Cryogenic **Rare Event Search**
with Superconducting Thermometers

The low energy excess in CRESST-III

Excess Workshop Vienna 2023

Dominik Fuchs

Sarah Kuckuk
Vanessa Zema

for the CRESST collaboration

August 26, 2023

Outline

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

MAX PLANCK INSTITUTE FOR PHYSICS

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

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UNIVERSITAS COMENIANA BRATISLAVENSIS MCMXIX

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HEPHY
INSTITUTE OF HIGH ENERGY PHYSICS

TECHNISCHE UNIVERSITÄT WIEN

UNIVERSITY OF OXFORD

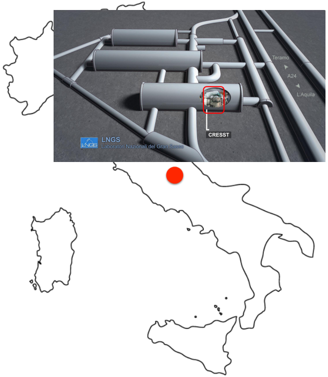
The CRESST Experiment

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

Goal: direct detection of dark matter particles via their scattering off target nuclei in cryogenic detectors, operated at $\sim$15 mK

The CRESST Experiment

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

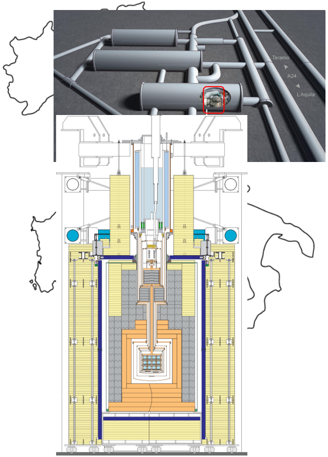


Goal: direct detection of dark matter particles via their scattering off target nuclei in cryogenic detectors, operated at $\sim$15 mK

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

The CRESST Experiment

Cryogenic Rare Event Search with Superconducting Thermometers



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Detector Modules

Standard Design

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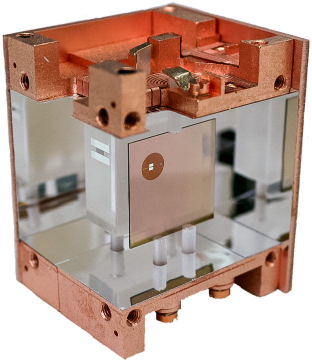
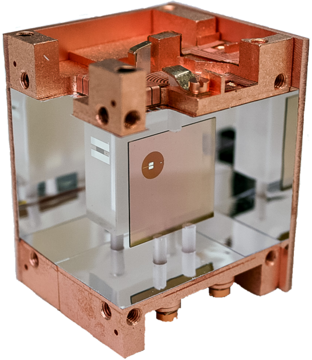


Detector Modules

Standard Design

- $(20x20x10)mm^3$ target crystals
- scintillating $CaWO_4$
- W-TES sensor
- $E_{thr} \leq 100eV$ (nuclear recoils)



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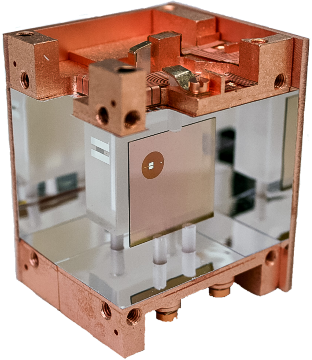

Light detector:

- Silicon-on-Sapphire $(20x20x0.4)mm^3$ wafer
- Particle discrimination

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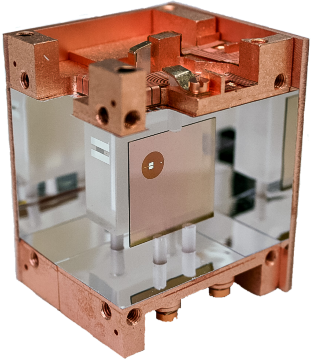


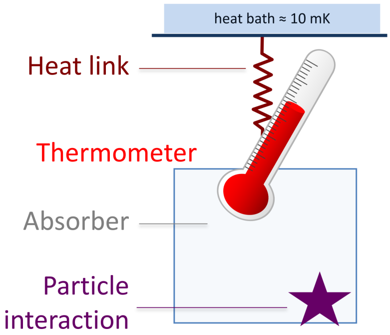
Light detector:

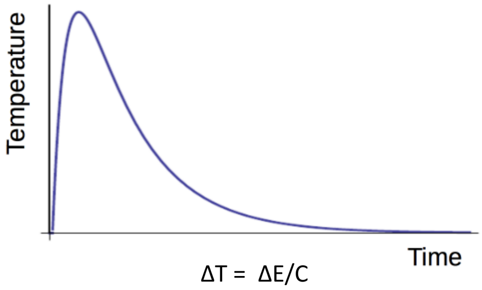
- Silicon-on-Sapphire $(20\text{x}20\text{x}0.4)\text{mm}^3$ wafer
- Particle discrimination

Housing & Holding:

- Scintillating reflective foil (Vikuiti™)
- (Instrumented) $CaWO_4$ holding sticks

Cryogenic Calorimeter

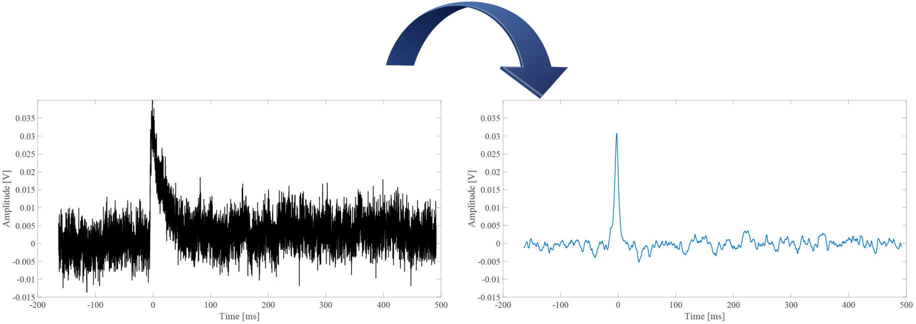




Data Analysis

Continuous DAQ + Optimum Filter

- Dead-time free DAQ: detector output is continuously recorded
- Maximize Signal-to-Noise ratio with Optimum Filter



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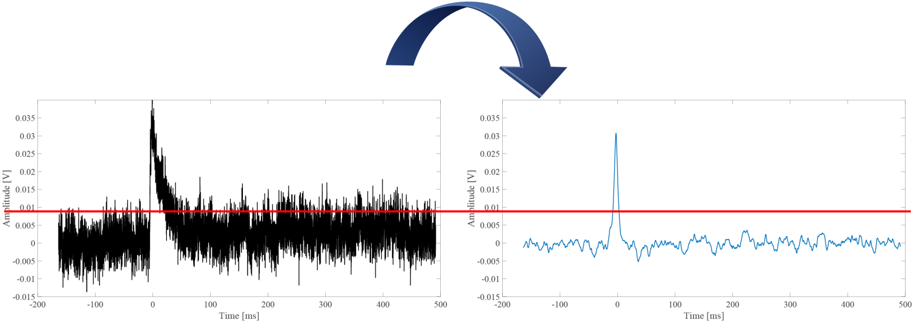

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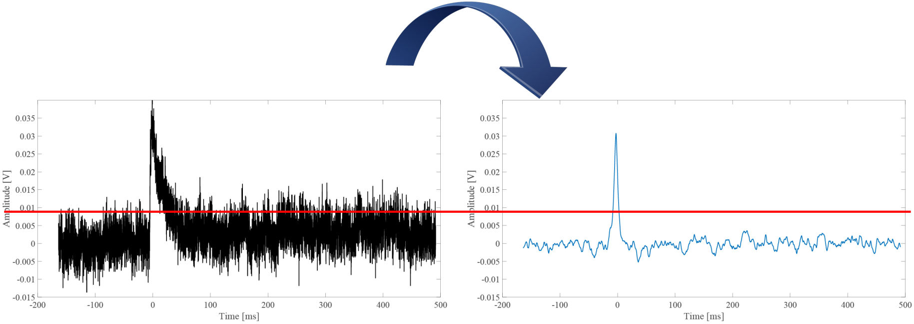
- Define threshold by choosing accepted number of noise triggers ($1\ \mathrm{kg}^{-1}\ \mathrm{d}^{-1}$)
- Select Events above threshold



Data Analysis

Event Selection and Energy Calibration

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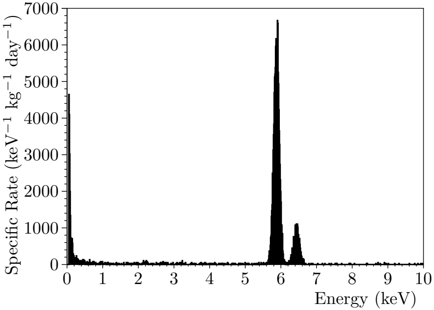
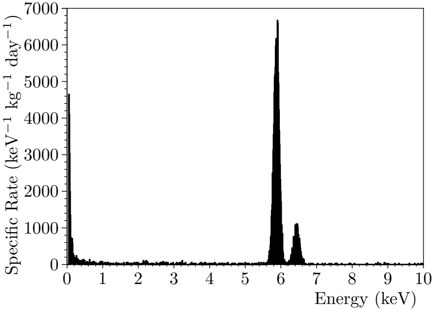
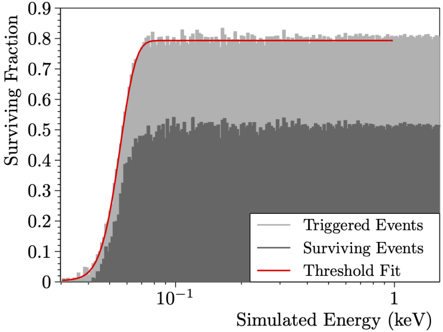


Data Analysis

Event Selection and Energy Calibration

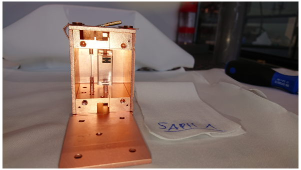
- Apply data selection criteria, designed to keep only valid pulses
- Calibration of cleaned data with radioactive source
- Perform simulation to calculate survival probabilities after trigger and selection criteria

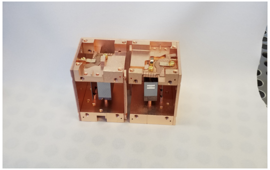


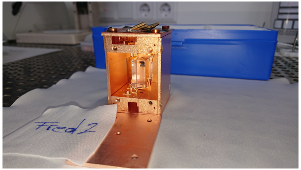


Outline

List of Modified Detector Modules



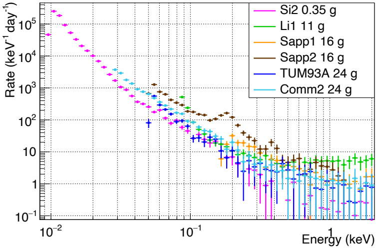


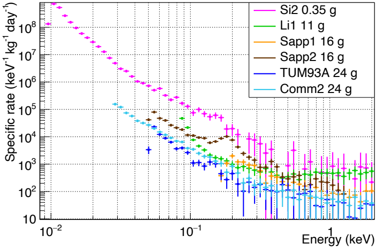


Module	Material	Holding	Foil	Mass (g)	Threshold (eV)
Si2	Si	Cu	No	0.35	10
Sapp1	Al_2O_3	Cu	No	16	157
Sapp2	Al_2O_3	Cu	No	16	52
Li1	$LiAlO_2$	Cu	Yes	11	84
TUM93A	$CaWO_4$	2 Cu + 1 $CaWO_4$	Yes	24	54
Comm2	$CaWO_4$	Bronze Clamps	No	24	29

Observations

- LEE present in all detectors
- No significant impact on the presence of the LEE by detector modifications





Latest observations on the low energy excess in CRESST-III

doi: 10.21468/SciPostPhysProc.12.013

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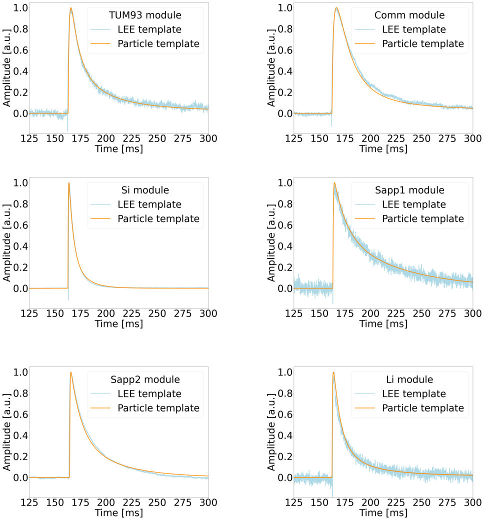

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Observations

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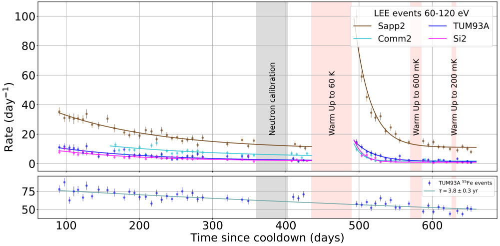
- LEE events have same pulse shape as particle recoil events
- Exponential decay of rate
- Increased rate after warm-up to 60 K
- Faster decay after warm-up to 60 K
- No effect of warm-up to 600 mK and 200 mK



Latest observations on the low energy excess in CRESST-III

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Conclusions

Exluded hypotheses on major contributions:

- Dark matter interactions
- External and intrinsic radioactivity
- Noise triggers and electronic artifacts
- Scintillation light

Latest observations on the low energy excess in CRESST-III
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Possible options under further investigation:

- Intrinsic crystal effects
- Sensor related effects (e.g. from TES film deposition)
- Holding induced stress

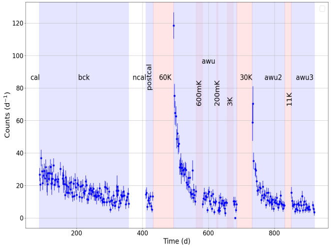
- R & D ongoing

Outline

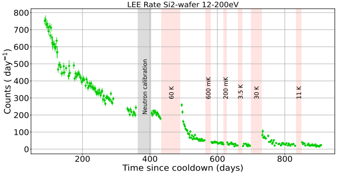
New Data

Warm up tests to temperatures: 3K, 30K, 11K

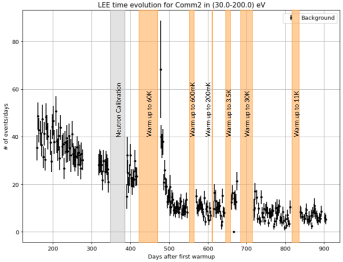
Al_2O_3



Si



$CaWO_4$



Unbinned 2D-likelihood analysis of LEE

Goal:

- Find common empirical model for fitting LEE in energy and time
- Compare model parameters between detectors
- Investigate temperature/time dependence of parameters and rate

Poster at TAUP

"Modeling the Low Energy Excess in CRESST" by Sarah Kuckuk

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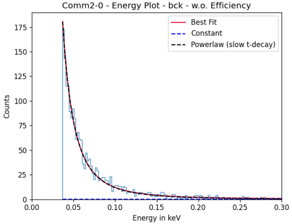
Model:

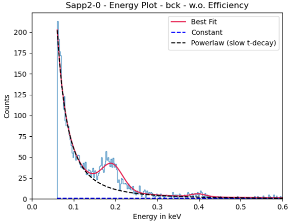
- Energy: Constant + Power law (+ Gauss in some cases)
- Time: Exponential slow decay (τ_s) over entire run + Exponential fast decays (τ_f) after recharged rate ($i = 60K, ..., 11K$ warm up tests)

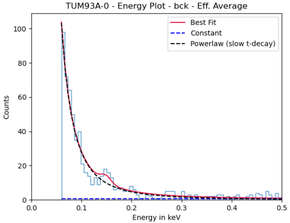
$$\rightarrow R(E,t) = C + E^{-k} \cdot \left(A_s \cdot e^{-t/\tau_s} + \sum_i A_{fi} \cdot e^{-(t-t_i)/\tau_f} \cdot \Theta(t - t_i) \right)$$

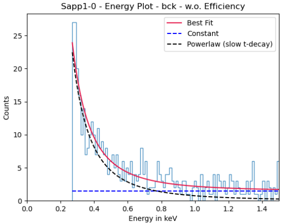
Results

Energy spectrum fits of Comm2, Sapp2, TUM93A, Sapp1:



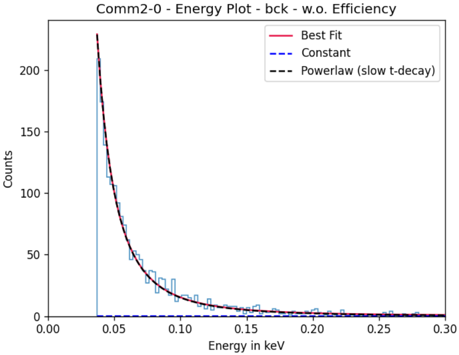




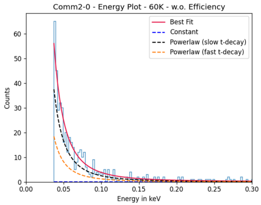


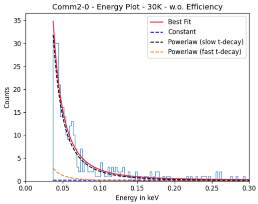
Comm2

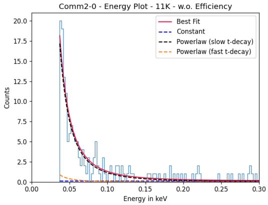
BCK:



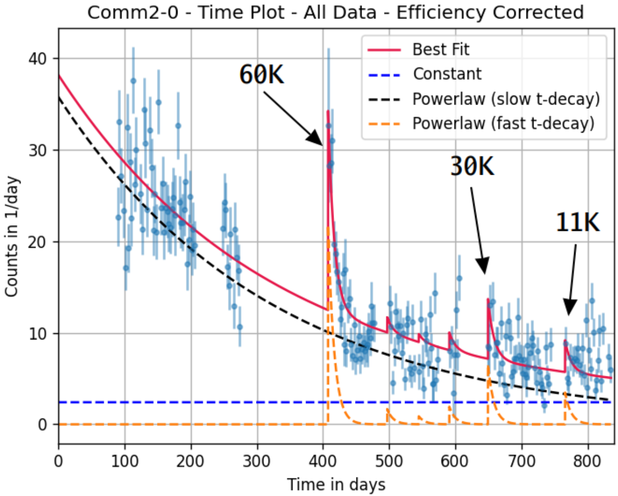
AWU 60K, 30K, 11K:





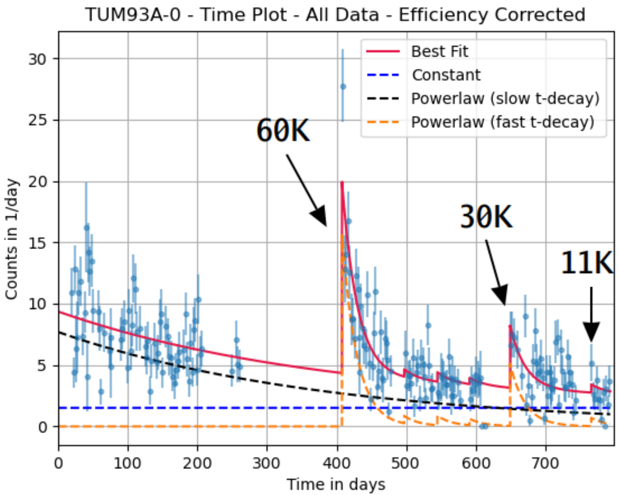


Comm2



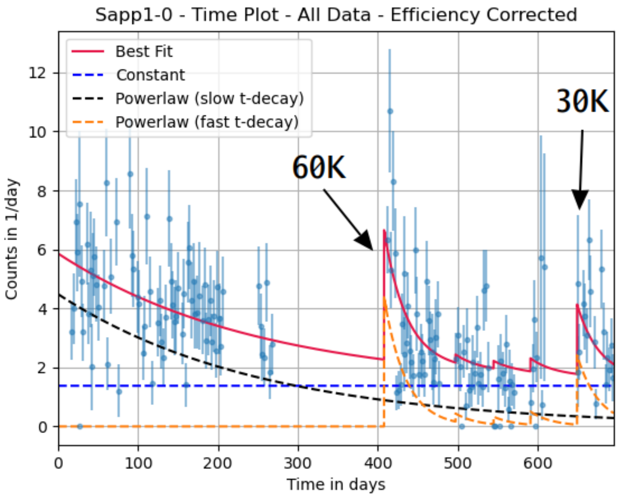
Comm2-0 - Time Plot - All Data - Efficiency Corrected
Best Fit
Constant
Powerlaw (slow t-decay)
Powerlaw (fast t-decay)
60K
30K
11K
Counts in 1/day
Time in days
0
10
20
30
40
0
100
200
300
400
500
600
700
800

TUM93A



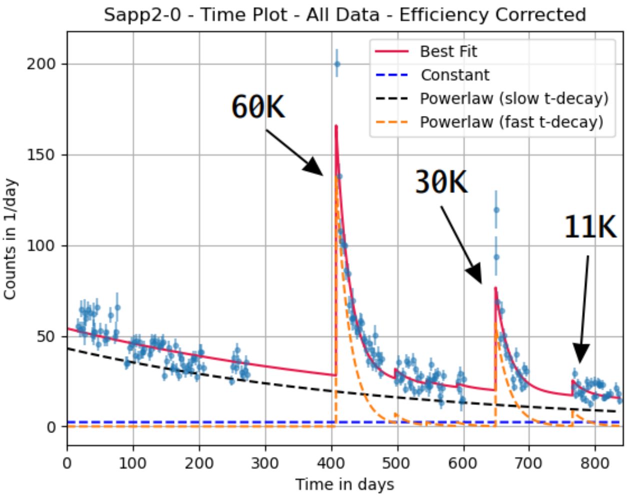
TUM93A-0 - Time Plot - All Data - Efficiency Corrected
Best Fit
Constant
Powerlaw (slow t-decay)
Powerlaw (fast t-decay)
60K
30K
11K
Counts in 1/day
Time in days
0
5
10
15
20
25
30
0
100
200
300
400
500
600
700

Sapp1



Sapp1-0 - Time Plot - All Data - Efficiency Corrected
Best Fit
Constant
Powerlaw (slow t-decay)
Powerlaw (fast t-decay)
60K
30K
Counts in 1/day
Time in days
0
2
4
6
8
10
12
0
100
200
300
400
500
600

Sapp2


Sapp2-0 - Time Plot - All Data - Efficiency Corrected
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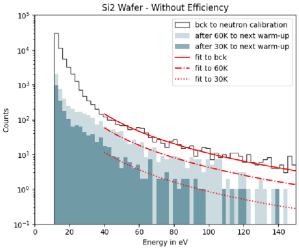
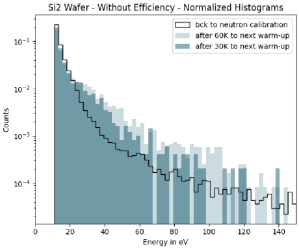
Powerlaw (fast t-decay)
60K
30K
11K
Counts in 1/day
Time in days
0
100
200
300
400
500
600
700
800
0
50
100
150
200

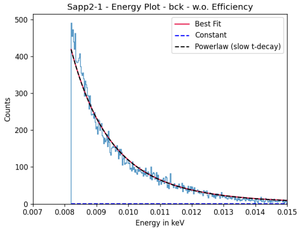
Model not sufficient below $\sim$ 40 eV

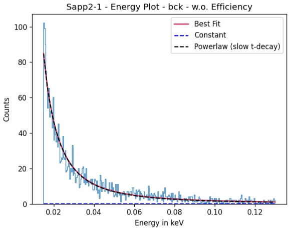




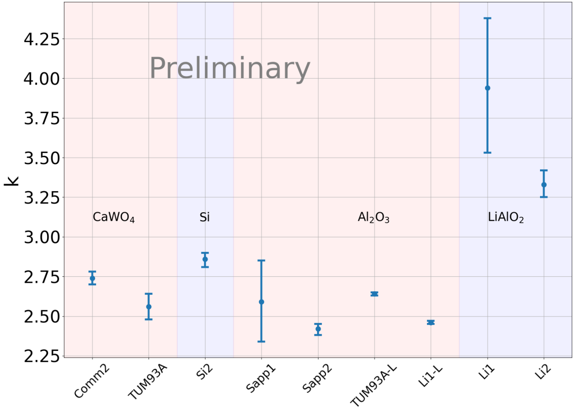
- At least one additional component needed
- Shape of spectrum changes over time

- Two detectors with thresholds of $\sim$ 10 eV



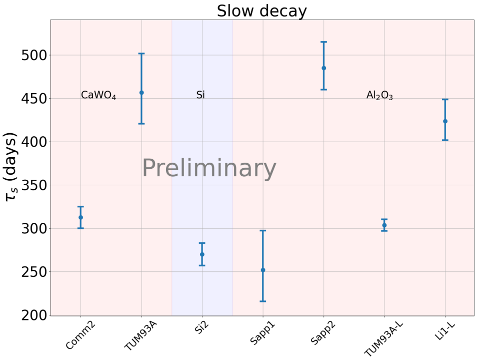


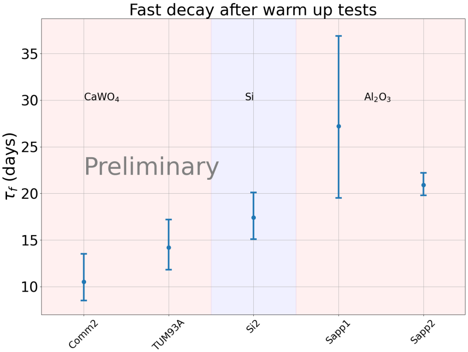
Power law parameters



$$R(E,t) = C + E^{-k} \cdot \left(A_s \cdot e^{-t/\tau_s} + \sum_i A_{fi} \cdot e^{-(t-t_i)/\tau_f} \cdot \Theta(t - t_i) \right)$$

Decay times





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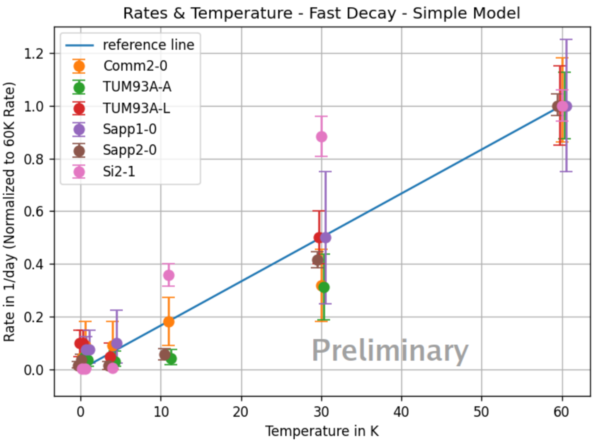
Temperature dependence of the rate



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Outline

Hypothesis:

Possible origin of part of LEE at interface between crystal and TES

caused by mismatch of Thermal Expansion Coefficients (TEC)

TEC:

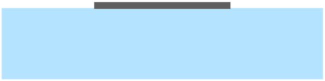
$$\alpha = \frac{1}{L}\frac{dL}{dT} \qquad \text{(Linear thermal expansion)}$$

$$\beta = \frac{1}{V}\frac{dV}{dT} \qquad \text{(Volumetric thermal expansion)}$$

TEC mismatch

Intermediate diffusion barrier of SiO_2 between crystal and TES

T_1



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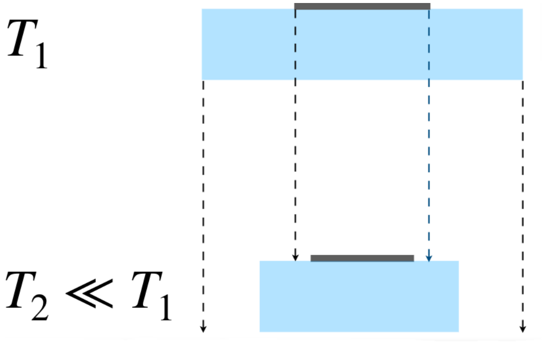

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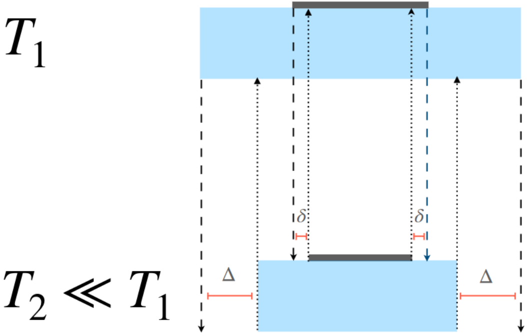
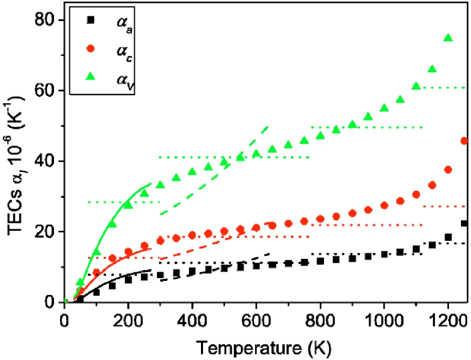
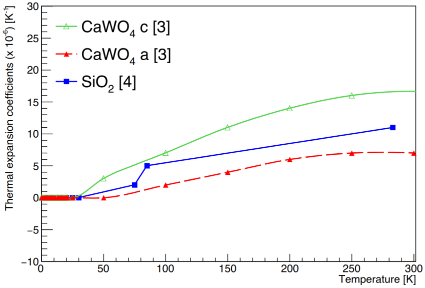


Dependence on Lattice Orientation in $CaWO_4$



Lattice dynamic simulation (2004): PHYSICAL REVIEW B 70, 214306

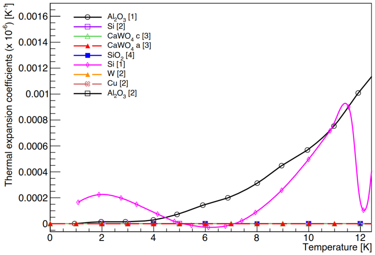
Dependence on Lattice Orientation in $CaWO_4$

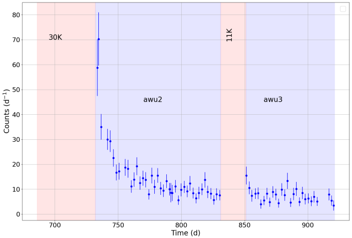


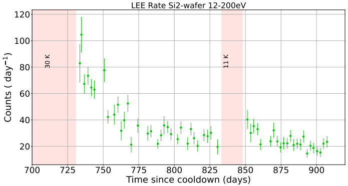
PHYSICAL REVIEW B 70, 214306

- Similar behaviour of $CaWO_4$ and SiO_2 TECs below 30K
- Difference in data at 30K warm up might be caused by lattice orientation
- No/very weak effect expected at 11K warm up

Silicon and Sapphire







[1] https://arxiv.org/abs/0912.0107

[2] Advances in Physics, 29:4, 609-730

[3] PHYSICAL REVIEW B 70, 214306 (2004) + A. Senyshyn simulation (internal)

[4] Volume 4, Issue 1, February 1964, Pages 2-7

[5] International Journal of Thermophysics volume 18, pages 1269-1327 (1997)

Outline

Summary

- Energy spectra can be described by single power law above ~ 40 eV
- Low threshold (~ 10 eV) detectors need at least one additional component in energy
- Decay of energy spectra can be described by two exponential components
- Increase of rate after warm up seems to be function of temperature
- TEC mismatch hypothesis could be explanation for part of the LEE

$\Rightarrow$ Test with **Double-TES** modules $\rightarrow$ **Next Talk!**

Summary

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$\Rightarrow$ Test with **Double-TES** modules $\rightarrow$ **Next Talk!**

Thank you!

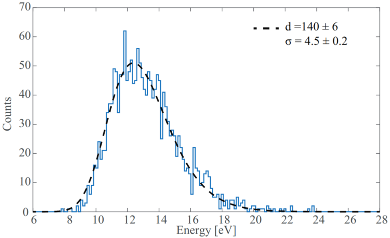
BACKUP

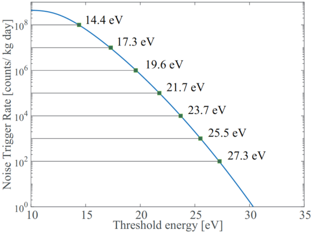
Data Analysis

Threshold determination

- Analytical description of amplitude distribution of filtered empty baselines
- Define threshold choosing accepted number of noise triggers per kgd

$$NTR(x_{thr}) = \frac{1}{t_{win} \cdot m_{det}} \cdot \int_{x_{thr}}^{\infty} P_d(x_{max})$$

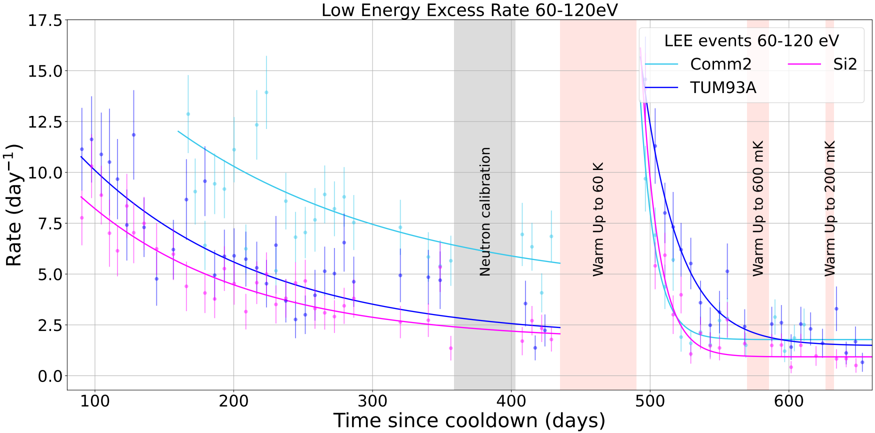




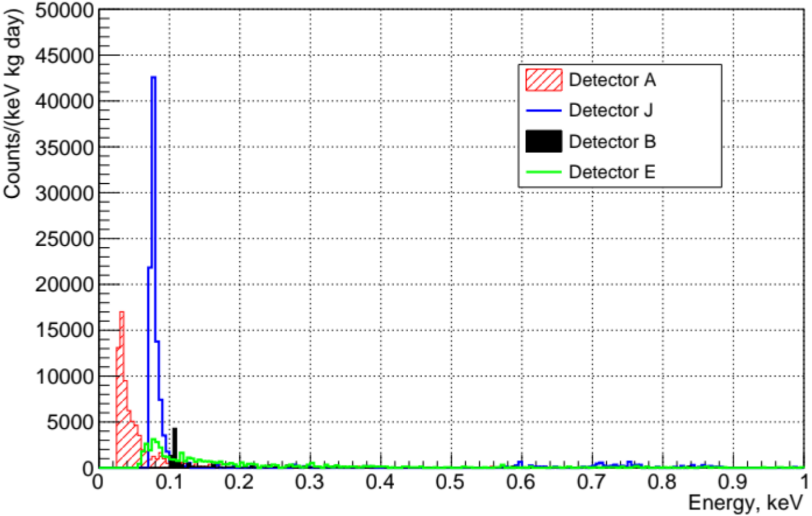
(J Low Temp Phys (2019) | doi.org/10.1007/s10909-018-1948-6)

Time dependence

without Sapp2

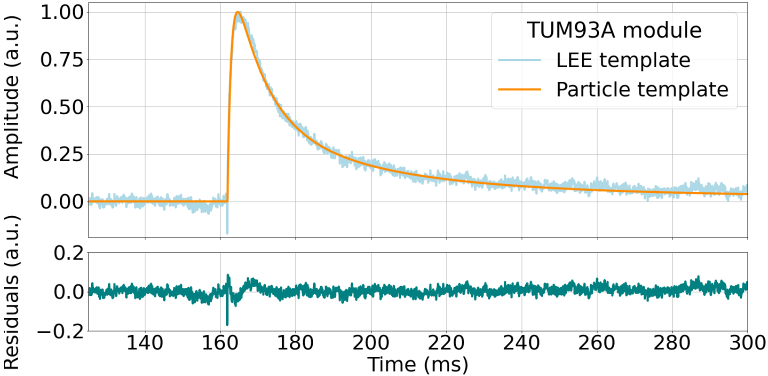


Excess in CRESST-III First Run



LEE vs Particle template

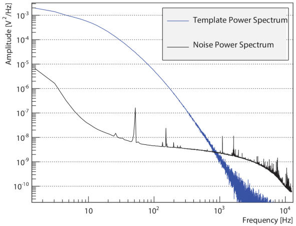
Residuals

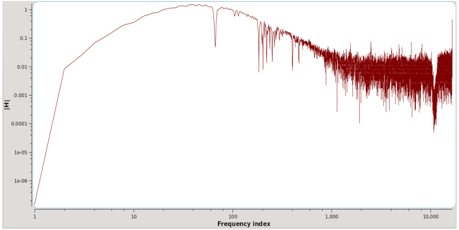


Optimum Filter

- Filter kernel $H(\omega)$: maximize Signal-to-Noise ratio in frequency space:

$$H(\omega) = K \frac{\widehat{s}^*(\omega)}{N(\omega)} e^{-i\omega\tau_M}$$





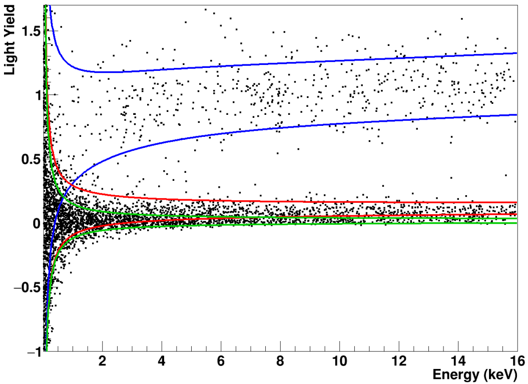
- Convolute real pulse with filter kernel:

$$y_F(t) = \frac{A}{\sqrt{2\pi}} \int_{-\infty}^{\infty} H(\omega)\widehat{s}(\omega)e^{i\omega t}\,\mathrm{d}\omega$$

Neutron Calibration

Light Yield: $\mathrm{LY} = \mathrm{E_L}/\mathrm{E_{Ph}}$

Band Fits QF

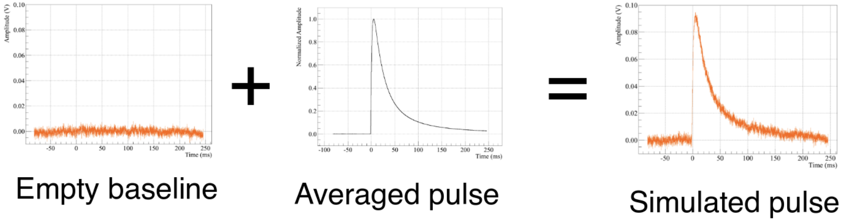


e/γ events

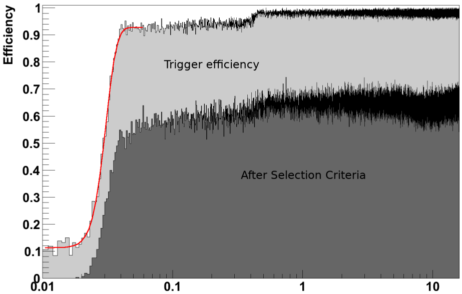
Oxygen nuclear recoils

Tungsten nuclear recoils

Efficiency



Empty baseline
+
Averaged pulse
=
Simulated pulse



Efficiency
Trigger efficiency
After Selection Criteria

Thermal Expansion Coefficient mismatch

Elastic Theory of Solids

$$\alpha = \frac{1}{L}\frac{dL}{dT}$$

$$E = \frac{1}{2}K\,(2\Delta - 2\delta)^2 \sim C_{ij}\,(2\Delta - 2\delta)^3$$

$$F = -kx \rightarrow \sigma = C\,\epsilon$$

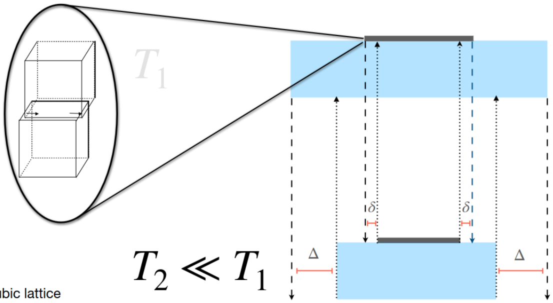
Stress tensor

Double tensor of elastic constants

Strain tensor

$$C_{reduced} = \begin{pmatrix} C_{11} & C_{12} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{11} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{12} & C_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{44} \end{pmatrix}$$

Reduced elastic tensor for a cubic lattice



Thermal Expansion Coefficient mismatch

Elastic Theory of Solids

$$E = \frac{1}{2} K (2\Delta - 2\delta)^2 \sim C_{ij} (2\Delta - 2\delta)^3$$

$$\alpha = \frac{1}{L}\frac{dL}{dT} \rightarrow L(T) = L(T_0)\, e^{\alpha(T)\, T}$$

$$\Delta_{CaWO_4} = L(50\ K) - L(1\ K) \sim O(10^{-6})\ cm$$

$$\Delta_{SiO_2} = L(50\ K) - L(4\ K) \sim O(10^{-7})\ cm$$

$E \sim 10$ MeV