# Direct Dark Matter Search with the CRESST-III experiment

## State of the art and results

MAX-PLANCK-INSTITUT FÜR PHYSIK

Dr. Beatrice Mauri

on behalf of the CRESST collaboration

# The CRESST collaboration

MAX-PLANCK-INSTITUT FÜR PHYSIK

COMENIUS UNIVERSITY BRATISLAVA

EBERHARD KARLS UNIVERSITÄT TÜBINGEN

TU WIEN TECHNISCHE UNIVERSITÄT WIEN

Technische Universität München TUM


HEPHY INSTITUTE OF HIGH ENERGY PHYSICS

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

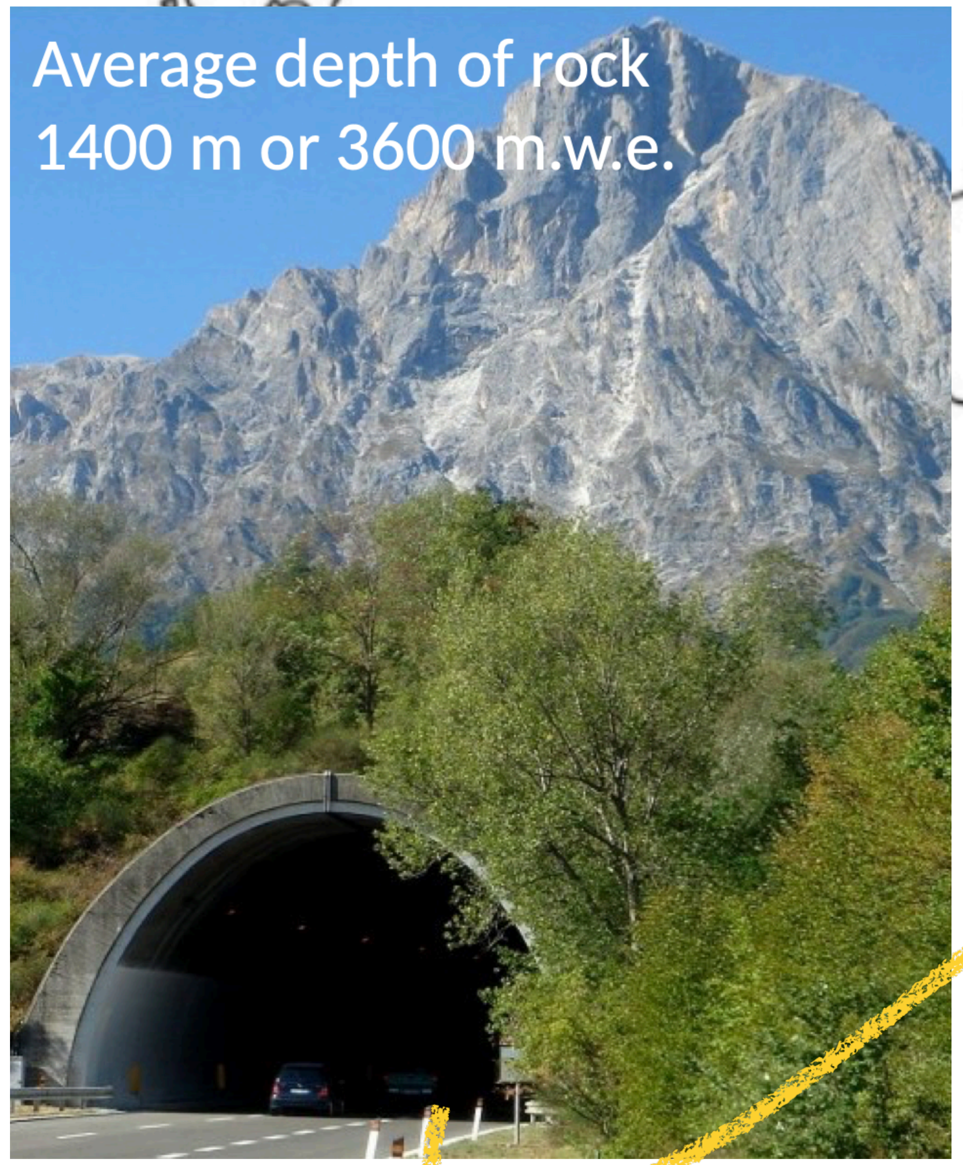
INFN LNGS Istituto Nazionale di Fisica Nucleare Laboratori Nazionali del Gran Sasso

UNIVERSITY OF OXFORD

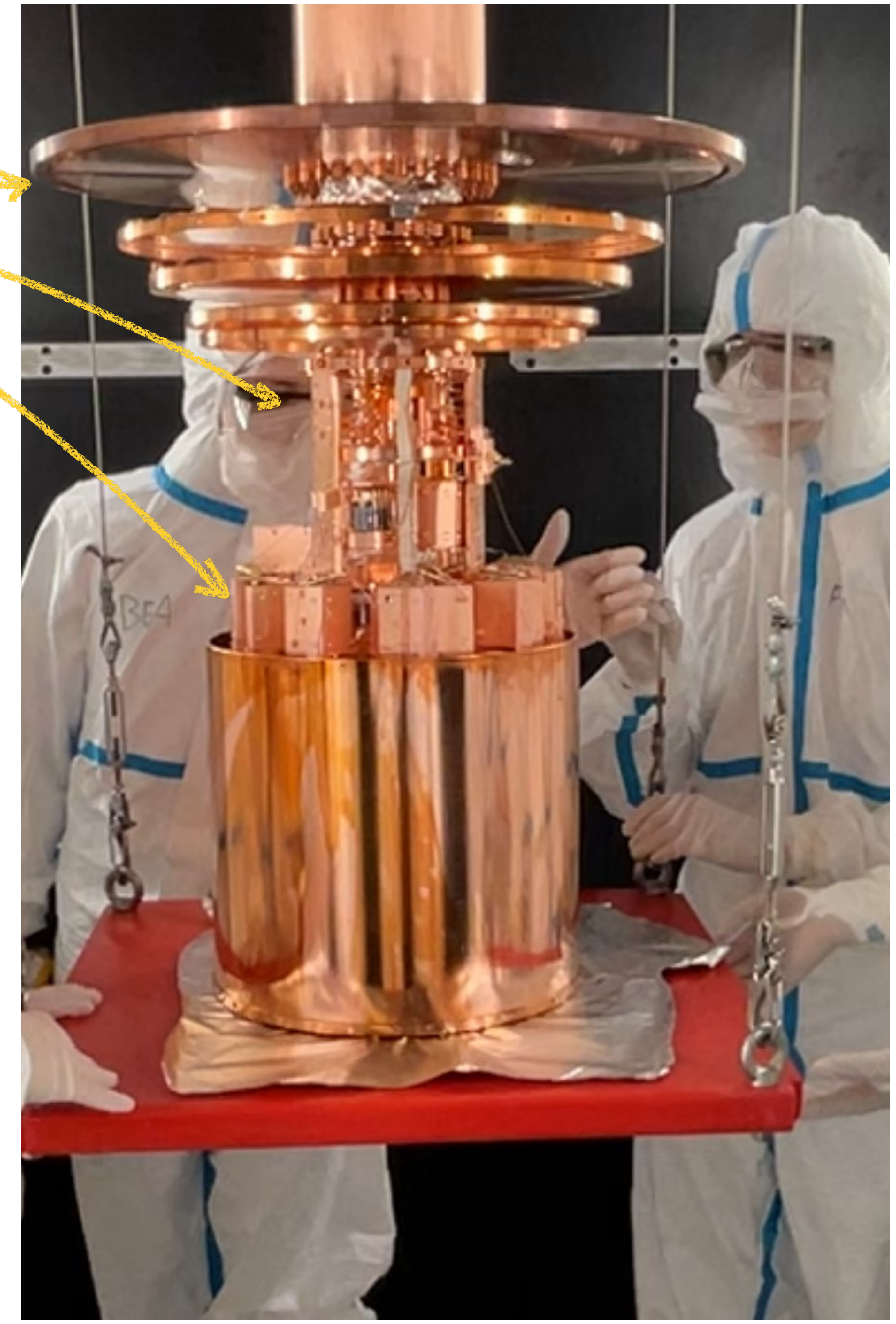
~ 60 members from 9 institutions in 5 European countries

# The CRESST experiment

## Location

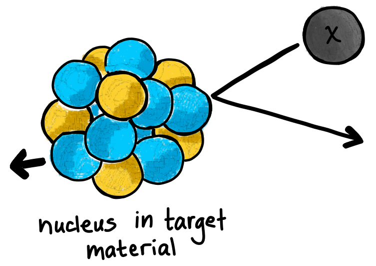


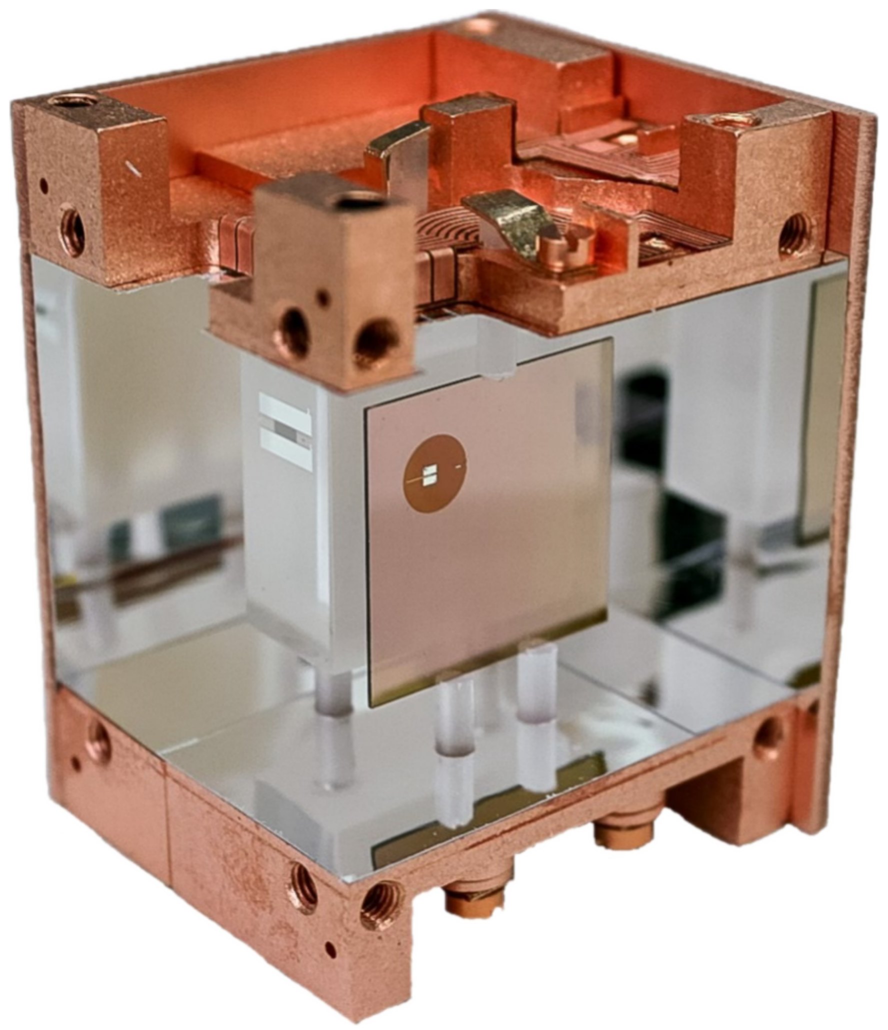



# CRESST-III detectors

**Cryogenic detectors**

- Direct detection of potential **DM particles** via scatter off target nuclei
- Operated at $\sim$**15 mK**
- Energy deposited in the target causes a proportional **temperature rise** $\Delta T = \frac{\Delta E}{C}$

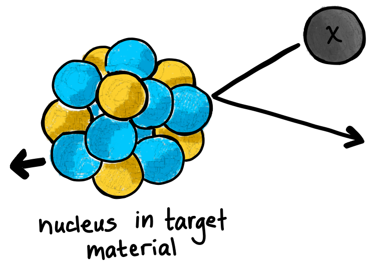


# CRESST-III detectors

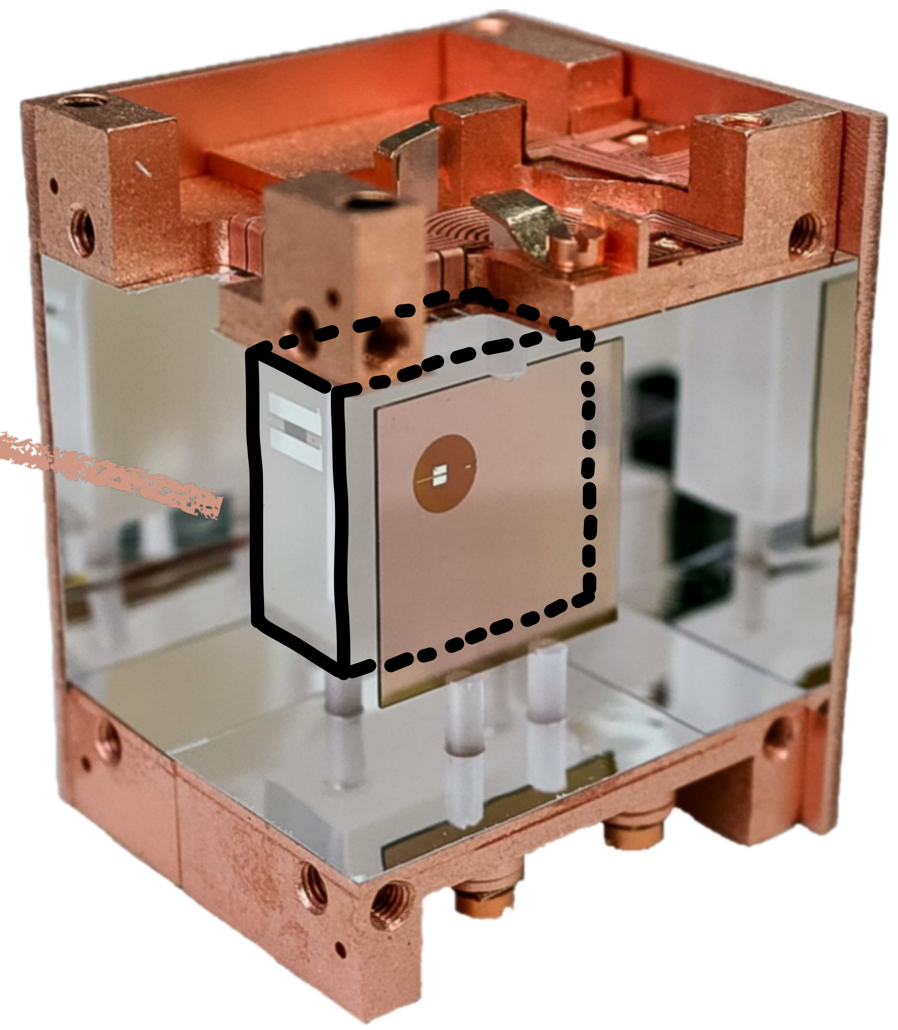
**Cryogenic detectors**

- Direct detection of potential **DM particles** via scatter off target nuclei
- Operated at ~**15 mK**
- Energy deposited in the target causes a proportional **temperature rise** $\Delta T = \frac{\Delta E}{C}$




**Target crystal/Absorber**

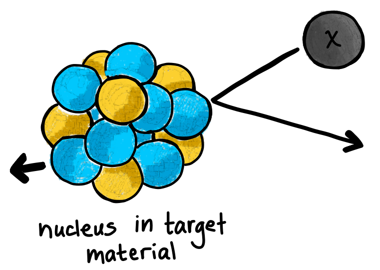
- Material: $CaWO_4$, Si, $Al_2O_3$, $LiAlO_2$
- Volume: 4 $cm^3$



# CRESST-III detectors

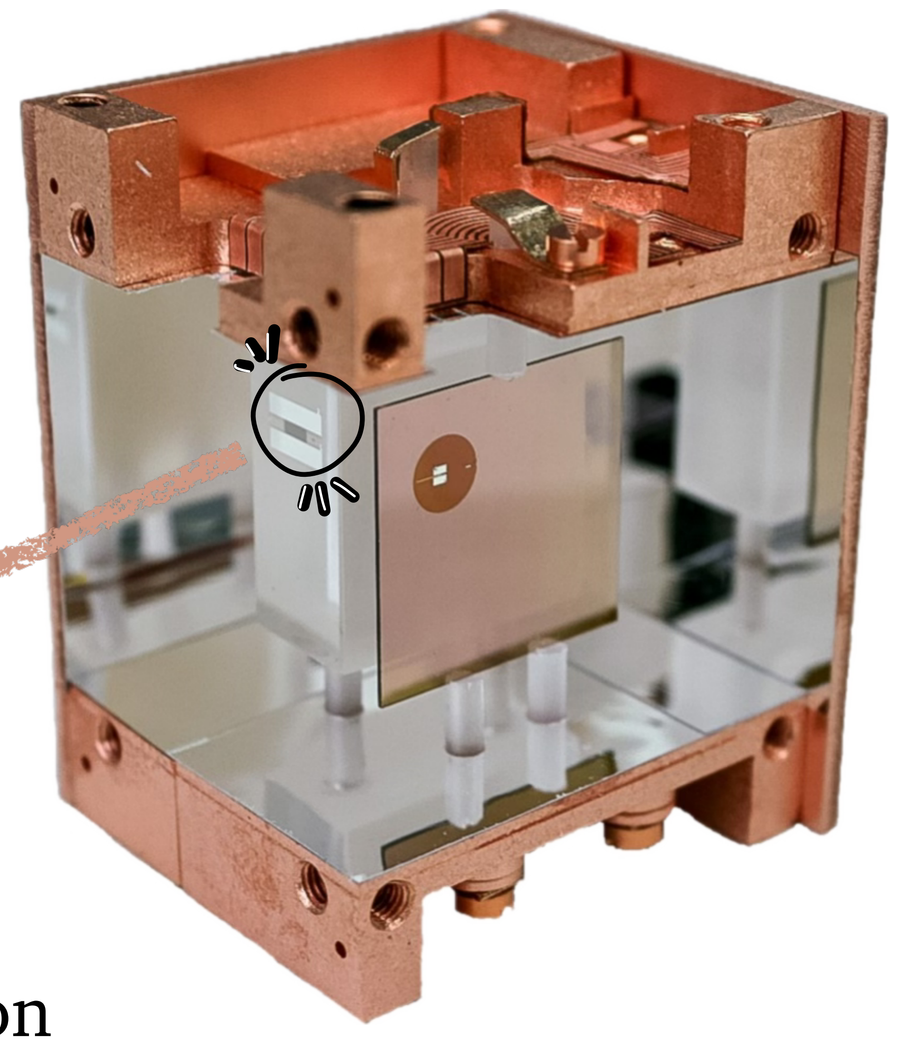
**Cryogenic detectors**

- Direct detection of potential **DM particles** via scatter off target nuclei
- Operated at ~**15 mK**
- Energy deposited in the target causes a proportional **temperature rise** $\Delta T = \frac{\Delta E}{C}$



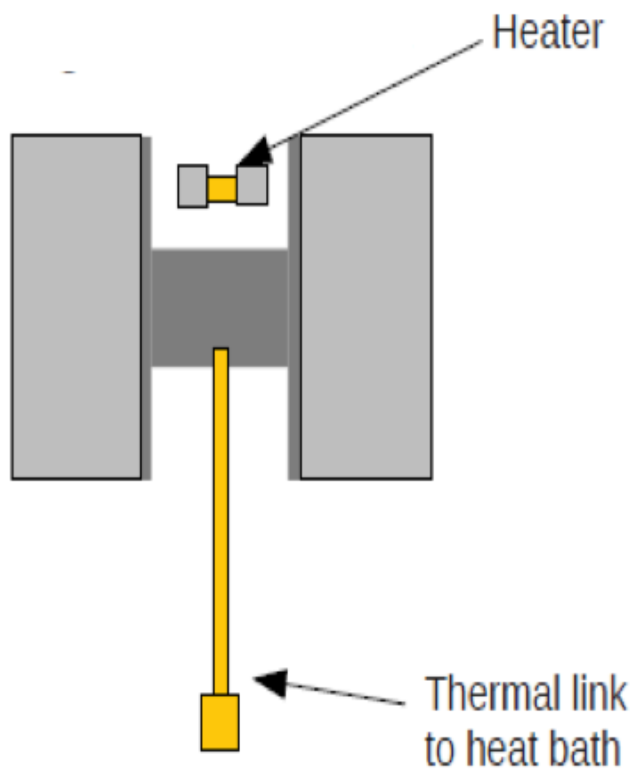

**Target crystal/Absorber**

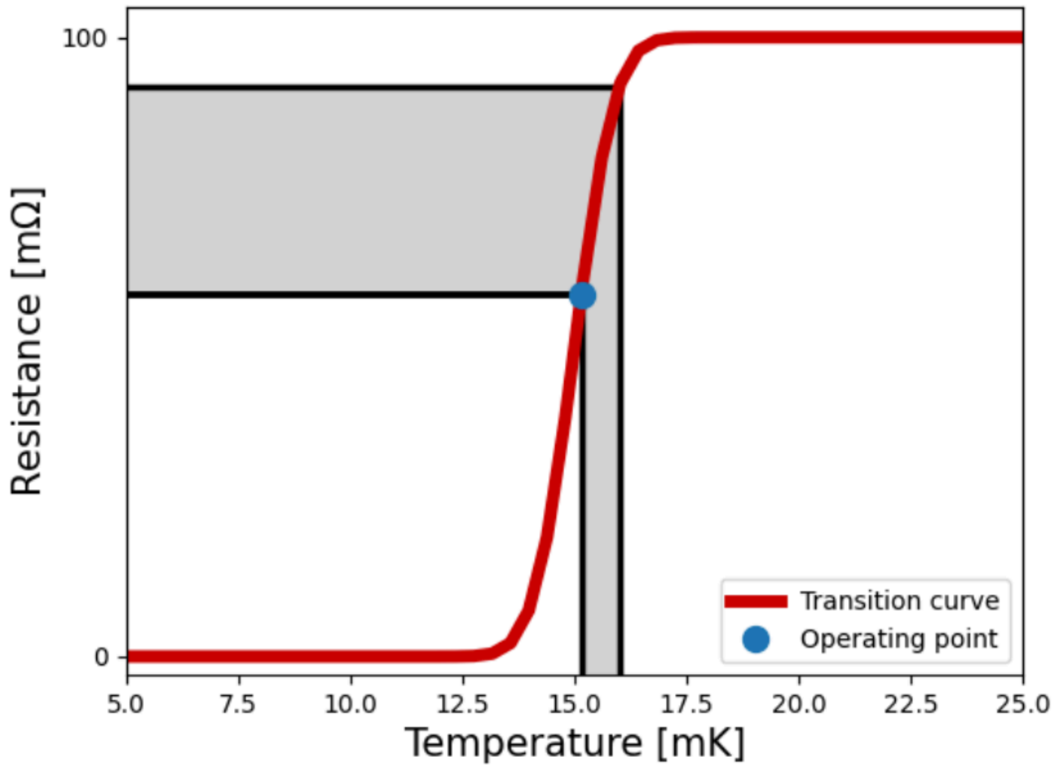
- Material: $CaWO_4$, Si, $Al_2O_3$, $LiAlO_2$
- Volume: 4 $cm^3$



**Temperature sensor**

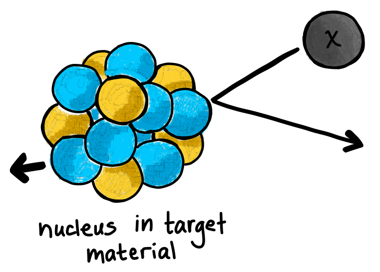
- W Transition Edge Sensor (TES)
- Operated in the middle of its superconducting transition



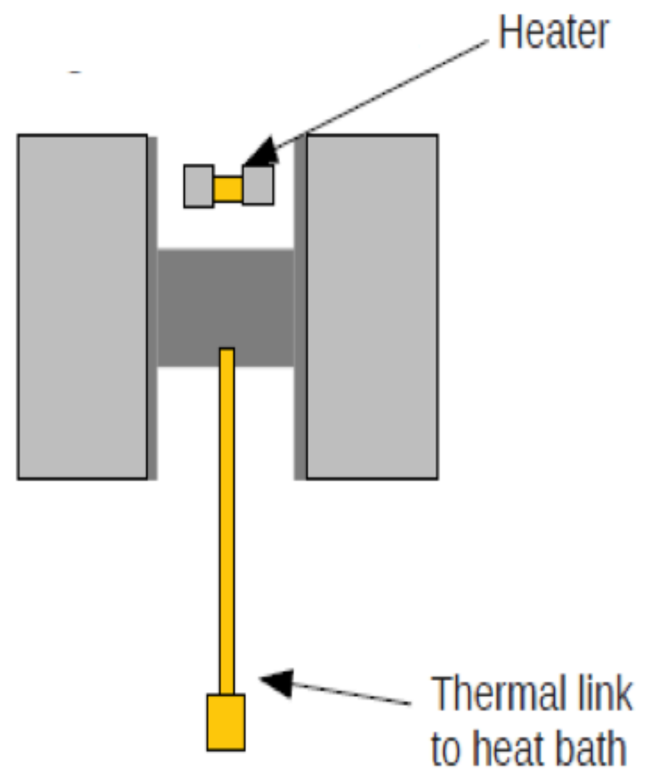
# CRESST-III detectors

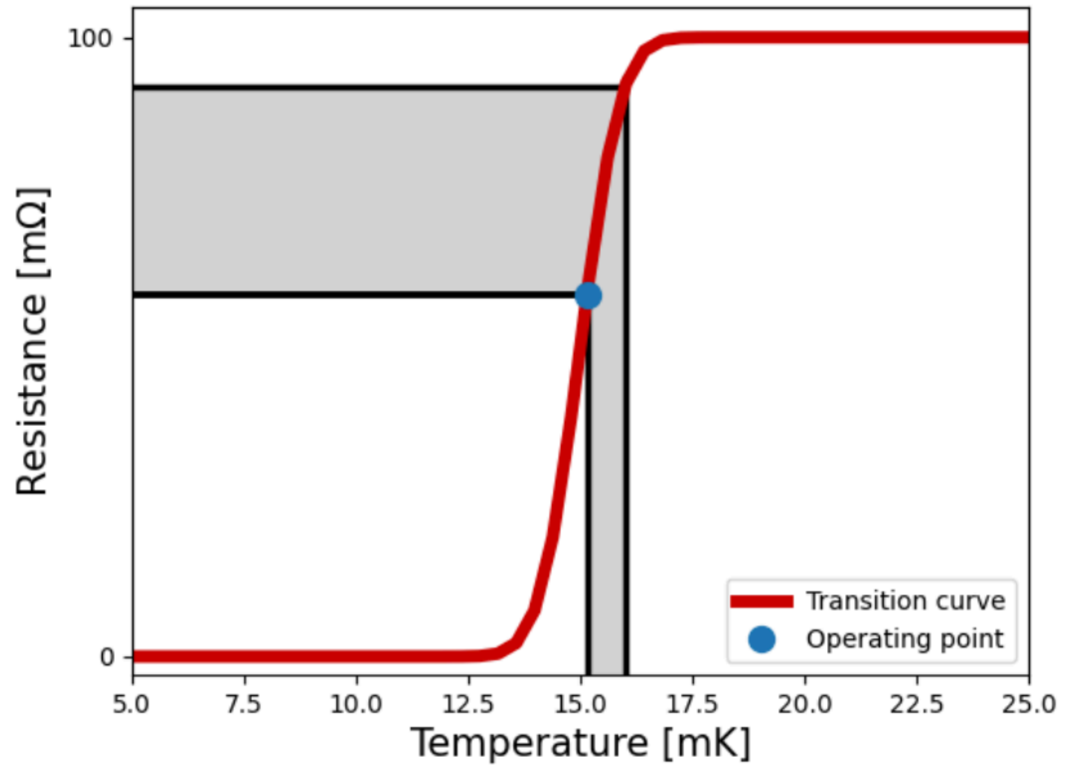
**Cryogenic detectors**
- Direct detection of potential **DM particles** via scatter off target nuclei
- Operated at $\sim$**15 mK**
- Energy deposited in the target causes a proportional **temperature rise** $\Delta T = \frac{\Delta E}{C}$

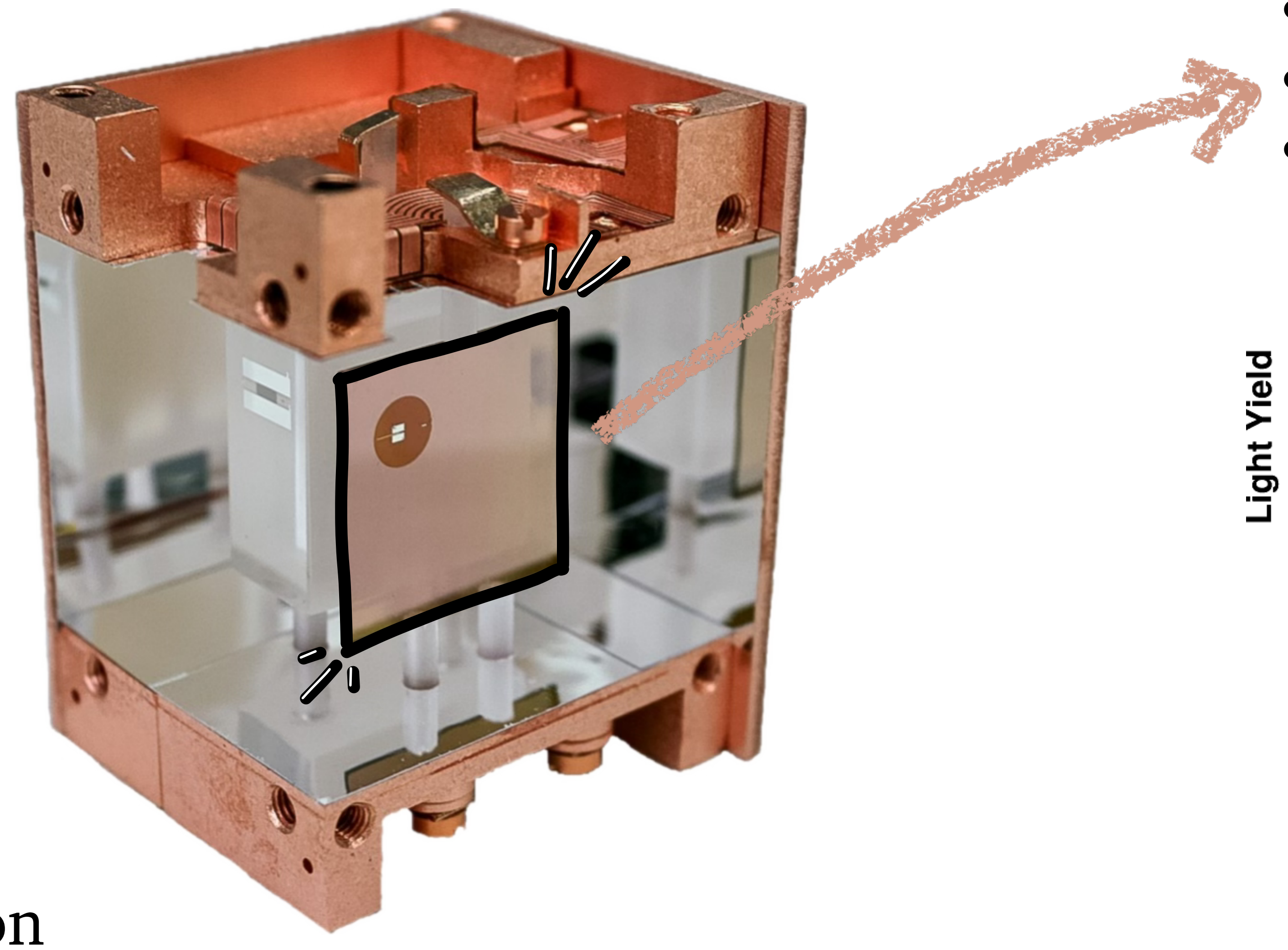



**Target crystal/Absorber**
- Material: $CaWO_4$, Si, $Al_2O_3$, $LiAlO_2$
- Volume: 4 $cm^3$

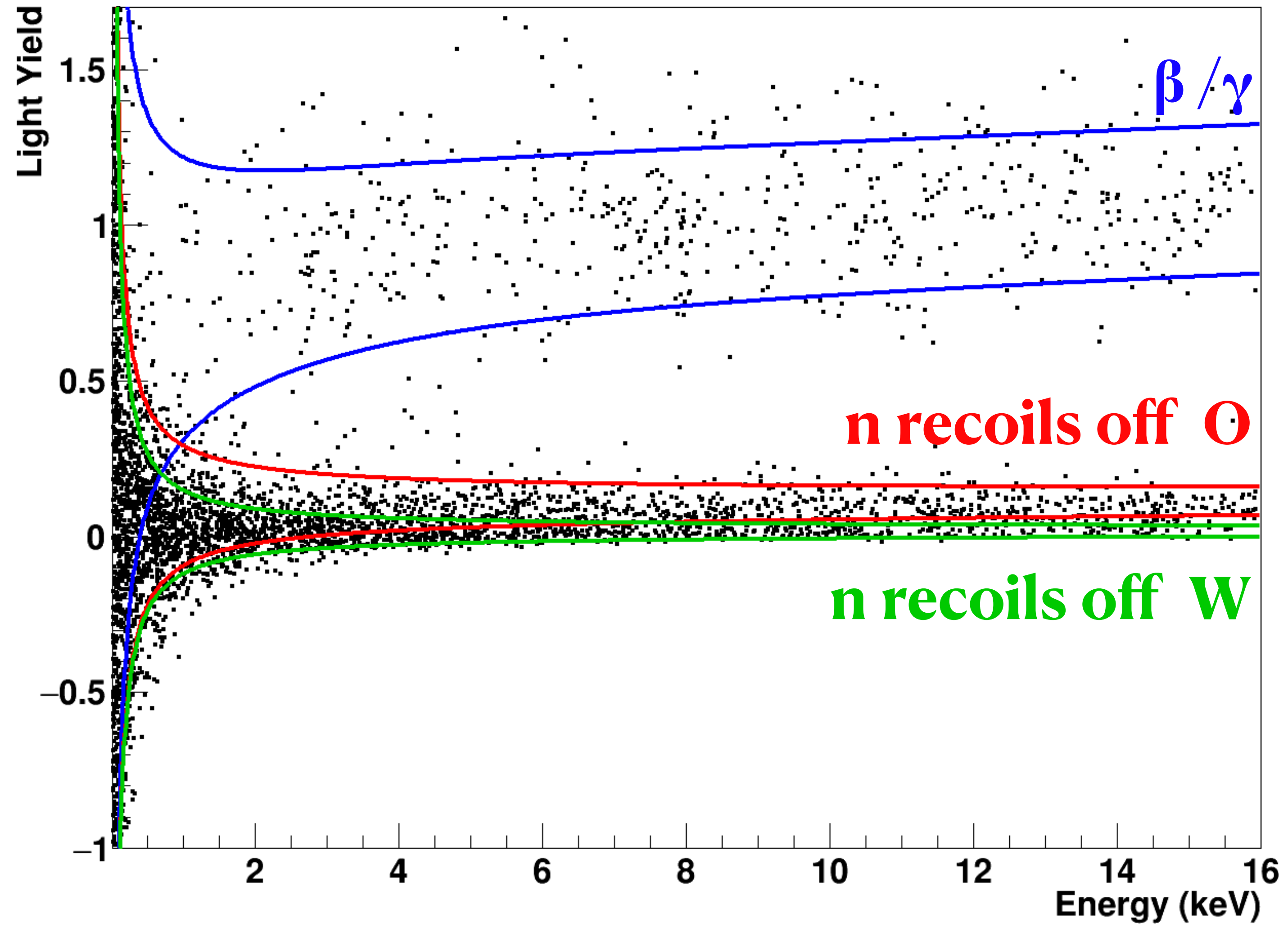
**Temperature sensor**
- W Transition Edge Sensor (TES)
- Operated in the middle of its superconducting transition



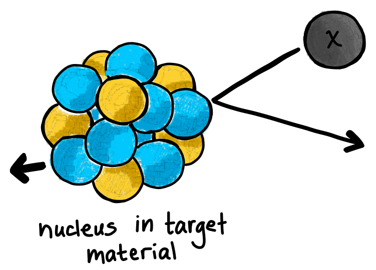



**Light detector (LD)**
- Material: Silicon-On-Sapphire (SOS) wafer
- Coupled to a scintillating target crystal
- Equipped with TES
- Used for particle discrimination



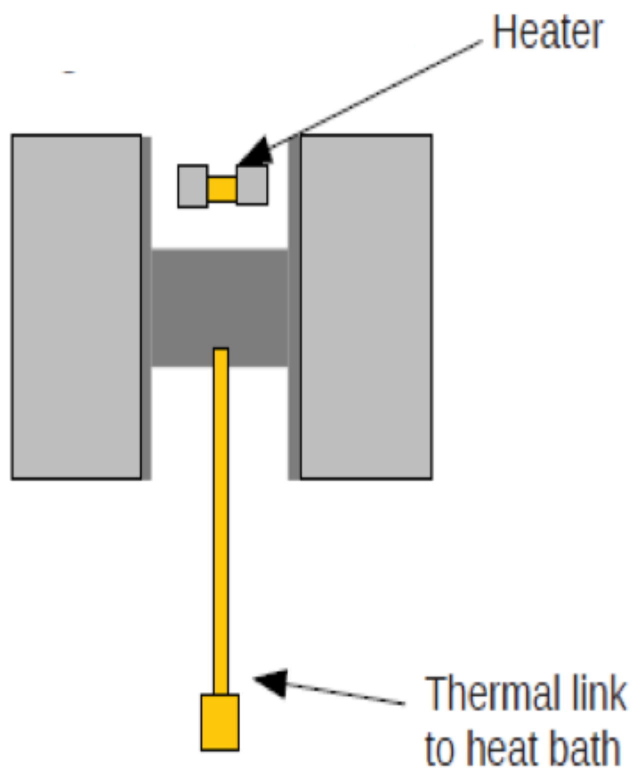
# CRESST-III detectors

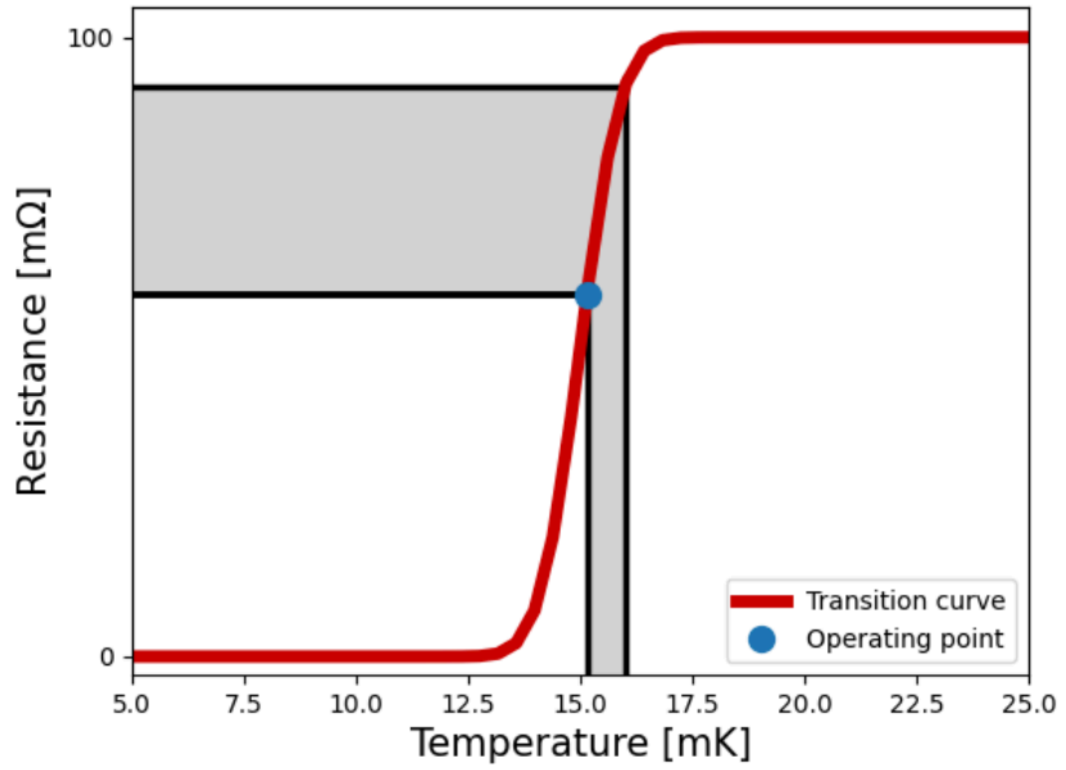
## Cryogenic detectors
- Direct detection of potential **DM particles** via scatter off target nuclei
- Operated at ~**15 mK**
- Energy deposited in the target causes a proportional **temperature rise** $\Delta T = \frac{\Delta E}{C}$

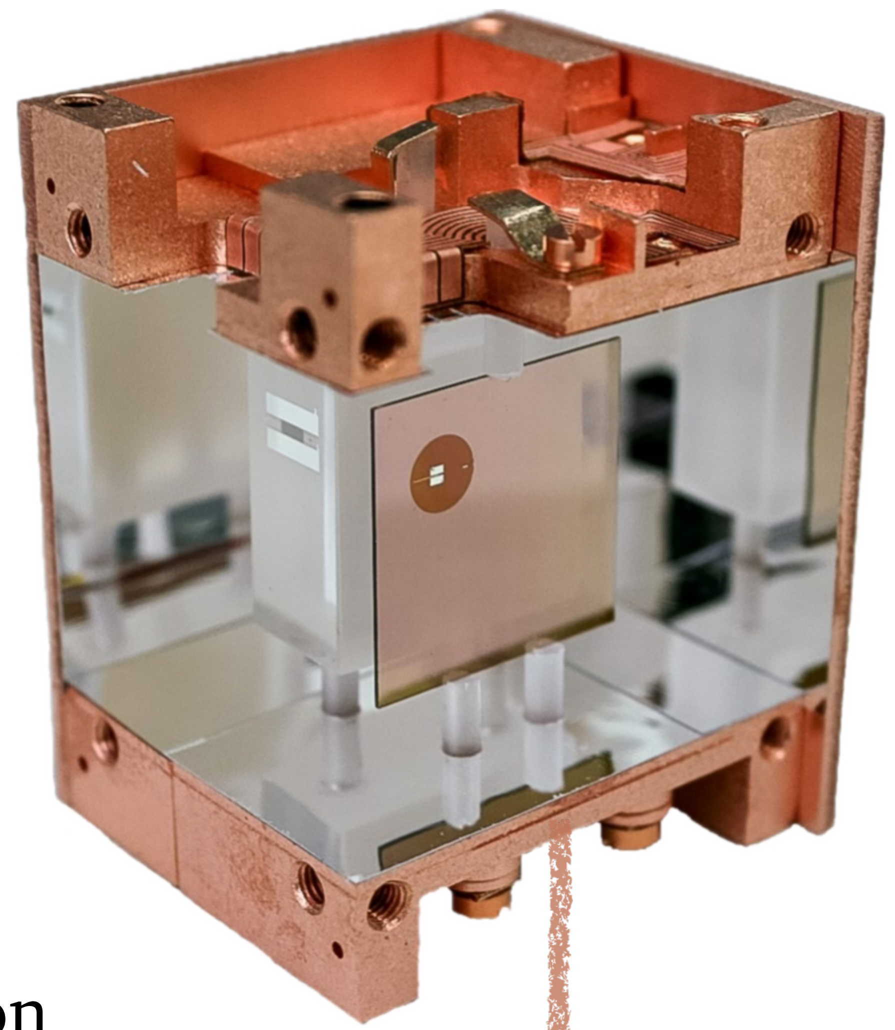



## Target crystal/Absorber
- Material: $CaWO_4$, Si, $Al_2O_3$, $LiAlO_2$
- Volume: 4 $cm^3$

## Temperature sensor
- W Transition Edge Sensor (TES)
- Operated in the middle of its superconducting transition



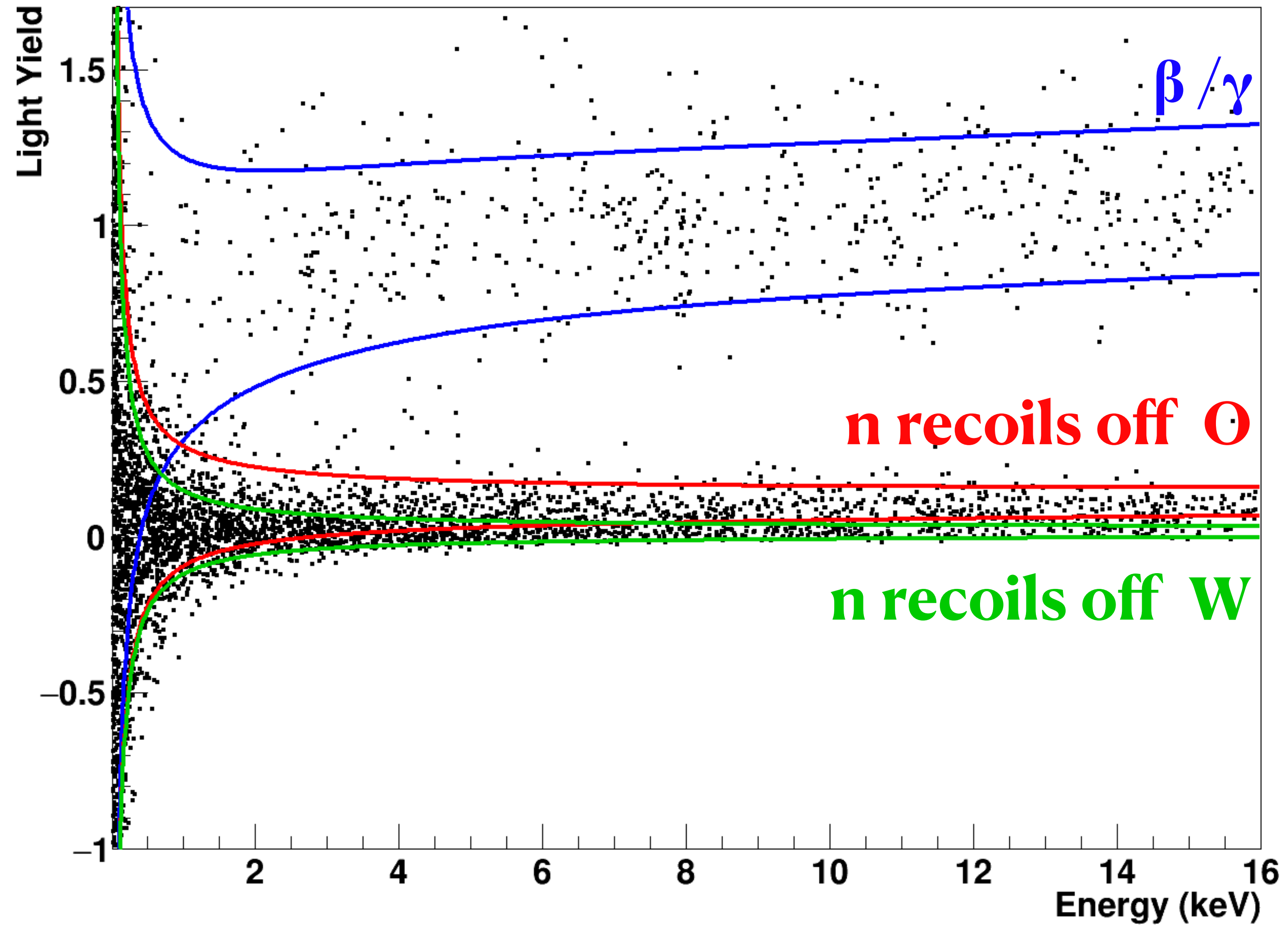



- Copper holder
- Holding provided by $CaWO_4$ sticks
- Reflecting foil

Phys. Rev. D 100, 102002

## Light detector (LD)
- Material: Silicon-On-Sapphire (SOS) wafer
- Coupled to a scintillating target crystal
- Equipped with TES
- Used for particle discrimination




CRESST-III detectors optimised for sub-GeV DM searches

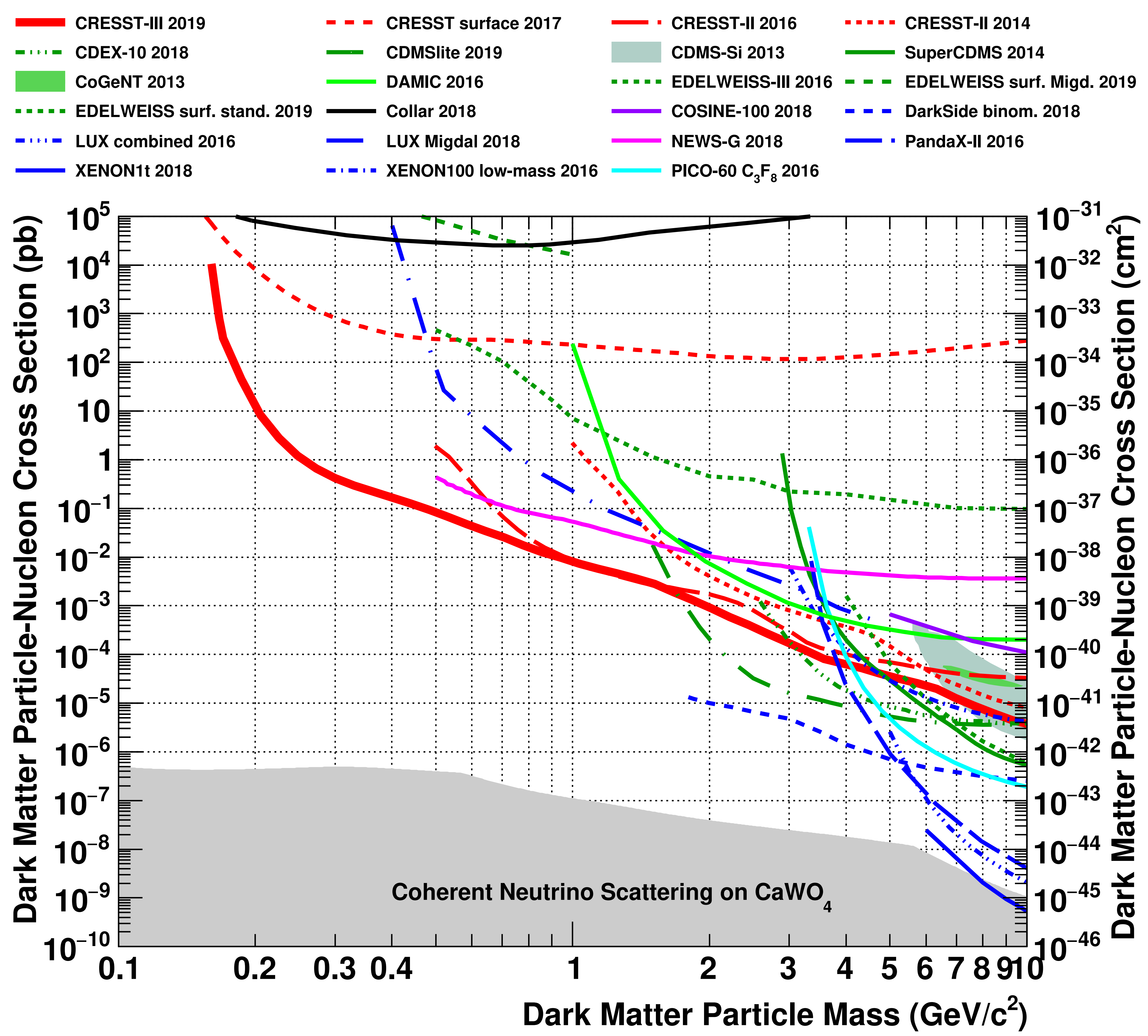
# CRESST-III: 1st run

## Sharply rising energy spectrum below 200 eV

**CRESST-III 1st run:**
- 10 detector modules
- Goal: low threshold

**Detector**
- Target: $CaWO_4$
- Exposure: 3.64 kg·days
- Baseline resolution: 4.6 eV
- Nuclear recoil threshold: 30.1 eV

Best sensitivity under standard assumption in range 0.16-1.8 GeV/$c^2$




Phys. Rev. D 100, 102002

# CRESST-III: 1st run

## Sharply rising energy spectrum below 200 eV

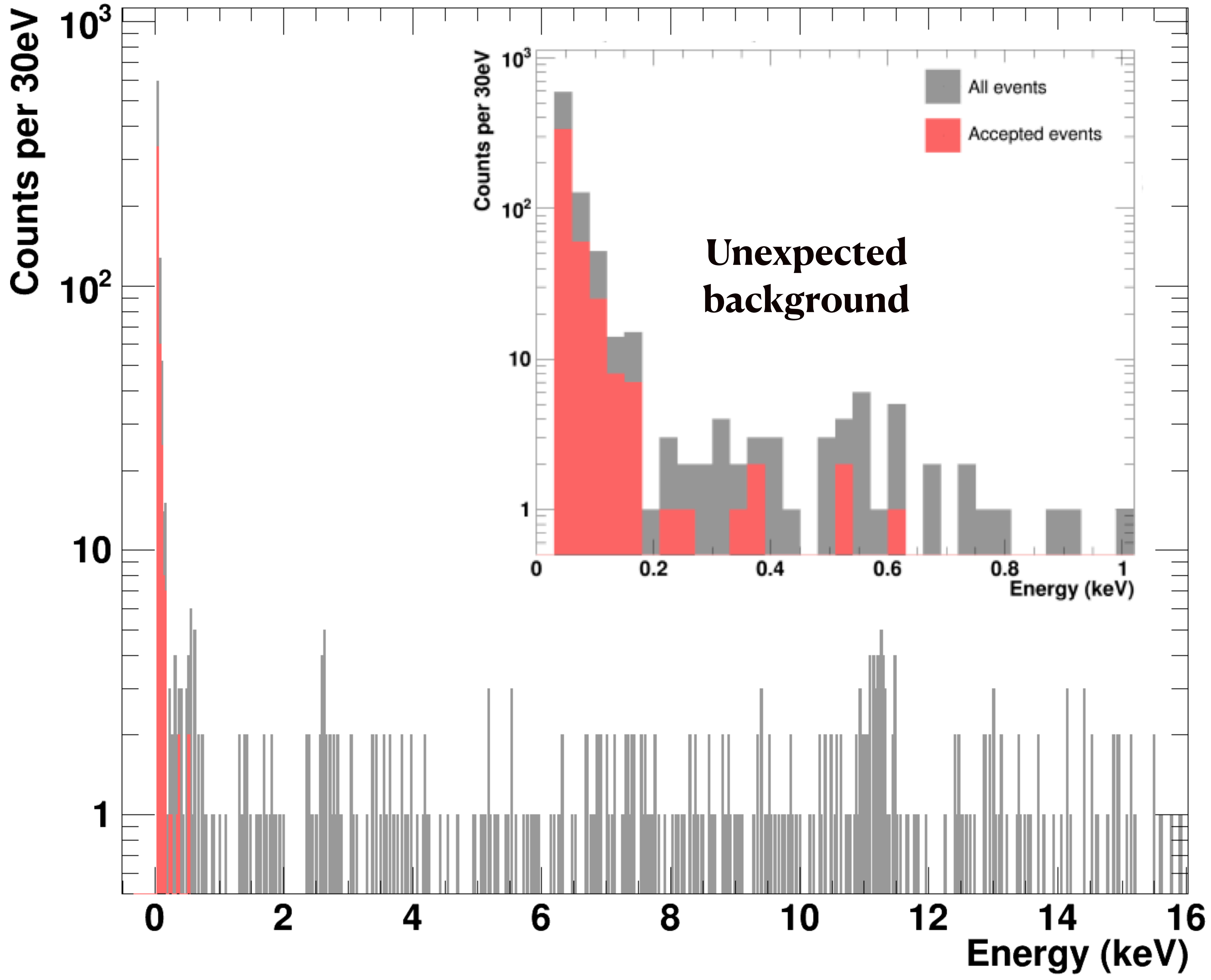
**CRESST-III 1st run:**
- 10 detector modules
- Goal: low threshold

**Detector**
- Target: $CaWO_4$
- Exposure: 3.64 kg·days
- Baseline resolution: 4.6 eV
- Nuclear recoil threshold: 30.1 eV

Low Energy Excess (LEE) is a global challenge


SciPost Phys. Proc. 9, 001 (2022)

The understanding of this LEE is **fundamental** in order to further improve the sensitivity to DM

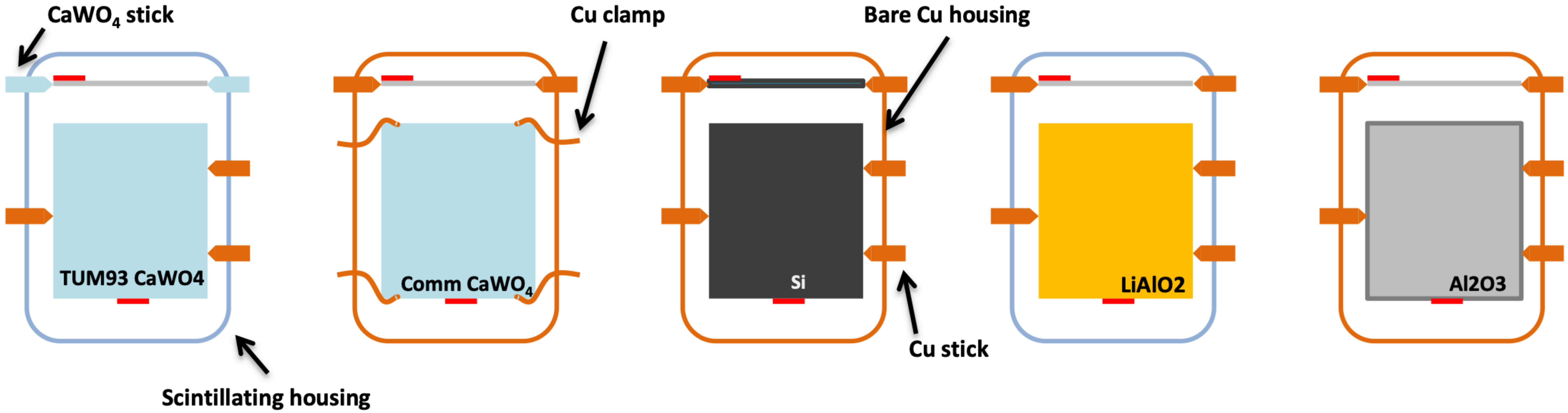



Phys. Rev. D 100, 102002

# CRESST-III: 2nd run

## LEE origins? Multiple detector designs to find out

- Different LEE spectral shape found in multiple identical detectors
- Preparation for the following run: **detector design modifications**

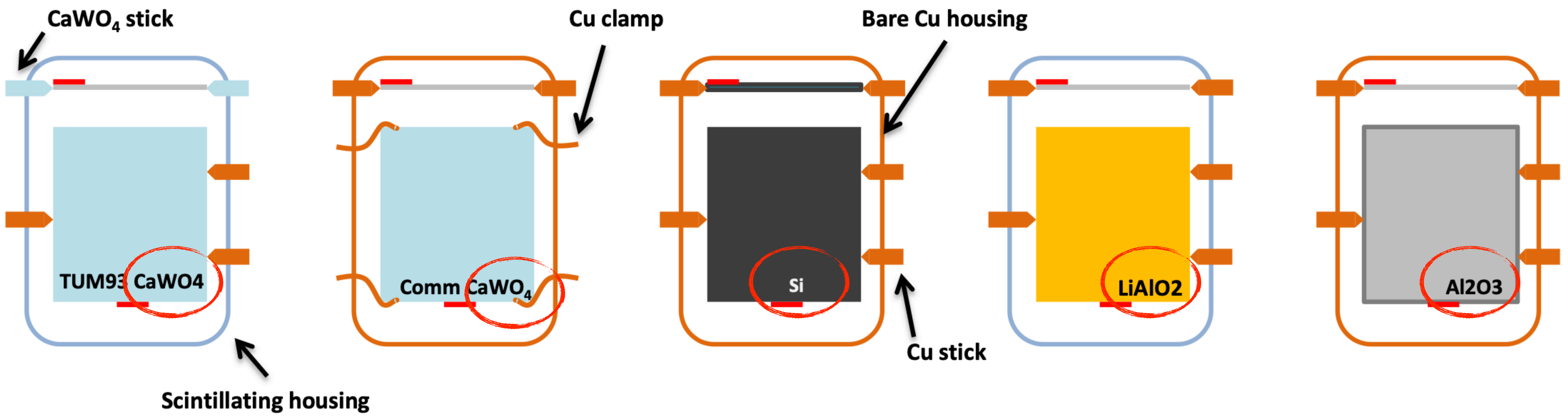


# CRESST-III: 2nd run

## LEE origins? Multiple detector designs to find out

- Different LEE spectral shape found in multiple identical detectors
- Preparation for the following run: **detector design modifications**

1. **Material dependence** → different target materials ($CaWO_4$, $Al_2O_3$, $LiAlO_3$, Si)

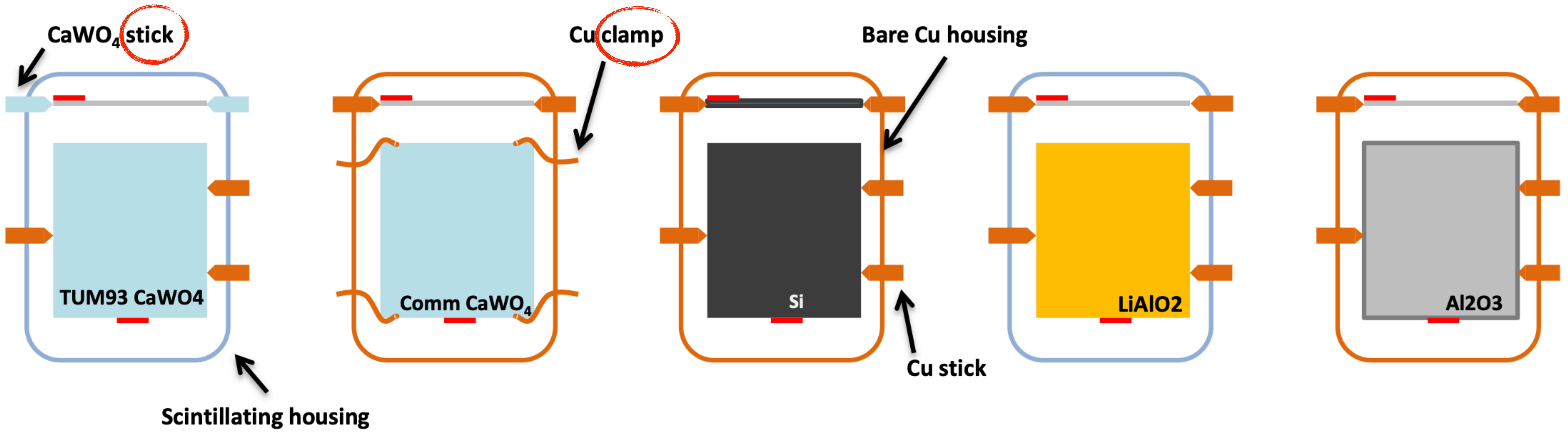


# CRESST-III: 2nd run

## LEE origins? Multiple detector designs to find out

- Different LEE spectral shape found in multiple identical detectors
- Preparation for the following run: **detector design modifications**

1. **Material dependence** → different target materials ($CaWO_4$, $Al_2O_3$, $LiAlO_3$, Si)
2. **Stress holder related** → two holding systems (sticks, clamps)

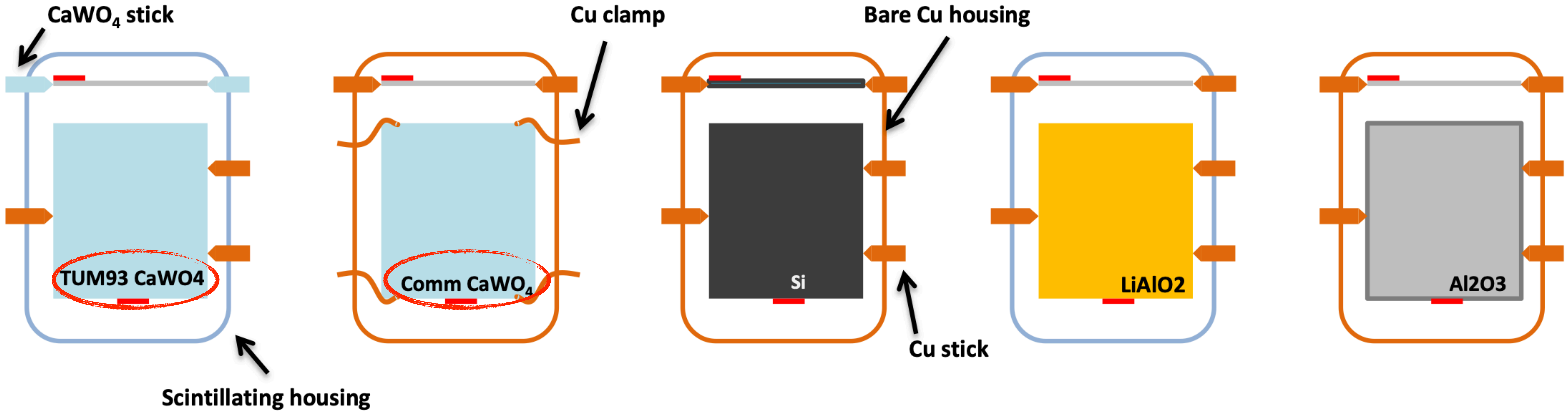


# CRESST-III: 2nd run

## LEE origins? Multiple detector designs to find out

- Different LEE spectral shape found in multiple identical detectors
- Preparation for the following run: **detector design modifications**

1. **Material dependence** → different target materials ($CaWO_4$, $Al_2O_3$, $LiAlO_3$, Si)
2. **Stress holder related** → two holding systems (sticks, clamps)
3. **Intrinsic stress** → different crystalline structure

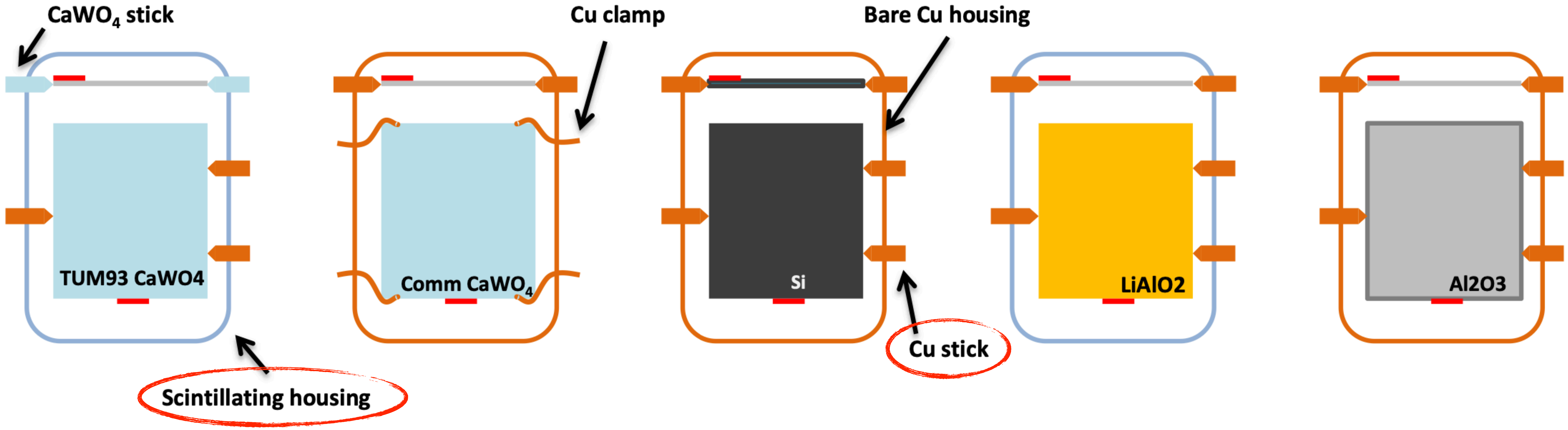


# CRESST-III: 2nd run

## LEE origins? Multiple detector designs to find out

- Different LEE spectral shape found in multiple identical detectors
- Preparation for the following run: **detector design modifications**

1. **Material dependence** → different target materials ($CaWO_4$, $Al_2O_3$, $LiAlO_3$, Si)
2. **Stress holder related** → two holding systems (sticks, clamps)
3. **Intrinsic stress** → different crystalline structure
4. **Scintillation light** → scintillating materials removed (reflecting foil, sticks, scintillating crystals)

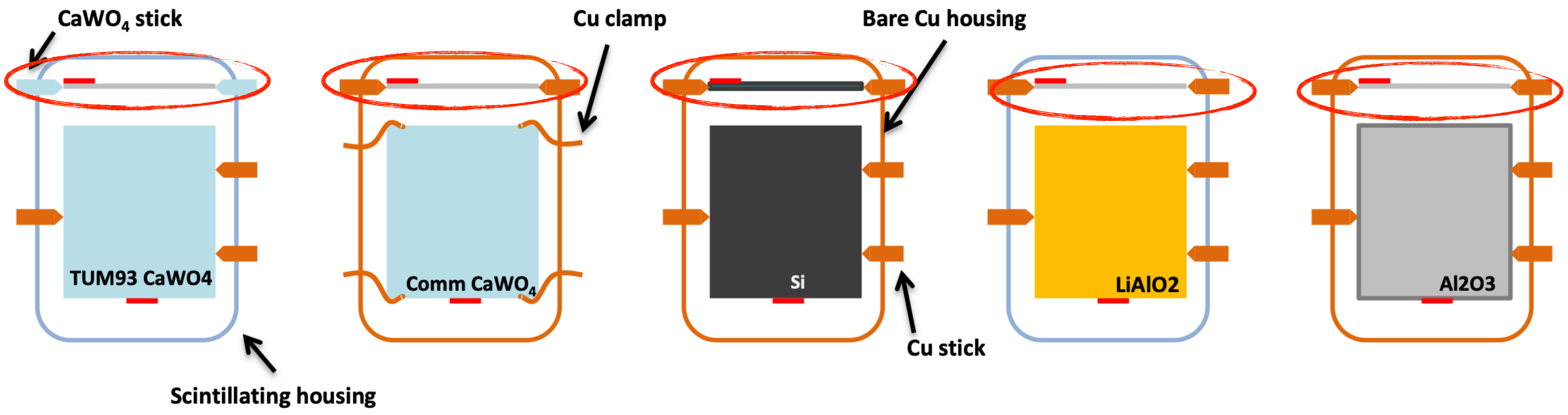


# CRESST-III: 2nd run

## LEE origins? Multiple detector designs to find out

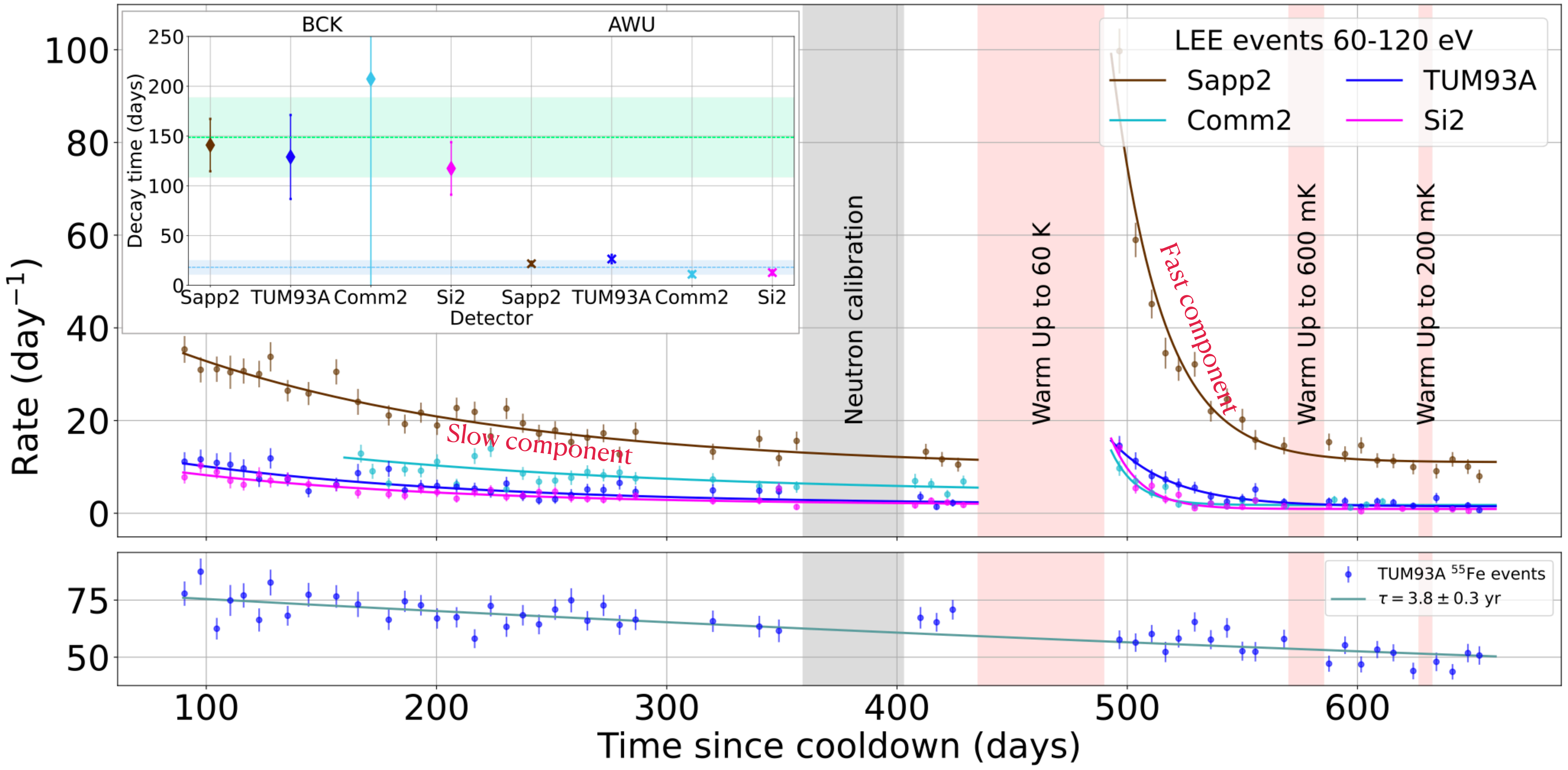
- Different LEE spectral shape found in multiple identical detectors
- Preparation for the following run: **detector design modifications**

1. **Material dependence** → different target materials ($CaWO_4$, $Al_2O_3$, $LiAlO_3$, Si)
2. **Stress holder related** → two holding systems (sticks, clamps)
3. **Intrinsic stress** → different crystalline structure
4. **Scintillation light** → scintillating materials removed (reflecting foil, sticks, scintillating crystals)
5. **Detector geometry** → LD as target detector



# CRESST-III: 2$^{nd}$ run

## LEE: observations




At least two components in the LEE rate:

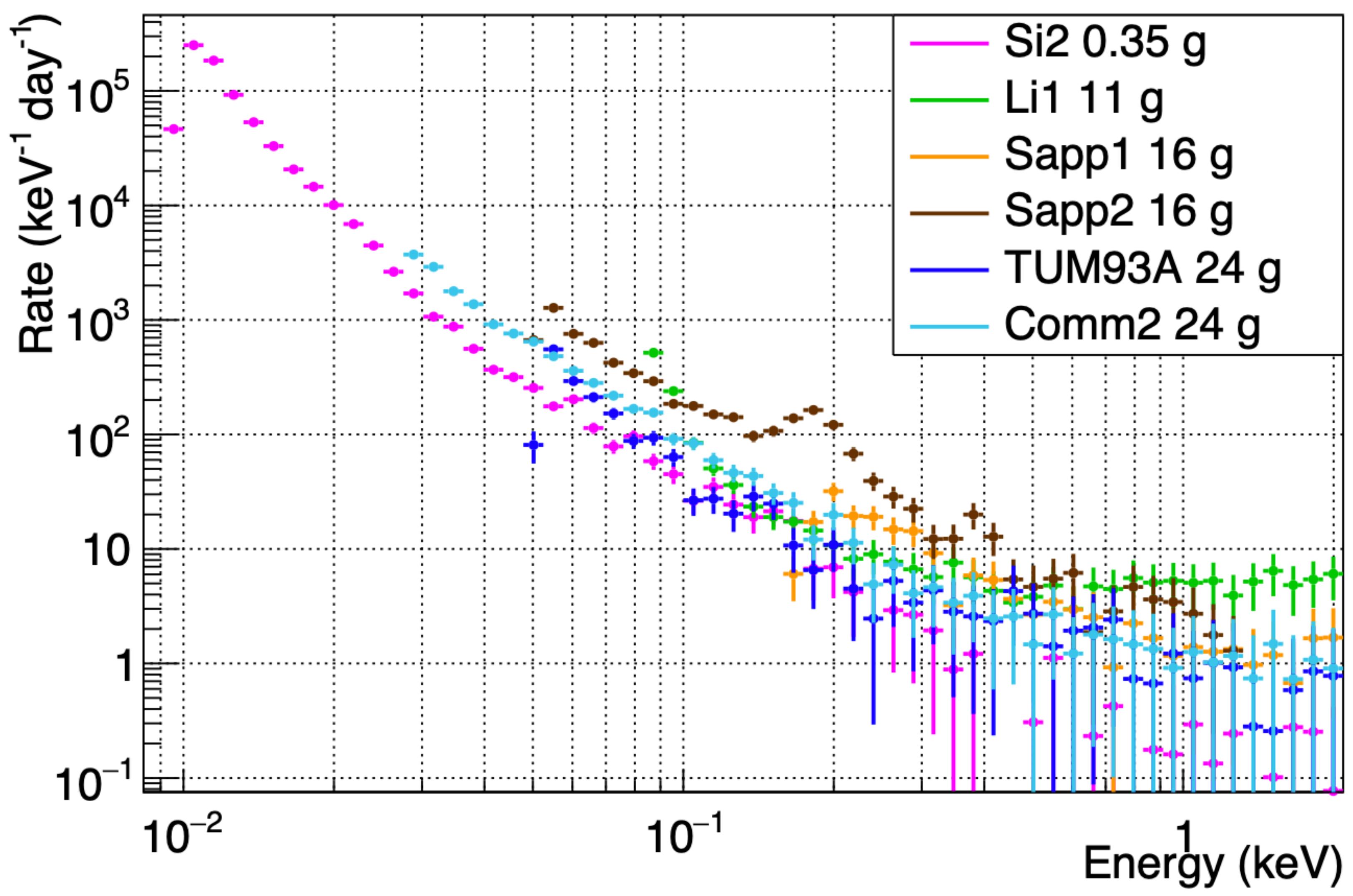
- **Slow component**: LEE rate constantly decreases with time (149±40 d)
- **Fast component**: LEE rate "resets" after warming up the cryostat to O(10 K) (18±7 d)

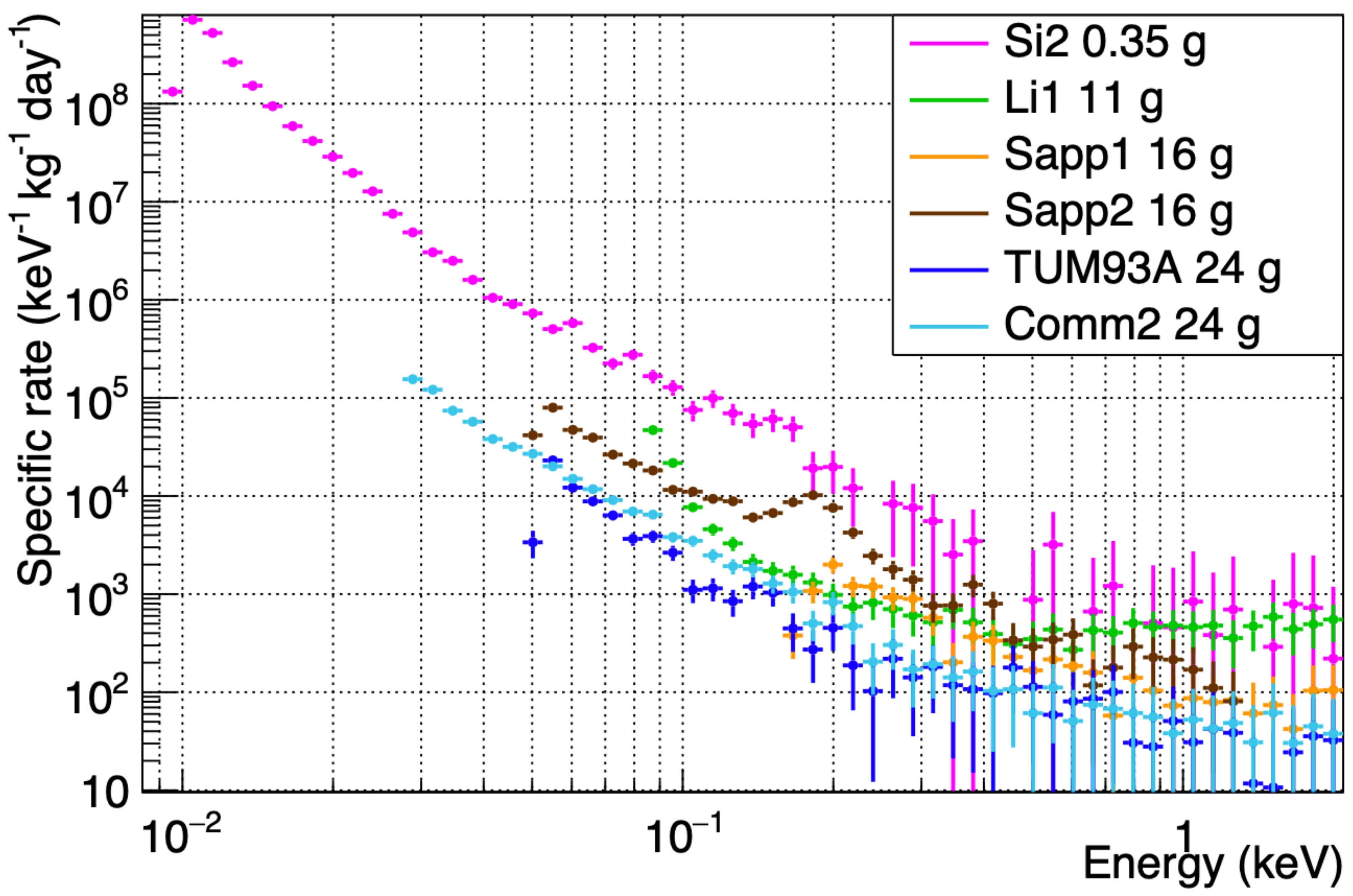
→ DM, internal and external radioactivity are excluded as main LEE source

10.21468/SciPostPhysProc.12.013

# CRESST-III: 2nd run

## LEE: observations




→ LEE is observed in **every material, geometry** and **holding system**

→ LEE rate **doesn't scale** with mass

**None of the modifications had a significant impact on the LEE**

**Open possibilities**

→ holding-induced stress

→ sensor induced stress

10.21468/SciPostPhysProc.12.013

# CRESST-III: 3rd run

## What else? New detector designs

JLTP s10909-024-03154-6

**Strategy**

→ 3 new detectors designs developed

→ designs tested above-ground

→ Currently installed at LNGS!!!

**Double TES**

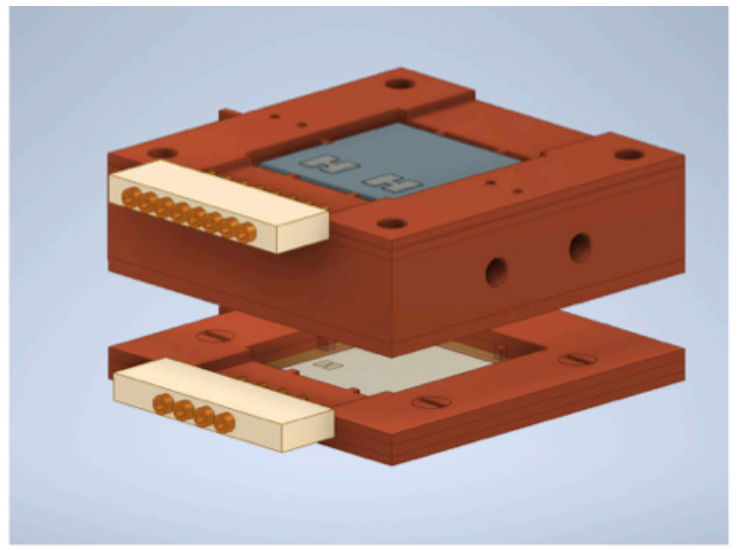
- $CaWO_4$ crystal
- Stress-free holding
- Sensitive to events originated in the TES
- Coupled to LD

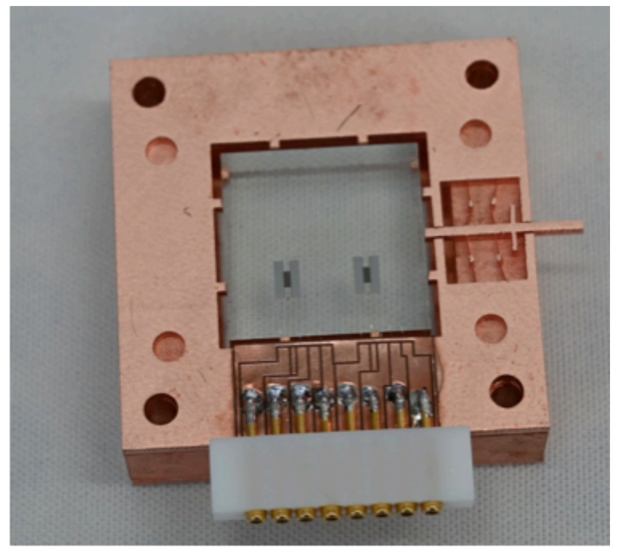
**Double TES Stack**

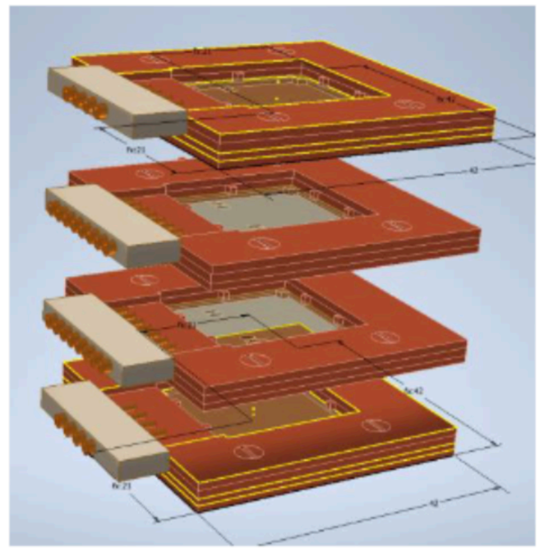
- 4 SOS wafers
- Stress-free holding
- Sensitive to events originated in the TES
- Full surface coverage of inner crystals

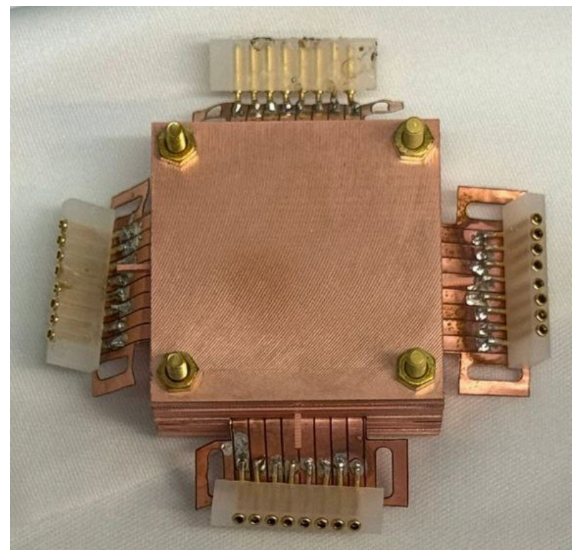
**Mini Beaker**

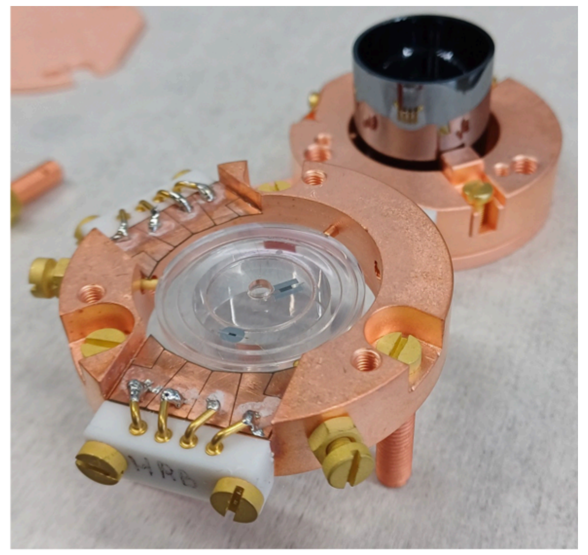
- Instrumented holder: target crystals in contact just with other detectors
- Surface coverage by silicon beaker
- Sensitive to holder transmitted events

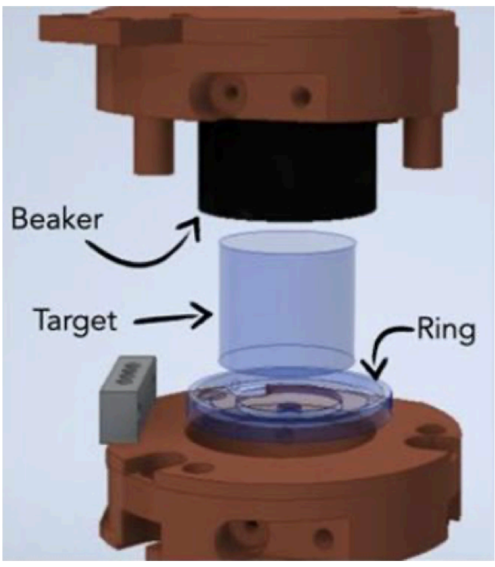












# CRESST-III: 3rd run

## What else? New detector designs

JLTP s10909-024-03154-6

**Strategy**

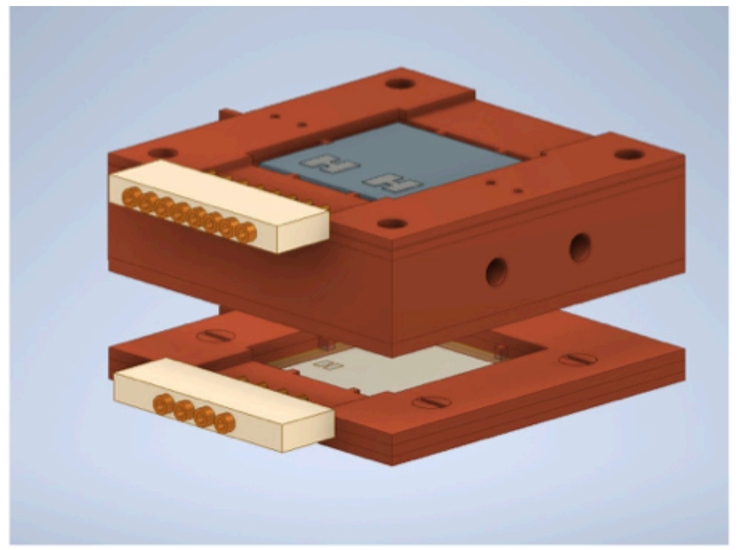
→ 3 new detectors designs developed

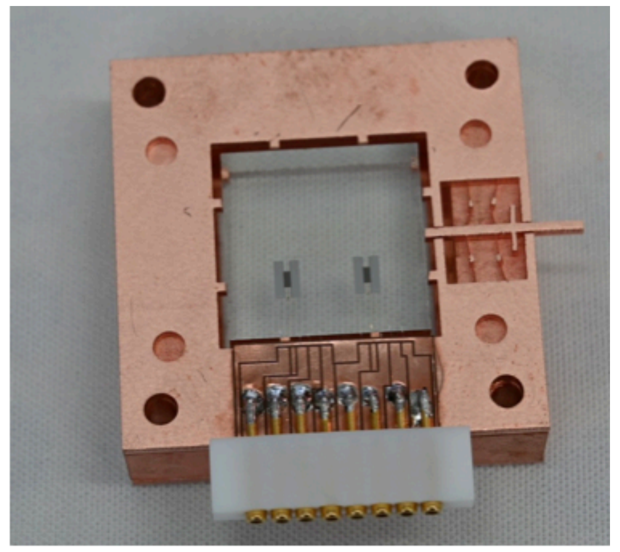
→ designs tested above-ground

→ Currently installed at LNGS!!!

### Double TES

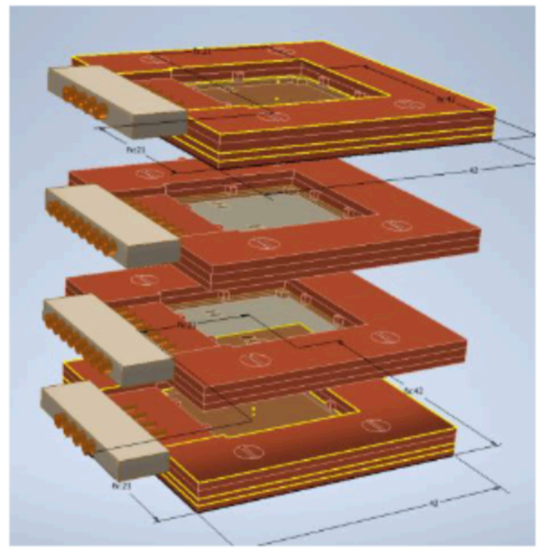
- $CaWO_4$ crystal
- Stress-free holding
- Sensitive to events originated in the TES
- Coupled to LD

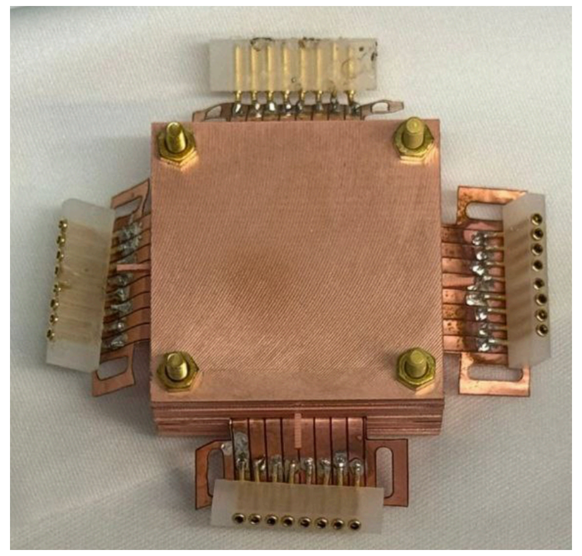




### Double TES Stack

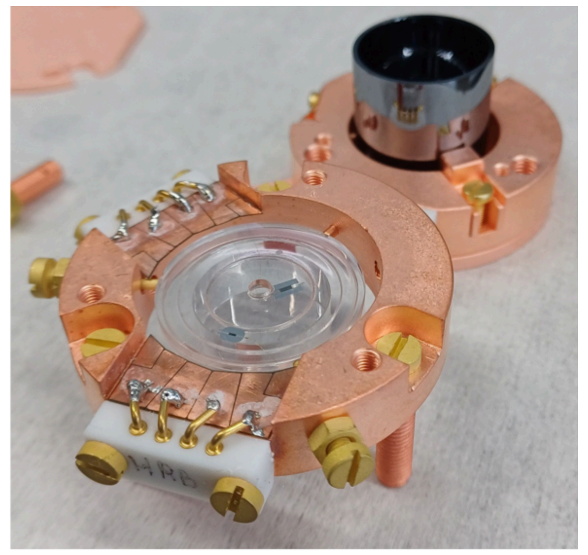
- 4 SOS wafers
- Stress-free holding
- Sensitive to events originated in the TES
- Full surface coverage of inner crystals

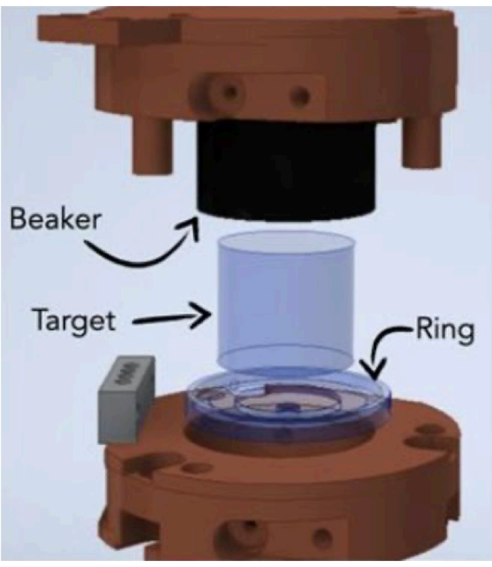




### Mini Beaker

- Instrumented holder: target crystals in contact just with other detectors
- Surface coverage by silicon beaker
- Sensitive to holder transmitted events





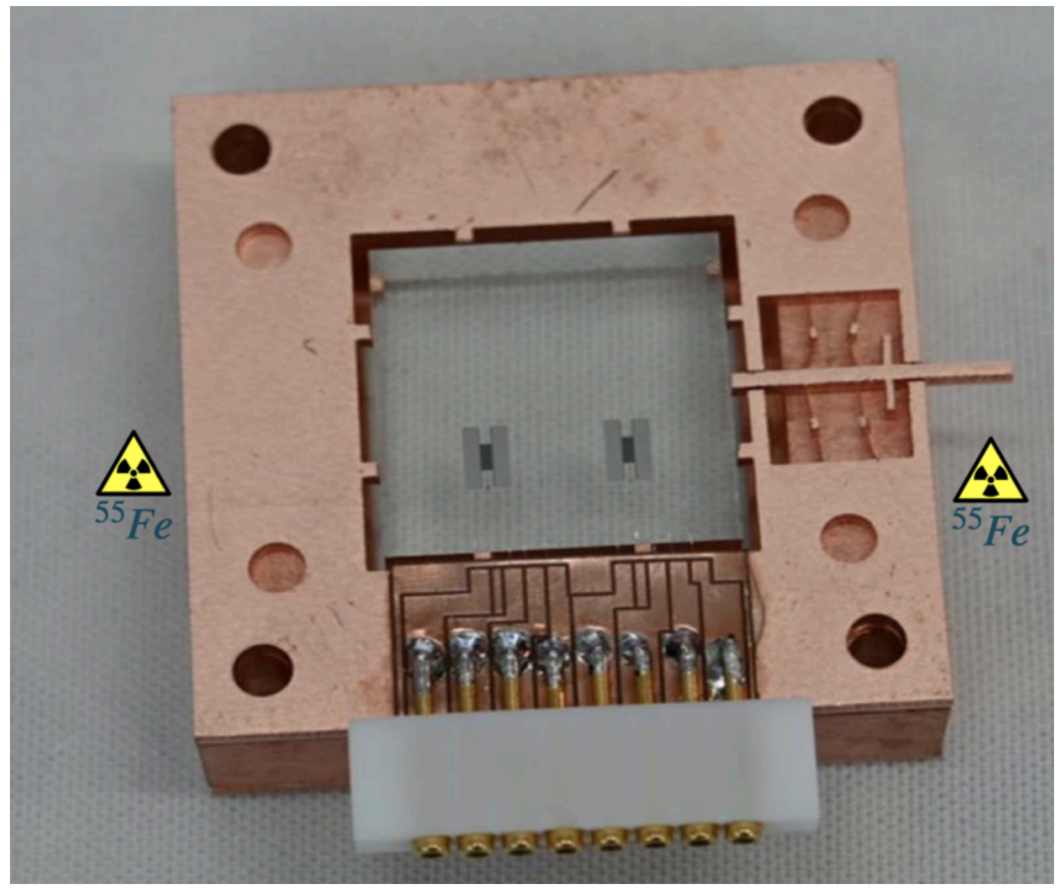
# Behind CRESST-III 3rd run

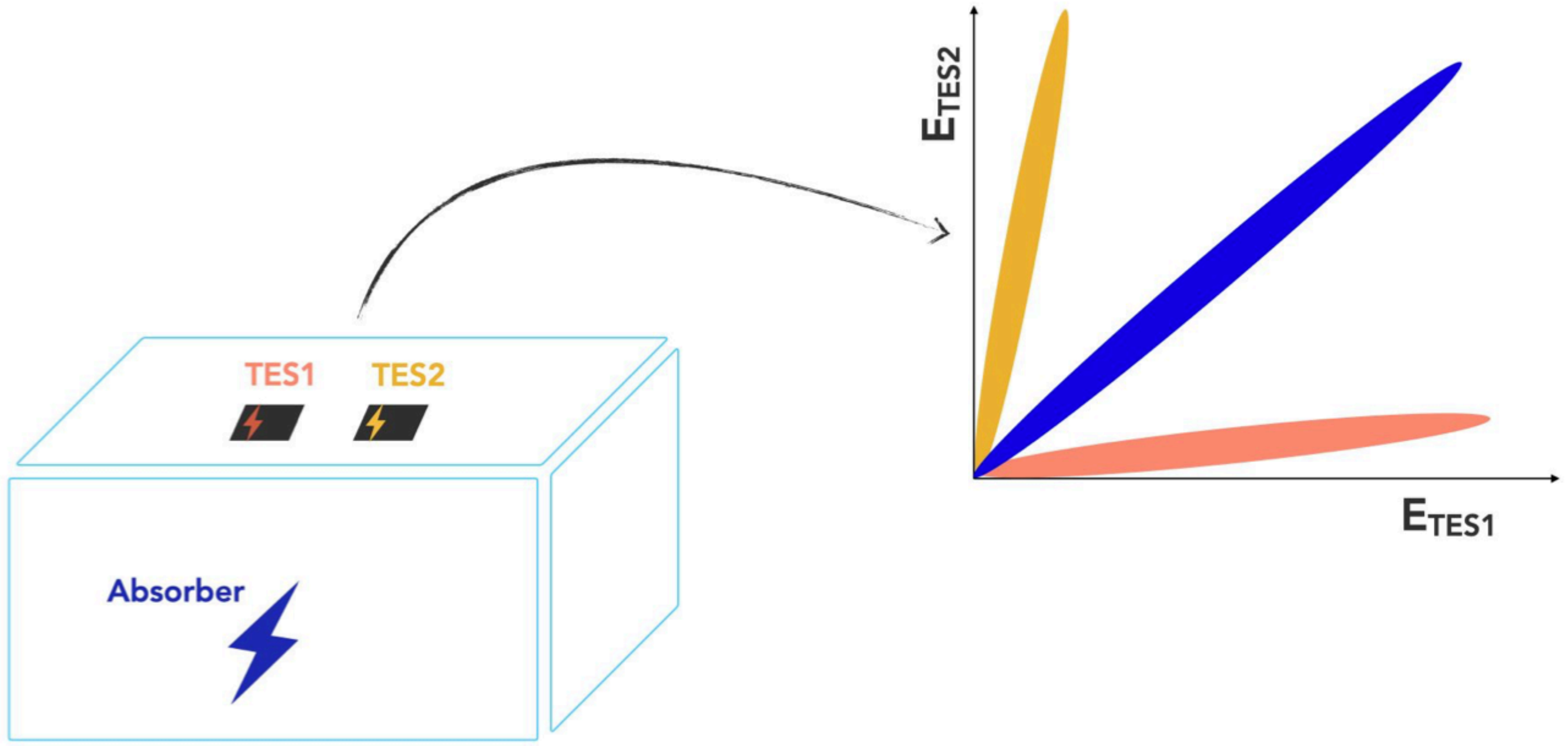
## Double TES R&D: above-ground measurements

arXiv 240402607
Accepted by EPJC

### Double TES

- 2 TESs, independently read-out
- $CaWO_4$ target crystal (20x20x10 mm$^3$)
- Stress-free holding
- Scintillating parts removed (except for the target)
- 2 collimated $^{55}$Fe sources
- **Proof of principle** measurement: TESs can be simultaneously optimised




### Scenario

- Events in the absorber
  → the 2 TESs must measure the same amount of energy
- Events in the sensor/ close to one of the sensors
  → different response

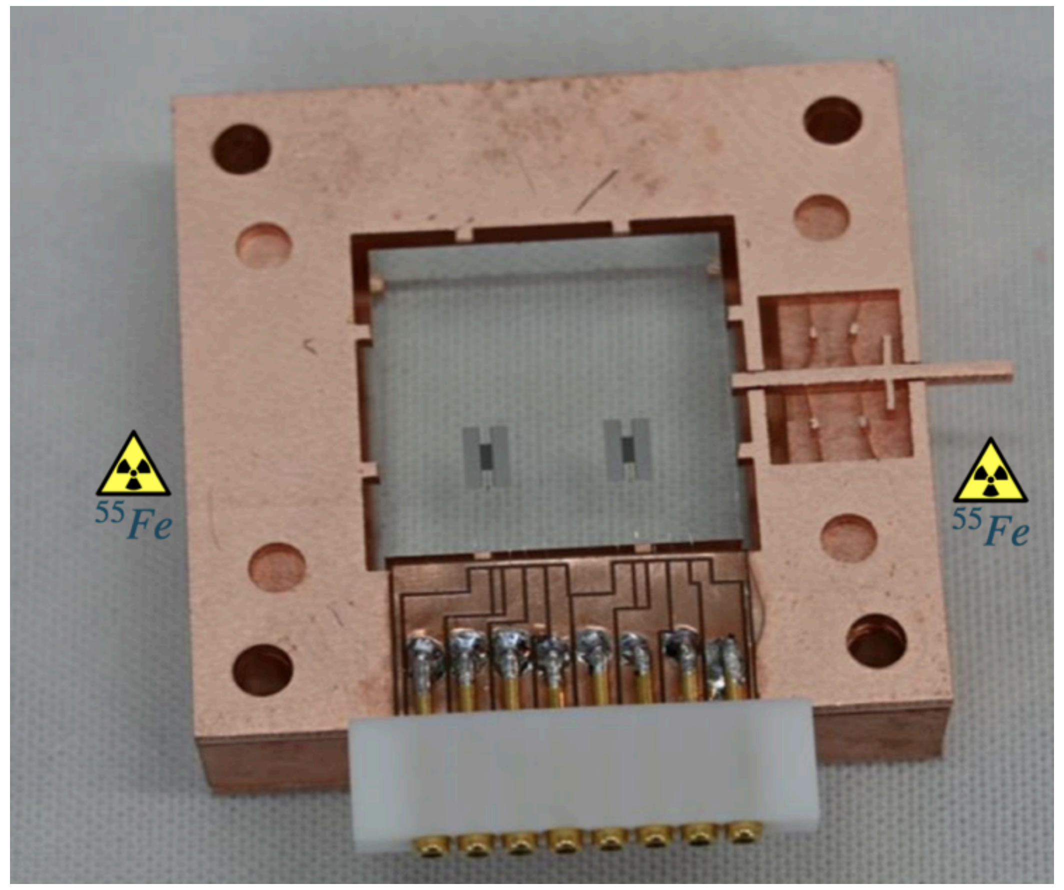
# Behind CRESST-III 3rd run

## Double TES R&D: above-ground measurements

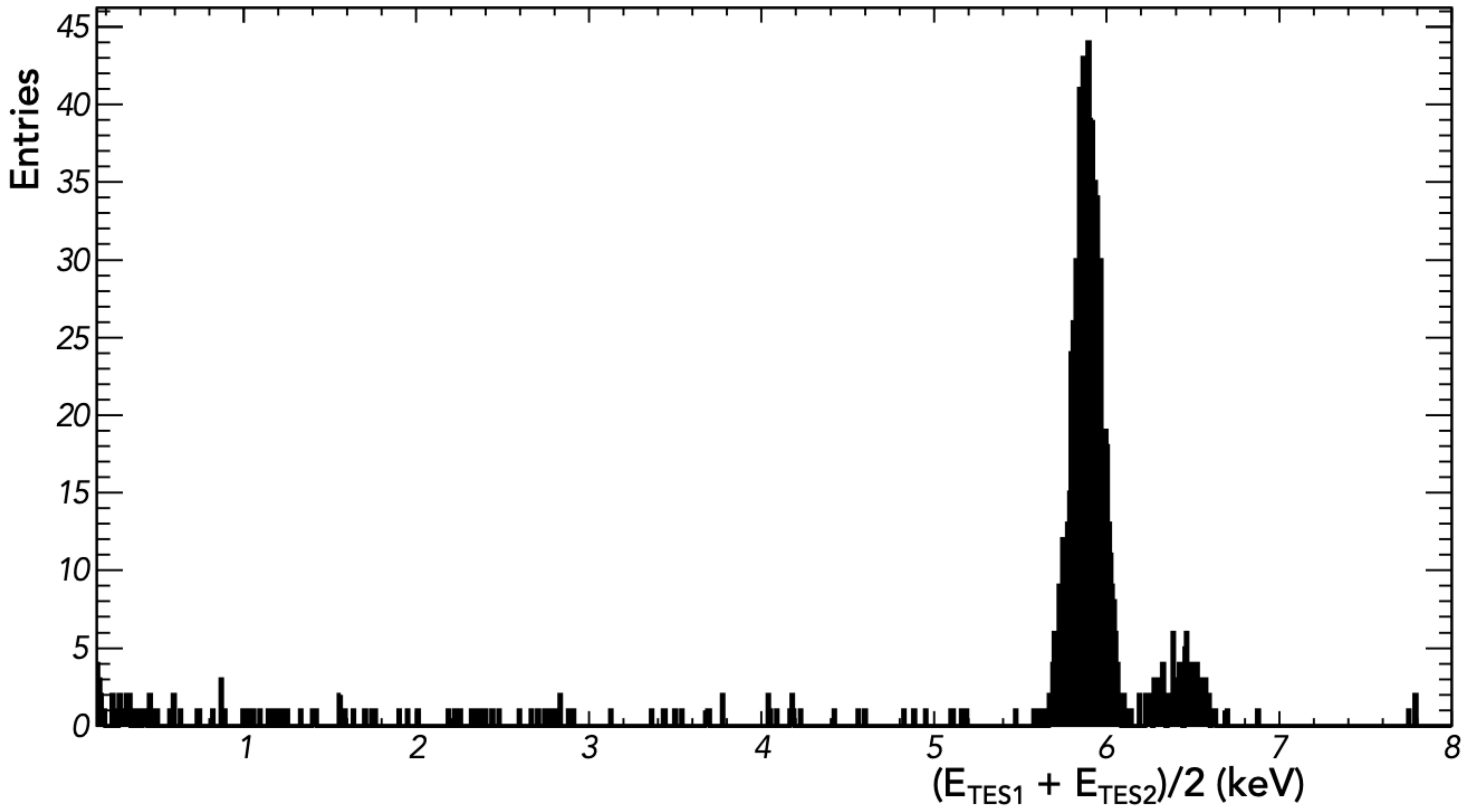
arXiv 240402607
Accepted by EPJC

### Double TES

- 2 TESs, independently read-out
- $CaWO_4$ target crystal (20x20x10 mm$^3$)
- Stress-free holding
- Scintillating parts removed (except for the target)
- 2 collimated $^{55}Fe$ sources
- **Proof of principle** measurement: TESs can be simultaneously optimised




| | TES 1 | TES 2 |
|---|---|---|
| Energy threshold [eV] | 137 | 148 |
| $\sigma_{Baseline}$ [eV] | 27.1 ± 0.3 | 29.6 ± 0.3 |
| $\sigma_{Fe}$ [eV] | 117 ± 3 | 118 ± 2 |




Improved $\sigma_{Fe}$ making an average event by event of the two TESs: (81 ± 2) eV

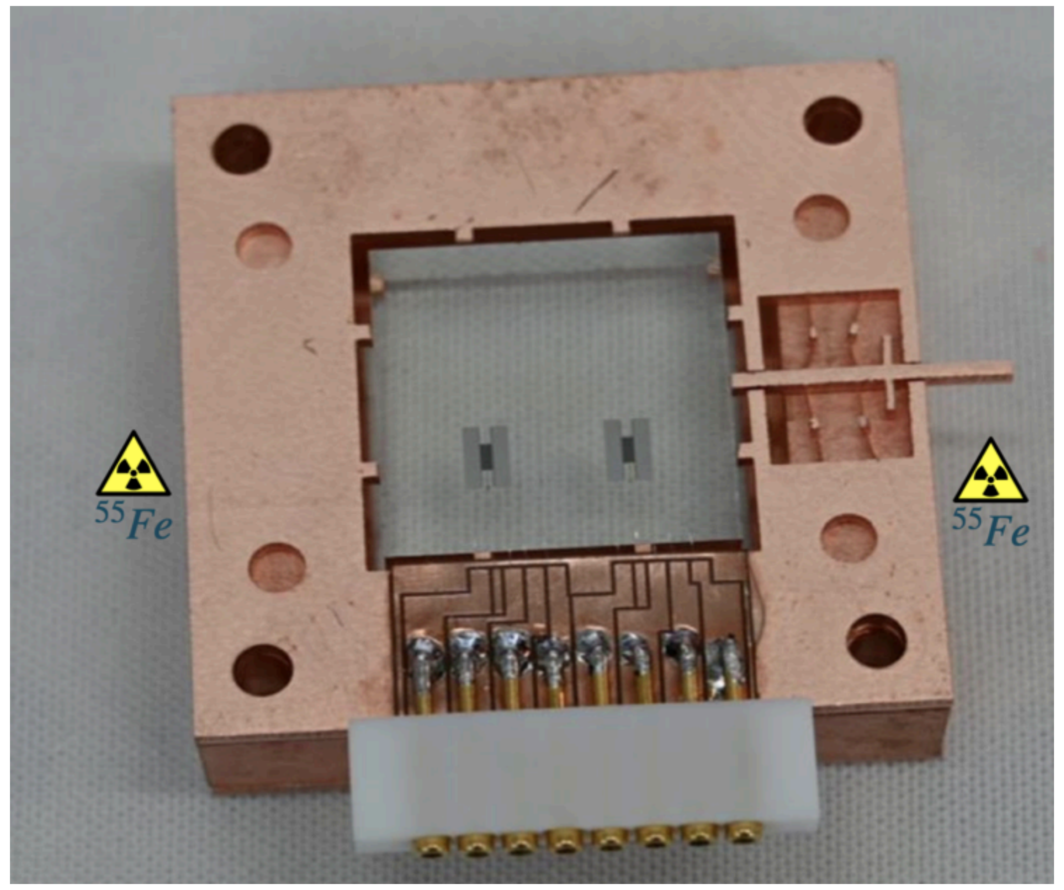
# Behind CRESST-III 3rd run

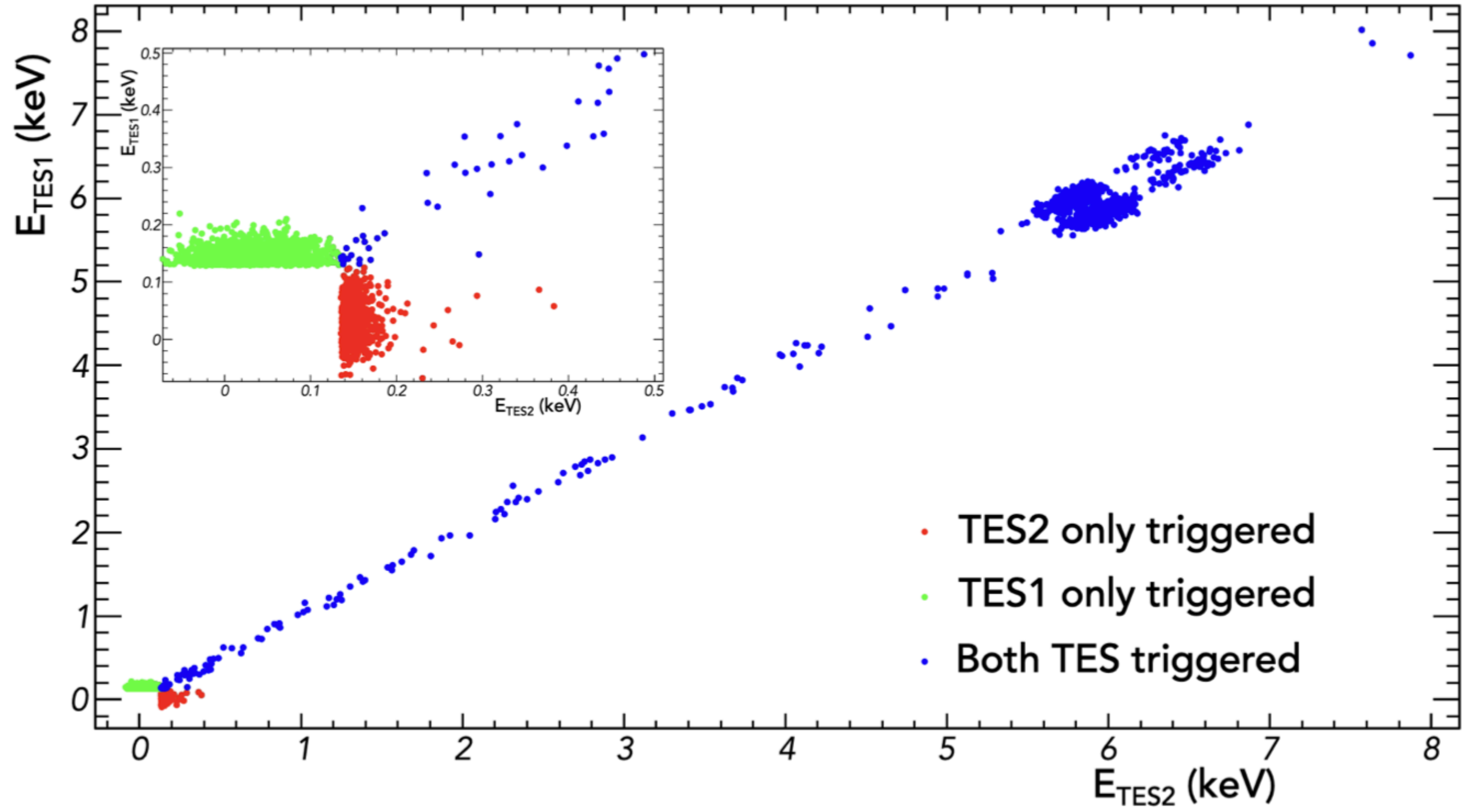
## Double TES R&D: above-ground measurements

arXiv 240402607
Accepted by EPJC

### Double TES

- 2 TESs, independently read-out
- $CaWO_4$ target crystal (20x20x10 mm$^3$)
- Stress-free holding
- Scintillating parts removed (except for the target)
- 2 collimated $^{55}Fe$ sources
- **Proof of principle** measurement: TESs can be simultaneously optimised



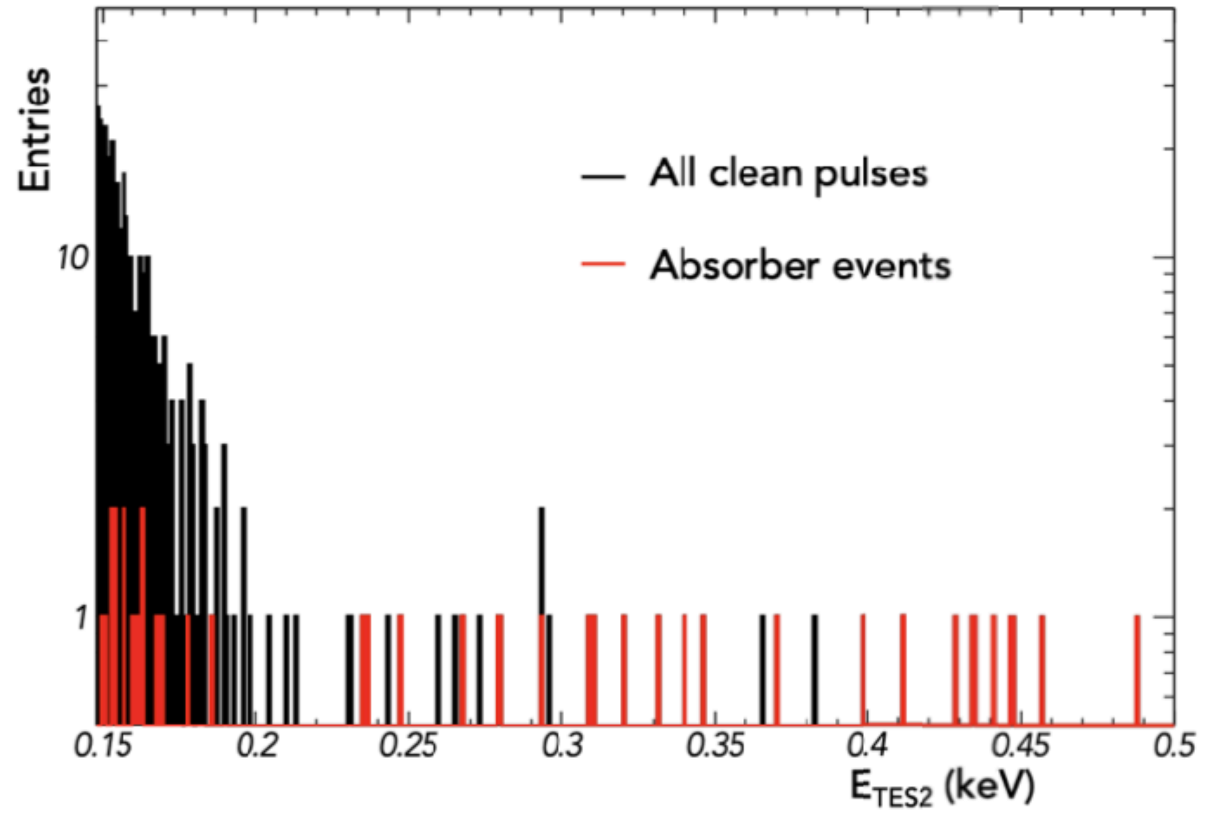



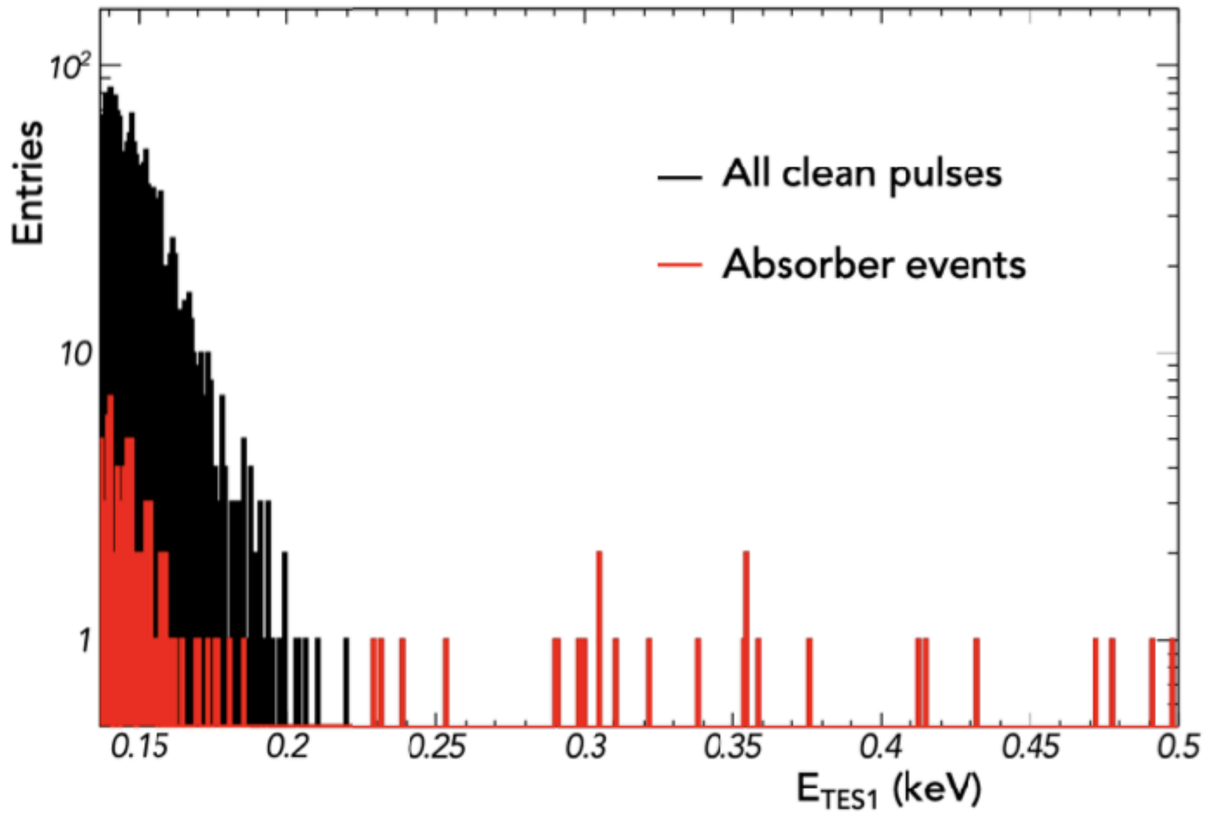

→ All populations are genuine pulses
→ Discrimination possible with double TES

# Behind CRESST-III 3rd run

## Double TES R&D: above-ground measurements

arXiv 240402607
Accepted by EPJC




More tests performed:
Double TES also applied to SOS wafers

LEE: above-ground measurement observations

- Sensor related events contribute to LEE
  → LEE has more than one component
- Rate rise towards low energy for shared events
- LEE time dependence compatible with what was previously measured by CRESST

# CRESST-III: novel calibration technique

**Standard calibration**
5.9 X-ray line from $^{55}Fe$

**New technique** proposed by the CRAB collaboration

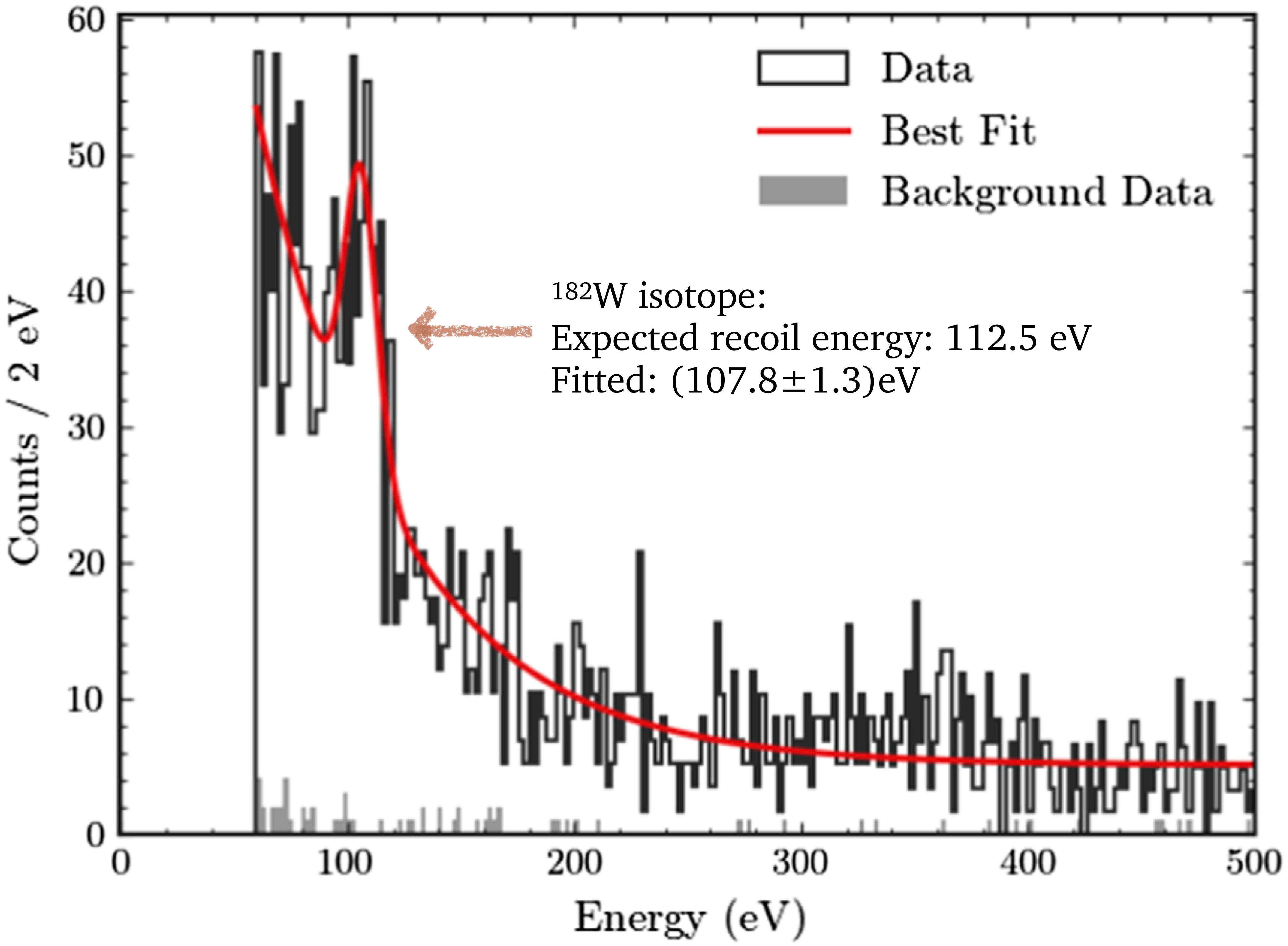
Thermal neutron capture: $^{182}W(n, \gamma)\,^{183}W$
→ De-excitation with a single $\gamma$ (6.1 MeV)
→→ **Mono-energetic** nuclear recoil 112.4 eV

JINST 16 P07032

Nuclear recoil peaks observed around the predicted value in multiple detectors:

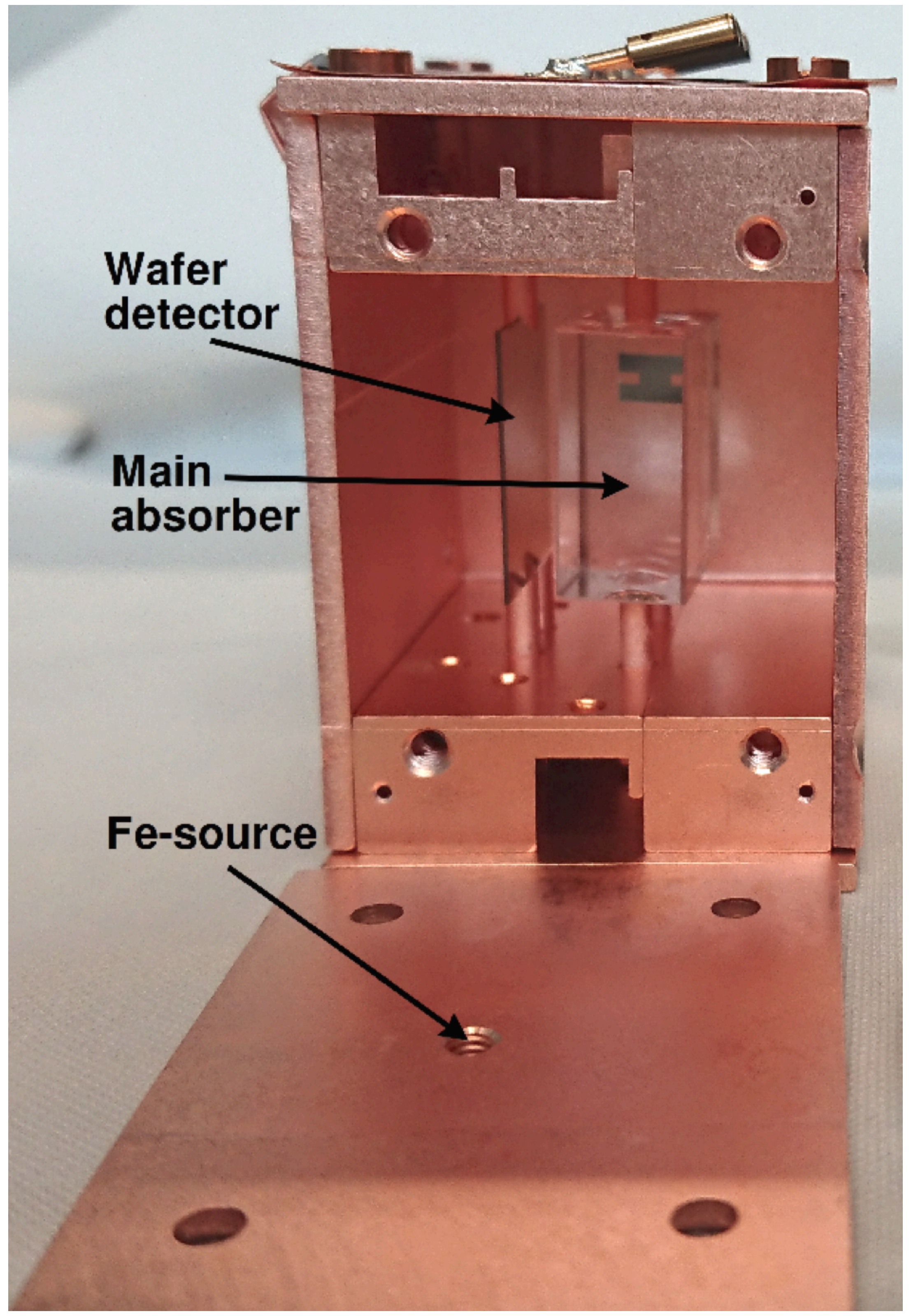
**CRESST low energy calibration confirmation**

Phys. Rev. D 108, 022005



# CRESST-III: DM results

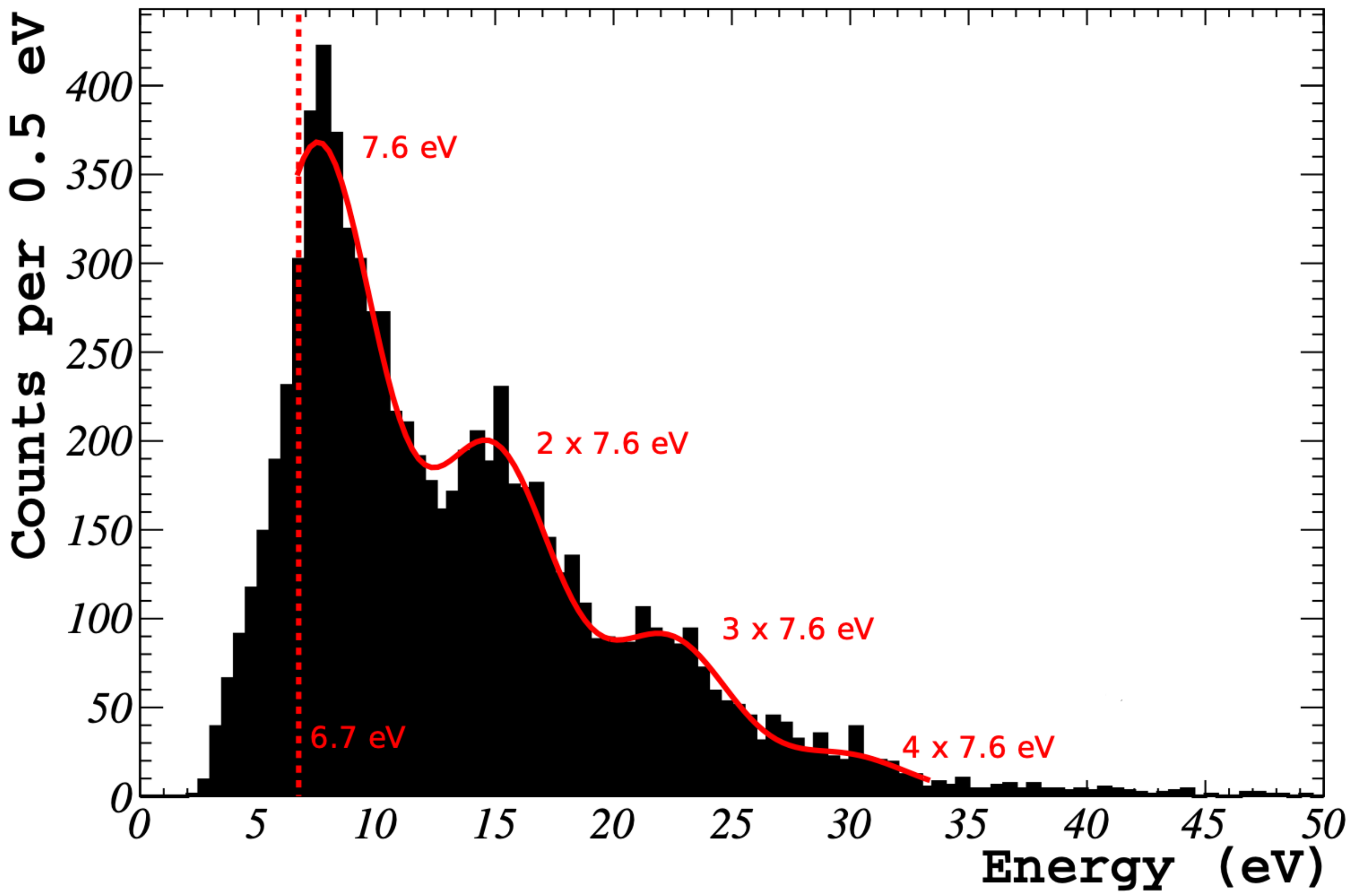
## Results: Silicon-On-Sapphire (SOS) wafer




- Detector: SOS wafer
- Exposure: 0.14 kg·d
- Energy threshold: 6.7 eV

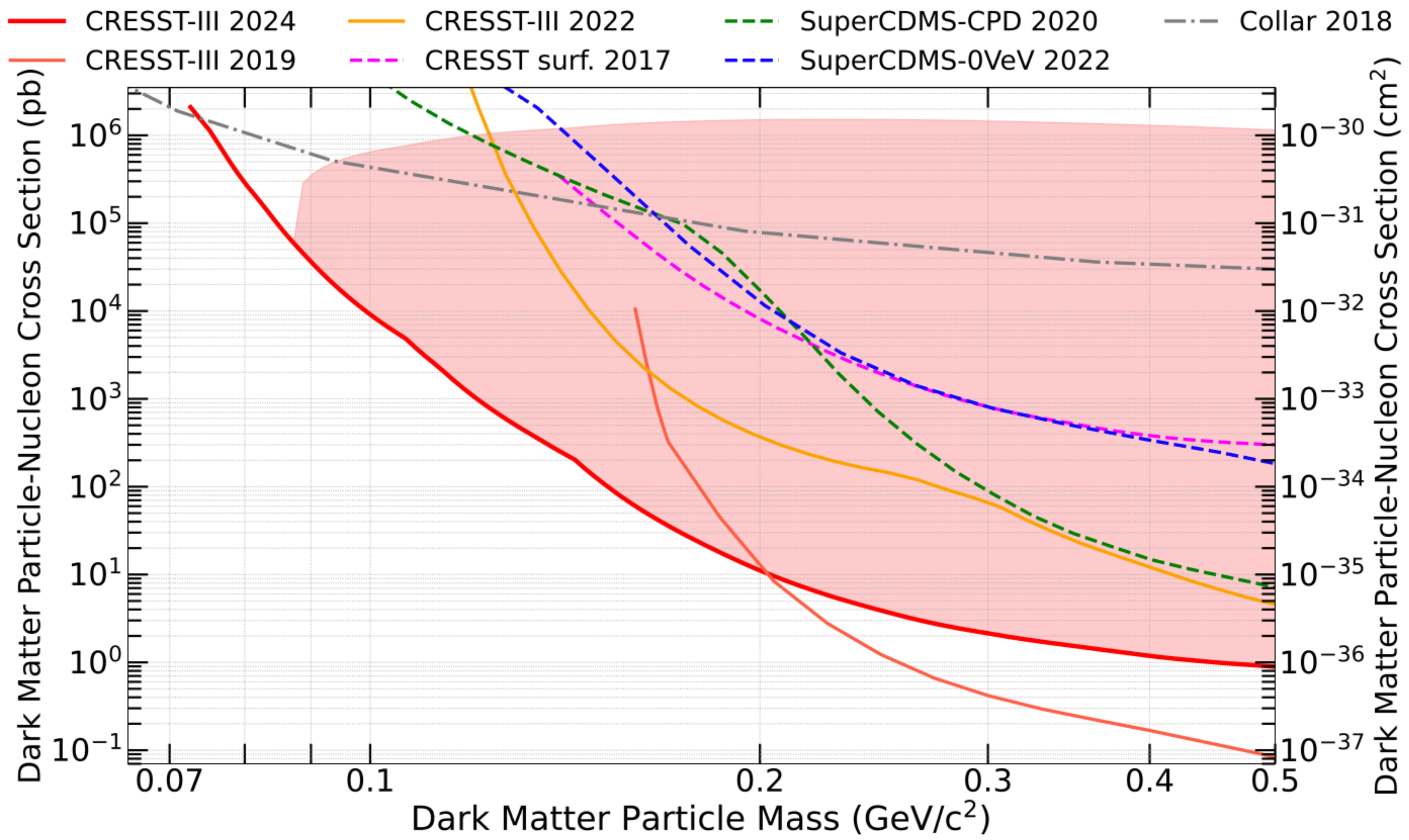
### New calibration method

- vacuum ultraviolet (VUV) luminescence @ 7.6 eV from the $Al_2O_3$ crystal irradiated by $^{55}Fe$ source
- precise calibration at threshold




First **single photons** observation in CRESST

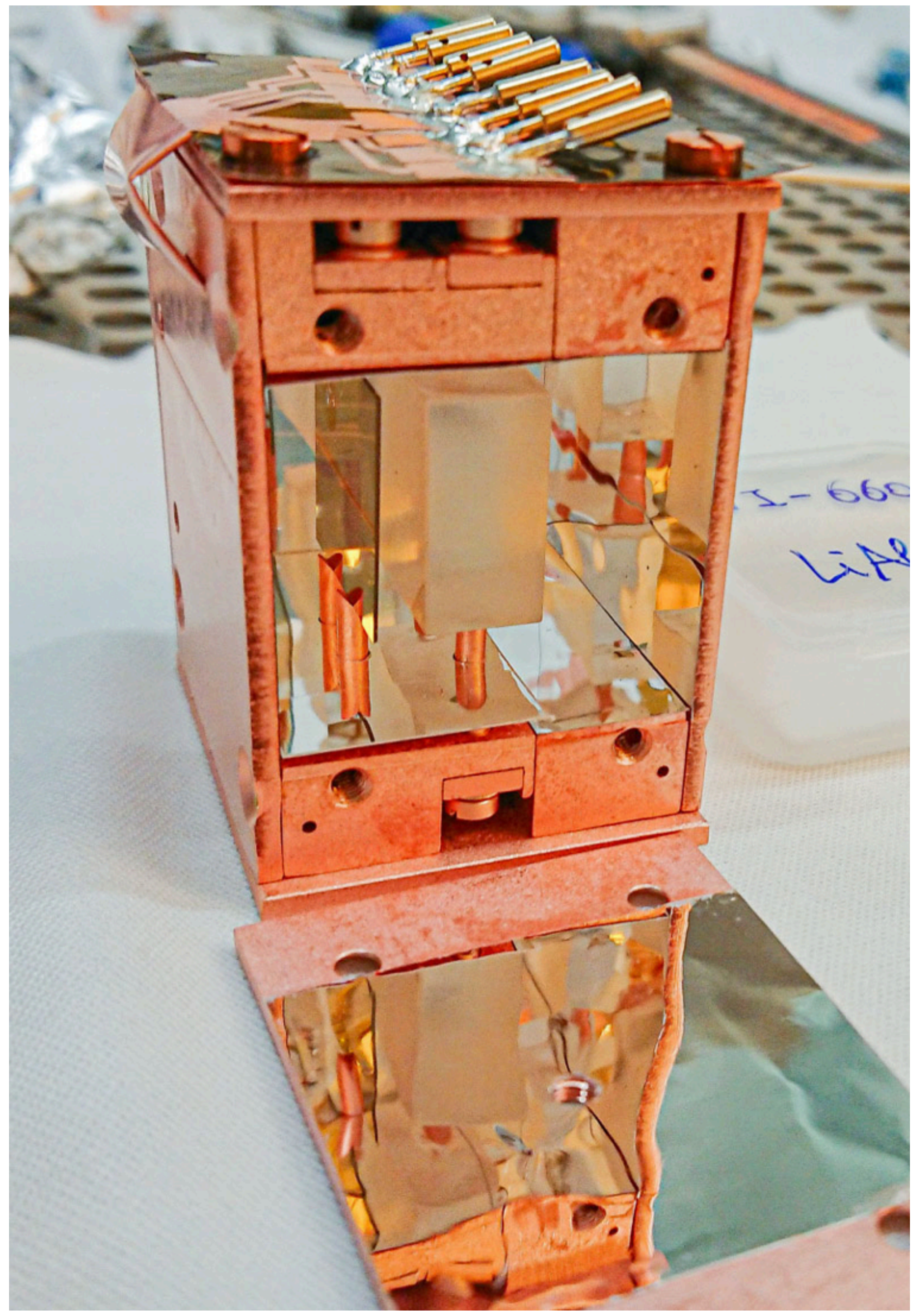
Sensitive to DM masses below **100 MeV/c²**

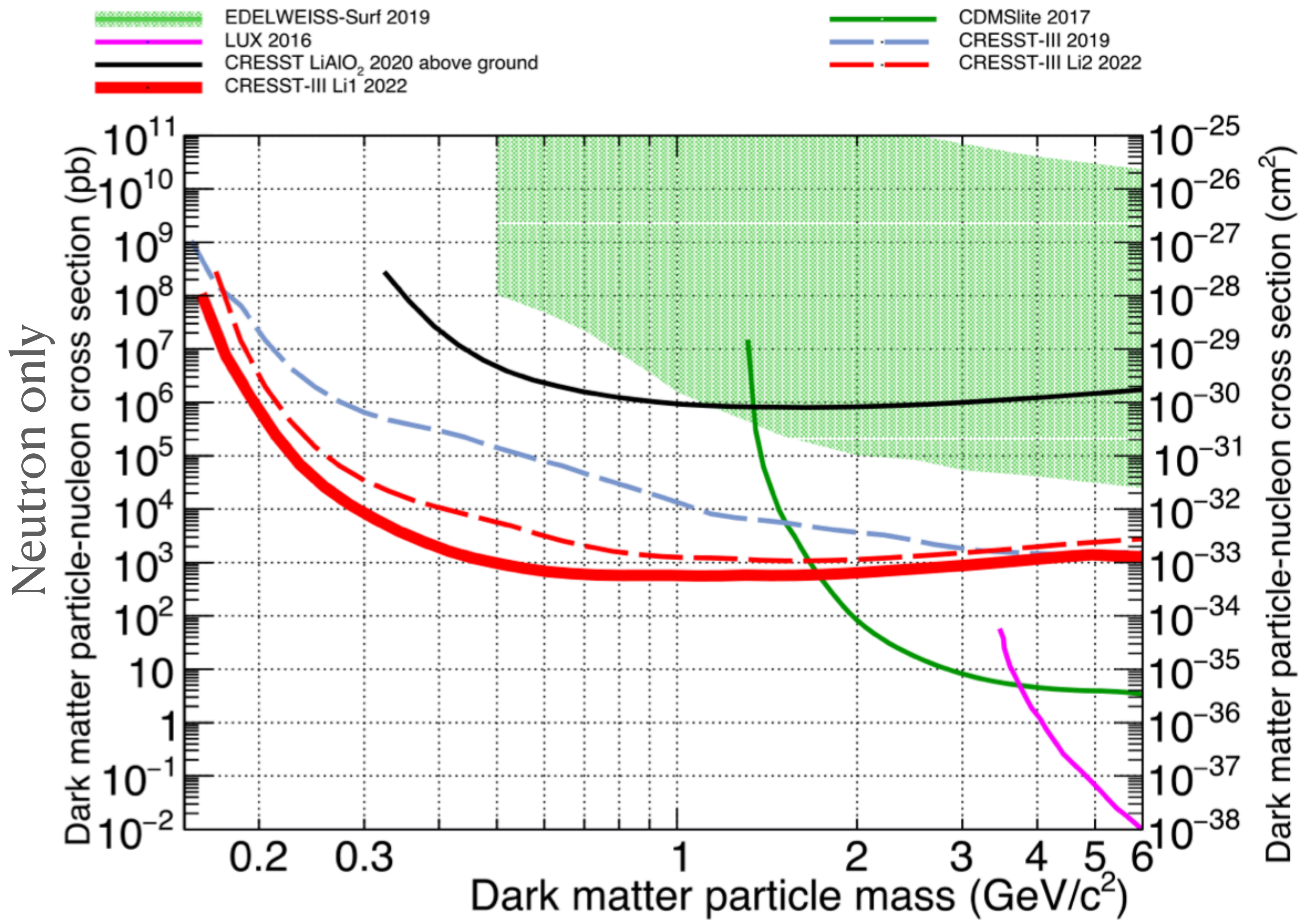


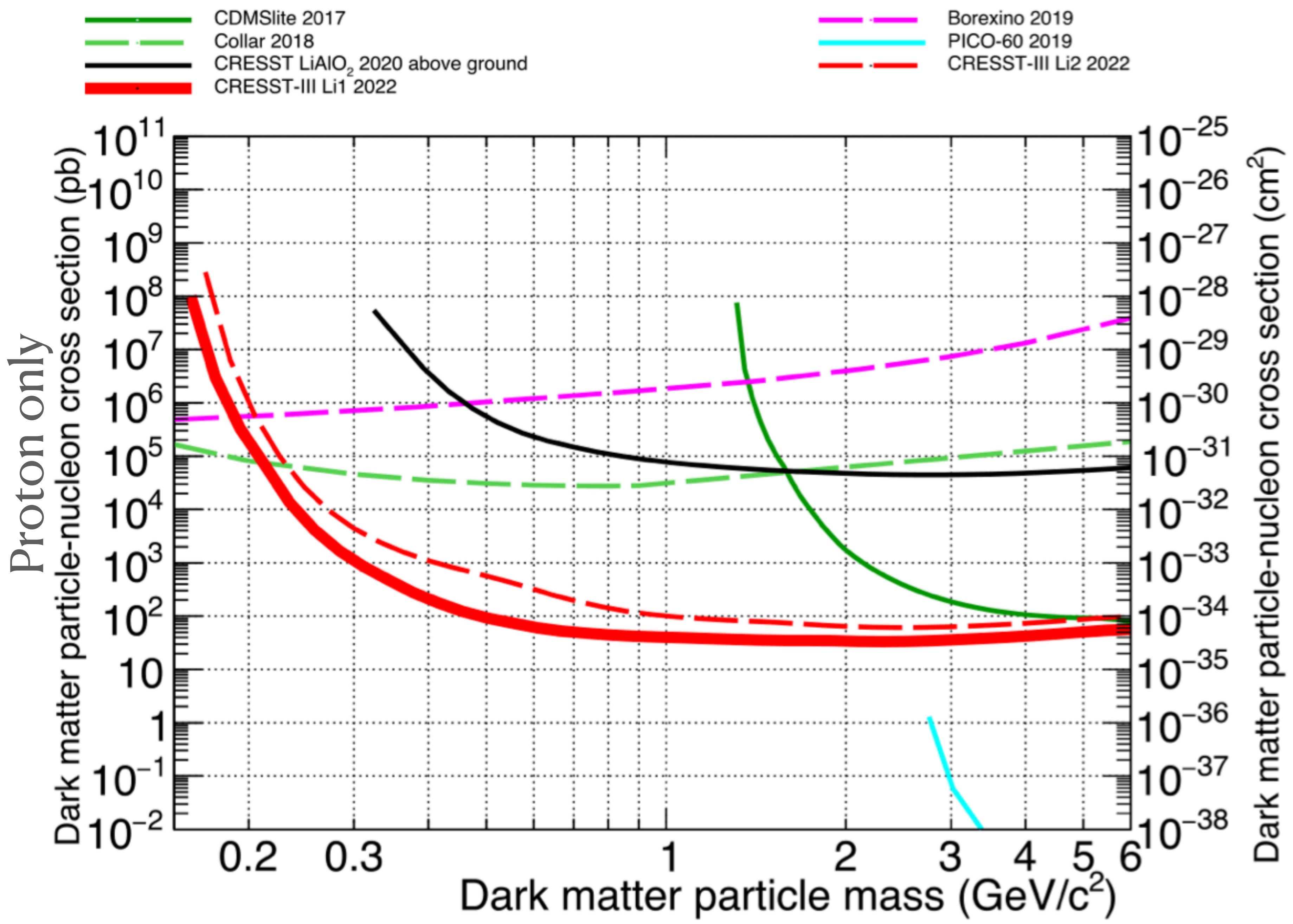

arXiv:2405.06527

# CRESST-III: DM results

## Results: Spin Dependent (SD) Limits






- Detector: $LiAlO_2$
- Exposure: 1.161 kg·d
- Energy threshold: 83.6 eV

The European Physical Journal C 82(3):207

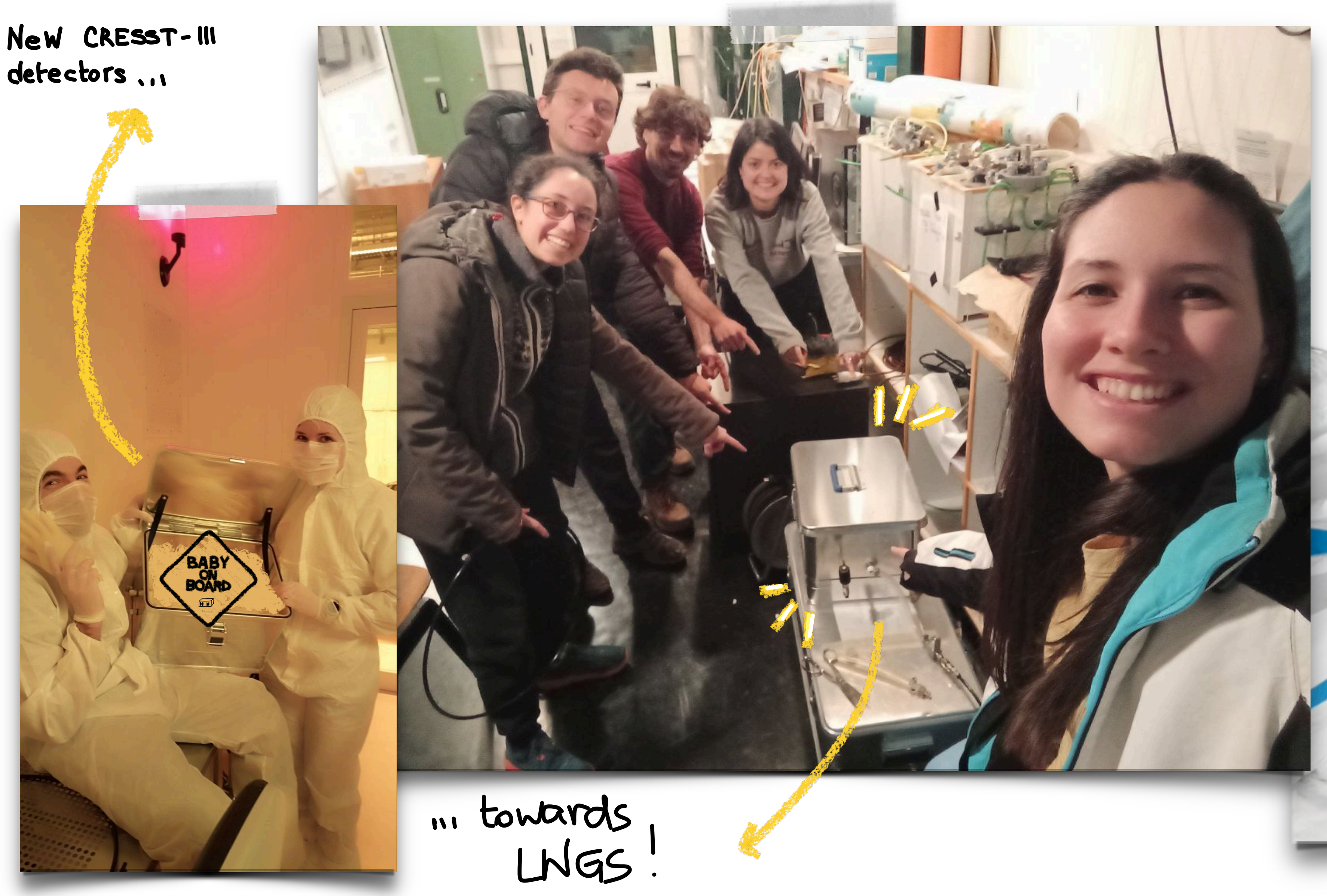
- Improved SD limits for both proton and neutron only case
  - → Proton only: **leading sensitivity** in mass range 0.25 GeV/c²-2.5 GeV/c²
  - → Neutron only: **leading sensitivity** in mass range 0.16 GeV/c² - 1.5 GeV/c²

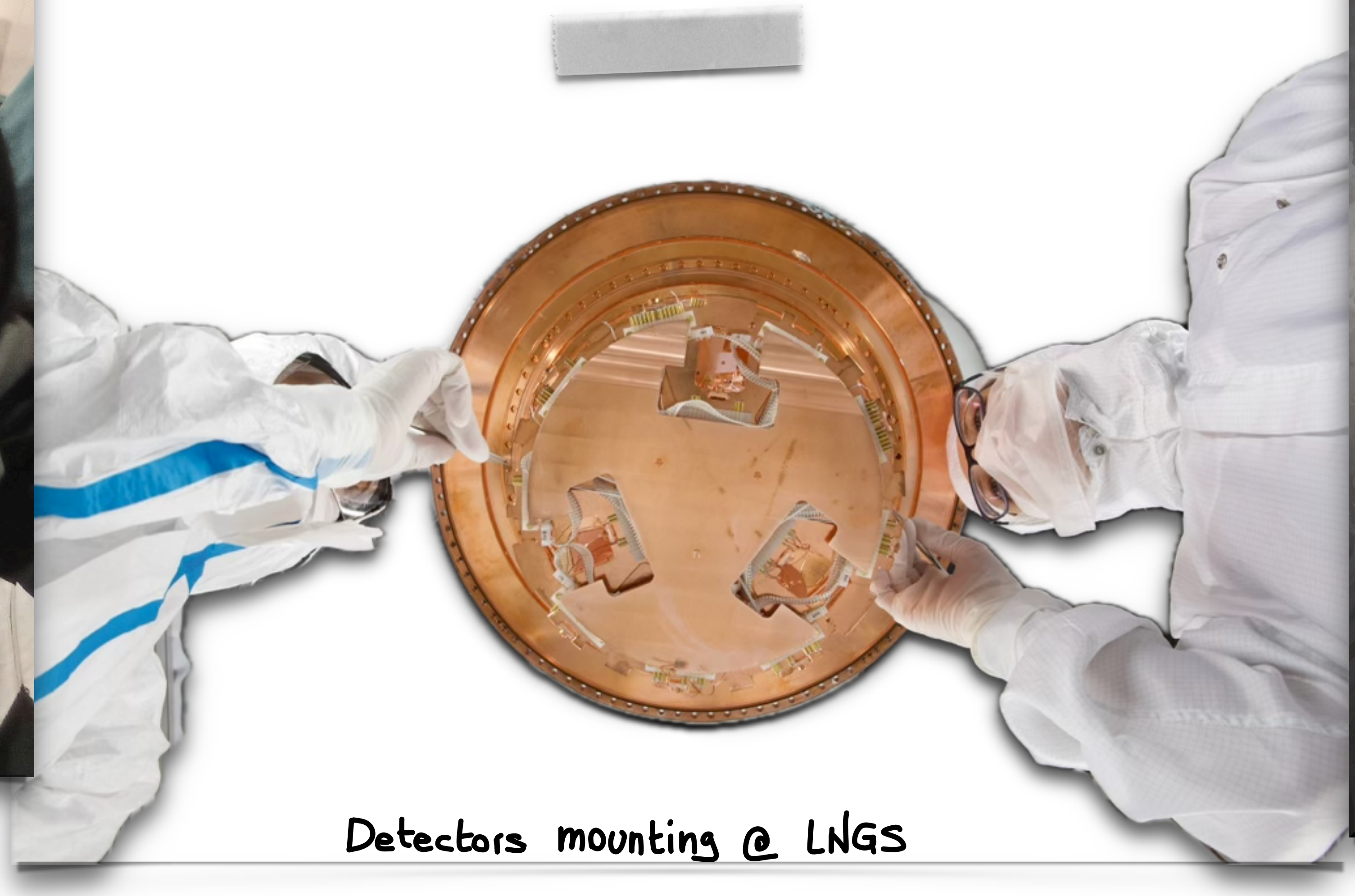
# Current status

## News from the underground

**February 2024**
Detectors with new designs installed at LNGS

**April 2024**
3rd run started
- Detectors optimisation: done
- Calibration & data taking: ongoing





Cryogenic
Rare Event Search
Superconducting Thermometers

# Back-up

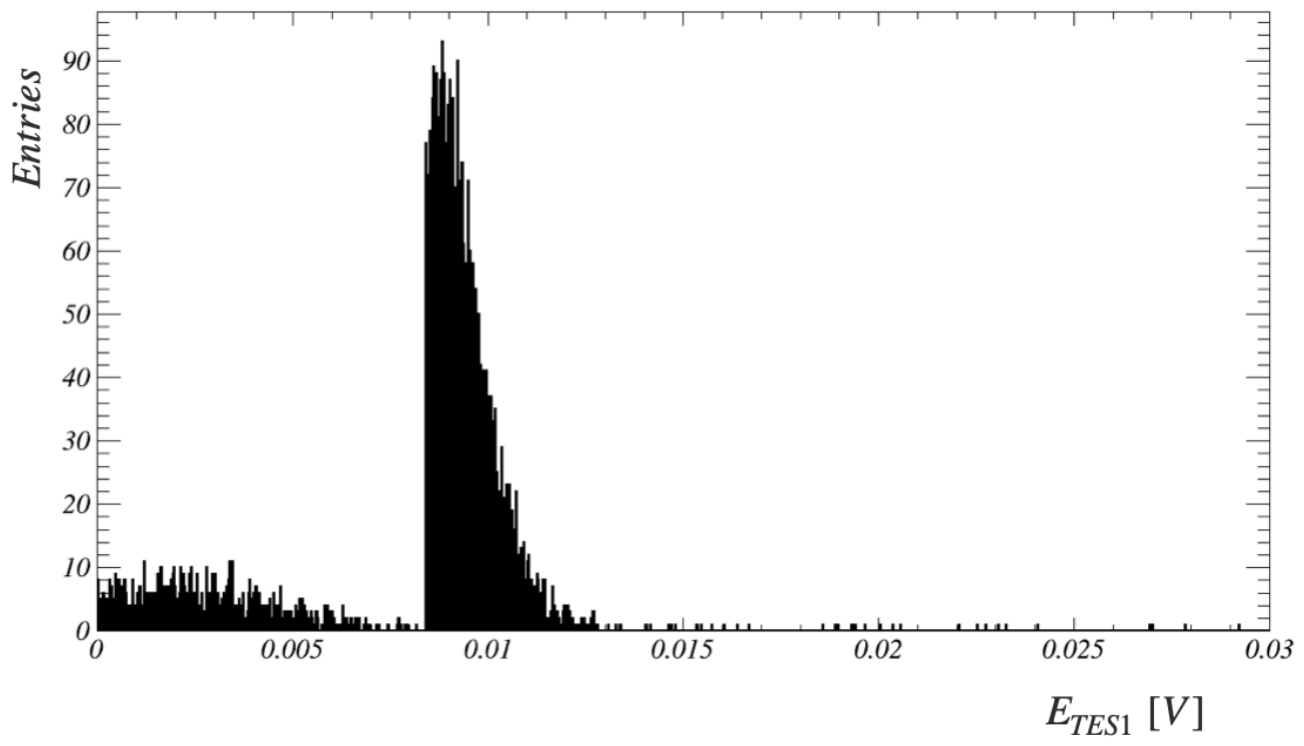

Cryogenic
Rare Event Search
Superconducting Thermometers

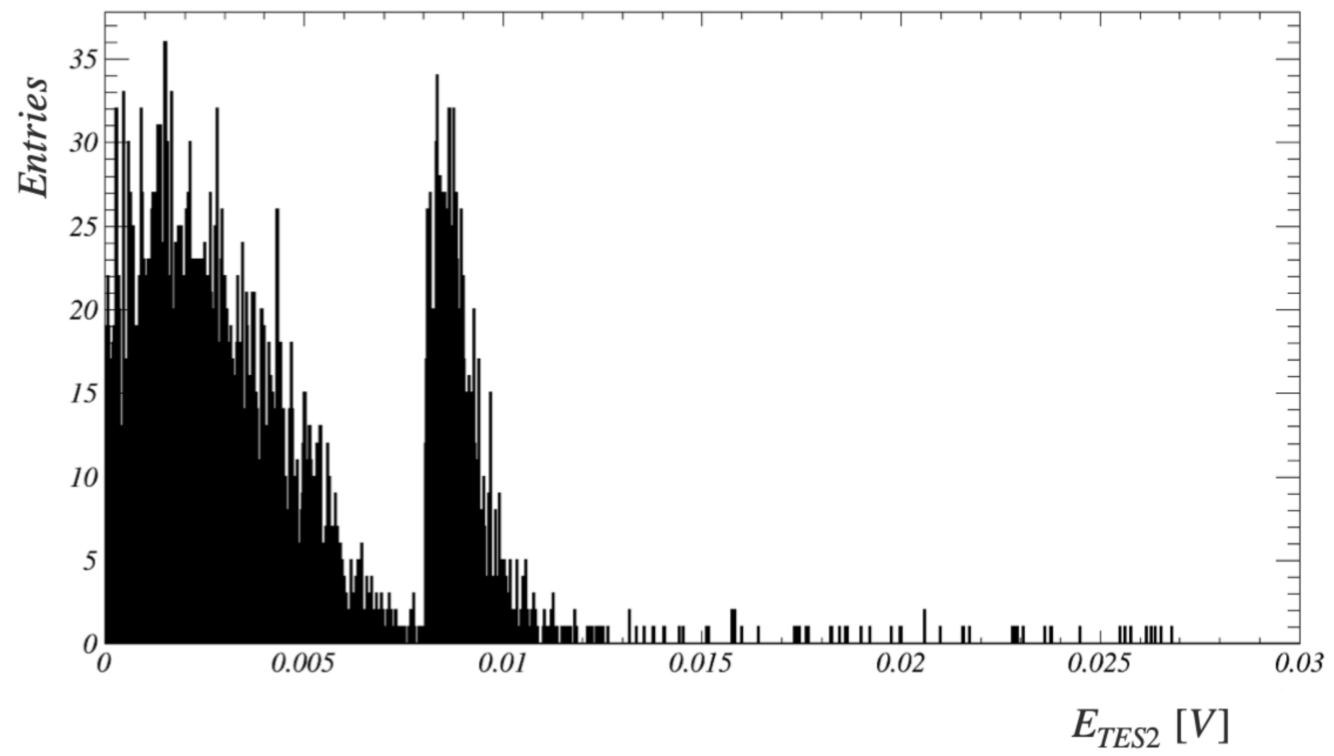
# Behind CRESST-III 3rd run

arXiv 240402607
Accepted by EPJC

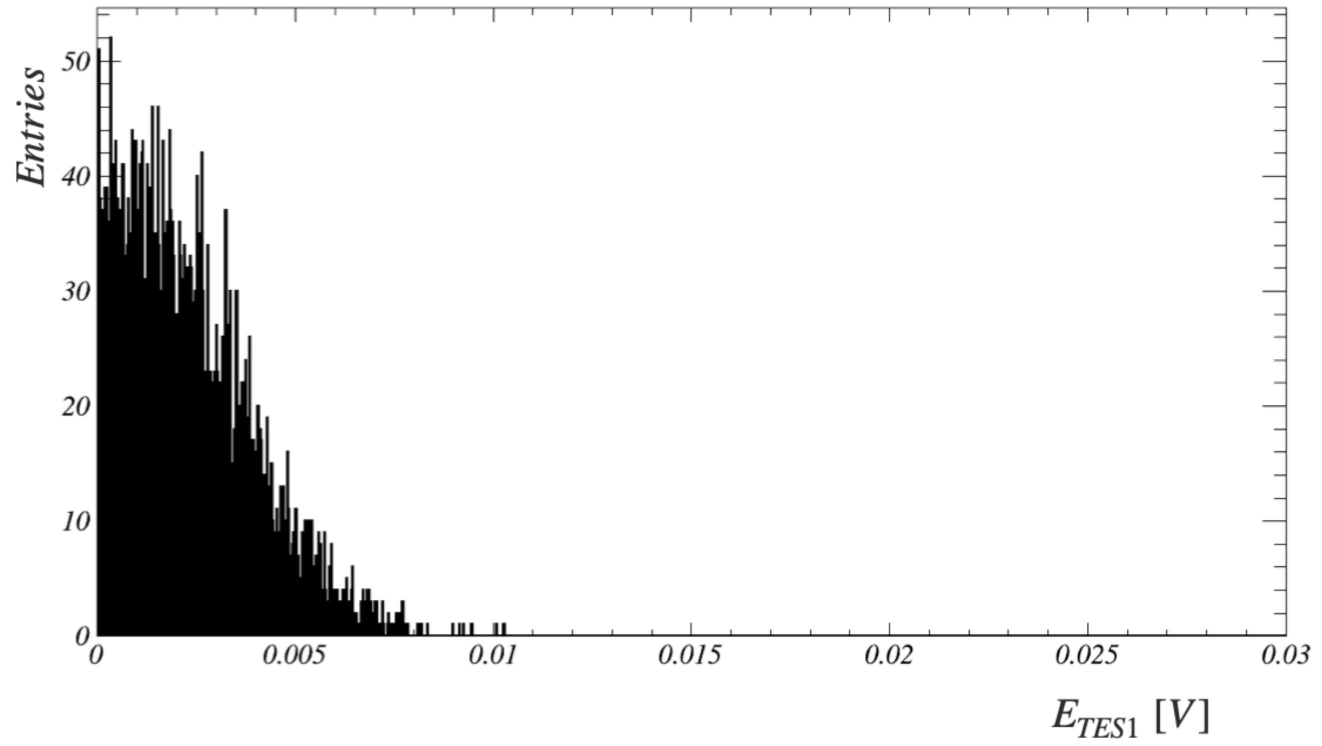
## Double TES R&D: above-ground measurements

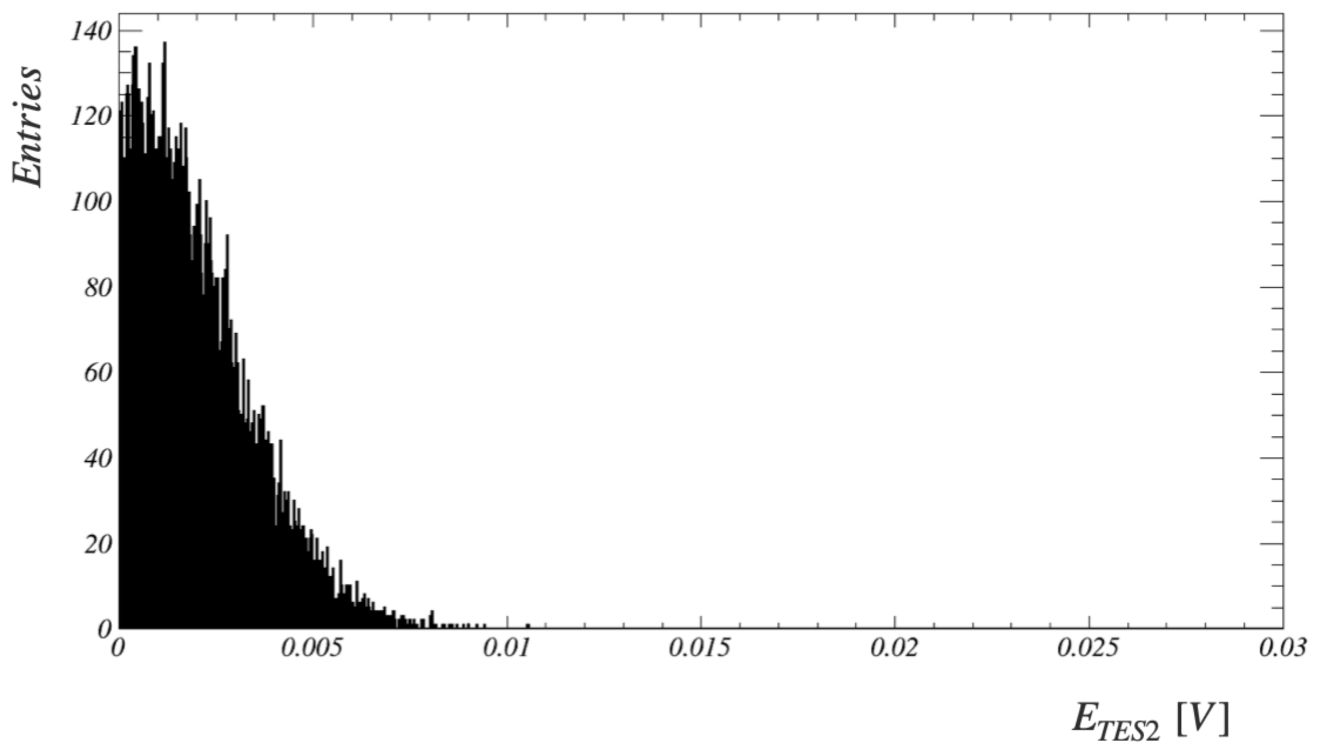
- Non calibrated spectra below threshold




- Inverted stream data: non calibrated noise spectra from empty baselines

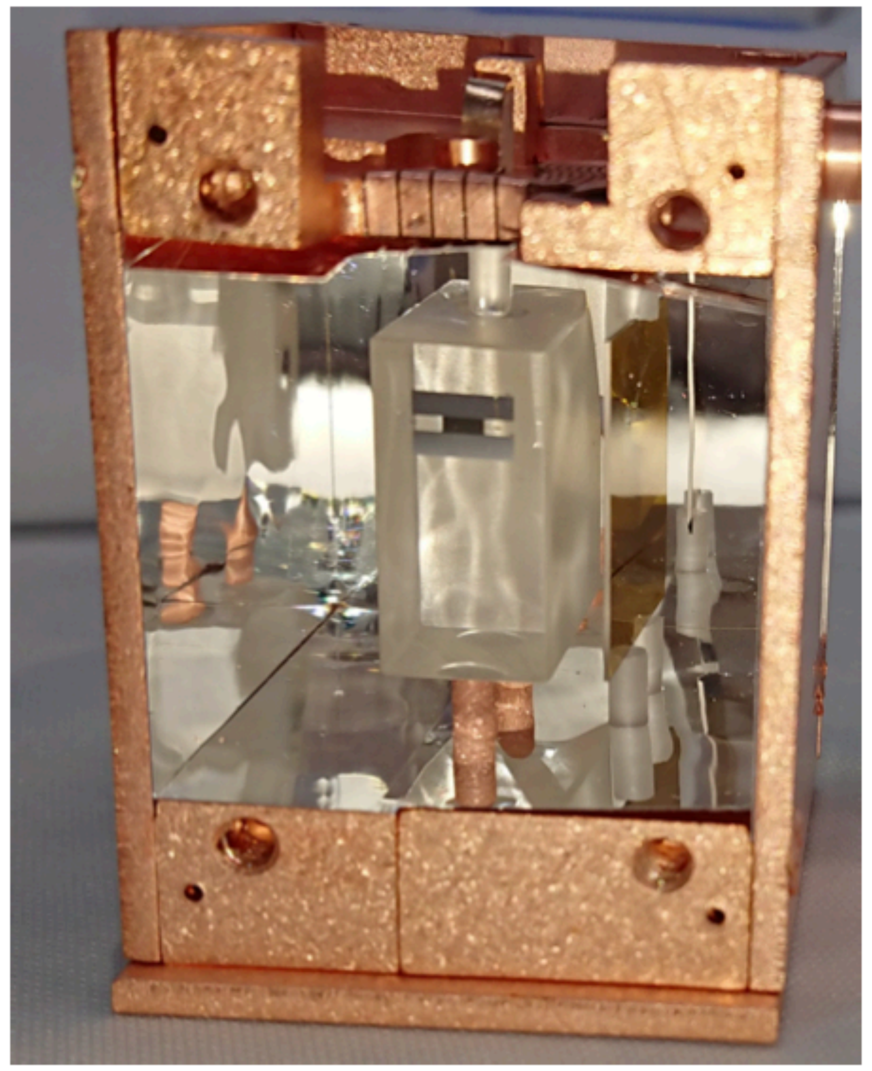


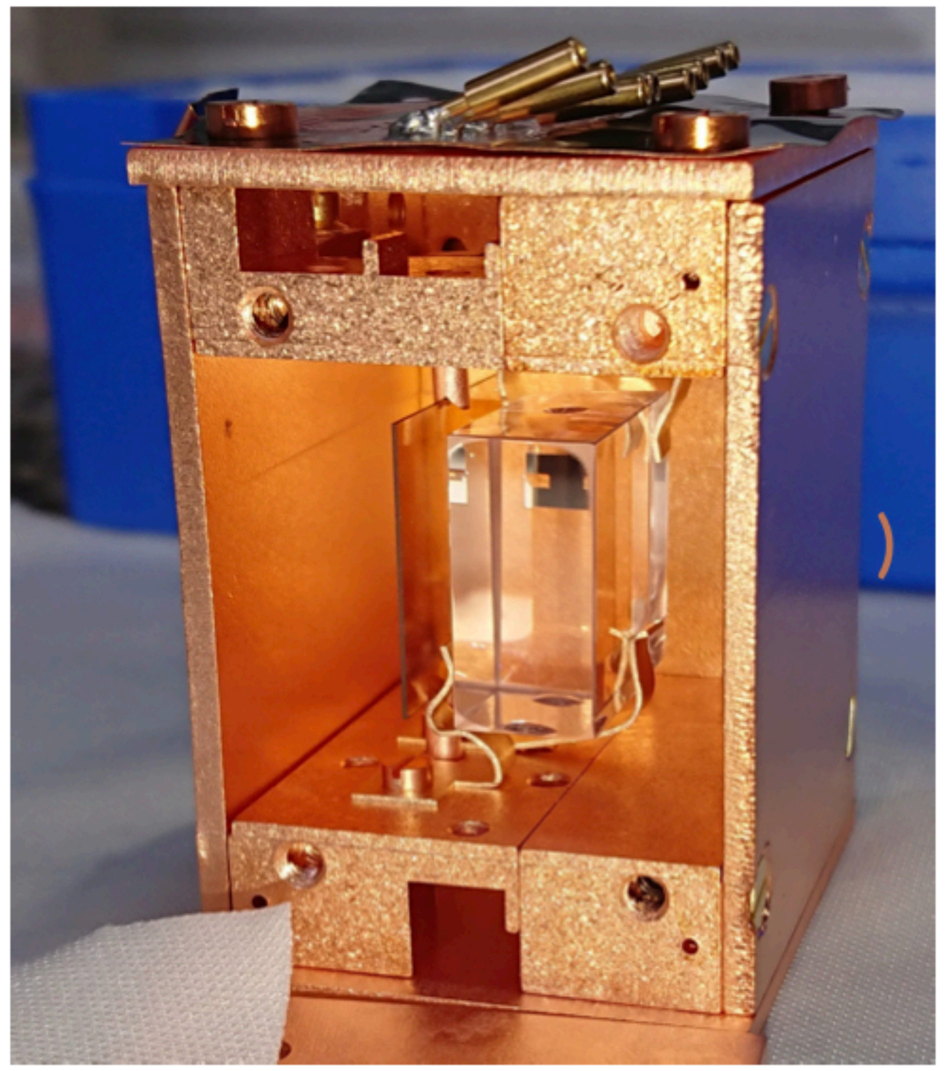
# CRESST-III Phase II

## LEE origins? Multiple detector designs to find out

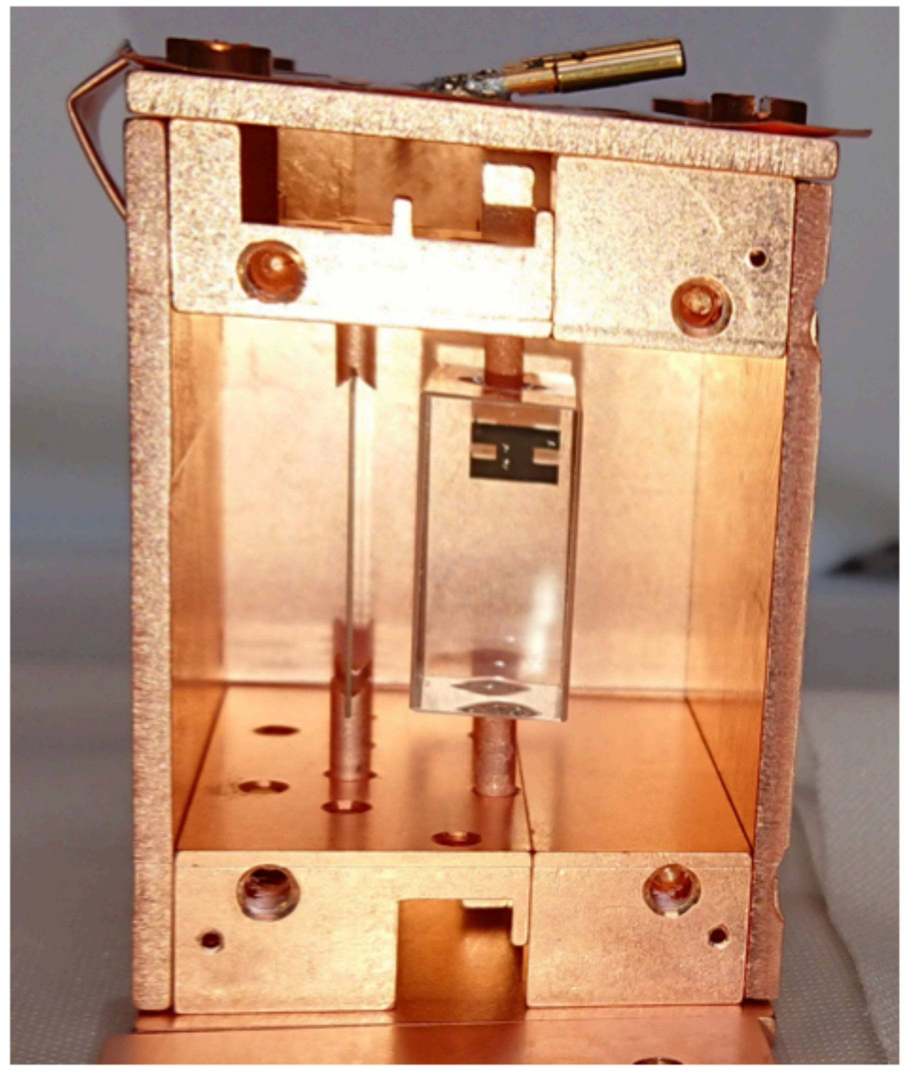
$CaWO_4$ (TUM)



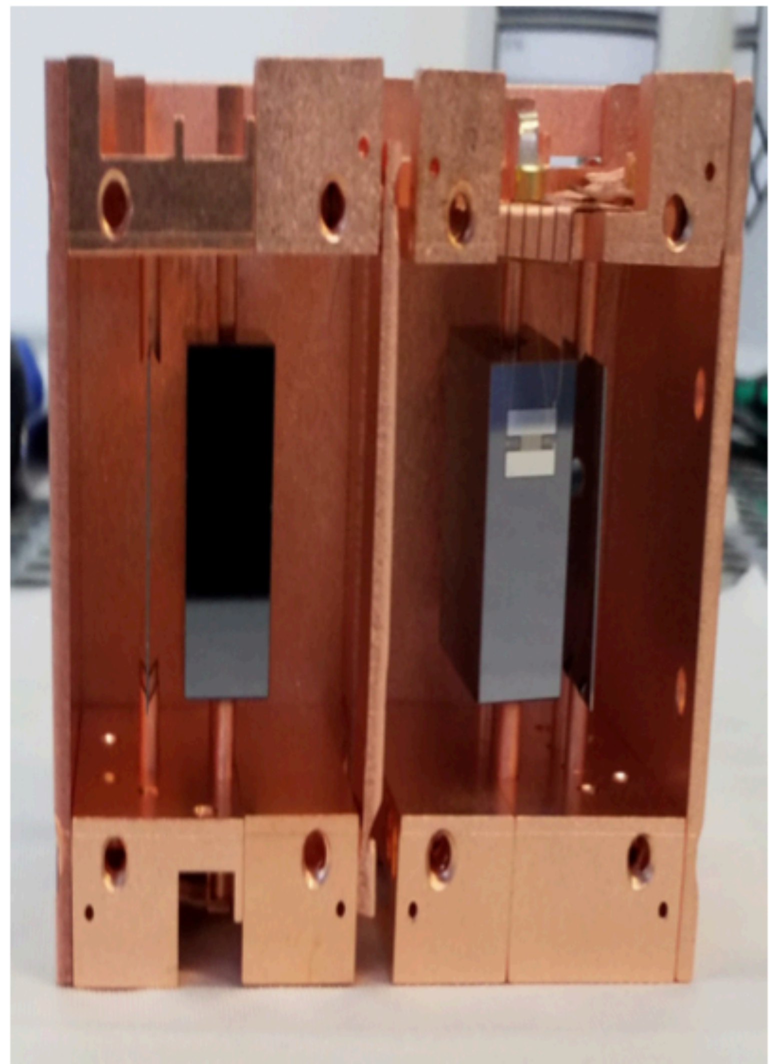
$CaWO_4$ (commercial)



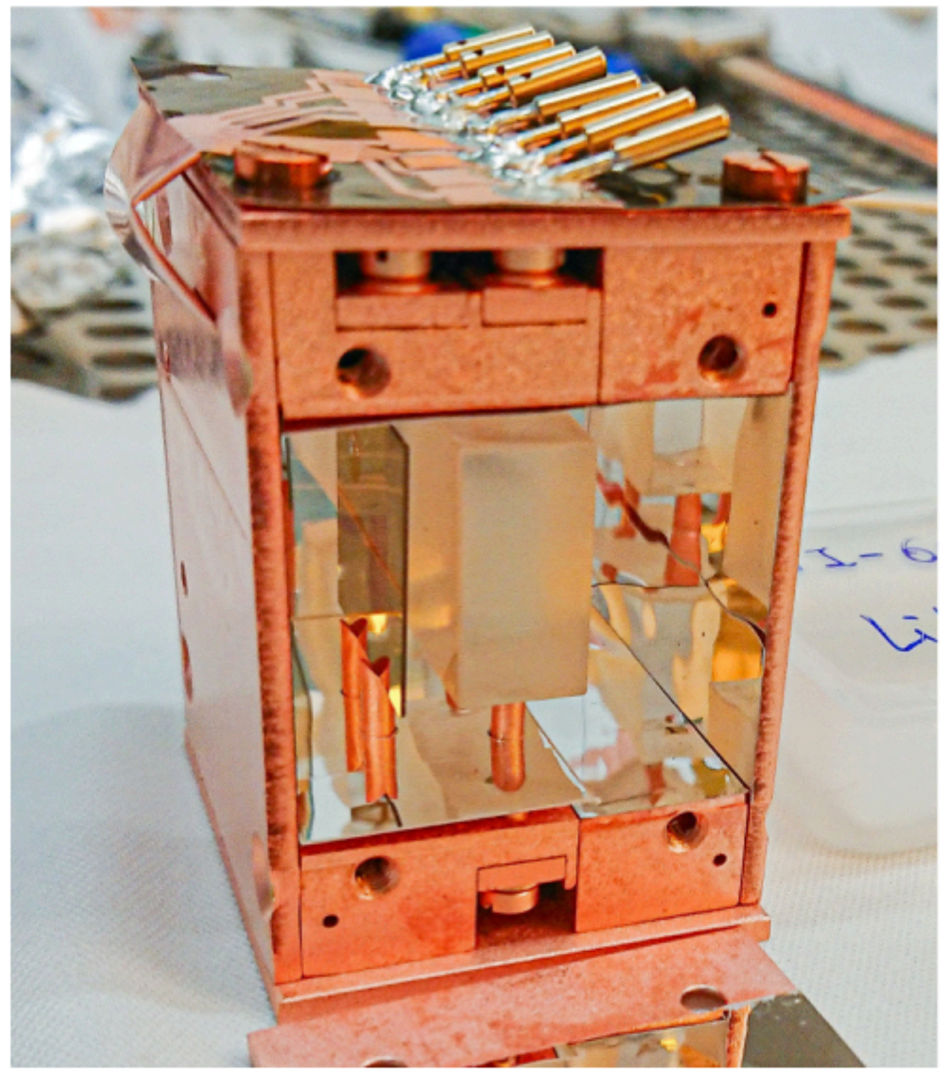
$Al_2O_3$



Si



$LiAlO_2$



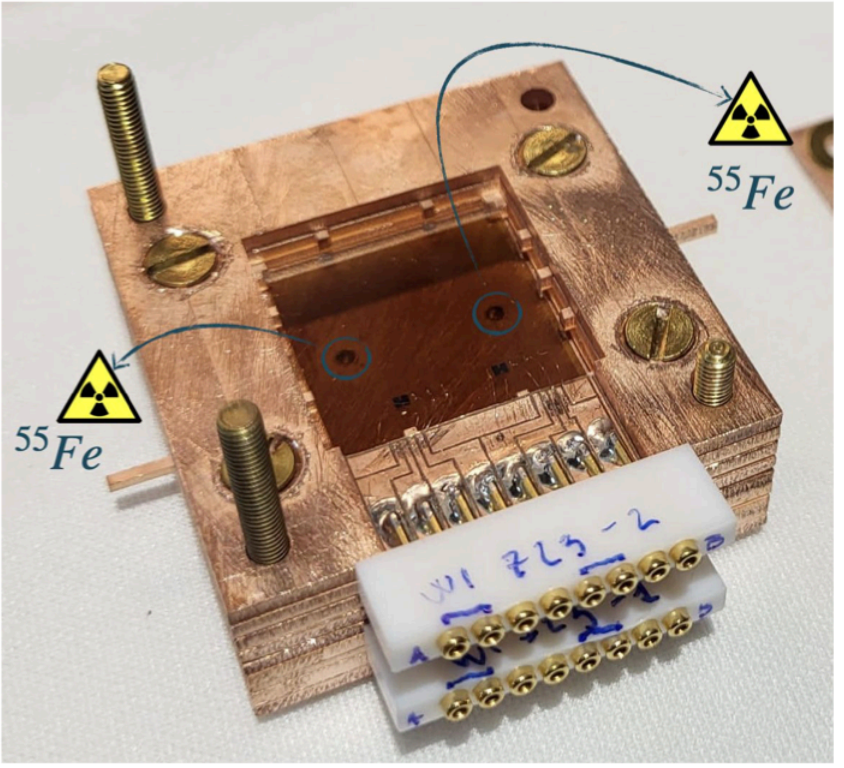
# Behind CRESST-III 3rd run

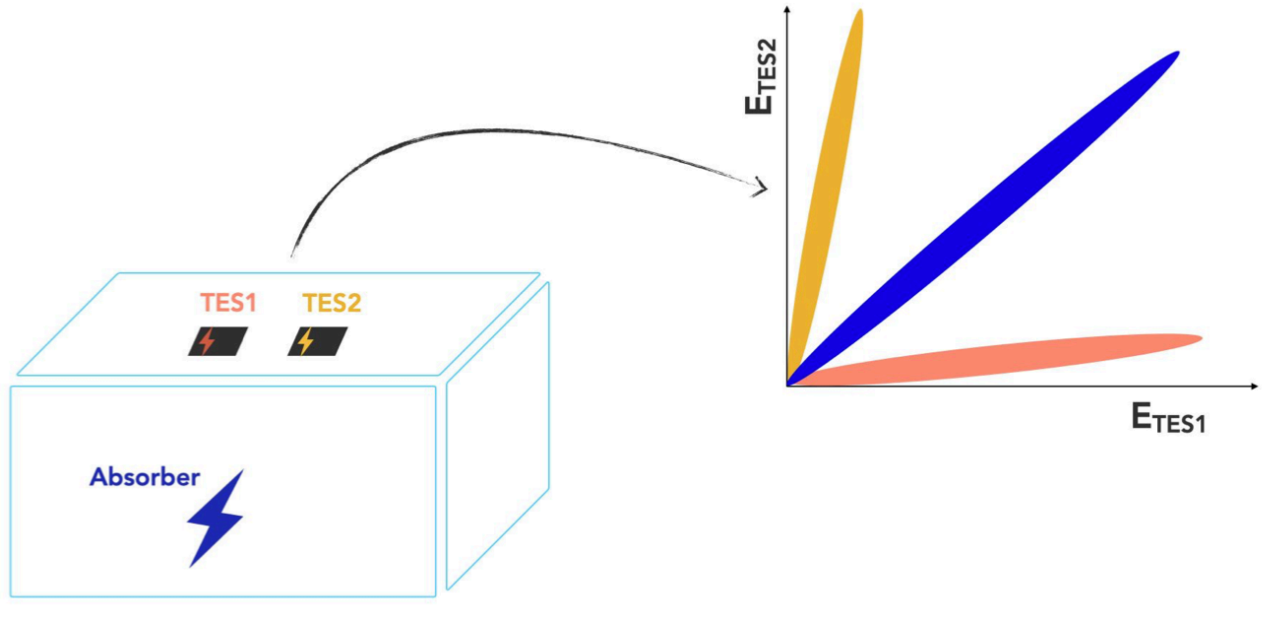
arXiv 240402607
Accepted by EPJC

## Double TES R&D: above-ground measurements

### Double TES

- 2 TESs on the same crystal, independently read-out
- Stress-free holding
- No scintillating parts
- 2 collimated $^{55}Fe$ source
- **Proof of principle** measurement: TESs can be simultaneously optimised




SOS wafer (20x20x0.4 mm³)

| | TES 1-L | TES 2-L |
|---|---|---|
| Energy threshold [eV] | 27 | 20.5 |
| $\sigma_{Baseline}$ [eV] | 5.4 ± 0.1 | 4.1 ± 0.1 |
| $\sigma_{Fe}$ [eV] | 149.0 ± 3.8 | 121 ± 2.3 |

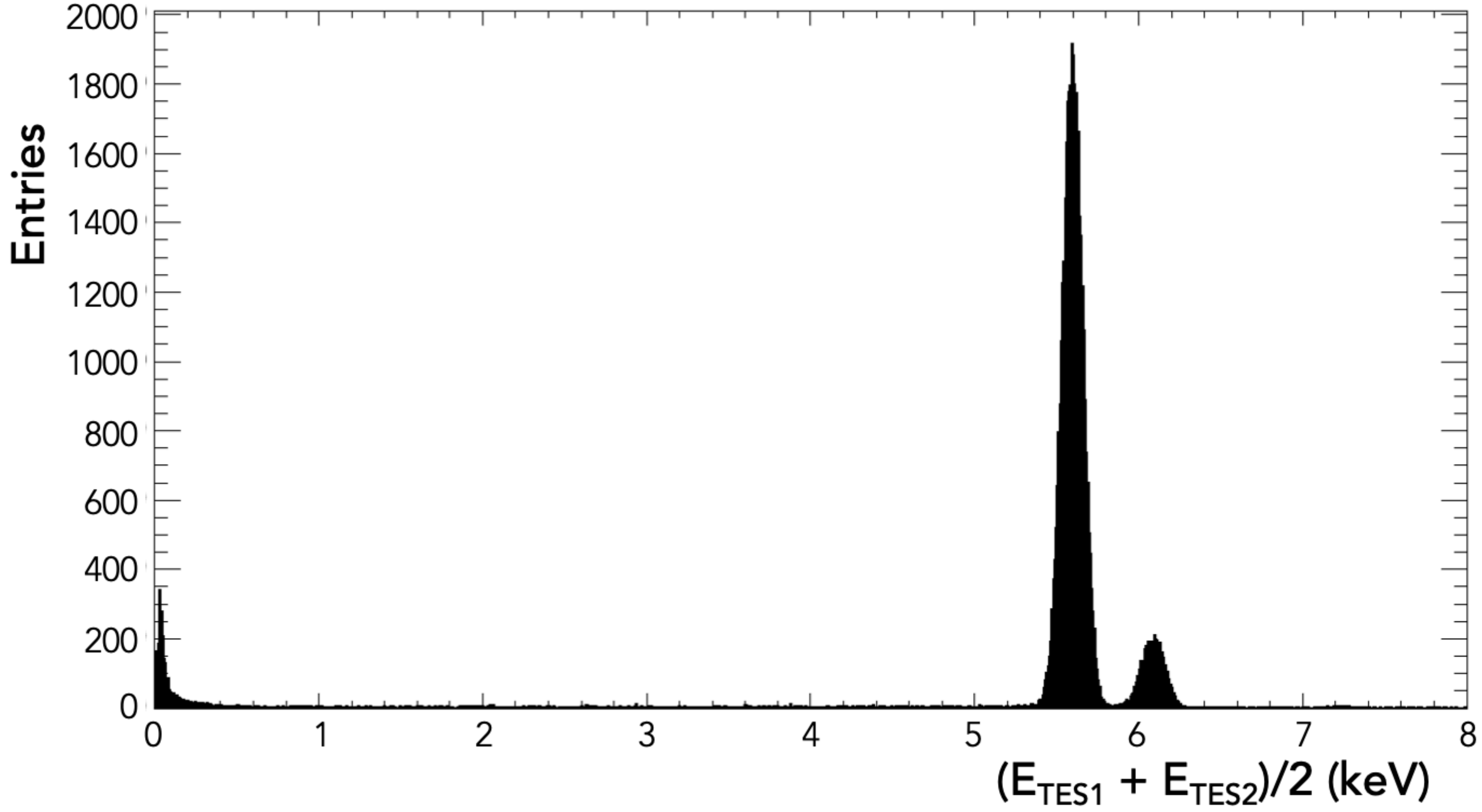
# Behind CRESST-III 3rd run

arXiv 240402607
Accepted by EPJC

## Double TES R&D: above-ground measurements

### Double TES

- 2 TESs on the same crystal, independently read-out
- Stress-free holding
- No scintillating parts
- 2 collimated $^{55}Fe$ source
- **Proof of principle** measurement: TESs can be simultaneously optimised

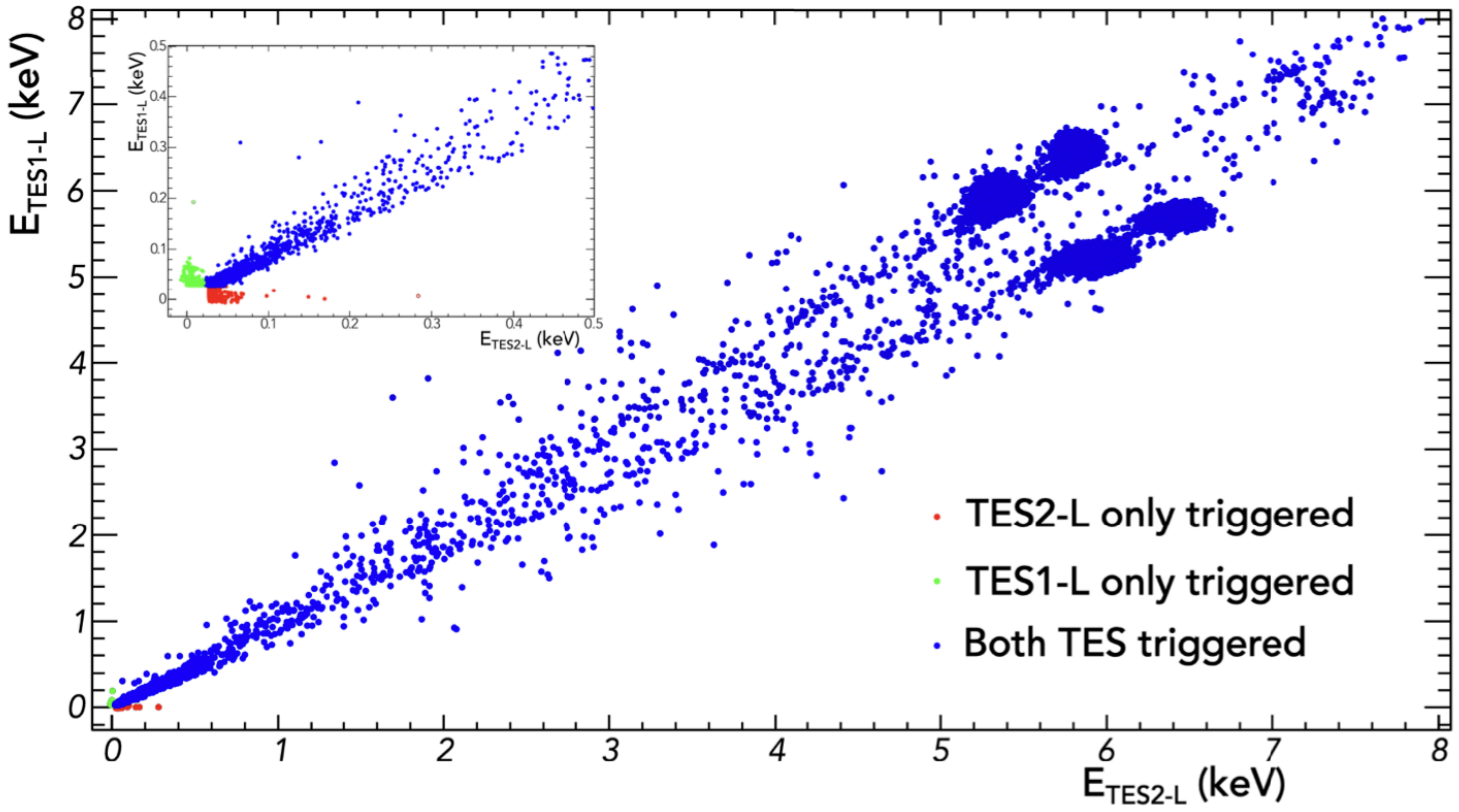



Improved $\sigma_{Fe}$ combining the outputs from both TESs: (90.0 ± 1.1) eV

# Behind CRESST-III 3rd run

arXiv 240402607
Accepted by EPJC

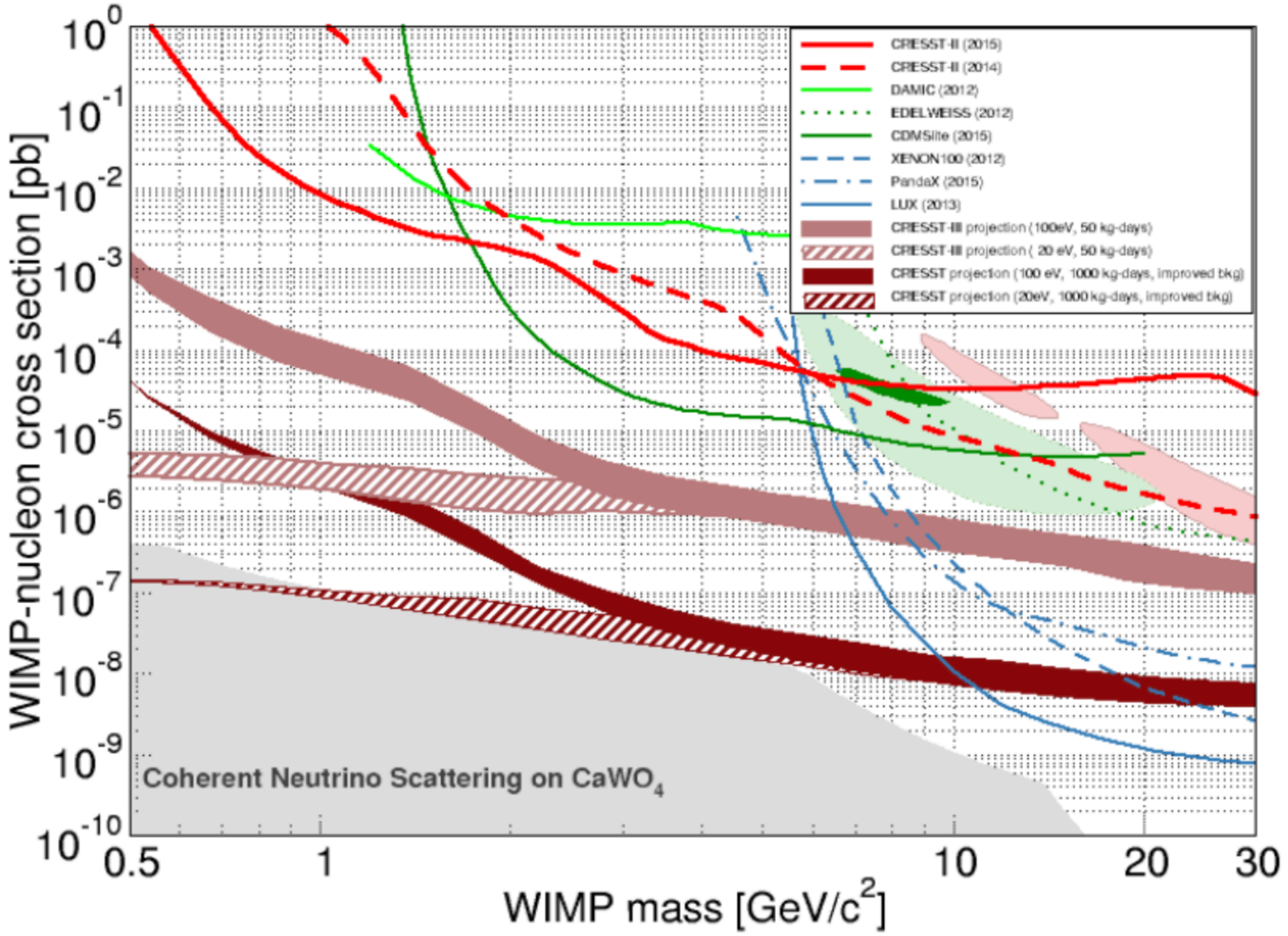
## Double TES R&D: above-ground measurements



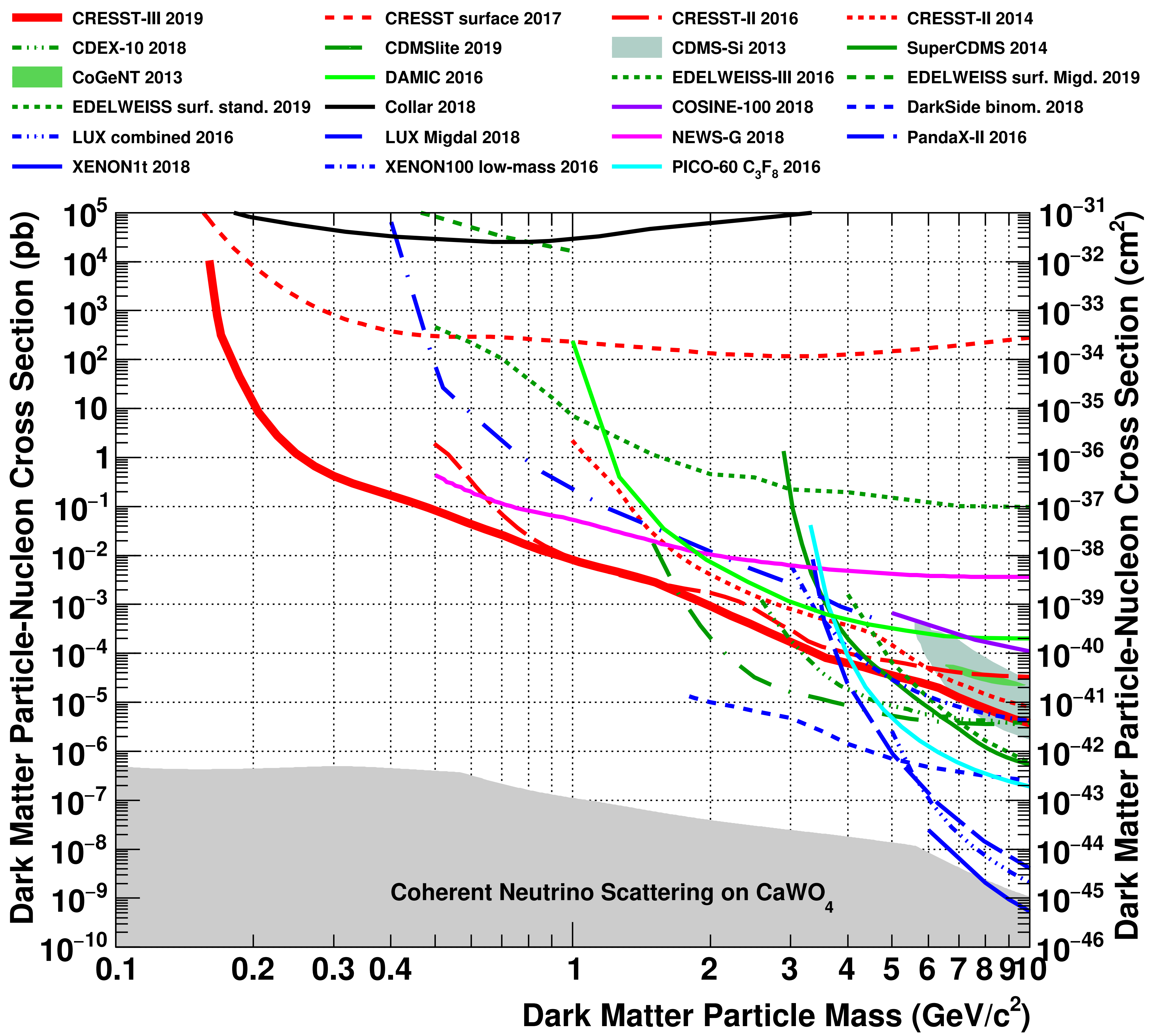

→ Single TES and absorber events show differences in pulse shapes

→ Discrimination possible with double TES

# CRESST-III: 1st run




Detector A, assuming no LEE




Detector A


# But that is not all!


## Other CRESST-III achievements

**Observation of a low energy nuclear recoil peak im the neutron calibration data of the CRESST-III experiment**

Phys. Rev. D 108, 022005

**Testing spin-dependent dark matter interactions with lithium aluminate targets in CRESST-III**

Phys. Rev. D 106, 092008

**First results from the CRESST-III low-mass dark matter program**

Phys. Rev. D 100, 102002

**Probing spin-dependent dark matter interactions with $^{6}Li$**

The European Physical Journal C 82(3):207

**First observation of single photons in a CRESST detector and new dark matter exclusion limits**

arXiv:2405.06527

**A Low Nuclear Recoil Energy Threshold for Dark Matter Search with CRESST-III Detectors**

J.Low Temp.Phys. 193 (2018)

…and many others!