Latest results from the CUORE experiment

Alice Campani on behalf of the CUORE collaboration

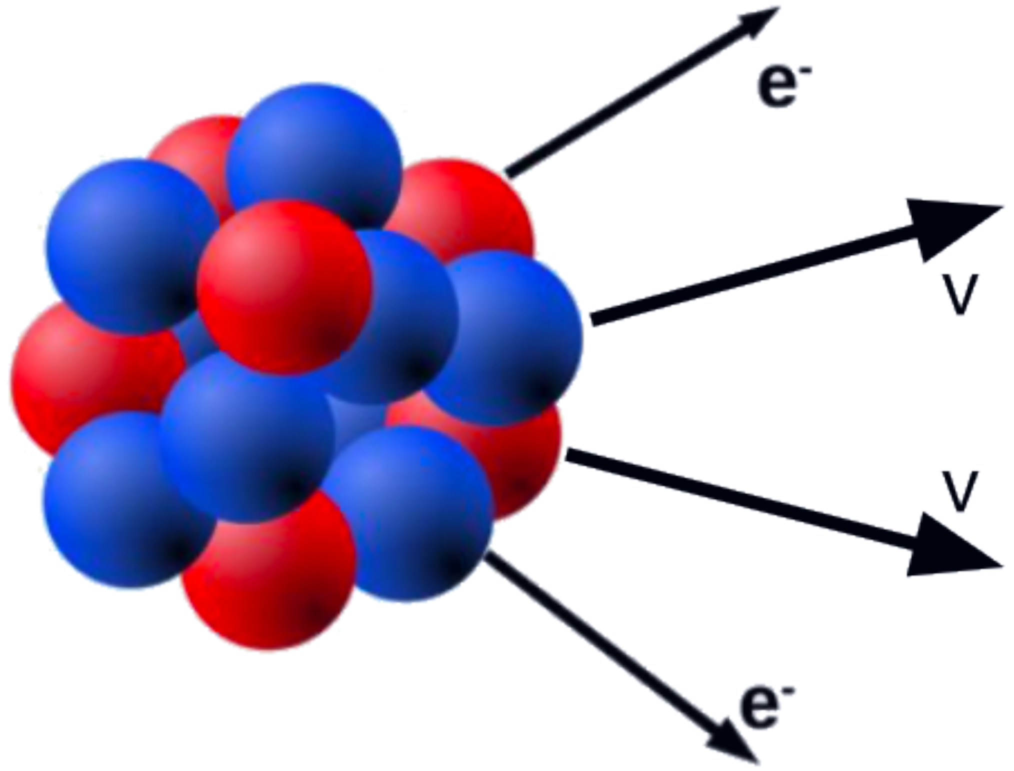
BSM 2023 - Hurghada, 9/11/2023

Summary

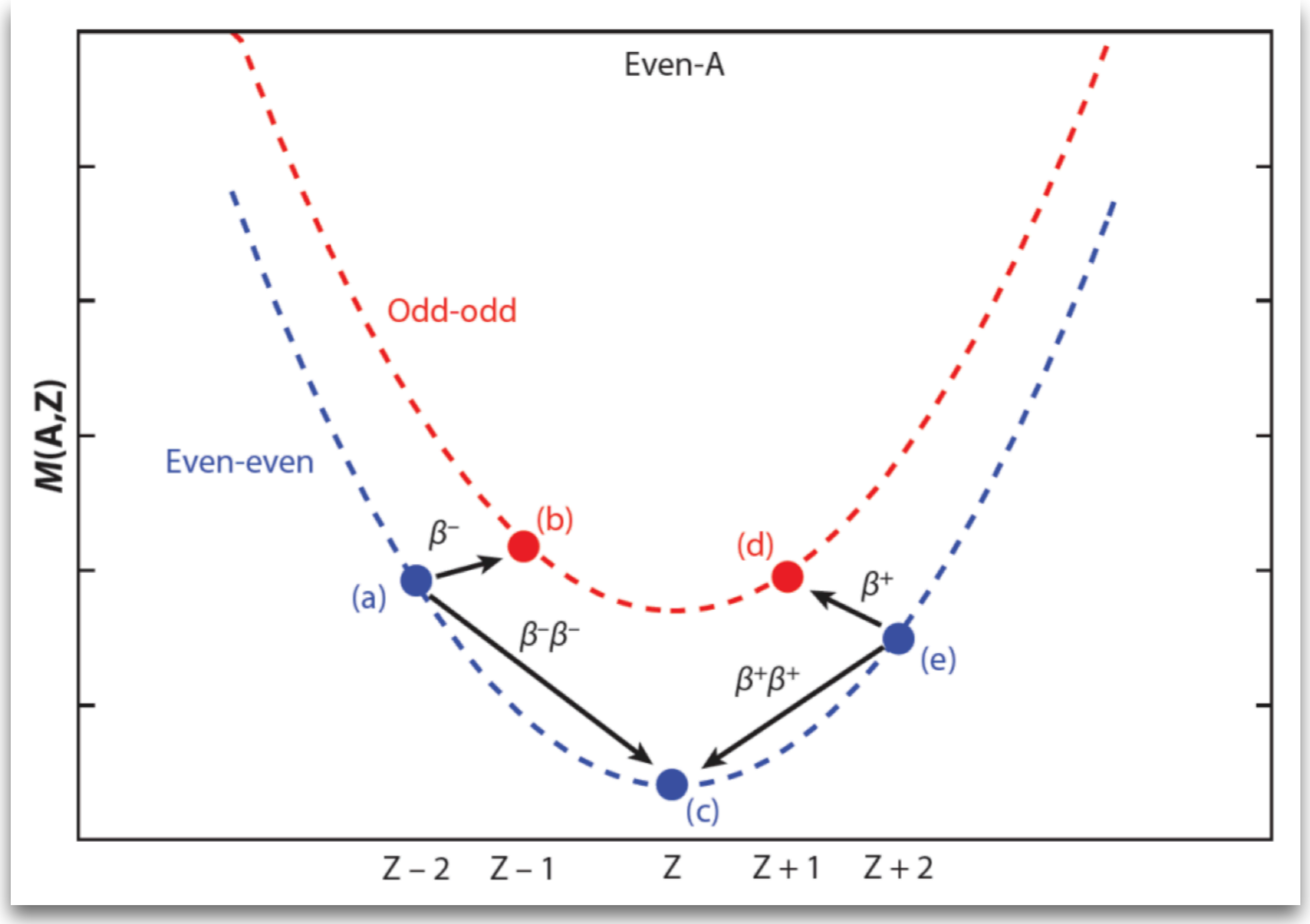
- Double beta decay overview
- Cryogenic calorimeters for the $0\nu\beta\beta$ decay search
- CUORE experiment
- Data acquisition and analysis
- Recent results on the search for $0\nu\beta\beta$ decay in ^{130}Te
- Other rare decays search and analyses with CUORE
- Conclusions and perspectives

Double beta decay

$2\nu\beta\beta$



- Allowed in the Standard Model only for ***even-even*** nuclei (**ΔL = 0**)
- Observed in several nuclei, ^{76}Ge,^{82}Se,^{100}Mo,^{136}Xe, …
- Half-life $T^{2\nu}_{1/2} \sim 10^{18} - 10^{22}$ yr



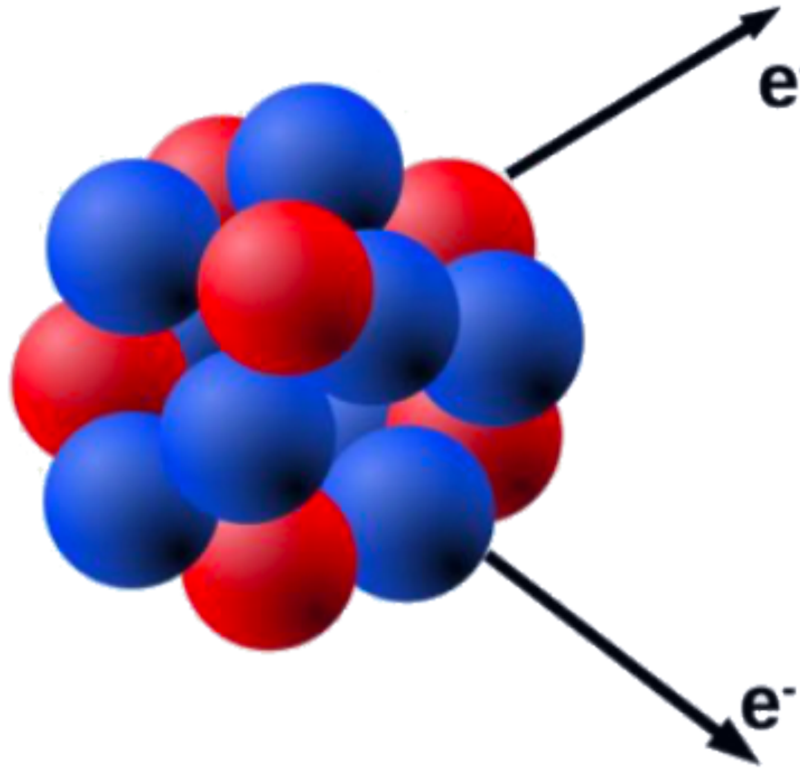
$2\nu\beta\beta$

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

$0\nu\beta\beta$

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

$0\nu\beta\beta$



- Beyond the Standard Model: lepton number symmetry violation (**ΔL = 2**)
- Simplest model: Majorana ν
- No evidence observed so far
- Half-life $T^{0\nu}_{1/2} > 10^{24} - 10^{26}$ yr

The importance of $0\nu\beta\beta$ for particle physics and cosmology

- **Lepton asymmetry** could play an important role in the ***matter-antimatter asymmetry*** in the Universe

- Assuming the exchange of a light Majorana neutrino the $0\nu\beta\beta$ decay rate is

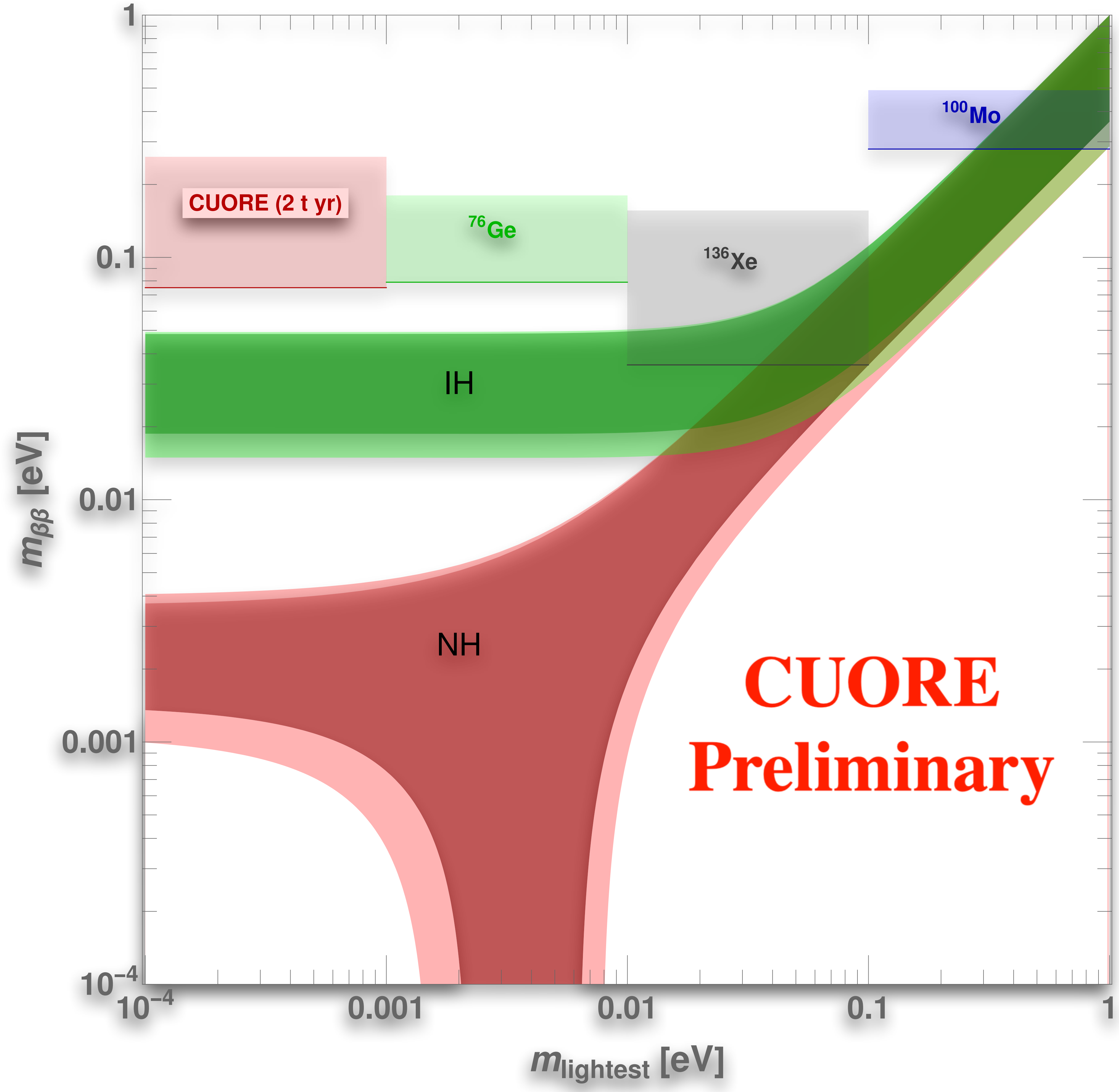
$$\Gamma_{0\nu\beta\beta} \propto G_{0\nu}(Q,Z)\left|M_{0\nu}\right|^2 \frac{\left| < m_{\beta\beta} > \right|^2}{{m_e}^2}$$

Phase space factor

Nuclear matrix element

Effective Majorana mass

$$| < m_{\beta\beta} > | = \sum_{i=1,2,3} U_{ei}^2\, m_i$$

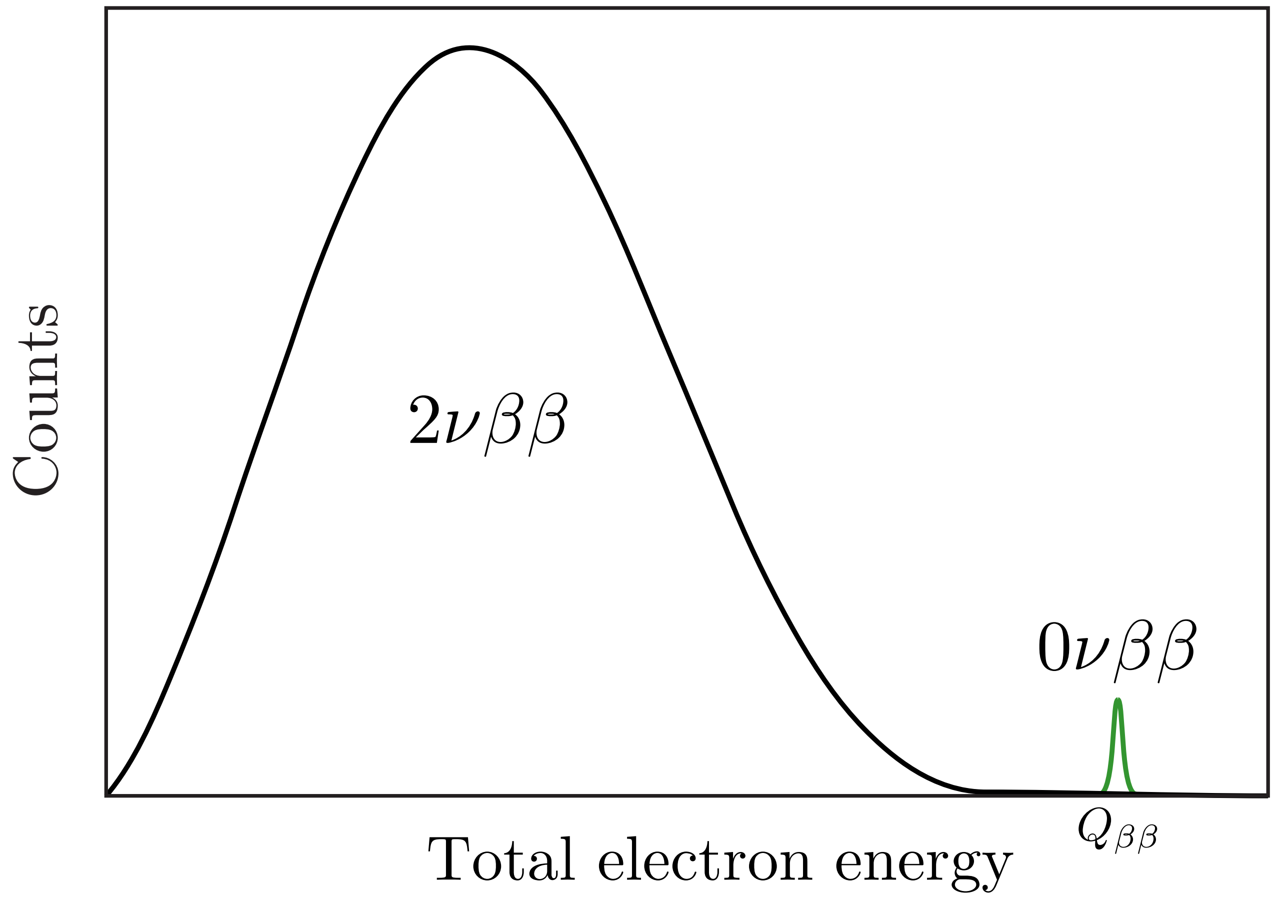


- Any observation would provide information on the neutrino ***mass scale*** and ***ordering***

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

The experimental sensitivity is

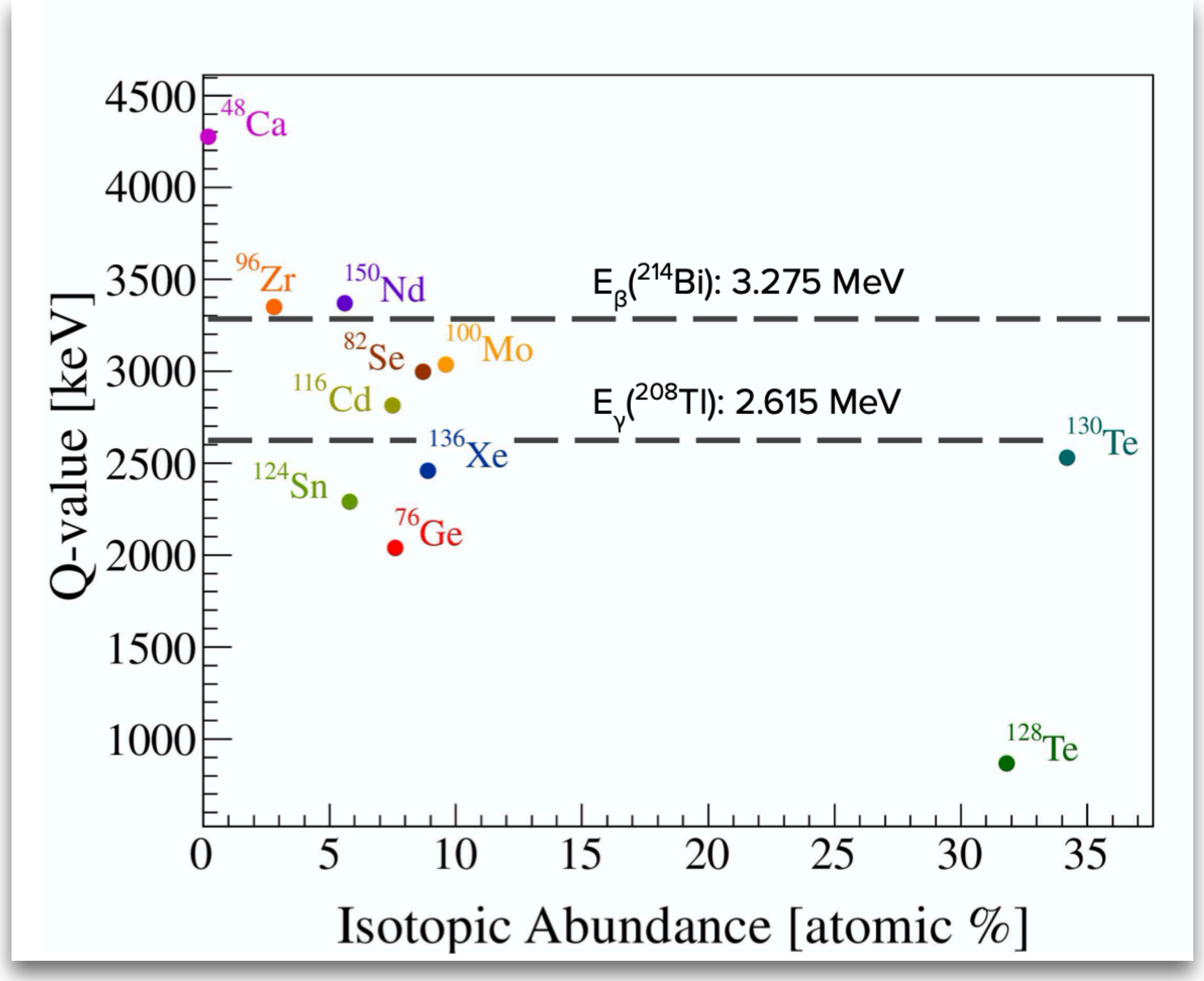
$$S^{0\nu}_{T_{1/2}} \propto \sqrt{\frac{M \cdot T}{b \cdot \Delta E}} \qquad \left[\text{for negligible background } S^{0\nu}_{T_{1/2}} \propto M \cdot T\right]$$



Fundamental requirements for $0\nu\beta\beta$ decay experiments are:

- Scalability of the technique to achieve high ***exposure***, which means high mass and time stability
- Minimum ***background***
- High **resolution** to distinguish the signal peak
- Wise choice of the ***isotope*** (isotopic abundance and γ, α background)

Cryogenic calorimeters represent a mature and competitive technology in the field of $0\nu\beta\beta$ decay search as demonstrated by several detectors (CUORE, CUPID-0, CUPID-Mo, AMORE)



The CUORE collaboration

27 Institutions from **4** different countries: **China**, **France**, **Italy** and **USA**

Further information is available on our website: https://cuore.lngs.infn.it

The CUORE experiment in a nutshell

Cryogenic ***U****nderground* ***O****bservatory for* ***R****are* ***E****vents*

- Scientific goal: search for $0\nu\beta\beta$ decay of ^{130}**Te** (isotopic fraction ~34%, $Q_{\beta\beta}$~2528 keV, only ^{208}Tl γ line @ 2615 keV above)
- **Tonne-scale detector**: 988 $^{(nat)}$TeO$_2$ crystals arranged in 19 towers and operated at ~10 mK TeO$_2$ mass is 742 kg (206 kg of ^{130}Te)
- **Underground** at the **LNGS** (Abruzzo, Italy)

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

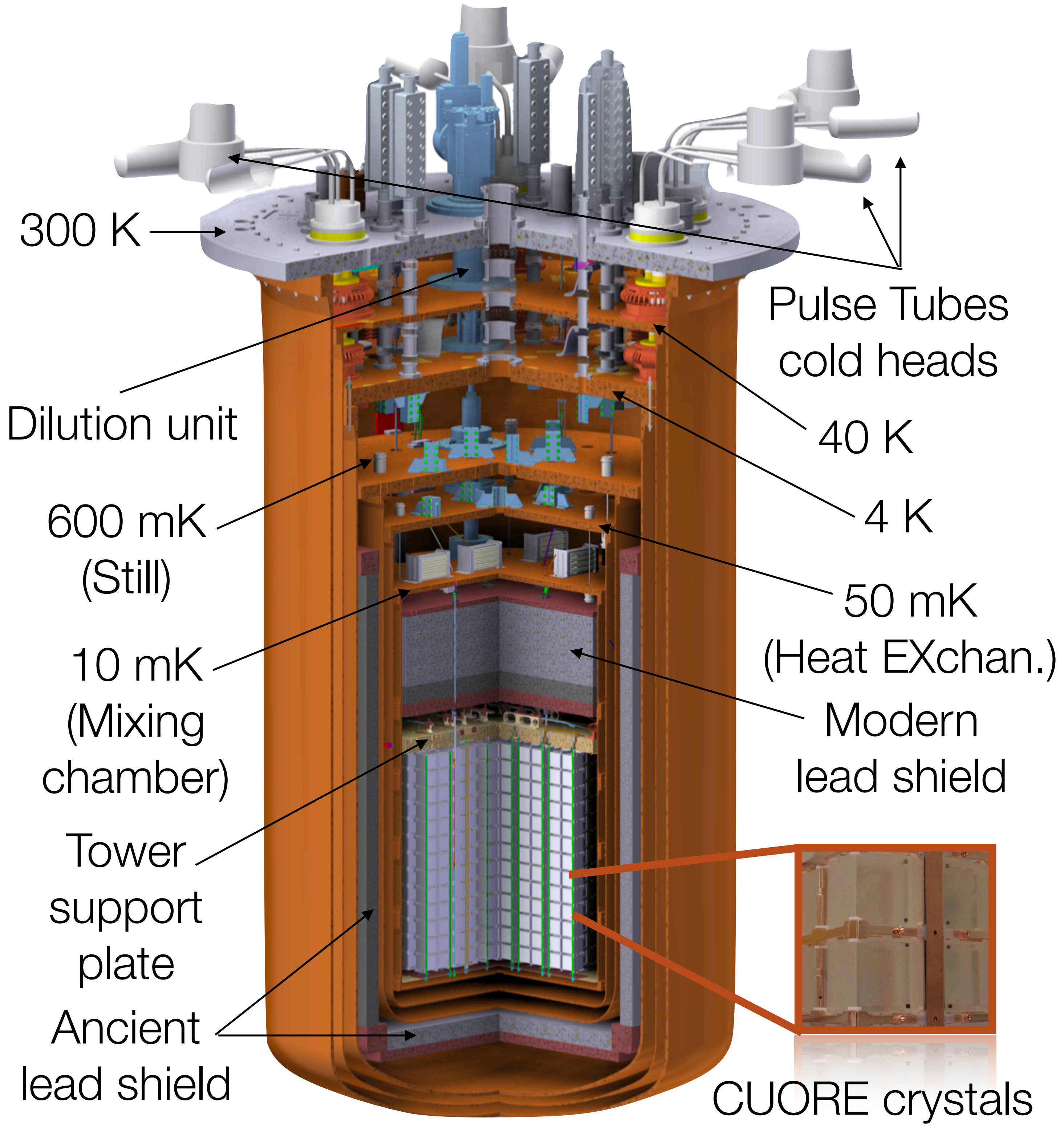
TAUP 2023 results

Effective 2nd tonne · yr (TY) **FWHM** at $Q_{\beta\beta} = \left(7.26^{+0.43}_{-0.47}\right)$ keV

2nd TY **Background index** in the ROI: 1.30(3)·10^{-2} counts/keV/kg/yr

The CUORE experiment challenge: cryostat, radiation shielding and noise abatement

Cryogenics 102 (2019) 9-21



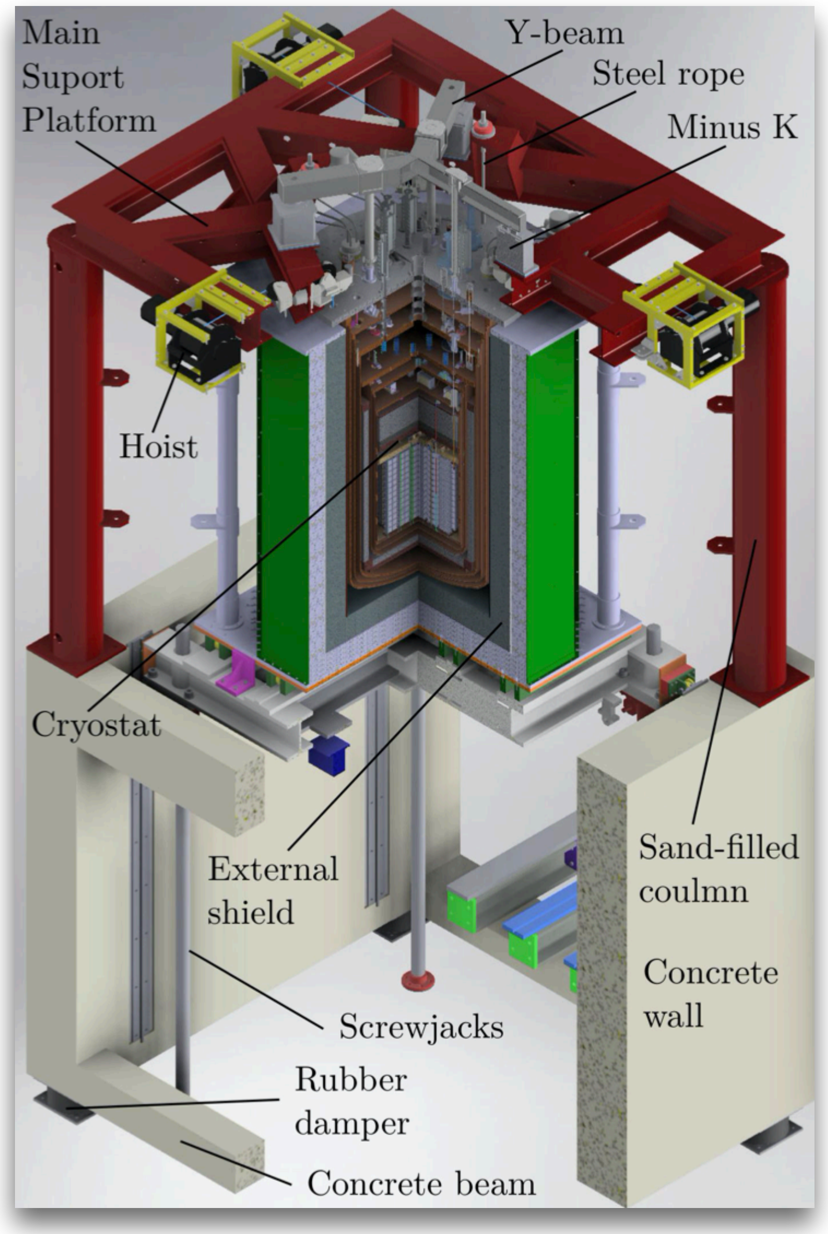
- Cryogen free dilution cryostat
- Strict constraints on the materials radiopurity and mechanical stability

LNGS natural shielding: cosmic rays flux 10^{-6} relative to the surface

External shields:
from γs: 25-cm thick Pb layer
from neutrons: 20-cm layer in polyethylene + H_3BO_3 panels

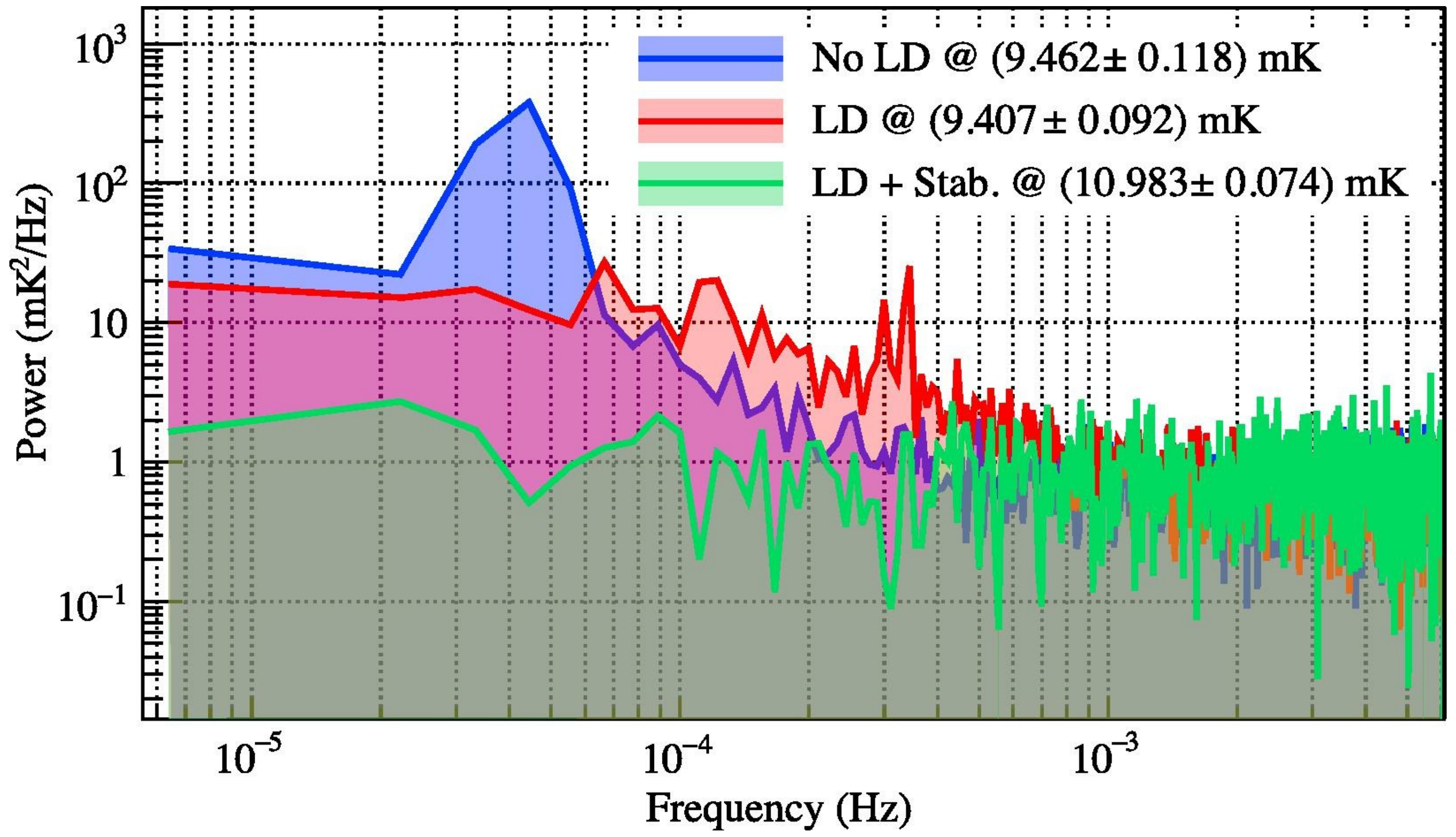
Internal shields:
Top: 30-cm modern lead
Side and bottom: 6-cm ancient roman Pb from a shipwreck (^{210}Po<4 mBq/kg)

External support structure to decouple the detector from the cryostat



Linear drives and active noise cancellation

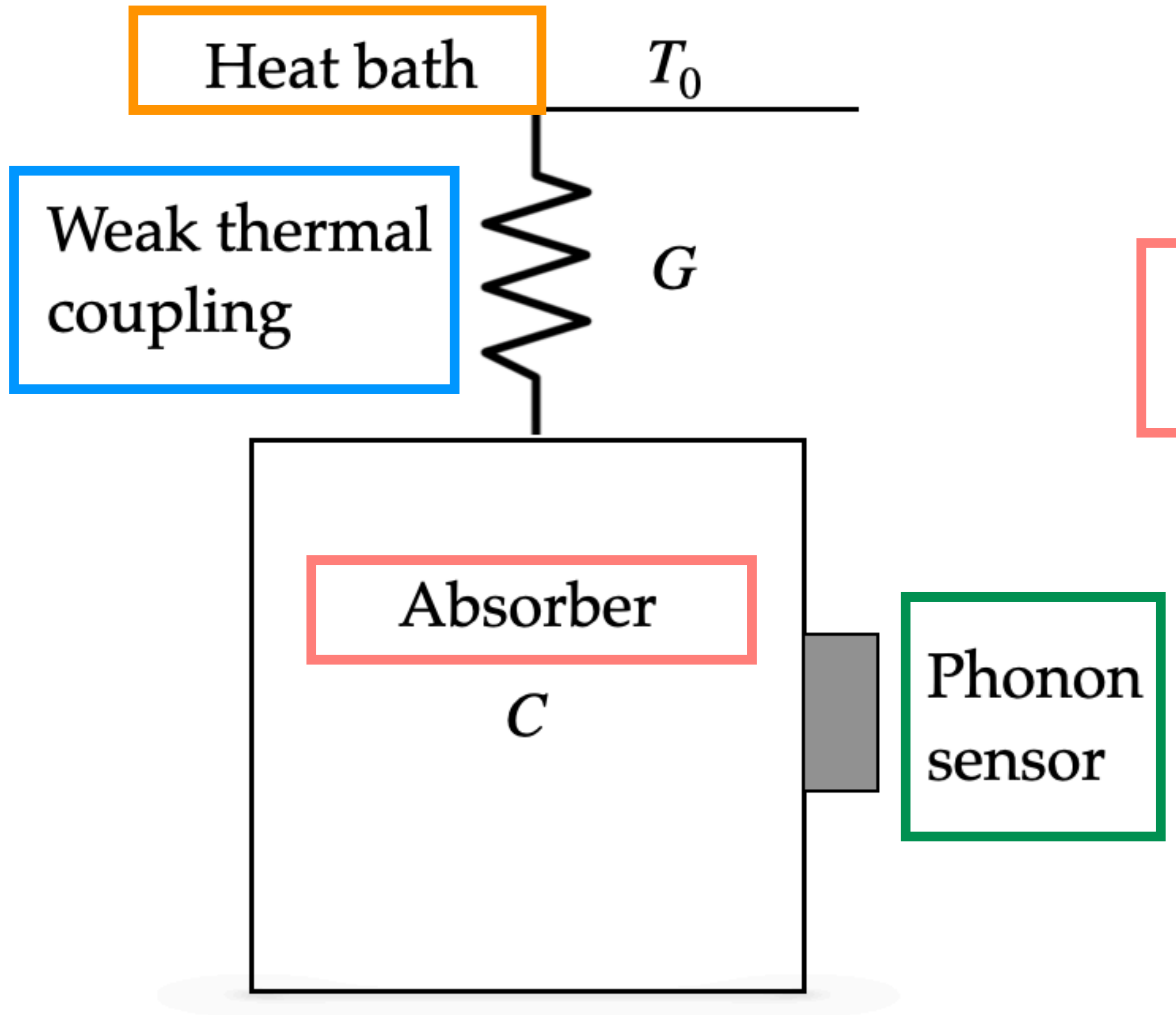
Cryogenics 93, 55-56 (2018)



Cryogenic calorimeters for rare decays search

The **energy** released in a particle interaction is measured via **thermal excitations** (*phonons*)

The **temperature increase** is converted into an **electric signal** by a cryogenic sensor (e.g. a thermistor)

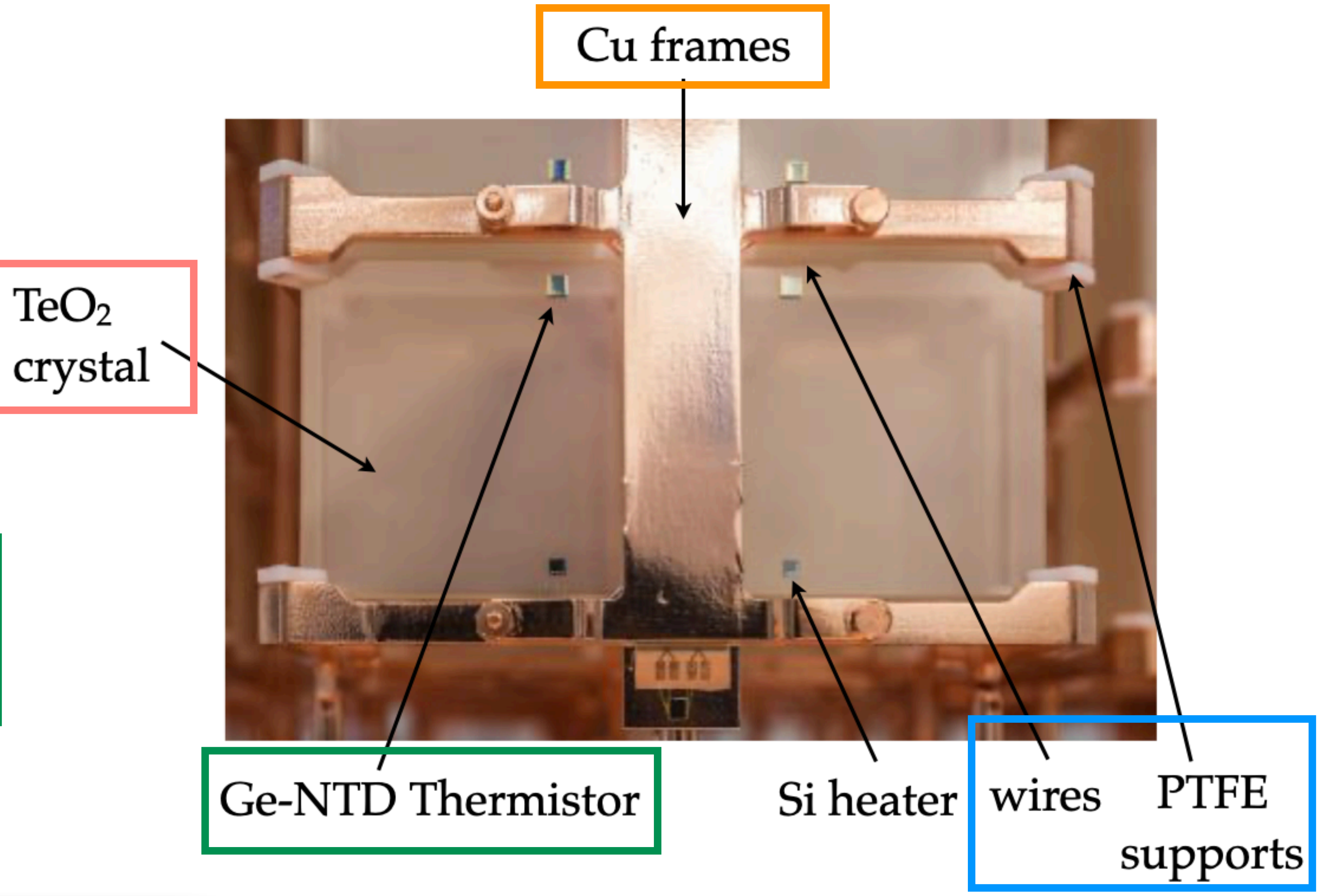


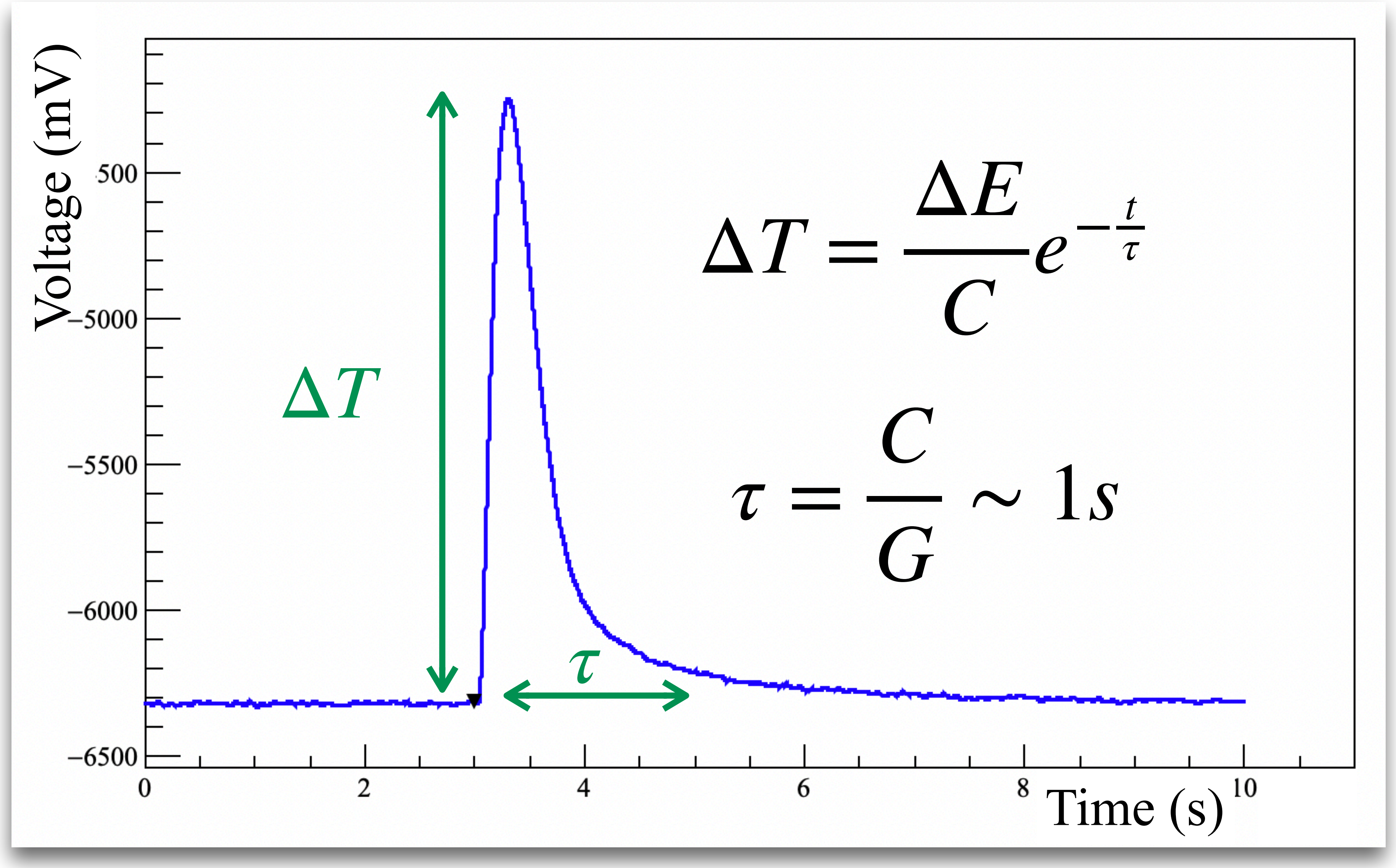
Heat bath T_0

Weak thermal coupling G

Absorber C

Phonon sensor





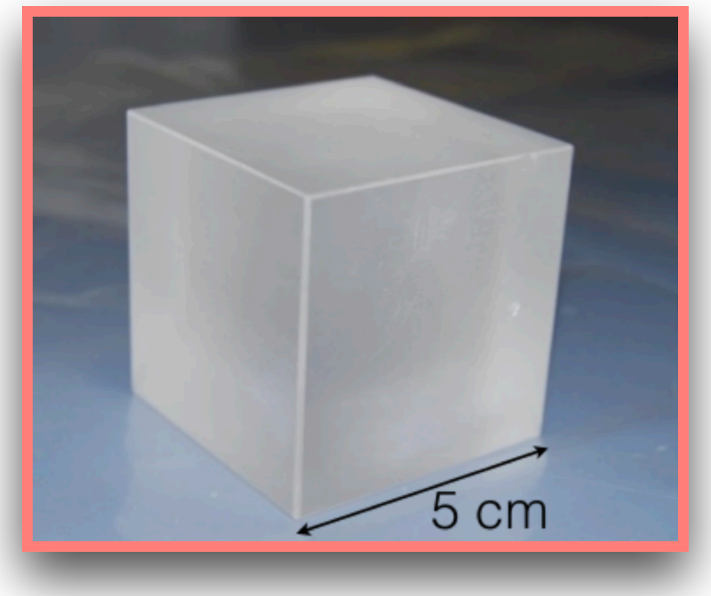
$$\Delta T = \frac{\Delta E}{C} e^{-\frac{t}{\tau}}$$

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

TeO₂ crystal

$C \propto T^3 (\text{Debye law})$

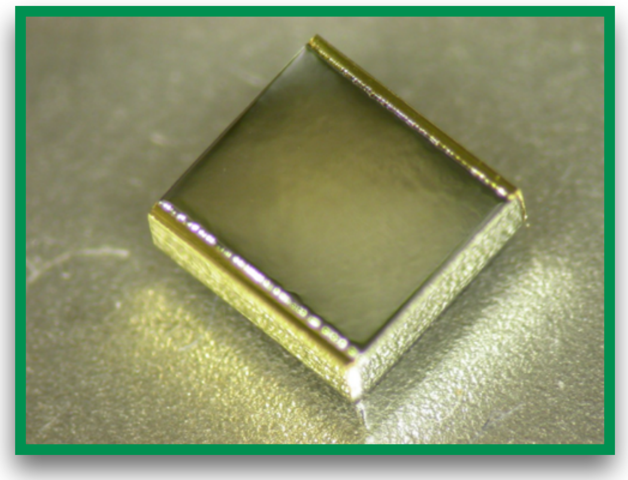
C≈ nJ/K



Ge-NTD thermistor

$R \propto e^{\sqrt{T_0/T}}$

ΔR~3MΩ/MeV



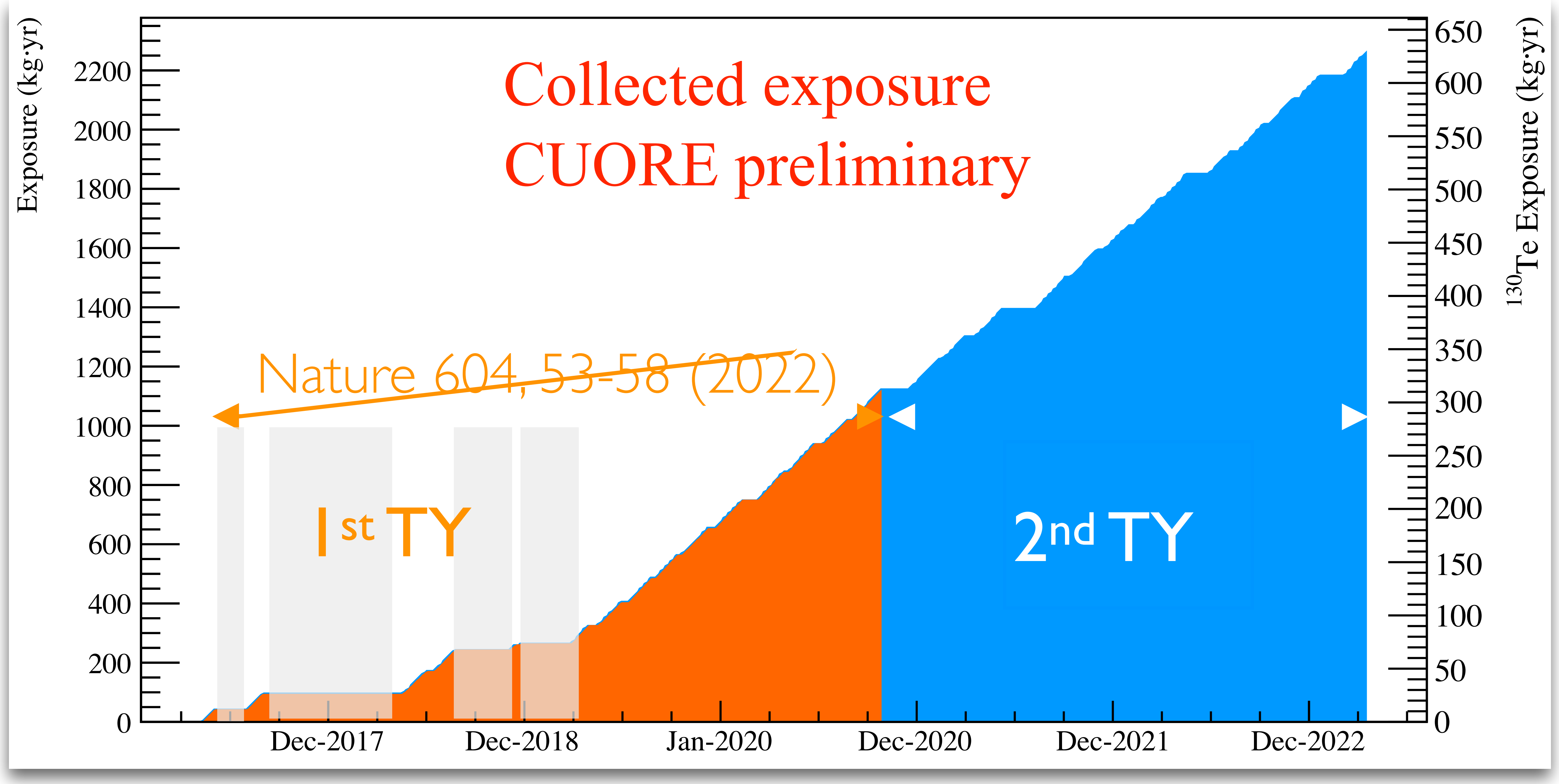
Operating at a temperature of **~10 mK**:

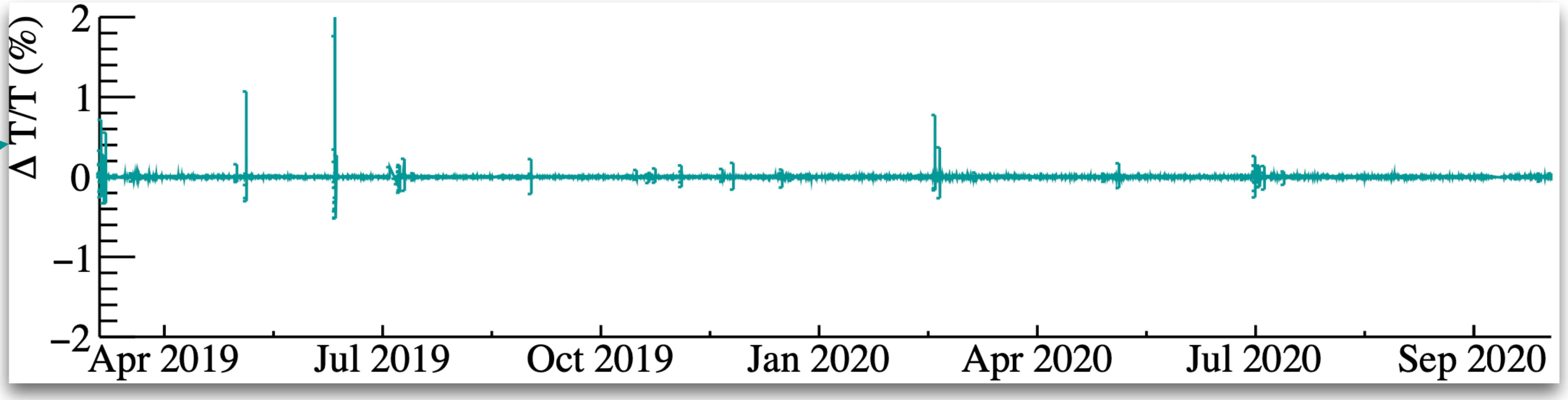
1 MeV energy release causes **ΔT~100 μK**

We use a **Si heater** to inject stable voltage pulses and do **thermal gain stabilization**

Data taking with CUORE

- Data split in *datasets*: 1-2 months of physics data bookended by calibration
- Typical trigger rate 50 mHz in calibration, ~6 mHz during physics runs
- Voltage across NTD Ge thermistors continuously sampled at 1kHz, we use a software trigger that is applied offline
- Data taking started in 2017, 2017-2019: several optimization campaigns
- Since march 2019 steady data taking with > 90% uptime in stable temperature conditions
- Average data taking rate of ~50 kg·yr/month

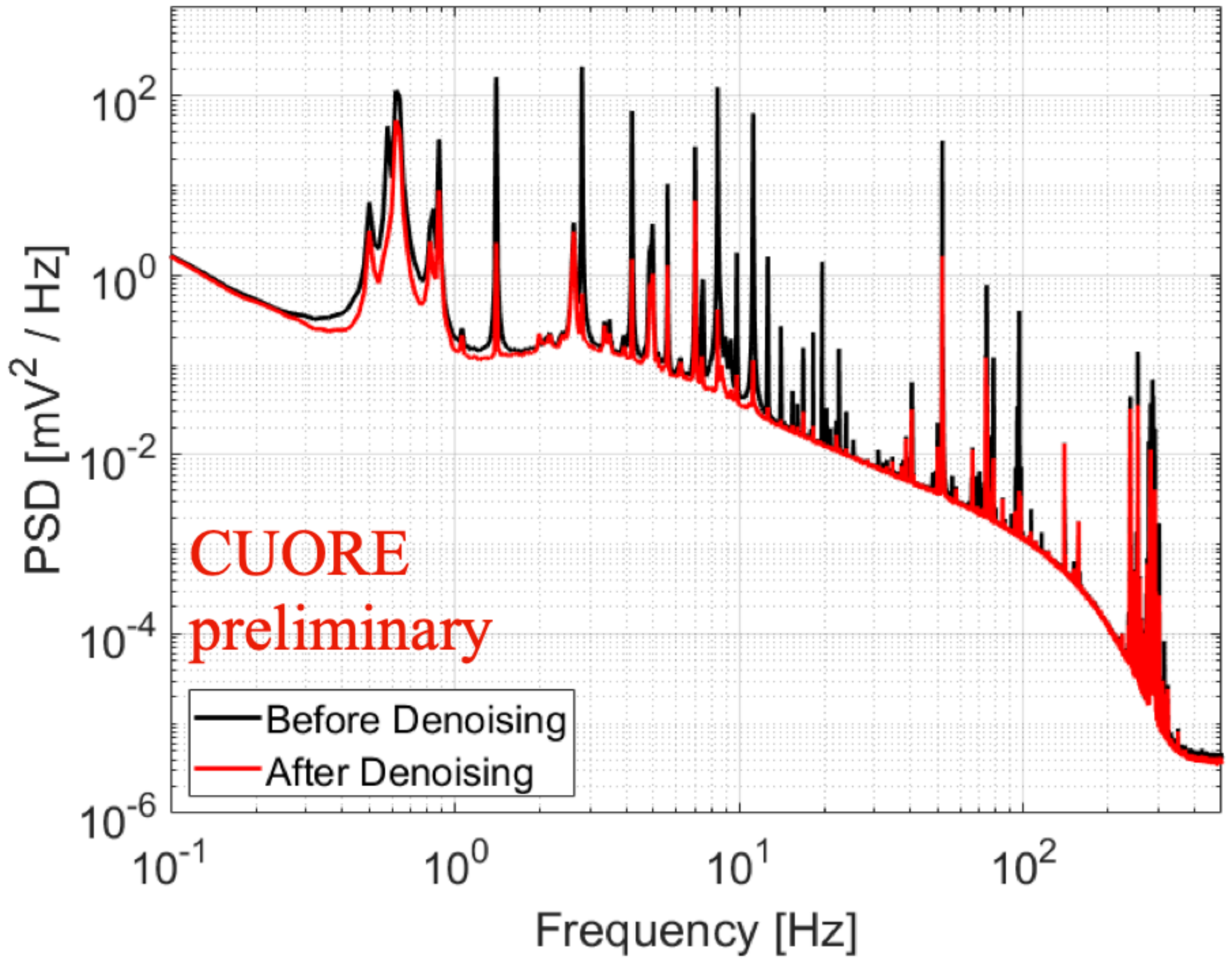




Nature 604, 53-58 (2022)

Data processing in CUORE

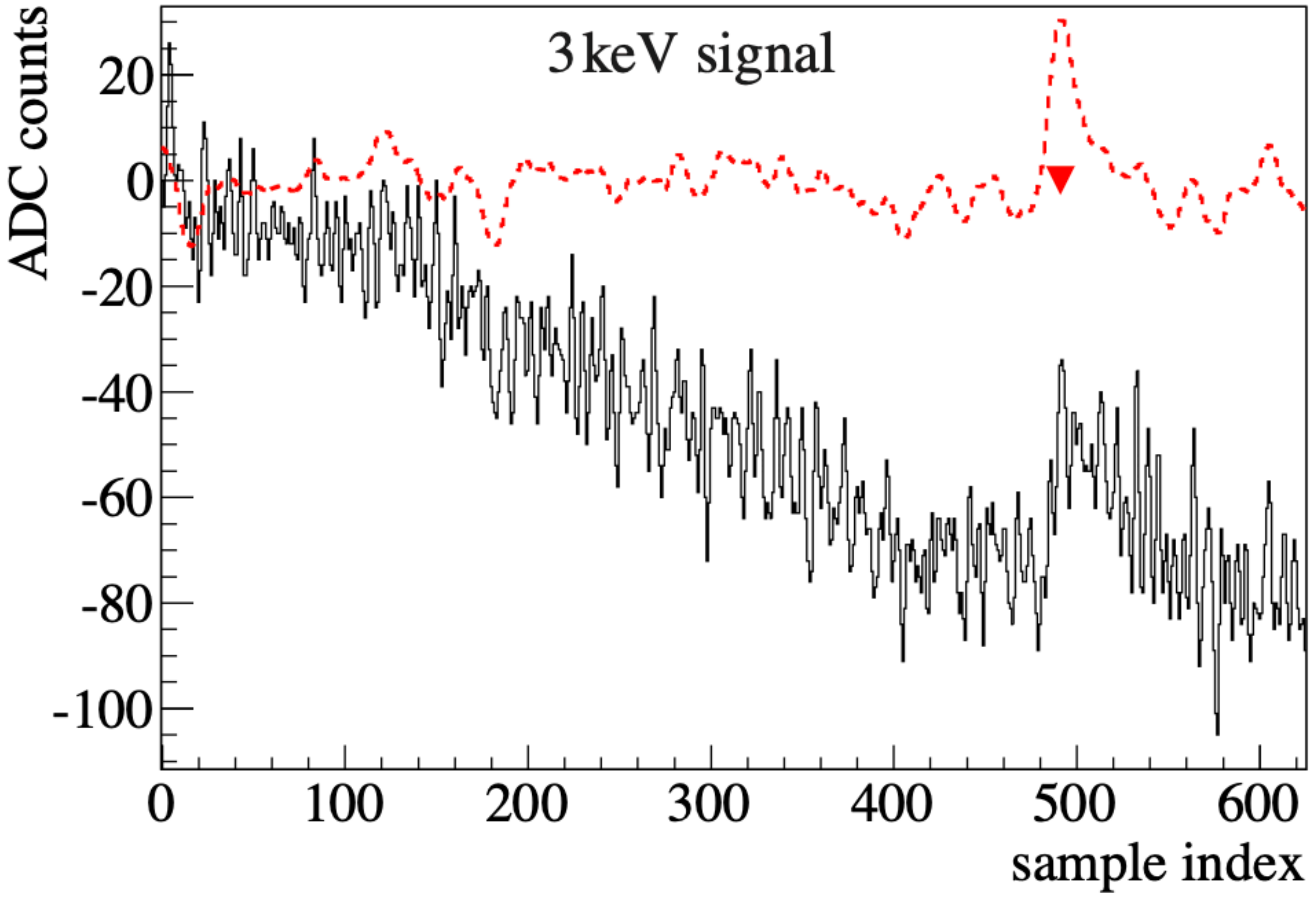
Denoising (New!)

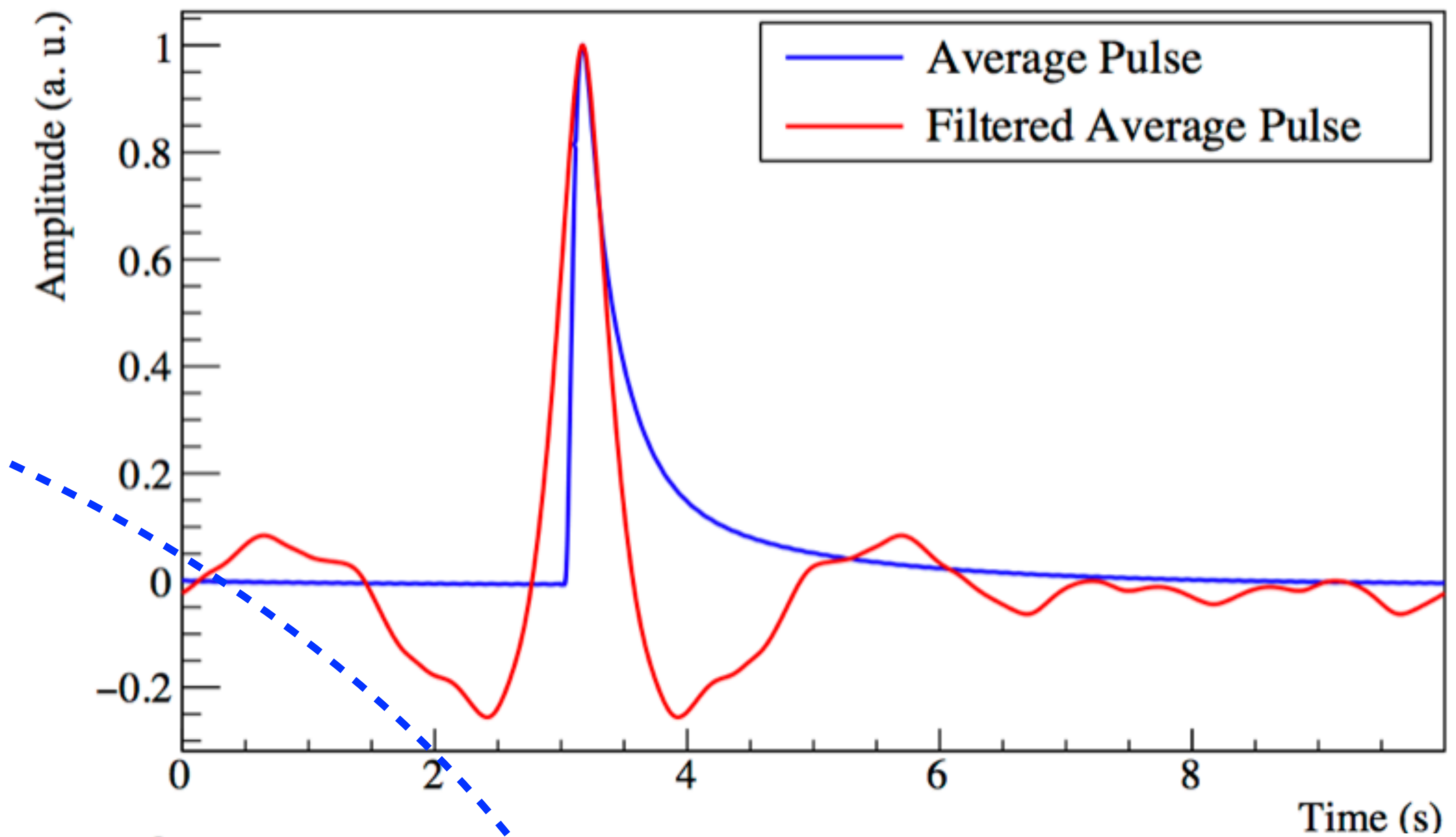


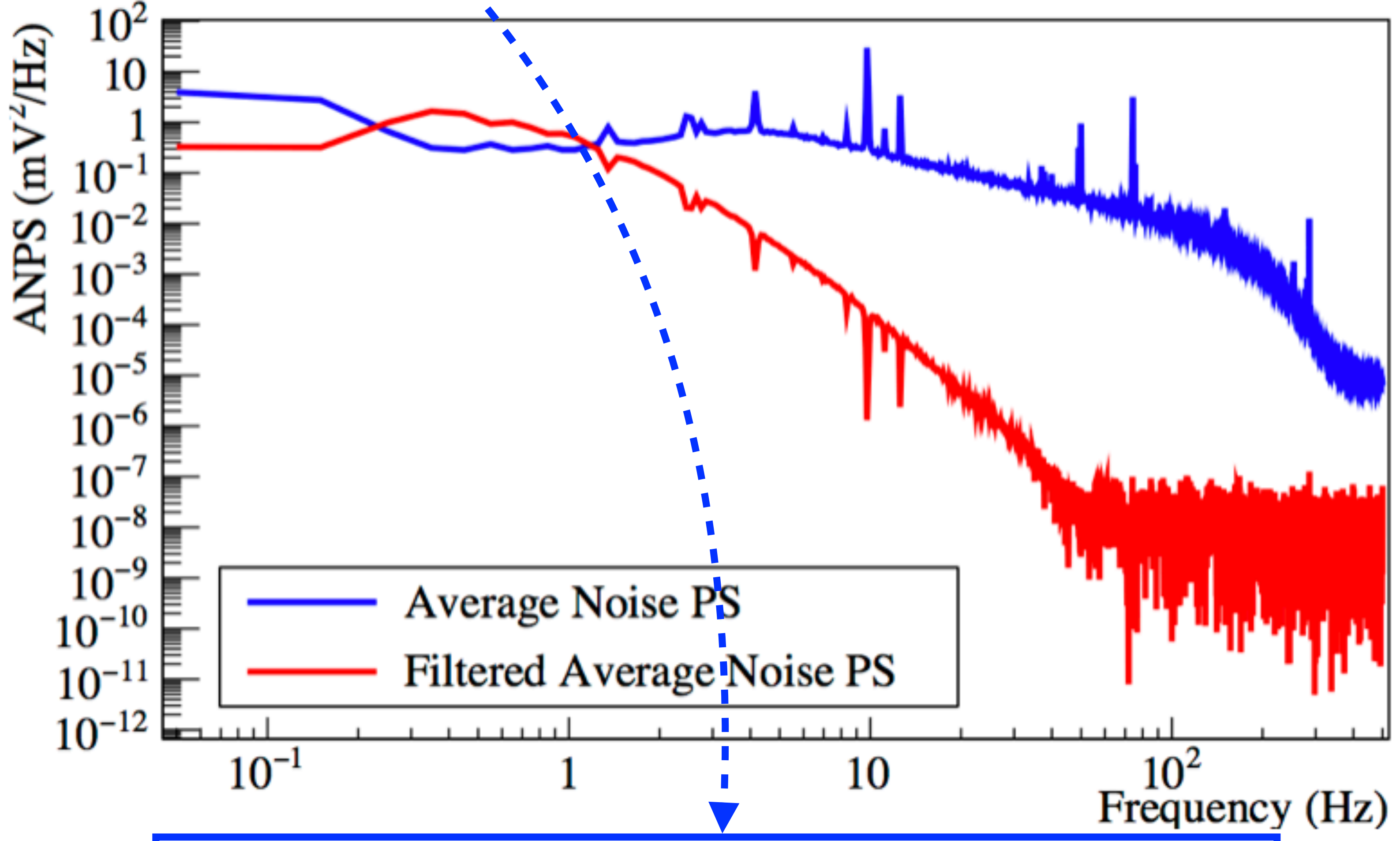
Noise is mitigated correlating *vibrations* with measurements obtained with *auxiliary devices*, i.e. microphones, accelerometers, seismometers

Optimum trigger (OT)

Offline data retrigger with OT to maximize SNR exploiting the distinct power spectra of particle induced and noise waveforms.





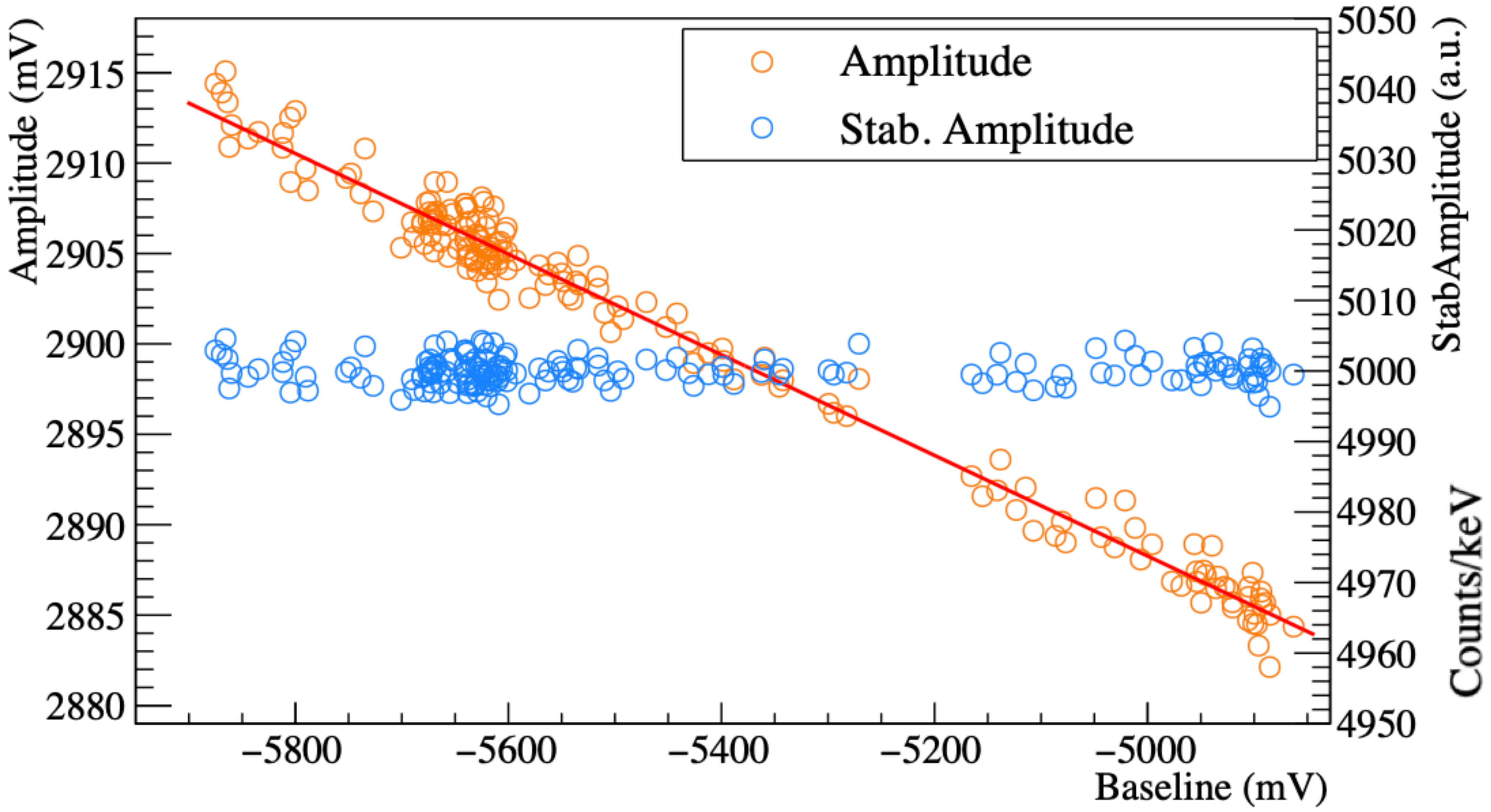


Optimum Filter technique

We evaluate *filtered* signal amplitude

Data processing in CUORE

Thermal gain stabilization (TGS)

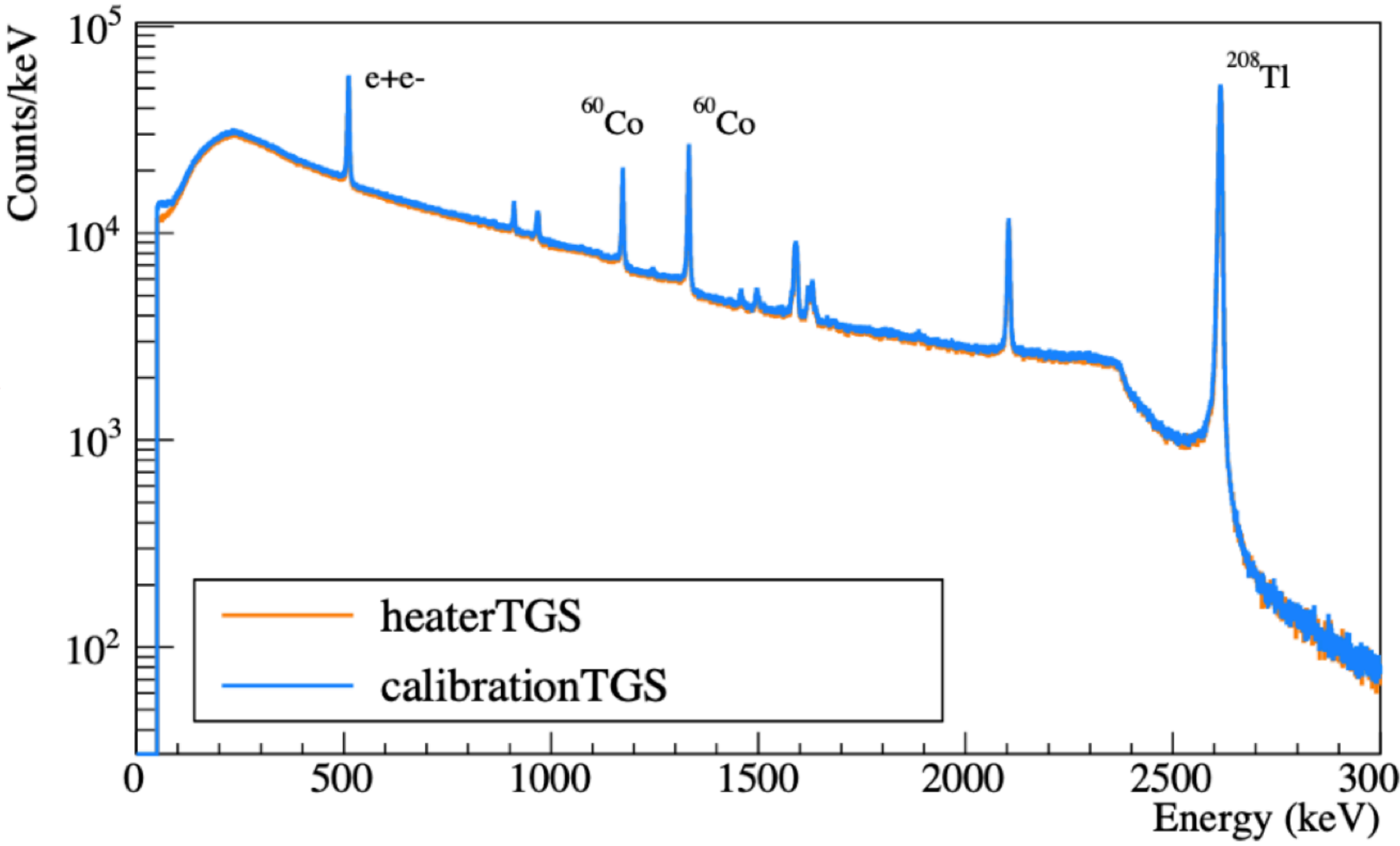


We employ fixed energy pulses to correct for drifts in the thermal gain

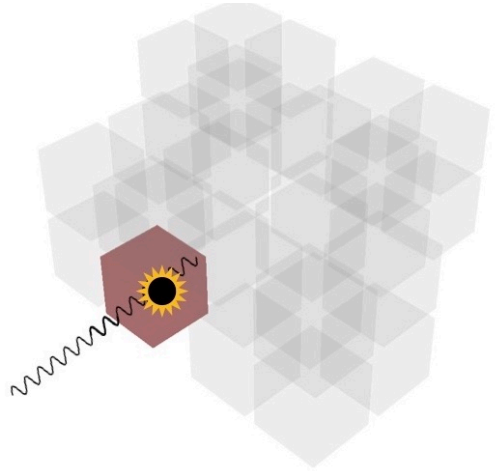
Energy calibration

This is based on measurements with ^{232}Th + ^{60}Co external strings, periodically deployed in the detector

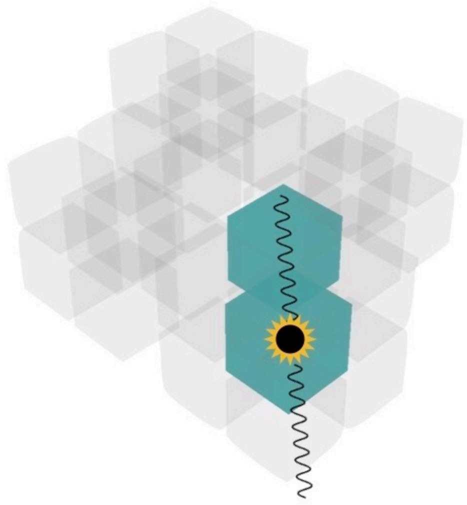
We use a 2nd order polynomial fit to extract our calibration coefficients



We identify *simultaneous* (±5 ms) particle events on multiple crystals



single-site event (M=1)



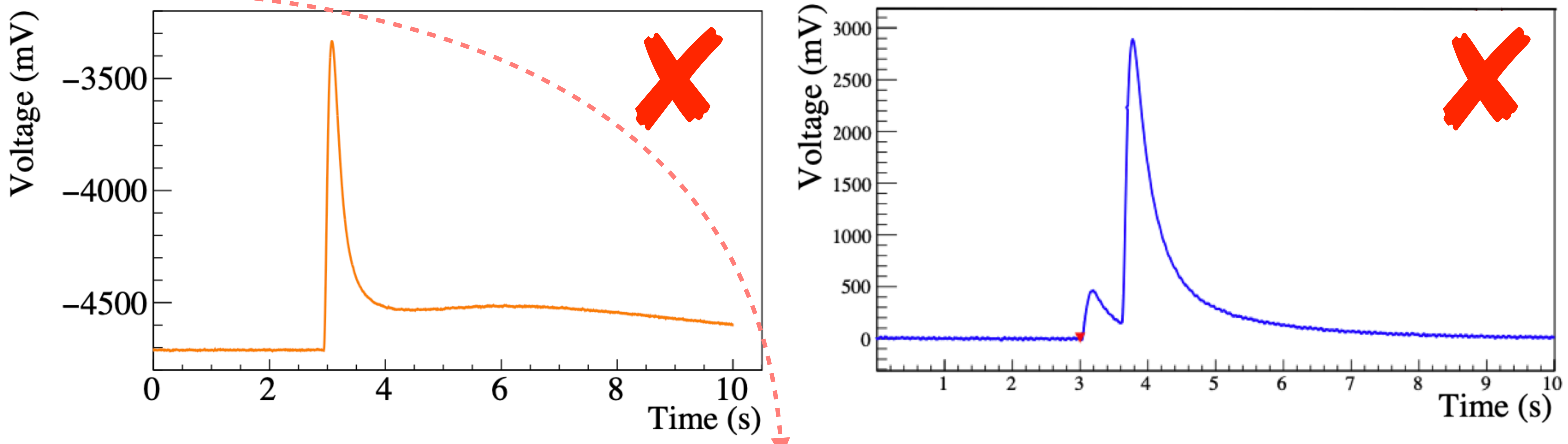
multi-site event (M=2)

Coincidences

Event selection for the $0\nu\beta\beta$ decay search

Anti-coincidence (AC) selection

From MC simulations, we expect ~88% of $0\nu\beta\beta$ events to release all the energy in the same crystal in which the decay occurred. Thus, we reject multi-site events, i.e. events with *Multiplicity* > 1



Pulse shape discrimination (PSD)

We use Principal Component Analysis (PCA) to reject non-signal like and noisy events

ROI blinding

To avoid biasing our result, we exchange events from ^{208}Tl line at 2615 keV with events at the ^{130}Te $0\nu\beta\beta$ Q-value

Analysis efficiency evaluation

Detector response

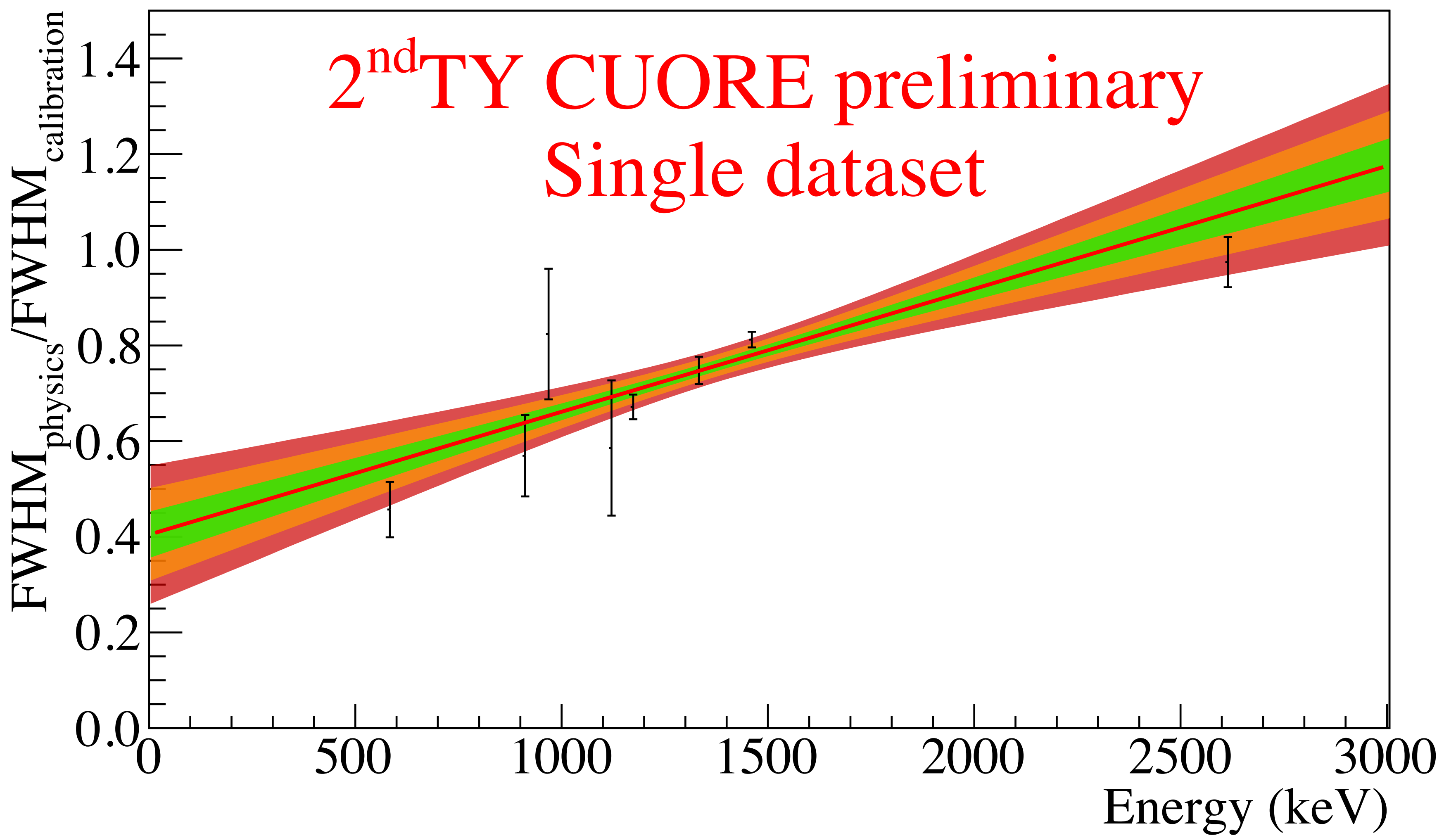
ROI model and blinded fit

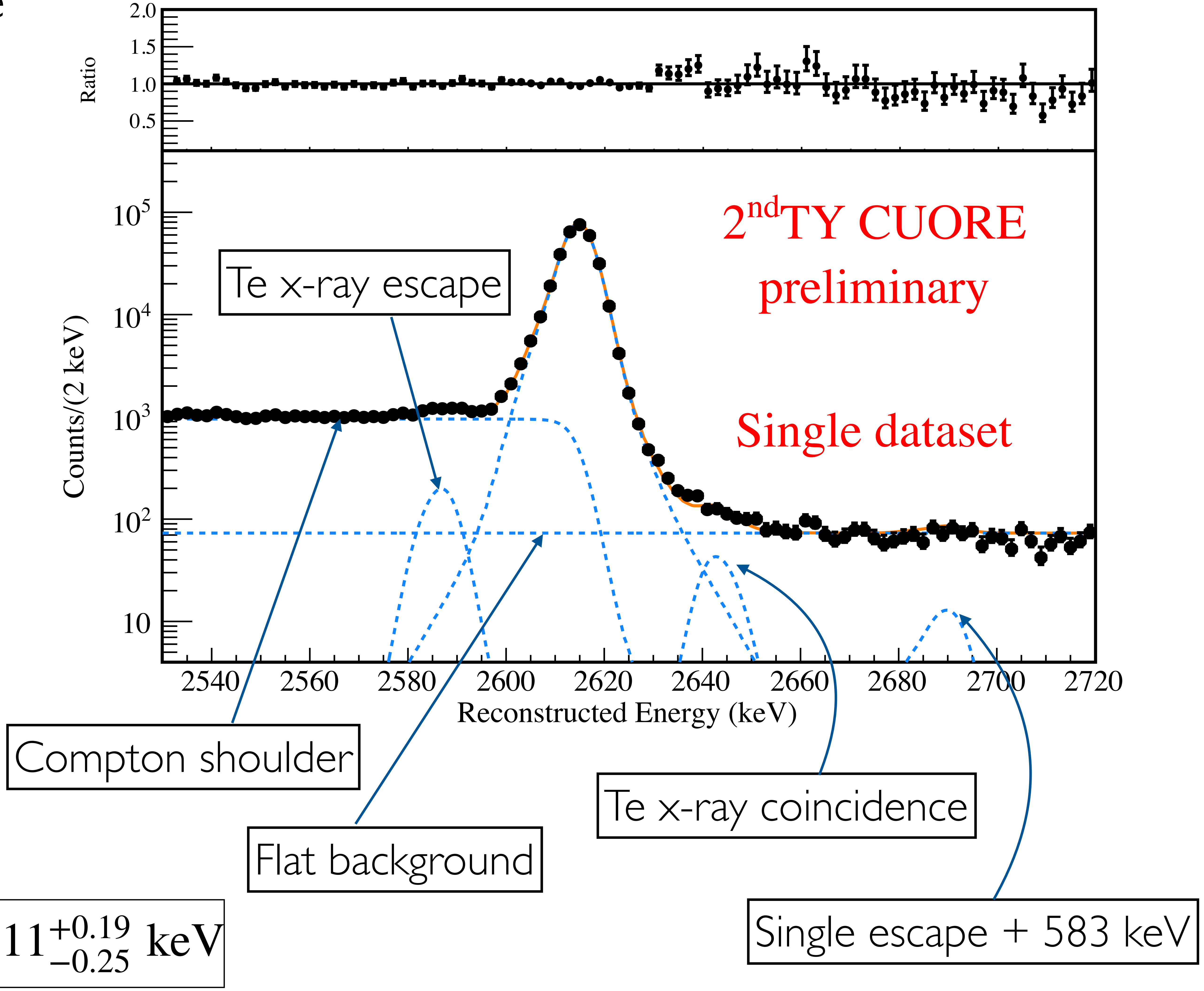
Data unblinding and fit

This is the strategy we adopted for the 2nd tonne · yr (**2nd TY**) data

Detector response evaluation

- We extract the detector response on events from the ^{208}Tl line at 2615 keV in calibration data separately for each bolometer and dataset
- The signal peak is modeled as a sum of 3 Gaussians
- We fit the most prominent γ lines in physics data to scale the energy resolution and calibration bias at $Q_{\beta\beta}$

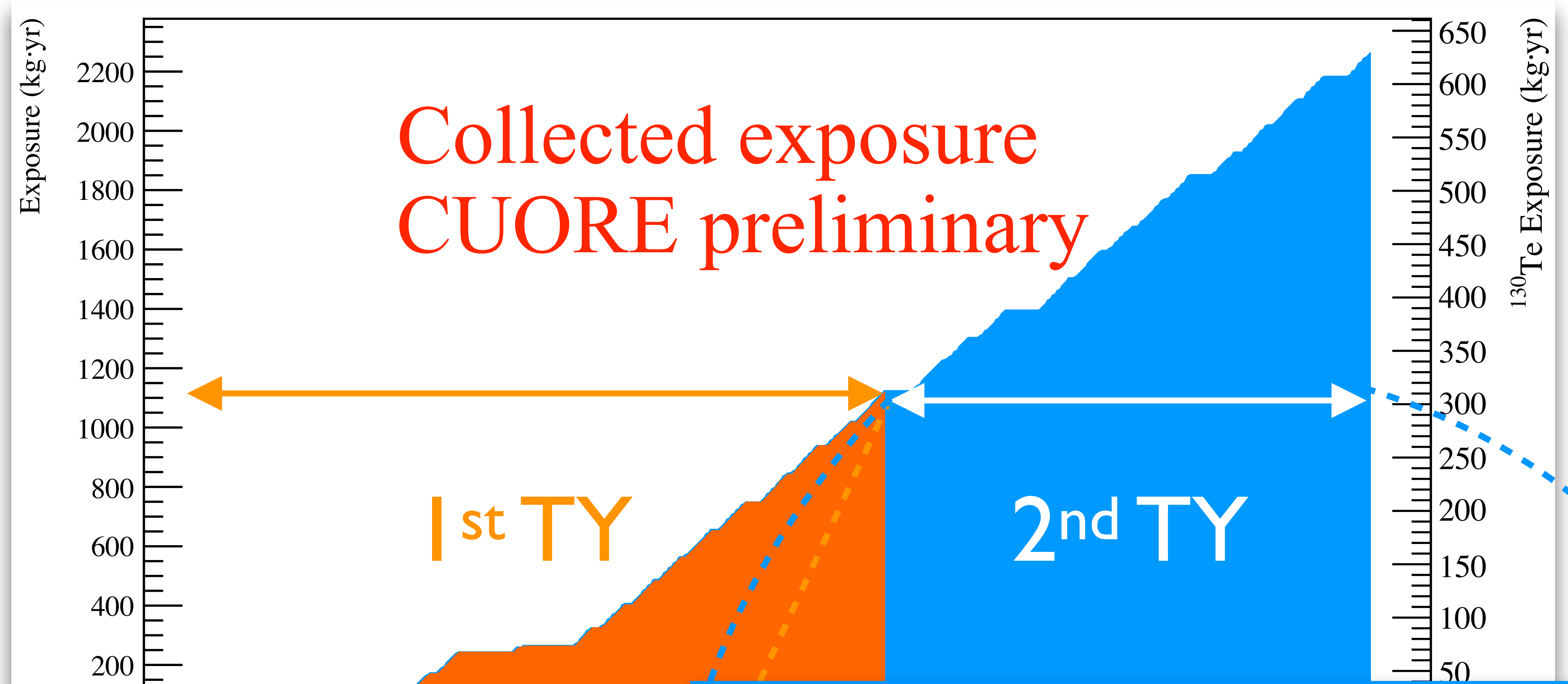




$$\mathrm{FWHM}_{2^{nd}\mathrm{TY}}\left(Q_{\beta\beta}\right) = 7.26^{+0.43}_{-0.47}\ \mathrm{keV}$$

$$\Delta\mathrm{E}_{2^{nd}\mathrm{TY}}\left(Q_{\beta\beta}\right) = -0.11^{+0.19}_{-0.25}\ \mathrm{keV}$$

The 2nd tonne · yr CUORE data



Nature 604, 53-58 (2022)

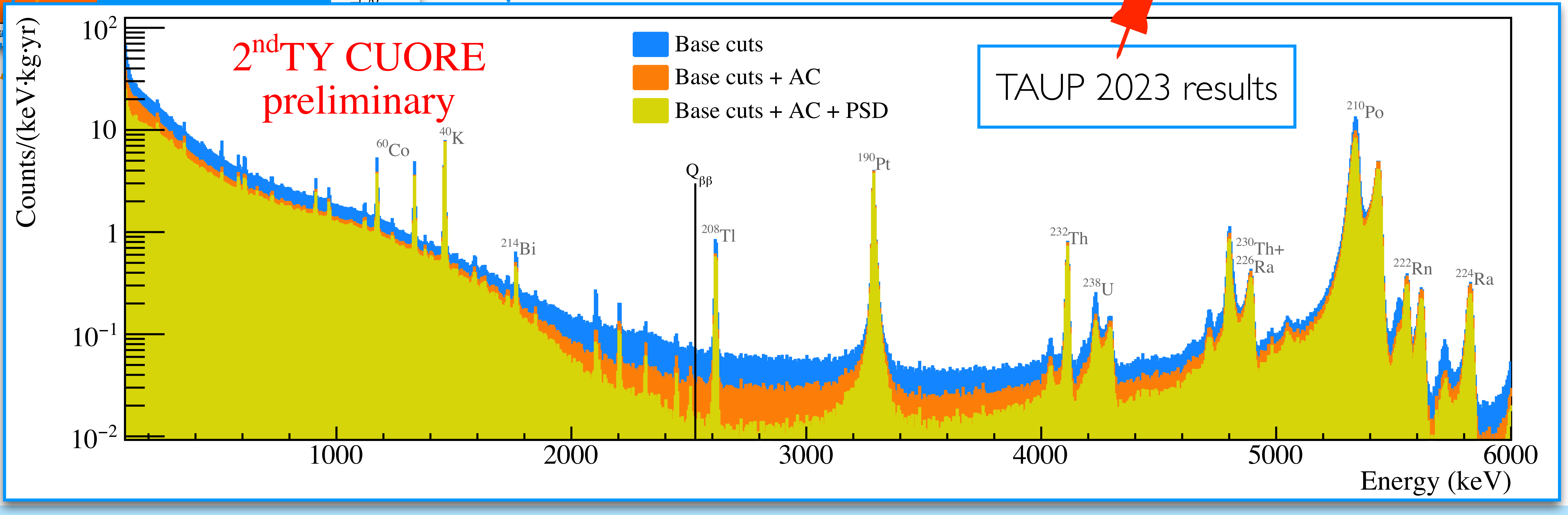
Final event selection: $0\nu\beta\beta$ candidates

<u>Base cuts</u>: trigger, energy reconstruction, pile-up removal

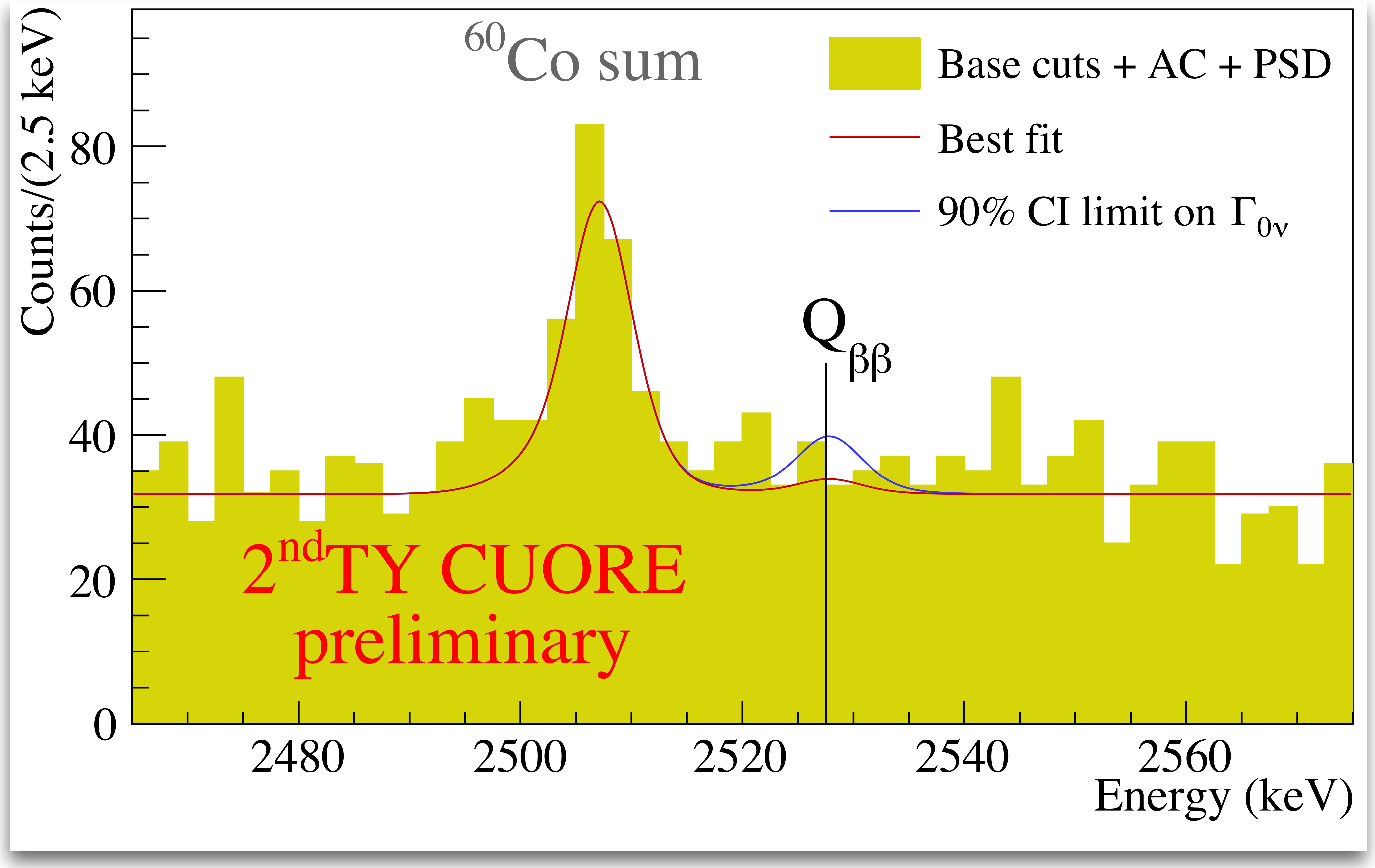
<u>Anti-coincidence</u> (AC) : we accept only single crystal events

<u>Pulse shape discrimination</u> (PSD): only signal-like events

TAUP 2023 results



The search for $0\nu\beta\beta$ decay with 2nd tonne · yr data



We model the region of interest (2465, 2575) keV with

- linear background
- ^{60}Co sum peak at 2505.7 keV
- posited peak at 2528 keV for the signal

We perform an unbinned Bayesian fit with $\Gamma_{0\nu\beta\beta} > 0$

Systematics are treated as nuisance parameters

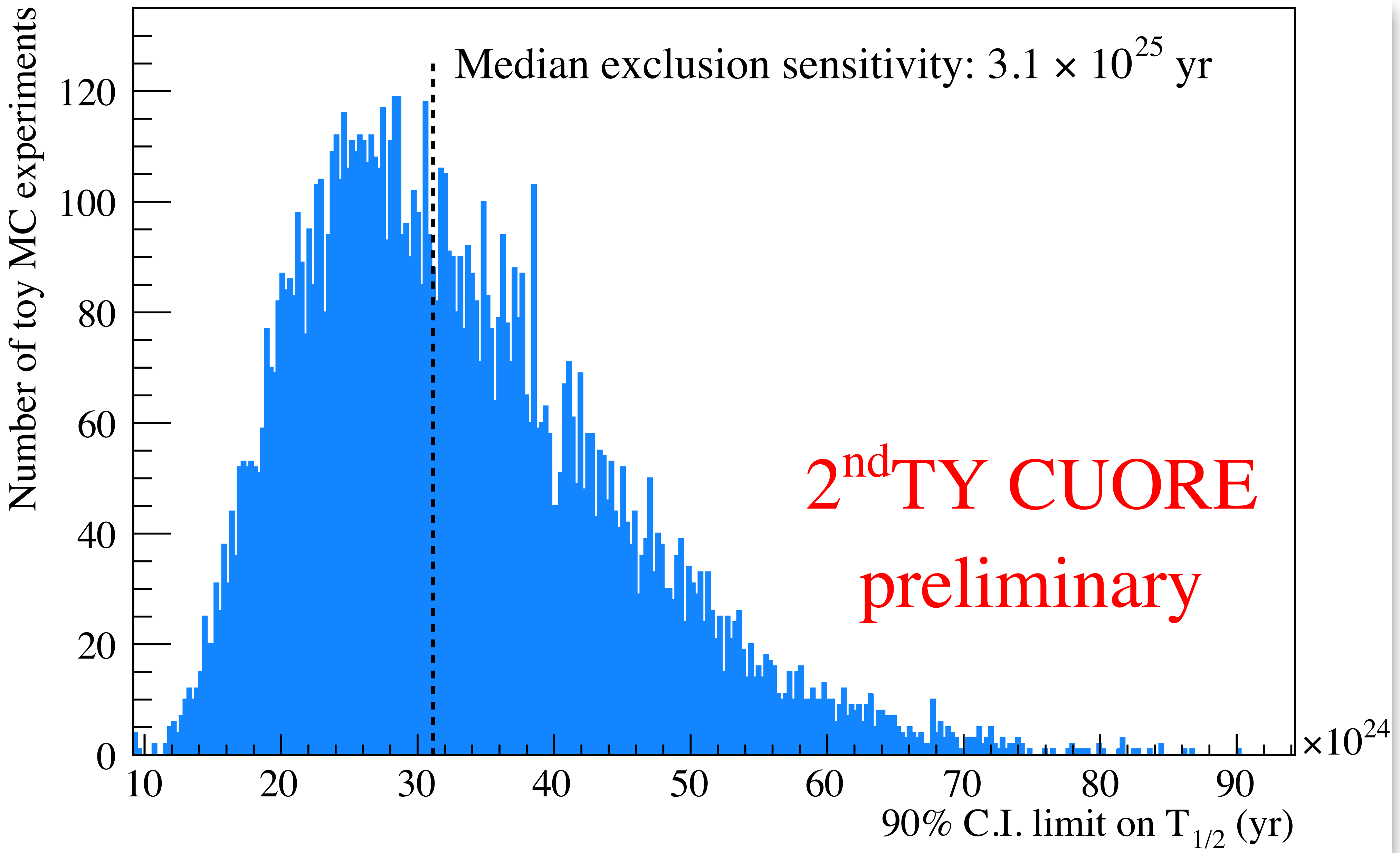
We find no evidence of $0\nu\beta\beta$ and set a new limit on ^{130}Te half-life of $T^{1/2}_{0\nu\beta\beta} > 2.7 \cdot 10^{25}$ yr (90 % C . I.)

We measure an average background index of

$$b = (1.30 \pm 0.03) \cdot 10^{-2}\,(\mathrm{counts/keV/kg/yr})$$

Our median exclusion sensitivity is

$$T^{1/2}_{0\nu\beta\beta} = 3.1 \cdot 10^{25}\ \mathrm{yr}\ (90\,\%\ \mathrm{C\,.\,I.})$$



Combine 1st and 2nd tonne · yr data to extract a result

We combine our new result from the analysis of the 2nd tonne · yr (2nd TY) data with our limit from the 1 tonne · yr data (1 TY) [*Nature 604, 53-58 (2022)*]

The overall exposure is $2023\ \mathrm{kg \cdot yr}$

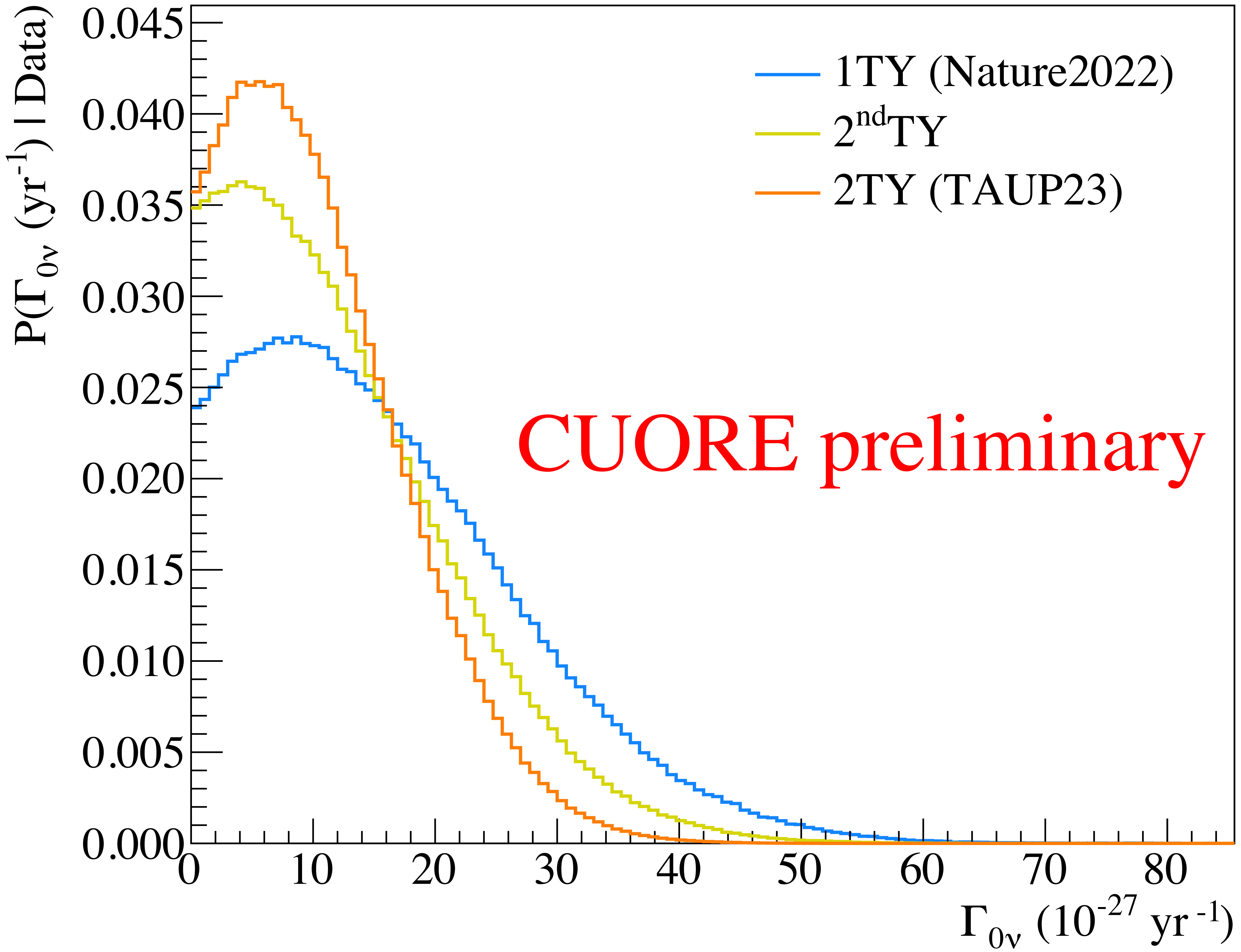
We find no evidence of $0\nu\beta\beta$

and set a limit on the decay rate

$$\Gamma_{0\nu\beta\beta} < 2.1 \cdot 10^{-26}\ \mathrm{yr}^{-1}\ (90\,\%\,\mathrm{C.I.})$$

The corresponding limit on ^{130}Te half-life is

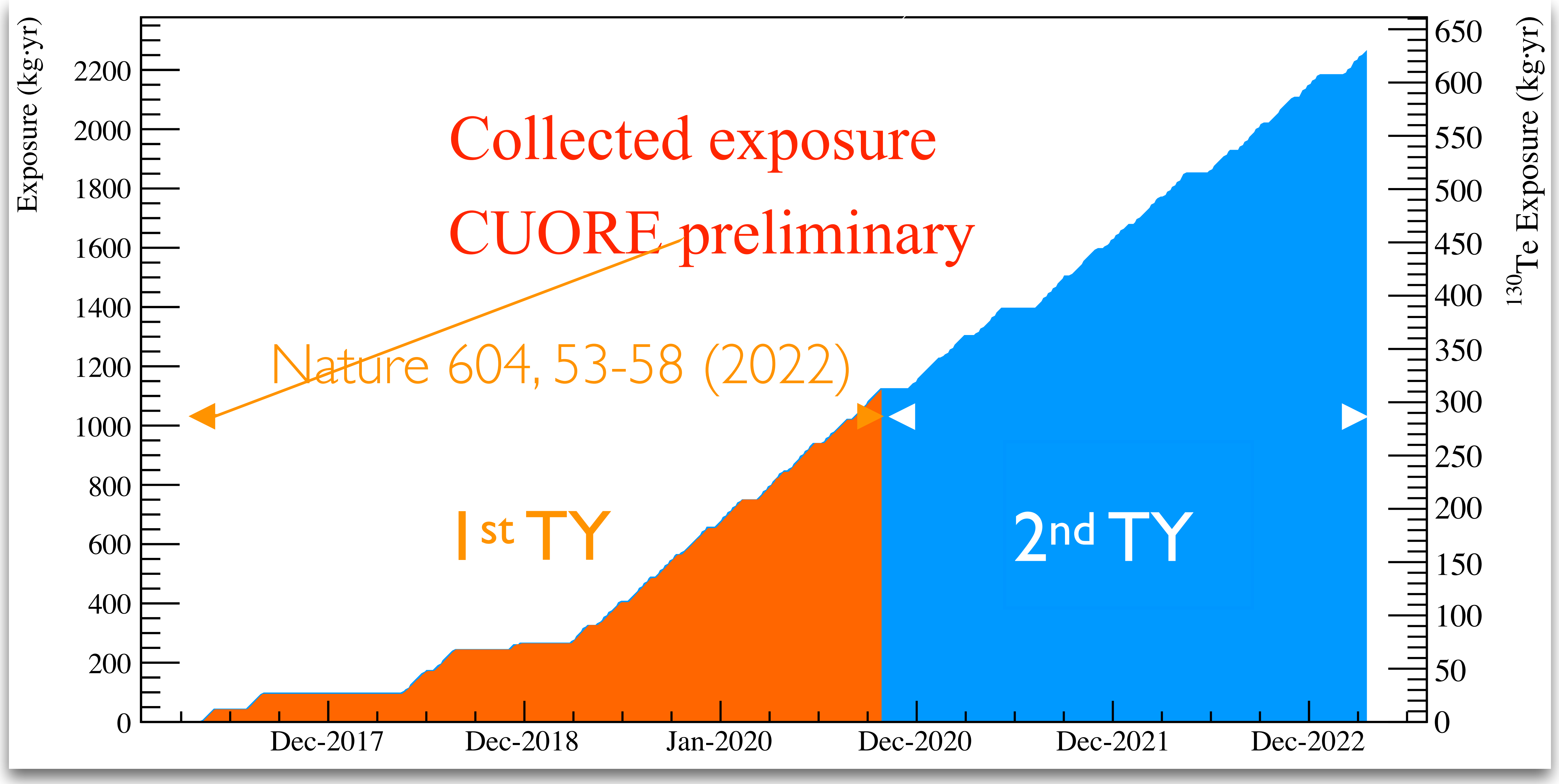
$$\mathrm{T}^{1/2}_{0\nu\beta\beta} > 3.3 \cdot 10^{25}\ \mathrm{yr}\ (90\,\%\,\mathrm{C.I.})$$



If $0\nu\beta\beta$ is mediated by light neutrino exchange CUORE preliminary limit on the effective Majorana mass is $m_{\beta\beta} < 75 - 255\ \mathrm{meV}$ where the spread is induced by different nuclear matrix element calculations

Next steps towards the final 2 tonne · yr data analysis

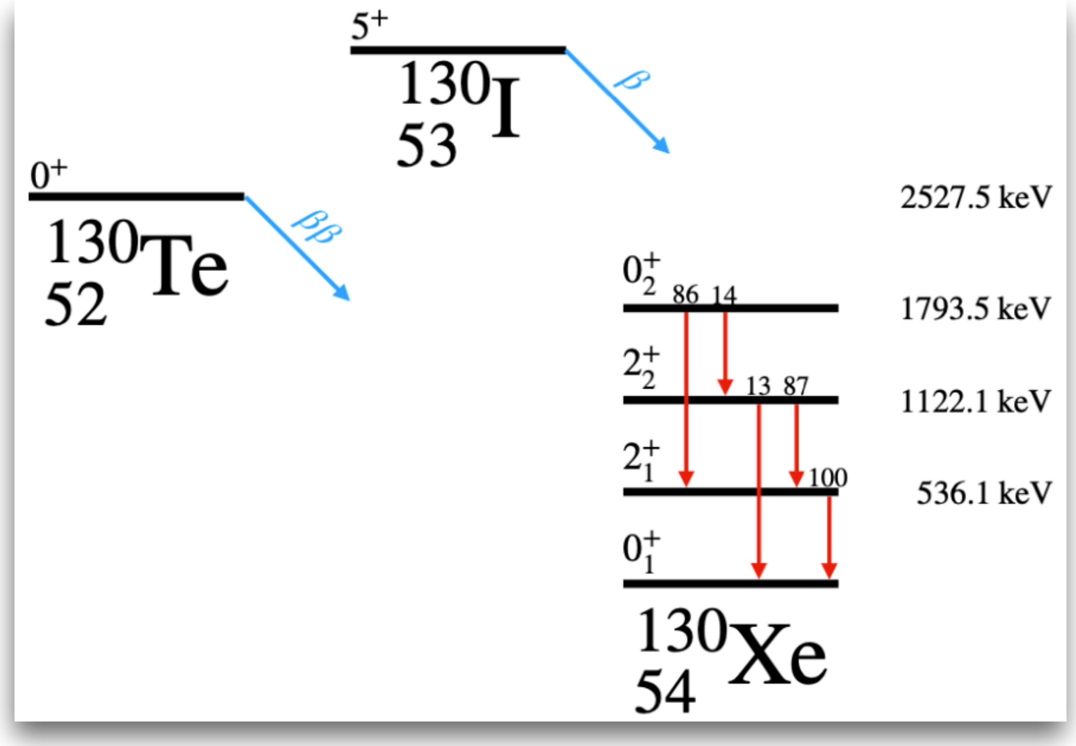
- Reprocess the 1 tonne · yr data with the new analysis chain that includes the denoising algorithm to mitigate vibrational noise
- Repeat the fit on the $0\nu\beta\beta$ candidate events extracted from the *full* CUORE statistics
- Finalise the study of systematic effects
- Release a final result on the 2TY CUORE data analysis



Stay tuned!

Other $\beta\beta$ decay searches with CUORE

^{130}Te $\beta\beta$ decay to the 1st 0^+ excited state



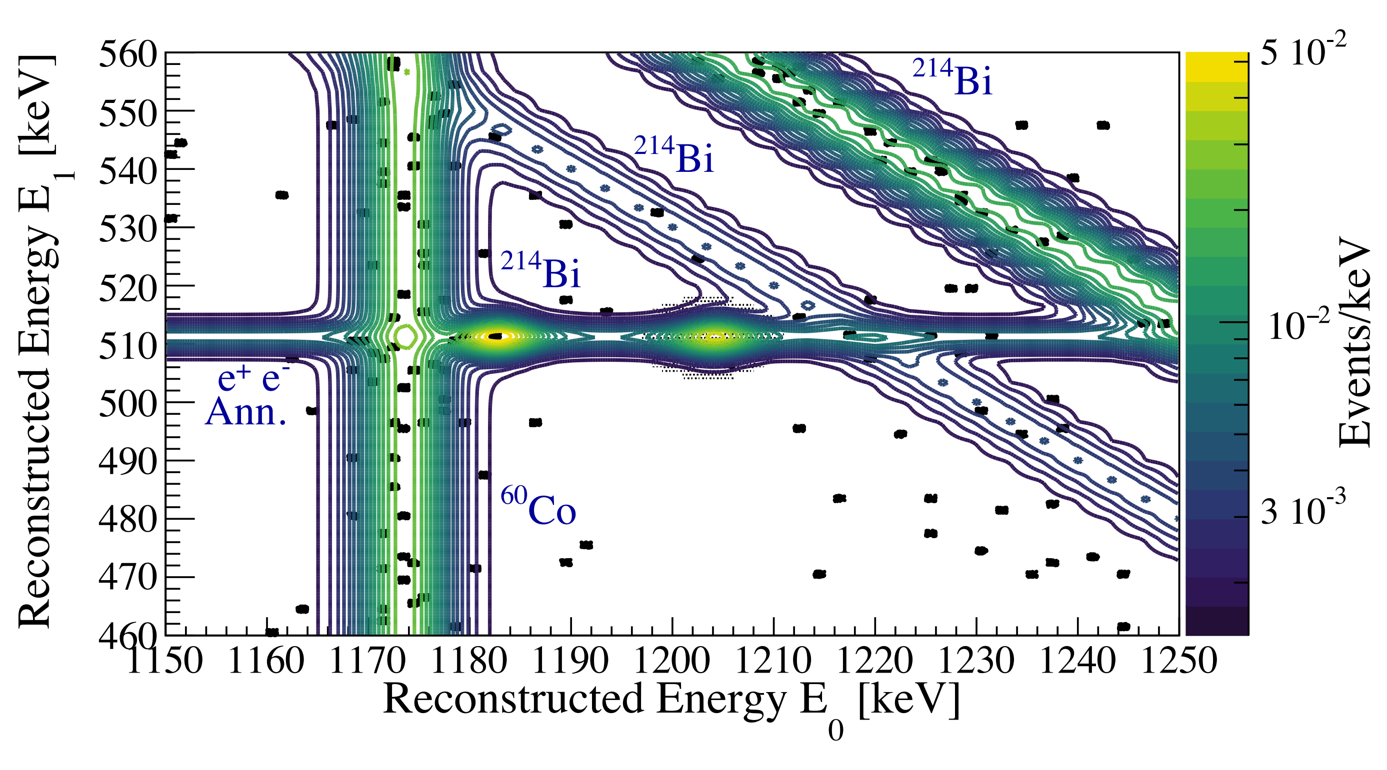
$$T^{0\nu}_{1/2} > 5.9 \times 10^{24}\ \mathrm{yr}\ (90\,\%\ \mathrm{C.I.})$$

$$T^{2\nu}_{1/2} > 1.3 \times 10^{24}\ \mathrm{yr}\ (90\,\%\ \mathrm{C.I.})$$

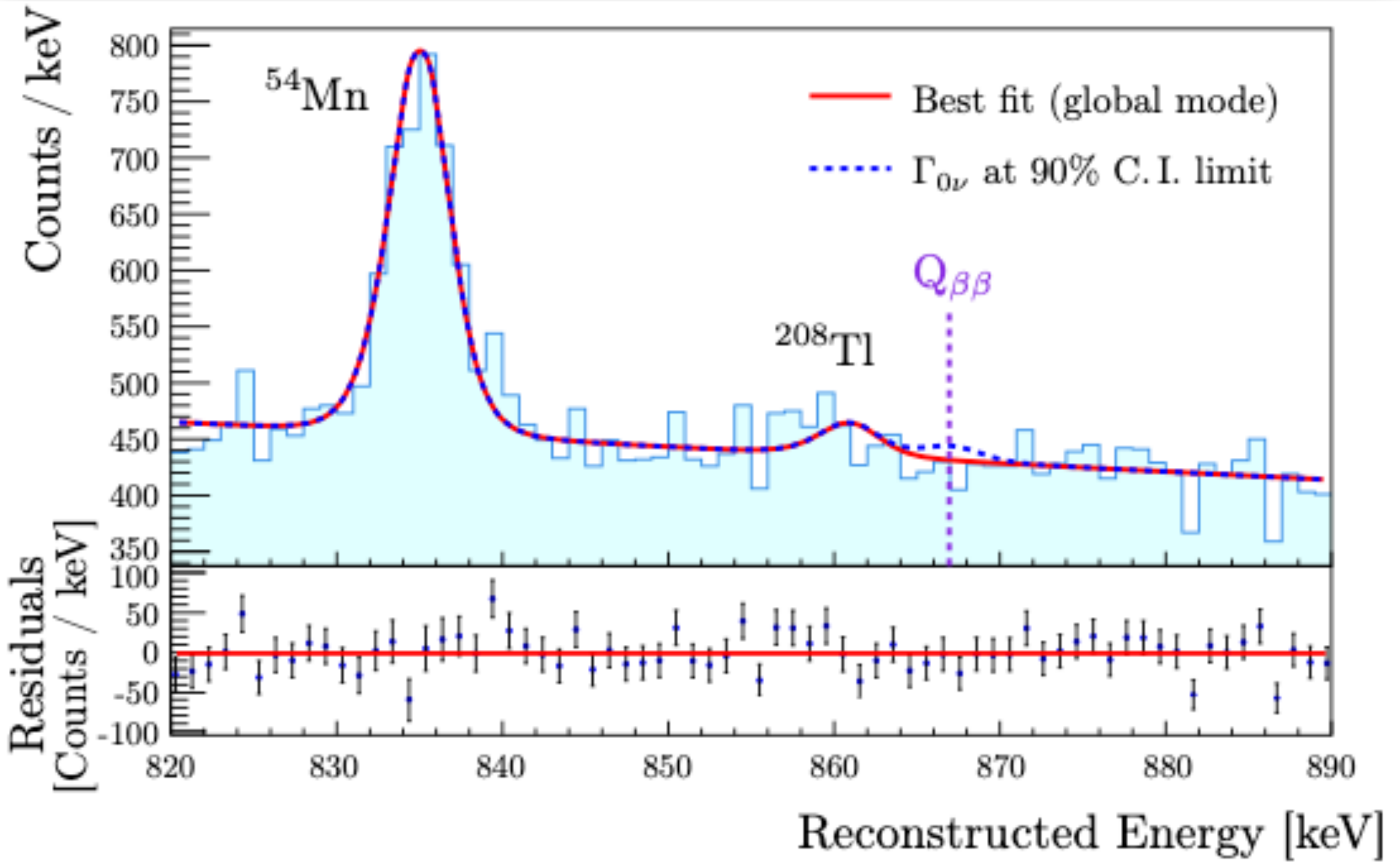
Eur. Phys. J. C, 81 57 (2021)

^{120}Te $0\nu\beta^+$EC decay to the ground state

Phys. Rev. C, 105 065504 (2022)



$$T^{0\nu}_{1/2} > 2.9 \cdot 10^{22}\ \mathrm{yr}\ \ (90\,\%\ \mathrm{C.I.})$$



^{128}Te $0\nu\beta\beta$ to the ground state

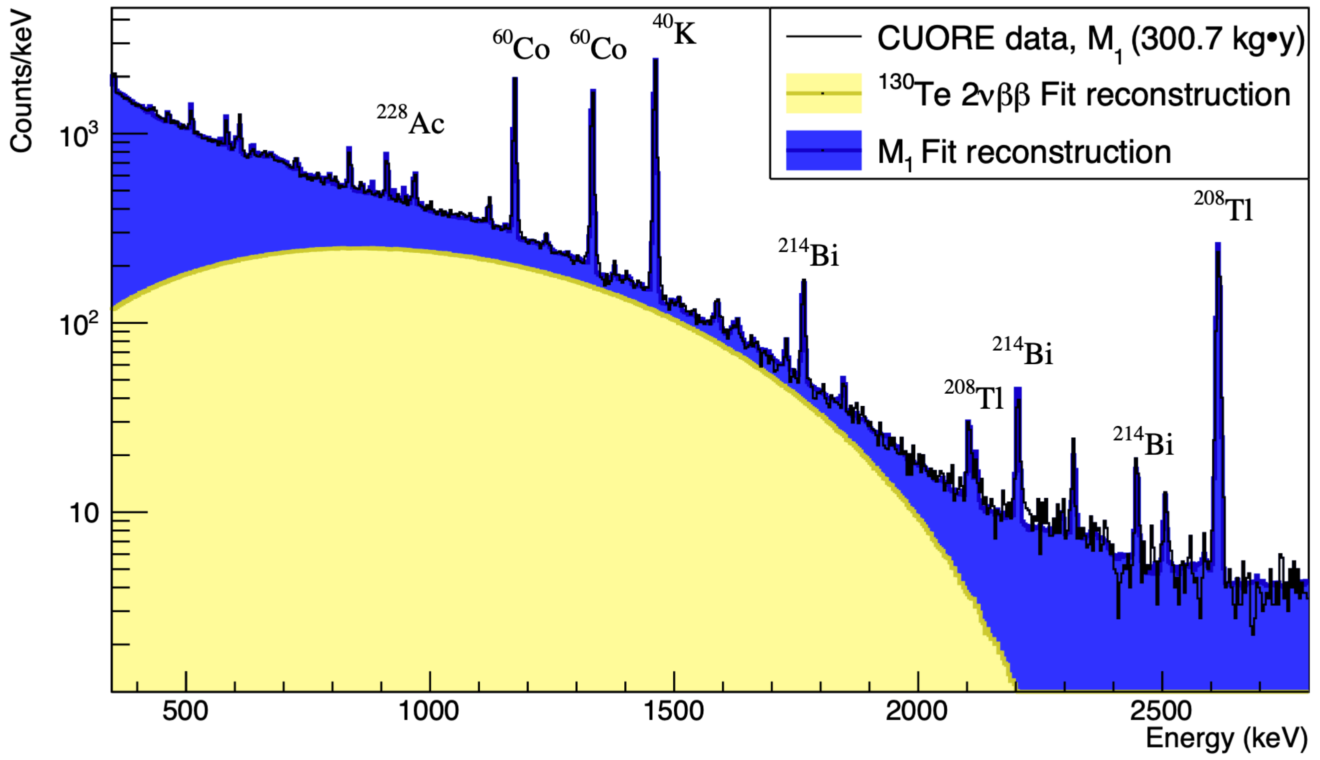
PRL 129, 222501 (2022)

Phys. Rev. Lett. 126, 171801 (2021)

$$T^{1/2}_{0\nu\beta\beta} > 3.6 \cdot 10^{24}\ \mathrm{yr}\ (90\,\%\ \mathrm{C.I.})$$

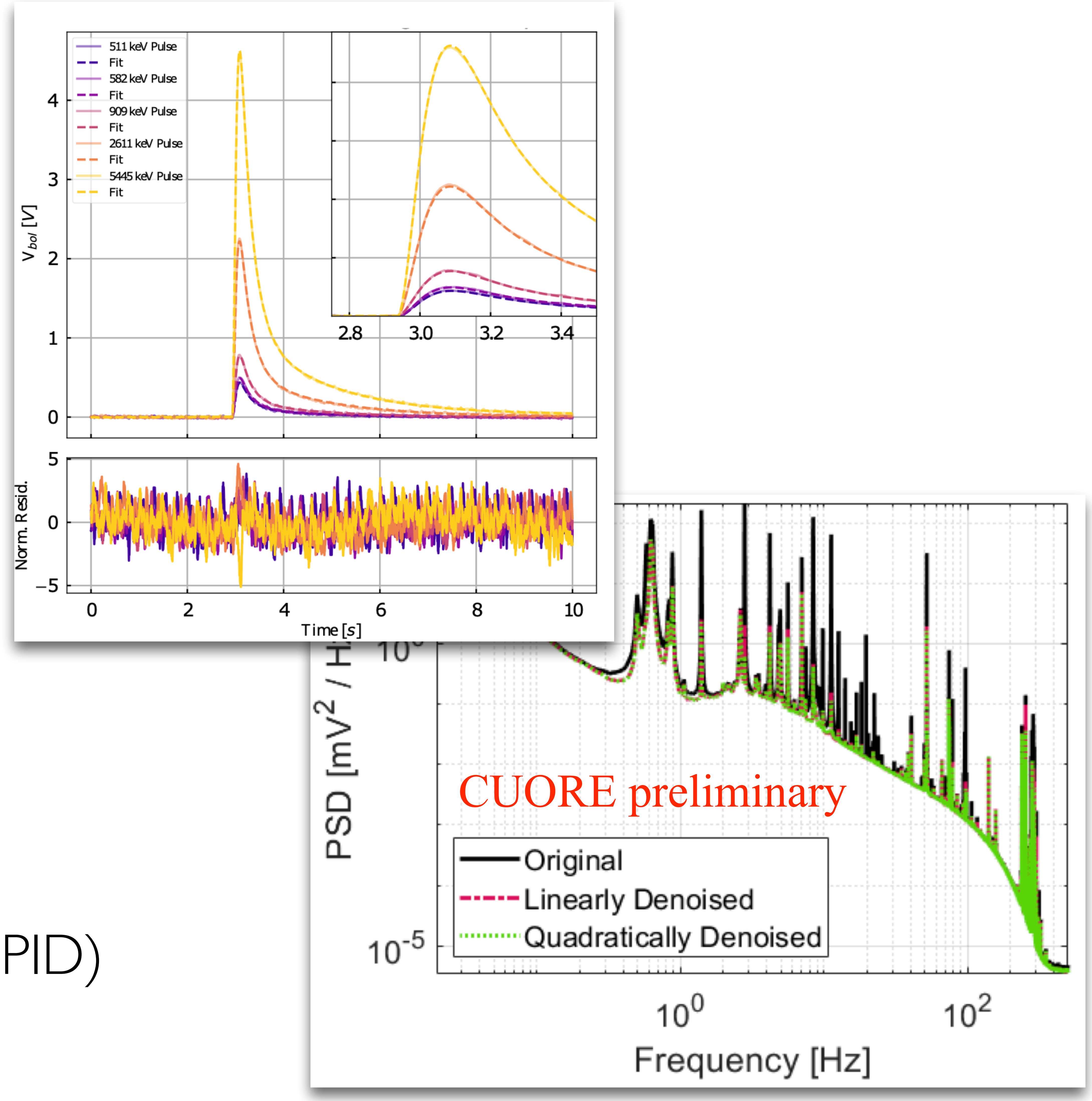
$$T^{1/2}_{2\nu\beta\beta} = \left[7.71^{+0.08}_{-0.06}(\mathrm{stat.})^{+0.12}_{-0.15}(\mathrm{syst.})\right] \cdot 10^{20}\ \mathrm{yr}$$

Most precise measurement of ^{130}Te $2\nu\beta\beta$ to date



Other interesting analyses beyond double beta decay

- Detailed **thermal model** of our detector response
  JINST 17 P11023 (2022)
- **Denoising techniques** in CUORE analysis - *Coming soon!*
- Study of **environmental vibrational sources** in CUORE:
  how marine microseisms affect our detector response
  Coming soon!
- **Low energy analyses**:
  dark matter searches (WIMPs, solar axions,…)
  Coming soon!
- CUORE **background model** (background budget for CUPID)
  Coming soon!



Conclusions and perspectives

- CUORE proved the scalability of the cryogenic calorimeters technique to tonne-scale detectors thereby paving the way to rare decay searches with cryogenic calorimeters
- We exceeded 2 tonne · yr TeO_2 analyzed exposure and data collection is proceeding smoothly
- Our goal (2025) is to reach a final 3 tonne · yr TeO_2 exposure (corresponding to $\sim$1 tonne · yr ^{130}Te)
- We found no evidence of $0\nu\beta\beta$ decay with 2023 kg · yr TeO_2 exposure
- Many interesting activities and results in $\beta\beta$ decay searches and beyond
- Important feedback for the CUPID project that will come after CUORE, both for the cryogenic system and background budget

Thank you on behalf of the CUORE collaboration