

FIRST OBSERVATION OF SINGLE PHOTONS IN A CRESST DETECTOR AND NEW DARK MATTER EXCLUSION LIMITS

Dominik Fuchs

August 28, 2023

Outline

1 The CRESST Experiment

2 Data Analysis

3 Dark matter exclusion Limit



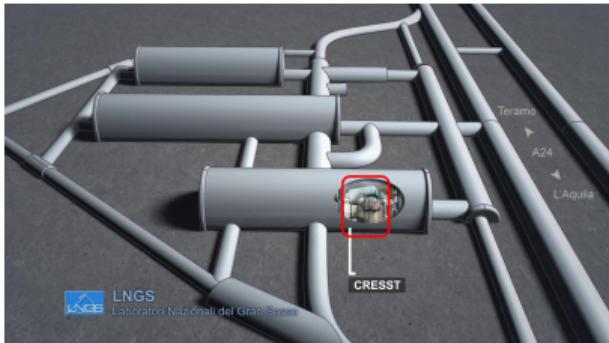
Cryogenic Rare Event Search
with Superconducting Thermometers



MAX PLANCK INSTITUTE
FOR PHYSICS



Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Gran Sasso



Goal: Direct detection of dark matter particles via their scattering off target nuclei in cryogenic detectors, operated at ~ 15 mK.

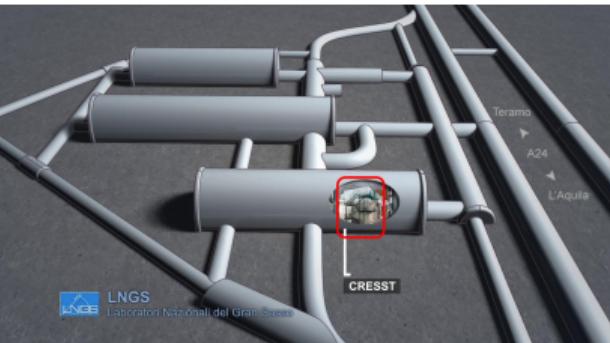


Cryogenic Rare Event Search
with Superconducting Thermometers

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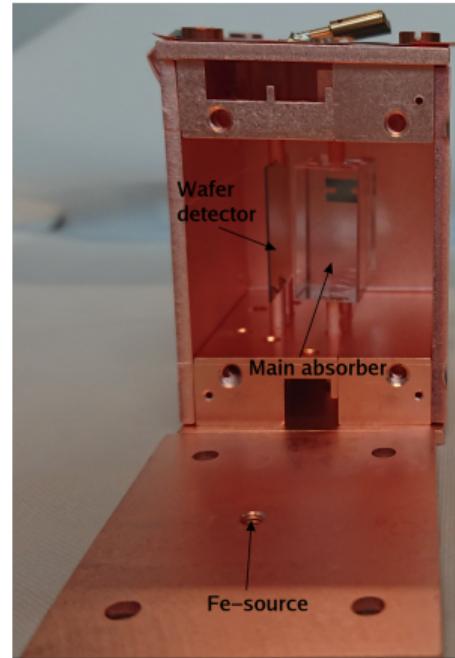
Talk on wednesday by M. Kaznacheeva

"Direct Dark Matter search with the CRESST-III experiment - Status and prospects"

Sapphire Detector Module

Main absorber:

- ▶ $(20 \times 20 \times 10) \text{ mm}^3$ Al_2O_3 crystal
- ▶ W-TES Sensor
- ▶ $E_{\text{thr}} = 52 \text{ eV}$



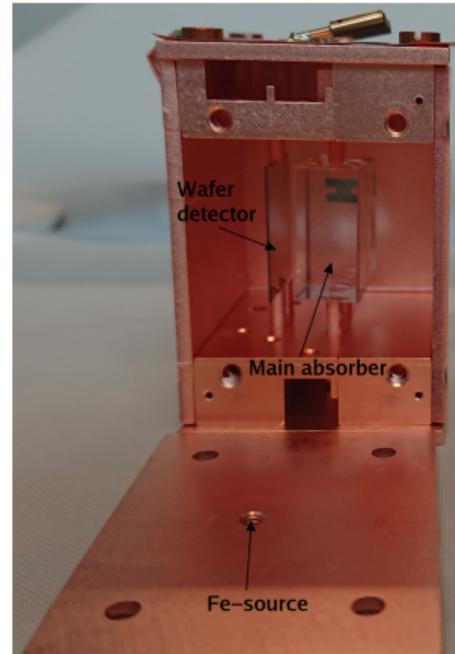
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Wafer detector:

- ▶ $(20 \times 20 \times 0.4) \text{mm}^3$ Silicon-On-Sapphire crystal ($\sim 1 \mu\text{m}$ Si layer)
- ▶ W-TES Sensor
- ▶ $E_{\text{thr}} < 10 \text{ eV}$



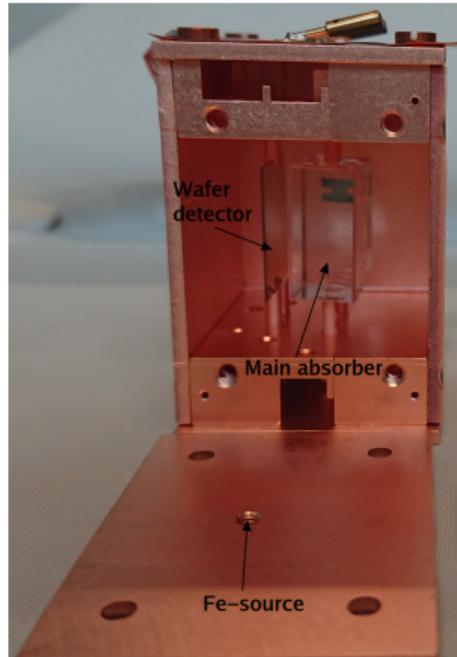
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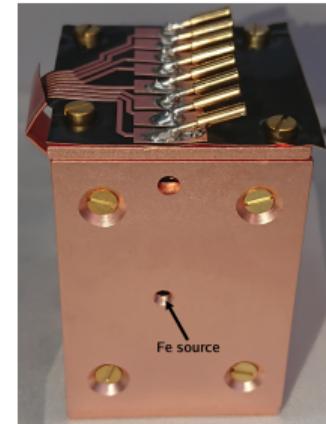
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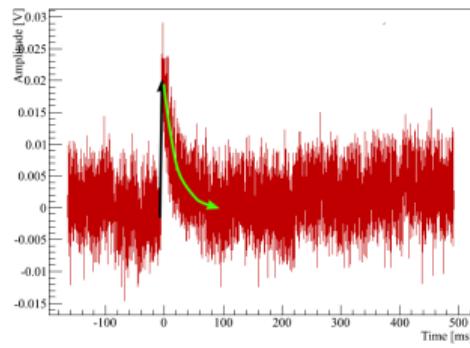
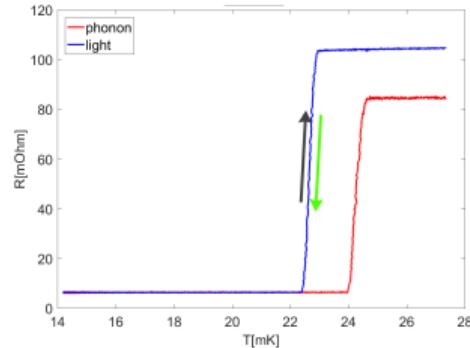
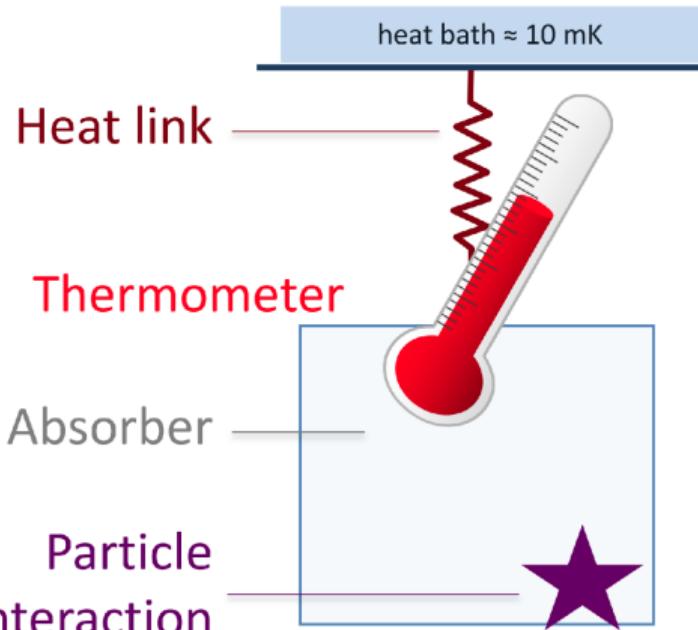


Housing & Holding:

- ▶ Bare Cu housing
- ▶ Cu holding sticks
- ▶ ^{55}Fe calibration source (5.89 keV, 6.49 keV)



Cryogenic Calorimeter



Outline

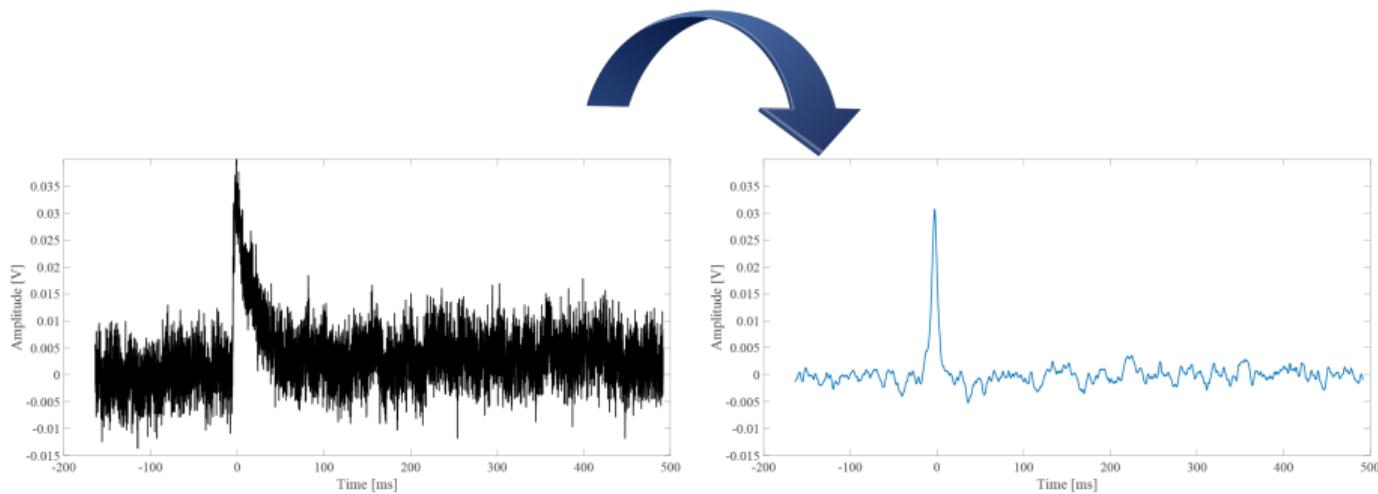
1 The CRESST Experiment

2 Data Analysis

3 Dark matter exclusion Limit

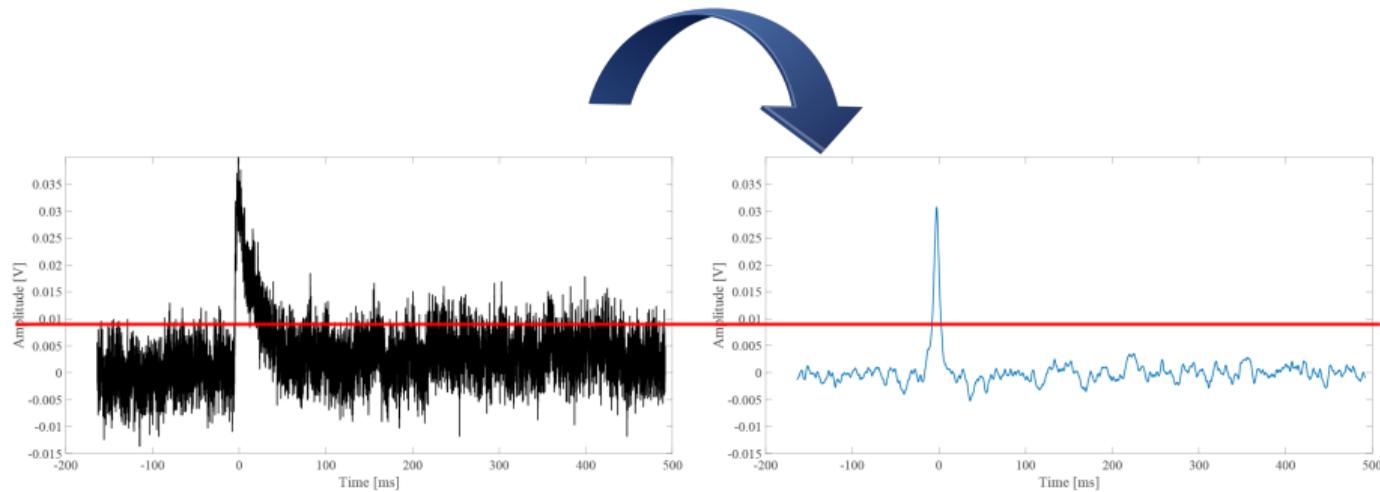
Continuous DAQ + Optimum Filter

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



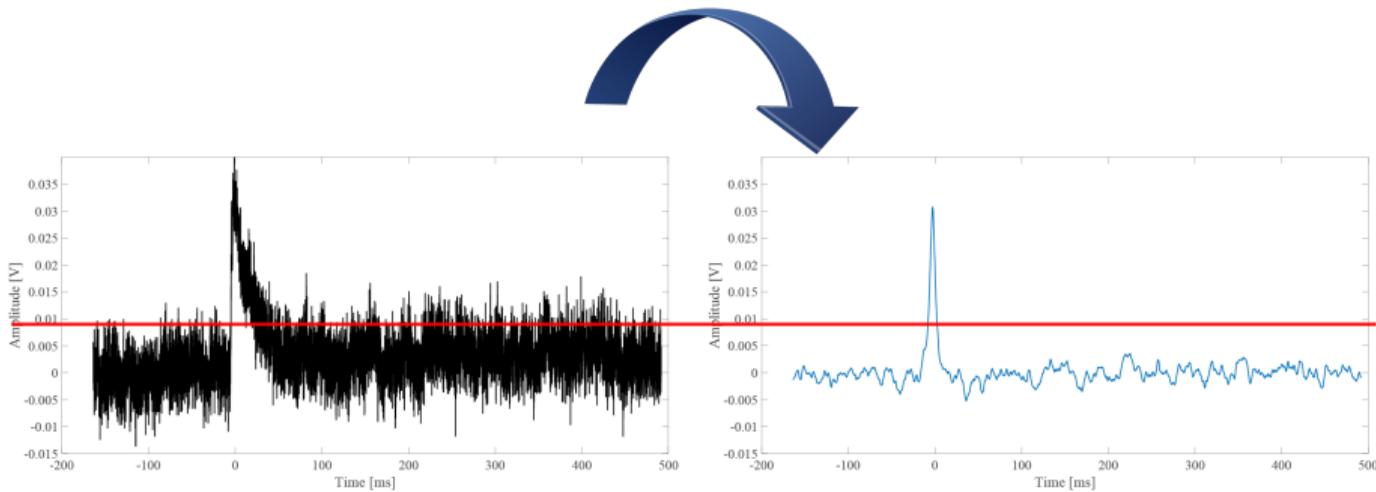
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- ▶ Define threshold by choosing accepted number of noise triggers ($1 \text{ kg}^{-1} \text{ d}^{-1}$)



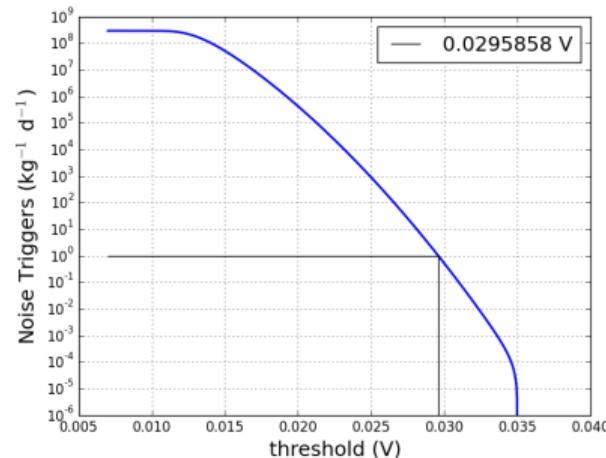
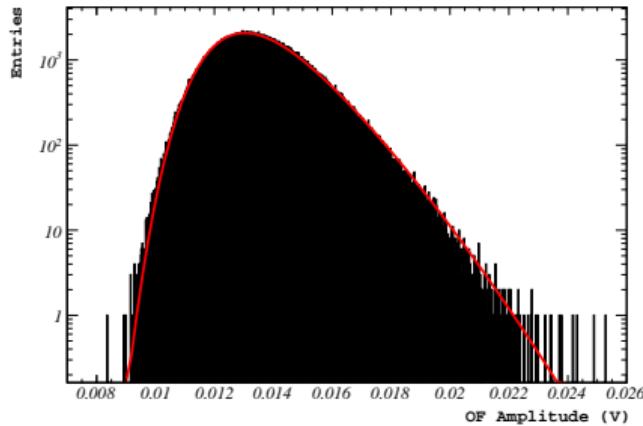
Continuous DAQ + Optimum Filter

- ▶ Dead-time free DAQ: detector output is continuously recorded
- ▶ Maximize Signal-to-Noise ratio with Optimum Filter
- ▶ Define threshold by choosing accepted number of noise triggers ($1 \text{ kg}^{-1} \text{ d}^{-1}$)
- ▶ Select Events above threshold



Threshold determination

- ▶ Analytical model of distribution of amplitudes of filtered noise
- ▶ Noise trigger rate as a function of the threshold



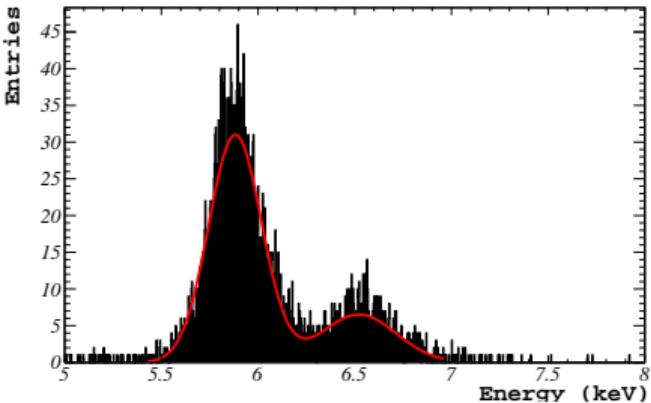
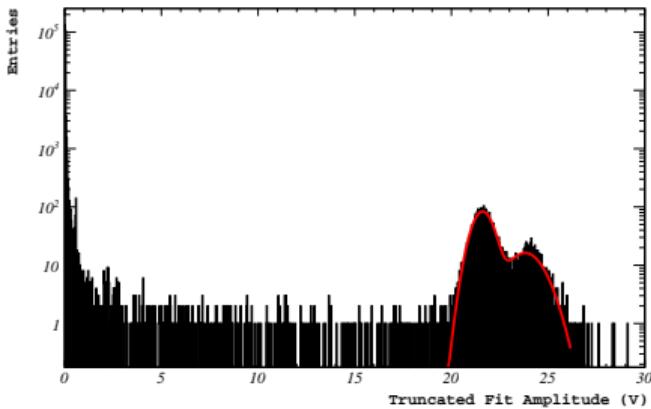
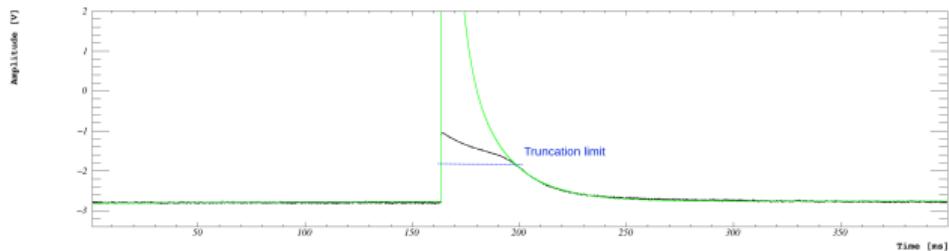
Threshold: 29.6 mV \Rightarrow 6.70 eV

Calibration

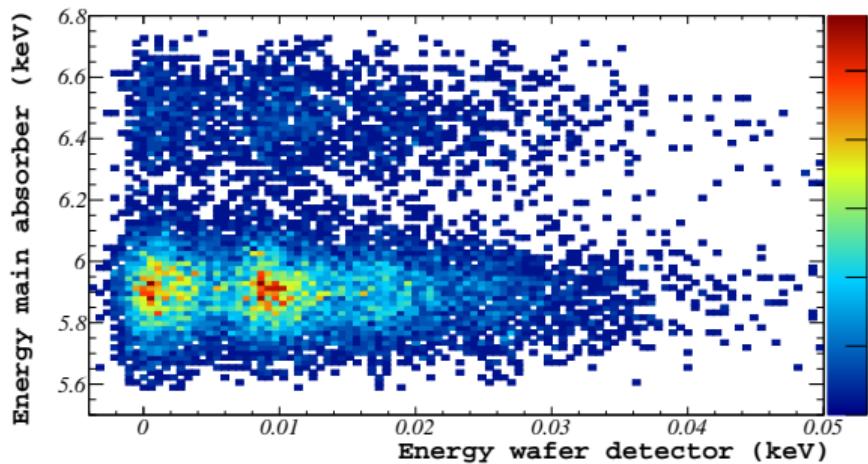
Wafer detector is optimized for very low energies

→ Direct hits of ^{55}Fe source highly saturated

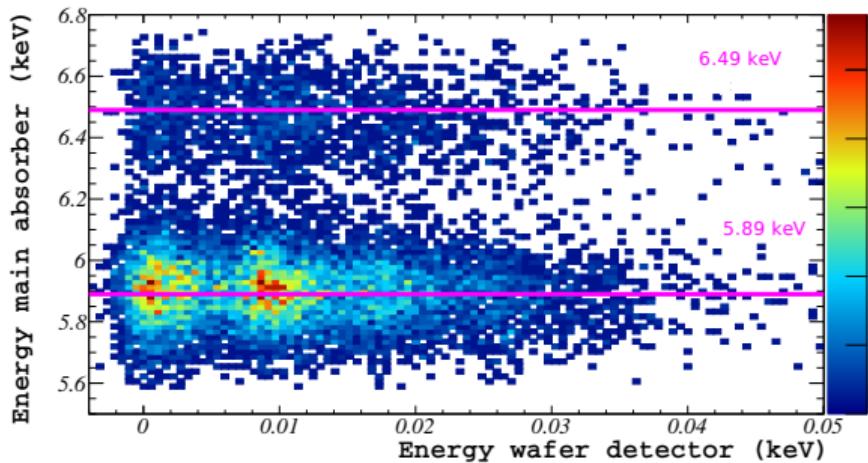
Reconstruction with truncated fit:



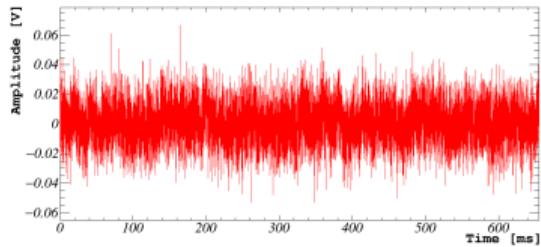
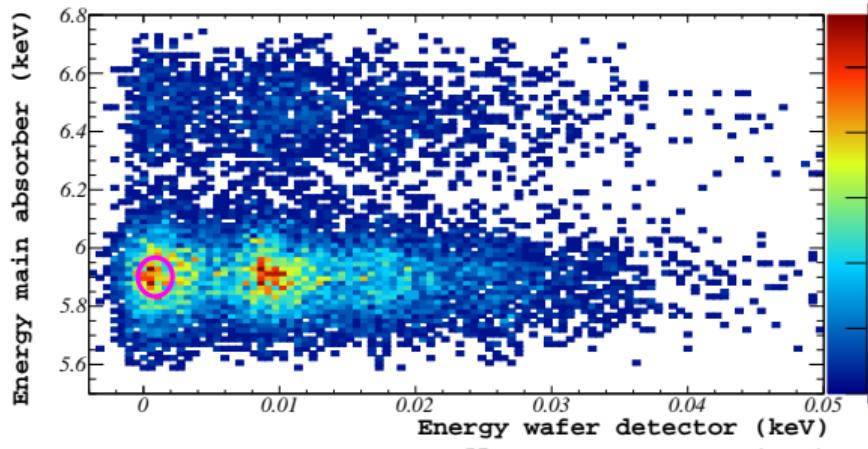
Luminescence of main absorber



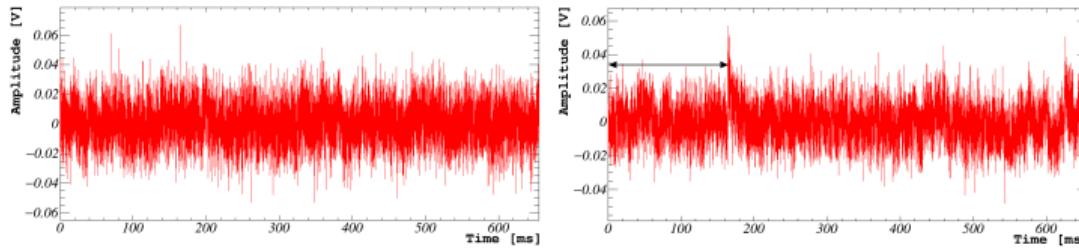
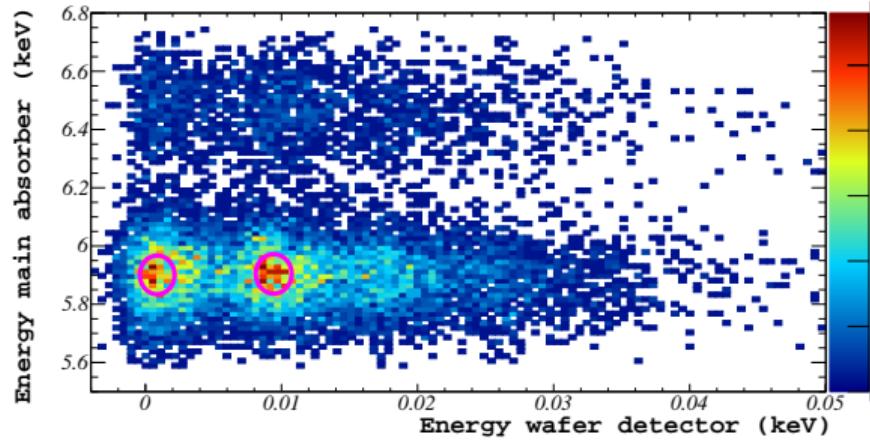
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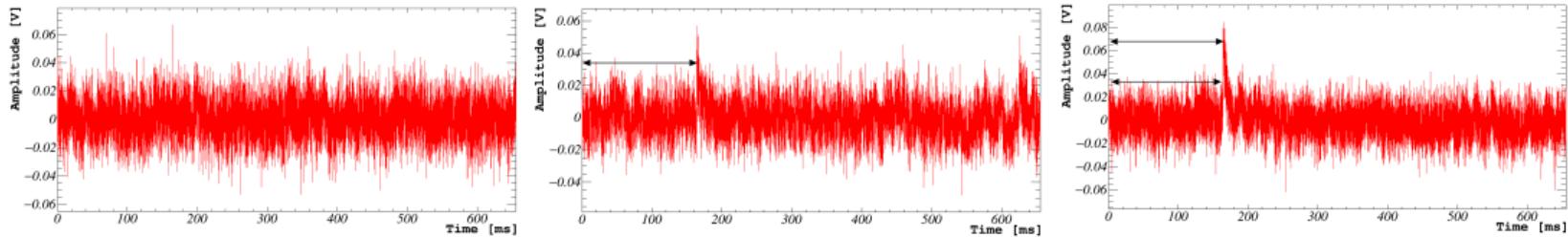
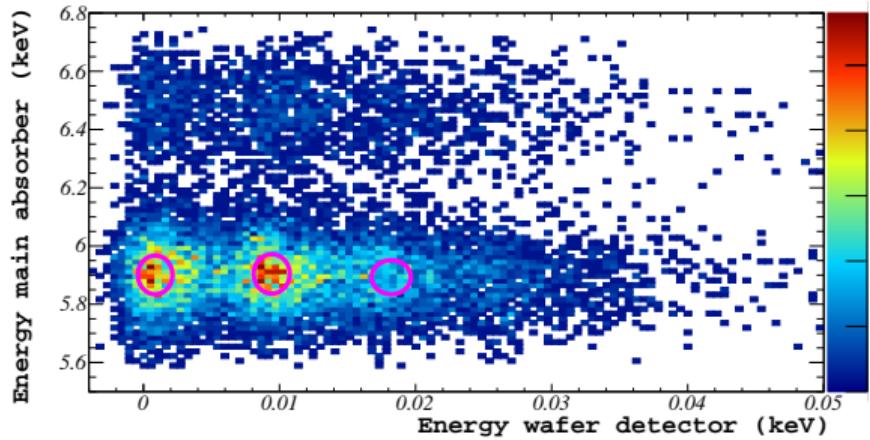
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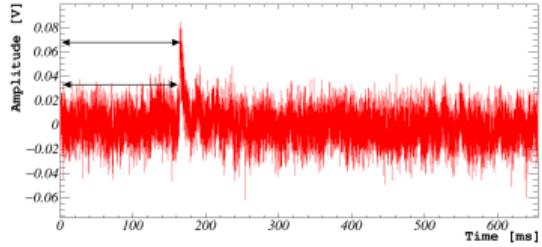
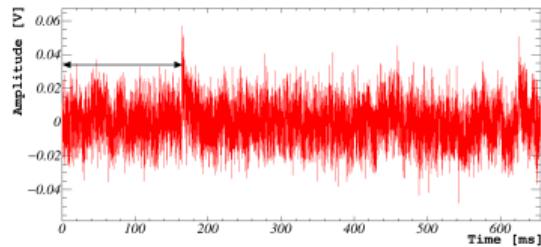
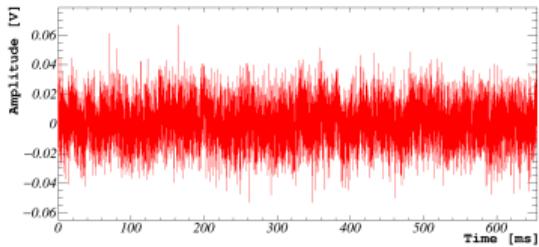
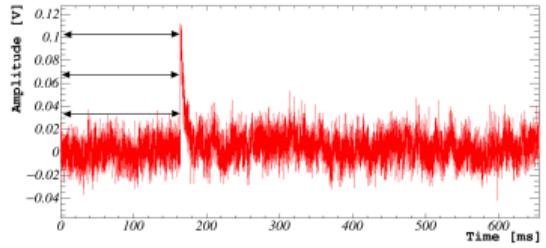
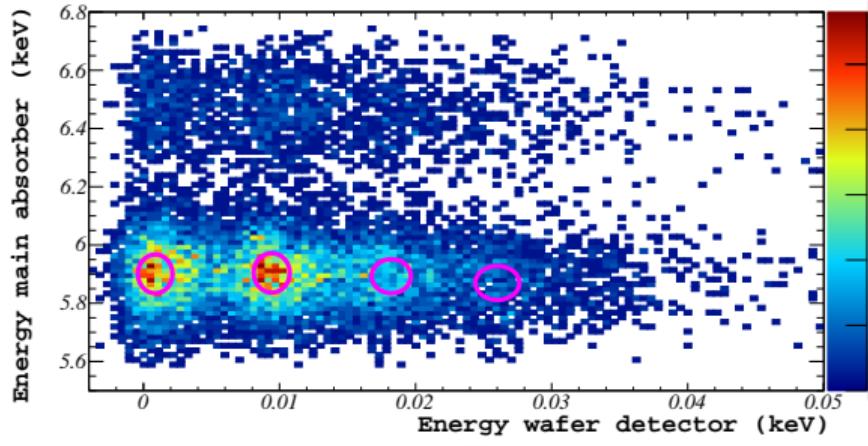
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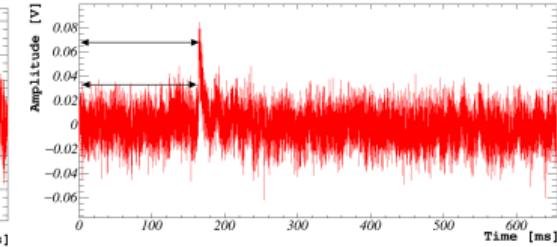
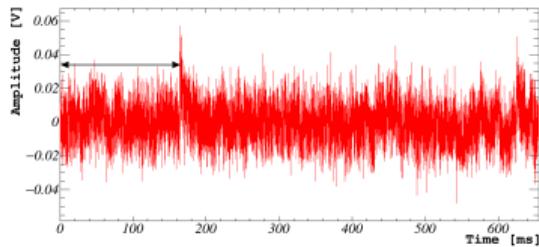
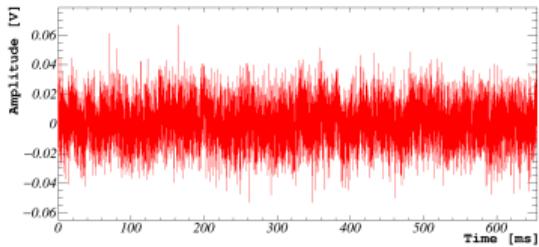
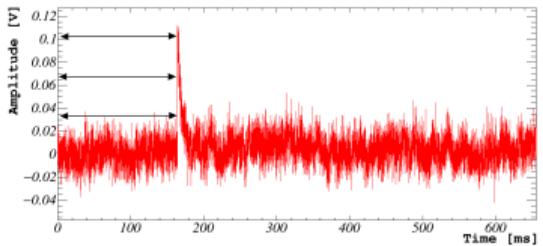
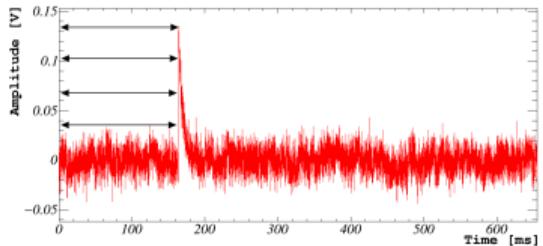
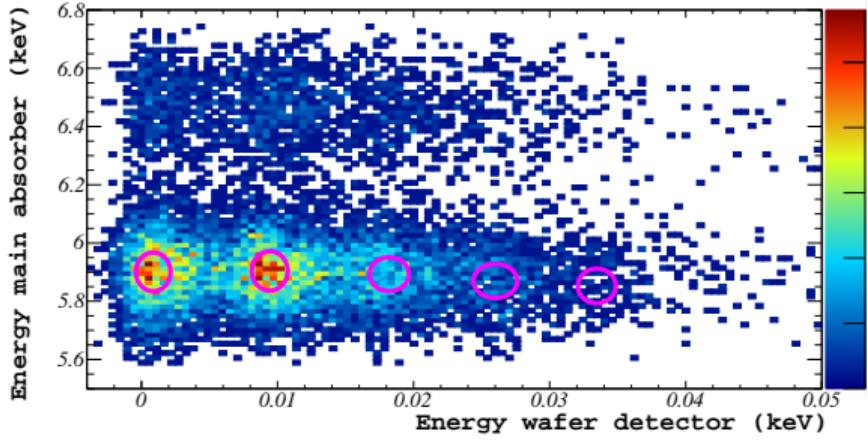
Luminescence of main absorber



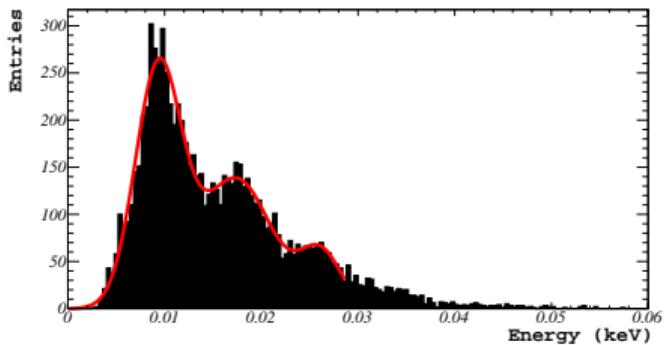
Luminescence of main absorber



Luminescence of main absorber



Simple Fit

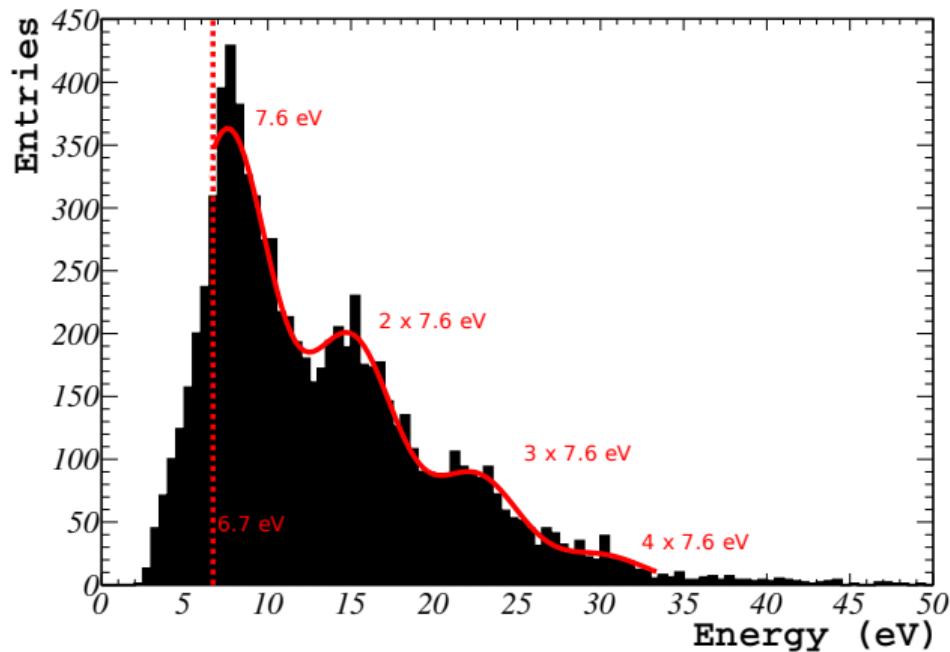


| Parameter | Peak 1 | Peak 2 | Peak 3 |
|----------------------------|-----------------|------------------|------------------|
| Position μ_i (eV) | 9.34 ± 0.11 | 17.38 ± 0.21 | 26.11 ± 0.24 |
| Resolution σ_i (eV) | 2.39 ± 0.06 | 3.63 ± 0.35 | 2.16 ± 0.27 |

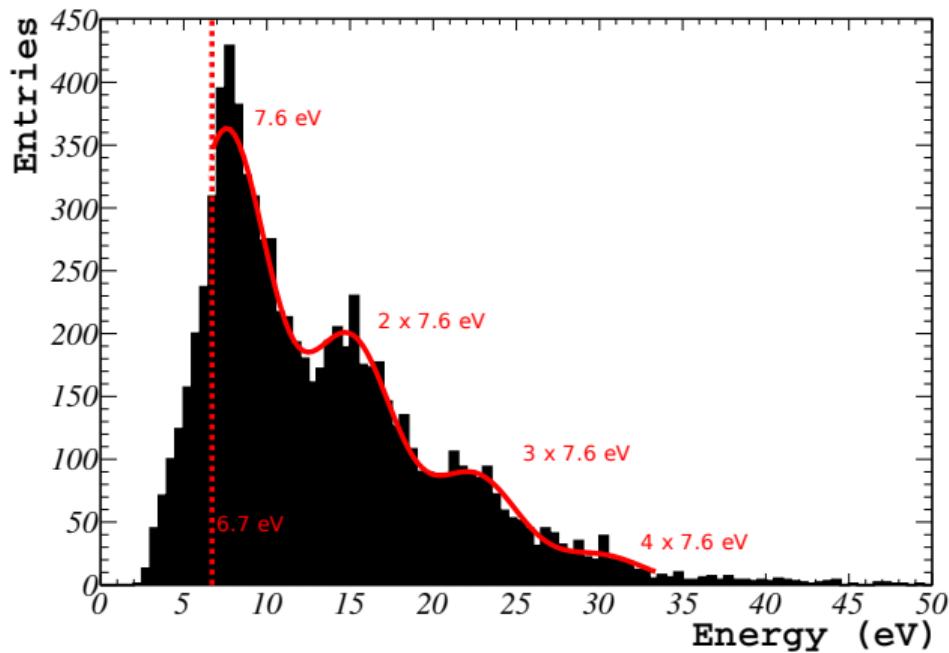
Interpretation: VUV luminescence

- ▶ Ultra pure sapphire crystals emit luminescence at 7.6 eV via radiative decay of excitons [1][2]
- ▶ High initial energy deposition can lead to multiplication of electronic excitations → creation of several luminescence photons [2]
- ▶ Process is fast [2][3][4] → several photons hitting wafer detector can appear as single event with multiple of single photon energy

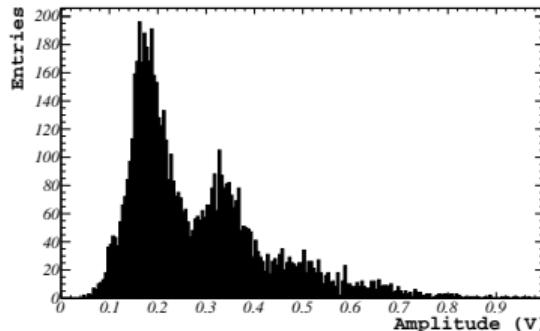
Finetune calibration at low energies



Finetune calibration at low energies



Effect also observed in other Sapphire detector in same measurement:

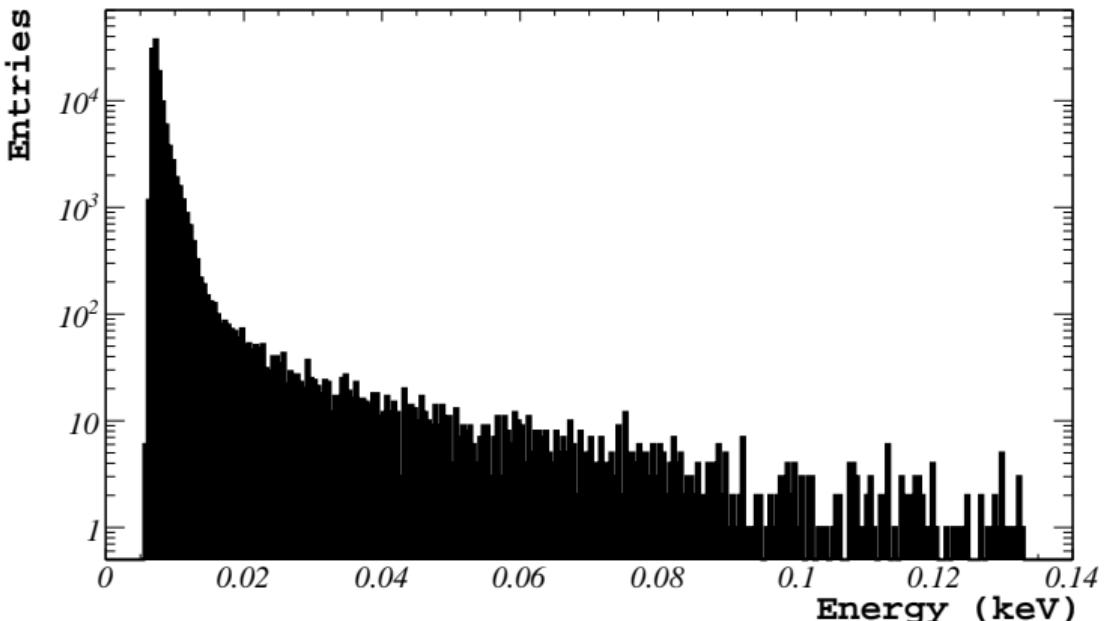


Spectrum

- ▶ Material: Al_2O_3
- ▶ Exposure: 0.138 kg d
(full dataset, no blind analysis)

Threshold:

- ▶ Original calibration with ^{55}Fe source:
 $(8.0 \pm 1.2) \text{ eV}$
- ▶ Fine tuned calibration with luminescence peaks:
 $(6.7 \pm 1.0) \text{ eV}$

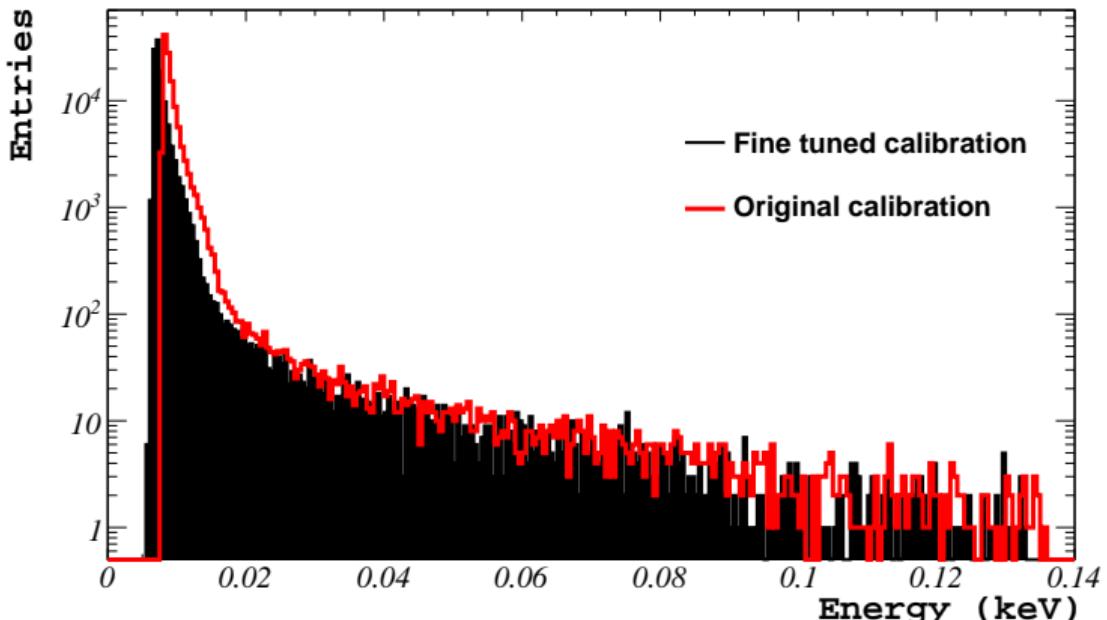


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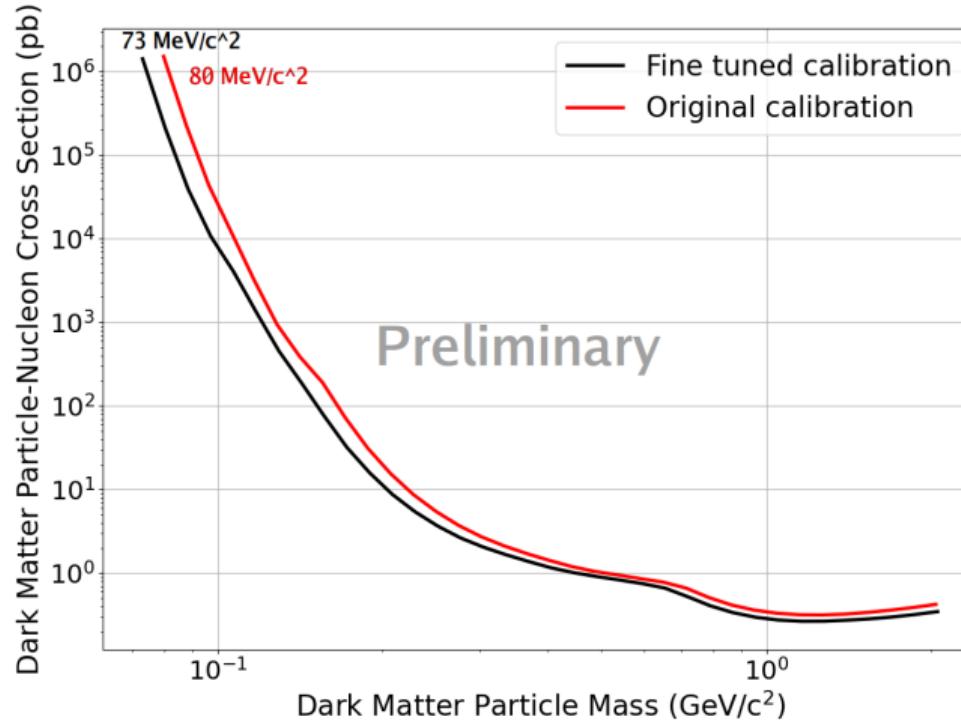
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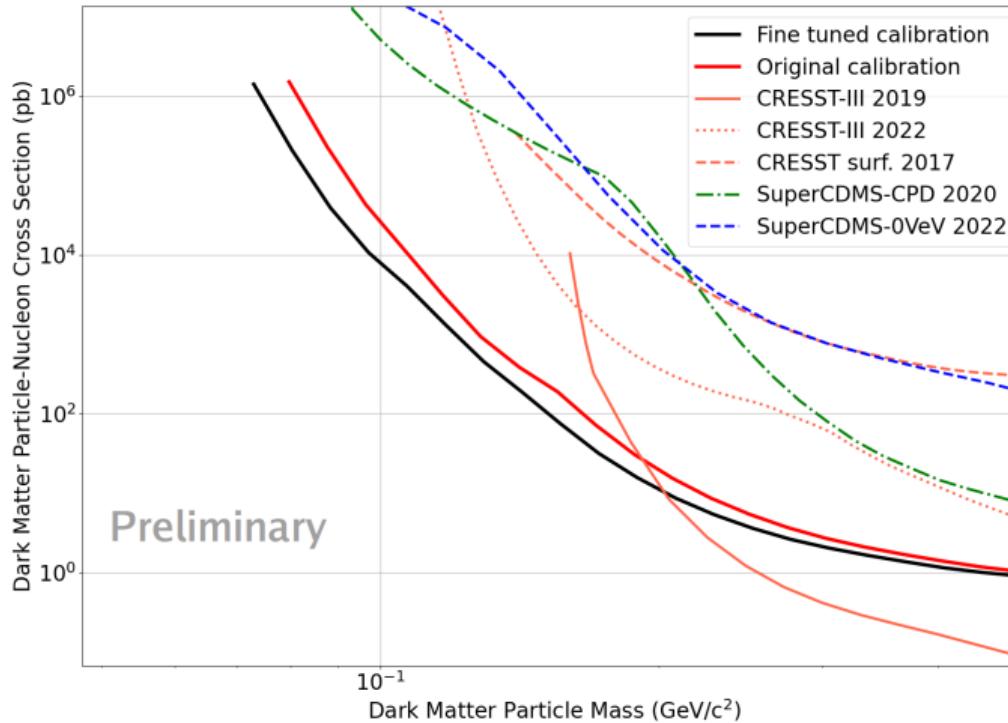
2 Data Analysis

3 Dark matter exclusion Limit

Spin-independent exclusion Limit



Spin-independent exclusion Limit



Summary

- ▶ First observation of single photons in a CRESST detector
- ▶ Can be used for fine tuning of calibration at very low energies
- ▶ Leading to sub 100 MeV/c² dark matter exclusion limits
- ▶ Al₂O₃ also suitable for calculation of spin-dependent limits (WIP)

Summary

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Thank you!

BACKUP

Amplitude Distribution of filtered EBLs

- ▶ Probability of one sample being equal to x_{max} and all others being smaller described by Binomial Distribution (arXiv:1711.11459):

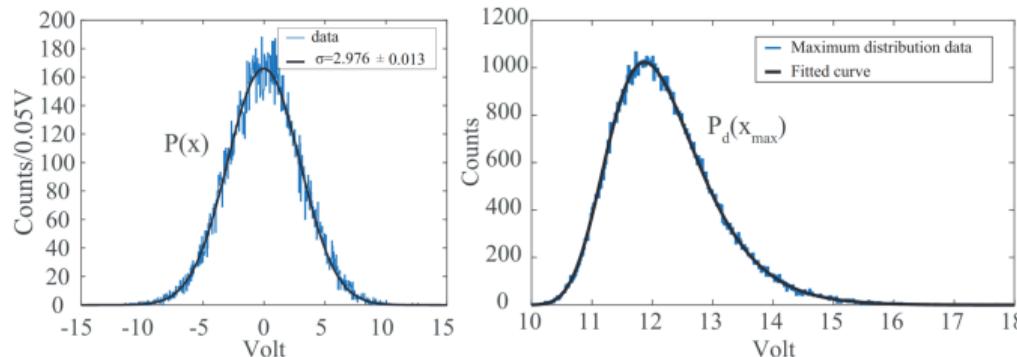
$$P_d(x_{max}) = \frac{d!}{1!(d-1)!} \cdot (P(x_{max})) \cdot \left(\int_{-\infty}^{x_{max}} P(x) dx \right)^{d-1}$$

- ▶ $d \rightarrow$ Number of statistically independent samples
- ▶ $P(x)$ Distribution of noise samples

Gaussian noise

$$P(x) = \frac{1}{\sqrt{2\pi}\sigma} \cdot e^{-\left(\frac{x}{\sqrt{2}\sigma}\right)^2}$$

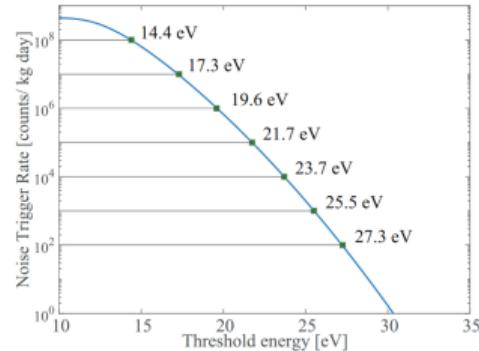
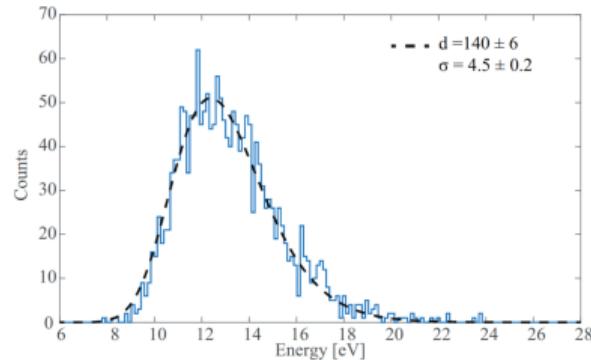
$$P_d(x_{max}) = \frac{d}{\sqrt{2\pi}\sigma} \cdot \left(e^{-\left(\frac{x_{max}}{\sqrt{2}\sigma}\right)^2} \right) \cdot \left(\frac{1}{2} + \frac{\operatorname{erf}\left(\frac{x_{max}}{\sqrt{2}\sigma}\right)}{2} \right)$$



(arXiv:1711.11459)

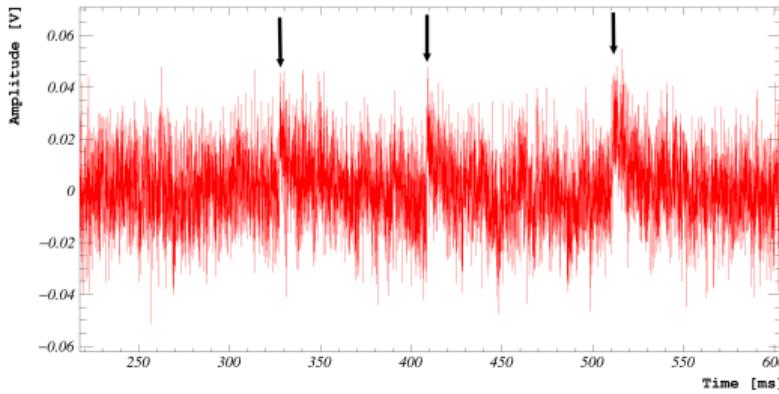
Noise Trigger Rate

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

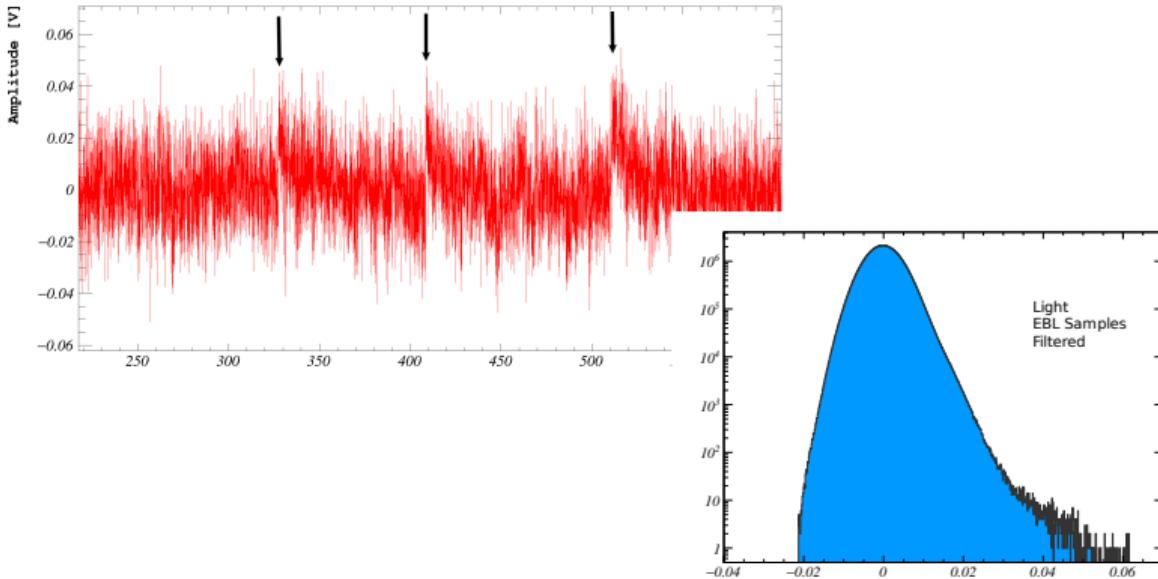


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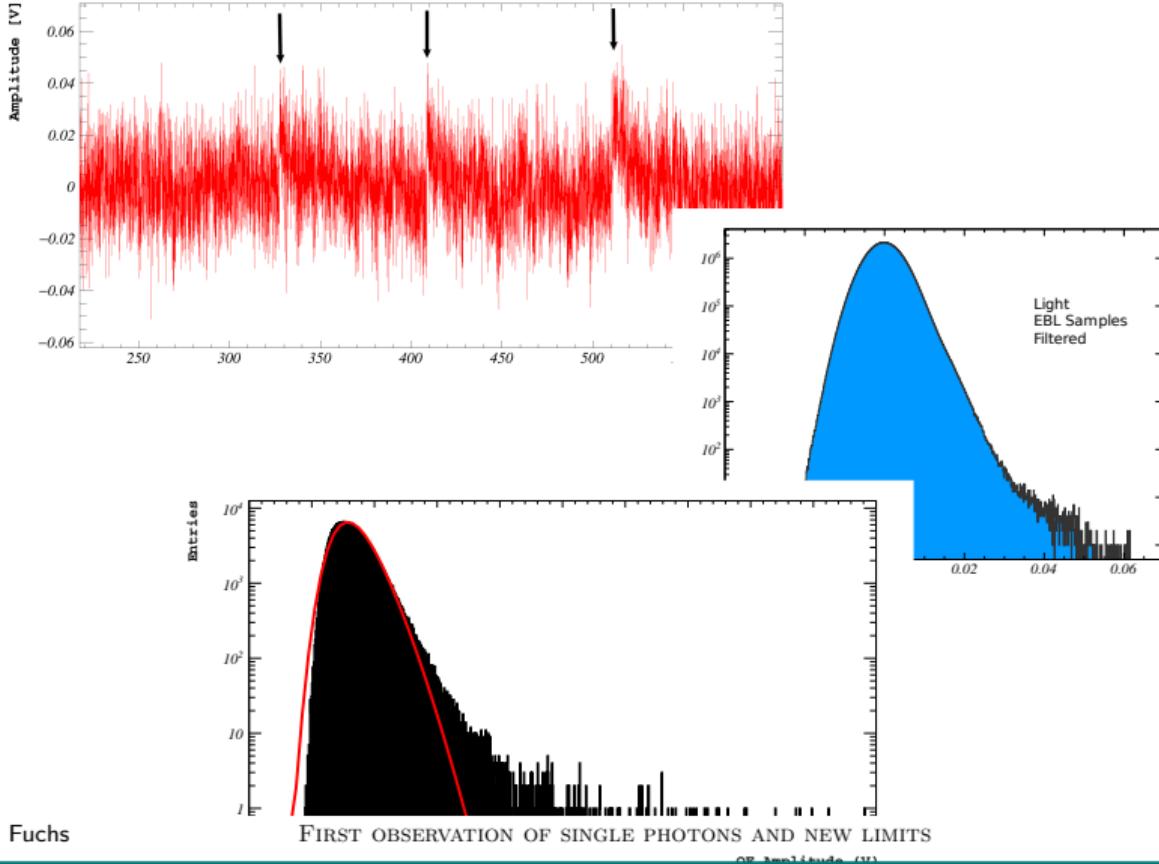
Noise distribution



Noise distribution

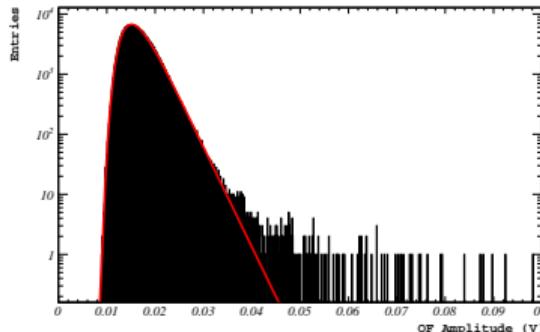


Noise distribution

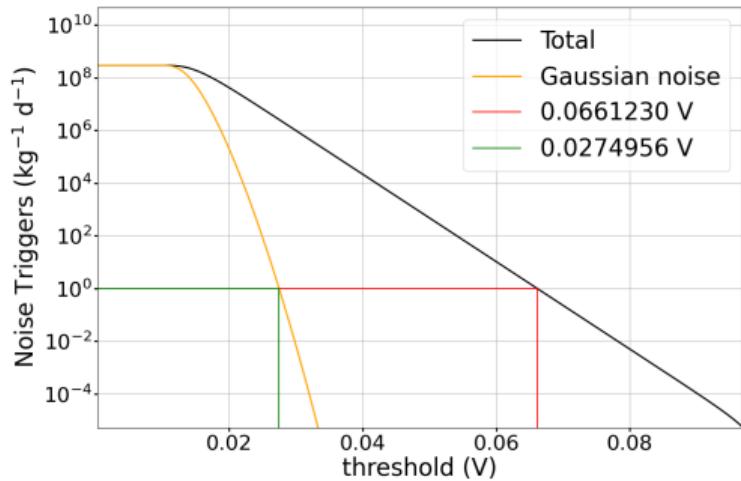
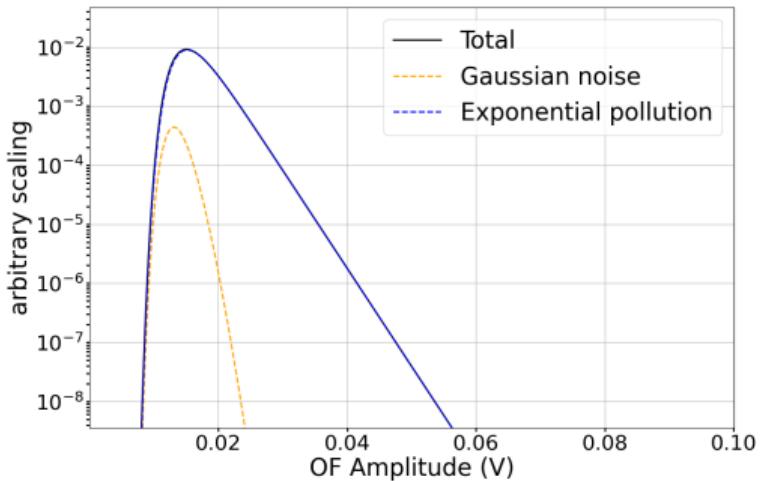


Pollution term: $F(x) = A \cdot e^{-\frac{x}{\lambda}}$

$$\begin{aligned} P_d(x_{max}) &= \frac{(d-n)}{\sqrt{2\pi}\sigma} \cdot e^{-\left(\frac{x_{max}}{\sqrt{2}\sigma}\right)^2} \cdot \left(\frac{1}{2} + \frac{erf\left(\frac{x_{max}}{\sqrt{2}\sigma}\right)}{2}\right)^{d-n-1} \cdot \left(A\lambda \cdot \left(1 - e^{-\frac{x_{max}}{\lambda}}\right)\right)^n \\ &+ nA \cdot e^{-\frac{x_{max}}{\lambda}} \cdot \left(\frac{1}{2} + \frac{erf\left(\frac{x_{max}}{\sqrt{2}\sigma}\right)}{2}\right)^{d-n} \cdot \left(A\lambda \cdot \left(1 - e^{-\frac{x_{max}}{\lambda}}\right)\right)^{n-1} \end{aligned}$$



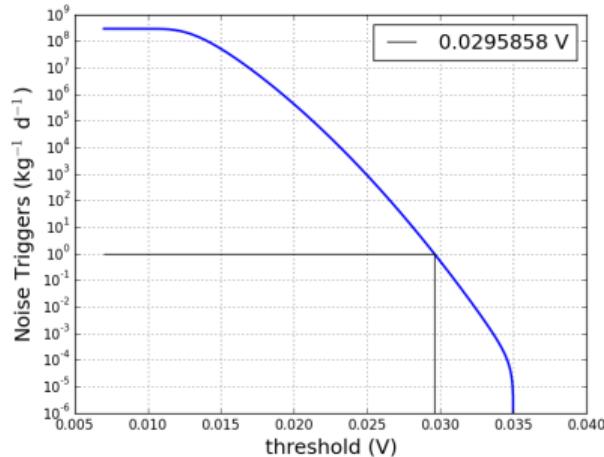
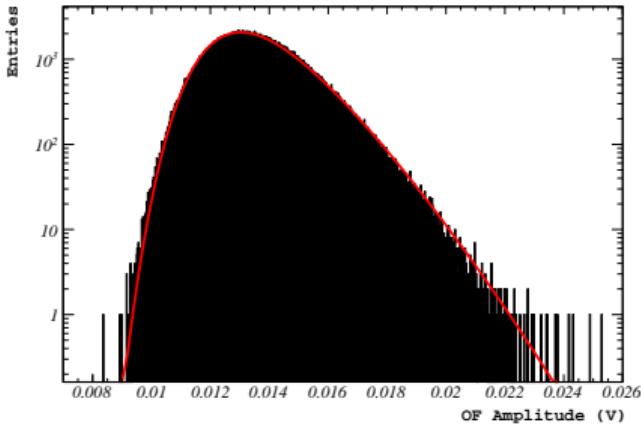
Contribution of gaussian noise



Threshold: 27.5 mV \Rightarrow 6.20 eV

Threshold determination

Cross check on inverted stream:



Threshold: 29.6 mV \Rightarrow 6.70 eV

References luminescence

- [1] W.A. Runciman. Sapphire luminescence under X-ray excitation. *Solid State Communications*, 6(8):537-539, 1968.
- [2] M. Kirm, G. Zimmerer, E. Feldbach, A. Lushchik, Ch. Lushchik, and F. Savikhin. Self-trapping and multiplication of electronic excitations in Al_2O_3 and $\text{Al}_2\text{O}_3:\text{Sc}$ crystals. *Phys. Rev. B*, 60:502-510, Jul 1999.
- [3] A. Lushchik, M. Kirm, Ch. Lushchik, I. Martinson, and G. Zimmerer. Luminescence of free and self-trapped excitons in wide-gap oxides. *Journal of Luminescence*, 87-89:232-234, 2000.
- [4] Marco Kirm, Vachagan Harutunyan, Vladimir Makhov, and Sebastian Vielhauer. VUV luminescence of as-grown and electron irradiated corundum single crystals. In Arnold Rosenthal, editor, *Optical Materials and Applications*, volume 5946, page 594606, International Society for Optics and Photonics, SPIE, 2006.