EuNPC

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SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

INFN

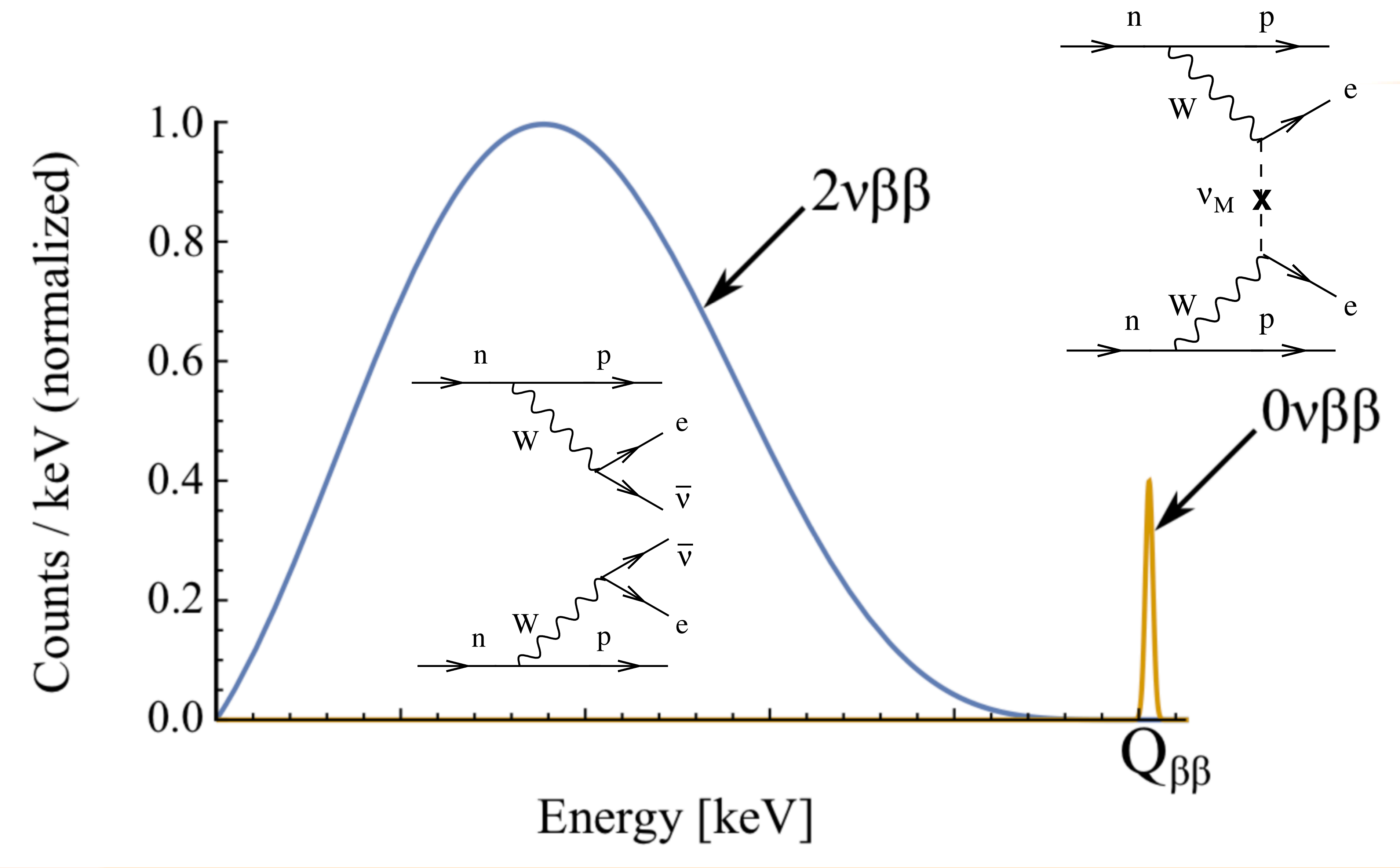
Latest results from the CUORE experiment

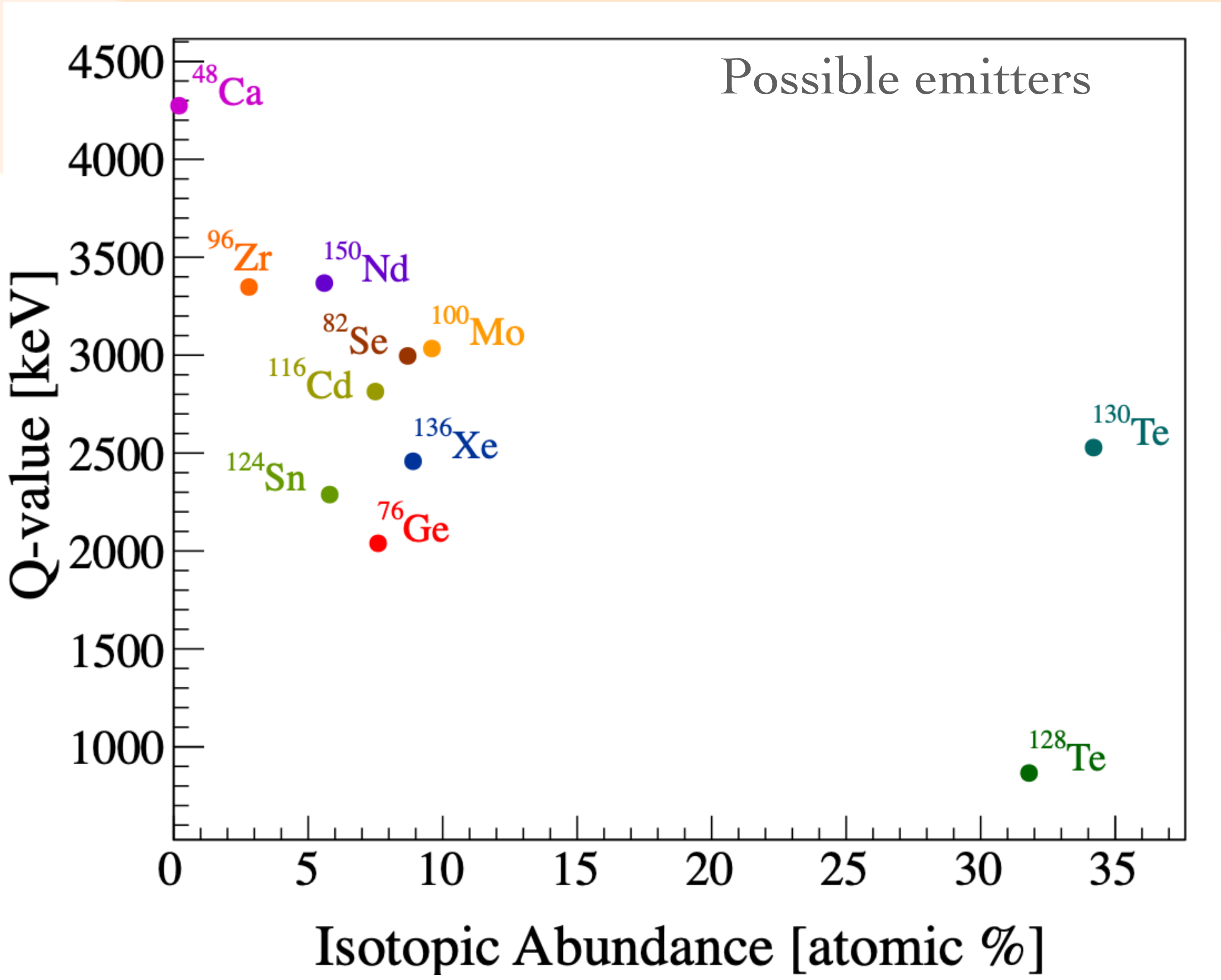
Emanuela Celi on behalf of the CUORE collaboration

Neutrinoless double beta decay (0νββ)

Why to search for 0νββ?

- Would establish Lepton Number Violation (ΔL = 2) not conserving the B-L symmetry of the SM
- Important to understand the origin of neutrino masses
- It is the only practical way to probe if neutrinos are Majorana particles
- If YES: would provide limits on neutrinos absolute mass scale





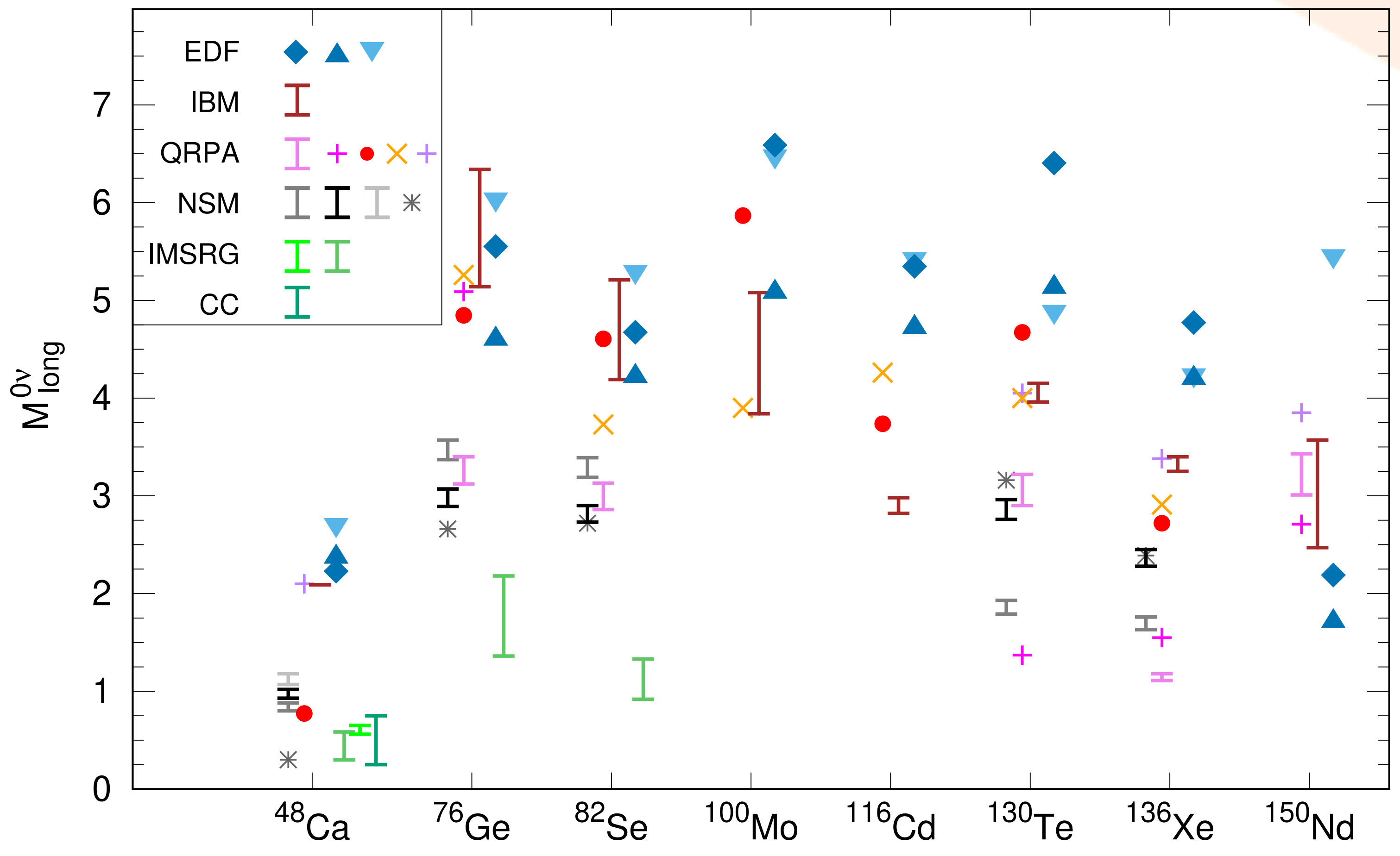
Neutrinoless double beta decay - half life

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\left|M^{0\nu}\right|^2\left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

Phase Space Factor,
needs to be high

$G_{0\nu} \propto Q^5_{\beta\beta}$

Nuclear Matrix Element
depends on nuclear
models.

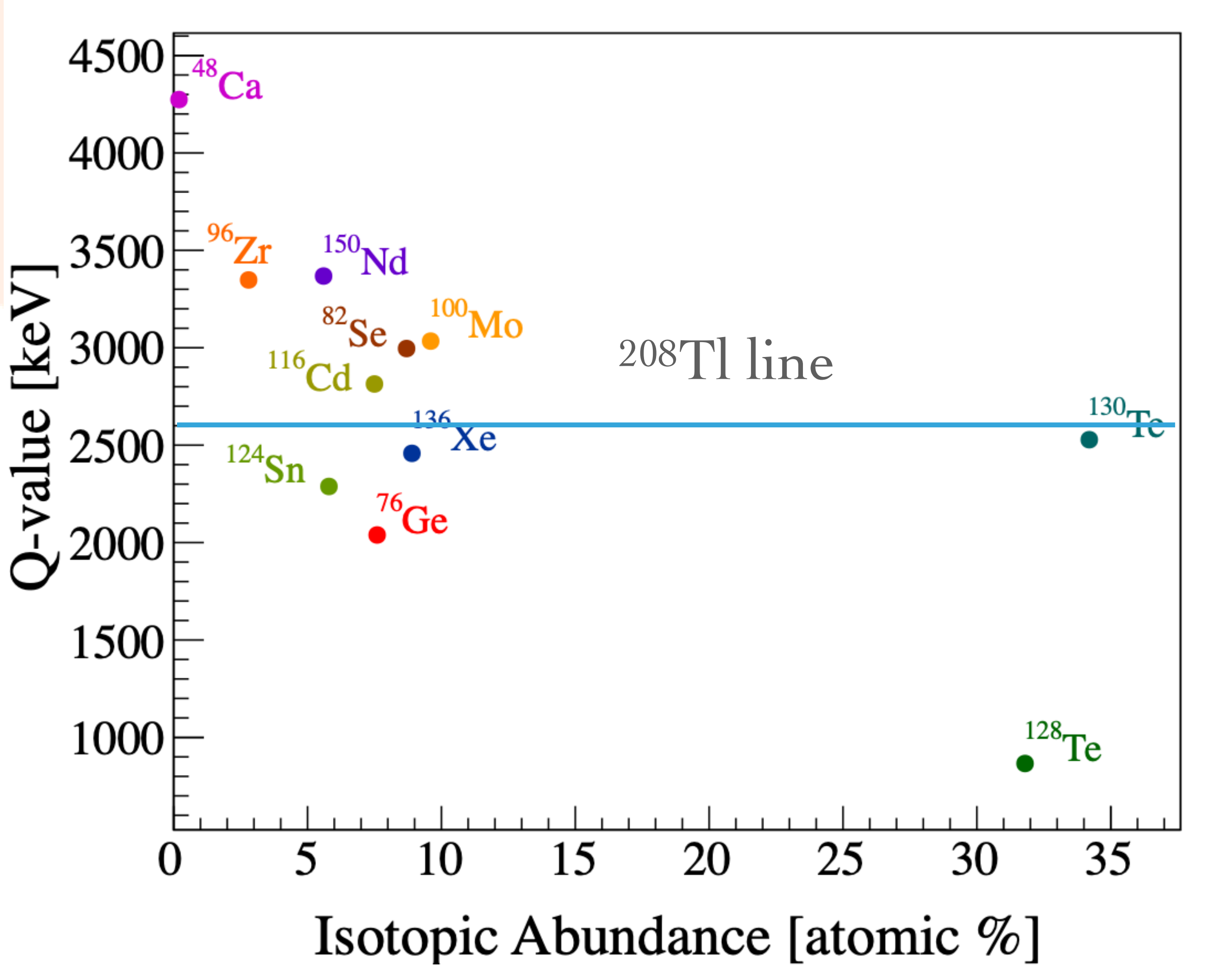


Effective Majorana Mass,
our parameter of interest

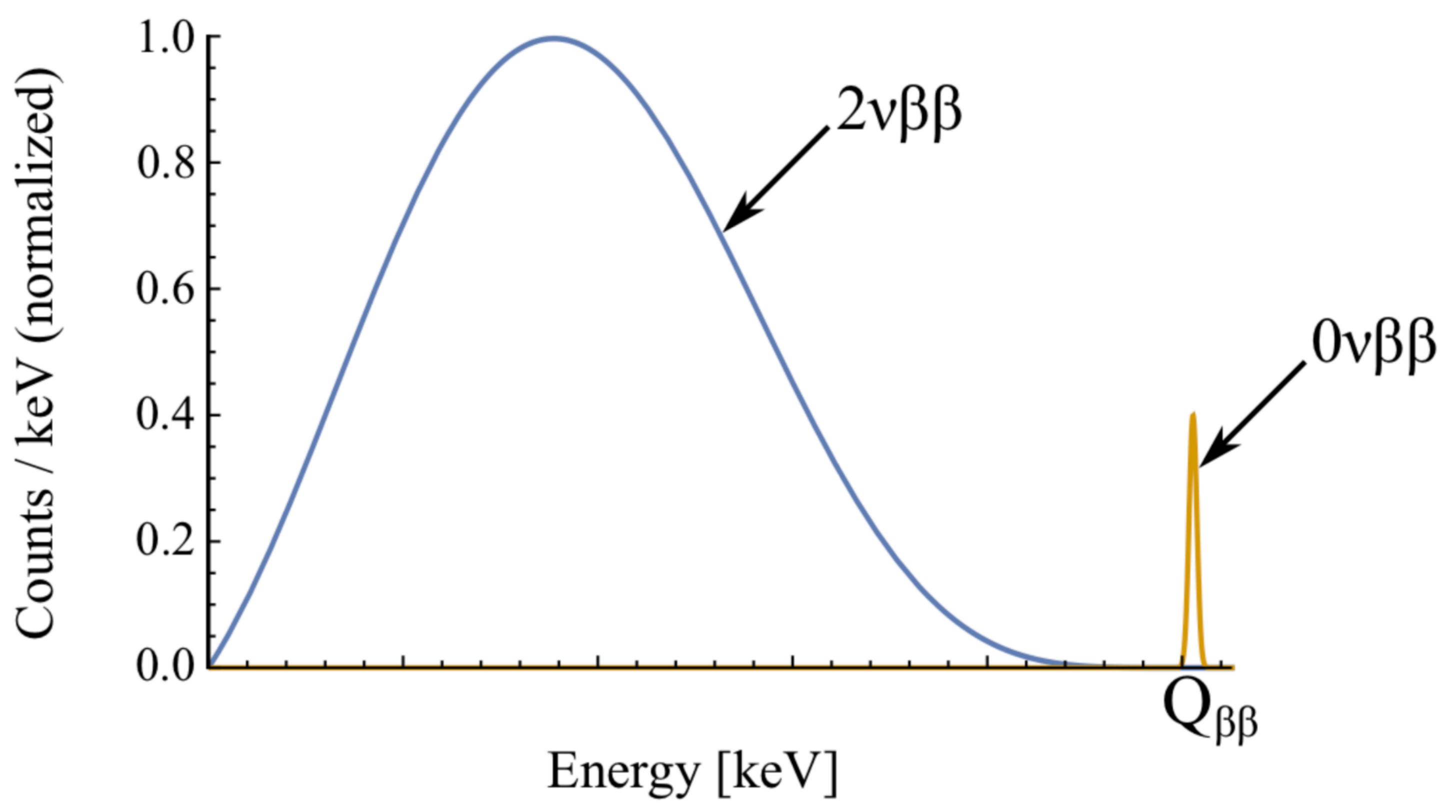
Neutrinoless double beta decay - sensitivity

$$T^{0\nu}_{1/2}(n_\sigma) = \frac{\ln 2}{n_\sigma} \frac{N_A i \epsilon}{A} \sqrt{\frac{Mt}{B \Delta E}}$$

Large exposure would allow to reach high sensitivities



High energy resolution to reject the continuum spectrum of 2ν from the ROI



Low background: at the zero-counts limit the sensitivity starts scaling linearly with the exposure

$$T_{0\nu} > \ln 2 \frac{x \eta \epsilon N_A}{A} \frac{Mt}{n_L}$$

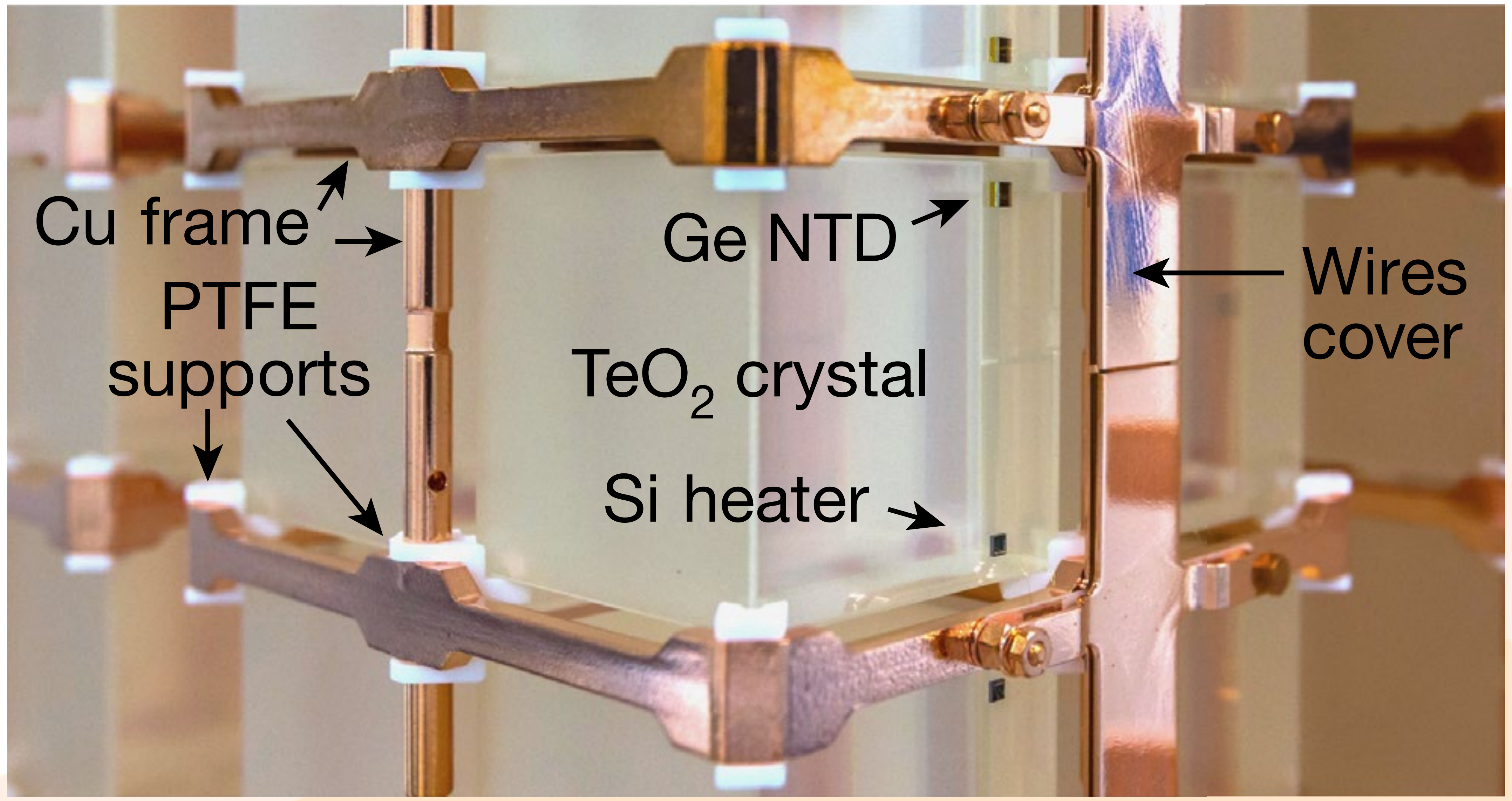
Cryogenic calorimeters

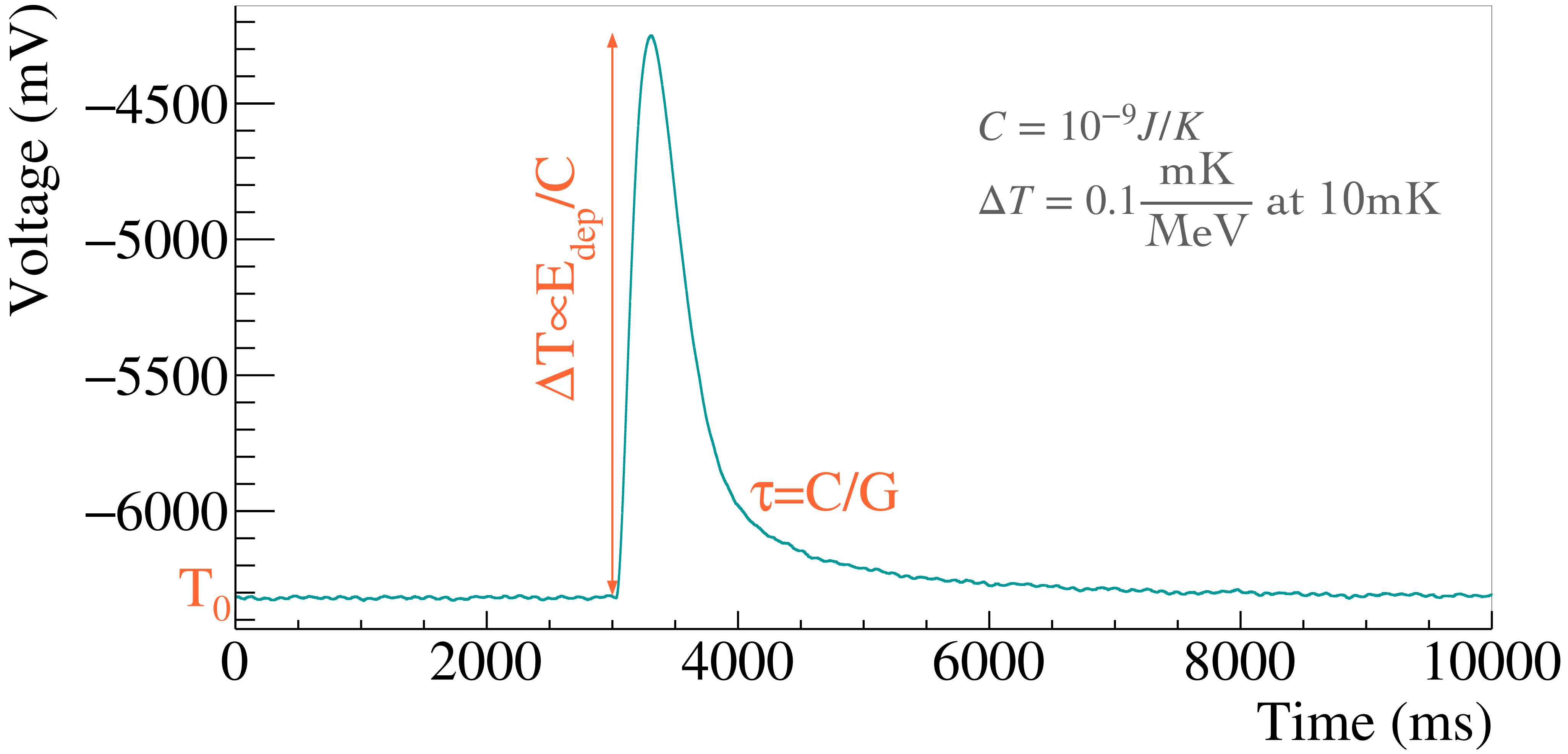
Highly sensitive calorimeters operated at cryogenic temperature (~10 mK)

$$\Delta T(t) = \frac{\Delta E}{C} \exp\left(-\frac{t}{\tau}\right) \quad \text{where} \quad \tau = \frac{C}{G}$$

C = heat capacity

G = thermal conductance

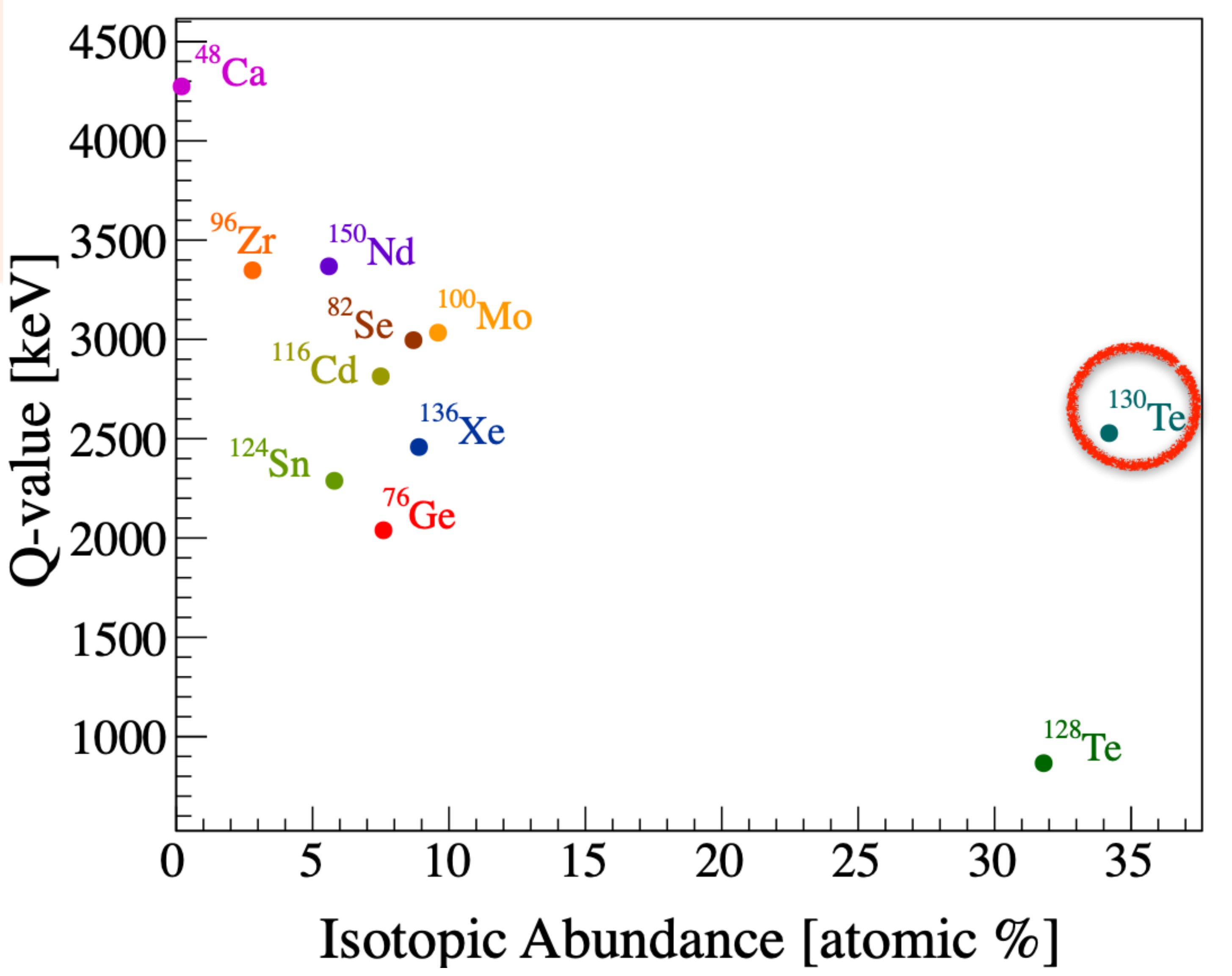


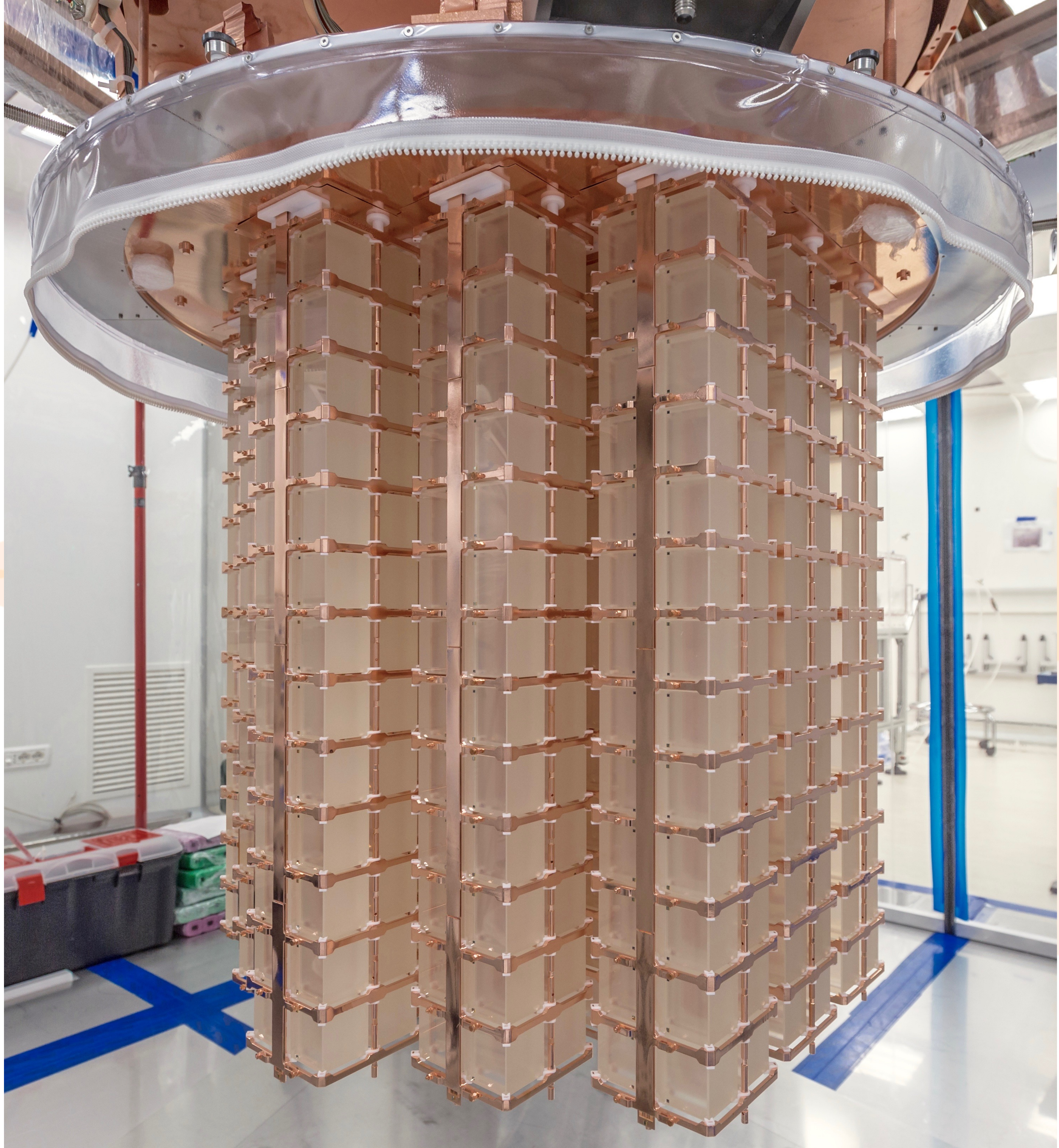


- Excellent energy resolution (<1%)
- High detection efficiency, the emitting isotope is embedded in the detector
- Possibility to build ton-scale experiments
- Radio-pure materials

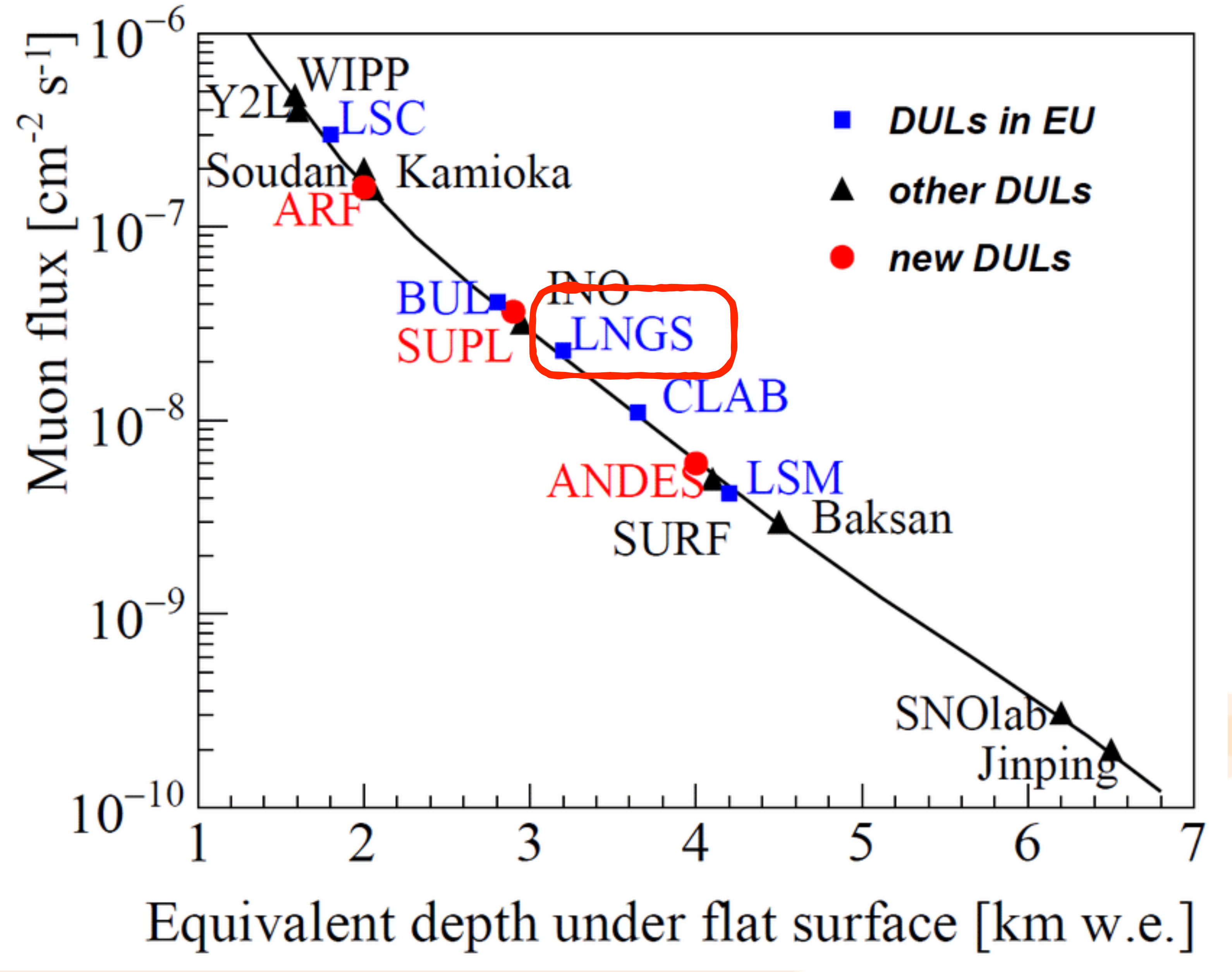
The CUORE detector

- 988 TeO_2 crystals ($5{\times}5{\times}5$ cm^3)
- 19 towers of 52 crystals each
- 742 kg of TeO_2
- Active mass ~ 206 kg



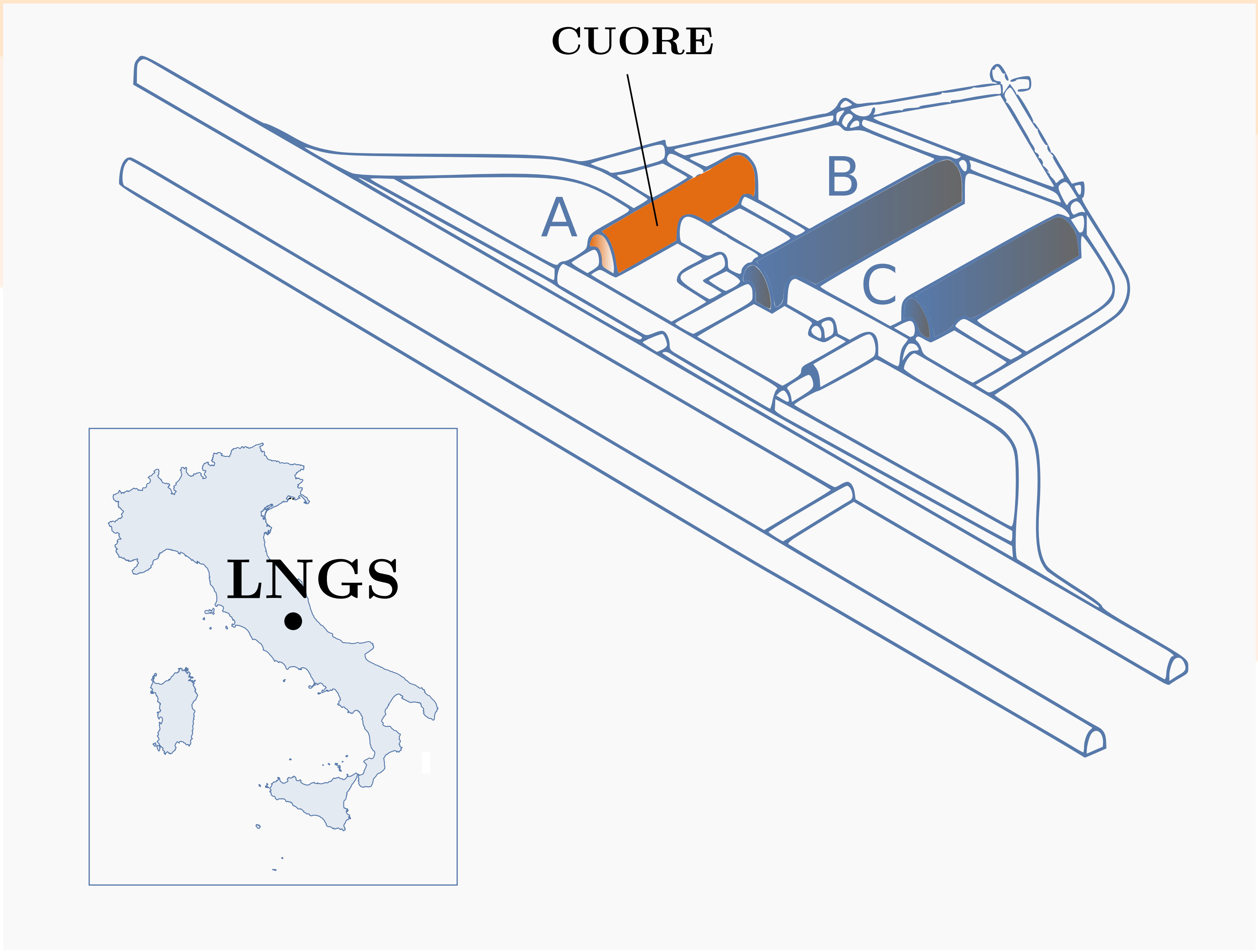


Laboratori Nazionali del Gran Sasso



External lab

Underground lab

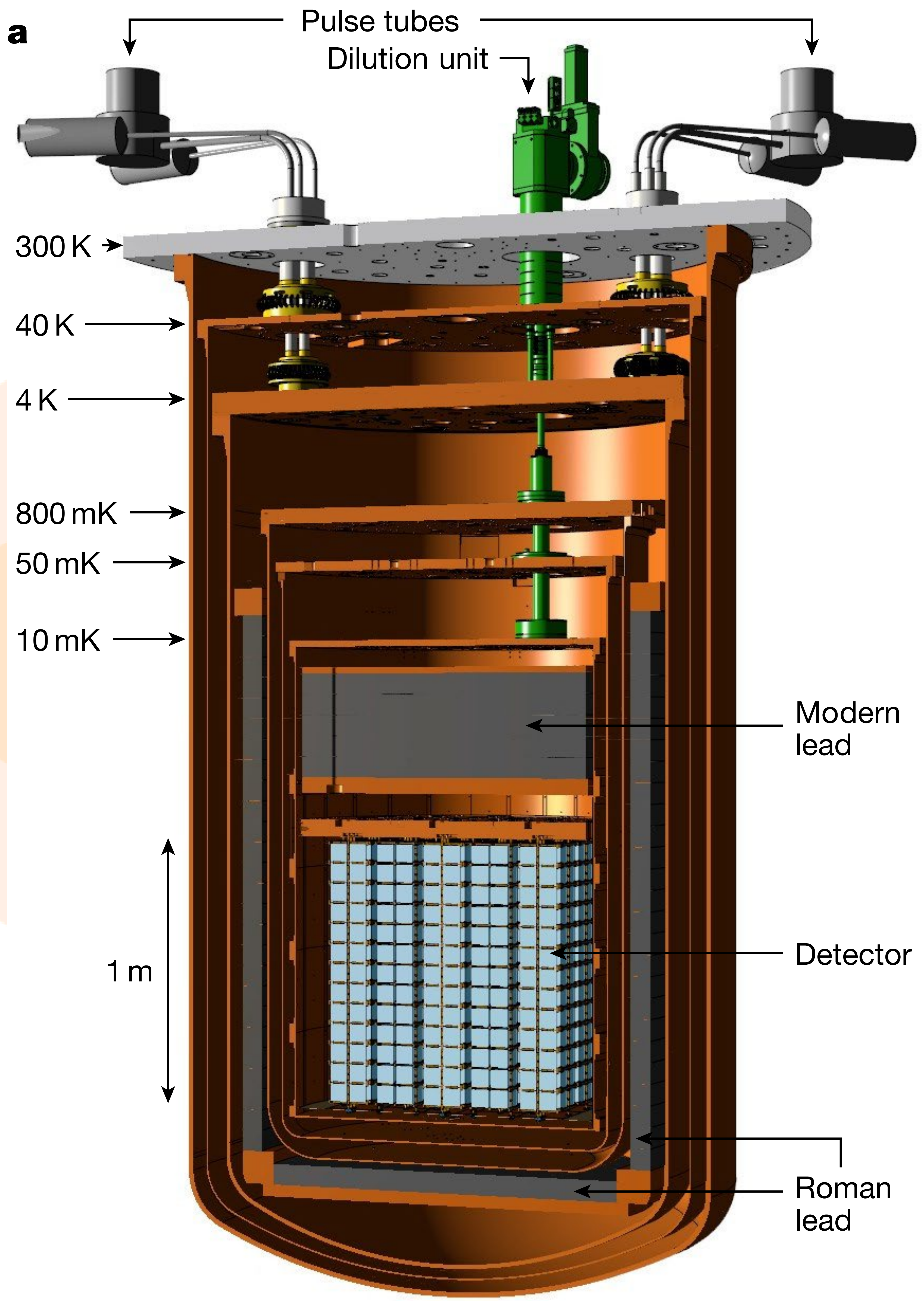


- 3600 m.w.e of rock to shield from cosmic rays
- Largest underground laboratory in the world

The incredible cryostat

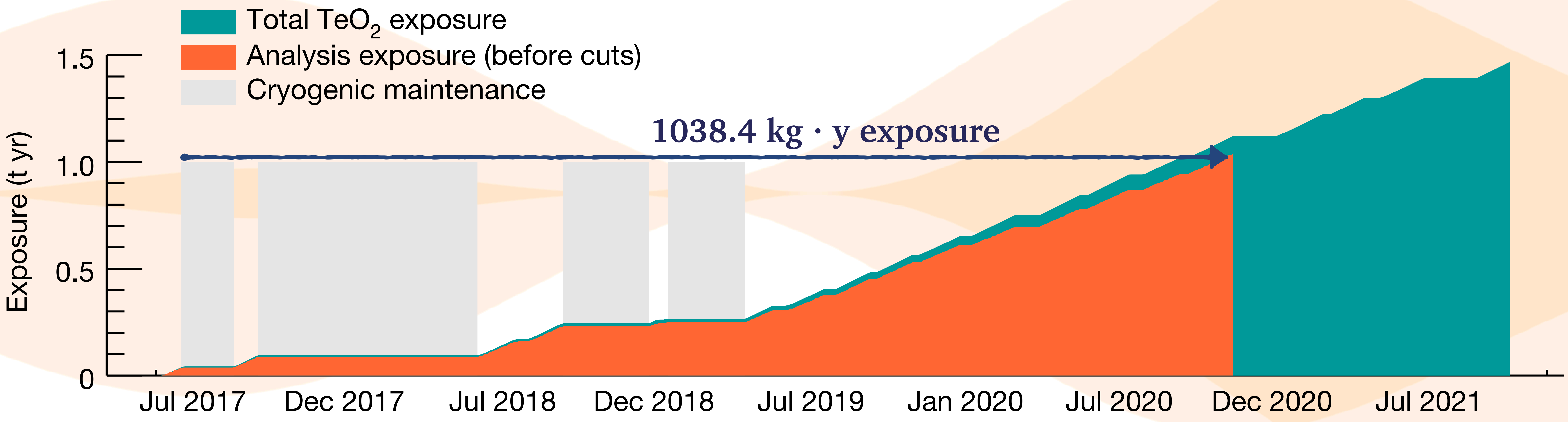
- 6 stages and nested vessels
- Cooling through pulse tubes and dilution unit
- ~10 mK working temperature
- 15 tonnes of materials below 4 K and 3 tonnes below 50 mK
- Material selection with radio-purity constraints
- Vibration isolation and noise cancellation

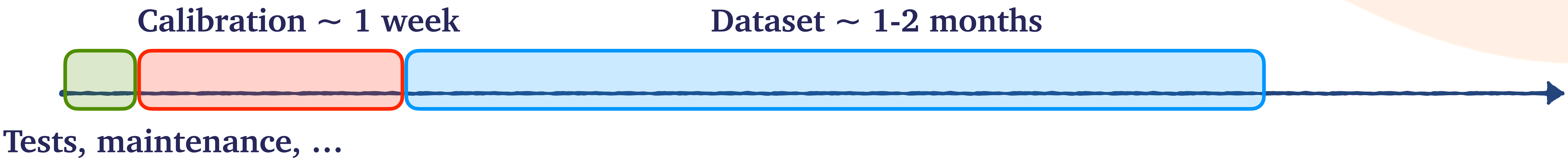
WORLD LEADING CRYOSTAT IN SIZE AND POWER



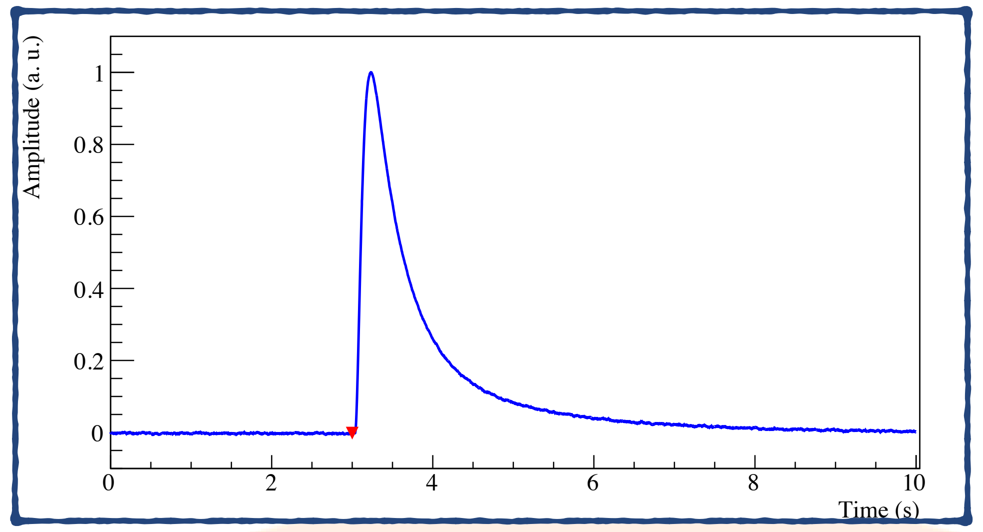
Timeline

- Stable after optimization since 2019 → duty cycle from 35.8% to 93%
- 984 / 988 active channels





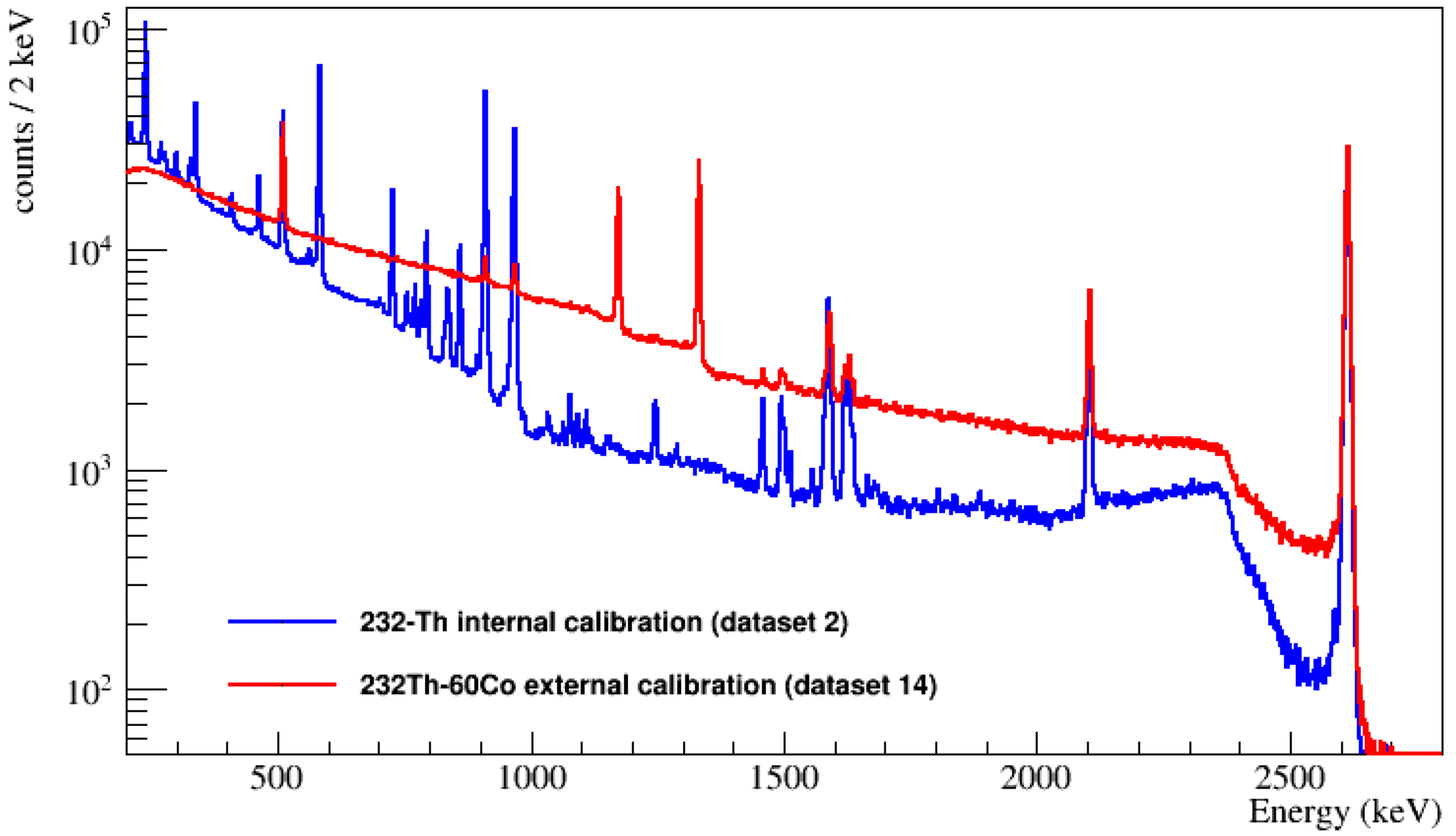
Analysis workflow



Optimum filter → Gain correction → Energy calibration → coincidences → Pulse shape discrimination → Salting in the ROI → Selections → Unblinding

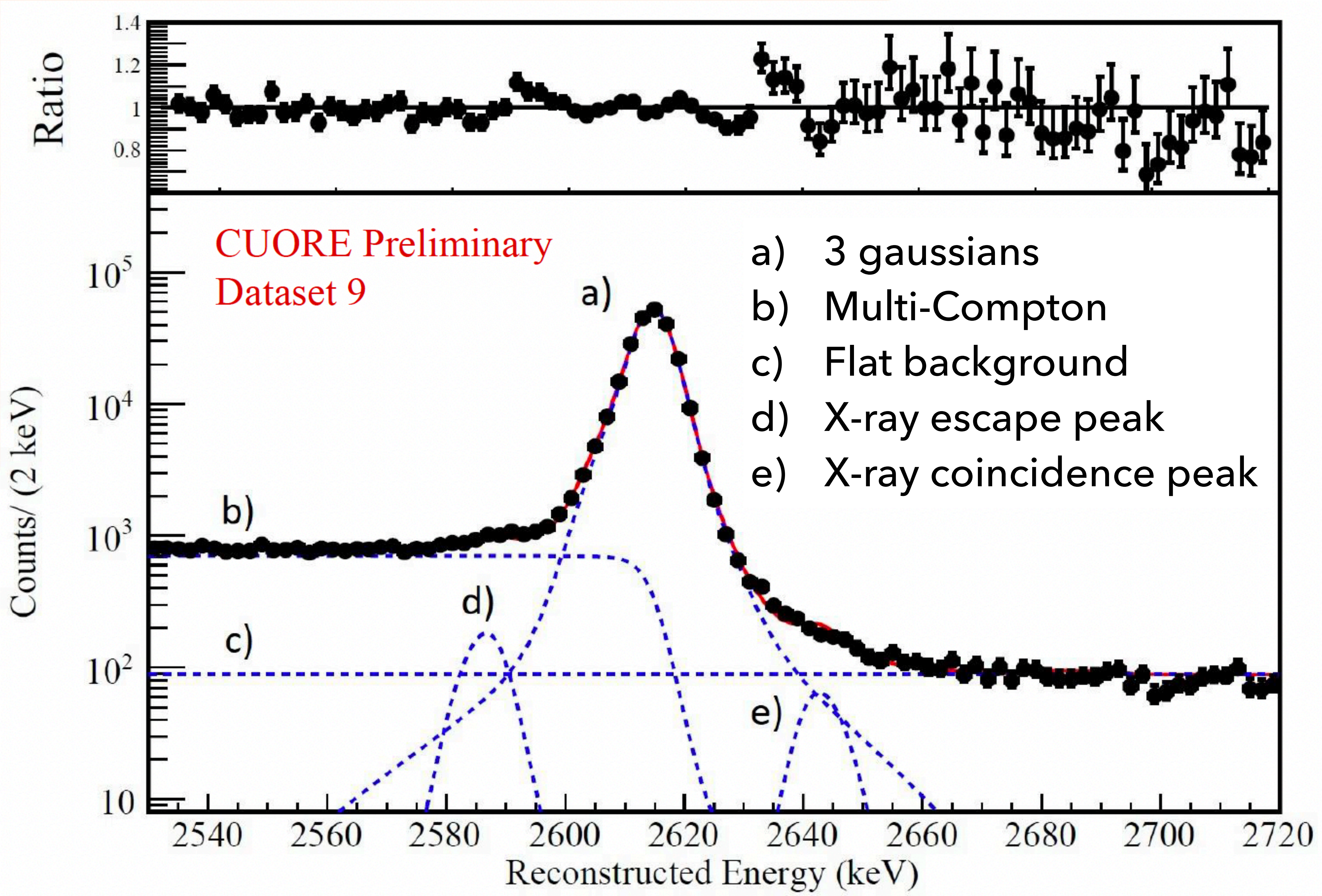
First 3 datasets were calibrated with internal ^{232}Th sources

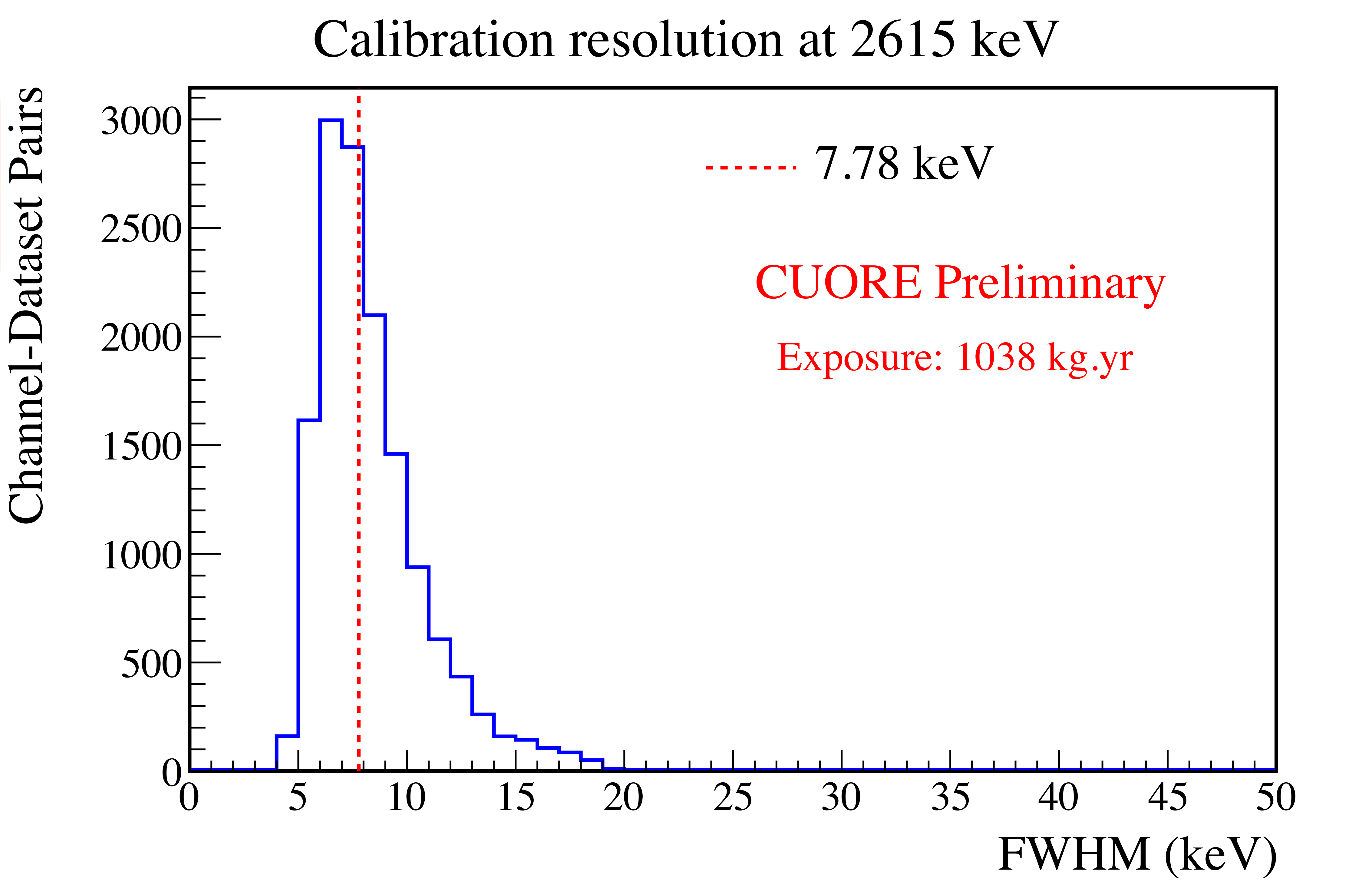
Data is now calibrated with external ^{232}Th-^{60}Co sources



Energy calibration and resolution

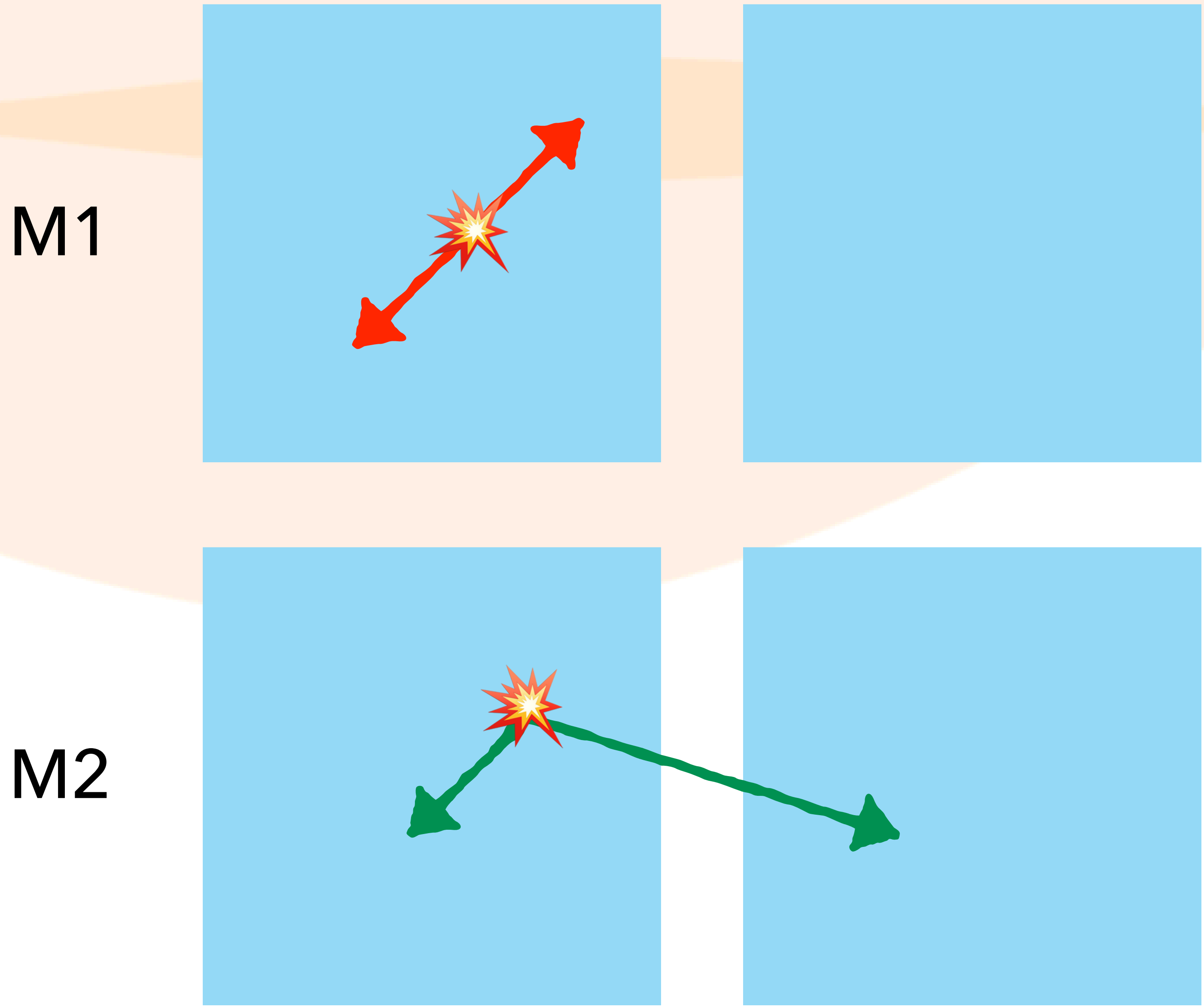
- Model of detector response on calibration data
- Fit of the 2615 keV line and extrapolation of the resolution to the ROI → (7.8±0.5) keV at $Q_{\beta\beta}$



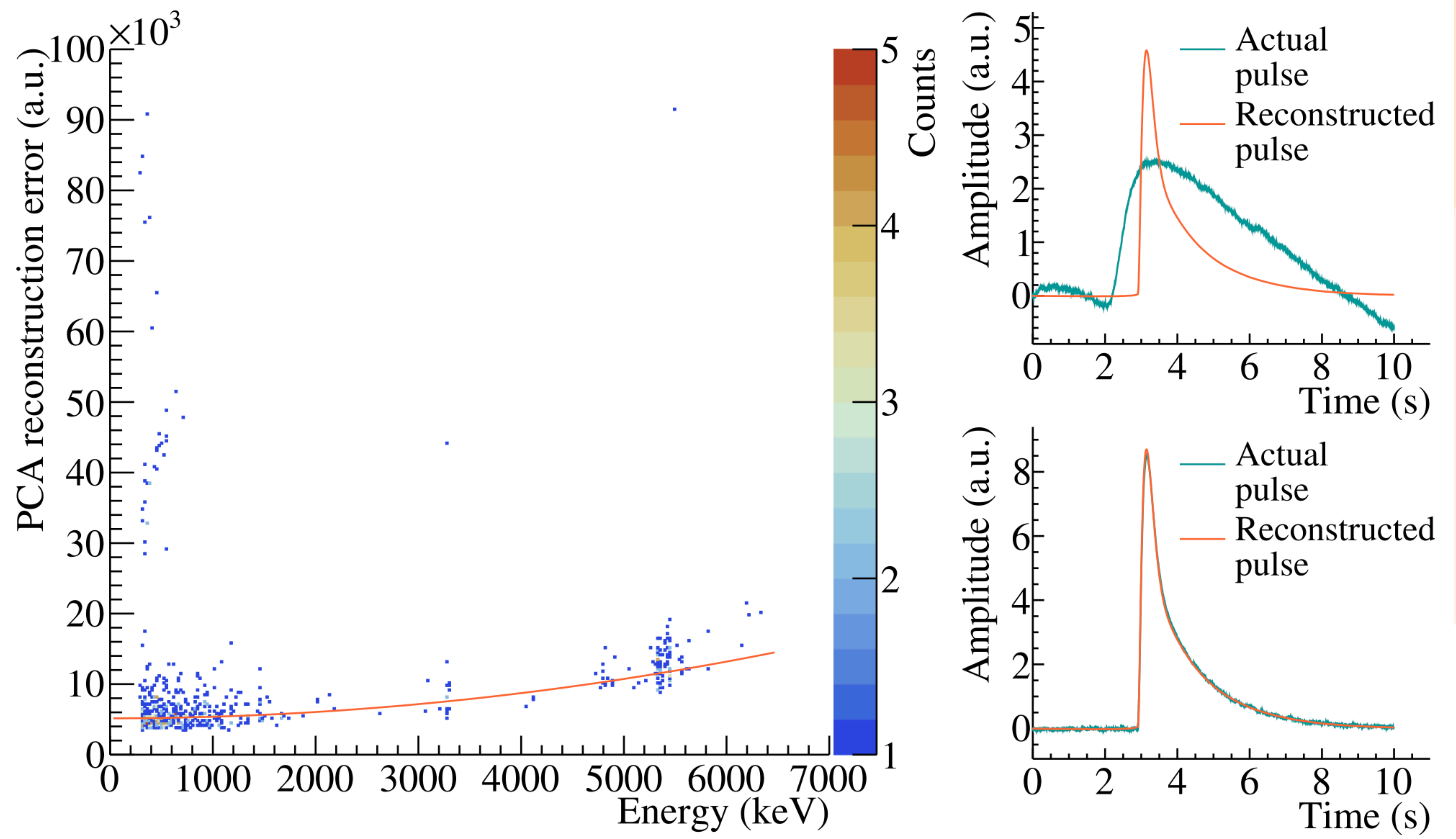


Coincidences and pulse shape discrimination

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



- 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



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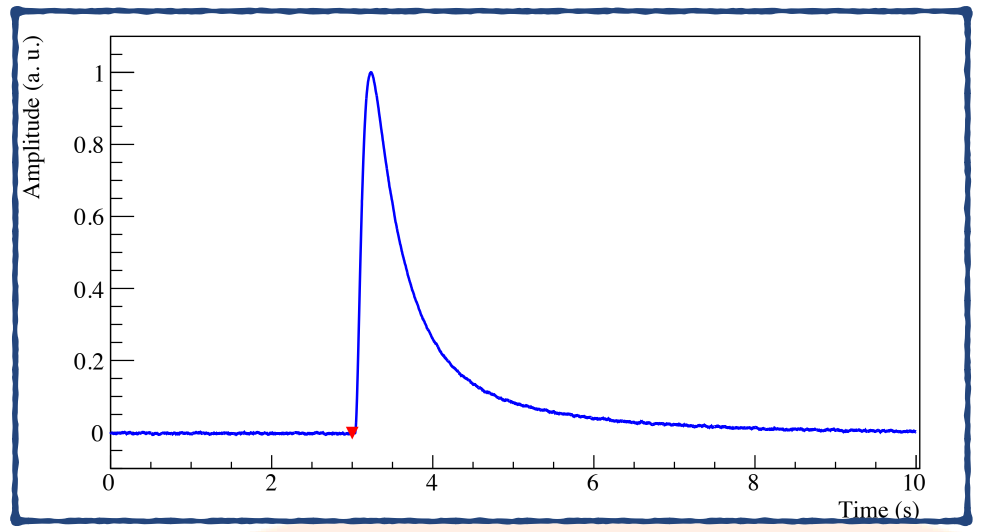
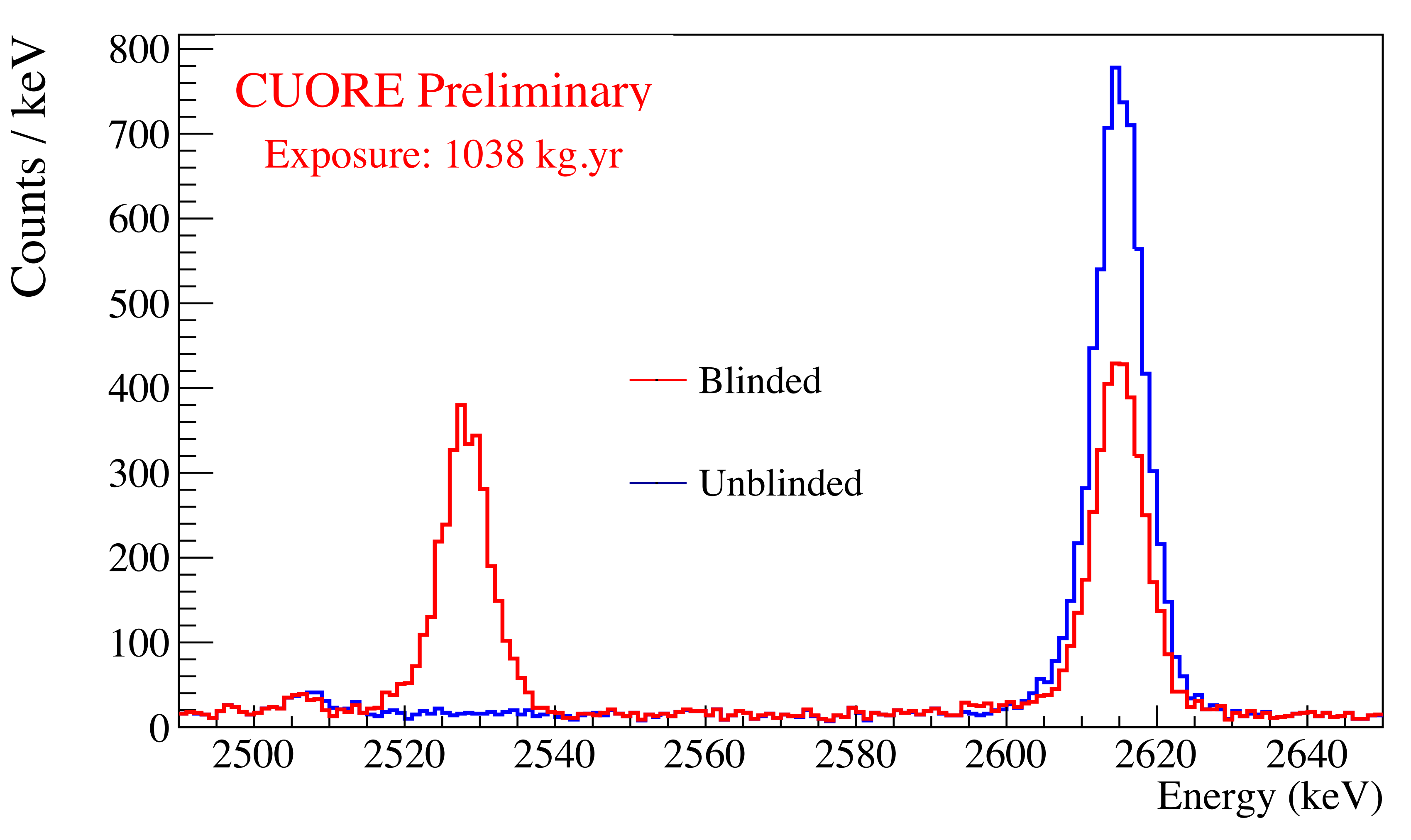


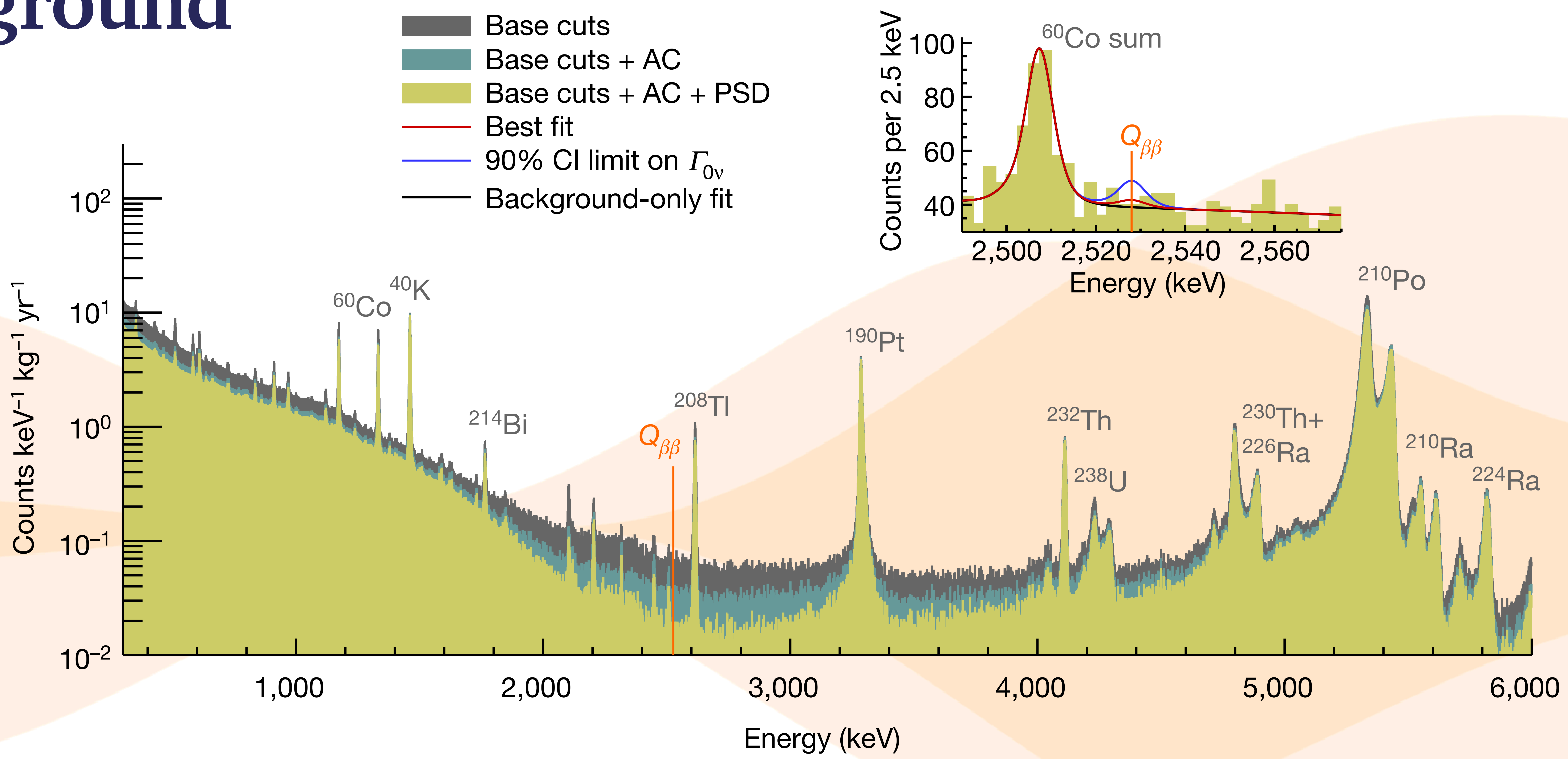
Optimum filter → Gain correction → Energy calibration → coincidences → Pulse shape discrimination → Salting in the ROI → Selections → Unblinding

- 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



The background

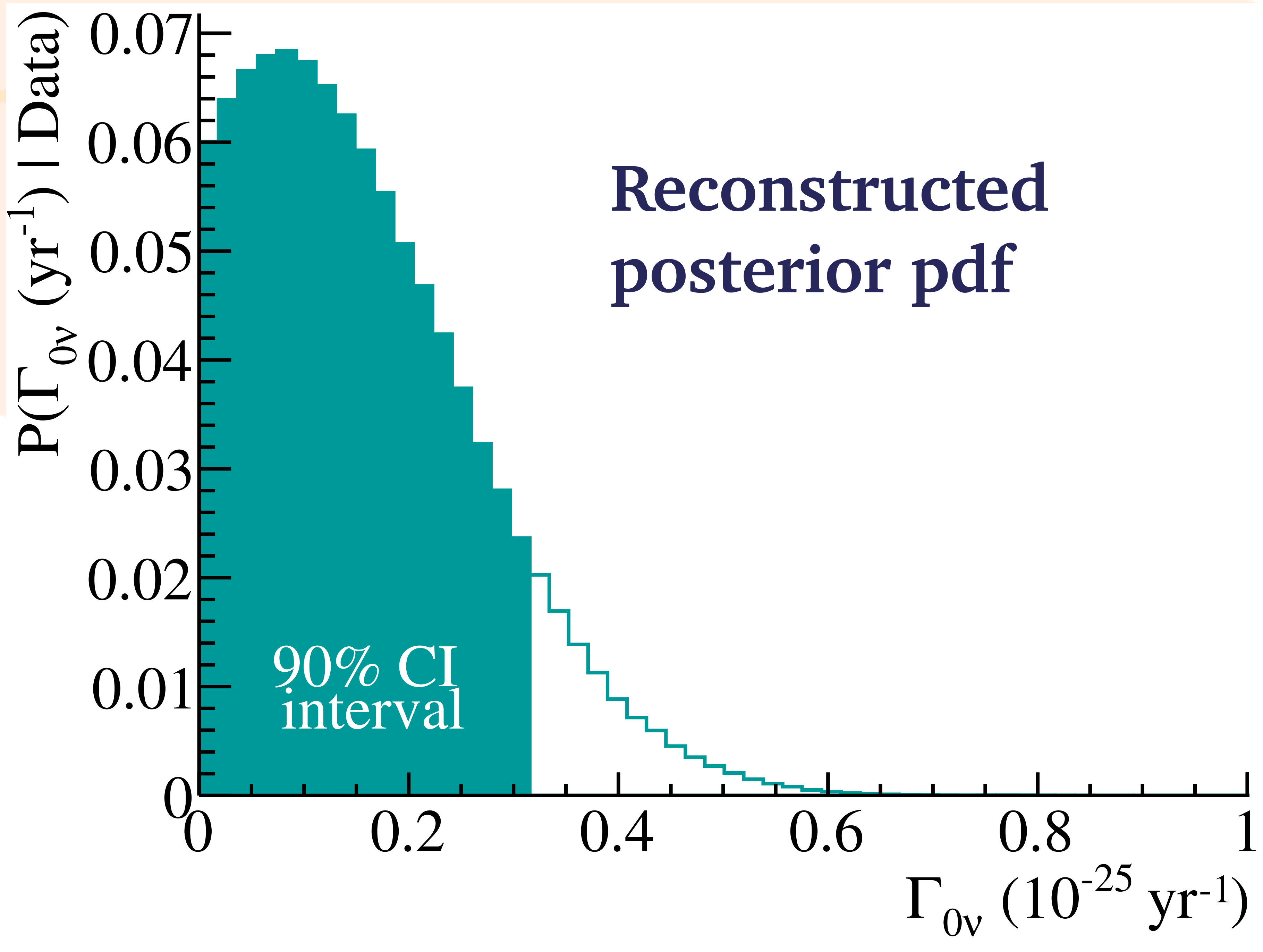
90% OF THE BACKGROUND IN THE ROI COMES FROM DEGRADED ALPHAS

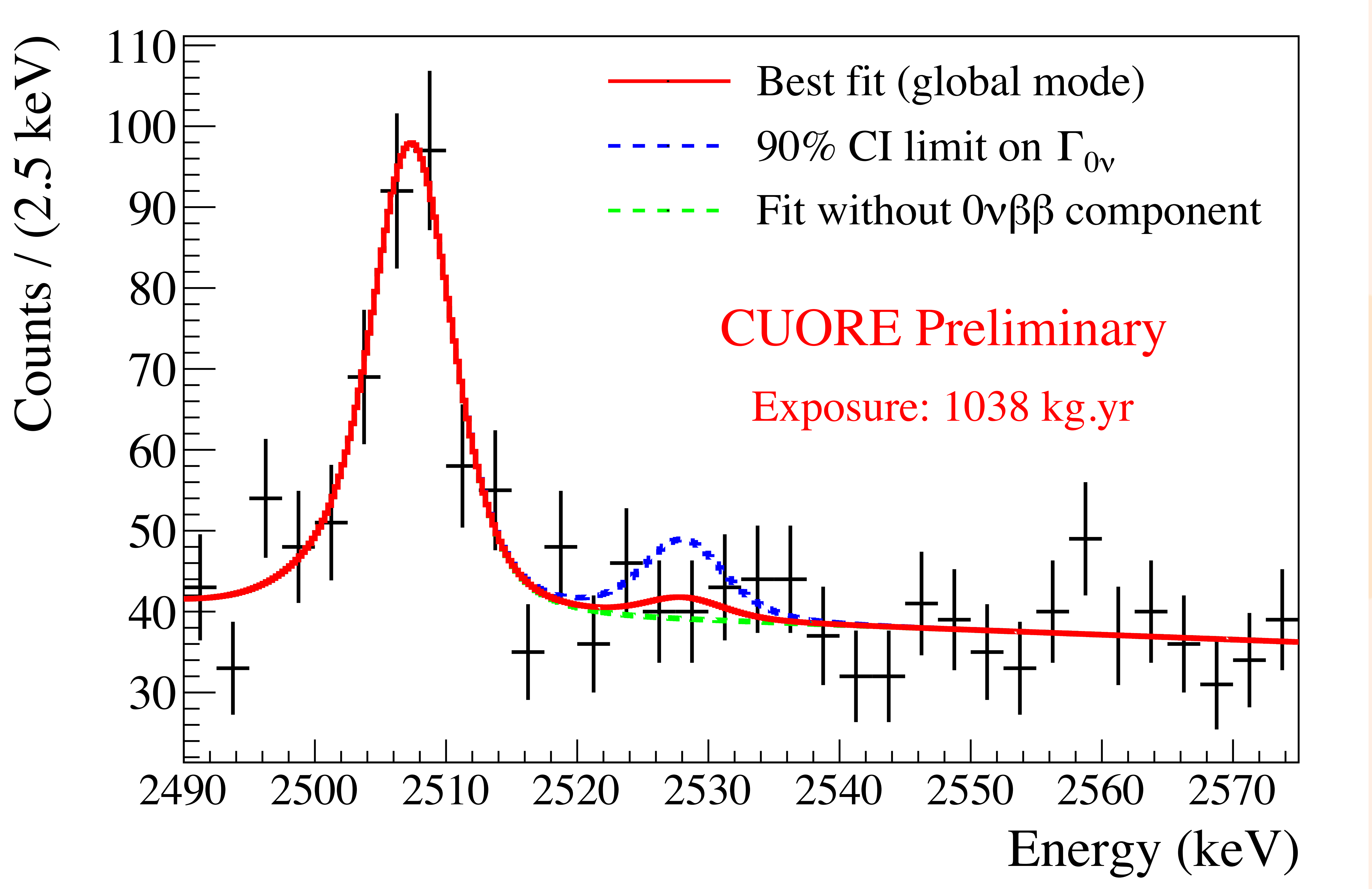


- Base cuts: trigger, reconstruction, pileup, external noise (earthquakes) → 96.4% efficiency
- Accidental-Coincidence → 99.3% efficiency
- PCA-based PSD → 96.4% efficiency

1ton-year analysis - ROI background & fit

- Bayesian analysis with BAT (Bayesian Analysis Toolkit)
- Limit on the half-life at 90% C.I.: $T^{0\nu}_{1/2} > 2.2 \times 10^{25}\,\mathrm{yr}$

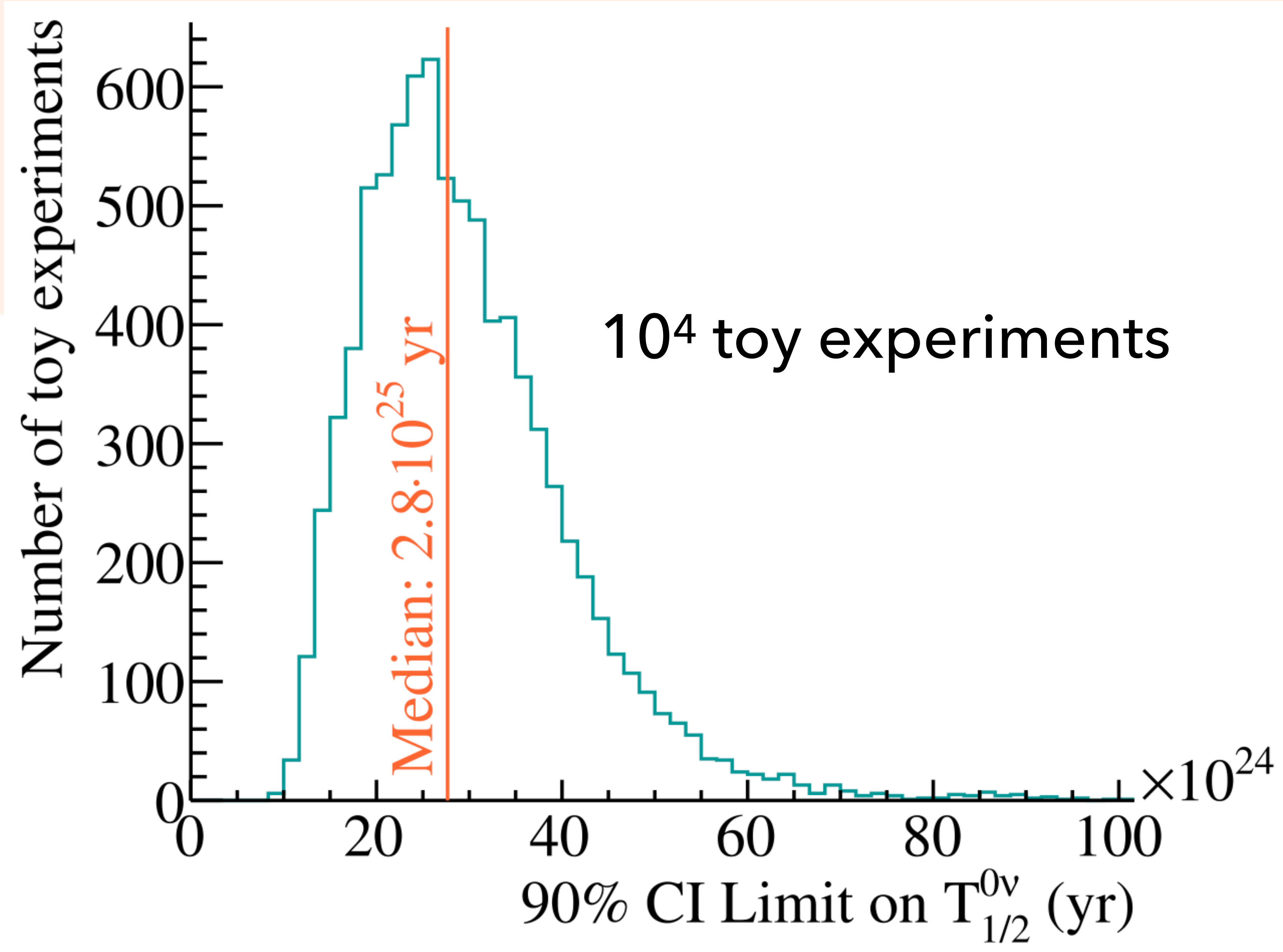


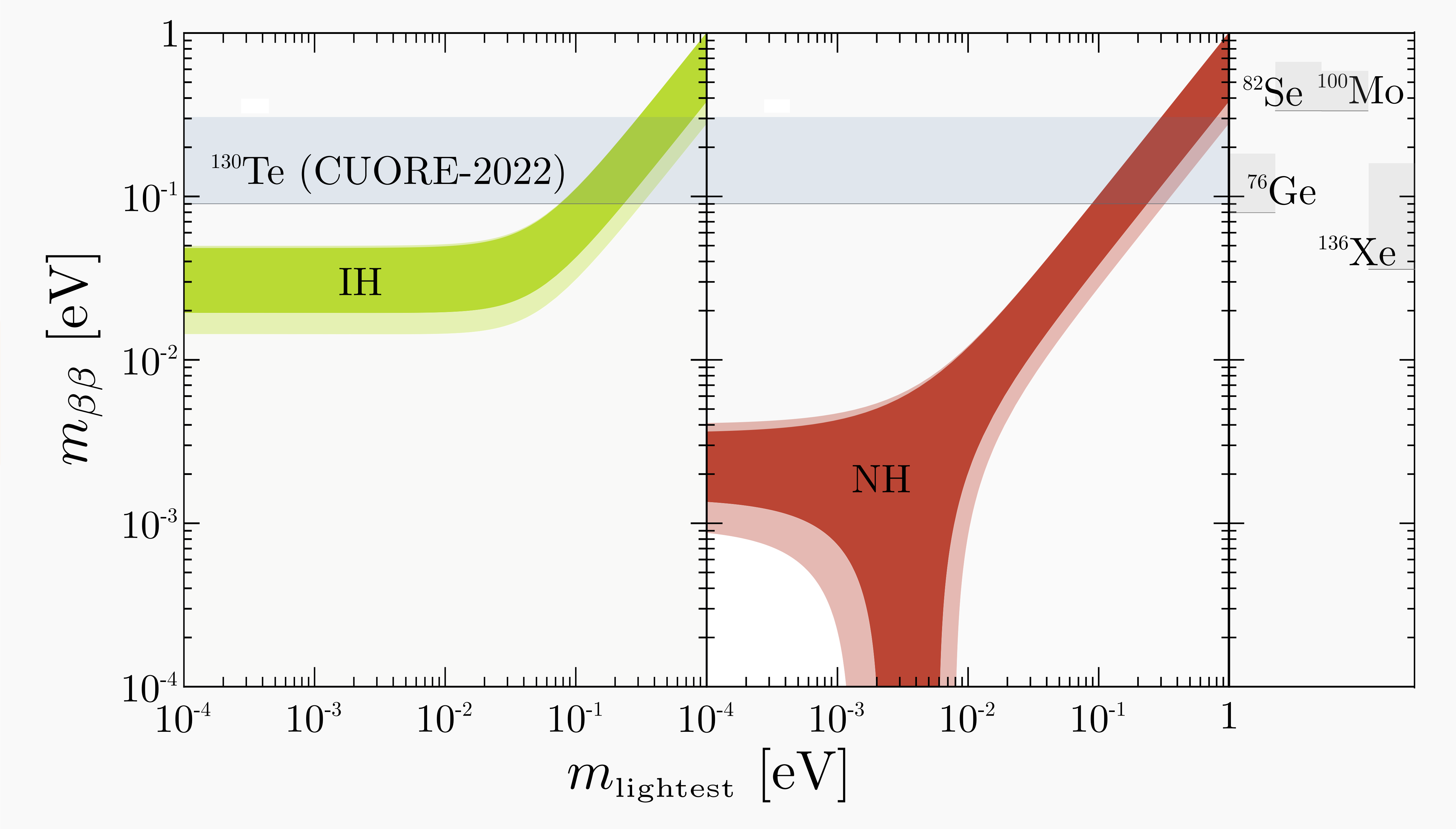


Nature 604 (2022) 7904, 53-58

1ton-year analysis - Sensitivity

- Median 90% exclusion sensitivity $T^{0\nu}_{1/2} > 2.8 \times 10^{25}$ yr
- Limit on the effective Majorana mass: $m_{\beta\beta} < 90 - 305$ eV (90% C.I.)





Nature 604 (2022) 7904, 53-58

Background model

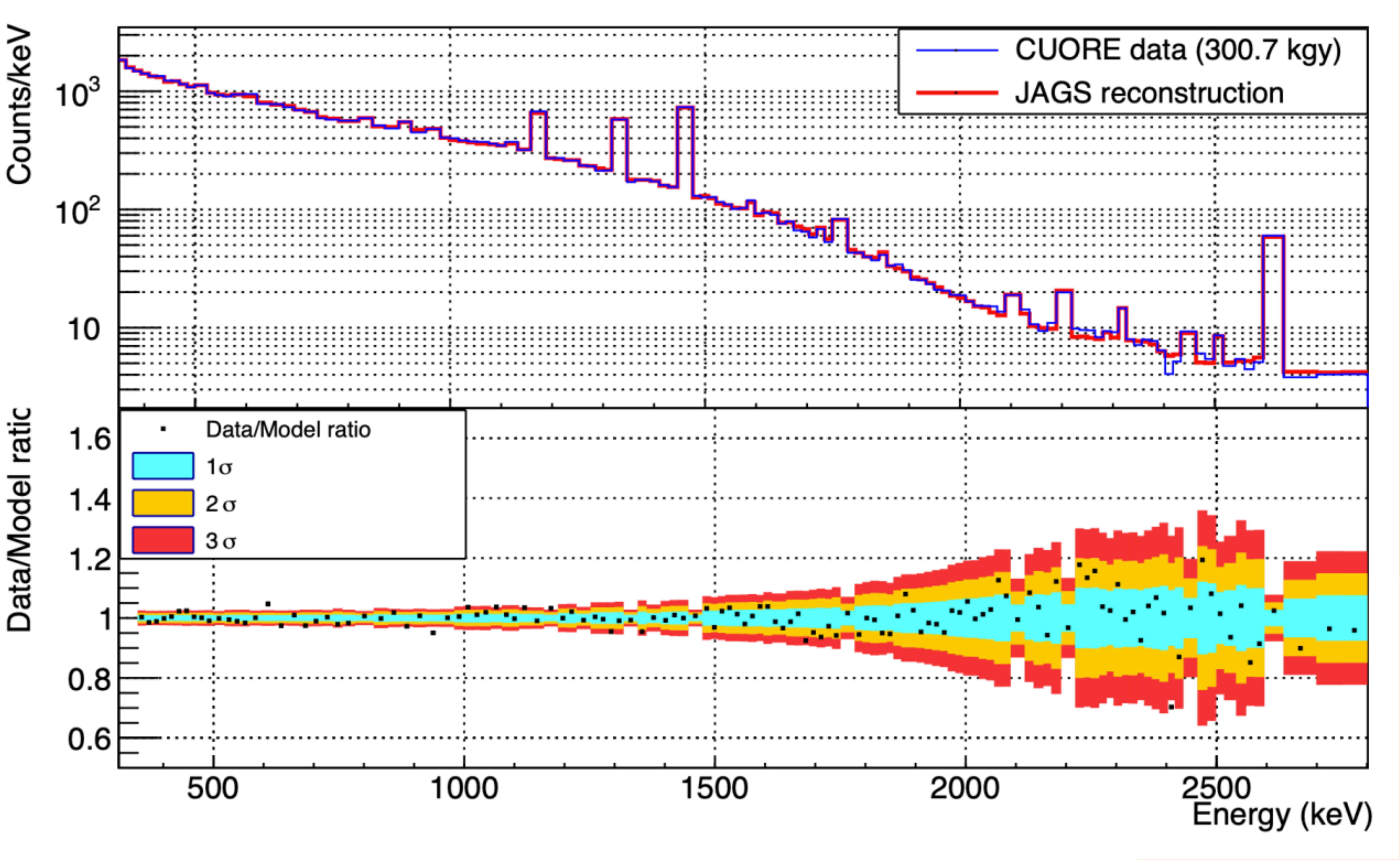
Reproduce the CUORE background considering geometry and materials with a Geant4 based software (62 contaminants)

↓

Smear the detector response feature with the Geant4 output

↓

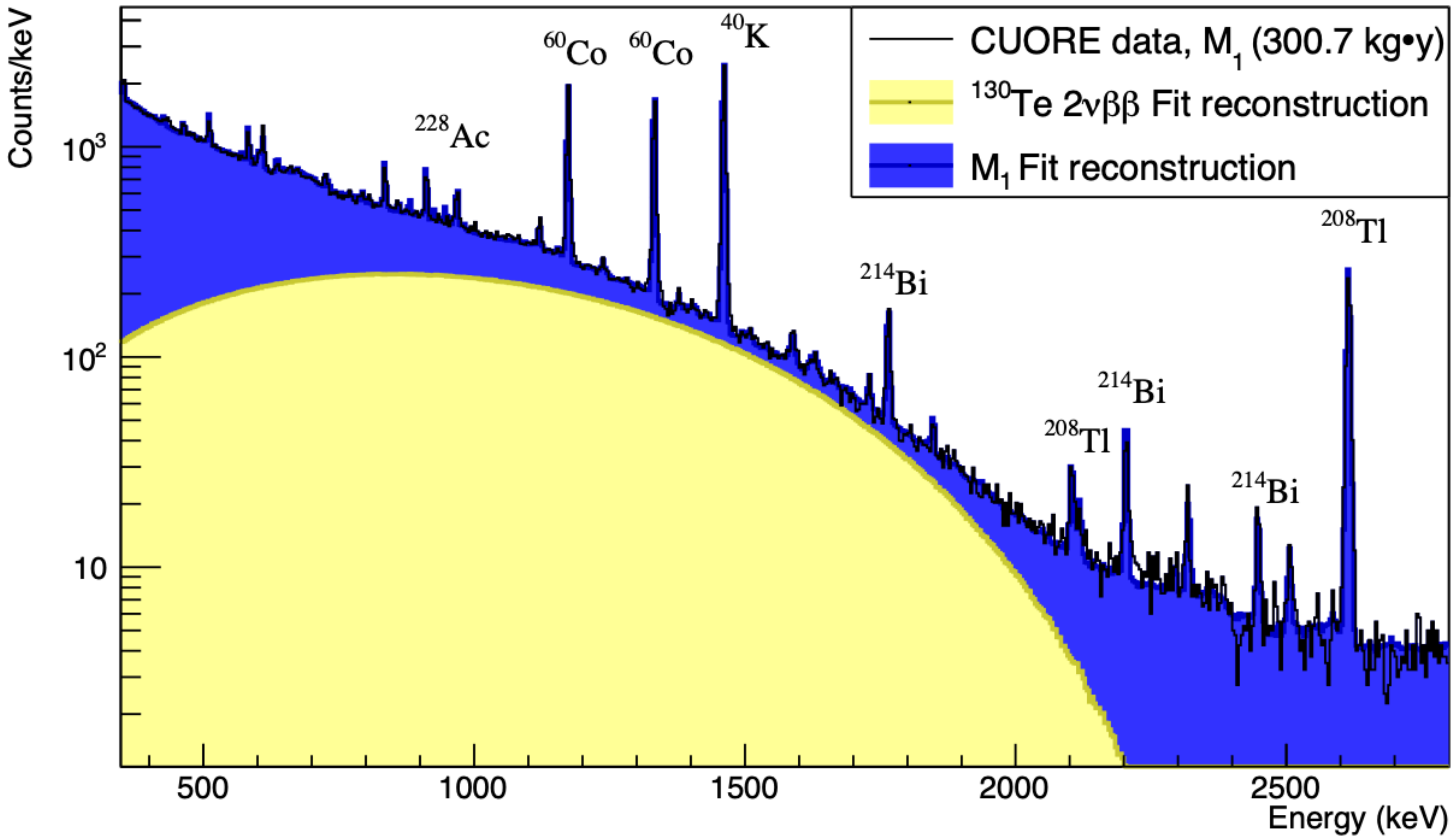
MCMC binned Bayesian fit of the generated simulations to data with JAGS



Final results are coming soon!

Two neutrino double beta decay

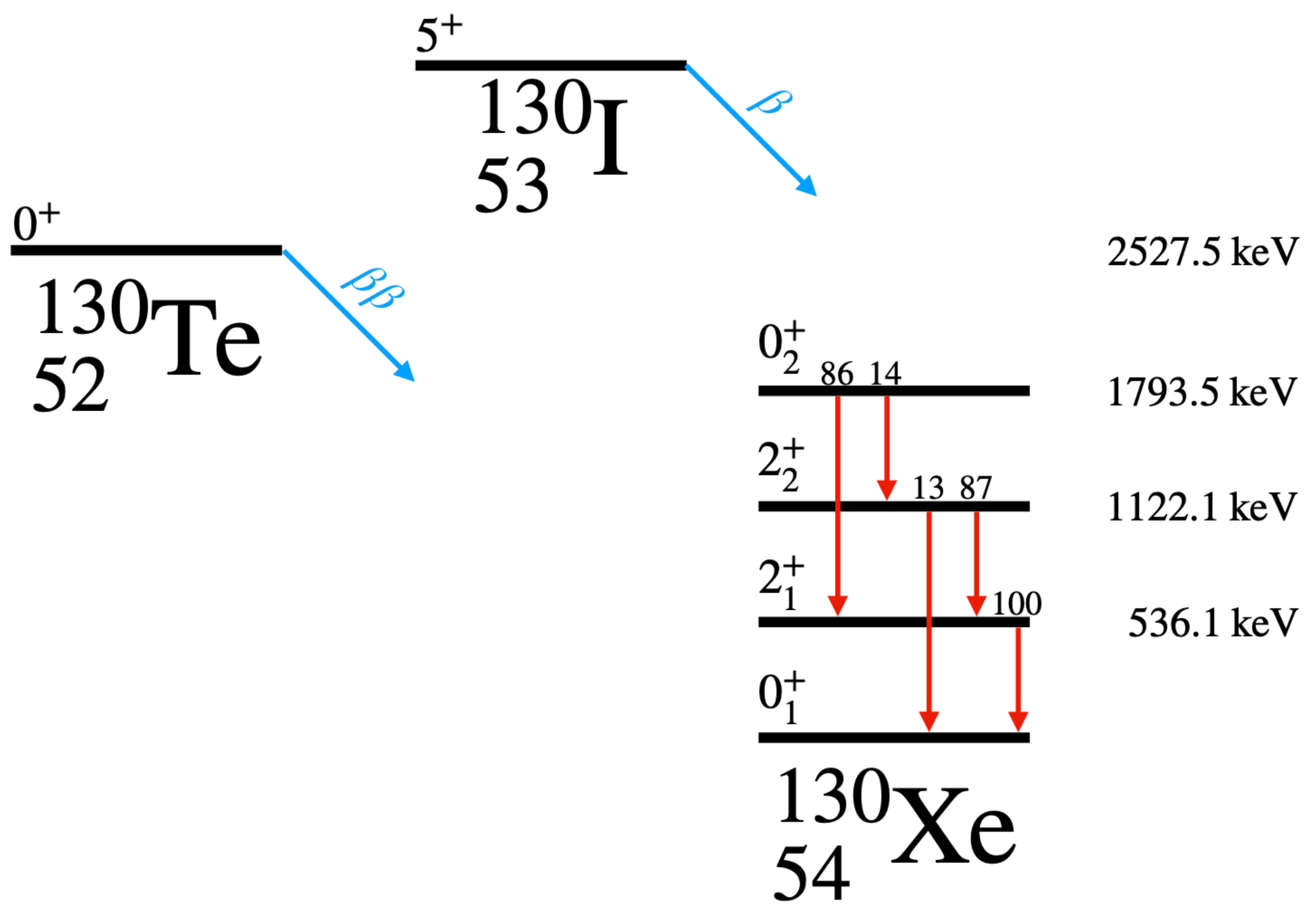
Most precise ^{130}Te $2\nu\beta\beta$ half-life to date → $T^{2\nu}_{1/2} = 7.71^{+0.08}_{-0.06}(\text{stat.})^{+0.12}_{-0.15}(\text{syst.}) \times 10^{20}$ yr

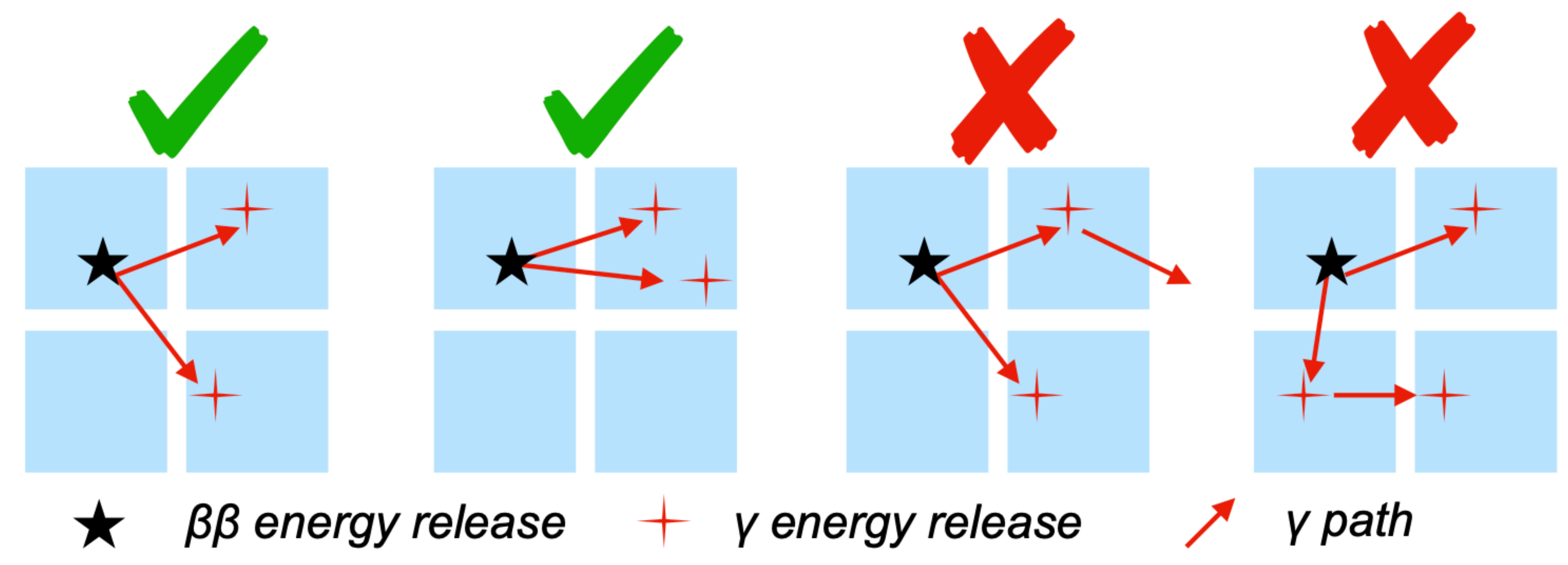


- 300.7 kg.yr of TeO_2
- 350 keV analysis threshold
- Data-MonteCarlo fit
- Assuming Single State Dominance
- Will be updated with more exposure

Phys. Rev. Lett. 126, 171801

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

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

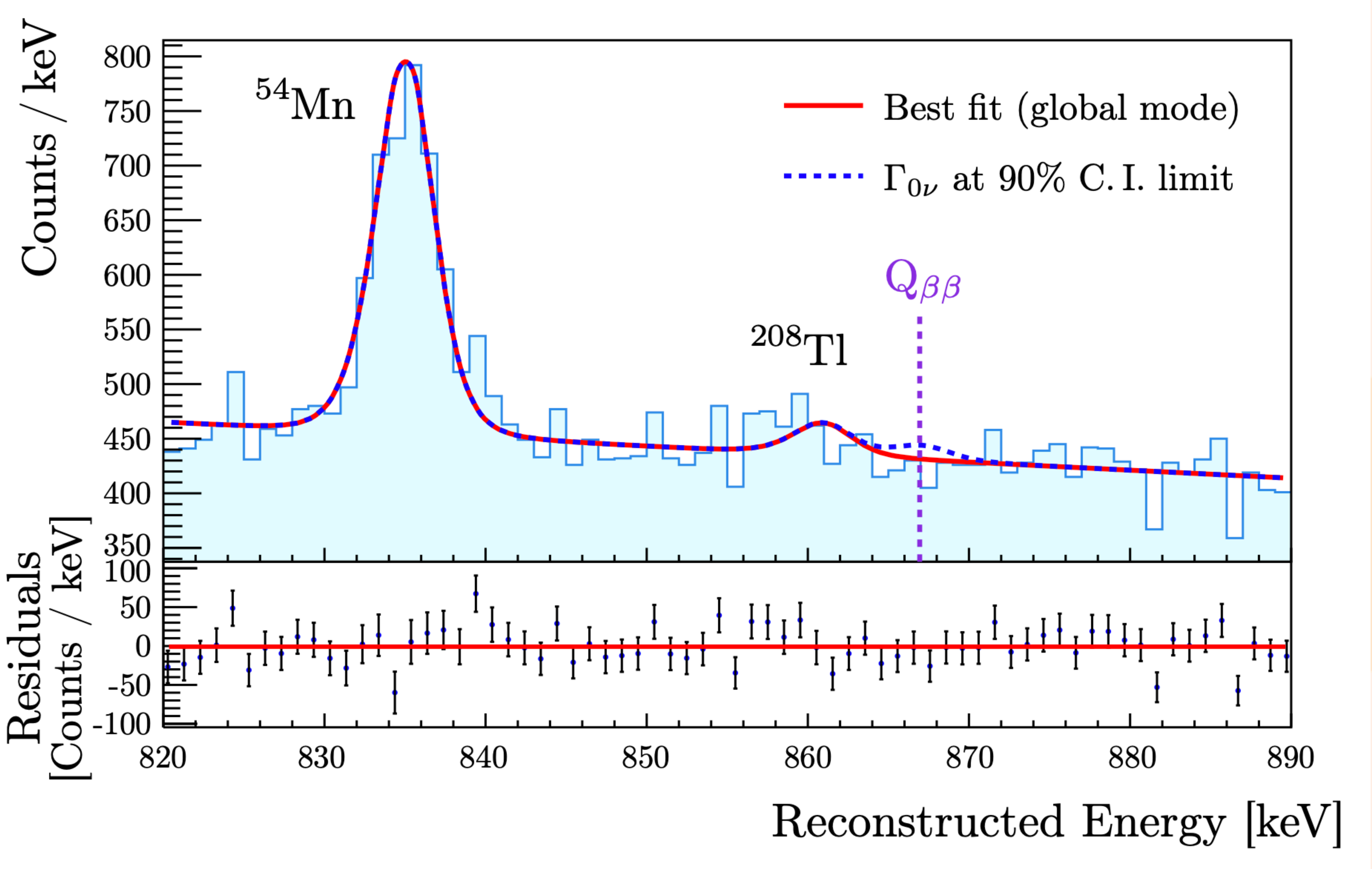
$$T_{1/2}^{2\nu} > 1.3 \times 10^{24} \text{ yr at } 90\% \text{ C.I.}$$

Eur.Phys.J.C 81 (2021) 7, 567

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

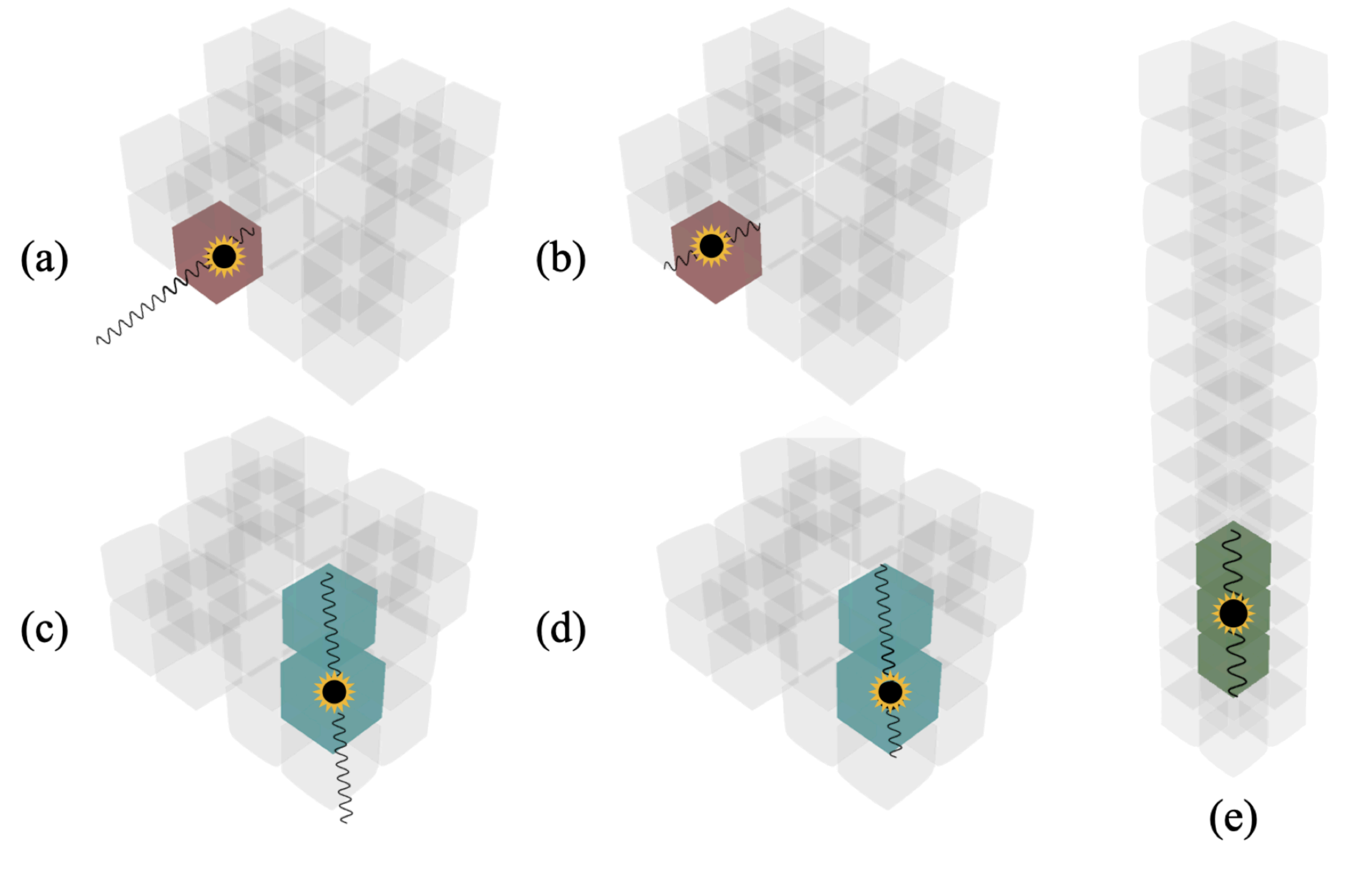


$$T^{0\nu}_{1/2} > 3.6 \times 10^{24} \text{ yr (at 90 \% C.I.)}$$

Neutrinoless $\beta^+ EC$ decay of ^{120}Te

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

- Clear signature:
  $^{120}Te + e^- \rightarrow ^{120}Sn + X + 2\gamma_{511}$
- 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



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

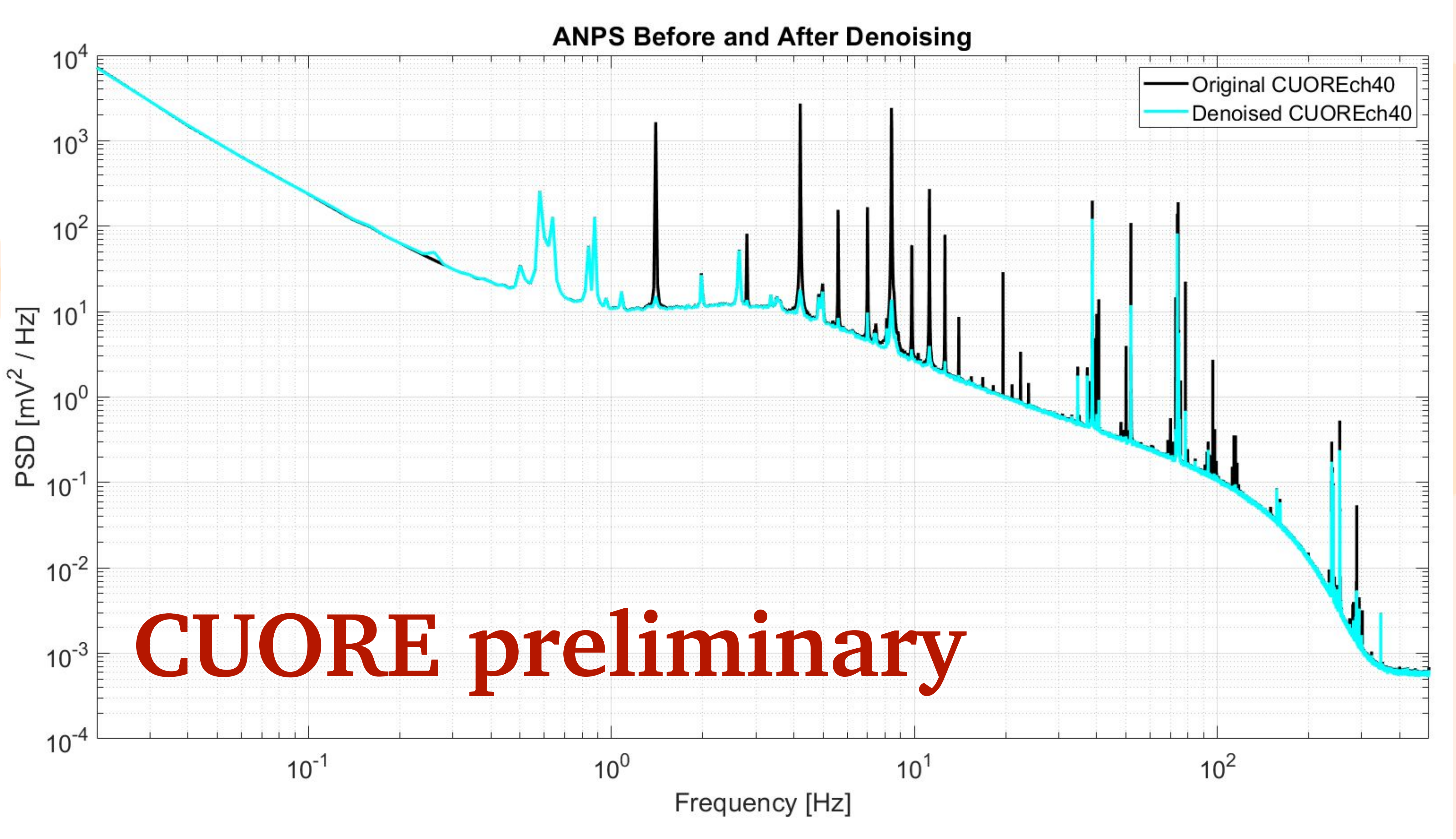
Signature	Particles Detected	Signal Peak Position [keV]	Multiplicity	Energy range [keV] ΔE_0	ΔE_1	ΔE_2	Containment efficiency ε_{mc} [%]
(a)	$\beta^+ + X + \gamma_{511}$	1203.8	1	[1150,1250]			12.8(5)
(b)	$\beta^+ + X + 2\gamma_{511}$	1714.8	1	[1703,1775]			13.1(5)
(c)	$(\beta^+ + X,\ \gamma_{511})$	(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)

Future plans

- Data reprocessing for the 2-ton analysis with the de-noising, an algorithm developed to de-correlate the vibrational noise in the bolometers using diagnostic devices (accelerometers, antennas etc…)

- Keep taking data still ~2024

- Many other analyses:
  - Tri proton Decay
  - Axion searches
  - $2\nu\beta\beta$ spectral shape studies
  - Etc…



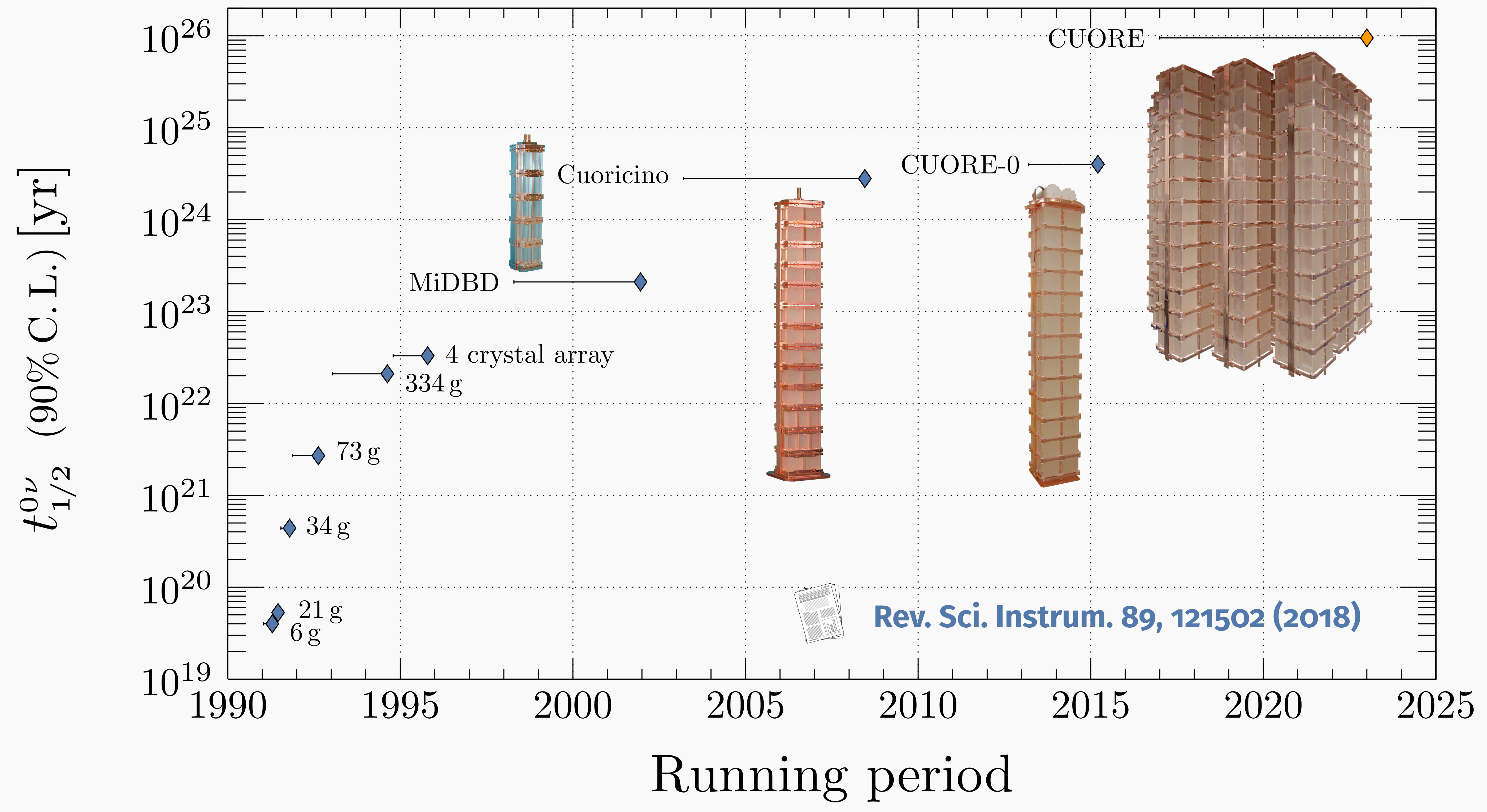
Stay tuned!!

Thanks for the attetion

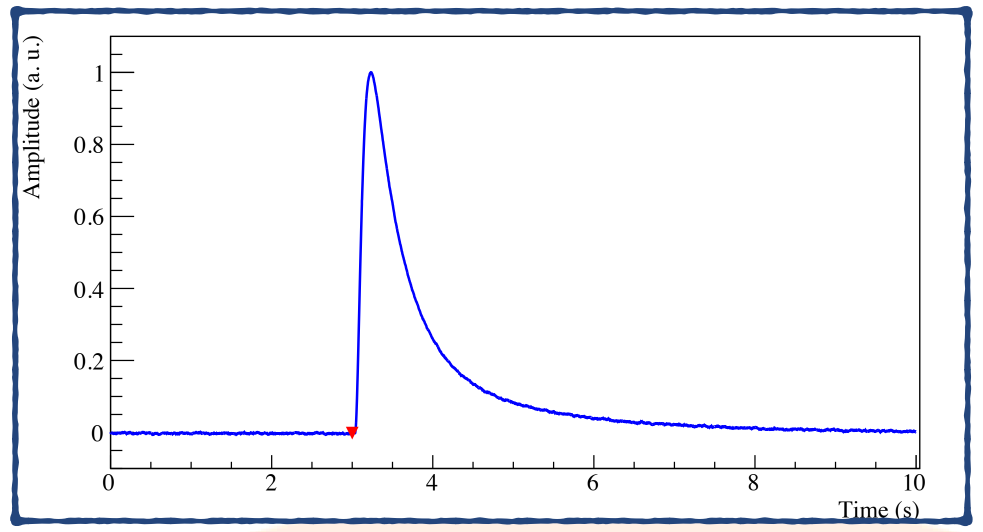
Backup

A long path...

- 30 years of technical development for crystal growing, low temperature cryogenic, material handling, computing resources,...
- CUORE is the last of a long series of experiments, from few grams to 741 kg of detector material
- First ton-scale bolometric experiment in the world



Analysis workflow



→ Optimum filter → Gain correction → Energy calibration ↓ coincidences ↓ Pulse shape discrimination ↙ Salting in the ROI ← Selections ← Unblinding

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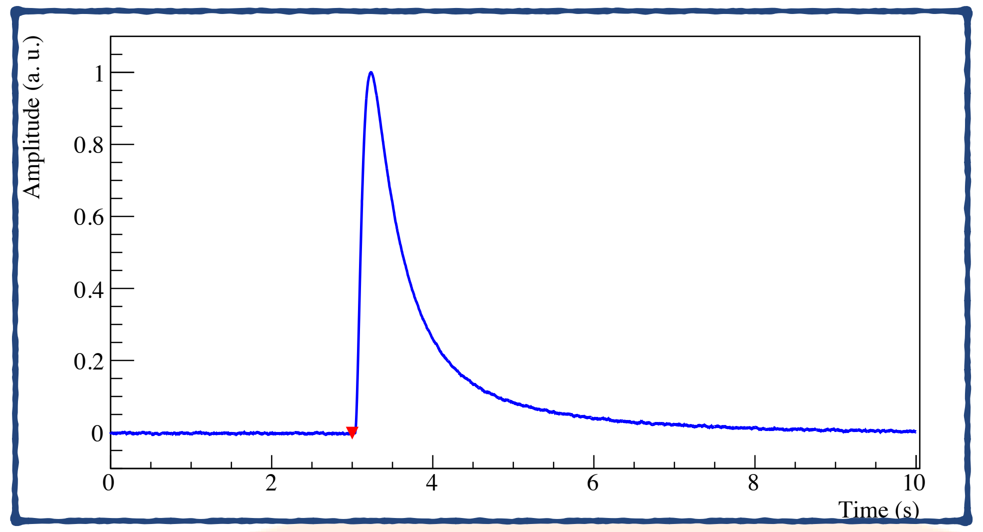

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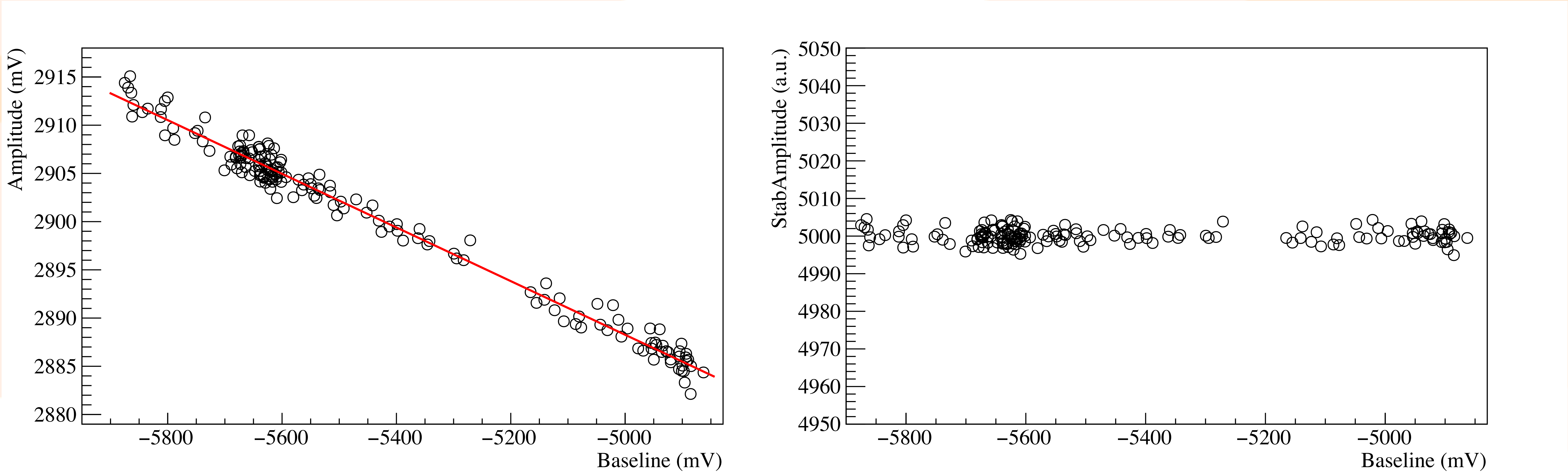
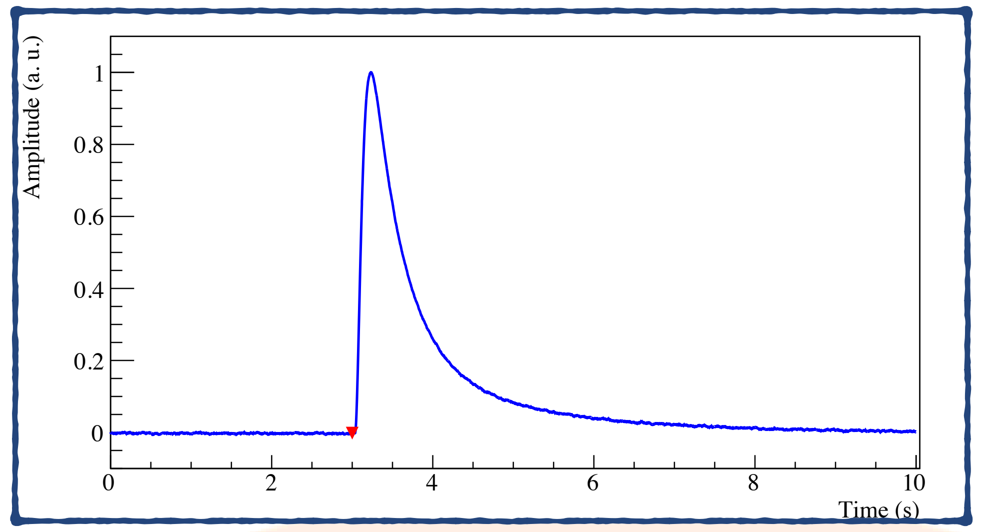
Heater thermal gain stabilization



Analysis workflow



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