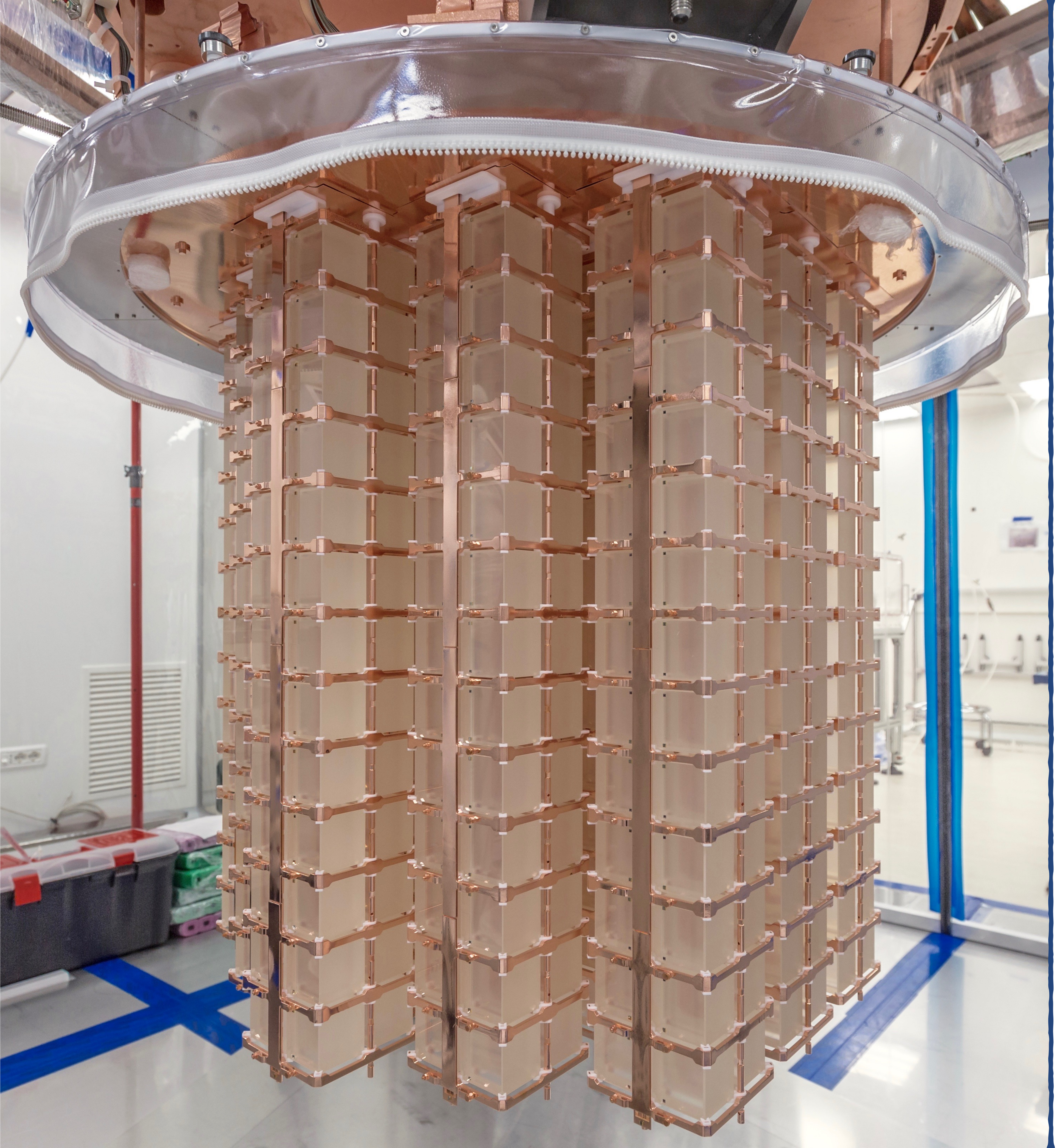


CUORE

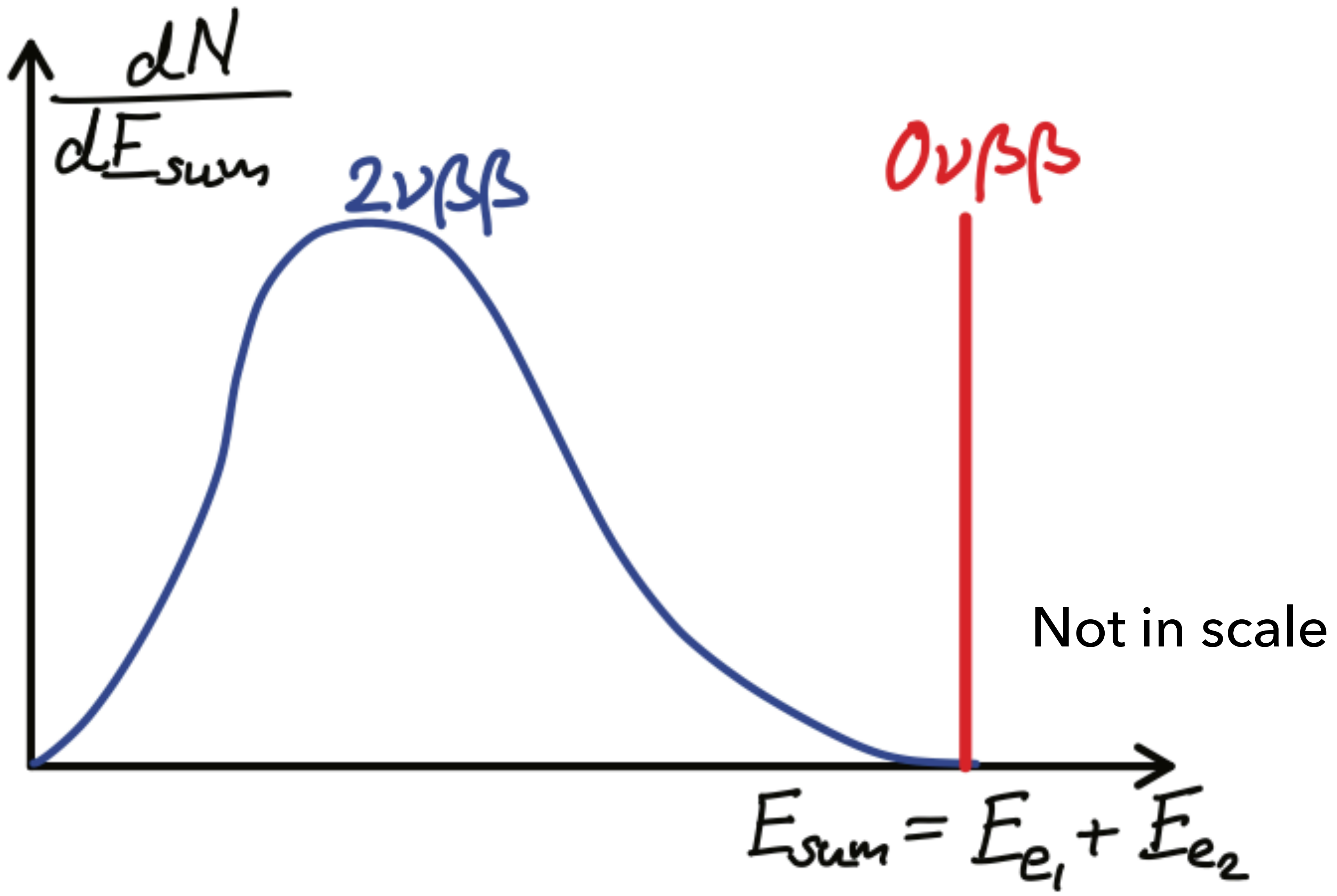
BERKELEY LAB

Latest results from the CUORE experiment

Chiara Capelli (Berkeley Lab)
On behalf of the CUORE collaboration

Rencontres du Vietnam - Neutrino Physics
Quy Nhon, Vietnam
July 17th - 23rd 2022

Double beta decay searches

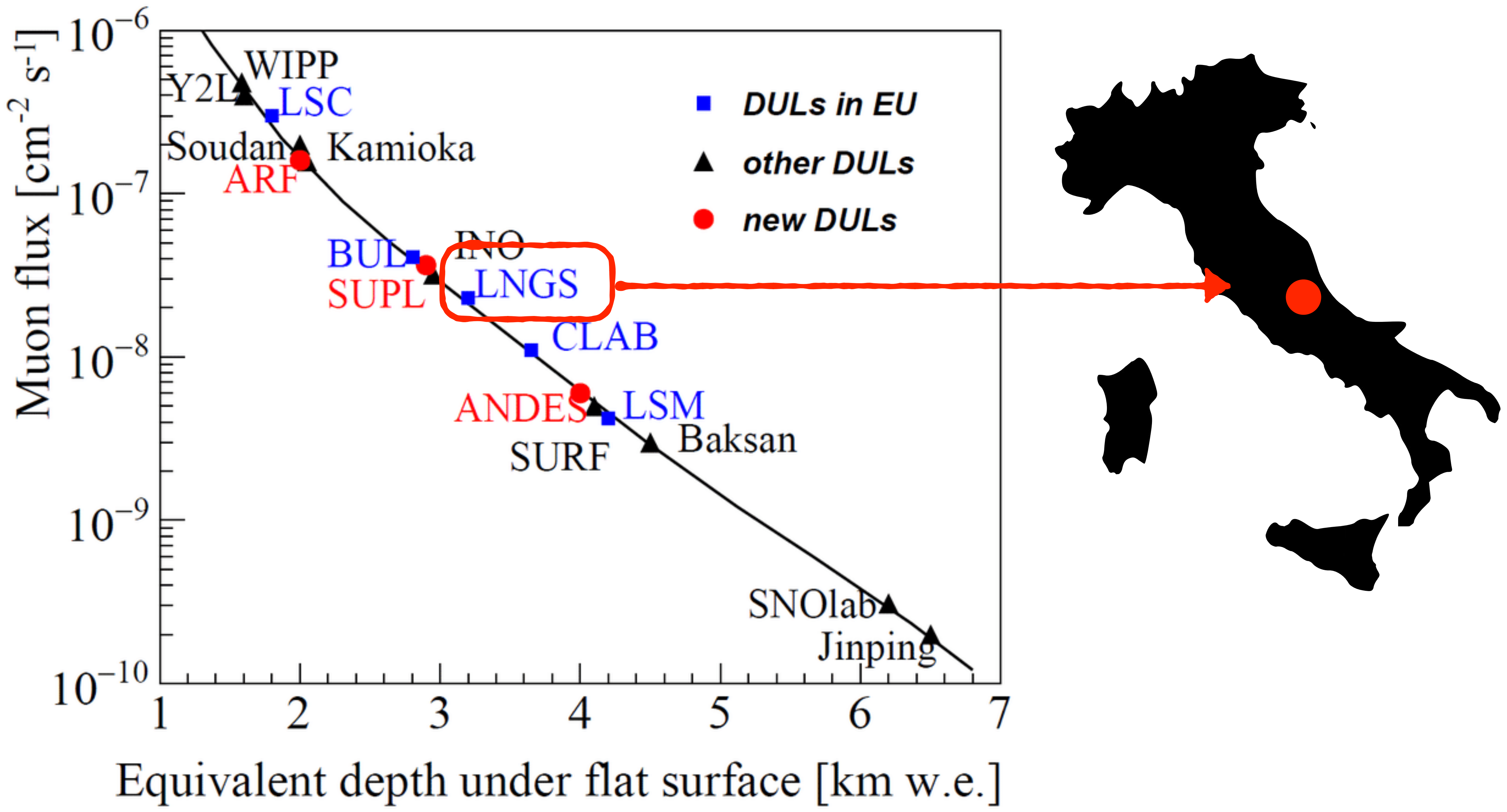


$\beta\beta$ Transition			$Q_{\beta\beta}$ [keV]	Nat.Ab. [%]
^{48}Ca	→	^{48}Ti	4274	0.2
^{76}Ge	→	^{76}Se	2039	7.6
^{82}Se	→	^{82}Kr	2996	8.7
^{96}Zr	→	^{96}Mo	3348	2.8
^{100}Mo	→	^{100}Ru	3034	9.6
^{110}Pd	→	^{110}Cd	2018	11.8
^{116}Cd	→	^{116}Sn	2814	7.5
^{124}Sn	→	^{124}Te	2288	5.8
^{130}Te	→	^{130}Xe	2528	34.2
^{136}Xe	→	^{136}Ba	2458	8.9
^{150}Nd	→	^{150}Sm	3368	5.6

→ CUORE

- High $Q_{\beta\beta}$ ($\gamma\beta$ background and phase space factor)
- High isotopic abundance (or enrichment)
- Long exposure ($M \cdot t$)
- Good energy resolution
- Low background rate

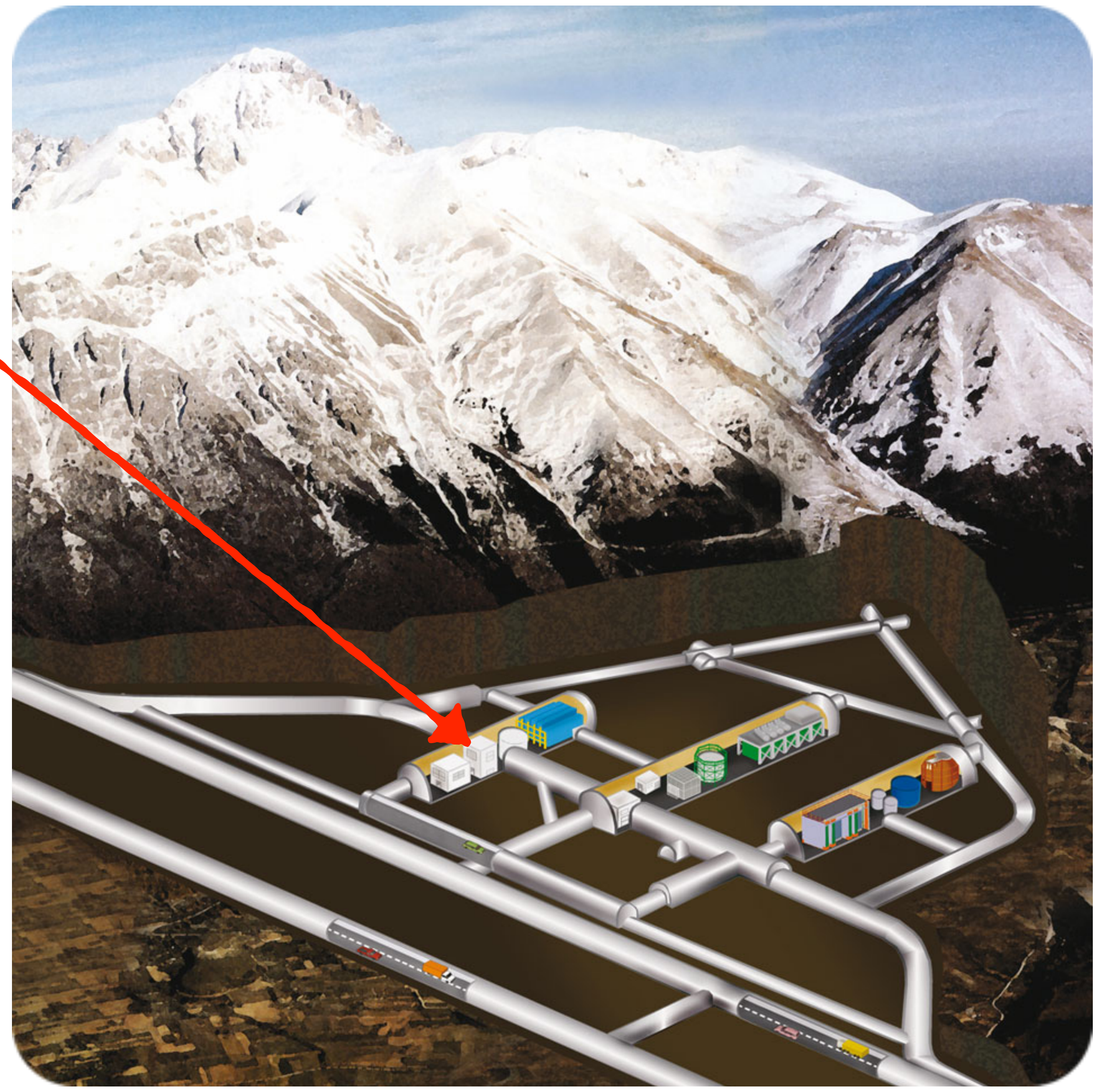
Laboratori Nazionali del Gran Sasso



External Lab

Underground Lab

CUORE



- 3600 m.w.e of rock to shield from cosmic rays
- Largest underground laboratory in the world

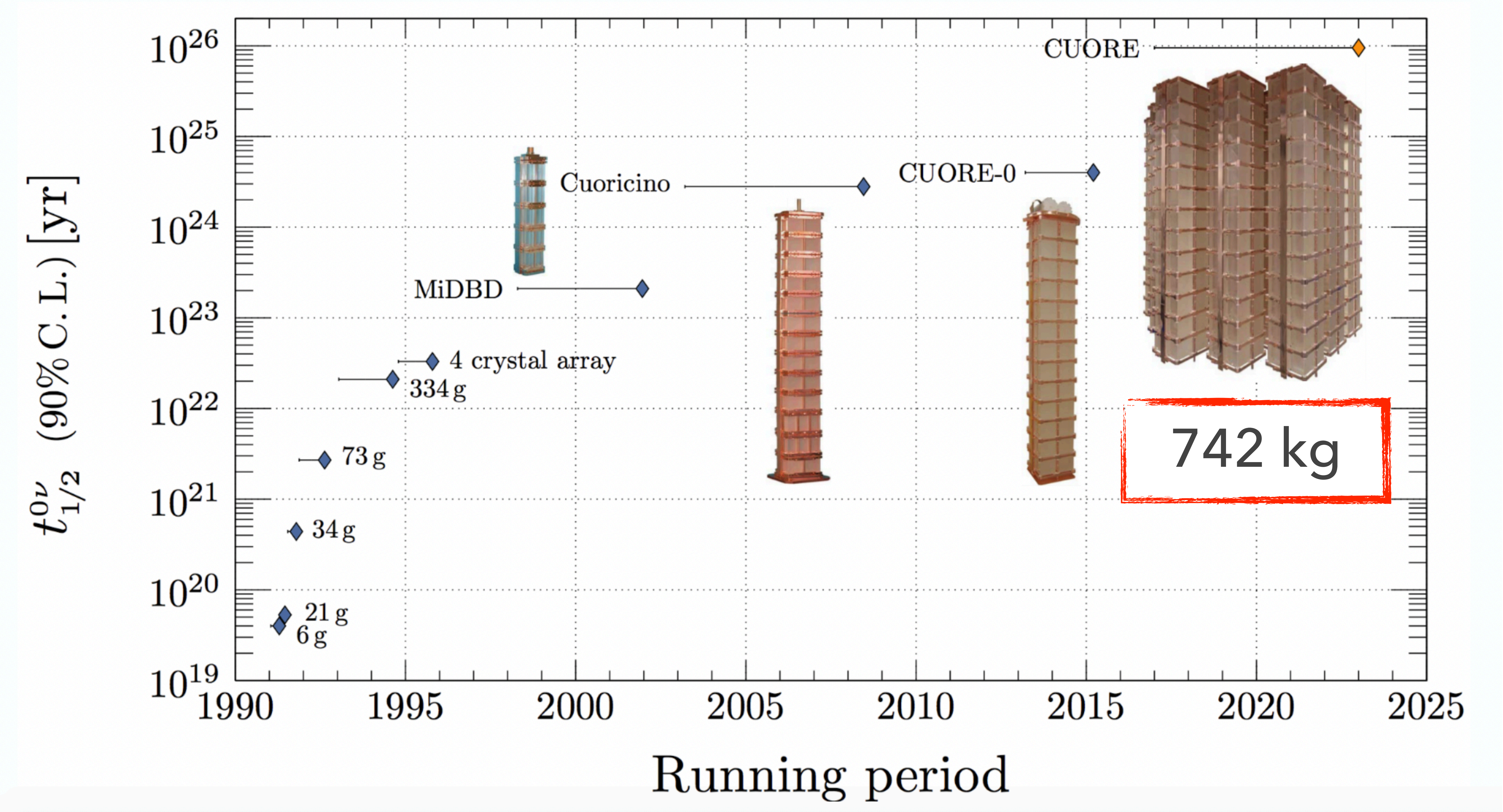
The CUORE collaboration

The CUORE collaboration

> 110 scientists
from 27 institutions
in 4 countries

Cryogenic Underground Observatory for Rare Events

- Search for $0\nu\beta\beta$ in ^{130}Te (and more)
- 988 TeO_2 5x5x5 cm^3 crystals
- 19 towers of 13 floors
- Total mass of 742 kg
- ^{130}Te mass of 206 kg

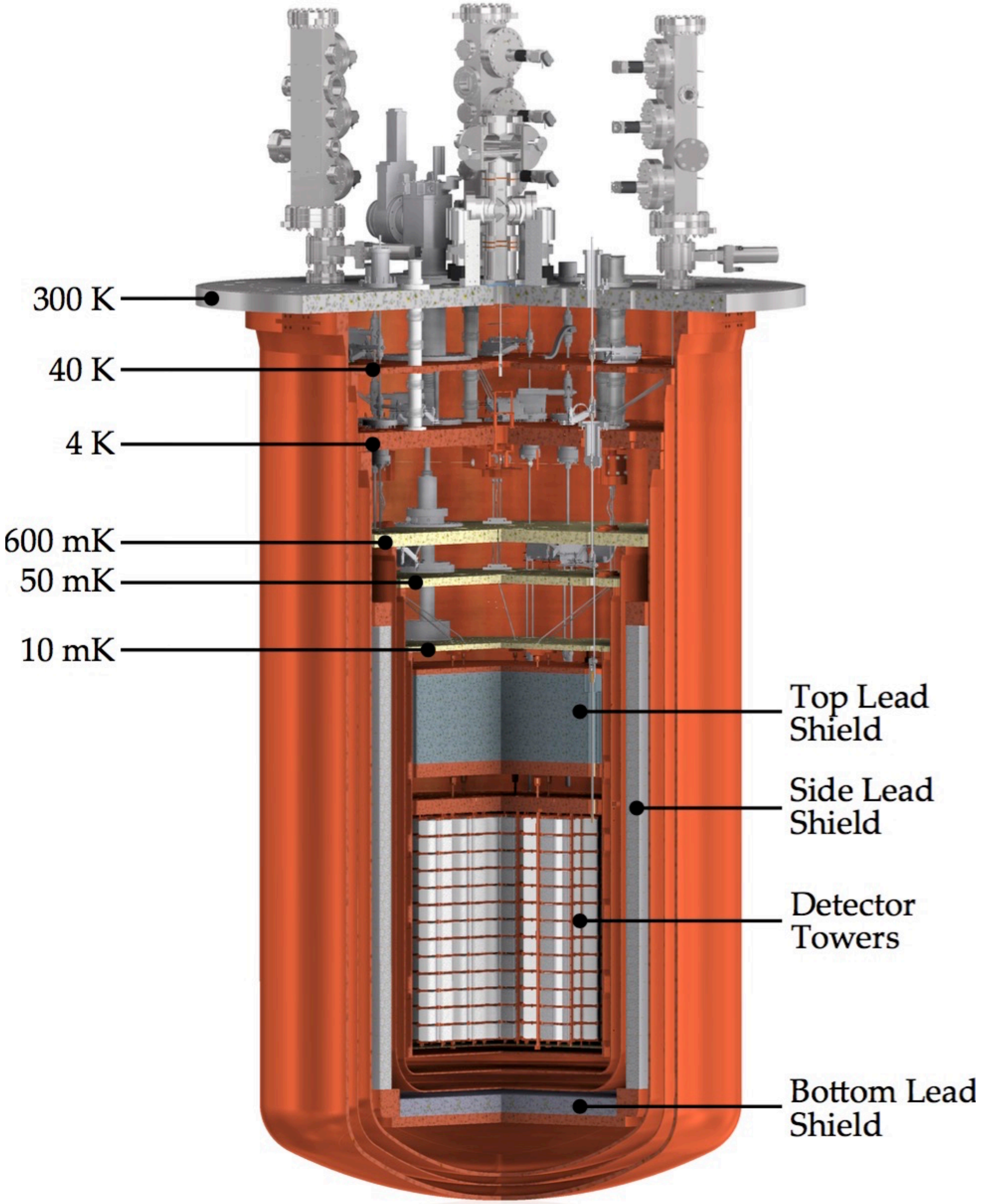


Starting from a few grams ➜ 30 years of technical development for crystal growing, low temperature cryogenic, material handling, computing resources,…

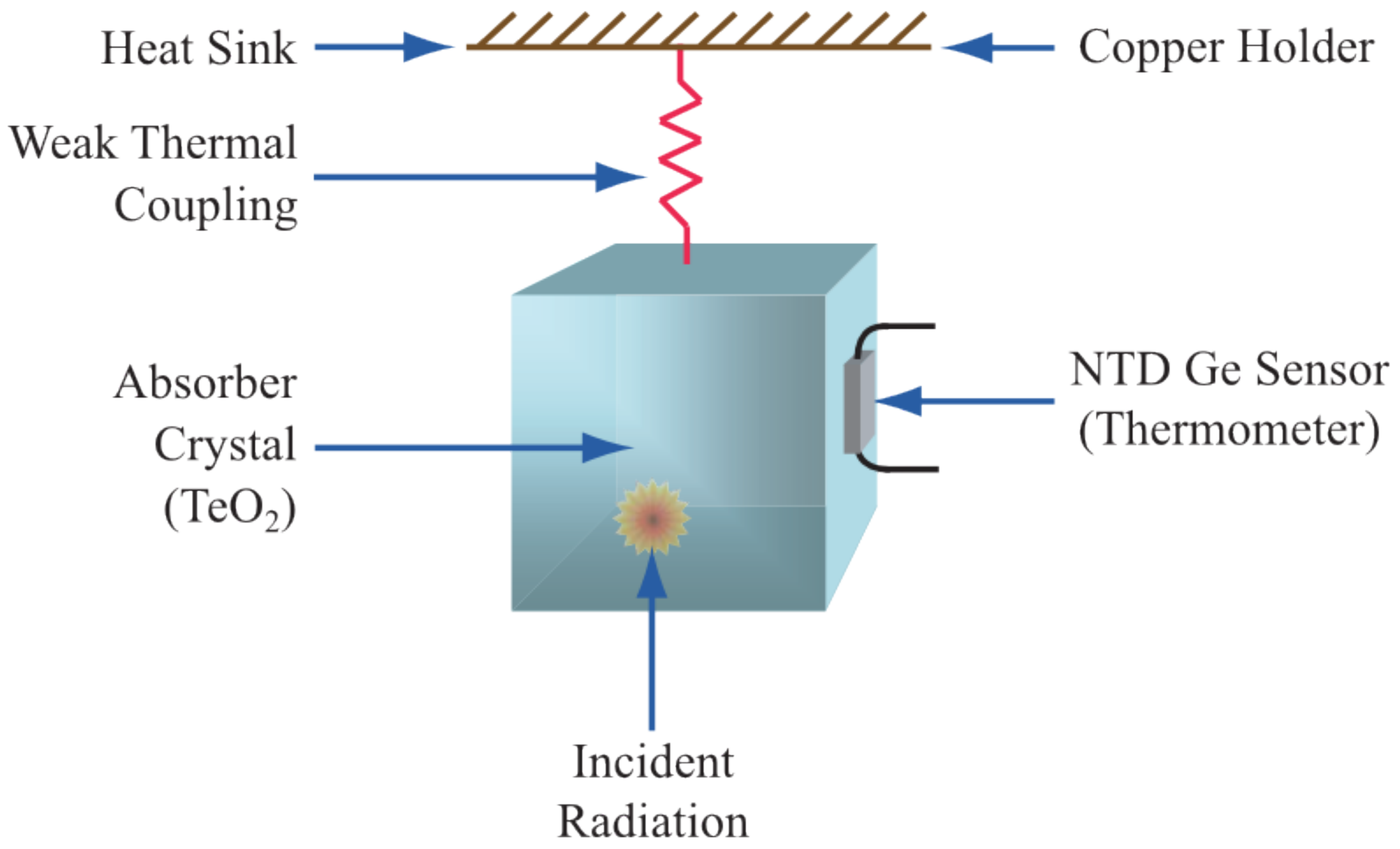
CUORE cryostat

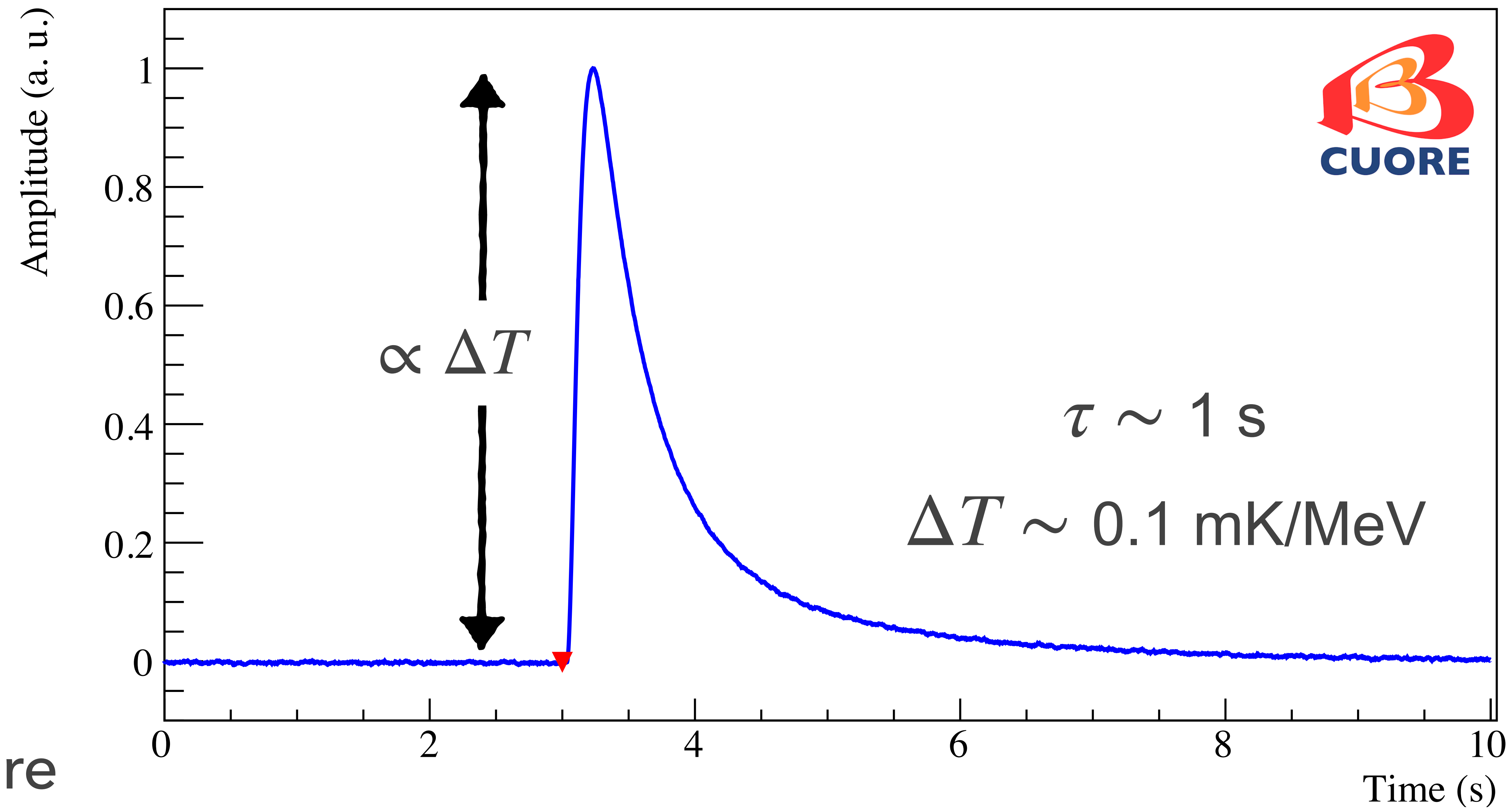
Cryogenics 102, 9 (2019)

- 6 stages and nested vessels
- Cooling through pulse tubes and dilution unit
- ~10 mK working temperature
- 15 tonnes of materials below 4 K and 3 tonnes below 50 mK
- Material selection with radio-purity constraints
- Vibration isolation and noise cancellation



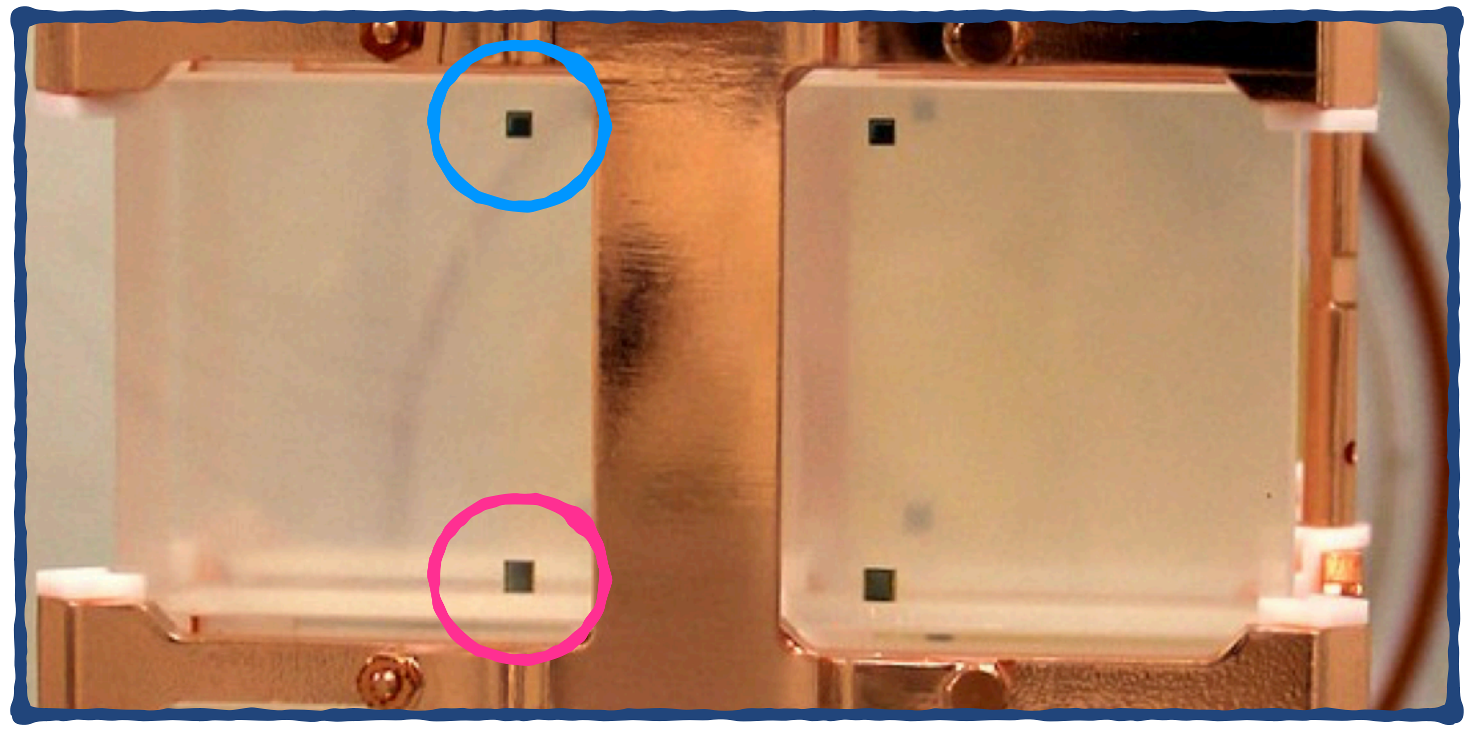
Cryogenic calorimeters





- Release energy converted into increase of temperature $\Delta T \propto \Delta E / C$
- $C \propto T^3$ ➜ low detector working temperature
- $\tau \sim C/G$ with G thermal conductance to heat bath to restore temperature after interactions
- Signal readout with NTD-Ge sensors, $R(t) \propto \exp\left(T_0/T^{1/2}\right)$

Heater

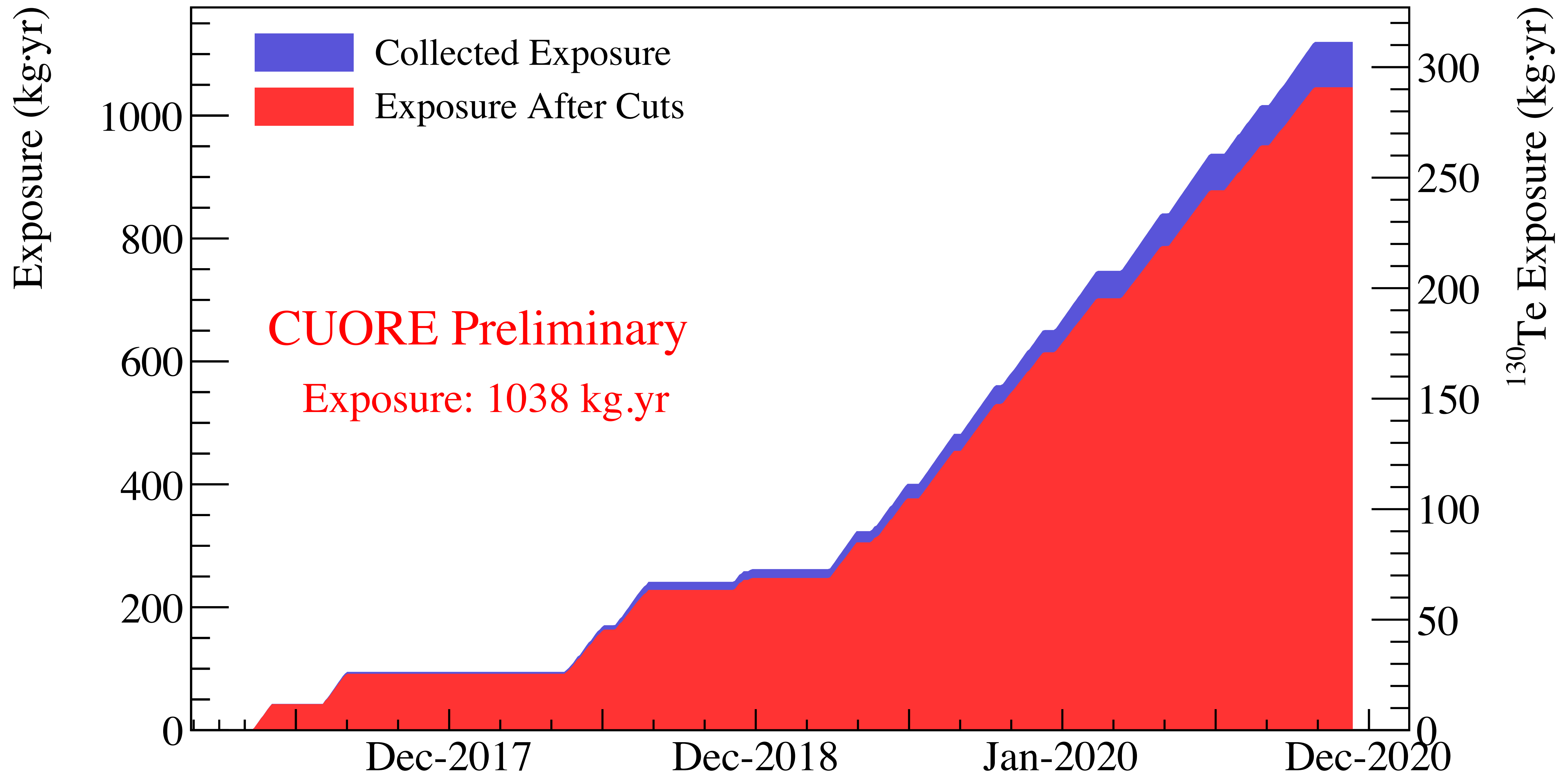


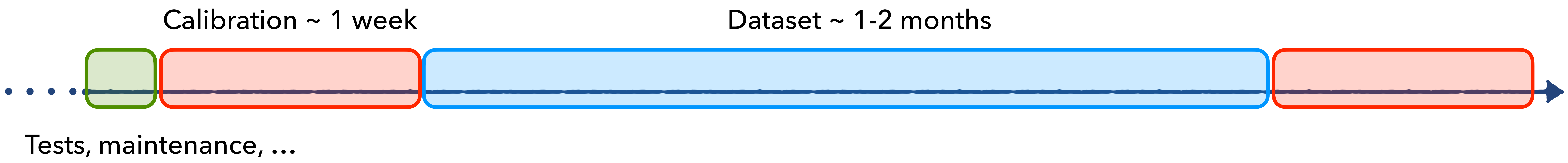
NTD-Ge

Latest data release

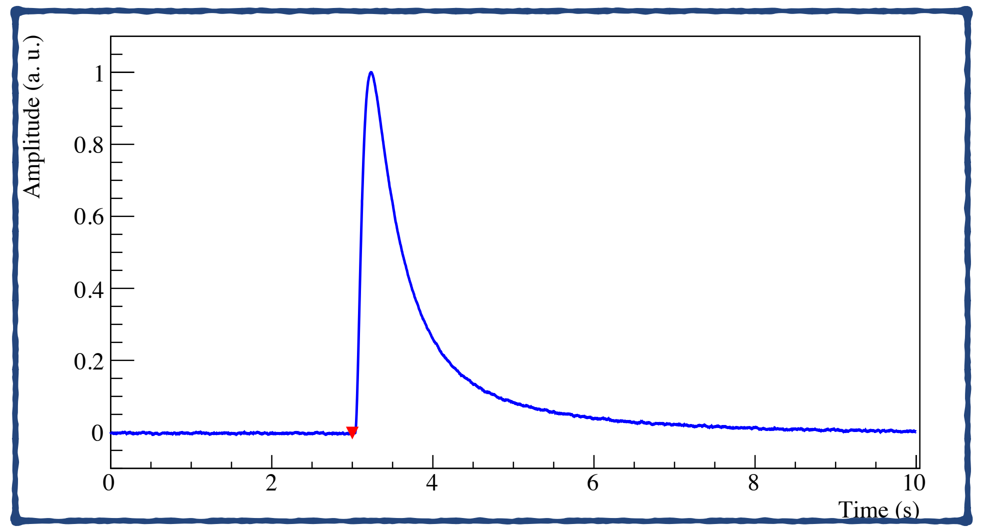
Nature 604, 53-58 (2022)

- Operating since 2017
- Stable after optimization since 2019
  ➜ duty cycle from 35.8% to 93%
- 984 / 988 active channels
- Runs of 24 hours
- 15 datasets in the 1 t·yr (TeO_2) analysis, and keep taking data





Analysis workflow



OPTIMUM FILTER

GAIN CORRECTION

ENERGY CALIBRATION

COINCIDENCES

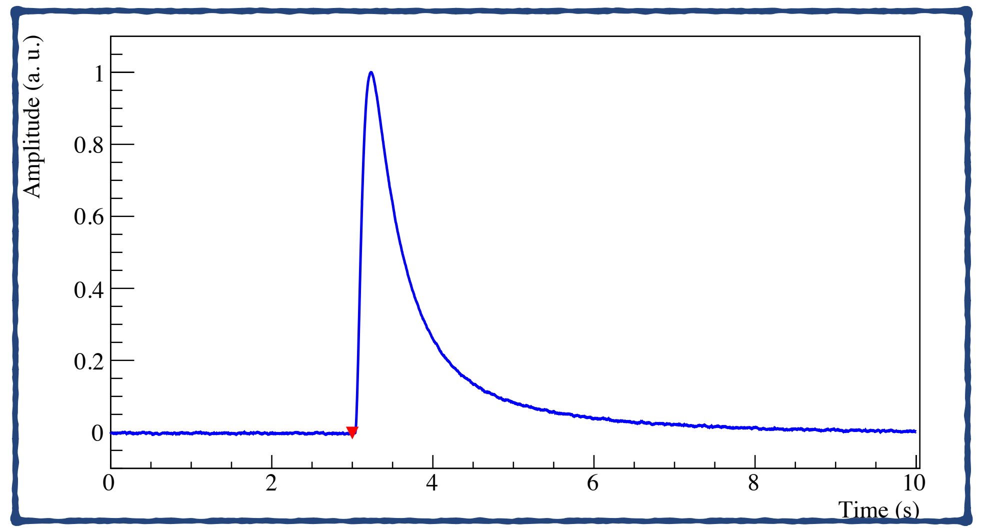
PULSE SHAPE DISCRIMINATION

SALTING IN THE ROI

SELECTIONS

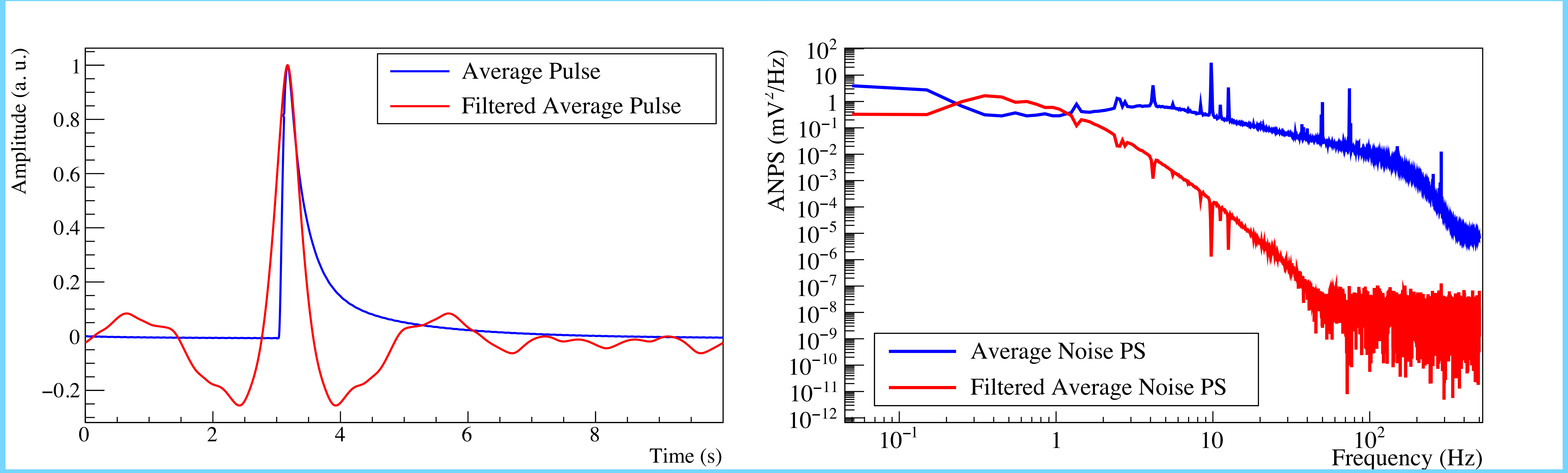
UNBLINDING

Analysis workflow

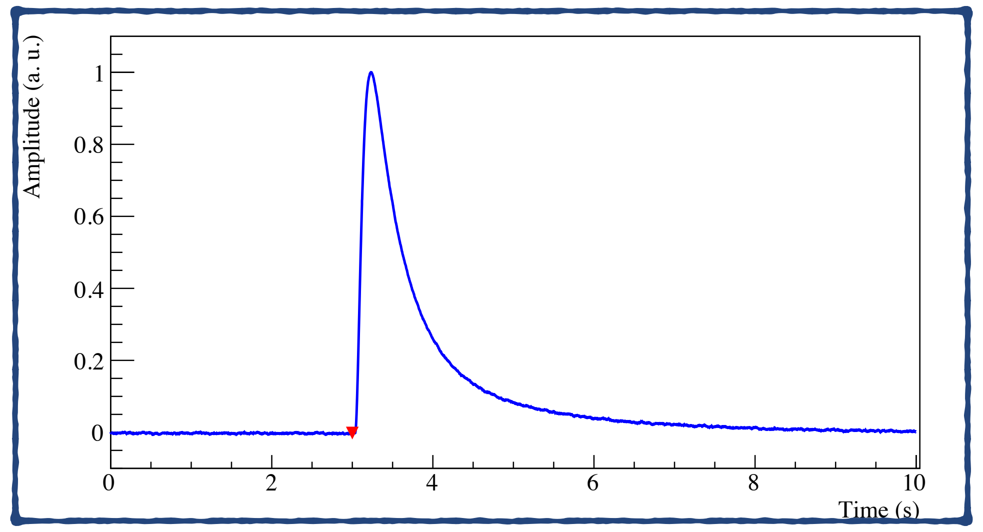


OPTIMUM FILTER → GAIN CORRECTION → ENERGY CALIBRATION → COINCIDENCES → PULSE SHAPE DISCRIMINATION → SALTING IN THE ROI → SELECTIONS → UNBLINDING

Matched filter that maximizes the Signal-to-Noise Ratio

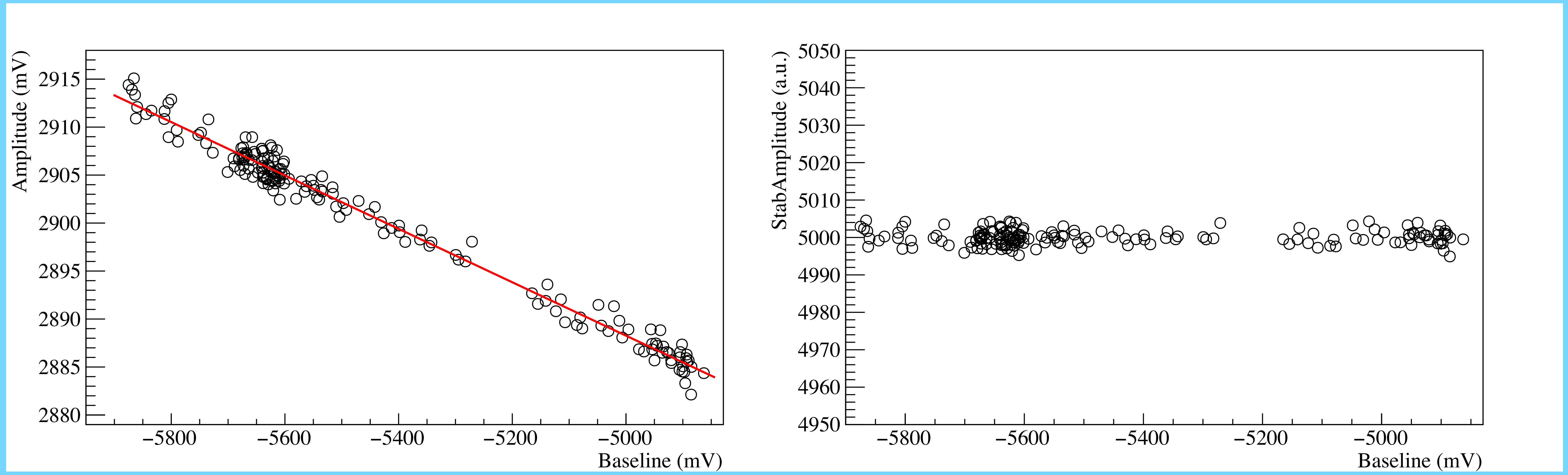


Analysis workflow

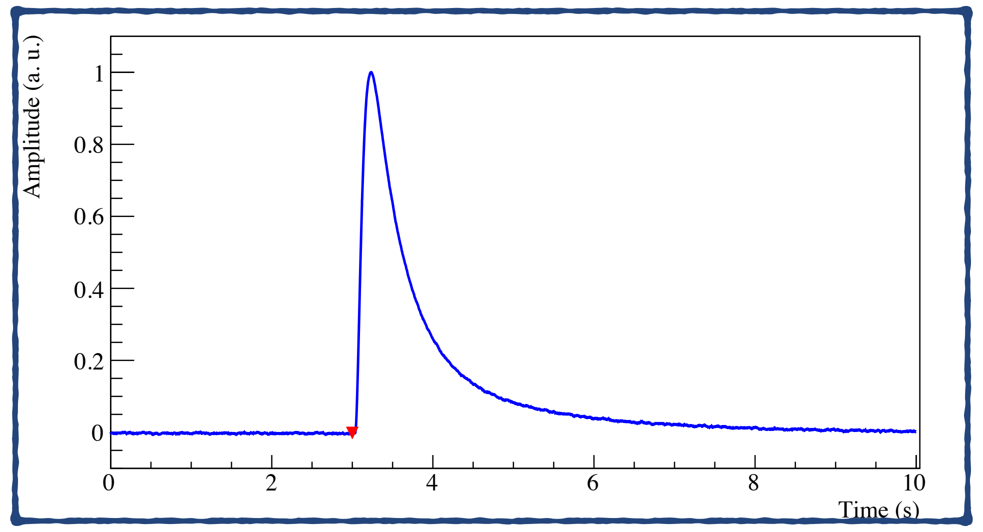


OPTIMUM FILTER → **GAIN CORRECTION** → ENERGY CALIBRATION → COINCIDENCES → PULSE SHAPE DISCRIMINATION → SALTING IN THE ROI → SELECTIONS → UNBLINDING

Heater thermal gain stabilization



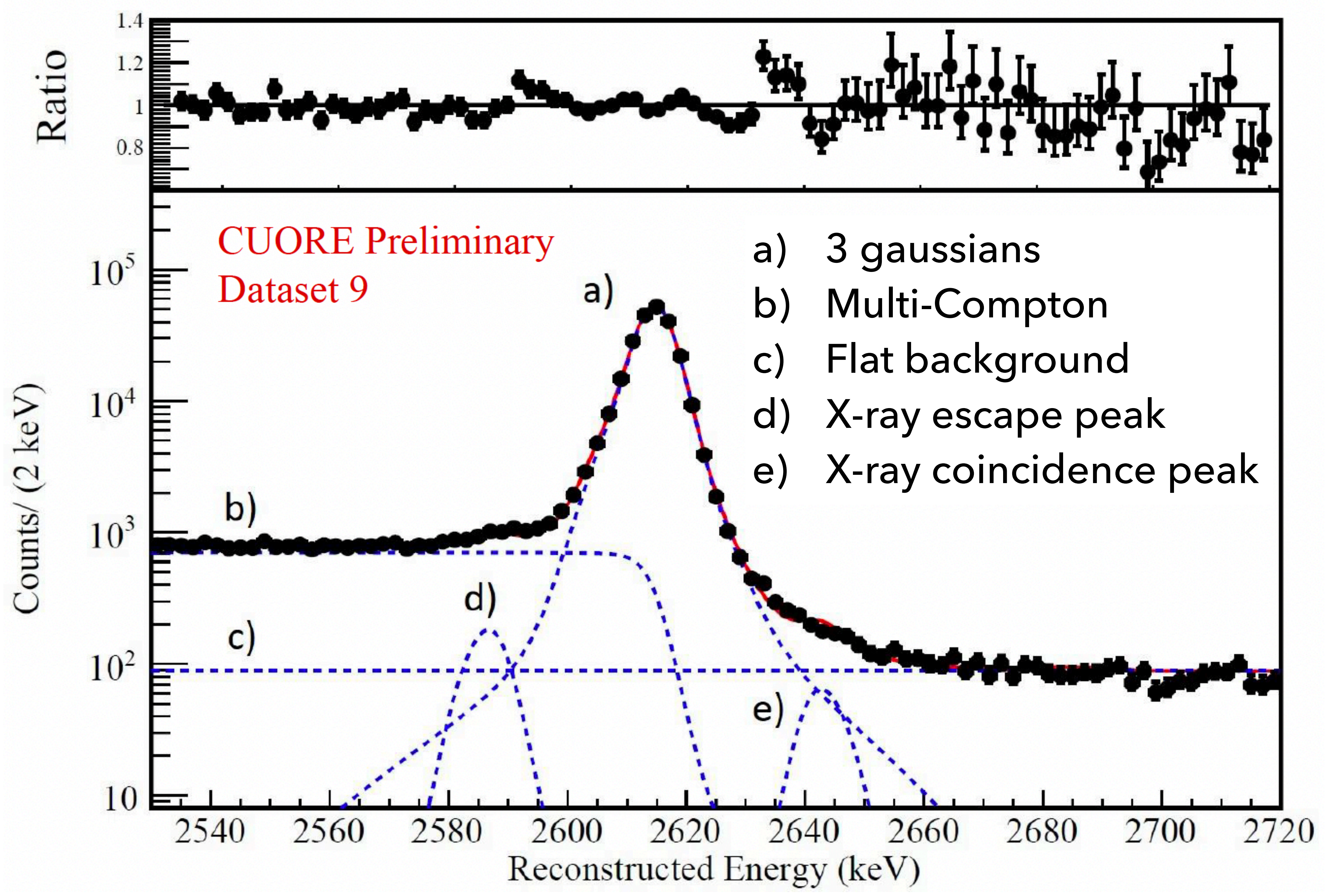
Analysis workflow

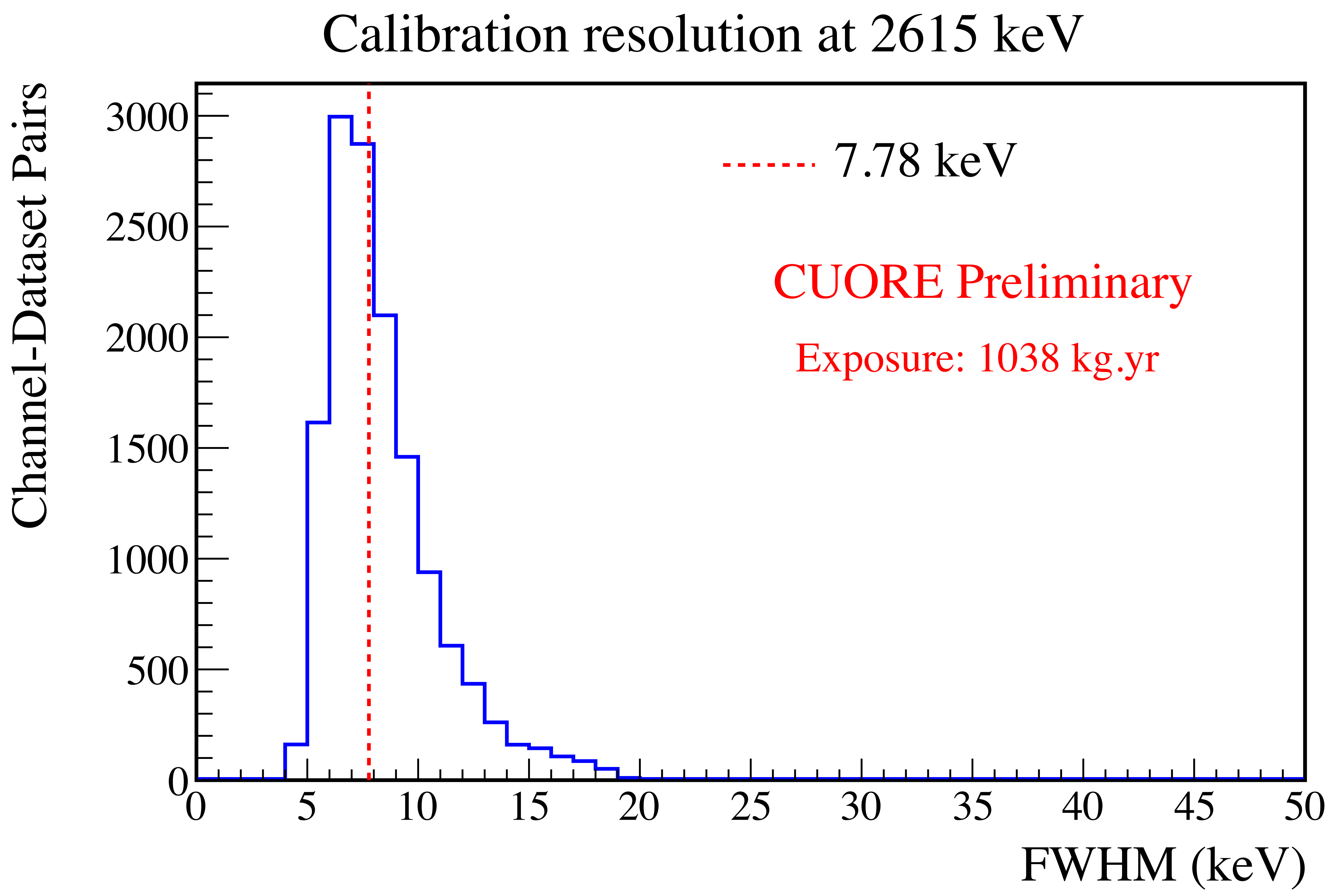


OPTIMUM FILTER → GAIN CORRECTION → ENERGY CALIBRATION → COINCIDENCES → PULSE SHAPE DISCRIMINATION → SALTING IN THE ROI → SELECTIONS → UNBLINDING

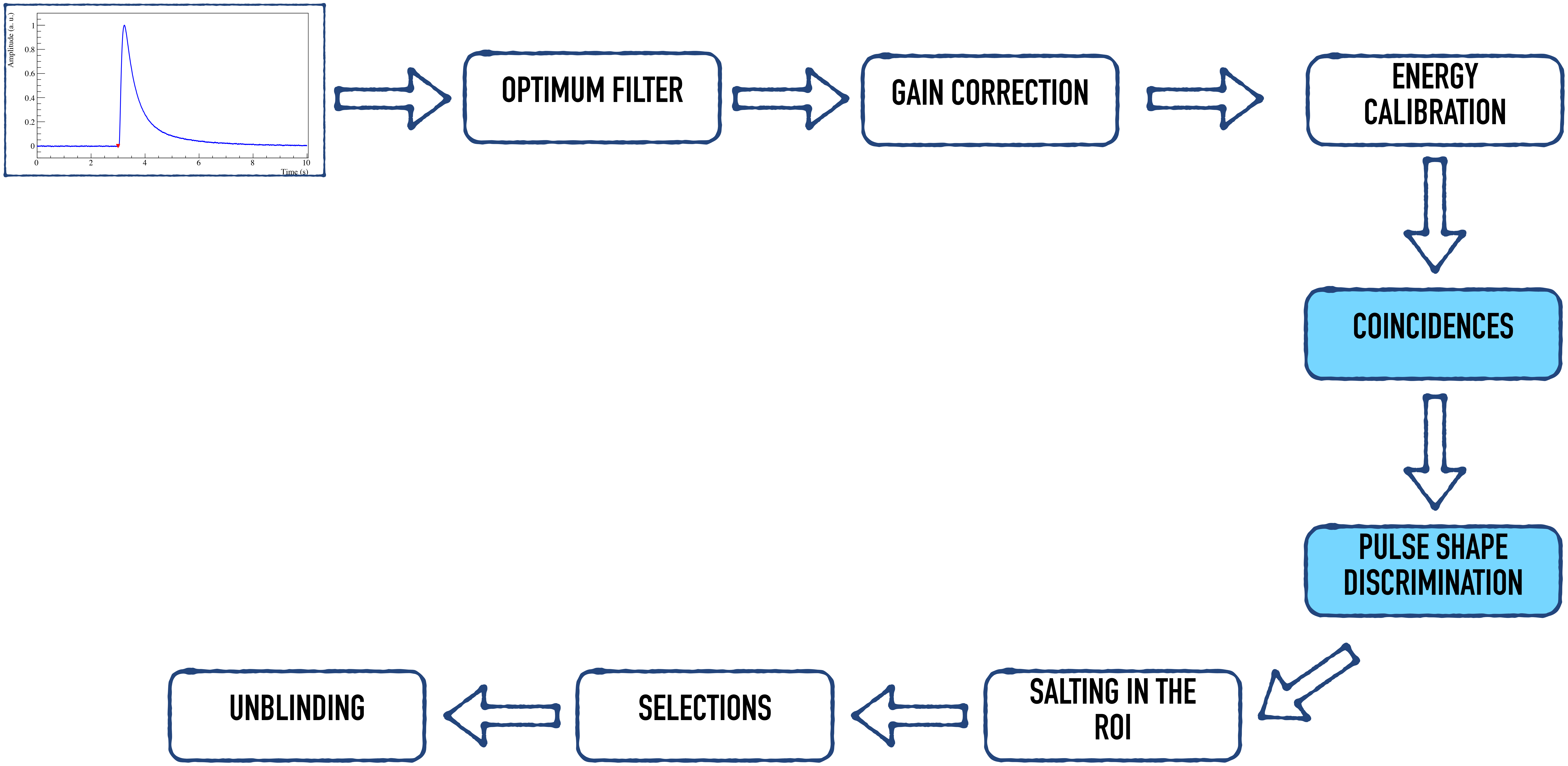
Energy calibration and resolution

- Calibration with ^{232}Th and ^{60}Co external sources ➜ 511, 1173, 1332, 2615 keV energy lines
- Model of detector response on calibration data
- Fit of the 2615 keV line and extrapolation of the resolution to the ROI ➜ (7.8±0.5) keV at $Q_{\beta\beta}$



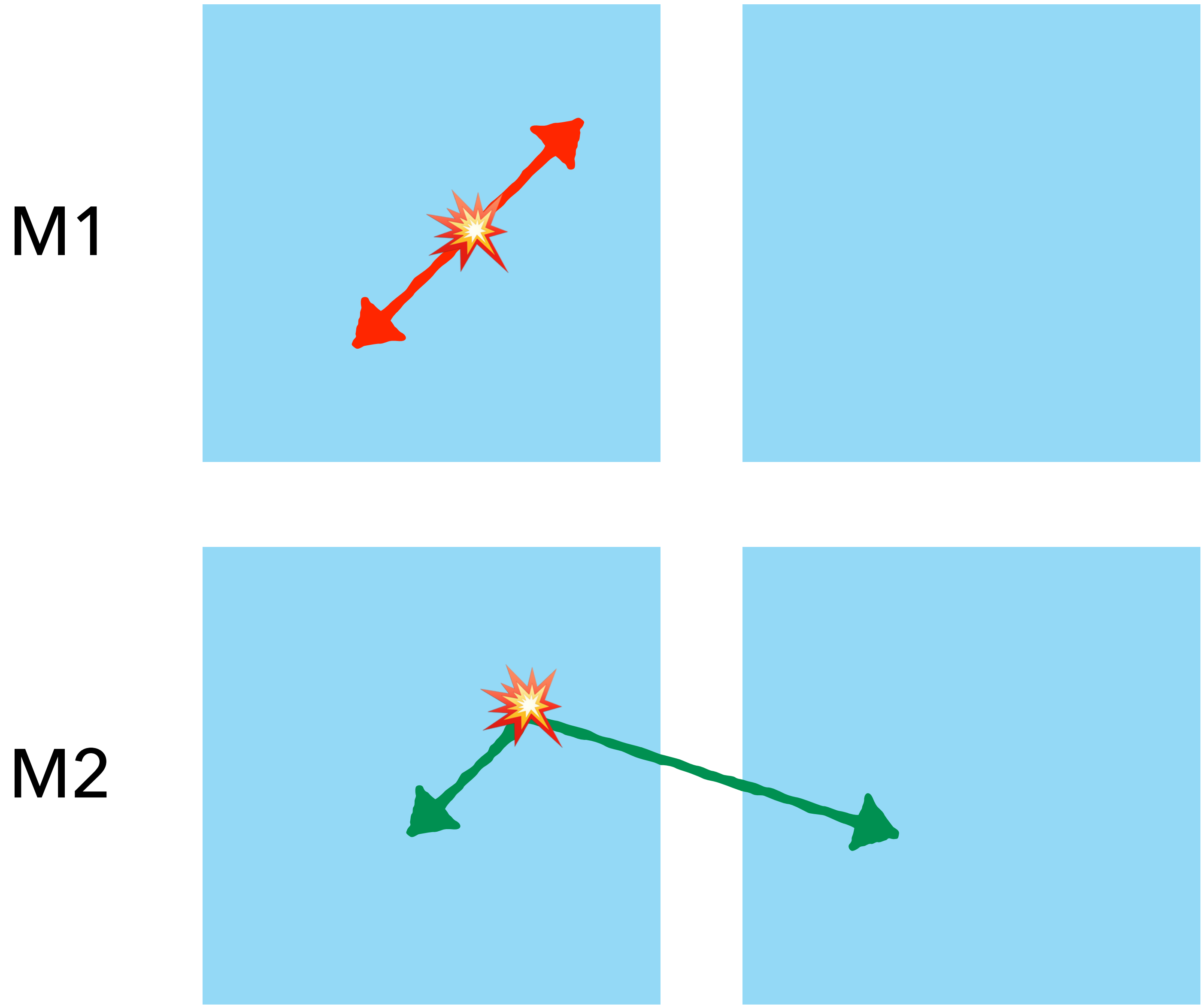


Analysis workflow

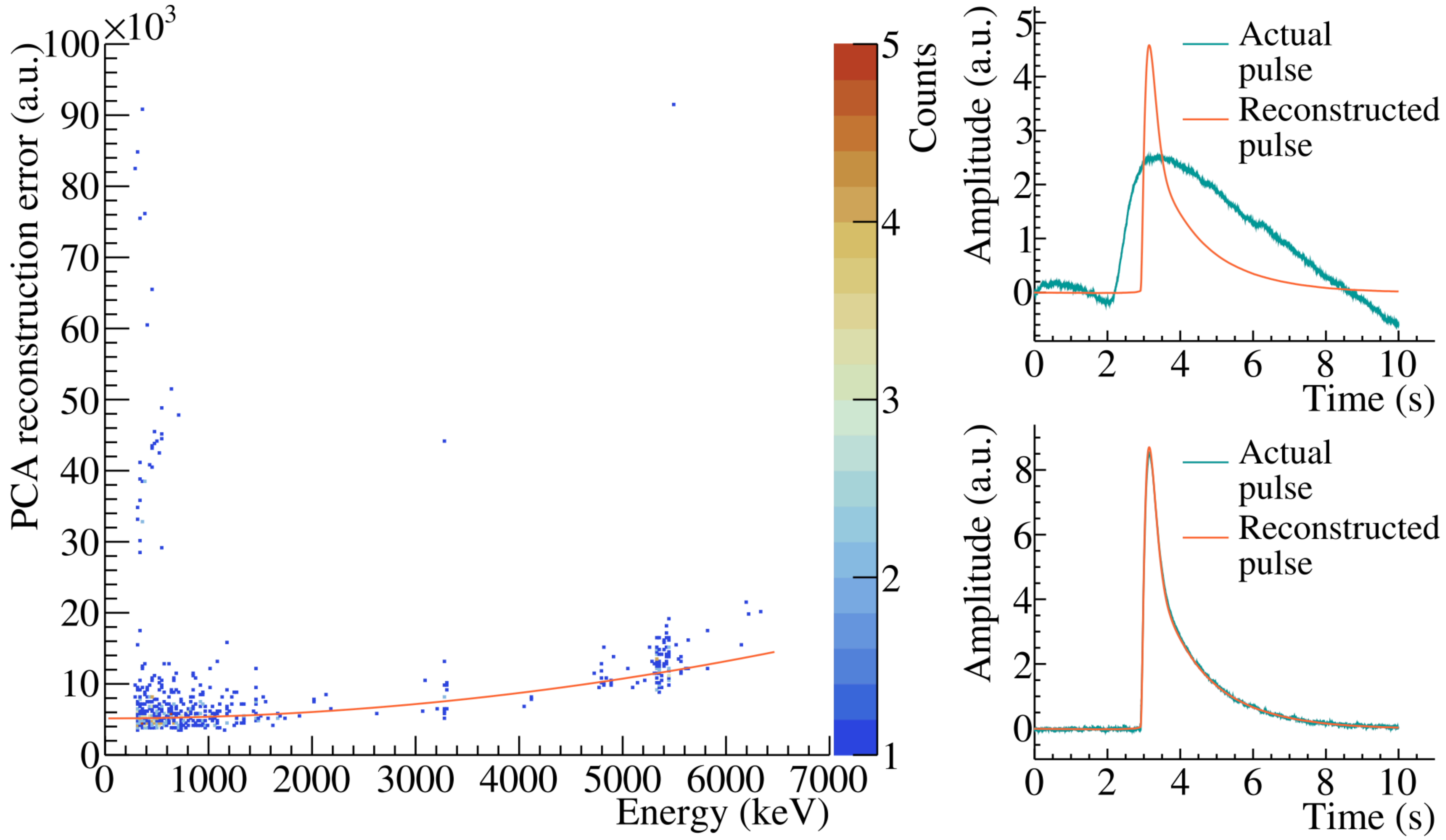


Coincidences and PSD

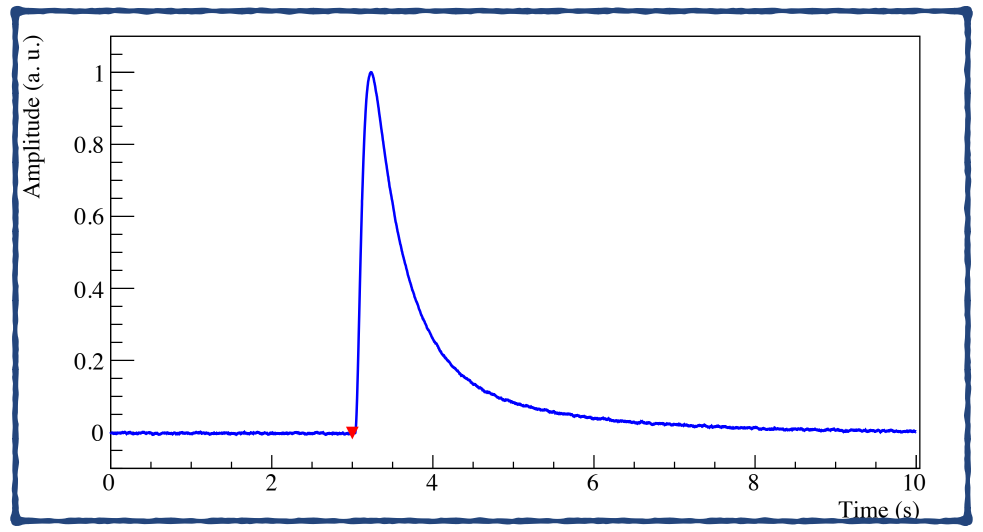
- Containment efficiency from MC: ~88% of $0\nu\beta\beta$ events in one crystal (M1)
- M2 mostly from contamination, muons, noise



- Principal component analysis used for pulse shape discrimination
- Cut on the reconstructed error between single pulses and principal components of average pulse in each channel-dataset

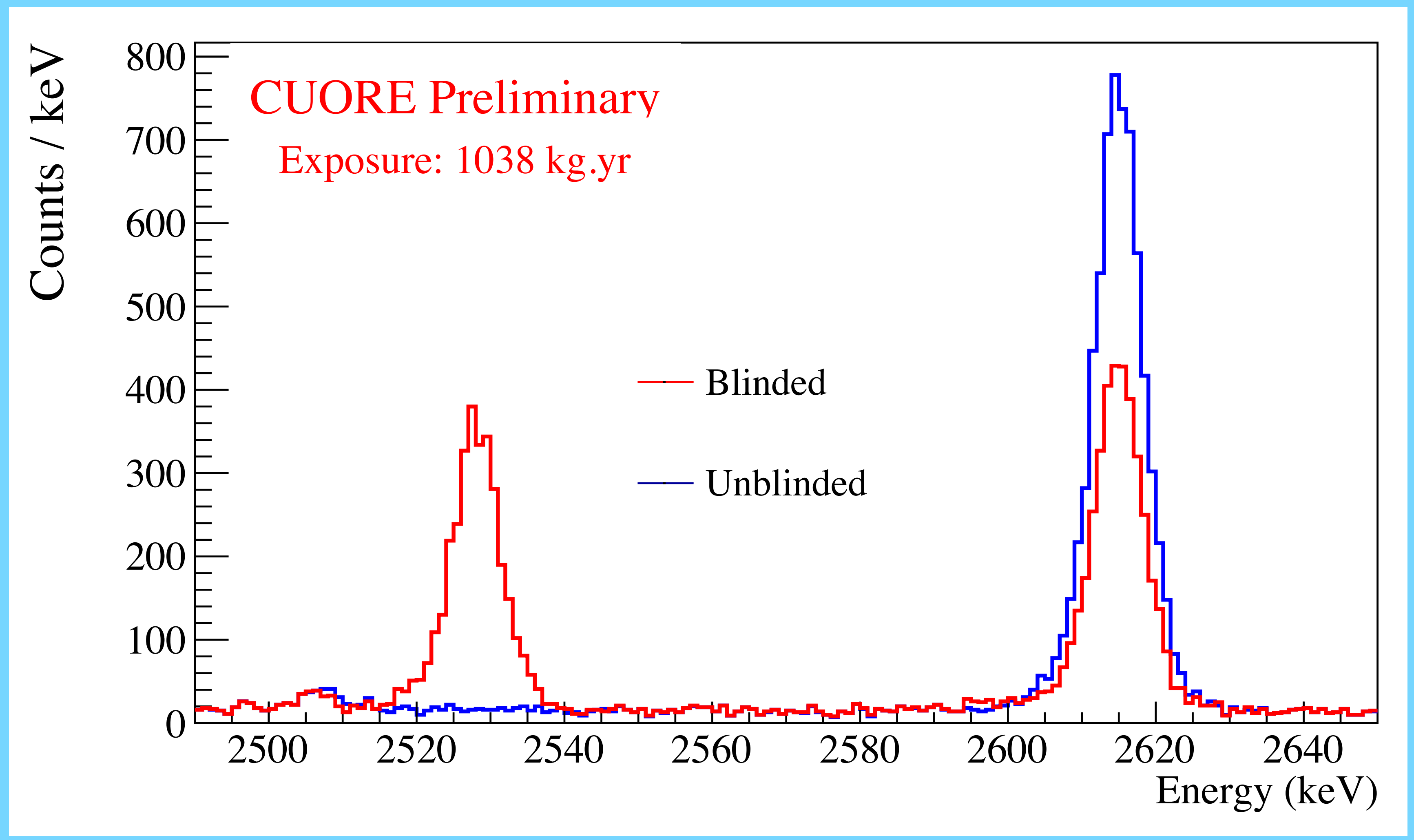


Analysis workflow

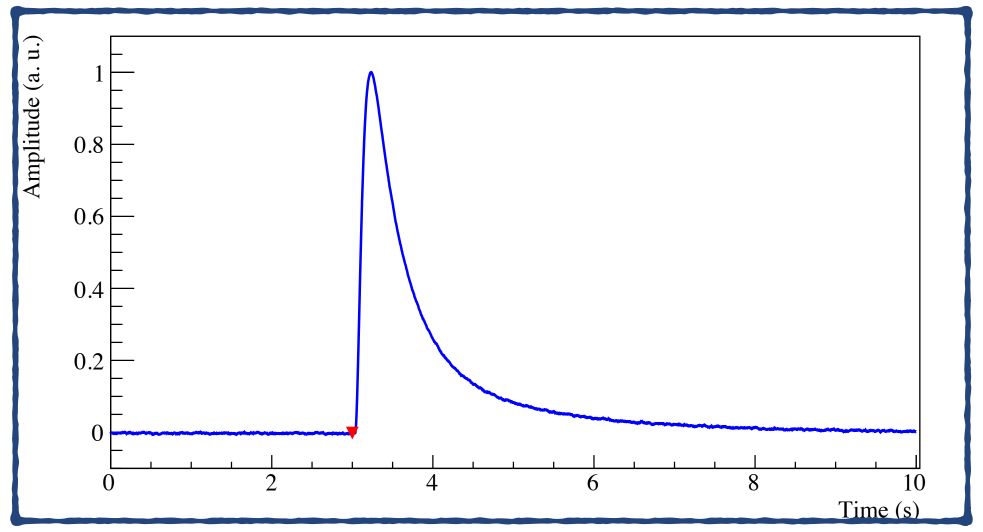


OPTIMUM FILTER → GAIN CORRECTION → ENERGY CALIBRATION → COINCIDENCES → PULSE SHAPE DISCRIMINATION → SALTING IN THE ROI → SELECTIONS → UNBLINDING

- Blinding through salting
- Random fraction of events from ^{208}Tl peak shifted around the $Q_{\beta\beta}$
- Unblinding after all steps of the analysis are fixed



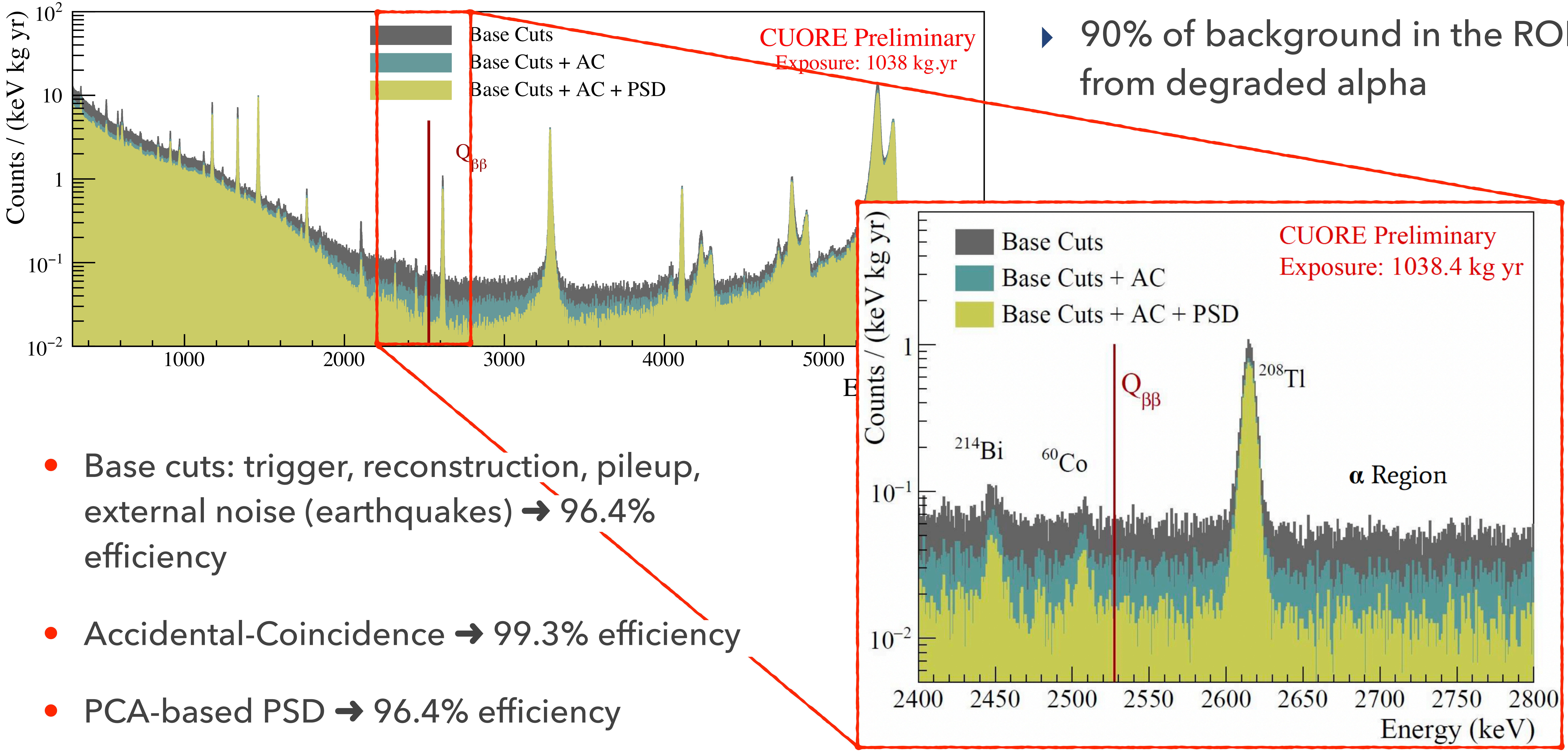
Analysis workflow



1. OPTIMUM FILTER
2. GAIN CORRECTION
3. ENERGY CALIBRATION
4. COINCIDENCES
5. PULSE SHAPE DISCRIMINATION
6. SALTING IN THE ROI
7. SELECTIONS
8. UNBLINDING

The background

Nature 604, 53-58 (2022)

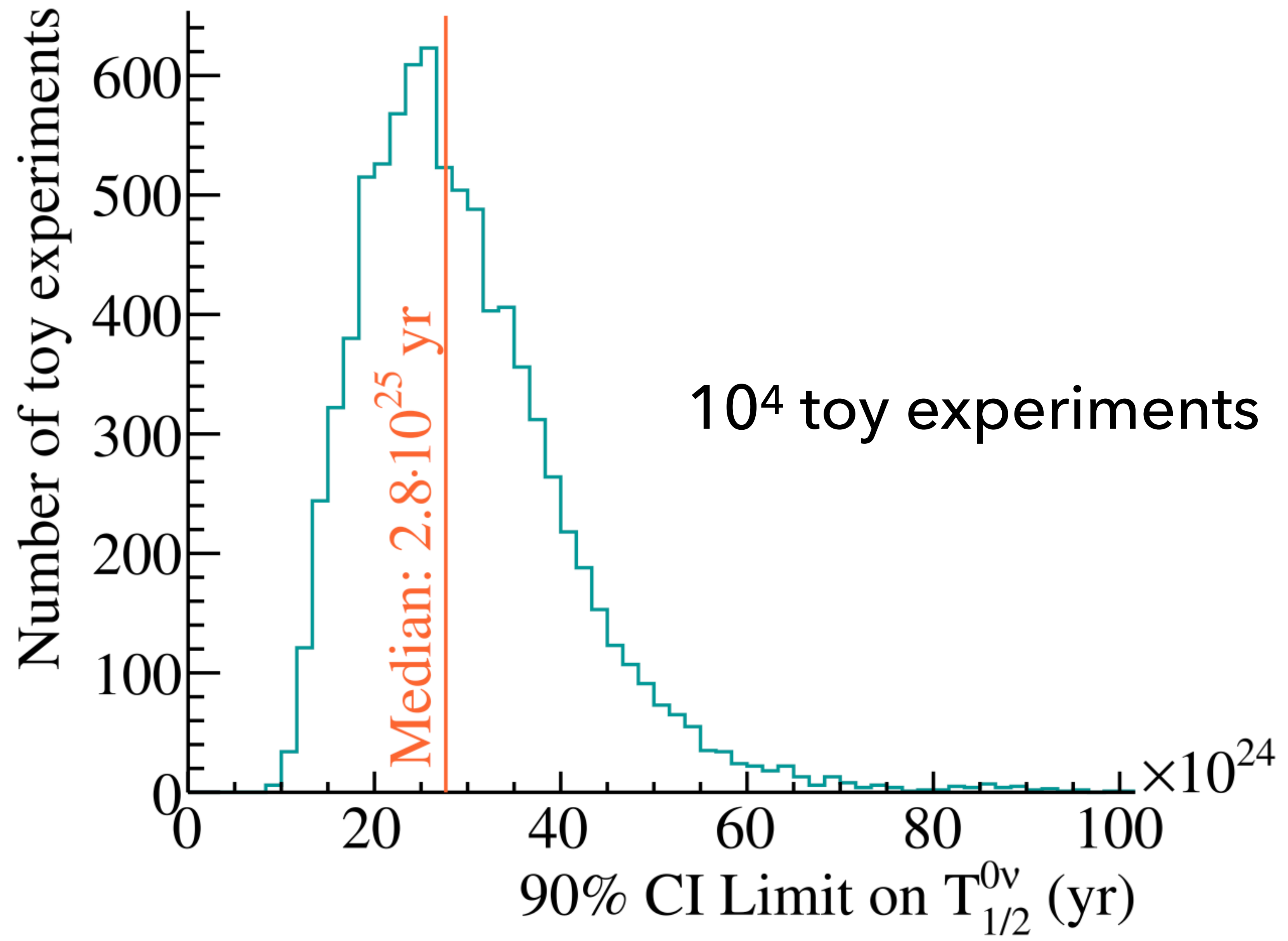


- 90% of background in the ROI from degraded alpha

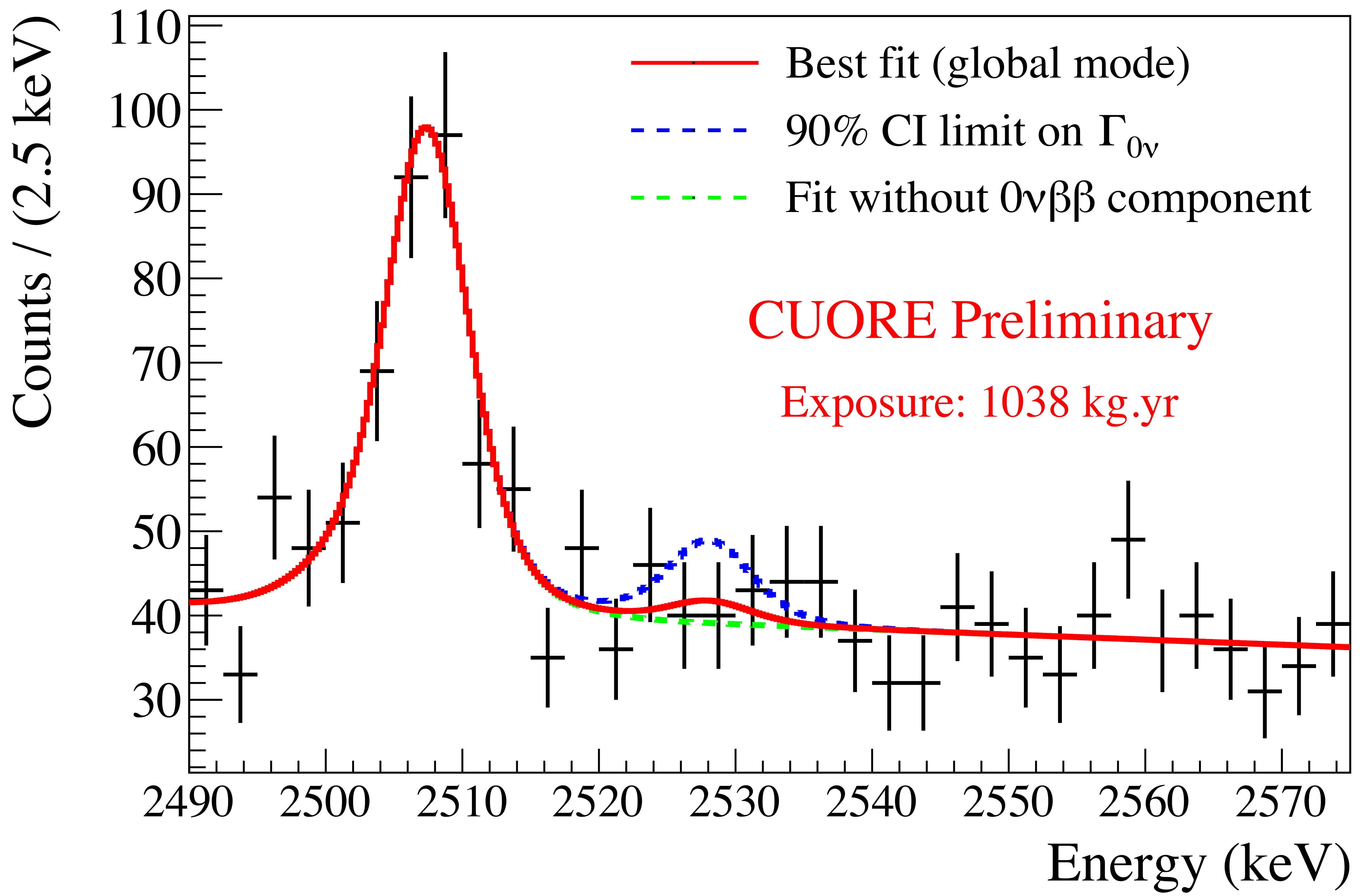
- Base cuts: trigger, reconstruction, pileup, external noise (earthquakes) ➜ 96.4% efficiency
- Accidental-Coincidence ➜ 99.3% efficiency
- PCA-based PSD ➜ 96.4% efficiency

Inference

- Bayesian analysis with BAT
- Median 90% exclusion sensitivity
  $T_{1/2}^{0\nu} = 2.8 \times 10^{25}$ yr
- Best fit value
  $\Gamma^{0\nu} = (0.9 \pm 1.4) \times 10^{-26}$ yr^{-1}

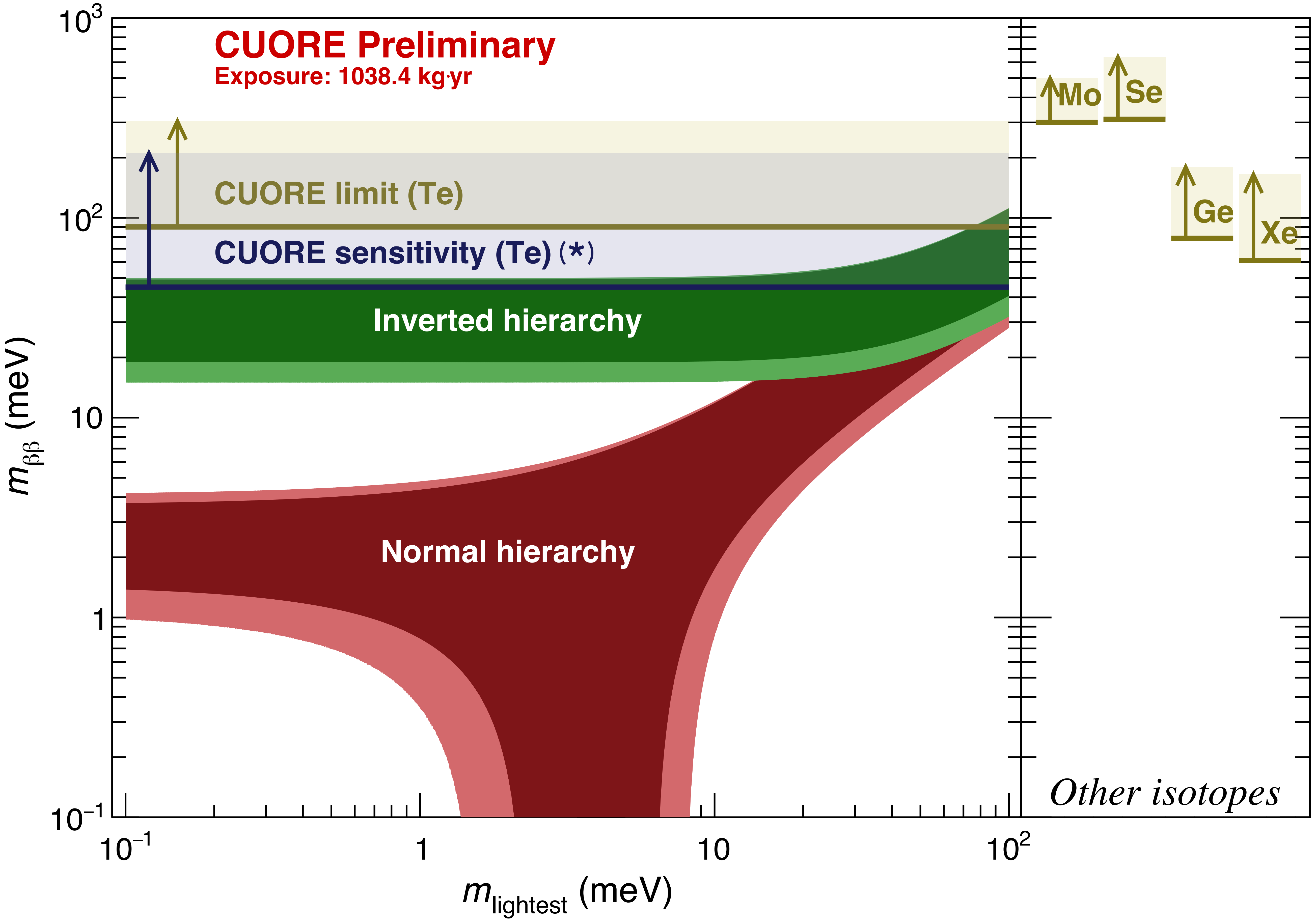


10^4 toy experiments



Free parameters:
- $\Gamma^{0\nu}$ rate
- ^{60}Co peak rate scaled according to lifetime
- Background rate for each dataset and shared linear slope

Results



Bayesian limit at 90% C.L.

$$T_{1/2}^{0\nu} > 2.2 \times 10^{25}\ \text{yr}$$

Using NME range for ^{130}Te

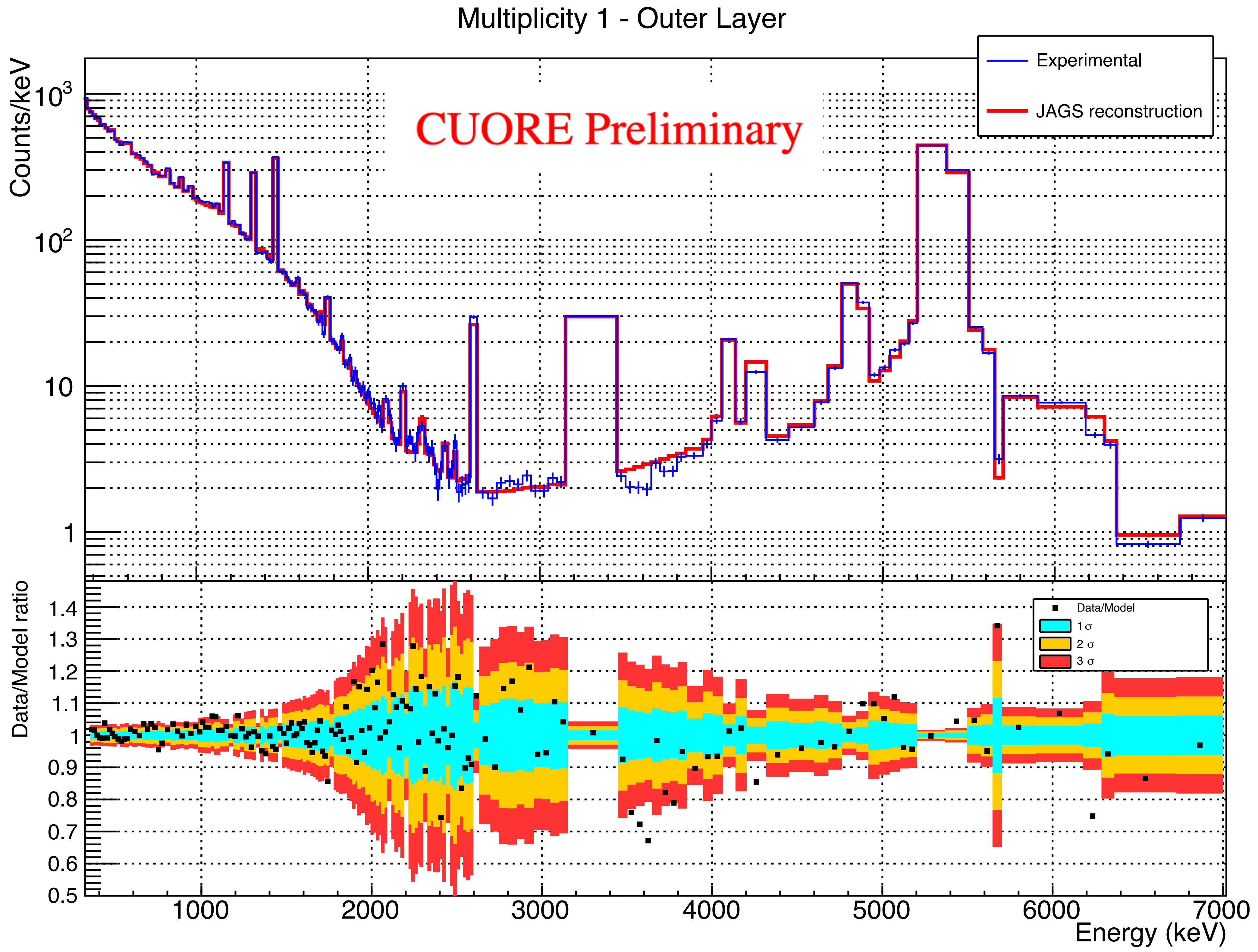
$$m_{\beta\beta} < (90 - 305)\ \text{meV}$$

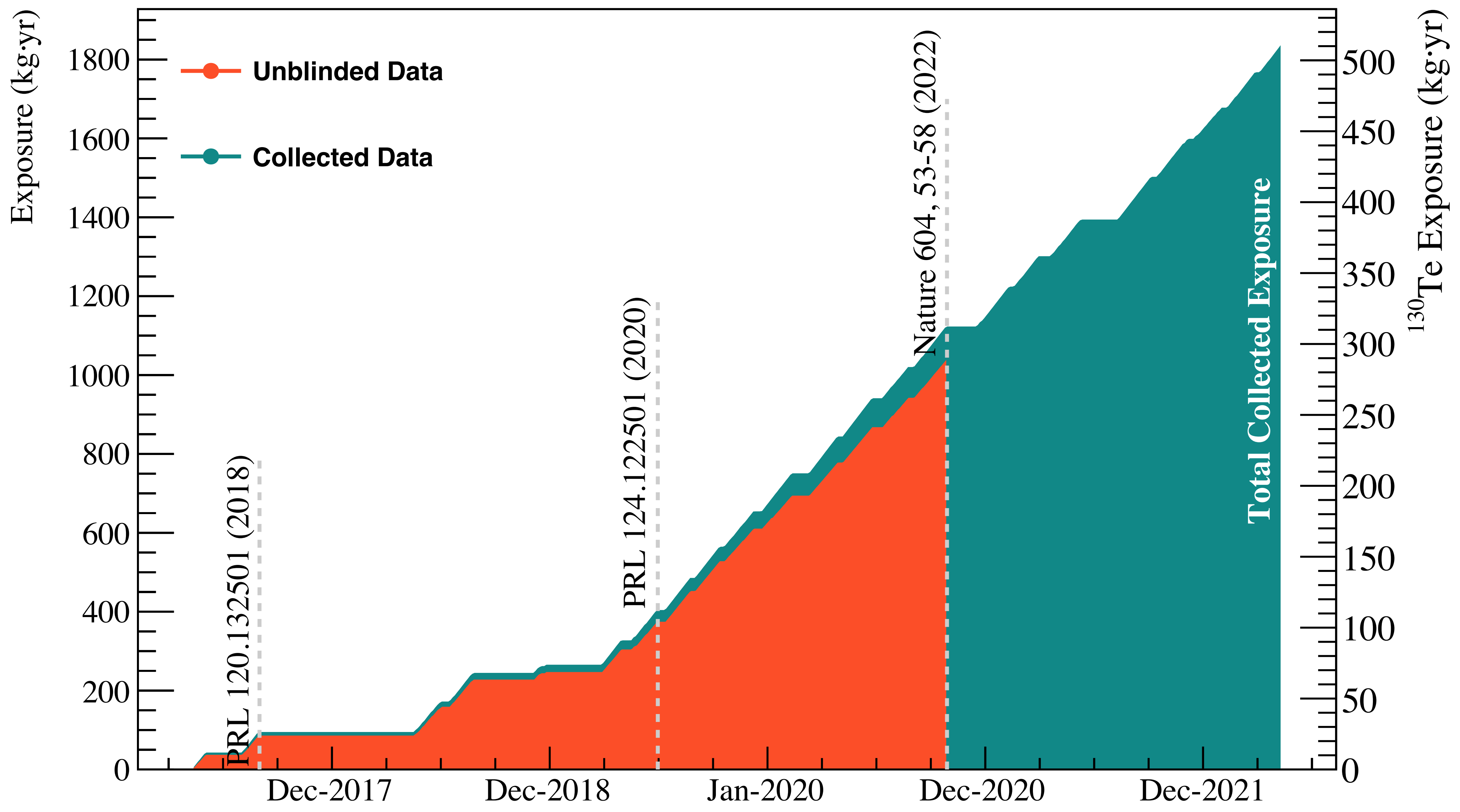
CUPID-Mo: Phys. Rev. Lett. 126, 181802 (2021)
CUPID-0: Phys. Rev. Lett. 123, 032501 (2019)
GERDA: Phys. Rev. Lett. 125, 252502 (2020)
KamLAND-Zen: Phys. Rev. Lett. 117, 082503 (2016)

(*) CUORE goal

Current status and future plans

- Keep taking data till ~2024 (upgrade)
- Improve analysis and noise conditions





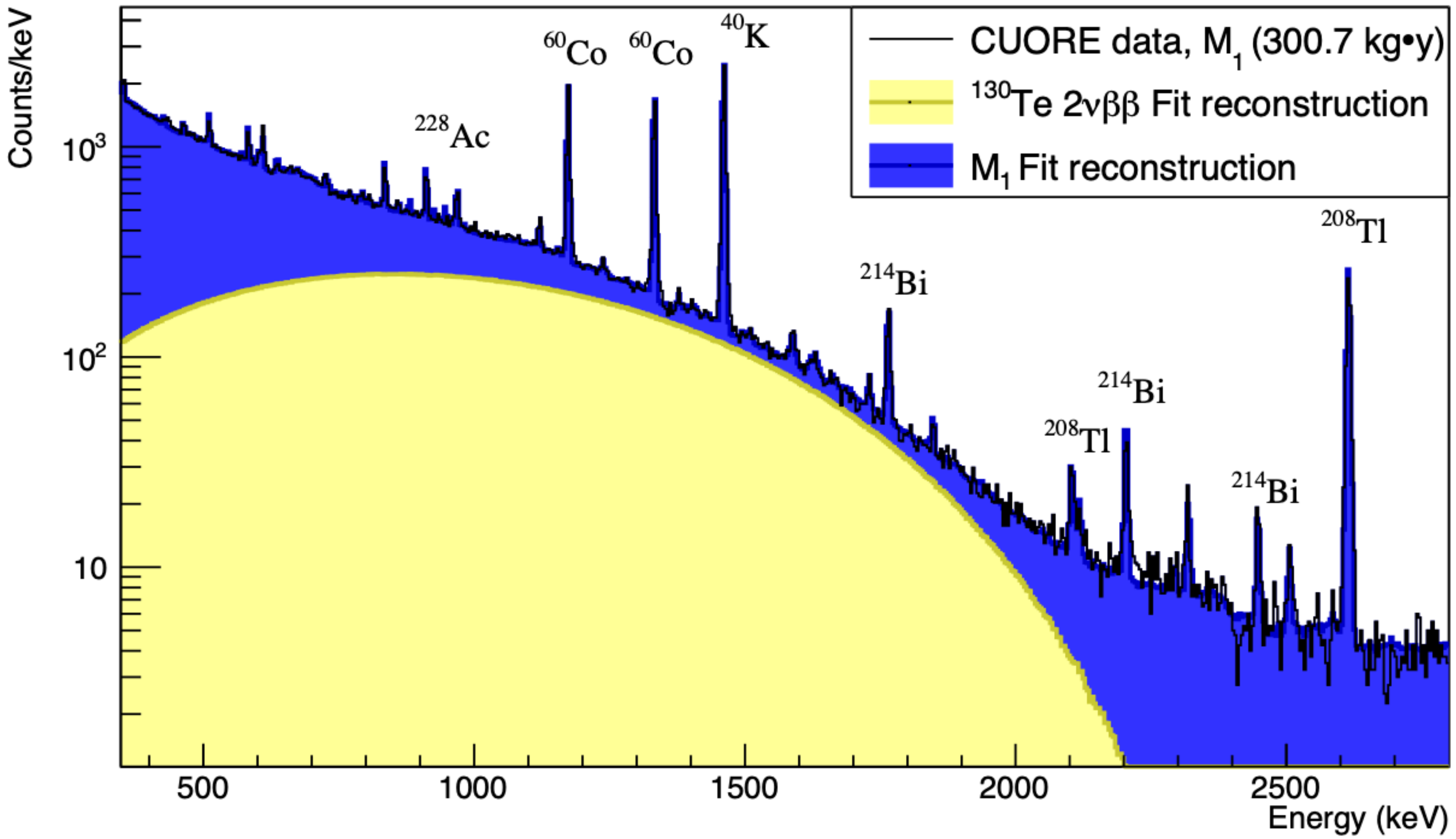
Other analyses ongoing

- $2\nu\beta\beta$ of ^{130}Te
- Full background model
- Double beta on excited states
- other M2 or higher analyses

Two neutrino double beta decay

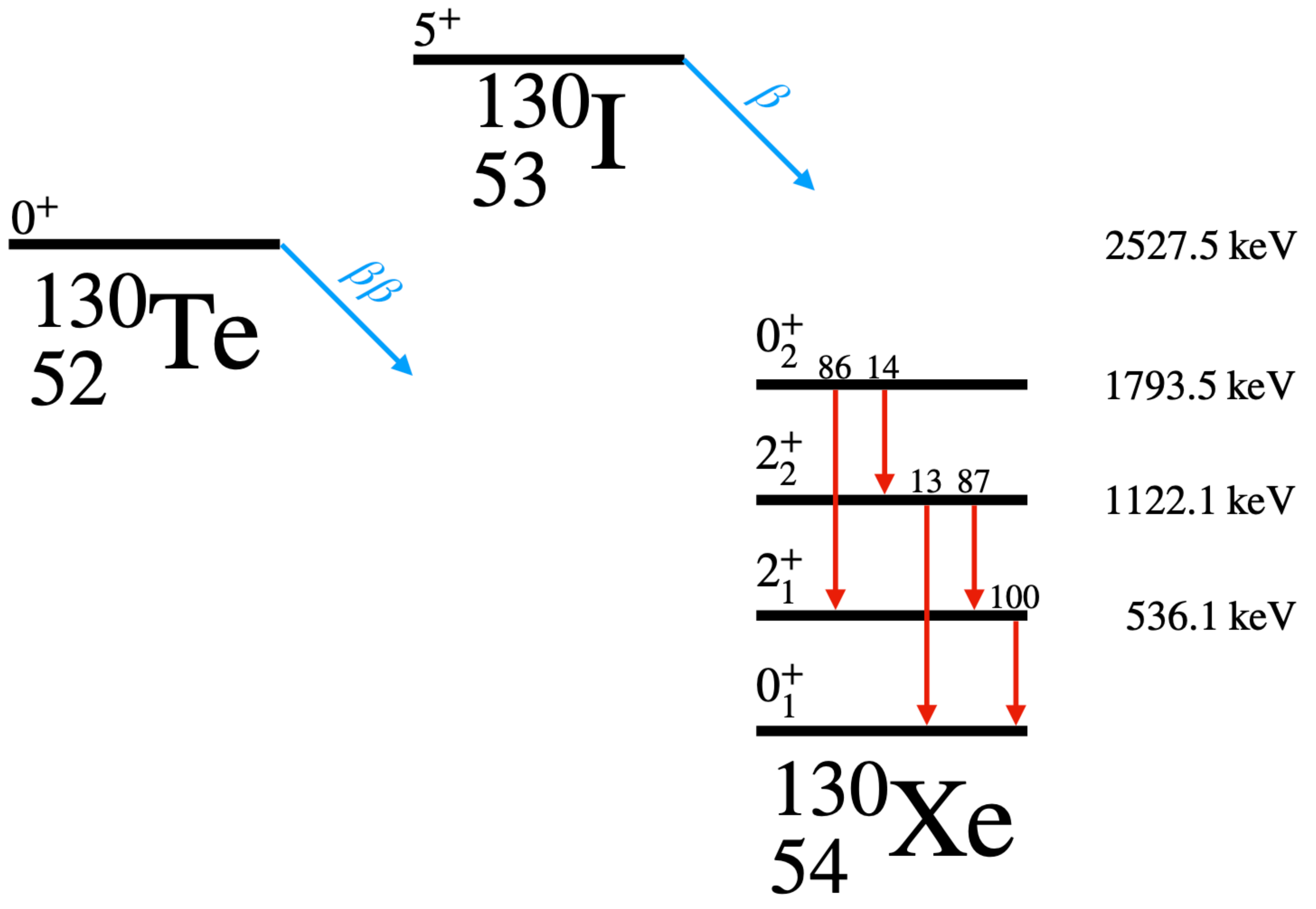
Phys. Rev. Lett. 126, 171801 (2021)

- Most precise ^{130}Te $2\nu\beta\beta$ half-life to date ➜ $T^{2\nu}_{1/2} = 7.71^{+0.08}_{-0.06}(\text{stat.})^{+0.12}_{-0.15}(\text{syst.}) \times 10^{20}$ yr

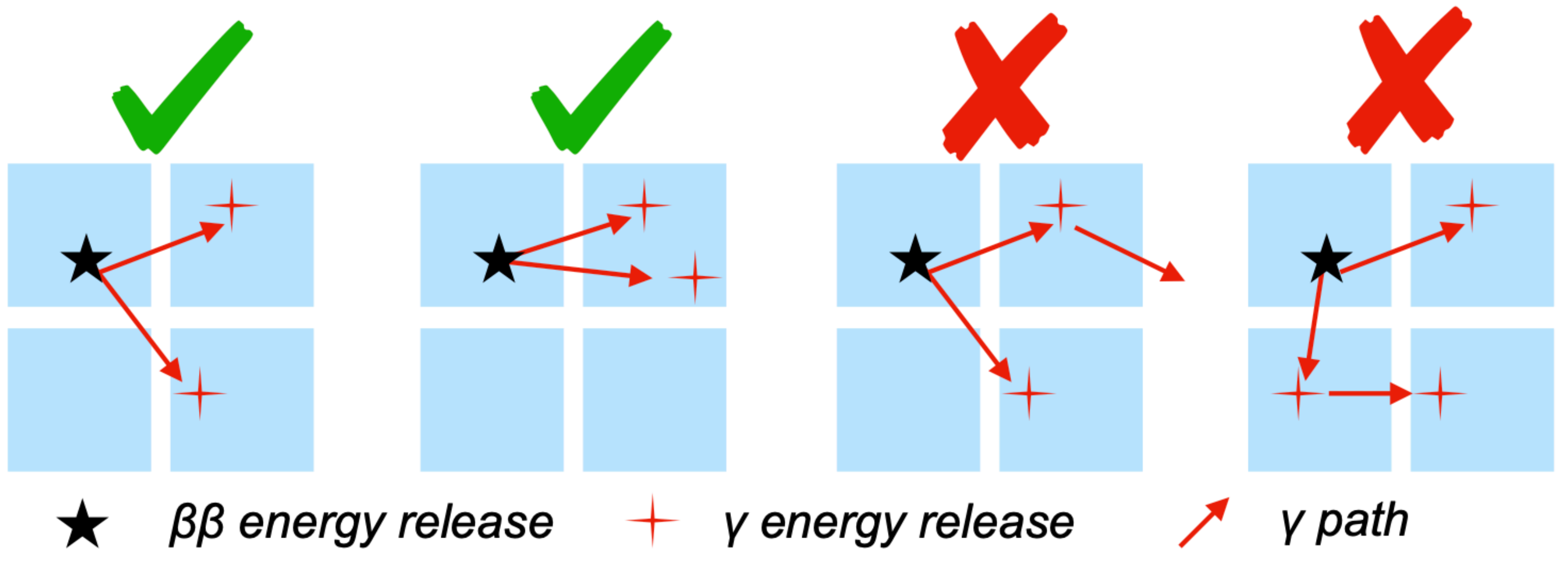


- 300.7 kg·yr of TeO_2
- 350 keV to 2.8 MeV
- Data-MonteCarlo fit
- Assuming Single State Dominance
- Will be updated with more exposure

Double beta decay of ^{130}Te to 0^+ states of ^{130}Xe



- Three possible patterns with betas and de-excitations gammas
- Analysis on fully contained decays with coincident M2 or M3
- 372.5 kg·yr of TeO_2
- Improved previous result by factor 5



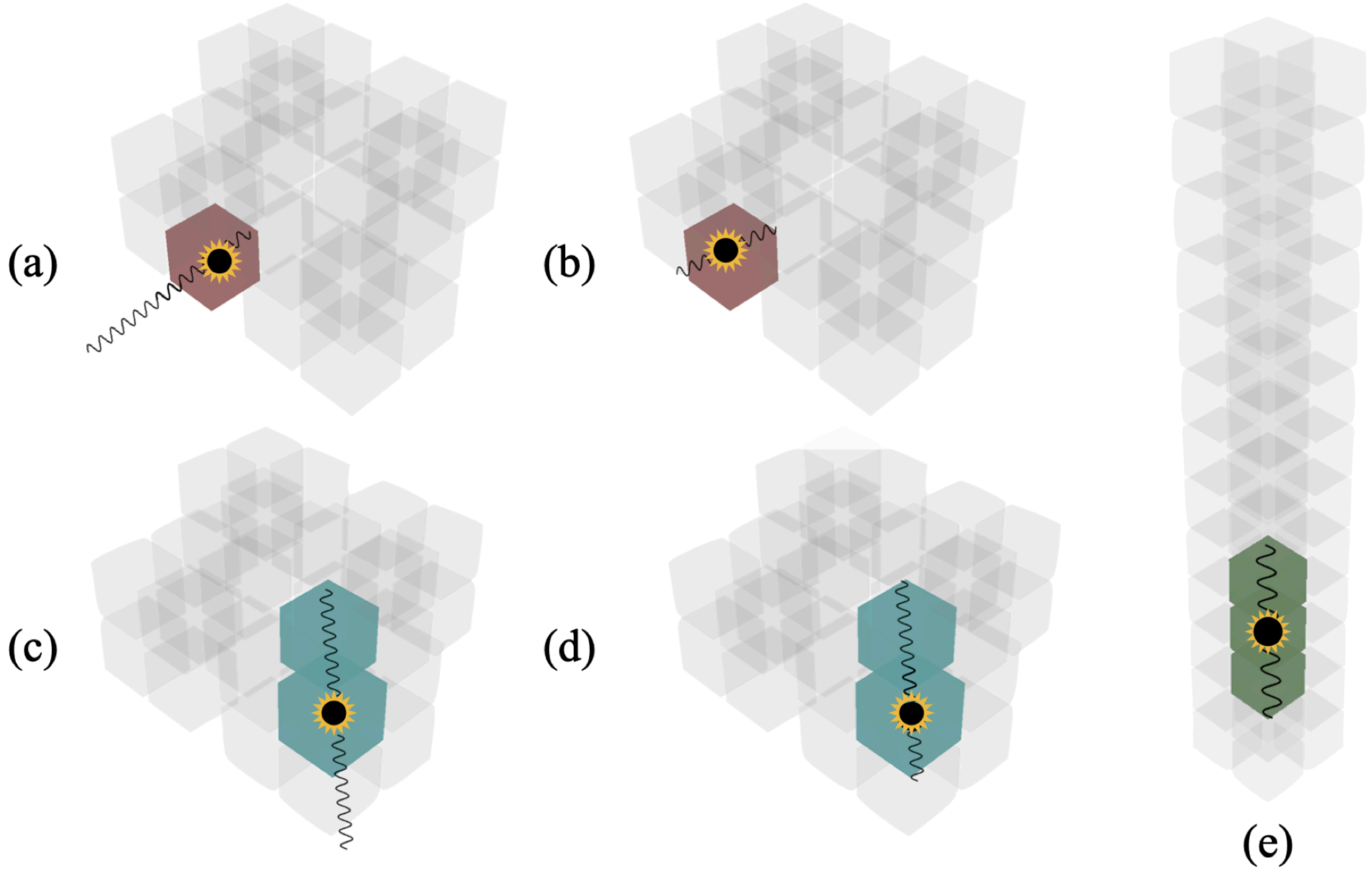
$$T^{0\nu}_{1/2} = 5.9 \times 10^{24} \text{ yr at 90\% C.I.}$$

$$T^{2\nu}_{1/2} = 1.3 \times 10^{24} \text{ yr at 90\% C.I.}$$

Neutrinoless β^+EC decay of ^{120}Te

Phys. Rev. C. 105, 065504 (2022)

- Clear signature: $^{120}\text{Te} + e^- \rightarrow ^{120}Sn + X + 2\gamma_{511}$
- 0.09% abundance: 355.7 kg·yr of TeO_2 ➜ 0.24 kg·yr of ^{120}Te
- Multiple signatures in M1, M2 and M3
- One order of magnitude better the previous result



$$T^{0\nu}_{1/2} = 2.9 \times 10^{22}\ \text{yr}$$

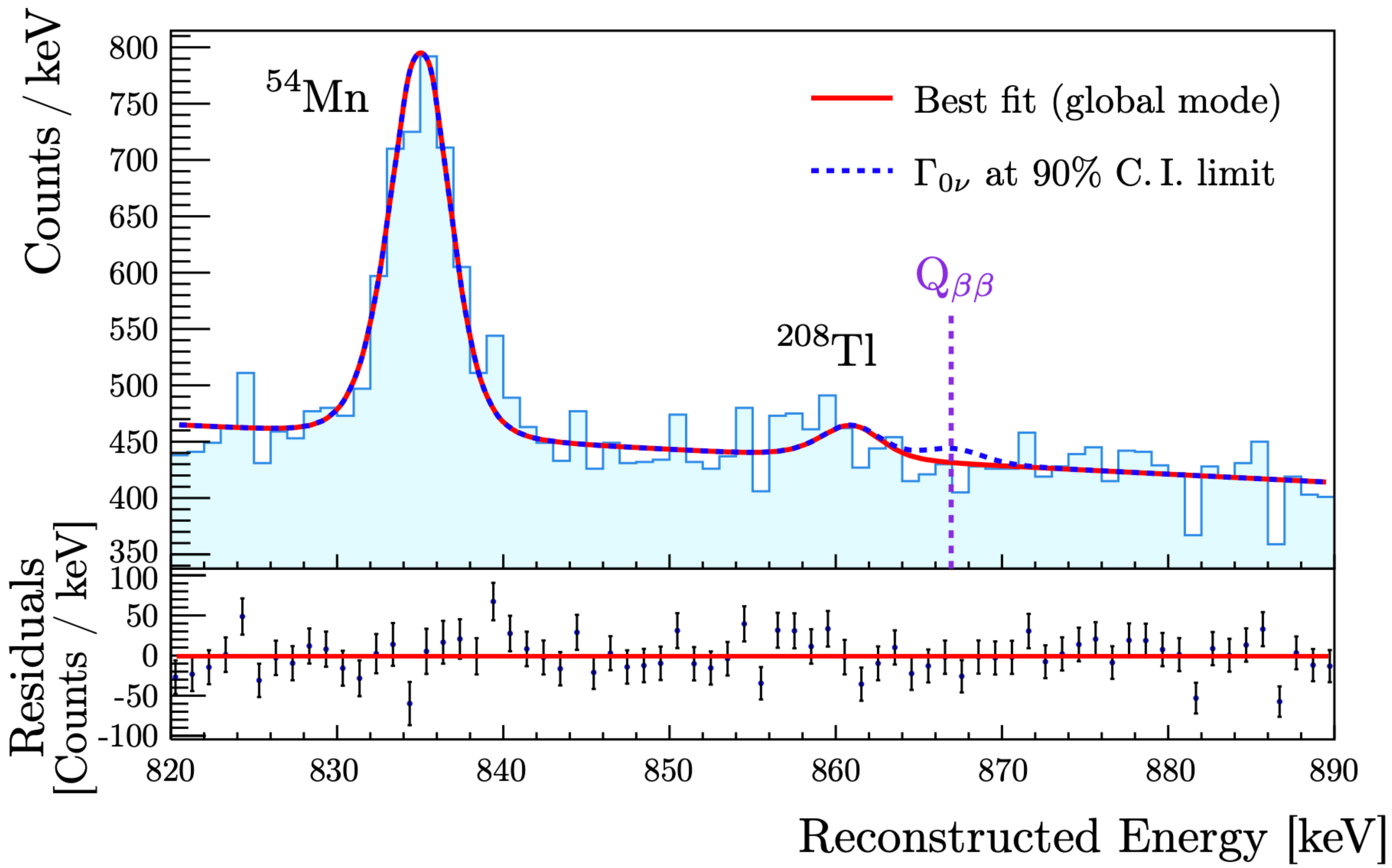
at 90% C.I

Signature	Particles Detected	Signal Peak Position [keV]	Multiplicity	Energy range [keV] ΔE_0	ΔE_1	ΔE_2	Containment efficiency ε_{mc} [%]
(a)	$\beta^+ + X + \gamma_{511}$	1203.8	1	[1150,1250]			12.8(5)
(b)	$\beta^+ + X + 2\gamma_{511}$	1714.8	1	[1703,1775]			13.1(5)
(c)	$(\beta^+ + X,\ \gamma_{511})$	(692.8, 511)	2	[650,750]	[460,560]		4.10(20)
(d)	$(\beta^+ + X + \gamma_{511},\ \gamma_{511})$	(1203.8, 511)	2	[1150,1250]	[460,560]		13.8(6)
(e)	$(\beta^+ + X,\ \gamma_{511},\ \gamma_{511})$	(692.8, 511, 511)	3	[650,750]	[460,560]	[460,560]	2.15(9)

Neutrinoless double beta decay of ^{128}Te

arXiv:2205.03132

- Second most abundant isotope: 31.75% ➜ 188 kg of ^{128}Te
- Low $Q_{\beta\beta}$ of 866.7 keV ➜ two neutrino from ^{130}Te and $\gamma\beta$ background
- 309.33 kg·yr of TeO_2 ➜ 78.56 kg·yr of ^{128}Te
- M1 events in the [820-890] keV region of interest
- 30 times better than previous direct limit

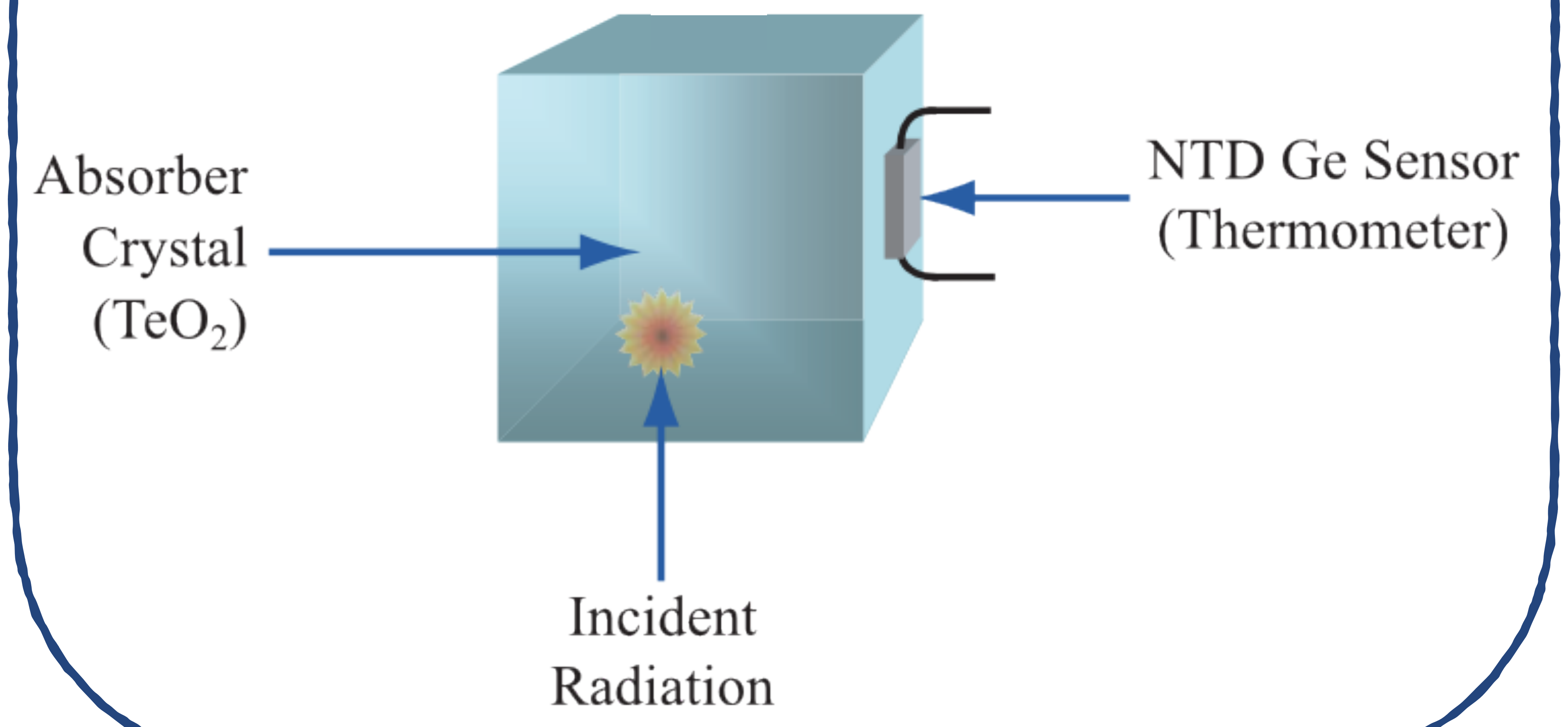


$$T^{0\nu}_{1/2} = 3.6 \times 10^{24} \text{ yr at } 90\,\% \text{ C.I.}$$

From CUORE to CUPID

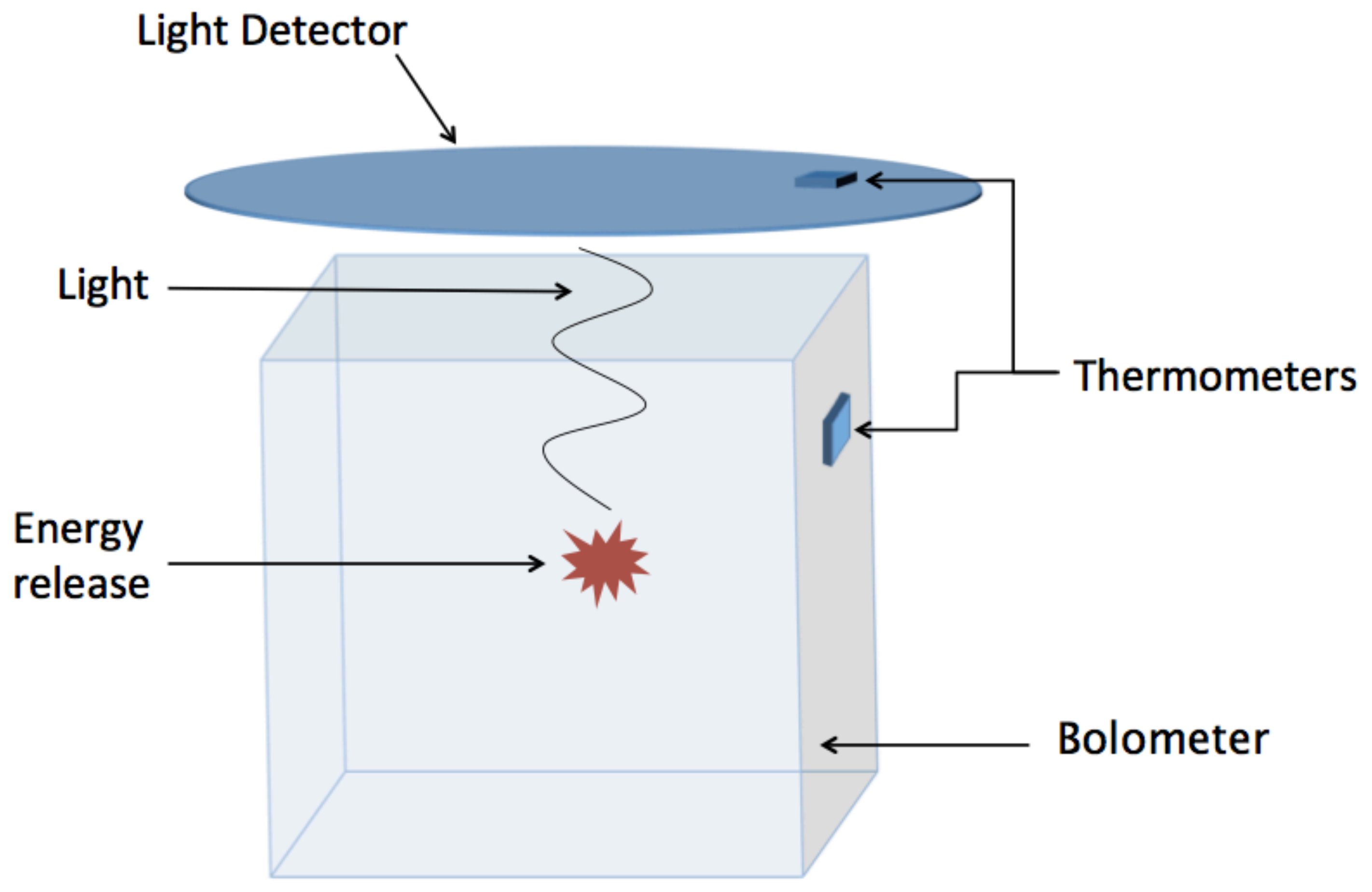
arXiv:1907.09376

- ^{130}Te ➜ $Q_{\beta\beta} \simeq 2527.5$ keV
- Calorimeter only (heat) ➜ No particle ID
- Readout through NTD Ge thermistors
- BI ~ $1.49 \cdot 10^{-2}$ counts/keV/kg/yr



See next talk

- ^{100}Mo ➜ $Q_{\beta\beta} \simeq 3034$ keV
- Scintillating calorimeter (heat + light) ➜ Particle ID
- NTD or faster sensors for light detectors
- BI < 10^{-4} counts/keV/kg/yr



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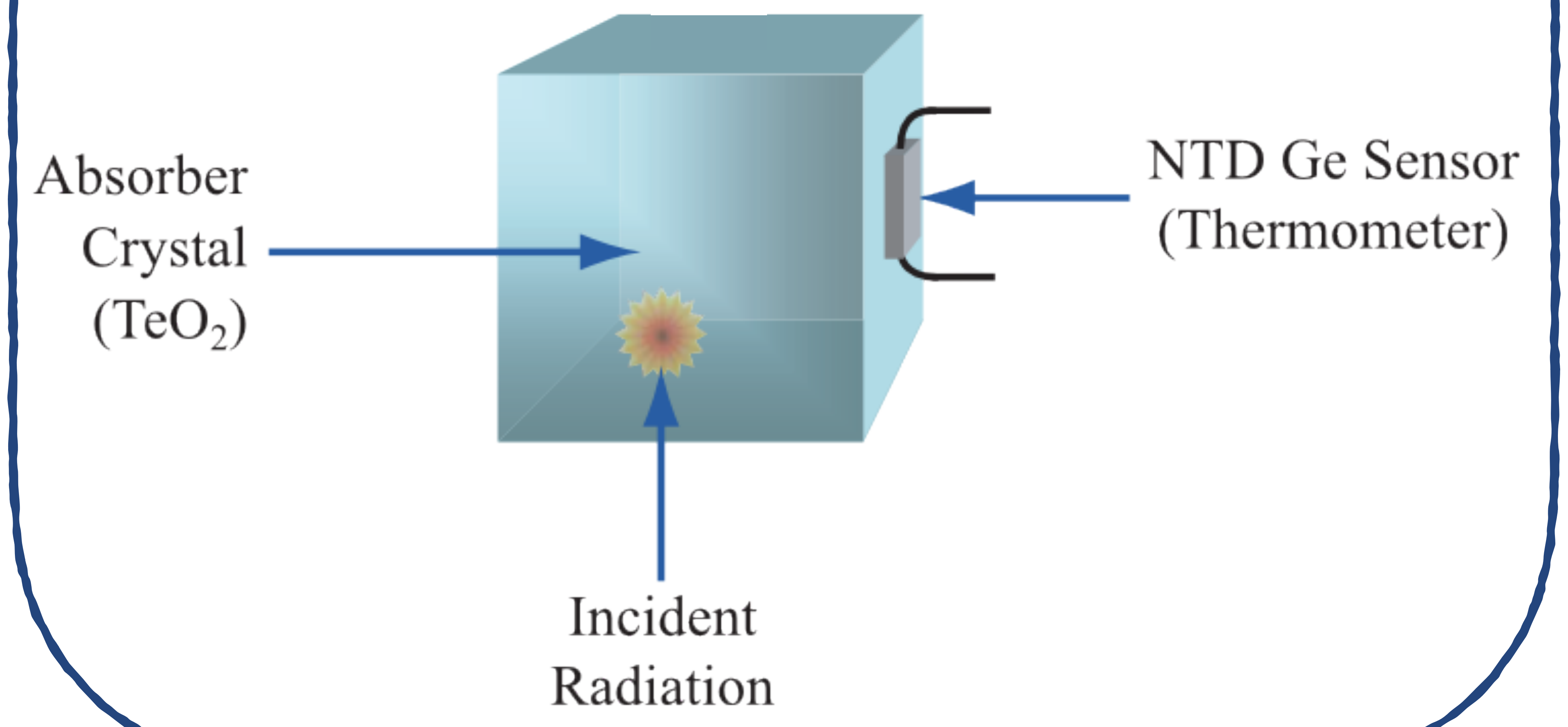
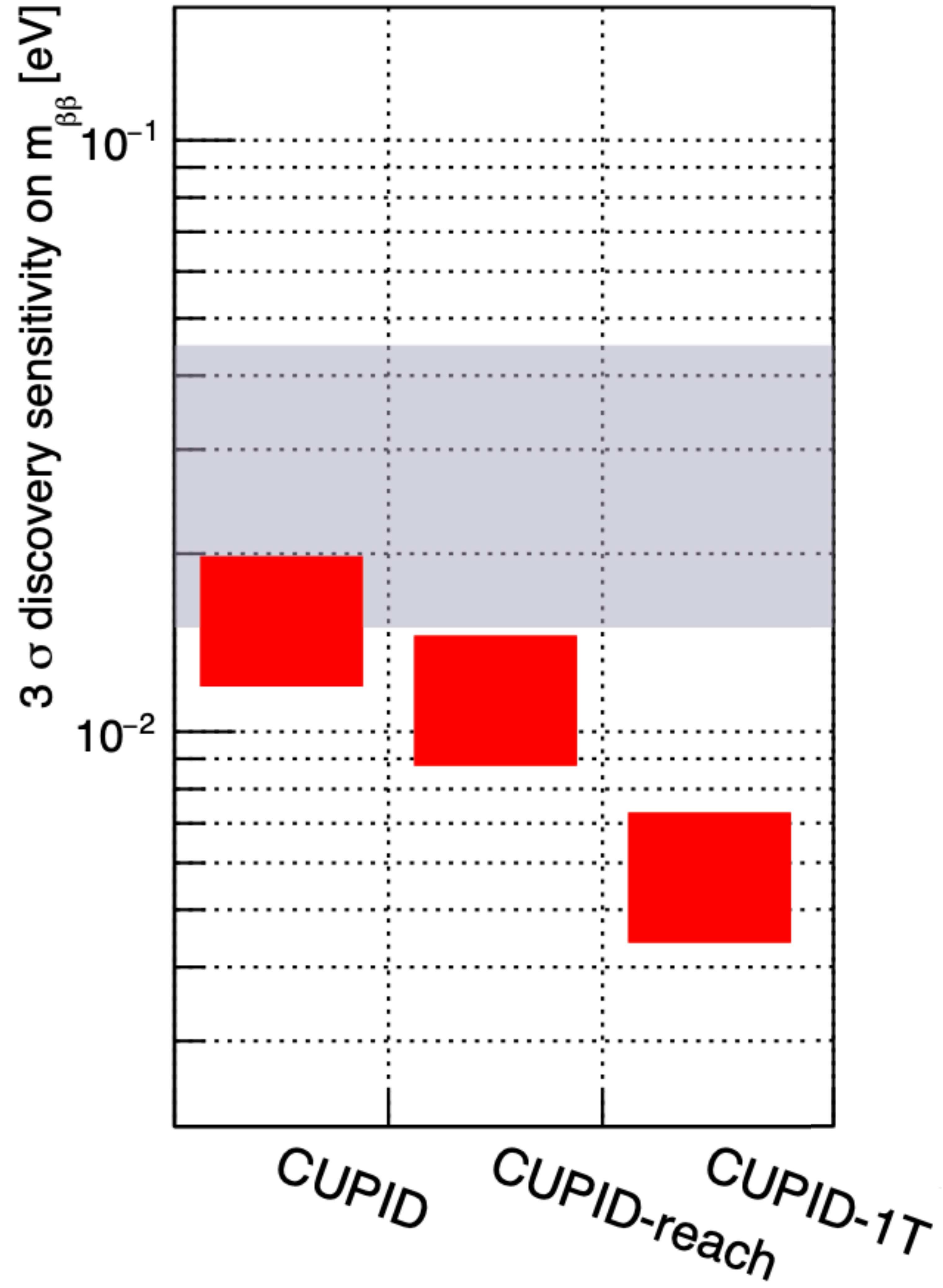


See next talk



Conclusions

- Tonne-scale cryogenic calorimeter experiment operating stable at ~10 mK
- 1038.4 t·yr exposure of TeO_2 data for $0\nu\beta\beta$ in ^{130}Te :
  - Energy resolution: FWHM = (7.8±0.5) keV at $Q_{\beta\beta}$
  - Background in the ROI mostly from alphas
  - Median 90% exclusion sensitivity $T^{0\nu}_{1/2} = 2.8 \times 10^{25}$ yr
  - Bayesian limit at 90% C.L. $T^{0\nu}_{1/2} > 2.2 \times 10^{25}$ yr
- Keep taking data and other analyses ongoing
- Activities for next-generation already ongoing

STAY TUNED !!