Search for double beta decay of ^{130}Te to the 0^+ states of ^{130}Xe with the CUORE experiment

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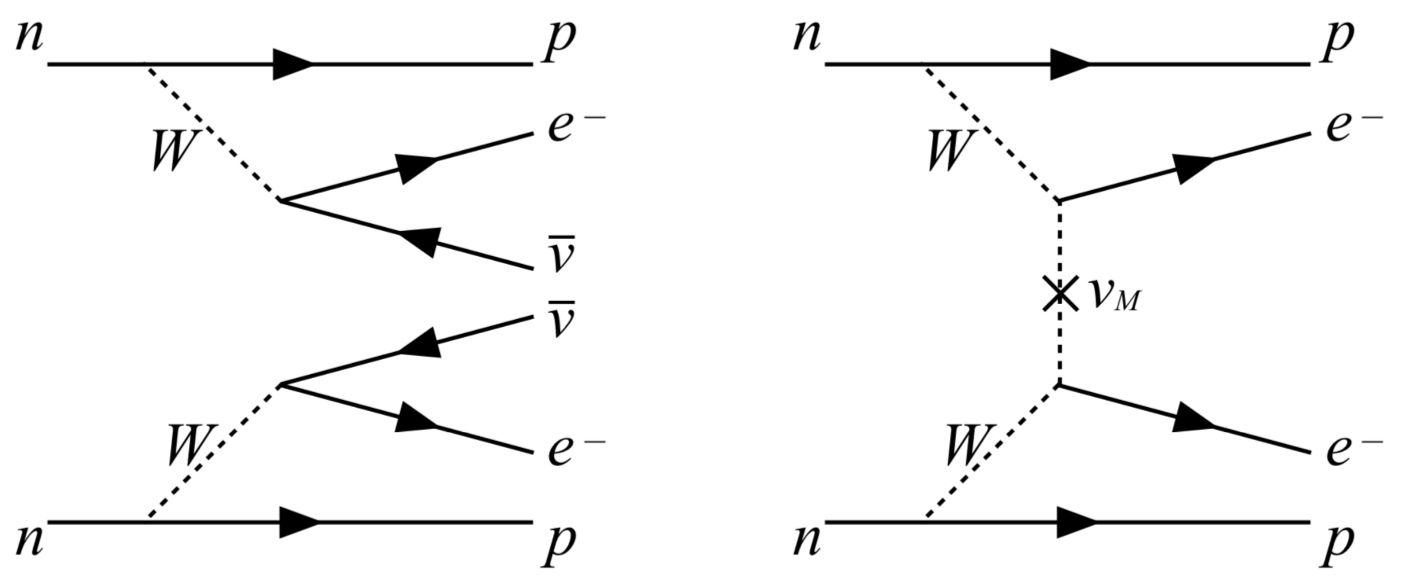
Outline

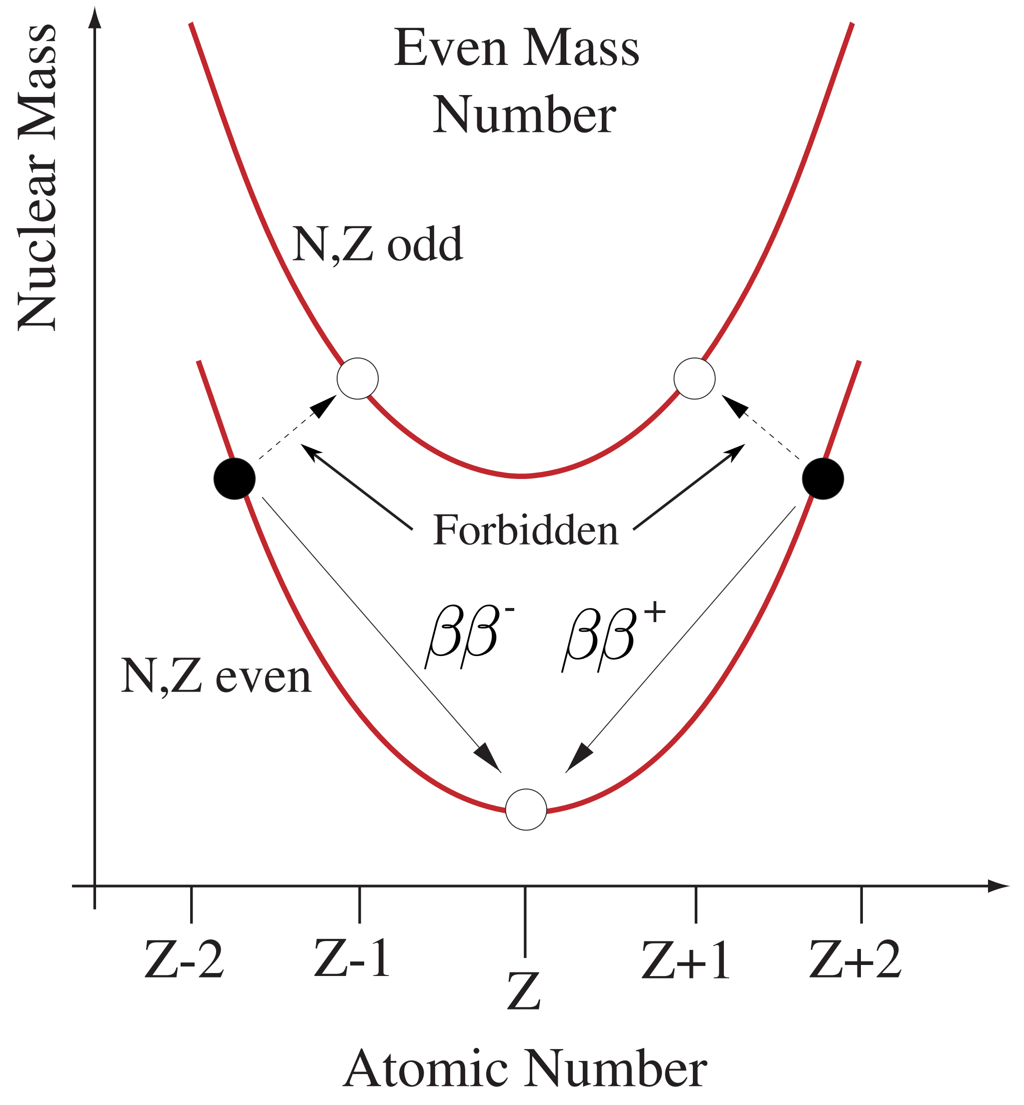
- Introduction
- The CUORE experiment
  - Operating principles
  - Data processing
  - Detector characterization
- Ground state $0\nu\beta\beta$ decay search
- Excited state searches

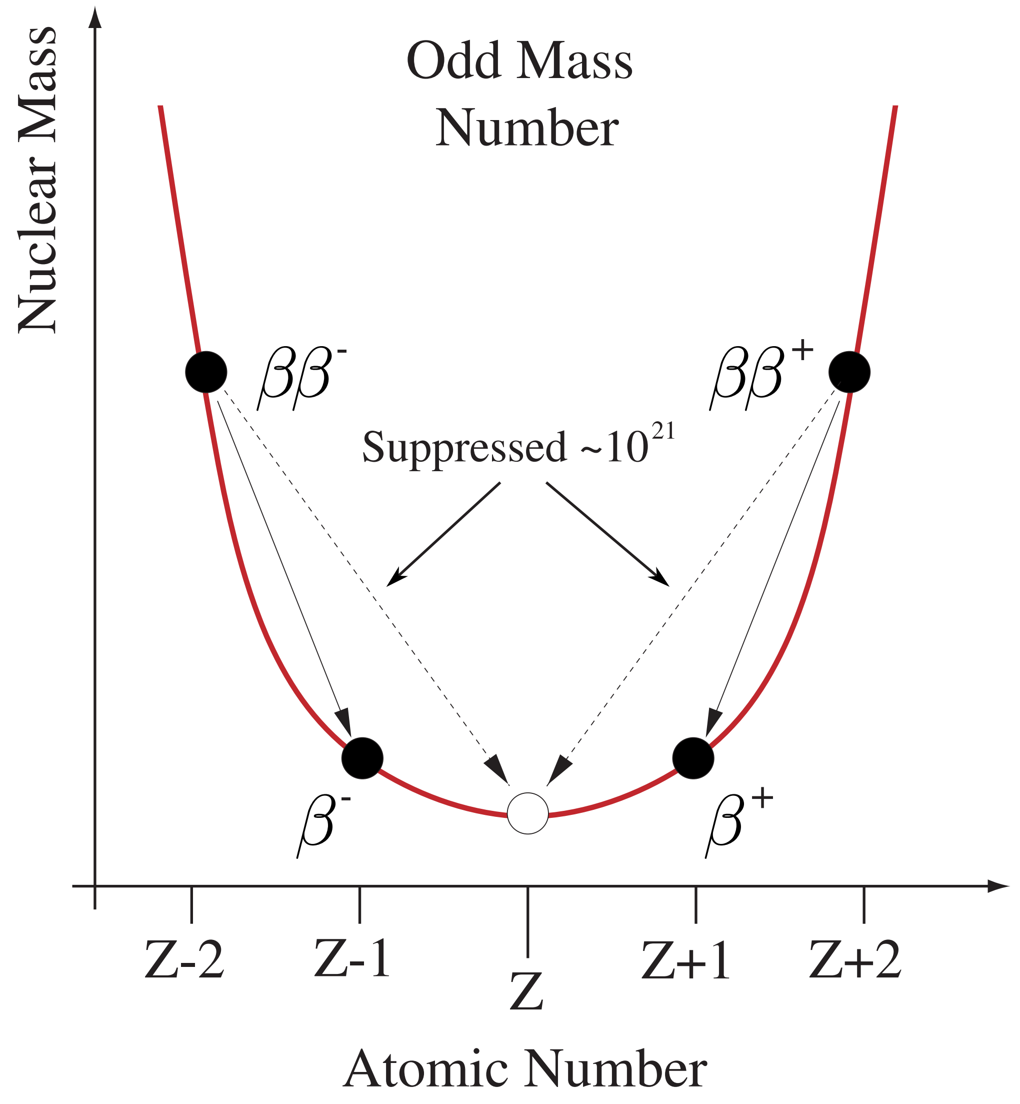
Introduction

Double Beta Decay



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





$$X = 2\bar{\nu}_e$$

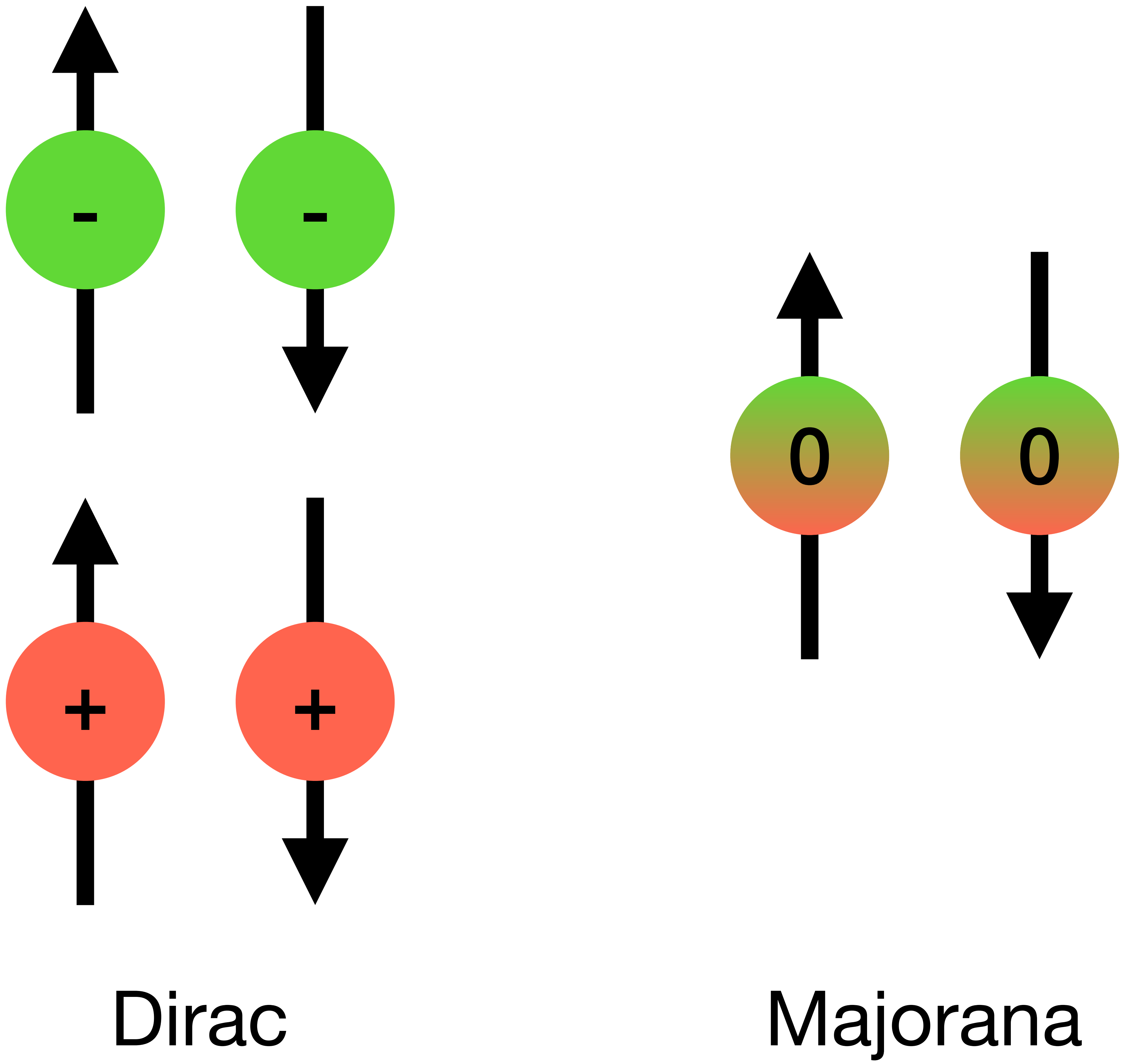
- Allowed within the Standard Model
- 2nd order process
- observed in 12 isotopes

$$X = \varnothing$$

- Beyond Standard Model
- Majorana nature of neutrinos
- Lepton number violation

Introduction

Majorana neutrinos



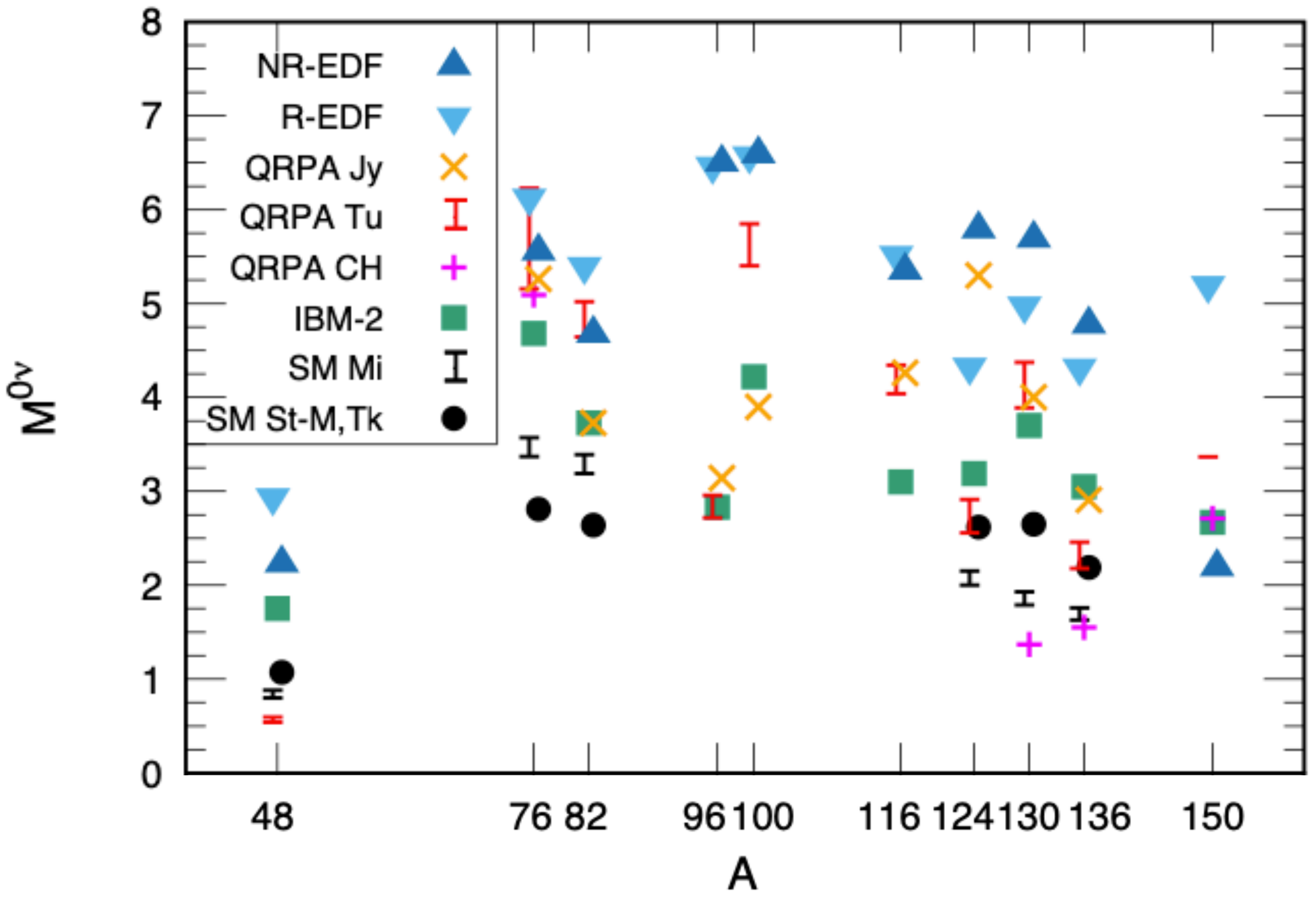
- Vanishing internal quantum numbers (lepton number)
- Their own anti-particles
- Neutrino mass generation mechanism
- Mediate neutrino-less double beta decay
- Leptogenesis

Introduction

Neutrinoless Double Beta Decay

$$\langle m_{\beta\beta} \rangle = \left| \sum_i U_{ei}^2 m_i \right|$$

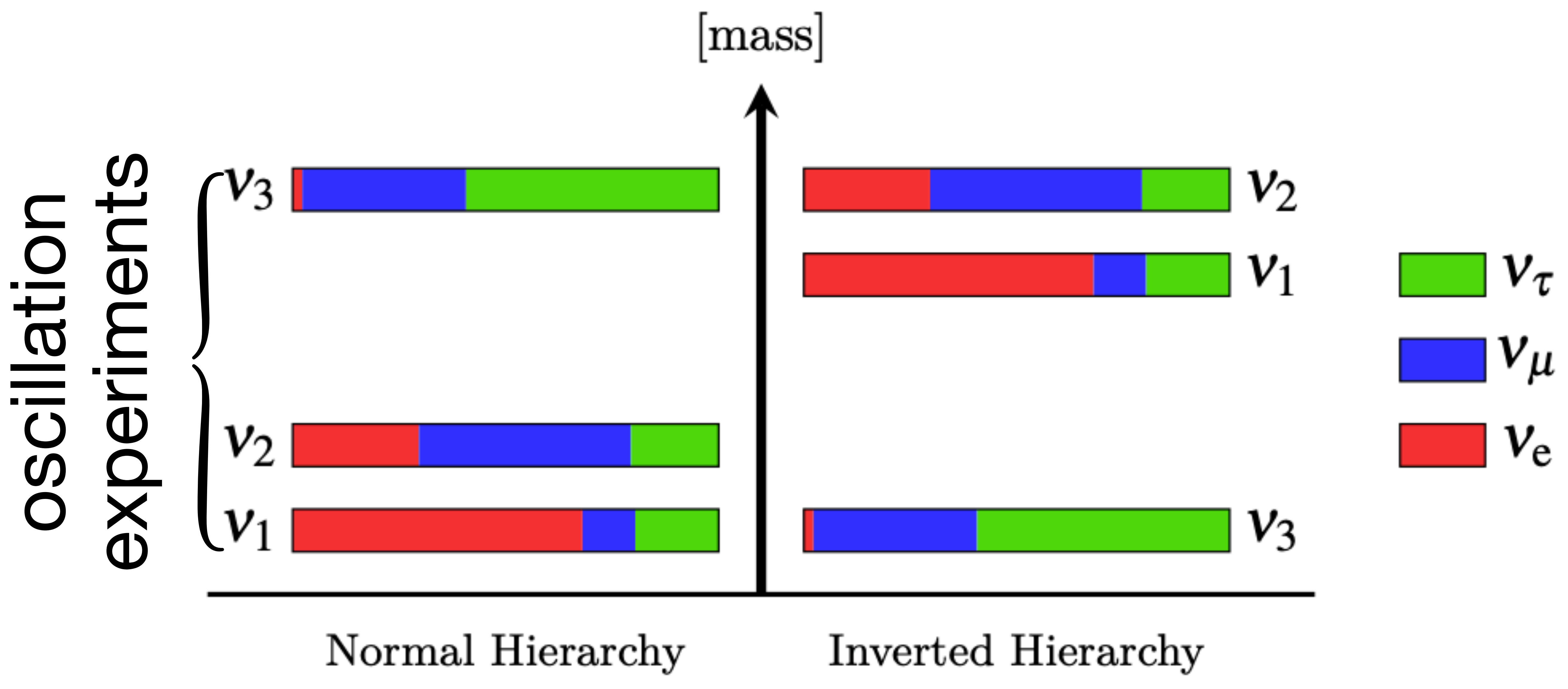
$$\Gamma_{0\nu} = G_{0\nu}\, g_A^4 \,|\, M_{0\nu} \,|^2 \,\frac{\langle m_{\beta\beta} \rangle^2}{m_e^2}$$



[J.Engel, J.Menéndez, Rep. Prog. Phys. 80, 4 (2017)]

- $G_{0\nu}$ phase space factor (well known, small uncertainty)
- Nuclear Matrix Element (NME) (model dependence, large uncertainty)
- Effective Majorana mass (unknown)

Introduction

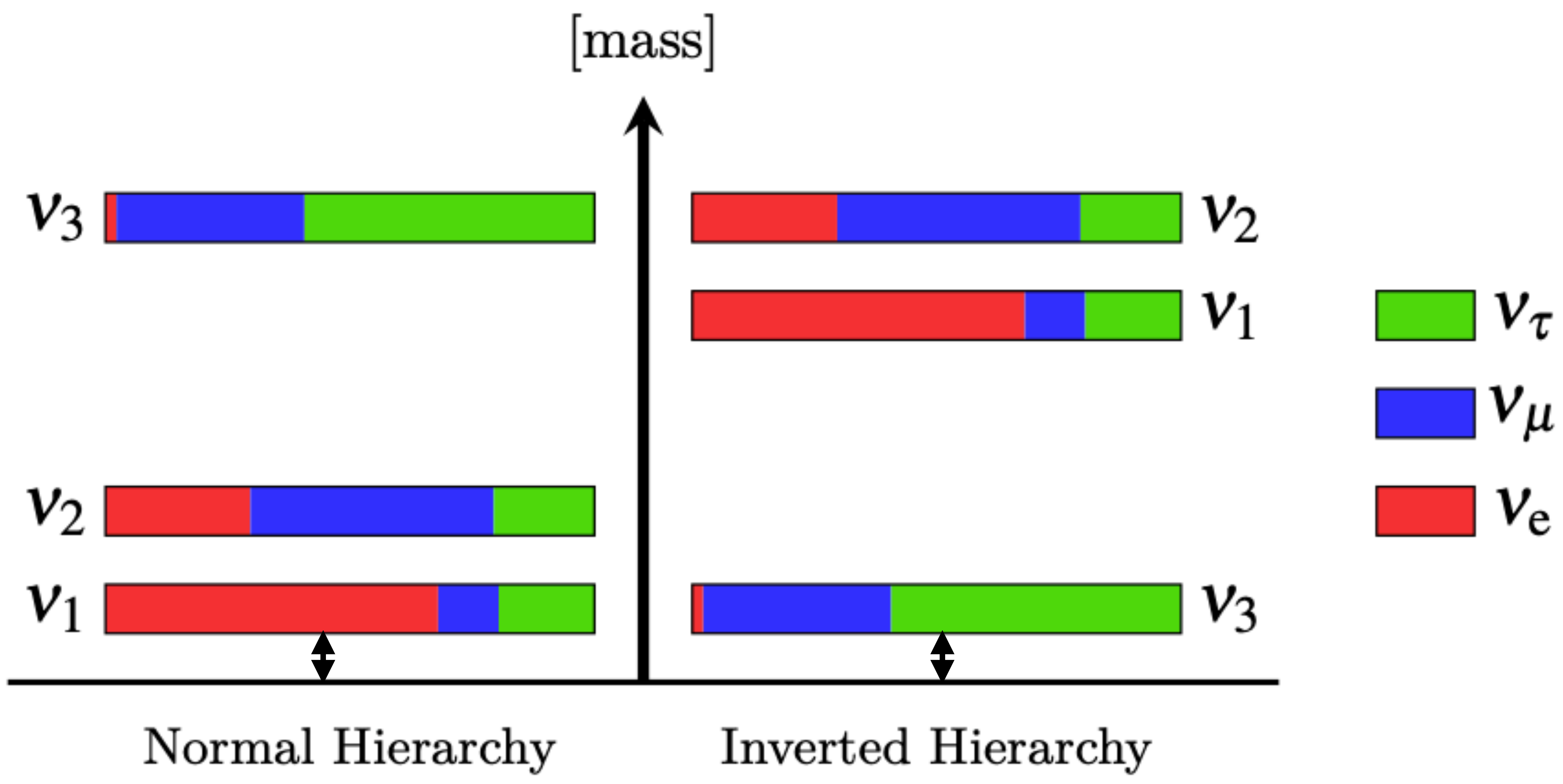


[G. Fantini, A. Gallo Rosso, F. Vissani, V. Zema, Adv. Ser. Direct. High Energy Phys. 28 (2018) 37-119]

$$\nu_{f,L} = \sum_{j=1}^{3} U_{l,j}\, \nu_{j,L}$$

- Pontecorvo-Maki-Nakagawa-Sakata mixing matrix
- 3 mixing angles
- 1 (Dirac) / 3 (Majorana) CP violating phases

Introduction



cosmology
β decay
0νββ

[G. Fantini, A. Gallo Rosso, F. Vissani, V. Zema, Adv. Ser. Direct. High Energy Phys. 28 (2018) 37-119]

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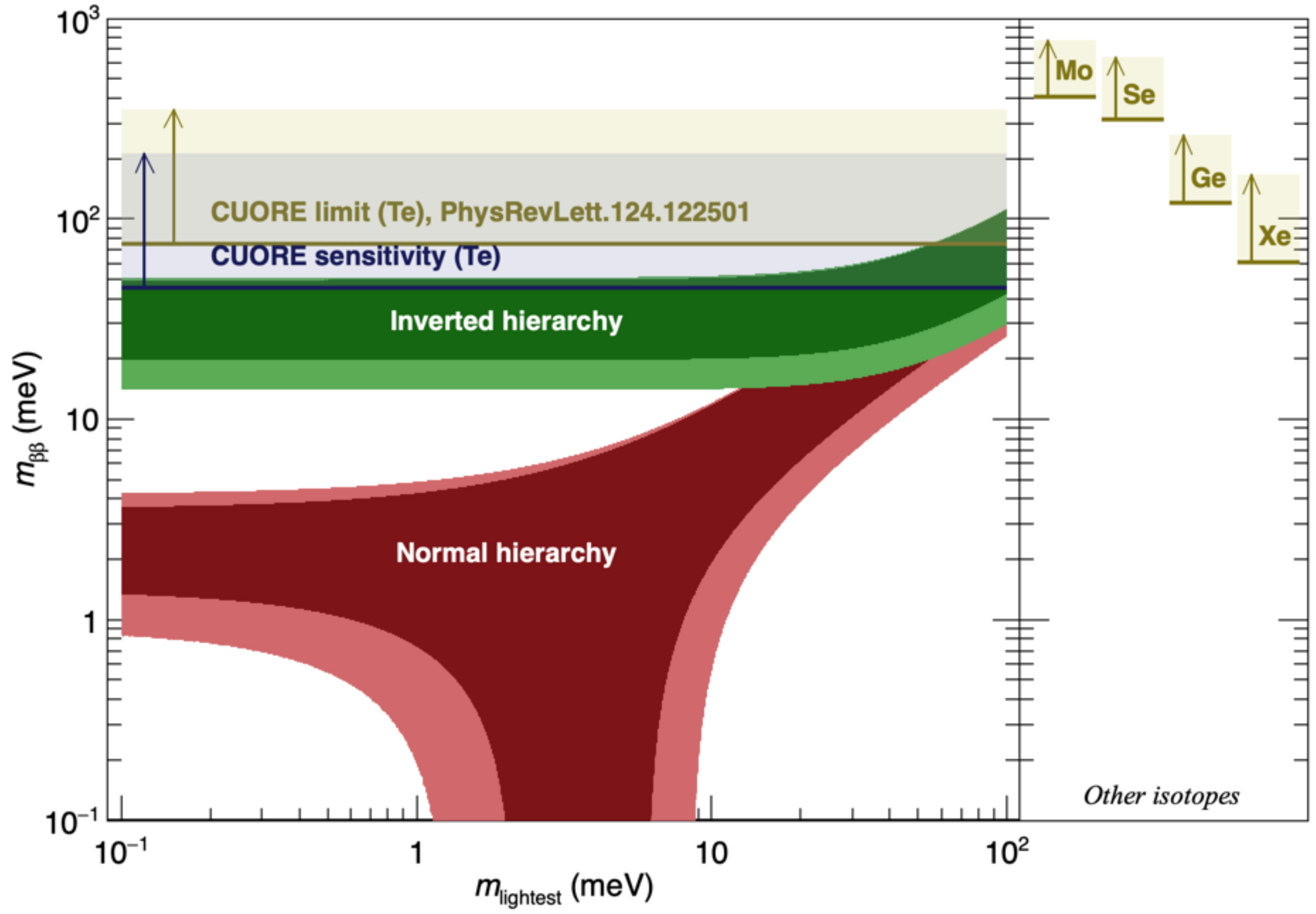
Introduction

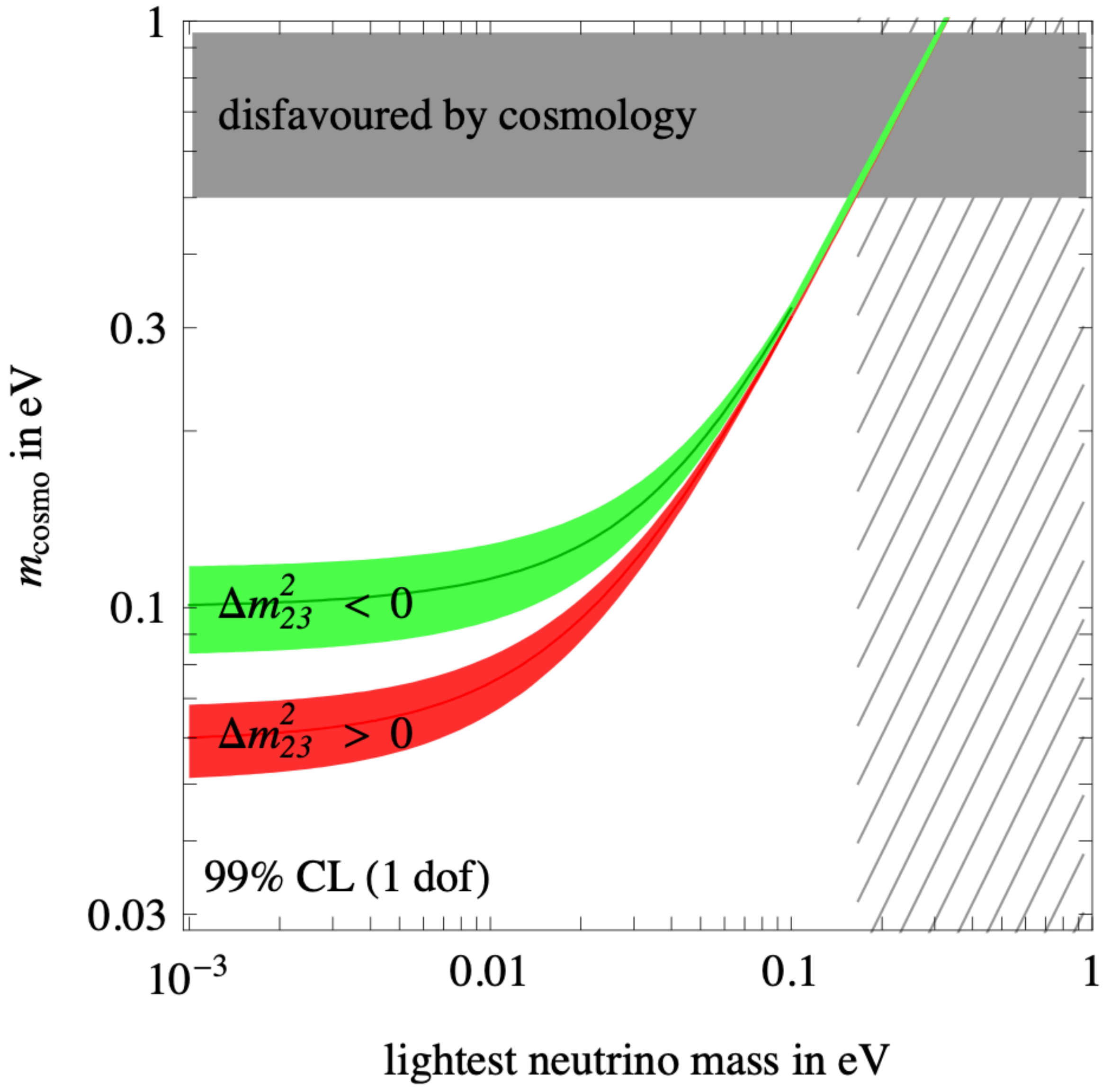
$$\langle m_{\beta\beta} \rangle = \left| \sum_i U_{ei}^2 m_i \right|$$

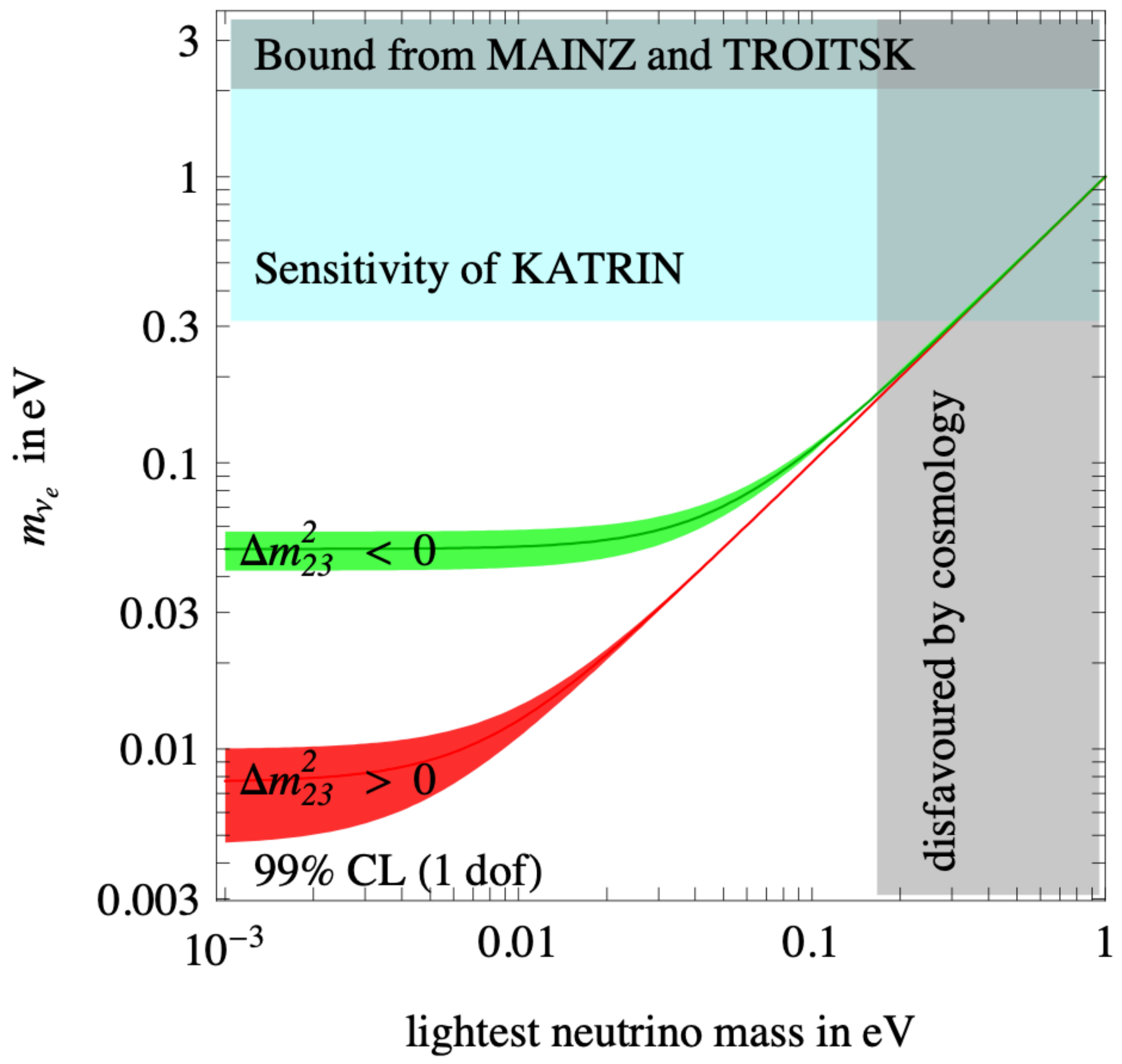
$$\Gamma_{0\nu} = G_{0\nu}\, g_A^4\, |M_{0\nu}|^2 \frac{\langle m_{\beta\beta} \rangle^2}{m_e^2}$$

- Neutrino-less double beta decay
- Cosmology
- Beta decay endpoint



$$\Sigma = m_1 + m_2 + m_3$$



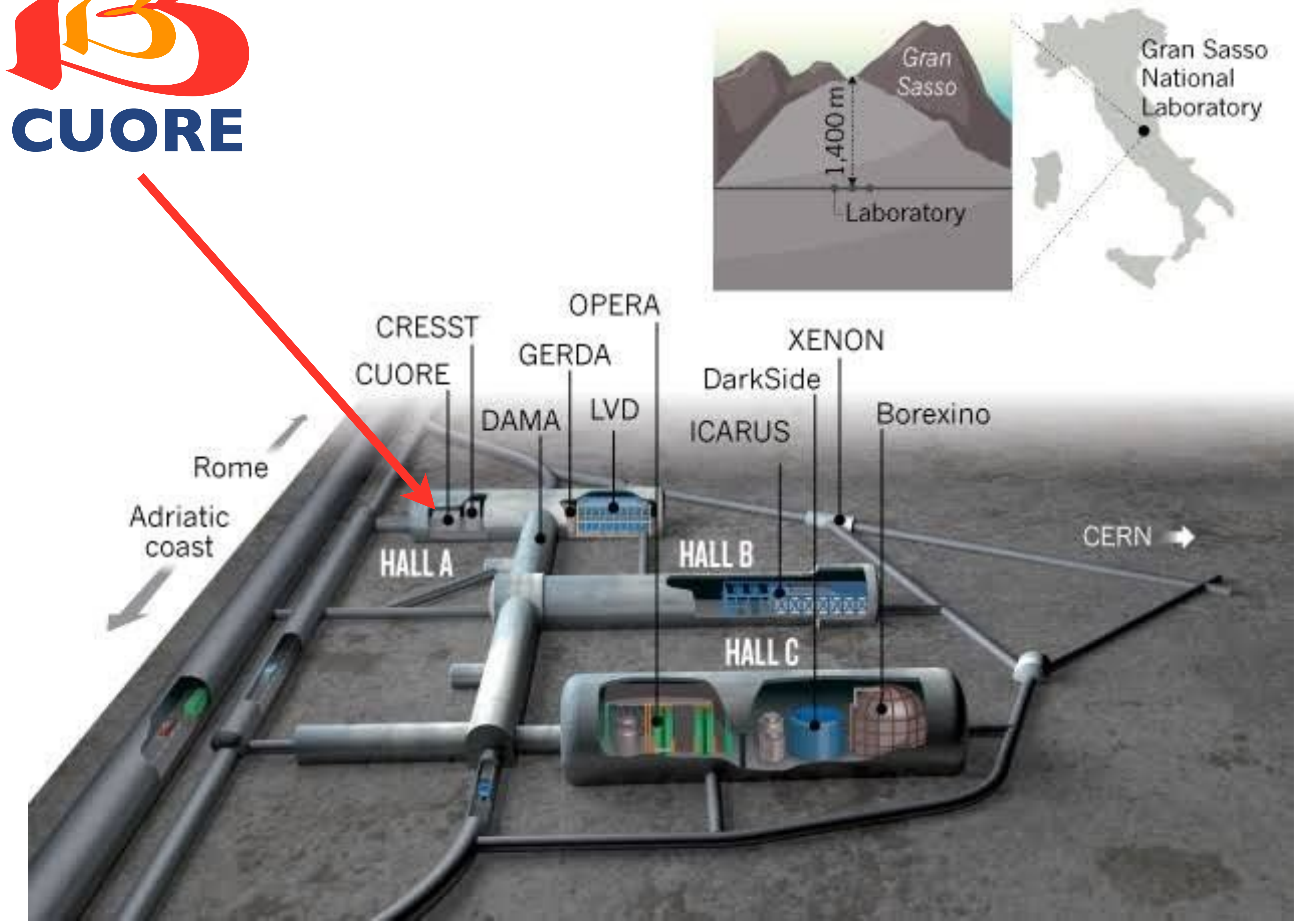


[A. Strumia and F. Vissani, IFUP-TH2004-1; arXiv:0606054]

The CUORE experiment

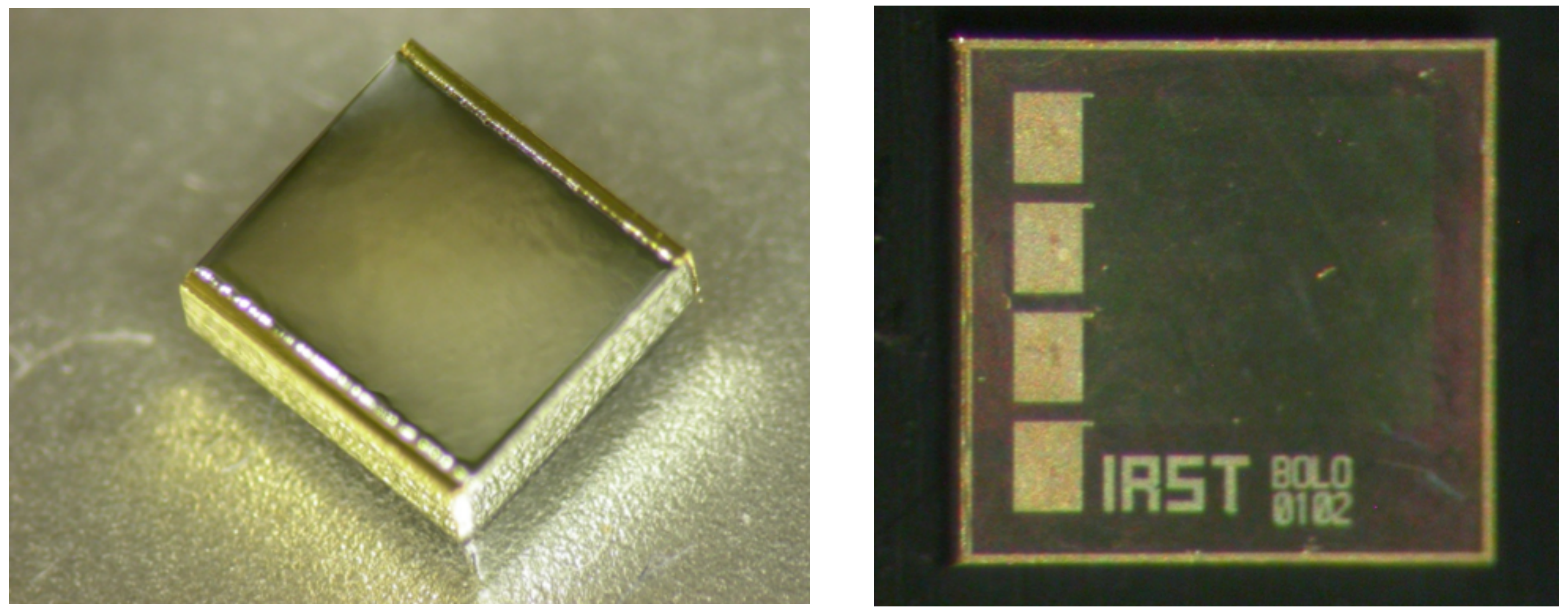
The CUORE experiment

- Cryogenic Underground Observatory for Rare Events
- Hosted underground in the Hall A of the INFN Laboratori Nazionali del Gran Sasso
- 3600 m.w.e. rock overburden
- Main physics goal $0\nu\beta\beta$
- High efficiency (source = detector)
- Ton scale bolometer array
- ~ 10 mK operating temperature

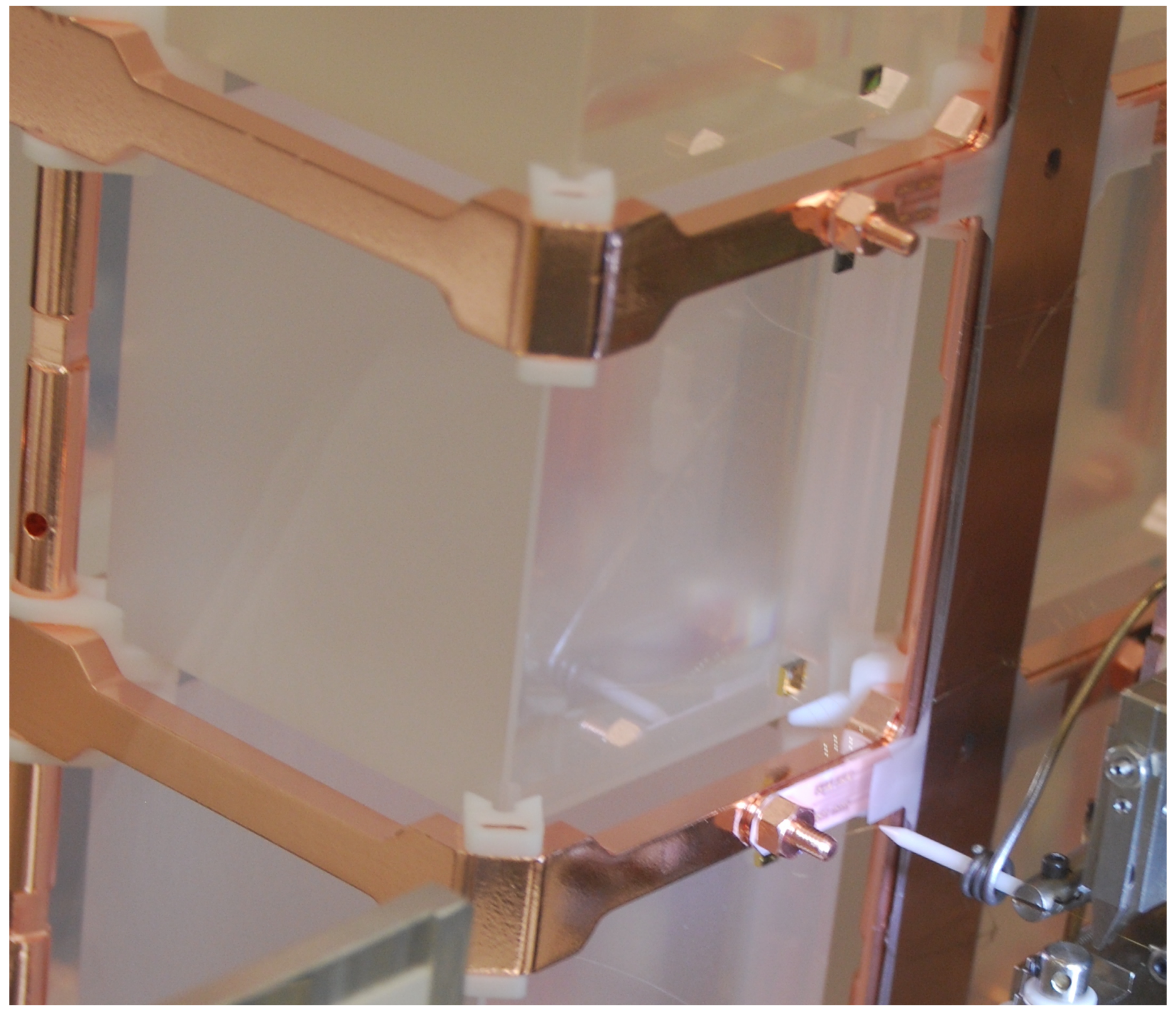


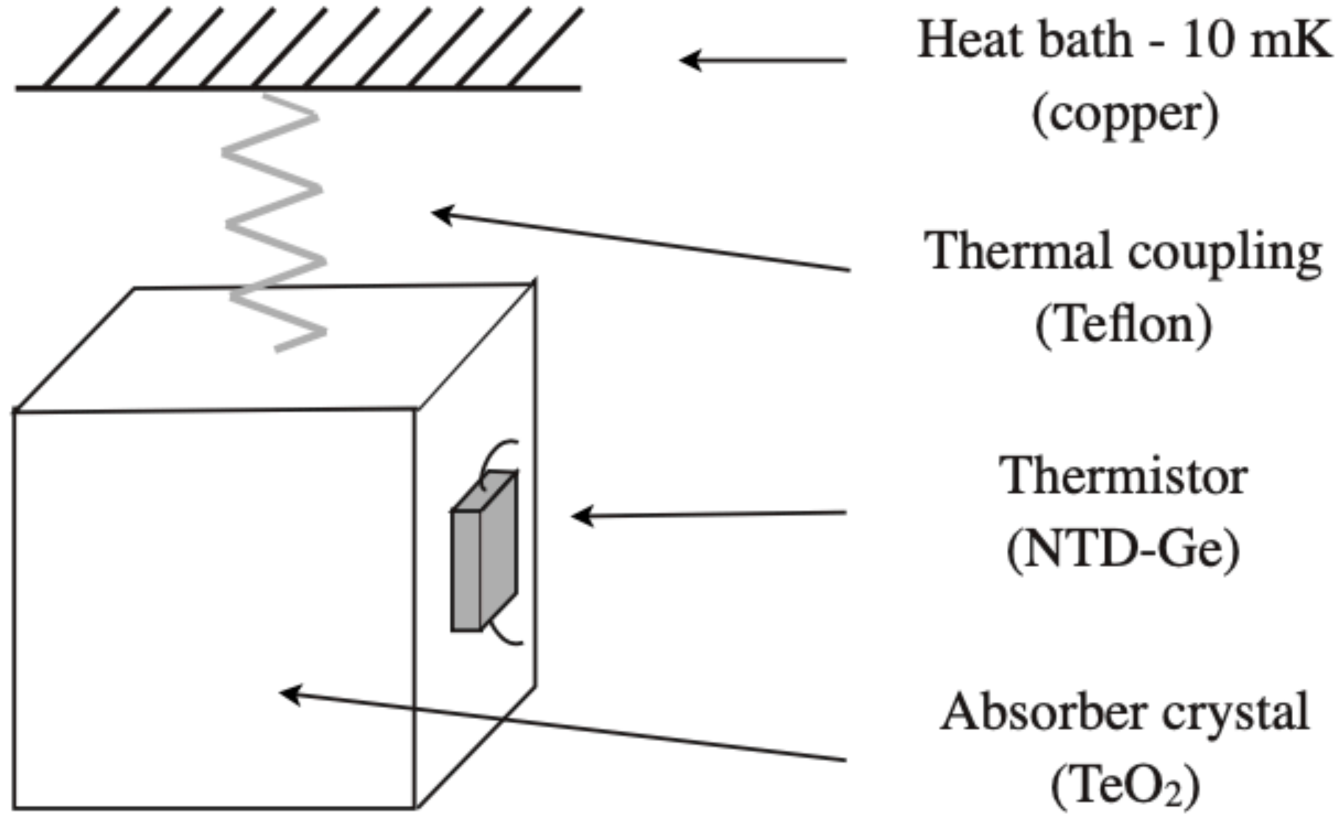
The CUORE experiment

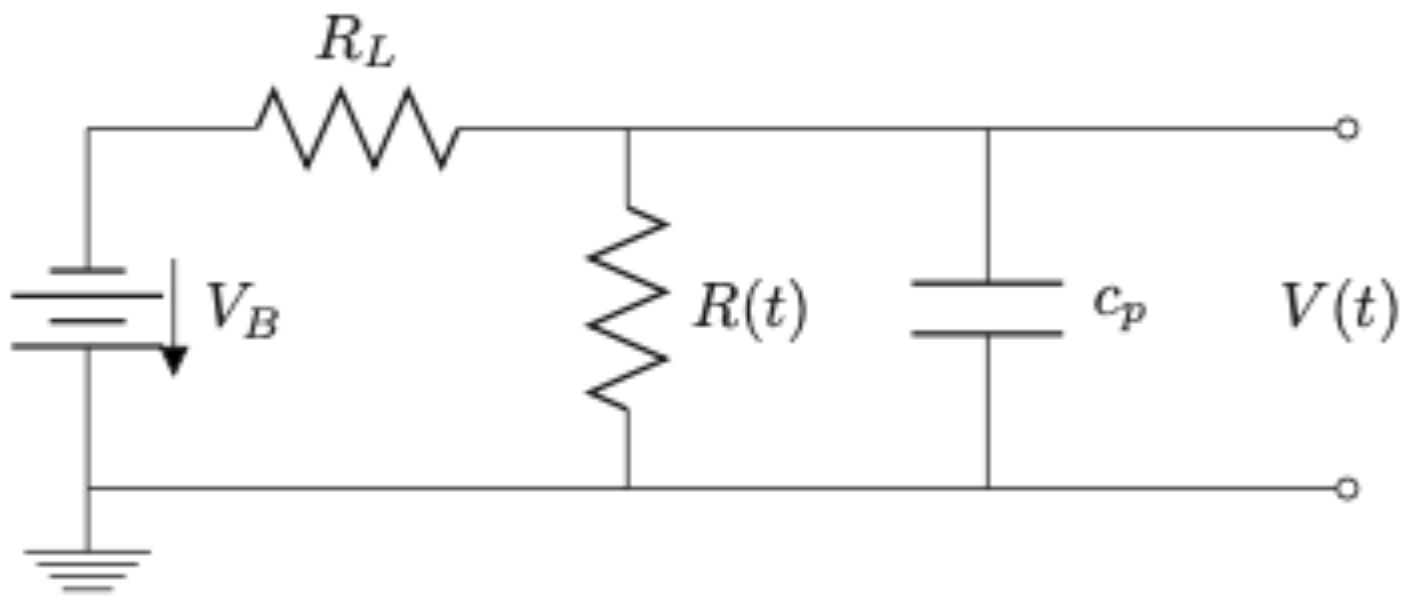
Operating principles

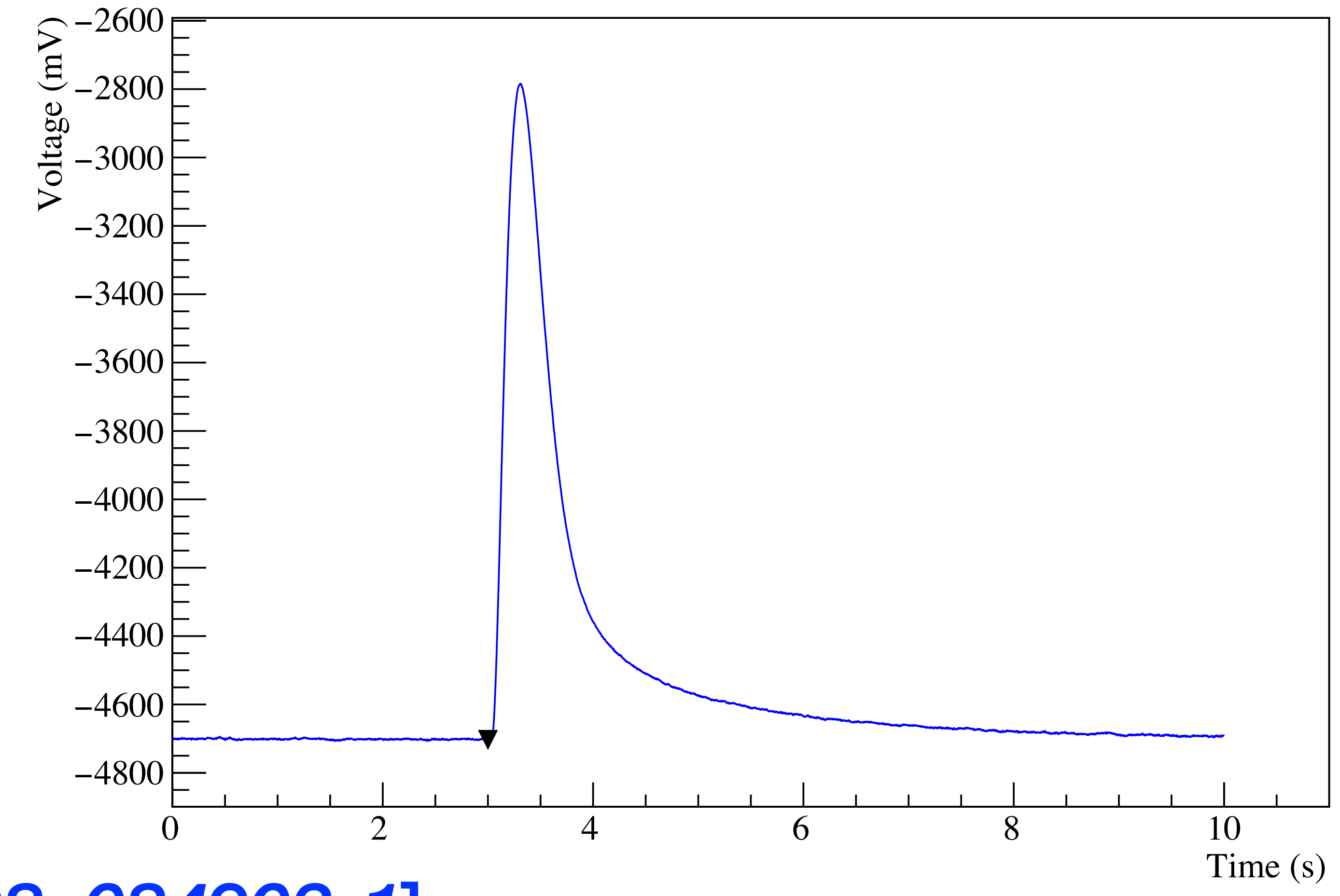


[C. Alduino et al., JINST 11 P07009 (2016)]









[M. Vignati, Journal of Applied Physics 108, 084903-1]

Crystals instrumented with

- NTD Ge thermistor
- Si heater

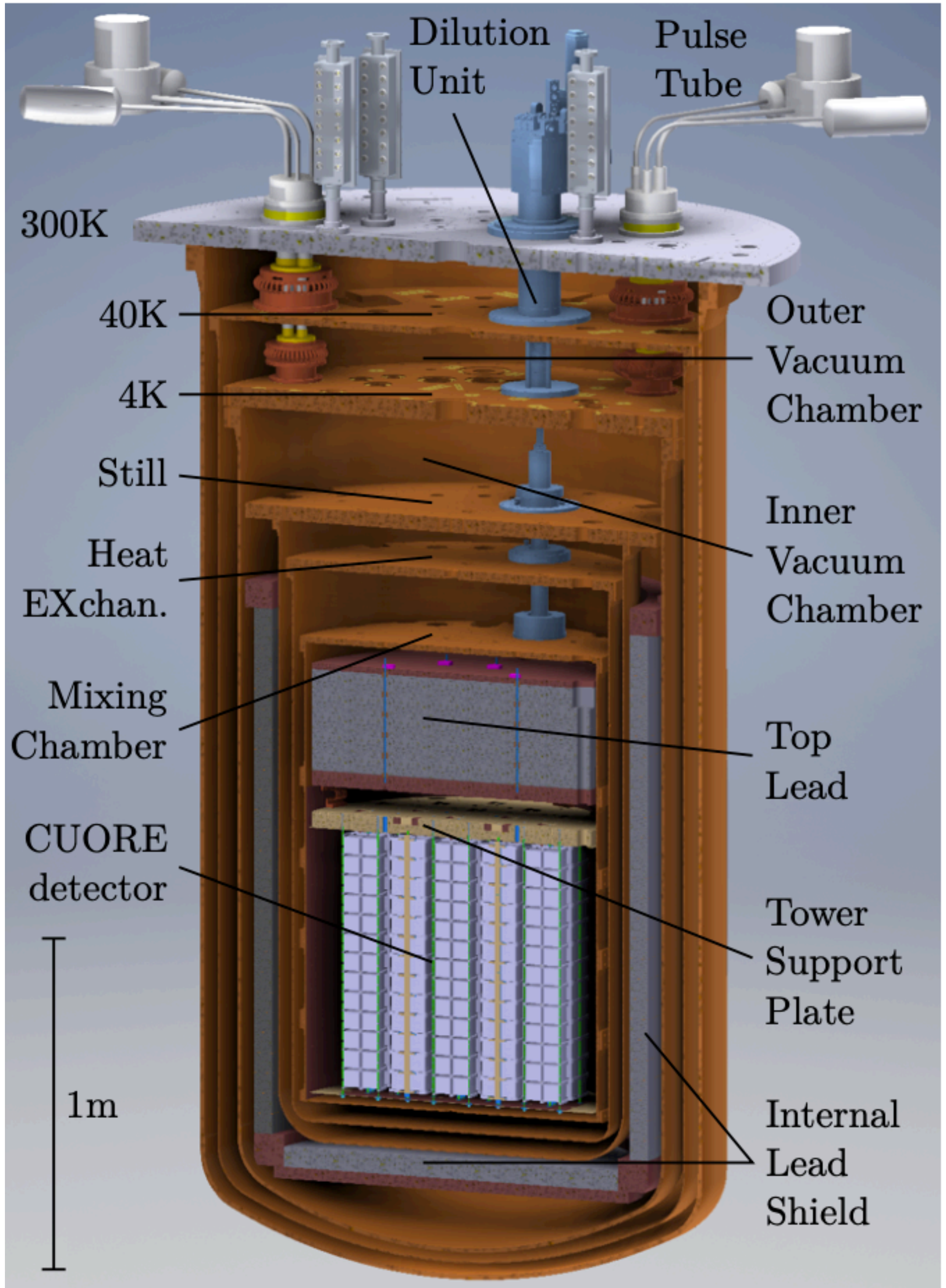
Weak thermal link to heat bath

Particle interactions in the crystals heat them up

Constant NTD current bias produces voltage pulses from temperature variations

The CUORE experiment

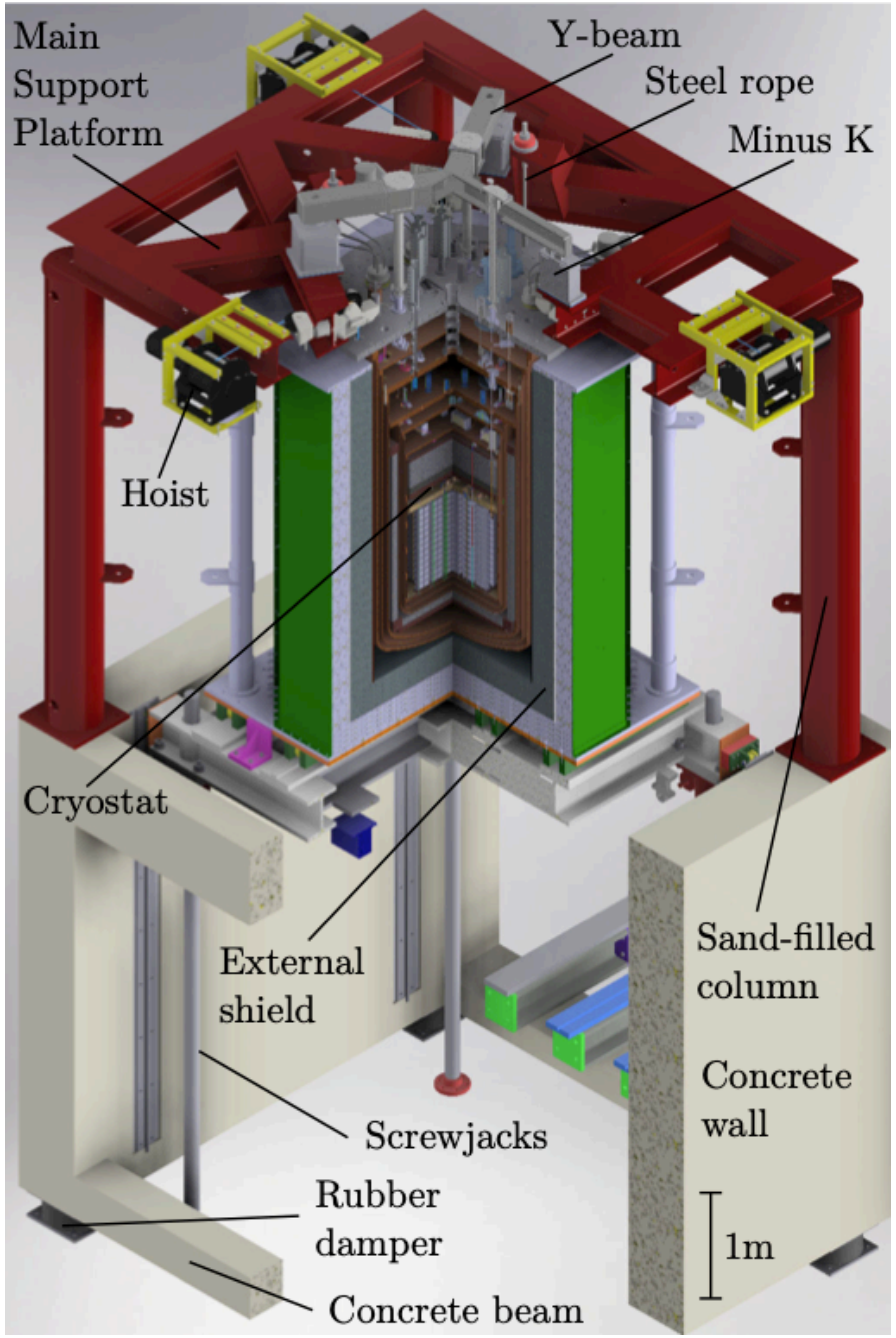
- 988 5x5x5 cm^3 crystals arranged in 19 towers of 52 channels each
- Total active mass 742 kg
- High natural isotopic abundance (~206 kg ^{130}Te)
- Multi-stage cryogen-free $^3He/^4He$ dilution refrigerator
- Pre-cooling supplied by Pulse Tube cryocoolers
- ~ 10 mK operating temperature
- Good energy resolution ~0.2% FWHM/E



[C. Alduino et al., Cryogenics 102, 9 (2019)]

The CUORE experiment

- Low background goal of 0.01 cts/(keV kg yr) at $Q_{\beta\beta}$
  - 18 cm polyethilene + 2 cm borated material
  - 30 cm lead
  - Inner ^{210}Pb depleted Roman lead shielding
- Thorough campaign of material assay
- Strict construction, transportation, assembly protocols
- Designed to reduce vibrations

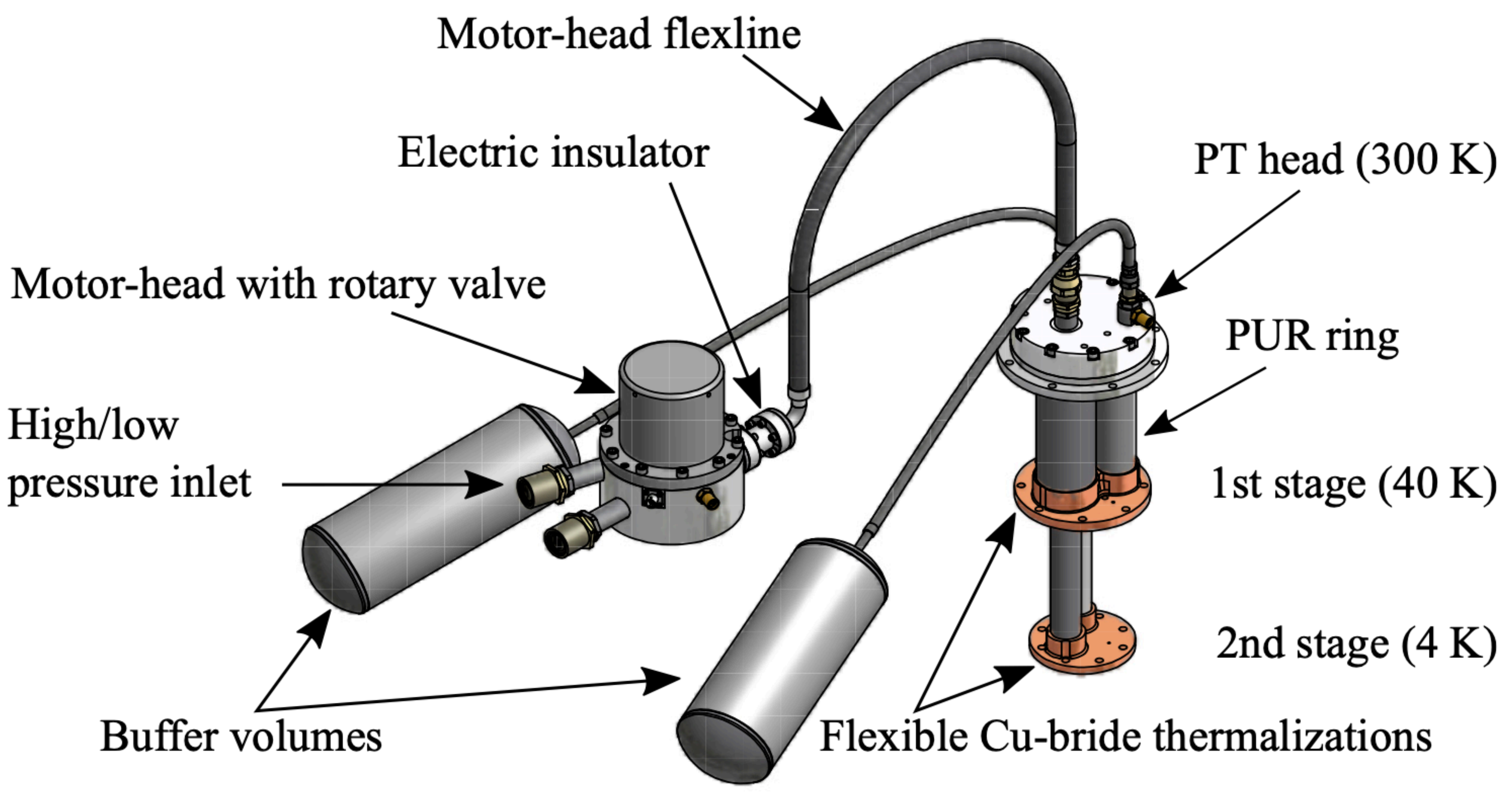


[C. Alduino et al., Cryogenics 102, 9 (2019)]

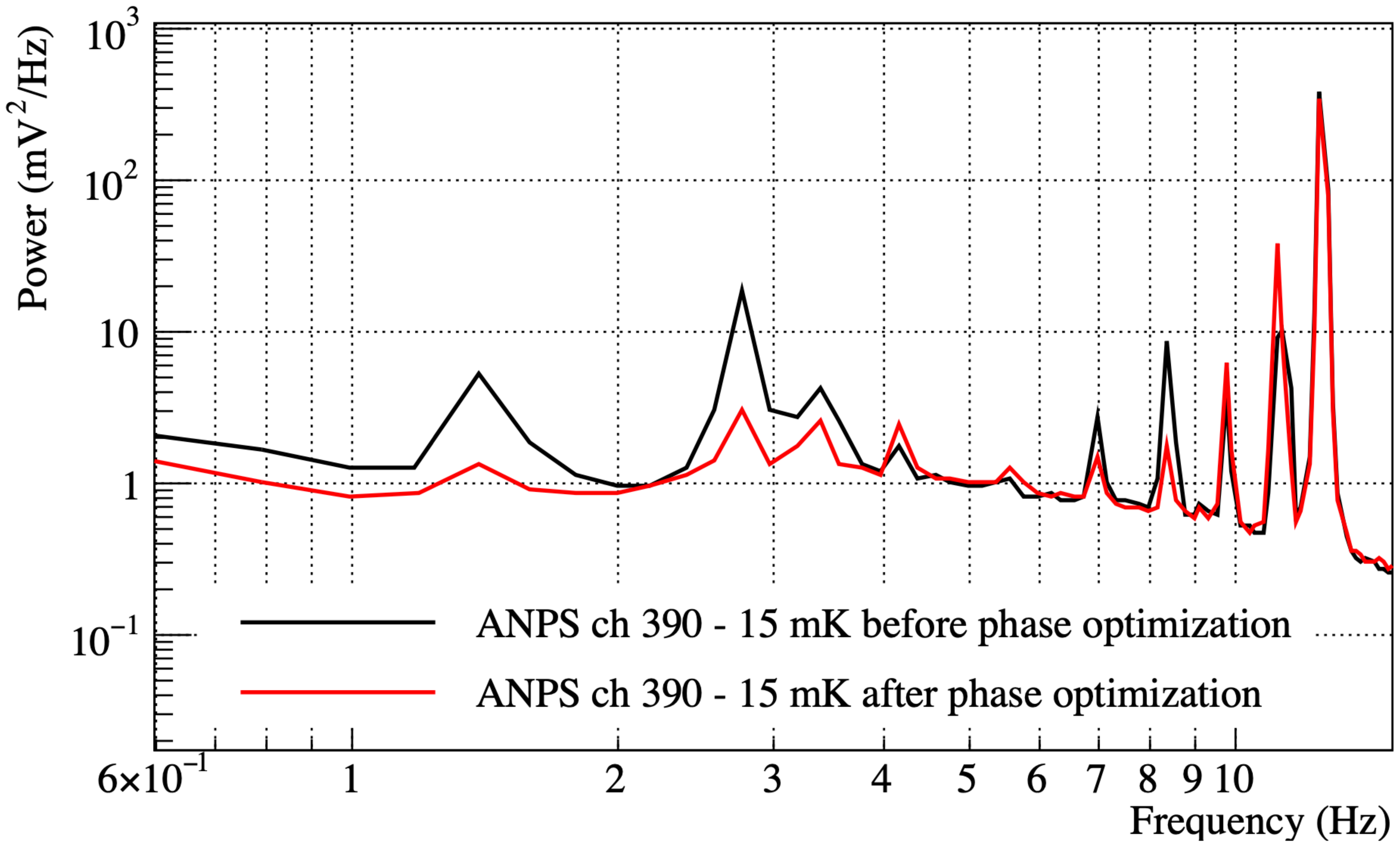
The CUORE experiment

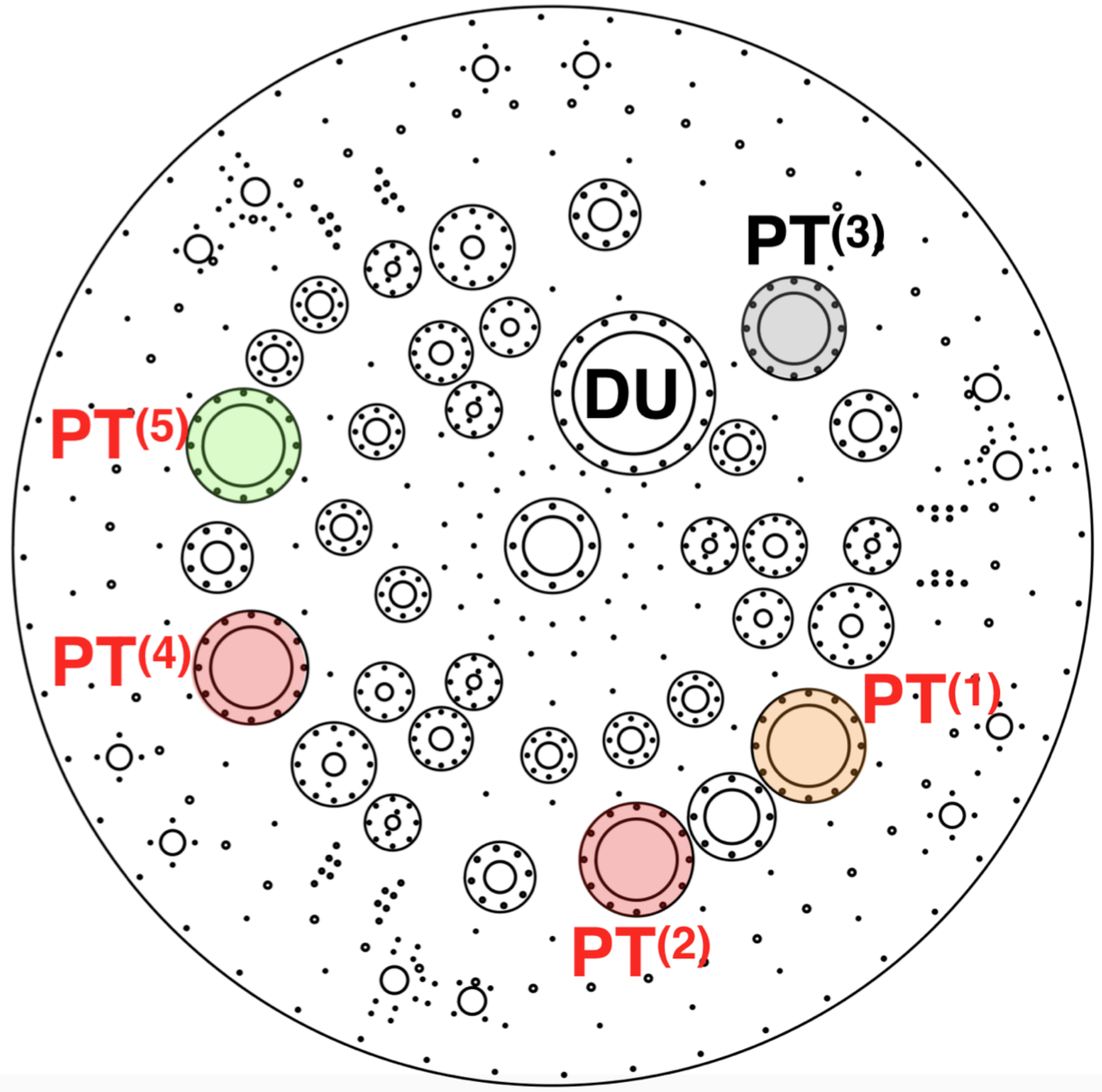
Pulse Tubes noise reduction

Tuning the relative phase of the PT rotary valves allows 1.4 Hz (and higher harmonics) coherent noise suppression



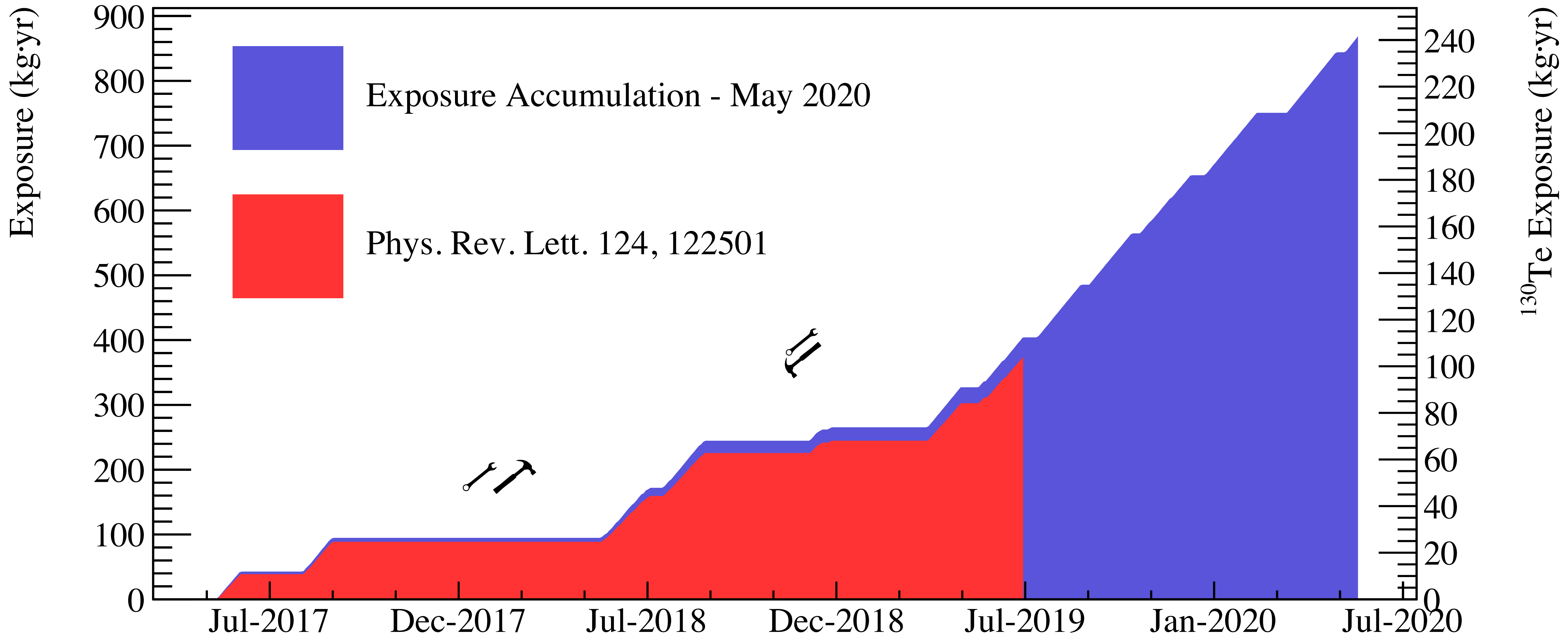
[A. D'Addabbo, Cryogenics 93, 56-65 (2018)]



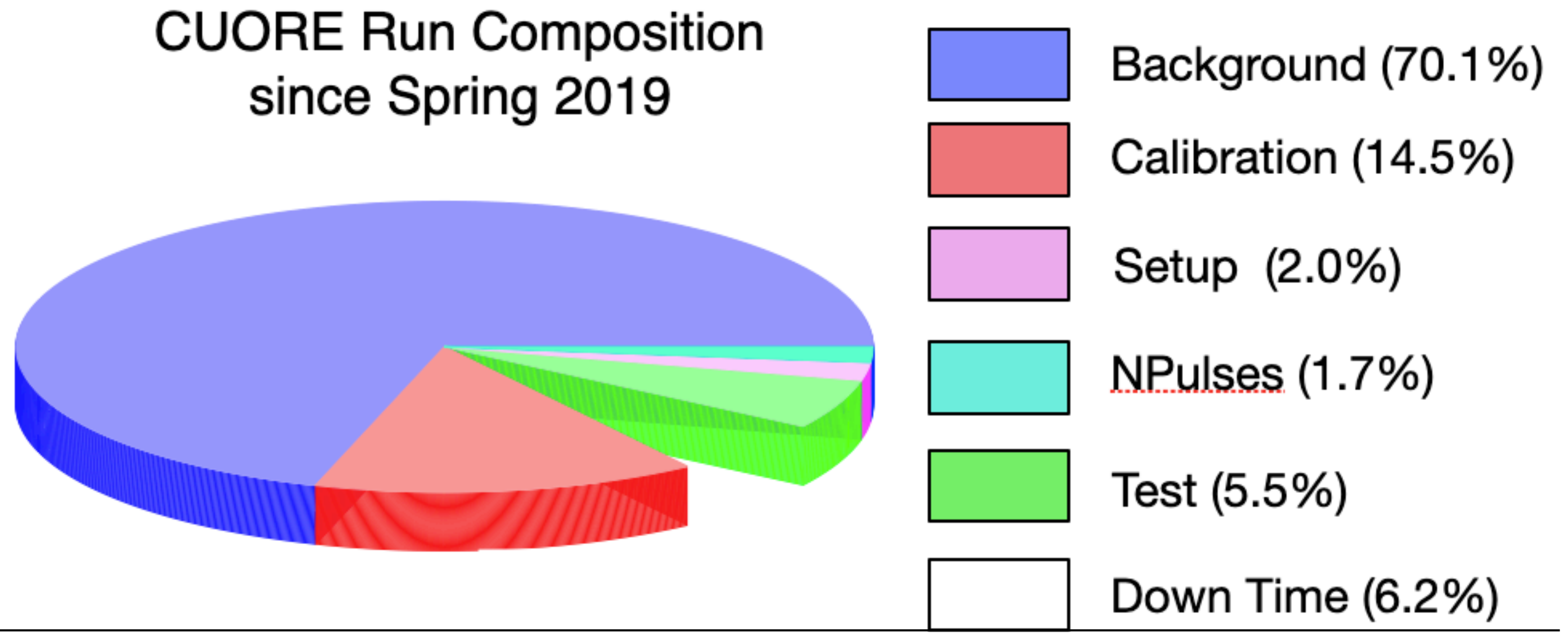


The CUORE experiment

Detector operation



[*D. Q. Adams et al.*, Phys. Rev. Lett. 124, 122501 (2020)]

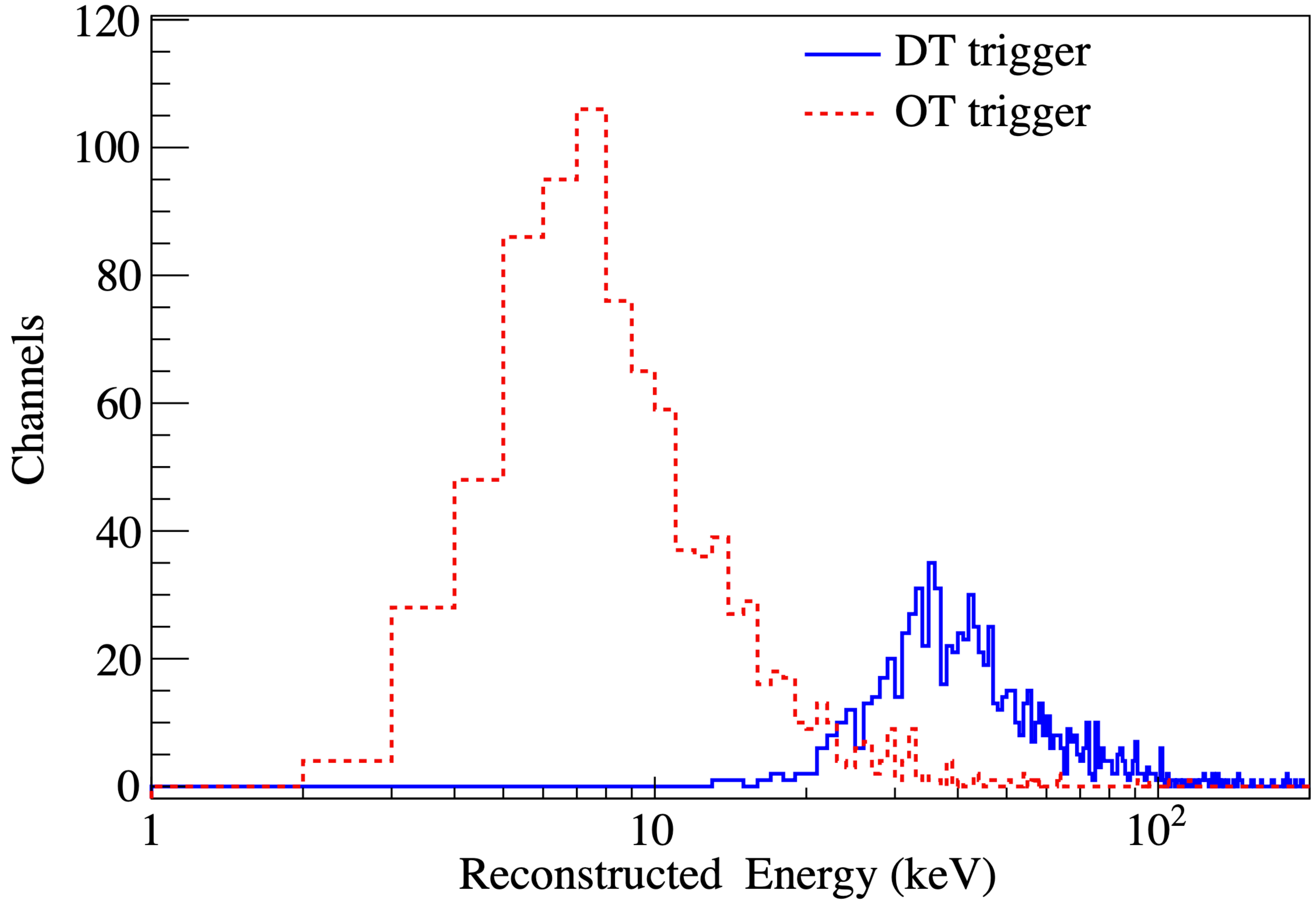


- Data taking started in Spring 2017
- CUORE "data set": ~1 month of background data taking with a few days of calibration at the start and end
- Unblinded accumulated exposure $372.5\ \text{kg} \cdot \text{yr}$
- Cryogenic facility for ton-scale bolometer arrays

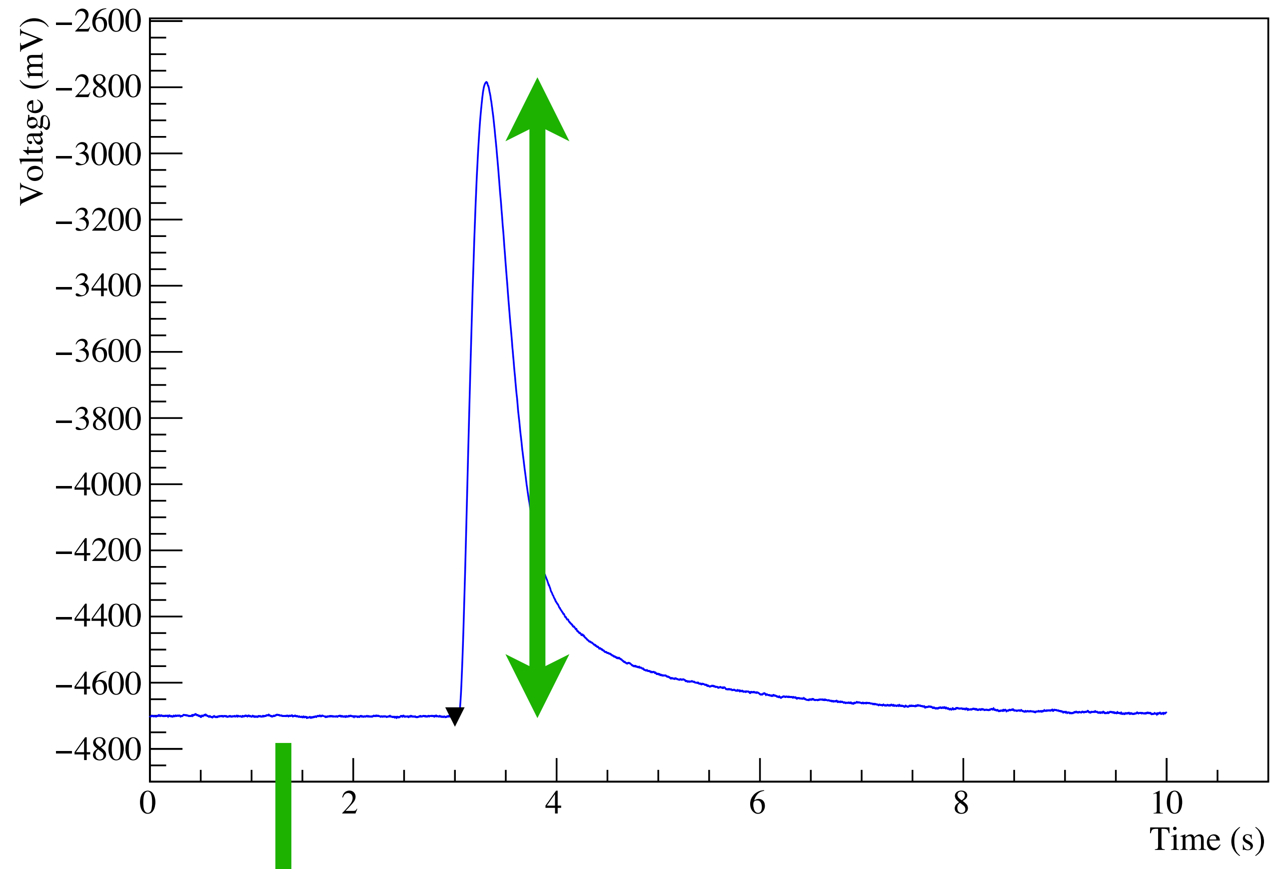
The CUORE experiment

Data processing

90% efficiency trigger thresholds



PREPROCESS



Baseline basic parameters
- value (temperature)
- slope (pile-up)
- RMS (noise)

Waveform basic parameters
- Amplitude (max - min)
- Number of pulses (pile-up)

[S. Di Domizio et al., JINST 6 (2011) P02007] [A. Campani et al., J. Low Temp. Phys. (2020)]

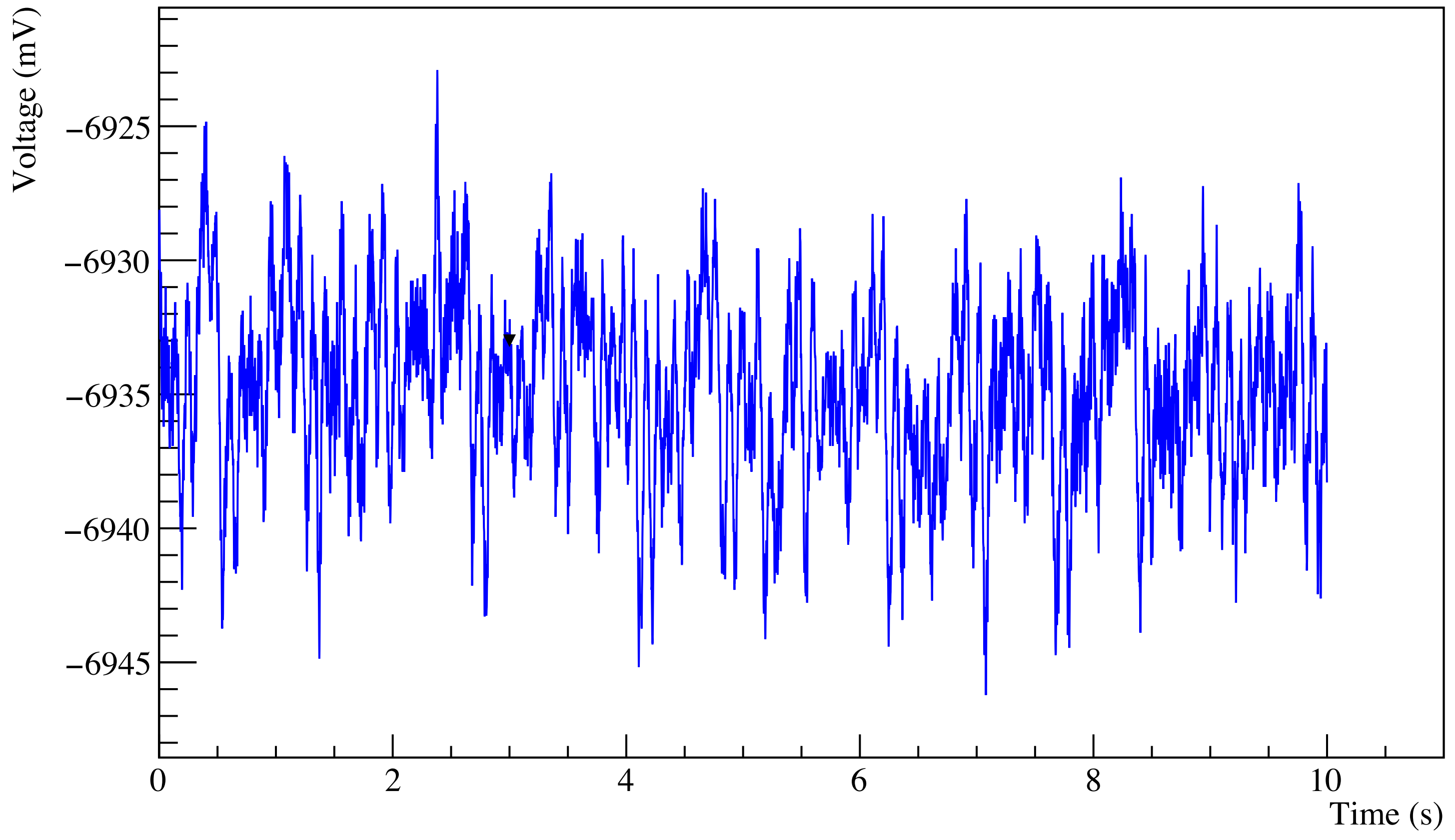
The CUORE experiment

Data processing

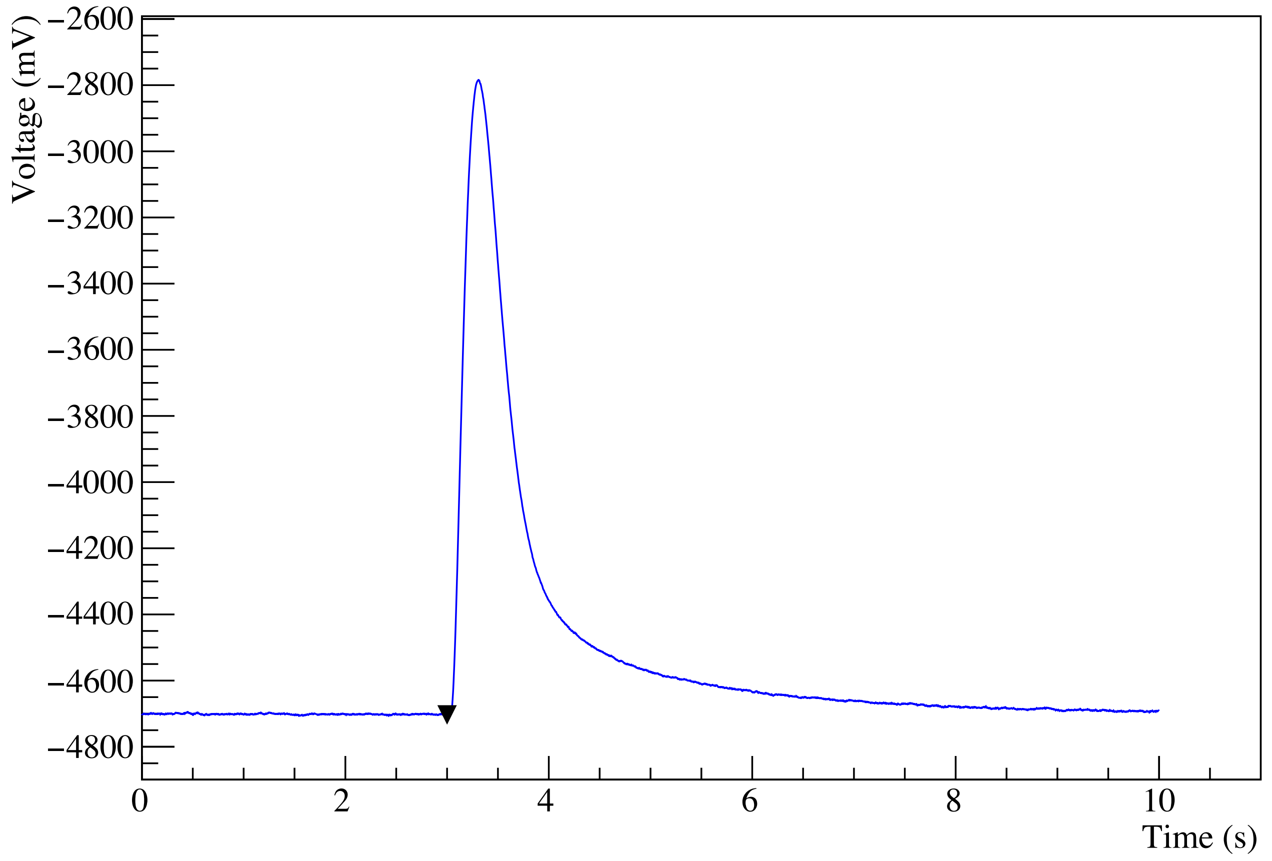
- A sample of clean noise waveforms is used to extract each channel’s average noise
- A sample of clean particle pulses is used to compute the average response of each detector

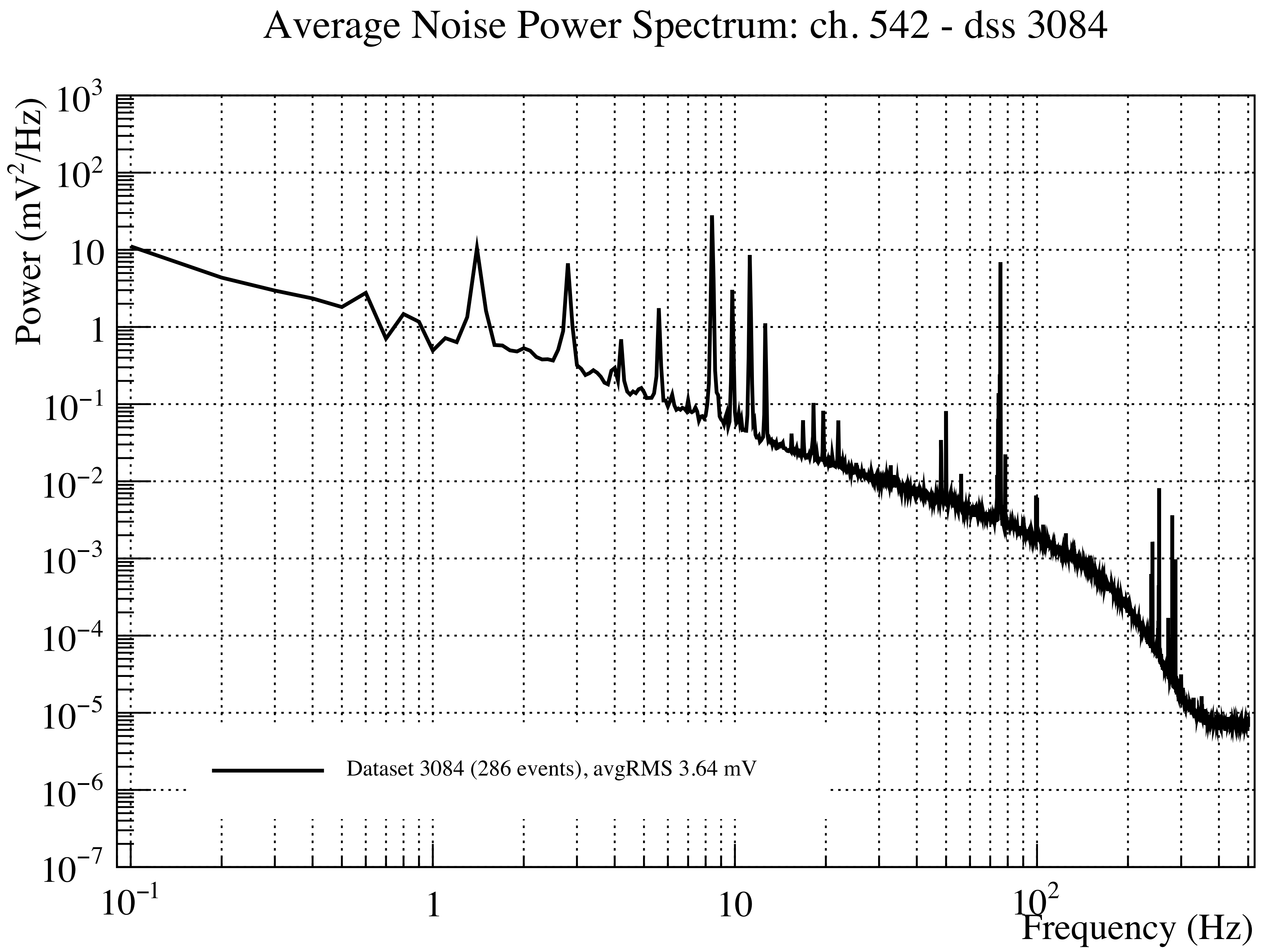
PREPROCESS

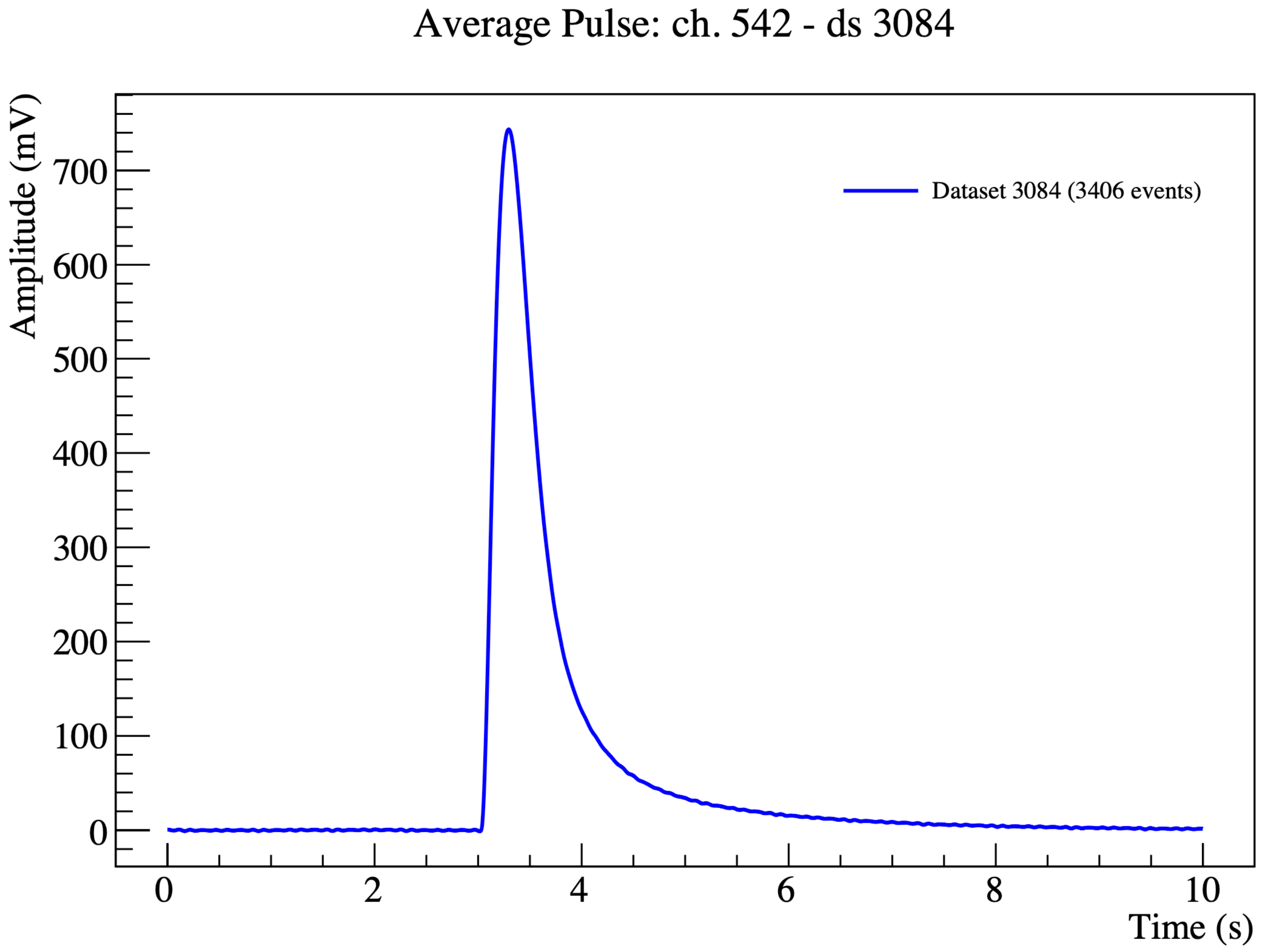
AVERAGE NOISE



AVERAGE PULSE



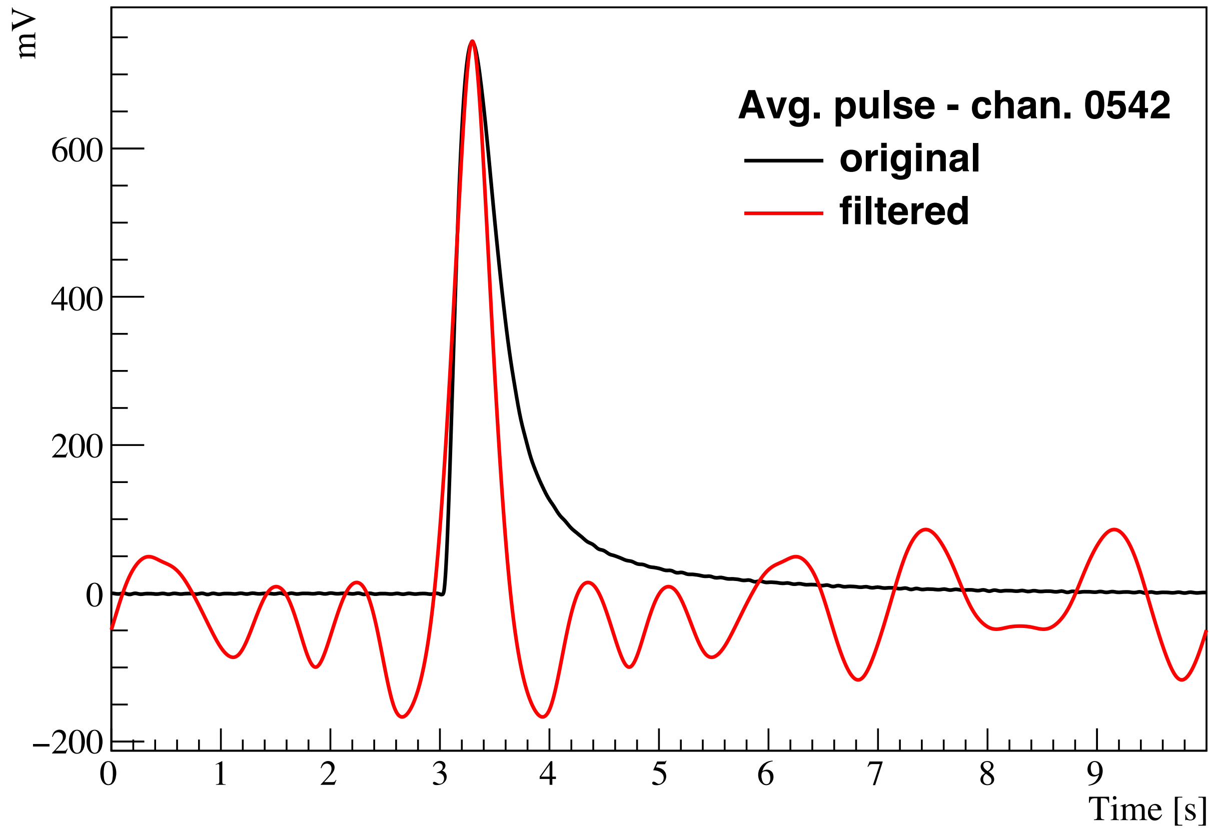




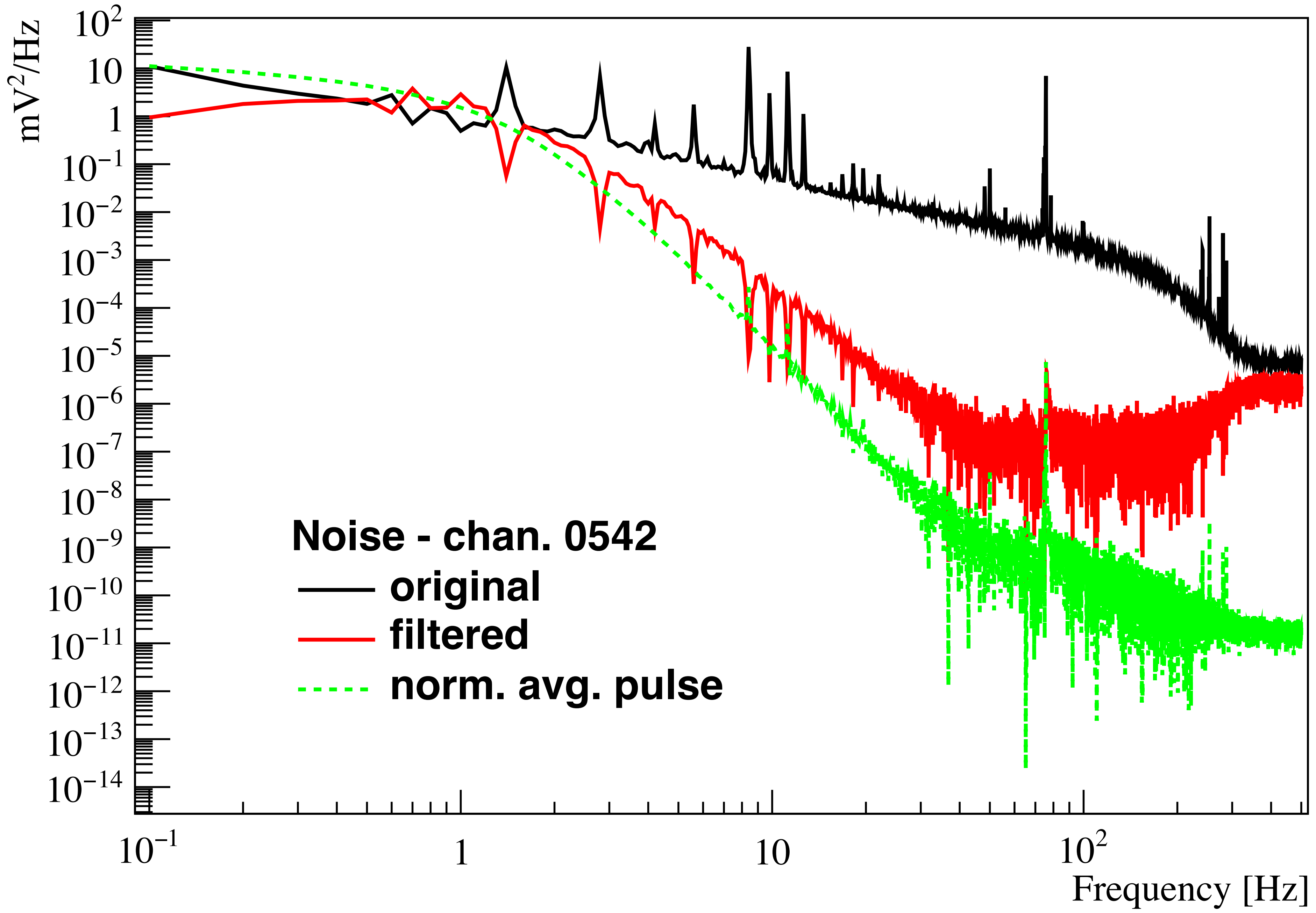
The CUORE experiment

Data processing

- PREPROCESS
- AVERAGE PULSE
- AVERAGE NOISE
- **AMPLITUDE**



- STABILIZATION
- CALIBRATION
- BLINDING
- COINCIDENCES
- PULSE SHAPE ANALYSIS

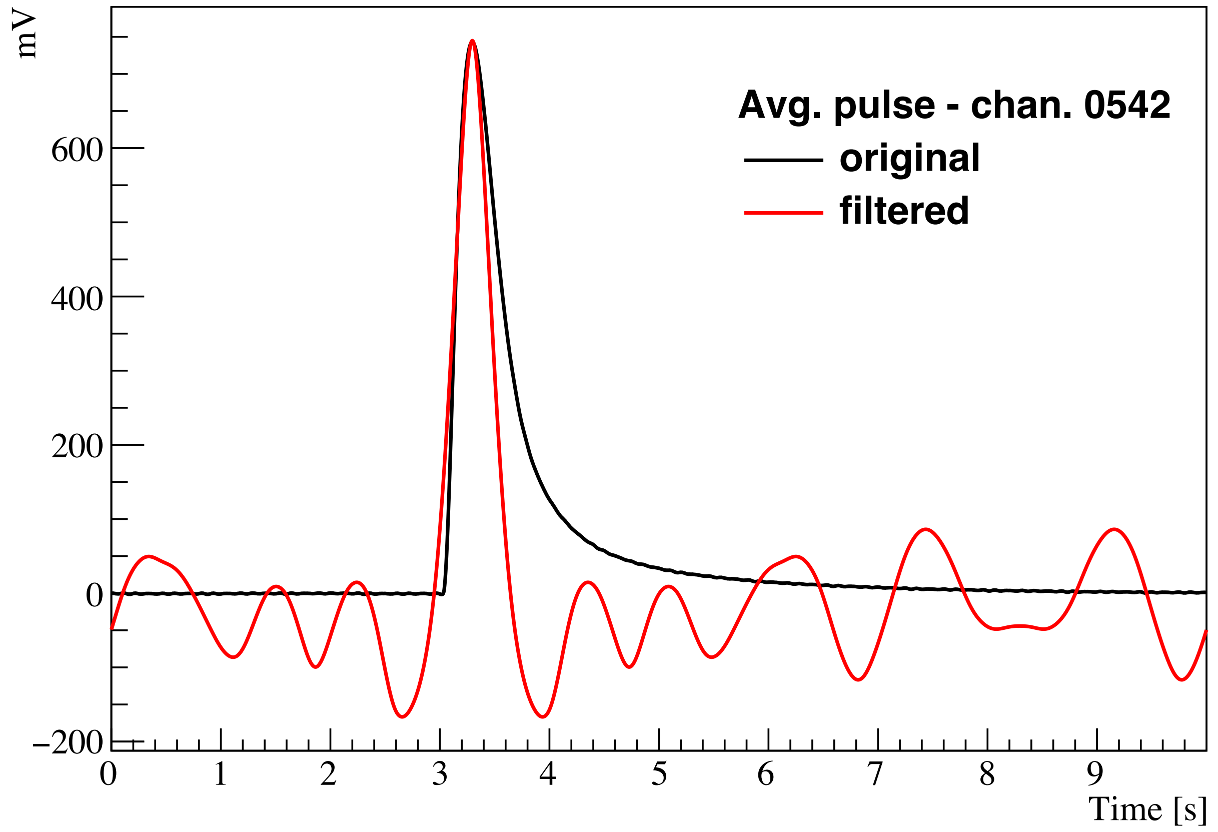


- Stationary noise assumption
- Energy independent pulse shape
- Amplitude extracted with matched filter

The CUORE experiment

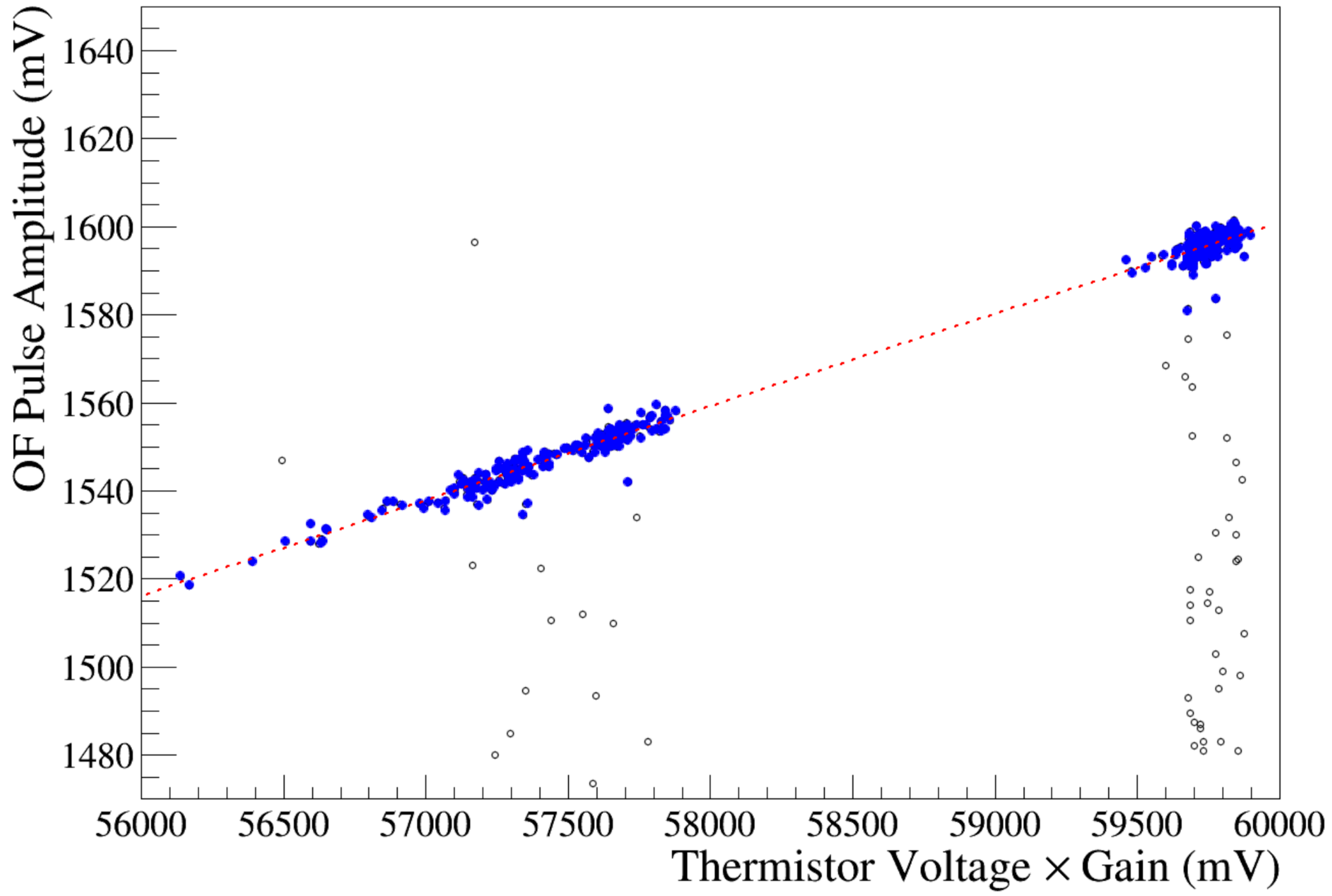
Data processing

- PREPROCESS
- AVERAGE PULSE
- AVERAGE NOISE
- AMPLITUDE
- STABILIZATION



- CALIBRATION
- BLINDING
- COINCIDENCES
- PULSE SHAPE ANALYSIS

[C. Alduino *et al.*, Phys. Rev. C 93, 045503 (2016)]

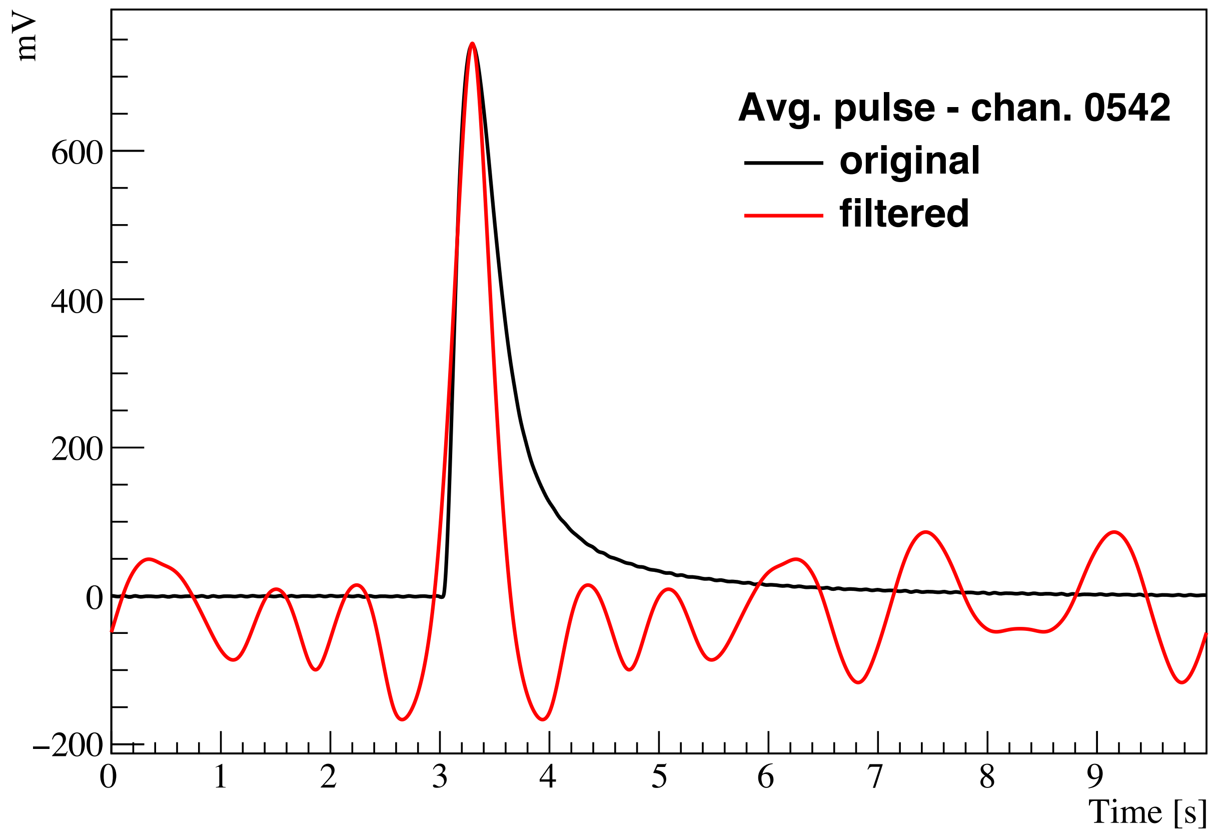


- Fixed amounts of energy periodically injected via heater pulses
- High-statistics 2615 keV line from calibration data
- Temperature fluctuations produce small variations in the heat capacity of the CUORE bolometers (thermal gain)
- A linear correction is applied

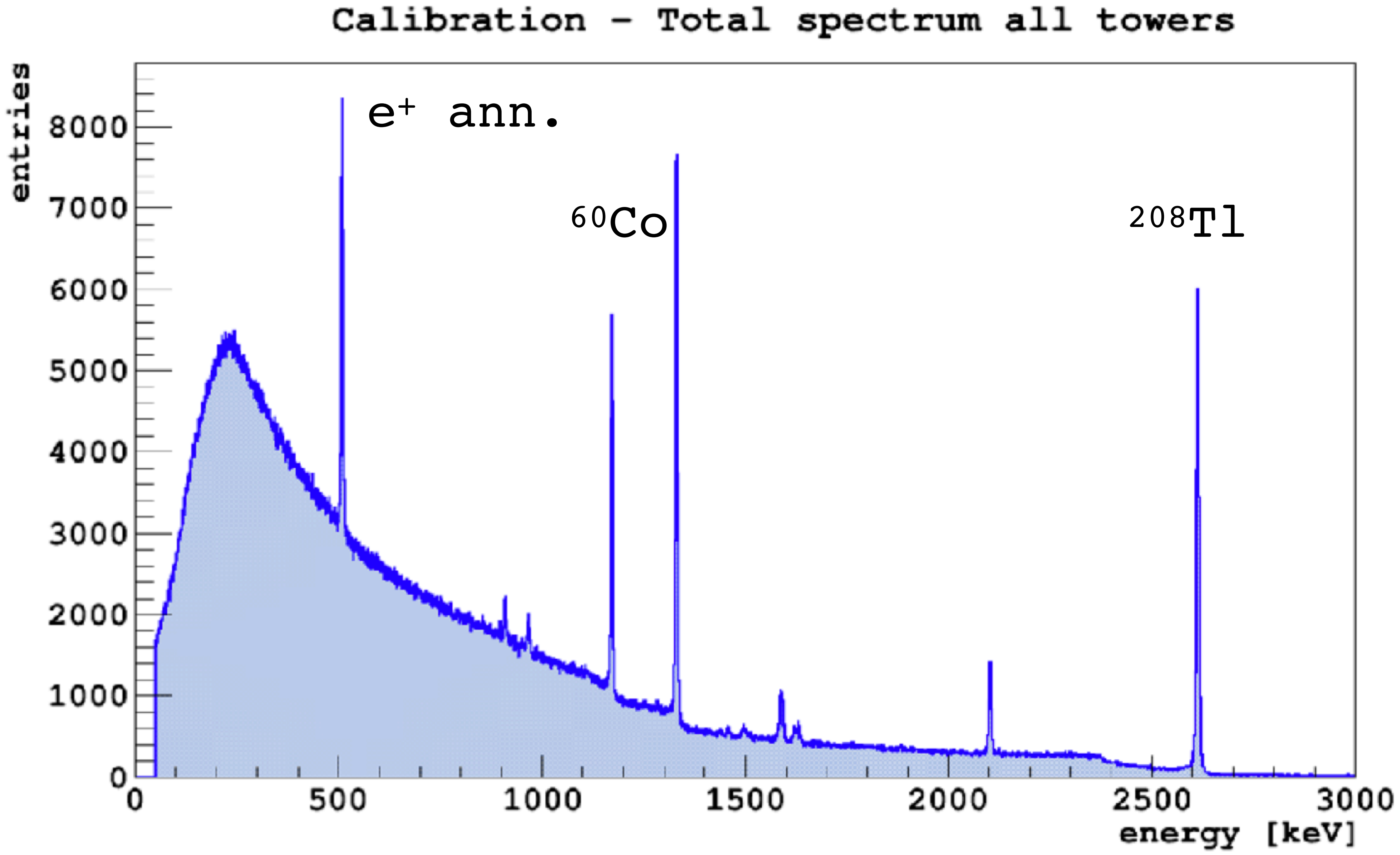
The CUORE experiment

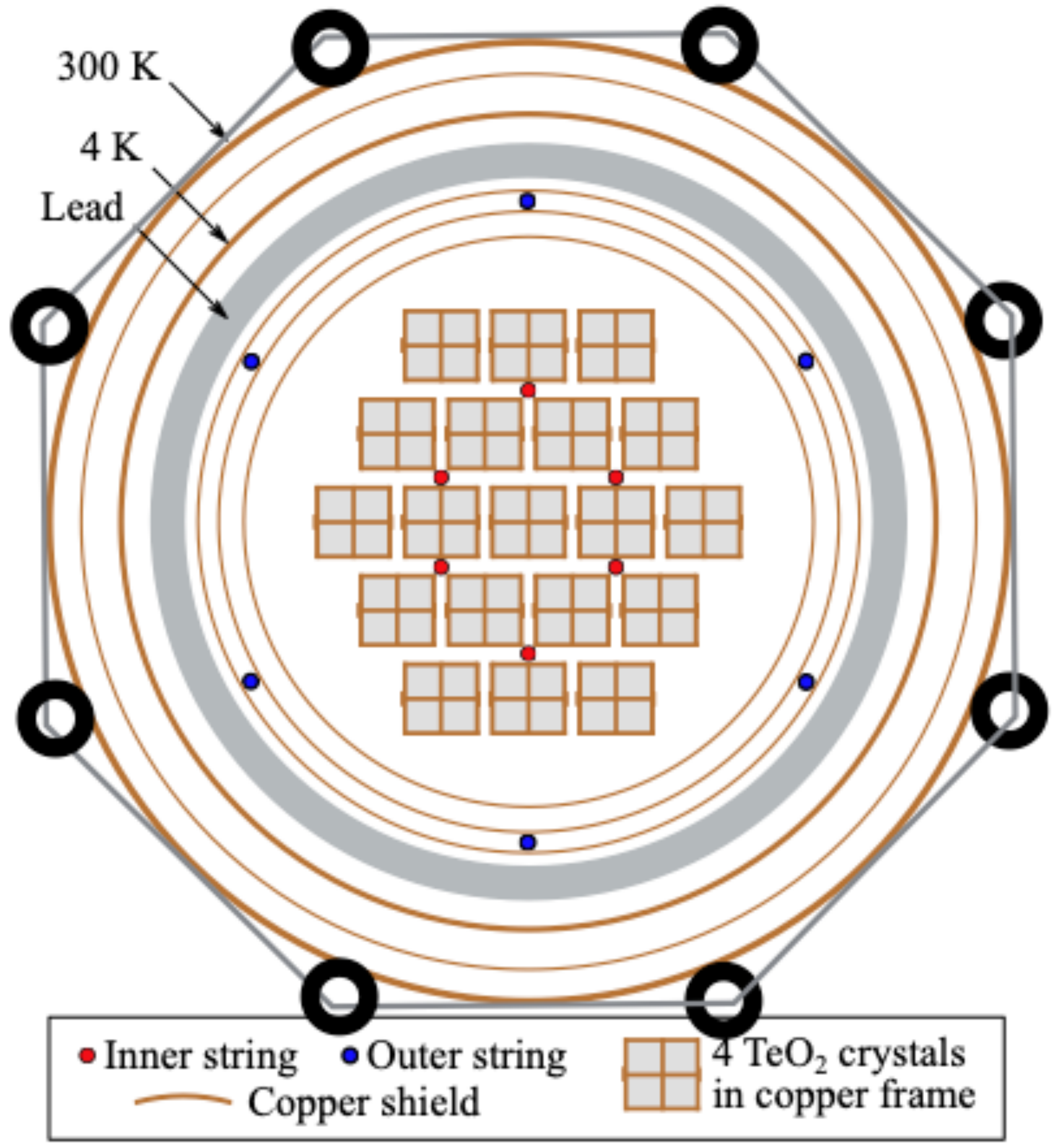
Data processing

- PREPROCESS
- AVERAGE PULSE
- AVERAGE NOISE
- AMPLITUDE
- STABILIZATION
- CALIBRATION



- BLINDING
- COINCIDENCES
- PULSE SHAPE ANALYSIS



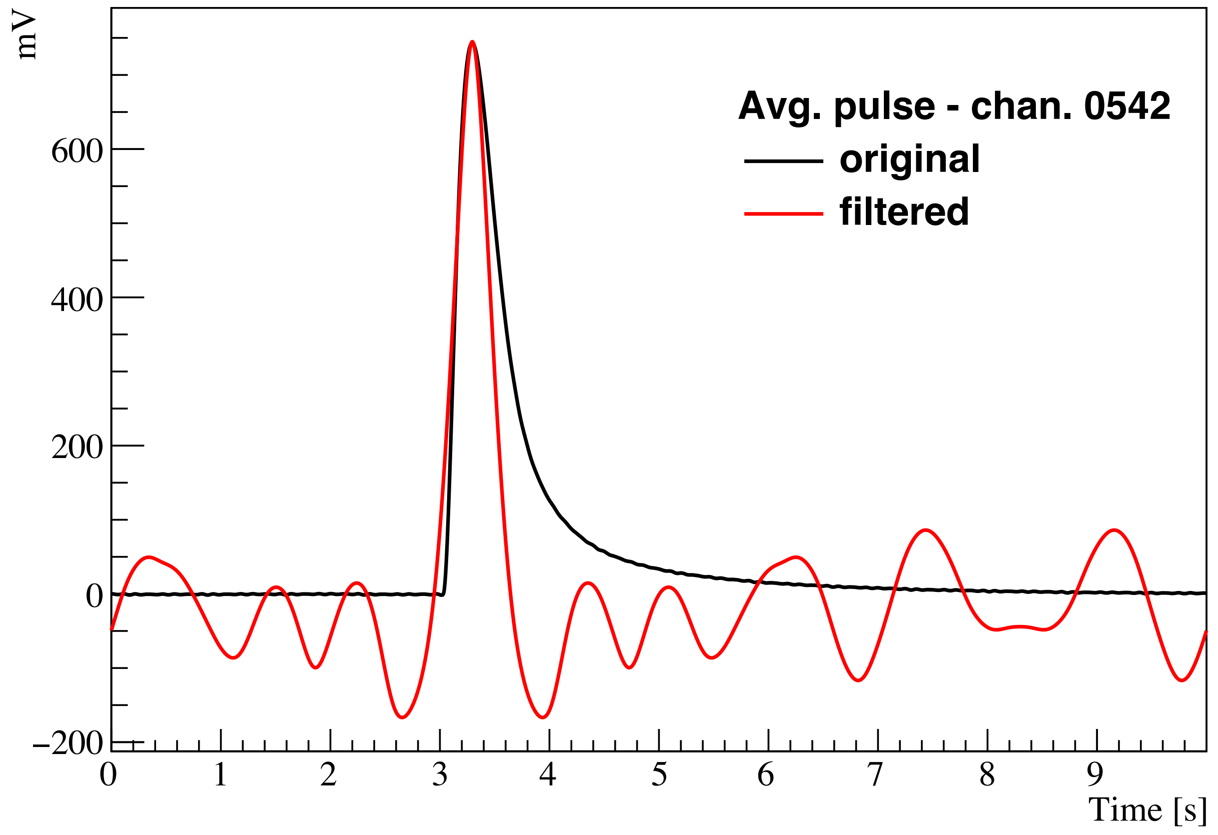


- 8 room temperature calibration strings
- $^{232}Th + ^{60}Co$ sources
- 2nd order polynomial calibration function

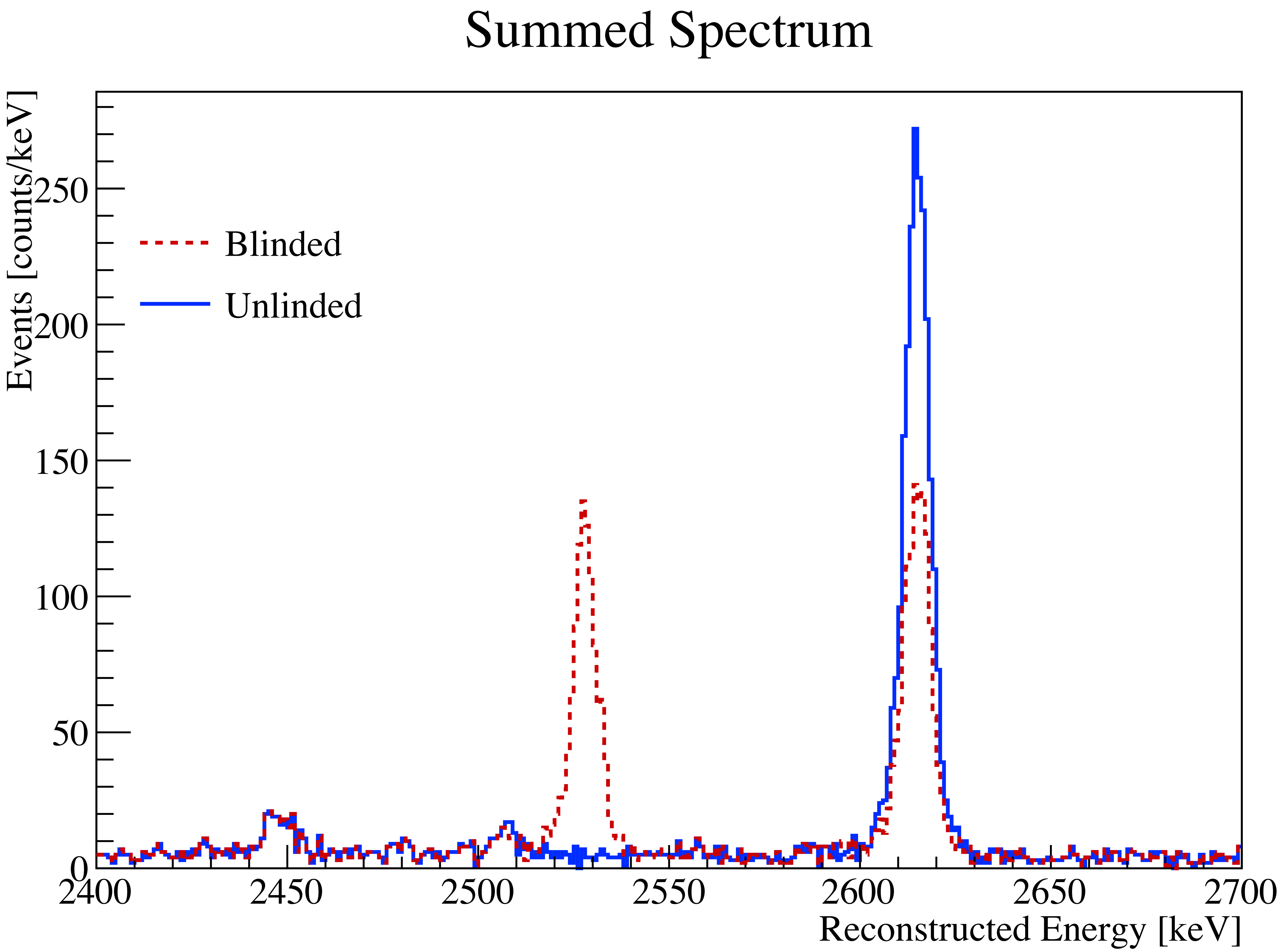
The CUORE experiment

Data processing

- PREPROCESS
- AVERAGE PULSE
- AVERAGE NOISE
- AMPLITUDE
- STABILIZATION
- CALIBRATION
- BLINDING



- COINCIDENCES
- PULSE SHAPE ANALYSIS

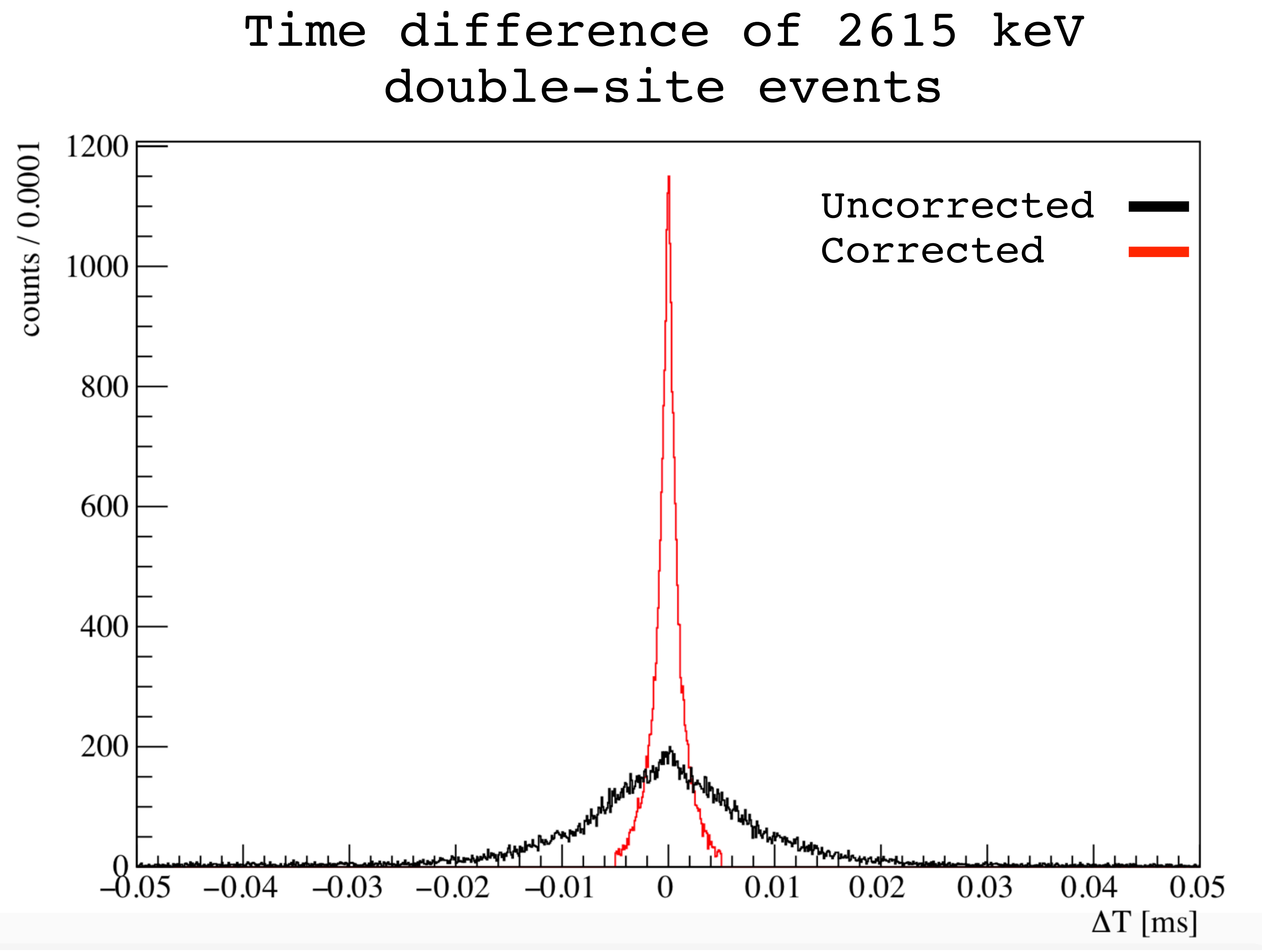


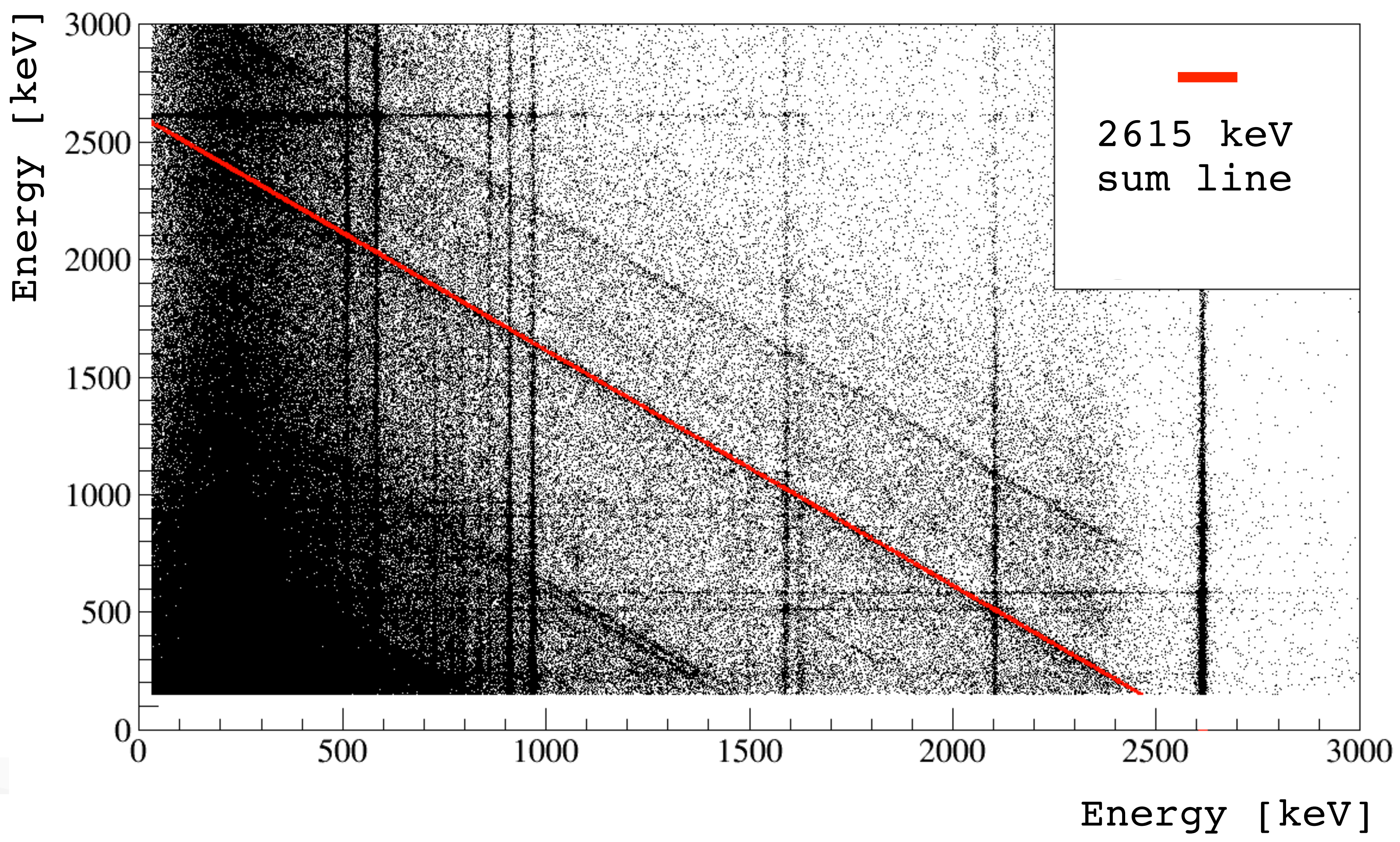
Given the seed, a random fraction of events is shifted from the 2615 keV ^{208}Tl peak to $Q_{\beta\beta}$

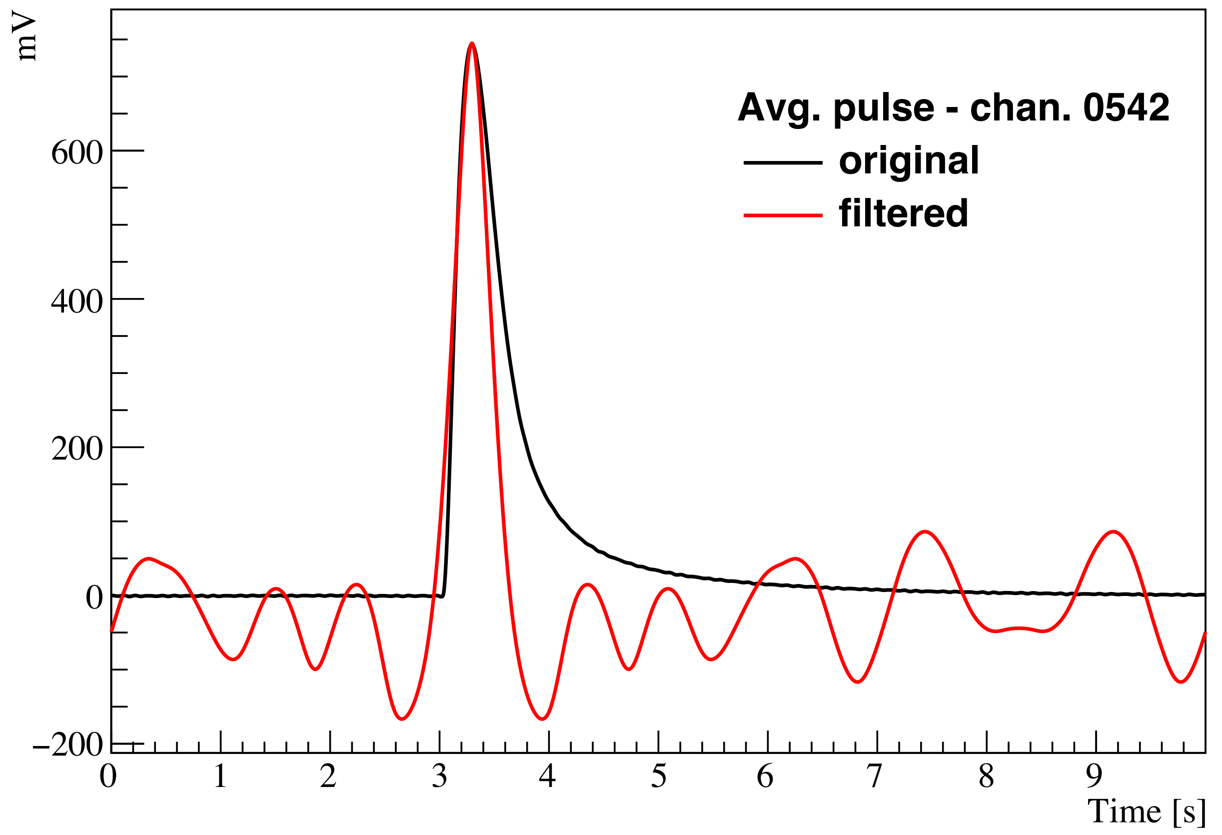
The CUORE experiment

Data processing

- PREPROCESS
- AVERAGE PULSE
- AVERAGE NOISE
- AMPLITUDE
- STABILIZATION
- CALIBRATION
- BLINDING
- COINCIDENCES







- PULSE SHAPE ANALYSIS

The event time reconstruction is affected by differences in the pulse rise time among different channels.

A by-channel correction allows to select coincident events in a time window as narrow as ± 5 ms

The CUORE experiment

Data processing

- PREPROCESS
- AVERAGE PULSE
- AVERAGE NOISE
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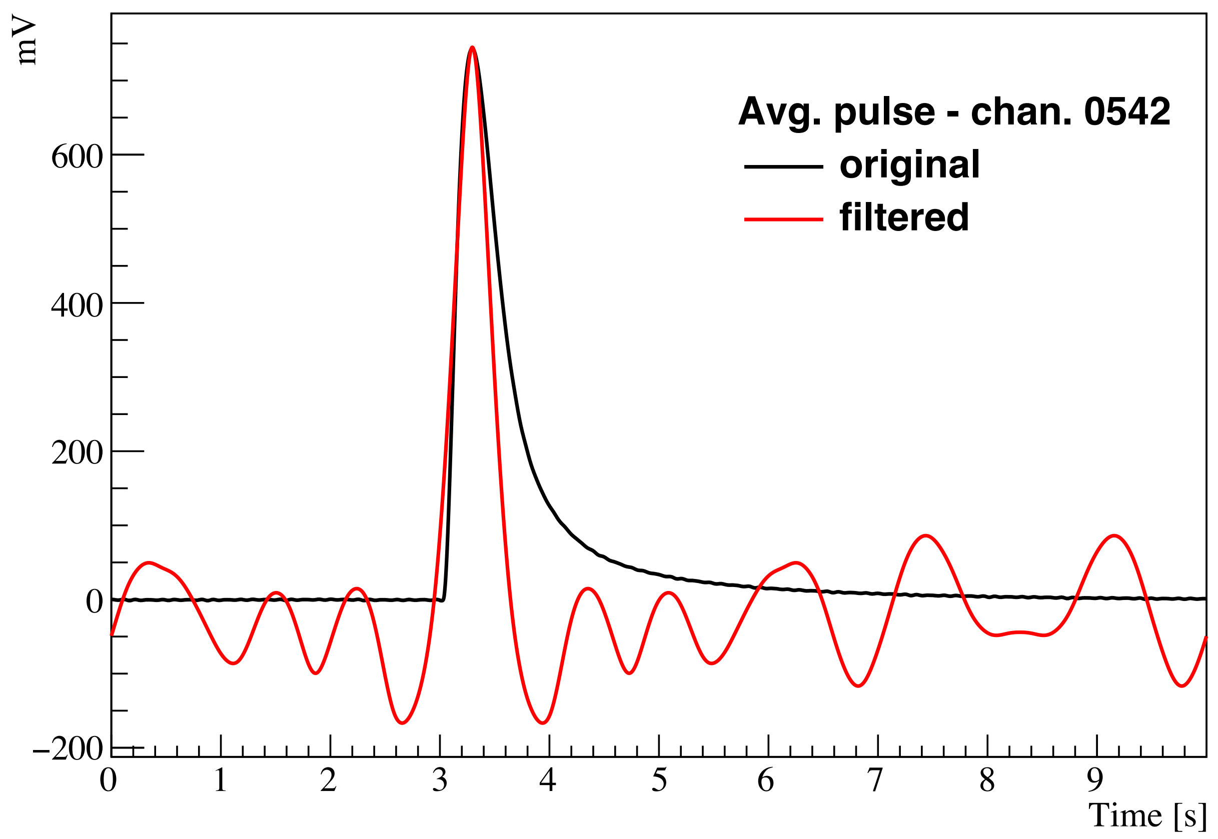
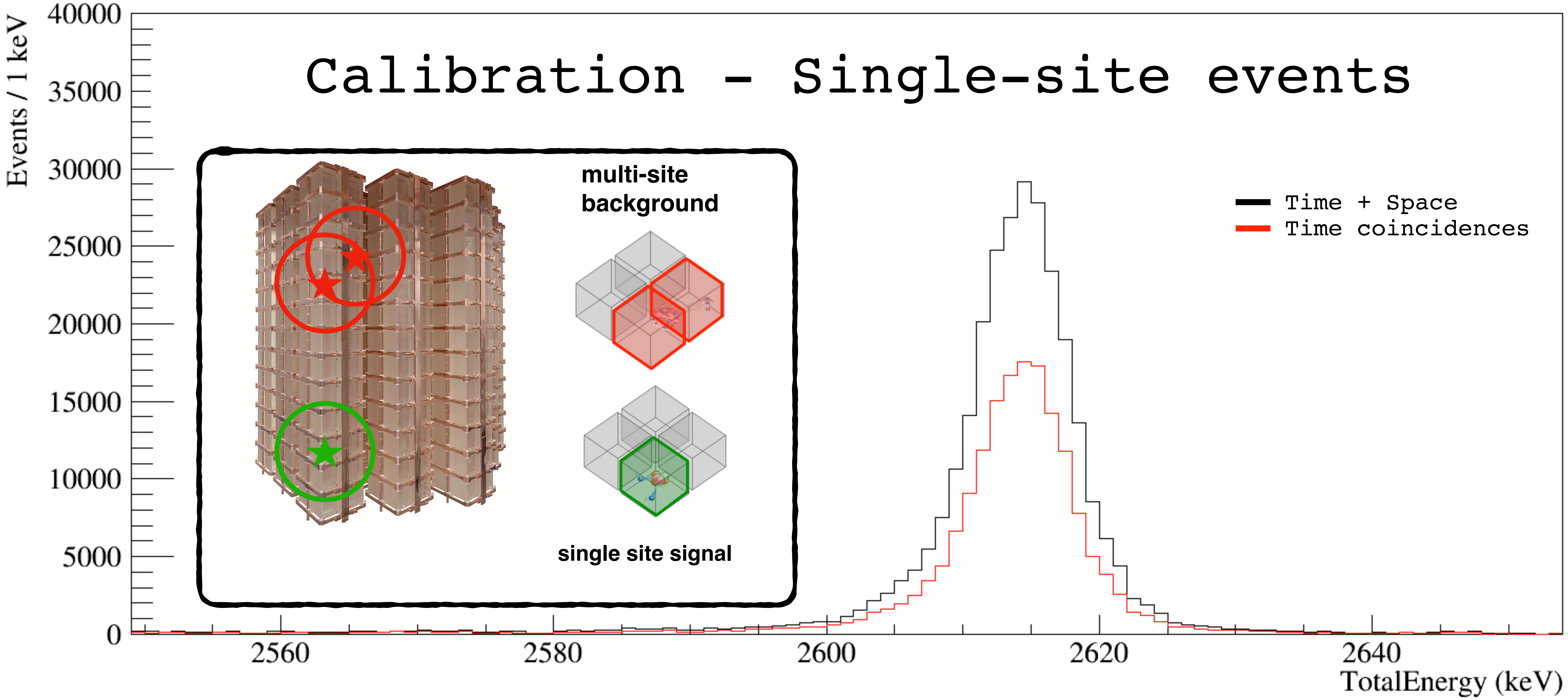
- COINCIDENCES



PULSE SHAPE ANALYSIS



A space-based definition of coincident events improves signal purity in coincident multiplets

Accidental coincidences strongly suppressed

The CUORE experiment

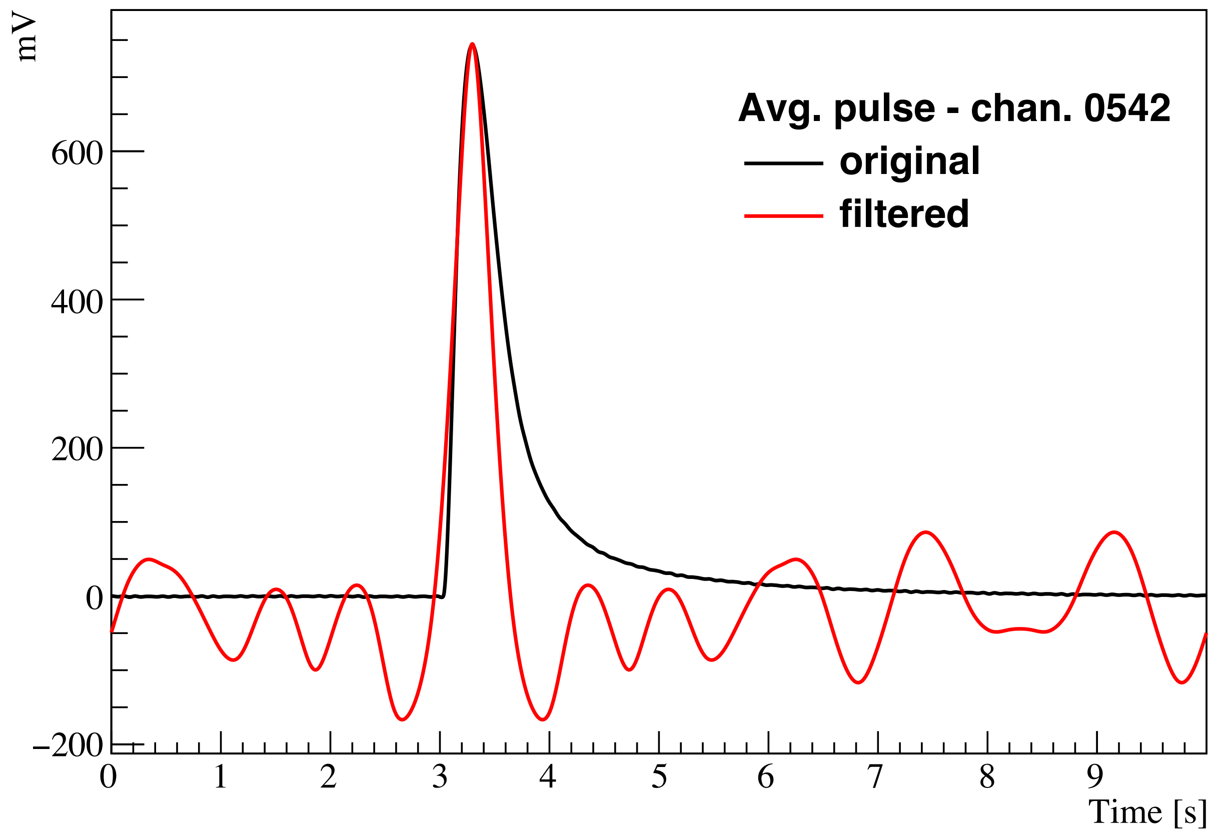
Data processing

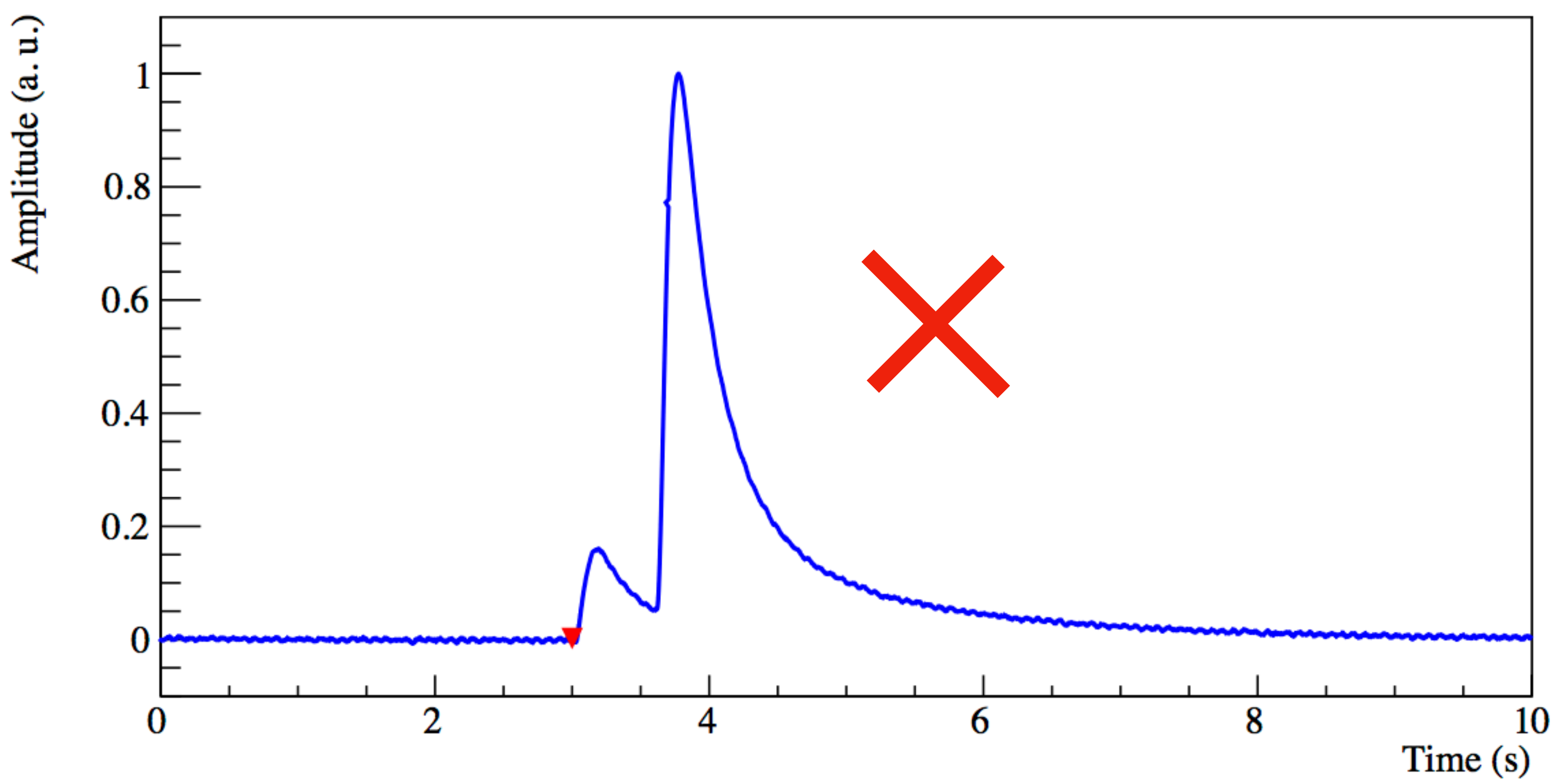
- PREPROCESS
- AVERAGE PULSE
- AVERAGE NOISE
- AMPLITUDE
- STABILIZATION
- CALIBRATION
- BLINDING
- COINCIDENCES
- **PULSE SHAPE ANALYSIS**

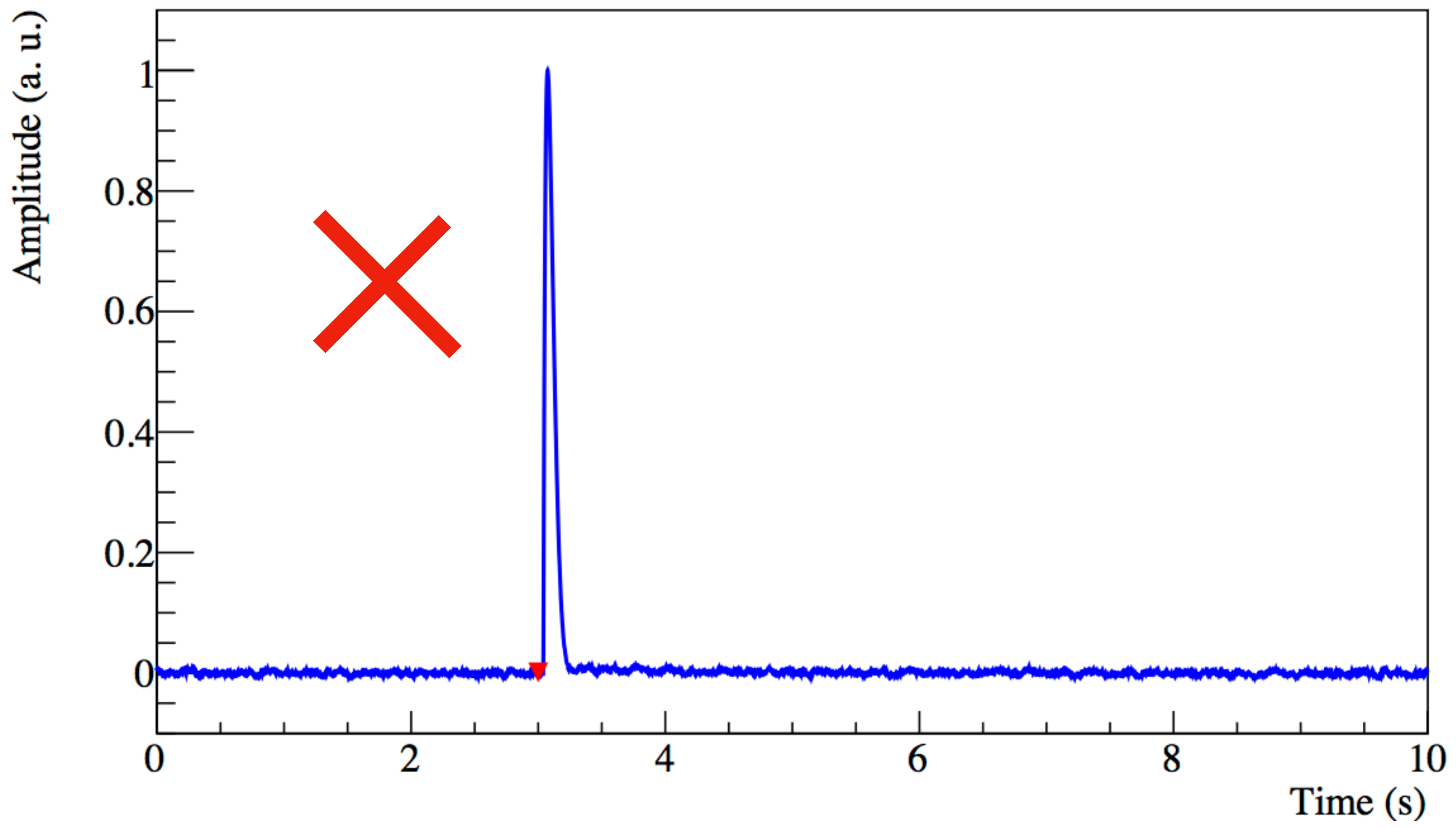
6 pulse shape parameters are computed for each event (e.g. rise time) and a 6-dim distance from a control sample is evaluated (Mahalanobis distance)

Discards pile-up events

Discards NTD particle interactions

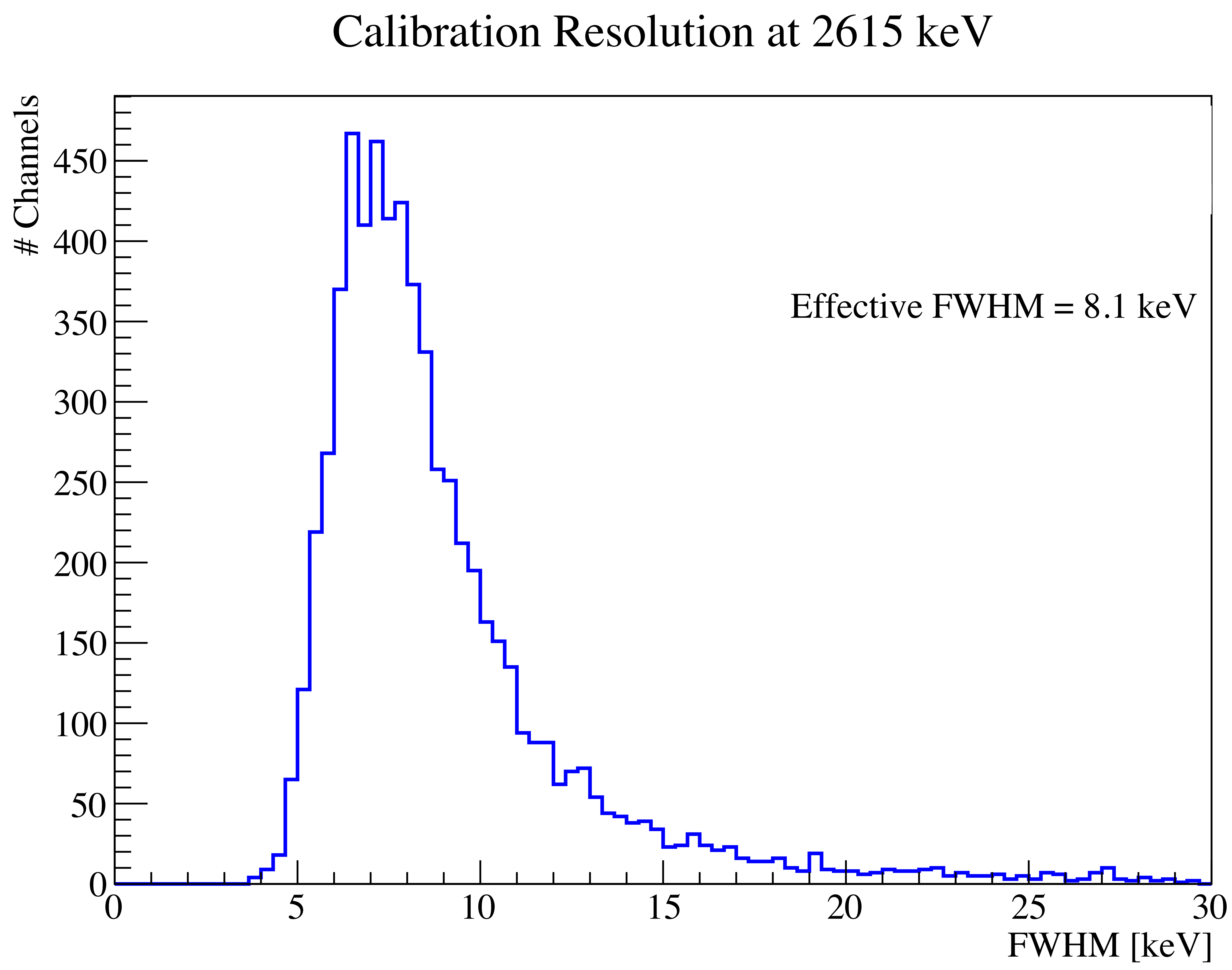






The CUORE experiment

Resolution

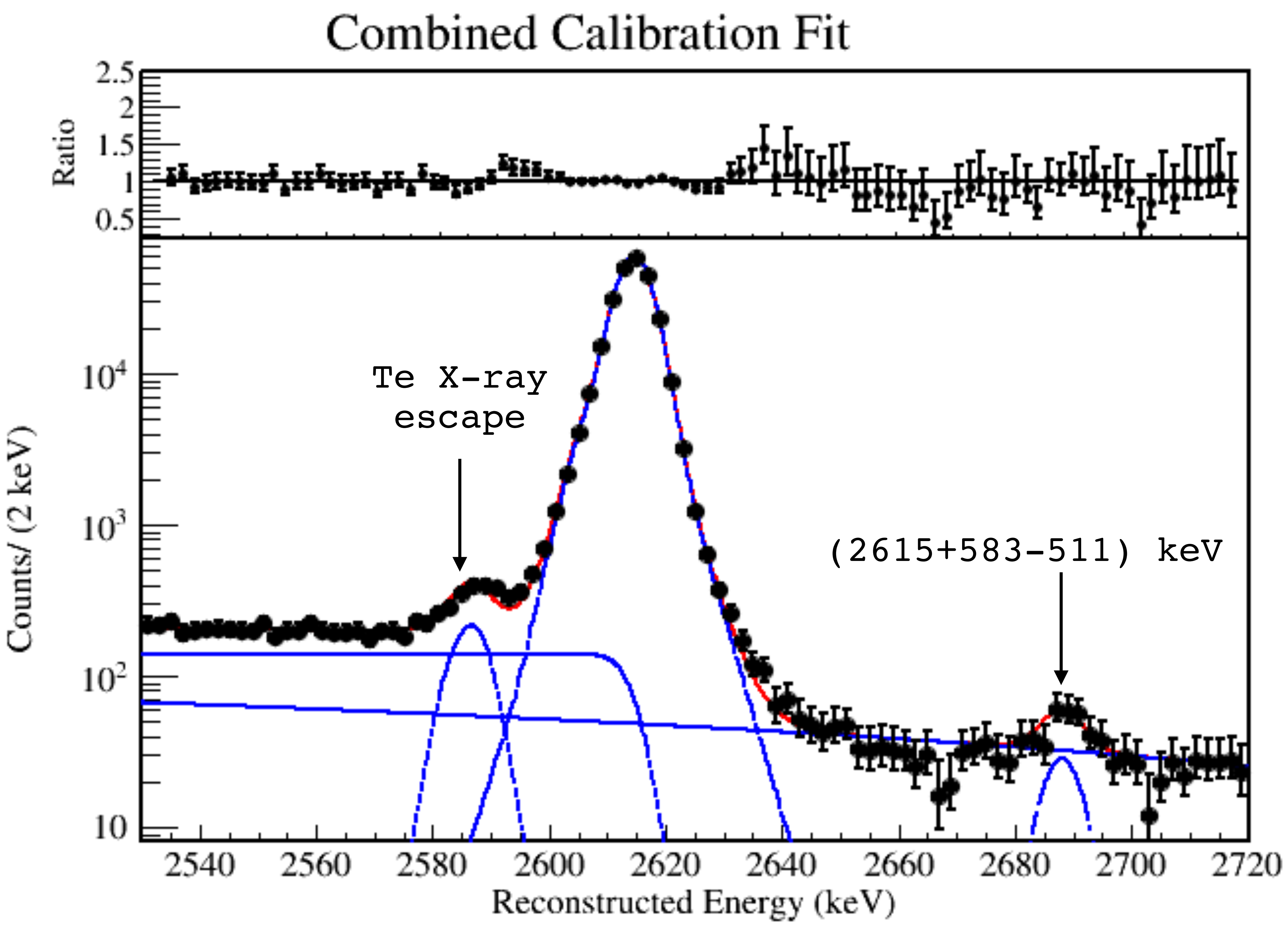


- Full Width Half Maximum (FWHM) resolution computed for each channel-dataset pair
- Exposure weighted harmonic mean effective resolution

$$\frac{1}{\Delta E} = \frac{\sum_{ch,ds} M\Delta t_{ch,ds} / \Delta E_{ch,ds}}{\sum_{ch,ds} M\Delta t_{ch,ds}}$$

The CUORE experiment

Detector response model

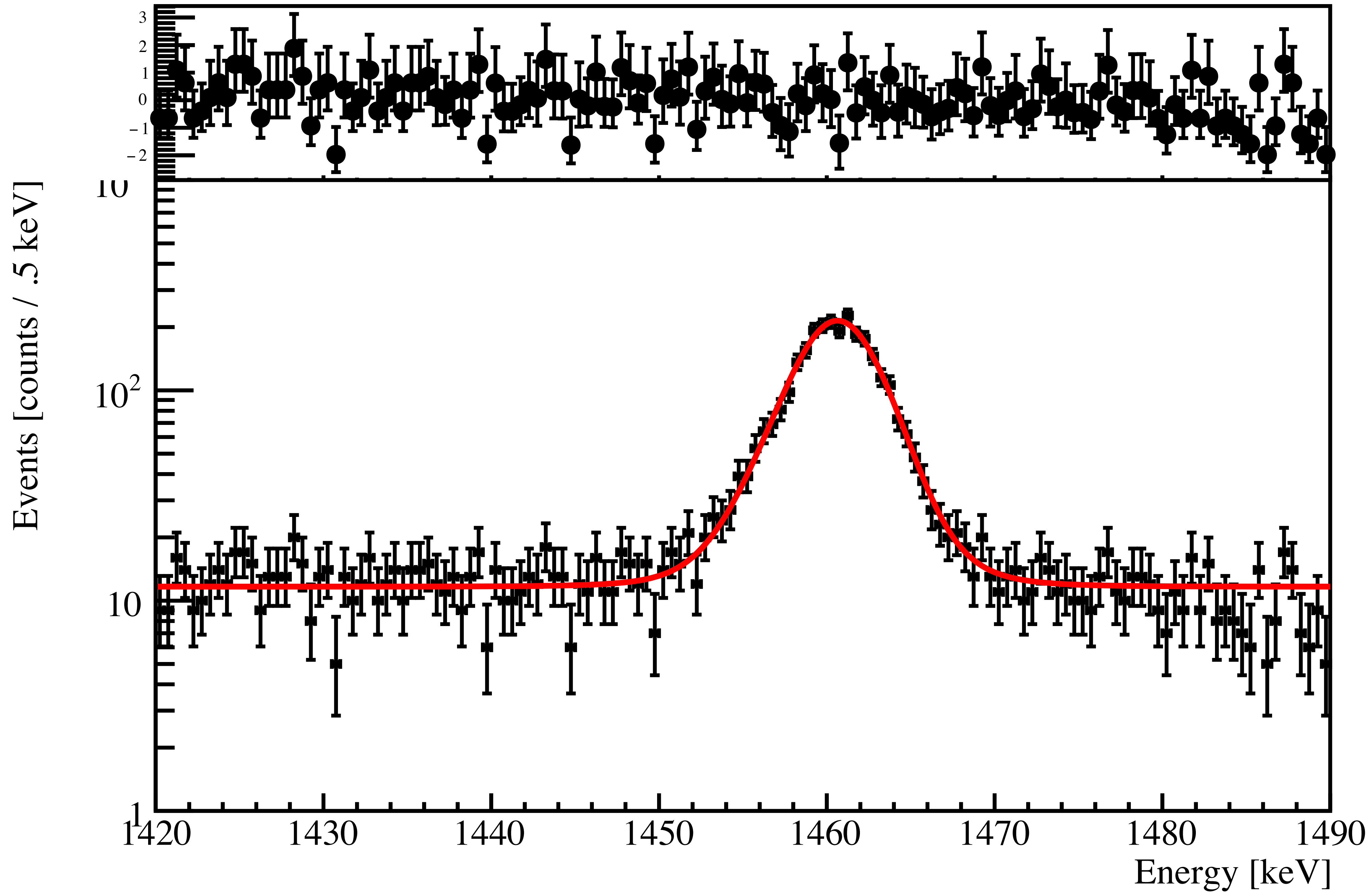


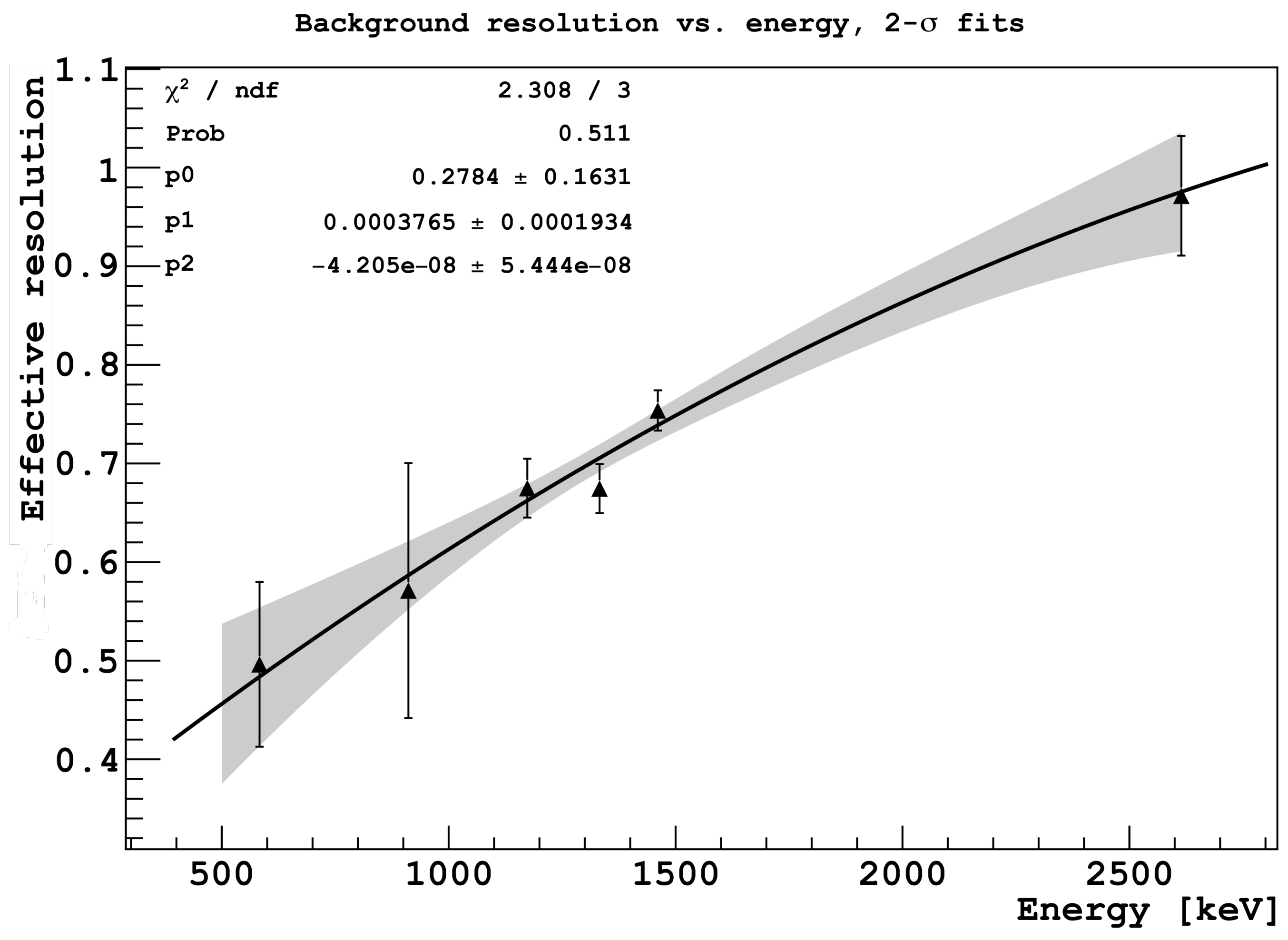
- Fit ^{208}Tl line at 2614.5 keV in calibration spectra to precisely evaluate the lineshape on a channel-dataset basis
- Main peak parameterized with a 3-Gaussian superposition
- Fit run simultaneously on each tower to constrain backgrounds and side-structures

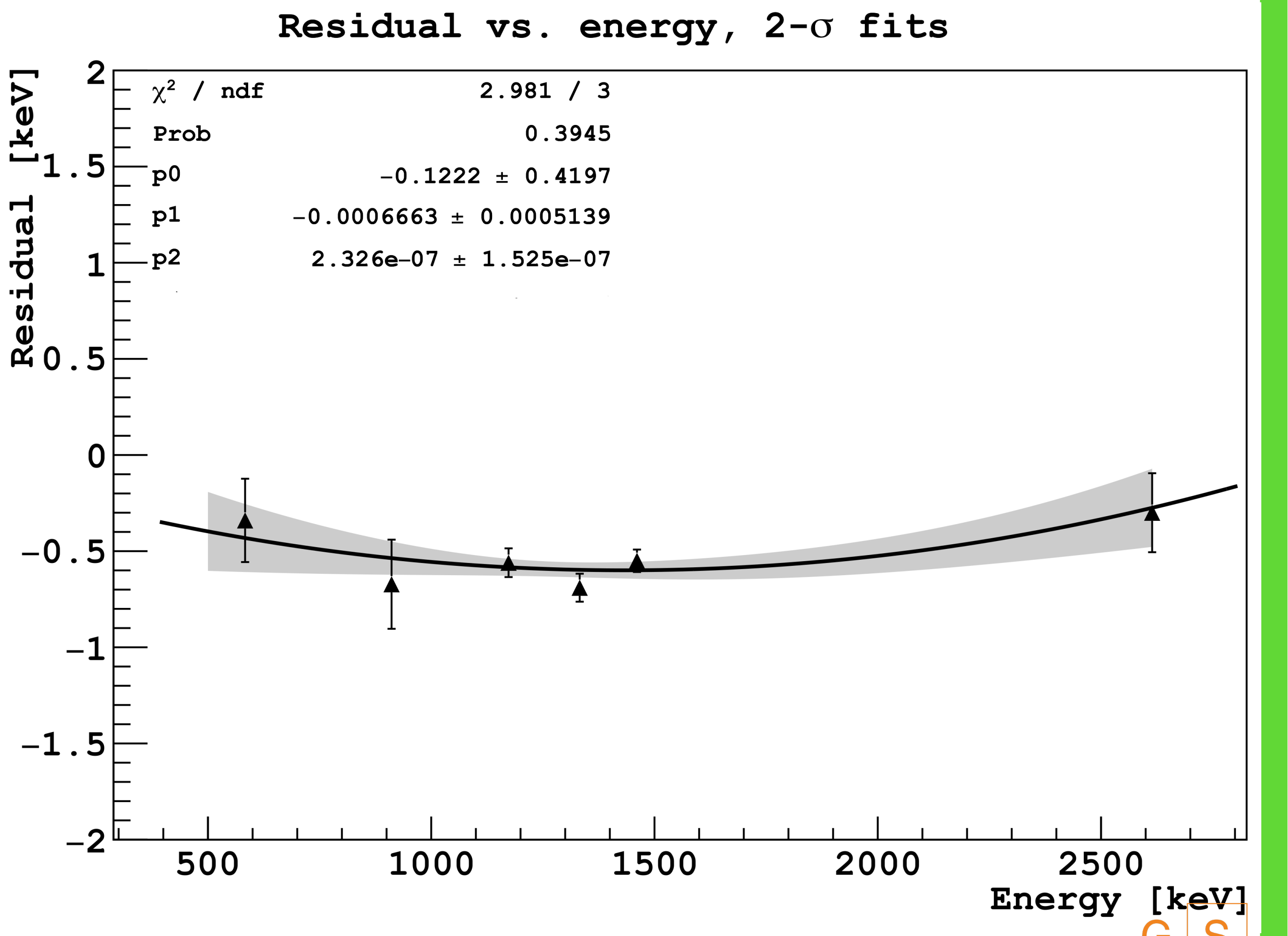
The CUORE experiment

Detector response model

- Extract FWHM from peak fit to physics data
- Fit with 2nd order polynomial and extrapolation to any energy (e.g. $Q_{\beta\beta}$)
- Compute peak position residual from literature values
- Fit with 2nd order polynomial as a function of energy
- Resolution and energy scale uncertainty (systematics)



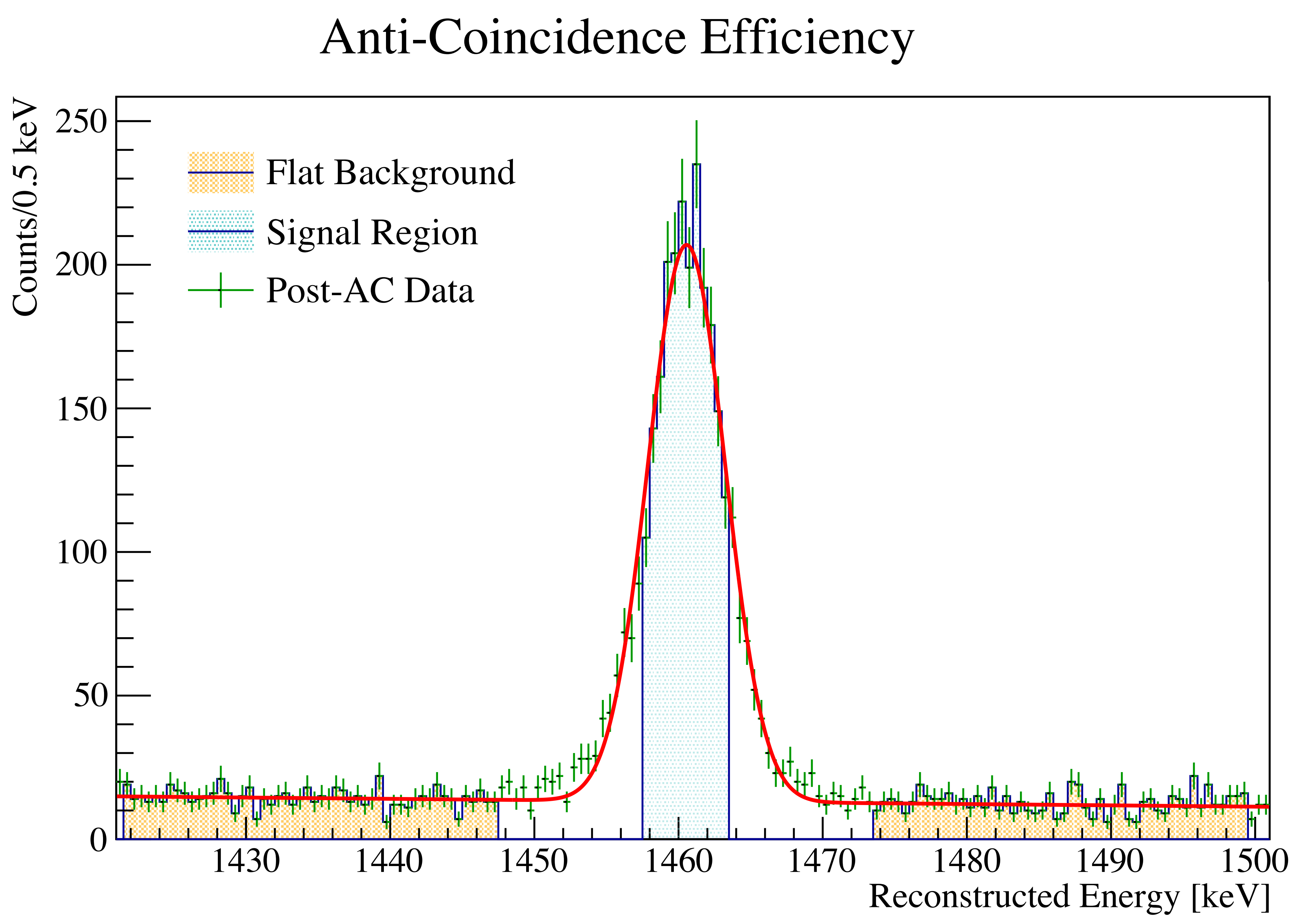


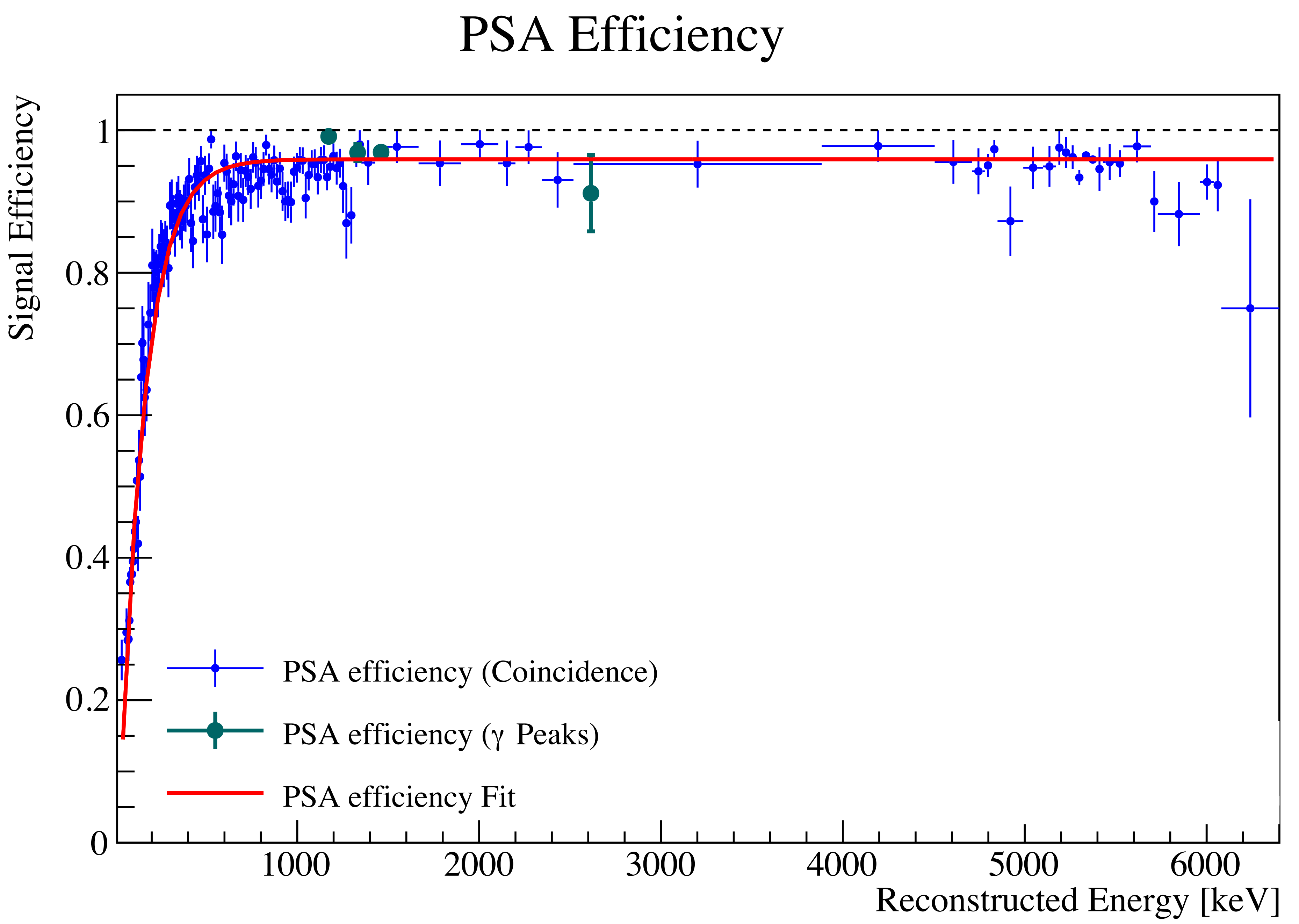


The CUORE experiment

Detector response model

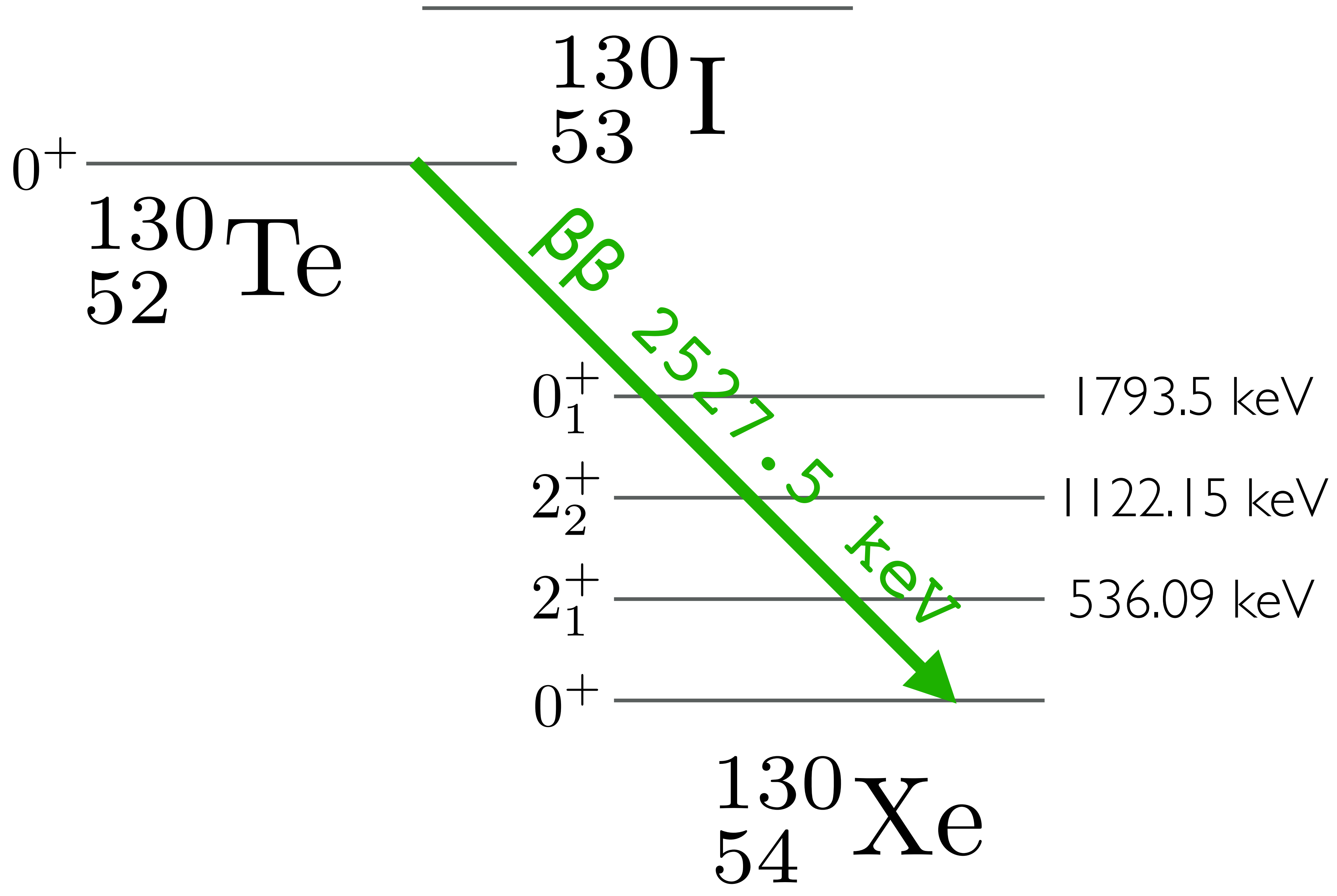
- Reconstruction efficiency includes
  - Trigger
  - Event reconstruction
  - Pile-up rejection
- Anti-coincidence efficiency quantifies the probability of correctly identifying single-site events
- Pulse Shape Analysis (PSA) Efficiency: fraction of events selected in a 6-dimensional pulse-shape parameter space





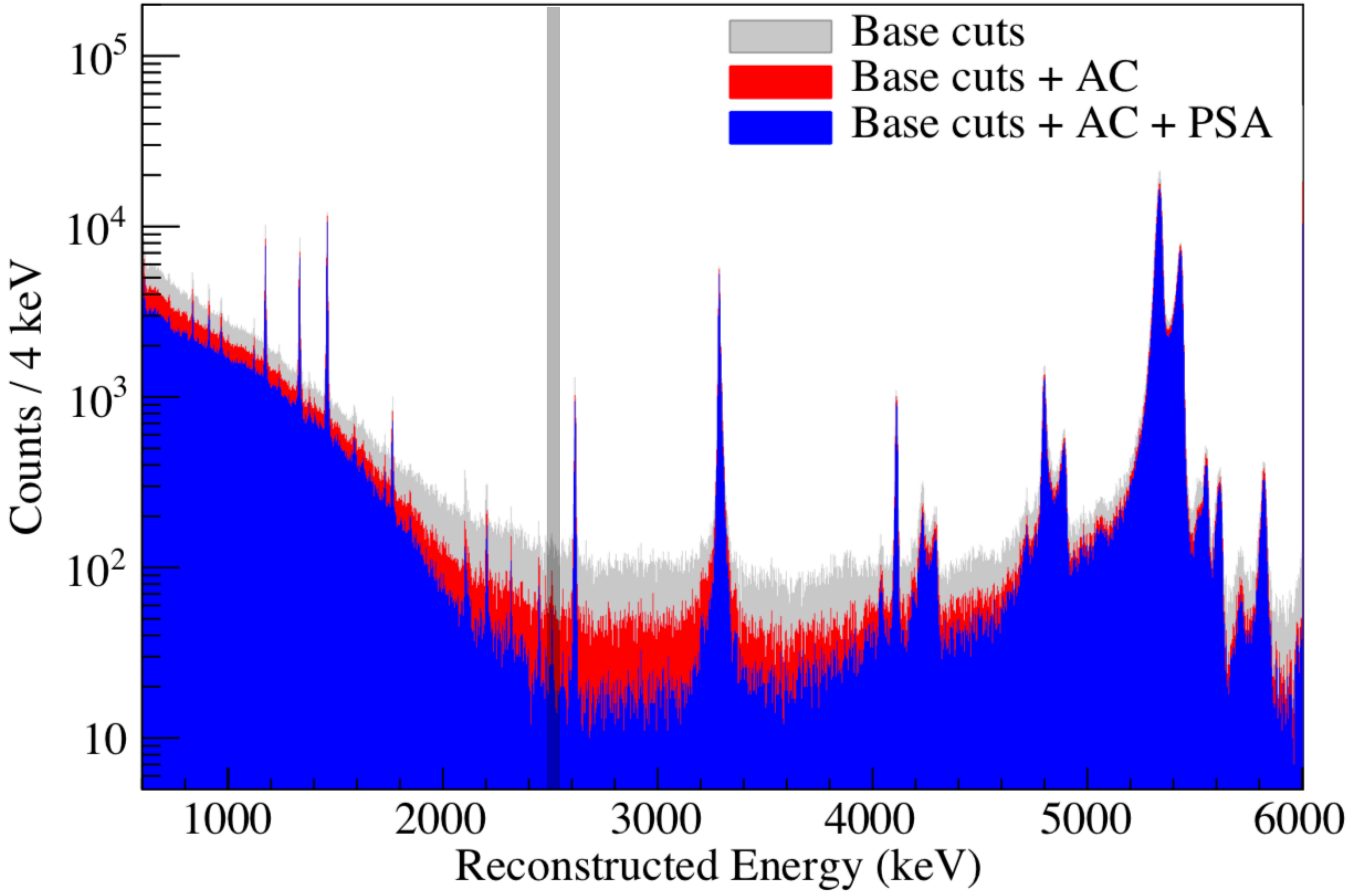
$0\nu\beta\beta$ Search
Ground State Analysis

Ground state analysis



[B. Singh, Nuclear Data Sheets 93, 33 (2001)]

[C. Alduino et al., Phys. Rev. Lett. 124, 12 122501 (2020)]

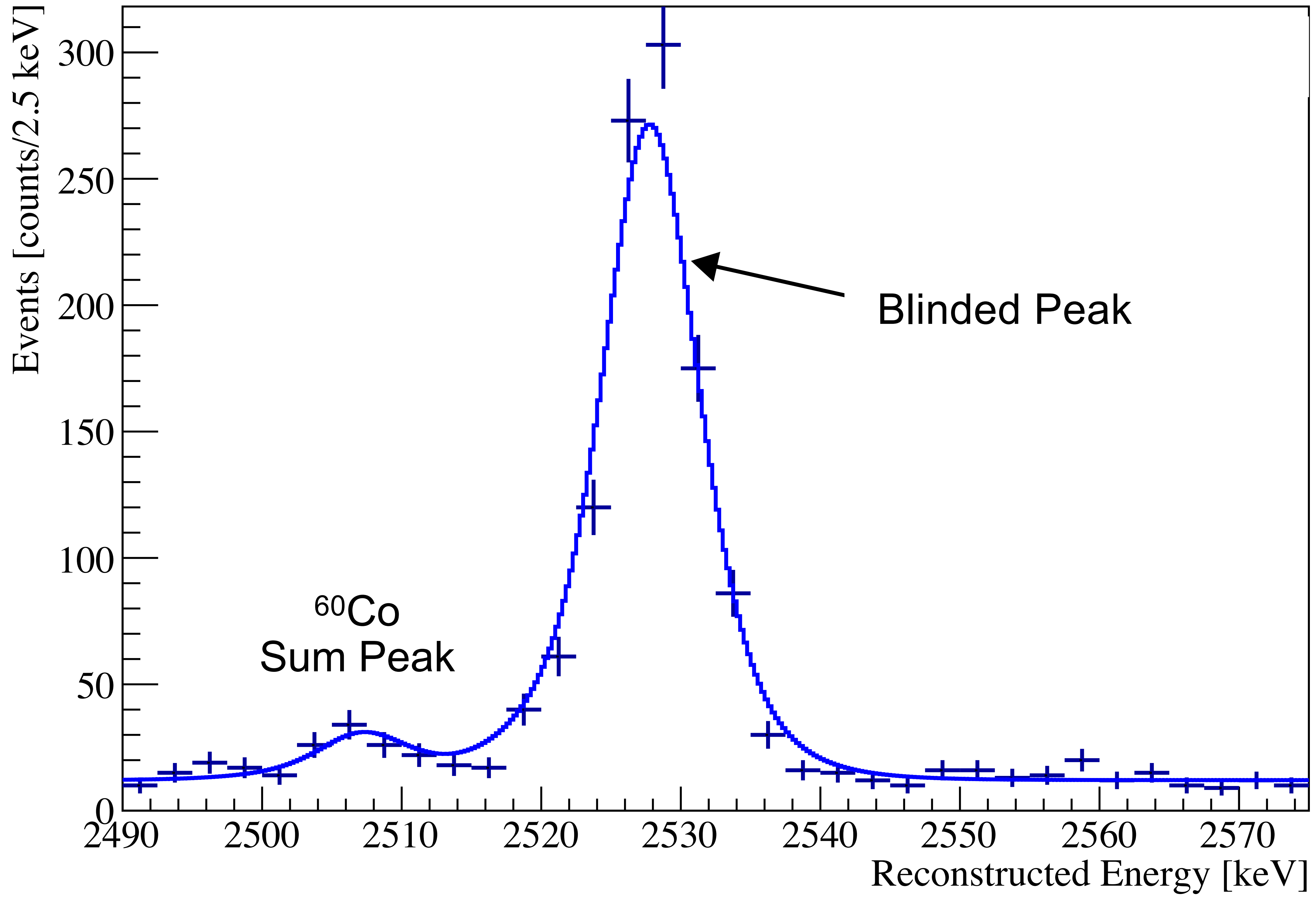


Signal events mostly single-site $\epsilon = 88.3(5)\ \%$

Ground state analysis

$$P(\vec{\theta} \mid \vec{E}, H_{S+B}) = \frac{\mathscr{L}(\vec{E} \mid \vec{\theta}, H_{S+B}) \cdot \pi(\vec{\theta} \mid H_{S+B})}{\int_\Omega \mathscr{L} \pi \, d\vec{\theta}}$$

$$\mathscr{L}(\vec{E} \mid \vec{\theta}, H_{S+B}) = \prod_{dataset} \prod_{channel} \left[\frac{e^{-\lambda} \lambda^n}{n!} \prod_{event\ i} \left(\frac{S}{\lambda} pdf_{0\nu\beta\beta}(E_i \mid \vec{\theta}) + \frac{C}{\lambda} pdf_{^{60}Co}(E_i \mid \vec{\theta}) + \frac{b}{\lambda} \frac{1}{\Delta E} \right) \right]$$

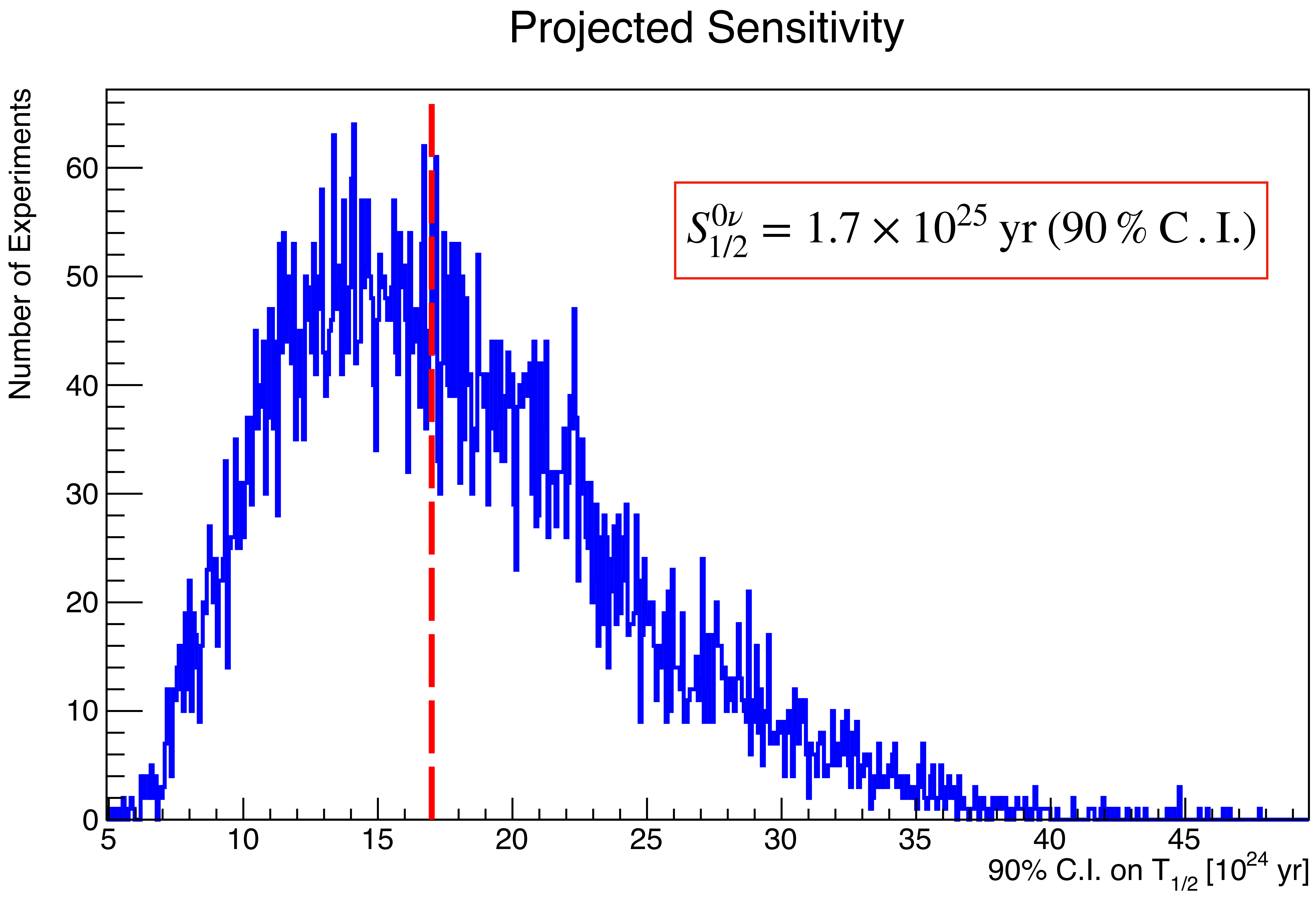


Region Of Interest (ROI)

[2490, 2575] keV

[C. Alduino et al., Phys. Rev. Lett. 124, 12 122501 (2020)]

Ground state analysis

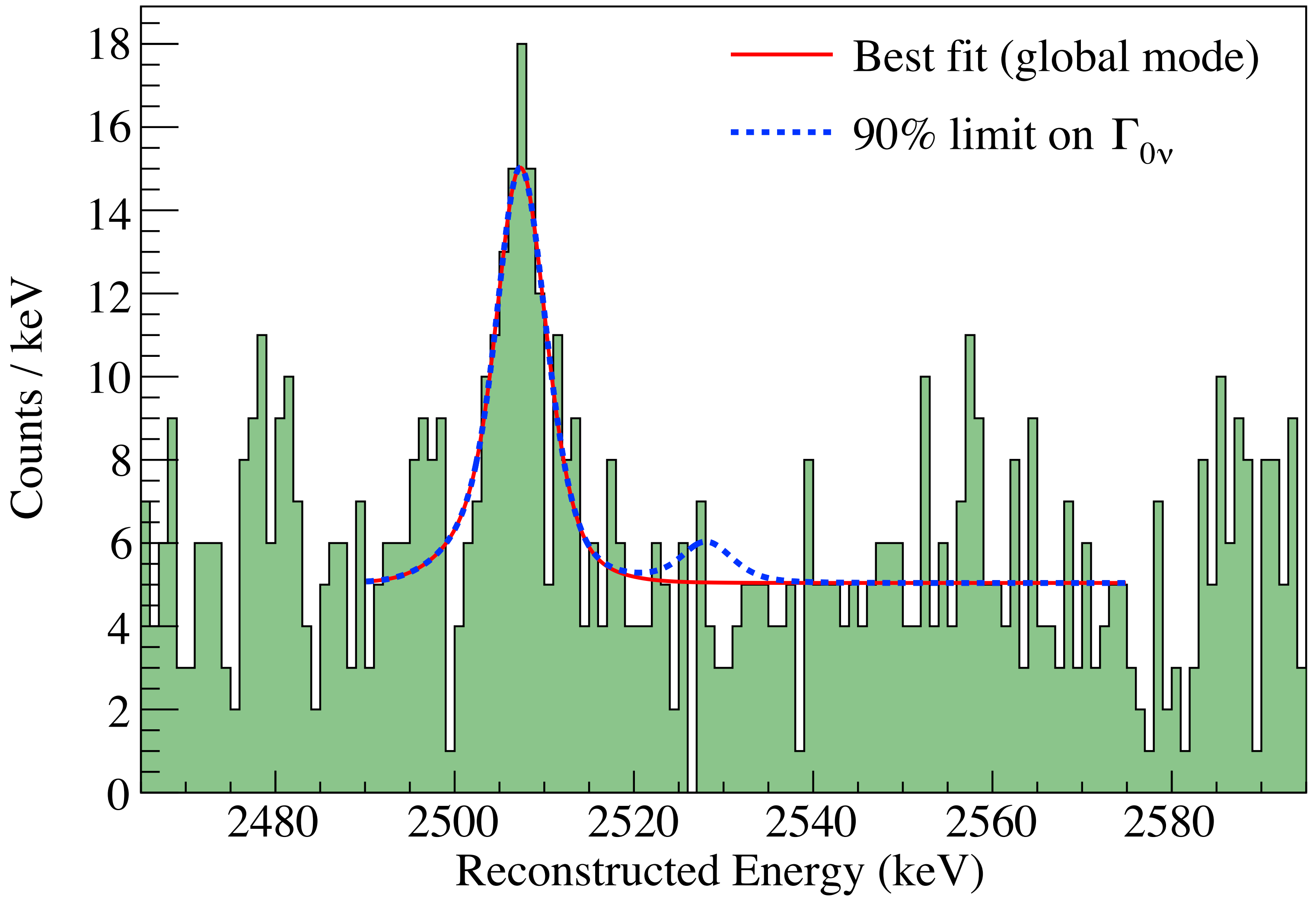


[C. Alduino et al., Phys. Rev. Lett. 124, 12 122501 (2020)]

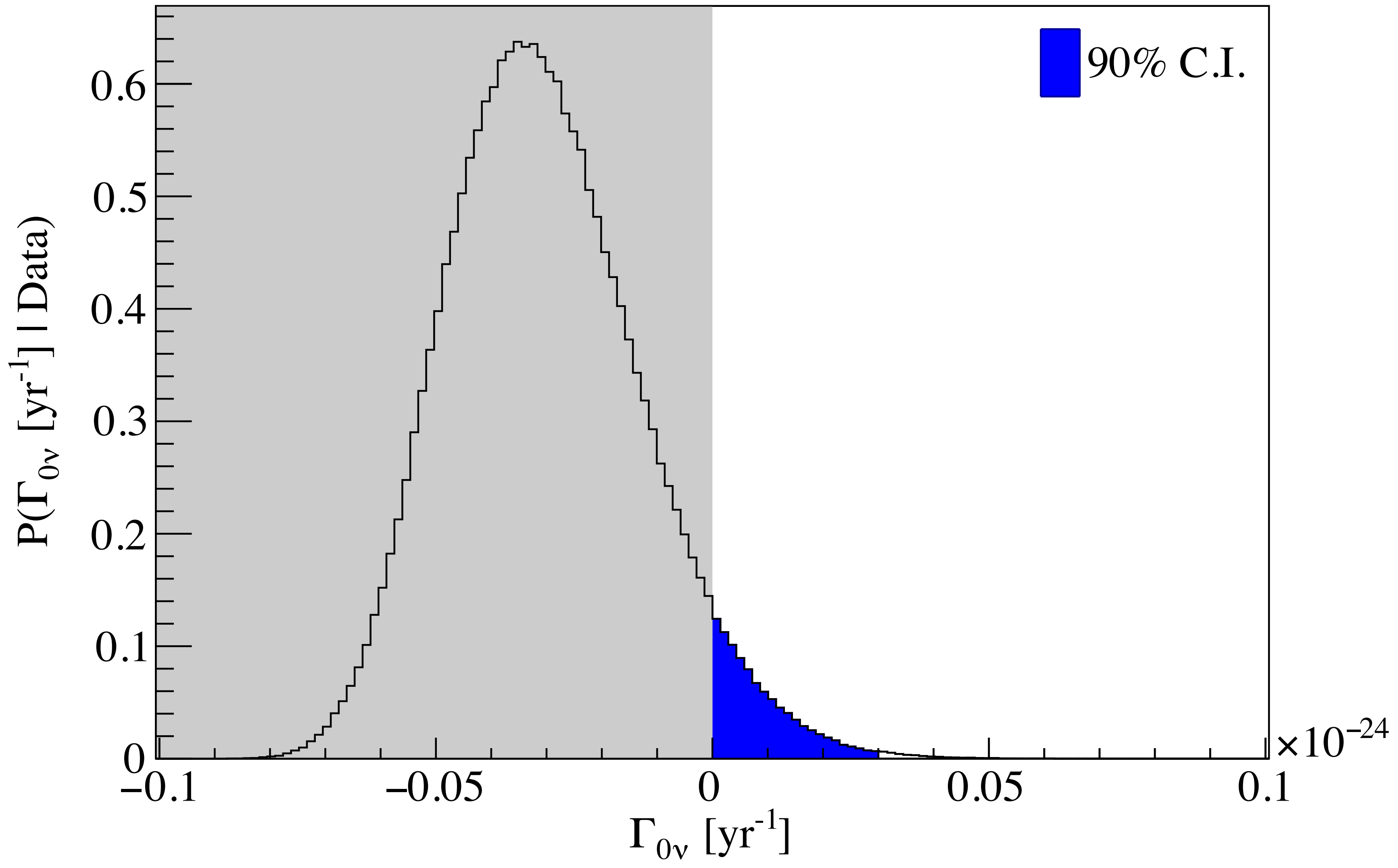
10^4 Toy Monte Carlo pseudo-experiments are generated and fit to extract the median sensitivity

Ground state analysis

CUORE ROI Spectrum



Posterior for $\Gamma_{0\nu}$



[C. Alduino et al., Phys. Rev. Lett. 124, 12 122501 (2020)]

- No evidence for 0vββ decay

$$T^{0\nu}_{1/2} > 3.2 \times 10^{25}\ \text{yr}\ (90\%\ \text{C.I.})$$

- Interpretation in context of light Majorana neutrino exchange

$$m_{\beta\beta} < 75 - 350\,\text{meV}$$

- Total exposure TeO_2: $372.5\ \text{kg} \cdot \text{yr}$
- Likelihood model: flat continuum (BI), posited peak for 0vββ (rate), peak for ^{60}Co (rate + position)
- Unbinned fit on physical range (rates non-negative), uniform prior on the rate parameter $\Gamma_{0\nu}$
- Systematics: repeat fits with nuisance parameters, allow negative rates (<0.4% impact on limit)

Detector Performance Parameters

Background Index

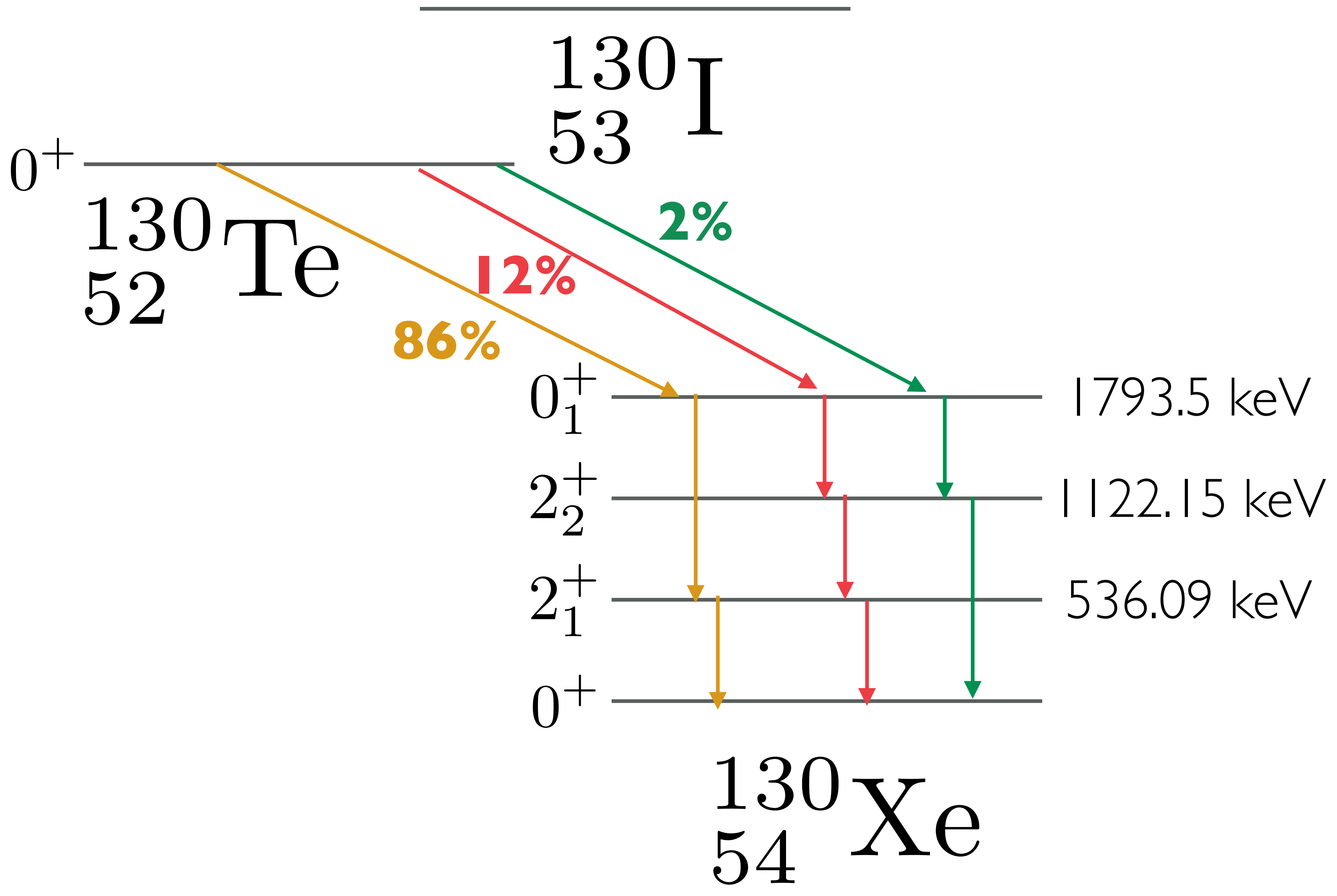
$$(1.38 \pm 0.07) \times 10^{-2} \text{cnts}/(\text{keV} \cdot \text{kg} \cdot \text{yr})$$

Characteristic FWHM ΔE at $Q_{\beta\beta}$

$$7.0 \pm 0.3\ \text{keV}$$

ββ Search
Excited State Analyses

Excited states analysis



[B. Singh, Nuclear Data Sheets 93, 33 (2001)]

There are 3 possible de-excitation patterns:

A. (86%) $\beta\beta_{0\text{-}734} + \gamma_{1257} + \gamma_{536}$

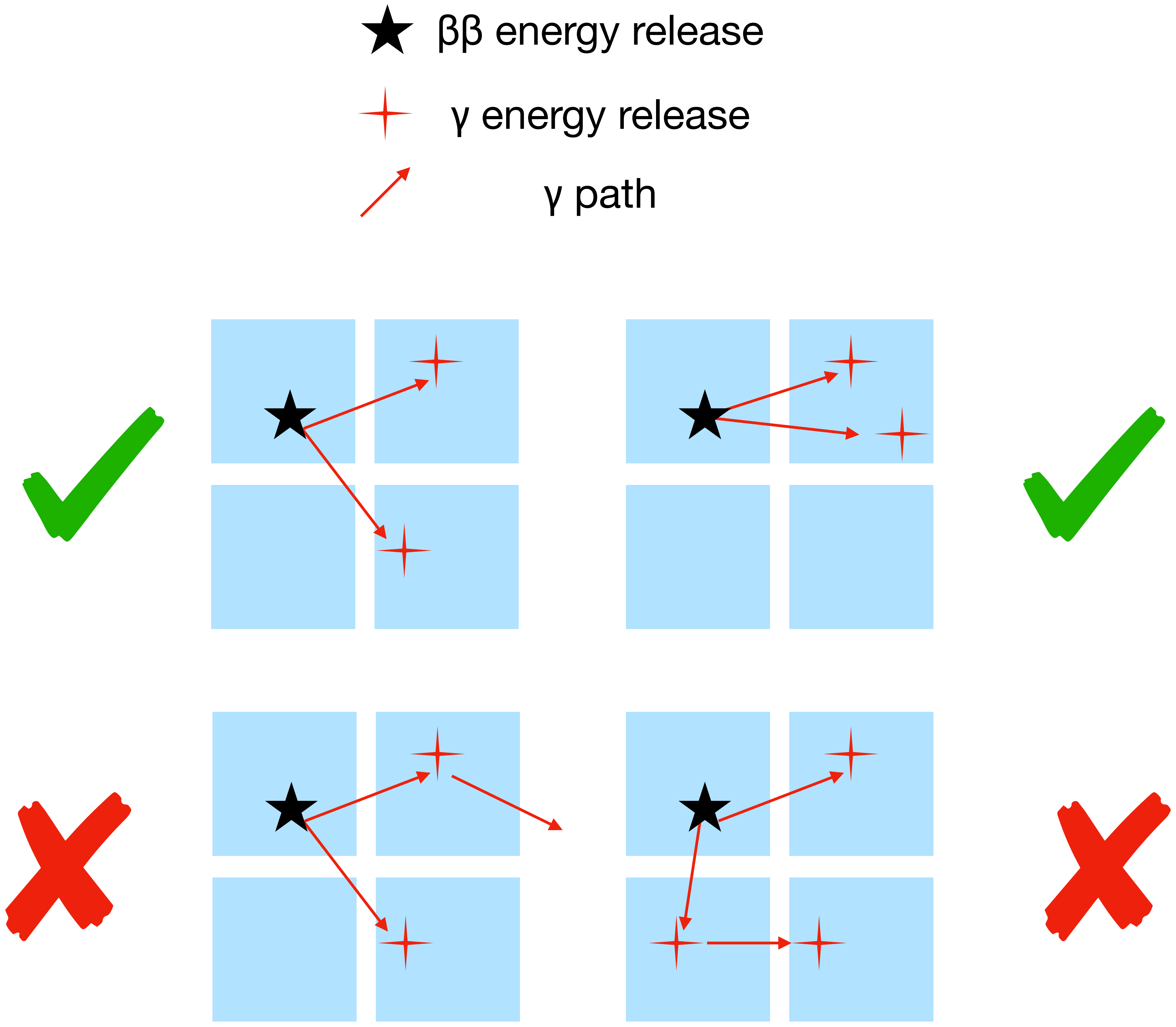
B. (12%) $\beta\beta_{0\text{-}734} + \gamma_{671} + \gamma_{586} + \gamma_{536}$

C. (2%) $\beta\beta_{0\text{-}734} + \gamma_{1122} + \gamma_{671}$

Excited states analysis

Full containment requirement

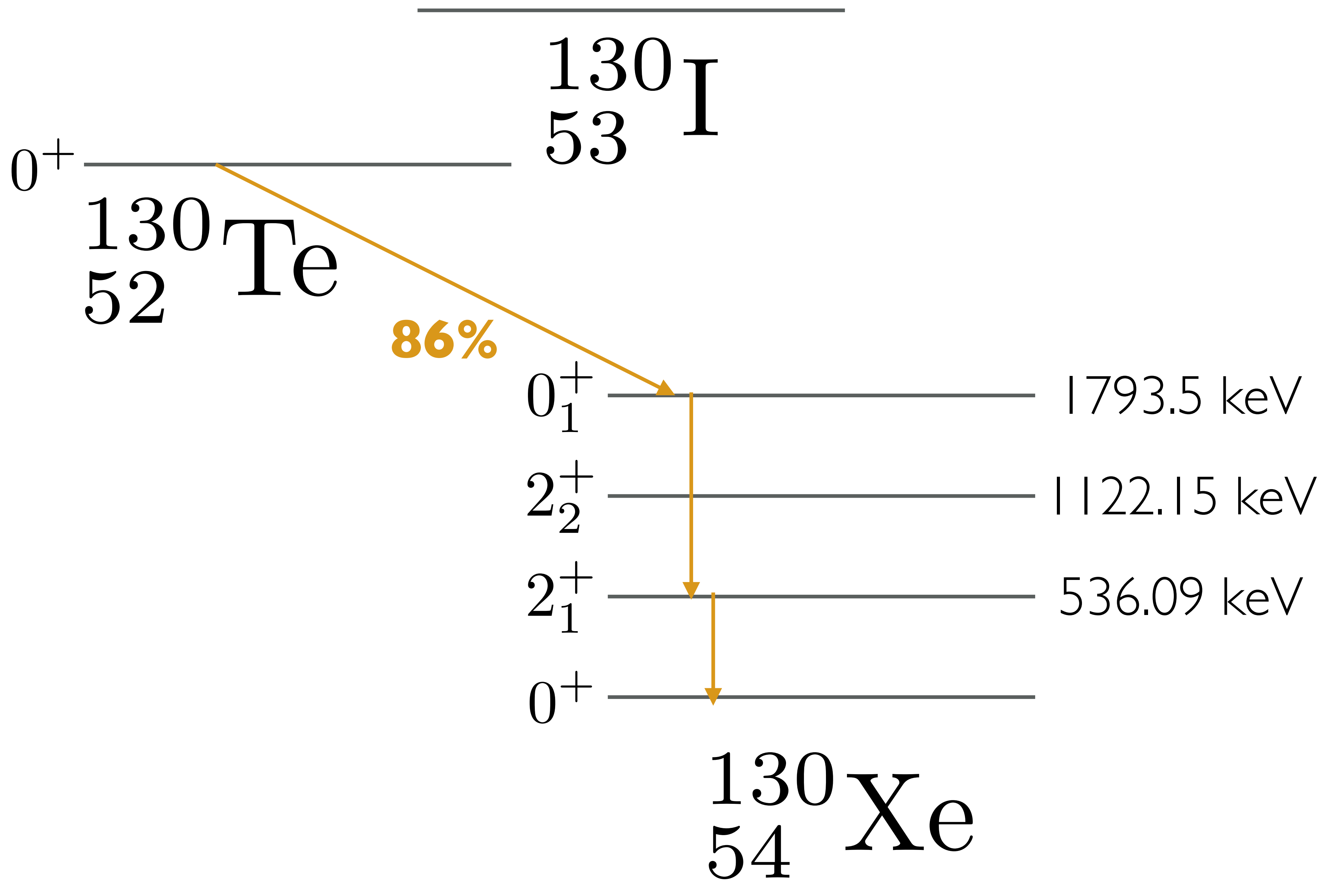
- Each final state particle (except neutrinos) must fully release its energy in no more than one crystal
- Not considering partially contained signatures
- Significantly simpler analysis
- Significant efficiency loss due to this choice

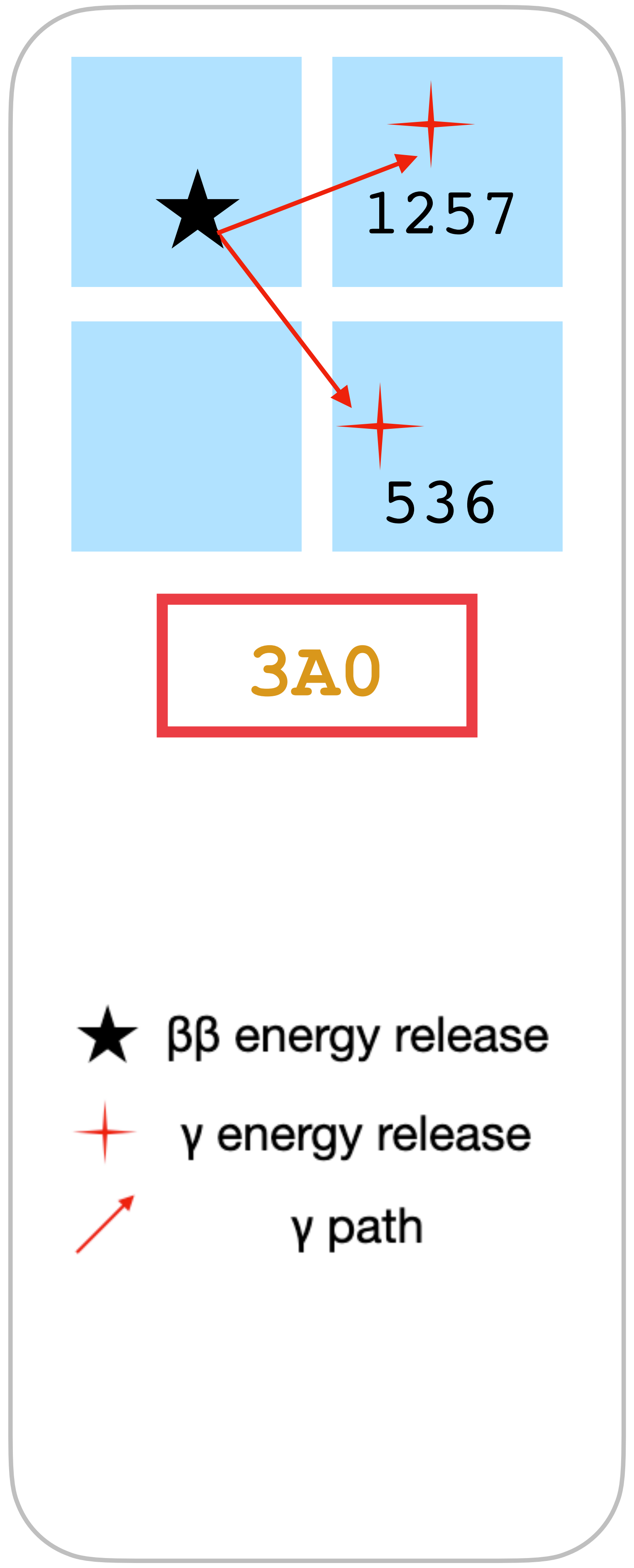


Excited states analysis

Labelling signatures

Let us build a **Multiplicity 3** (3 crystals involved) signature coming from de-excitation pattern A





Number of involved crystals

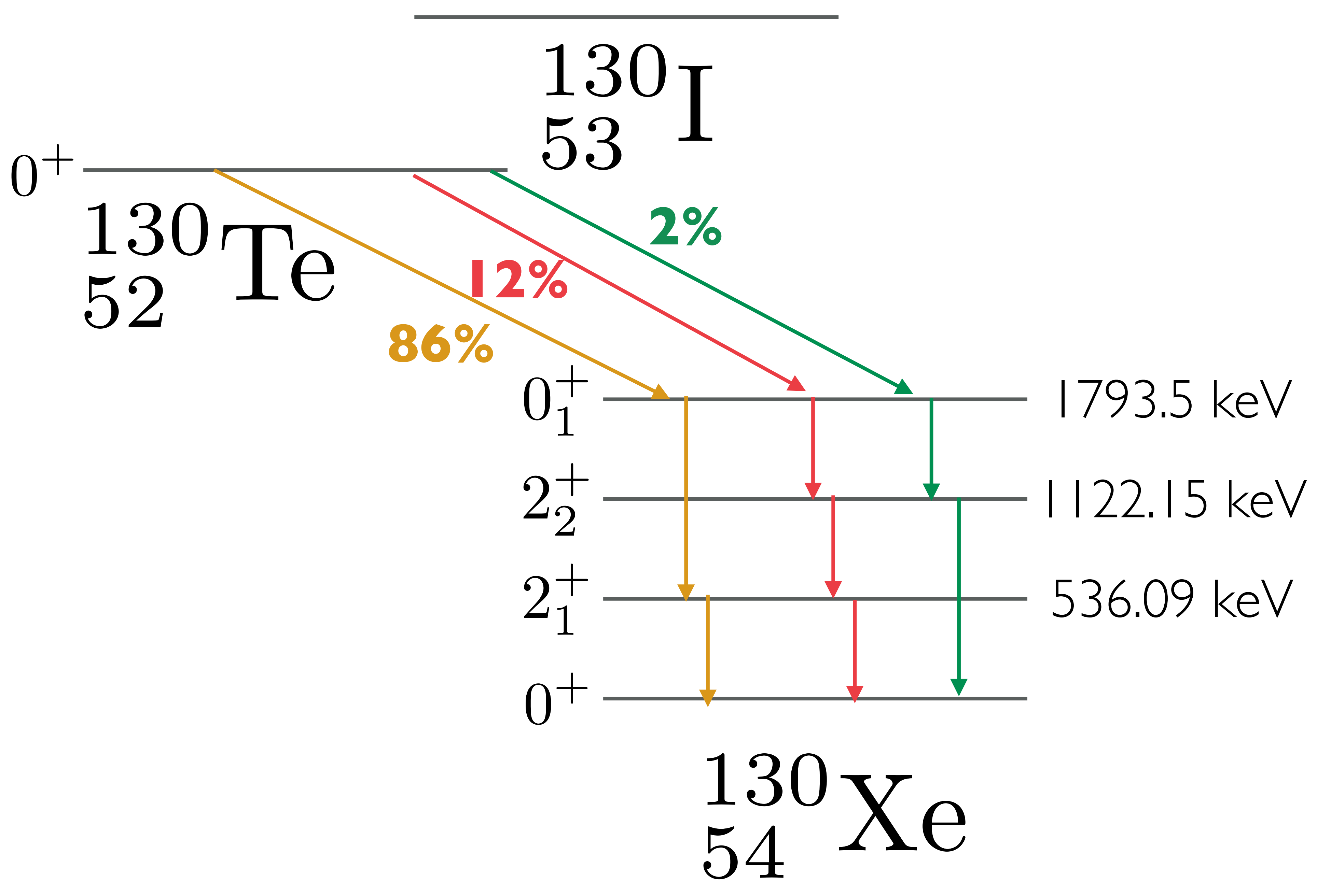
[Multiplicity] [Pattern] [integer index]

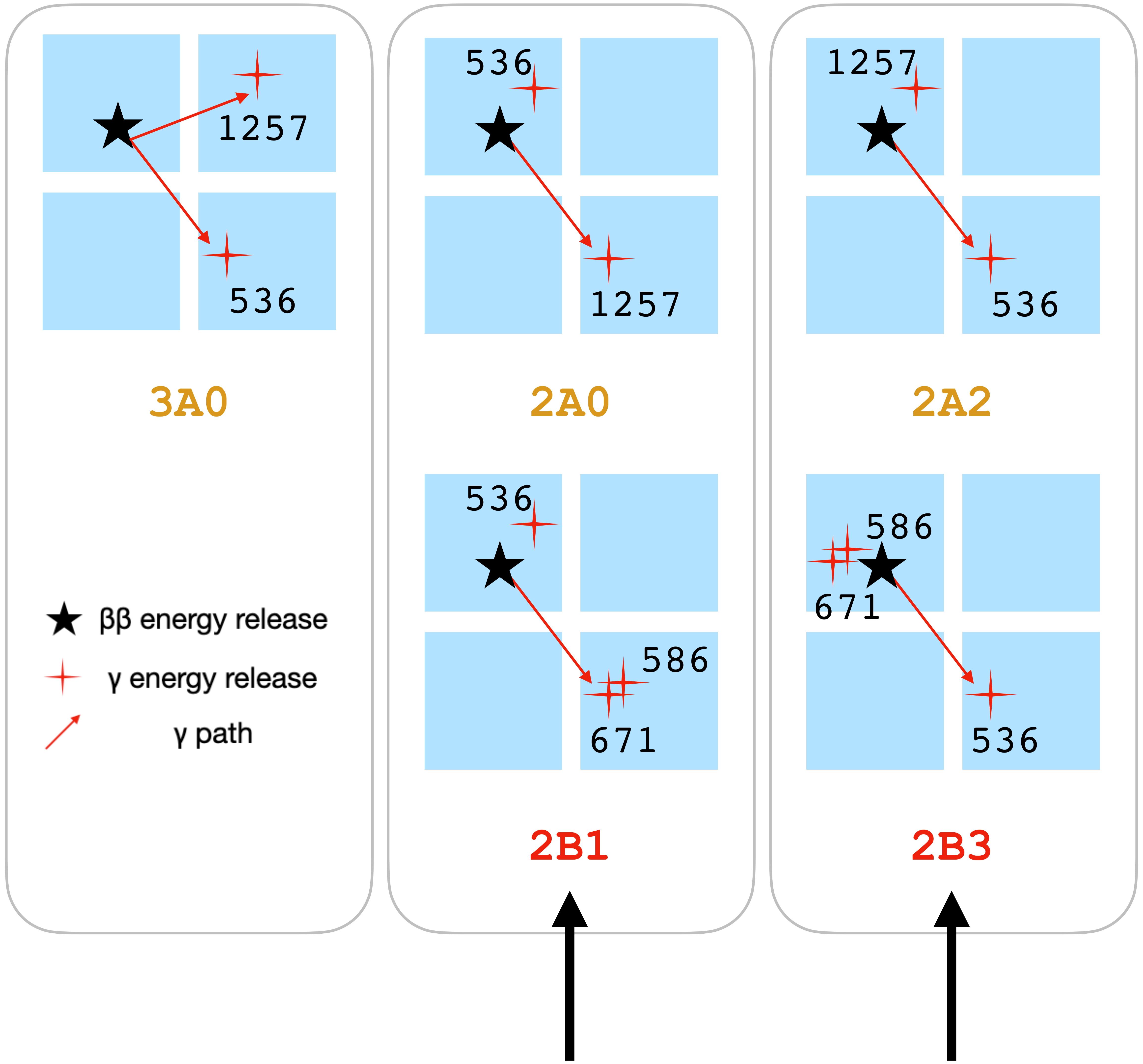
^{130}Xe de-excitation gamma pattern

Indexing possible combinations

Excited states analysis

Experimental signatures





Same experimental signature, 2 different de-excitation patterns

Excited states analysis

Ranking experimental signatures

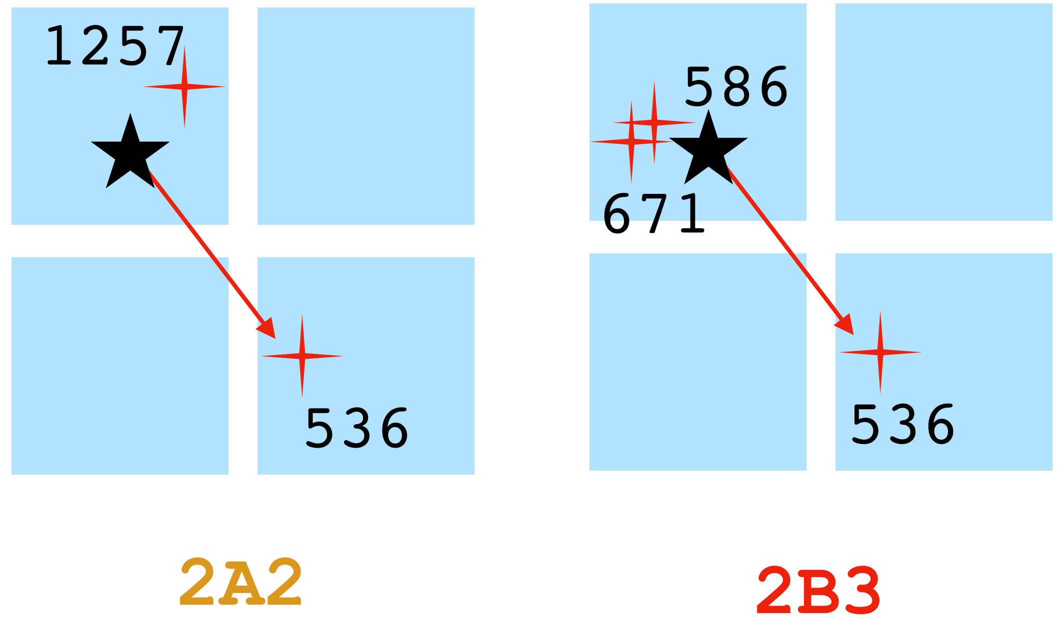
$$S(\epsilon_s, B_s) = \underbrace{\theta(B_s - 1)\frac{\epsilon_s}{\sqrt{B}}}_{\text{background-free}} + \underbrace{\theta(1 - B_s)\frac{5\epsilon_s}{-\ln(3 \cdot 10^{-7})}}_{\text{background-dominated}}$$

- Many possible signatures
- Most contribute negligibly to the sensitivity
- A threshold of S > 5 % was set
- Three signatures account for 80-90% of the overall sensitivity

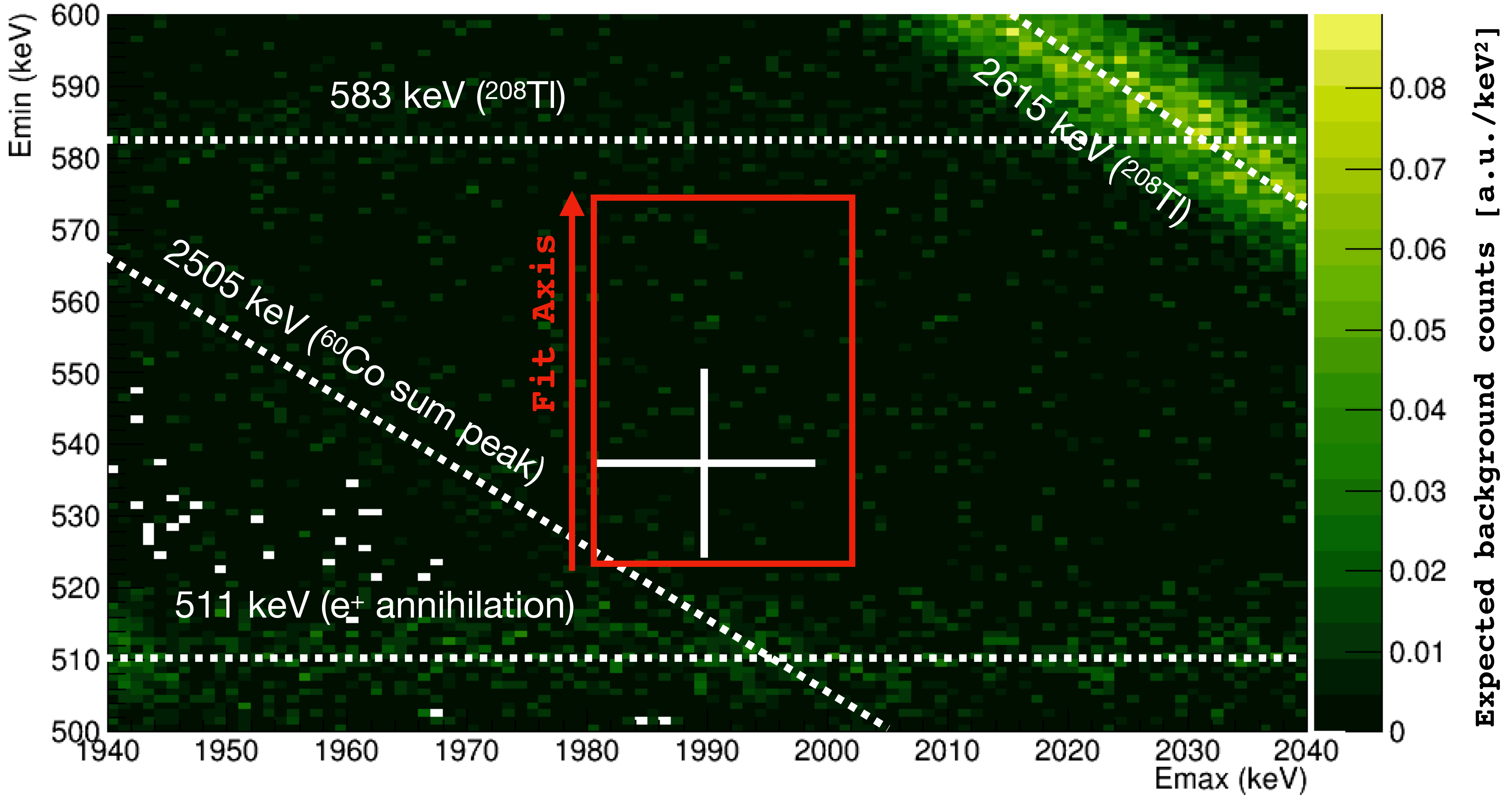
$S_{2\nu}(S_{0\nu})$ Signature	Crystal 1 [keV]	Crystal 2 [keV]	Crystal 3 [keV]	Crystal 4 [keV]
39.8% (38.5%) 2A0-2B1	$\beta\beta + \gamma_{(A2)}$ $\beta\beta + \gamma_{(B3)}$ 536 - 1270	$\gamma_{(A1)}$ $\gamma_{(B1)} + \gamma_{(B2)}$ 1257		
2.3% (2.3%) 2A1-2B2-2C1	$\gamma_{(A1)} + \gamma_{(A2)}$ $\gamma_{(B1)} + \gamma_{(B2)} + \gamma_{(B3)}$ $\gamma_{(C1)} + \gamma_{(C2)}$ 1793	$\beta\beta$ $\beta\beta$ $\beta\beta$ 0 - 734		
21.6% (24.7%) 2A2-2B3	$\beta\beta + \gamma_{(A1)}$ $\beta\beta + \gamma_{(B1)} + \gamma_{(B2)}$ 1257 - 1991	$\gamma_{(A2)}$ $\gamma_{(B3)}$ 536		
25.5% (20.3%) 3A0	$\gamma_{(A1)}$ 1257	$\beta\beta$ 0 - 734	$\gamma_{(A2)}$ 536	
2.4% (2.8%) 2B0-2C2	$\beta\beta + \gamma_{(B2)} + \gamma_{(B3)}$ $\beta\beta + \gamma_{(C1)}$ 1122 - 1856	$\gamma_{(B1)}$ $\gamma_{(C2)}$ 671		
0.2% (0.1%) 2B4	$\beta\beta + \gamma_{(B2)}$ 586 - 1320	$\gamma_{(B1)} + \gamma_{(B3)}$ 1207		
1.4% (2.0%) 2B5	$\beta\beta + \gamma_{(B1)} + \gamma_{(B3)}$ 1207 - 1941	$\gamma_{(B2)}$ 536		
1.0% (0.9%) 2B6-2C0	$\beta\beta + \gamma_{(B1)}$ $\beta\beta + \gamma_{(C2)}$ 671 - 1405	$\gamma_{(B2)} + \gamma_{(B3)}$ $\gamma_{(C1)}$ 1122		
1.1% (1.1%) 3B0	$\beta\beta + \gamma_{(B3)}$ 536 - 1270	$\gamma_{(B1)}$ 671	$\gamma_{(B2)}$ 586	
0.8% (0.5%) 3B1-3C0	$\gamma_{(B2)} + \gamma_{(B3)}$ $\gamma_{(C1)}$ 1122	$\beta\beta$ $\beta\beta$ 0 - 734	$\gamma_{(B1)}$ $\gamma_{(C2)}$ 671	
0.1% (0.1%) 3B2	$\gamma_{(B1)} + \gamma_{(B2)}$ 1257	$\beta\beta$ 0 - 734	$\gamma_{(B3)}$ 536	
1.3% (1.0%) 3B3	$\beta\beta + \gamma_{(B2)}$ 586 - 1320	$\gamma_{(B1)}$ 671	$\gamma_{(B3)}$ 536	
0.1% (0.1%) 3B4	$\gamma_{(B1)} + \gamma_{(B3)}$ 1207	$\beta\beta$ 0 - 734	$\gamma_{(B2)}$ 536	
1.5% (1.0%) 3B5	$\beta\beta + \gamma_{(B1)}$ 671 - 1405	$\gamma_{(B2)}$ 586	$\gamma_{(B3)}$ 536	
0.8% (0.6%) 4B0	$\beta\beta$ 0 - 734	$\gamma_{(B1)}$ 671	$\gamma_{(B2)}$ 586	$\gamma_{(B3)}$ 536

Excited states analysis

Selection cut definition



- The ROI for each signature is defined in an ordered energy space
- Selection cuts based on Monte Carlo (MC) simulations of the CUORE background
- Analytical description of the background based on simulations



Excited states analysis

Ranking experimental signatures

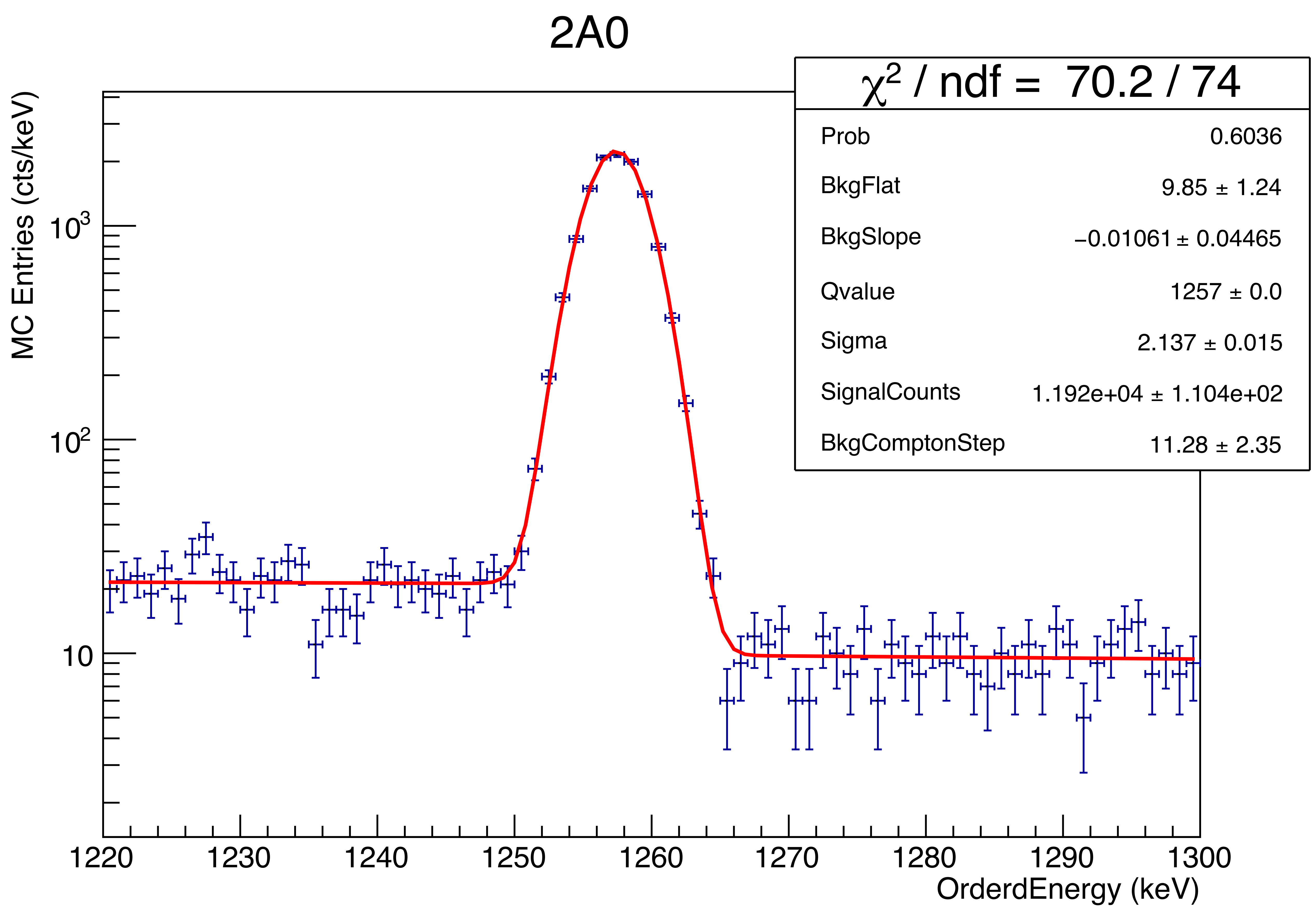
0νββ				
Scenario	**Multiplicity**	**Score**	**Cut**	**Selection**
2A0 - 2B1	2	39%	1247 keV < E_{min} < 1280 keV	E_{min} = γ(1257)
			1247 keV < E_{max} < 1280 keV	E_{max} = ββ(734) + γ(536)
2A2 - 2B3	2	25%	523 keV < E_{min} < 573 keV	E_{min} = γ(536)
			1981 keV < E_{max} < 2001 keV	E_{max} = ββ(734) + γ(1257)
3A0	3	20%	526 keV < E_{min} < 546 keV	E_{min} = γ(536)
			700 keV < E_{med} < 760 keV	E_{med} = ββ(734)
			1247 keV < E_{max} < 1267 keV	E_{max} = γ(1257)

2νββ				
Scenario	**Multiplicity**	**Score**	**Cut**	**Selection**
2A0 - 2B1	2	40%	620 keV < E_{min} < 1150 keV	E_{min} = ββ(0-734) + γ(536)
			1220 keV < E_{max} < 1300 keV	E_{max} = γ(1257)
2A2 - 2B3	2	22%	523 keV < E_{min} < 573 keV	E_{min} = γ(536)
			1360 keV < E_{max} < 1990 keV	E_{max} = ββ(0-734) + γ(1257)
3A0	3	26%	400 keV < E_{min} < 523 keV	E_{min} = ββ(0-734)
			523 keV < E_{med} < 573 keV	E_{med} = γ(536)
			1779 keV < E_{med} + E_{max} < 1807 keV	E_{max} = γ(1257)

- Blind selections (defined on MC simulations) in ordered energy space
- Expected background shape: flat or linear
- No background peaks expected

Excited states analysis

Containment efficiency



Once the selection cuts are fixed, the efficiency is obtained from a fit to Monte Carlo simulations of signal events

Excited states analysis

Model

$$\log \mathscr{L}_{s,ds}(\vec{E} \mid \vec{\theta}, H_{S+B}) = -(\lambda^{(S)}_{s,ds} + \lambda^{(B)}_{s,ds}) + \sum_{ev \in (s,ds)} \log\left[\lambda^{(S)}_{s,ds} \frac{M\Delta t_{ch}}{M\Delta t_{ds}} pdf^{(S)}(\vec{E}) + \lambda^{(B)}_{s,ds} \frac{M\Delta t_{ch}}{M\Delta t_{ds}} pdf^{(B)}(\vec{E})\right]$$

- Bayesian Analysis (BAT)
- Likelihood model: linear background, peak for ββ/γ
- Unbinned fit on physical range (non-negative rate), uniform prior on Γ
- Systematics addressed repeating fit with additional nuisance parameters

$$\epsilon_s = \left[\sum_p \mathrm{BR}_p \cdot \frac{\left[N^{(sel)}_{MC}\right]^{(s)}_p}{\left[N^{(tot)}_{MC}\right]_p}\right] \epsilon^M_{cut}\, \epsilon_{acc}$$

leading efficiency term

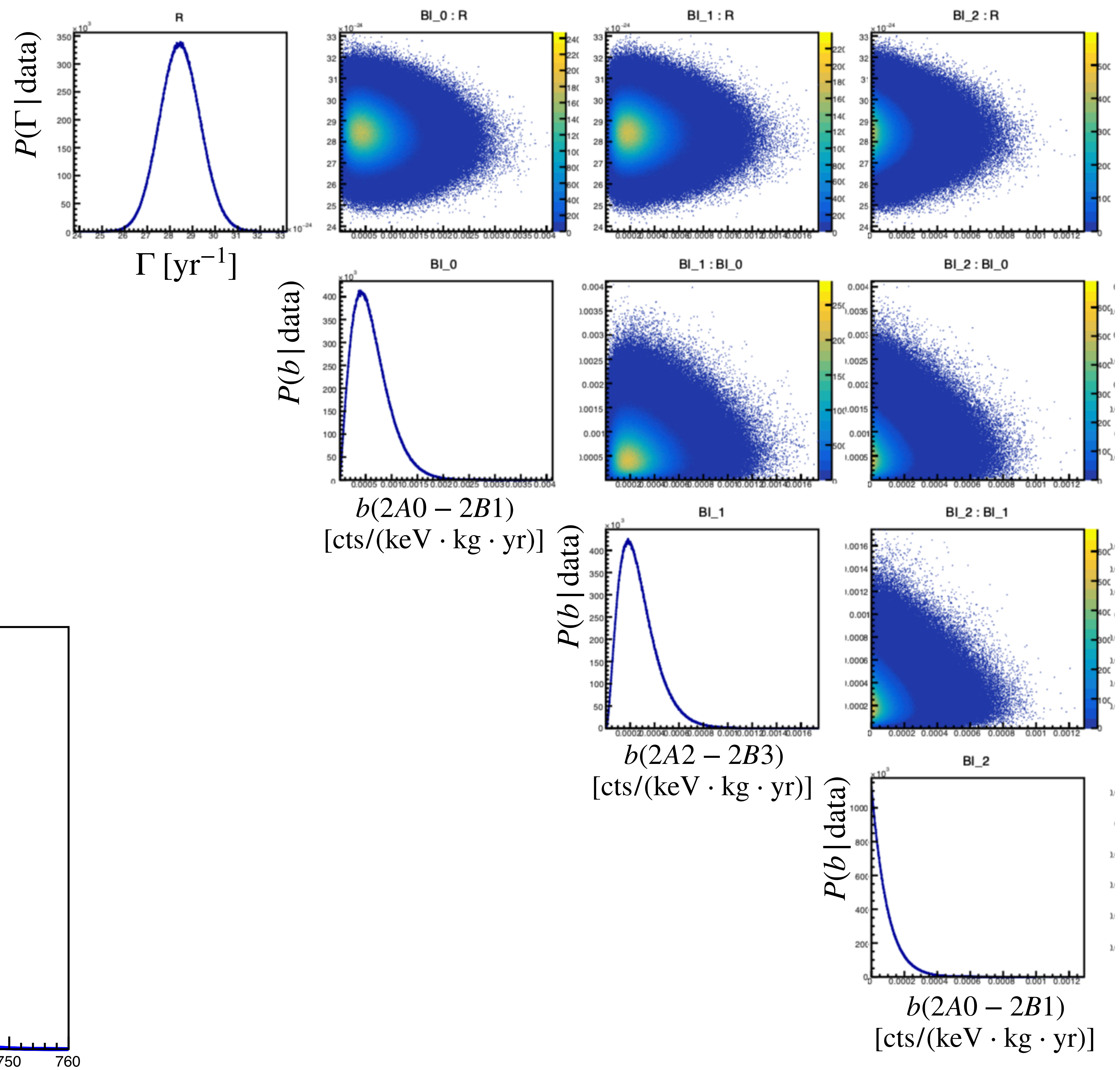
Process	Containment	Cut	Accidentals	Total
0νββ	10.0%	88.7%	98.7%	8.7%
2νββ	6.8%			5.9%

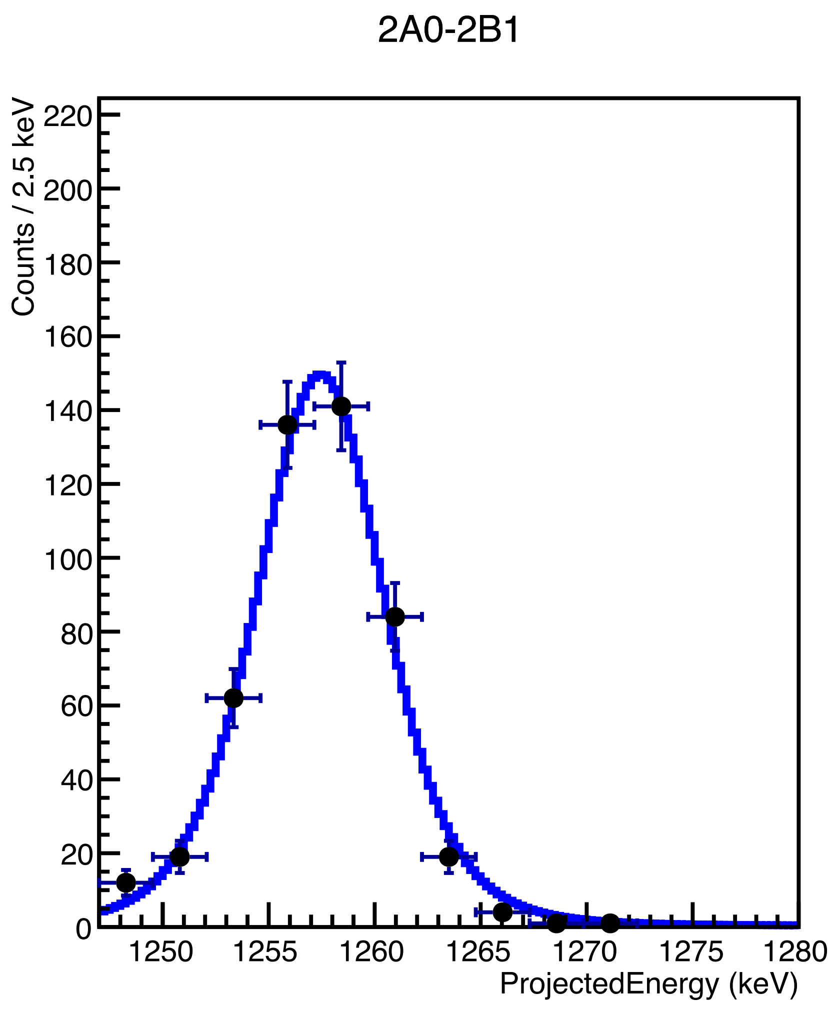
Effective efficiencies
containment summed over signatures
other components exposure averaged

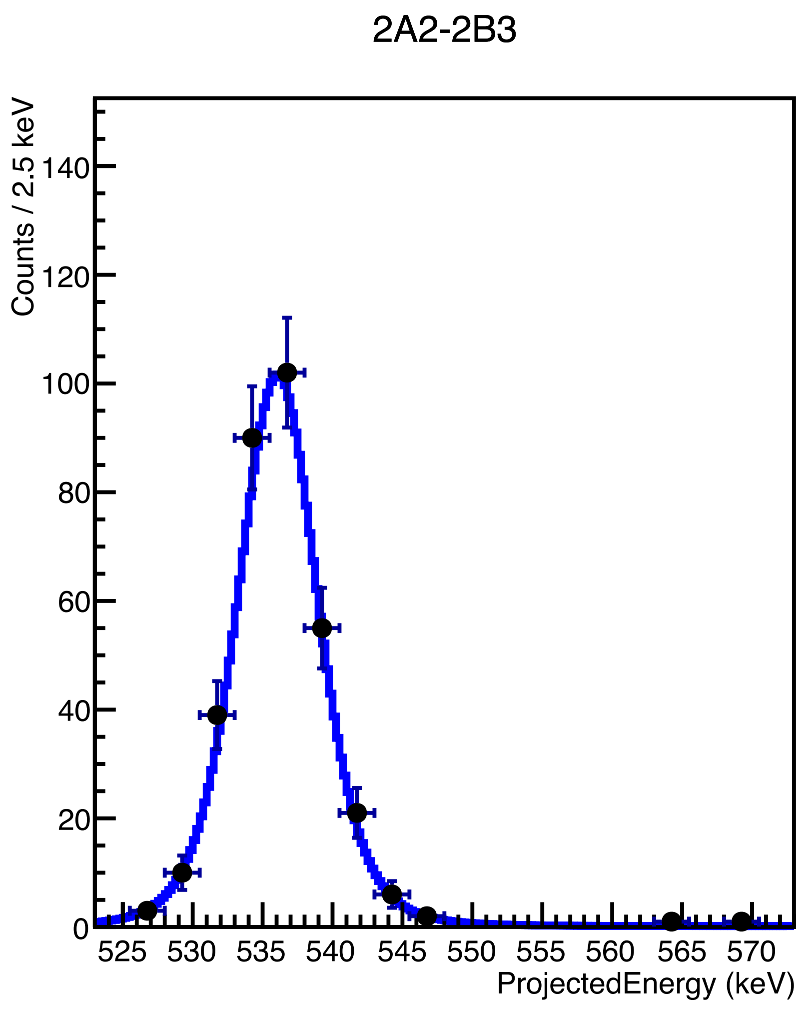
Excited states analysis

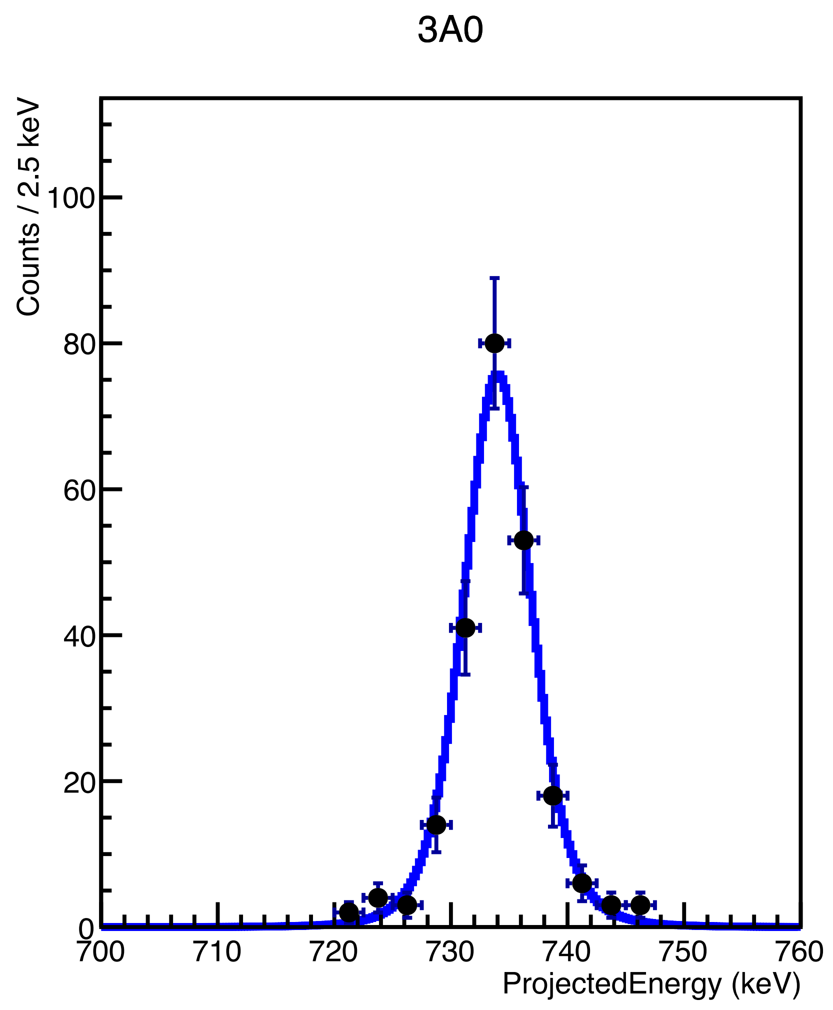
Blinded fit (0νββ)

- Monte Carlo signal events injected into physics data
- Background shape validation
- Unbiased background estimation
- Allows a preliminary sensitivity computation



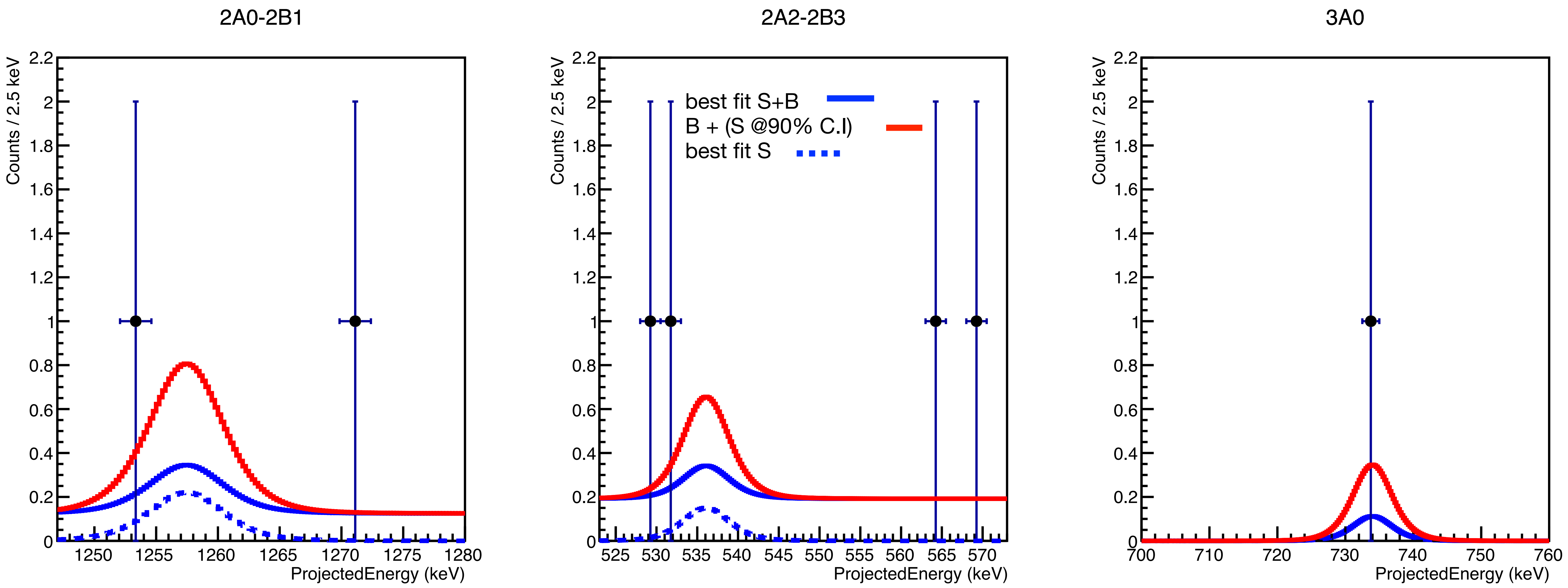


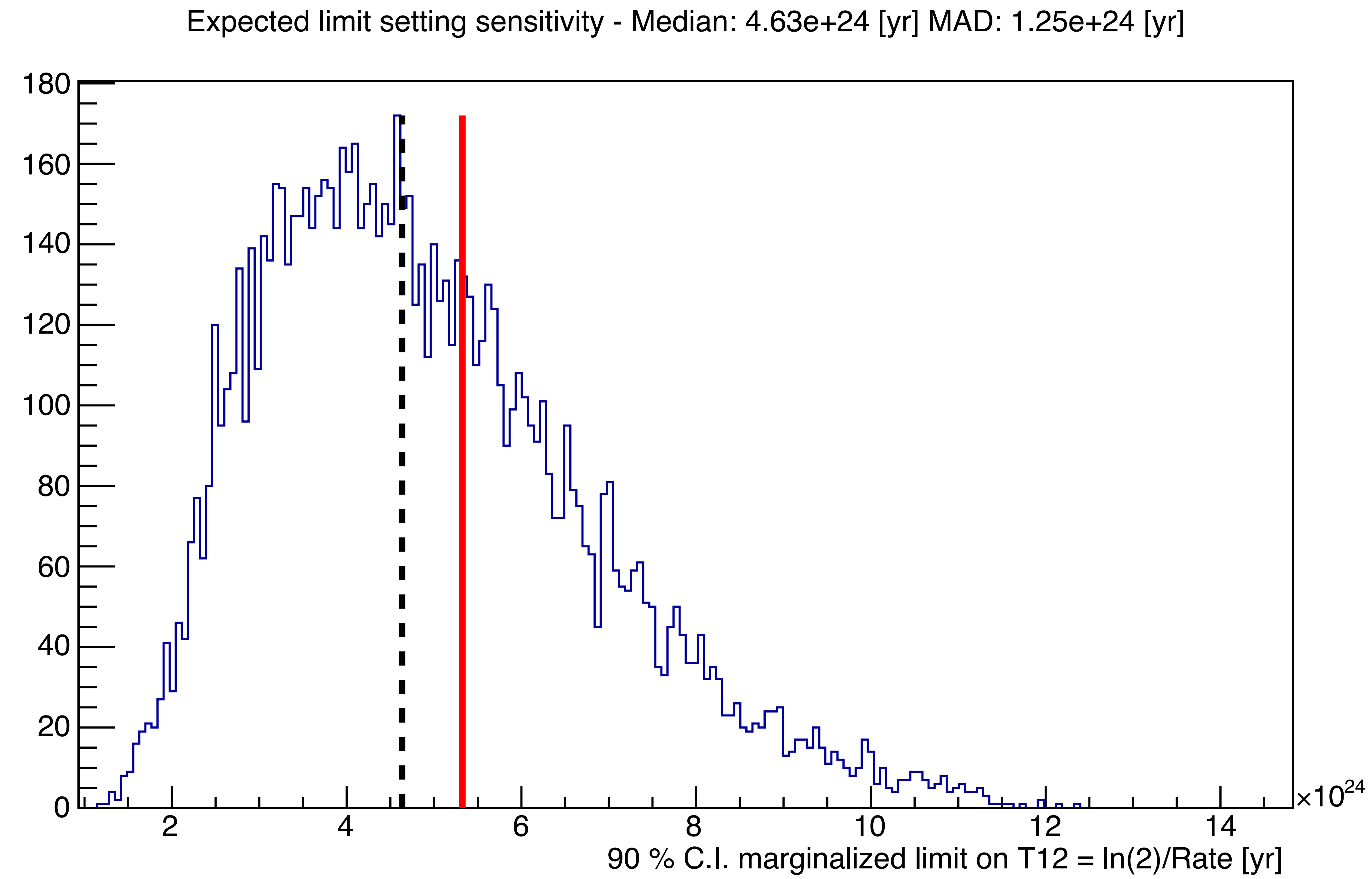




Excited states analysis

0νββ unblinded fit and sensitivity





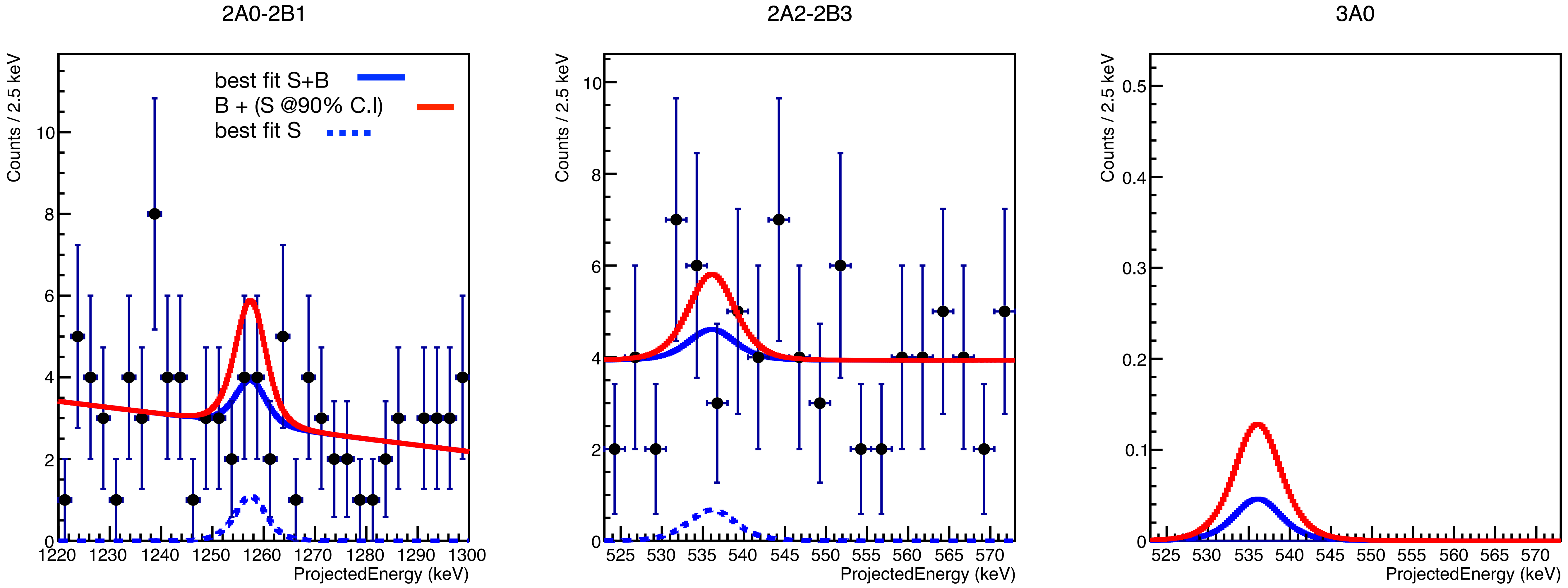
Marg. Post.	Mean	St. Dev.	Units
Rate	6.37	4.85	10^{-26} 1/yr
b (2A0-2B1)	2.15	1.38	10^{-4} cts/(keV kg yr)
b (2A2-2B3)	2.56	1.20	10^{-4} cts/(keV kg yr)
b (3A0)	5.67	5.42	10^{-5} cts/(keV kg yr)

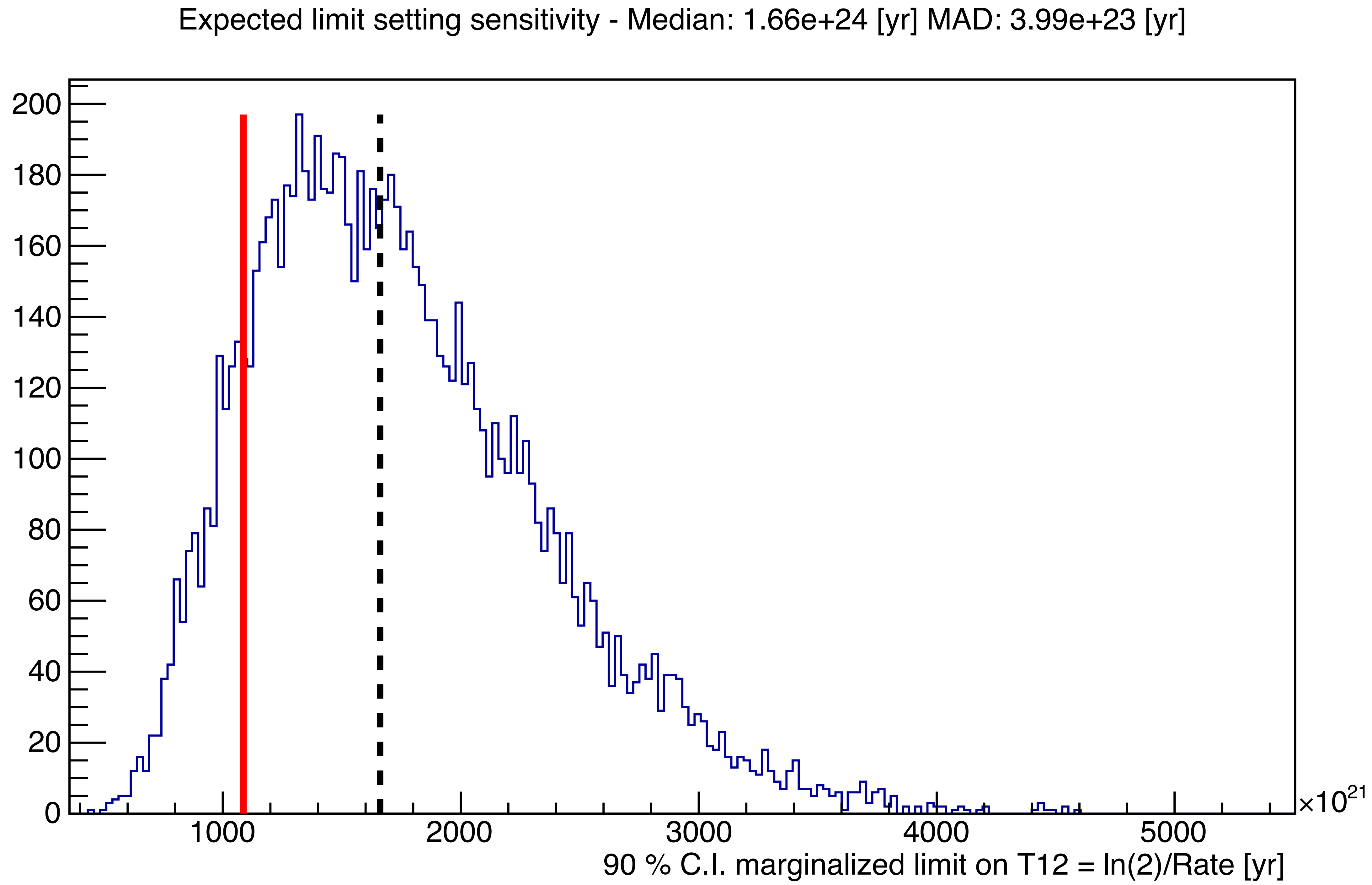
$$T^{0\nu}_{1/2} > 5.4 \times 10^{24}\ \mathrm{yr}\ (90\ \%\ \mathrm{C.I.})$$

systematics not included

Excited states analysis

2νββ unblinded fit and sensitivity





Marg. Post.	Mean	St. Dev.	Units
Rate	3.33	2.18	10^{-25} 1/yr
b (2A0-2B1)	3.01	0.33	10^{-3} cts/(keV kg yr)
b (2A2-2B3)	4.23	0.49	10^{-3} cts/(keV kg yr)
b (3A0)	5.37	5.36	10^{-5} cts/(keV kg yr)
slope (3A0)	-5.17	4.23	10^{-3} 1/keV

$$T^{2\nu}_{1/2} > 1.1 \times 10^{24}\ \mathrm{yr}\ (90\ \%\ \mathrm{C.I.})$$

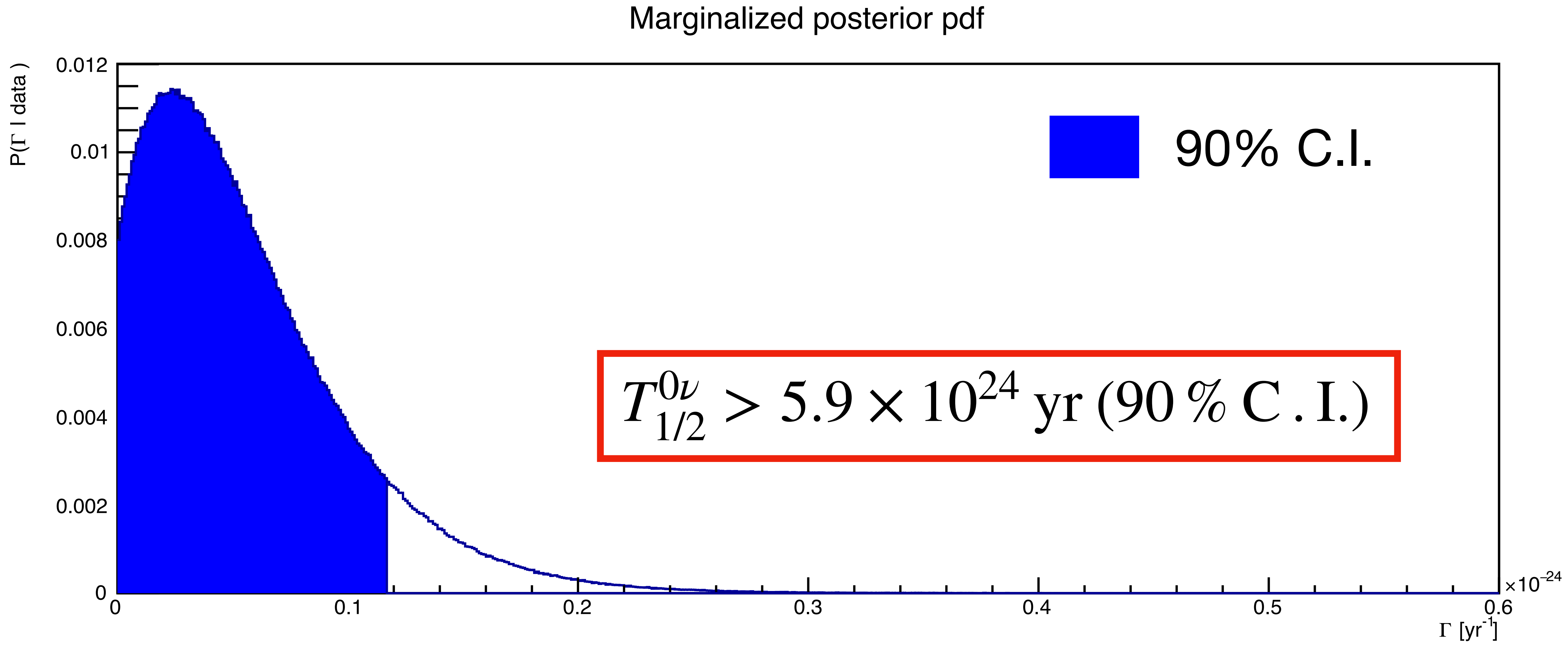
systematics not included

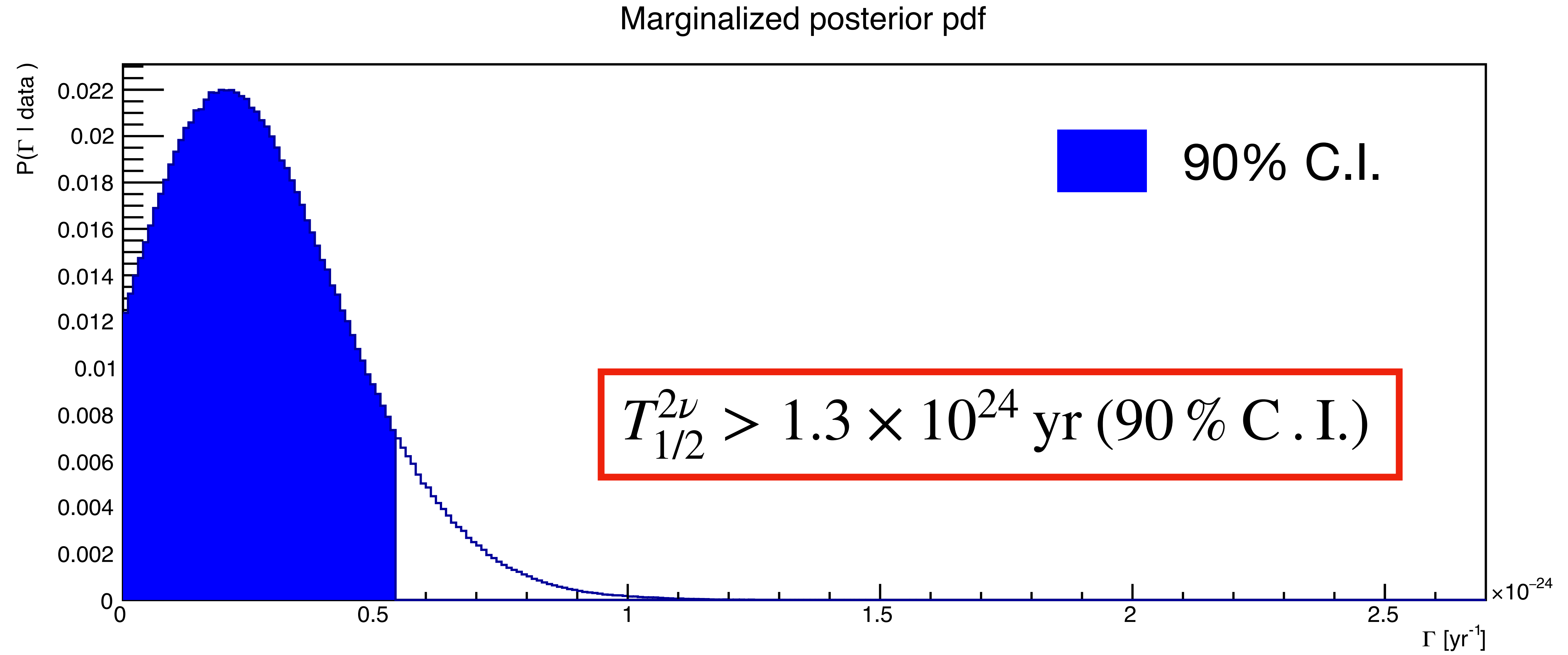
Excited states analysis

Systematics

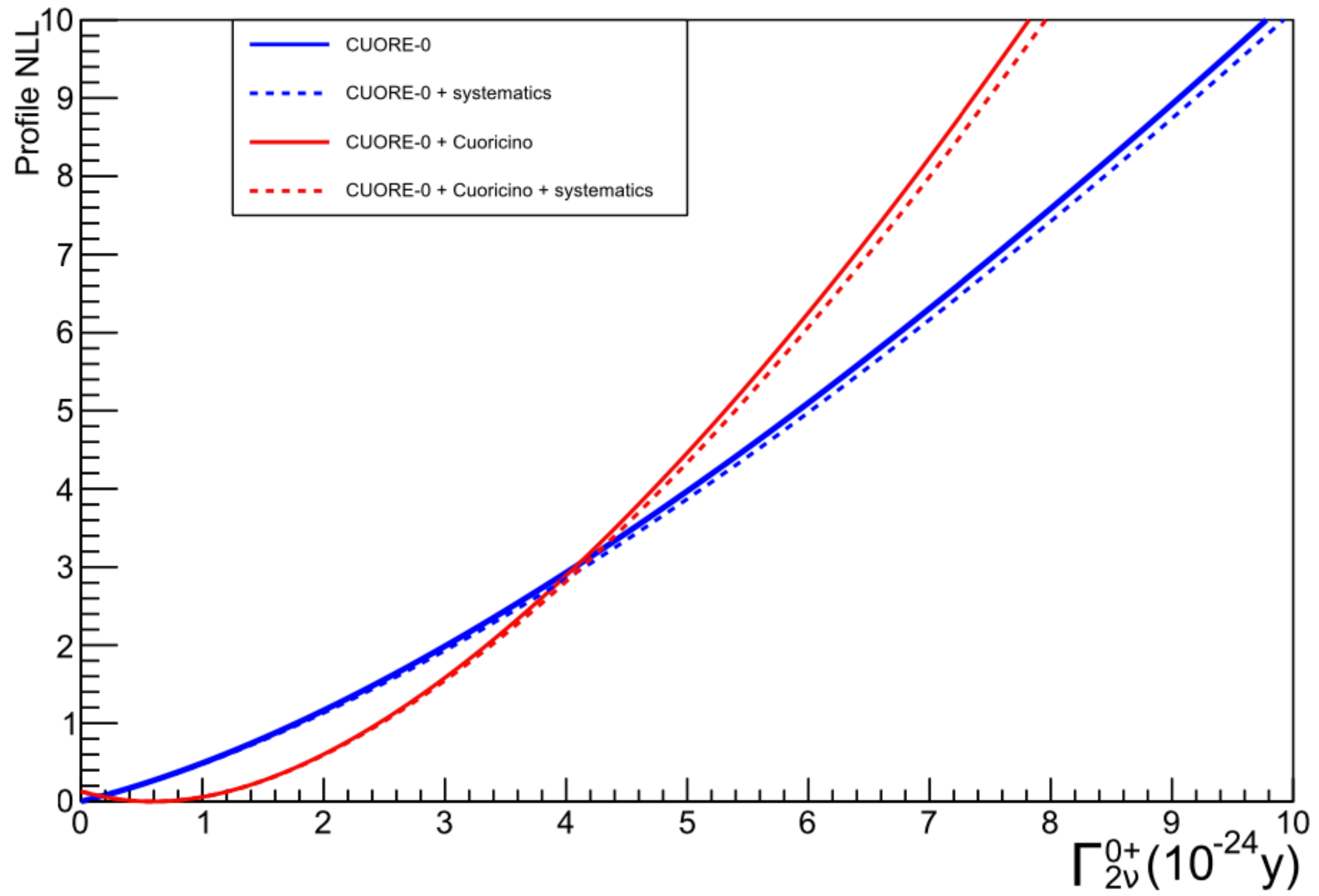
Nuisance Parameter	Prior	$0\nu\beta\beta$ $\Delta T^{90}_{1/2}$	$2\nu\beta\beta$ $\Delta T^{90}_{1/2}$
Detector response	multivariate	10.1%	17.6%
Cut efficiency	gaussian	-0.1%	< 0.1%
PSA efficiency	uniform	-0.7%	-0.2%
Accidental coincidences	gaussian	-0.4%	0.1%
Containment efficiency	gaussian	-0.6%	-0.4%
Isotopic abundance	gaussian	-0.1%	-0.2%
Combined	multivariate	10.1%	17.2%

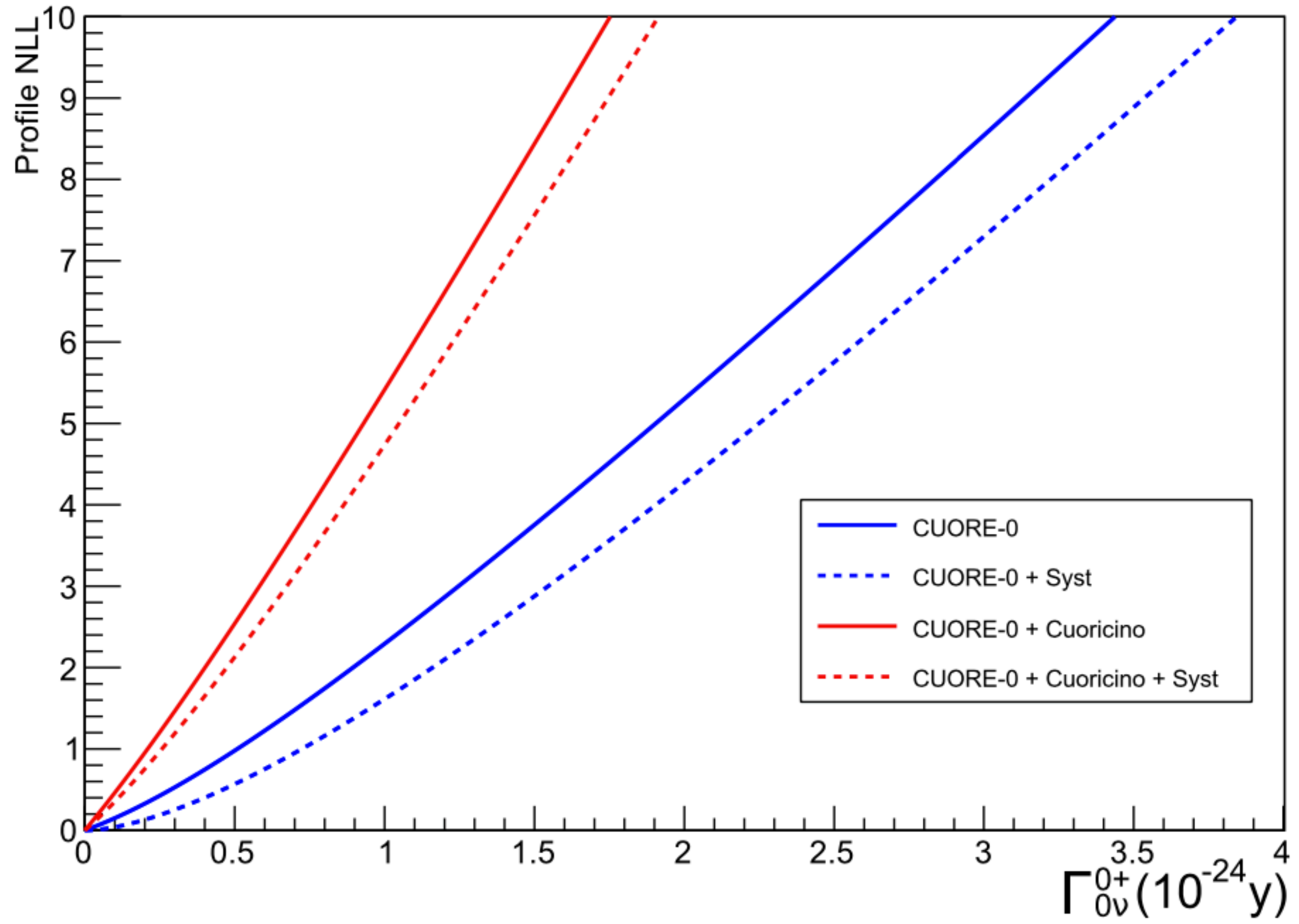
[G. Fantini *et al.,* paper in preparation]





Excited states analysis





$T^{2\nu}_{1/2} > 2.5 \times 10^{23}$ yr, 90 % C.L. $\quad T^{0\nu}_{1/2} > 1.4 \times 10^{24}$ yr, 90 % C.L. [C. Alduino *et al.*, Eur. Phys. J. C **79**, 795 (2019)]

$T^{2\nu}_{1/2} > 1.3 \times 10^{24}$ yr (90 % C.I.) $\quad T^{0\nu}_{1/2} > 5.9 \times 10^{24}$ yr (90 % C.I.) This work: [G. Fantini *et al.*, paper in preparation]

$T^{2\nu}_{1/2} = (7.2 - 16) \times 10^{24}$ yr QRPA [P. Pirinen, J. Suhonen, Phys. Rev. C **91**, 054309 (2015)]

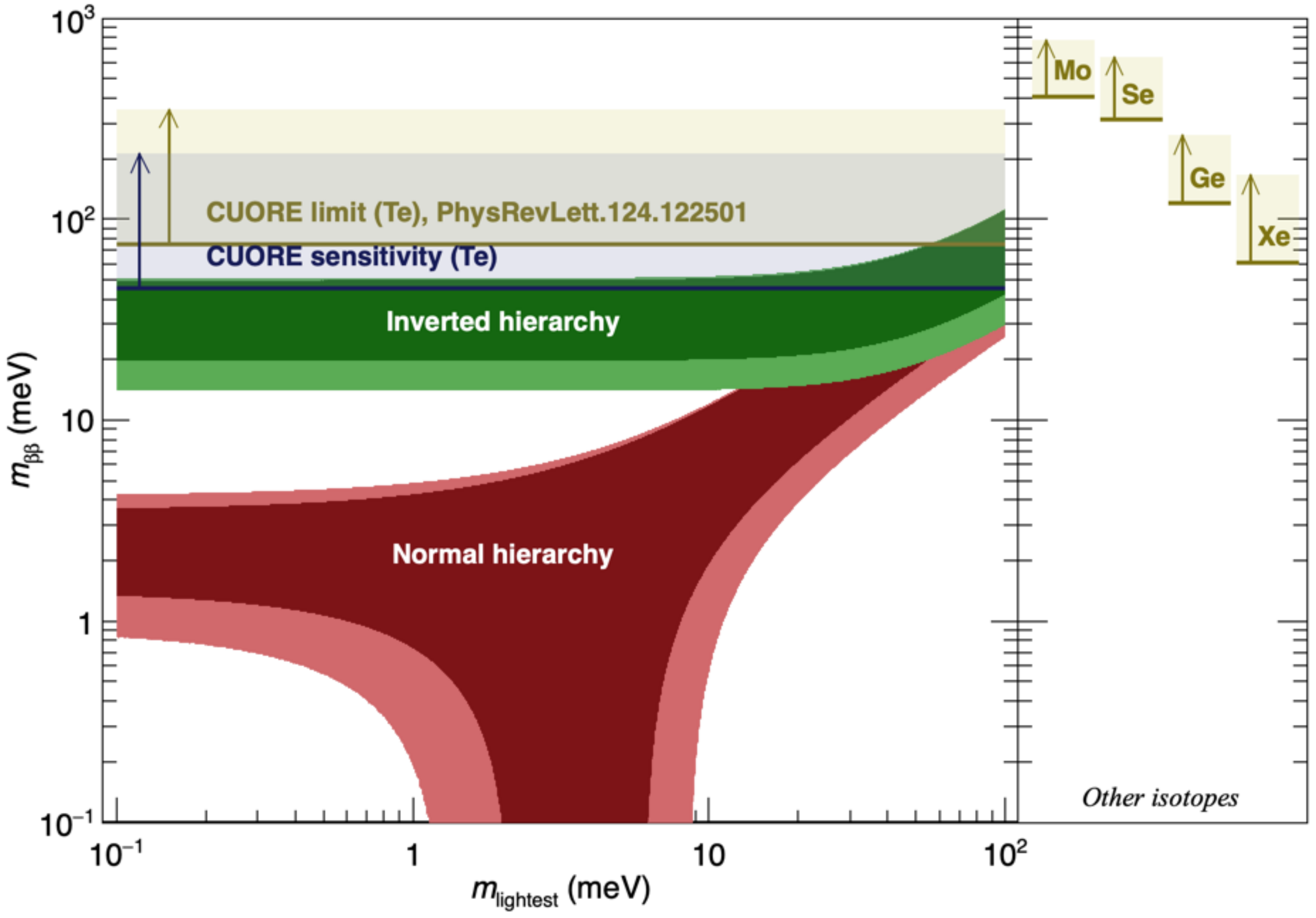
$T^{2\nu}_{1/2} = 2.2 \times 10^{25}$ yr IBM-II + experimental input [B. Lehnert, 10.1051/epjconf/20159301025]

Summary

- Original contributions to the CUORE analysis
- New result on the double beta decay to excited states both in the neutrino-less and Standard Model mode
- No evidence for signal in either mode
- A factor 5 more stringent Bayesian limit with respect to the current most sensitive search (CUORE-0)

Backup

Effective Majorana Mass Interpretation



$$m_{\beta\beta} < 75 - 350\,\mathrm{meV}$$

NMEs Used

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[67] A. Meroni, S. T. Petcov, and F. Simkovic, JHEP **02**, 025 (2013).

See-saw mechanism

$$\mathscr{L}_{D+M} = -\bar{N}_L^c M N \qquad N_L = \begin{bmatrix} \nu_L \\ \nu_R^c \end{bmatrix} \qquad M = \begin{bmatrix} m_L & m_D \\ m_D & m_R \end{bmatrix}$$

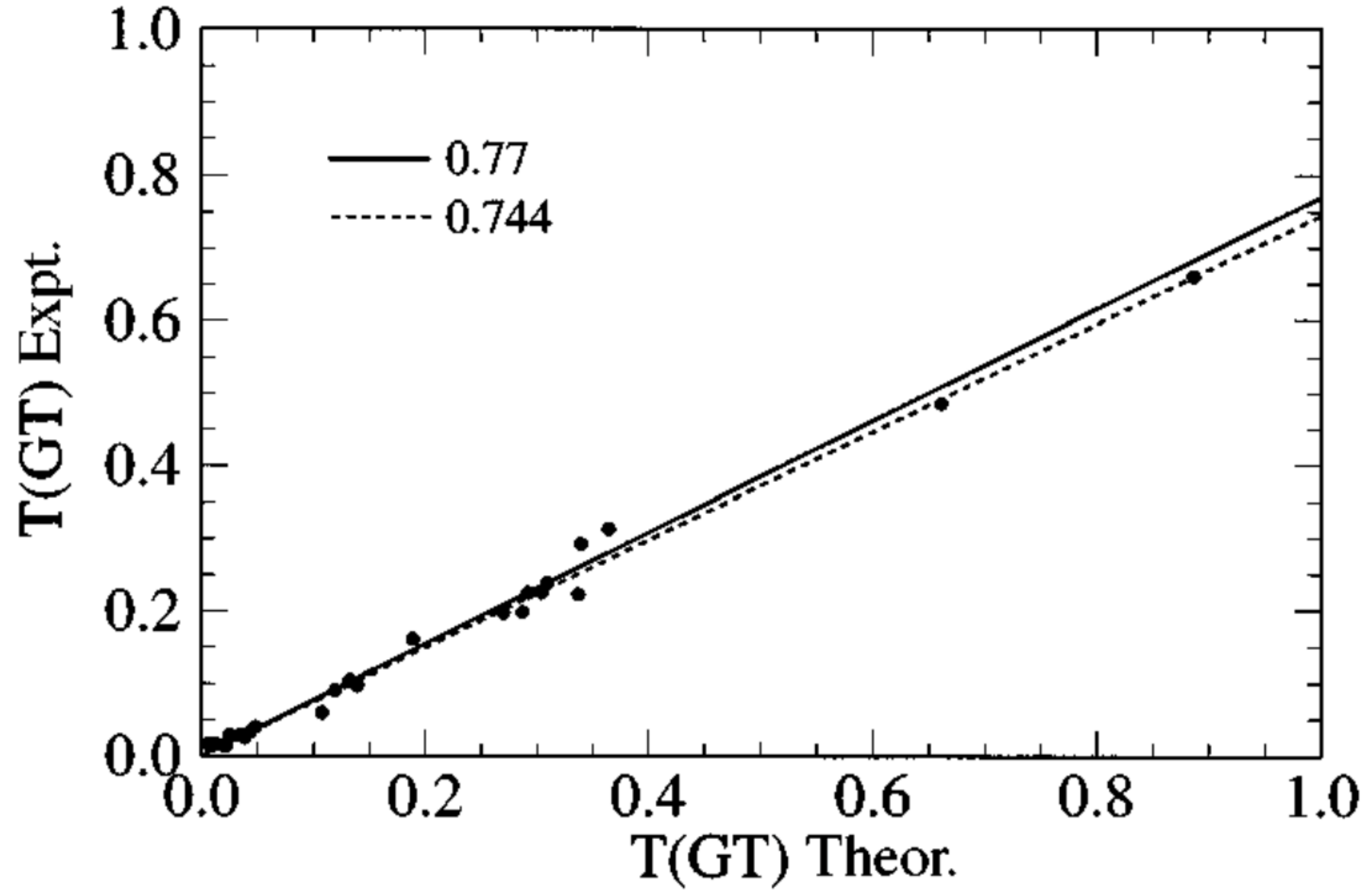
Assuming $SU(3)_C$ x $SU(2)_L$ x $U(1)_Y$ gauge invariance and renormalizability $m_L = 0$

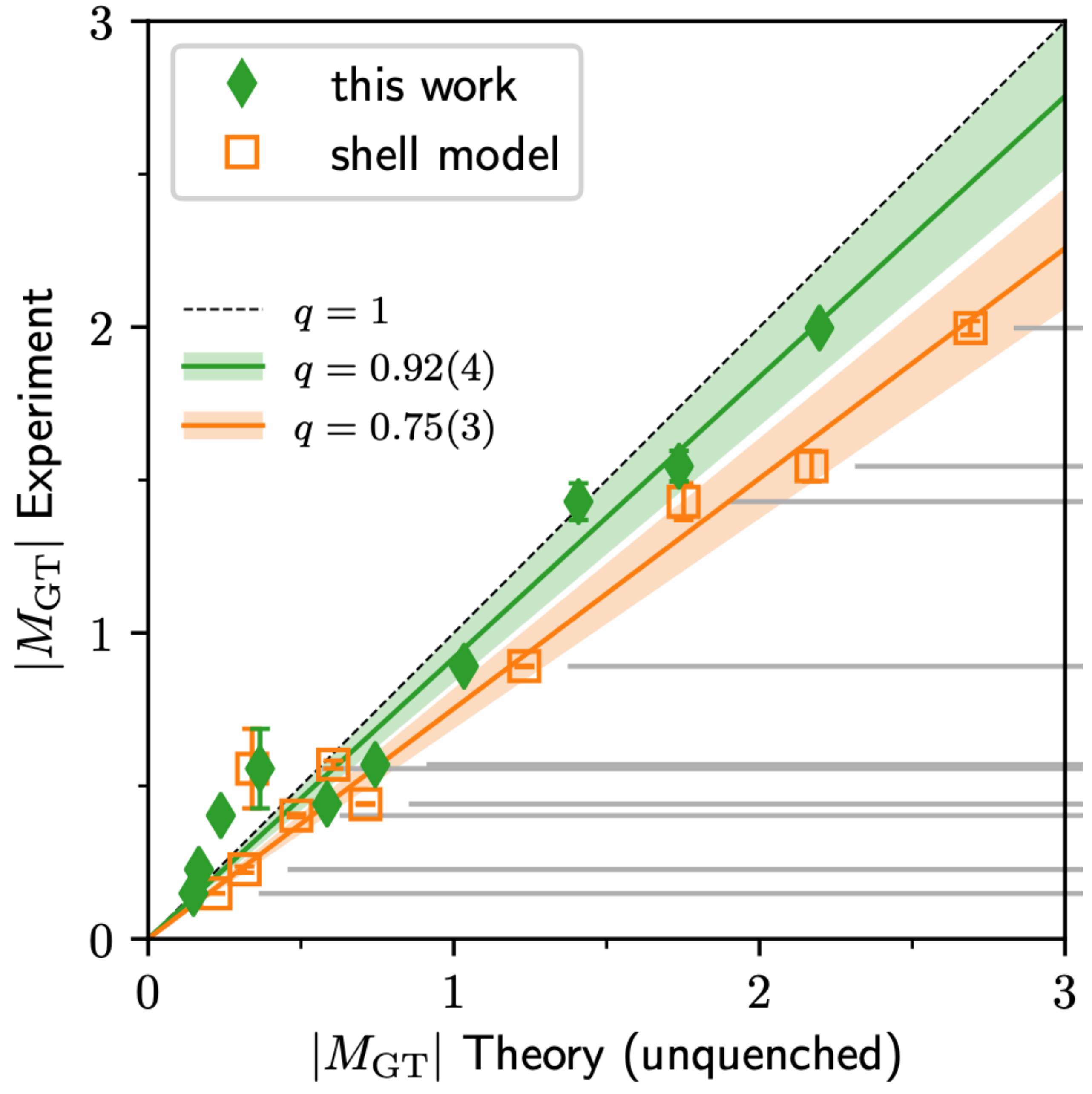
m_D of the order of the Higgs v.e.v., m_R arbitrarily large

$$m_\pm = \frac{m_R}{2} + \frac{m_R}{2}\sqrt{1 + \frac{4m_D^2}{m_R^2}} \quad \xrightarrow{m_R \gg m_D} \quad \begin{array}{l} m_+ \sim m_D^2/m_R \\ m_- \sim m_R \end{array}$$

g_A quenching

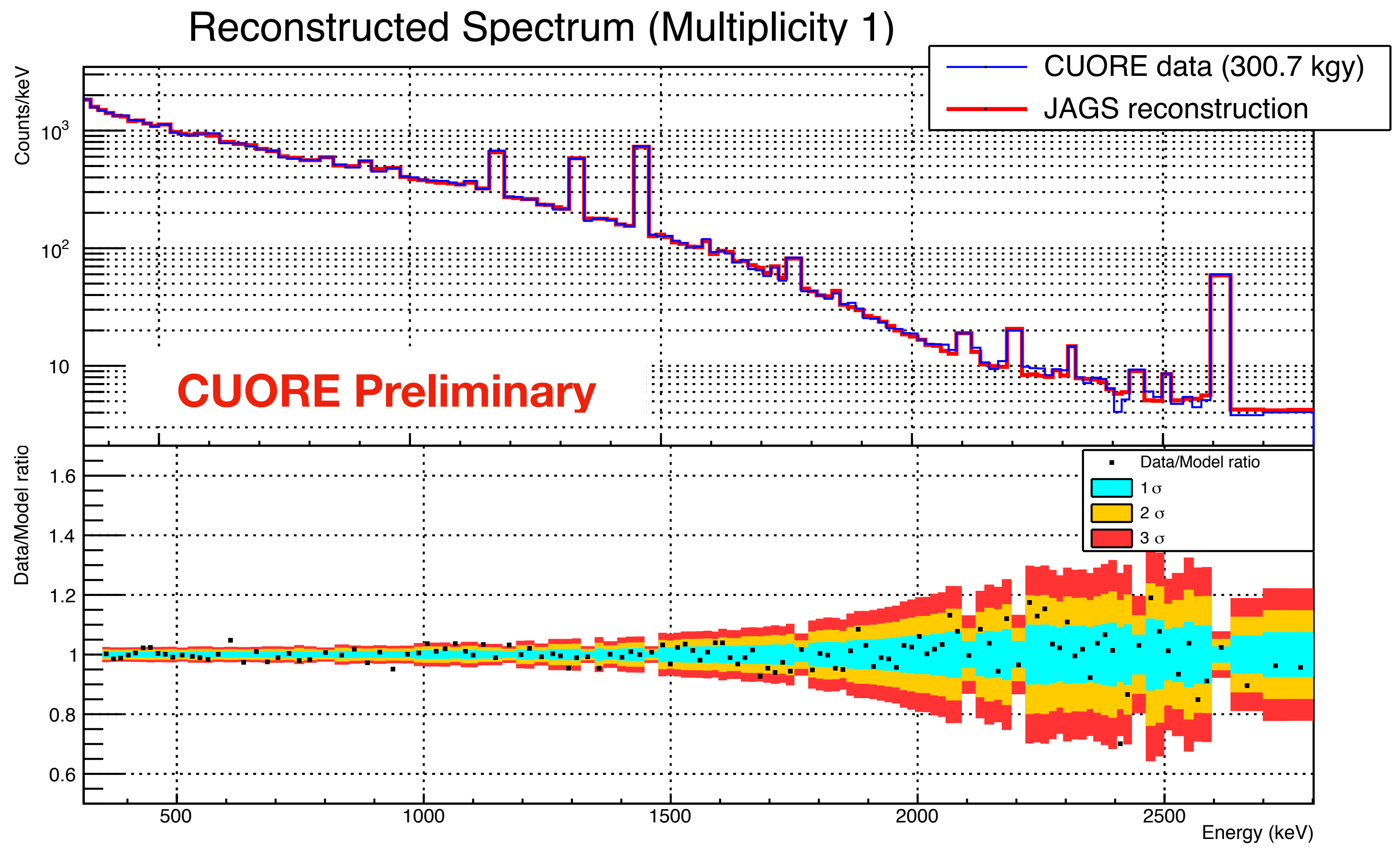
- Parameterization of theory vs experiment mismatch
- Difference between the Gamow-Teller calculation and experimental results in beta-decay motivates quenching
  $g_A^{eff} = q\, g_A$
- Important uncertainty in neutrino-less double beta decay NME
- Ab-initio calculations including two-body / meson-exchange currents and additional nuclear correlations do not need any "quenching"

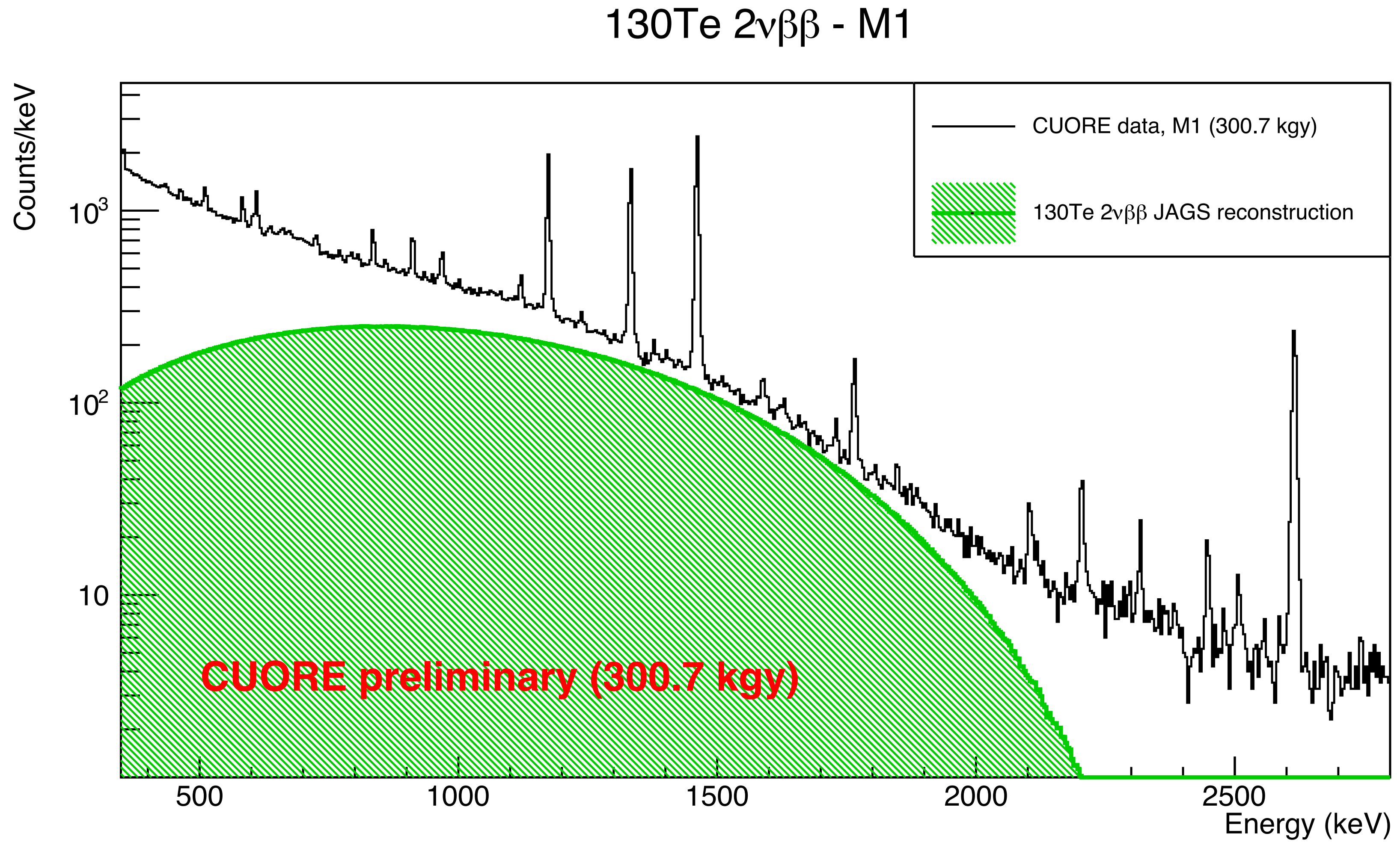




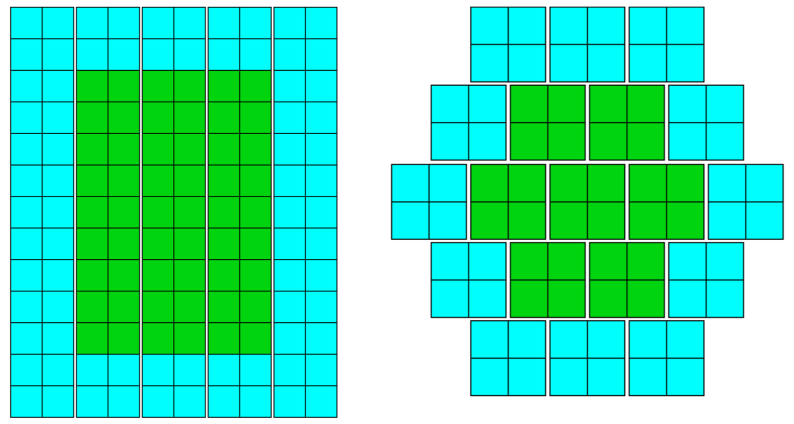
[Gysbers *et al.*, Nature Physics **15**, 428-431 (2019)]

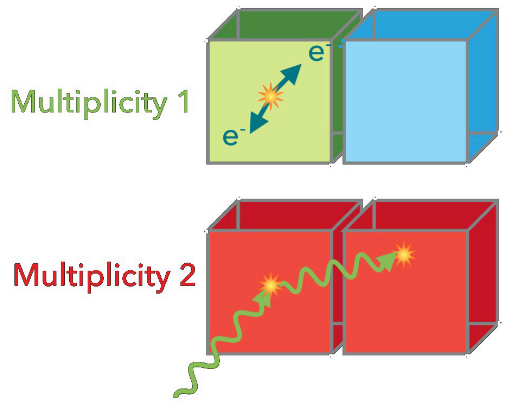
Background model

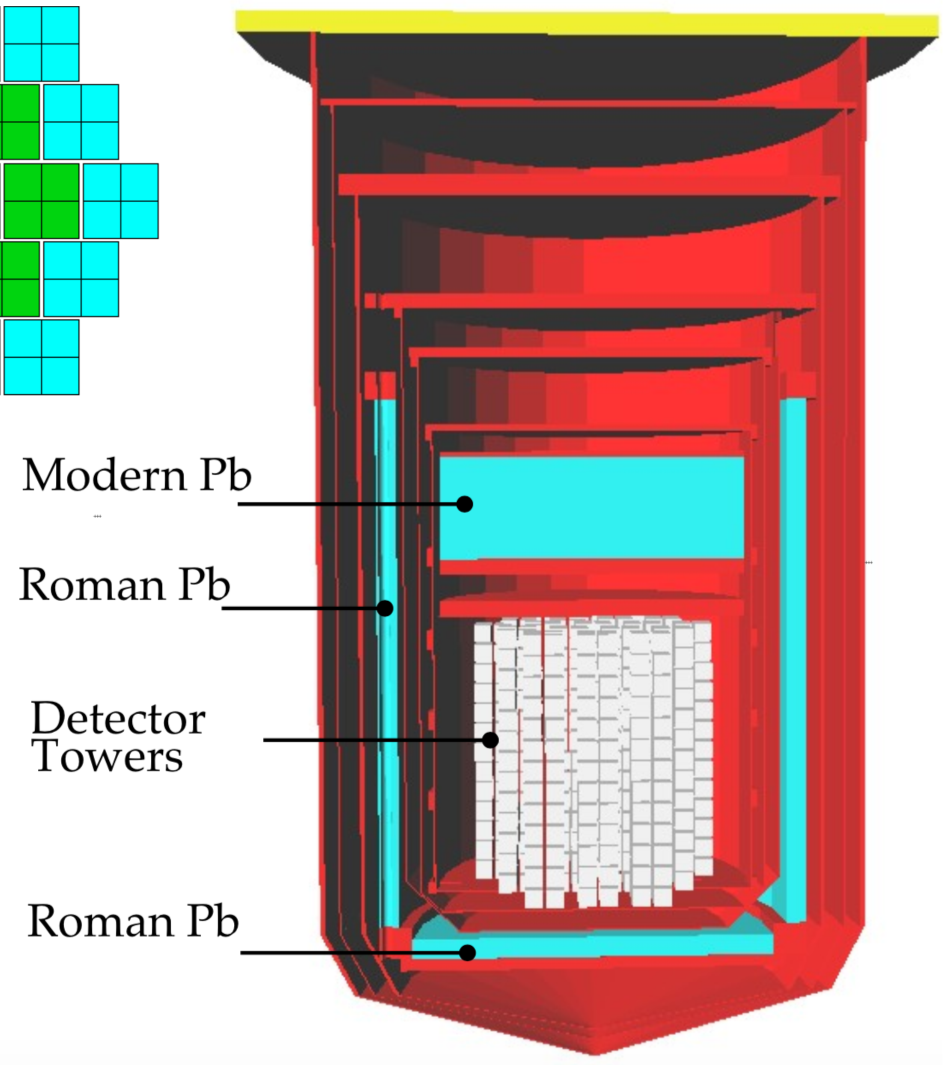




$$T_{1/2}^{2\nu} = [7.71^{+0.08}_{-0.06}(\text{stat.})\,^{+0.17}_{-0.15}(\text{syst.})] \times 10^{20}\ \text{yr}$$







- GEANT4 simulation + detector response function to produce expected spectra
- 62 sources considered, Bayesian fit flat priors (except muons)
- Coincidences and self-shielding exploited to constrain source position

Baryon Asymmetry in the Universe

Sakharov Conditions

- Baryon number violation
- C-symmetry and CP symmetry violation
- Interactions out of thermal equilibrium

$$\eta = \frac{n_B - \bar{n}_B}{n_\gamma} \sim 10^{-10}$$

CP violation in the quark sector is not enough to explain the observed asymmetry

$$\frac{D_{CKM}}{T_{sph}^{12}} \sim 10^{-20} \ll \eta$$

Baryogenesis via leptogenesis is a possibility