Yale
Wright Laboratory

Latest Results from the CUORE Experiment

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(for the CUORE collaboration)

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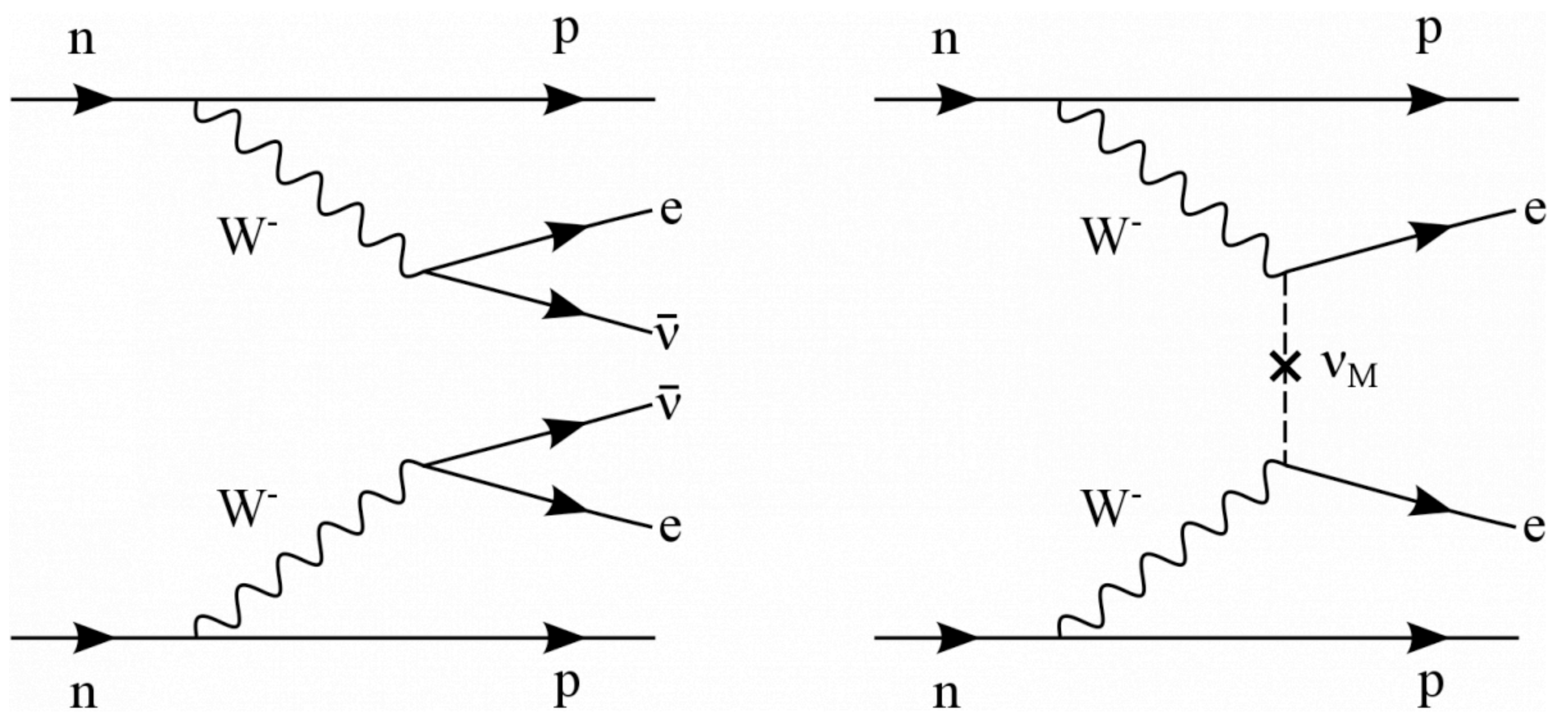
CUORE

Neutrinoless Double Beta Decay (0νββ)



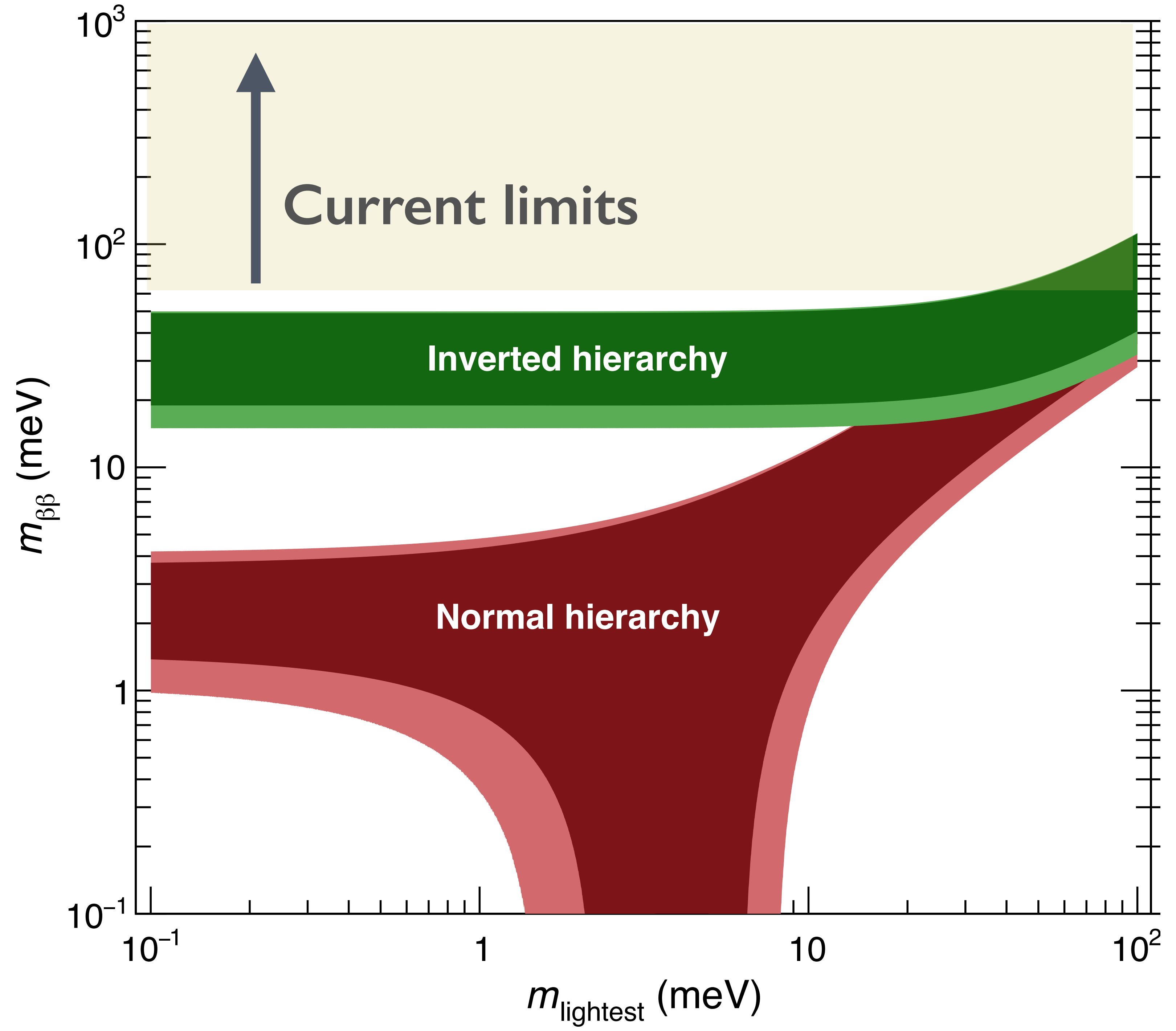
- Hypothesized nuclear process - Neutrinoless counterpart to observed double beta decay
- If observed, implies:
  - ν is Majorana fermion
  - Lepton number violation
  - Hints to matter-antimatter asymmetry
- 0νββ experiments measure half-life (or decay rate)
- Constrain the ν mass and ordering

$$\langle m_{\beta\beta}\rangle = \left|\sum_j m_j U_{ej}^2\right|$$

Nuclear Matrix elements

$$T^{0\nu}_{1/2} \; \alpha \; \left(G|\mathcal{M}|^2 \langle m_{\beta\beta}\rangle^2\right)^{-1} \simeq 10^{27-28} \left(\frac{0.01\,\mathrm{eV}}{\langle m_{\beta\beta}\rangle}\right)^2 \mathrm{y}$$

Phase space factor   Effective neutrino mass



Important to observe 0νββ in multiple isotopes

Cryogenic Underground Observatory for Rare Events

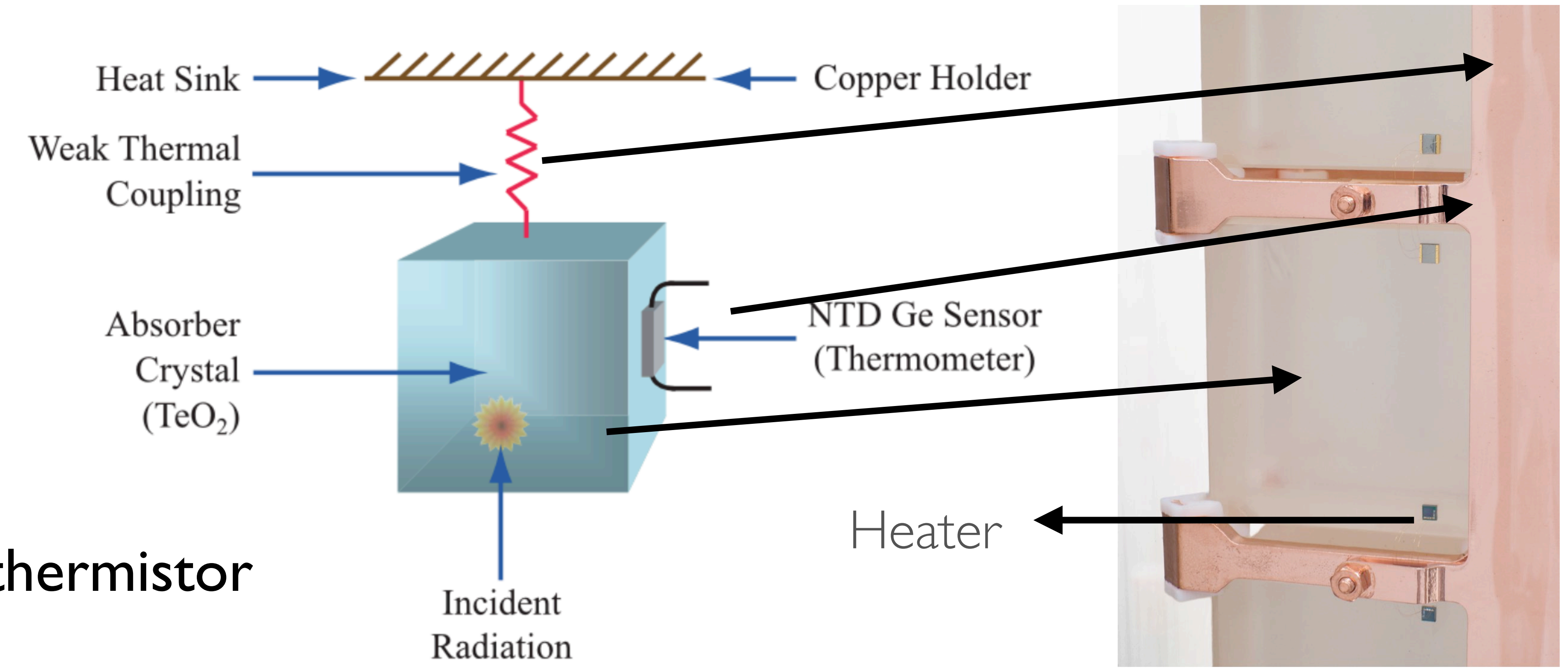
- Located in LNGS under the mountain of Gran Sasso
- **Primary Goal:** Search for 0νββ decay in ^{130}Te
- **Design:**
  - 19 towers (total of 988 TeO_2 crystals)
  - *Large mass:* 742 kg of TeO_2 ,206 kg of ^{130}Te
    - $Q_{\beta\beta}$ (2528 keV) - above most γ natural radioactivity
    - Isotope within the absorber
  - *Low background goal:* 10^{-2} cts/(keV. kg. yr)
  - *Energy resolution:* Goal of 5 keV FWHM at $Q_{\beta\beta}$
  - High efficiency and duty cycle
- **Sensitivity:**
  - $T^{0\nu}_{1/2}$ ~ 9 x 10^{25} yrs (90% C.L) in 5 yrs
  - $m_{\beta\beta}$ < 50-130 meV

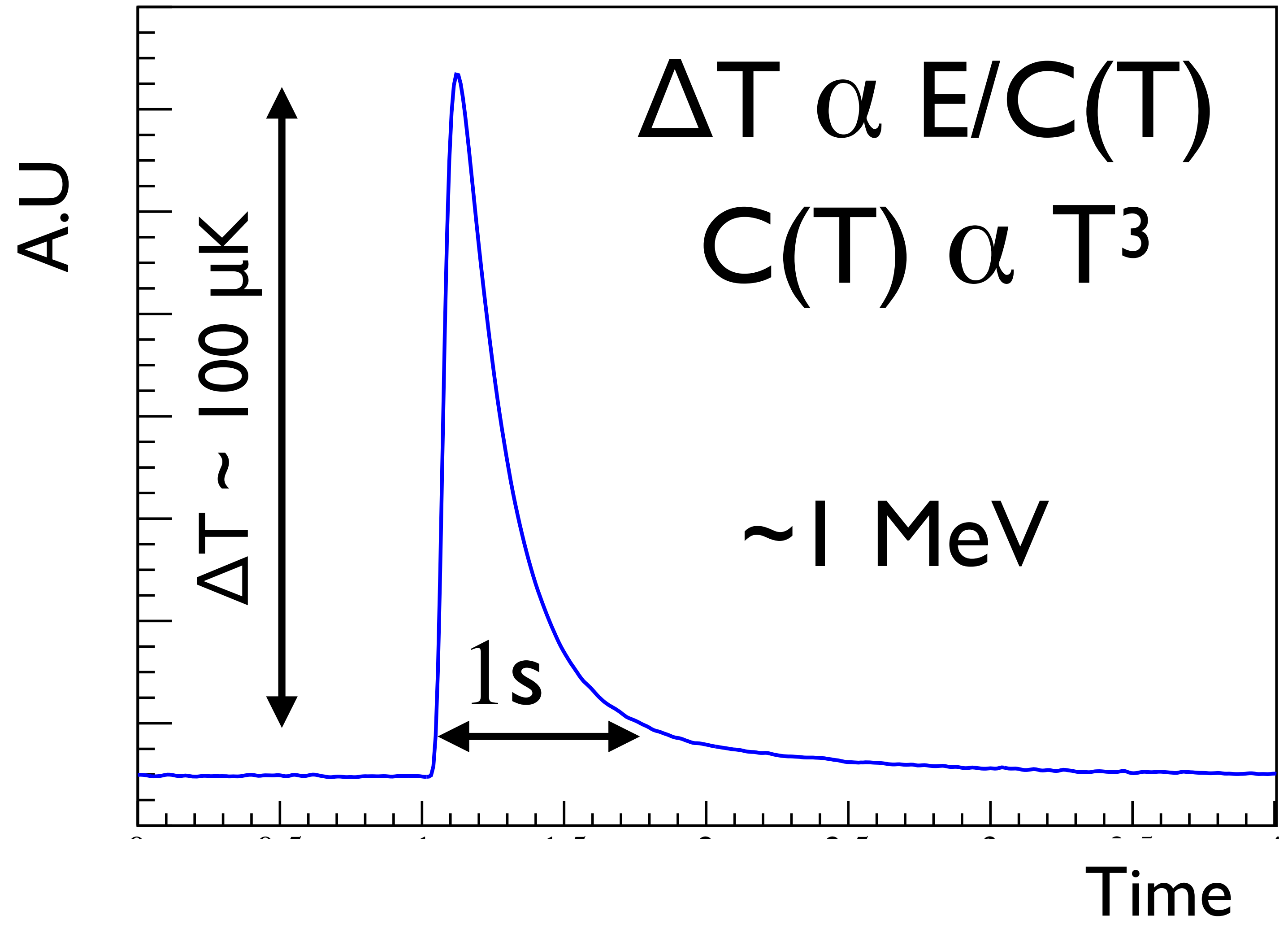
$$S_{0\nu} \propto N_a \epsilon \sqrt{\frac{Mt}{B \Delta E}}$$

Calorimetric Technique

Crystal temperature rises when energy is deposited

- Each crystal:
  - **Absorber:** 5x5x5 cm^3 TeO_2 crystal
  - **Operational temperature:** ~10 mK
  - **Thermal coupling:** PTFE holder
  - **Sensor:** Ge neutron transmutation doped (NTD) thermistor
  - **Heater:** Gain calibration

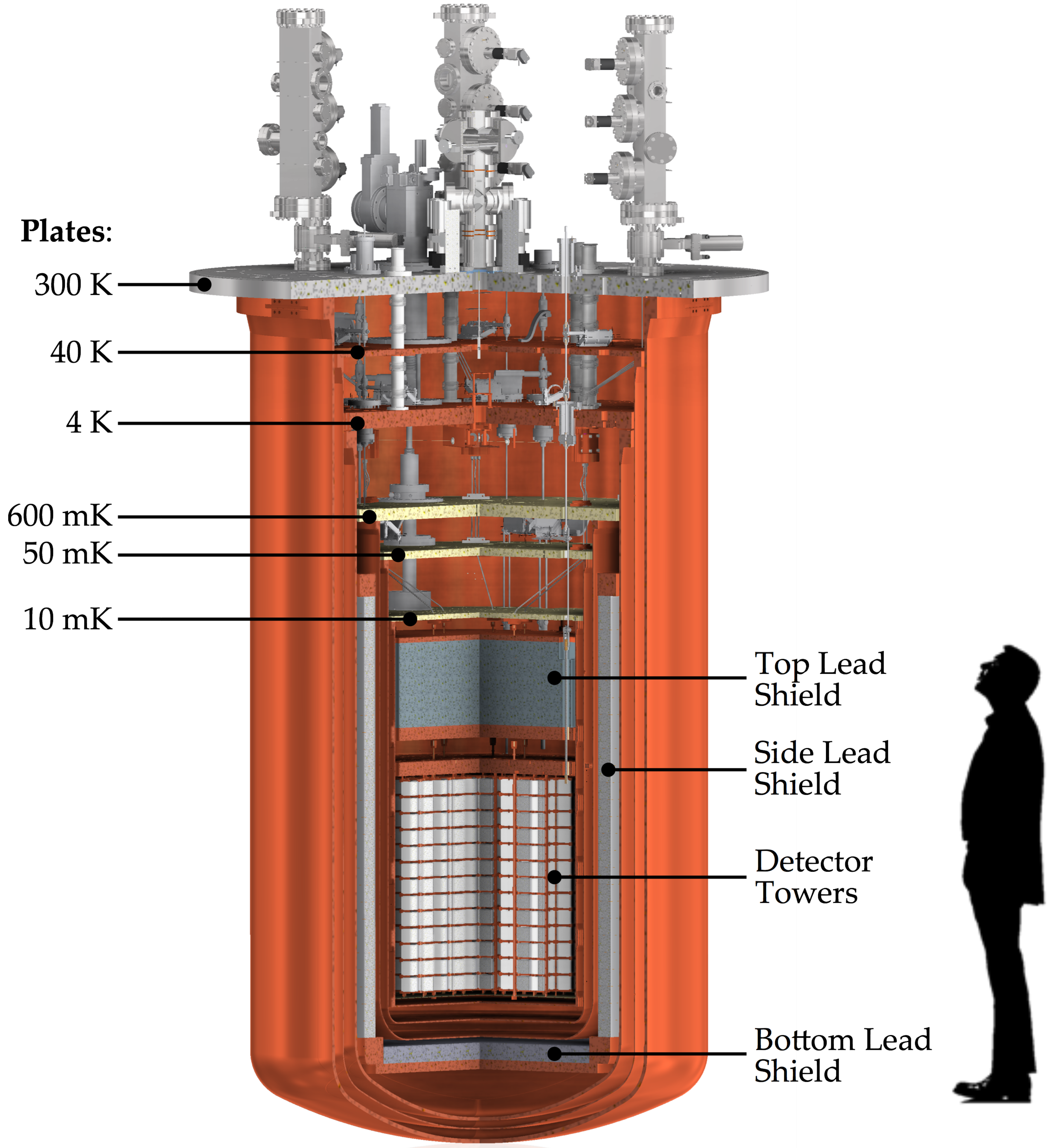




- Excellent energy resolution (~0.2% ΔE/E FWHM)
- Detector response independent of particle type
- Flexibility in $0\nu\beta\beta$ candidate choice

CUORE Cryostat

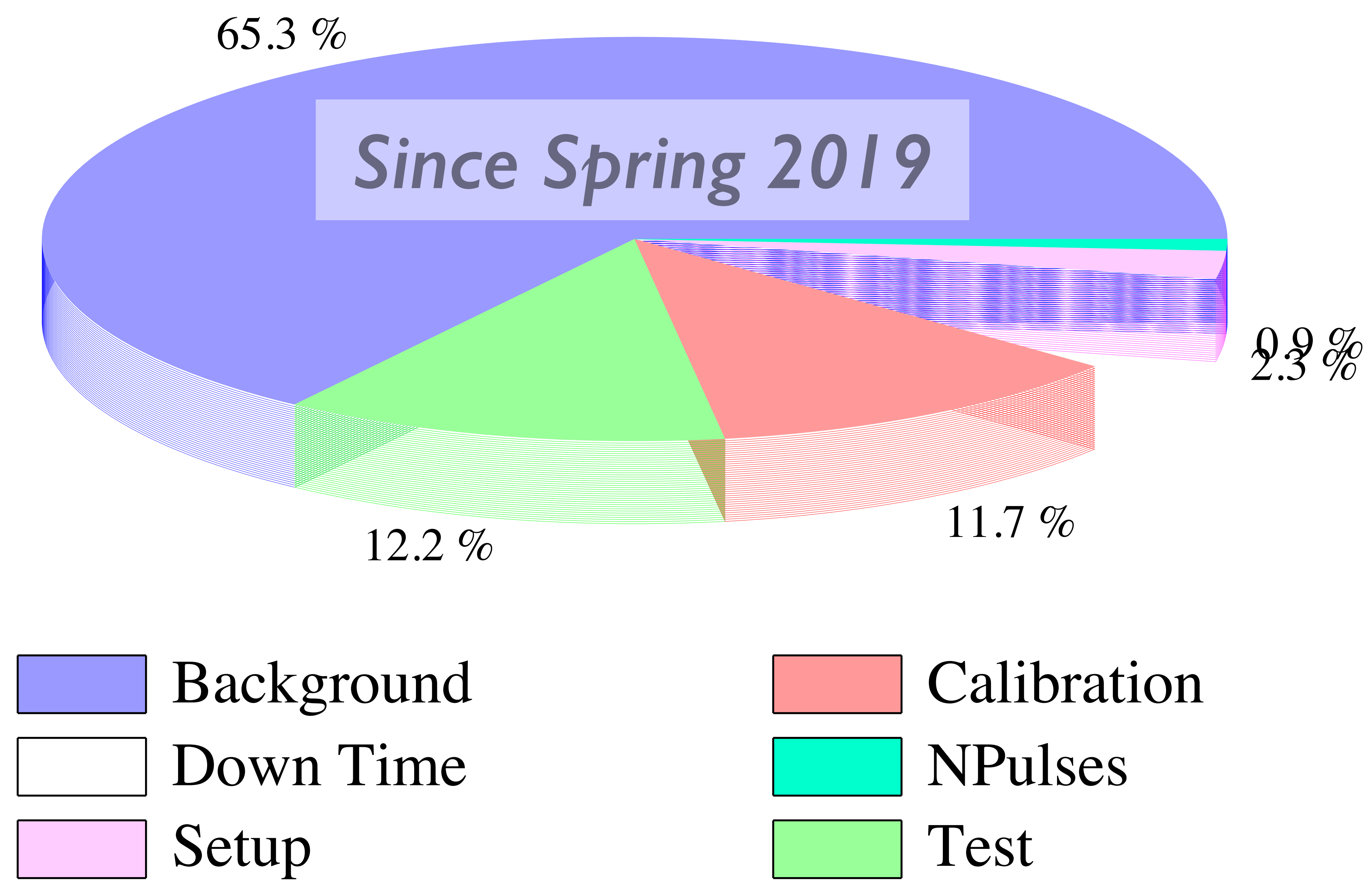
- Multiple stage cryogen-free cryostat:
  - Nested co-axial cylinders
  - Pulse Tubes for cooling **40 K** and **4 K** stages
  - Dilution Unit to cool rest of the stages
- Total mass: ~30 tonne; **~1 tonne @ 10 mK**
- Background mitigation
  - 3600 meter water equivalent natural overburden
  - Passive lead, polyethylene, and H_3BO_3 shielding
  - Careful material selection and radiopure controls
  - Active background reduction from event selection

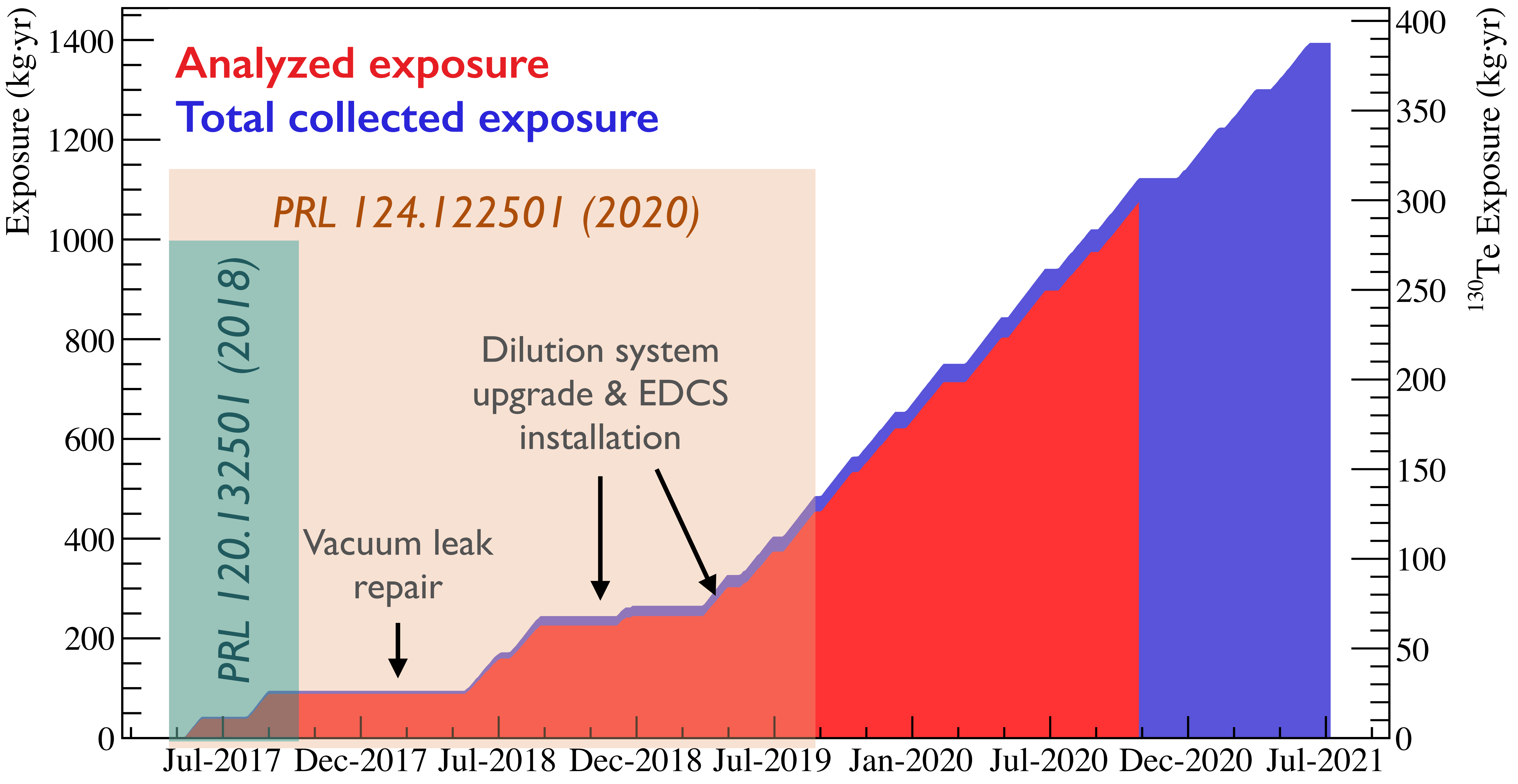


Low background cryostat maintained at low temperature with minimal vibrations

Data Taking

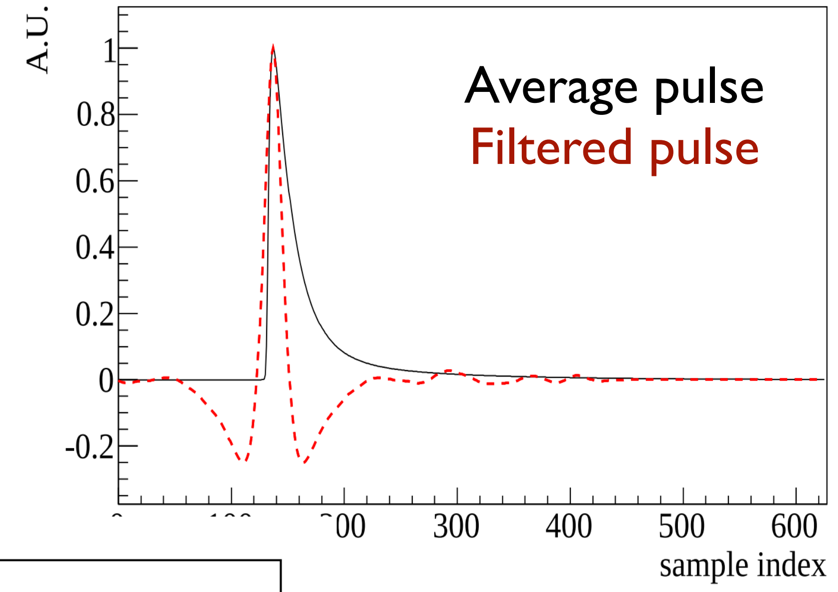
- Jan 2017: Data taking started
- 2017-2019: Low duty cycle detector optimization and upgrades
- Since 2019: Continues data taking with low downtime (~92% duty cycle)
- 18 datasets completed; each dataset ~1 month long (~ 1400 kg.yr data collected)
- 15 datasets analyzed (**1038.4** kg.yr)

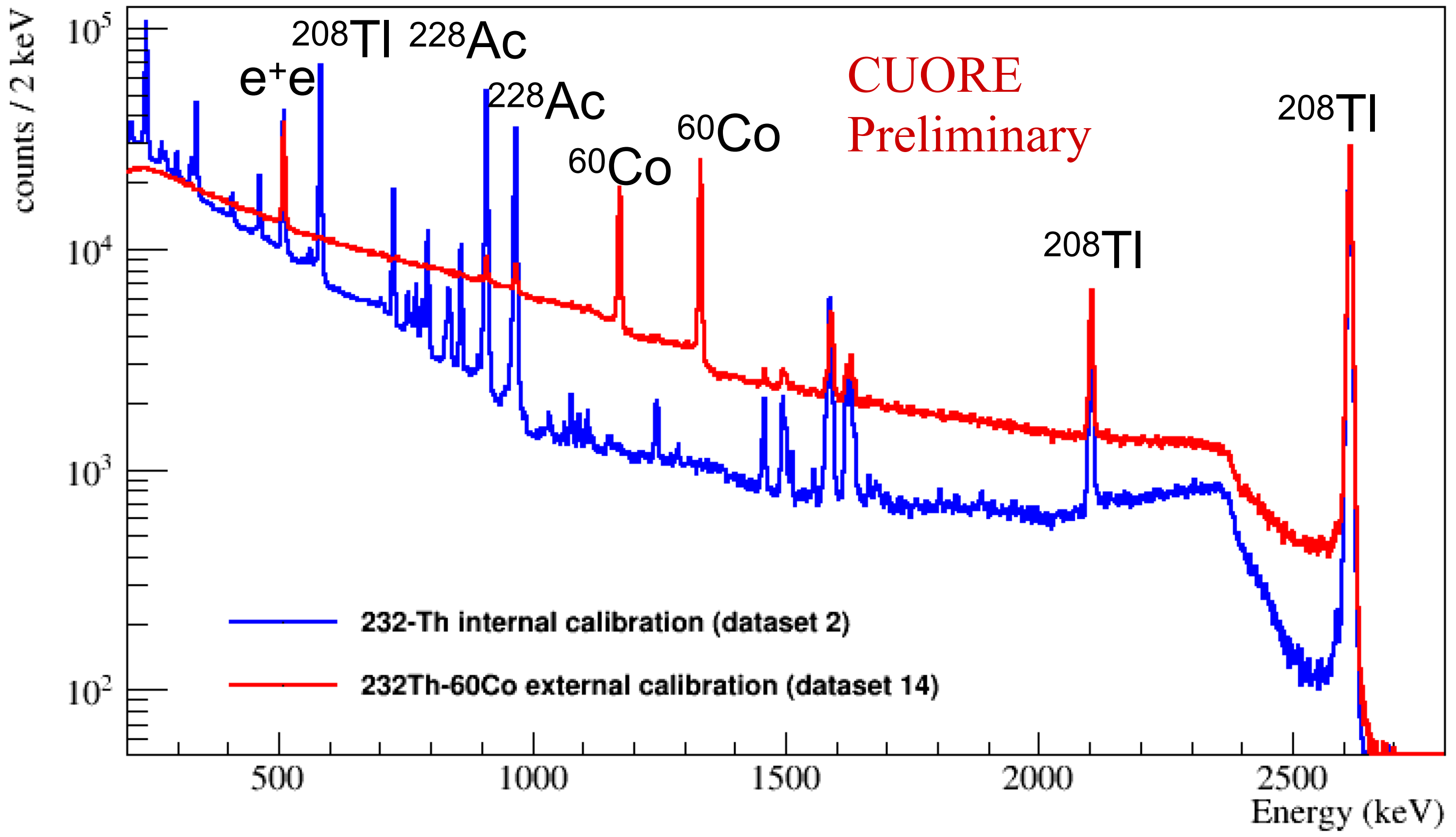


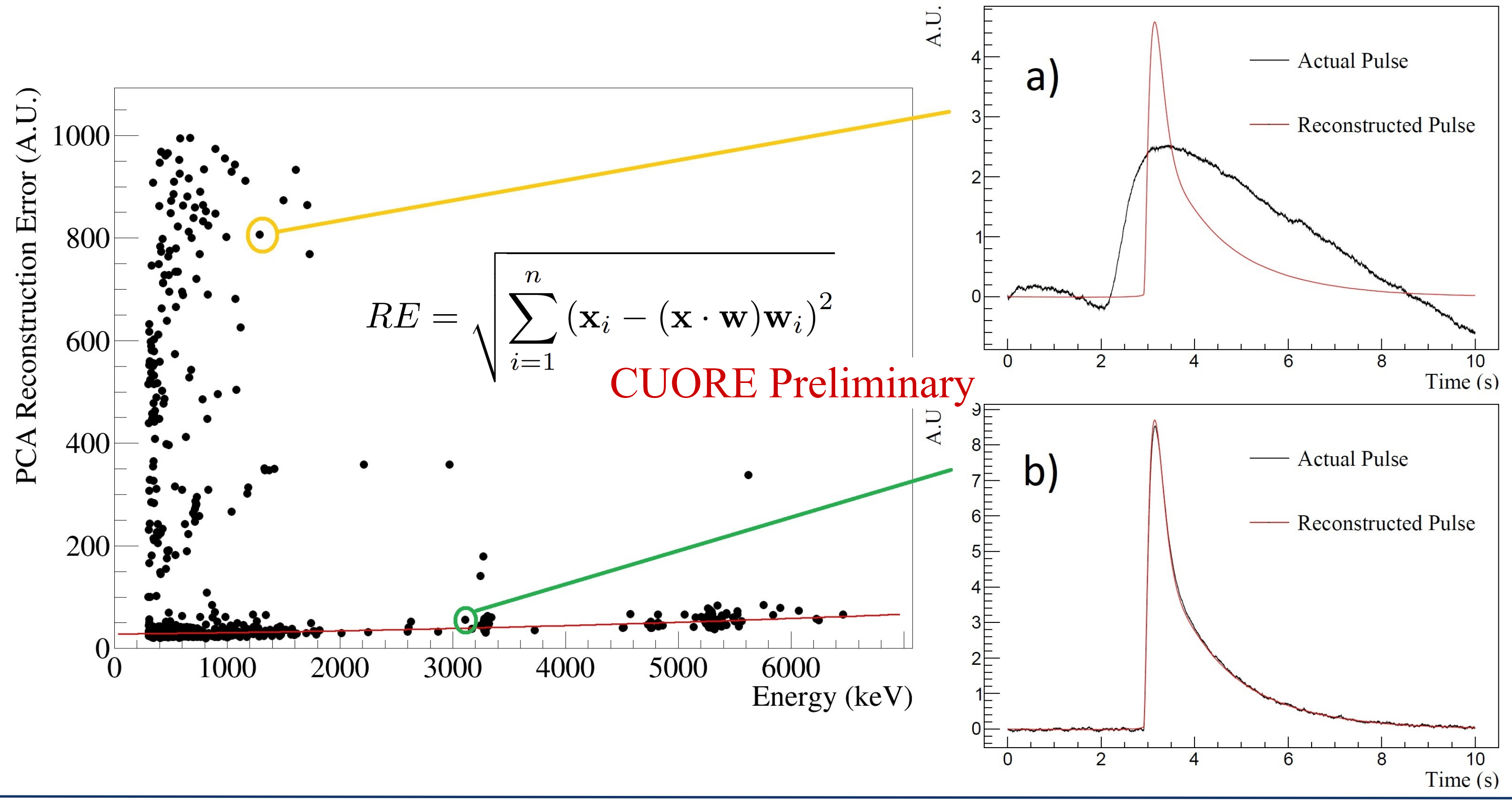


Stable data taking by CUORE since early 2019

Analysis Chain







Trigger

Amplitude evaluation

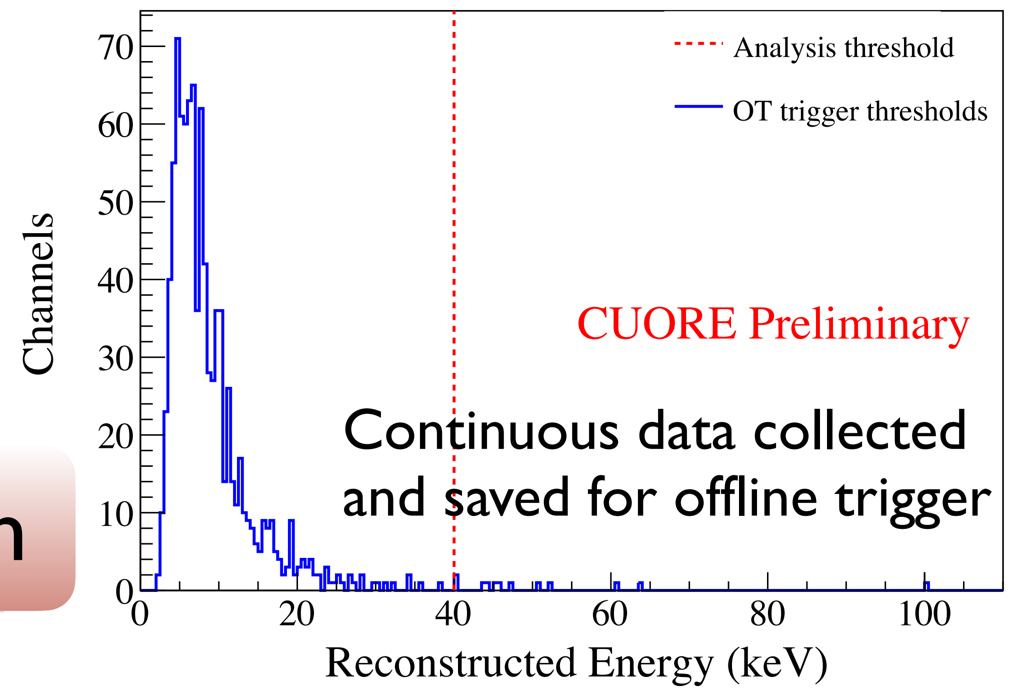
Gain stabilization

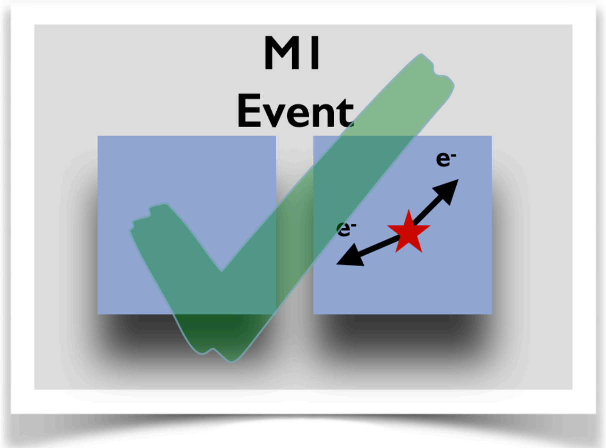
Energy calibration

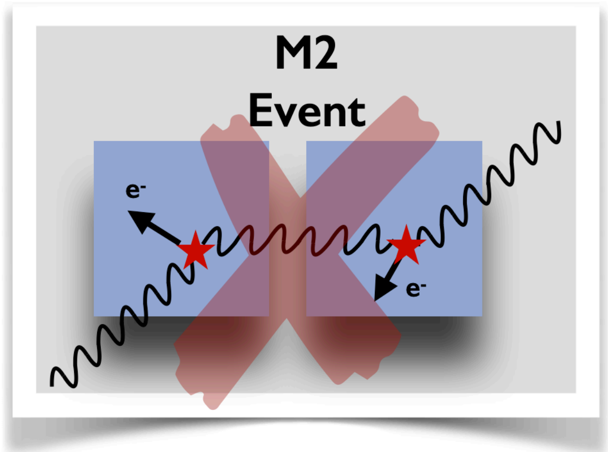
Multiplicity cut

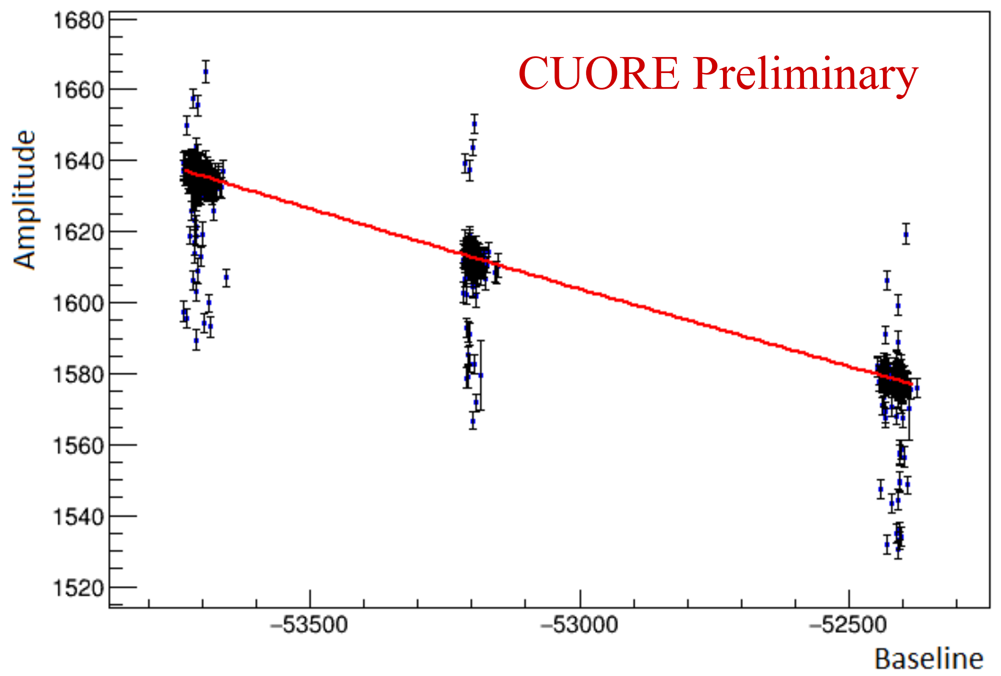
PSA

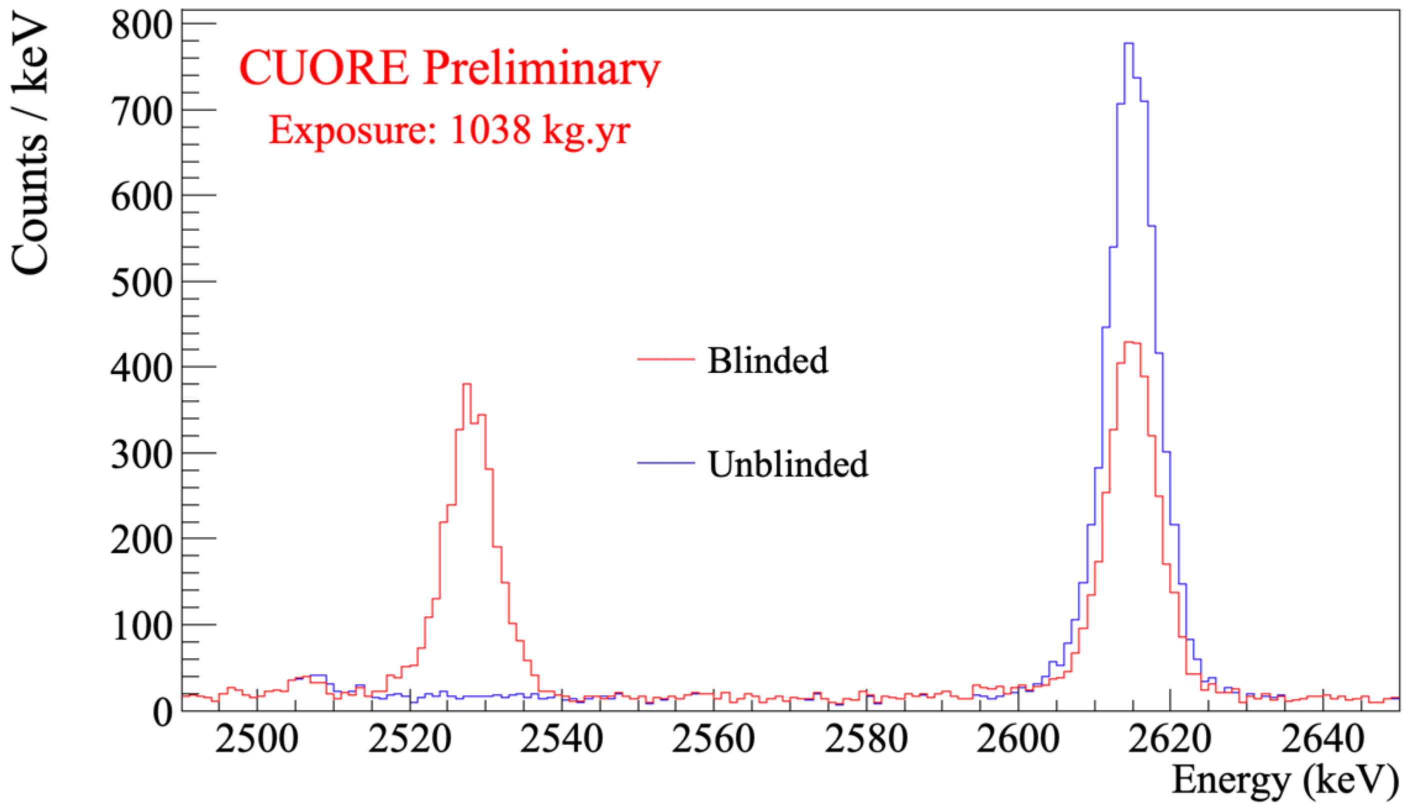
Blinding



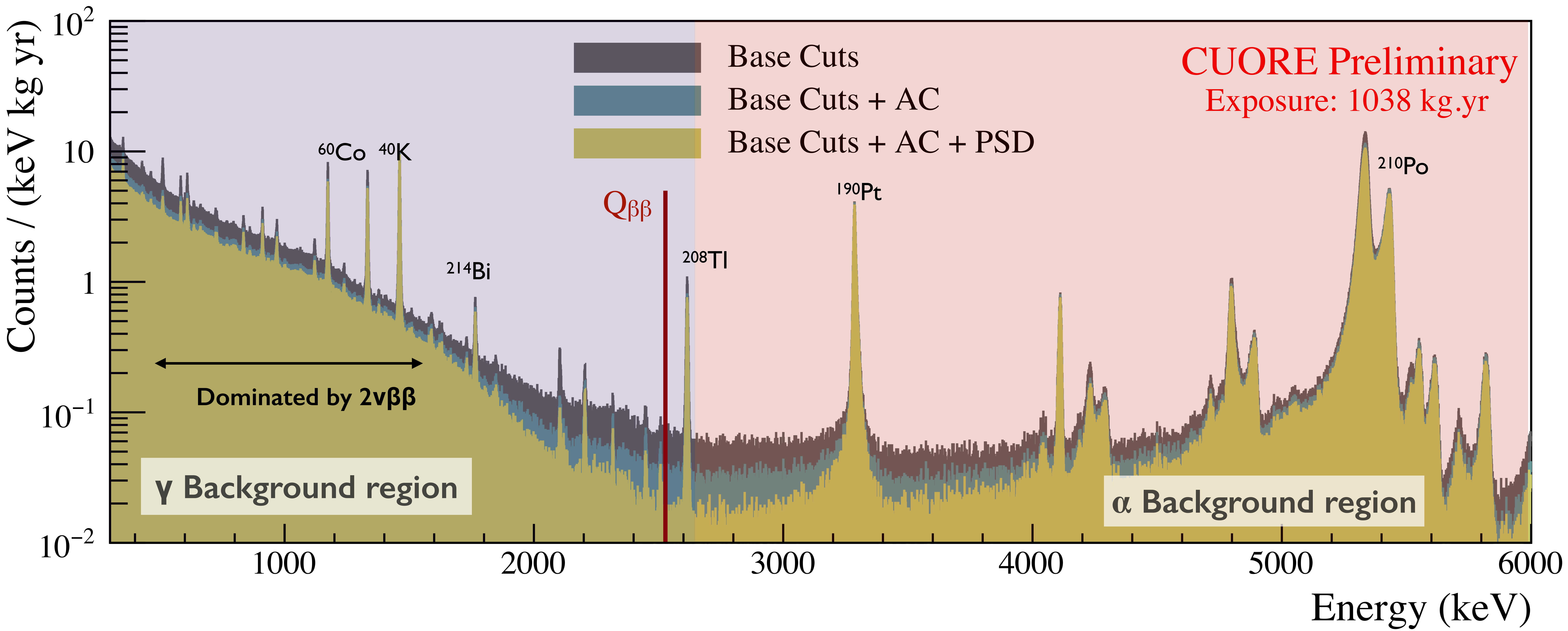








Spectrum: All Datasets

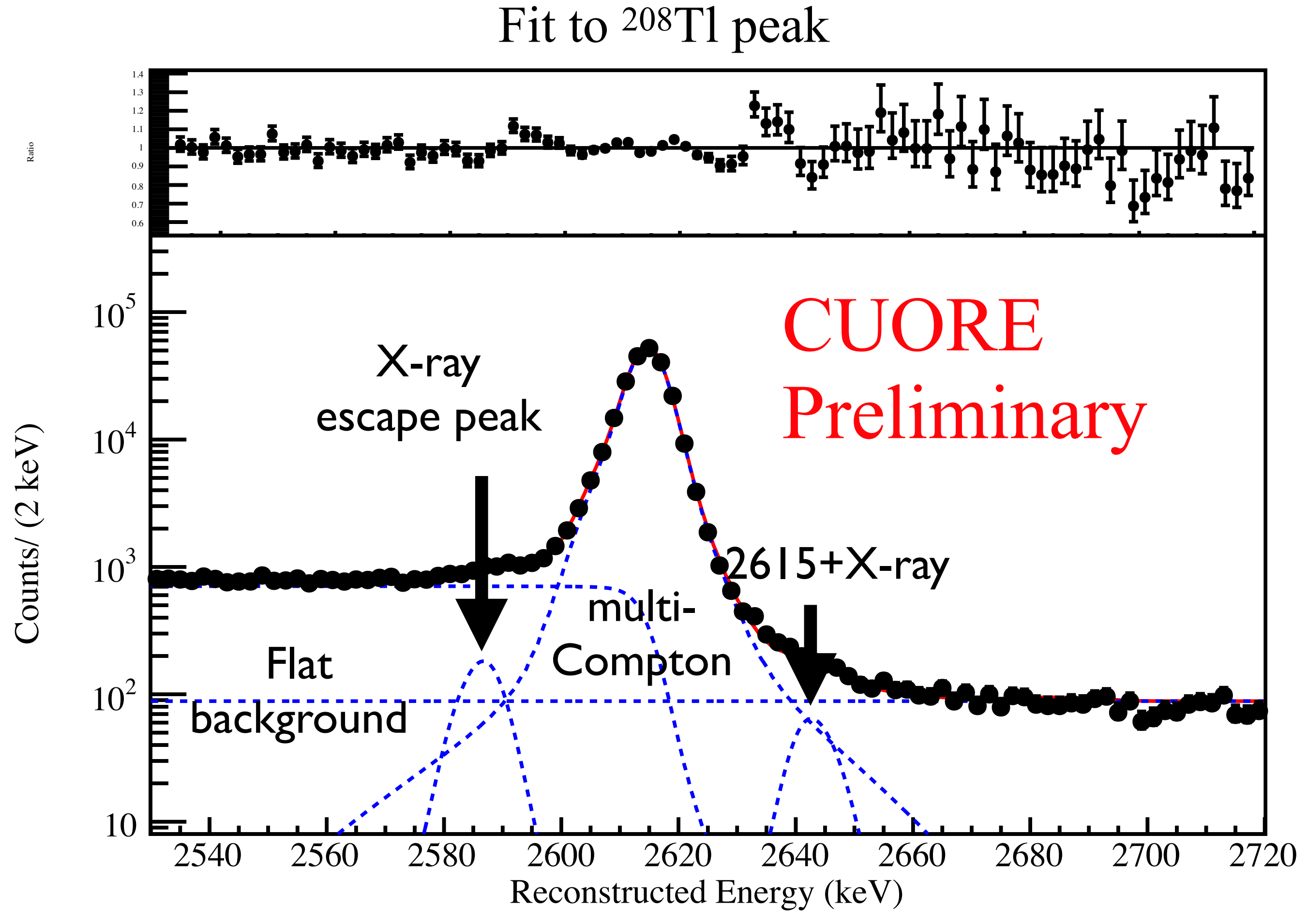


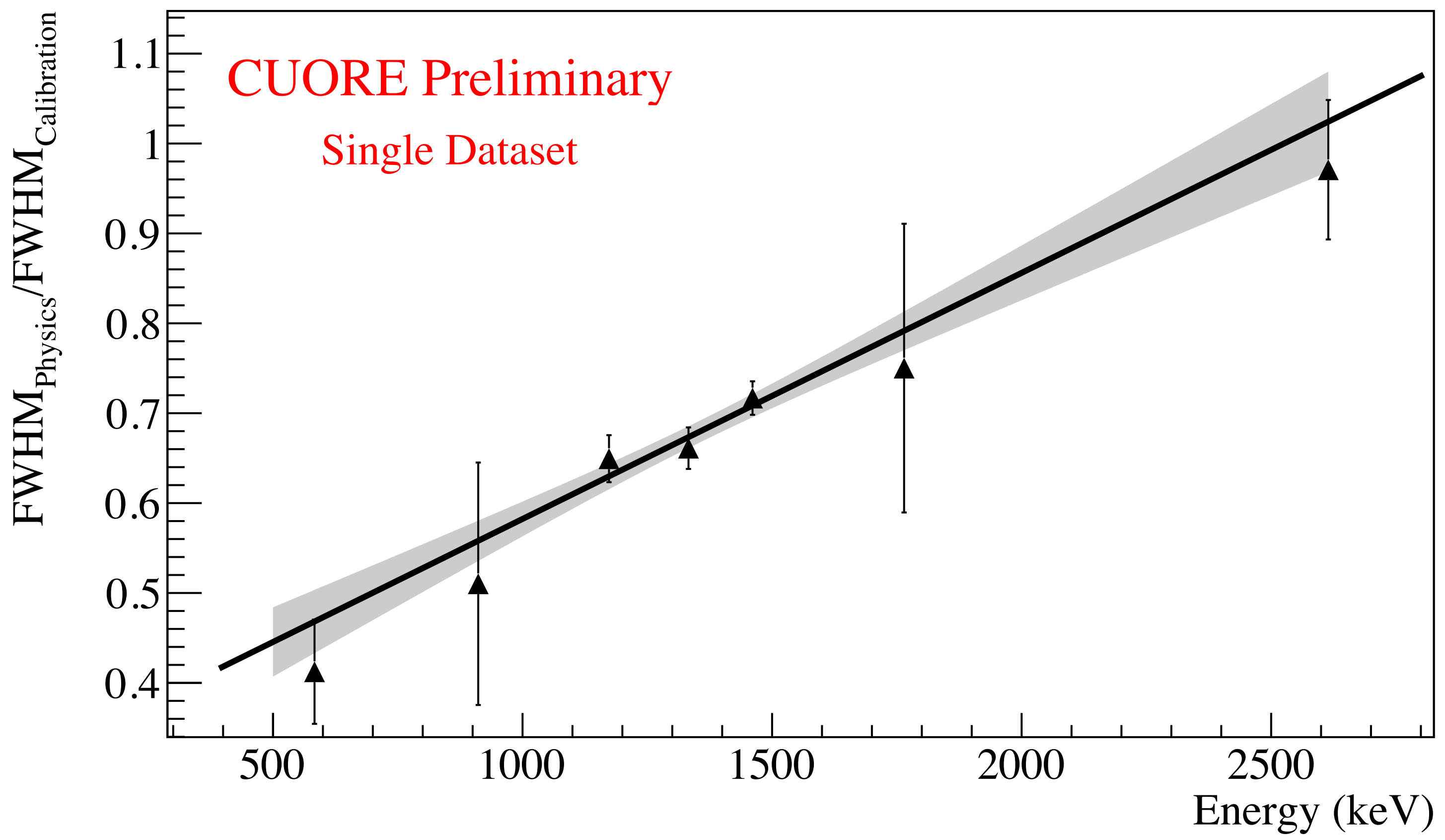
Detector Response and Efficiency

- Detector response modeled based on a fit to **2615 ^{208}Tl peak**
- Parametrized by 3 Gaussian peaks + X-ray escape + flat background + multi-Compton peak
- Determine energy bias and resolution scaling to $Q_{\beta\beta}$ by scaling this to peaks in physics data
- Efficiencies determined using a combination of MC, heaters and single-site radioactive decays

	Containment efficiency	Evaluated with MC simulations	MC	88.35 ± 0.09 %
Crystal level	**Reconstruction efficiency**	Comprises: ➔ trigger ➔ event reconstruction ➔ pile-up identification	Heater	96.418 ± 0.002 %
Dataset level	**Anti-coincidence efficiency**	Quantifies the probability of properly identifying a single-crystal event	^{40}K	99.3 ± 0.1 %
Dataset level	**Pulse-shape discrimination efficiency**	Fraction of events passing a multi-dimensional cut on 6 pulse-shape variables	M1 ^{40}K 2x^{60}C ^{208}Tl	96.4 ± 0.2 %

Total analysis efficiency 92.4 ± 0.2%





FWHM at 2615 keV in calibration data - 7.78(3) keV

FWHM at $Q_{\beta\beta}$ in physics data - 7.8(5) keV

Bias at $Q_{\beta\beta}$ < 0.7 keV

Fit to ROI

CUORE

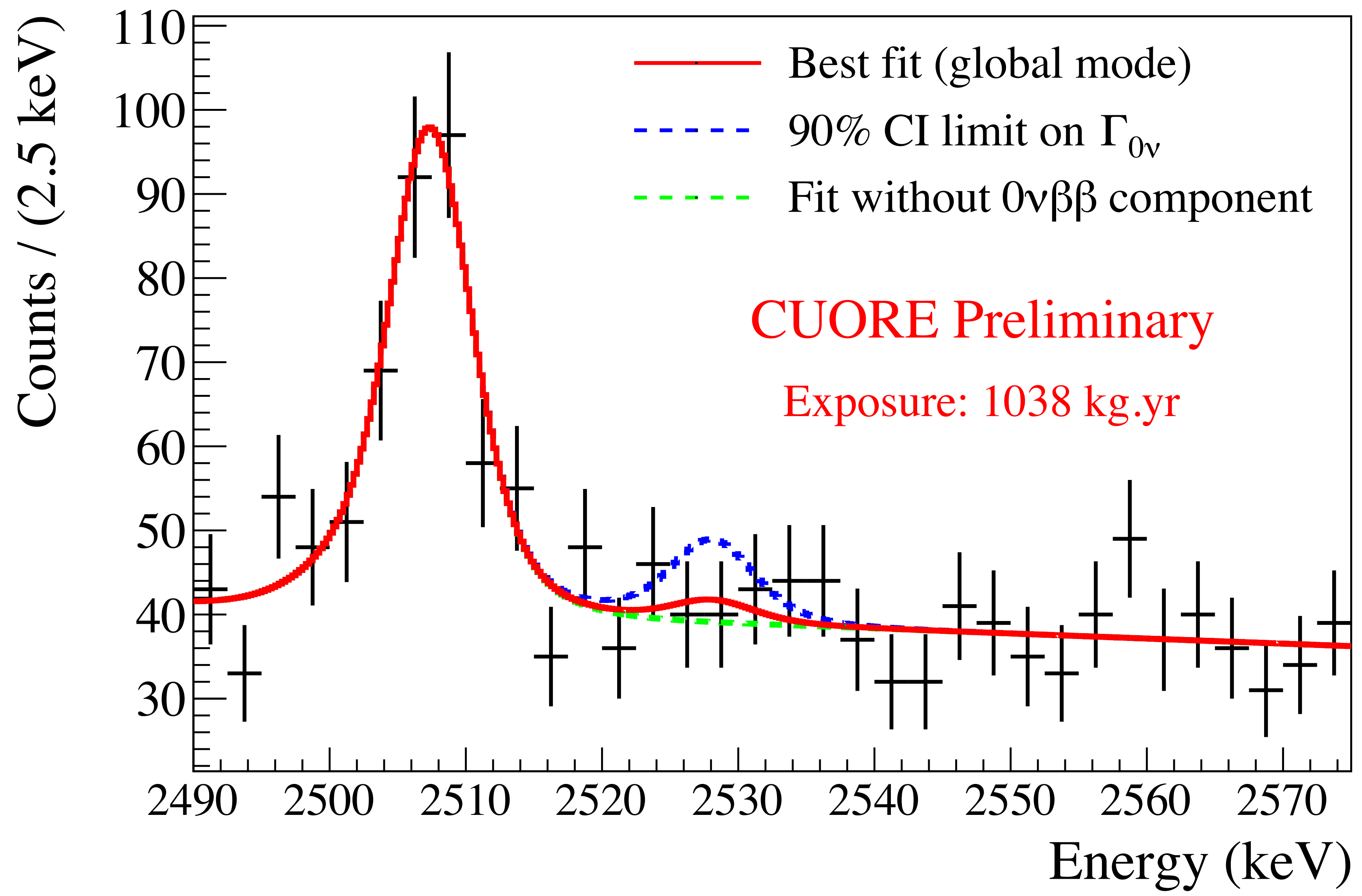
- Unbinned Bayesian fit using Bayesian Analysis Toolkit (BAT)
- Fit region: [2490, 2575] keV
- Systematics implemented as nuisance parameters
- No evidence of 0νββ
- Best fit rate: **(0.9 ± 1.4)x10^{-26}** yr^{-1}
- Background index = **1.49(4)x10^{-2}** cts/keV/kg/yr
- $T^{0\nu}_{1/2}$ > **2.2 x10^{25}** yr at 90% C.I
- Median expected $T^{0\nu}_{1/2}$ = **2.8 x10^{25}** yr at 90% C.I

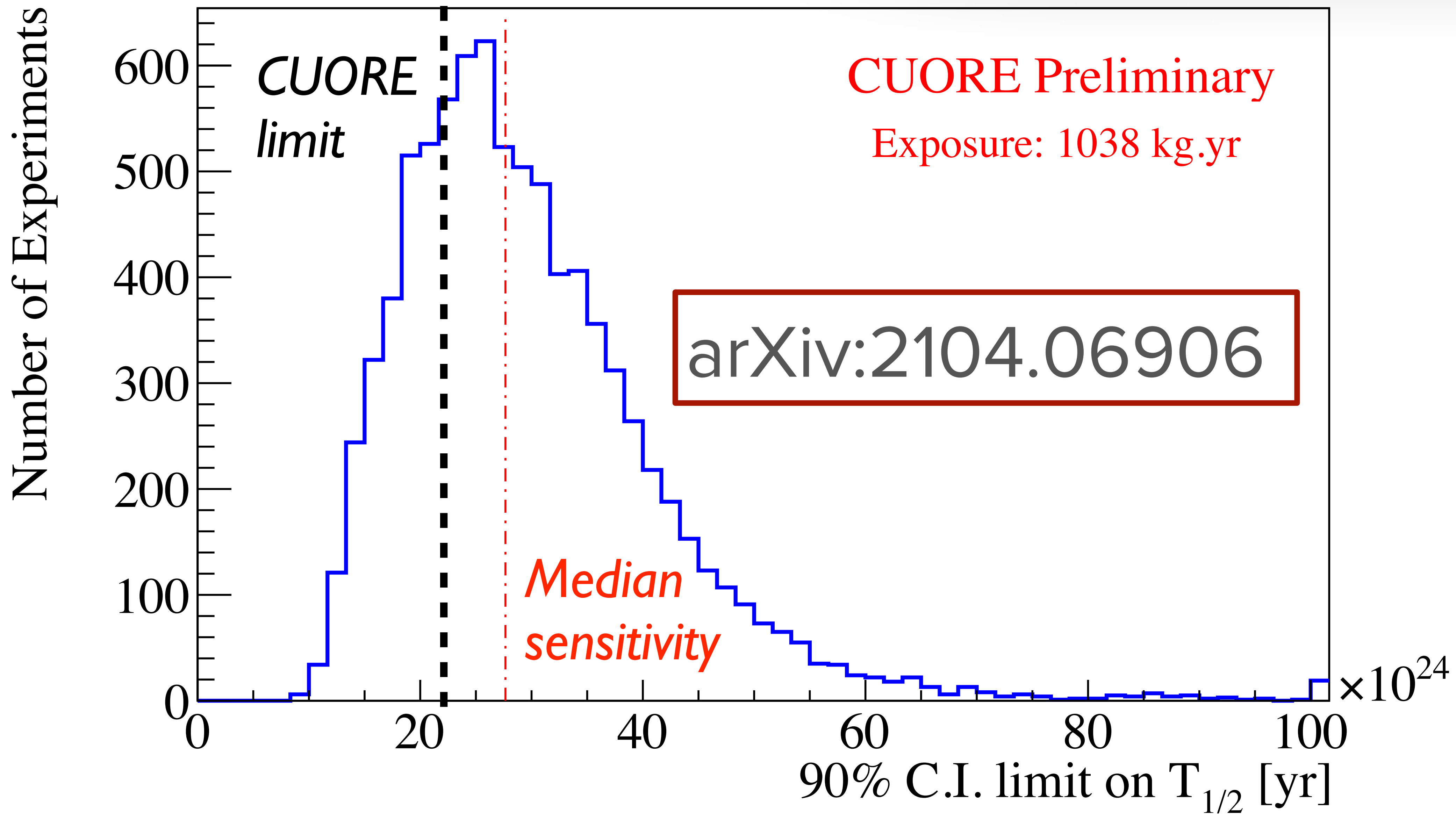
Fit parameters:

- 0νββ decay rate @ 2527.518 keV
- ^{60}Co sum peak amplitude
- Background index
- Background slope

Systematics:

- Analysis efficiencies
- Containment efficiency
- Energy scale
- Energy resolution
- $Q_{\beta\beta}$
- ^{130}Te abundance

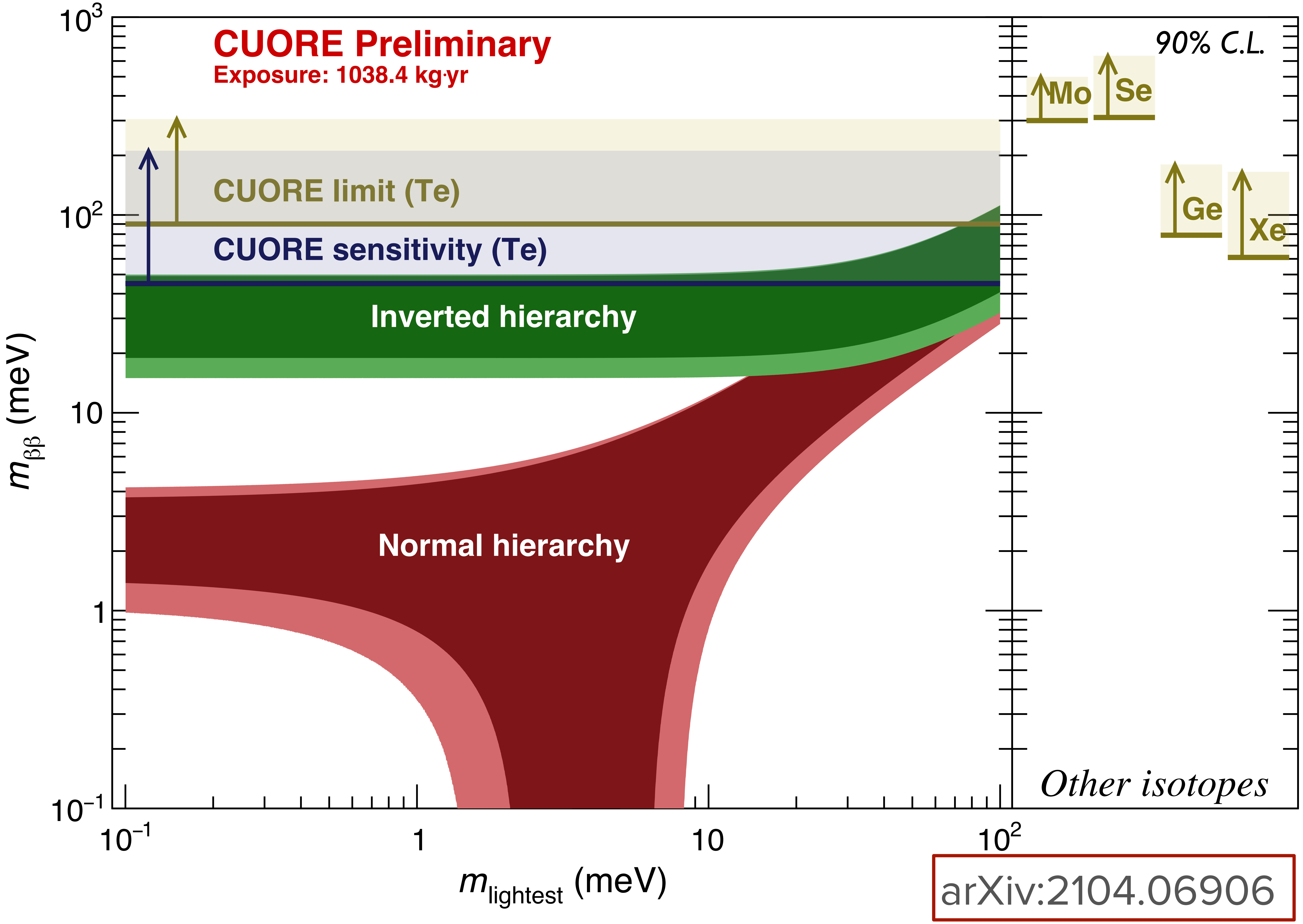




Limit on Effective Majorana Mass

CUORE

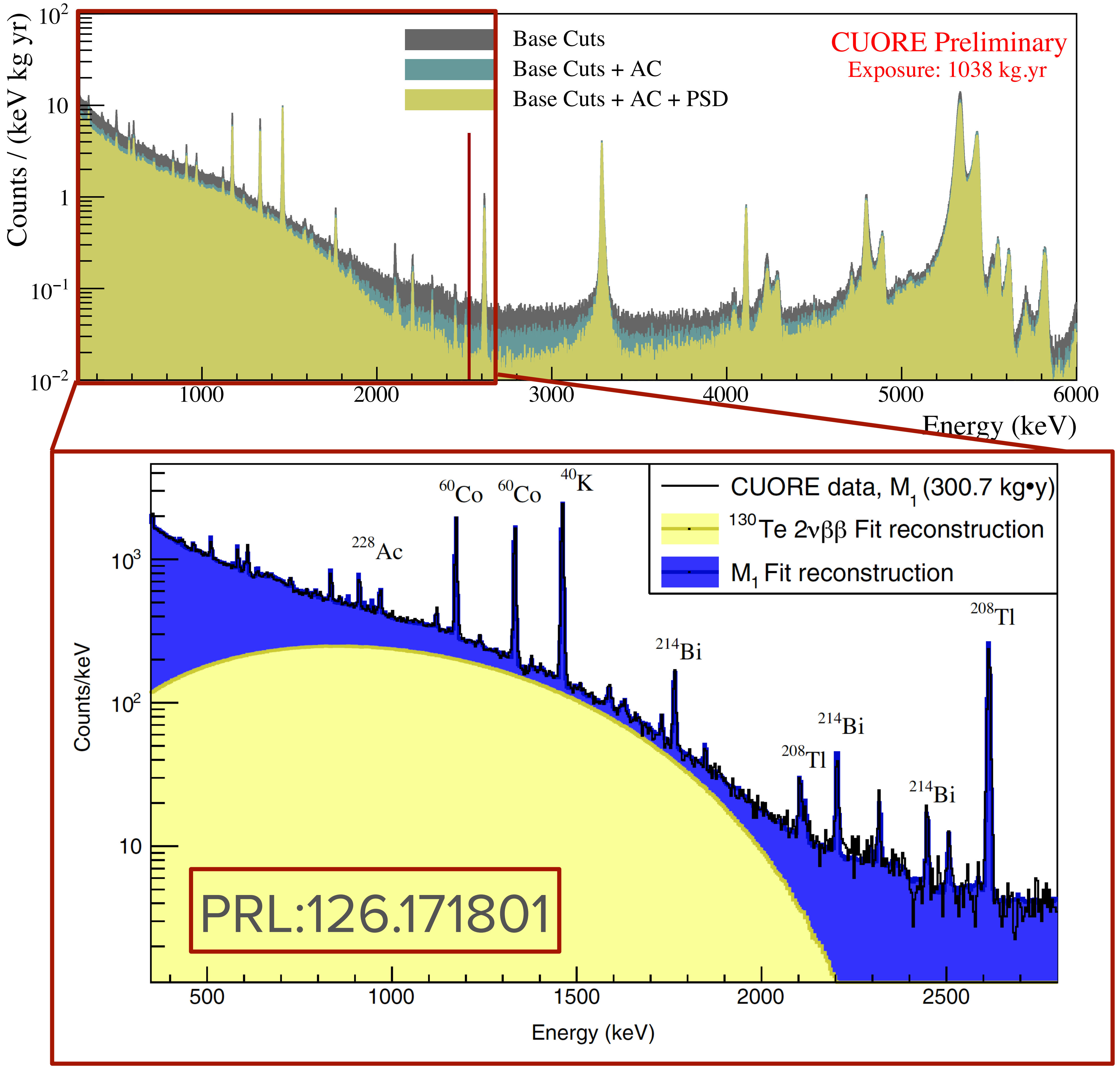
- $T^{0\nu}_{1/2}$ > **2.2 x10²⁵** yr at 90% C.I
- Assuming light neutrino exchange: $m_{\beta\beta}$ < **90 - 305 meV**
- Uncertainities in nuclear matrix elements dominates the range
- Sensitivity (5 yr data taking): ^{130}Te $T^{0\nu}_{1/2}$ > **9.0 x10²⁵** yr $m_{\beta\beta}$ < **50 - 130 meV**



arXiv:2104.06906

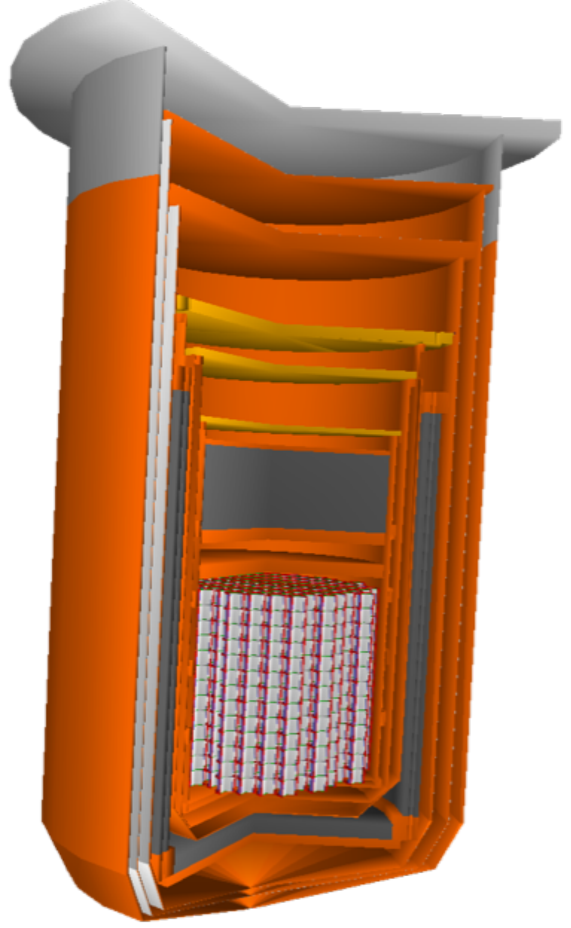
^{130}Te $2\nu\beta\beta$ Decay Half-life

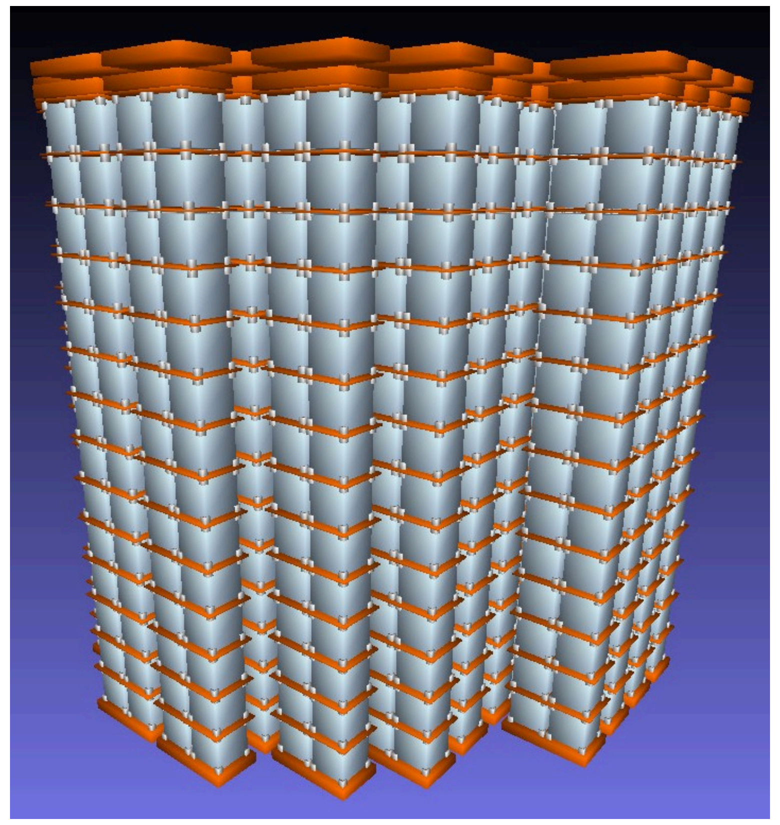
- $2\nu\beta\beta$ decays deposit energy primarily (~90%) in a single channel while backgrounds deposit in multiple channels
- Develop CUORE background model: 60 radioactive contaminants + muons + $2\nu\beta\beta$
- Perform simultaneous Bayesian fit to 62 MC simulated spectra
- $2\nu\beta\beta$ rate extracted as marginalized posterior PDF
- Most precise measurement of ^{130}Te half-life with exposure of 300.7 kg · yr
- Refined background model in preparation

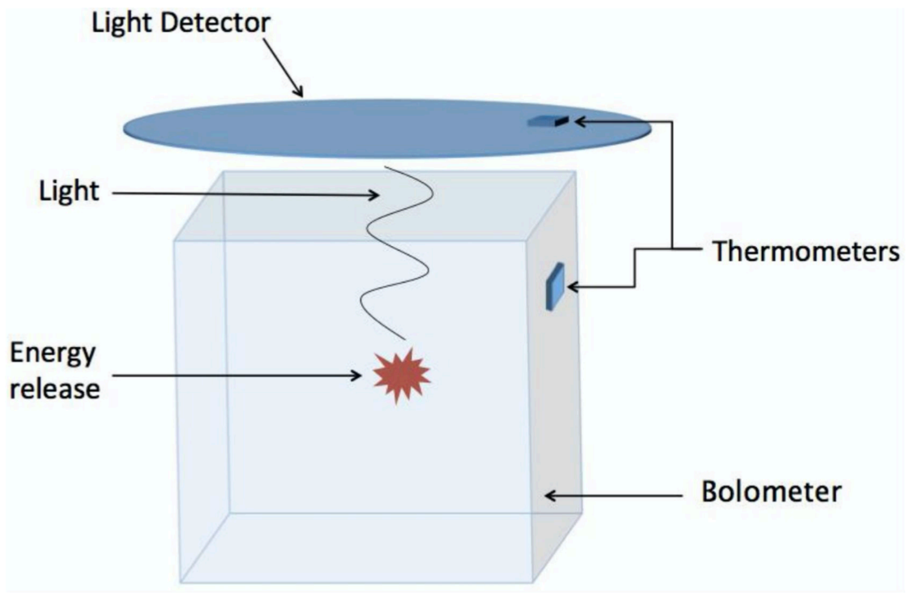


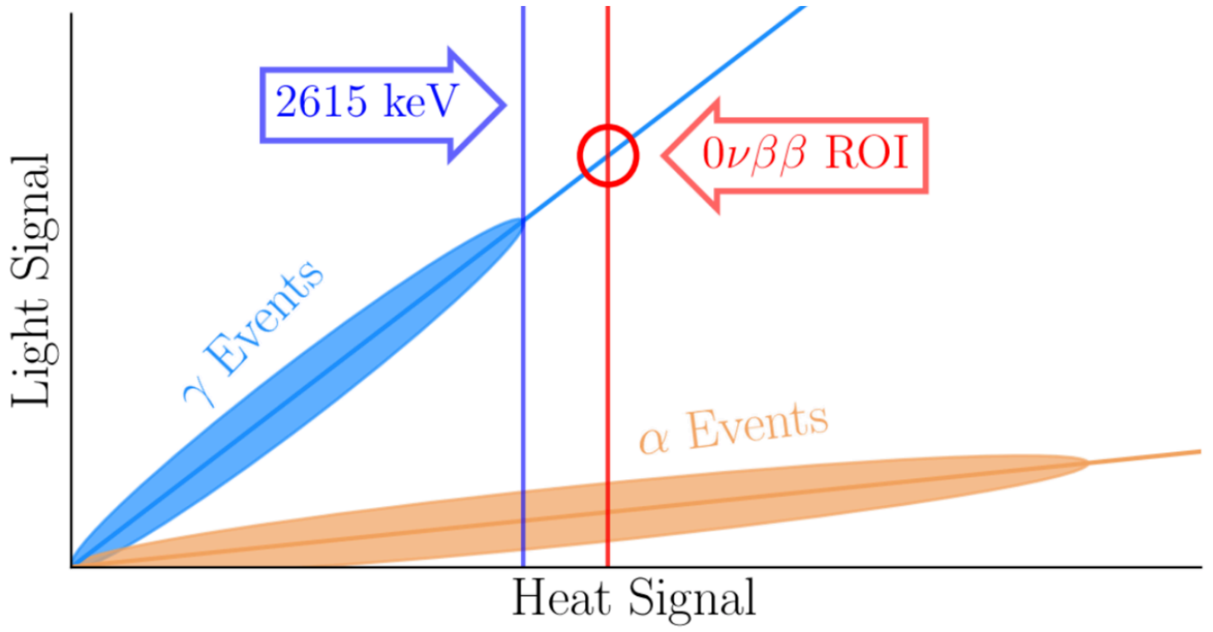
$$T^{2\nu}_{1/2}(^{130}Te) = 7.71\ ^{+0.08\,(stat)\ +0.12\,(syst)}_{-0.06\,(stat)\ -0.15\,(syst)} \times 10^{20}\ yr$$

CUPID: CUORE Upgrade with Particle Identification

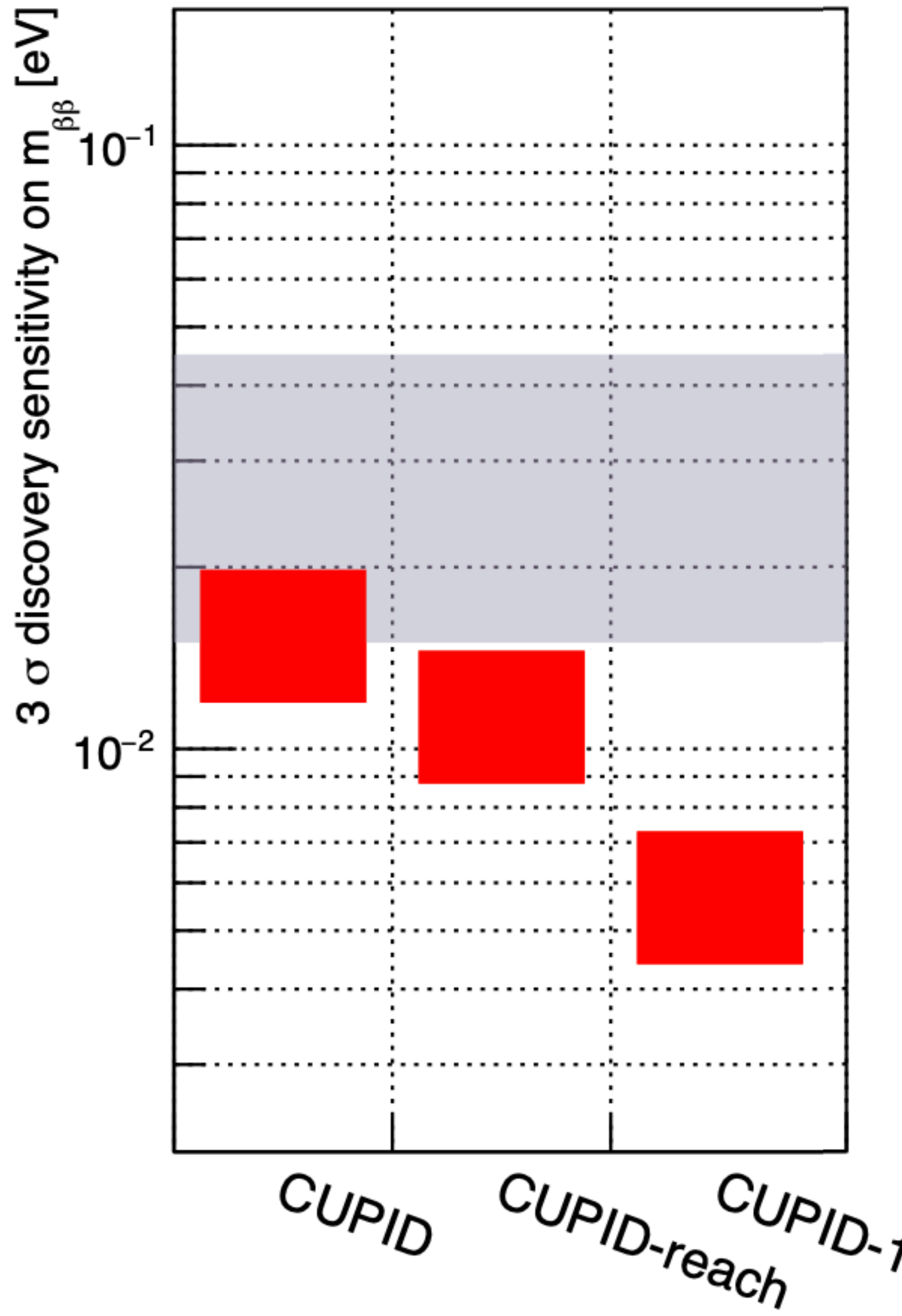








- ~**1596** $Li_2{}^{100}MoO_4$ scintillating crystals (~250 kg of ^{100}Mo)
  - Instrument each crystal with a light detector for particle ID
- Use existing CUORE cryostat
- Low background targeted (**10^{-4} cts/keV/kg/yr**):
  - Active α discrimination
  - $Q_{\beta\beta}$ = **3034** keV (above all gamma backgrounds)
  - Muon veto system
- Builds on experience from CUPID-0 and CUPID-MO
- Projected sensitivity: **12 - 20 meV** with ~ 240 kg of ^{100}Mo
- Improvement in sensitivity and change in isotopes possible



Conclusions

- CUORE is the largest ultra-cryogenic calorimeter searching for 0νββ
- CUORE started data taking in 2017 and continuing stable data taking since early 2019 at ~ 50kg.yr/month
- More than 1 tonne.yr data analyzed
- Limits placed on ^{130}Te $\mathbf{T^{0\nu}_{1/2} > 2.2 \times 10^{25}}$ yr and $\boldsymbol{m_{\beta\beta} <}$ **90- 305 meV**
- $\mathbf{T^{2\nu}_{1/2} = 7.71 \times 10^{25}}$ **yr** measured; most precise measurement so far
- CUORE paves way for the next generation cryogenic 0νββ experiments (CUPID)

Thank you