Cryogenic **Rare Event Search** with Superconducting Thermometers

Status and new results of the CRESST Experiment

PATRAS 2022

Dominik Fuchs

August 12, 2022

Outline

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

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

TUM
TECHNISCHE
UNIVERSITÄT
MÜNCHEN

UNIVERSITAS COMENIANA BRATISLAVENSIS · MCMXIX ·

MAX PLANCK INSTITUTE
FOR PHYSICS

EBERHARD KARLS
UNIVERSITÄT
TÜBINGEN

HEPHY
INSTITUTE OF HIGH ENERGY PHYSICS

TU WIEN
TECHNISCHE
UNIVERSITÄT
WIEN

UNIVERSITY OF
OXFORD

The CRESST Experiment

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

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

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

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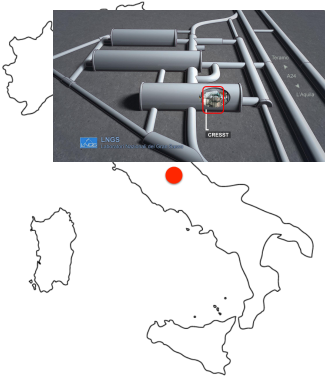

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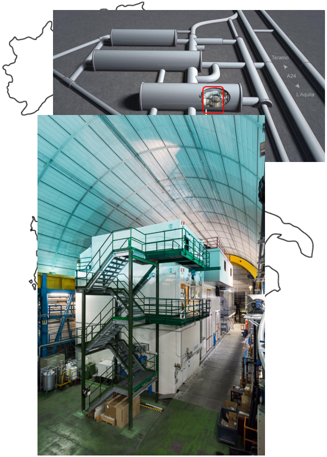

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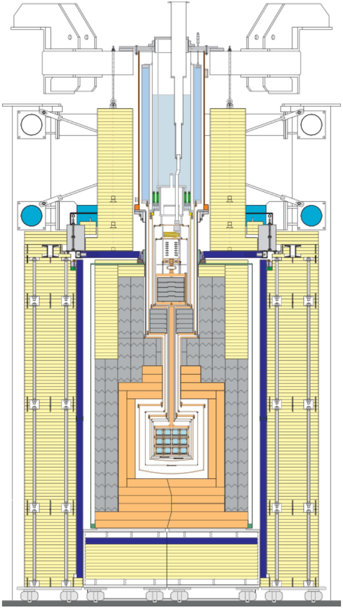
CRESST goal: direct detection of dark matter particles via their scattering off target nuclei in cryogenic detectors, operated at $\sim$15 mK

CRESST Setup

Shielding:

- polyethylene (10t)
- muon veto system
- lead (24t)
- copper (10t)



Detector Modules

Standard design

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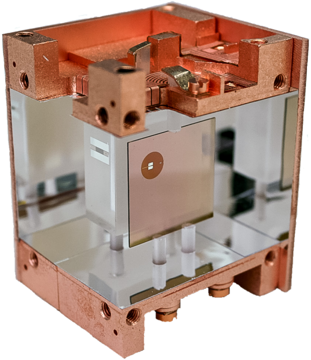
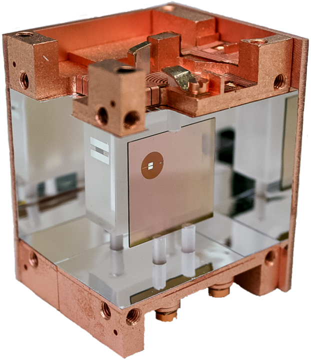


Detector Modules

Standard design

Phonon detector:

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



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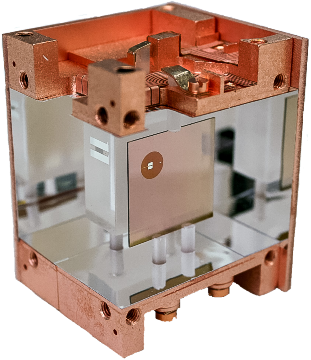

Light detector:

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

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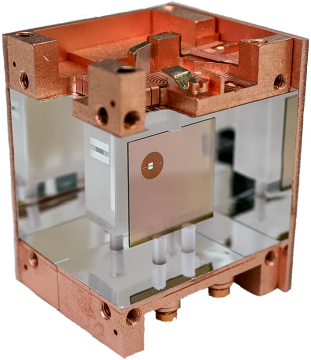

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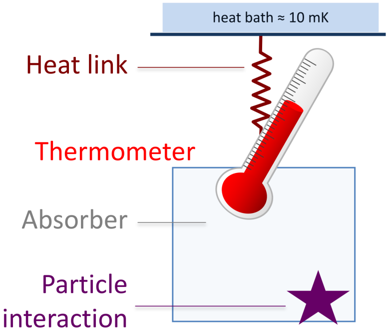
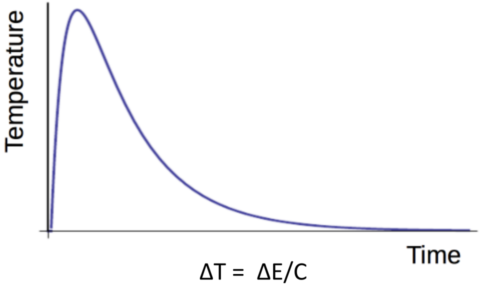
- Silicon-on-Sapphire $(20\text{x}20\text{x}0.4)\text{mm}^3$ wafer
- Particle discrimination

Housing & Holding:

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

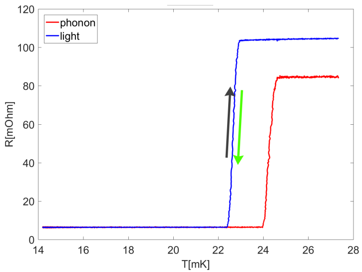
Cryogenic Calorimeter

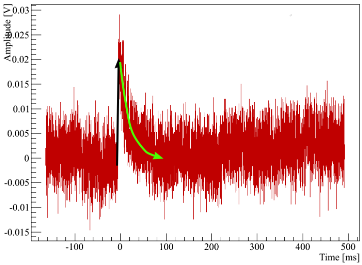




Signal

- Nuclear Recoil heats up crystal $\mathcal{O}(\mu K)$
- Change of resistance in bias current $\mathcal{O}(m\Omega)$
- SQUID readout and signal amplification $\mathcal{O}(mV)$



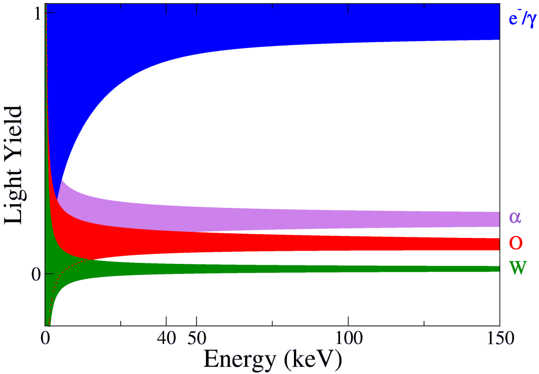


Event Discrimination

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

Characteristic of event type

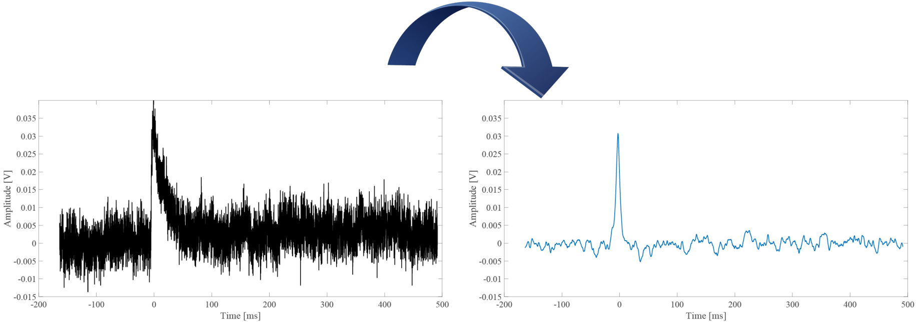
Discrimination between potential signal events (**nuclear recoils**) and dominant radioactive background (**electron recoils**)



Data Analysis

Continuous DAQ + Optimum Filter

- Dead-time free DAQ: detector output is continuously recorded
- Maximize Signal-to-Noise ratio in frequency space



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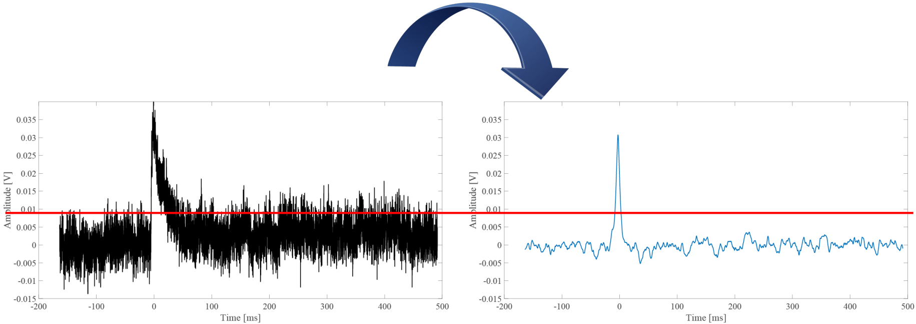
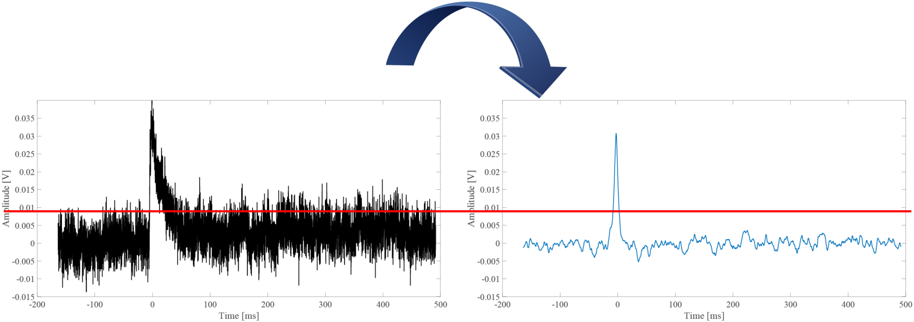


Data Analysis

Continuous DAQ + Optimum Filter

- Dead-time free DAQ: detector output is continuously recorded
- Maximize Signal-to-Noise ratio in frequency space
- Define threshold by choosing accepted number of noise triggers
- Select Events above threshold



Data Analysis

Event Selection and Energy Calibration

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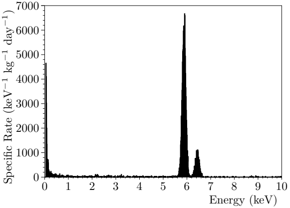
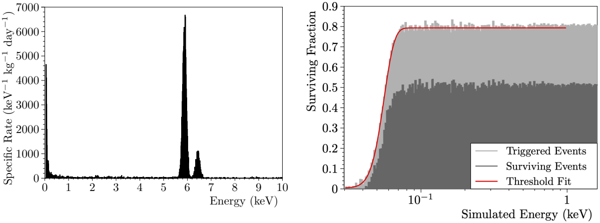


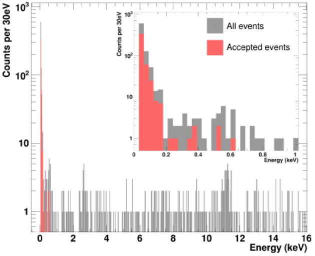
Data Analysis

Event Selection and Energy Calibration

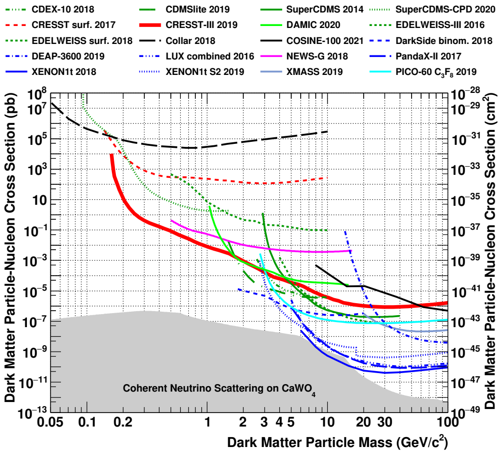
- Apply data selection criteria, designed to keep only valid pulses
- Calibration of cleaned data with radioactive source
- Perform simulation to calculate survival probabilities after trigger and selection criteria



First Results from CRESST-III (2019)



- Data taking: 10/2016 - 01/2018
- Mass: 23.6 g
- Gross exposure: 5.689 kgd
- Nuclear recoil threshold: 30.1 eV



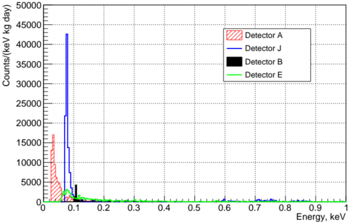
Phys. Rev.D100(2019) 10 102002

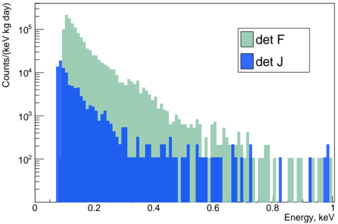
Outline

First observations of Excess

Run34 (05/2016 - 02/2018):
$CaWO_4$ crystals
$\sim$24 g
30.1, 64.8, 83.4, 120 eV thresholds
scintillating foil
(instrumented) $CaWO_4$-holding sticks

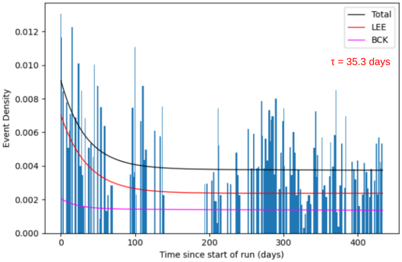
Run35 (11/2018 - 10/2019):
Al_2O_3 (Sapphire) crystals
15.9 g
76.9, 66.5 eV thresholds
scintillating foil
non instrumented $CaWO_4$-holding sticks

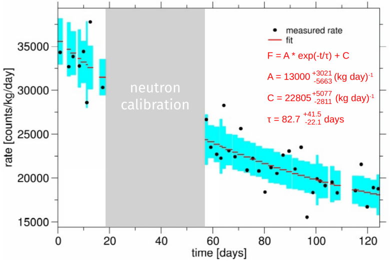




First observations of Excess

Decrease of rate over time:





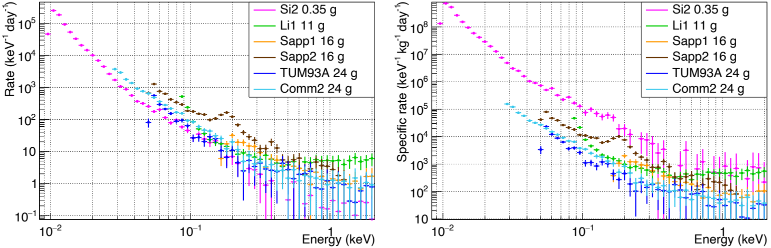
Modifications of modules
for Run36 (11/2020 - still running)

Test different configurations to find source of unknown background:

- Materials ($CaWO_4$, $LiAlO_2$, Al_2O_3, Si)
- Replace $CaWO_4$ holding sticks with Cu sticks
- Some modules with bronze clamps instead of sticks
- Remove scintillating foil
- One fully non-scintillating module
  (Si as main absorber and wafer detector)
- Introduction of ^{55}Fe source for low energy calibration (since Run35)

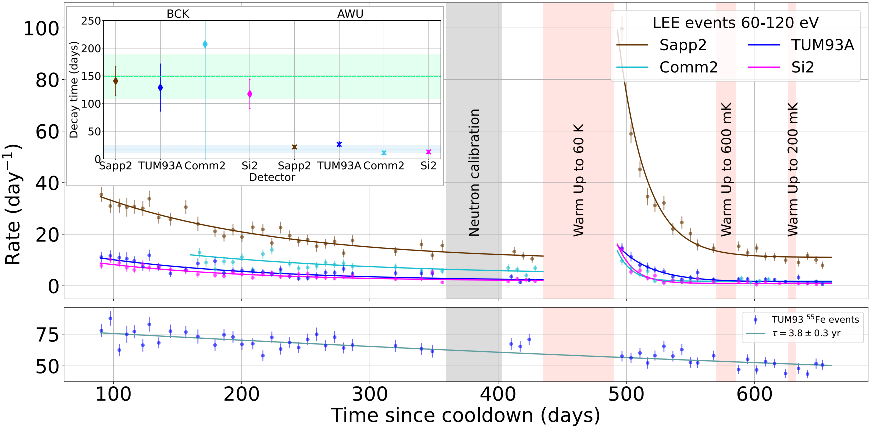
Outline

Energy spectra



- Excess seen in all detectors!
- Rate does not scale with mass
- Common single particle origin like DM or external radiation disfavoured

Time dependence



$\Rightarrow$ Can exclude external and intrinsic radioactivity

And another argument against a DM origin

arxiv:2207.09375

Conclusions

Exluded hypotheses on major contributions:

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

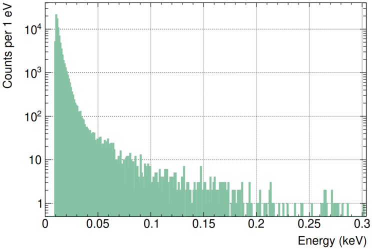
Possible options under further investigation:

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

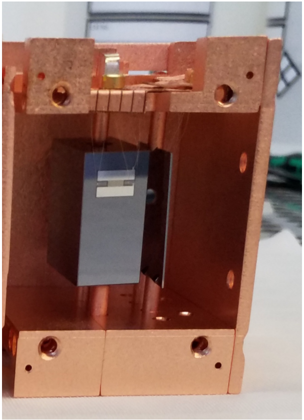
- R & D ongoing

Outline

Results from a Si Wafer Detector



- Data taking: 11/2020 - 08/2021
- Mass: 0.35 g
- Gross exposure: 55.06 g days
- Nuclear recoil threshold: 10.0 eV



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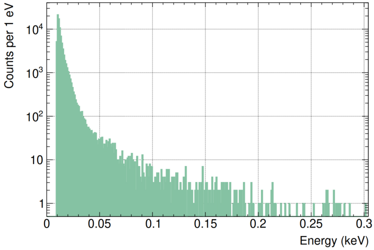

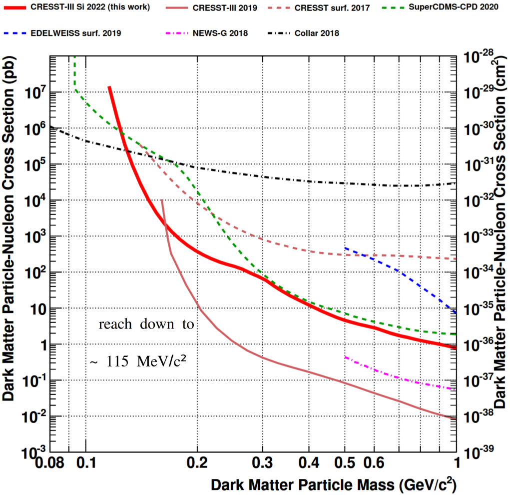

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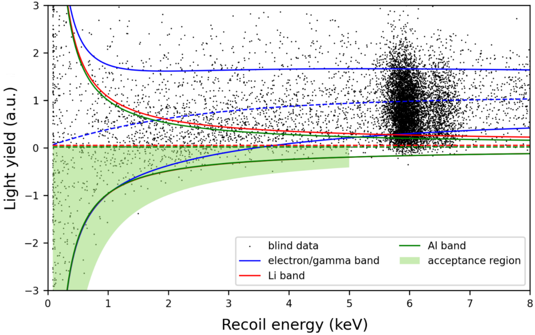
SD Limits with $LiAlO_2$ Detectors

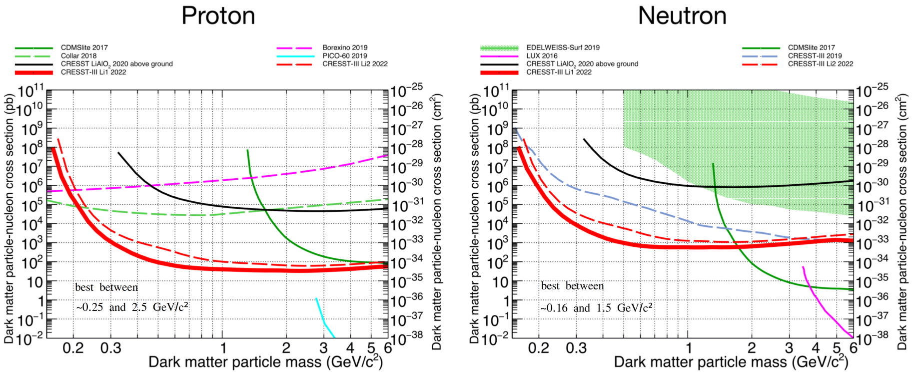
- Data taking: 11/2020 - 08/2021
- Mass: 11.2 g
- Gross exposure: 1.161 kgd
- Nuclear recoil threshold: 83.6 eV



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

a_p and a_n: effective couplings to protons and neutrons
$\langle S^p \rangle$ and $\langle S^n \rangle$: expectation values of n and p spins within the nucleus

SD Limits with $LiAlO_2$ Detectors



arxiv:2207.07640

Outline

CRESST-III Program

Upgrade of CRESST-III to read-out 288 channels
Reach tonne day exposures

Readout:
2021: Finalized prototyping and testing of

- Wiring
- SQUID readout electronics

2022-2023:

- Finalize installation inside CRESST facility at LNGS

Detector R & D:
2021-2022:

- Lower threshold
- High production rate

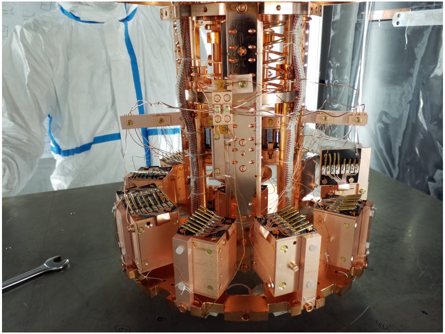
2022-2023:

- Production and testing of detectors
- Upgrade setup at LNGS

2023: Restart data taking

Summary

- New dark matter results:
  - Si detector limit down to 115 MeV/c^2 (threshold of 10 eV)
  - SD limits with $LiAlO_2$ detectors
- R & D to identify LEE
- Ongoing efforts to improve detectors
- Major upgrade of setup in preparation



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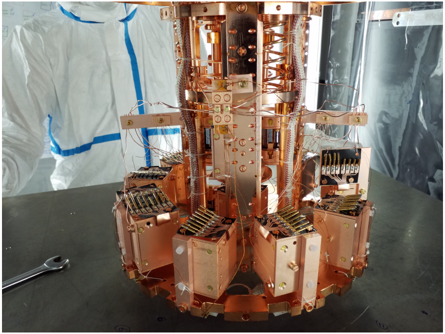


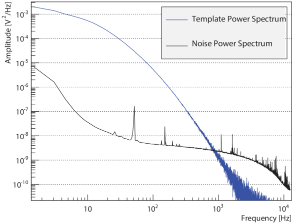
Thank you for your attention!

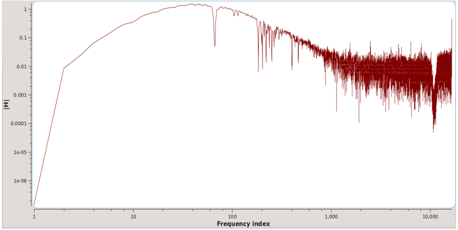
BACKUP

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:

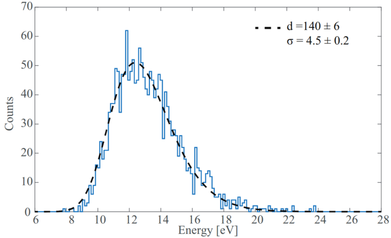
$$y_F(t) = \frac{A}{\sqrt{2\pi}} \int_{-\infty}^{\infty} H(\omega)\widehat{s}(\omega)e^{i\omega t}\,\mathrm{d}\omega$$

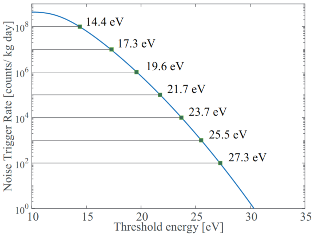
Data Analysis

Threshold determination

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

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



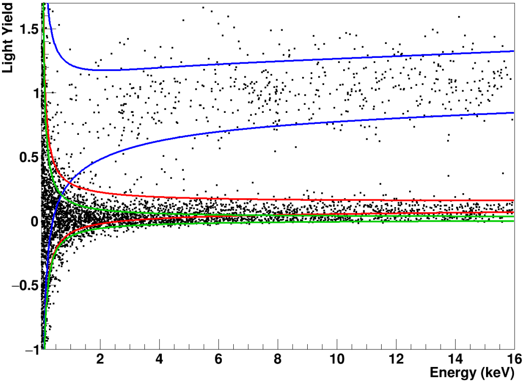


(J Low Temp Phys (2019) | doi.org/10.1007/s10909-018-1948-6)

Neutron Calibration

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

Band Fits QF

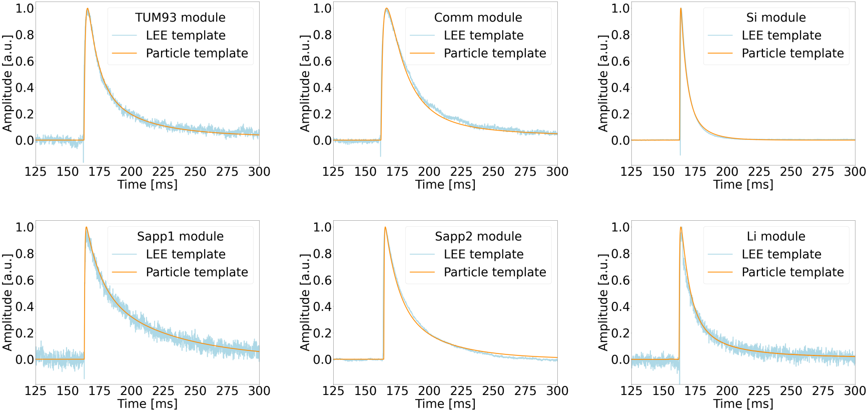


e/γ events

Oxygen nuclear recoils

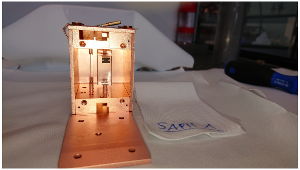
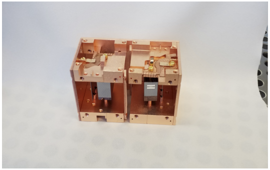
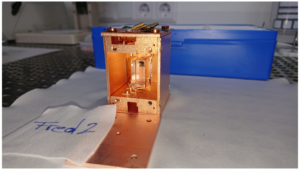
Tungsten nuclear recoils

Averaged LEE Pulse vs Particle Templates



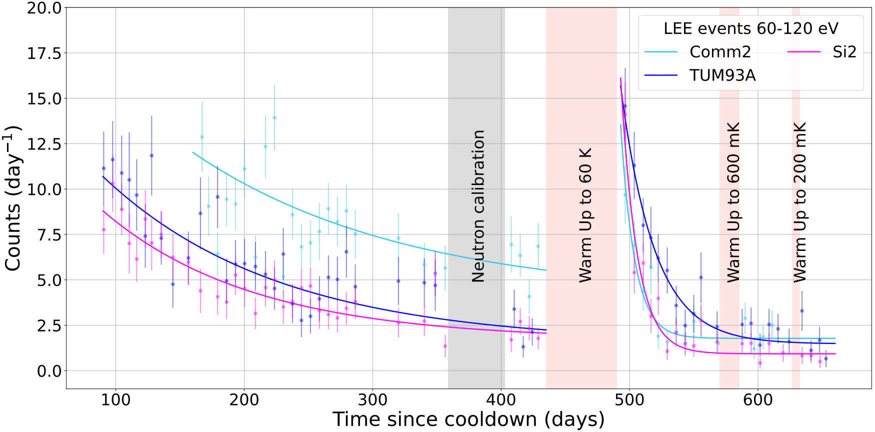
⇒ Excludes noise or electronic artifacts

List of Modules

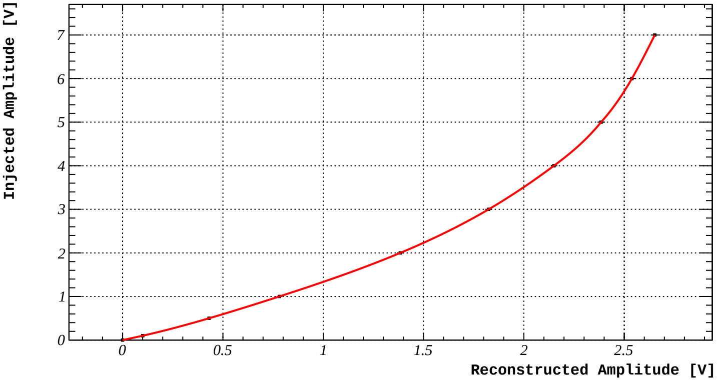
Module	Material	Holding	Foil	Mass (g)	Threshold (eV)
Si2	Si	Cu	No	0.35	10
Sapp1	Al_2O_3	Cu	No	16	157
Sapp2	Al_2O_3	Cu	No	16	52
Li1	$LiAlO_2$	Cu	Yes	11	84
TUM93A	$CaWO_4$	2 Cu + 1 $CaWO_4$	Yes	24	54
Comm2	$CaWO_4$	Bronze Clamps	No	24	29

Time dependence II

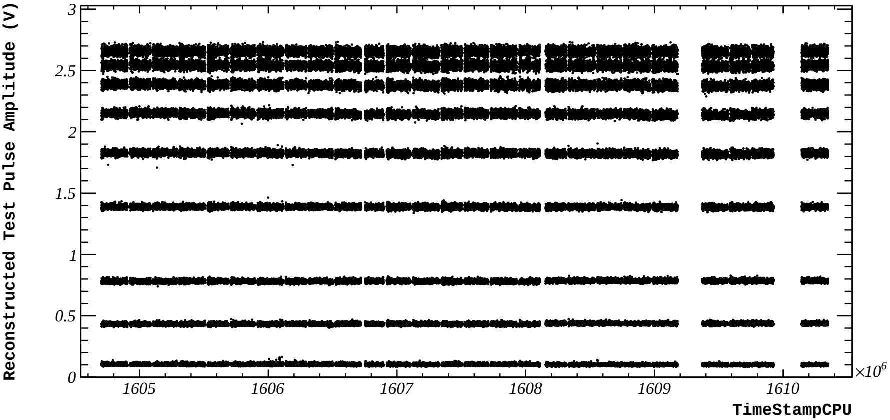


Transfer function

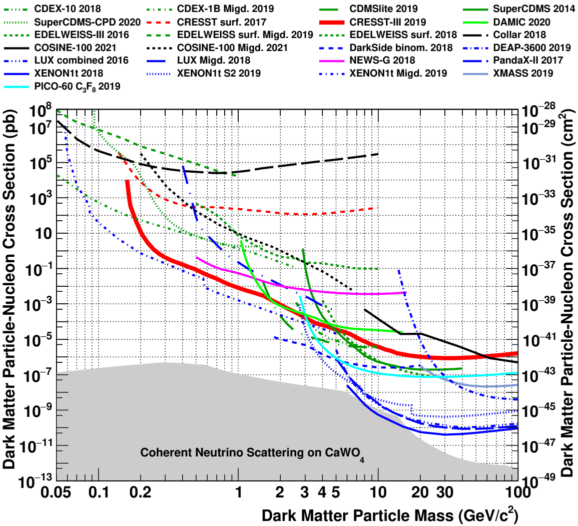
for Calibration



Detector Response



Limits including Migdal effect



Effect of correcting the energy scale