Latest Results and Future Directions of CRESST-III

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The CRESST collaboration

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

Cryogenic **R**are **E**vent **S**earch with
Superconducting **T**hermometers

Is a **direct detection of Dark Matter** experiment

8 Institutions
58 Members

CRESST located at LNGS (Laboratori Nazionali del Gran Sasso) in Italy

<u>CRESST detector :</u>

- Cryogenic scintillating calorimeter
- Target material: $CaWO_4$
- Read out channels: Phonon and Scintillation light

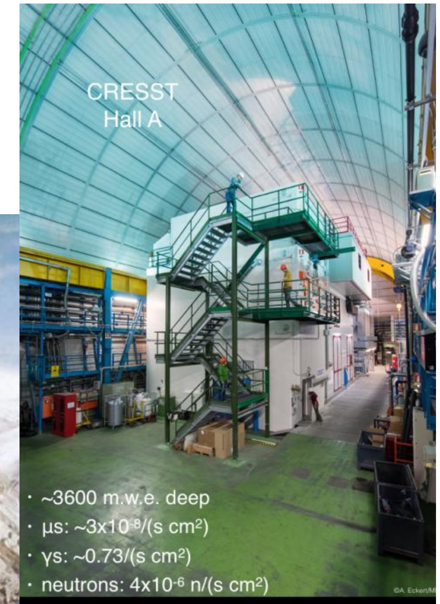
CRESST-III Phase 1 (Low threshold)

- 10 detector modules

CRESST-III Phase 2 (LEE investigation)

- Run1 : 10 modified detector modules
- Run2 : novel detector design

CRESST HUT at LNGS

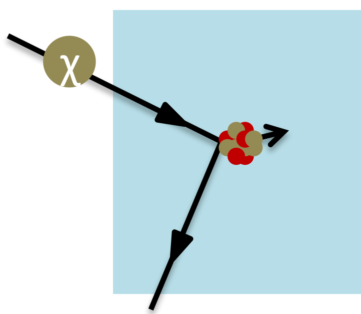


Towards low mass dark matter sensitivity

The signature of dark matter in a direct detection experiment consists of a recoil spectrum of single scattering events.

$$\frac{dR}{dE}(E,t) = \boxed{\frac{\sigma_0}{m_\chi}} \cdot F^2 \cdot \frac{\rho_0}{2\mu_A^2} \int_{v_{min}}^{v_{esc}} \frac{f(\mathbf{v},t)}{v} d^3v$$

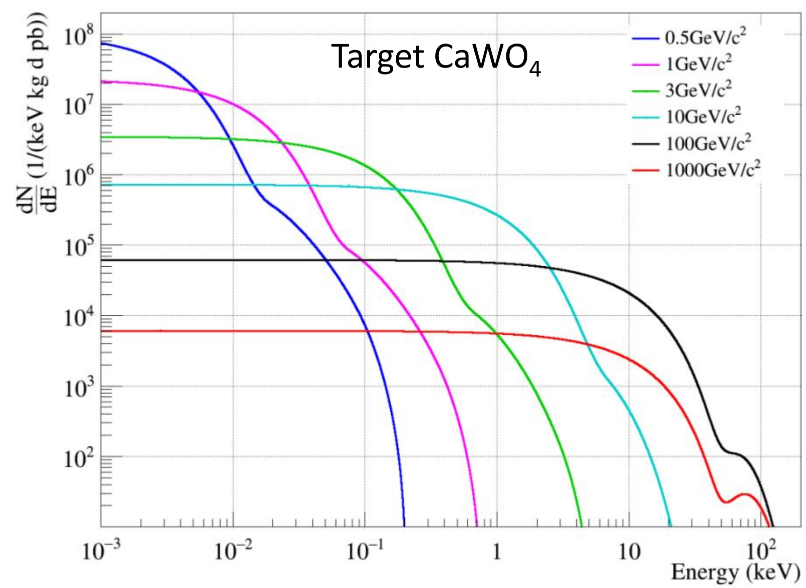
Dark matter particles scatter
- off nuclei
- elastically
- coherently: ~A^2
- (spin-independent)



- ρ_0 : local DM density
- σ_0 : cross section at 0 momentum transfer
- m_χ : DM particle mass
- μ_A : reduced mass
- F : nuclear form factor
- $\int_{v_{min}}^{v_{esc}} \frac{f(\mathbf{v},t)}{v} d^3v$ Integral of the velocity distribution
- v_{min} : minimal velocity to produce a recoil of energy E

For a given cross-section:
- The rate increases exponentially towards lower energy
- End point of the spectrum decreases for lower DM particle mass

Expected nuclear recoil spectra

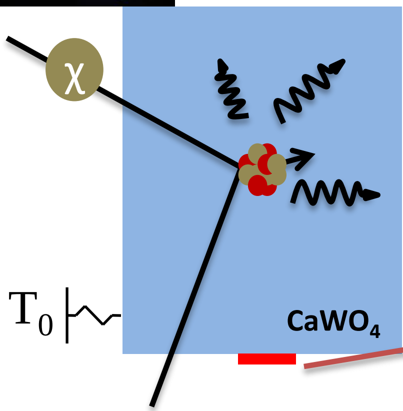


Lower threshold -> better sensitivity

CRESST has the best nuclear recoil threshold in the field

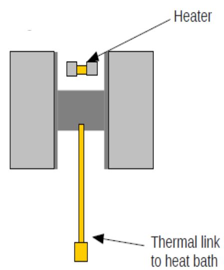
Cryogenic calorimeter detectors

- Cryogenic detector $T_0 \approx 10mK$

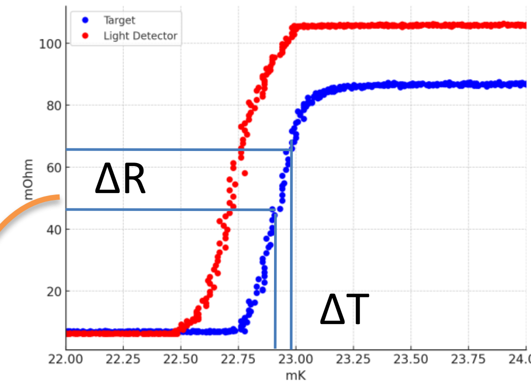


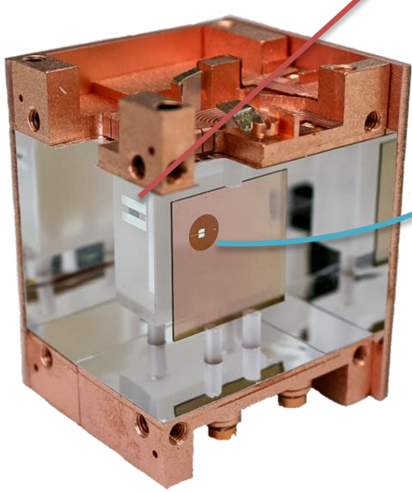
- An energy deposit in the target leads to a proportional temperature rise

$$\Delta T = \frac{\Delta E}{C} \cdot e^{\frac{G}{C}t}$$



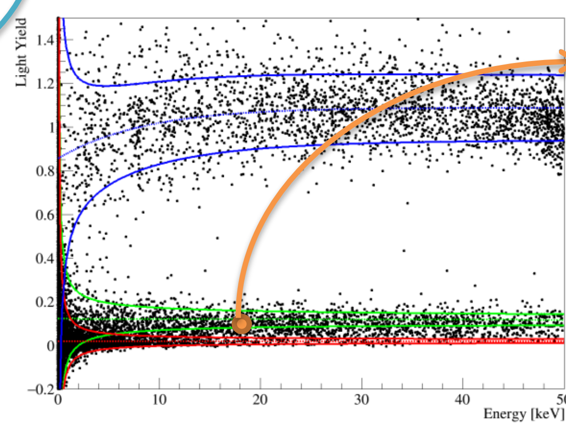
The temperature readout is made with a tungsten transition edge sensor

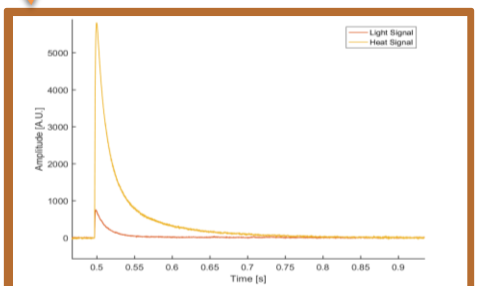




Light detector silicon on sapphire

Neutron calibration data





Light yield characteristic of the type of particle
→ **Particle discrimination**

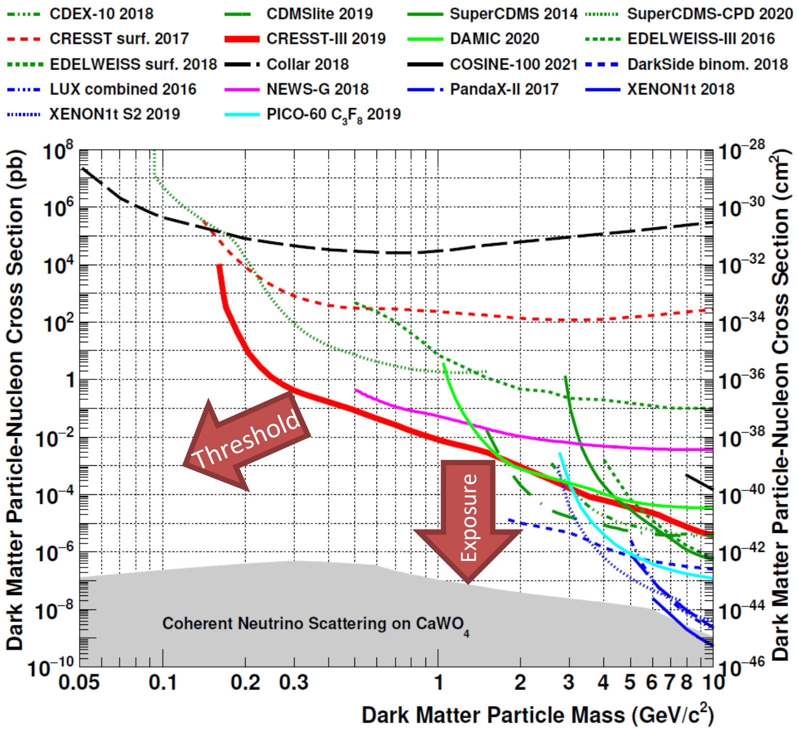
CRESST-III Phase 1 (Low threshold) - 2019

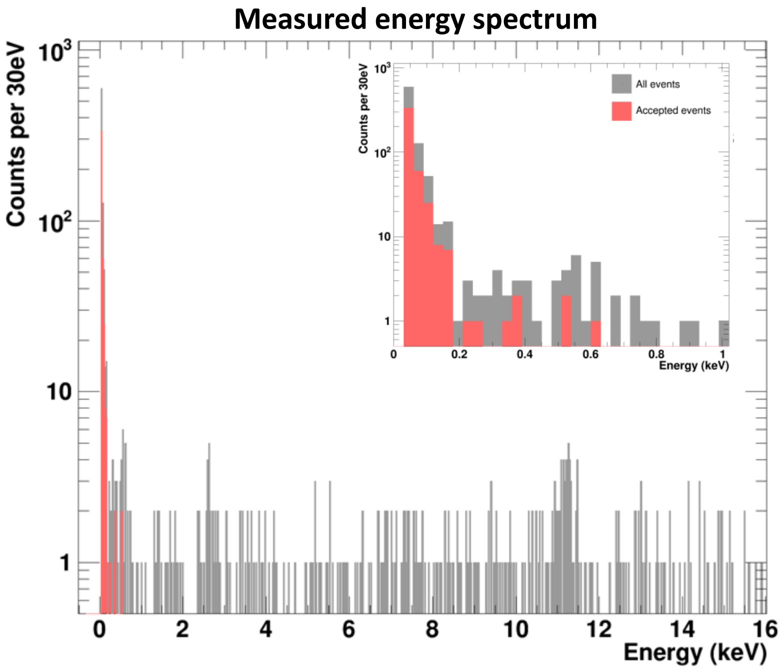
Latest result standard scenario

Measured background below ~300eV with a massive calorimeter for the first time

- **Data taking period:** 11/2016 to 02/2018
- **Detector mass:** 24 g
- **Total exposure:** 5.7 kg day
- **Analysis Threshold:** 30.1 eV

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





Leading sensitivity between 0.16-1.7 GeV

Unknown background at low energy

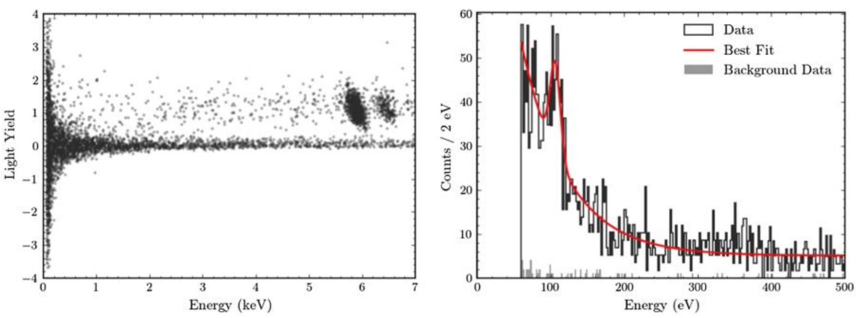
Exponential increase in detected events rate for energies below 200eV (low energy excess)

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

To further improve sensitivity to DM, and access to this part of the parameter space it is important to understand the LEE.

In-depth study of detector response

➢ **Study of energy calibration at low energy**.



Phys. Rev. D: https://doi.org/10.1103/PhysRevD.108.022005

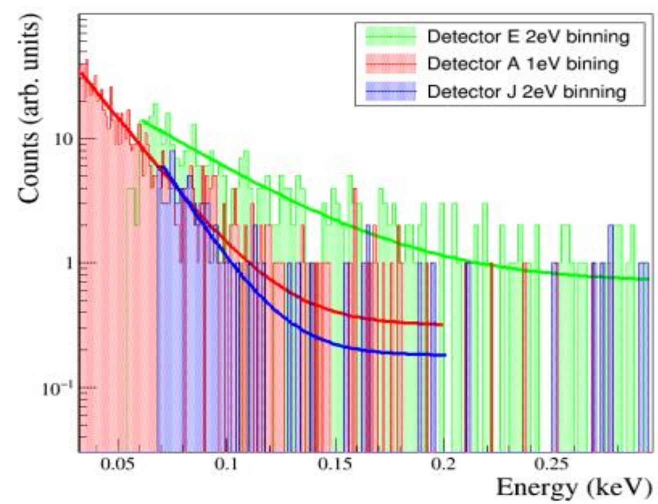
Energy calibration for nuclear recoil

$^{182}W(n,\gamma)^{183}W$

de-excitation with a single γ (6.1MeV)

→ mono-energetic nuclear recoil 112.4eV

➢ **Not Dark Matter**



Different identical detector measure different spectral shape not compatible with a single common source

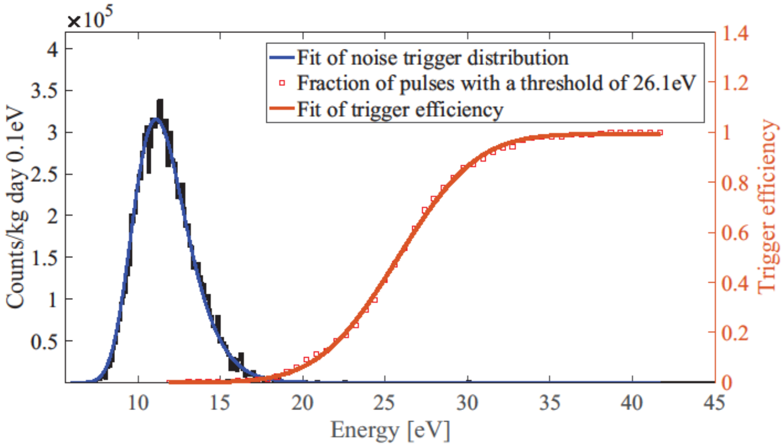
PhD thesis P. Bauer(TUM) - 2020 : https://mediatum.ub.tum.de/node?id=1543574

➢ **Rigorous threshold analysis**:

threshold determined by accepted noise trigger rate

50% trigger efficiency **@threshold of 26.1 eV**

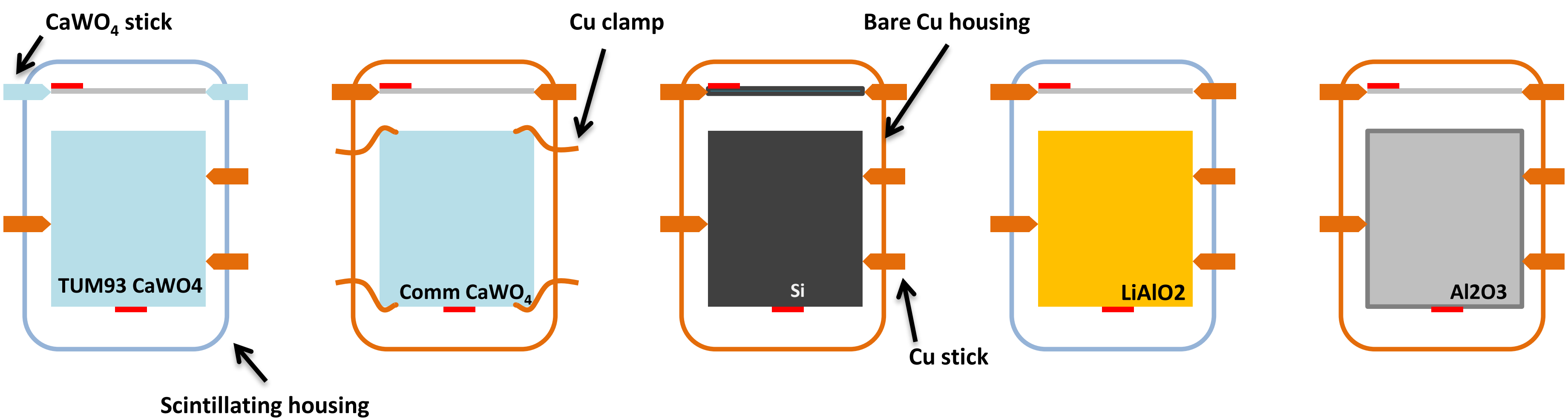
Analysis Threshold: 30.1 eV -> 1 noise event/(kg day)



[J Low Temp Phys. https://doi.org/10.1007/s10909-018-1948-6]

CRESST-III Phase 2 (LEE investigation)

Multiple design modifications were applied in the followed data-taking campaign to identify the source of the LEE background



- Material dependence
  - different target material
- Stress induced by holding
  - two holding structure
- Internal stress
  - two crystal suppliers (different internal stress)
- Scintillation light
  - no scintillating material
- Detector geometry
  - analysis of LD as target

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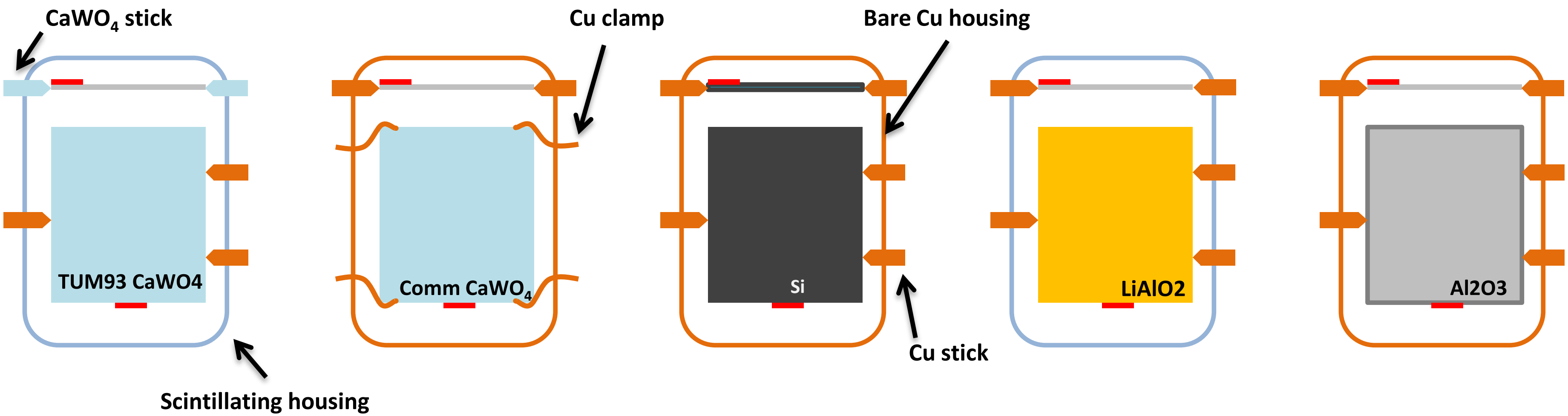
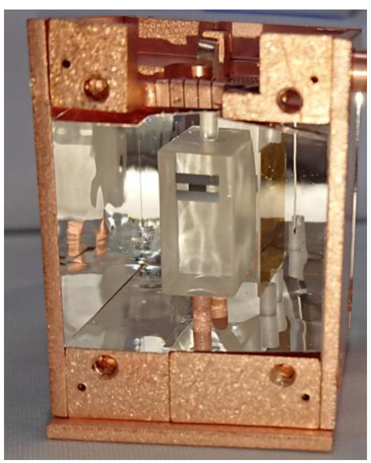
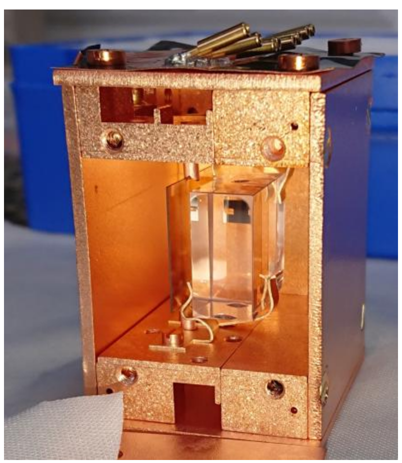
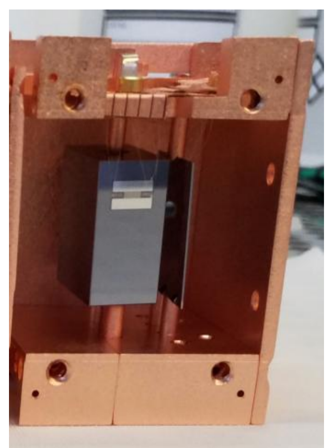
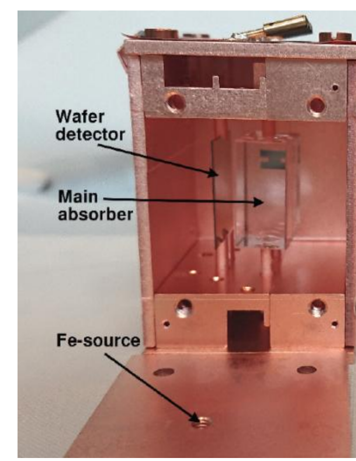




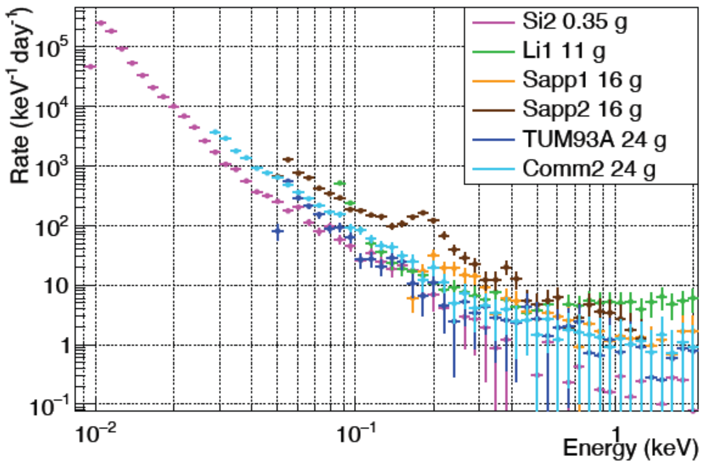


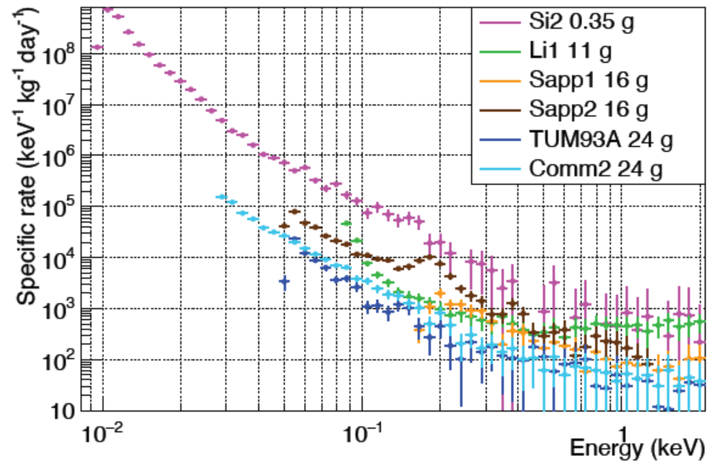




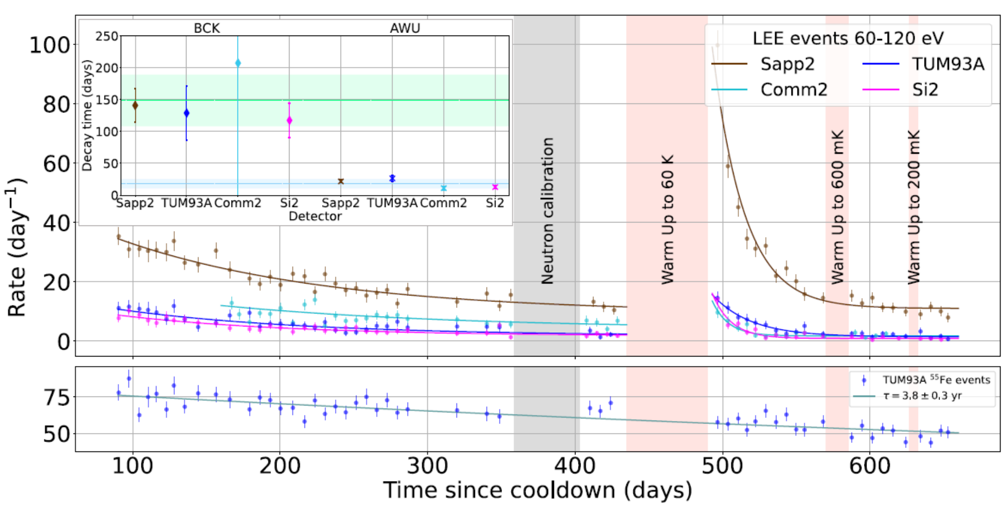
CRESST-III Phase 2 (LEE investigation)

Comparison of rate measured with different detectors





None of the modifications had a significant impact on the LEE



exponential decay in the LEE rate

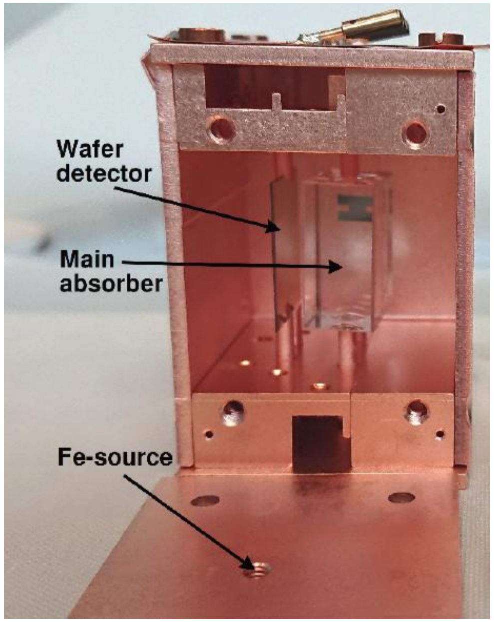
We select a common energy range from 60 eV to 120 eV

Two decay constant:
$\tau_1 = 18 \pm 7$ (fast)
$\tau_2 = 149 \pm 40$ (slow)

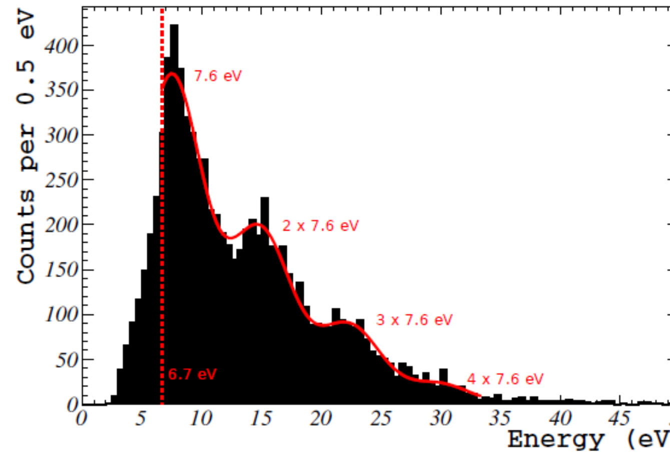
The rate “resets” after warm-up cycles

[https://scipost.org/10.21468/SciPostPhysProc.12.013]

CRESST-III Phase 2 RESULTS - Sapphire

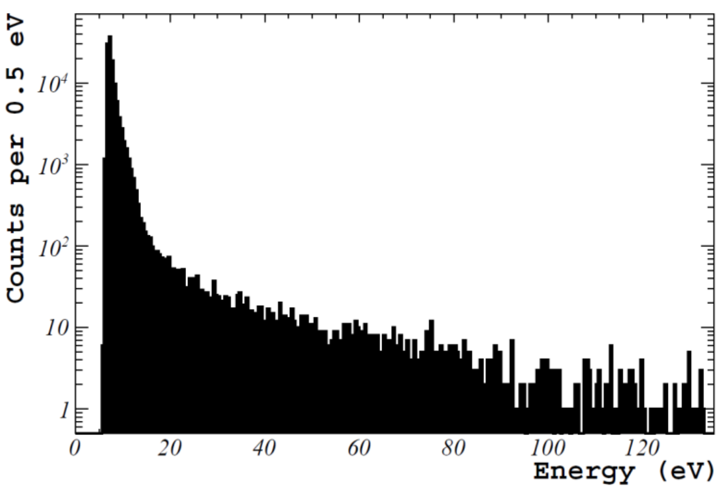


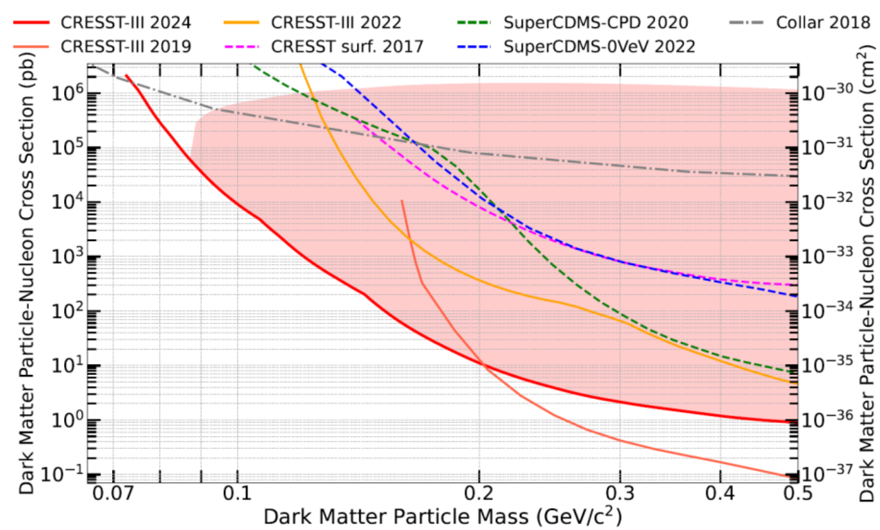
We observe vacuum ultra violet (VUV) luminescence photons (7.6eV) from a nearby Al_2O_3 crystal → Precise calibration at threshold



Al_2O_3 wafer detector

- **Data period:** 11/2020 to 08/2021
- **Detector mass:** 0.6 g
- **Total exposure:** 0.14 kg day
- **Analysis Threshold:** 6.7 eV





Submitted PRD : e-Print: [2405.06527]

CRESST-III Phase 2 RESULTS - Lithium Aluminate

$LiAlO_2$ detector

- **Data taking period:** 11/2020 to 08/2021
- **Detector mass:** 10.48 g
- **Total exposure:** 1.161 kg days
- **Analysis Threshold:** 85.71 eV

Expected rate for spin-dependent interaction

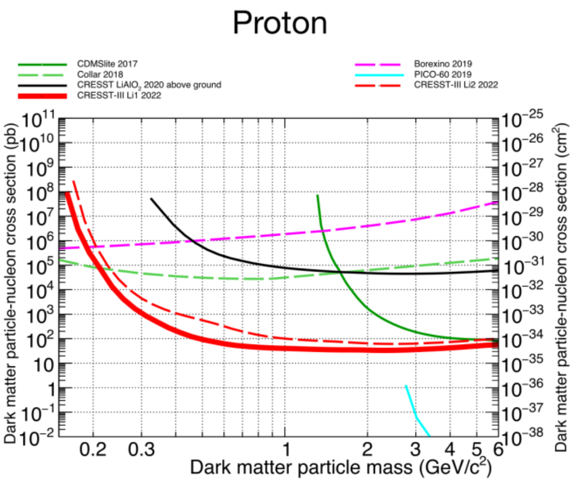
$$\frac{dR}{dE_R} = \frac{2\rho_0}{m_\chi}\sigma_{p/n}^{SD}\sum_{i,T} f_{i,T}\left(\frac{J_{i,T}+1}{3J_{i,T}}\right)\cdot\left(\frac{\langle S_{p/n,i,T}\rangle^2}{\mu_{p/n}^2}\right)\eta(v_{min})$$

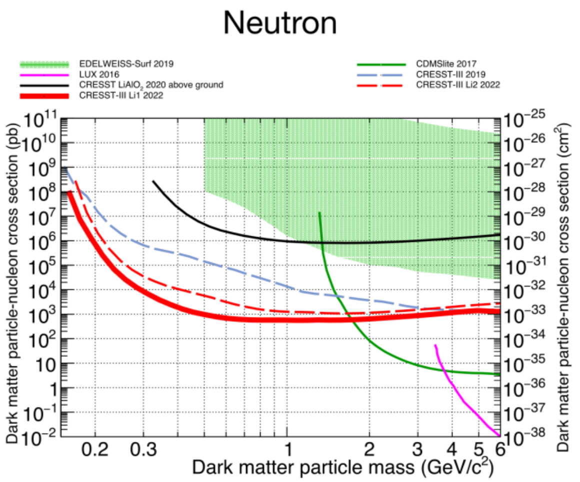
^{6}Li (7,5%) and ^{7}Li (92,5%)

Ideal element for probing SD DM interactions

‹ Sn › = ‹ Sp › = 0.472 for ^{6}Li,
‹ Sp › = 0.497 for ^{7}Li
‹ Sp › = 0.343 for ^{27}Al

DOI: 10.1140/epjc/s10052-022-10140-3





proton: leading sensitivity for mass range between 0.25 and 2.5 GeV/c2
neutron: leading sensitivity for mass range between 0.16 and 1.5 GeV/c2.

DOI:https://doi.org/10.1103/PhysRevD.106.092008

What next?

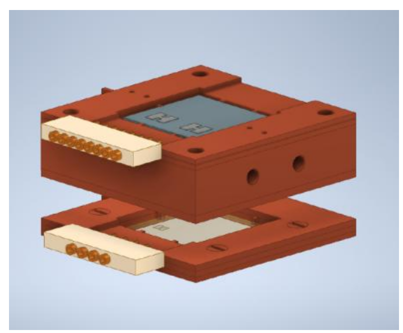
<u>What do we have learned from this long investigation campaign?</u>

- Rate decays over time
- The rate “resets” after warm-up cycles
- It is not external radioactivity
- different internal/external stress does not reflect in the measured excess
- Excess is not due to passive scintillating parts
- Similar rate shows up in all detector of the same material regardless difference in mass, surface and TES dimension

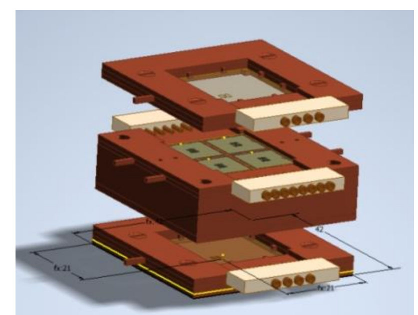
Detector development for the CRESST experiment
JLTP - e-Print: 2311.07318

<u>Development of 3 new detector designs</u>

4π veto, sensitive to holder transmitted events



Stress free, sensitive to TES events origin

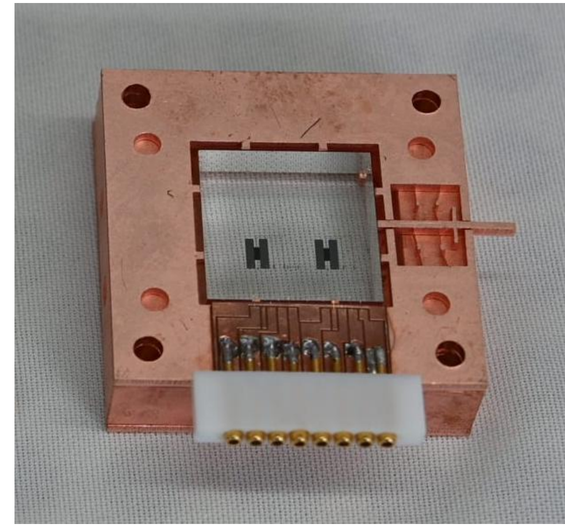


Stress free detector, size of the target is optimized for DM sensitivity, suited for scaling up

CRESST-III Phase 2 – New detectors

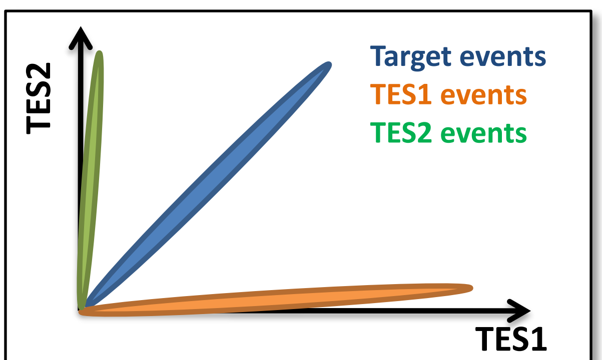
Novel detector module designs to study the low energy events

- Stress free
- Two TES
- No scintillating parts
- Only copper in the line of sight with the absorber

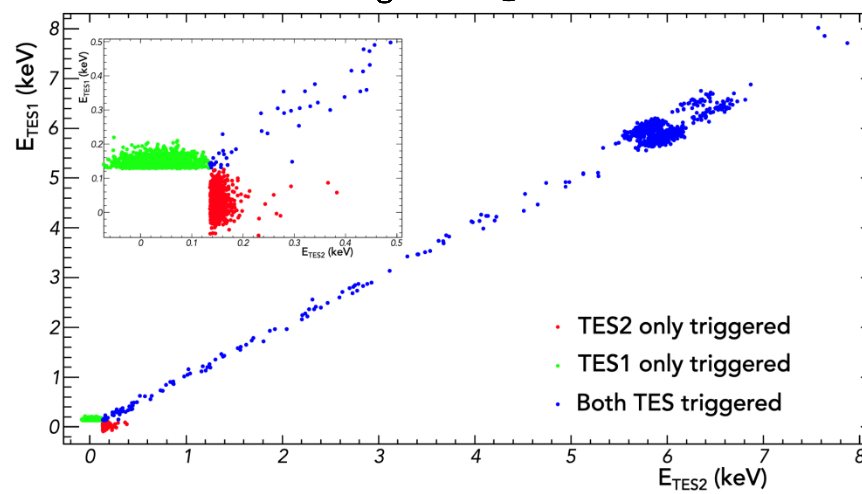


Goal: Measure the excess in coincidence within the two sensors

- Test electronic sources
- Test TES induced events
- Events induced by mismatch of sensor/absorber differential thermal contraction

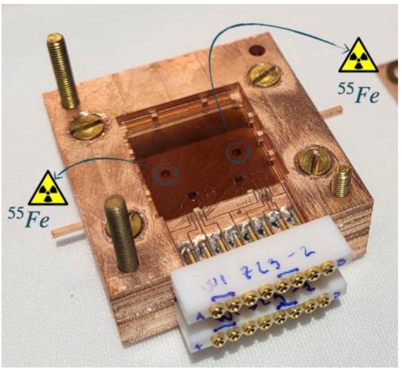


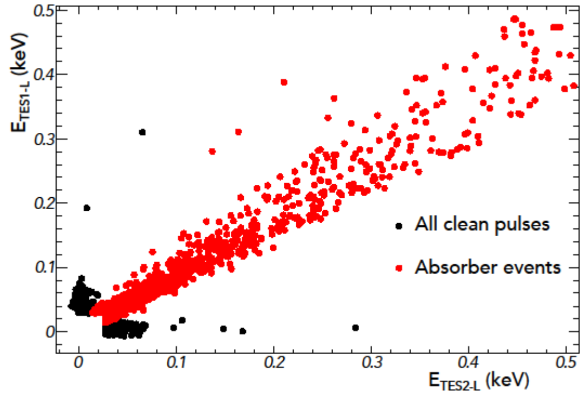
test aboveground @ MPP Munich

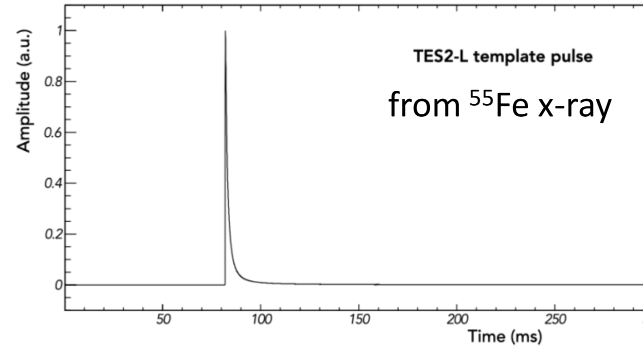


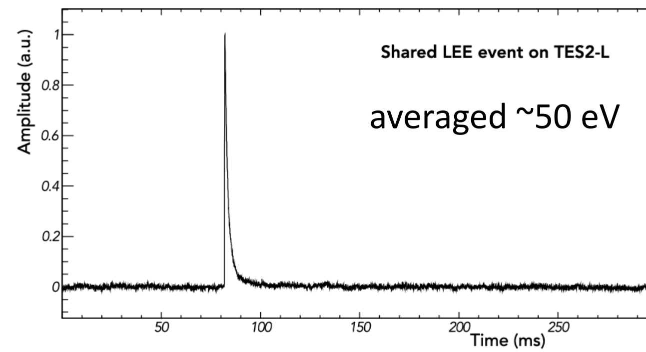
CRESST-III Phase 2 – New detectors

To access to lower energies we developed a double sensor onto sapphire wafers









From test above ground:

- TES related events are 1 component of the excess
- Rise in rate towards low energy for shared events
- Rate decays with a compatible fast decay constant compared to the one measured in CRESST

Submitted epjc: e-Print: 2404.02607

Current data taking:

5X $CaWO_4$ detectors with double sensor paired to standard light detector
4X Silicon on sapphire wafer with double sensor
1X Beaker module

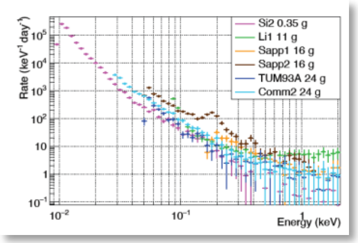
Conclusion and perspective

CRESST has the best nuclear recoil threshold with massive calorimeters

- Leading densitivity for dark matter masses 0.08-1.65 GeV

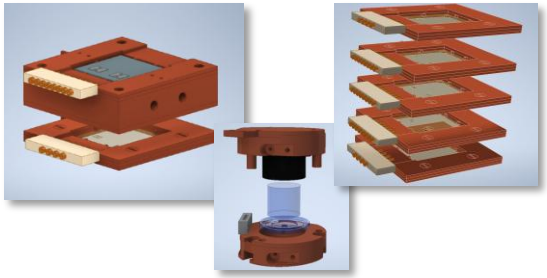
Low energy excess strongly limits the sensitivity of the experiment

- Detailed study and modeling of the low energy excess with a variety of detector disfavors particle, intrinsic stress or external stress origins.



Novel detectors have been designed and are currently in data taking

- 5X $CaWO_4$ detectors with double sensor paired to standard LD
- 4X Silicon on sapphire wafer with double sensor
- 1X Beaker module



Dark matter results

- Exploiting $LiAlO_2$ improves the existing limits for **spin-dependent interactions.**
- Using low-threshold wafer detectors of Al_2O_3 as targets extends reach to dark matter masses of 80 MeV/c^2 for spin-independent interaction.