LOW-MASS DARK MATTER SEARCH WITH THE CRESST-III EXPERIMENT

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for the CRESST collaboration

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

14th International Workshop Dark Side Of the Universe – Annecy, June 2018

The CRESST collaboration

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

HEPHY Institut für Hochenergiephysik

EBERHARD KARLS UNIVERSITÄT TÜBINGEN

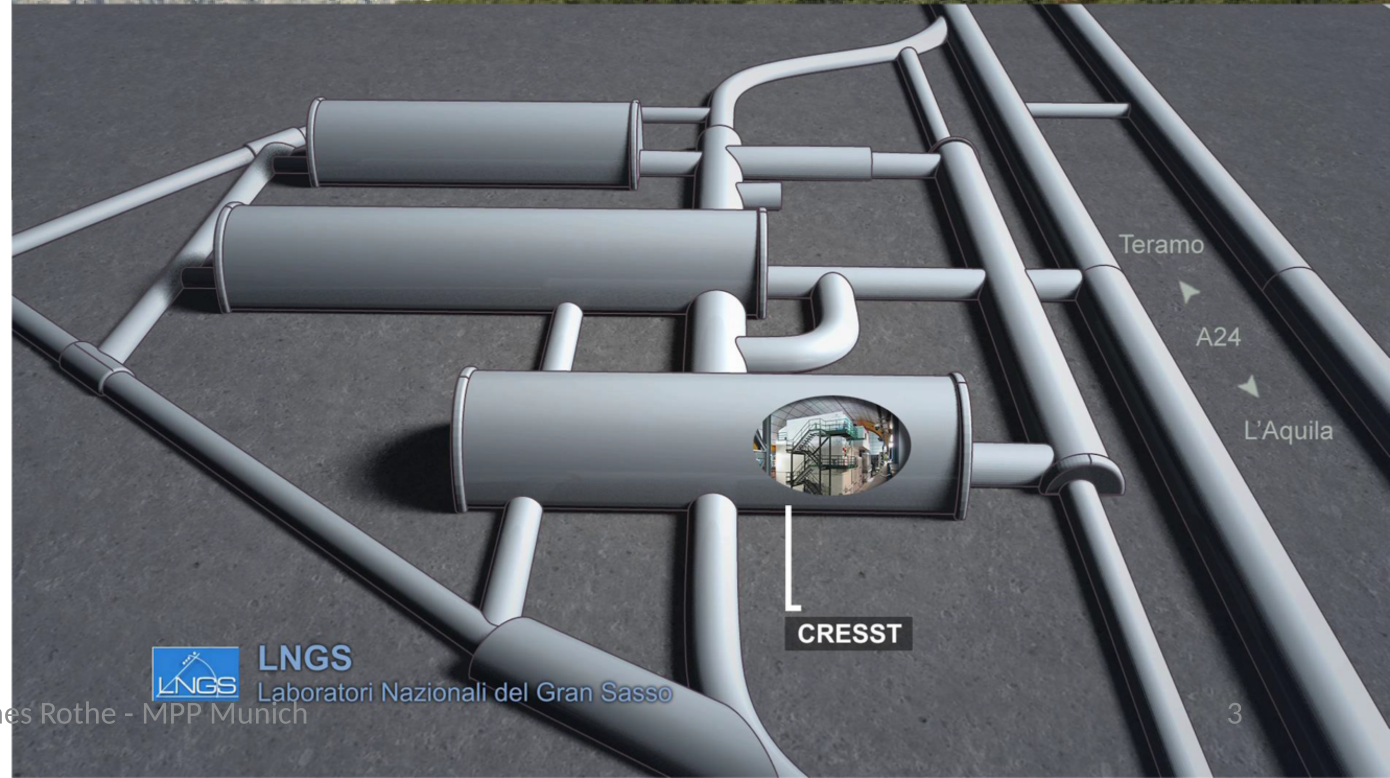
TECHNISCHE UNIVERSITÄT MÜNCHEN

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

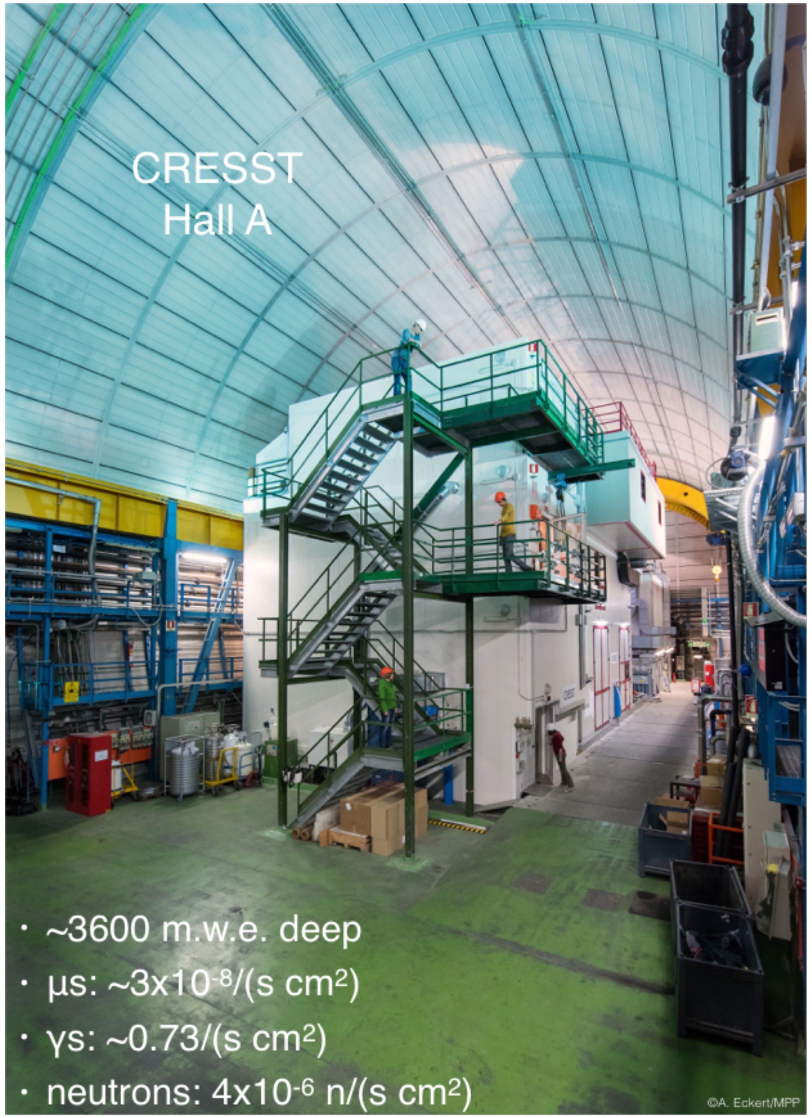
INFN LNGS Istituto Nazionale di Fisica Nucleare Laboratori Nazionali del Gran Sasso

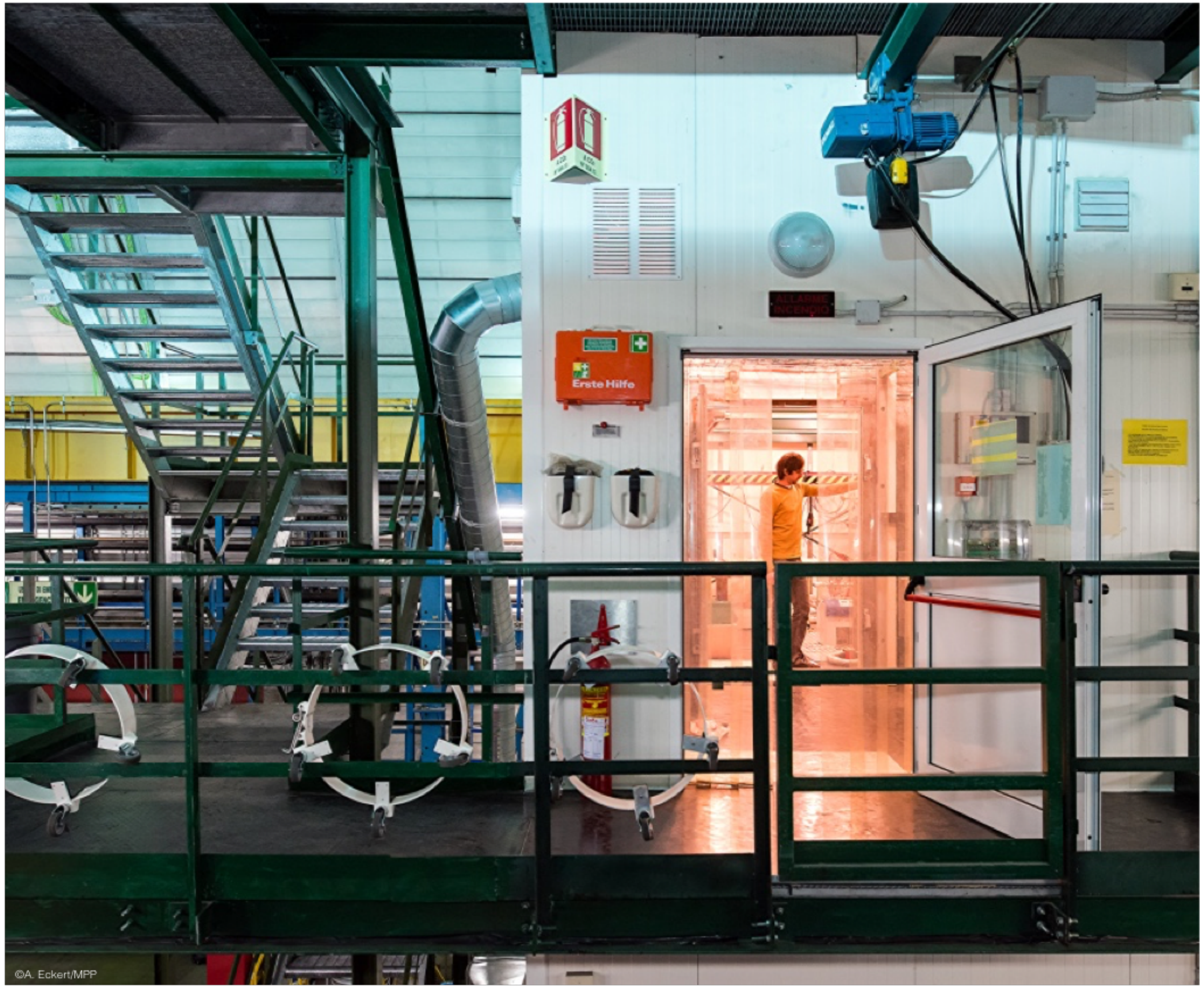
UNIVERSITY OF OXFORD

Laboratori Nazionali del Gran Sasso (LNGS)

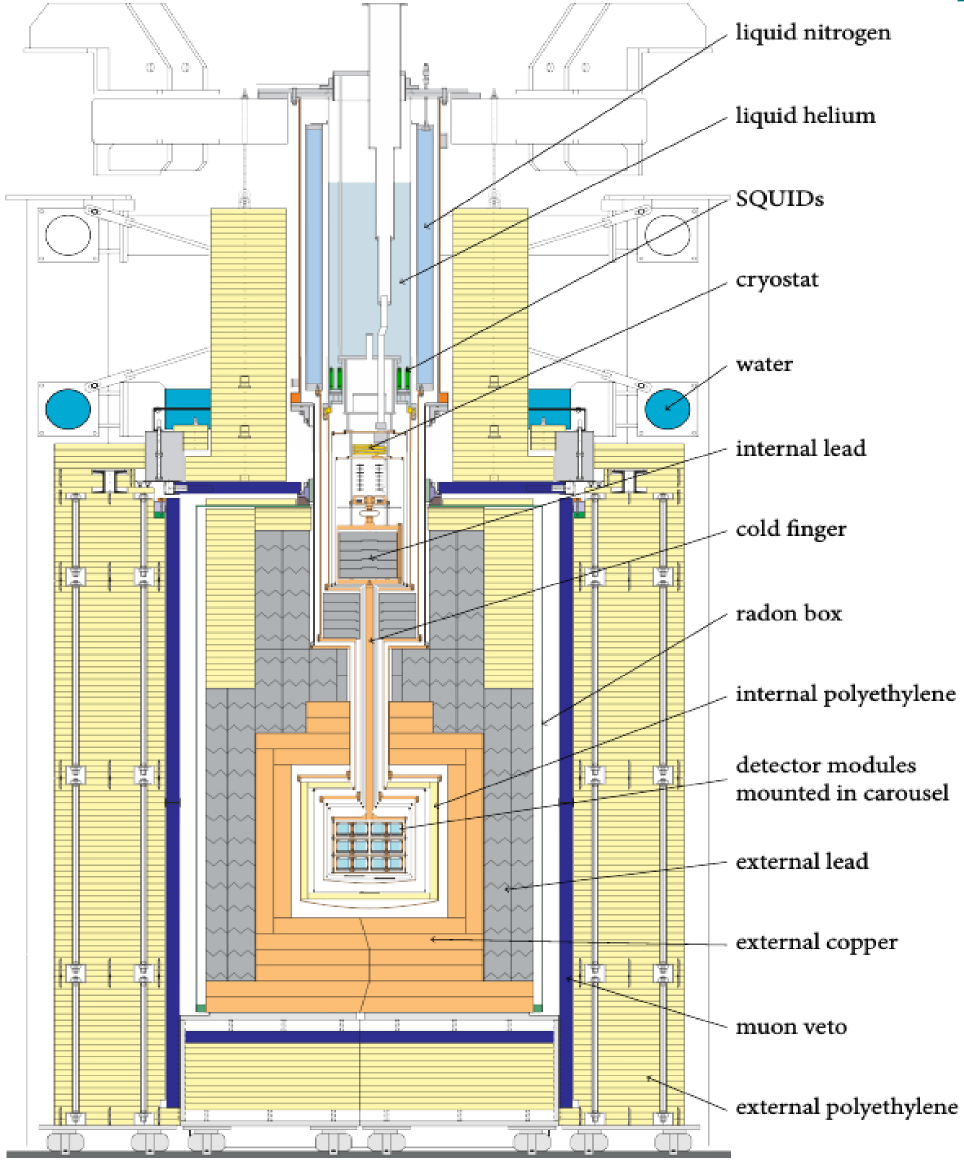


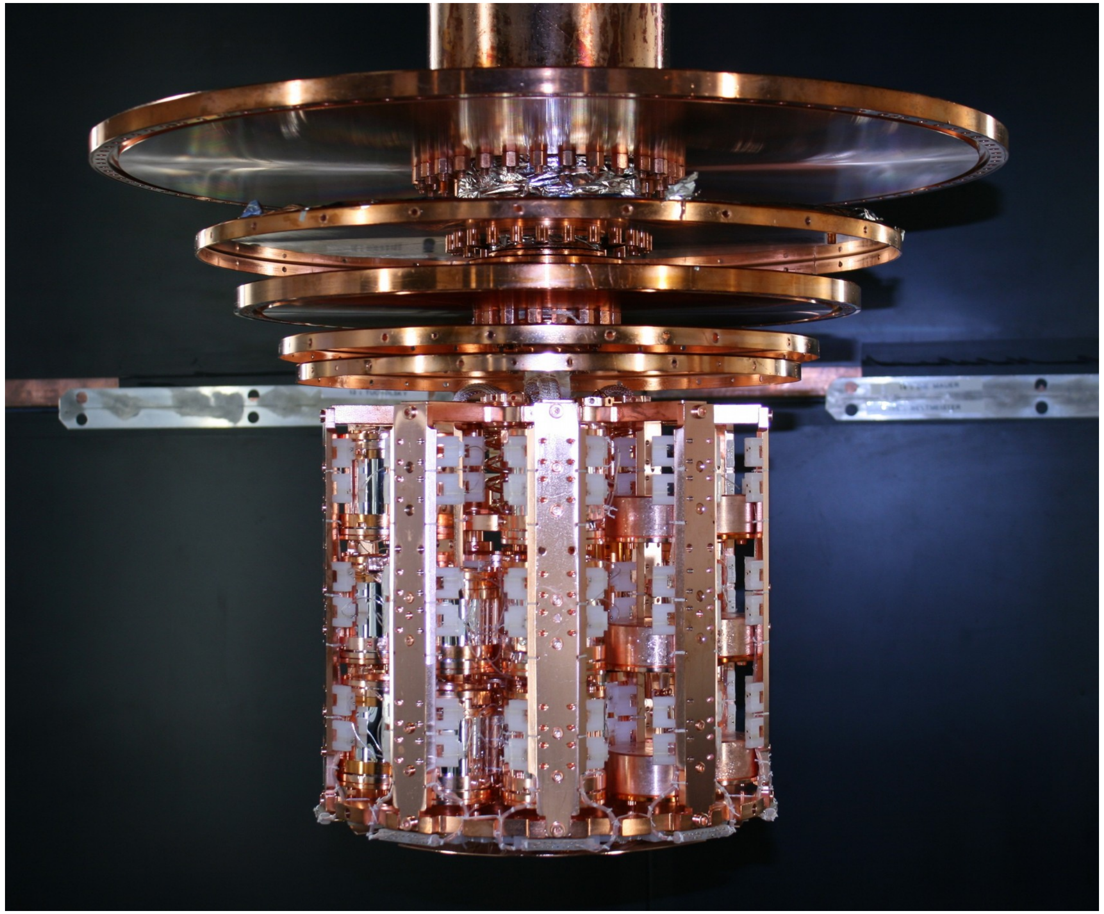
CRESST @ LNGS


CRESST
Hall A
• ~3600 m.w.e. deep
• µs: ~$3x10^{-8}$/(s cm^2)
• γs: ~0.73/(s cm^2)
• neutrons: $4x10^{-6}$ n/(s cm^2)
©A. Eckert/MPP

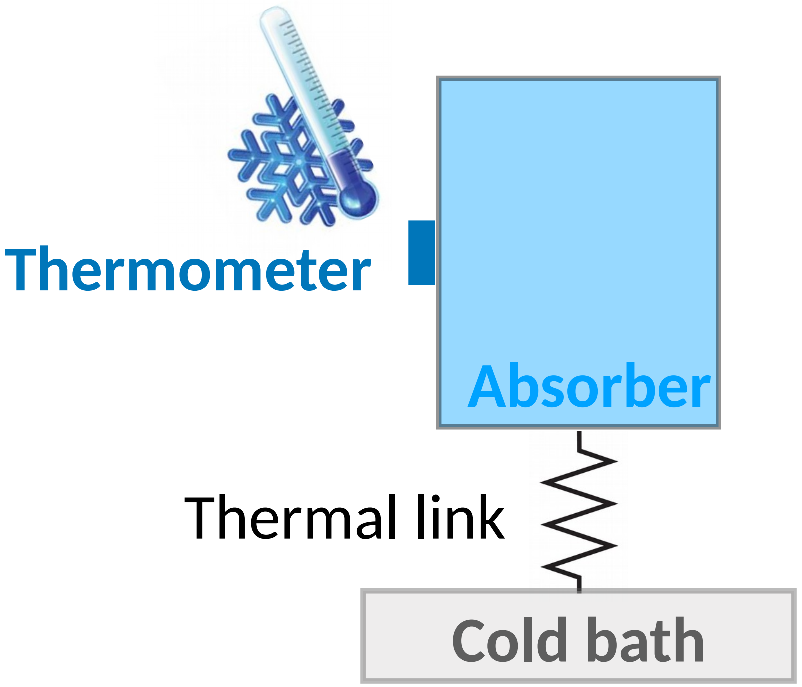

Erste Hilfe
©A. Eckert/MPP

The experimental setup

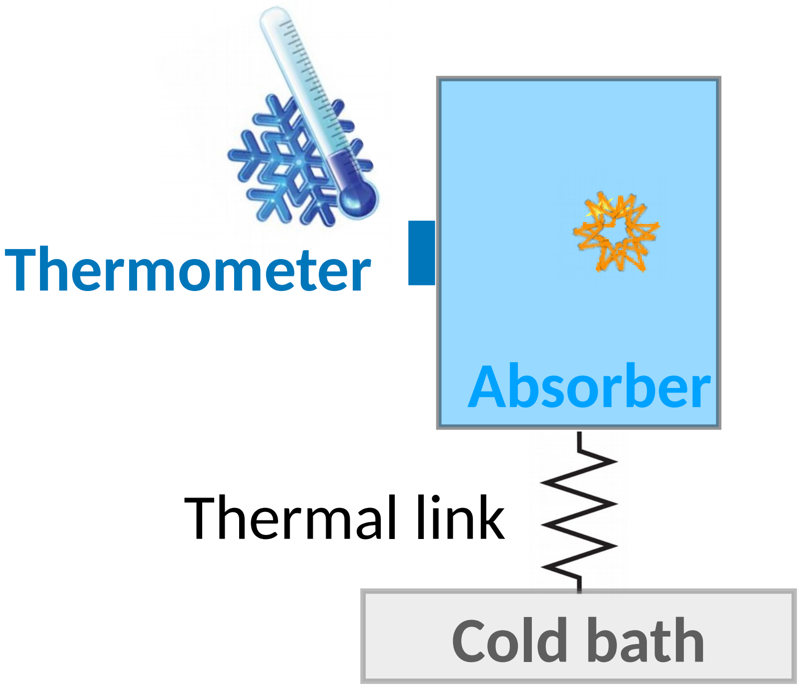


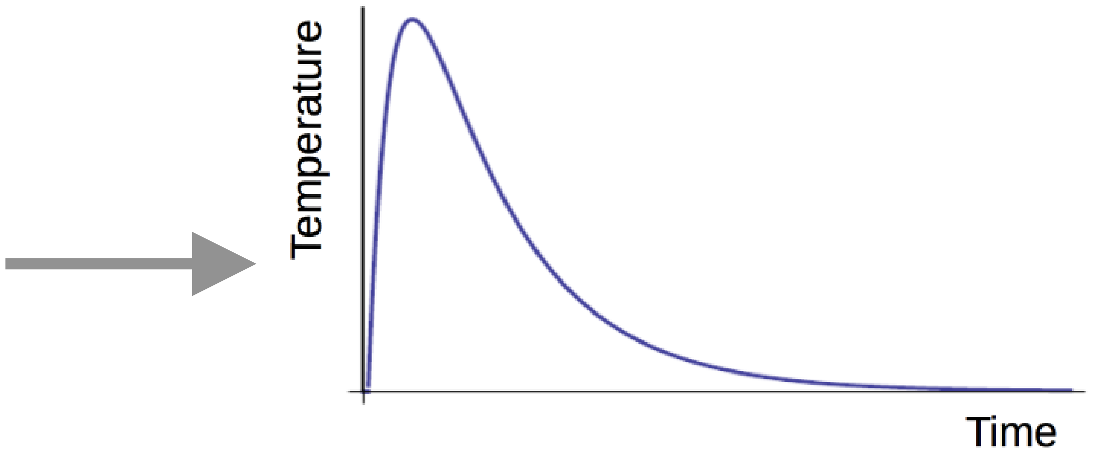


Cryogenic Calorimeters



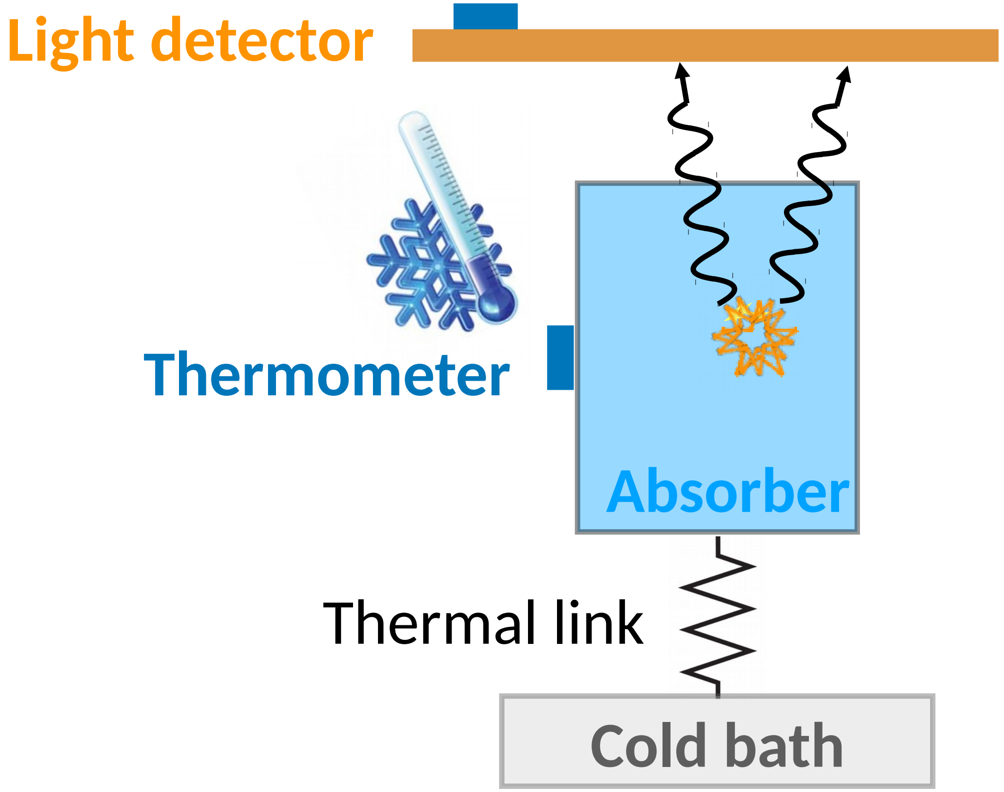
Cryogenic Calorimeters

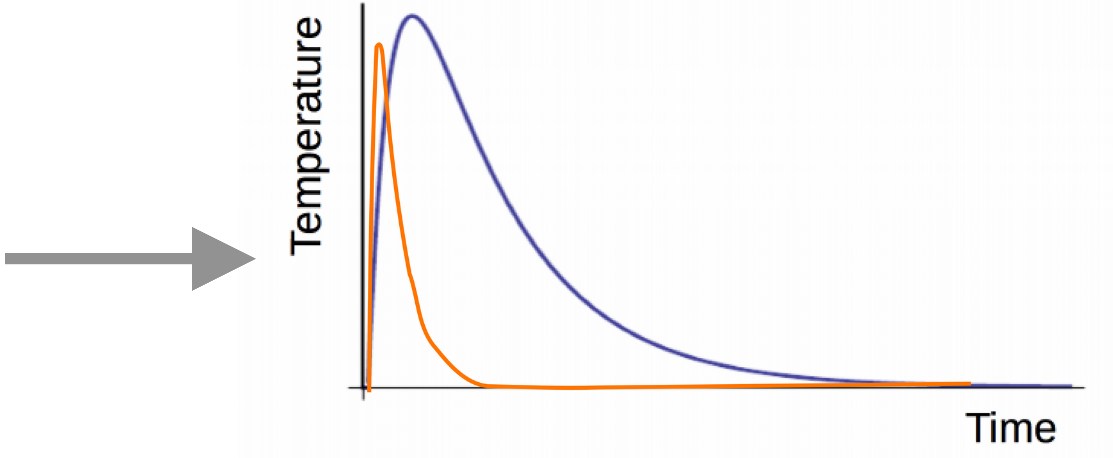




- Measurement of total deposited **energy** (~particle independent).

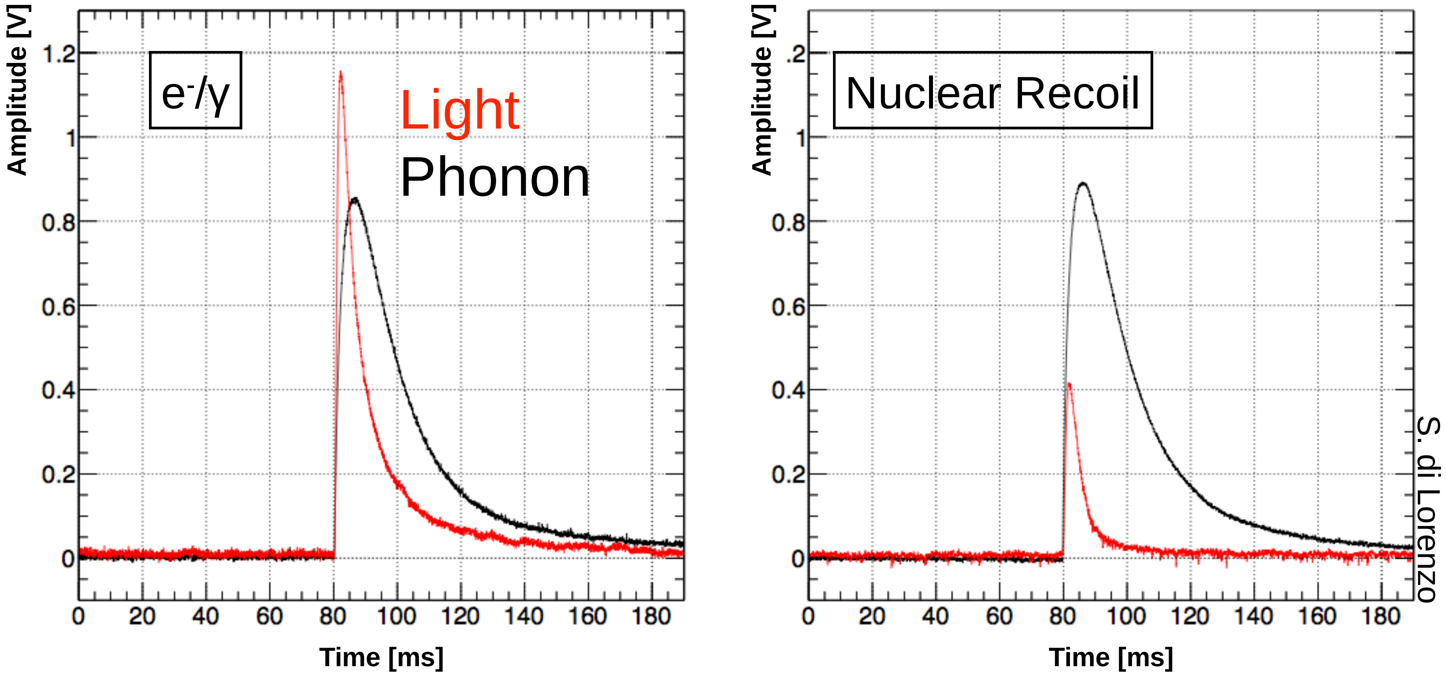
Scintillating Cryogenic Calorimeters





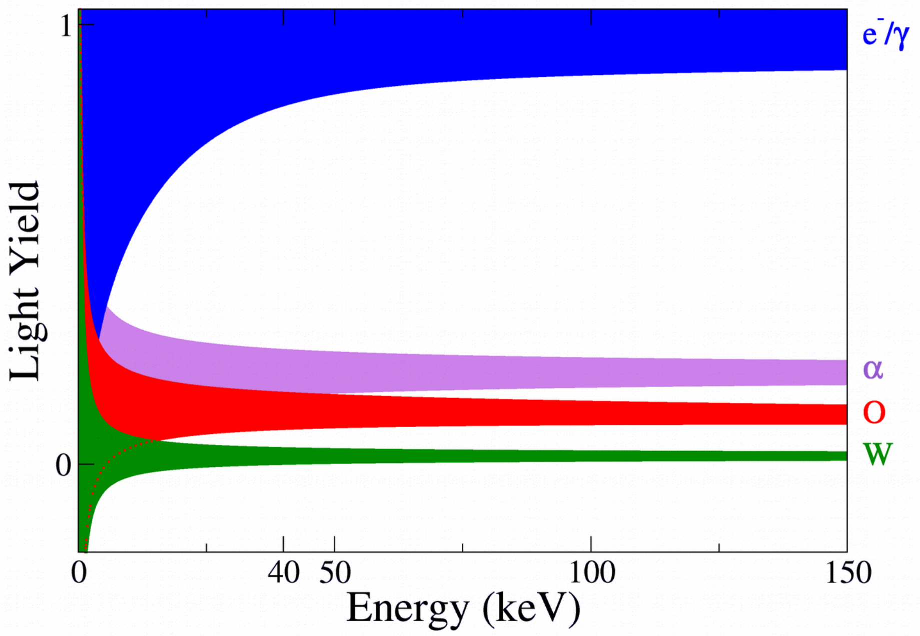
- Measurement of total deposited **energy** (~particle independent).
- **Particle identification** given by the measurement of the scintillation light (Light yield).

Event Discrimination



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

Characteristic of the event type



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

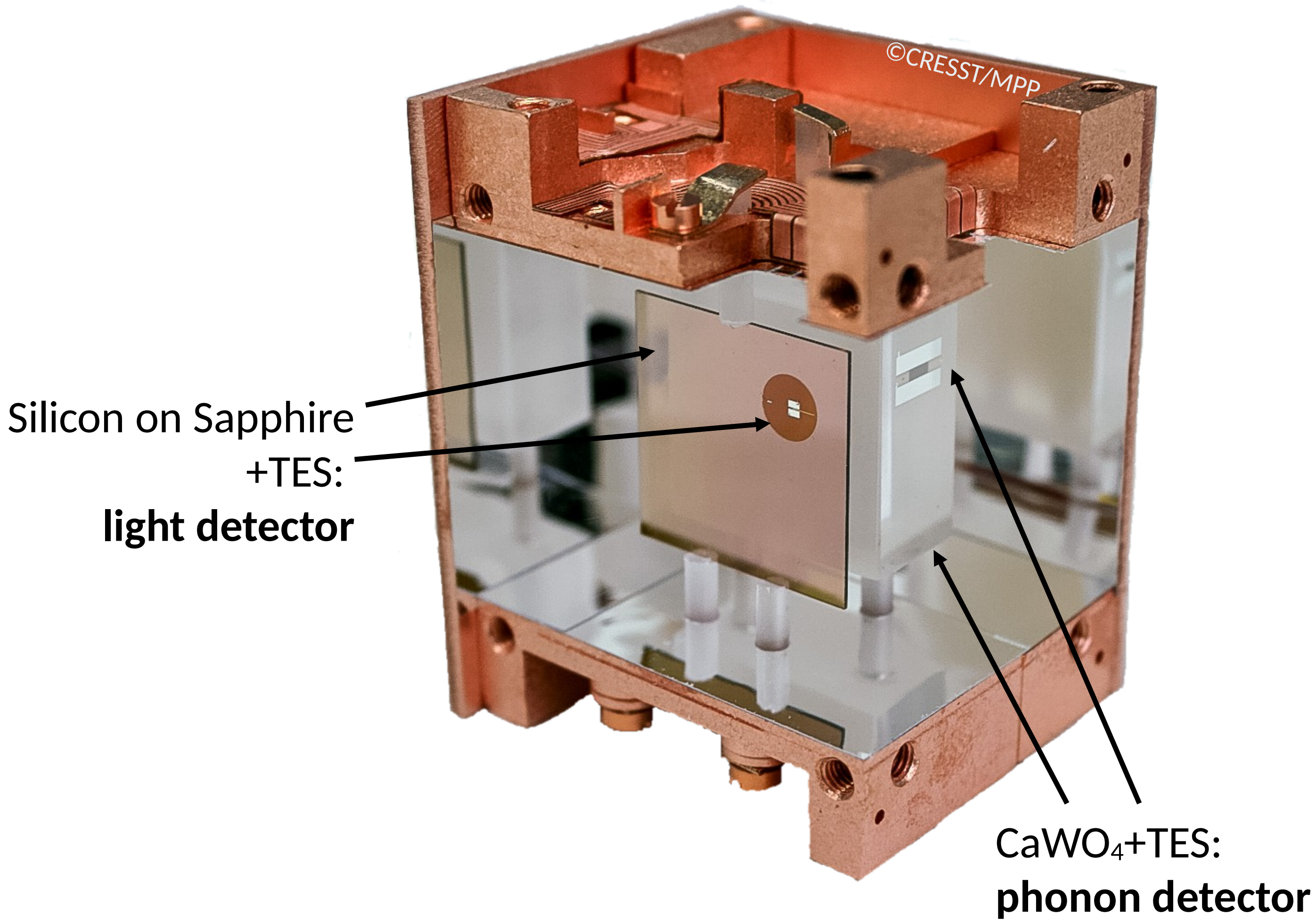
CRESST Modules: scintillating cryogenic calorimeters

Crystals operated as
cryogenic calorimeters (~15mK)

Target crystal (phonon signal):
Scintillating $CaWO_4$, 2x2x1 cm^3

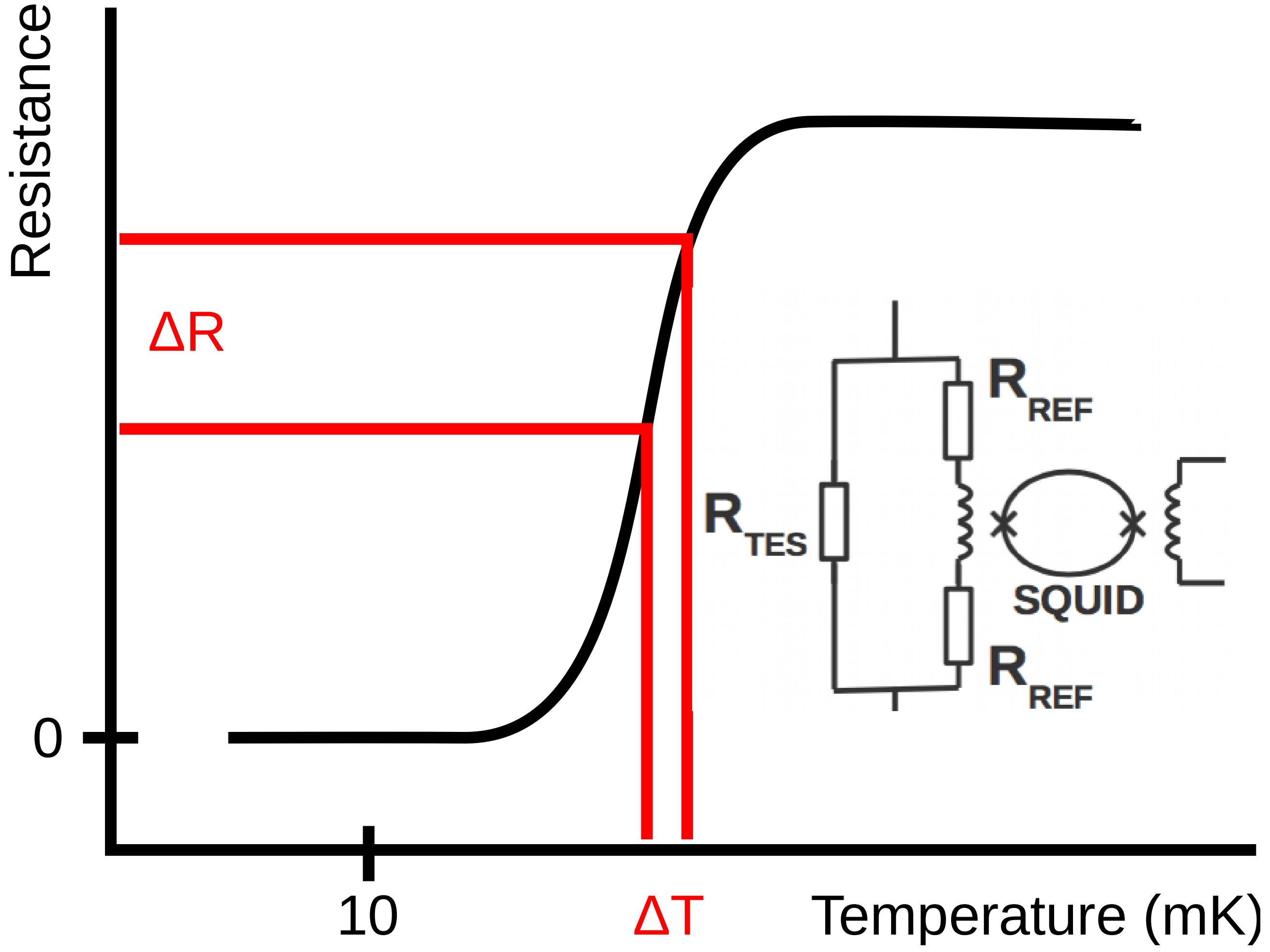
Light detector:
Silicon on Sapphire (SOS)
detects scintillation light signal

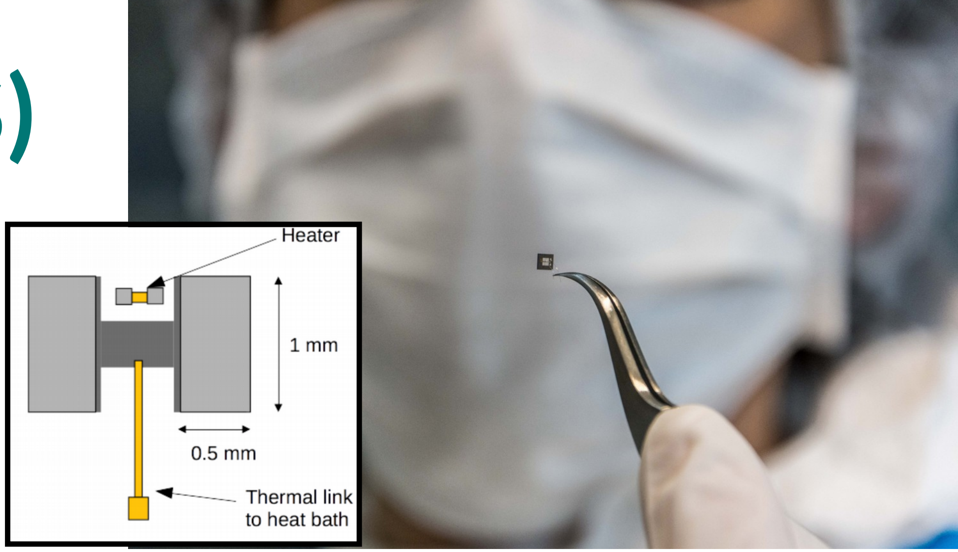
Tungsten **Transition Edge Sensors** (TES)
detect temperature fluctuations



Transition edge sensor (TES)

Working principle





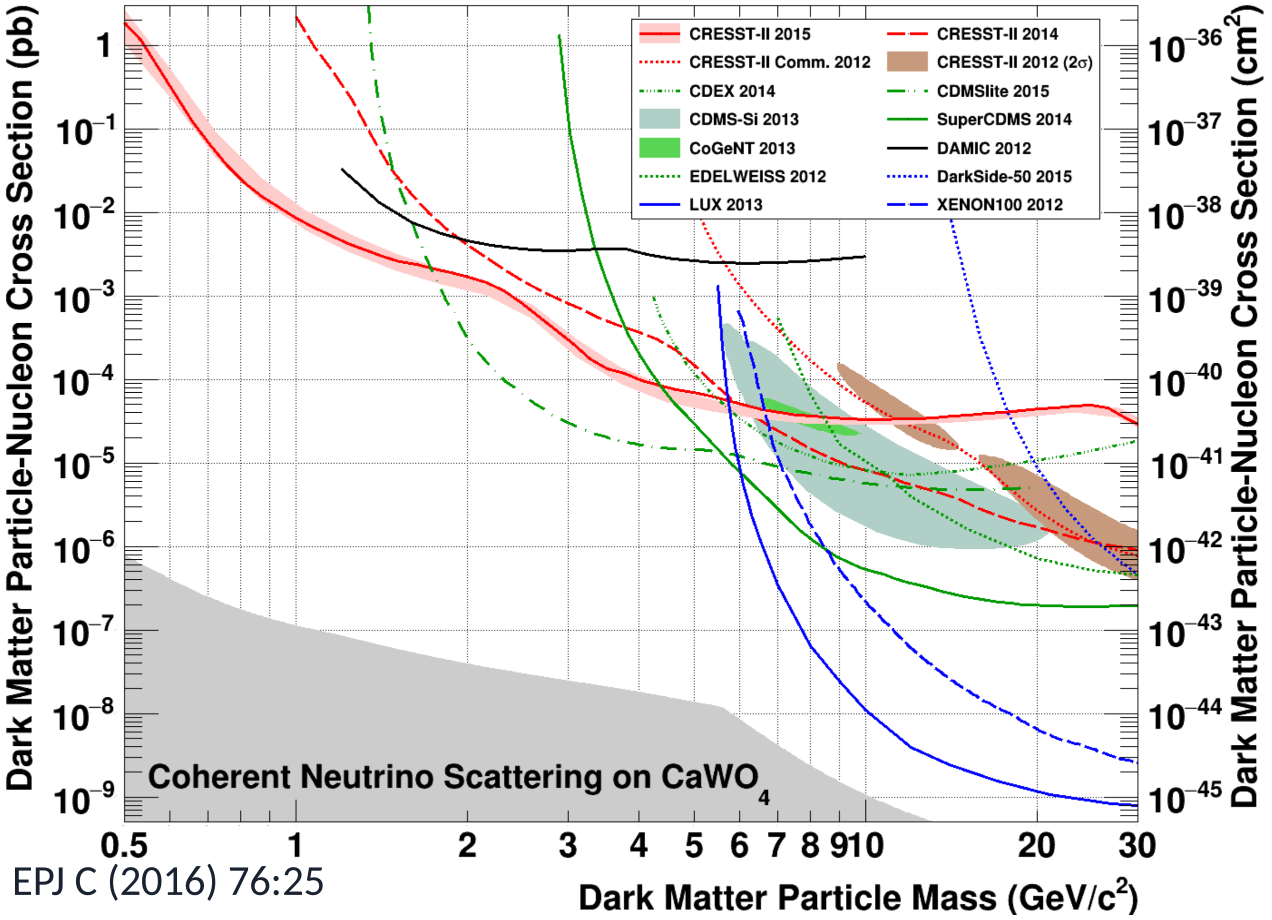
Energy deposition
~keV

Temperature rise
~µK

Resistance change
~mΩ

CRESST-II results (2015)

Most sensitive module **(Lise)**:
Detector mass: **300g** $CaWO_4$
Phonon detector threshold: **307eV**
Background level: **~8.5 cts/ (keV kg d)**
Exposure: **52 kg d**

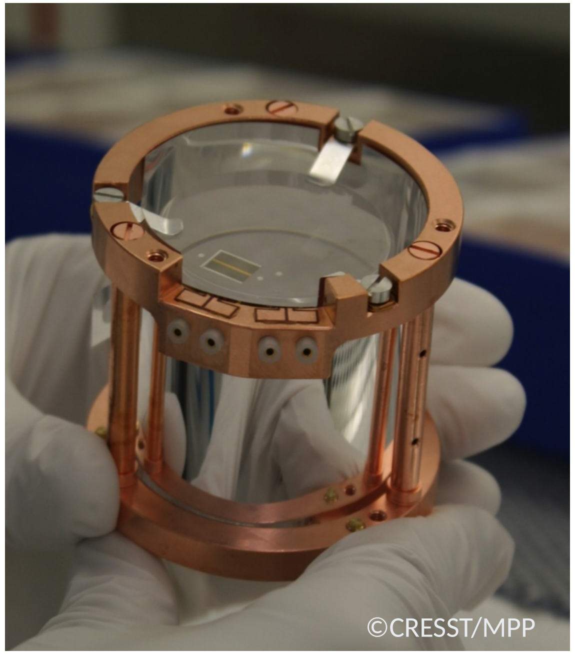


EPJ C (2016) 76:25

World-leading below 1.7GeV/c^2

Exploring new parameter space down to 0.5GeV/c^2

Hunting light dark matter requires a low threshold!



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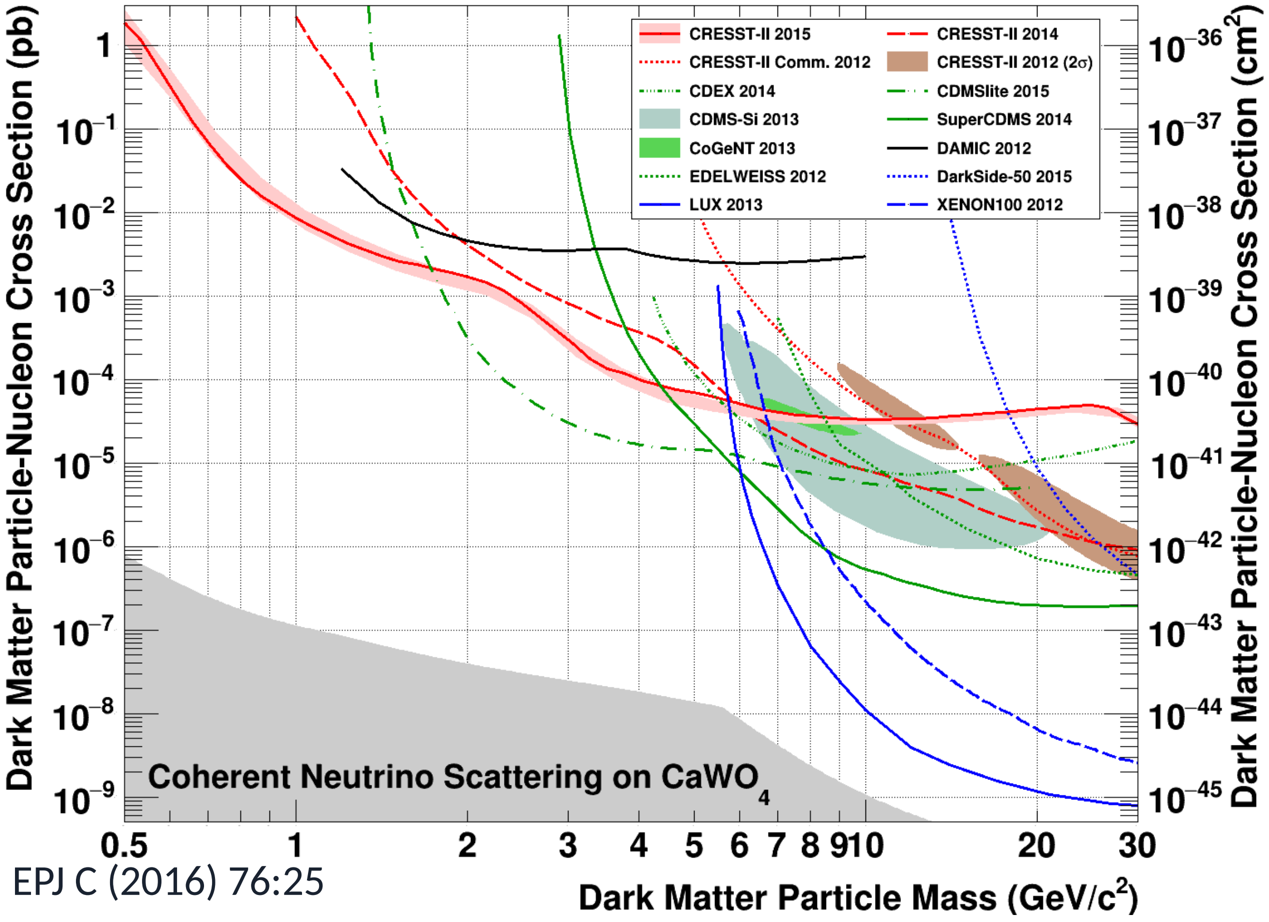

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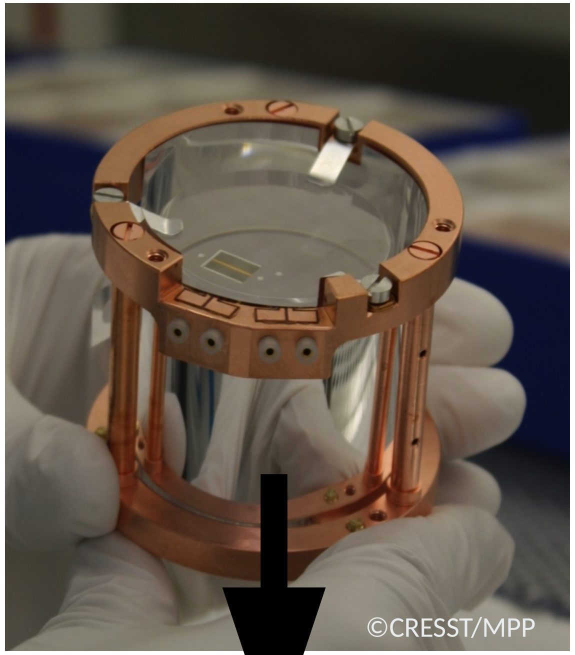
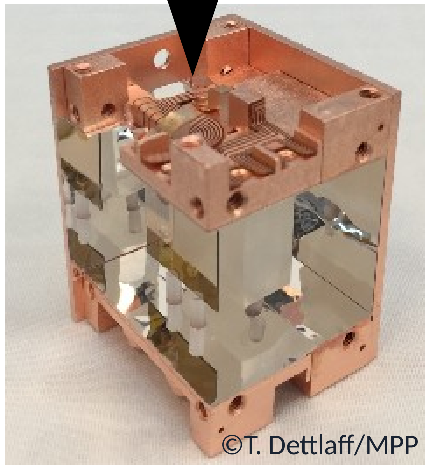


Layout optimized for low-mass dark matter

Radical reduction of dimension (300g → 24g)

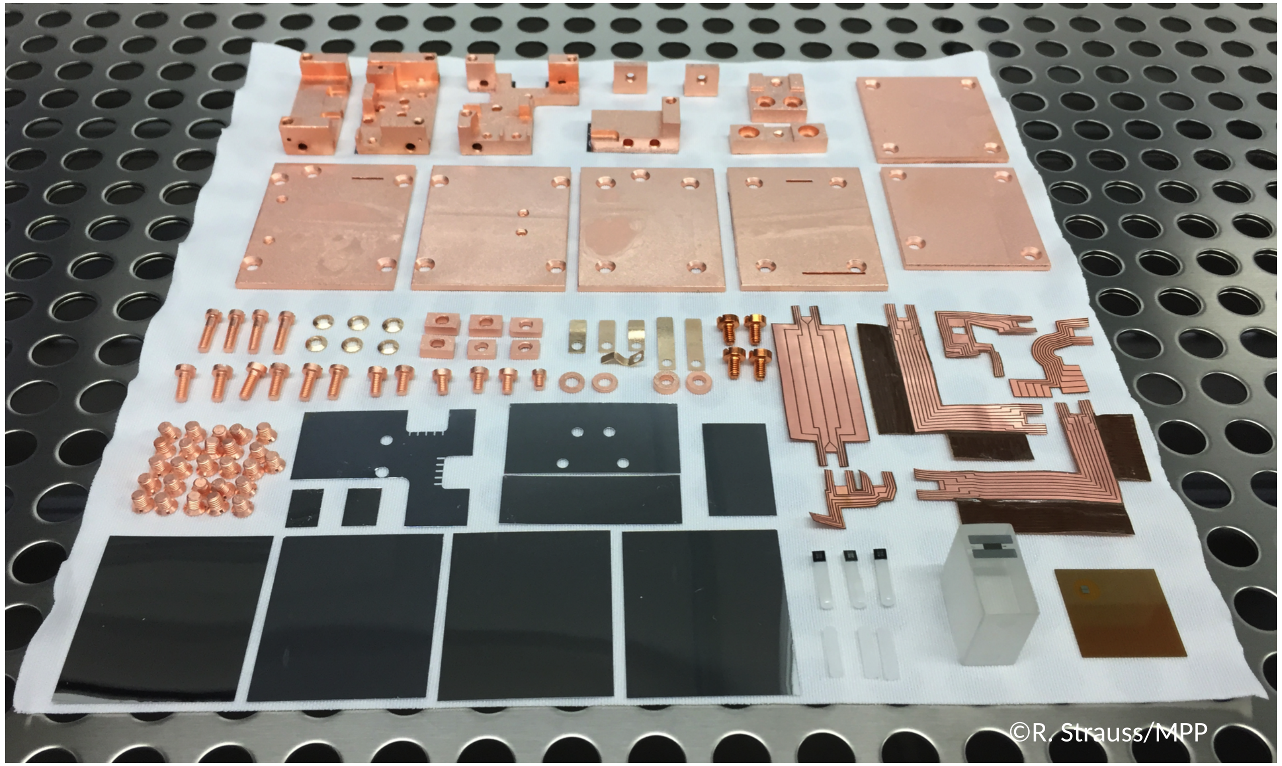
Threshold design goal **100 eV**

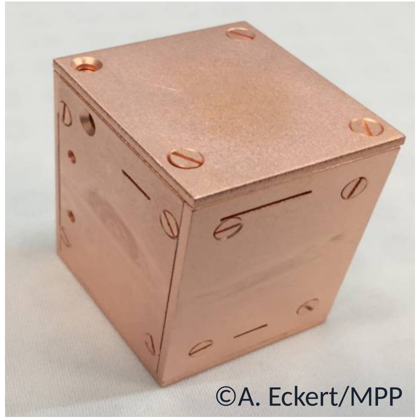


- Fully scintillating housing
- Instrumented sticks

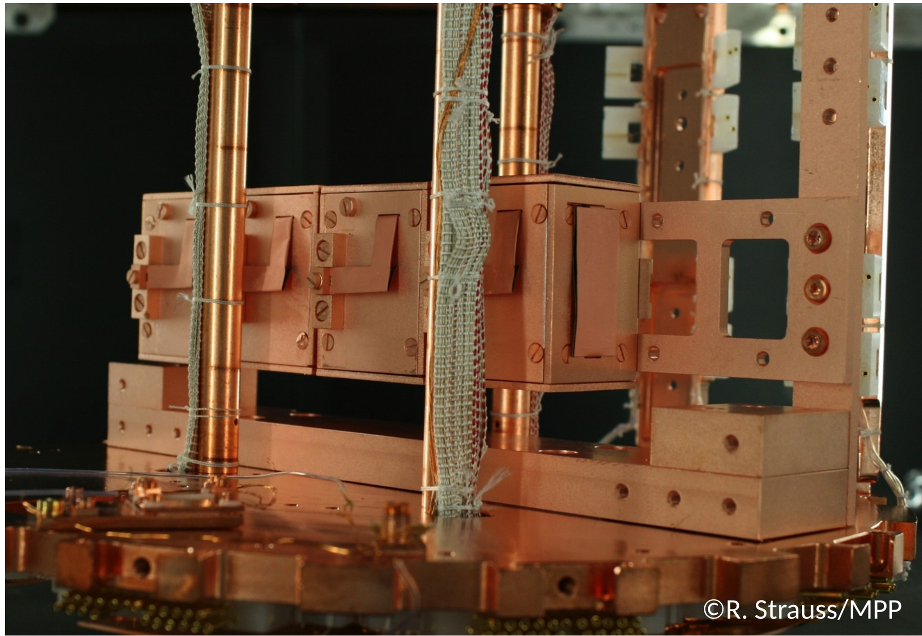
} Veto surface-related background

First Run of CRESST-III





x10

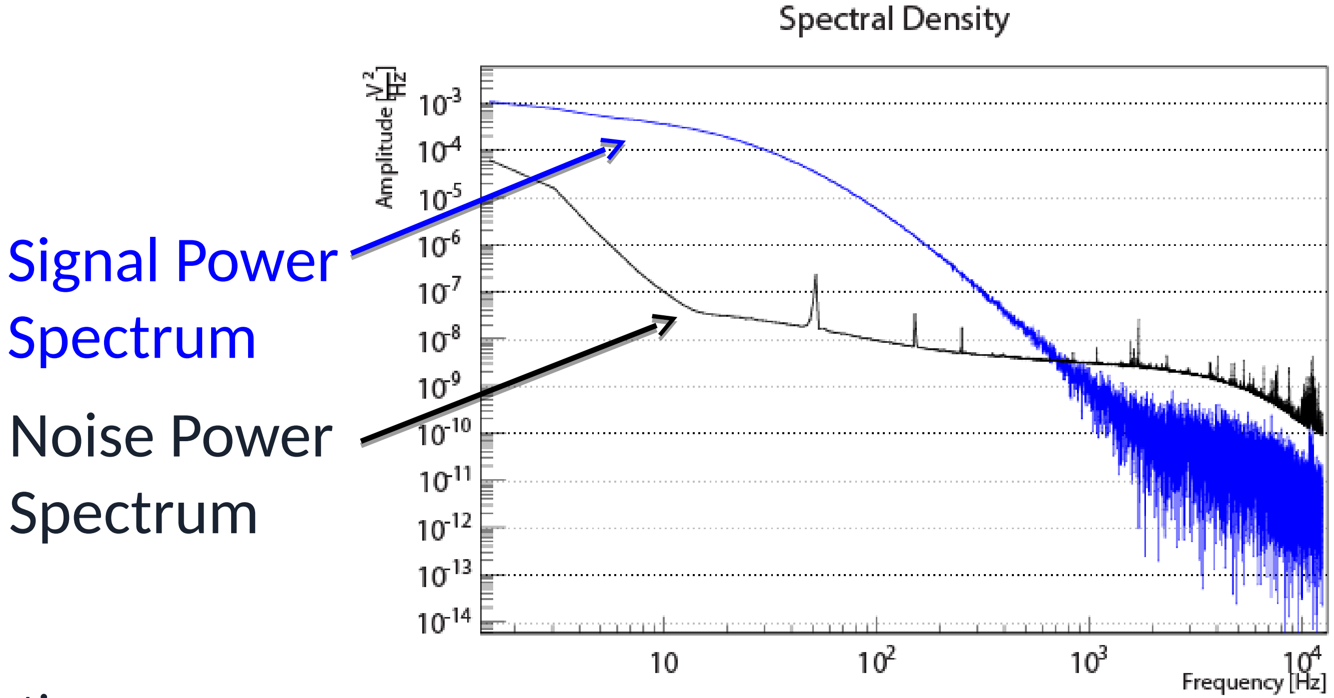


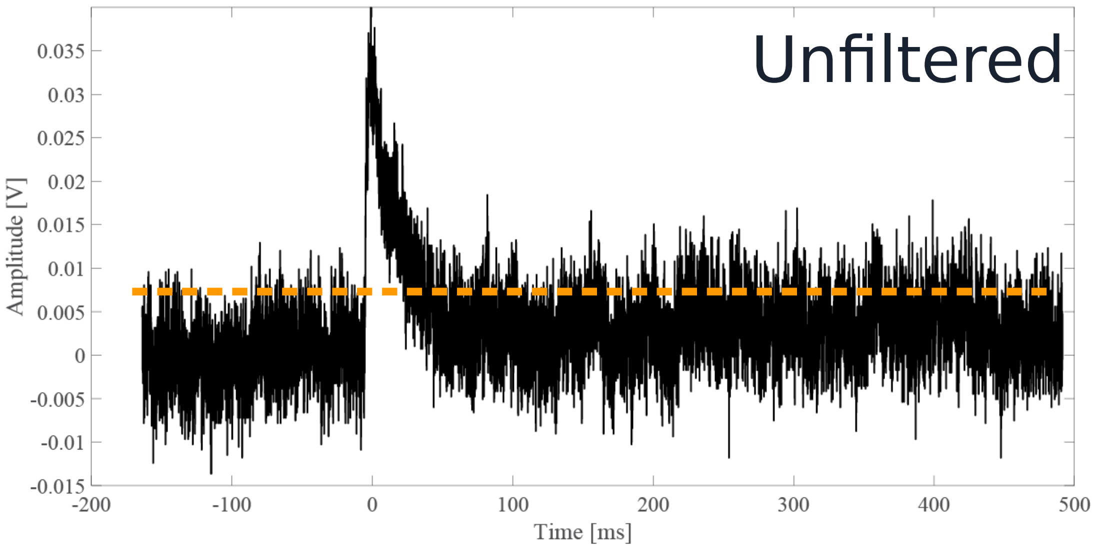
Data taking from July 2016 to February 2018

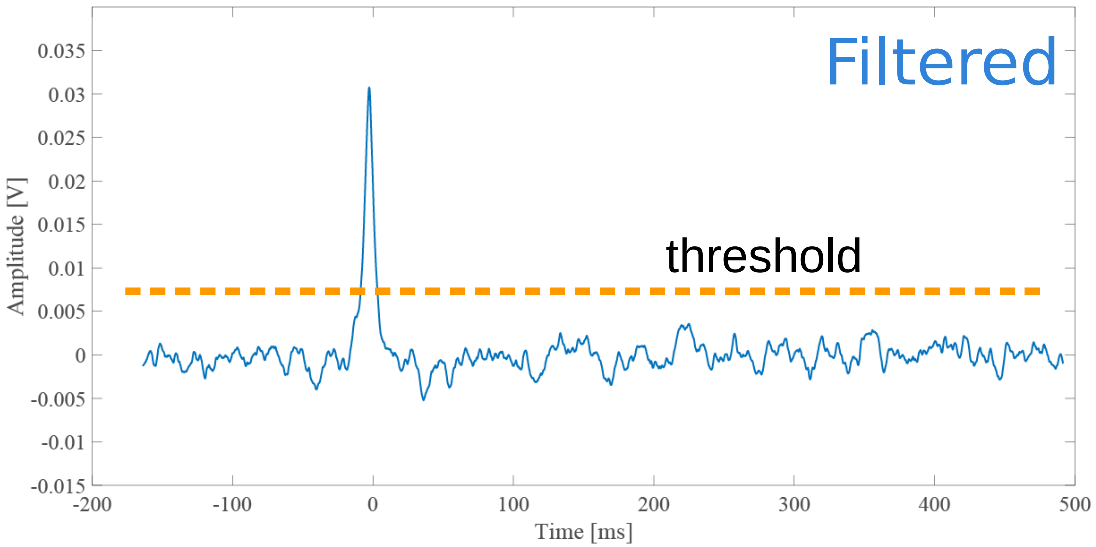
- Gamma calibration (350h)
- Neutron calibration (840h)

Optimum filter

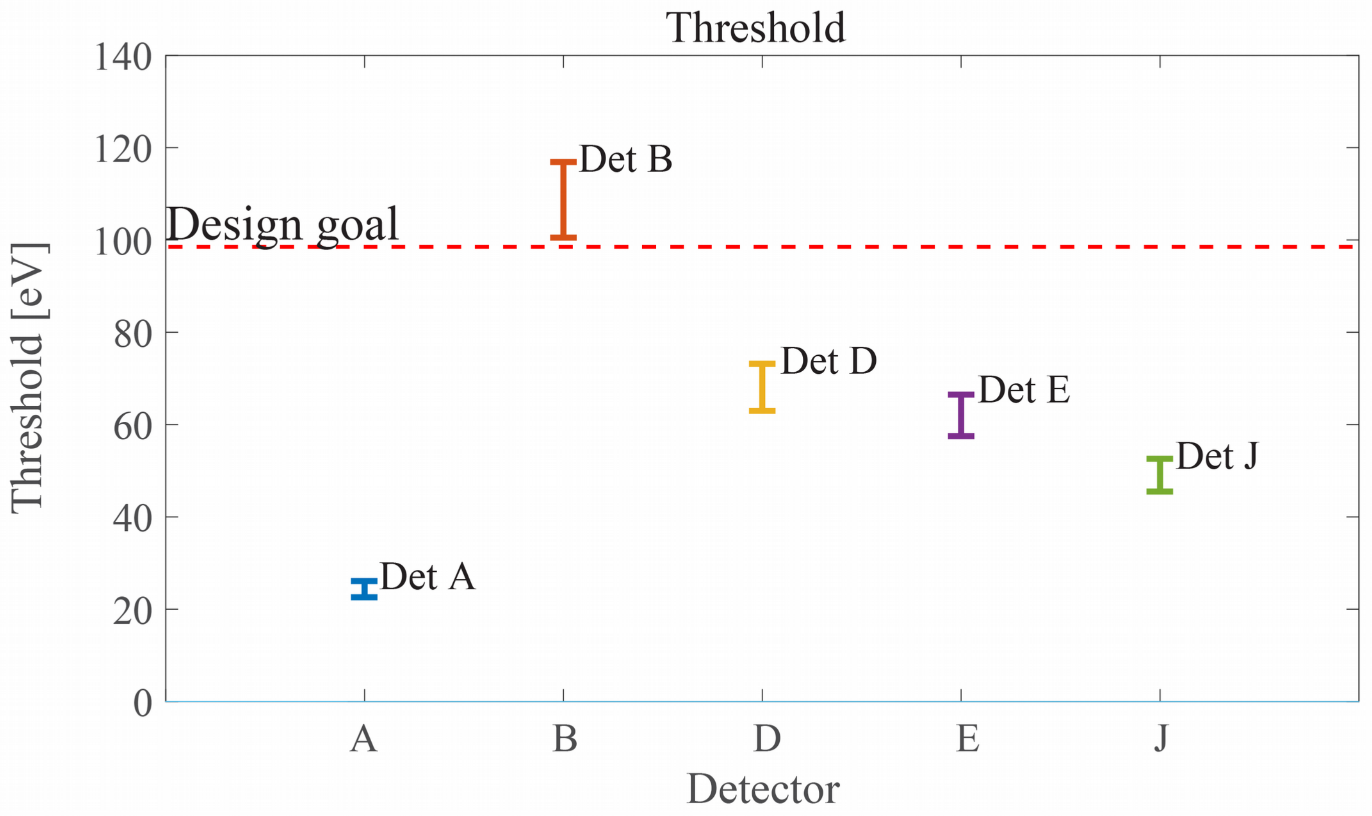
- Implemented in software
- Allows off-line triggering
- Maximizes signal-to-noise ratio (in frequency space)
- Factor 2-3 typical improvement in resolution







Detector thresholds



Threshold set as a function of accepted noise trigger rate

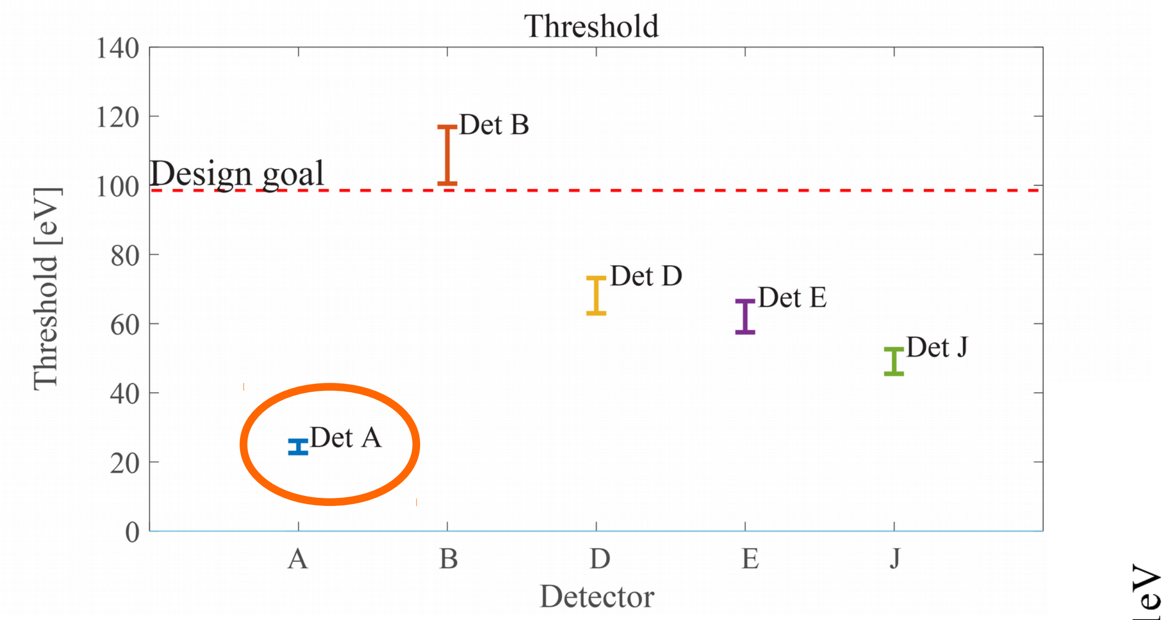
5 detectors reach/exceed the CRESST-III design goal

accepted noise trigger rate {

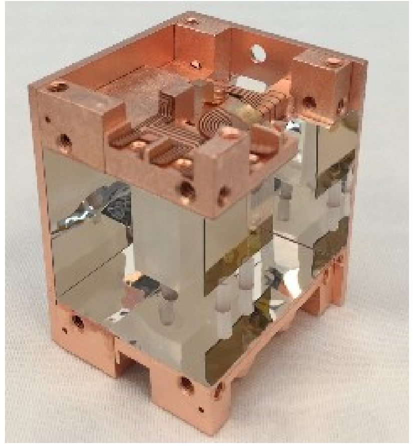
Threshold[eV]	Det A	Det B	Det D	Det E	Det J
100 cts/keV/day	22.6	100.5	63.0	57.5	45.5
1 count/keV/day	26.1	116.9	73.2	66.5	52.6

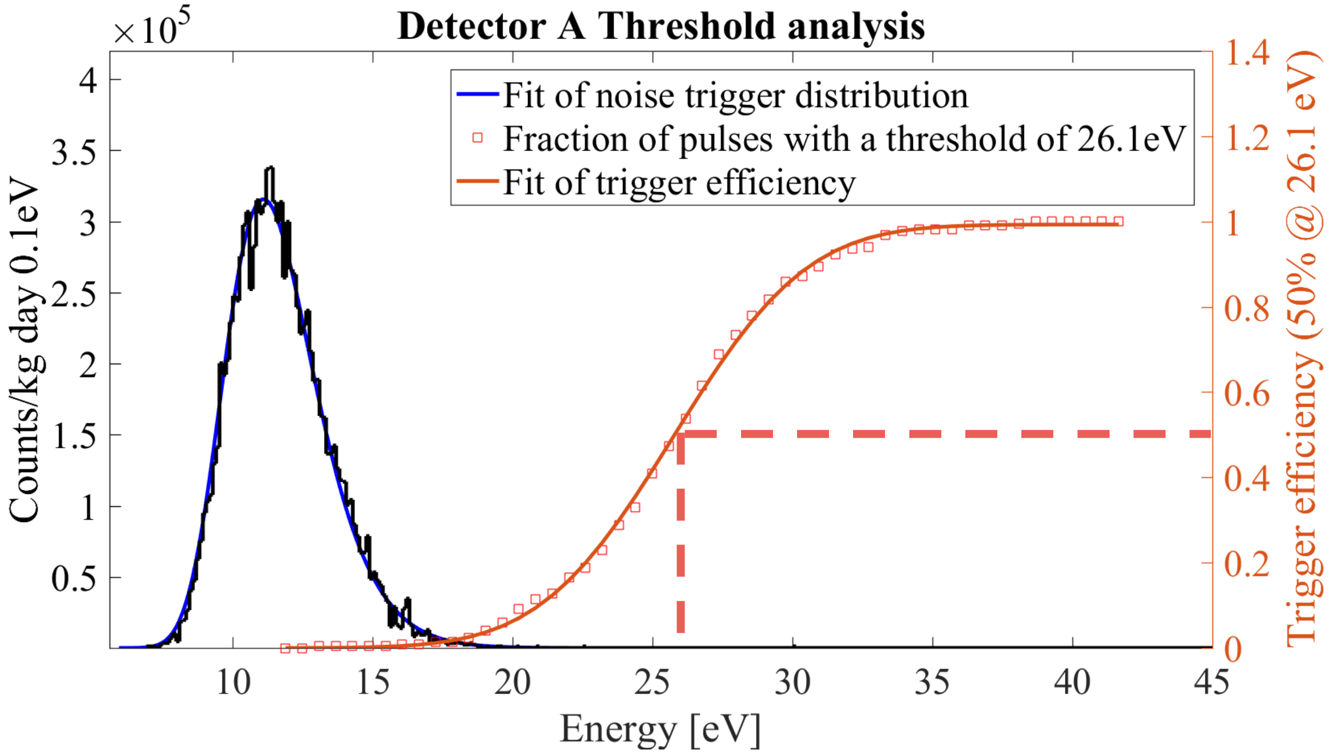
Mancuso, M. et al. (CRESST collaboration)
J Low Temp Phys (2018).
https://doi.org/10.1007/s10909-018-1948-6

Lowest Threshold: Detector A

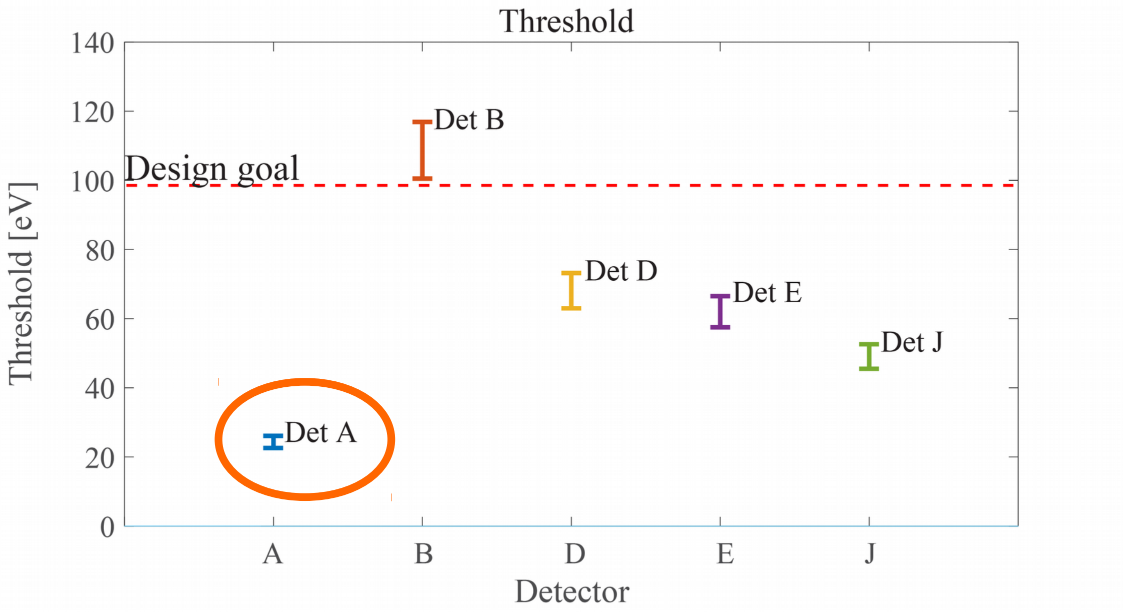


50% trigger efficiency
@threshold of 26.1 eV





First Data Analysis: Detector A



- **Data taking period**: 31/10/16 to 05/07/17
- **Detector mass**: 24 g
- **Total exposure**: 2.39 kg days
- **Net exposure** (after cuts): 2.21 kg days
- **Analysis Threshold**: 100 eV

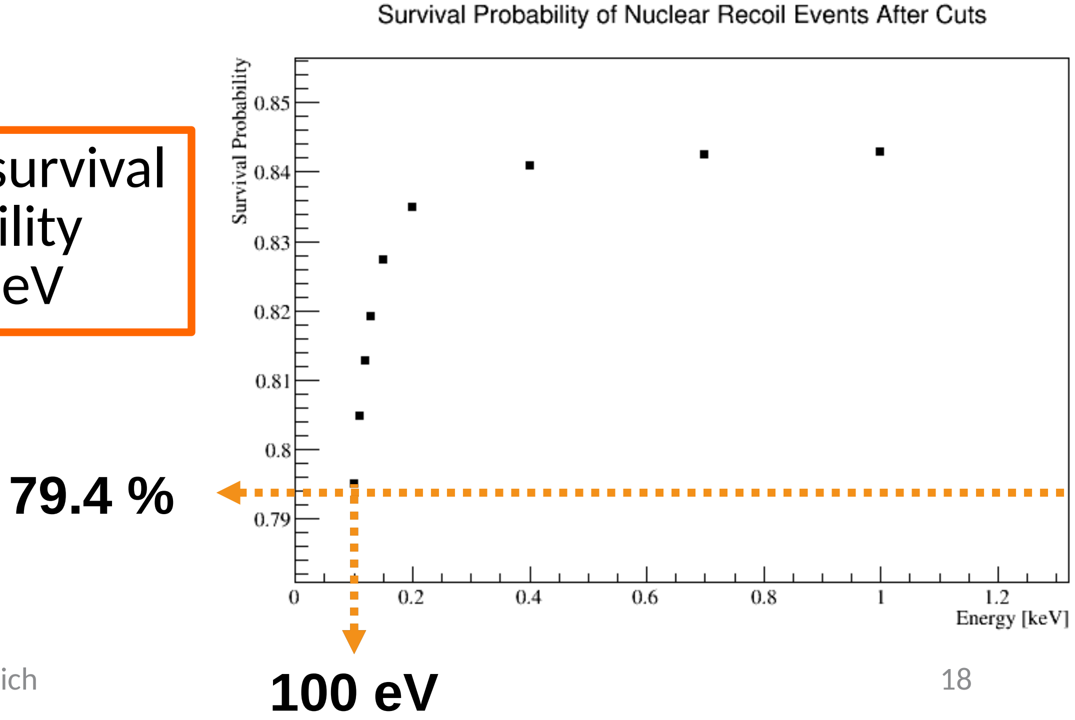
Data Selection

Keep only events where a correct determination of the amplitude (→energy) is guaranteed

Unbiased (blind) analysis

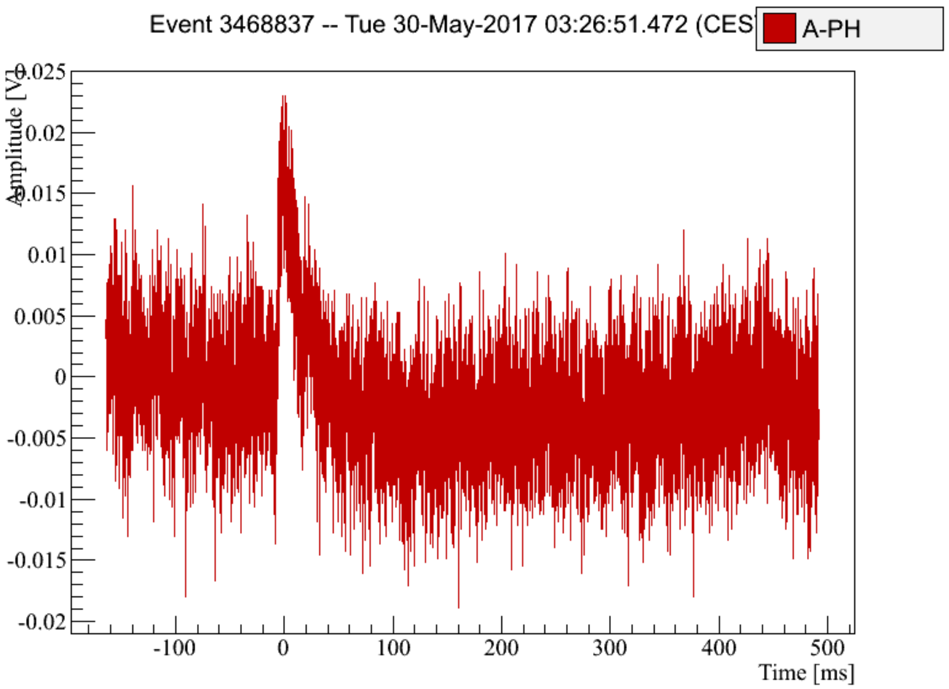
1. Design cuts on non-blind training set (~20%, excluded from DM data set)
2. Apply without change to blind DM data set

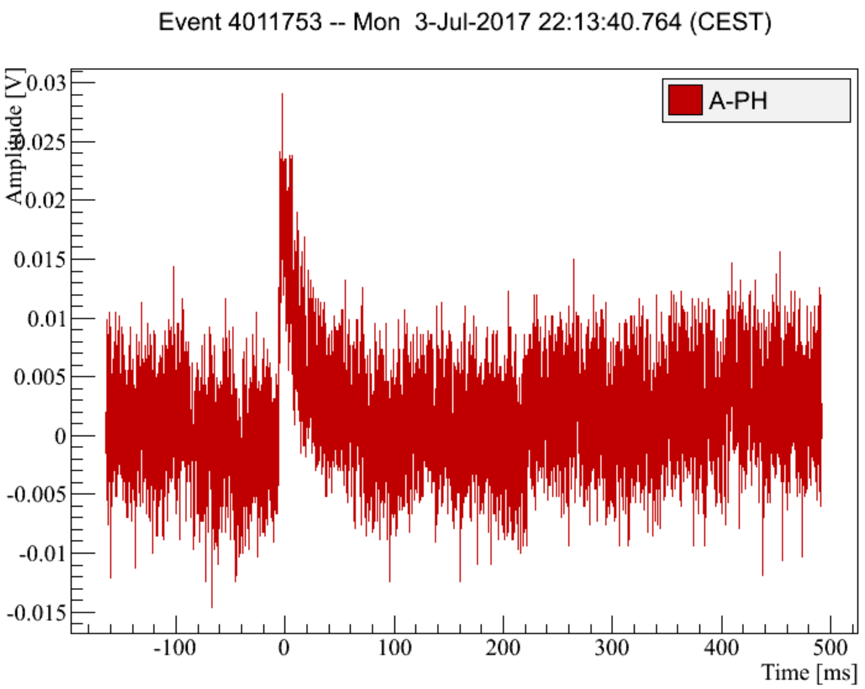
79.4% survival probability at 100 eV



Detector A – 100 eV events

Raw signals: no filtering, fitting etc.

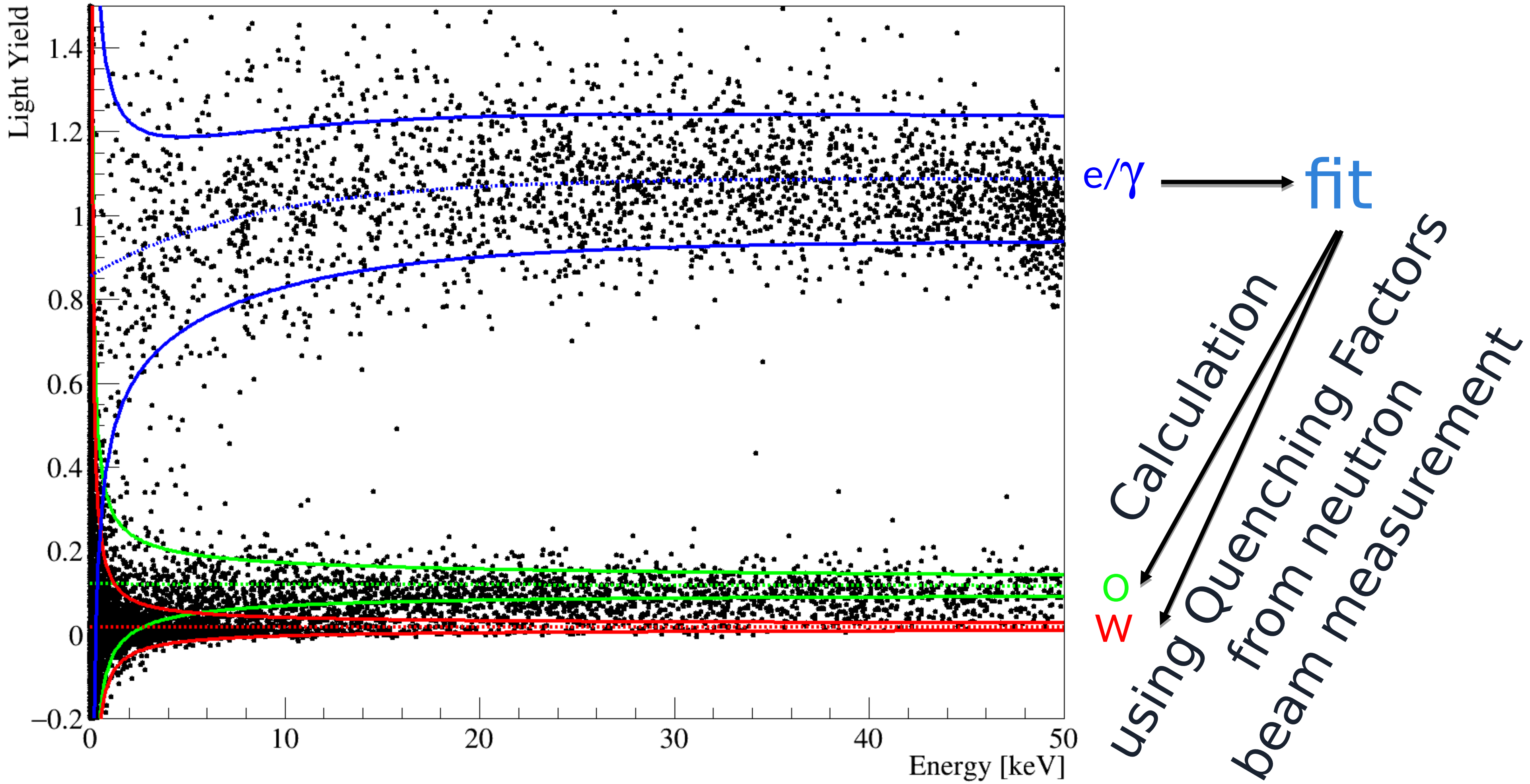




100eV pulses are no challenge for amplitude determination

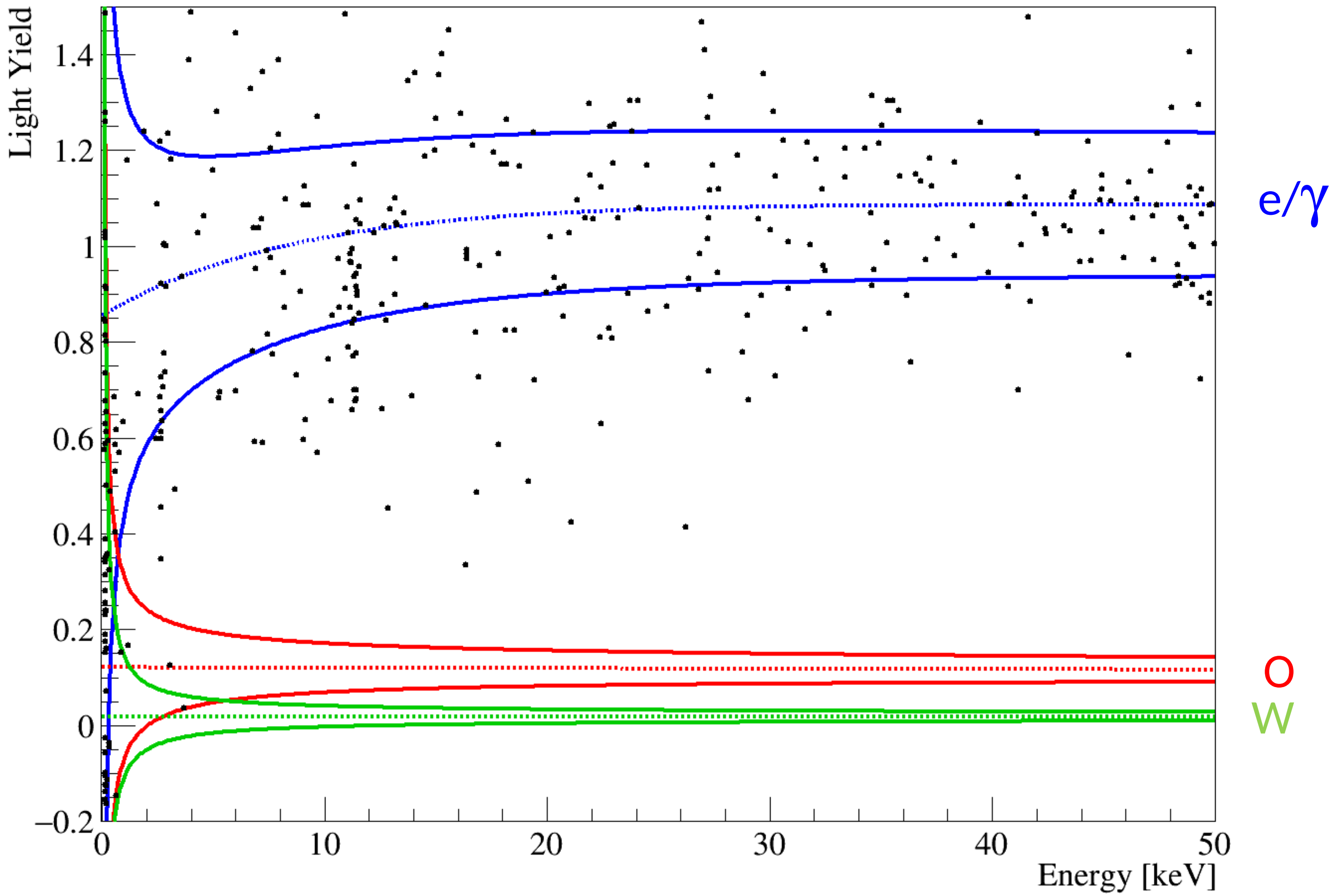
Detector A – 100eV threshold analysis

Neutron calibration data



Detector A – 100eV threshold analysis

Dark Matter data

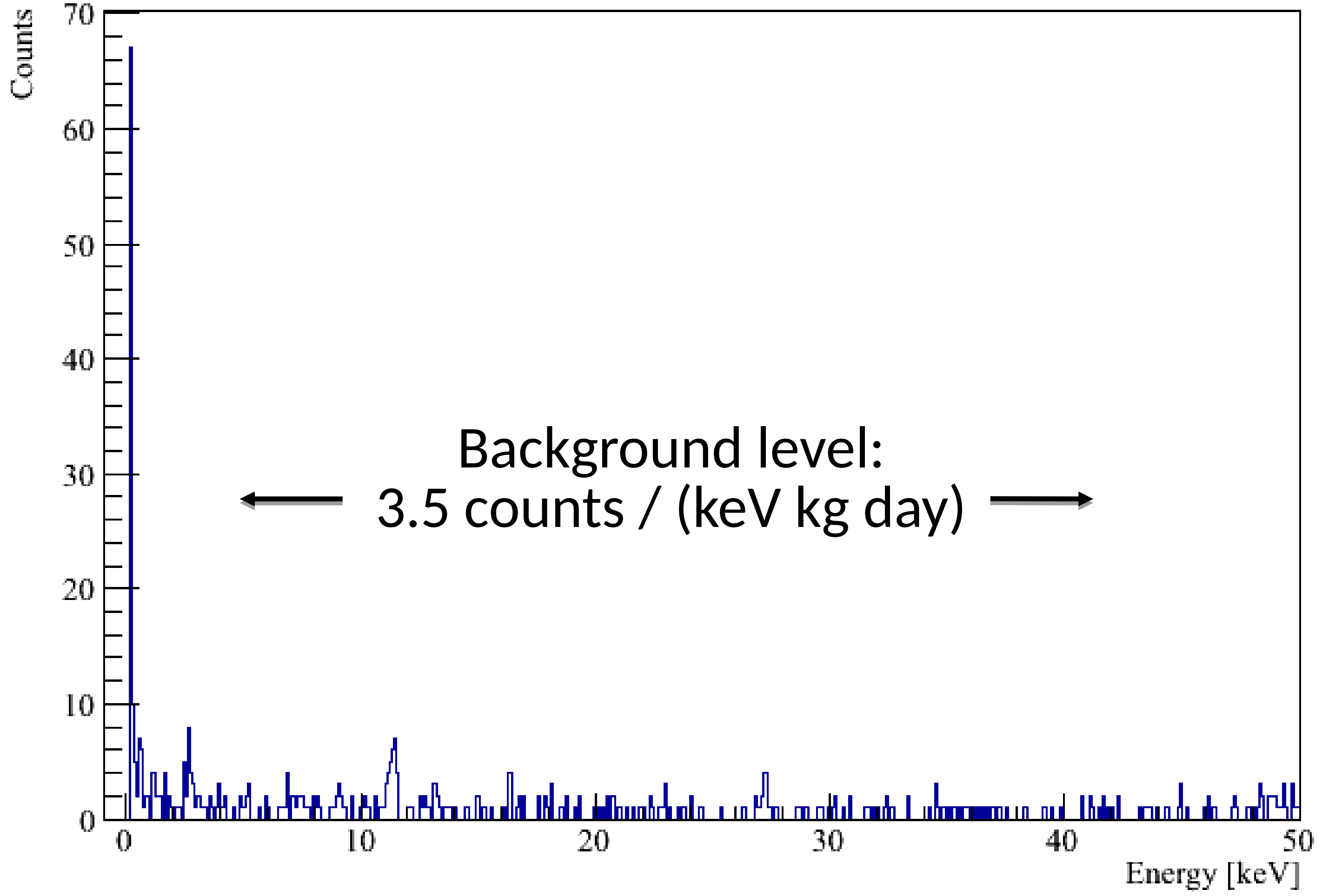


Unblinded:
Det. A
E>100eV

Still blinded:
Det. A <100eV
Other detectors

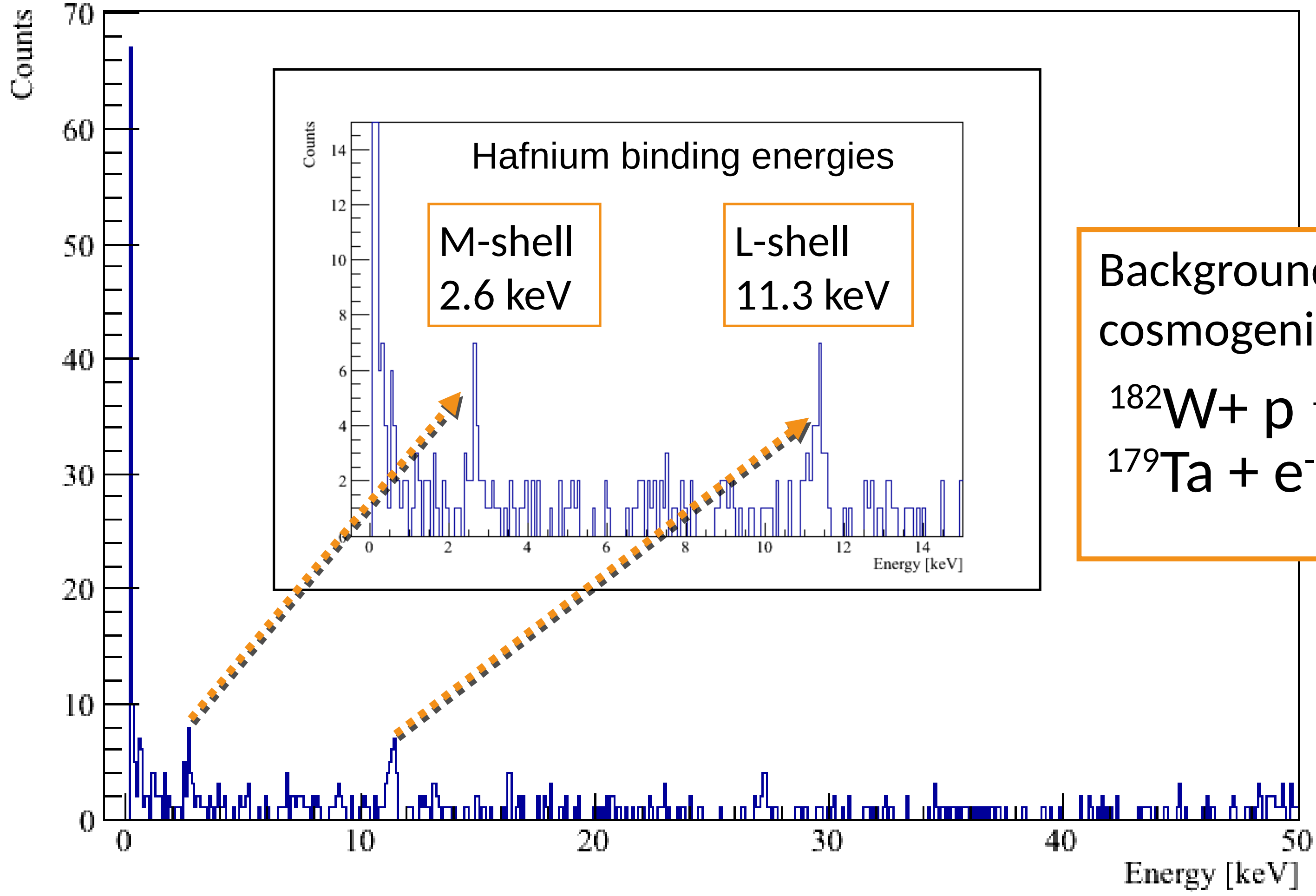
Detector A – 100eV threshold analysis

Dark Matter data – Energy spectrum



Detector A – 100eV threshold analysis

Dark Matter data – Energy spectrum



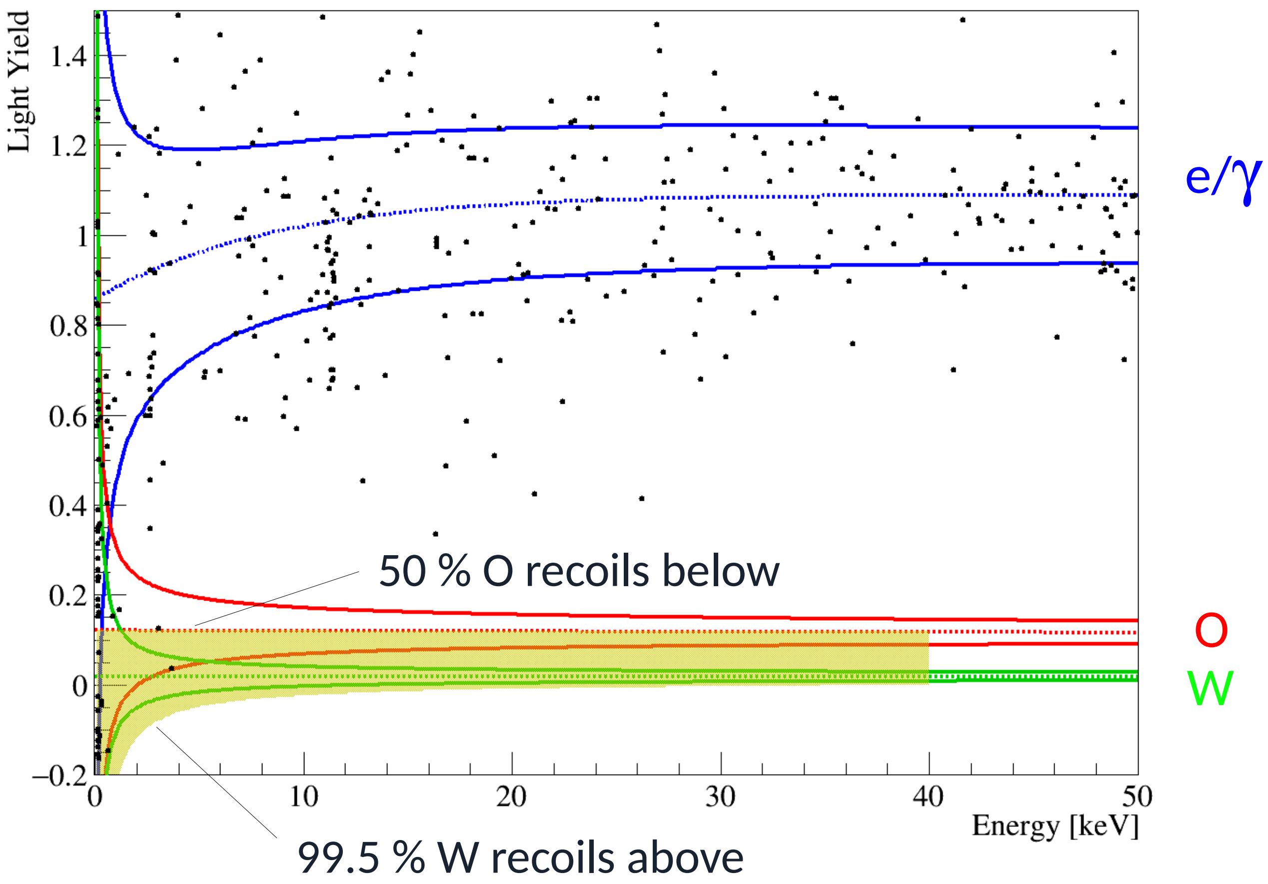
Background events from cosmogenic activation

$^{182}W + p \longrightarrow {}^{179}Ta + \alpha$

$^{179}Ta + e^{-} \longrightarrow {}^{179}Hf + \nu_e$

Detector A – 100eV threshold analysis

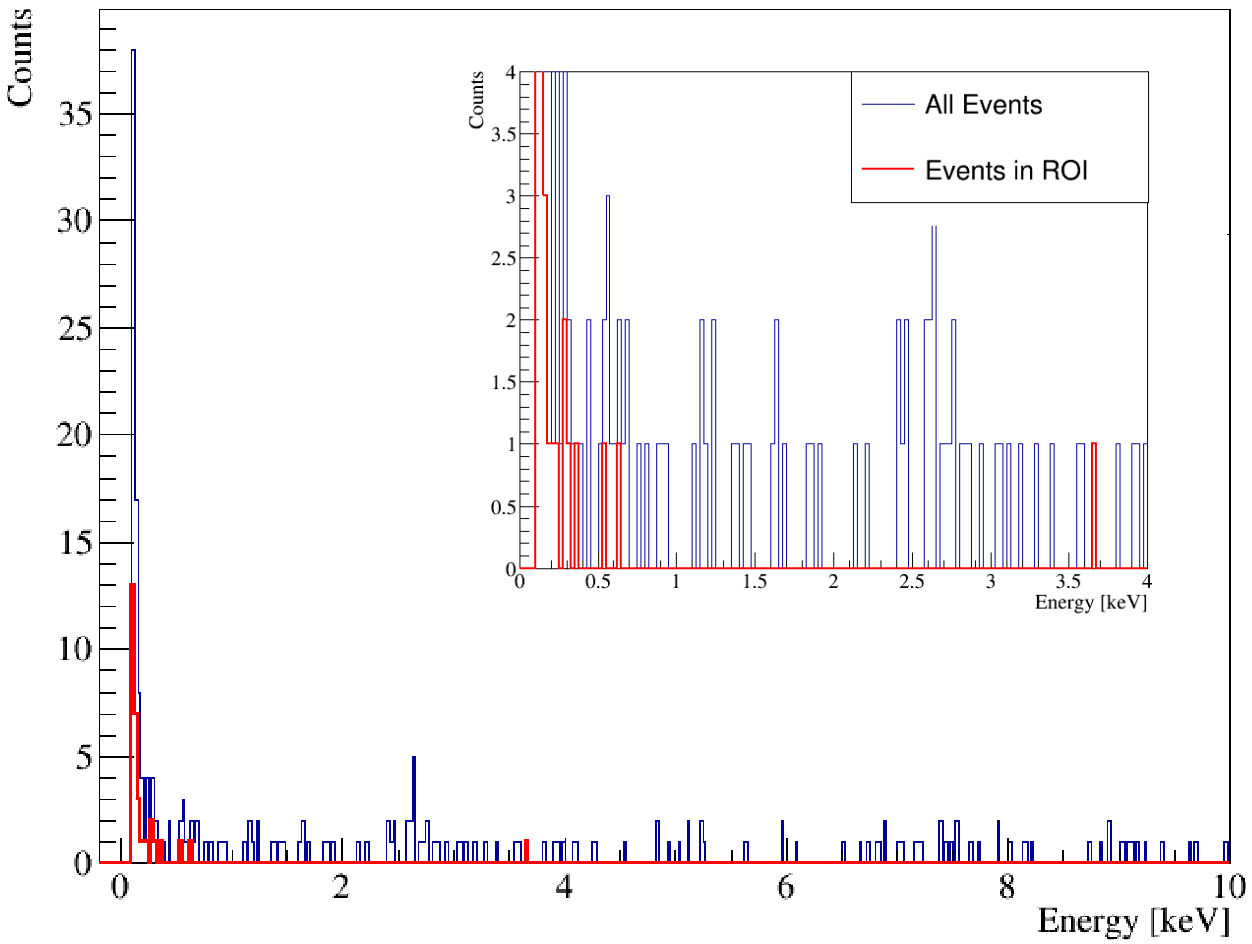
Dark Matter data – Energy spectrum



Acceptance region fixed before unblinding

Detector A – 100eV threshold analysis

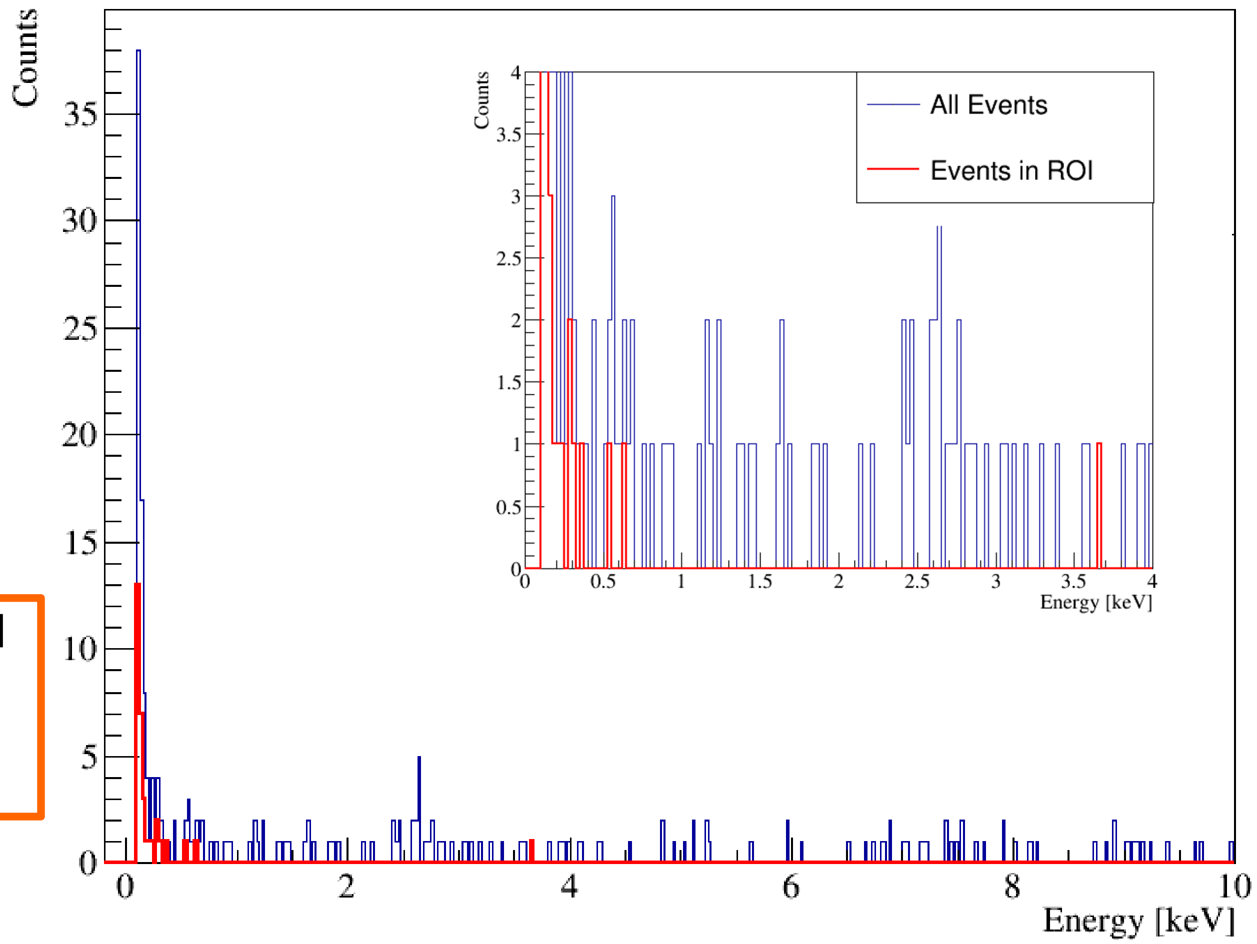
Dark Matter data – Accepted Events



Detector A – 100eV threshold analysis

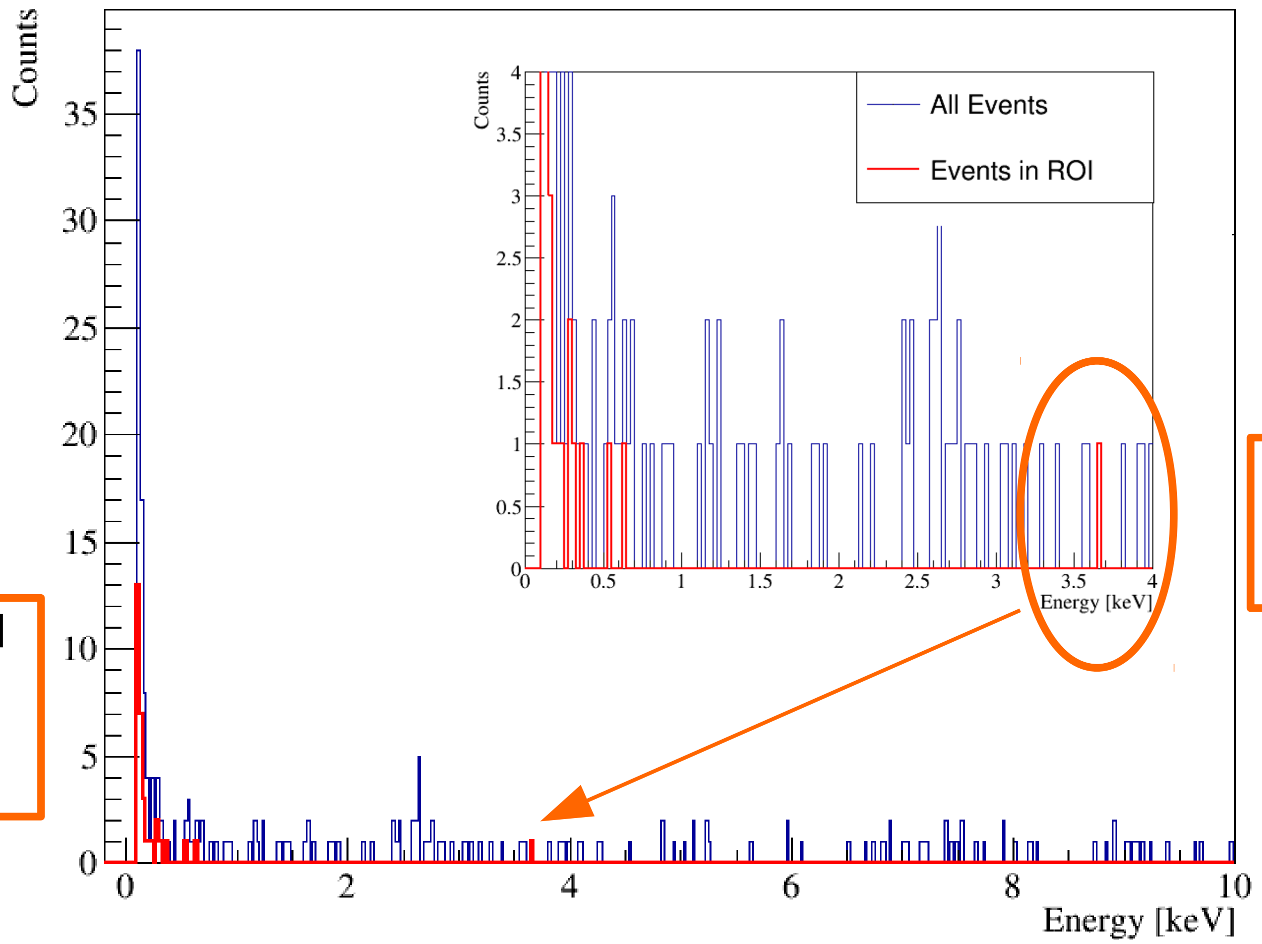
Dark Matter data – Accepted Events

Background rising towards threshold



Detector A – 100eV threshold analysis

Dark Matter data – Accepted Events



Background rising towards threshold

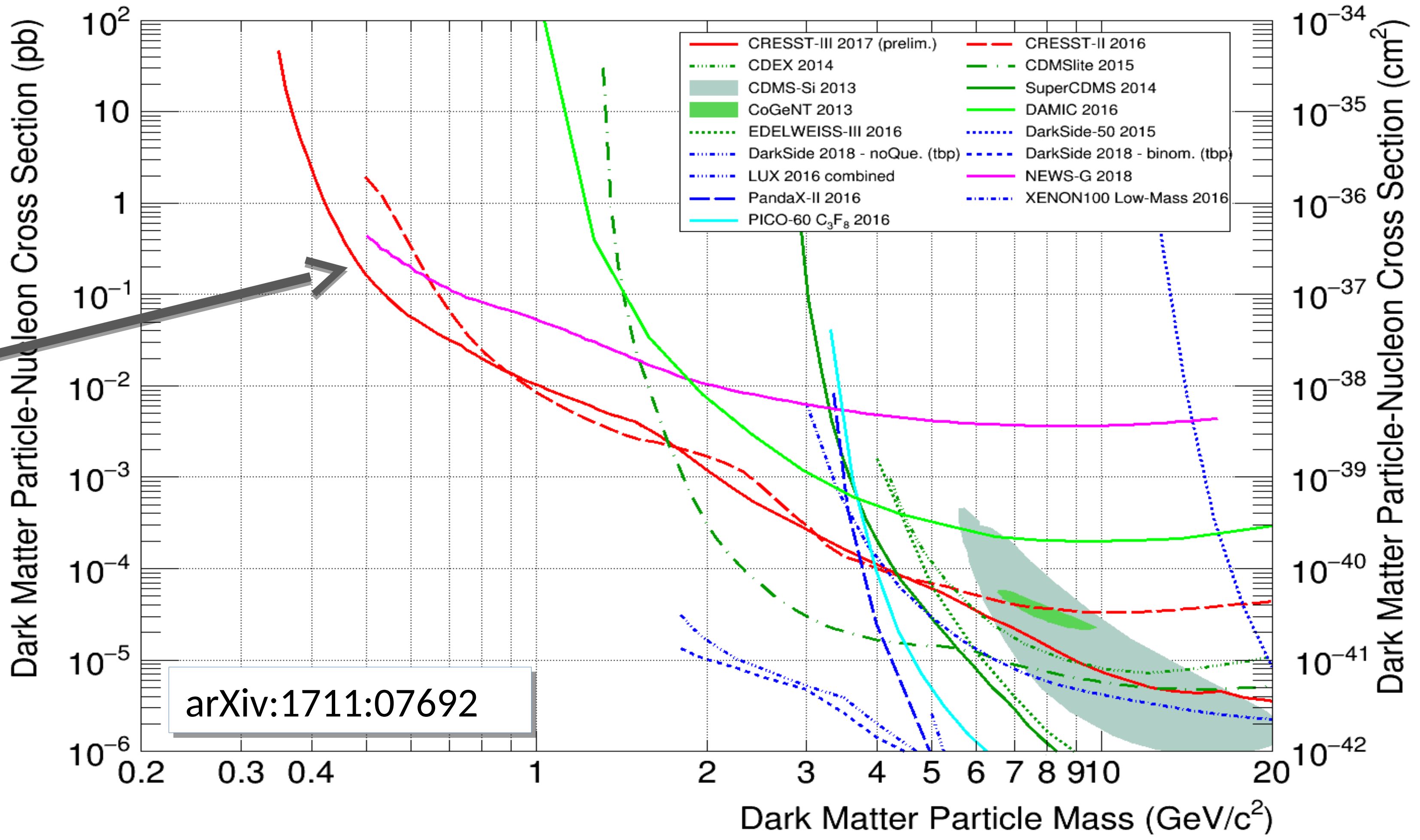
Single accepted event at higher energies

Detector A – 100 eV threshold – Dark Matter limit

Energy spectrum of accepted events

Yellin 1D optimum interval method

Energy spectrum expected for DM

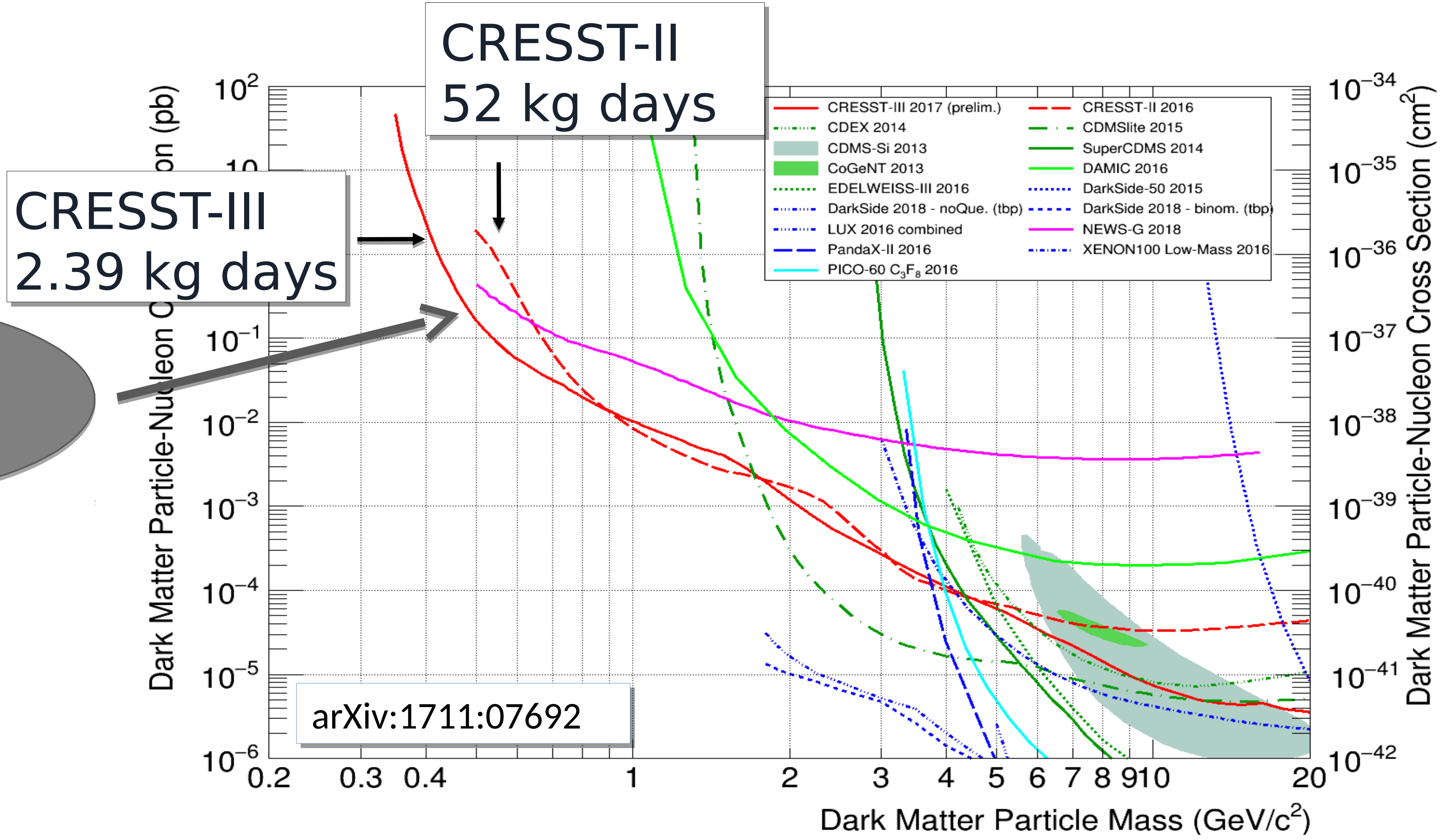


Detector A – 100 eV threshold – Dark Matter limit

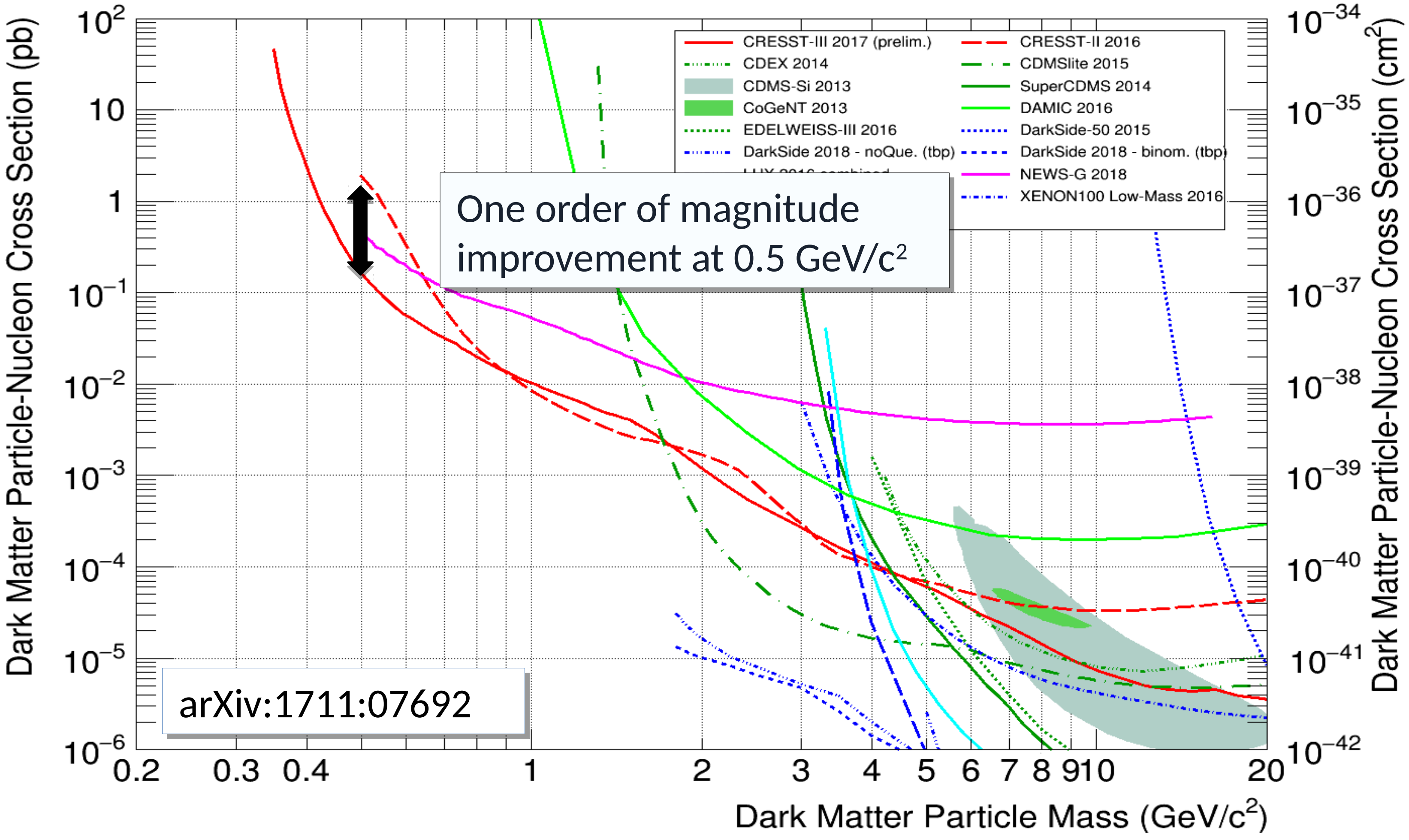
Energy spectrum of accepted events

Yellin 1D optimum interval method

Energy spectrum expected for DM

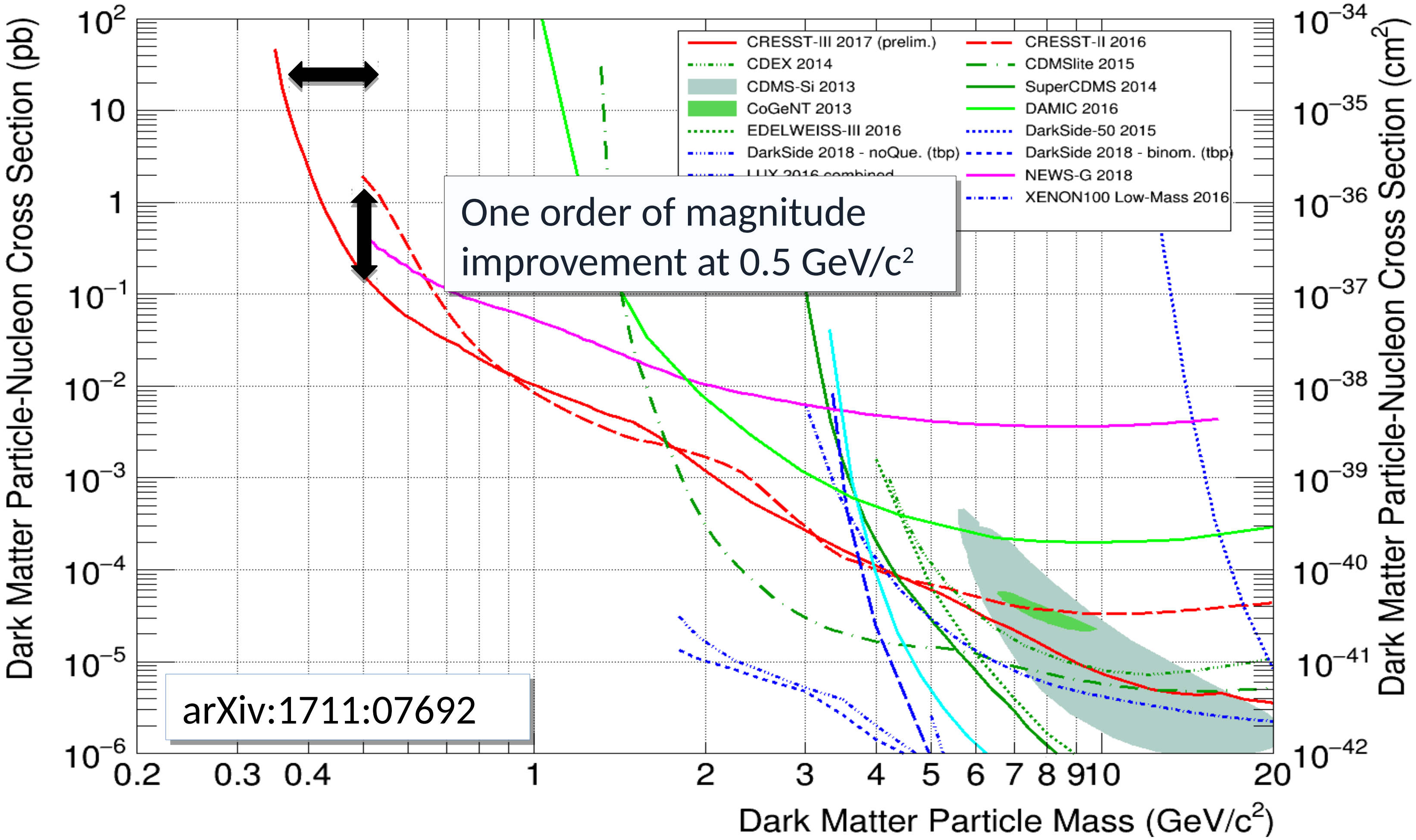


Detector A – 100 eV threshold – Dark Matter limit



Detector A – 100 eV threshold – Dark Matter limit

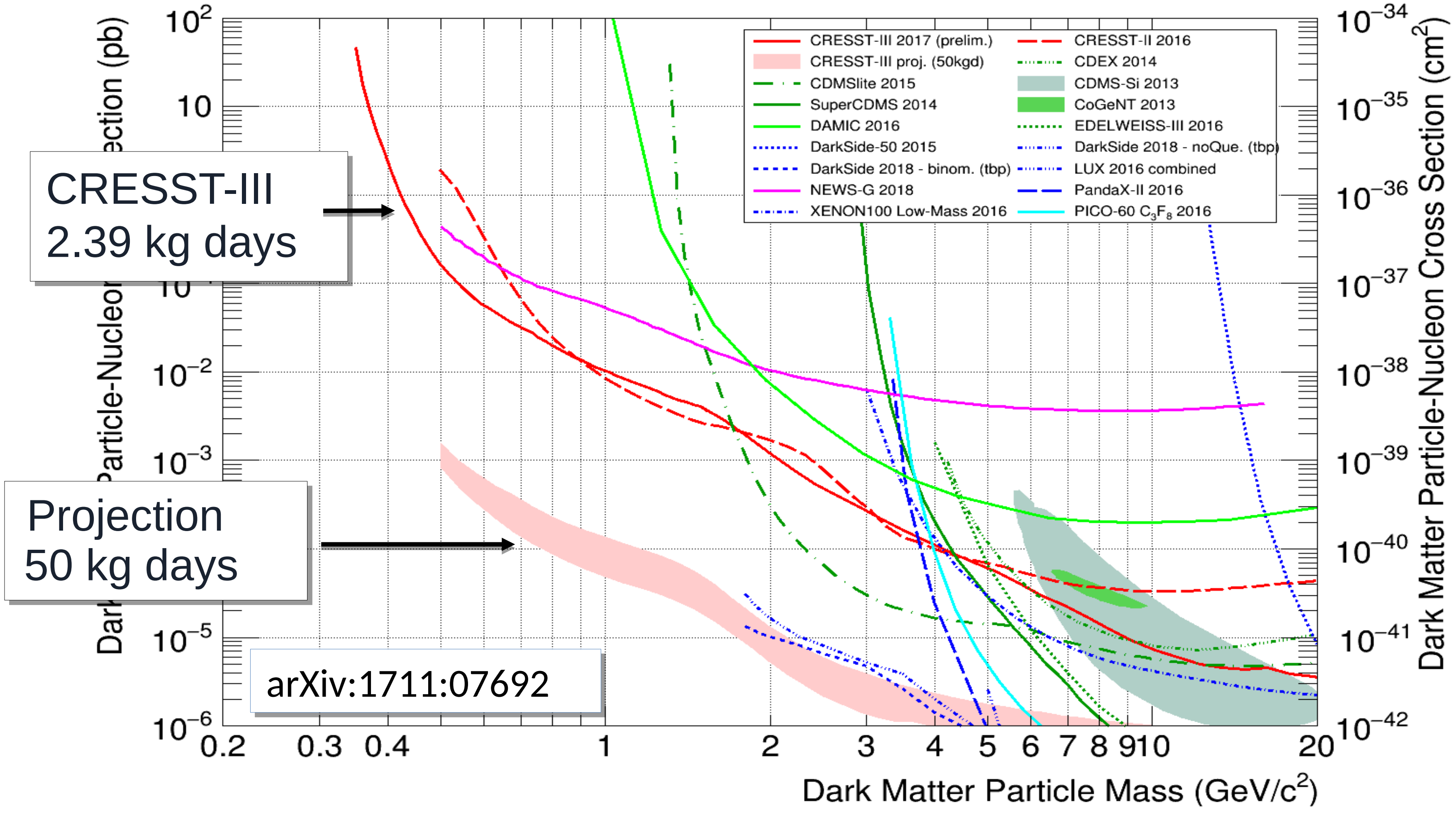
Extend reach from 0.5 GeV/c^2 to 0.35GeV/c^2



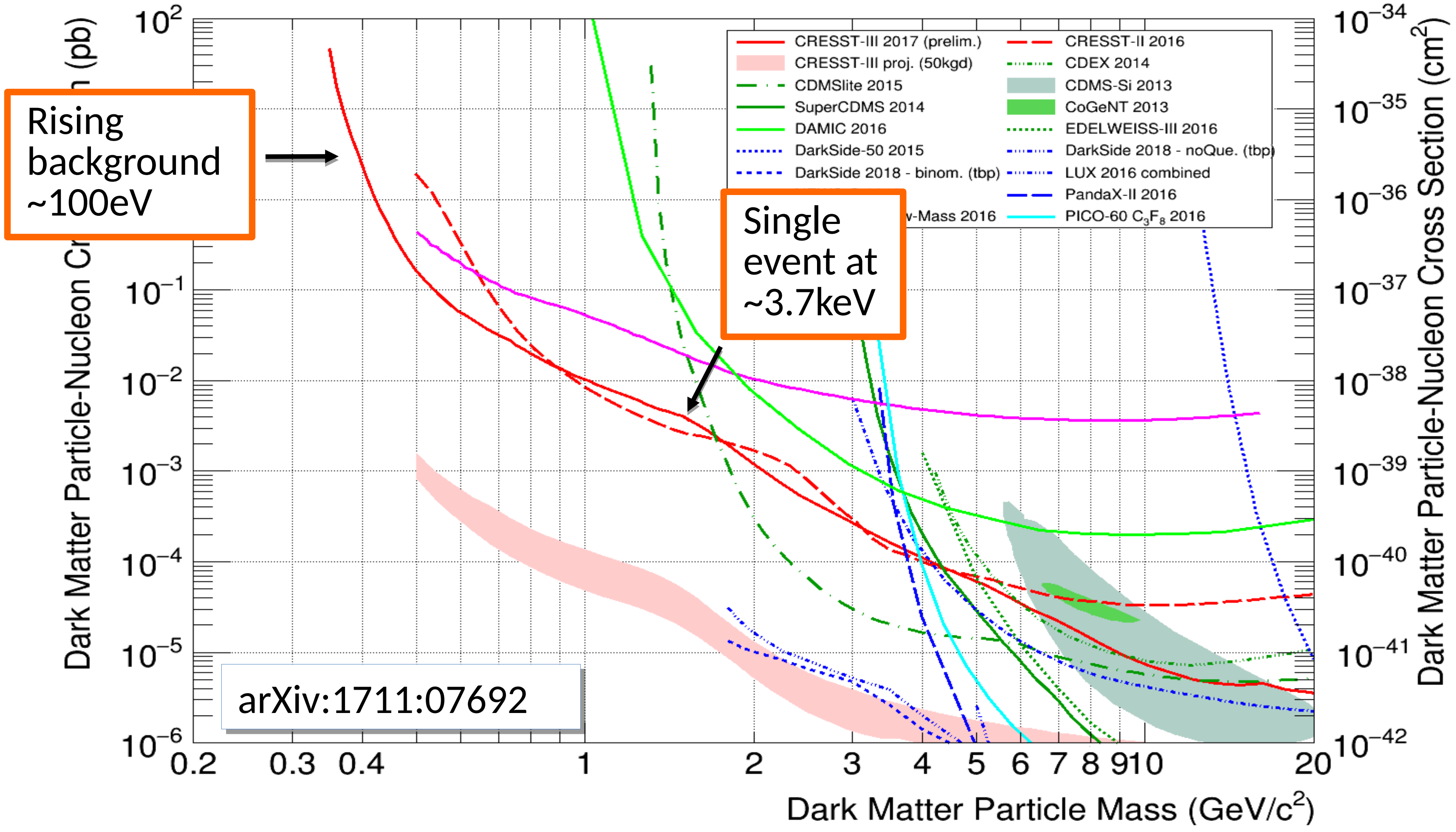
One order of magnitude improvement at 0.5 GeV/c^2

arXiv:1711:07692

Detector A – 100 eV threshold – Dark Matter limit



Detector A – 100 eV threshold – Dark Matter limit



There's more to come...

First CRESST-III run 07/2016 - 02/2018: Analysis ongoing

3 times lower optimum threshold for detector A

3 other detectors with thresholds << 100eV

3 times more statistics → deeper understanding of backgrounds

There's more to come...

Coming up: CRESST-II EFT Analysis

$$\boxed{\mathbb{1}, v^{\perp}, q, S_{\chi}, S_N}$$

Galilean invariants

$$\hat{\mathcal{O}}_1 = \mathbb{1}_{\chi} \cdot \mathbb{1}_N \to \text{(standard SI)}$$
$$\hat{\mathcal{O}}_2 = (\vec{v}^{\perp})^2$$
$$\hat{\mathcal{O}}_3 = i\vec{S}_N \cdot \left(\vec{q}/m_N \times \vec{v}^{\perp}\right)$$
$$\hat{\mathcal{O}}_4 = \vec{S}_{\chi} \cdot \vec{S}_N \to \text{(standard SD)}$$
$$\hat{\mathcal{O}}_5 = i\vec{S}_{\chi} \cdot \left(\vec{q}/m_N \times \vec{v}^{\perp}\right)$$
$$\hat{\mathcal{O}}_6 = \left(\vec{S}_{\chi} \cdot \vec{q}/m_N\right)\left(\vec{S}_N \cdot \vec{q}/m_N\right)$$
$$\hat{\mathcal{O}}_7 = \vec{S}_N \cdot \vec{v}^{\perp}$$
$$\hat{\mathcal{O}}_8 = \vec{S}_{\chi} \cdot \vec{v}^{\perp}$$
$$\hat{\mathcal{O}}_9 = i\vec{S}_{\chi} \cdot \left(\vec{S}_N \times \vec{q}/m_N\right)$$
$$\hat{\mathcal{O}}_{10} = i\vec{S}_N \cdot \vec{q}/m_N$$
$$\ldots$$

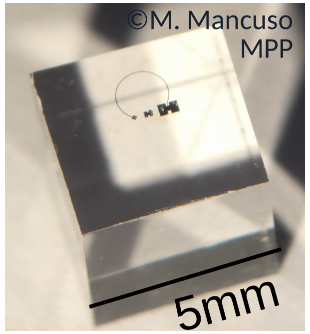
Anand et al. arXiv:1308.6288 [hep-ph]

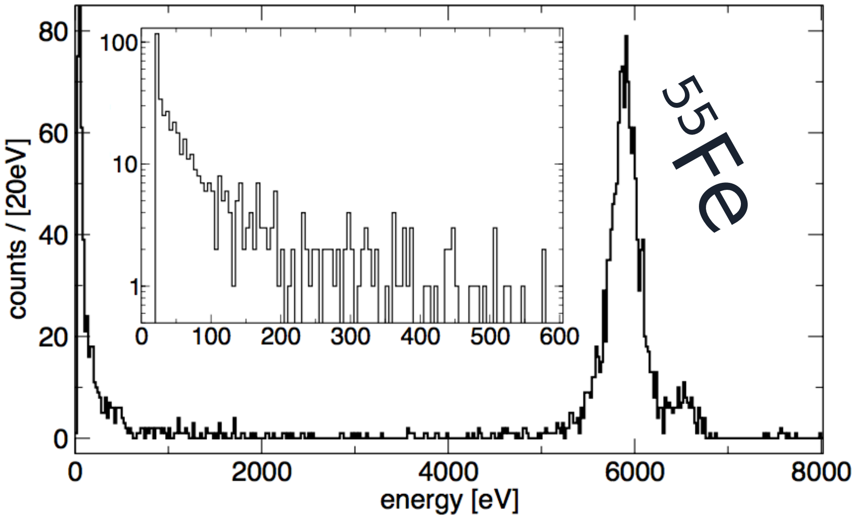
One more limit: gram-scale detector

Al_2O_3 0.49g 5x5x5mm^3

E_{th} = (19.7 ± 0.9) eV

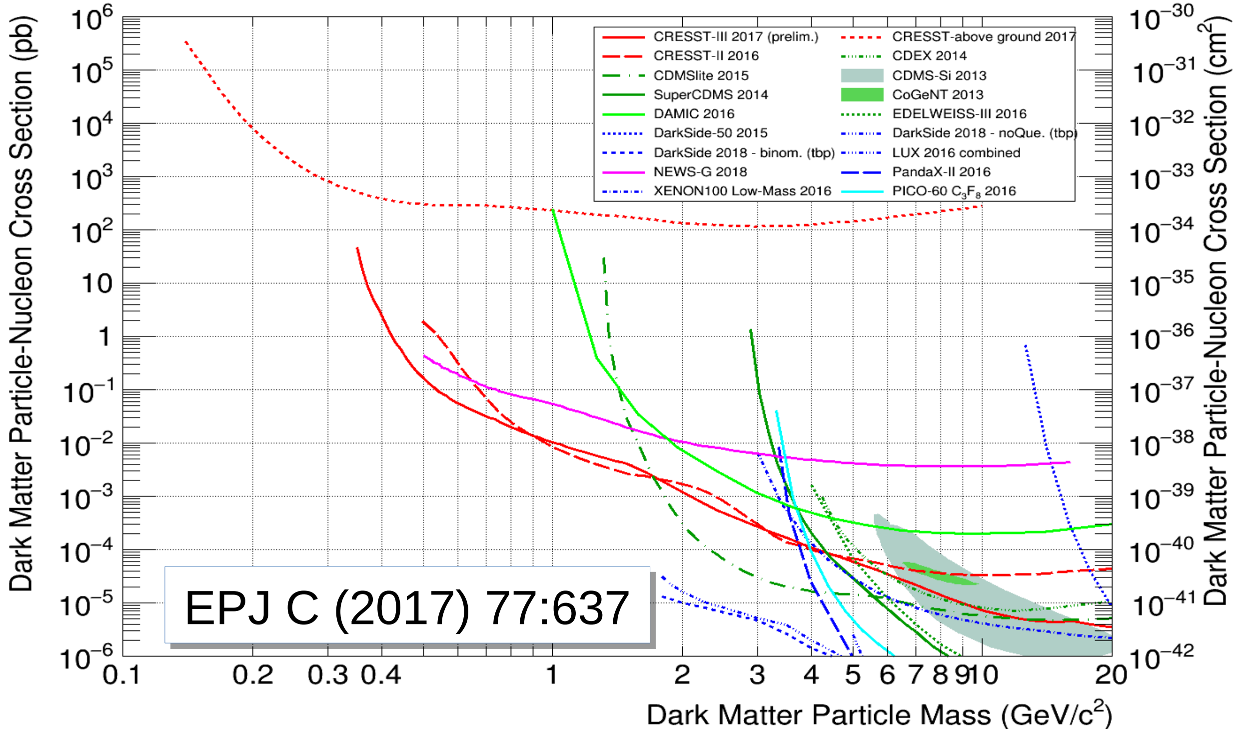
Measured above ground





Measuring time 5.3h

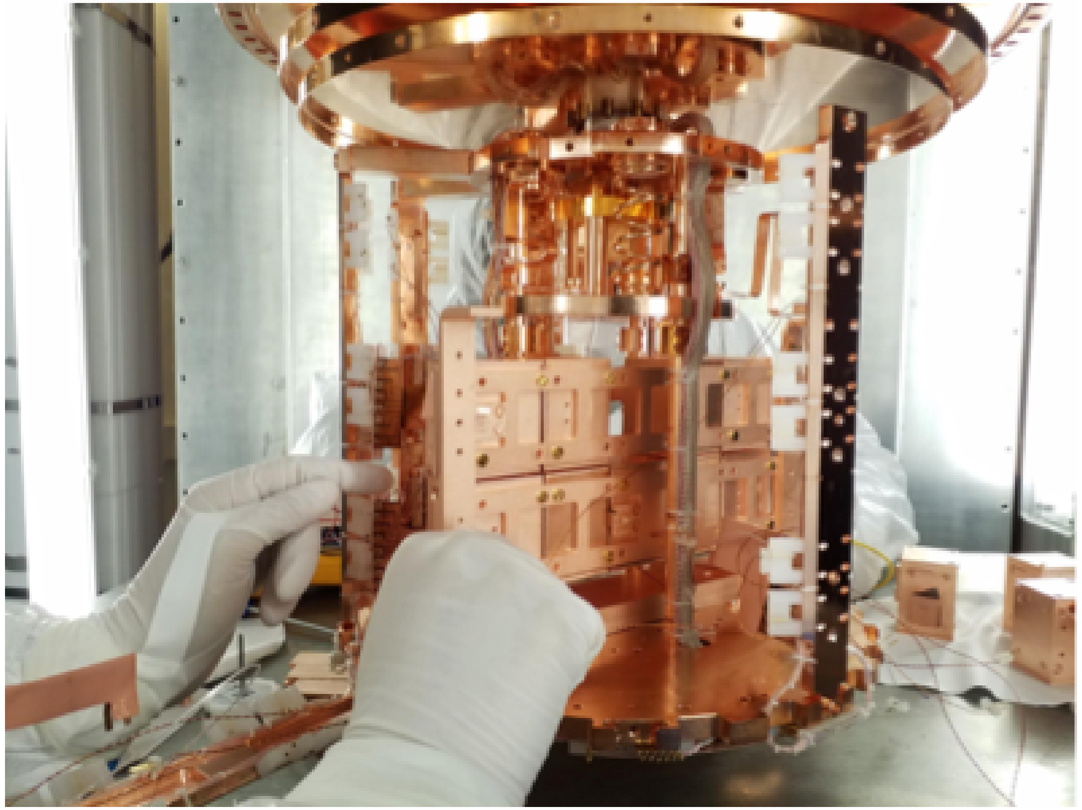
No data quality cuts



Second CRESST-III run 06/2018: just starting

Key innovation

Upgraded detector modules with dedicated hardware changes to understand backgrounds

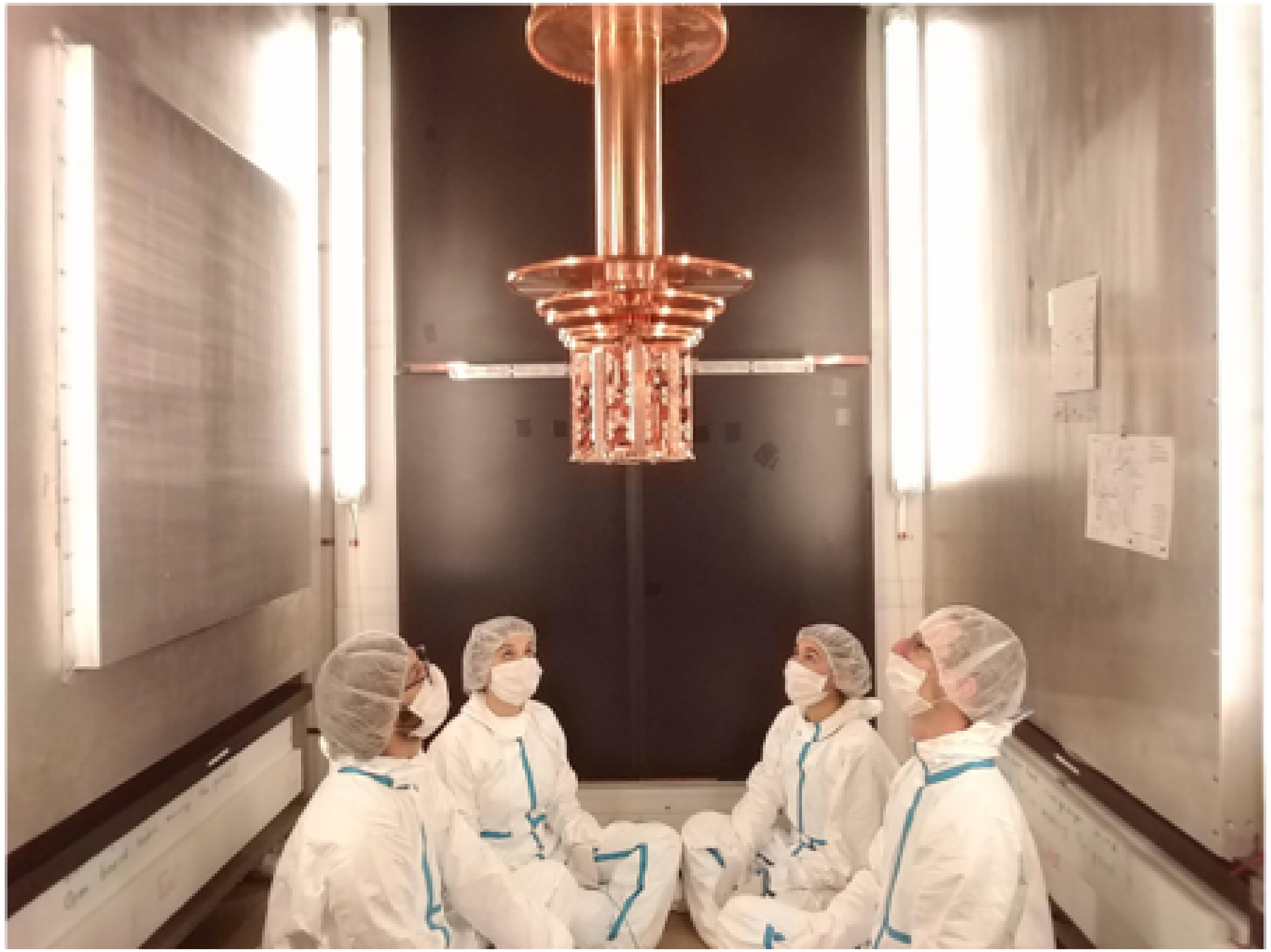


CRESST-III: now waiting for dark matter

Key innovation

Upgraded detector modules with dedicated hardware changes to understand backgrounds

- The cryostat is cold
- First pulses measured
- Commissioning phase



BACKUP

Gram-scale detector: Theorists love it 😻

above ground: Sensitivity for strongly interacting DM

1) By J.I. Collar., [arXiv:1805.02646 [astro-ph.CO]].

2) By M. Shafi Mahdawi, Glennys R. Farrar., [arXiv:1804.03073 [hep-ph]].

3) By SENSEI Collaboration (Michael Crisler et al.)., [arXiv:1804.00088 [hep-ex]].

4) By Jason Wyenberg, Ian M. Shoemaker., [arXiv:1803.08146 [hep-ph]].

5) By Jae Hyeok Chang, Rouven Essig, Samuel D. McDermott., [arXiv:1803.00993 [hep-ph]].

6) By Weishuang Linda Xu, Cora Dvorkin, Andrew Chael., Phys.Rev. D97 (2018) no.10, 103530.

7) By Timon Emken, Chris Kouvaris., [arXiv:1802.04764 [hep-ph]].

8) By Dan Hooper, Samuel D. McDermott., Phys.Rev. D97 (2018) 115006.

9) By David G. Cerdeno, Jonathan H. Davis, Malcolm Fairbairn, Aaron C. Vincent., JCAP 1804 (2018) 037.

10) By Bradley J. Kavanagh., [arXiv:1712.04901 [hep-ph]].

11) By Jared A. Evans, Stefania Gori, Jessie Shelton., JHEP 1802 (2018) 100.

12) By M. Mancuso, A. Bento, N. Ferreiro Iachellini, D. Hauff, F. Petricca, F. Pröbst, J. Rothe, R. Strauss. [arXiv:1711.11459 [physics.ins-det]].

13) By Matthew J. Dolan, Felix Kahlhoefer, Christopher McCabe., [arXiv:1711.09906 [hep-ph]].

14) By Jonathan H. Davis., Phys.Rev.Lett. 119 (2017) no.21, 211302.

15) By R. Strauss et al.., Phys.Rev. D96 (2017) no.2, 022009.

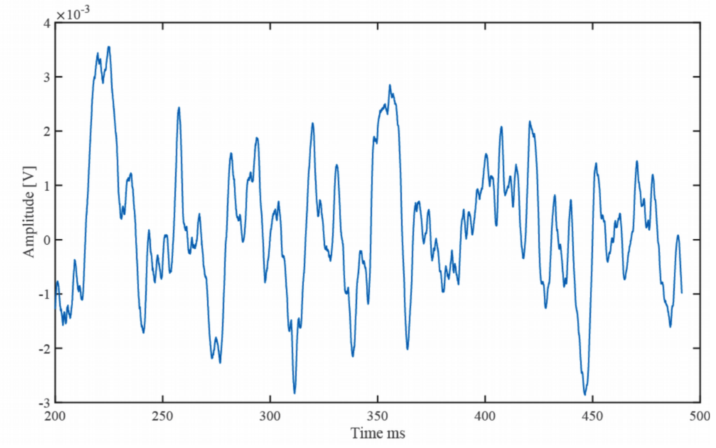
Source: (11/06/2018), paper on arXiv since 07/2018

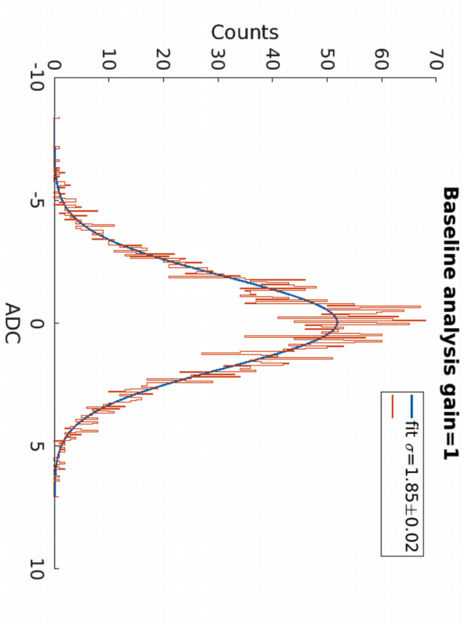

New frontiers …
… new potentials …
… new challenges!
"Going West"
Image courtesy of

Optimum trigger – Detector A

Optimum filter for threshold analysis

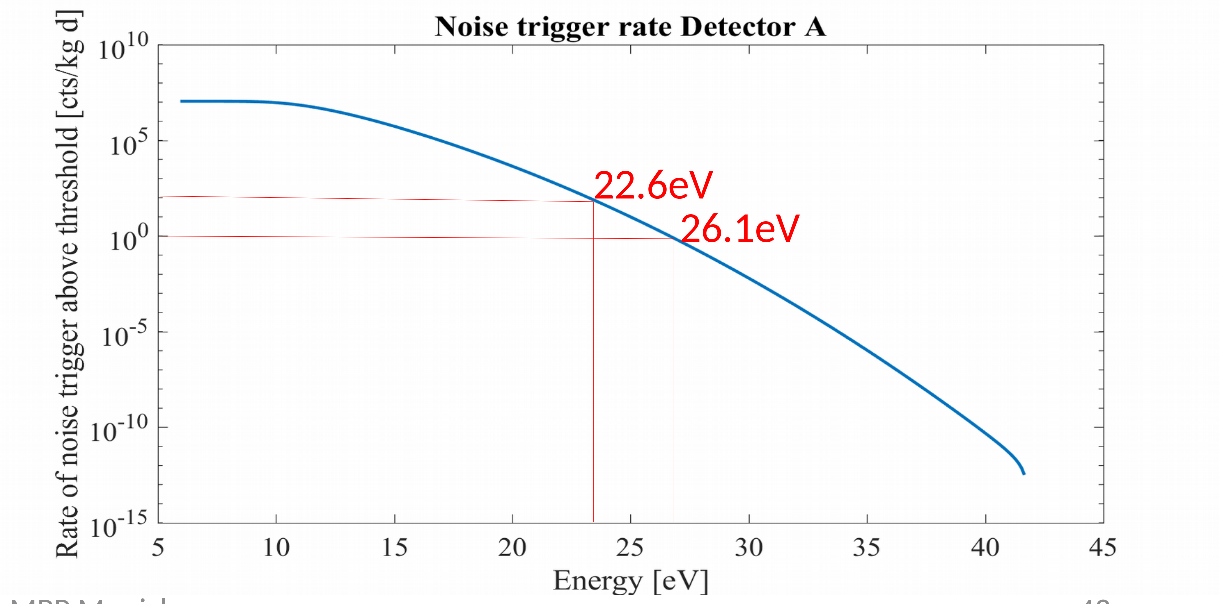
Empty base line trace





Histogram of a typical baseline trace

- Continuous sampling of raw data
- Study the noise distribution after optimum filter in order to set the threshold



Analytical description of amplitude distribution in empty baselines

Det. A – 100ev threshold analysis

Selection criteria (AKA “Cuts”)

Rate: noise conditions

Stability: Detector(s) in operating point

Data quality: Non-standard pulse shapes (in particular iStick events and pileup)

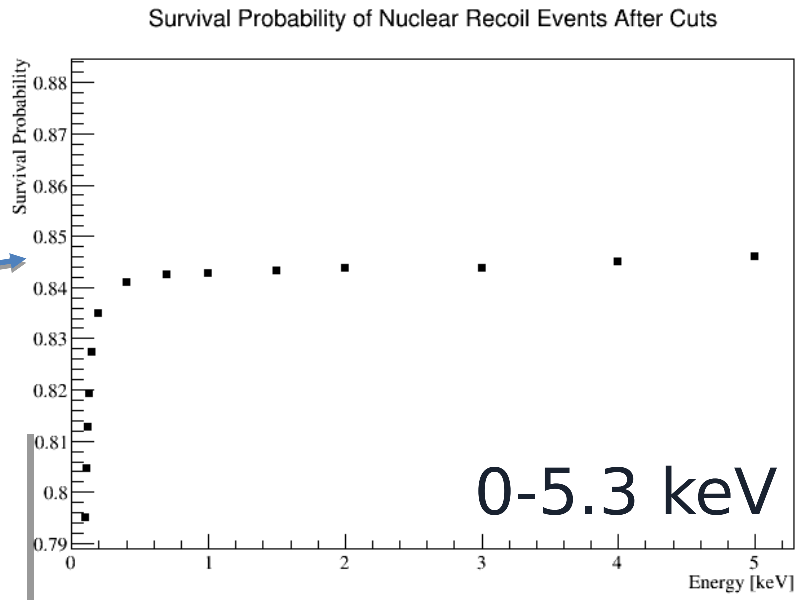
Coincidences: with muon veto and iSticks only (will be expanded to “with other detector modules")

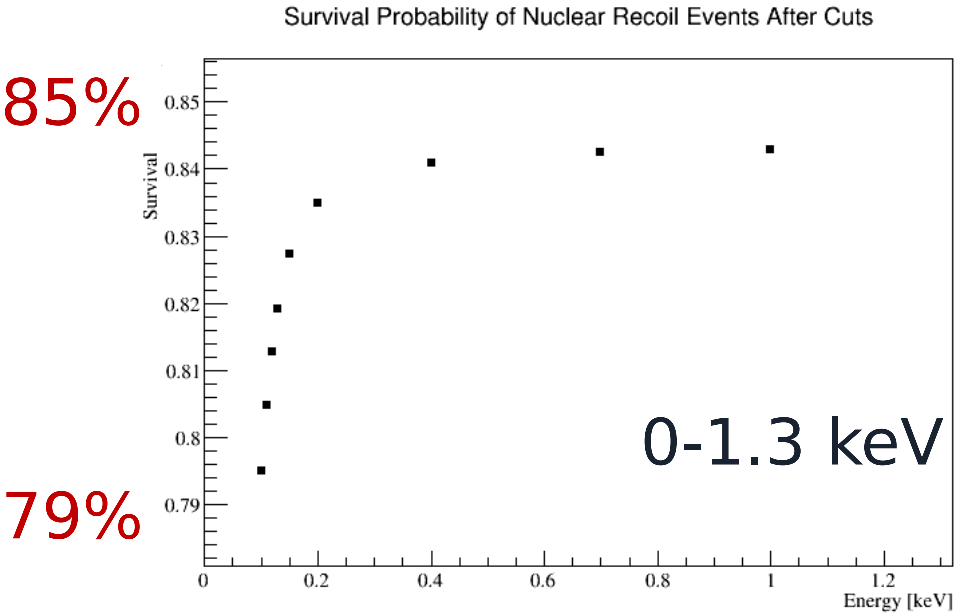
Det. A – 100ev threshold analysis

Efficiency of data quality cuts

Rate, Stability:
92.5% survival = 2.21 kg days net exposure

Data quality, Coincidences



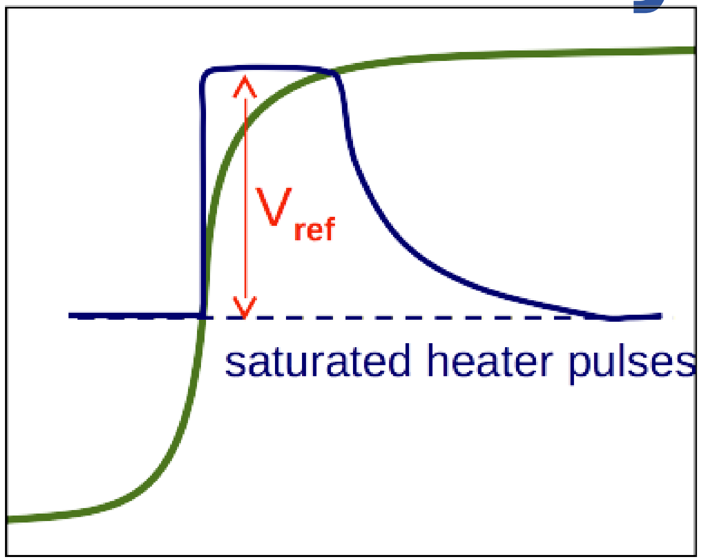


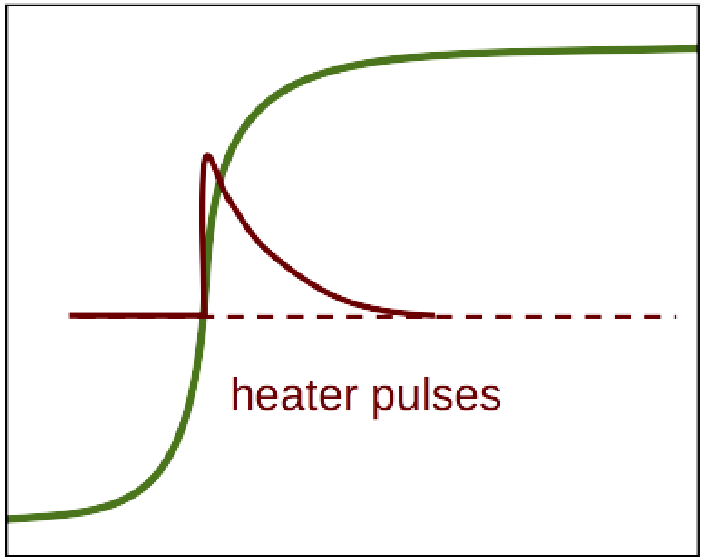
79.5% at threshold of 100eV

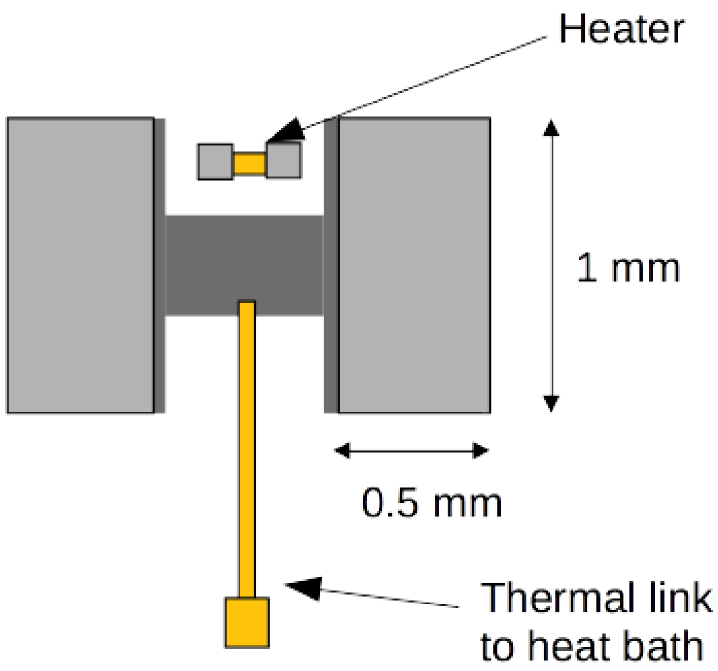
Detector stability

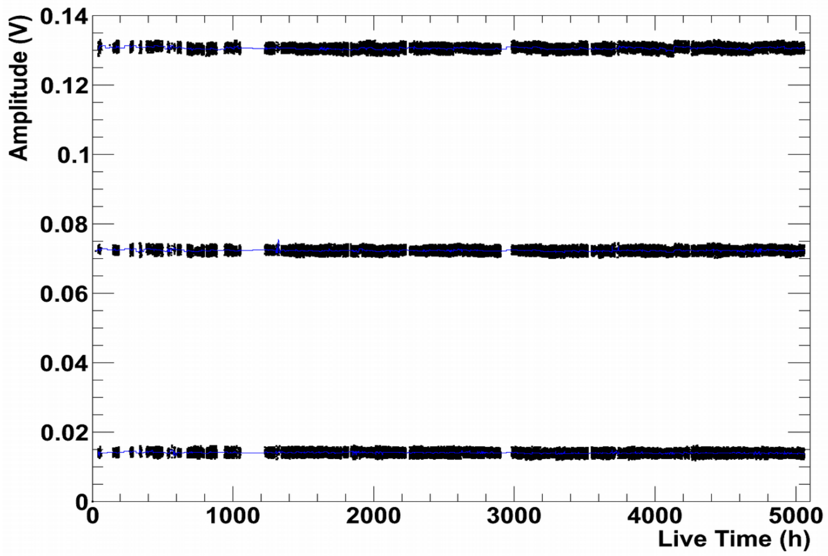
W-TES equipped with heaters

- Stabilization of detectors in the operating point
- Injection of heat pulses for calibration and determination of trigger threshold

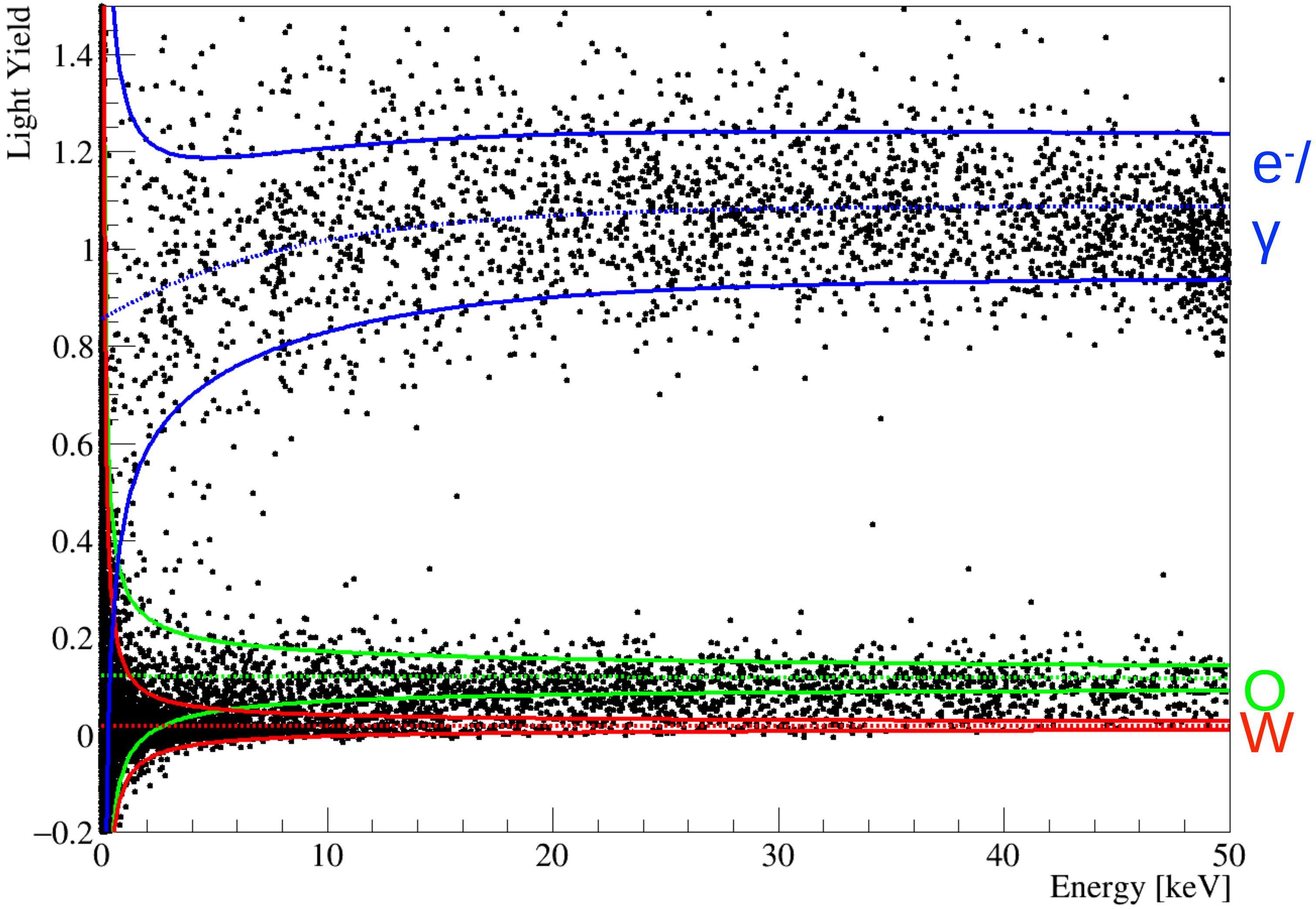








Neutron Calibration Data

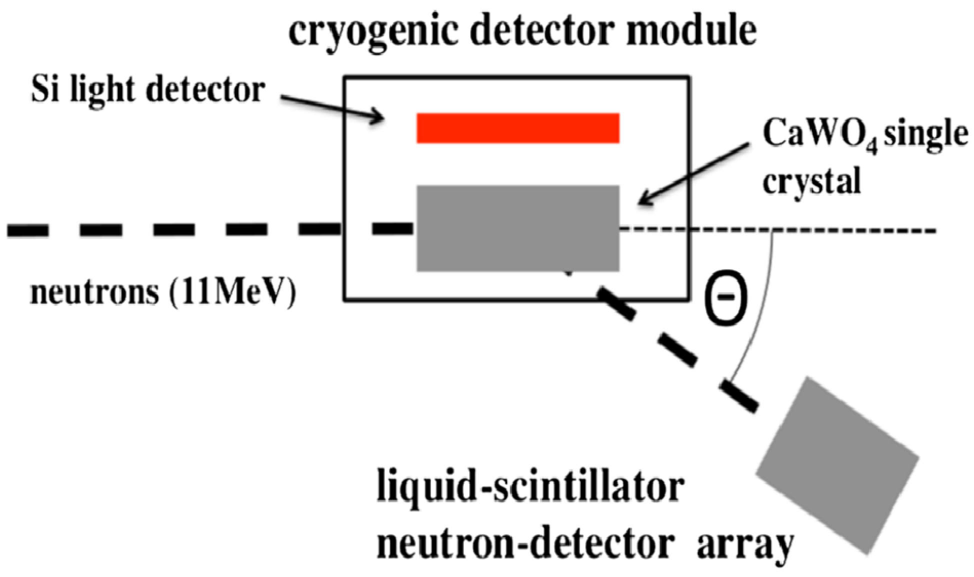


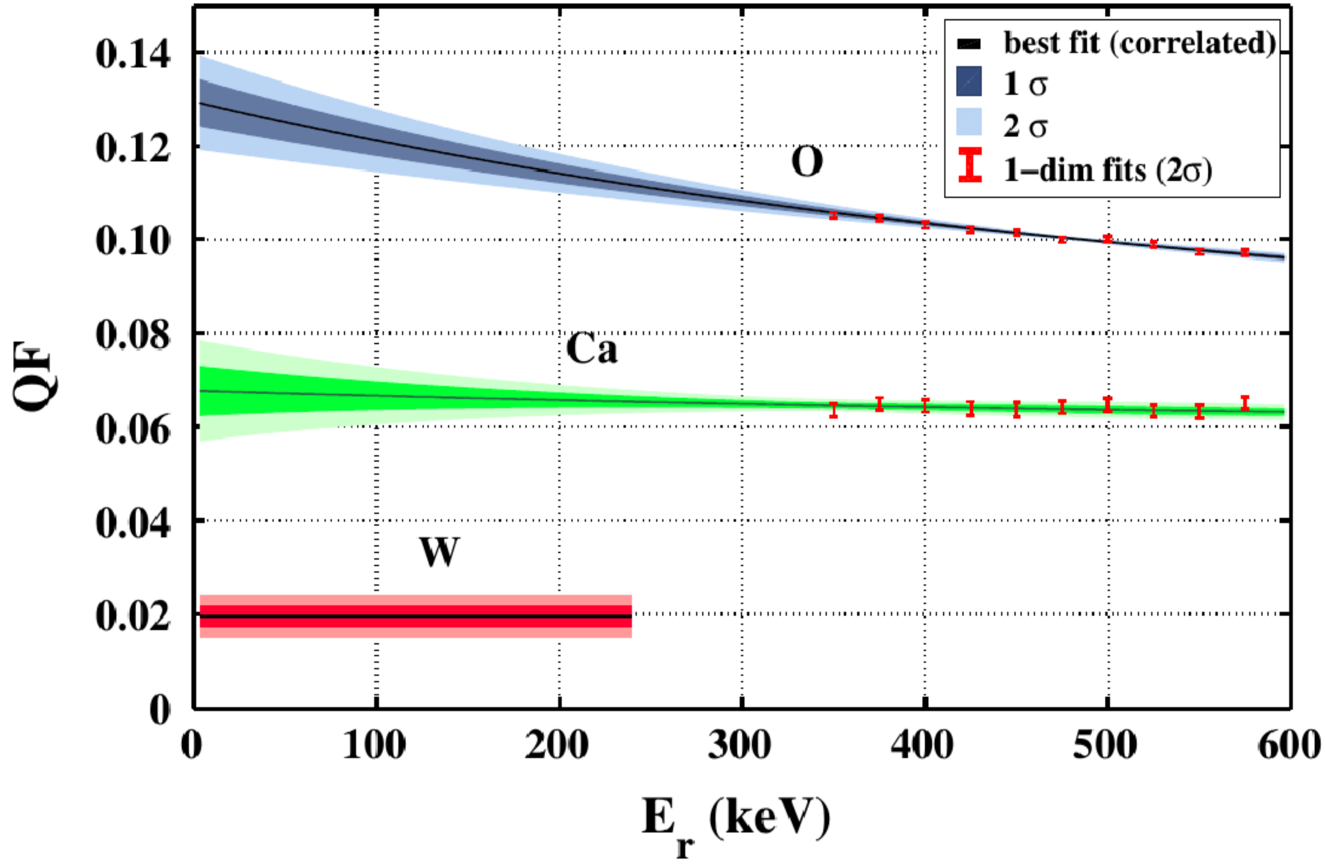
Quenching factors measured at the Maier-Leibnitz-Laboratory (MLL)

Strauss, R., Angloher, G., Bento, A. et al. Eur. Phys. J. C (2014) 74: 2957.

Quenching factor measurement

@ accelerator of Maier-Leibnitz-Laboratorium





Precise determination of QFs for O, Ca & W **@mK temperatures**

O: (11.2 ± 0.5)% Ca: (5.94 ± 0.49)% W: (1.72 ± 0.21)%

Low threshold detectors