NuPhys 2023

PROSPECTS IN NEUTRINO PHYSICS

Latest results of the **CUORE experiment** and the status and prospects of the **CUPID experiment**

CUORE CUPID

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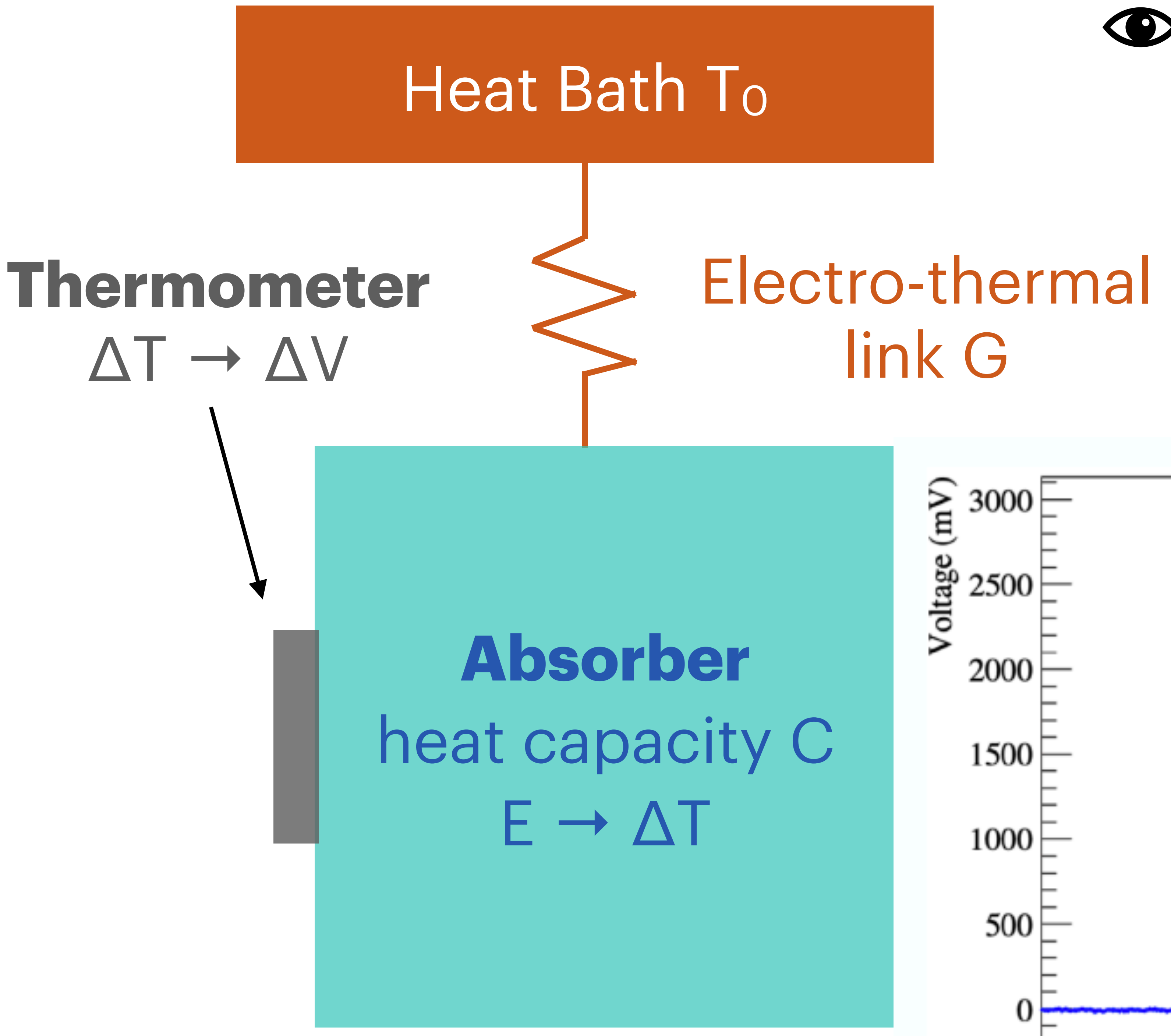
Calorimetric search for $0\nu\beta\beta$ decay

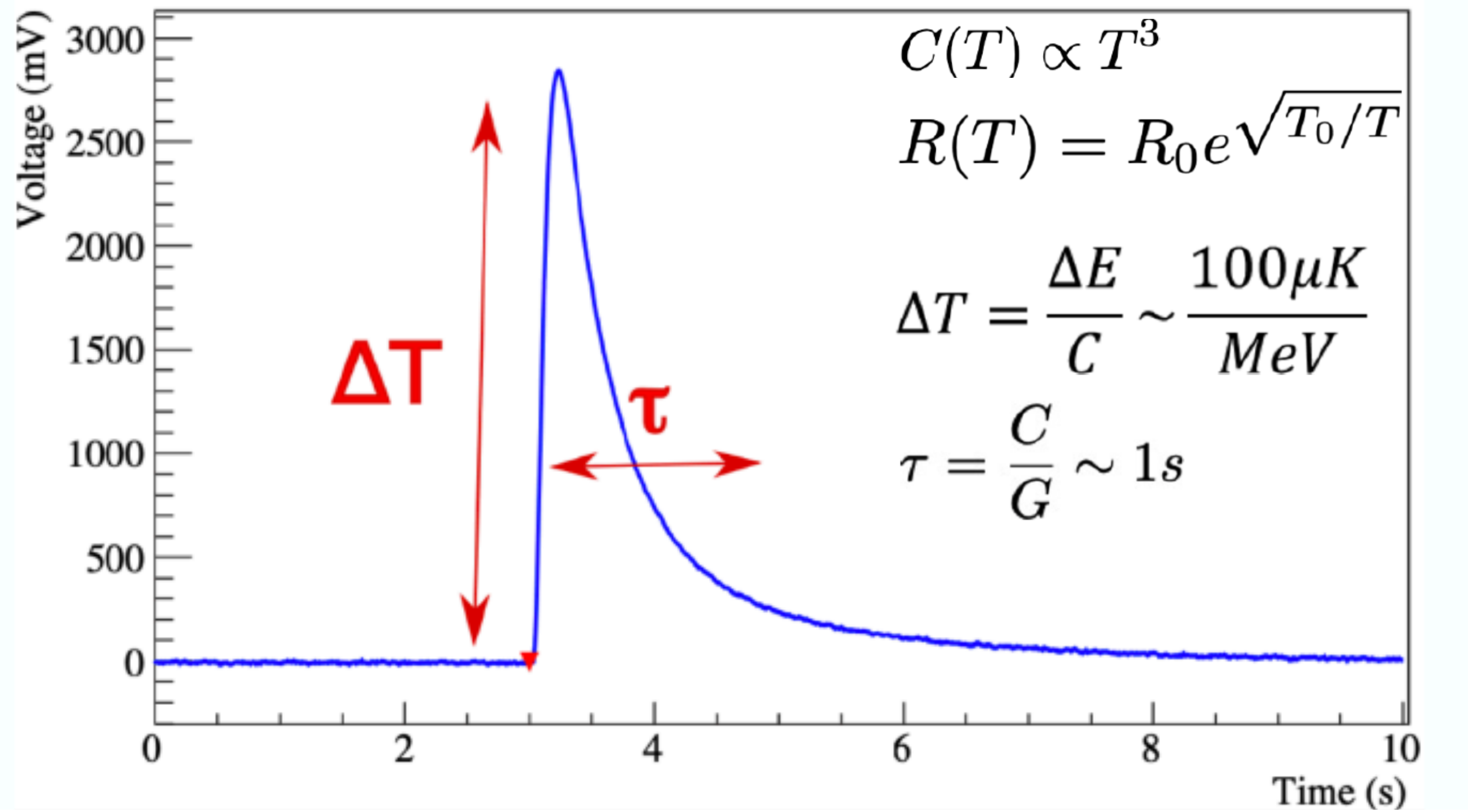
with Cryogenic Detectors (or Bolometers)

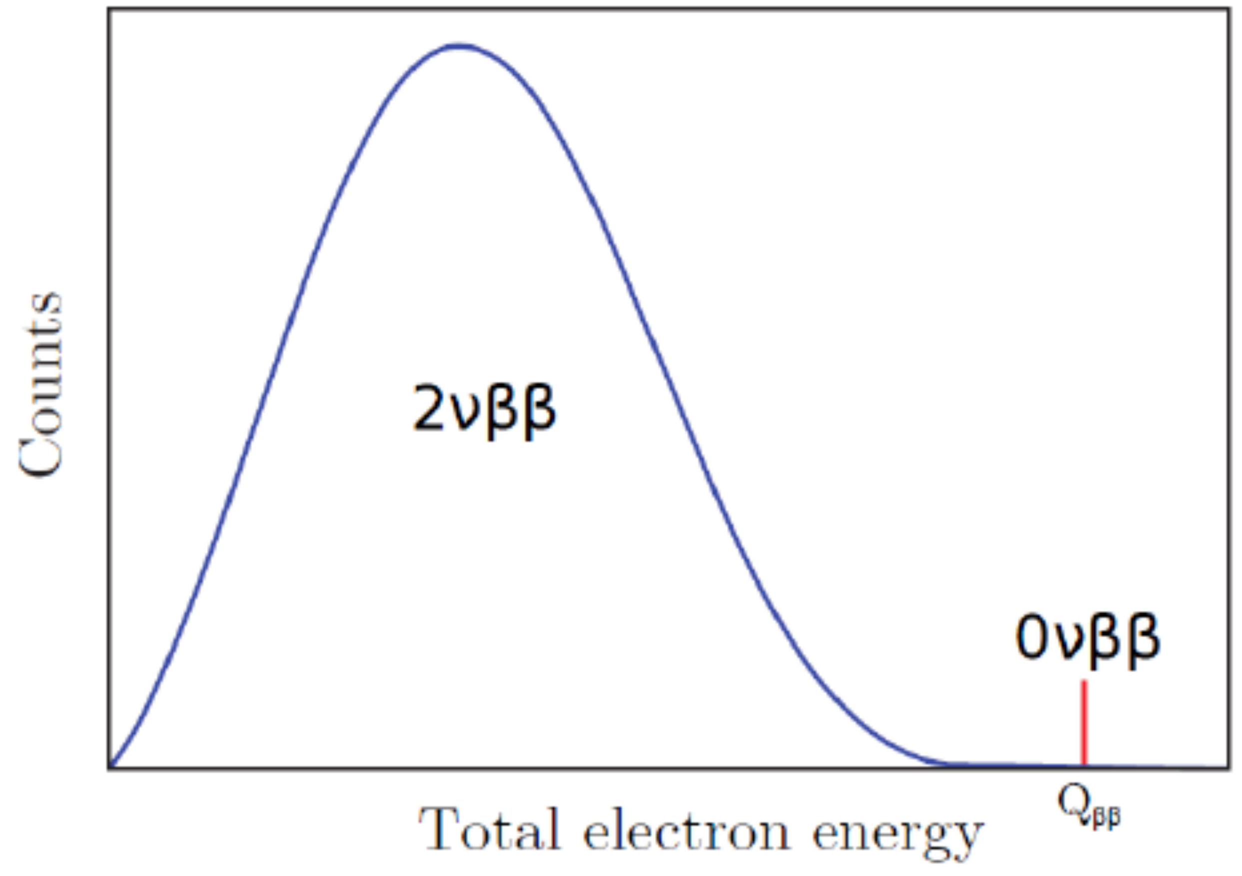
Properties of cryogenic detectors

- Excellent energy resolution: $(k_B C T^2)^{1/2}$
- Large choice of absorber materials
- True calorimeters
- Source ≡ Detector: high efficiency



J.Low Temp.Phys.151(2008)5





Experimental sensitivity:
(for bkg ≠ 0)

$$S^{0\nu}(\tau_{1/2}) \propto \epsilon \cdot \frac{i.a.}{A} \sqrt{\frac{M\, t_{meas}}{\Delta E \cdot bkg}}$$

- **ε** detector efficiency
- **i.a.** $0\nu\beta\beta$ isotope abundance
- **A** atomic mass
- **ΔE** FWHM resolution
- **M** total active mass
- $\mathbf{t_{meas}}$ measuring time
- **bkg** background @ ROI in counts/keV/kg/y

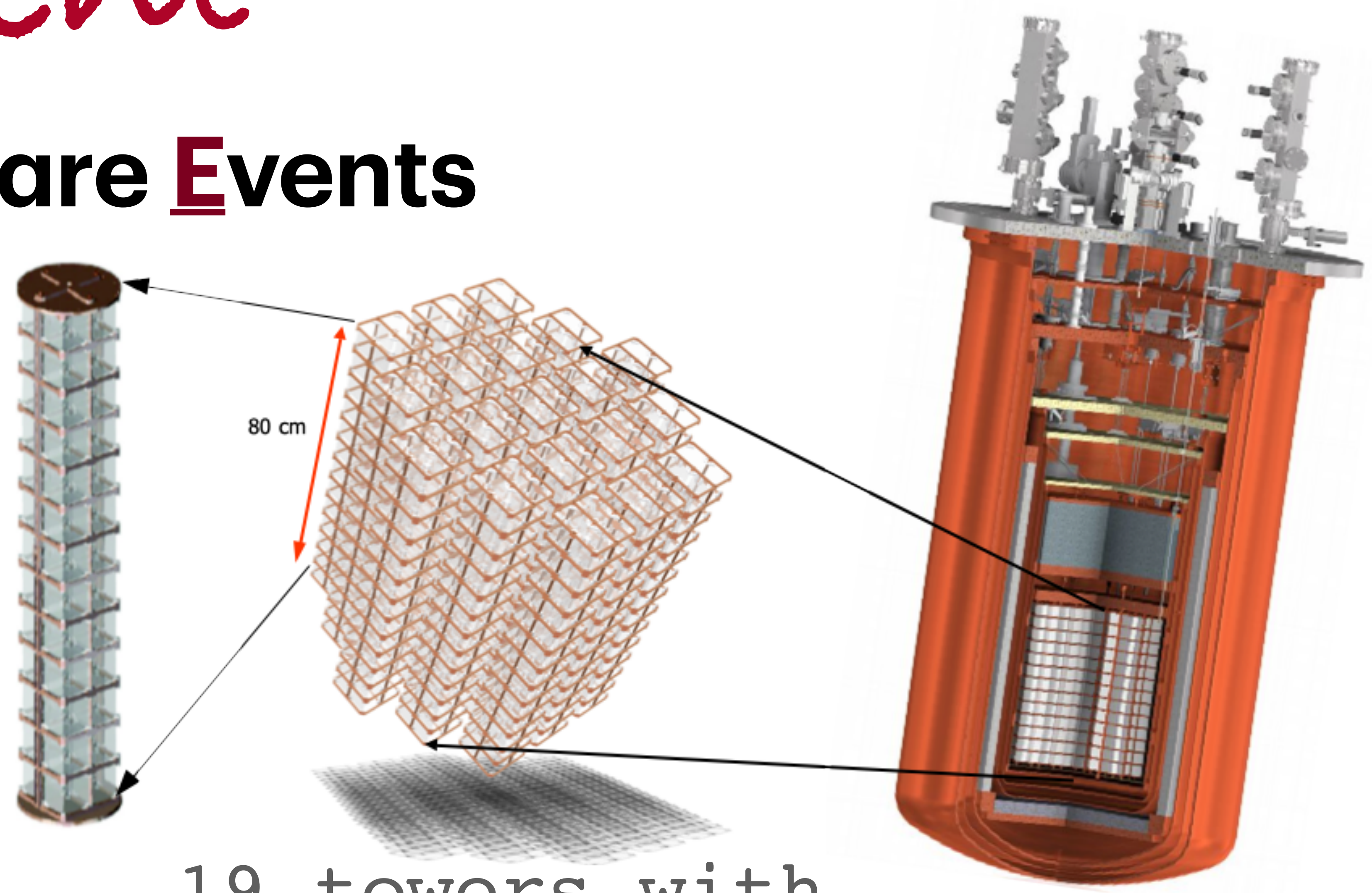
The CUORE experiment

Cryogenic Underground Observatory for Rare Events

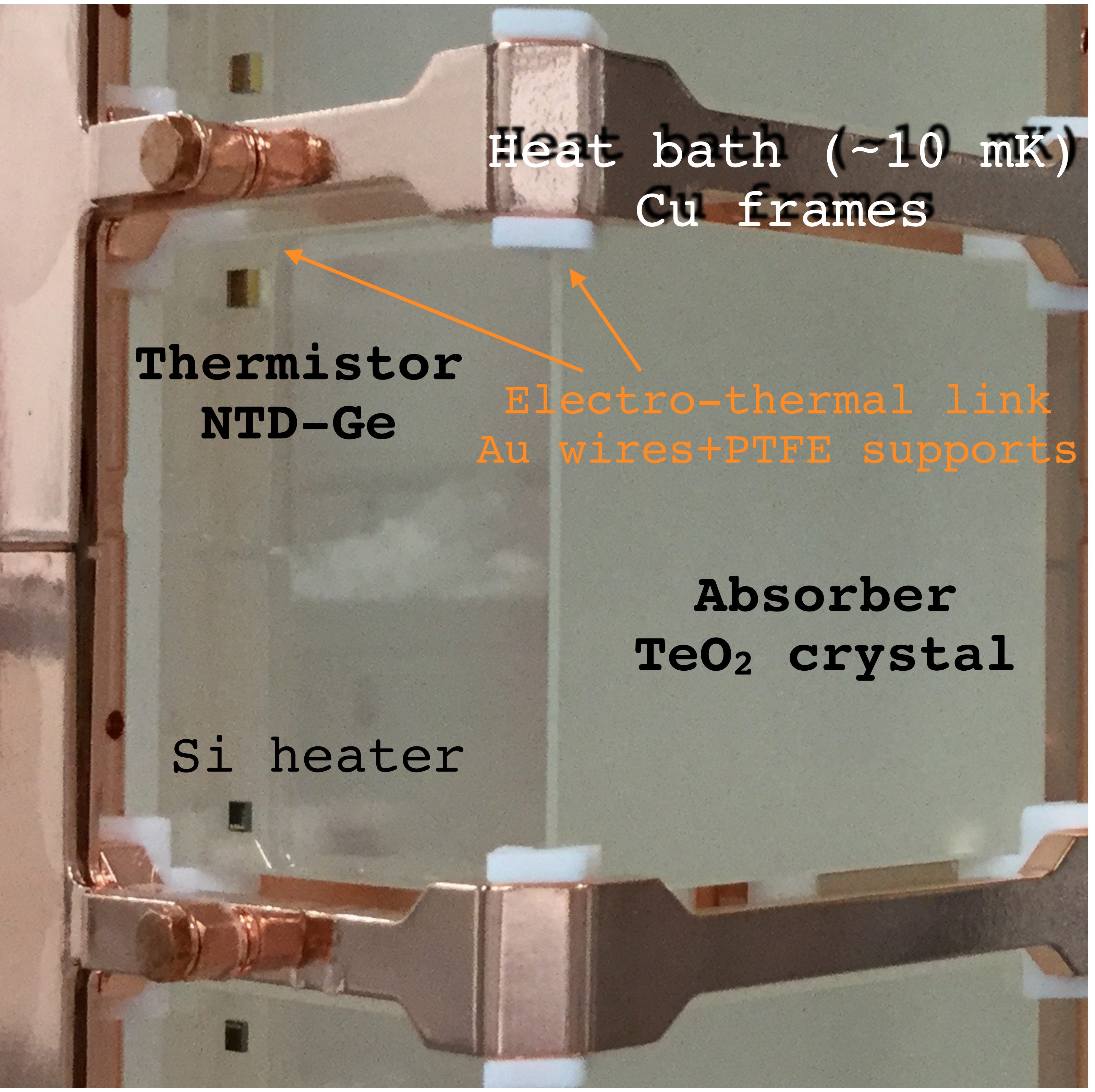
Primary goal: search for $0\nu\beta\beta$ decay of ^{130}Te

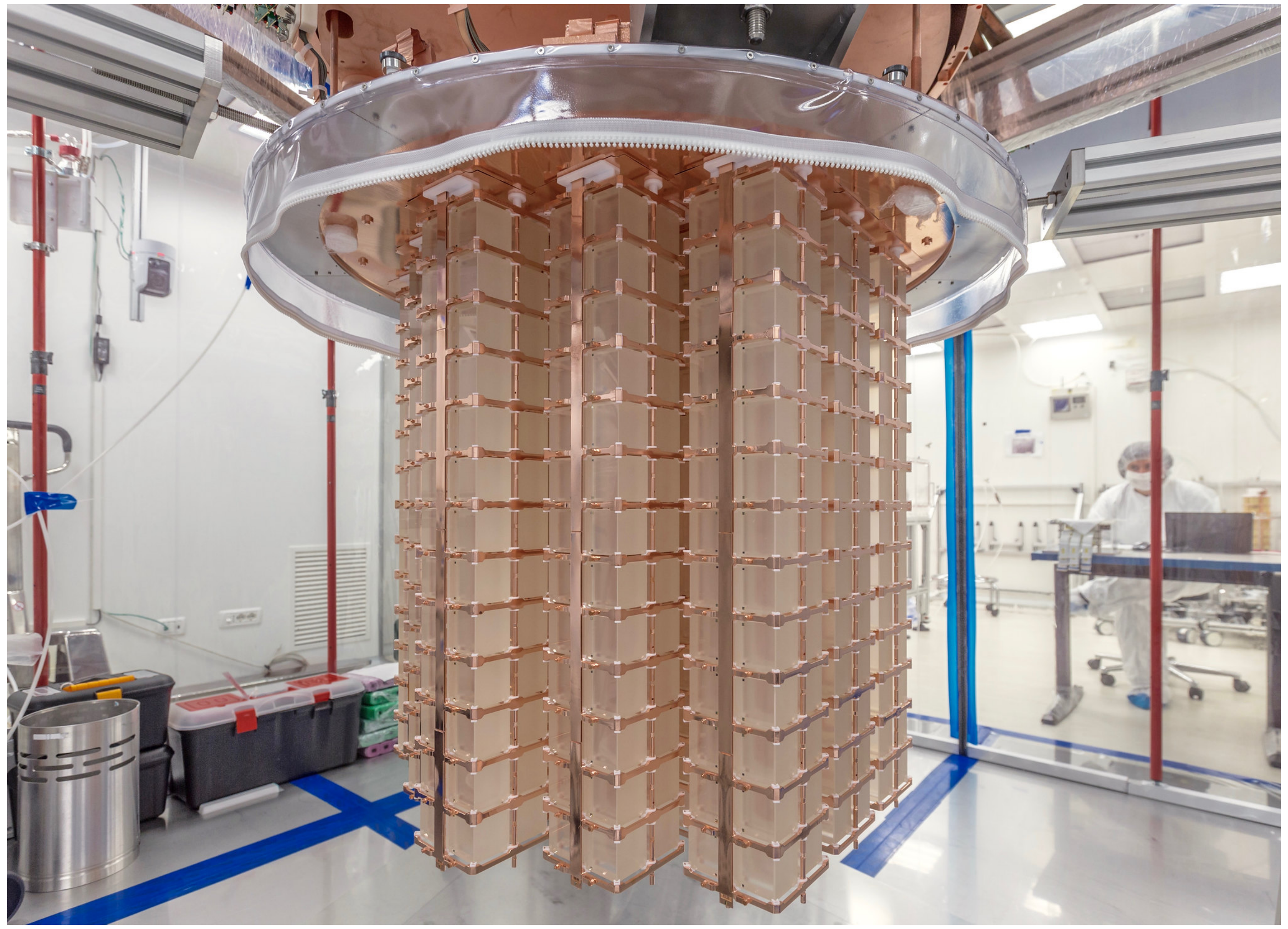
^{130}Te as $0\nu\beta\beta$ candidate:

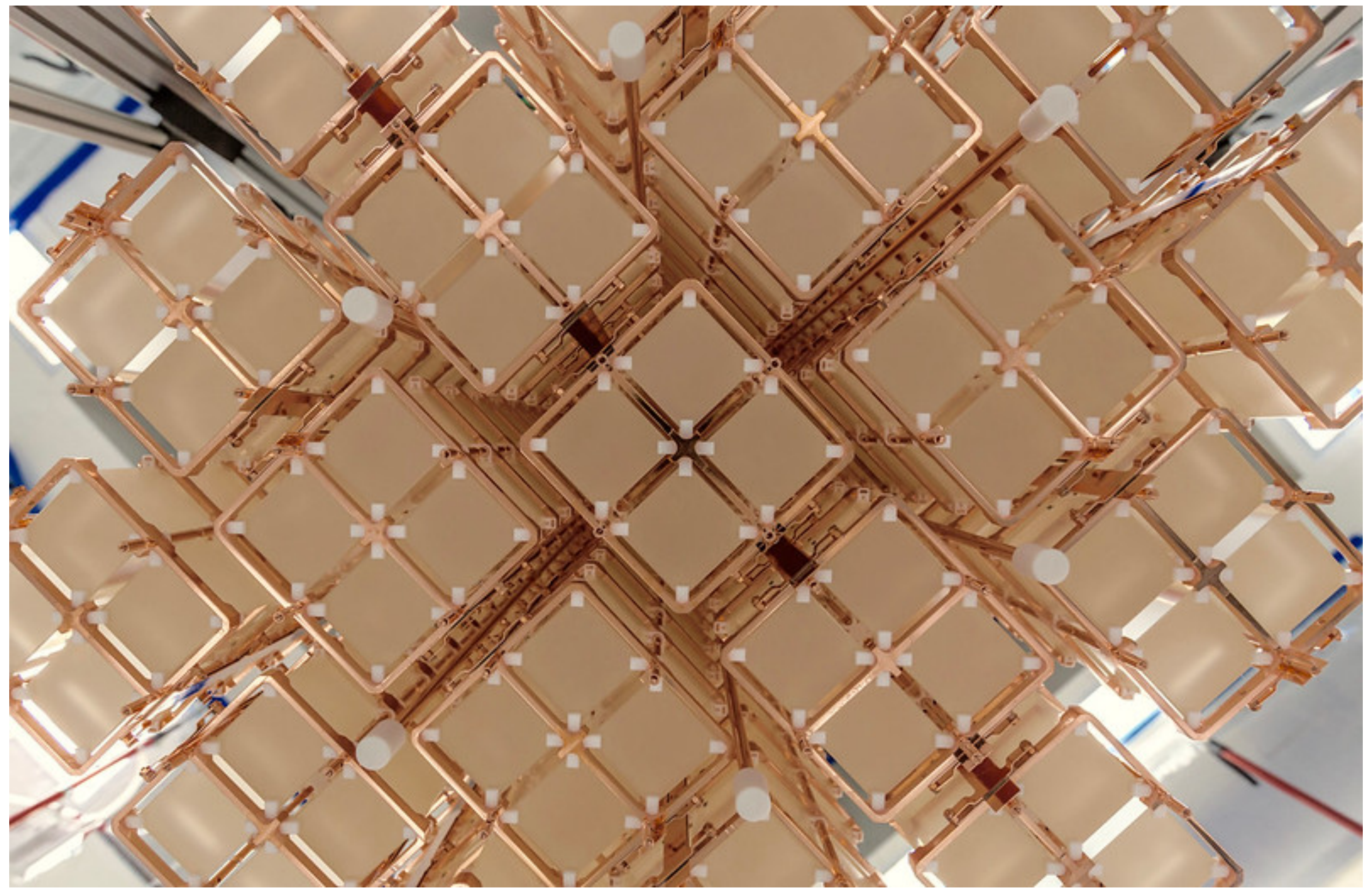
- High natural isotopic abundance: 34.2%
- Transition energy: $Q_{\beta\beta}$ = 2527.5 keV



19 towers with
13 planes of
4 detectors each





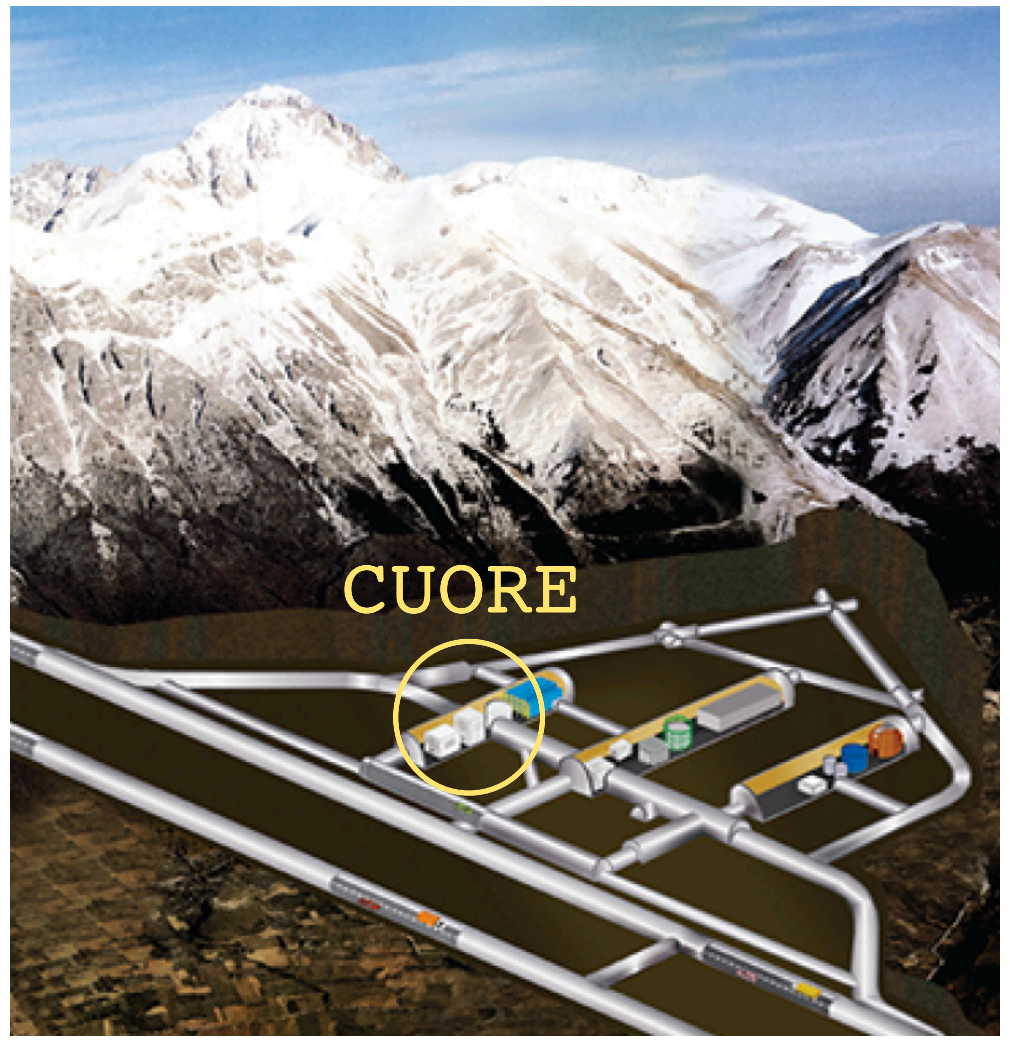


Array of 988 TeO_2 5×5×5 cm^3 detectors (750 g each)
Total mass: M = 742 kg of TeO_2 = 206 kg of ^{130}Te

Adv.High.En.Phys(2015)879871 Eur.Phys.J.C77(2017)532

CUORE location and infrastructure

LABORATORI NAZIONALI DEL GRAN SASSO



Average depth ~ 3600 m.w.e.

μ flux: 3×10^{-8} μ/s/cm^2

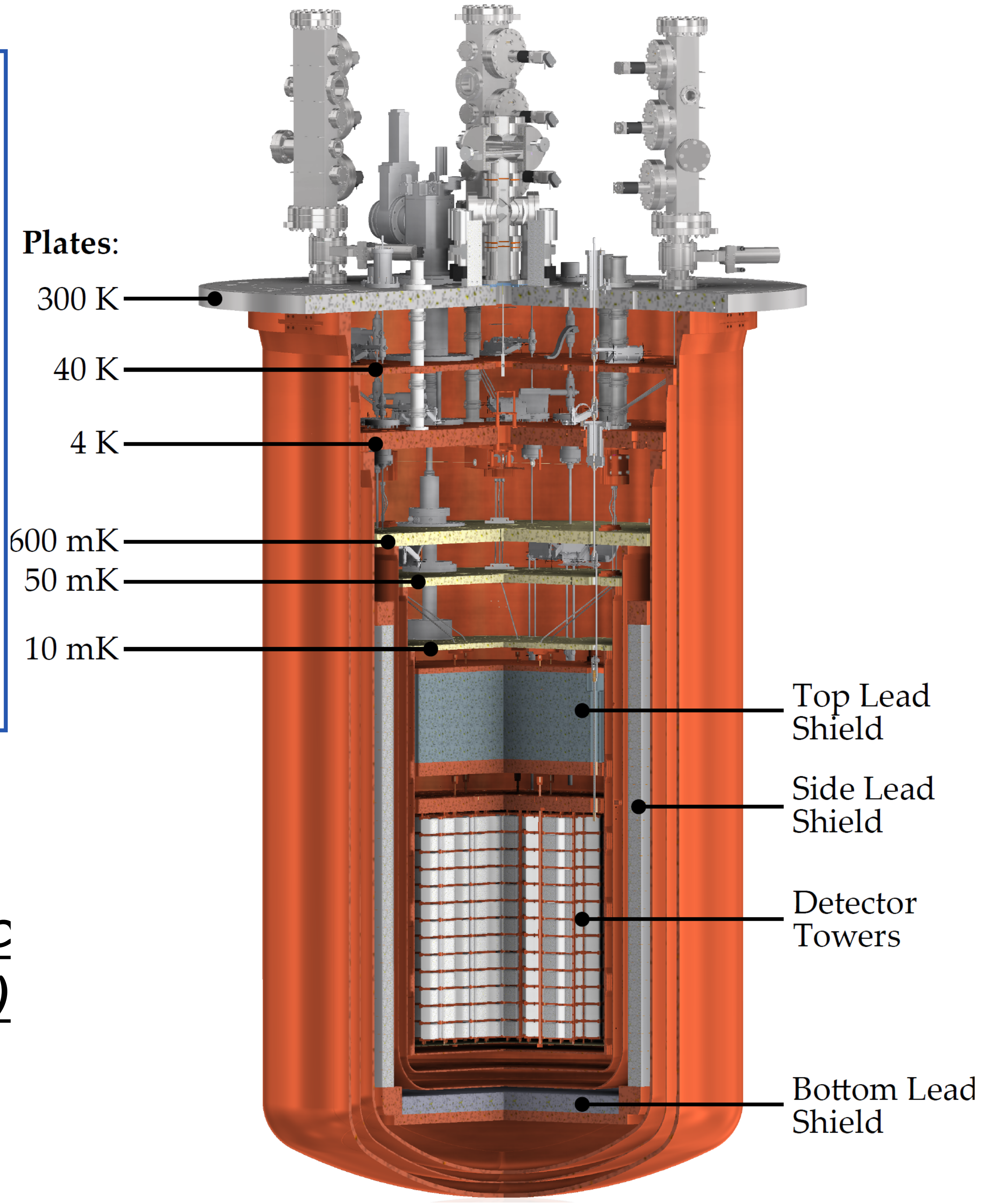
n flux: 4×10^{-6} n/s/cm^2 < 10 MeV

γ flux: ~0.73 γ/s/cm^2 < 3 MeV

CUORE cryogenic system

- Designed to cool down ~1 ton detector to ~10 mK.
- Detectors mechanically decoupled for extremely low vibrations.
- Careful selection of materials for low background

Cryogenic 102(2019)



TeO_2 crystals kept at 11-15 mK

- Cryostat total mass: ~30 ton
- Mass cooled below 4K: ~15 ton
- Mass cooled below 50 mK: ~3 ton (Pb, Cu, TeO_2)

The CUORE collaboration

27 institutions from 4 different countries
(Italy, USA, France, China)

https://cuore.lngs.infn.it/

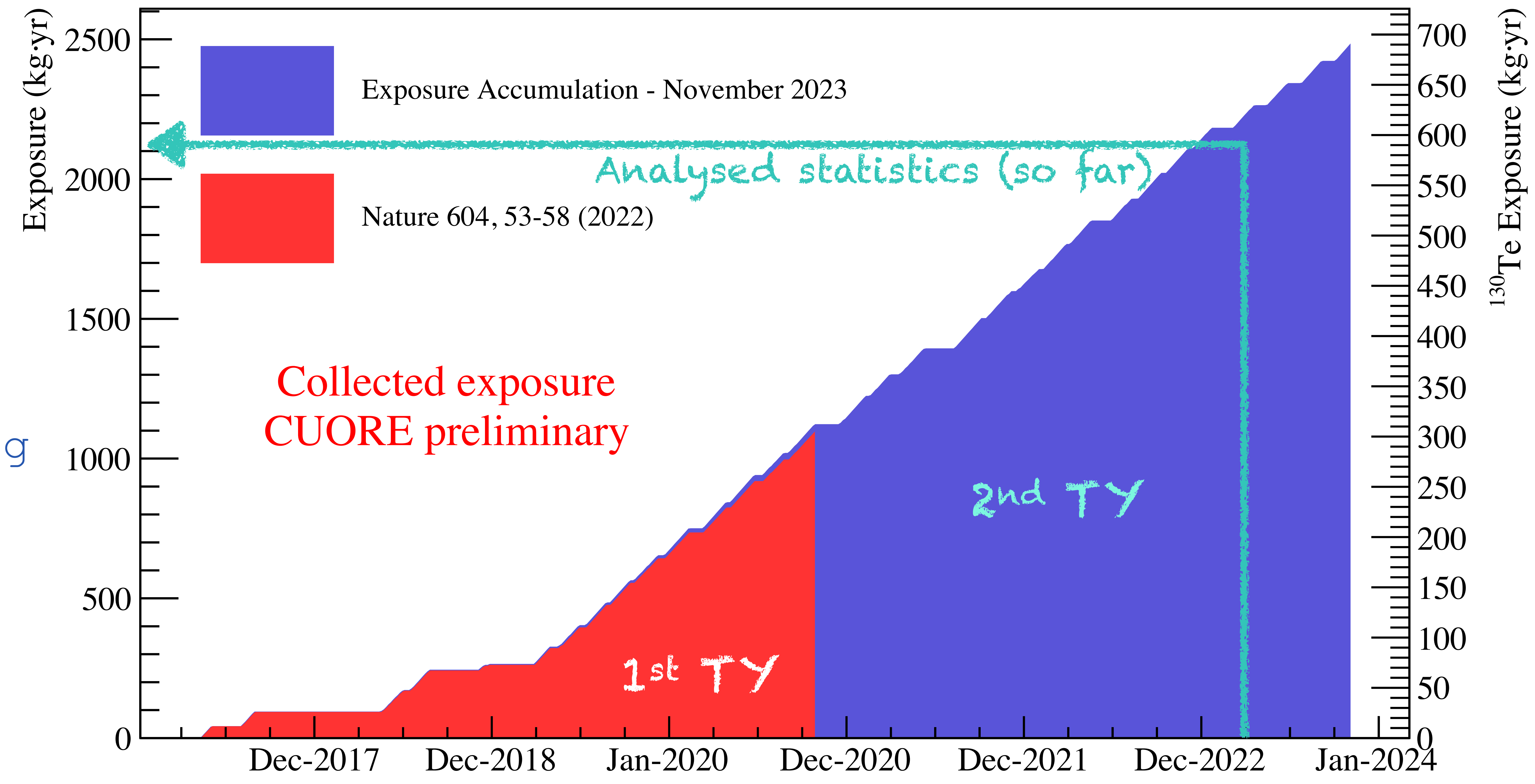
CUORE accumulated statistics

more than 2 ton•yr of TeO_2 data

Nature 604(2022)53

Data taking with CUORE

- Continuous data taking since 2017 (with few optimisation campaigns): since March 2019, more than 90% uptime in stable temperature conditions.
- Data split in datasets: 1-2 months of physics data bookended by calibrations.
- Typical trigger rate: ~50 mHz during calibration, ~6 mHz during physics runs.
- Voltage across NTD-Ge thermistors continuously sampled at 1 kHz: we use an offline software trigger.



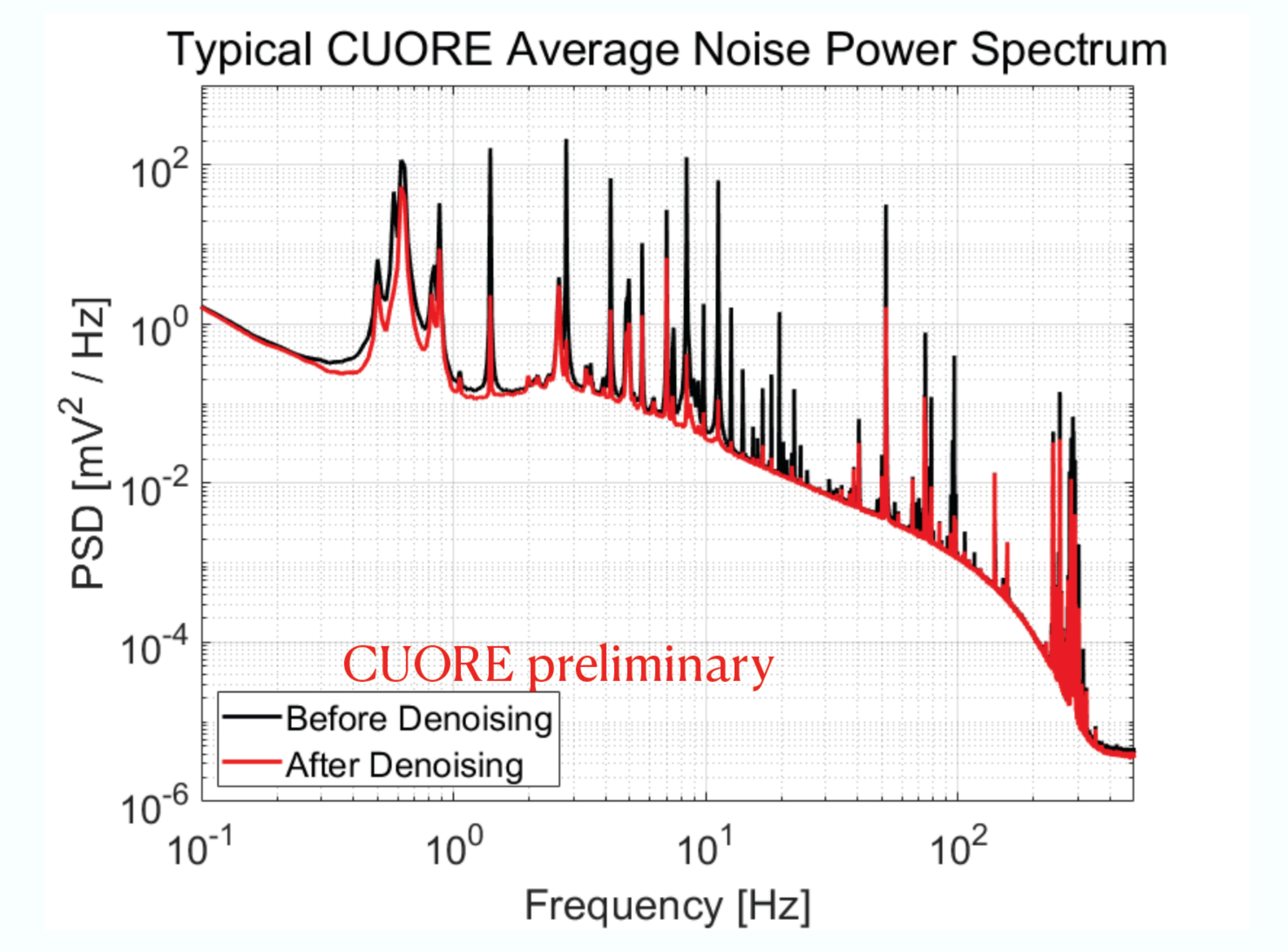
CUORE is the first to demonstrate stable operation of a tonne-scale milli-kelvin cryogenic calorimeter.

Average data taking rate: ~50 kg×yr/month

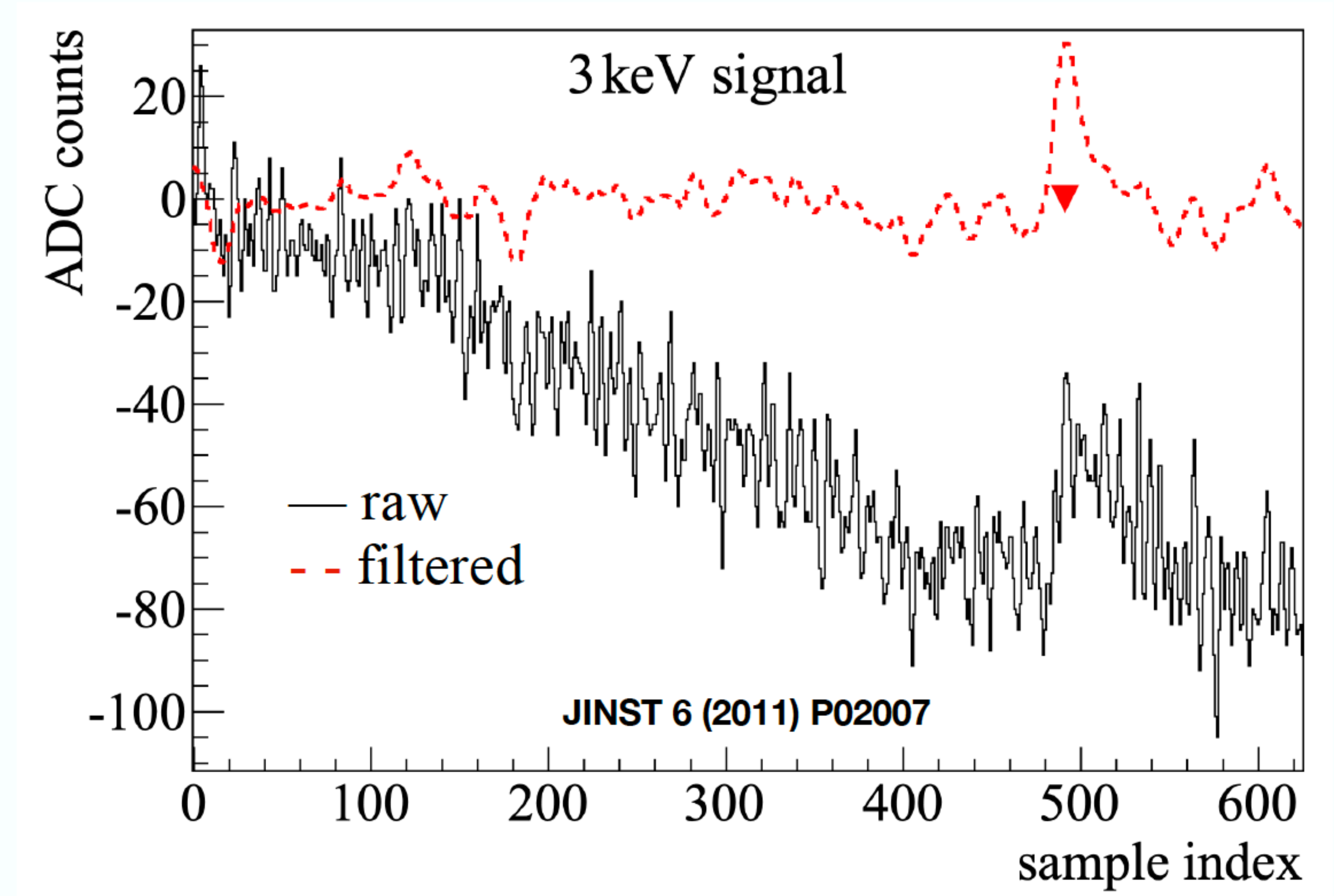
CUORE data analysis

Signal processing

- **Denoising (new!):** mitigates the noise by correlating it with auxiliary devices (microphones, accelerometers, seismometers)



- **Optimum trigger:** applies an offline trigger on filtered waveforms to lower the energy threshold

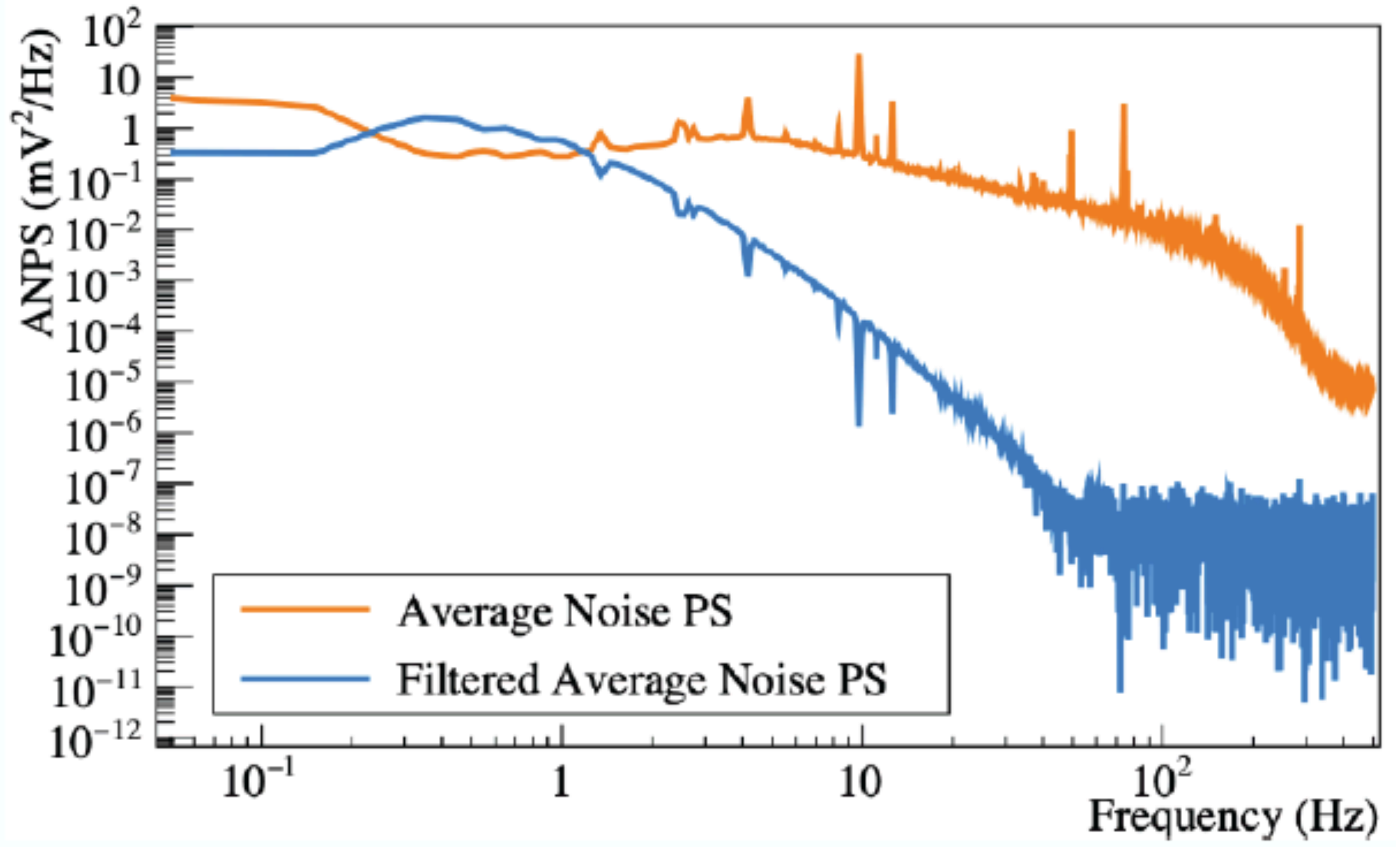


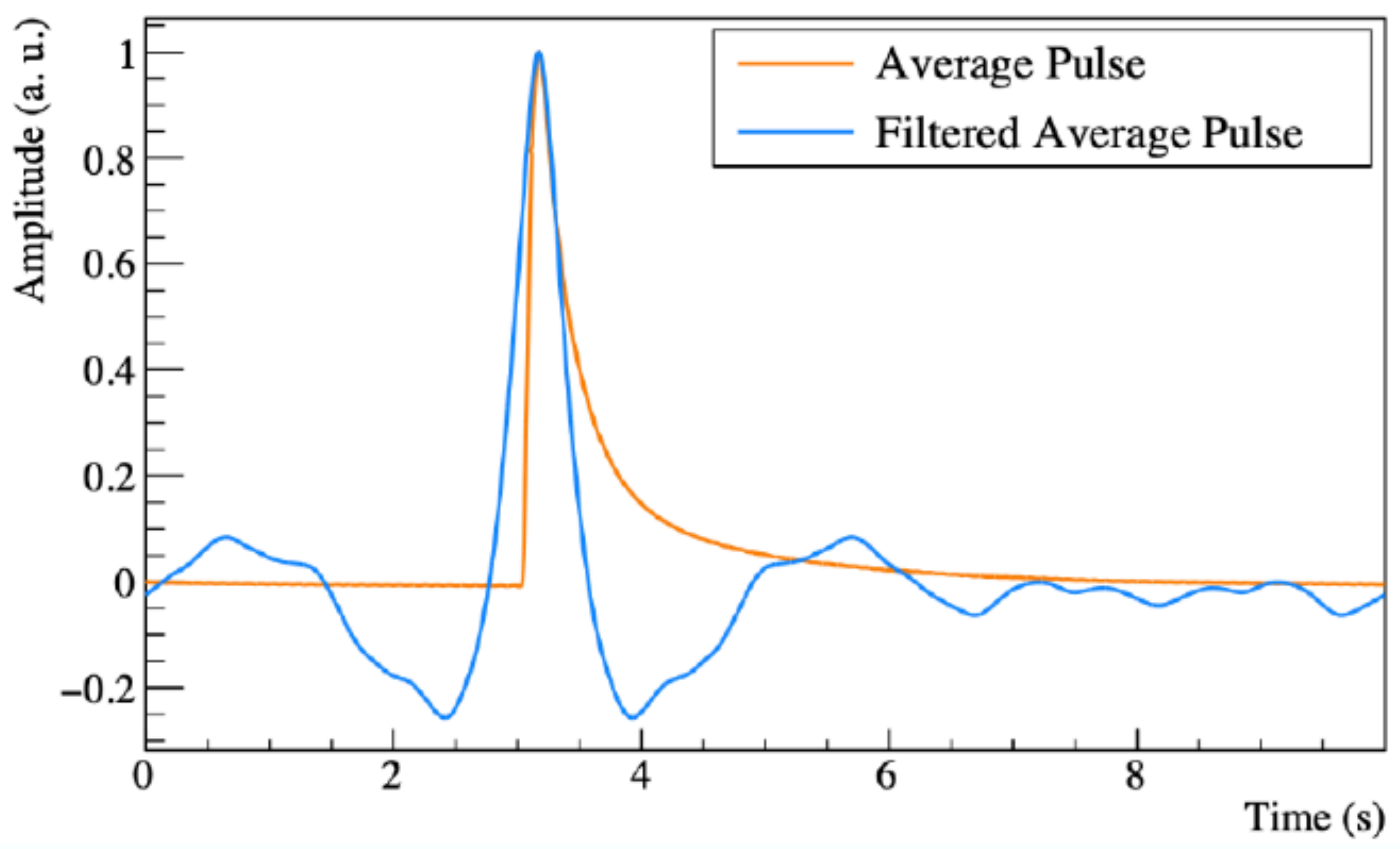
https://indico.cern.ch/event/1199289/contributions/5447391/

CUORE data analysis

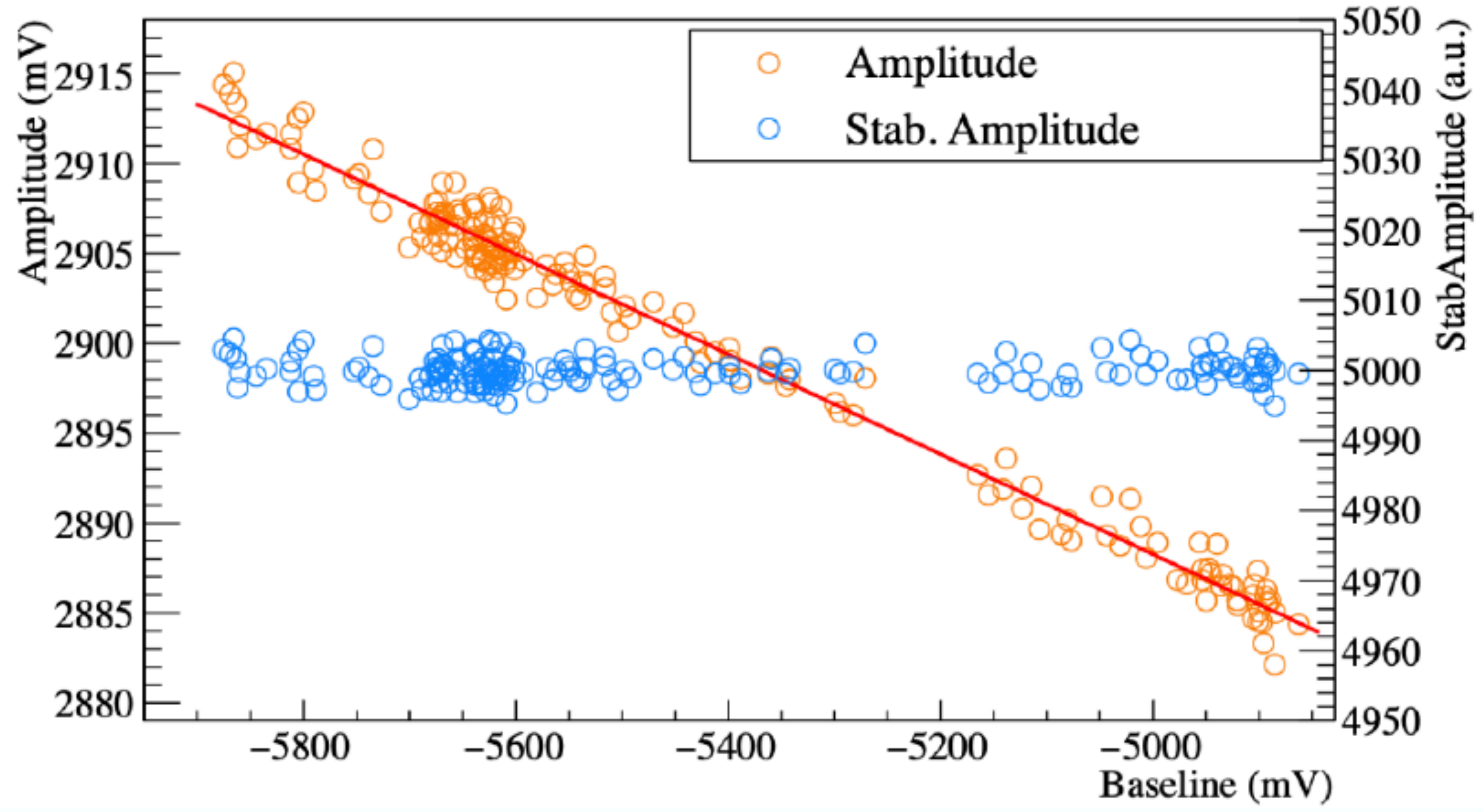
Energy reconstruction

- **Optimum filter:** maximises signal-to-noise ratio. Pulse amplitude is evaluated from the filtered pulse peak.

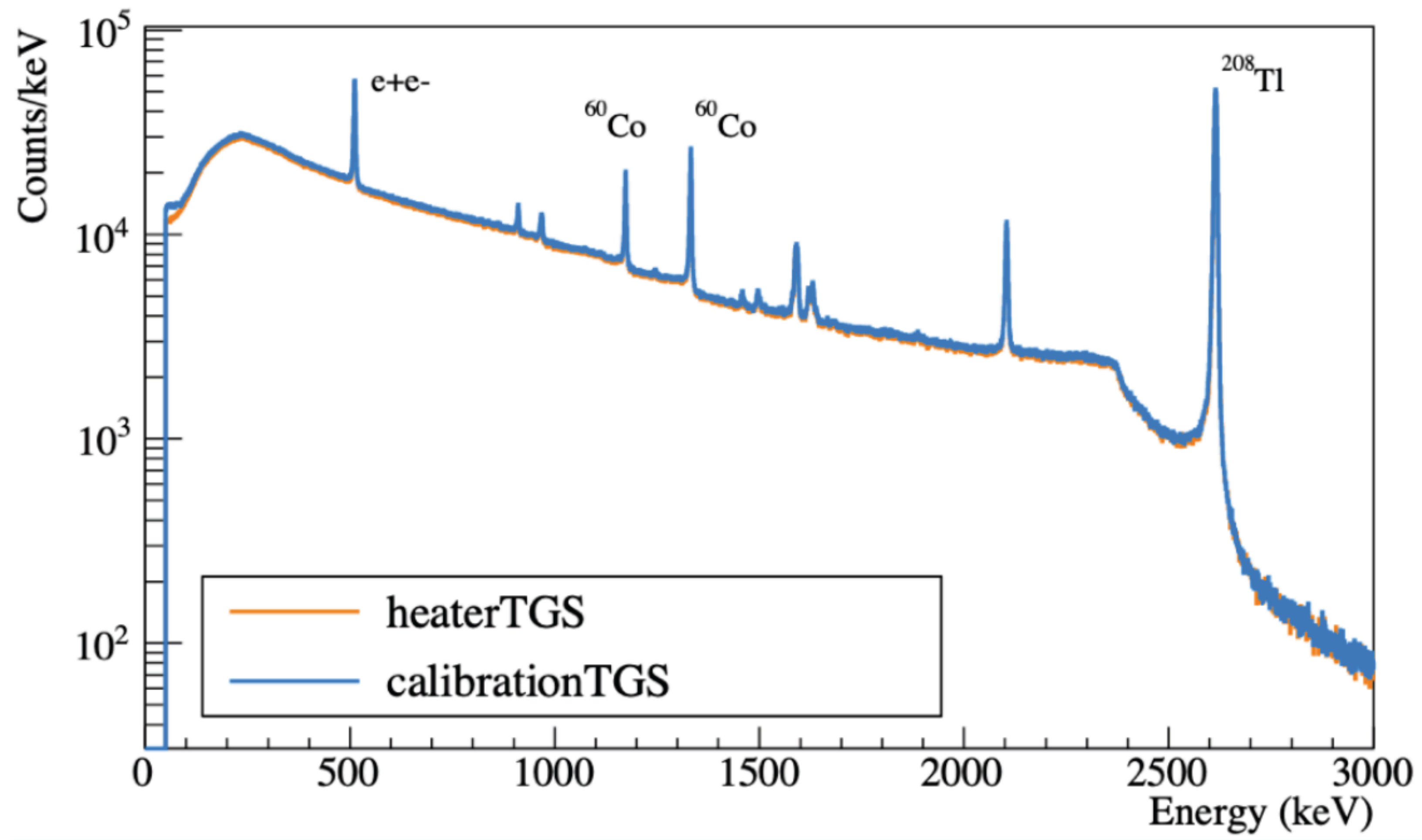




- **Thermal gain correction:** corrects the pulse amplitude dependence on temperature (baseline drifts) by using the thermal pulses injected through Si heaters.



- **Energy calibration:** based on periodic measurements taken during external $^{232}Th+^{60}Co$ source deployment.

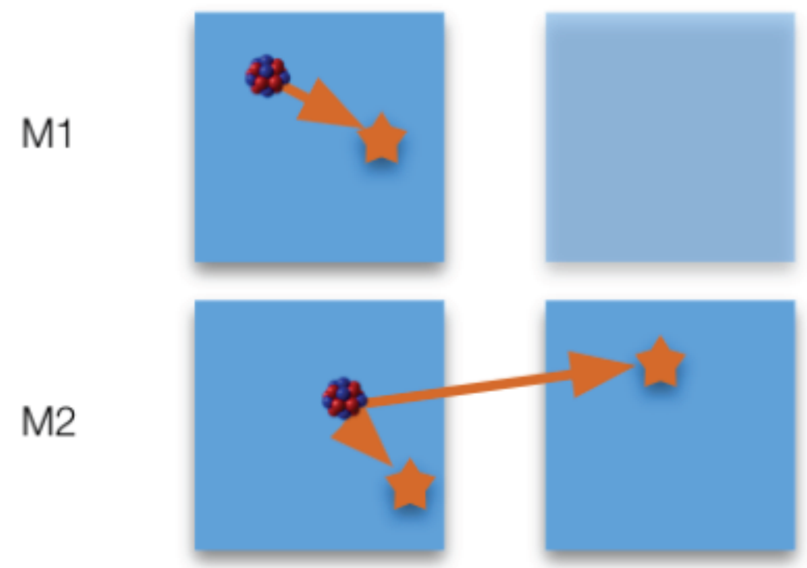


👁 https://indico.cern.ch/event/1199289/contributions/5447391/

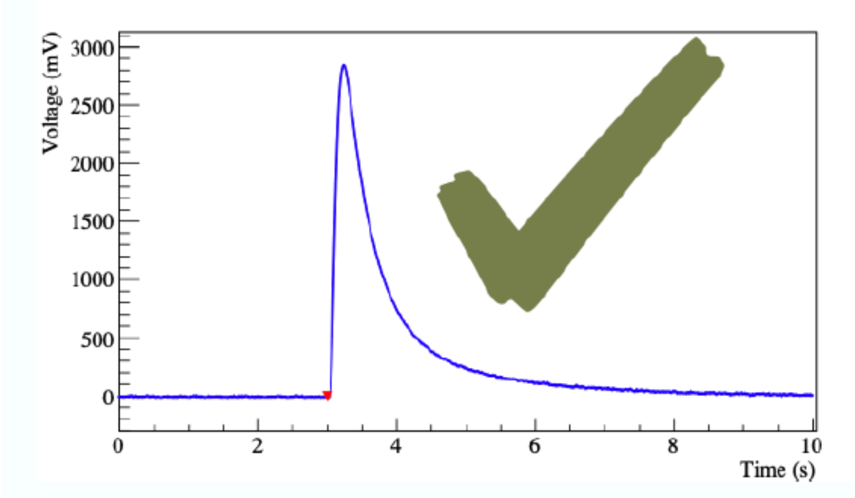
CUORE data analysis

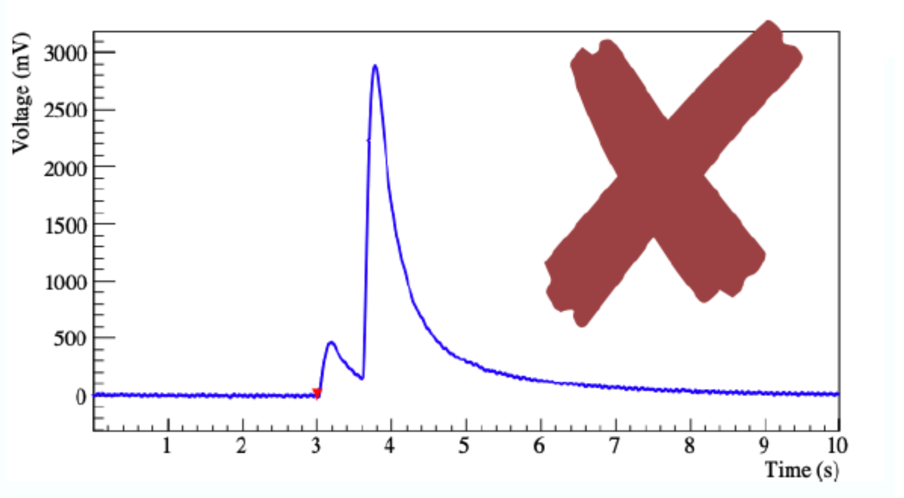
Event selection for $0\nu\beta\beta$ analysis

- **Anti-Coincidence cut (AC):** selects events depositing energy in only one crystal (M1 - Multiplicity 1 events) -> ~88% containment (MC)



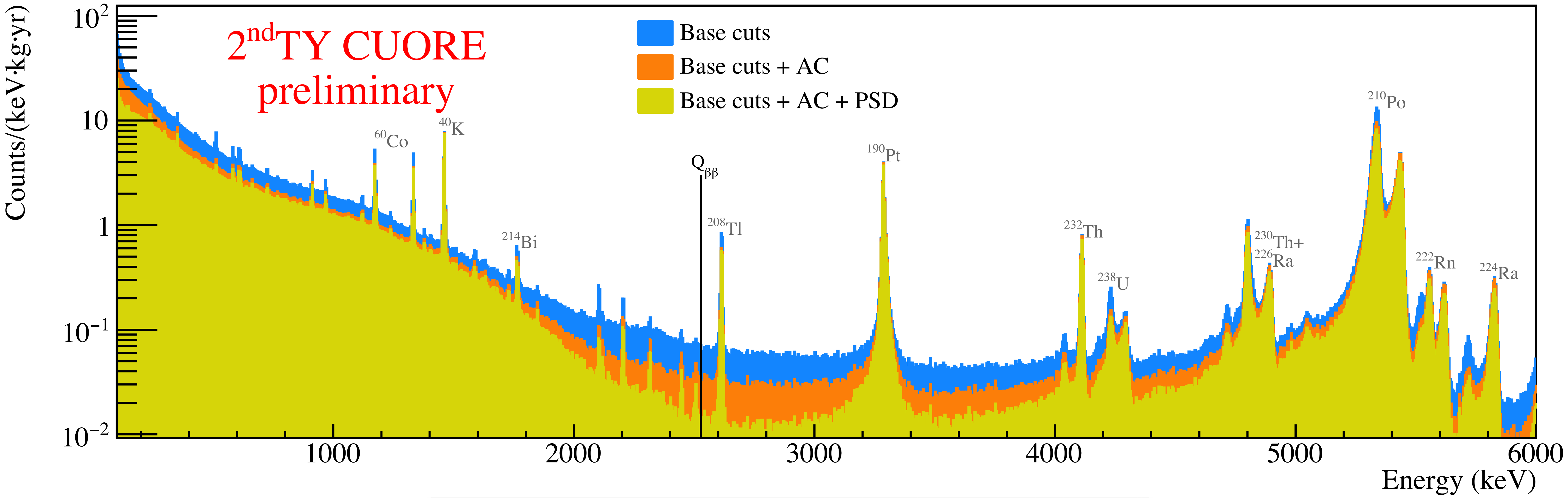
- **Pulse Shape Discrimination (PSD):** implemented by means of Principal Component Analysis techniques





- **Blinding:** we perform a blinded analysis to prevent bias -> events exchanged between $Q_{\beta\beta}$ and the 2615 keV peak from ^{208}Tl decay

  ⇨ Finalize fit model parameters before running unblinded fit



Overall cut efficiency (except containment) for 2nd TY analysis: **93.2%**

CUORE data analysis

Detector response

Peak shape model: physics peaks are modeled on ^{208}Tl 2615 keV line from calibration data.
Peak shape model:

➡ Sum of 3 Gaussians

- simultaneously fit with nearby structures:
  - Te X-rays (escape+coincident)
  - Annihilation escape peak in coincidence with the gamma line at 583 keV
  - Multi-Compton
  - Flat background

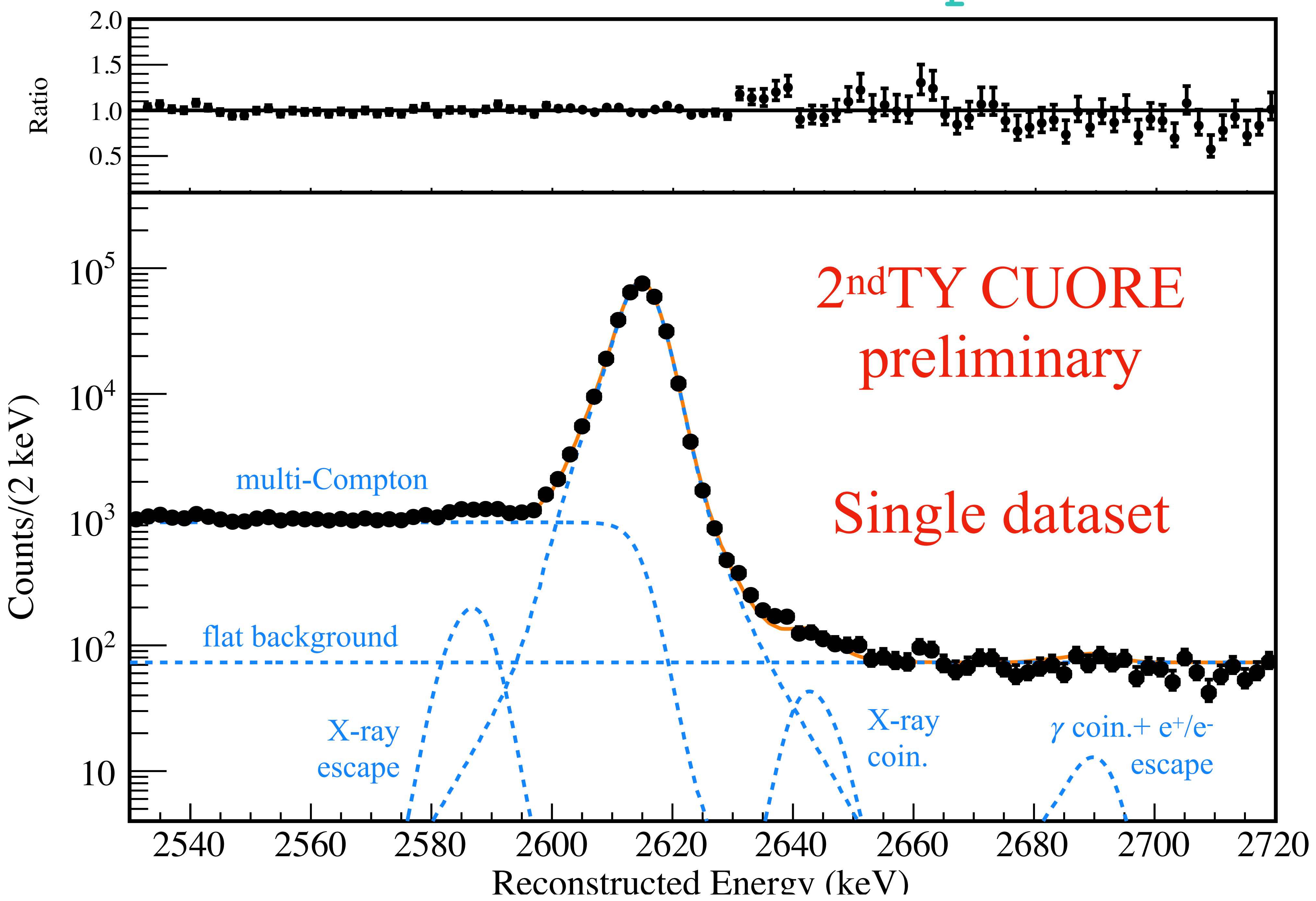
⇨ $\Delta E_{FWHM}(2615 keV, 2^{nd}TY) = 7.43 \pm 0.37$ keV

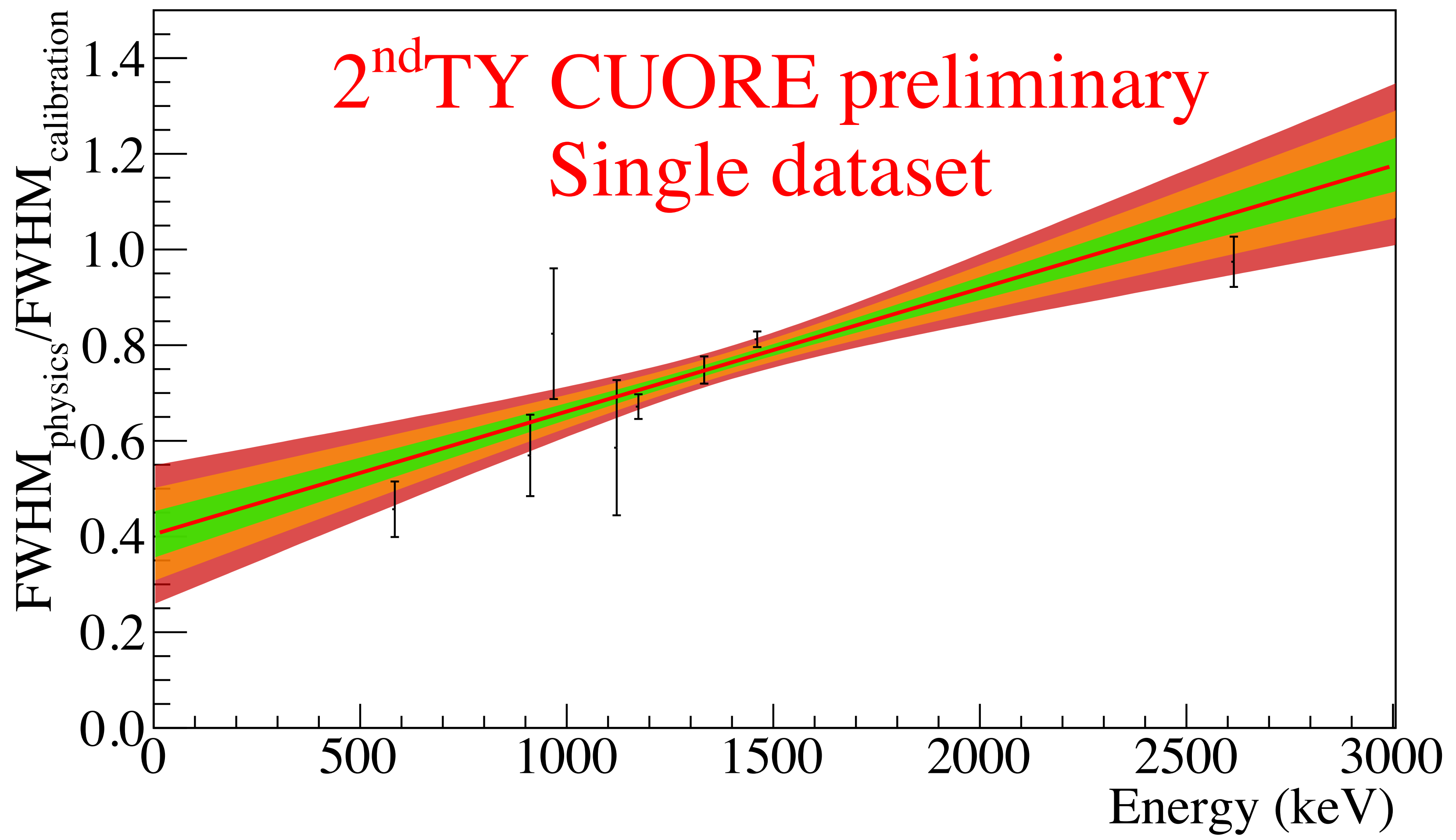
Gamma peaks in the physics data are fit with the 2615 keV calibration-based line shape to determine the detector response parameters in the Region Of Interest (ROI):

$$\Delta E_{FWHM}(Q_{\beta\beta}, 2^{nd}TY) = 7.26^{+0.43}_{-0.47} \text{ keV}$$

$$E_{bias}(Q_{\beta\beta}, 2^{nd}TY) = -0.11^{+0.19}_{-0.25} \text{ keV}$$

^{208}Tl calibration peak

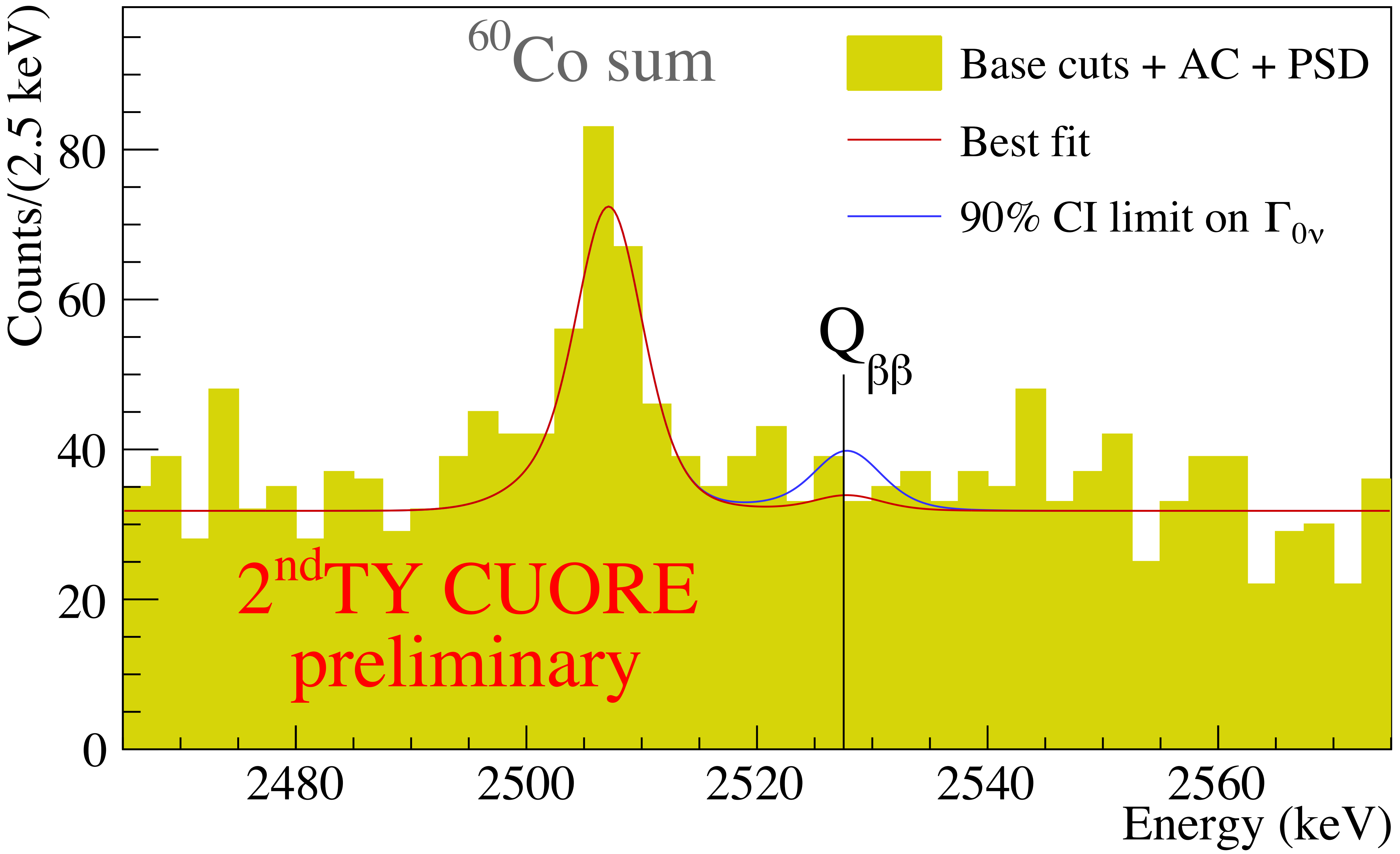




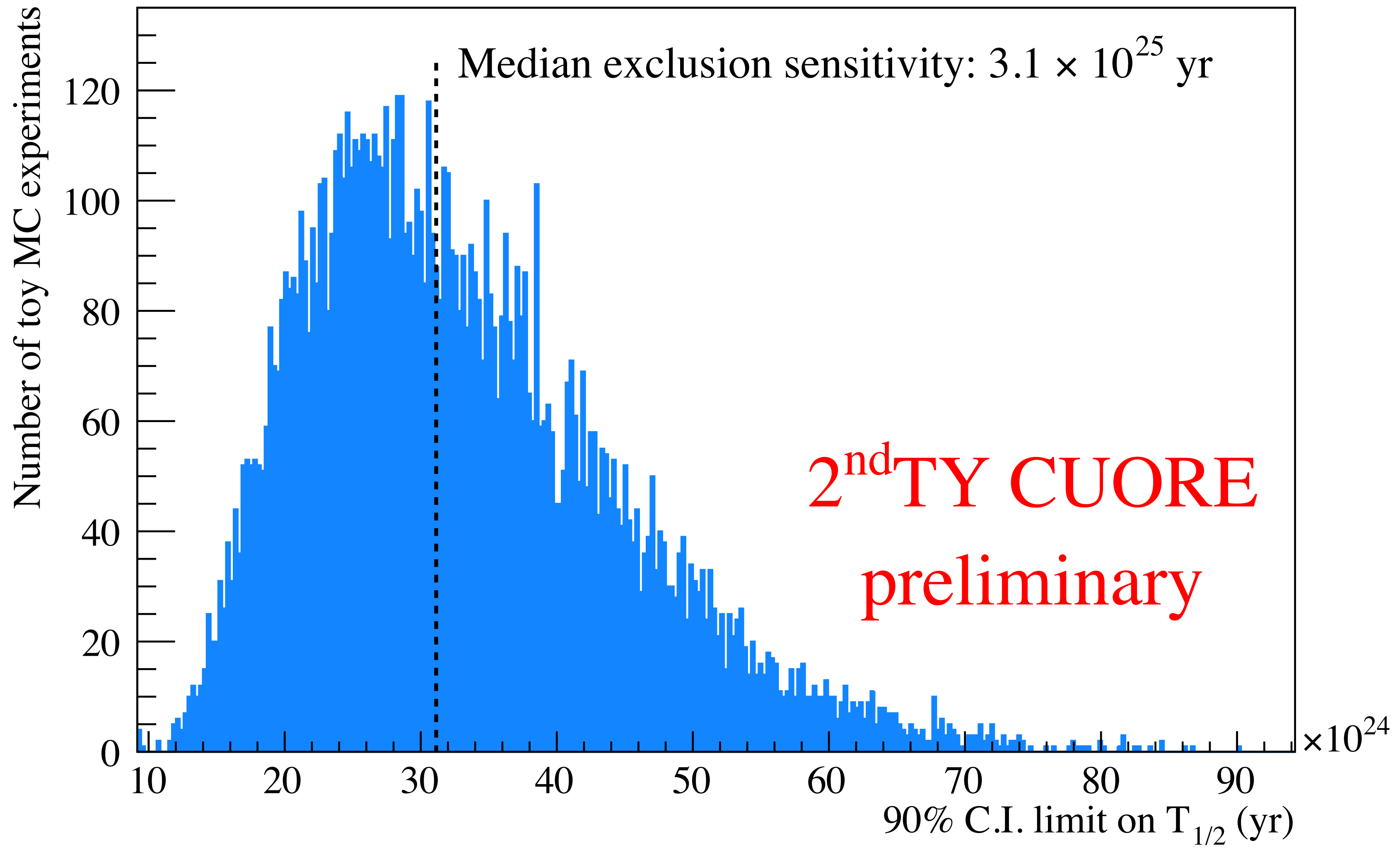
CUORE $0\nu\beta\beta$ decay search

Data from 2nd TY (tonne × year) only

- ROI: [2465, 2575] keV
- Fit Model: ^{130}Te $Q_{\beta\beta}$ peak + ^{60}Co sum peak + flat background
  -> rates ($\Gamma_{0\nu}$, Γ_{Co}) and background index (BI) as free parameters
- Unbinned Bayesian fit with $\Gamma_{0\nu} > 0$
- Systematics are treated as nuisance parameters



- Median exclusion sensitivity evaluated from 10^4 toy MC experiments in background only hypothesis
- Median expected $T_{1/2}$ 90% limit = 3.1×10^{25} yr



We find no evidence of ^{130}Te $0\nu\beta\beta$ decay

Decay rate limit $\Gamma_{0\nu} < 2.5\times10^{-26}$/yr (90% C.I.)

Half life limit $T_{1/2} > 2.7\times10^{25}$ yr (90% C.I.)

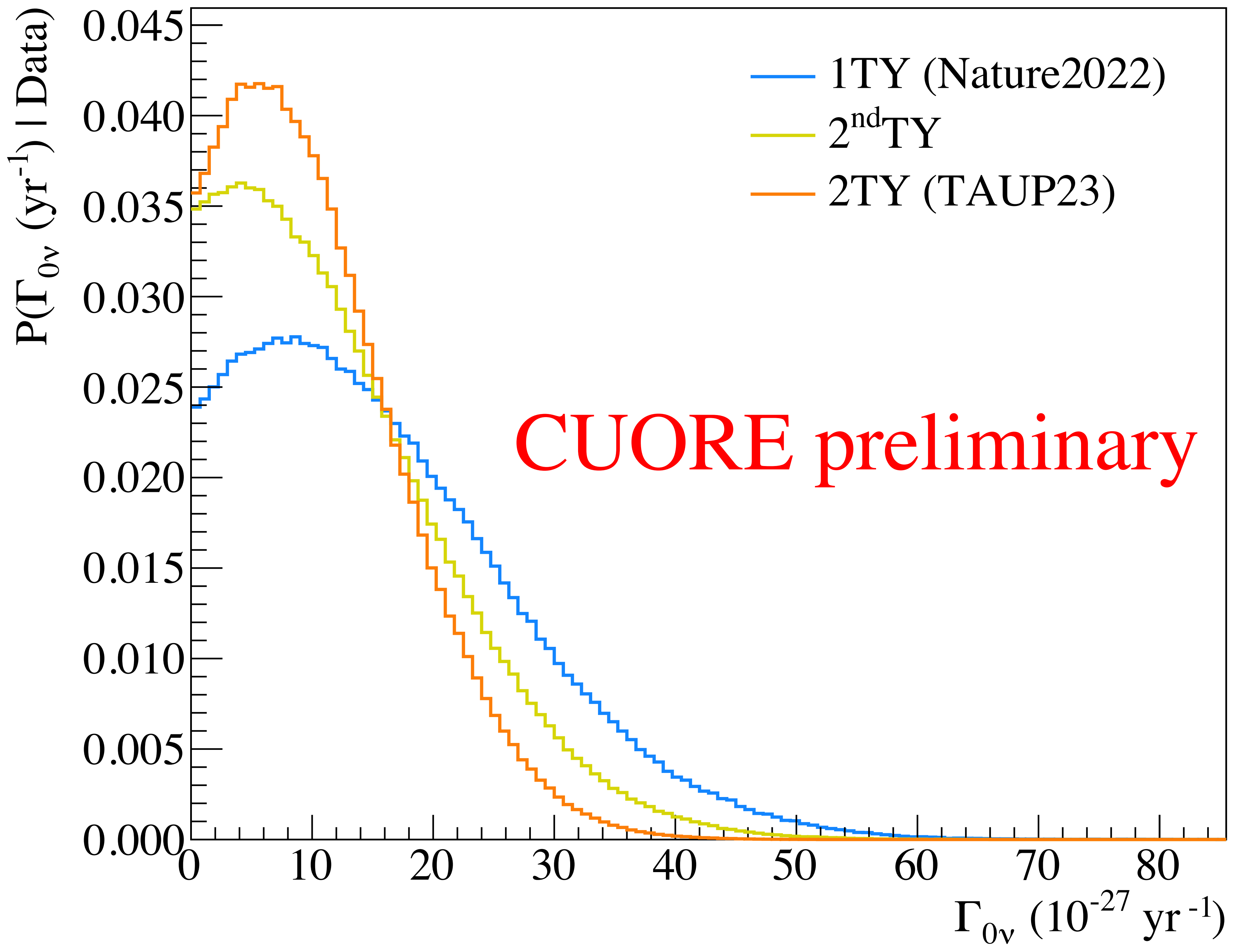
Average BI = $(1.30\pm0.03)\times10^{-2}$ counts/keV/kg/yr

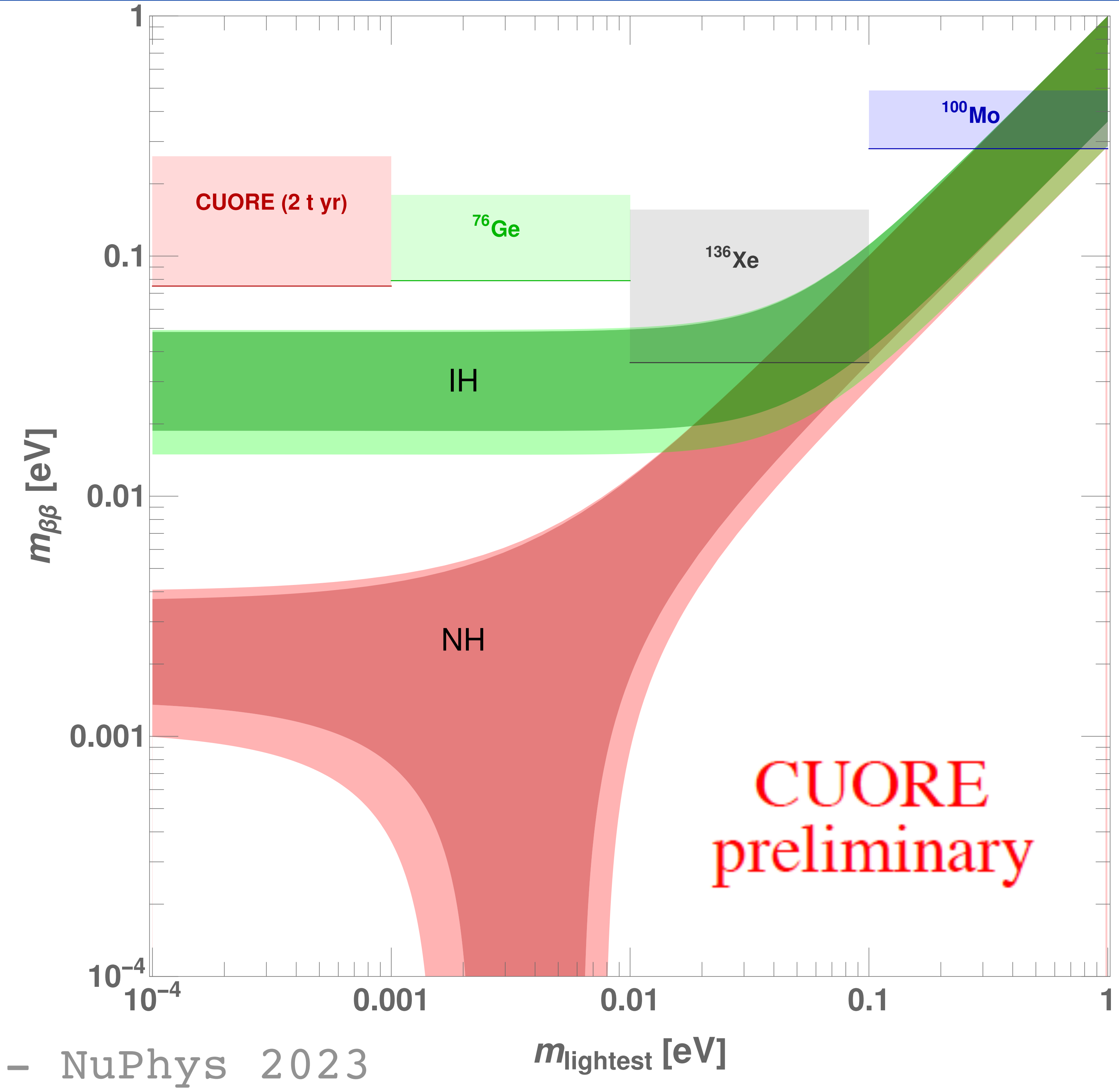
CUORE $0\nu\beta\beta$ decay search

Combining 1st TY and 2nd TY data

- 1st TY $0\nu\beta\beta$ half life 90% limit: $T_{1/2} > 2.2\times10^{25}$ yr (Nature 604(2022)53)
- We combined the posteriors on the $0\nu\beta\beta$ half lives resulting from the analysis of the 1st TY and 2nd TY of CUORE data

⇨ **Overall analysed exposure: 2023 kg×yr (TeO_2)**





We (still) find no evidence of ^{130}Te $0\nu\beta\beta$ decay

Decay rate limit $\Gamma_{0\nu} < 2.1\times10^{-26}$/yr (90% C.I.)

Half life limit $T_{1/2} > 3.3\times10^{25}$ yr (90% C.I.)

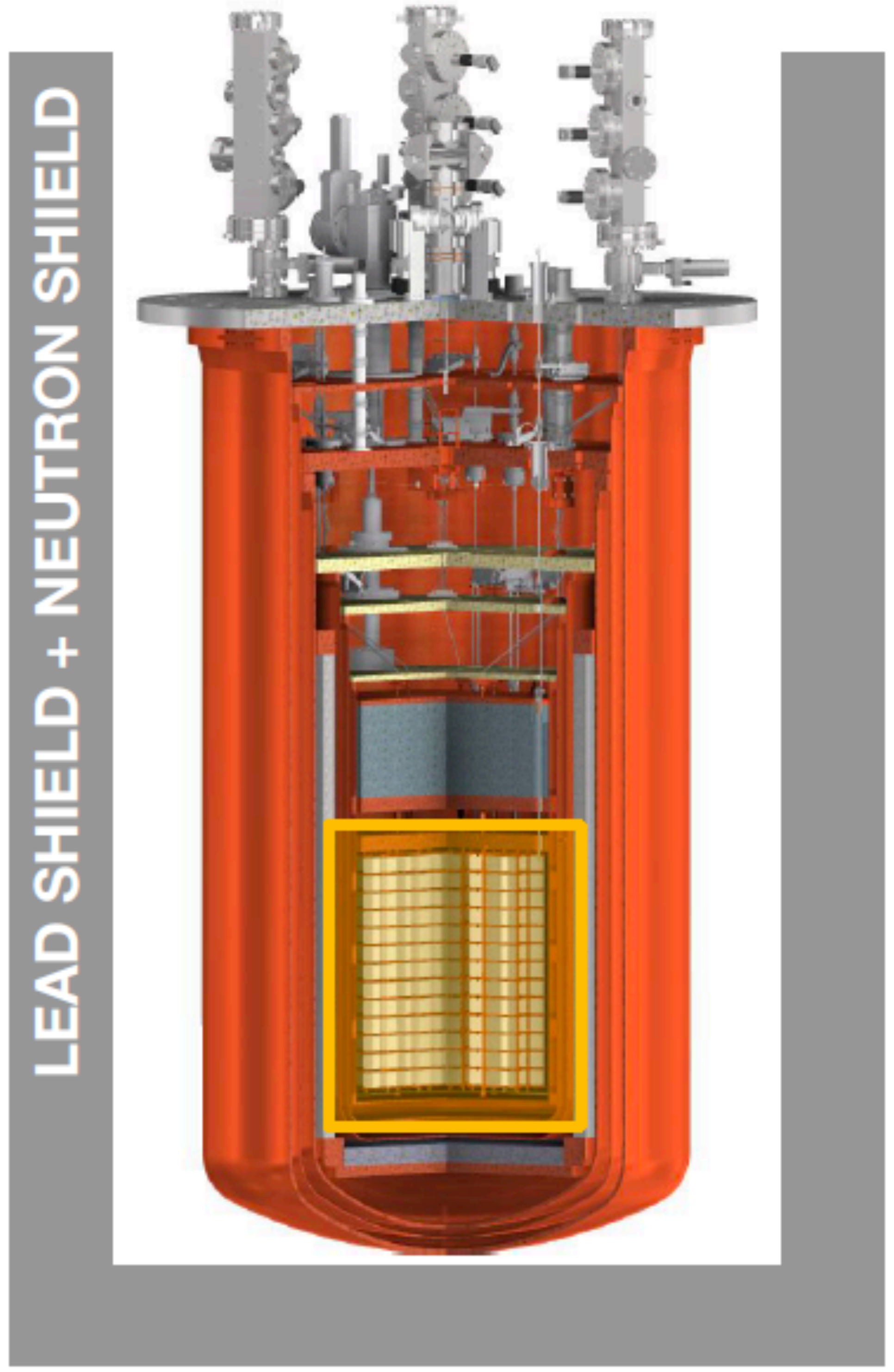
Effective Majorana mass limit $m_{\beta\beta} < 75\text{–}255$ meV

How to go beyond CUORE?

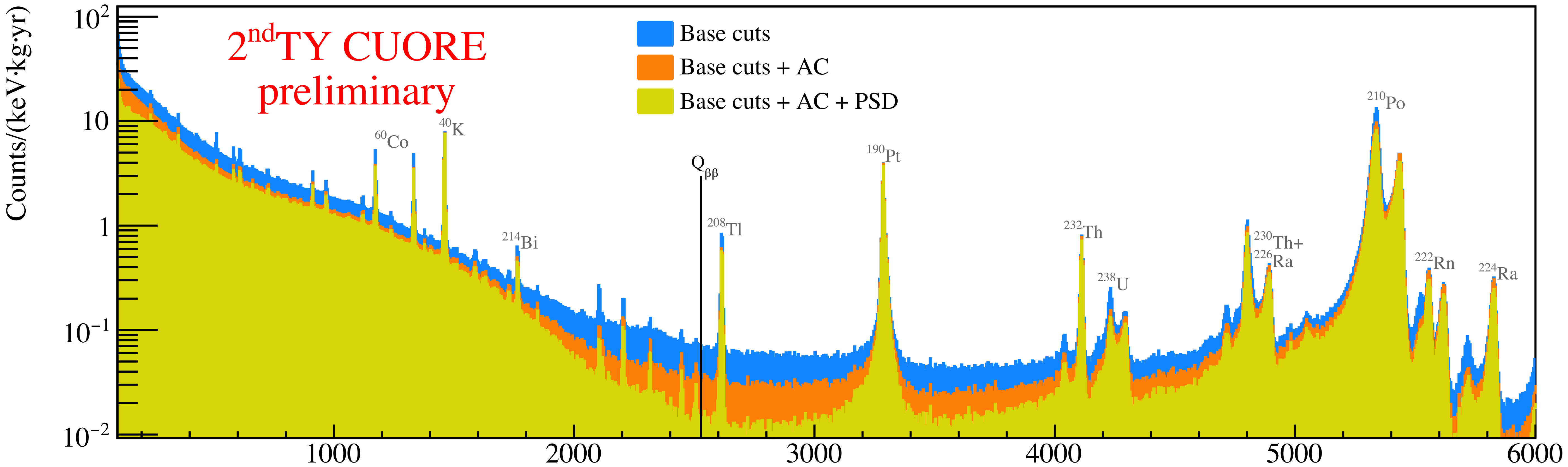
Modeling CUORE background index

CUORE background components:

- *Bulk contaminations in the materials of the experimental setup:*
  - Main decay chains: ^{232}Th, ^{238}U, ^{235}U
  - Ubiquitous contaminants: ^{40}K, ^{60}Co
  - Fallout: ^{137}Cs, ^{90}Sr, ^{207}Bi
  - Activation: ^{125}Sb, ^{54}Mn, ^{110m}Ag, ^{108m}Ag
  - Others: ^{147}Sm, ^{190}Pt (crystal growing)
- *Surface contaminations of copper and crystals from main decay chains*
- *Muons and muon induced background*

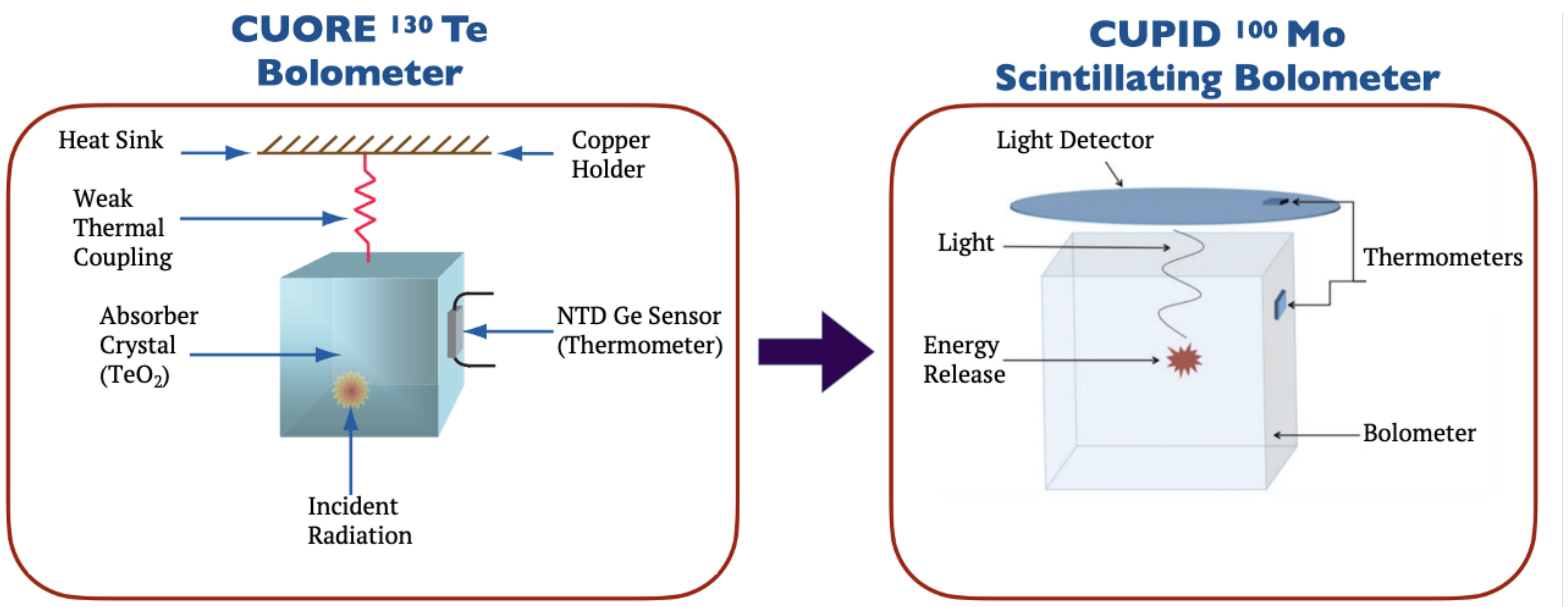


https://indico.cern.ch/event/1199289/contributions/5447161/

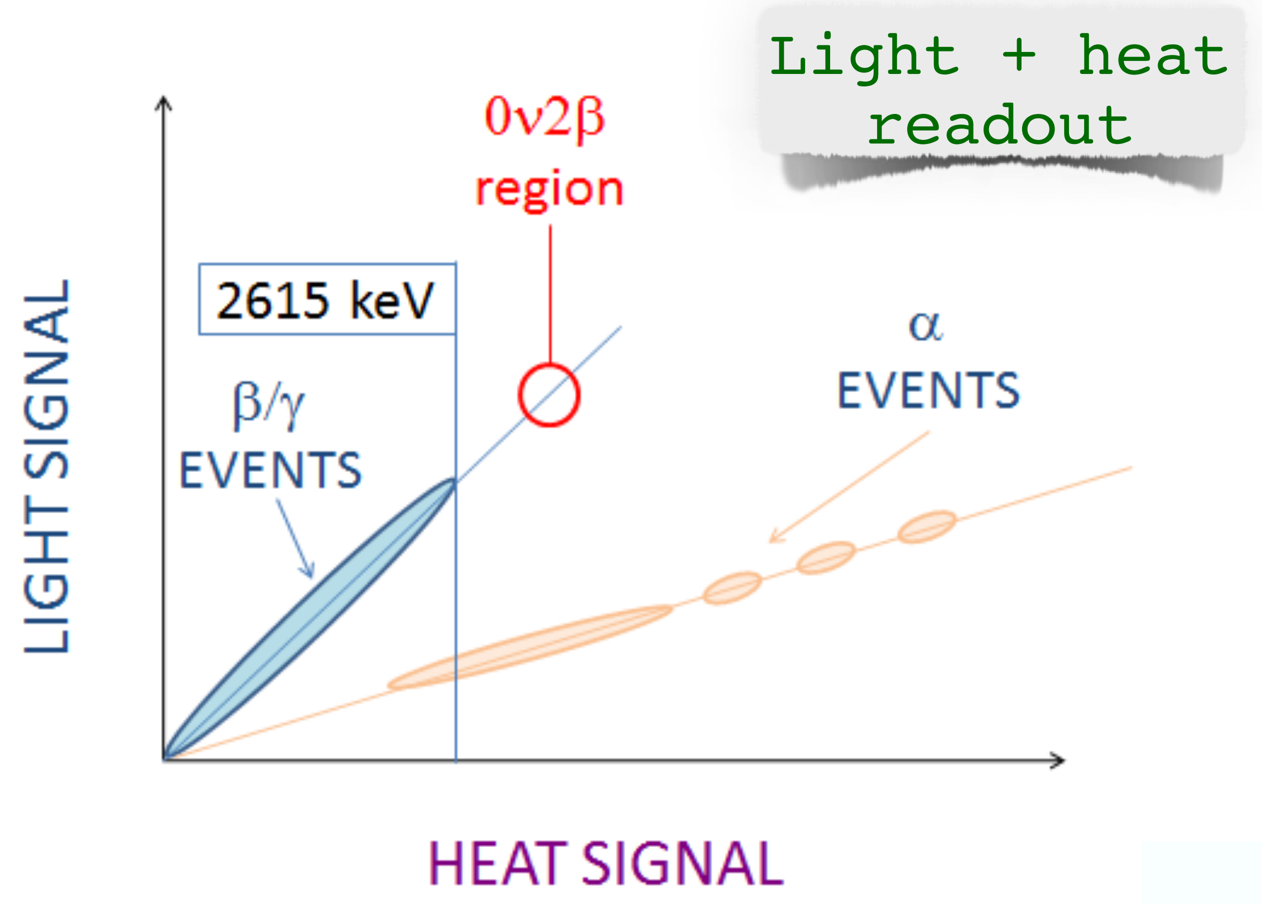


CUPID concept

A new detector concept to lower the background index

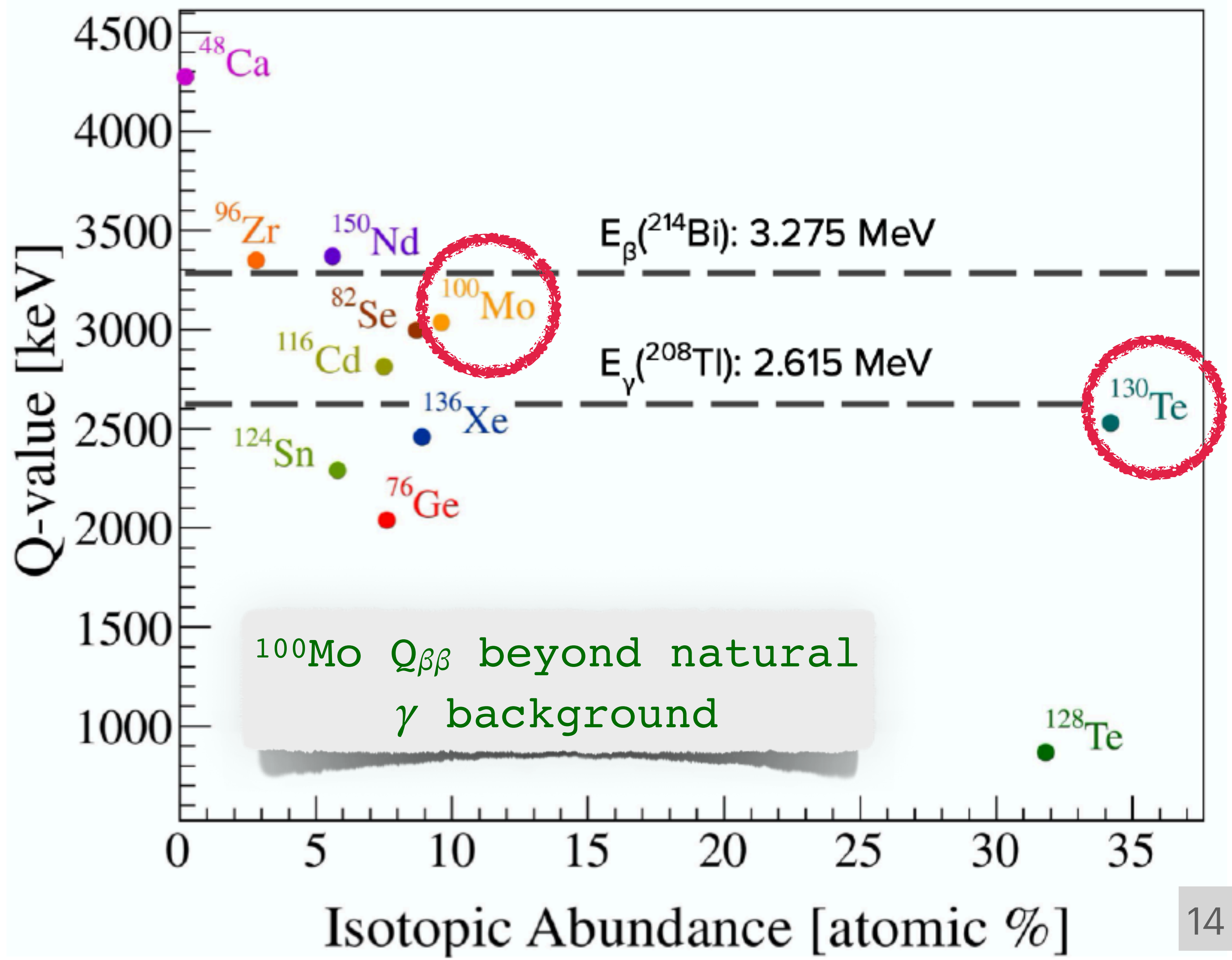


Particle Identification



CUORE: no PID

CUPID: PID allows to separate β/γ from α events



A Li_2MoO_4 (LMO) scintillating cryogenic detector to search for the $0\nu\beta\beta$ decay of ^{100}Mo

CUPID Pre-CDR

CUPID collaboration

~140 collaborators from 7 different countries

Major participants: Italy (~60), USA (~40), France (~25)
Other participants: Ukraine, Russia, China, Spain

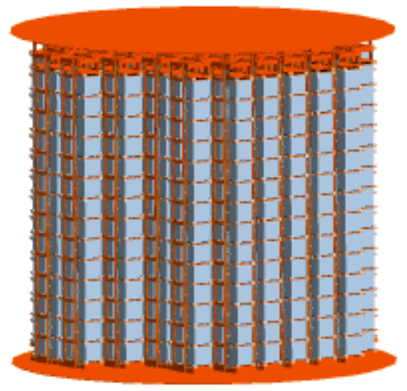
https://cupid.lngs.infn.it/

Leverages previous collaborative experience:

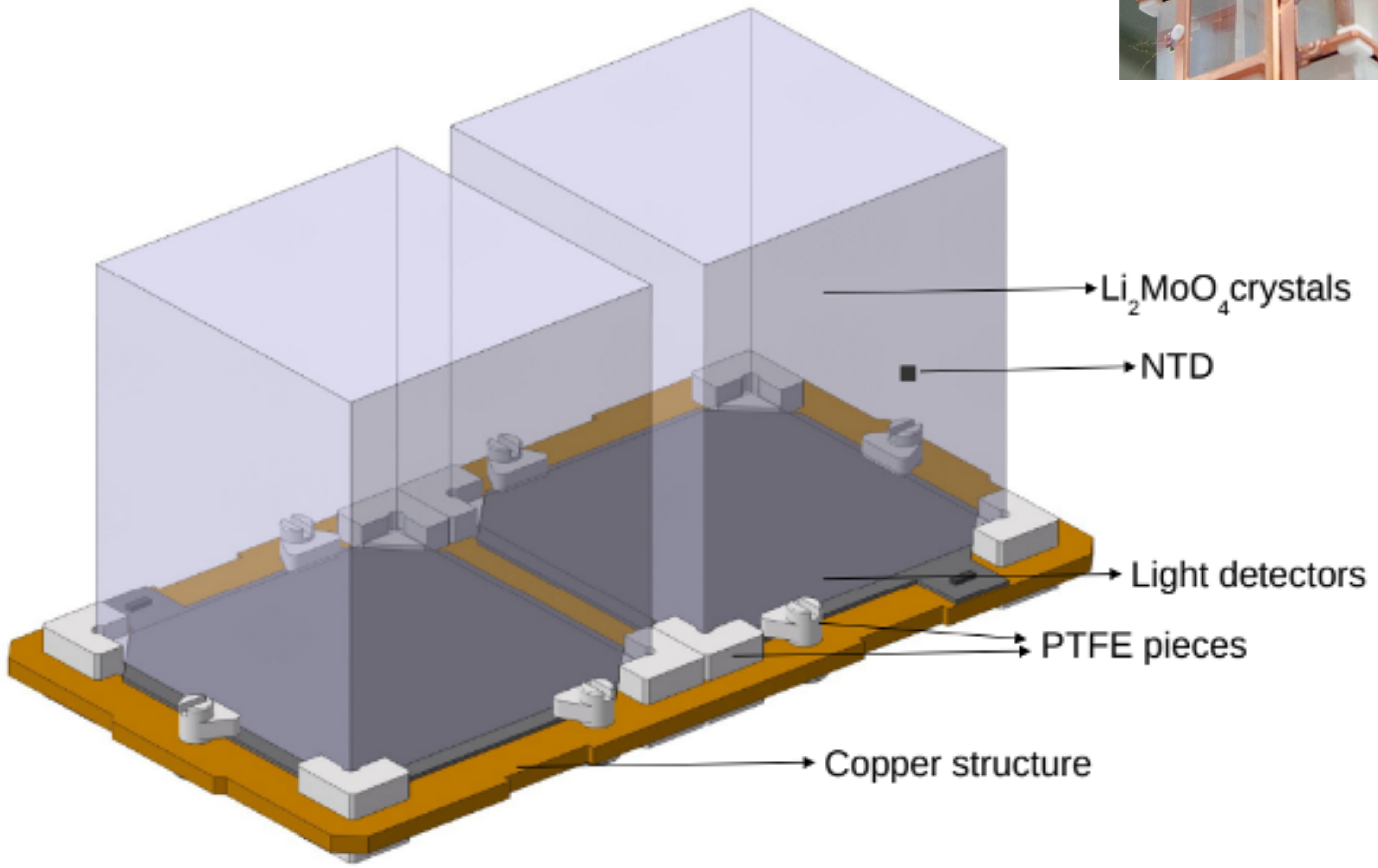
- CUORE
- CUPID-0
- Cupid-Mo

CUPID detector array

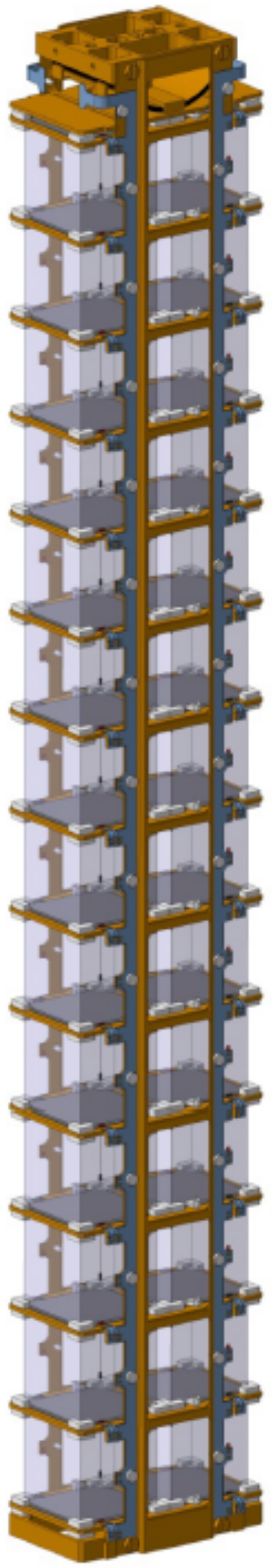
The baseline design



- **45×45×45 mm³ $Li_2{}^{100}MoO_4$ crystals:**
  - Single crystal mass: 280 g
- **1596 crystals in the array**
  - 450 kg of $Li_2{}^{100}MoO_4$
  - 95% enrichment in ^{100}Mo: 240 kg of ^{100}Mo
  - 57 towers of 28 crystals each. 14-floors of 2×1 crystal pairs. Gravity assisted design
- **Ge light detectors (LD) with SiO anti-reflective coating.**
  - Top and bottom light detectors for each crystal: 1710 light detectors
  - No reflective foils
- **Muon veto for muon-induced background suppression**



Gravity stacked structure tower



- **CUPID performance goal**
  - Energy resolution: 5 keV FWHM
  - Light Yield: 0.3 keV/MeV
  - LD: $\sigma_{baseline}$ ~100 eV for PID
  - Background: 10^{-4} ckky (counts/keV/kg/y)

Eur.Phys.J. C82(2022)810

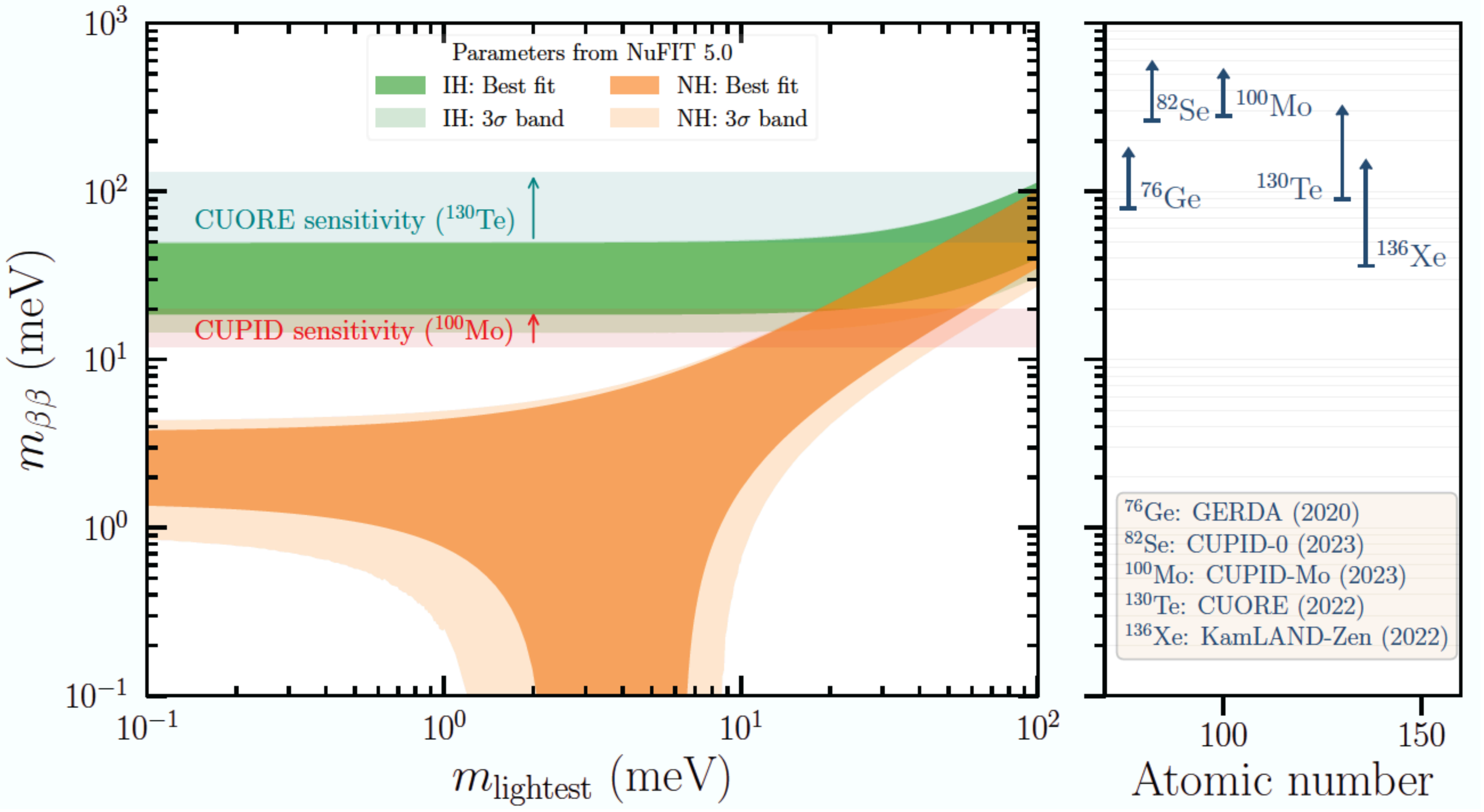
CUPID strategy and goal

A ton scale high resolution array for the search of $0\nu\beta\beta$ decay

- Re-use CUORE infrastructure
- Replace CUORE $^{nat}TeO_2$ detectors with an array of $Li_2{}^{100}MoO_4$ enriched at 95% in ^{100}Mo

Enough to take a leap forward in sensitivity because background reduces dramatically (~ ×100):

- ^{100}Mo has higher $Q_{\beta\beta}$ (3034 keV) than ^{130}Te: lower γ-induced background, more favourable phase space and matrix element factors
- New detector with α particle rejection: removes the dominant background of CUORE



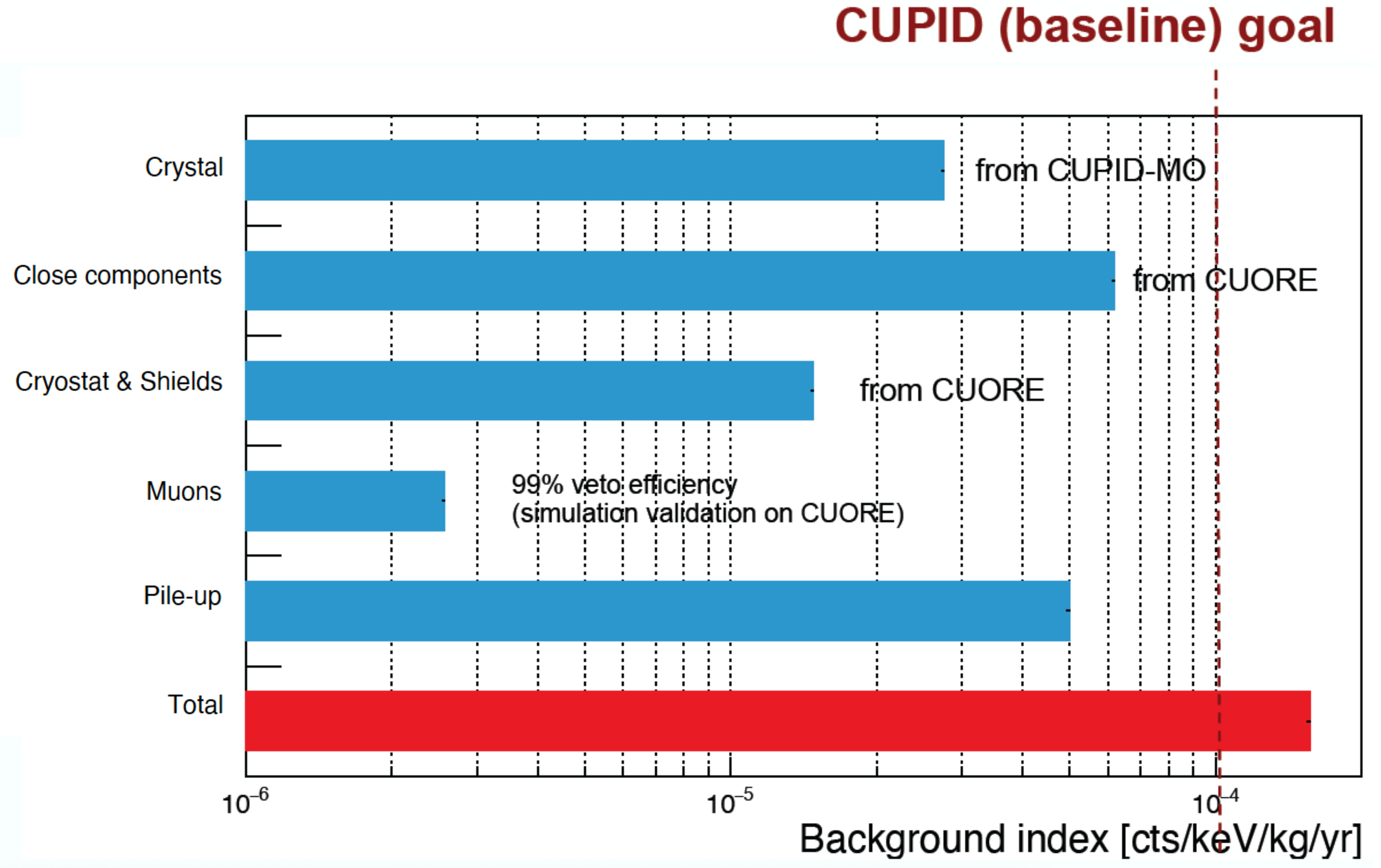
3σ discovery sensitivity:
$m_{\beta\beta}$: [13–21] meV
$T_{1/2} > 10^{27}$ yr

CUPID background budget

The expected background rate in the ROI

CUPID background model reconstruction approach is well validated by multiple experiments:

- **CUORE background model validates:**
  - The β/γ background contribution from the cryogenic system and the detector holders at ~3 MeV
- **CUPID-Mo confirms:**
  - α tagging
  - Energy resolution
  - Crystal radiopurity
- **CUPID-0 confirms:**
  - α rejection
  - β/γ bkg from detector holders



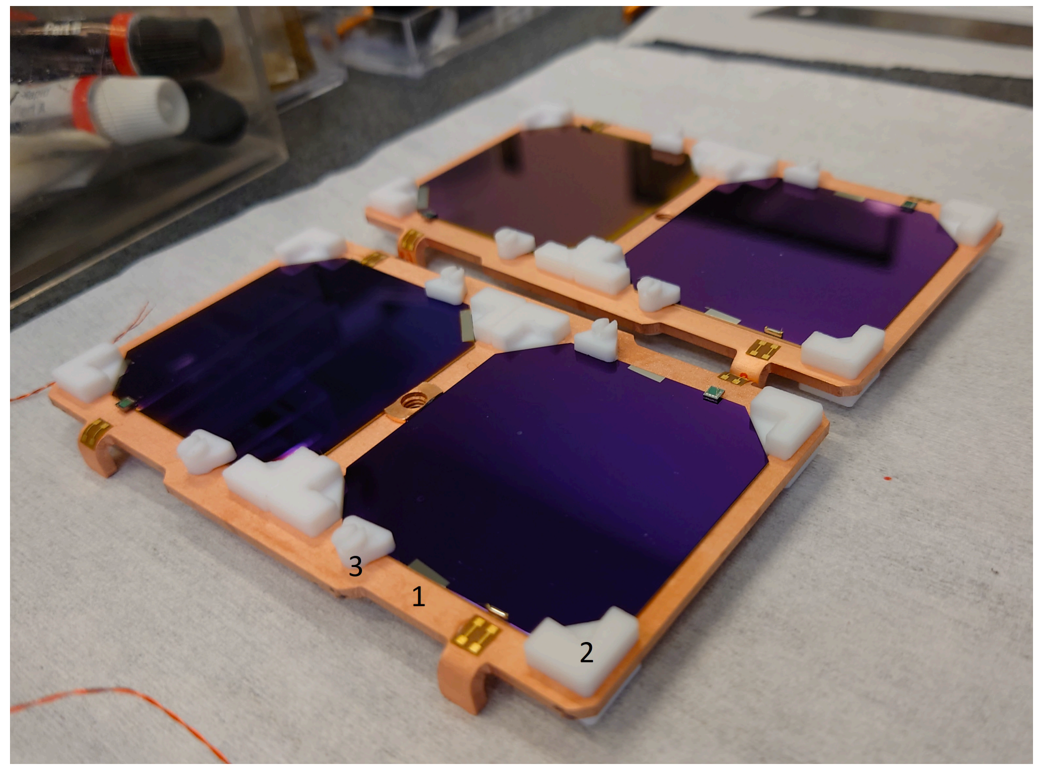
Using past experiment achievements, the total estimated background in CUPID ROI ([3034 ± 15] keV) is: 1.36×10^{-4} ckky

On the way to CUPID

Presently ongoing activities

- We are working on the strategies to improve the surface cleaning of crystals and close components, to reach the 10^{-4} ckky baseline bkg goal.
- Enriched LMO crystal pre-production is ongoing. Production at large scale of the CUPID array is possible and under negotiation.
- Mock-up towers to optimise the new assembly design are being tested in one of the LNGS test cryostats.
- Light detectors with NTD readout are a robust technology compliant with CUPID baseline requests, but at limit for pile-up rejection. Goal for pile-up background contribution: 5×10^{-5} ckky —> currently working on read-out schemes to reduce the signal-to-noise ratio, on the NTD size and doping to have faster time responses.

Assembled light detectors for test in a Pulse Tube cryostat at IJCLab



JINST 18 P06033

Conclusions and outlook

CUORE

- CUORE has exceeded 2 tonne years (2TY) of exposure and is in stable data taking.
- No evidence of $0\nu\beta\beta$ decay with 2023 kg×yr of analyzed exposure.
- Next step: reprocess the 1st TY data with the new analysis techniques, repeat the $0\nu\beta\beta$ fit and finalise the systematics.
- Final CUORE goal: reach 3TY TeO_2 exposure (1TY ^{130}Te) – expected in 2025.

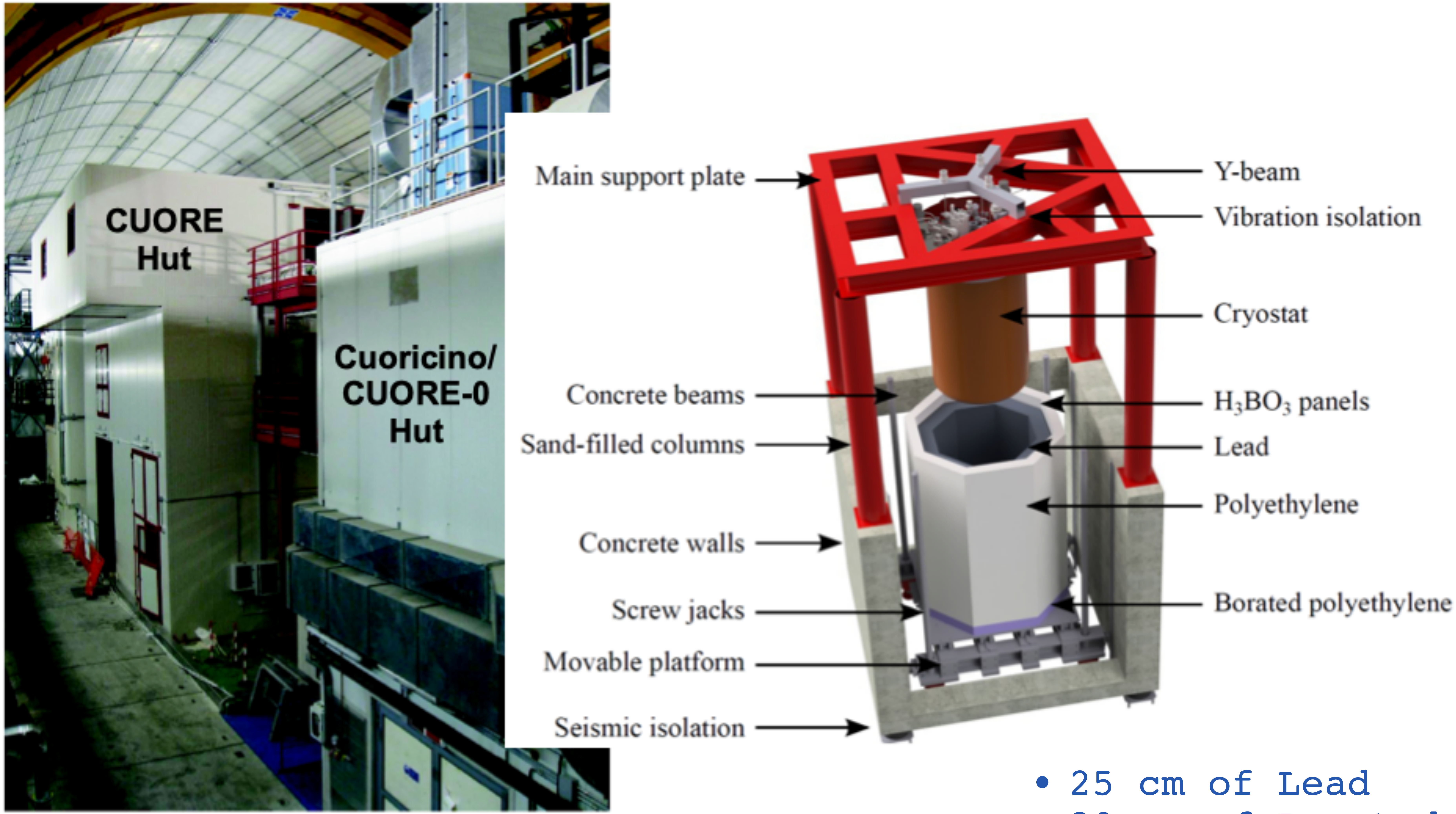
CUPID

- CUPID builds on an existing and well-established international collaboration.
- We have operational experience of ton-scale cryogenic experiments and will use the CUORE infrastructure (cost effective, leverages international investments).
- The collaboration is working on getting ready for CUPID.

BACK UP slides

CUORE external shielding

External gamma and neutron shielding



- 25 cm of Lead
- 20 cm of Borated Polyethylene and boric acid

CUORE ROI fit

- Bayesian Analysis Toolkit (BAT) - MCMC based evaluation of posteriors
  - UEML fit in ROI: [2465,2575] keV
  - likelihood model: ^{130}Te $Q_{\beta\beta}$ peak $(\Gamma_{0\nu})$ + ^{60}Co sum peak (Γ_{Co}) + flat background (BI)
- Dataset-dependent parameters:
  - Background Index (BI)
  - Efficiencies
  - Resolution and bias scaling
- Global parameters:
  - Γ_{Co}: one activity rate with a time-dependent correction for each DS
  - $Q_{\beta\beta}$
  - Isotopic abundance of ^{130}Te
  - Containment Efficiency
  - $\underline{\Gamma_{0\nu}}$

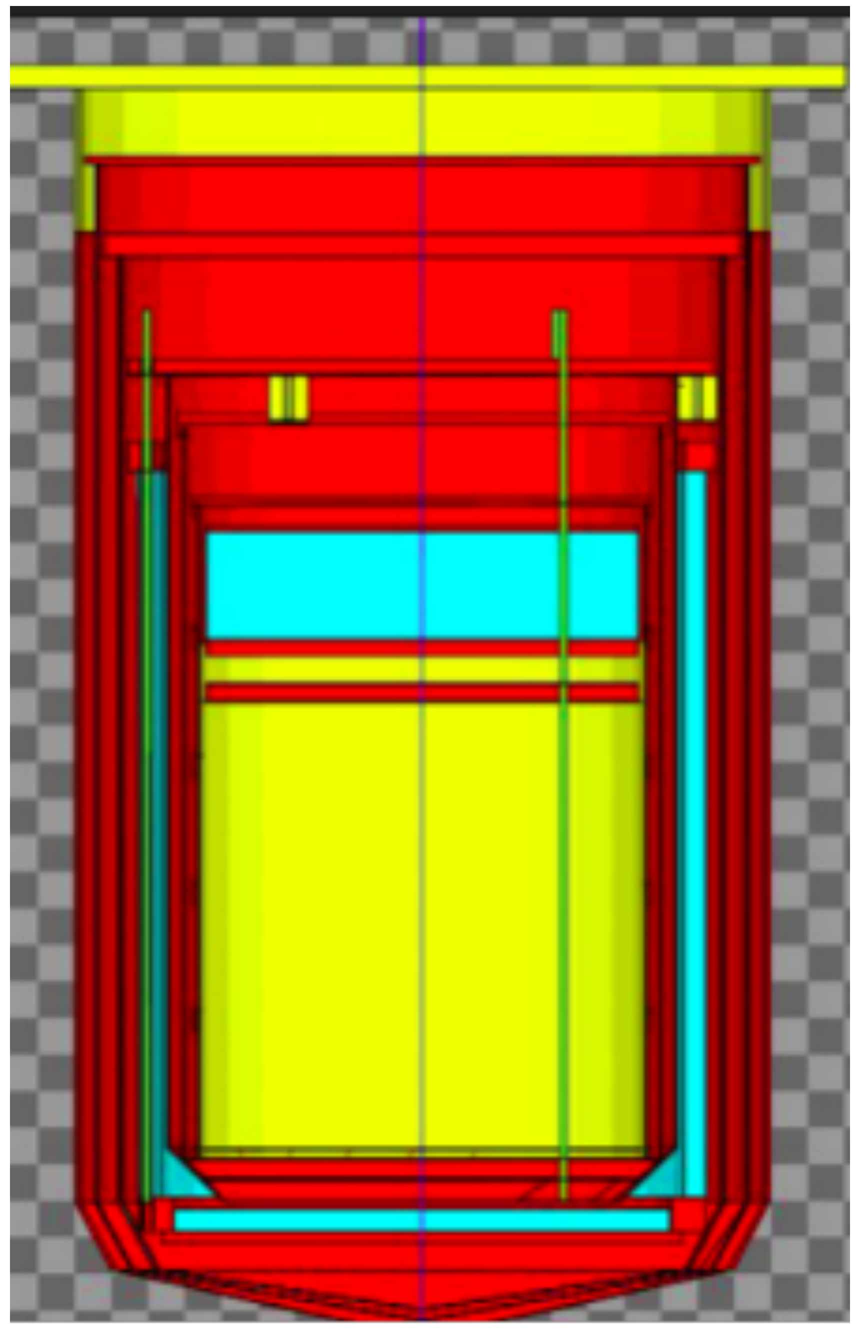
CUPID scenarios

CUPID baseline

240 kg ^{100}Mo
CUORE cryostat
Bkg: 10^{-4} ckky

$T_{1/2} > 1\times10^{27}$ yr
$m_{\beta\beta}$: [13–21] meV

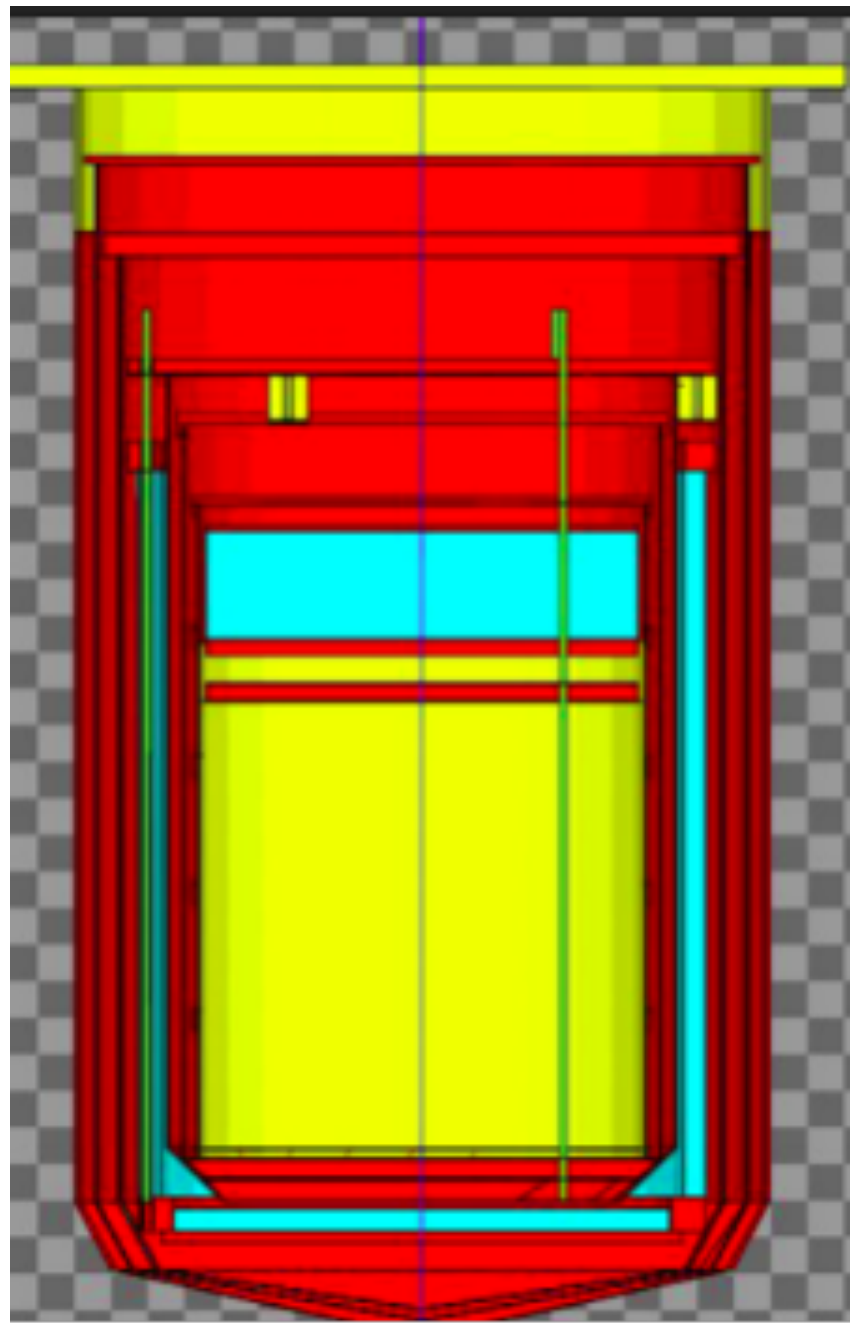
CUPID Reach



240 kg ^{100}Mo
CUORE cryostat
Bkg: 2×10^{-5} ckky

$T_{1/2} > 2\times10^{27}$ yr
$m_{\beta\beta}$: [9–15] meV

CUPID 1 ton



1000 kg ^{100}Mo
NEW cryostat
Bkg: 5×10^{-6} ckky

$T_{1/2} > 9\times10^{27}$ yr
$m_{\beta\beta}$: [4–7] meV