Revealing the laws of nature with detectors at mK temperatures: the CUORE, CRESST and CUPID experiments

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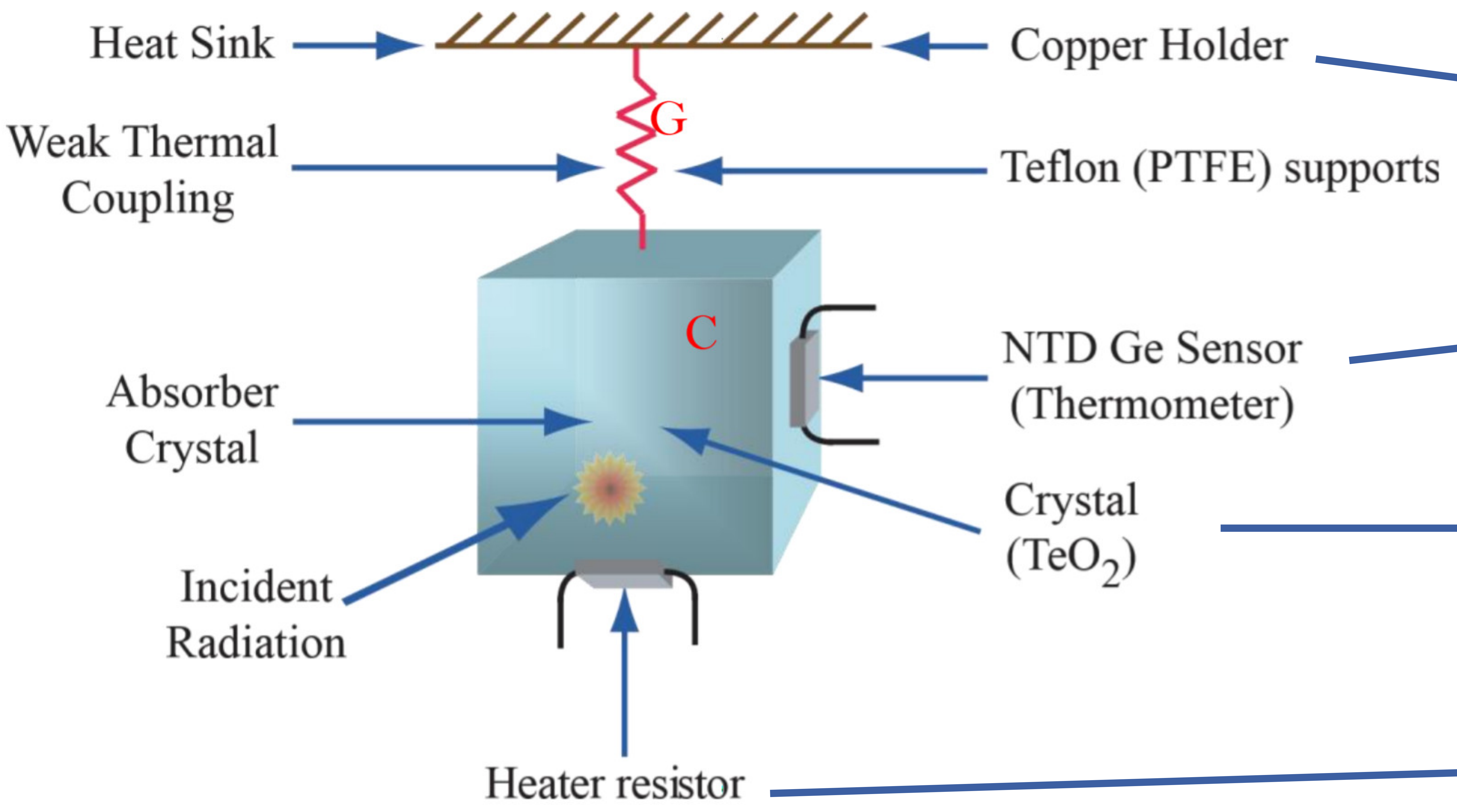
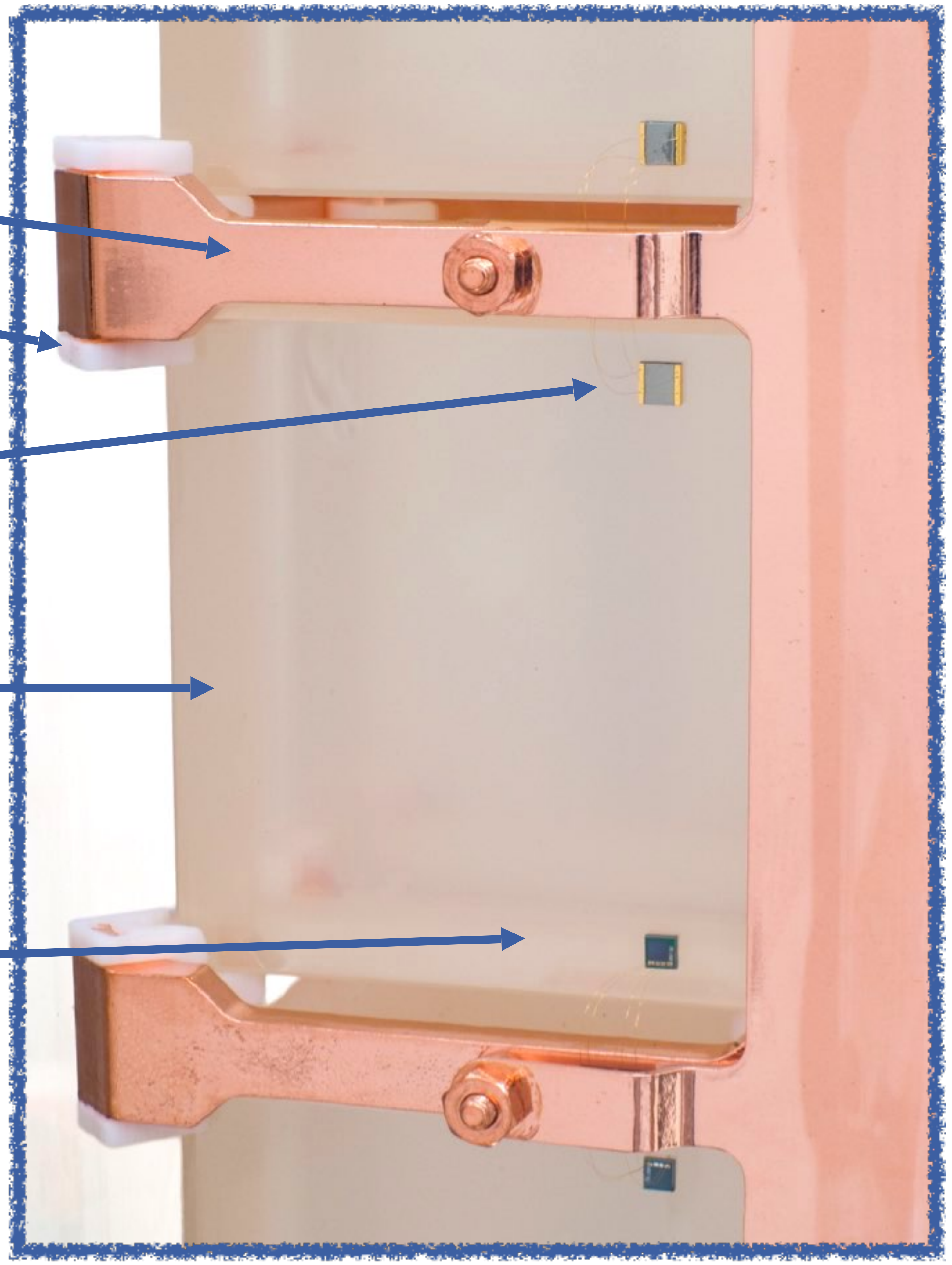
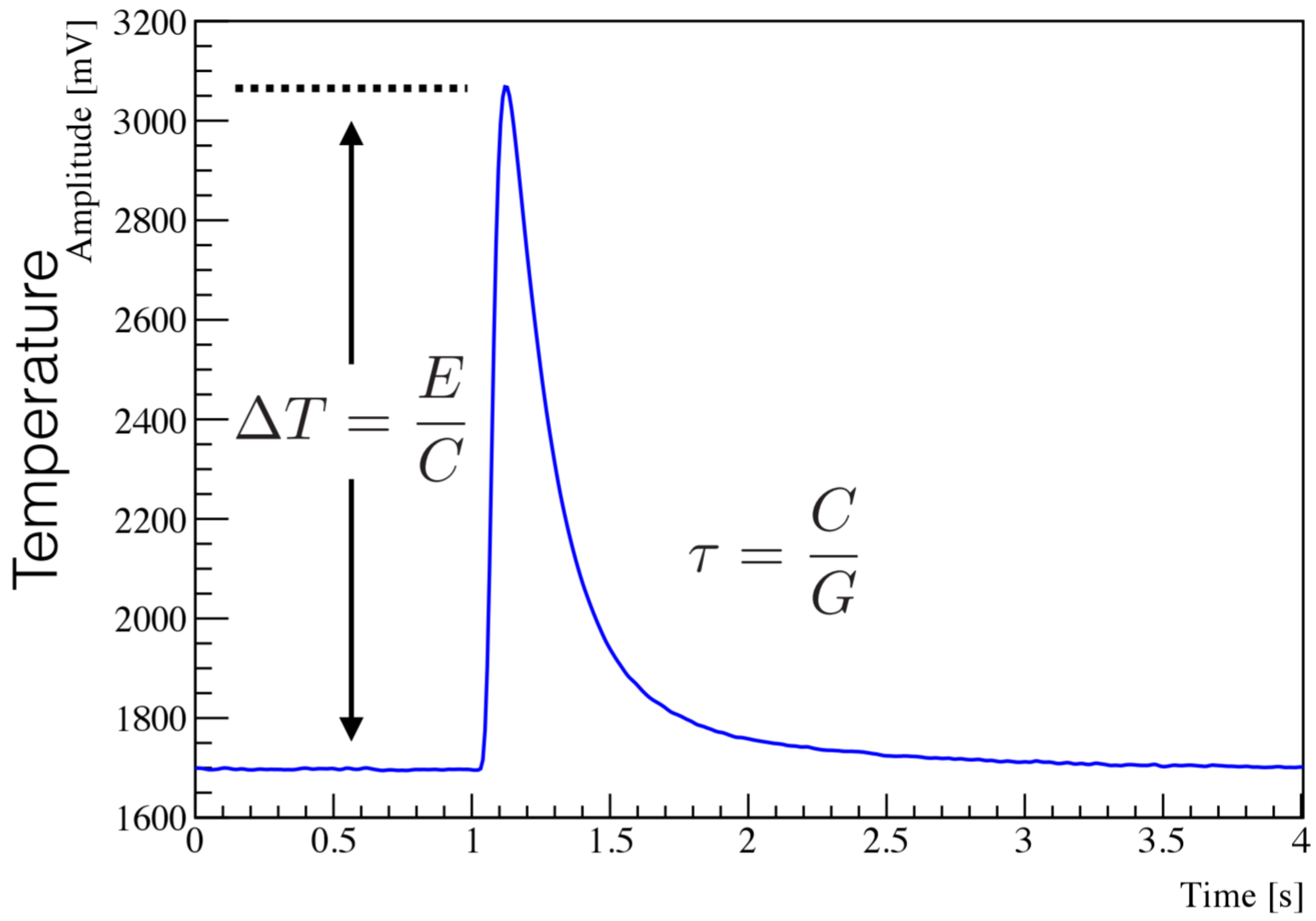
Cryogenic detectors





A particle interaction in the absorber causes an increase in temperature, measured by the thermistor

Working principle



$$\Delta T = \frac{\Delta E}{C} \sim \frac{100\mu K}{MeV}$$

$$\tau = \frac{G}{C} \sim 1s$$

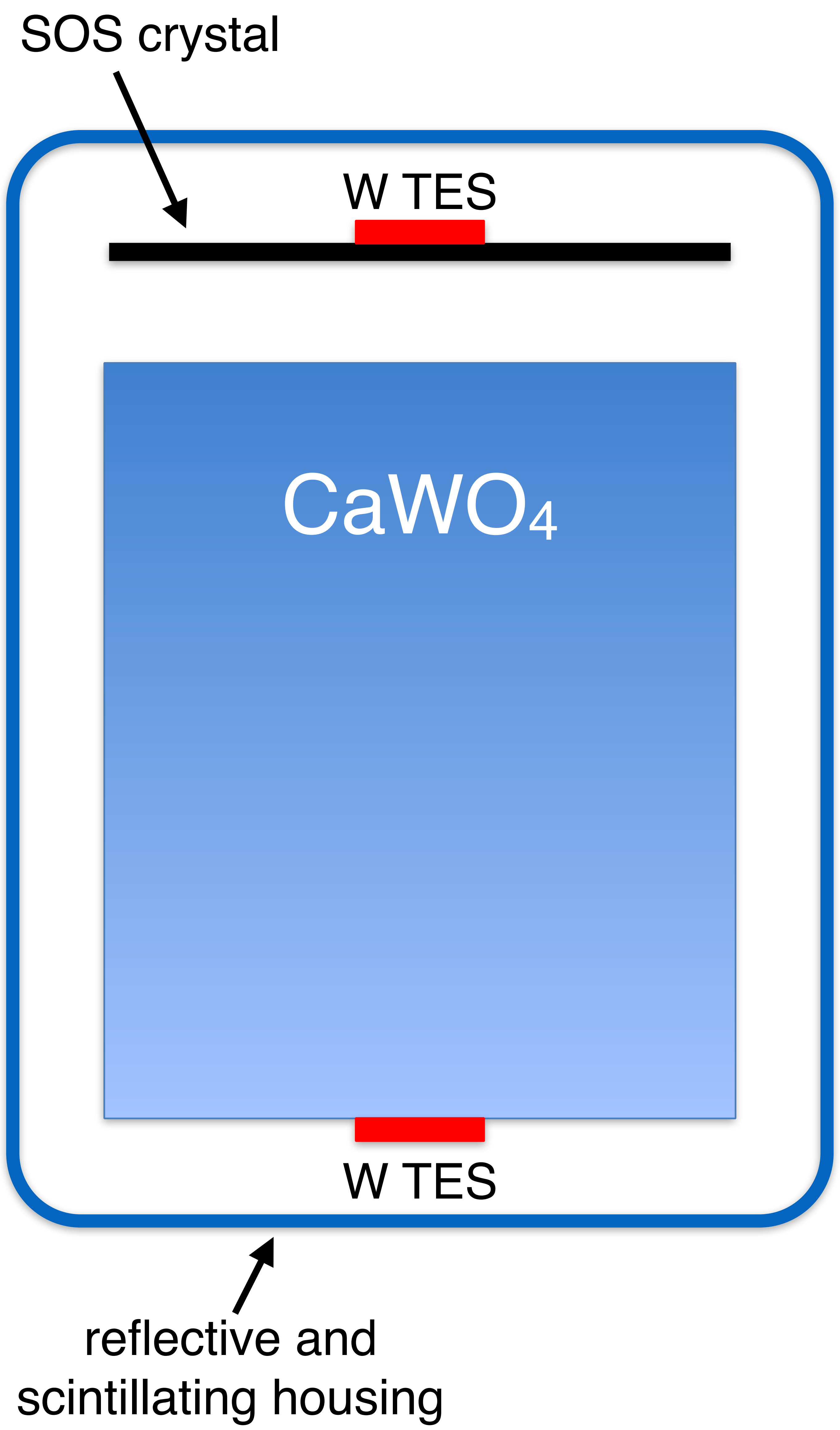
$$C(T) \propto T^3$$

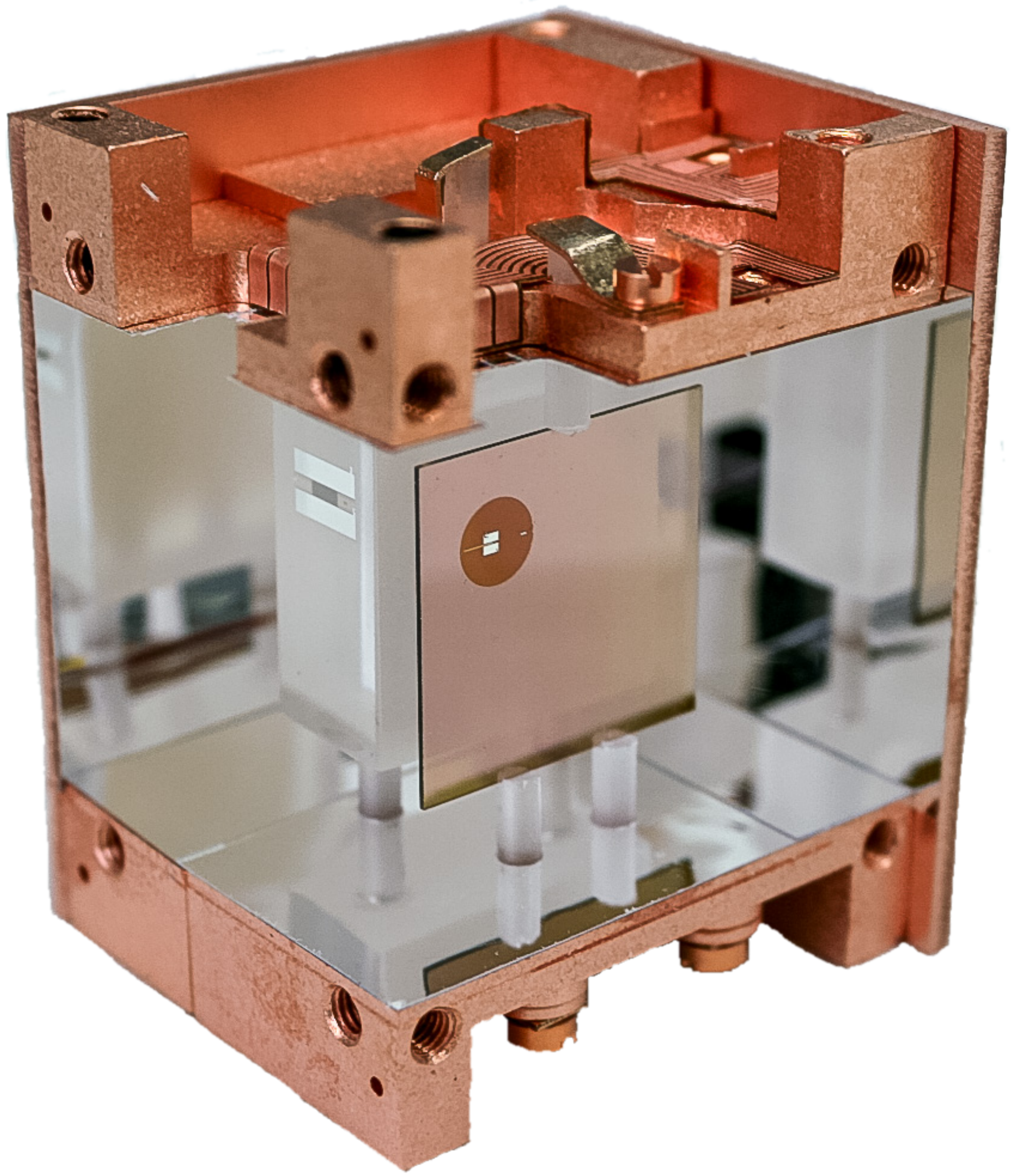
$$R(T) = R_0 e^{\sqrt{T_0/T}}$$

C: absorber capacity
ΔT: temperature variation
ΔE: energy deposition
G: thermal conductance
t: signal decay time

- low heat capacity @ T_{work}
- excellent energy resolution (~1 ‰ FWHM)
  - huge number of energy carriers (phonons)
- equal detector response for different particles
- slowness (suitable for rare event searches)

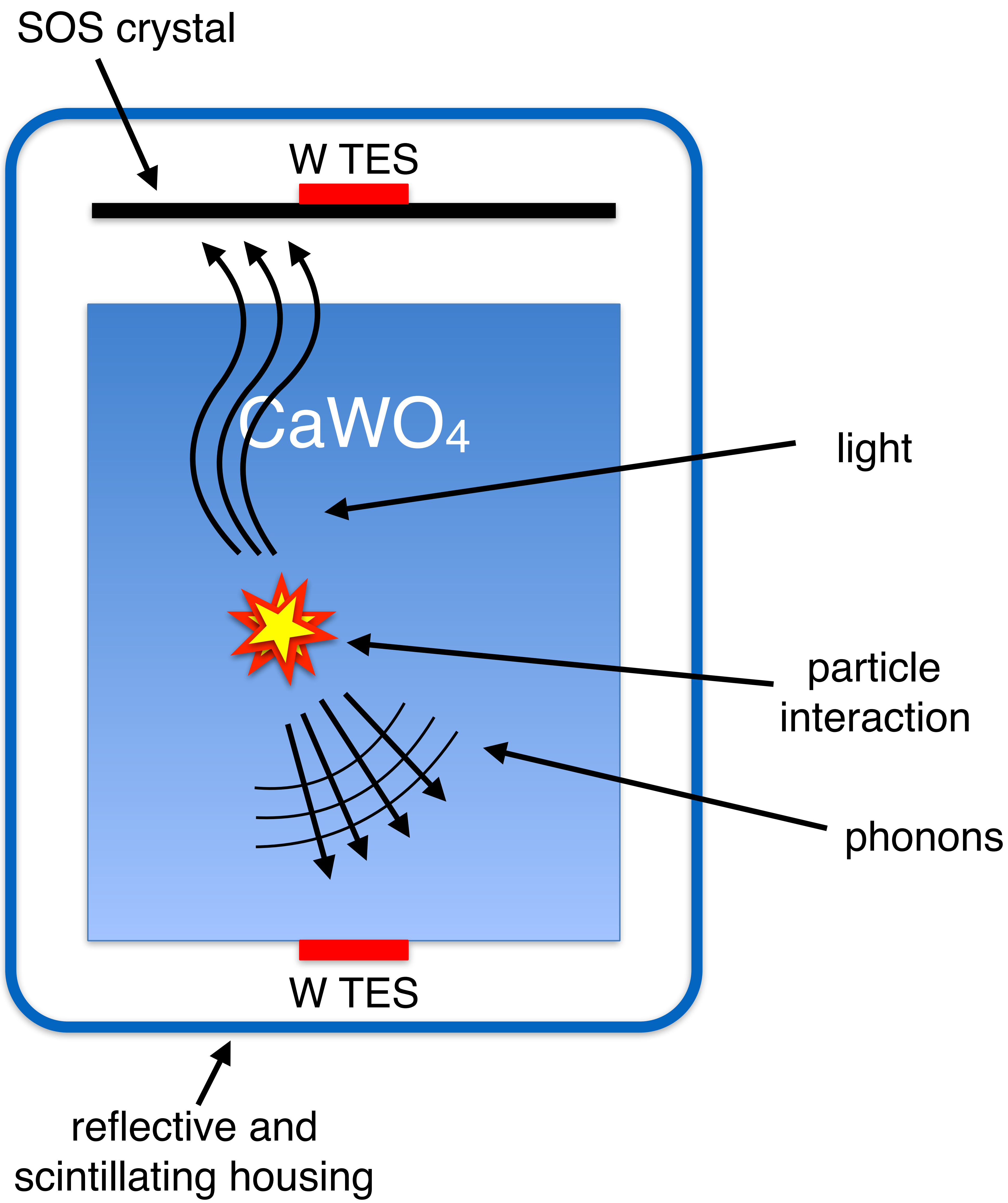
Composite Detectors





Simultaneous signals
from the transition edge sensors (TESs)

Composite Detectors



Phonon signal (≳90 %)

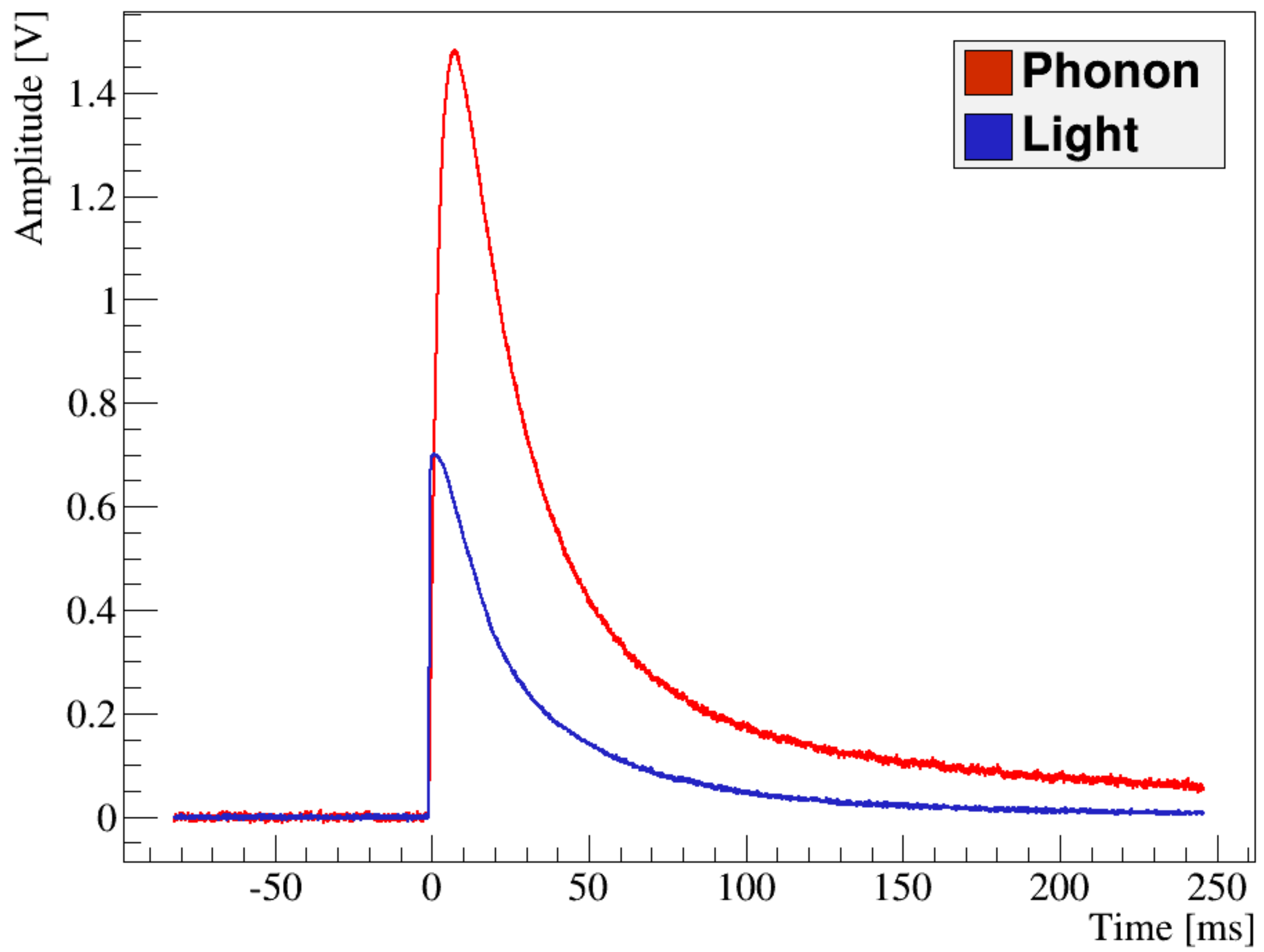
(almost) independent of particle type

precise measurement of the deposited energy

Scintillation light (few %)

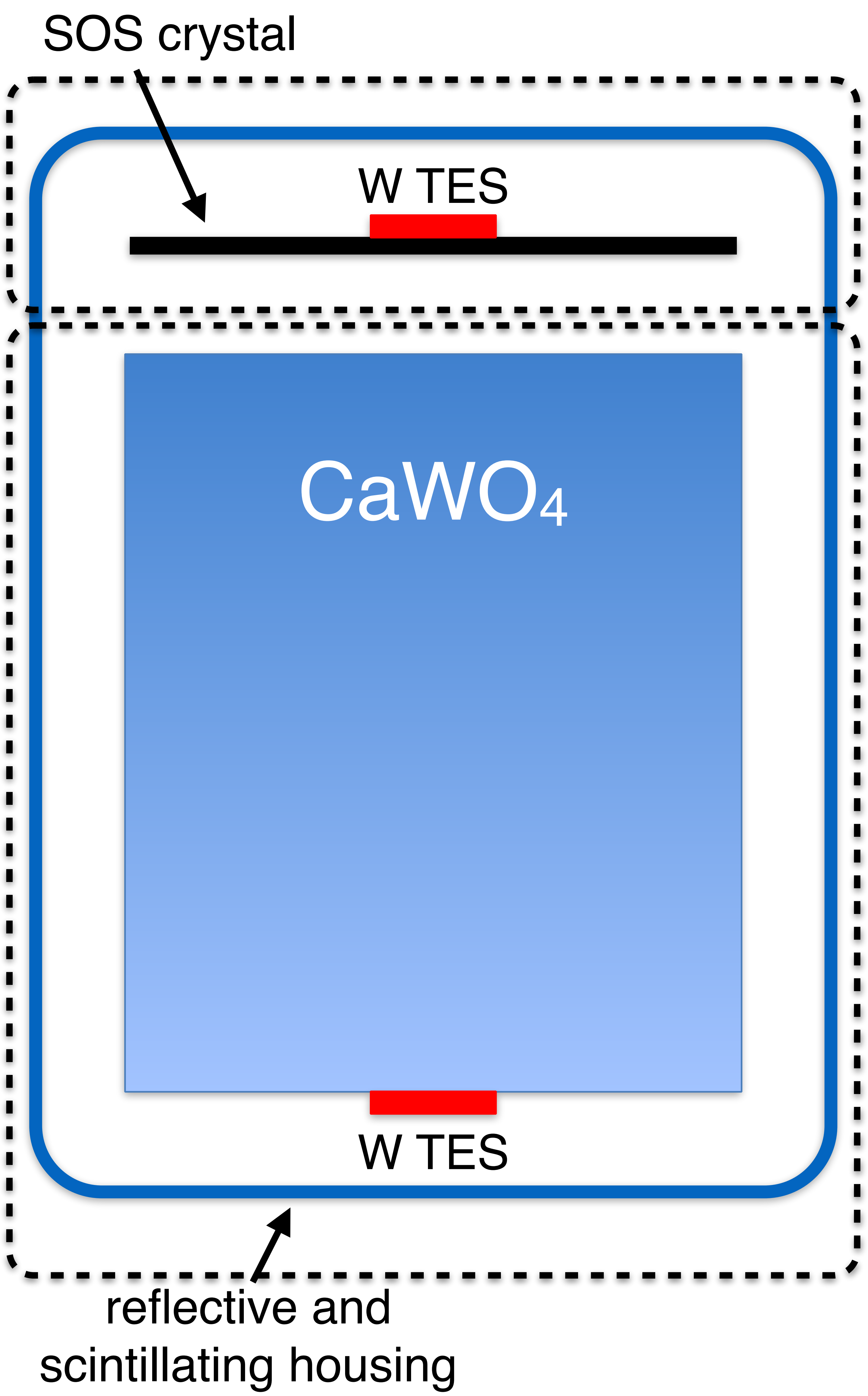
particle-type dependent

→ LIGHT QUENCHING



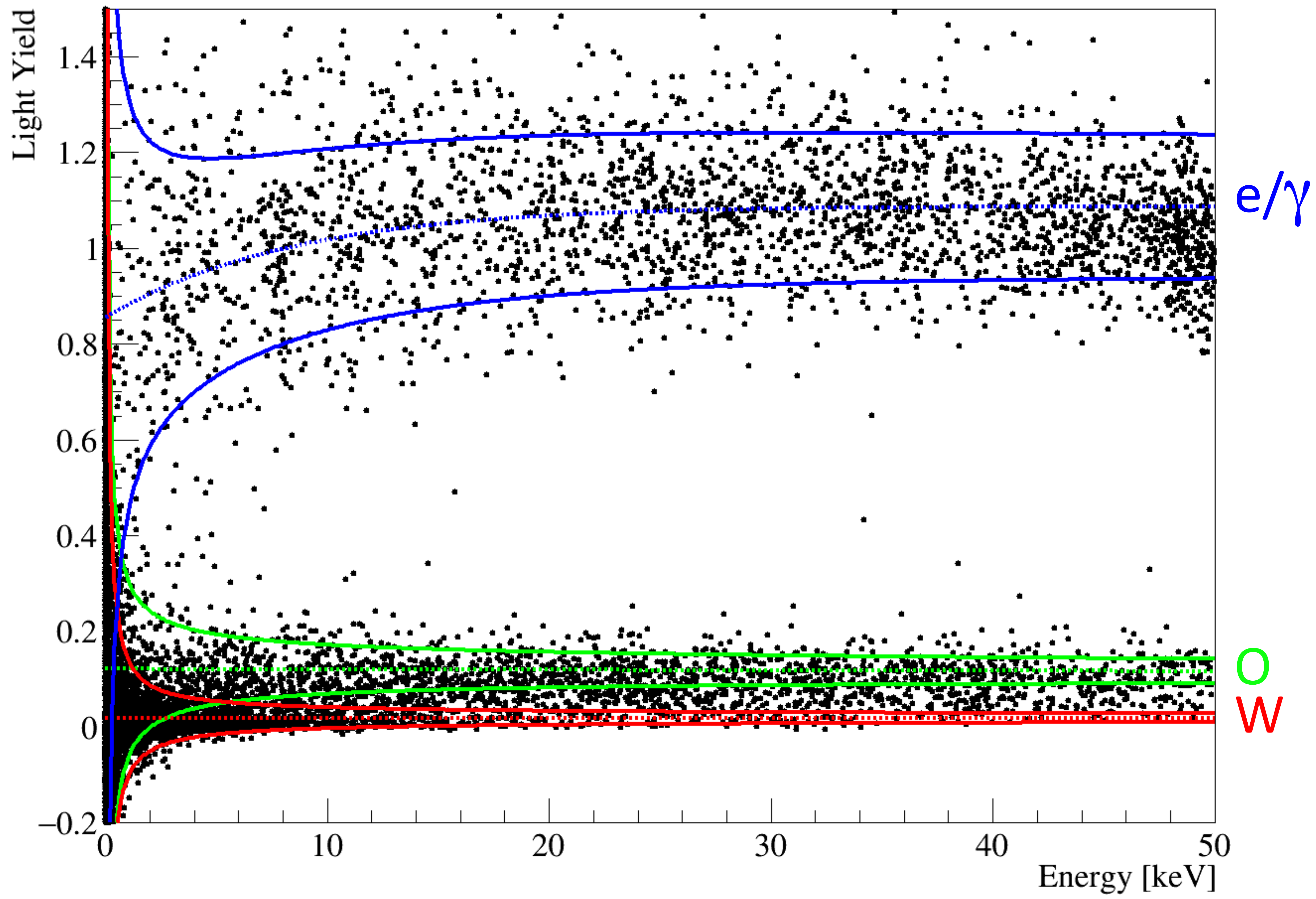
Composite Detectors

light yield = $\frac{\text{energy detected in light channel}}{\text{energy detected in the phonon channel}}$



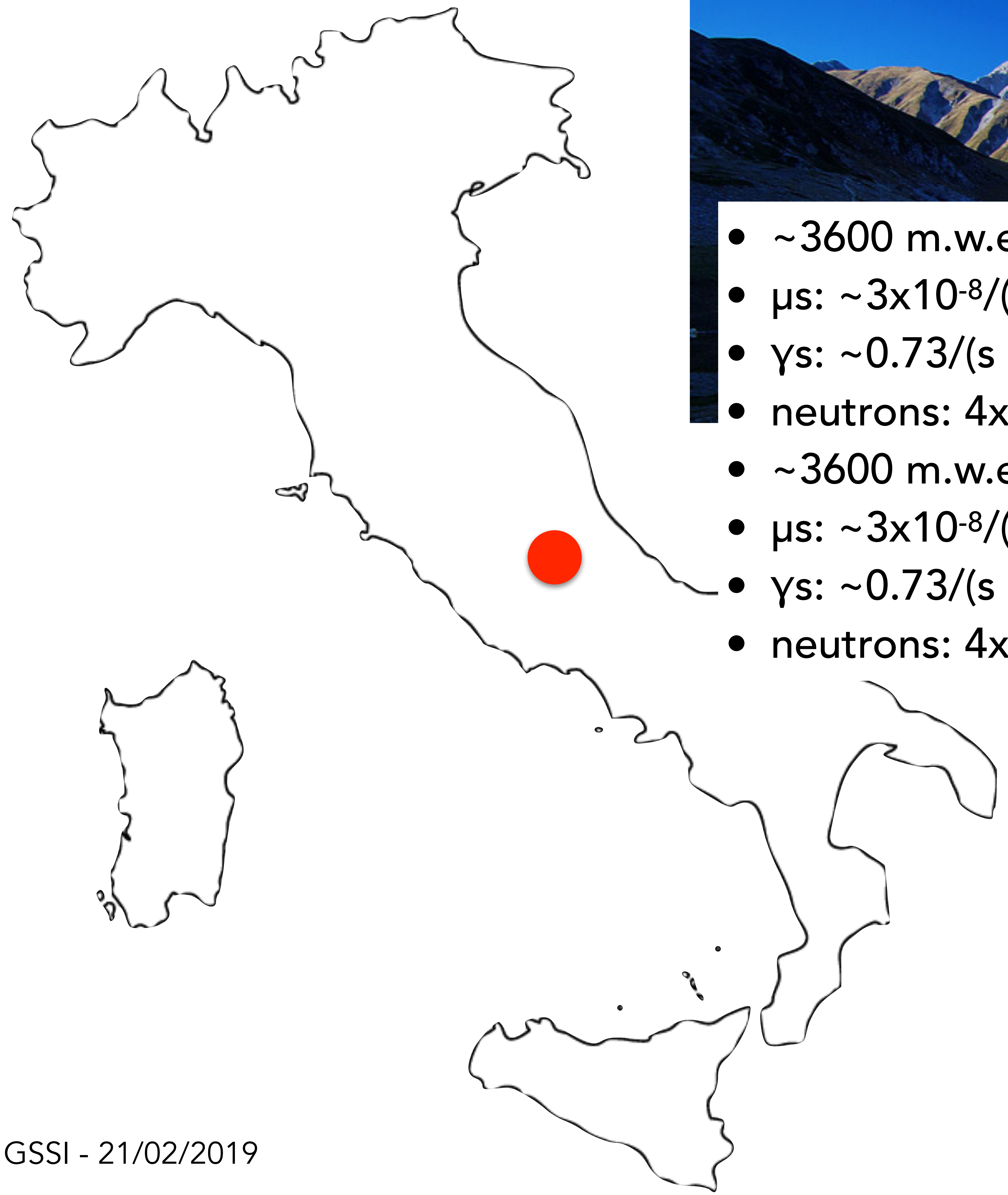
Scintillating light:
particle discrimination

Phonon signal:
deposited energy



Radiation identification/discrimination crucial for specific physic processes

LNGS



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

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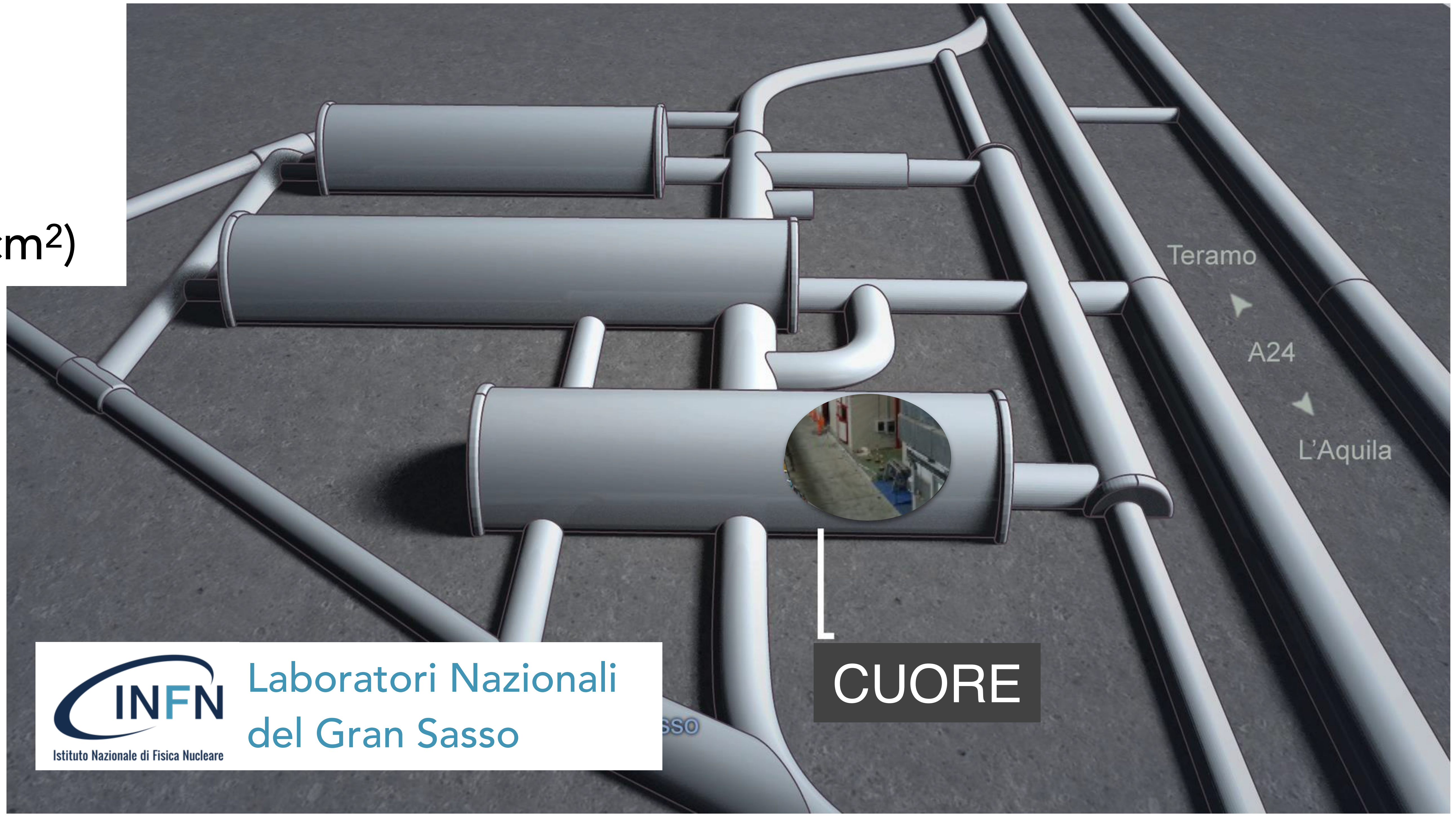


Majorana neutrinos

The Majorana neutrino

E. Majorana (1937):
theory of massive and real fermions

$$\chi = C\bar{\chi}^t \quad \left(\bar{\chi} \ \equiv \ \chi^\dagger\gamma_0, \quad C\gamma_0^t = 1\right)$$

$$\mathcal{L}_{Majorana} = \frac{1}{2}\bar{\chi}(i\partial - m)\chi$$

$$\chi(x) = \sum_{\mathbf{p},\lambda}(a(\mathbf{p}\lambda)\ \psi(x;\mathbf{p}\lambda) + a^*(\mathbf{p}\lambda)\ \psi^*(x;\mathbf{p}\lambda))$$

→ for any value of **p**, there are 2 helicity states: |**p**↑⟩ and |**p**↓⟩

- L will be violated by the presence of Majorana mass
- the Majorana hypothesis can be implemented in the SM

$$\chi \equiv \psi_L + C\bar{\psi}_L^t$$

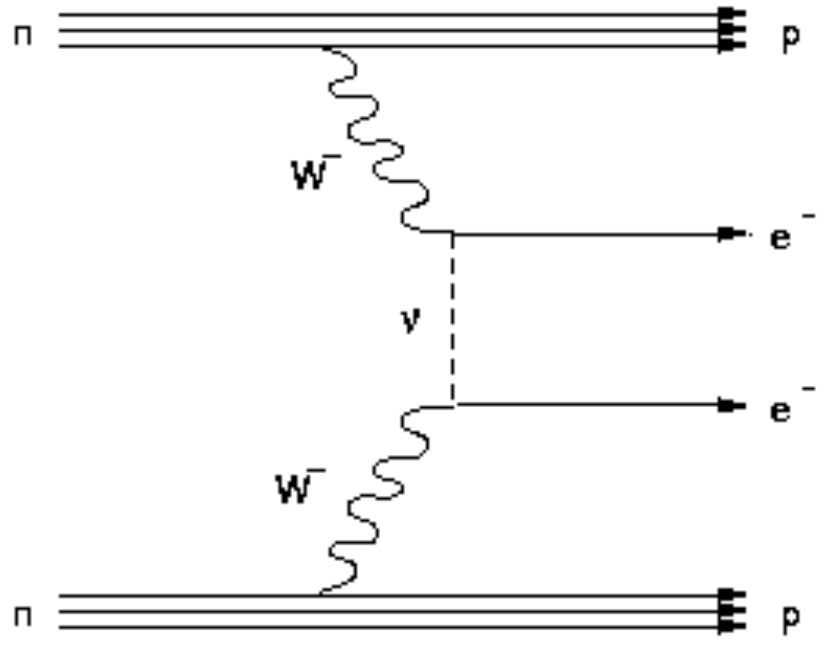
to obtain the *usual* SM field $\psi_L \equiv P_L\chi$ $\left(P_L \equiv \frac{1-\gamma_5}{2}\right)$

Double Beta Decay

0ν-DBD (W.H.Furry, 1939) is a lepton number violating (ΔL=2), not allowed by the Standard Model. The 0νDBD can occur only if two requirements are satisfied: i) the neutrino has to be a Majorana particle, and ii) the neutrino has to have a non-vanishing mass.

This is the crucial process for neutrino physics since can solve the puzzle of the Majorana nature of the neutrino

0ν-DBD: $(A,Z) \rightarrow (A,Z+2) + 2e^-$ ⟶ implies physics beyond SM

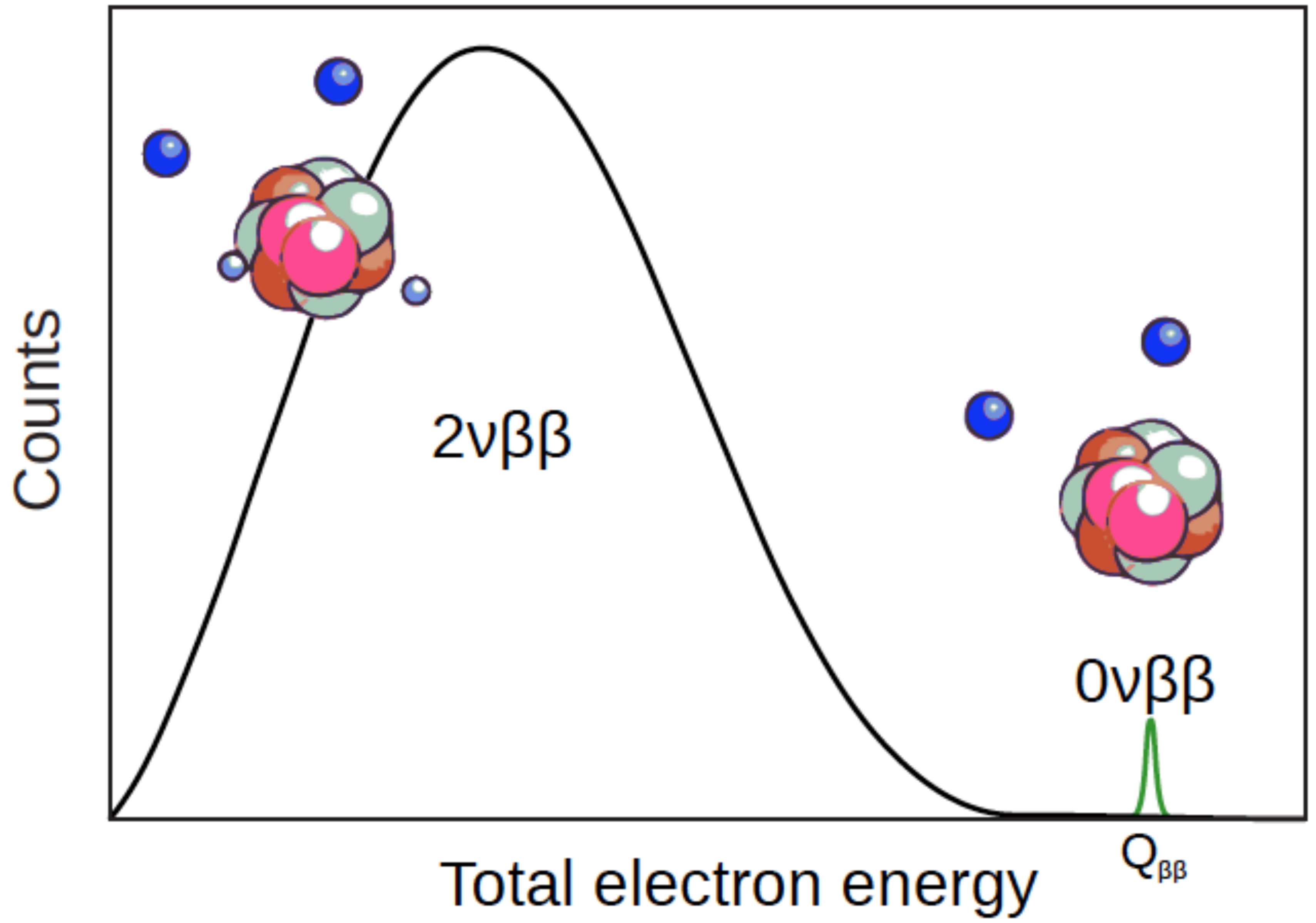


- 0ν-DBD is an extremely rare
- process: $\tau^{0\nu} > 10^{24}$-10^{25} y
- β radiation

If 0ν-DBD is observed: neutrino is a Majorana particle and m_ν is measured

Schetcher, Valle Phys. Rev. D25 2951 1982

For $2e^-$ sum energy, expected signature is a peak with $E \equiv Q_{\beta\beta}$



Majorana Mass

Observation of 0vDBD can give informations on the absolute mass scale:

$$[T^{0\nu}_{1/2}]^{-1} = G_{0\nu} g_A^4 |M_{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$$

0νββ decay rate

Phase space factor — Atomic physic

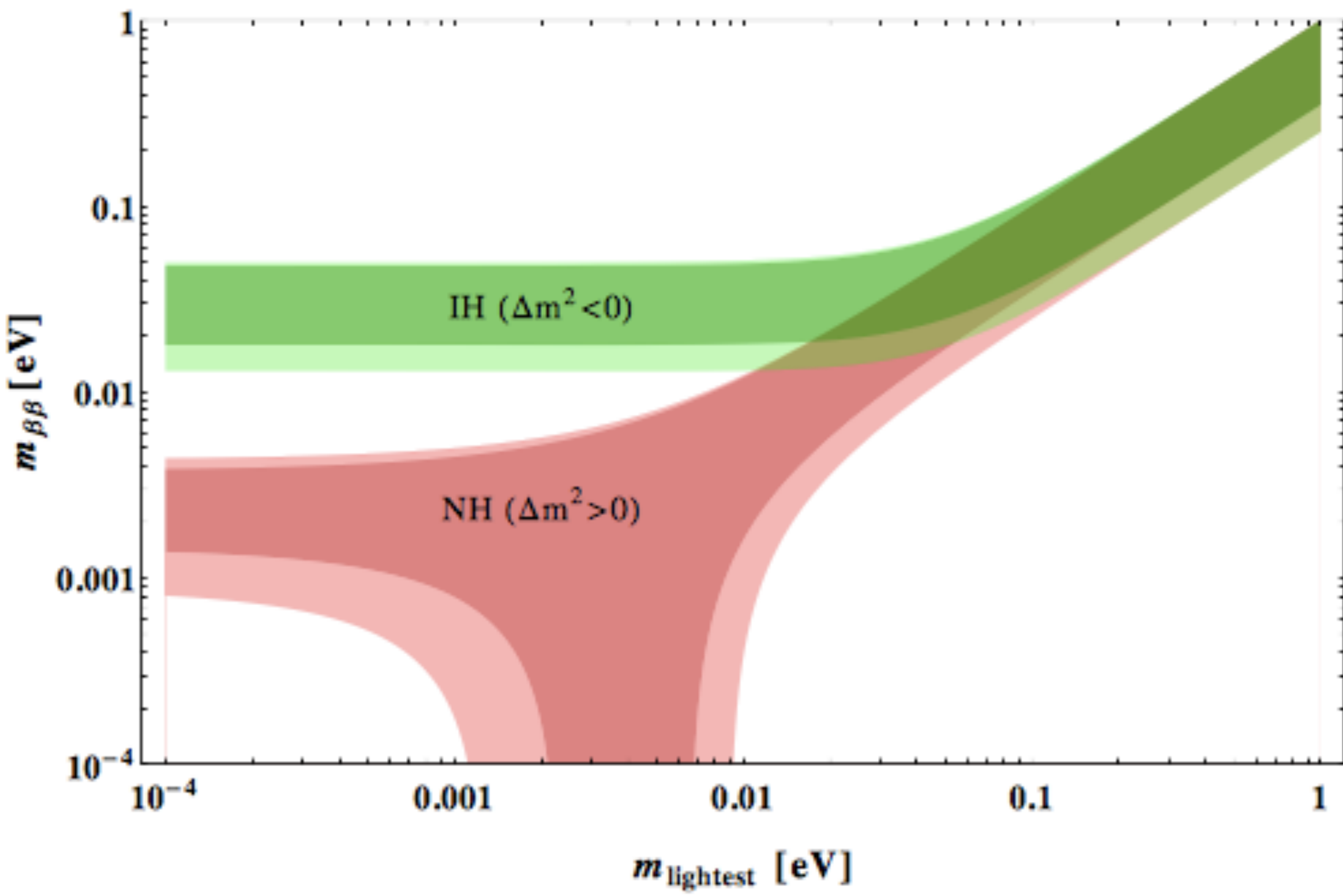
Axial vector coupling; Nuclear matrix element — Nuclear physic

Effective Majorana mass — Particle physic

where

$$\langle m_{\beta\beta} \rangle = | \, | U_{e1} |^2 m_1 + e^{i\alpha_1} | U_{e2} |^2 m_2 + e^{i\alpha_2} | U_{e3} |^2 m_3 \, |$$

$$\langle m_{\beta\beta} \rangle = F(m_1, \Delta m_{ij}{}^2, \theta_{ij}, \alpha_i)$$



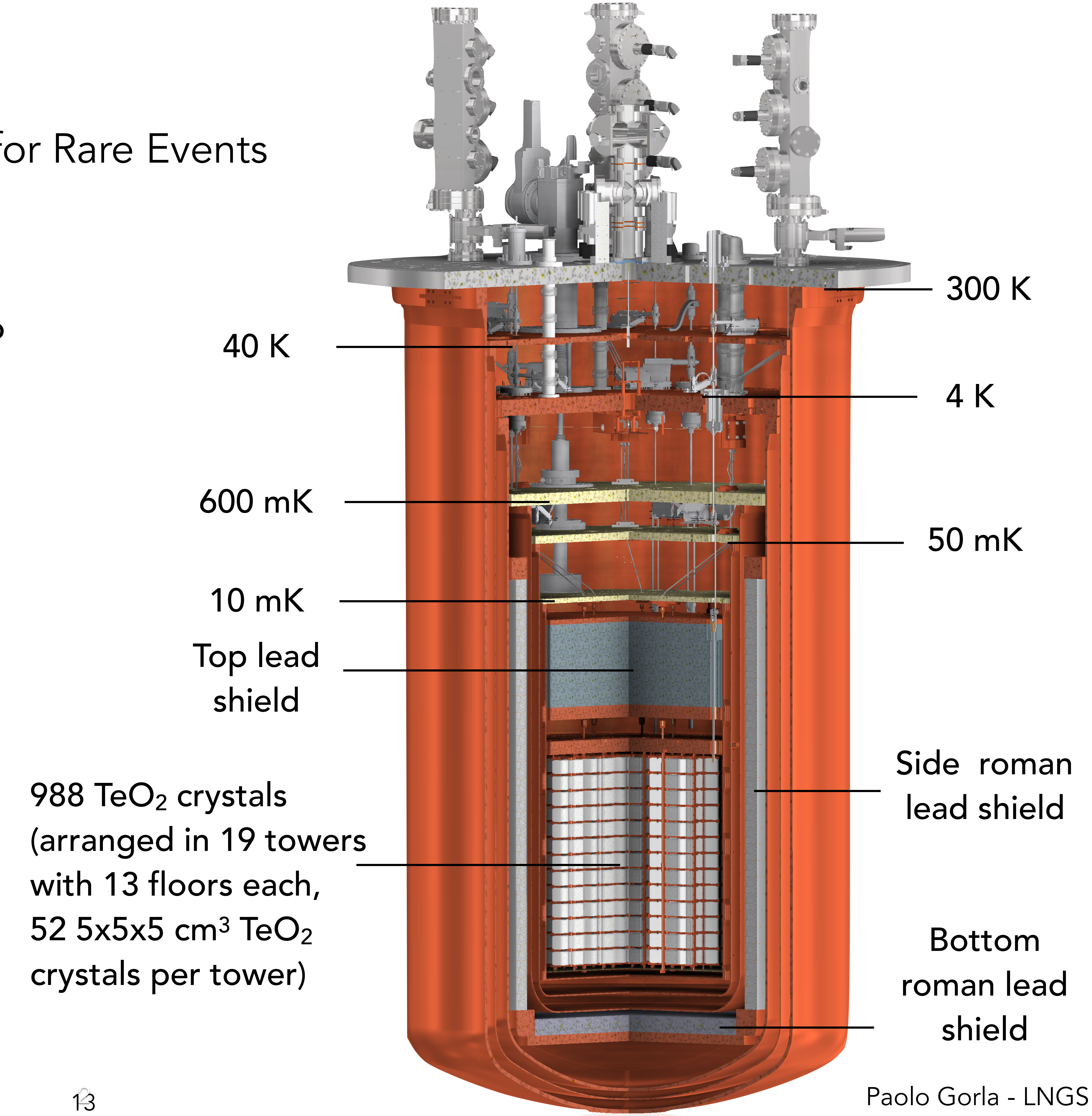
The CUORE collaboration

CUORE

CUORE Cryogenic Underground Observatory for Rare Events

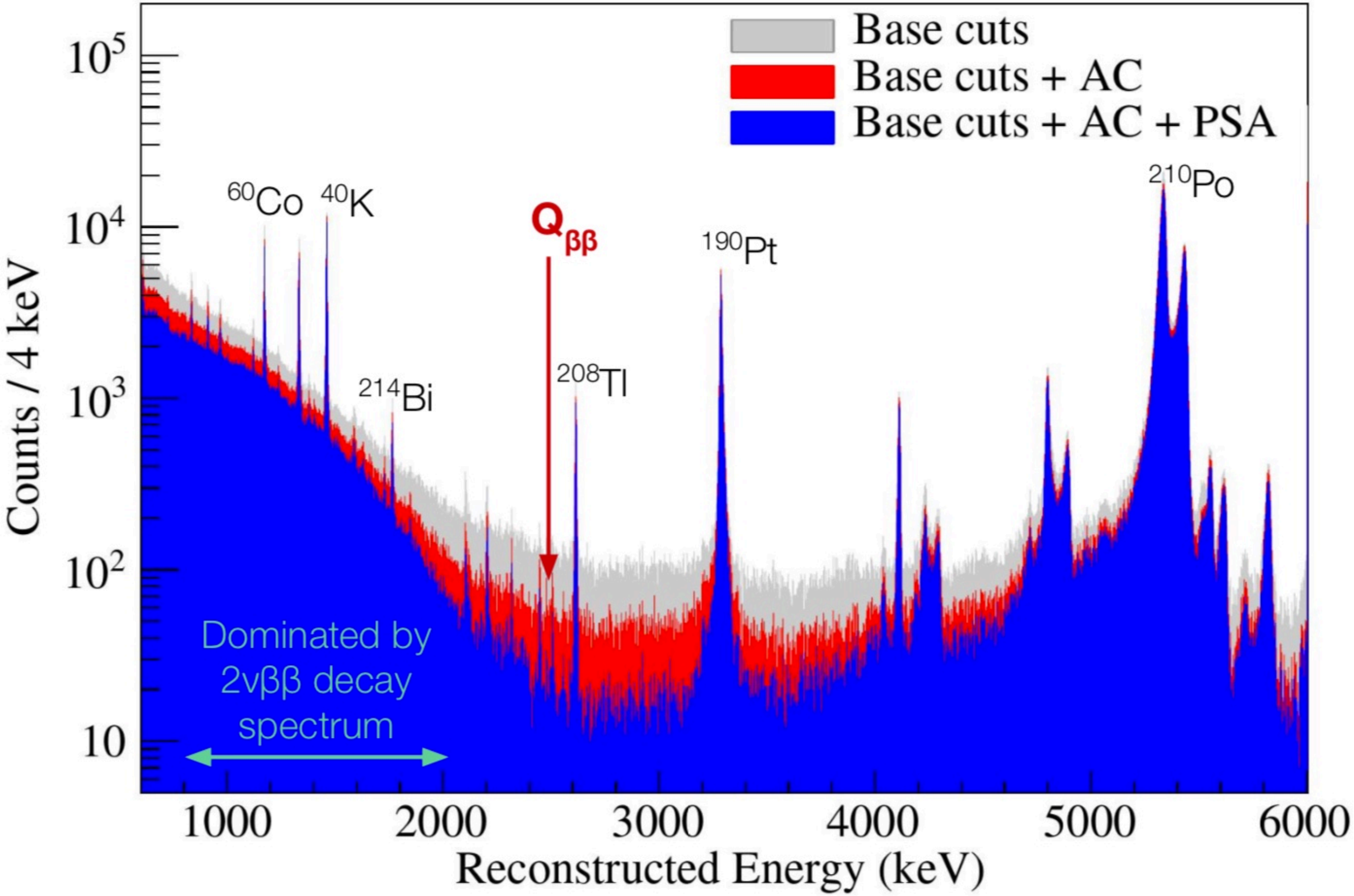
Main goal: detect $0\nu\beta\beta$ in ^{130}Te, in cryogenic TeO_2 bolometers, to prove the Majorana nature of the neutrino

- The CUORE detector is hosted in a cryogen-free cryostat (mass < 4K: ~15 tons of Pb, Cu and TeO_2)
- Operating temperature 11 mK (base T~7 mK)
- Designed to guarantee extremely low radioactivity and low vibrations environment
  - Energy resolution: goal of 5 keV at $Q_{\beta\beta}$
  - Low background: goal of 10^{-2} cts/(keV·kg·yr) at $Q_{\beta\beta}$




The CUORE
Detector

CUORE physics spectrum



0νββ search results

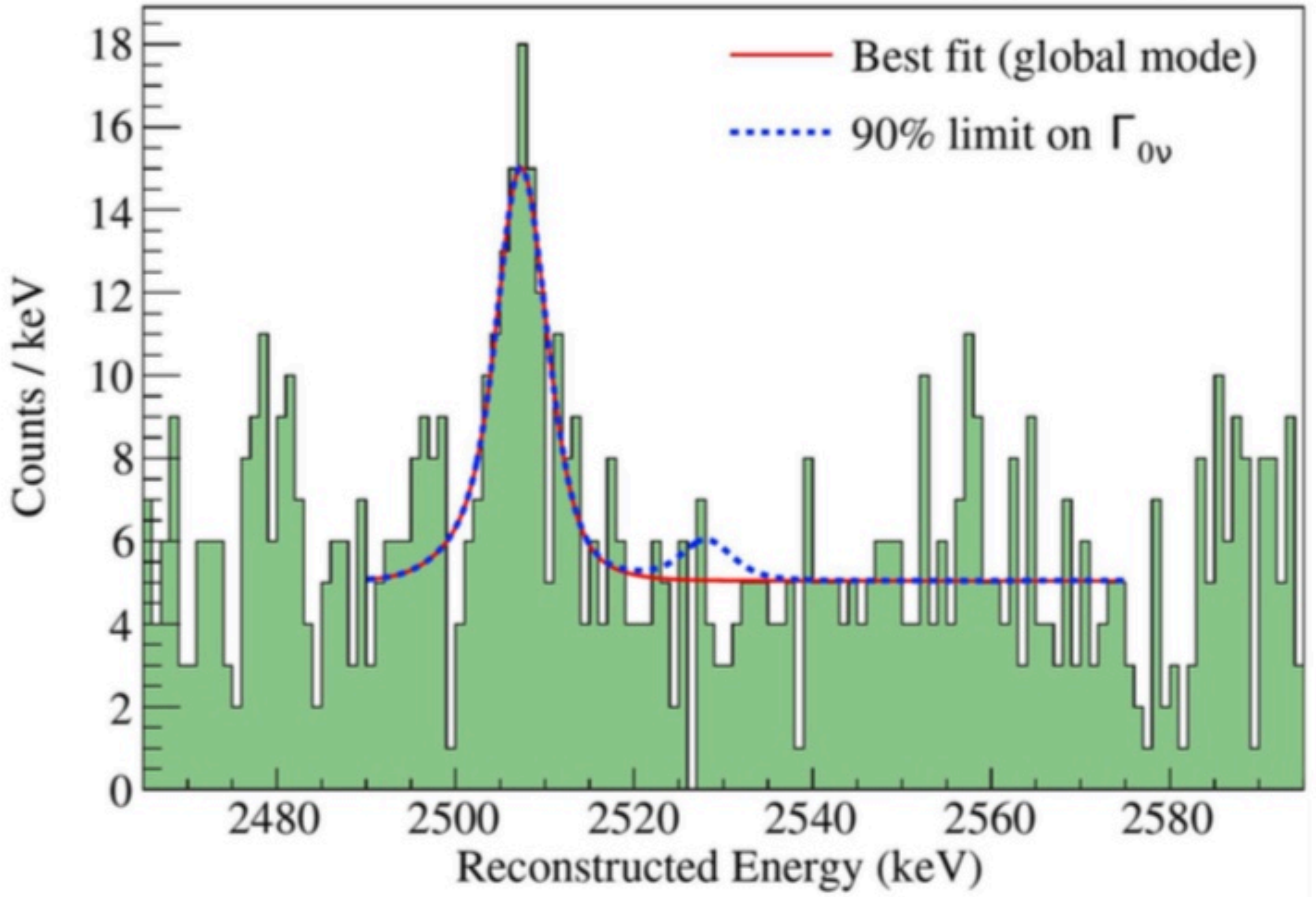
- Background index (BI) is a dataset dependent parameter
- Fit performed using BAT
- From bkg-only fit: **BI = (1.38±0.07) · 10^{-2} counts/(keV·kg·yr)**

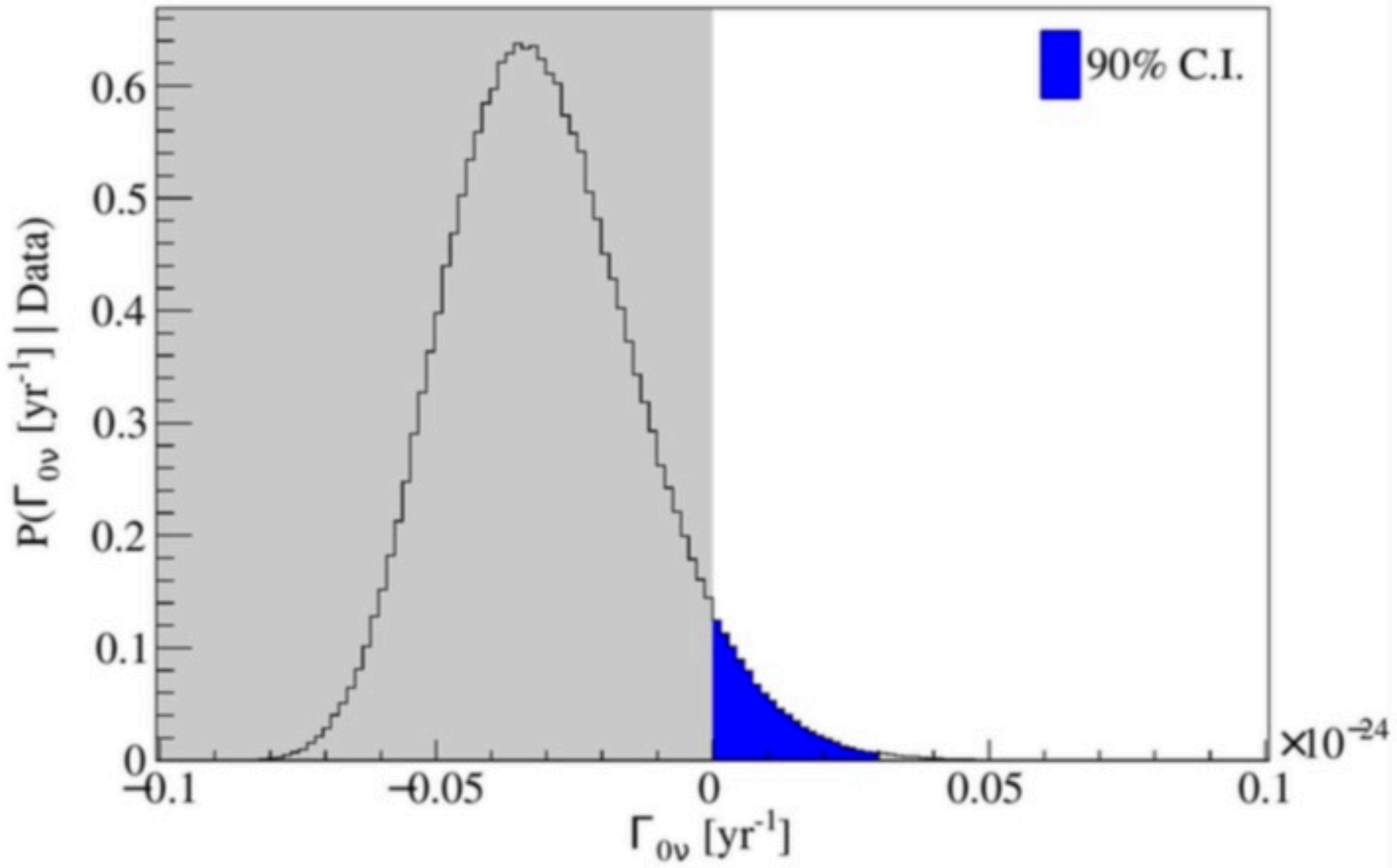
Sensitivity

- Generate toy-MC data using bkg-only model, fit them with the signal+bkg model, extract 90% c.i. Limit on $T_{1/2}^{0\nu}$
- Median exclusion sensitivity: $\mathbf{T_{1/2}^{0\nu} = 1.7 \cdot 10^{25}}$ **yr**

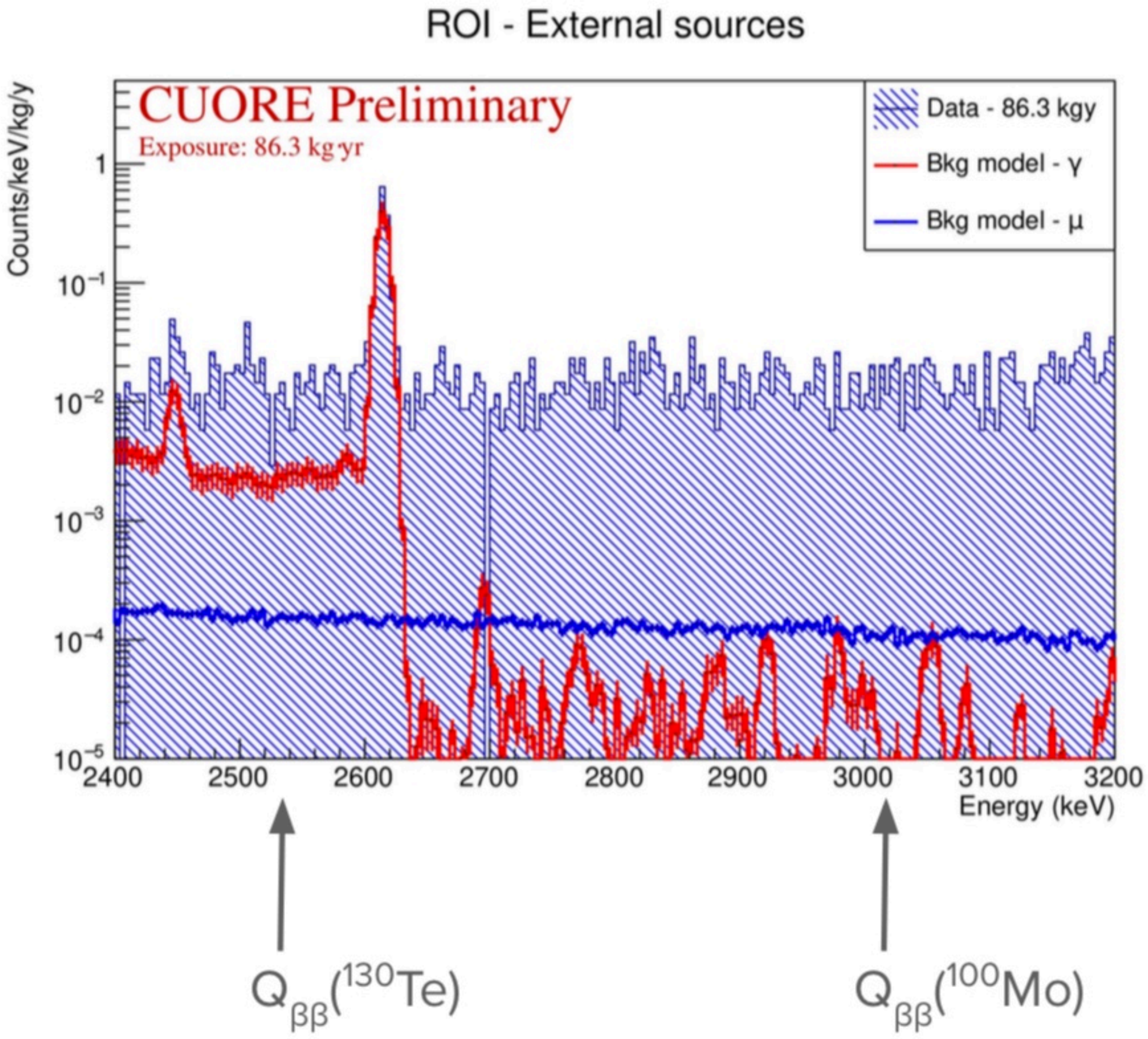
Results

- Best fit at $\Gamma_{0\nu} = 0$ yr^{-1}
- $\mathbf{T_{1/2}^{0\nu} > 3.2 \cdot 10^{25}}$ **yr @ 90% c.i.**
  ➔ 3% probability of getting a stronger limit
- Systematics affect limit by 0.4%
- Assuming light neutrino exchange: $\mathbf{m_{\beta\beta}}$ **< 75 - 350 meV**
- More infos: arXiv:1912.10966



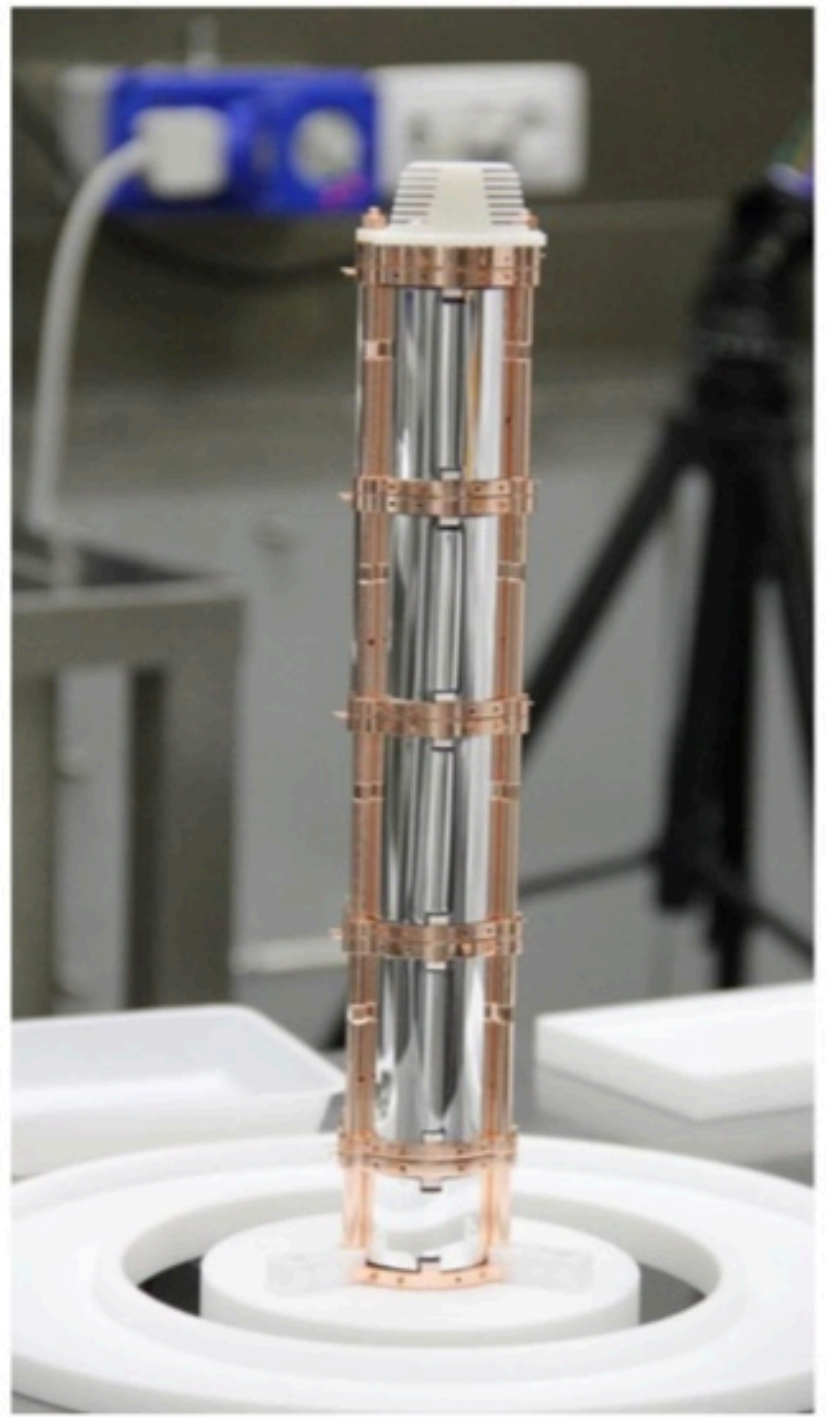


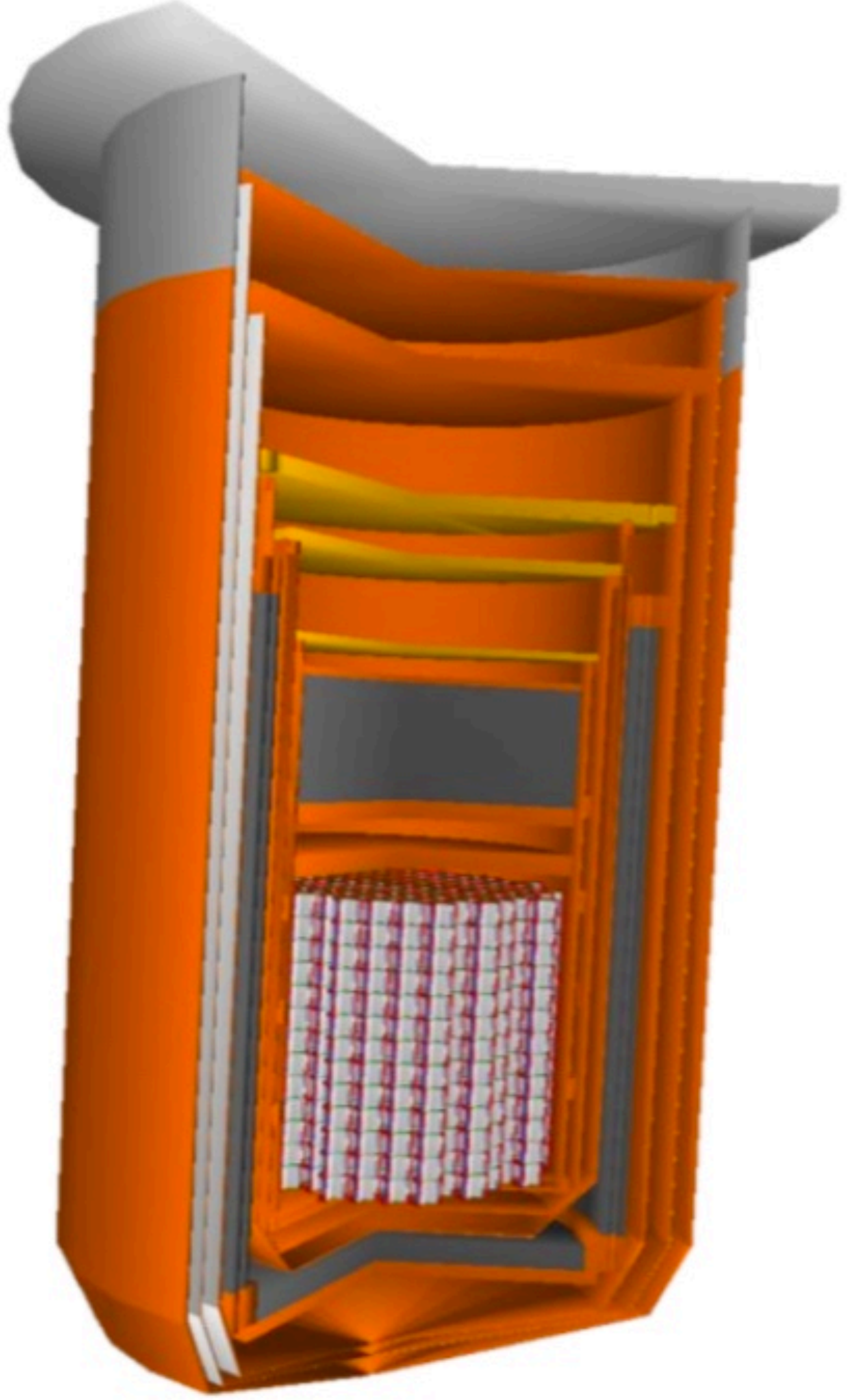
Lessons learned from CUORE

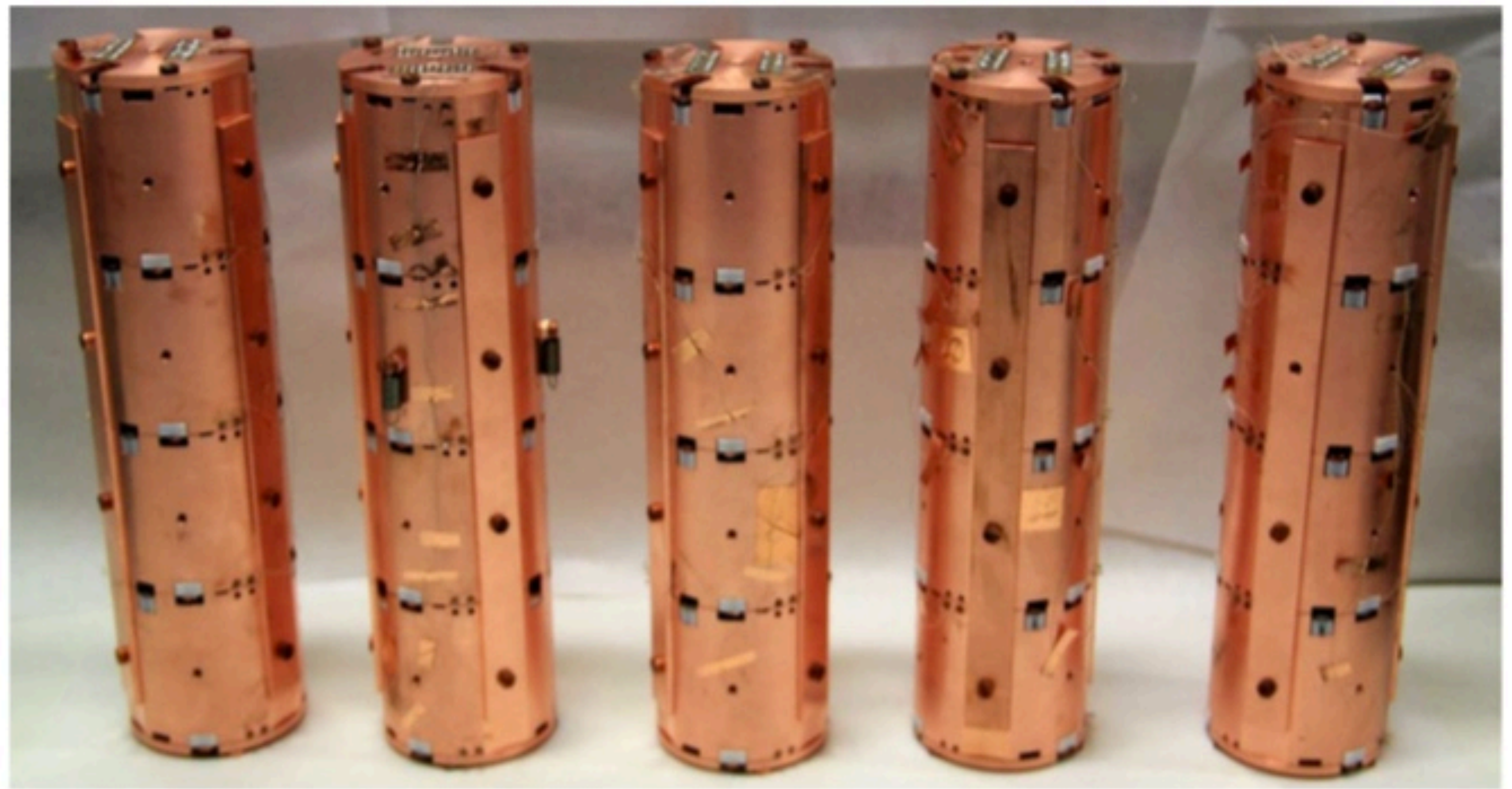


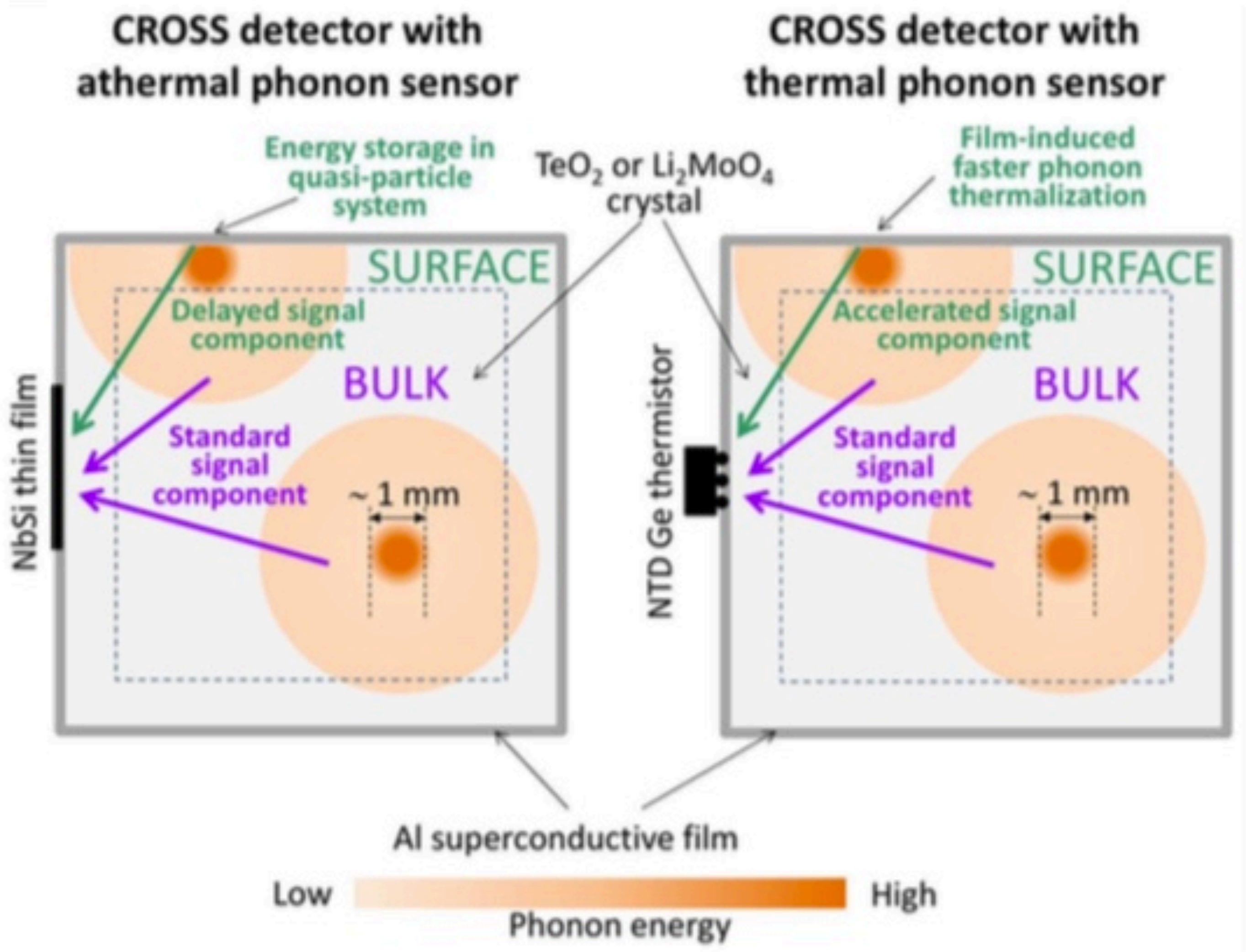
- Most measured background is due to α particles (U/Th contaminations close to TeO_2 crystals)
  ➜ α/β discrimination is required
- A $Q_{\beta\beta}$ > 2.6 MeV would automatically reduce the remaining non-α background by one order of magnitude
- Muons are the dominant contribution
  ➜ active muon veto

CUPID: CUORE Upgrade with Particle Identification



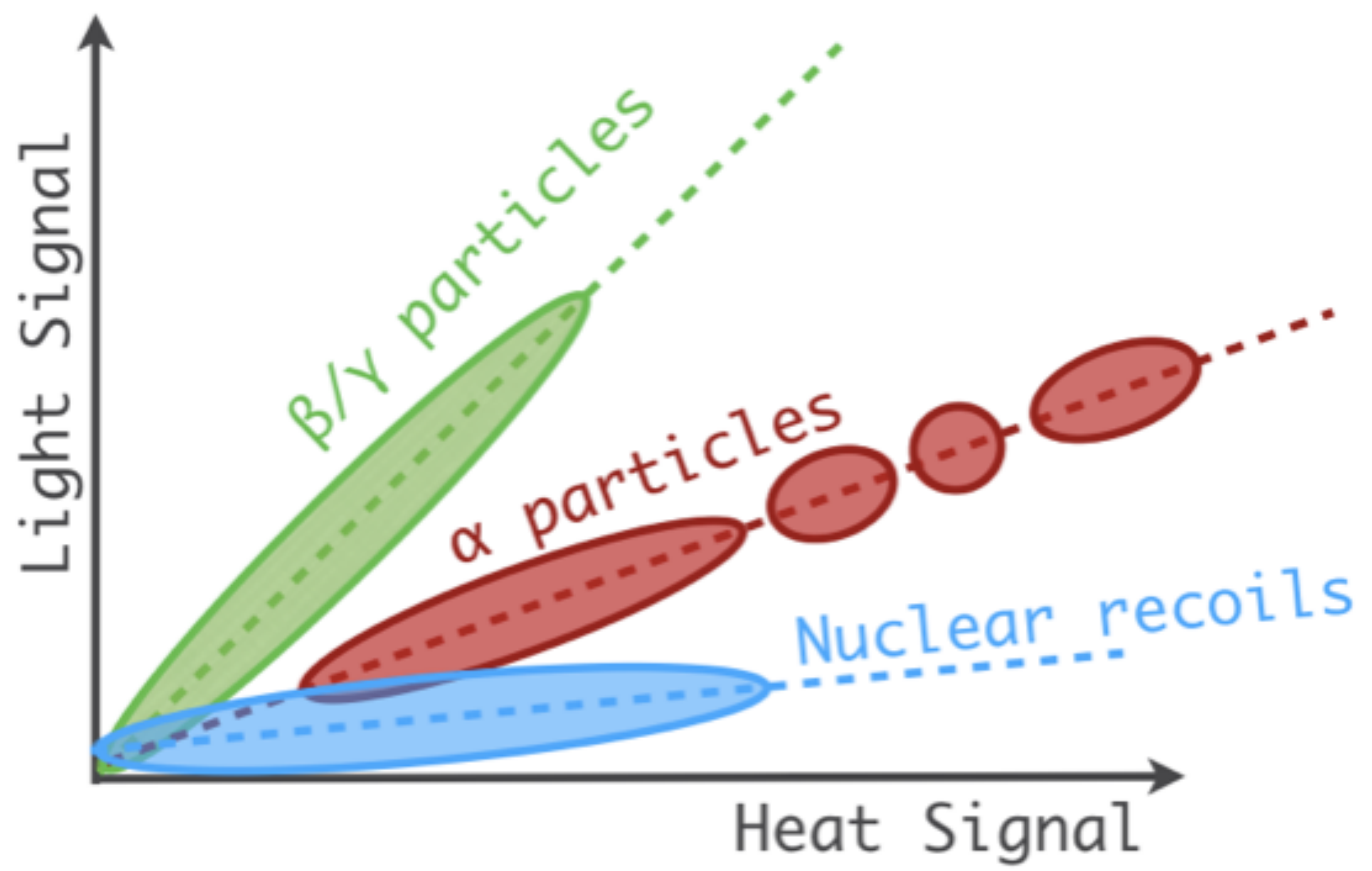


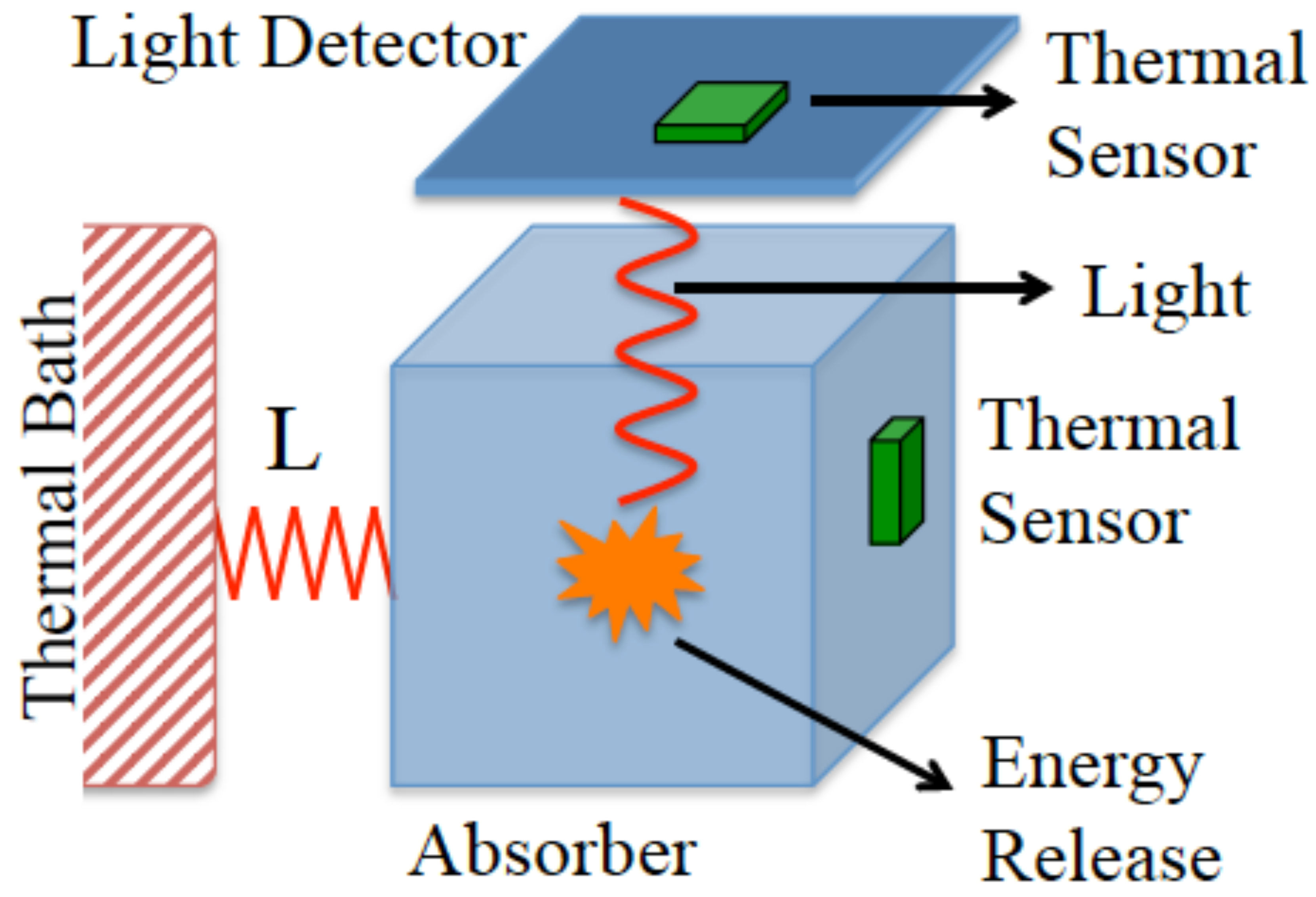




CUPID detector

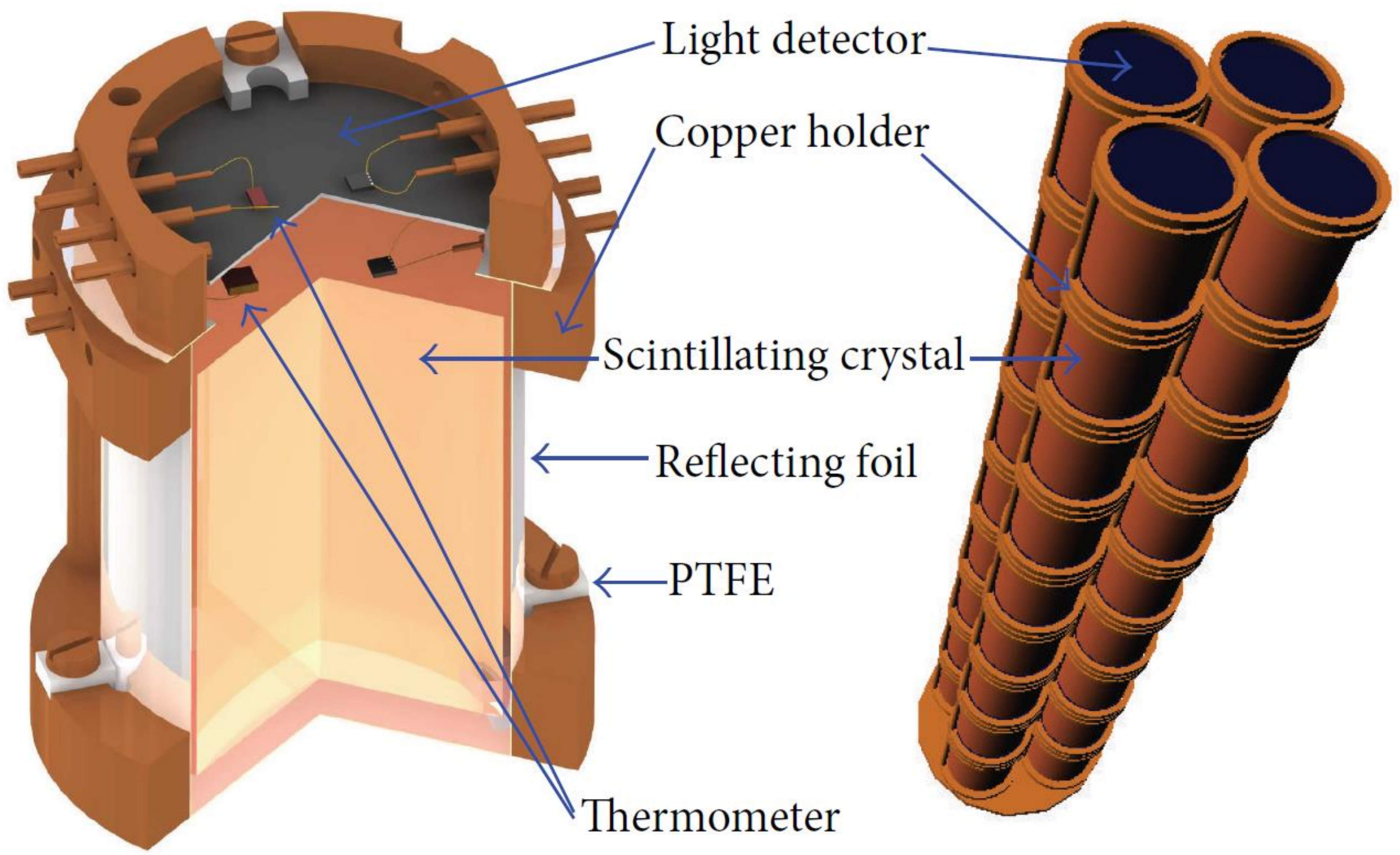
Leverage other energy loss mechanisms to tag particle type





Maturing R&D and demonstrator efforts

- ❑ Enriched $Li_2{}^{100}MoO_4$ scintillating bolometers

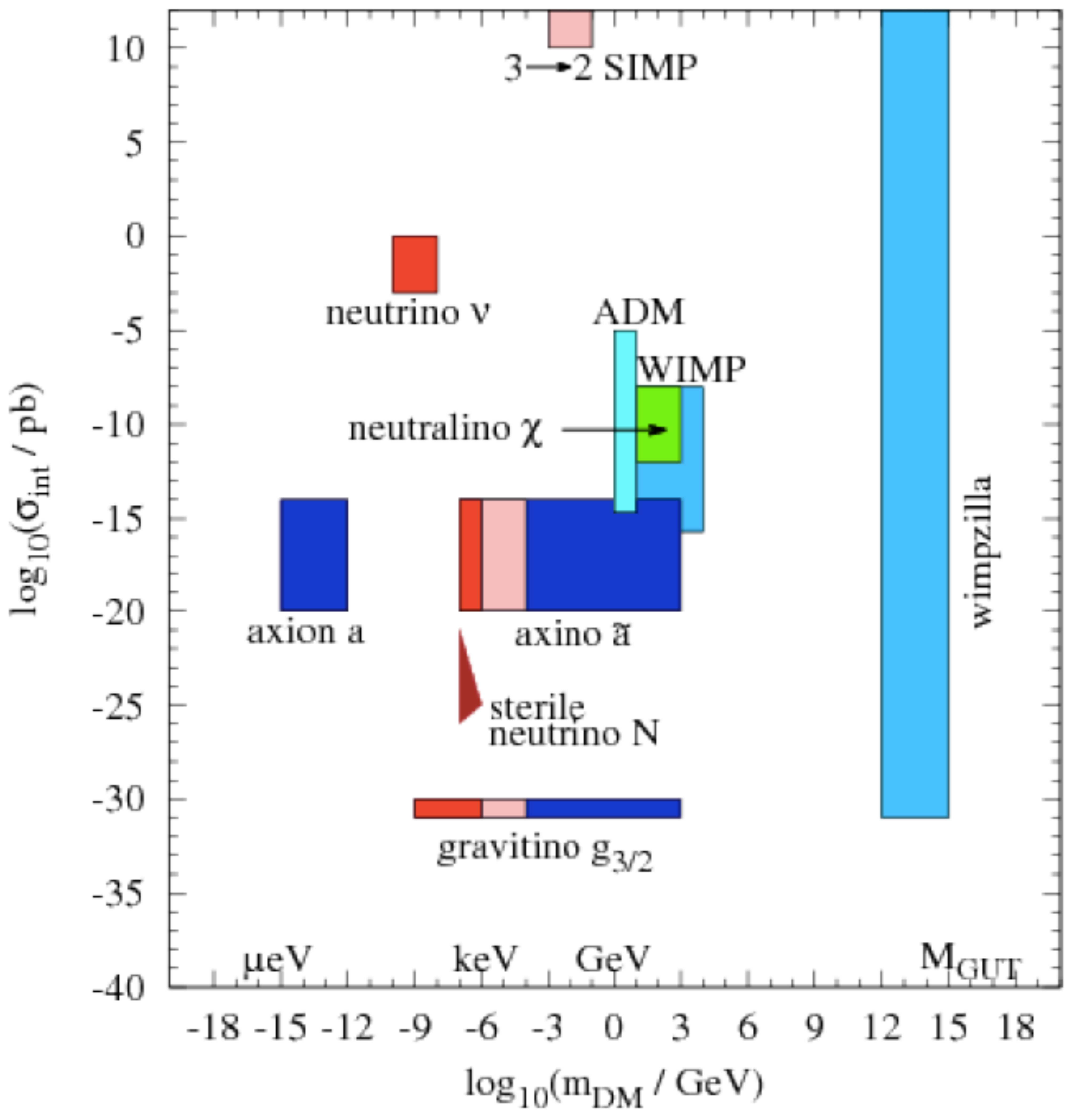


Dark Matter

THE NATURE OF DARK MATTER

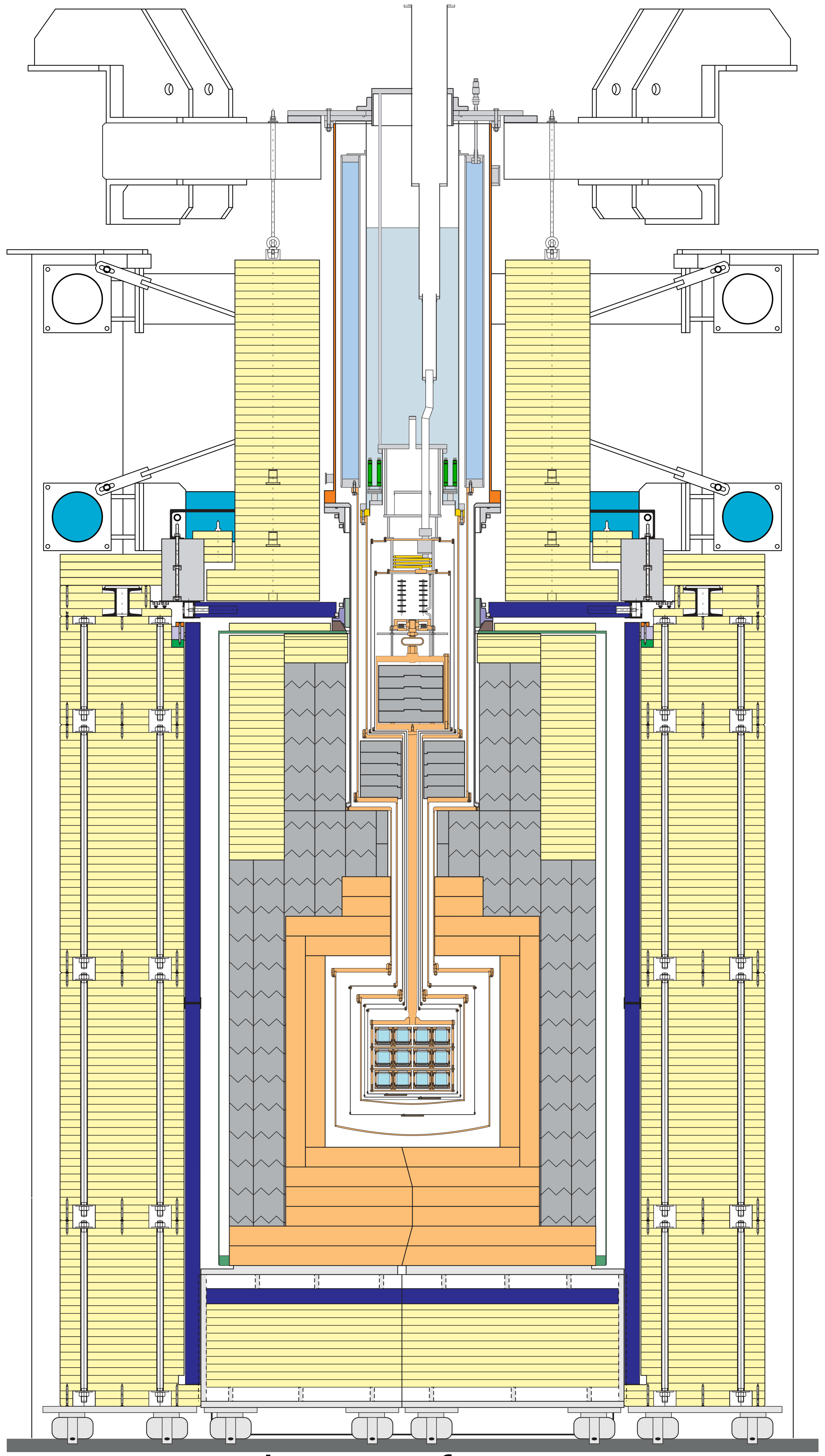
Once there was only the WIMP miracle...

Now WIMP only one out of a range of theoretical motivated dark matter candidates with wide range of mass and cross section



The CRESST Experiment

Cryogenic Rare Event Search with Superconducting Thermometers



Dilution Refrigerator

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

The CRESST Experiment

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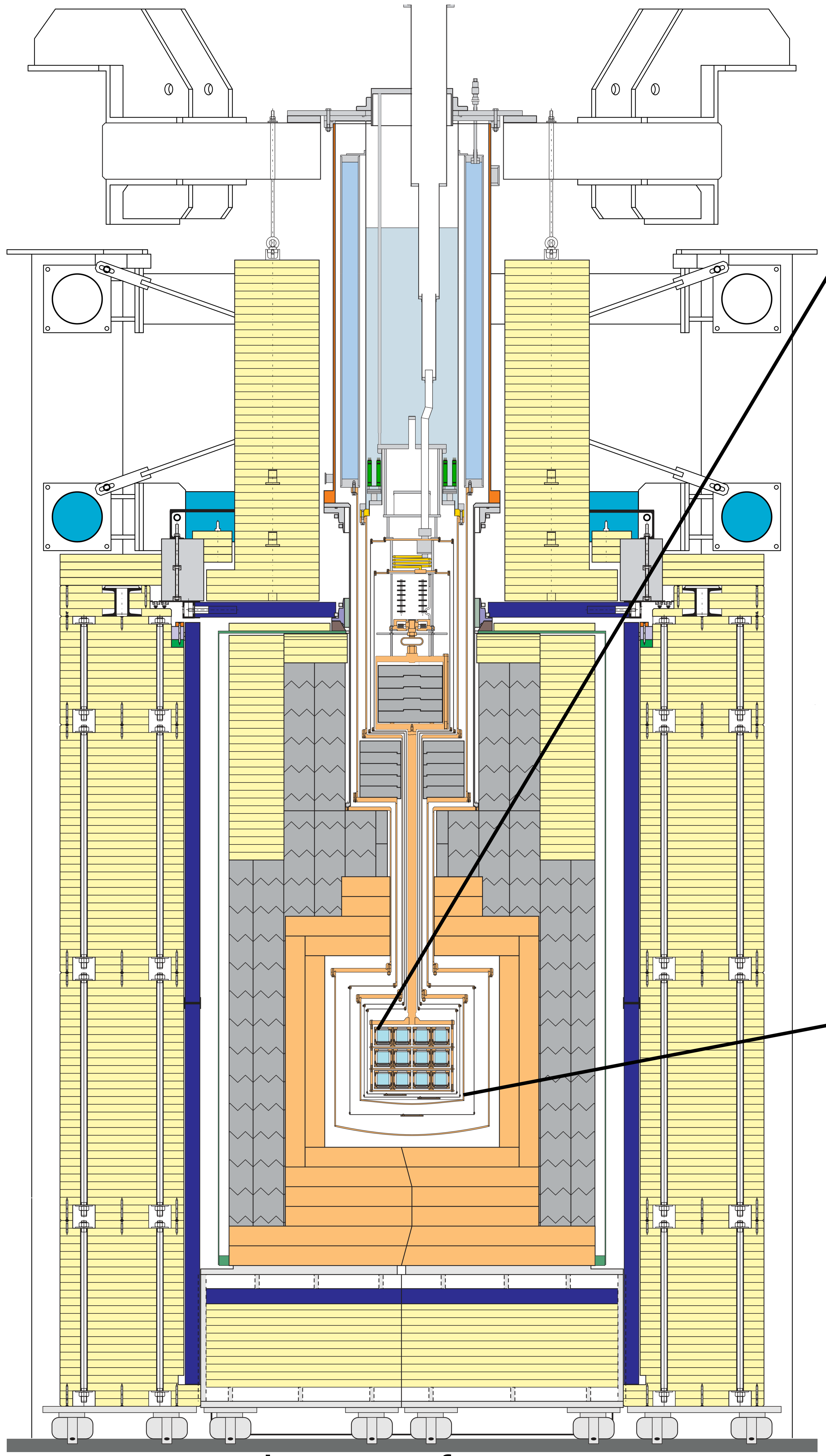
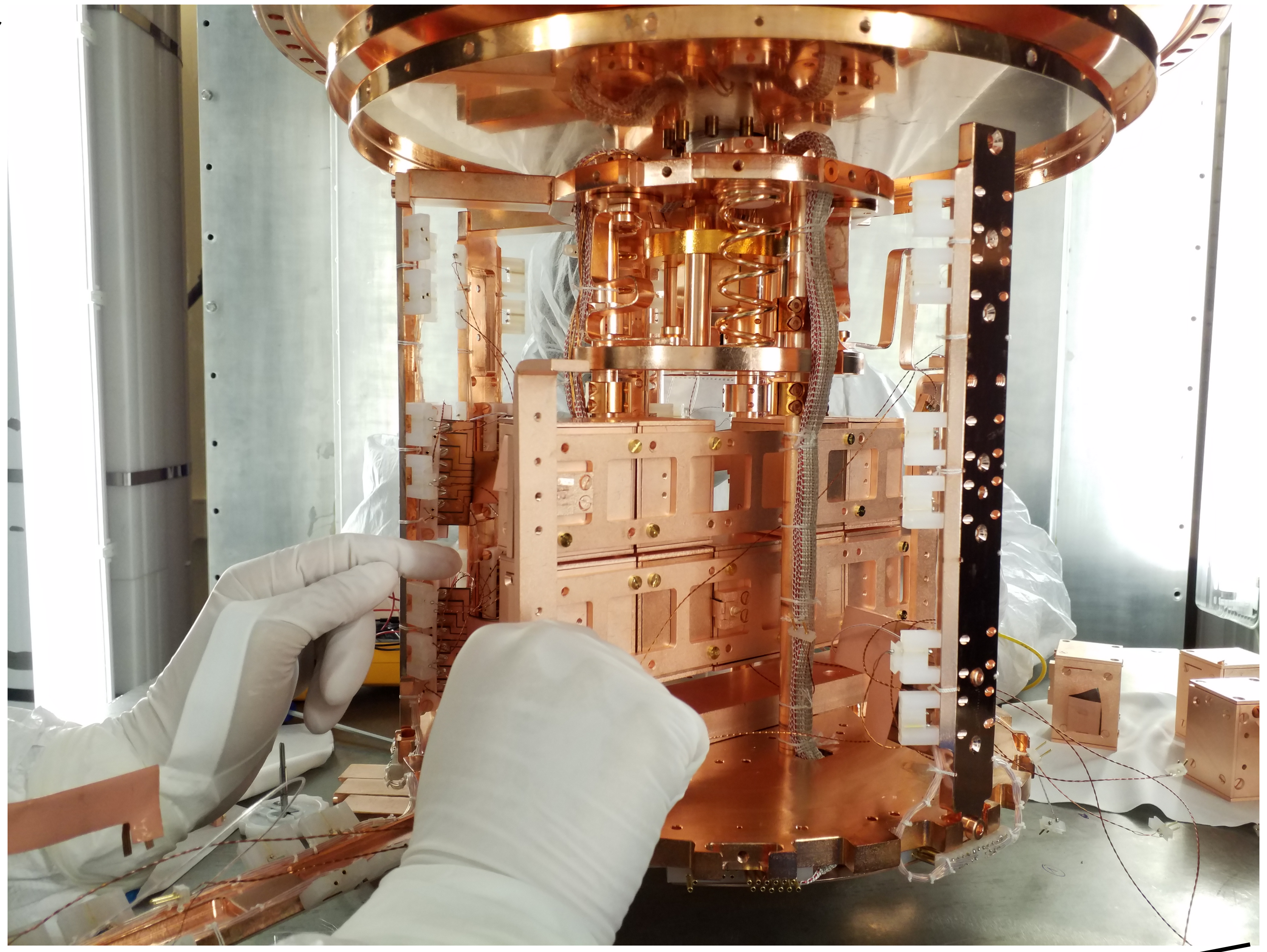


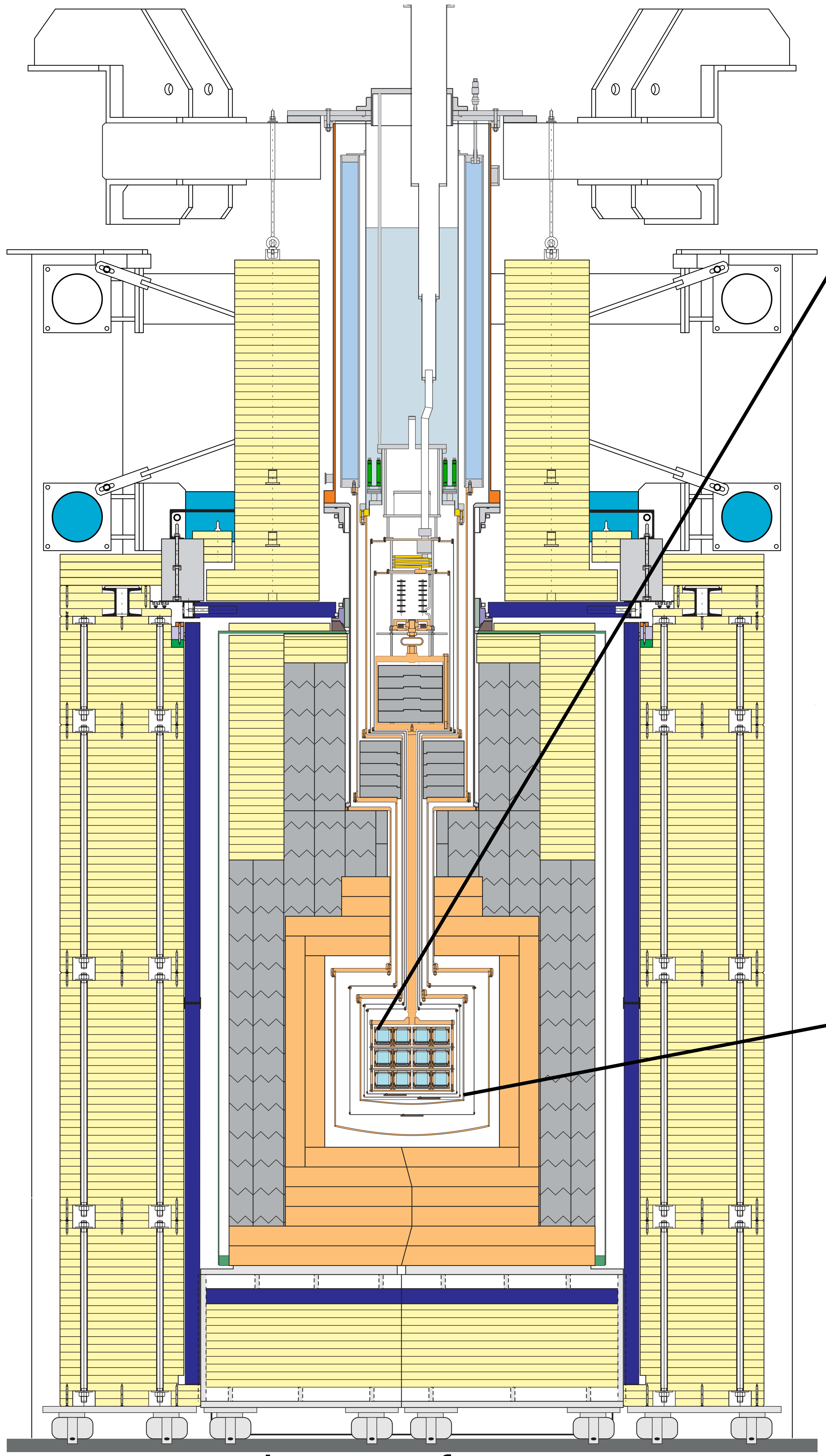
Dilution Refrigerator



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

The CRESST Experiment

Cryogenic Rare Event Search with Superconducting Thermometers



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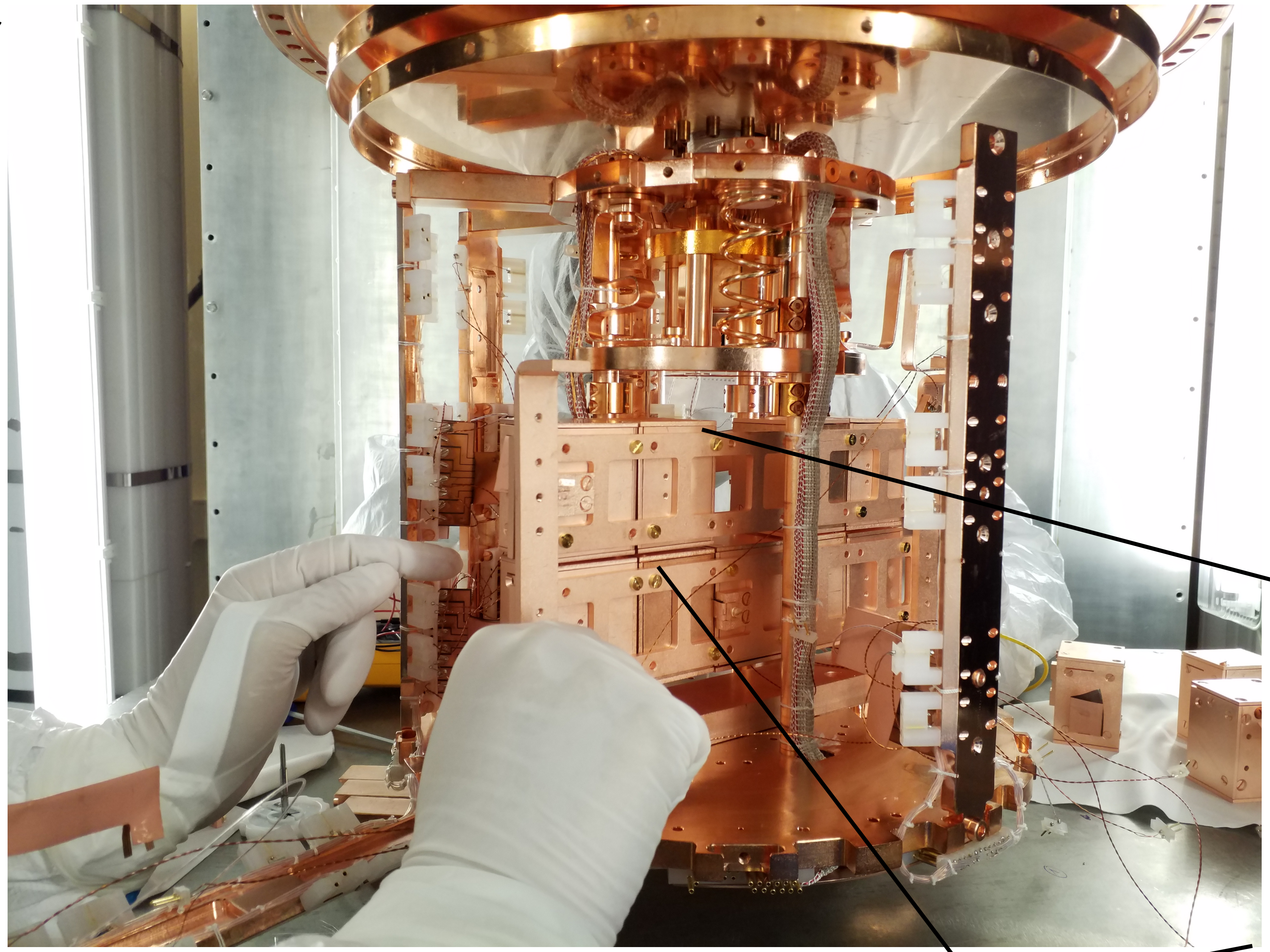
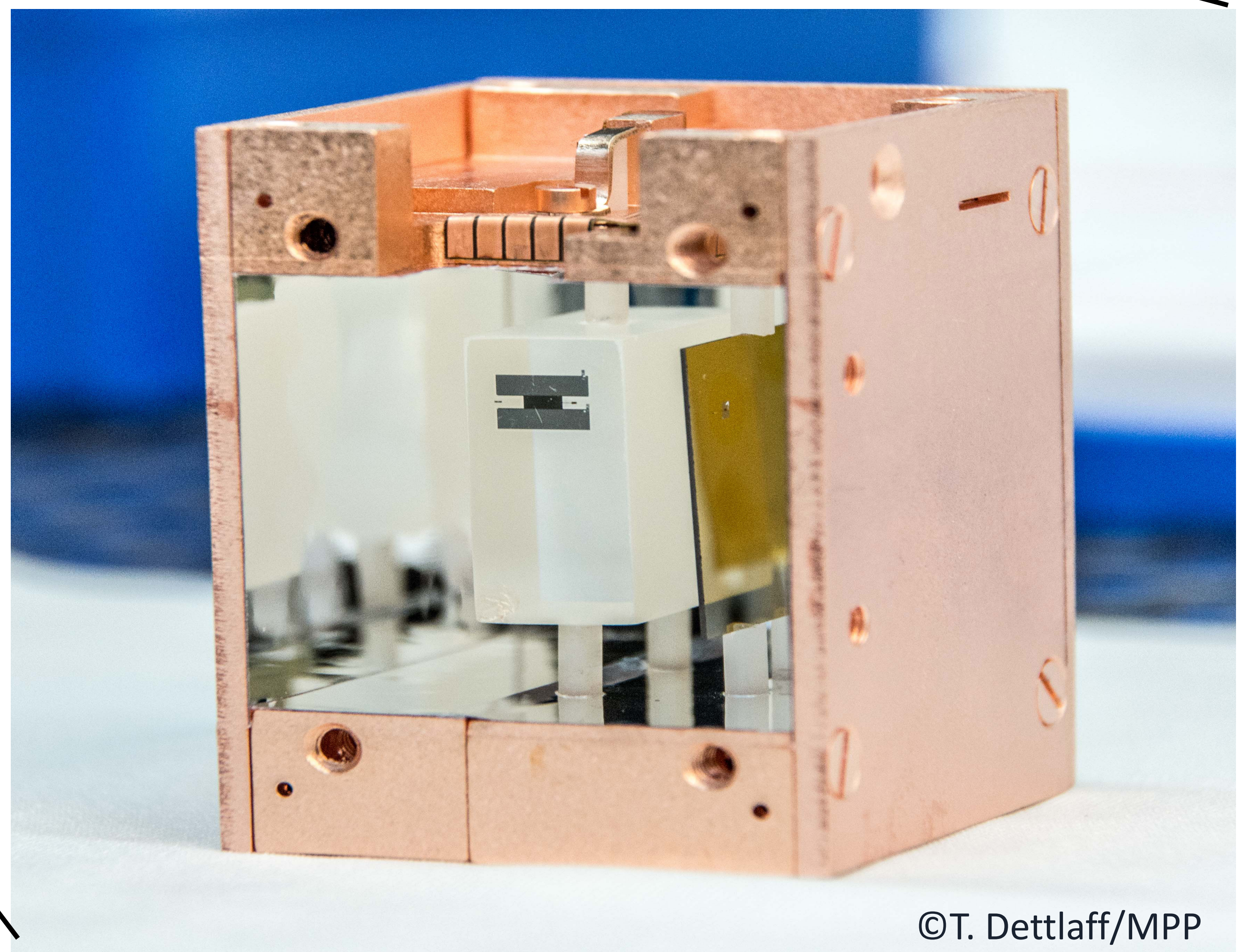


Scintillating $CaWO_4$ crystals as target

Separate **cryogenic light detector**



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

The CRESST Collaboration

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

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

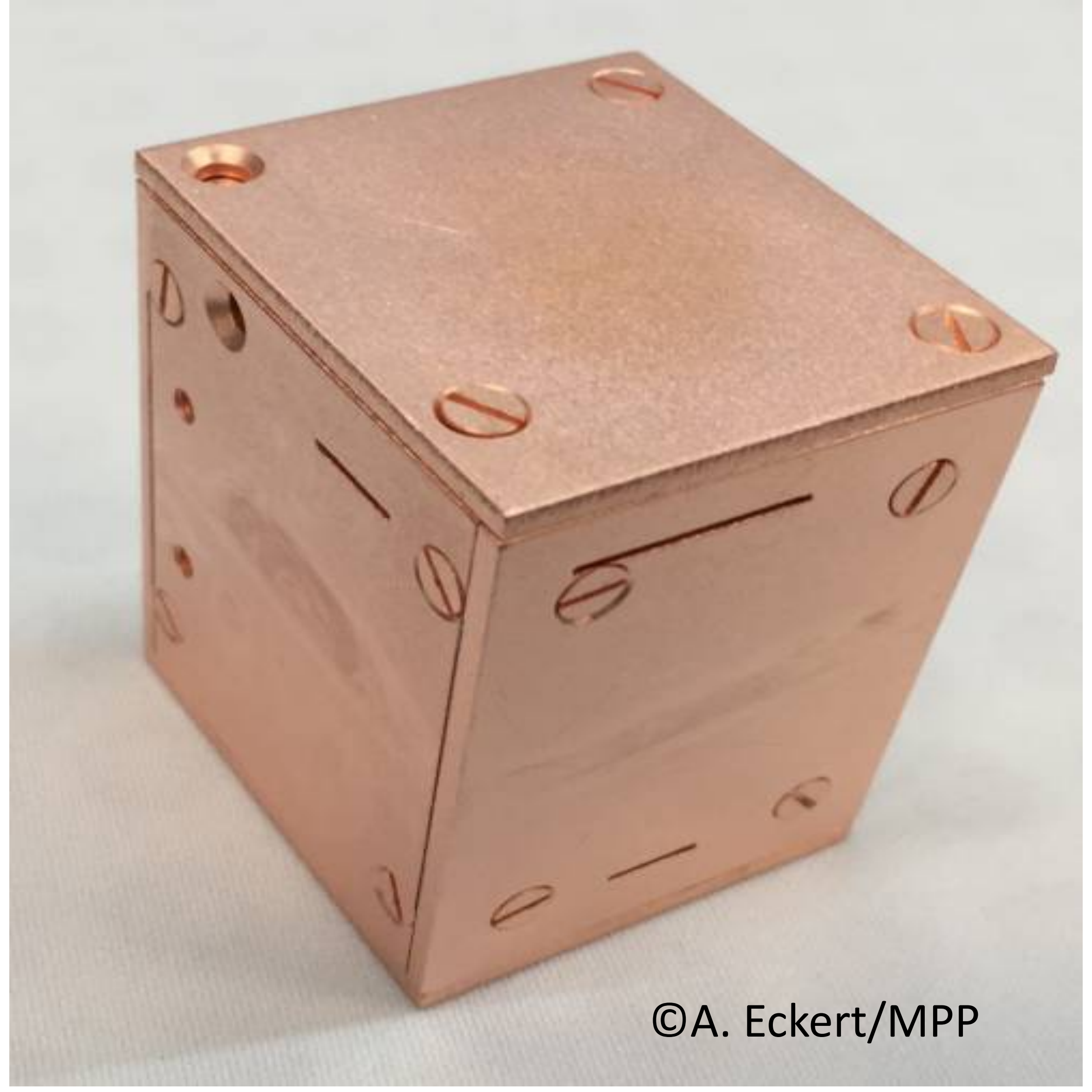
TUM
TECHNISCHE UNIVERSITÄT MÜNCHEN

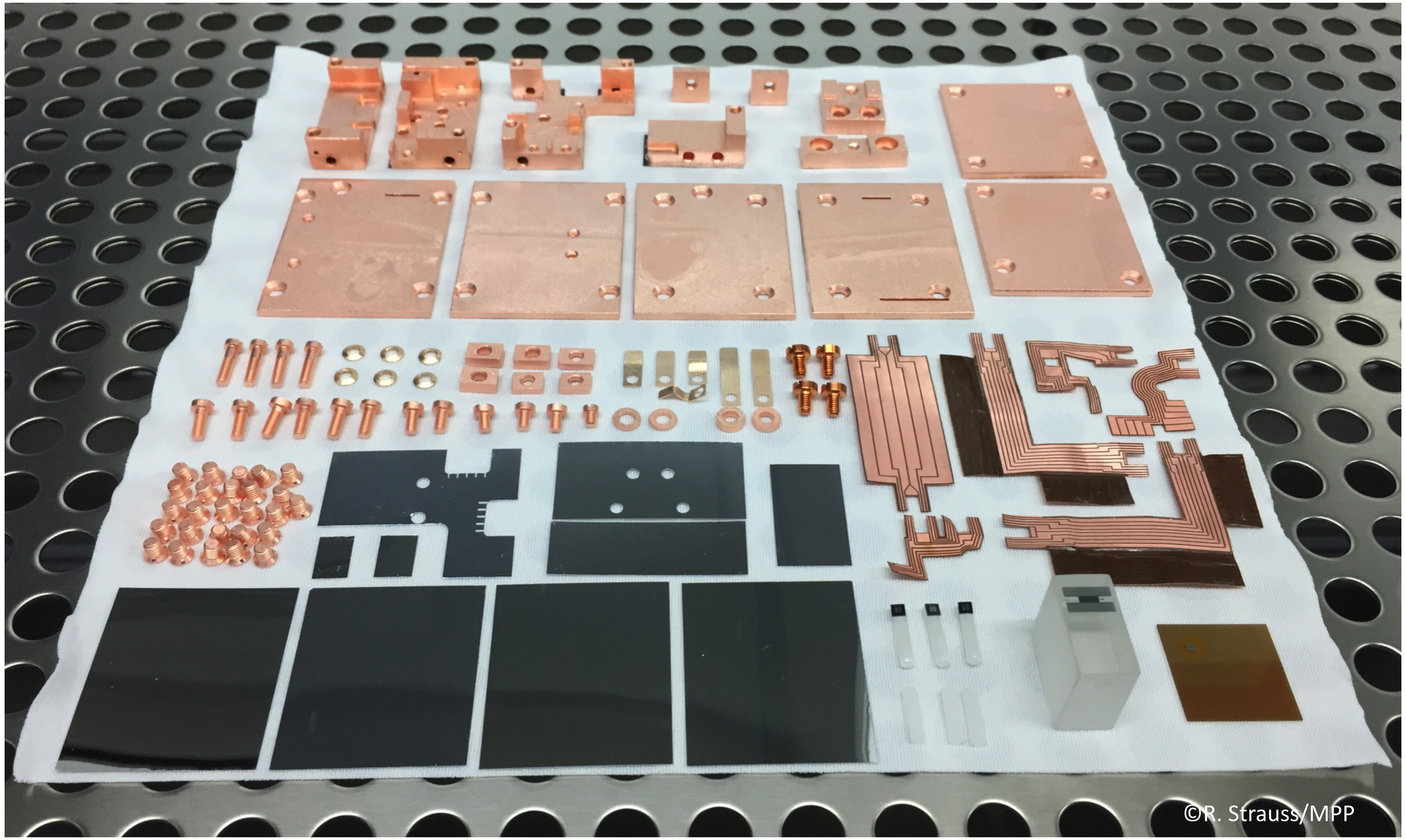
UNIVERSITY OF OXFORD

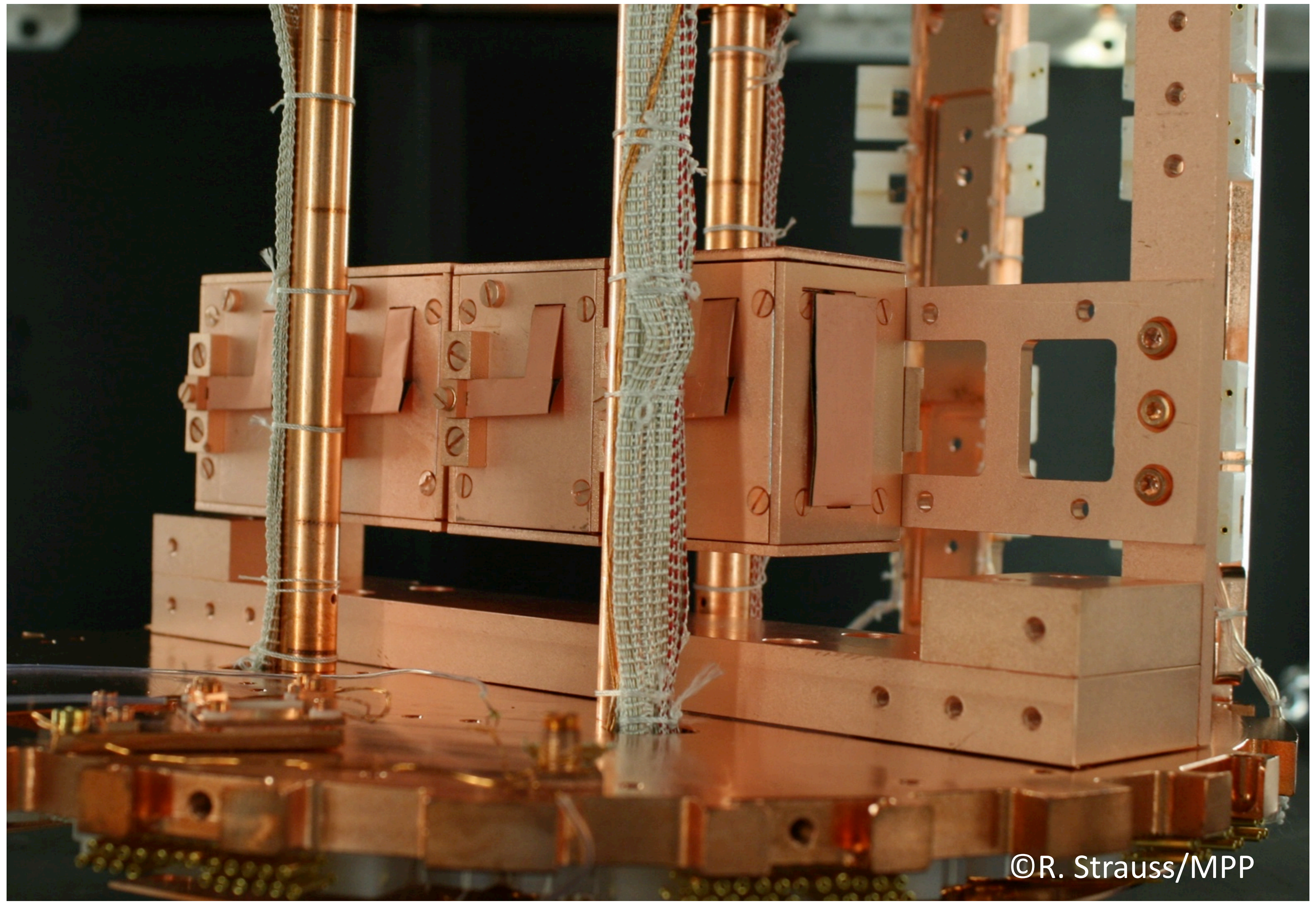
EBERHARD KARLS UNIVERSITÄT TÜBINGEN

HEPHY
Institut für Hochenergiephysik

CRESST-III PHASE 1



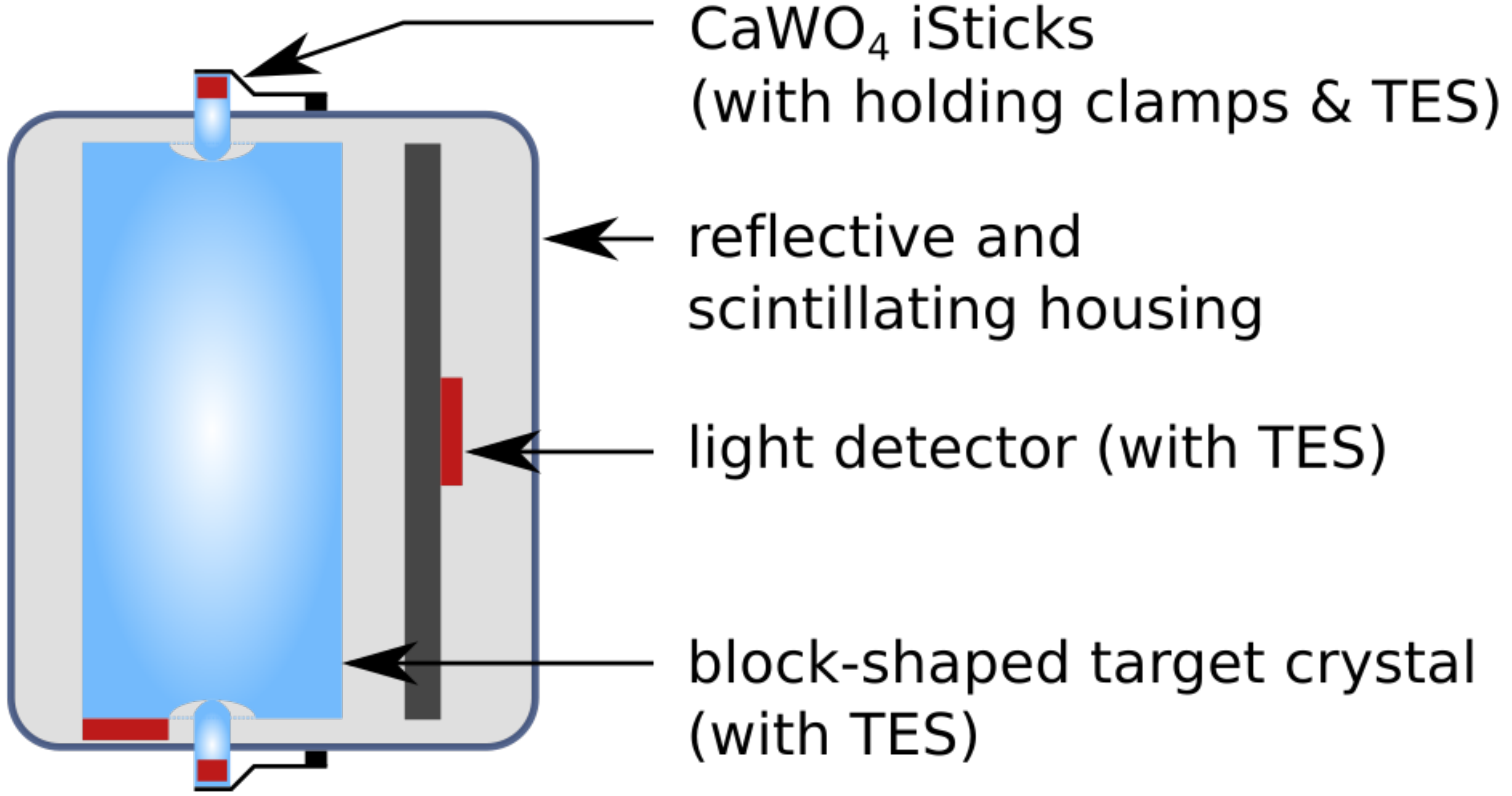


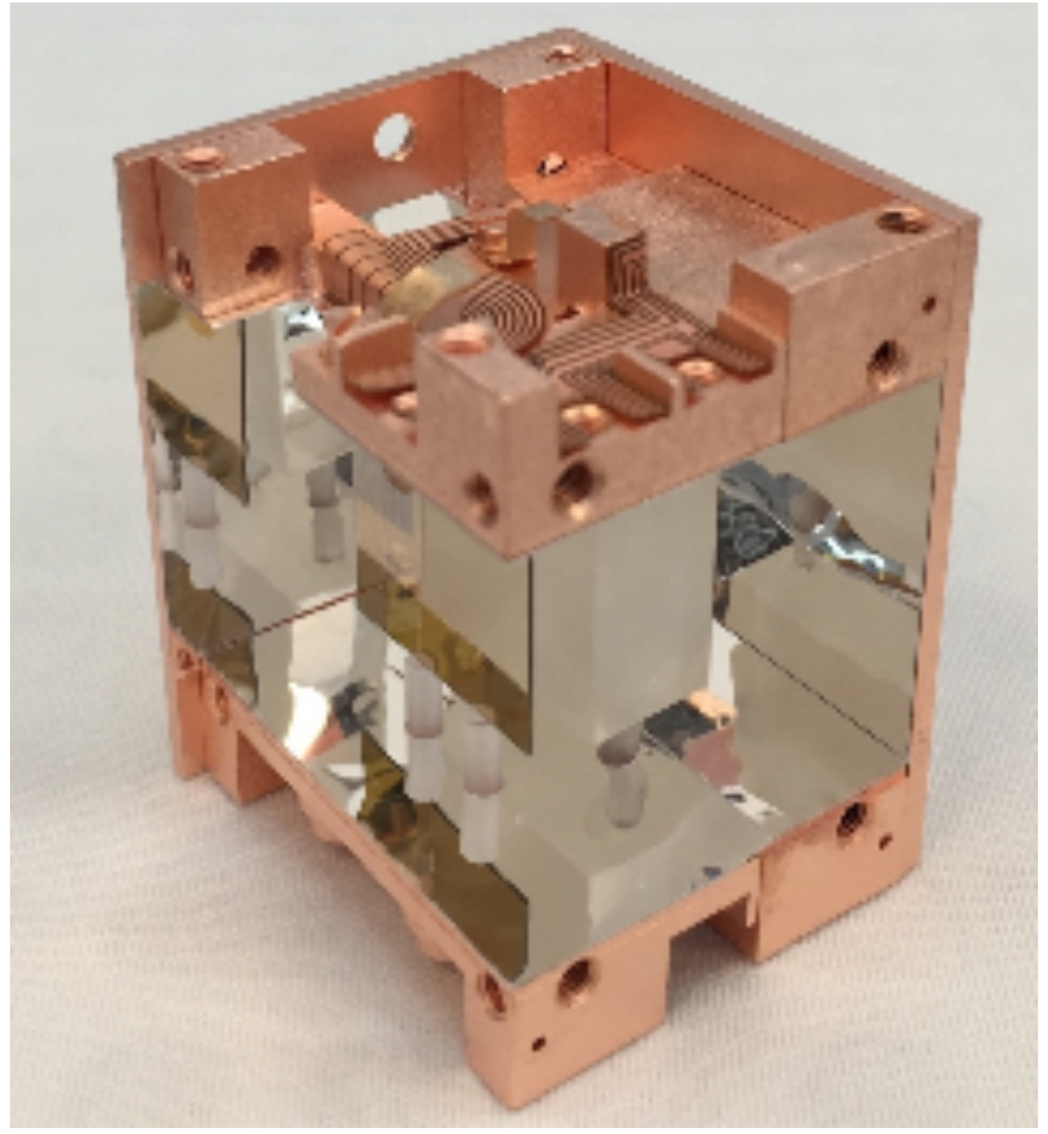


Data taking from May 2016 to February 2018

DETECTOR A

Lowest threshold in the first run of CRESST-III





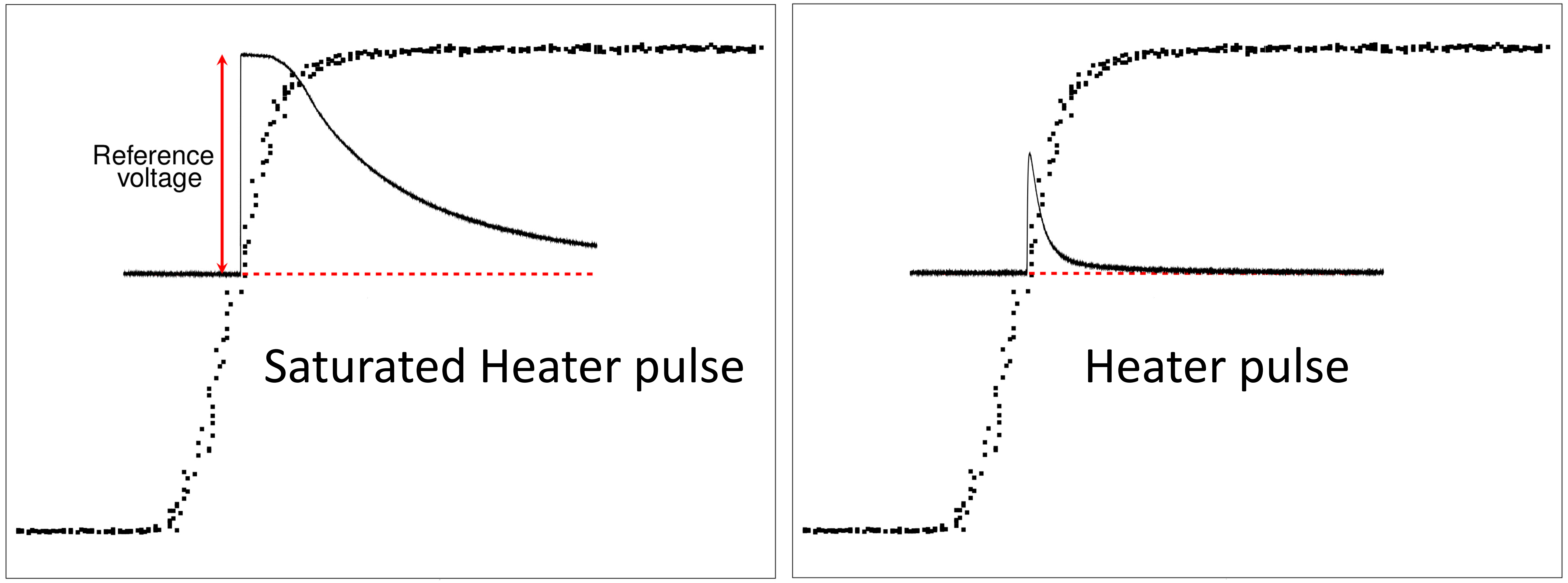
Data taking period:	10/2016 – 01/2018
Non-blind data (dynamically growing):	20% randomly selected
Target crystal mass:	23.6g
Gross exposure (before cuts):	5.689 kg days
Nuclear recoil threshold:	30.1 eV

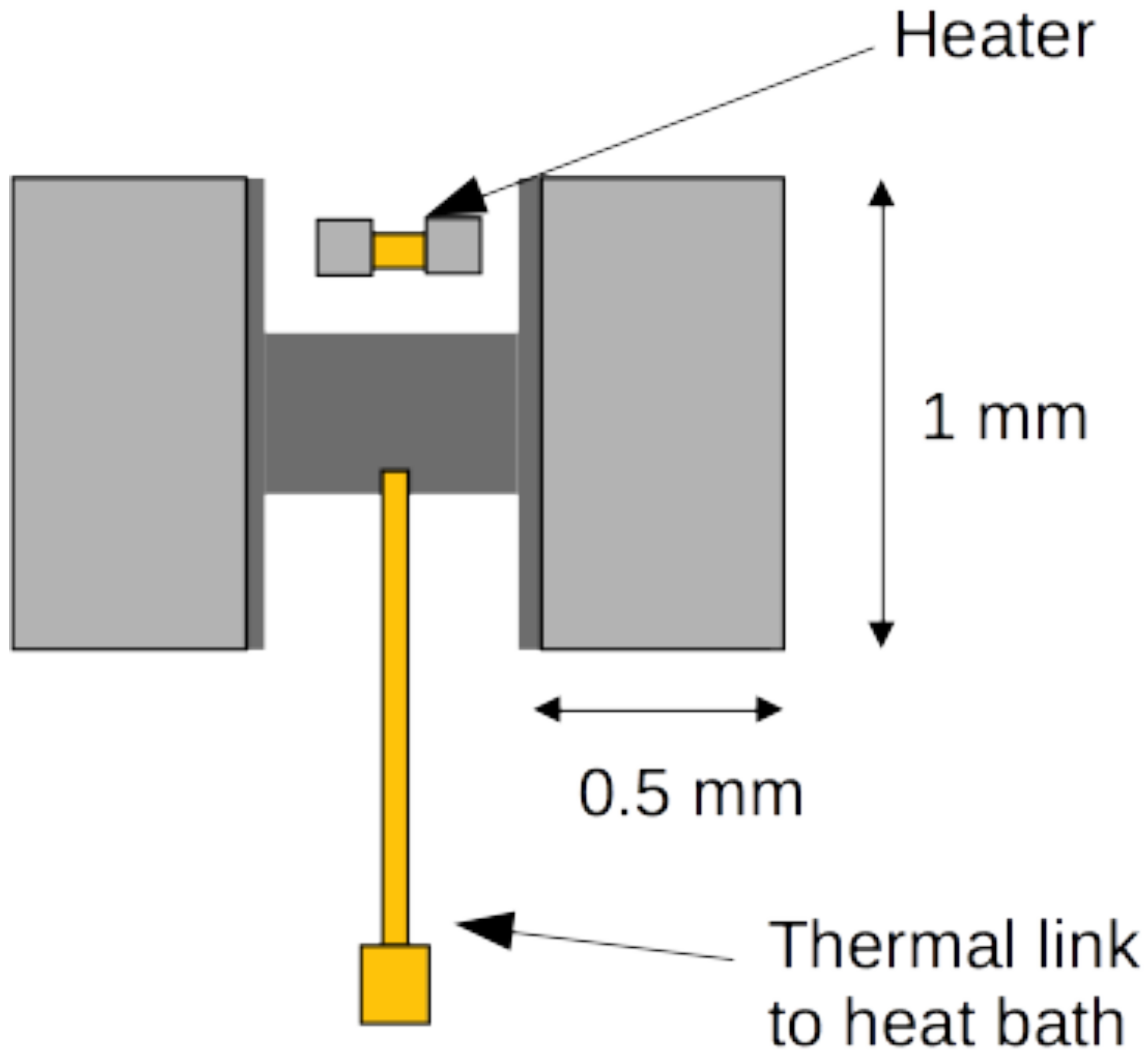
arXiv:1904.00498

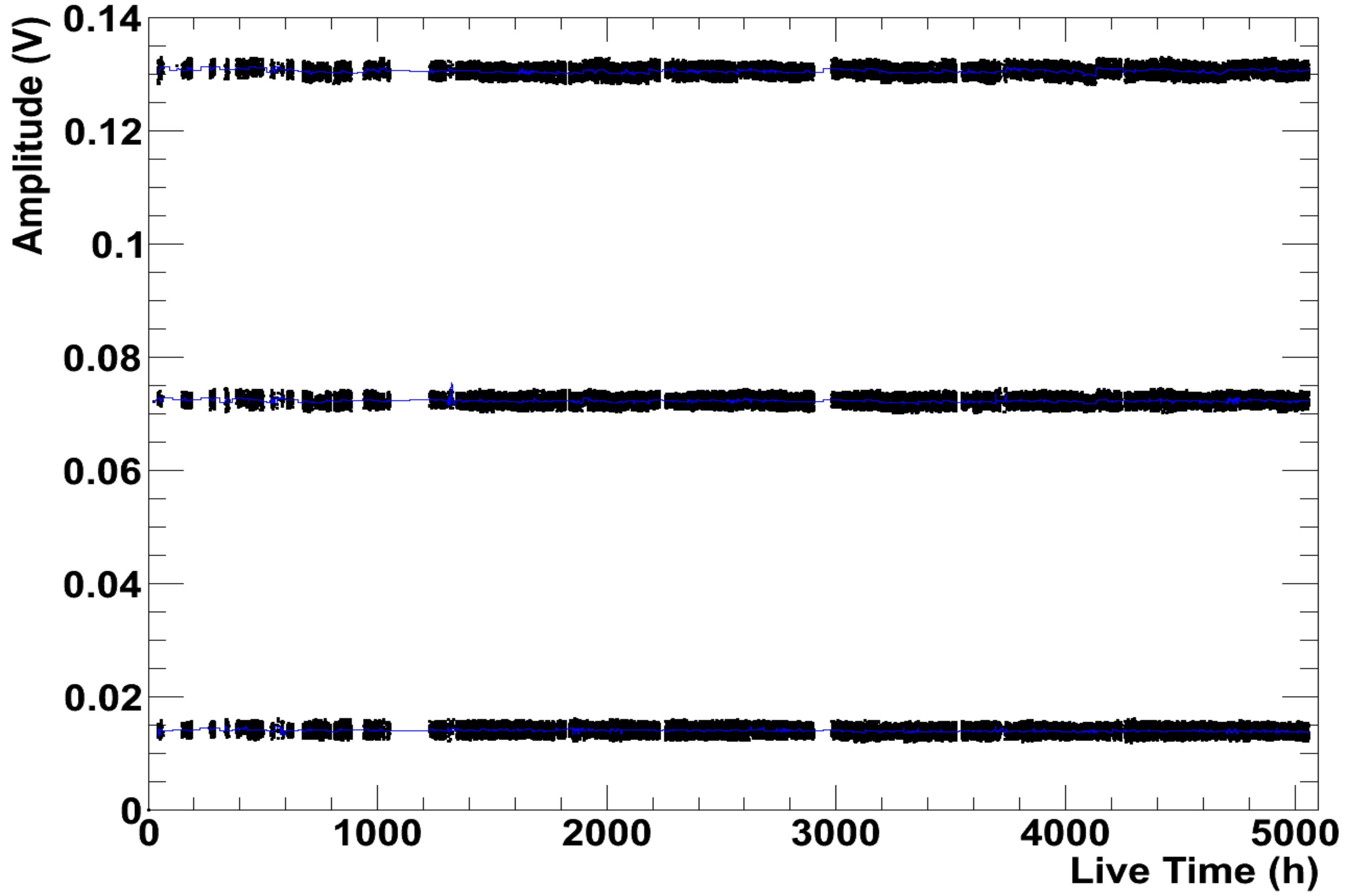
TRANSITION EDGE SENSORS

W-TES equipped with heaters

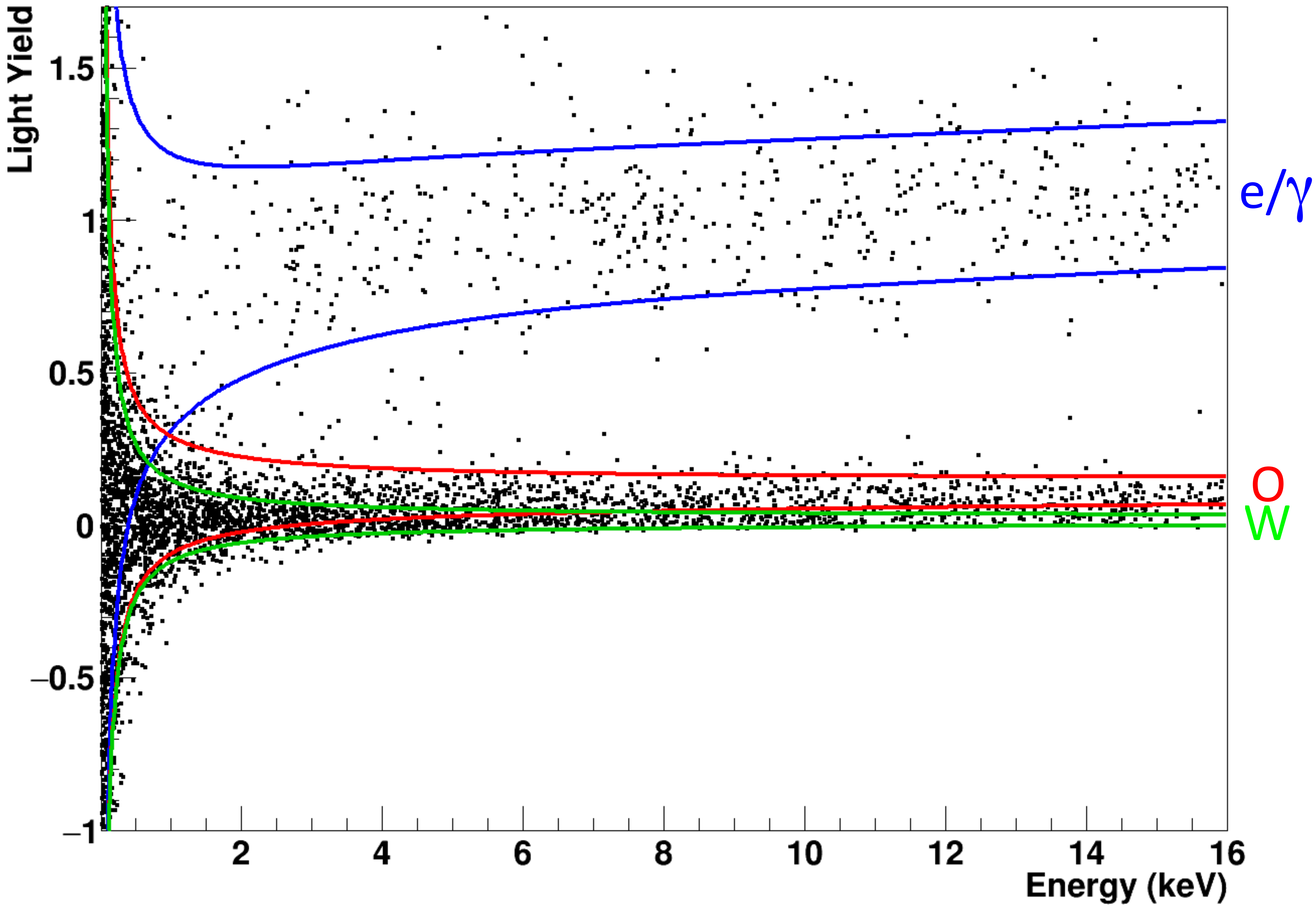
- Stabilization of detectors in the operating point
- Injection of heat pulses for calibration and determination of trigger threshold







DETECTOR A – NEUTRON CALIBRATION



Unbinned maximum likelihood fit

QFs from MLL neutron beam measurement

DARK MATTER DATA

Analysis optimized for very low energies: 30eV → 16keV

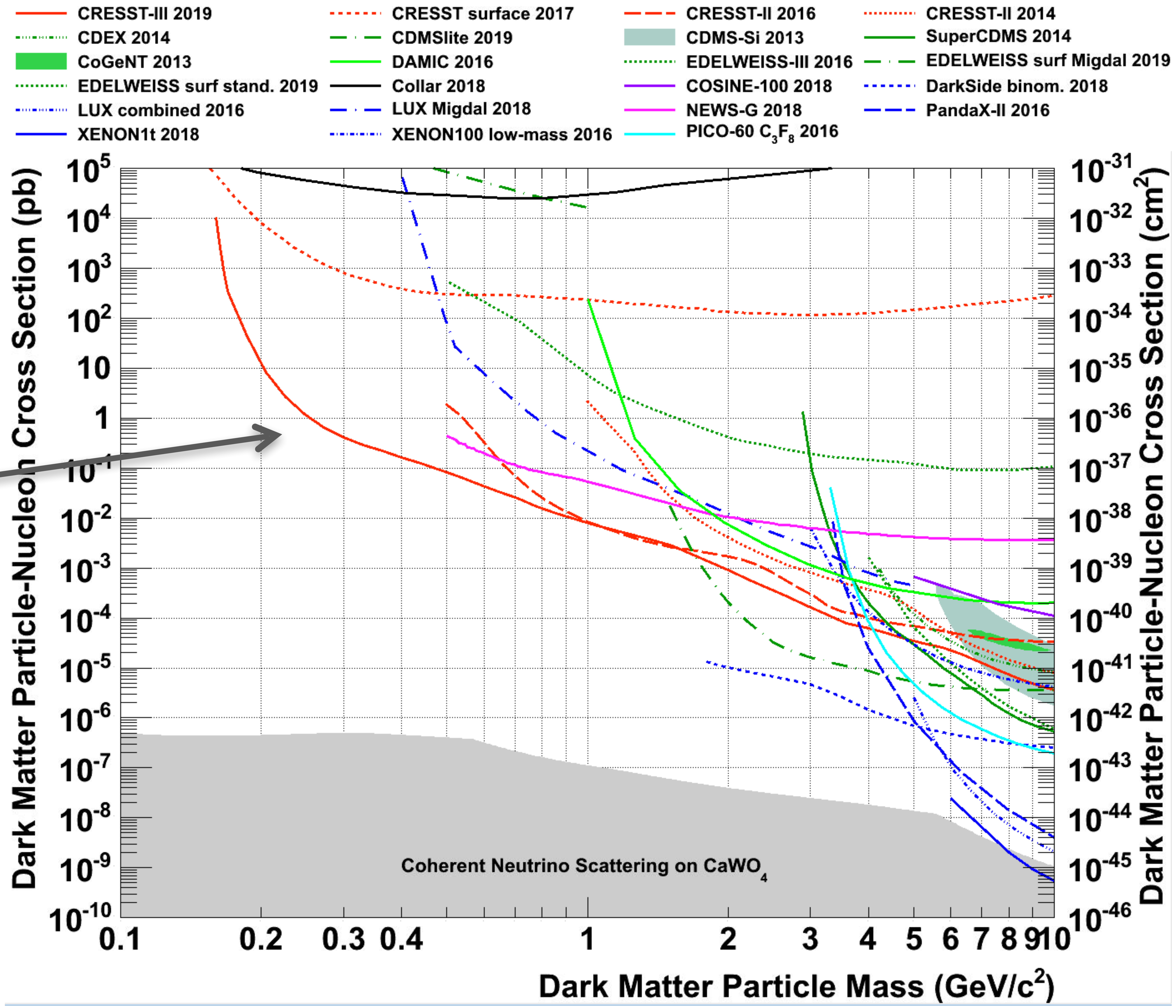
Acceptance region fixed before unblinding

FROM ACCEPTED EVENTS TO DARK MATTER LIMITS

Energy spectrum of accepted events

Yellin one dimensional optimum interval method

Simulated dark matter energy spectrum




The new CRESST array

Opportunities

- CUORE: analysis of the (many) physics channels, simulations and background reconstruction, optimisation of the response, detector modelling

- CUPID: development and optimisation of the $LiMoO_4$ detector, design of the final array, improvement of S/N.

- CRESST: analysis of the (many) physics channels, simulations and background reconstruction, optimisation of the response
- CRESST: detector development and optimisation, effects of magnetic fields, background identification and suppression