XII International Conference on New Frontiers in Physics

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The CUPID neutrinoless double-beta decay experiment

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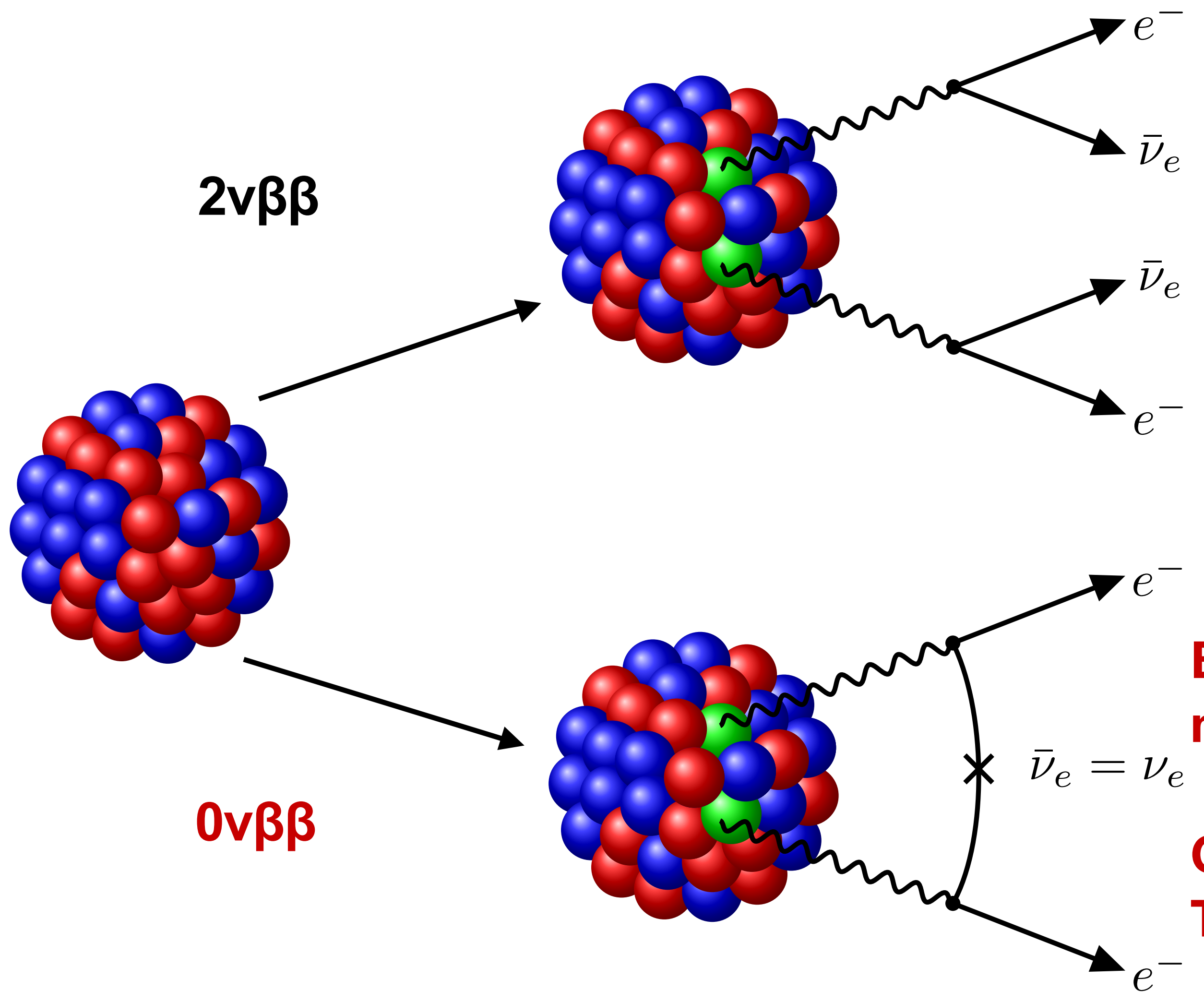
Overview

- Introduction to the neutrinoless double beta decay ($0\nu\beta\beta$)
- Our $0\nu\beta\beta$ search experimental technique
- From CUORE (present) to CUPID (next-gen)
- The CUPID project and the ongoing activities

Neutrinoless double beta decay (0vββ)

- Rare second order Fermi weak nuclear transition
- Candidates: even-even nuclei, when single β decay energetically forbidden

$$(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$$



Standard Model allowed, observed in 11 nuclei

$T_{1/2}$: (10^{18} - 10^{24}) years

Beyond Standard Model, not yet observed

Current limits:
$T_{1/2} > 10^{26}$ years

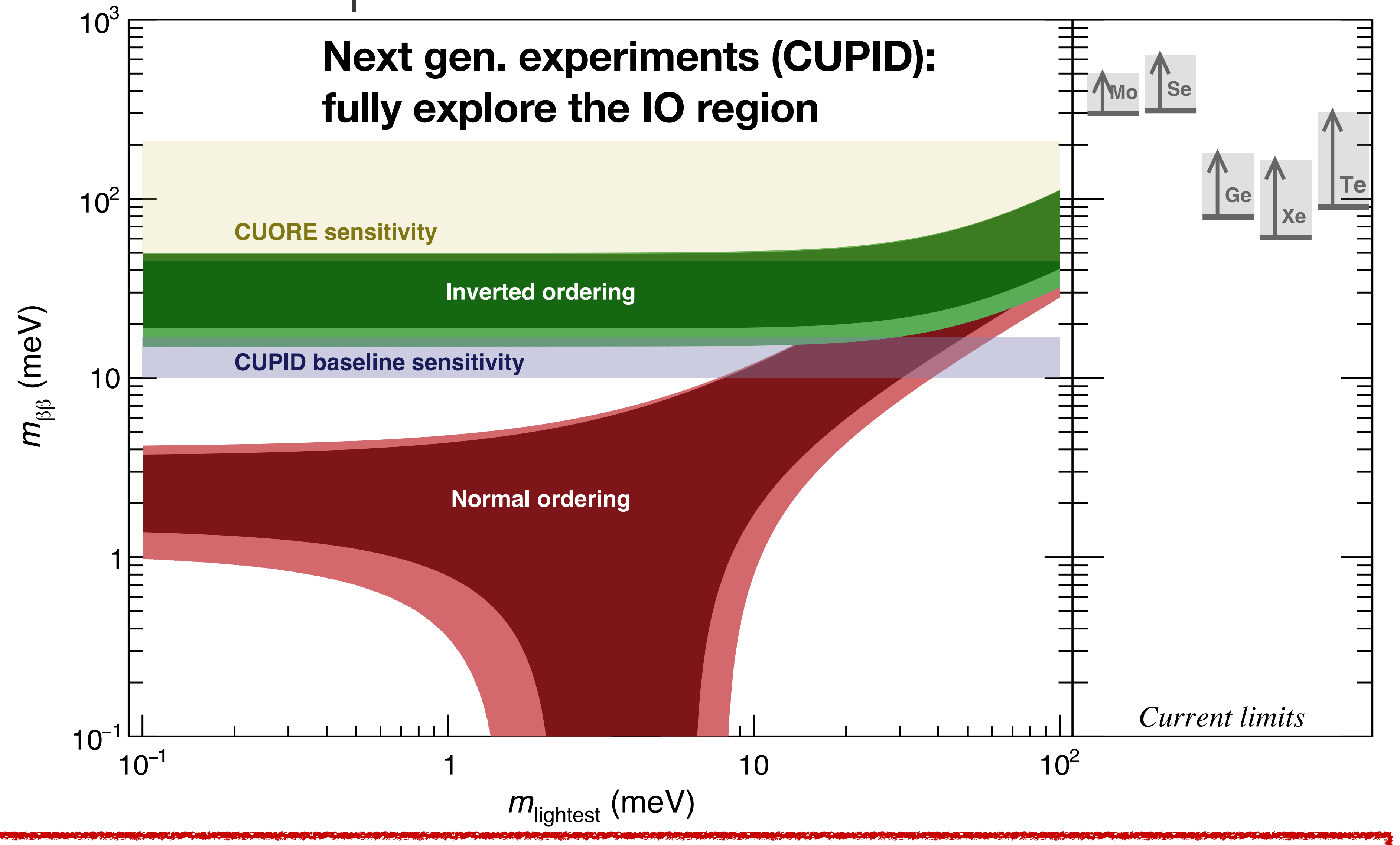
$$(A, Z) \rightarrow (A, Z+2) + 2e^-$$

- Light Majorana neutrino exchange mechanism for 0vββ decay
- In this case, we define the Effective Majorana mass $m_{\beta\beta}$

$$m_{\beta\beta} = \left| e^{i\eta_1} |U_{e1}^2| m_1 + e^{i\eta_2} |U_{e2}^2| m_2 + |U_{e3}^2| m_3 \right|$$

The 0vββ rate is proportional to $\langle m_{\beta\beta} \rangle^2$

$$\frac{1}{T_{1/2}} \propto \Gamma^{0\nu} = G^{0\nu} |M^{0\nu}|^2 \frac{\langle m_{\beta\beta} \rangle^2}{m_e^2}$$



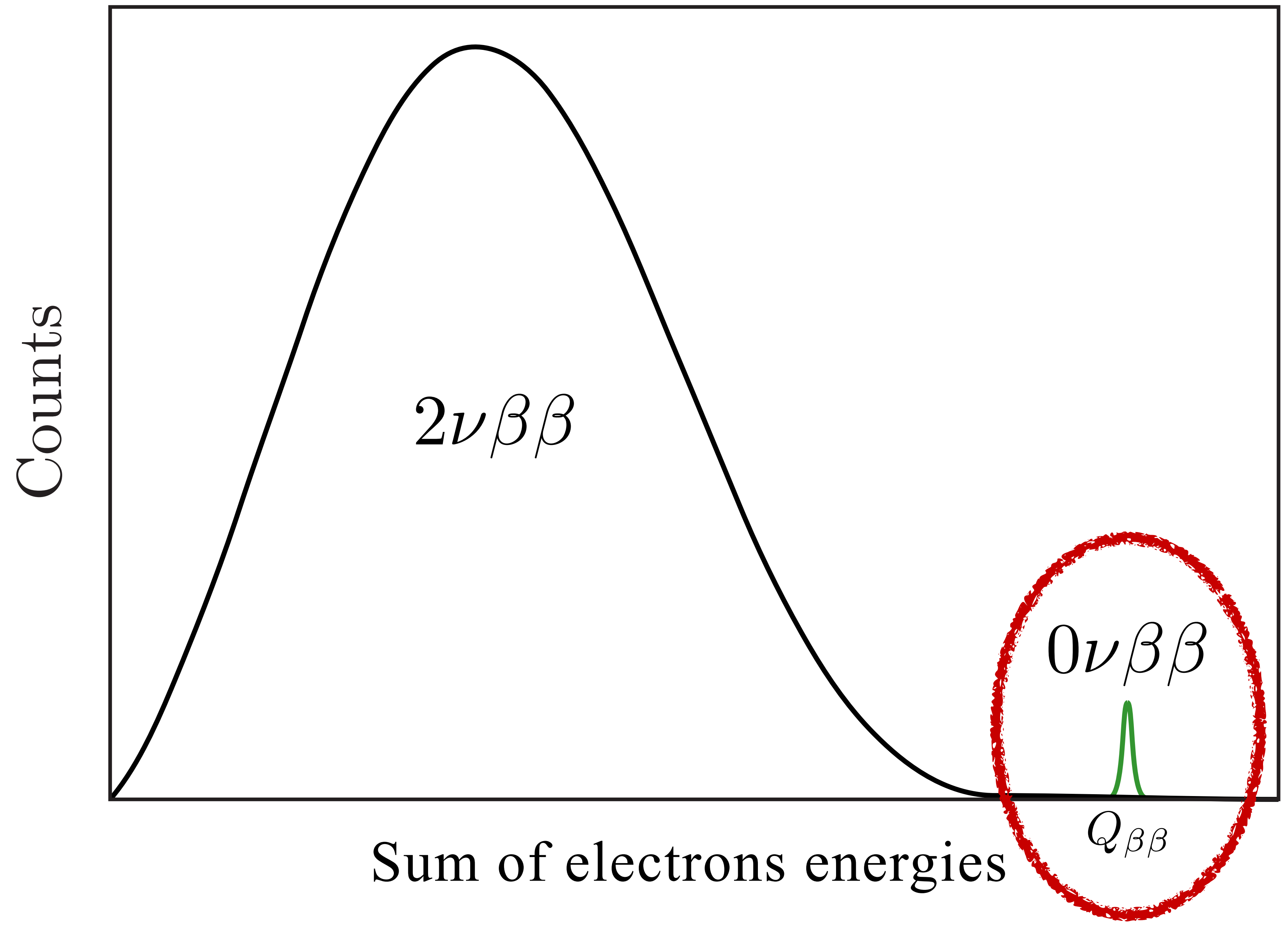
Scientific interest for 0vββ:

- Lepton number violating process: ΔL = 2 ⟶ **L is not a symmetry of nature**
- Only possible if neutrinos have a **Majorana component ($\nu = \bar{\nu}$)**: new possible mechanism giving rise to v mass
- Info on neutrino mass hierarchy problem
- Possible explanation of **matter-antimatter asymmetry** origin via Leptogenesis

Experimental search of 0νββ decay

The potential of an experiment to 0νββ decay is evaluated through the ***Sensitivity***

Experimental signature:



Sensitivity:
the half life corresponding to the minimum number of observable signal events above the background, at a given statistical significance n_σ

$$S^{0\nu}(n_\sigma) = \frac{\ln 2}{n_\sigma} \epsilon \eta \frac{N_a}{A} \sqrt{\frac{M \Delta t}{b \Delta E}}$$

scenario limited by background statistical fluctuations ($N_{bkg} \gg 1$)

- Detection efficiency
- Isotopic abundance of 0νββ emitter
- Exposure (large detector mass and long live time)
- Background level
- Energy resolution

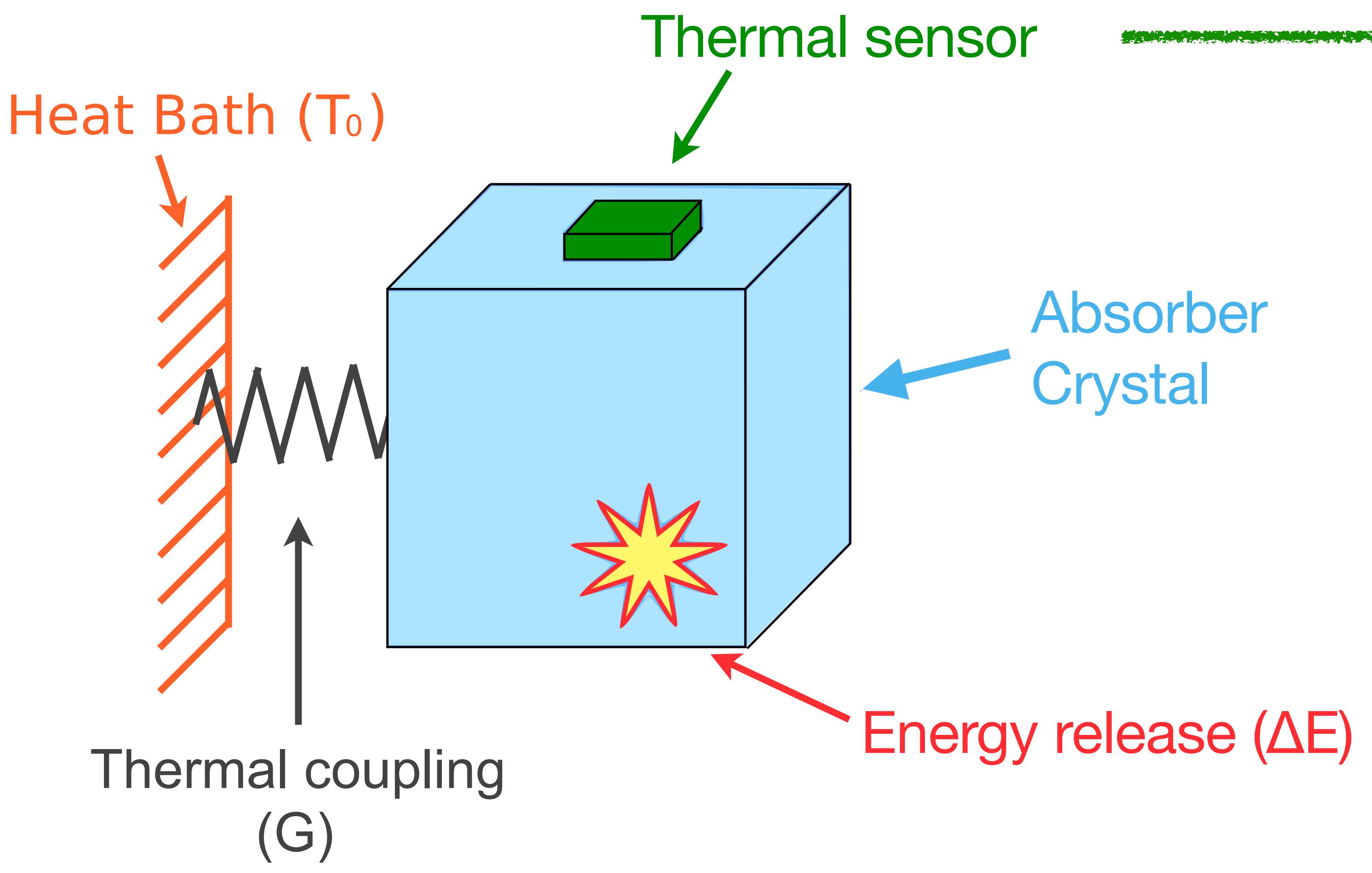
$$S^{0\nu}_{0-\mathrm{bkg}}(n_\sigma) = \frac{\ln 2}{n_\sigma} \epsilon \eta \frac{N_a}{A} M \Delta t$$

zero-background condition ($N_{bkg} < O(1)$)

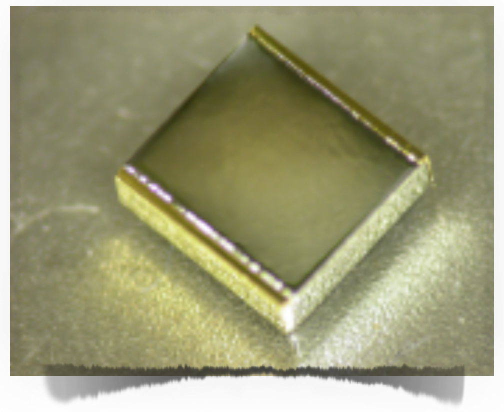
Sensitivity increases linearly with the exposure

The bolometric technique

- Bolometer: low temperature solid state detector working as calorimeter
- The energy of a particle interacting with the absorber is converted into phonons
- The temperature variation is measured by the thermal sensor

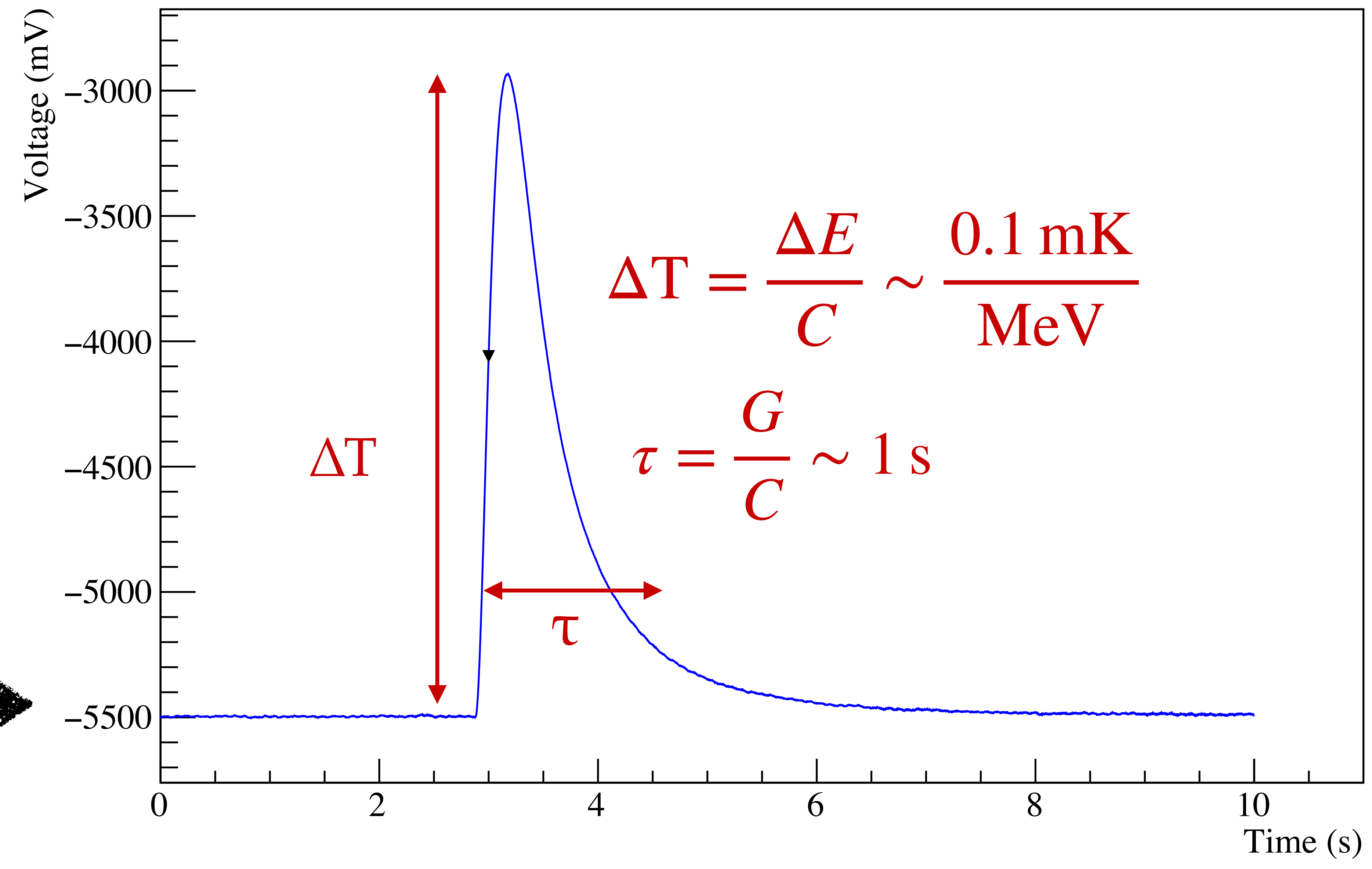


NTD-Ge = Neutron Transmutation Doped Ge thermistor



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

biased with a constant current, converts ΔT to voltage signal



$$\Delta T = \frac{\Delta E}{C}$$ heat capacity: $C \propto T^3$

$T_0 = 300$ K: $\Delta E = 1$ MeV ⟶ $\Delta T \sim 10^{-18} - 10^{-15}$ K

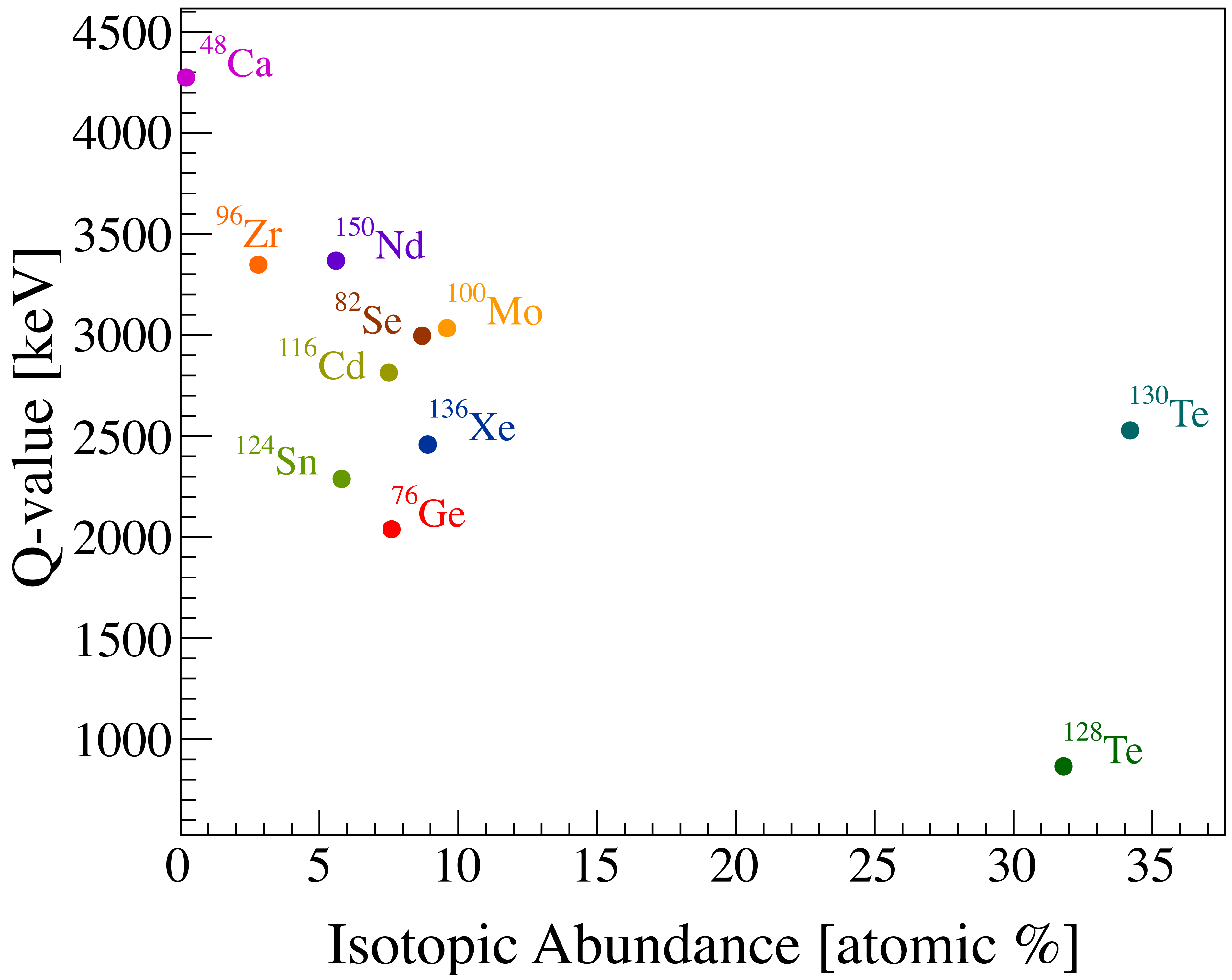
$T_0 = 10$ mK: $\Delta E = 1$ MeV ⟶ $\Delta T \sim 0.1$ mK

The bolometric technique

- Bolometer: low temperature solid state detector working as calorimeter
- The energy of a particle interacting with the absorber is converted into phonons
- The temperature variation is measured by the thermal sensor

Advantages:

- > 90% intrinsic efficiency (source = detector)
- Good energy resolution (few keV FWHM @ MeV scale)
- Easily scalable in mass
- Multi-isotope technique: flexible choice of isotopes, many available compounds

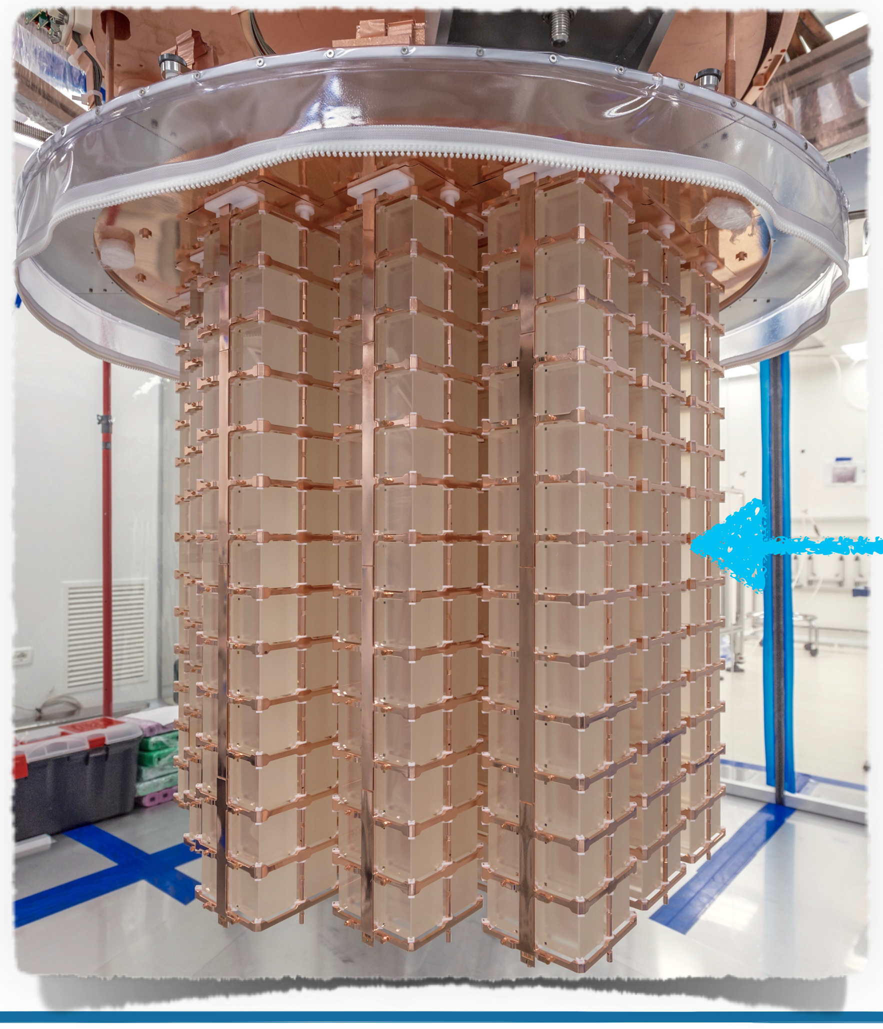


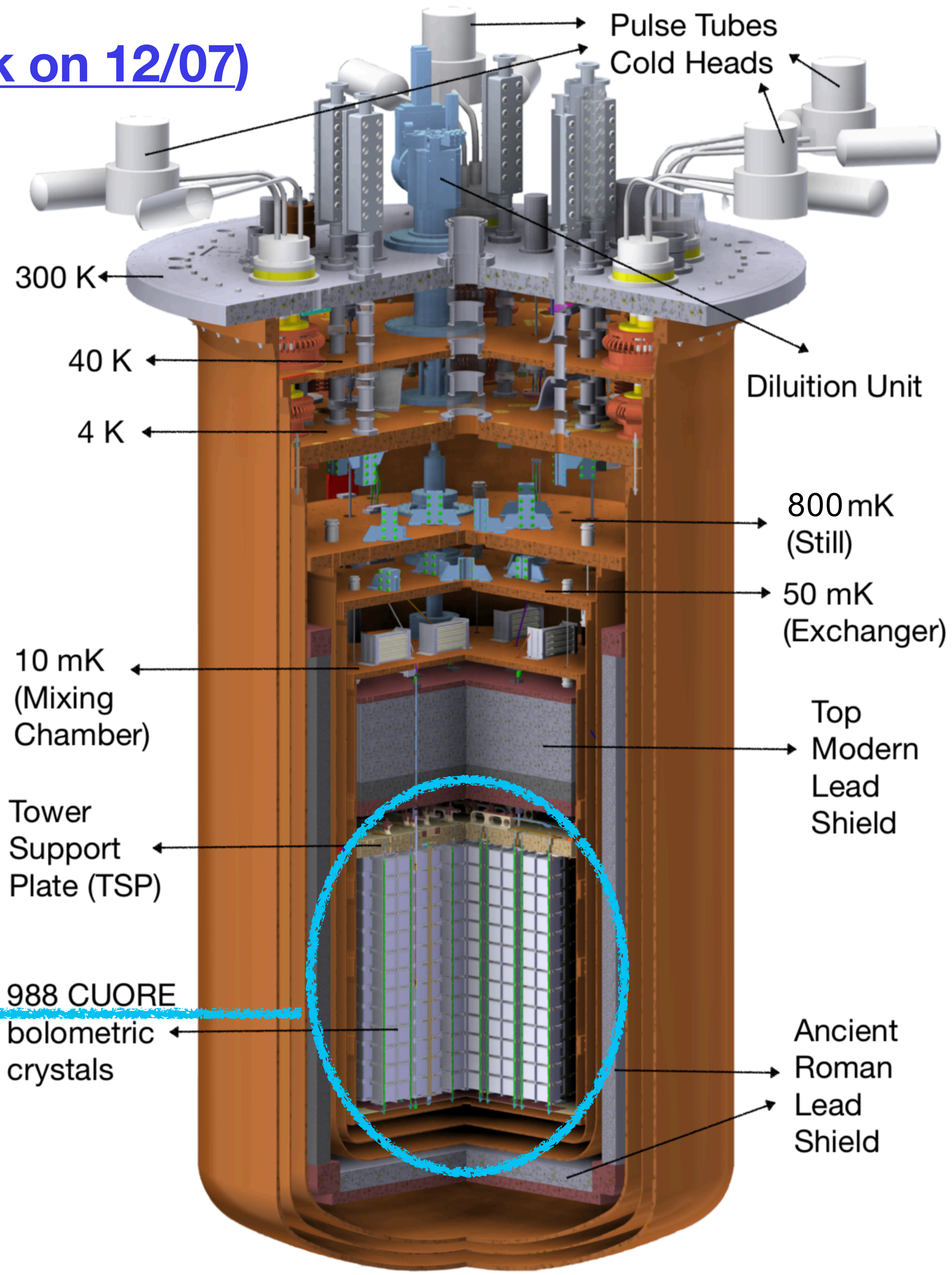
The CUORE experience

The feasibility of ton-scale bolometric experiments has been extensively proved by
CUORE - Cryogenic Underground Observatory for Rare Events (see M. Beretta's talk on 12/07)

- Isotope: ^{130}Te
- Located in Italy @ underground Laboratori Nazionali del Gran Sasso of INFN: 3650 m.w.e. of rock coverage to suppress the cosmic radiation
- 988 natural TeO_2 crystals (742 kg of TeO_2, 206 kg of ^{130}Te): **first ton-scale experiment with cryogenic bolometers (~10 mK) for 0νββ decay search**
- CUORE data taking is currently ongoing and proceeding in stable conditions at a rate of ~50 - 60 kg · y/month since spring 2019
- **2021: 1 ton · y analyzed exposure milestone**
- **2023: > 2 ton · y collected exposure**
  2 ton · y exposure analysis currently ongoing
- **Cryostat operation stable over ~O(years)**
- **Ultimate goal: > 3 ton · y collected exposure**

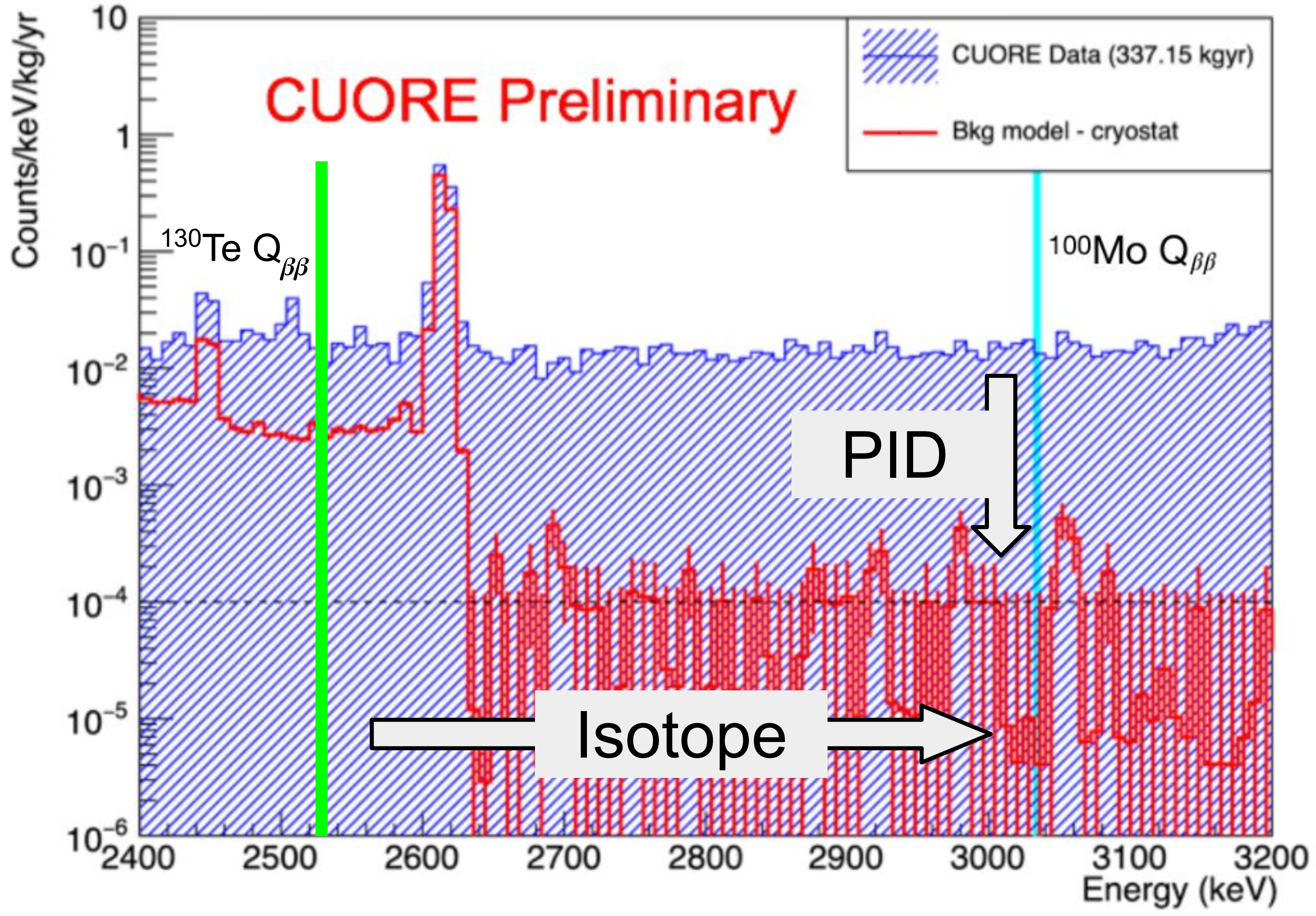
(2022) Nature, 604 (7904), pp. 53-58 DOI: 10.1038/s41586-022-04497-4

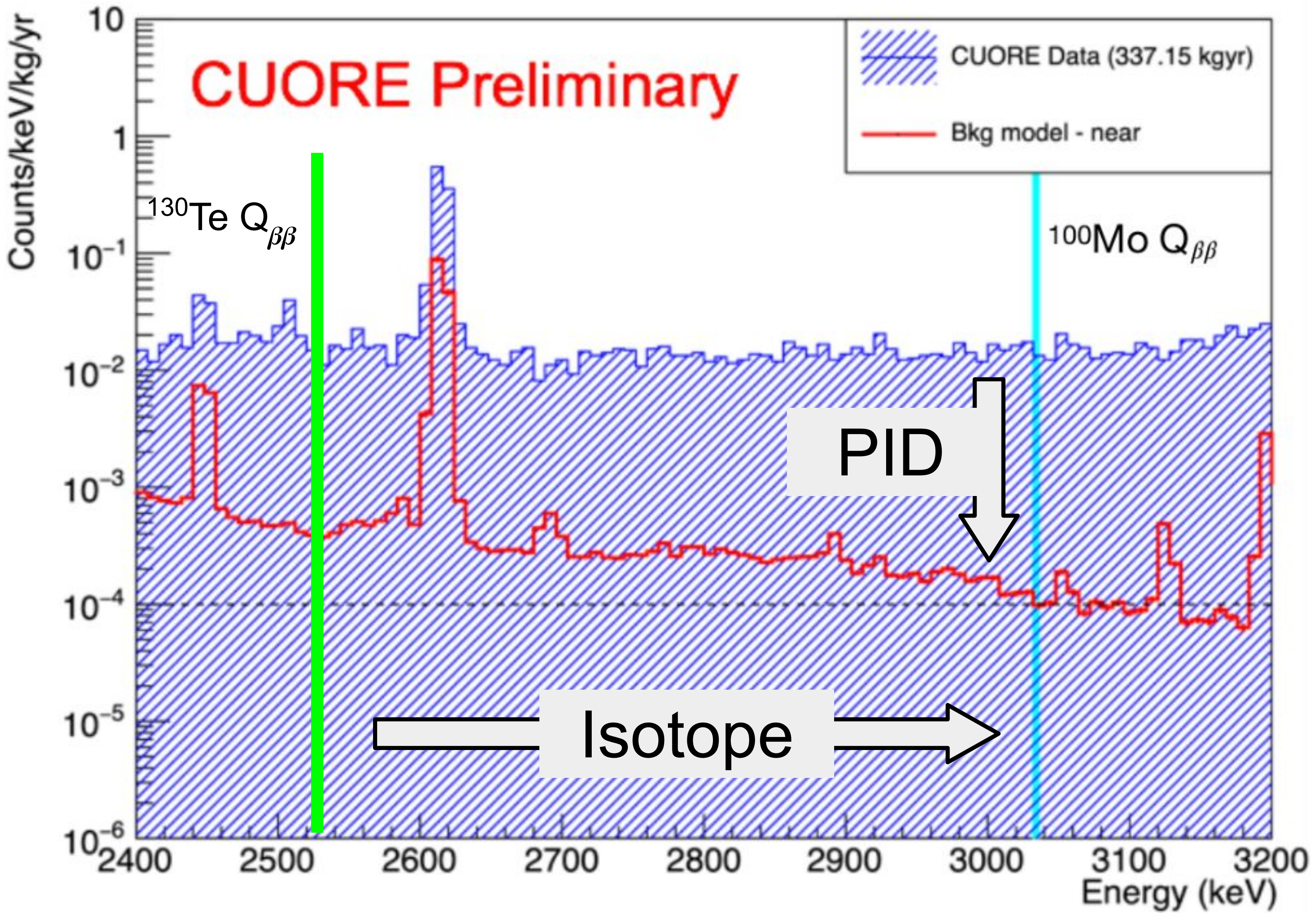




From CUORE to CUPID
(CUORE Upgrade with Particle IDentification)

Despite the low-radioactivity materials adopted for its construction, CUORE sensitivity is limited by surface alpha background





Total background level (α + β/γ) - from CUORE data

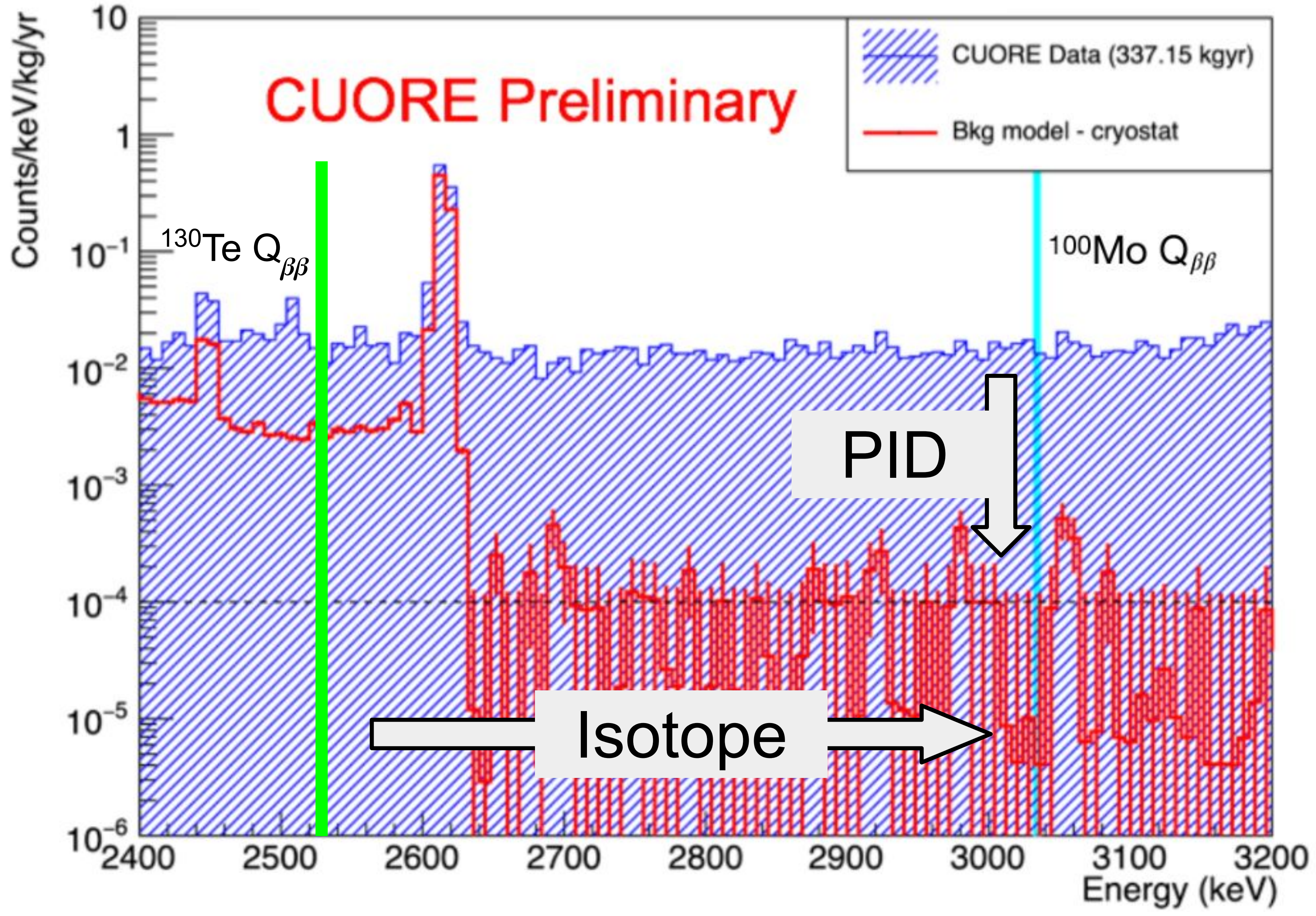
Background level **after α events rejection -** from background model simulations

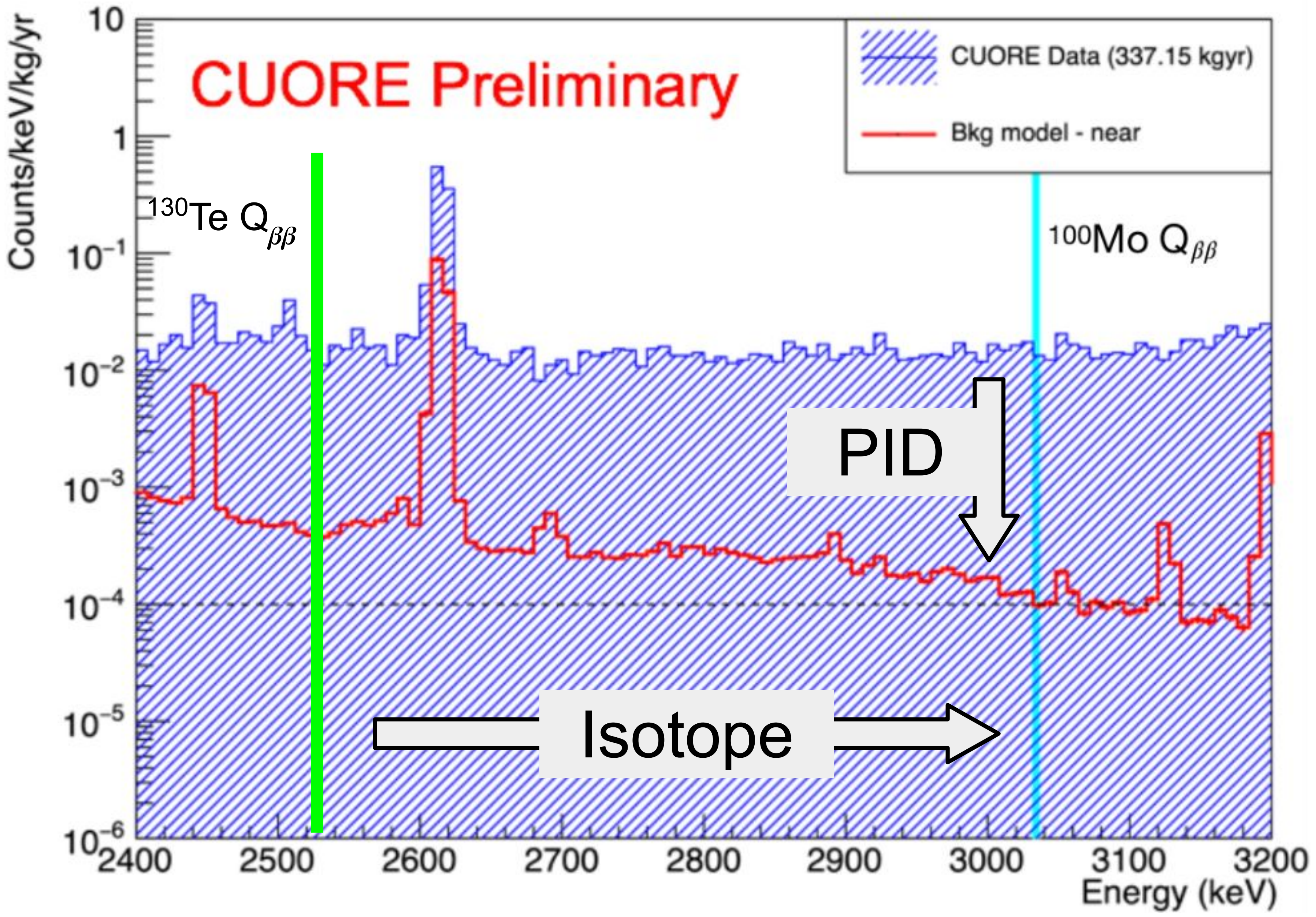
- CUORE uses TeO_2 crystals, which do not produce scintillation light; **surface alpha background reduction by means of particle identification is not possible in CUORE.**
- From the joint effort of several CUPID demonstrators and projects (LUCIFER, CUPID-0, LUMINEU, CUPID-Mo) we learnt that:
  - the **scintillating bolometers technique** is able to effectively reject the surface alpha background up to a factor 10^3;
  - **Li_2MoO_4 scintillating crystals** showed excellent performances in terms of energy resolution, background reduction capability through particle identification, reproducibility and radiopurity

From CUORE to CUPID
(CUORE Upgrade with Particle IDentification)

CUPID

Despite the low-radioactivity materials adopted for its construction, CUORE sensitivity is limited by surface alpha background





Total background level (α + β/γ) - from CUORE data

Background level **after α events rejection -** from background model simulations

CUORE:

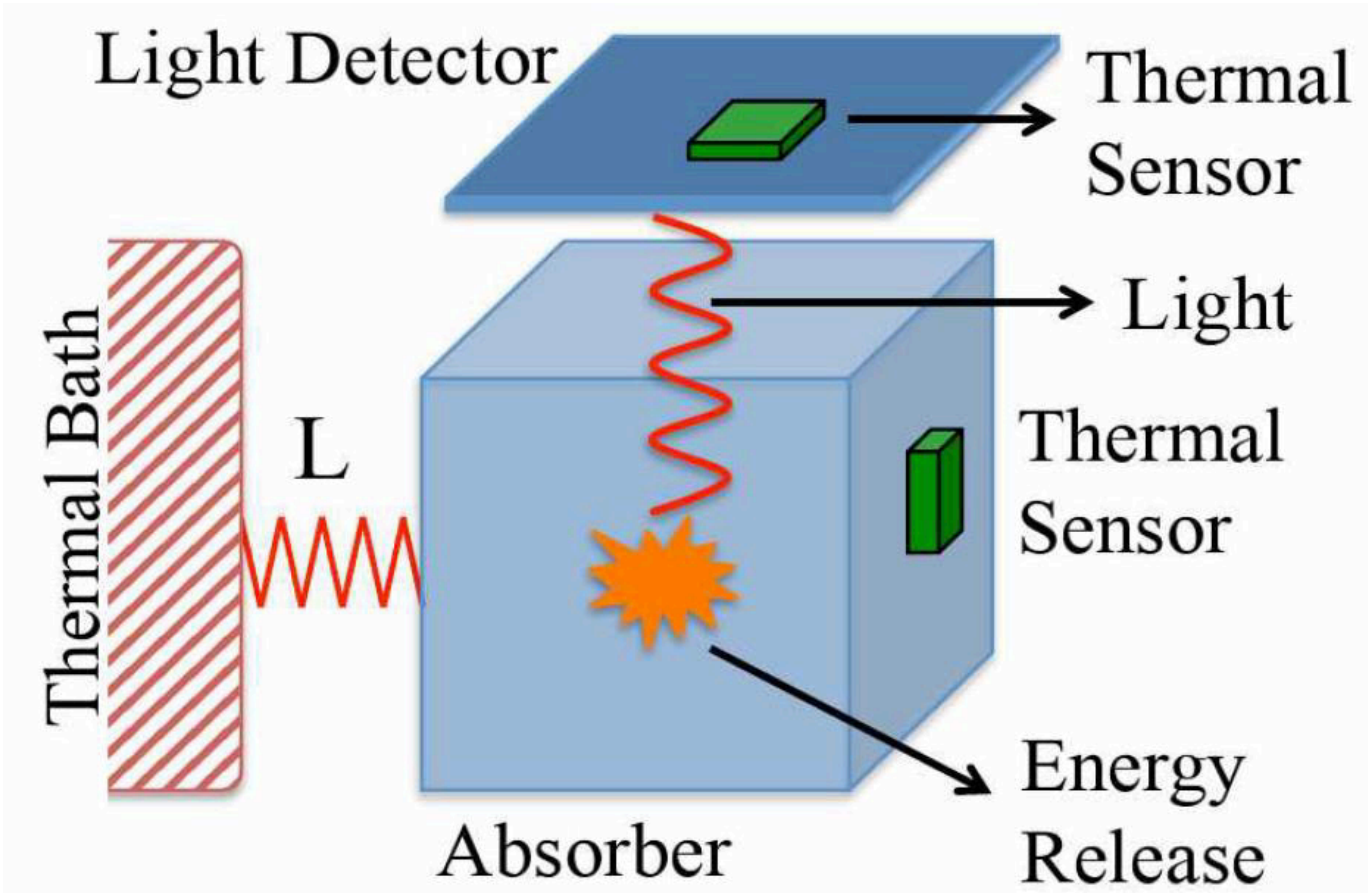
- Non-scintillating TeO_2 crystals ⟶ Heat signal ✔, Light signal ✘, PID ✘
- Isotope: ^{130}Te ⟶ $Q_{\beta\beta}$ = (2527.518 ± 0.013) keV
- High isotopic abundance (34%): no need for enrichment

CUPID:

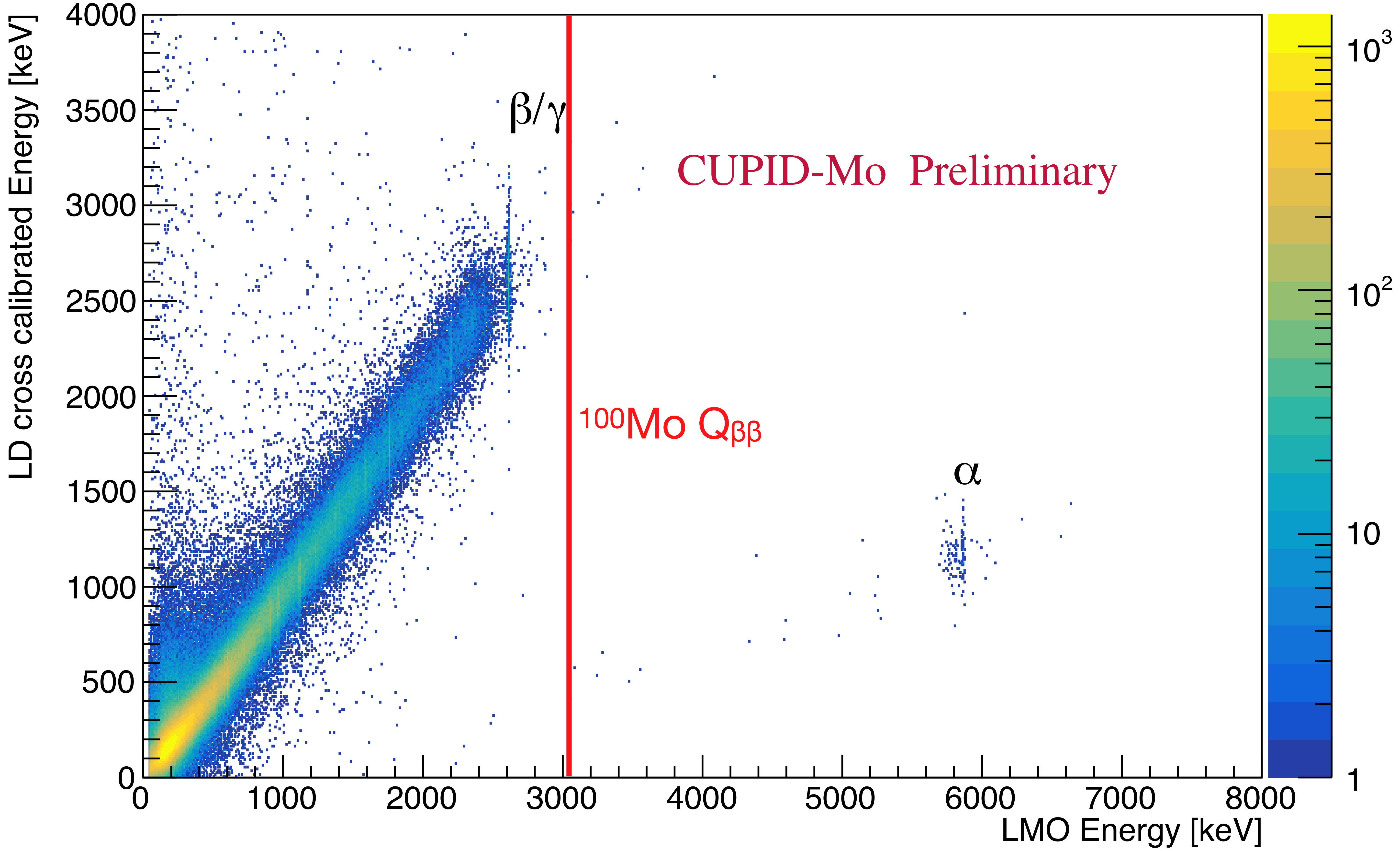
- Scintillating Li_2MoO_4 crystals ⟶ Heat signal ✔, Light signal ✔, PID ✔
- Isotope: ^{100}Mo ⟶ $Q_{\beta\beta}$ = (3034.40 ± 0.17) keV significant β/γ reduction
- < 10% isotopic abundance: enrichment recommended

The CUPID detection technique

Scintillating Bolometer



Particle Identification



The CUPID project: the collaboration

CUORE
Experience in operating ton-scale cryogenic bolometers for years

+

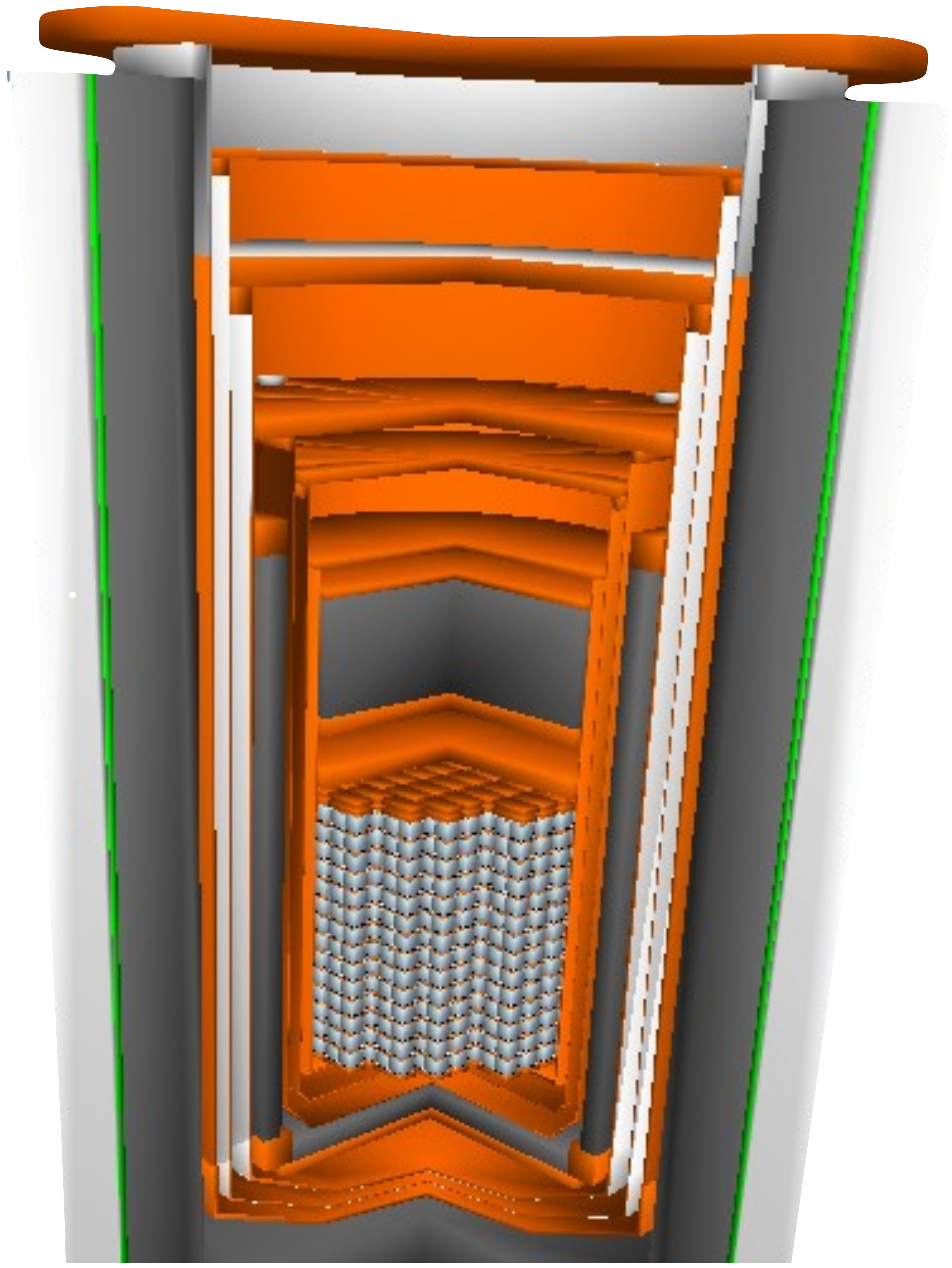
CUPID-0 and CUPID-Mo
Experience in operating detectors with particle identification technology

> 150 scientists, ~30 istitutions from all over the world
(Italy ~60 collaborators, US ~40 collaborators, France ~25 collaborators.
Other countries: Ukraine, Russia, Spain, China)

The CUPID project

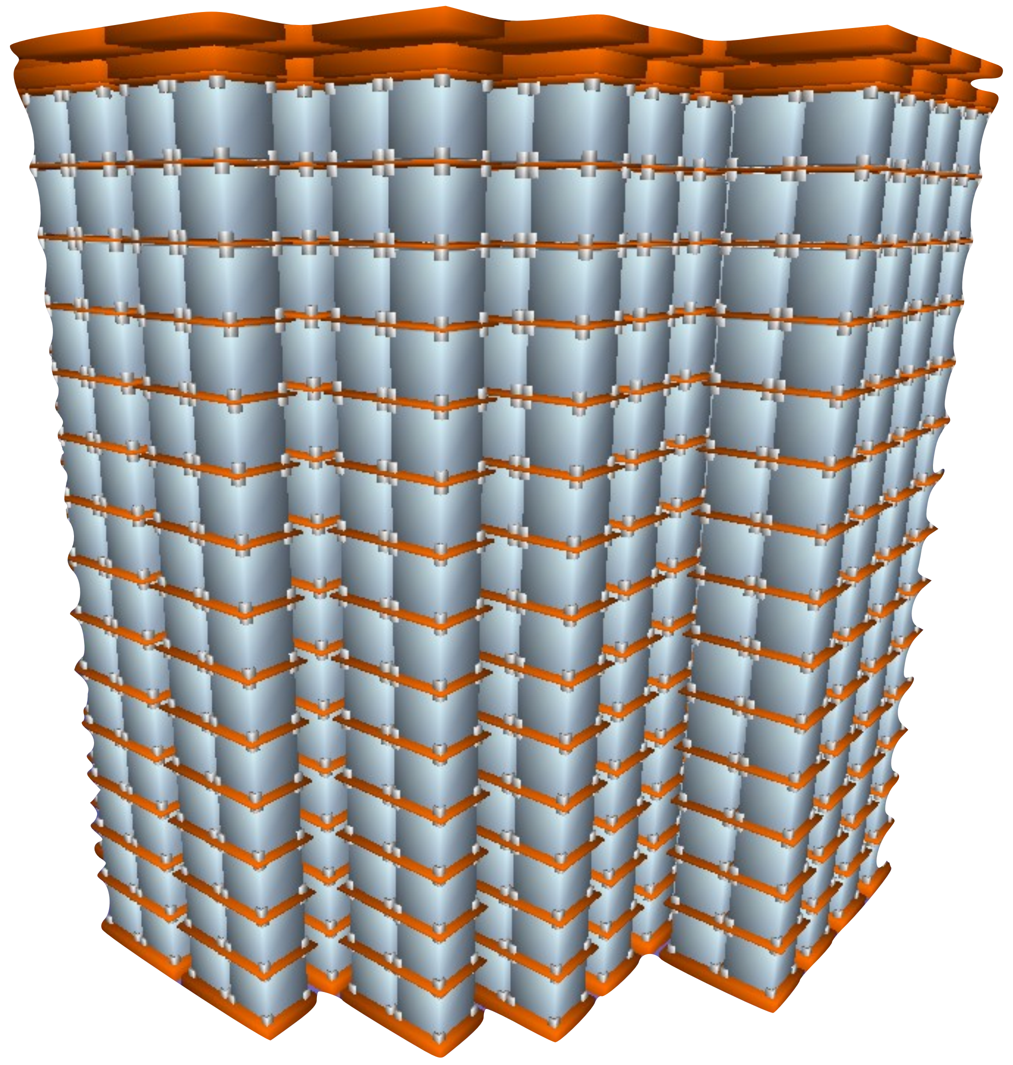
- 1596 scintillating cryogenic Li_2MoO_4 (LMO) crystals (total detector mass: 450 kg)
- Each crystal will be instrumented with a top and bottom Ge light detectors (LDs) with SiO anti-reflective coating (1710 LDs in total)
- 95% enrichment in ^{100}Mo: 240 kg of ^{100}Mo
- 57 towers of 28 crystals arranged in 14-floors of 2x1 crystal pairs. Gravity-assisted design (see next slide)
- Will be hosted by the CUORE cryostat, the CUORE towers will be replaced by the CUPID ones
- 10 years foreseen runtime

https://doi.org/10.48550/arXiv.1907.09376



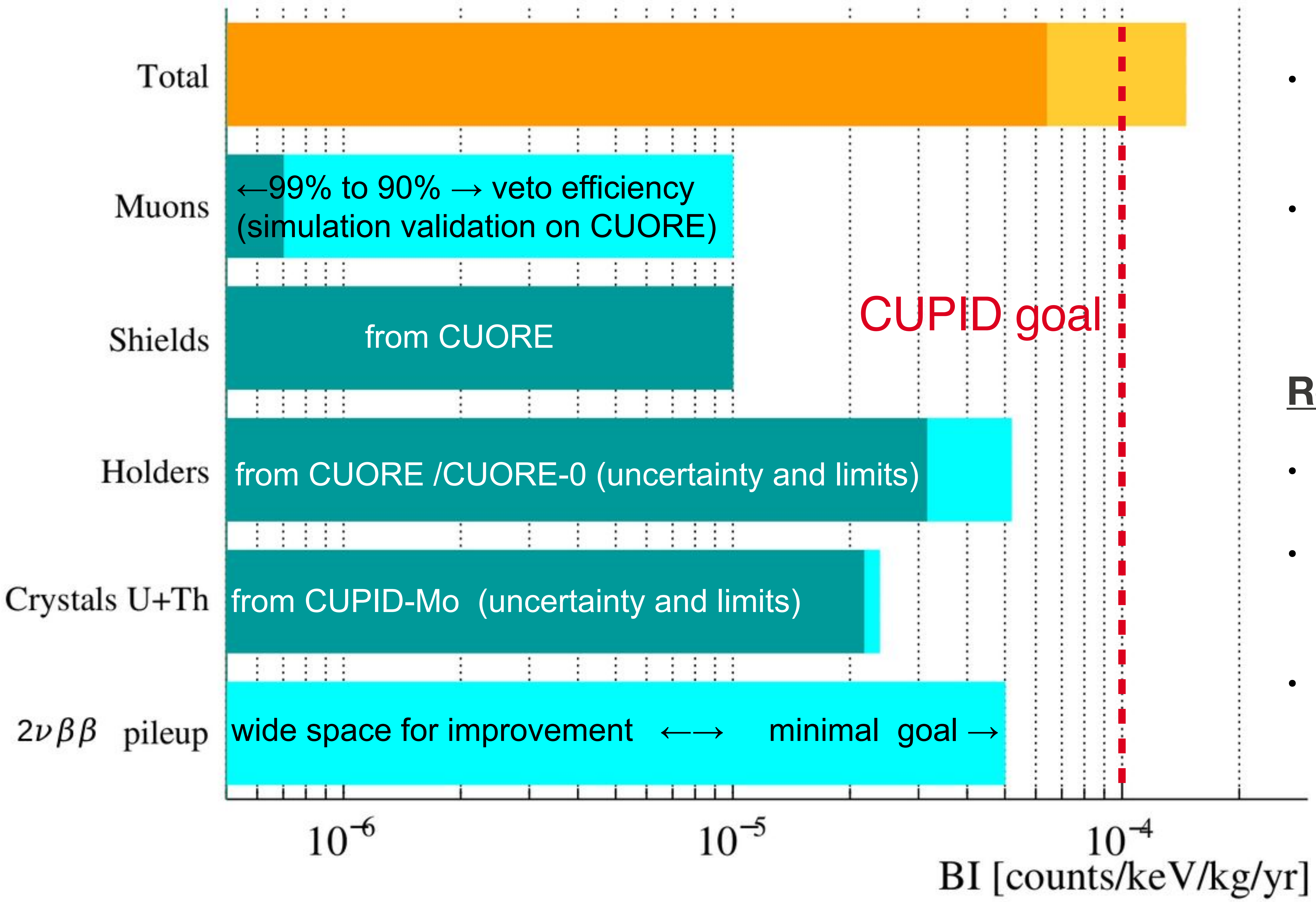
CUPID physics goals:

Background Index	**< 10^{-4} counts/keV/kg/yr**
Energy Resolution (FWHM)	**5 keV**
Sensitivity to 0νββ	**> 10^{27} yr**
$m_{\beta\beta}$	**< (12 - 20) meV**



The CUPID Background Budget

The CUPID background budget is well understood:



- From CUORE, CUPID-0, CUPID-Mo background models
- Materials screening campaigns provided measurements and limits
- Cryogenic infrastructure contamination is well known from CUORE

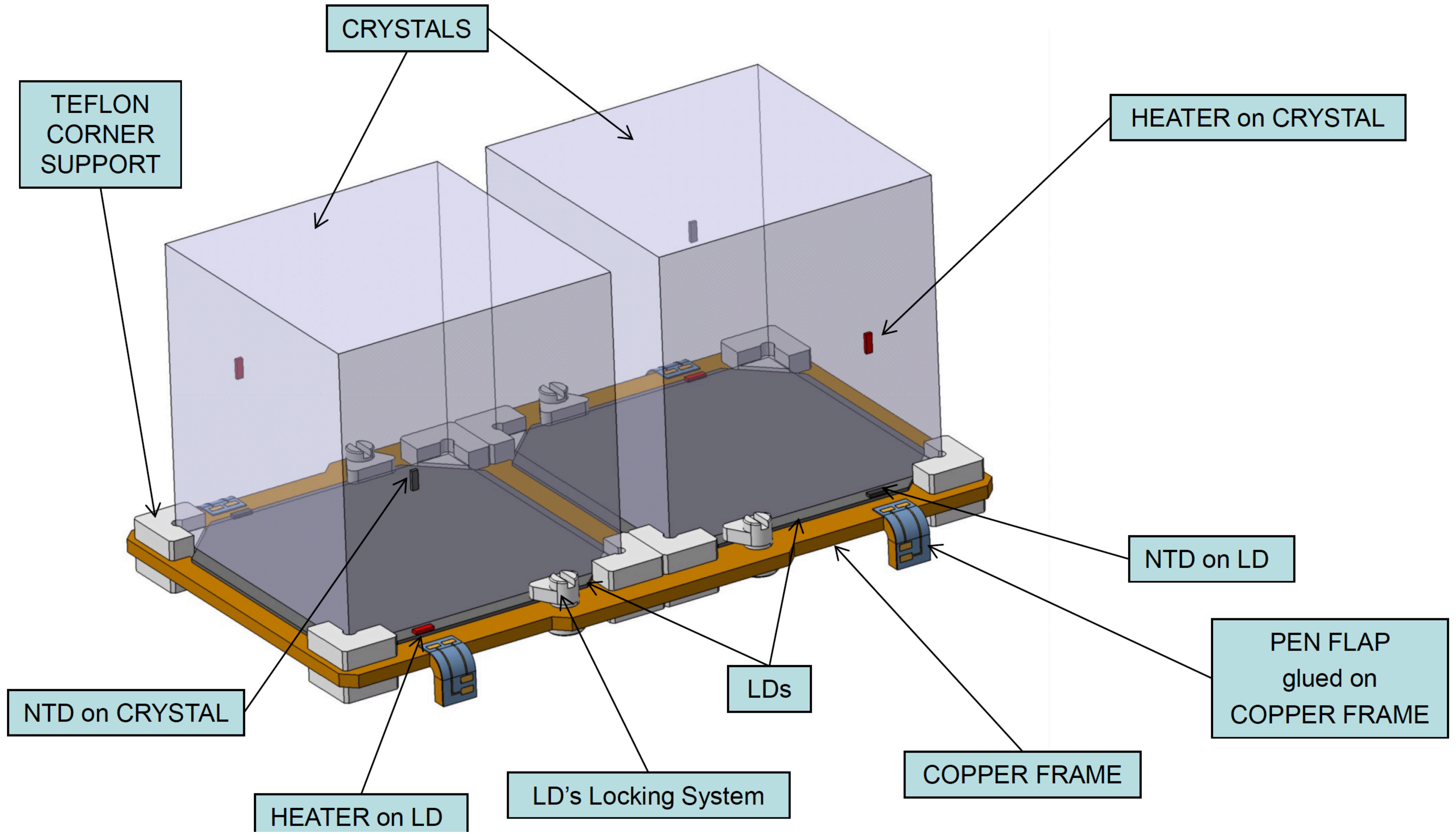
Requirements to reach the 10^{-4} counts/keV/kg/yr goal:

- Crystals purity level needed already calculated
- Cleaning of new towers holders and passive materials will follow the strict CUORE protocol
- Pile-up contribution due to ^{100}Mo 2νββ decay ($T_{1/2} = 7.1 \times 10^{18}$ years) modeled, reduction is possible

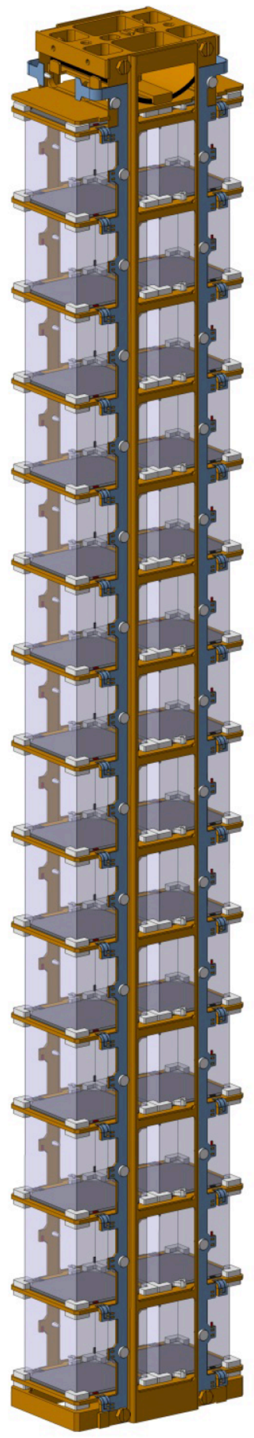
The CUPID project - baseline module

- A single Li_2MoO_4 crystal is cubic shaped 45 x 45 x 45 mm^3, 280 g
- Detector module: 2 LDs lying on copper frames + 1 floor of 2x1 crystals supported by teflon corners + another floor of 2 LDs
- The whole structure is gravity assisted: stack of crystals and light detectors sitting one on top of the other (crystals and LDs separated by angular teflon spacers), easy assembly - no screws, self-aligning structure

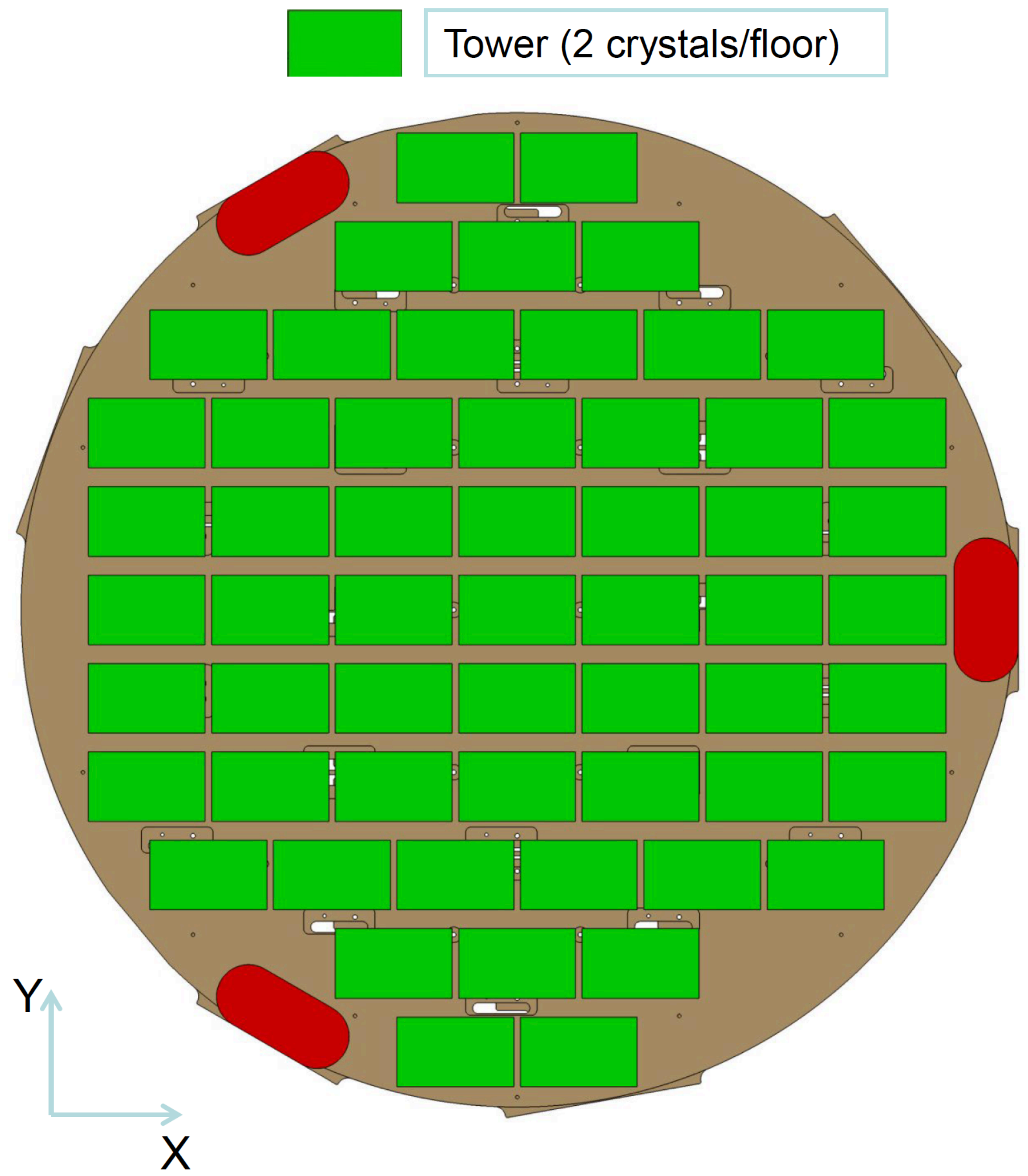
Detector Module



Tower



Tower Arrangement



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Ongoing activities:
Baseline Design Prototype Tower (BDPT)

First CUPID prototype tower!

- 14 floors - 28 crystal from different origin, 30 LDs
- Tunable spring at the top for vibration damping
- Validation of assembly procedure: done ✓
- Validation of mechanical tests and thermalization: done ✓

Next phase: early 2024

✦ Run with Neganov Trofimov Luke (NTL) effect boosted light detectors

✦ Evidence for possible better pile-up discrimination thanks to enhanced signal-to-noise ratio

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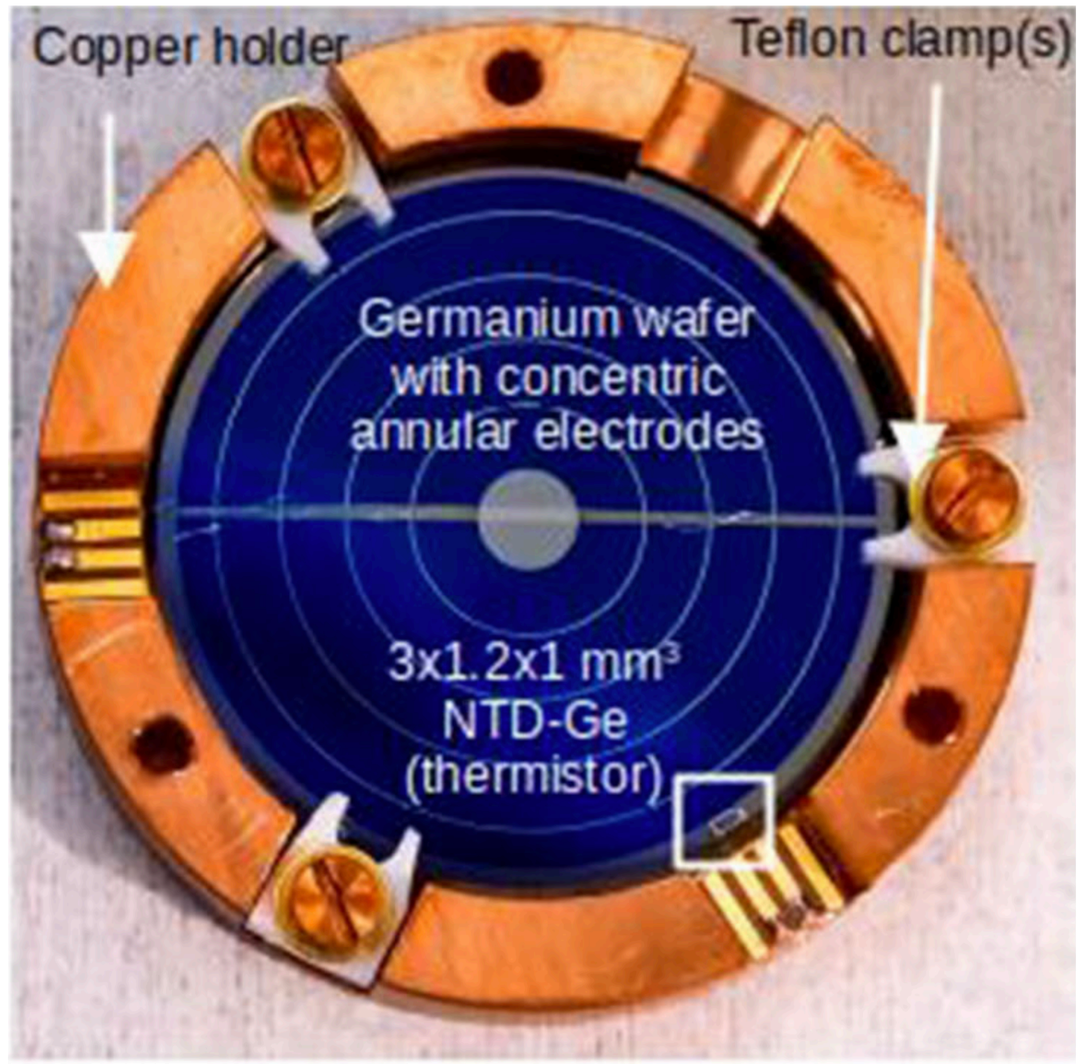
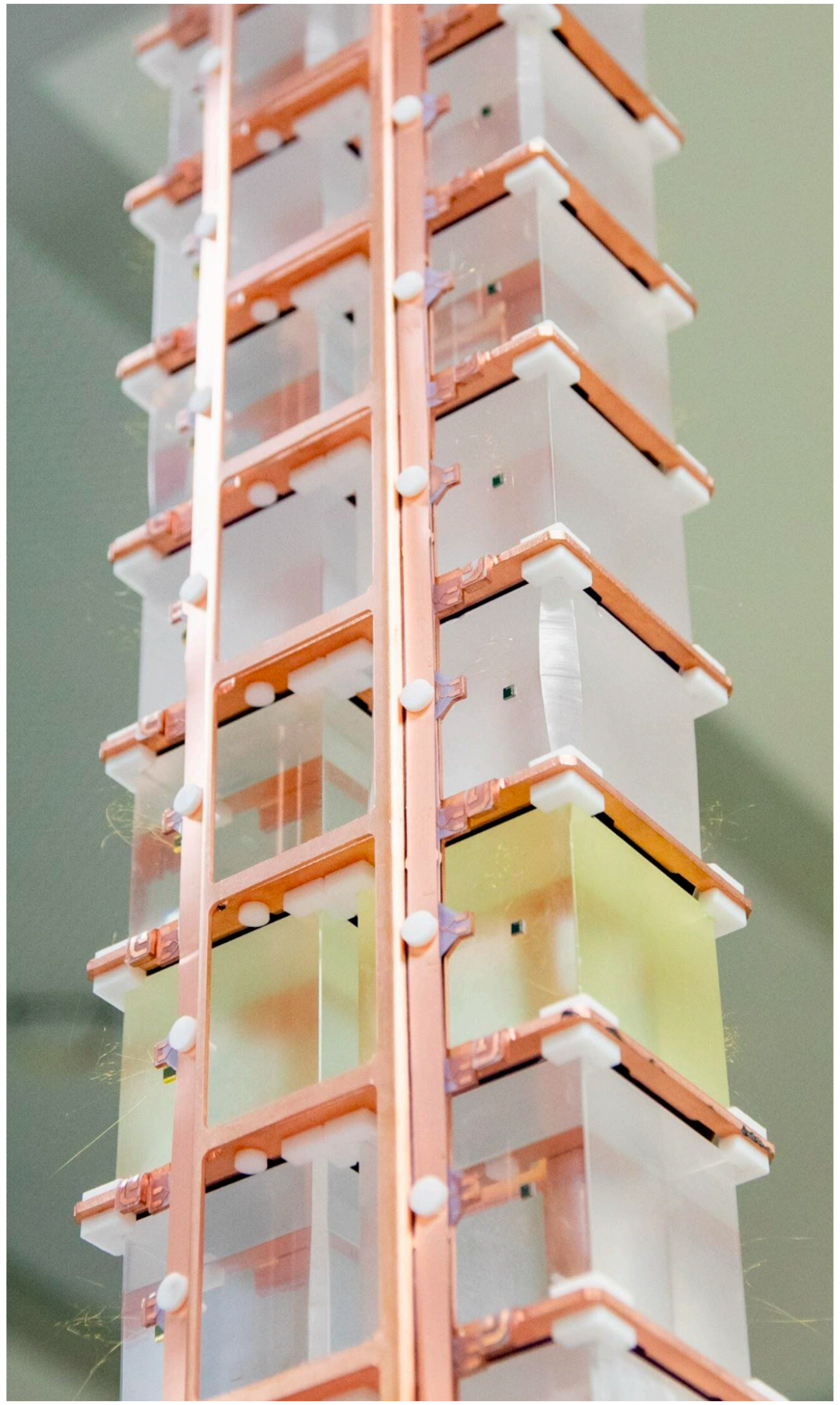
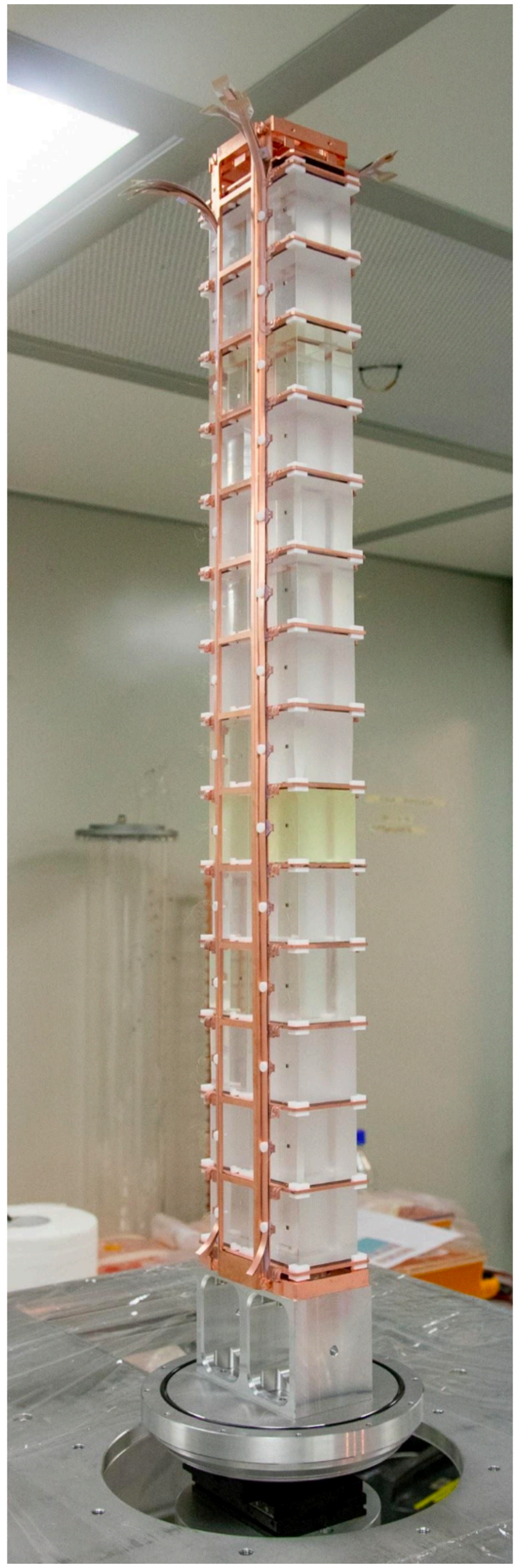
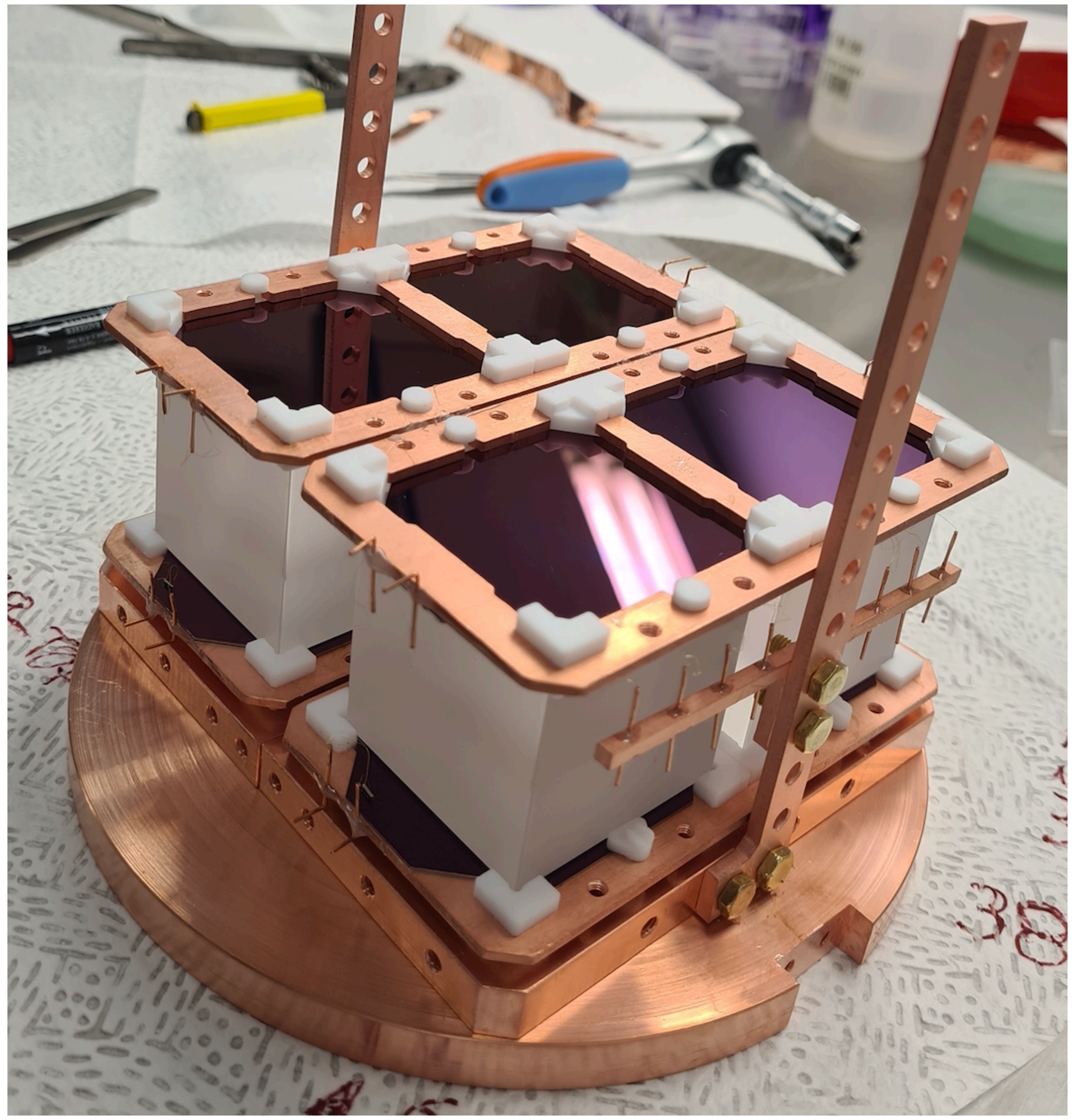
Nucl. Instrum. Methods Phys, Res., A 940 (2019) 320–327



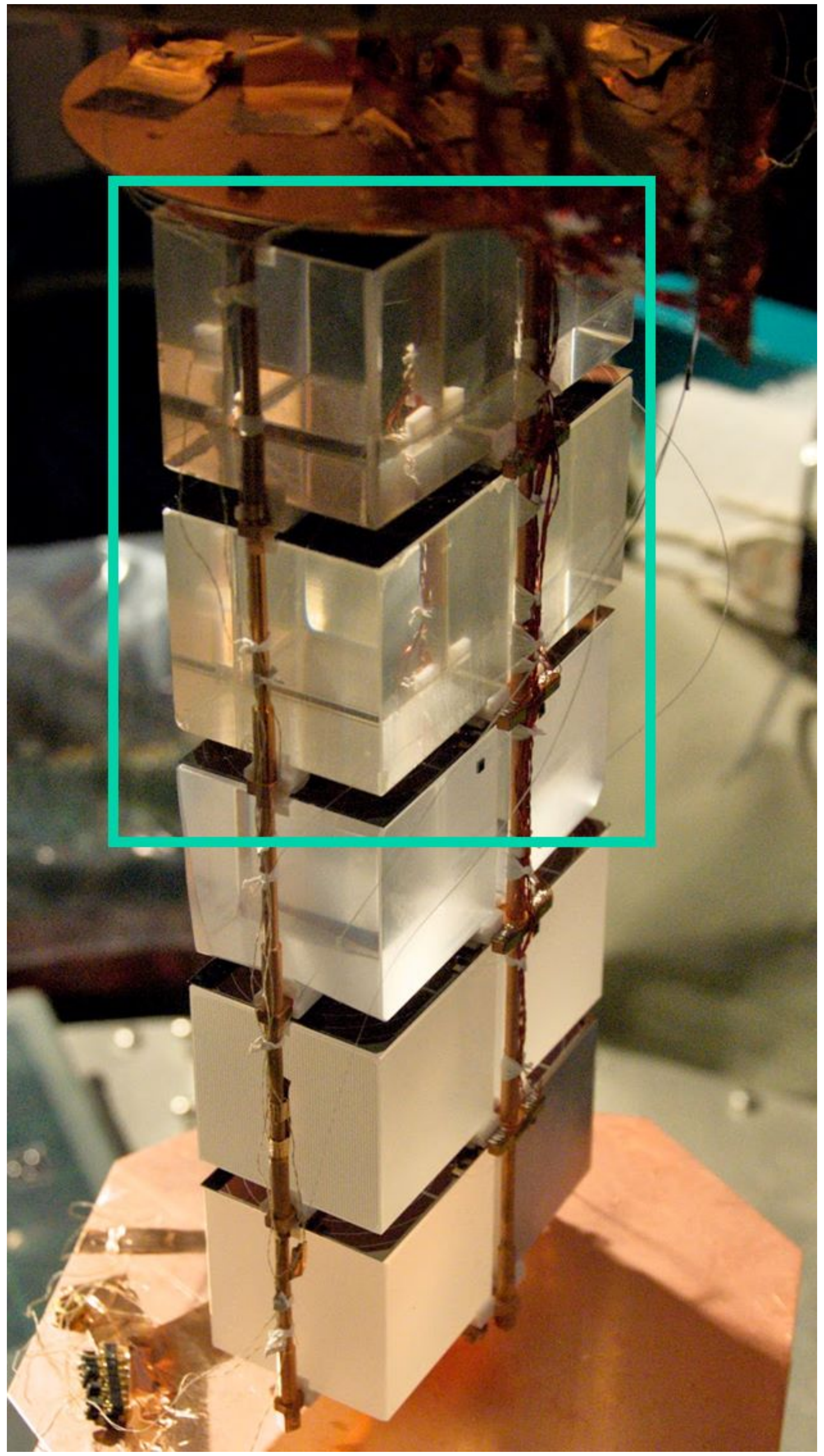




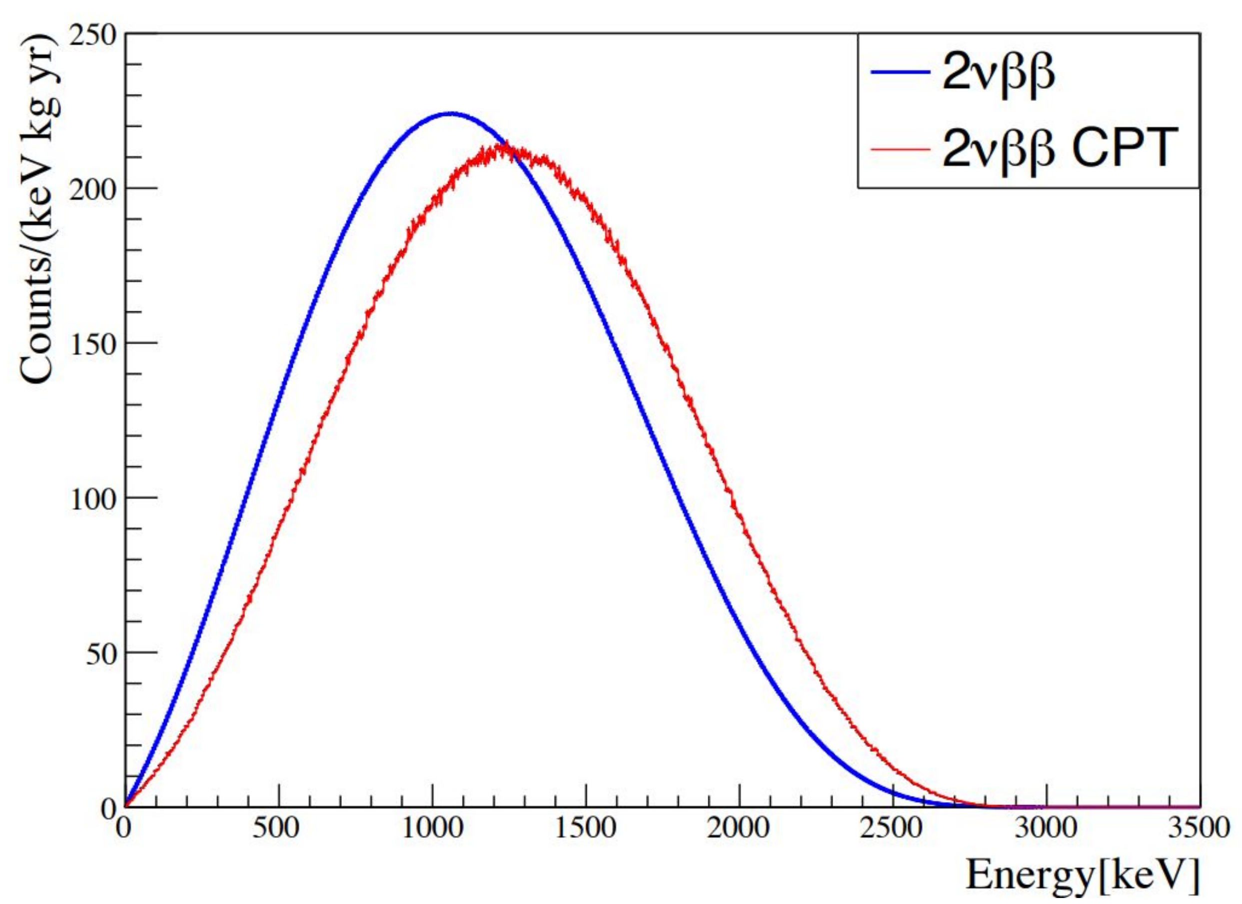
Ongoing activities:
CUPID Crystals Validation Runs (CCVR)

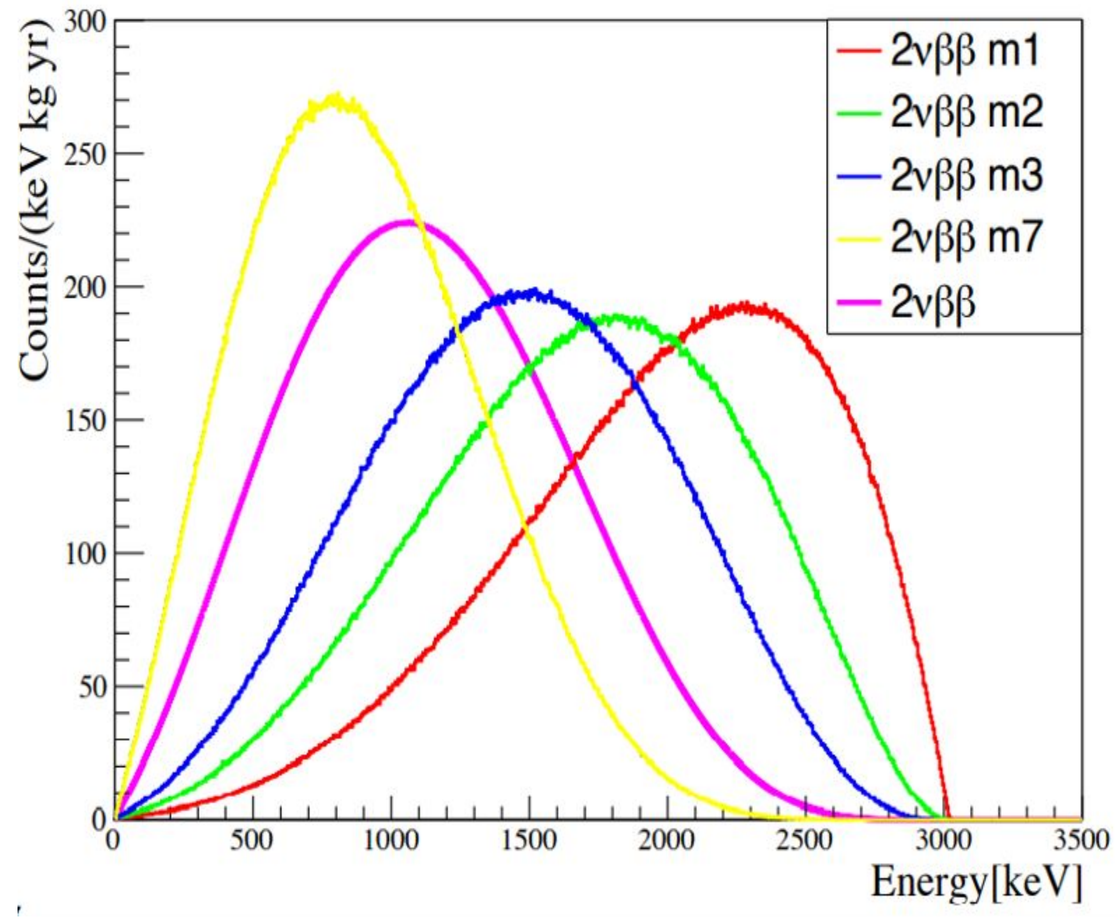


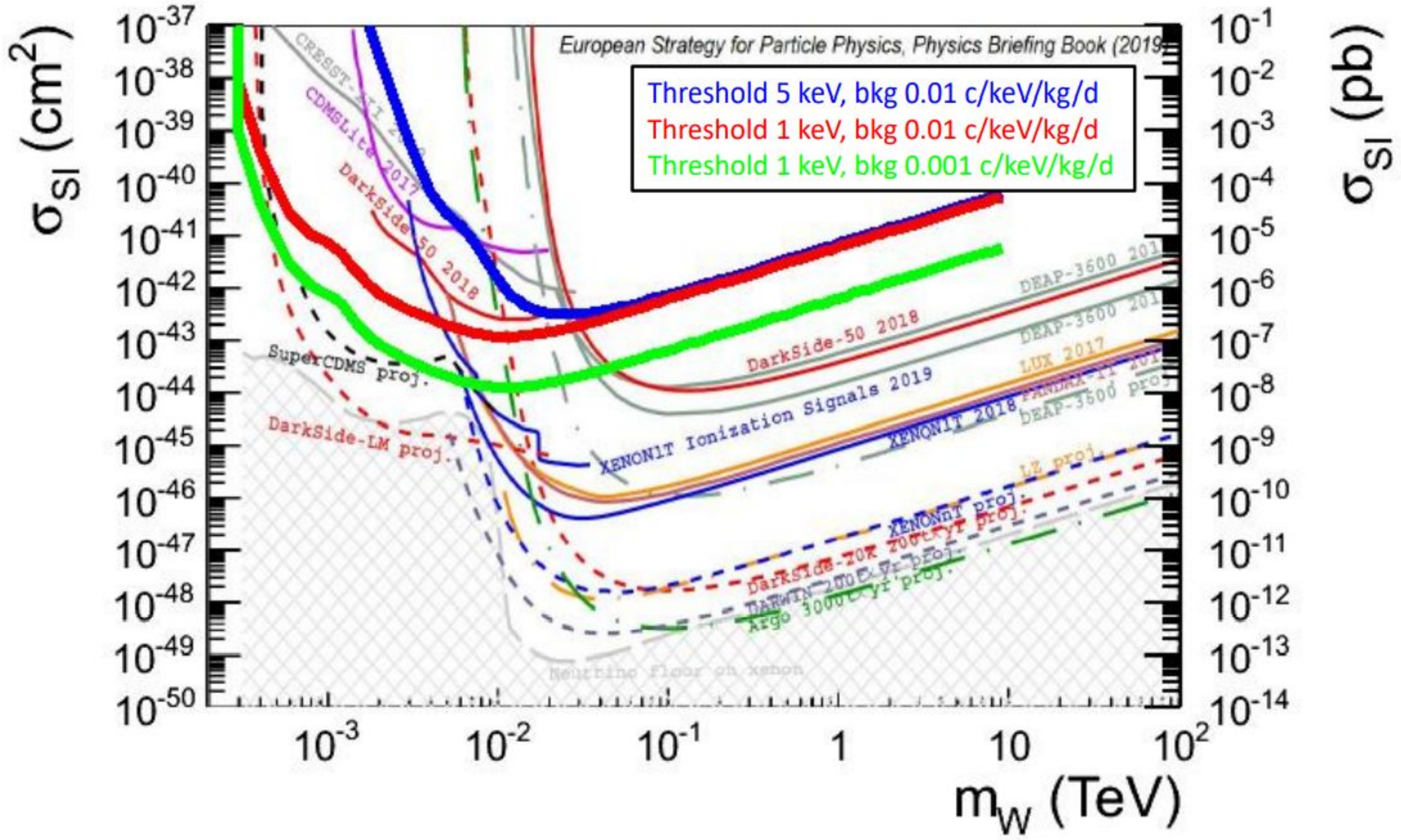
- Tests at different facilities:
  Laboratori Nazionali del Gran Sasso,
  CROSS Facility @ Canfranc Laboratories
- Validation of contamination level wrt the CUPID background requirements
- Validation of crystal production process
- Runs with LDs for crystals performance test (energy resolution, alpha events discrimination power)
- Run time required to reach the sensitivity goal on U, Th and ^{40}K is ~4 weeks



Other possible rare events searches







CUPID is suitable for the investigation of several other interesting rare physics processes:

Spectral shape

- Decays to excited states analyses
- Single State VS Higher State Dominance
- CPT violation search
- Majoron emission search

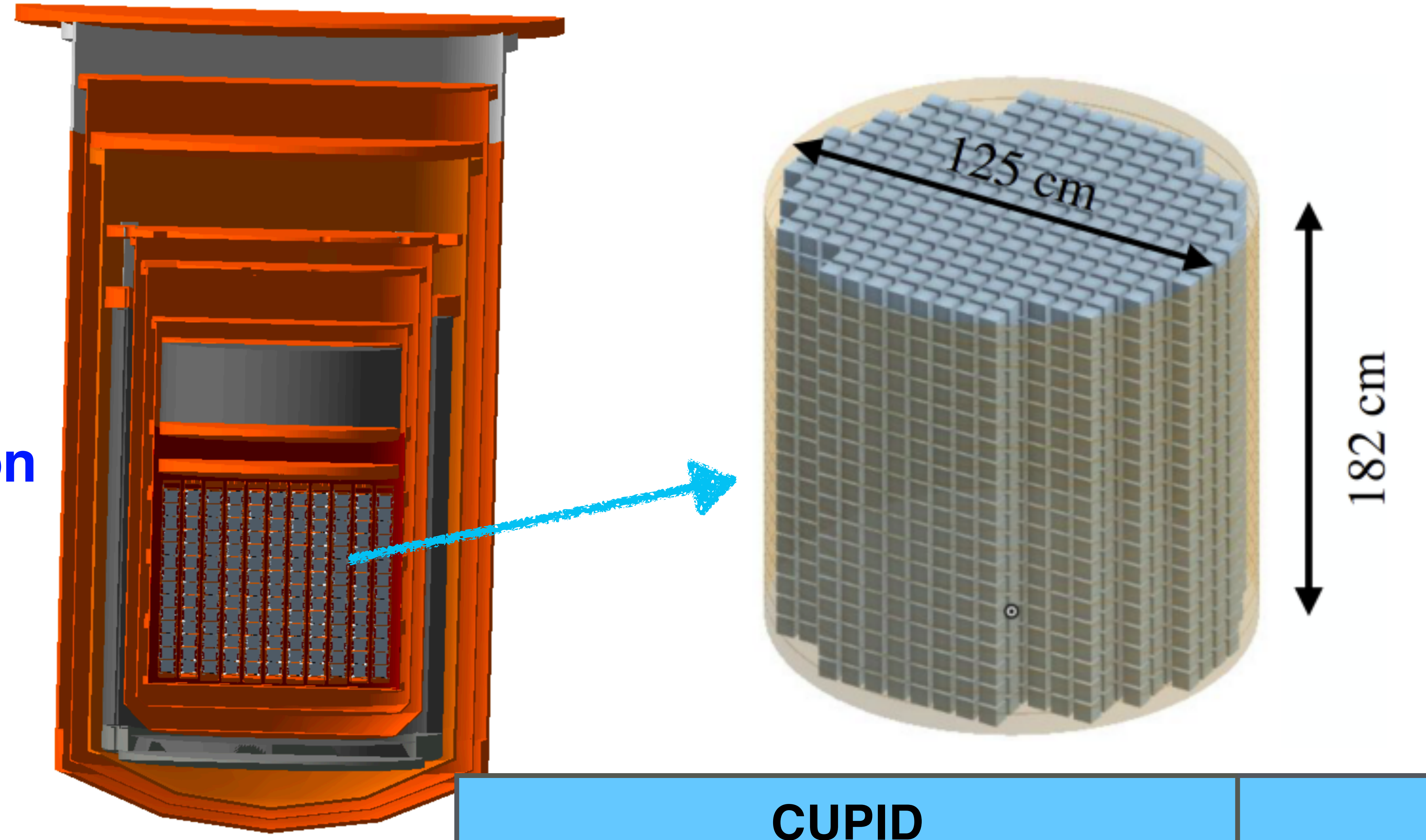
Low energy

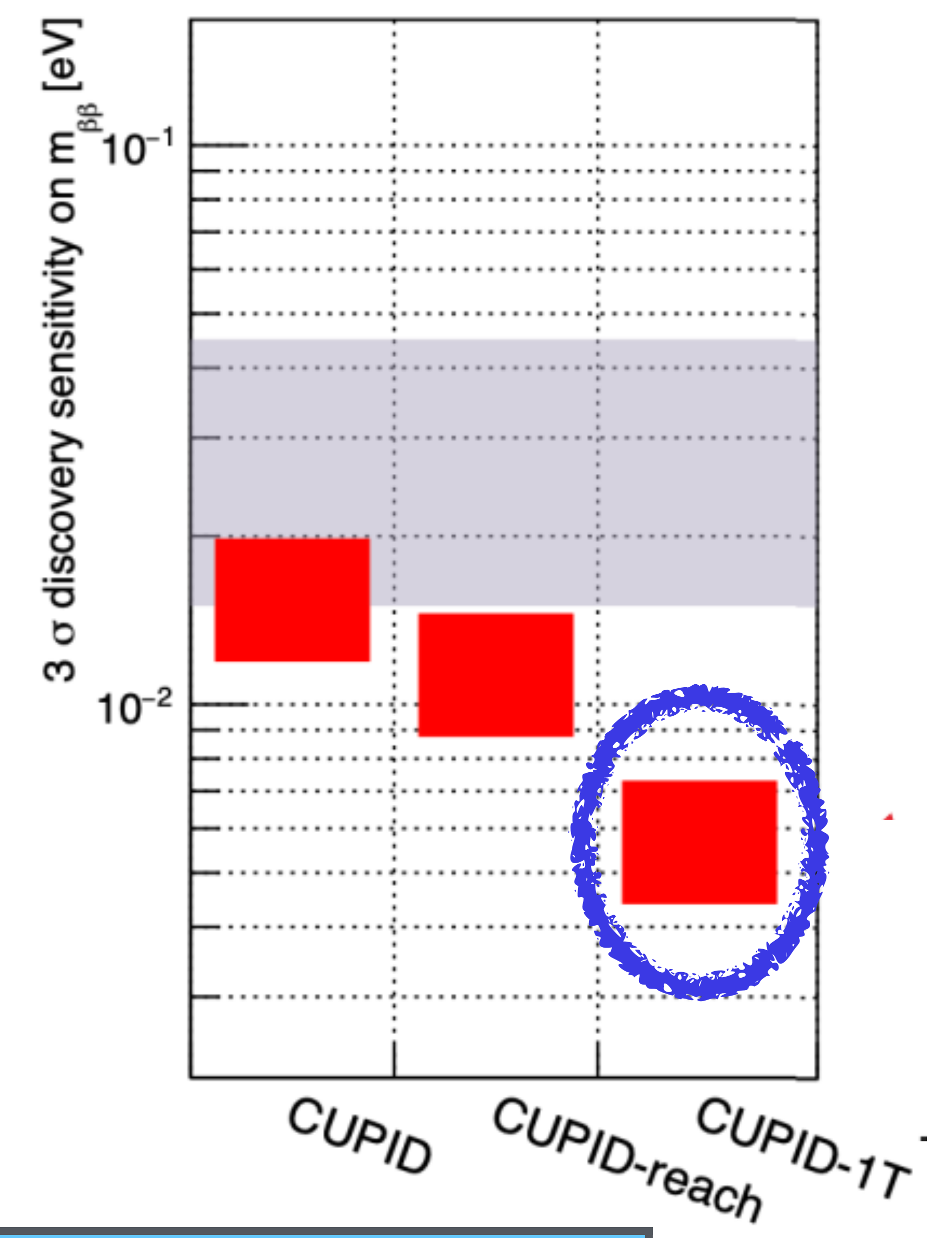
- Direct dark matter search
- Supernova neutrinos via coherent scattering
- Solar axions search

…………………

Ultimate goal: CUPID 1-ton

The CUPID future: next-to-next generation





	CUPID	CUPID 1-ton
^{100}Mo mass	240 kg	**1000 kg**
Cryogenic facility	same as CUORE	**new larger cryostat or multi-cryostat setup**
Background Index	< 10^{-4} counts/keV/kg/yr	**$5 \cdot 10^{-6}$ counts/keV/kg/yr**
Sensitivity to 0νββ	> 10^{27} yr	**> $9.1 \cdot 10^{27}$ yr**
$m_{\beta\beta}$	< (12 - 20) meV	**< (4.1 - 6.8) meV**

Summary and conclusions

- The currently operating CUORE has demonstrated that a ton-scale experiment using cryogenic crystals can run for O(years) in stable conditions
- **CUPID** is a next generation experiment and will be able to **explore the inverted mass ordering region**
- **CUPID physics goals: BI < 10^{-4} counts/keV/kg/yr , $T_{1/2}$ > 10^{27} years, $m_{\beta\beta}$ < (12 - 20) meV**
- Several ongoing activities to finalize the detector design!
- Looking at next-to-next generation future experiment towards NI exploration (CUPID 1-ton)

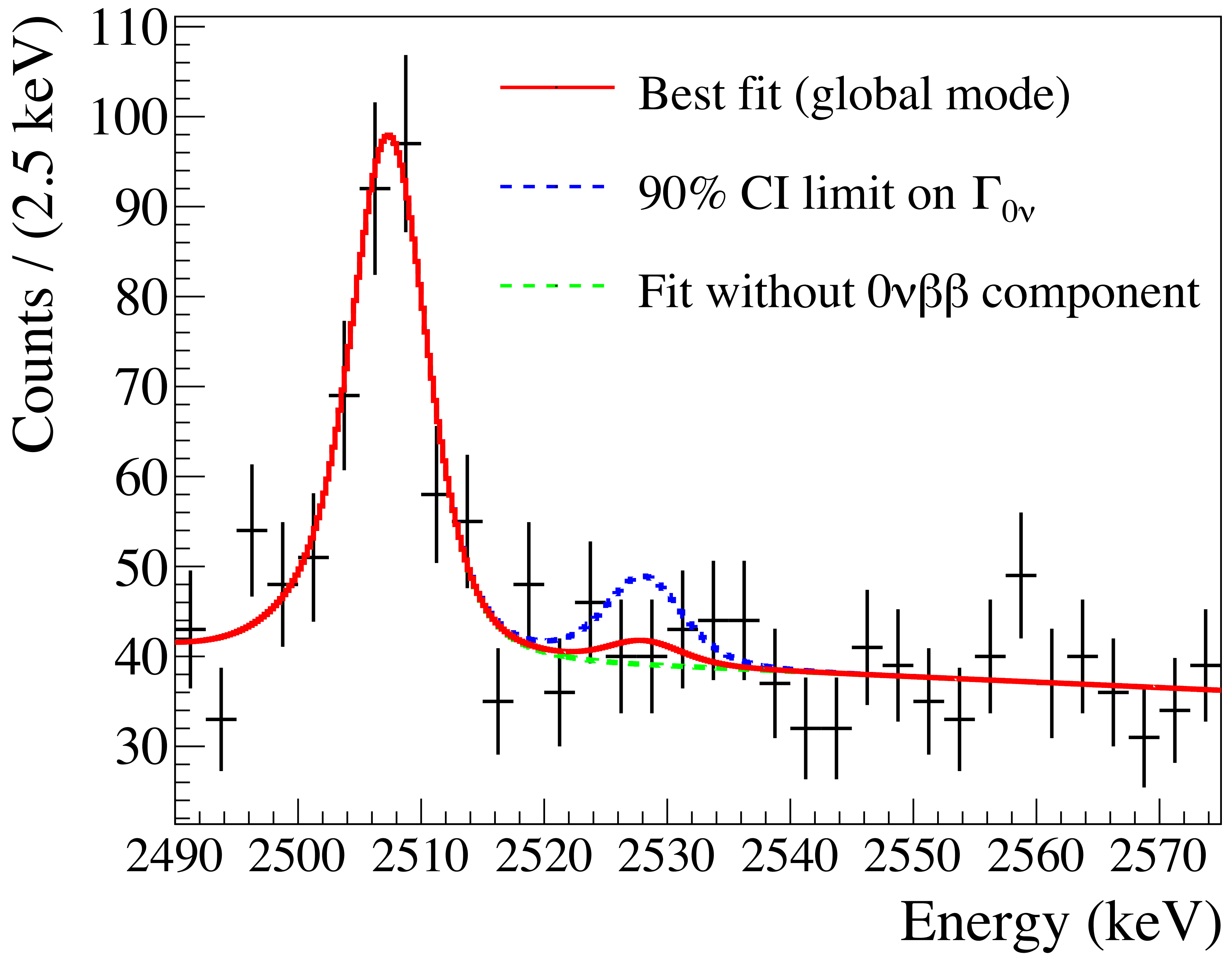
Thanks for your attention!

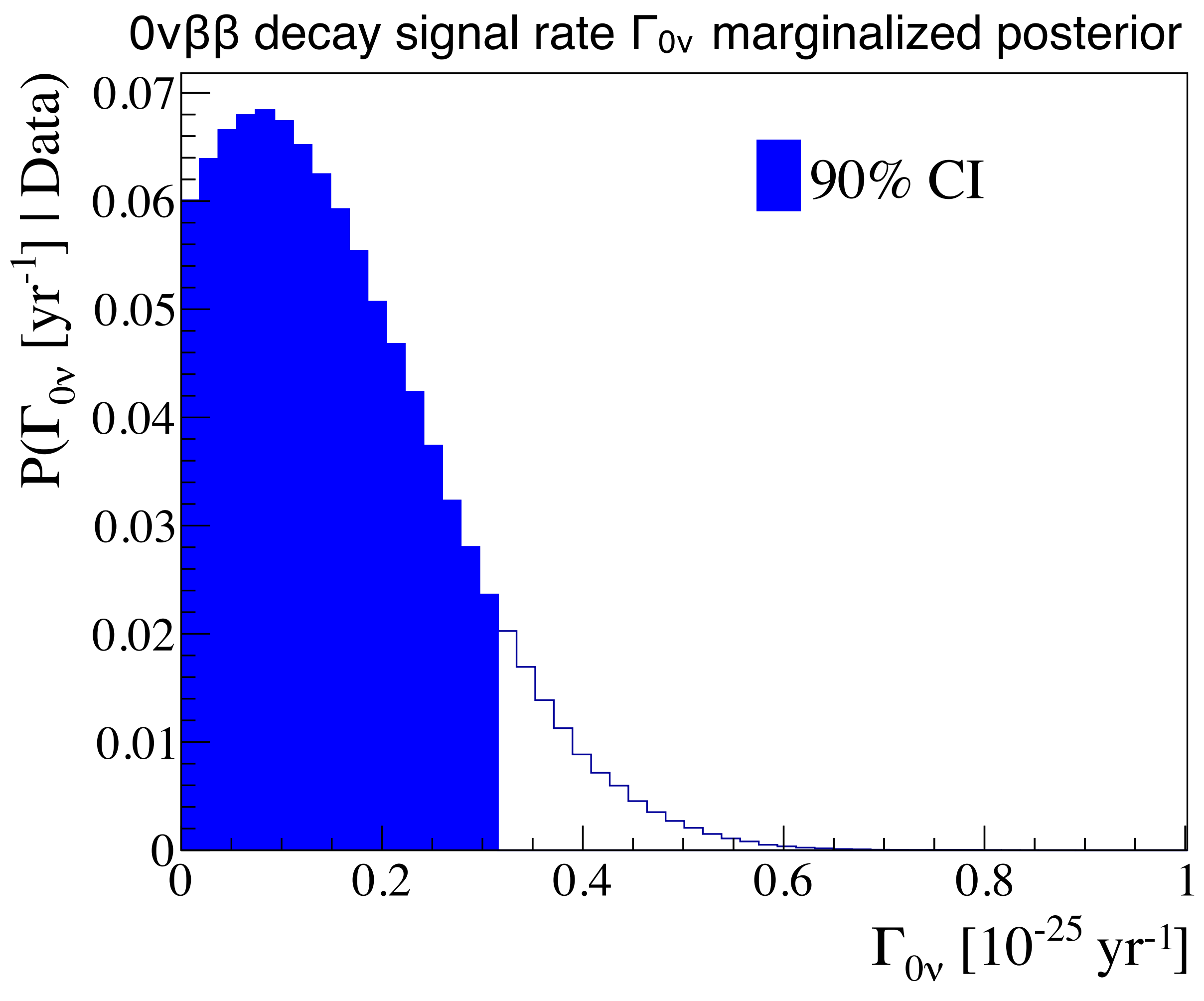
Backup

Latest CUORE results

- Simultaneous unbinned Bayesian fit for each detector-dataset (BAT)
- Uniform prior on the signal rate $\Gamma_{0\nu}$
- ROI: [2490 - 2575] keV
- **Total TeO_2 exposure: 1038.4 kg · yr** (15 datasets)
- No evidence of ^{130}Te 0νββ decay is observed
- Systematics effects as nuisance parameters in the Bayesian fit (0.8% total effect on the $\Gamma_{0\nu}$ limit):

- ***Efficiencies*** (reconstruction, anti-coincidence, PSD, containment)
- ***^{130}Te isotopic abundance***
- ***$Q_{\beta\beta}$***
- ***Lineshape parameters*** (energy bias and resolution scaling)





Bayesian limit: **$T_{1/2}$ > 2.2 · 10^{25} yr (90% C.I.)**

Majorana mass: **$m_{\beta\beta}$ < 90 - 305 meV (90% C.I.)**

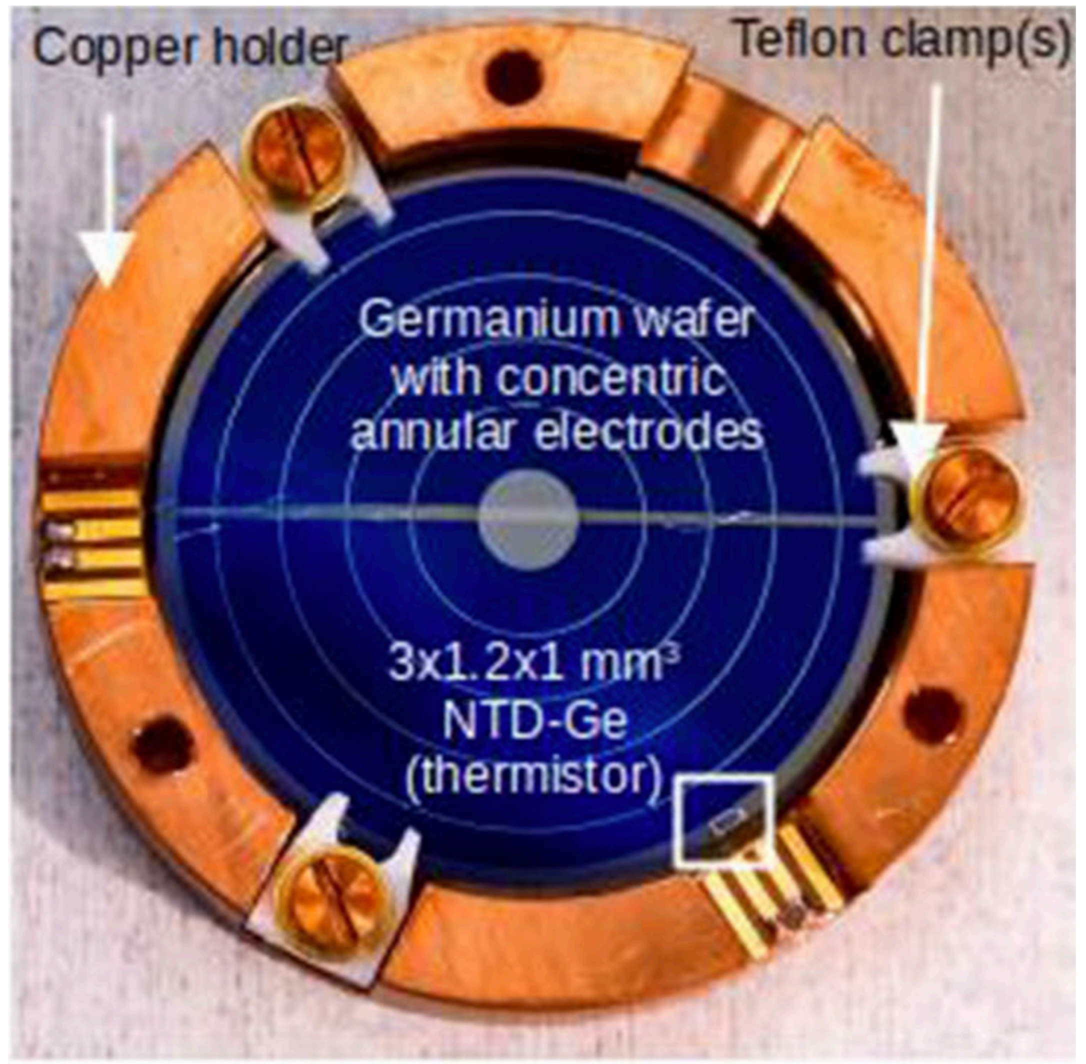
Background Index: **BI = (1.49 ± 0.04) · 10^{-2} cts/keV/kg/yr**

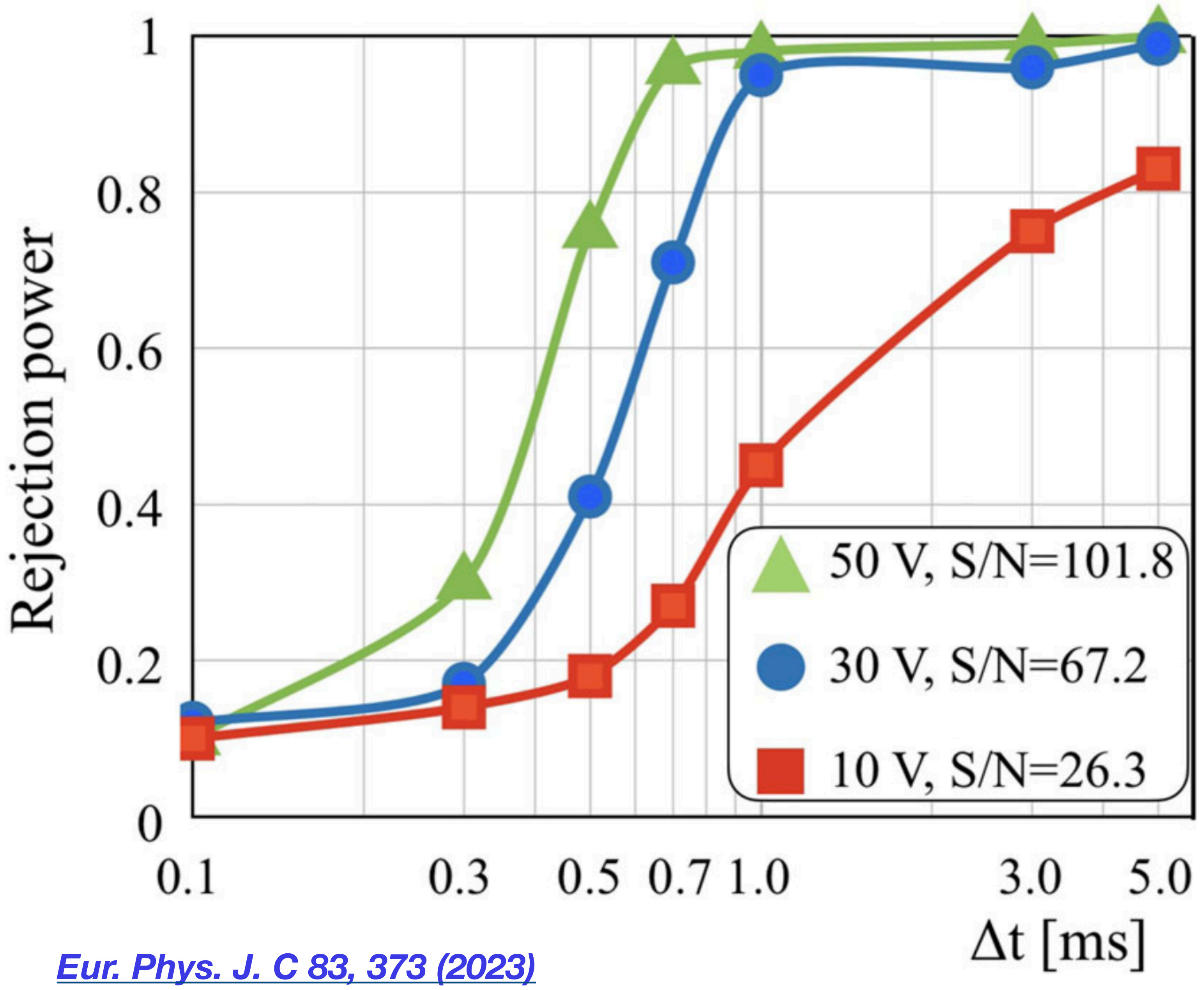
Nature 604, 53–58 (2022)

Neganov Trofimov Luke boosted light detectors

- The Neganov Trofimov Luke effect can be used to enhance the signal-to-noise ratio of high purity semiconductor bolometric detectors
- When a particle interacts depositing an energy E_0, an extra heat is produced if the charge carriers are drifted by an electric field
- The total energy measured is then: $E_{TOT} = E_0(1 + \frac{q \cdot V_{el} \cdot \eta}{\epsilon}) = E_0 \cdot G_{NTL}$

V_{el} = bias
η = amplification efficiency
ϵ = average energy require to generate e-h pair





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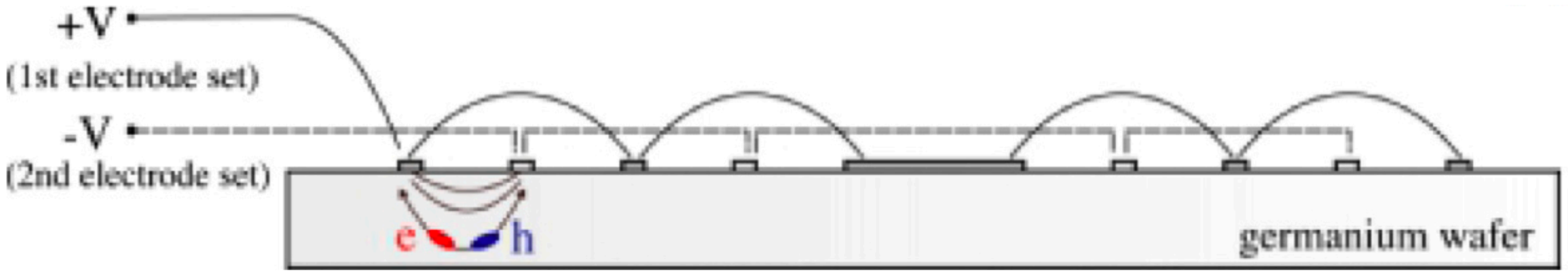
If $V_{el} \gg \frac{\epsilon}{q}$ → E_{TOT} is mainly due to the NTL effect → **the detector behaves as a voltage-controlled charge-to-heat amplifier!**



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