESST is moving ahead to increase the exposure to consolidate the capability of light DM detection

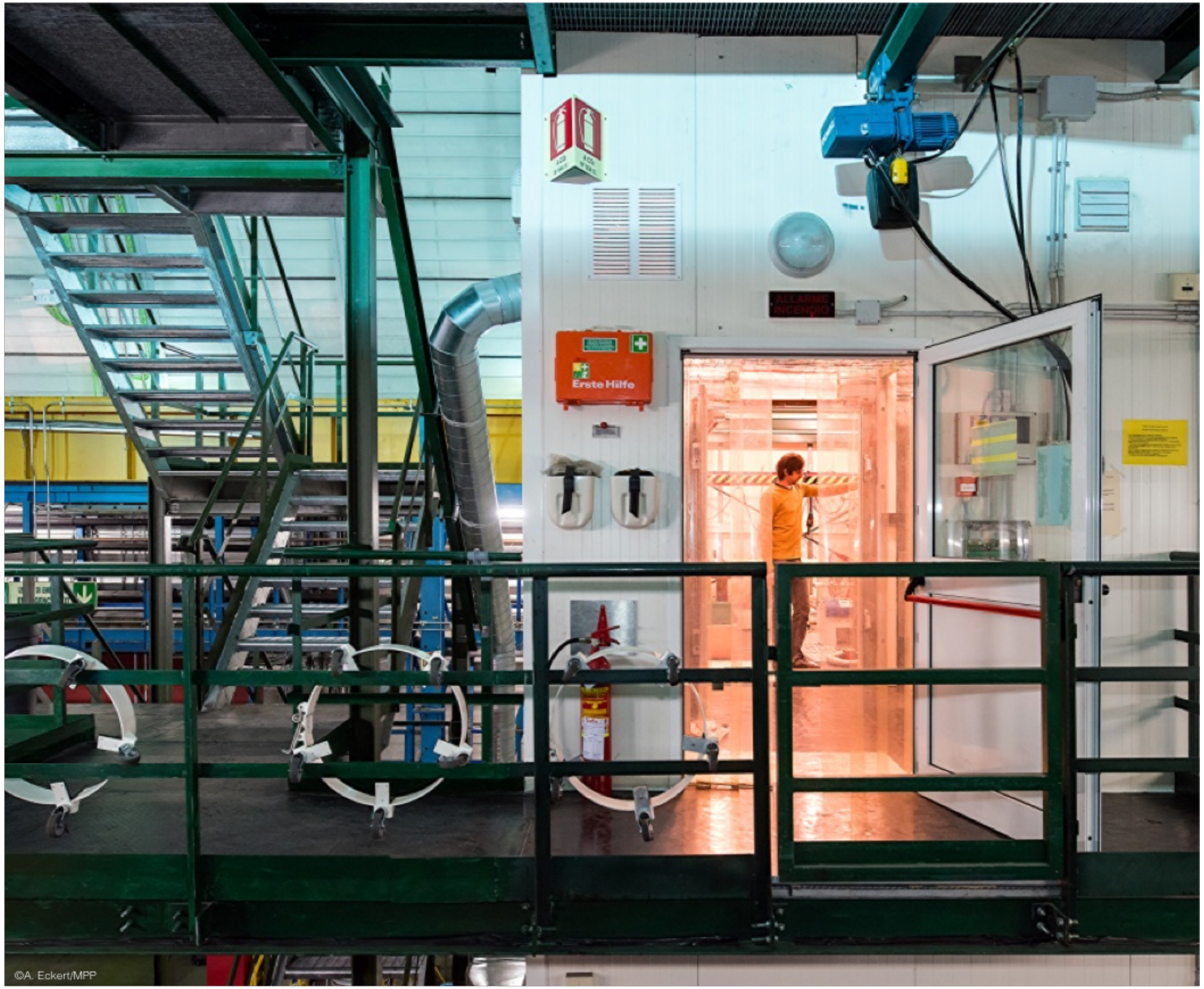
Backup slides

CRESST @LNGS



- ~3600 m.w.e. deep
- μs: ~3×10^{-8}/(s cm^2)
- γs: ~0.73/(s cm^2)
- neutrons: 4×10^{-6} n/(s cm^2)

©A. Eckert/MPP



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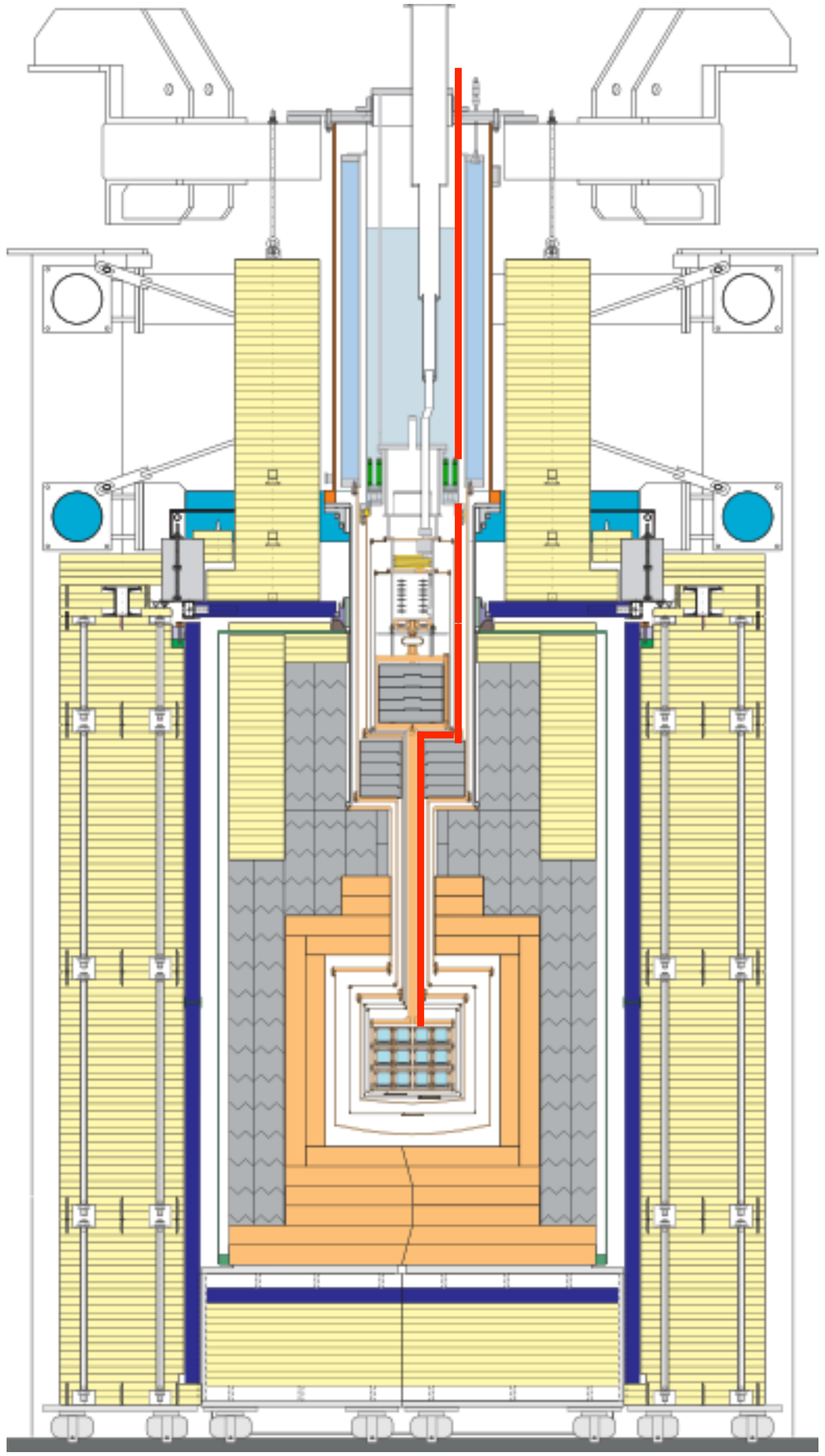
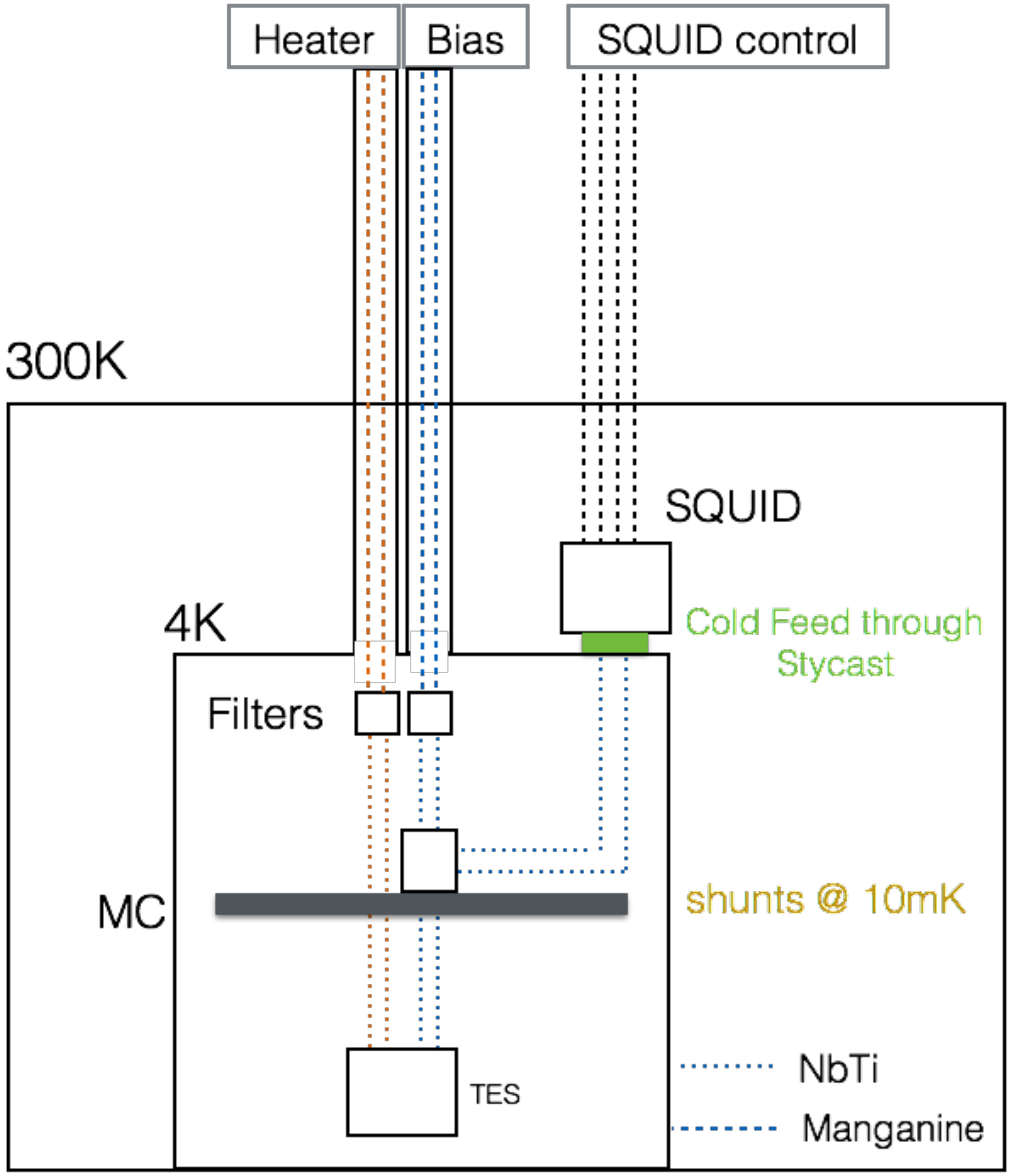
CRESST upgrade





CRESST upgrade to 100 modules (288 readout channels) already in the procurement phase.
Cryogenic infrastructure will remain mostly the same while readout chain is upgraded.

Selection criteria

Objective

Keep only events where a correct determination of the amplitude (→energy) is guaranteed

Unbiased (blind) analysis

1. Design cuts on non-blind training set (≦20%, excluded from DM data set)
2. Apply without change to blind DM data set

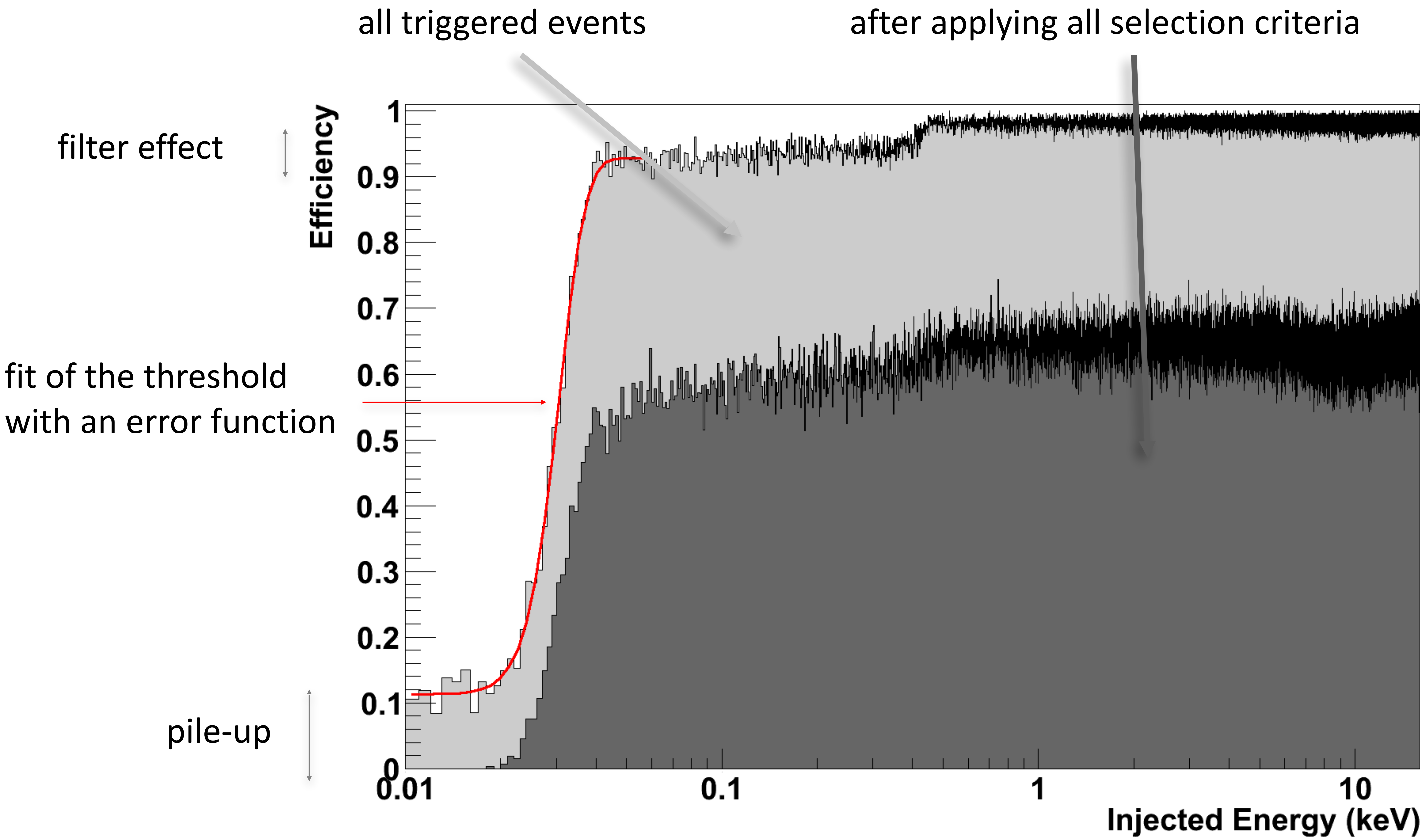
Rate: noise conditions (14% of measuring time)

Stability: Detector(s) in operating point (3% of measuring time)

Data quality: Non-standard pulse shapes (e.g. i-Stick events and pileup)

Coincidences: with μ-veto (7.6% of measuring time), i-Sticks, other detector modules

EFFICIENCY/SIGNAL SURVIVAL PROBABILITY



Simulated by artificial pulses placed at random positions in the data stream

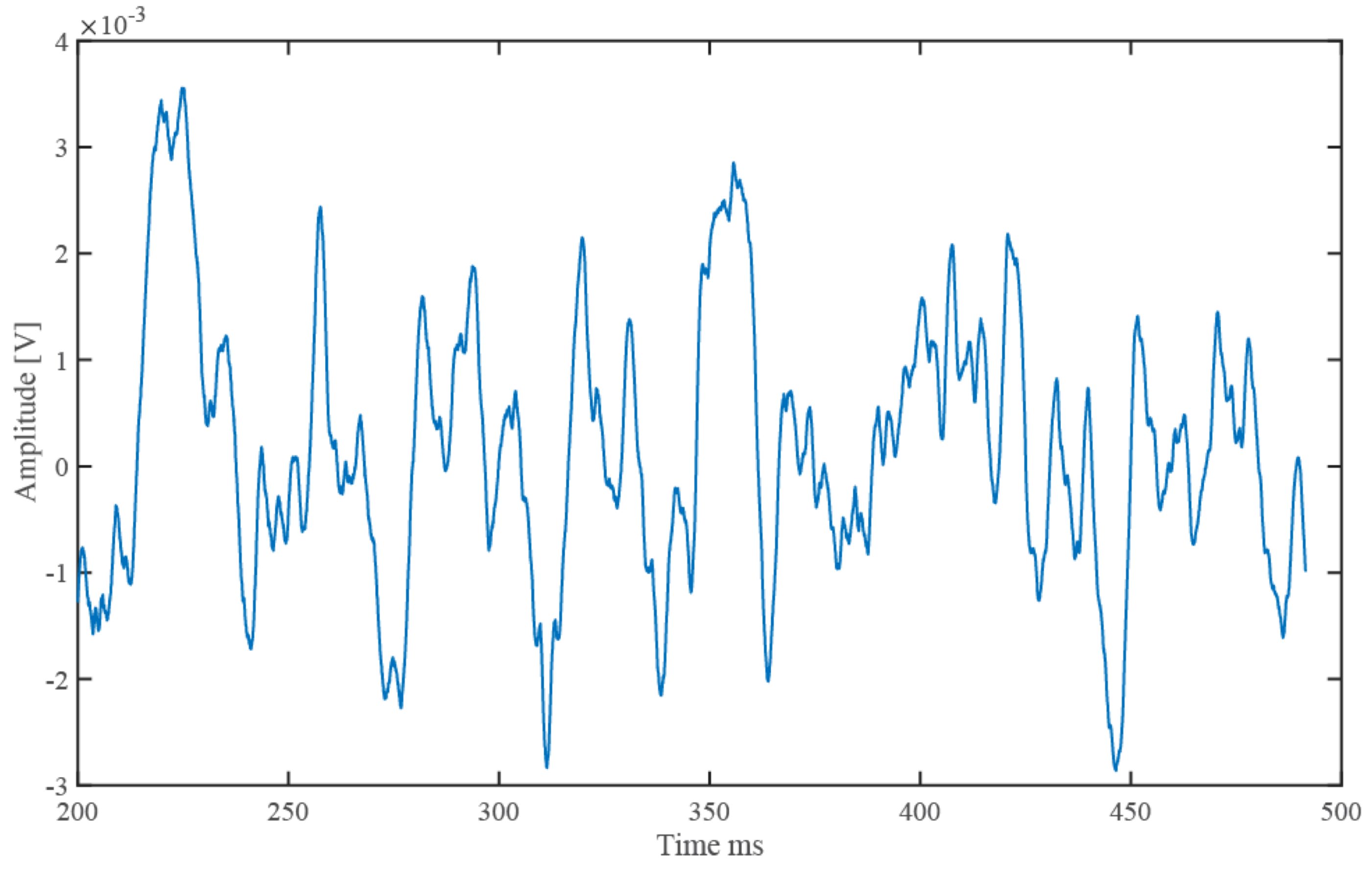
Includes trigger and cuts

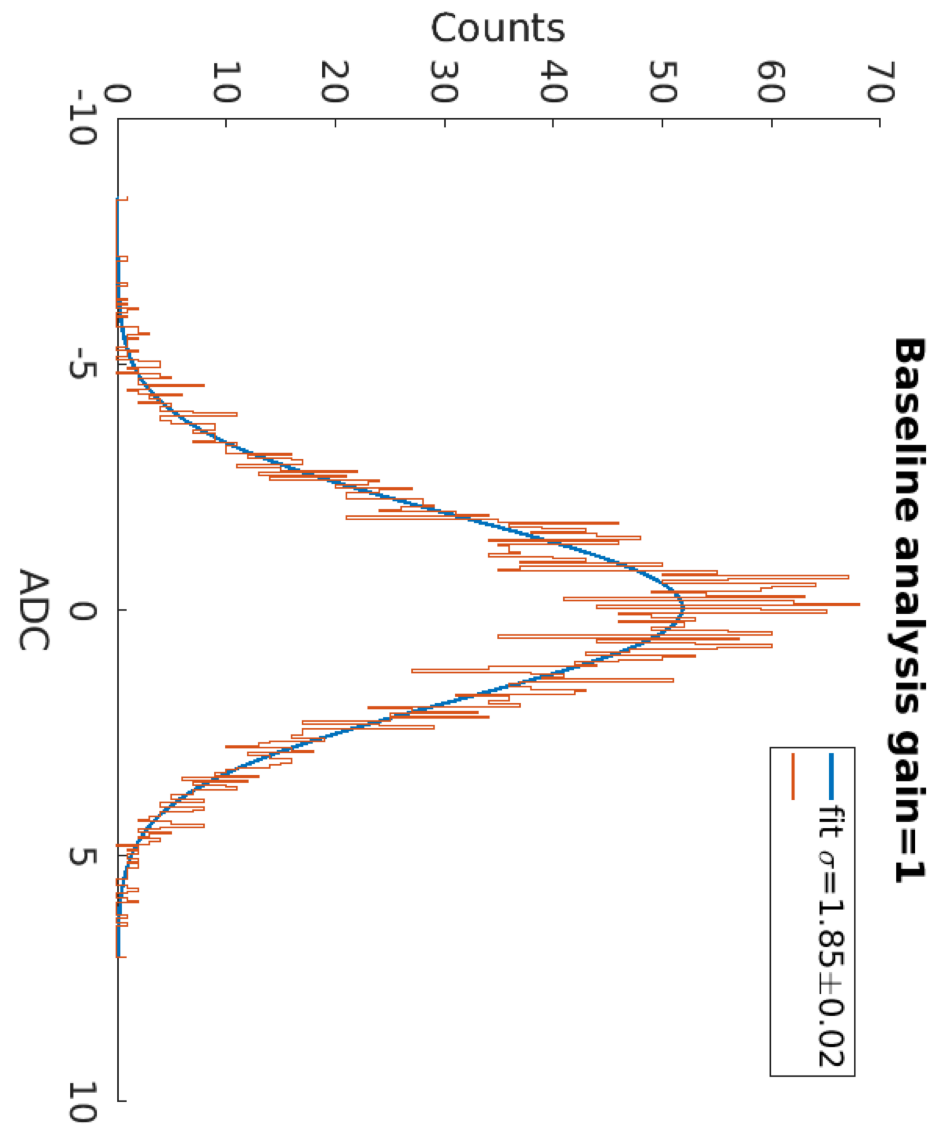
≳60% efficiency over broad energy range

OPTIMUM TRIGGER THRESHOLD

Optimum filter for threshold analysis

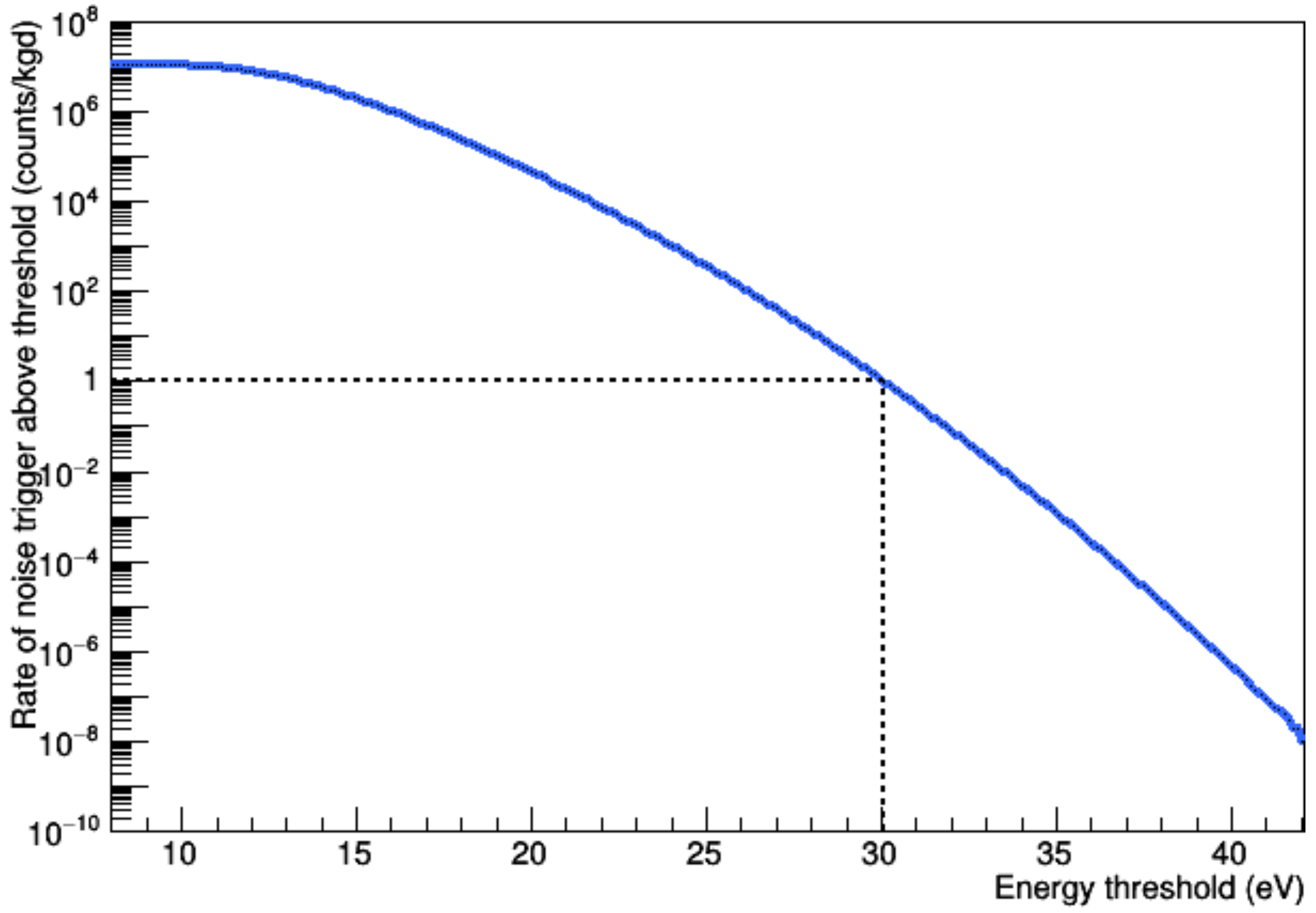
Empty base line trace





Histogram of a typical baseline trace

- Study the noise distribution after optimum filter in order to set the threshold
- Threshold optimised based on noise triggers in a given exposure



Analytical description of amplitude distribution in empty baselines

J Low Temp Phys (2019)
doi.org/10.1007/s10909-018-1948-6

DETECTOR STABILITY

W-TES equipped with heaters

- Stabilization of detectors in the operating point
- Injection of heat pulses for calibration and determination of trigger threshold