Search for neutrinoless double beta decay of ^{128}Te with the CUORE experiment

GRAN SASSO
SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

PhD Candidate:
Valentina Dompè

Astroparticle Physics - XXXIII cycle
14/05/2021

Advisors:
Dr. Oliviero Cremonesi
Dr. Paolo Gorla

Outline

- Majorana neutrinos and Double Beta Decay Physics
- The CUORE experiment & latest results
- The CUORE Background Model & α region studies
- Search of neutrinoless double beta decay of ^{128}Te

Outline

- Majorana neutrinos and Double Beta Decay Physics
- The CUORE experiment & latest results
- The CUORE Background Model & α region studies
- Search of neutrinoless double beta decay of ^{128}Te

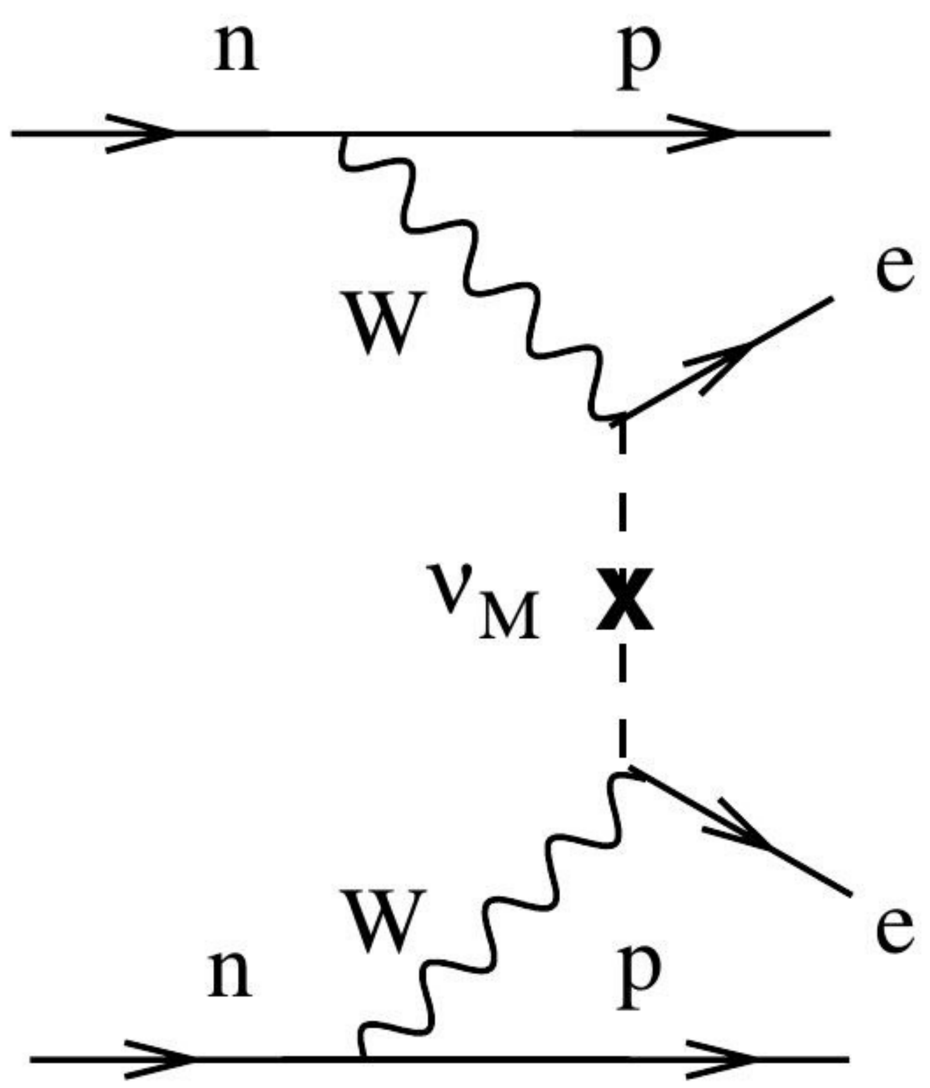
Open question in Astroparticle Physics

1) In the Standard Model, the Lepton number conservation is not associated to a fundamental symmetry.
Is the Lepton number conserved in nature?

2) First Standard Model formulation: $m_\nu = 0$, but neutrino flavor oscillations proved that $m_\nu \neq 0$.
How is the neutrino mass produced?

3) The Big Bang should have created the same amount of matter and anti-matter.
Why is there more matter than anti-matter in our Universe?

Neutrinoless double beta decay (0νββ)



- **Only matter is created:** first experimental evidence
- Lepton number-violating process: **would demonstrate that L is not a symmetry of nature**
- Only possible if **neutrinos have a Majorana component**

Dirac and Majorana Neutrinos

- 1937 - Ettore Majorana introduced a new theory of fermions: representations of elementary particles and antiparticles are coincident ($\nu = \bar{\nu}$)
- New possible mechanism giving rise to ν mass (e.g. see-saw mechanism)
- The general form of the Standard Model Lagrangian for neutrinos:

$$\mathscr{L}_{D,M} = \underbrace{M_D(\bar{\nu}_R\nu_L + \bar{\nu}_L\nu_R)} + \underbrace{M\nu_R^T C^{-1}\nu_R} + h.c.$$

Dirac neutrino

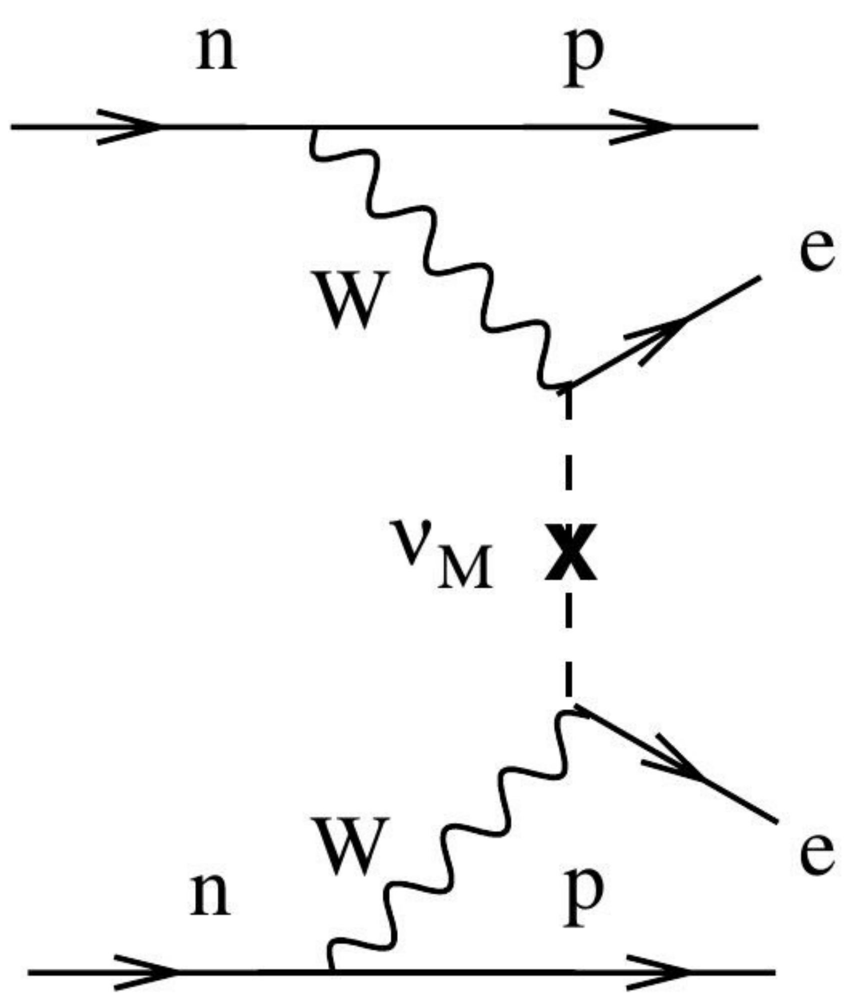
- 4 components required: ν_L, $\bar{\nu}_L$, ν_R, $\bar{\nu}_R$
- Lepton number is conserved

Majorana neutrino

- **$\nu = \bar{\nu}$: only 2 components with different helicity states**
- **Lepton number is violated**

- Possible explanation of matter-antimatter asymmetry origin via Leptogenesis

Neutrinoless double beta decay



- Light Majorana neutrino exchange mechanism for 0νββ decay
- In this case, we define the Effective Majorana mass $m_{\beta\beta}$
- The 0νββ rate is proportional to $m_{\beta\beta}$

$\eta_{1,2}$: Majorana phases

$$m_{\beta\beta} = \left| e^{i\eta_1} |U_{e1}^2| m_1 + e^{i\eta_2} |U_{e2}^2| m_2 + |U_{e3}^2| m_3 \right|$$

Elements of Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix

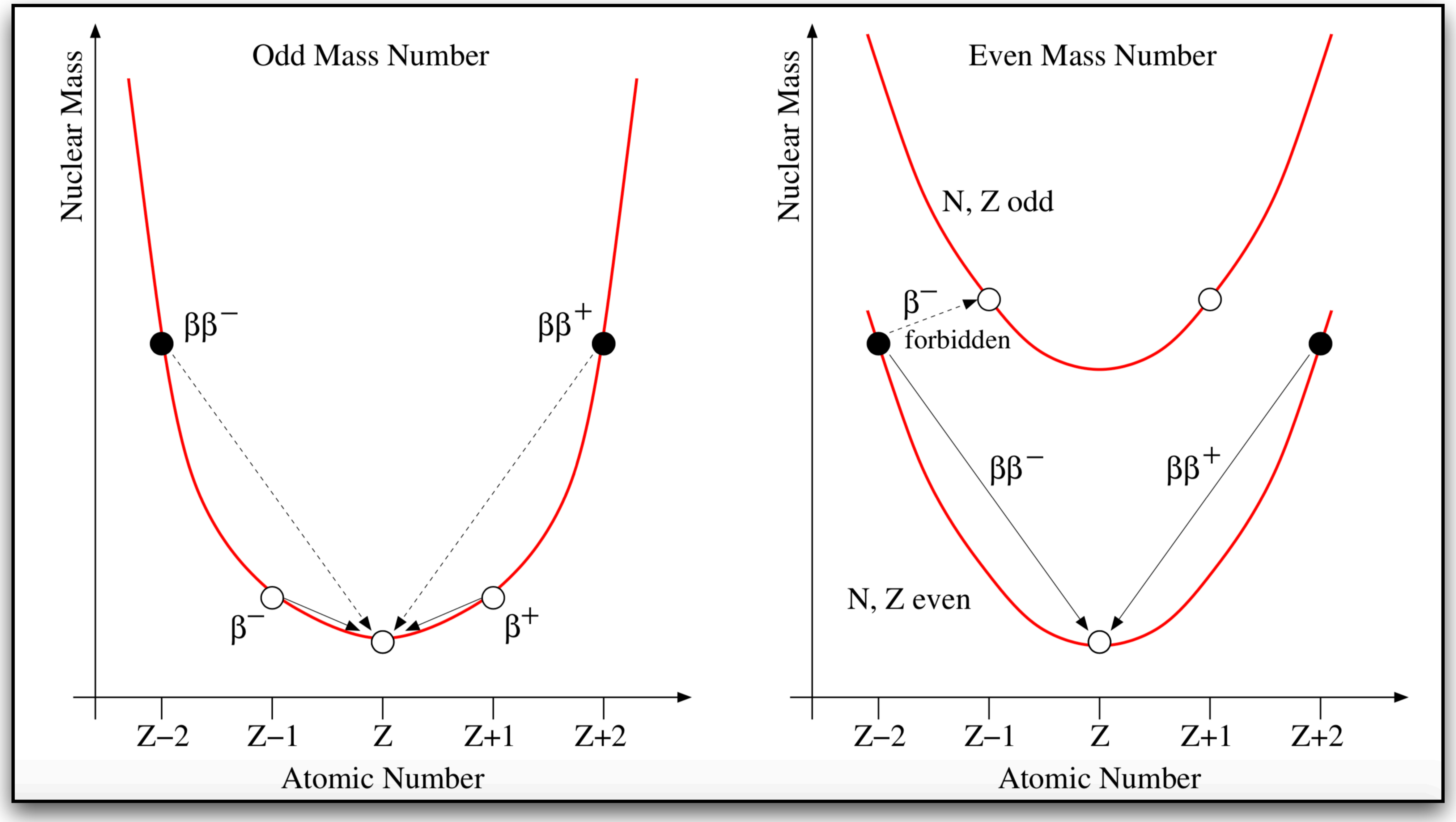
$$\Gamma^{0\nu} = G^{0\nu} |M^{0\nu}|^2 \frac{\langle m_{\beta\beta} \rangle^2}{m_e^2}$$

Phase space factor: precisely calculated

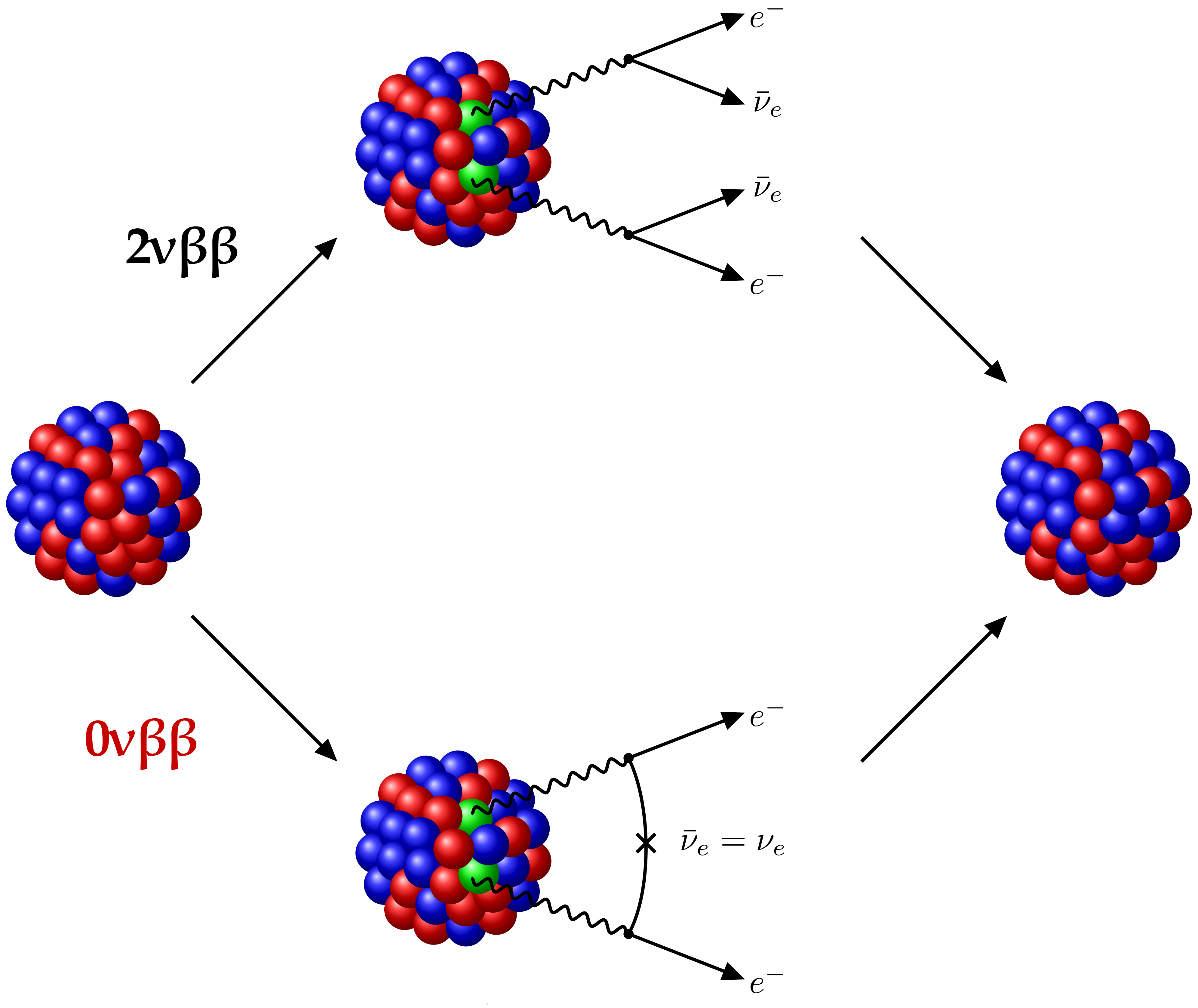
Nuclear Matrix Element (NME): source of uncertainty (different numerical calculations from several models)

Double beta decay: 2νββ and 0νββ

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

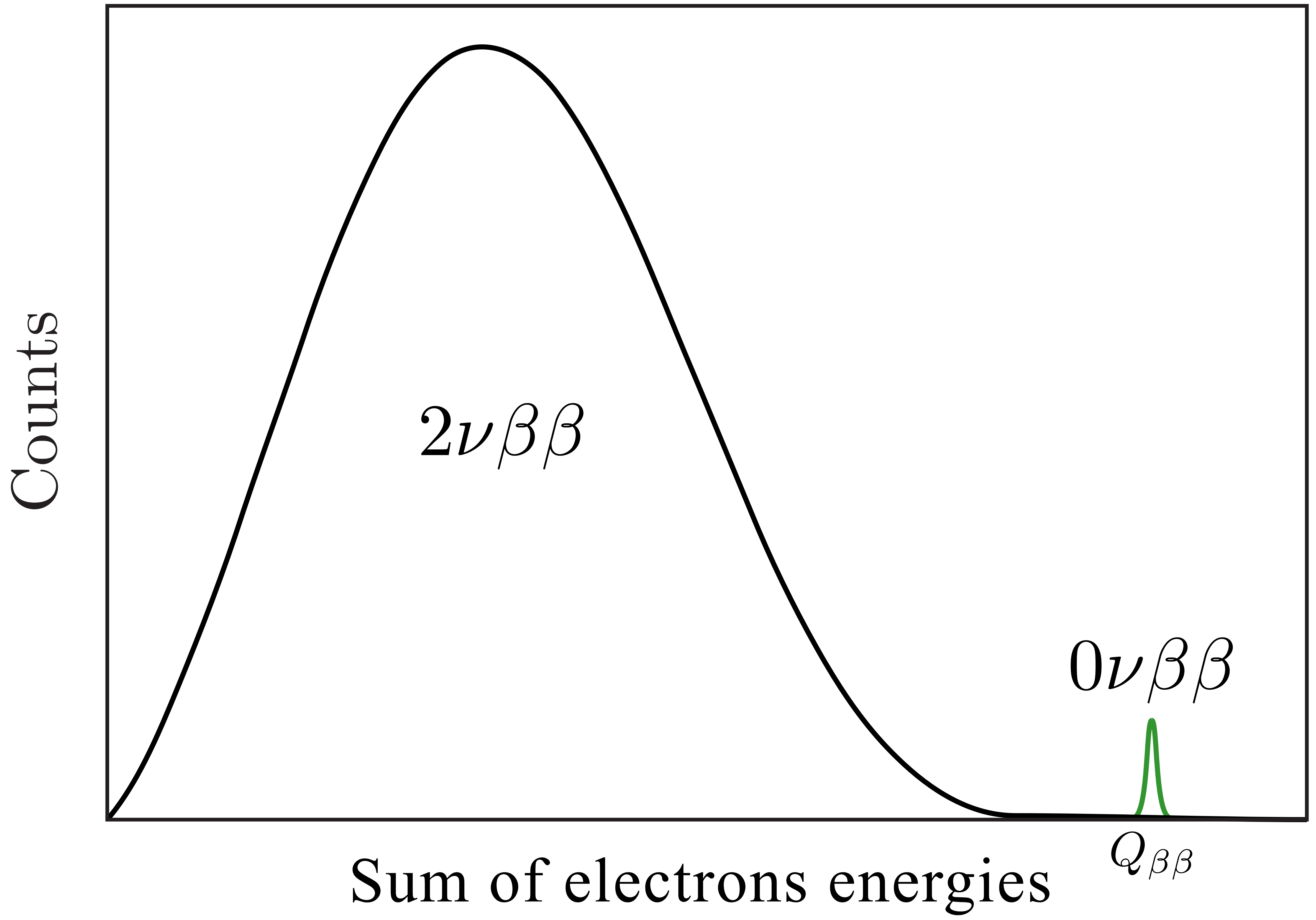


$$(A, Z) \rightarrow (A, Z+2) + 2e^{-} + 2\bar{\nu}_e$$



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

Experimental search of 0νββ decay



- Experimental signature of this process is the Q-value of the transition:

$$Q_{\beta\beta} = (M_{parent} - M_{daughter} - 2m_e)c^2$$

- 2νββ: continuous spectrum from 0 to $Q_{\beta\beta}$
- 0νββ: monochromatic peak at $Q_{\beta\beta}$

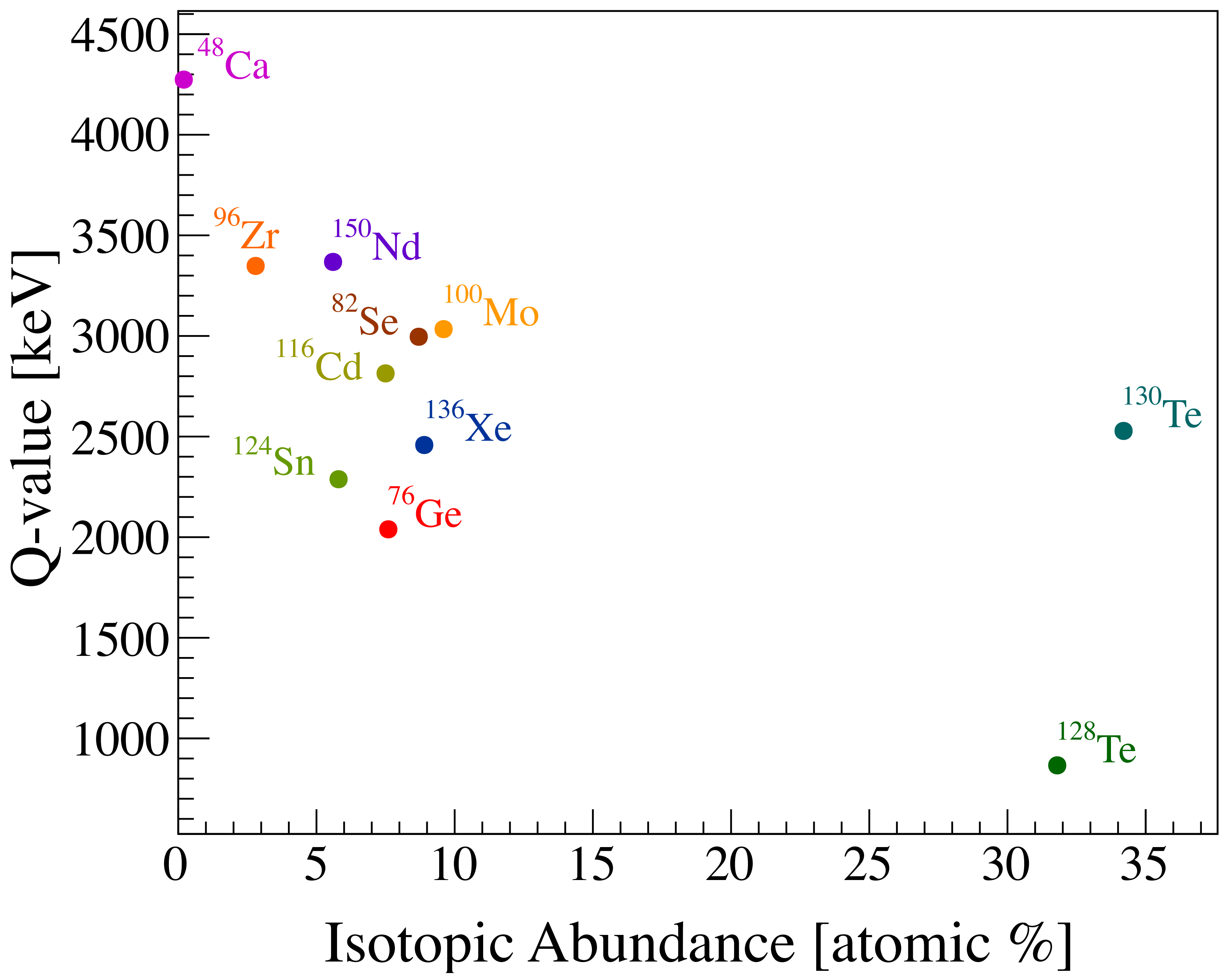
Experimental search of 0νββ decay

The potential of an experiment to 0νββ decay is evaluated through the ***Sensitivity***

Sensitivity:
the half life corresponding to the minimum number of observable signal events above the background, at a given statistical significance n_σ

$$S^{0\nu}(n_\sigma) = \frac{\ln 2}{n_\sigma}\,\epsilon\,\eta\,\frac{N_a}{A}\sqrt{\frac{M\Delta t}{b\Delta E}}$$

- Detection efficiency
- Isotopic abundance of 0νββ emitter
- Exposure (large detector mass and long live time)
- Background level
- Energy resolution



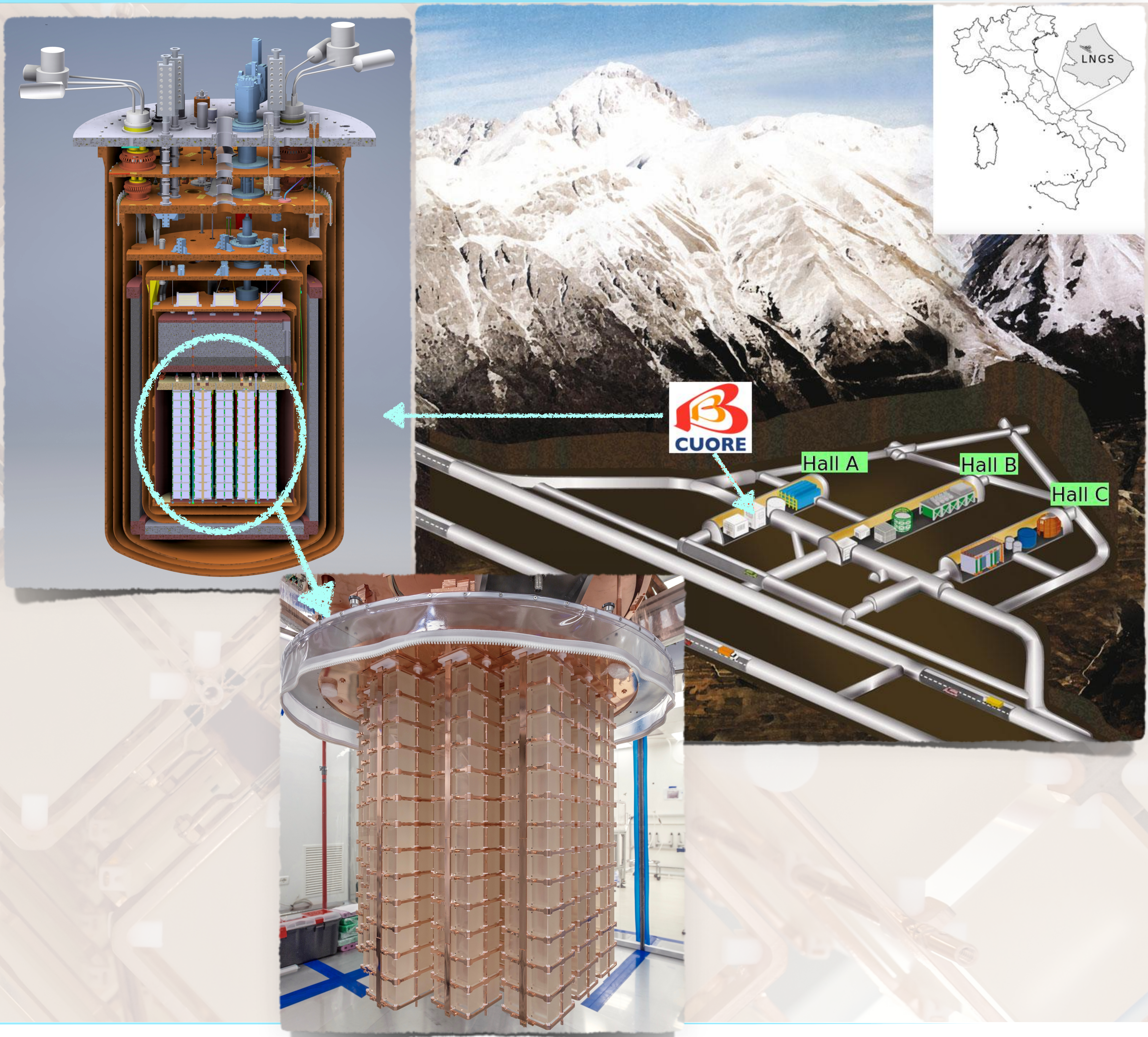
Outline

- Majorana neutrinos and Double Beta Decay Physics
- The CUORE experiment & latest results
- The CUORE Background Model & α region studies
- Search of neutrinoless double beta decay of ^{128}Te

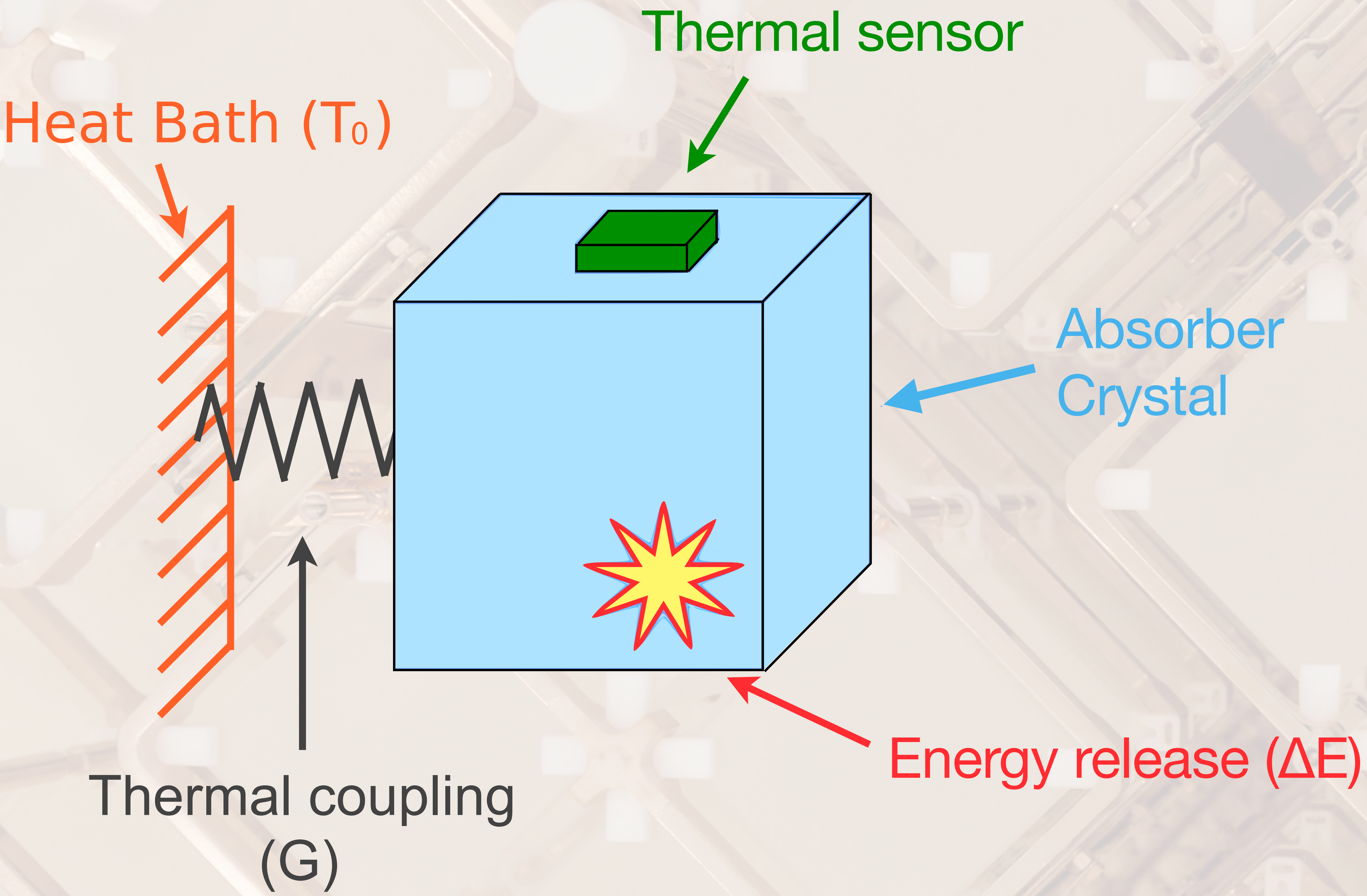
CUORE: Cryogenic Underground Observatory for Rare Events

CUORE: Cryogenic Underground Observatory for Rare Events

- Main Physics goal: search for 0νββ decay of ^{130}Te
- 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 bolometers at ~10 mK



CUORE - The Bolometric technique



- Bolometer: solid state detector working as calorimeter
- The energy of a particle interacting with the absorber is converted into phonons
- The temperature variation is measured by the thermal sensor

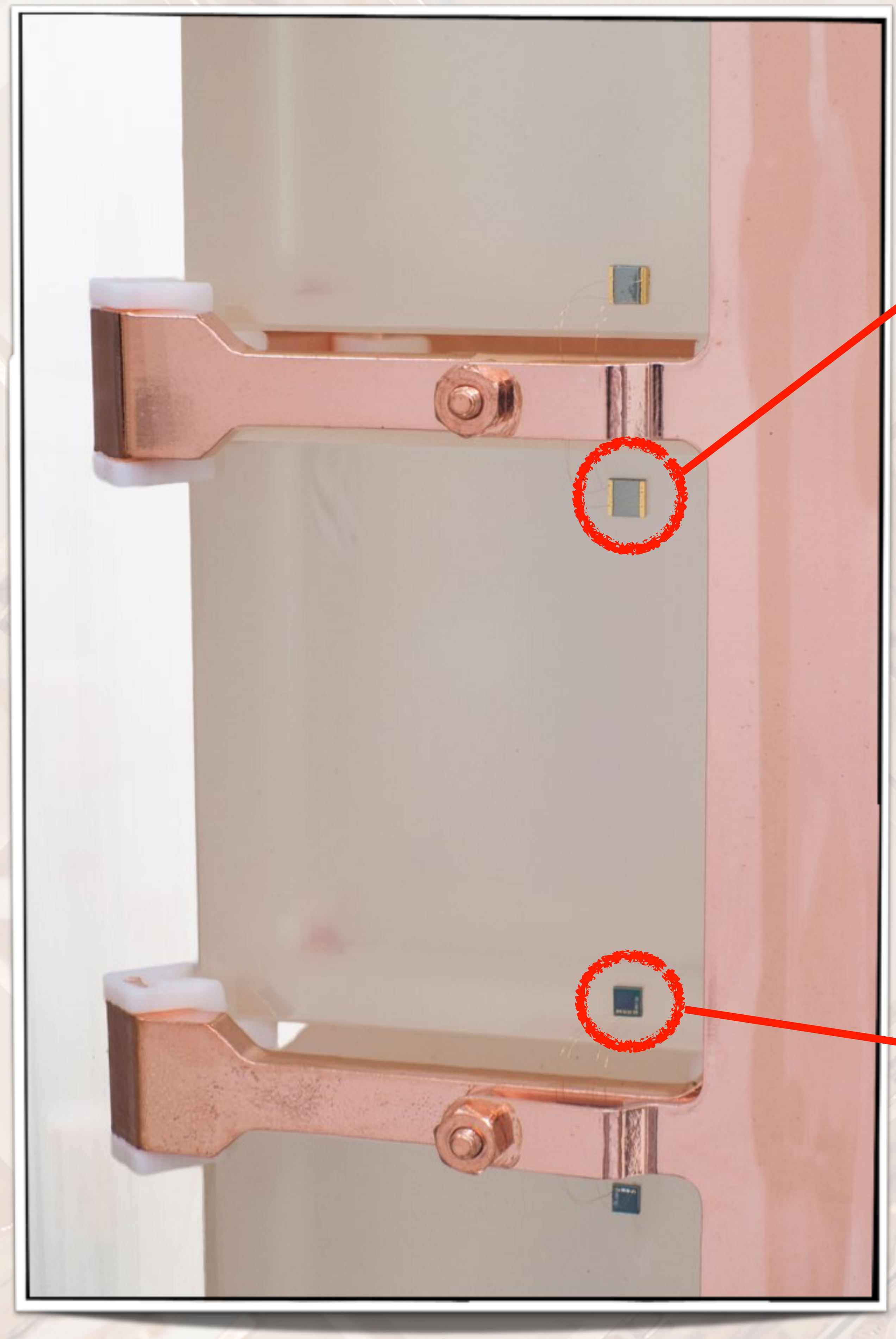
$$\Delta T = \frac{\Delta E}{C}$$

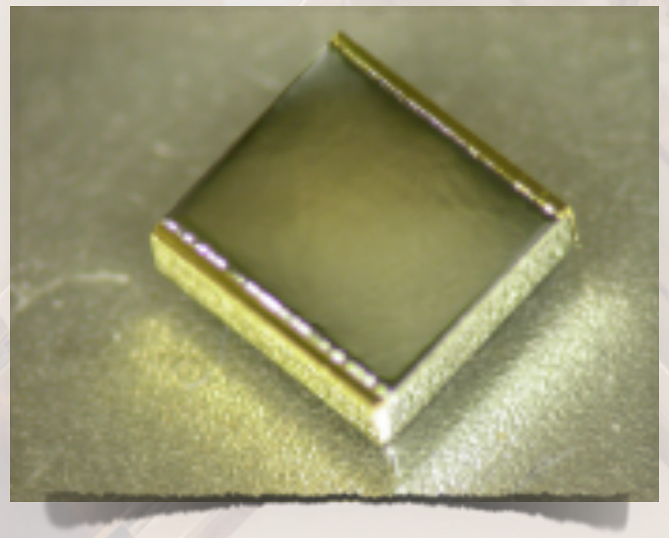
heat capacity: $C_{TeO_2} \propto T^3$

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

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

CUORE - Thermal Sensor and Heater

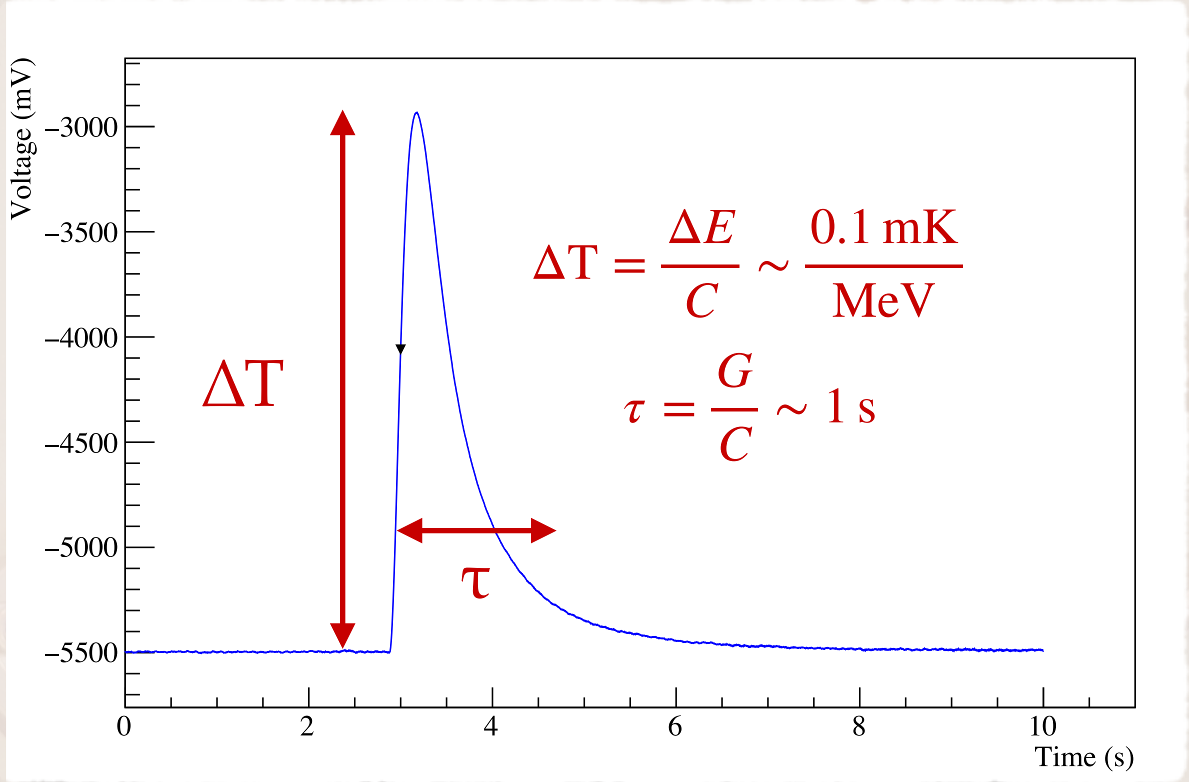


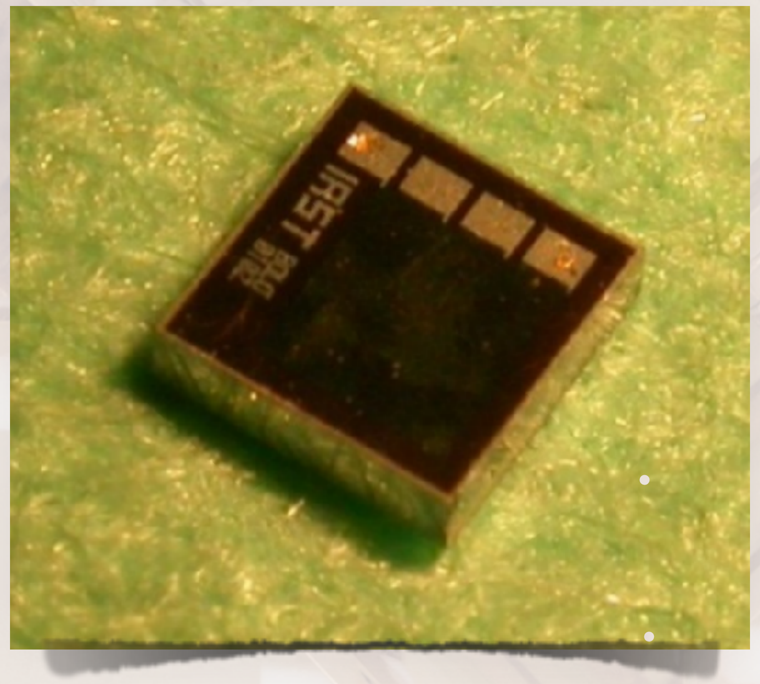


NTD = Neutron Transmutation Doped Ge thermistor

$$R(T) = R_0 e^{\sqrt{\frac{T_0}{T}}}$$

biased with a constant current, converts ΔT to voltage signal

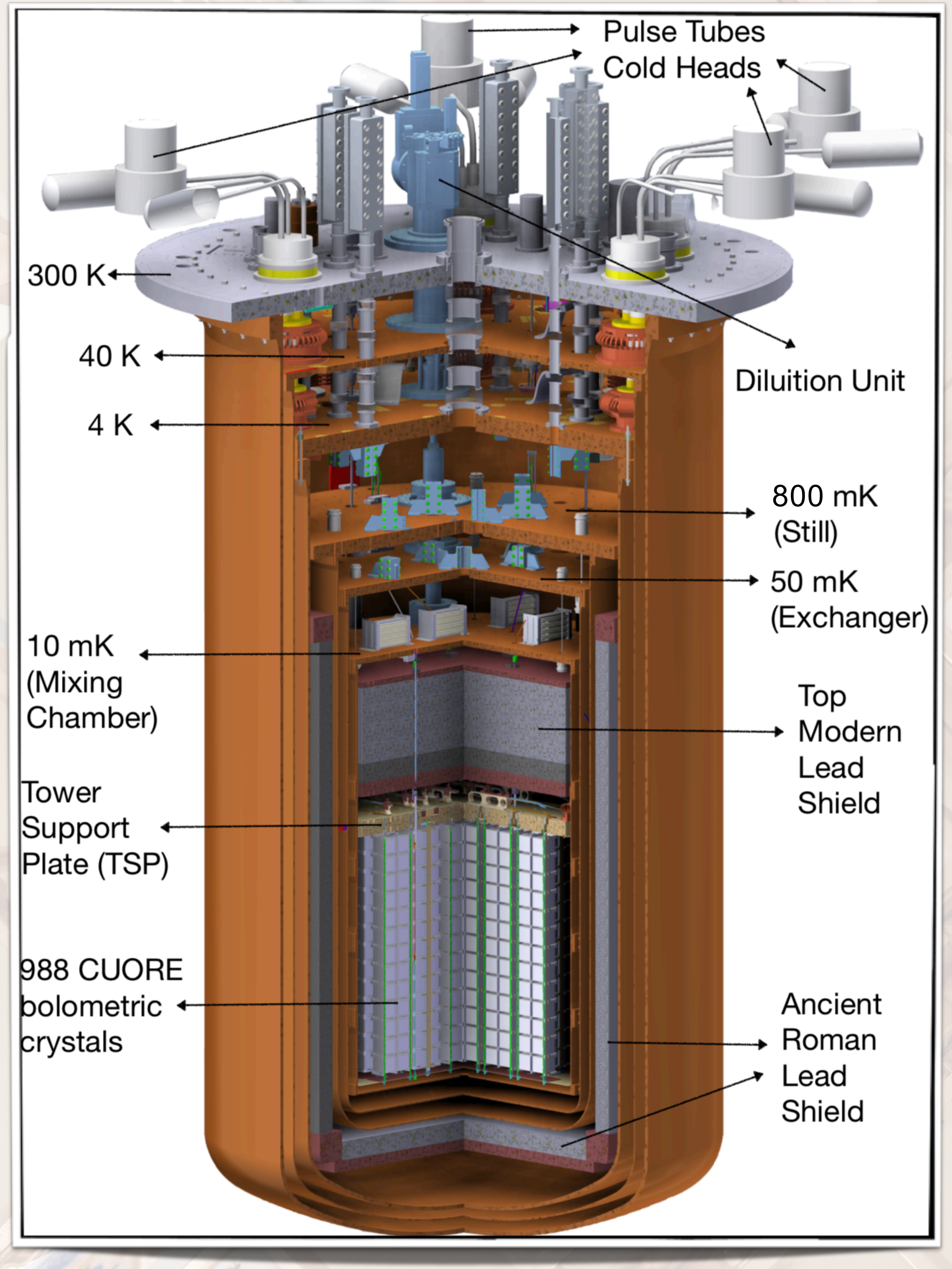




Silicon heater

Periodically fires a pulse at a fixed energy to measure the detector's gain and correct the effect of thermal instabilities (*stabilization*)

The CUORE Cryostat

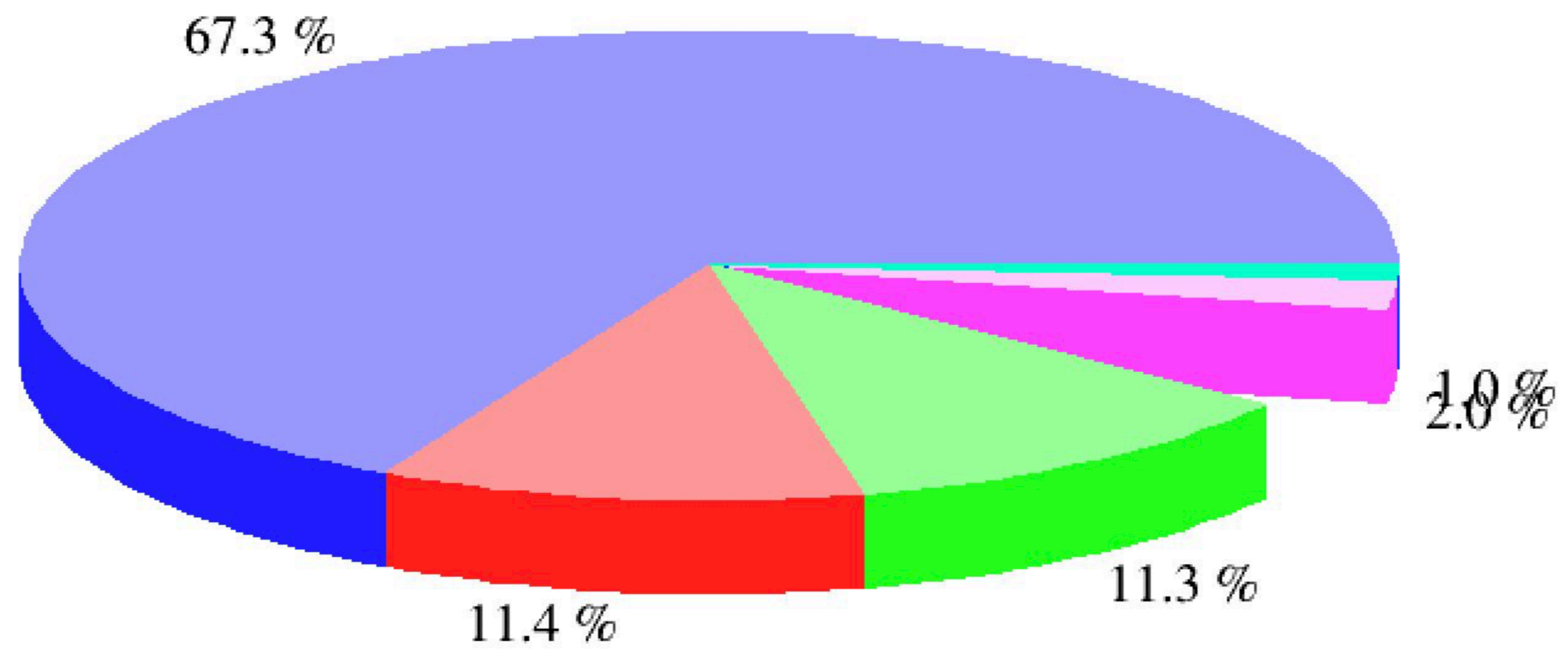


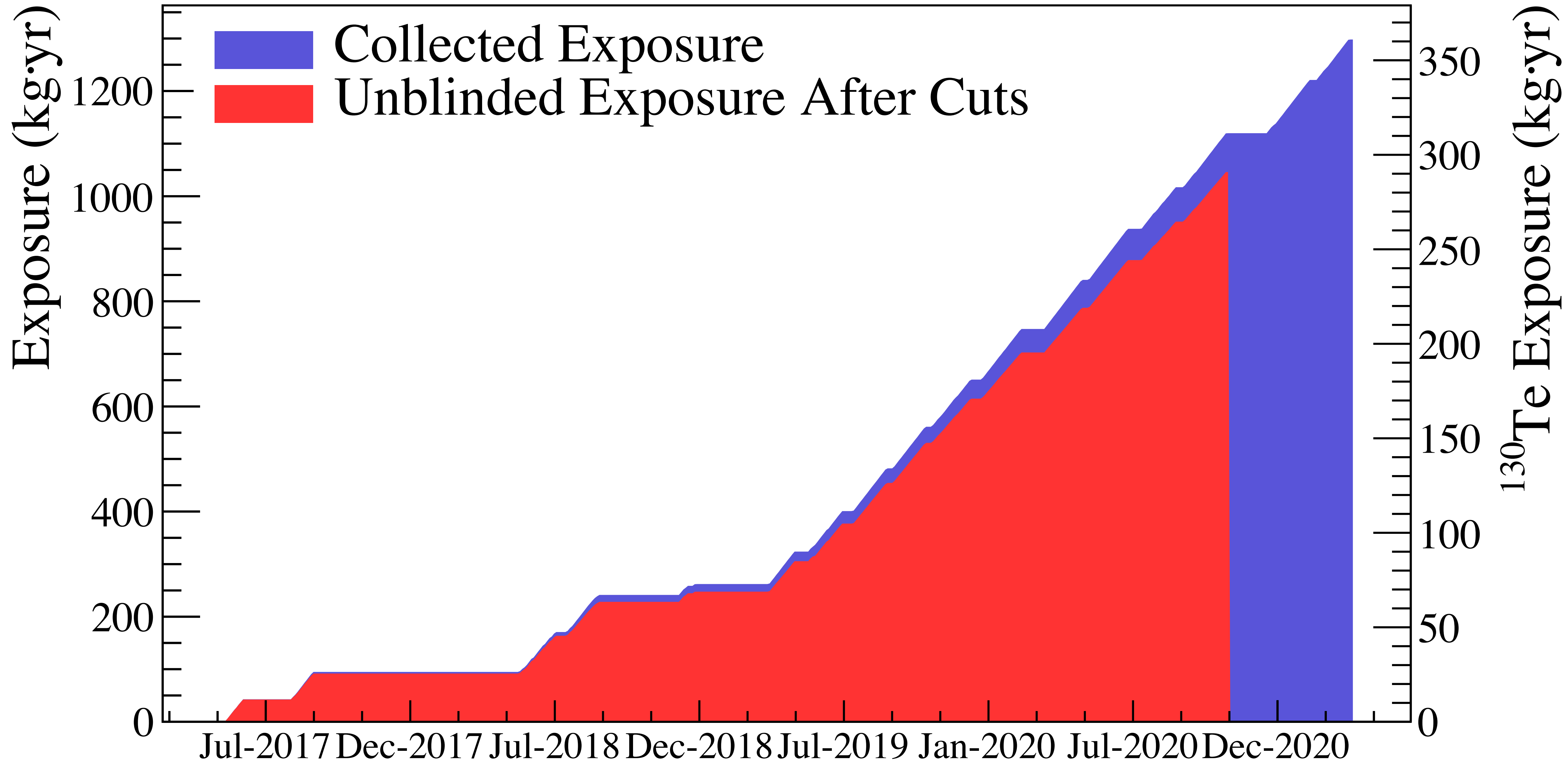
- Custom built cryogen-free structure: 5 pulse tubes + ^{3}He/^{4}He Dilution Refrigerator
- Operational T ~ 10 mK stable over years
- Background level goal of 10^{-2} counts/(keV·kg·y):
  - ➡ low-radioactivity materials choice, strict cleaning and assembling protocols
  - ➡ Roman ^{210}Pb-depleted + modern lead shields
  - ➡ Neutrons shield: external polyethylene layer with boric acid panels
- Energy resolution < 8 keV 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 is proceeding smoothly (~69 kg $\cdot$ y/month since spring 2019)

CUORE duty cycle: Jan 2019 - now





2021: 1-ton $\cdot$ y analyzed exposure milestone!

- Total collected exposure: 1221.06 kg$\cdot$y
- Total analyzed exposure: **1038.4 kg$\cdot$y**

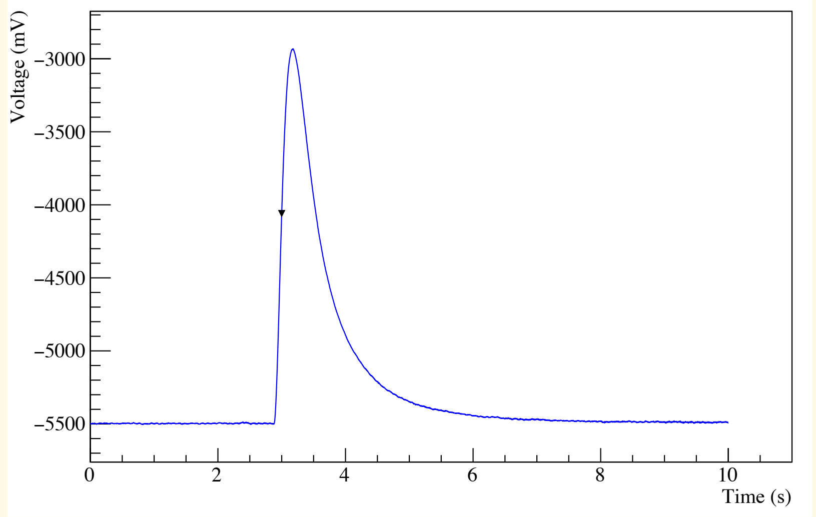
The CUORE data processing

From the raw triggered waveform to the energy spectrum:

Preprocess → **Amplitude** → **Stabilization** → **Calibration**

First basic quantities:

- *Baseline*, *BaselineRMS*, *BaselineSlope* (bolometer working conditions before particle interaction)
- Waveform parameters: *SingleTrigger*, *NumberOfPulses* (pile up parameters)

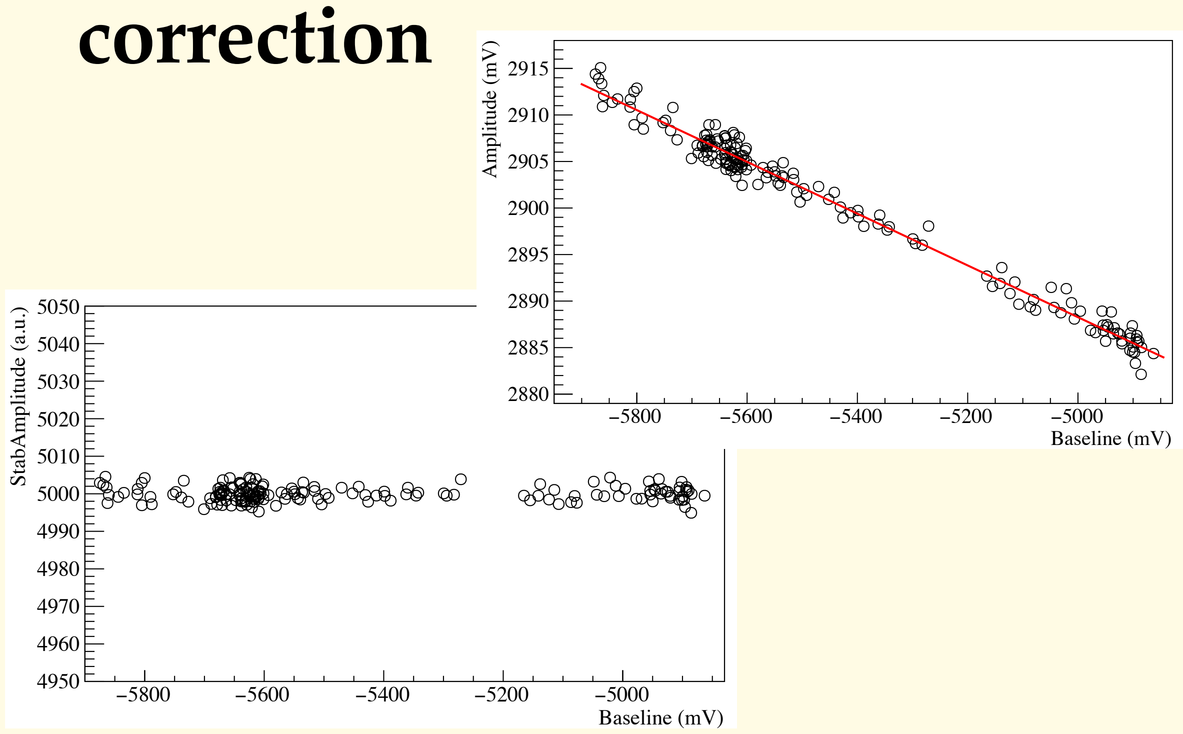


- **Signal amplitude evaluation**
- Optimum Filter: SNR is maximized

$$V_i^{OF}(\omega) \propto e^{i\omega t_M}\frac{S_i^*(\omega)}{N_i(\omega)}V_i(\omega)$$

- $V_i(\omega)$ = non-filtered signal
- $S_i(\omega)$ = response function
- $N_i(\omega)$ = noise power spectrum

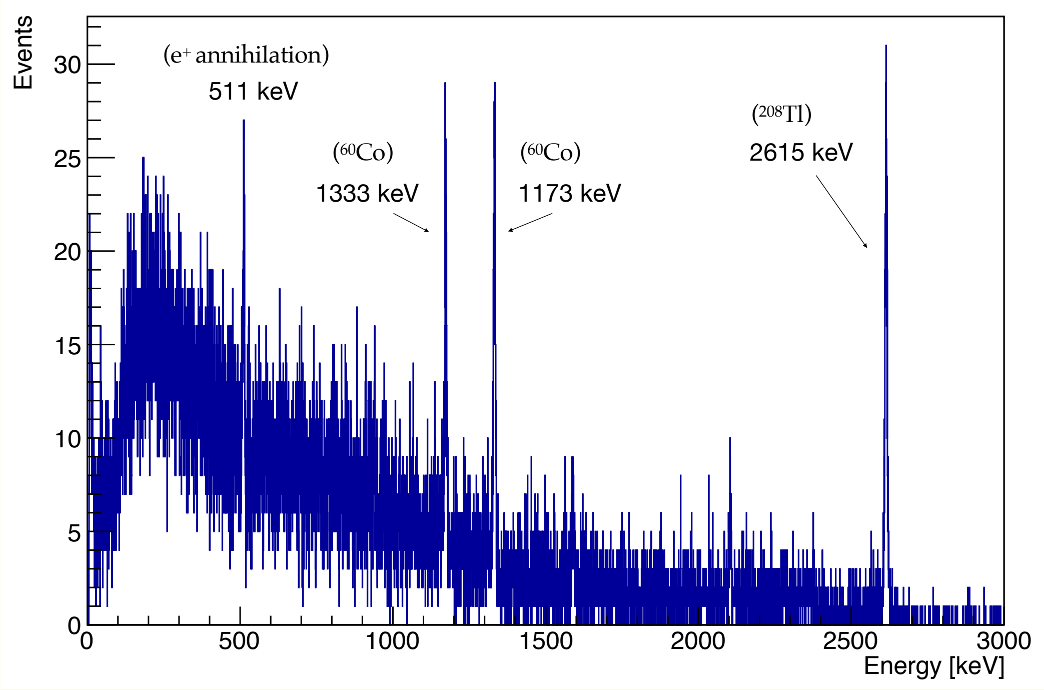
- T drifts ⟶ gain variations
- <u>*heaterTGS*</u>: heater pulses periodically fired @ fixed energy
- <u>*calibrationTGS*</u>: 2615 keV γ events from ^{208}Tl in calibration
- **Thermal gain stabilization correction**



Stabilized amplitude converted in Energy:

- ^{232}Th and ^{60}Co calibration sources
- Position of 4 peaks is determined

$$E = a \cdot A_{\text{stab}} + b \cdot A_{\text{stab}}^2$$



The CUORE data processing

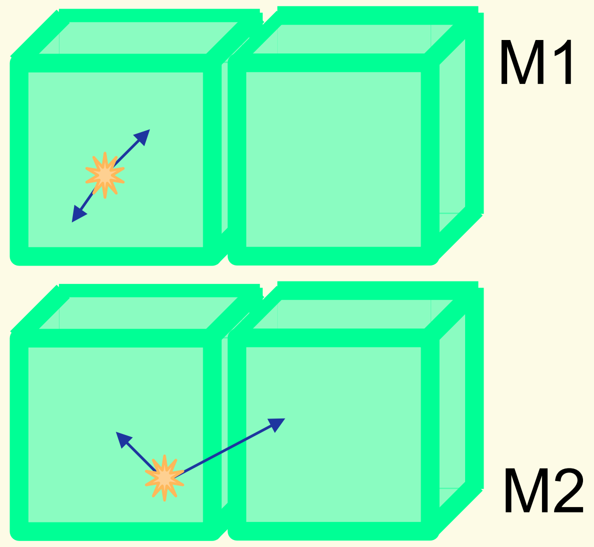
From the raw triggered waveform to the energy spectrum:

Preprocess → Amplitude → Stabilization → Calibration

From calibrated spectrum to finalized data:

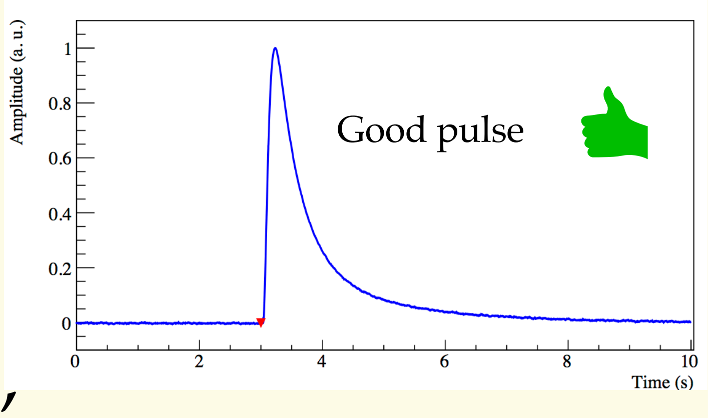
Coincidences → **Pulse Shape Analysis** → **Blinding**

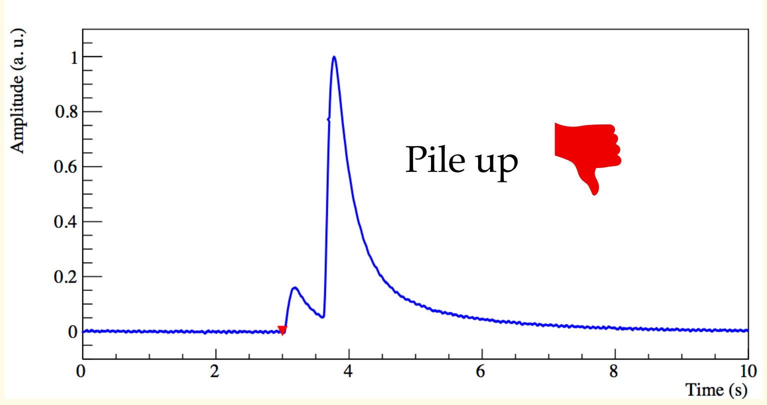
- 0νββ decay e⁻ : single-crystal event
- Other processes: multiple-crystal events (e.g. 2615 keV γ Compton: 2 crystals)

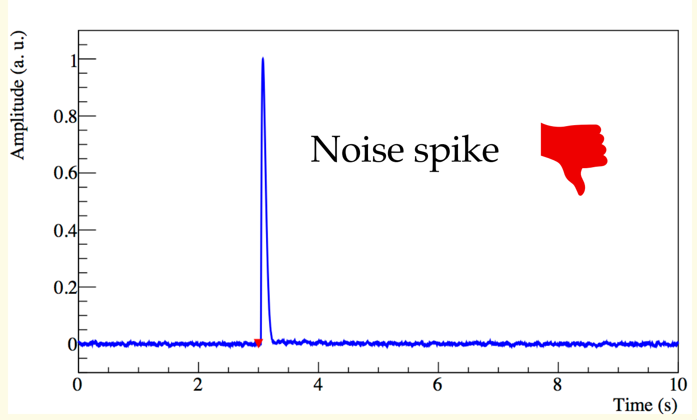


- Time-based coincidences
- Space-based coincidences
- **Event multiplicity assignment**

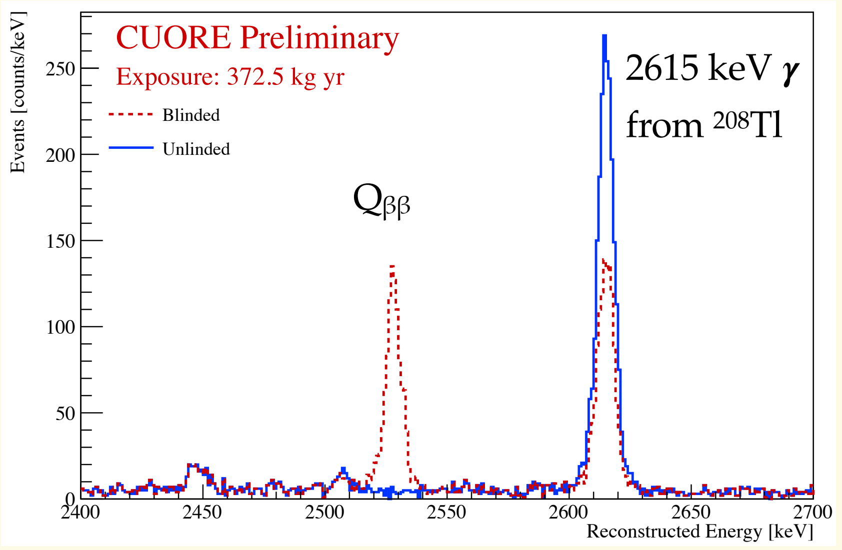
- **Pulses deviating from average pulse are discarded**
- 6 pulse shape parameters, 6-dim distance cut





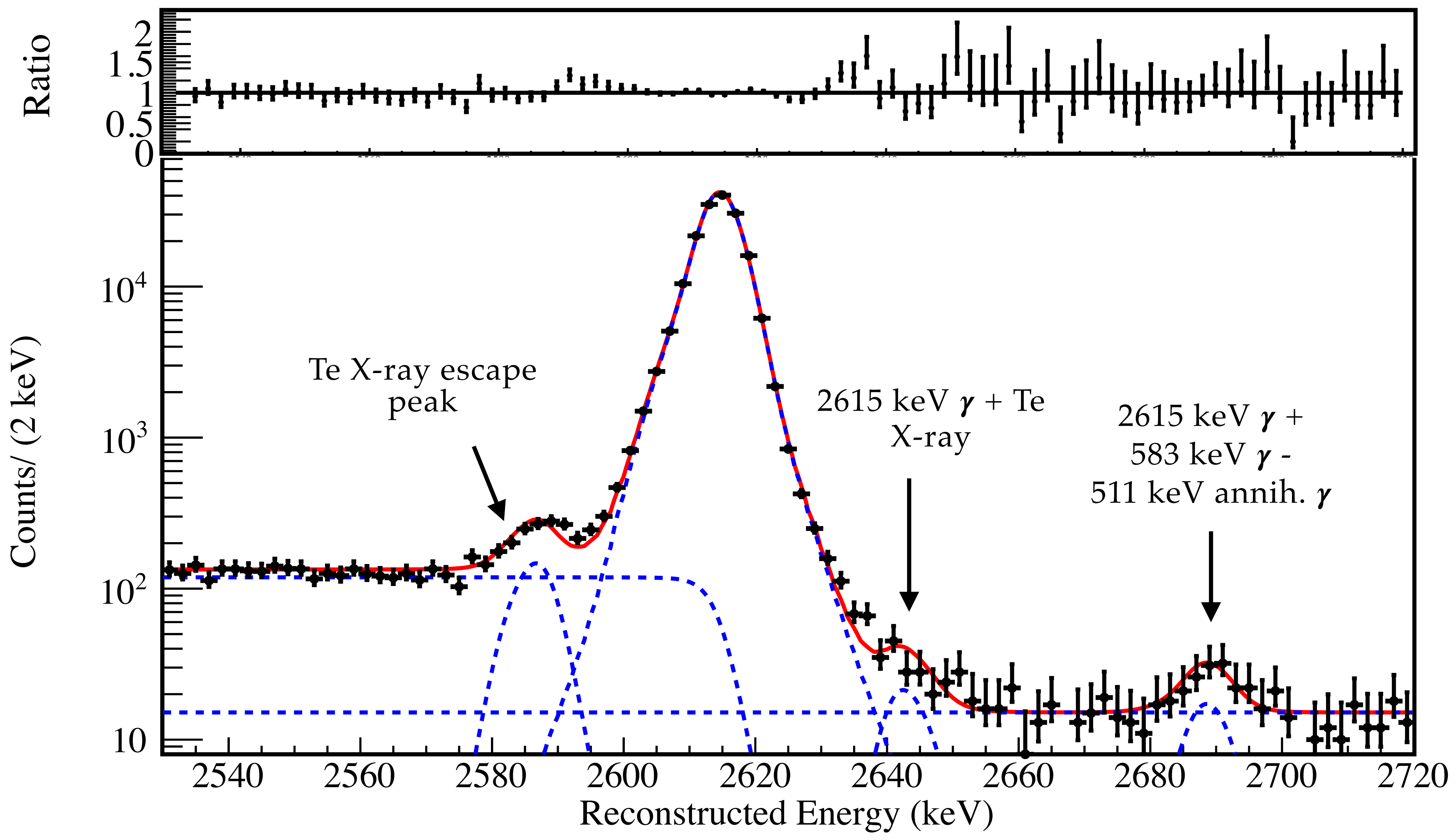


- **Data salting**: a fraction of 2615 keV γ events is shifted to $Q_{\beta\beta}$ and vice-versa



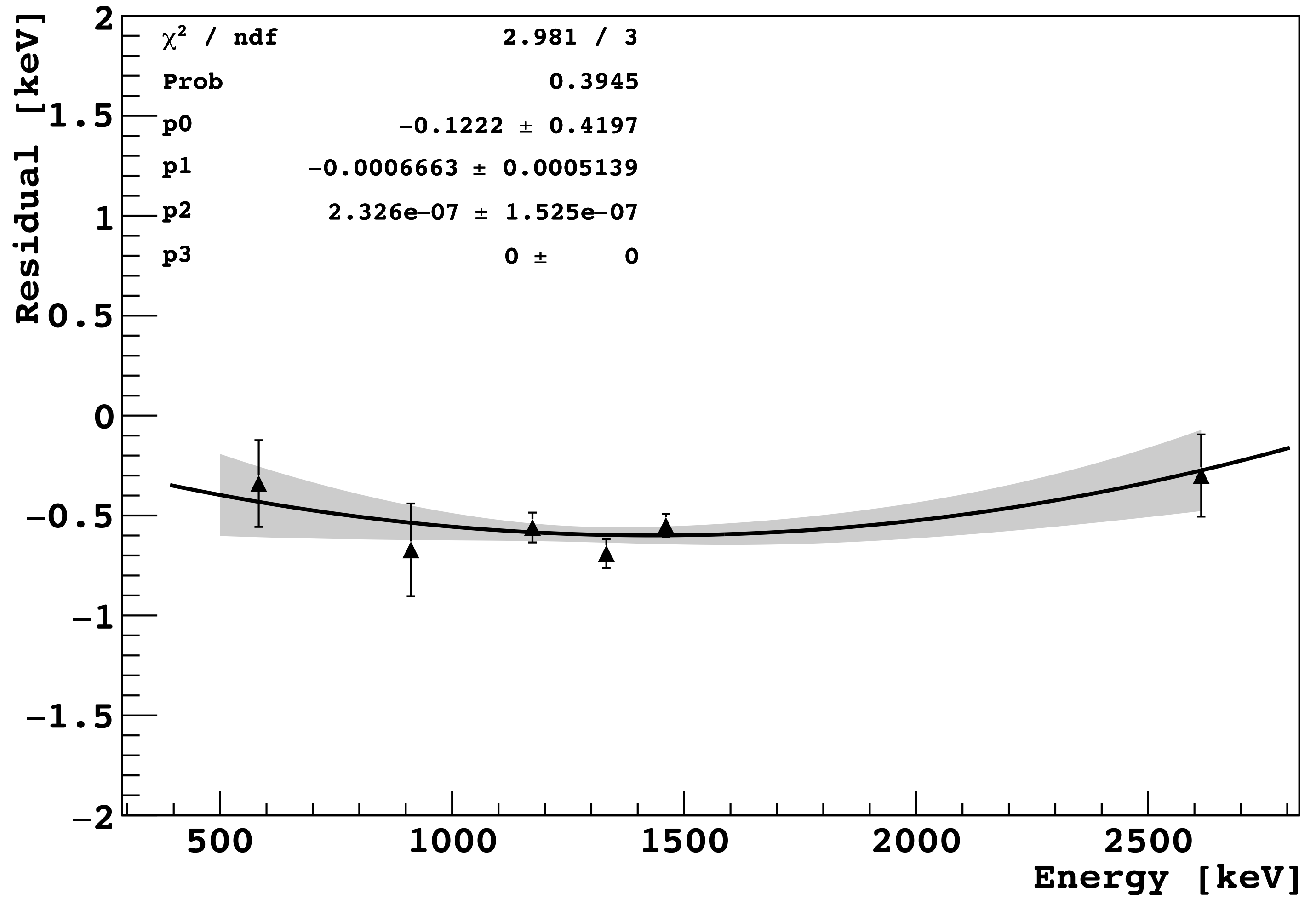
- **Hiding $Q_{\beta\beta}$ to avoid bias**
- True energy values encrypted until unblinding

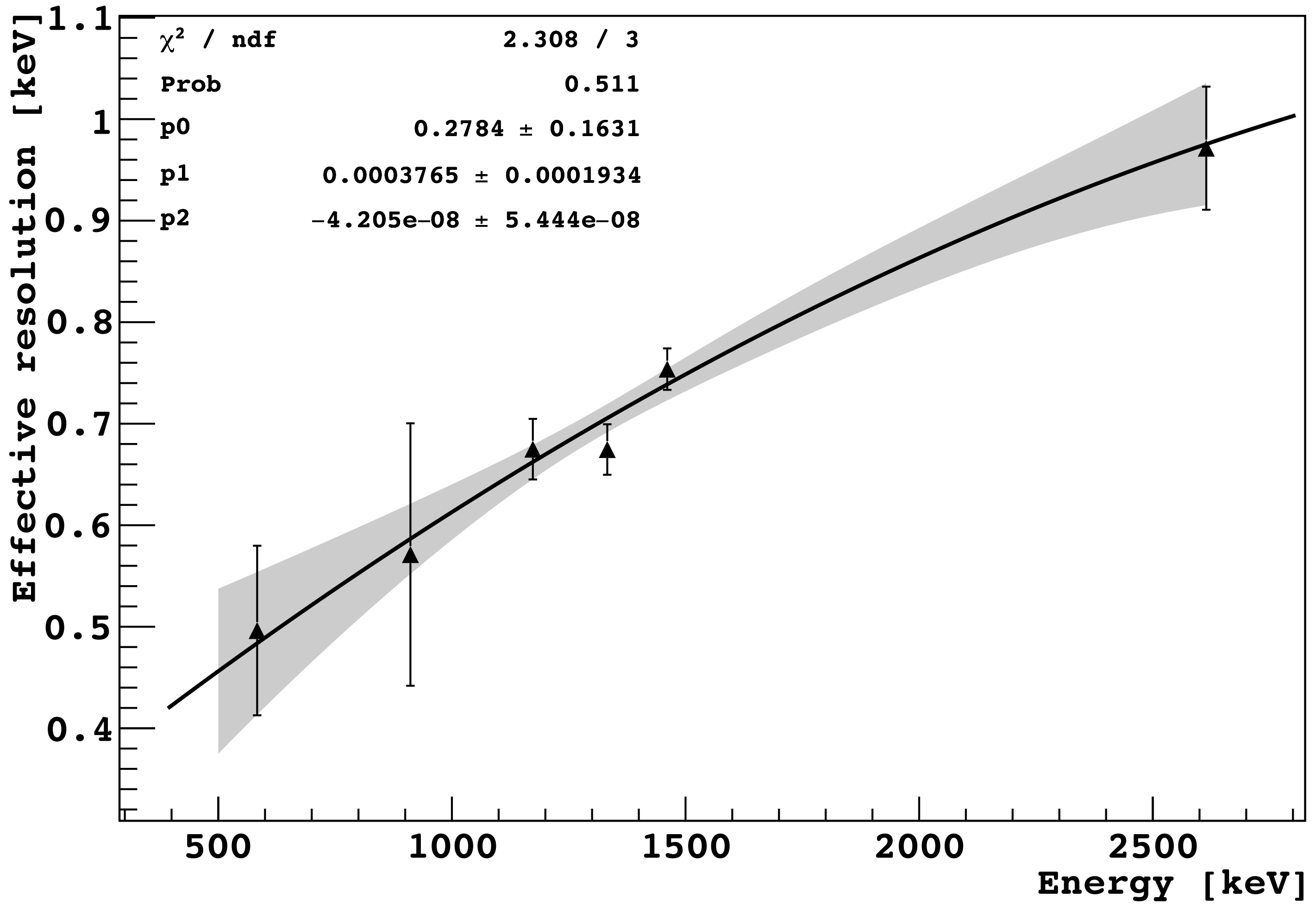
The CUORE detector response function (*lineshape*)



- TeO_2 bolometers 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 (~7.7 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





CUORE latest results on ^{130}Te 0νββ decay

- Unbinned Bayesian fit simultaneously performed for each detector-dataset

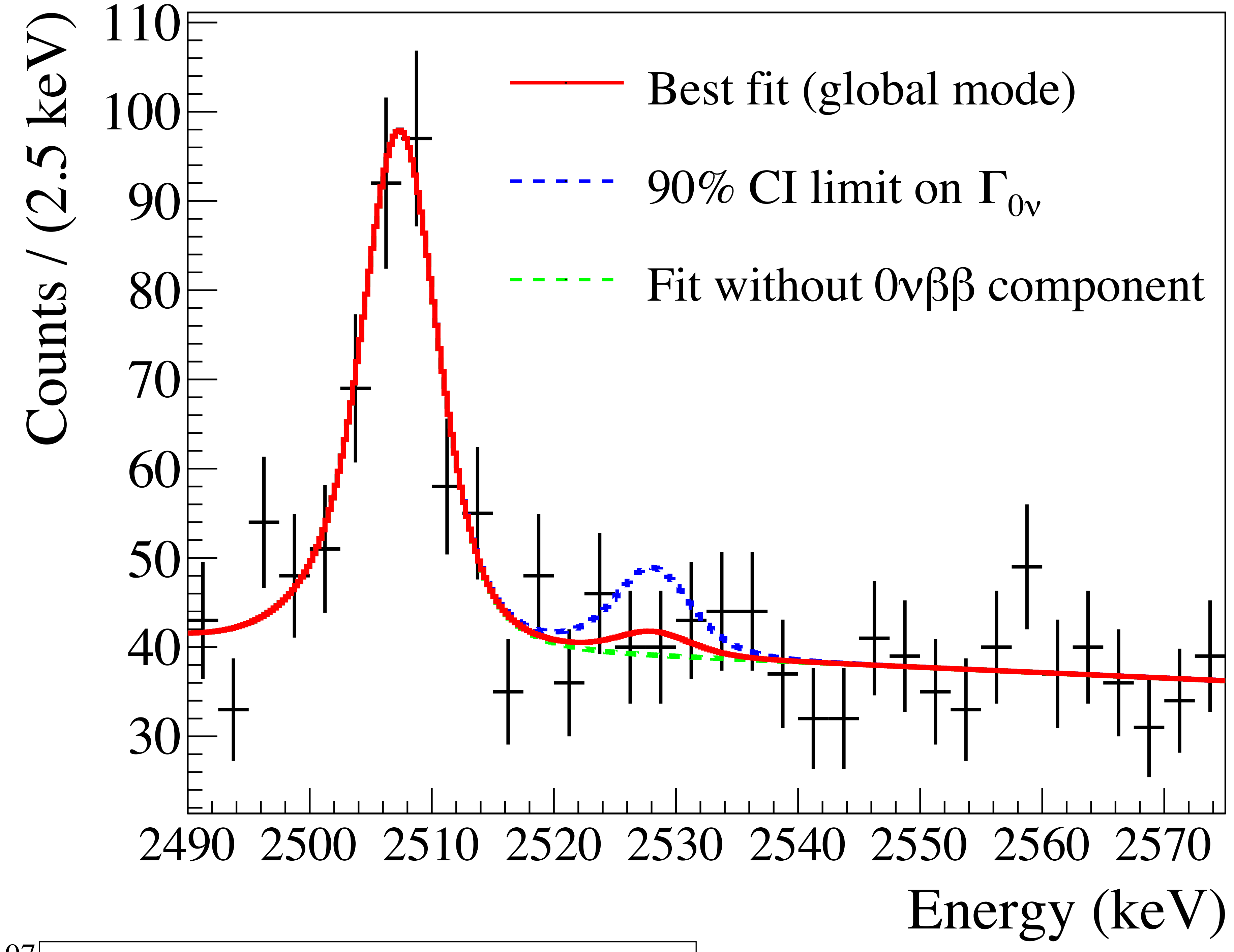
- Efficiencies:
  - ➡ Containment efficiency (0νββ decay in single crystal): from MC simulations
  - ➡ Reconstruction efficiency (trigger, event reconstruction, pile-up identification)
  - ➡ Anti-coincidence efficiency (probability that single-hit events are correctly identified)
  - ➡ PSD efficiency (fraction of events that survive the PSD cut)

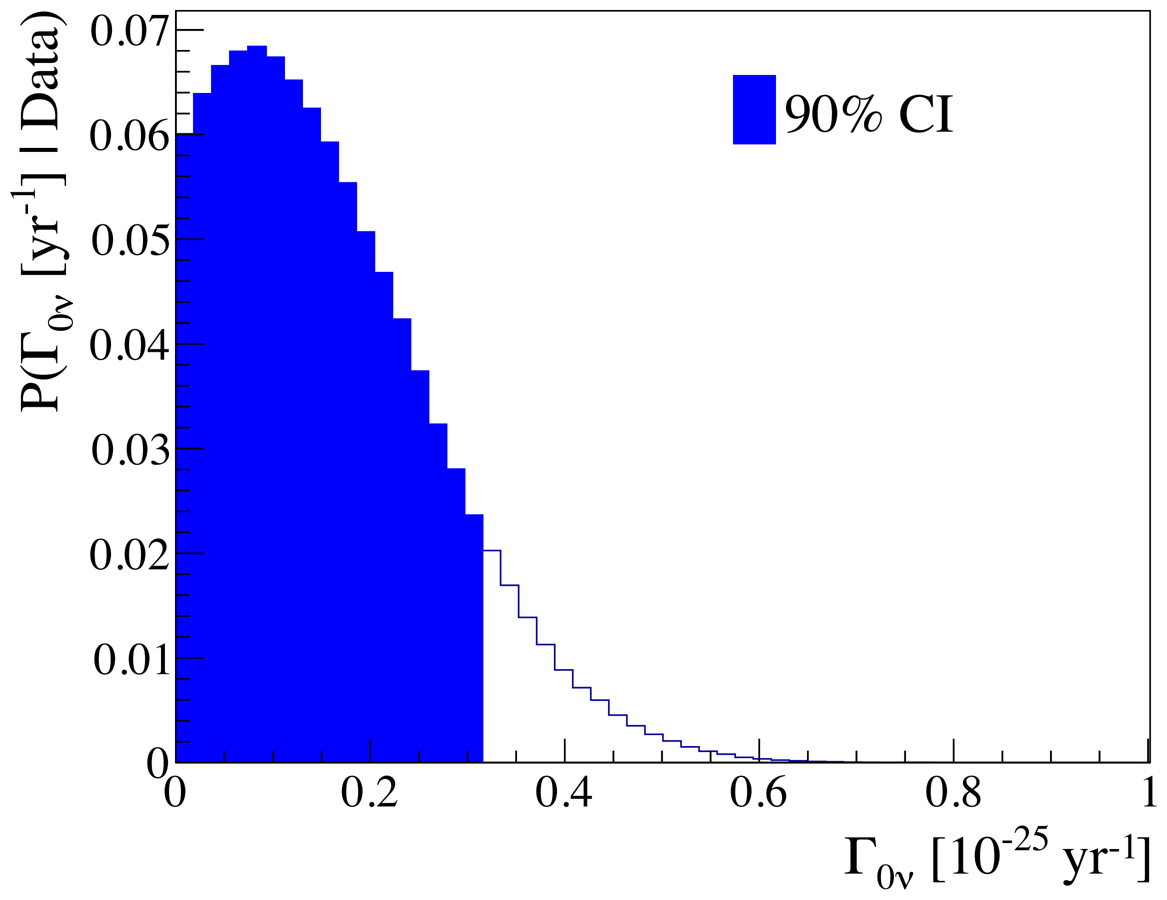
- No evidence of ^{130}Te 0νββ decay is observed

Exposure: 1038.4 kg·y

90% C.I. limit on ^{130}Te 0νββ decay half-life:

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





My contribution: data production and full processing

Outline

- Majorana neutrinos and Double Beta Decay Physics
- The CUORE experiment & latest results
- The CUORE Background Model & α region studies
- Search of neutrinoless double beta decay of ^{128}Te

Radioactive sources

- Radiopure material selection, cleaning and assembling protocols, …
- … but: dominant background sources come from crystals and copper residual contamination

^{232}Th chain nuclei

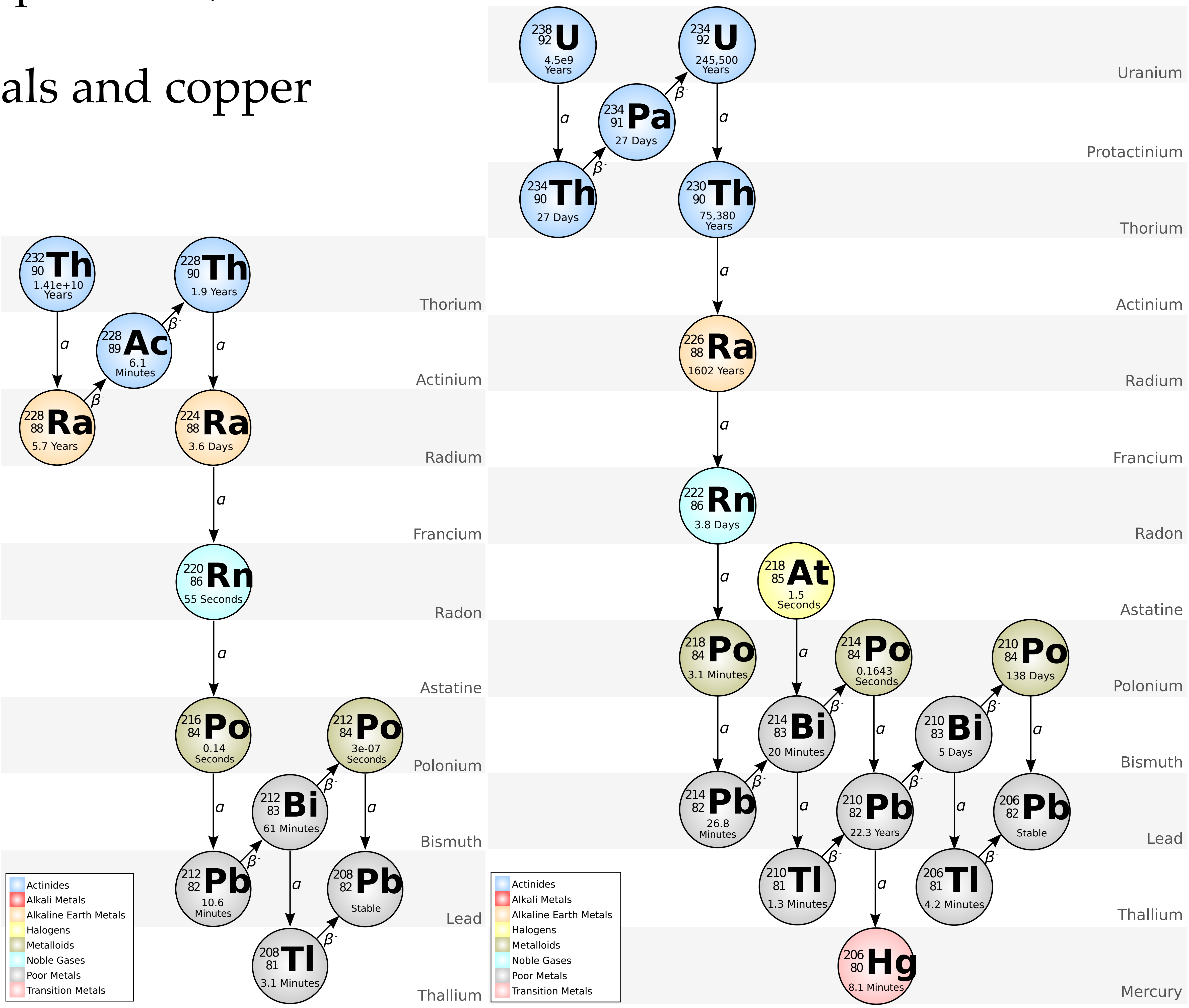
^{238}U chain nuclei

^{40}K (environment)

^{60}Co, ^{54}Mn (Cu cosmogenic activation)

^{190}Pt (crystal bulk)

……



Credits:

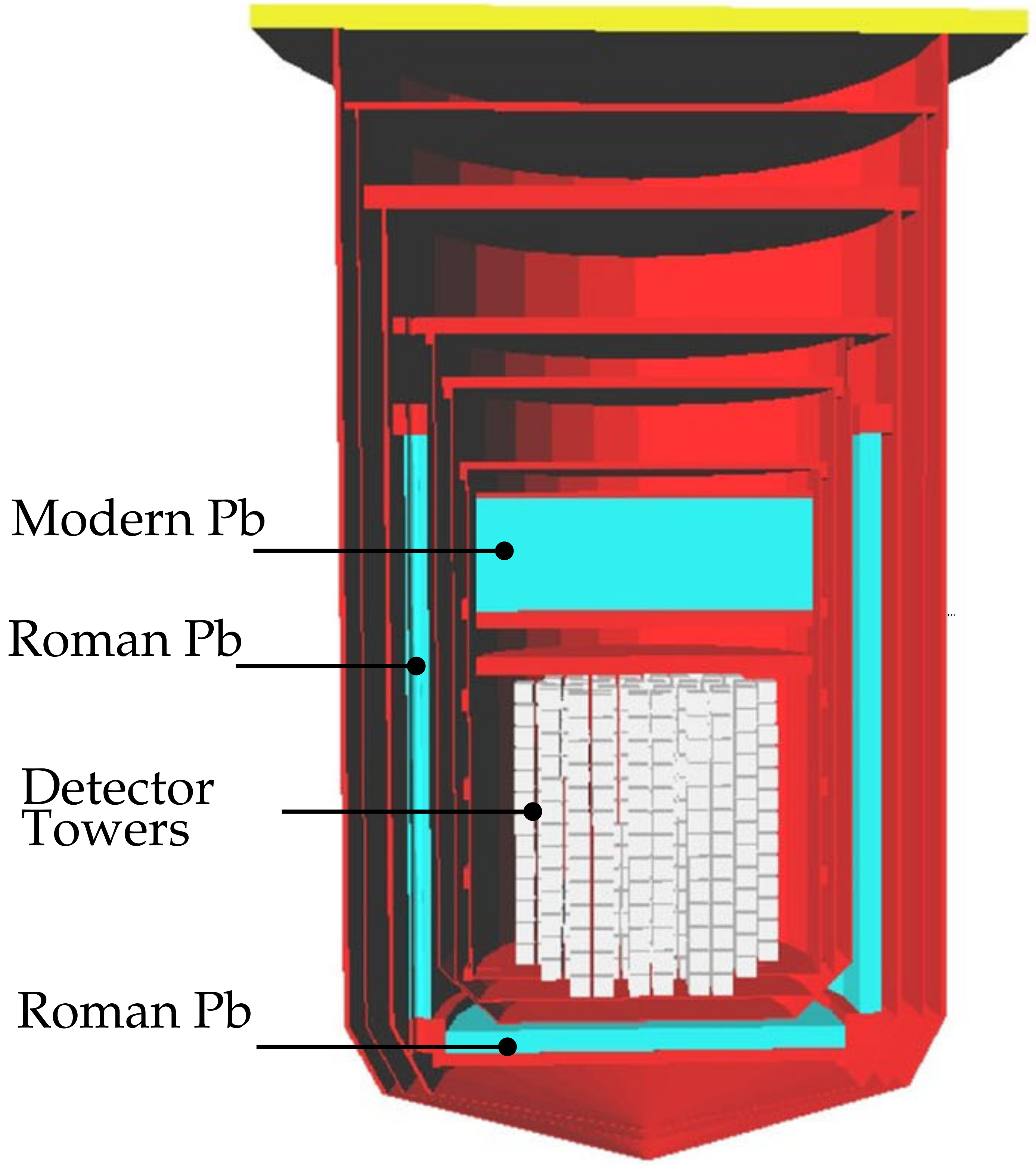
- Quantitative evaluation of the physics background contributing to the observed spectrum:

BACKGROUND MODEL

The CUORE Background Model (BM)

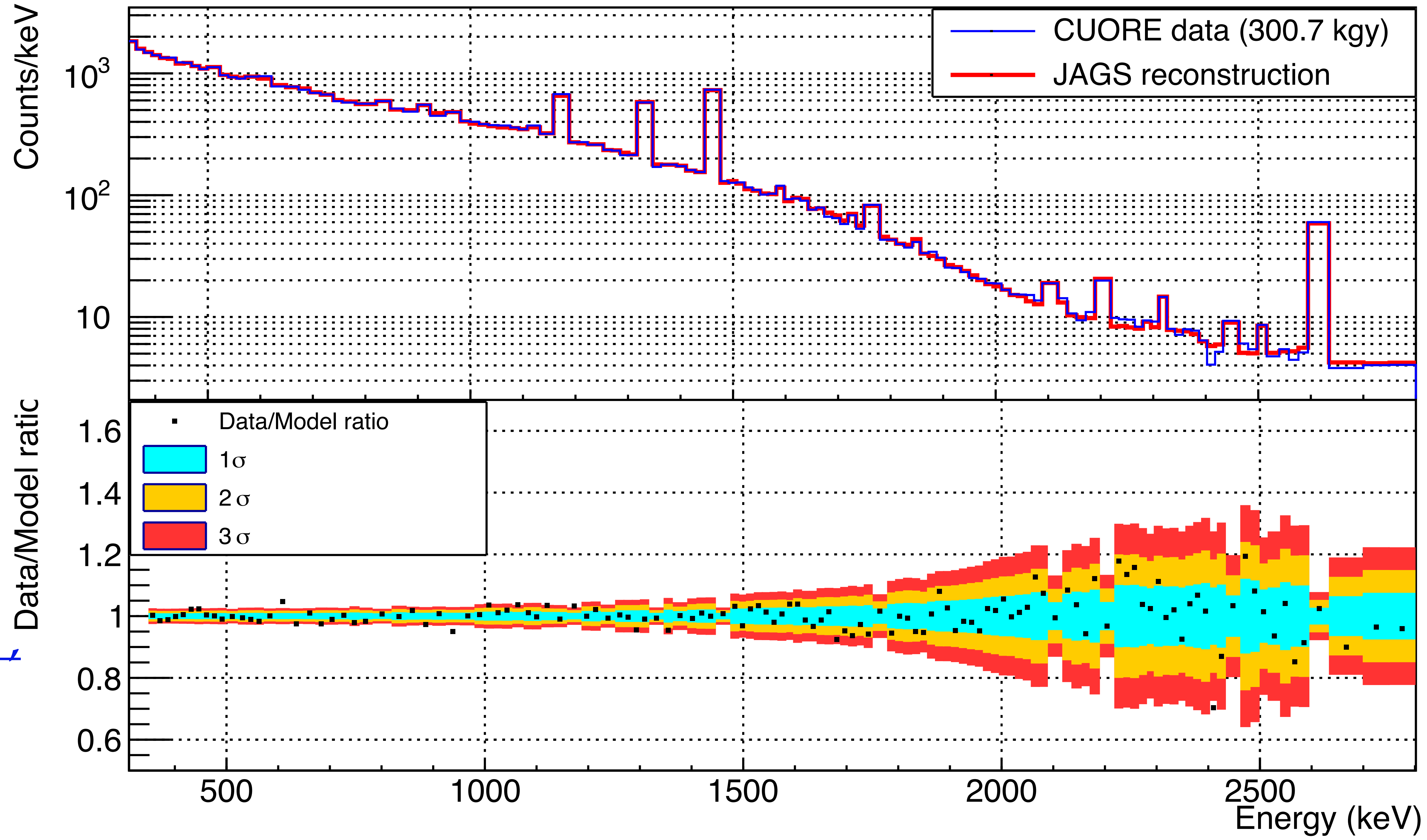
BACKGROUND MODEL - Detailed Monte Carlo simulations:

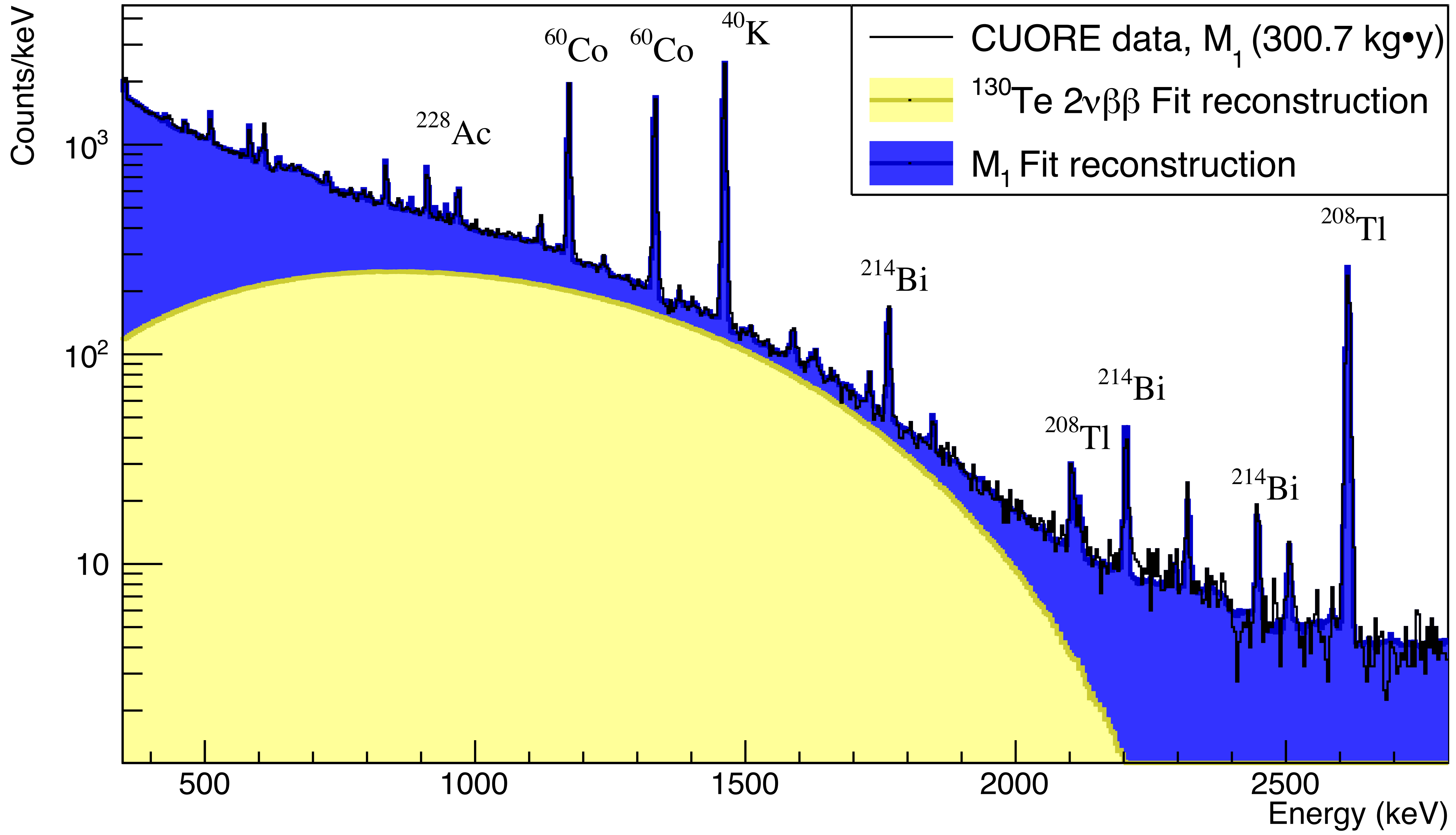
- Software based on GEANT4
- Geometry of the CUORE setup
- **Radioactive sources and their locations**
- Radiation interactions with the different parts of the detector
- Detector response, instrumental effects (thresholds, resolution,…)



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

- Identified background contributions are simulated
- Bayesian fit on experimental data with a linear combination of the MC simulations
- Fit parameters: a normalization factor N_j for each source j is extracted
- N_j used to extract the **activity** of the contaminants and **half lives** of processes (e.g. 2νββ decay $T_{1/2}$)





D.Q. Adams et al. , Phys. Rev. Lett., 126:171801, 2021

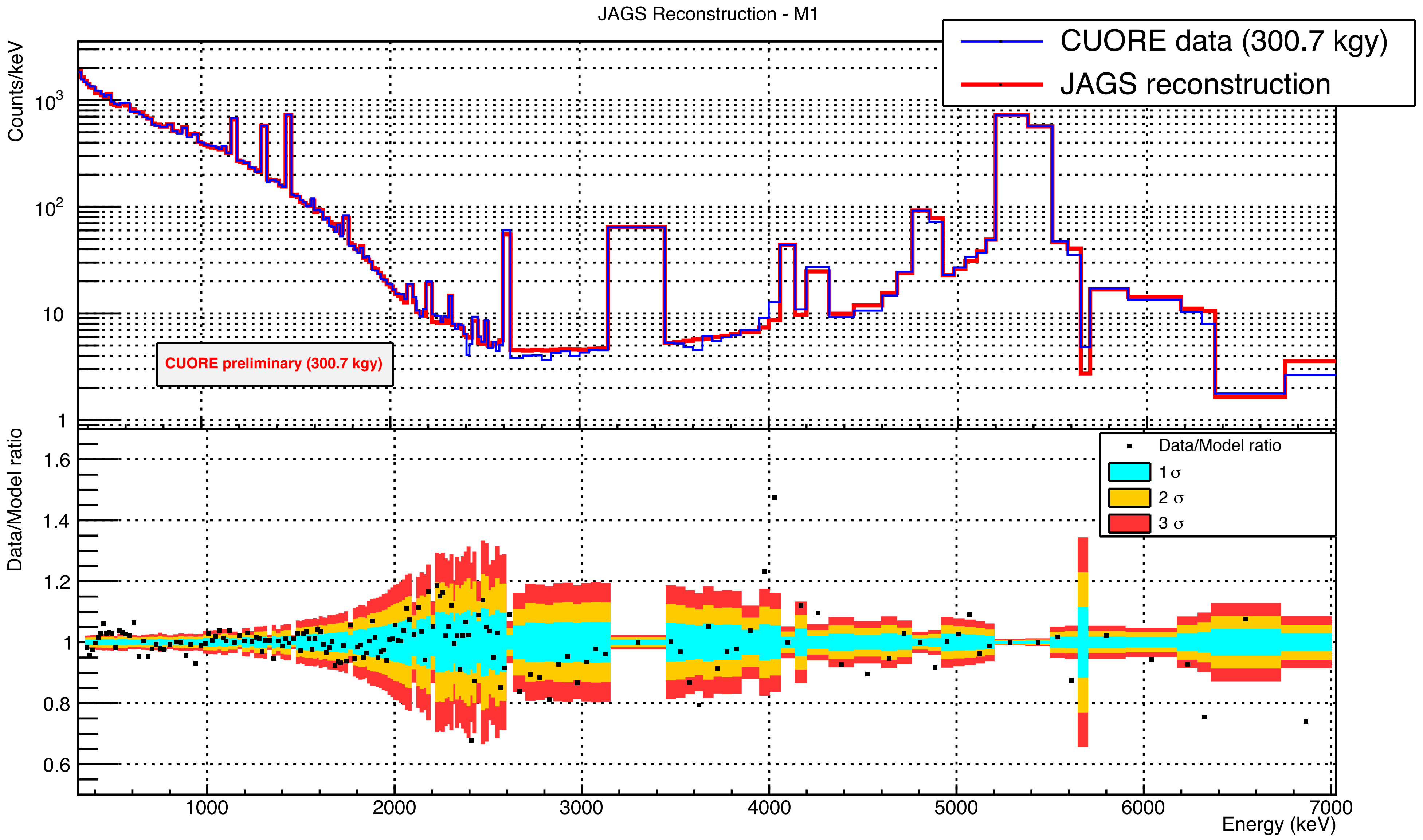
Most precise measurement of ^{130}Te 2νββ decay half-life:

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

Faithful reconstruction of the γ region (up to 2.8 MeV)

Improving the CUORE Background Model

- Fit range: 350 keV - 2.8 MeV → **the α region is excluded**
- **The α region reconstruction is challenging (non-ideal behavior of detector response, surface contamination profile modeling, …)**
- **Important to investigate since >90% of events in the ^{130}Te ROI is due to degraded alphas**
- **Fundamental for rare events analysis requiring a spectral fit (^{130}Te and ^{128}Te 2νββ half life, CPT violation signature, Majoron emission search,….)**



Possible improvements to the α region: more detailed knowledge of the sources

- **Contaminant position in the detector**
- **α particle quenching in TeO_2 crystals**
- **Breaking points in the radioactive chains**

New inputs to the Background Model

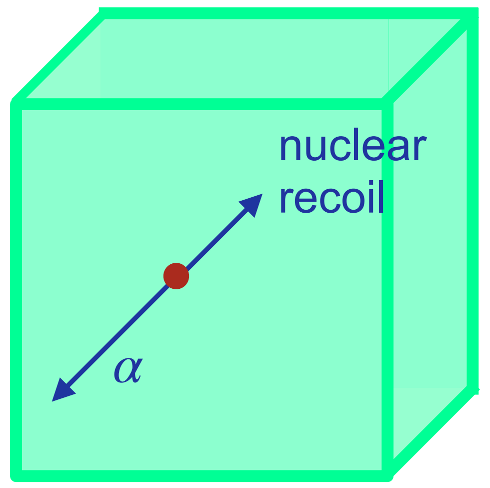
Fit quality improvement, more precise interpretation of the data

My contribution

CUORE alpha region - signatures

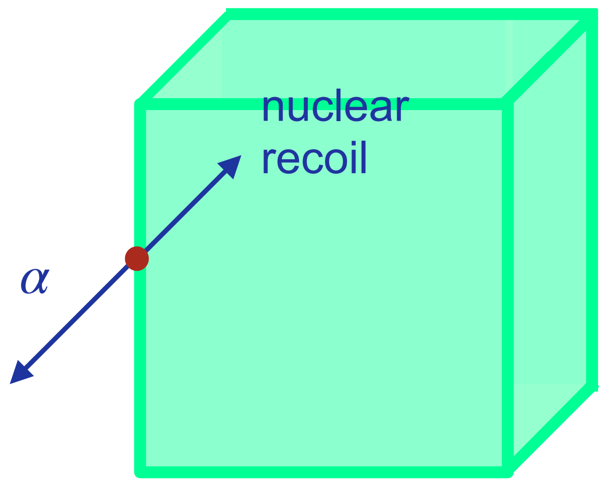
- α particles travel short distances (5 MeV α: 10 μm in Cu)
- Only visible if the contaminant is in the crystal's bulk/ surface or close to it
- Event coincidences study gives information on the source position
- **Bulk/surface contaminants produce different signatures in terms of released energy and event multiplicity**

α **decay:** $Q_{value} = E_{\alpha} + E_{recoil}$



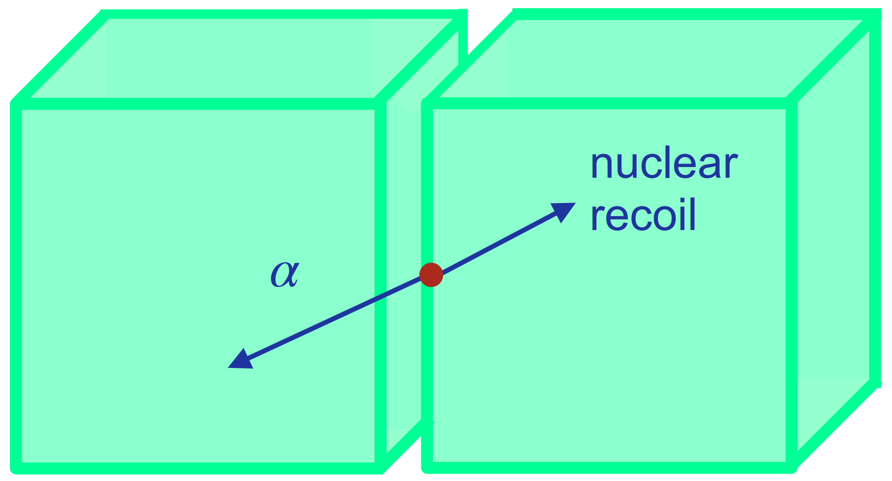
Bulk contaminant

M1, $E_{meas} = Q_{value}$



Surface contaminant

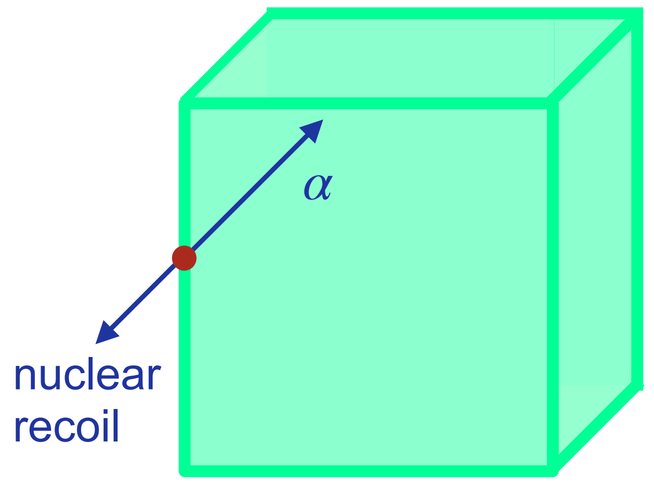
M1, $E_{meas} = E_{recoil}$



Surface contaminant

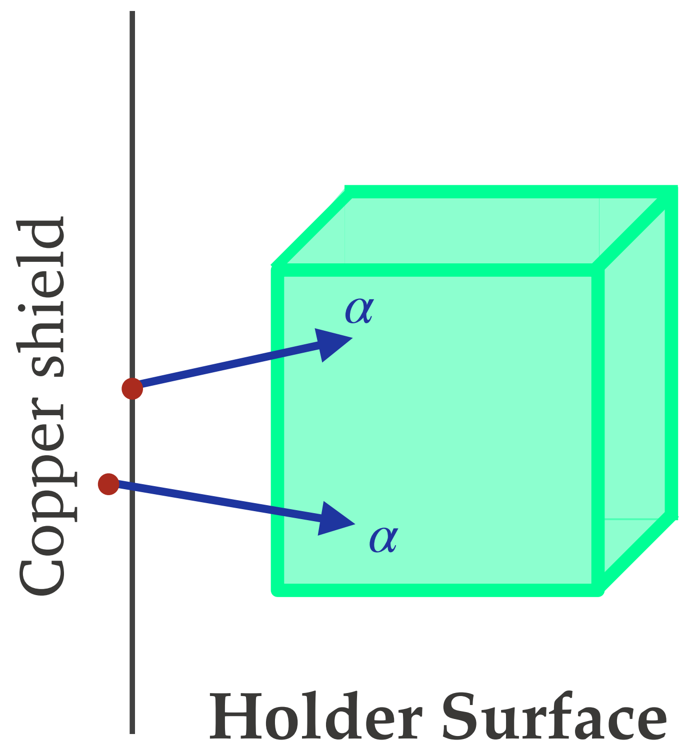
M2 single energy: $E^{(1)}_{meas} = E_{\alpha}$, $E^{(2)}_{meas} = E_{recoil}$

M2 total energy: $E_{meas} = Q_{value}$



Surface contaminant

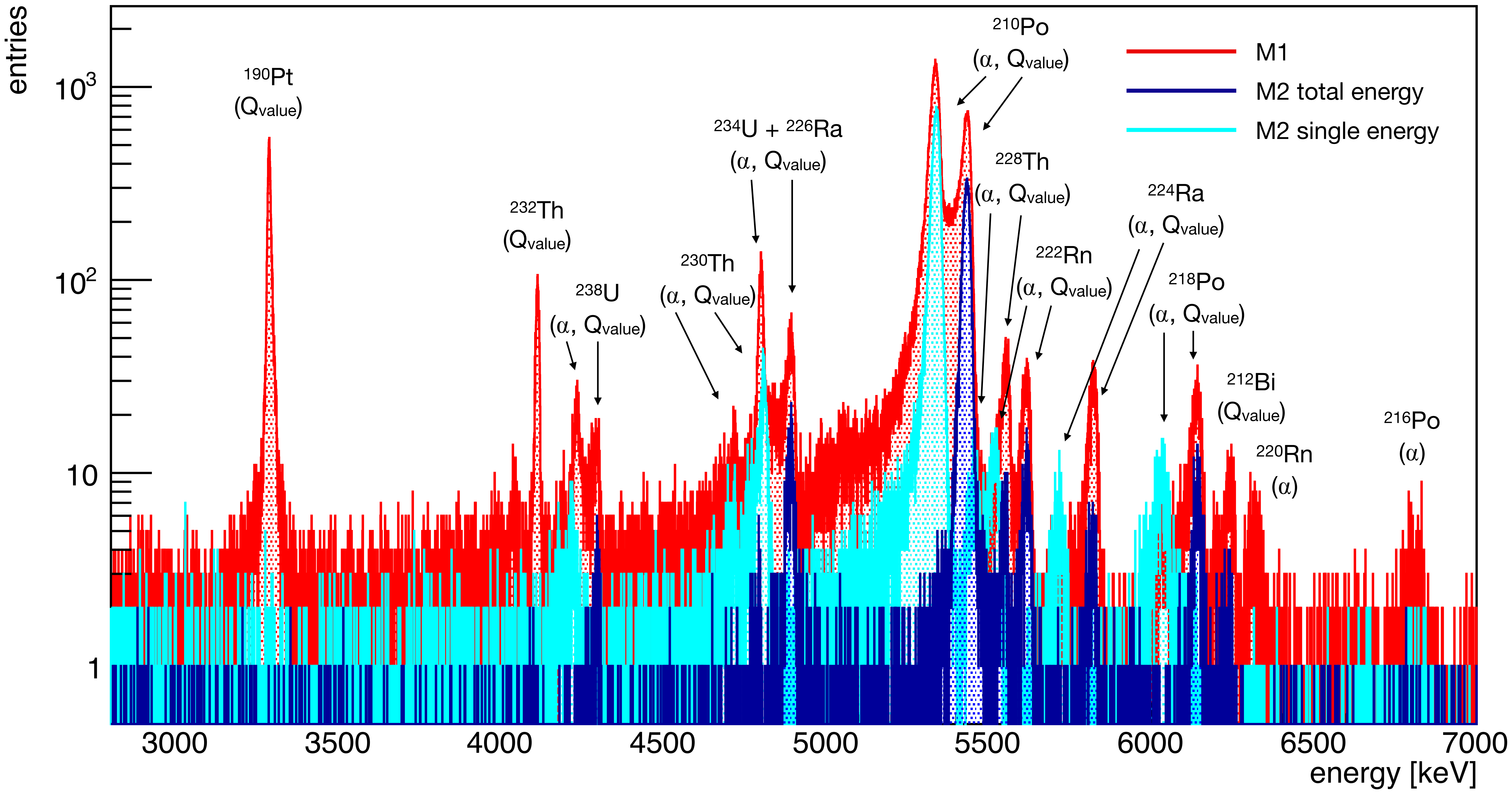
M1, $E_{meas} = E_{\alpha}$



Holder Surface contaminant

M1, $E_{meas} \leq E_{\alpha}$ (degraded α)

CUORE alpha region - contributions



- **^{238}U chain:**

<u>Q_{value}</u>: M1 and M2sum

<u>α</u>: M1 and M2

⇨ crystals' bulk
crystals' surface
holder's surface

- **^{232}Th chain:**

<u>Q_{value}</u>: M1 (all elem.)
M2sum (not all elem.)

<u>α</u>: M1 and M2 (not all elem.)

⇨ crystals' bulk dominant;
minor surface contribution

- **^{190}Pt:**

<u>Q_{value}</u>: M1 only

<u>α</u>: no line

⇨ crystals' bulk only

CUORE alpha region - peaks position in energy

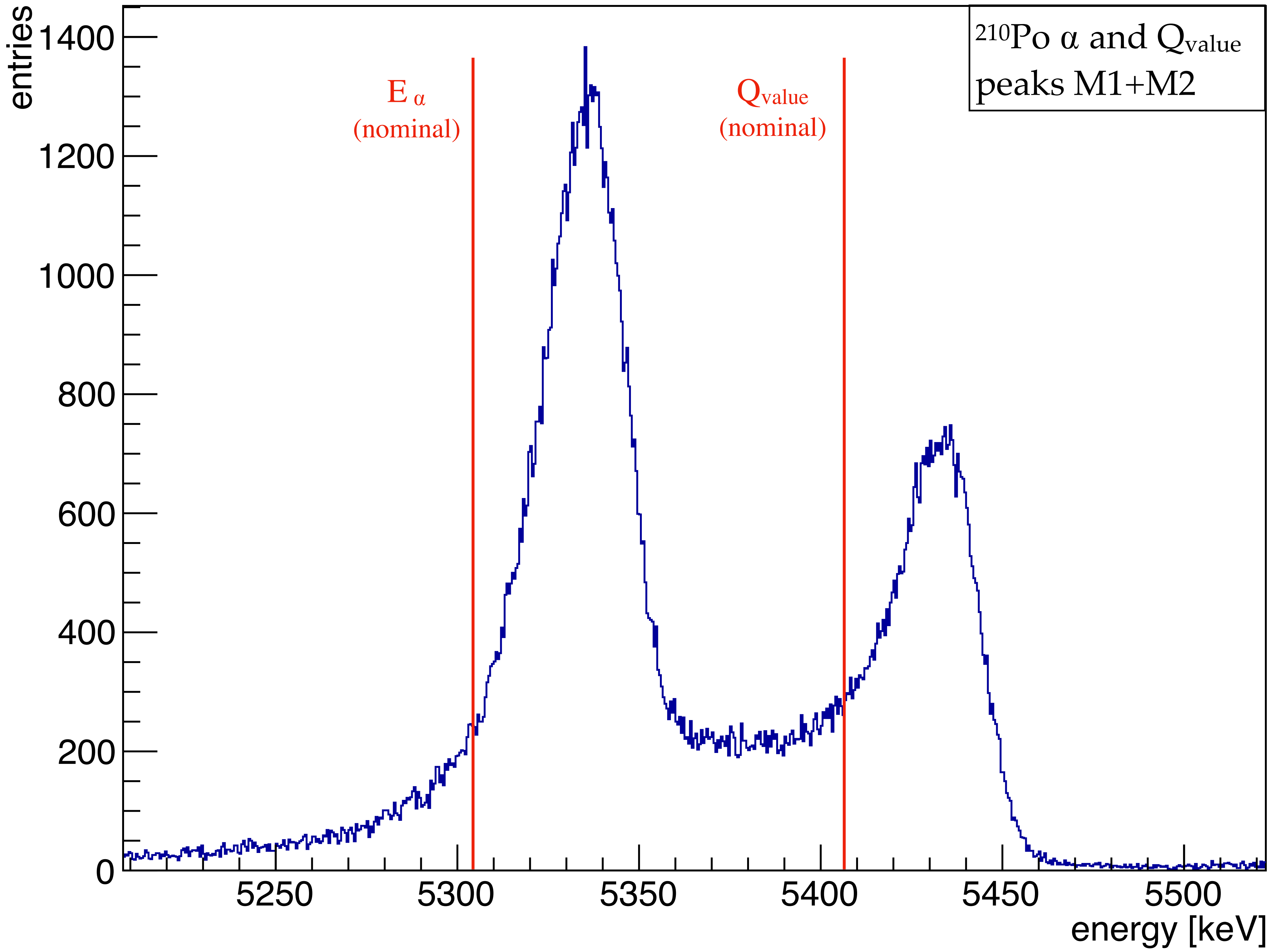
An α particle interacting with TeO_2 crystals generates a signal higher than expected from γ **calibration**

↓

- Measure *electron-equivalent energy*
- TeO_2 response to α particles appears to be different than e^-, γ

QUENCHING FACTOR:

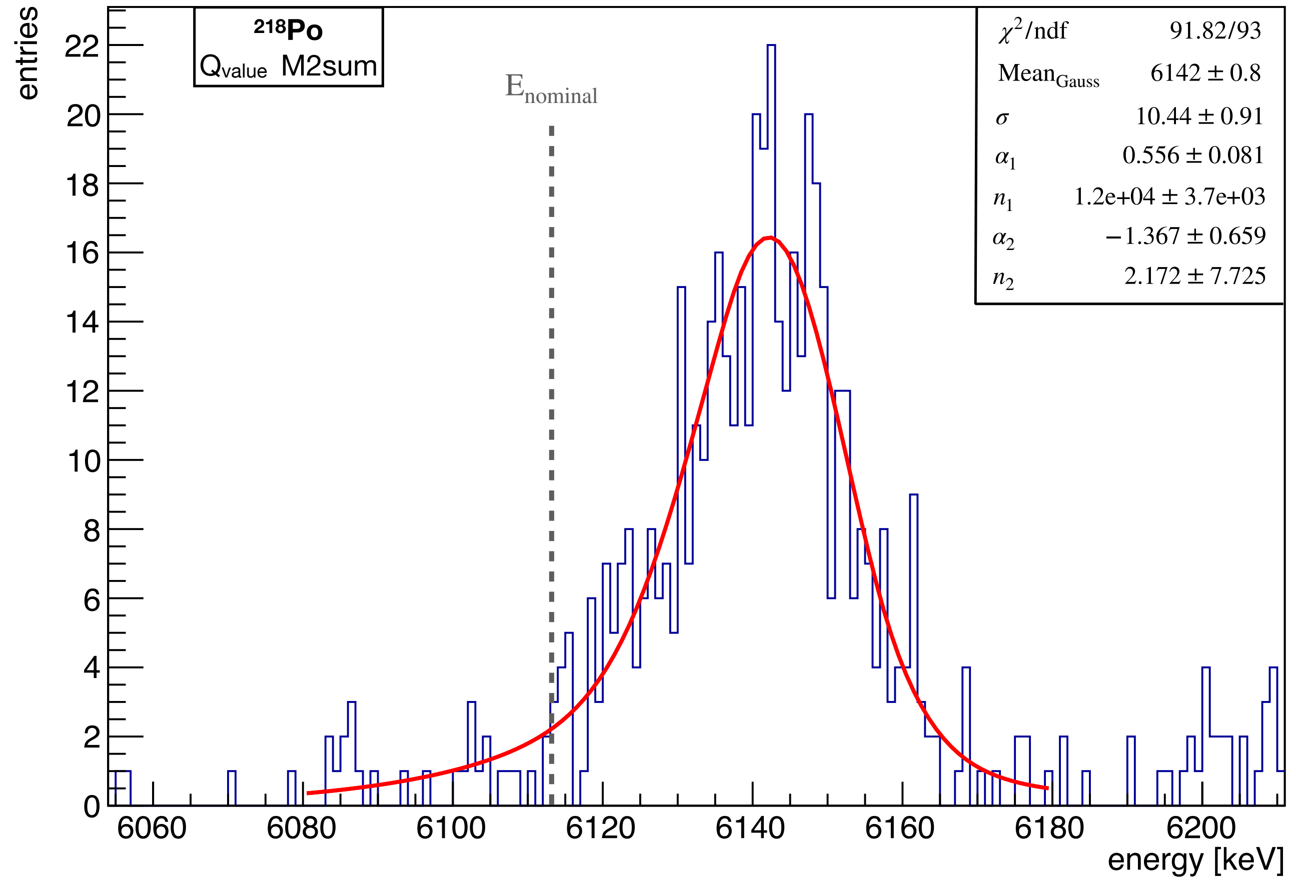
$$\frac{E_{measured}}{E_{nominal}} \equiv QF$$



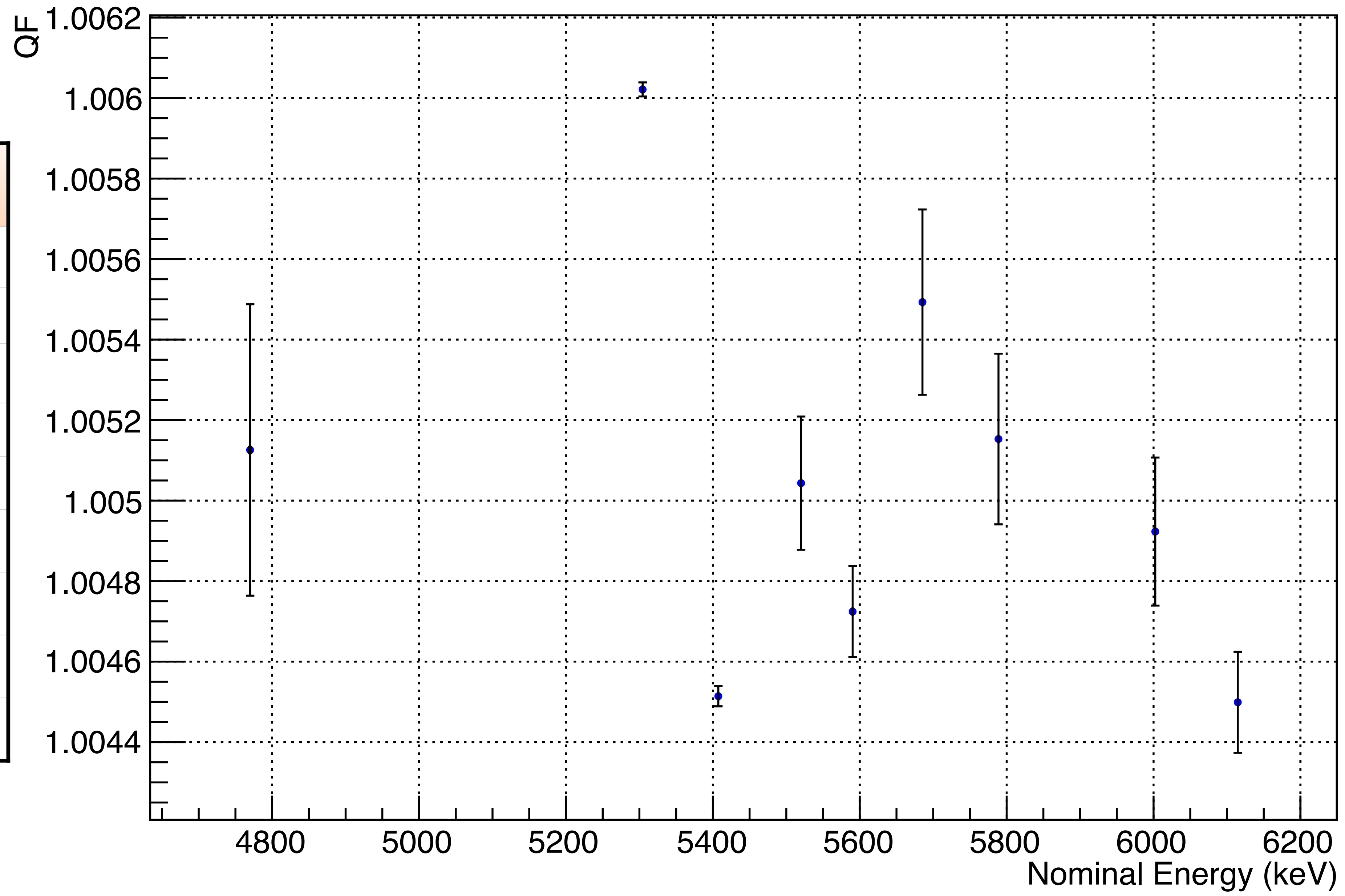
GOAL: quantify the QF in CUORE to include the appropriate correction in the Background Model MC simulations

CUORE alpha region - peaks position in energy

- Estimation of the peaks position in energy ⟶ fit function: combination of 2 Crystal Ball functions sharing the gaussian parameters
- Crystal Ball function = Gaussian function with a smoothly joined power law tail
- **$E_{measured}$ estimator: gaussian mean extracted from the fit**



Element	*Nominal energy (keV)*	*Measured Energy (keV)*
^{230}Th (Q_{value})	4770.0±1.5	**4794.45±0.84**
^{210}Po (Q_{value})	5407.46±0.07	**5431.87±0.12**
^{228}Th (Q_{value})	5520.12±0.22	**5547.96±0.89**
^{222}Rn (Q_{value})	5590.3±0.3	**5616.71±0.56**
^{224}Ra (Q_{value})	5788.87±0.15	**5818.7±1.2**
^{218}Po (Q_{value})	6114.68±0.09	**6142.19±0.76**
^{210}Po (single α)	5304.38±0.07	**5336.32±0.06**
^{224}Ra (single α)	5685.37±0.15	**5716.6±1.3**
^{218}Po (single α)	6002.35±0.09	**6031.9±1.1**

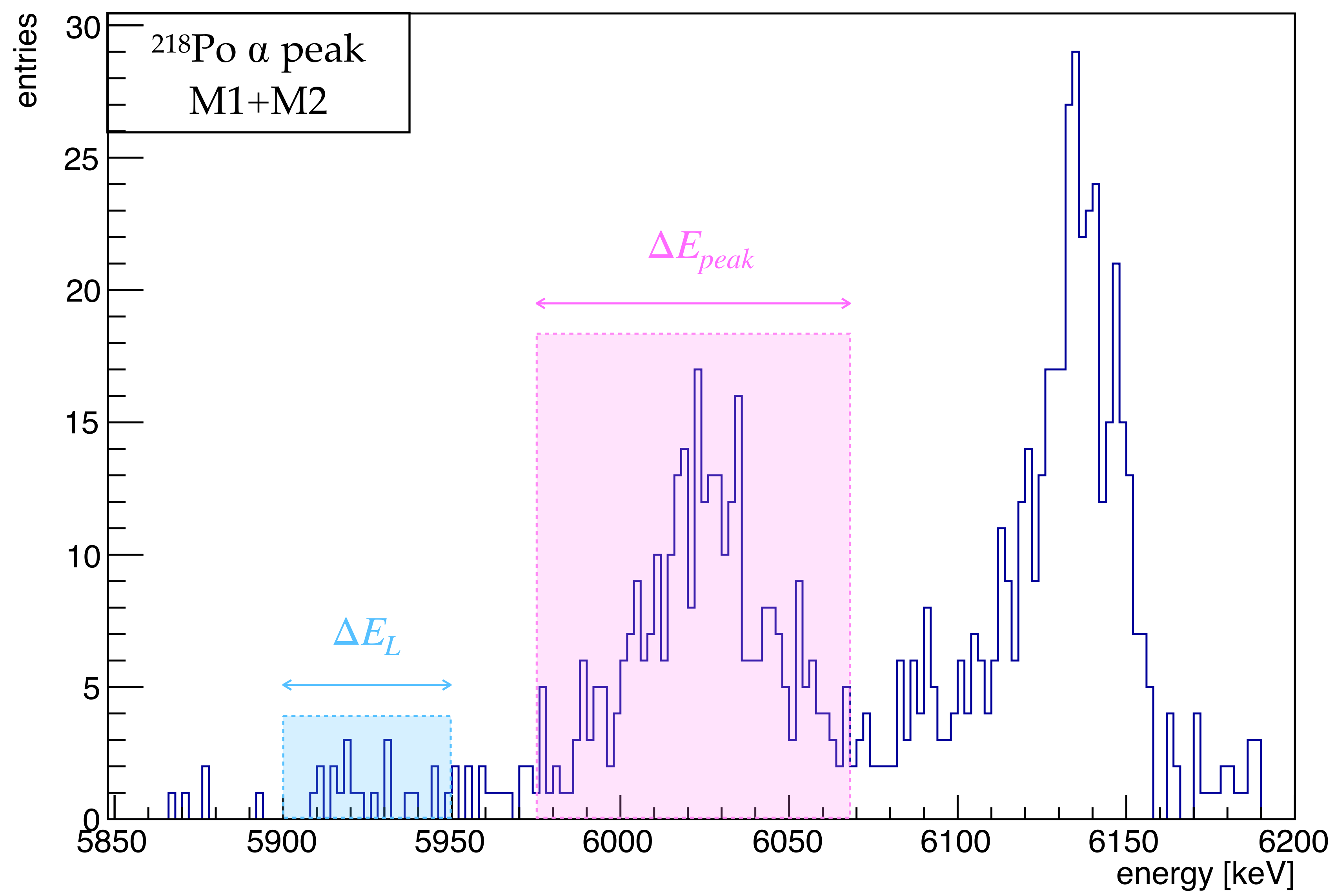


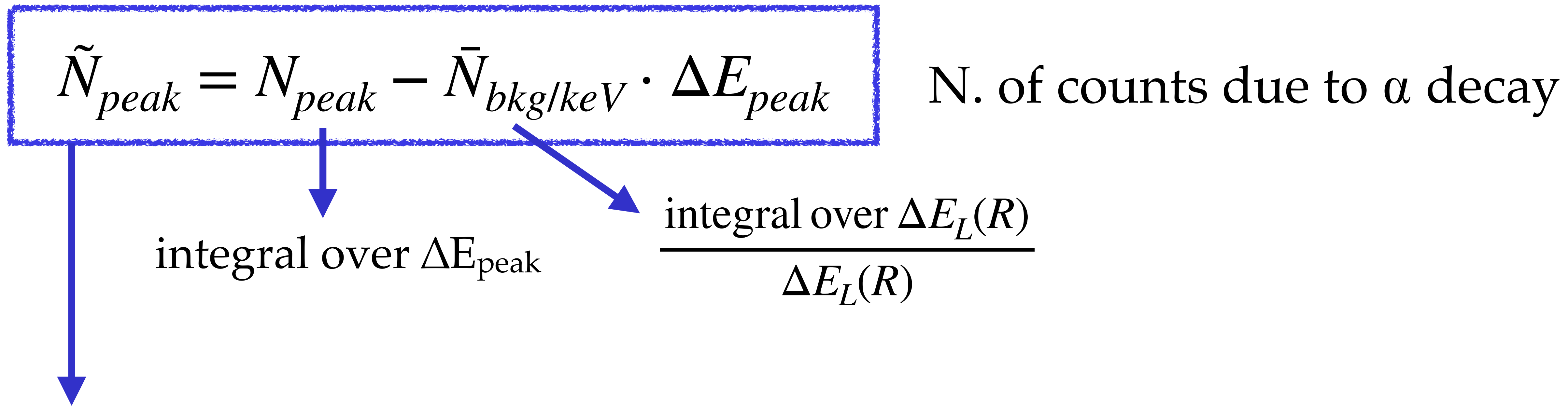
Results

- CUORE-0: QF ~ 1.007
  CUORE (this work): QF ~ 1.005
- Systematic uncertainties under investigation: fit model, choice of $E_{measured}$ estimator, calibration function
- A different QF in CUORE-0 and CUORE could be an effect of the different NTDs bias settings

CUORE alpha region - secular equilibrium of ^{238}U chain

- Evaluation of the activity of the ^{238}U chain isotopes (not enough statistics for ^{232}Th)
- Time dependence of the α peaks intensity over a period of 2 years
- Decay rates evaluated by integration of the peaks on spectra for each dataset
- Background subtraction from the peak integral:





$$\boxed{\tilde{N}_{peak} = N_{peak} - \bar{N}_{bkg/keV} \cdot \Delta E_{peak}}$$

N. of counts due to α decay

integral over ΔE_{peak}

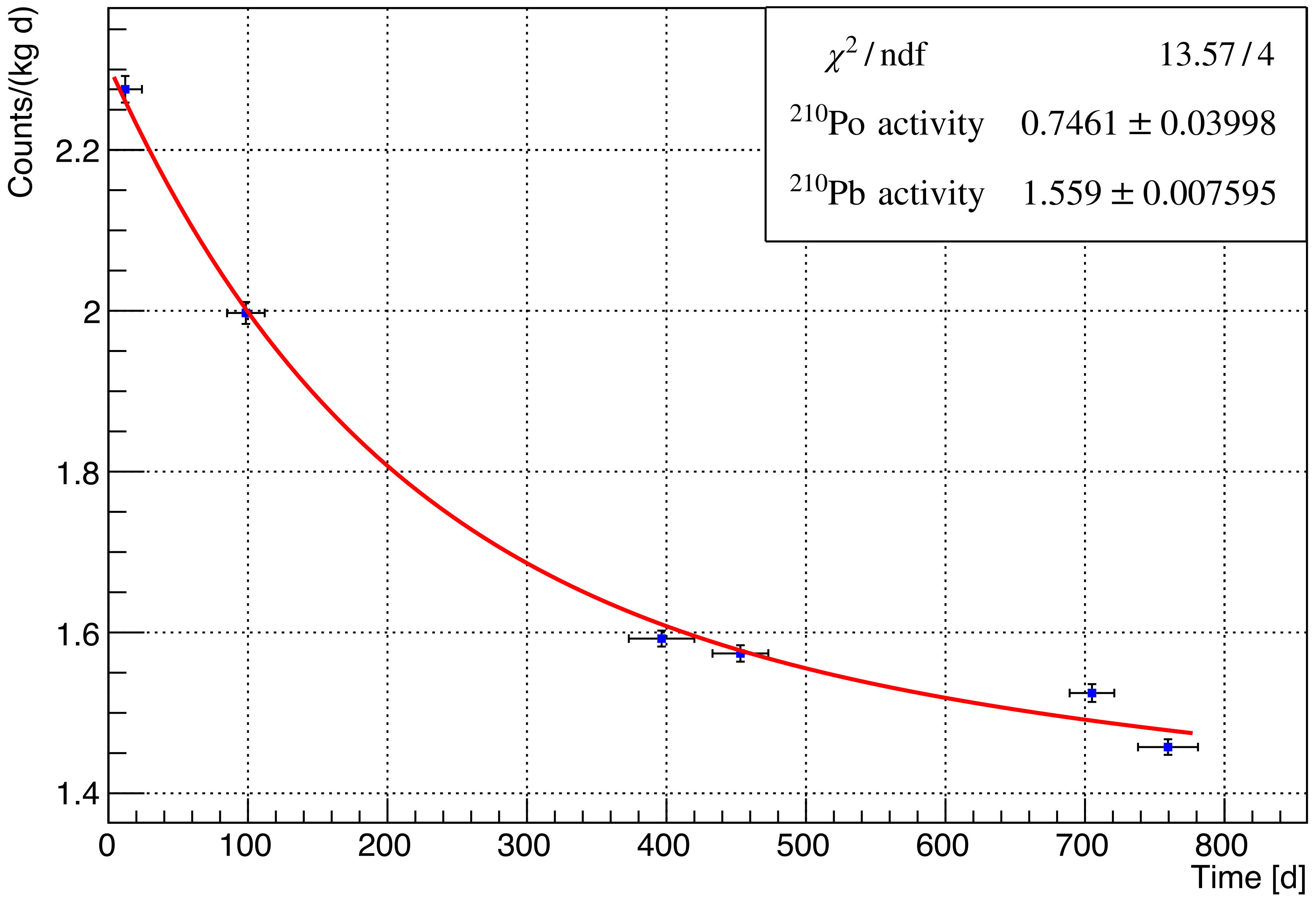
$$\frac{\text{integral over } \Delta E_L(R)}{\Delta E_L(R)}$$

- Scaled by dataset exposure: decay rate in counts/kg/day
- Time at half of the dataset associated

CUORE alpha region - secular equilibrium

I determined the activity of ^{238}U nuclei from their rate distributions over $\Delta t = 2$ years

- ^{238}U, ^{230}Th: $T_{1/2} >> \Delta t$, constant rate is expected
- ^{218}Po: $T_{1/2} << \Delta t$, constant rate is expected, equal to parent decay rate if secular equilibrium occurs
- ^{210}Po + ^{210}Pb: fit with 2 exponentials on the ^{210}Po α peak to determine the two contributions
- Extracted activities scaled by the decay branching ratio



Results

Element	*Half life*	*Activity (10^{-2} counts/kg/day)*
^{238}U	4.47 • 10^9 y	1.72 ± 0.08
^{230}Th	7.54 • 10^4 y	1.31 ± 0.08
^{218}Po	3.1 mins	1.48 ± 0.05
^{210}Pb	22.3 y	155.9 ± 0.8
^{210}Po	138.4 days	74.6 ± 3.9

- ^{238}U, ^{230}Th, ^{218}Po activities are constant and are very similar: **secular equilibrium down to ^{218}Po**
- ^{210}Pb and ^{210}Po: **two breaking points of the chain**
- ^{210}Po activity ~2 times lower than ^{210}Pb: **secular equilibrium between ^{210}Pb implanted on surfaces and daughters not reinstated yet**

Outline

- Majorana neutrinos and Double Beta Decay Physics
- The CUORE experiment & latest results
- The CUORE Background Model & α region studies
- Search of neutrinoless double beta decay of ^{128}Te

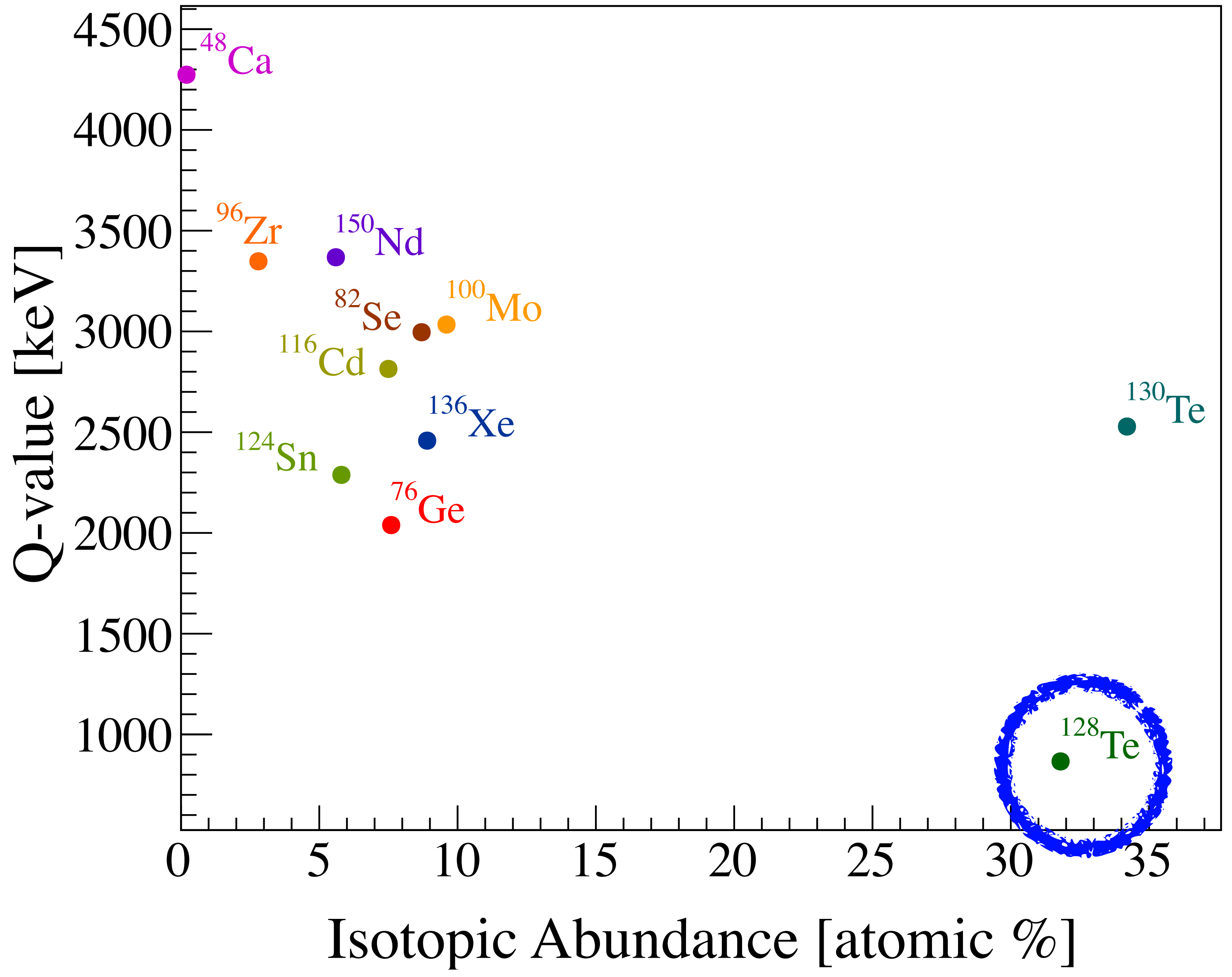
Motivations

- ^{128}Te is another ββ emitting tellurium isotope: $^{128}\text{Te} \longrightarrow {}^{128}\text{Xe}$
- High natural abundance: 31.75%
- $Q_{\beta\beta}$ = (866.6 ± 0.9) keV ⟶ Highly populated region: natural γ radioactivity, ^{130}Te 2νββ decay
- **Latest ^{128}Te 0νββ decay results:**
  - ➡ From direct experiments (MiDBD in 2003, 6.8 kg of TeO_2, 2 crystals enriched in ^{128}Te at 82.3%):

$$\boxed{T^{0\nu}_{1/2} > 1.1 \cdot 10^{23}\, y}$$

  - ➡ From geochemical experiments: **(refers to the sum of 2ν and 0ν modes)**

$$\boxed{T^{128Te}_{1/2} = (2.0 \pm 0.3) \cdot 10^{24}\, y}$$



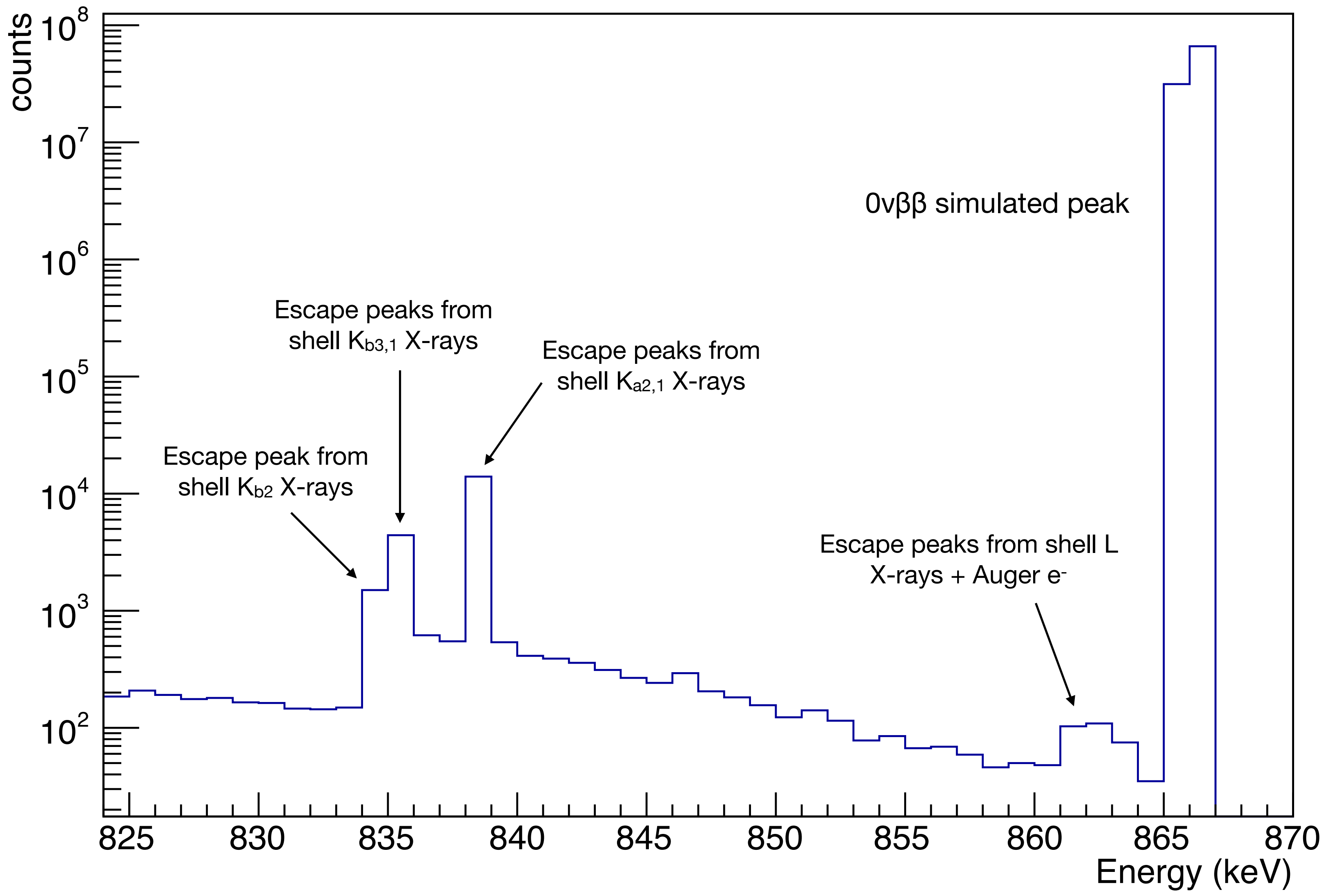
CUORE:

a factor ~10 higher sensitivity is expected, competitive with geochemical results

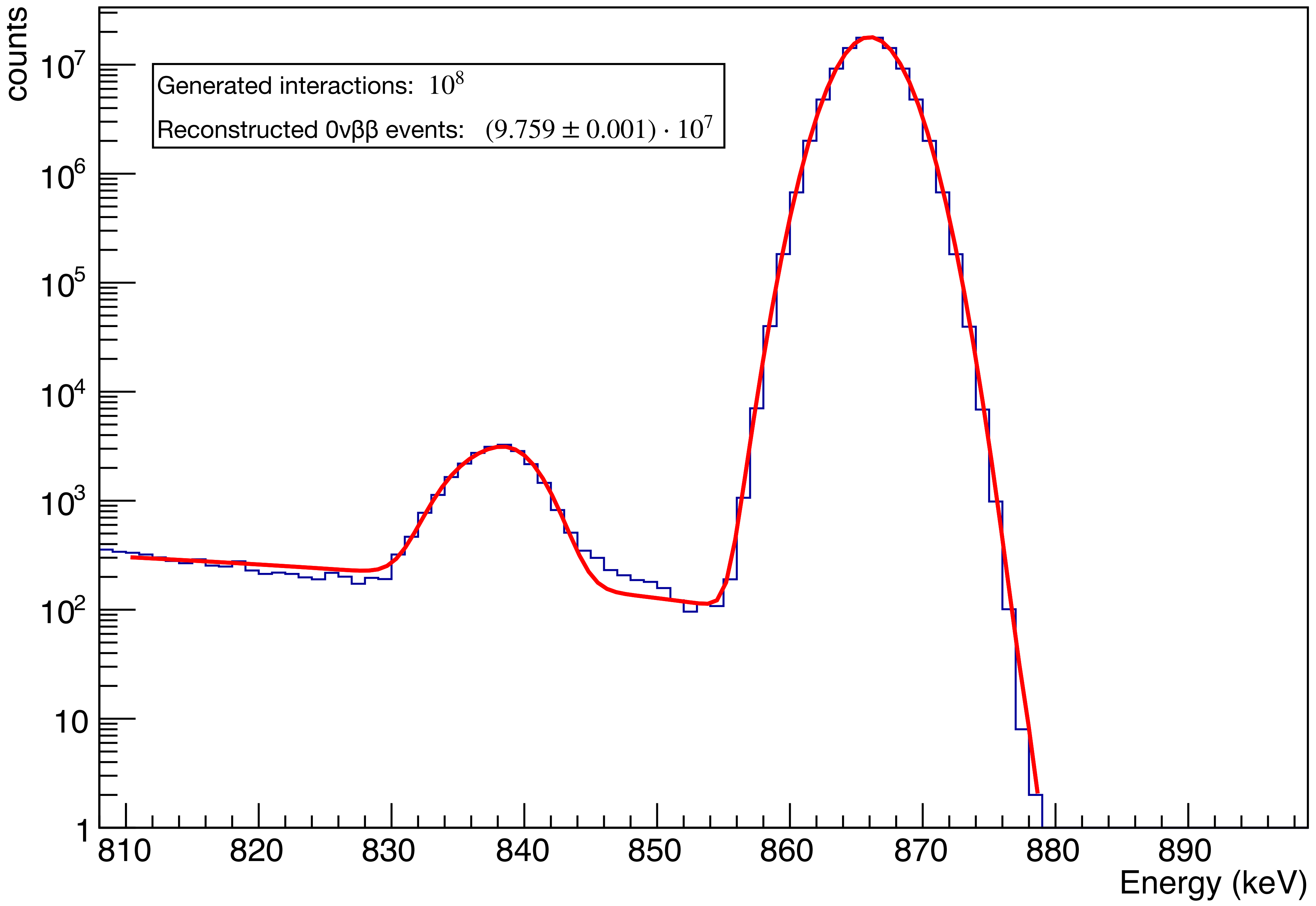
- N. of ^{128}Te ββ emitters in CUORE: $9.519 \cdot 10^{26}$
- ^{128}Te mass in CUORE: 188.5 kg

Full Containment Efficiency (ϵ_{MC})

- Estimation of the fraction of events where the e^- are fully absorbed by the same CUORE crystal
- MC simulation of $N_{MC} = 10^8$ ^{128}Te 0νββ decays
- Multiplicities distribution: **98.26% M1** 1.24% M2, 0.5% M>2



Main X-rays from Te	
Shell	*Energy (keV)*
K_{a2}	27.202
K_{a1}	27.472
K_{b3}	30.944
K_{b1}	30.995
K_{b2}	31.704



- $N_{0\nu}$ of events reconstructed at $Q_{\beta\beta}$ peak: fit on M1 simulated spectrum
- Model function: 3 X-ray escape peaks + 0νββ peak + linear background

Full containment efficiency:

$$\epsilon_{MC} = \frac{N_{0\nu}}{N_{MC}} = (97.59 \pm 0.01)\,\%$$

Region Of Interest (ROI) choice

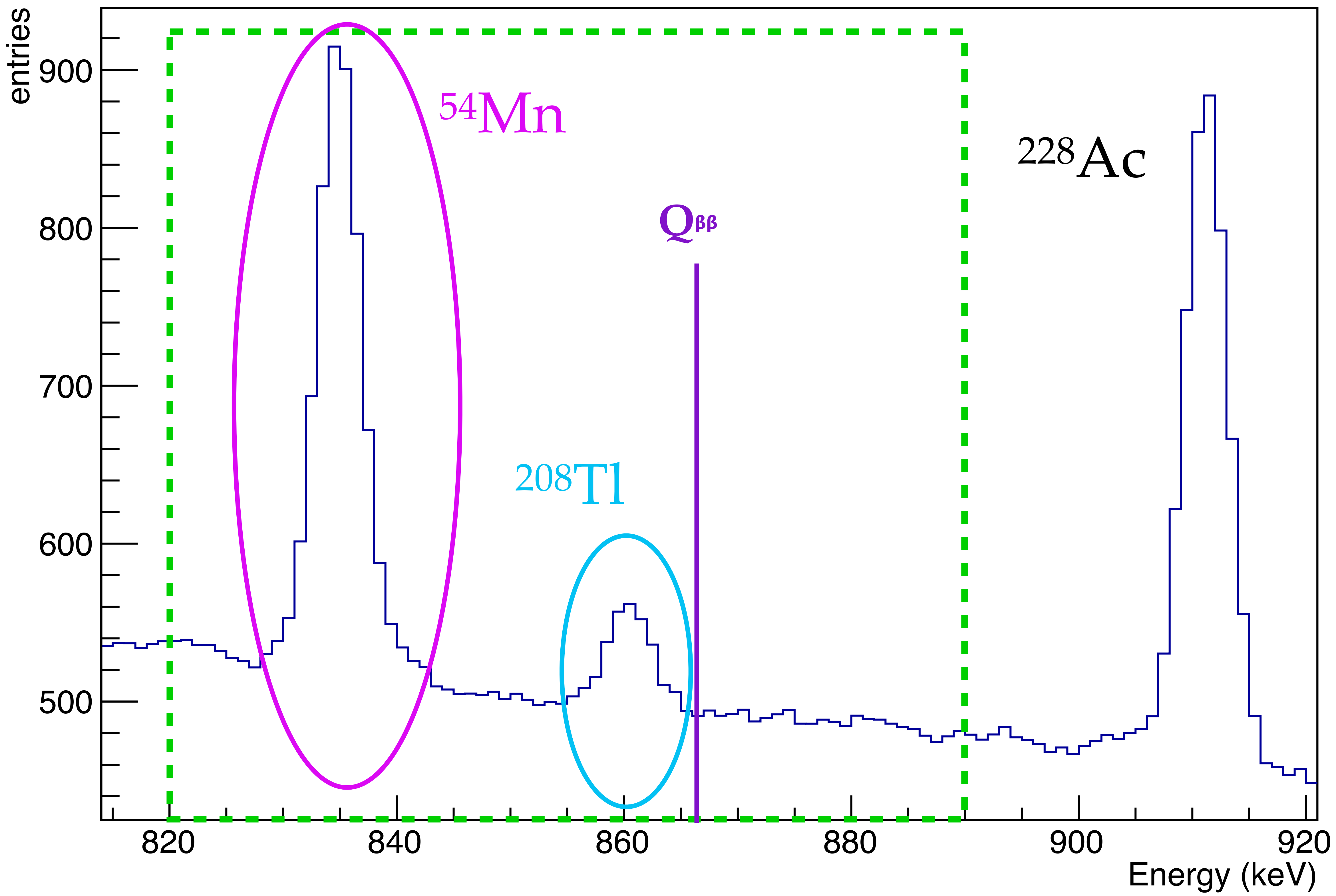
- Correctly identify and constrain the background close to the $Q_{\beta\beta}$ to avoid biases on the signal rate reconstruction
- Visible peaks:

^{208}Tl γ line at 860.56 keV, B.R.=12.4% (^{232}Th chain)

^{54}Mn γ line at 834.8 keV, B.R.=99.98% (Cu cosmogenic activation)

^{228}Ac γ line at 911.2 keV, B.R.=25.8% (^{232}Th chain)

M1 spectrum from Background Model Simulations



ROI = [820 - 890] keV

^{54}Mn peak fully included
(> 6σ away)

$Q_{\beta\beta}$ fully included (> 11σ away)
^{228}Ac peak fully excluded (> 9σ away)

Bayesian Fit

- Bayesian binned fit simultaneously performed on 5 datasets → **Analyzed exposure: 309.33 kg·y**
- **Bayes' theorem**: it is possible to make an inference on an observable by evaluating its posterior probability distribution from the product of the likelihood function and the prior probabilities

$$P(\vec{\theta}\,|\,D, M) = \frac{\mathscr{L}(D\,|\,\vec{\theta}, M)\,\pi(\vec{\theta})}{\int_{\Theta} \mathscr{L}(D\,|\,\vec{\theta}, M)\,\pi(\vec{\theta})\,d\vec{\theta}}$$

BAT software: sampling from the posterior distribution of all parameters with a Markov Chain Monte Carlo

➡ *Global mode*: parameter values corresponding to the maximum of the full posterior distribution

➡ *Marginalized posterior*: posterior distribution integrated over all the parameters with exception of one

Parameter of interest: ^{128}Te 0νββ decay rate $\Gamma^{0\nu}$

Bayesian Fit: model

- Binned likelihood for each dataset is product of Poissonian terms
- The expected number of counts μ_i for the i-th bin is given by the value of the model function at the center of the bin (small bin-width approximation):

$$\mathscr{L} = \prod_{ds}\prod_{i}^{N_{bins}} \frac{\mu_i^{n_i} e^{-\mu_i}}{n_i!}$$

$$\mu_i = \underbrace{S \cdot f_S^{ds}(i)}_{\text{Signal peak}} + \underbrace{C_{Mn} \cdot f_{Mn}^{ds}(i)}_{^{54}\text{Mn peak}} + \underbrace{C_{Tl} \cdot f_{Tl}^{ds}(i)}_{^{208}\text{Tl peak}} + \underbrace{C_b \cdot f_{flat}(i) + f_{linear}(i)}_{\text{Continuous background}}$$

Bayesian Fit: parameters

Modeled with the detector response function (*lineshape*)

$$\frac{C_b}{\Delta E_{ROI}} + \frac{m_{ds}}{\Delta E_{ROI}}(E_i - E_{1/2})$$

$$\mu_i = \underbrace{S \cdot f_S^{ds}(i)}_{\text{Signal peak}} + \underbrace{C_{Mn} \cdot f_{Mn}^{ds}(i)}_{^{54}\text{Mn peak}} + \underbrace{C_{Tl} \cdot f_{Tl}^{ds}(i)}_{^{208}\text{Tl peak}} + \underbrace{C_b \cdot f_{flat}(i) + f_{linear}(i)}_{\text{Continuous background}}$$

- N. of signal counts: $S = \Gamma^{0\nu} \cdot \frac{N_A}{A_{TeO_2}} \cdot \eta_{128} \cdot (M\Delta t)_{ds} \cdot \epsilon_{ds}^{cut} \cdot \epsilon_{MC}$
- N. of ^{54}Mn counts: $(T_{1/2}^{Mn} = 312.2\ d)$ $C_{Mn} = \Gamma_{Mn} \cdot e^{-\frac{t_{ds}}{\tau_{Mn}}} \cdot (M\Delta t)_{ds} \cdot \epsilon_{ds}^{cut}$
- N. of ^{208}Tl counts: $(T_{1/2}^{Tl} = 3.1\ min)$ $C_{Tl} = \Gamma_{Tl} \cdot (M\Delta t)_{ds} \cdot \epsilon_{ds}^{cut}$
- N. of continuous background counts: $C_b = BI_{ds} \cdot size_{bin} \cdot (M\Delta t)_{ds}$
- Linear background slope: m_{ds}

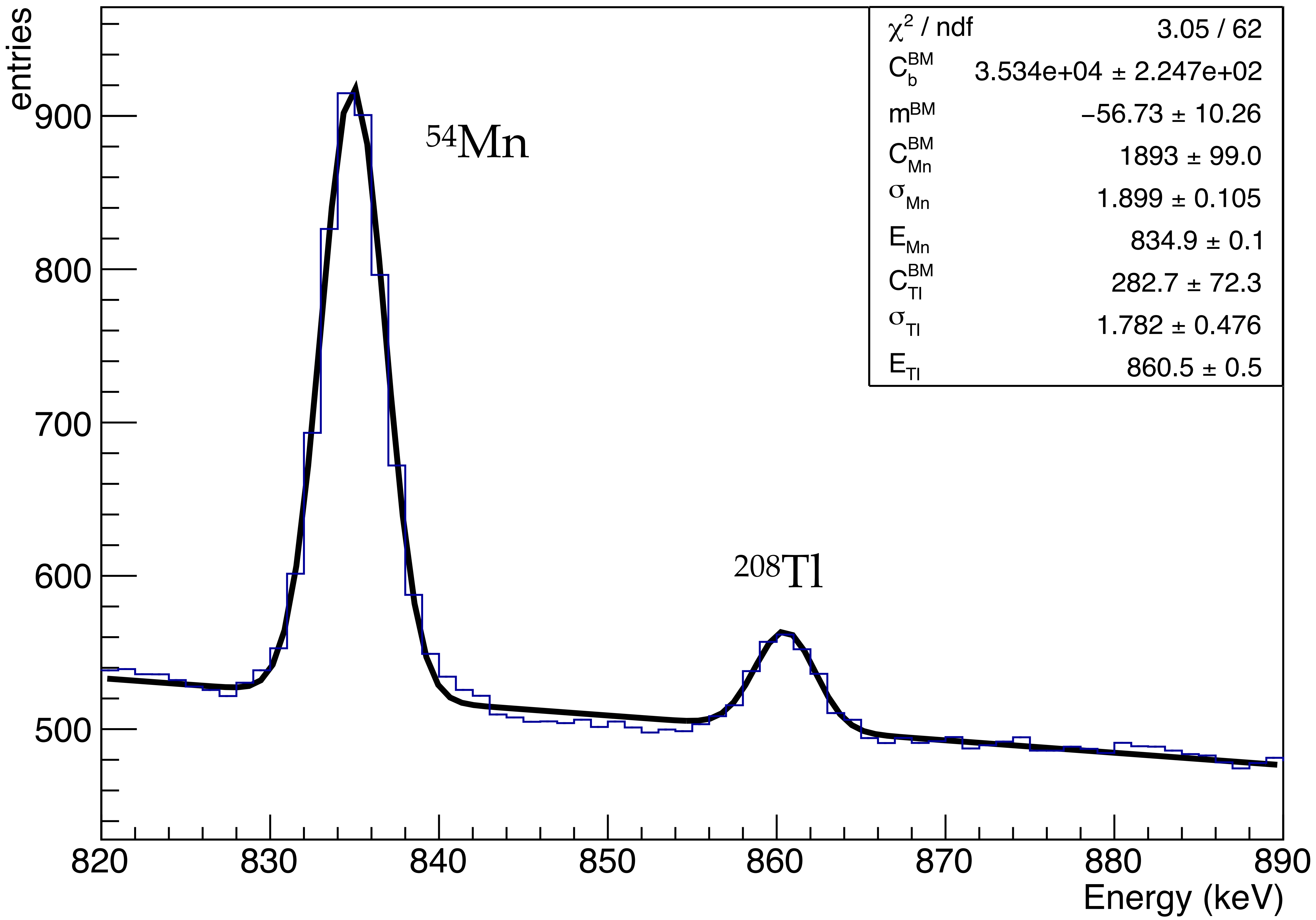
Parameter		*Units*
$\Gamma^{0\nu}$	**Signal rate**	**y^{-1}**
Γ_{Mn}	^{54}Mn rate	cts/(kg·y)
Γ_{Tl}	^{208}Tl rate	cts/(kg·y)
BI_{ds} (x 5)	Background Index	cts/(keV·kg·y)
m_{ds} (x 5)	Background slope	1/keV

13 parameters

Uniform priors on all the parameters (no independent measurements available)

Fit validation: toyMC generation

- Fit model validated on toyMC simulations
- I developed a dedicated code to simulate the various components of the ROI spectrum
- I extracted the parameters to produce the toyMC from a fit on the BM simulations with 2 gaussians + linear background



Parameter	*Units*	*Value for toyMC*
Γ_{Mn}^{toy}	cts/(kg · y)	16.27
Γ_{Tl}^{toy}	cts/(kg · y)	0.95
BI^{toy}	cts/(keV · kg · y)	1.68
m^{toy}	1/keV	-0.4

Fit validation: Background reconstruction test

1st test: verify that the fit correctly reconstructs the simulated background contributions

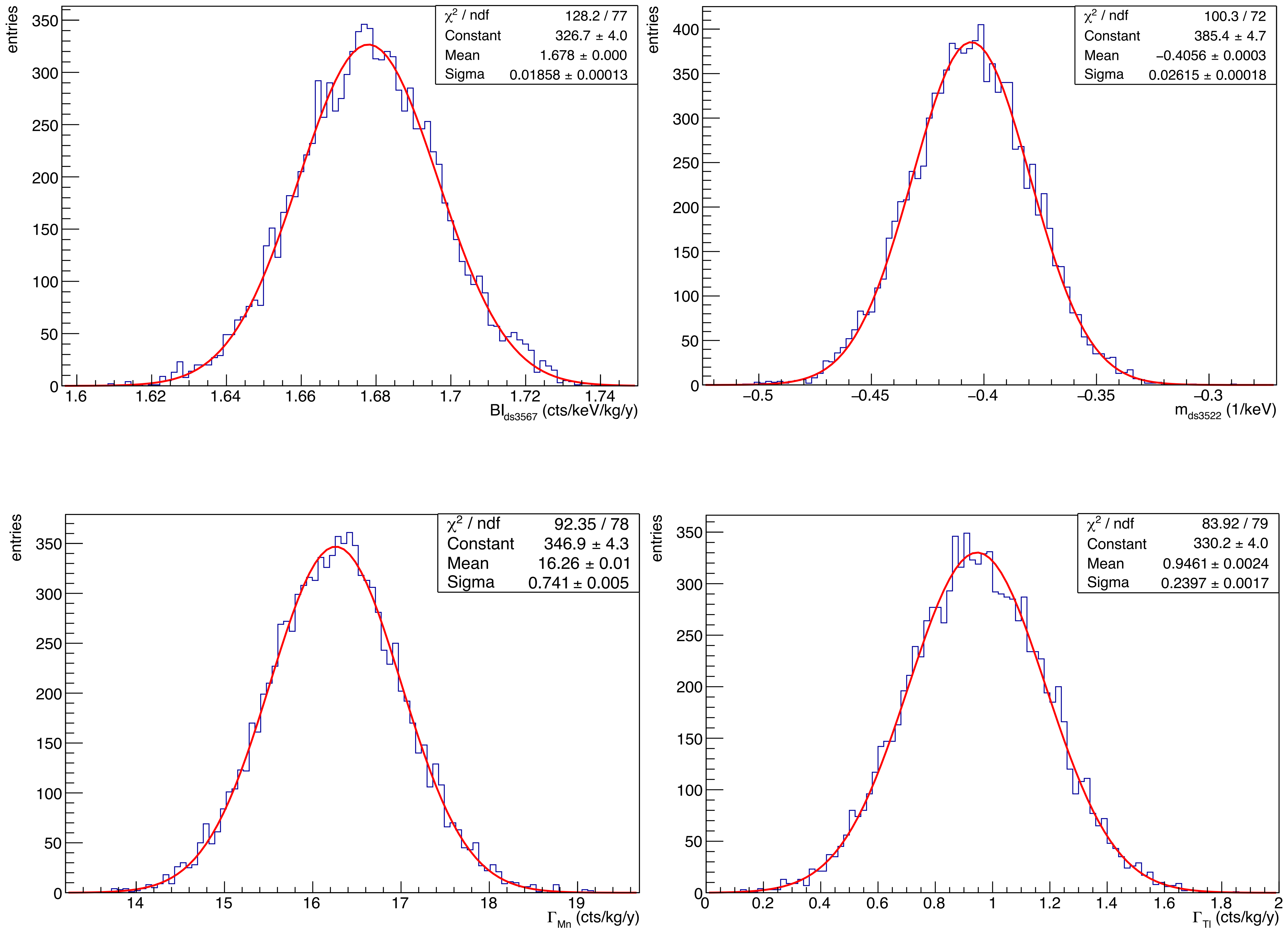
- I generated 10^4 toyMC spectra with bkg components only (^{54}Mn and ^{208}Tl peaks, linear background) according to →

Parameter	*Units*	*Value for toyMC*
Γ^{toy}_{Mn}	cts/(kg·y)	16.27
Γ^{toy}_{Tl}	cts/(kg·y)	0.95
BI^{toy}	cts/(keV·kg·y)	1.68
m^{toy}	1/keV	-0.4

- Bayesian fit with signal + background components independently run on each toyMC ($\Gamma^{0\nu} > 0$ only allowed)
- Reconstructed VS generated parameters: the distributions of the global modes was built for each parameter
- **The distributions are expected to be centered at the generated ones.**

Fit validation: Background reconstruction test

Parameter	*Units*	*Mean Reconstructed Value*	*Generated value*
BI_{ds3522}	*counts/(keV • kg • y)*	1.6775 ± 0.0002	**1.68**
BI_{ds3552}	*counts/(keV • kg • y)*	1.6782 ± 0.0002	
BI_{ds3555}	*counts/(keV • kg • y)*	1.6781 ± 0.0002	
BI_{ds3564}	*counts/(keV • kg • y)*	1.6776 ± 0.0002	
BI_{ds3567}	*counts/(keV • kg • y)*	1.6779 ± 0.0002	
m_{ds3522}	*1/keV*	-0.4056 ± 0.0003	**-0.4**
m_{ds3552}	*1/keV*	-0.4064 ± 0.0003	
m_{ds3555}	*1/keV*	-0.4064 ± 0.0003	
m_{ds3564}	*1/keV*	-0.4060 ± 0.0003	
m_{ds3567}	*1/keV*	-0.4055 ± 0.0003	
Γ_{Mn}	*1/(kg • y)*	16.259 ± 0.007	**16.27**
Γ_{Tl}	*1/(kg • y)*	0.946 ± 0.002	**0.95**



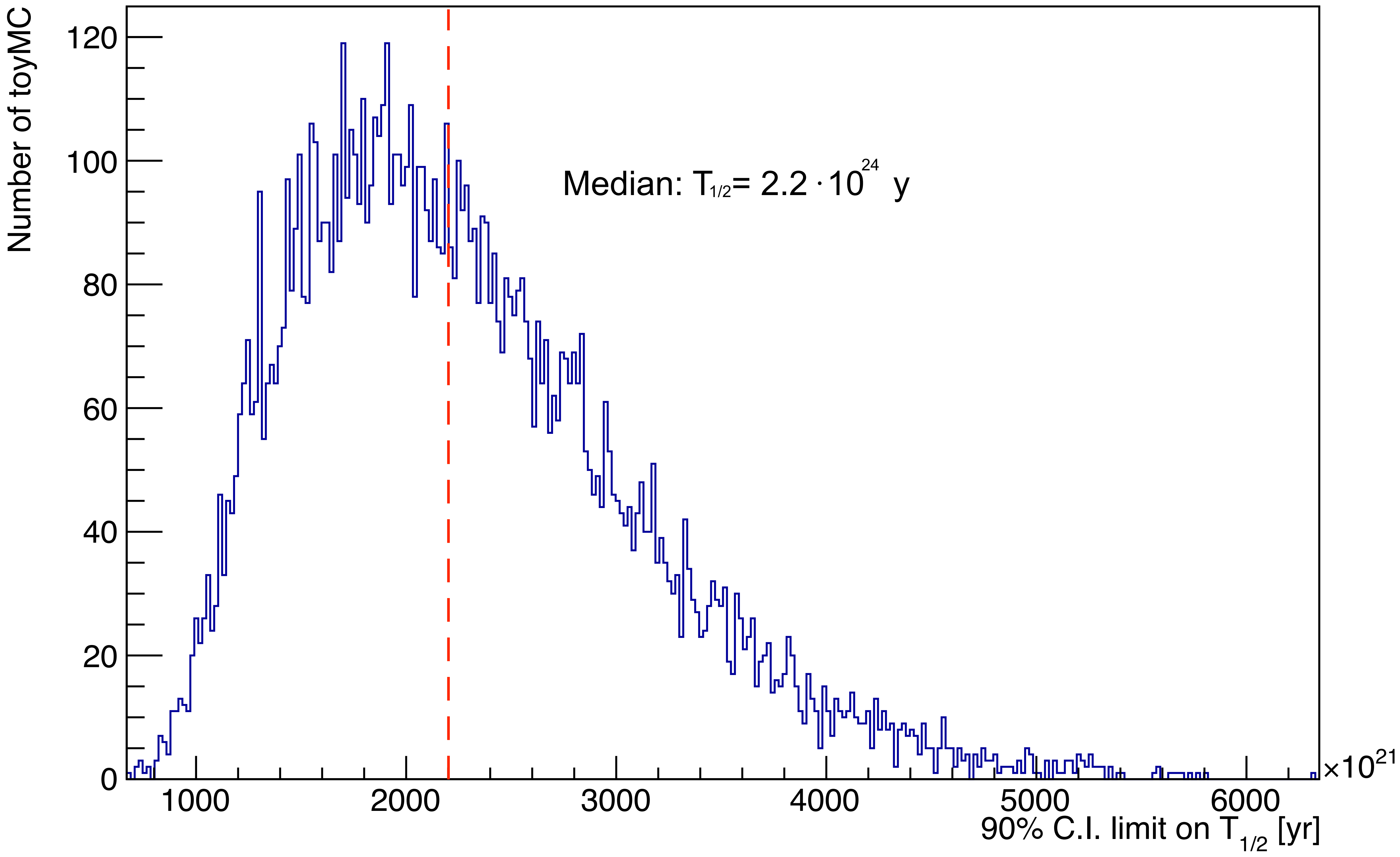
G S
S I

Exclusion Sensitivity test

2nd test: CUORE Exclusion Sensitivity (or Limit Setting Sensitivity) extraction procedure

↓

median of the distribution of the 90% C.I. limits on $T_{1/2}$



Extraction of the 90% C.I. half life limit from each of the 10^4 Bayesian fits on the toyMC with BM parameters

Distribution of the half life limits and extraction of the median

CUORE exclusion sensitivity test: $T_{1/2} = 2.2 \cdot 10^{24} y$

This value provides an indication of the CUORE exclusion sensitivity extracted from the measured data.

Signal Rate reconstruction test

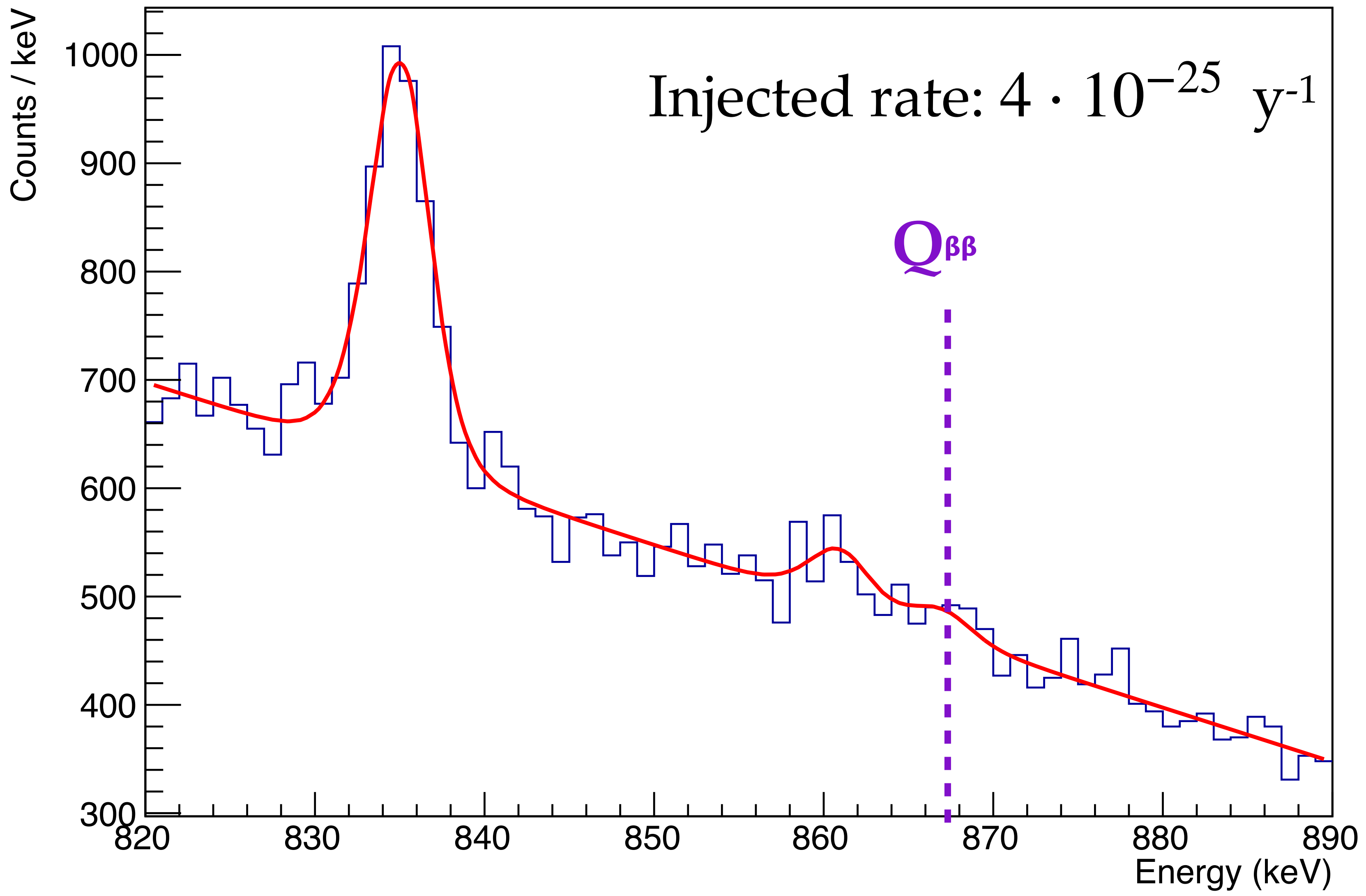
3rd test: study of possible bias in the signal reconstruction

- I introduced the signal component: I tested the Bayesian fit for 5 different signal rates
- I took the test median sensitivity as reference:

$$T_{1/2} = 2.2 \cdot 10^{24}\ \mathrm{y} \longrightarrow \Gamma^{0\nu} = 3.2 \cdot 10^{-25}\ \mathrm{y}^{-1}$$

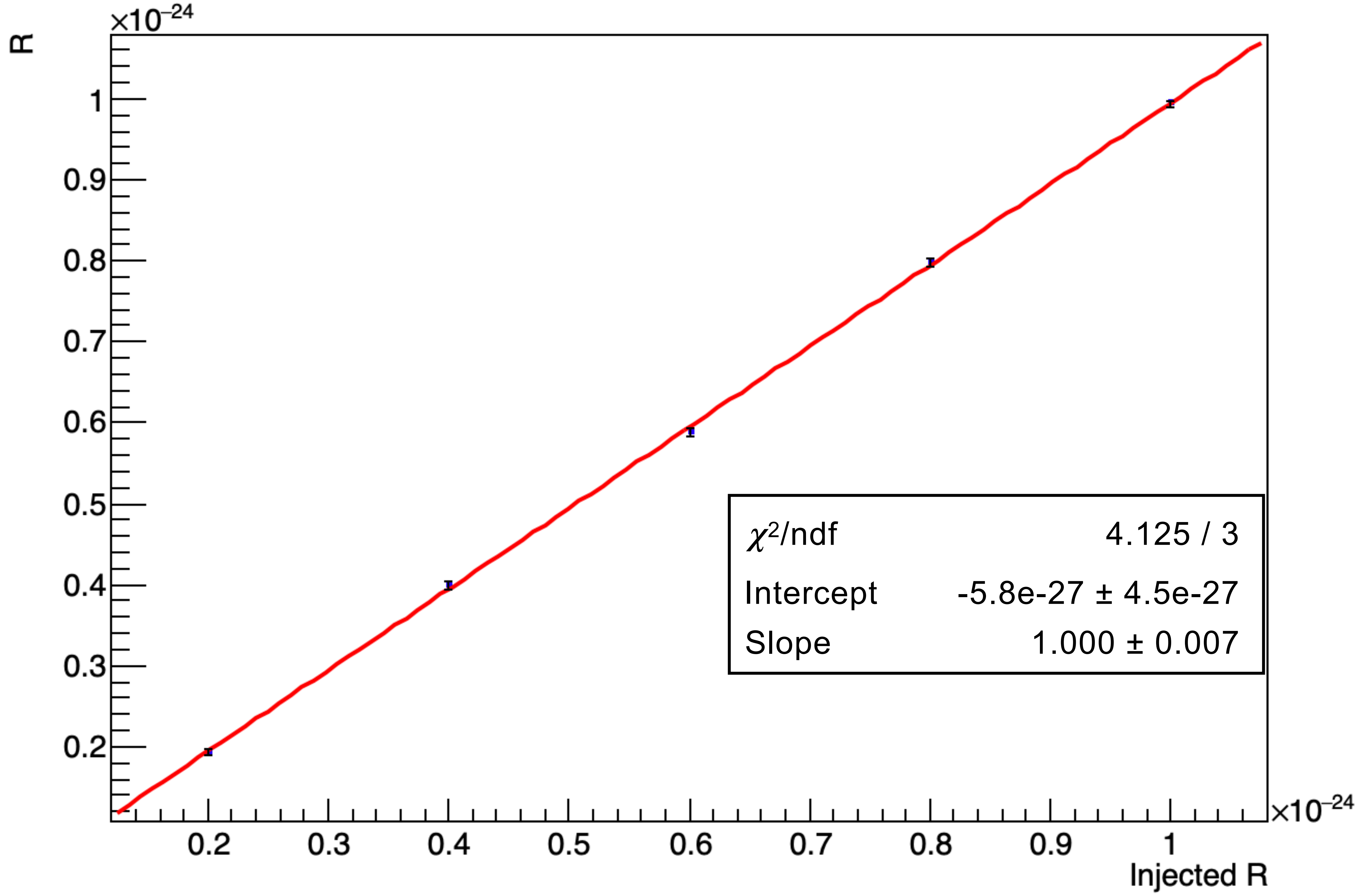
- Five rates: $(2, 4, 6, 8) \cdot 10^{-25}, 10^{-24}\ \mathrm{y}^{-1}$
- 2000 toyMC with for each rate
- All the toys were fitted allowing also negative values for $\Gamma^{0\nu}$.

toyMC



Signal Rate reconstruction test

- Distributions of the $\Gamma^{0\nu}$ global modes built for each of the five injected rates
- Mean of each distribution: mean reconstructed rate
- Mean reconstructed VS injected signal rates:



Results of the linear fit:

Intercept: compatible with 0 at 1.3σ

Slope: compatible with 1 at < 1σ

No bias is introduced on $\Gamma^{0\nu}$ reconstruction.

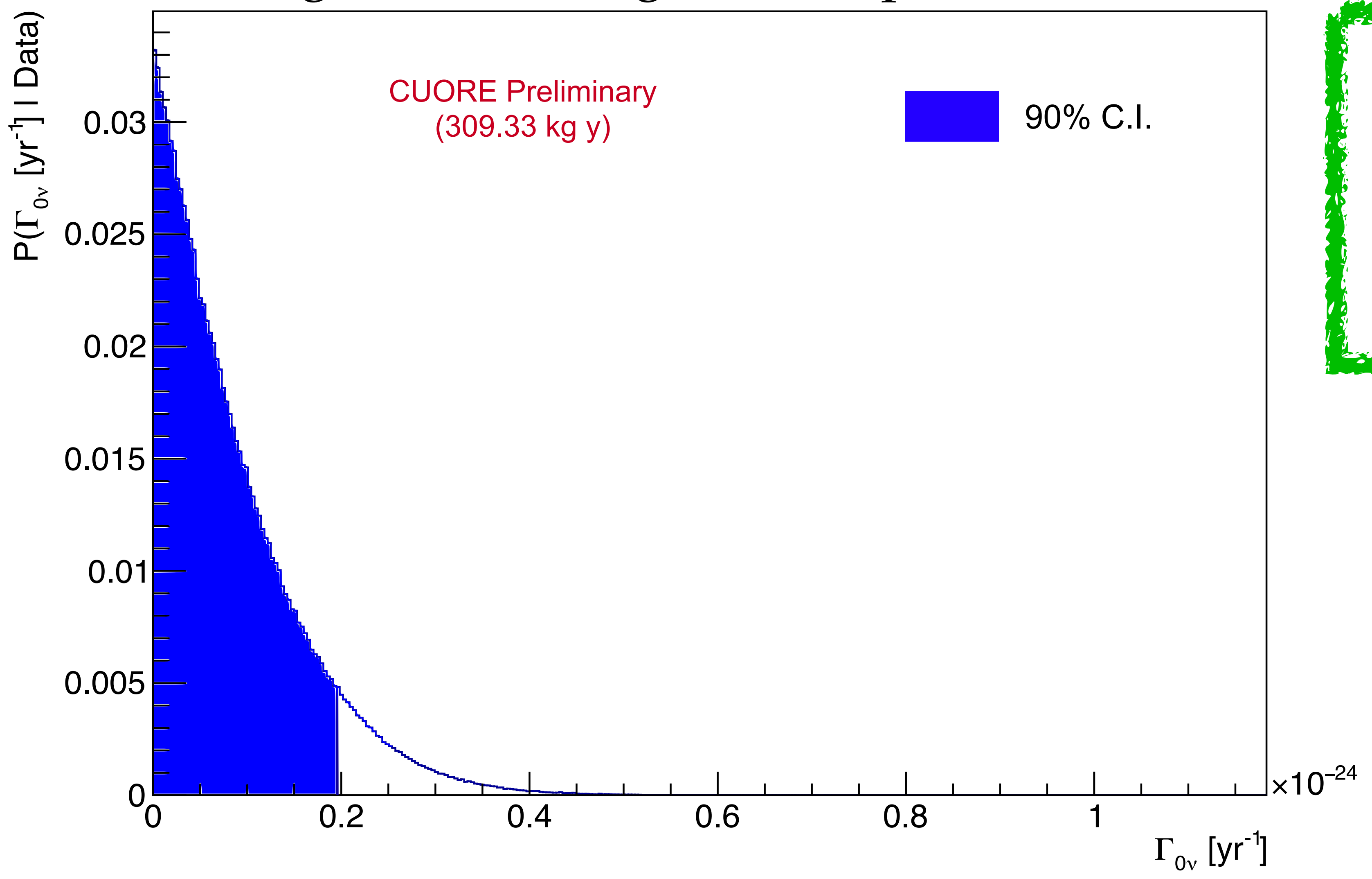
Results on 0νββ decay of ^{128}Te

Results

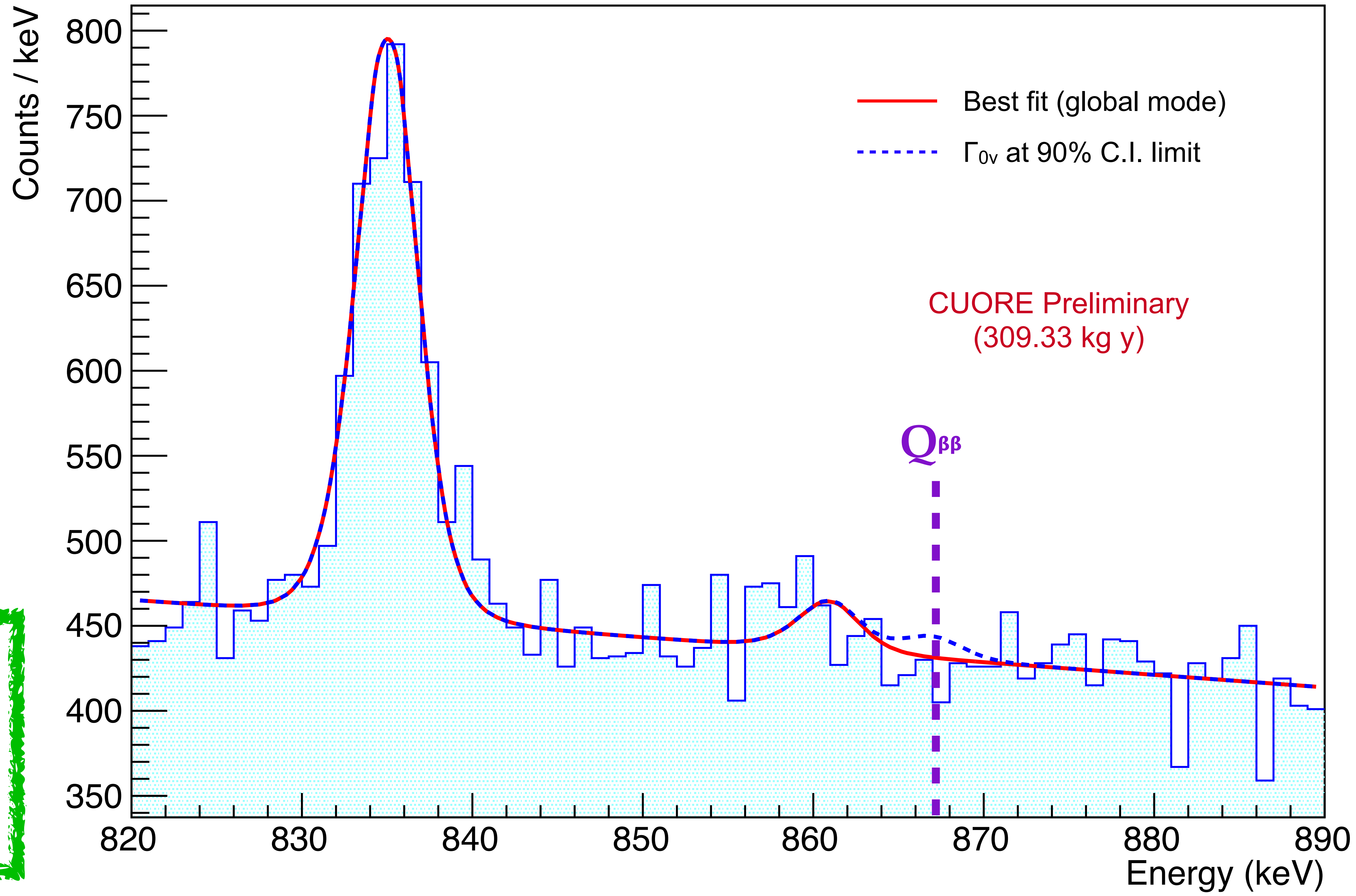
Results on $0\nu\beta\beta$ decay of ^{128}Te

- Bayesian fit on CUORE data (exposure: 309.33 kg·y)
- $\Gamma^{0\nu}$ prior restricted to physical values only ($\Gamma^{0\nu}>0$)
- **No evidence of ^{128}Te $0\nu\beta\beta$ decay is observed.**

Limits from marginalized posterior at 90% C.I. :


Signal rate marginalized posterior

$$\Gamma^{0\nu} < 1.9 \cdot 10^{-25}\ \mathrm{y}^{-1}$$
$$T^{0\nu}_{1/2} > 3.6 \cdot 10^{24}\ \mathrm{y}$$



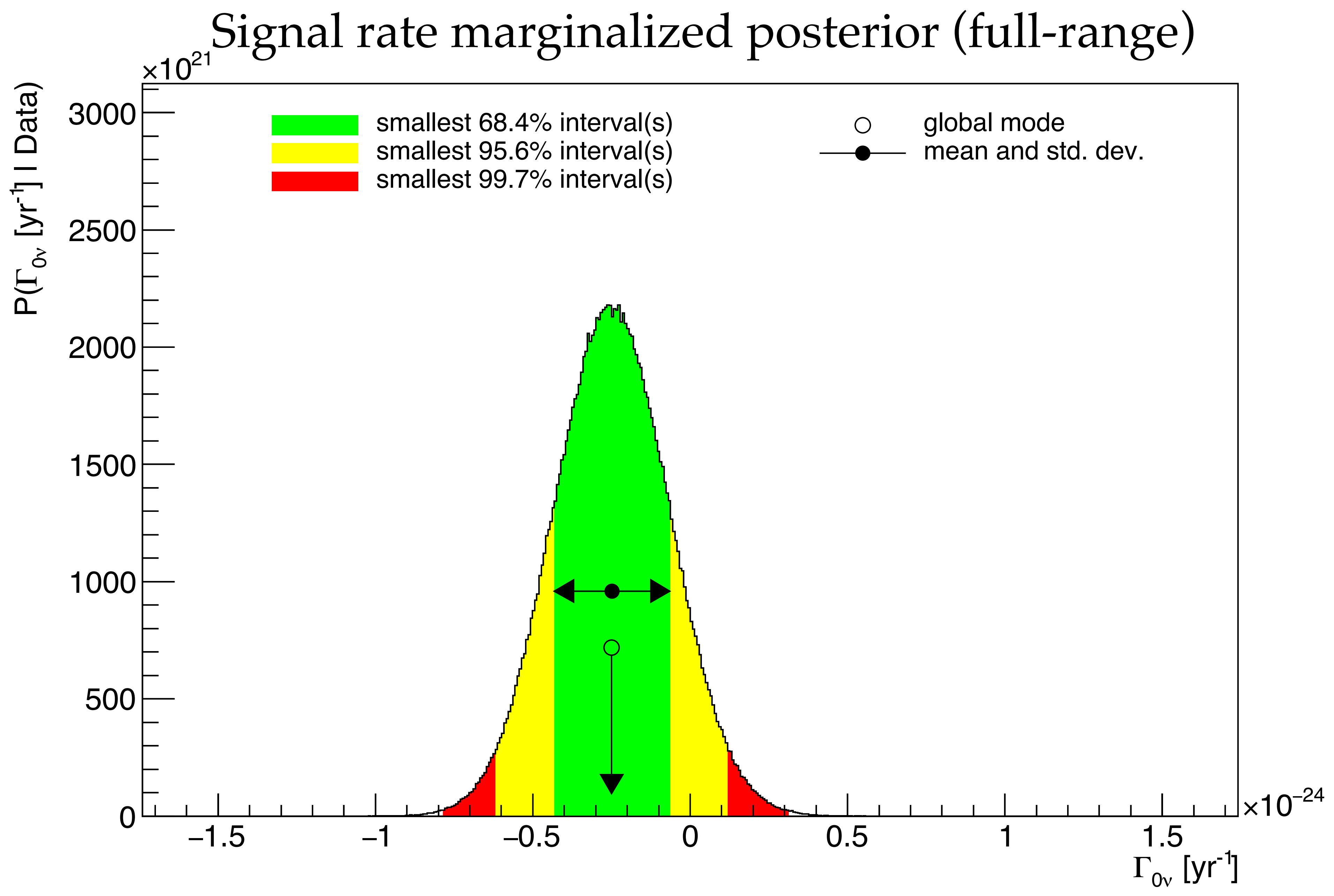
Most stringent limits on $0\nu\beta\beta$ decay of ^{128}Te to date

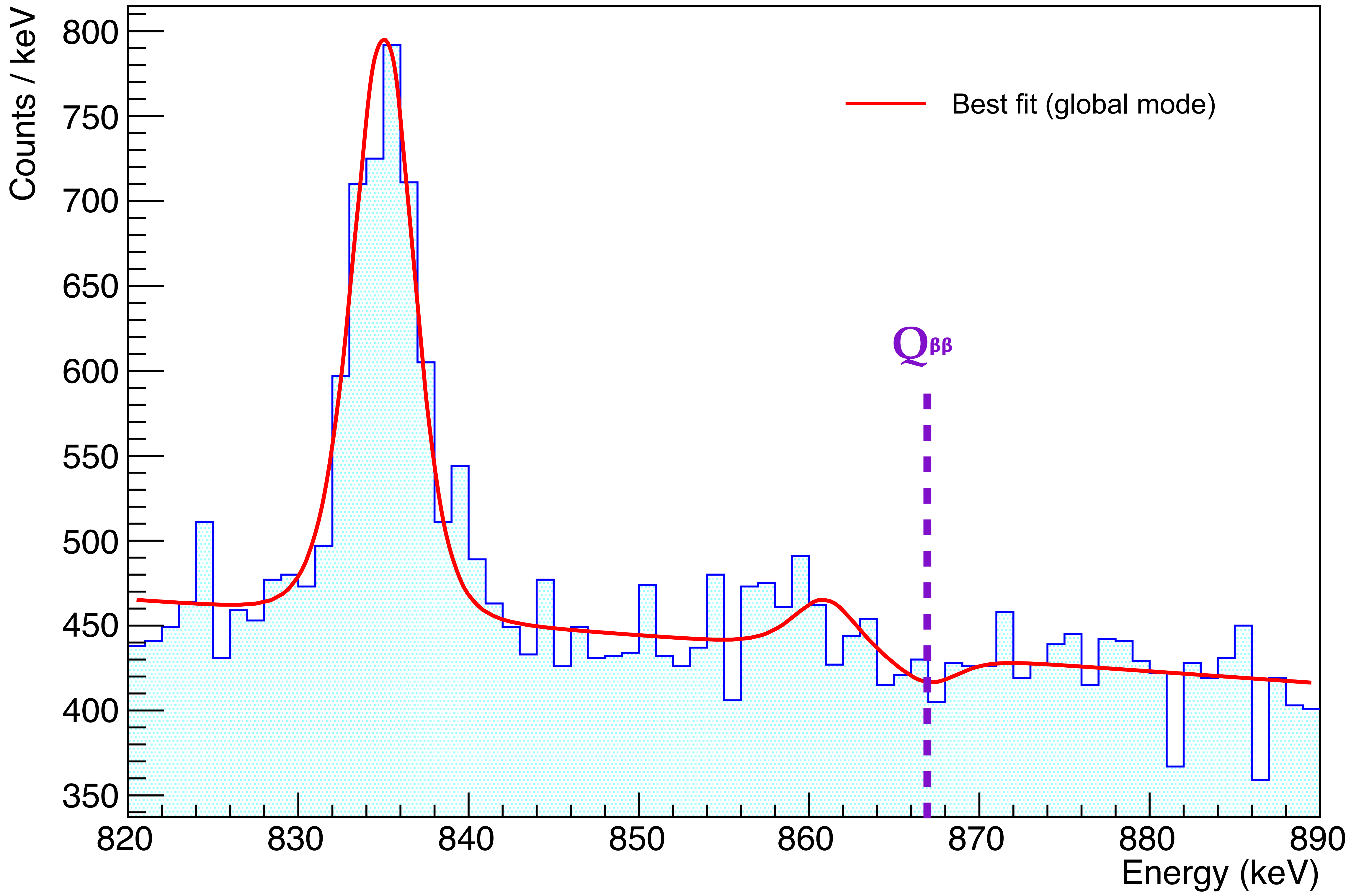
$T_{1/2}$ more than 30 times higher than the last direct experiment result

Overcoming geochemical results

Results on 0νββ decay of ^{128}Te

Fit repeated with $\Gamma_{0\nu}$ prior allowed to assume negative values





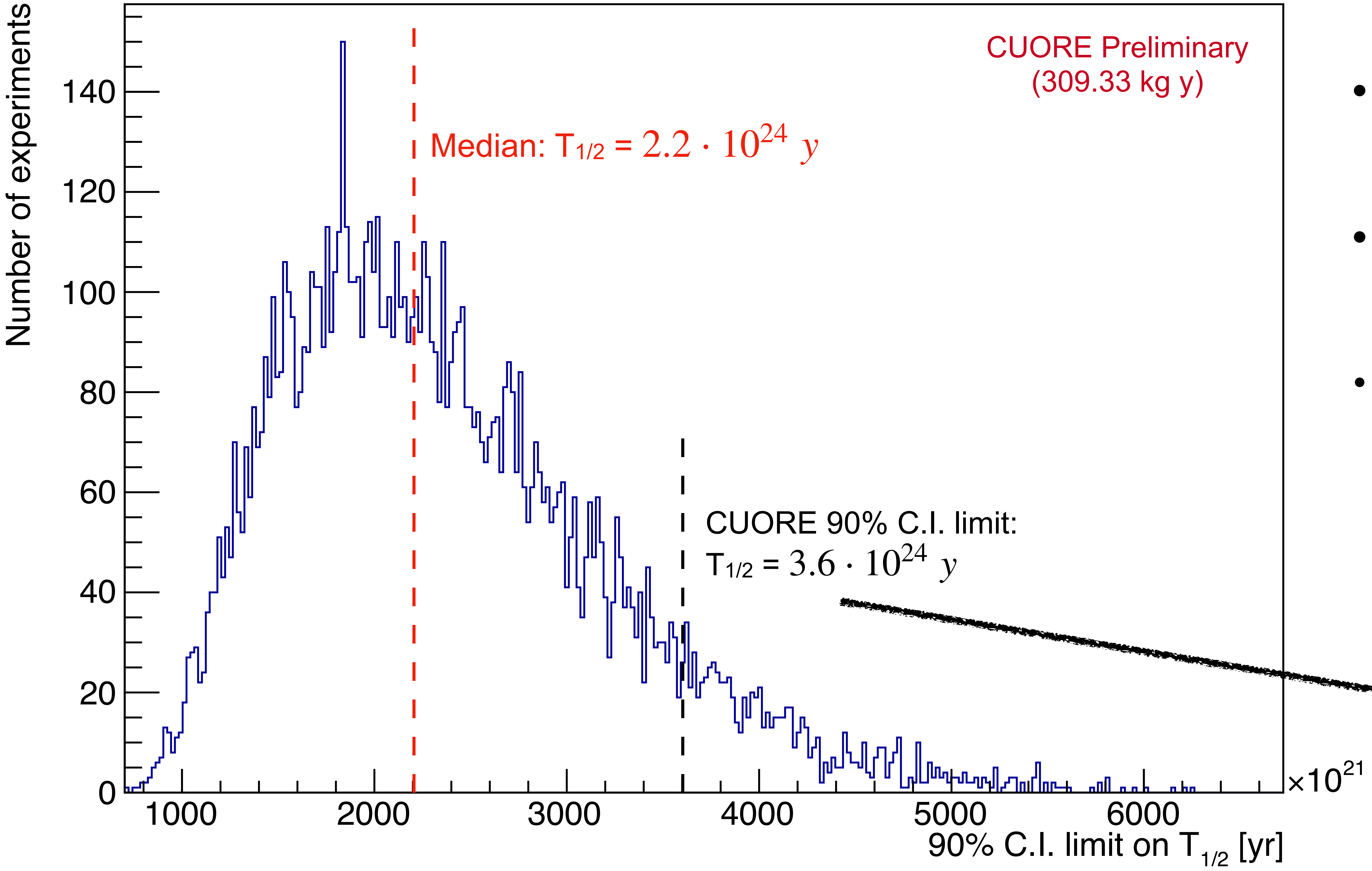
Signal rate global mode:

$$\Gamma^{0\nu} = (-2.5 \pm 1.8) \cdot 10^{-25}\ y^{-1}$$

→ Signal rate underfluctuation of ~1.4σ significance

Results on $0\nu\beta\beta$ decay of ^{128}Te

CUORE Exclusion Sensitivity to $0\nu\beta\beta$ decay of ^{128}Te



- Bayesian fit on CUORE data without the signal component
- 10^4 toyMC with the extracted background parameters
- **CUORE Exclusion Sensitivity:**

$$\boxed{T_{1/2} = 2.2 \cdot 10^{24}\ y}$$

8.8% probability to get a more stringent limit given the obtained sensitivity distribution

0νββ decay of ^{128}Te: perspectives

- This analysis has been approved by the CUORE Collaboration
- The paper is in preparation
- Evaluation of the systematics is ongoing and will be included in the final publication.

Summary & Conclusions

Analysis of ^{128}Te 0νββ decay in CUORE with 309.33 kg · y exposure:

- **No evidence of 0νββ decay**
- **NEW Bayesian 90% C.I. lower limit on ^{128}Te 0νββ decay:** $\boxed{T^{0\nu}_{1/2} > 3.6 \cdot 10^{24}\ \mathrm{y}}$ → **MOST STRINGENT IN LITERATURE**
- **More than a factor 30 improvement with respect to the previous direct limit (MiDBD)**
- **Overcoming the limits obtained from geochemical experiments for the first time**
- **CUORE exclusion sensitivity: $T_{1/2} = 2.2 \cdot 10^{24}$ y** → 8.8% probability of a more stringent limit

CUORE Background Model - α region:

- **Identification of the contaminations and their position** (surface, bulk)
- **α quenching in CUORE**: investigation and quantification
- **Secular equilibrium and breaking points in radioactive chains (^{238}U)**

Will be included in the CUORE Background Model

Main CUORE results on ^{130}Te 0νββ and 2νββ decay:

- **Data production**: online data monitoring and full reprocessing analysis sequence
- **Detector optimization**: vibrational noise reduction by tuning the Pulse Tubes phases

Backup slides

Systematics in ^{128}Te 0νββ decay fit

The study of the following systematics is currently ongoing:

- ✓ - ^{128}Te $Q_{\beta\beta}$ energy
- ✓ - Containment efficiency (ϵ_{MC})
- ✓ - ^{128}Te Isotopic abundance (η)

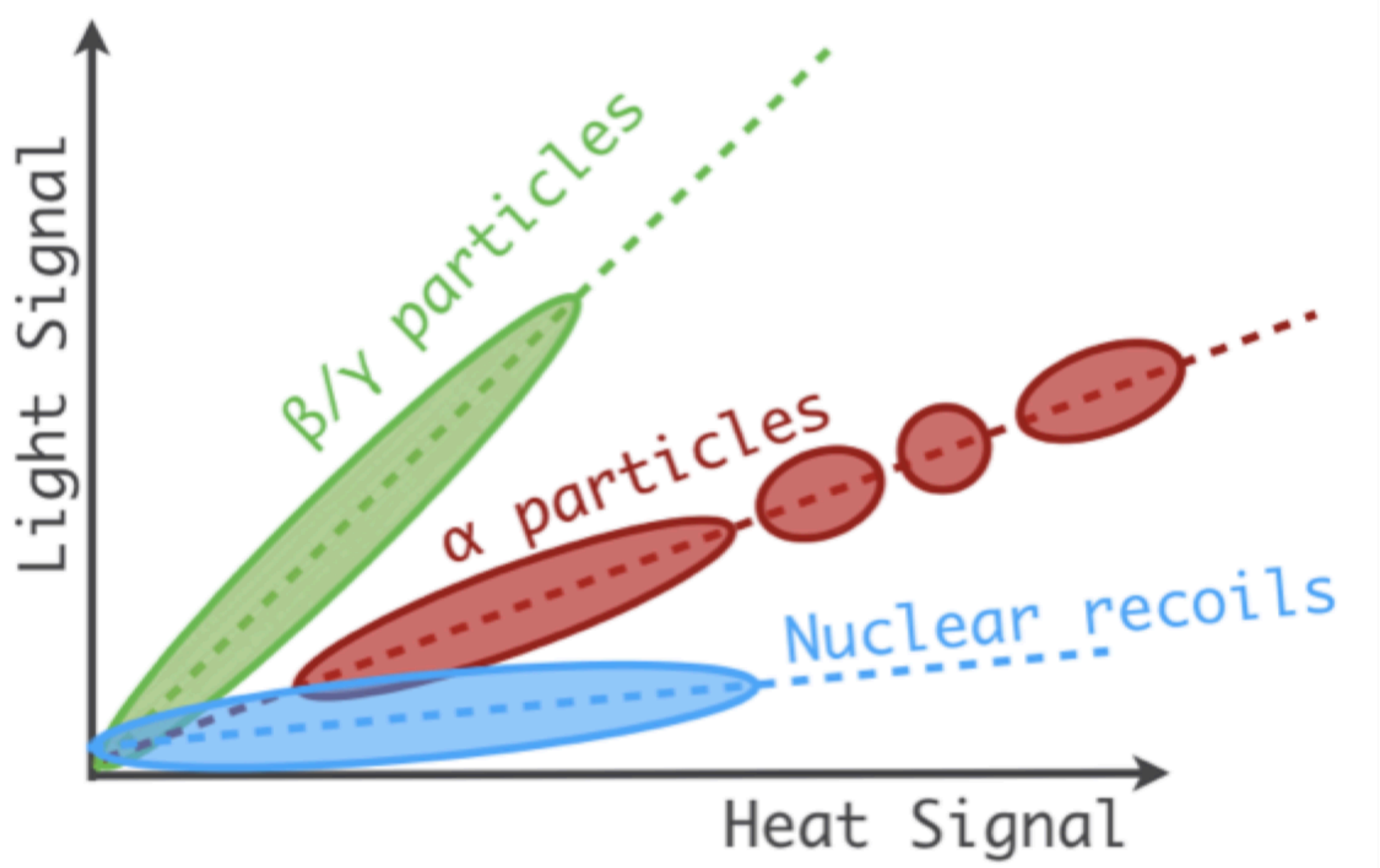
to do [
- - Cut Efficiency
- - Lineshape parameters

Fit model	*90% C.I. limit on $T_{1/2}$ (y)*
Stat. Only	$> 3.63 \cdot 10^{24}$
w/ ^{128}Te $Q_{\beta\beta}$	$> 3.20 \cdot 10^{24}$
w/ ^{128}Te isotopic abundance	$> 3.58 \cdot 10^{24}$
w/ Containment Efficiency	$> 3.63 \cdot 10^{24}$

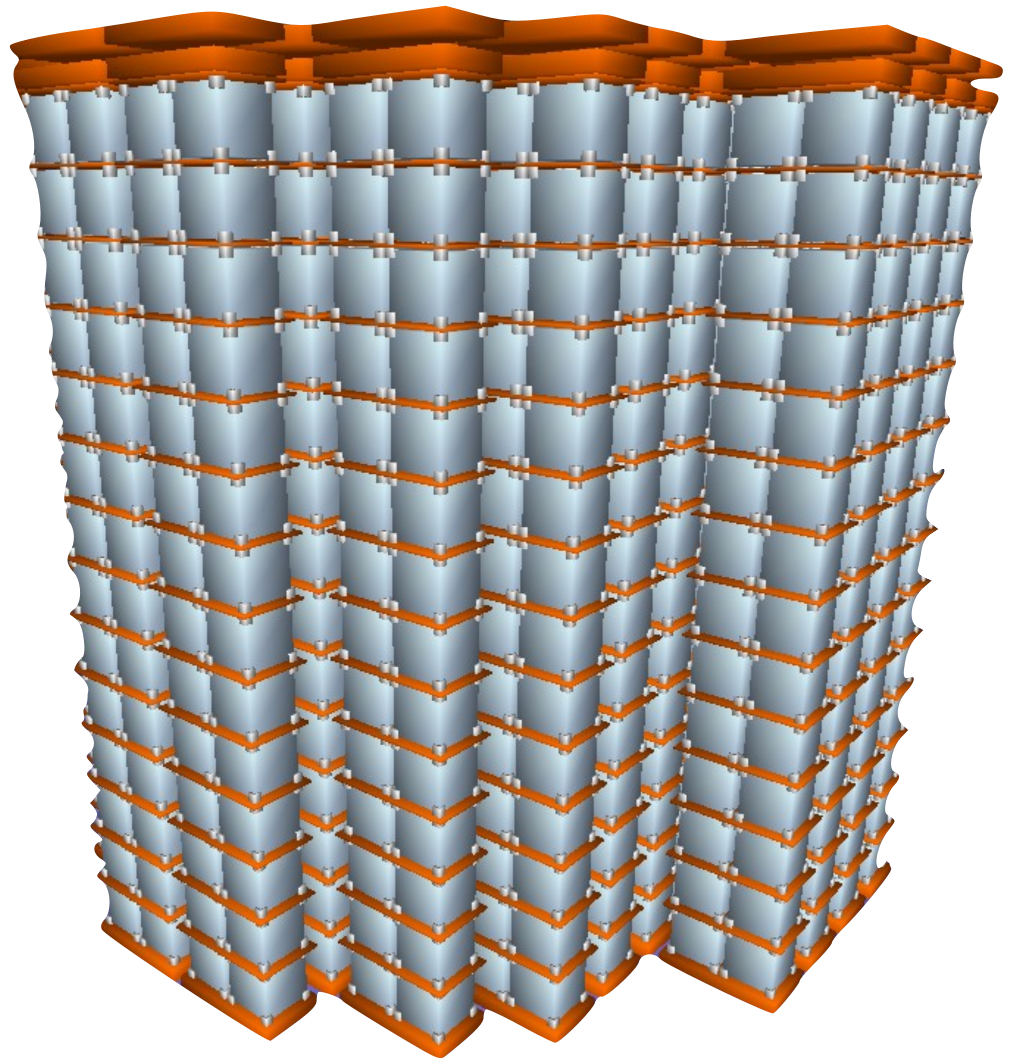
- ϵ_{MC}, η, ϵ_{cut} : nuisance parameters in the fit
- $Q_{\beta\beta}$, Lineshape parameters: I repeat the fit varying the value of the systematic parameters, then I merge the posteriors weighting on the respective prior

CUPID: Cuore Upgrade with Particle Identification

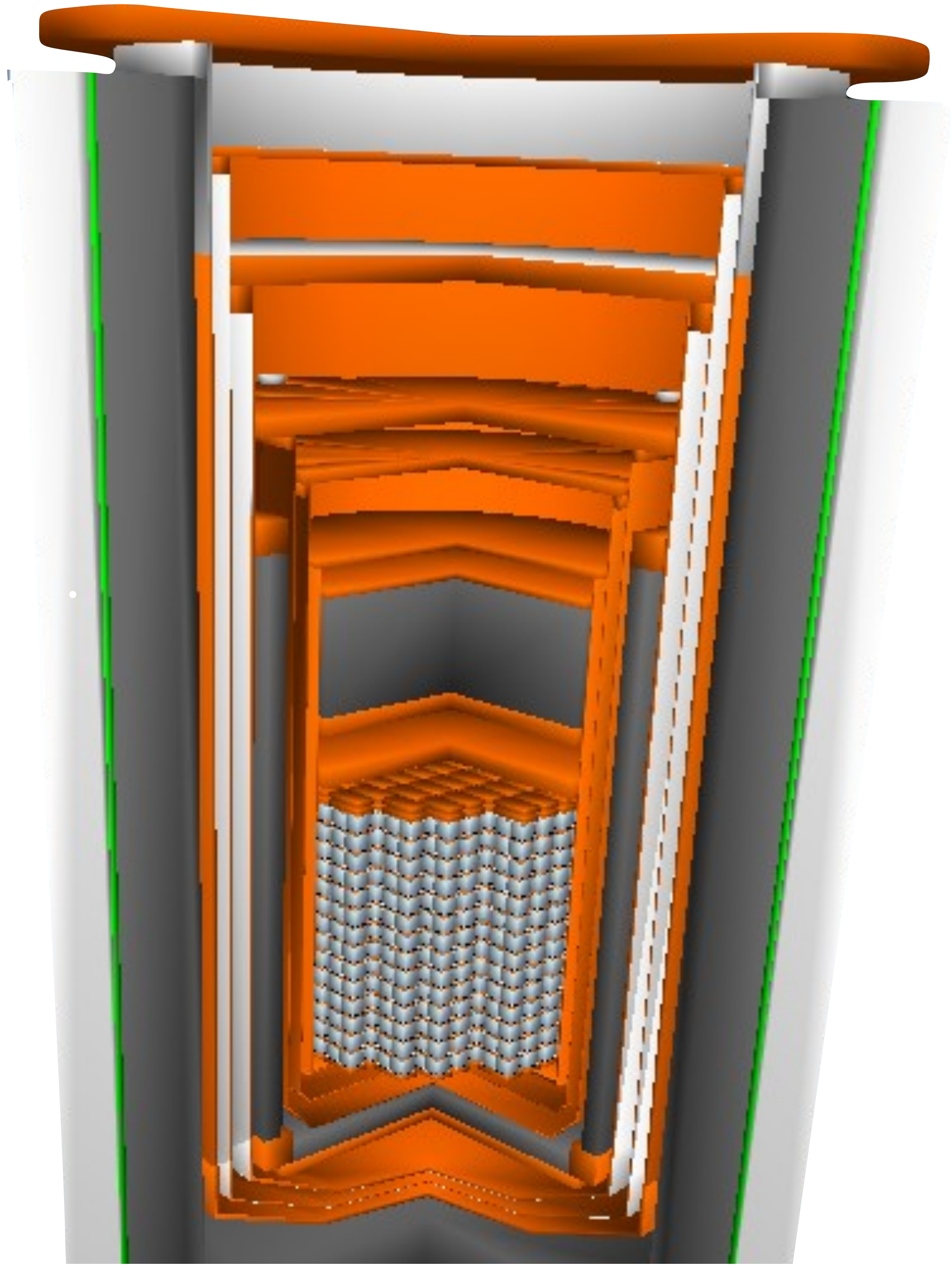
- $0\nu\beta\beta$ of ^{100}Mo, $Q_{\beta\beta} = (3034.40 \pm 0.17)$ keV ⟶ above γ radioactivity
- Ton-scale array of ~1500 $Li_2{}^{100}MoO_4$ scintillating bolometers (240 kg of ^{100}Mo) + light detectors
- Will be hosted by the CUORE cryostat
- **Background-free technology**: simultaneous read-out of thermal signal + scintillation light allows to reject α background



CUPID towers



CUORE cryostat



Lineshape function in Binned Fit

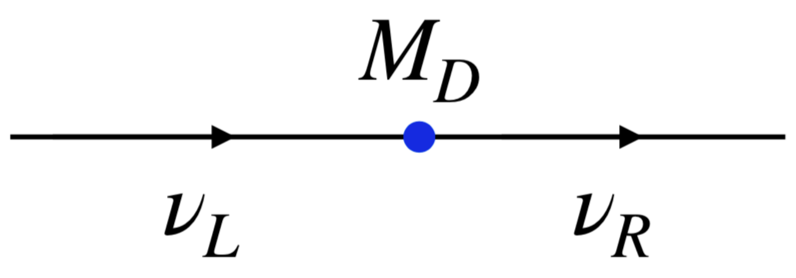
- In the unbinned fit, the lineshape response function is defined as a continuous function of energy
- A lineshape function is evaluated for each detector-dataset pair, and its value is computed for each event.
- **The binned fit does not operate on each event, but on histograms: one histogram for each dataset**
- **In the binned fit, the lineshape should be applied to each bin**
- **An average lineshape function f^{ds} mediated over all the detectors c is defined for each dataset:**

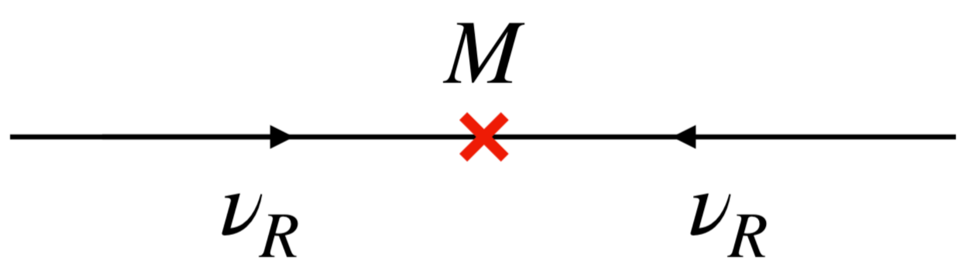
$$f_j^{ds}(i) = \frac{\sum_c f_j^{c-ds}(i) \cdot exposure_{c-ds} \cdot size_{bin}}{\sum_{ch} exposure_{c-ds}} \qquad j = S, Mn, Tl$$

See-saw mechanism

$$\mathscr{L}_{D,M} = \underbrace{M_D(\bar{\nu}_R\nu_L + \bar{\nu}_L\nu_R)} + \underbrace{M\nu_R^T C^{-1}\nu_R} + h.c.$$

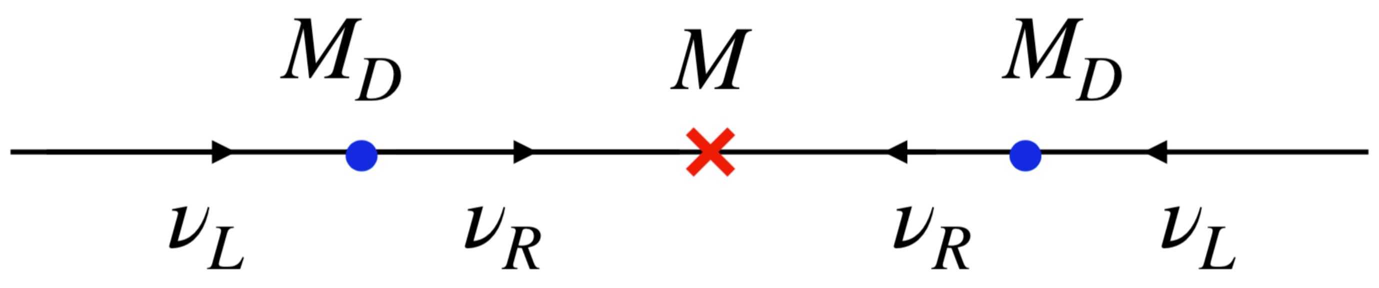
Dirac mass term:
M_D ~ mass of charged leptons





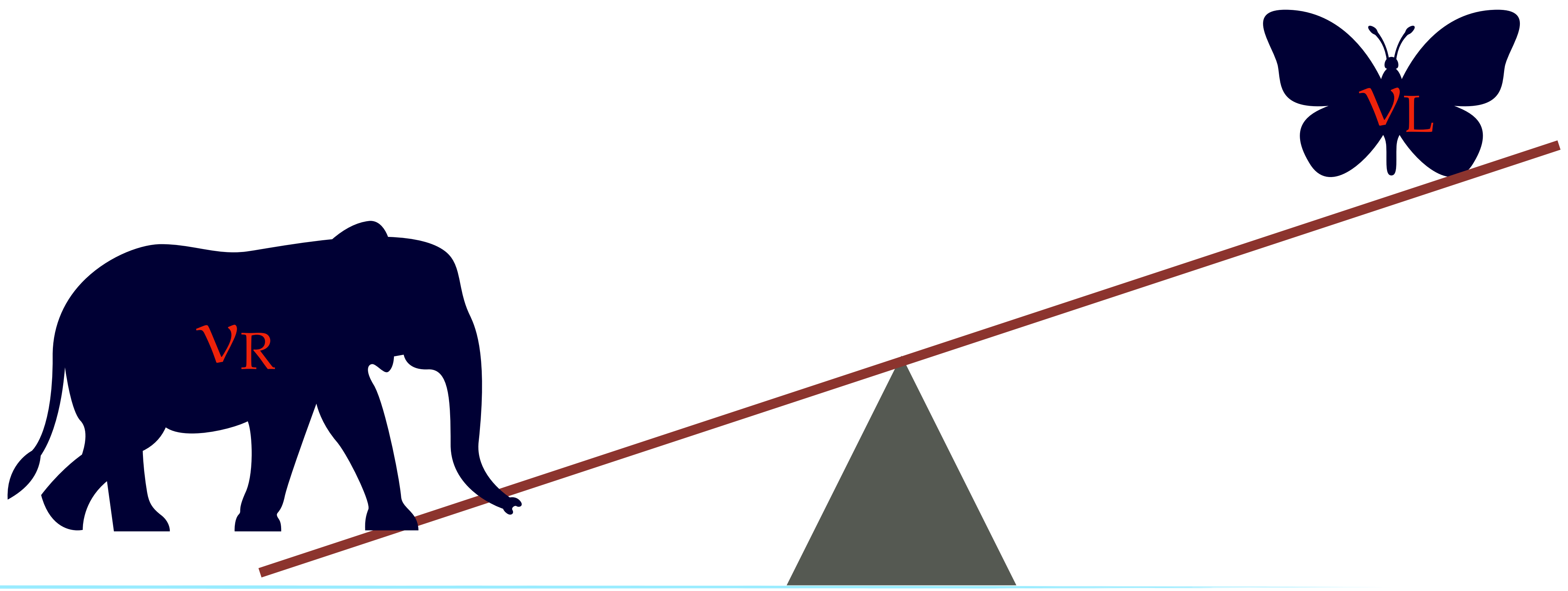
Majorana mass term:
M = mass of ν_R

Combining the two vertexes:



Can be interpreted as a
Majorana mass term for ν_L

Mass induced for ν_L: $\boxed{m \approx \frac{M_D^2}{M}}$



Leptogenesis

- The observation of a lepton number violating process would suggest that leptons played an important role in the creation of matter - antimatter asymmetry in the Universe
- The asymmetry could have been generated in leptons and possibly propagated to the baryonic sector

Sakharov conditions:

1. Lepton number is violated
2. C and CP are violated
3. Universe not in thermal equilibrium

Zero-background counts condition

$$N_S = \frac{ln2}{T_{1/2}} \epsilon\,\eta \frac{N_A}{A} (M\Delta t)$$ N. of signal counts

$$N_B = b\,\Delta E\,(M\Delta t)$$ N. of background counts

Scenario limited by background statistical fluctuations	**Zero-background condition**
$N_B \gg 1$: signal is observable if $N_S \geq \sqrt{N_B}$ $S^{0\nu}(n_\sigma) = \frac{\ln 2}{n_\sigma} \epsilon\,\eta \frac{N_a}{A} \sqrt{\frac{M\Delta t}{b\Delta E}}$	$N_B \leq \mathcal{O}(1)$: no background fluctuations $\boxed{S^{0\nu}_{0-bkg} = \frac{\ln 2}{n_\sigma} \epsilon\,\eta \frac{N_a}{A} M\,\Delta t}$

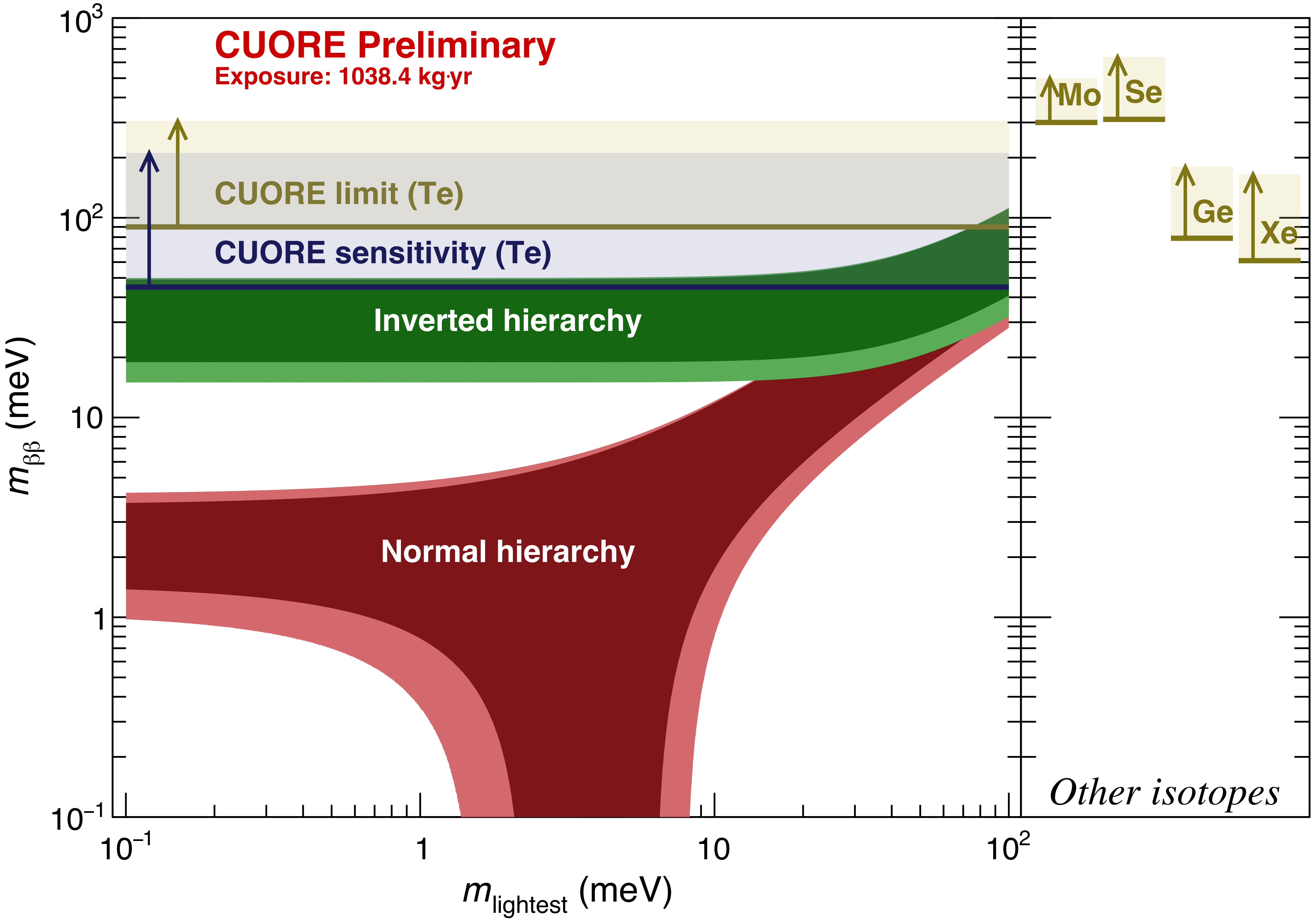
Conversion to effective Majorana mass

$$m_{\beta\beta} = \left| e^{i\eta_1} | U_{e1}^2 | m_1 + e^{i\eta_2} | U_{e2}^2 | m_2 + | U_{e3}^2 | m_3 \right|$$

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

$$^{130}\mathrm{Te} : m_{\beta\beta} < (90 - 305)\,\mathrm{meV}$$

$$^{128}\mathrm{Te} : m_{\beta\beta} < (1.1 - 3.0)\,\mathrm{eV}$$



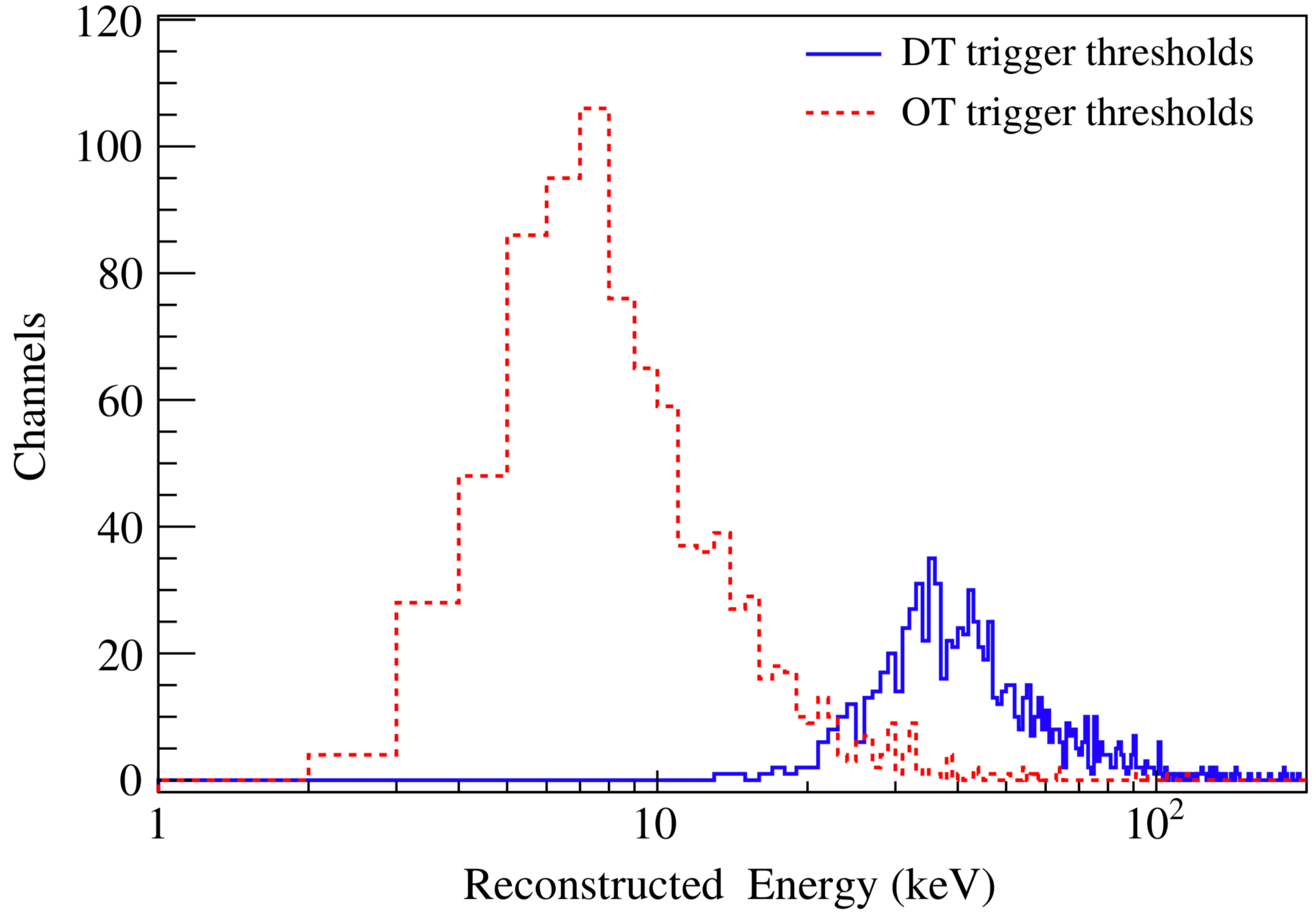
Ref. NME

[1] Menendez et al. NPA 818 (2009)130	ISM(-StMa)
[2] Neacsu and Horoi PHYS. REV. C 91, 024309 (2015)	ISM(-CMU)
[3] Faessler et al. JoP G: Nucl. Part. Phys. 39 (2012) 124006	QRPA-T
[4] Fang et al. PRC 83 (2011) 034320	
[5] Simkovic et al. PHYS. REV. C 87, 045501 (2013)	
[6] Suhonen et al. JoP G: Nucl. Part. Phys. 39 (2012) 124005	QRPA-J
[7] Hyva rinen and Suhonen PHYS. REV. C 91, 024613 (2015)	
[8] Iachello et al. PRC 87 (2013) 014315	IBM
[9] Barea et al. PHYS. REV. C 91 034304 (2015)	
[10] P.K. Rath et al. PHYS. REV. C 82 064310 (2010)	PHFB
[11] T.R. Rodriguez et al. Phys. Rev. Lett. 105 252503 (2010)	GCM

Derivative and Optimum Trigger

Derivative trigger:

- Fires when the baseline slope is above threshold for a certain number of samples (no info about signal pulse shape)
- Threshold: tens of keV



Optimum trigger:

- Threshold trigger applied on waveform previously filtered with OF
- Filtered data have higher SNR
- Distinguishes between physical and non-physical pulses
- **Threshold: few keV**

<u>Perspectives of lowering CUORE thresholds:</u>
dark matter searches (WIMP - Te/O nuclei scattering), solar axions, supernova neutrinos

Results on 0νββ decay of ^{128}Te

Bayesian fit signal + background on CUORE data - $\Gamma_{0\nu}$ prior restricted to physical values only ($\Gamma_{0\nu}>0$)

Parameter	*Units*	*Global mode*	*Marginalized mode*
$\mathbf{\Gamma^{0\nu}}$	**1/y**	**$1.5 \cdot 10^{-32} \pm 6.8 \cdot 10^{-26}$**	$\mathbf{2^{+103}_{-2} \cdot 10^{-27}}$
BI_{ds3522}	cts/(keV·kg·y)	1.48 ± 0.02	$1.48^{+0.02}_{-0.02}$
BI_{ds3552}	cts/(keV·kg·y)	1.43 ± 0.02	$1.43^{+0.02}_{-0.02}$
BI_{ds3555}	cts/(keV·kg·y)	1.49 ± 0.02	$1.49^{+0.02}_{-0.02}$
BI_{ds3564}	cts/(keV·kg·y)	1.48 ± 0.02	$1.48^{+0.02}_{-0.02}$
BI_{ds3567}	cts/(keV·kg·y)	1.26 ± 0.02	$1.26^{+0.02}_{-0.02}$
m_{ds3522}	1/keV	-0.07 ± 0.03	$-0.06^{+0.02}_{-0.03}$
m_{ds3552}	1/keV	-0.06 ± 0.03	$-0.06^{+0.03}_{-0.03}$
m_{ds3555}	1/keV	-0.08 ± 0.03	$-0.08^{+0.03}_{-0.03}$
m_{ds3564}	1/keV	-0.04 ± 0.03	$-0.04^{+0.03}_{-0.02}$
m_{ds3567}	1/keV	-0.12 ± 0.03	$-0.12^{+0.03}_{-0.03}$
Γ^{Mn}	cts/(kg·y)	15.3 ± 0.7	$15.3^{+0.7}_{-0.6}$
Γ^{Tl}	cts/(kg·y)	0.5 ± 0.2	$0.5^{+0.2}_{-0.2}$

Results on 0νββ decay of ^{128}Te

Bayesian fit signal + background on CUORE data - $\Gamma_{0\nu}$ prior allowed to non-physical values

Parameter	*Units*	*Global mode*	*Marginalized mode*
$\Gamma^{0\nu}$	**1/y**	**$(-2.5 \pm 1.8) \cdot 10^{-25}$**	$\mathbf{-2.3^{+1.6}_{-2.1} \cdot 10^{-25}}$
BI_{ds3522}	cts/(keV·kg·y)	1.48 ± 0.02	$1.48^{+0.02}_{-0.02}$
BI_{ds3552}	cts/(keV·kg·y)	1.44 ± 0.02	$1.43^{+0.02}_{-0.02}$
BI_{ds3555}	cts/(keV·kg·y)	1.50 ± 0.02	$1.50^{+0.02}_{-0.02}$
BI_{ds3564}	cts/(keV·kg·y)	1.48 ± 0.02	$1.48^{+0.02}_{-0.02}$
BI_{ds3567}	cts/(keV·kg·y)	1.26 ± 0.02	$1.26^{+0.02}_{-0.02}$
m_{ds3522}	1/keV	-0.06 ± 0.03	$-0.06^{+0.03}_{-0.03}$
m_{ds3552}	1/keV	-0.06 ± 0.03	$-0.06^{+0.03}_{-0.03}$
m_{ds3555}	1/keV	-0.08 ± 0.03	$-0.08^{+0.03}_{-0.03}$
m_{ds3564}	1/keV	-0.04 ± 0.03	$-0.04^{+0.03}_{-0.03}$
m_{ds3567}	1/keV	-0.12 ± 0.03	$-0.12^{+0.03}_{-0.03}$
Γ^{Mn}	cts/(kg·y)	15.3 ± 0.7	$15.3^{+0.7}_{-0.7}$
Γ^{Tl}	cts/(kg·y)	0.5 ± 0.2	$0.5^{+0.2}_{-0.2}$

Results on 0νββ decay of ^{128}Te

Bayesian fit background-only on CUORE data

Parameter	*Units*	*Global mode*	*Marginalized mode*
BI_{ds3522}	cts/keV/kg/y	1.48 ± 0.02	$1.48^{+0.02}_{-0.02}$
BI_{ds3552}	cts/keV/kg/y	1.43 ± 0.02	$1.43^{+0.02}_{-0.02}$
BI_{ds3555}	cts/keV/kg/y	1.49 ± 0.02	$1.49^{+0.02}_{-0.02}$
BI_{ds3564}	cts/keV/kg/y	1.48 ± 0.02	$1.48^{+0.02}_{-0.02}$
BI_{ds3567}	cts/keV/kg/y	1.26 ± 0.02	$1.26^{+0.01}_{-0.02}$
m_{ds3522}	1/keV	-0.07 ± 0.03	$-0.06^{+0.02}_{-0.03}$
m_{ds3552}	1/keV	-0.06 ± 0.03	$-0.06^{+0.03}_{-0.03}$
m_{ds3555}	1/keV	-0.08 ± 0.03	$-0.08^{+0.03}_{-0.03}$
m_{ds3564}	1/keV	-0.04 ± 0.03	$-0.04^{+0.03}_{-0.03}$
m_{ds3567}	1/keV	-0.12 ± 0.03	$-0.12^{+0.03}_{-0.03}$
Γ^{Mn}	cts/kg/y	15.3 ± 0.7	$15.3^{+0.07}_{-0.07}$
Γ^{Tl}	cts/(kg y)	0.5 ± 0.2	$0.5^{+0.2}_{-0.2}$