Latest results from the CUORE experiment

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CUORE

INFN Istituto Nazionale di Fisica Nucleare

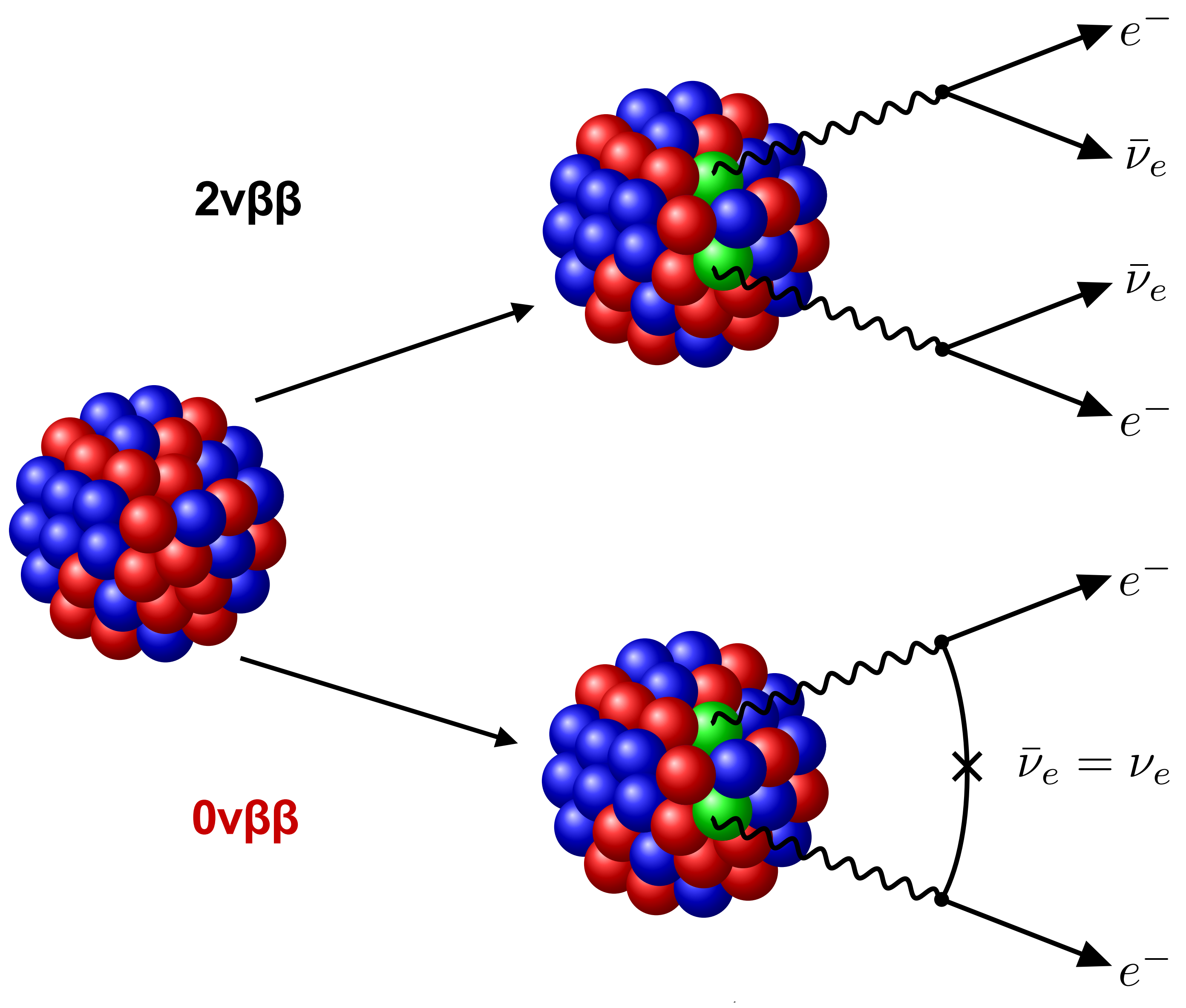
Sapienza Università di Roma

22nd edition Particles and Nuclei International Conference - Sep the 8th, 2021

Neutrinoless double beta decay (0νββ)

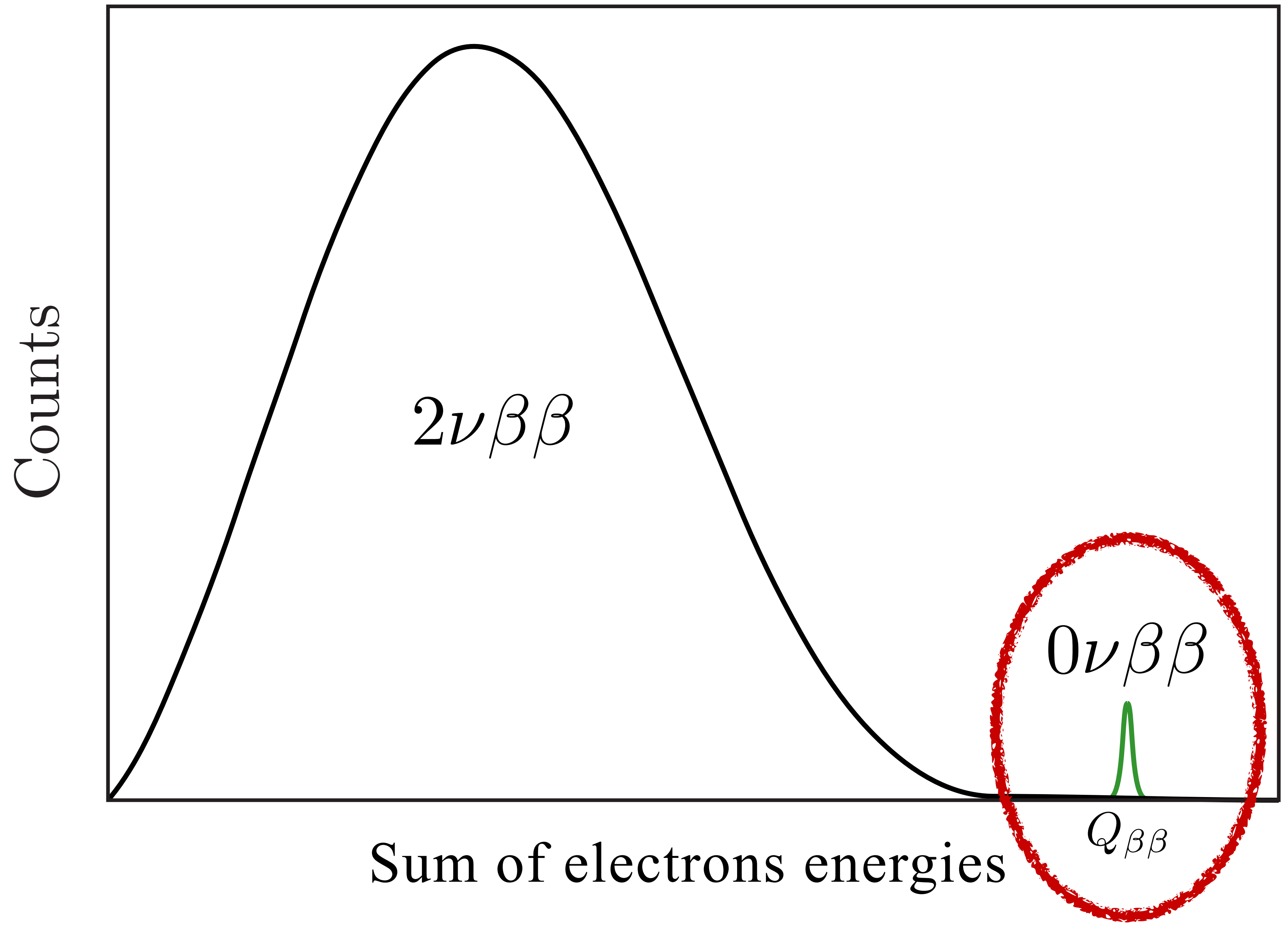
Double beta decay:

- Rare second order Fermi weak nuclear transition
- Candidates: even-even nuclei, when single β decay energetically forbidden



Standard Model allowed, observed in 11 nuclei

Beyond Standard Model, not yet observed



- Lepton number violating process: ΔL = 2 , would demonstrate that **L is not a symmetry of nature**
- Only possible if neutrinos have a **Majorana component ($\nu = \bar{\nu}$)**: new possible mechanism giving rise to ν mass
- Possible explanation of **matter-antimatter asymmetry** origin via Leptogenesis

CUORE: Cryogenic Underground Observatory for Rare Events

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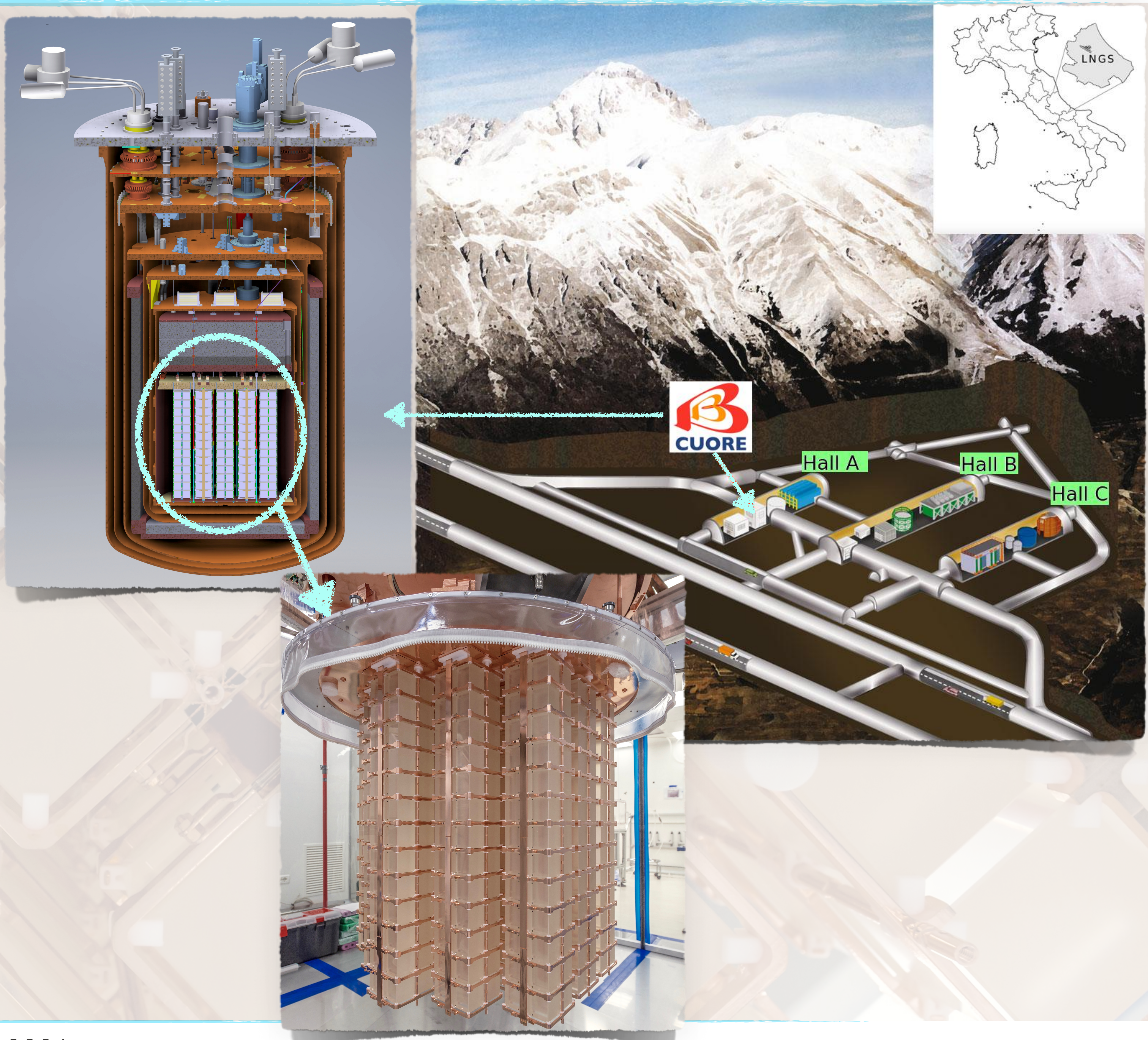
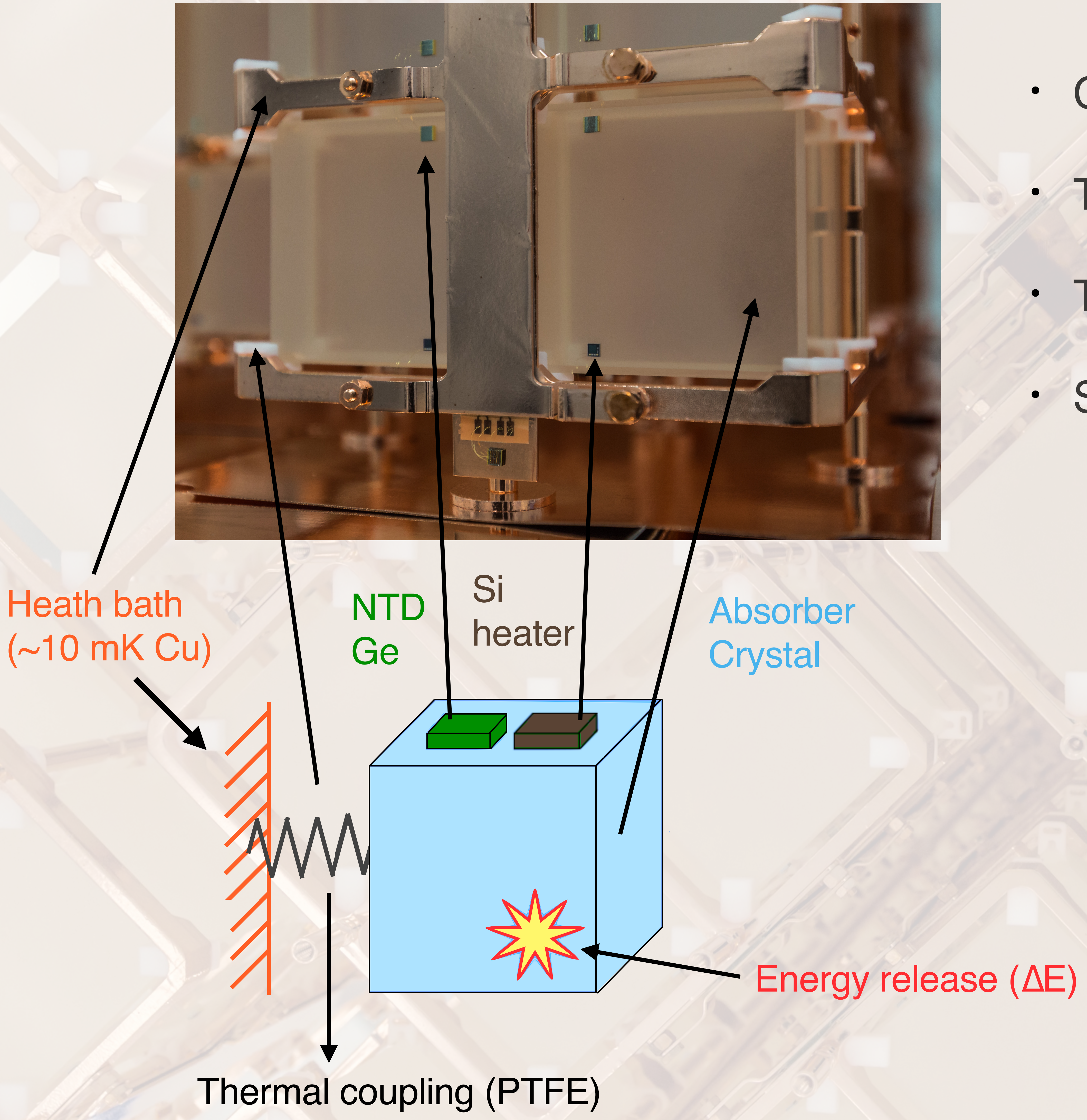
- Main Physics goal: search for $0\nu\beta\beta$ decay of ^{130}Te ($Q_{\beta\beta} \sim 2528$ keV)
- Located at the underground Laboratori Nazionali del Gran Sasso of INFN: 3650 m.w.e. of rock coverage to suppress the cosmic radiation
- 988 natural TeO_2 crystals (742 kg of TeO_2, 206 kg of ^{130}Te) arranged in 19 towers
- ^{130}Te embedded in the detector itself: ~90% detection efficiency
- Crystals operated as calorimeters at ~10 mK



The CUORE experimental technique



- Crystal: solid state detector working as calorimeter
- TeO_2 absorber where the particle energy is deposited
- The temperature variation is measured by the thermal sensor (NTD Ge)
- Si heater periodically injecting a fixed energy for the thermal gain stabilization

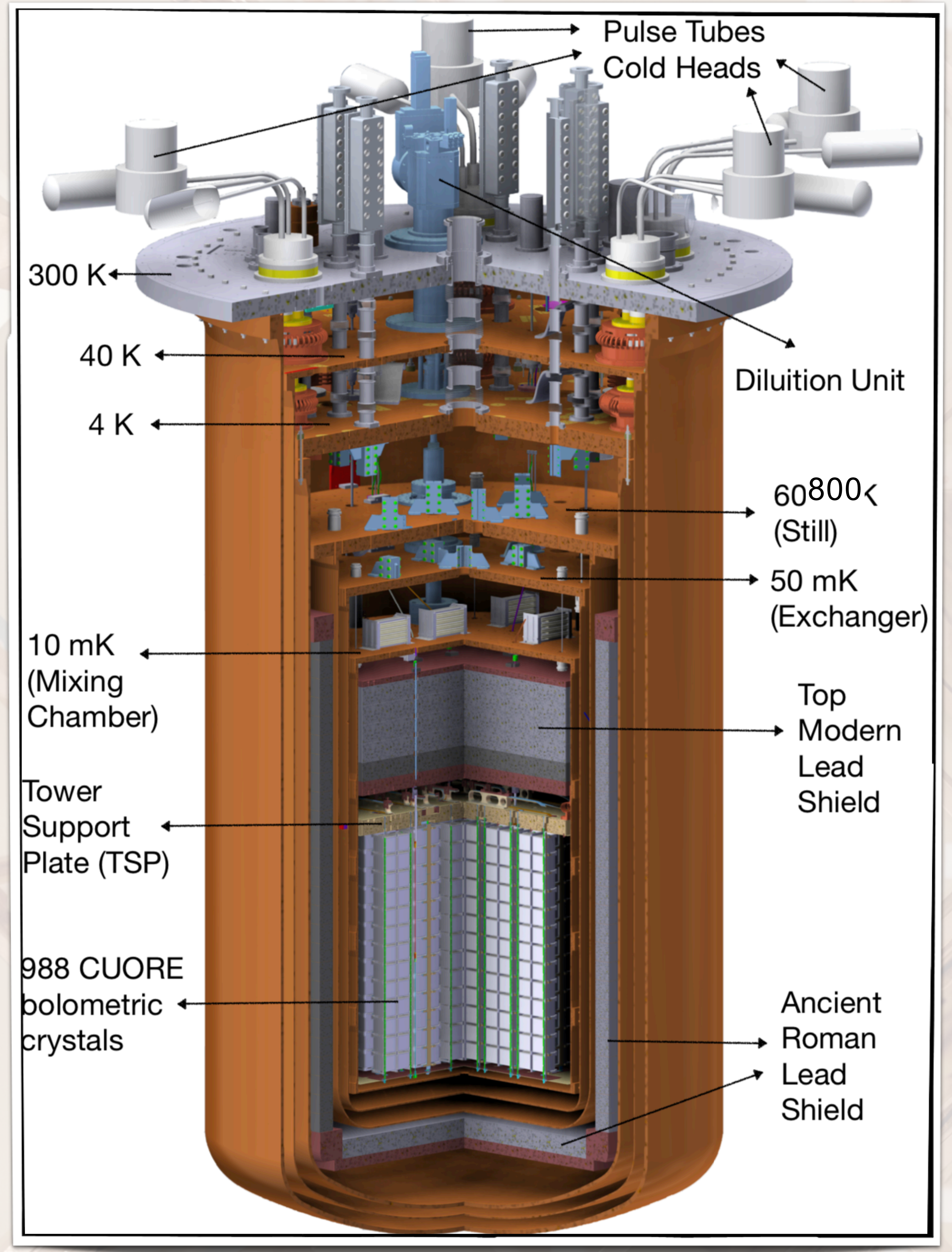
$$\Delta T = \frac{\Delta E}{C}$$

heat capacity: $C_{TeO_2} \propto T^3$

$T_0 = 300$ K: $\Delta E = 1$ MeV ⟶ $\Delta T \sim 10^{-18} - 10^{-15}$ K

$T_0 = 10$ mK: $\Delta E = 1$ MeV ⟶ $\Delta T \sim 0.1$ mK

The CUORE Challenges

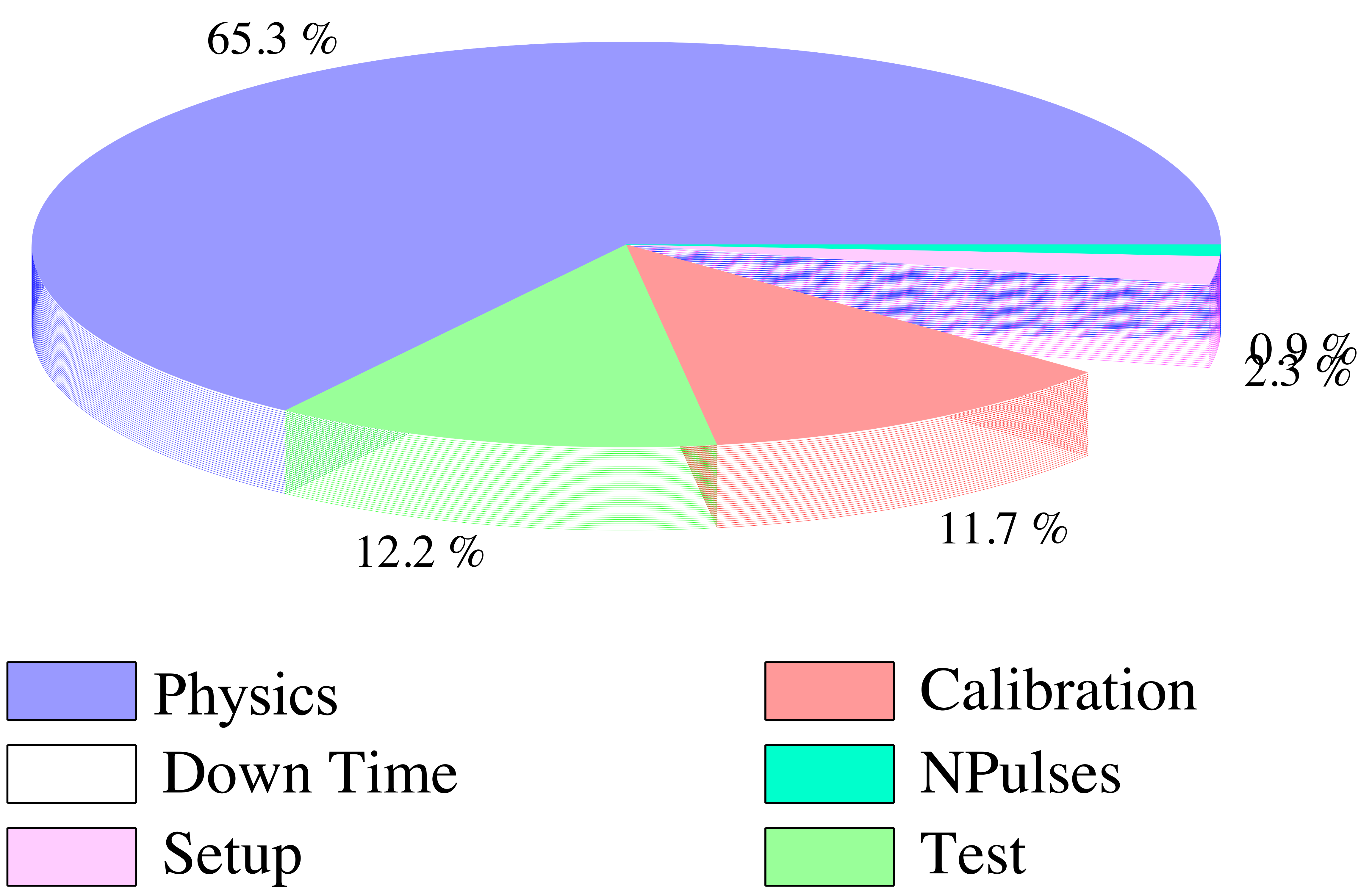


- Ton-scale infrastructure cooled down by a custom built cryogen-free structure: 5 pulse tubes + $^{3}He/^{4}He$ Dilution Refrigerator
- Operational T ~ 10 mK stable over years
- Background level goal of 10^{-2} counts/(keV·kg·yr):
  - ➡ low-radioactivity materials choice, strict cleaning and assembling protocols
  - ➡ Roman ^{210}Pb-depleted + modern lead shields
  - ➡ Neutrons shield: external polyethylene layer with boric acid panels
- Energy resolution < 8 keV FWHM at ^{130}Te $Q_{\beta\beta}$:
  - ➡ Minimization of vibrational noise: external support structure mechanically decouples the detectors from the cryostat

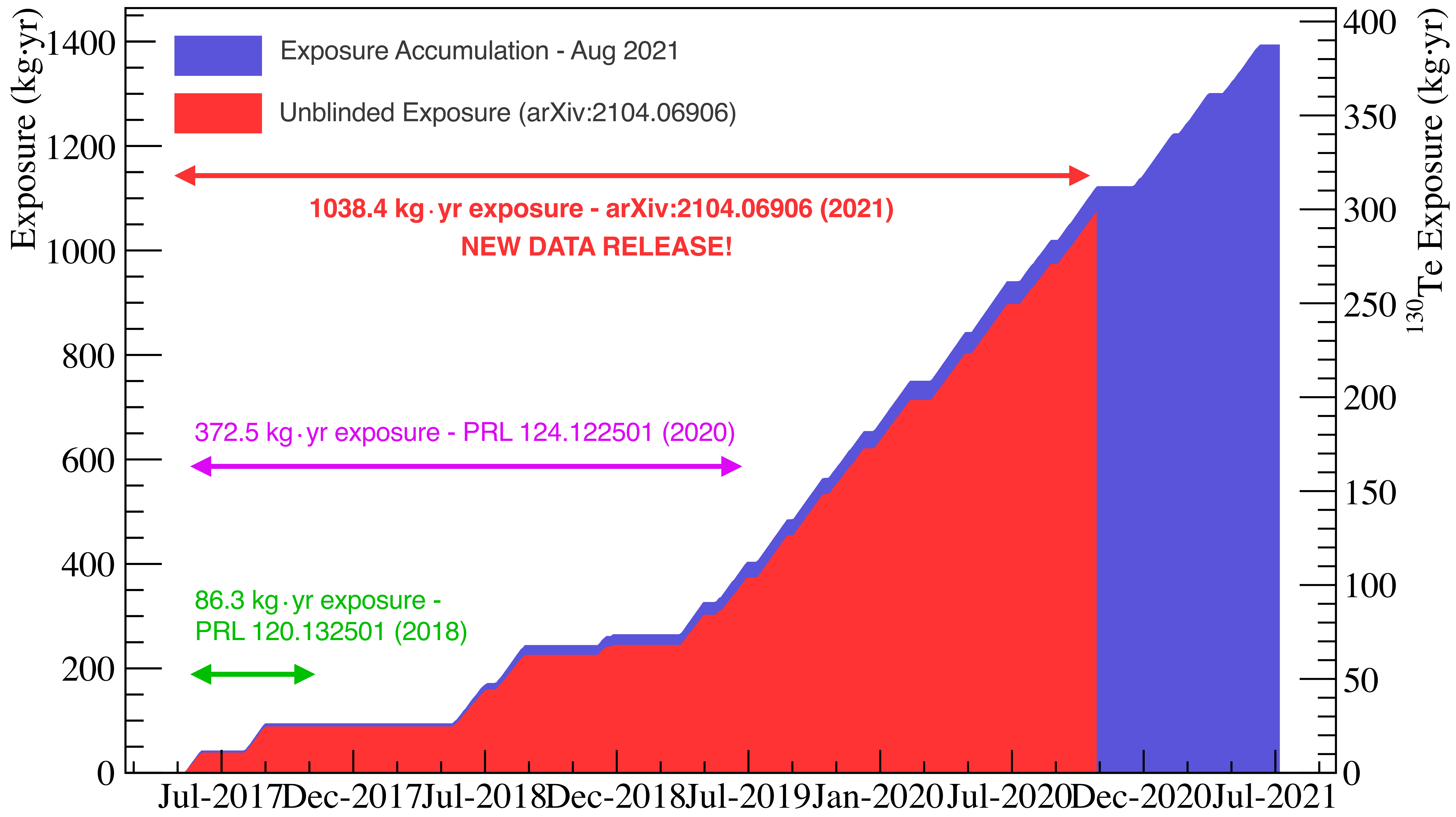
The CUORE data collection

- Data taking organization: *runs* (physics, calibration, test,…)
- 1 *Dataset* (40 - 60 days) = initial calibration runs + physics runs + final calibration runs
- CUORE data taking started in Spring 2017
- 2017 - beginning of 2019: mostly devoted to cryogenic interventions and detector optimizations
- **From 2019 on: duty cycle improved from 36.1% to 92.4% (65.3% of physics data)**
- **CUORE data taking is proceeding smoothly (~69 kg · yr/month since spring 2019)**
- 5 years live time is foreseen

CUORE duty cycle: March 2019 - now



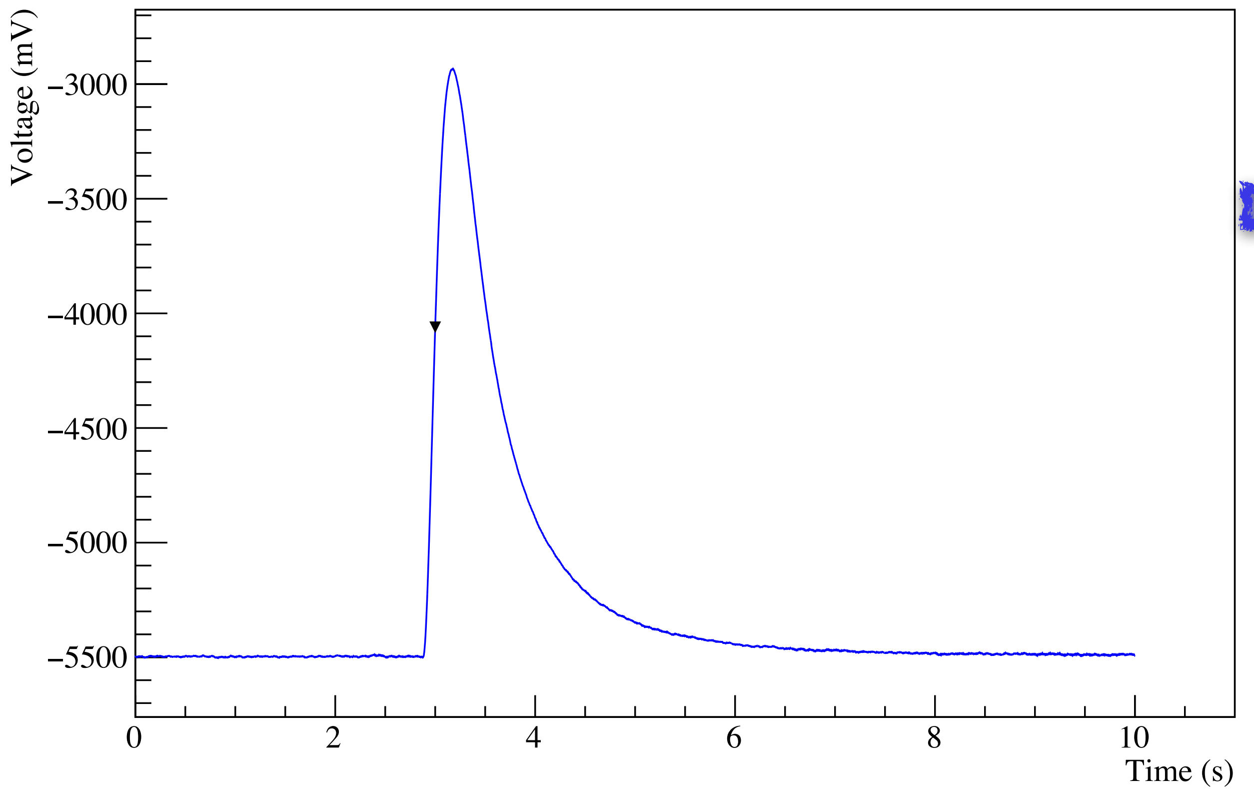
The CUORE data collection



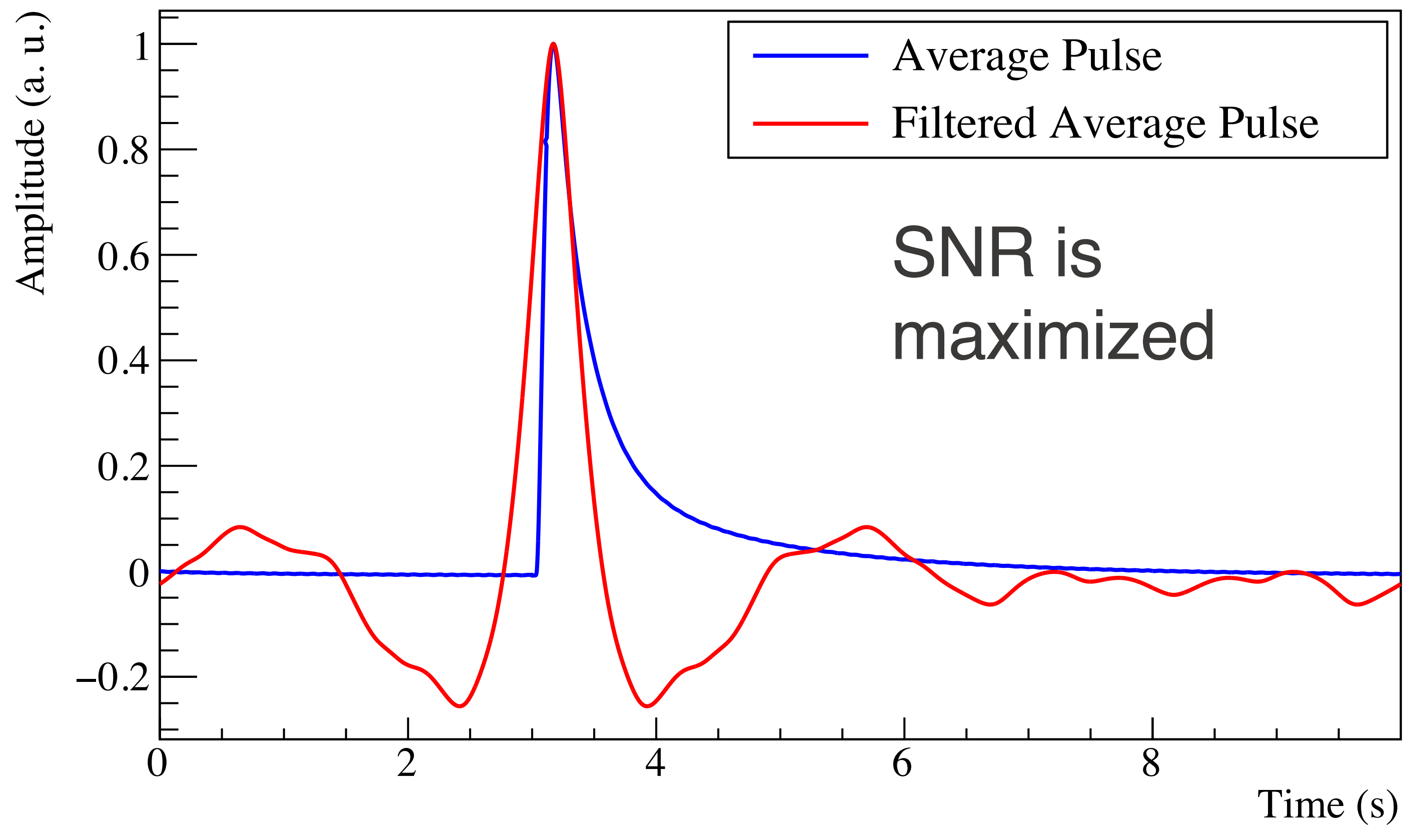
2021: 1-ton · yr analyzed exposure milestone!

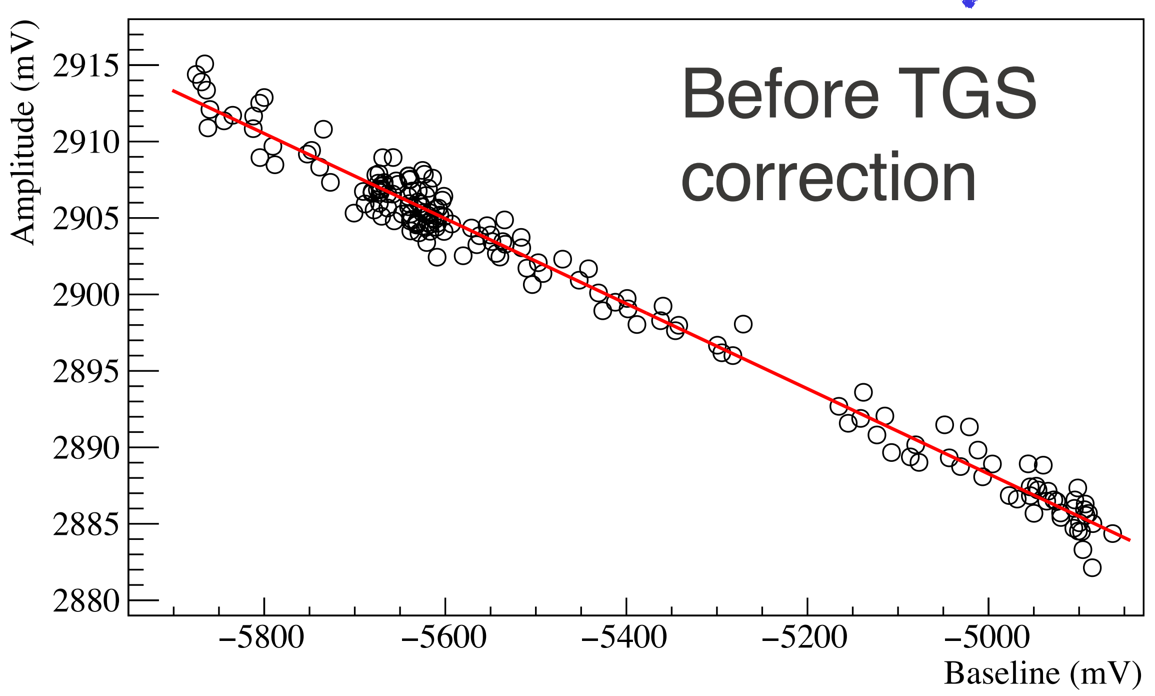
- Total collected raw exposure: 1409.28 kg · yr
- Total analyzed exposure: **1038.4 kg · yr**

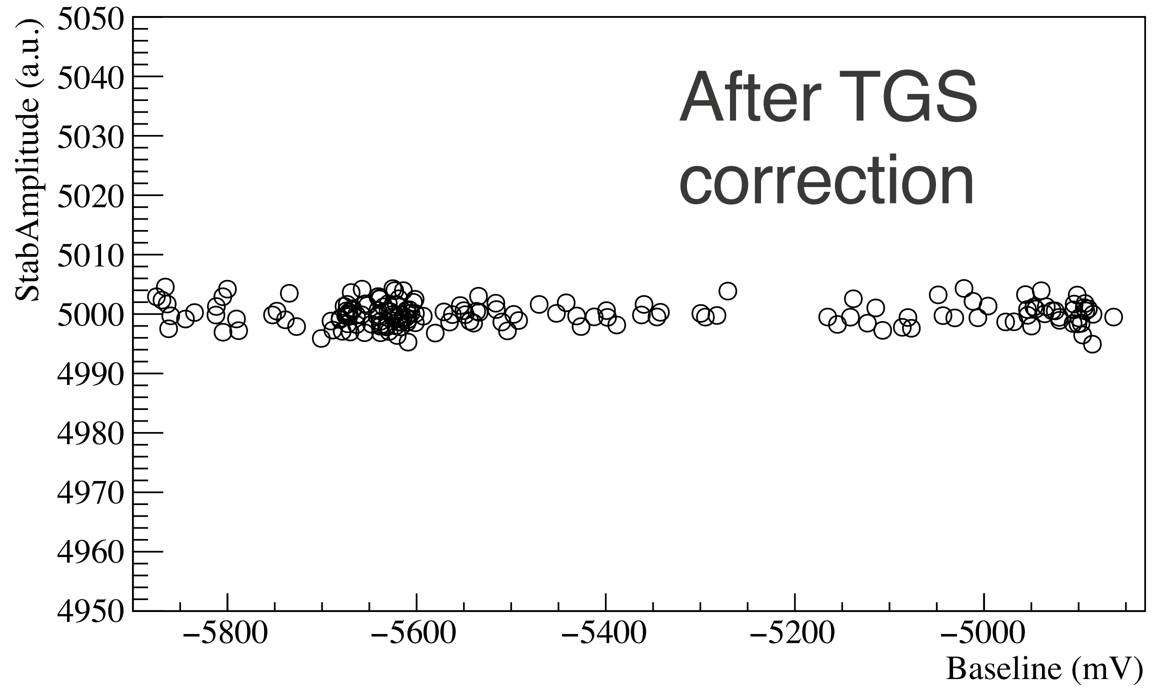
The CUORE data processing

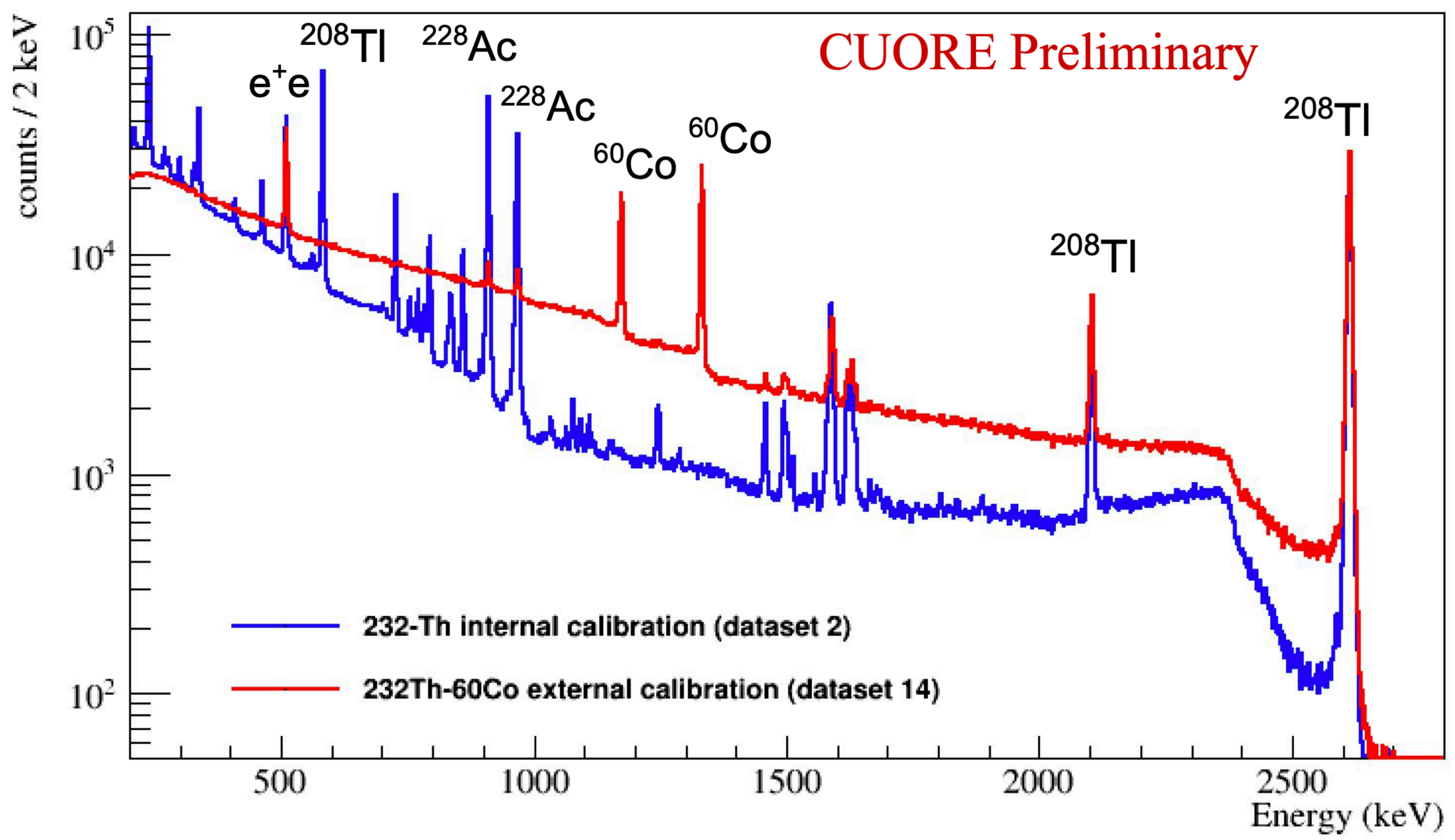


Amplitude (Optimum Filter) → **Thermal Gain Stabilization** → **Energy Calibration**





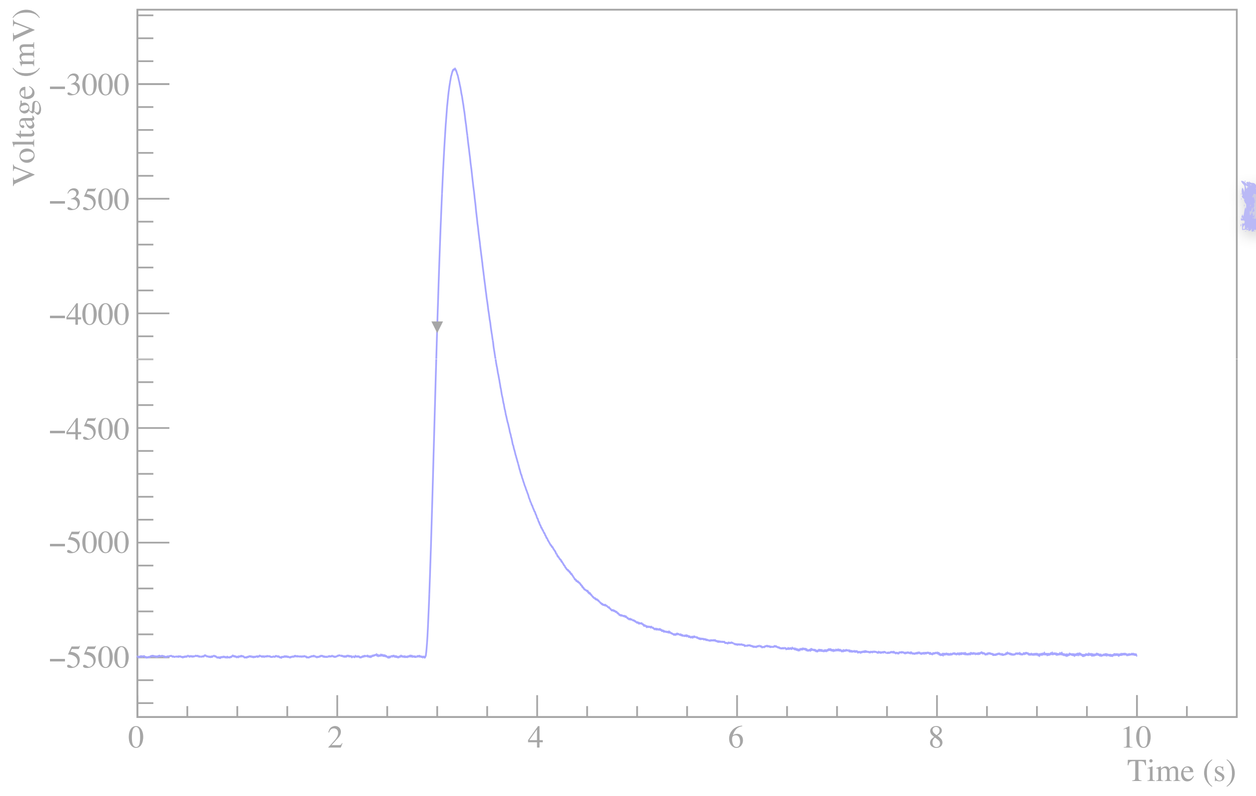




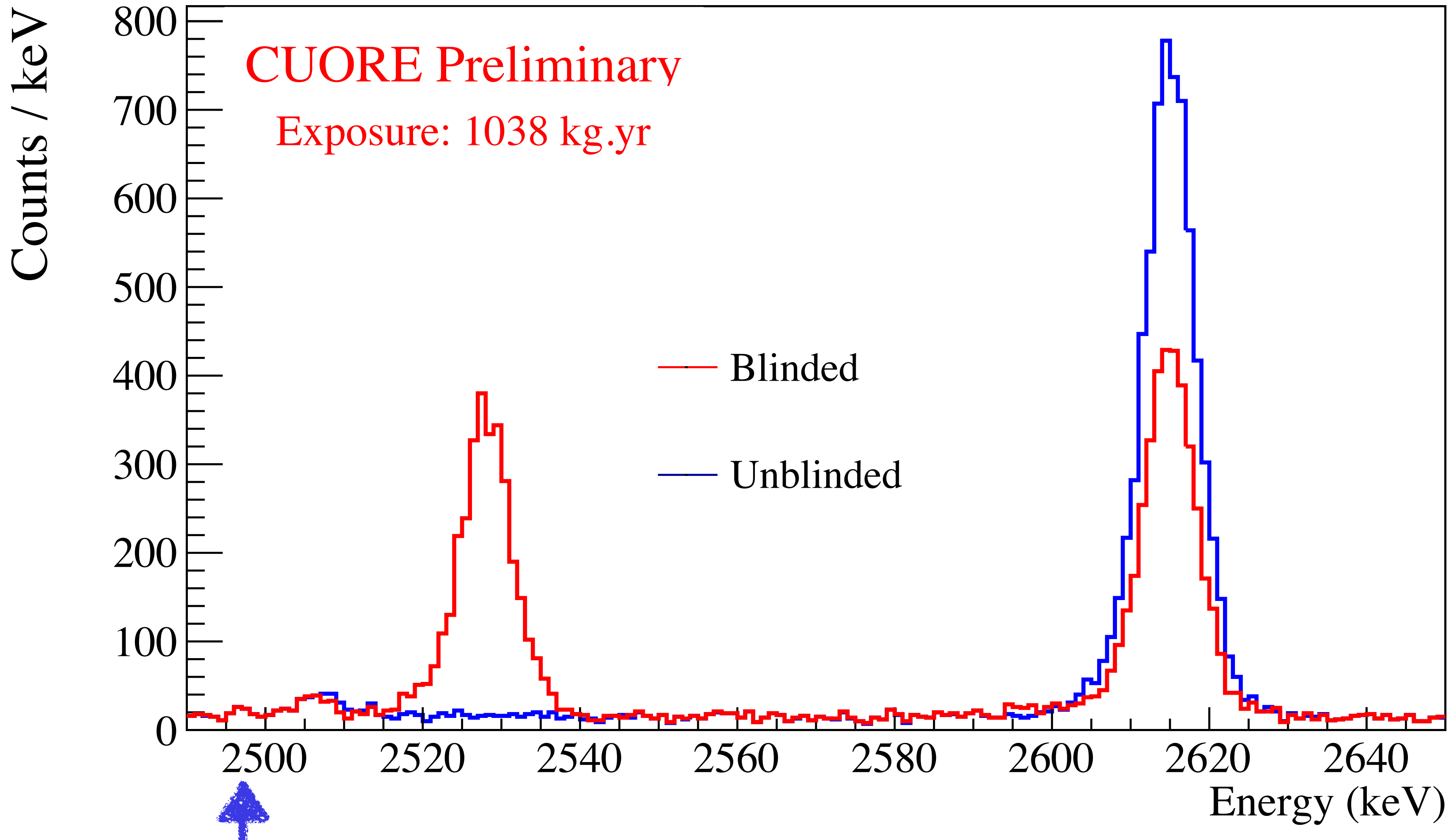
Stabilized amplitude is converted in Energy

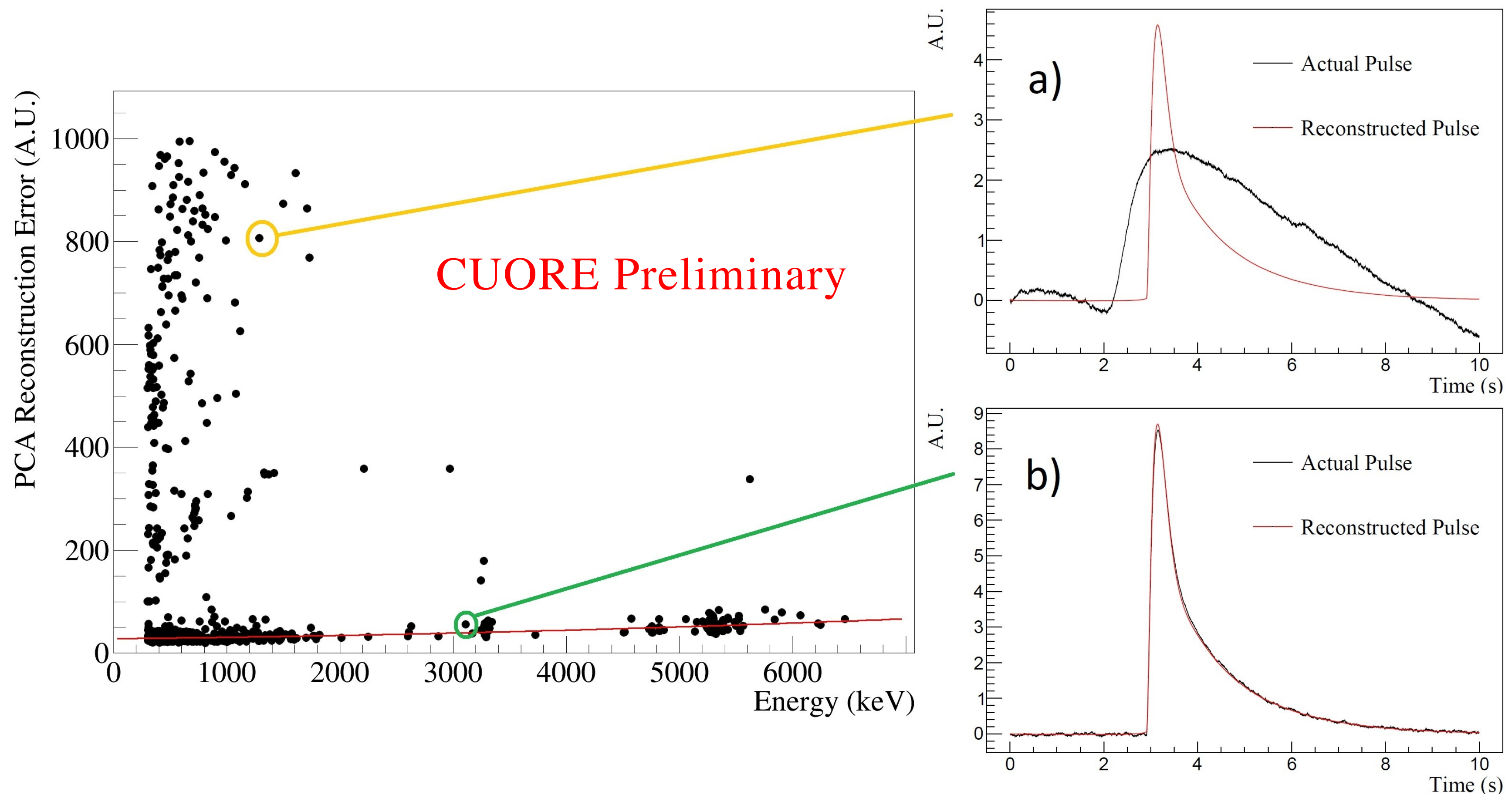
Coincidences → **Pulse Shape Discrimination** → **ROI Blinding** → **ROI fit optimization** → **Unblinding**

The CUORE data processing

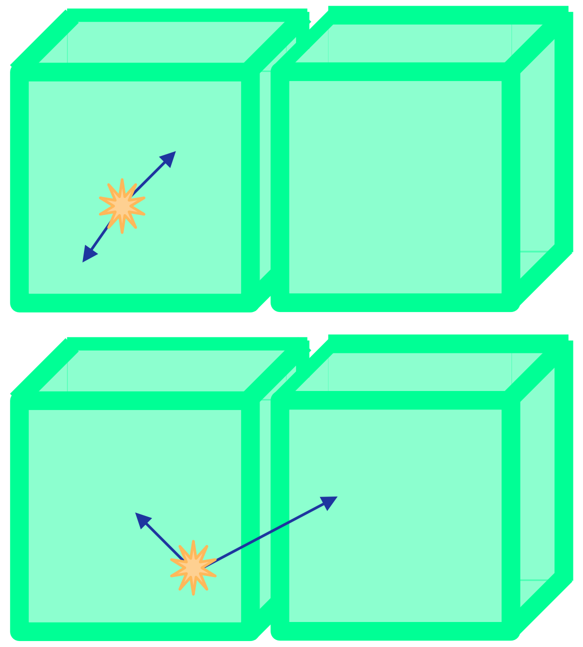


Amplitude (Optimum Filter) → Thermal Gain Stabilization → Energy Calibration → Coincidences → Pulse Shape Discrimination → ROI Blinding → ROI fit optimization → Unblinding





Principal Component Analysis: waveforms deviating from the average pulse (leading principal component) are poorly reconstructed and rejected

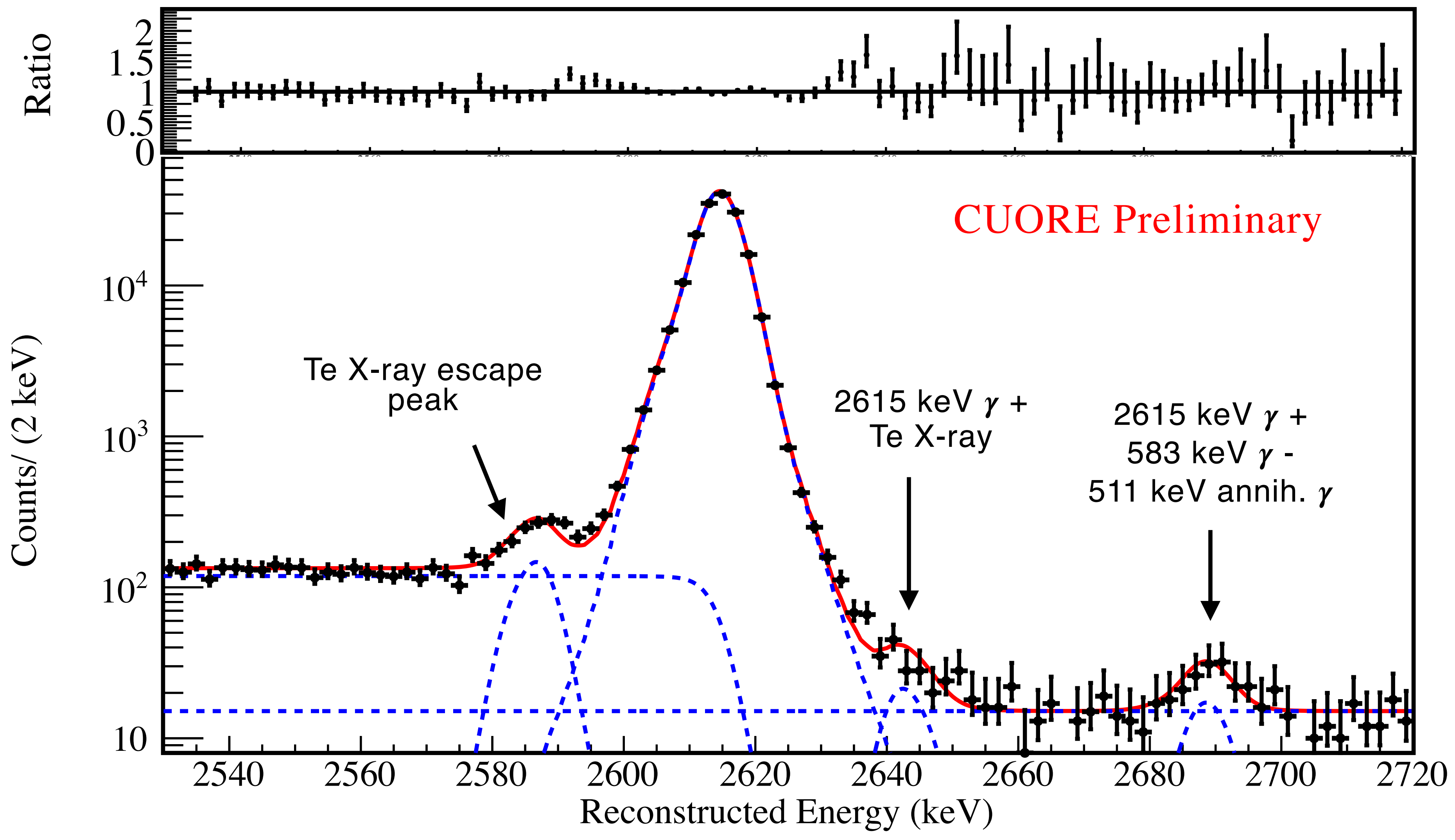


M1 ($0\nu\beta\beta$ expected signature)

M≥2 (background events)

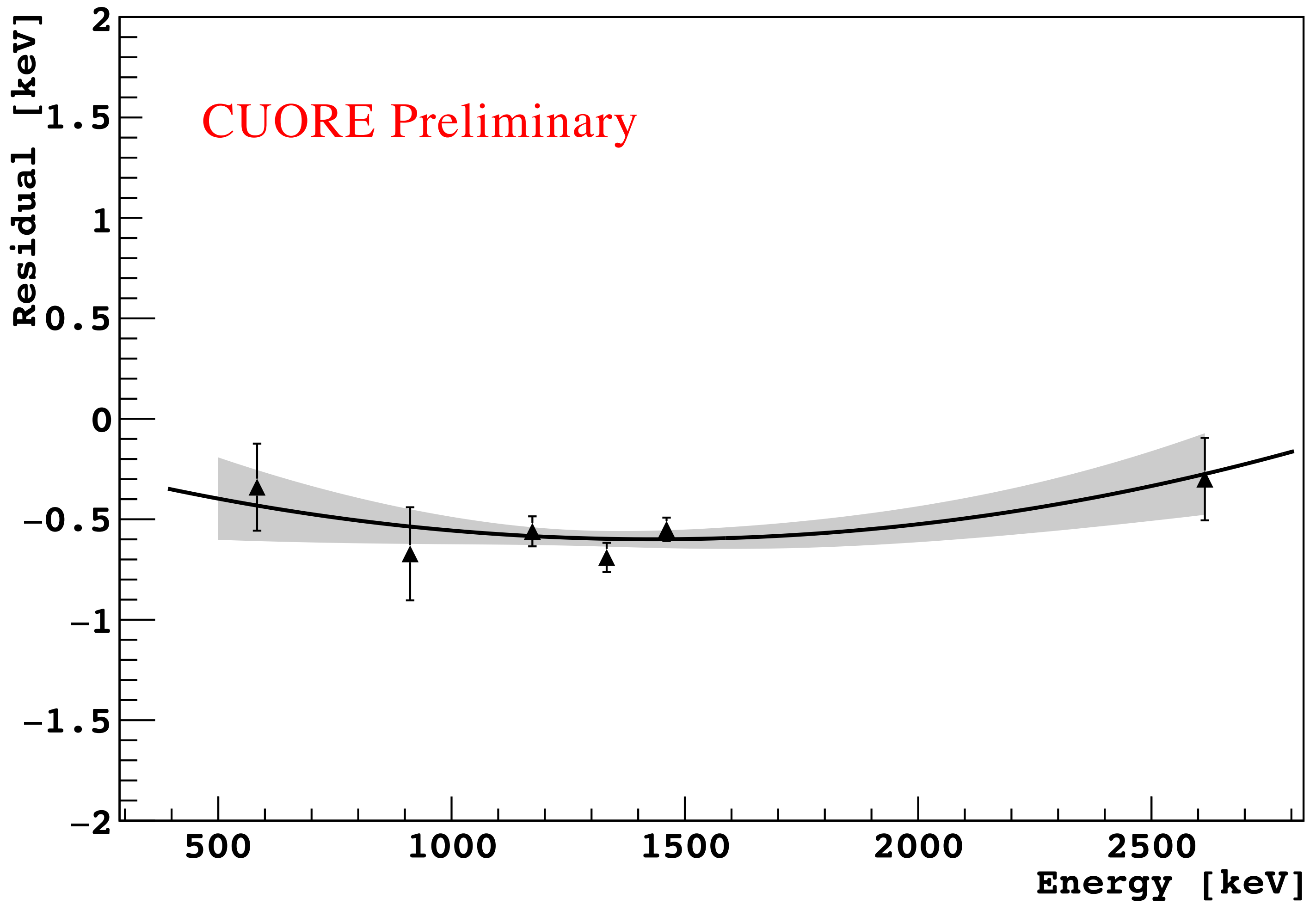
Time/space-based coincidences calculation and event multiplicity assignment

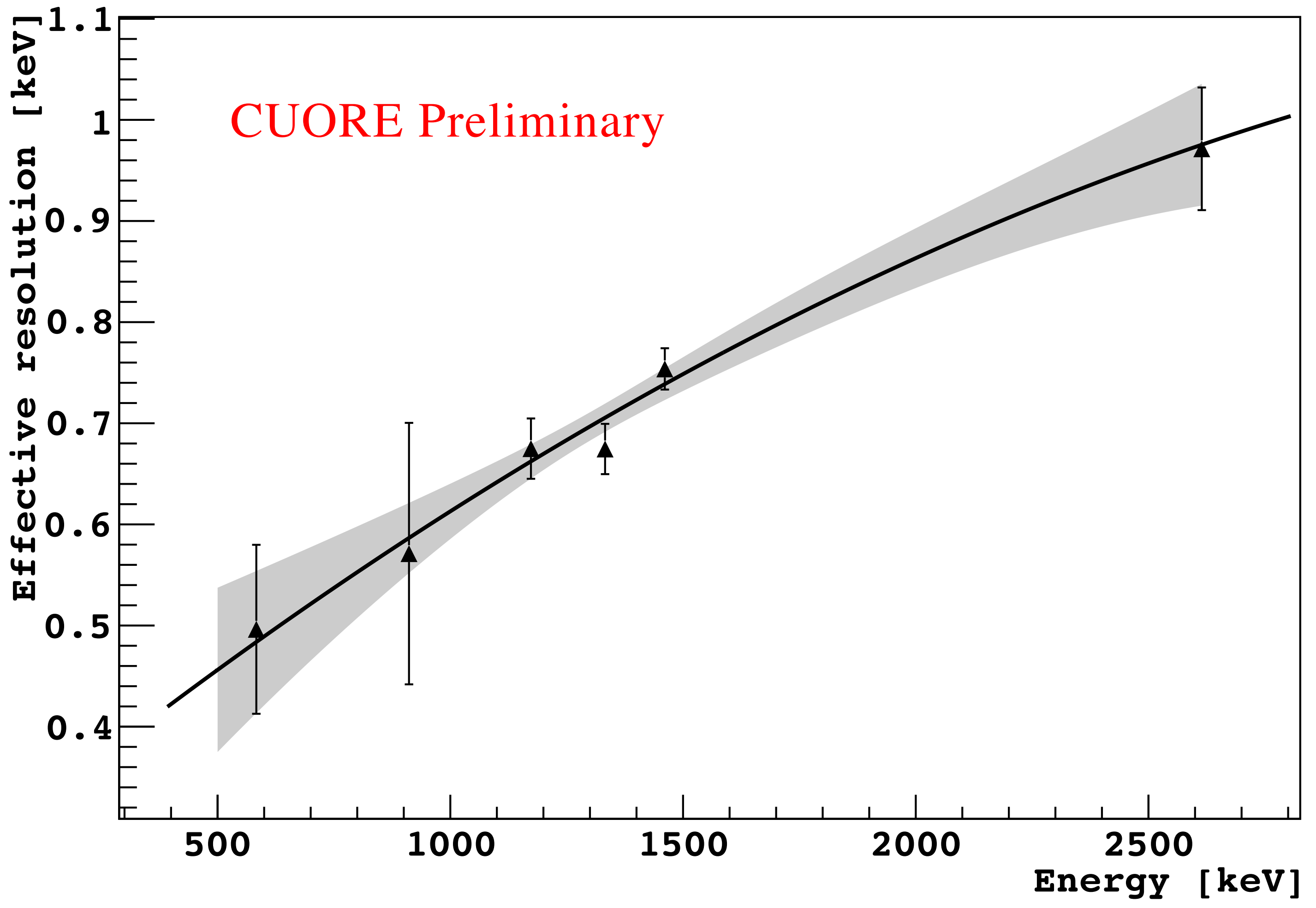
The CUORE detector response function (*lineshape*)



- TeO_2 detectors exhibit a slightly non-gaussian response function
- Lineshape evaluated on the 2615 keV line in calibration: fit with 3 Gaussian for each detector-dataset
- Energy resolution in calibration is extracted (7.8(5) keV)

- Lineshape in physics data: most prominent peaks fitted
- Resolution appears energy dependent, small bias on energy reconstruction
- 2nd order polynomial fit to extract the resolution and bias energy dependence

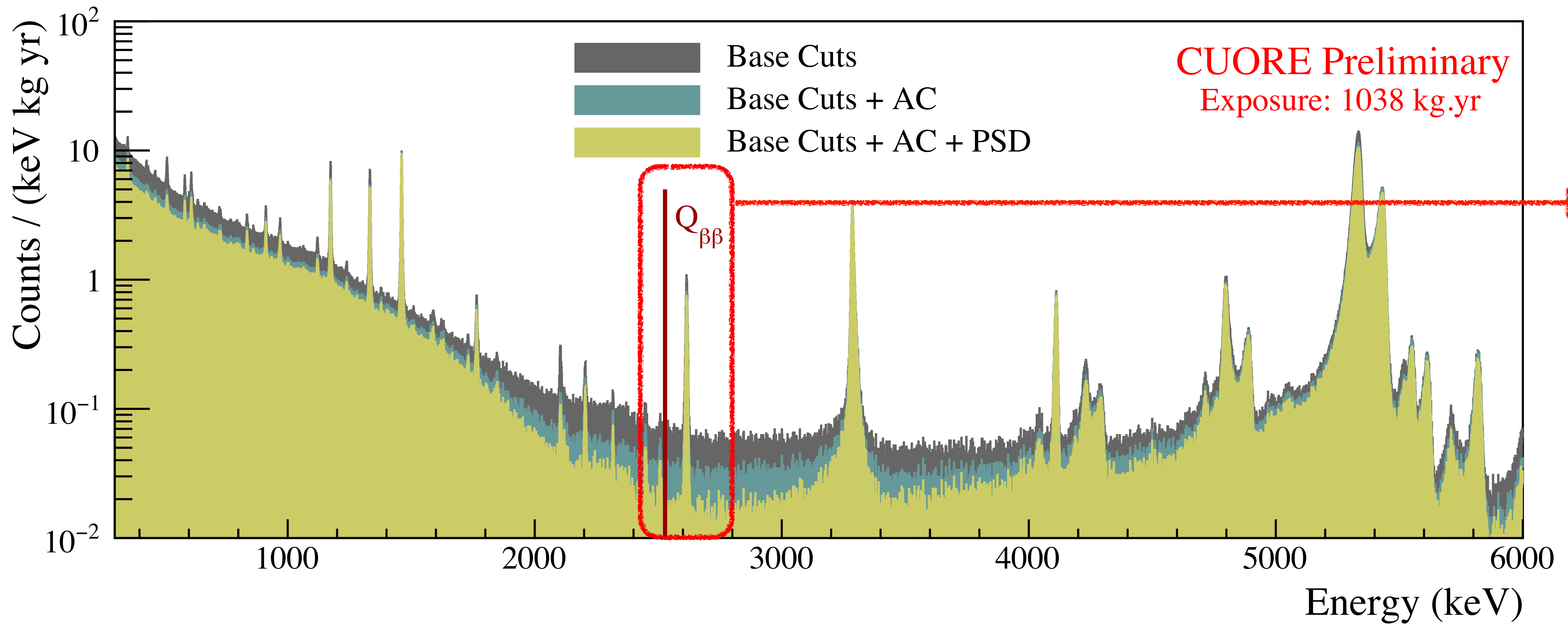


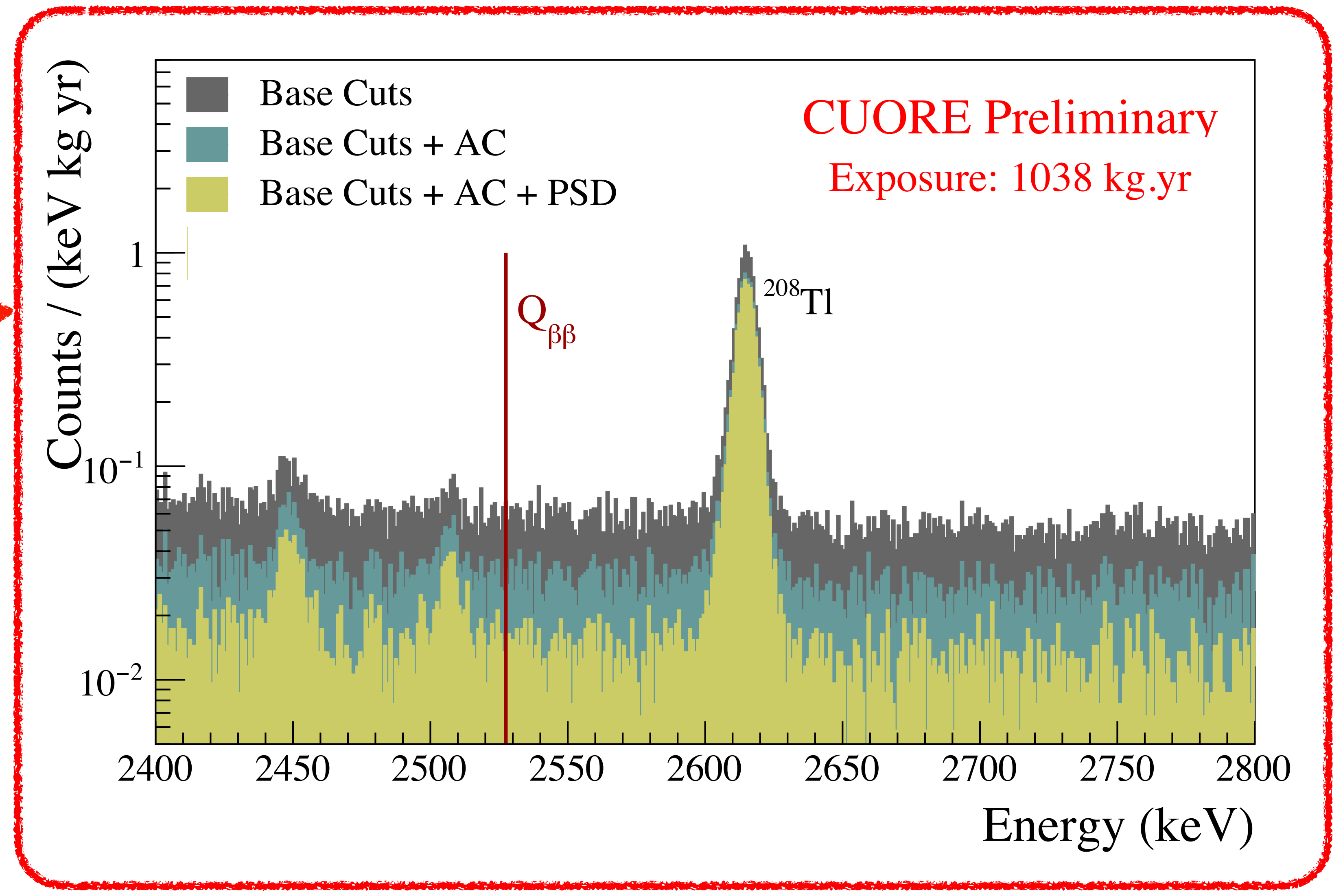


Data cuts and efficiencies

- ***Base cuts***: periods of time with high noise level, processing failures, poor resolution detectors are excluded
- ***Anti-coincidence cut (AC)***: events within ± 5ms from another triggered event at > 40 keV in a distinct crystal are excluded
- ***Pulse shape discrimination cut (PSD)***: abnormal pulse shape events (pile-up, non-physical pulses) are excluded

Containment efficiency	Single-hit event probability for ^{130}Te 0νββ	**88.35(9)%**
Reconstruction efficiency	Probability that a signal event is triggered and not rejected by base cuts, the energy is properly reconstructed	**96.418(2)%**
AC efficiency	Probability that a signal event is not cut due to an accidental coincidence with an unrelated event	**99.3(1)%**
PSD efficiency	Probability of a physical event to survive the PSD cut	**96.4(2)%**

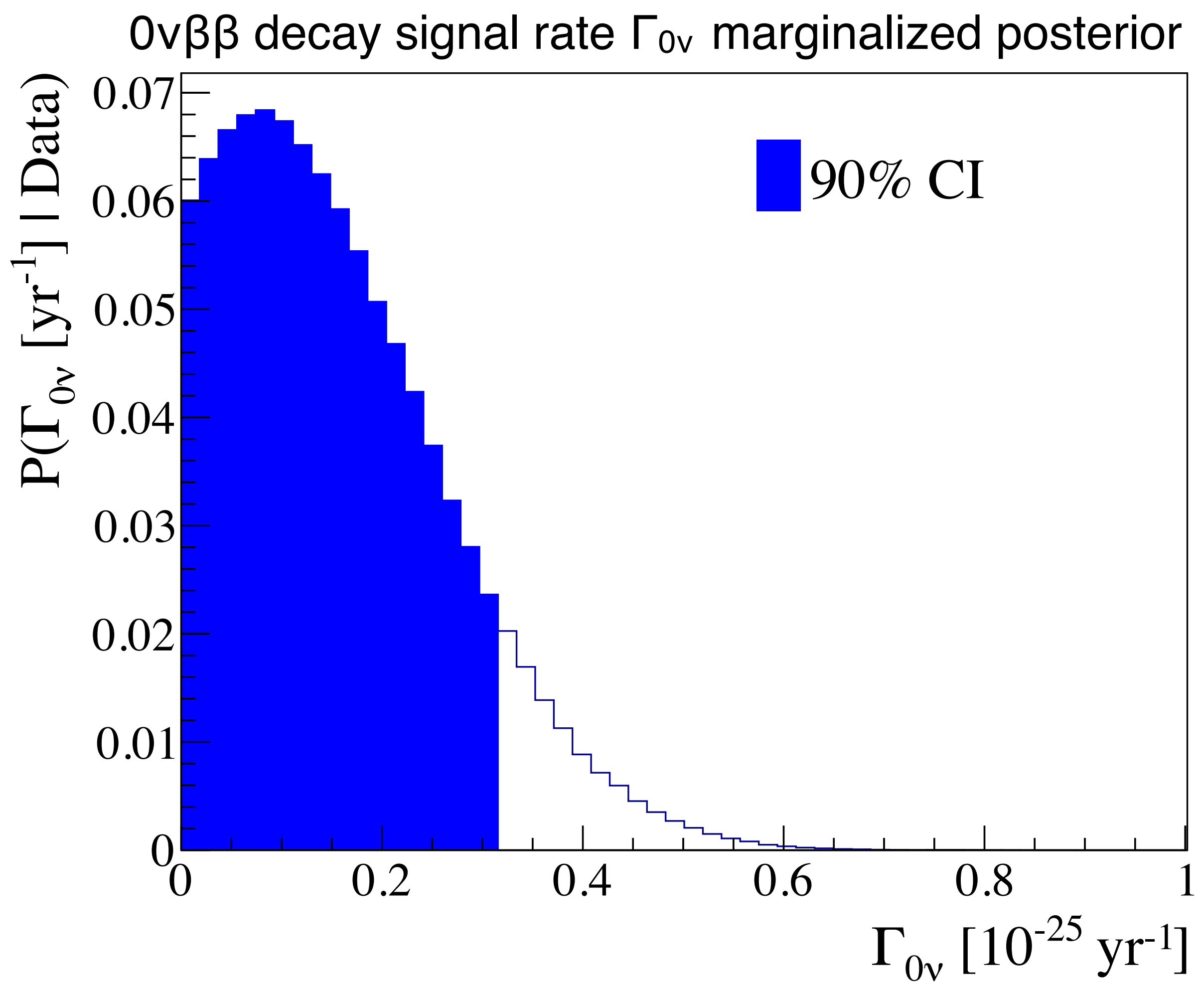


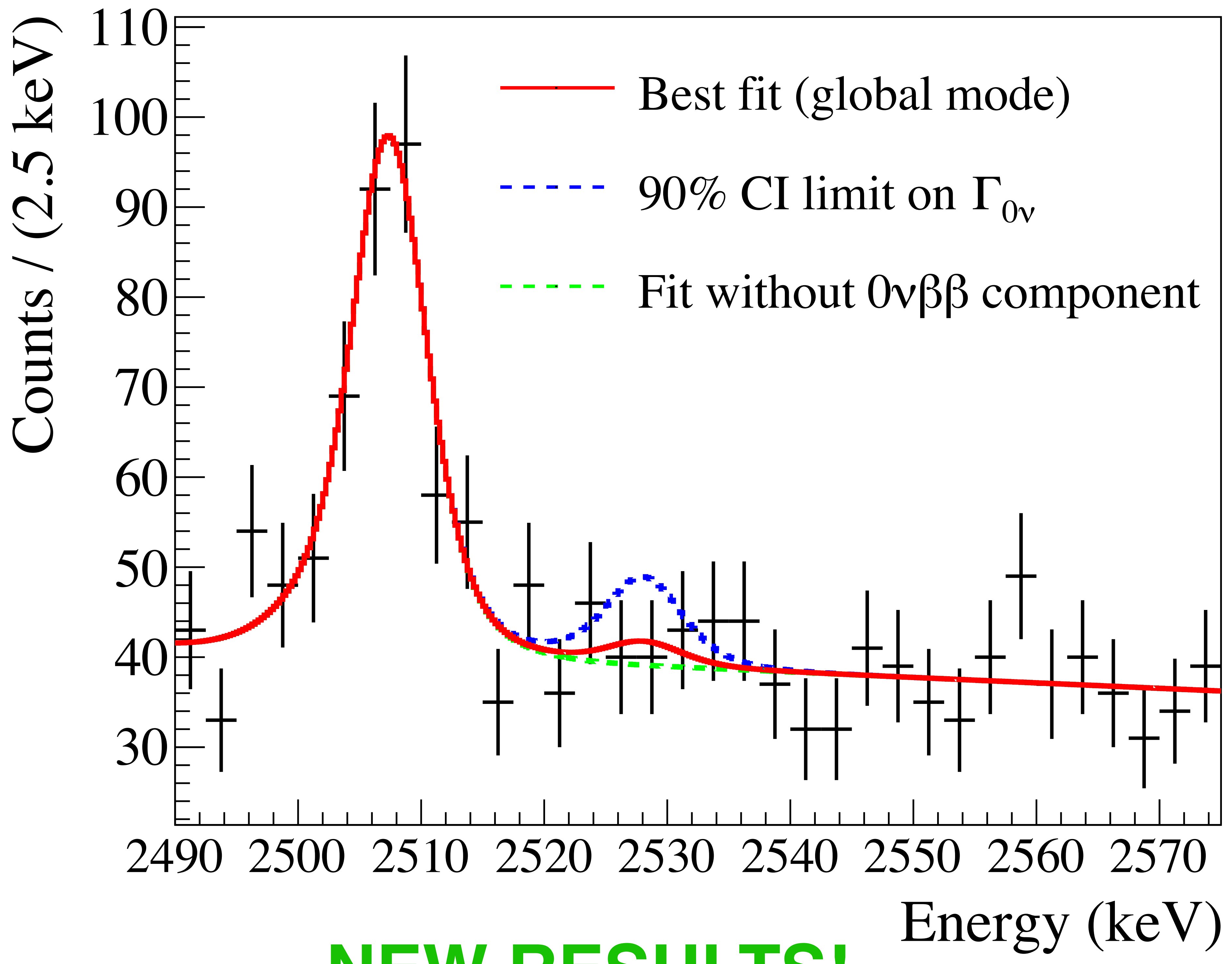


ROI fit: new results on $0\nu\beta\beta$ decay of ^{130}Te

- Unbinned Bayesian fit simultaneously performed for each detector-dataset with BAT ⟶ samples from the posterior distribution of all the parameters of the model with a Markov Chain Monte Carlo
- Uniform prior on the signal rate $\Gamma_{0\nu}$
- ROI: [2490 - 2575] keV
- **Total TeO_2 exposure: 1038.4 kg · yr** (15 datasets)
- No evidence of ^{130}Te $0\nu\beta\beta$ decay is observed
- Systematics effects as nuisance parameters in the Bayesian fit (0.8% total effect on the $\Gamma_{0\nu}$ limit):

- ***Efficiencies*** (reconstruction, anti-coincidence, PSD, containment)
- ***^{130}Te isotopic abundance***
- ***$Q_{\beta\beta}$***
- ***Lineshape parameters*** (energy bias and resolution scaling)





NEW RESULTS!

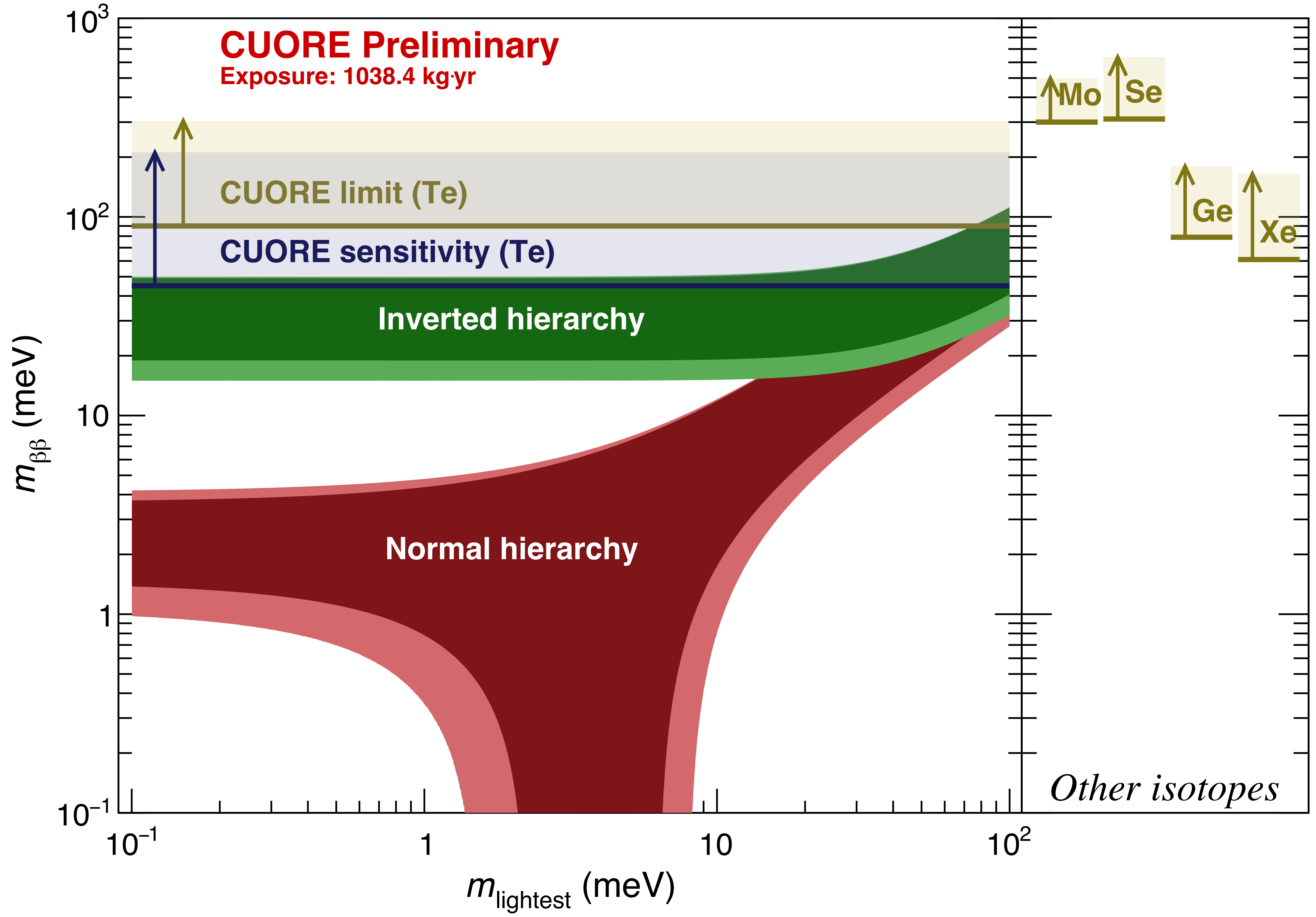
Best fit: **$\Gamma_{0\nu} = (0.9 \pm 1.4) \cdot 10^{-26}$ yr^{-1}**

90% C.I. Bayesian limit: **$T_{1/2} > 2.2 \cdot 10^{25}$ yr**

Background Index: **BI = $(1.49 \pm 0.04) \cdot 10^{-2}$ cts/keV/kg/yr**

arXiv:2104.06906 (2021)

0νββ ROI fit: limit on effective Majorana mass ($m_{\beta\beta}$)



In the assumption that the 0νββ decay is mediated by the exchange of a light Majorana neutrino:

$$\Gamma^{0\nu} = G^{0\nu} |M^{0\nu}|^2 \frac{\langle m_{\beta\beta} \rangle^2}{m_e^2}$$

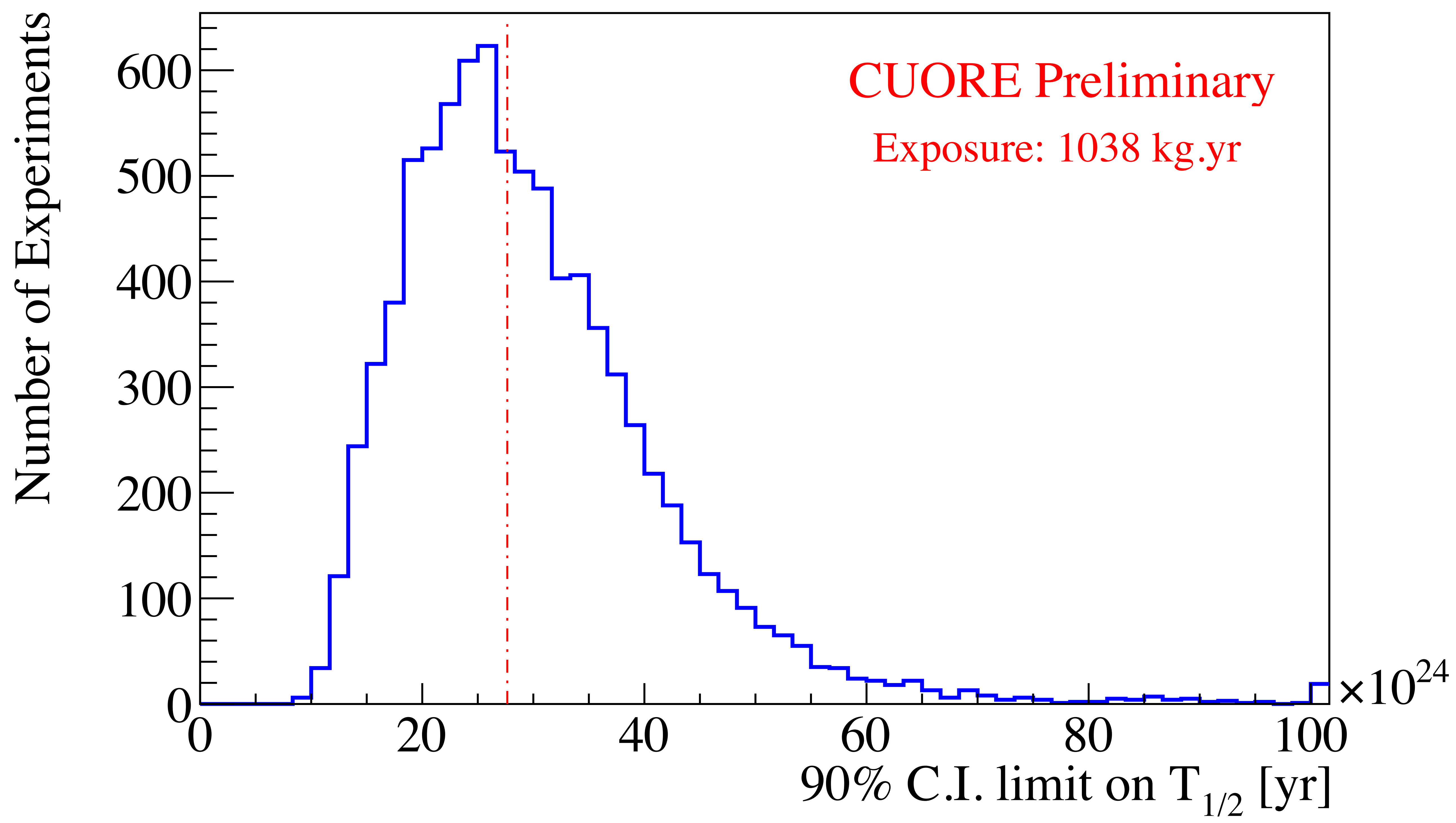
$T_{1/2} > 2.2 \cdot 10^{25}$ yr (limit 90% C.I.)

$m_{\beta\beta} < 90$ - 305 meV (90% C.I.)

arXiv:2104.06906 (2021)

Exclusion sensitivity on ^{130}Te $0\nu\beta\beta$ half-life

- 10^4 toyMC with background components only (no signal), floating the parameters extracted from the fit on data
- Bayesian fit with signal + background components independently run on each toyMC
- Extraction of the 90% C.I. half-life limit from each of the 10^4 Bayesian fits
- **Exclusion Sensitivity = median of the half-life limits distribution**



$T_{1/2} = 2.8 \cdot 10^{25}$ yr

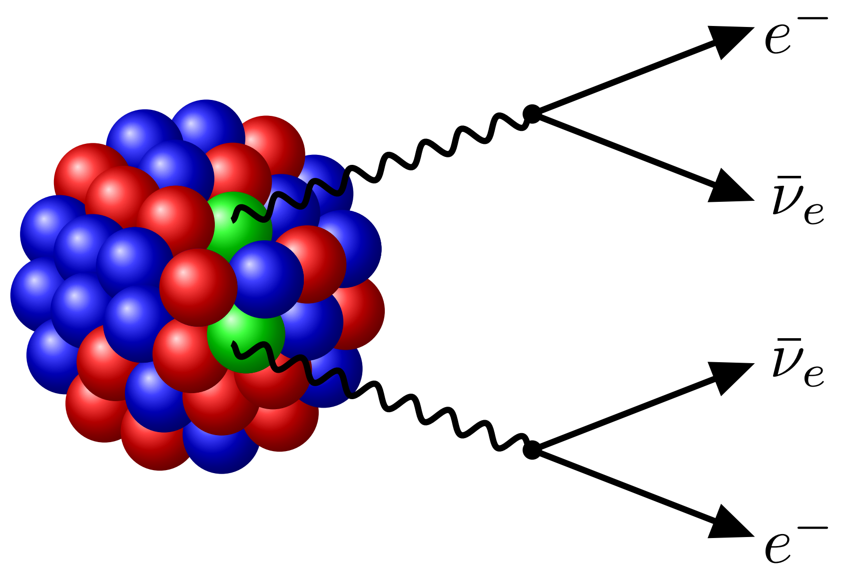
Median expected $T_{1/2}$ 90% C.I. limit

90% C.I. $T_{1/2}$ from the fit on CUORE data:
$T_{1/2} > 2.2 \cdot 10^{25}$ yr

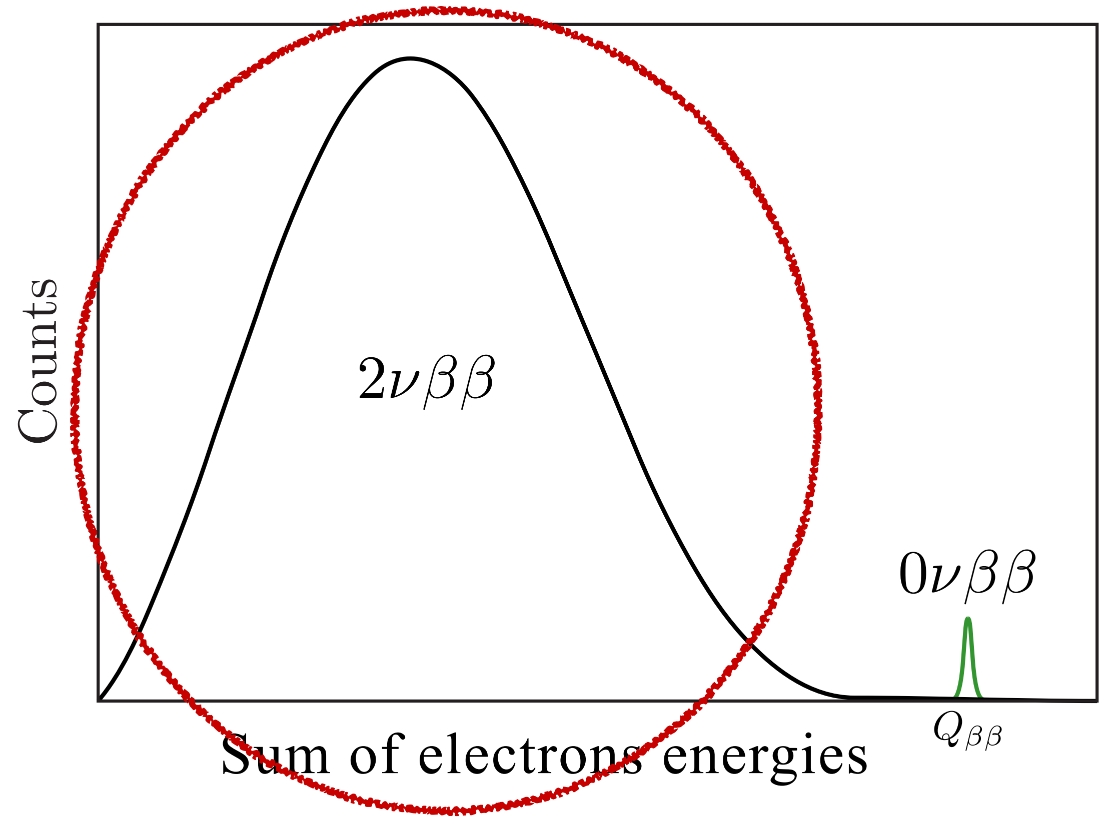
72% probability to get a more stringent limit given the obtained sensitivity distribution

arXiv:2104.06906 (2021)

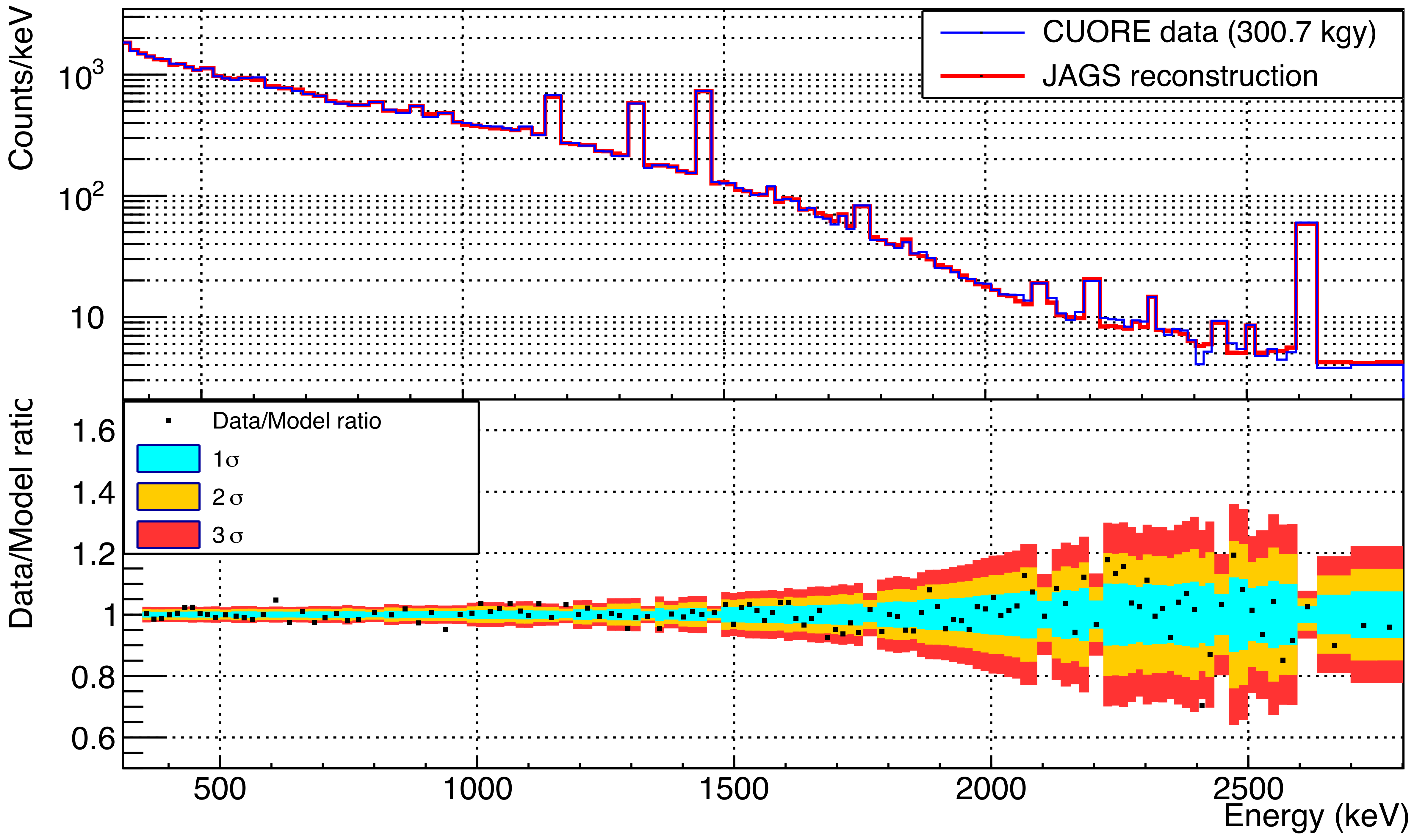
The CUORE Background Model: $2\nu\beta\beta$ decay of ^{130}Te



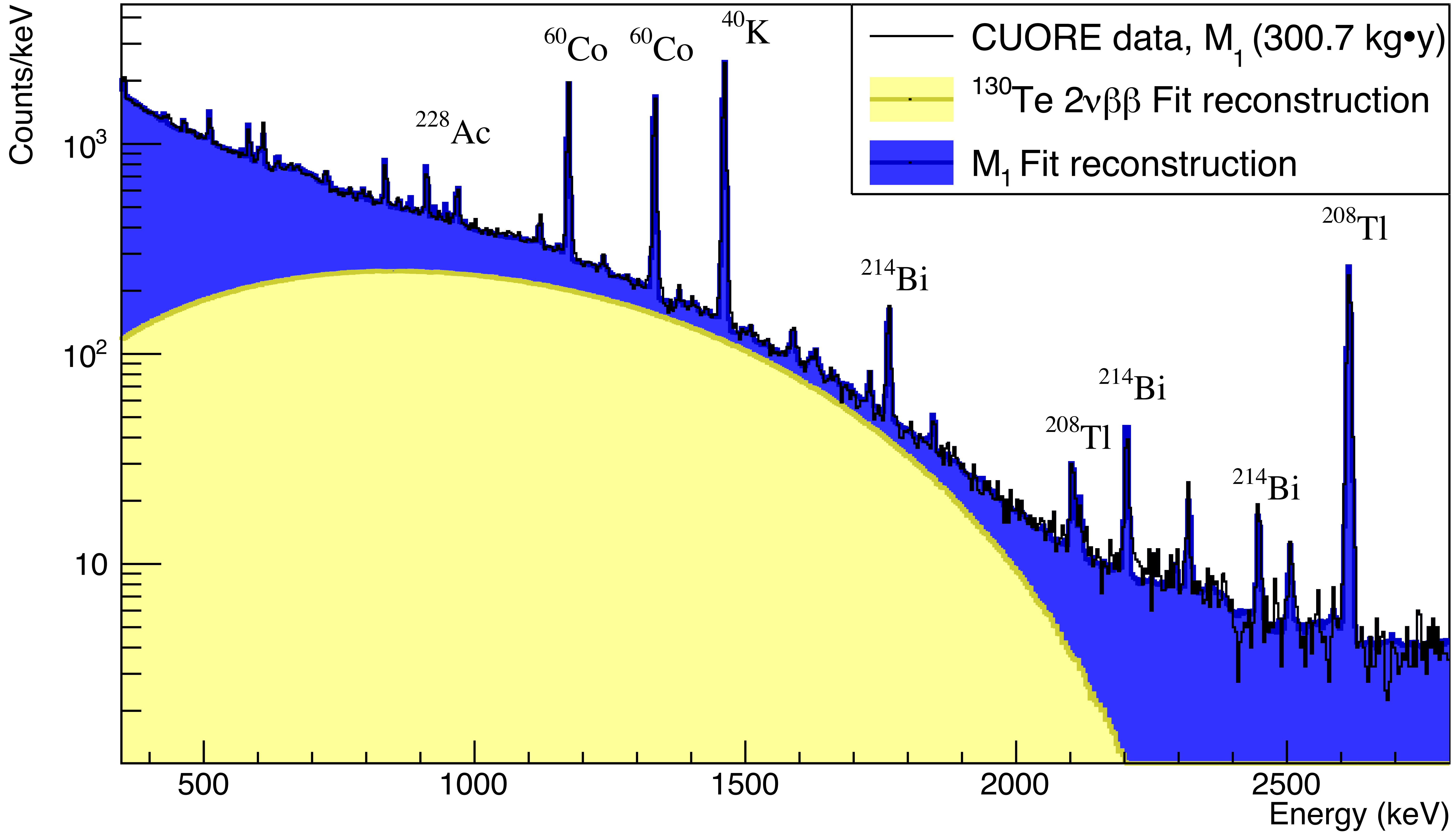
$2\nu\beta\beta$ contribution to the CUORE spectrum can be disentangled through the **Background Model fit**



- Detailed GEANT4 MC simulation of the background sources
- Bayesian fit on experimental data with a linear combination of the MC simulations
- Fit on 350 keV - 2.8 MeV energy region (dominated by $2\nu\beta\beta$ decay of ^{130}Te)
- Fit parameters: a normalization factor for each source is extracted and used to obtain the **activity** of the contaminants and **half-lives** of processes (e.g. $2\nu\beta\beta$ decay $T_{1/2}$)



The CUORE Background Model: 2νββ decay of ^{130}Te



$$T^{2\nu}_{1/2} = 7.71^{+0.08}_{-0.06}\,(\text{stat})^{+0.12}_{-0.15}(\text{syst}) \cdot 10^{20} \;\; \text{yr}$$

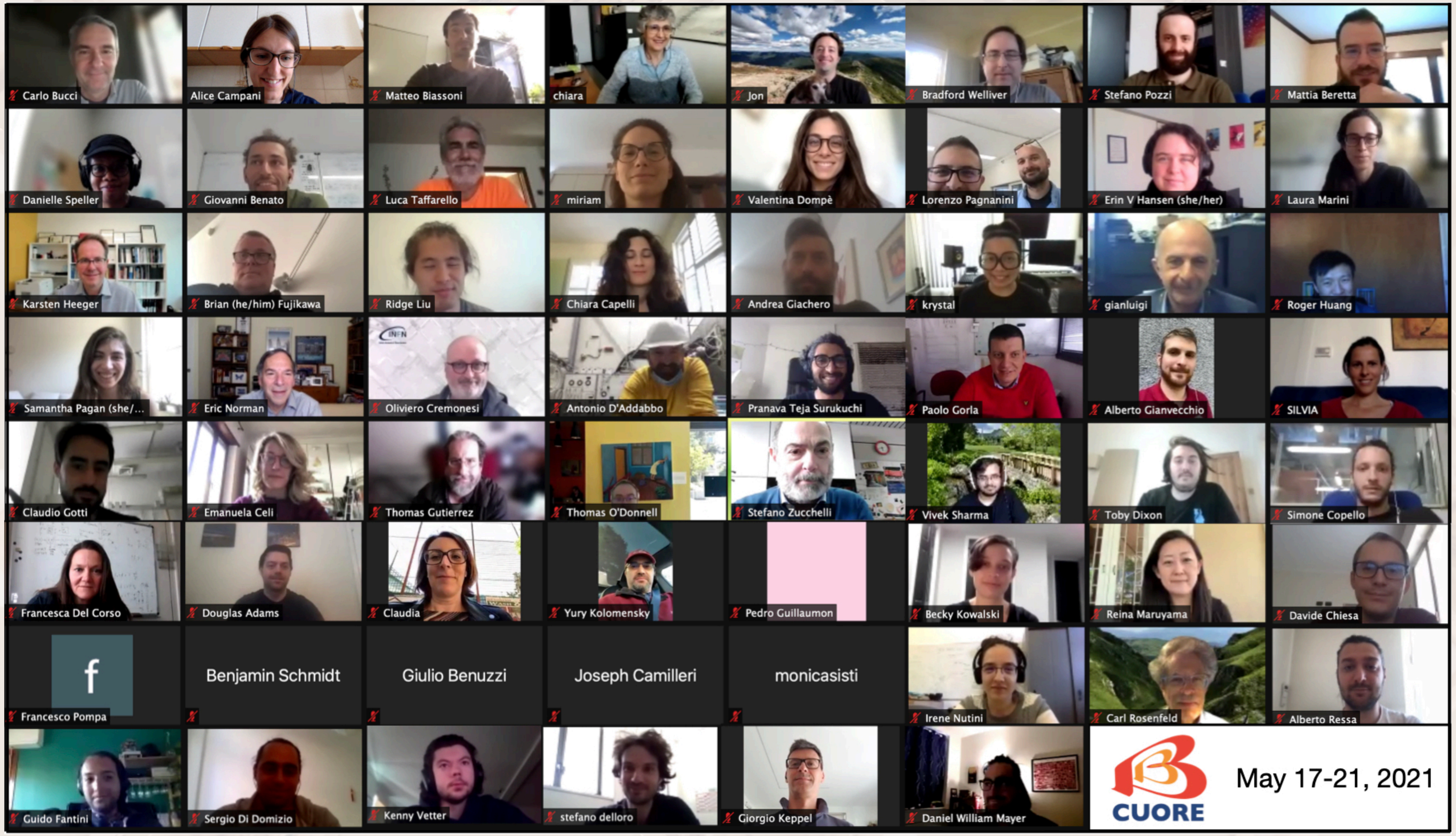
Most precise measurement of ^{130}Te 2νββ decay half-life to date

Phys. Rev. Lett., 126:171801, 2021

Summary & Conclusions

- CUORE is the first ton-scale experiment for double beta decay search operating cryogenic detectors
- 1 ton · yr analyzed data milestone achieved, stable operation for ton-scale cryogenic detector is possible
- Data taking is smoothly ongoing aiming at 5 years live time
- **New results on ^{130}Te 0νββ decay (1038.4 kg · yr exposure): most stringent half-life limit to date**
  arXiv:2104.06906 (2021)
- **New results on ^{130}Te 2νββ decay (300.7 kg · yr exposure): most precise half-life measurement to date**
  Phys. Rev. Lett., 126:171801, 2021
- Other rare decay searches in CUORE: ^{130}Te 0ν and 2ν to excited states (*Eur. Phys. J. C, (2021) 81:567*), ^{128}Te and ^{120}Te 0ν/2ν, ^{130}Te 0ν in M2 spectrum, low energy studies, …

Thank you!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