LATEST RESULTS OF THE CUORE EXPERIMENT

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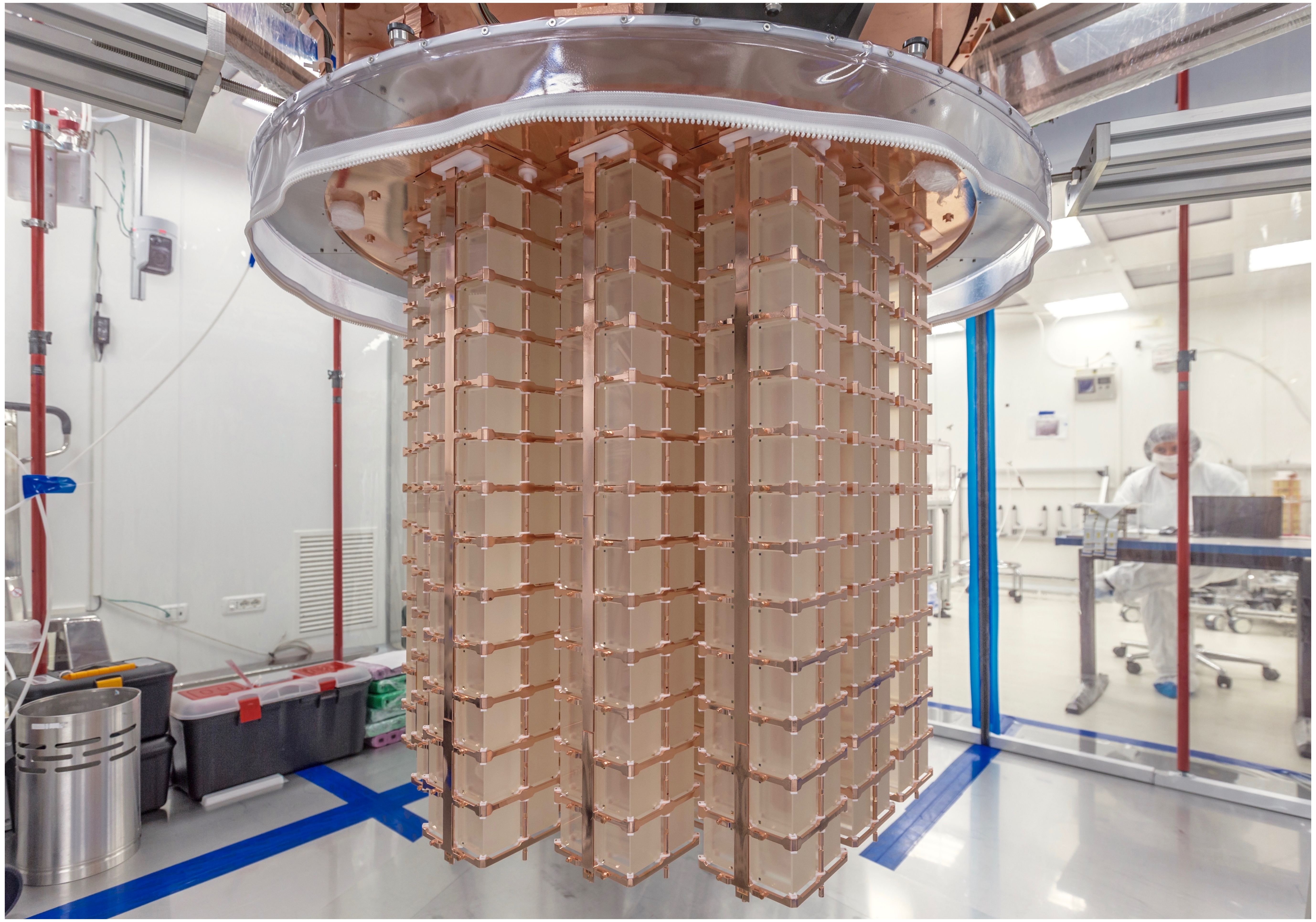
CUORE

INFN

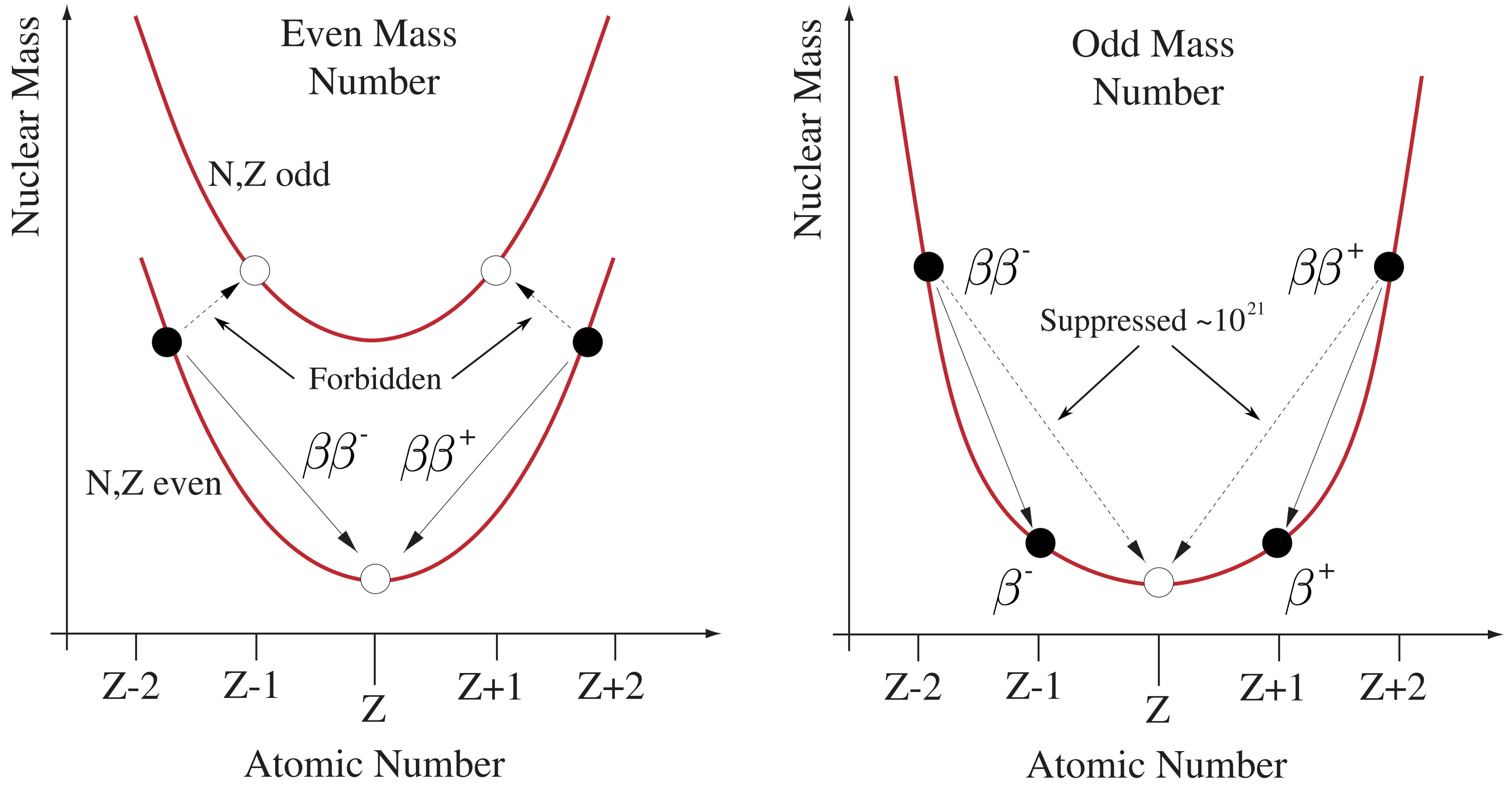
OUTLINE

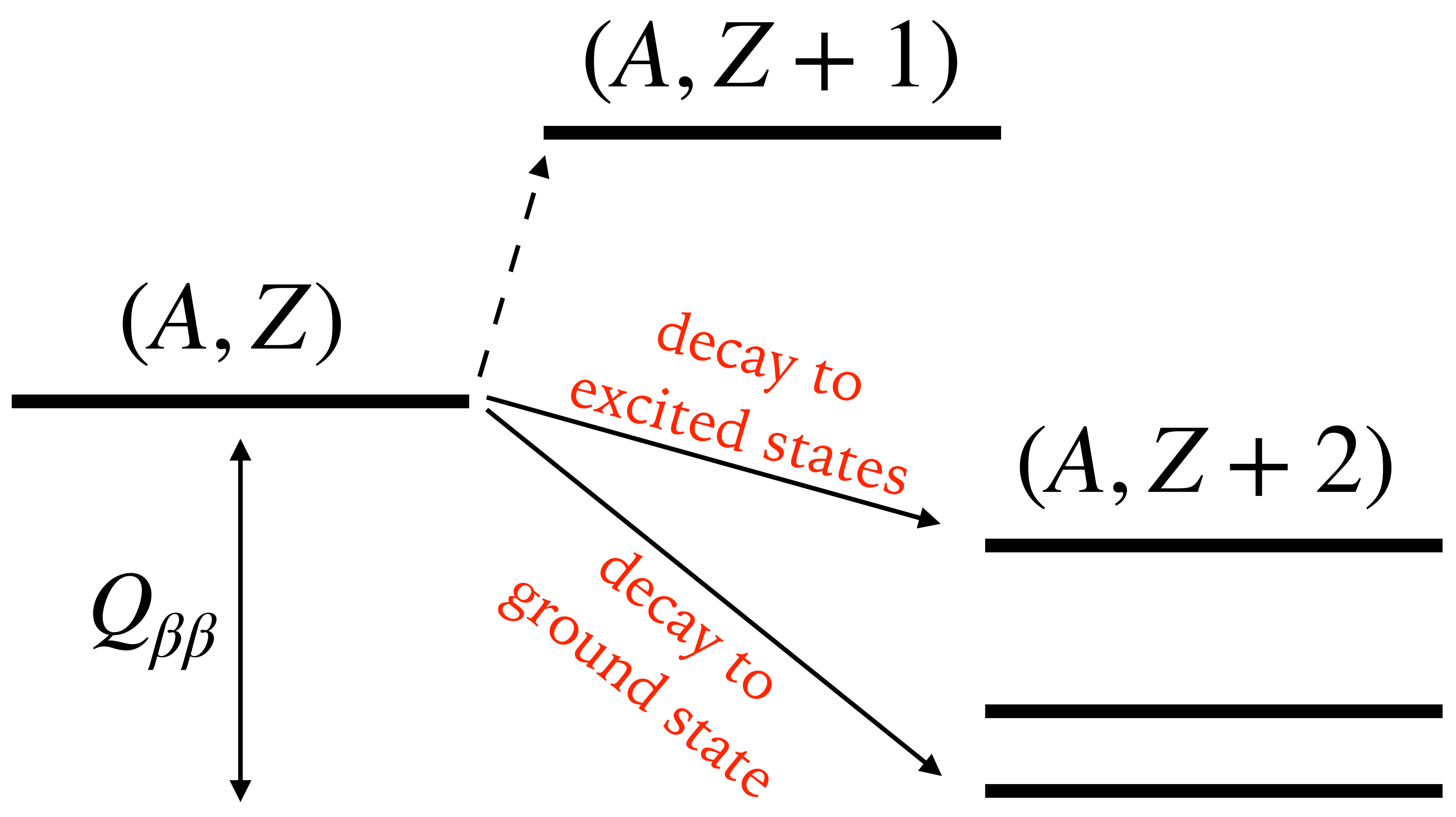
- Double Beta Decay
- The CUORE experiment
- Detector performance
- $0\nu\beta\beta$ (new!) results
- ^{130}Te half life ($2\nu\beta\beta$)
- Other rare decay searches
- Conclusion



DOUBLE BETA DECAY

$$(A, Z) \longrightarrow (A, Z+2) + X$$





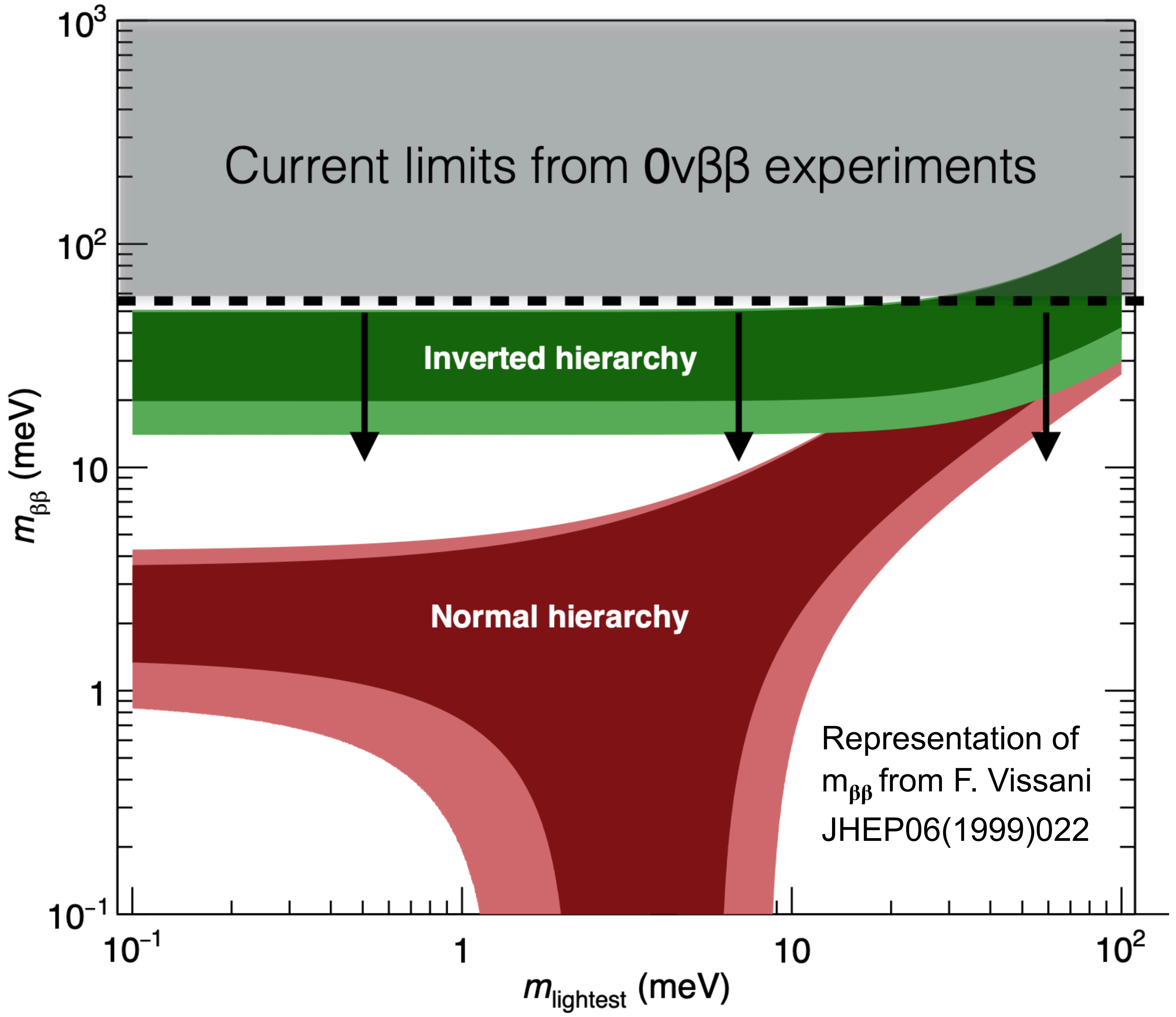
- SM 2nd order weak transition
- even-even nuclei
- half lives 10^{18} - 10^{24} yr

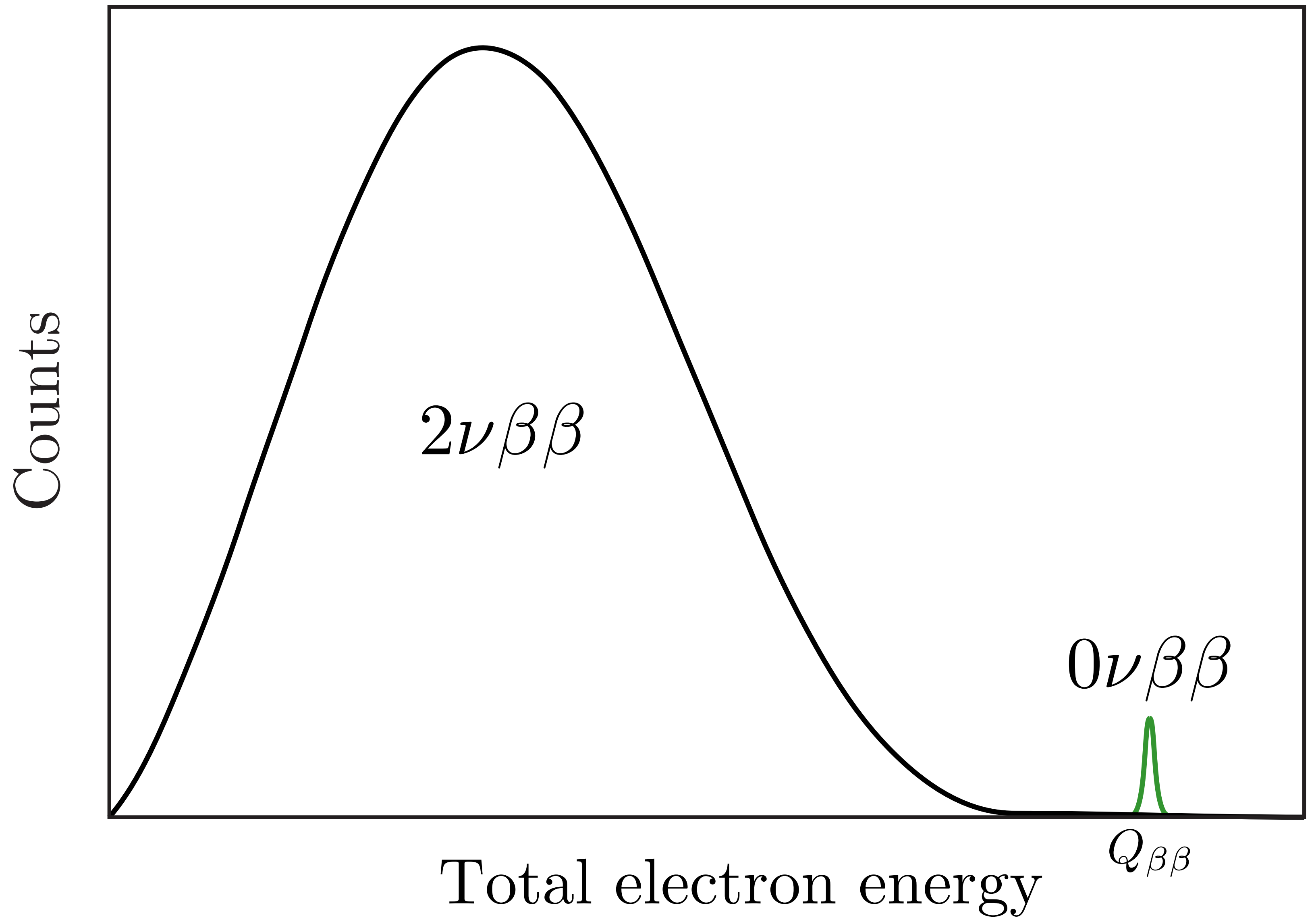
NEUTRINO-LESS DOUBLE BETA DECAY

CUORE

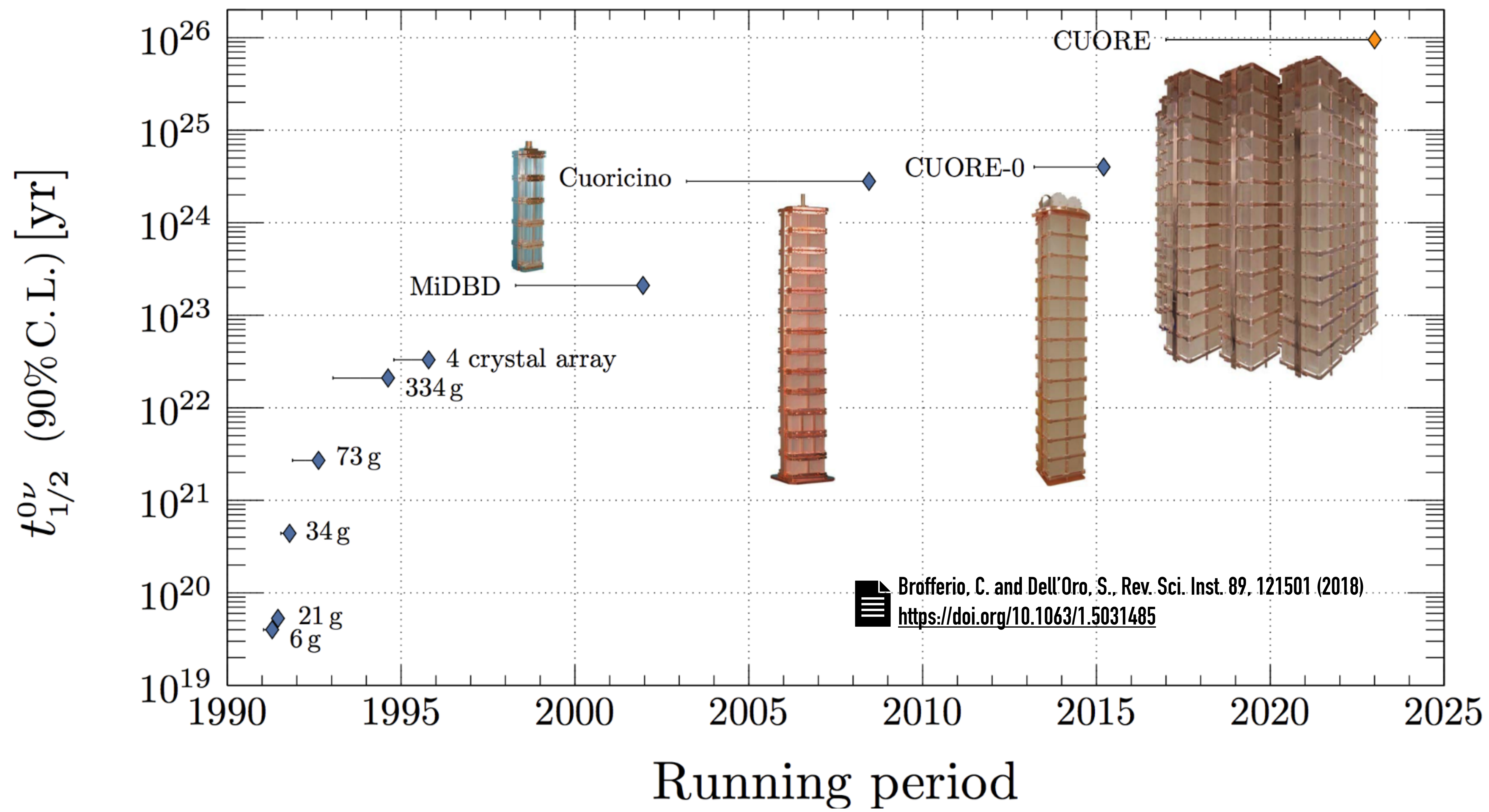
- Beyond Standard Model process accommodating for Majorana neutrinos
- Lepton Number Violation ($\Delta L = 2$)
- Constraints on neutrino mass hierarchy and scale
- Hints on origin of matter/anti-matter asymmetry
- Experimental signature: peak at $2\nu\beta\beta$ endpoint

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





A BIT OF HISTORY

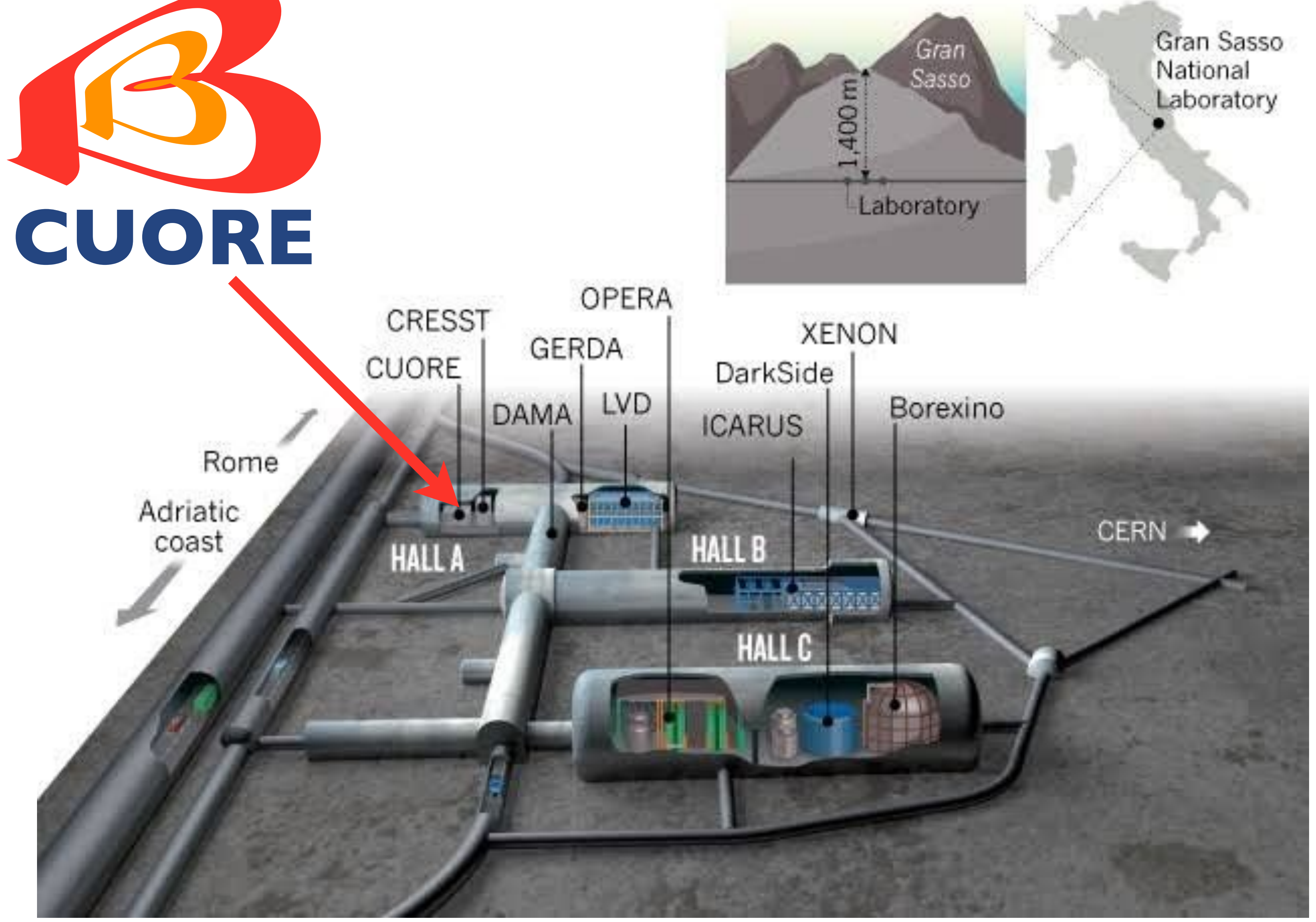


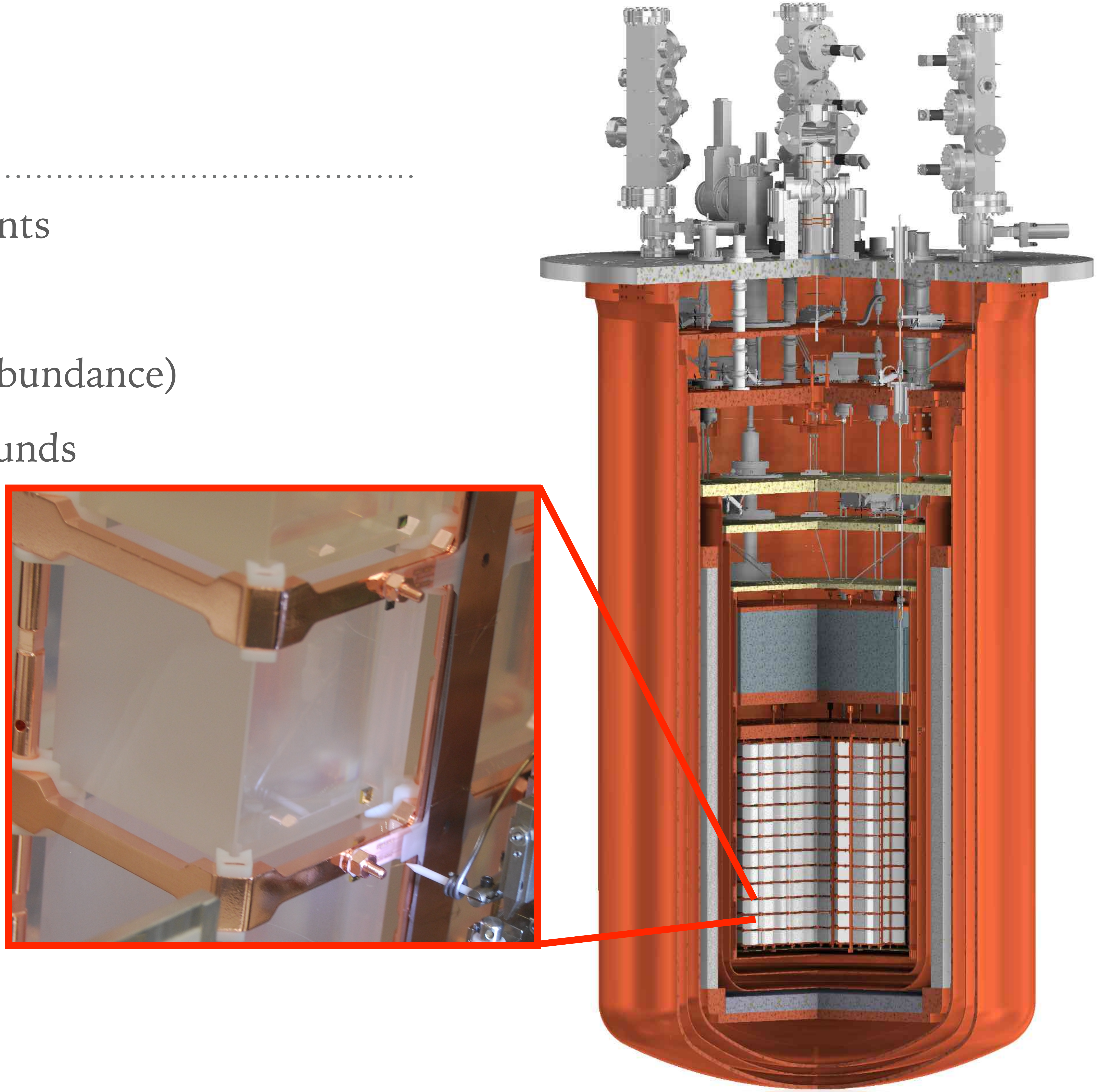
- 30 years of experience in searching for 0νββ with cryogenic bolometers, from the pioneering work of Ettore Fiorini
- CUORE is the last of a long series of experiments, from few grams to 742 kg of detector material
- First tonne-scale bolometric experiment in the world

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

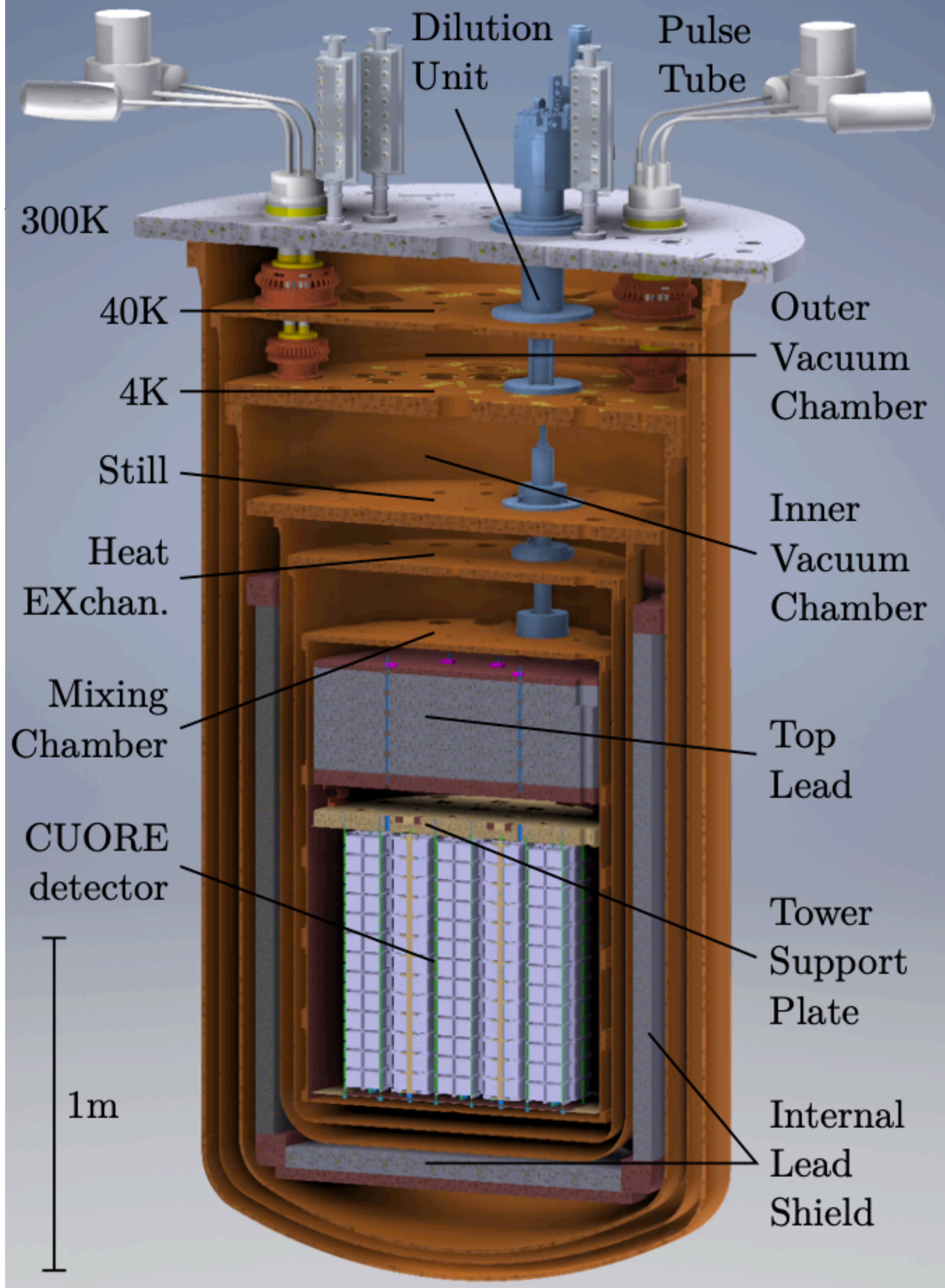




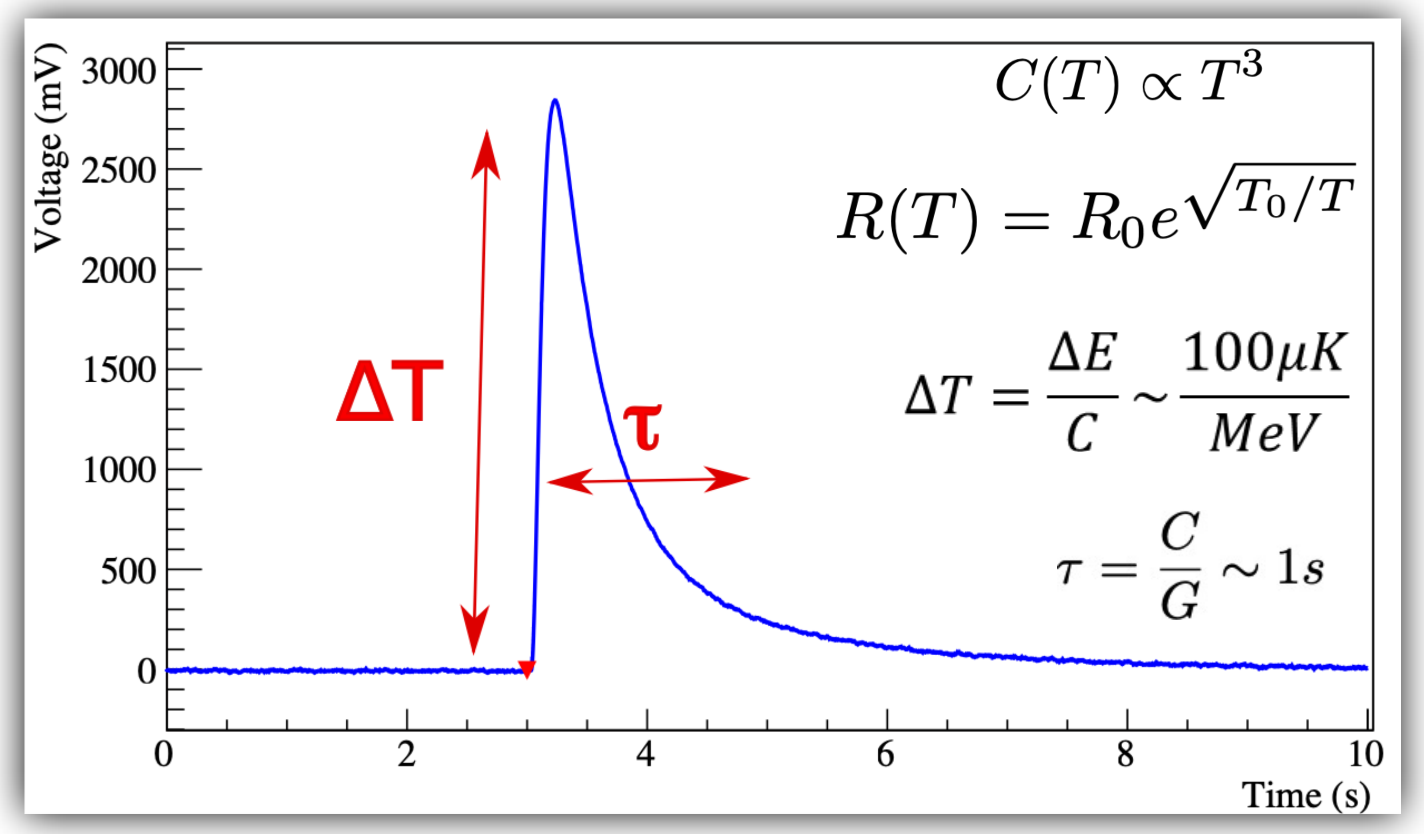
Artusa, D.R. (CUORE Collaboration), Adv. High Energy Phys., 879871, 2015
https://doi.org/10.1155/2015/879871

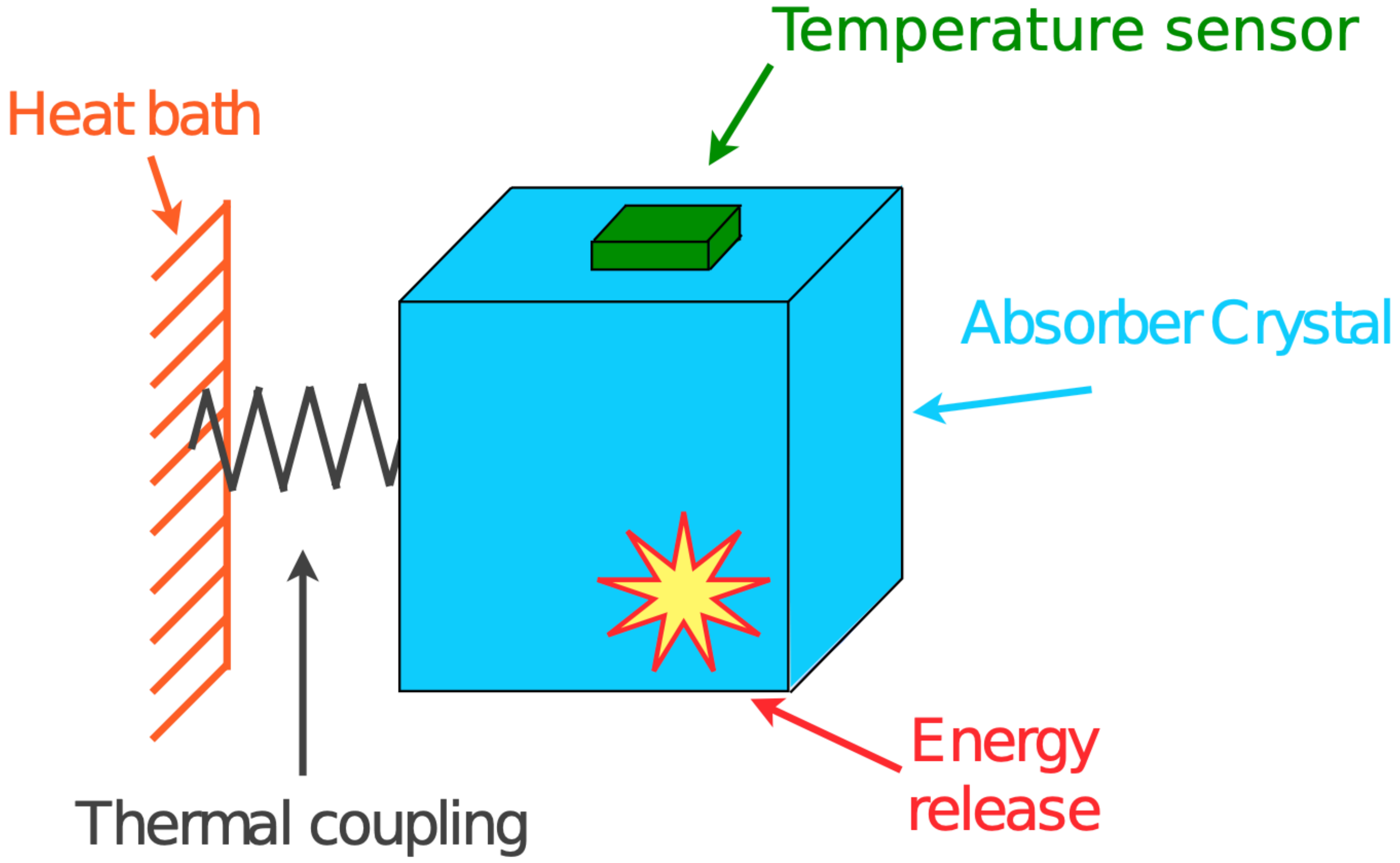
THE CUORE EXPERIMENT

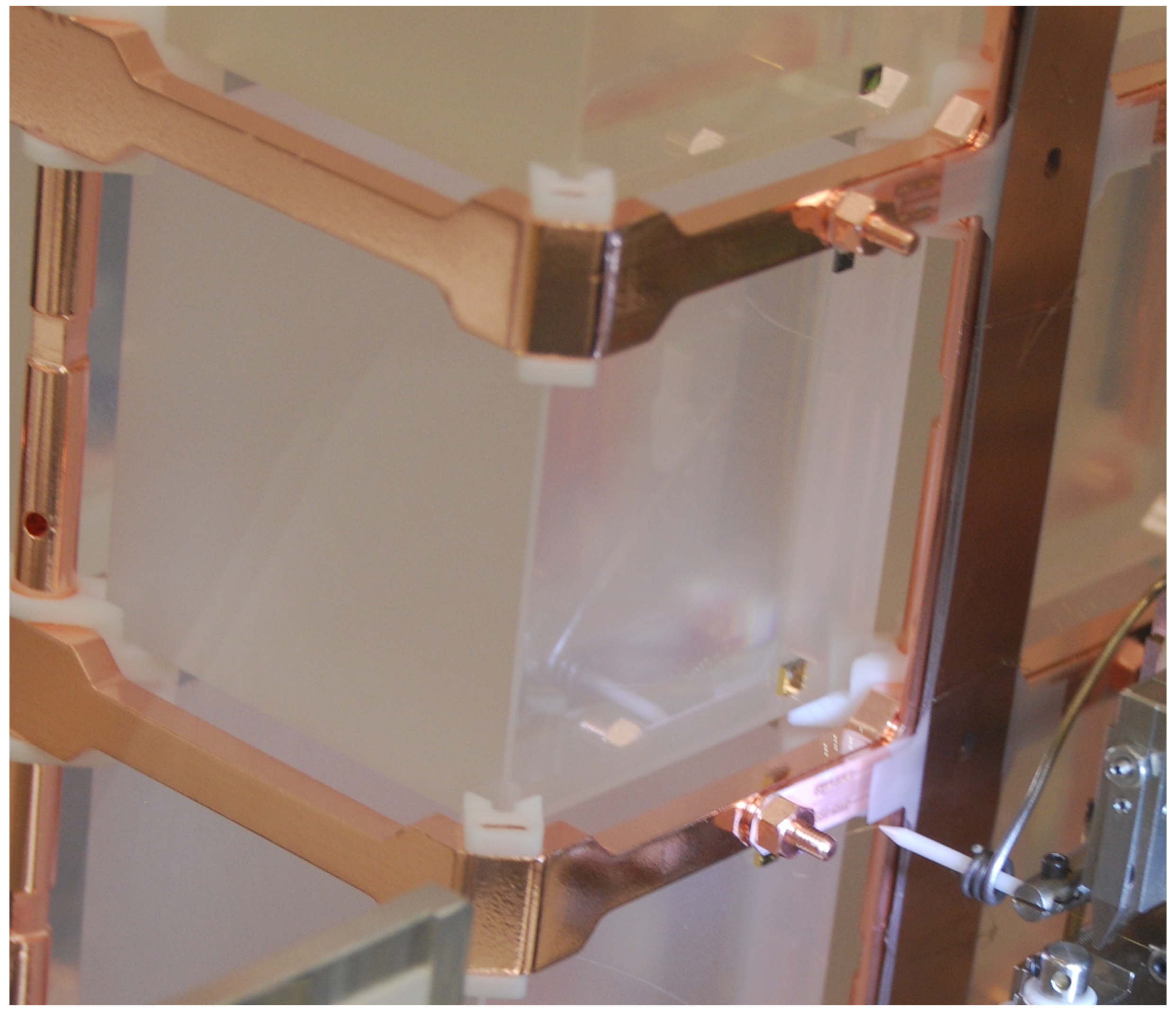
- Custom made dilution refrigerator
  ~ 10 mK base temperature
- 5 pulse tube cryocoolers (no helium bath)
- Nested copper vessels at decreasing temperatures
- Low temperature lead shielding (top)
- Low temperature roman lead shielding (side, bottom)



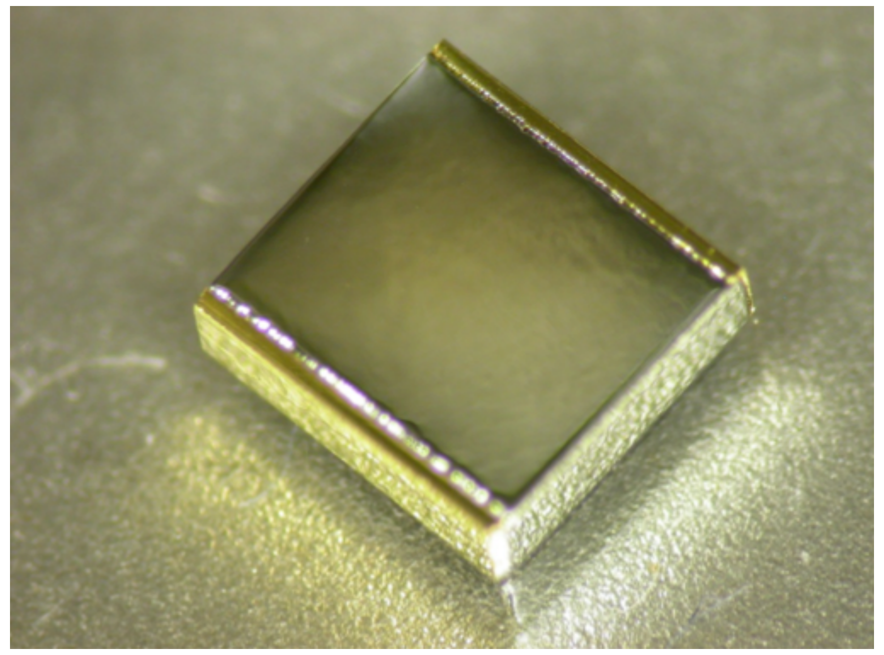
CRYOGENIC BOLOMETERS

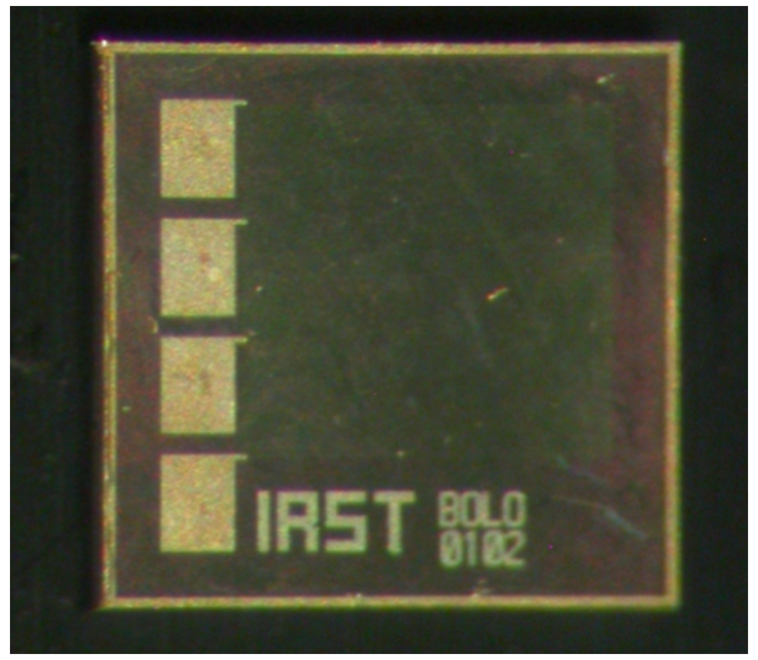






$$\Delta T \sim \frac{\Delta E}{C} \qquad \tau \sim \frac{C}{G}$$



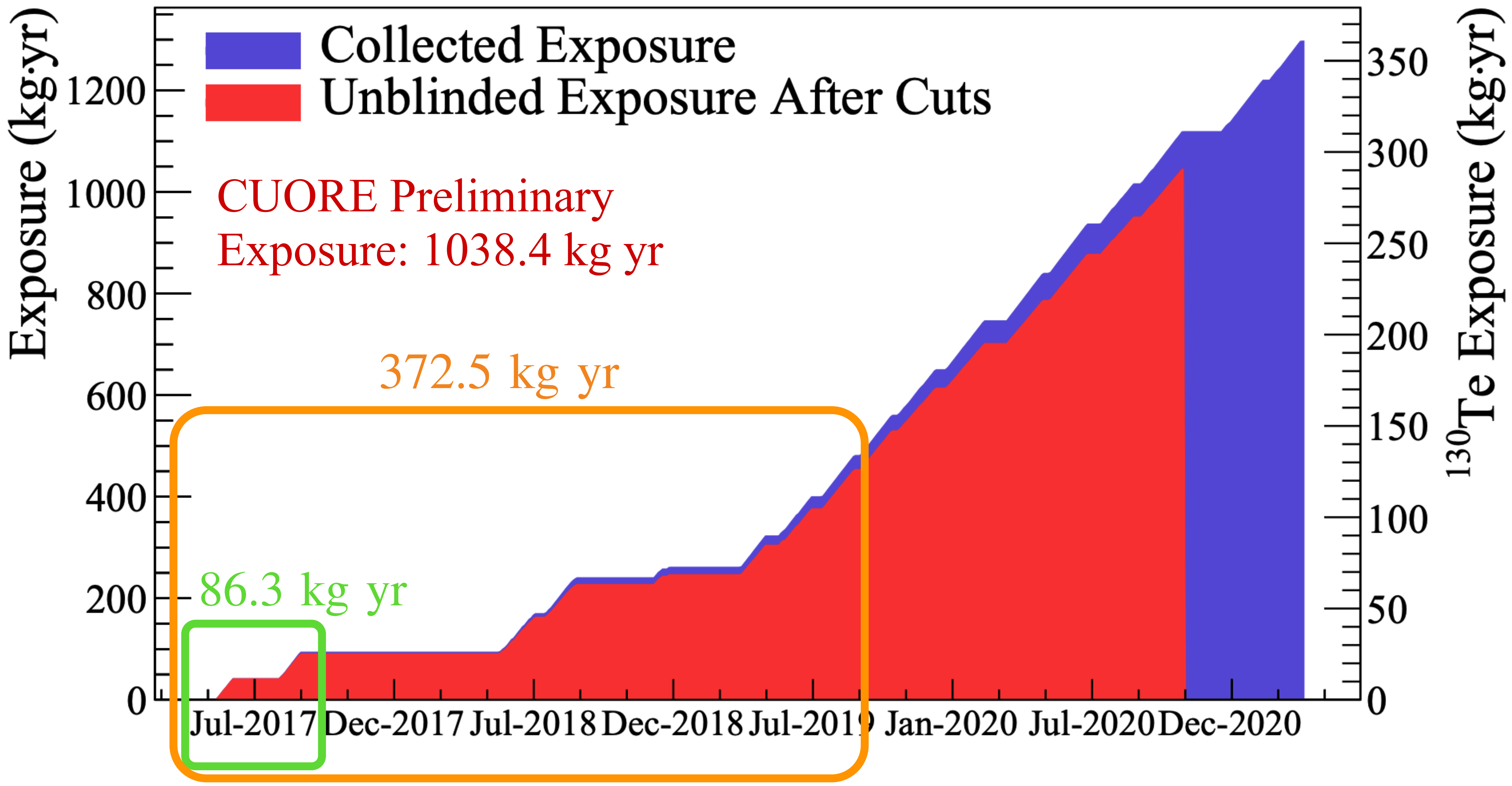


- NTD Ge thermistors biased with constant current
- Si heaters
- weak thermal link to heat bath
- particle interactions heat crystals up
- voltage pulses induced in NTDs

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

CUORE DATA TAKING



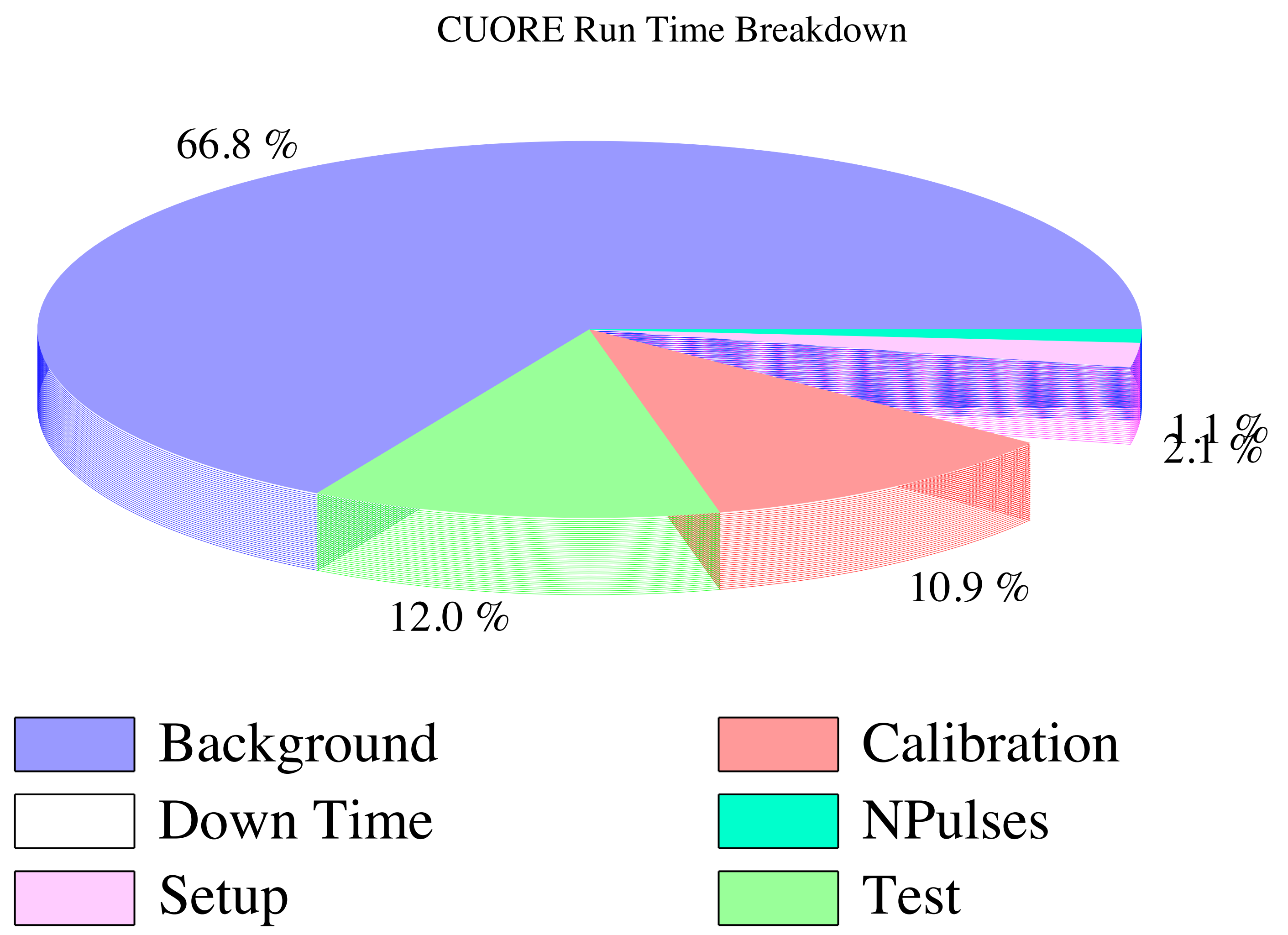
Alduino, C. et al. (CUORE Collaboration), Phys. Rev. Lett. 120, 132501, 2018
https://doi.org/10.1103/PhysRevLett.120.132501

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

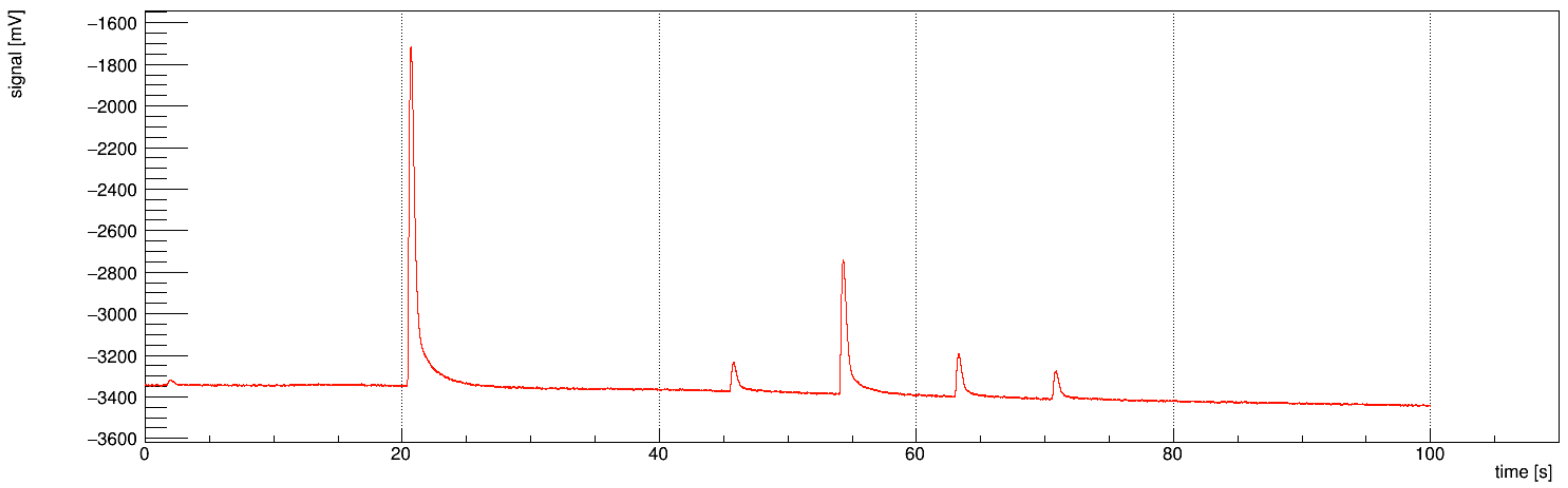
- data taking started in 2017
- optimization campaigns improved understanding and stability of the experiment
- since march 2019 steady data taking with >90% uptime
- > 1.29 tonne × yr raw exposure
- steadily collecting data at an average rate of ~ 69 kg × yr / month

CUORE DATA TAKING

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

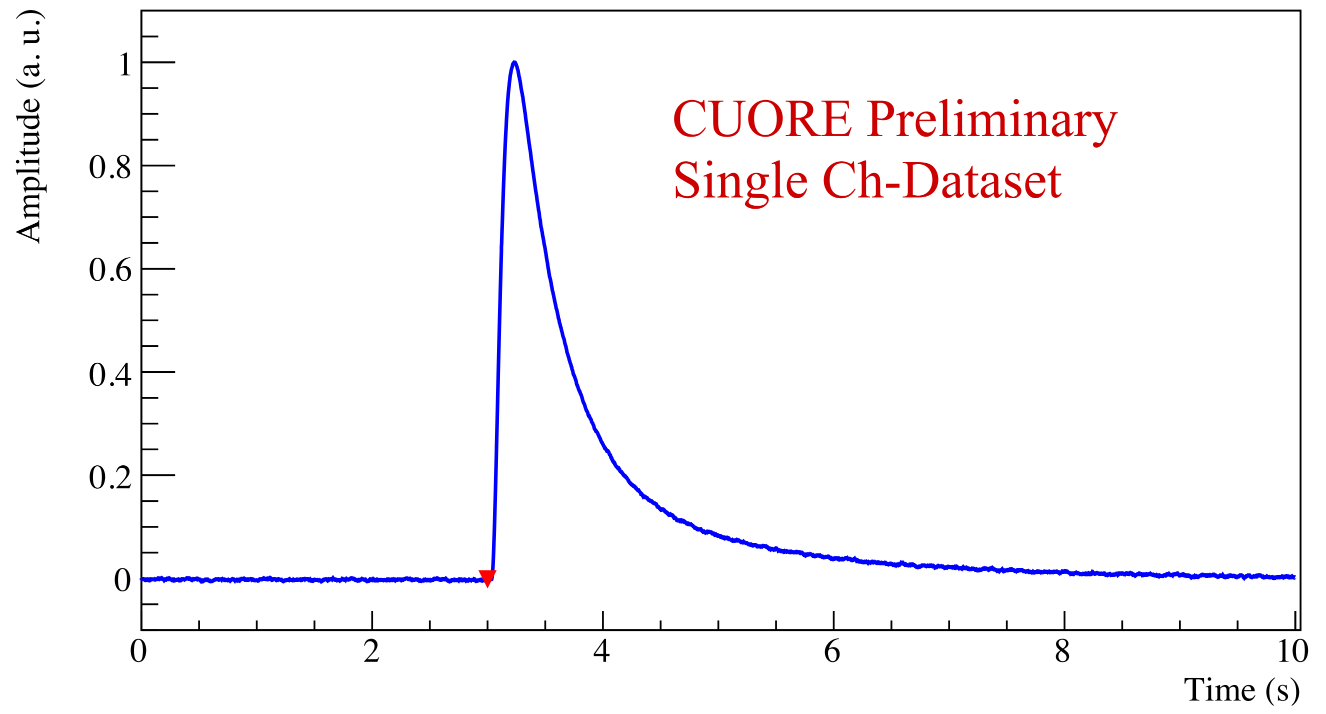


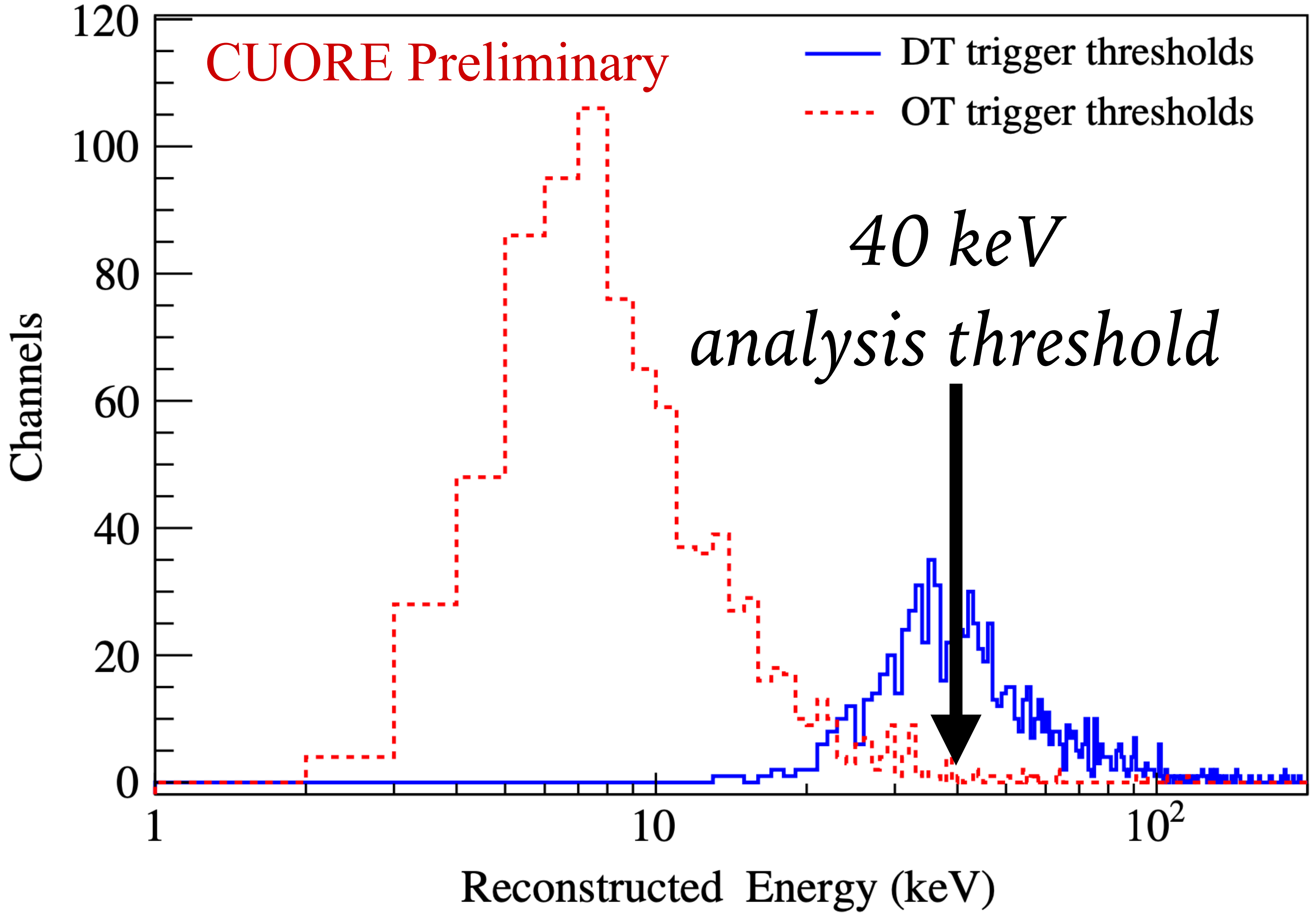
- Voltage output continuously sampled (1 kHz) and stored on disk
- Periods with unstable data taking conditions excluded (e.g. earthquakes)



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

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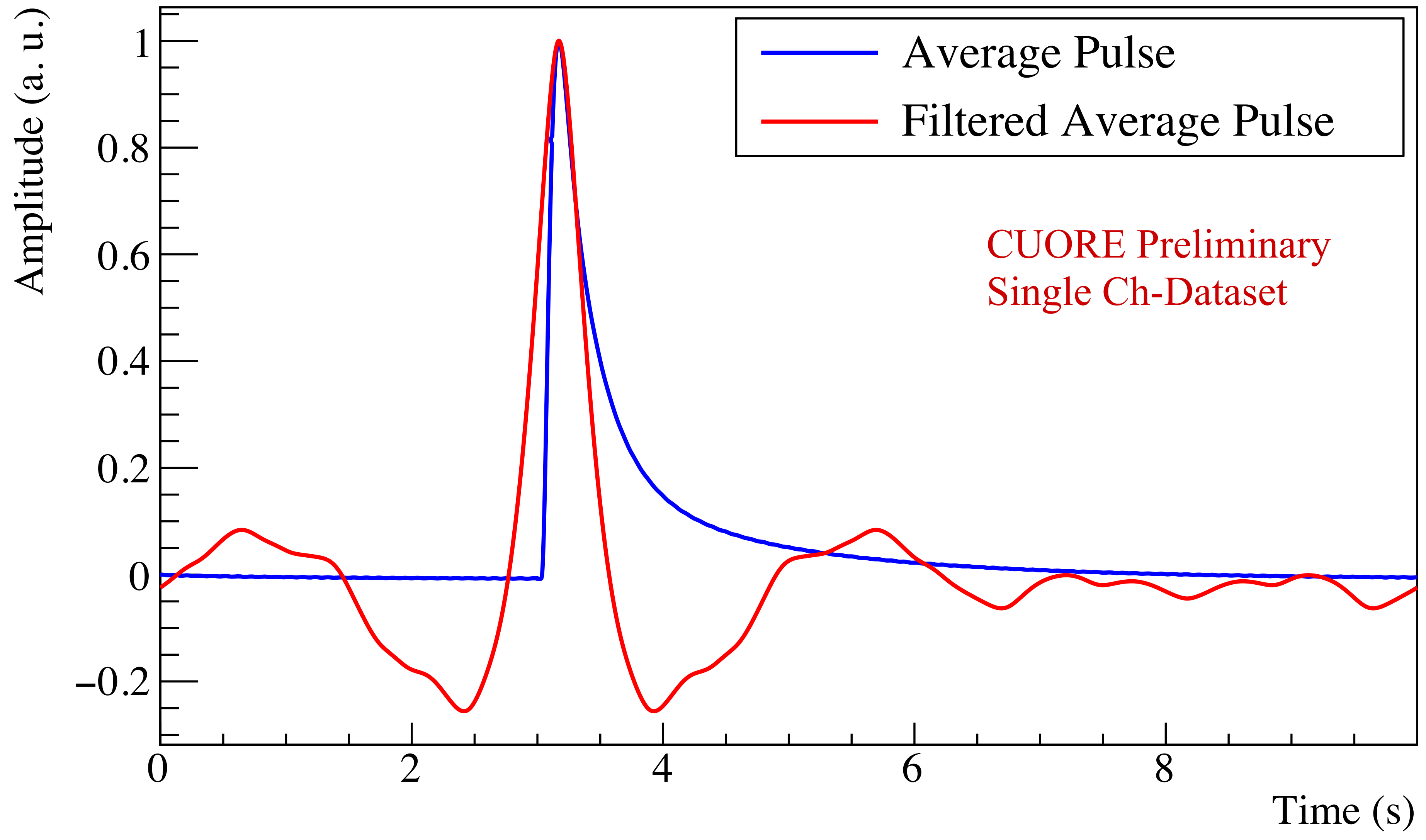

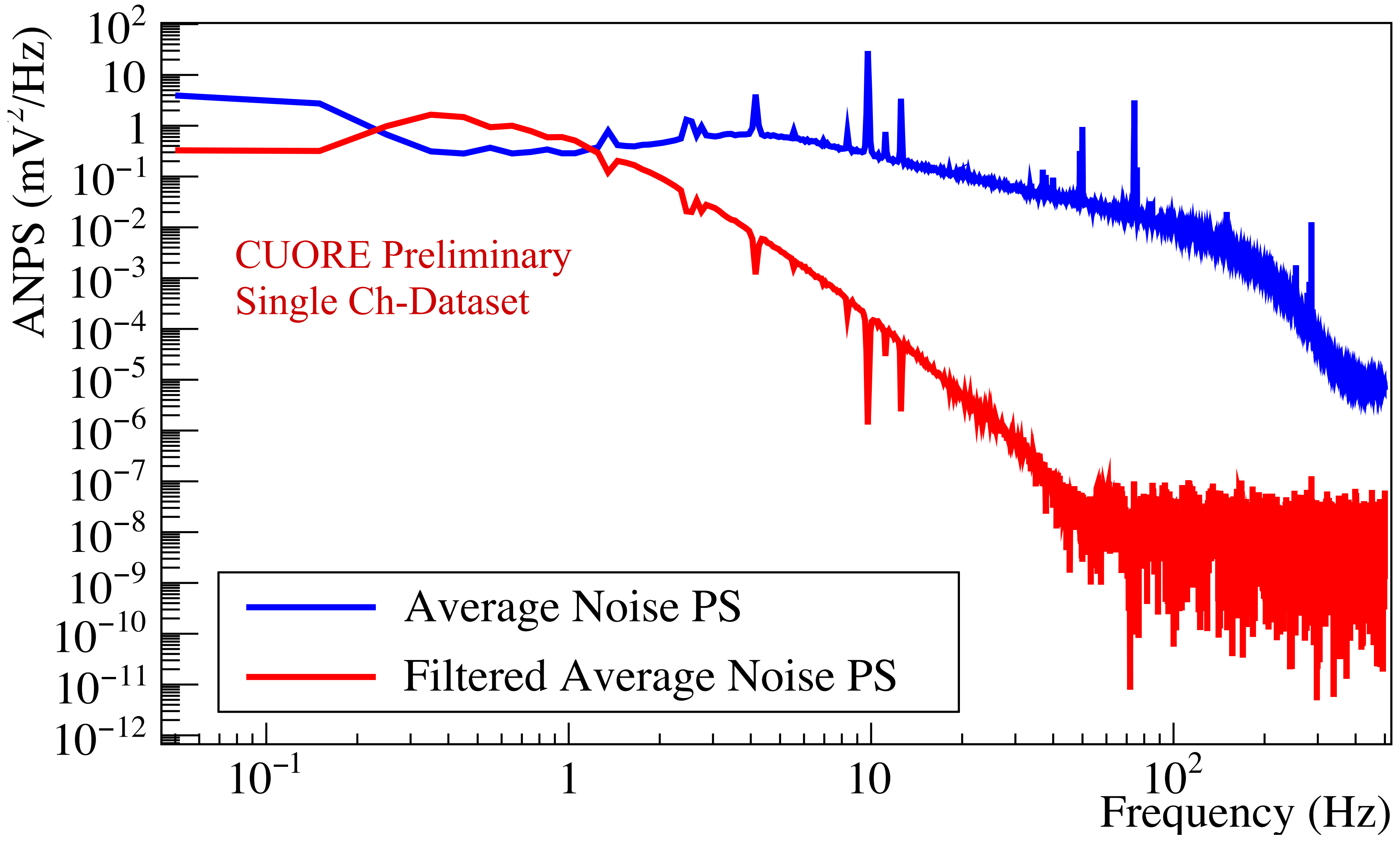

Matched filter maximizes signal-to-noise ratio

CUORE DATA ANALYSIS

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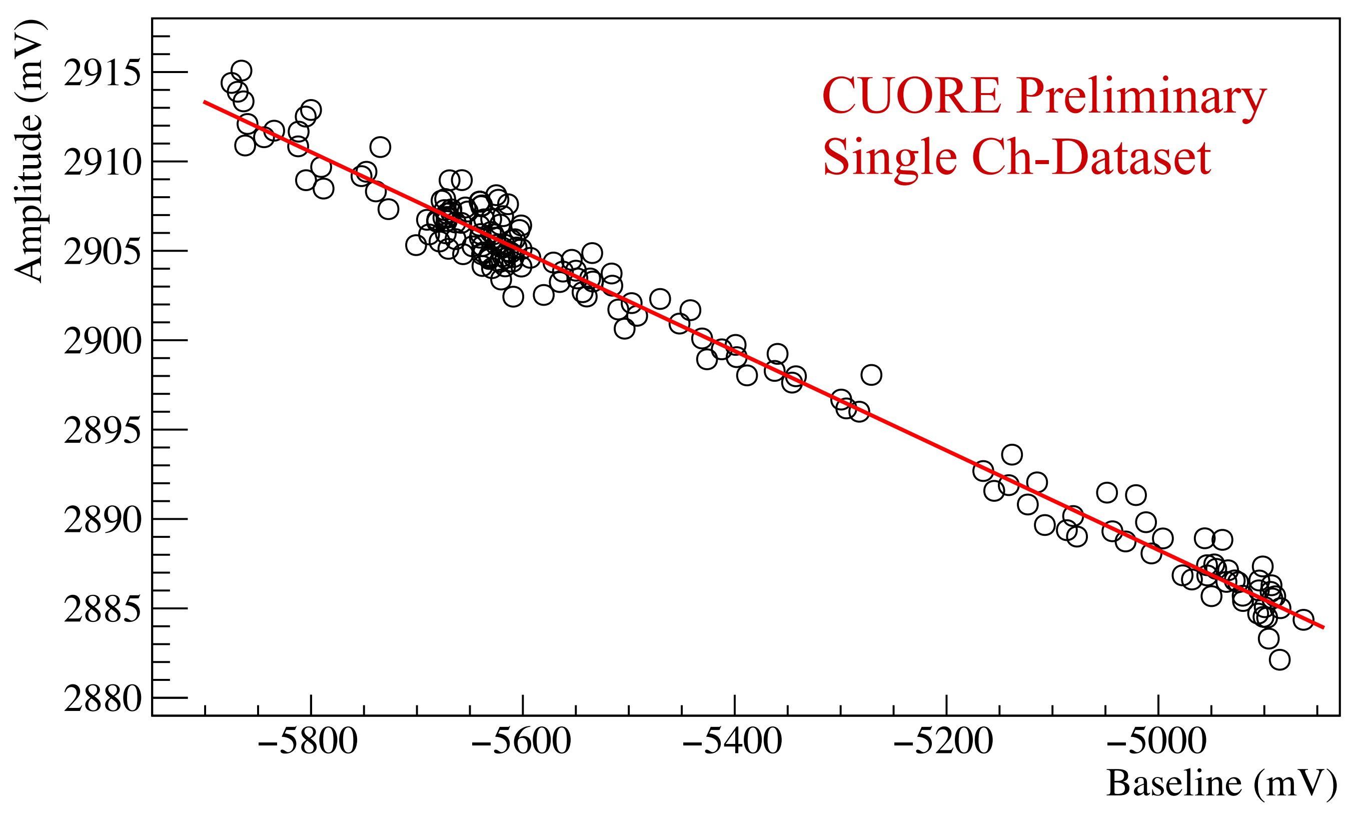
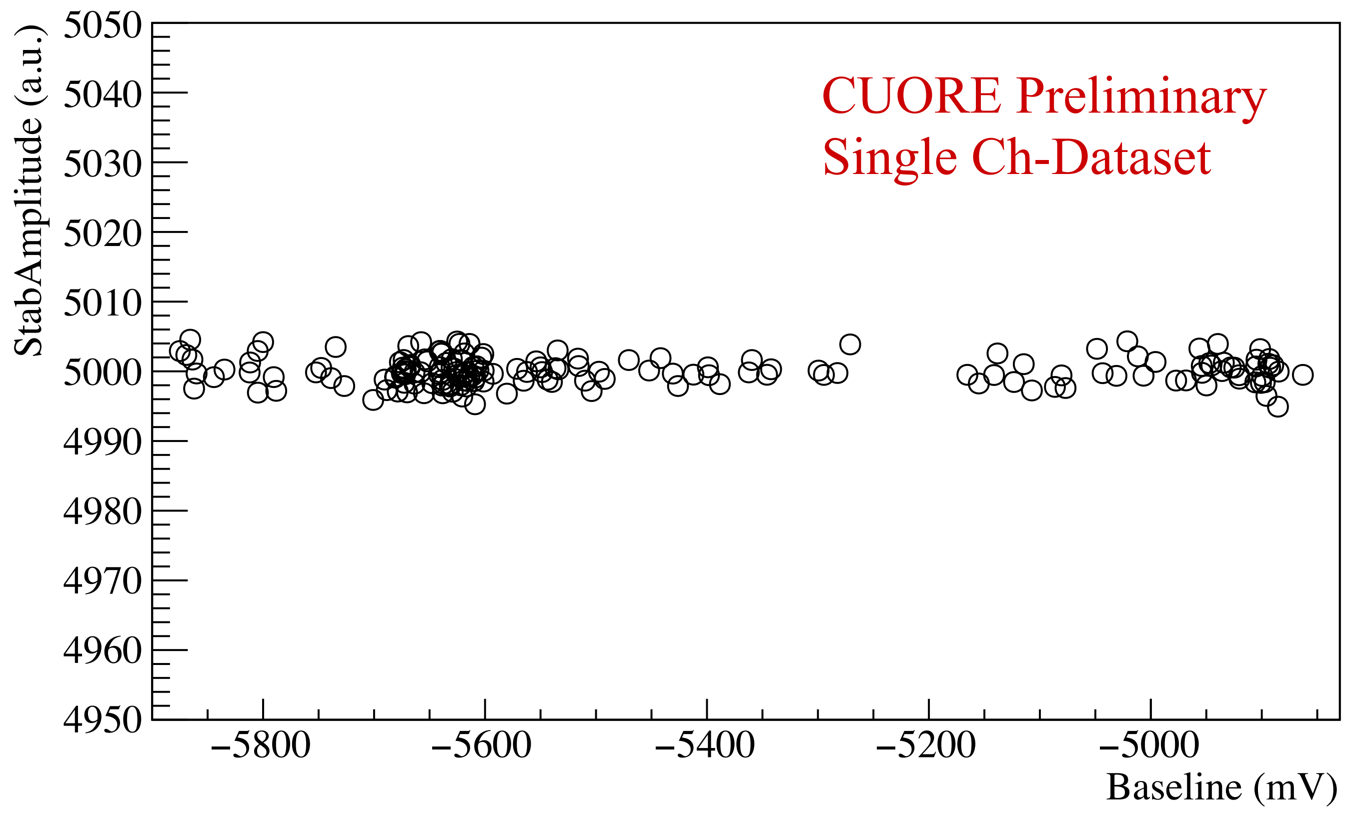
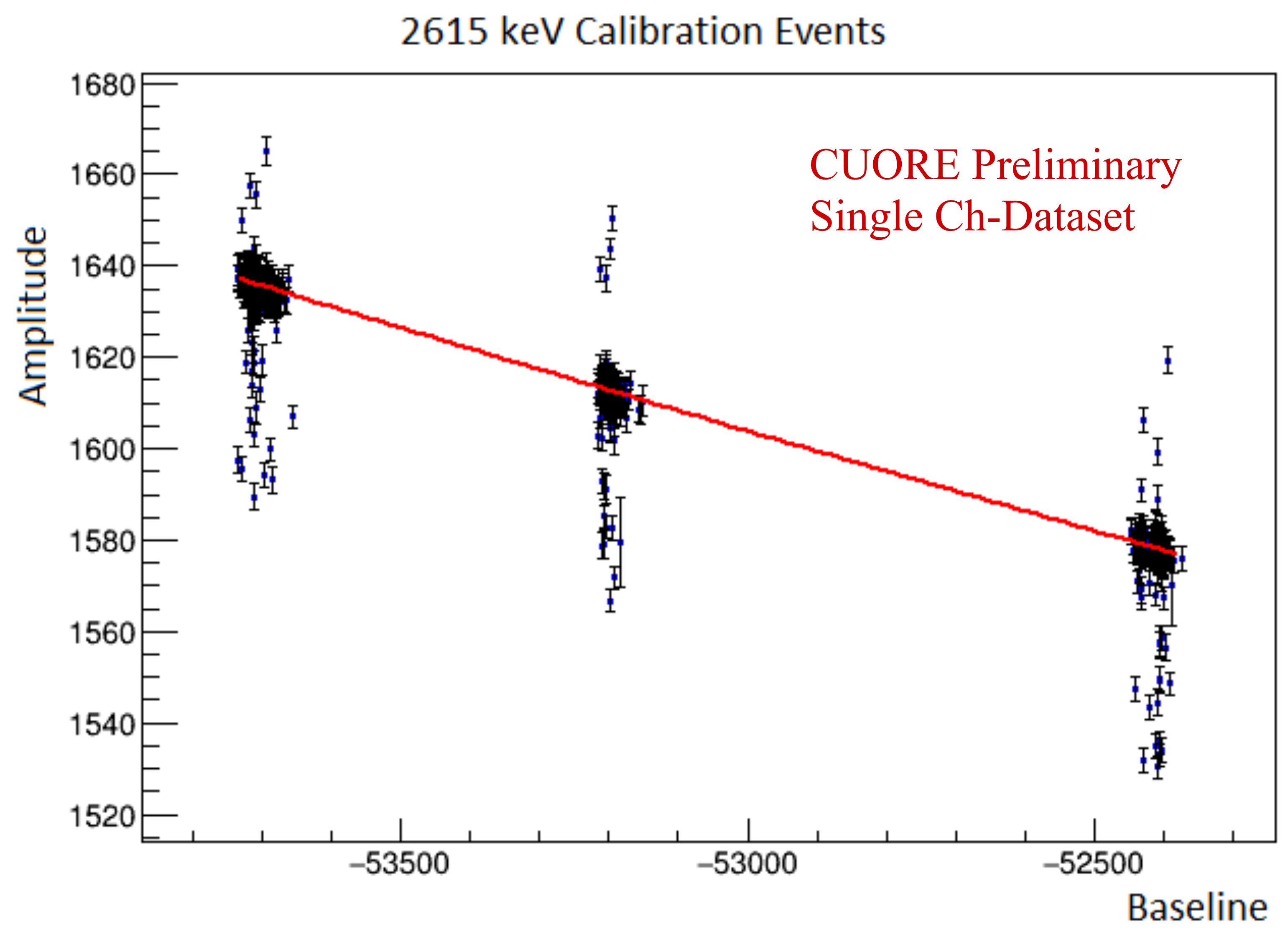




Heater pulses for thermal gain stabilization

- ➤ 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

- Trigger
- Optimum Filter
- Gain Correction
- **Energy Calibration**
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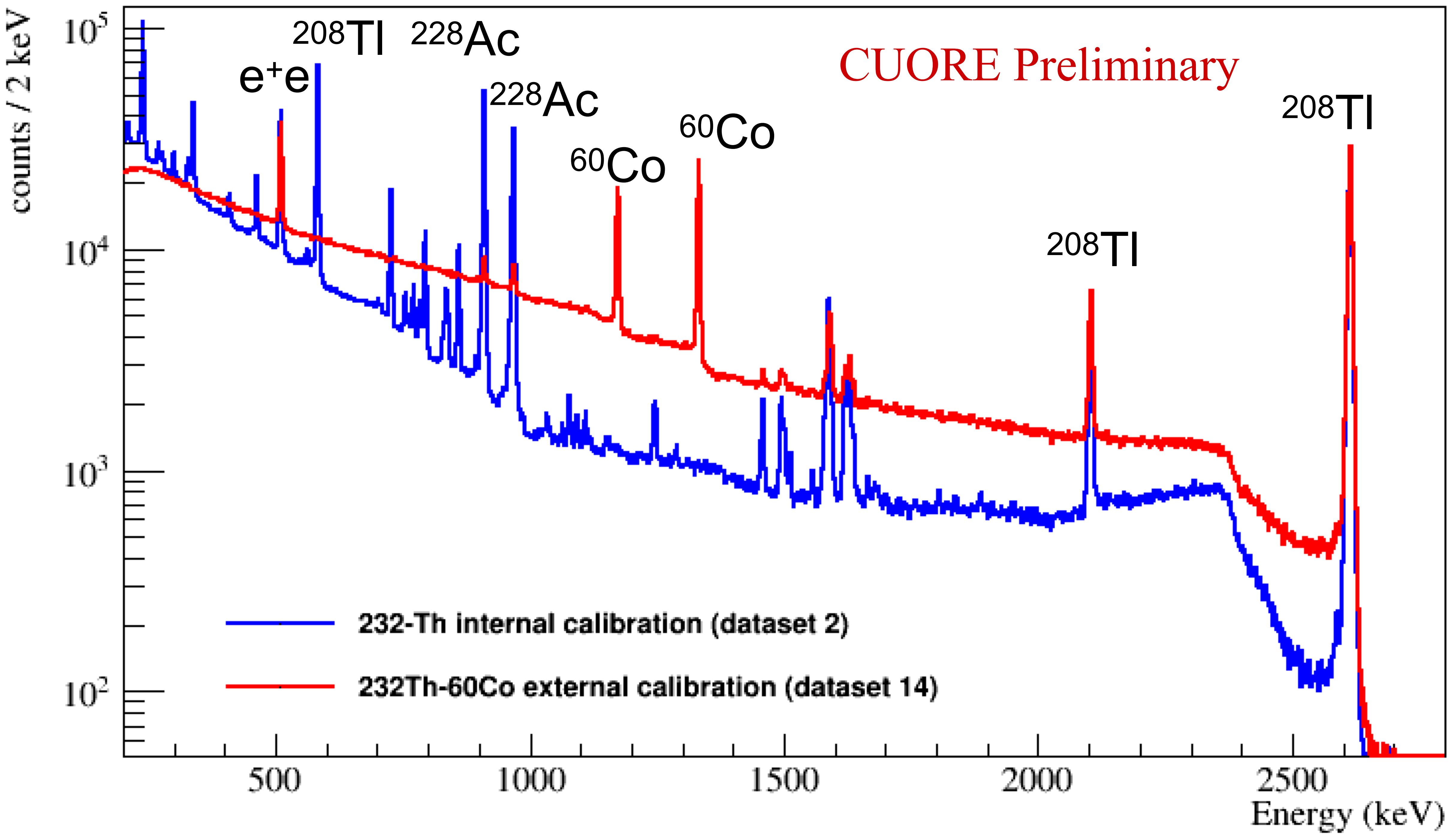
➤ First 3 datasets used internal ^{232}Th source

➤ 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
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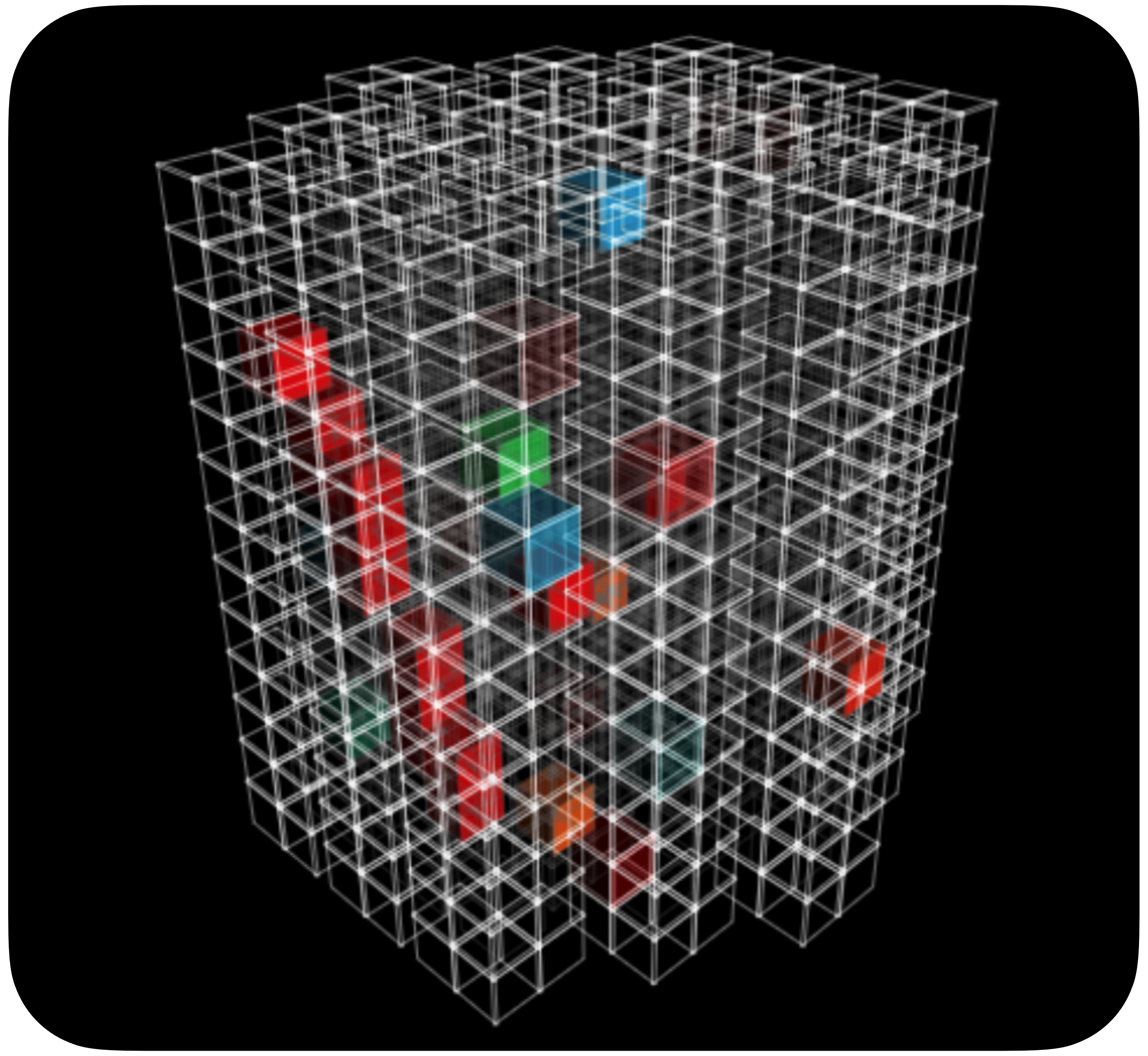
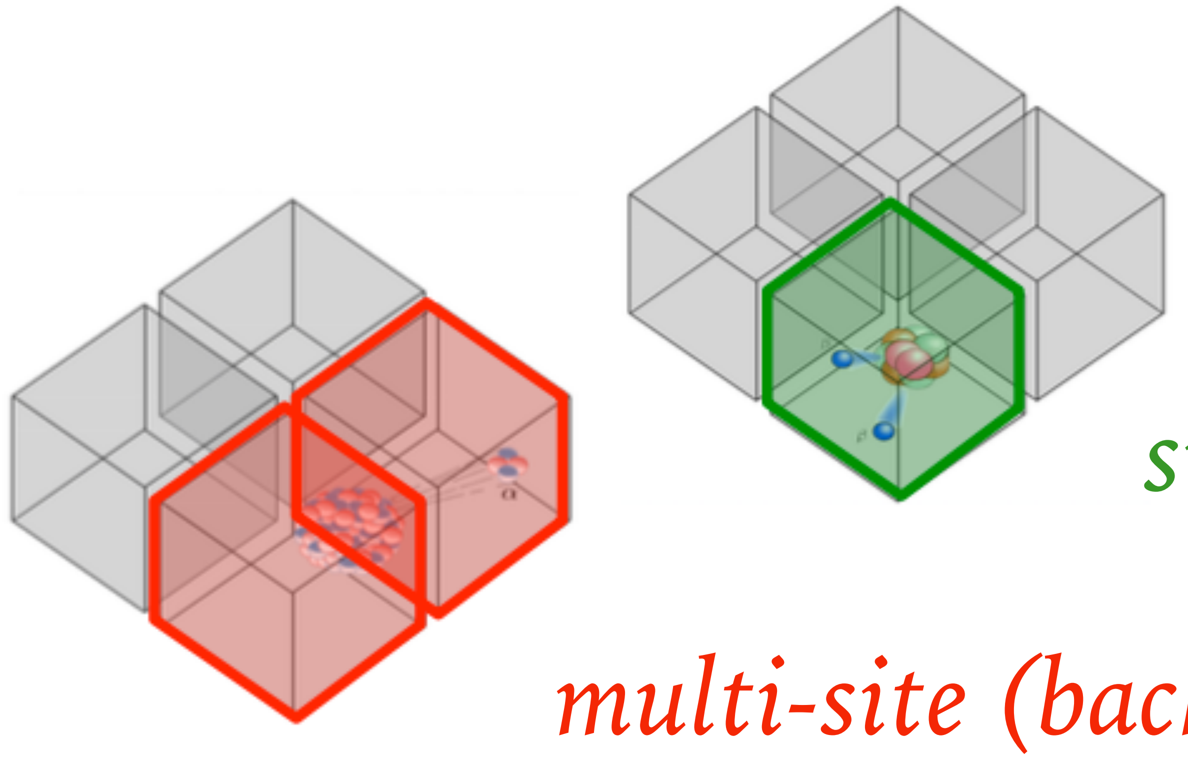


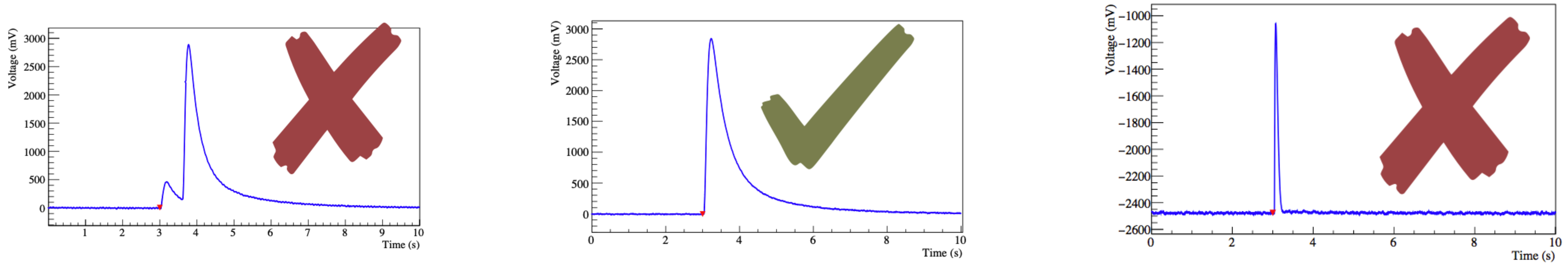
- ~88% of $0\nu\beta\beta$ events involve just one crystal
- when multiple bolometers fire in a small (5 ms) time window, the event is likely to be due to radioactive contaminations or muons
- assign multiplicity (number of involved crystals) and total energy
- apply anti-coincidence veto for $0\nu\beta\beta$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



single-site (signal-like)

multi-site (background-like)

CUORE DATA ANALYSIS



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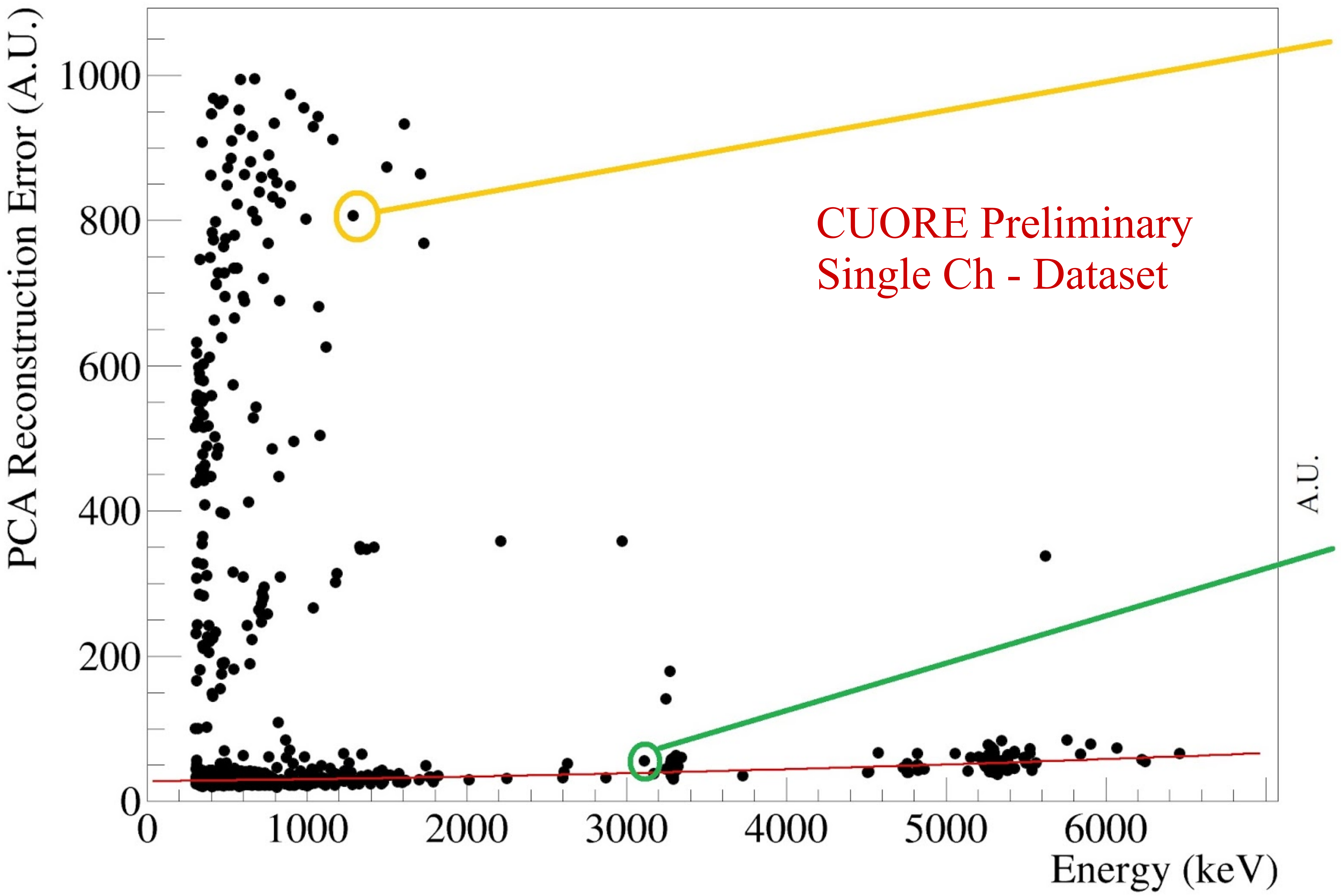
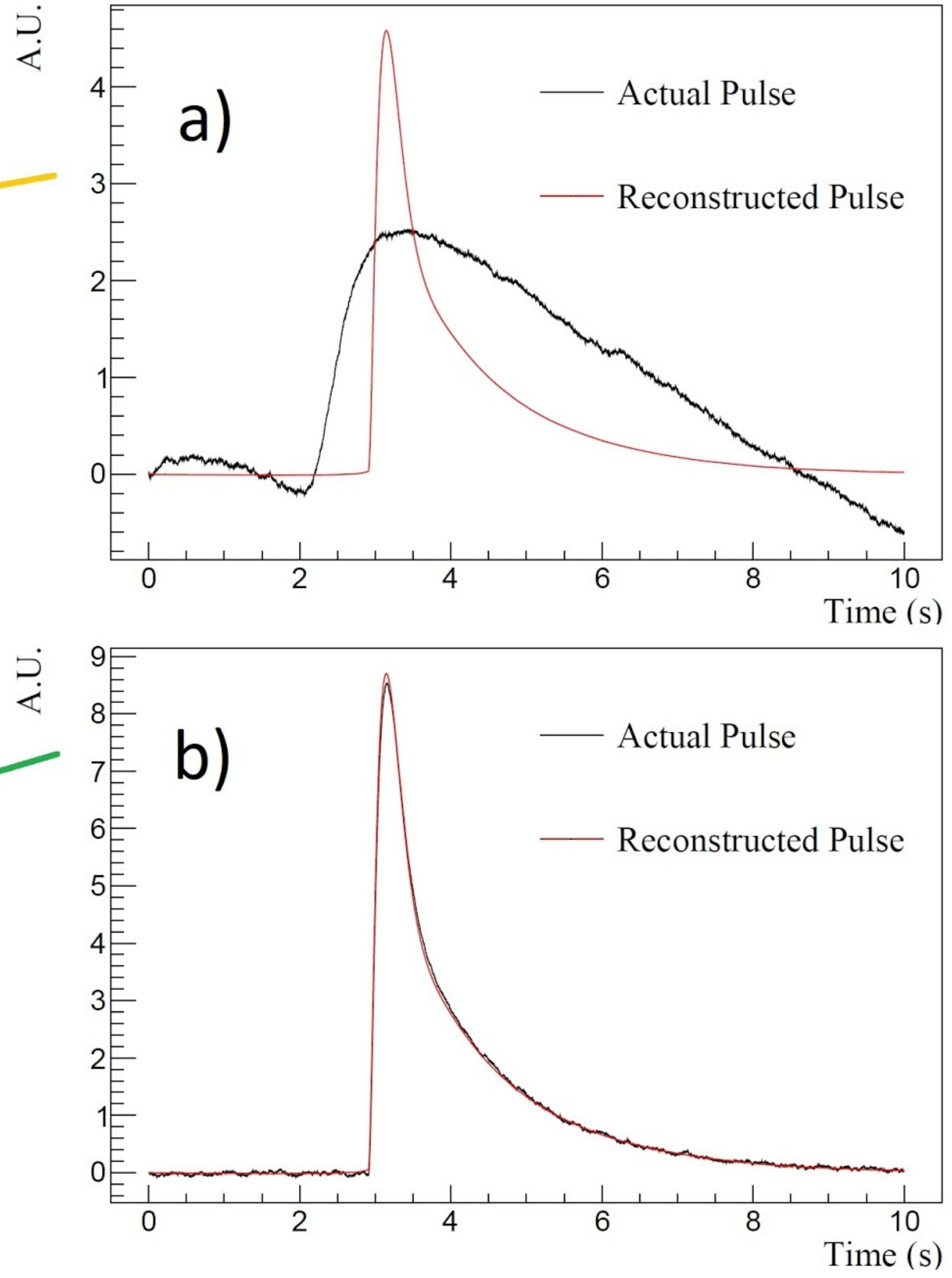
- **Pulse Shape Discrimination (PSD)**
- Blinding

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





CUORE DATA ANALYSIS

- Trigger
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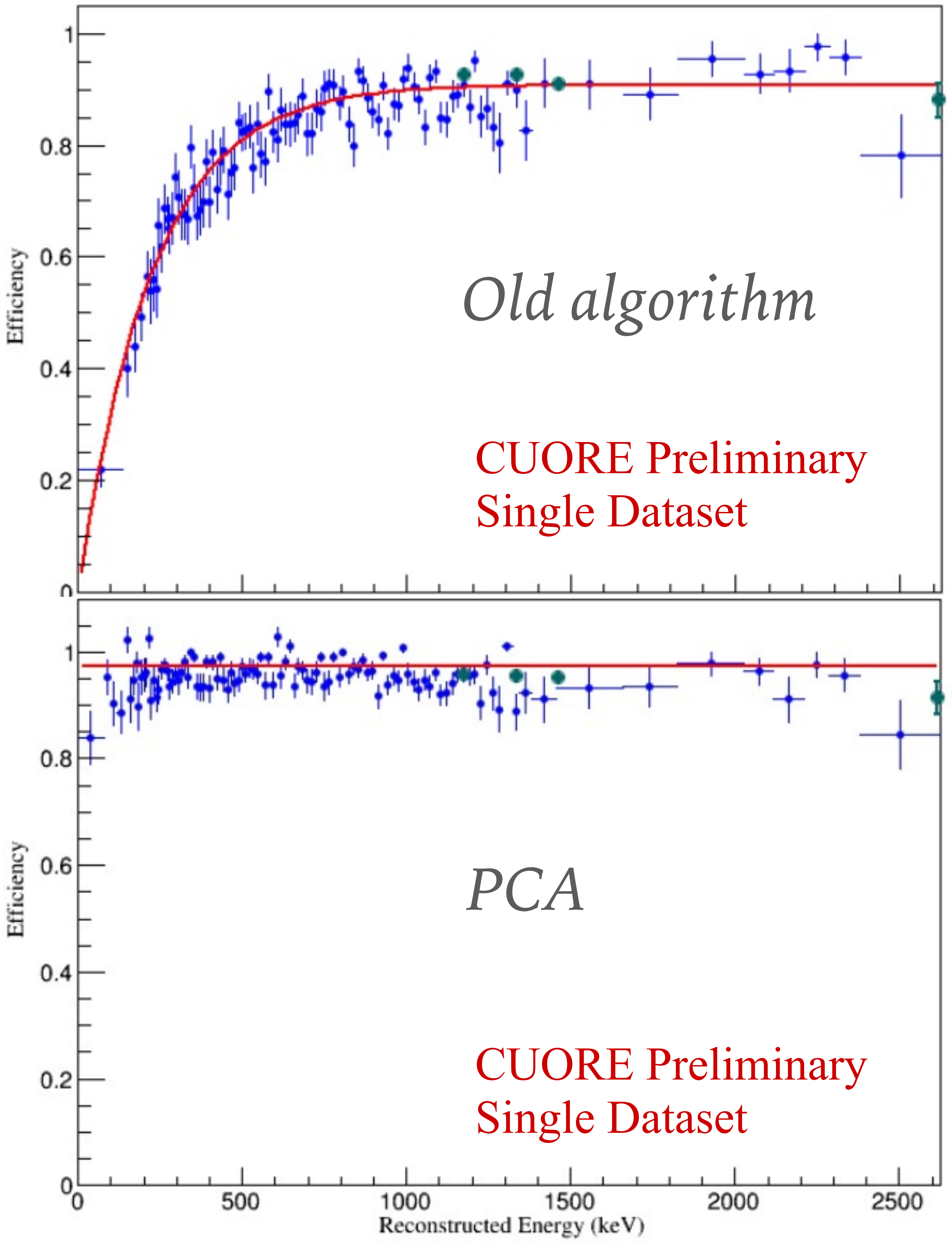
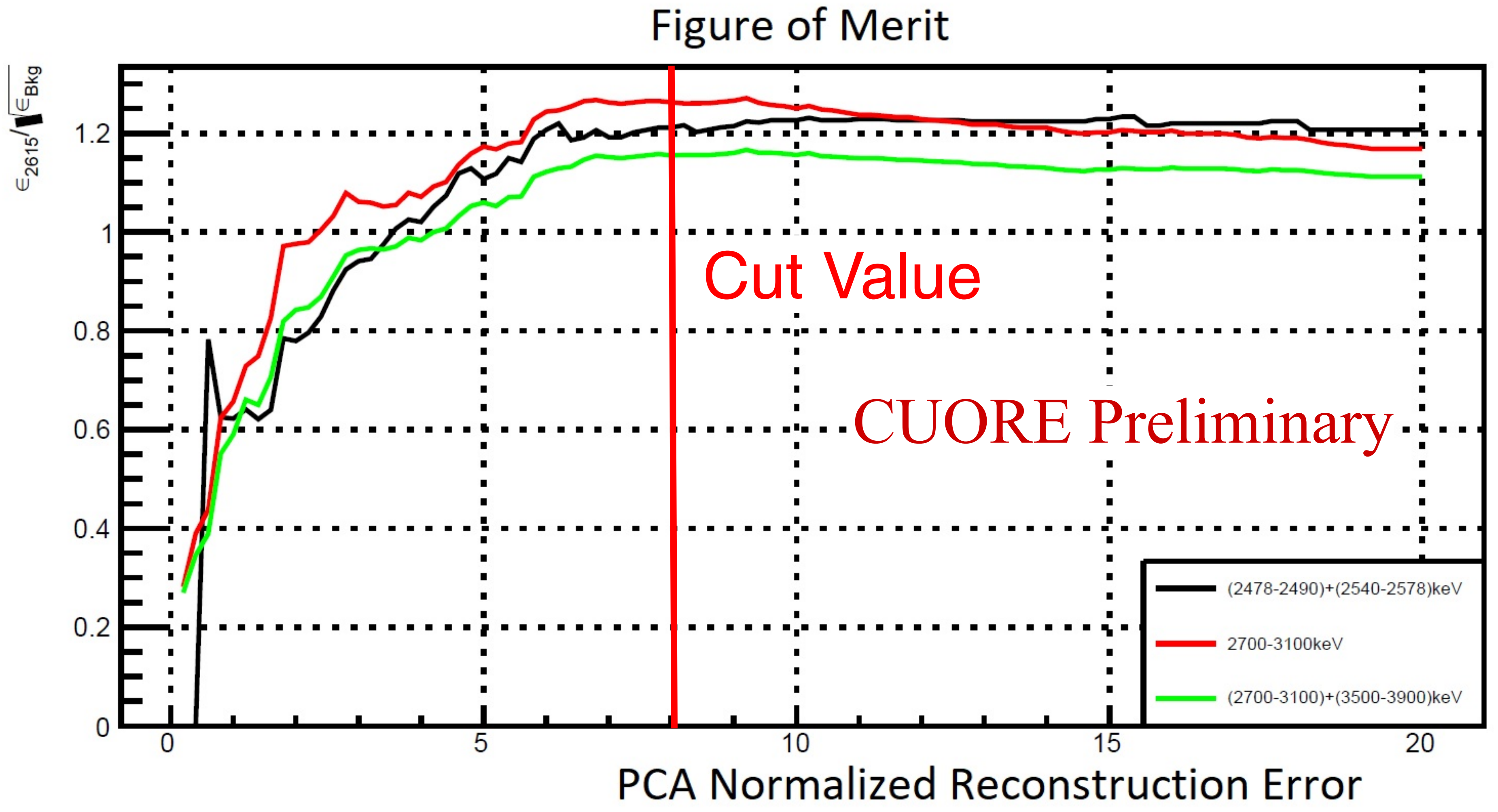




- Tune cut on a $S/\sqrt{B}$ figure of merit
- Gamma peaks for efficiency
- Alpha region as background proxy
- PCA method shows increased efficiency at all energies
- Similar background rejection

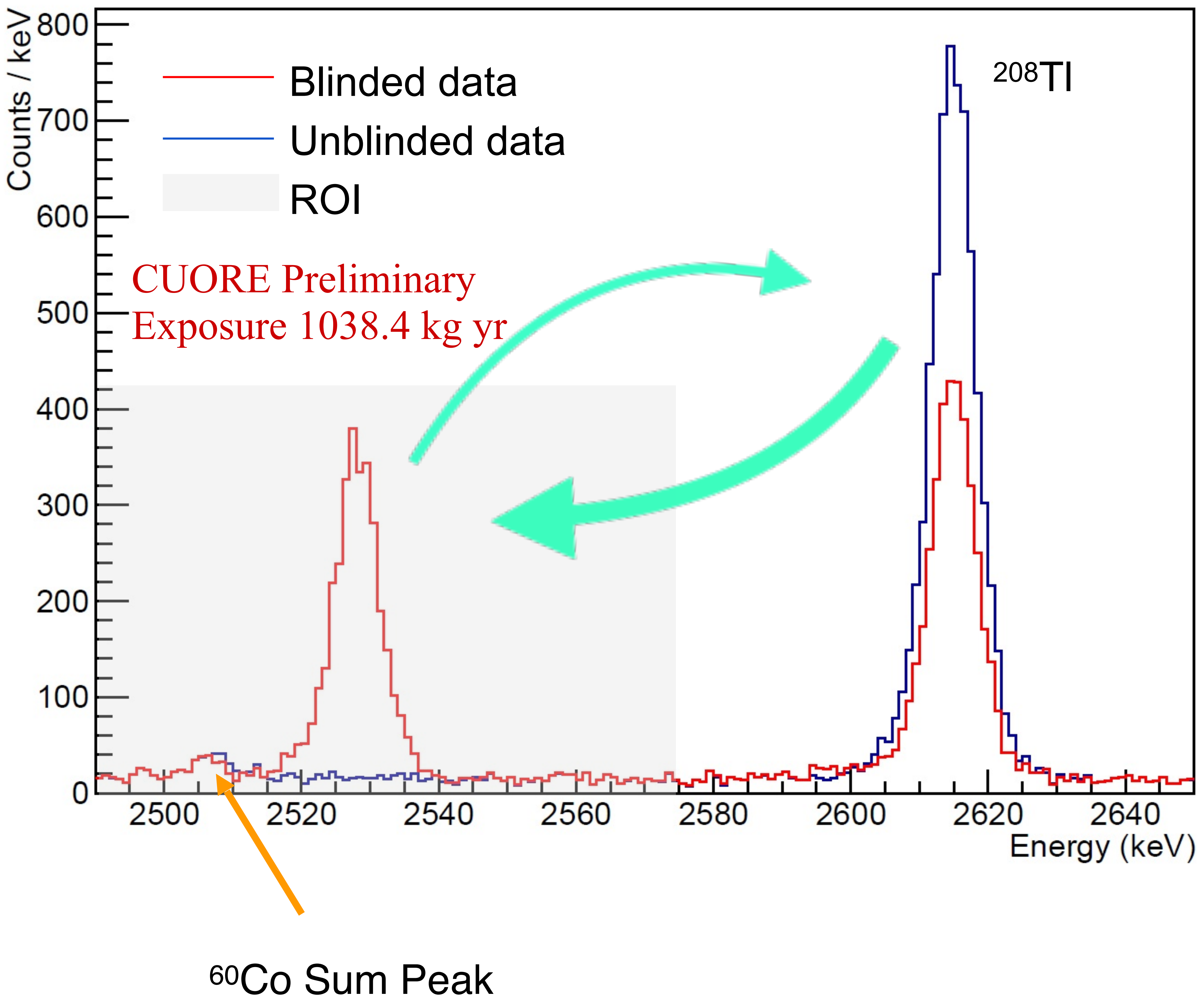
CUORE DATA ANALYSIS

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

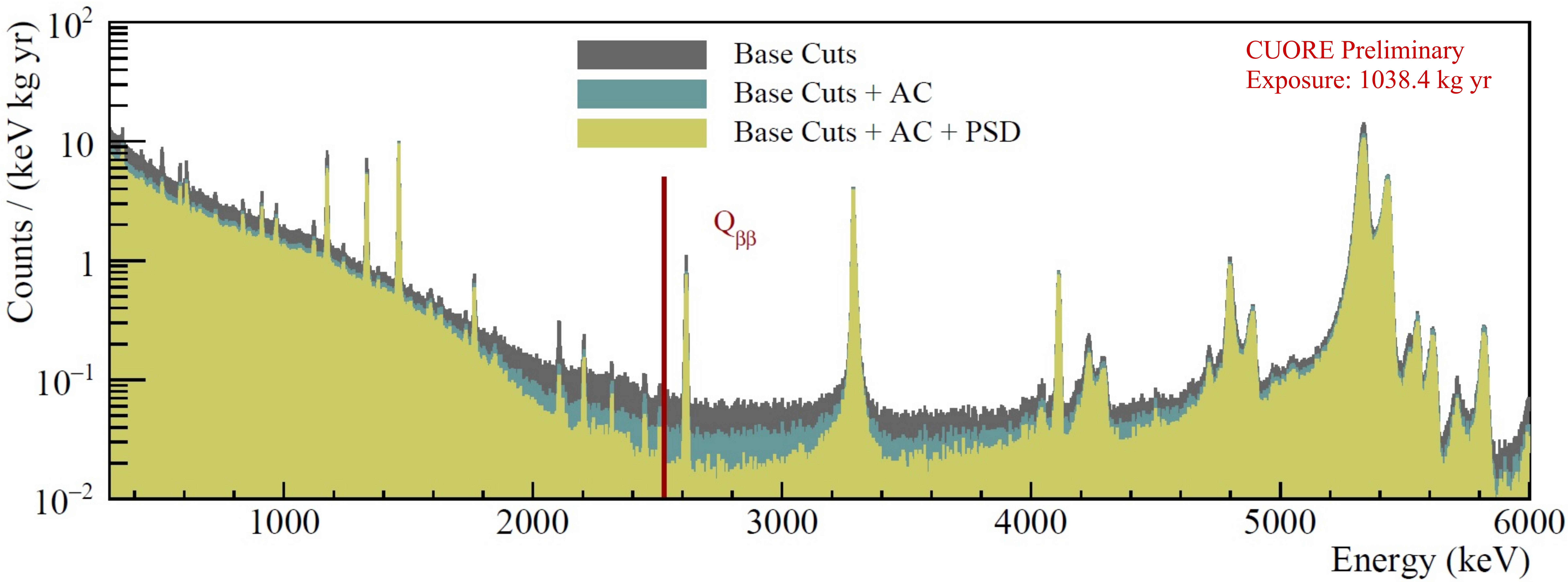
➤ Random fraction of events in ^{208}Tl line shifted to $Q_{\beta\beta}$ and vice versa

➤ Original energies stay encrypted until unblinding

➤ Unblinding happens only after full analysis procedure is finalized



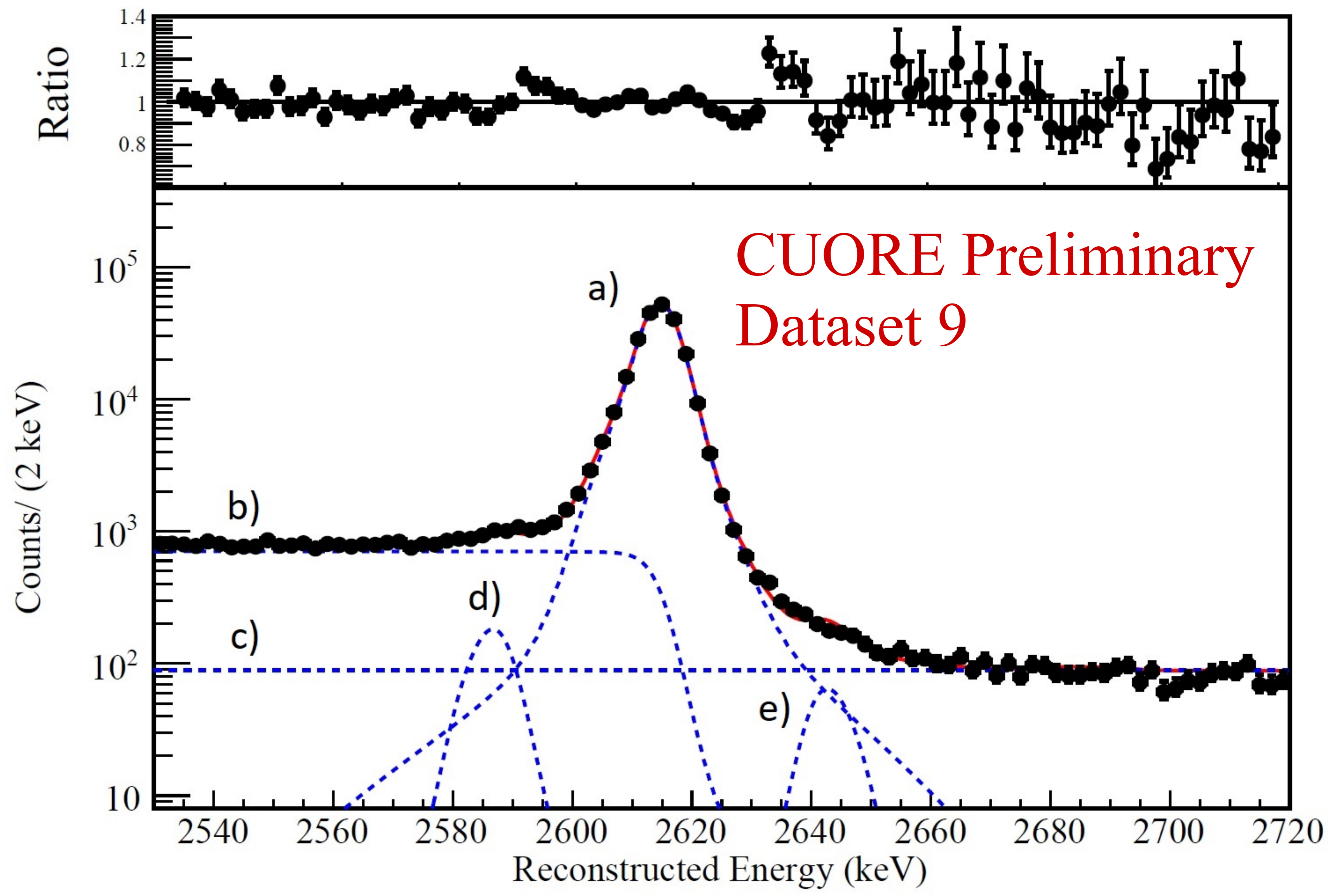
DATA

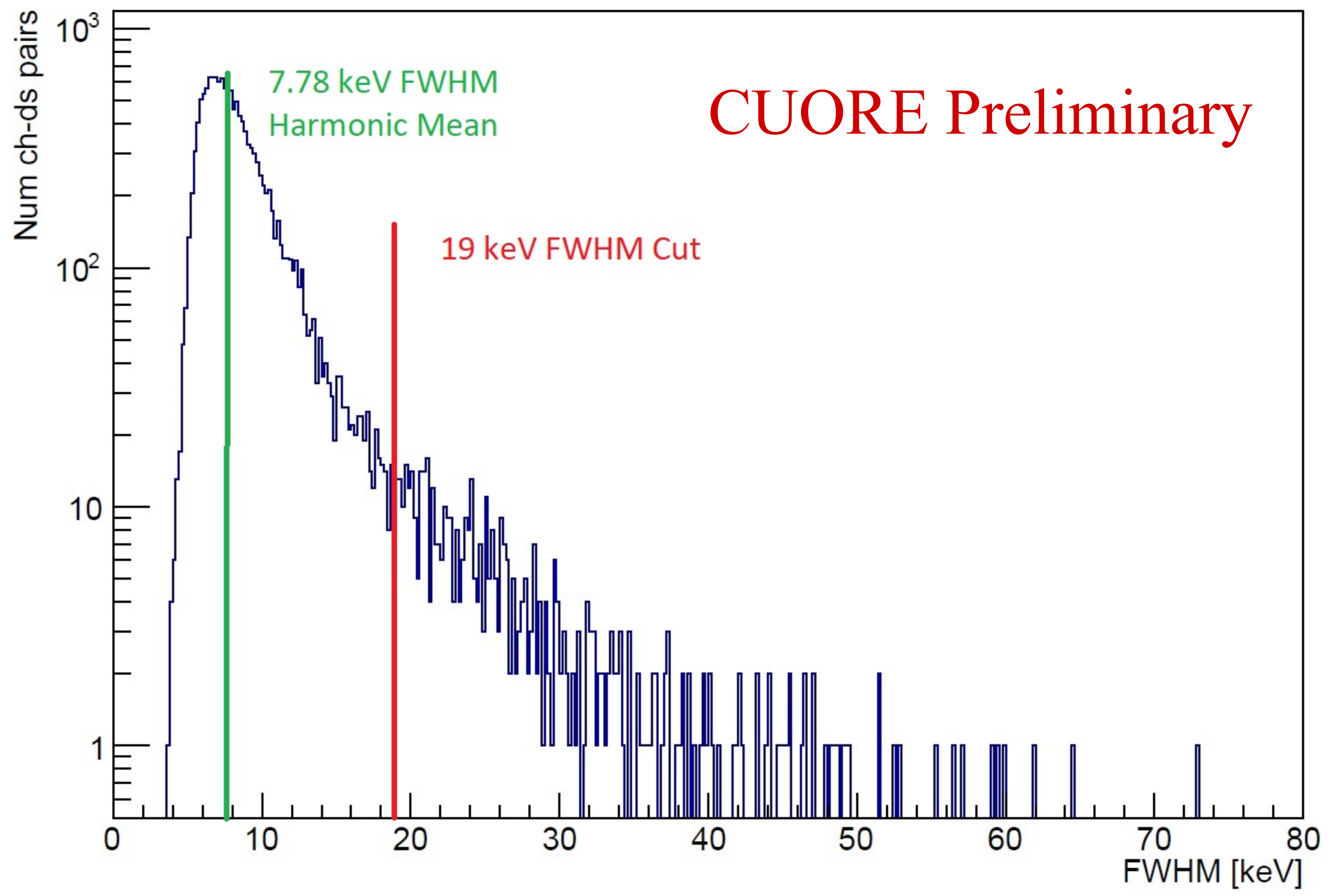


Counts / (keV kg yr)
10^2
10
1
10^{-1}
10^{-2}
1000
2000
3000
4000
5000
6000
Energy (keV)
Base Cuts
Base Cuts + AC
Base Cuts + AC + PSD
CUORE Preliminary
Exposure: 1038.4 kg yr
$Q_{\beta\beta}$

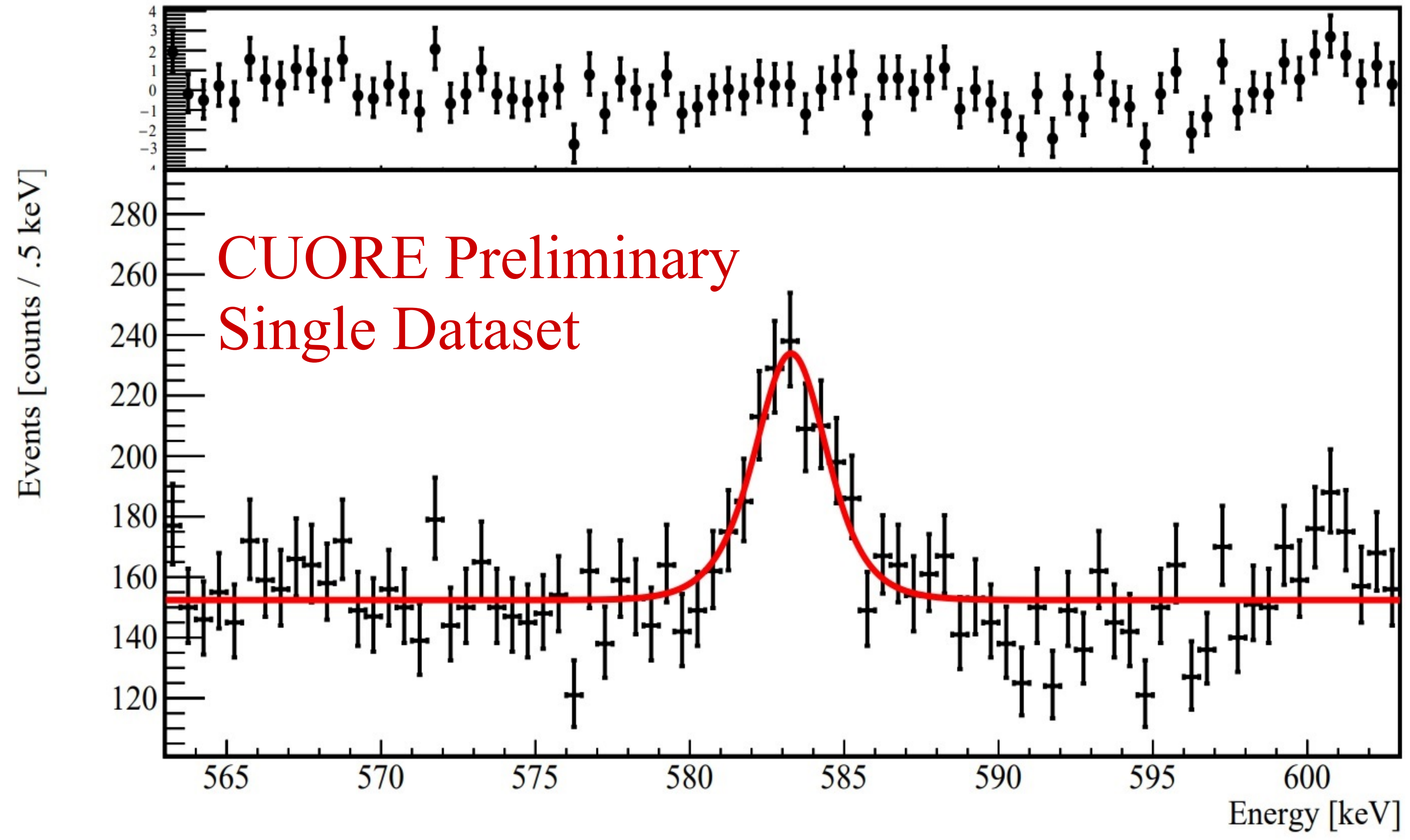
CUORE DATA ANALYSIS - DETECTOR RESPONSE

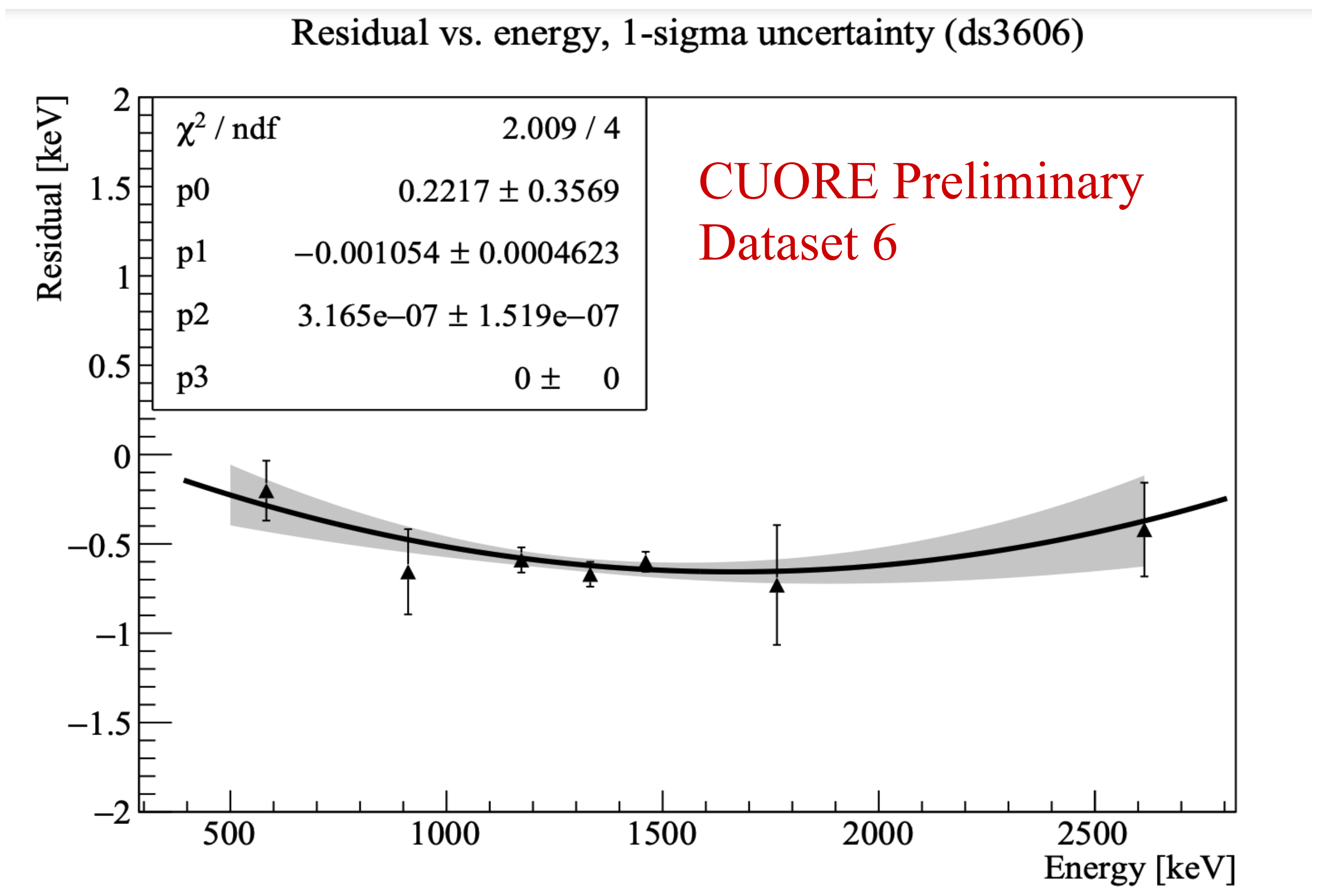
- Fit 2615 keV calibration peak for each channel
  a) 3-Gaussian signal peak
  b) Compton background
  c) Flat background
  d) 30 keV X-ray escape peak (background)
  e) 30 keV X-ray sum peak (background)
- Detector response function is just component (a)
- Exclude channels with FWHM > 19 keV for this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

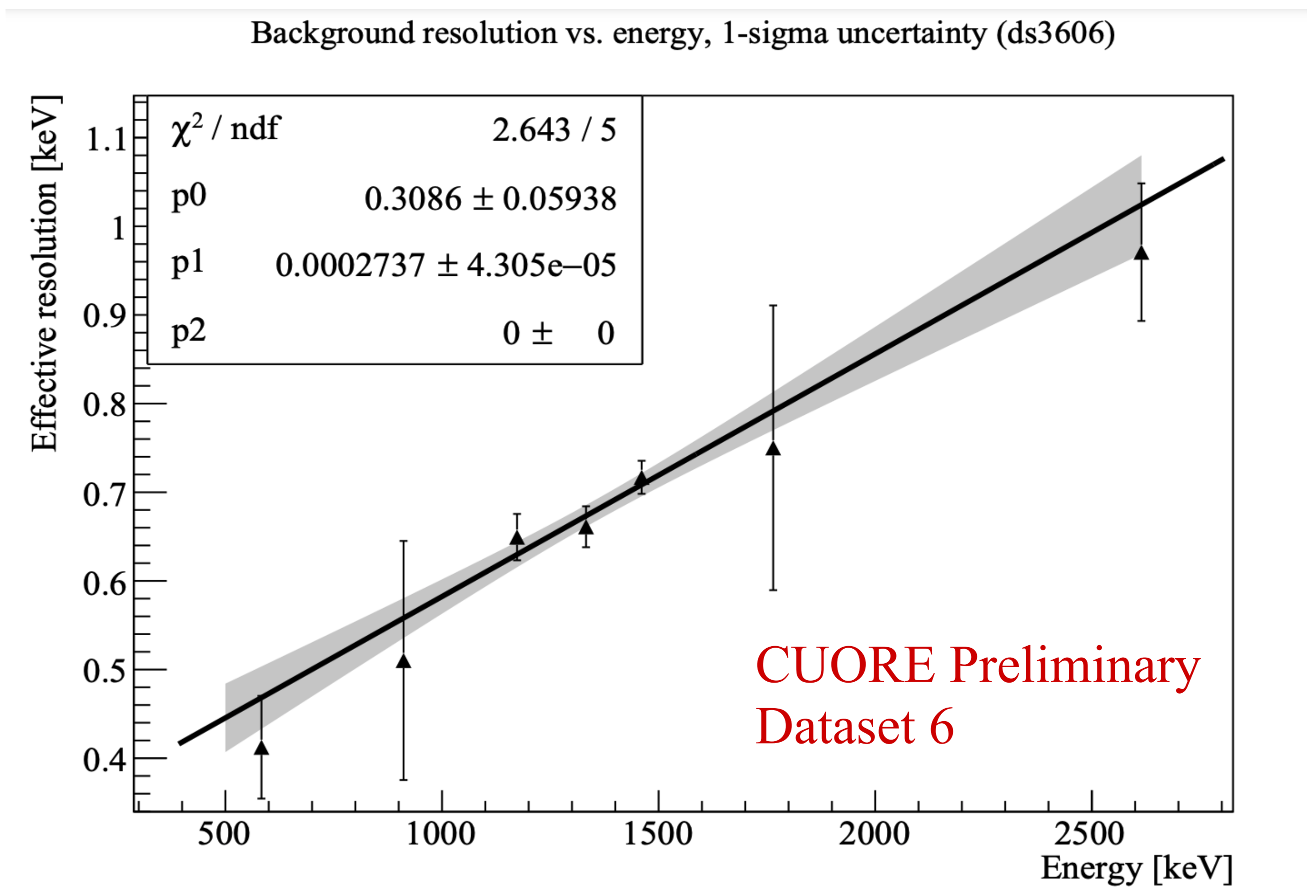




CUORE DATA ANALYSIS – DETECTOR RESPONSE







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

1 TONNE-YR DATA RELEASE: FIGURES

CUORE

Parameters	Values
Number of datasets	15
Number of channels	~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)
https://arxiv.org/abs/2104.06906

FIT METHOD

CUORE

BAT

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

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

Input from data

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

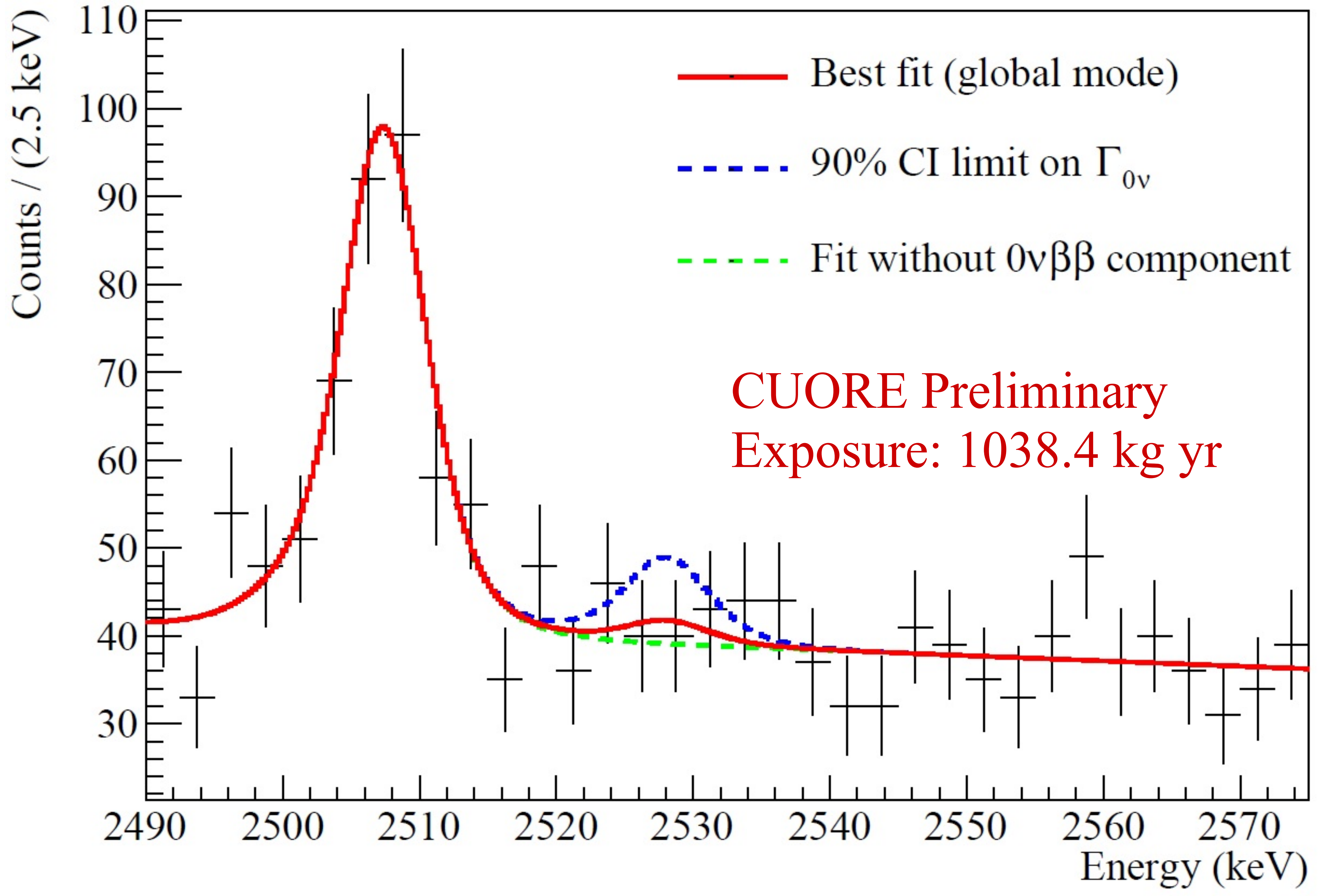
Minimal model

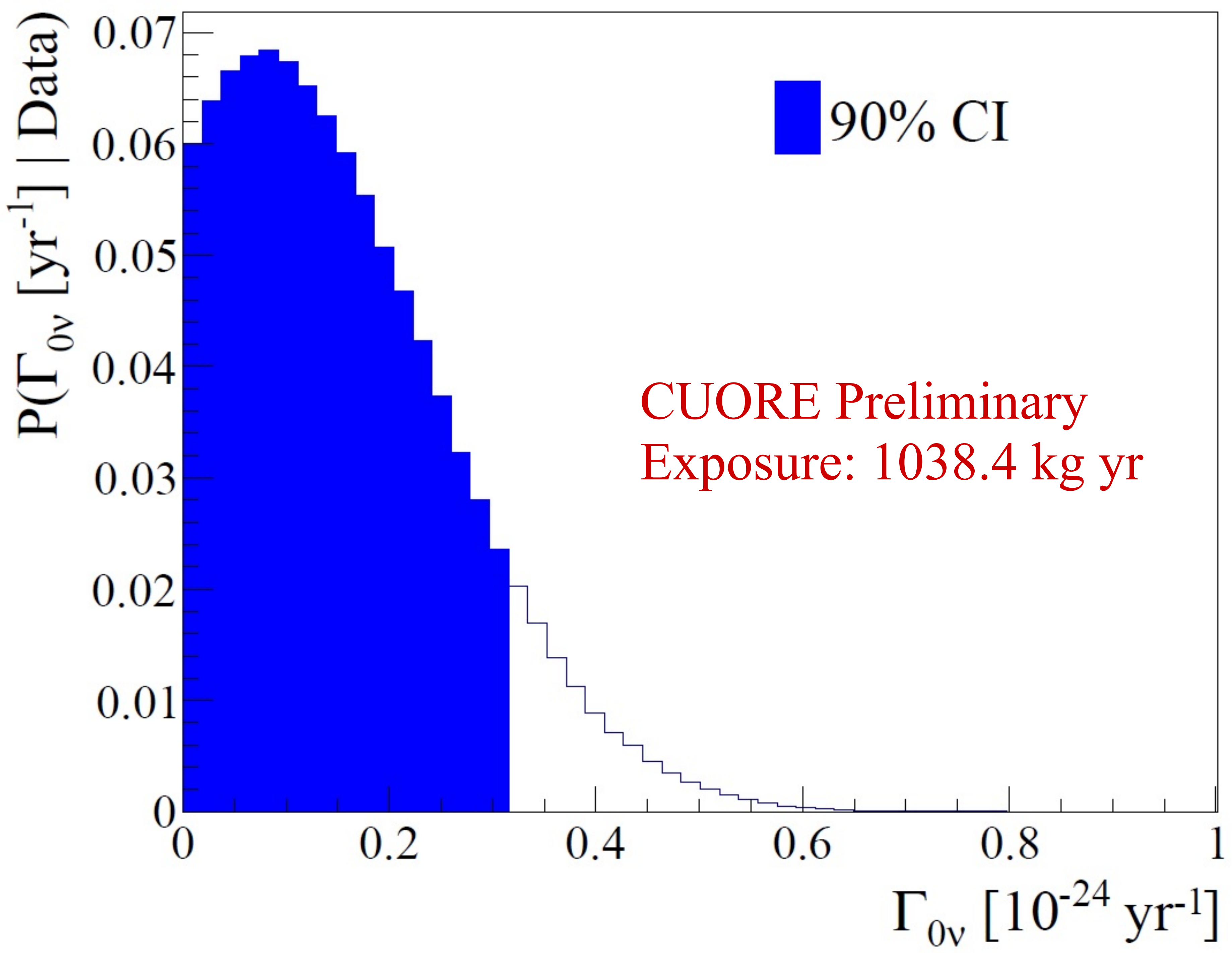
- signal rate $\Gamma_{0\nu}$
- ^{60}Co peak rate, modulated in each dataset by its lifetime
- linear background

Systematics (<0.8% effect on limit)

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

FIT RESULT



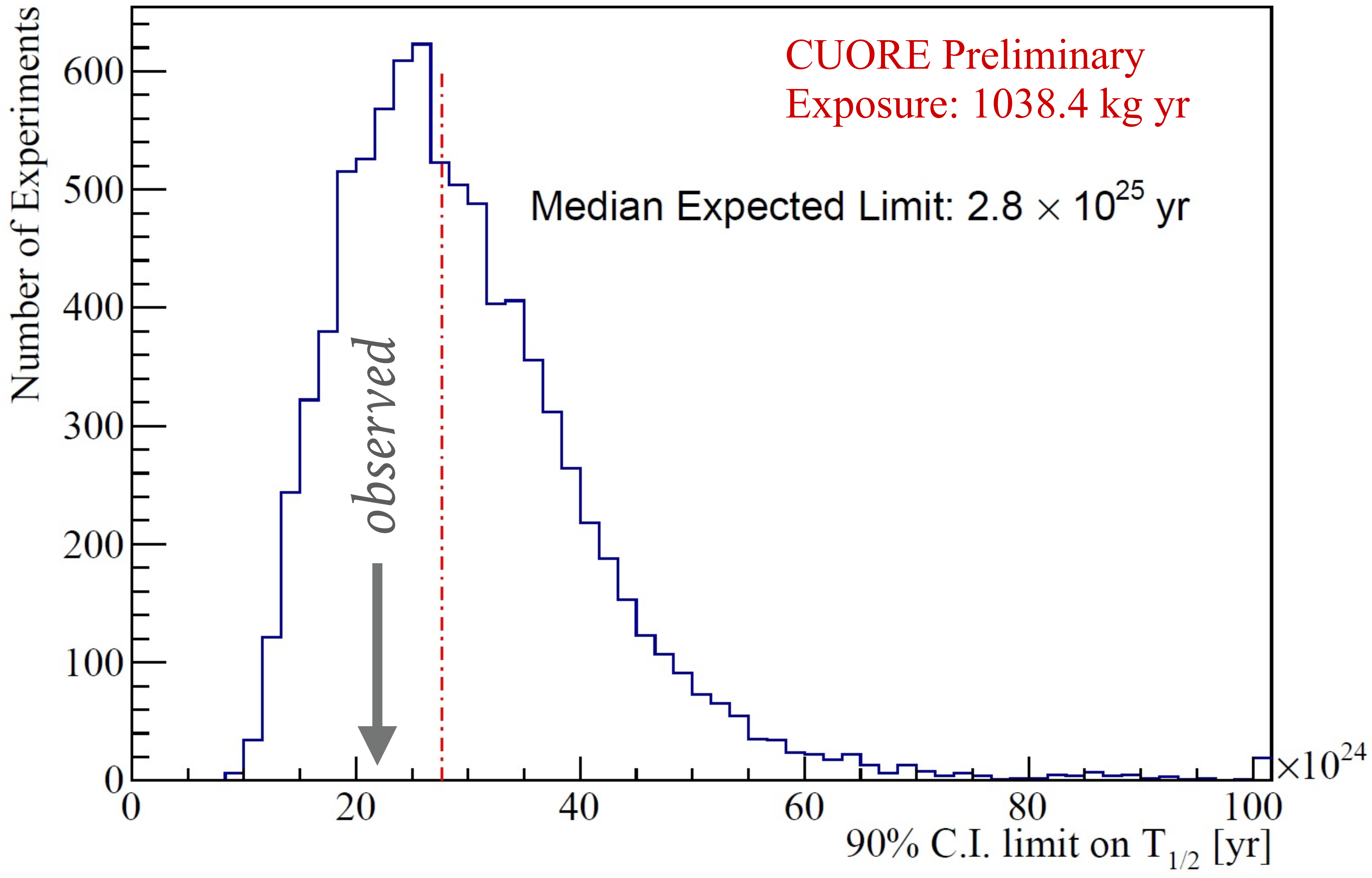


$$b = 1.49(4) \times 10^{-2} \text{ counts/(keV kg yr)}$$

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

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

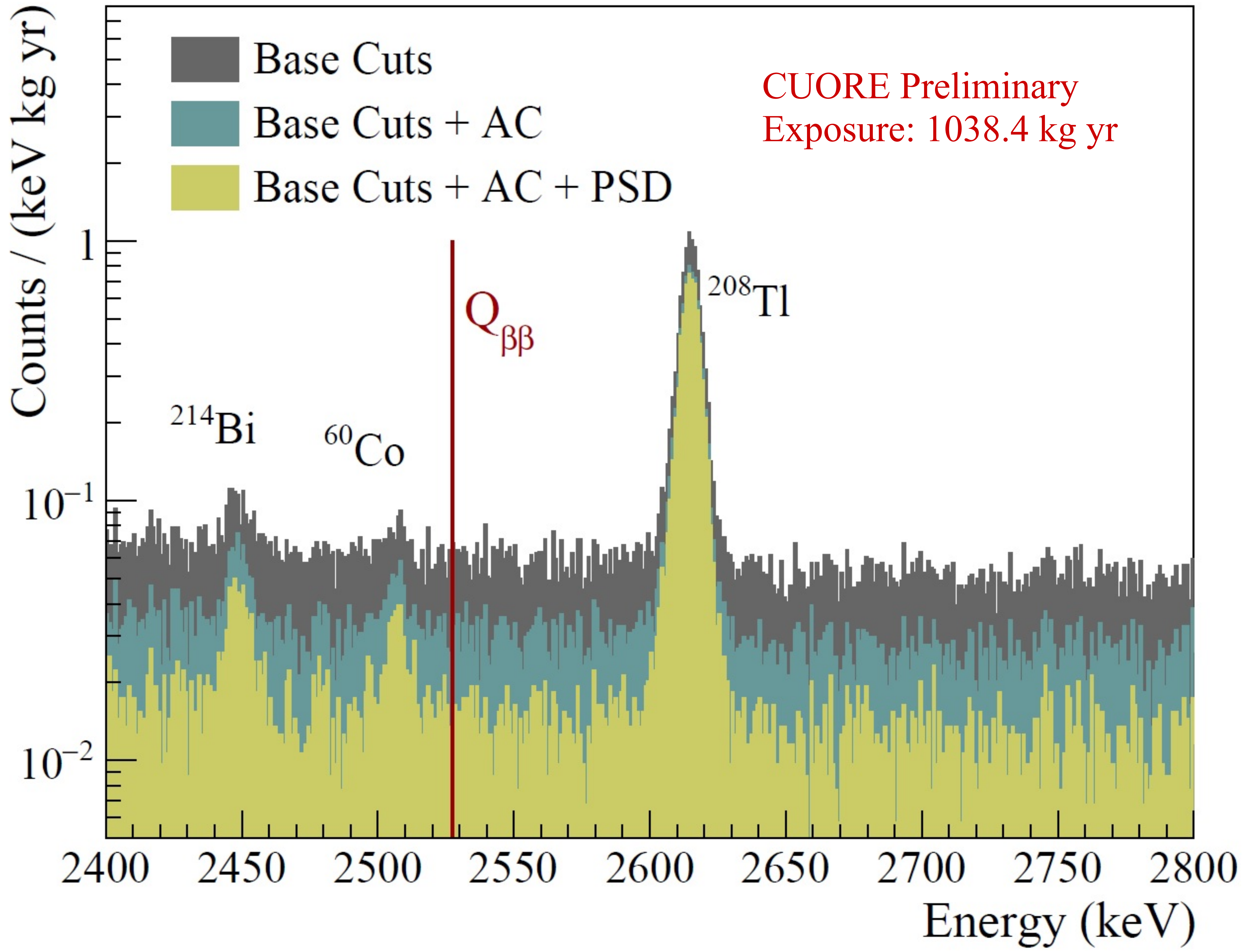
SENSITIVITY



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

- 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

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)

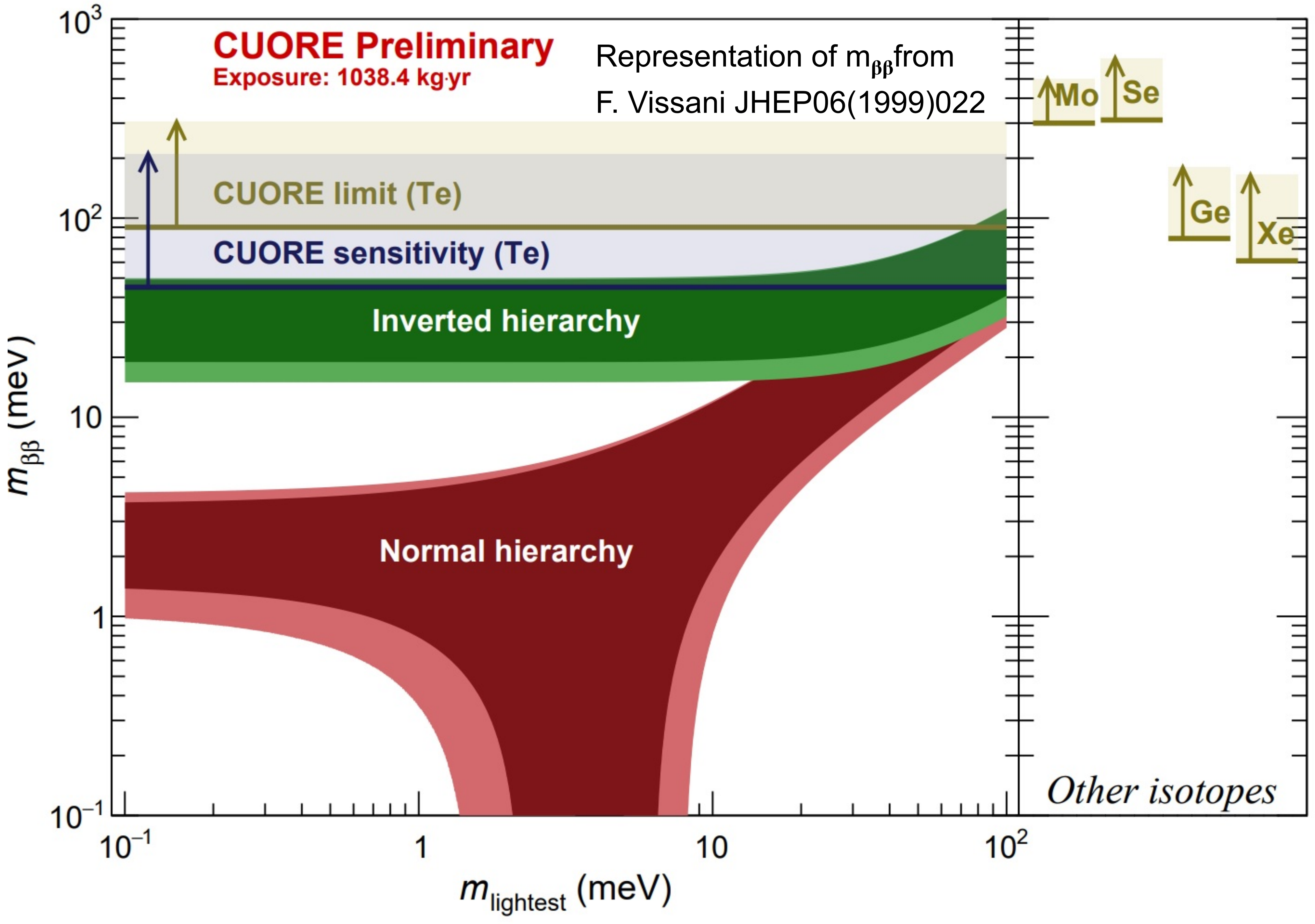
$Q_{\beta\beta}$ region

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

FIT RESULT



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

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

- 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

- limits on other isotopes from

  Agostini, M. et al. (GERDA Collaboration), Phys. Rev. Lett. 125, 252502 (2020)
  https://doi.org/10.1103/PhysRevLett.125.252502

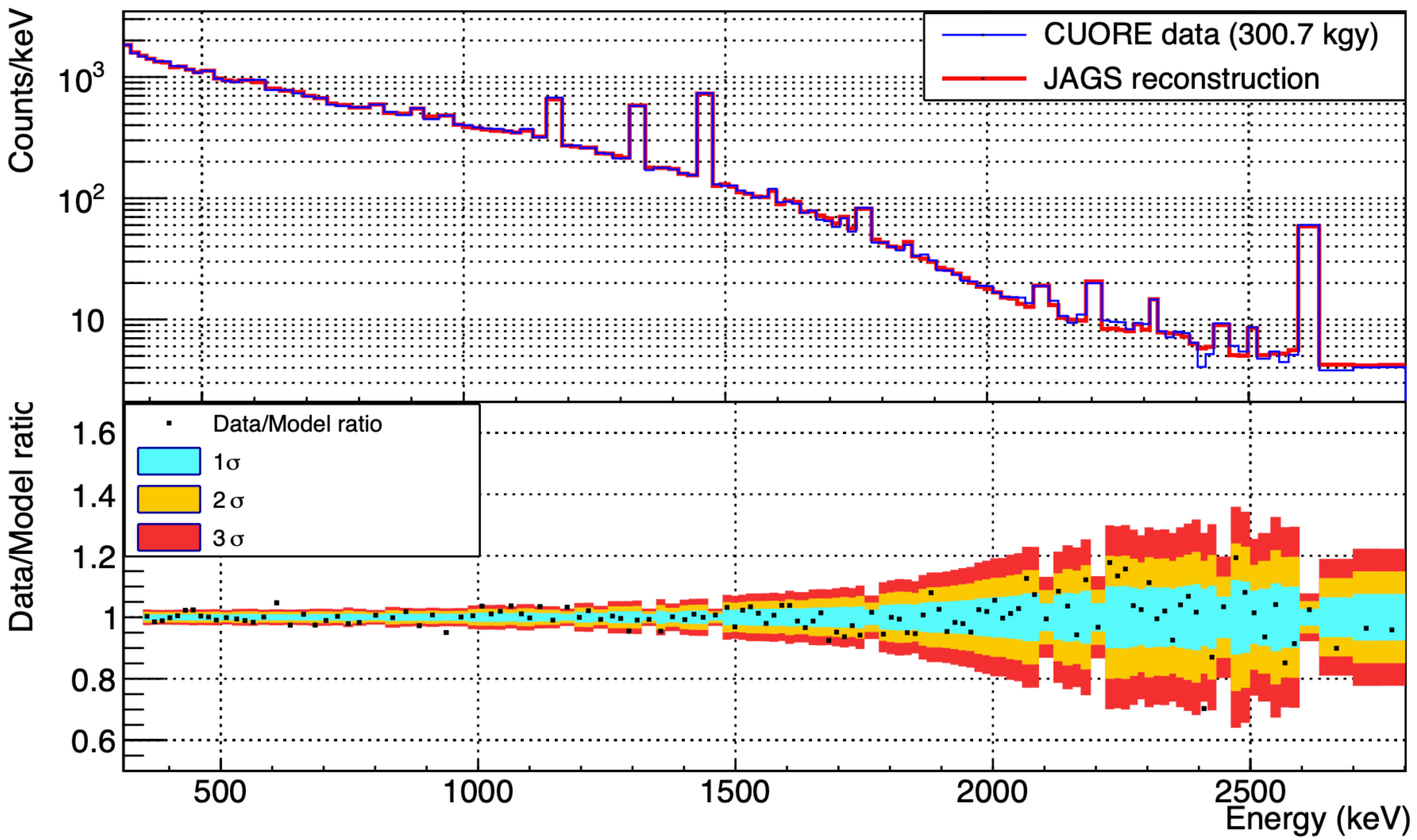
  Armengaus, E. et al. (CUPID-Mo Collaboration)
  https://arxiv.org/abs/2011.13243

  Azzolini, O. et al. (CUPID-0 Collaboration), Phys. Rev. Lett. 123, 032501 (2019)
  https://doi.org/10.1103/PhysRevLett.123.032501

  Gando, A. et al. (KamLAND-Zen Collaboration), Phys. Rev. Lett. 117, 082503 (2016)
  https://doi.org/10.1103/PhysRevLett.117.082503

OTHER RARE DECAYS

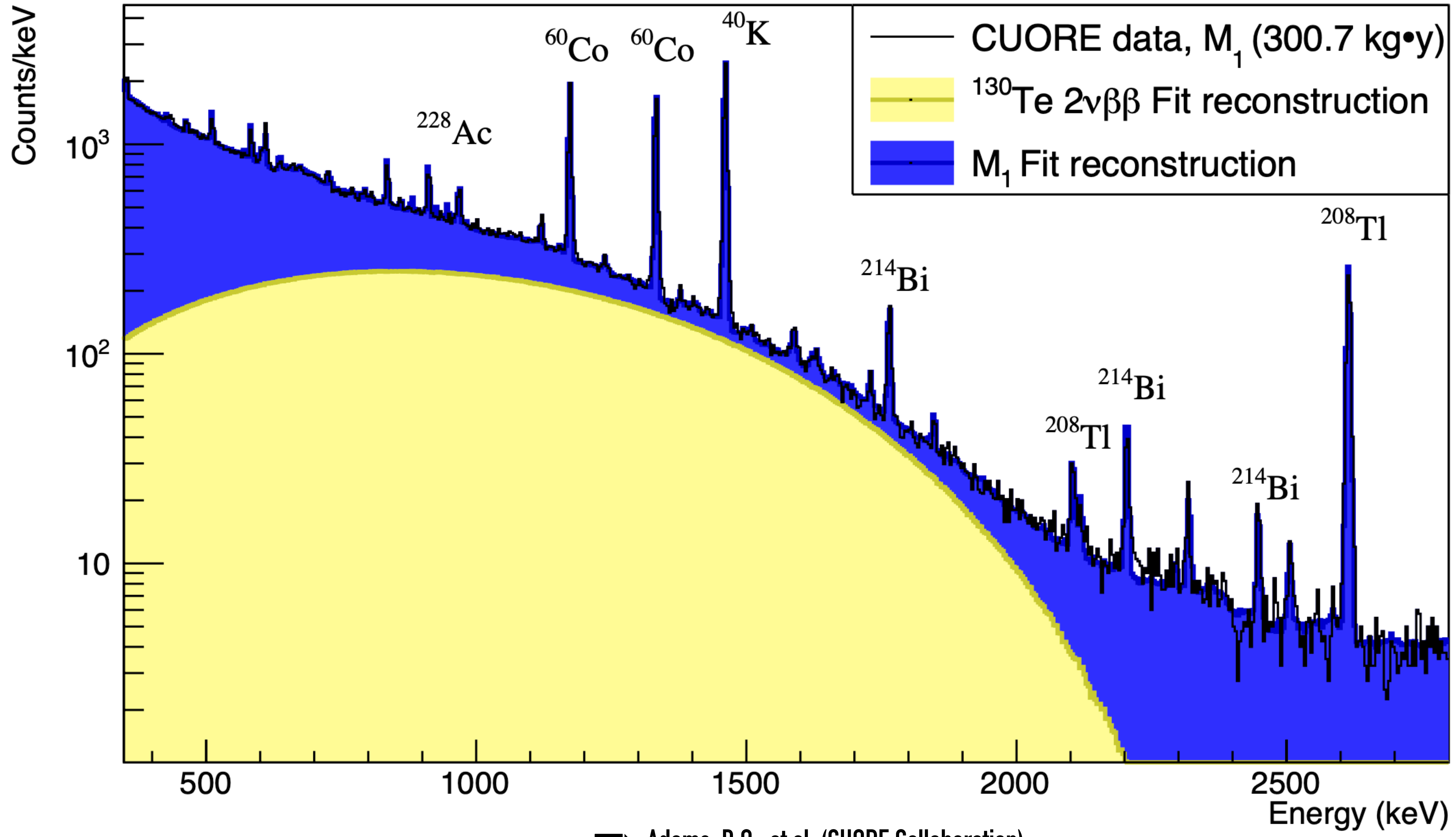
STANDARD MODEL DOUBLE BETA DECAY (GROUND STATE)



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

- 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

Literature

- NEMO-3

  $$T_{1/2} = (7.0 \pm 0.9_{\text{stat}} \pm 1.1_{\text{syst}}) \times 10^{20}\ \text{yr}$$

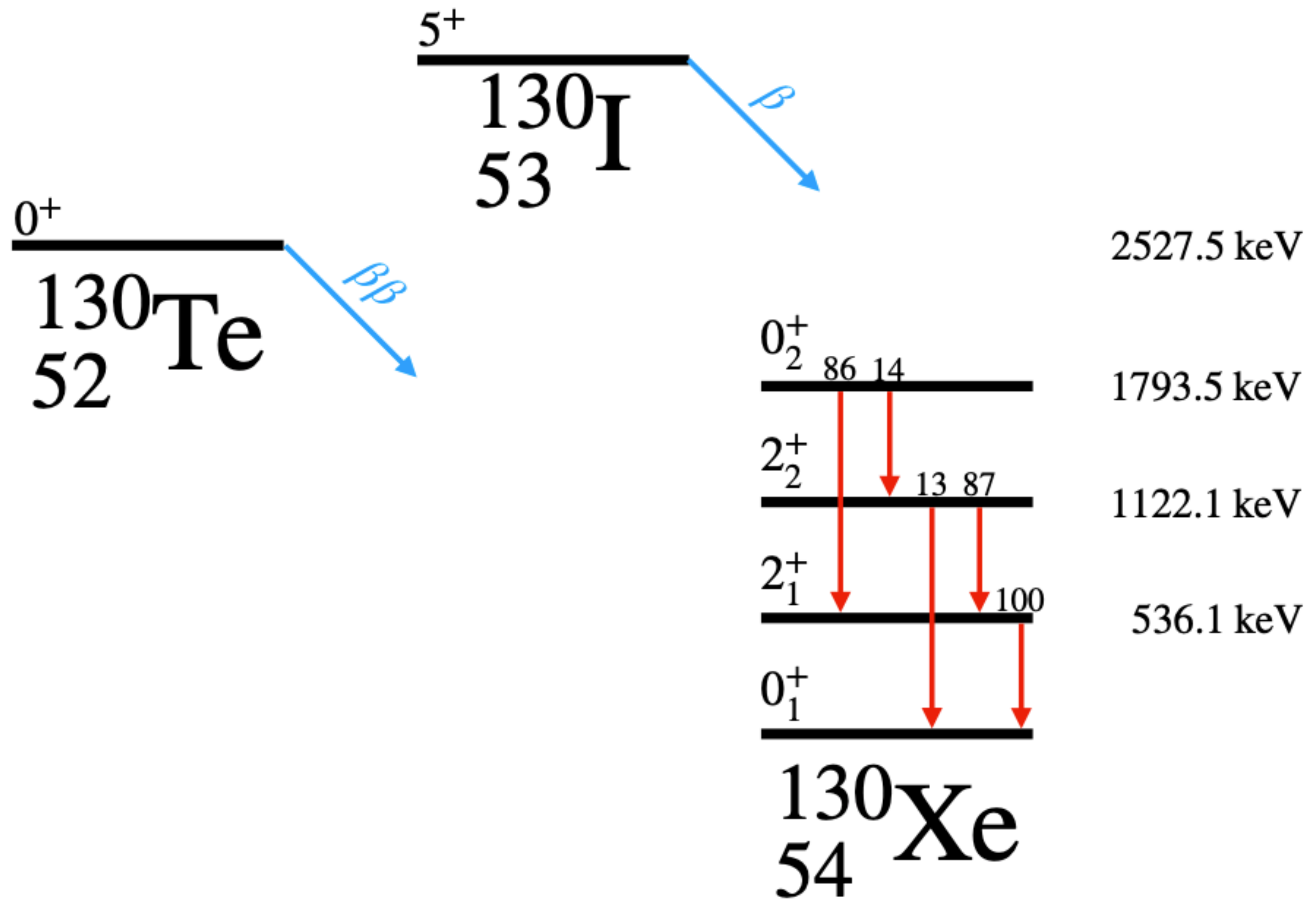
  Arnold, R. et al. (NEMO-3 Collaboration), Phys. Rev. Lett. 107, 062504 (2011)
  https://doi.org/10.1103/PhysRevLett.107.062504

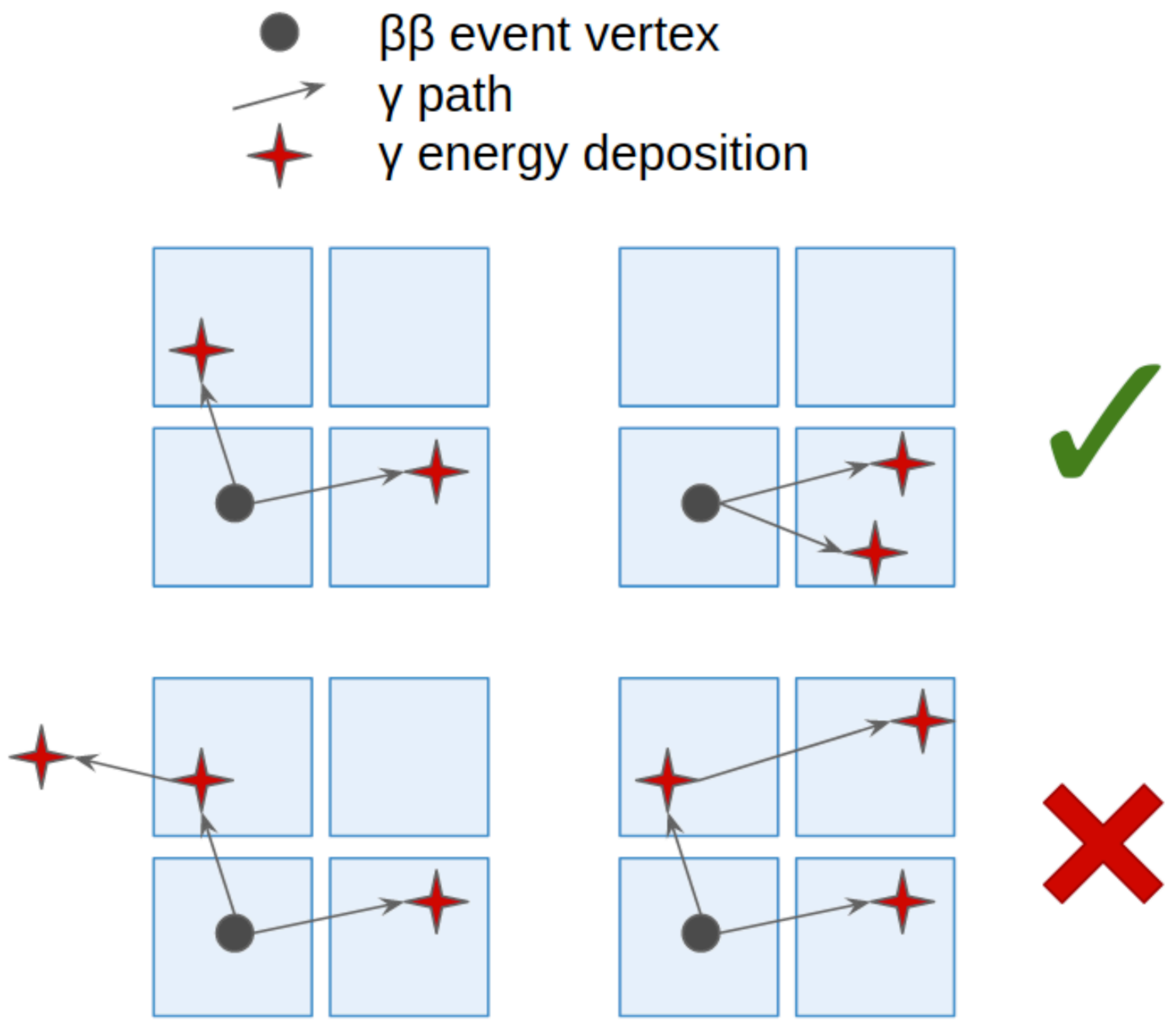
- CUORE-0

  $$T_{1/2} = (8.2 \pm 0.2_{\text{stat}} \pm 0.6_{\text{syst}}) \times 10^{20}\ \text{yr}$$

  Alduino,C. et al. (CUORE-0 Collaboration), Eur. Phys. J. C 77, 13 (2017)
  https://doi.org/10.1140/epjc/s10052-016-4498-6

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

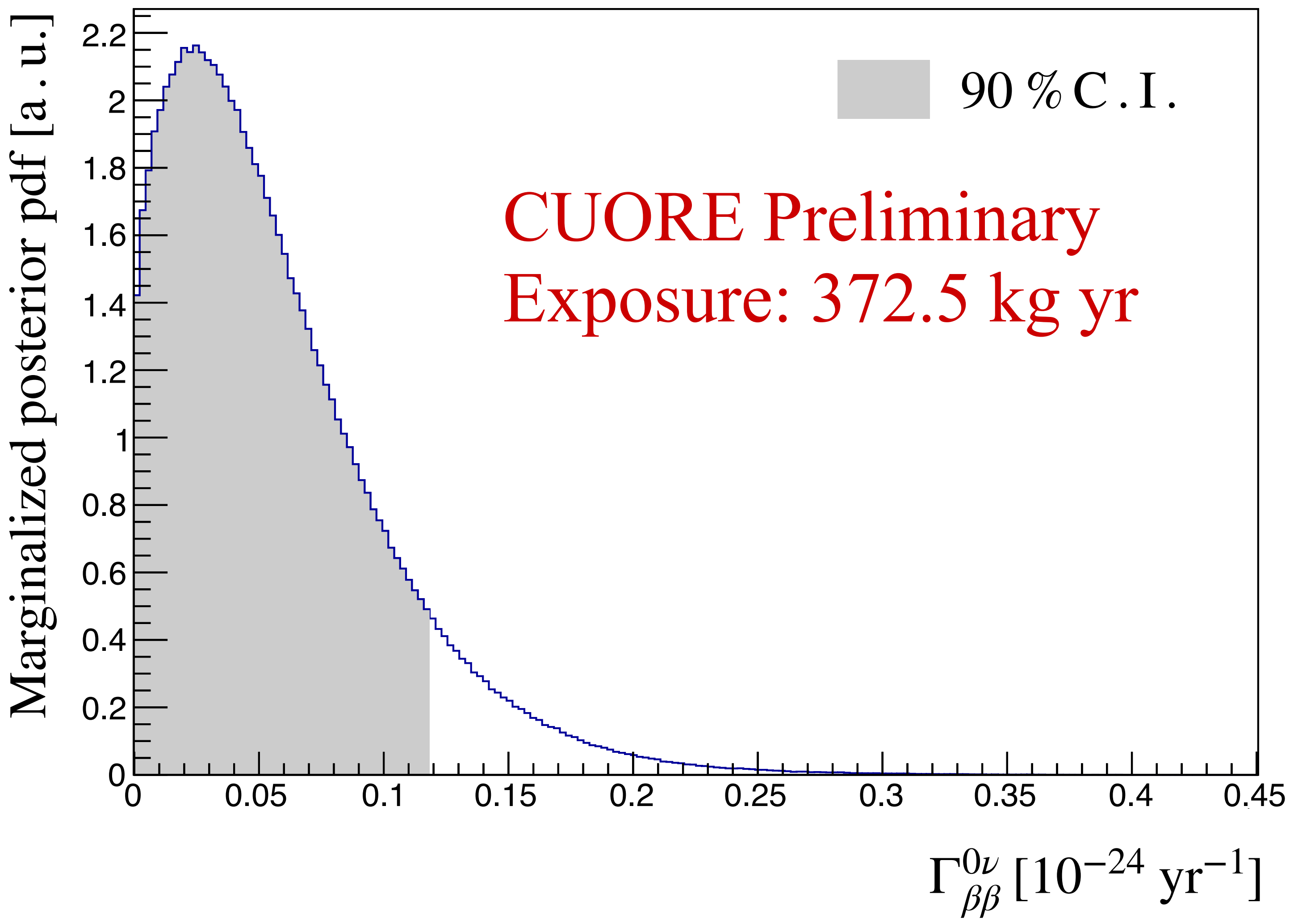
DOUBLE BETA DECAY TO EXCITED STATES

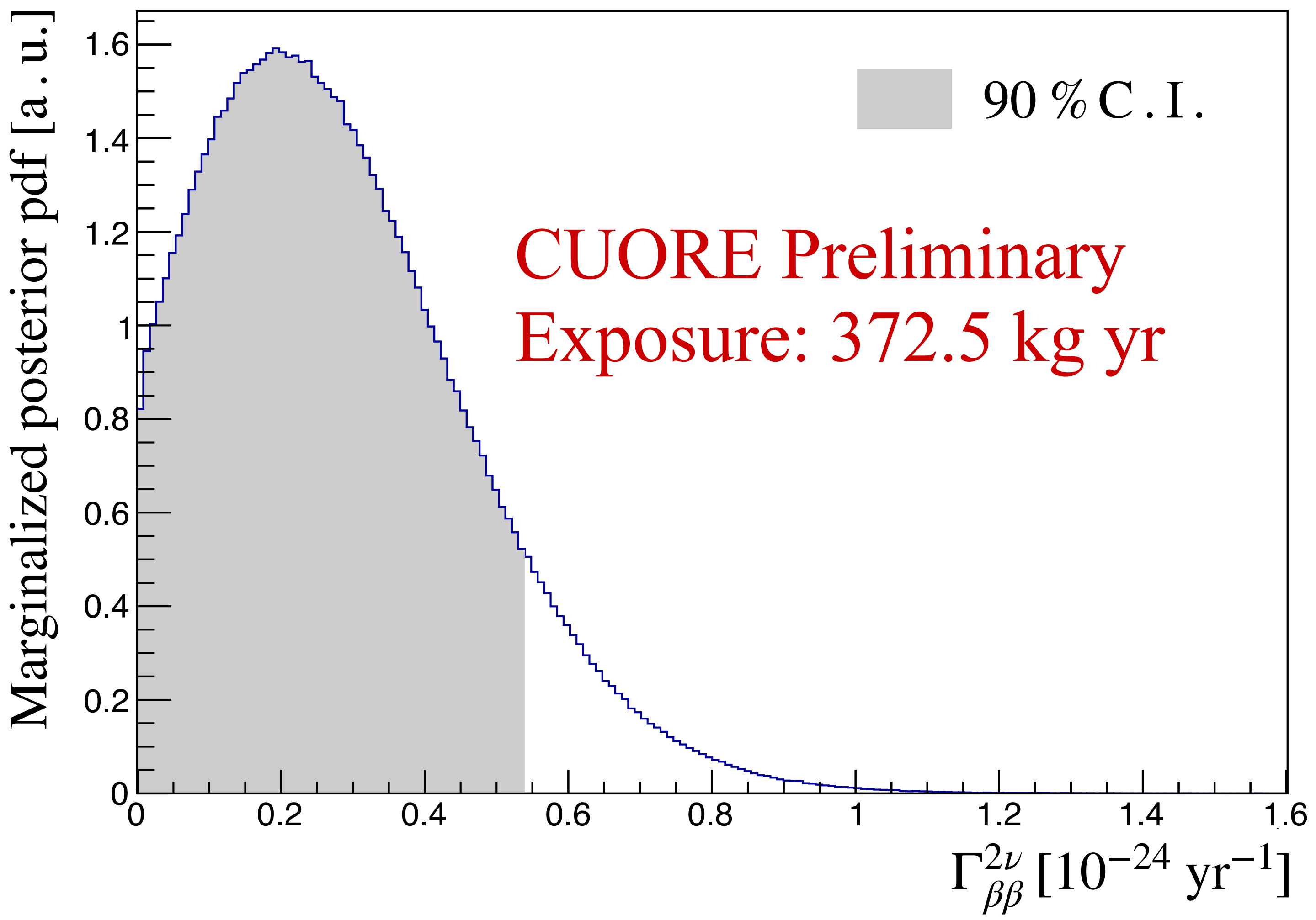
- Fully contained events only (ββ and de-excitation γs all detected)
- Coincident events up to 3 crystals
- Only most sensitive experimental signatures

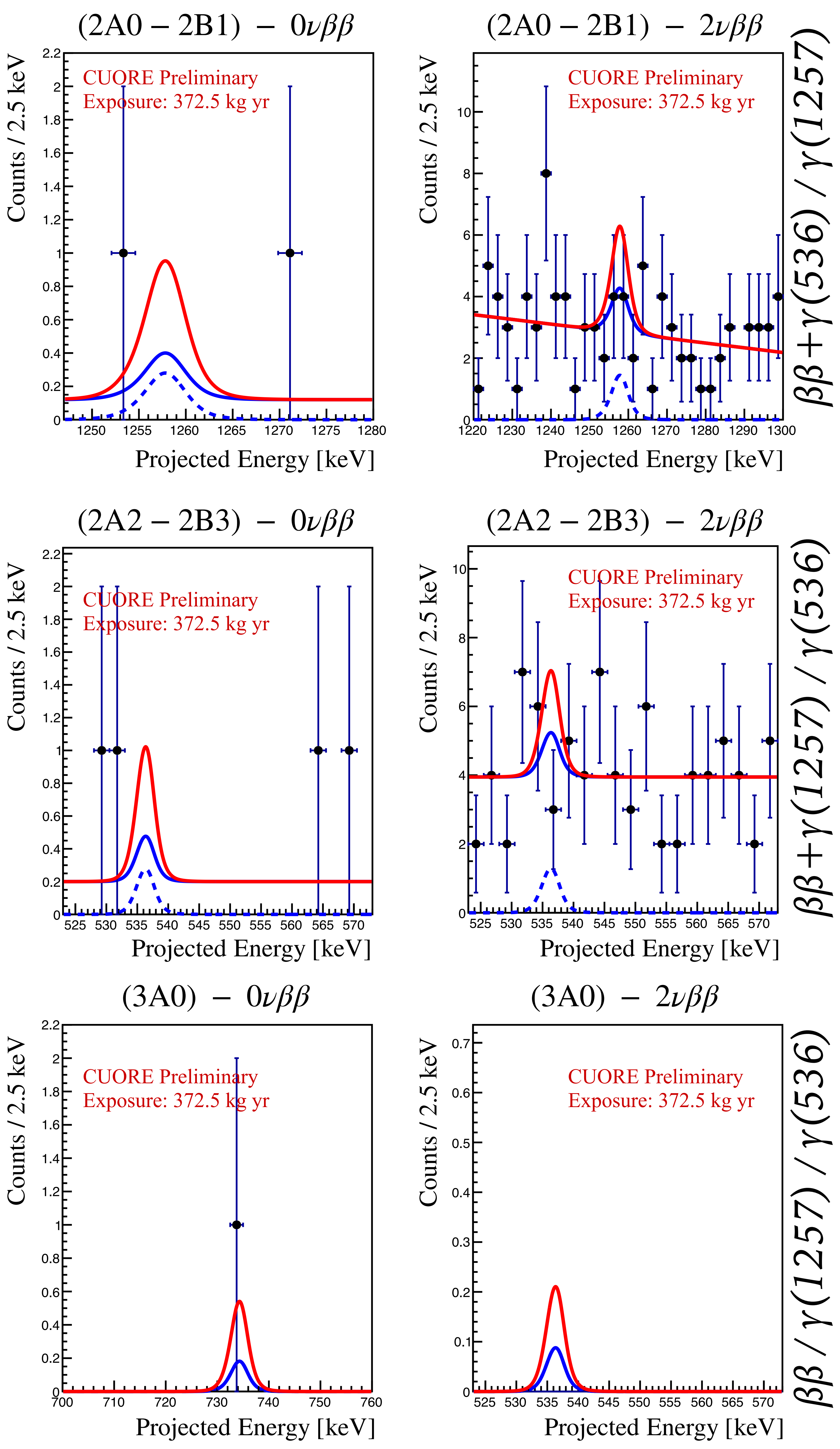
$T^{0\nu}_{1/2} > 5.9 \times 10^{24}$ yr (90 % C.I.)

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

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







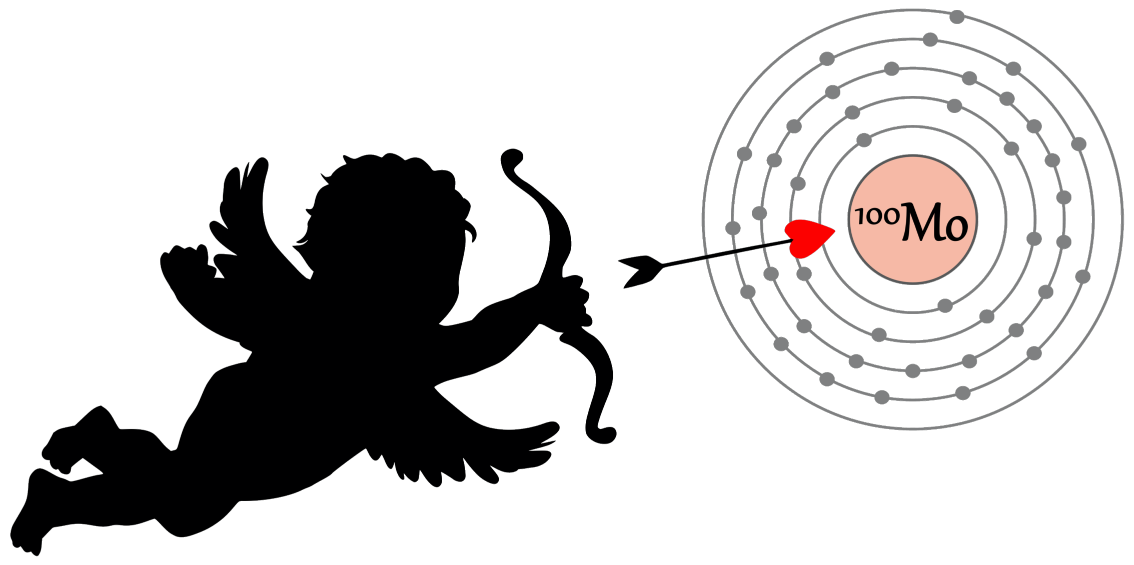
Literature (CUORE-0)

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

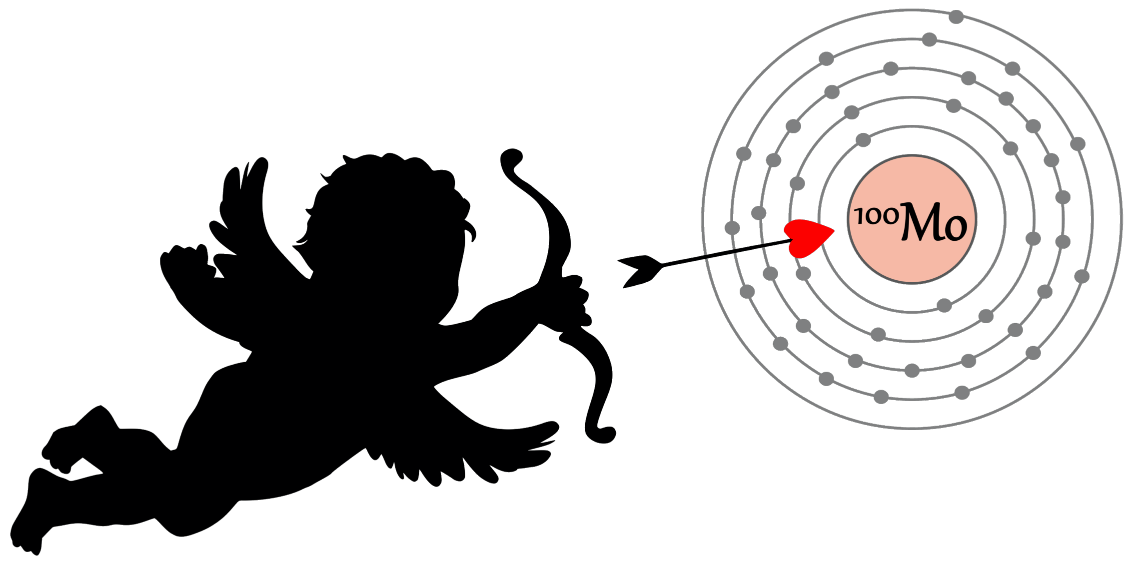
$T^{2\nu}_{1/2} > 0.25 \times 10^{24}$ yr (90 % C.L.)

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

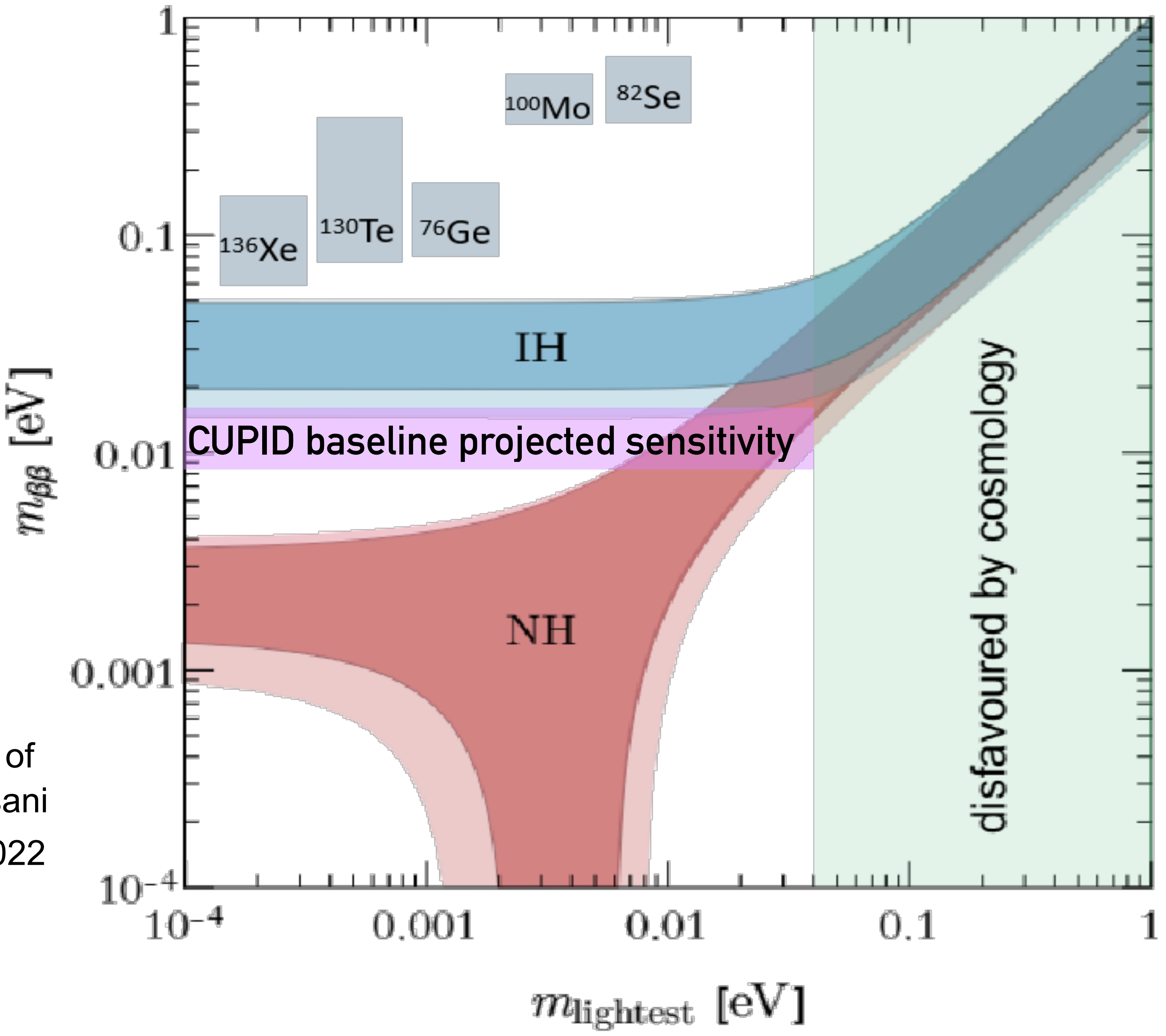
WHAT NEXT?



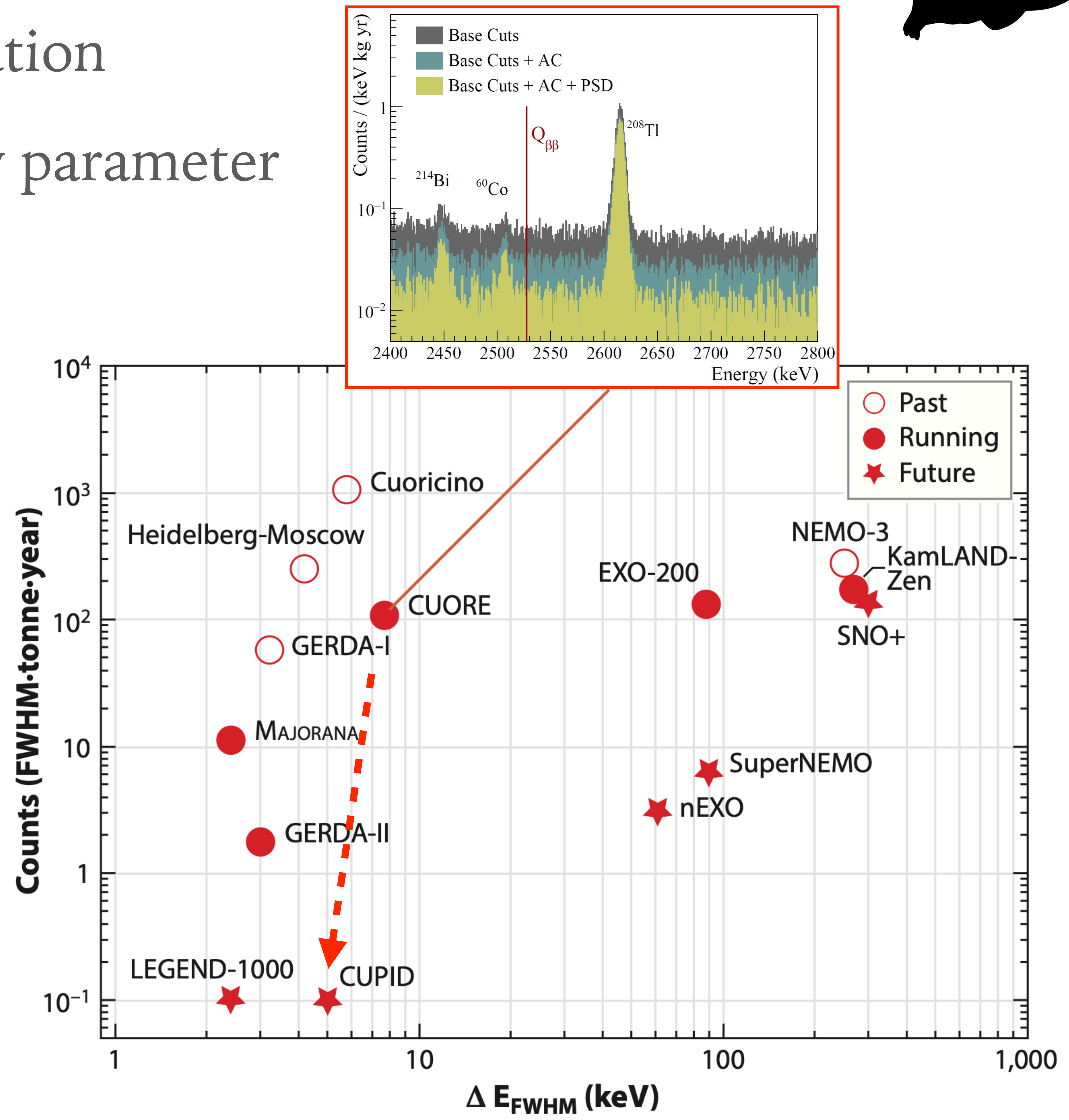
CUPID – NEXT GENERATION



- CUORE Upgrade with Particle IDentification
- Goal: fully explore the inverted hierarchy parameter space



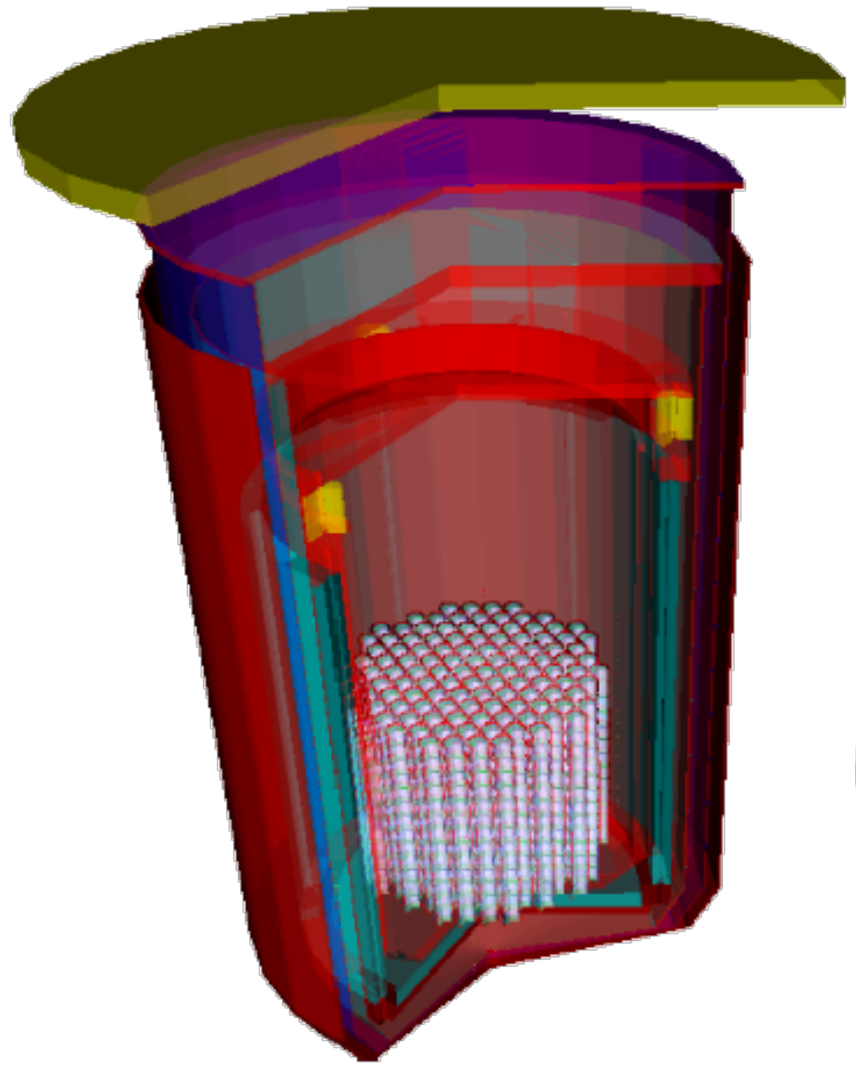
Representation of $m_{\beta\beta}$ from F. Vissani JHEP06(1999)022

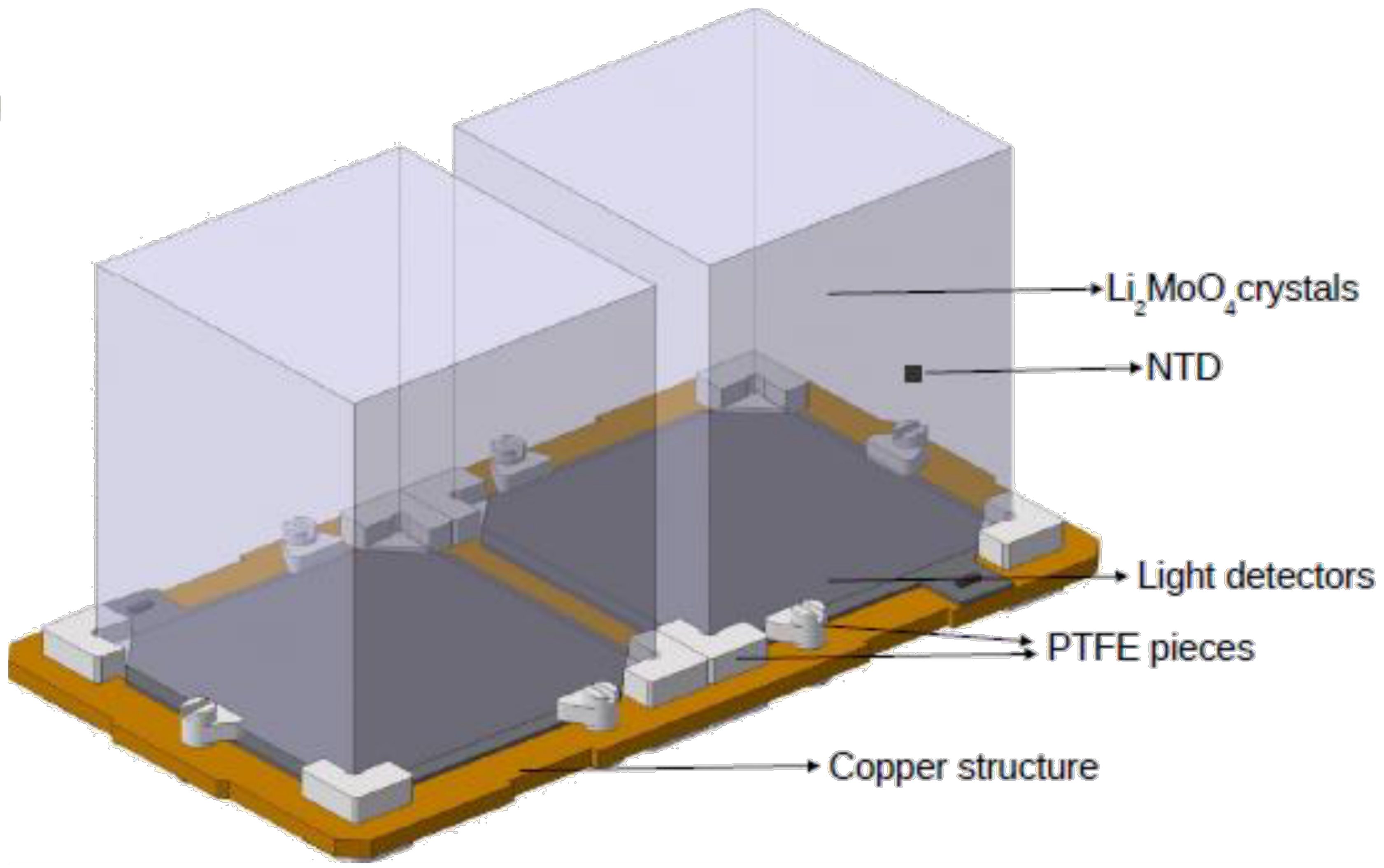


Dolinski M. et al., Ann. Rev. Nucl. Part. Sci. 2019.69:219-251
https://www.annualreviews.org/doi/pdf/10.1146/annurev-nucl-101918-023407

CUPID – NEXT GENERATION

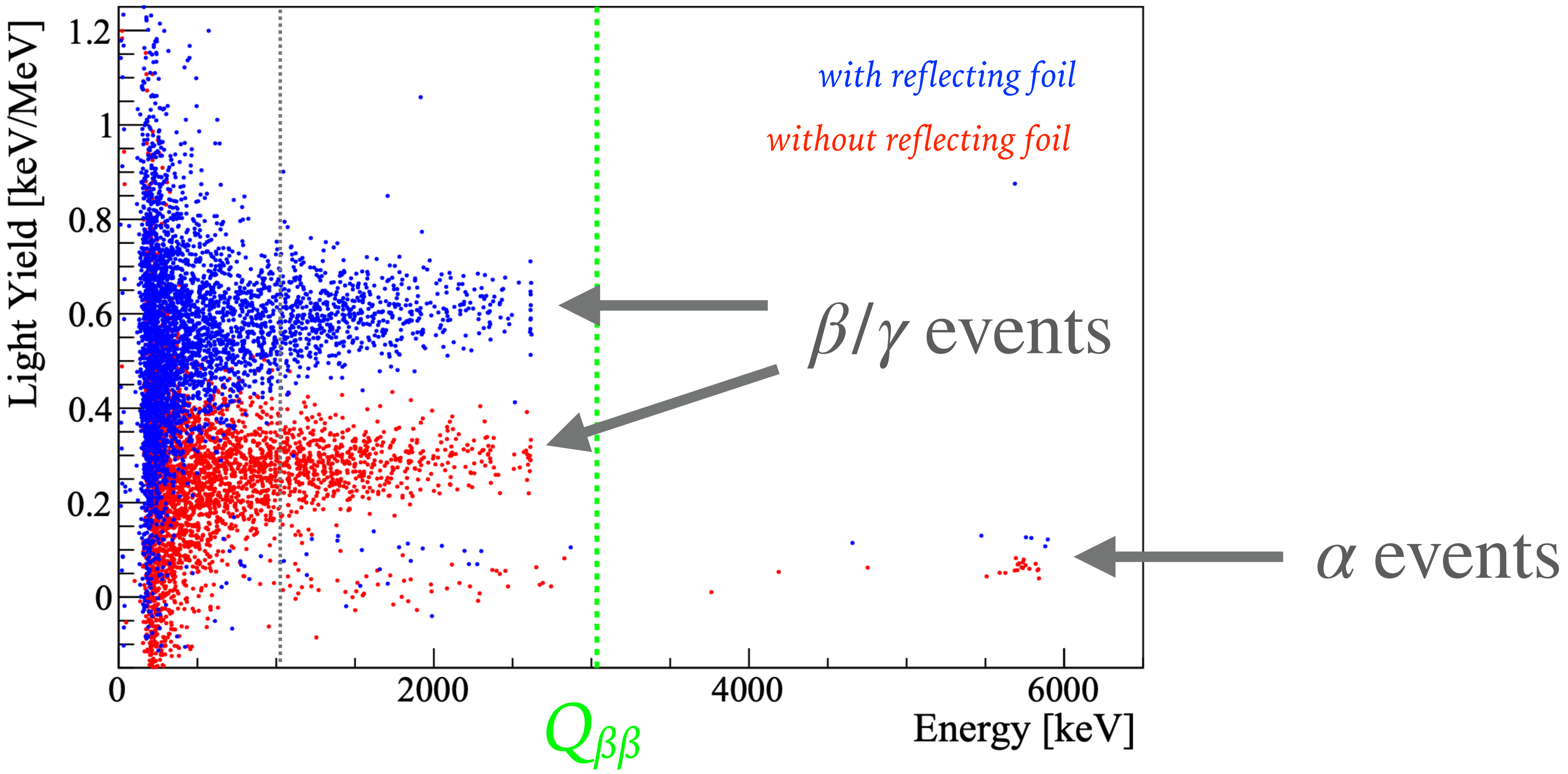
- CUPID-Mo technology is chosen:
  - ~1600 $Li_2^{100}MoO_4$ scintillating bolometers (240 kg of ^{100}Mo)
  - high energy resolution (~ 5 keV)
  - excellent radio-purity
  - full (>99.9%) $\beta(\gamma)/\alpha$ separation





Rahman, S. et al., Phys. Lett. B 662(2), 111 (2008) https://doi.org/10.1016/j.physletb.2008.02.047

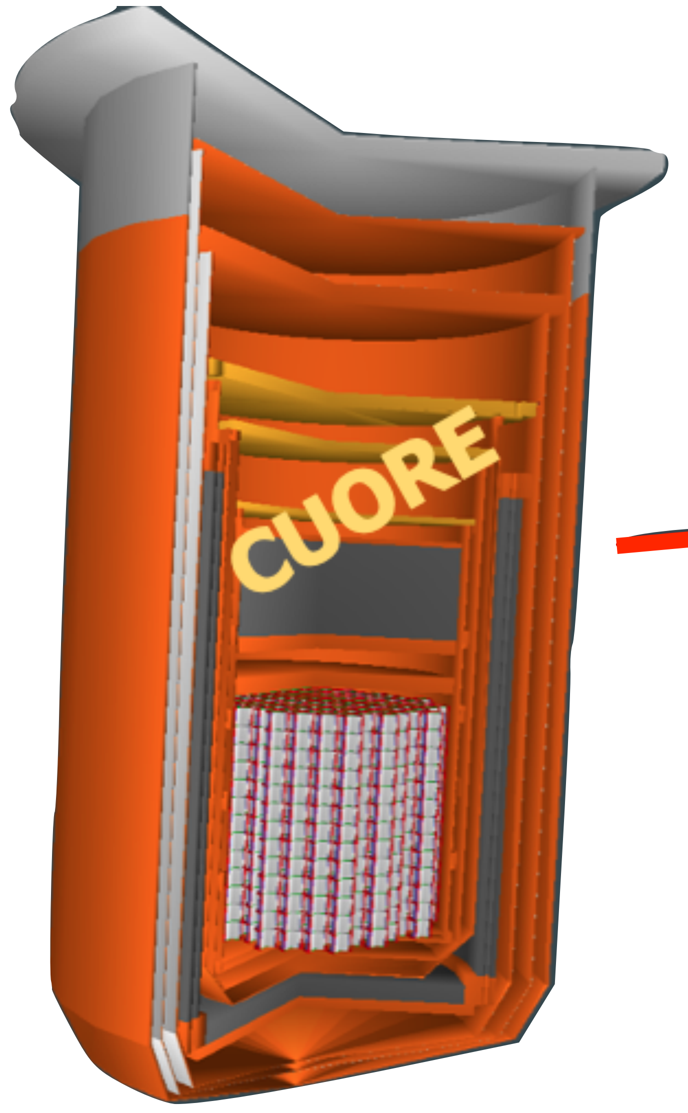
$Q_{\beta\beta} = 3034.4(2)\ keV$



Armatol, A. et al (CUPID Collaboration), Eur. Phys. J. C (2021) 81:104 https://doi.org/10.1140/epjc/s10052-020-08809-8

CUPID – NEXT GENERATION

- Both CUPID-Mo and CUPID-0 proved the robustness of technology for a potentially background-free experiment
- Reuse proven CUORE cryogenic infrastructure at LNGS for cost-effective deployment
- Expansion to 1-tonne scale (CUPID-1T) technically possible



Best world limit on ^{130}Te
$T_{1/2} > 2.2 \; 10^{25}$ y (90% C.I.)

Best world limit on ^{82}Se
$T_{1/2} > 3.5 \; 10^{24}$ y (90% C.I.)

Best world limit on ^{100}Mo
$T_{1/2} > 1.5 \; 10^{24}$ y (90% C.I.)

FRESH FORCES!

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
  - 2νββ of ^{130}Te
  - 0νββ and 2νββ decay on ^{130}Te excited states and ^{128}Te
  - β+β+ / 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 1 tonne year of exposure and is in stable data taking
- No evidence of 0νββ decay with 1038.4 kg yr of data
  - Bayesian 90% C.I. limit $T^{0\nu}_{1/2} > 2.2 \times 10^{25}\ \mathrm{yr}\ (90\,\%\ \mathrm{C.I.})$
  - Effective Majorana Mass limit $m_{\beta\beta} < 90 - 305\ \mathrm{meV}$

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

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

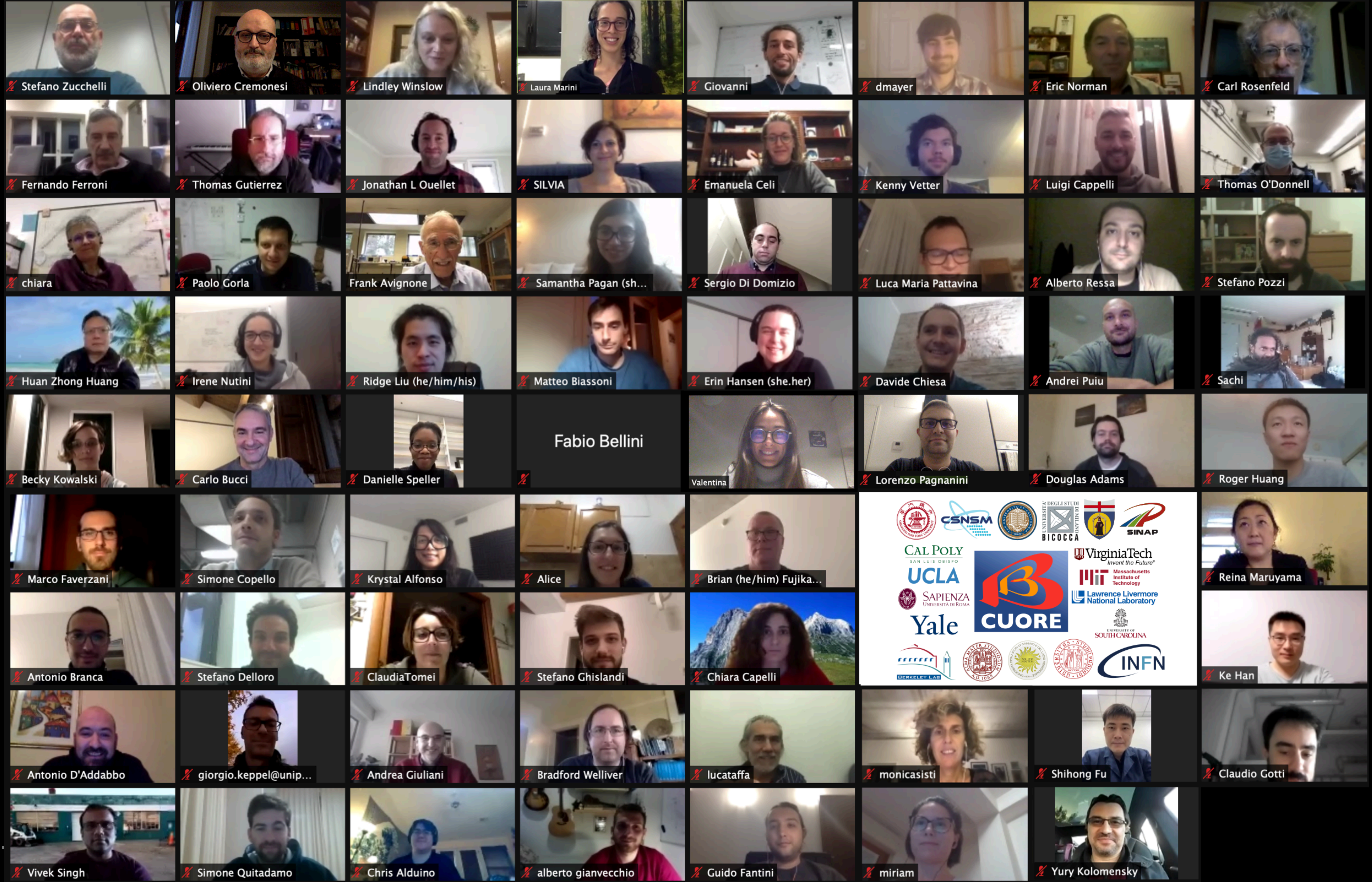
Adams, D.Q. et al. (CUORE Collaboration) https://arxiv.org/abs/2012.11749

- Most stringent limits on ^{130}Te ββ decay to 0^+_1 excited state of ^{130}Xe

$T^{0\nu}_{1/2} > 5.9 \times 10^{24}\ \mathrm{yr}\ (90\,\%\ \mathrm{C.I.})$ $T^{2\nu}_{1/2} > 1.3 \times 10^{24}\ \mathrm{yr}\ (90\,\%\ \mathrm{C.I.})$

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

- Proves feasibility of large-scale bolometric detectors: CUPID


Stefano Zucchelli
Oliviero Cremonesi
Lindley Winslow
Laura Marini
Giovanni
dmayer
Eric Norman
Carl Rosenfeld
Fernando Ferroni
Thomas Gutierrez
Jonathan L Ouellet
SILVIA
Emanuela Celi
Kenny Vetter
Luigi Cappelli
Thomas O'Donnell
chiara
Paolo Gorla
Frank Avignone
Samantha Pagan (sh...
Sergio Di Domizio
Luca Maria Pattavina
Alberto Ressa
Stefano Pozzi
Huan Zhong Huang
Irene Nutini
Ridge Liu (he/him/his)
Matteo Biassoni
Erin Hansen (she.her)
Davide Chiesa
Andrei Puiu
Sachi
Becky Kowalski
Carlo Bucci
Danielle Speller
Fabio Bellini
Valentina
Lorenzo Pagnanini
Douglas Adams
Roger Huang
Marco Faverzani
Simone Copello
Krystal Alfonso
Alice
Brian (he/him) Fujika...
CSNSM
BICOCCA
SINAP
CAL POLY
UCLA
SAPIENZA
Yale
CUORE
VirginiaTech
Invent the Future
Massachusetts Institute of Technology
Lawrence Livermore National Laboratory
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BERKELEY LAB
INFN
Reina Maruyama
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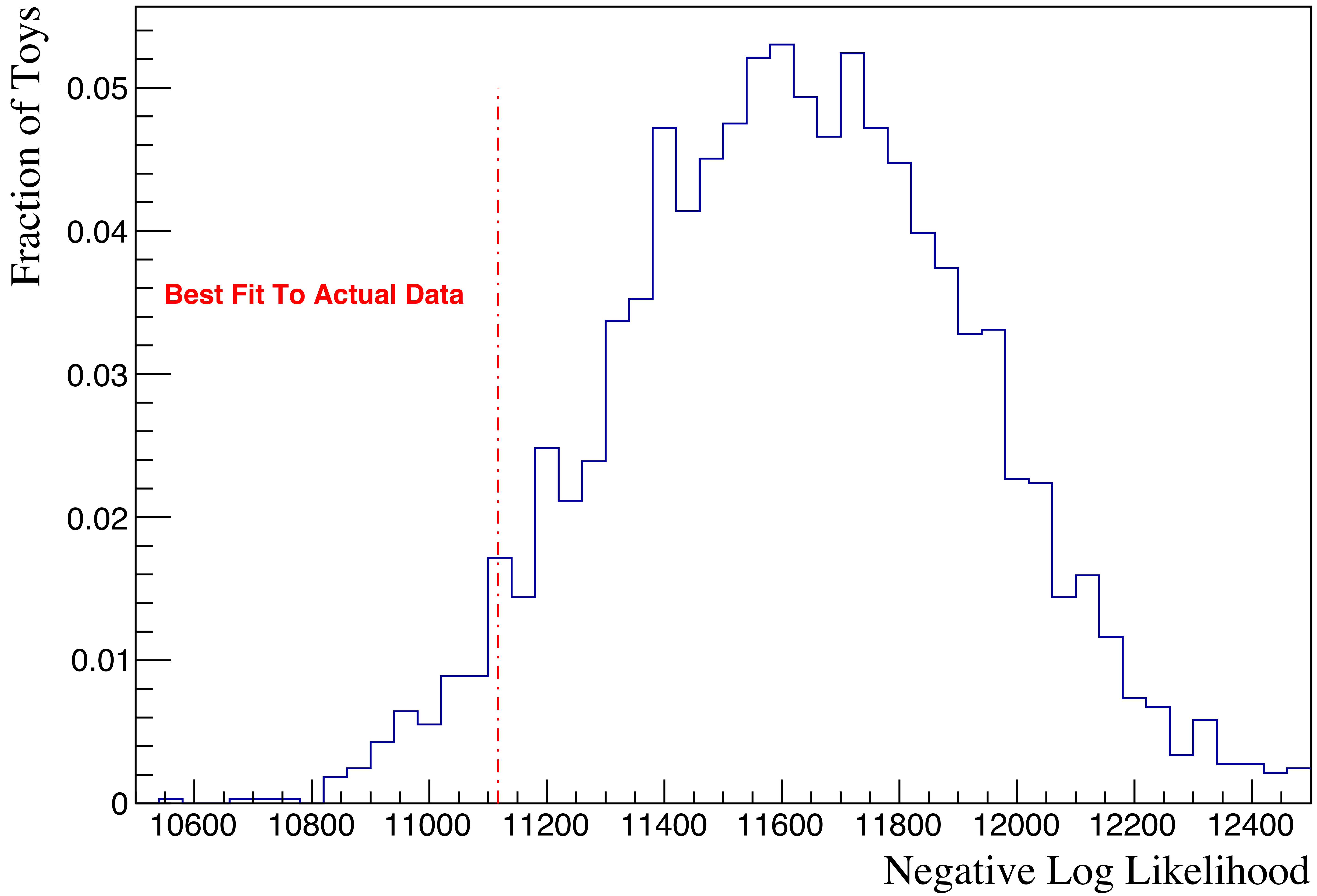
Simone Quitadamo
Chris Alduino
alberto gianvecchio
Guido Fantini
miriam
Yury Kolomensky

G.

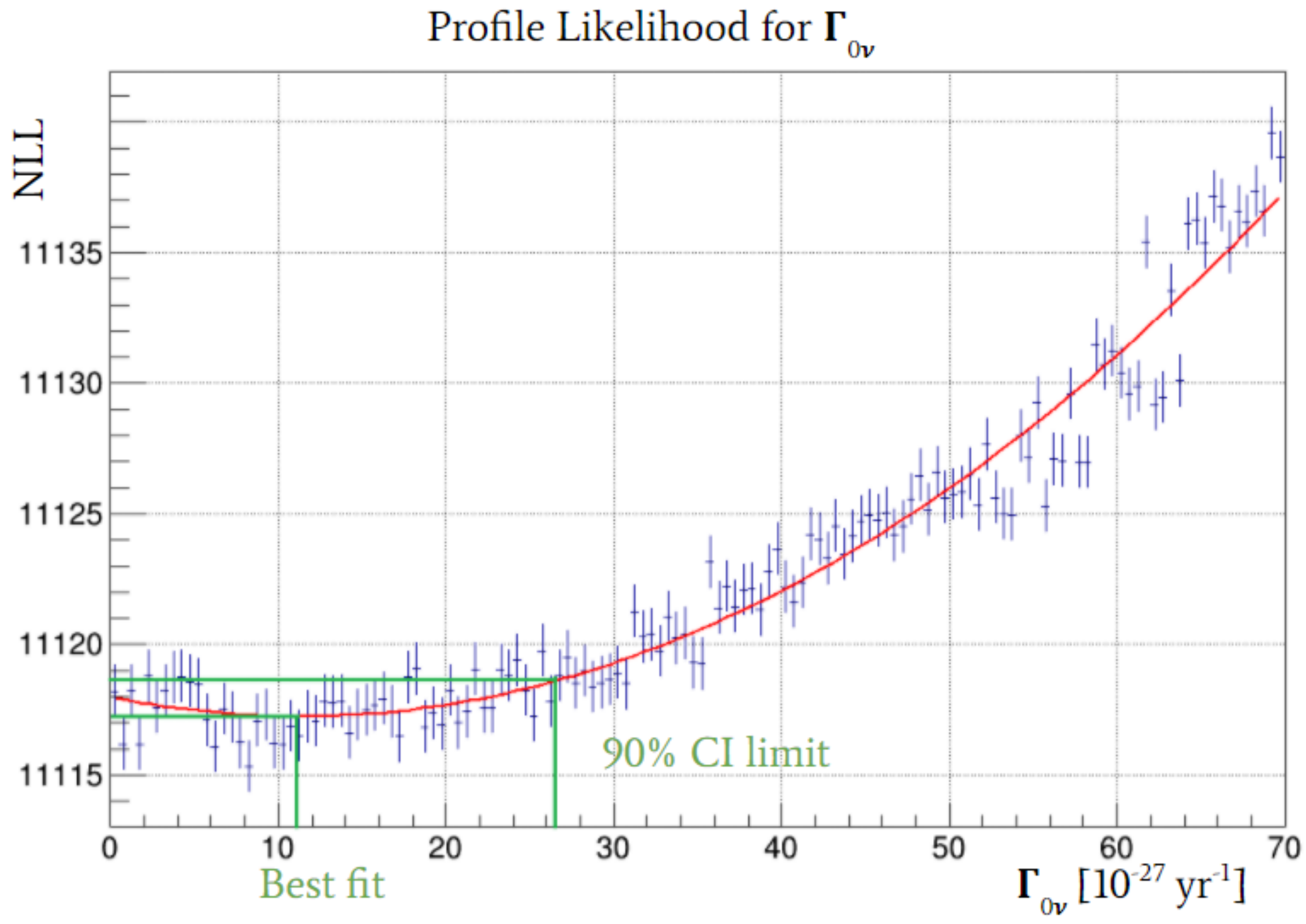
BACKUP

NEUTRINOLESS DOUBLE BETA DECAY ANALYSIS – NLL DISTRIBUTION



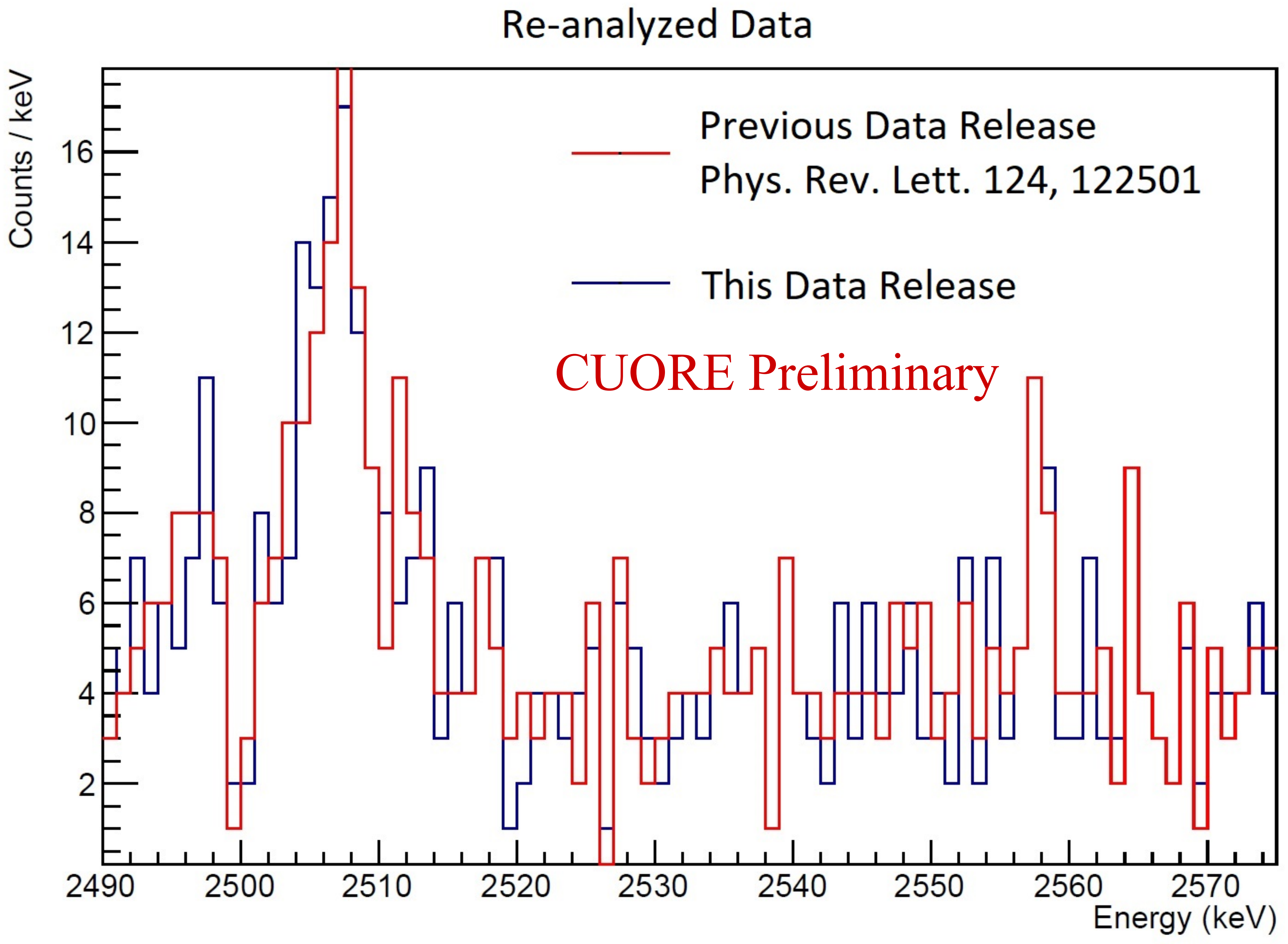
NEUTRINOLESS DOUBLE BETA DECAY ANALYSIS - FREQUENTIST LIMIT

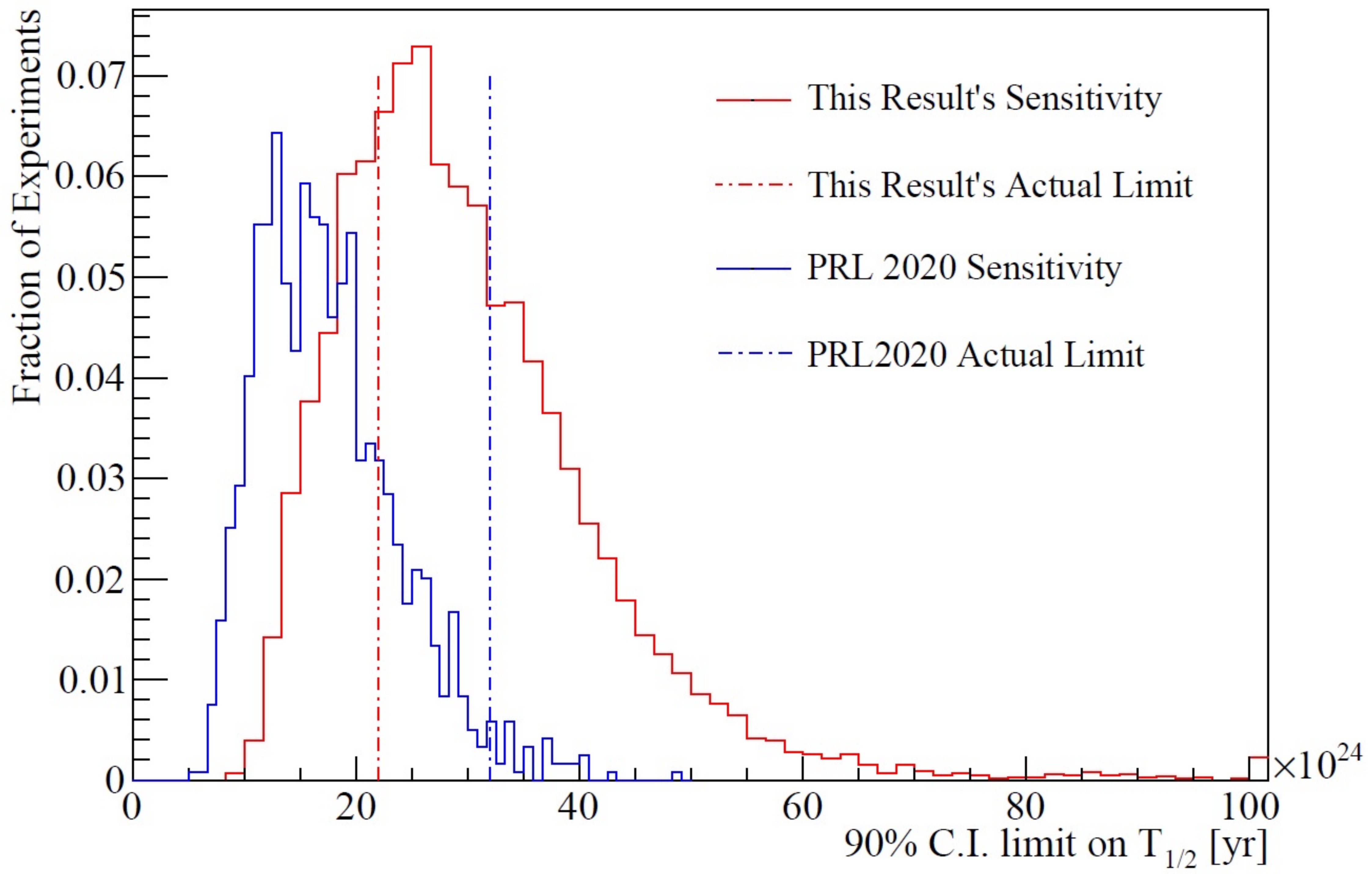
- Frequentist limit with Rolke method
- Profile likelihood obtained from the Markov Chain generated for Bayesian fit
  - -2logL as χ^2 with 1 degree of freedom
  - 90% C.L. limit obtained from rate 1.35 NLL units above the best fit



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

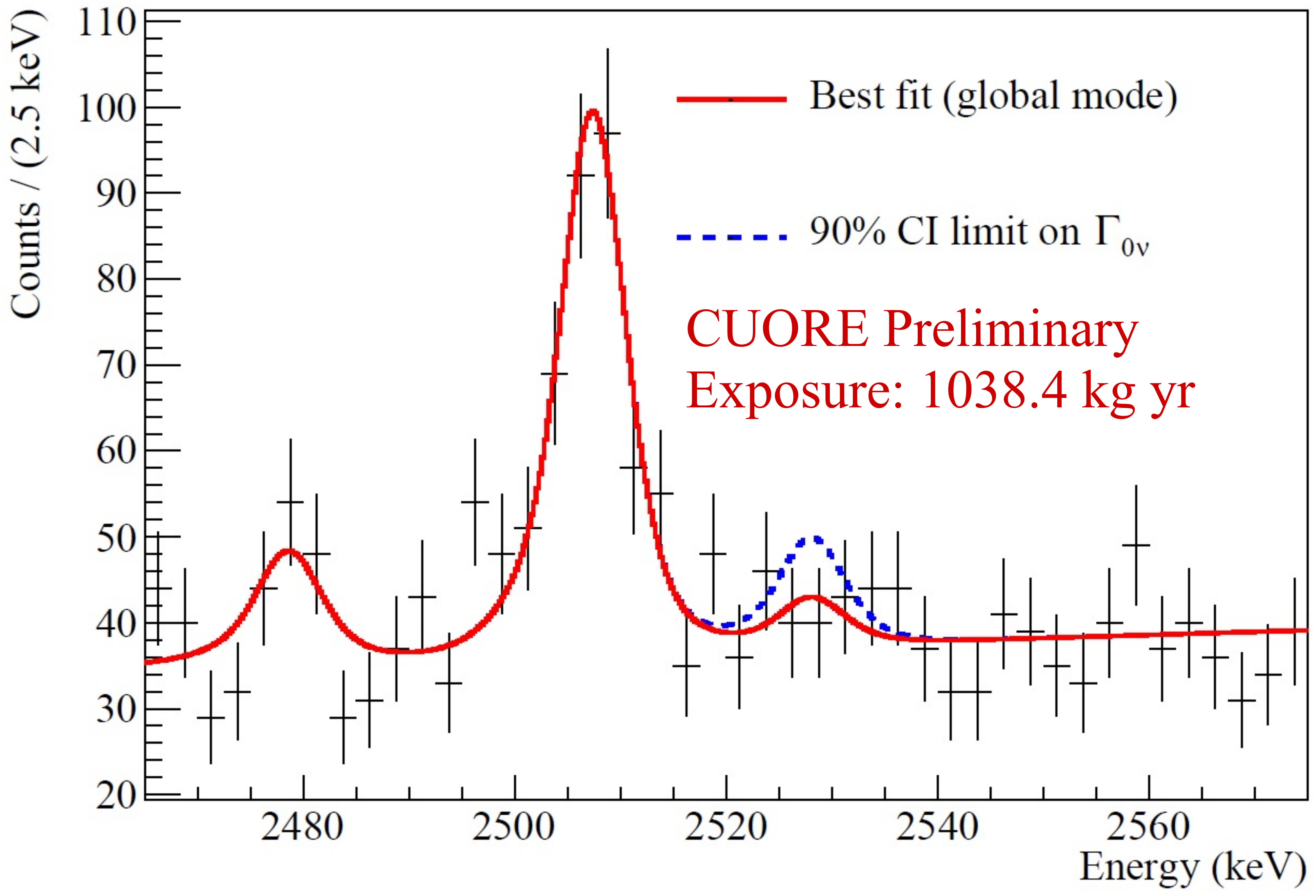
COMPARISON WITH PREVIOUS RESULTS

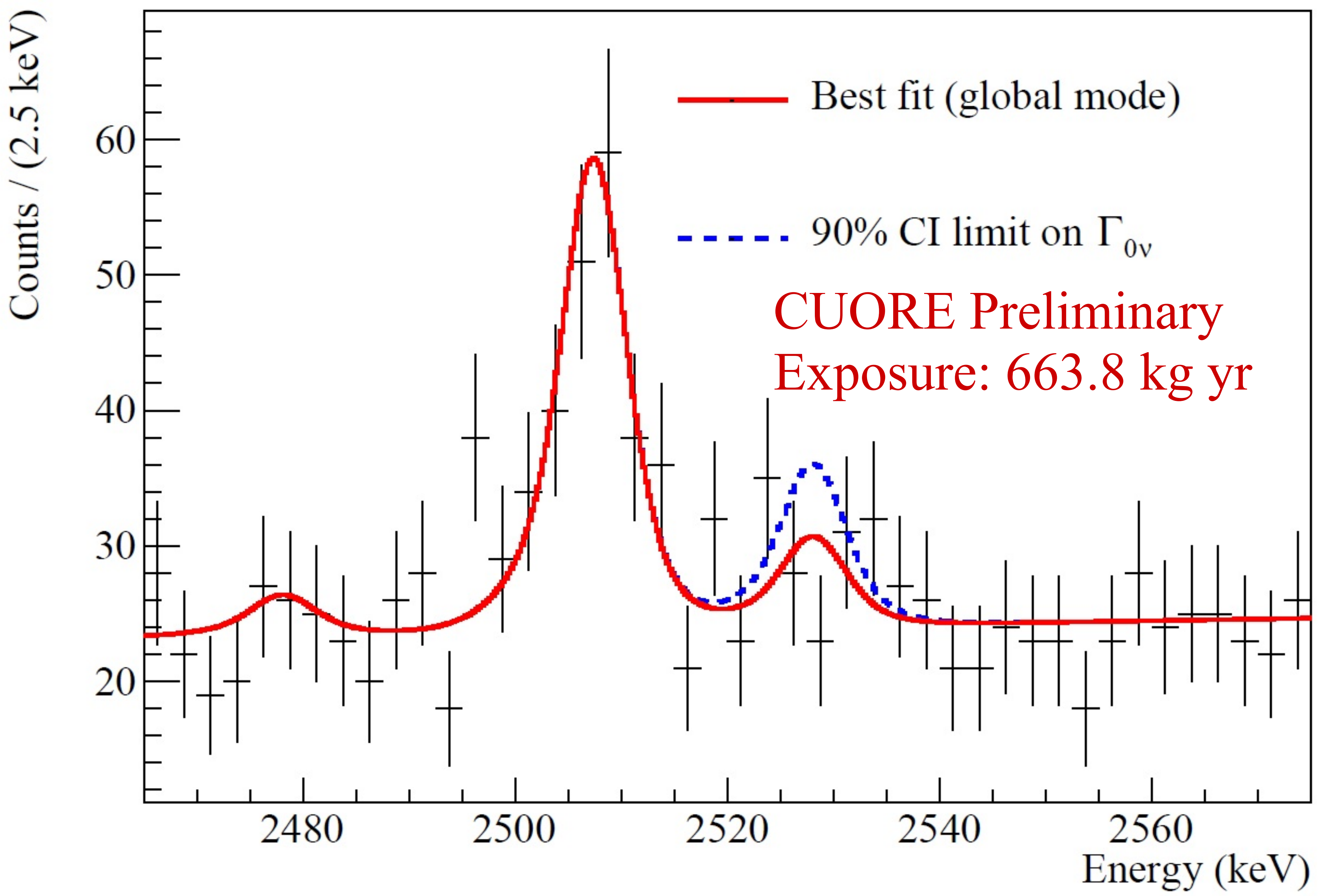




- different pulse shape discrimination, analysis efficiency
- 90% of reconstructed events common to both analyses
- 3% probability of obtaining old limit $T_{1/2} > 3.2\ 10^{25}$ yr (or stronger) with new event reconstruction
- re-analysis yields $T_{1/2} > 2.0\ 10^{25}$ yr limit, in the top 30% of expected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

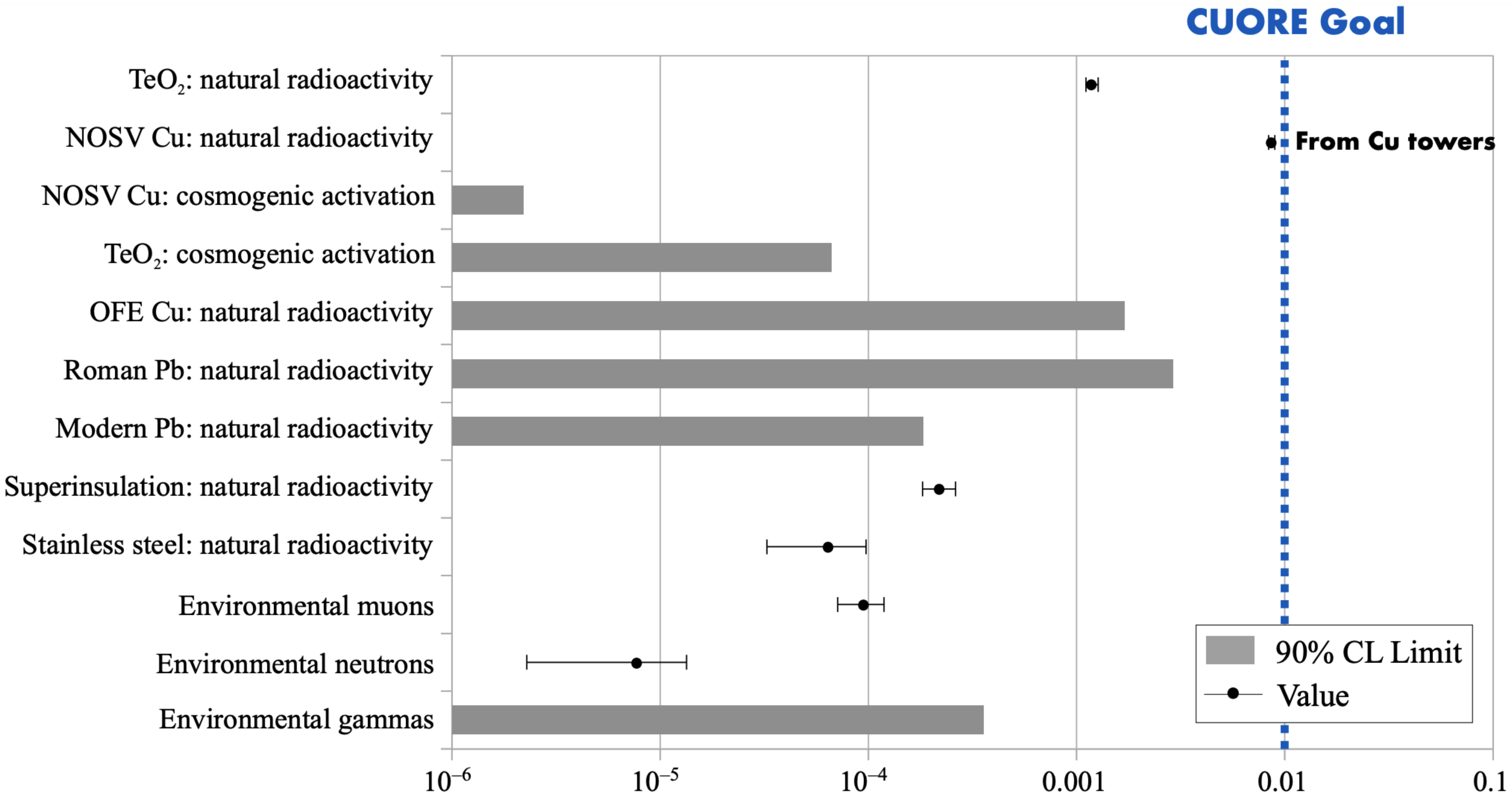
2480 KEV STRUCTURE





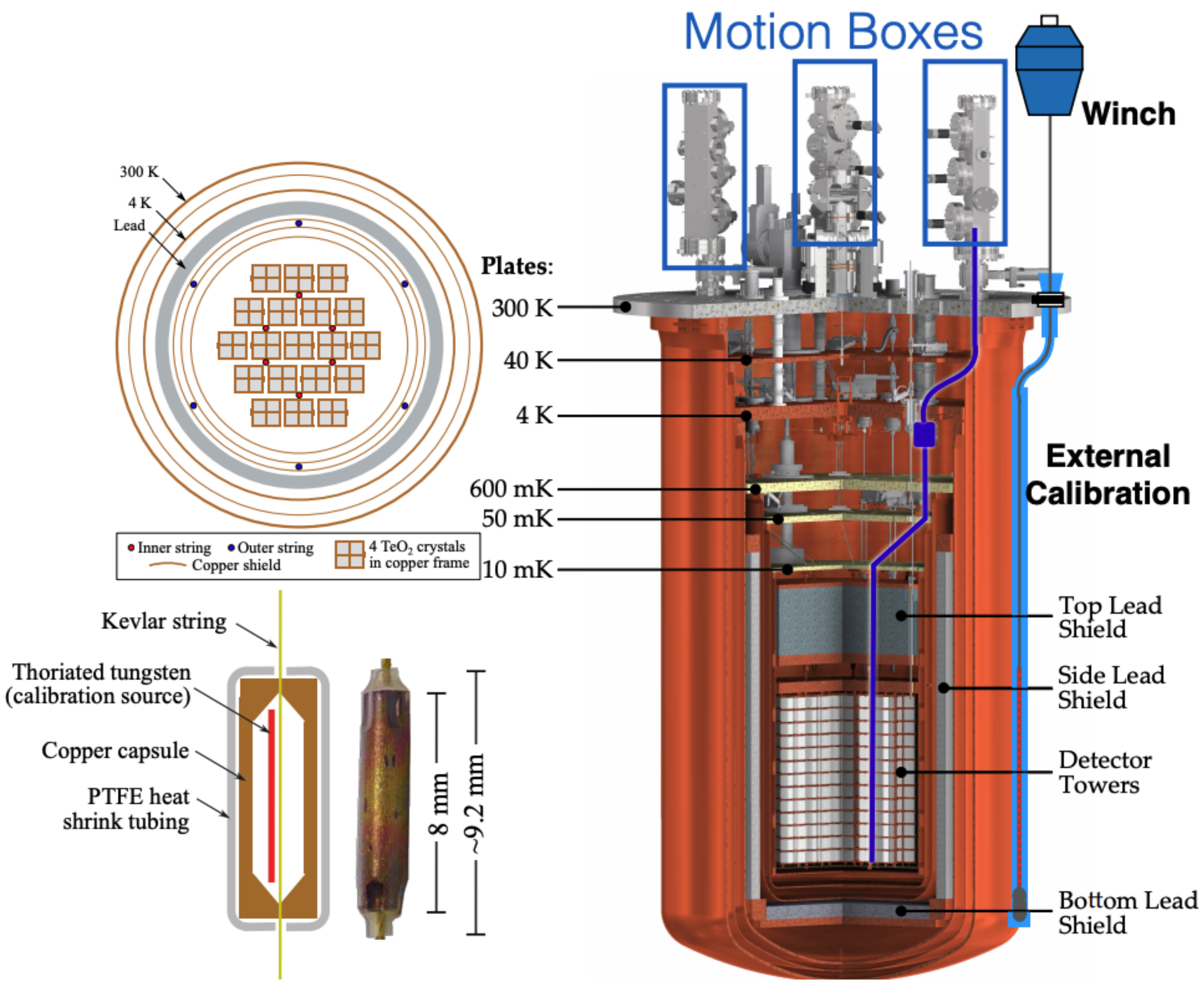
- Previously found 2σ hints of unexpected peak at ~2480 keV
- Statistical significance decreased with new data (< 1 σ with just new data)

CUORE BACKGROUND BUDGET

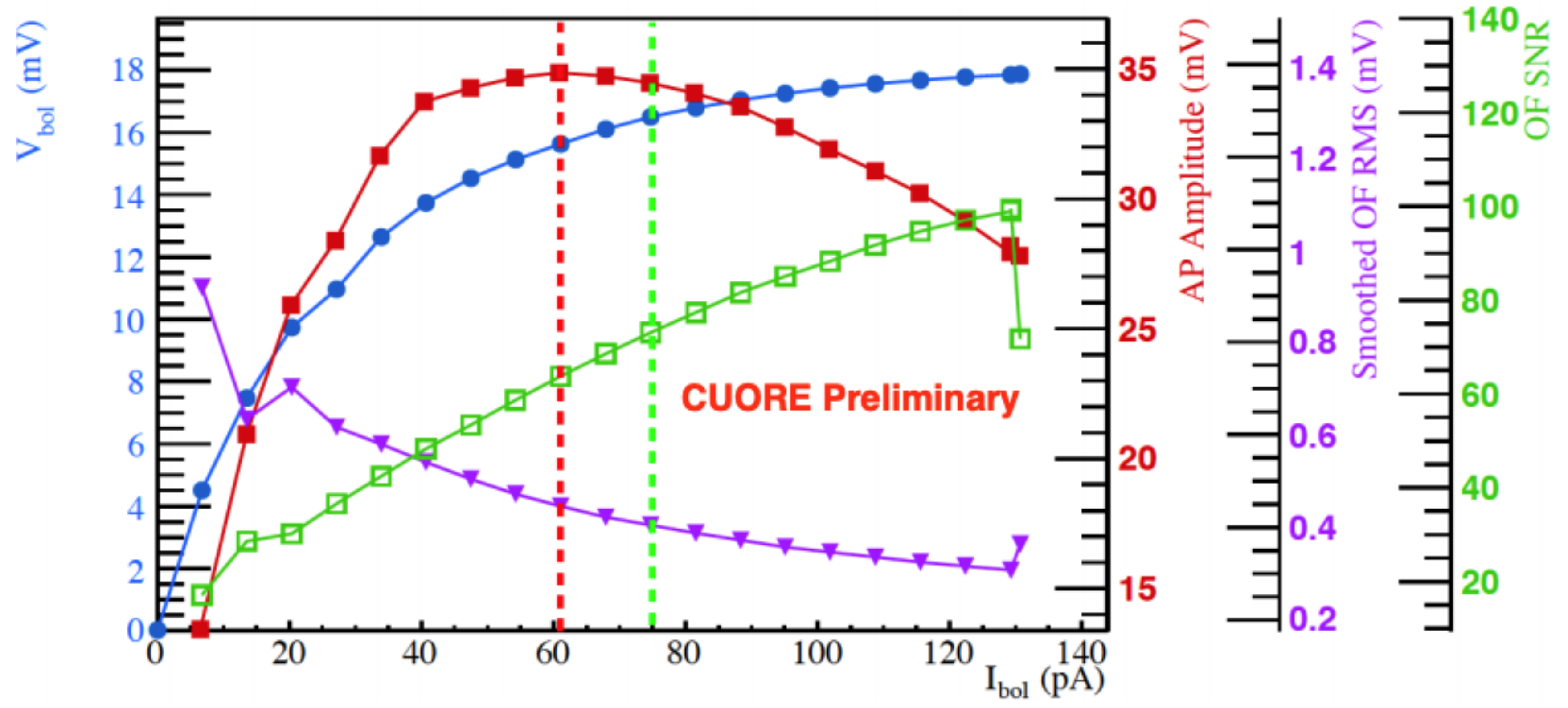


European Physical Journal C 77, 543 (2017)

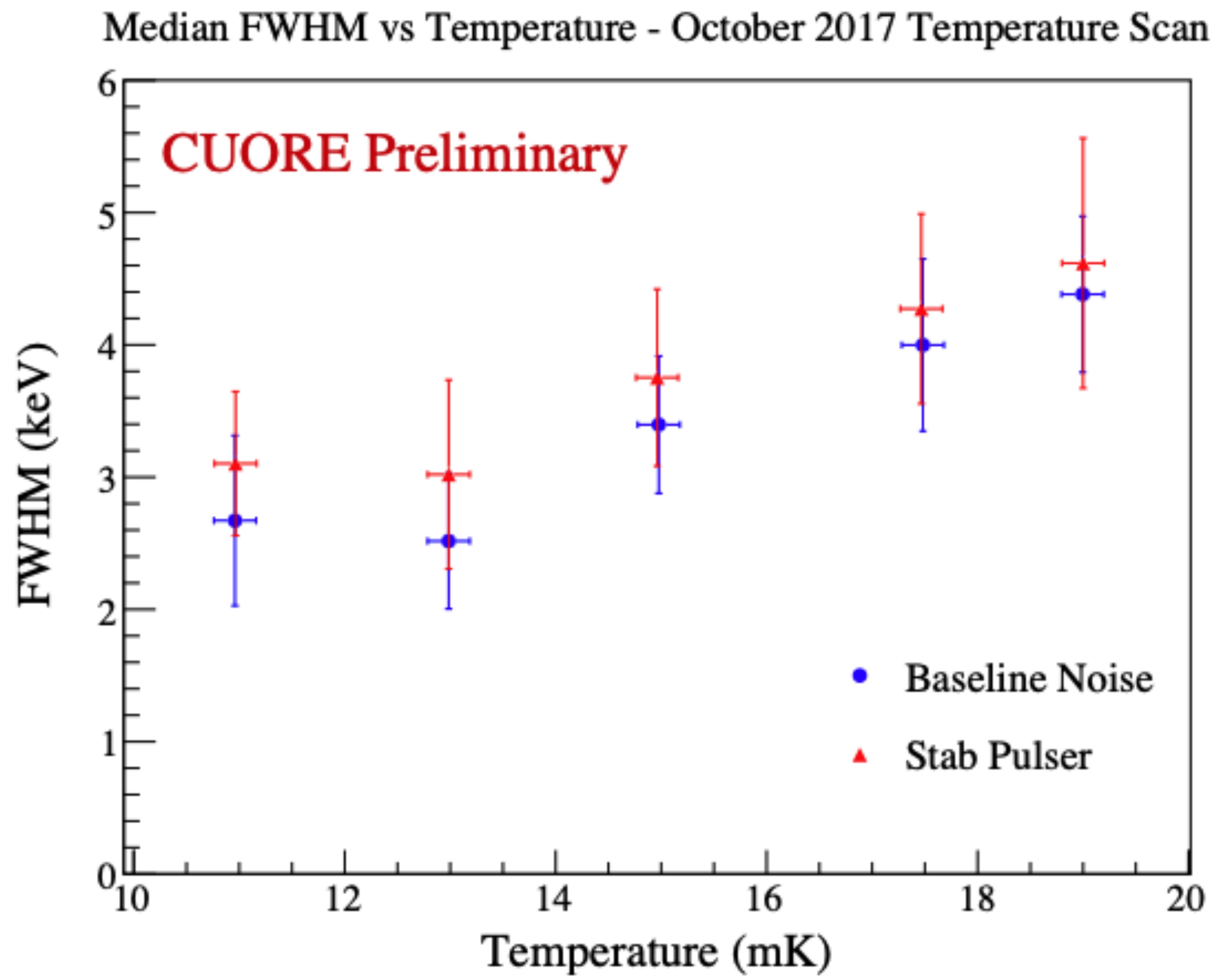
CALIBRATION SYSTEM



DETECTOR OPTIMIZATION

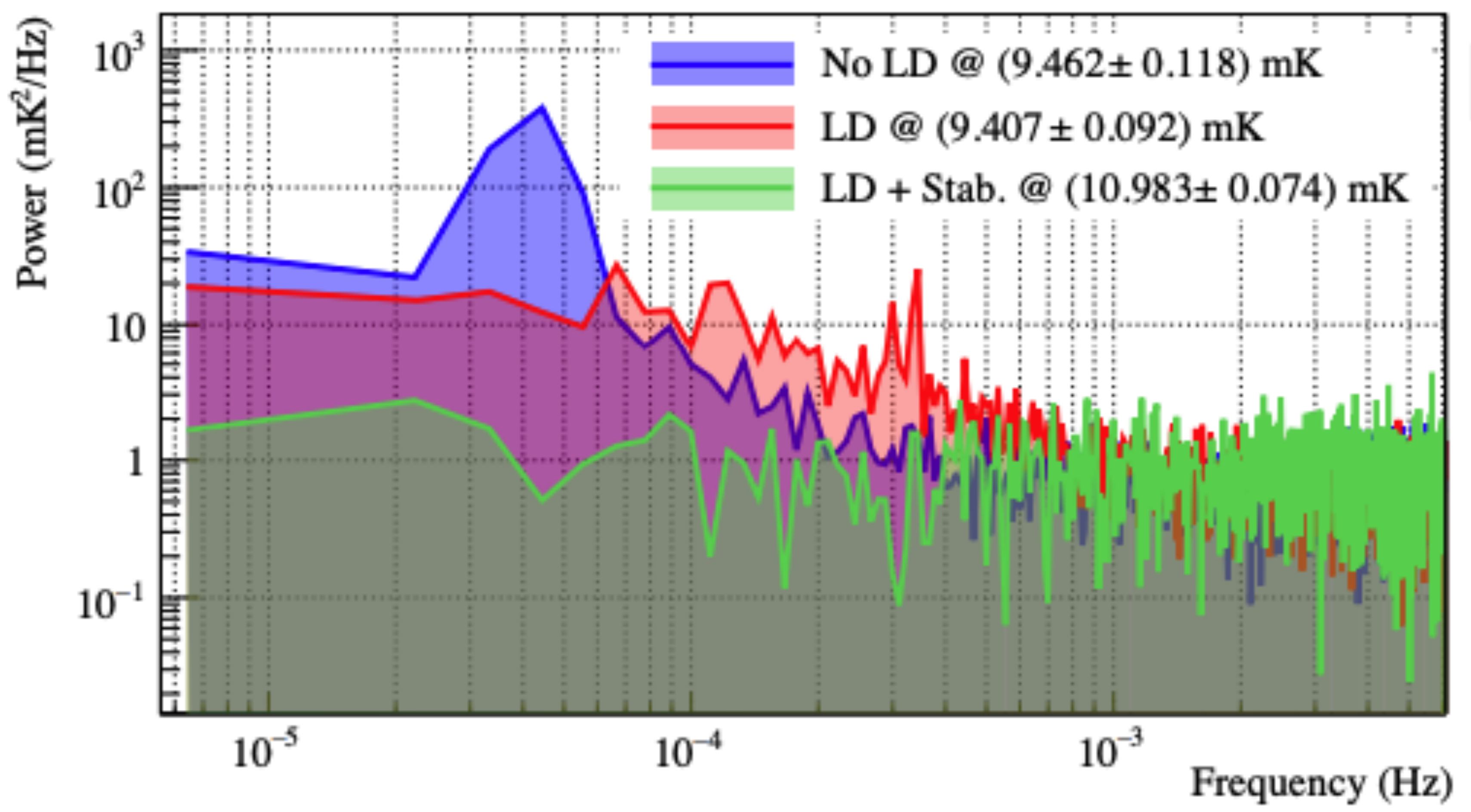


load curves

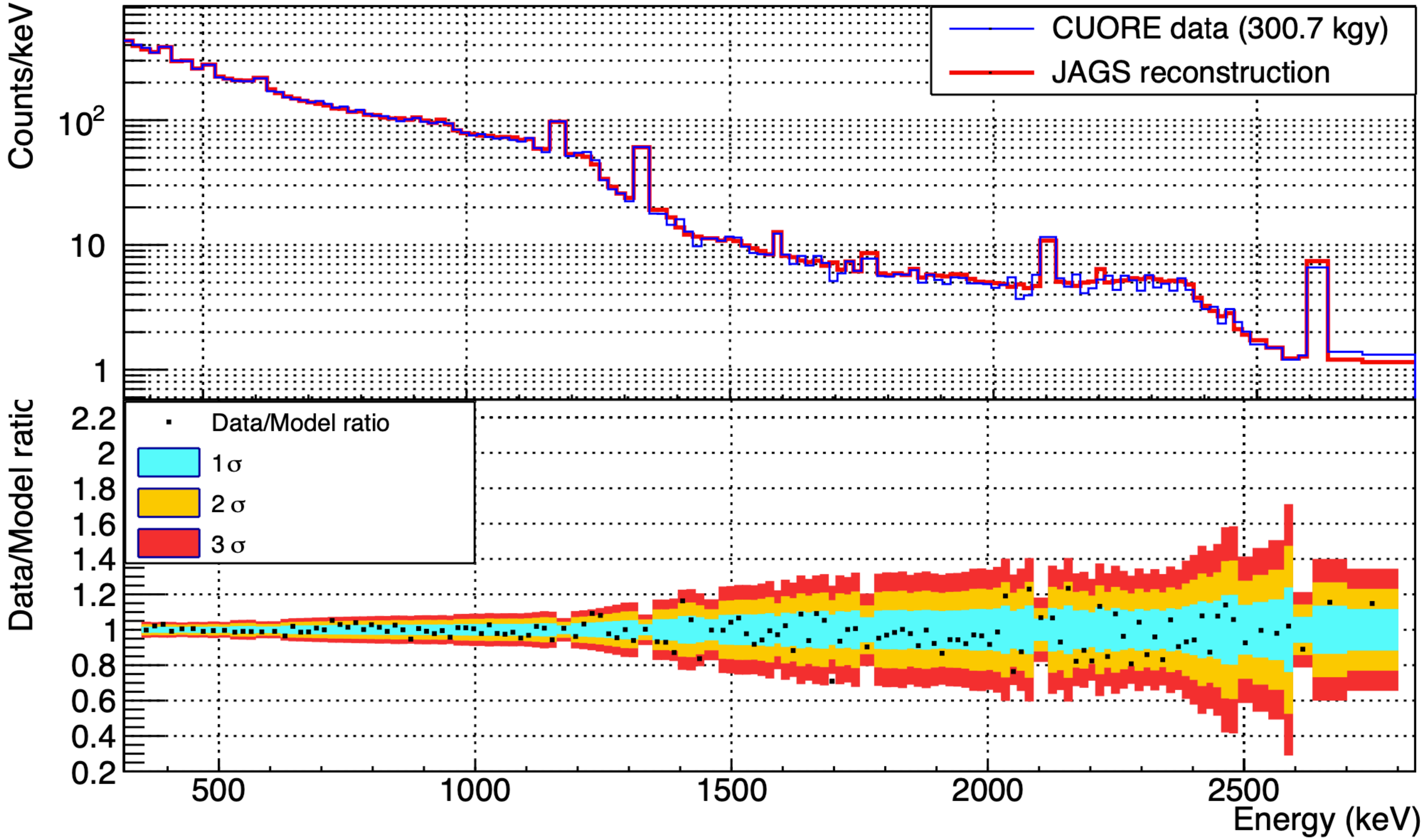


temperature scan

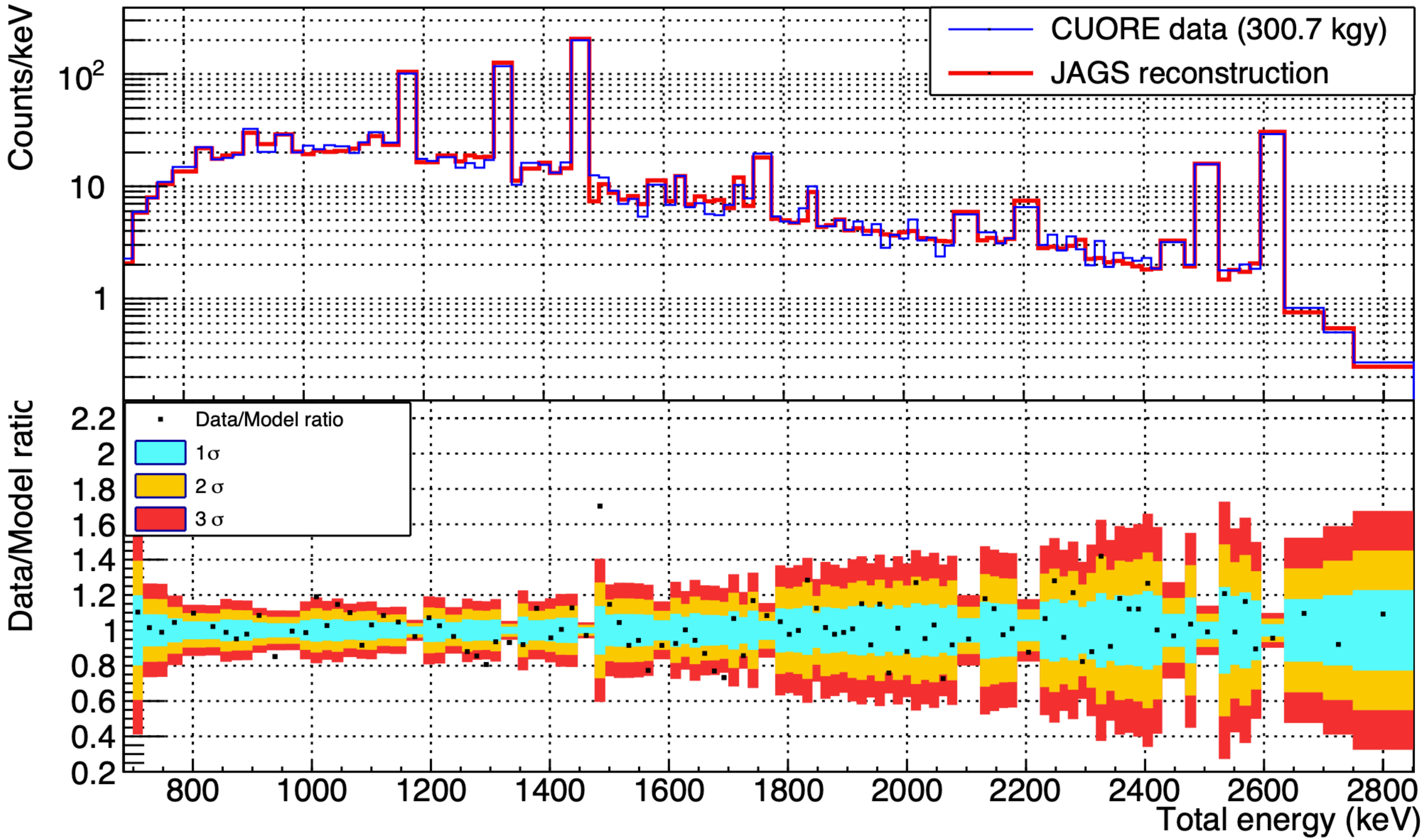
PT phase scan



M2 SPECTRUM FIT (JAGS)



M2-SUM SPECTRUM FIT (JAGS)



EFFECT OF 90SR REMOVAL