TAUP VIENNA 2023

Direct Dark Matter search with the CRESST-III experiment

Status and prospects

XVIII International Conference on Topics in Astroparticle and Underground Physics 2023

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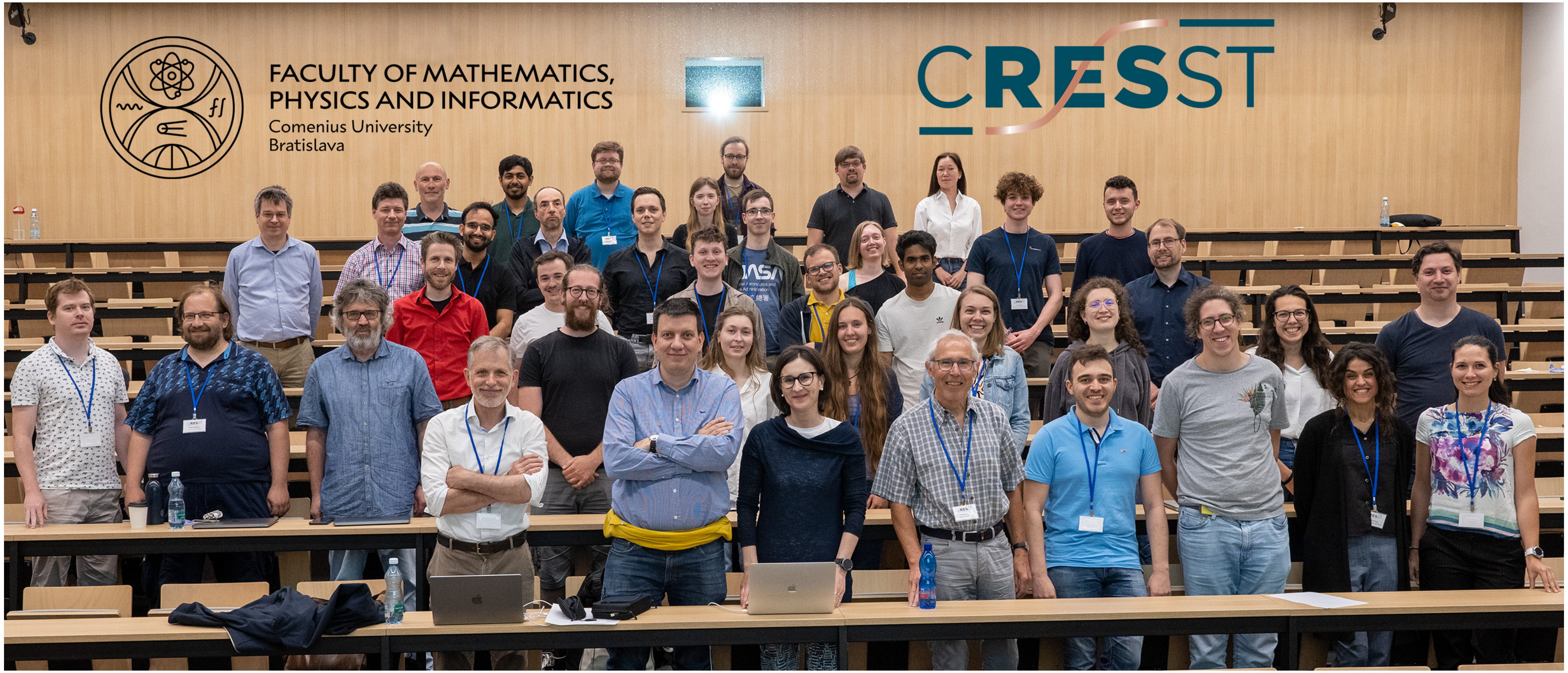
On behalf of the CRESST Collaboration

CRESST Cryogenic **Rare Event Search** with Superconducting Thermometers

https://cresst-experiment.org

CRESST collaboration

~60 people from 8 institutions from 5 countries in Europe



June 2023, CRESST collaboration meeting in Bratislava

TUM | MAX PLANCK INSTITUTE FOR PHYSICS | TU WIEN | HEPHY INSTITUTE OF HIGH ENERGY PHYSICS | COMENIUS UNIVERSITY BRATISLAVA | INFN LNGS Istituto Nazionale di Fisica Nucleare Laboratori Nazionali del Gran Sasso | EBERHARD KARLS UNIVERSITÄT TÜBINGEN | UNIVERSITY OF OXFORD

The CRESST experiment searches for sub-GeV DM particles.

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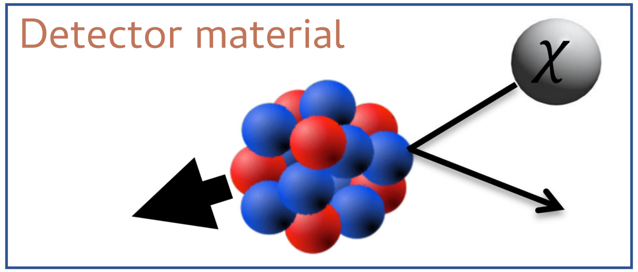
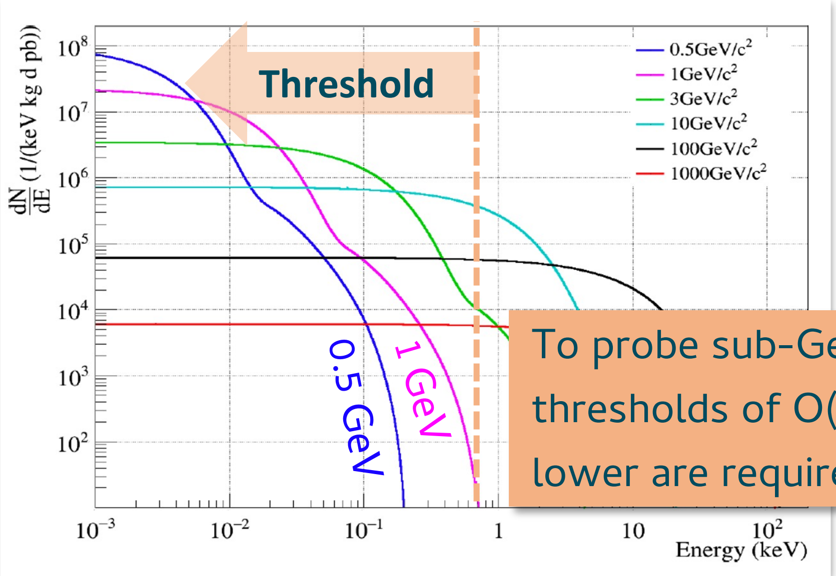


Signal: nuclear recoil energy

Expected differential energy spectrum in CaWO4



F. Reindl (2016), PhD Thesis: http://mediatum.ub.tum.de/?id=1294132

To probe sub-GeV DM, energy thresholds of O(100 eV) and lower are required!

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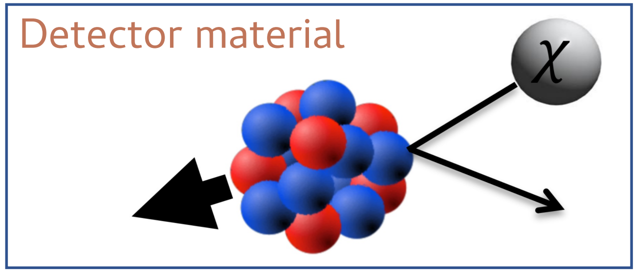

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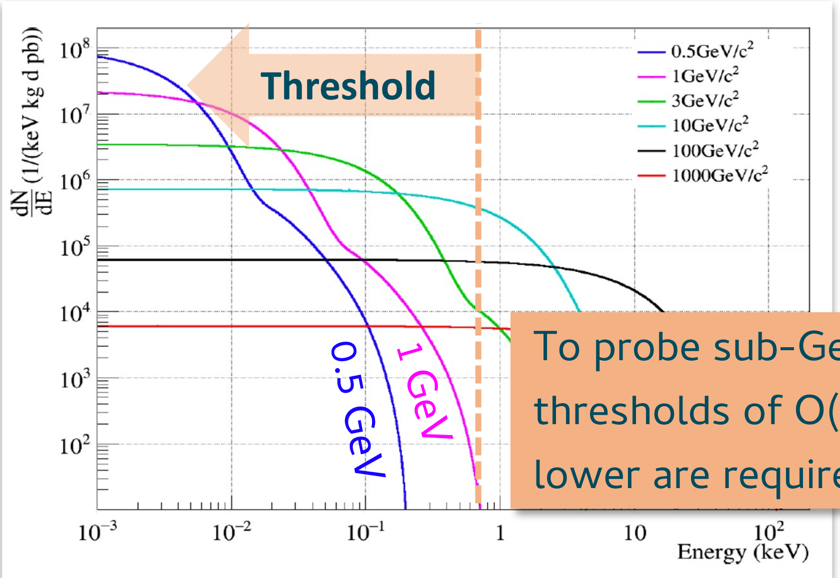

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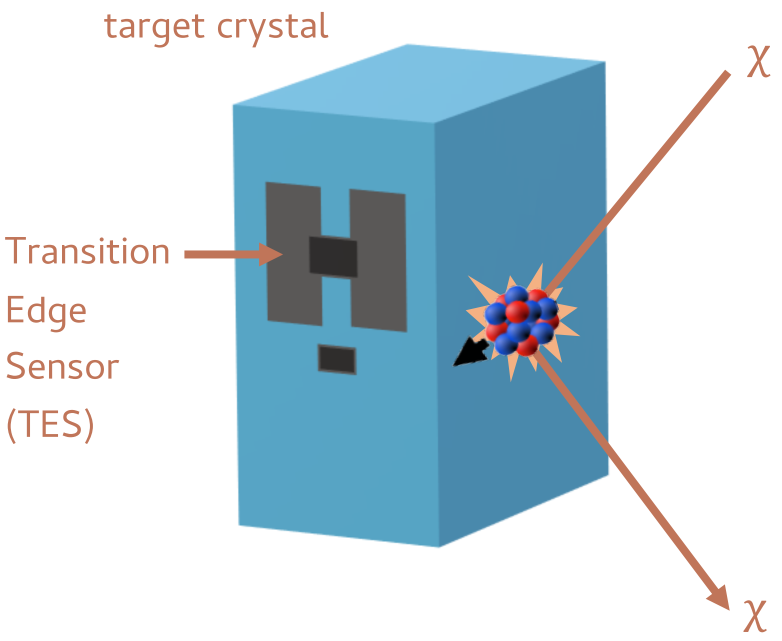
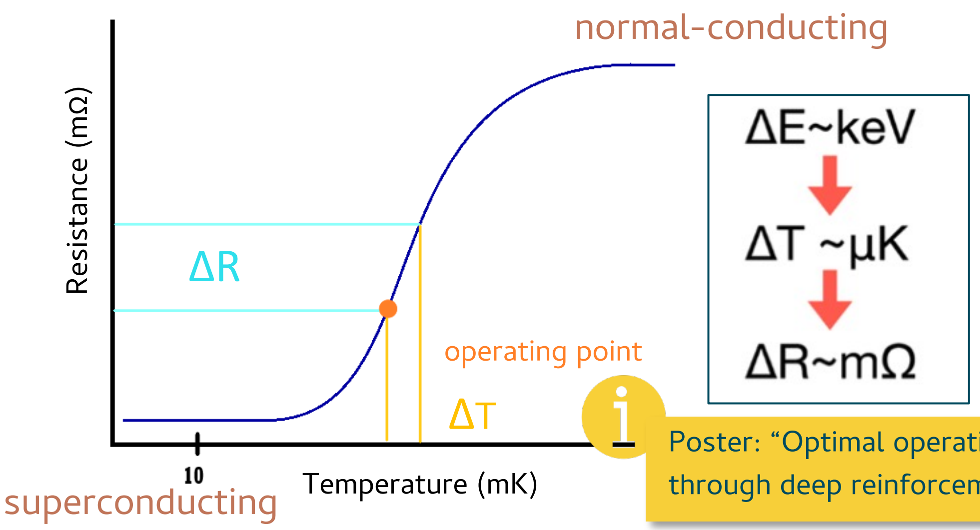


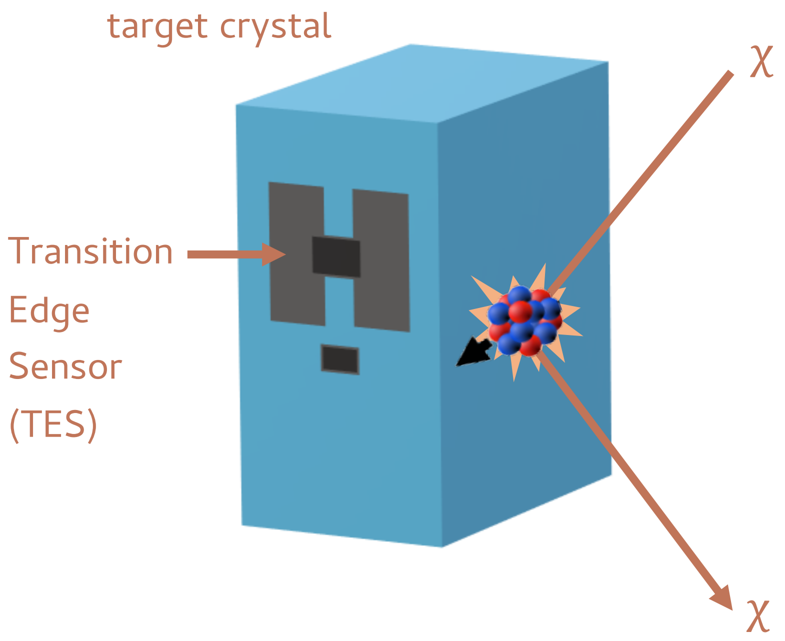
Target: various crystal materials ($CaWO_4$, Al_2O_3, $LiAlO_2$, Si)

Small energy deposition in the crystal leads to a measurable TES resistance change.



Poster: "Optimal operation of cryogenic calorimeter through deep reinforcement learning" by Felix Wagner

Detector:



Target: various crystal materials ($CaWO_4$, Al_2O_3, $LiAlO_2$, Si)

Sensor: W-TES at 15 mK

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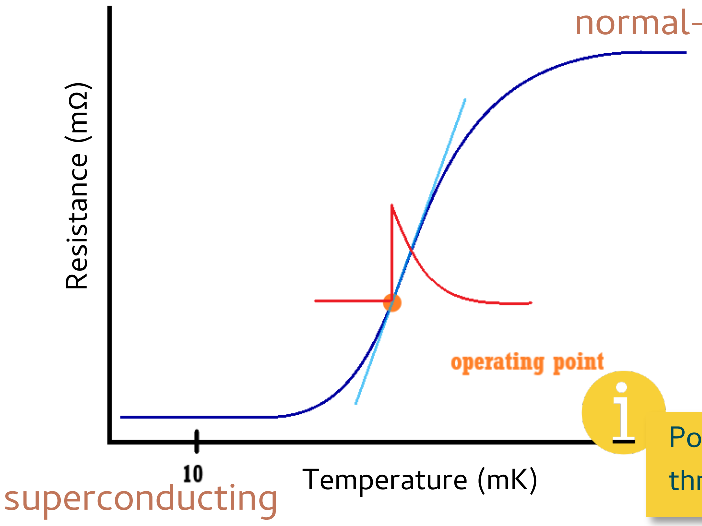

ΔE~keV
↓
ΔT ~µK
↓
ΔR~mΩ

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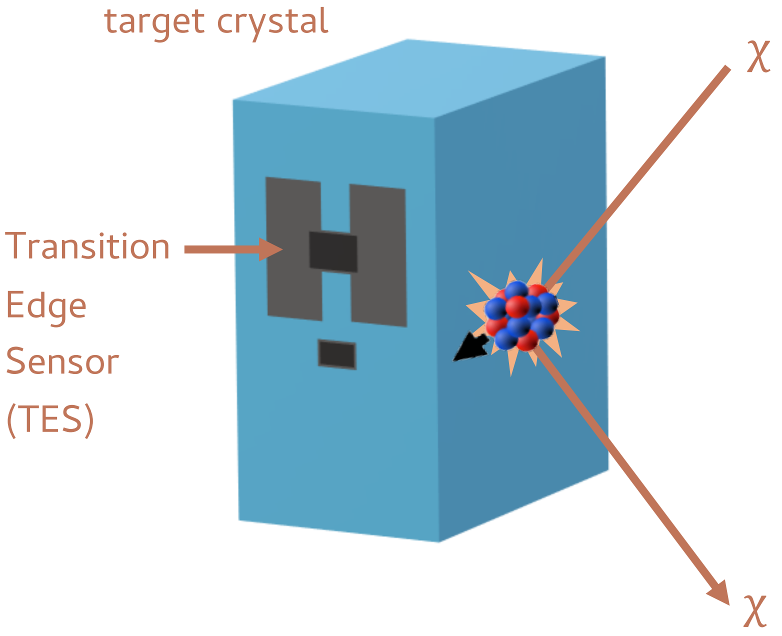
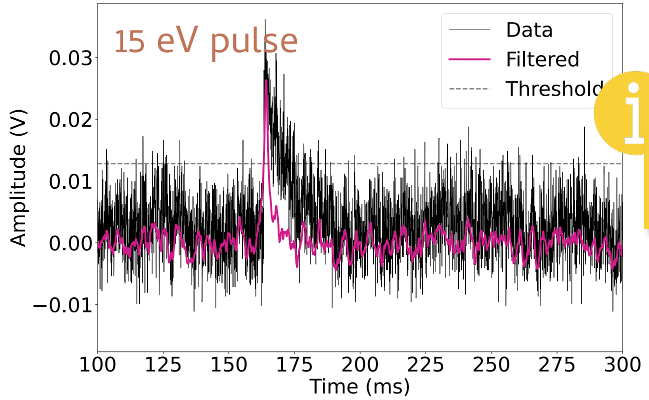
Detector:





Pulse height is a measure of energy deposition.

Poster: "Optimum Filter Analysis in CRESST-III" by Lena Meyer

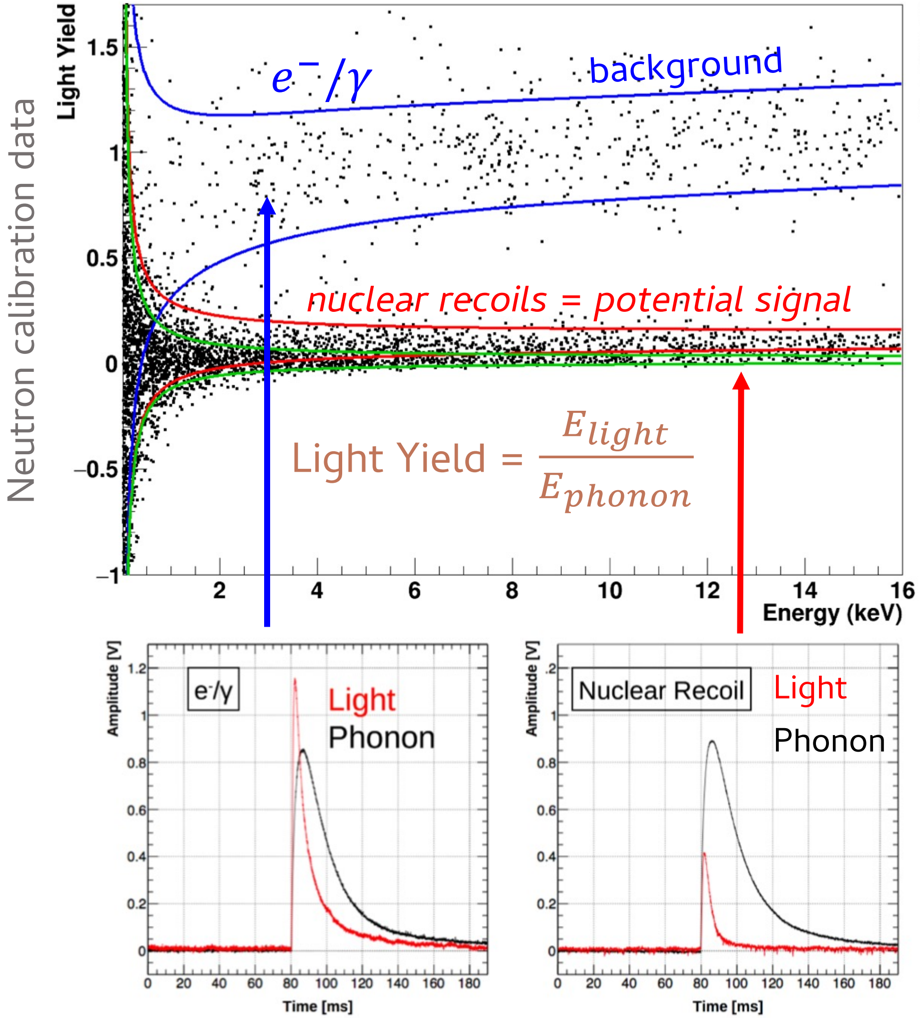
Energy calibration with X-rays from a ^{55}Fe source@6 keV

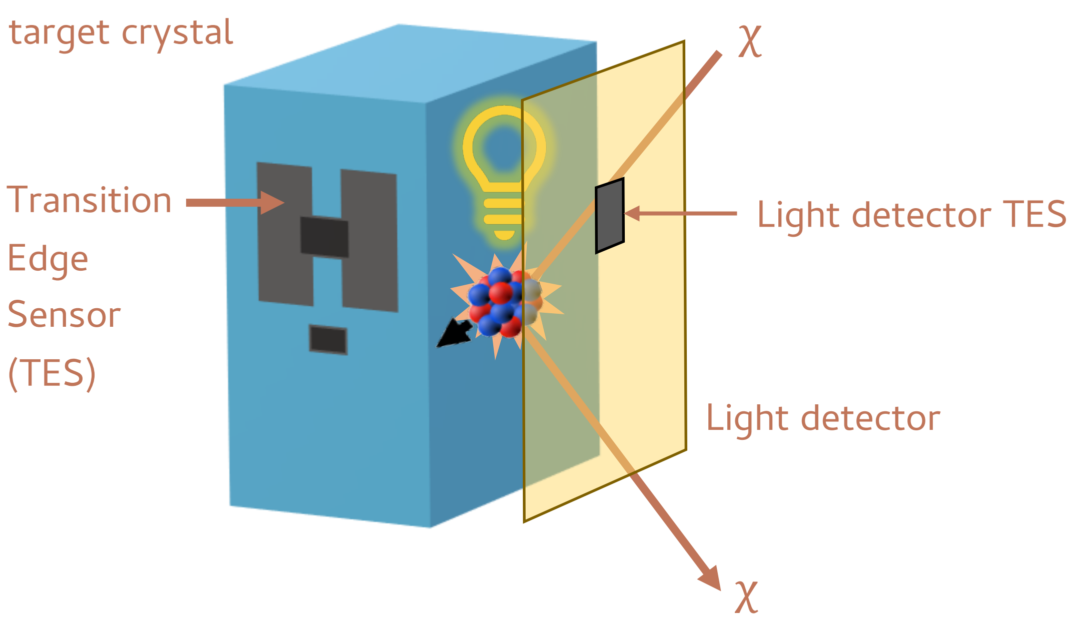
Target: various crystal materials ($CaWO_4$, Al_2O_3, $LiAlO_2$, Si)

Sensor: W-TES at 15 mK

Energy threshold of O(10 eV) ✅

Additional light signal allows to discriminate electron and nuclear recoils to reduce background signal.





For scintillating target materials (e.g.$CaWO_4$), a small part of the deposited energy is released as *light.*

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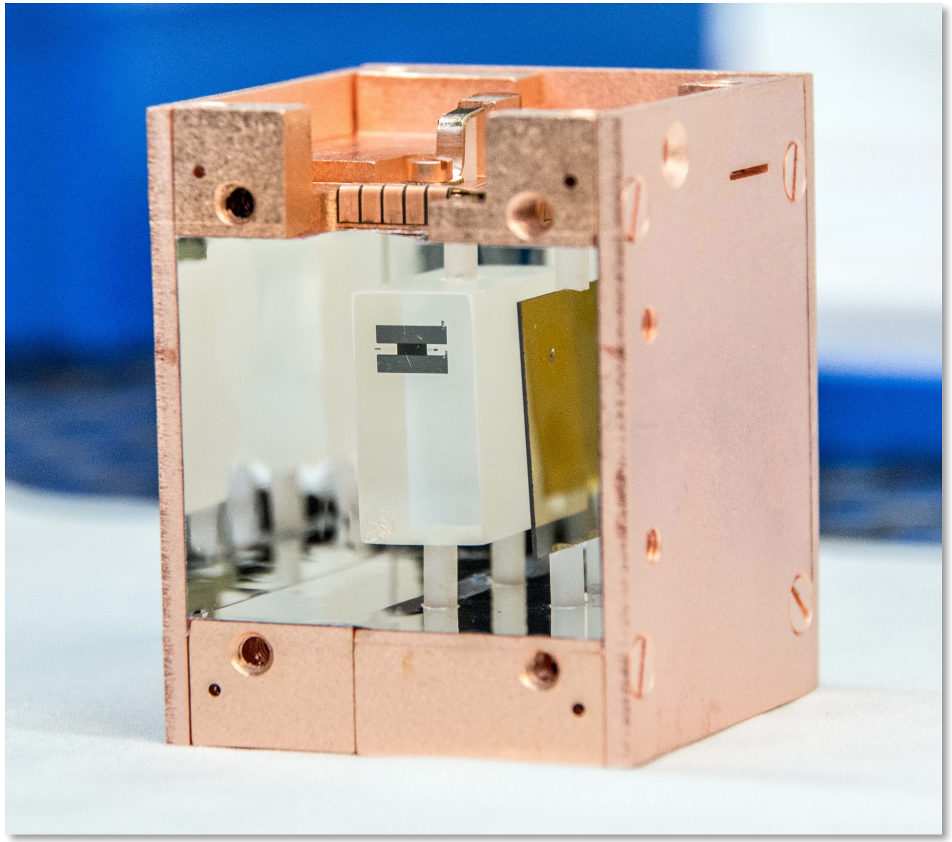
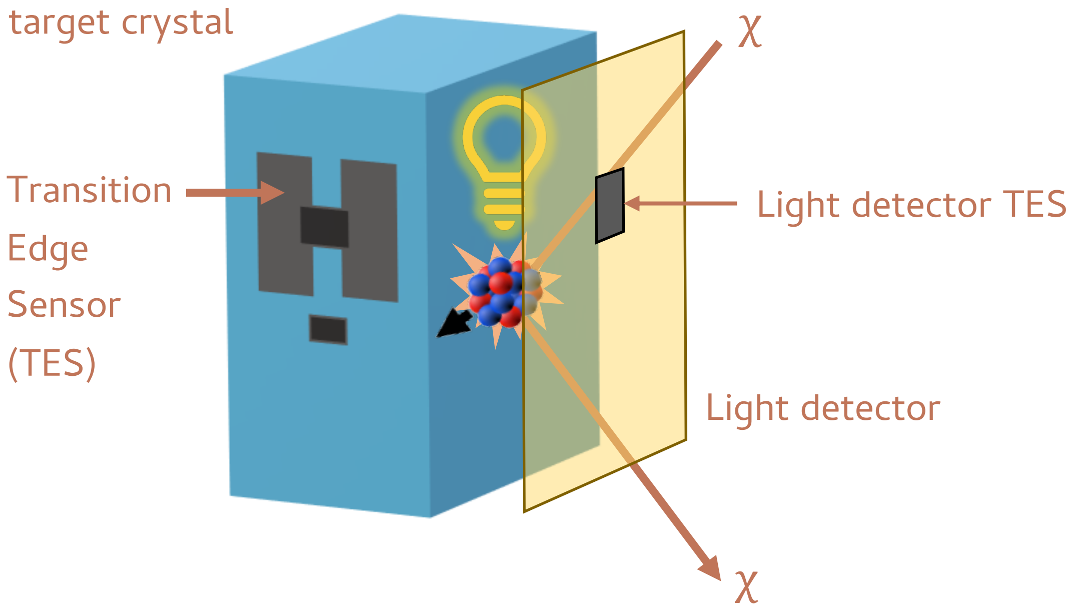
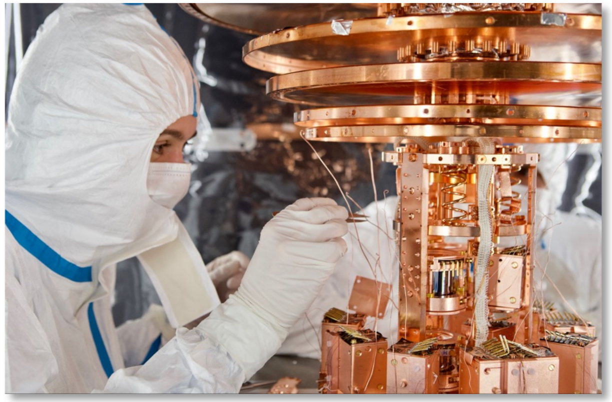
CRESST-III detector module

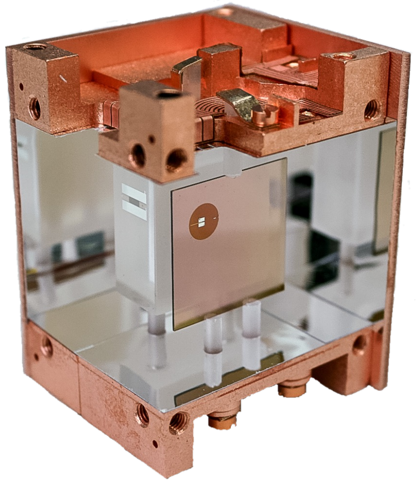




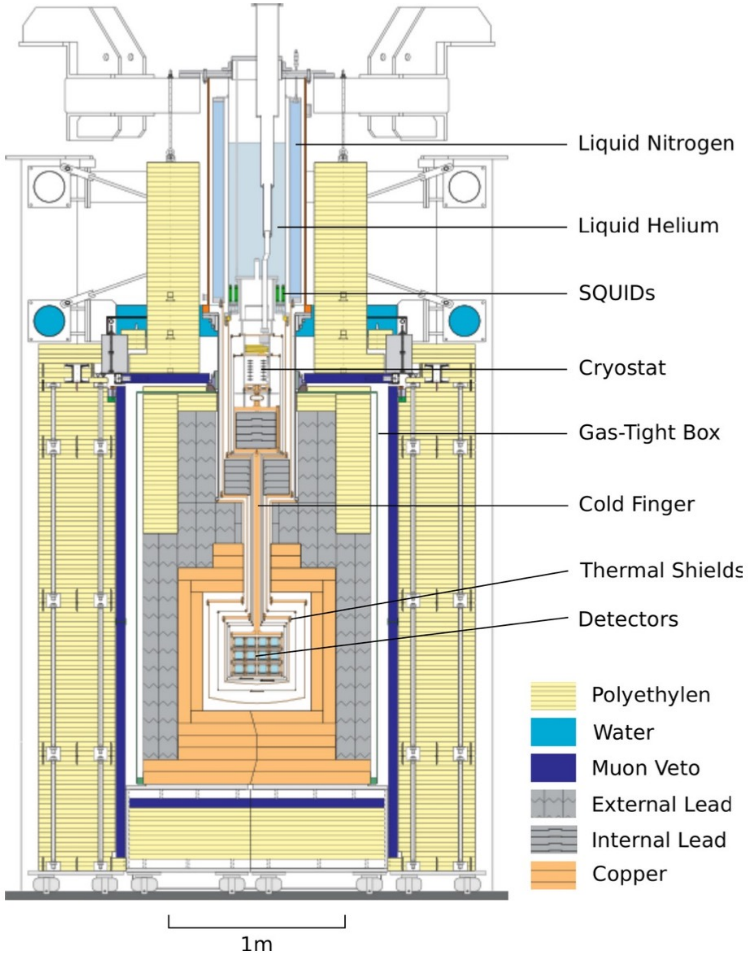
For scintillating target materials (e.g.$CaWO_4$), a small part of the deposited energy is released as *light*.

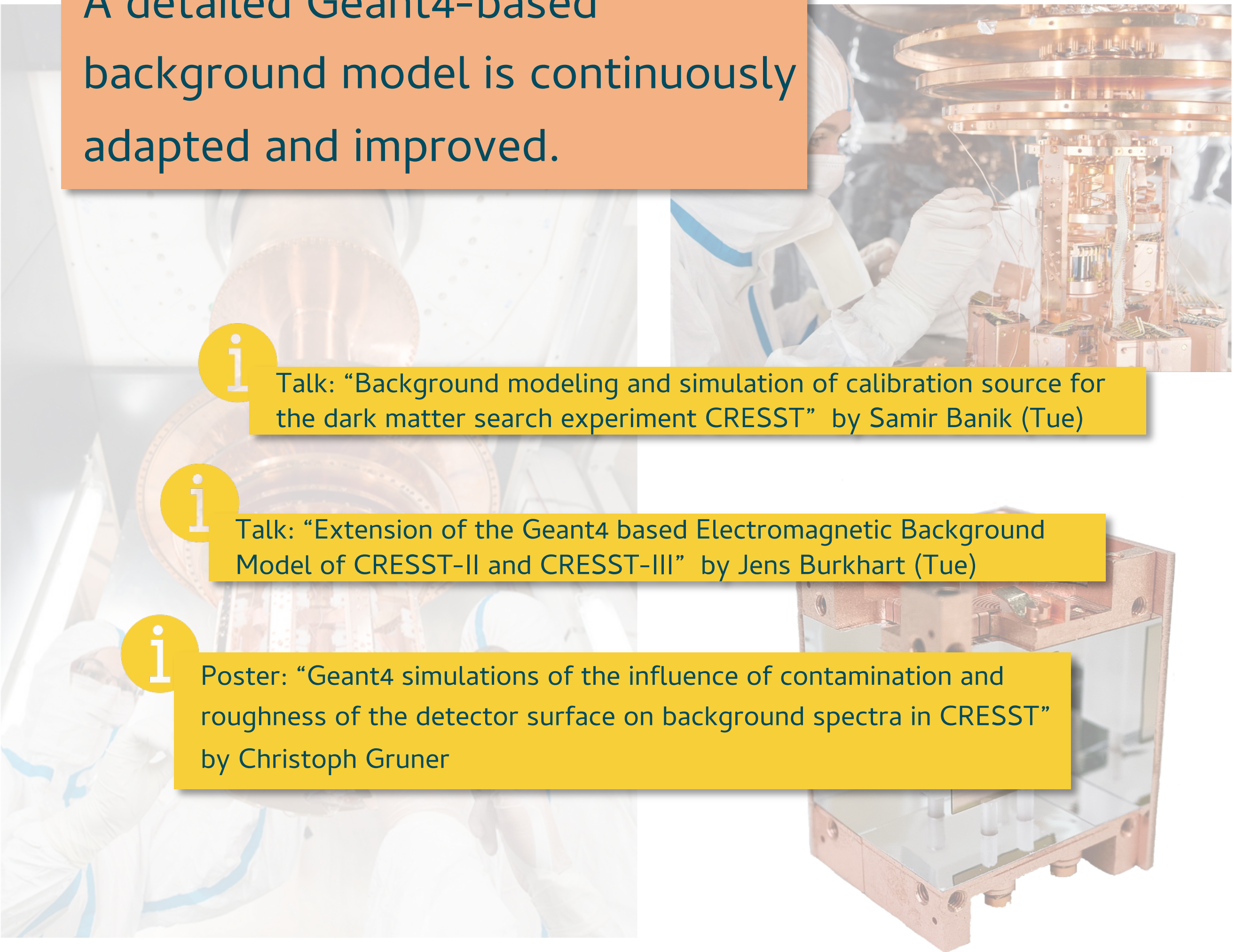
The CRESST experiment is located in the deep underground laboratory LNGS in Italy that provides excellent shielding against cosmic radiation.





Additional layers of shielding materials and an active muon veto further reduce backgrounds.





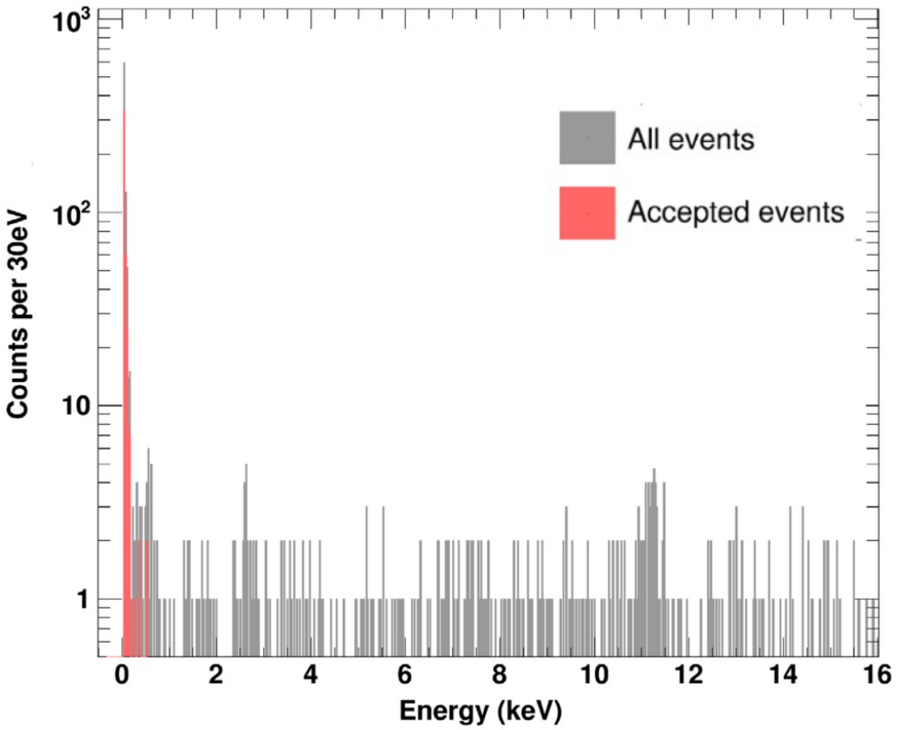
A detailed Geant4-based background model is continuously adapted and improved.

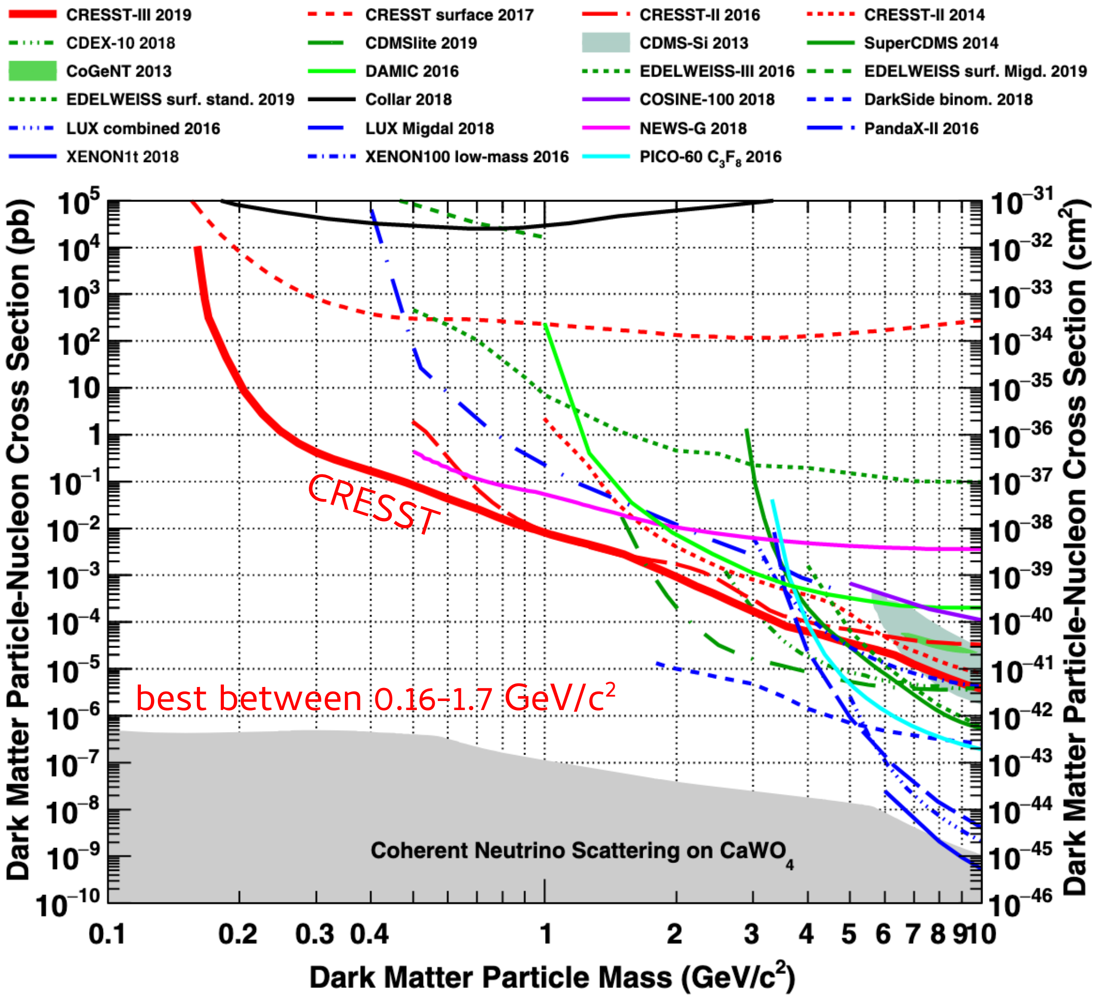
- Talk: "Background modeling and simulation of calibration source for the dark matter search experiment CRESST" by Samir Banik (Tue)
- Talk: "Extension of the Geant4 based Electromagnetic Background Model of CRESST-II and CRESST-III" by Jens Burkhart (Tue)
- Poster: "Geant4 simulations of the influence of contamination and roughness of the detector surface on background spectra in CRESST" by Christoph Gruner

First results from CRESST-III (2019): leading limit for sub-GeV DM with a **30 eV** energy threshold detector.

Detector A: 23.6 g CaWO4
Data-taking period: Oct 2016 – Jan 2018

Exposure: 5.698 kg · days
Energy threshold: **30.1 eV**





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

Sharply rising energy spectrum below 200 eV - **low energy excess (LEE)** - is observed in CRESST-III detectors and limits the sensitivity to sub-GeV DM.

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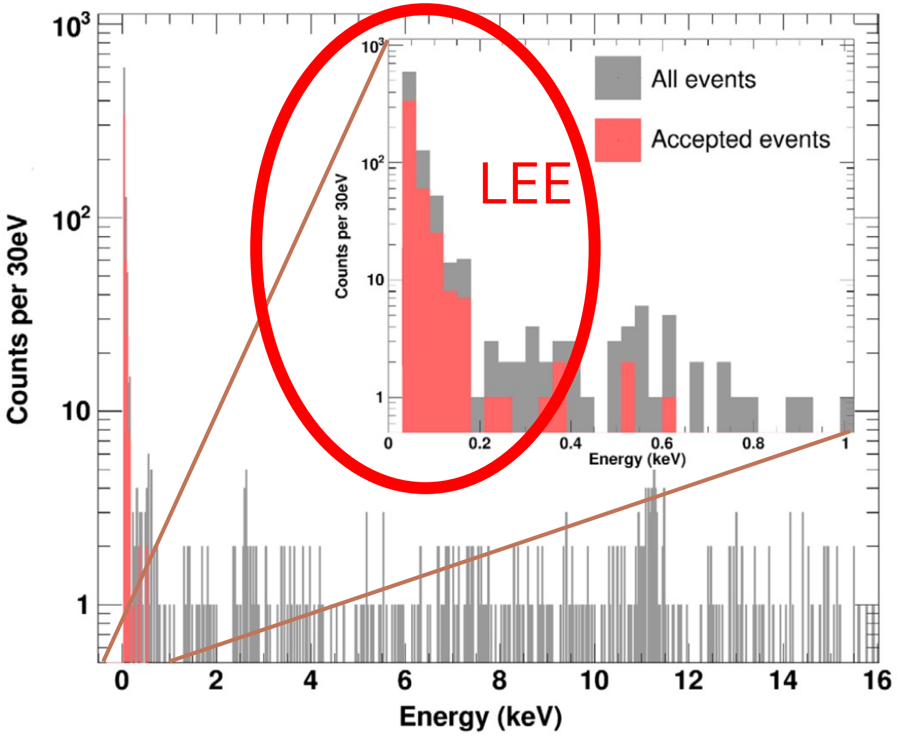

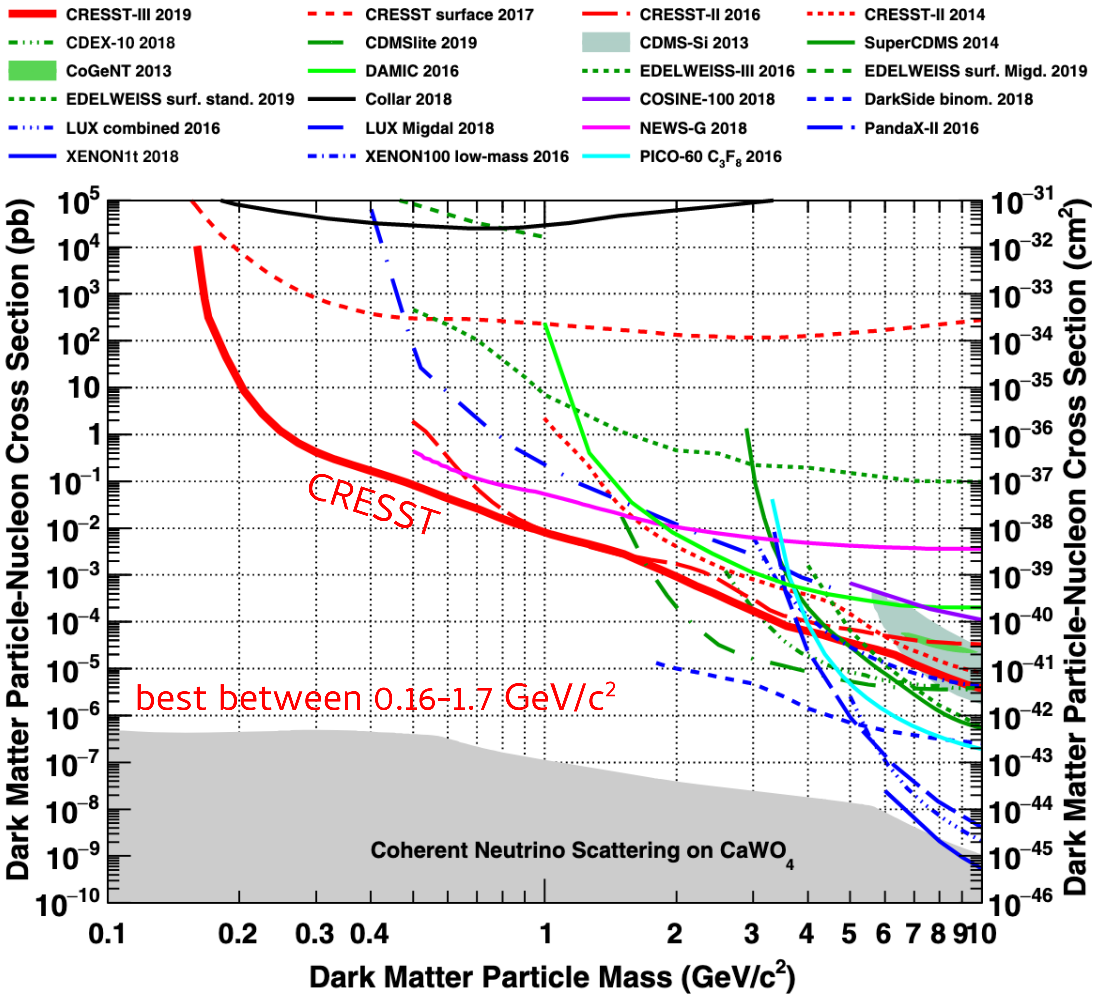

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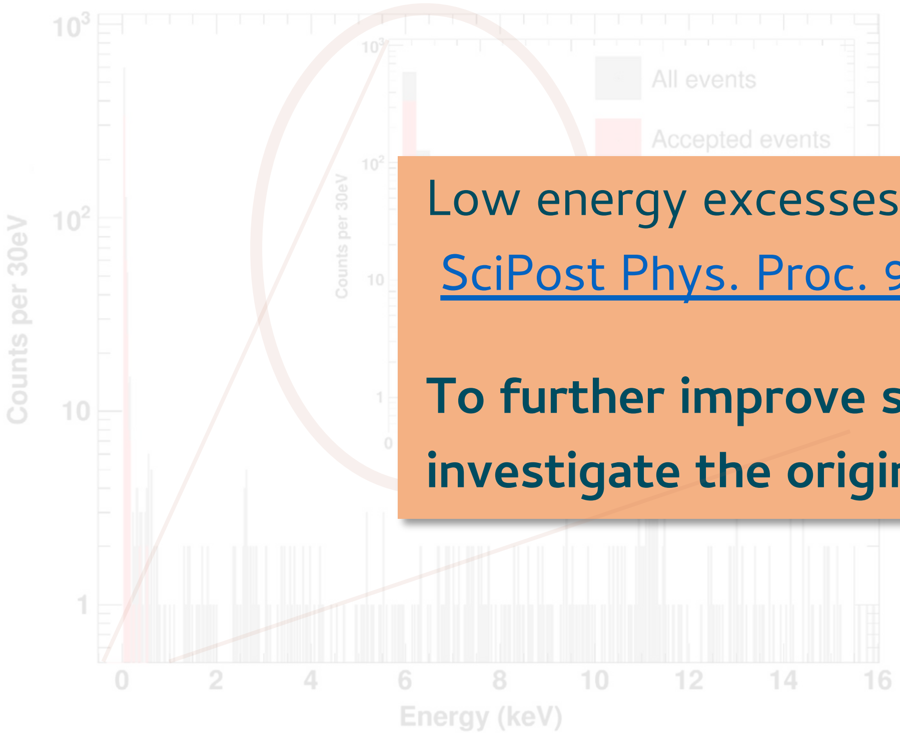
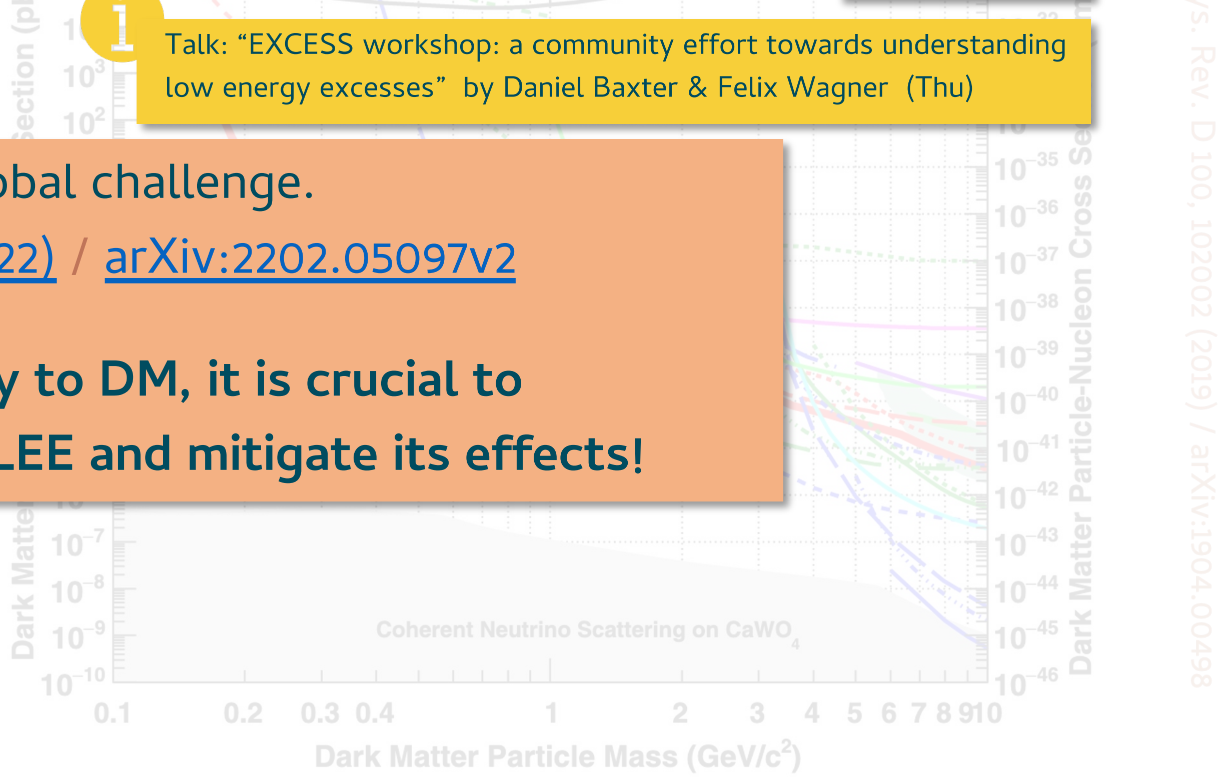




Talk: "EXCESS workshop: a community effort towards understanding low energy excesses" by Daniel Baxter & Felix Wagner (Thu)

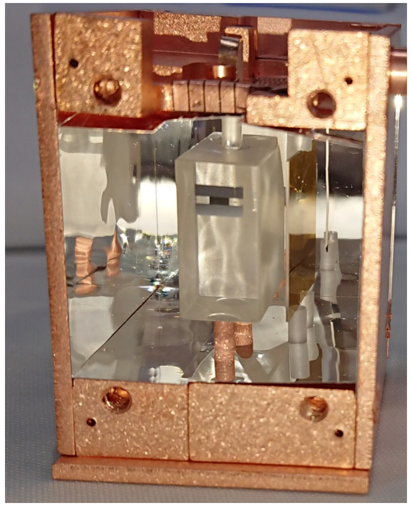
Low energy excesses are a global challenge.

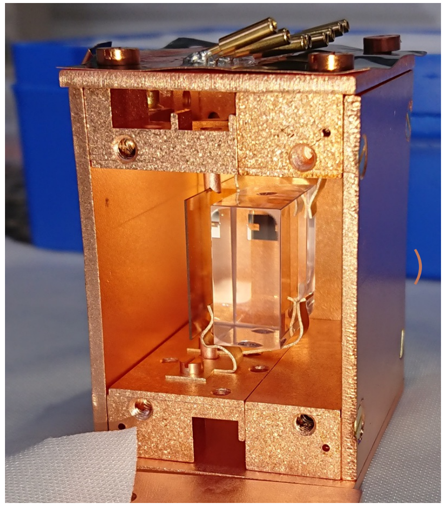
SciPost Phys. Proc. 9, 001 (2022) / arXiv:2202.05097v2

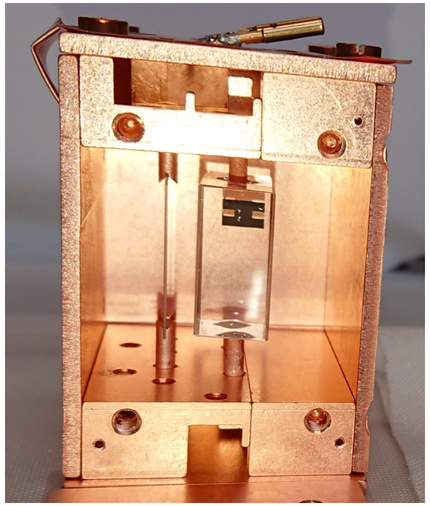
To further improve sensitivity to DM, it is crucial to investigate the origin of the LEE and mitigate its effects!

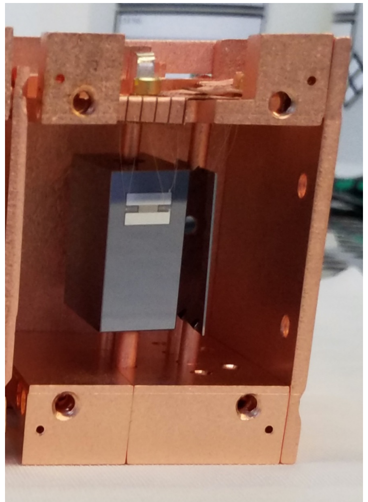
Multiple design modifications were applied in the current data-taking campaign to test ideas about the LEE origin.

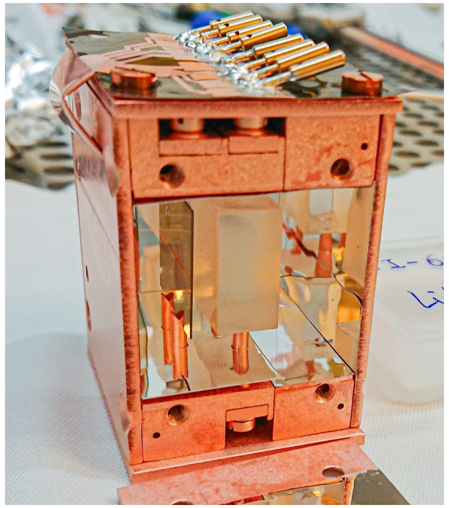
SciPost Phys. Proc. 12, 013 (2023) / arXiv:2207.09375


$CaWO_4$ grown at TUM


Commercially grown $CaWO_4$


Al_2O_3


Si


$LiAlO_2$

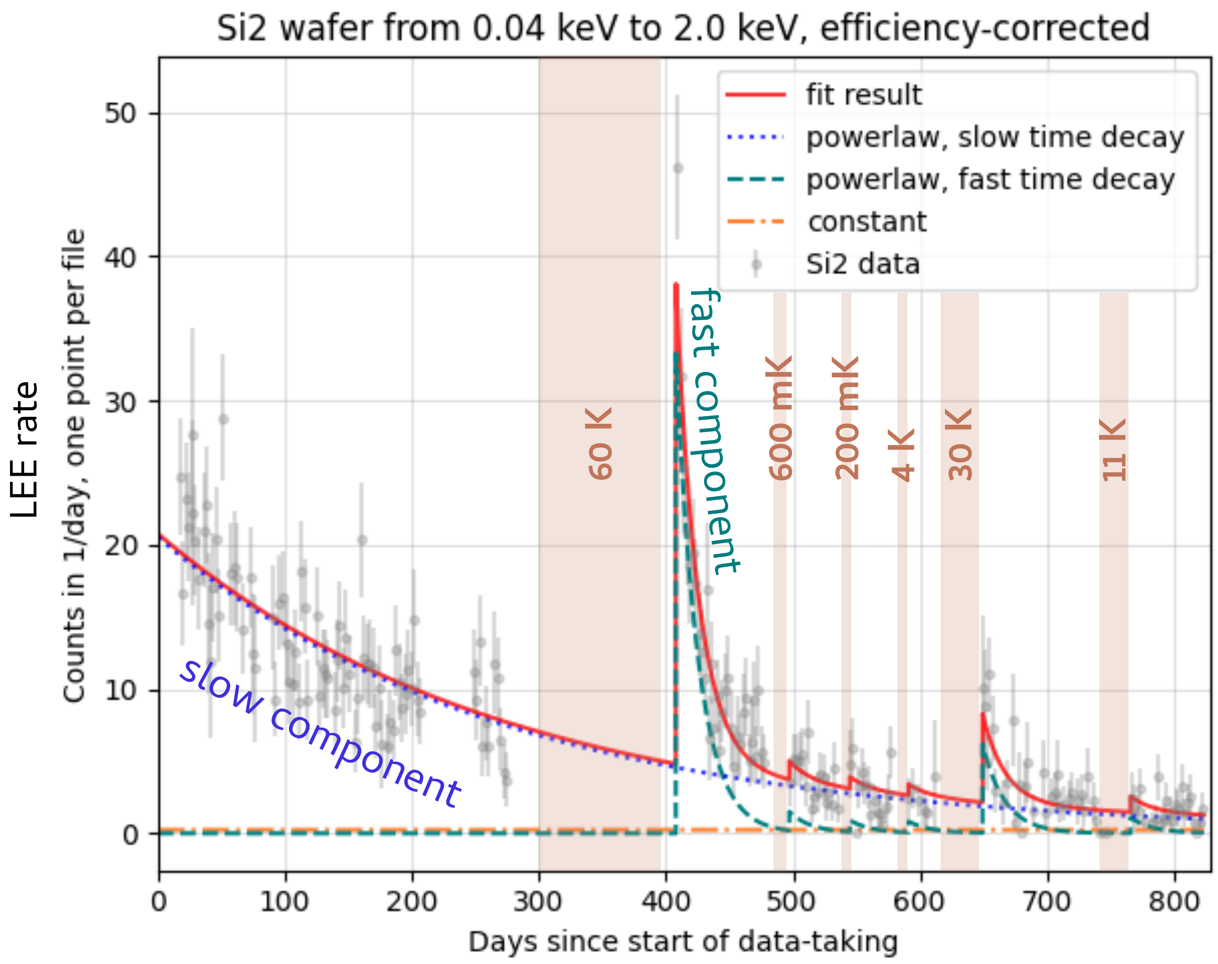
Current measurement campaign started in November 2020 and is now at the last stage.

- 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

LEE rate is decaying with time.
Excess rate increases after warming up the cryostat to O(10K).



1. Continuous decaying trend since the start of the data taking O(100 days)
→ **slow component**

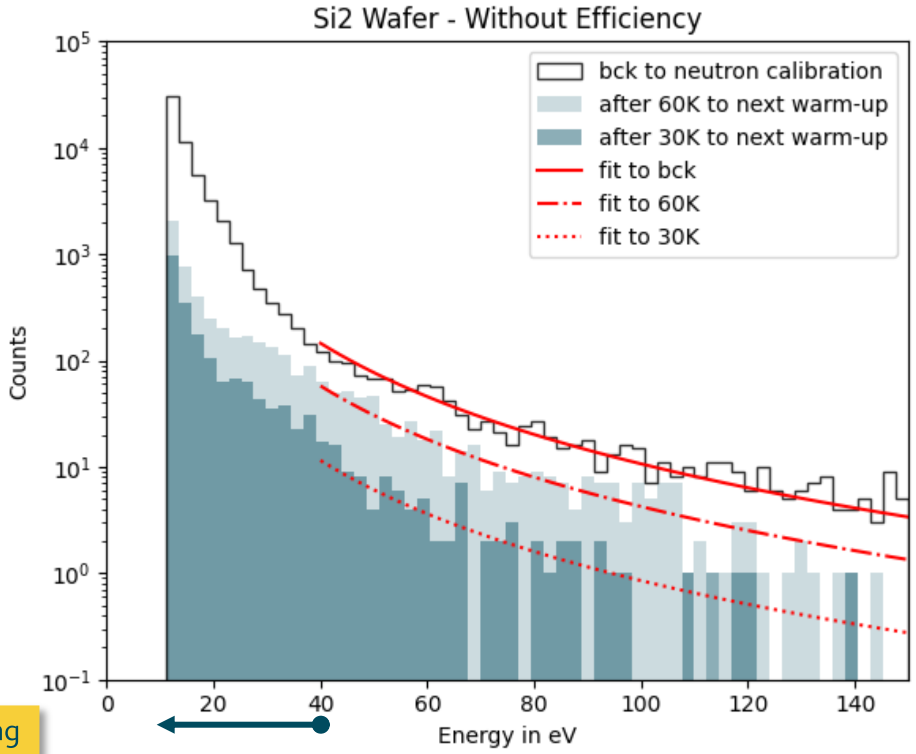
2. An additional component of about 15 days appears after warming up to O(10K)
→ **fast component**

Rate increase after warm-ups excludes external and internal radioactivity as well as DM as a major origin of the LEE.

For all detectors, **spectral shape above 40 eV**:

- is well described by a single power law
- has two time components.

$$N(E,t) = C + E^{-\varepsilon}(N_{slow} \cdot e^{-t/\tau_{slow}} + N_{fast} \cdot e^{-t/\tau_{fast}})$$



Extension of the model is needed at lower energies <40 eV.

Poster: "Description of the low energy excess in CRESST using two-dimensional unbinned likelihood fits" by Sarah Kuckuk

Talk at the Excess@TAUP workshop last Saturday: "The low energy excess in CRESST-III" by Dominik Fuchs

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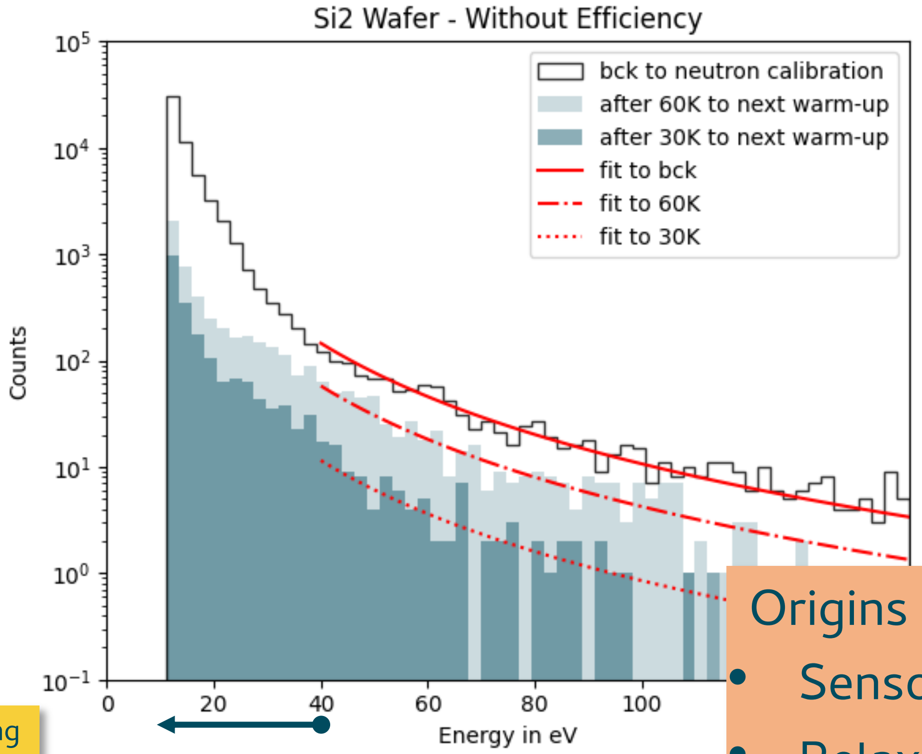

Extension of the model is needed at lower energies <40 eV.

Origins under investigation:

- Sensor related events
- Relaxation of holding-induced stress
- Intrinsic crystal effects

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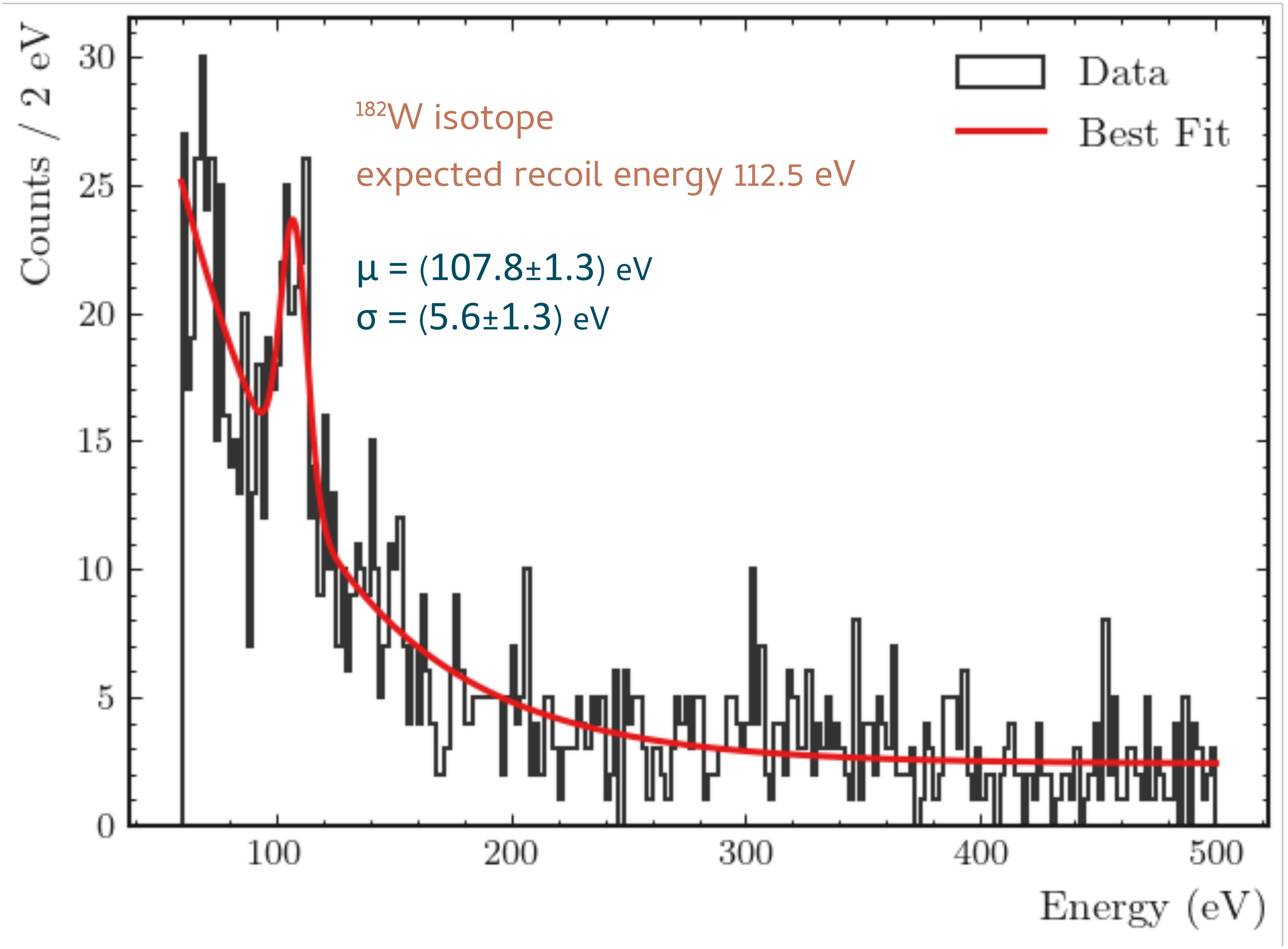
Talk at the Excess@TAUP workshop last Saturday: "The low energy excess in CRESST-III" by Dominik Fuchs

Observation of a mono-energetic nuclear recoil peak at **112 eV** in three CRESST-III $CaWO_4$ detectors -> **new calibration technique**

Phys. Rev. D **108**, 022005 / arXiv:2303.15315

Neutron calibration data (AmBe source)



Thermal neutron capture

→ de-excitation with a single γ

→ mono-energetic nuclear recoil

Proposed as a low-energy calibration method for cryogenic detectors (CRAB collaboration).

L. Thulliez *et al* 2021 *JINST* 16 P07032 / arXiv:2011.13803

Observation of the nuclear recoil peaks around the predicted value in multiple detectors

1. confirms CRESST energy calibration approach,
2. provides a potential for **precise energy calibration for nuclear recoils at 100 eV scale**.

DM results with different target materials

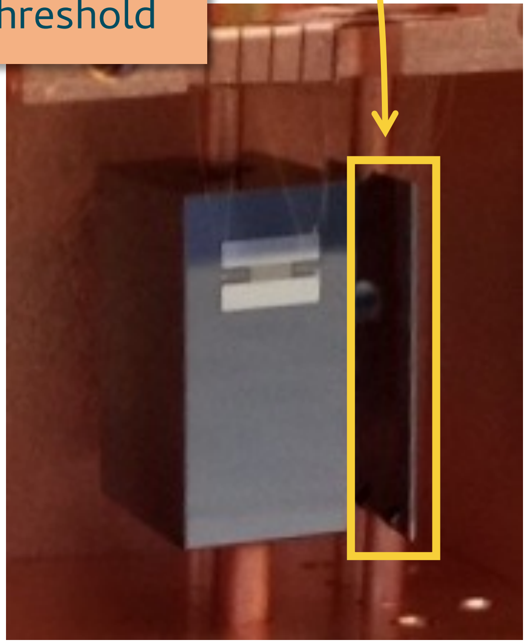
Si wafer detector: energy threshold of **10 eV** extends sensitivity to DM particles with the mass down to **115 MeV/c²**.

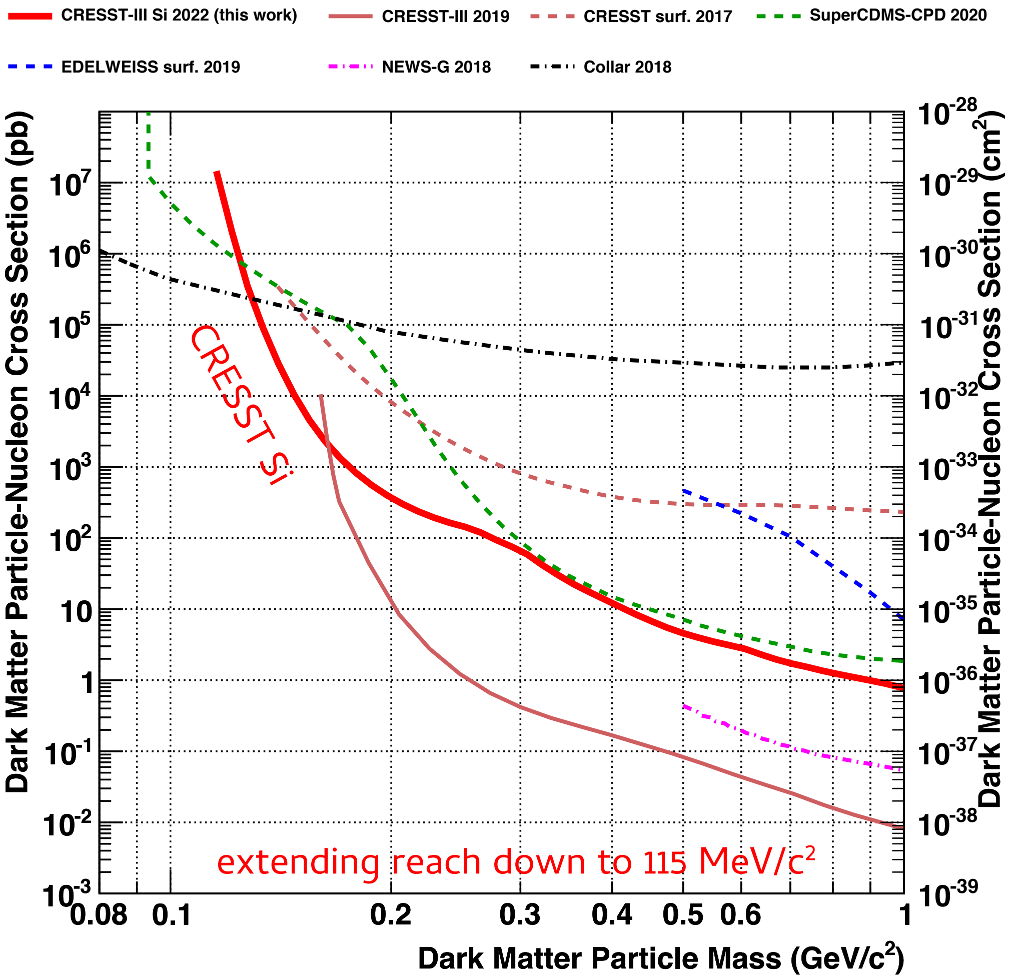
Si wafer detector: 0.35 g
Data-taking period: Nov 2020 – Aug 2021

Exposure: 55.06 g · days
Energy threshold: **10.0 eV**

Thin wafer detector is a target
Bulky detector is a veto to remove coincidence events.

10.0±0.2 eV energy threshold





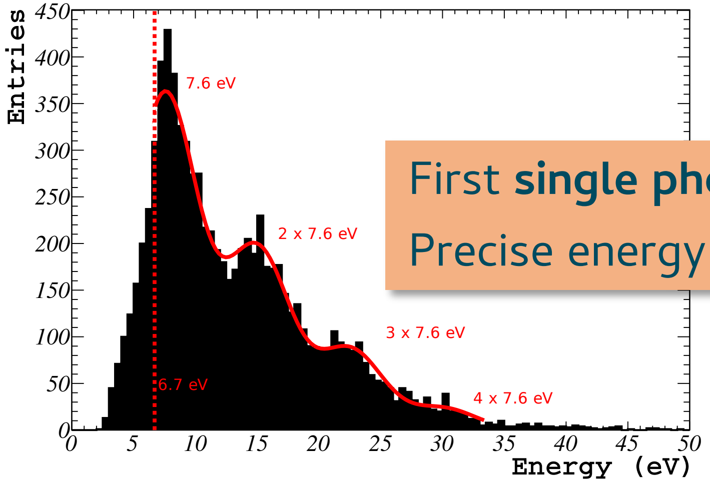
Phys. Rev. D **107**, 122003 / arXiv:2212.12513

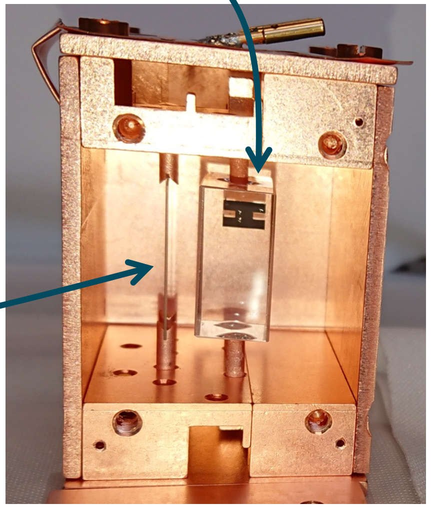
Silicon-on-sapphire wafer detector achieves an **energy threshold < 10 eV and reaches sensitivity to DM mass < 100 MeV/c²**.

Al_2O_3 bulky crystal is exposed to a ^{55}Fe calibration source

⟶ luminescence emission at 7.6 eV

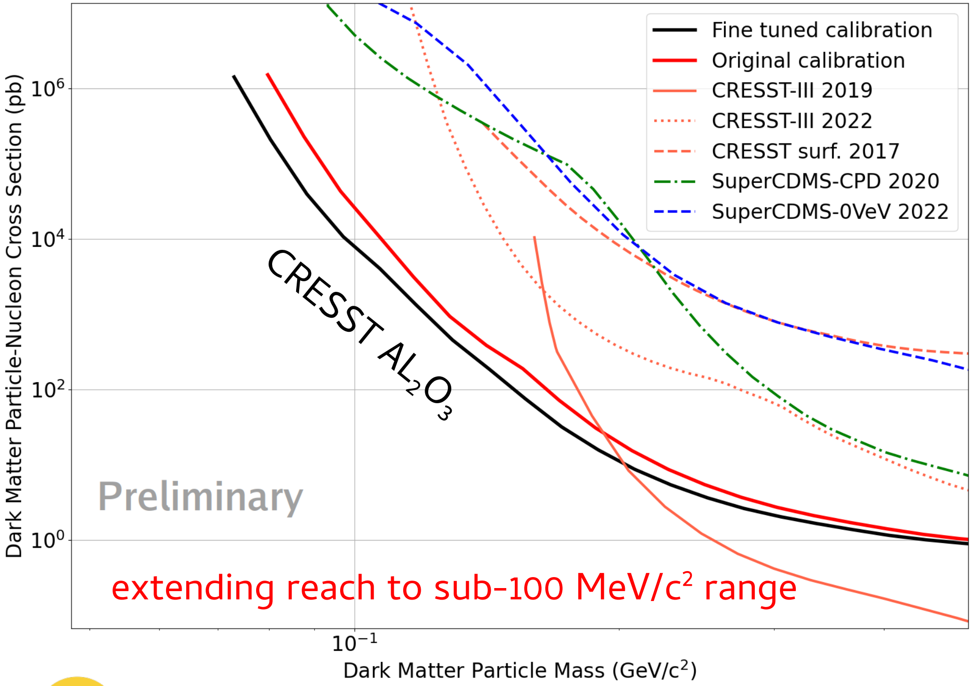
⟶ single photon detection by a facing wafer detector @ n x 7.6 eV





First **single photons** observation in CRESST!
Precise energy calibration **at eV-scale!**

Al_2O_3 wafer detector: 0.6 g
Data-taking period: Nov 2020 – Aug 2021
Exposure: 0.14 kg · days
Energy threshold: **6.7 eV**

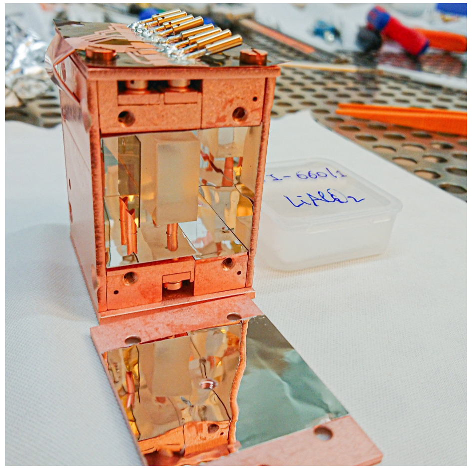


extending reach to sub-100 MeV/c² range

Talk: "First observation of single photons in a CRESST detector and new Dark Matter exclusion limits" by Dominik Fuchs (Mon)

Well performing $LiAlO_2$ detector allowed to greatly improve the limits for **spin-dependent** DM-nucleon interactions.

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

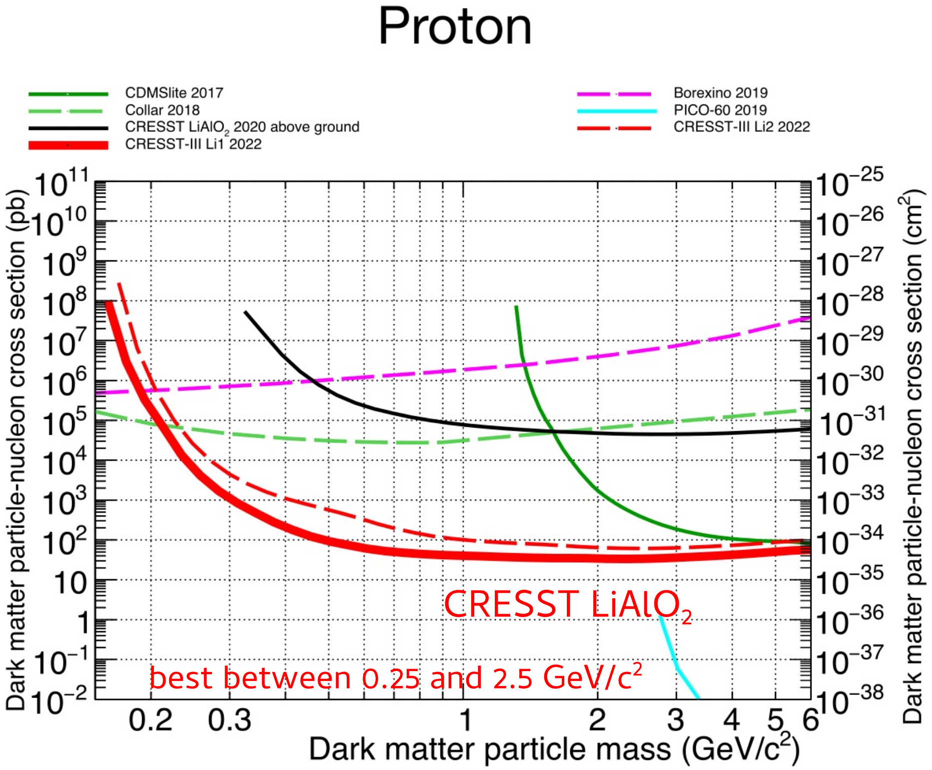


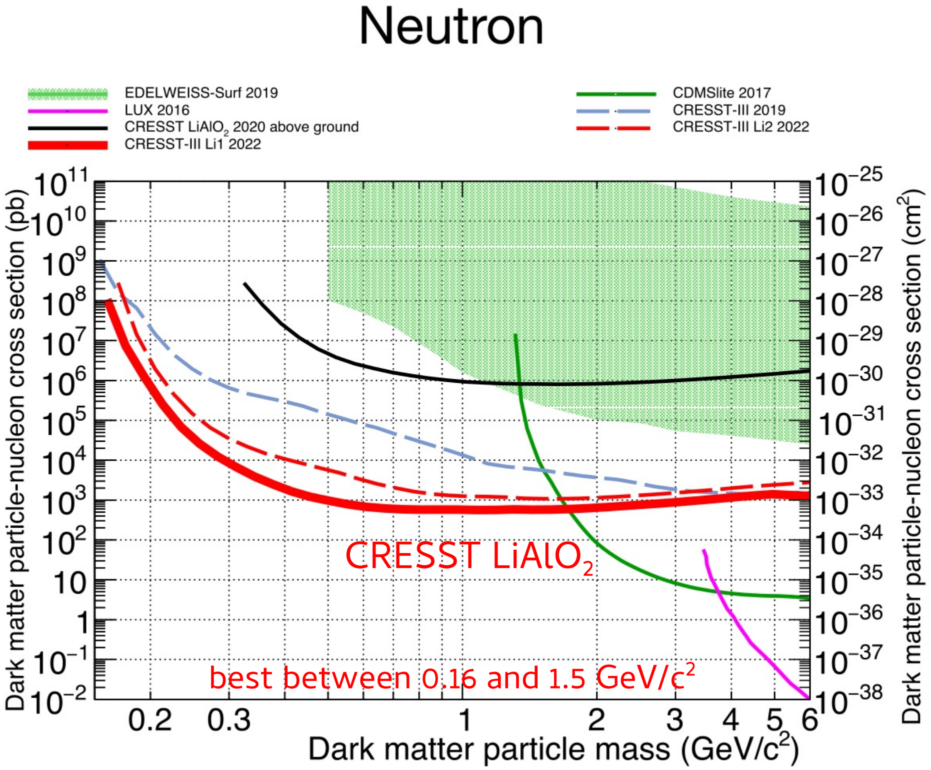
Li1 detector: 10.5 g LiAlO2

Data-taking period: Feb 2021 – Aug 2021

Exposure: 1.161 kg · days

Energy threshold: 83.6 eV





CRESST technique allows to use various target materials to test different interaction channels!

Poster: “First Results on ^{17}O Enrichment of $CaWO_4$ Crystals for Spin-dependent DM search with CRESST” by Angelina Kinast

Future: New CRESST detectors

New material: **diamond crystal** operated as a cryogenic detector **showed a high potential for sub-GeV DM search.**

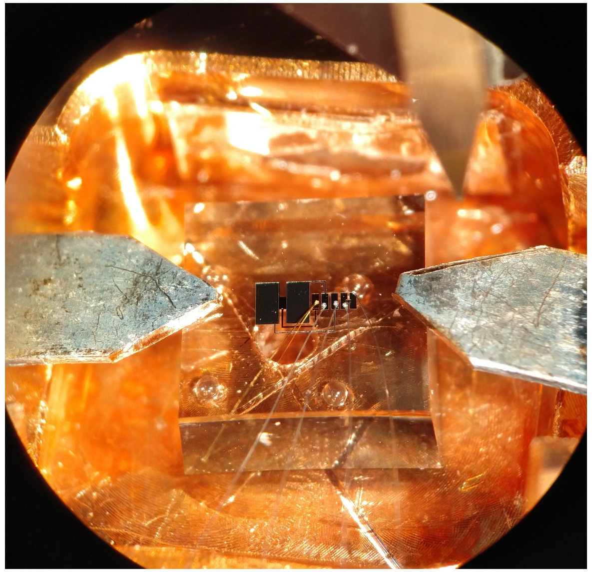
Eur. Phys. J. C (2022) 82:851 / arXiv:2203.11999

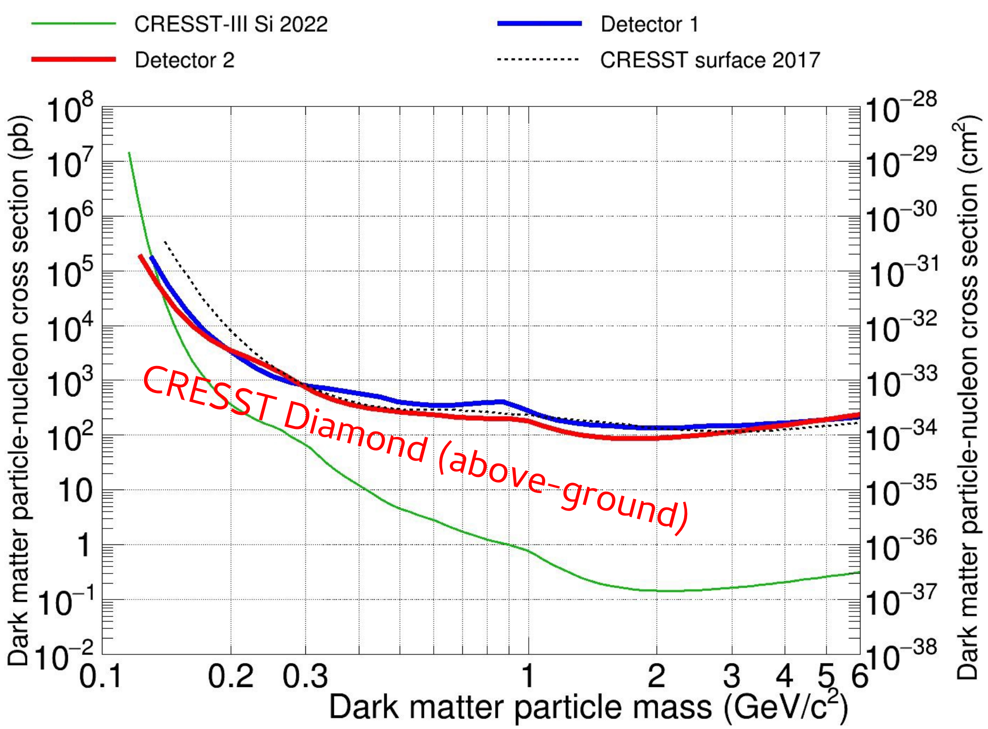
Diamond detector: 0.175 g

37 h of stable data **above-ground**

Exposure: 0.27 g · days

Nuclear recoil threshold: **16.8 eV**



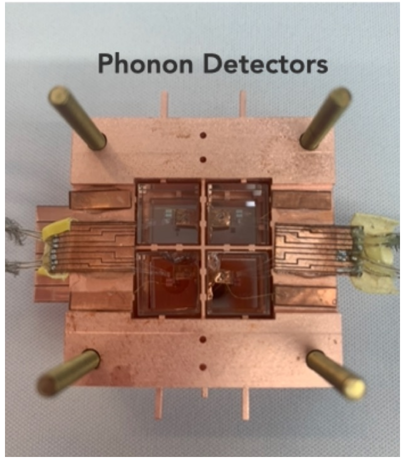


Poster: "A low-threshold diamond cryogenic detector for sub-GeV Dark Matter searches" by Anna Bertolini

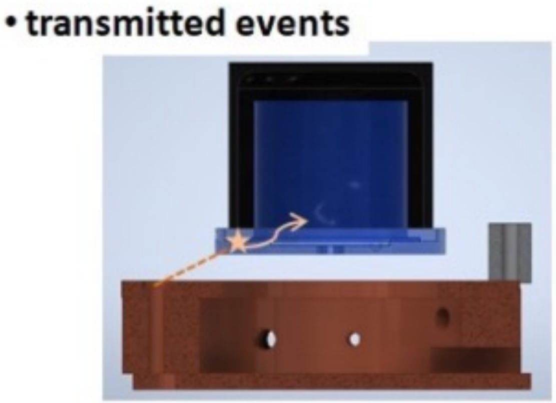
Detectors with new module designs to study the LEE origin will be installed at LNGS in the next run starting at the end of 2023.

Holding structures

novel stress-free holding structure
-> LEE reduction?

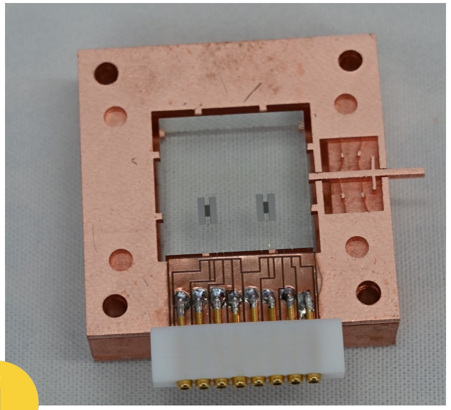


instrumented holders
-> discriminate events transmitted through the holding structure



Double TES read-out

-> discriminate events in the absorber from events in the TES films or material interfaces



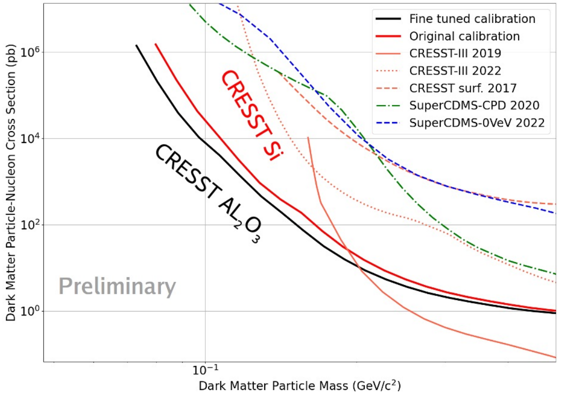
Talk: "Results of doubleTES detectors" by Francesca Pucci at the Excess@TAUP workshop last Saturday

More features

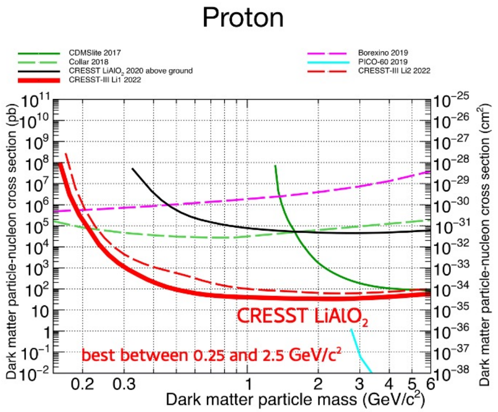
- maximize sensitivity to dark matter recoils
- 4π veto

Above-ground measurements show very promising performance!

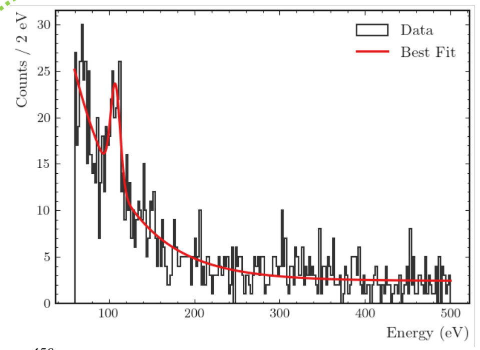
Conclusions & Outlook

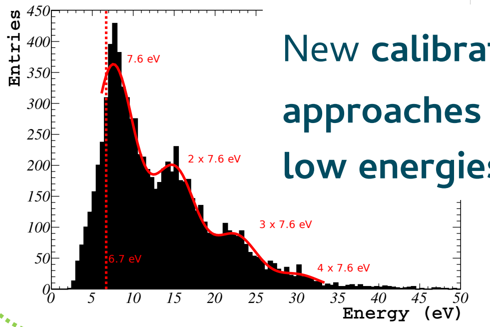


Reach to DM masses <100 MeV/c² with low threshold detectors



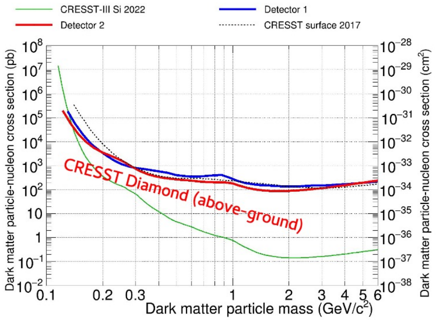
Improved limits for **spin-dependent interactions with** $LiAlO_2$ target.

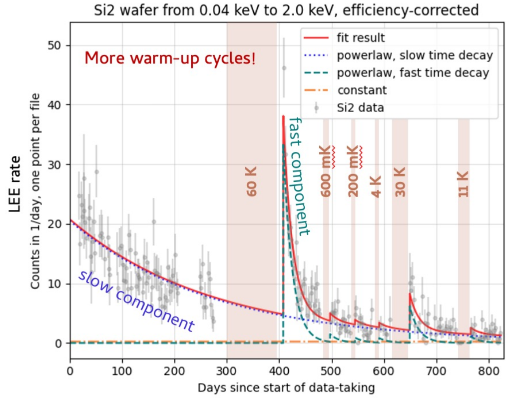




New **calibration approaches at low energies**

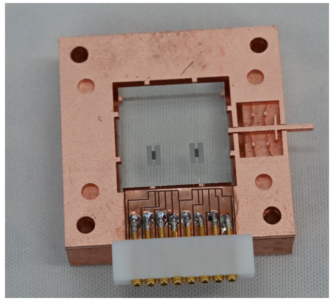
New target material: **diamond detectors for sub-GeV DM searches.**





Strong hints towards **solid state physics effects playing a major role for low energy excess**.

Coming to LNGS late 2023

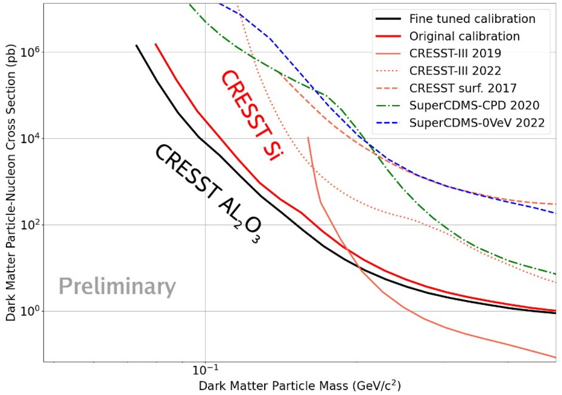


Novel detector module designs to study sensor-related events and the impact of the stress from holders

A **major CRESST setup upgrade** to 288 read-out channels is in preparation:

- SQUIDs and wiring are already produced
- new DAQ and bias electronics are designed
- goal: installation at LNGS in 2024

Conclusions & Outlook



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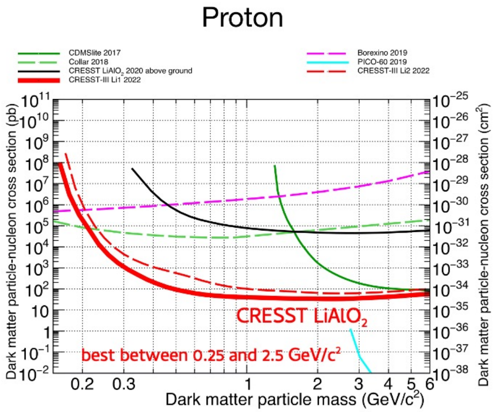

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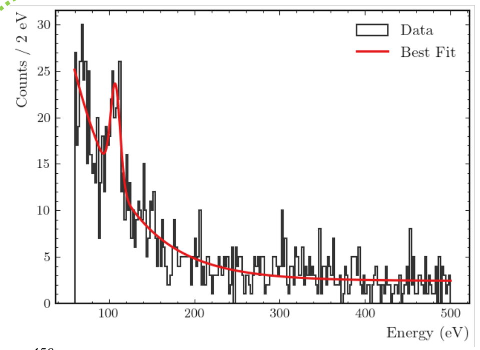

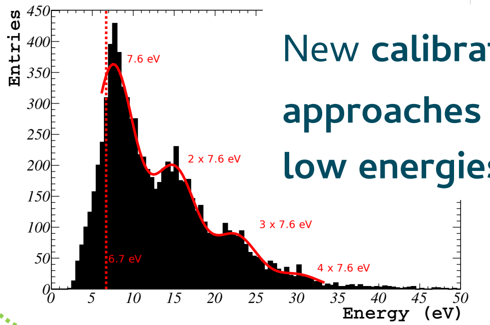

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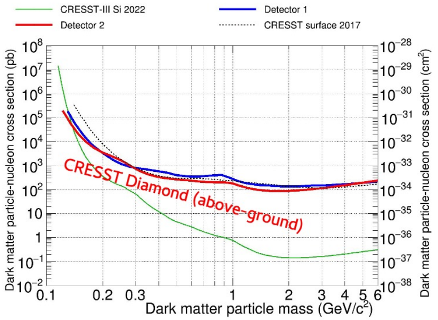

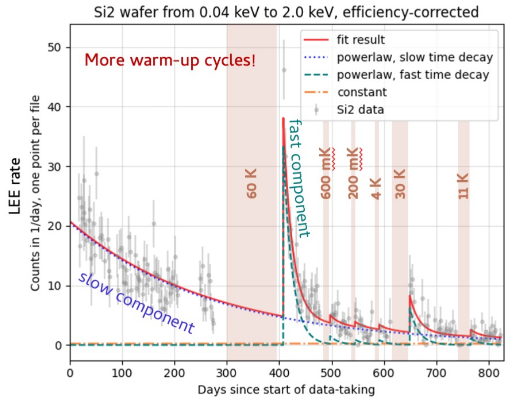

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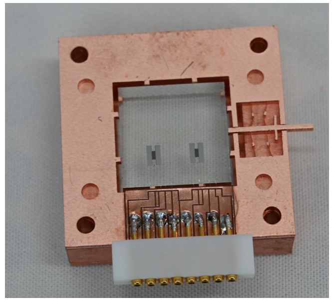

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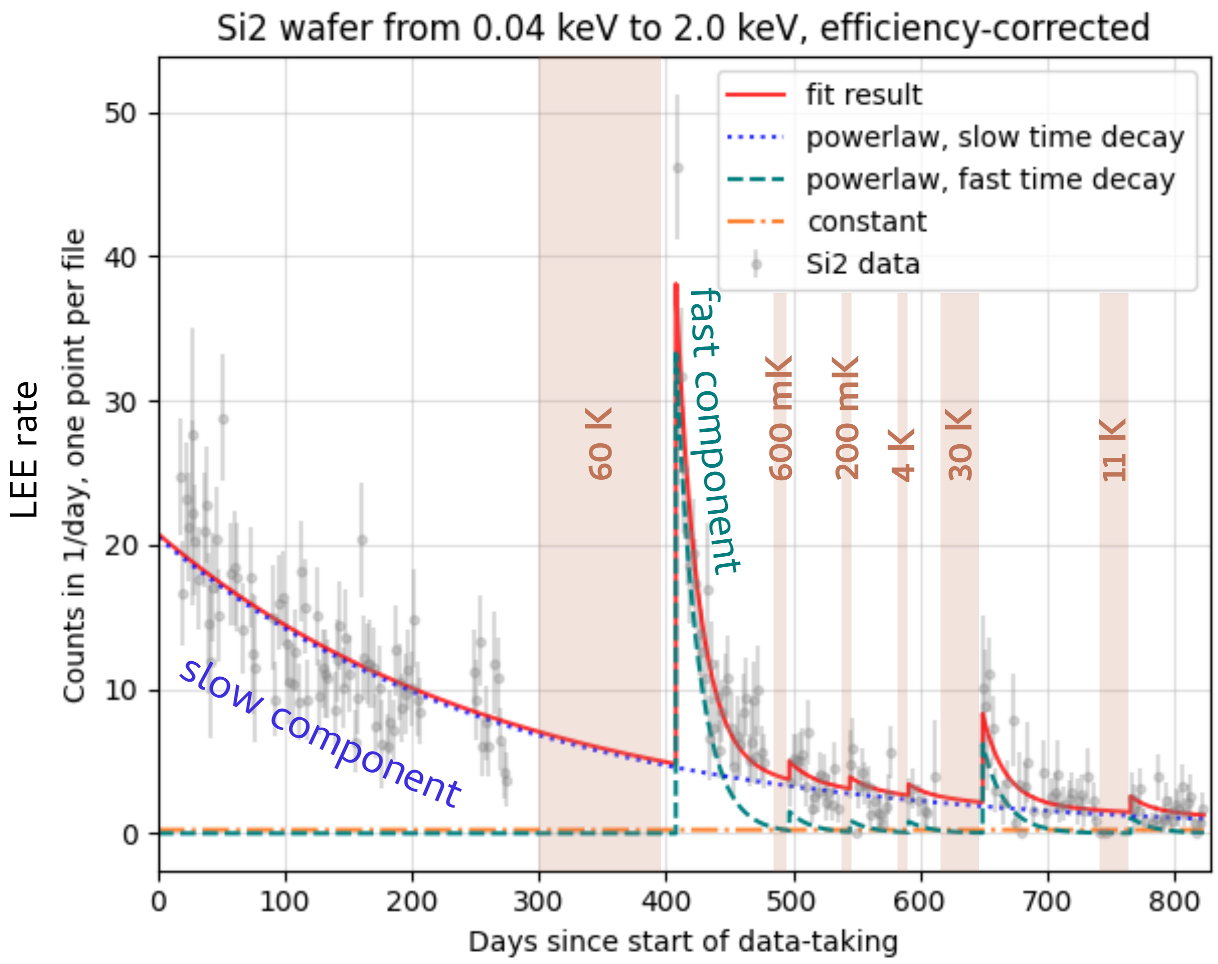
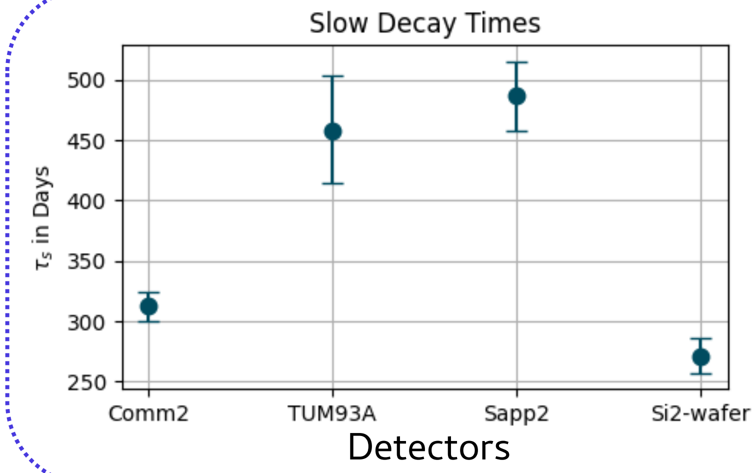
Thank you for your attention!

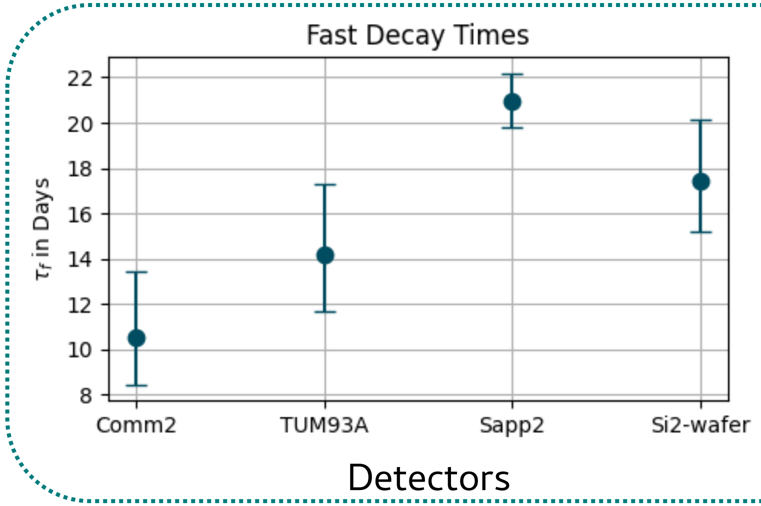
Back up

Excess rate increases after warming up the cryostat to O(10K).





1. Continuous decaying trend since the start of the data taking
⟶ **slow component**

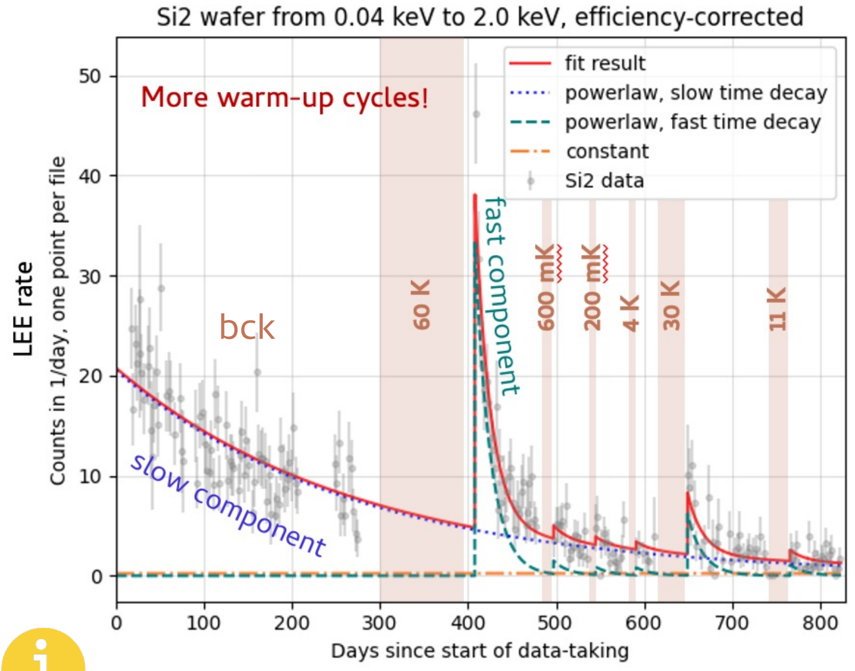


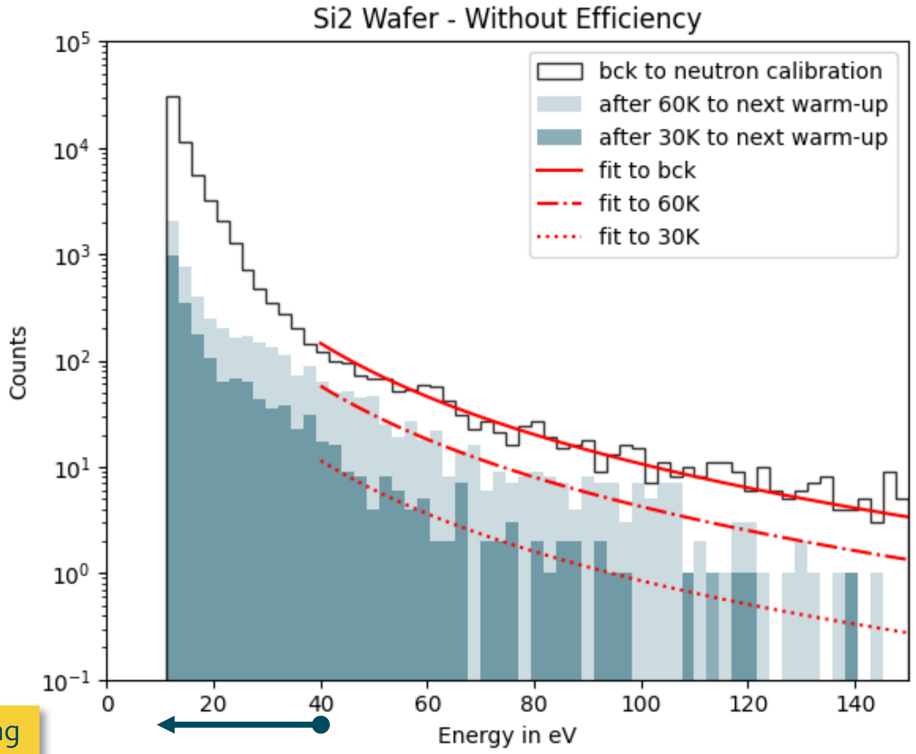
2. An additional component of about 15 days appears after warming up to O(10K)
⟶ **fast component**

For all detectors, **spectral shape above 40 eV**:

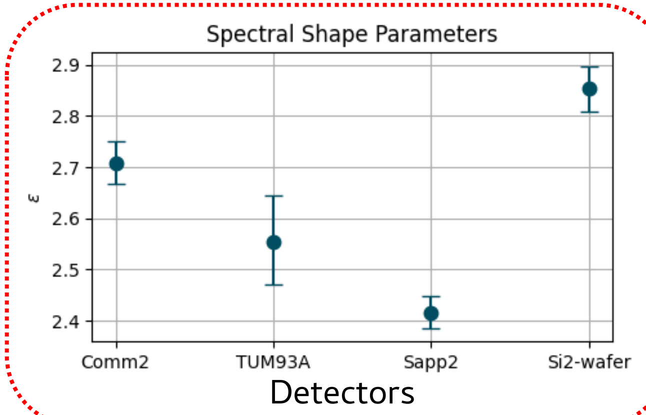
- is well described by one power law
- has two time components.

$$N(E,t) = C + E^{-\varepsilon}(N_{slow} \cdot e^{-t/\tau_{slow}} + N_{fast} \cdot e^{-t/\tau_{fast}})$$





Extension of the model is needed at lower energies <40 eV.

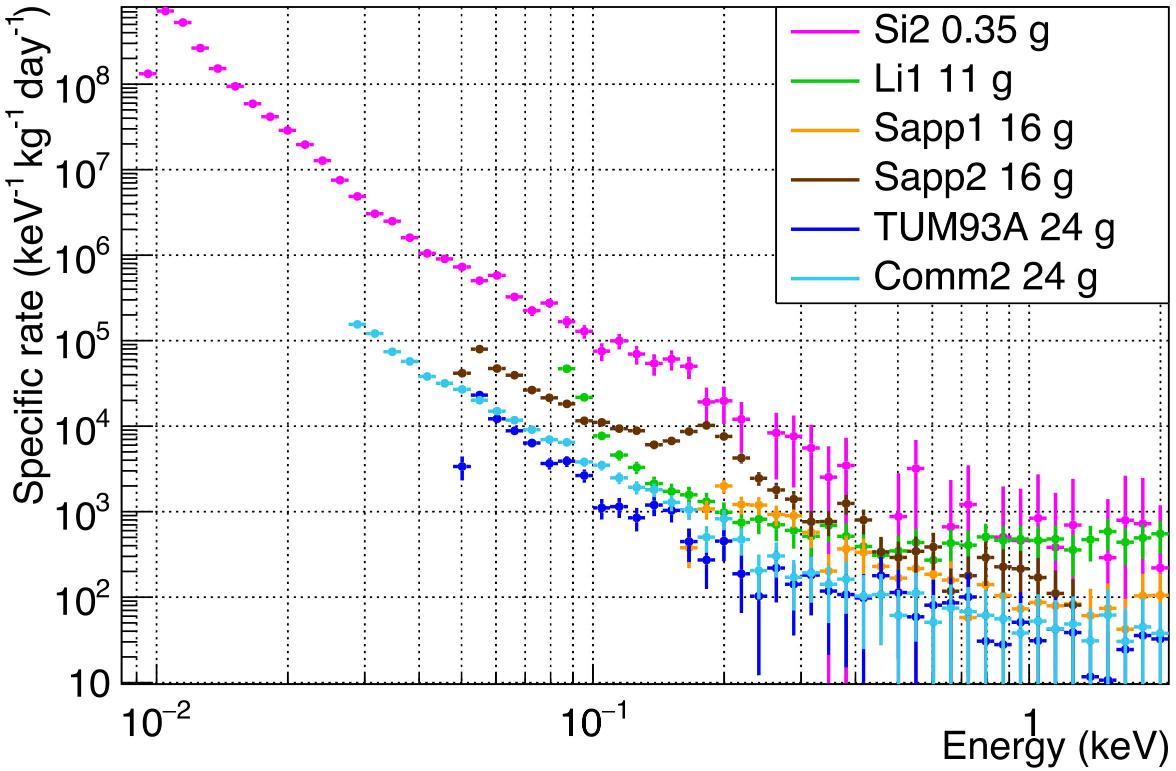


Poster: "Description of the low energy excess in CRESST using two-dimensional unbinned likelihood fits" by Sarah Kuckuk

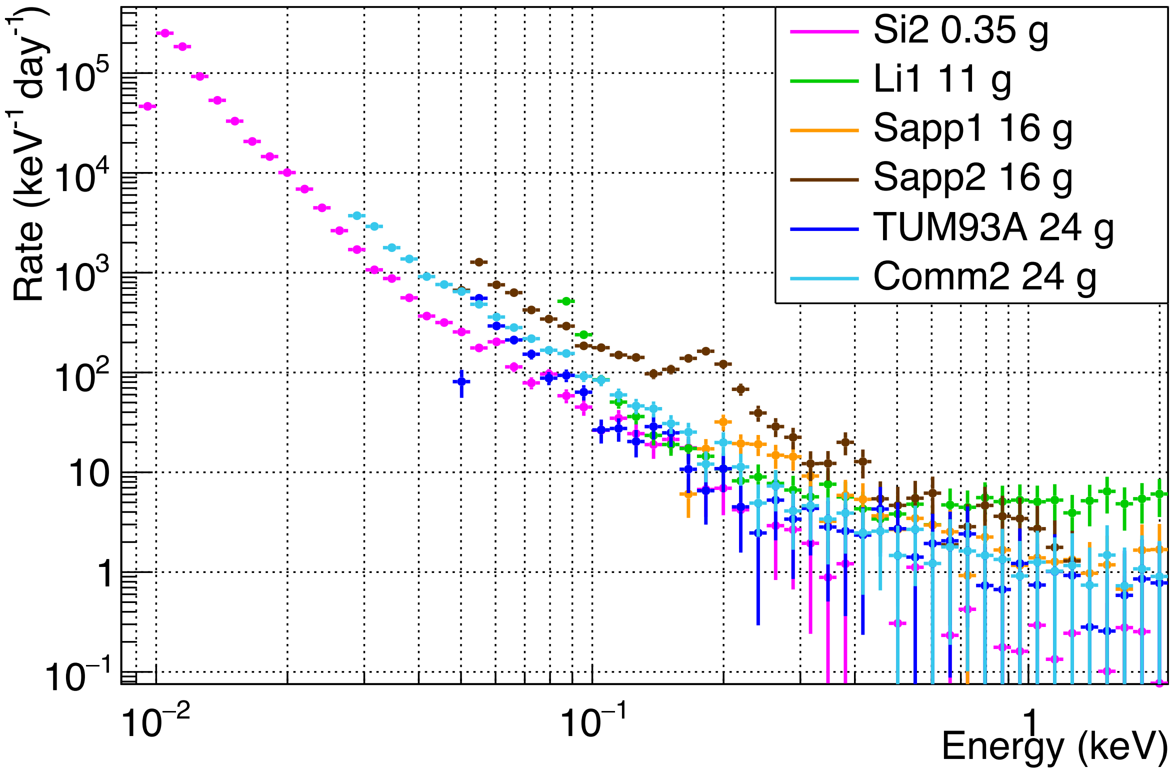
Talk at the Excess@TAUP workshop last Saturday: "The low energy excess in CRESST-III" by Dominik Fuchs

LEE is observed in all detector materials and its rate does not scale with the absorber mass.

Scaled with the absorber crystal mass

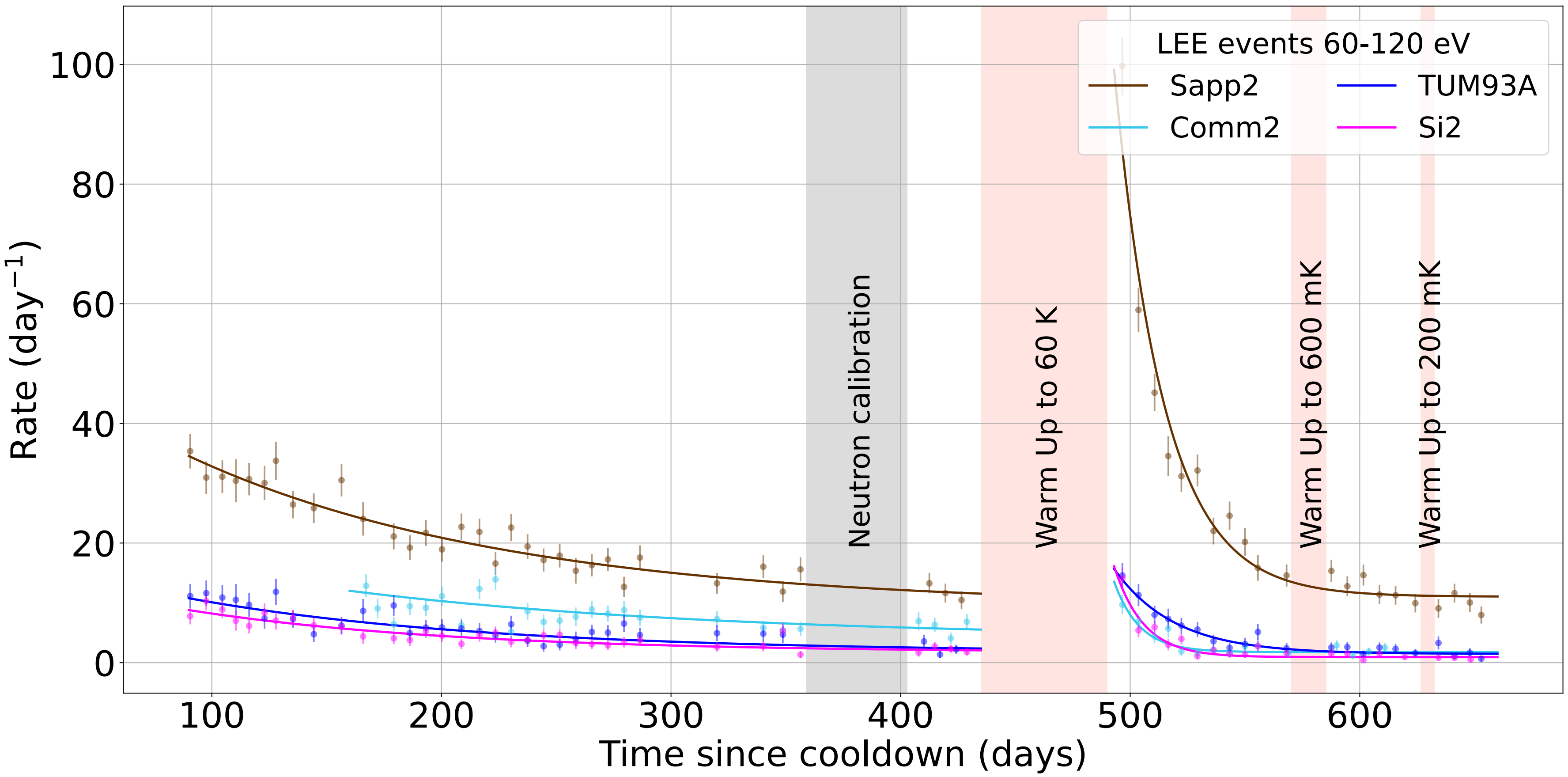


NOT scaled with the absorber crystal mass



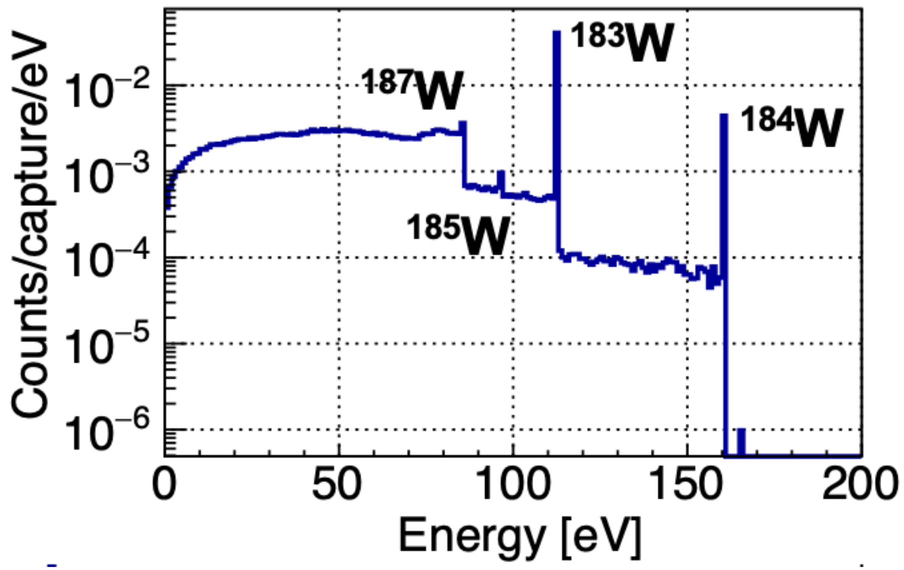
SciPost Phys. Proc. 12, 013 (2023) / arXiv:2207.09375

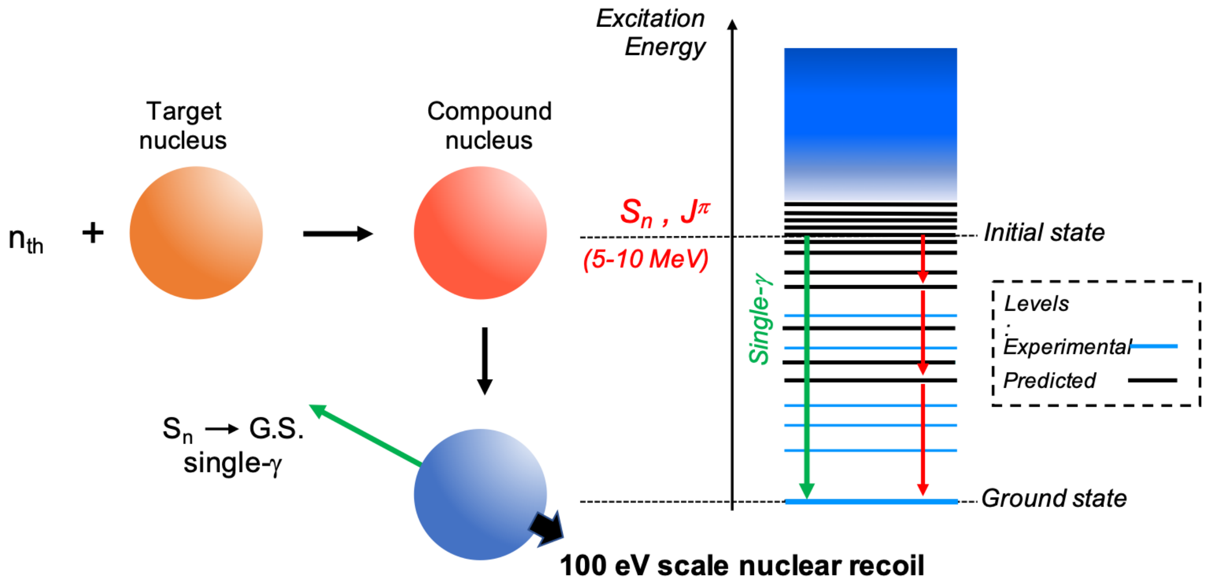
Time evolution of LEE rates (60-120 eV)



SciPost Phys. Proc. 12, 013 (2023) / arXiv:2207.09375

CRAB (Calibrated nuclear Recoils for Accurate Bolometry)





Target nucleus (A)			Compound nucleus (A+1)			
Isotope	Y_{ab} [24] (%)	$\sigma_{n,\gamma}$ [25] (barn)	S_n [26] (keV)	I^s_γ [26, 27] (%)	Recoil (eV)	FoM (a.u.)
^{182}W	26.50	20.32	6191	13.94	112.5	7506
^{183}W	14.31	9.87	7411	5.83	160.3	823
^{184}W	30.64	1.63	5754	1.48	96.1	74
^{186}W	28.43	37.89	5467	0.26	85.8	280
^{70}Ge	20.53	3.05	7416	1.95	416.2	122
^{72}Ge	27.45	0.89	6783	0.0	338.7	0
^{73}Ge	7.76	14.70	10196	0.0	754.9	0
^{74}Ge	36.52	0.52	6506	2.83	303.2	54
^{76}Ge	7.74	0.15	6073	0.0	257.3	0

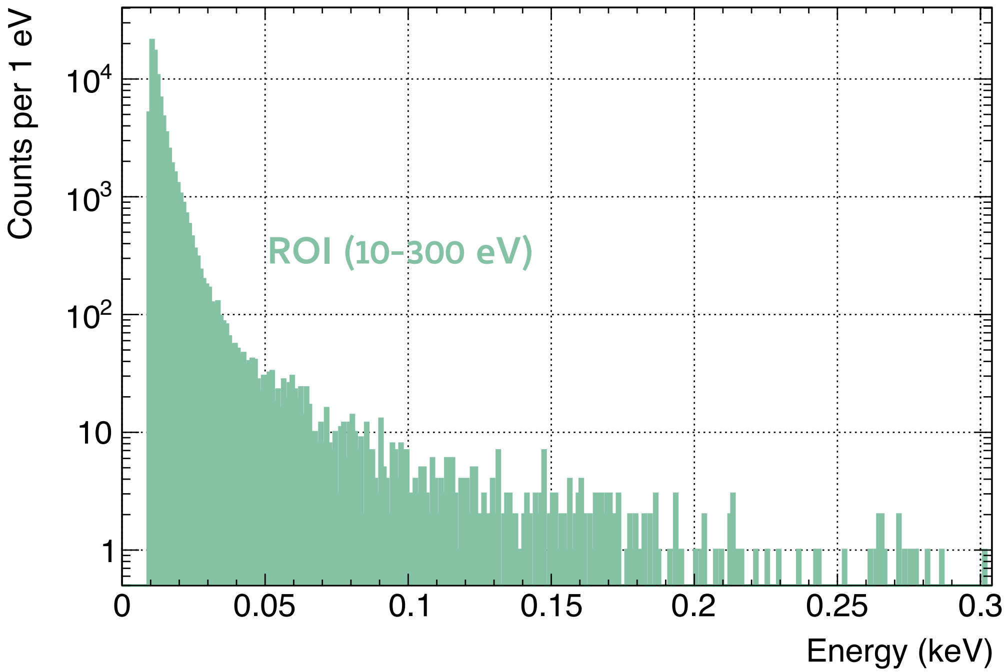
L. Thulliez *et al* 2021 *JINST* 16 P07032

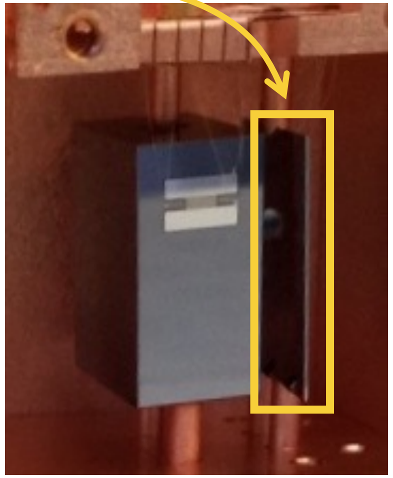
Si wafer detector: energy spectrum

Si wafer detector: 0.35 g
Data-taking period: Nov 2020 – Aug 2021

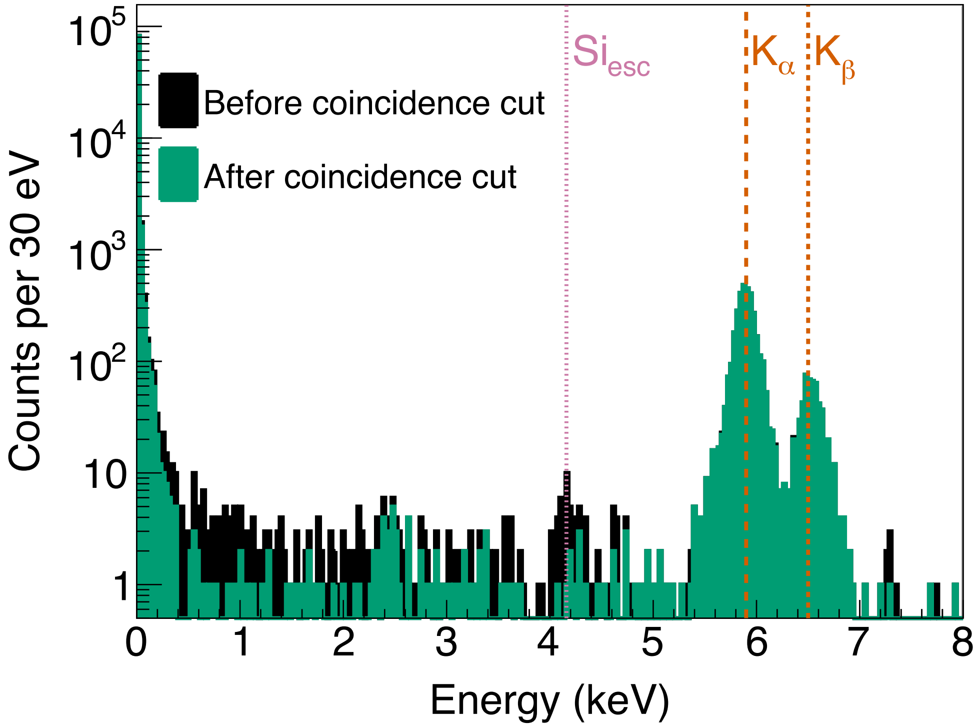
Exposure: 55.06 g · days
Energy threshold: **10.0 eV**

Thin wafer detector is a target
Bulky detector is a veto to remove coincidence events.



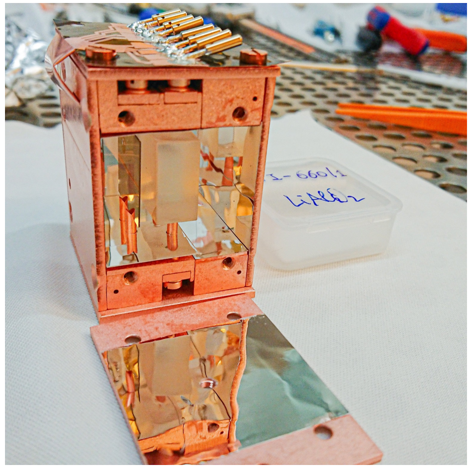


Only 1% of the LEE events are in coincidence with any signal in the bulk detector!



Phys. Rev. D **107**, 122003 / arXiv:2212.12513

Well performing $LiAlO_2$ detector allowed to greatly improve the limits for **spin-dependent** DM-nucleon interactions.



Li1 detector (Run36): 10.5 g LiAlO2

Data taking period: Feb 2021 – Aug 2021

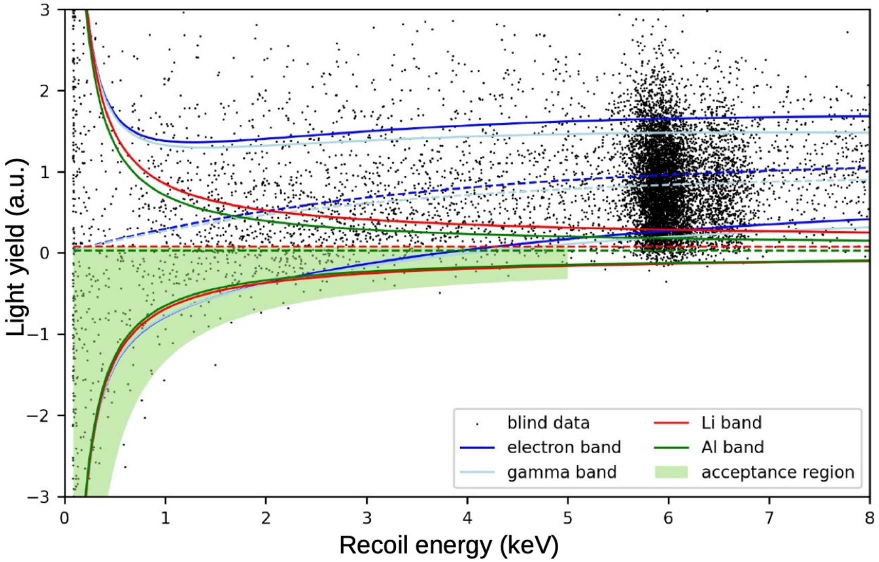
Exposure: 1.161 kg · days

Nuclear recoil threshold: 83.6 eV

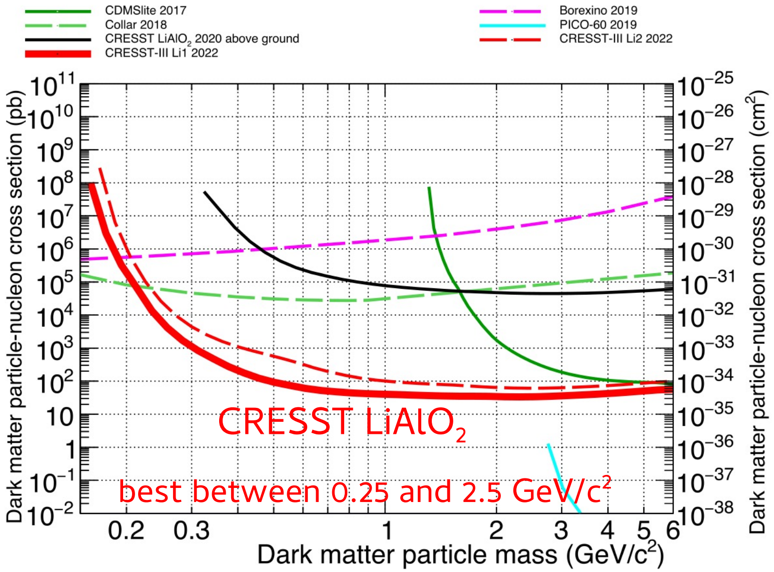
$$\sigma_0^{SD} \propto \mu_N^2 \cdot \frac{J_N + 1}{J_N} \cdot [a_p \cdot \langle S^p \rangle + a_n \cdot \langle S^n \rangle]^2$$

Isotopes sensitive to SD interactions:

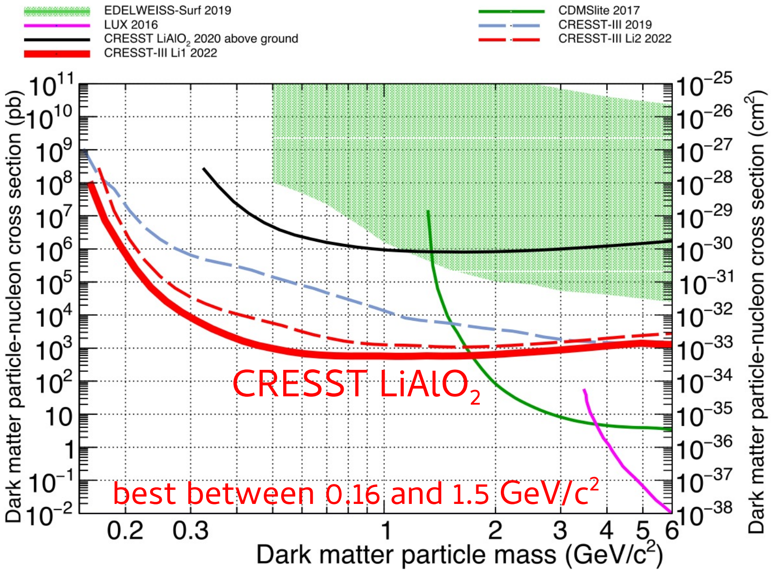
Isotope	$\langle S_p \rangle$	$\langle S_n \rangle$
^{6}Li	0.472	0.472
^{7}Li	0.497	---
^{27}Al	0.343	0.0296



Proton



Neutron



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

New material: **diamond crystal** operated as a cryogenic detector showed a high potential for sub-GeV DM search.

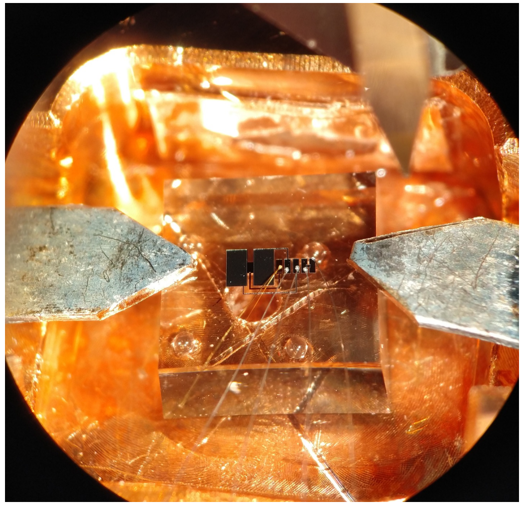
Eur. Phys. J. C (2022) 82:851 / arXiv:2203.11999

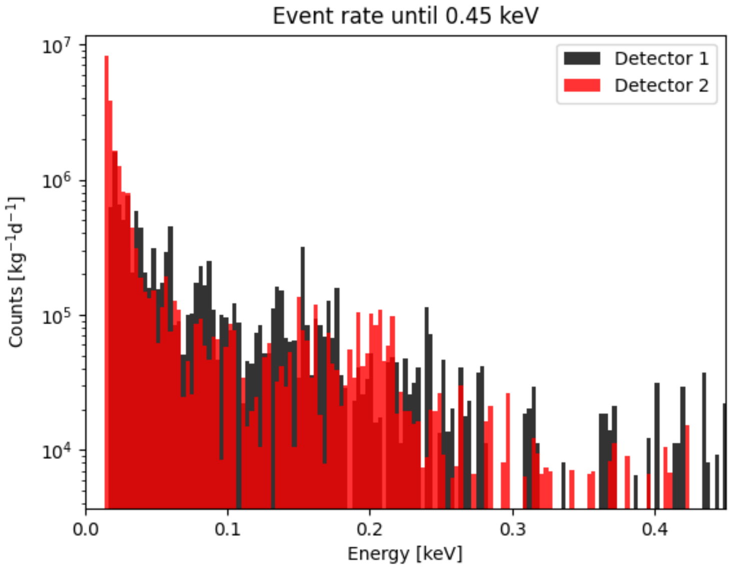
Diamond detector: 0.175 g

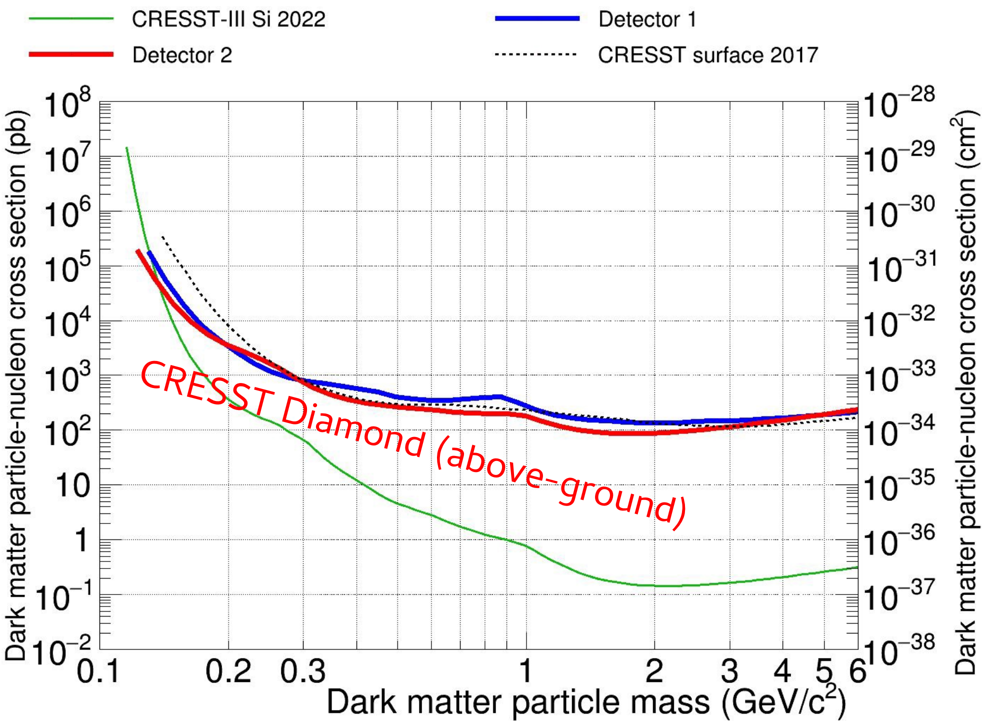
37 h of stable data **above-ground**

Exposure: 0.27 g · days

Nuclear recoil threshold: **16.8 eV**







Why diamond?

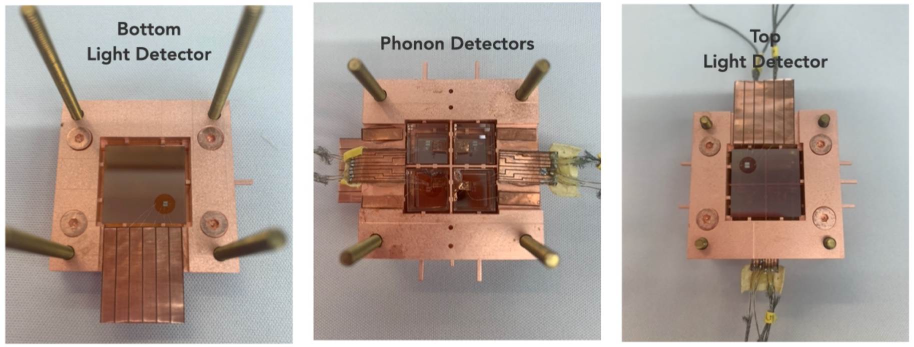
- High Debye temperature
- Light nucleus

Poster: "A low-threshold diamond cryogenic detector for sub-GeV Dark Matter searches" by Anna Bertolini

New detector module designs to study the LEE origin

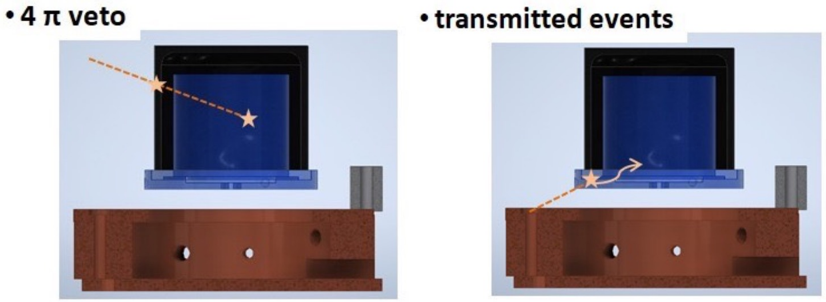
Cm³ module (4 cubes, 2 light detectors):

- maximize sensitivity to dark matter recoils
- novel stress-free holding structure



MiniBeaker module :

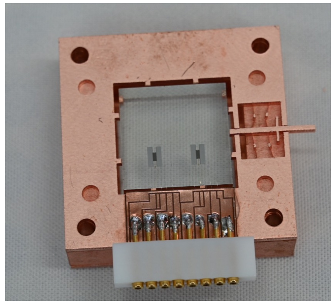
- instrumented Si beaker -> 4π veto
- active holders -> discriminate events transmitted through the holding structure



Double TES module:

- novel stress-free holding structure
- discriminate events in the absorber from events in the TES films
- TES-crystal interfaces studies

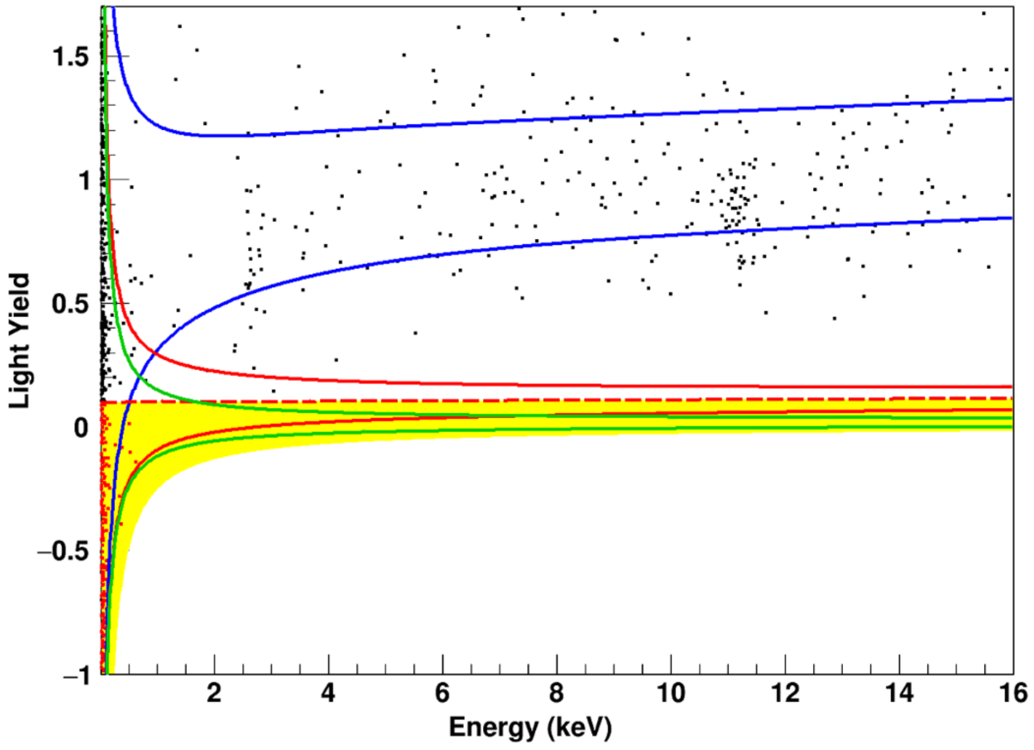
Talk at the Excess workshop last Saturday by Francesca Pucci

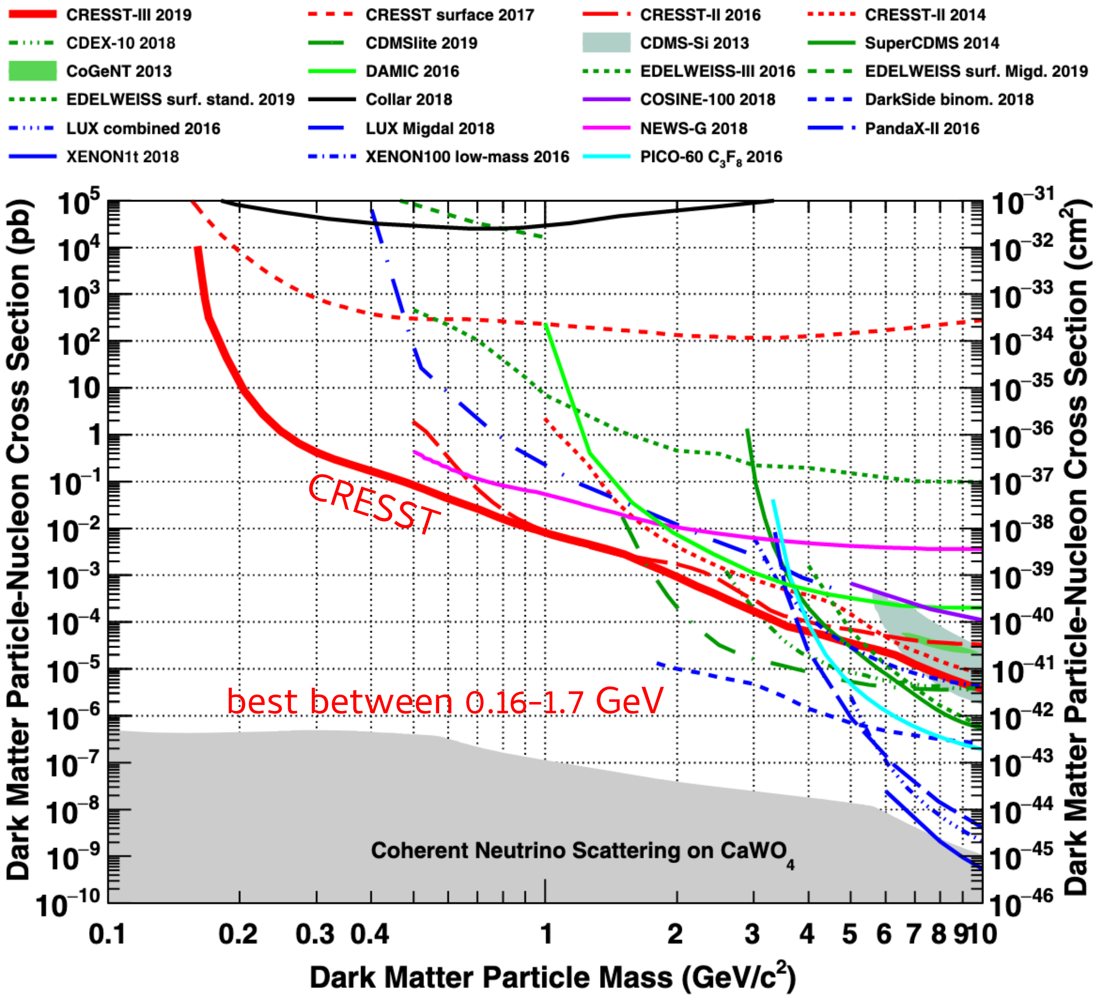


First results from CRESST-III: leading limit for sub-GeV DM with a **30 eV** energy threshold detector.

Detector A (Run34) – 23.6 g CaWO4
Data taking period Oct 2016 – Jan 2018

Exposure 5.698 kg · days
Energy threshold **30.1 eV**





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