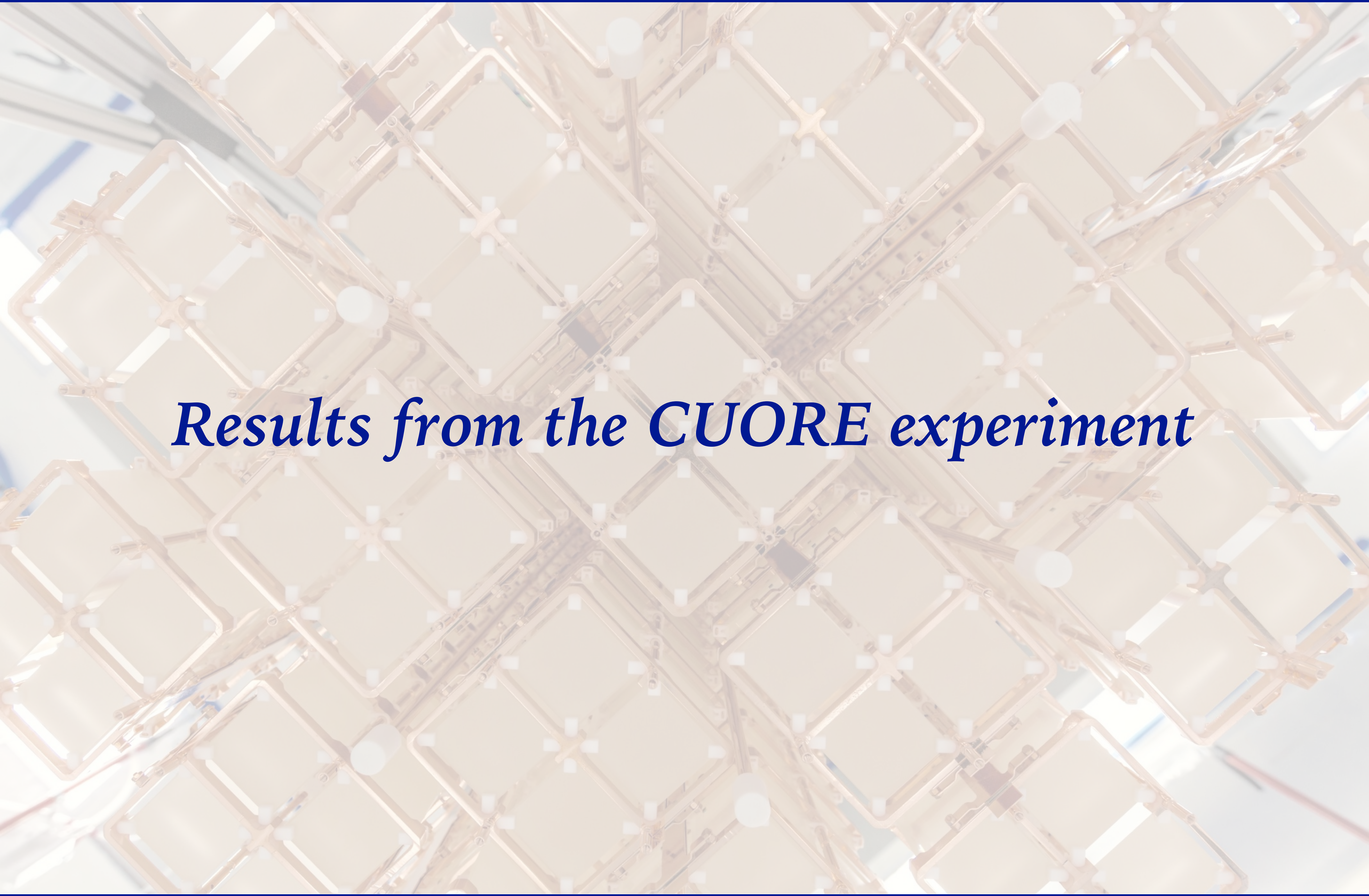
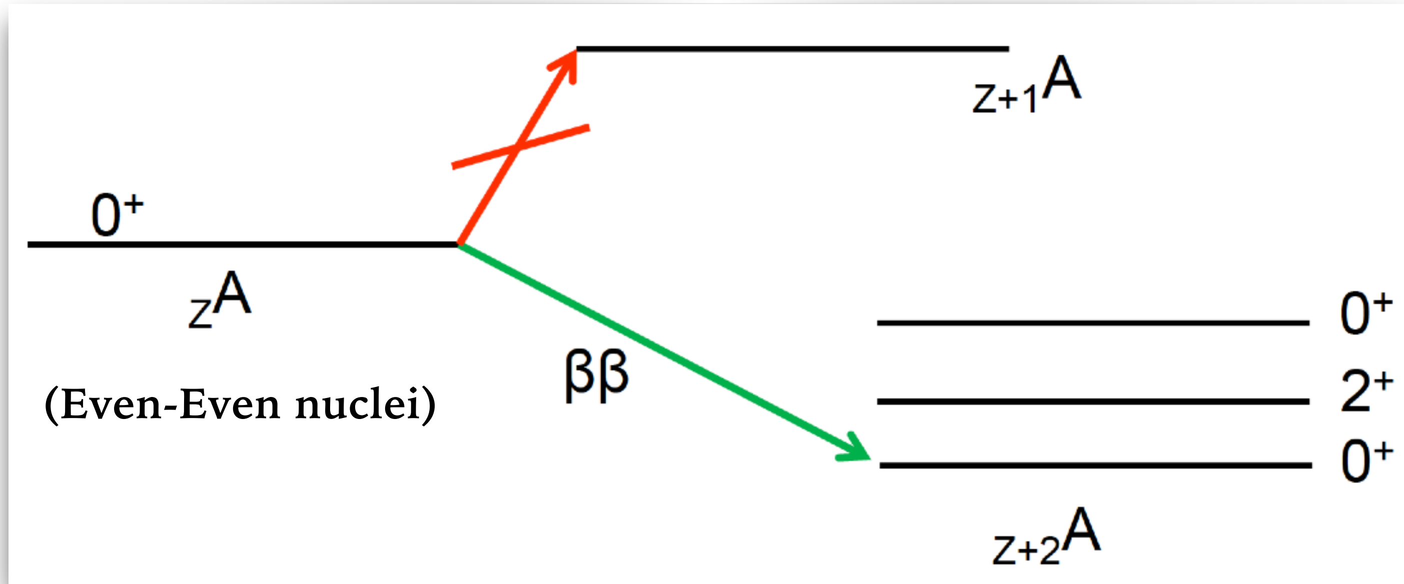


Results from the CUORE experiment

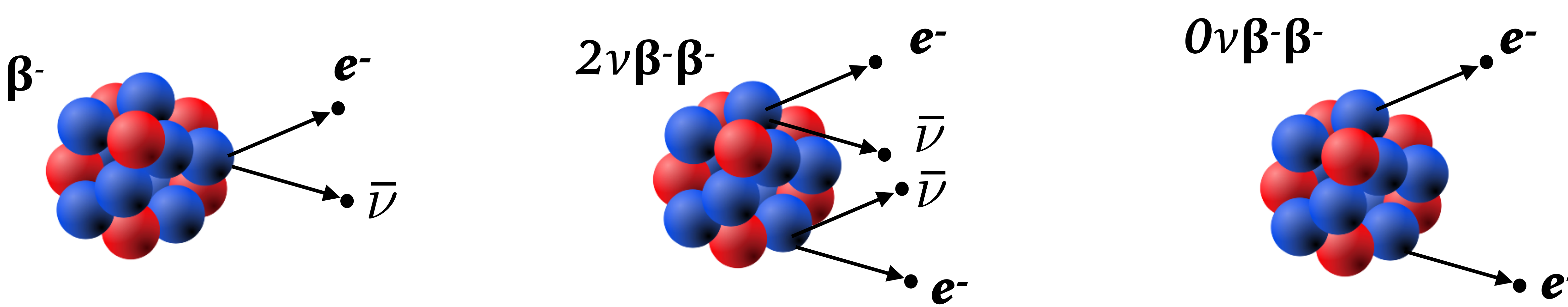
University of California, Berkeley

Vivek Singh

DOUBLE BETA DECAY



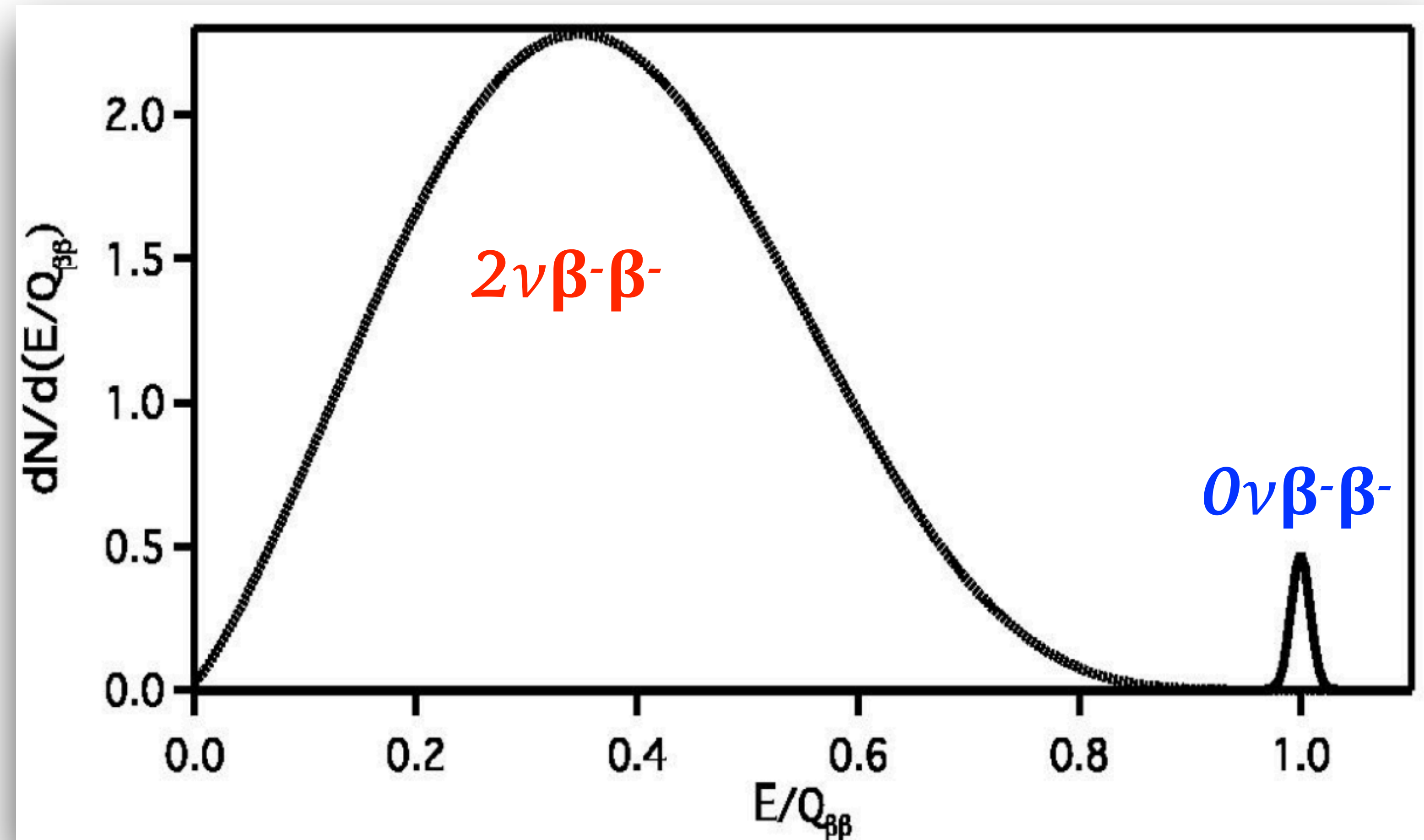
- 2nd order weak interaction
- Normal beta decay suppressed by Q value or J^π



Processes explained by the Standard Model

- *Lepton number not conserved*
- *Occurs if neutrinos have mass and are their own antiparticle*

EXPERIMENTAL SIGNATURE



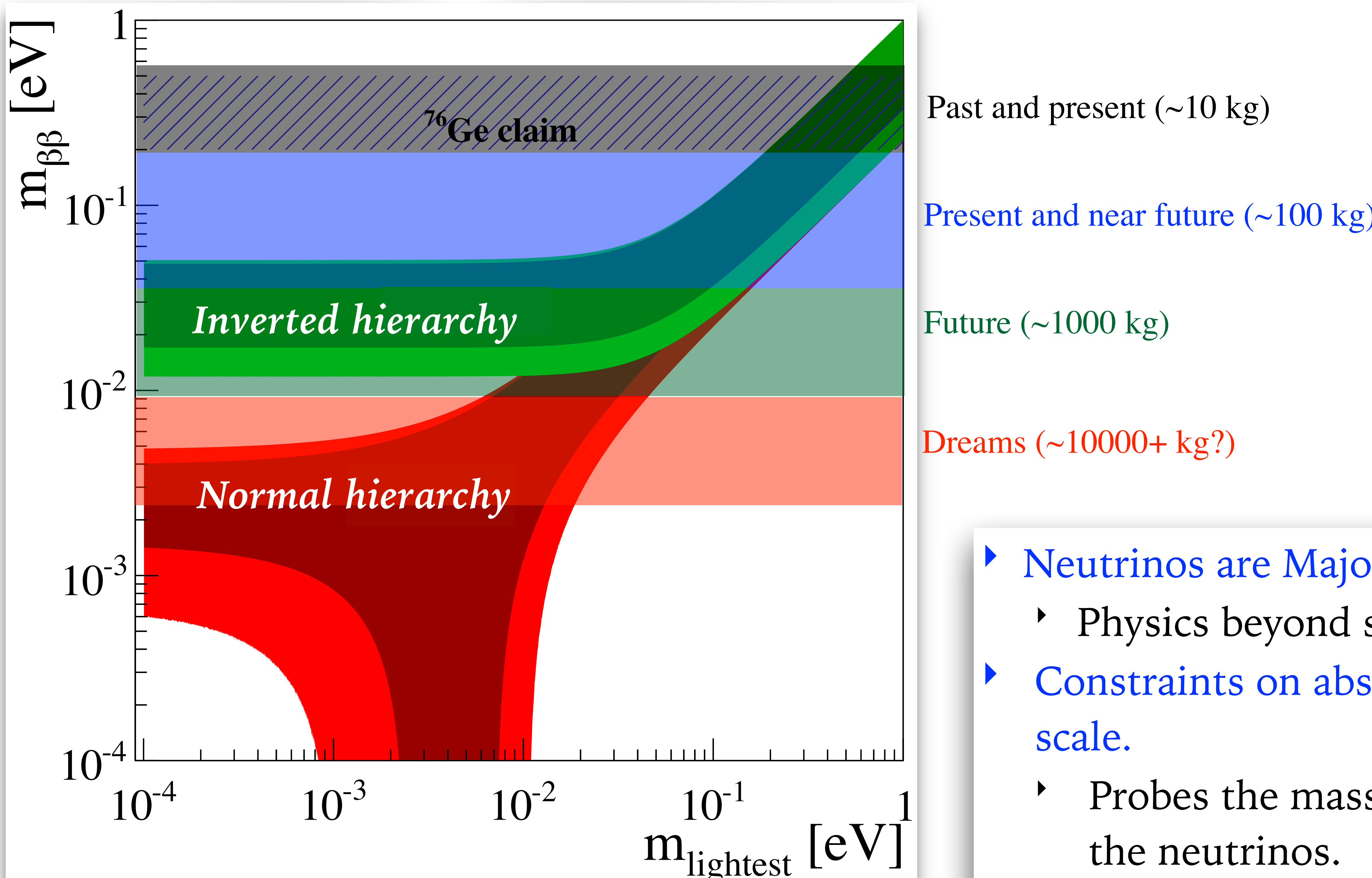
- Sum energy of emitted electrons: Peak at Q value of the decay.

Sensitivity of the search →

$$T^{0\nu}_{1/2}(n_\sigma) = \frac{ln2}{n_\sigma}\frac{N_A\, i\, \varepsilon}{A} f(\Delta E)\sqrt{\frac{M\, t}{B\, \Delta E}}$$

IMPLICATIONS

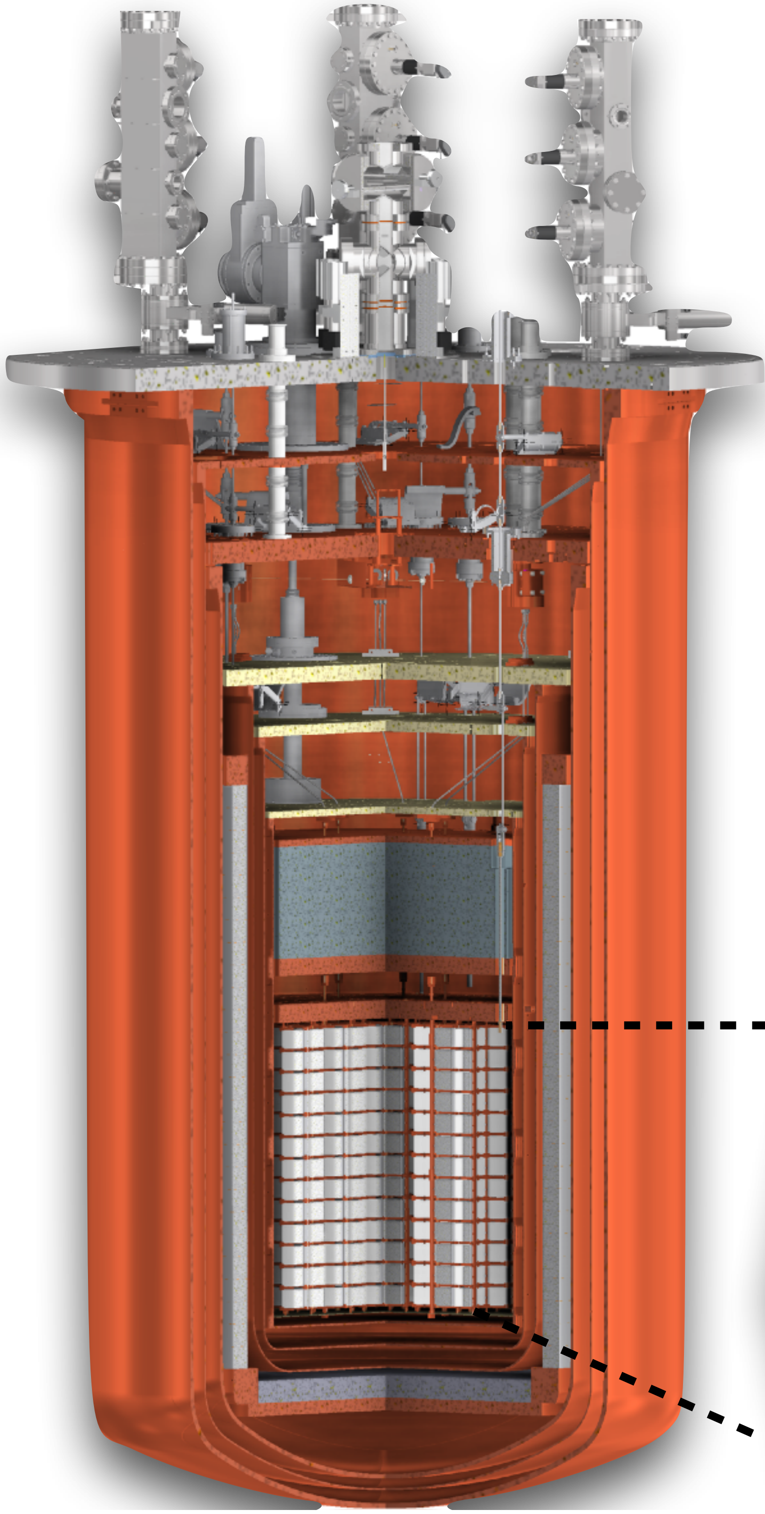
$$\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu} \mid M^{0\nu} \mid^2 \frac{|m_{\beta\beta}|^2}{m_e^2}$$

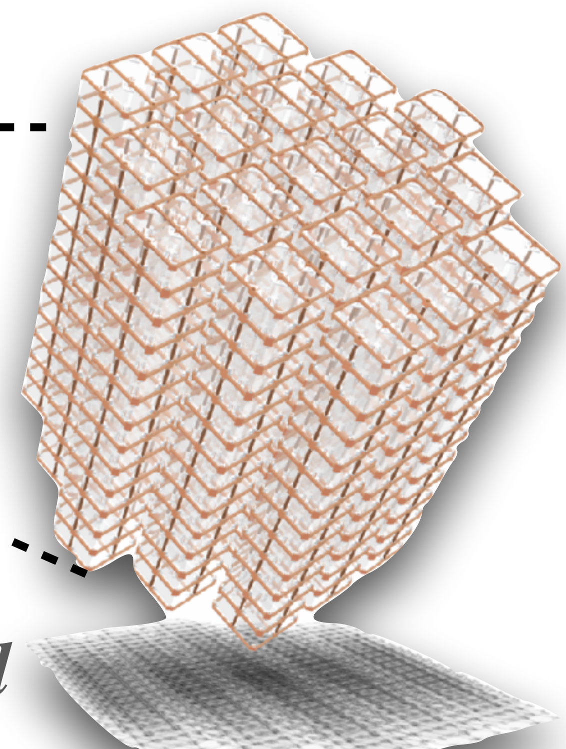


- Neutrinos are Majorana fermions.
  - Physics beyond standard model.
- Constraints on absolute mass scale.
  - Probes the mass hierarchy of the neutrinos.
- Constraints on CP violating phases?

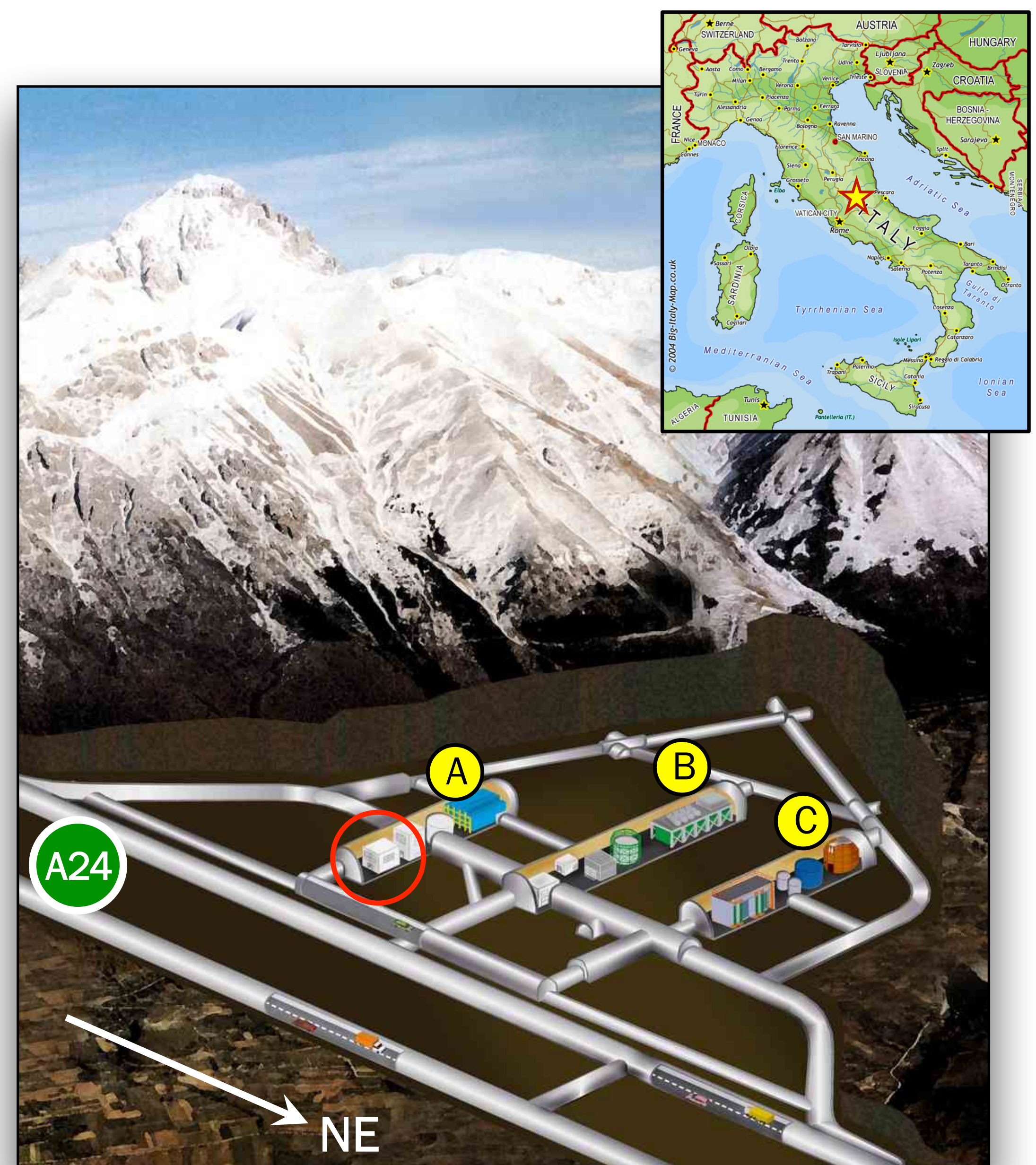
CUORE

- Search for $0\nu\beta\beta$ in ^{130}Te at LNGS, Italy (depth ~ 3600 m.w.e)

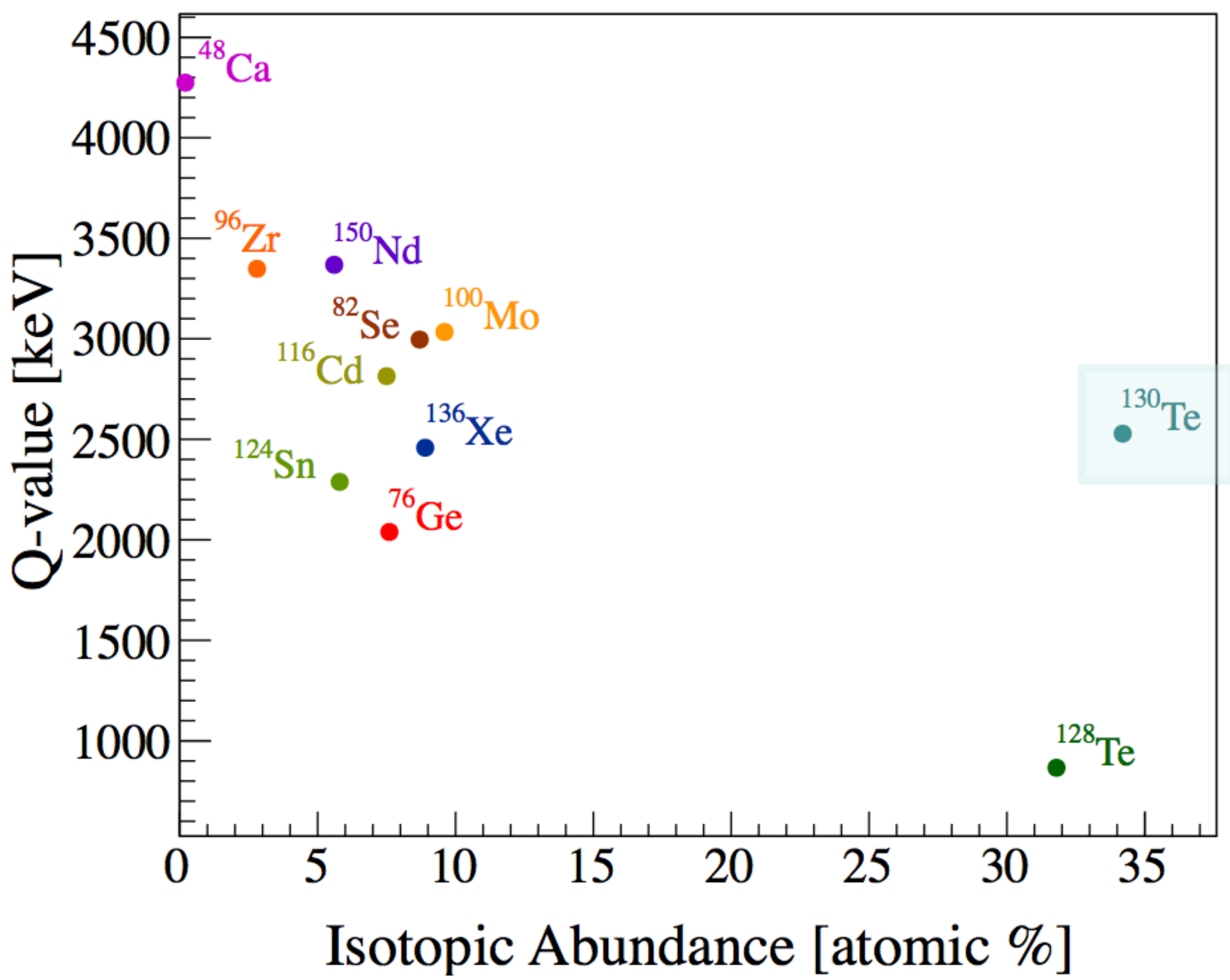




*The **C**ryogenic **U**nderground **O**bservatory for **R**are **E**vents*



CUORE



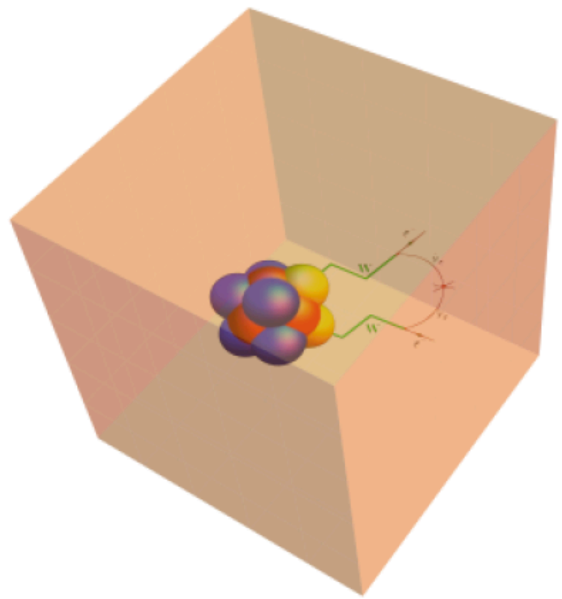
$$T^{0\nu}_{1/2}(n_\sigma) = \frac{ln2}{n_\sigma} \frac{N_A\, i\, \varepsilon}{A} f(\Delta E) \sqrt{\frac{M\, t}{B\, \Delta E}}$$

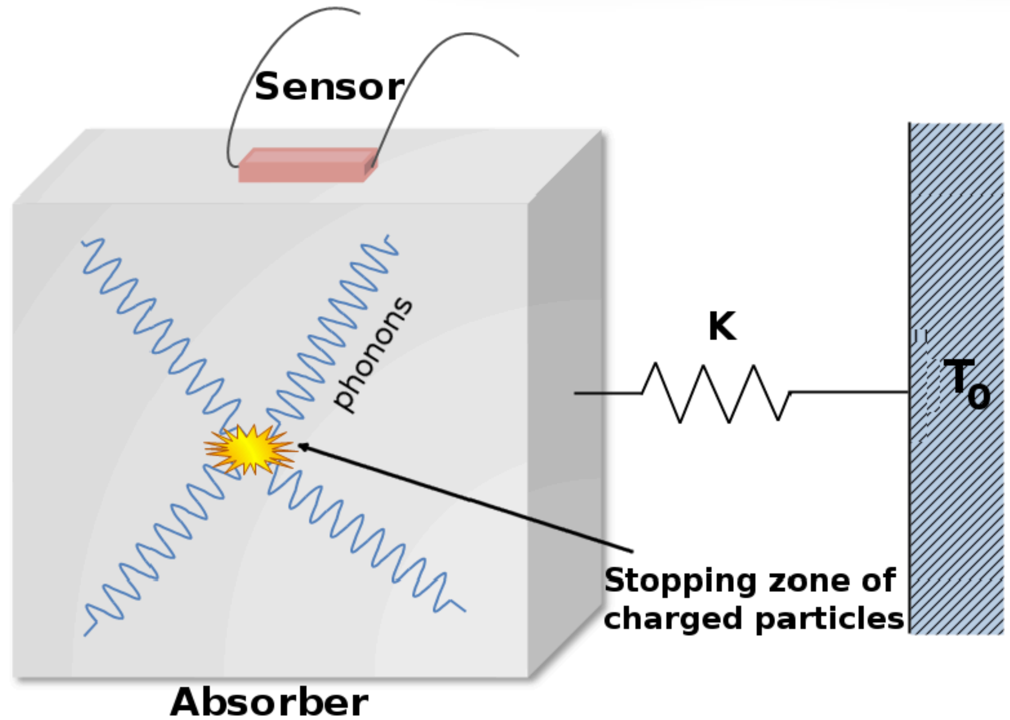
- $Q_{\beta\beta}$ = 2527.515 keV
- Isotopic mass of ^{130}Te : 206 kg
- 988 TeO_2 crystals (arranged in 19 towers with 13 floors each)
- Massive thermal calorimeters operated at ~10 mK
- Goal:
  - $\triangle E_{FWHM} \leq 5$ keV @ 2615 keV
  - B = 0.010 cnts/(keV·kg·yr)
  - $T_{1/2}$ (90% C.L.) > 9 x 10^{25} y
    5 yrs of live time ;
    $<m_{\beta\beta}>$ ~ 45 - 210 meV.

DETECTOR PRINCIPLE : THERMAL CALORIMETERS

$$\Delta E_{TFN} = \sqrt{k_B T^2 C(T)}$$

Source = Detector



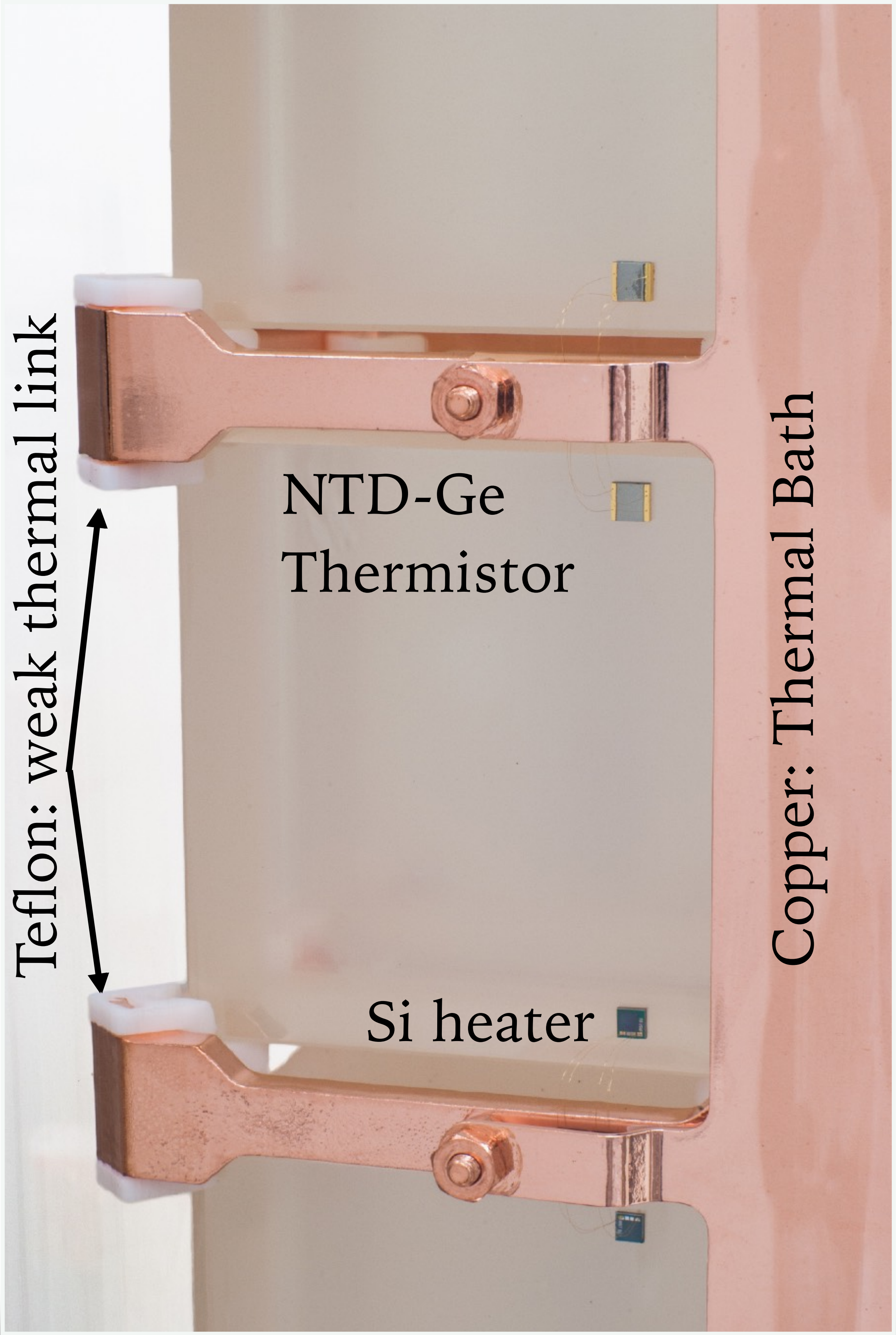


$$< \Delta E_{FWHM} >^2 = < \Delta E_{TFN} >^2 + < \Delta E_{electronics} >^2 + < \Delta E_{vibration} >^2 + ...$$

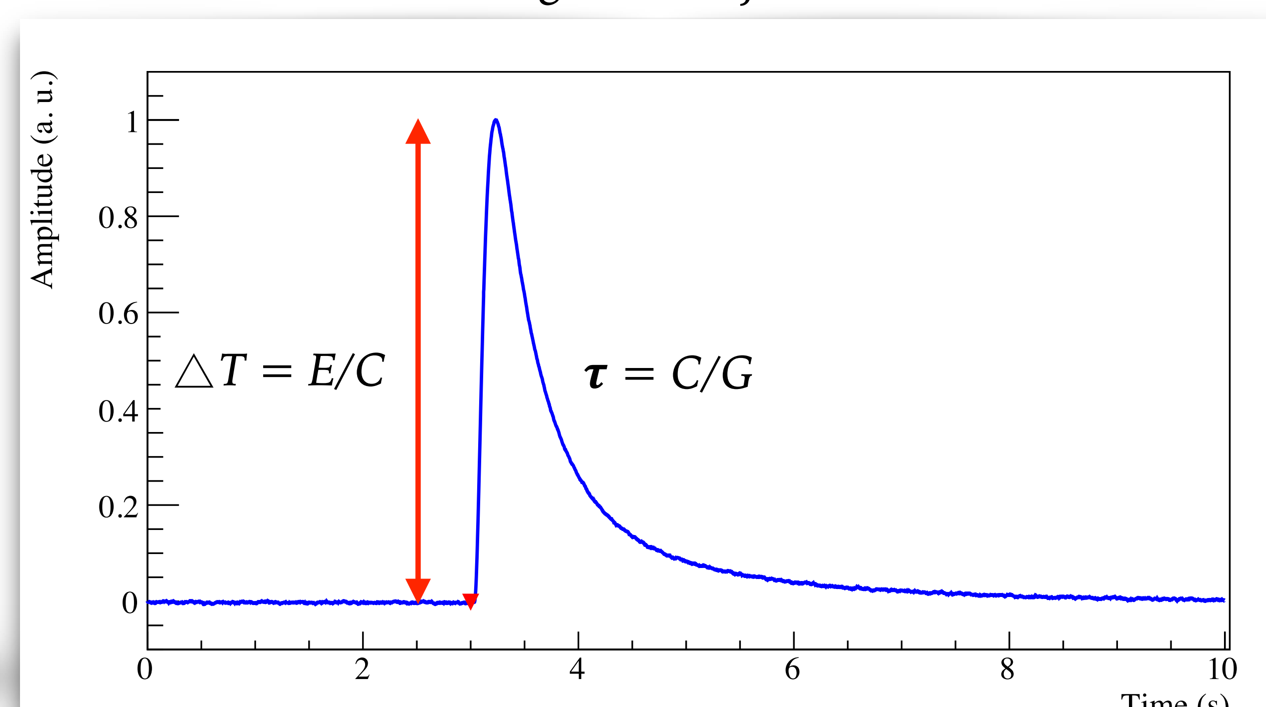
- Electron events mostly contained in the bulk : Large detection efficiency.
- The calorimeter cannot discriminate background from signal events easily.

- Thermodynamic limit for energy resolution can be made small by operating the detectors at a very low temperature.
- Requires ultra-low temperature facility with ultra-stable operating conditions.

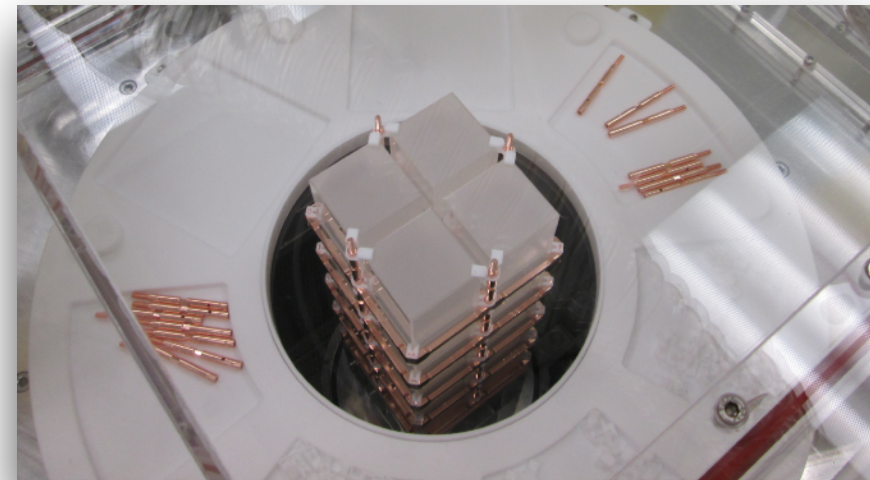
DETECTOR PRINCIPLE

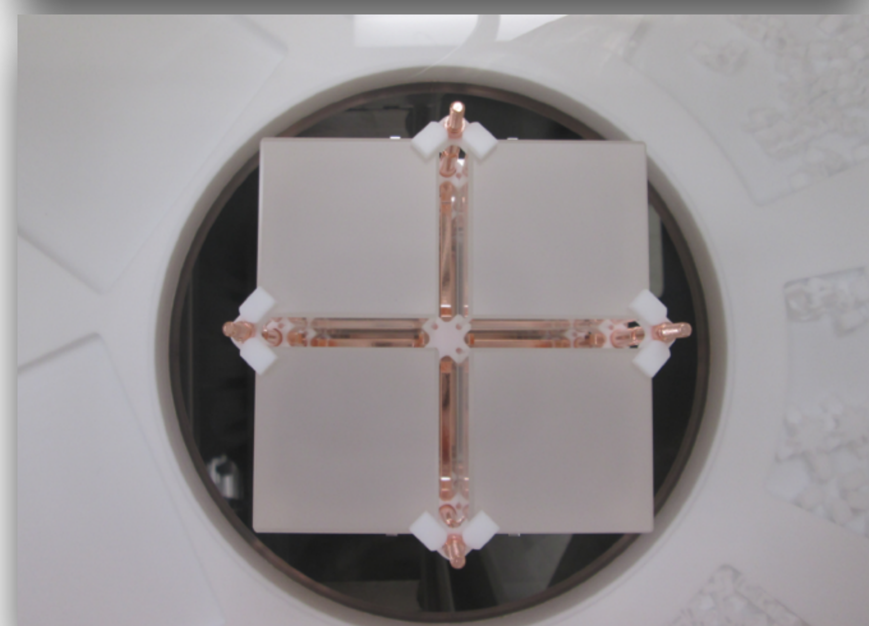


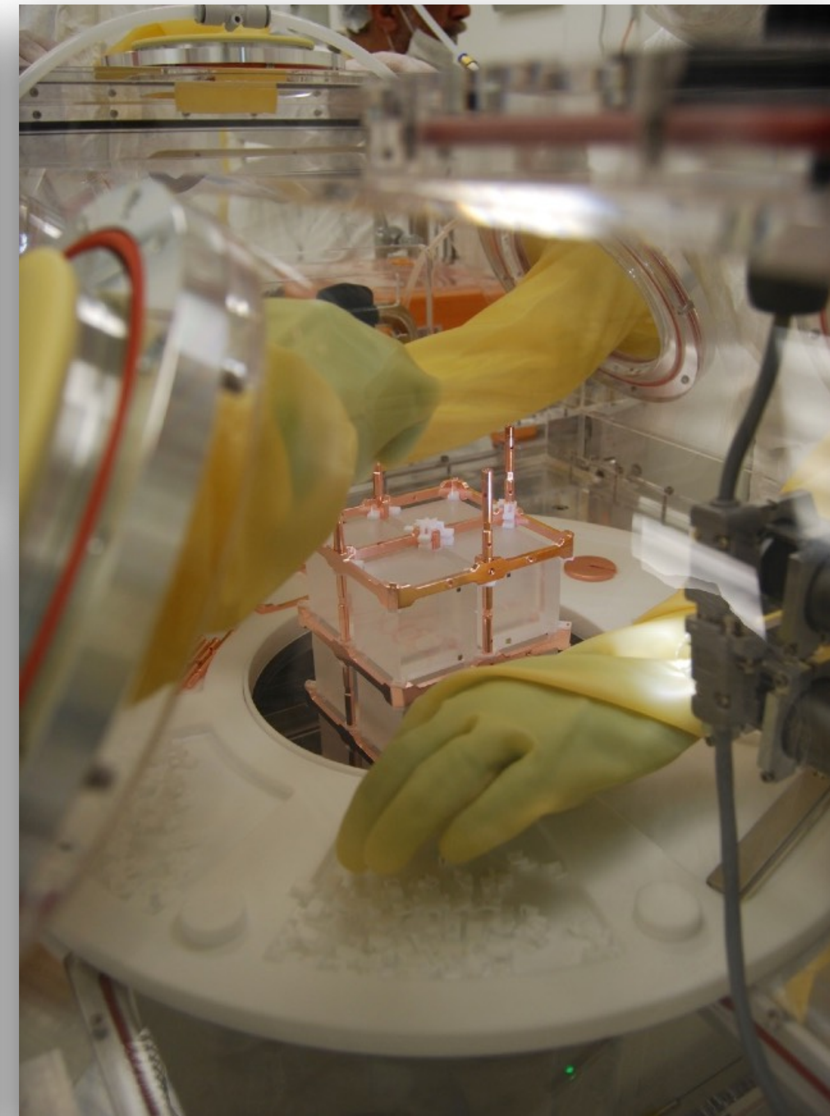
- 750 g ($5 \times 5 \times 5$ cm^3) crystal
- $\triangle T \sim 100\ \mu K$ for 1 MeV energy deposit
- NTD-Ge thermistor read out
  - $R(T) \sim R_0 \exp [(T_0/T)^{1/2}]$ (large sensitivity at low T)
- Energy response calibrated using known gamma sources
- Note:
  - Signal ➛ thermal channel only
  - No active background rejection

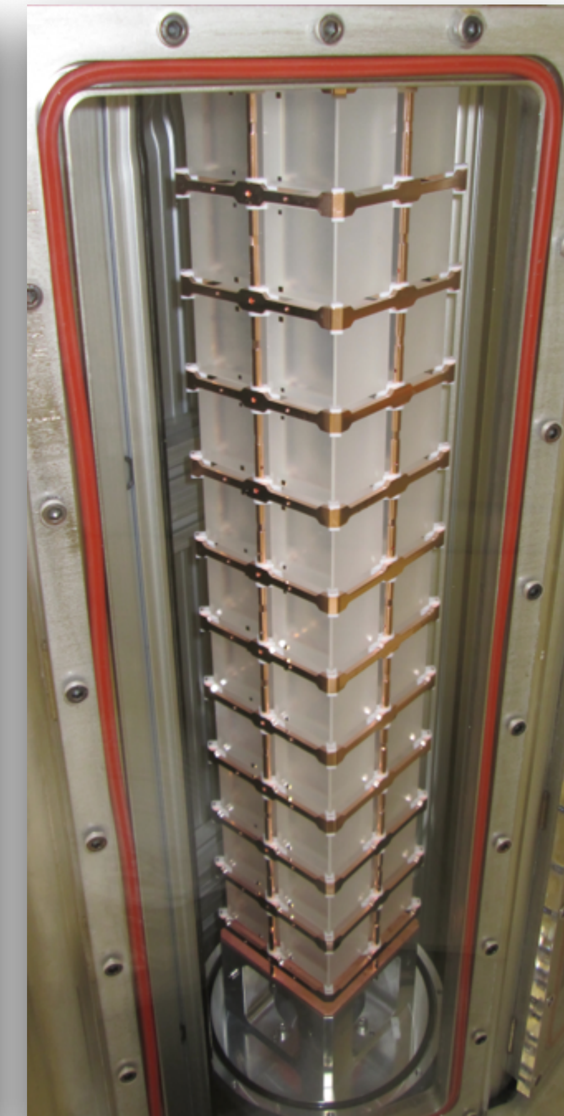


DETECTOR ASSEMBLY



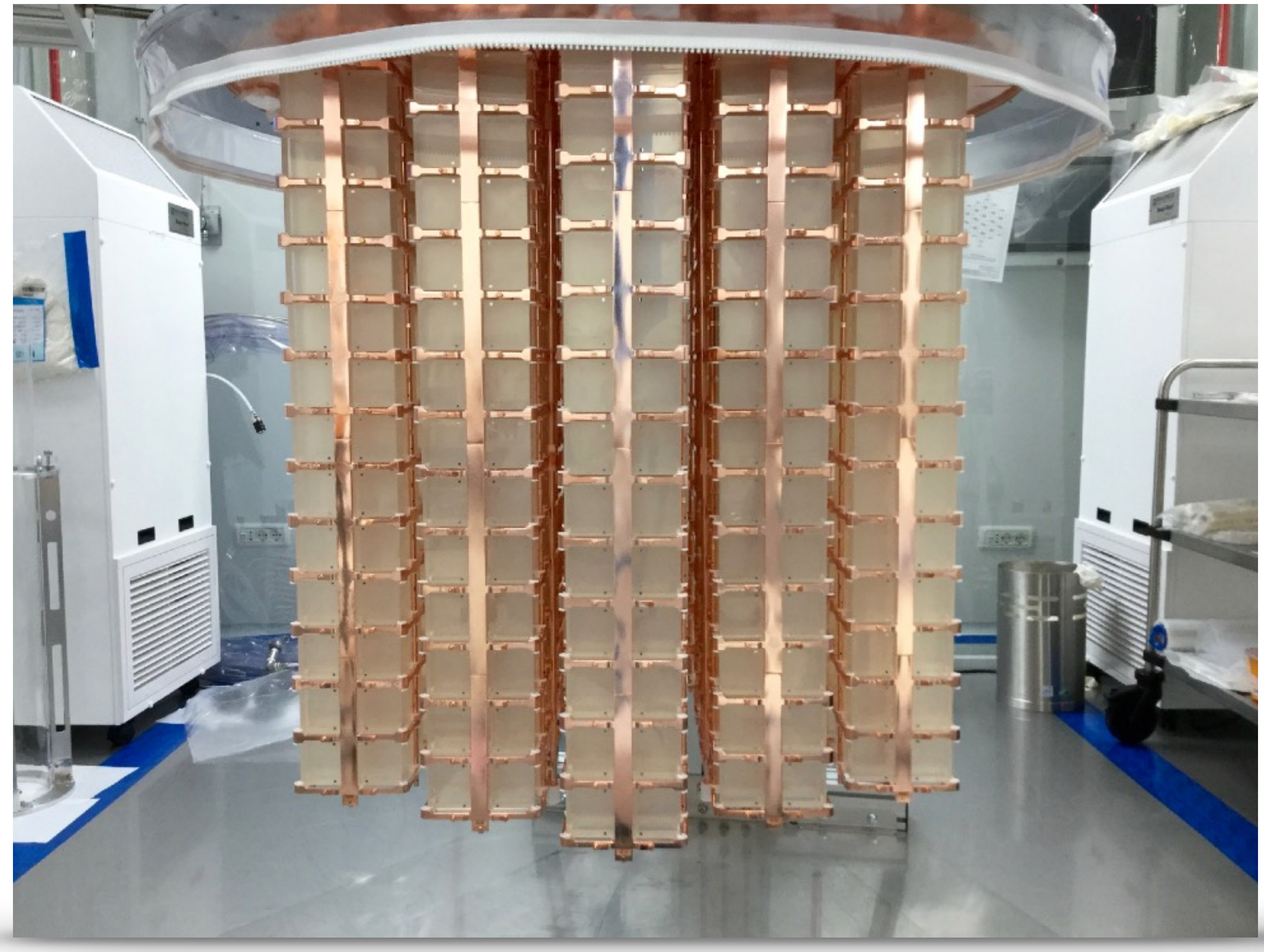


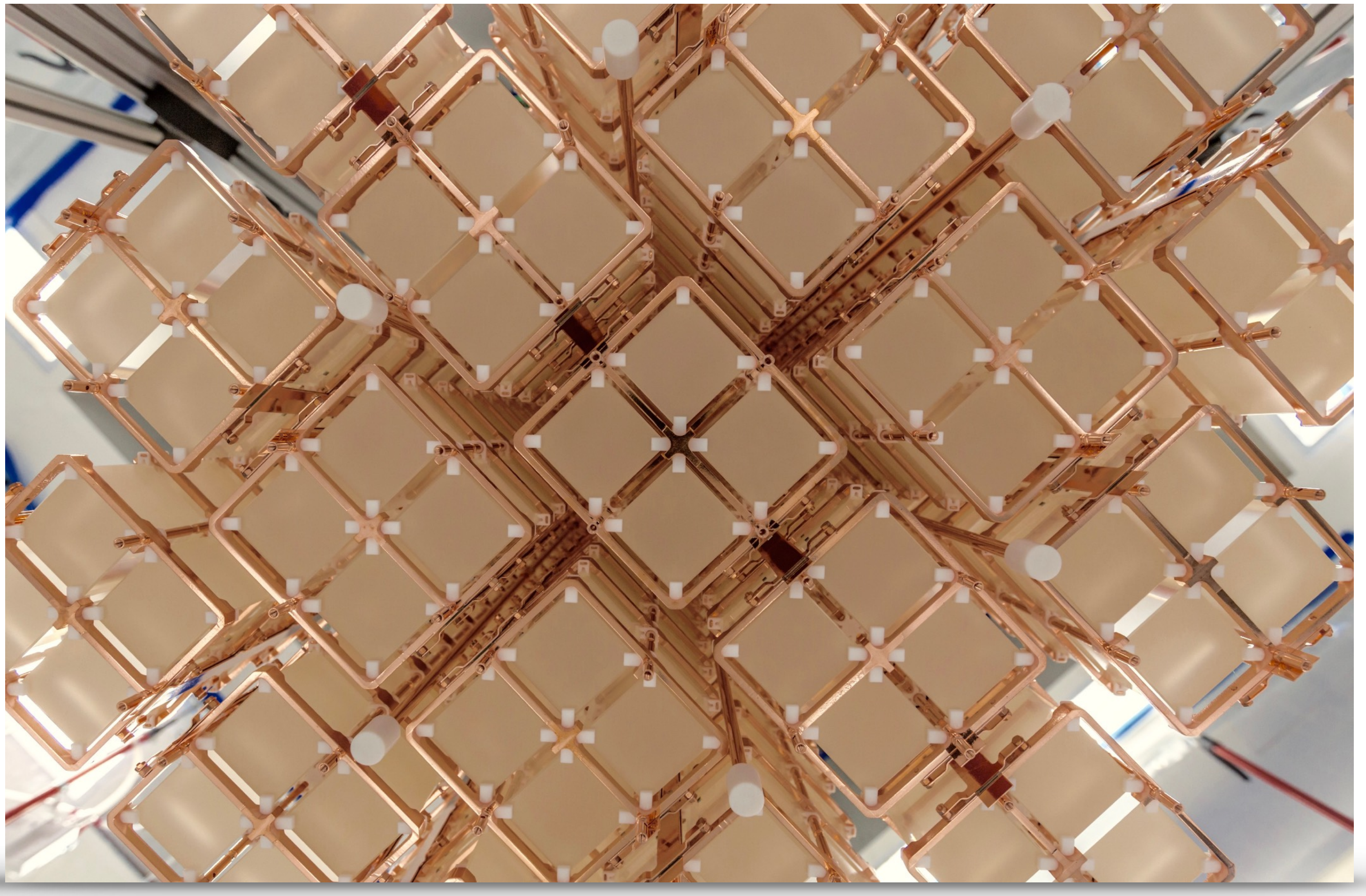




- Strict material selection
- Stringent surface cleaning procedures for detectors and materials nearby the detectors
- Minimize radon contamination at every step of the detector assembly.

DETECTOR ARRAY

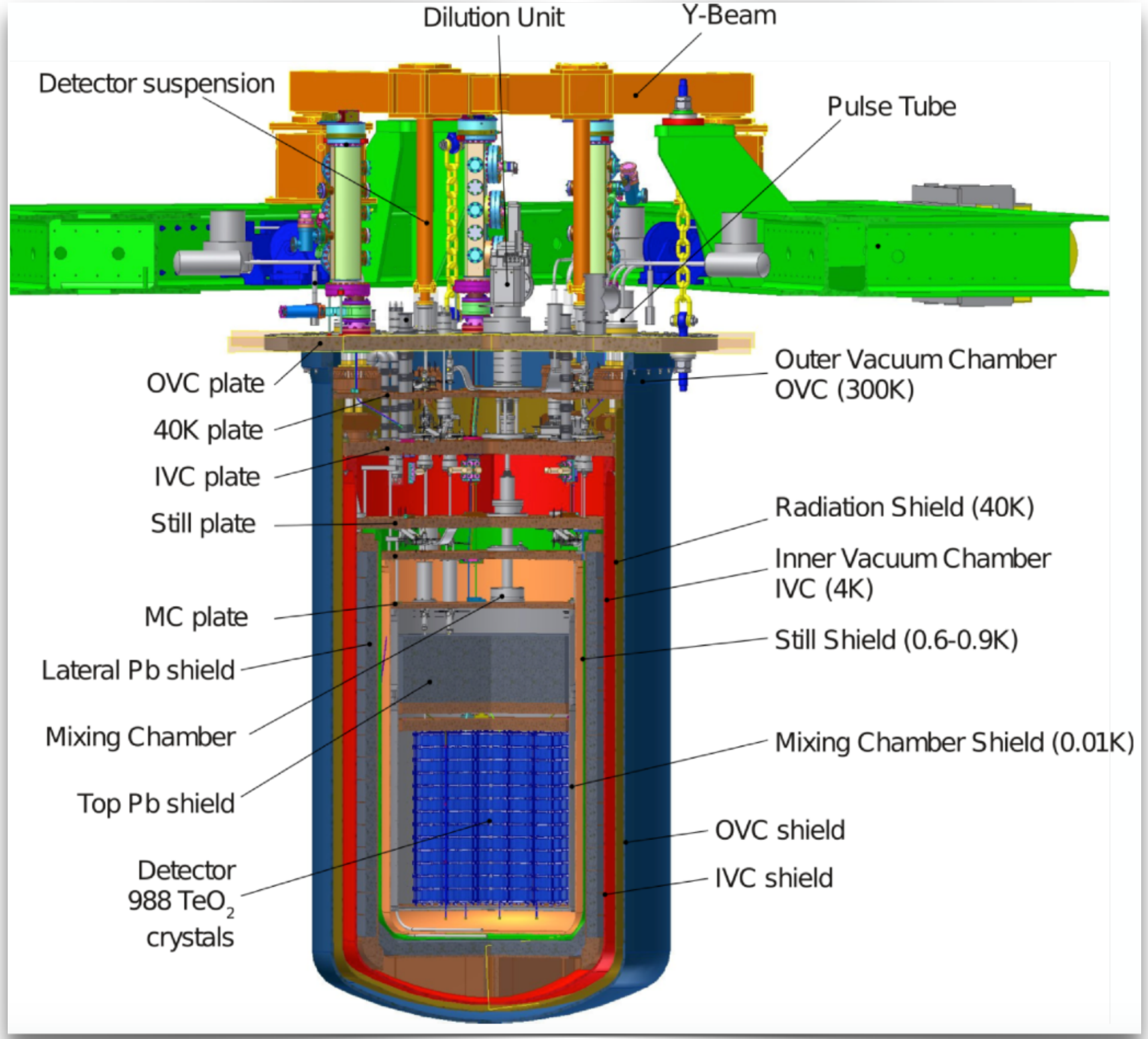




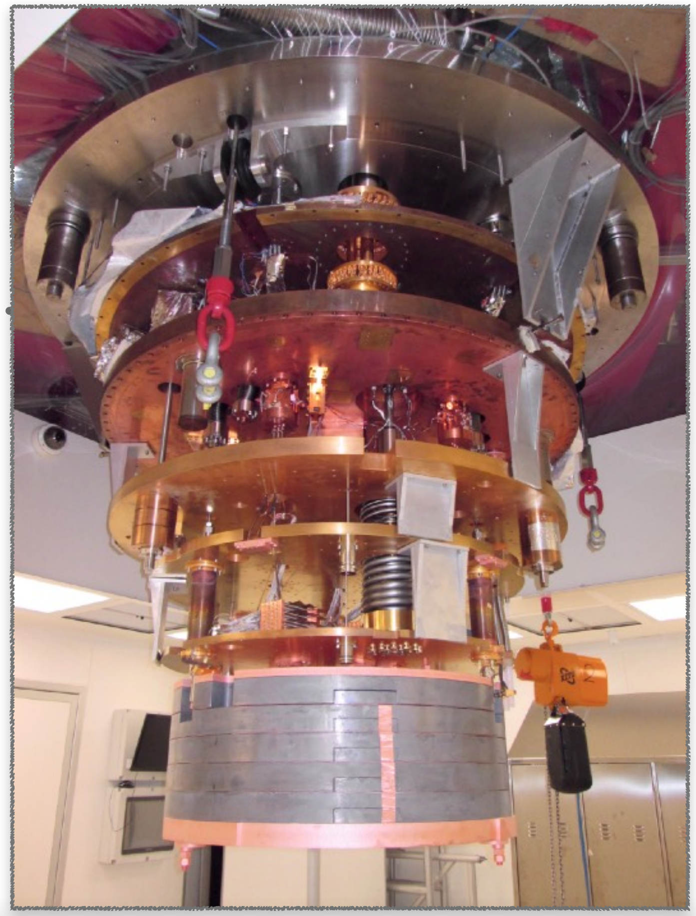
CUORE Assembly efficiency

- *984/988 NTD-Ge thermistors connected*
- *> 99.5% functional detectors.*
- *942/988 heaters connected*

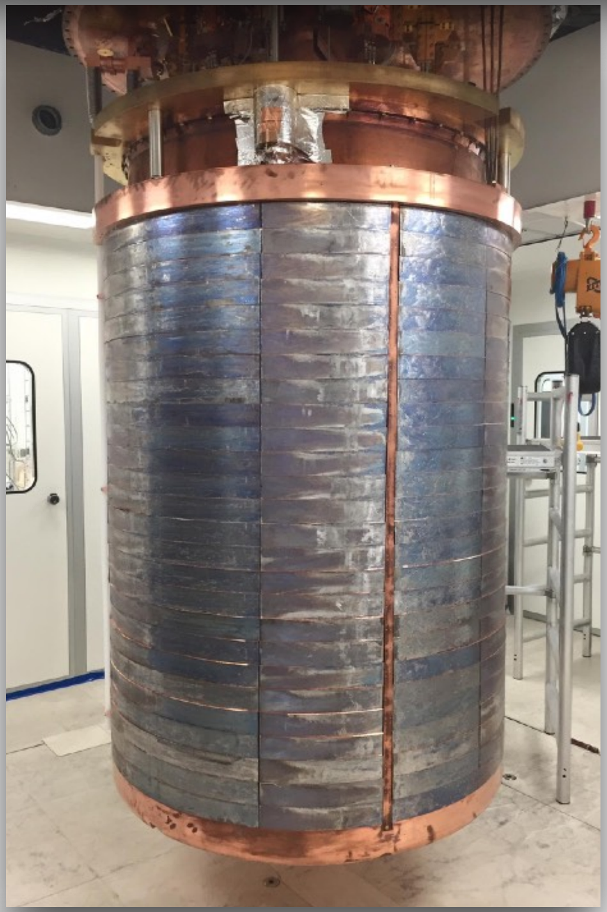
CUORE CRYOSTAT



- Experimental Conditions
  - Low radioactivity environment
  - Stable ultra-low temperatures
  - Extremely low vibrations

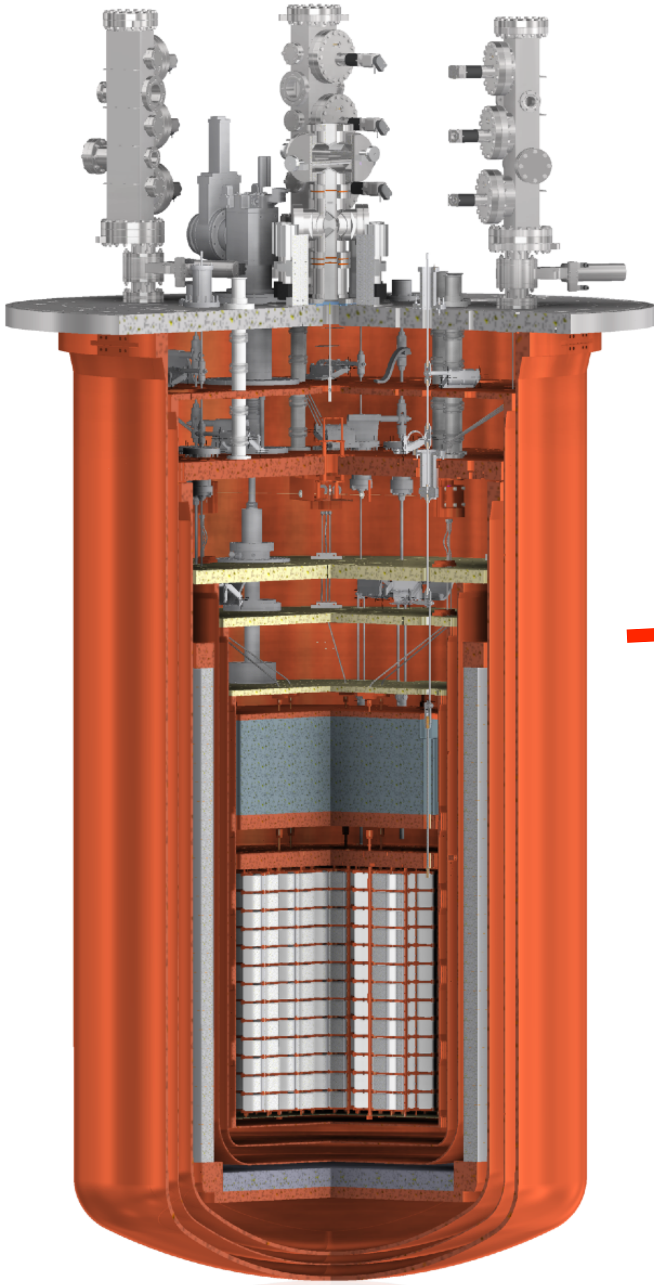


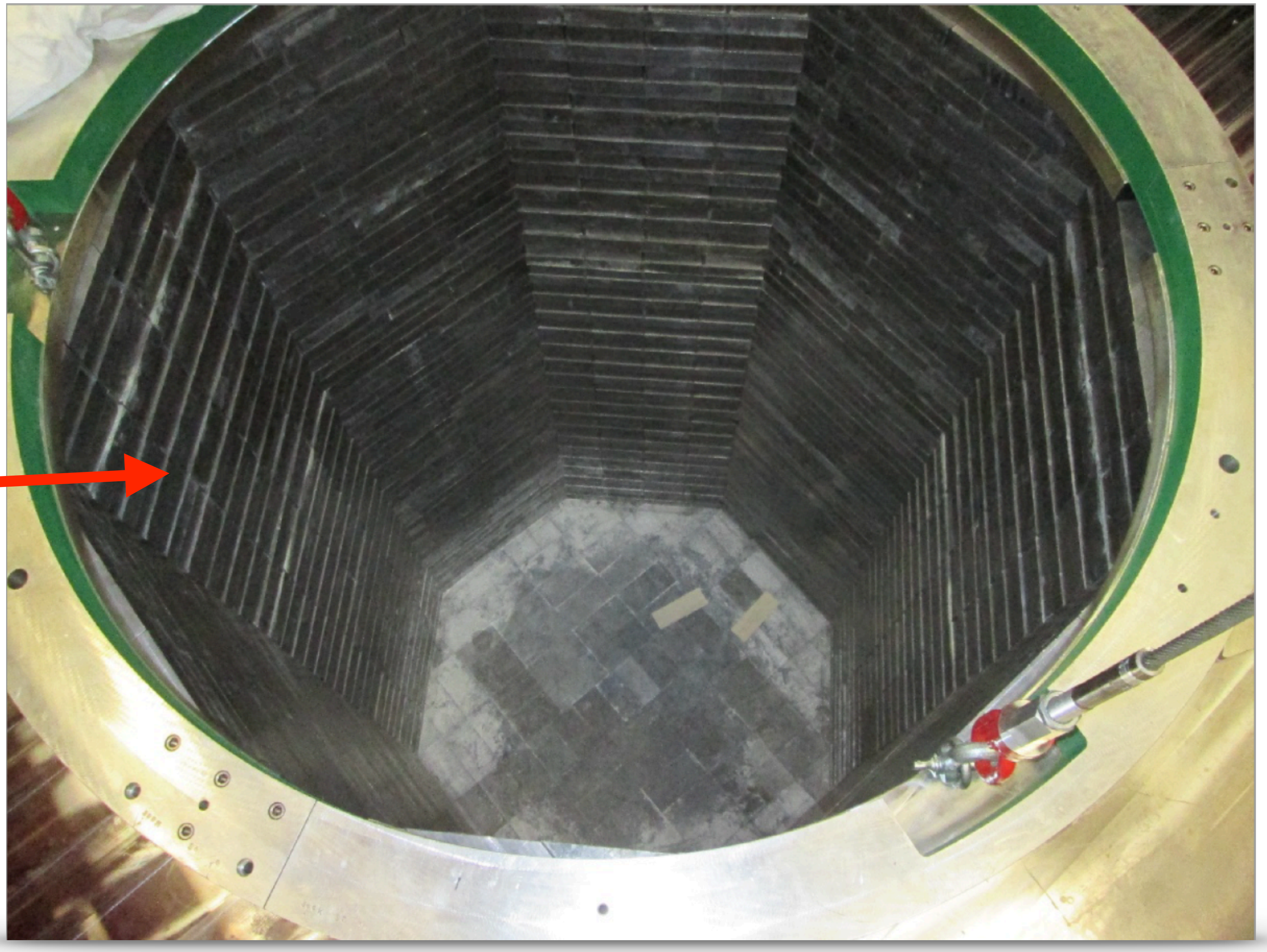
30 cm of Pb Top Shield (2.5 tons@50 mK)



6 cm Roman Pb Shield (5 tons@4K)

EXTERNAL SHIELDING





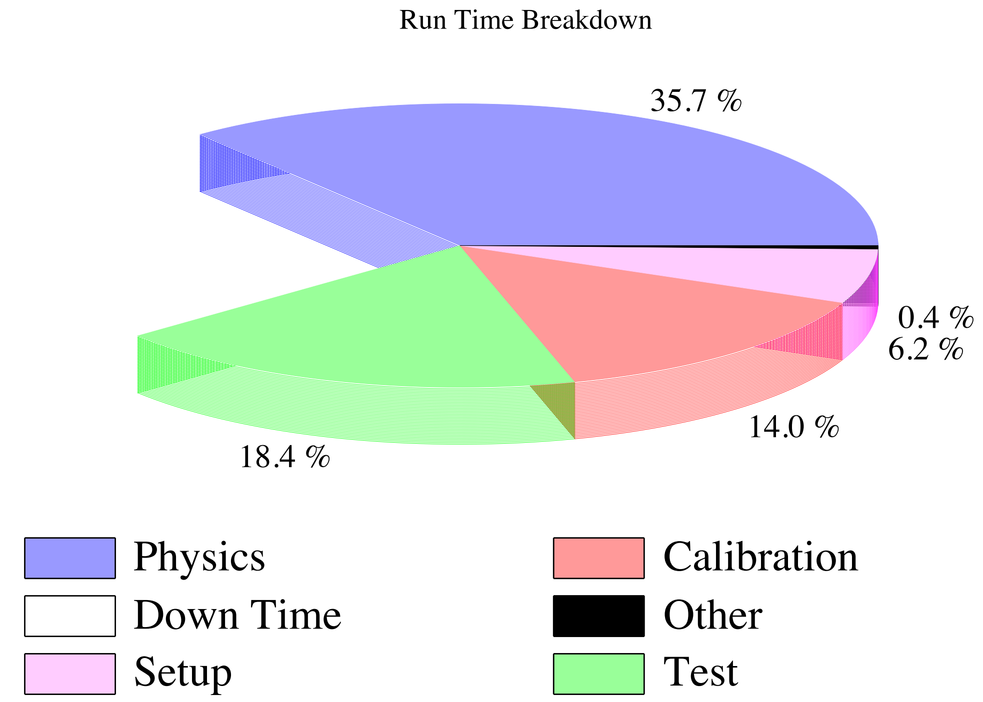
External lead: 25 cm thick

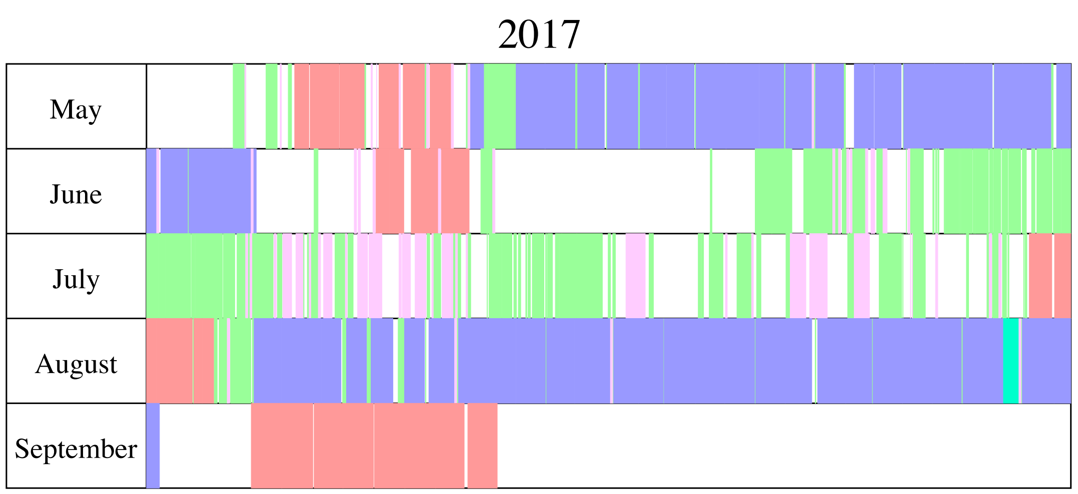
Neutron shield: 18 cm of PET + 2 cm of H_3BO_3

SCIENCE RUNS

Science operations :
Very short commissioning run (identified issue with the thermistor bias on about 1/3 of the channels)

- First optimization of the detector working point
- **Dataset 1**: 3 weeks of physics data (May - June 2017)
- Second optimization campaign
- **Dataset 2**: 4 weeks of physics data (August - September 2017)





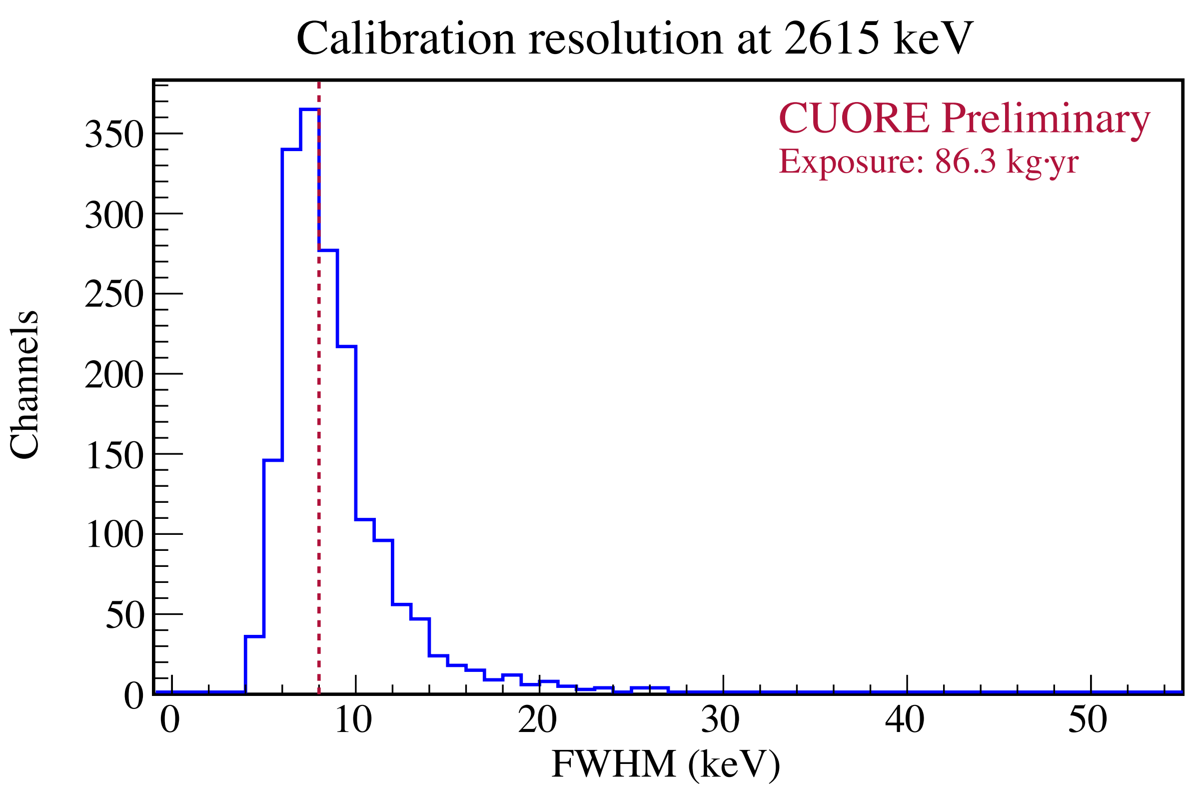
Operational performance:

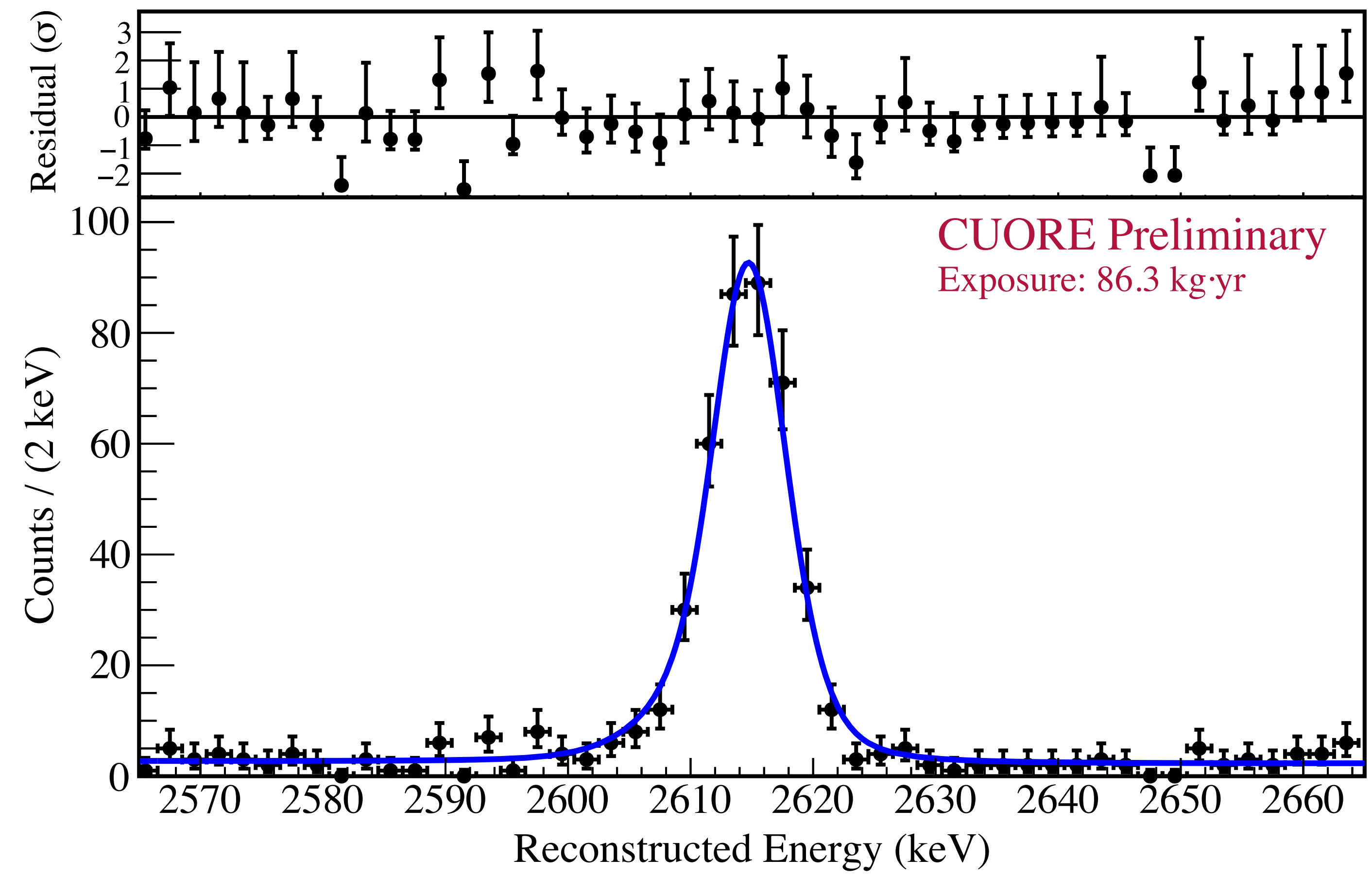
- 984/988 operational channels
- Improved detector stability, compared to Cuoricino/CUORE-0
- Calibrations/physics ratio data to be optimized to maximize $0\nu\beta\beta$ sensitivity

Acquired statistics used for this $0\nu\beta\beta$ decay search (Dataset 1 + Dataset 2):

- $^{nat}TeO_2$ exposure: **86.3 kg yr** (37.6 + 48.7)
- ^{130}Te exposure: **24.0 kg yr**

CUORE : ENERGY RESOLUTION IN ROI





Calibration Resolution@ 2615 keV

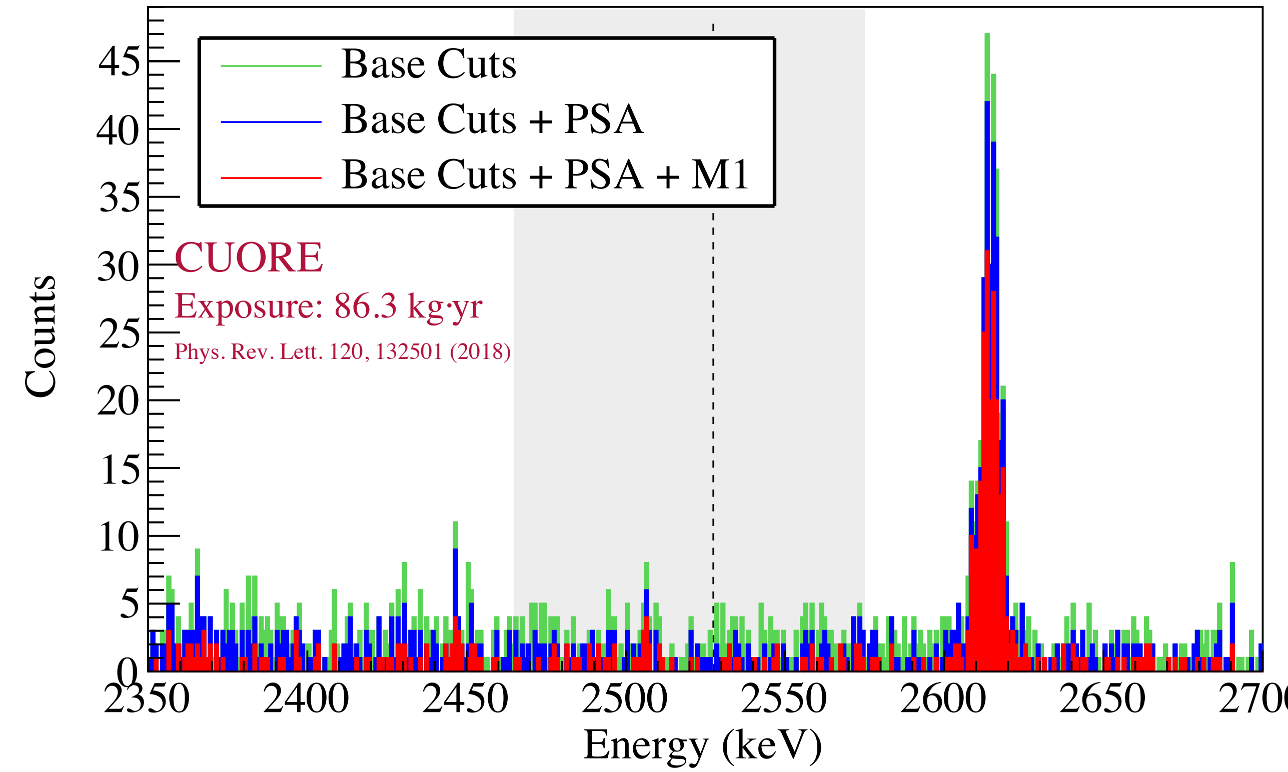
- Dataset 1: 9 keV FWHM
- Dataset 2: 7.4 keV FWHM
- Effective (exposure-weighted): 8 keV FWHM

Physics data Resolution@ Q-value

- Dataset 1: (8.3 ± 0.4) keV FWHM
- Dataset 2: (7.4 ± 0.7) keV FWHM
- Effective (exposure-weighted): (7.7 ± 0.5) keV FWHM

CUORE : EFFICIENCIES FOR $0\nu\beta\beta$ ANALYSIS

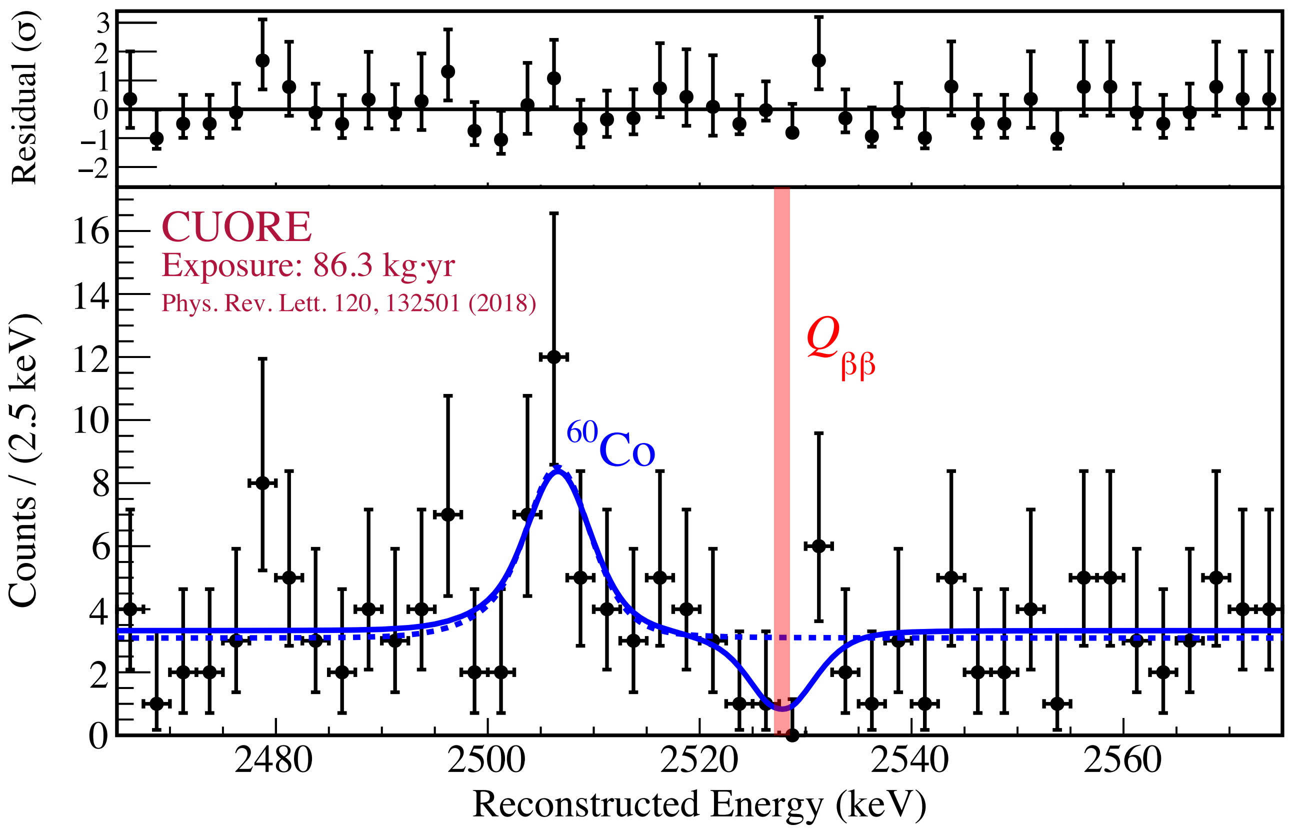
- First we remove events from periods of low-quality data (~1% of total live time)
- Base cuts (number of pulses in the window, baseline stability)
- Anti-coincidence : accept/reject events based on a multiplicity cut.
- Pulse shape analysis and cuts: reject deformed events

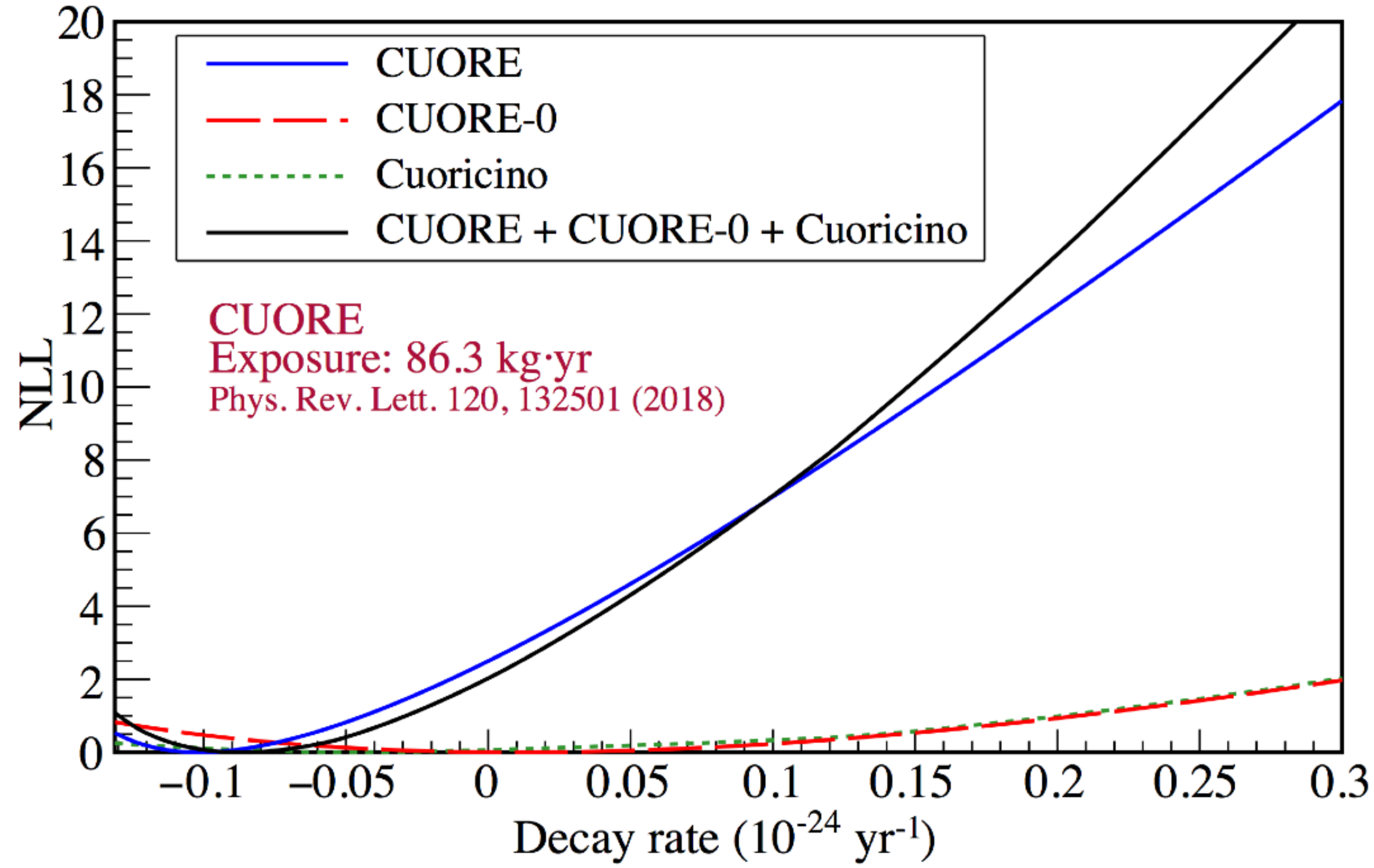


	DATASET 1	DATASET 2
Trigger	(99.766 ± 0.003) %	(99.735 ± 0.004) %
Energy reconstruction	(99.168 ± 0.006) %	(99.218 ± 0.006) %
Base cuts	(95.63 ± 0.01) %	(96.69 ±0.01) %
Anti-coincidence	(99.4 ± 0.5) %	(100.0 ± 0.4) %
Pulse Shape Analysis	(91.1 ± 3.6) %	(98.2 ± 3.0) %
$0\nu\beta\beta$ containment	(88.345 ± 0.085)%	
Total	(75.7 ± 3.0) %	(83.0 ± 2.6) %

CUORE: $0\nu\beta\beta$ RESULTS

Phys. Rev. Lett. 120, 132501 (2018)



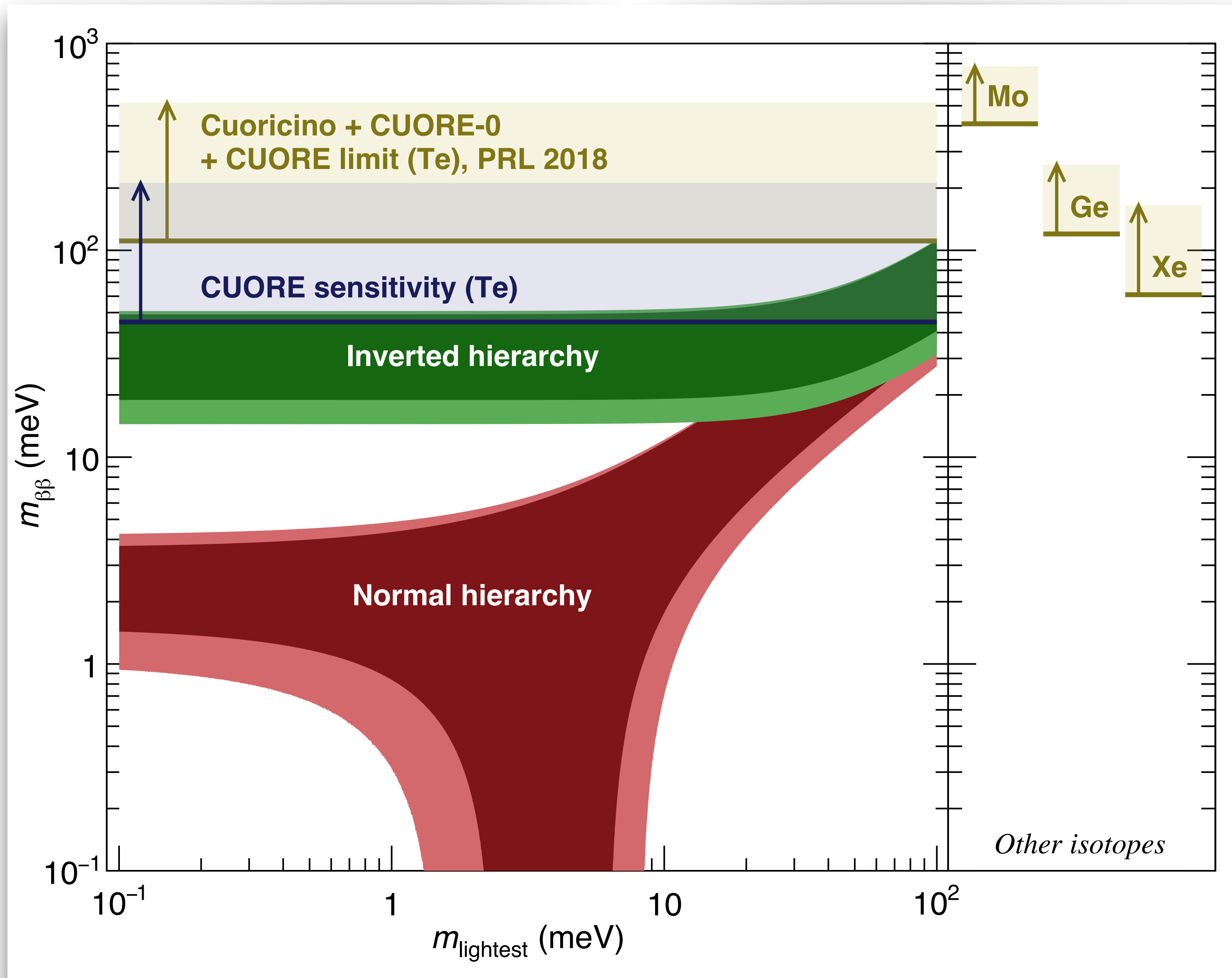


Region of interest : [2465..2575] keV
Overall efficiency : $(75.7 \pm 3.0)\%$
$(83.0 \pm 2.6)\%$
ROI background index: $(1.49_{-0.17}^{+0.18}) \times 10^{-2}$ counts/(keV·kg·yr)
$(1.35_{-0.18}^{+0.20}) \times 10^{-2}$ counts/(keV·kg·yr)
Events in the ROI : 155
Best fit for ^{60}Co mean : (2506.4 ± 1.2) keV
Best fit decay rate: $[-1.0_{-0.3}^{+0.4}$ (stat.) $\pm$ 0.1 (syst.)$] \times 10^{-25}$ yr^{-1}

Limits combining CUORE with CUORE-0 and Cuoricino:

- Bayesian limit @ 90% c.i. (flat prior for $\Gamma_{\beta\beta}>0$):
1.5×10^{25} yr
- Profile likelihood ("frequentist") limit @ 90% CL:
2.2×10^{25} yr

CUORE: $<m_{\beta\beta}>$ SENSITIVITY



$m_{\beta\beta}$ < 110 - 520 meV

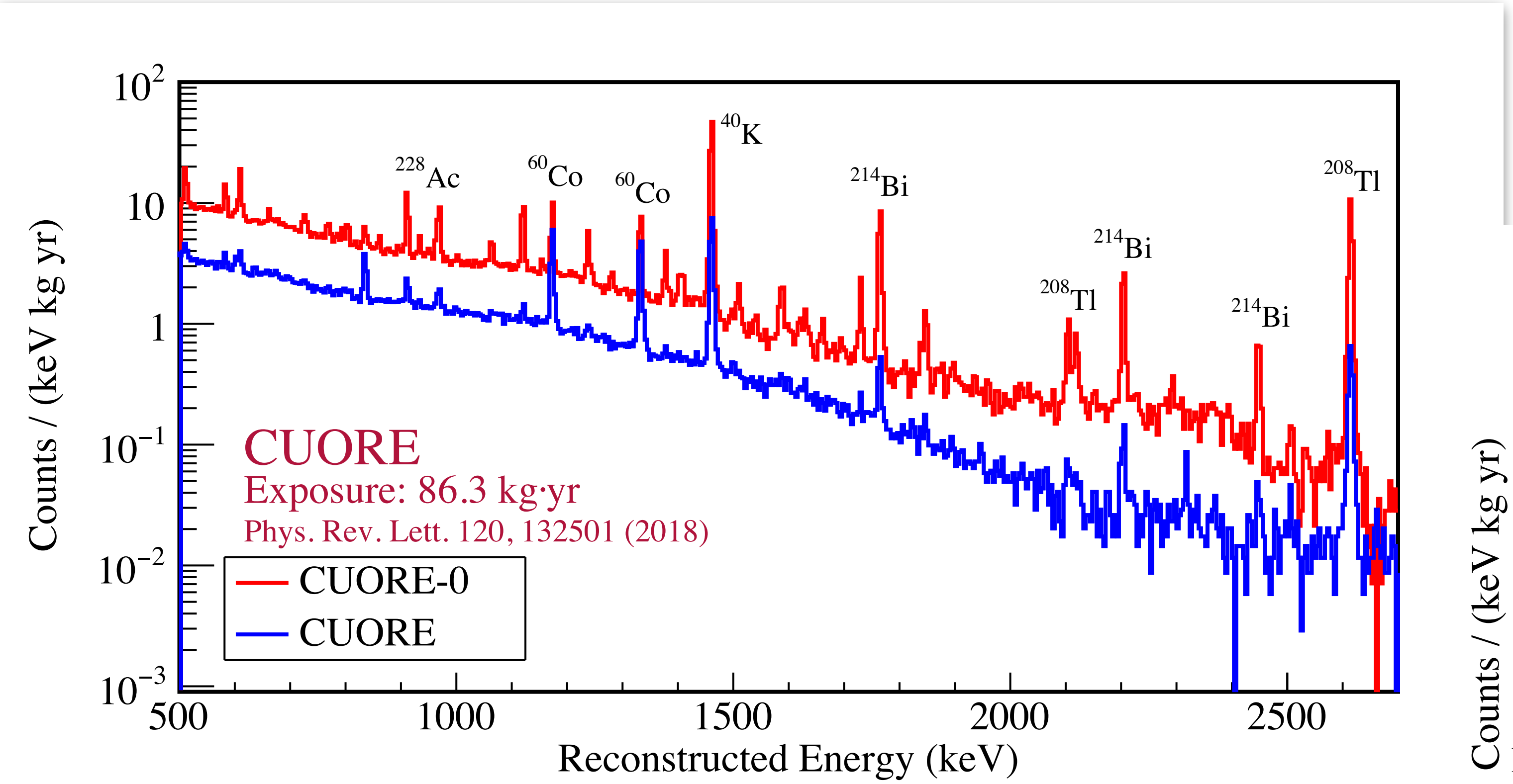
CUORE Nuclear Transition Matrix Element (NTME) calculations from:

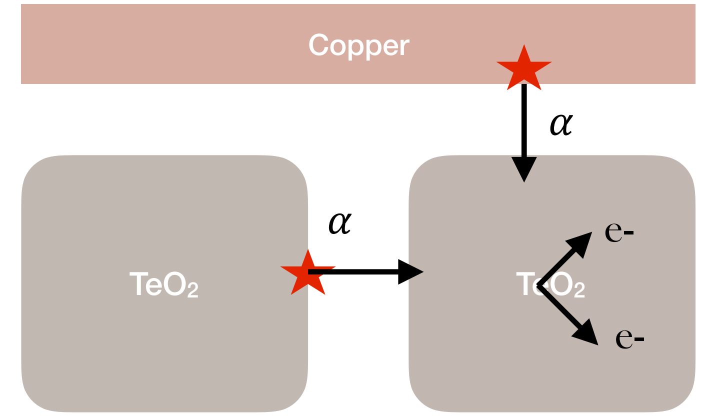
- JHEP02 (2013) 025
- Nucl. Phys. A 818, 139 (2009)
- Phys. Rev. C 87, 045501 (2013)
- Phys. Rev. C 87, 064302 (2014)
- Phys. Rev. C 91, 034304 (2015)
- Phys. Rev. C 91, 024613 (2015)
- Phys. Rev. C 91, 024309 (2015)
- Phys. Rev. C 91, 024316 (2015)
- Phys. Rev. Lett. 105, 252503 (2010)
- Phys. Rev.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

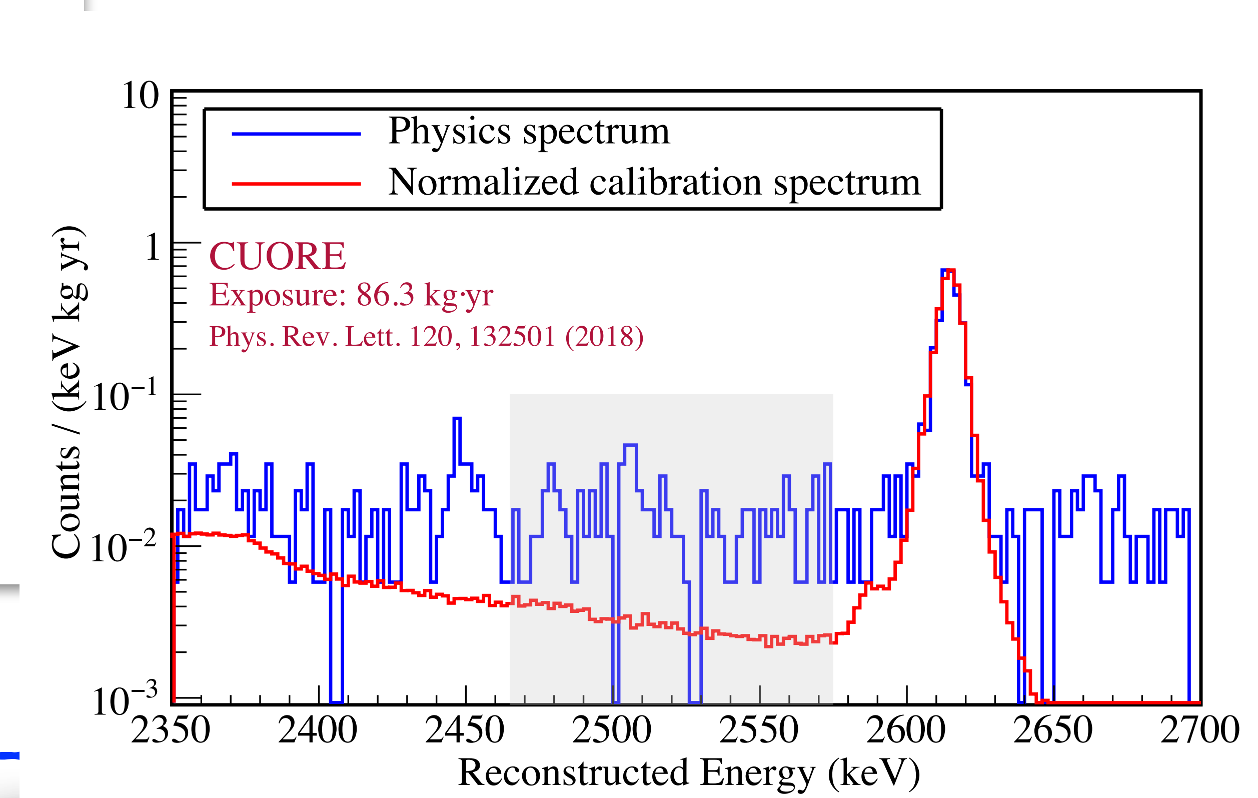
Half-life limits:

- ^{130}Te: 1.5×10^{25} yr from PRL 120, 132501 (2018)
- ^{76}Ge: 8.0×10^{25} yr from PRL 120, 132503 (2018)
- ^{136}Xe: 1.1×10^{26} yr from Phys. Rev. Lett. 117, 082503 (2016)
- ^{100}Mo: 1.1×10^{24} yr from Phys. Rev. D 89, 111101 (2014)
- CUORE sensitivity: 9.0×10^{25} yr

BACKGROUND SPECTRUM



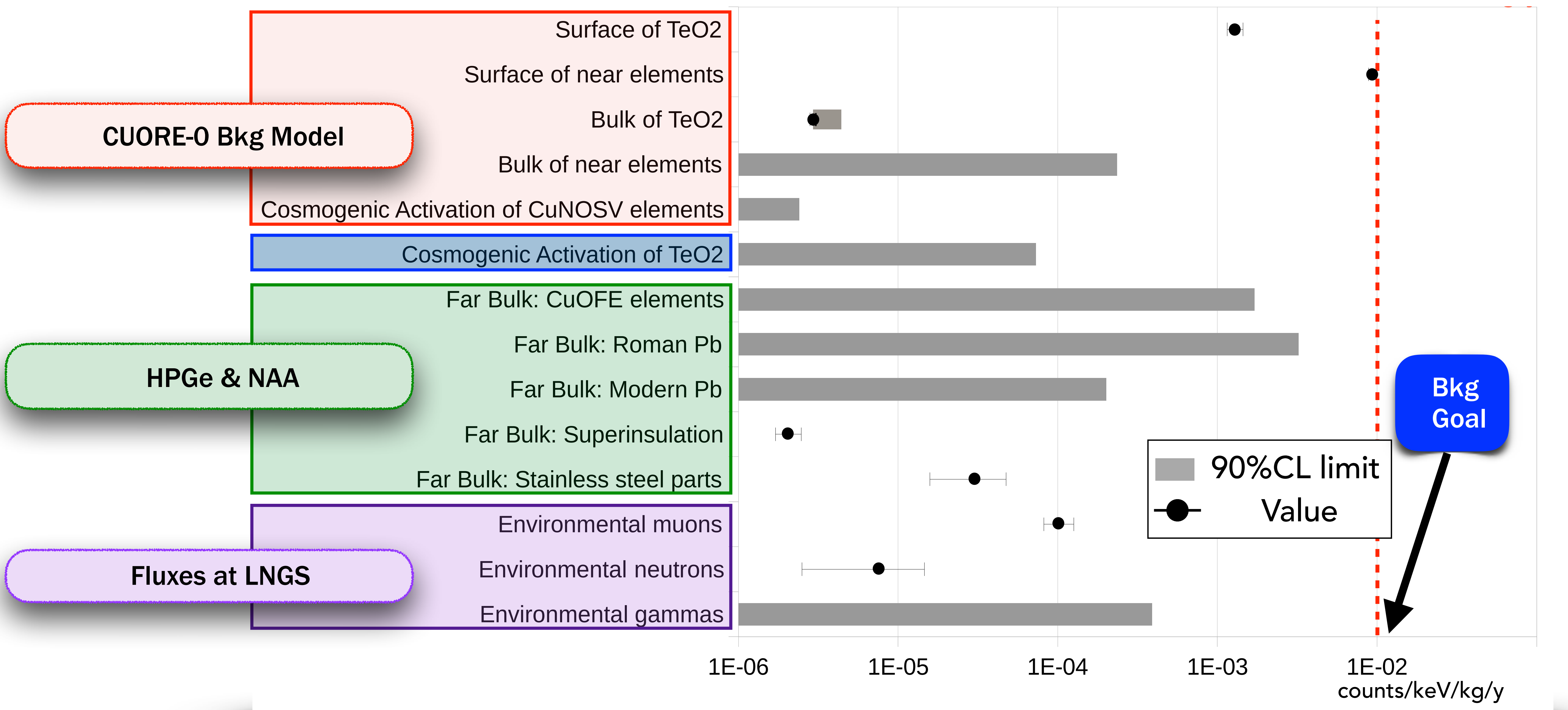




- Relevant reduction in the γ region, compared to CUORE-0
- Spectrum is consistent with the background expectations

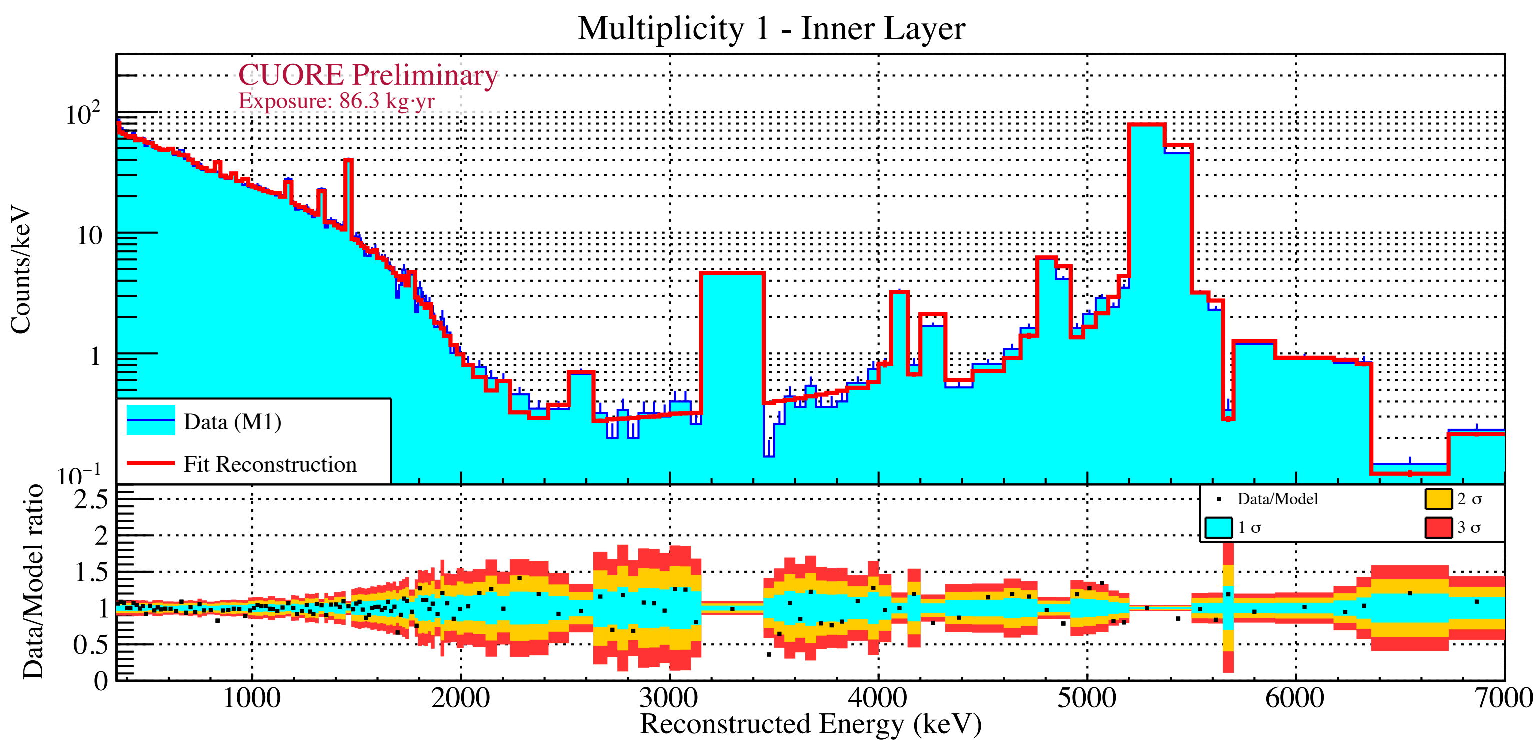
- 2615 keV in calibration normalized to physics data
- Shows background in ROI dominated by alphas

BACKGROUND EXPECTATION



Eur.Phys.J. **C77**, 543 (2017)

CUORE : BACKGROUND MODEL



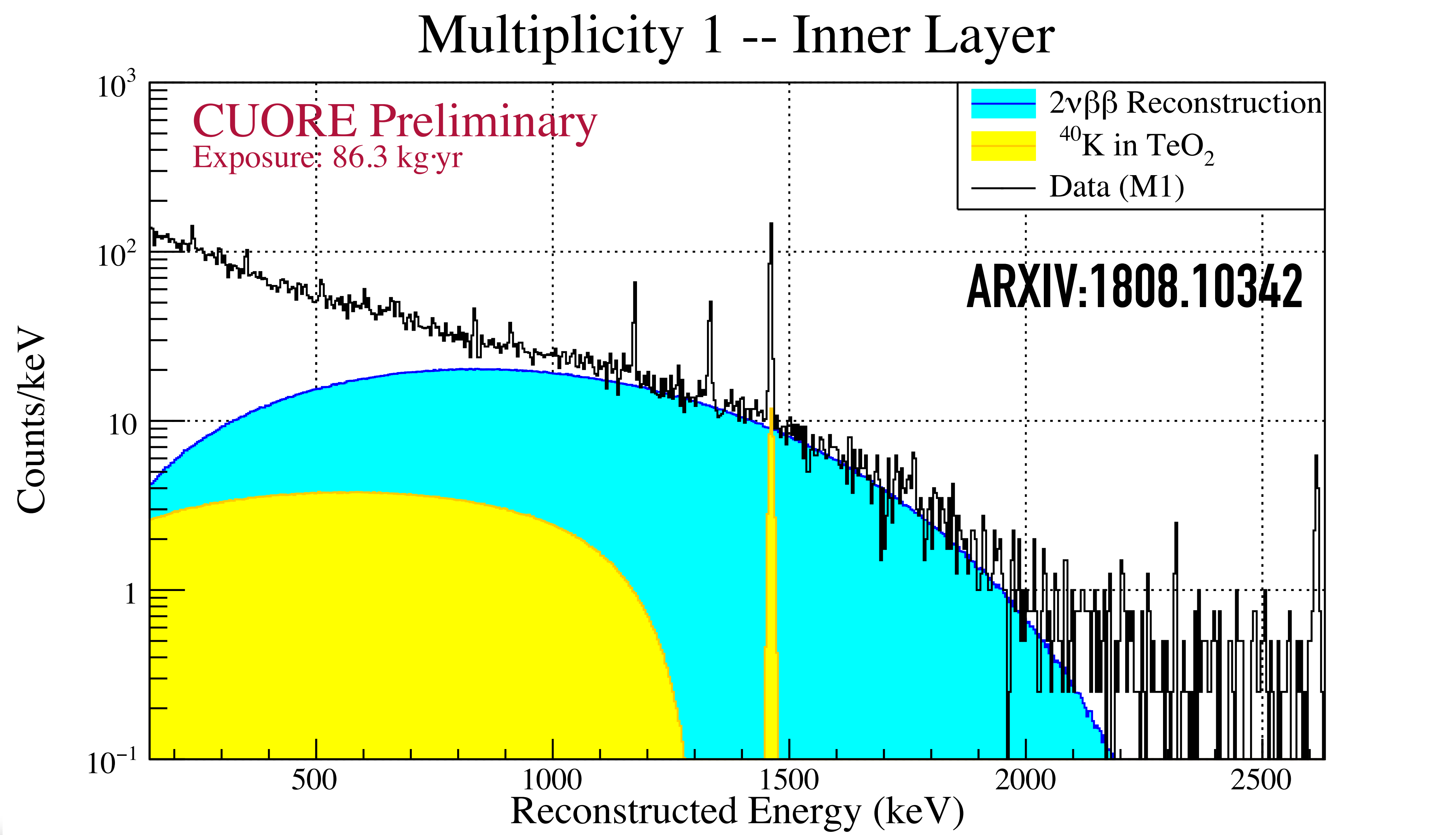
Major background sources identified and ascribed to different locations in the experimental setup using

- Coincidence analysis
- Gamma peaks
- Alpha peaks
- Radio-assay measurements
- Data from neutron activation

Bayesian Fit:

- Split data into inner and outer layers: utilize self shielding by the outer layers.
- Split data by Multiplicities: different multiplicities are sensitive to different types of backgrounds

CUORE: $2\nu\beta\beta$

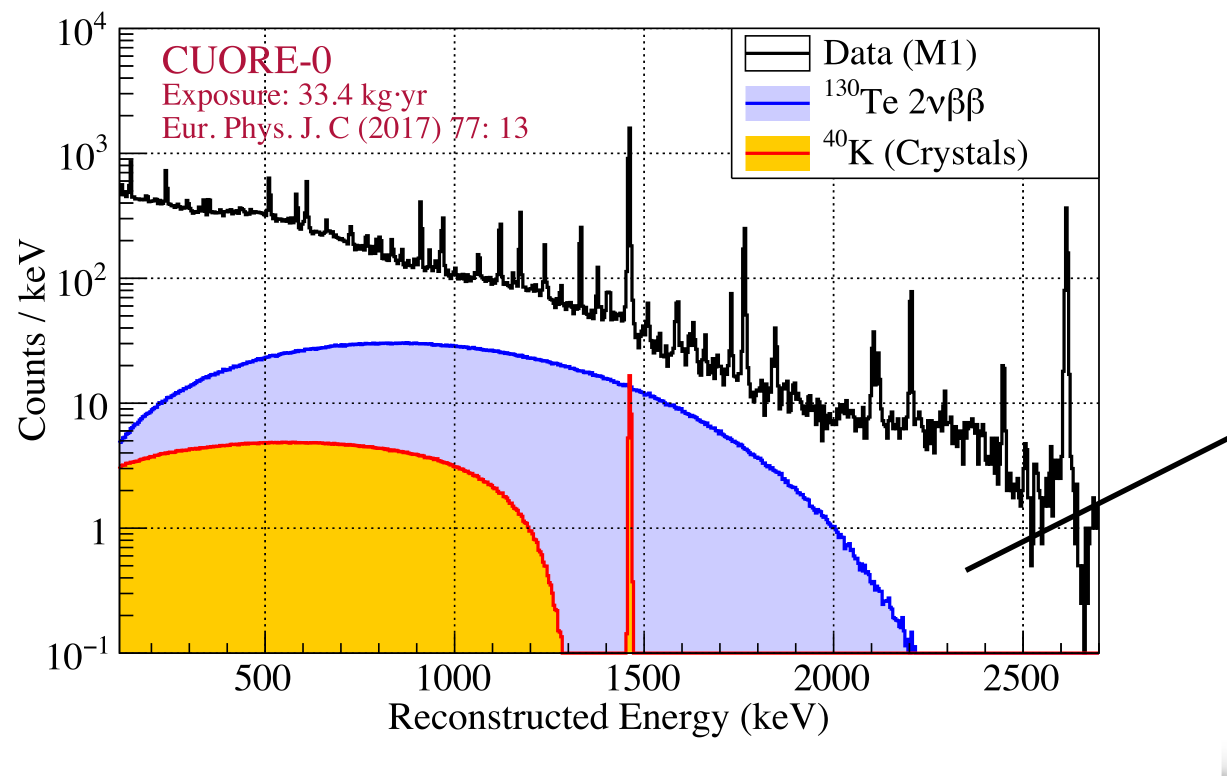


Excellent agreement of the data with the $2\nu\beta\beta$ background model

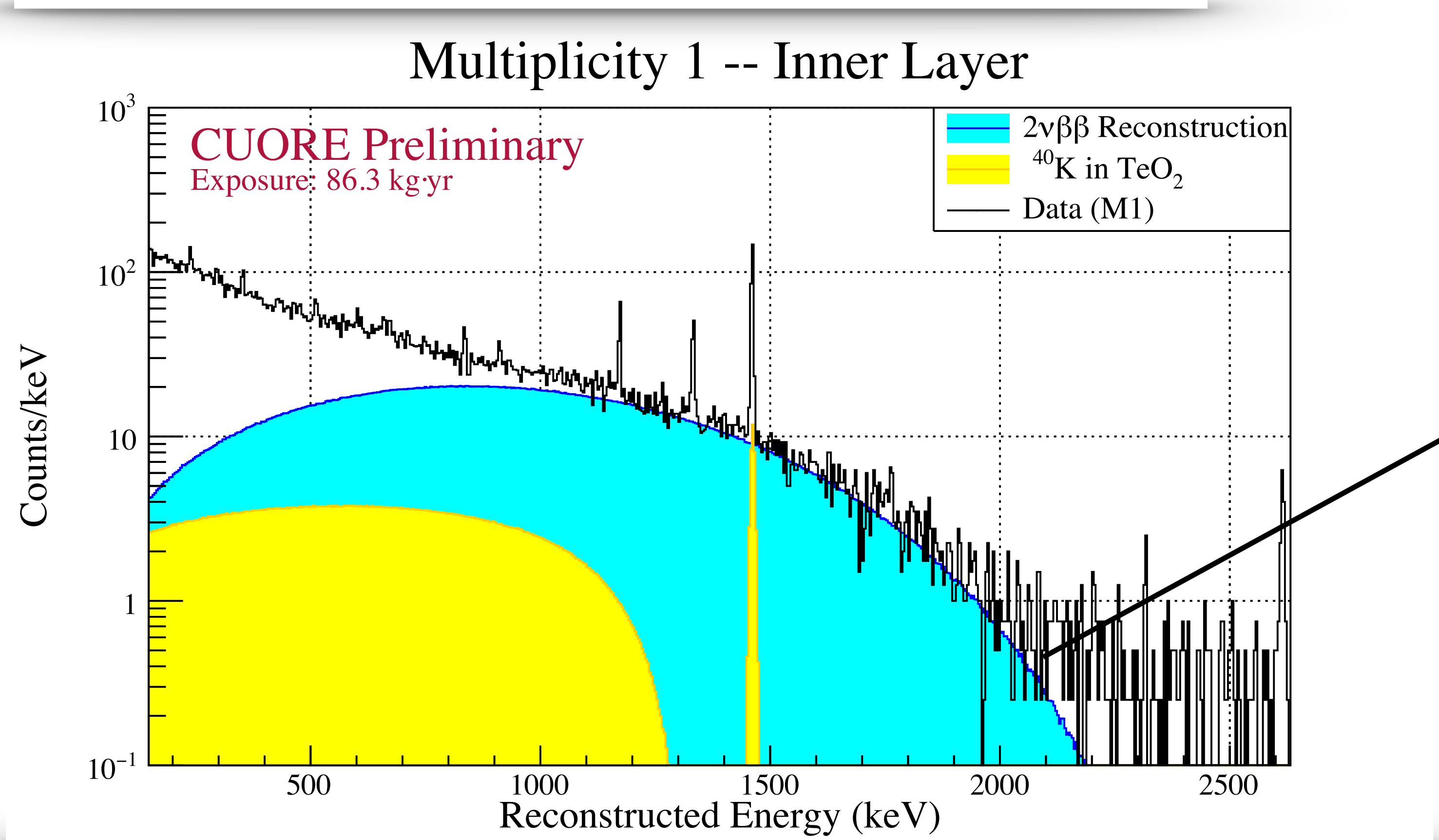
CUORE : $T_{1/2}$ = [7.9 ± 0.1 (stat.) ± 0.2 (syst.)] × 10^{20} y

- CUORE-0: $T_{1/2}$ = [8.2 ± 0.2 (stat.) ± 0.6 (syst.)] × 10^{20} y
- NEMO: $T_{1/2}$ = [7.0 ± 0.9 (stat.) ± 1.1 (syst.)] × 10^{20} y

CUORE: $2\nu\beta\beta$



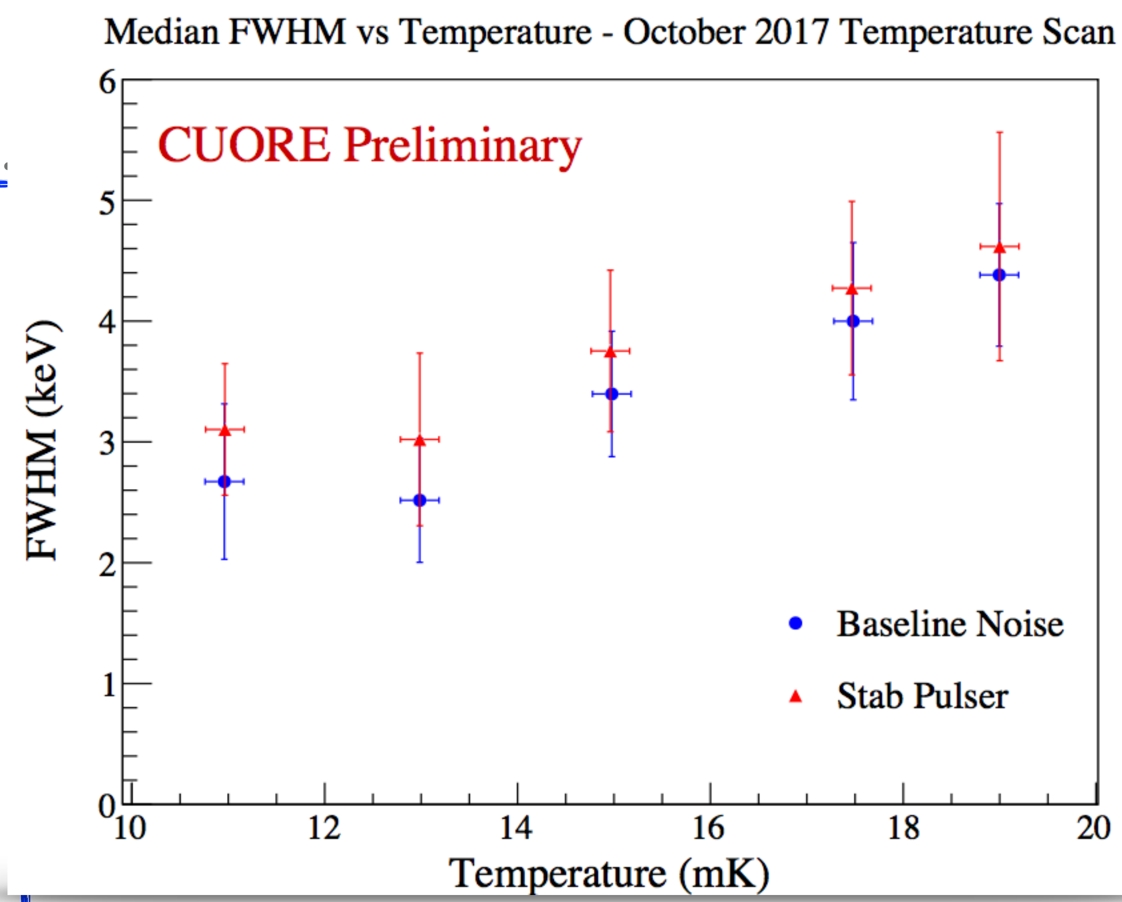
In CUORE-0, 20% of the counts in the region of 1 - 2 MeV were from $2\nu\beta\beta$.



In CUORE, almost all the counts in the region of 1-2 MeV are accounted by $2\nu\beta\beta$

CUORE : STATUS

- We found a small leak into the cryostat in the previous phase of data taking and had to warm up the cryostat to 100 K.
- We cooled down to the base temperature in March 2018.
- We spent quite some time in optimizing the detector performance (towards 5 keV FWHM goal)
- **May 2018 - Back to the data taking mode!**



Finding optimal working temperature for the best Signal-to-noise ratio

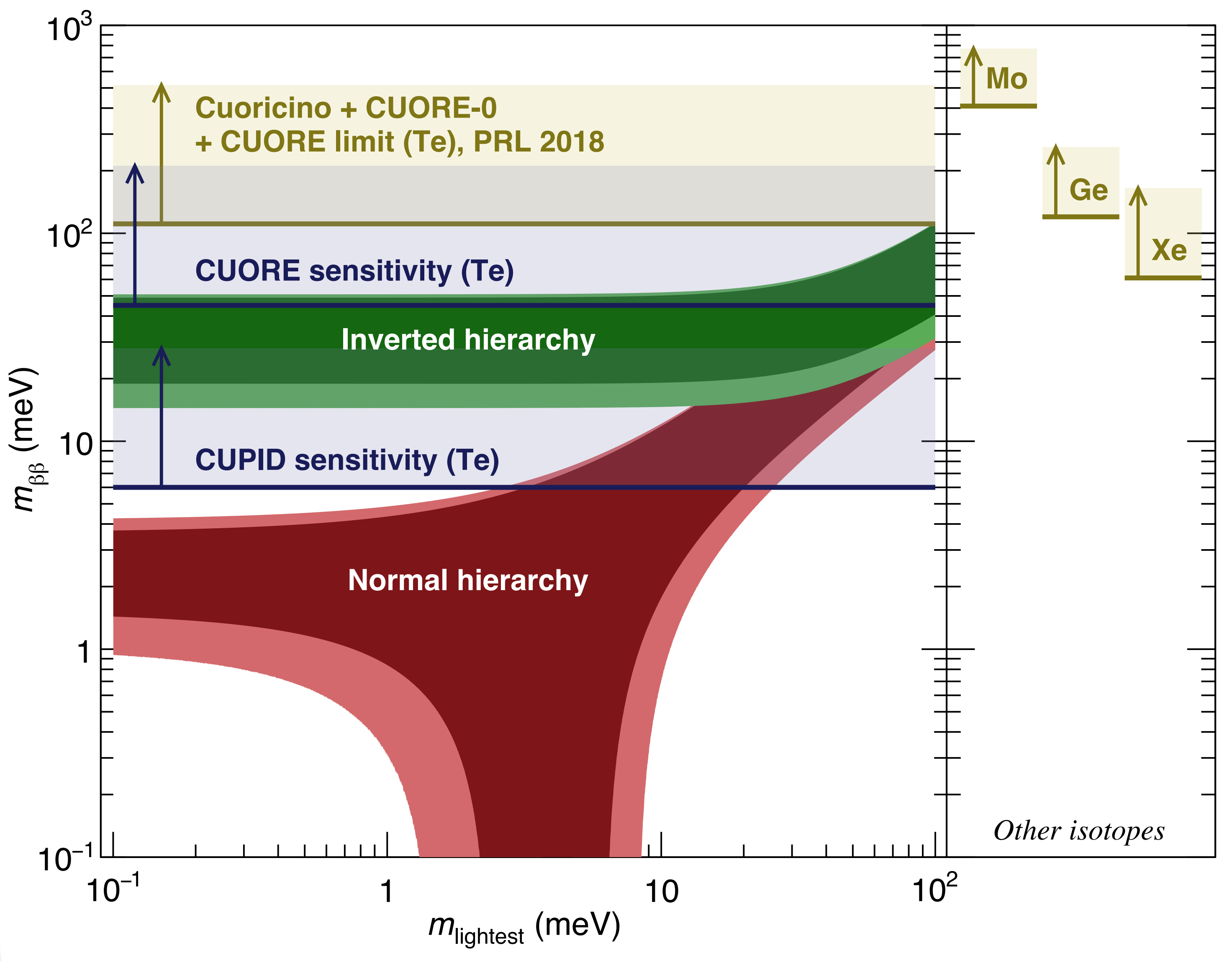
DEVELOPING ANALYSIS TECHNIQUES

- Signal separation using multi-channel decorrelation.
- Thermal model to describe the pulse template and noise in bolometers.
- Possibility of using delayed coincidences to develop a better background model.

More updates at TAUP 2019

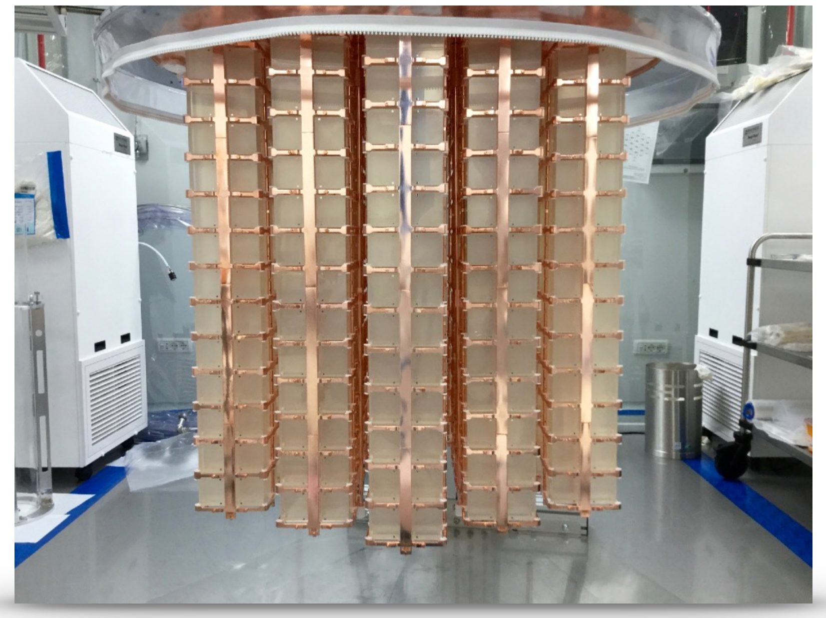
LIFE BEYOND CUORE

CUPID = CUORE UPGRADE WITH PARTICLE IDENTIFICATION

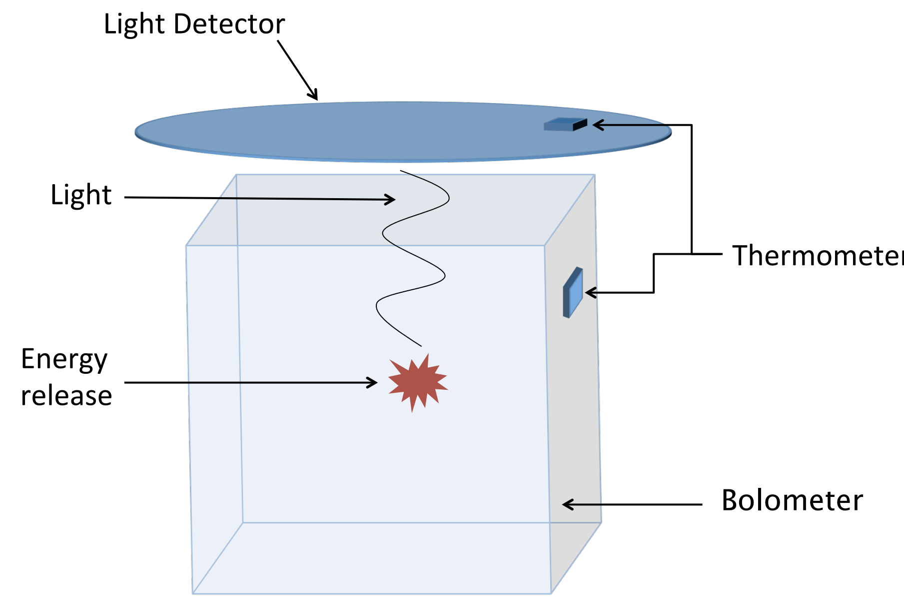


- Increase Sensitive mass ☛ Enrichment
- Active background rejection
  ☛ α / (β-γ) separation
- Goal:
  - $\triangle E_{FWHM} \leq 5$ keV @ 2615 keV
  - B = 0.1 c/ton/y in ROI
  - $<m_{\beta\beta}>$ ~ 10 meV discovery sensitivity
    (10 yrs of live time)

CUPID = CUORE UPGRADE WITH PARTICLE IDENTIFICATION



+



$Li_2{}^{100}MoO_4$ bolometers have been recognized as the baseline for next generation high sensitivity background experiment

- Large scale enriched crystal production feasible.
- Internal radio-purity targets met.
- Demonstrated active background rejection.
- Energy resolution of ~5 keV demonstrated.
- Total background of 0.1 c/ton/y achievable.

SUMMARY:

- CUORE a ton scale cryogenic experiment will be able to probe $<m_{\beta\beta}> \sim 45$ - 210 meV
- CUORE → Limited by the surface α background near the detector.
- Natural successor → CUPID, one tonne experiment with particle identification
  - $B = 0.1$ c/ton/y in ROI
  - $<m_{\beta\beta}> \sim 10$ meV discovery sensitivity (covers IHE)
- Heat + Light channel most favorable technique for particle ID.
- $Li_2{}^{100}MoO_4$ bolometers have been recognized as the baseline for next generation high sensitivity background experiment
- TeO_2 with enrichment and Cherenkov is a viable alternative.
- Extensive ongoing R&D on crystal production and sensor technology.
- CUPID collaboration to be formed soon.

COLLABORATION

Yale
INFN
Berkeley Lab
Cal Poly San Luis Obispo
Massachusetts Institute of Technology
VirginiaTech Invent the Future®
Lawrence Livermore National Laboratory
Sapienza Università di Roma
Università degli Studi di Milano Bicocca
UCLA
University of South Carolina
CUORE

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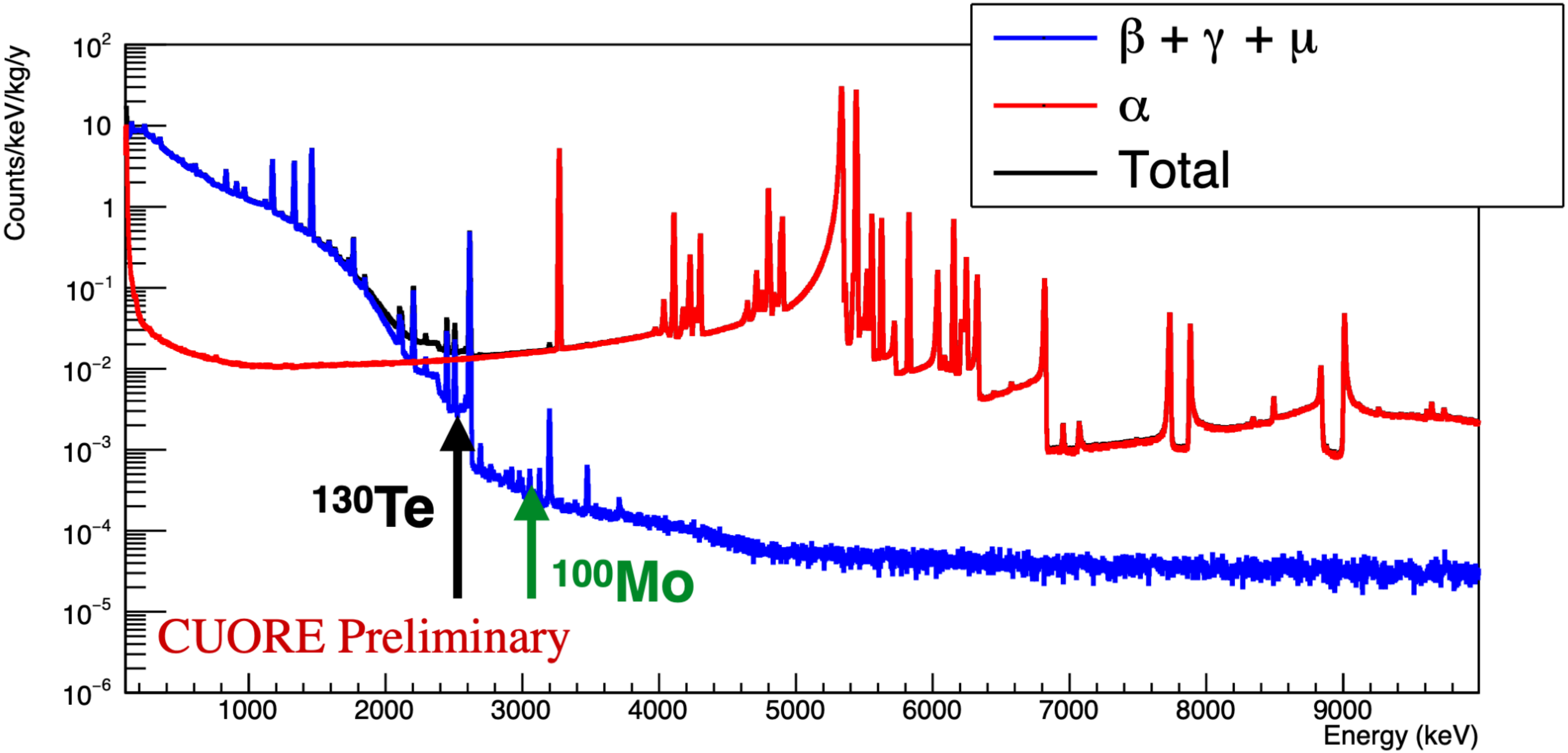
THANK YOU

BACK UP



Counts/keV/kg/y
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
1000
2000
3000
4000
5000
6000
7000
8000
9000
Energy (keV)
$\beta + \gamma + \mu$
α
Total
^{130}Te
^{100}Mo
CUORE Preliminary