ICHEP 2020 | PRAGUE

40th INTERNATIONAL CONFERENCE ON HIGH ENERGY PHYSICS

VIRTUAL CONFERENCE

28 JULY - 6 AUGUST 2020

PRAGUE, CZECH REPUBLIC

Searches for Dark Matter with the CRESST-III Experiment

Jochen Schieck

Institute of High Energy Physics
Austrian Academy of Sciences
https://www.oeaw.ac.at/hephy/staff/jochen-schieck/

Technische Universität Wien
Atominstitut

for the CRESST Collaboration (www.cresst.de)

HEPHY
INSTITUT FÜR HOCHENERGIEPHYSIK

TU WIEN
TECHNISCHE UNIVERSITÄT WIEN

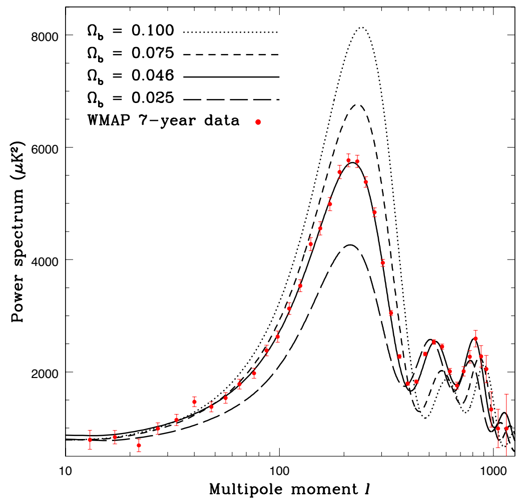
Search for low mass dark matter

- observation of dark matter on different astrophysical scales

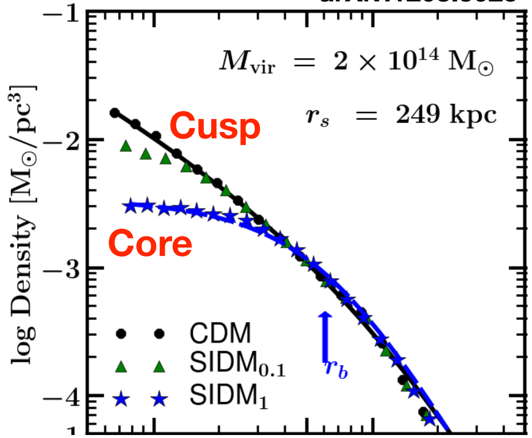
- microscopic character of dark matter unclear
  → search for particle dark matter

- several models predict dark matter beyond the traditional WIMP mass window between ~2 GeV to ~120 TeV
  → search for low mass dark matter

CMB power spectrum



arXiv:1208.3025



SIDM: self interacting Dark Matter

Direct detection of dark matter - basic principle

- weakly interacting massive particles scatter elastically with baryonic dark matter

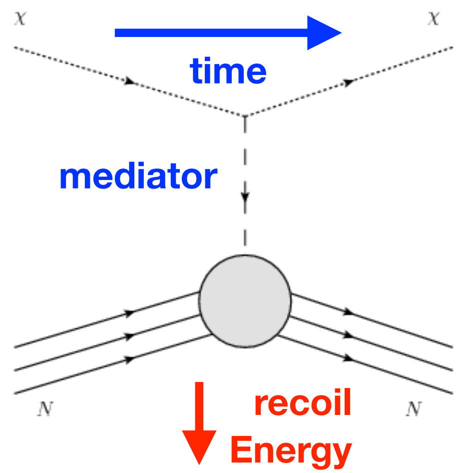
    1. recoil of nucleus leads to

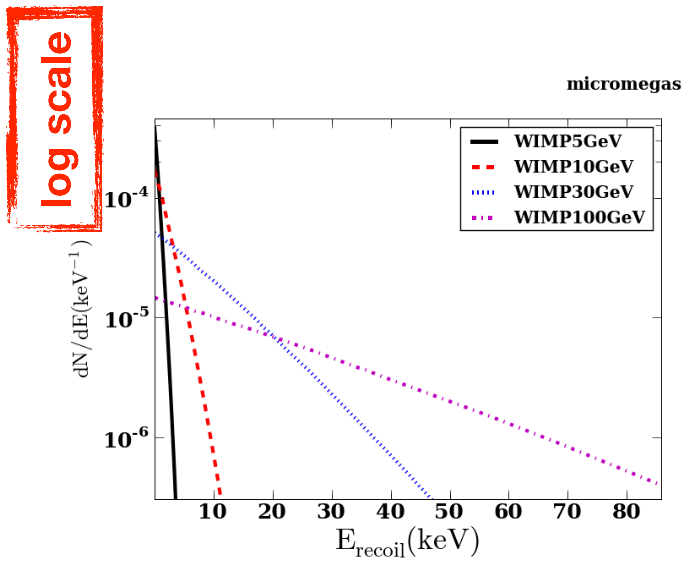
    2. deposition of energy followed by

    3. measurement of deposited energy

- exact interaction rate and size of deposited energy (=mass of Dark Matter particle) unknown

- **low mass dark matter requires sensitivity to low energy deposition ~ 100 eV**





WIMP - ^{78}Ge nucleon scattering

The CRESST Collaboration

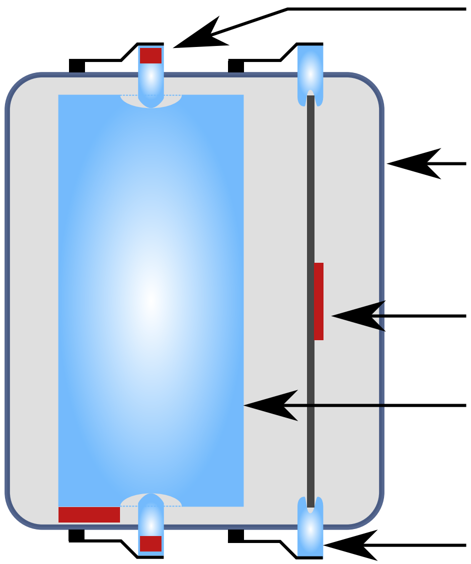
About 40-50 scientists from 8 institutions and 5 countries

CRESST - detection principle I

simultaneous read-out of two signals

- **phonon channel:** particle independent measurement of deposited energy (= nuclear recoil energy)

- **(scintillation) light:** different response for signal and background events for background rejection ("quenching")



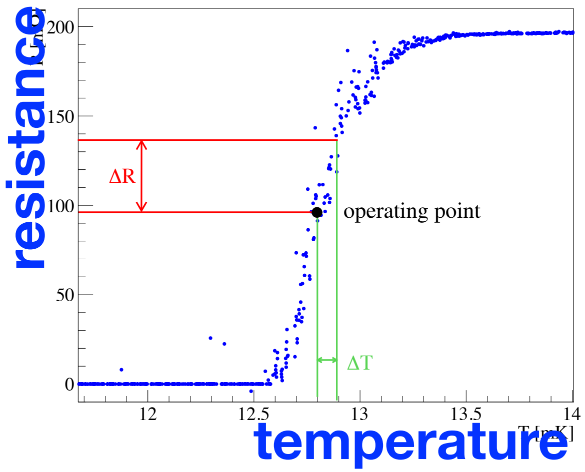
CRESST - detection principle II

- experiment operated at cryogenic temperature (~15 mK)
- nuclear recoil will deposit energy in the crystal leading to a temperature rise proportional to energy

$$\Delta T \propto \frac{\Delta Q}{c \cdot m} \qquad c \propto (T/\theta_D)^3$$

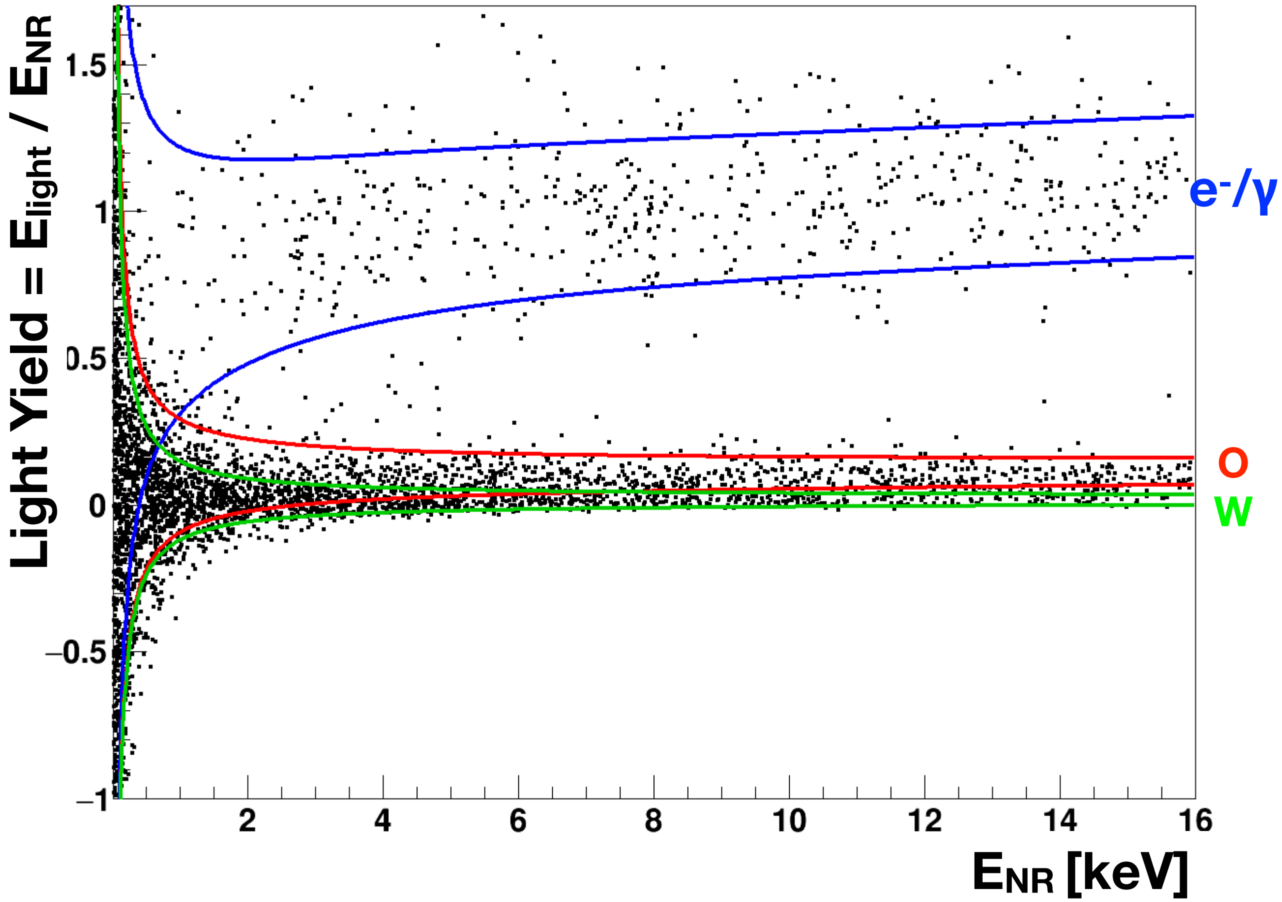
Θ_D:Debye temperature

- detection of small energy depositions requires very small heat capacity C
- detection of temperature rise with superconductor operated at the phase transition from normal to superconducting



Signal-background separation

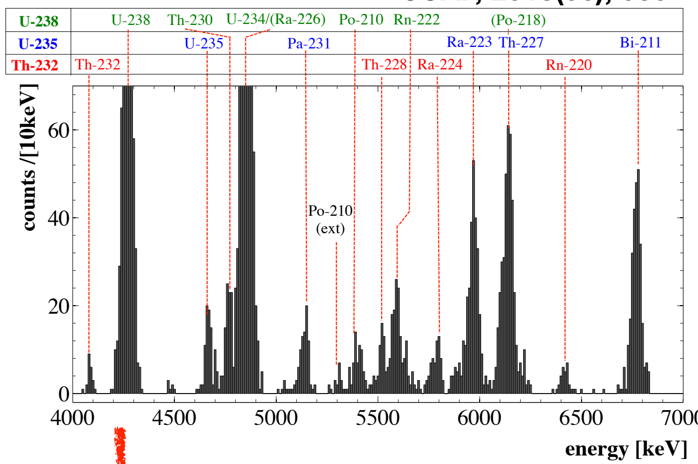
- simultaneous readout of light and phonon channel allows background reduction
- less scintillation light for nuclear recoils ("quenching")
  - clear separation between signal and background at large E_{NR}
  - **significant overlap of bands at low energies (= low mass dark matter)**

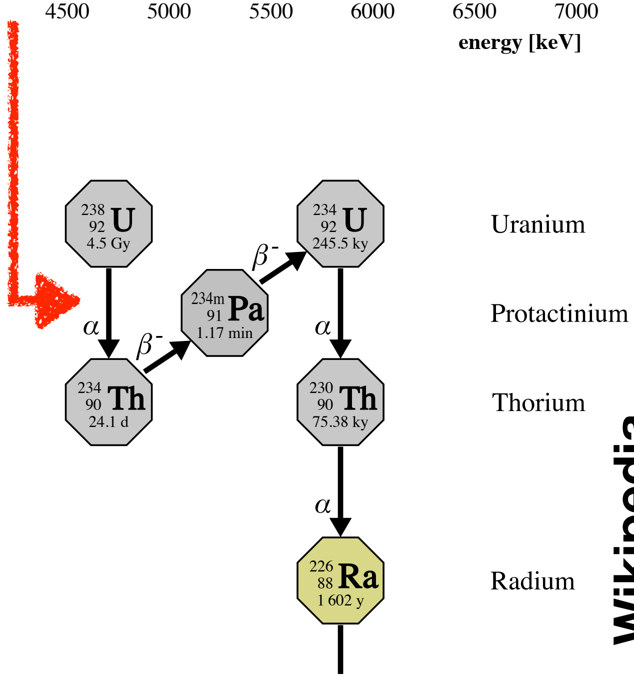


Background simulation for CRESST - method I

- Geant4 based simulation to estimate intrinsic background
- use α-activity as input:
  - identification of decay / isotope
  - measured activity reflects size of contamination
- determine energy spectrum of isotope decay and scale it accordingly to the measured activity

JCAP, 2015(06), 030

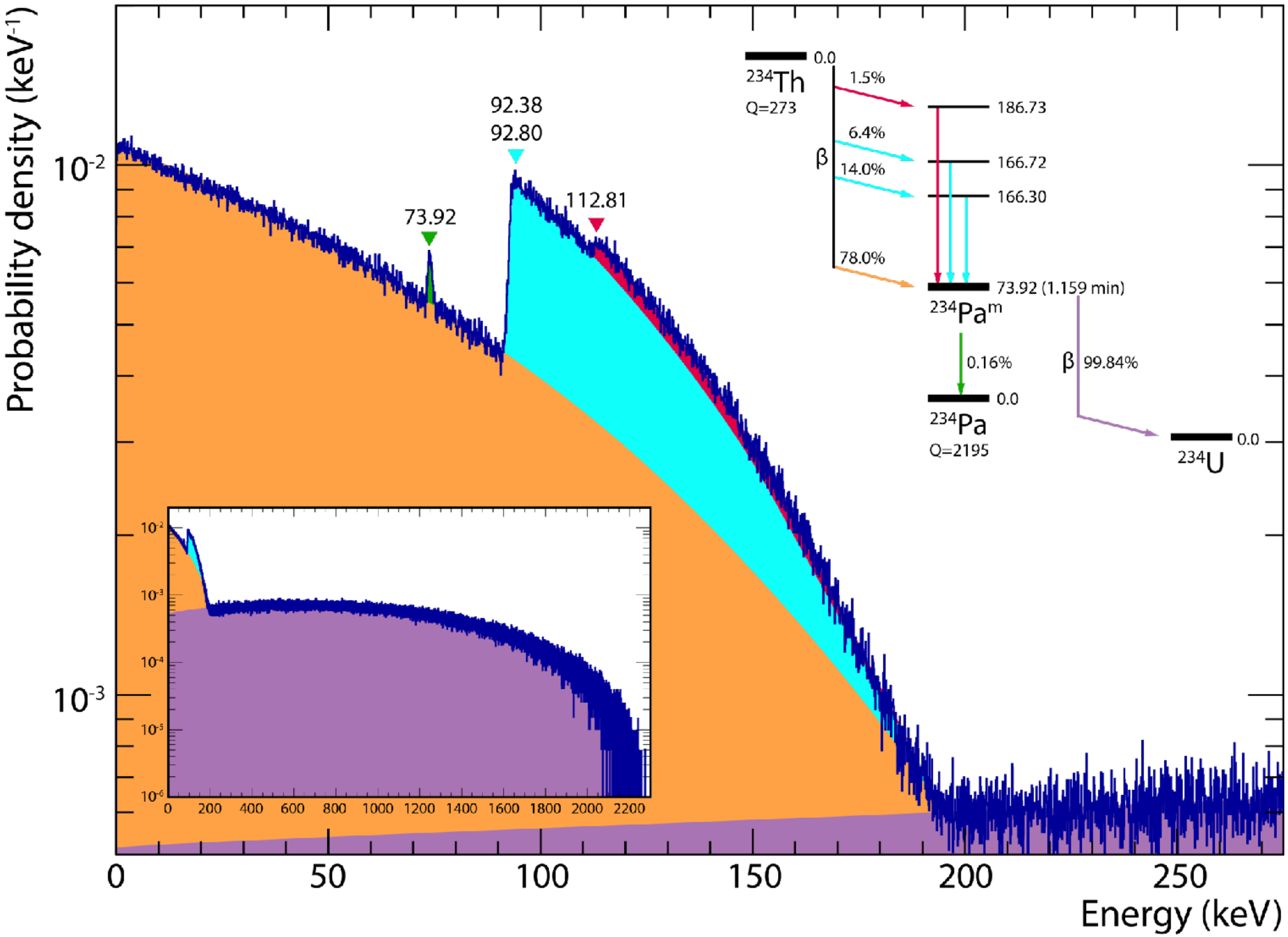




Wikipedia

Background simulation for CRESST - method II

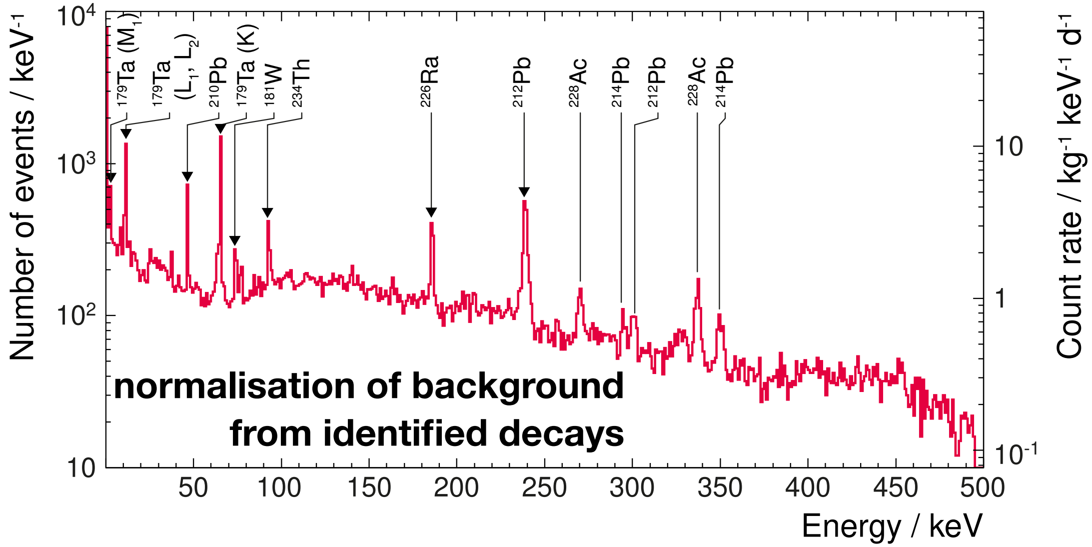
energy spectrum of simulated ^{234}Th decay with Geant4

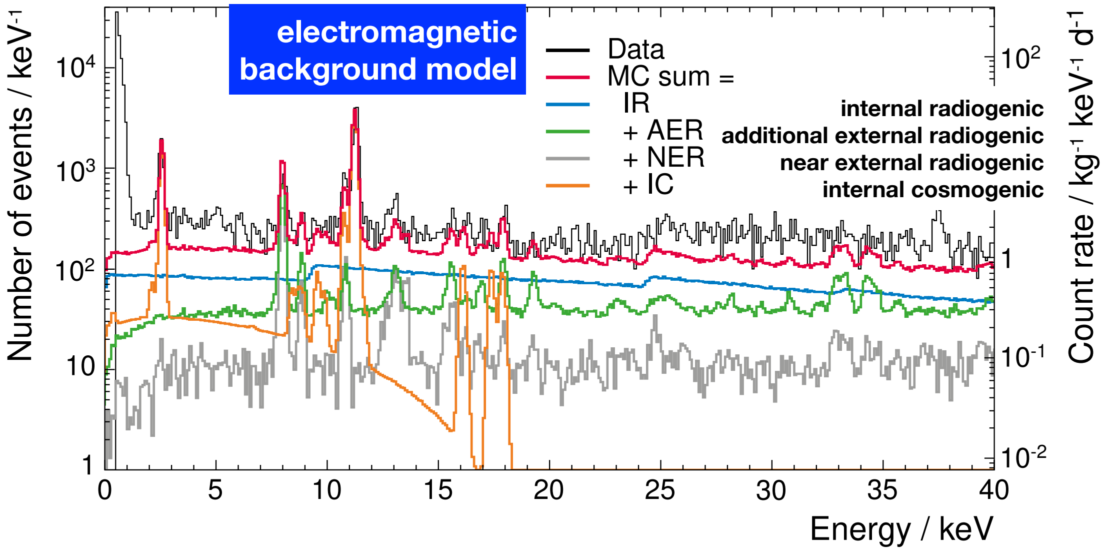


Background simulation for CRESST - result

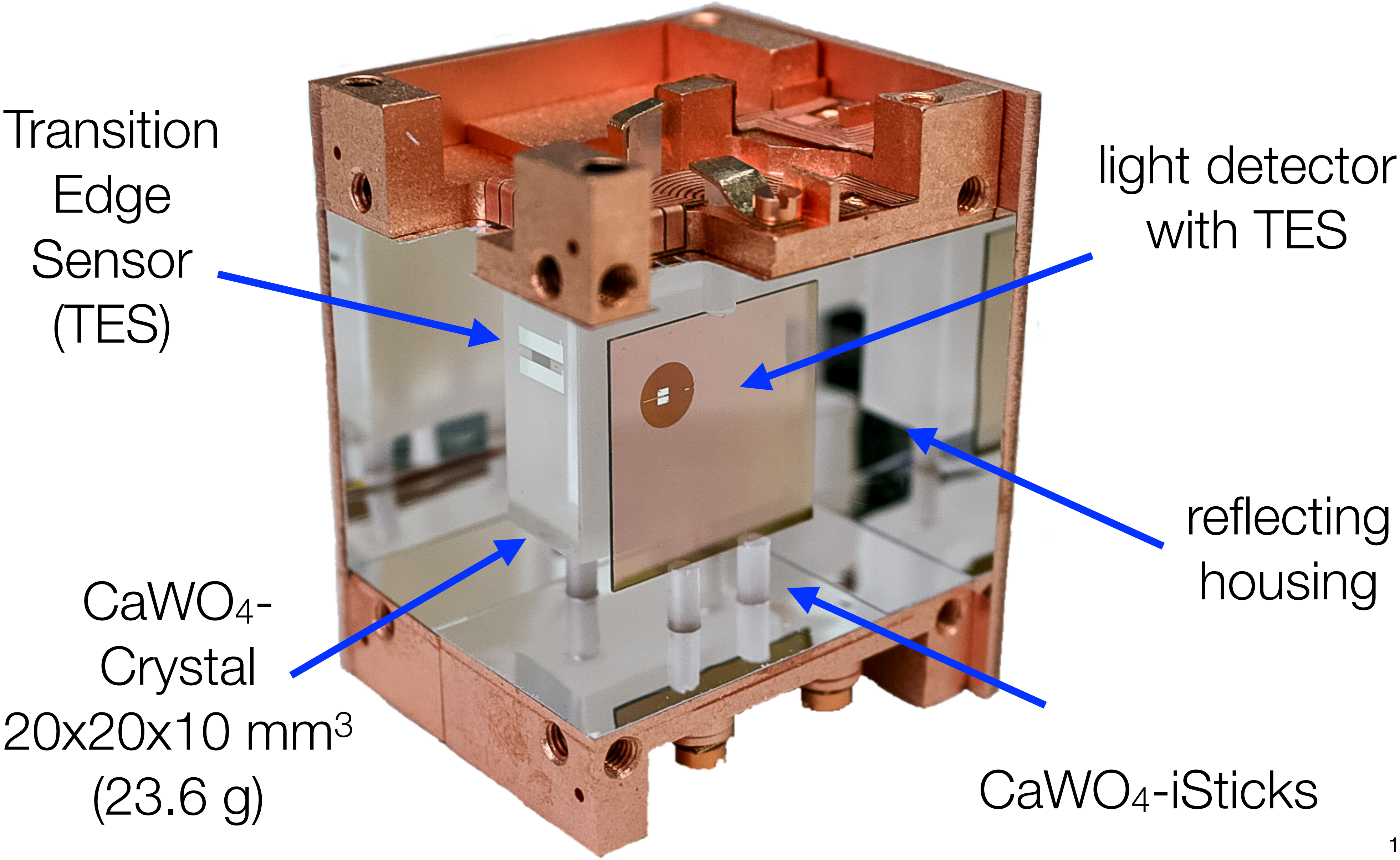
Eur.Phys.J.C 79 (2019) 10, 881

- contribution of identified γ-peaks from external radiogenic background
- **electromagnetic background reproduces (68±16)% of the observed events**
- simulation of neutron background component and material screening ongoing





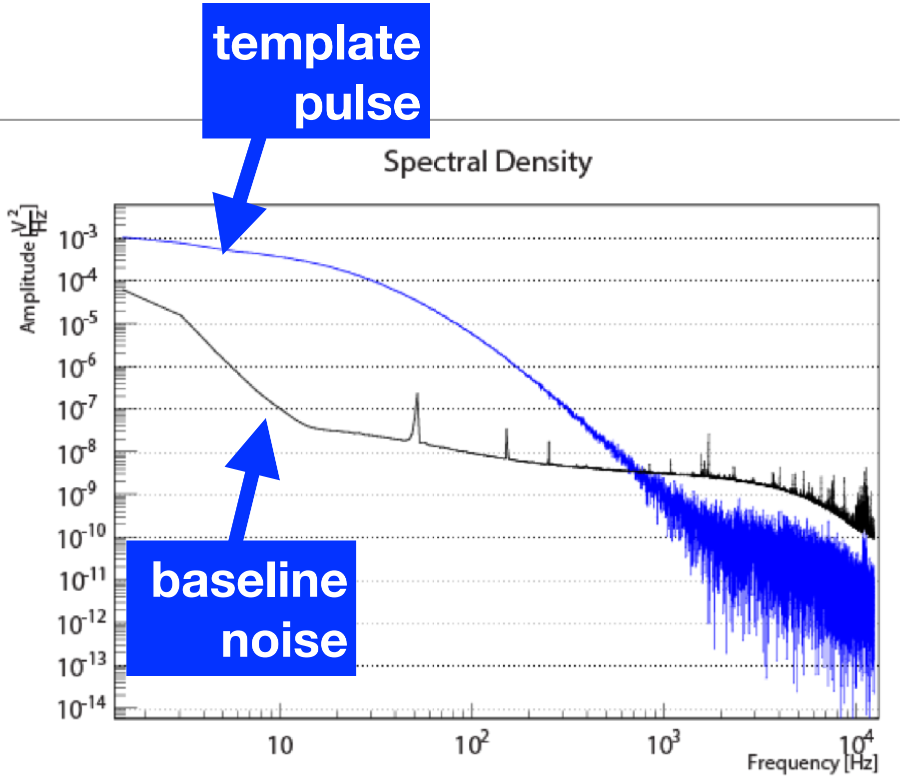
CRESST III - detector module

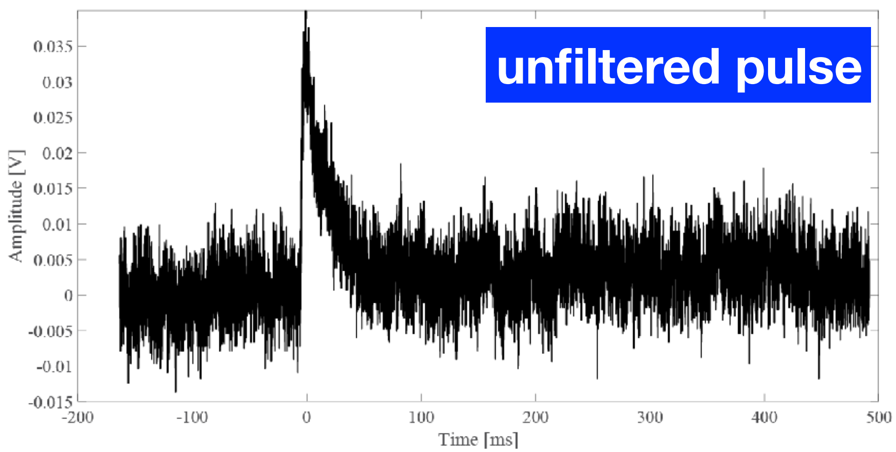


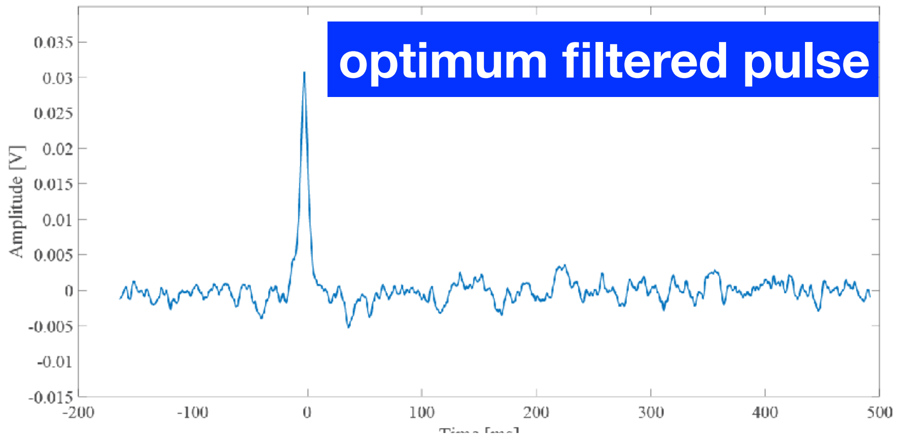
10.1016/j.nima.2019.06.030

CRESST-III optimum filter

- implementation of the Gatti-Manfredi filter
- optimum filter maximizes signal-to-noise ratio
- typical improvement about factor 2-3
- new DAQ for CRESST-III with continuous data sampling
- threshold set after optimum filter



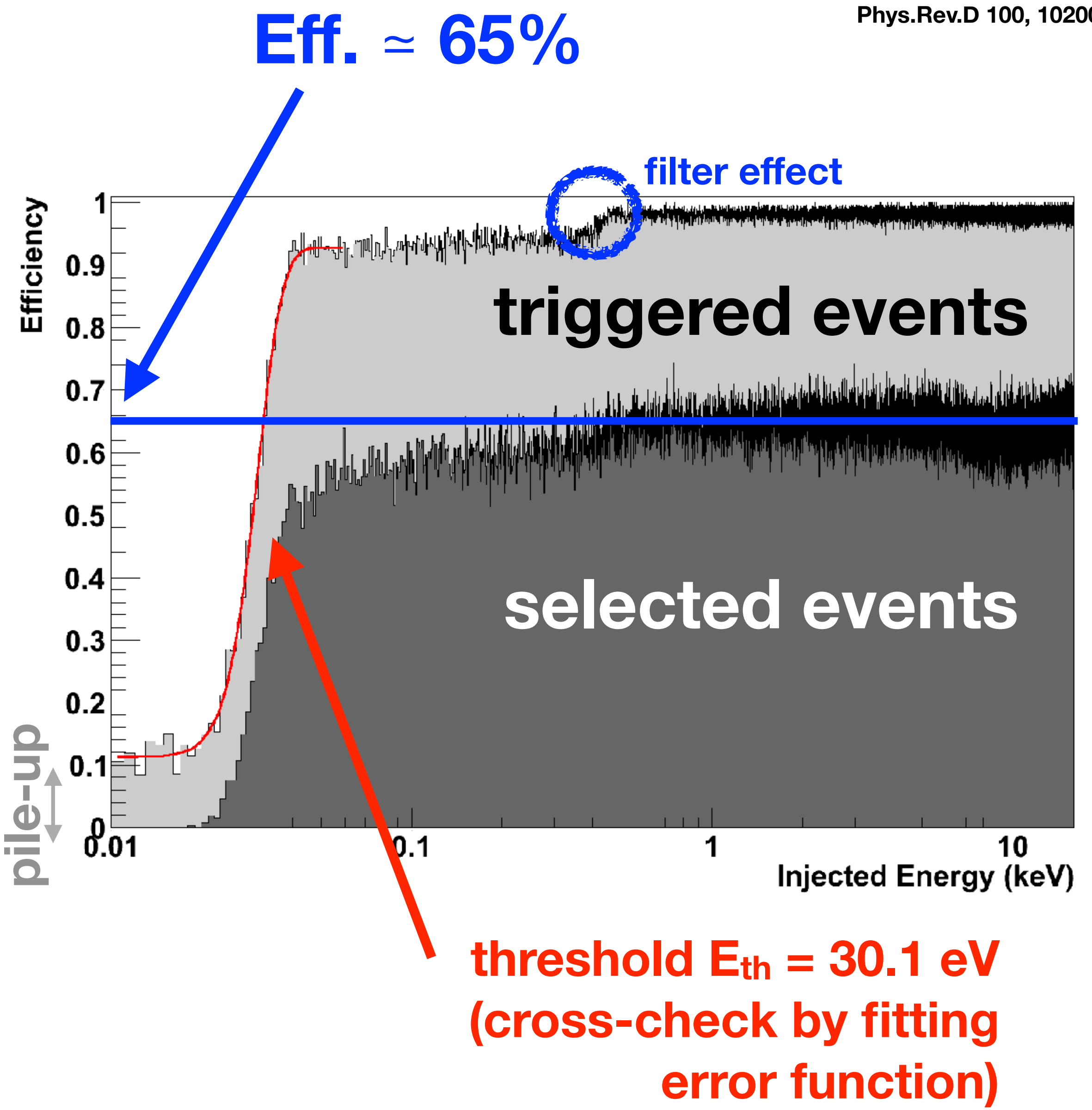




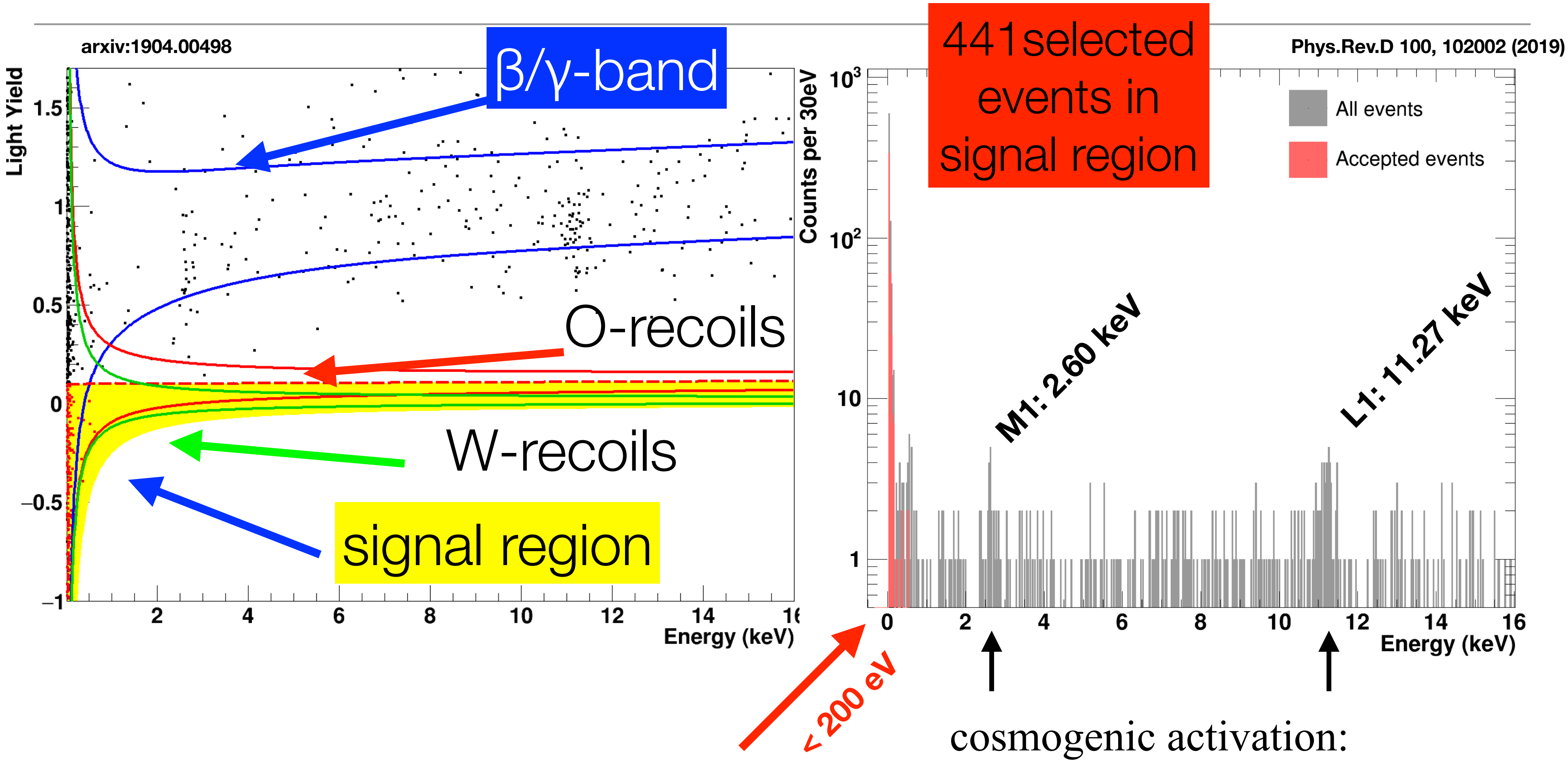
Selection efficiency

- data taking period: 5/2016-02/2018
- 20% of data as non-blind training set randomly selected
- size of selected data set (after cuts): 3.64 kg·d
- efficiency (energy dependence not taken into account) ~65%

Phys.Rev.D 100, 102002 (2019)



CRESST III - selected data



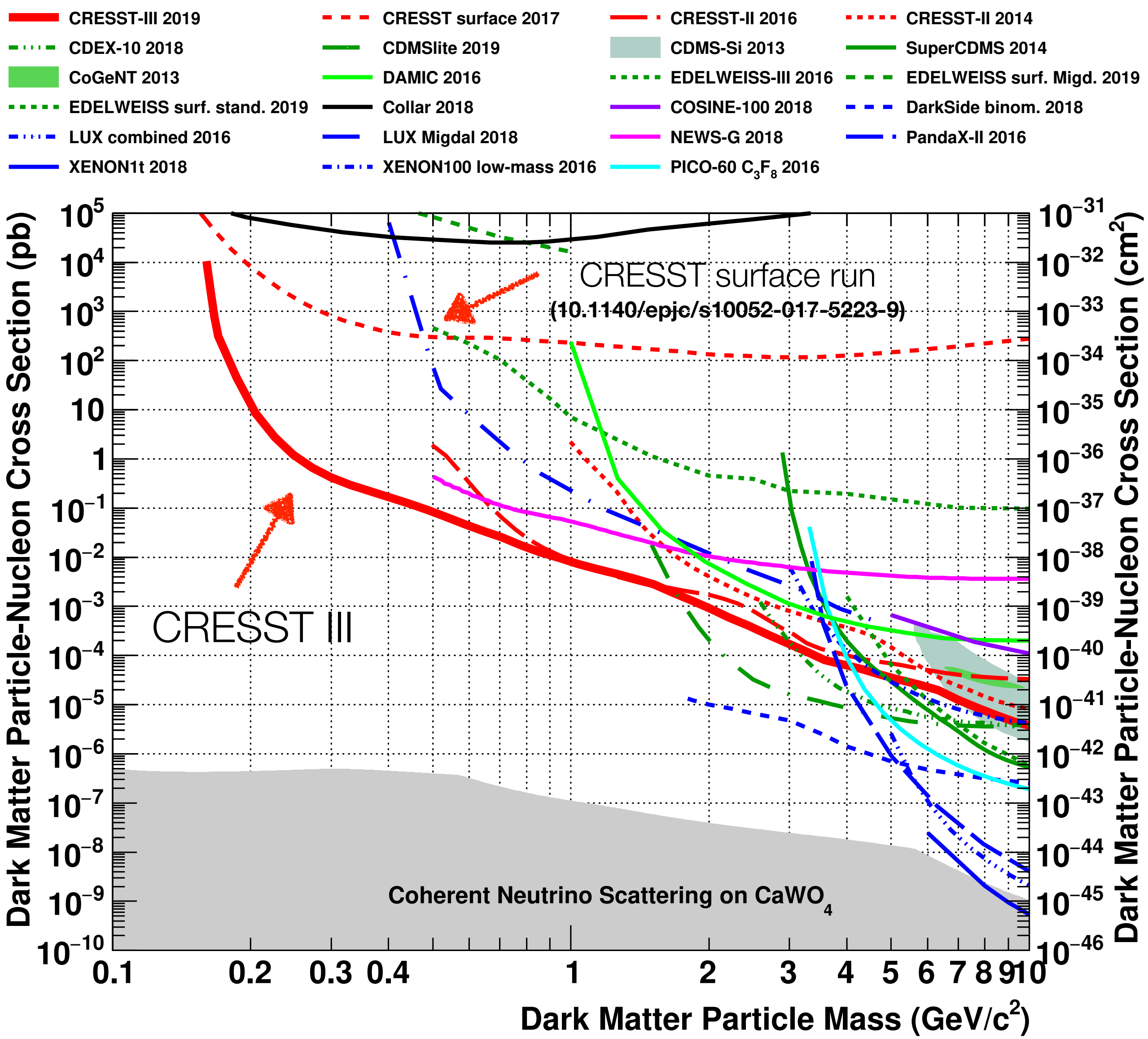
cosmogenic activation:

$$^{182}\mathrm{W} + \mathrm{p} \rightarrow {}^{179}\mathrm{Ta} + \alpha, \quad {}^{179}\mathrm{Ta} \xrightarrow{\mathrm{EC}} {}^{179}\mathrm{Hf} + \gamma.$$

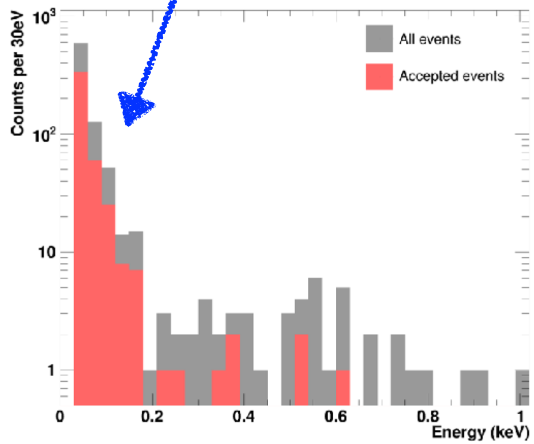
- number of events exponentially increasing for low energies

Limit on spin-independent dark matter

Phys.Rev.D 100, 102002 (2019)



- extend sensitivity down to 160 MeV/c^2
- **unexpected rise of event rate below 200 eV**



CRESST III - Low-mass dark Matter Detection

Run1
07/2016 - 02/2018

30 eV threshold reached

Leading sensitivity over one order of magnitude: 160 MeV/c^2 - 1.8 GeV/c^2

Unexplained rise of event rate for E<200 eV

Run2
12/2018 - 10/2019

Upgraded detector modules with dedicated hardware changes to understand unexplained rise

Successful test of active magnetic field compensation

Run3
07/2020

2nd round with additional modifications

Successful cool-down in 03/2020, but stopped due to Corona pandemic

Next cool-down started Monday, July 20

Cryogenic Operation of $LiAlO_2$ crystals

- Lithium offers unique potential for direct dark matter searches

  - Lithium lightest element which can be operated with cryogenic CRESST technology
    → increased sensitivity for light dark matter

  - ^{7}Li (~92% natural abundance) offers the possibility to investigate spin-dependent interactions with dark matter

  - measurement of ambient neutrons via detection of ^{6}Li(n,α)^{3}H events

Cryogenic Operation of $LiAlO_2$ crystals

- first cryogenic operation of $LiAlO_2$ crystals to identify potential for future dark matter application

- study three key properties at cryogenic temperatures

  (i) study of scintillating properties, light yield and quenching factors

  (ii) energy detection threshold and dark matter operation

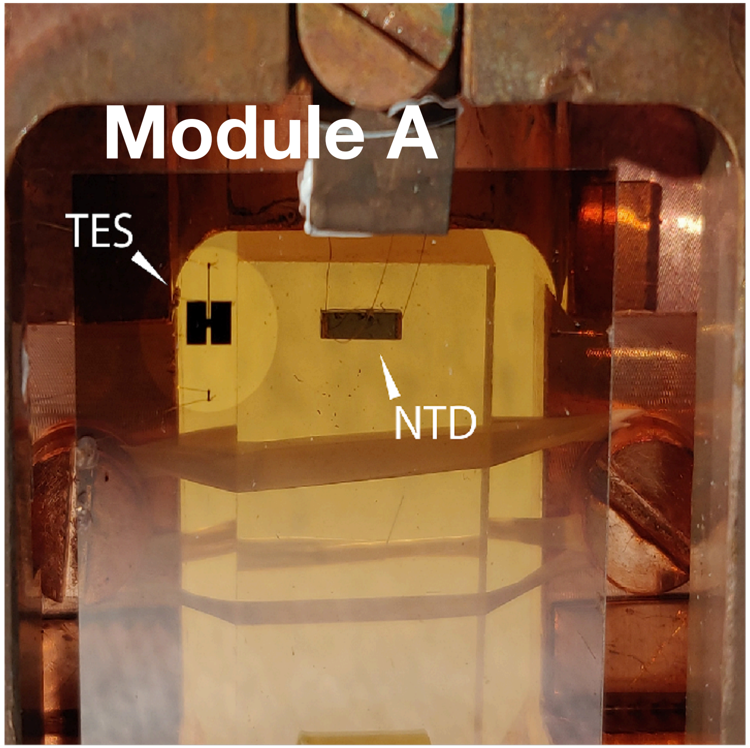
spin of the target

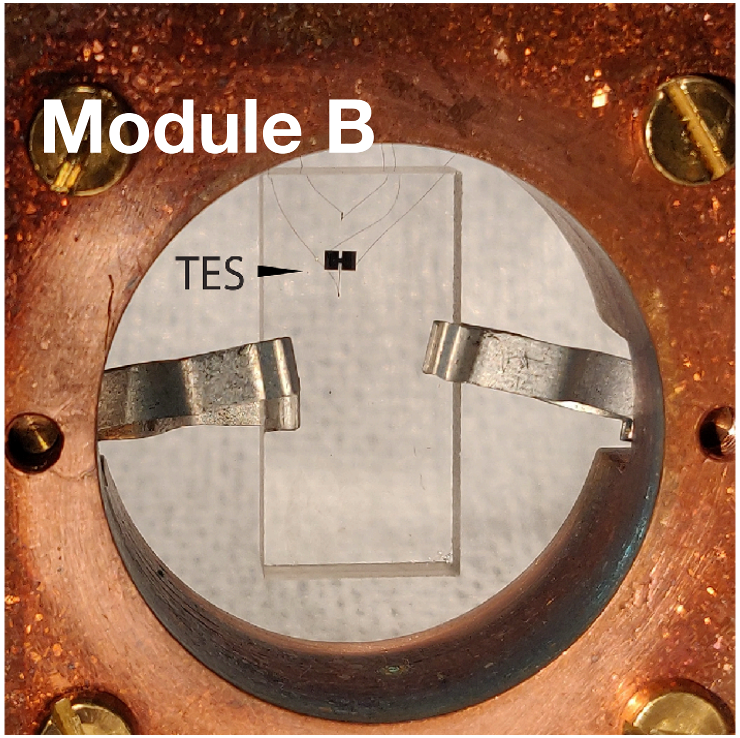
$$\left(\frac{d\sigma_{WN}}{dE_R}\right)_{SD} = \frac{16 m_N}{\pi v^2}\Lambda^2 G_F^2 J(J+1)\frac{S(E_R)}{S(0)}$$

  (iii) neutron detection and radiopurity measurement

$LiAlO_2$ Crystals

- $LiAlO_2$ crystal grown at Leibniz-Institut für Kristallzüchtung





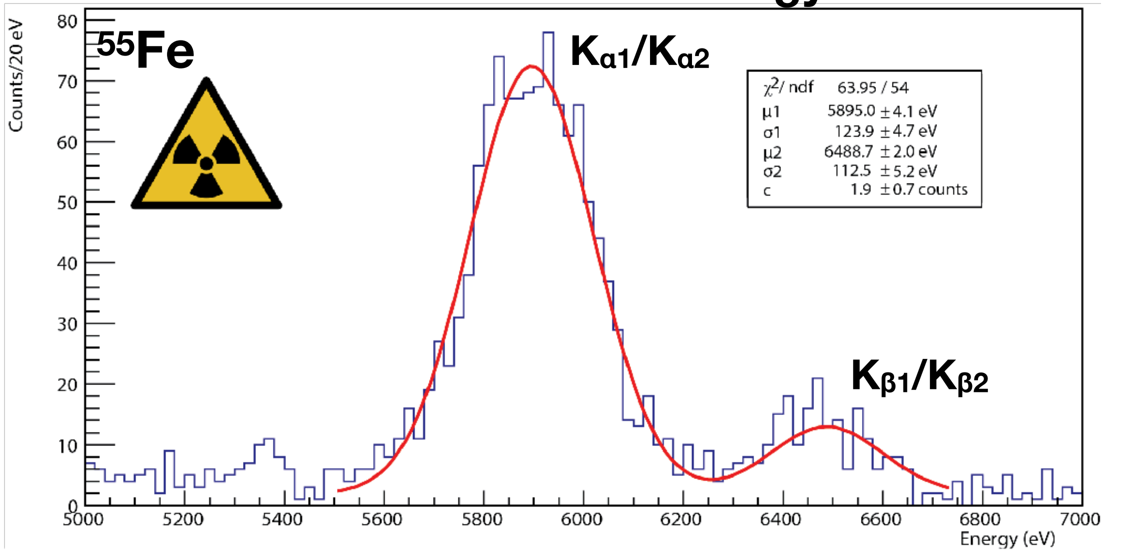
- characterisation of $LiAlO_2$ at cryogenic temperatures
- scintillating properties

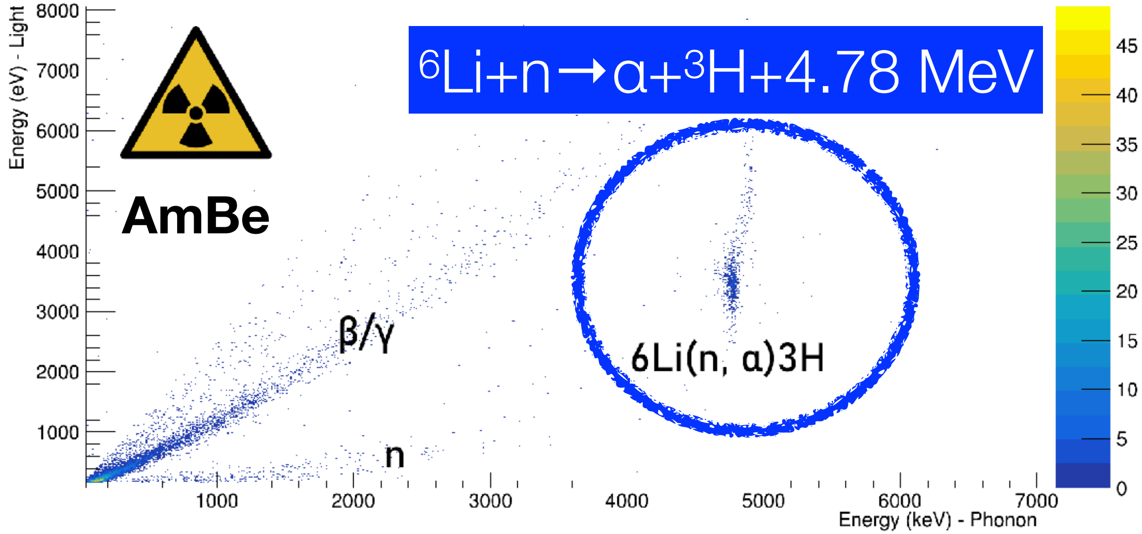
- study of spin dependent dark matter interactions
- determination of energy threshold

$LiAlO_2$ Crystals - Module A - Surface Operation

- energy calibration using a ^{55}Fe X-ray source
- AmBe neutron source for quenching factor measurements
- clear separation between β/γ and neutrons above ~170 keV

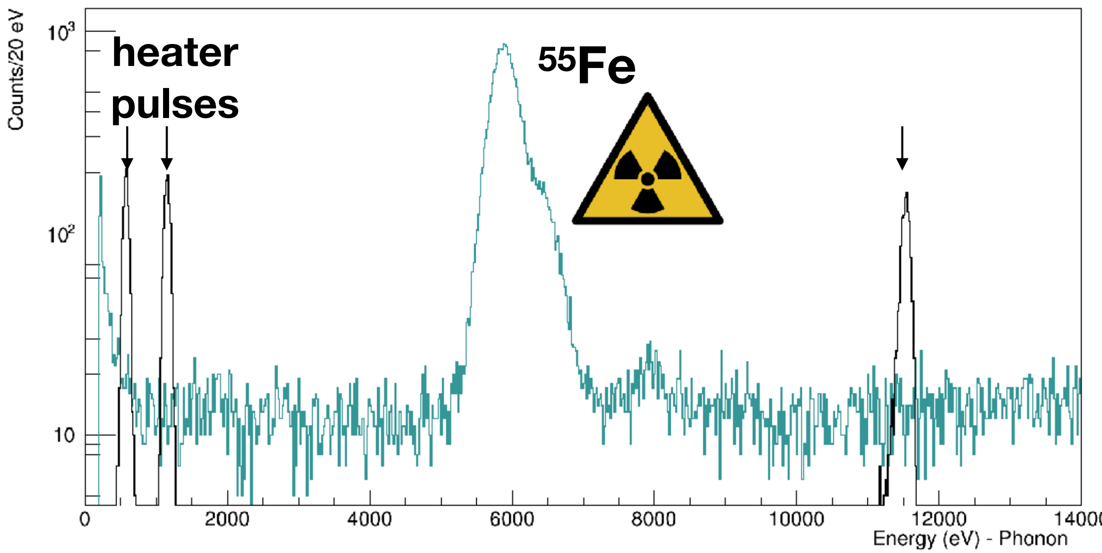
energy calibration





$LiAlO_2$ Crystals - Module B - Surface Operation

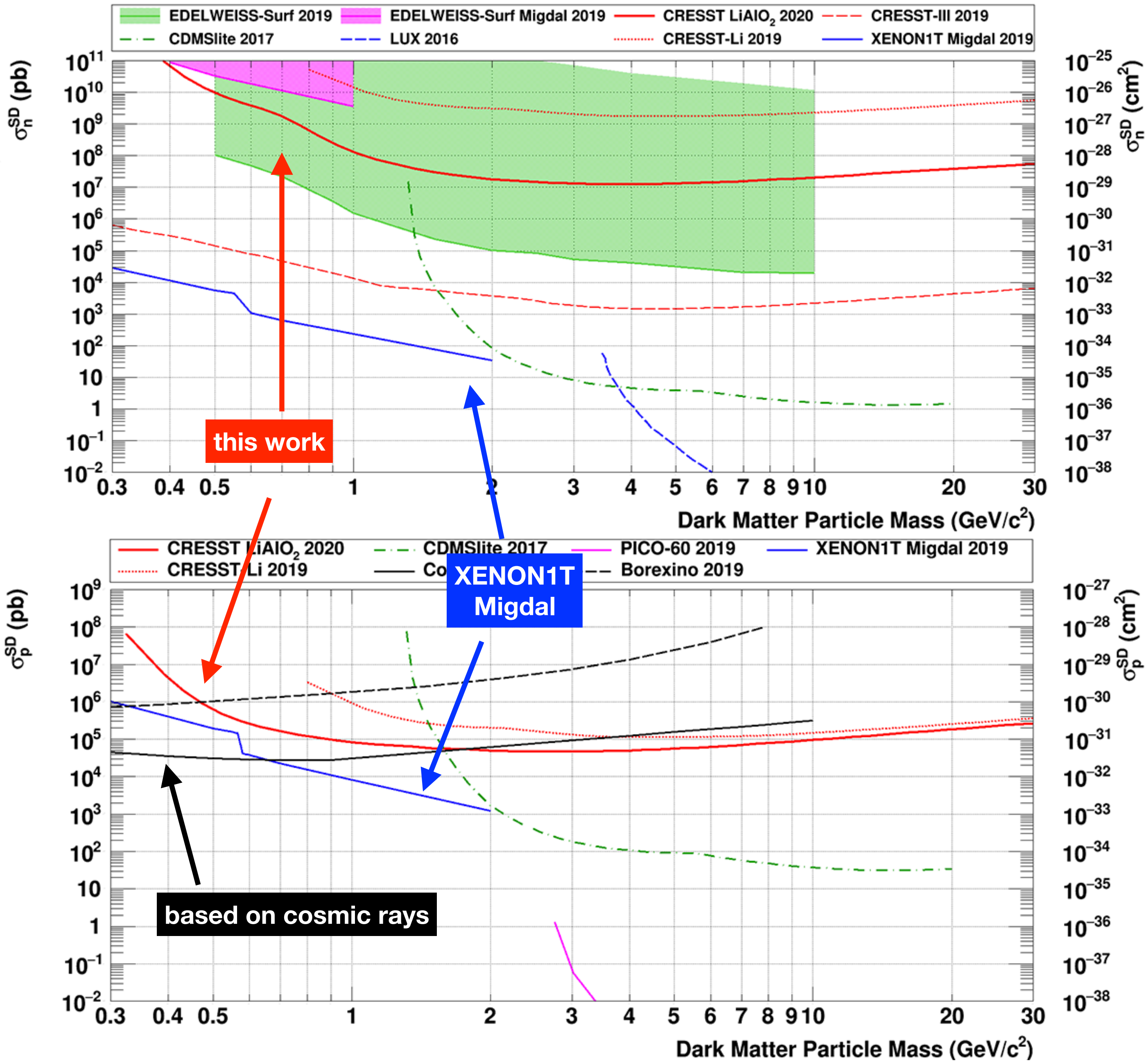
- dedicated dark matter surface run
  - limited by background rate of $2 \cdot 10^5$ counts/(keV · kg · day)
- energy calibration using ^{55}Fe X-ray source
- 22.2 h of data taking
  - exposure:
    - total: $2.01 \cdot 10^{-3}$ kg · d
    - ^7Li: $1.95 \cdot 10^{-4}$ kg · d
    - ^{27}Al: $8.22 \cdot 10^{-4}$ kg · d
- energy threshold of 213±1.48 eV
  baseline resolution σbaseline = (39.75±1.23) eV



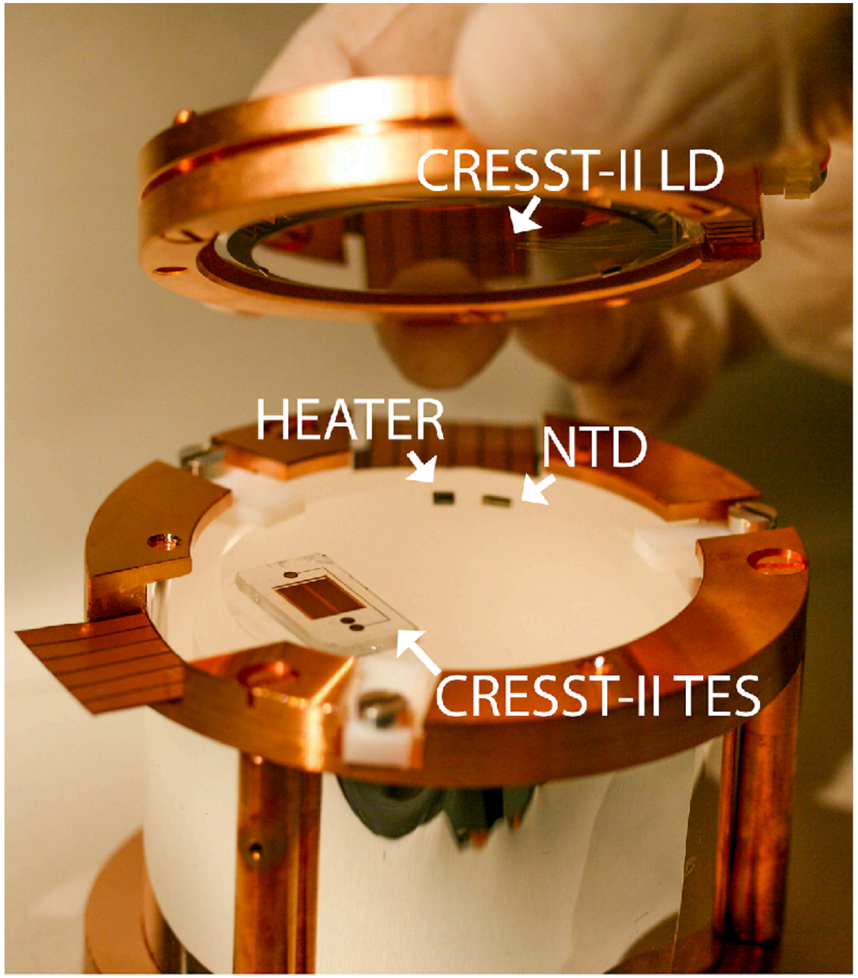
arXiv:2005.02692

Dark Matter Interpretation

- dark matter interpretation using standard astrophysical assumptions
- limit for proton-only and neutron-only interaction calculated
- best reach in mass for direct spin-dependent dark matter detection



$LiAlO_2$ Crystals - Module C - Operation at LNGS

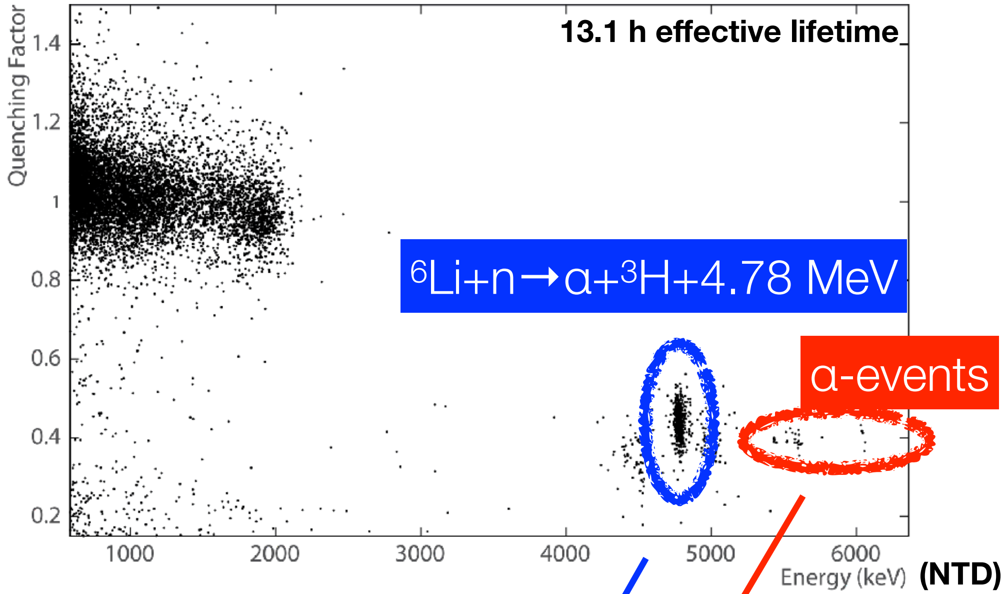


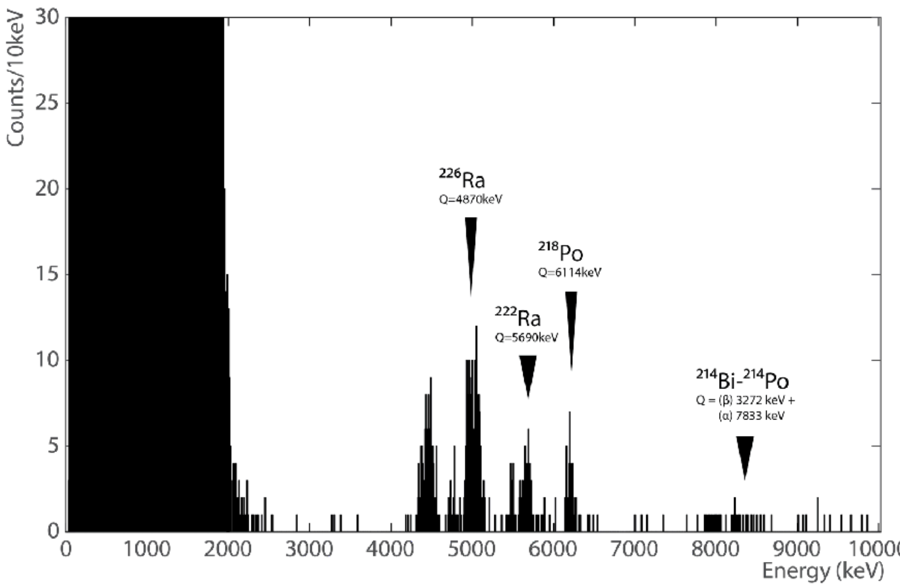
- measurement done in a test cryostat @ LNGS
- feasibility study to use $LiAlO_2$ as a neutron monitor
- measurement of intrinsic background
- 373 g crystal
- crystal equipped with two phonon sensors (TES, NTD) and light detector

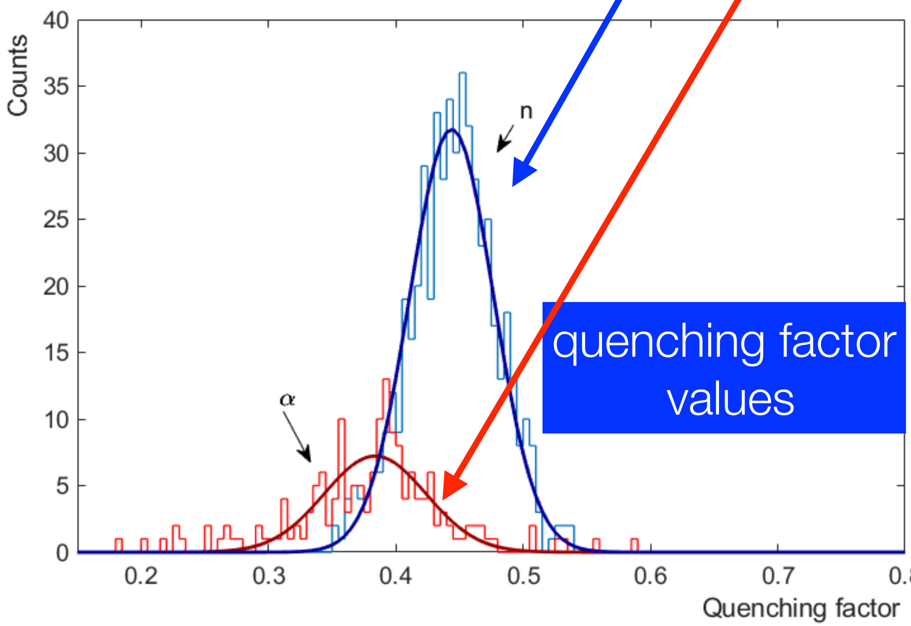
arXiv:2005.02692

$LiAlO_2$ Crystals - Module C - Operation at LNGS

- AmBe neutron source allows to show a clear separation of n-events
- measurement of neutron flux with $LiAlO_2$ possible
- α-activity: (10.1±0.5) mB/kg (above 3 MeV)
- ~3 times worse compared to best $CaWO_4$







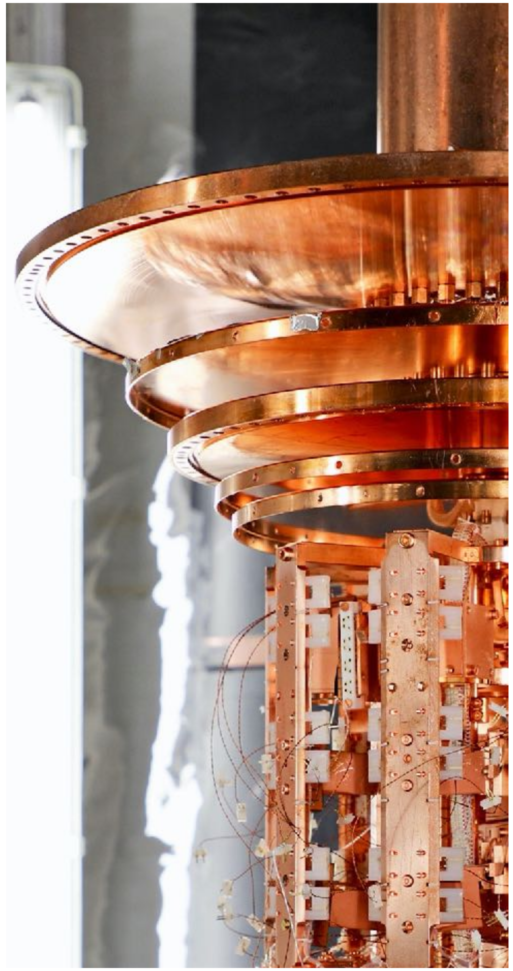
CRESST 2020/21 Upgrade

- Upgrade to 200 readout channels to accommodate 100 modules for O(2 kg) target mass

- New cryostat cabling designed and prototyped

- Sensor development to further push detector threshold (10 eV)

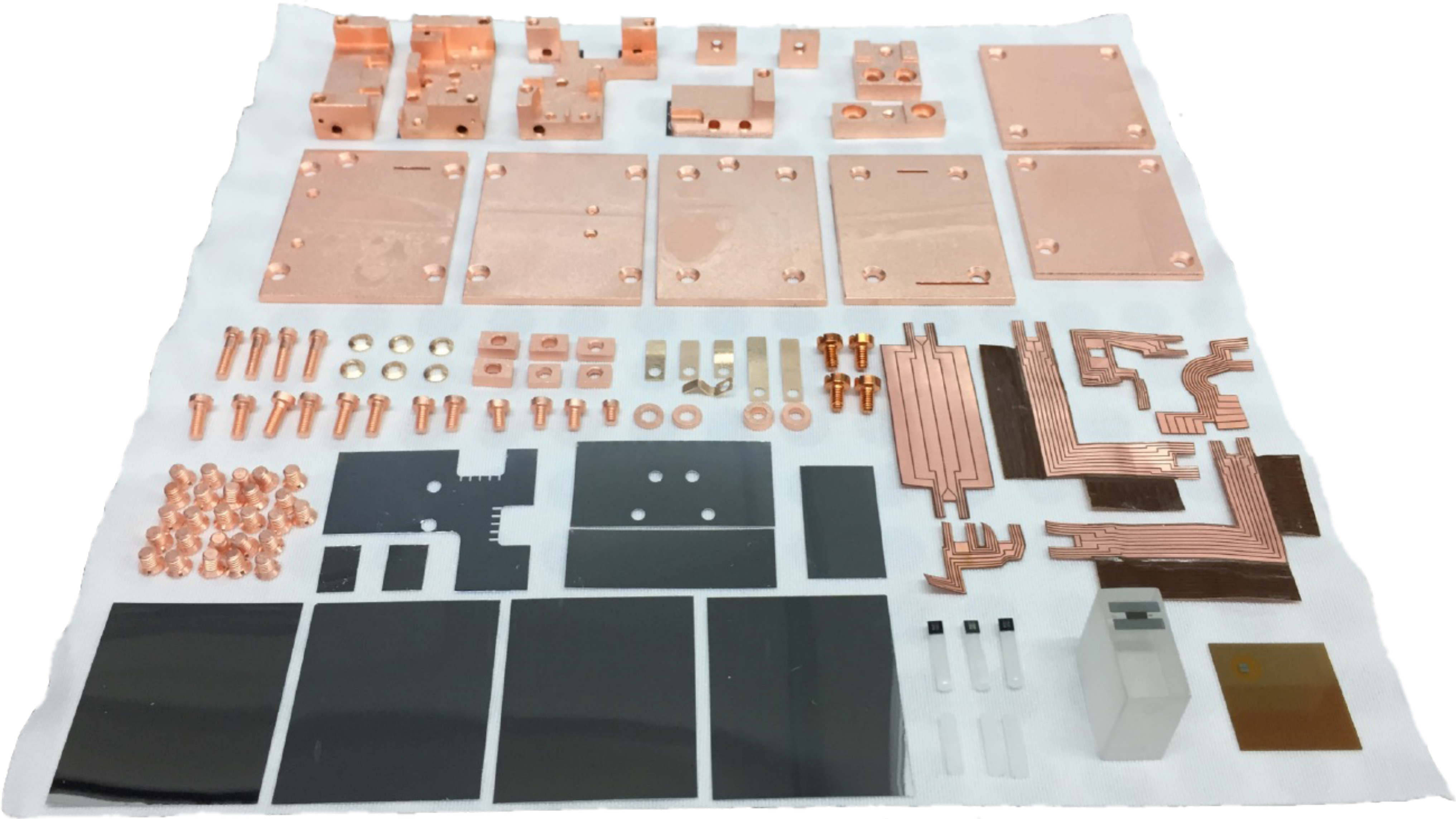
- Continuation of studies with alternative detector materials ($LiAlO_2$, Al_2O_3) which also yield sensitivity for spin-dependent interactions



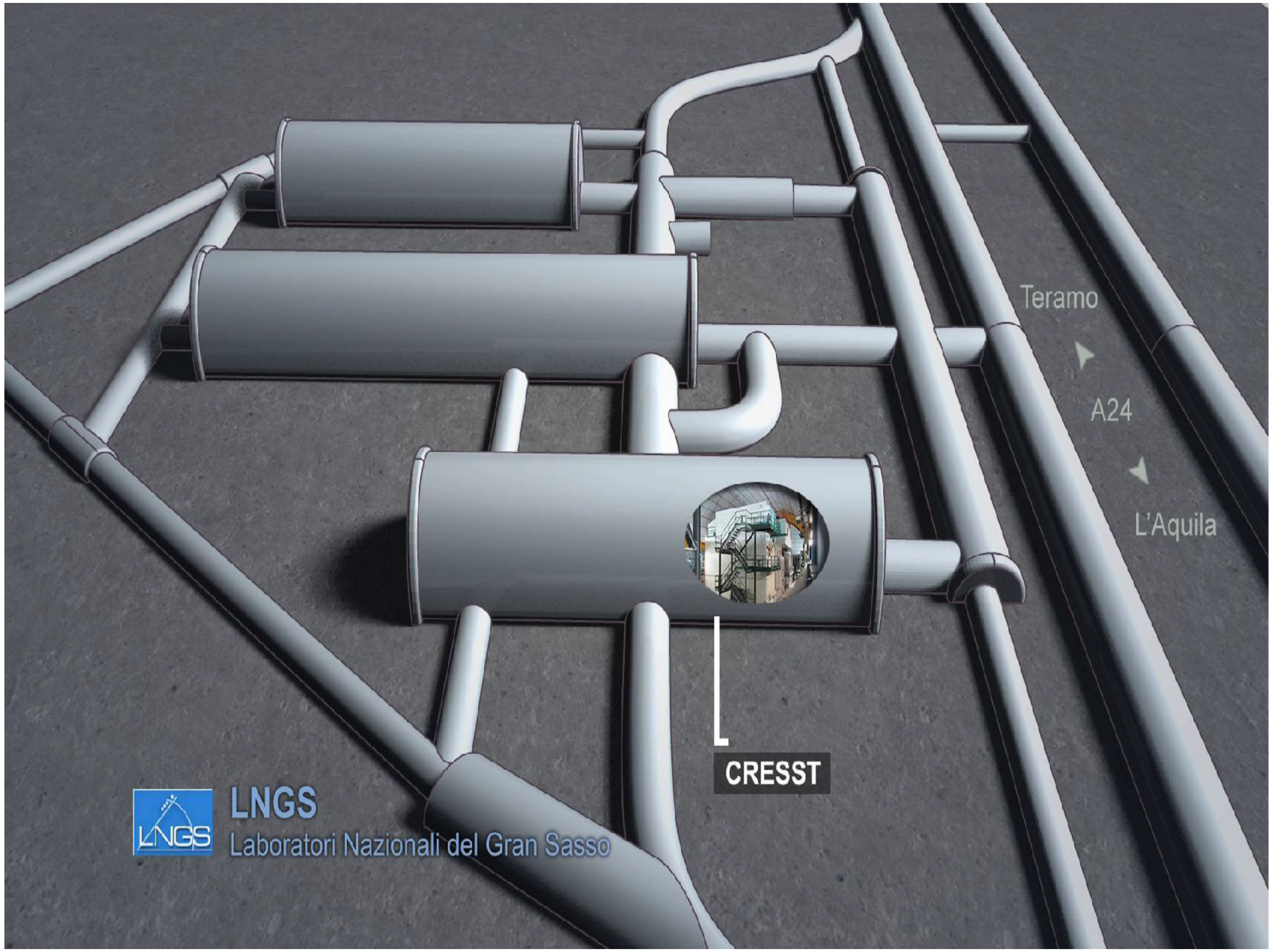
Summary

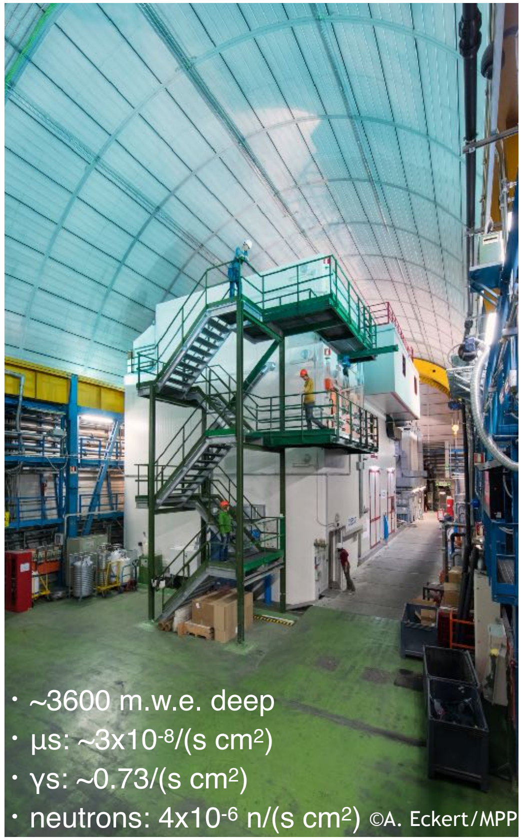
- **CRESST-III** with **23.6 g** CaWO4 crystals from 05/2016-02/2018
- unprecedented low nuclear recoil **threshold of 30 eV**
- **best limit** for dark matter masses between **160 MeV/c^2 and 1.8 GeV/c^2**
  - unexpected **rising event rate below 200 eV**
- detailed studies of **$LiAlO_2$-crystals**
  - **spin-dependent dark matter** searches
  - in-situ measurement of **neutron-flux**
- Discussion: Fr. 31.7. 14:30h https://cern.zoom.us/j/94156181934

CRESST III Module Construction Kit



CRESST @ LNGS


Teramo
A24
L'Aquila
CRESST
LNGS
Laboratori Nazionali del Gran Sasso


~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