LATEST RESULTS FROM THE CUORE EXPERIMENT

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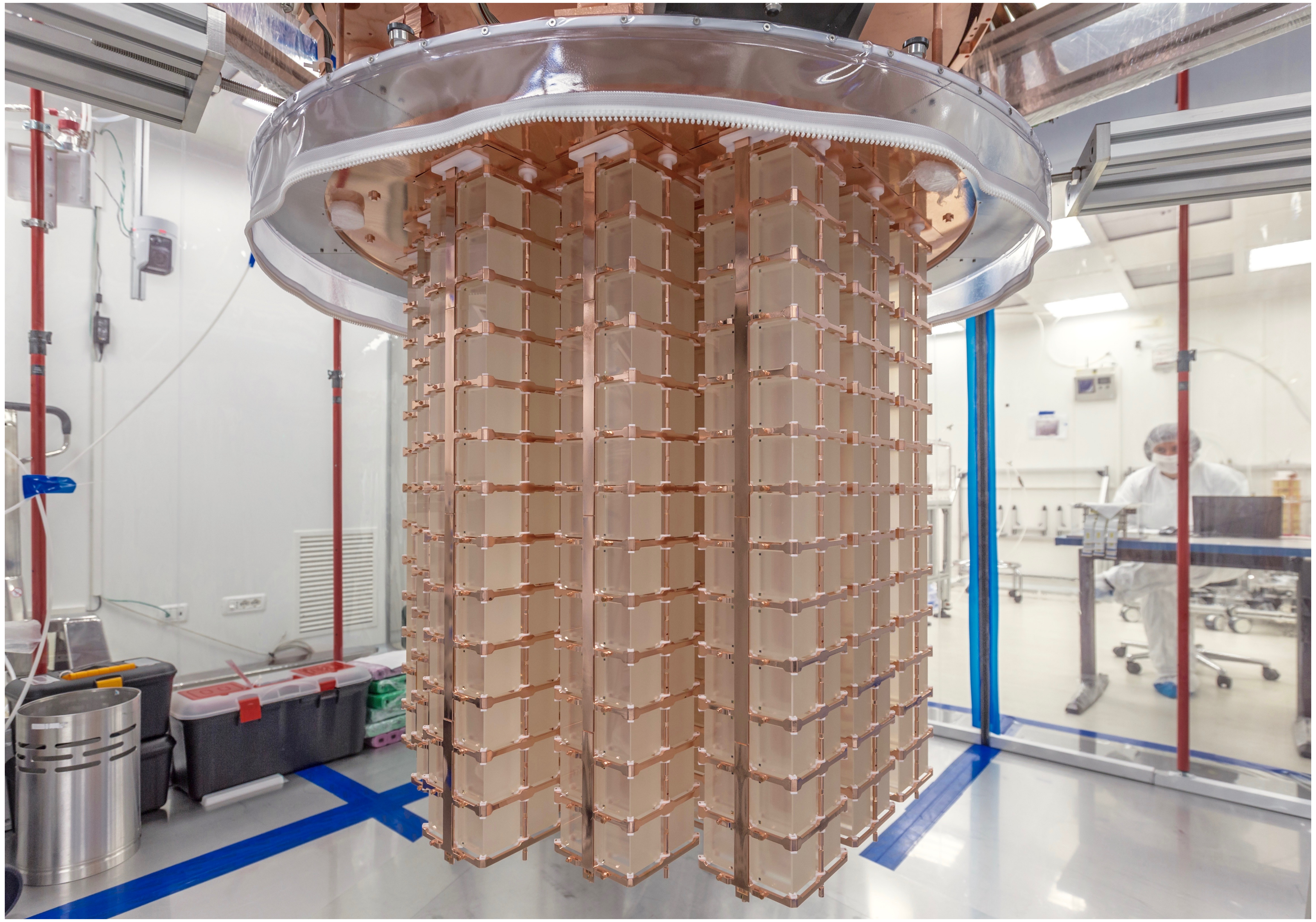
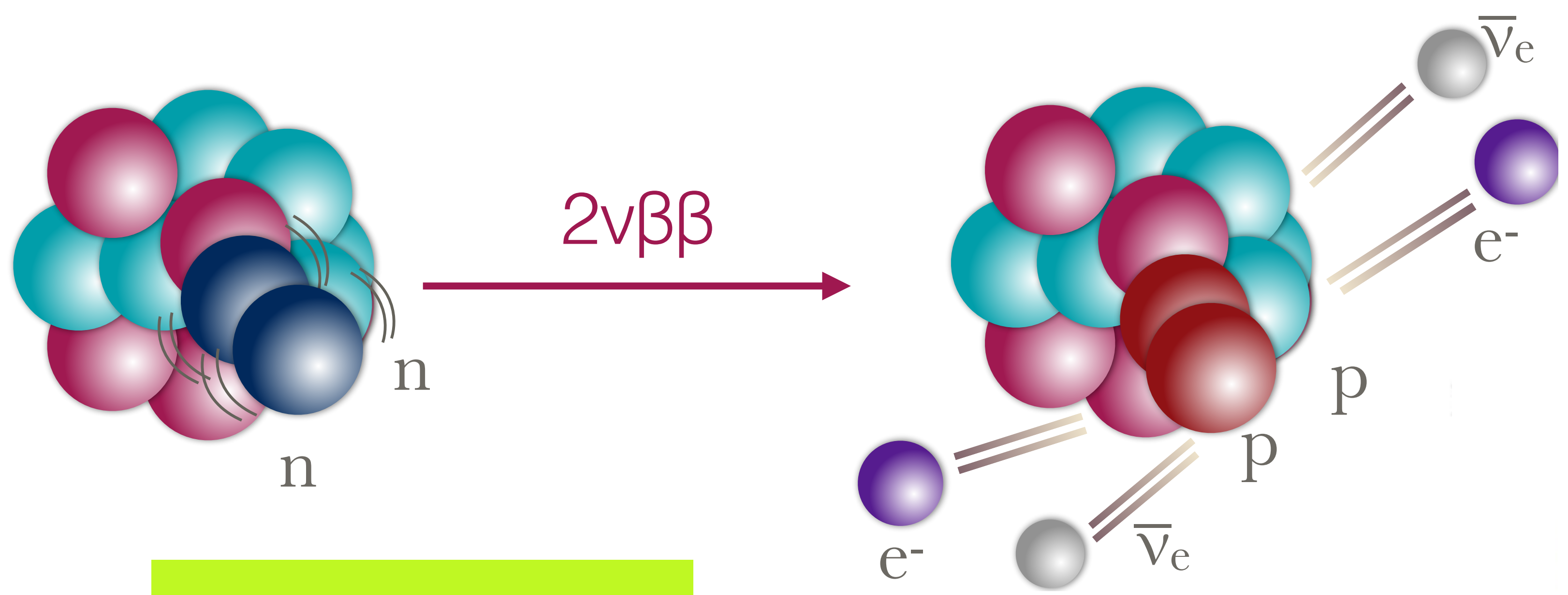
OUTLINE

- Double Beta Decay
- The CUORE experiment
- Detector performance and data analysis
- $0\nu\beta\beta$ results
- Other rare decay searches
- Conclusions

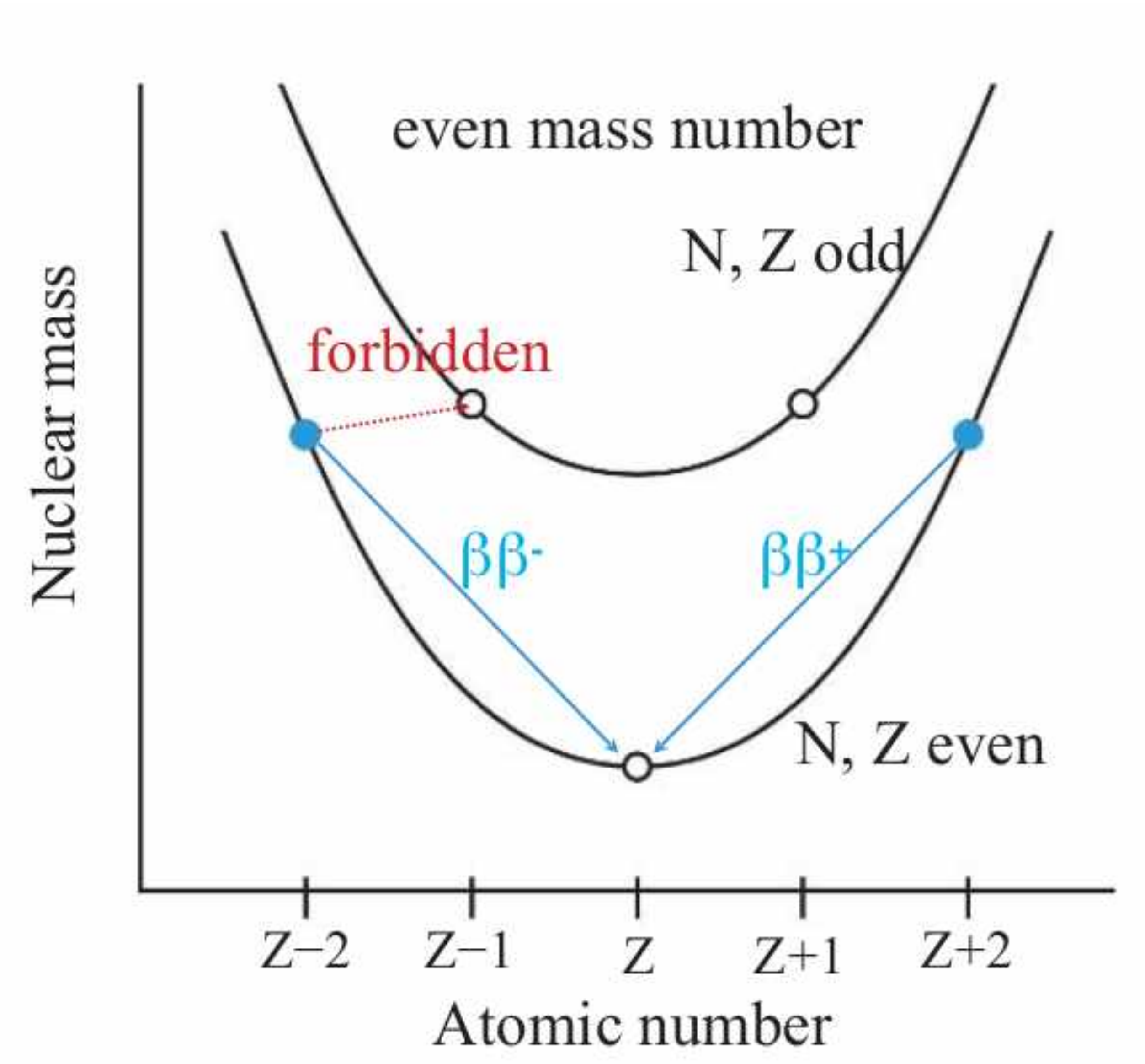


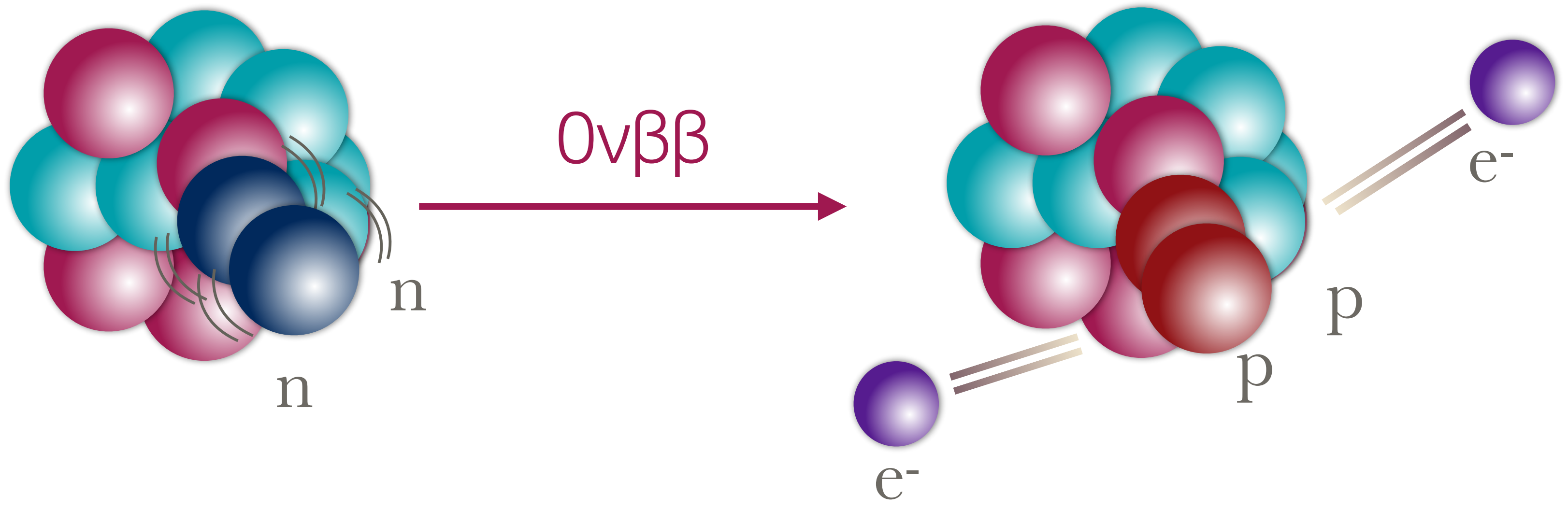
DOUBLE BETA DECAY

CUORE



ΔL = 0
Δ(B-L) = 0





ΔL = 2
Δ(B-L) = -2

(A,Z) → (A,Z+2) + $2e^-$ + $2\overline{\nu}$

2nd order weak process allowed by the SM

Observed in several nuclei with half-life 10^{18} yr - 10^{21} yr

(A,Z) → (A,Z+2) + $2e^-$

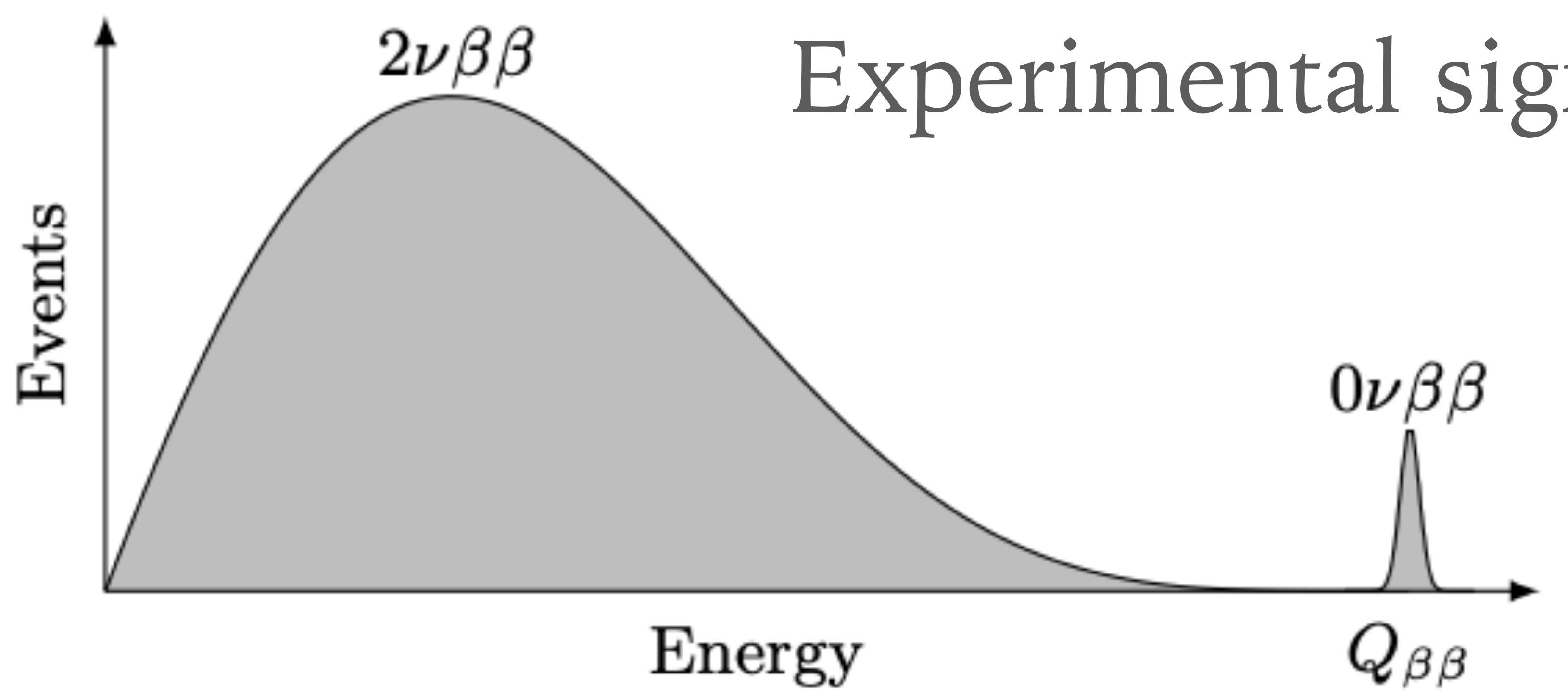
Forbidden by the SM, violates L and B-L

$m_\nu \neq 0$ and $\Psi \equiv \Psi^C$ (unique among fermions)

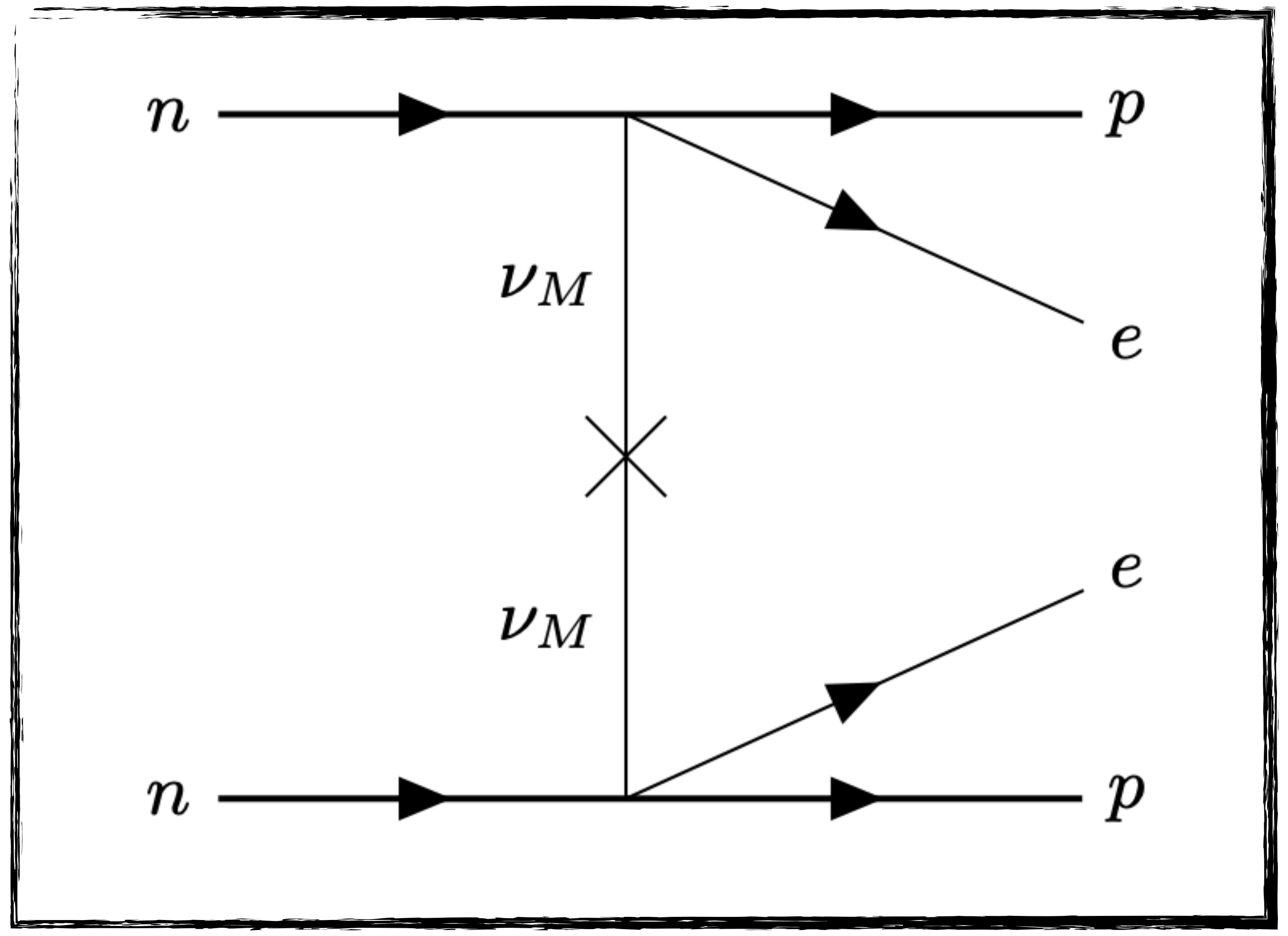
Half-life ≳ $10^{25\text{-}26}$ yr

Link to matter/anti-matter asymmetry in the Universe (?)

THE HALF-LIFE



Experimental signature: peak at the Q-value



Decay mechanism (particle physics) is unknown

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}|M^{0\nu}_{\eta}|^2\eta^2$$

Phase space factor: known with good accuracy from atomic physics. Contains the information on the kinematics in the final state.

Nuclear matrix element (nuclear physics) is affected by a large uncertainty

- If mediated by light Majorana neutrinos, constraints on neutrino mass ordering and scale

$$m_{\beta\beta} = |\sum_i m_i \cdot U^2_{ie}|$$

EXPERIMENTAL SENSITIVITY

CUORE

- Probed half-lives so far are of the order of 10^{25} - 10^{26} y, many orders of magnitude longer than the age of the Universe;
- Experiments have to monitor thousands of moles of atoms for years and be able to detect the decay in a single one of them.

Half-life corresponding to the minimum number of detectable signal events above background at a given C.L.

$$T_{0\nu} \propto i.a. \sqrt{\frac{M \cdot T}{\Delta E \cdot b}}$$

Detector mass

Isotopic abundance

Measuring time

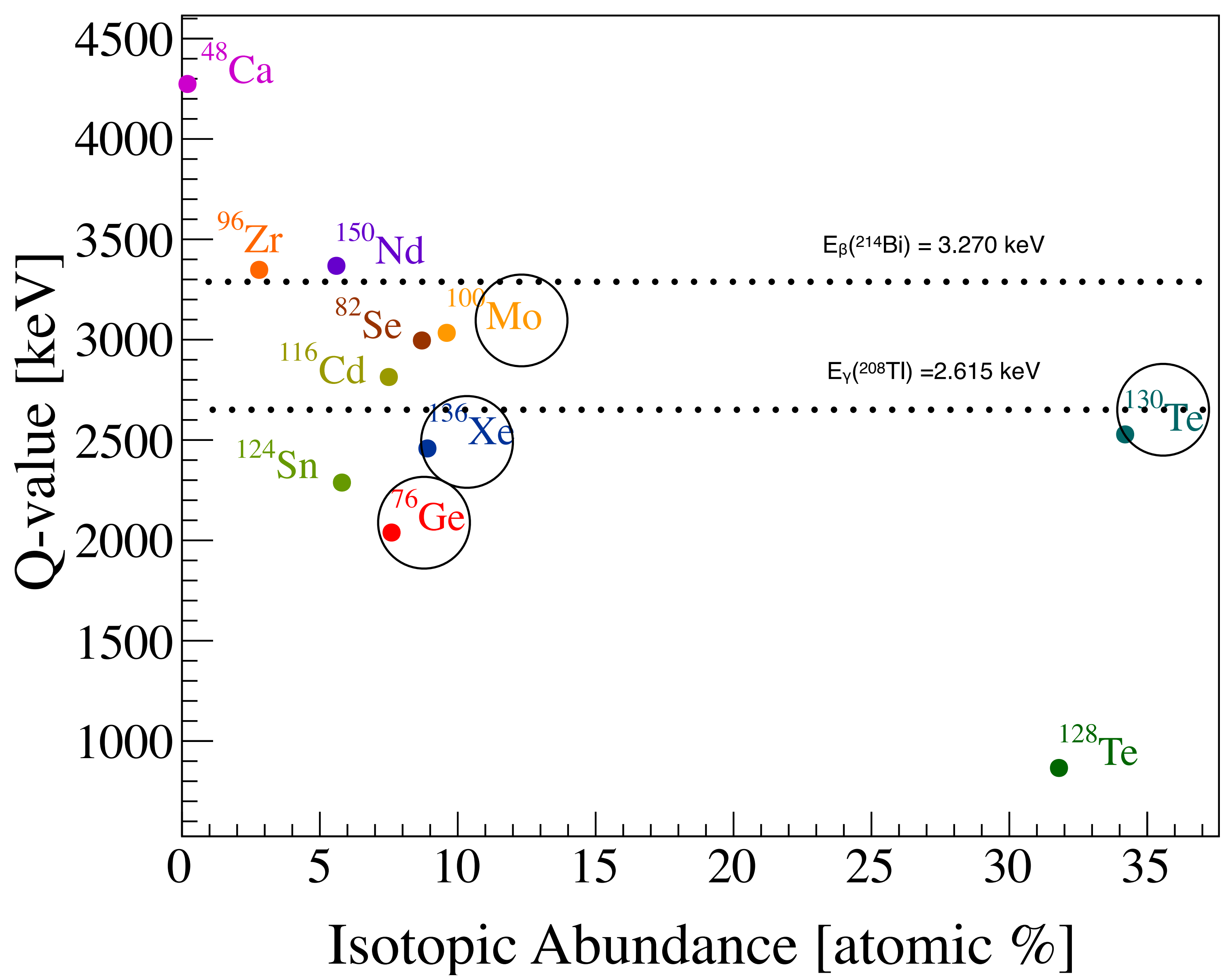
Energy resolution

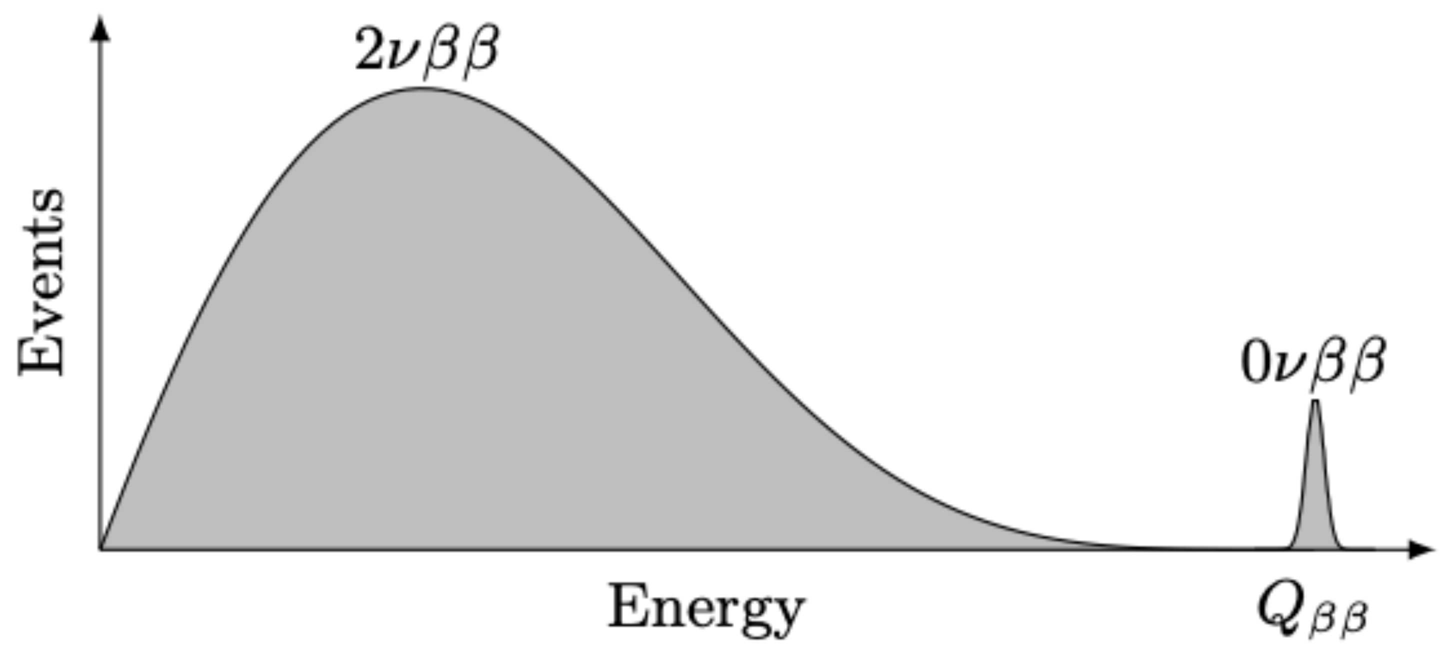
Background

EXPERIMENTAL SENSITIVITY

- Isotopic abundance → enrichment
- Exposure (M·T) → tons of isotope
- Energy resolution:
  - high (‰ of $Q_{\beta\beta}$)
  - low (% of $Q_{\beta\beta}$)

IMPORTANT TO MITIGATE IRREDUCIBLE BKG FROM $2\nu\beta\beta$ DECAY AND IDENTIFY AND DISENTANGLE THE VARIOUS CONTRIBUTION TO THE BACKGROUND





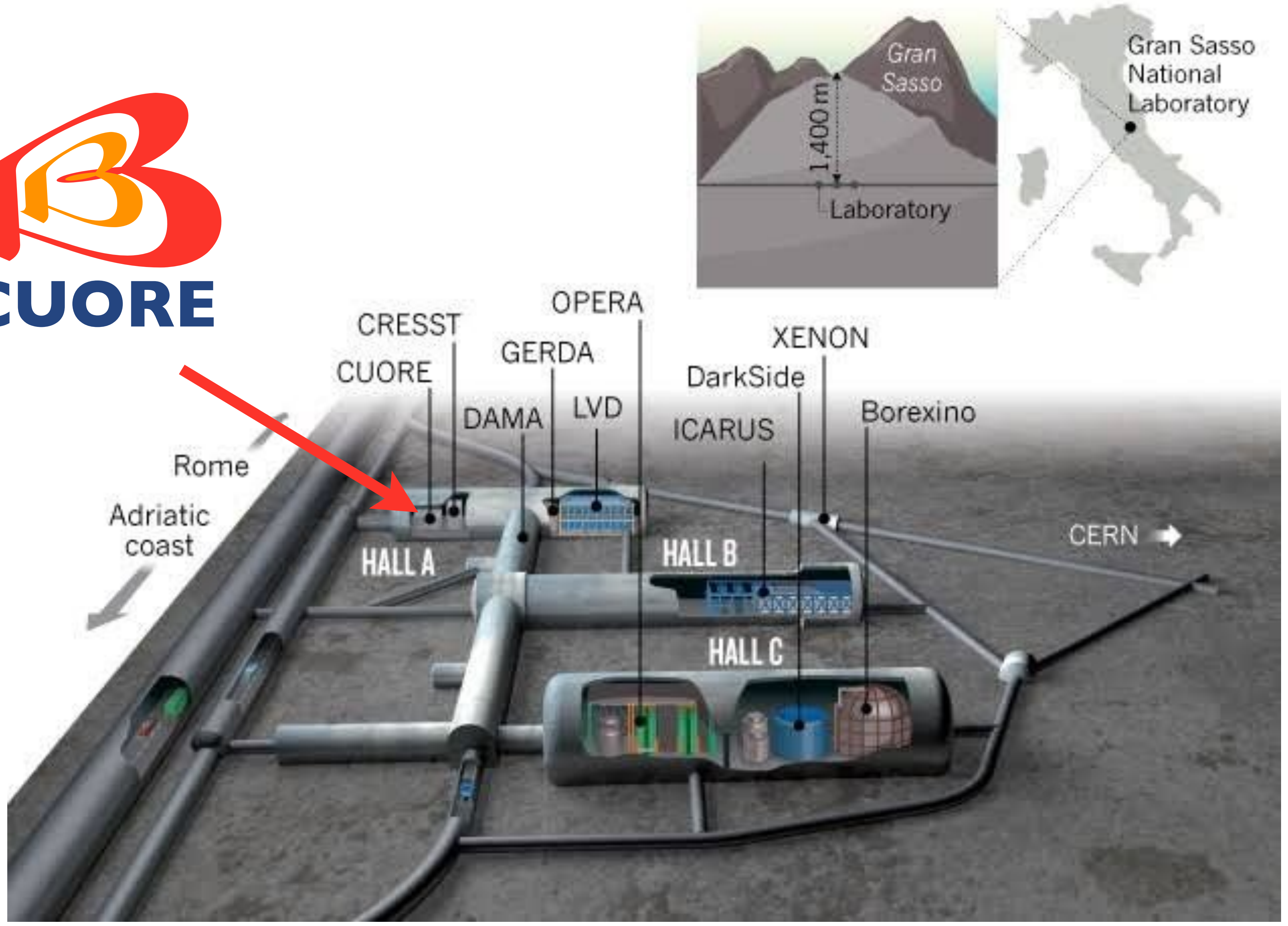
Background

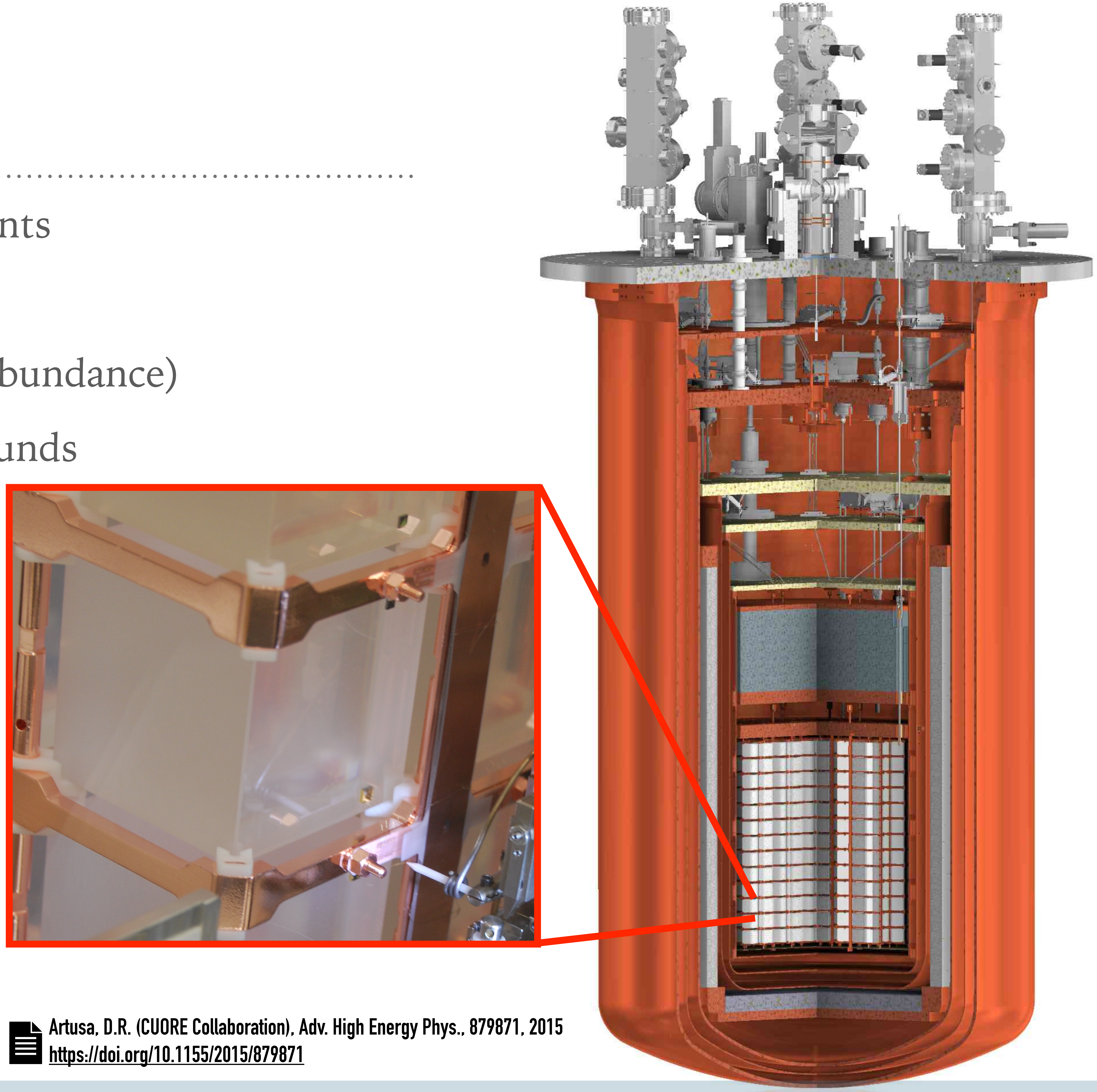
- external background: neutrons, gammas and cosmic ray fluxes from the environment
- internal background: trace amounts of radioactivity in the detectors and the materials constituting the experimental apparatus
- 2-neutrino double beta decay of the same isotope
  - events leaking from the 2ν continuum spectrum
  - pile-up

THE CUORE EXPERIMENT

- Cryogenic Underground Observatory for Rare Events
- 988 $^{nat}TeO_2$ crystals at ~10 mK
- 742 kg TeO_2 , 206 kg ^{130}Te (34% natural isotopic abundance)
- $Q_{\beta\beta}$ = 2527.5 keV above (most) natural γ backgrounds

CUORE

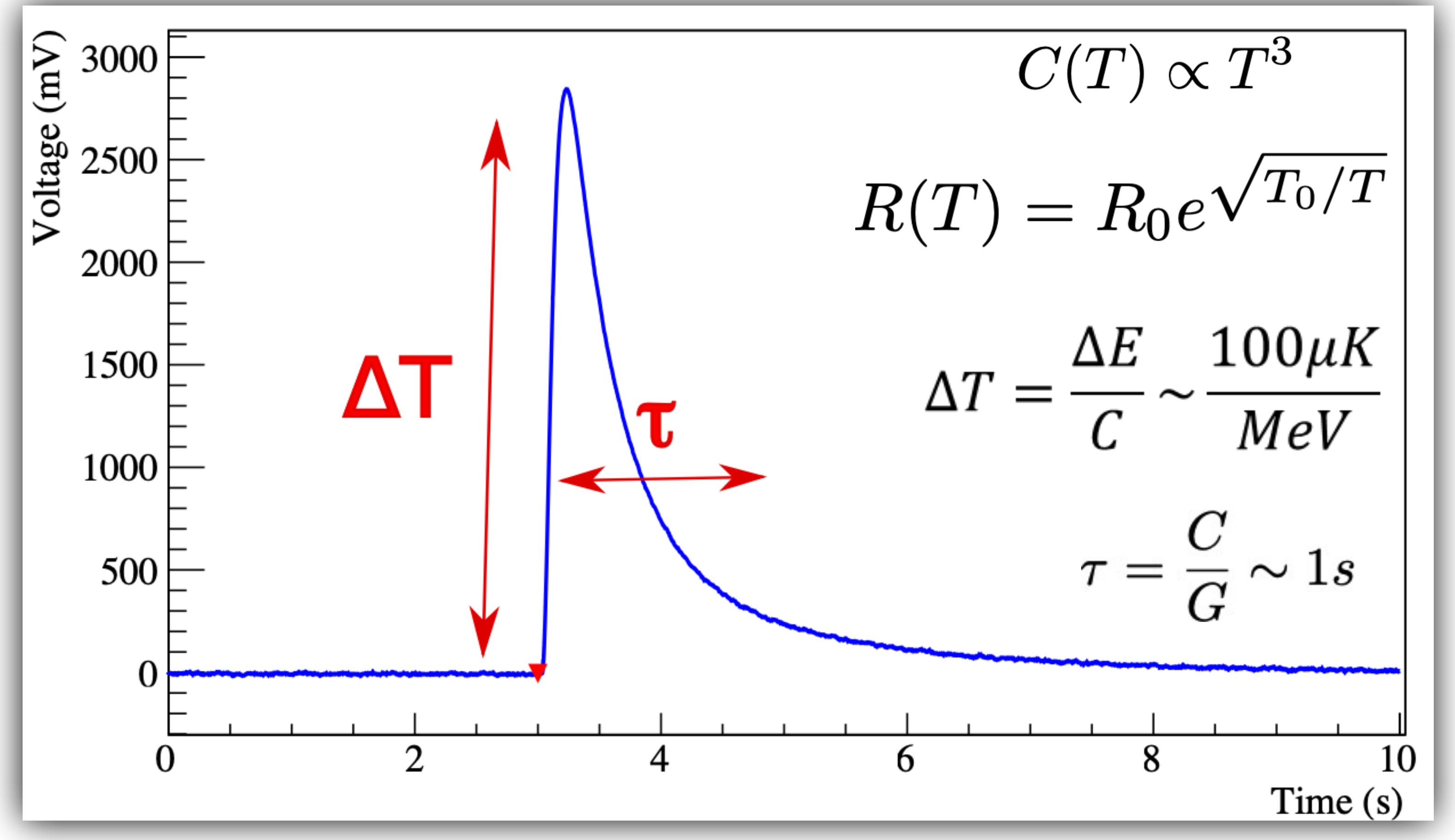


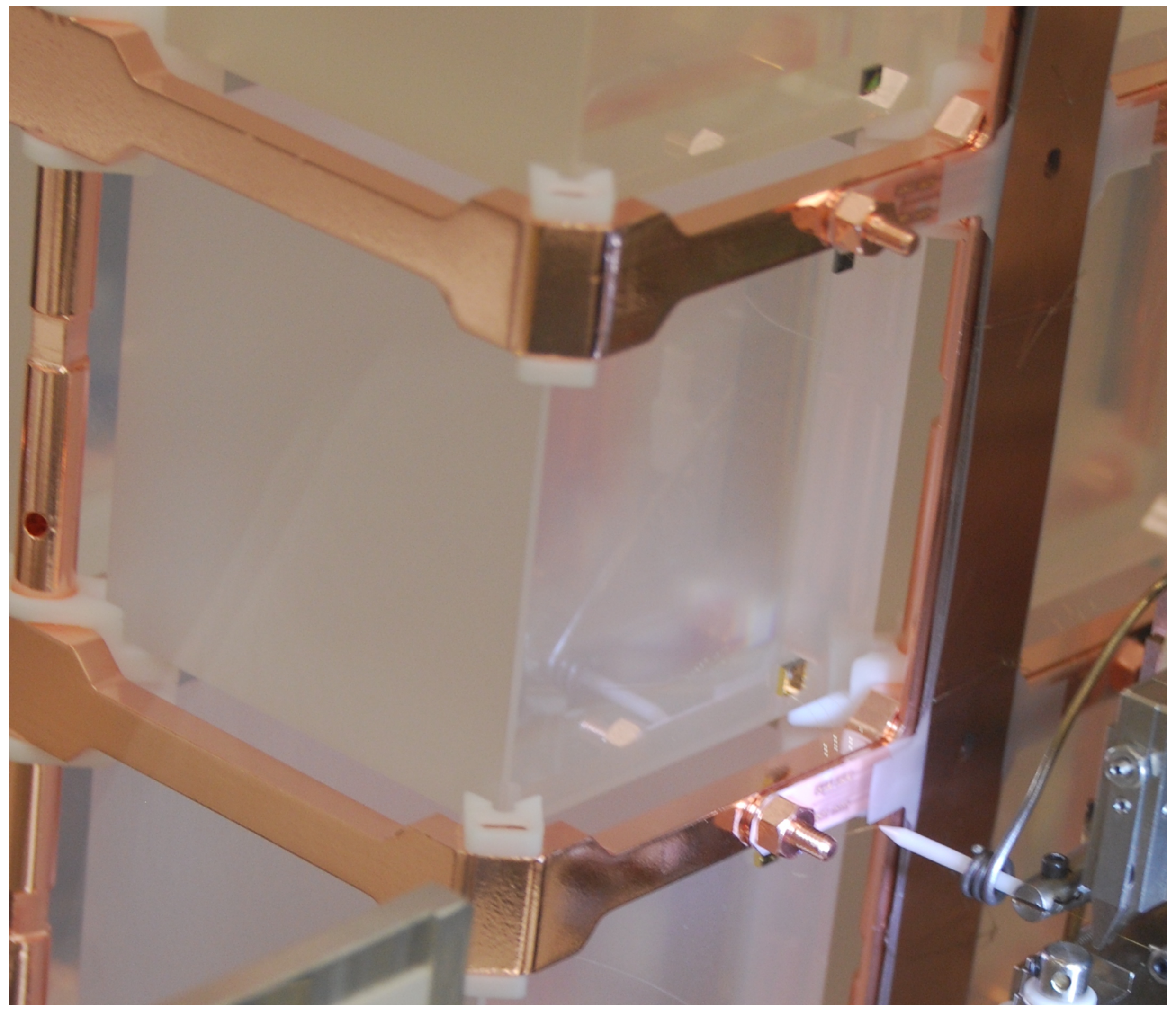


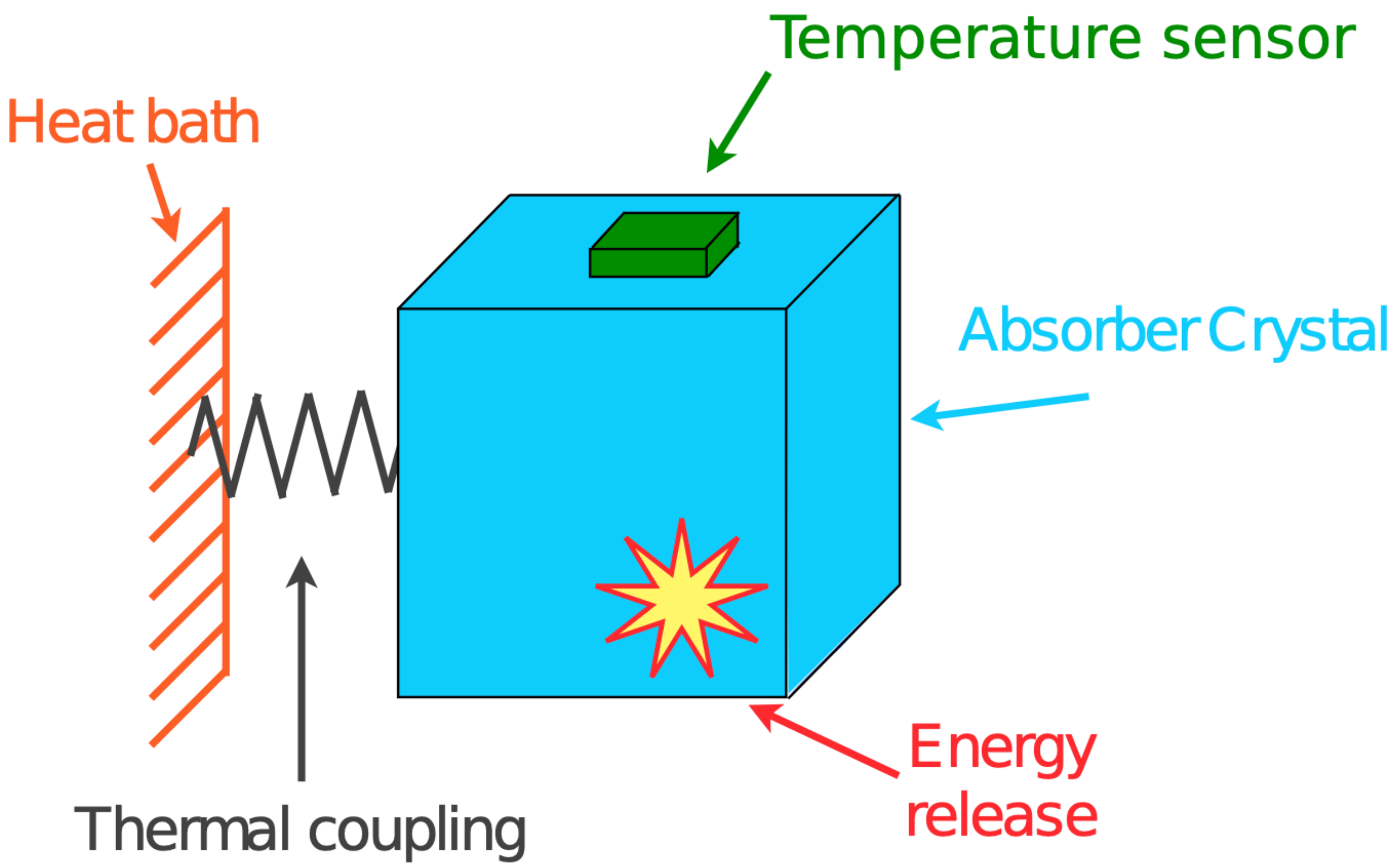
Artusa, D.R. (CUORE Collaboration), Adv. High Energy Phys., 879871, 2015
https://doi.org/10.1155/2015/879871

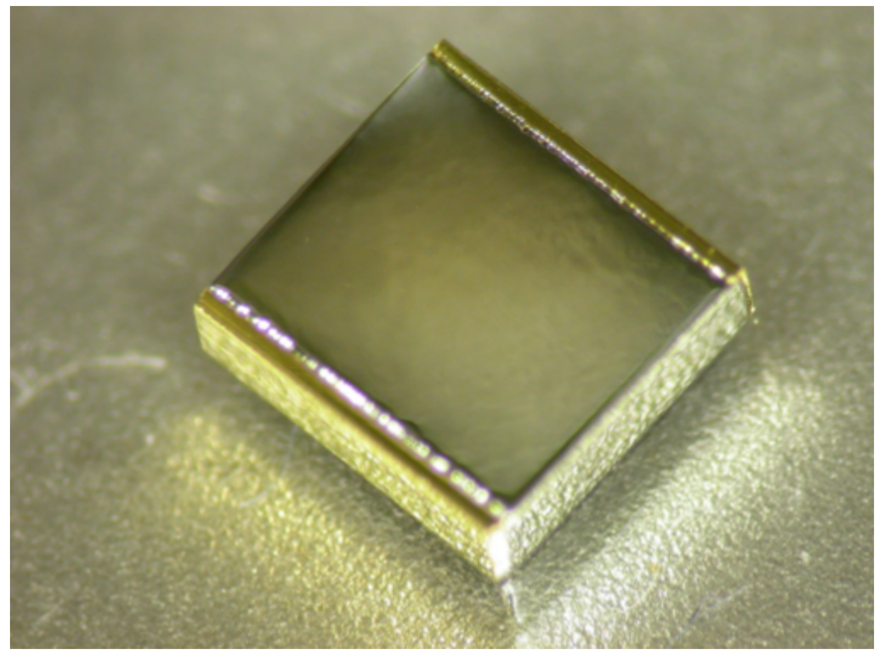
CRYOGENIC BOLOMETERS

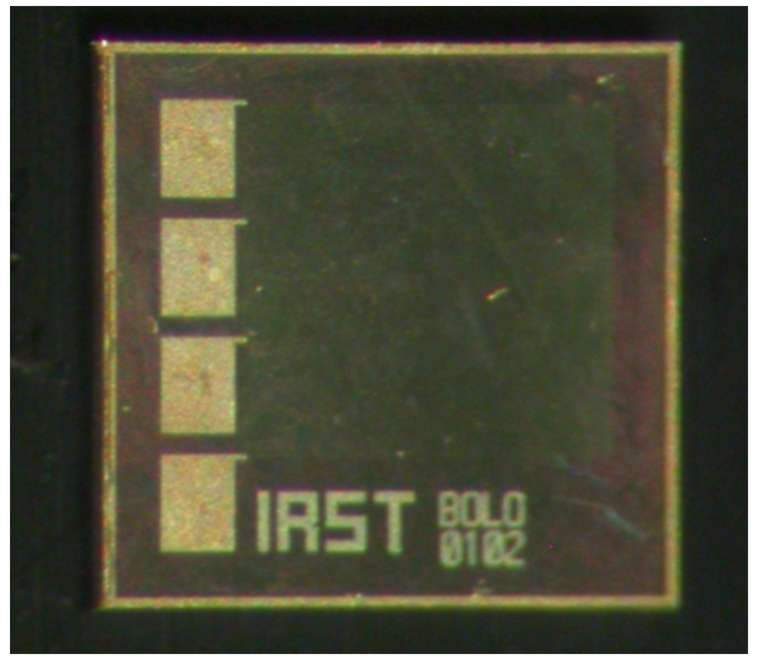
CUORE











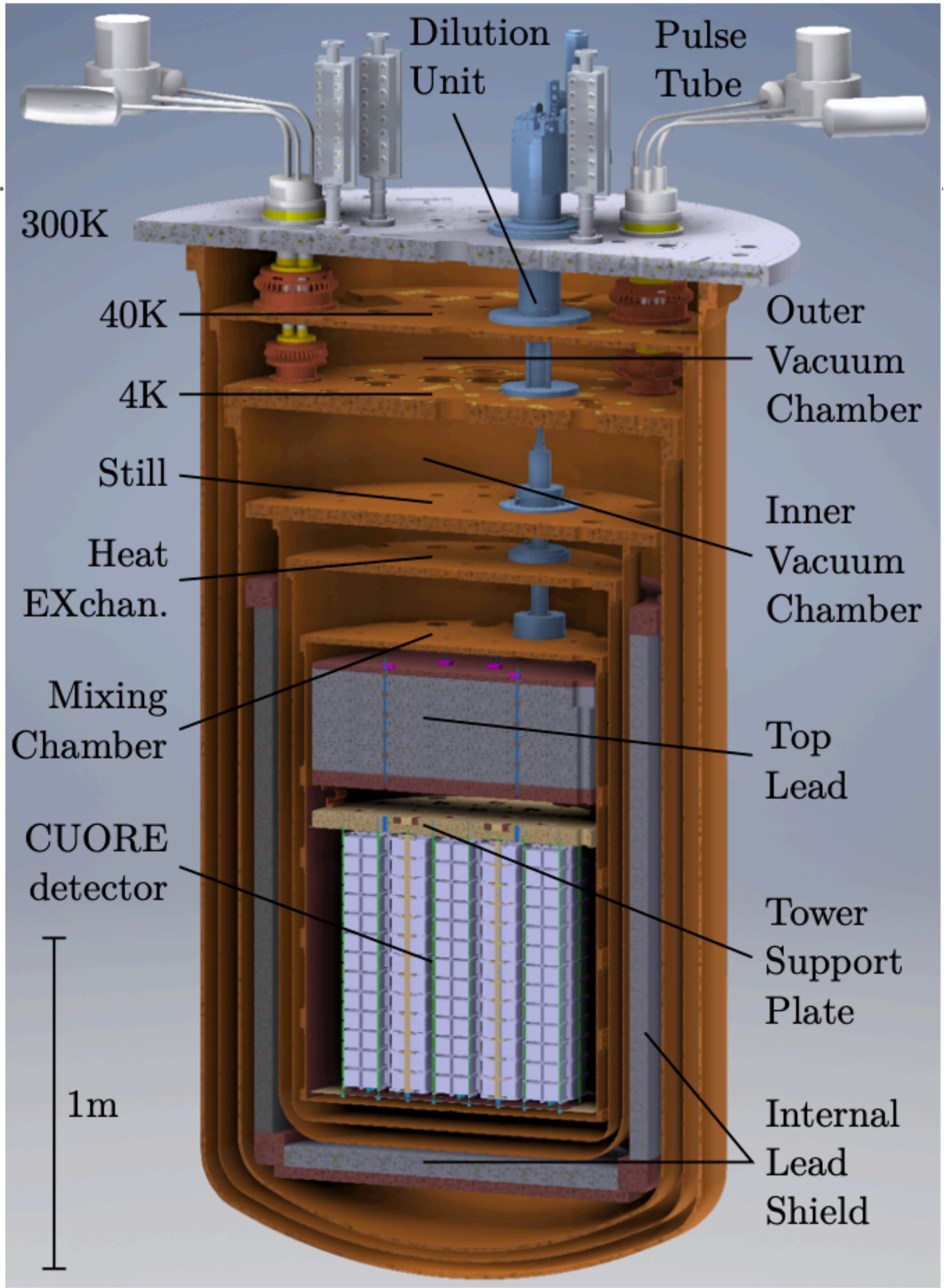
- NTD Ge thermistors biased with constant current
- Si heaters
- weak thermal link to heat bath
- particle interactions heat crystals up
- voltage pulses induced in NTDs

Alduino, C. et al. (CUORE Collaboration), J. Inst. 11(07), P07009, 2016
https://doi.org/10.1088/1748-0221/11/07/p07009

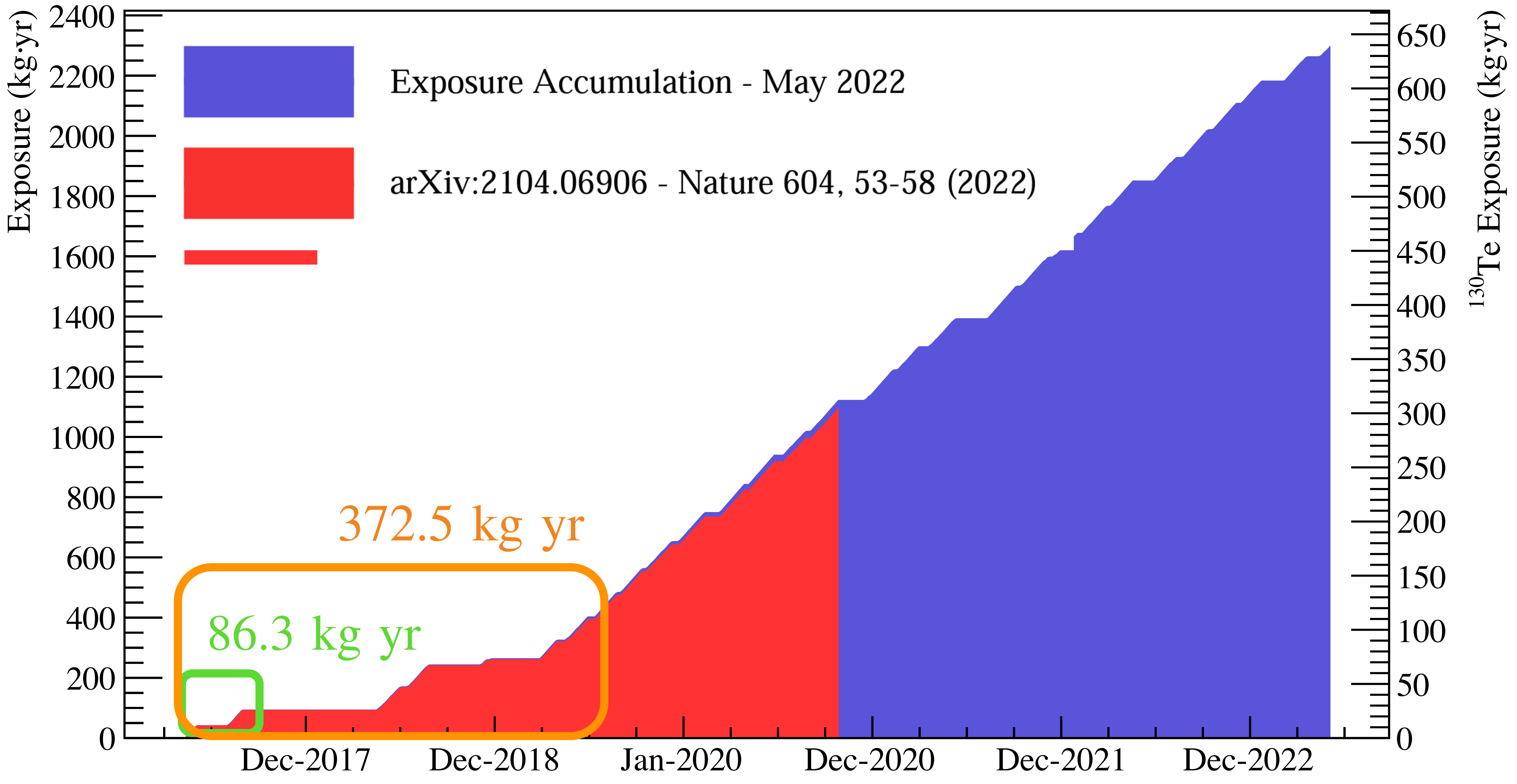
Vignati, M., J. Appl. Phys. 108, 084903, 2010
https://doi.org/10.1063/1.3498808

THE CUORE CRYOSTAT

- Custom made dilution refrigerator
  ~ 10 mK base temperature
- 5 pulse tube cryocoolers (no helium bath)
- Nested copper vessels at decreasing temperatures
- Low temperature lead shielding (top)
- Low temperature roman lead shielding (side, bottom)



CUORE DATA TAKING



Alduino, C. et al. (CUORE Collaboration), Phys. Rev. Lett. 120, 132501, 2018
https://doi.org/10.1103/PhysRevLett.120.132501

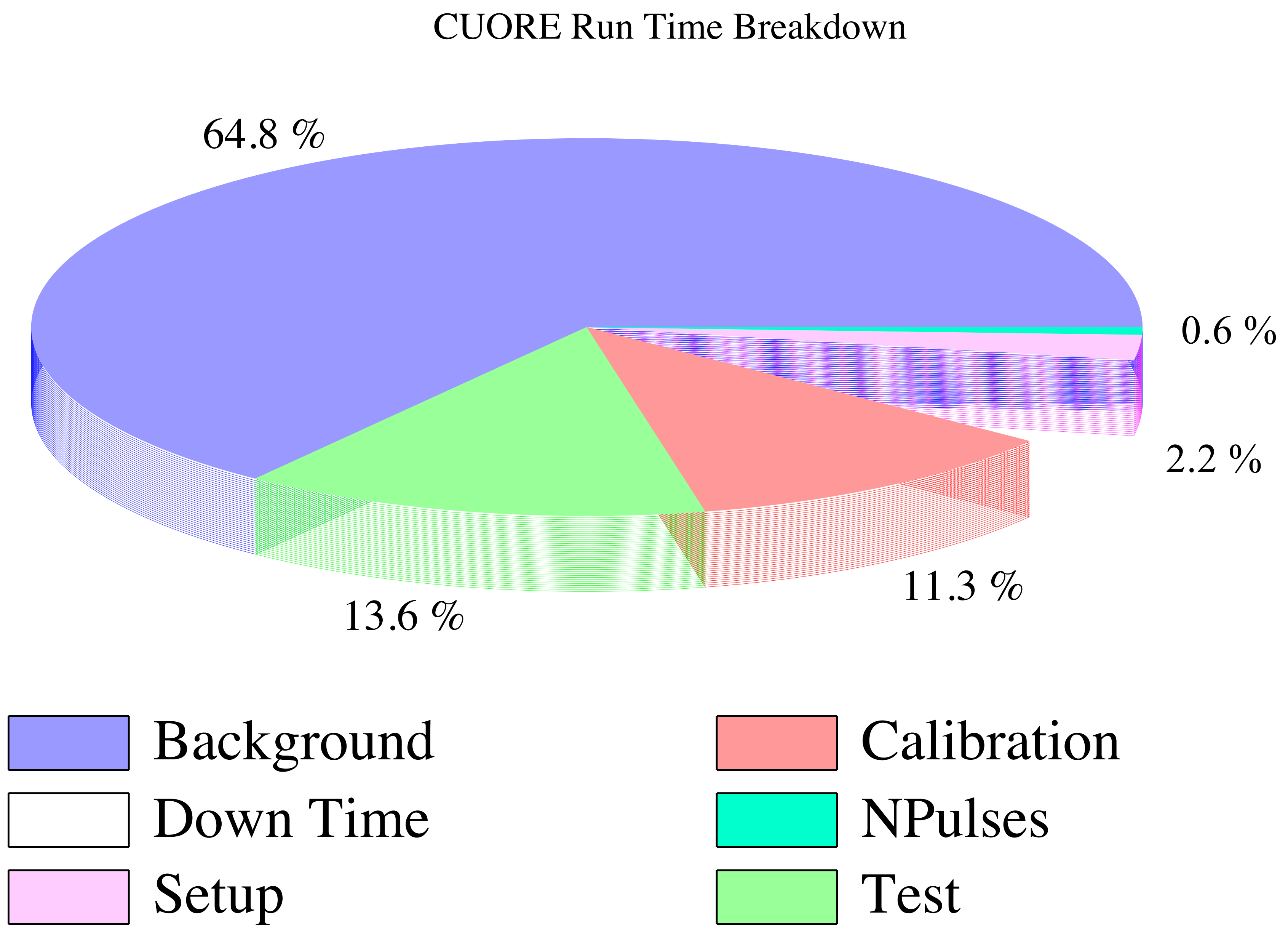
Adams, D.Q. et al. (CUORE Collaboration), Phys. Rev. Lett. 124, 122501, 2020
https://doi.org/10.1103/PhysRevLett.124.122501

1 ton × yr data analysed and published

- Data taking started in 2017
- Optimization campaigns improved understanding and stability of the experiment
- Since march 2019 steady data taking with >90% uptime
- steadily collecting data at an average rate of ~ 50 - 60 kg × yr / month
- > 2 ton × yr raw exposure collected
- 2 ton × yr exposure being reprocessed now

CUORE DATA TAKING

- CUORE "data set": 1 month of background (physics) data taking, few days of calibration before and after



- Voltage output continuously sampled (1 kHz) and stored on disk
- Periods with unstable data taking conditions excluded (e.g. earthquakes)

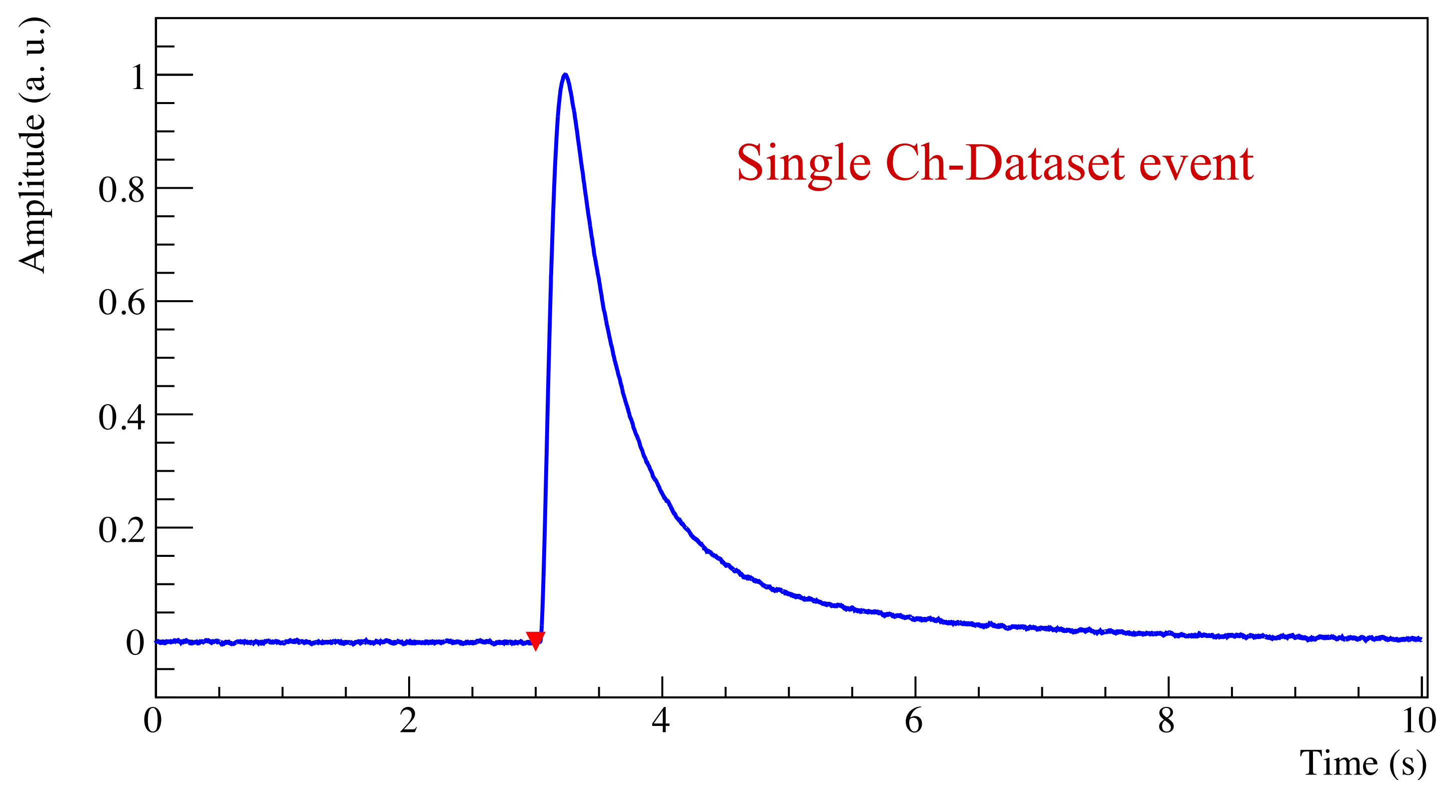
Operational performance:

- *operating $T = 11 - 15$ mK*
- *99.5% of channels active (984/988)*

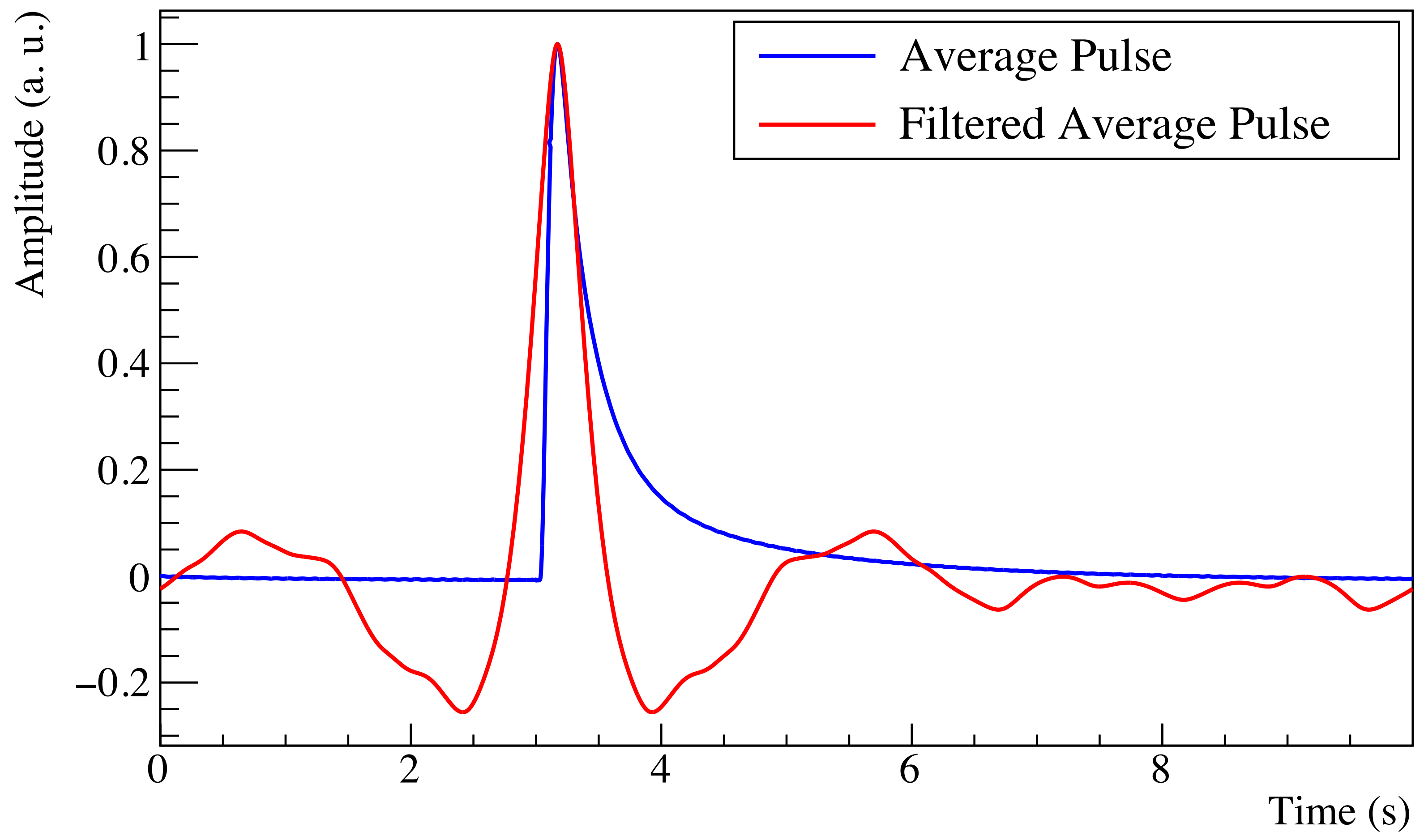
Year-long cryogenic stability!

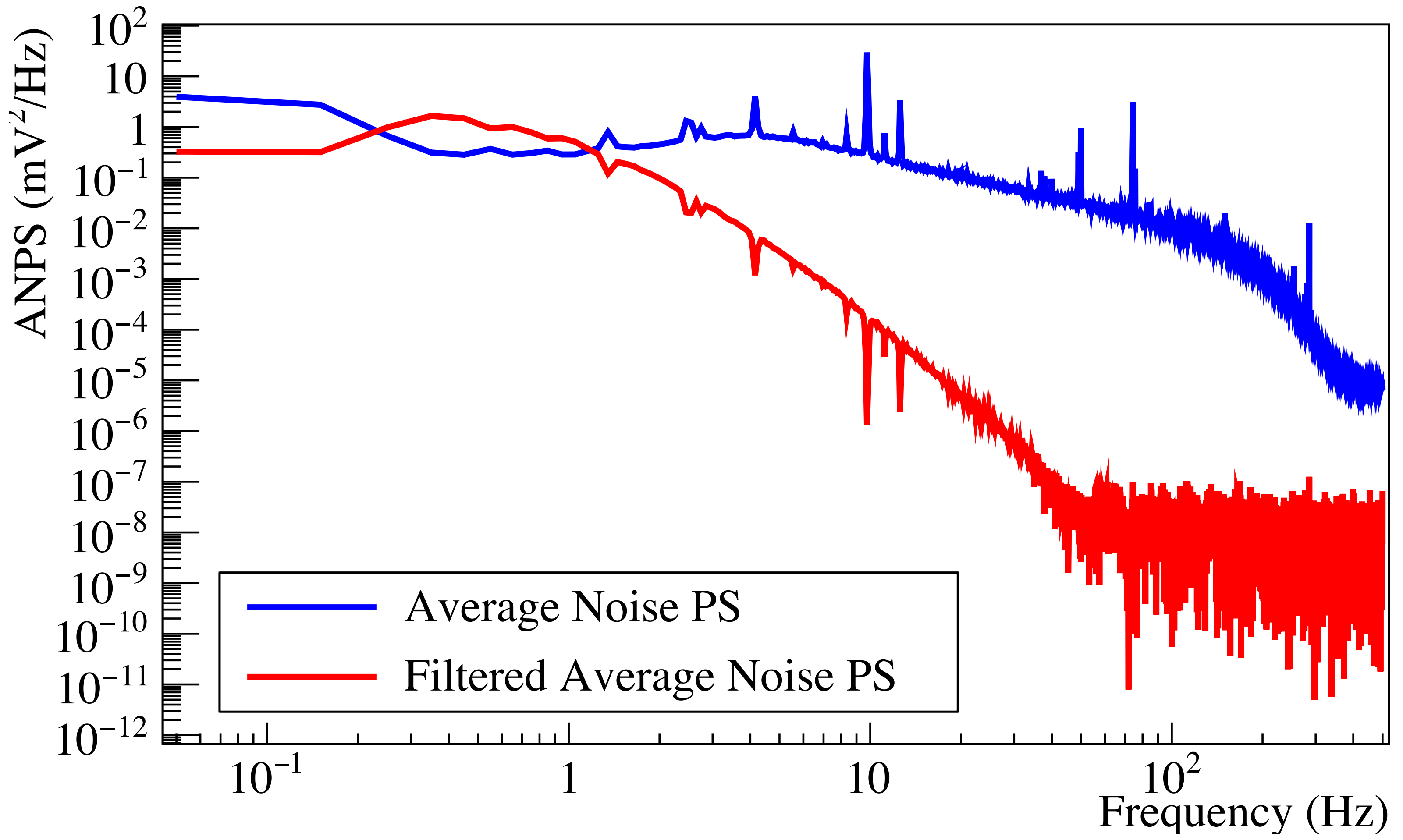
CUORE DATA ANALYSIS

- **Trigger**
- **Optimum Filter**
- Gain Correction
- Energy Calibration
- Coincidences
- Pulse Shape Discrimination (PSD)
- Blinding



- Derivative trigger: online analysis for quick data quality feedback
- Offline re-triggering (Optimum Trigger)
  - disentangle small signals from noise fluctuations
  - lower threshold





Matched filter maximizes signal-to-noise ratio

CUORE DATA ANALYSIS

- Trigger
- Optimum Filter
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- **Energy Calibration**
- Coincidences
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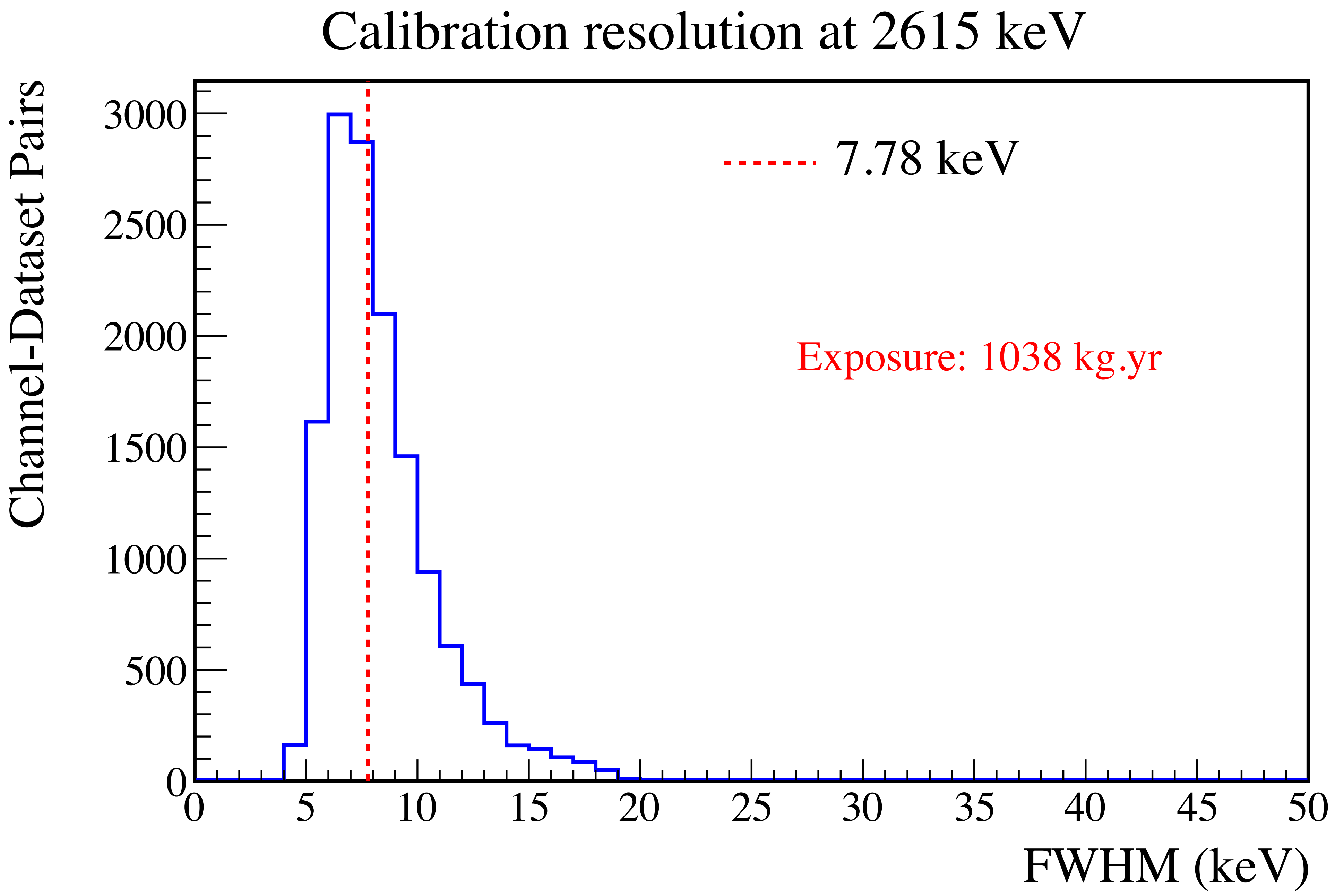
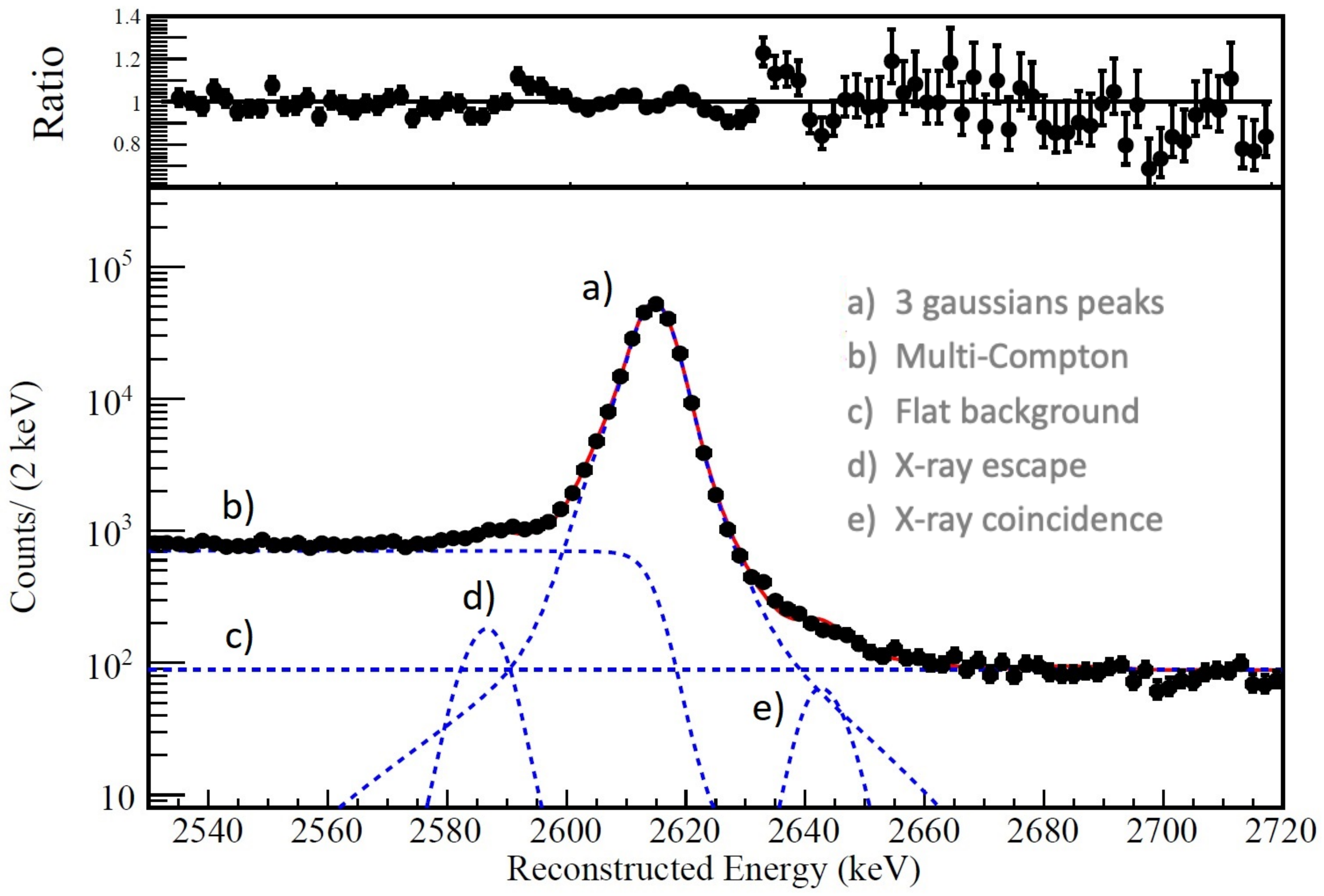
➤ Calibration performed with external ^{232}Th-^{60}Co source



Calibration FWHM resolution
(7.78 ± 0.03) keV at 2615 keV
Background resolution rescaled to the Q_{value} (7.8 ± 0.5) keV at 2527 keV

Detector Response modelled on the 2615 keV line from ^{232}Th chain. Accounts for non idealities.



CUORE DATA ANALYSIS

- Trigger
- Optimum Filter
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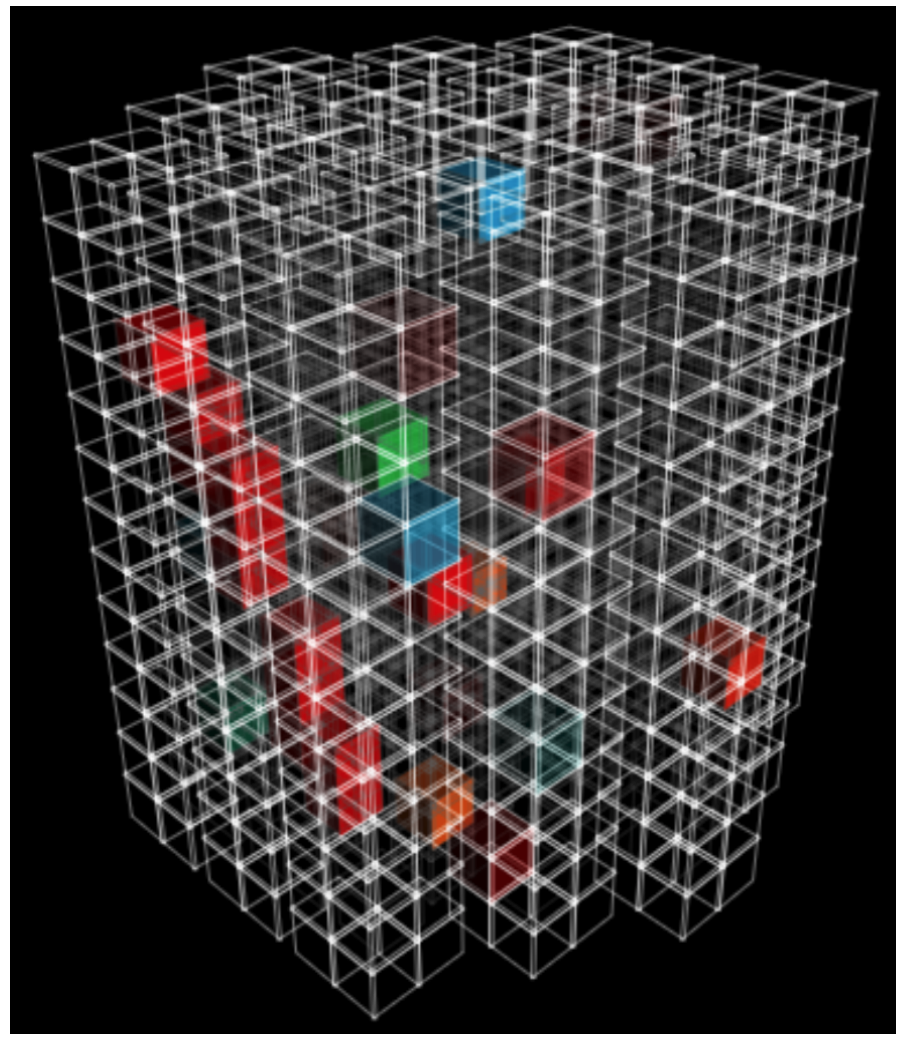
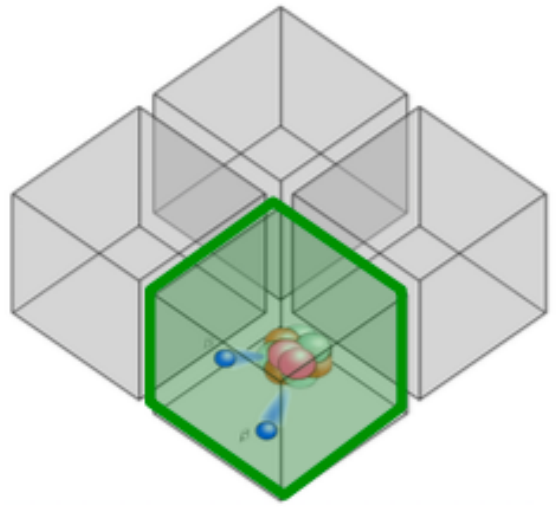
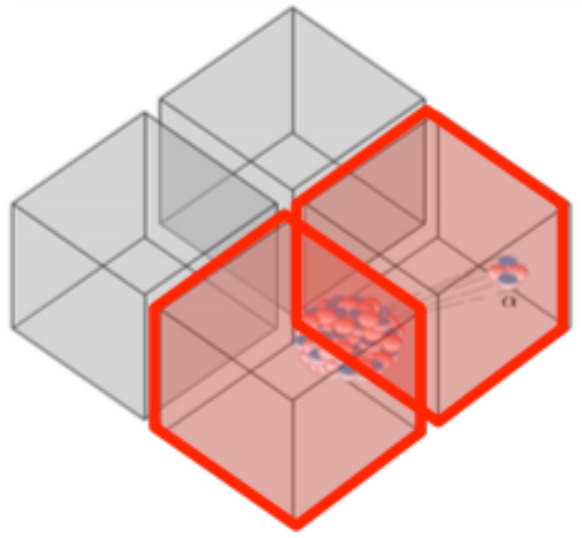
- Energy Calibration
- **Coincidences**
- **Pulse Shape Discrimination (PSD)**
- Blinding





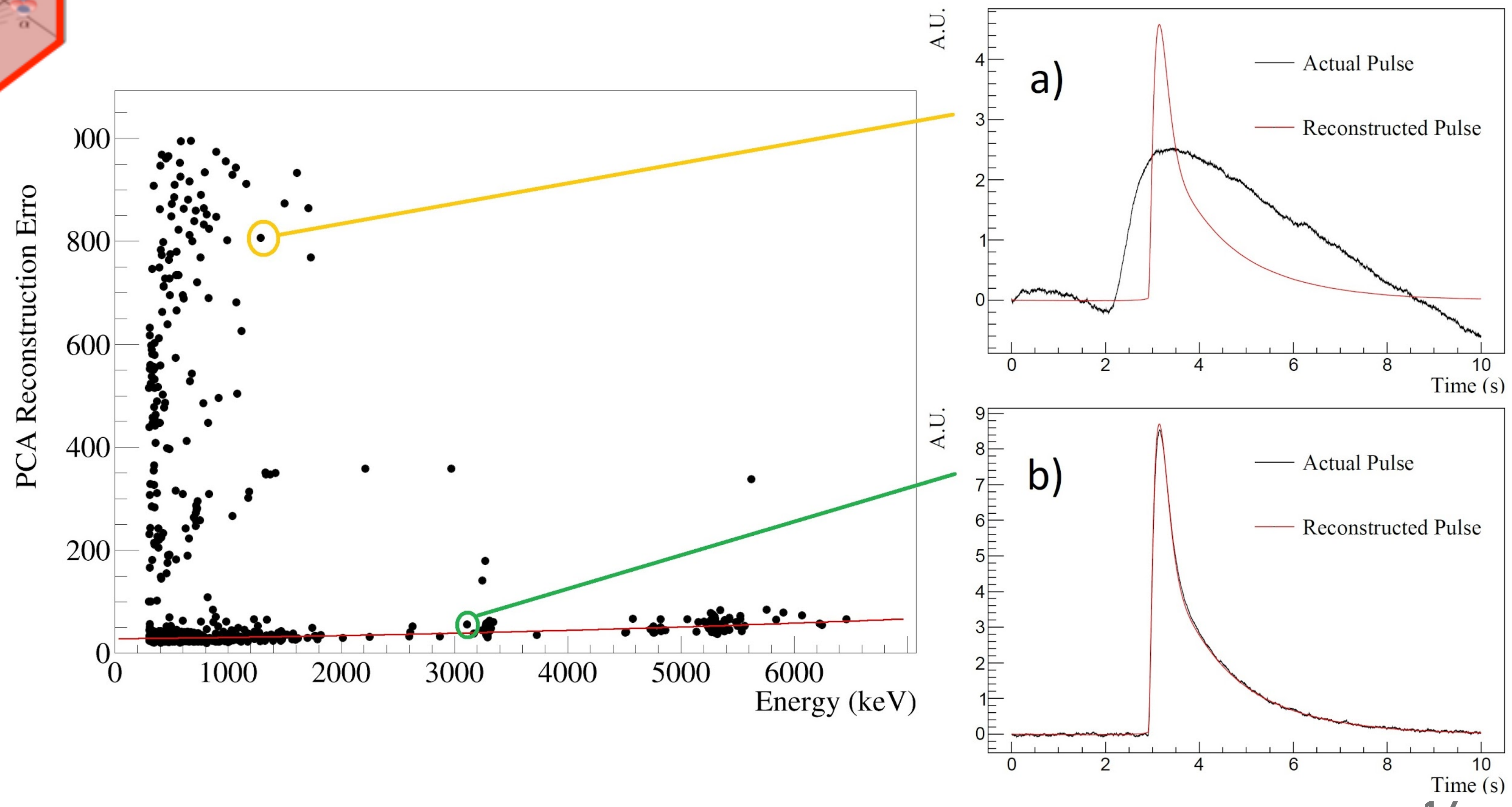
single-site (signal-like)



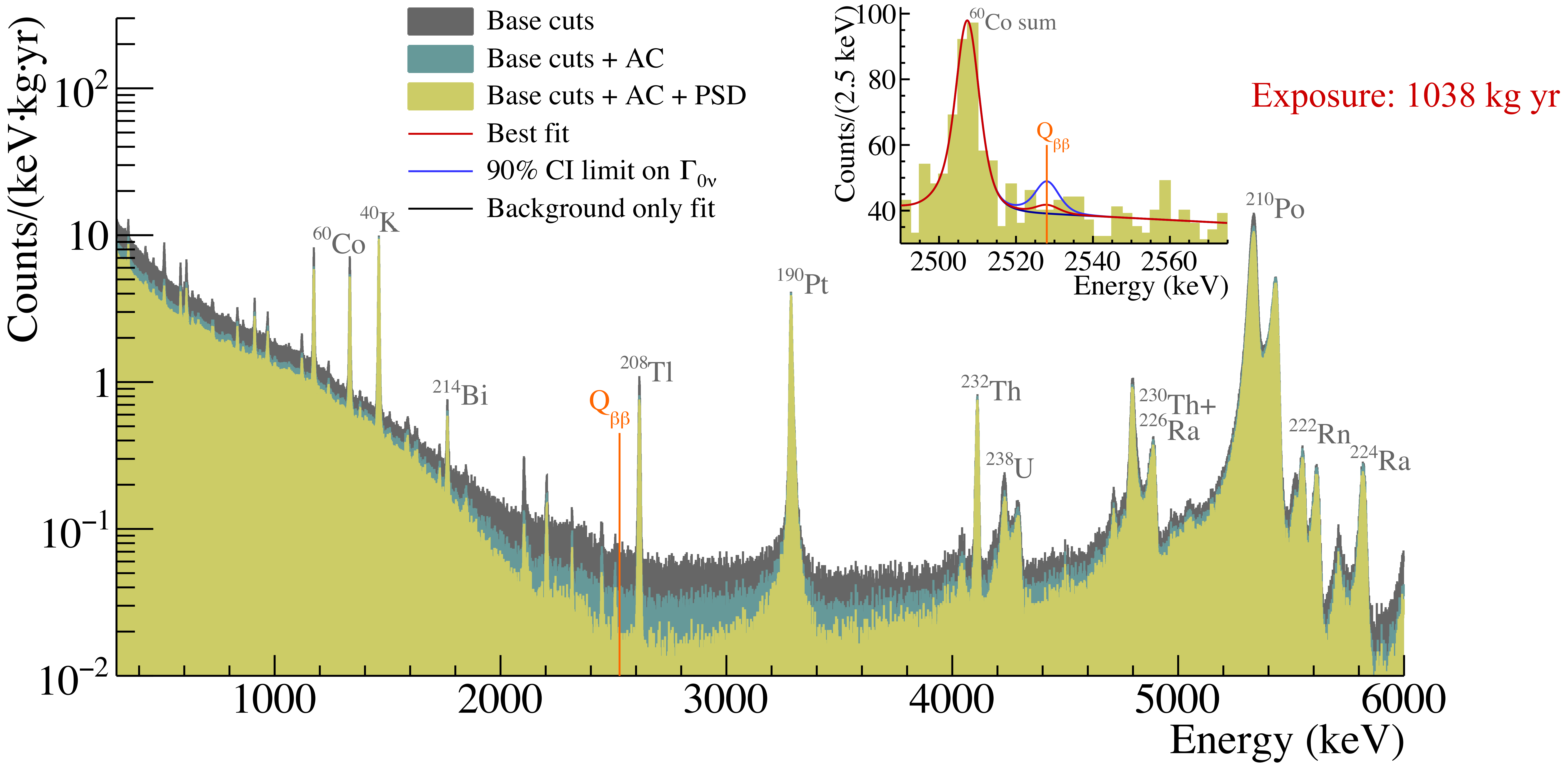
multi-site (background-like)

- ~88% of $0\nu\beta\beta$ events involve just one crystal
- assign multiplicity (number of involved crystals) and total energy
- apply anti-coincidence veto for $0\nu\beta\beta$ analysis

Principal Component Analysis (PCA) where the leading component is the average pulse



DATA



Base cuts
Base cuts + AC
Base cuts + AC + PSD
Best fit
90% CI limit on $\Gamma_{0\nu}$
Background only fit
Counts/(keV·kg·yr)
Energy (keV)
^{60}Co
^{40}K
^{214}Bi
$Q_{\beta\beta}$
^{208}Tl
^{190}Pt
^{232}Th
^{238}U
^{230}Th+
^{226}Ra
^{210}Po
^{222}Rn
^{224}Ra
^{60}Co sum
Counts/(2.5 keV)
Exposure: 1038 kg yr

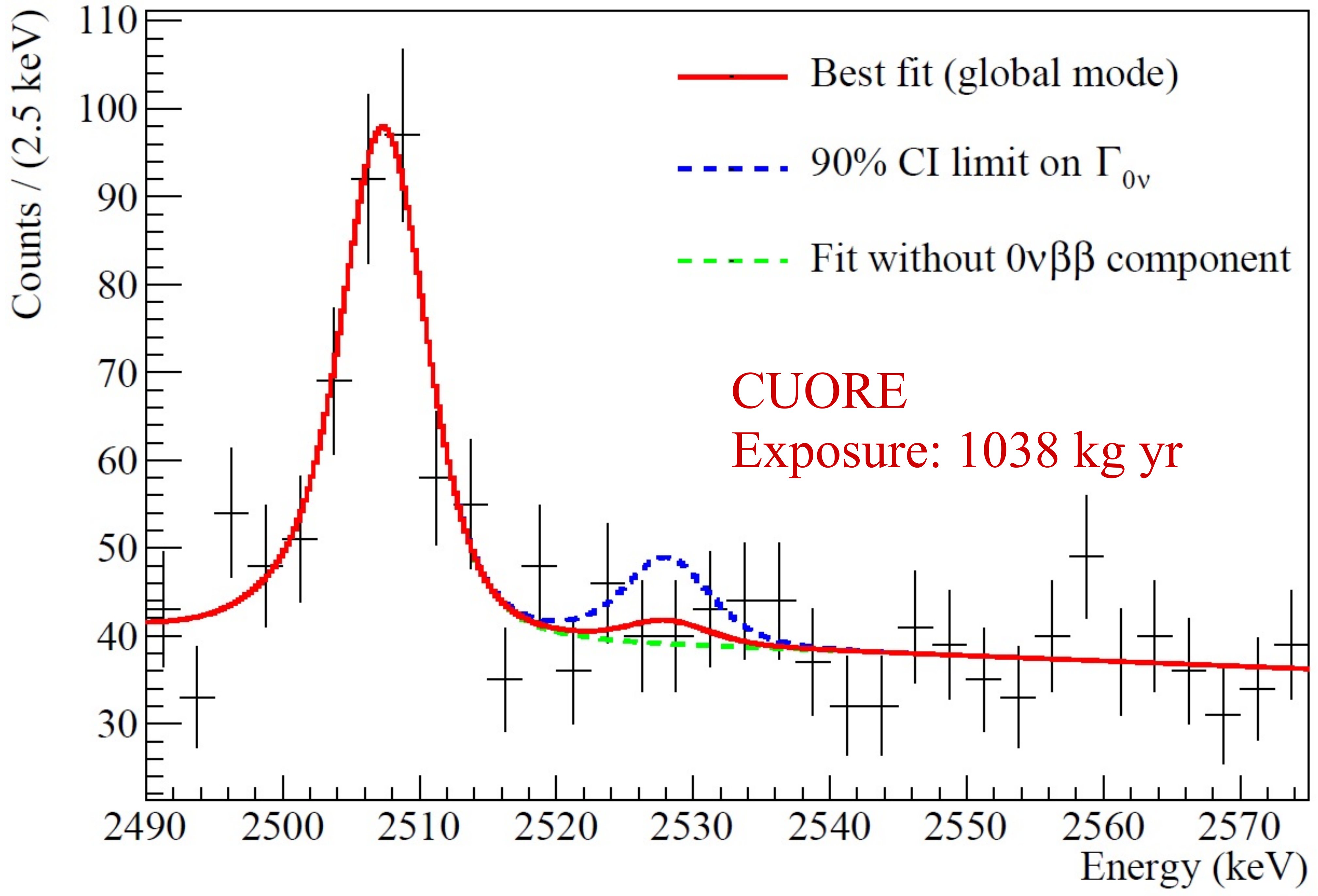
1 TONNE-YR DATA RELEASE: FIGURES

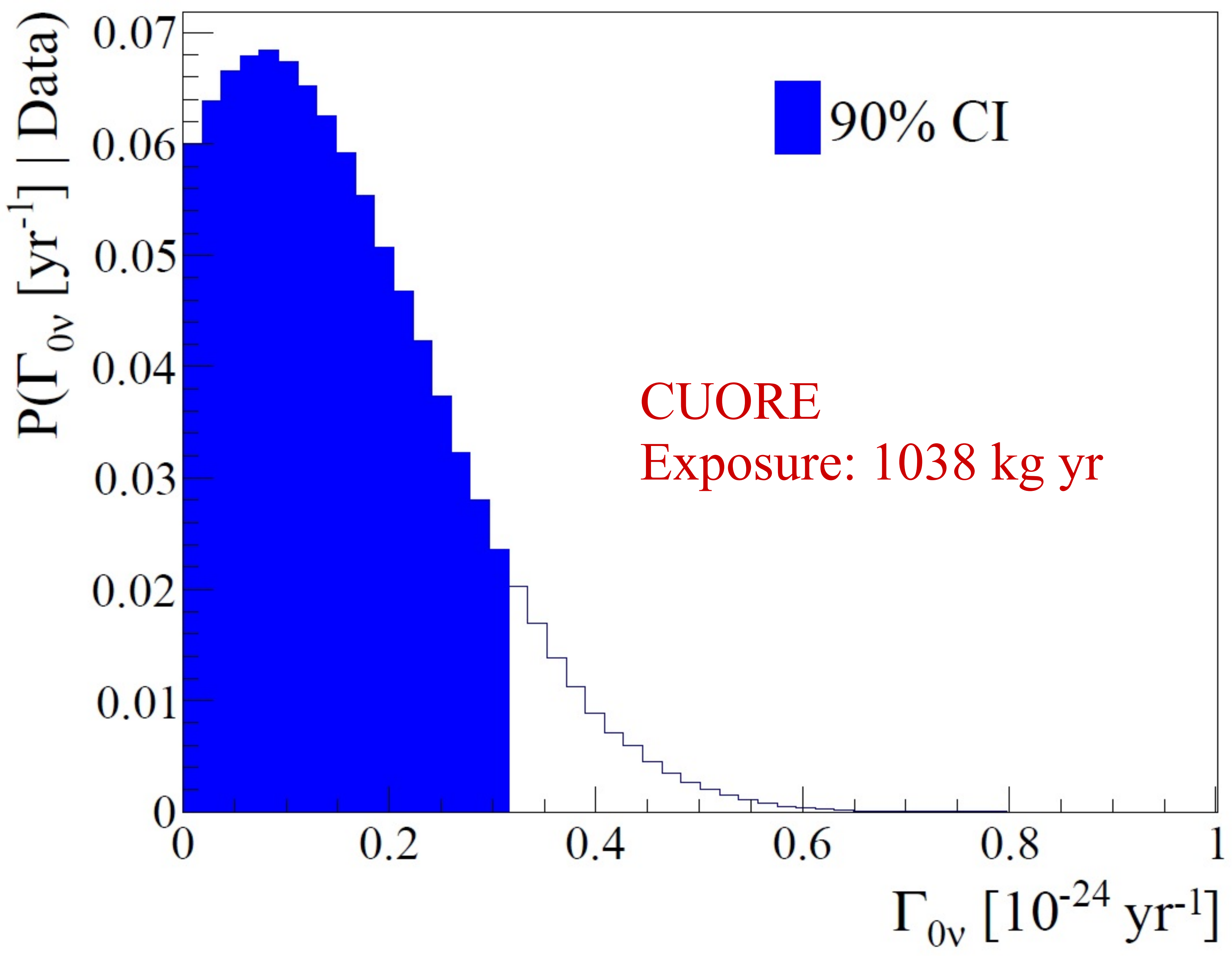
CUORE

Parameters	Values
Number of datasets	15
Number of channels	$\sim$934 average per dataset
TeO_2 exposure	1038.4 kg yr
^{130}Te exposure	288 kg yr
FWHM at 2615 keV in calibration	(7.78 ± 0.03) keV
FWHM at $Q_{\beta\beta}$ in physics data	(7.8 ± 0.5) keV
Total analysis efficiency	(92.4 ± 0.2)%
Reconstruction efficiency	(96.418 ± 0.002)%
Anticoincidence efficiency	(99.3 ± 0.1)%
PSD efficiency	(96.4 ± 0.2)%
Containment efficiency	(88.35 ± 0.09)%

Adams, D.Q. et al. (CUORE Collaboration), Nature 604, 53-58 (2022) https://doi.org/10.1038/s41586-022-04497-4

FIT RESULT



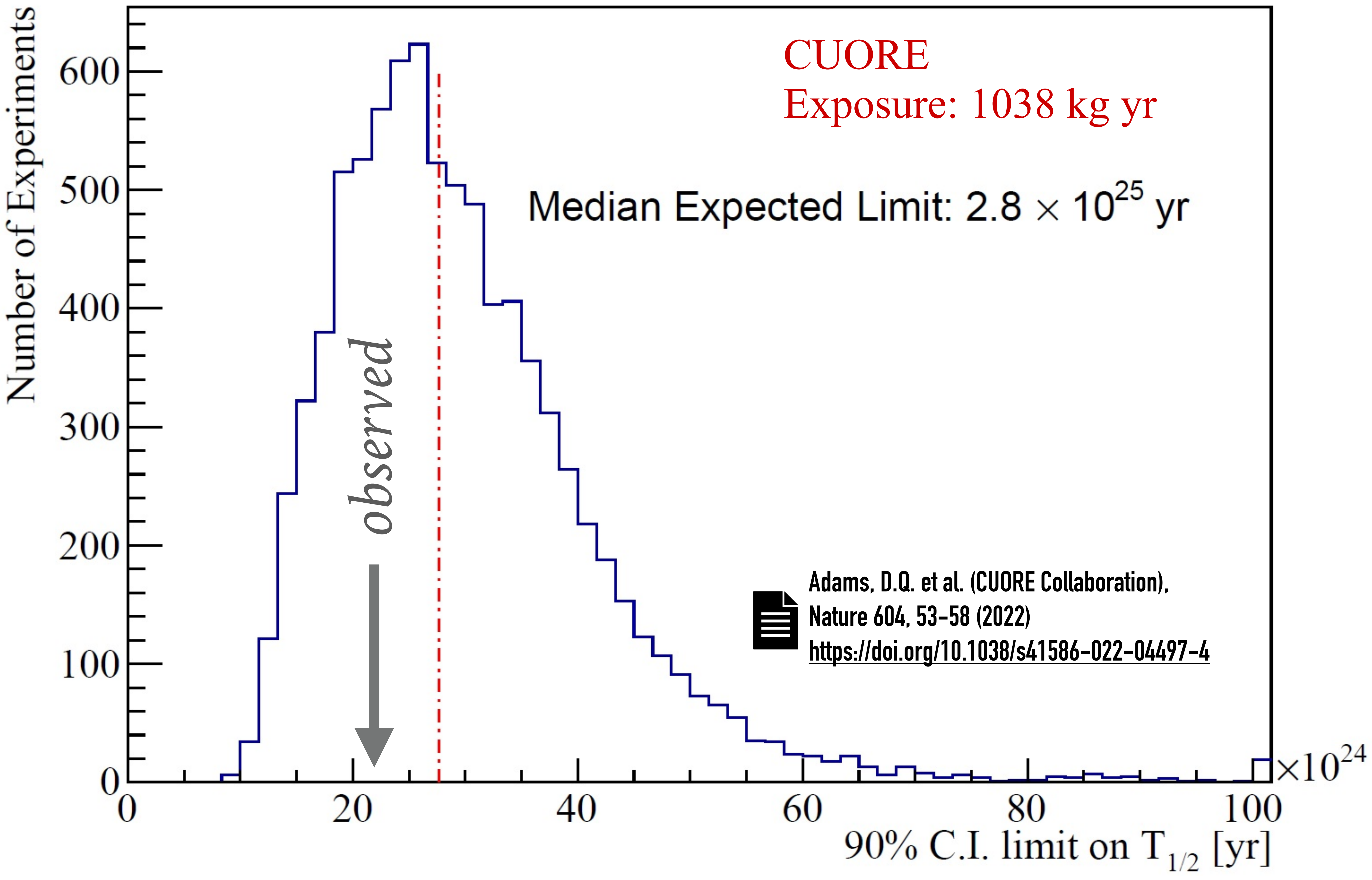


$$b = 1.49(4) \times 10^{-2}\ \text{counts/(keV kg yr)}$$

$$T^{0\nu}_{1/2} > 2.2 \times 10^{25}\ \text{yr (90 \% C.I.)}$$

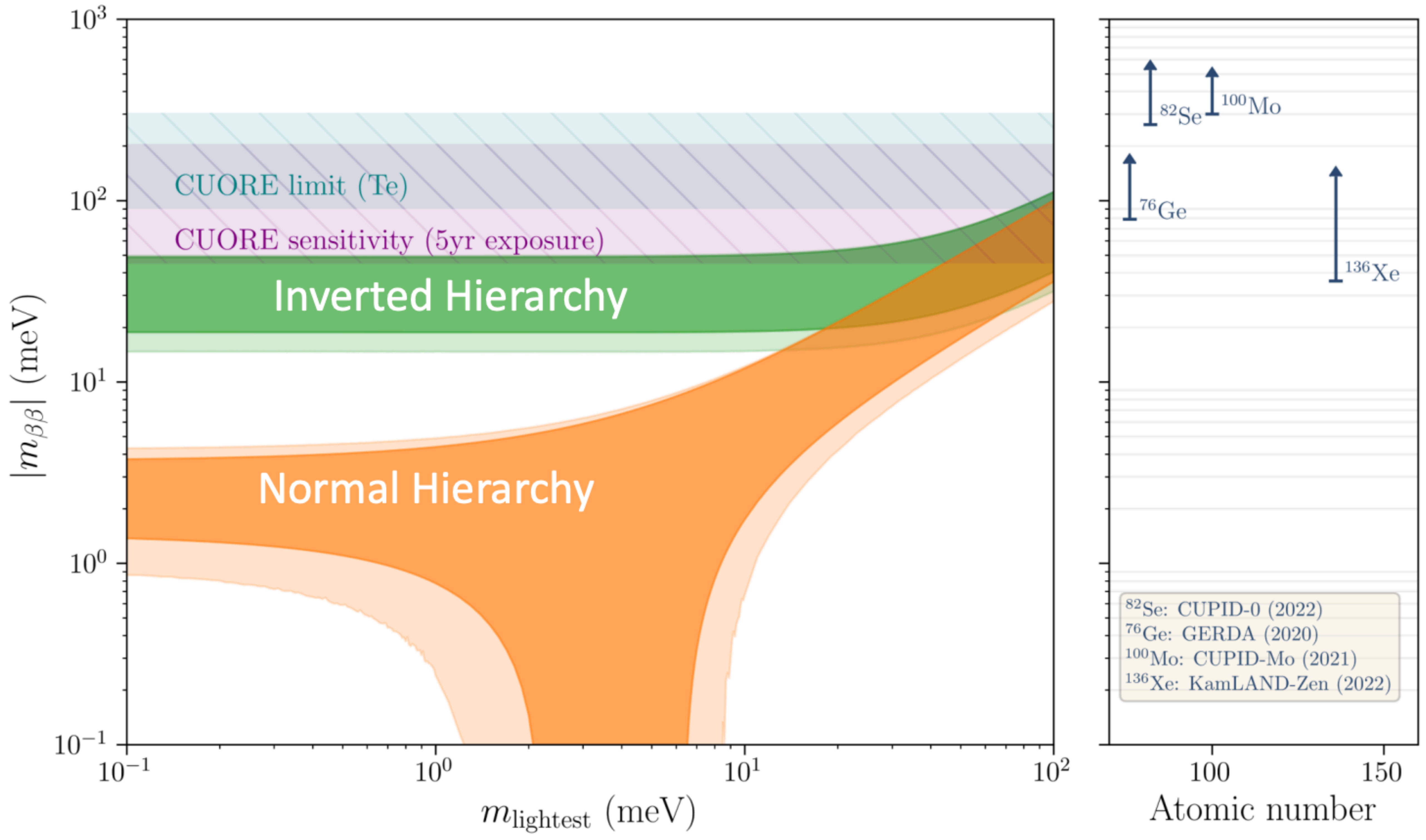
Adams, D.Q. et al. (CUORE Collaboration),
Nature 604, 53-58 (2022)
https://doi.org/10.1038/s41586-022-04497-4

SENSITIVITY



- Median exclusion sensitivity 2.8 10^{25} yr
- 10^4 toy experiments in background-only hypothesis
- background and ^{60}Co event rate from fit to the data
- fit with signal + background model
- 72% chance of obtaining stronger limit than the one observed

FIT RESULT



Representation of $m_{\beta\beta}$ from
F. Vissani JHEP06(1999)022

Adams, D.Q. et al. (CUORE Collaboration),
Nature 604, 53–58 (2022)
https://doi.org/10.1038/s41586-022-04497-4

- oscillation parameters from NUFIT2020

  Esteban, I. et al., J. High En. Phys. 2020 (178)
  https://doi.org/10.1007/JHEP09(2020)178

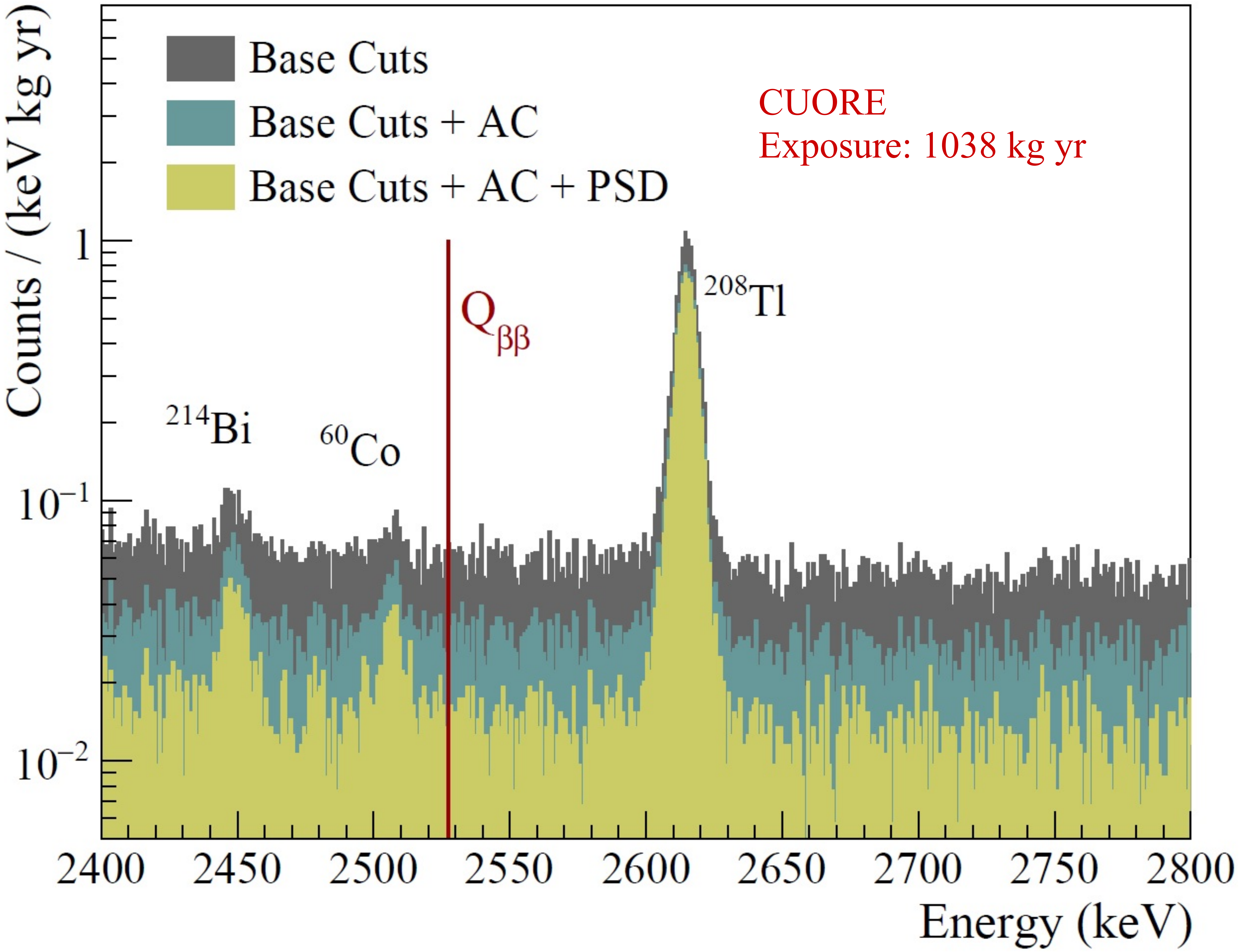
- all limits are 90% C.I. and shaded areas in the normal (inverted) hierarchy correspond to 3σ uncertainty

- sensitivity from

  Alduino, C. et al. (CUORE Collaboration), Eur. Phys. J. C (2017) 77: 532
  https://doi.org/10.1140/epjc/s10052-017-5098-9

$$m_{\beta\beta} < 90 - 305 \text{ meV}$$

BACKGROUND IN THE REGION OF INTEREST (ROI)



α region

fit flat background in [2650,3100] keV
1.40(2) 10^{-2} counts/(keV kg yr)

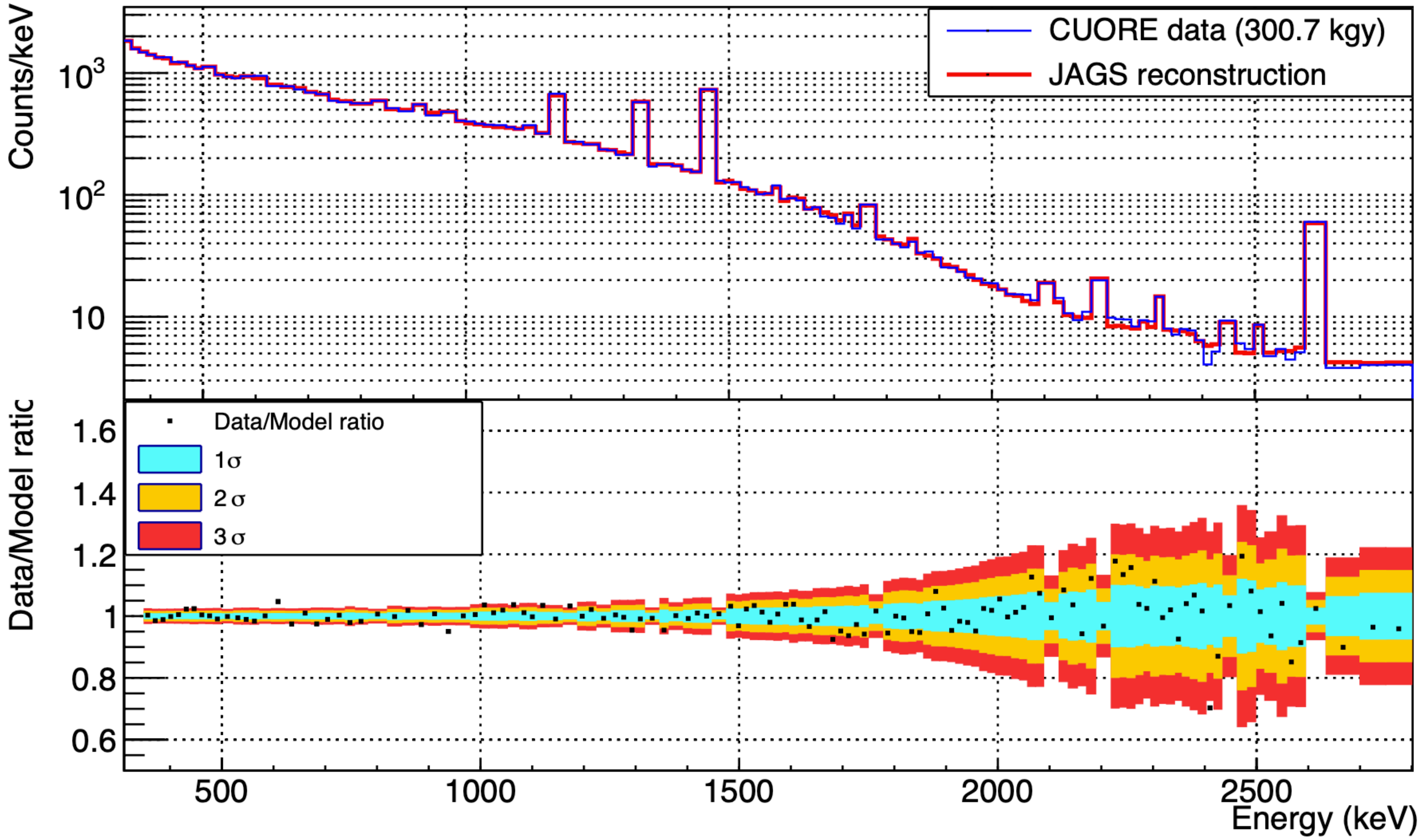
$Q_{\beta\beta}$ region

fit background + ^{60}Co peak in [2490,2575] keV
1.49(4) 10^{-2} counts/(keV kg yr)

source

~90% of the background in the ROI is given by degraded alpha interactions

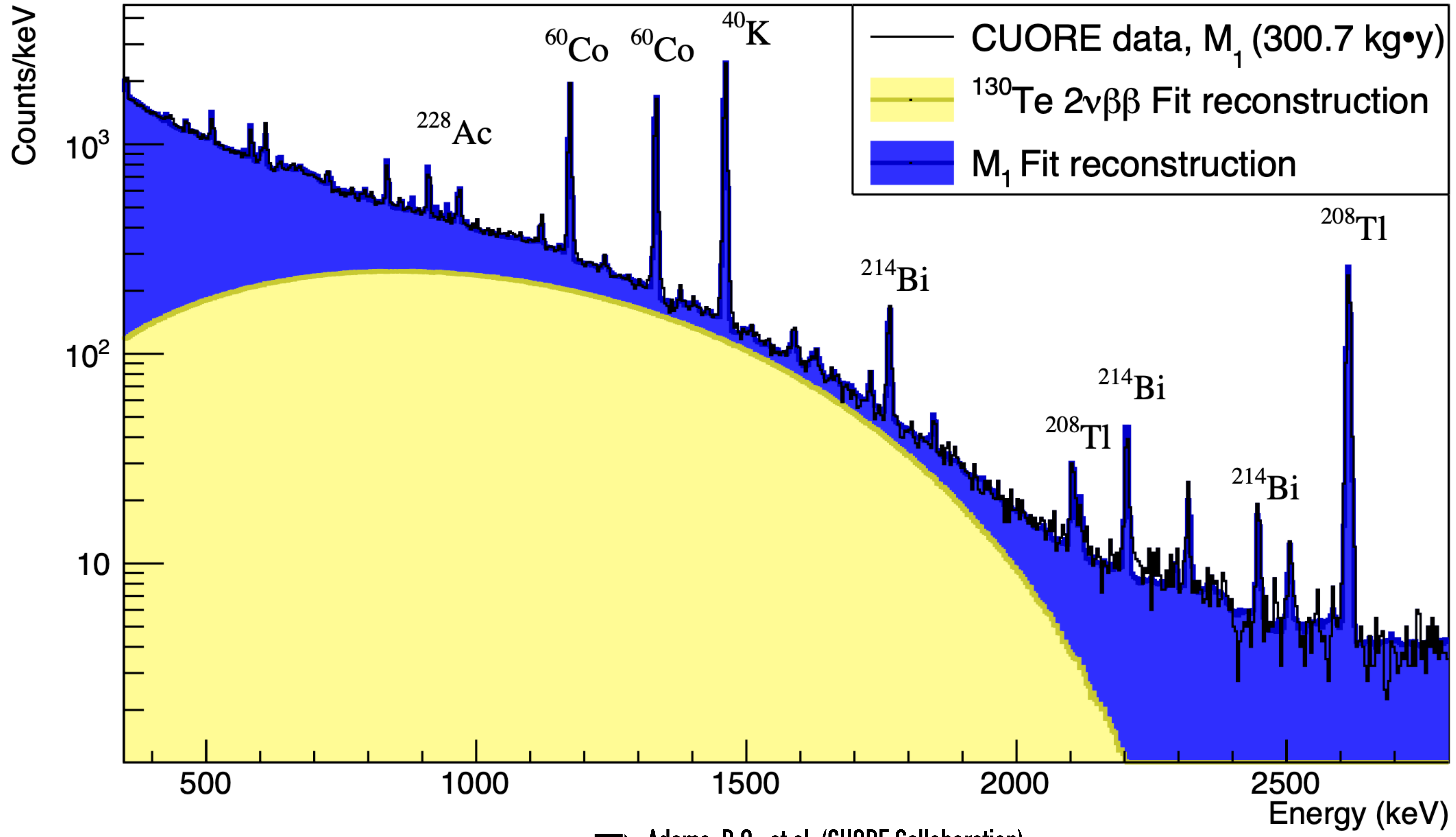
BACKGROUND MODEL



Adams, D.Q. et al. (CUORE Collaboration)
Phys. Rev. Lett. 126, 171801 (2021)
https://doi.org/10.1103/PhysRevLett.126.171801

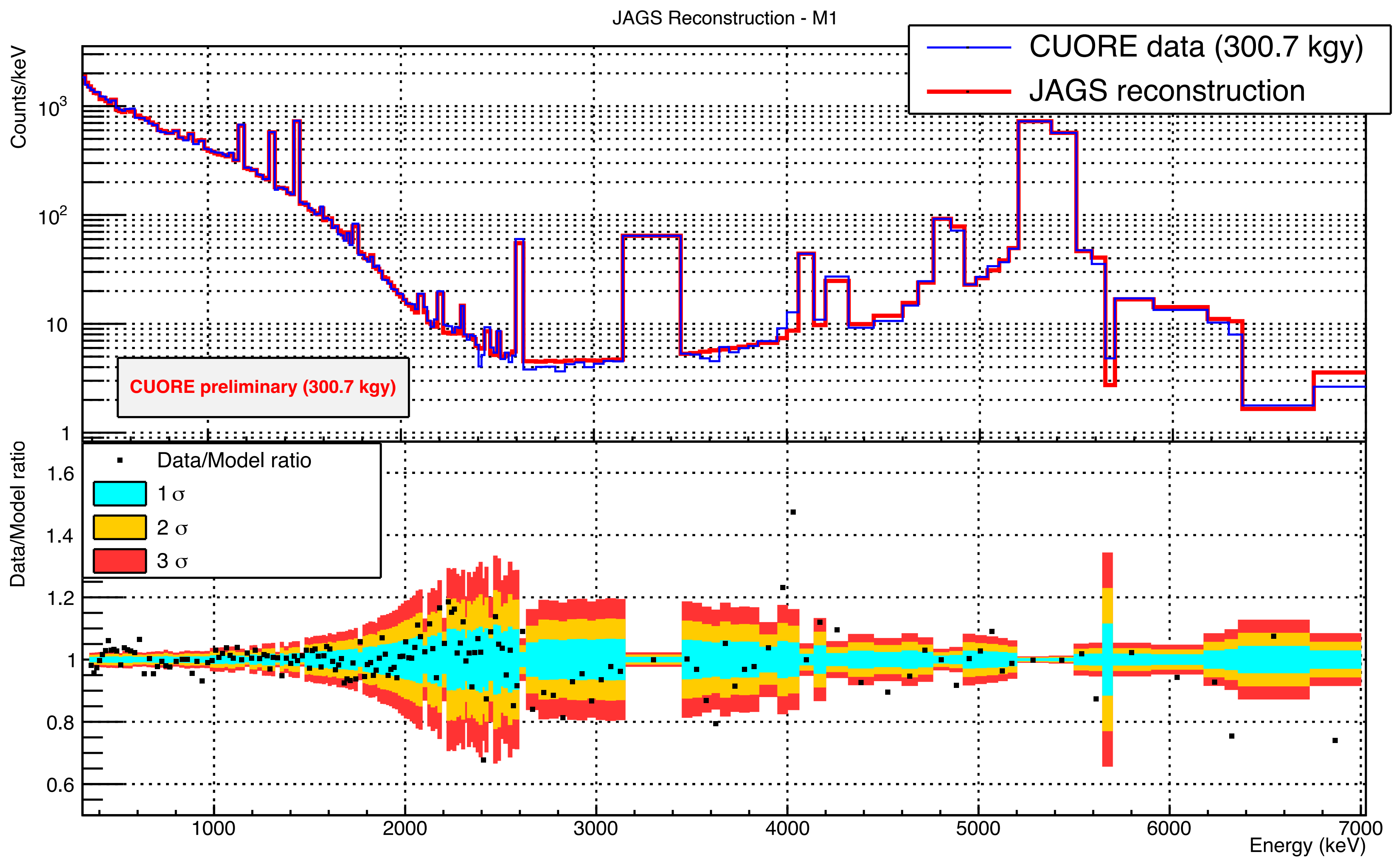
- GEANT4 simulation + detector response to produce expected spectra
- 62 simulated sources (bulk, surface, muons)
- use coincidences to constrain source location
- MCMC binned Bayesian fit
- uniform priors (except muons)

STANDARD MODEL DOUBLE BETA DECAY (GROUND STATE)



Adams, D.Q. et al. (CUORE Collaboration)
https://arxiv.org/abs/2012.11749

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

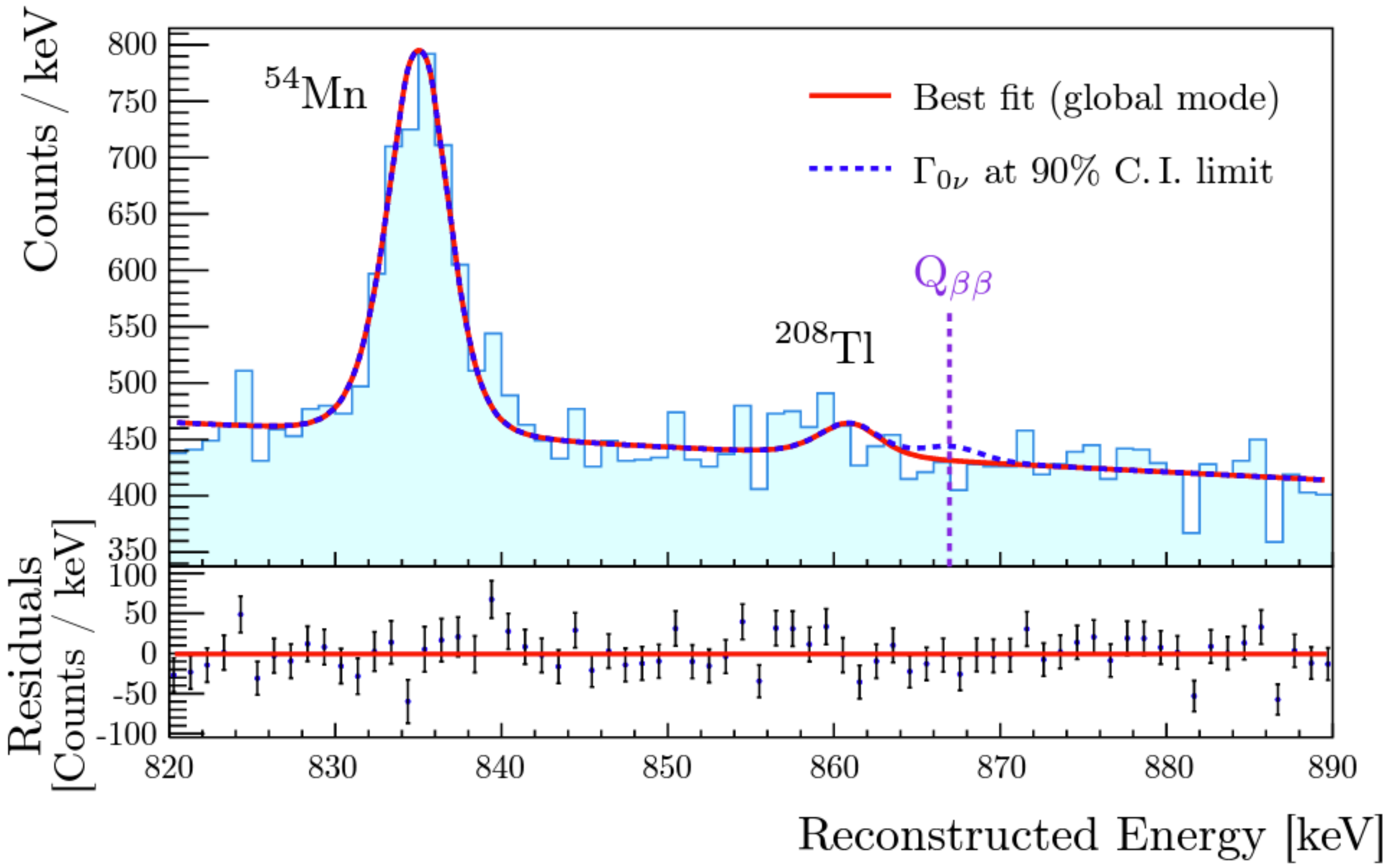


Systematic uncertainties

- 2νββ model (SSD-HSD)
- energy threshold (300-800 keV)
- geometrical splitting
- ^{90}Sr removal / source list

OTHER RARE DECAY SEARCHES

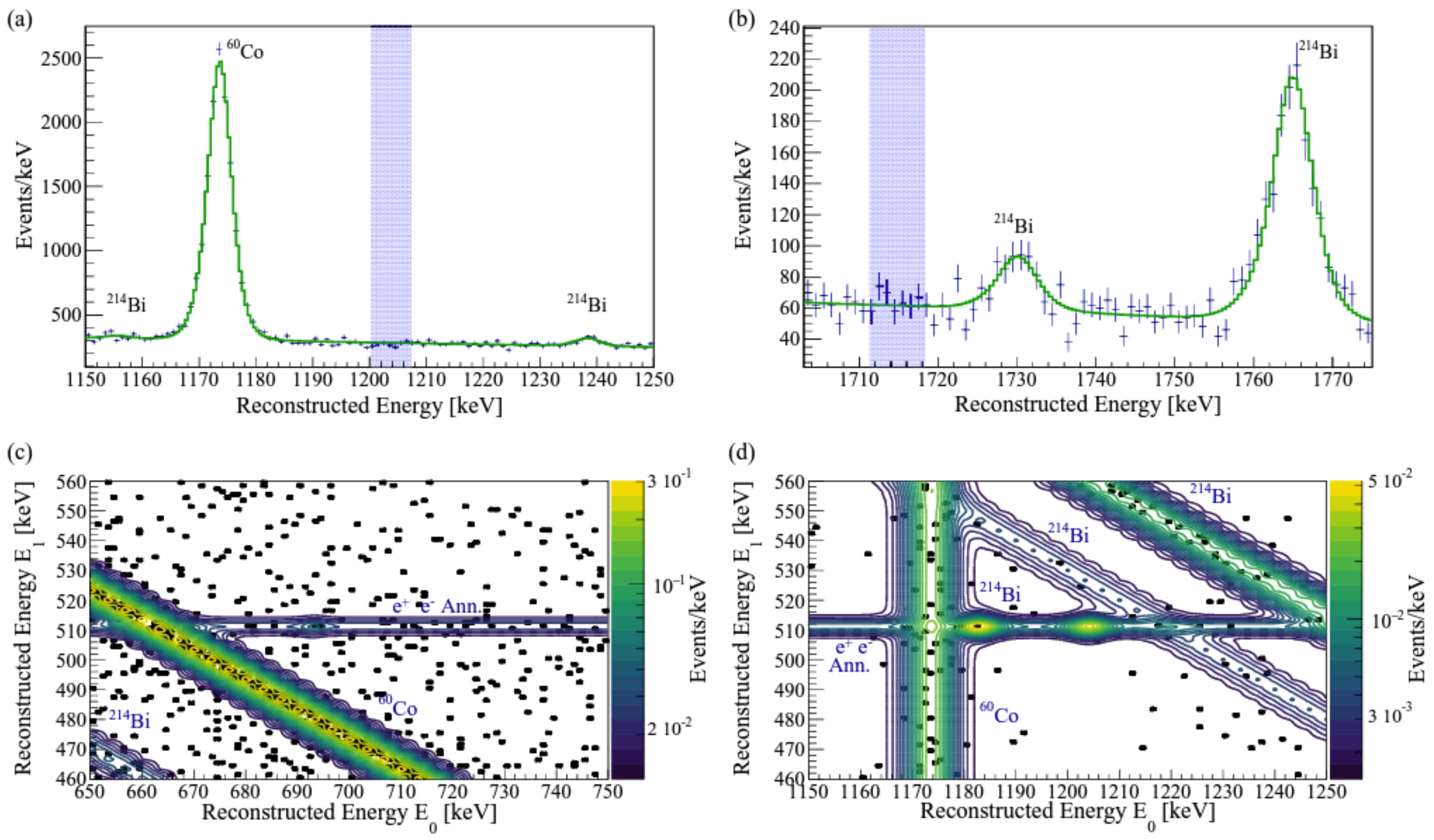
^{128}Te 0νββ



$$T_{1/2}^{0\nu\beta\beta}(^{128}Te) > 3.6 \times 10^{24}\ yr\ (90\,\%\ C.I.)$$

Adams, D.Q. et al. (CUORE Collaboration)
https://doi.org/10.48550/arXiv.2205.03132

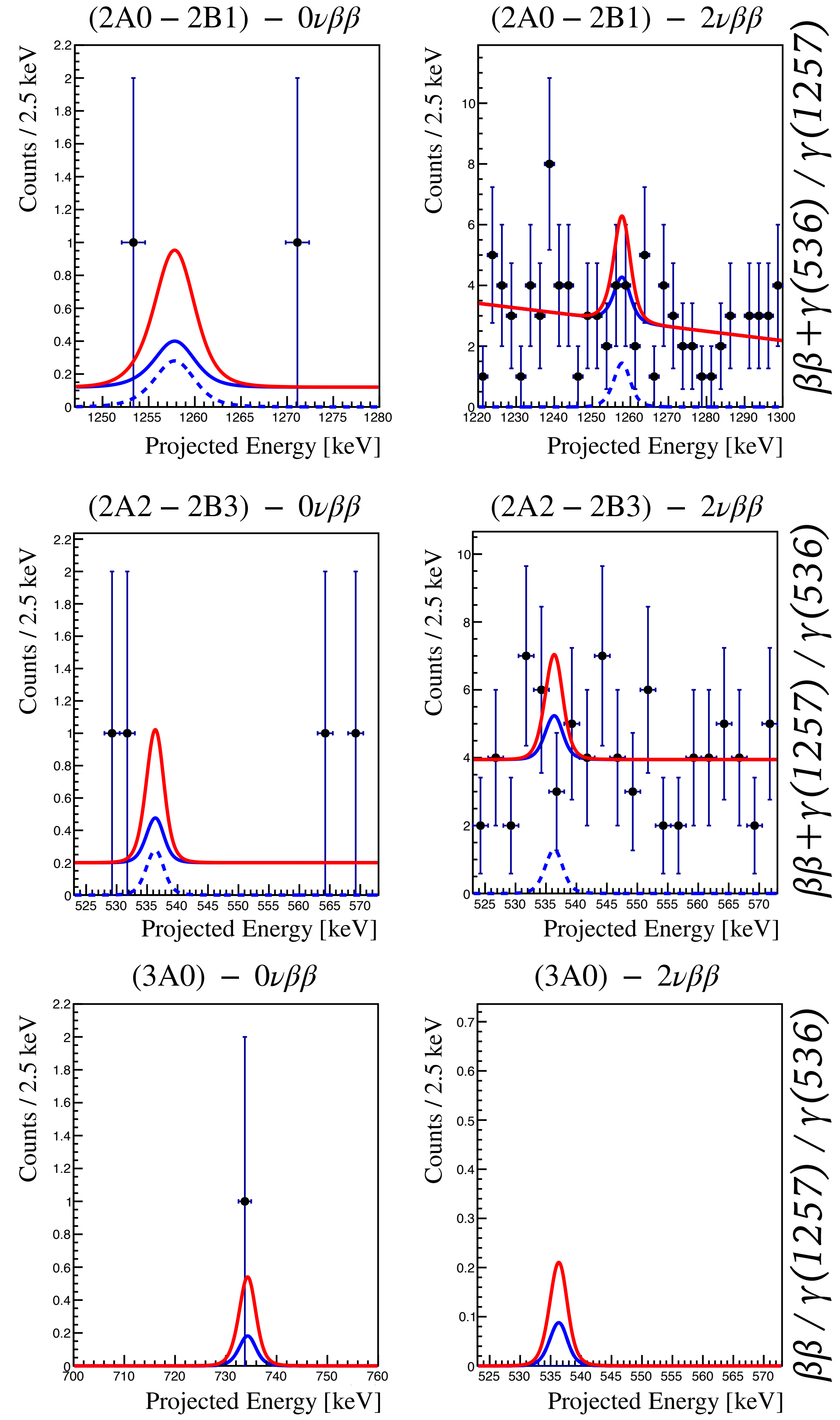
^{120}Te β+/EC



$$T_{1/2}^{0\nu\beta^{+}EC}(^{120}Te) > 2.9 \times 10^{22}\ yr\ (90\,\%\ C.I.)$$

Adams, D.Q. et al. (CUORE Collaboration)
Phys.Rev.C 105 (2022) 065504
https://doi.org/10.1103/PhysRevC.105.065504

^{130}Te ββ decay to first 0+ excited state



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

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

Adams, D.Q. et al. (CUORE Collaboration)
Eur. Phys. J. C 81, 567 (2021)
https://doi.org/10.1140/epjc/s10052-021-09317-z

FUTURE OF CUORE

- Ultimate goal of collecting > 3 tonne yr of exposure
- CUORE will run until the beginning of the CUPID commissioning
- Working on other rare events searches such as
  - $2\nu\beta\beta$ of ^{130}Te
  - $0\nu\beta\beta$ and $2\nu\beta\beta$ decay on ^{130}Te excited states and ^{128}Te
  - $\beta^+\beta^+$ / β^+EC / ECEC searches on ^{120}Te
  - low energy analyses (dark matter, axions, supernova neutrinos, …)
- Working to investigate and mitigate noise sources to improve resolution
  - diagnostic devices (accelerometers, microphones, seismometers)
  - noise de-correlation

CONCLUSION

CUORE

- CUORE has exceeded 2 ton y of exposure and is in stable data taking
- No evidence of 0vββ decay with 1038 kg yr of data
  - Bayesian 90% C.I. limit $T^{0\nu}_{1/2} > 2.2 \times 10^{25}$ yr (90 % C . I.)
  - Effective Majorana Mass limit $m_{\beta\beta} < 90 - 305$ meV

Adams, D.Q. et al. (CUORE Collaboration) https://arxiv.org/abs/2104.06906

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

Adams, D.Q. et al. (CUORE Collaboration) https://arxiv.org/abs/2012.11749

- Many other results on rare decays

Adams, D.Q. et al. (CUORE Collaboration) https://doi.org/10.48550/arXiv.2205.03132

Adams, D.Q. et al. (CUORE Collaboration) Phys.Rev.C 105 (2022) 065504 https://doi.org/10.1103/PhysRevC.105.065504

Adams, D.Q. et al. (CUORE Collaboration) Eur. Phys. J. C 81, 567 (2021) https://doi.org/10.1140/epjc/s10052-021-09317-z

- Proves feasibility of large-scale bolometric detectors: CUPID

SEE TALK FROM LONG MA IN THIS SESSION

BACKUP

FIT METHOD

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

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

Input from data

- detector response function for each channel-dataset pair
- resolution and bias scaling from calibration to physics data
- efficiency numbers

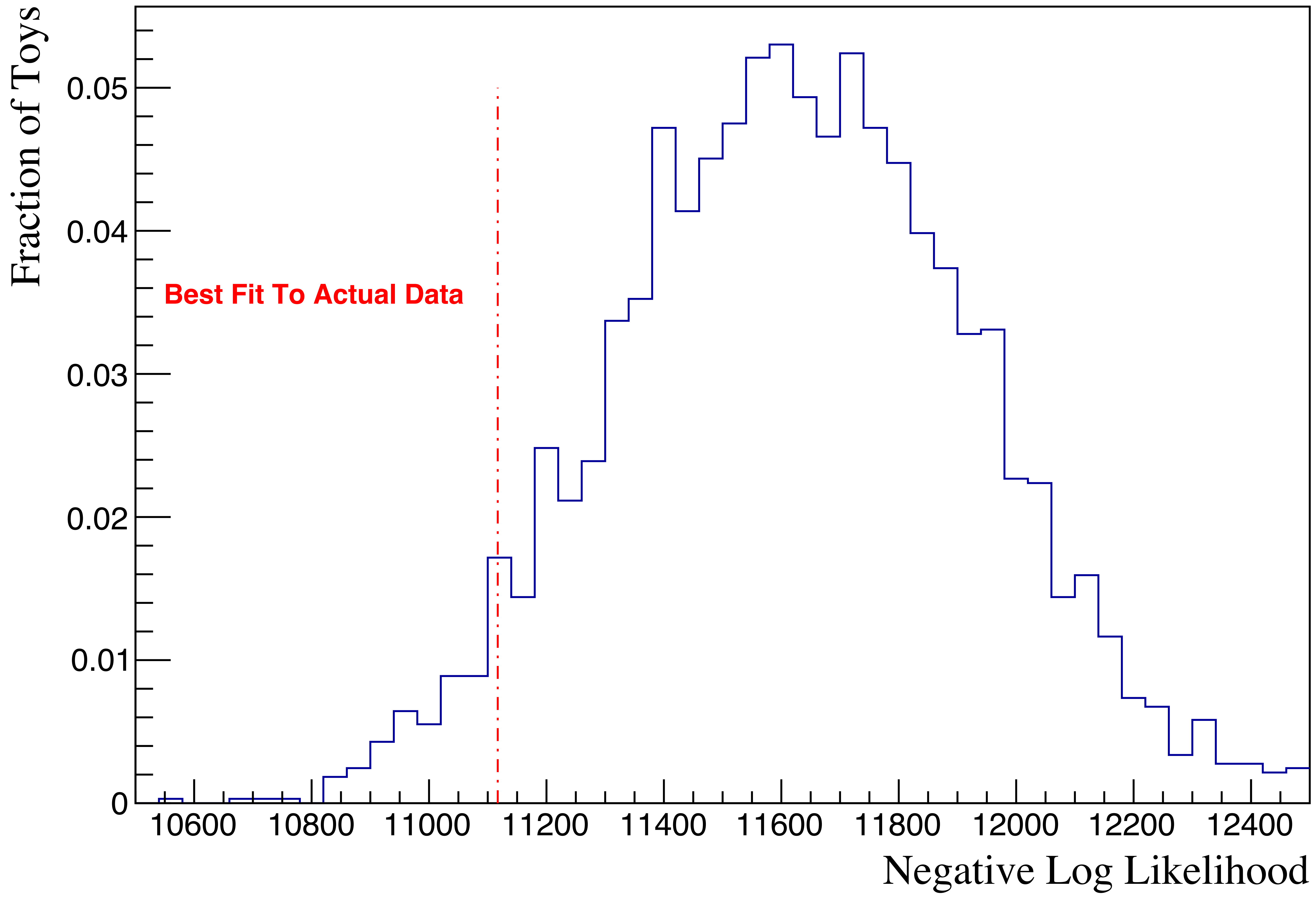
Minimal model

- signal rate $\Gamma_{0\nu}$
- ^{60}Co peak rate, modulated in each dataset by its lifetime
- linear background

Systematics (<0.8% effect on limit)

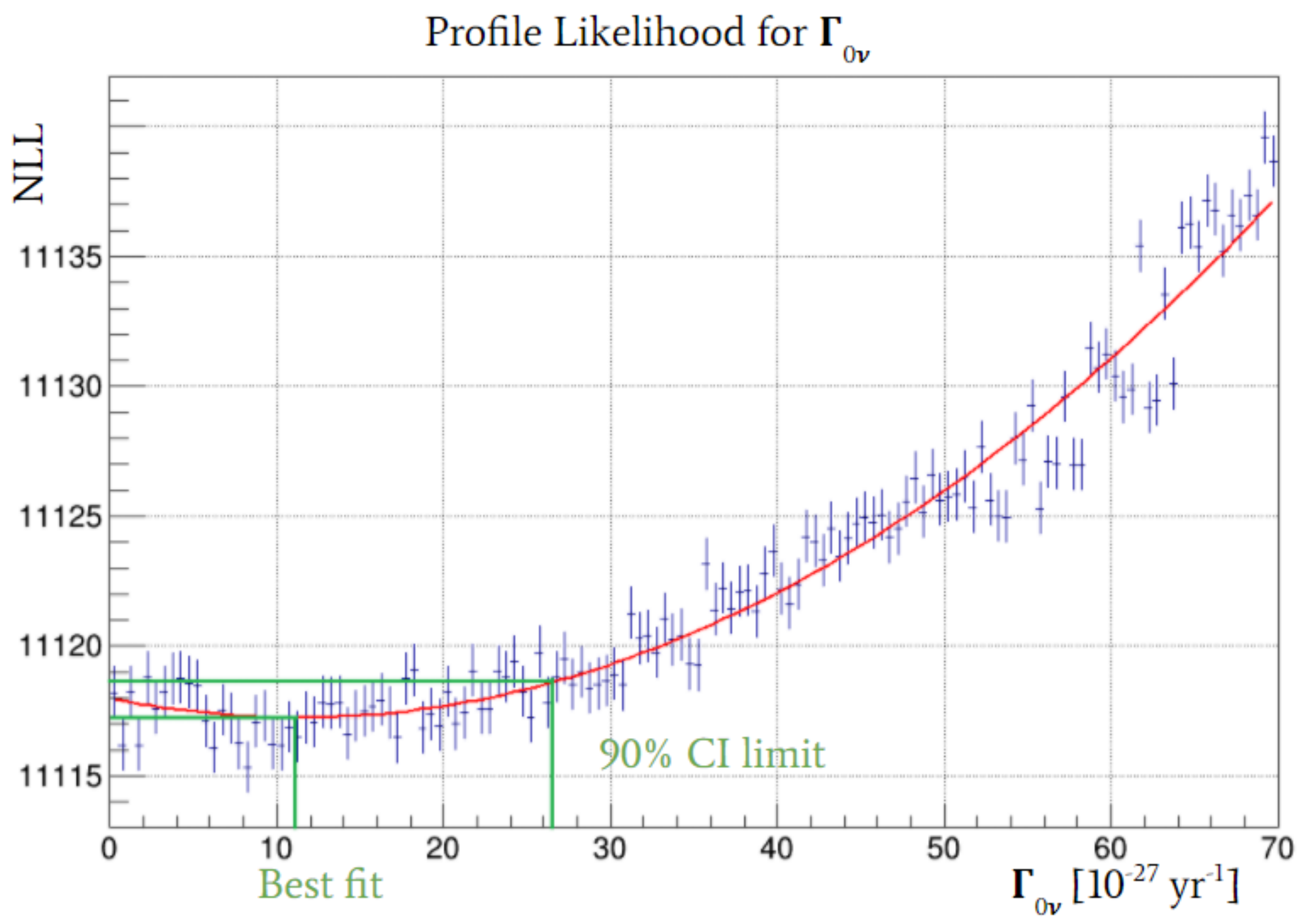
- analysis efficiency (Gaussian prior)
- containment efficiency (Gaussian prior)
- isotopic abundance (Gaussian prior)
- bias and resolution scaling (Multivariate prior)

NEUTRINOLESS DOUBLE BETA DECAY ANALYSIS – NLL DISTRIBUTION



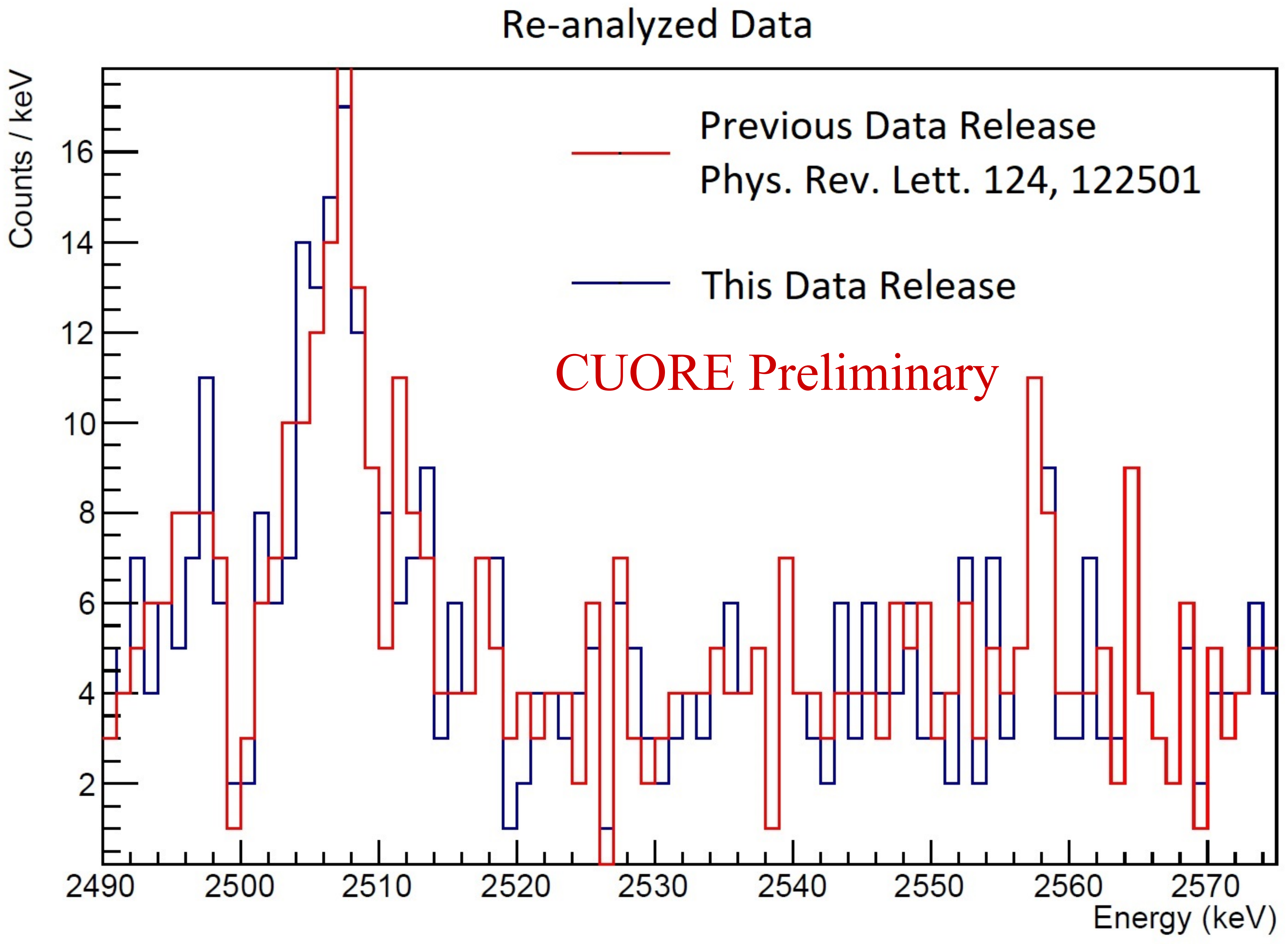
NEUTRINOLESS DOUBLE BETA DECAY ANALYSIS – FREQUENTIST LIMIT

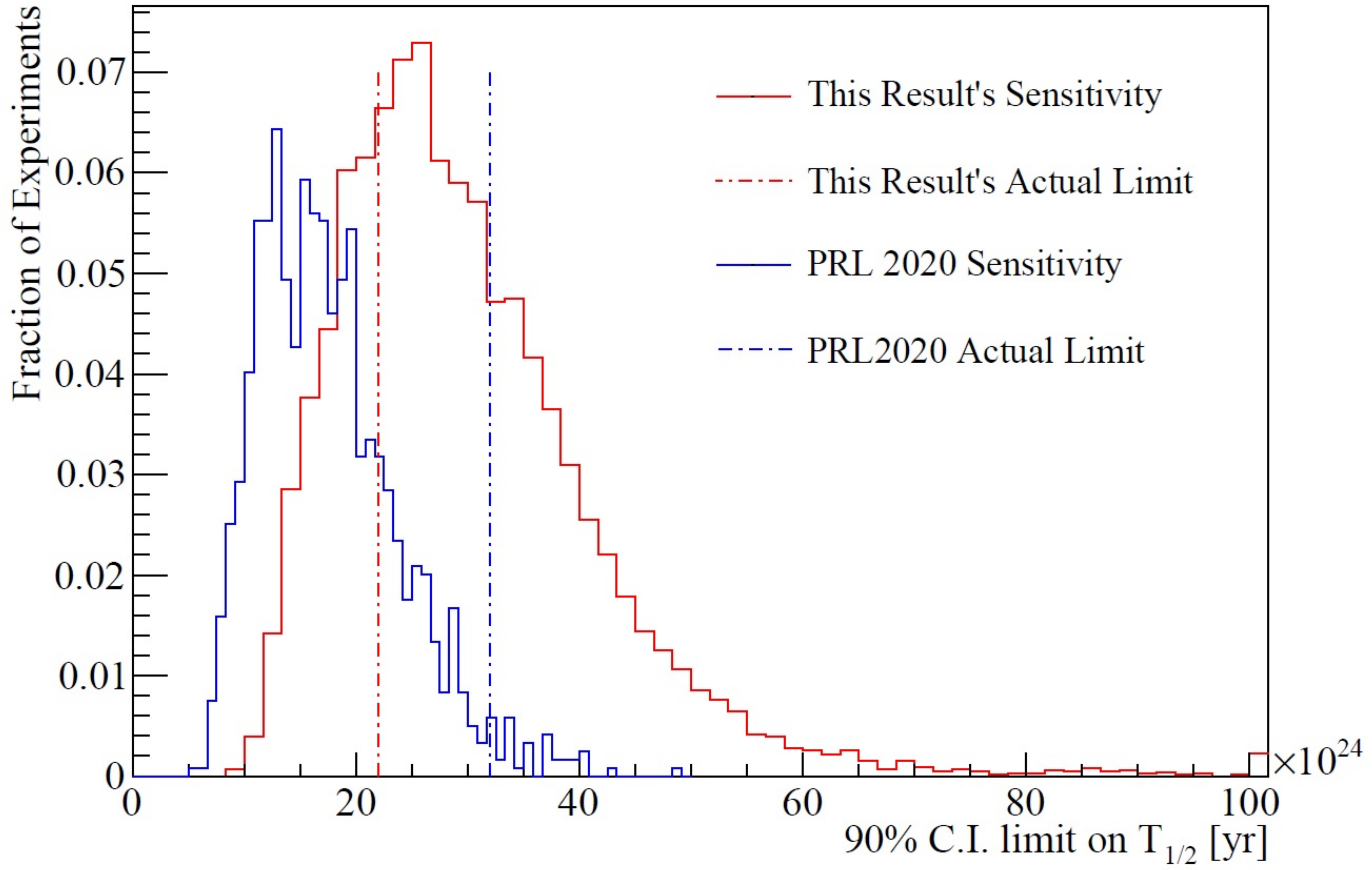
- Frequentist limit with Rolke method
- Profile likelihood obtained from the Markov Chain generated for Bayesian fit
  - -2logL as χ^2 with 1 degree of freedom
  - 90% C.L. limit obtained from rate 1.35 NLL units above the best fit



$$T^{0\nu}_{1/2} > 2.6 \times 10^{25}\ \text{yr}\ (90\,\%\ \text{C.L.})$$

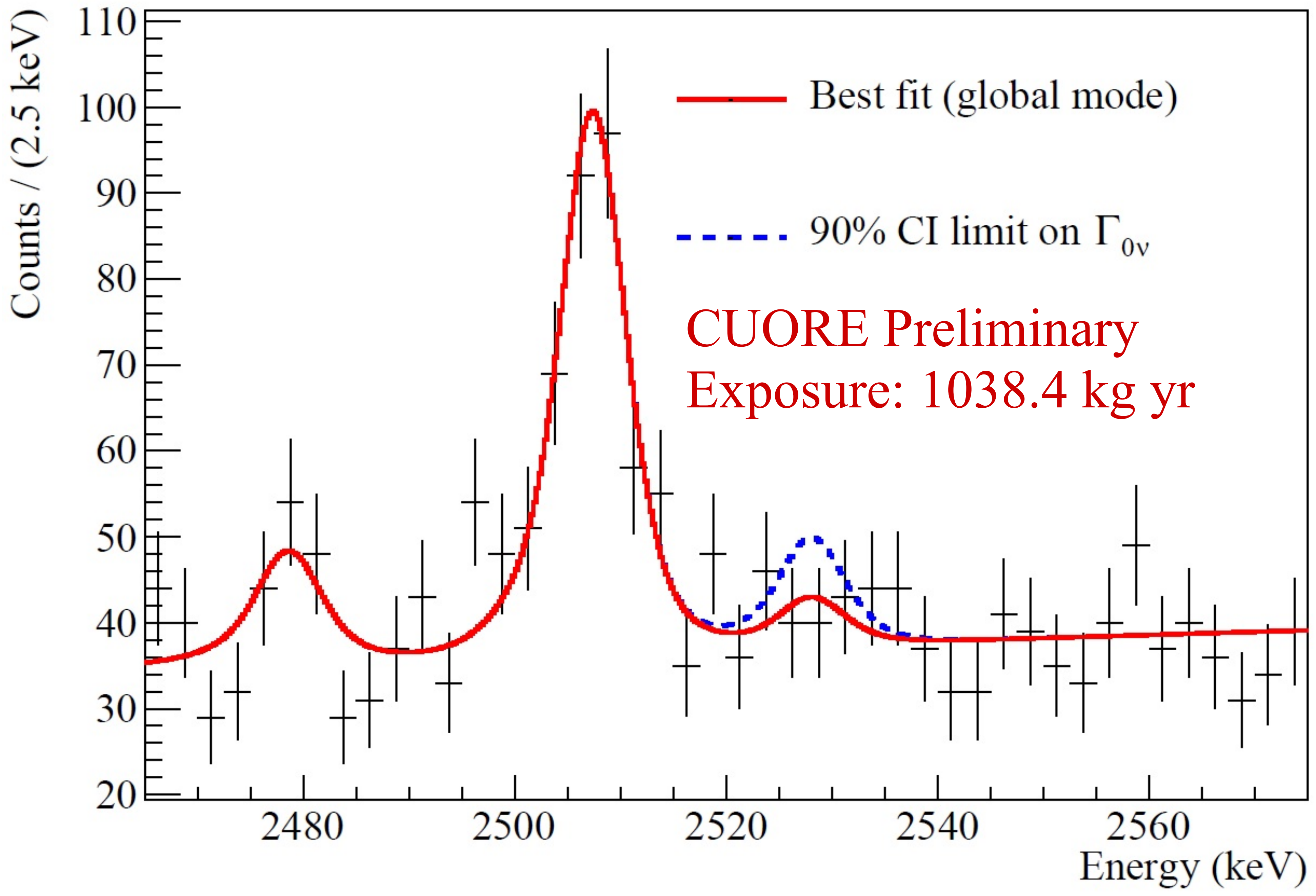
COMPARISON WITH PREVIOUS RESULTS

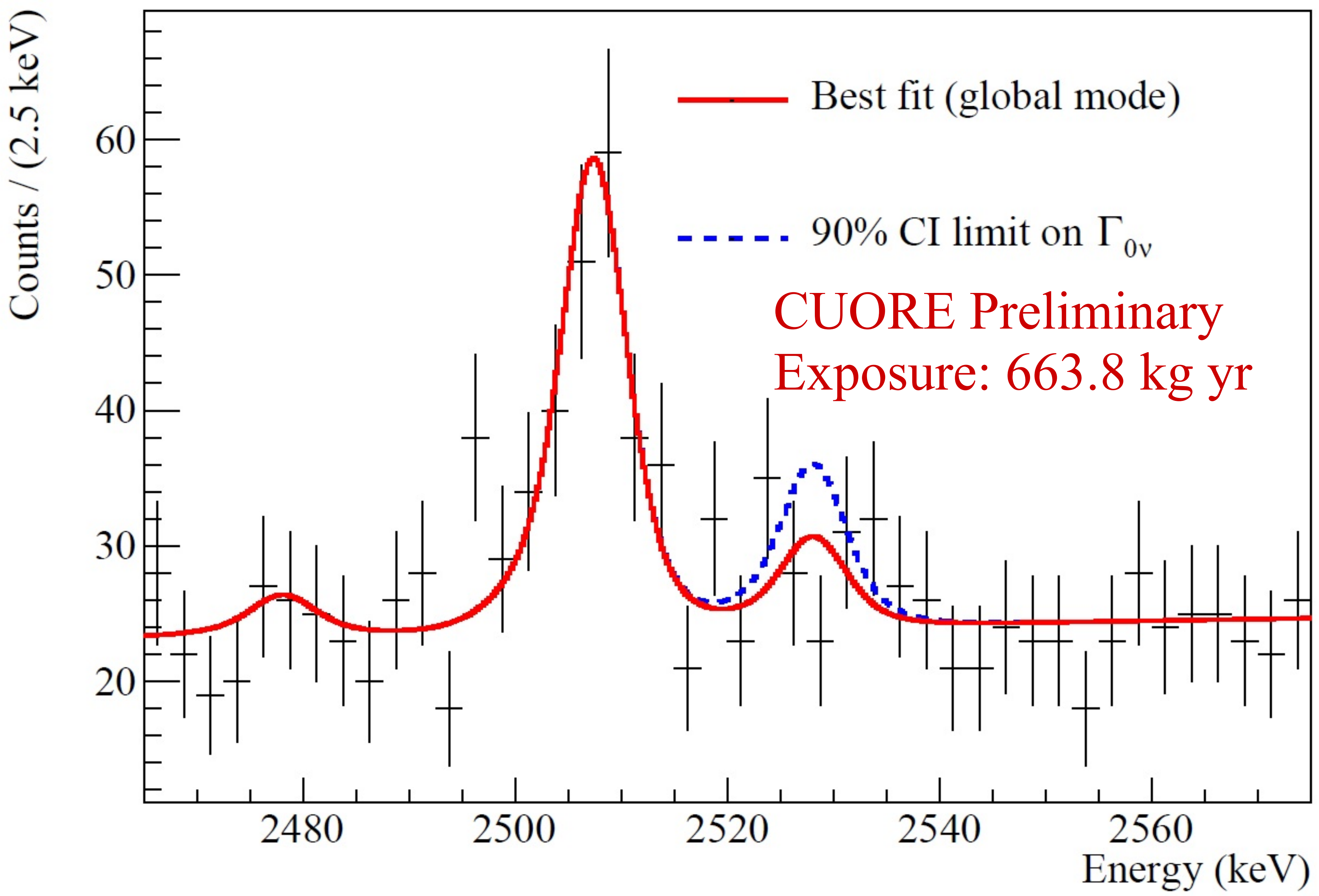




- different pulse shape discrimination, analysis efficiency
- 90% of reconstructed events common to both analyses
- 3% probability of obtaining old limit $T_{1/2} > 3.2\ 10^{25}$ yr (or stronger) with new event reconstruction
- re-analysis yields $T_{1/2} > 2.0\ 10^{25}$ yr limit, in the top 30% of expected results

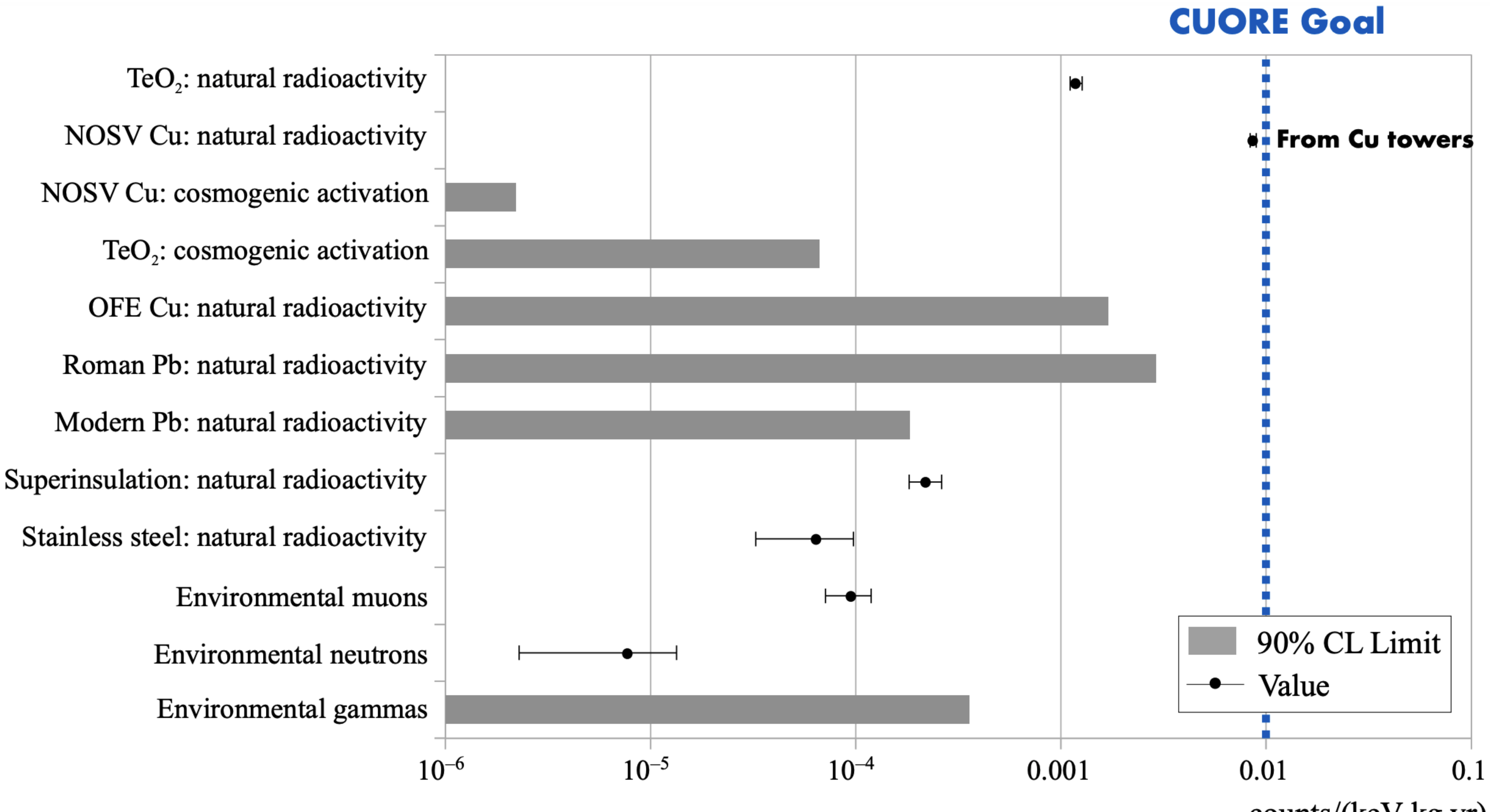
2480 KEV STRUCTURE





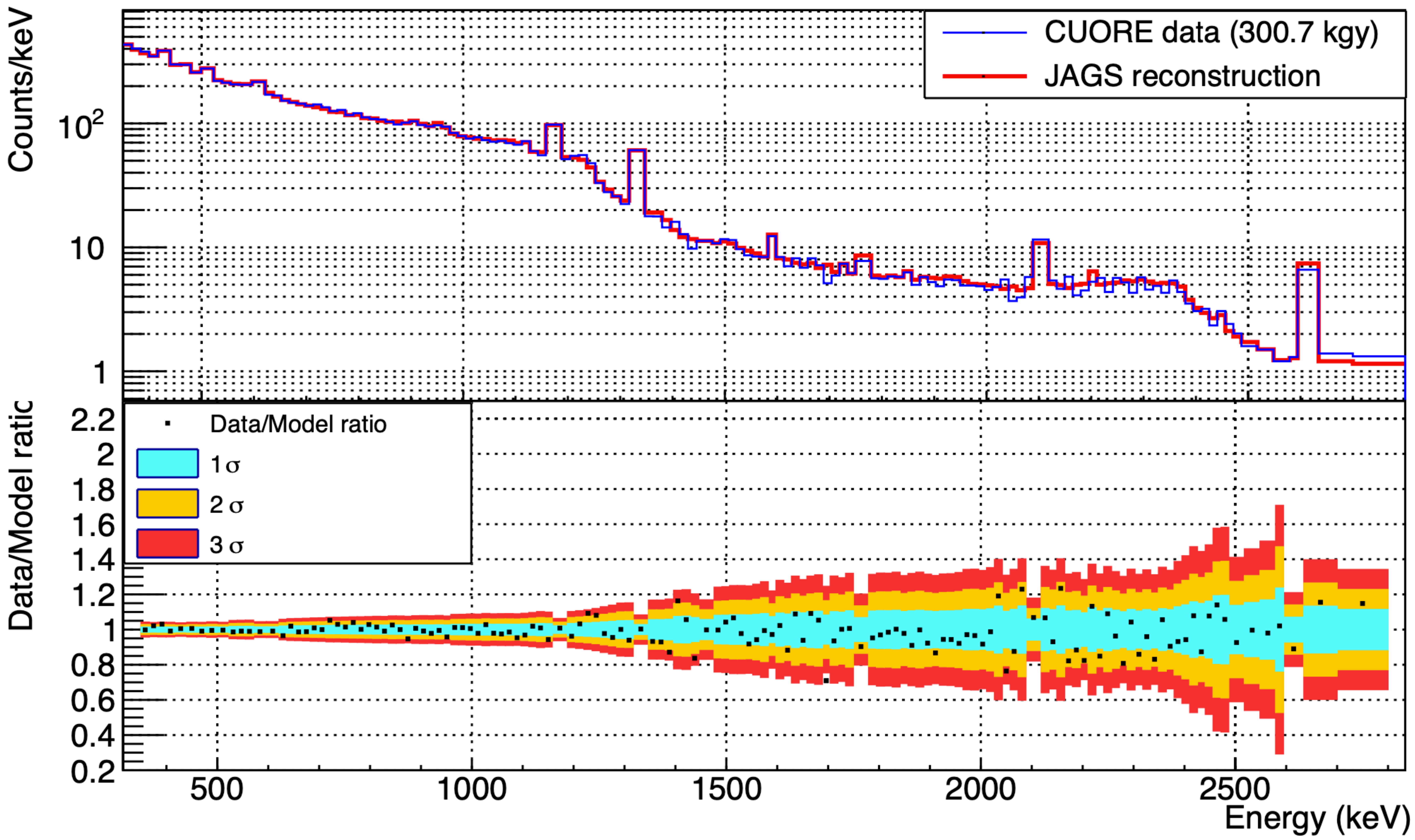
- Previously found 2σ hints of unexpected peak at ~2480 keV
- Statistical significance decreased with new data (< 1 σ with just new data)

CUORE BACKGROUND BUDGET

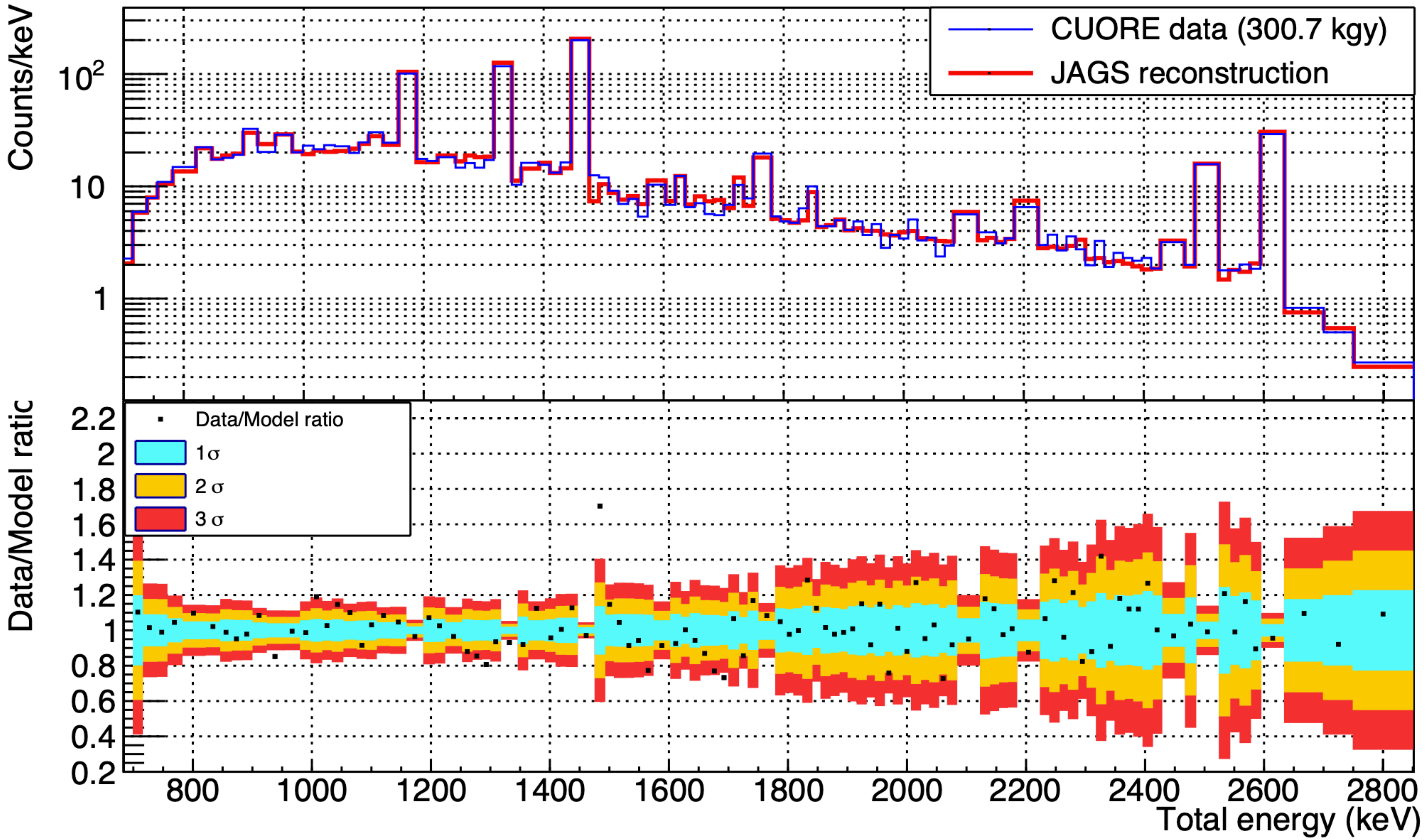


European Physical Journal C 77, 543 (2017)

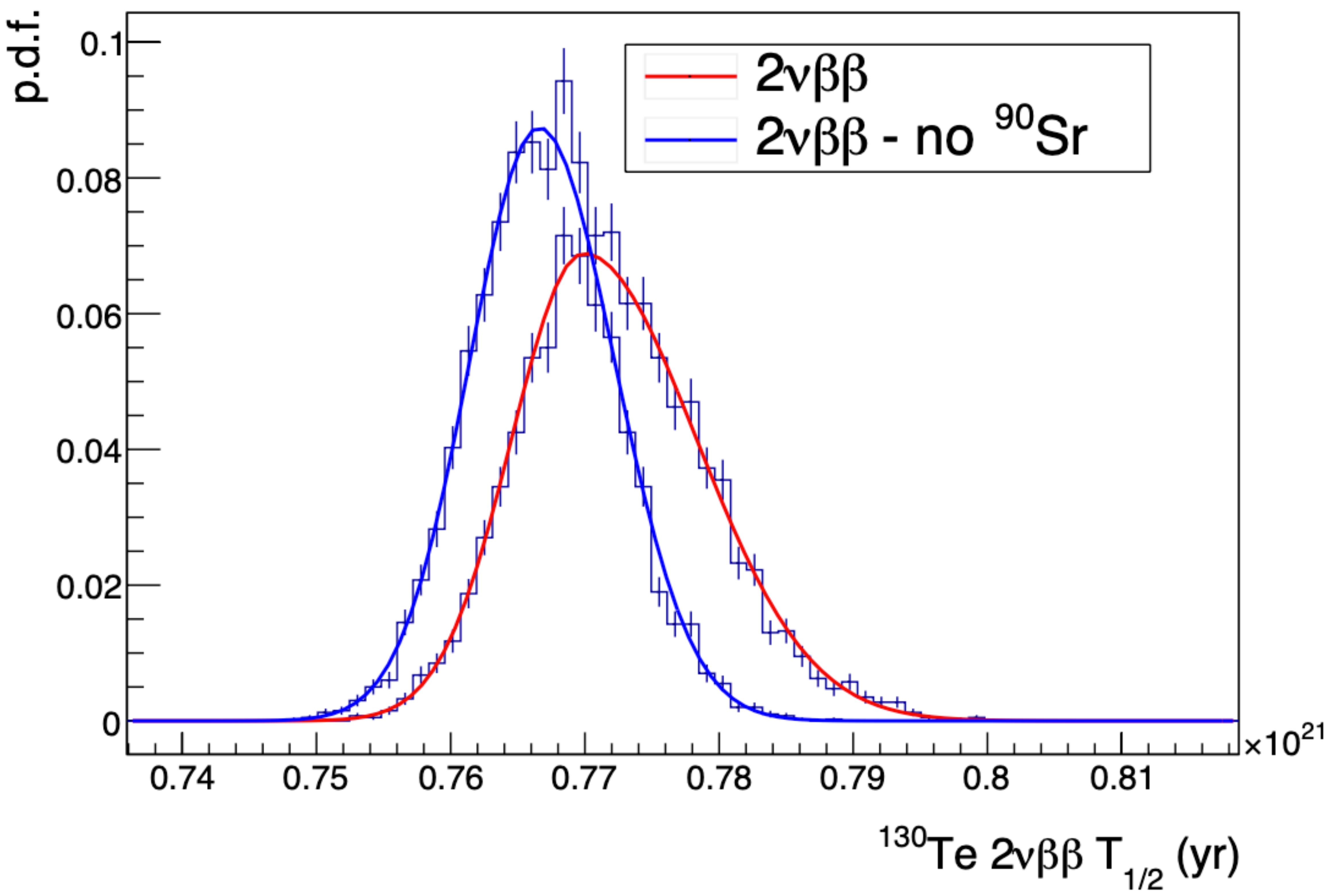
M2 SPECTRUM FIT (JAGS)

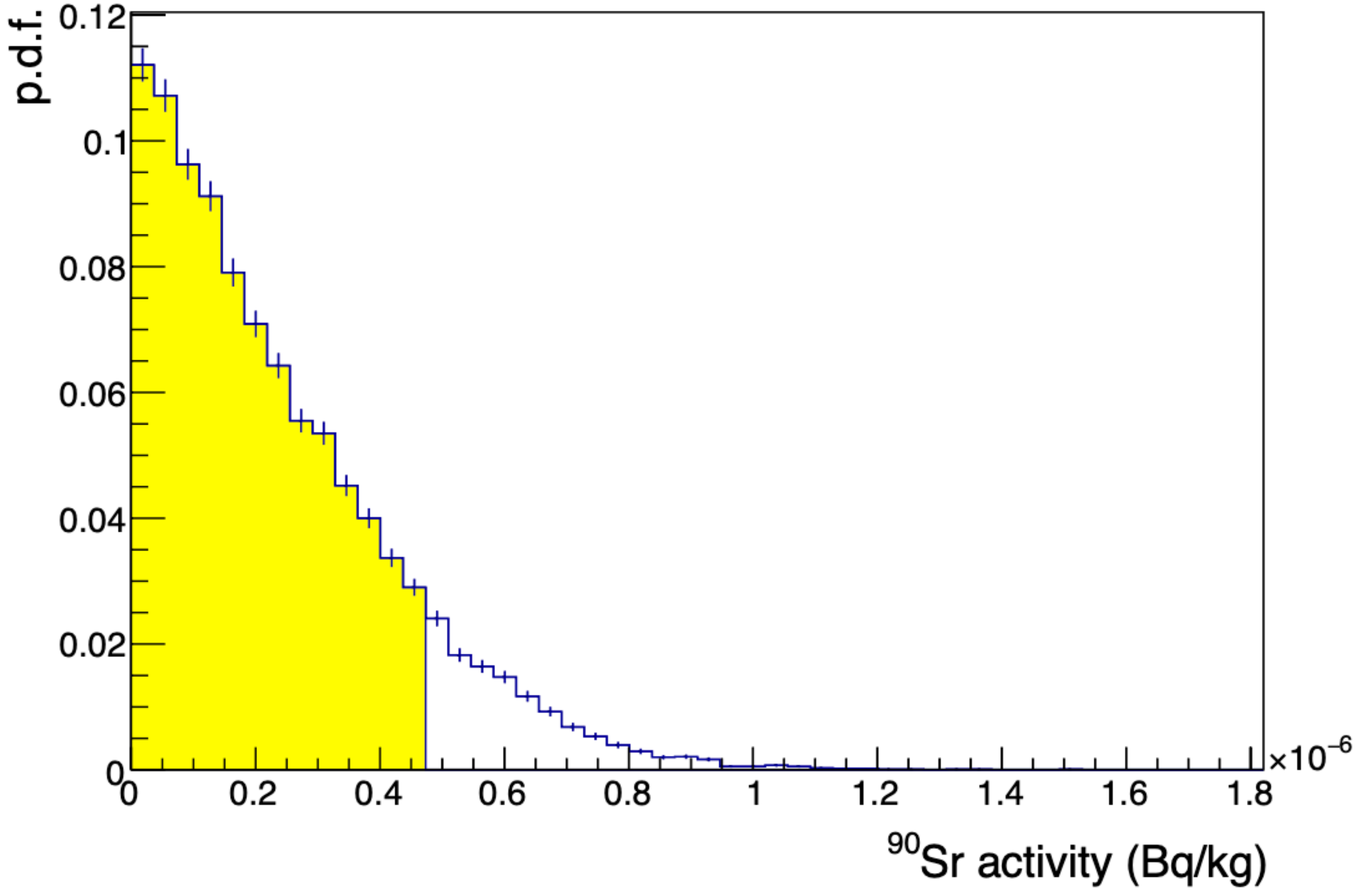


M2-SUM SPECTRUM FIT (JAGS)



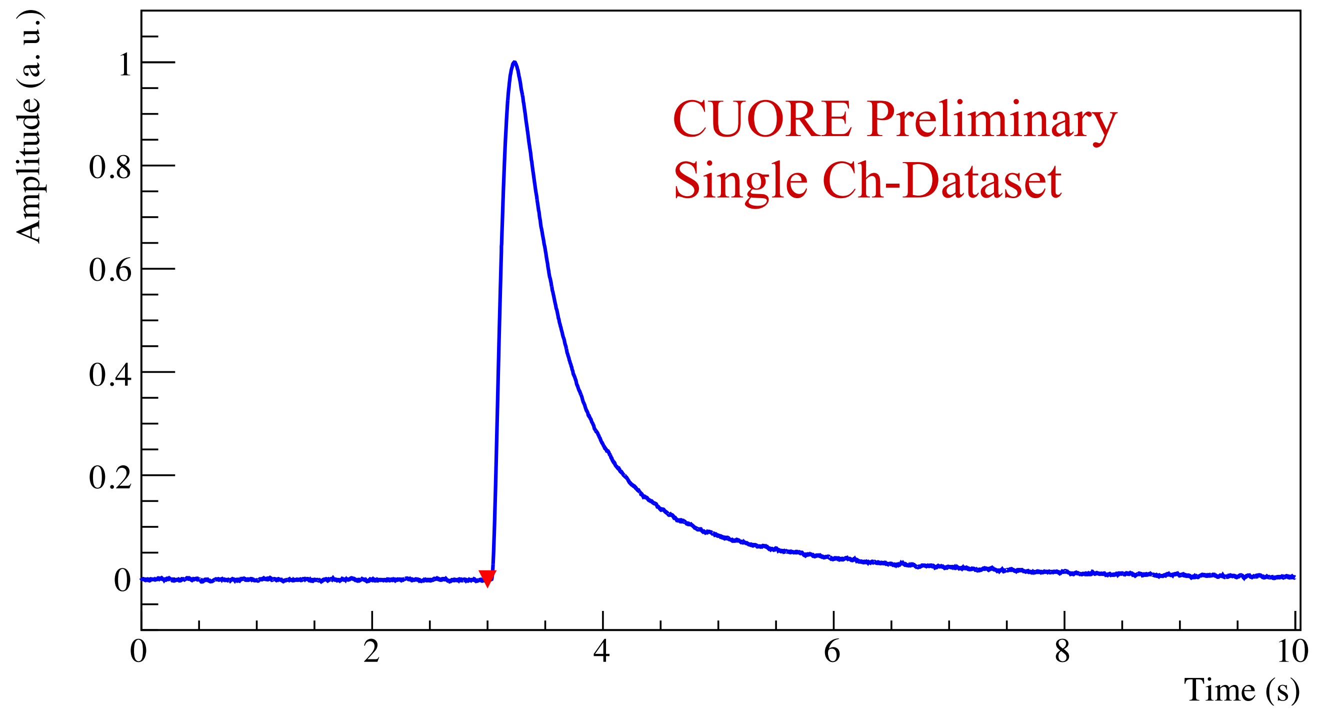
EFFECT OF 90SR REMOVAL

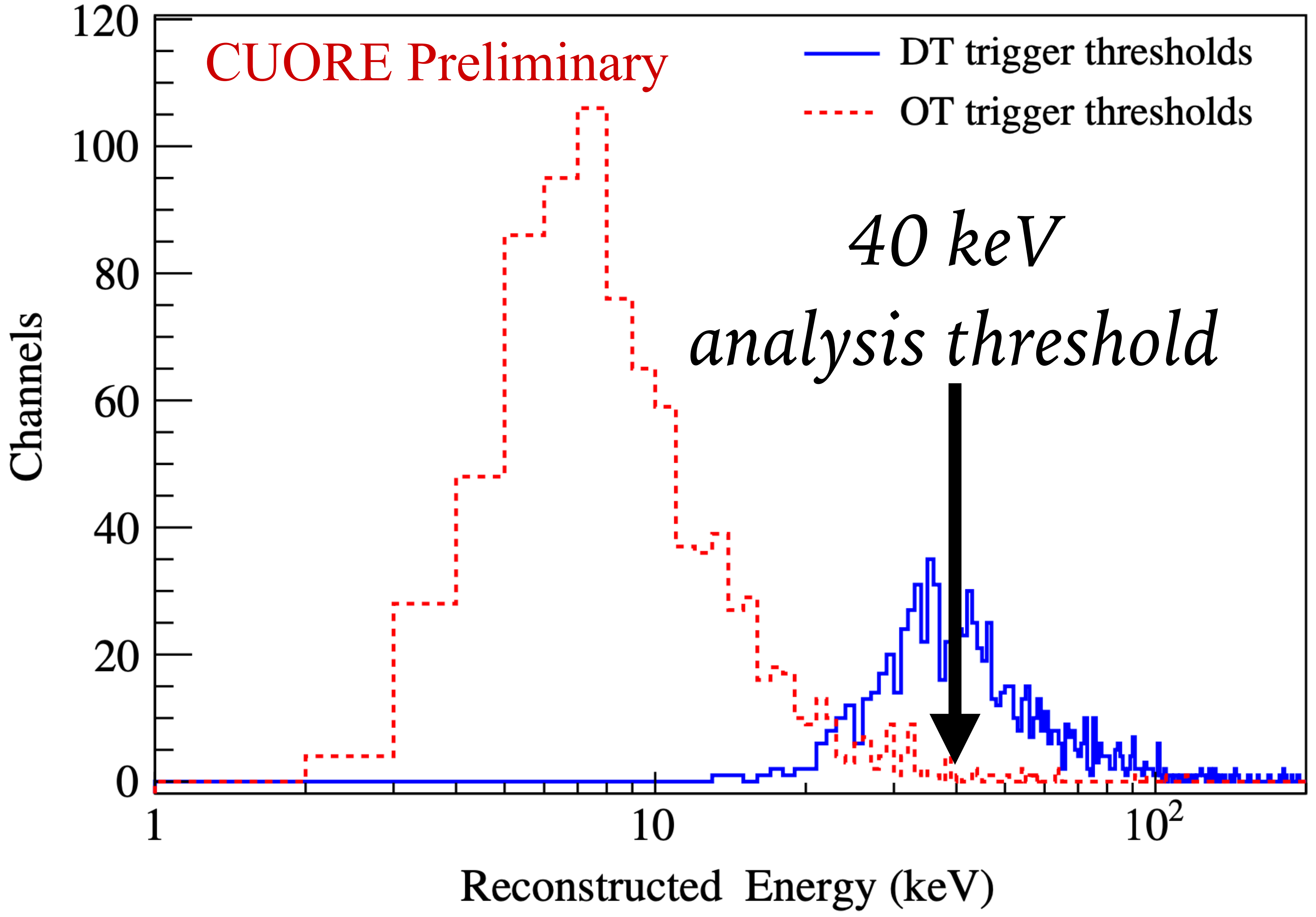




CUORE DATA ANALYSIS

- **Trigger**
- Optimum Filter
- Gain Correction
- Energy Calibration
- Coincidences
- Pulse Shape Discrimination (PSD)
- Blinding



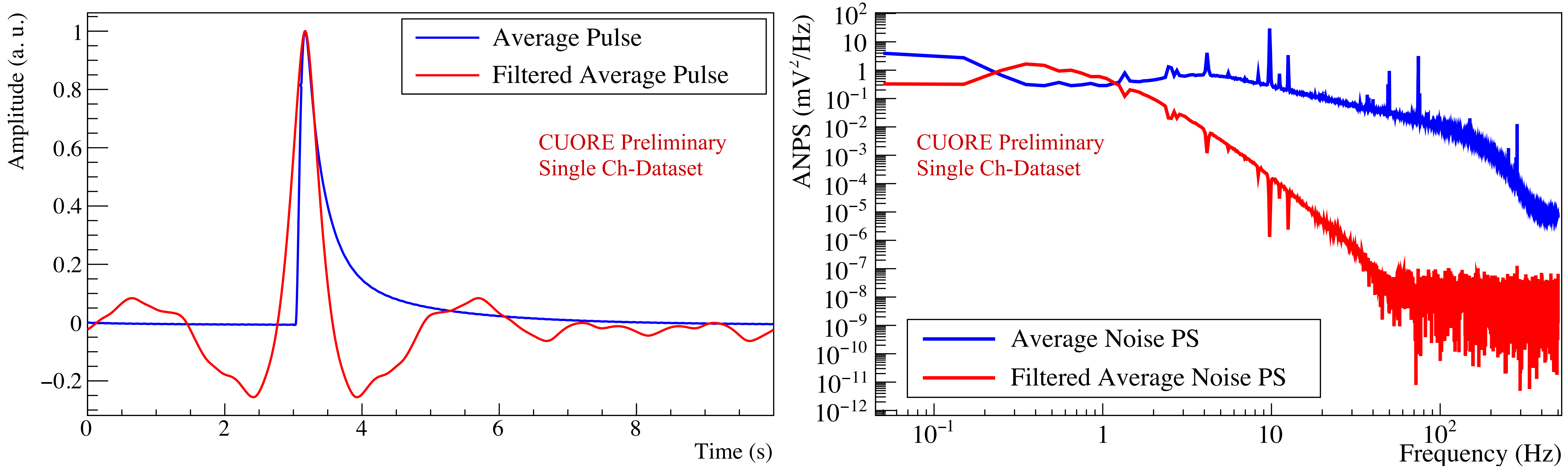


- Online analysis for quick data quality feedback (DT)
- Offline re-triggering (OT)
  - disentangle small signals from noise fluctuations
  - median trigger threshold < 10 keV
  - 40 keV analysis threshold guarantees 97% of channels have > 90% trigger efficiency
  - minimize γ background from low energy Compton scattering events

CUORE DATA ANALYSIS

CUORE

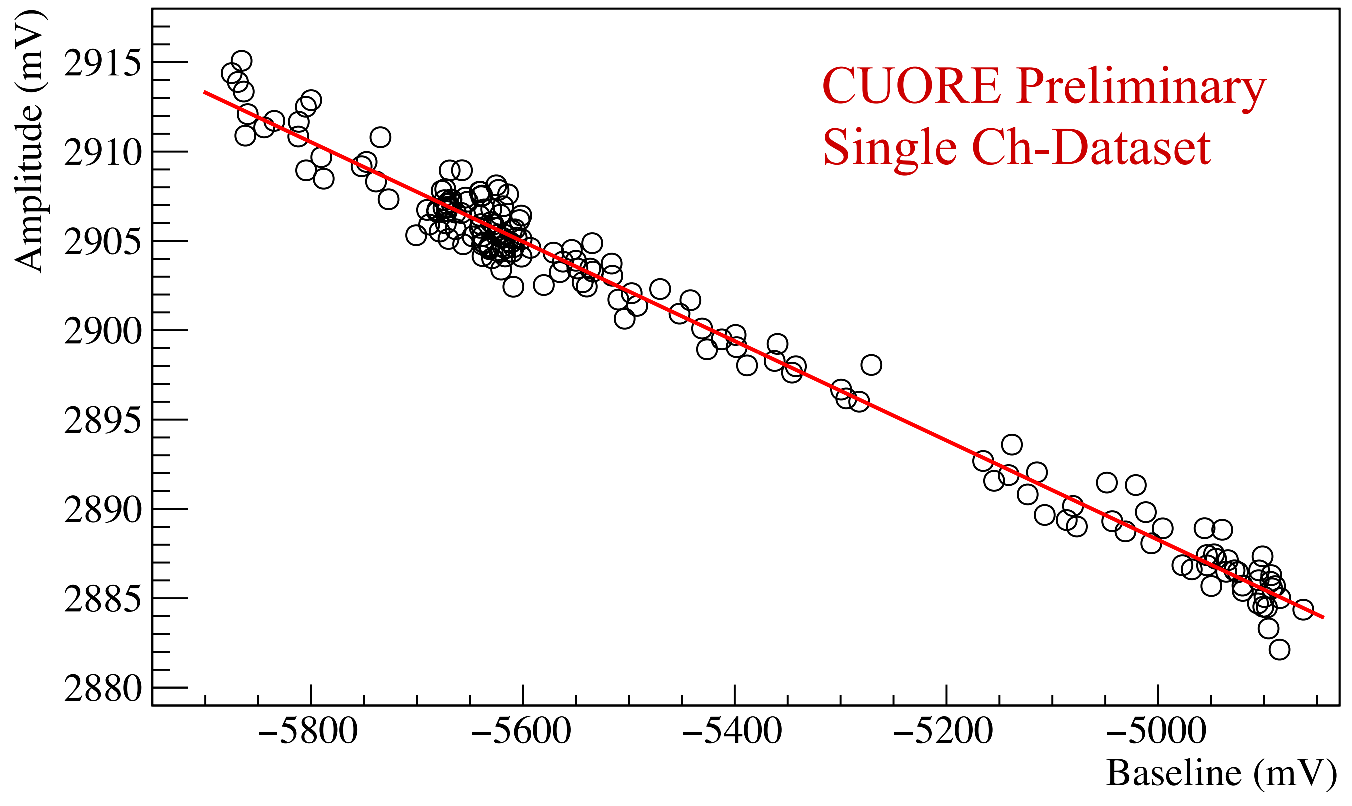
- Trigger
- **Optimum Filter**
- Gain Correction
- Energy Calibration
- Coincidences
- Pulse Shape Discrimination (PSD)
- Blinding

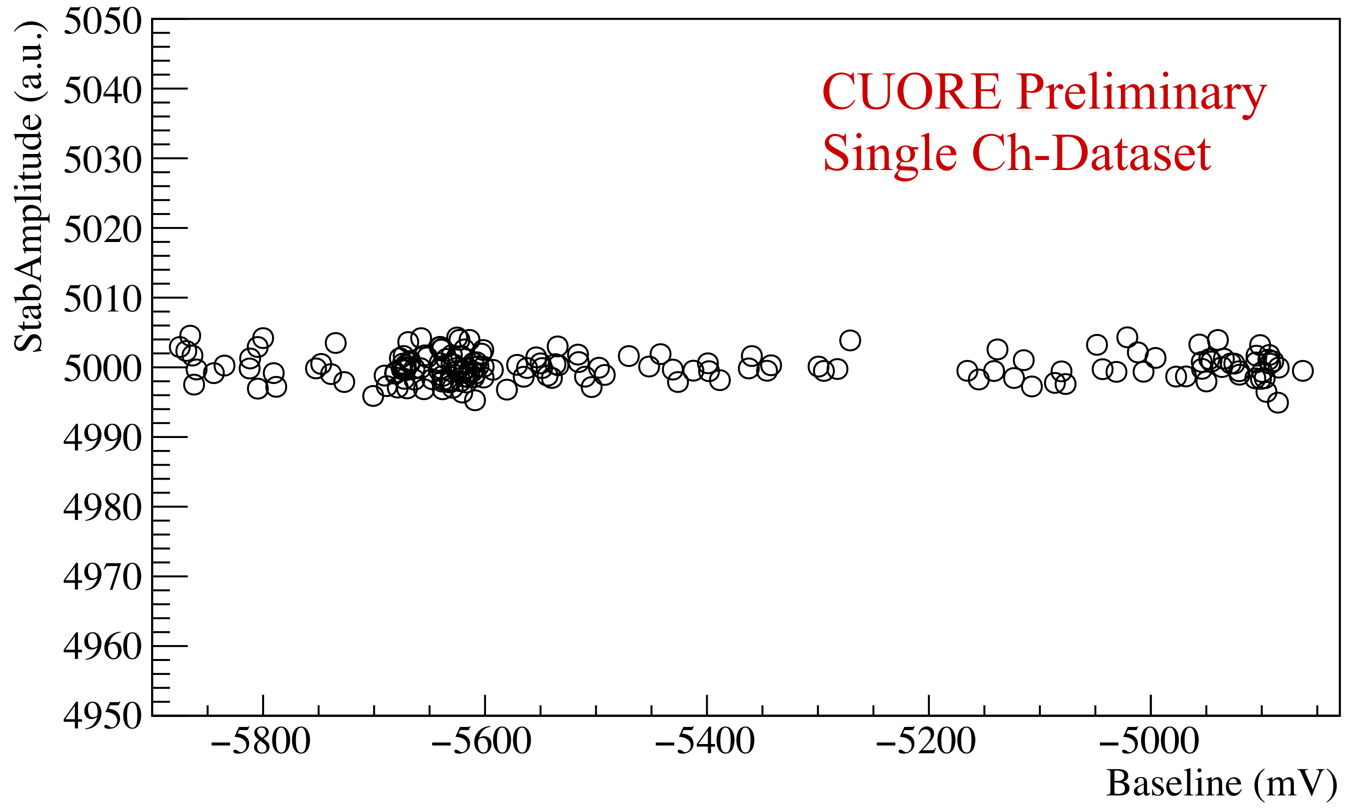


Matched filter maximizes signal-to-noise ratio

CUORE DATA ANALYSIS

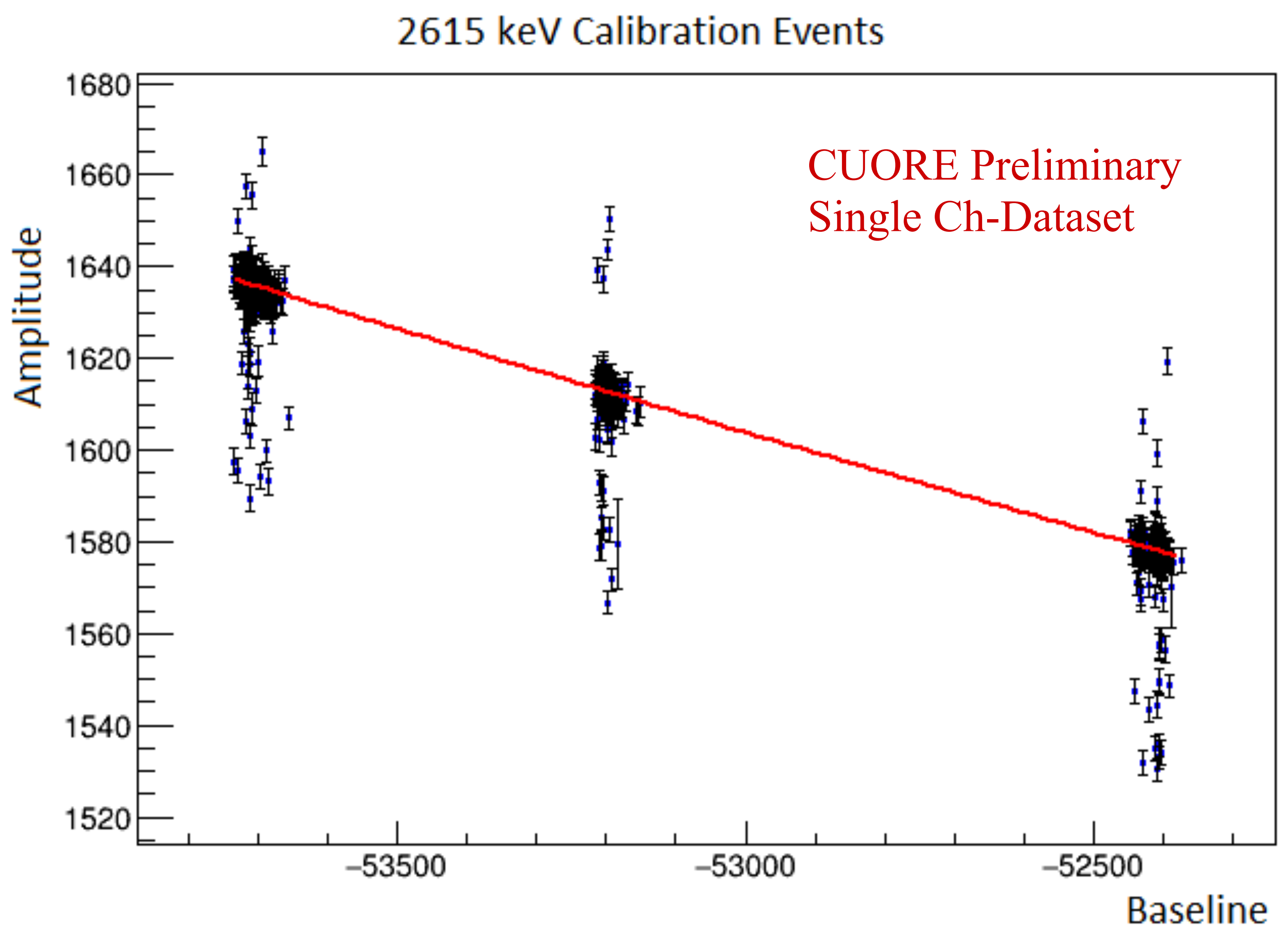
- Trigger
- Optimum Filter
- **Gain Correction**
- Energy Calibration
- Coincidences
- Pulse Shape Discrimination (PSD)
- Blinding





Heater pulses for thermal gain stabilization

- ➤ Use fixed energy heater events to correct amplitude dependence on operating temperature
- ➤ Interpolate calibration peak at 2615 keV for non-functional or underperforming heaters



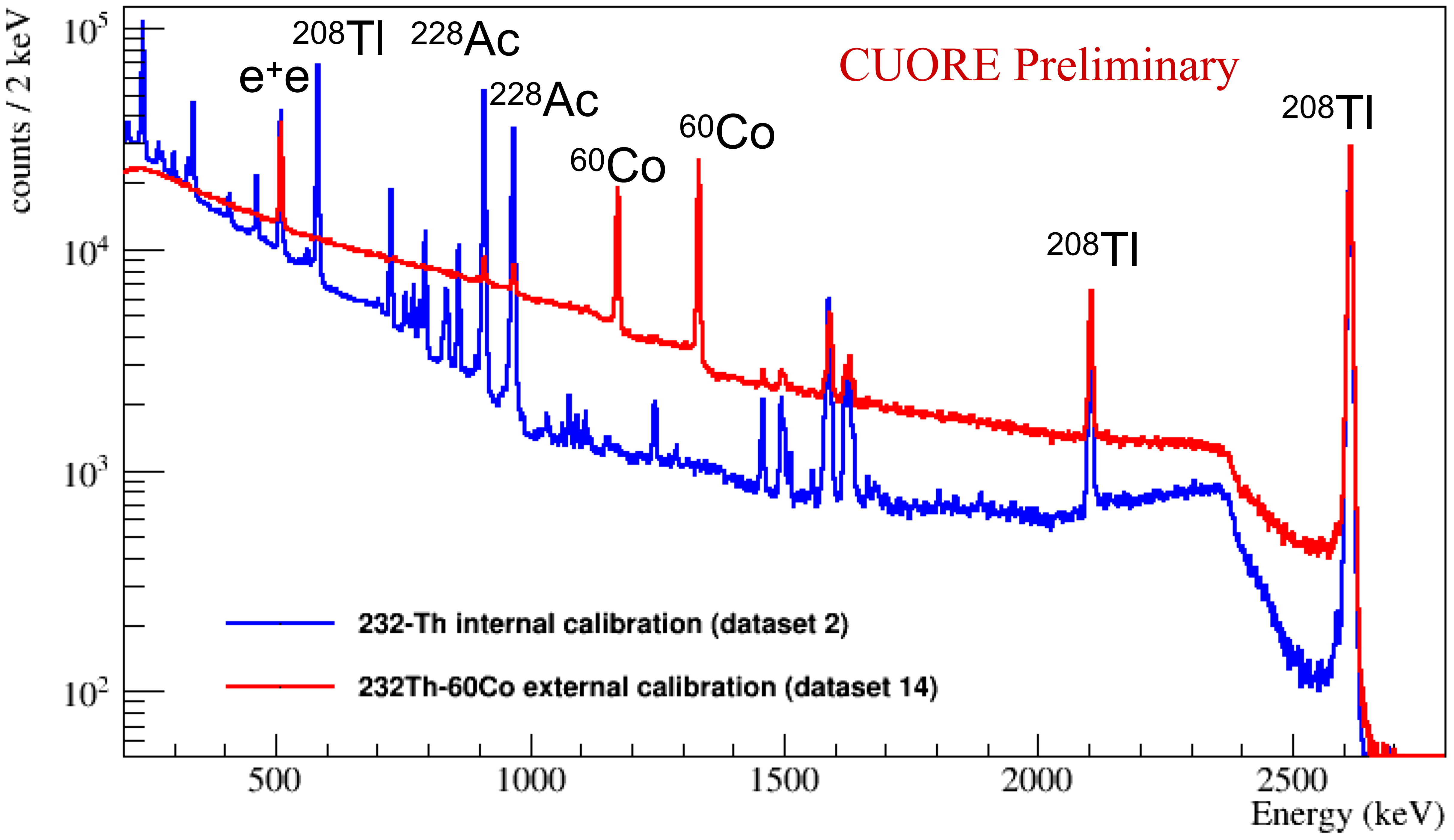
CUORE DATA ANALYSIS

CUORE

- Trigger
- Optimum Filter
- Gain Correction
- **Energy Calibration**
- Coincidences
- Pulse Shape Discrimination (PSD)
- Blinding

➤ First 3 datasets used internal ^{232}Th source

➤ Internal calibration system replaced with simpler external one in later datasets

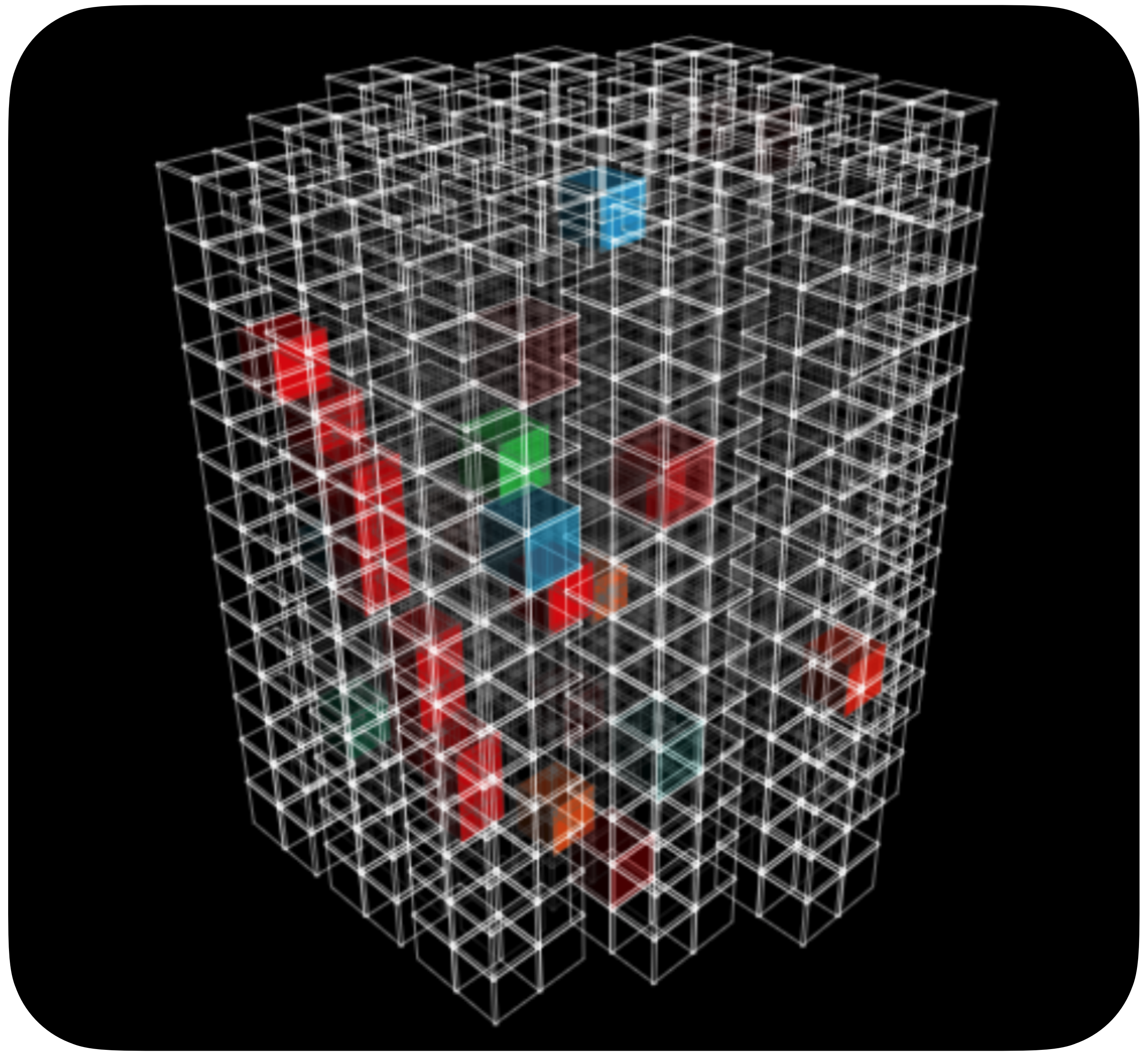


➤ Data is now calibrated with external ^{232}Th-^{60}Co source

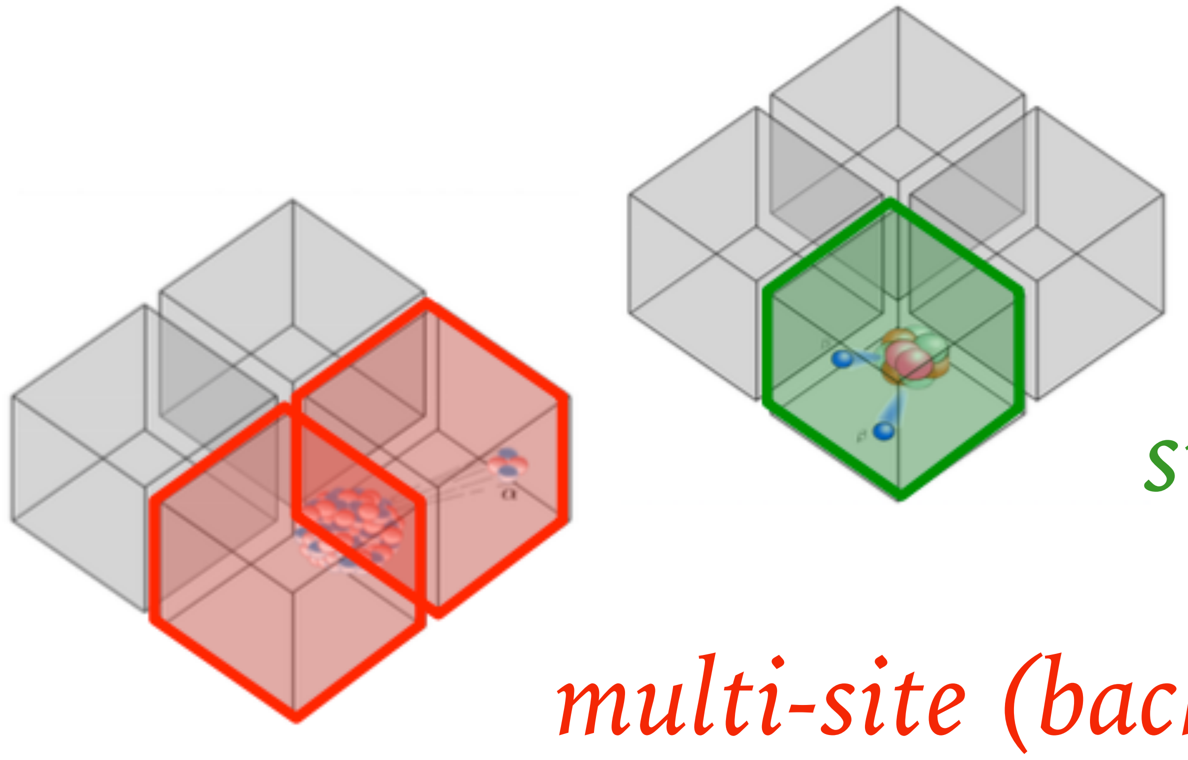
➤ 2nd order polynomial calibration function with 0 intercept fits 511, 1173, 1333, 2615 keV calibration lines

CUORE DATA ANALYSIS

- Trigger
- Optimum Filter
- Gain Correction
- Energy Calibration
- **Coincidences**
- Pulse Shape Discrimination (PSD)
- Blinding



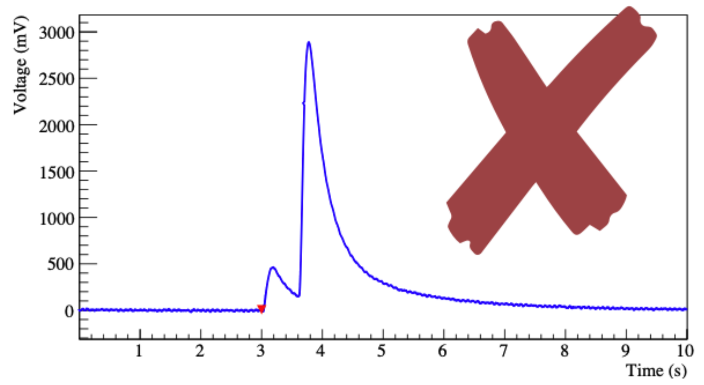
- ~88% of 0νββ events involve just one crystal
- when multiple bolometers fire in a small (5 ms) time window, the event is likely to be due to radioactive contaminations or muons
- assign multiplicity (number of involved crystals) and total energy
- apply anti-coincidence veto for 0νββ analysis

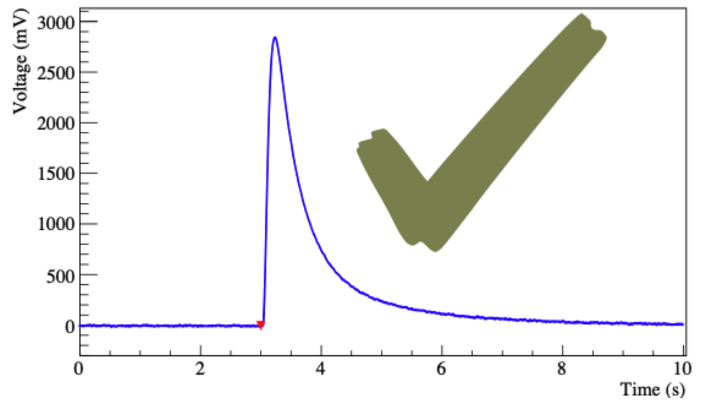


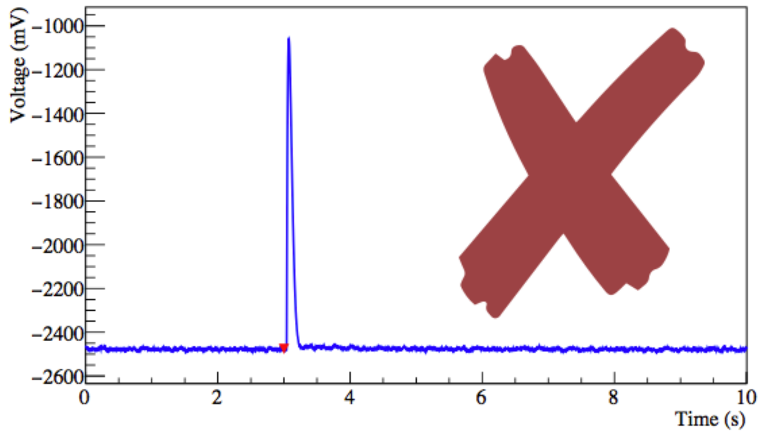
single-site (signal-like)

multi-site (background-like)

CUORE DATA ANALYSIS

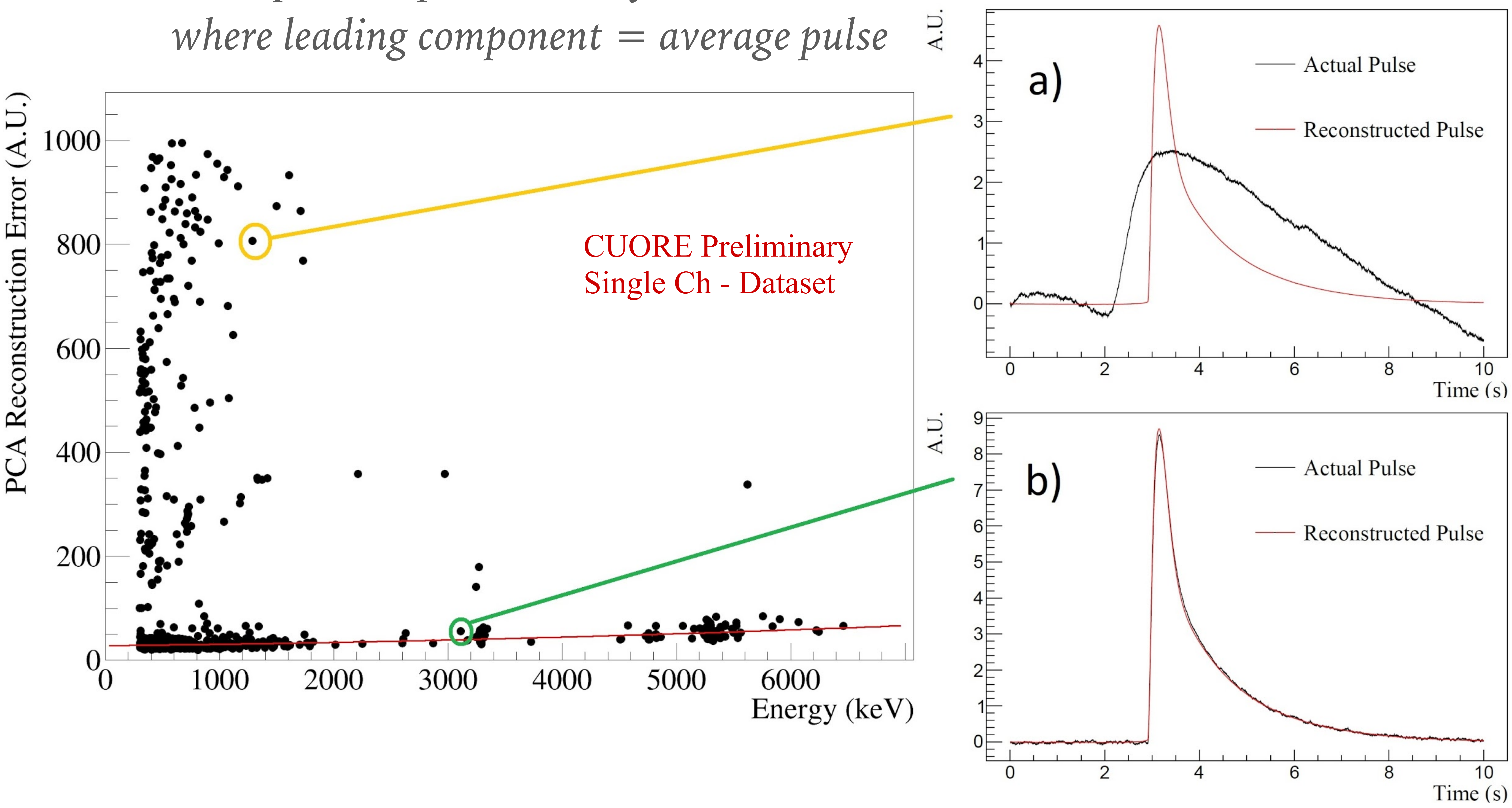






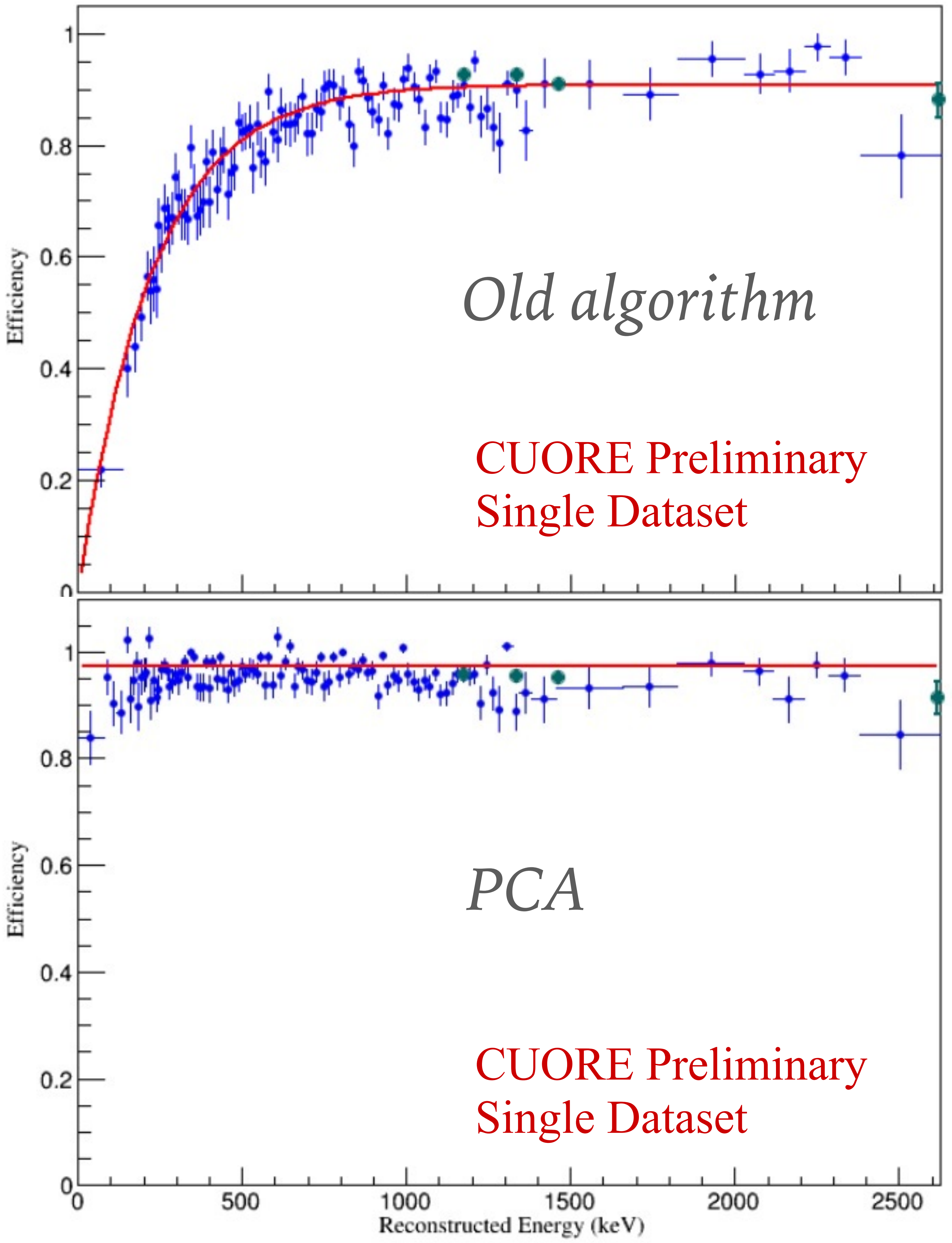
- Trigger
- Optimum Filter
- Gain Correction
- Energy Calibration
- Coincidences
- **Pulse Shape Discrimination (PSD)**
- Blinding

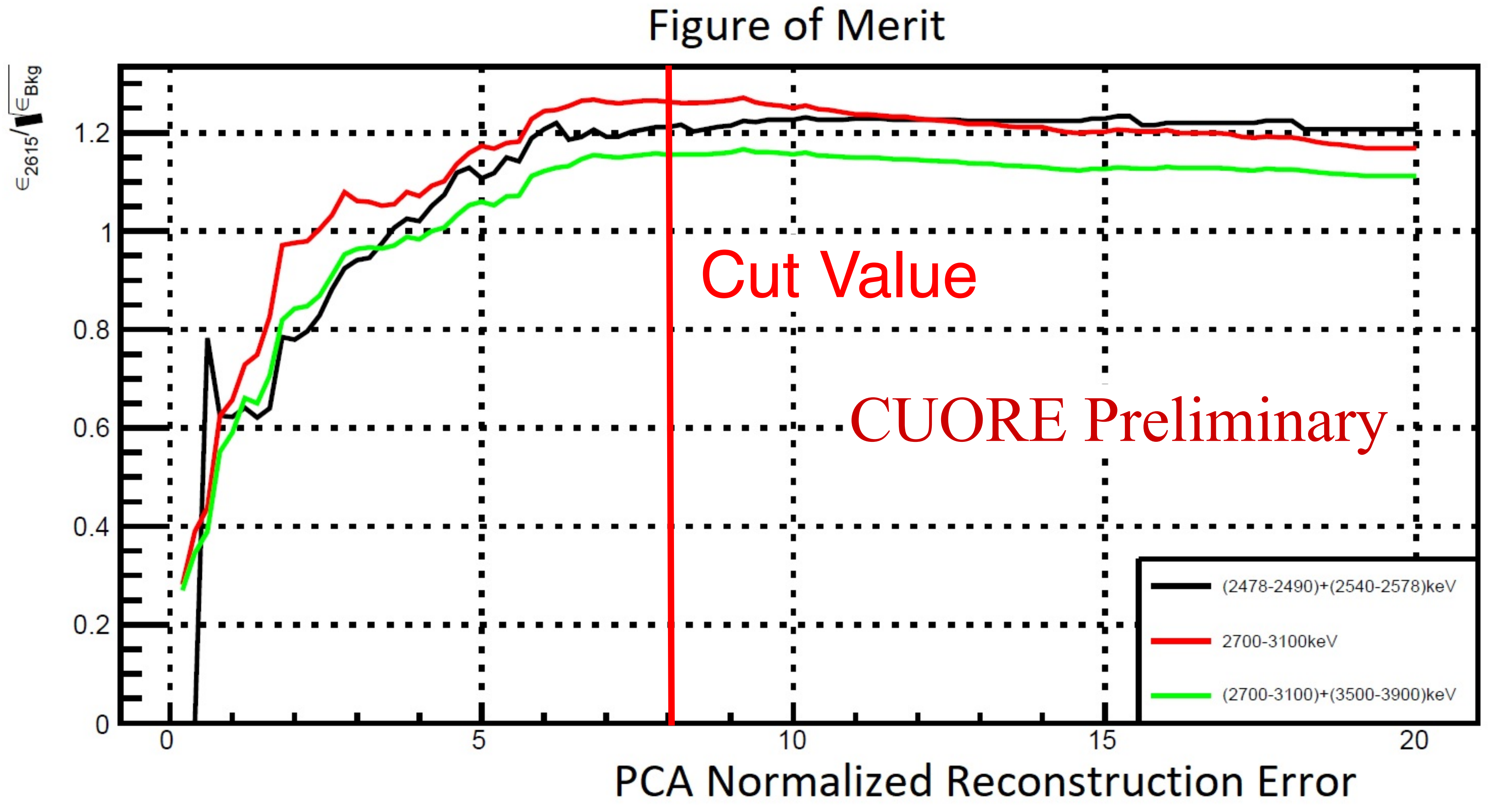
Principal Component Analysis (PCA)
where leading component = average pulse



CUORE DATA ANALYSIS

- Trigger
- Optimum Filter
- Gain Correction
- Energy Calibration
- Coincidences
- **Pulse Shape Discrimination (PSD)**
- Blinding



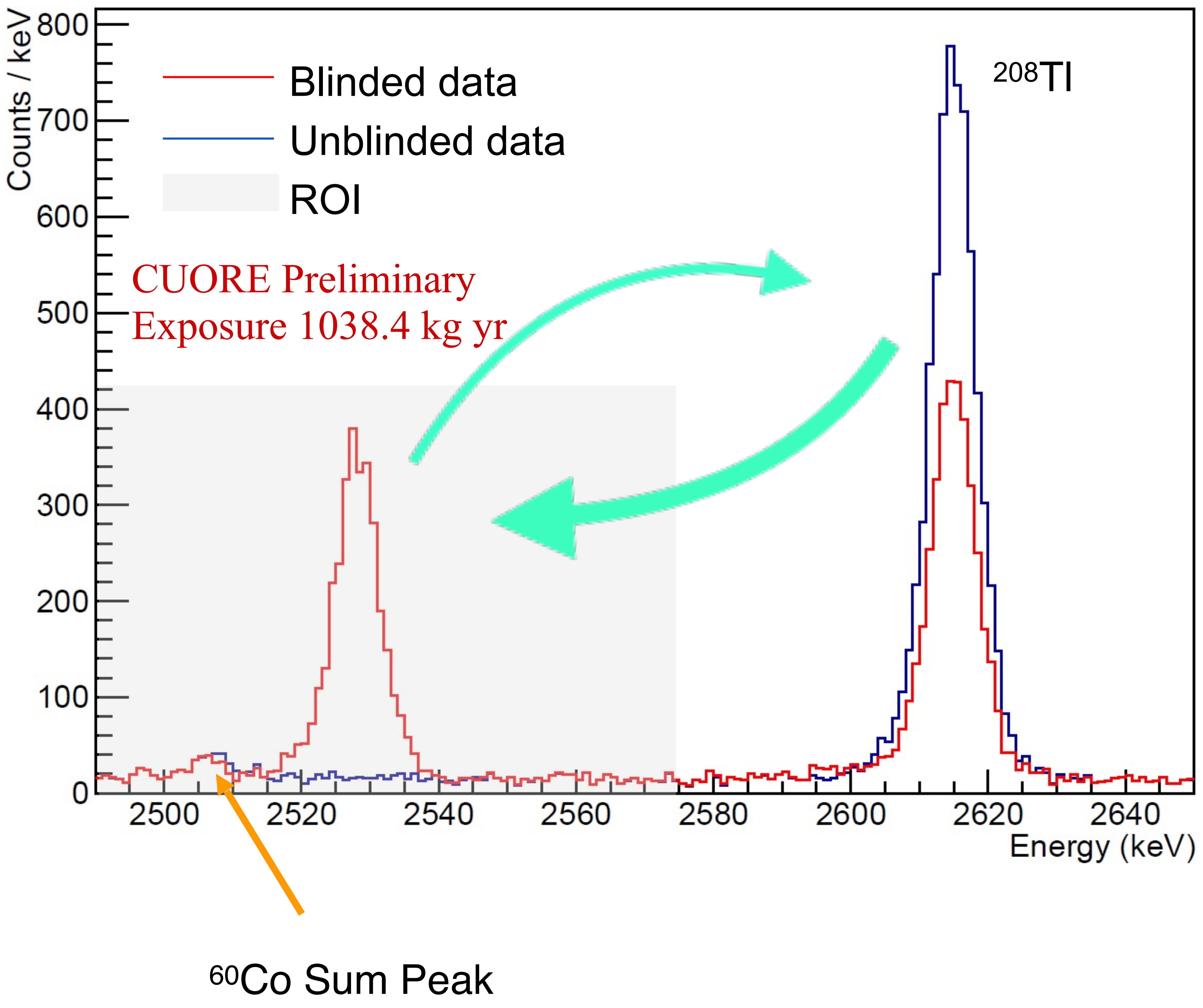


- Tune cut on a $S/\sqrt{B}$ figure of merit
- Gamma peaks for efficiency
- Alpha region as background proxy
- PCA method shows increased efficiency at all energies
- Similar background rejection

CUORE DATA ANALYSIS

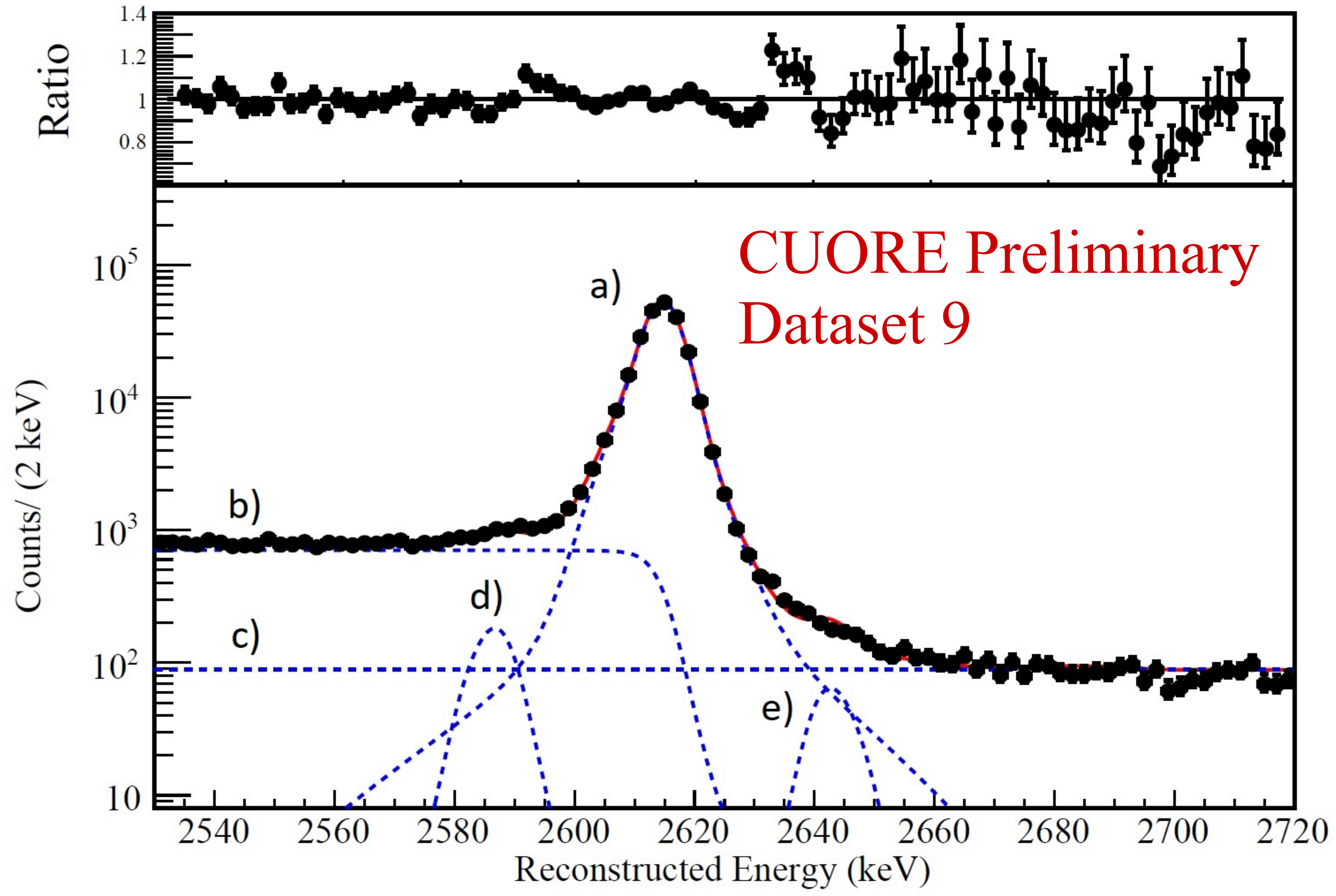
- Trigger
- Optimum Filter
- Gain Correction
- Energy Calibration
- Coincidences
- Pulse Shape Discrimination (PSD)
- **Blinding**

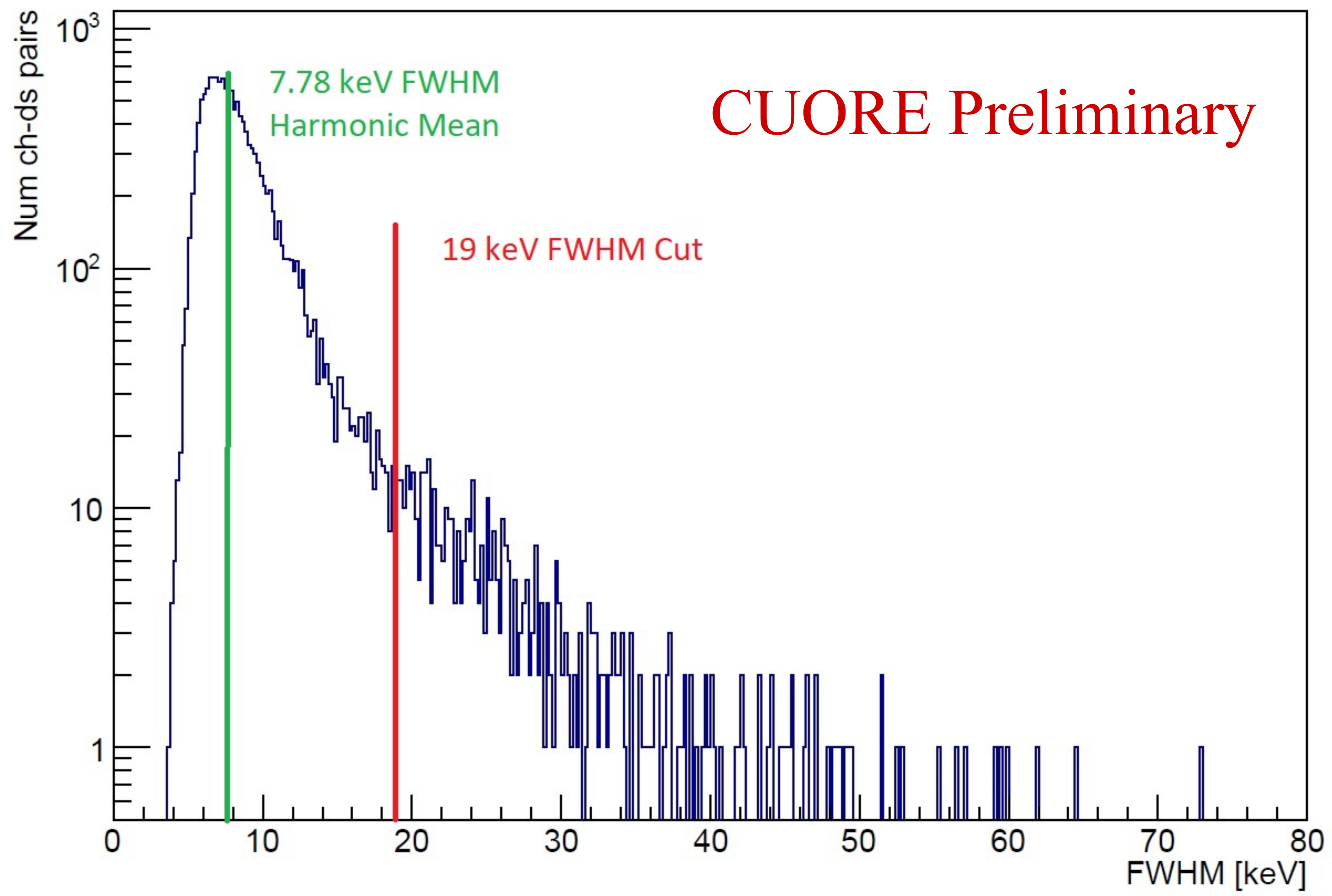
- Random fraction of events in ^{208}Tl line shifted to $Q_{\beta\beta}$ and vice versa
- Original energies stay encrypted until unblinding
- Unblinding happens only after full analysis procedure is finalized



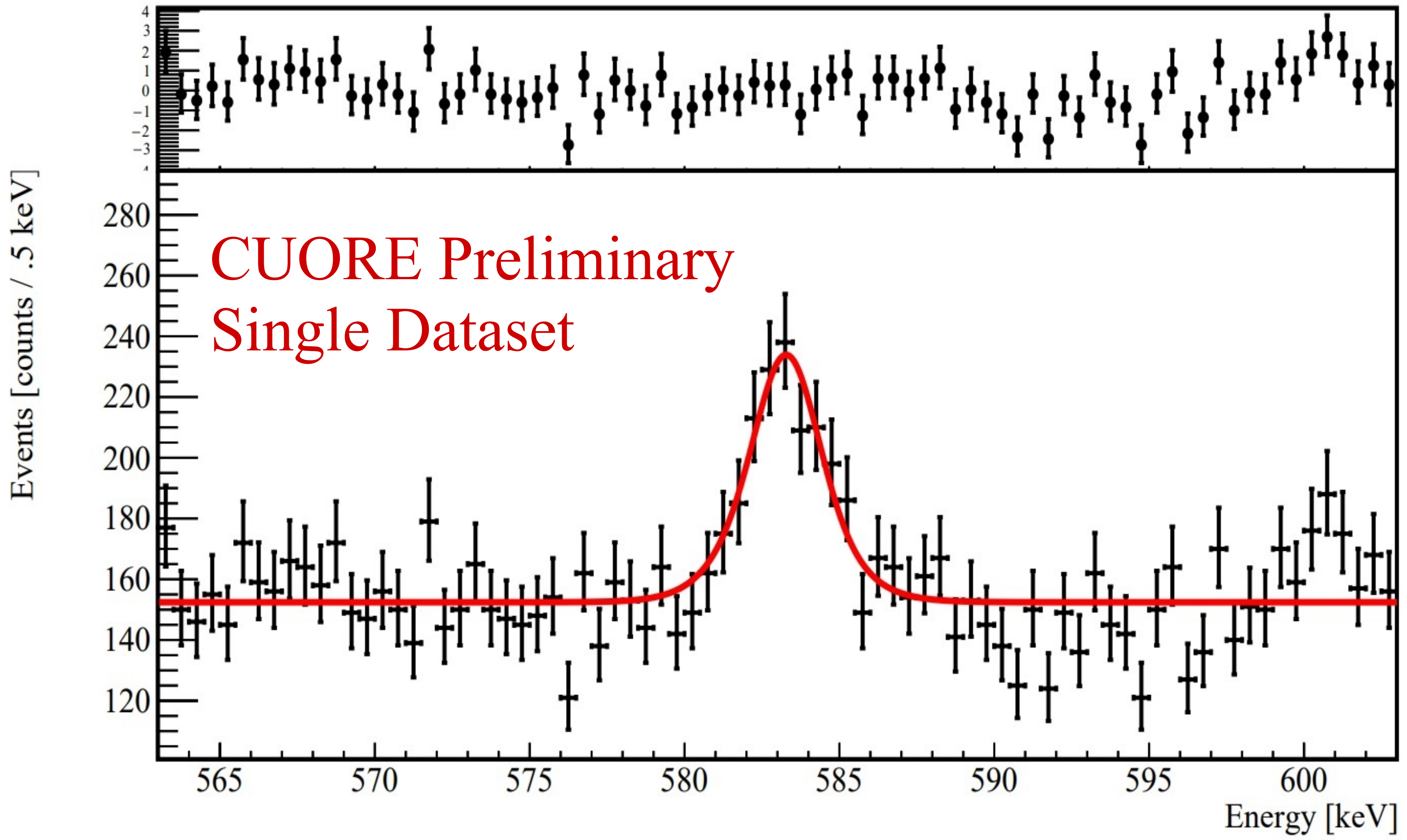
CUORE DATA ANALYSIS – DETECTOR RESPONSE

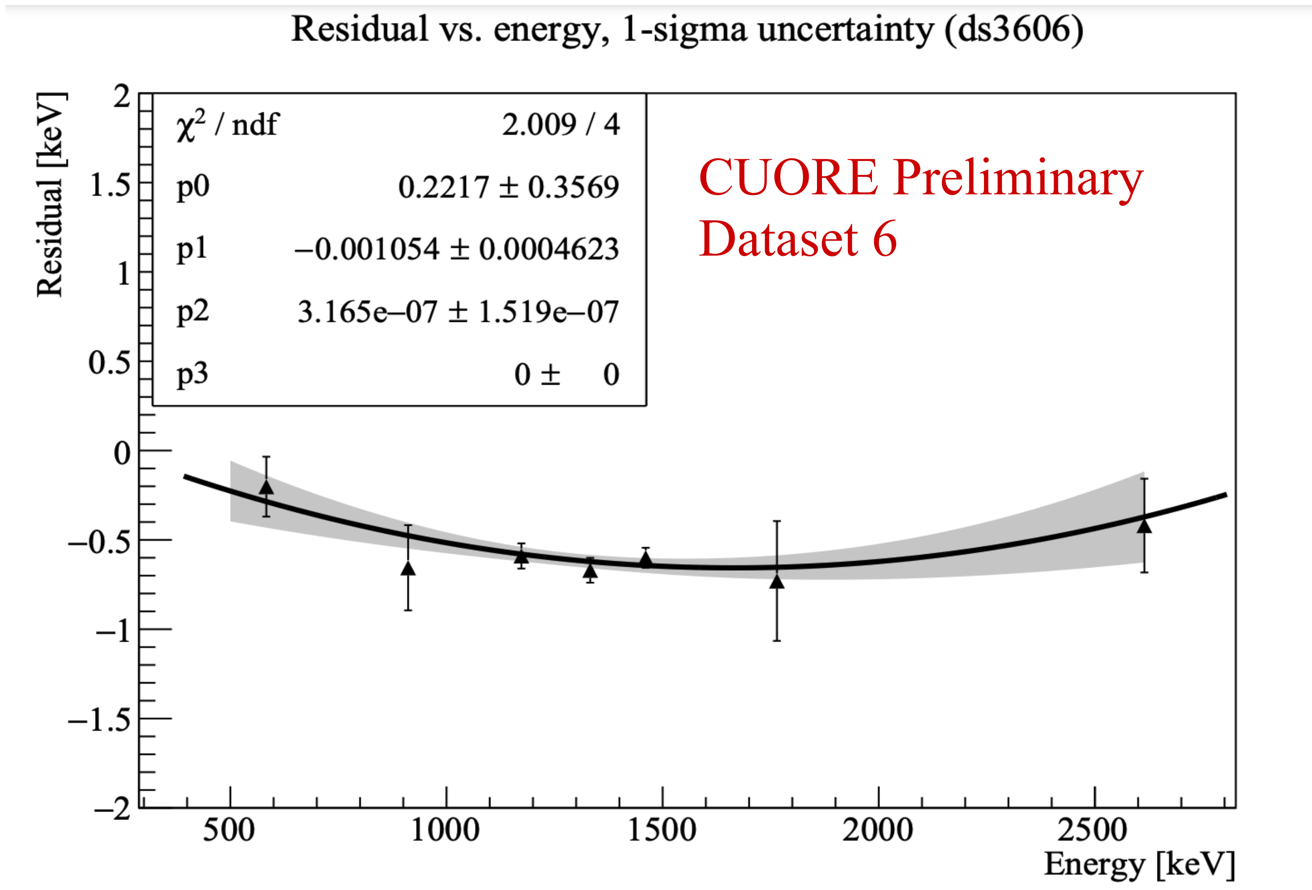
- Fit 2615 keV calibration peak for each channel
  a) 3-Gaussian signal peak
  b) Compton background
  c) Flat background
  d) 30 keV X-ray escape peak (background)
  e) 30 keV X-ray sum peak (background)
- Detector response function is just component (a)
- Exclude channels with FWHM > 19 keV for this analysis

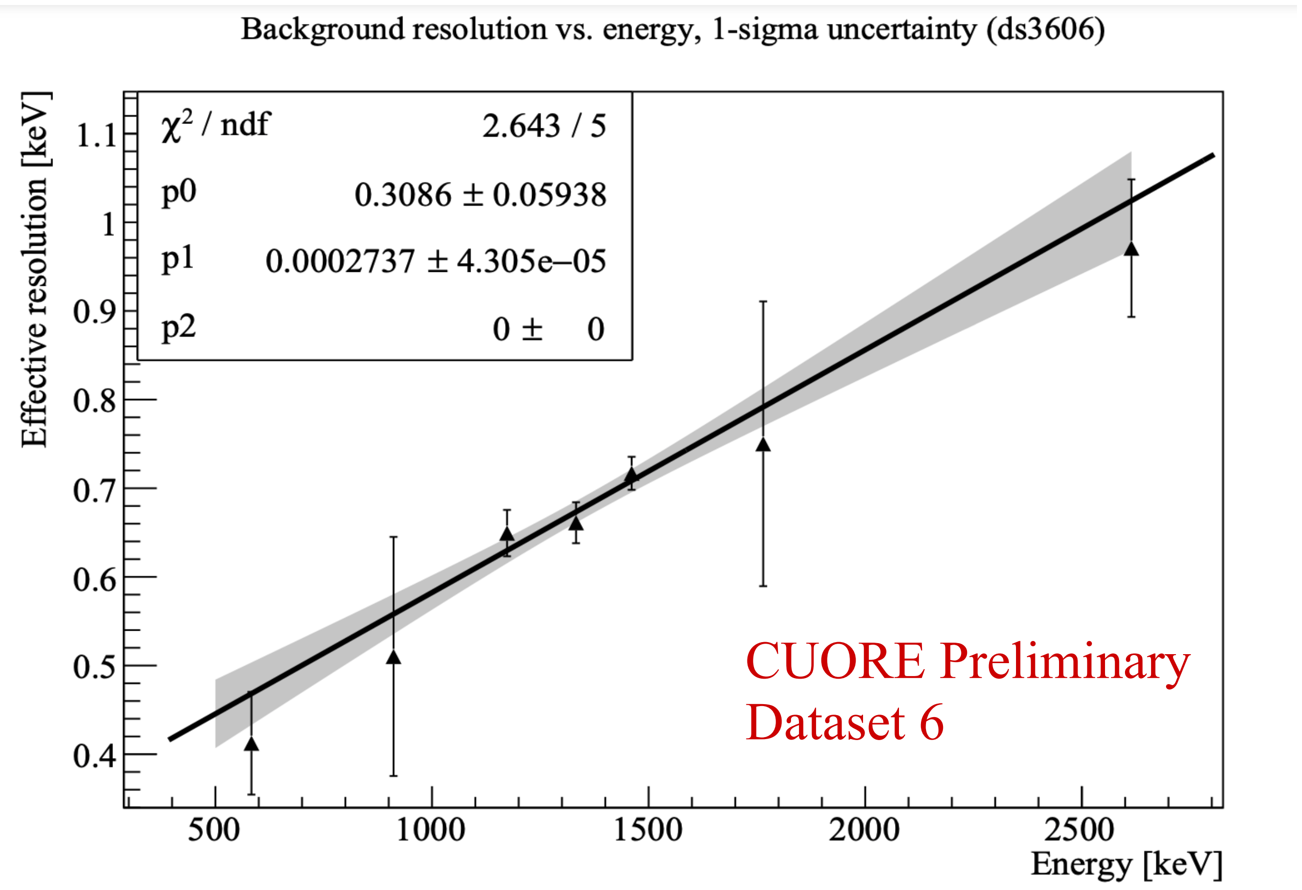




CUORE DATA ANALYSIS – DETECTOR RESPONSE

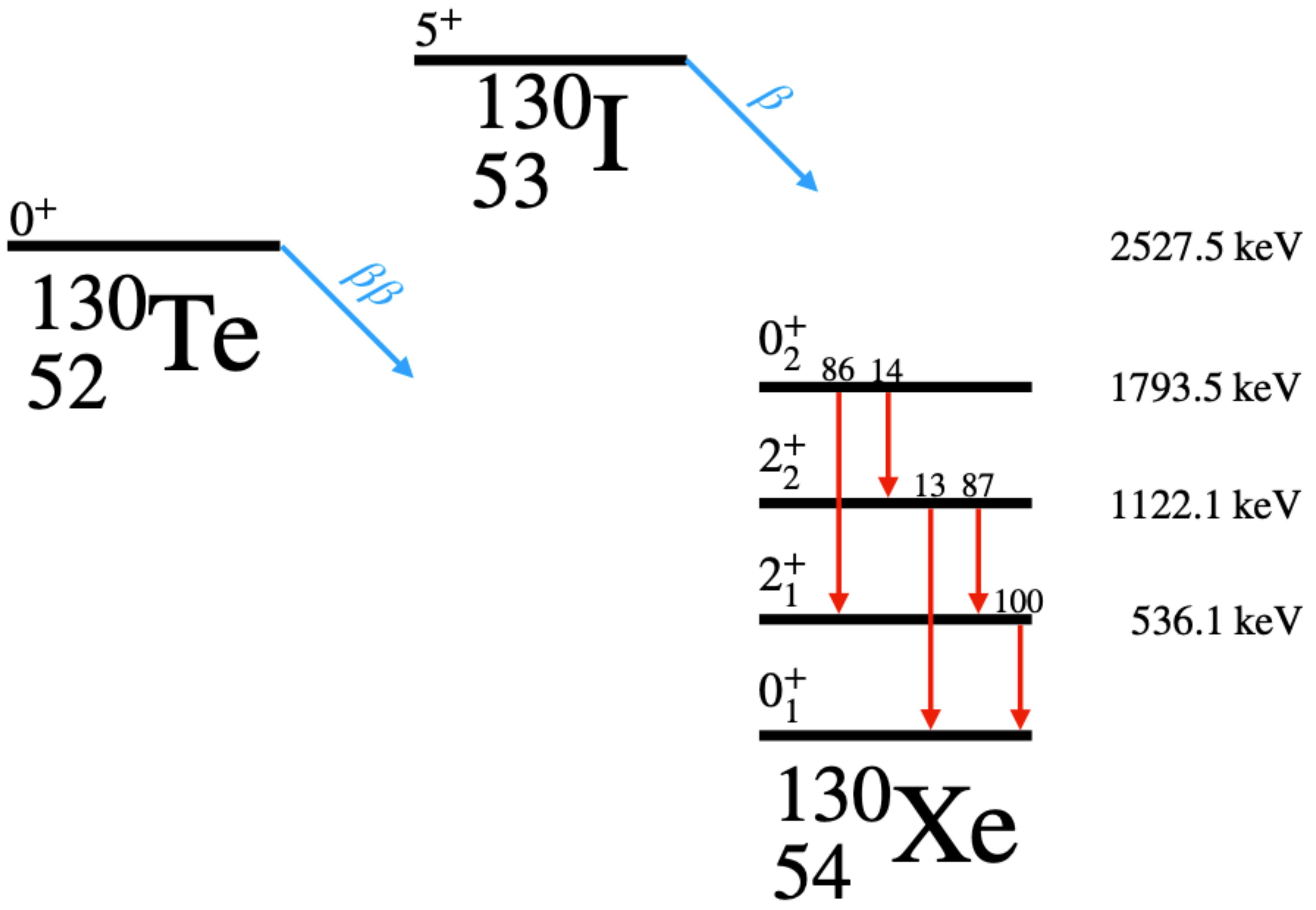


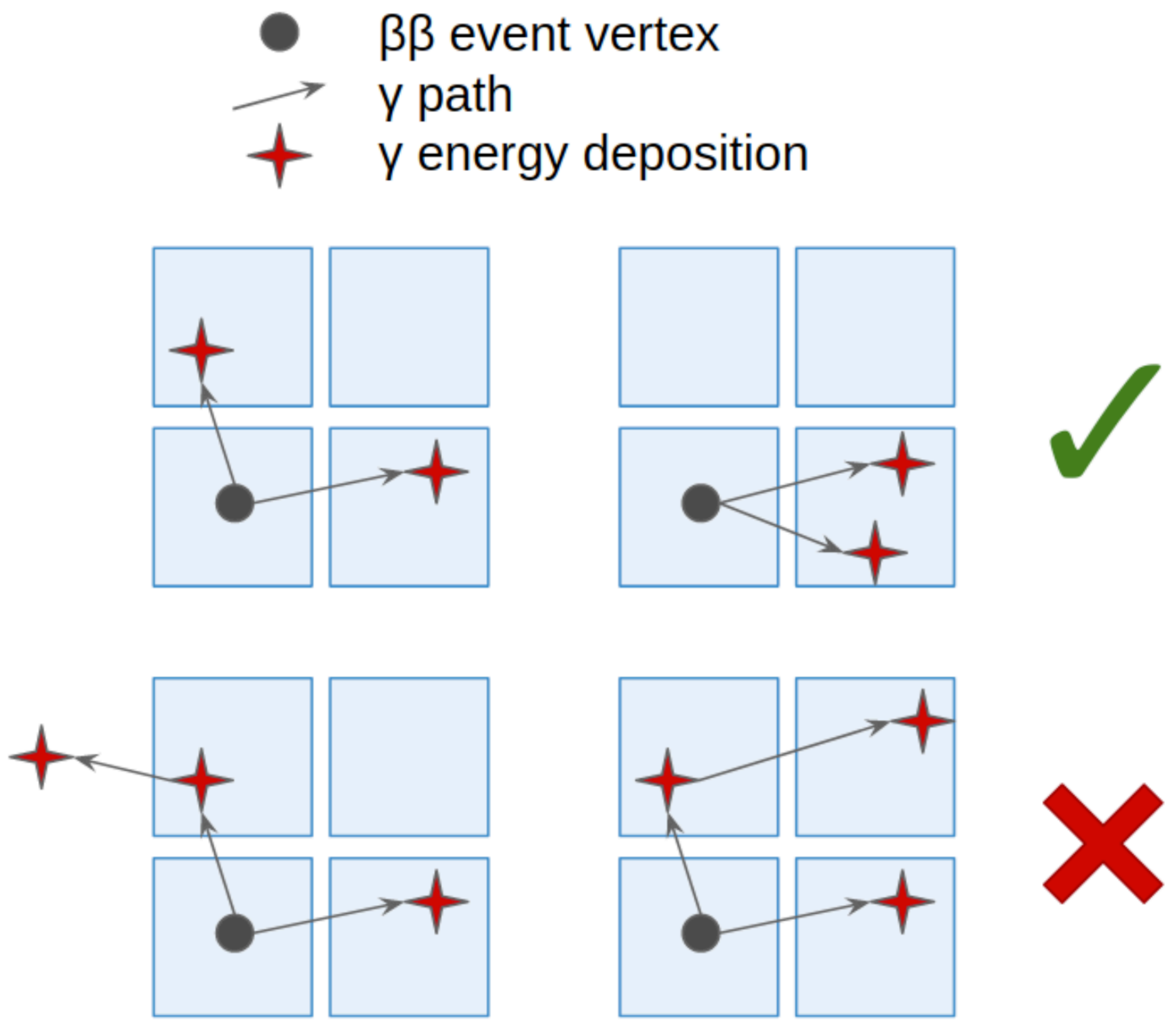




- Scale detector response fit from 2615 keV calibration to multiple peaks in physics data to determine
  - <u>energy bias</u>
    2nd order polynomial function of energy, < 0.7 keV
  - <u>resolution</u>
    linear function of energy
    FWHM harmonic mean @ $Q_{\beta\beta}$
    7.8 keV

DOUBLE BETA DECAY TO EXCITED STATES





Pattern	BR [%]	Energy γ_1	Energy γ_2	Energy γ_3
A	86%	1257 keV	536 keV	-
B	12%	671 keV	586 keV	536 keV
C	2%	1122 keV	671 keV	-

- $Q_{\beta\beta}$ = 734 keV
- signature: coincidence of beta and de-excitation gamma rays

Adams, D.Q. et al. (CUORE Collaboration)
https://arxiv.org/abs/2101.10702

DOUBLE BETA DECAY TO EXCITED STATES

- Fully contained events only (ββ and de-excitation γs all detected)
- Coincident events up to 3 crystals
- Only most sensitive experimental signatures

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

$T^{2\nu}_{1/2} > 1.3 \times 10^{24}$ yr (90 % C.I.)

Adams, D.Q. et al. (CUORE Collaboration) https://arxiv.org/abs/2101.10702

Literature (CUORE-0)

$T^{0\nu}_{1/2} > 1.4 \times 10^{24}$ yr (90 % C.L.)

$T^{2\nu}_{1/2} > 0.25 \times 10^{24}$ yr (90 % C.L.)

Alduino, C. et al (CUORE-0 Collaboration), Eur. Phys. J. C, 79(9):795, 2019 https://doi.org/10.1140/epjc/s10052-019-7275-5