Latest results from CUORE

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On behalf of the CUORE collaboration

> 110 scientists spanning 27 institutions in 4 countries

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Sol per noctem
1979

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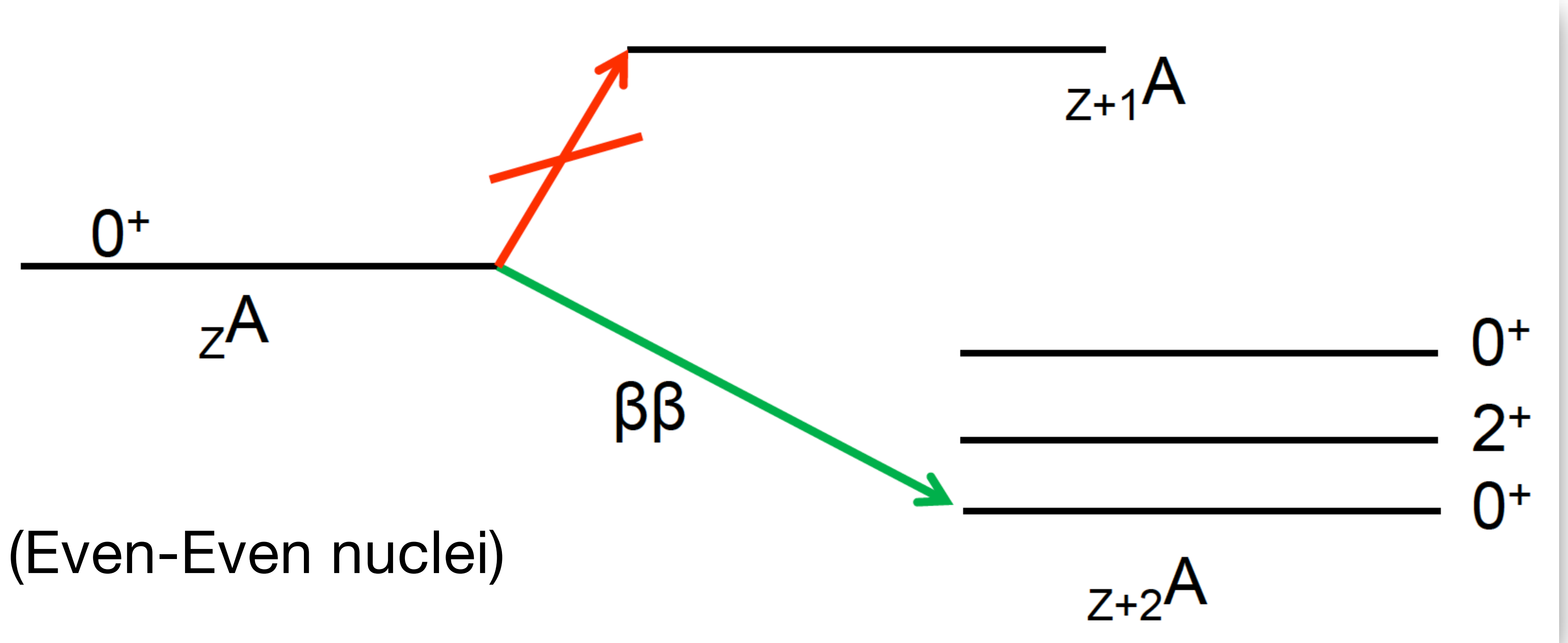
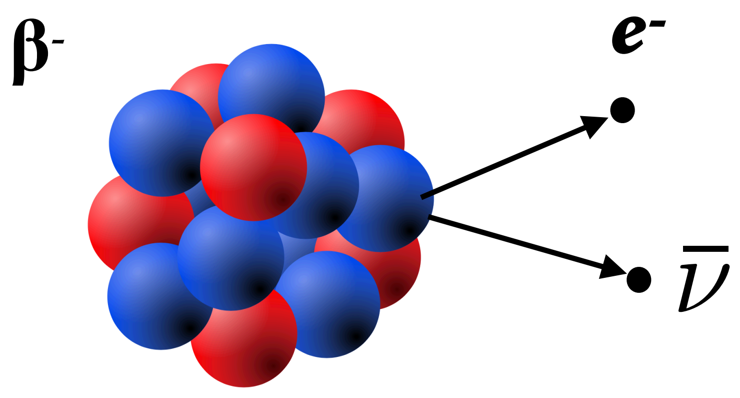
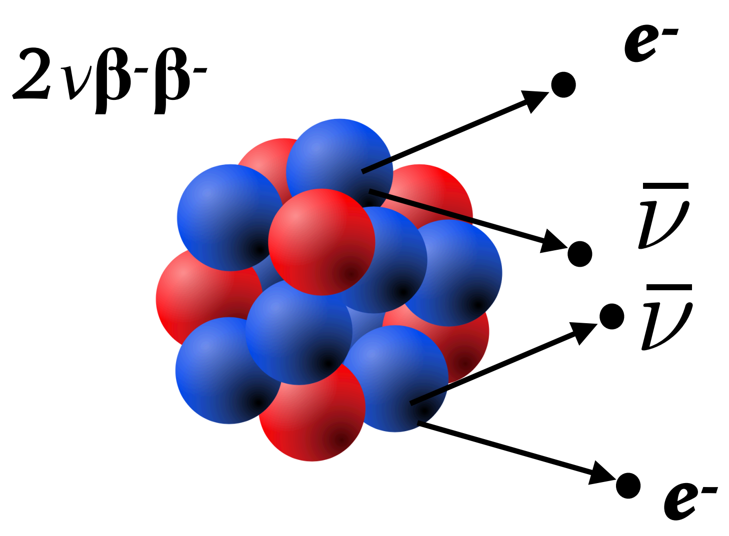
CUORE

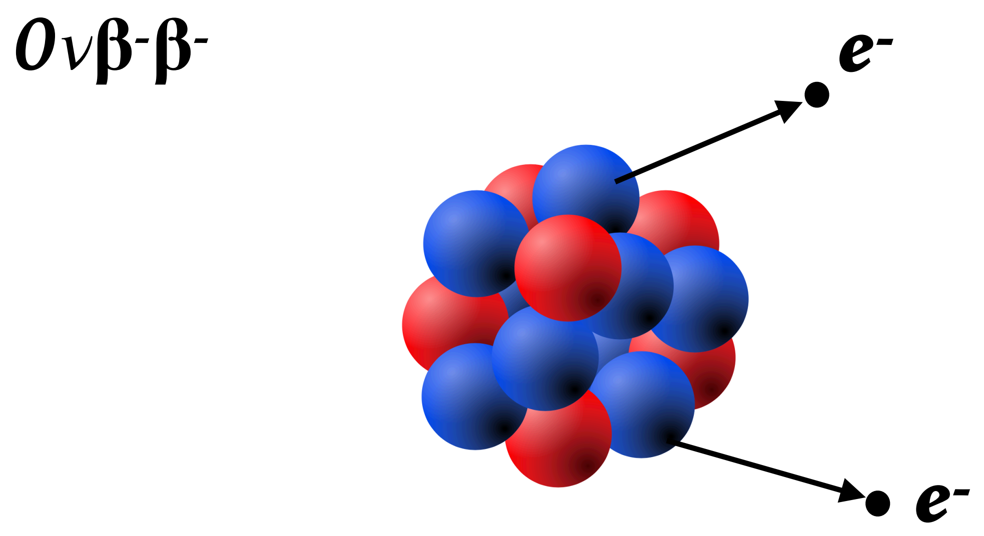
Neutrinoless Double Beta Decay



- 2^{nd} order weak interaction
- Normal beta decay suppressed by Q value or J^π



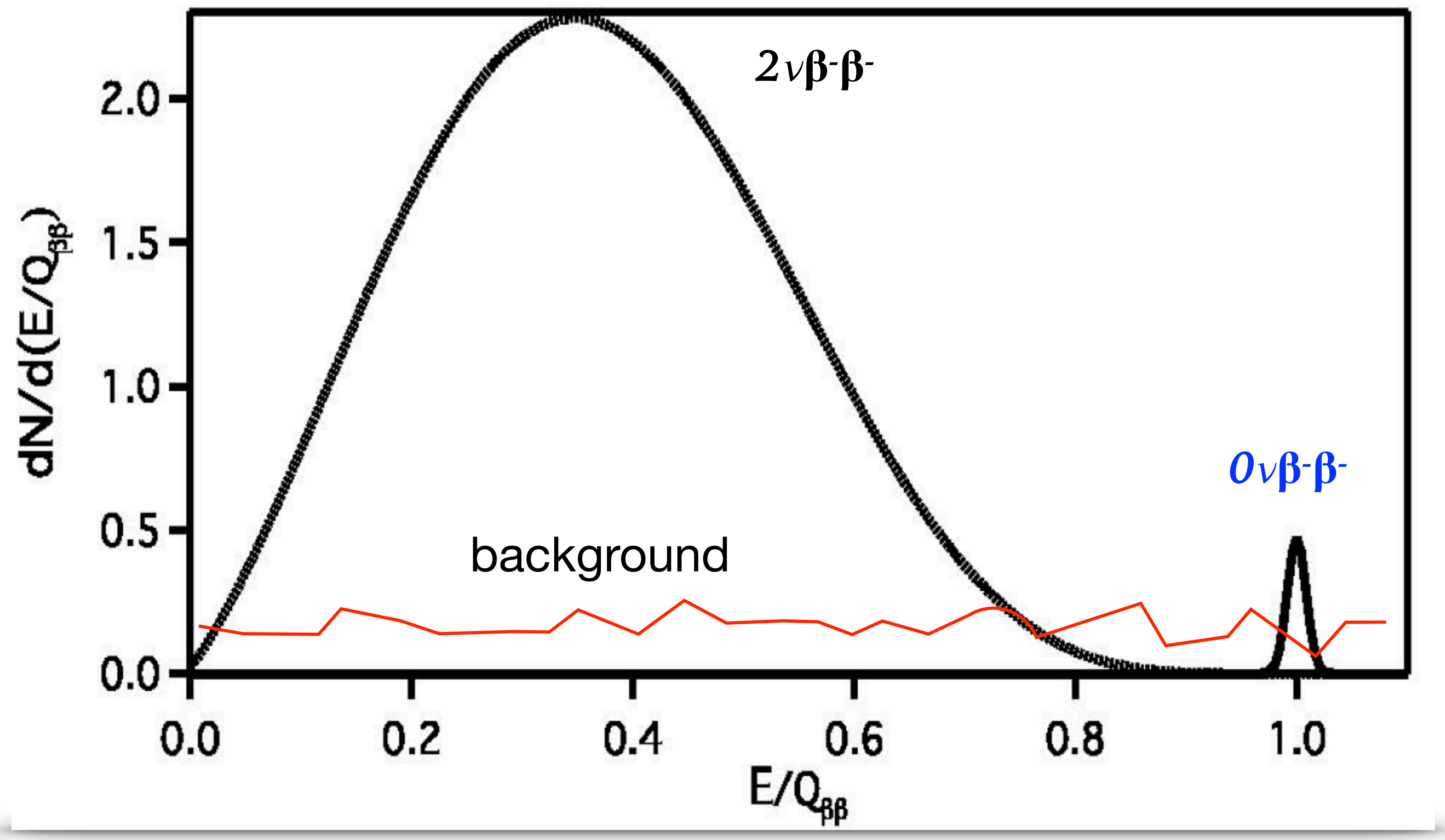




Processes explained by the Standard Model

- Lepton number not conserved
- Occurs if neutrinos have mass and are their own antiparticle

Experimental Signature



Sum energy of emitted electrons:
Peak at Q value of the decay.

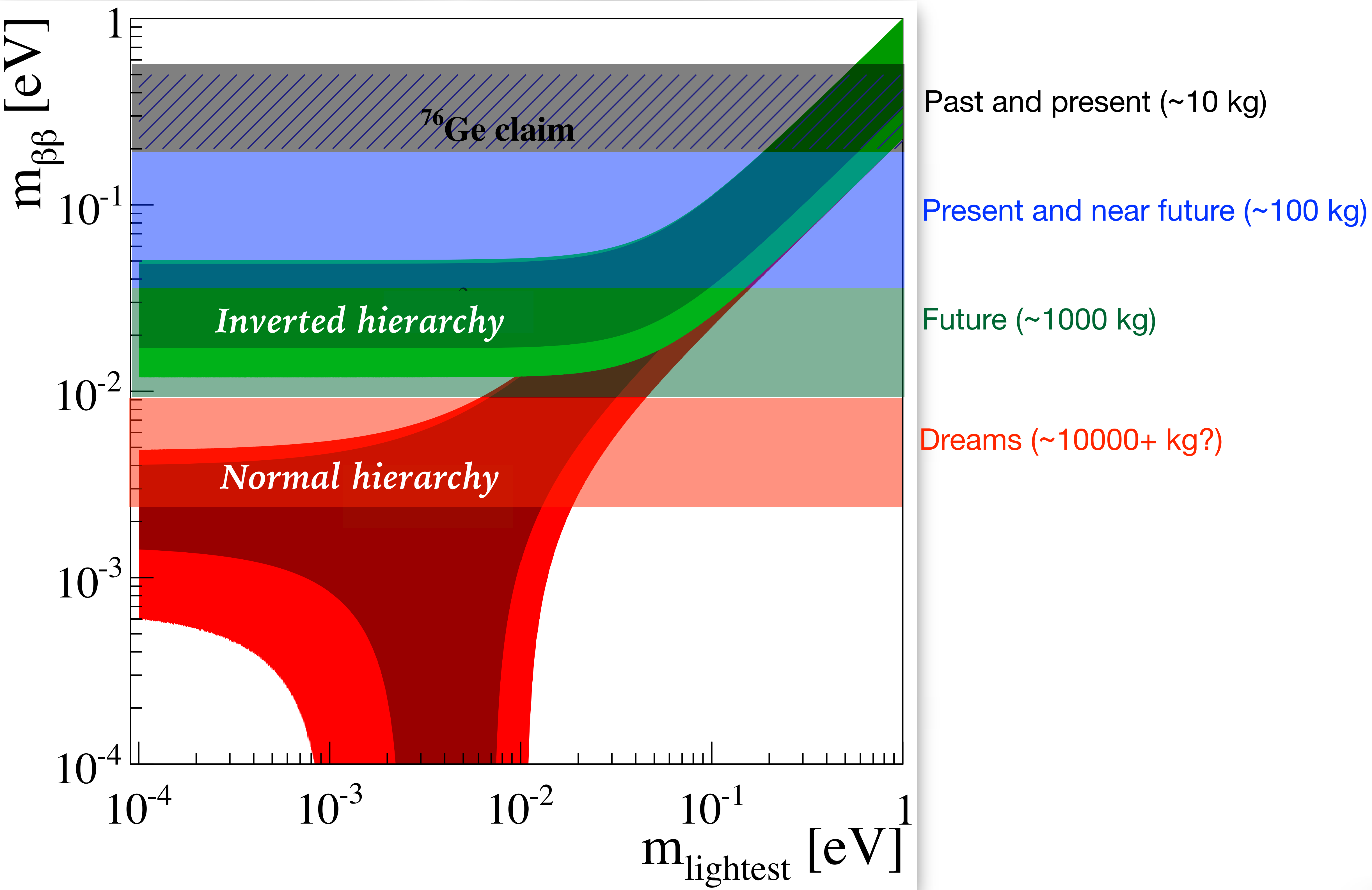
Sensitivity of the search

$$T^{0\nu}_{1/2}(n_\sigma) = \frac{ln2}{n_\sigma}\frac{N_A \cdot i \cdot \epsilon}{A} f(\Delta E)\sqrt{\frac{M \cdot t}{B \cdot \Delta E}}$$

- High $Q_{\beta\beta}$ (less $\gamma\beta$ background and large phase space factor)
- High isotopic abundance (or enrichment)

- Long exposure ($M \cdot t$)
- Good energy resolution
- Low background rate

Implications



$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu} \mid M^{0\nu} \mid^2 \frac{|m_{\beta\beta}|^2}{m_e^2}.$$

- Neutrinos are Majorana fermions.
  - Physics beyond standard model.
- Constraints on absolute mass scale.
  - Probes the mass hierarchy of the neutrinos.
- Constraints on CP violating phases?

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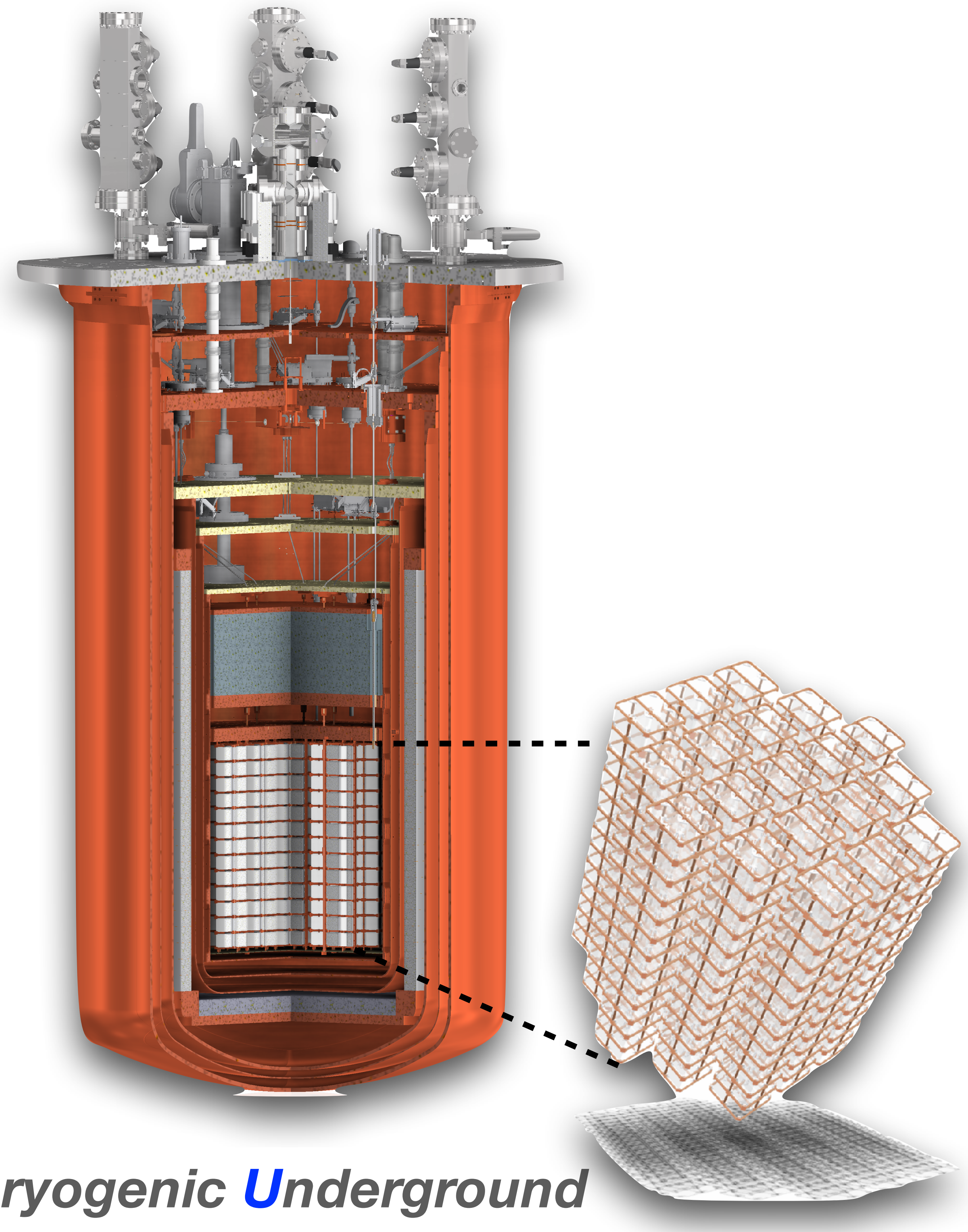
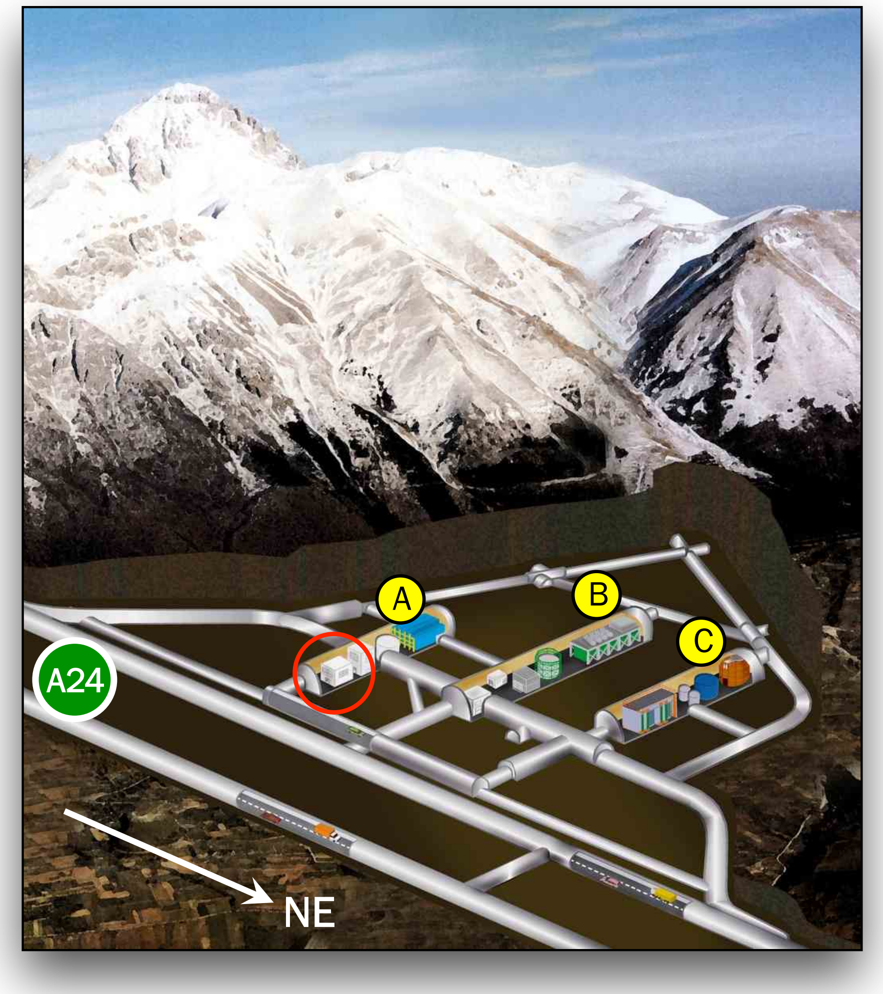
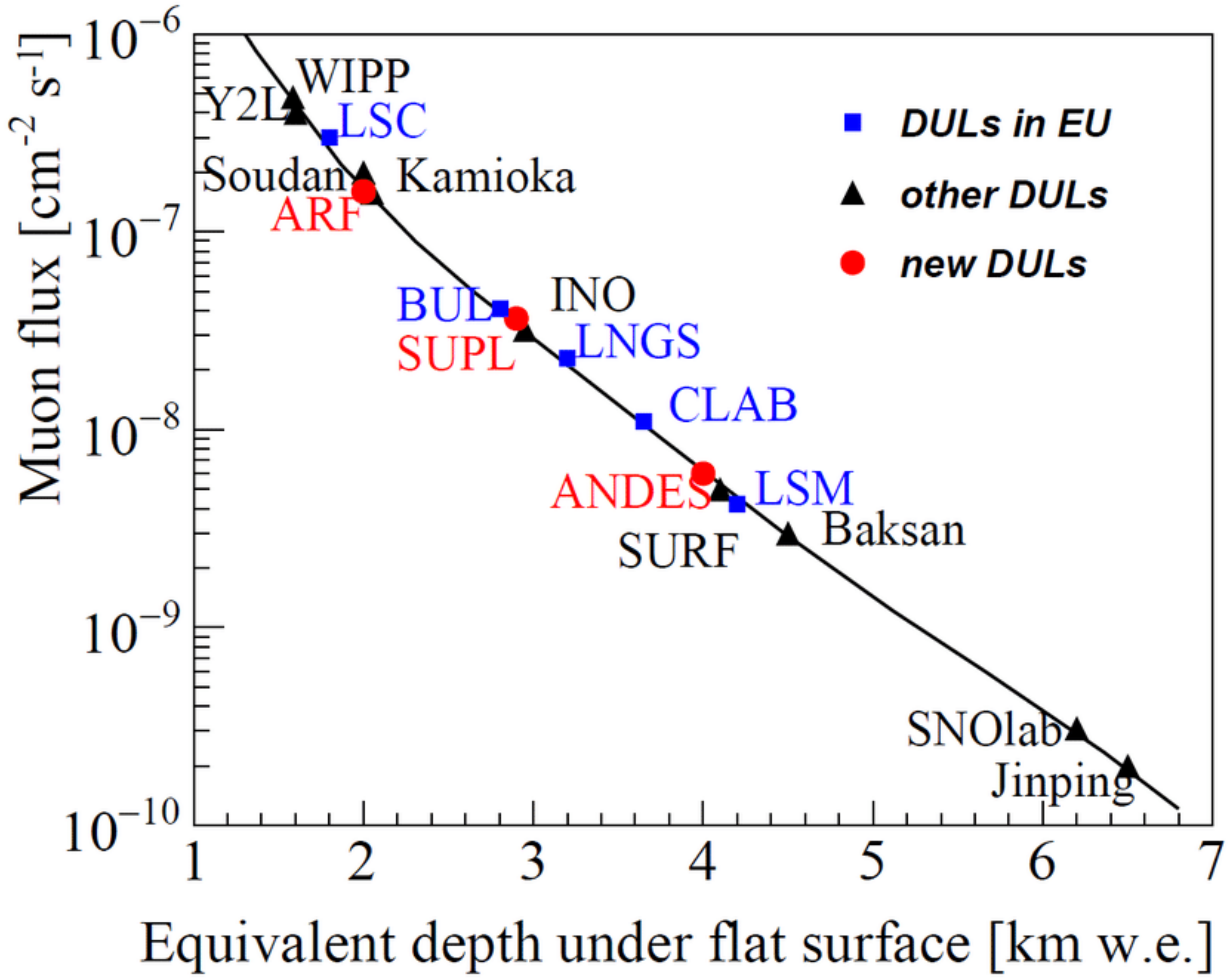


The Cryogenic Underground Observatory for Rare Events





- Search for $0\nu\beta\beta$ in ^{130}Te at LNGS, Italy
- 3600 m.w.e of rock to shield from cosmic rays

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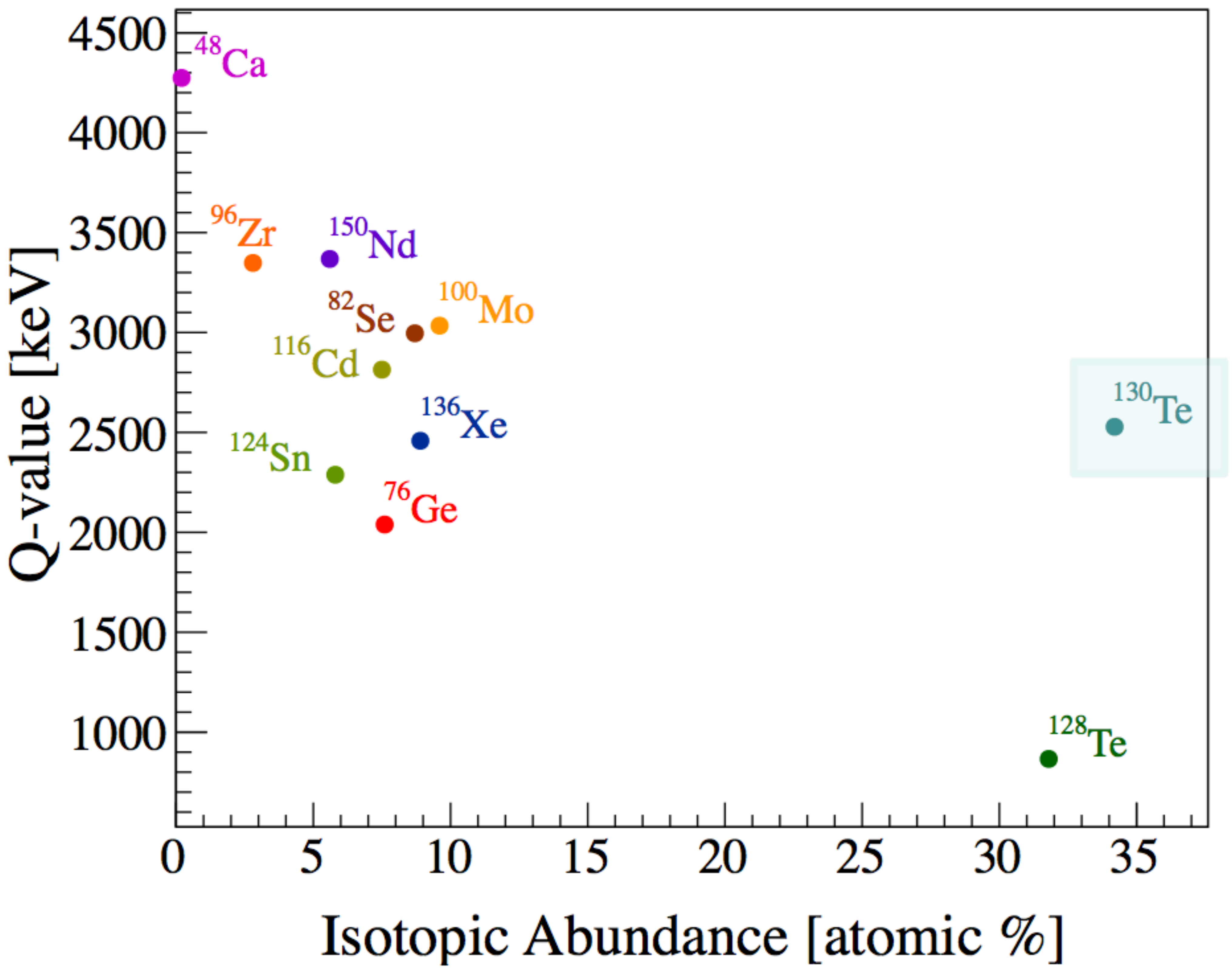
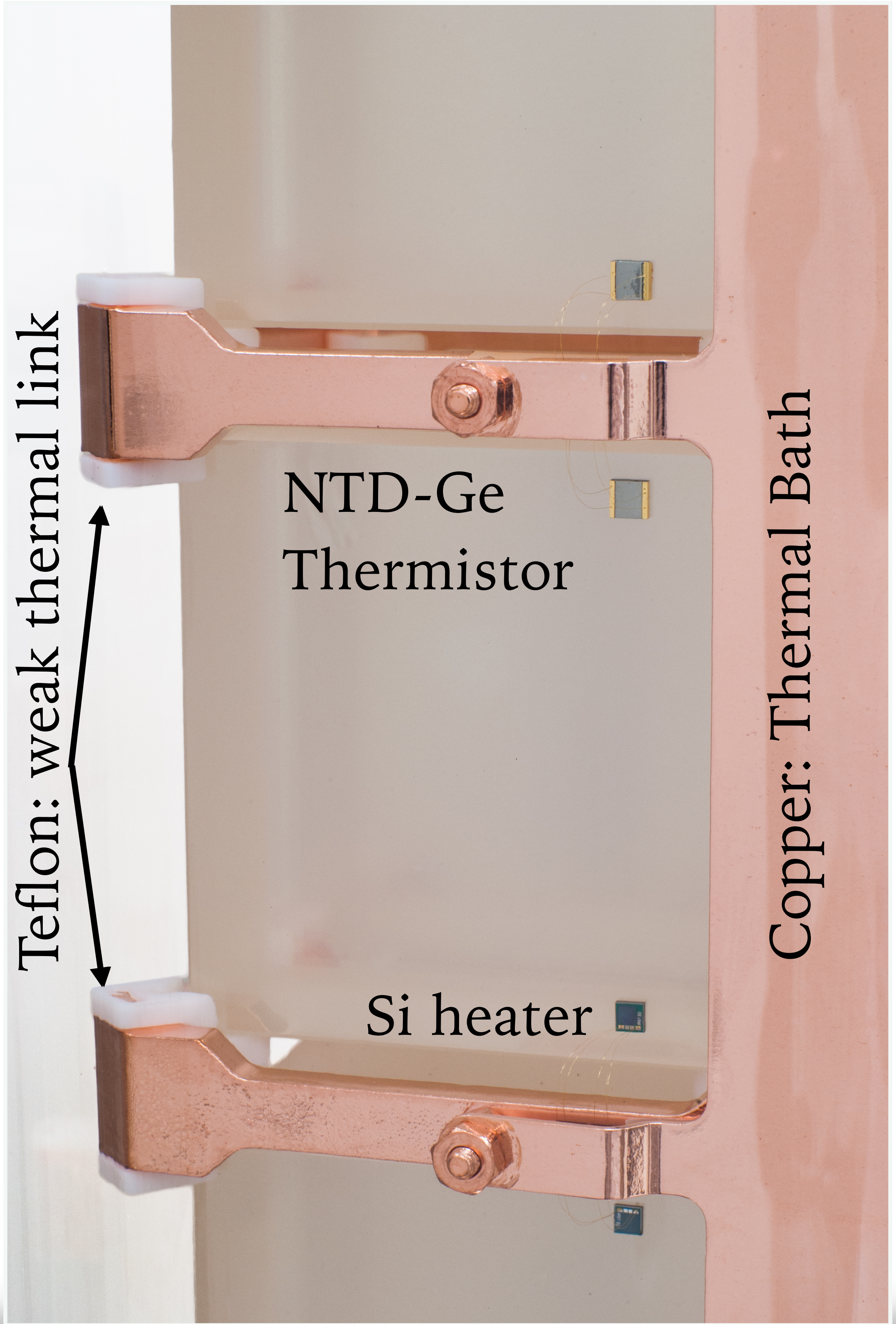


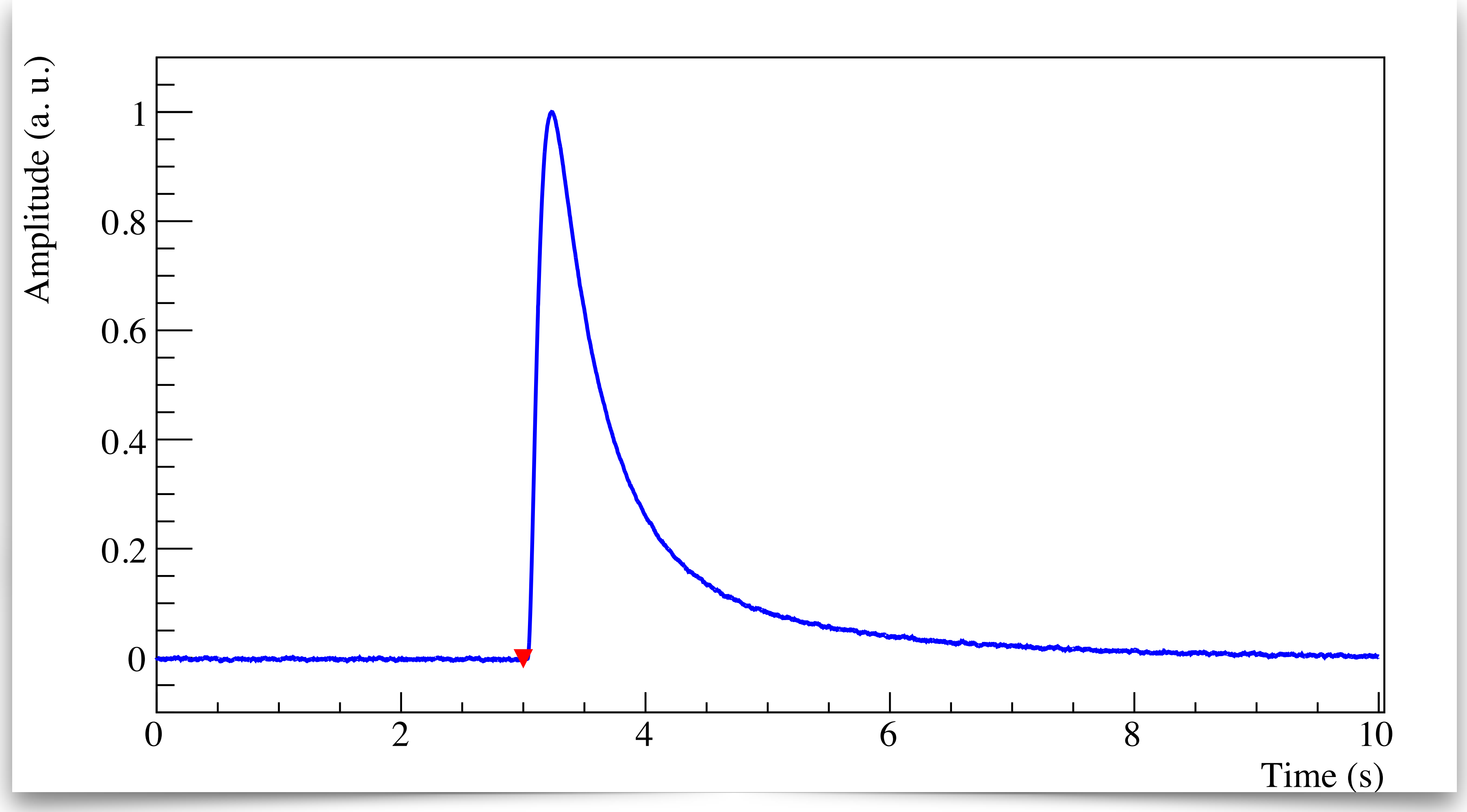
- $Q_{\beta\beta} = 2527.515$ keV
- Isotopic mass of ^{130}Te : 206 kg
- 988 TeO_2 crystals (arranged in 19 towers with 13 floors each)
- Massive thermal calorimeters operated at ~10 mK

➡ $T_{1/2}$ (90% C.L.) > 9 x 10^{25} y
5 yrs of live time ;
$<m_{\beta\beta}>$ ~ 45 - 210 meV.

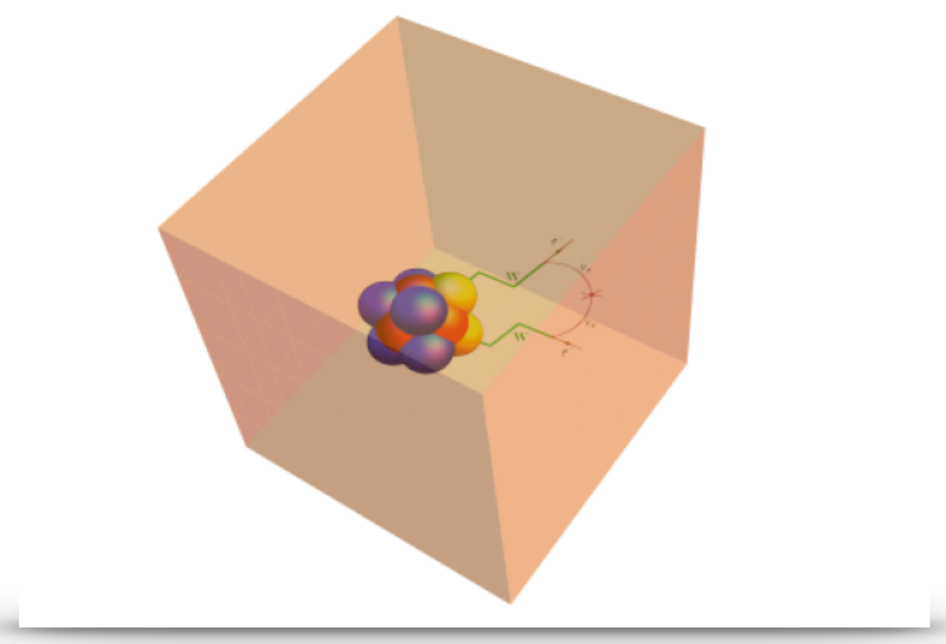
Detector Principle: Thermal Calorimeters



- 750 g (5x5x5 cm³) crystal
- △T ~ 100 μK for 1 MeV energy deposit
- NTD-Ge thermistor read out
  - $R(T) \sim R_0 \exp[(T_0/T)^{1/2}]$ (large sensitivity at low T)
- Energy response calibrated using known gamma sources
- Note:
  - Signal ➛ thermal channel only
  - No active background rejection



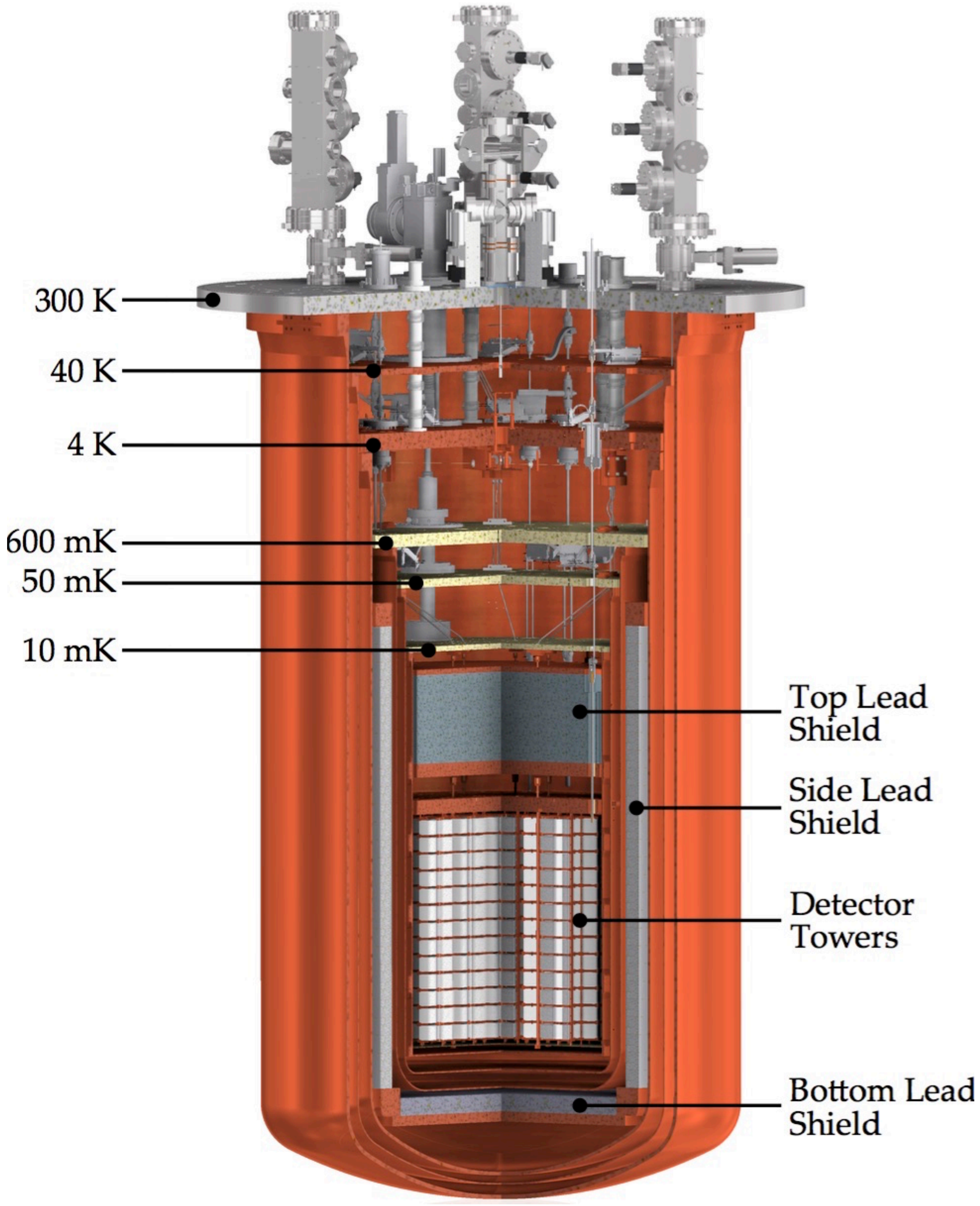
Source = Detector

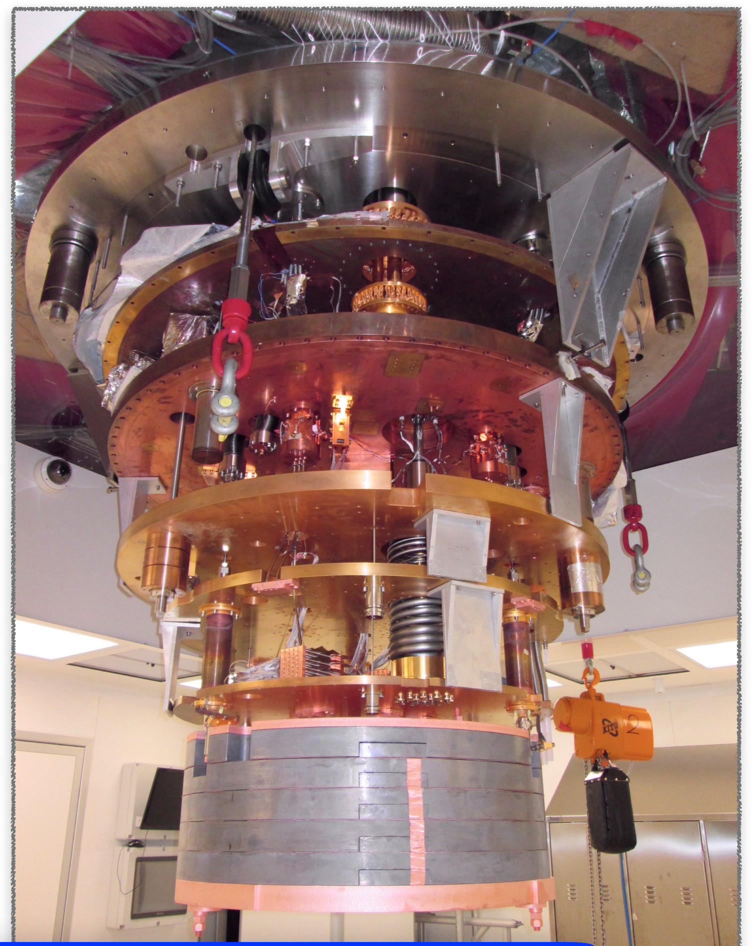


- Electron events mostly contained in the bulk : Large detection efficiency.
- The calorimeter cannot discriminate background from signal events easily.

CUORE Cryostat

Cryogenics 102, 9 (2019)





[redacted]

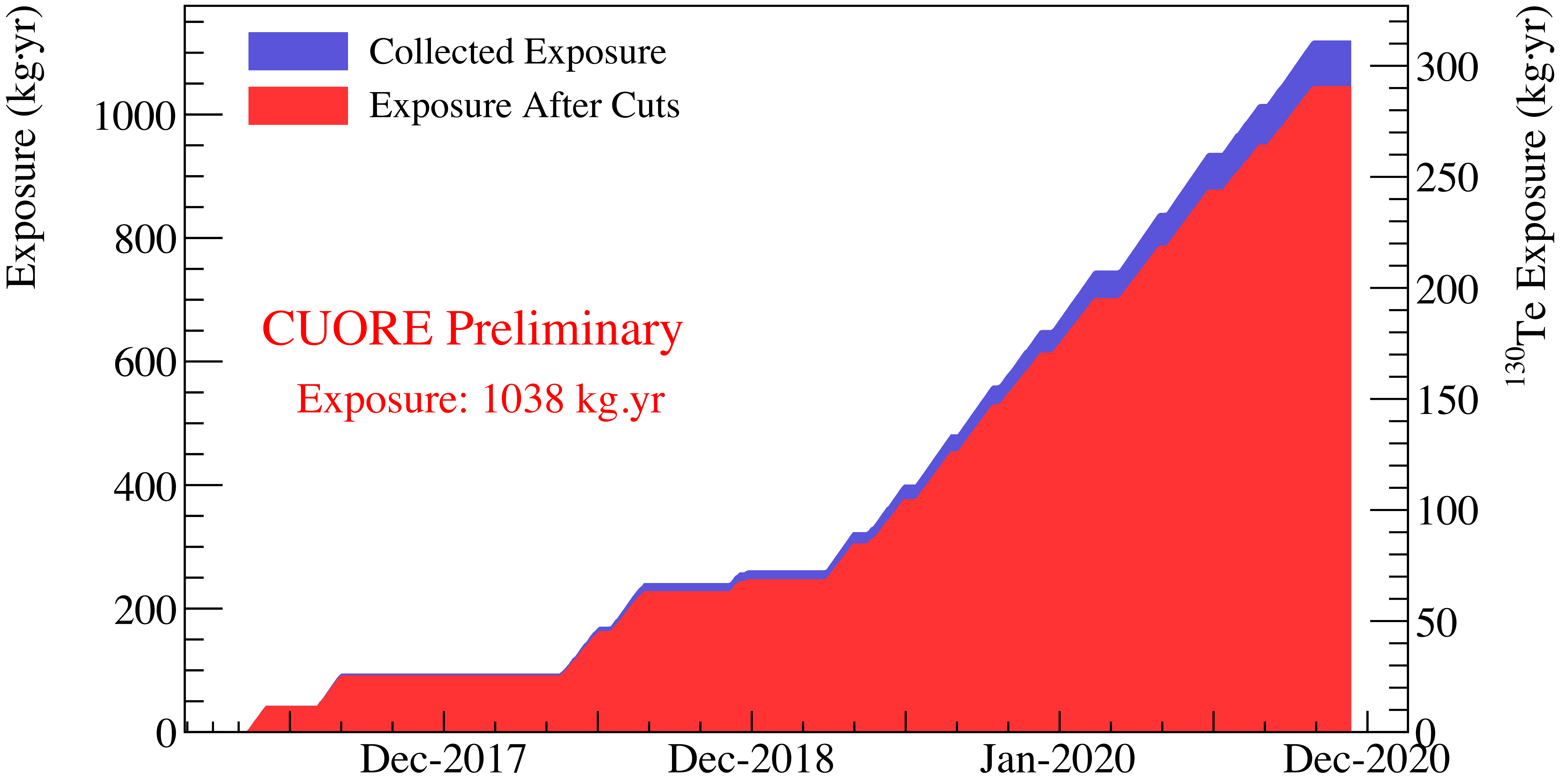
[redacted]

- 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

Science Runs

Latest 0ν results: Nature 604, 53-58 (2022)

- 984/988 operational channels
- Operating since 2017
  - 2019 : duty cycle improved from 35.8% to 93%
- Dataset: 1-2 months of physics runs flanked by a week of calibration on either end.
- 15 datasets in the recently published 1t.y (TeO_2)
- Ongoing data taking



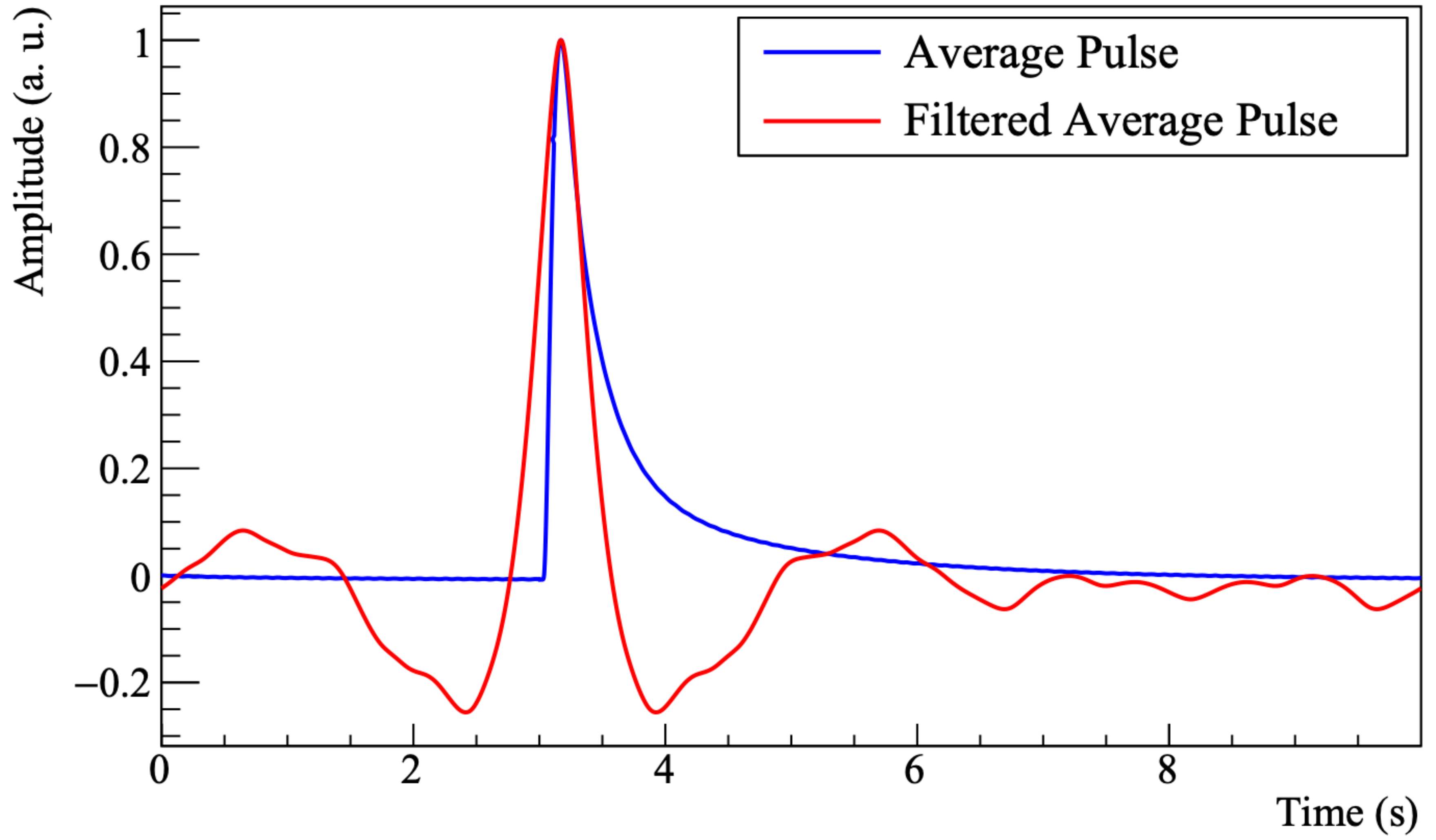
Analysis Workflow: Amplitude Estimation

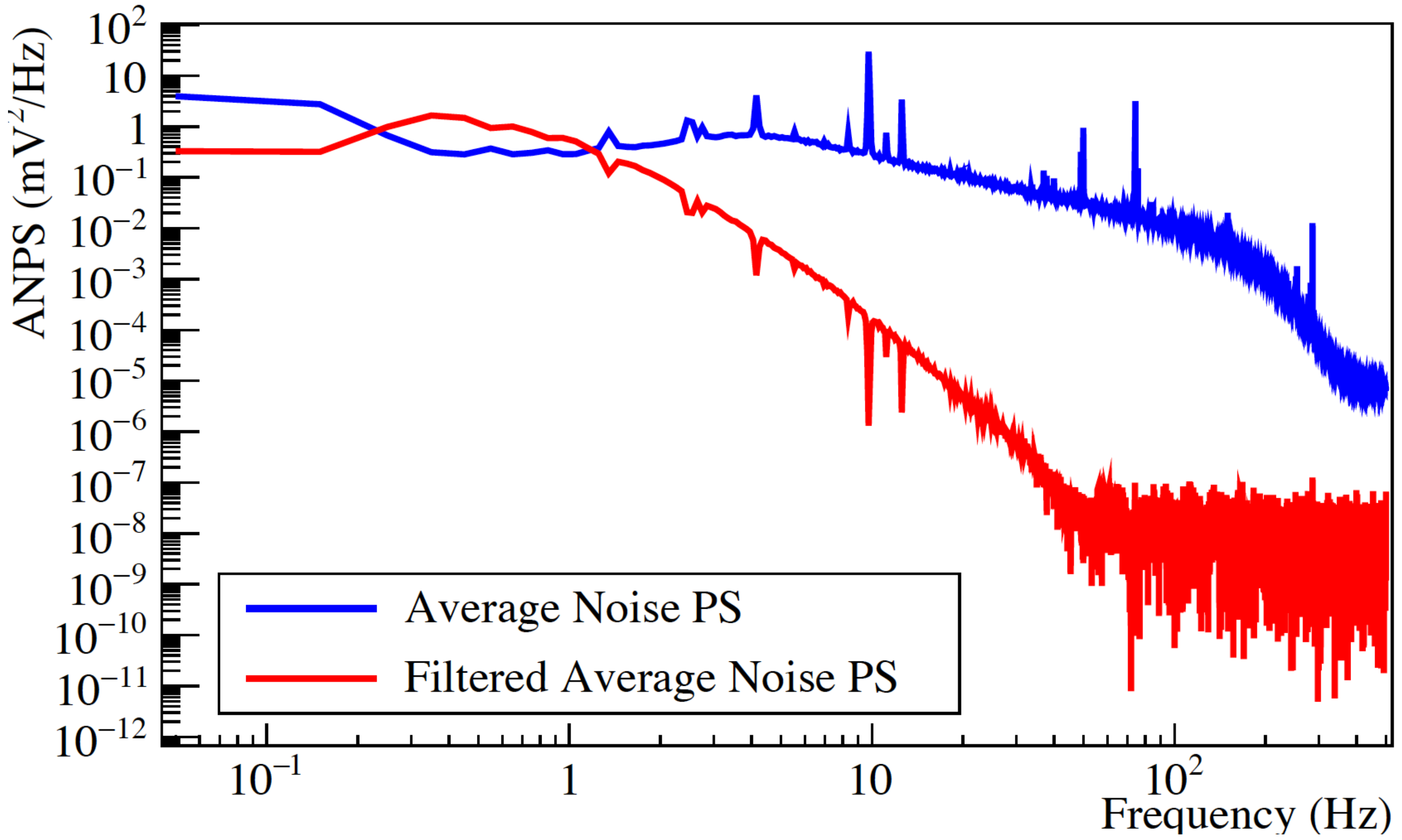
$$P(t) = H\,S(t) + N(t)$$

OF Transfer Function

$$H(\omega) = \frac{S^*(\omega)}{N(\omega)} e^{-i\omega t_M}$$

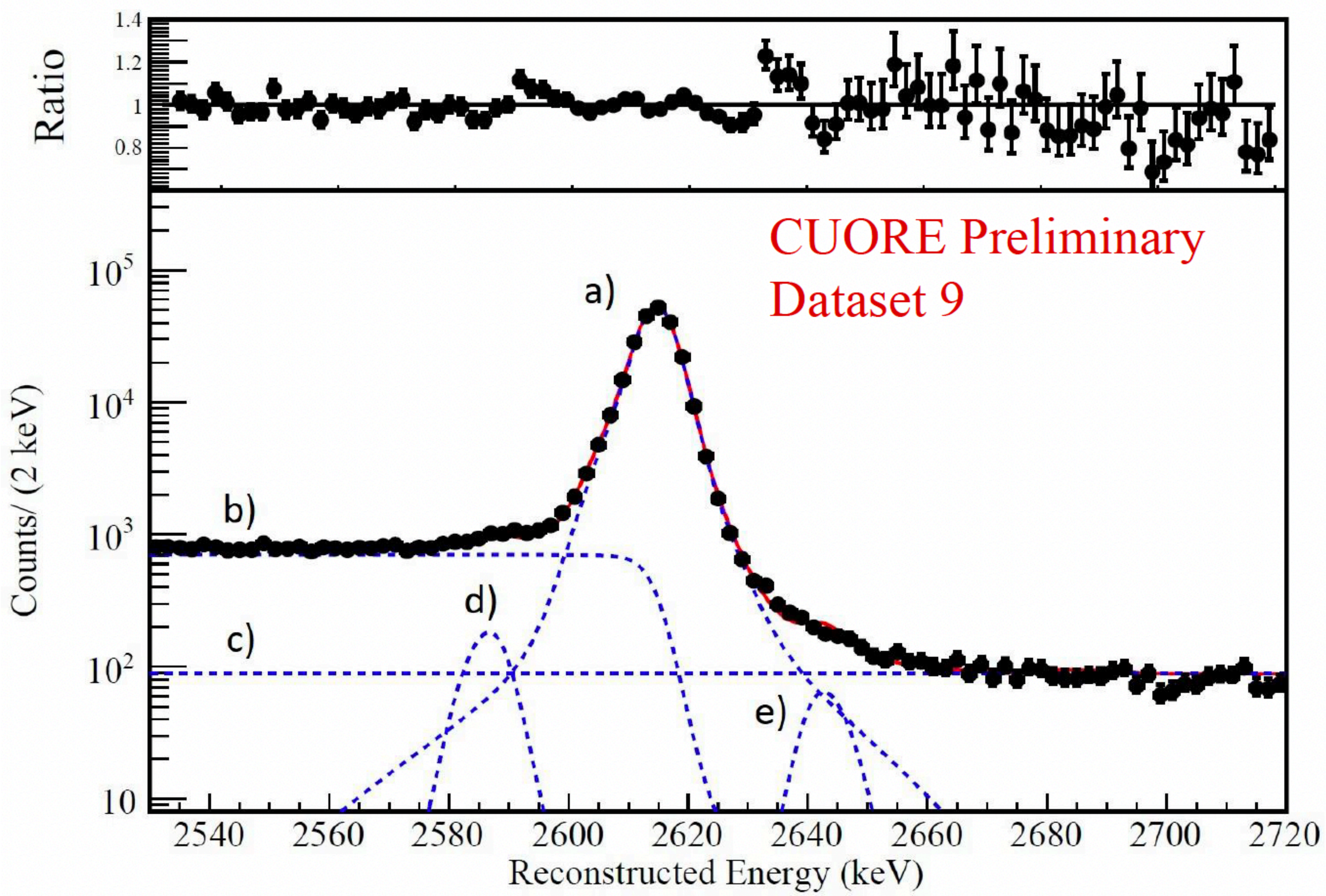
- Average signal obtained from selected calibration event.
- Trigger threshold ~ 10keV, depending on the channel.

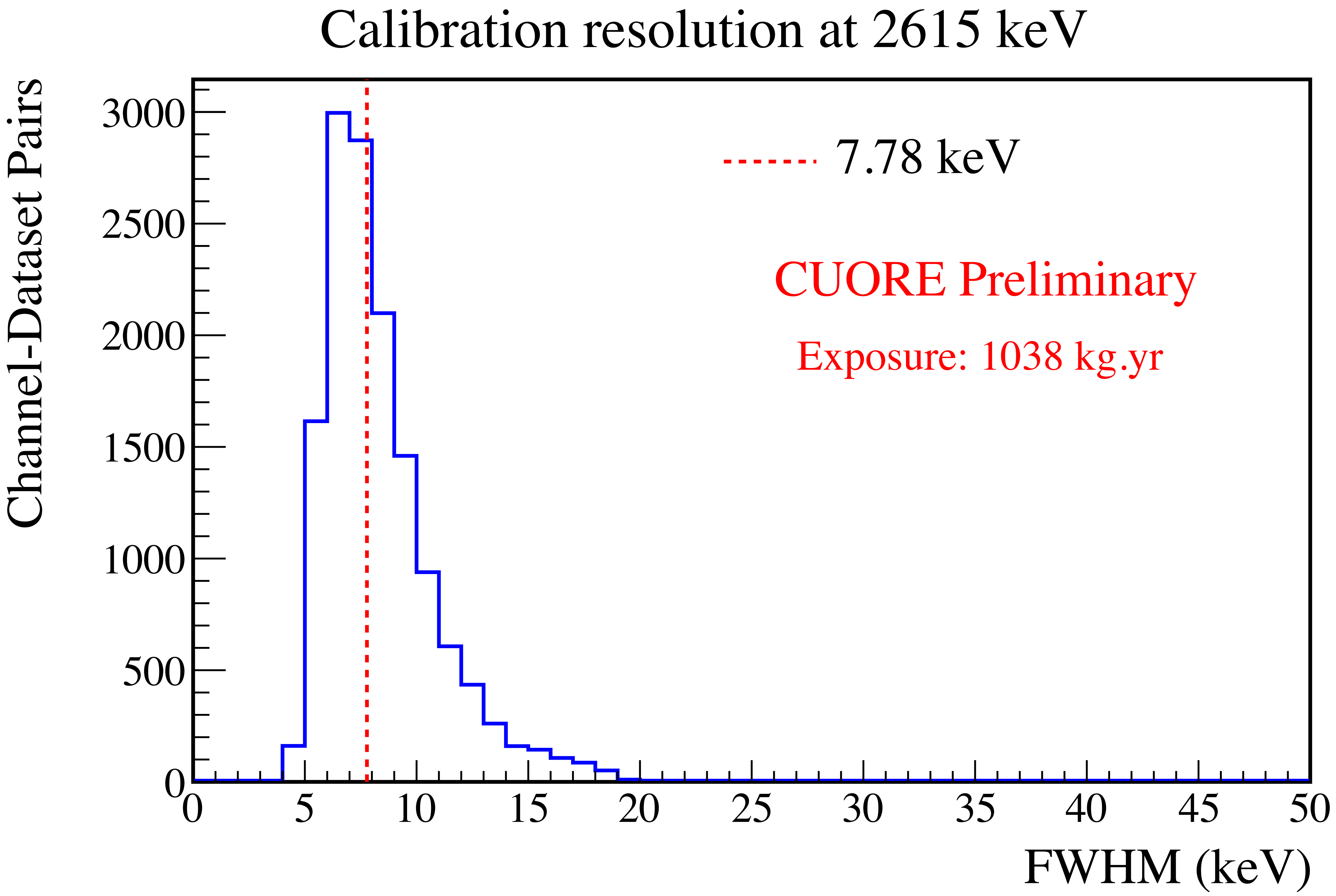




Analysis Workflow: Energy calibration

- 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 $Q_{\beta\beta}$

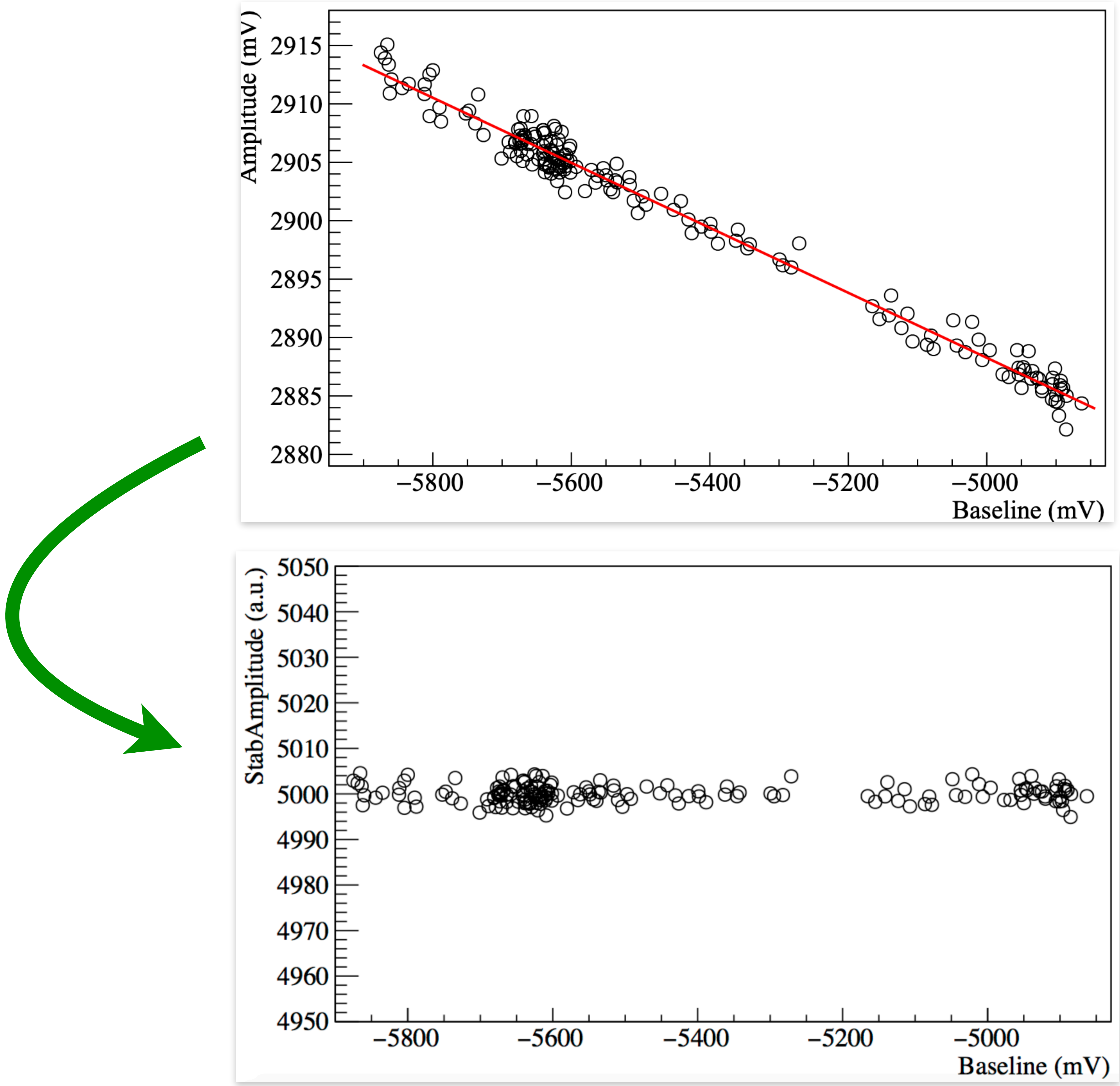




Analysis Workflow: Thermal gain correction

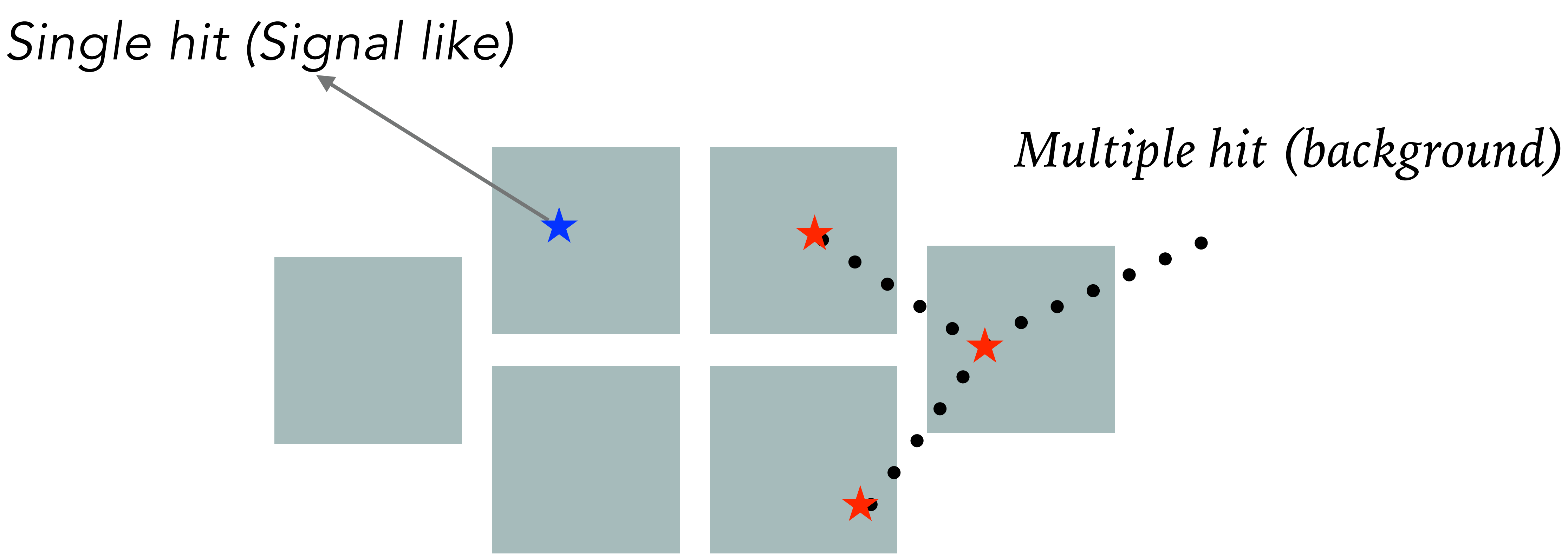
- Being a thermal detector the baseline can drift due to instabilities in temperature.

- We correct for the thermal gain instabilities using the amplitude of a fixed-energy reference pulse (typically, heater but can be 2615 keV pulse too)

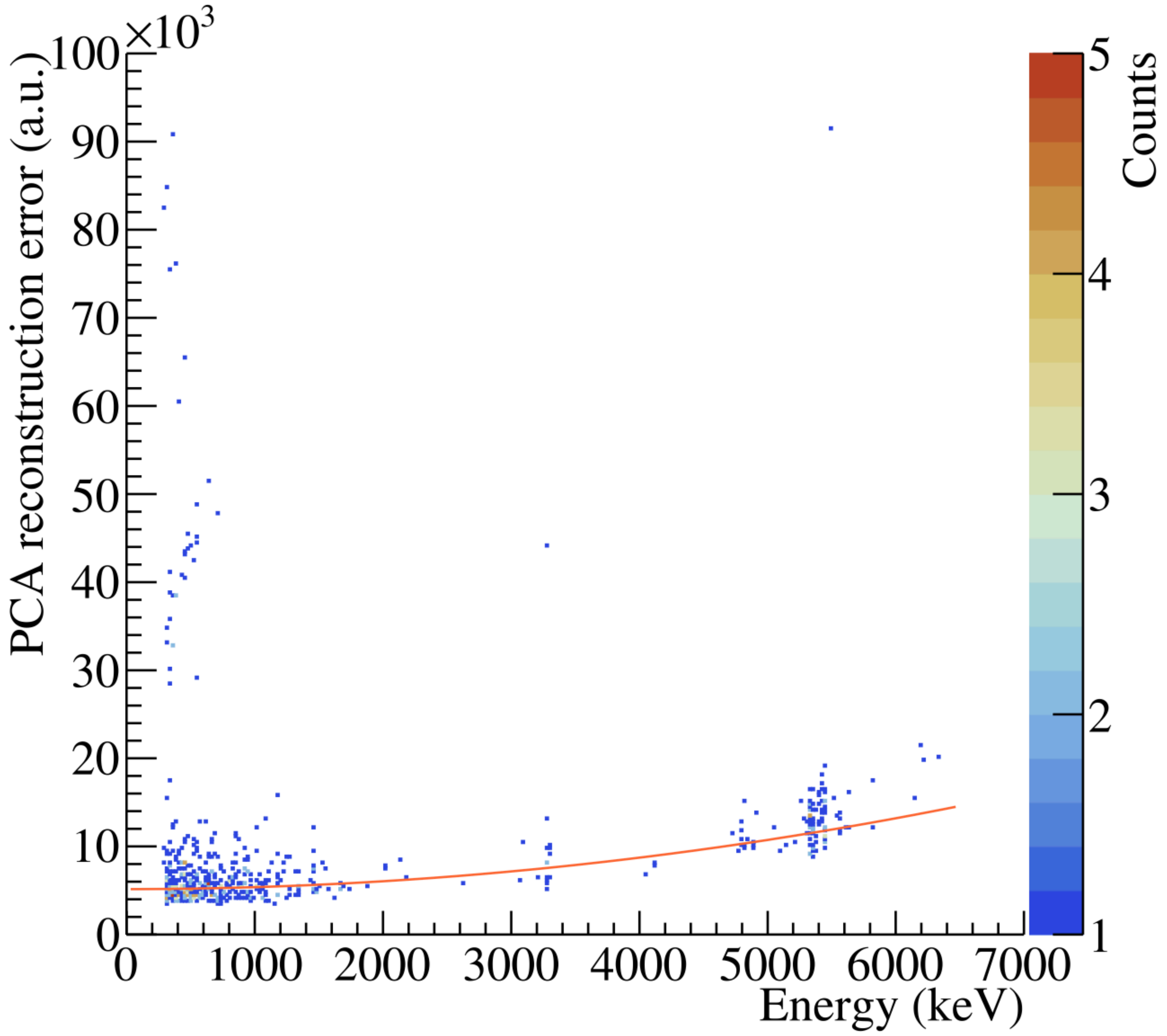


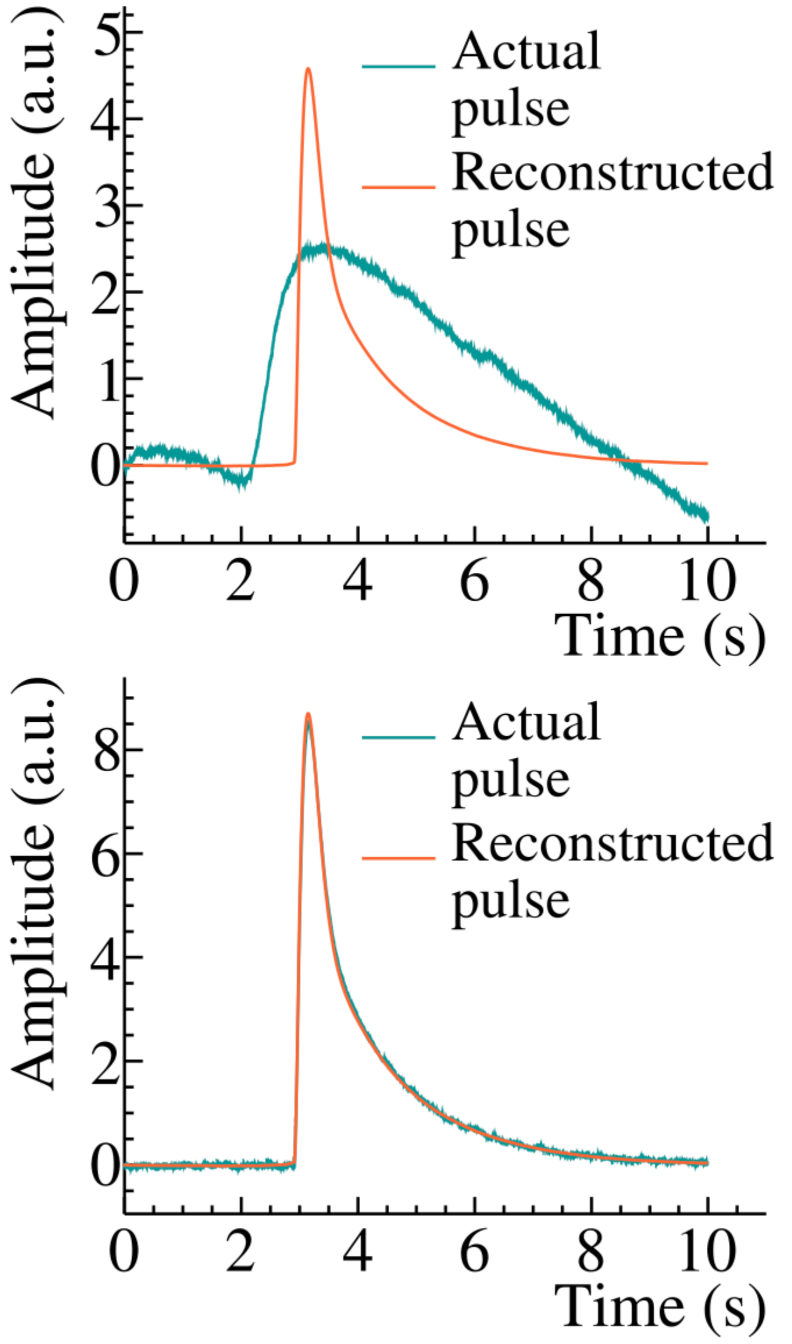
Analysis Workflow: Coincidences and Pulse Shape Discrimination

- Containment efficiency from MC: ~88% of $0\nu\beta\beta$ events in one crystal (M1)
- M2 mostly from gammas, muons, noise
- Assign multiplicity and a total energy to each group of events occurring at the same time

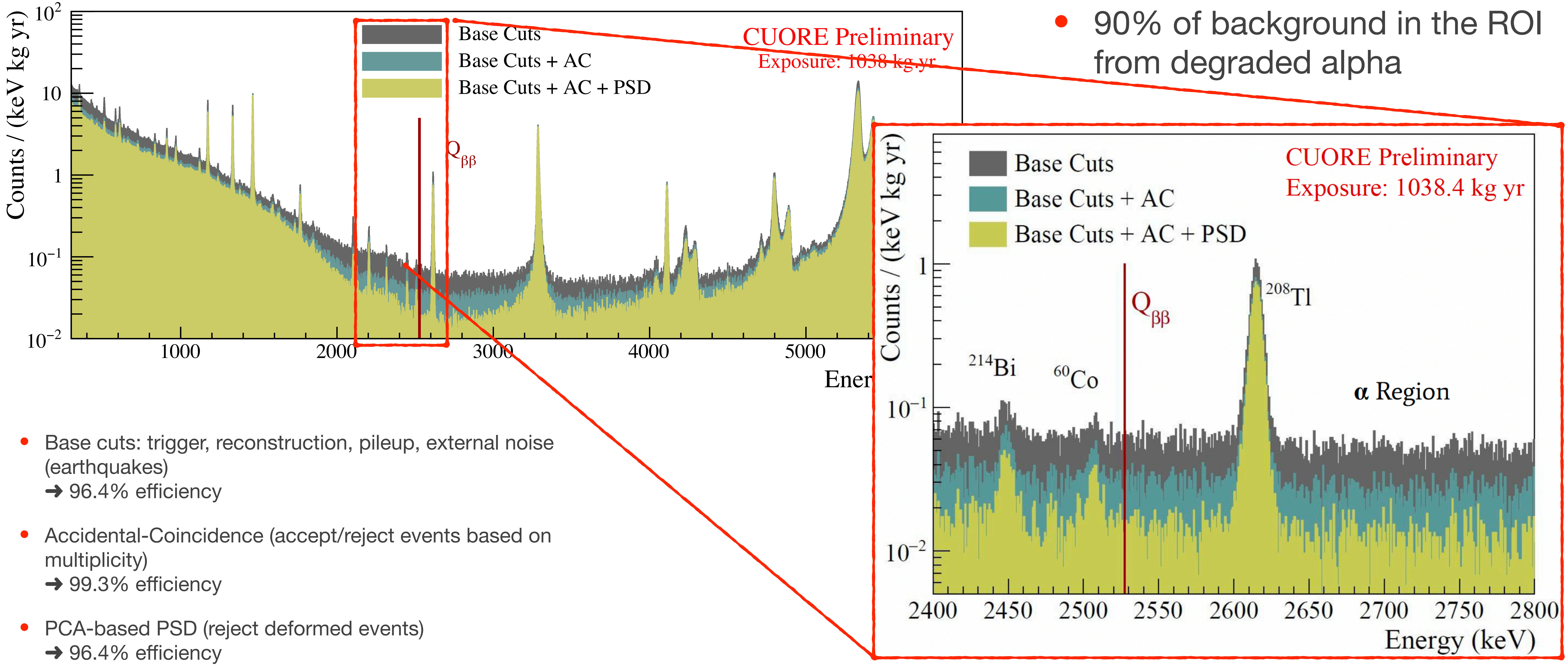


- Principal component analysis used for pulse shape discrimination
- Cut on the reconstructed error between single pulses and principal components of average pulse in each channel-dataset





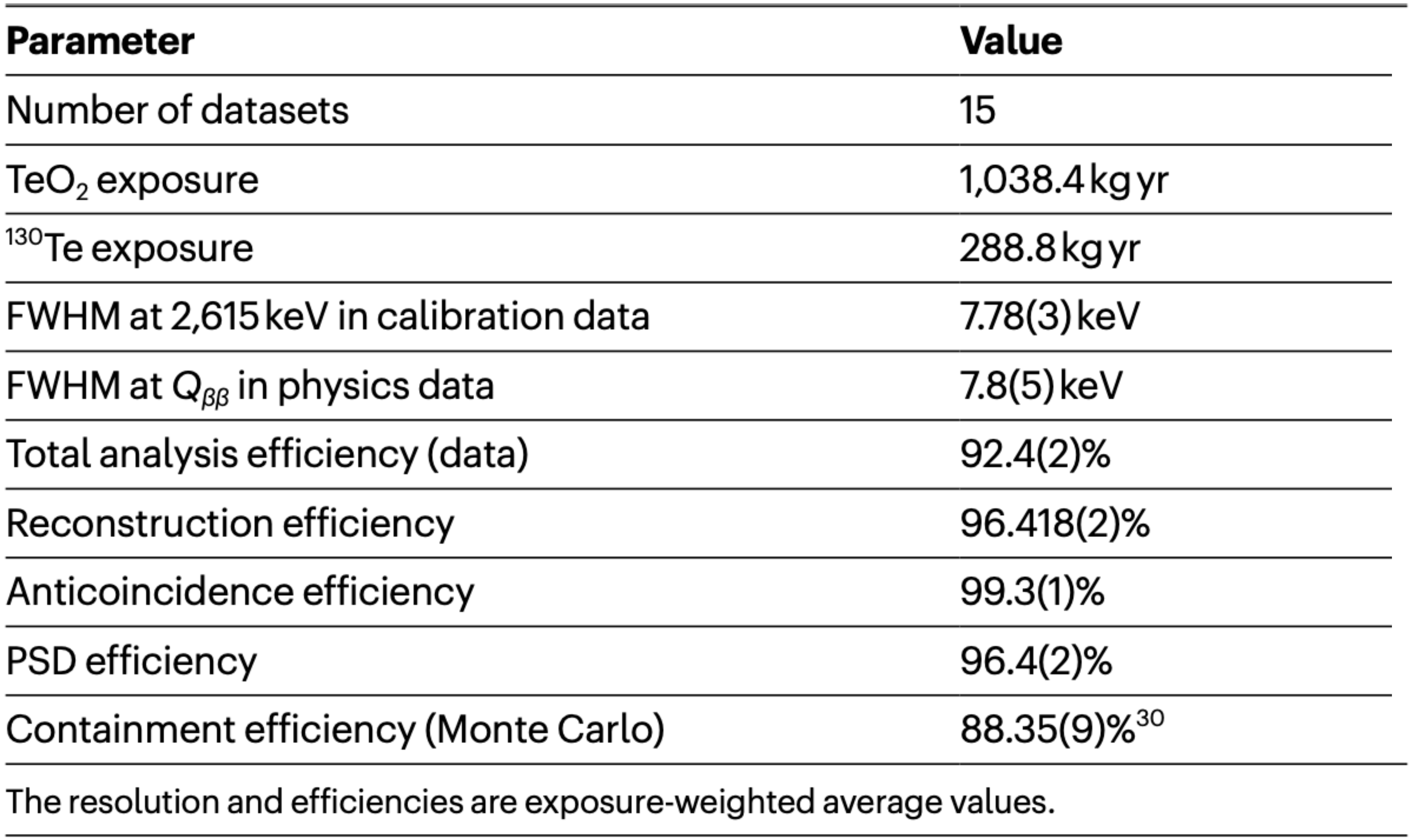
Analysis Workflow: Physics Spectrum



- 90% of background in the ROI from degraded alpha

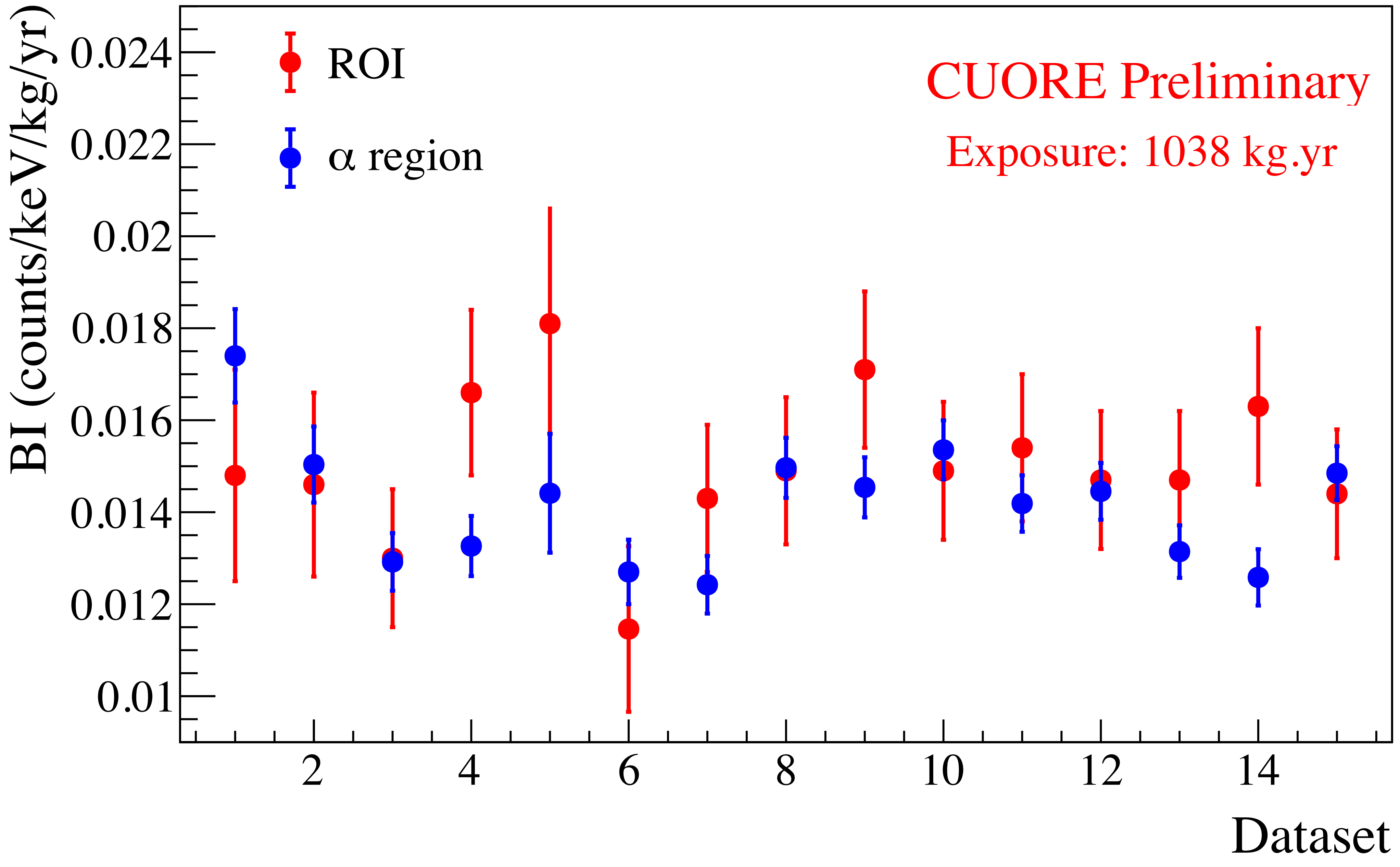
- Base cuts: trigger, reconstruction, pileup, external noise (earthquakes)
  ➜ 96.4% efficiency
- Accidental-Coincidence (accept/reject events based on multiplicity)
  ➜ 99.3% efficiency
- PCA-based PSD (reject deformed events)
  ➜ 96.4% efficiency

$0\nu\beta\beta$ Analysis Parameters



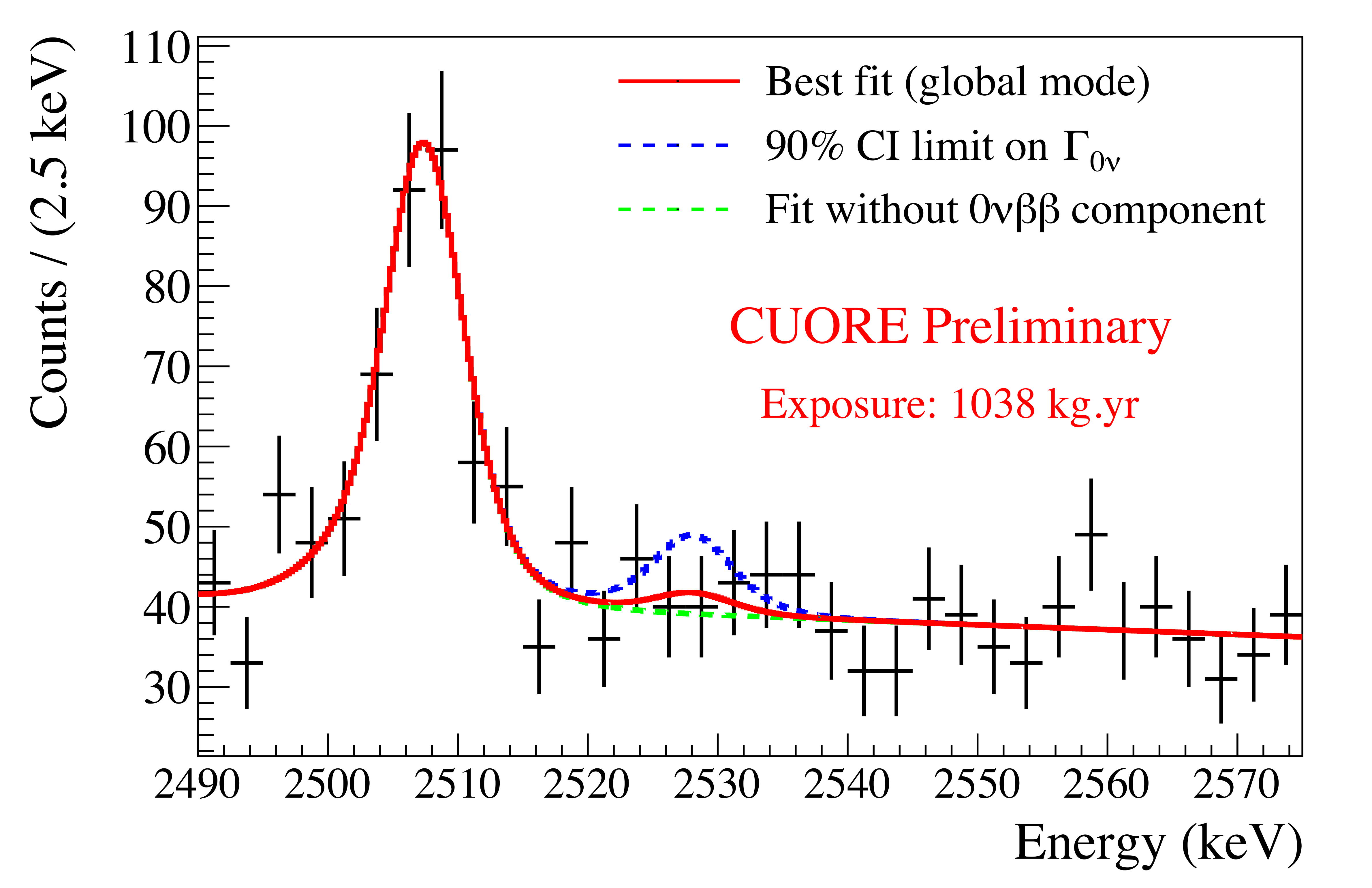
Parameter	Value
Number of datasets	15
TeO_2 exposure	1,038.4 kg yr
^{130}Te exposure	288.8 kg yr
FWHM at 2,615 keV in calibration data	7.78(3) keV
FWHM at $Q_{\beta\beta}$ in physics data	7.8(5) keV
Total analysis efficiency (data)	92.4(2)%
Reconstruction efficiency	96.418(2)%
Anticoincidence efficiency	99.3(1)%
PSD efficiency	96.4(2)%
Containment efficiency (Monte Carlo)	88.35(9)%[30]

The resolution and efficiencies are exposure-weighted average values.



- Fairly constant background rate across all datasets

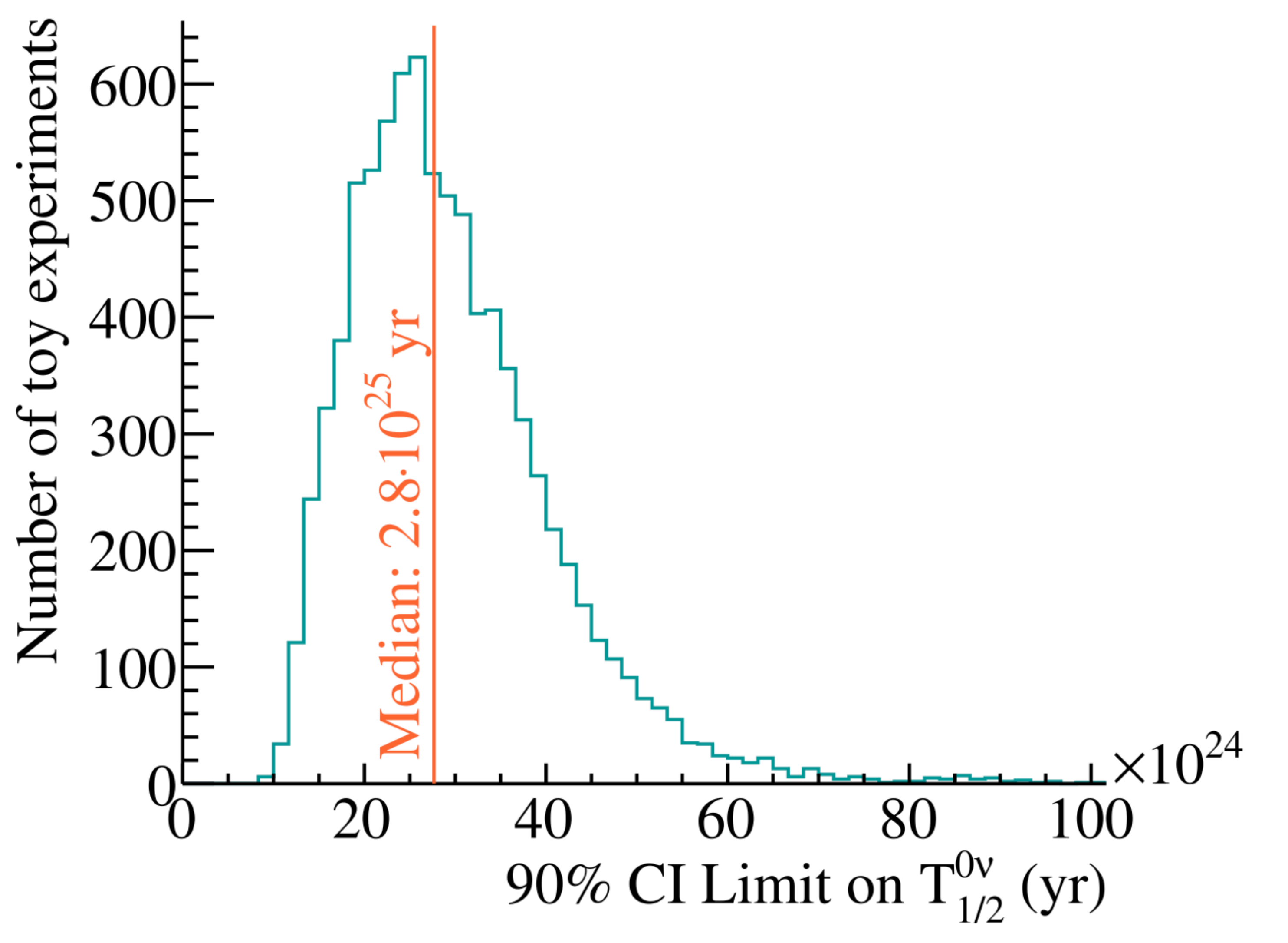
$0\nu\beta\beta$ Results



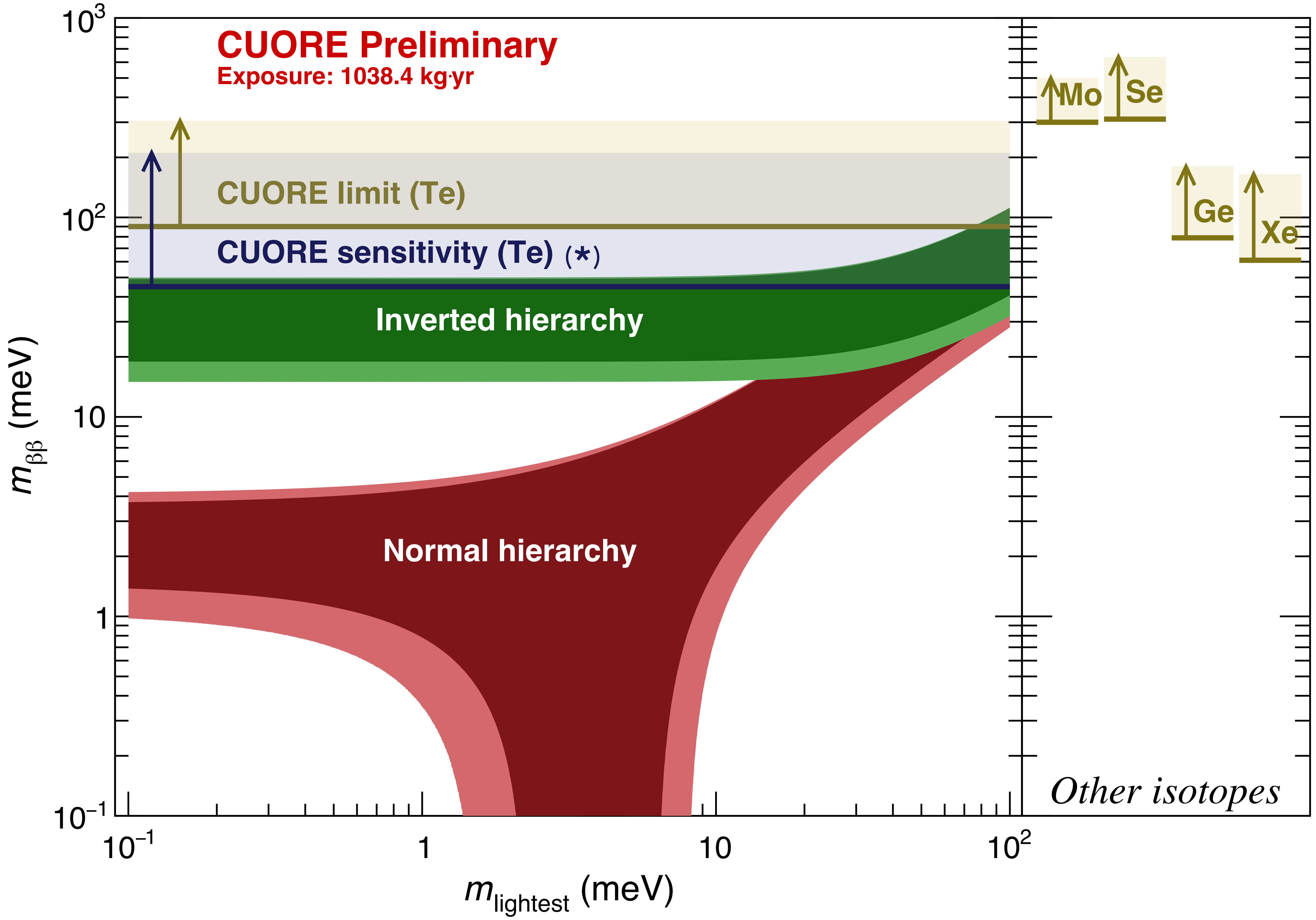
Bayesian limit at 90% C.I.

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

- Analysis with Bayesian Analysis Toolkit (BAT)
- Free parameters:
  - $\Gamma^{0\nu}$ rate
  - ^{60}Co peak rate
  - Background rate for each dataset and shared linear slope
- Median 90% exclusion sensitivity $T^{0\nu}_{1/2} = 2.8 \times 10^{25}$ yr
- Best fit value $\Gamma^{0\nu} = (0.9 \pm 1.4) \times 10^{-26}$ yr^{-1}



$0\nu\beta\beta$ Results



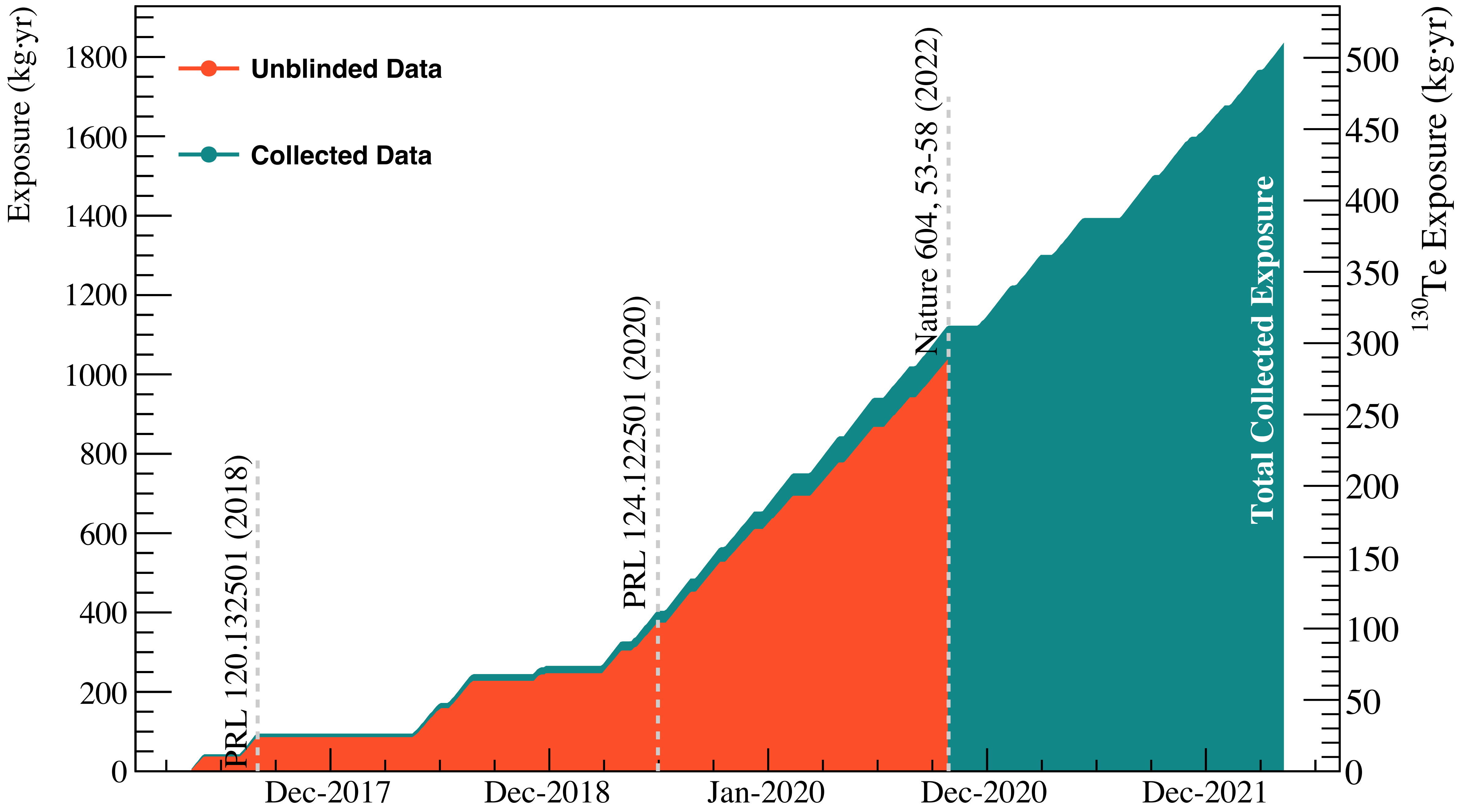
(*) CUORE goal with full exposure [not the current sensitivity]

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 Science Program



- Data taking to continue at least until ~2024
- Improve analysis methods and reconstruction tools

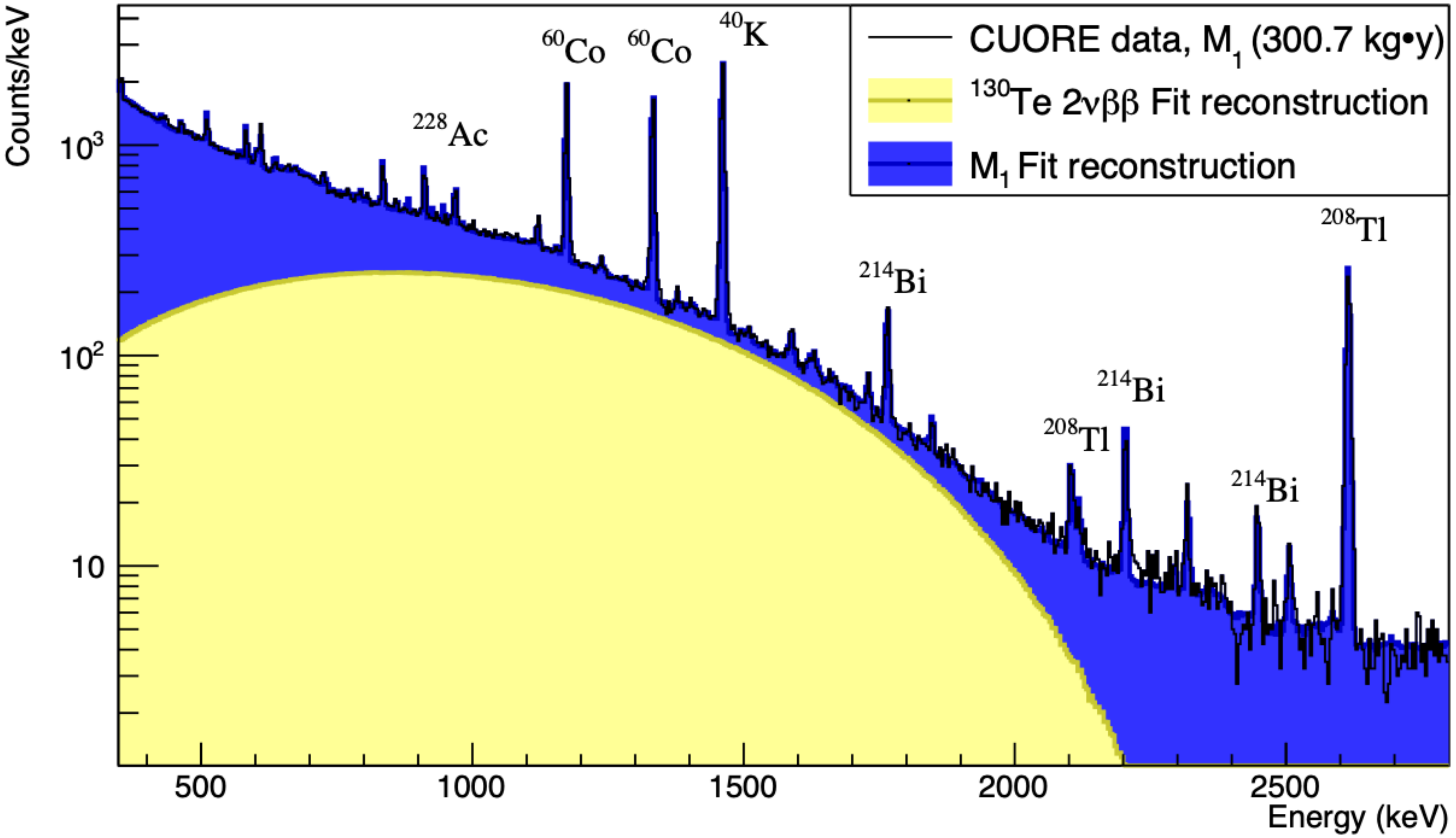
Other analyses ongoing

- $2\nu\beta\beta$ of ^{130}Te
- Full background model being developed as we collect more data
- Double beta on excited states and of other isotopes of Te
- Including $0\nu\beta\beta$ M2 events to increase sensitivity
- BSM searches and Dark Matter searches

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



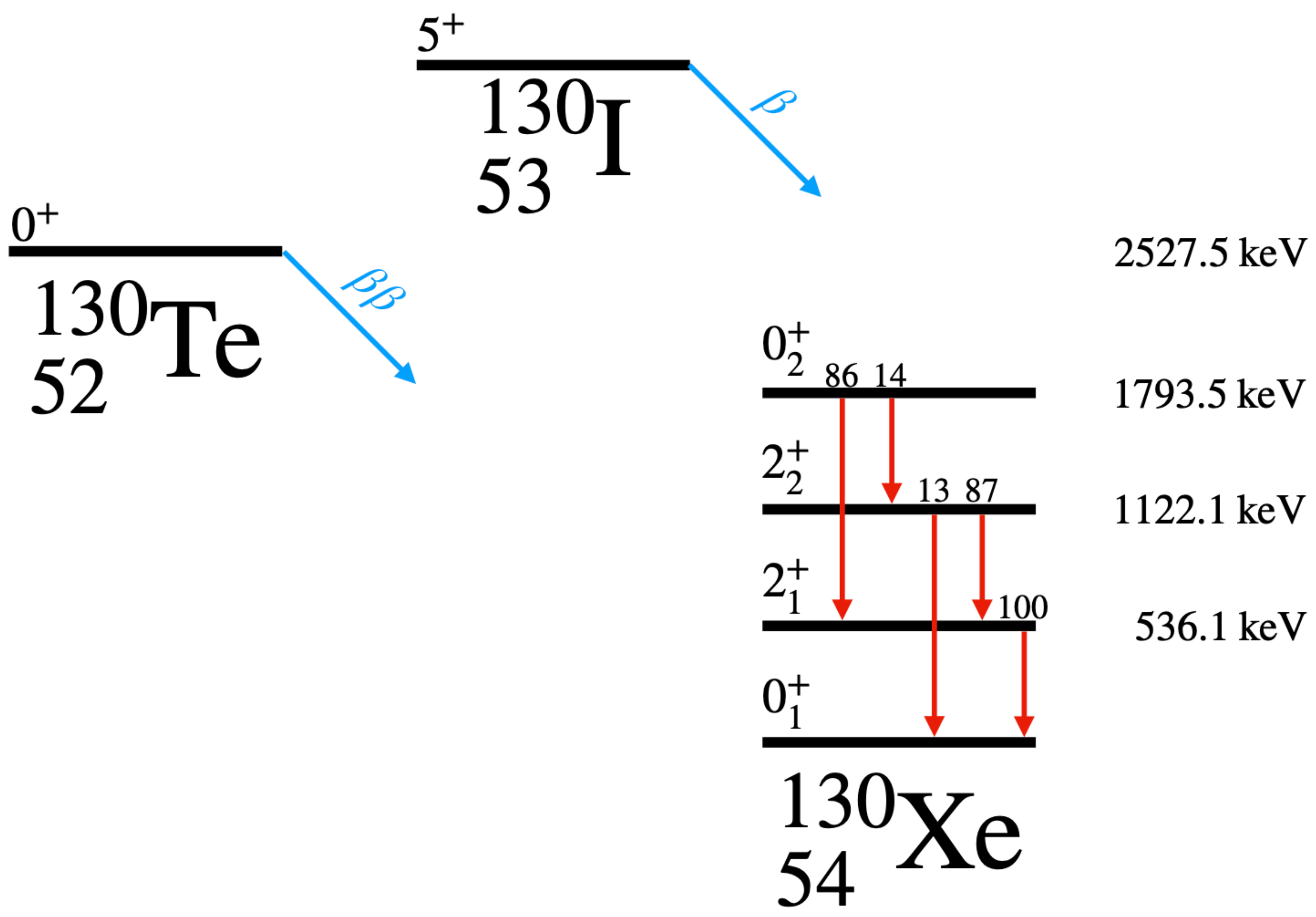
Major background sources identified and ascribed to different locations in the experimental setup using

- Coincidence analysis
- Gamma peaks
- Alpha peaks
- Radio-assay measurements
- Data from neutron activation

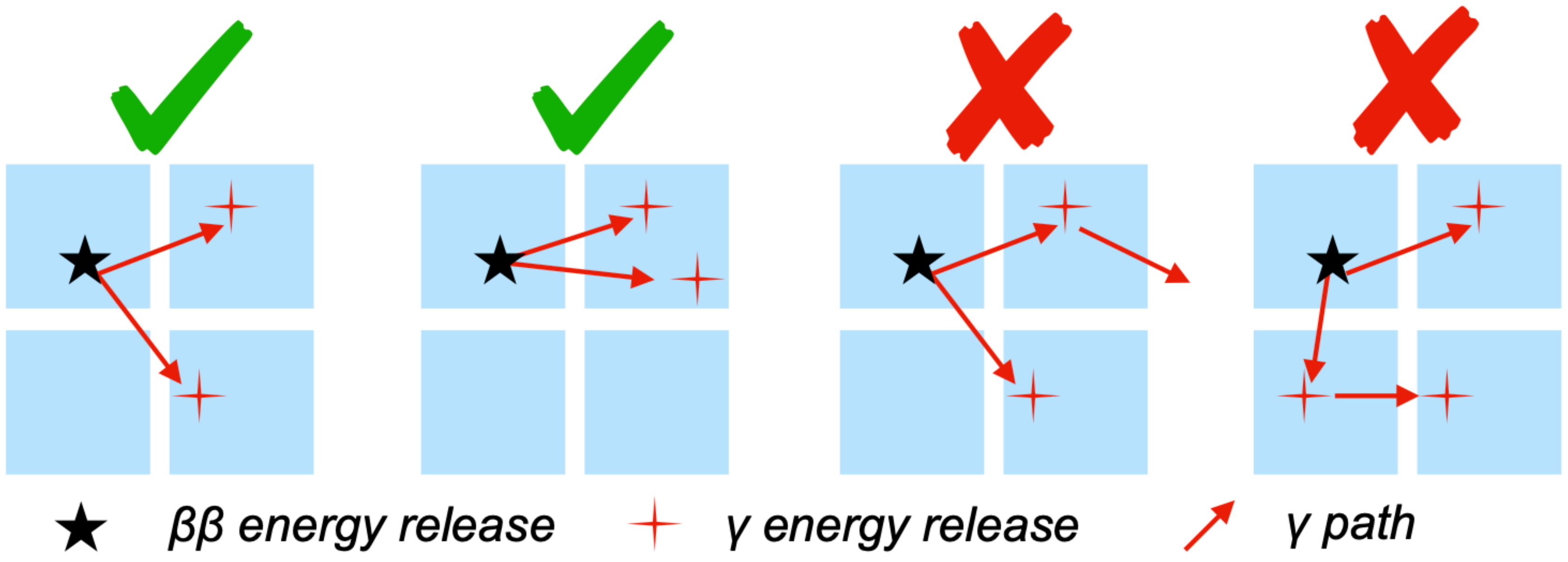
- 300.7 kg·yr of TeO_2
- Fit range: 350 keV to 2.8 MeV
- Data-MonteCarlo fit
- Background model being improved on with more data.

Double beta decay of ^{130}Te to excited states

EPJC 81, 567 (2021)



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



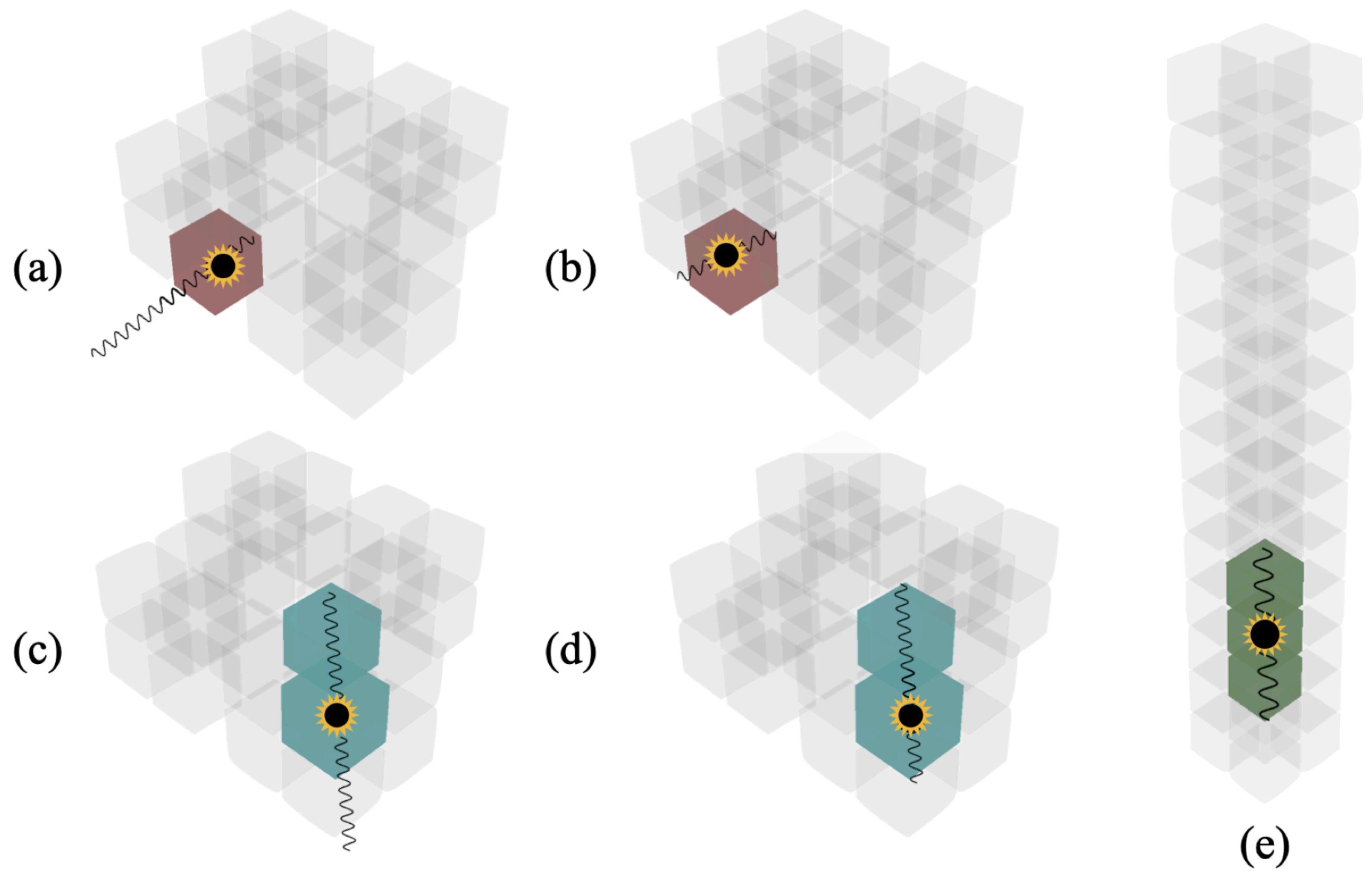
$$(T_{1/2})^{0\nu}_{0_2^+} > 5.9 \times 10^{24} \text{ yr at 90\% C.I.}$$

$$(T_{1/2})^{2\nu}_{0_2^+} > 1.3 \times 10^{24} \text{ yr at 90\% C.I.}$$

Neutrinoless β^+EC decay of ^{120}Te

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

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



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

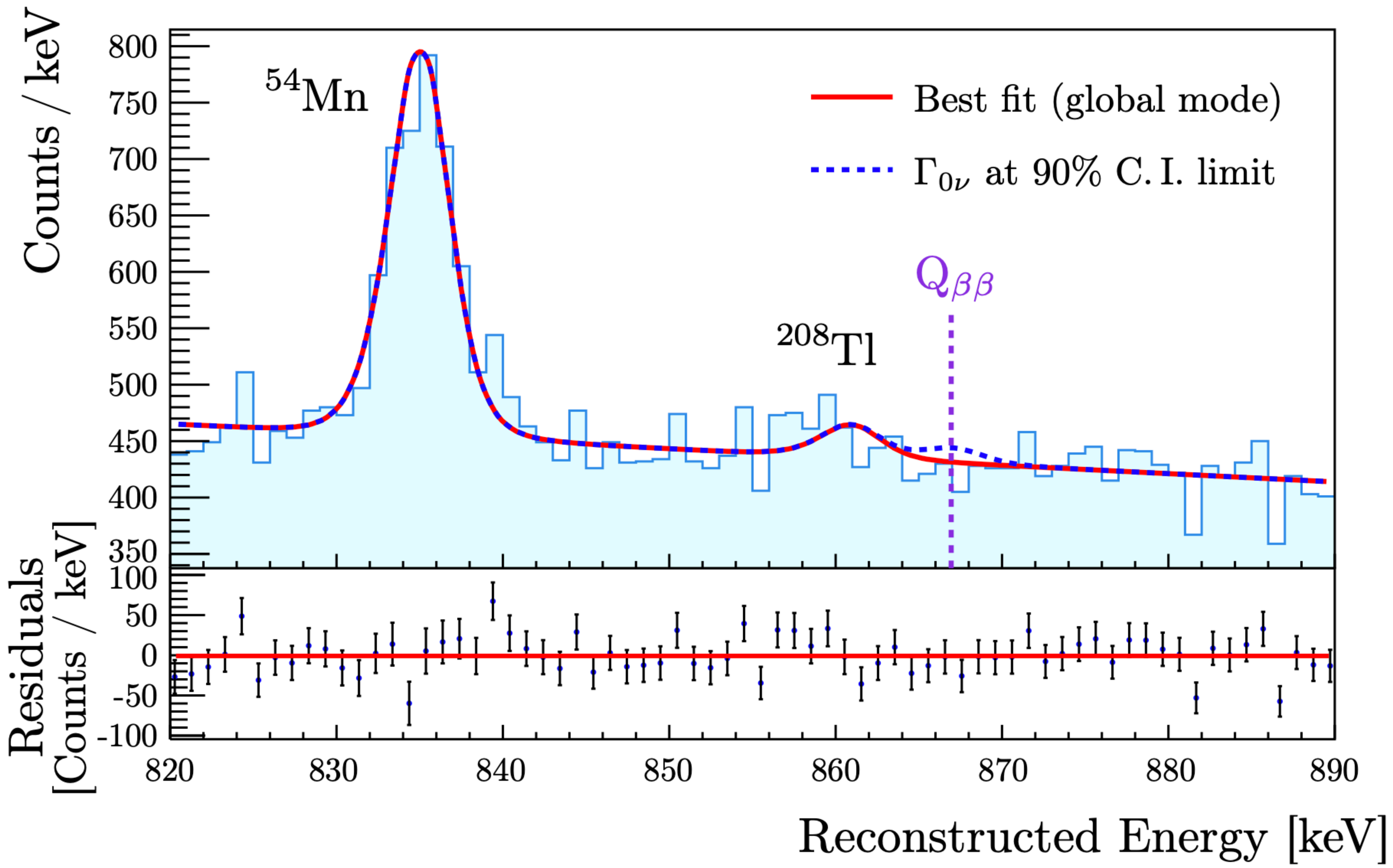
at 90% C.I

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

- Isotopic abundance: 31.75%
- 309.33 kg·yr of TeO_2 ➜ 78.56 kg·yr of ^{128}Te
- Low $Q_{\beta\beta}$ of 866.7 keV
  - Dominated by $2\nu\beta\beta$ events from ^{130}Te as well as ambient radioactivity
- M1 events in the [820-890] keV region of interest



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

30 times better than previous direct limit

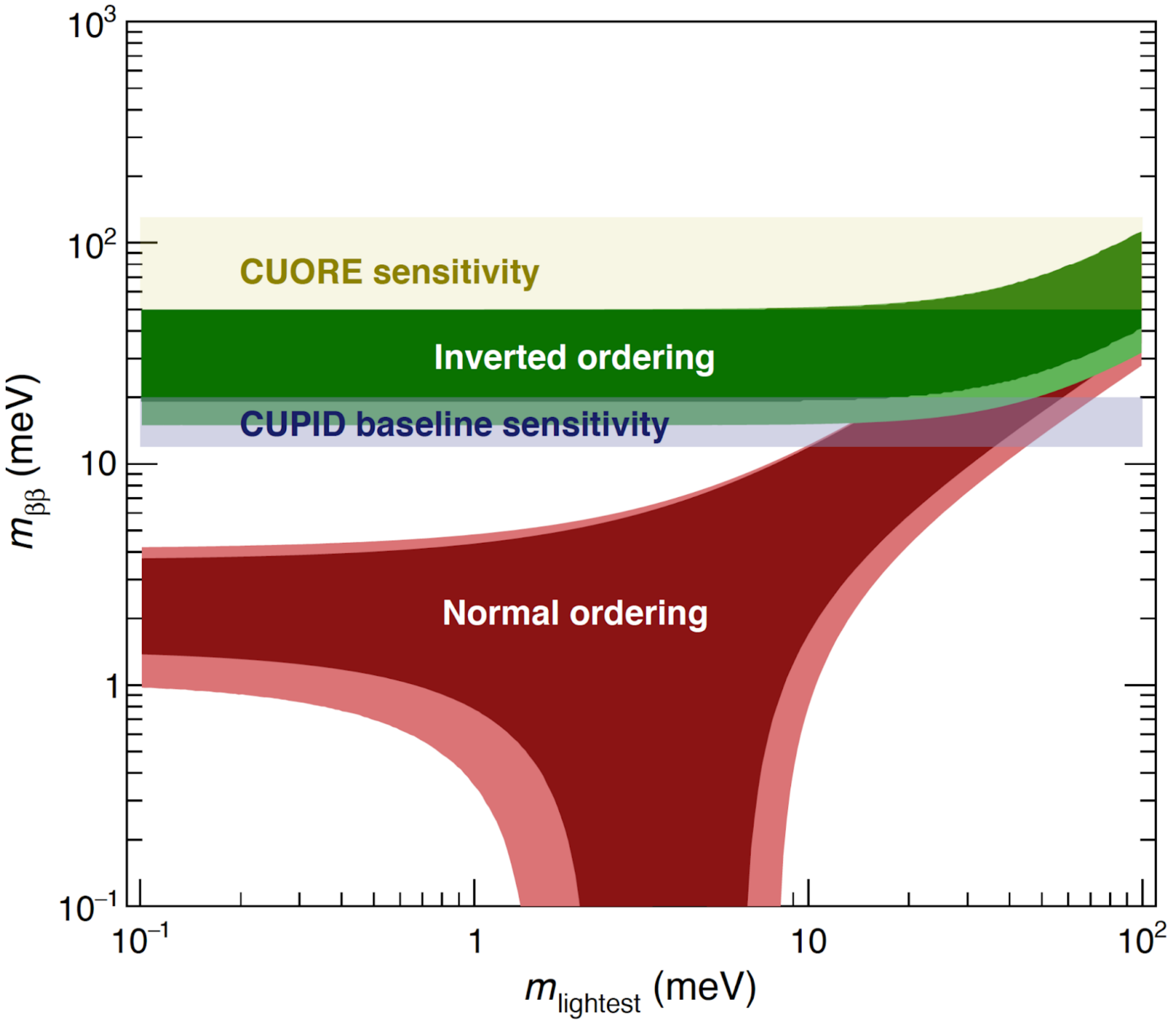
Life beyond CUORE: CUORE upgrade with Particle ID (CUPID)

CUPID Experiment

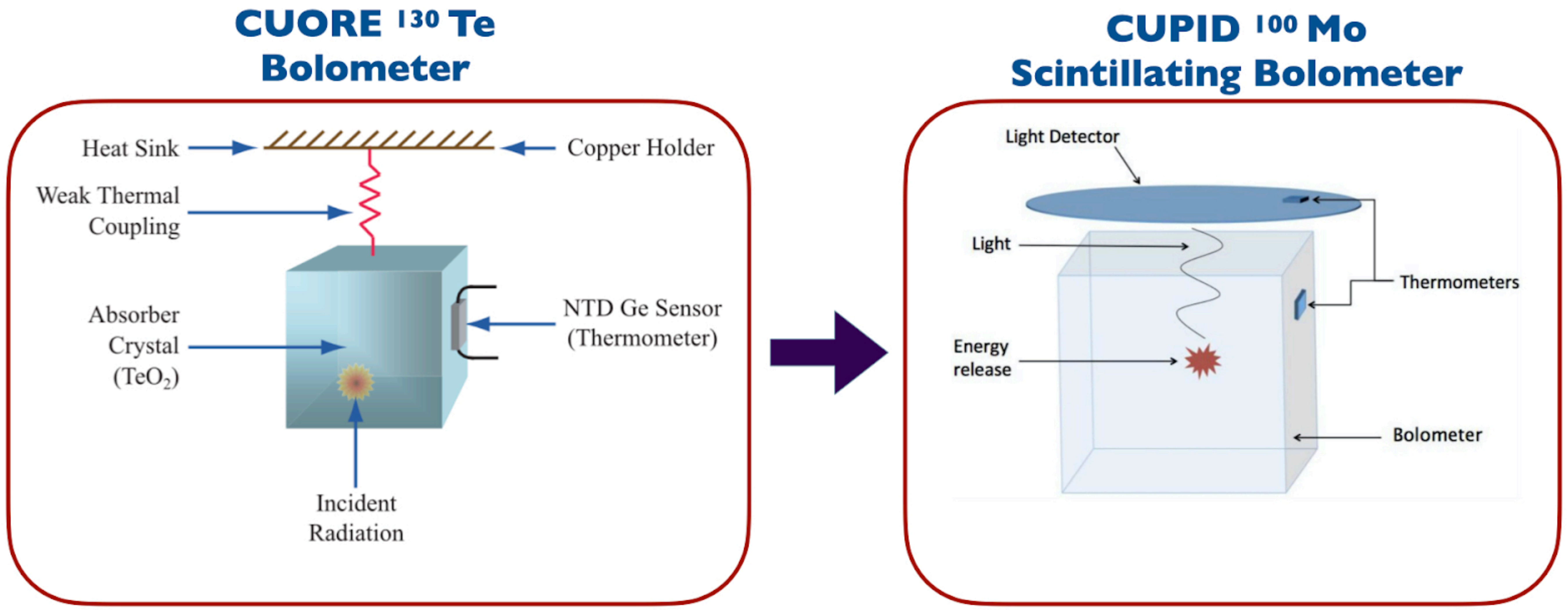
- Will operate in the same cryostat that currently houses CUORE
- Goal: Fully probe the "Inverted Hierarchy" region. Improve sensitivity to $m_{\beta\beta}$ by factor of ~5 relative to CUORE

Improved Sensitivity from Background Reduction

- Particle identification
- Muon veto
- Increased Q value for reduced γ/β backgrounds



CUPID



- $Q_{\beta\beta}$ = 2527 keV < 2615 keV peak
- Measure only heat
- No particle ID

- $Q_{\beta\beta}$= 3034 keV: Most β/γ backgrounds reduced
- Measure both heat + light
- Particle ID to actively discriminate α particles

Conservative

Feasible

	CUPID	CUPID Reach
Mass (kg)	450	450
^{100}Mo Mass (kg)	240	240
Resolution (keV FWHM)	5	5
Background Index (counts/(keV kg yr))	10^{-4}	2×10^{-5}
90% CL Half-life Exclusion (meV)	1.4×10^{27}	2.2×10^{27}
3σ Half-life Discovery (meV)	1×10^{27}	2×10^{27}
90% CL $m_{\beta\beta}$ Exclusion (meV)	10 - 17	8.4 - 14
3σ Discovery (meV)	12 - 20	9 - 15

CUPID Sensitivity

Summary

- Rich science program with $0\nu\beta\beta$ search at the frontier
- CUORE a ton scale cryogenic experiment will be able to probe <$m_{\beta\beta}$> ~ 45 - 210 meV
- Data taking at least till 2024 before possible upgrade.
- Natural successor → CUPID, one tonne experiment with particle identification (to cover IHE)

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