Latest Results from the CUORE Experiment

Beyond Standard Model 2021

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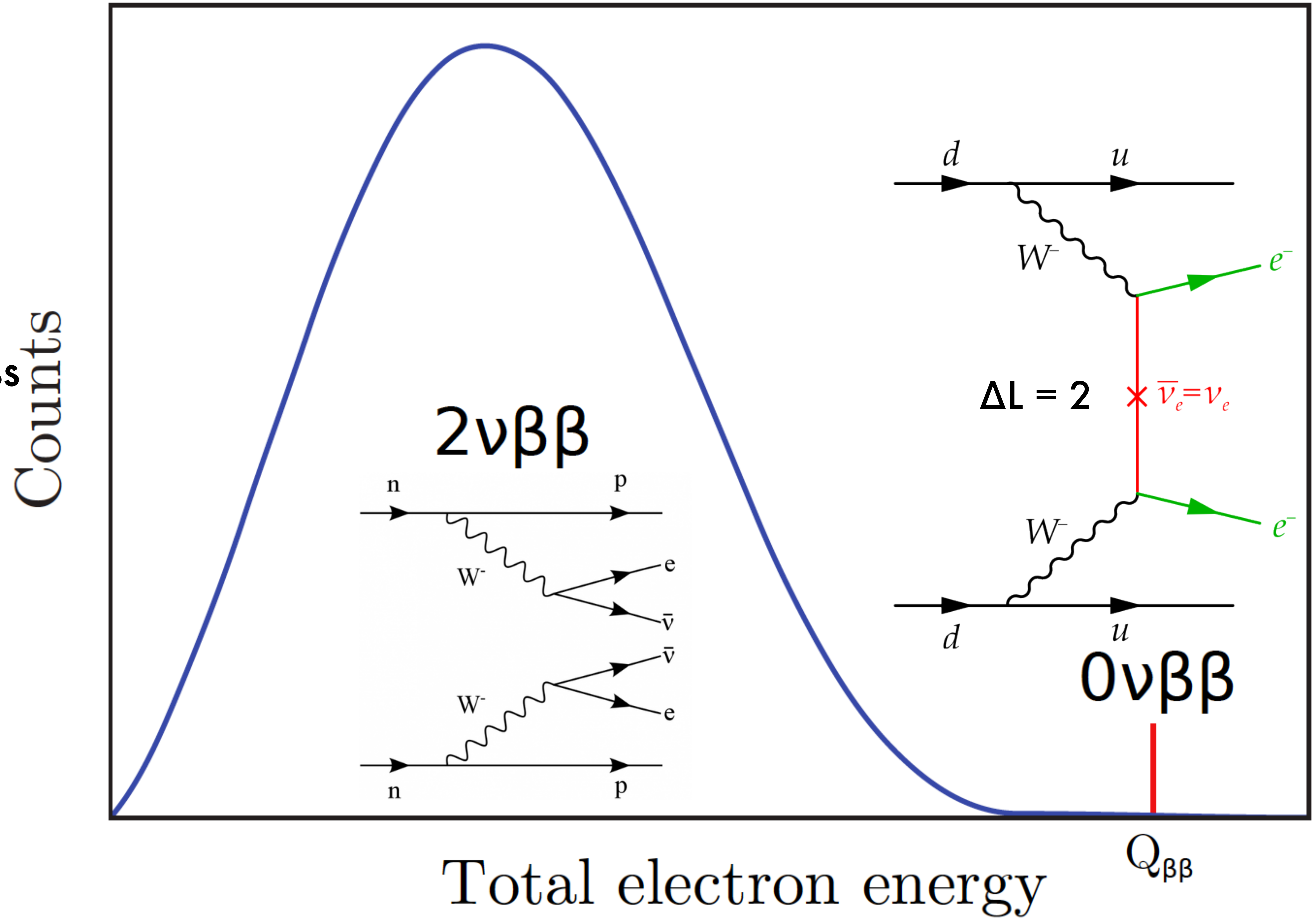
2021-03-30

Double Beta Decay

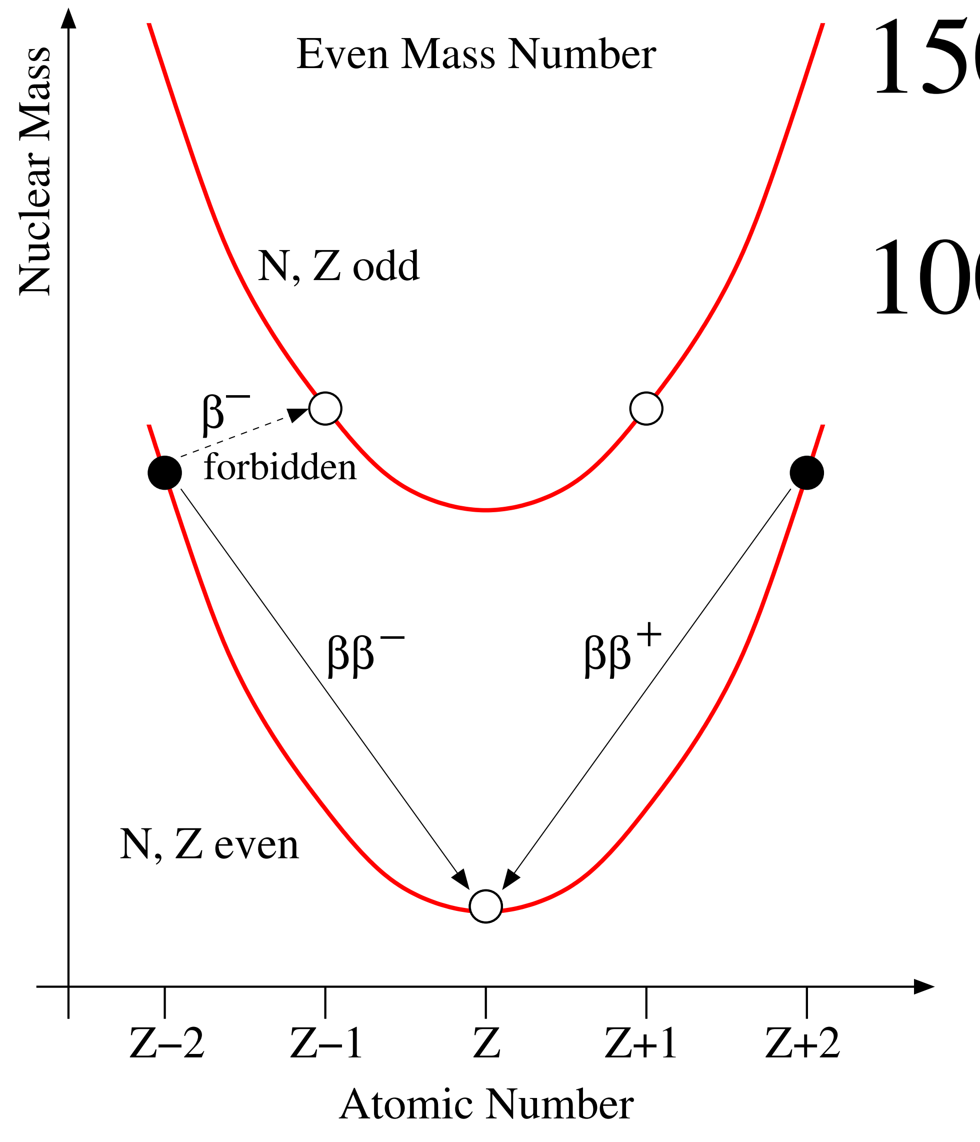
- $2\nu\beta\beta$ is a rare standard model process
- Broad energy distribution
- Observed half-life $\tau > 10^{19}$ years
- $0\nu\beta\beta$ is a hypothetical, unobserved process

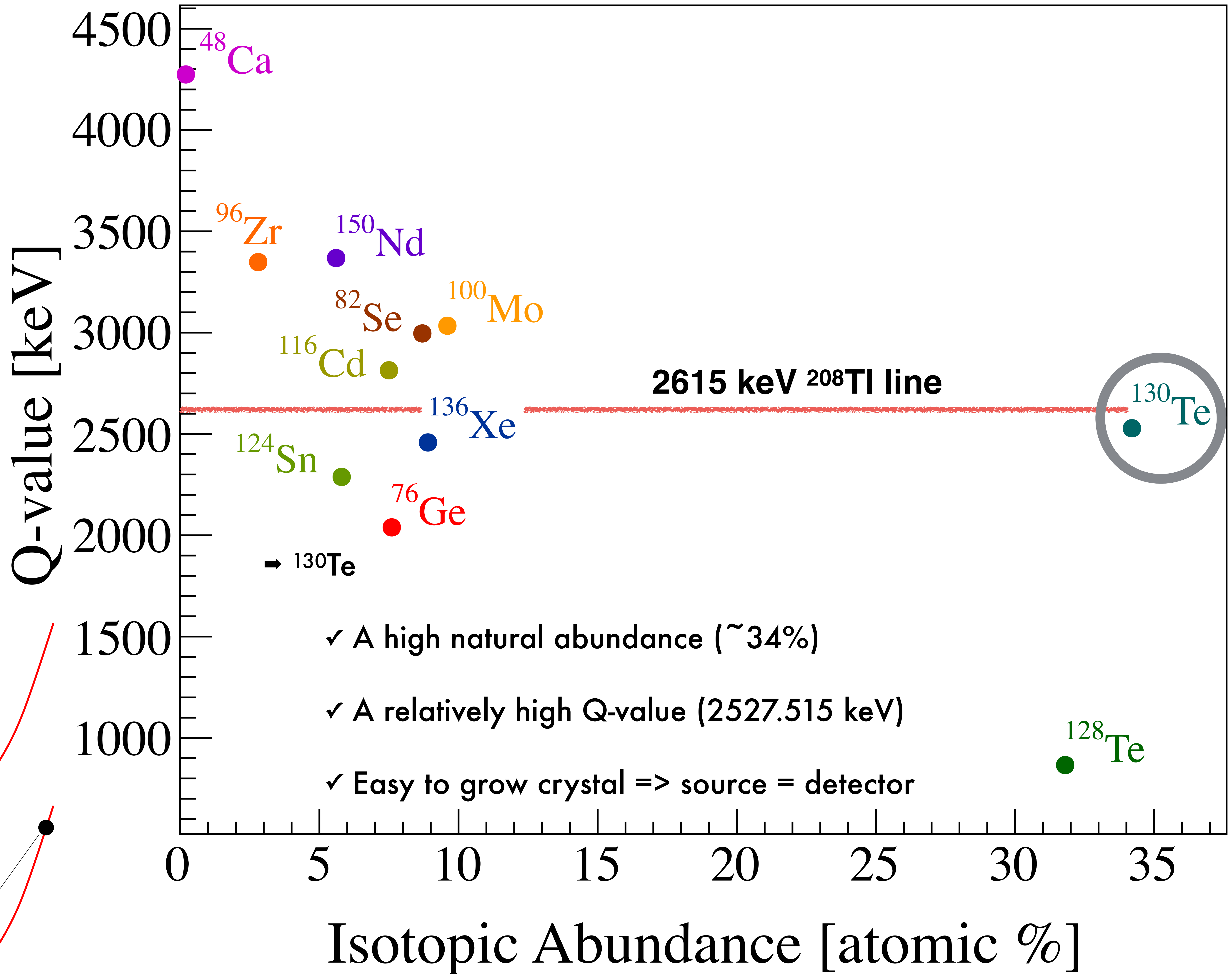
- Immediate implication of $\Delta L \neq 0$
  - Lepton number violation = new physics!
  - Implies Majorana mass of ν
  - Possible connection to baryon asymmetry



Isotope Choice

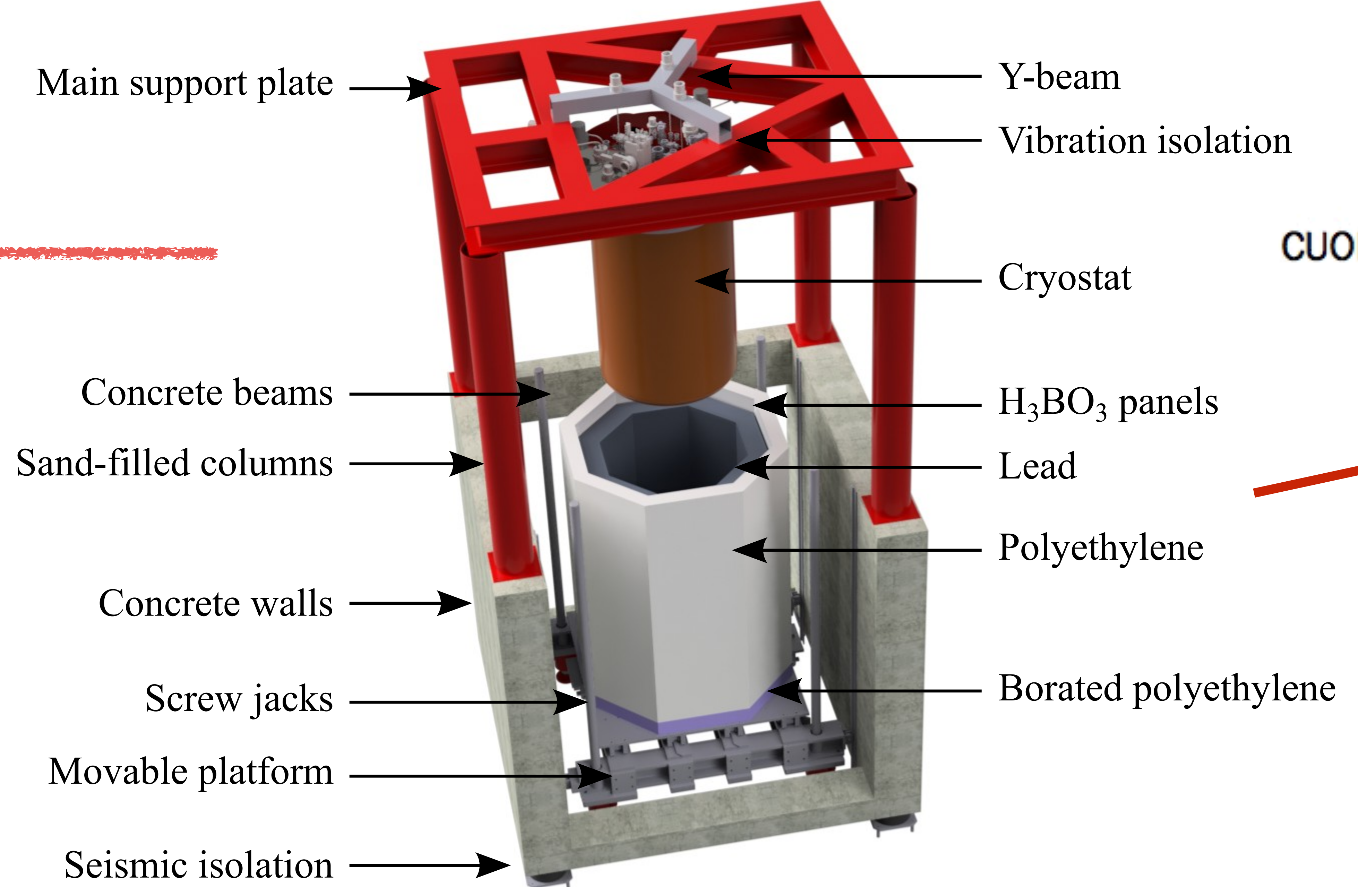
- Look at $2\nu\beta\beta$ isotopes with even-even nuclei
  - β-decay energetically forbidden or suppressed by nuclear spin (e.g., ^{48}Ca)
- Desired traits for $0\nu\beta\beta$ search isotope
  - High isotopic abundance (active mass)
  - High Q-value (low γ bkg)

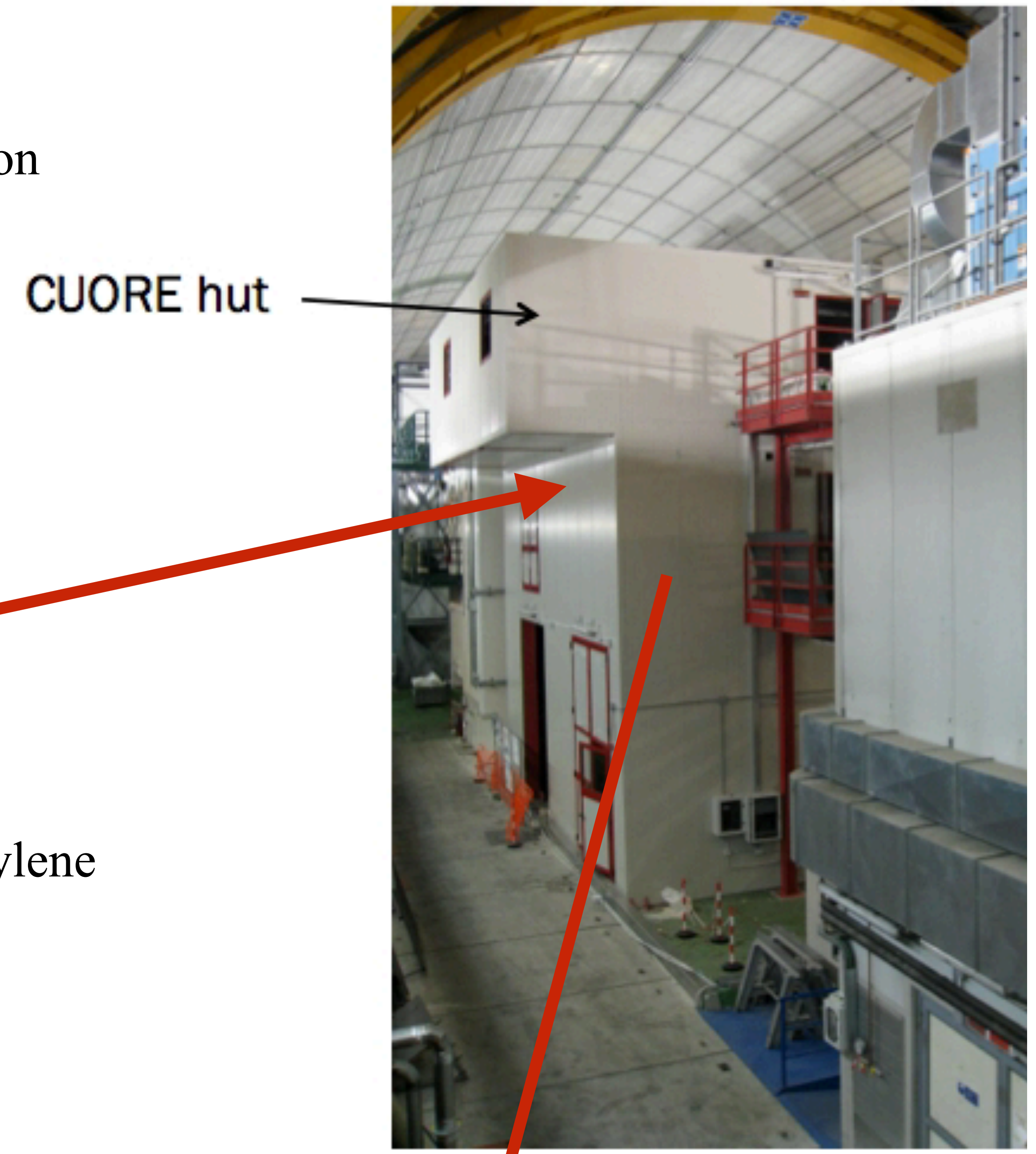


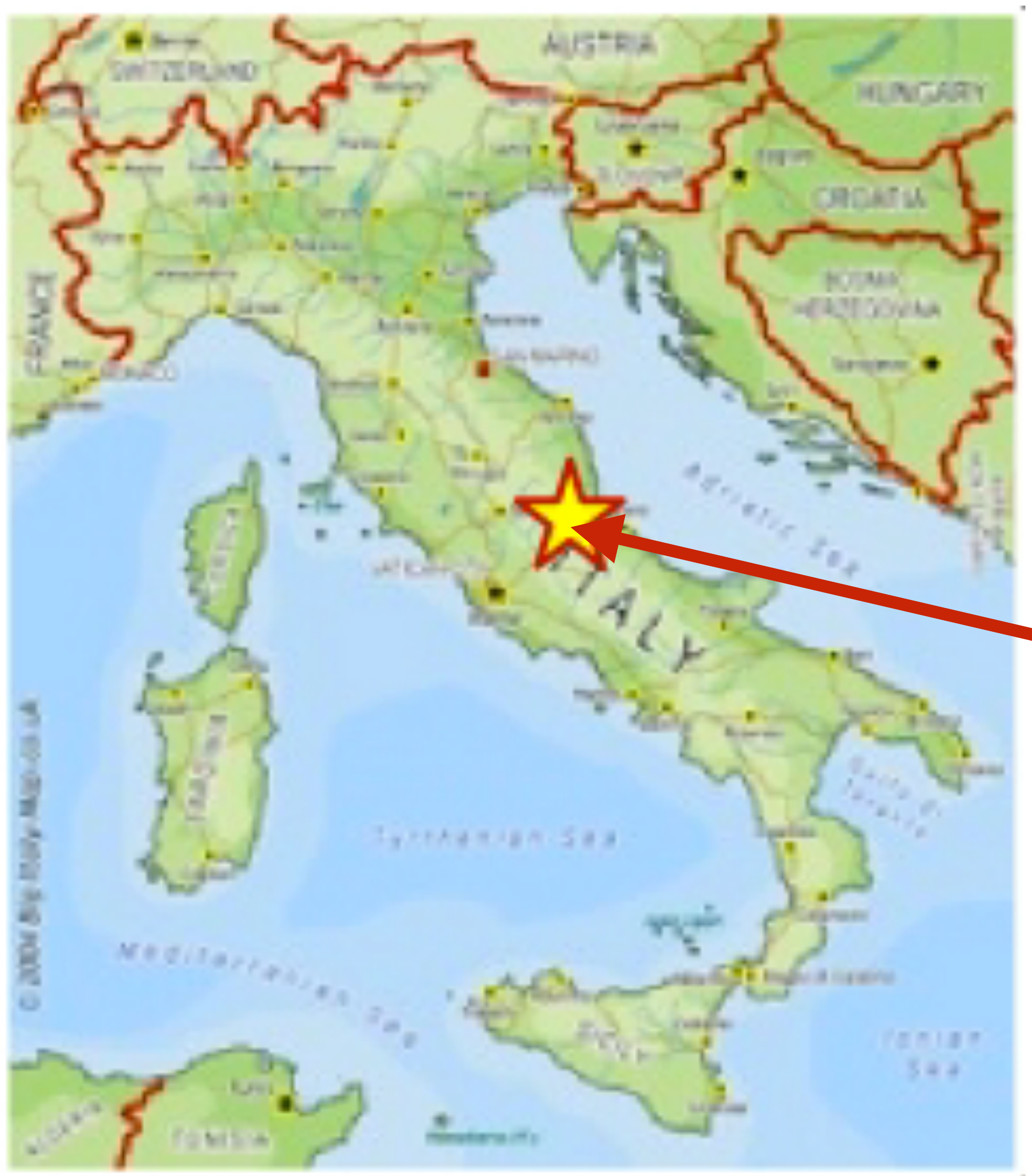


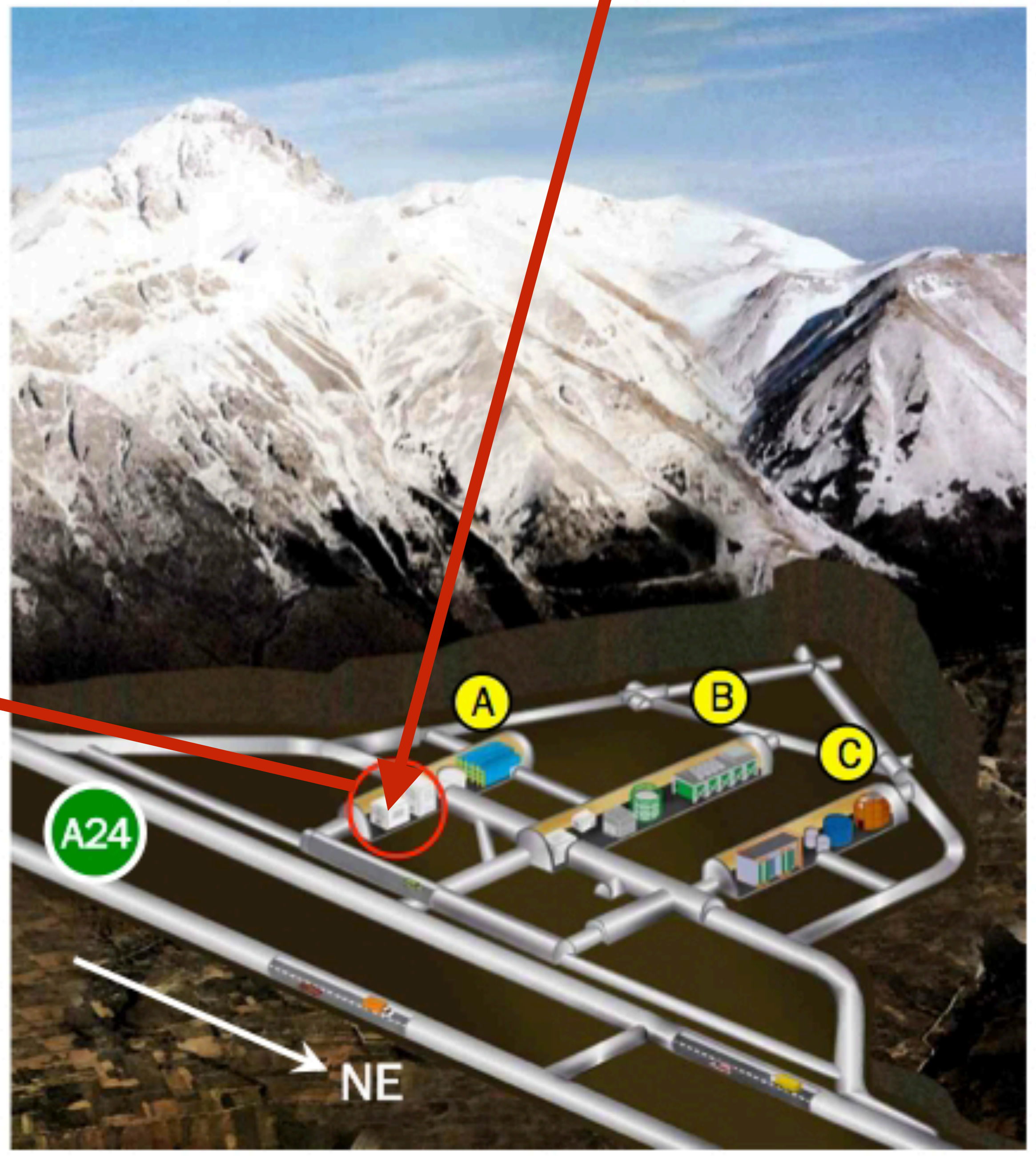
CUORE@LNGS

- **C**ryogenic **U**nderground **O**bservatory for **R**are **E**vents
- To detect rare events:
  - sensitive detector
  - very low background
- Located at LNGS in Hall A
- 3600 m.w.e overburden



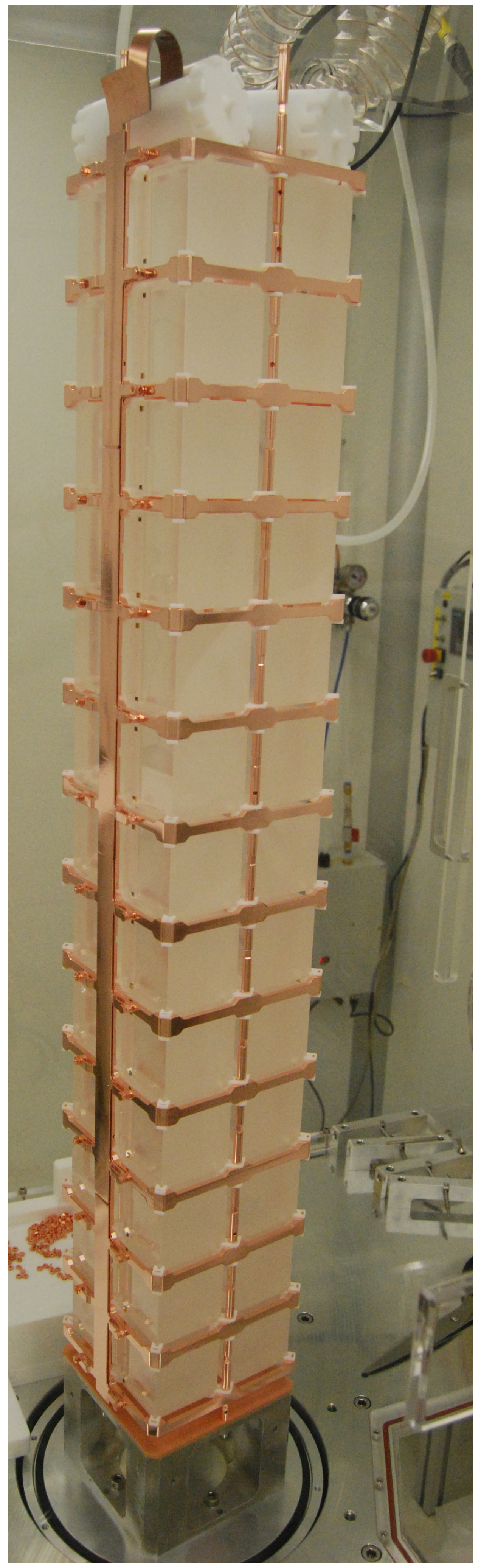




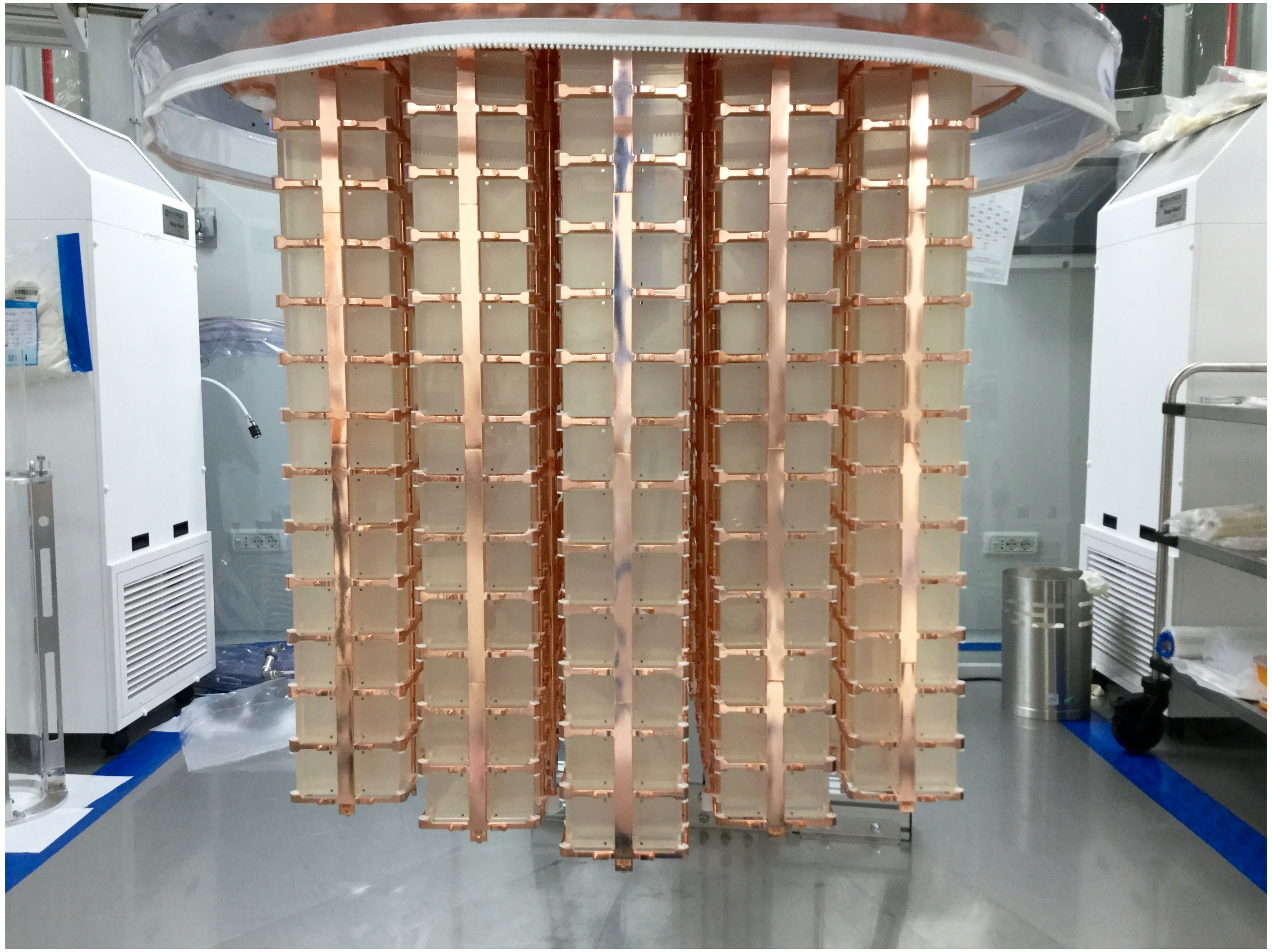


CUORE Detector

- Array of 988 5x5x5 cm^3 $^{nat}TeO_2$ crystals (742 kg)
  - ^{130}Te active isotope (206 kg)
- $Q_{\beta\beta}$ ~ 2527.52 keV
- Source = detector
  - $0\nu\beta\beta$ containment ε ~ 88%
- 984 active channels!



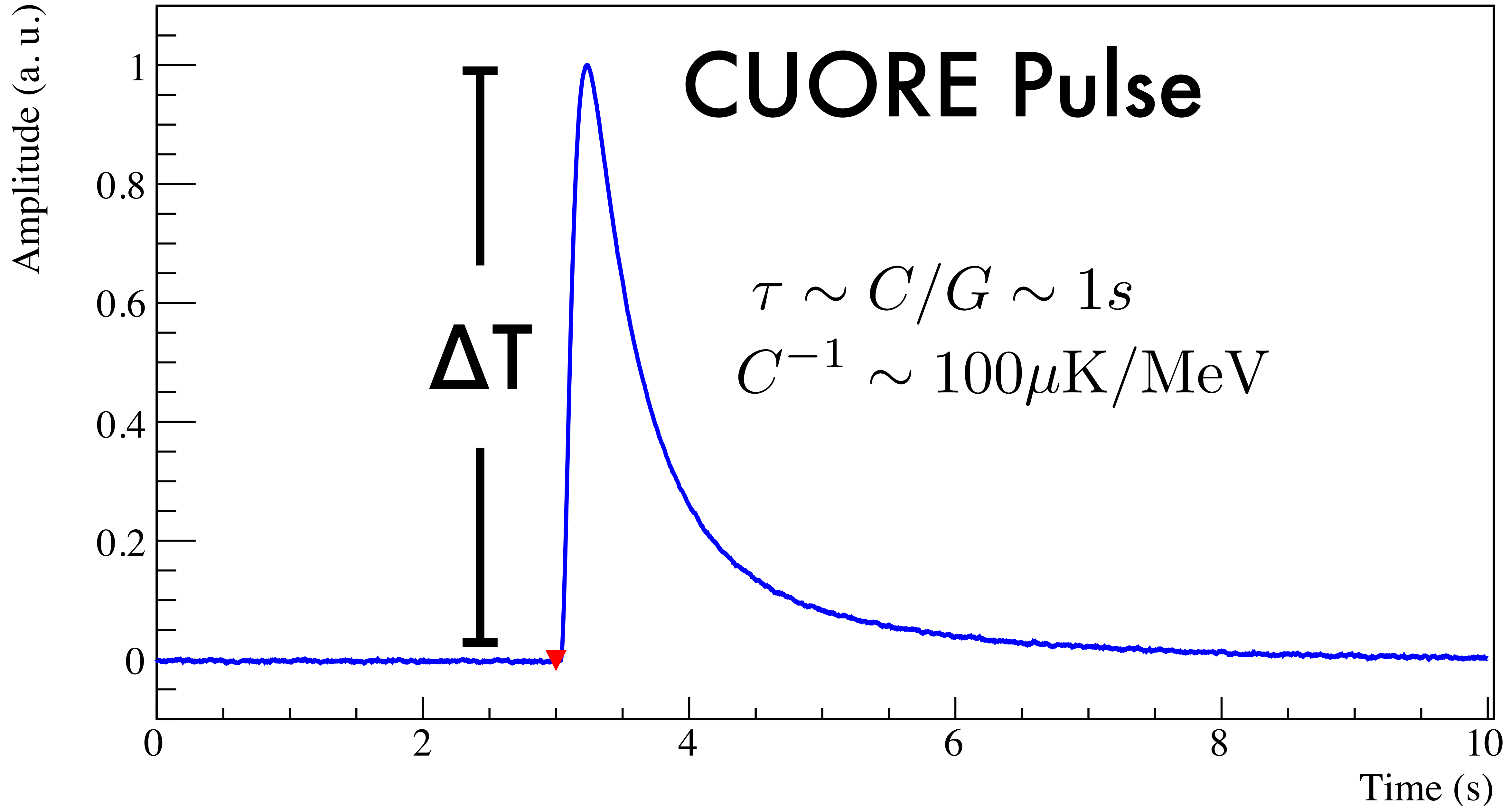
CUORE Tower



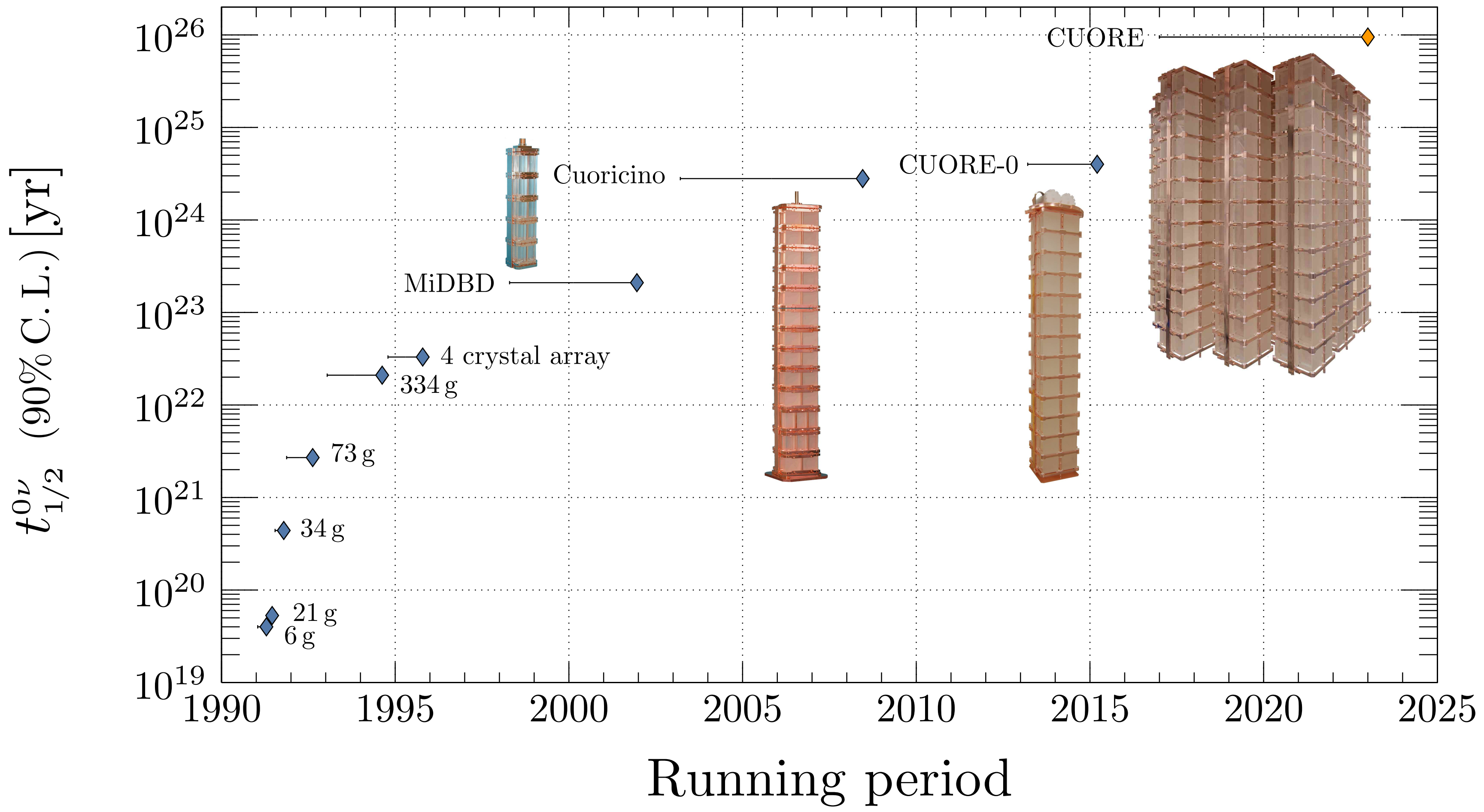
CUORE Detector Fully Assembled

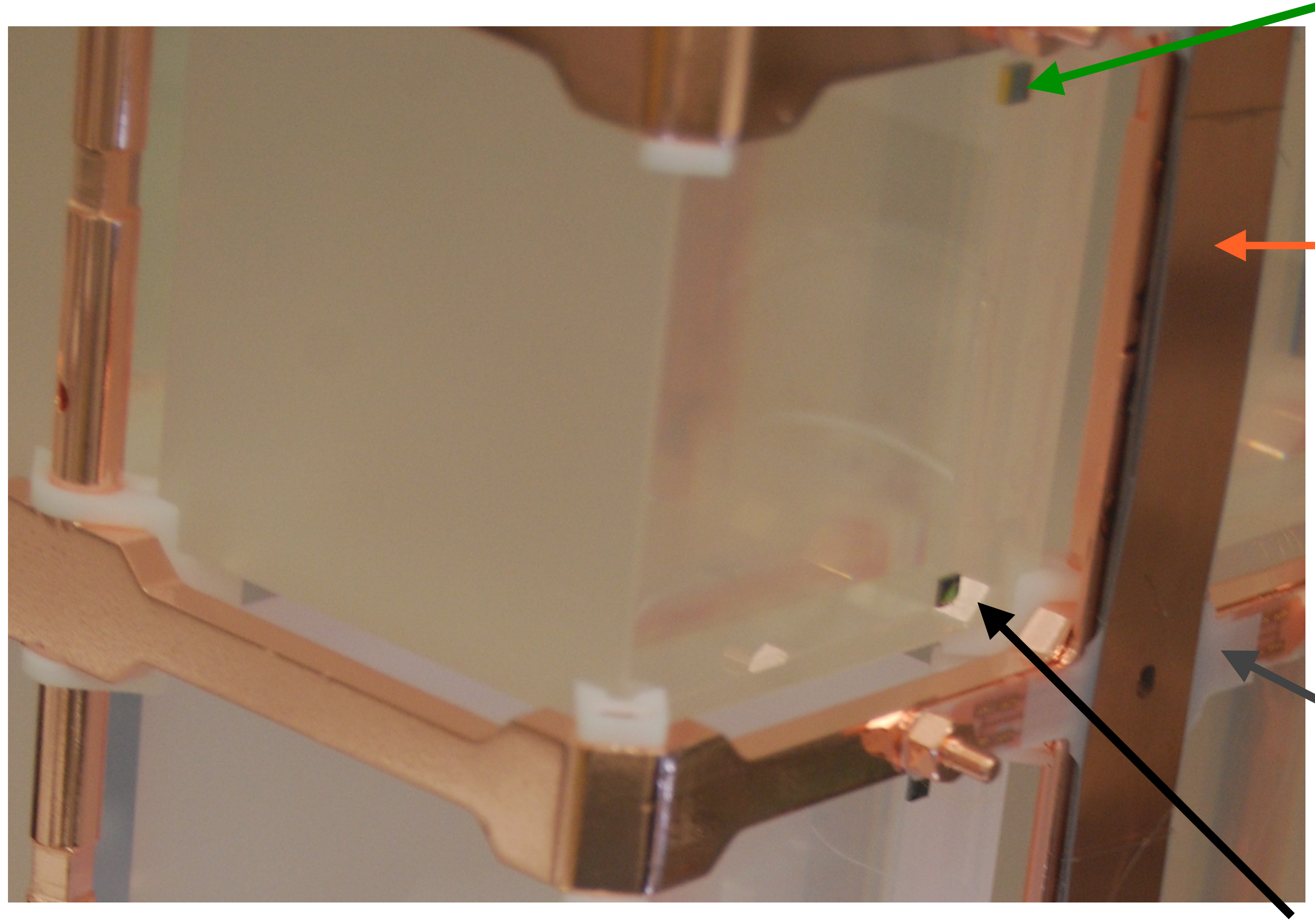
19 towers, 13 floors, 4 per floor

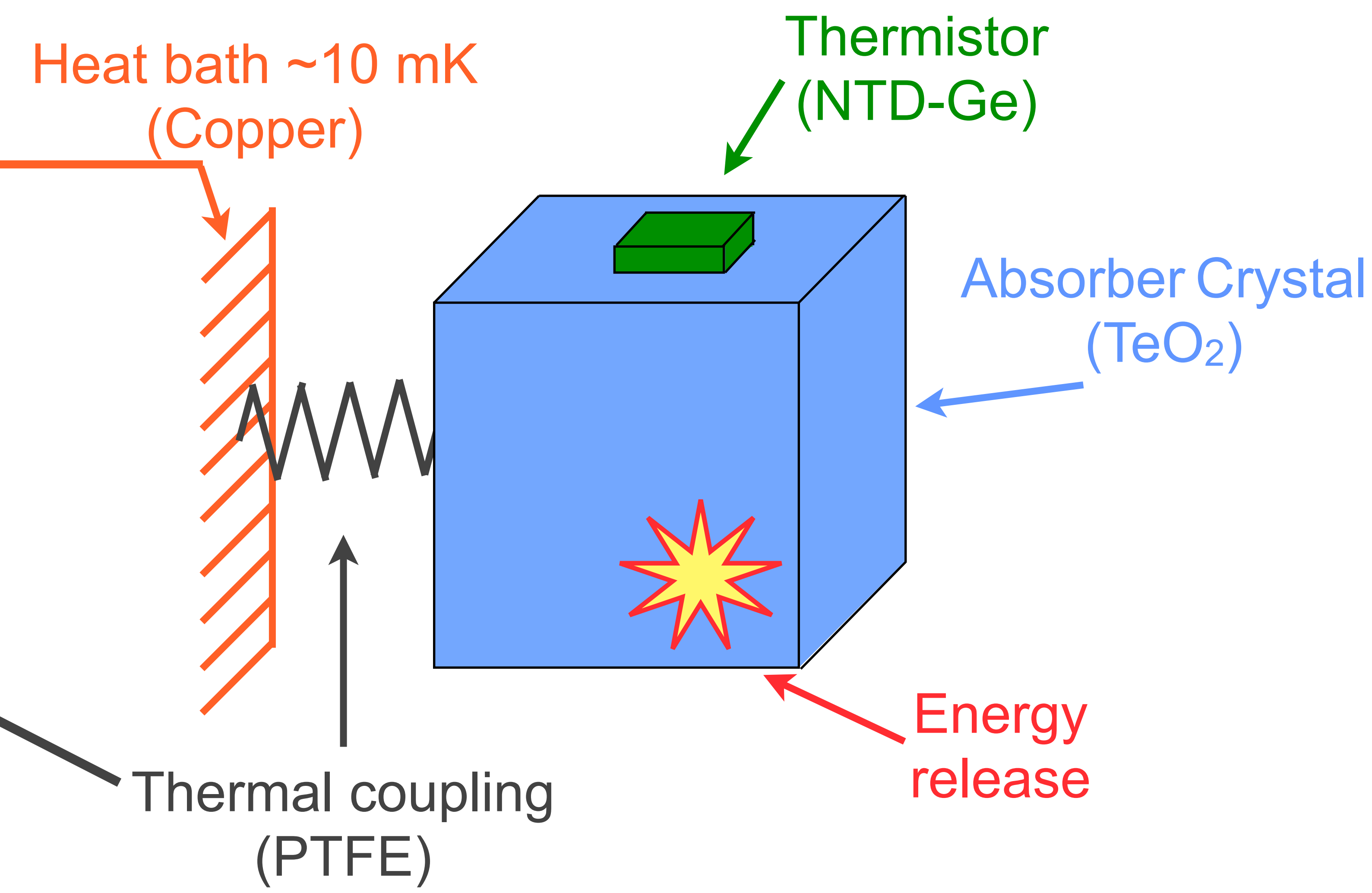
Bolometric Sensor



- Sensitive devices with good energy resolution
- Deposited energy changes temperature $\Delta T = E_{ev}/C_{crys}$
- CUORE TeO_2 crystals
  - 5 cm x 5cm x 5cm
  - Neutron transmutation doped (NTD) Ge sensor
- Temperature sensitive $R = R_0 e^{\sqrt{T_0/T}}$

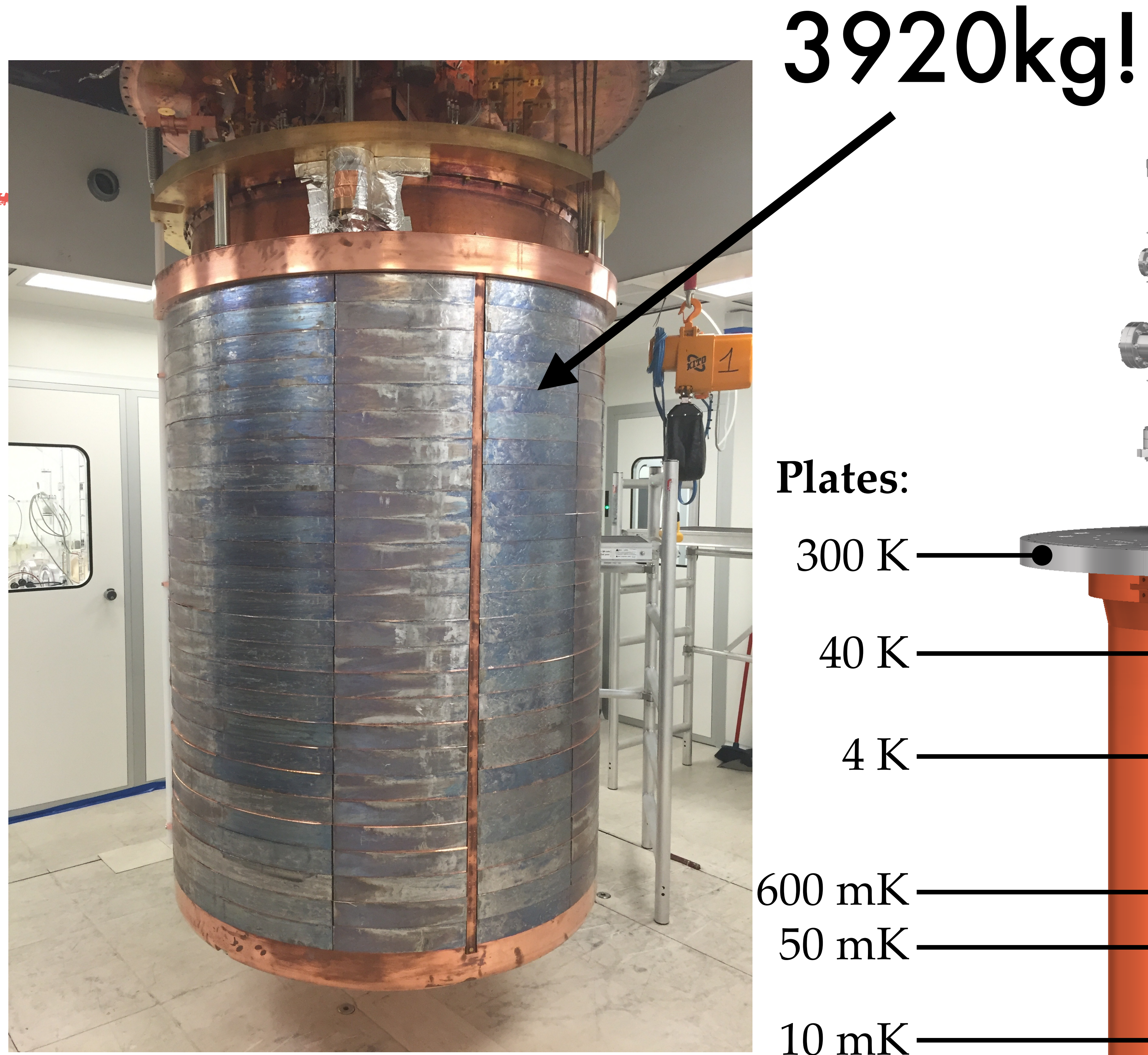


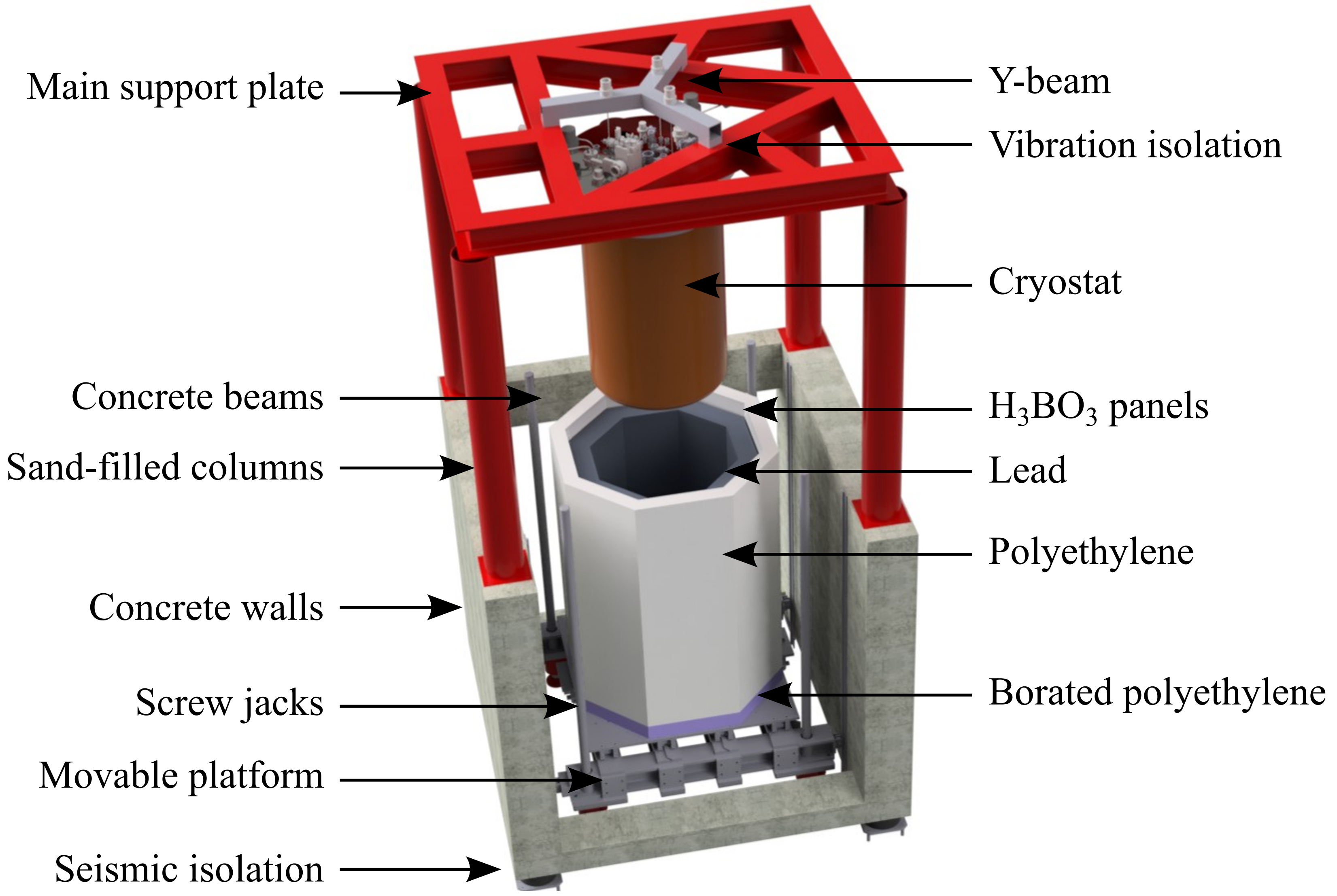


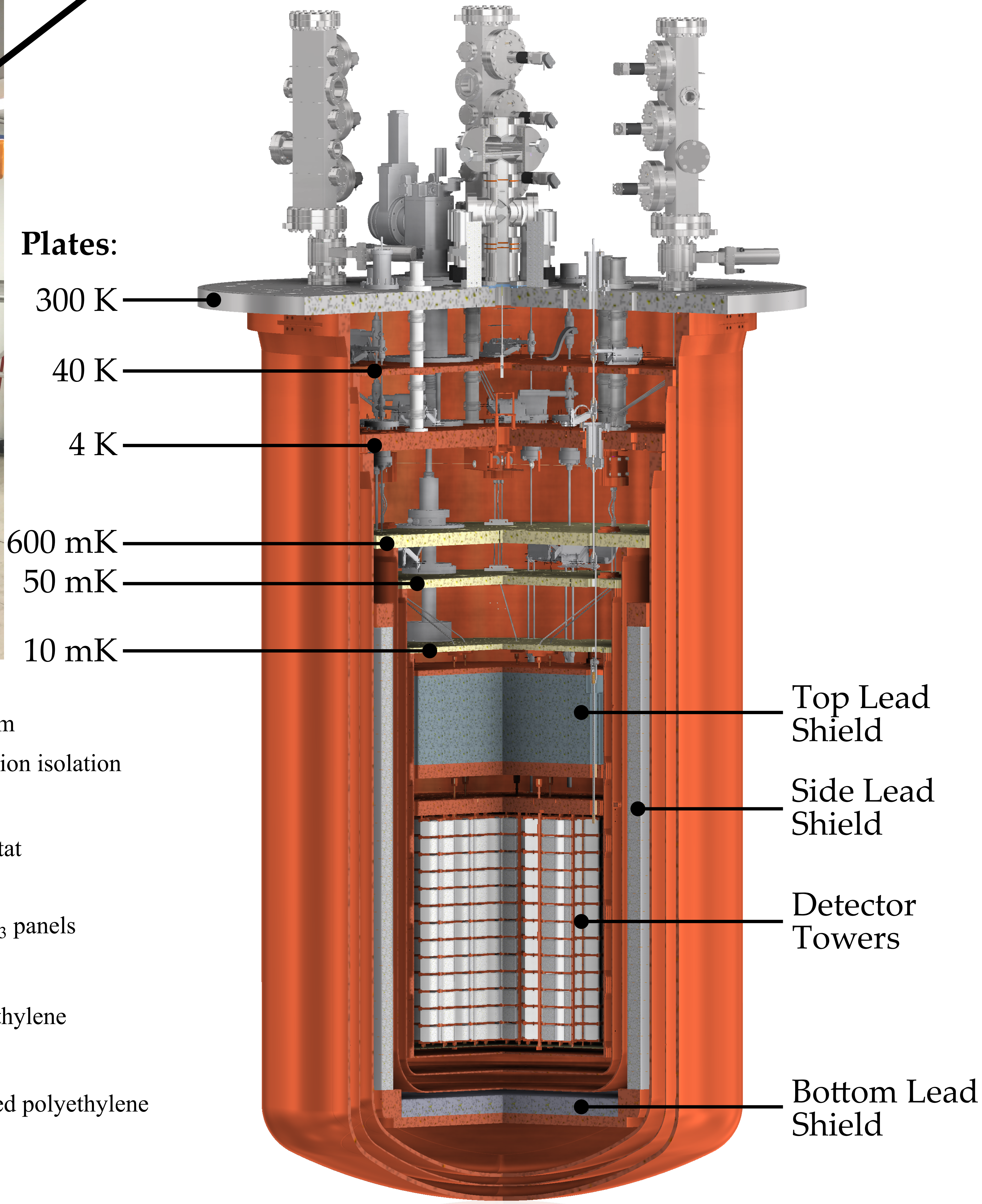


CUORE Cryostat

- Difficult task - cool 15 tons at or below 4K and 3 tons to below 50 mK
- World leading cryostat in size and power
- Five 1.2 W (@ 4.2 K) Cryomech pulse tube coolers
- DU from Leiden Cryogenics
  - 100 mK: 2 mW cooling power
  - 10 mK: 4 μW cooling power
- Radio-purity central to material selection
- Vibration isolation
- Cold Roman lead
- Lowest base temperature of 6.3 mK!







CUORE Background

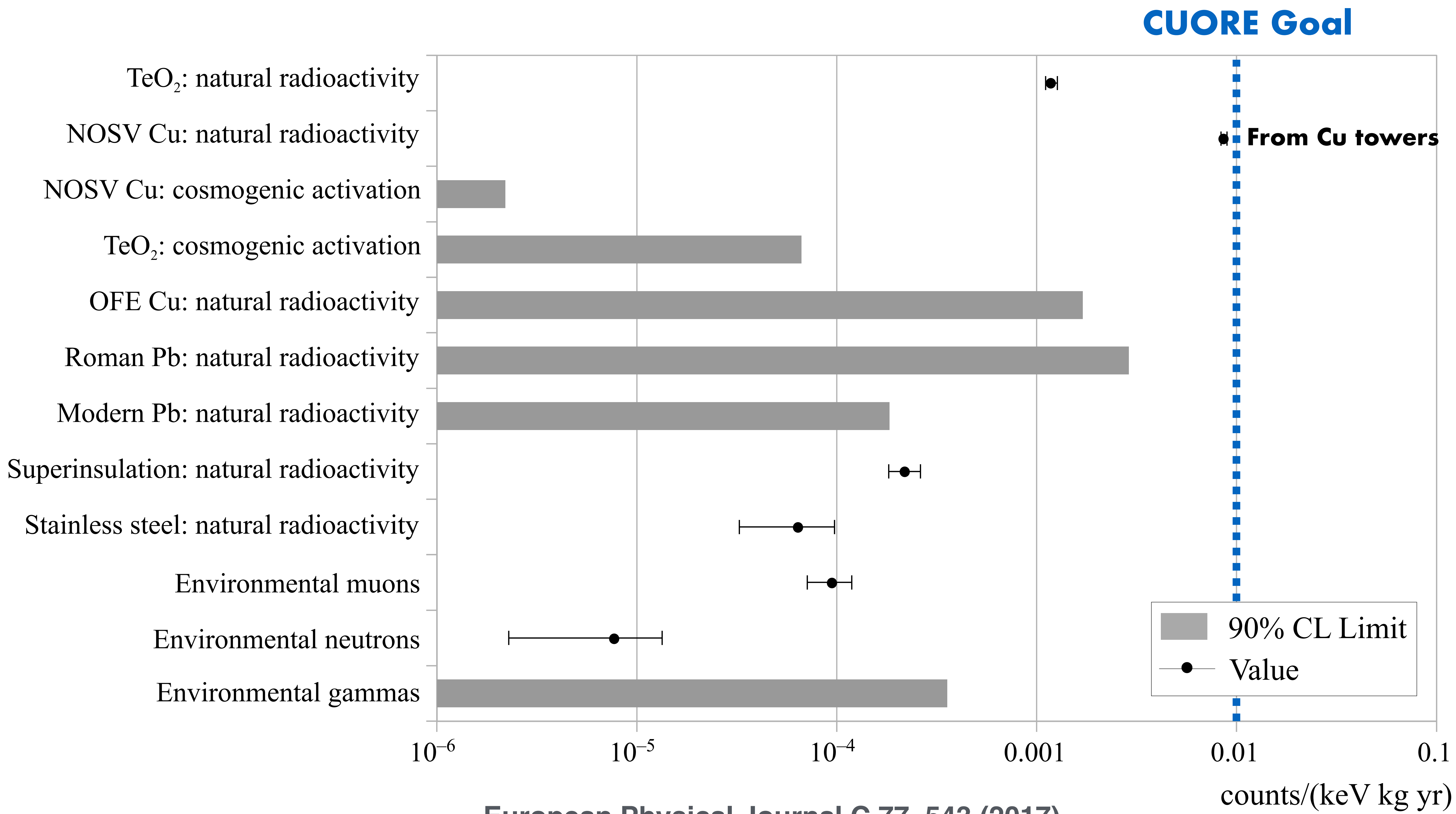
Background Limited

$$S \propto \frac{N_A a \eta \epsilon}{M_{mol}} \sqrt{\frac{MT}{b\Delta E}}$$

Background Free

$$S \propto \frac{N_A a \eta \epsilon}{M_{mol}} MT$$

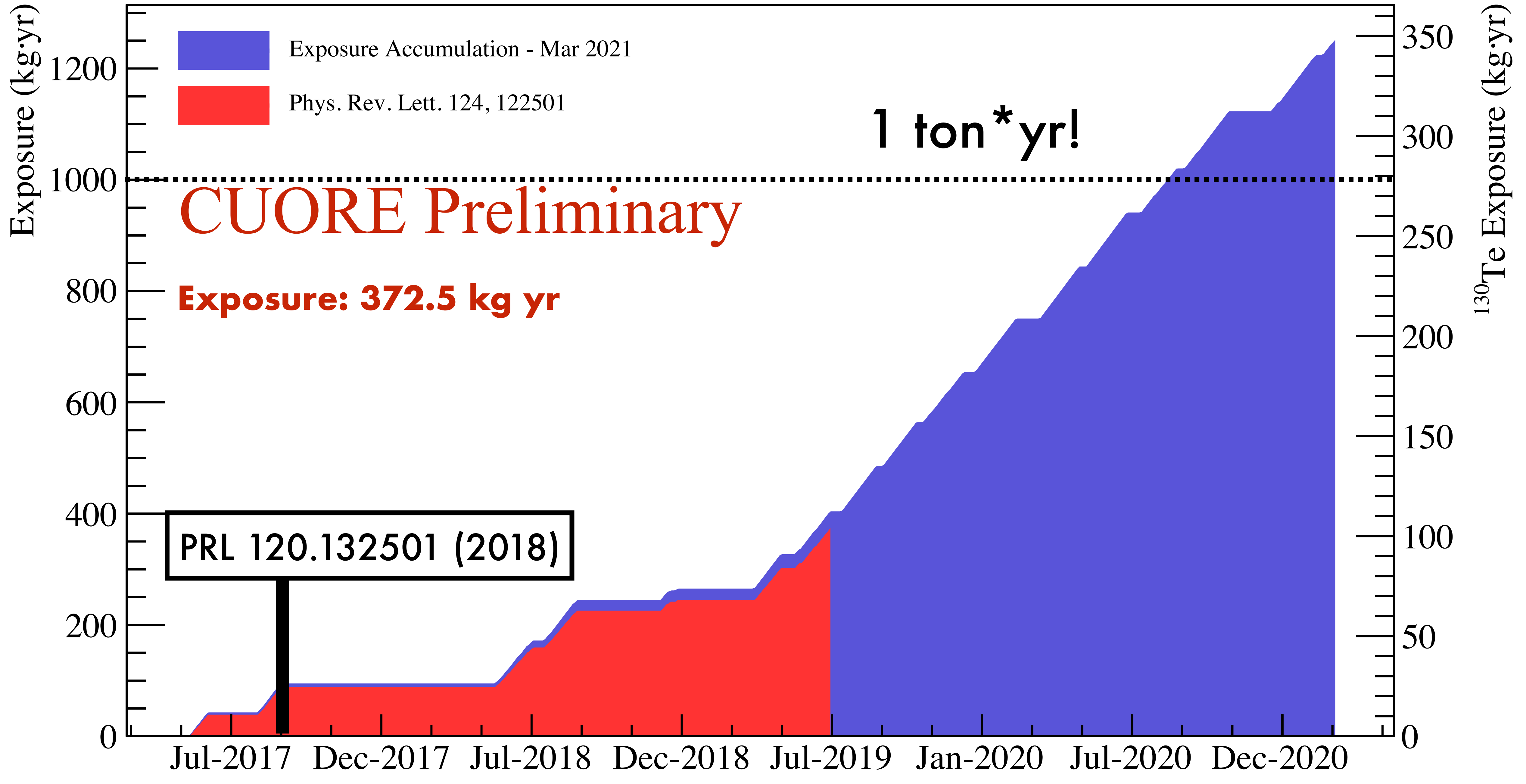
- CUORE background goals met
- Degraded α's pose problem
  - Bolometric technique provides only 1 channel
  - no particle ID
- Residual contamination from Cu housing is dominant source

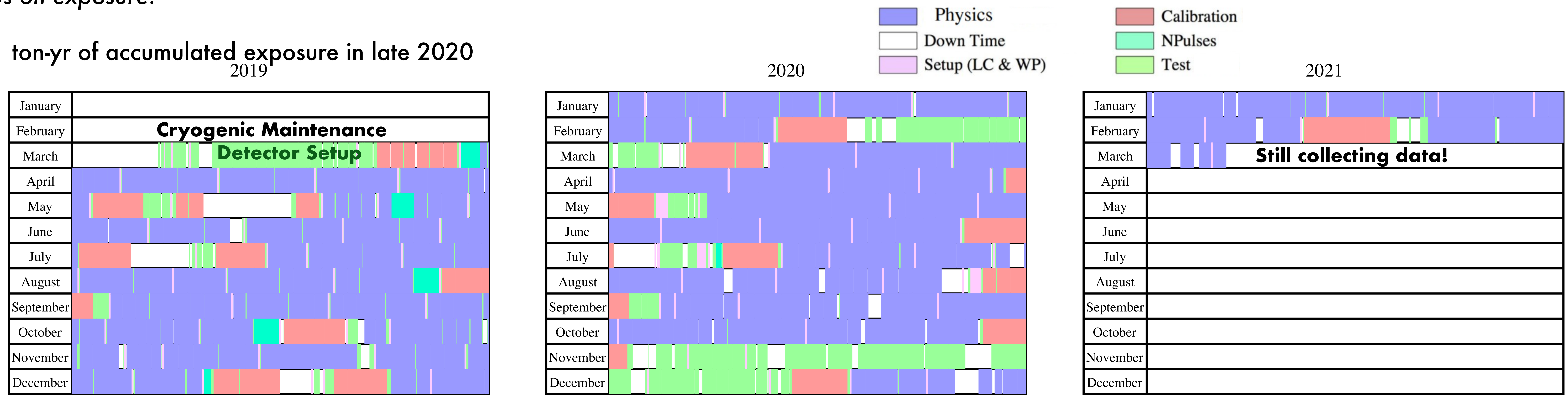


European Physical Journal C 77, 543 (2017)

CUORE Exposure

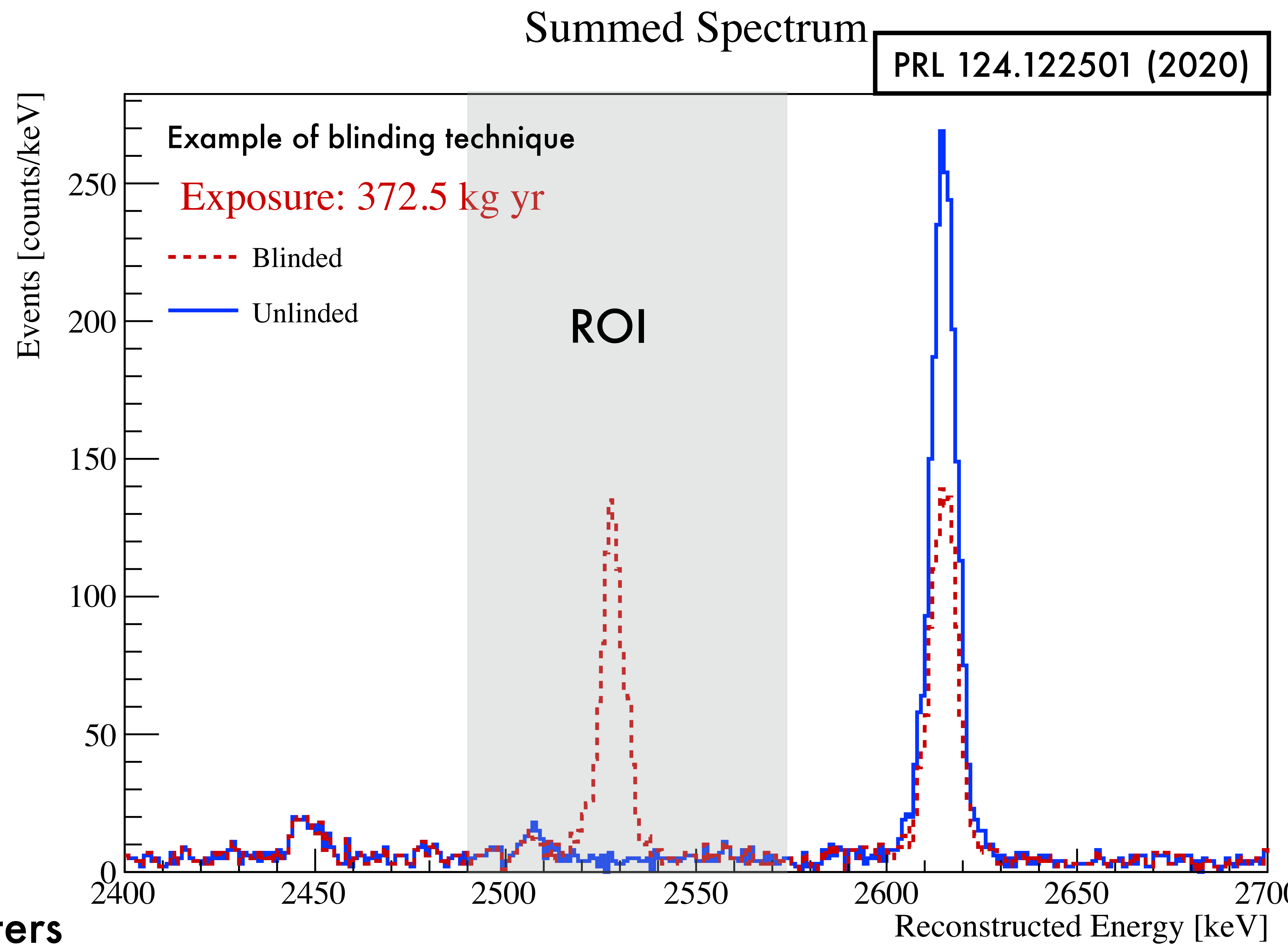
- Detector calibration system upgrade in late 2018 / early 2019
- Major cryogenic intervention and upgrade in early 2019
- Exposure increasing steadily since resumption of operations
- Detector and cryostat performance stable
- Short stops for routine checks of noise, detector response
- No further long duration optimization work planned
    - *focus on exposure!*
- Passed 1 ton-yr of accumulated exposure in late 2020

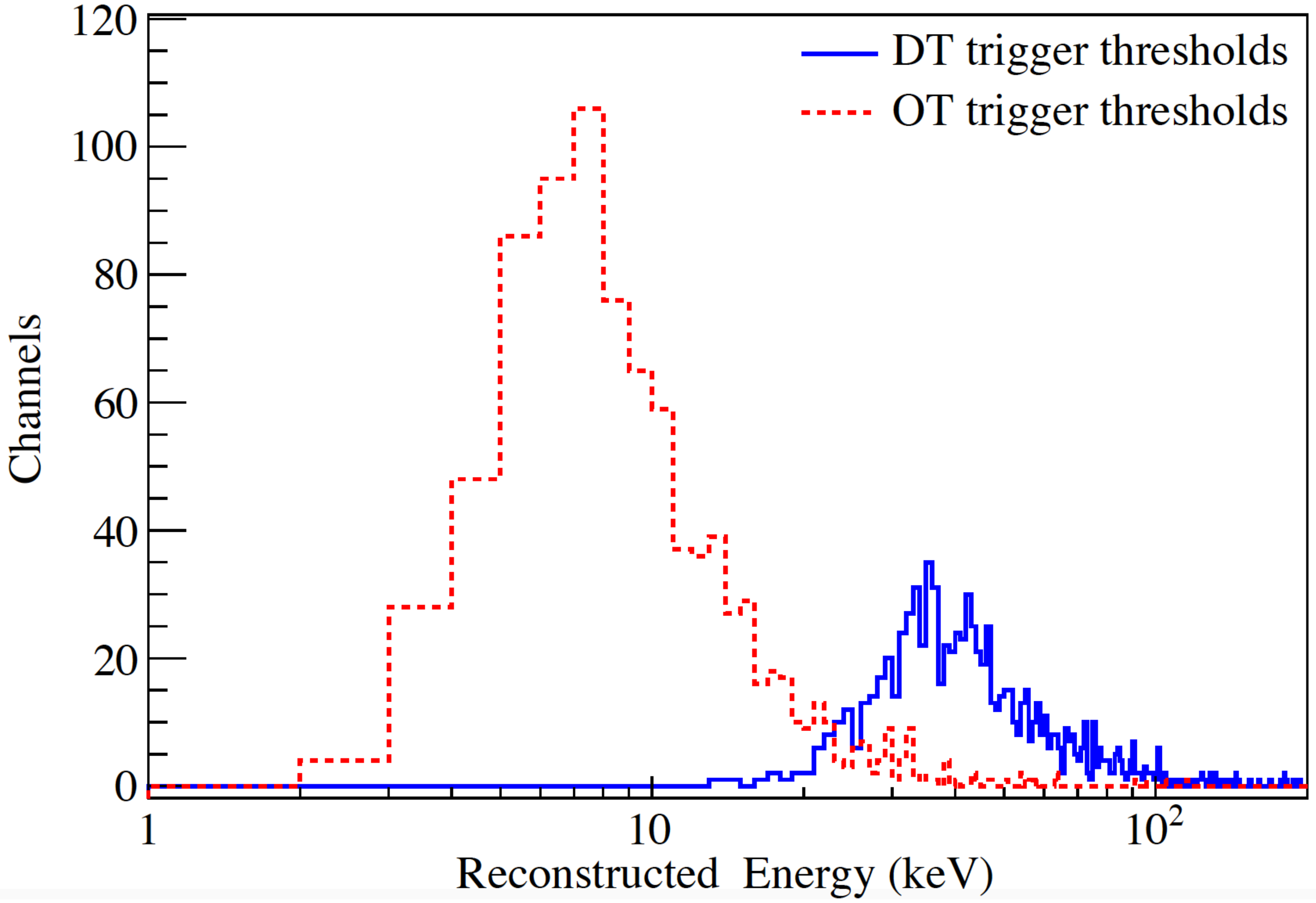




Data Processing and Analysis

- Improved trigger algorithm – optimum trigger (OT)
- Identifies a signal when the amplitude of a filtered waveform exceeds a certain threshold
- OT disentangles low-energy signals from noise better than derivative trigger (DT)
- Used to re-trigger all continuous data
- Entire data processing chain run on re-triggered data





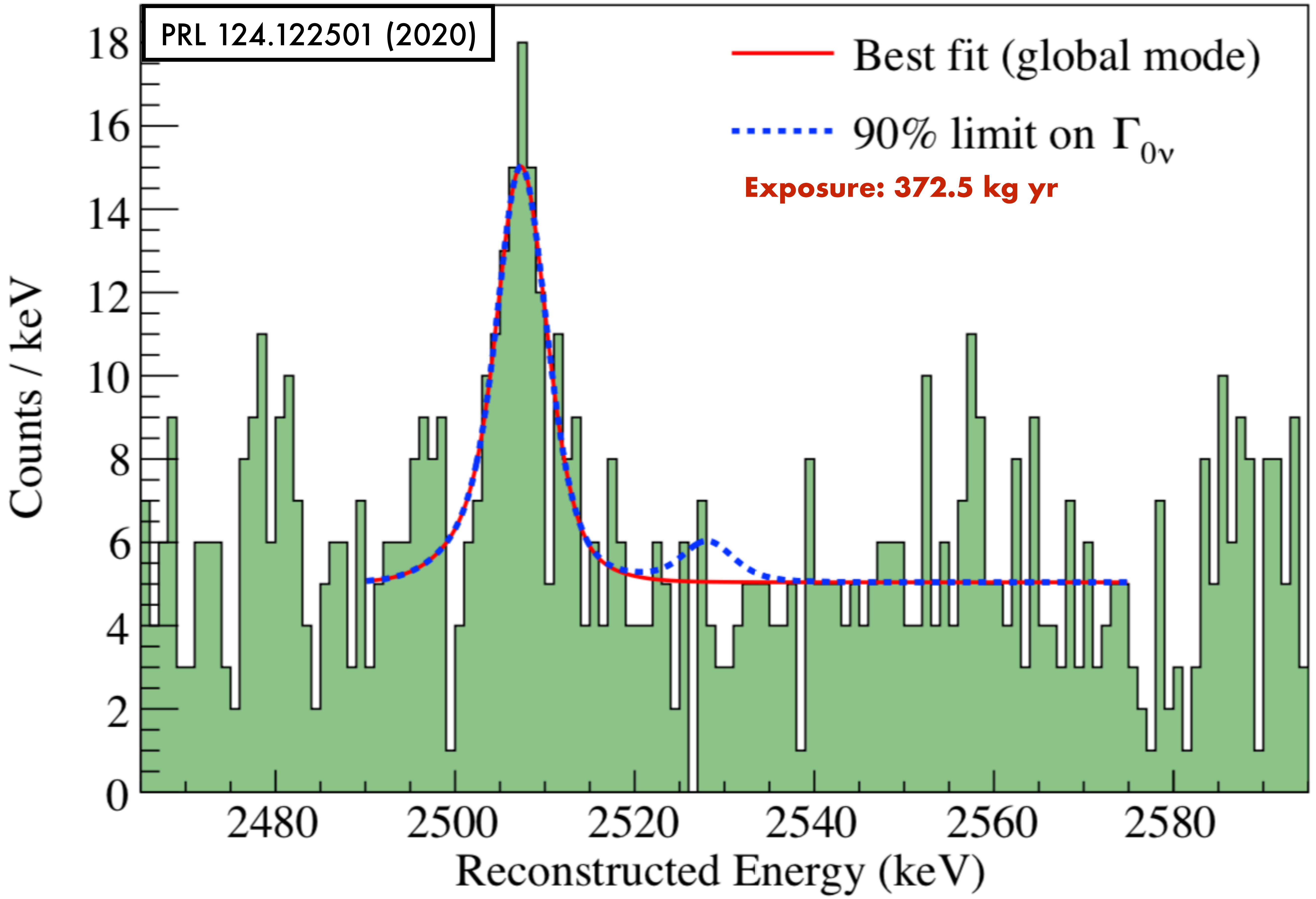
Analysis Parameters

Parameter	Value
Number of datasets	7
Number of channels	900-954
TeO_2 Exposure	372.5 kg-yr
FWHM @ 2615 keV (calibration)	7.73(3) keV
FWHM @ $Q_{\beta\beta}$ (physics)	7.0(4) keV
Reconstruction Efficiency	95.802(3) %
Anti-coincidence Efficiency	98.7(1) %
PSA Efficiency	92.6(1) %
Total Analysis Efficiency	87.5(2) %
Containment Efficiency	88.35(9) %

- ROI blinded by randomly swapping events at $Q_{\beta\beta}$ and the 2615 keV peak
- Cuts optimized on blinded data
- Afterwards unblind data and fit ROI

ROI Fit Results

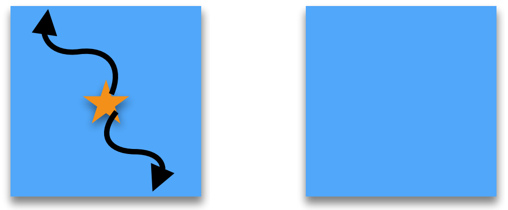
- Bayesian fit in the region of interest [2490, 2575] keV
  - Unexpected feature around 2480 keV => more statistics
- Free parameters: ^{60}Co peak (amplitude, location), background, and $\Gamma_{0\nu}$
- Background and rate consistent across datasets
- No evidence of a signal!
- Background index computed by running fit without $0\nu\beta\beta$ component, on a per-dataset basis
- Exclusion sensitivity computed by 10^4 pseudo-experiments with only ^{60}Co and flat backgrounds
  - 3% probability of a stronger limit

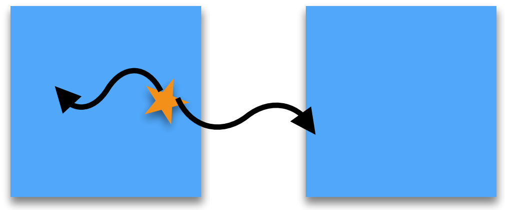


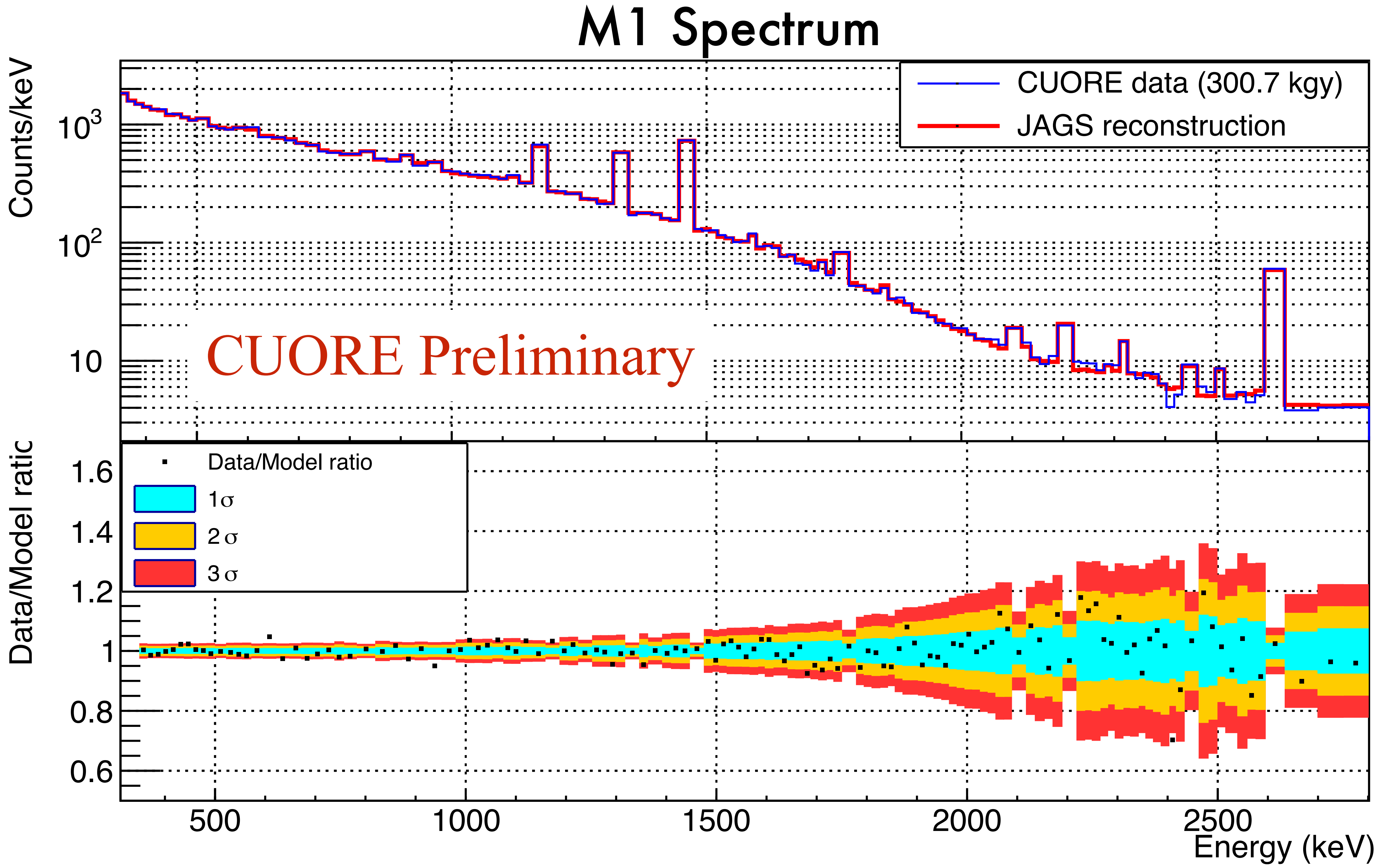
Average Background Index: $(1.38 \pm 0.07) \times 10^{-2}$ counts/(keV · kg · yr)
Half-life limit: $T_{1/2}^{0\nu} > 3.2 \times 10^{25}$ yr (90% CI exclusion)
$m_{\beta\beta} < 0.075 - 0.350\,\mathrm{eV}$ (90% CI)

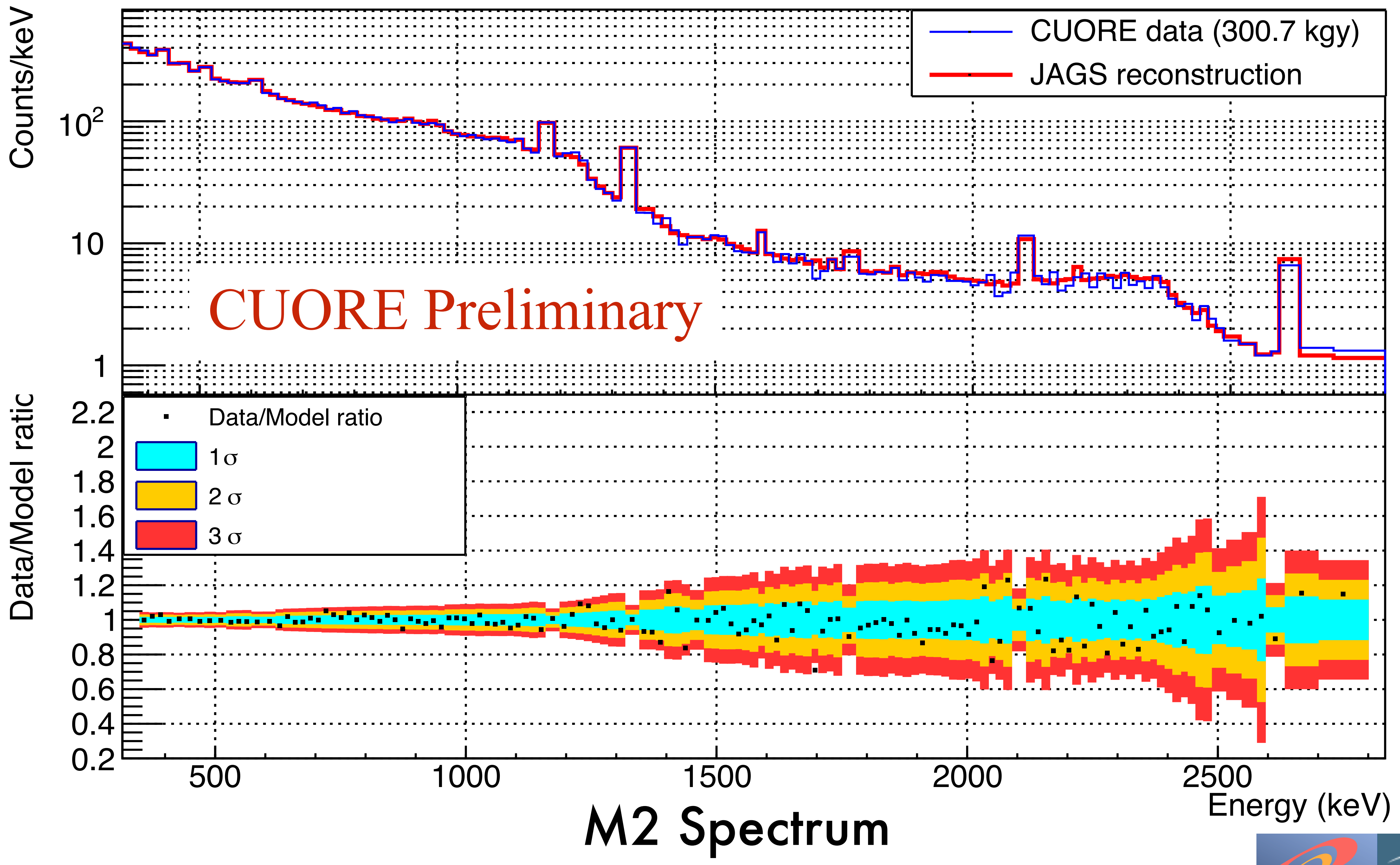
CUORE Background Model

- Background reconstruction with Bayesian fit
- 60 different contaminants across the whole cryostat + muons
- Geant4 simulations for each component of the model
- Data split based on event multiplicity
  - M1: Events in single crystal (~88% ββ events)
  - M2: Events shared across two crystals (γ scatters, α's)
- Detector split into two layers
  - Inner: Sensitive to tower contamination
  - Outer: Sensitive to cryostat contamination
- Remarkably good agreement between model and data





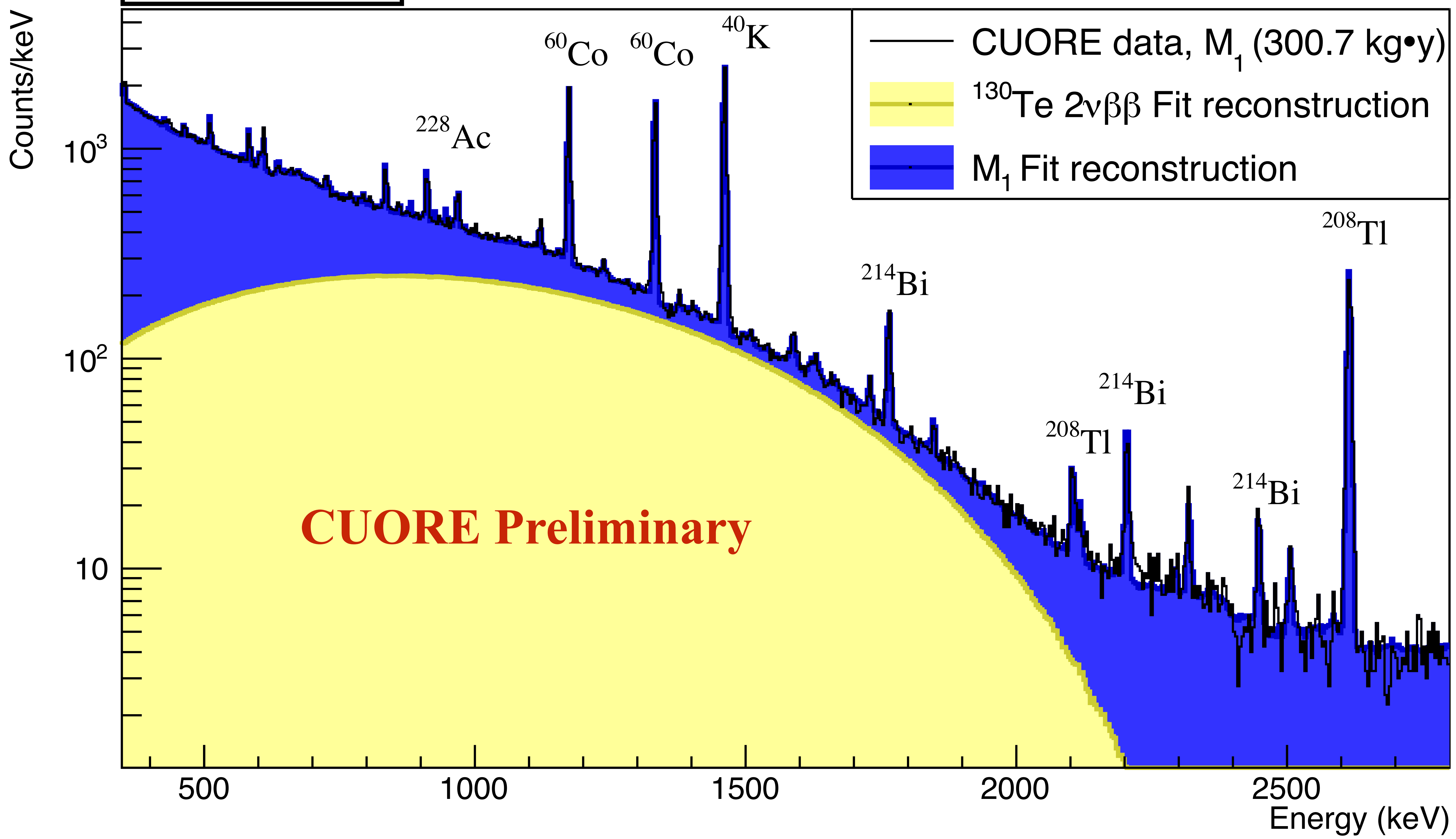




^{130}Te 2νββ

- With detailed background model can extract 2νββ half-life from CUORE data
- Result is most precise measurement of the decay half-life
- Accepted to PRL earlier this month

arXiv:2012.11749

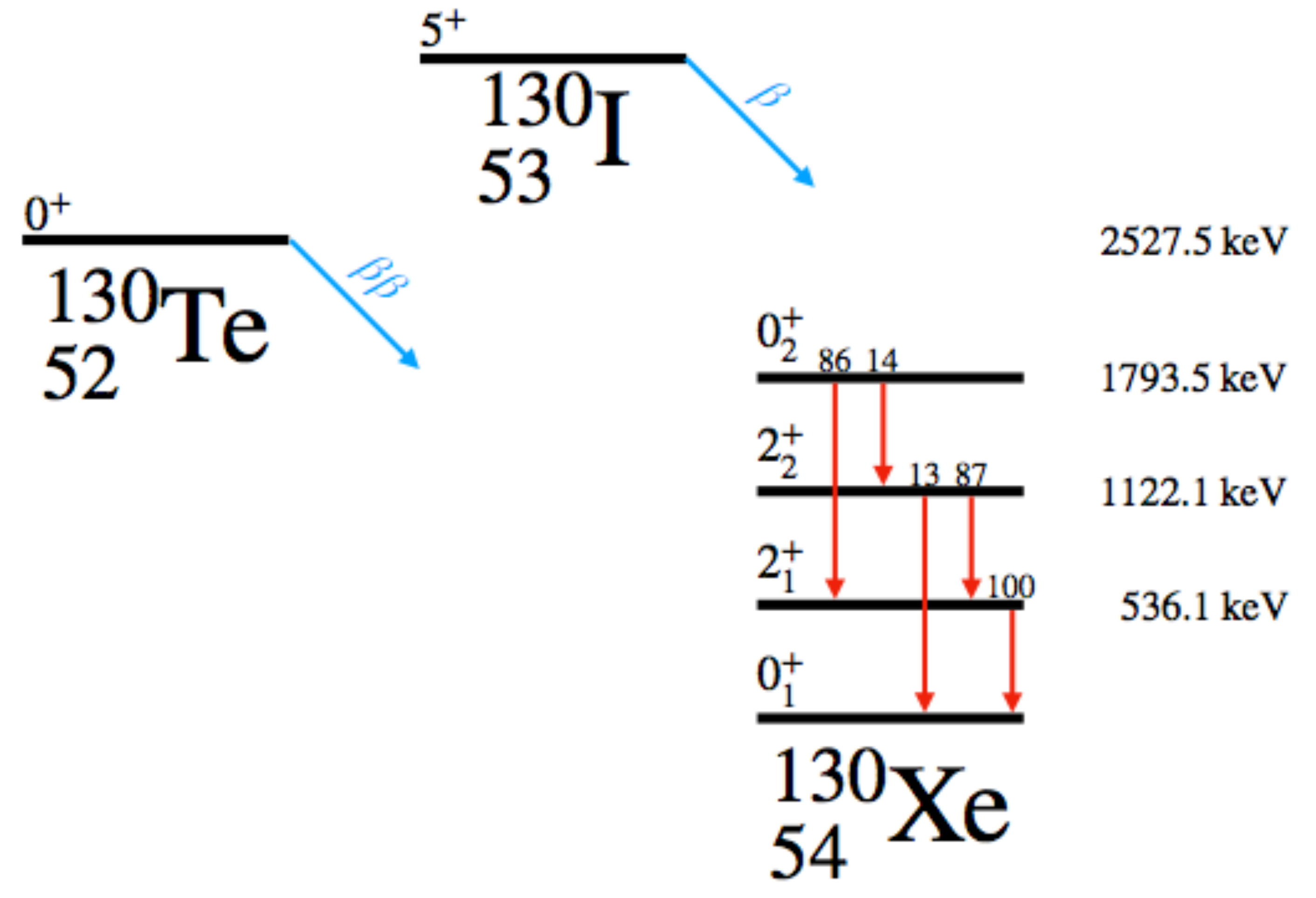


$$T_{1/2}^{2\nu} = \left(7.71^{+0.08}_{-0.06}\,(stat.)^{+0.12}_{-0.15}\,(syst.)\right) \times 10^{20}\,\mathrm{yr}$$

CUORE-0 $T_{1/2}^{2\nu} = \left(8.2 \pm 0.2\,(stat.) \pm 0.6\,(syst.)\right) \times 10^{20}\,\mathrm{yr}$

NEMO-III $T_{1/2}^{2\nu} = \left(7.0 \pm 0.9\,(stat.) \pm 1.1\,(syst.)\right) \times 10^{20}\,\mathrm{yr}$

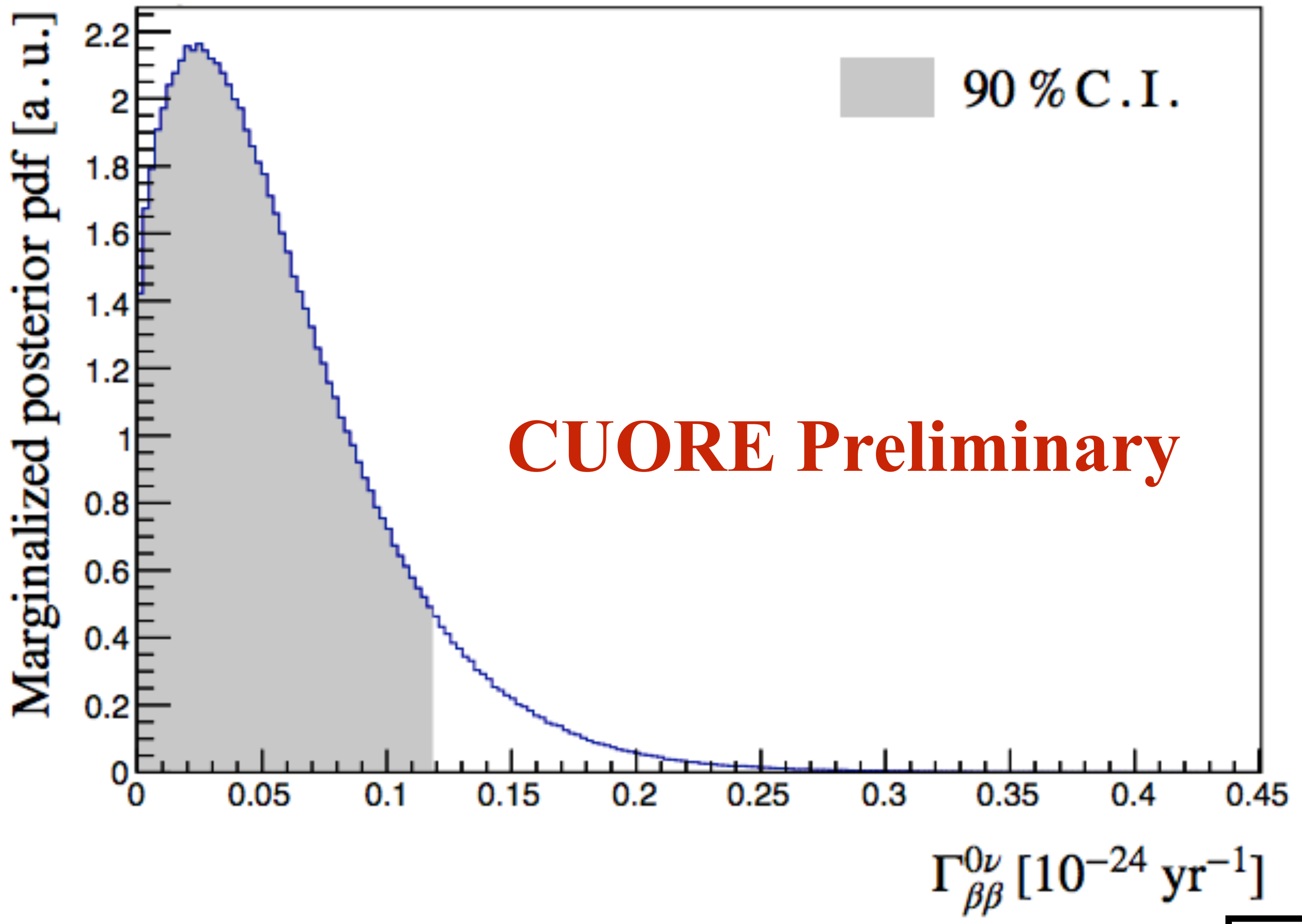
Decay to Excited States



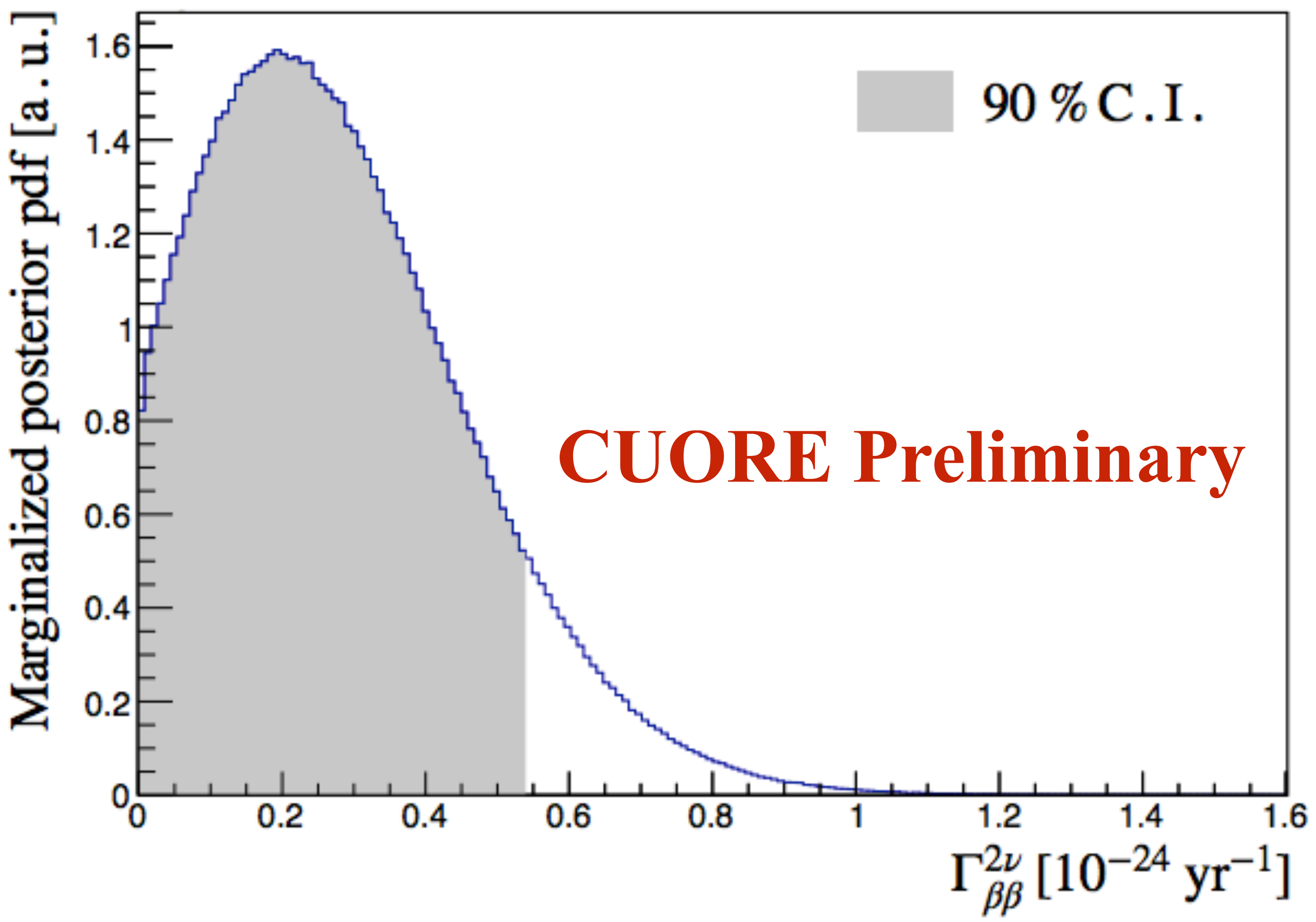
- Possible to search for rare decay of ^{130}Te to the first 0^+_2 excited state of ^{130}Xe

- Signature will be coincidence between ββ decay and a γ in up to 3 crystals

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



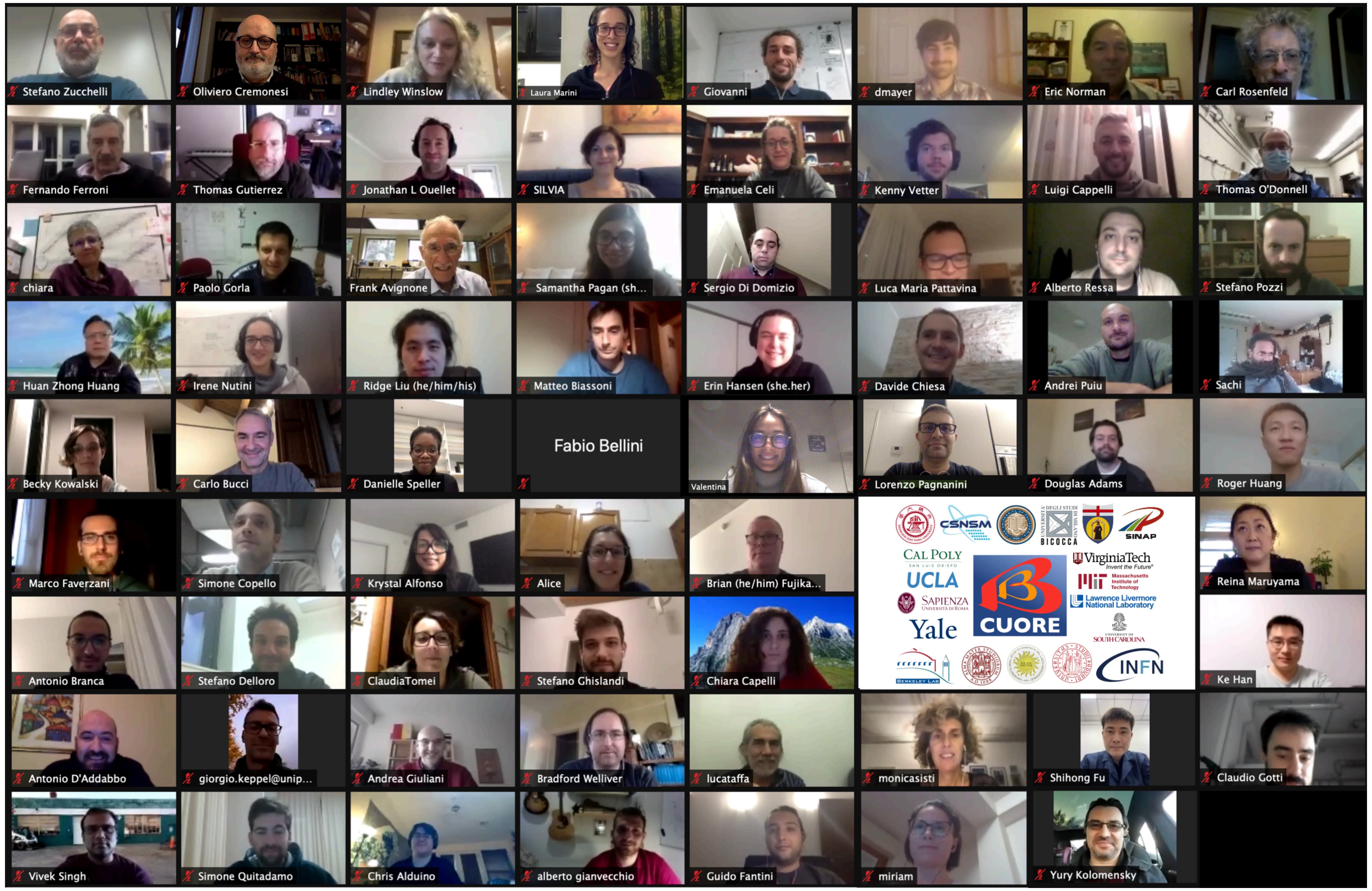
$T^{2\nu}_{1/2} > 5.9 \times 10^{24}$ yr (90% C.I.)

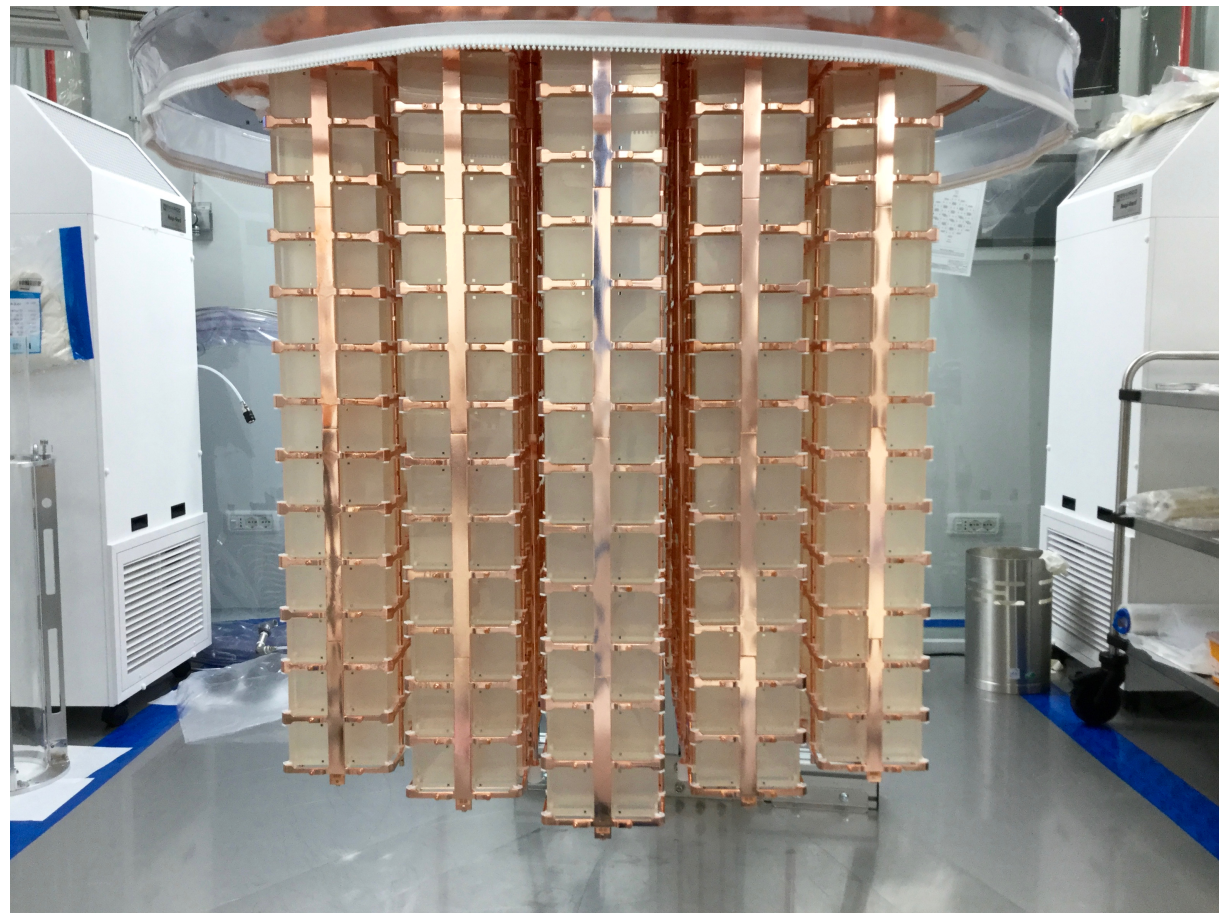


arXiv:2101.10702

Summary

- Operation of world's largest ton-scale cryogenic bolometric array
- Stable data taking since March 2019
- Over 1000 kg*yr of raw exposure already accumulated
- **New analysis result for 0νββ imminent!**
- Measurement on 2νββ half-life in ^{130}Te is most precise to date (accepted by PRL)
  - $T^{2\nu}_{1/2} = \left(7.71^{+0.08}_{-0.06}\,(stat.)^{+0.12}_{-0.15}\,(syst.)\right) \times 10^{20}\,\mathrm{yr}$
- Updated analysis algorithms can allow for better thresholds and expand potential for other rare event searches
- Success of CUORE motivates future tonne-scale bolometric experiments (CUPID) arXiV:1504.03599

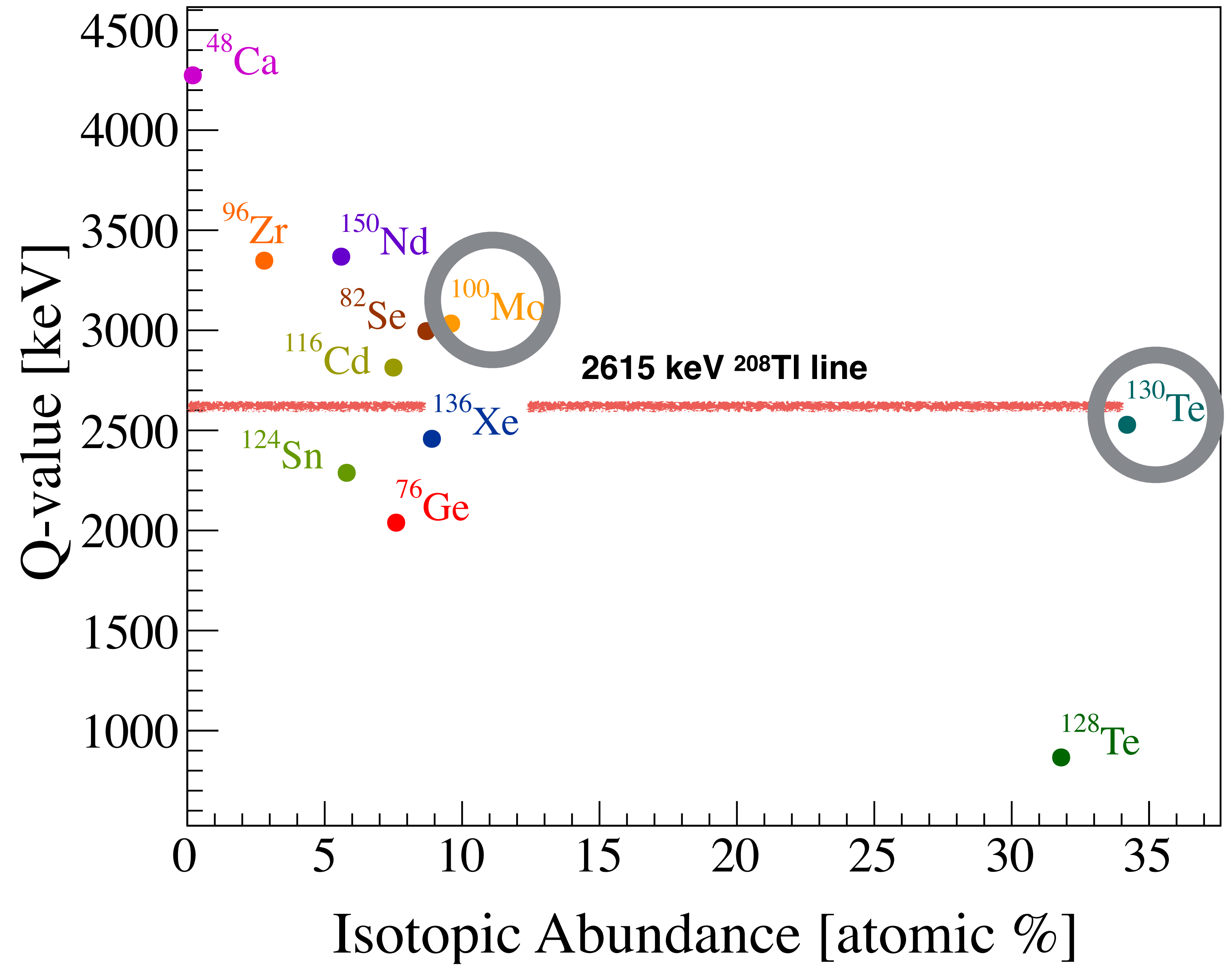


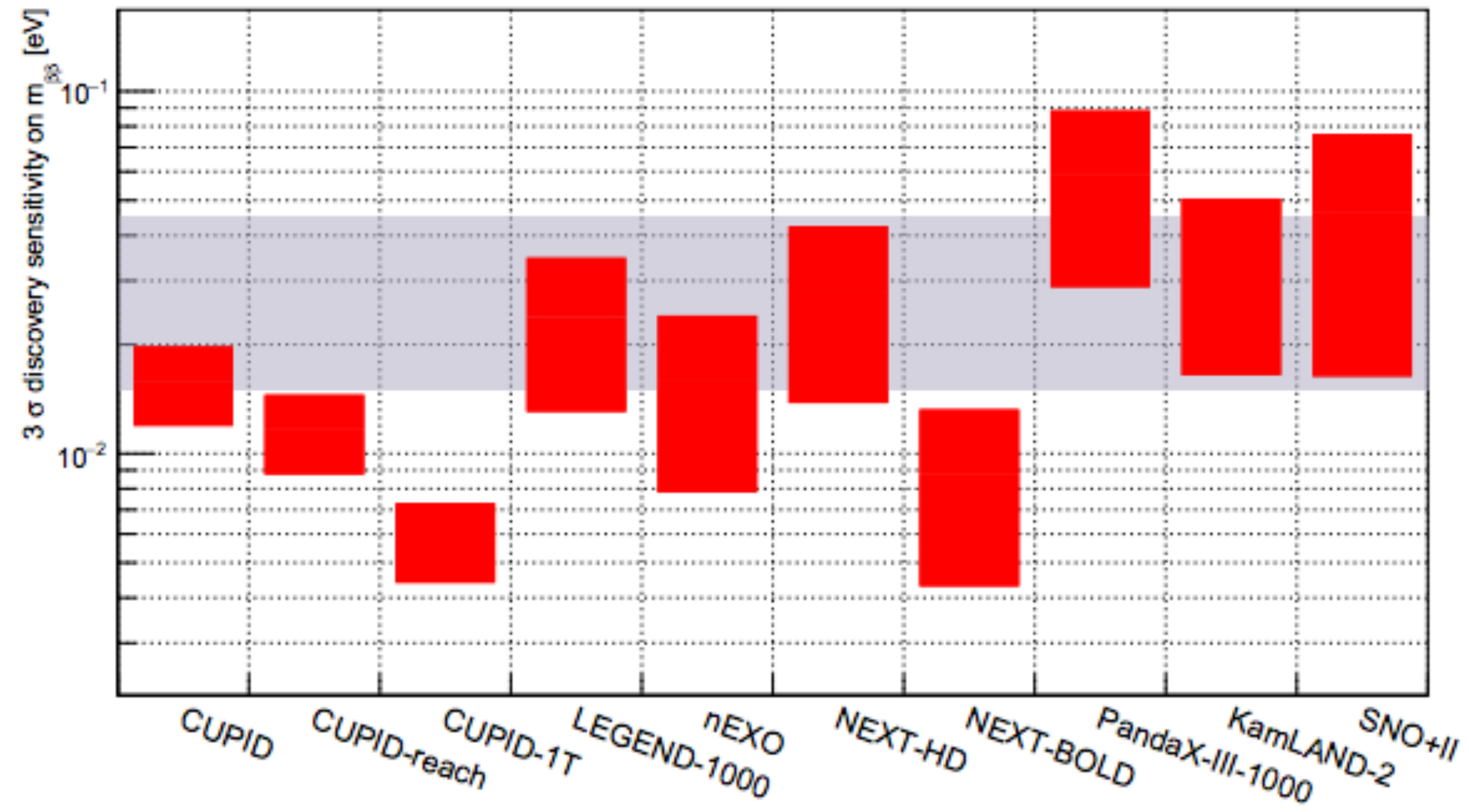


Backups

CUPID: CUORE Upgrade with Particle ID

- Array of $Li_2{}^{100}MoO_4$ scintillating bolometers (95% enrichment)
- Q-value at 3034 keV above natural gamma background
- Particle ID from light/heat reduces alpha background
  - CUPID-Mo and CUPID-0 demonstrators show this is successful technique
- Re-use CUORE infrastructure at LNGS
- CUPID goals are conservative and easily within reach of existing technology





Pre-CDR: arXiv:1907.09376

Fit Method

Bayes Theorem $$P\left(\vec{\theta},\vec{E}\right)=\frac{\mathscr{L}\left(\vec{\theta},\vec{E}\right)\cdot\pi\left(\vec{\theta}\right)}{\int_{\Omega}\mathscr{L}\left(\vec{\theta},\vec{E}\right)\cdot\pi\left(\vec{\theta}\right)d\vec{\theta}}$$

Likelihood $$\mathscr{L}\left(\vec{\theta},\vec{E}\right)=\prod_{dataset}\prod_{channel}\left[\frac{e^{-\lambda}\lambda^{n}}{n!}\prod_{i}\left(\frac{s}{\lambda}pdf_{0\nu\beta\beta}\left(E_i\,|\,\vec{\theta}\right)+\frac{c}{\lambda}pdf_{^{60}Co}\left(E_i\,|\,\vec{\theta}\right)+\frac{b}{\lambda}\frac{1}{\Delta E}\right)\right]$$

Expectation Value $$\lambda=s+c+b$$

Systematics Used as Nuisance Parameters

Parameter	Dependence	Method
Analysis Efficiency I	Dataset	Gaussian
Analysis Efficiency II (PSA)	Global	Flat in [0.993, 1.007]
Energy Bias	Dataset	Fit residuals of peaks in physics data from literature values with 2nd order polynomial
Energy Resolution	Dataset	Fit ratio of FWHM in physics and calibration data with a 2nd order polynomial
$Q_{\beta\beta}$	Global	Gaussian, 2527.518(13) keV
^{130}Te isotopic fraction	Global	Gaussian, 34.1668(16) %

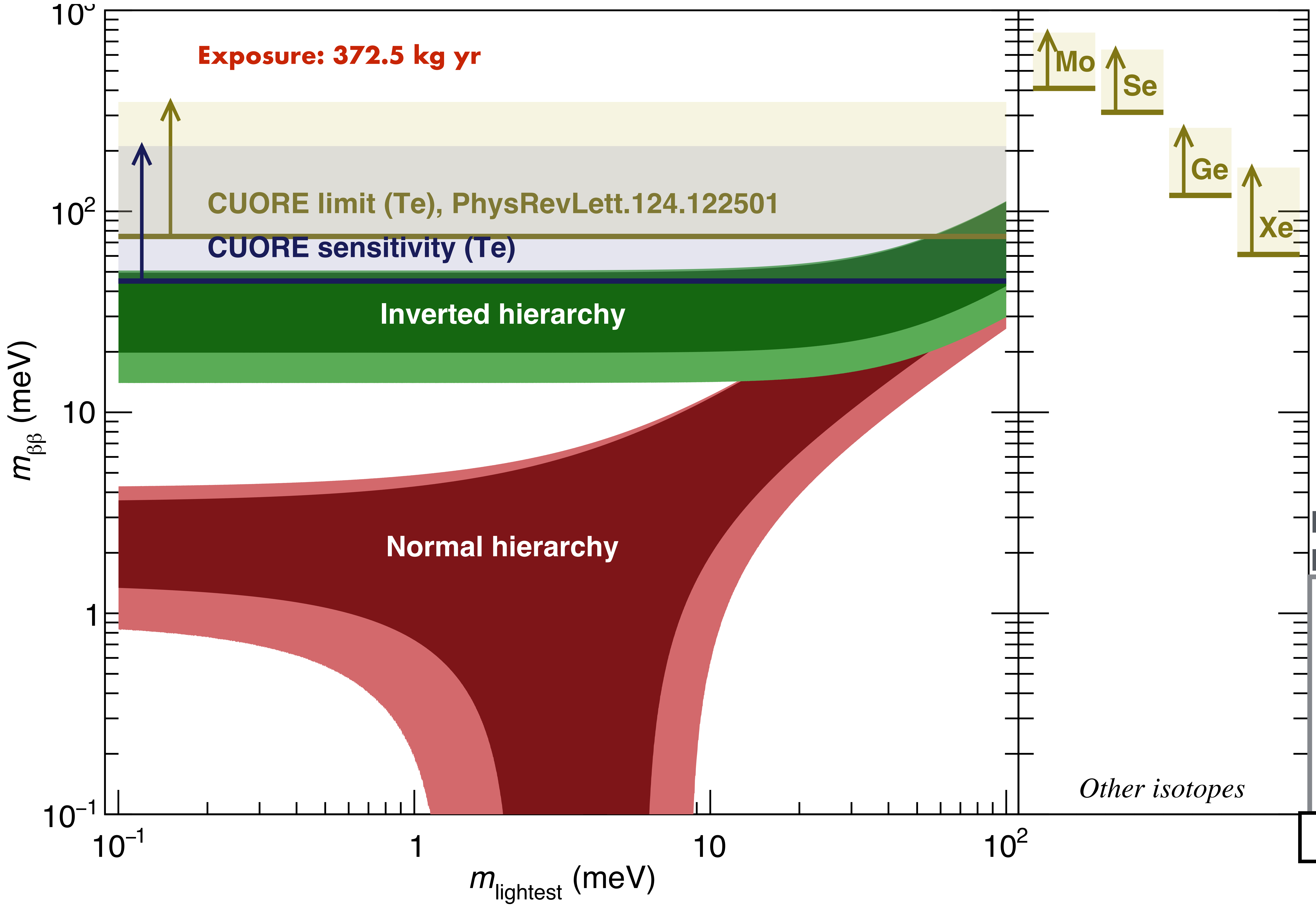
Results for 0νββ Search

CUORE Preliminary

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

$$m_{\beta\beta} < 0.075 - 0.350\,\mathrm{eV}\ (90\,\%\ \mathrm{C.I.})$$

- Limit set on $\Gamma_{0\nu} > 0$ (physical) range
- Sets new leading limit on the decay for ^{130}Te



Effective Majorana Mass

Phase Space

$$\left(T^{0\nu\beta\beta}_{1/2}\right)^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)\left|M^{0\nu}\right|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$

Nucl. Matrix Element

Nuclear Matrix Elements

JHEP02 (2013) 025
Nucl. Phys. A 818, 139 (2009)
Phys. Rev. C 87, 045501 (2013)
Phys. Rev. C 87, 064302 (2014)
Phys. Rev. C 91, 034304 (2015)
Phys. Rev. C 91, 024613 (2015)
Phys. Rev. C 91, 024309 (2015)
Phys. Rev. C 91, 024316 (2015)
Phys. Rev. Lett. 105, 252503 (2010)
Phys. Rev. Lett. 111, 142501 (2013)

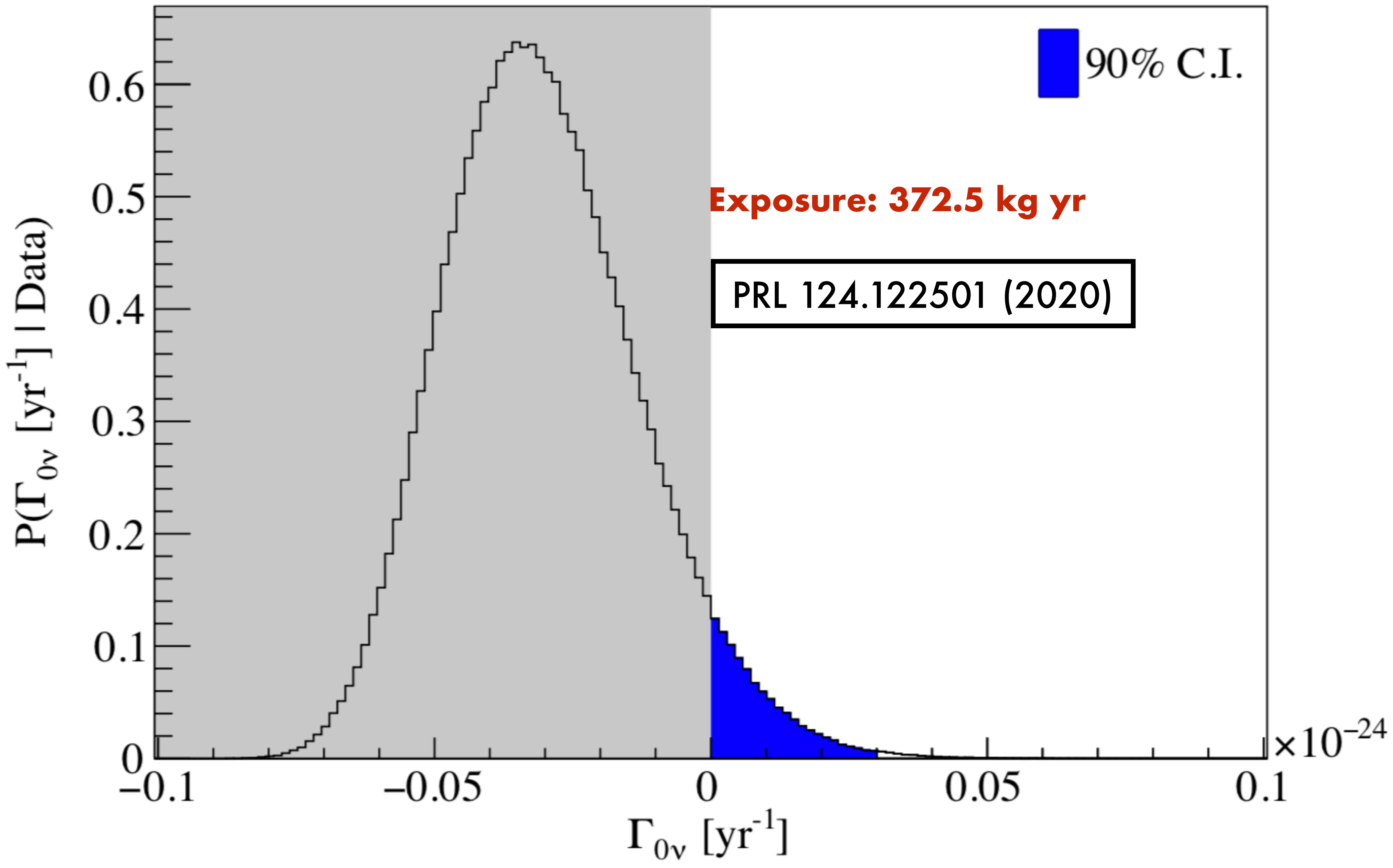
PRL 124.122501 (2020)

$$\langle m_{\beta\beta}\rangle^2 = \left|\sum_{i=0}^{3} U^2_{e,i} m_i\right|$$

Effective Majorana Mass

Systematics

- Systematics implemented as nuisance parameters in the fit
- Examine each parameter's impact on $\Gamma_{0\nu}$ by looking at the posterior global mode
  - $\Gamma_{0\nu}$ allowed to be negative
- Largest contribution from PSA systematics
- Total impact on global mode ≤ 0.04% and yields a 0.4% weaker limit



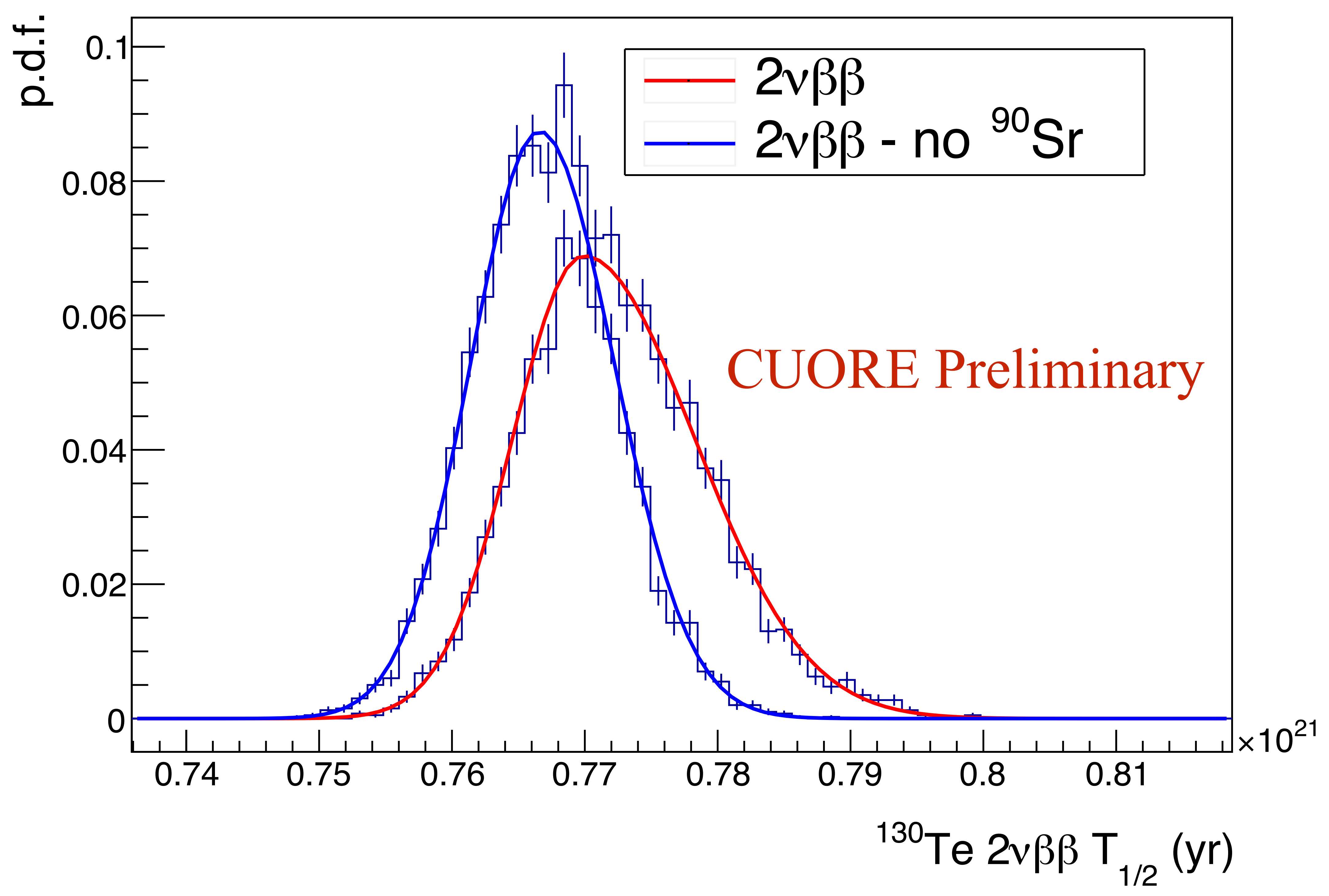
Posterior on $\Gamma_{0\nu}$ with all systematics included for the fit in the physical range and on the full range

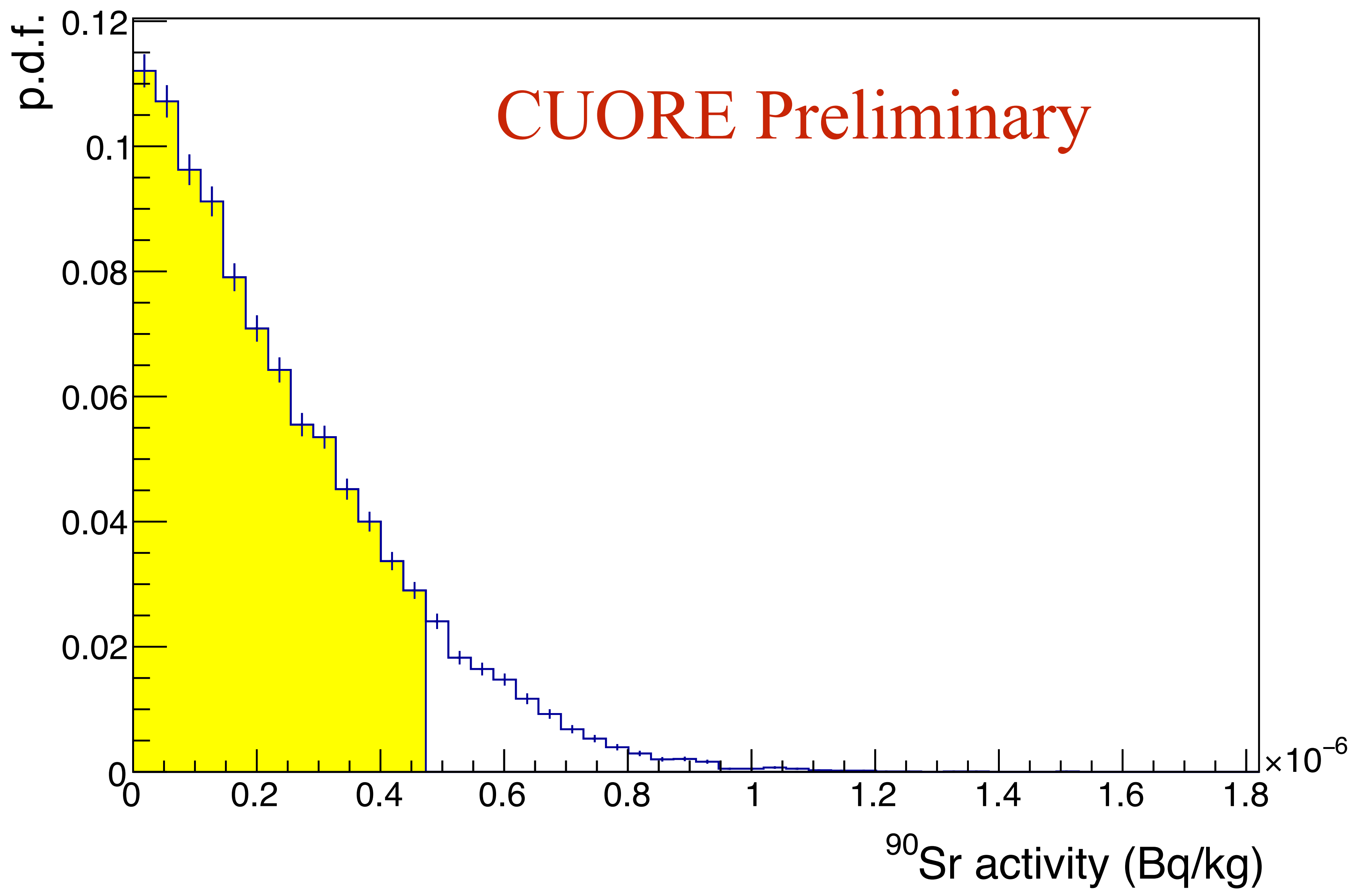
Systematics

Parameter	Prior	Effect on $\Gamma_{0\nu}$
Analysis Efficiency I	Gaussian	0.01%
Analysis Efficiency II (PSA)	Uniform	0.04%
Containment Efficiency	Gaussian	0.01%
Energy and resolution scaling	Multivariate	0.02%
$Q_{\beta\beta}$ Value	Gaussian	0.02%
Isotopic Fraction	Gaussian	0.02%

^{130}Te 2νββ

- Anti-correlation with 90Sr
- Fit posterior is slightly asymmetric with 90Sr included
- 90Sr activity is consistent with zero
- Left in the fit as a conservative choice





arXiv:2012.11749