30th International Conference on Low Temperature Physics
7-13 August, 2025, Bilbao, Spain

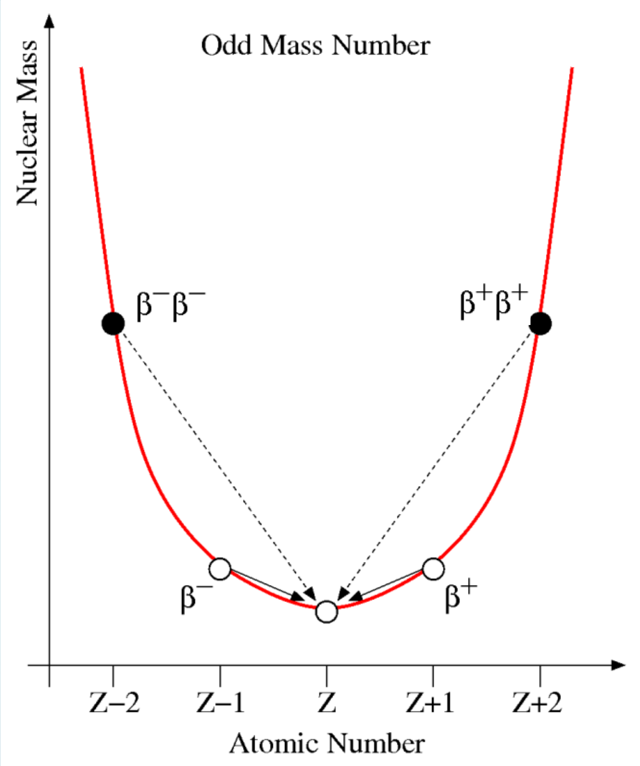
Recent results from **CUORE** and path towards **CUPID**

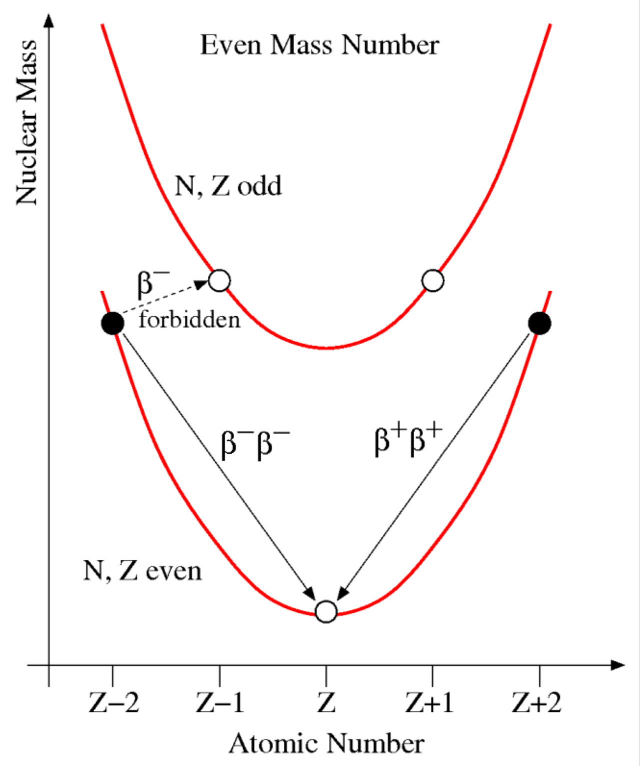
On behalf of the **CUORE** and **CUPID** collaborations

Shihong Fu · INFN-LNGS · 30th International Conference on Low Temperature Physics, August 8th, 2025

Double Beta Decay ($2\nu\beta\beta$)

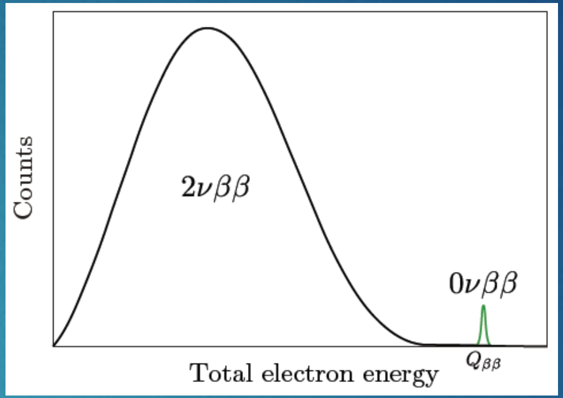
- Same mass number (A), changes the nuclear charge (Z) by two units.
- 2nd order weak transition, allowed by the Standard Model.
- Decay to the intermediate nucleus is forbidden.
- Only even mass number nuclei.
- Half-lives in the order of $10^{18} \sim 10^{21}$ yr.
- Two-neutrino double beta decay ($2\nu\beta\beta$) candidate isotopes:
  - $^{48}\mathrm{Ca}$, $^{76}\mathrm{Ge}$, $^{82}\mathrm{Se}$, $^{96}\mathrm{Zr}$, $^{100}\mathrm{Mo}$, $^{116}\mathrm{Cd}$, $^{124}\mathrm{Sn}$, $^{128}\mathrm{Te}$, $^{130}\mathrm{Te}$, $^{136}\mathrm{Xe}$, $^{150}\mathrm{Nd}$

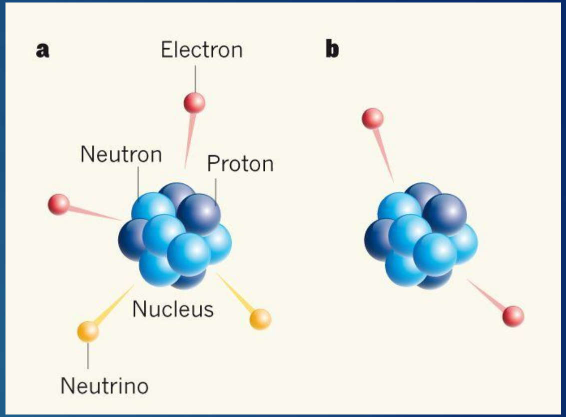


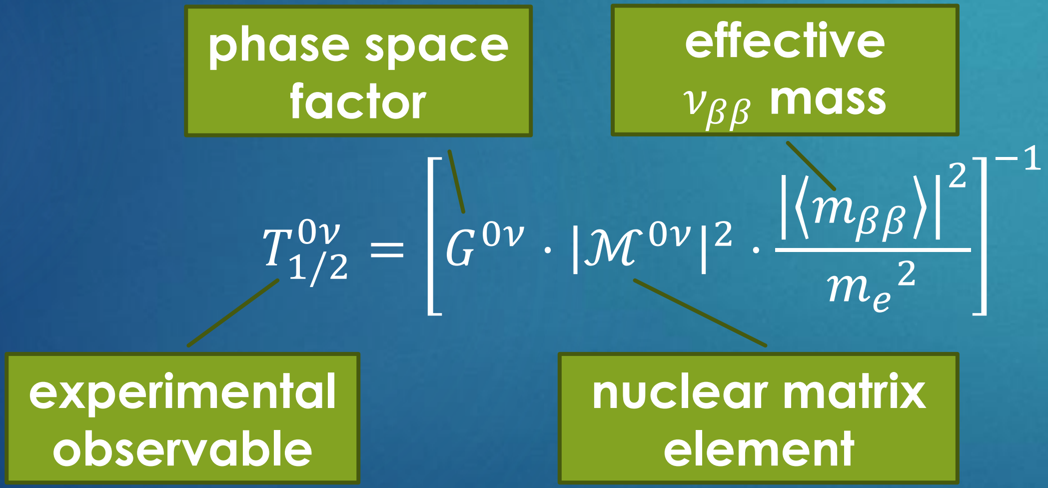


Neutrinoless Double Beta Decay (0νββ)

- Beyond Standard Model process
- Lepton Number Violation ($\Delta L = 2$)
- Constraints on neutrino mass hierarchy and scale
- Hint on origin of matter/anti-matter asymmetry







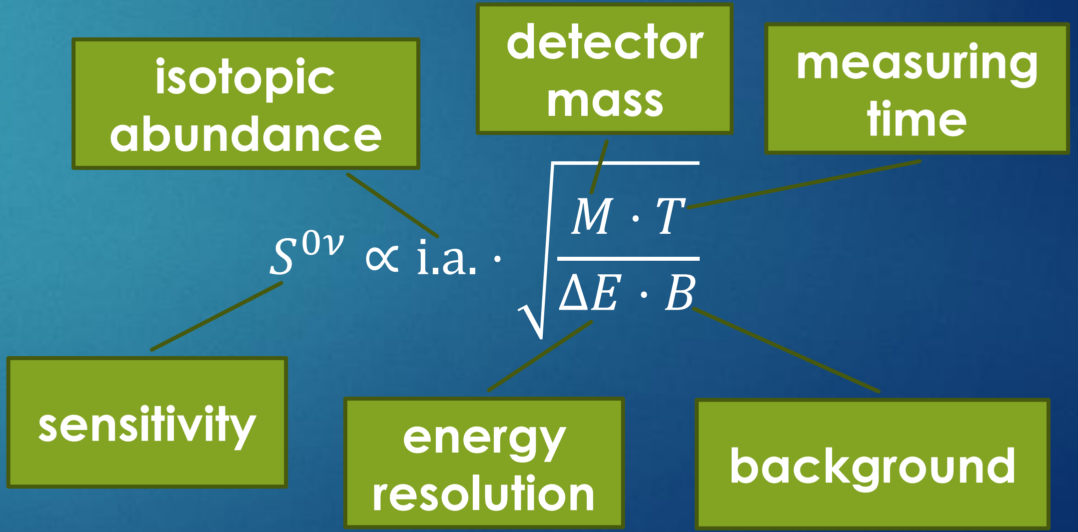
phase space factor

effective $\nu_{\beta\beta}$ mass

$$T^{0\nu}_{1/2} = \left[G^{0\nu} \cdot |\mathcal{M}^{0\nu}|^2 \cdot \frac{|\langle m_{\beta\beta} \rangle|^2}{{m_e}^2} \right]^{-1}$$

experimental observable

nuclear matrix element



isotopic abundance

detector mass

measuring time

$$S^{0\nu} \propto \text{i.a.} \cdot \sqrt{\frac{M \cdot T}{\Delta E \cdot B}}$$

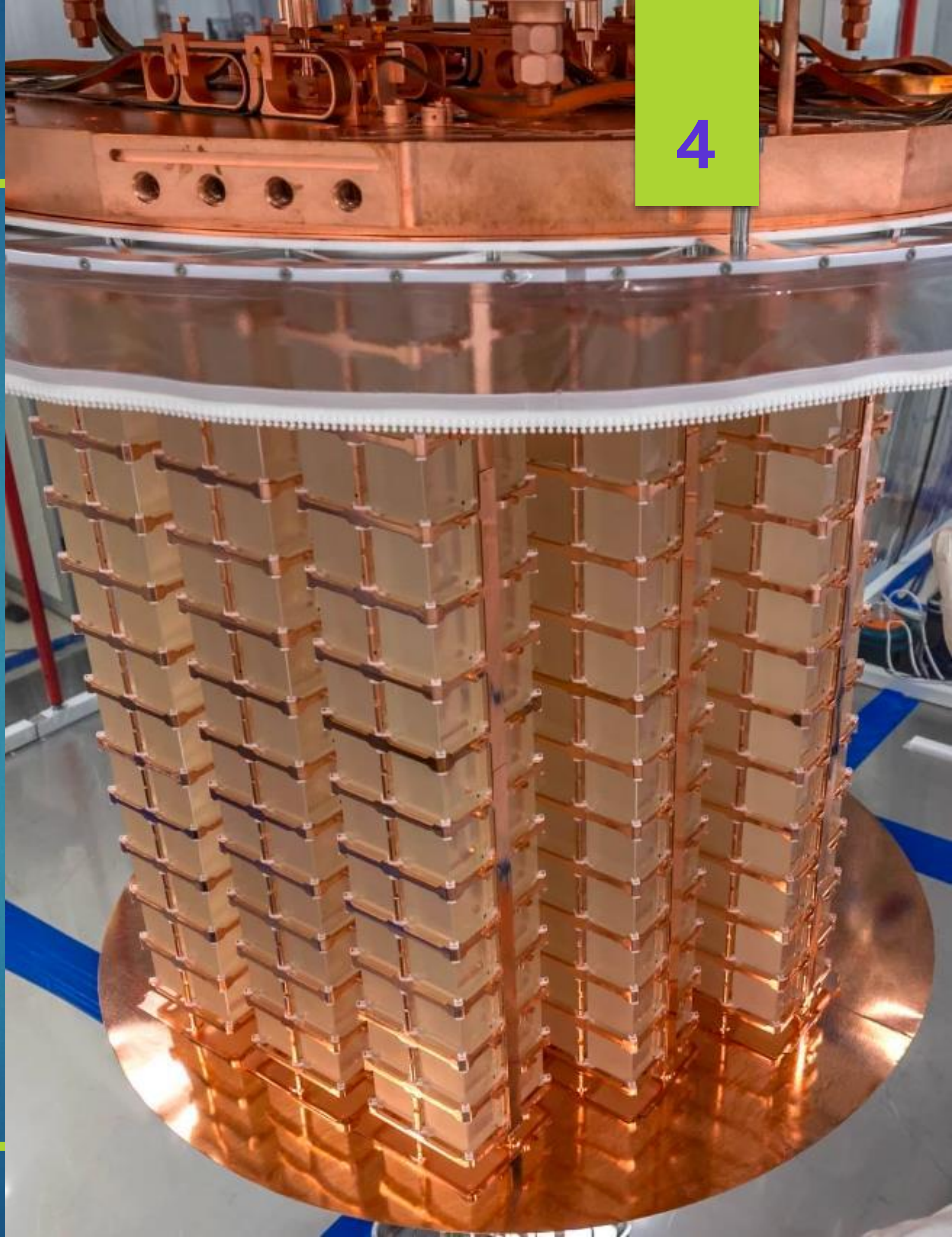
sensitivity

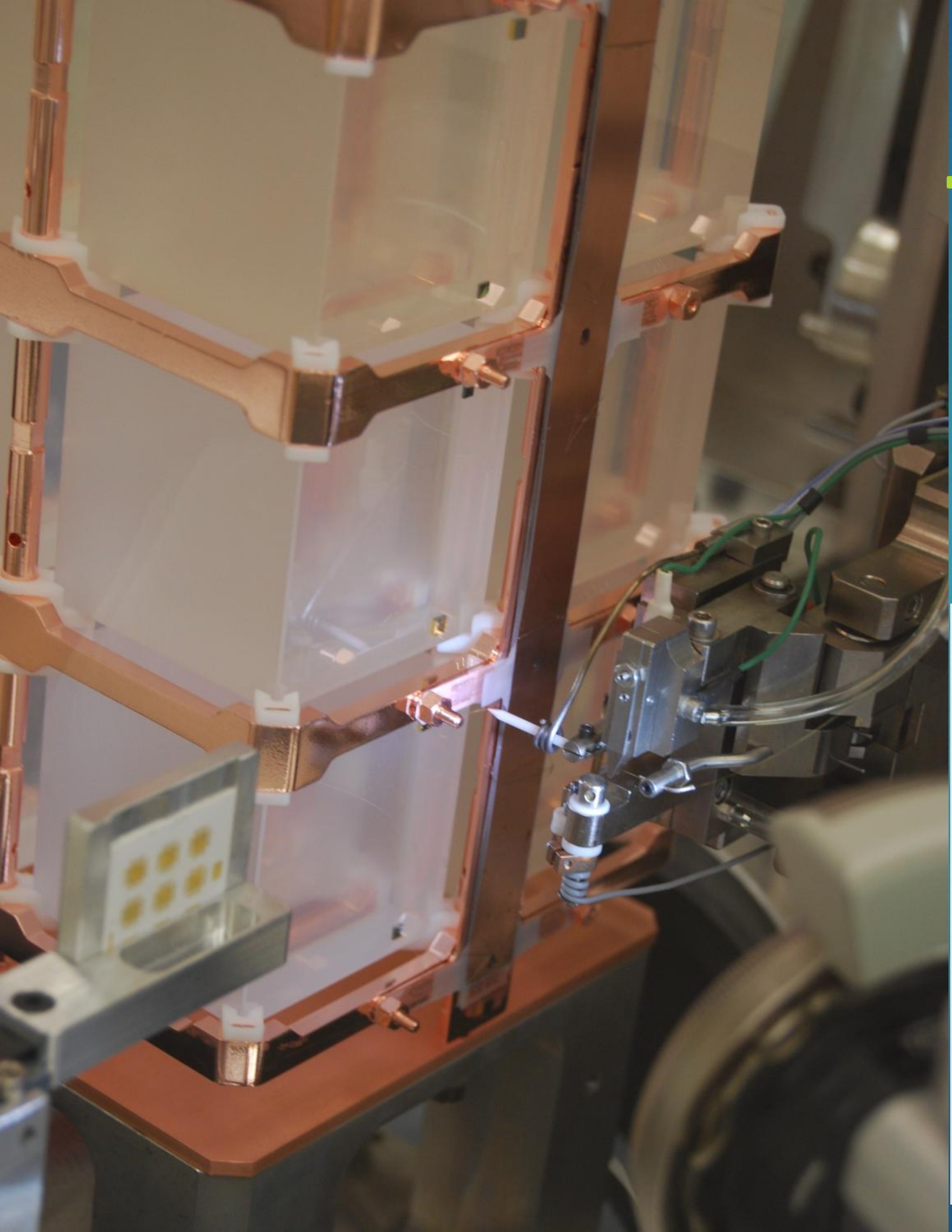
energy resolution

background

CUORE experiment

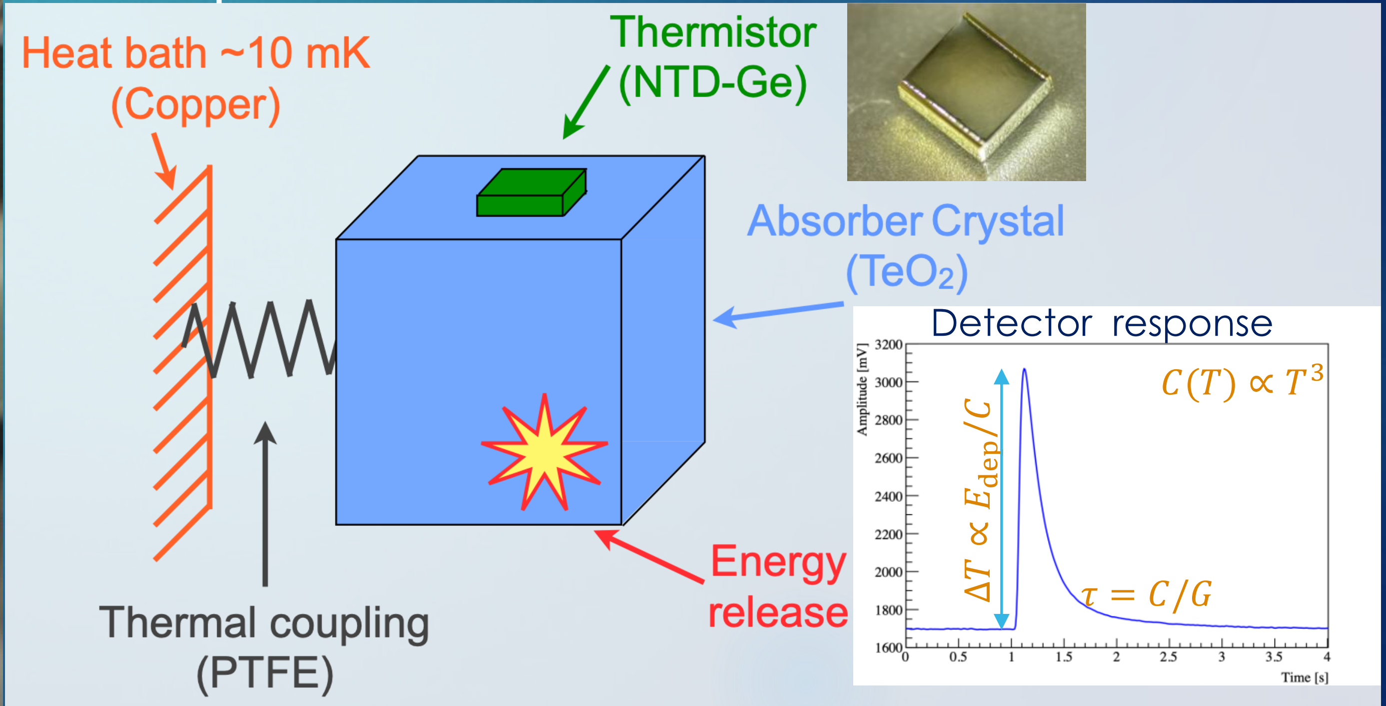
- **C**ryogenic **U**nderground **O**bservatory for **R**are **E**vents
- In operation at the Laboratori Nazionali del Gran Sasso, Italy
- Main objective: observe $0\nu\beta\beta$ in $^{130}\mathrm{Te}$
- The CUORE detector is hosted in a cryogen-free cryostat
  - Operating temperature $\sim 10\ \mathrm{mK}$
  - Designed for low radioactivity and low vibrations environment
- Energy resolution: goal of $\sim 5\ \mathrm{keV}$ at $Q_{\beta\beta}$ $(2527.5\ \mathrm{keV})$
- Low background: goal of $\sim 10^{-2}$ counts / $(\mathrm{keV} \cdot \mathrm{kg} \cdot \mathrm{yr})$ at $Q_{\beta\beta}$





Cryogenic Bolometer

- Detector mass
- Energy resolution
- Reproducibility
- Background level
- Bolometers must be operated at low temperatures.
- The thermal sensor is a Neutron Transmutation Doped (NTD) Ge thermistor, which is sensitive to temperature variation.



Heat bath ~10 mK (Copper)

Thermistor (NTD-Ge)

Absorber Crystal (TeO_2)

Energy release

Thermal coupling (PTFE)

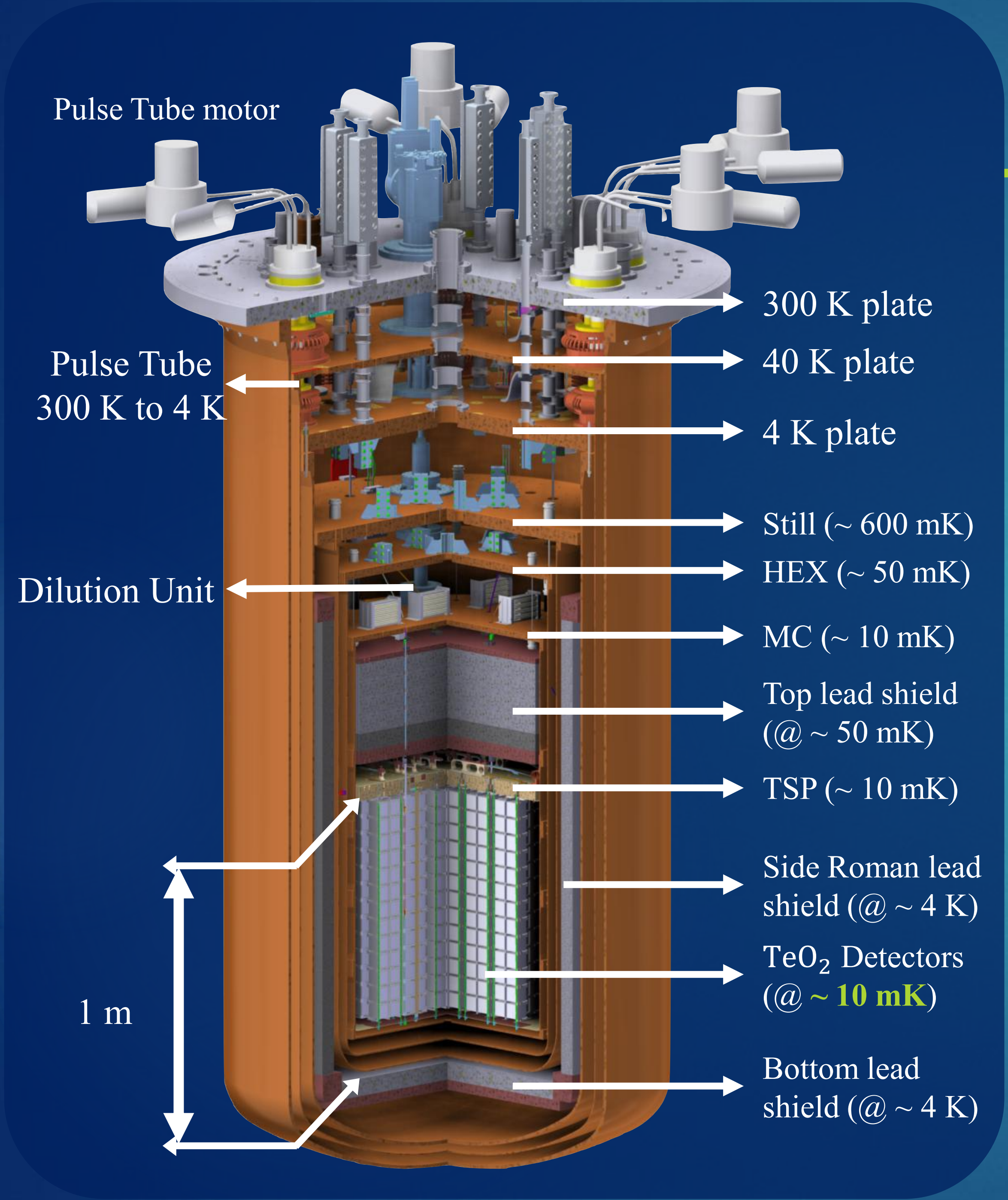
Detector response

$C(T) \propto T^3$

$\Delta T \propto E_{\mathrm{dep}}/C$

$\tau = C/G$

CUORE Cryostat



- Custom-made dry dilution refrigerator
- $1.5\ t$ of material at base temperature for ~8 years!
- 5 pulse-tube refrigerators (1 spare)
  - Relative phases tuned for noise cross-canceling
- 6 nested vessels at decreasing temperatures
- Low-temperature lead shielding
  - Modern lead on top of detectors to suppress γ's from cryogenic components
  - Side Roman lead shielding to suppress external γ's
- $742\ kg\ TeO_2$ detectors, $206\ kg\ ^{130}Te$ (34% natural isotopic abundance)
- 988 crystal bolometric array
- arranged in 19 towers with 13 floors each, 52 $5 \times 5 \times 5\ cm^3\ TeO_2$ crystals per tower

Data collection

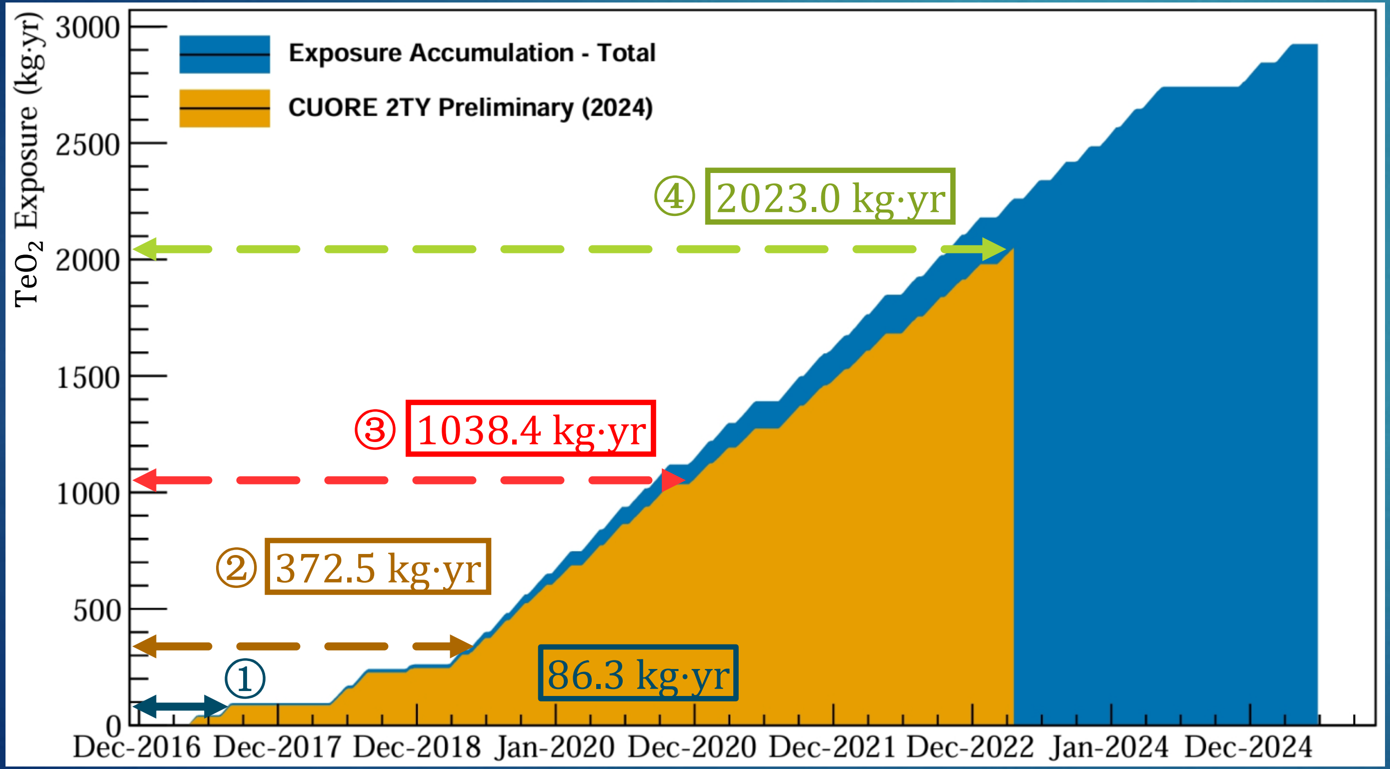
- Data taking started in 2017, with first 2 years for cryostat and detector optimization
- Stable data collection since 2019, with $\gtrsim 85\%$ uptime
- > 2.9 ton·yr of raw $\mathrm{TeO_2}$ exposure accumulated

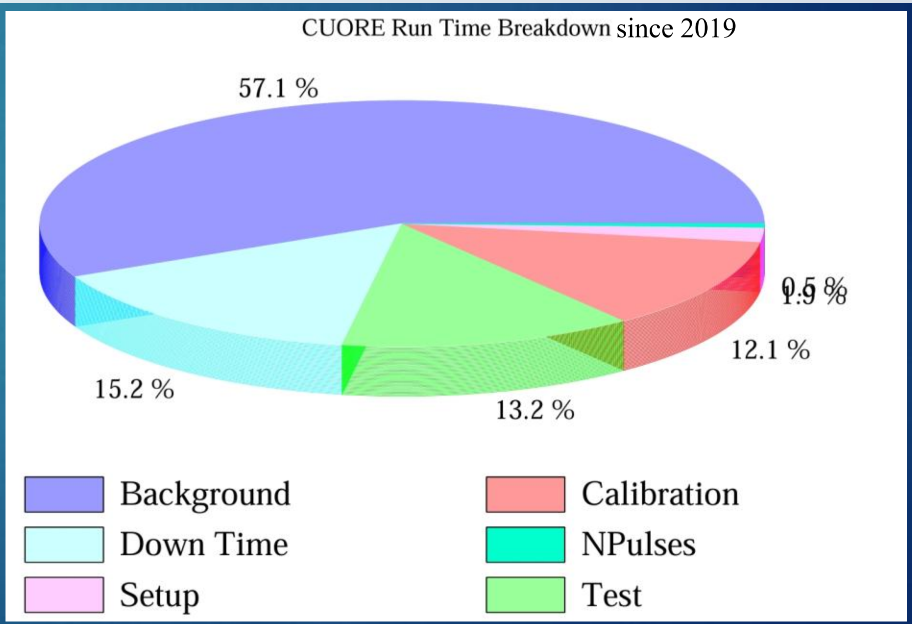
① Alduino, C. et al. (CUORE Collaboration), *Phys. Rev. Lett.* **120**, 132501 (2018)

② Adams, D.Q. et al. (CUORE Collaboration), *Phys. Rev. Lett.* **124**, 122501 (2020)

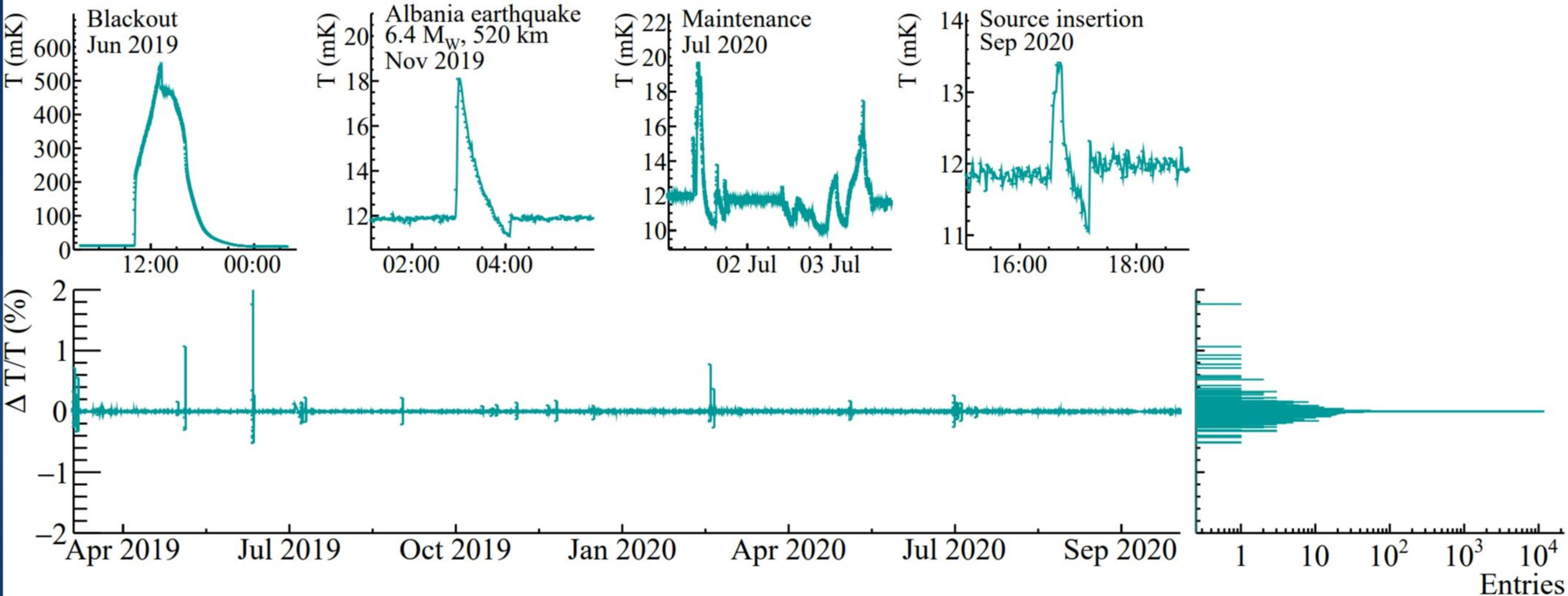
③ Adams, D.Q. et al. (CUORE Collaboration), ***Nature* 604**, 53-58 (2022)

④ **arXiv:2404.04453** (CUORE Collaboration)





The cryostat performance

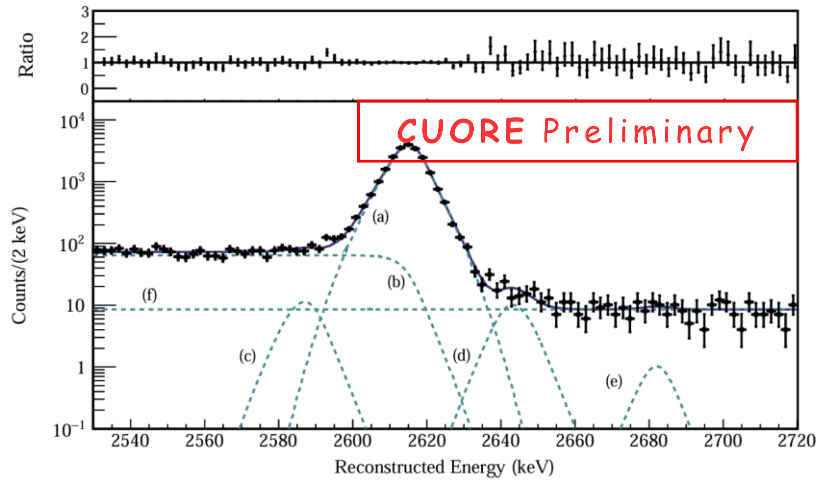


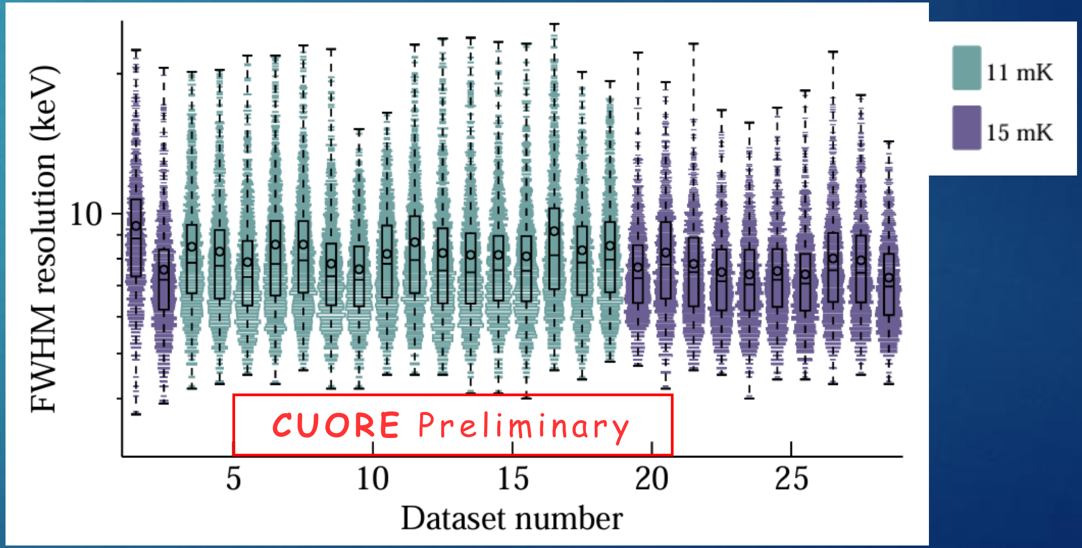
Adams, D.Q. et al. (CUORE Collaboration), ***Nature* 604**, 53-58 (2022)

Detector performance

arXiv:2404.04453 (CUORE Collaboration)

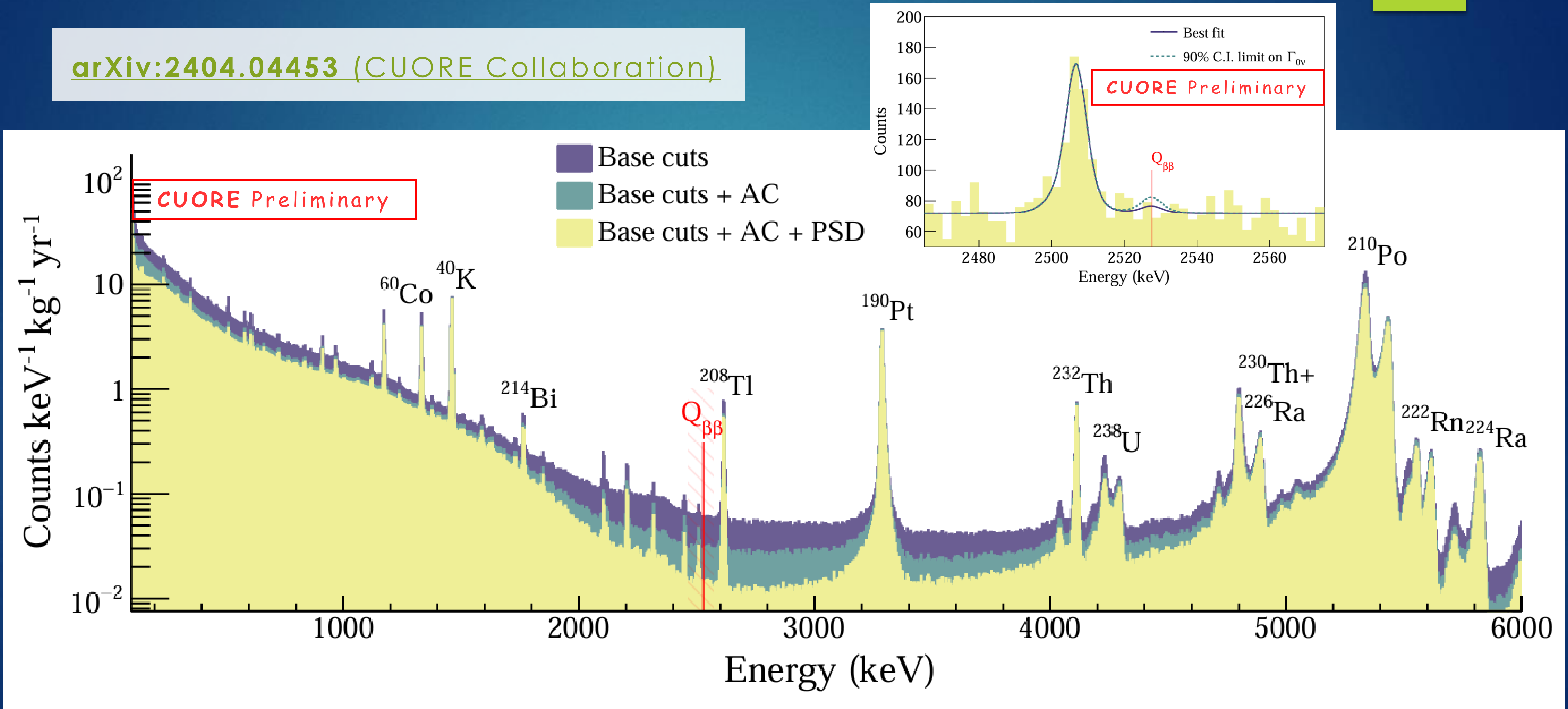
- Peak lineshape:
  - Reference $^{208}\mathrm{Tl}$ gamma peak at $2615\ \mathrm{keV}$ from calibration data
- Fit model:
  - (a) Multi-Gaussian photopeak
  - (b) Compton shoulder
  - (c), (d), (e) Coincidence/escape peaks
  - (f) Uniform background
- Fit at channel-dataset level
- Energy resolution at $2615\ \mathrm{keV}$
  - FWHM = $(7.540 \pm 0.024)\ \mathrm{keV}$
    - harmonic mean - exposure weighted





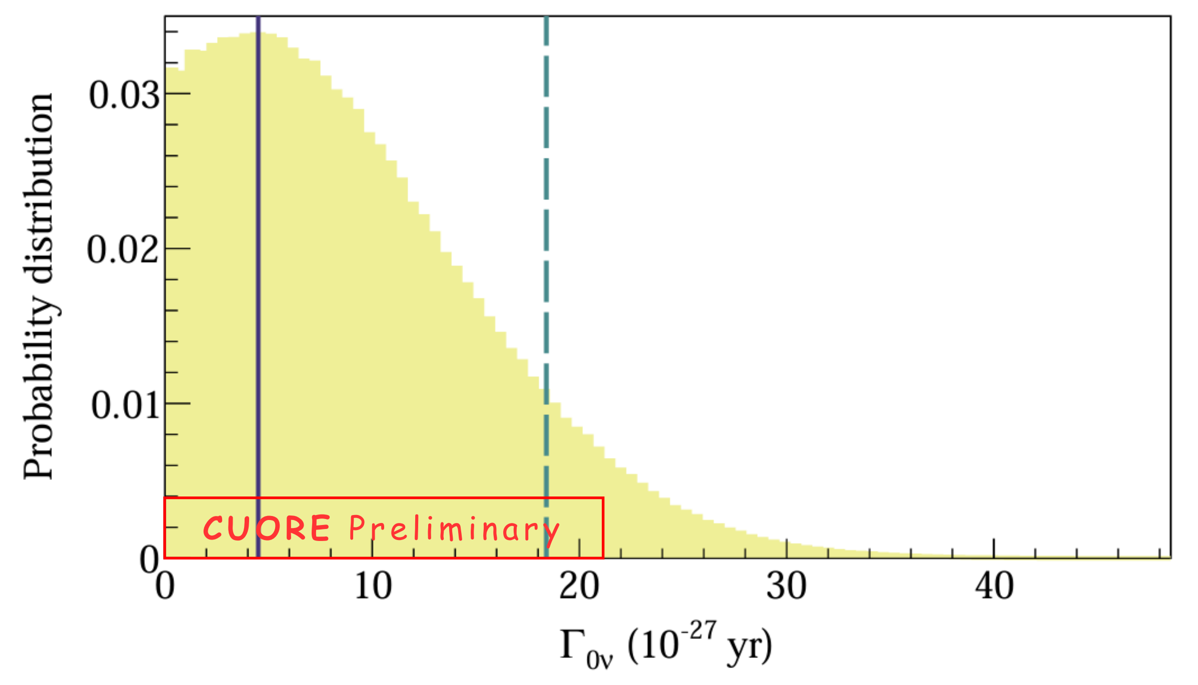
2 ton · yr exposure

arXiv:2404.04453 (CUORE Collaboration)

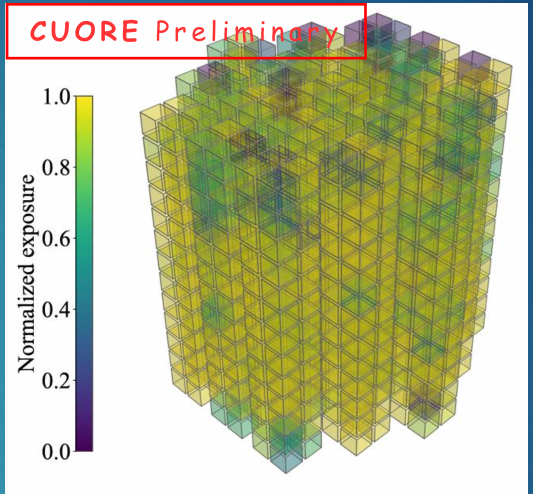


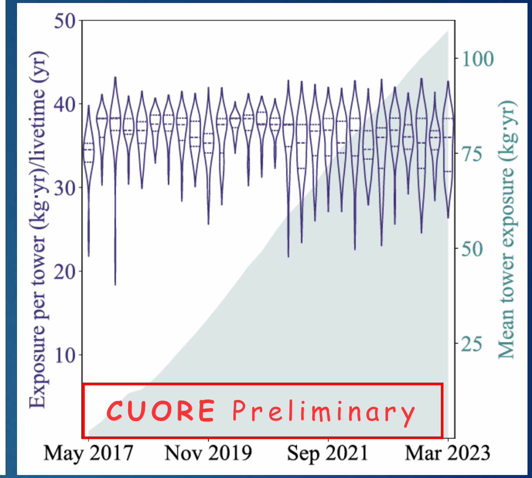
$0\nu\beta\beta$ decay search results

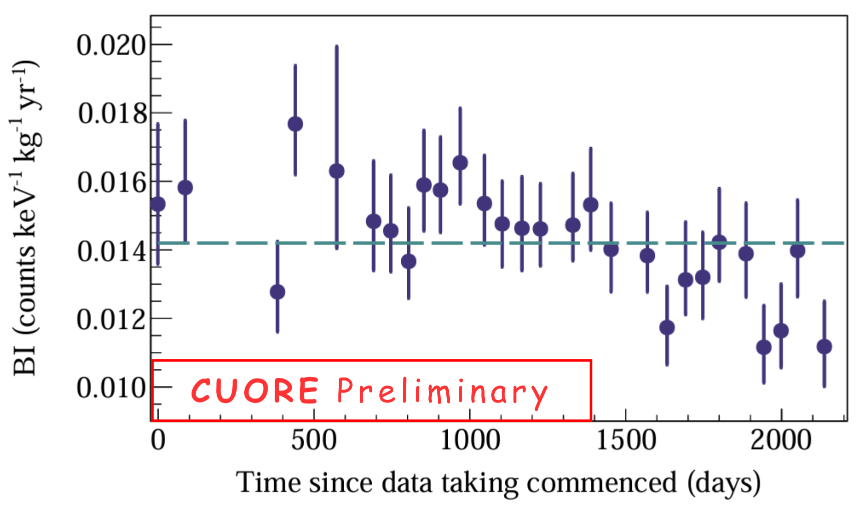
- Resolution scaling
  - FWHM at $Q_{\beta\beta} = (7.320 \pm 0.024)$ keV



- Bayesian limit: $T_{1/2}^{0\nu} > 3.8 \cdot 10^{25}$ yr @ 90% C.I.







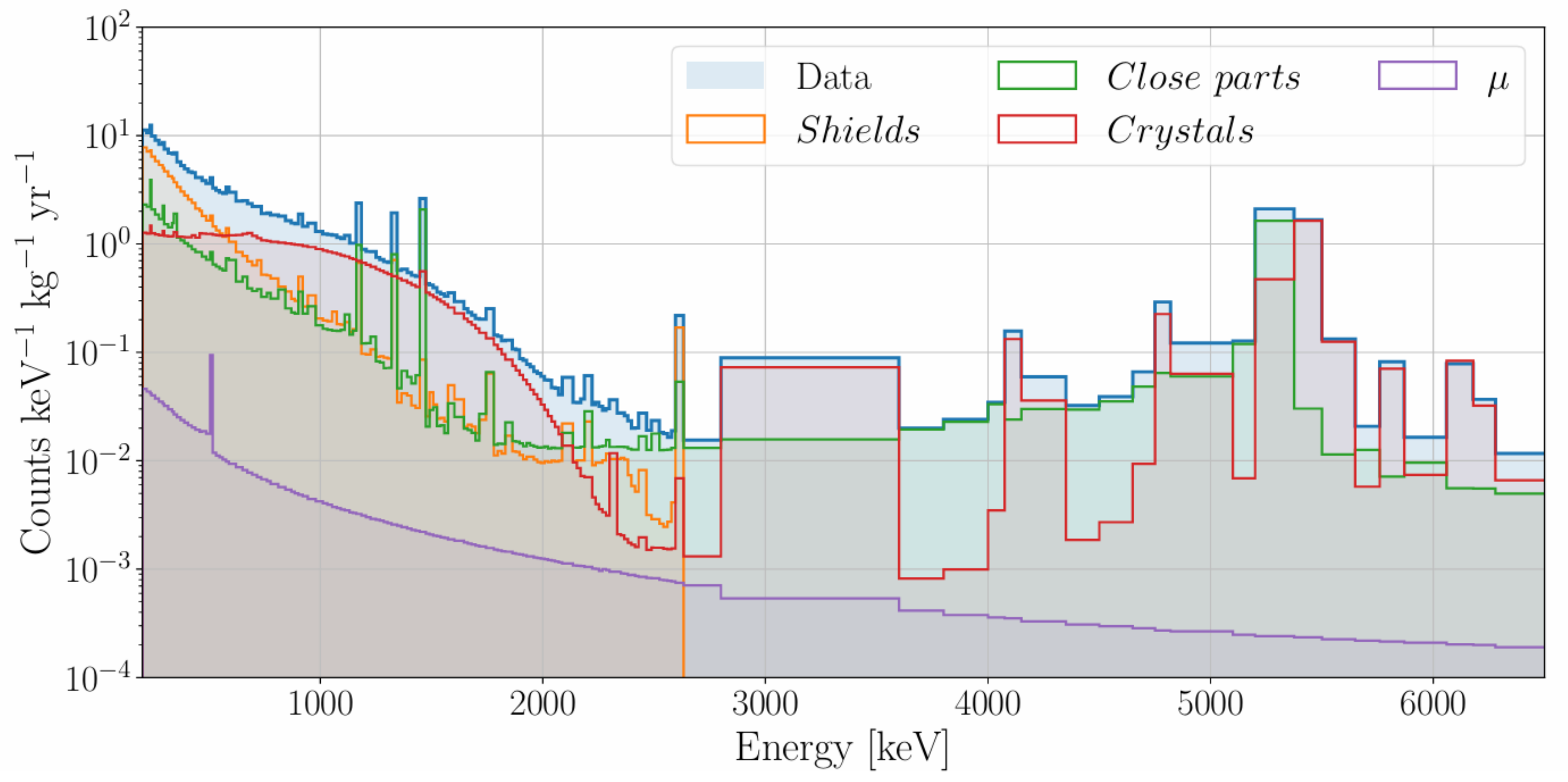
- BI: $(1.42 \pm 0.02) \cdot 10^{-2}$ counts / (keV · kg · yr)

Adams, D.Q. et al. (CUORE Collaboration), arXiv:2404.04453

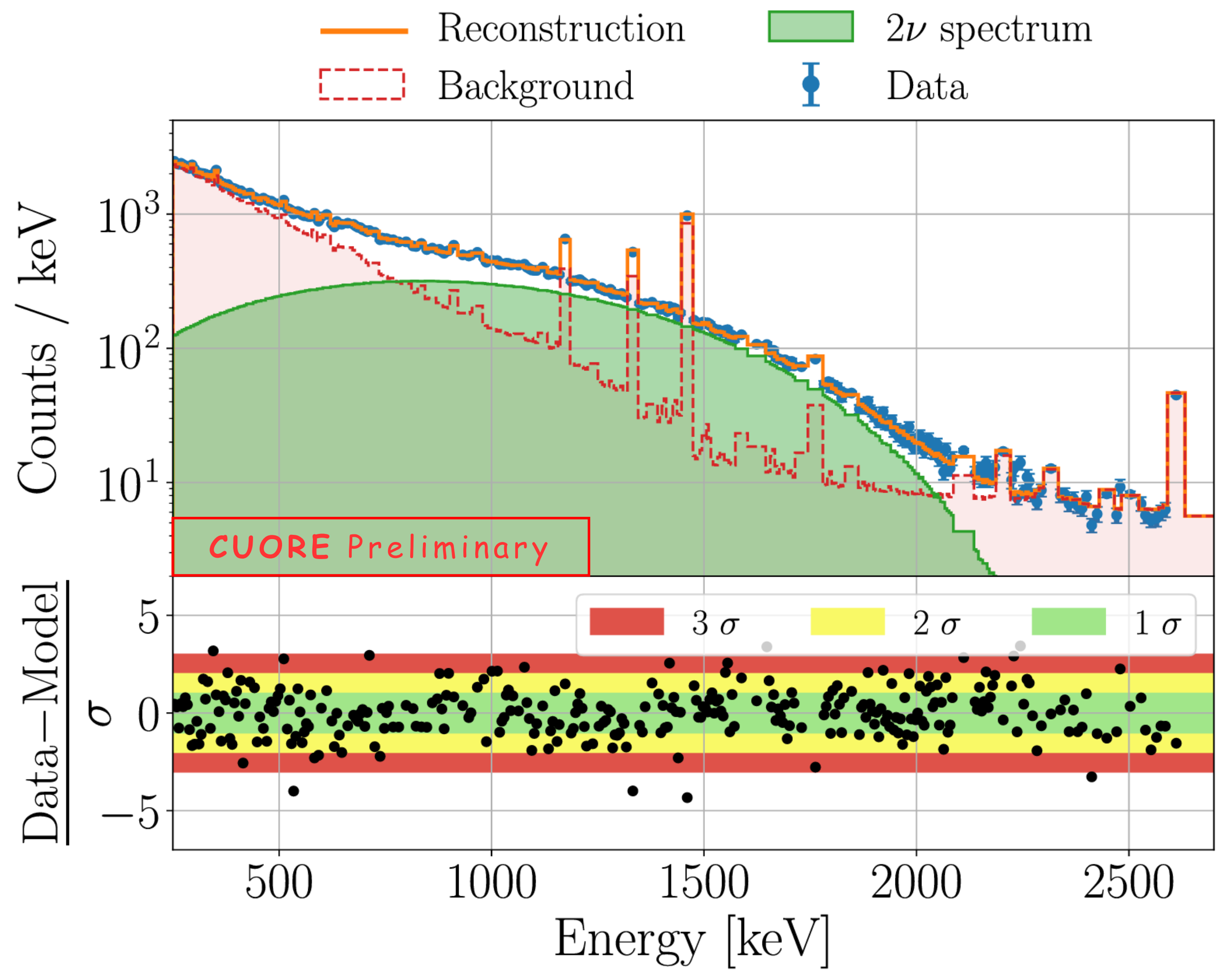
Background model results

- Full detector geometry and particle interaction implemented in Geant4
- Geant4 output post-processed to include detector response
- Comprehensive simulated sources (bulk, surface, muons)
- Multiparametric Bayesian fit of 39 spectra encompassing M1 and M2 events across (0.2, 6.8) MeV

Adams, D.Q. et al. (CUORE Collaboration), *Phys. Rev. D* **110**, 052003 (2024)



2νββ decay measurement

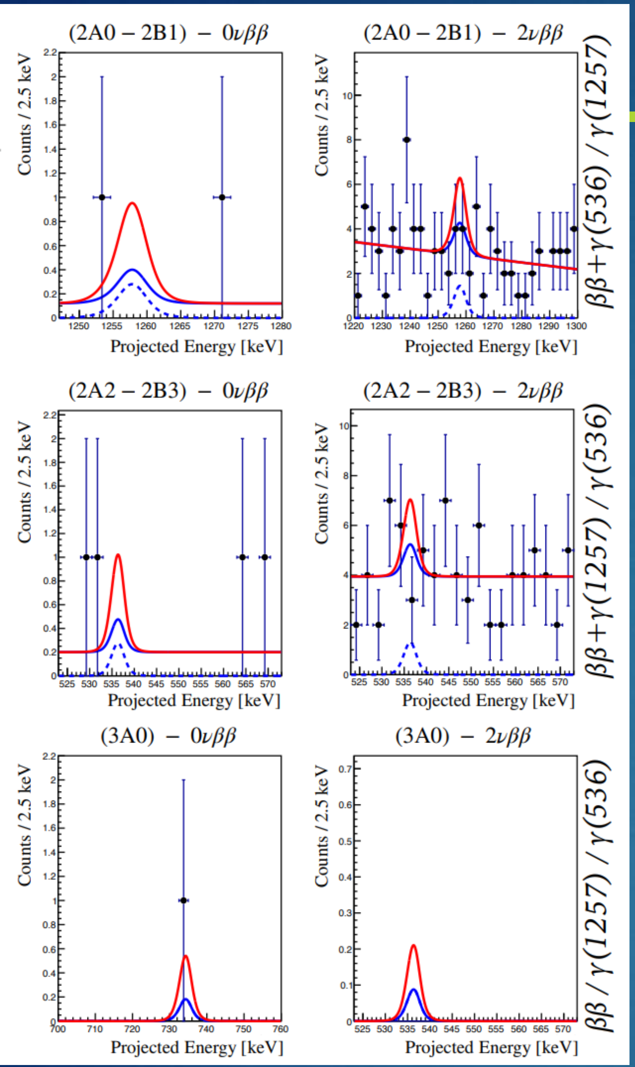


arXiv:2503.24137 (CUORE Collaboration)

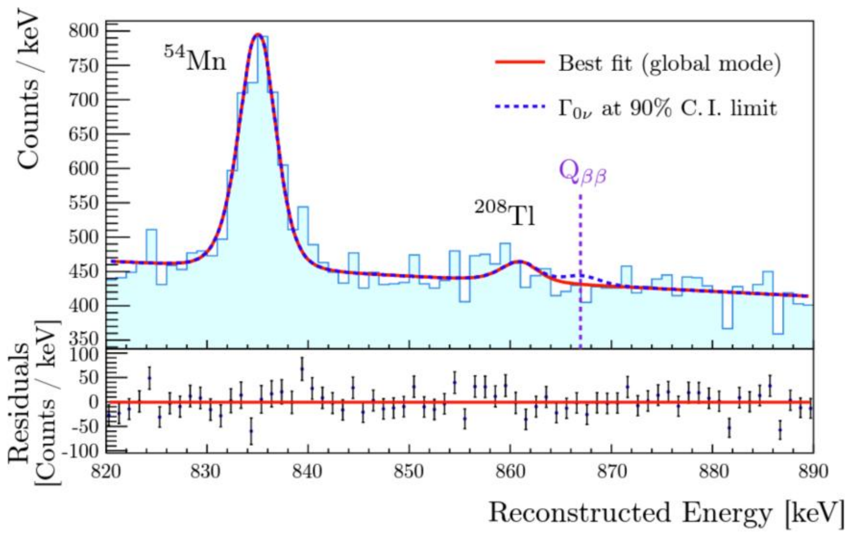
- ^{130}Te 2νββ component from best fit to the single-crystal-event energy spectrum with CUORE 1038.4 kg·yr TeO_2 exposure.
- Spectral fit
- $T_{1/2}^{2\nu} = 9.32^{+0.05}_{-0.04}(\text{stat.})^{+0.07}_{-0.07}(\text{syst.}) \times 10^{20}$ yr
- Most precise measurement of ^{130}Te 2νββ decay half-life to date

Other rare event searches

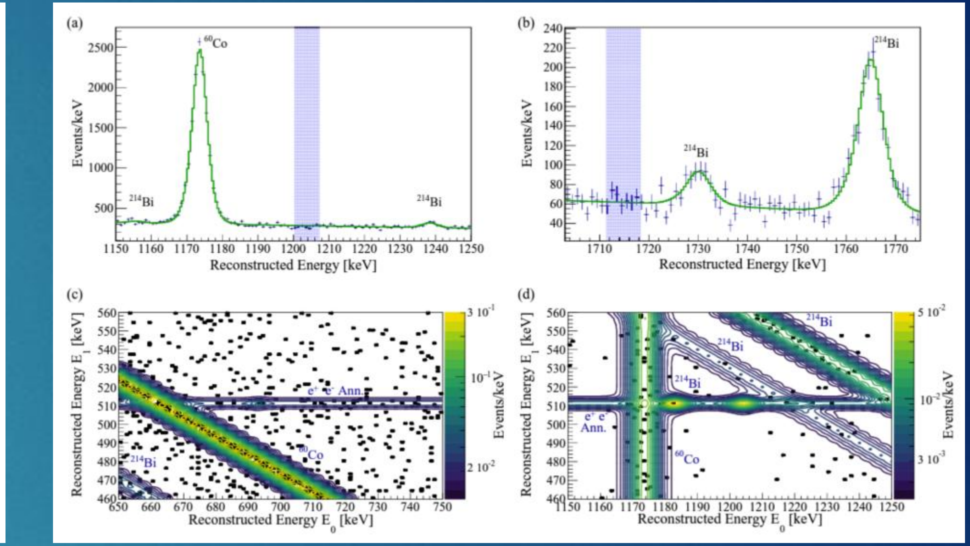
^{130}Te $\beta\beta$ to first 0^+ excited state



^{128}Te $0\nu\beta\beta$



^{128}Te β^+/EC



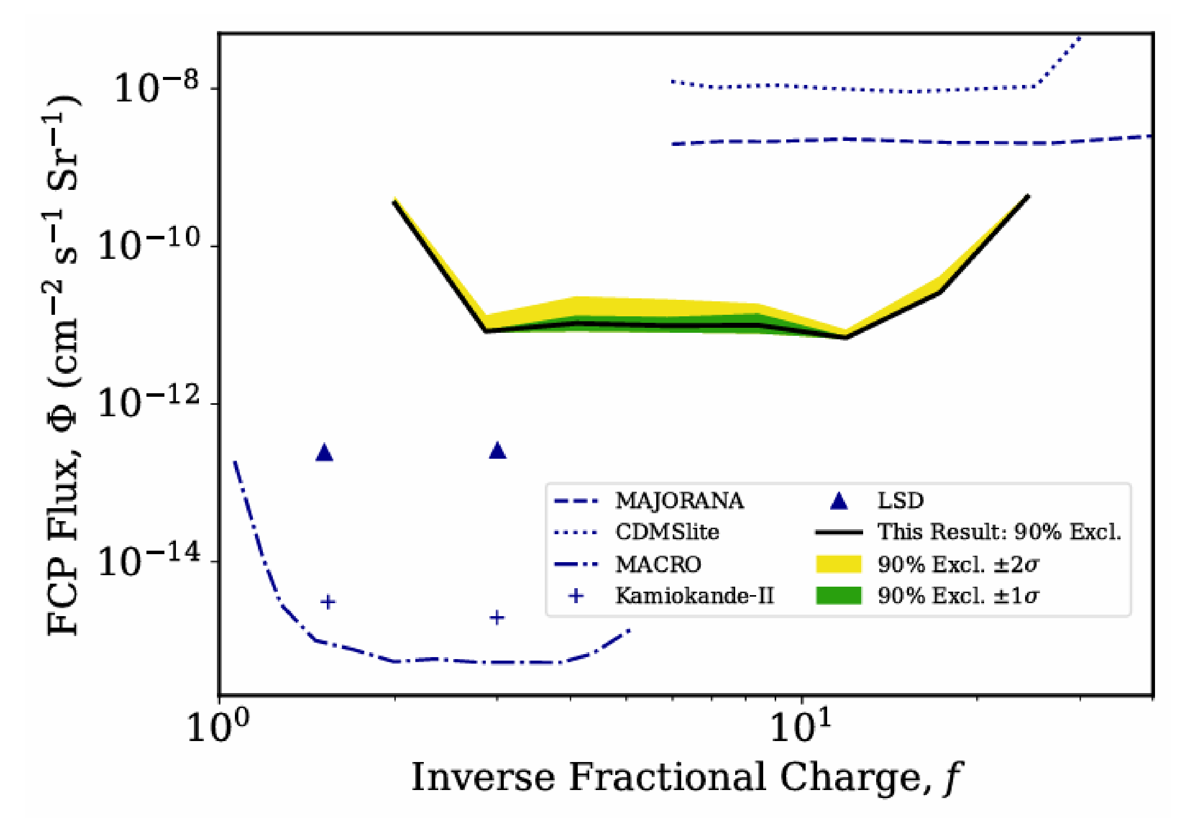
Adams, D.Q. et al. (CUORE Collaboration), *Phys. Rev. Lett.* **129**, 222501 (2022)

Adams, D.Q. et al. (CUORE Collaboration), *Eur. Phys. J. C* **81**, 567 (2021)

Adams, D.Q. et al. (CUORE Collaboration), *Phys. Rev. C* **105**, 065504 (2022)

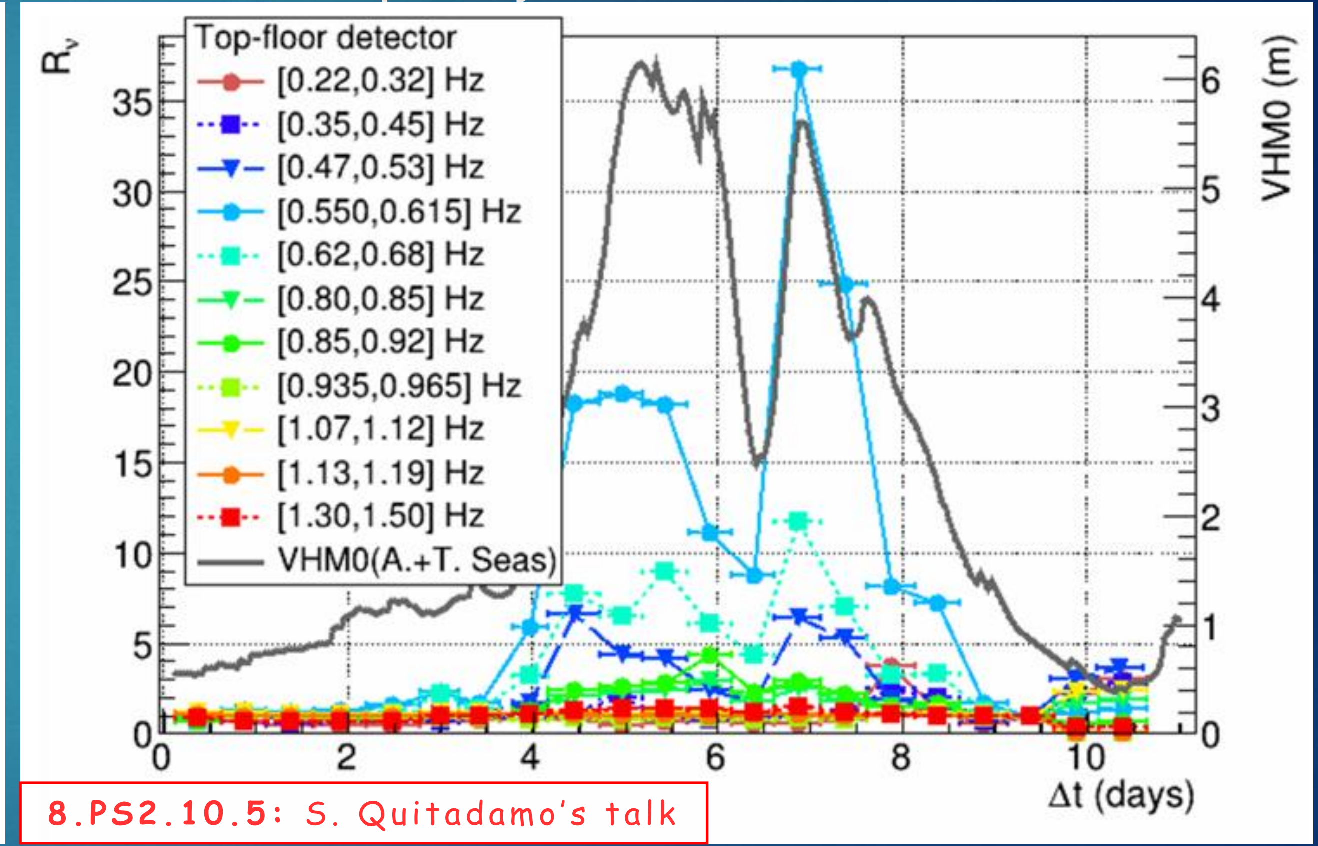
Other searches

Fractionally Charged Particles



Adams, D.Q. et al. (CUORE Collaboration), *Phys. Rev. Lett.* **133**, 241801 (2024)

Correlations between CUORE low frequency noise and sea waves



8.PS2.10.5: S. Quitadamo's talk

- Aragão, L. et al., *Eur. Phys. J. C* **84**, 728 (2024)
- arXiv:2505.09652 (CUORE Collaboration)

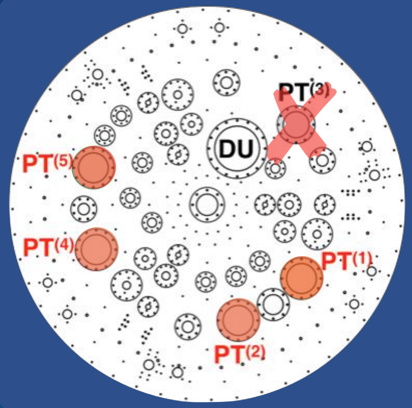
What’s next?

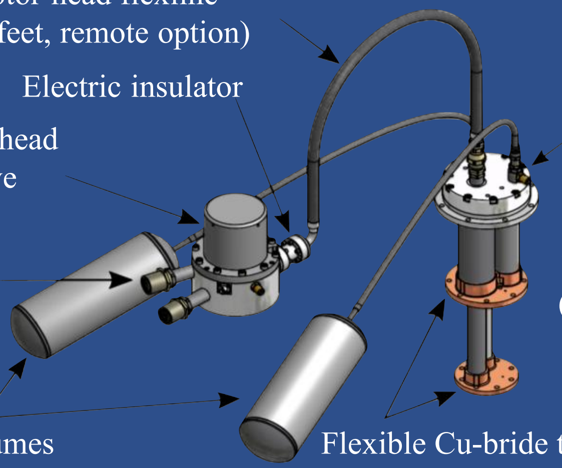
- CUORE phase-I (current)
  - Run up to mid-2026
  - Reach $> 3\ \mathrm{ton \cdot yr\ \ TeO_2}$, $1\ \mathrm{ton \cdot yr\ \ ^{130}Te}$ exposure (largest ever collected for $^{130}\mathrm{Te}$)
  - Room for multiple rare events searches with high statistic, optimal energy resolution and low background

- CUORE phase-II
  - Cryogenic interventions to mitigate vibrational noise and advance research in the low-energy regime
  - Plan to resume data-taking in 2026

- CUPID (CUORE Upgrade with Particle Identification)
  - Scintillating cryogenic calorimeters:
  - α vs β/γ and ββ pile-up rejection using light signal
  - Background: goal of $10^{-4}\ \mathrm{counts\ /\ (keV \cdot kg \cdot yr)}$
  - Energy resolution: goal of $5\ \mathrm{keV}$ at $Q_{\beta\beta}$

Cryostat: performance and future upgrades





Motor-head flexline
(2 feet, remote option)

Electric insulator

PUR ring

Remote-Motor-head
with rotary valve

PT head
(300 K)

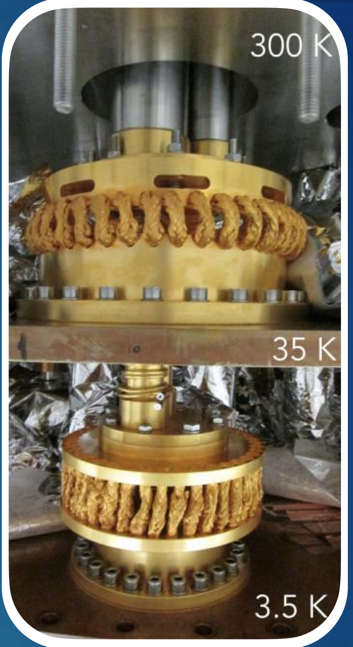
High/low
pressure inlet

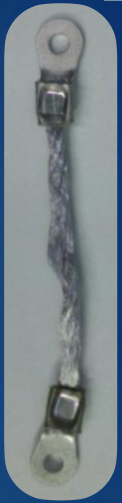
1st stage
(40 K 35 K)

2nd stage
(4 K 3.5 K)

Buffer volumes

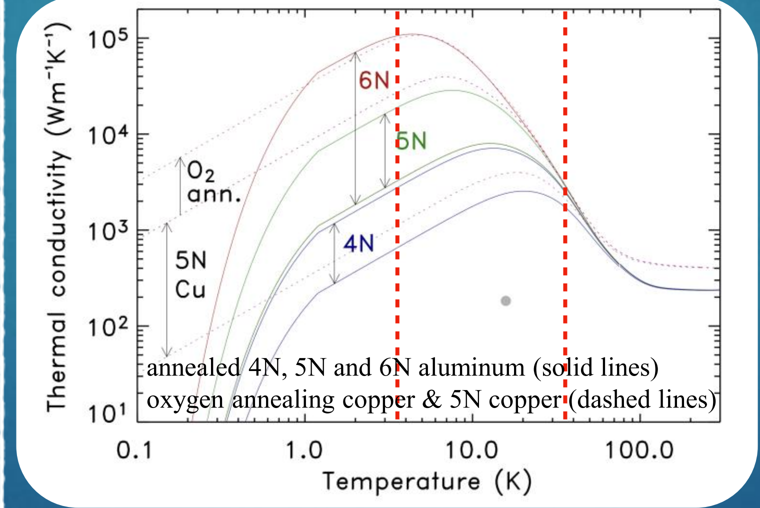
Flexible Cu-bride thermalizations





Cooling Power Estimation

- Pulse Tubes (PTs) down to ~ 4 K (~ 3.5 K)
  - 4 PTs plus 1 backup (Cryomech 415-RM)
    - (4 × 40 W) – 20 W = 140 W @ 45 K;
    - (4 × 1.35 W) – 0.675 W = 4.725 W @ 4.2 K
  - 3 PTs plus 1 backup (Cryomech 425-RM)
    - (3 × 50 W) – 25 W = 125 W @ 45 K;
    - (3 × 2.35 W) – 1.175 W = 5.875 W @ 4.2 K
    - (3 × 27.1 W) – 13.55 W = 67.75 W @ 35 K;
    - (3 × 1.28 W) – 0.64 W = 3.2 W @ 3.5 K



Adam L. Woodcraft, *Cryogenics* **45**, 626-636 (2005)

Pulse Tube Thermalization

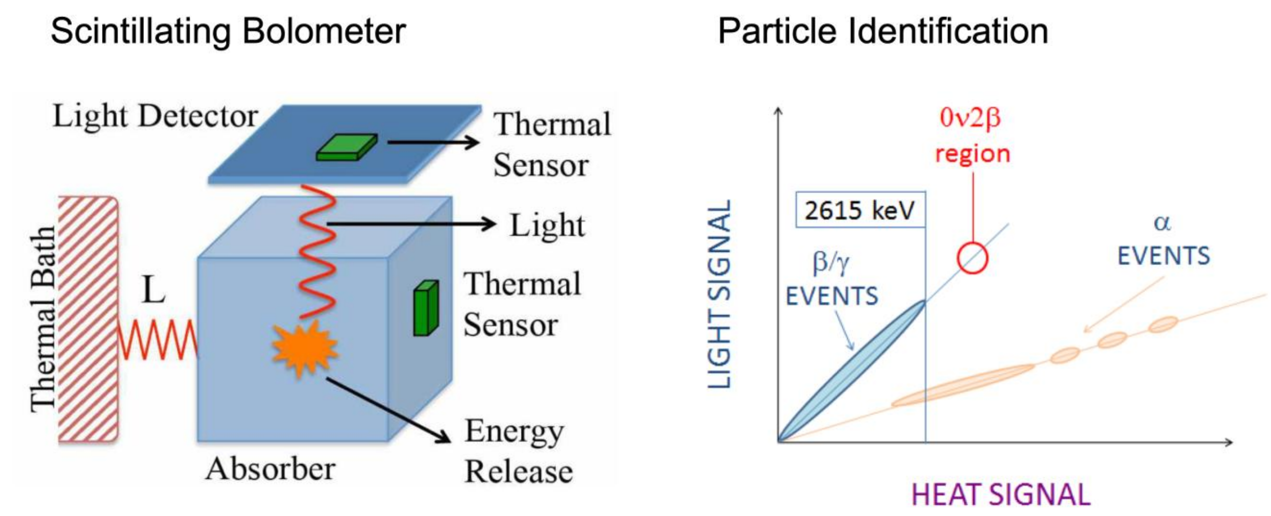
- Good thermal conductivity **Poster: PC6.447**
- Strong mechanical coupling
- More flexible
- Foresee vibration transmission reduction

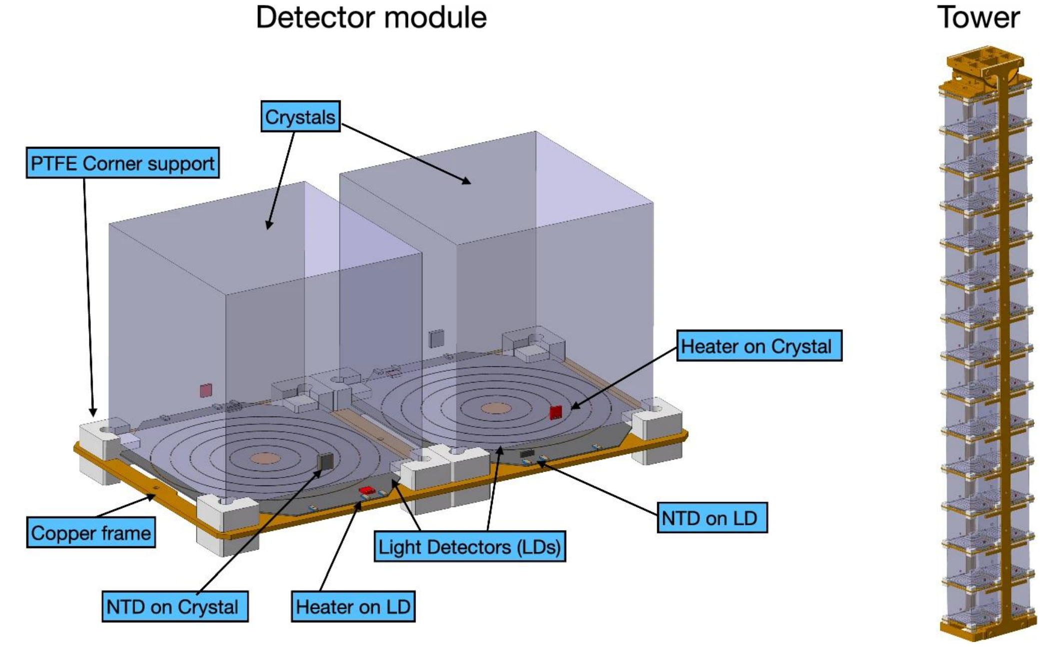
Poster: PC6.401

CUPID

arXiv:1907.09376 (CUPID Interest Group)
Alfonso, K. et al. (CUPID Collaboration), *Eur. Phys. J. C* **85**, 737 (2025)

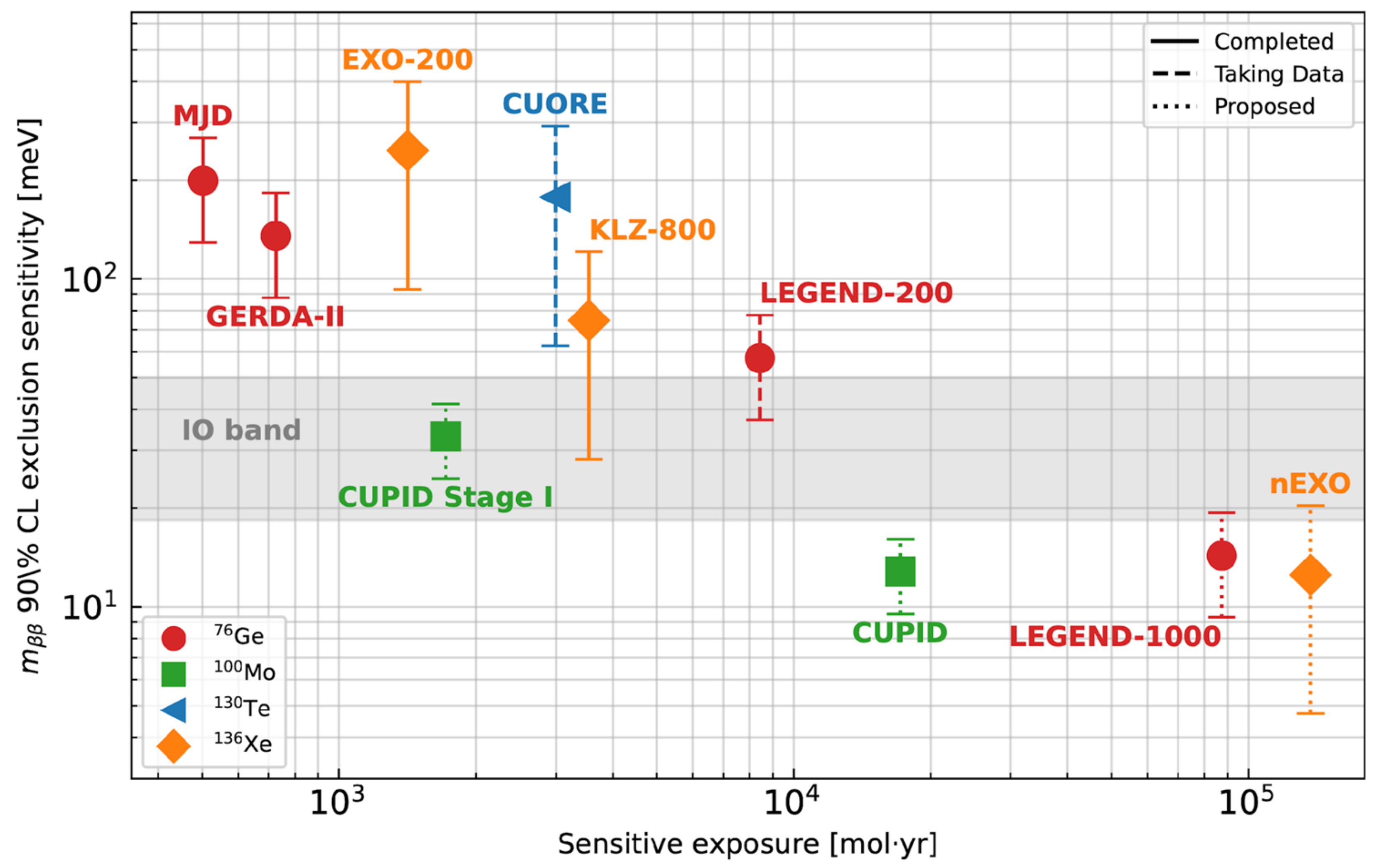
- **C**UORE **U**pgrade with **P**article **ID**entification
- $^{100}\mathrm{Mo}\ 0\nu\beta\beta$ decay candidate:
  - $Q_{\beta\beta}$ ~3034 keV
- New detector technology:
  - scintillating calorimeters
- Scintillation light:
  - >99% α/β discrimination
- ~1600 $\mathrm{Li_2MoO_4}$ crystals
- High energy resolution (~5 keV)

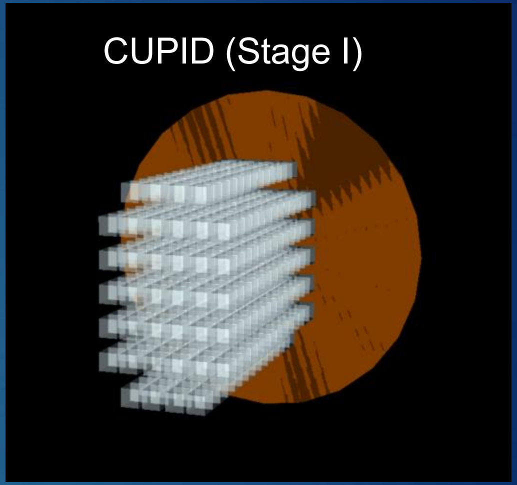


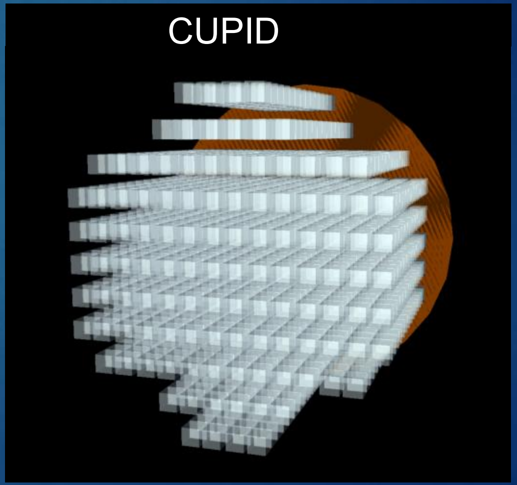


CUPID

arXiv:1907.09376 (CUPID Interest Group)
Alfonso, K. et al. (CUPID Collaboration), *Eur. Phys. J. C* **85**, 737 (2025)

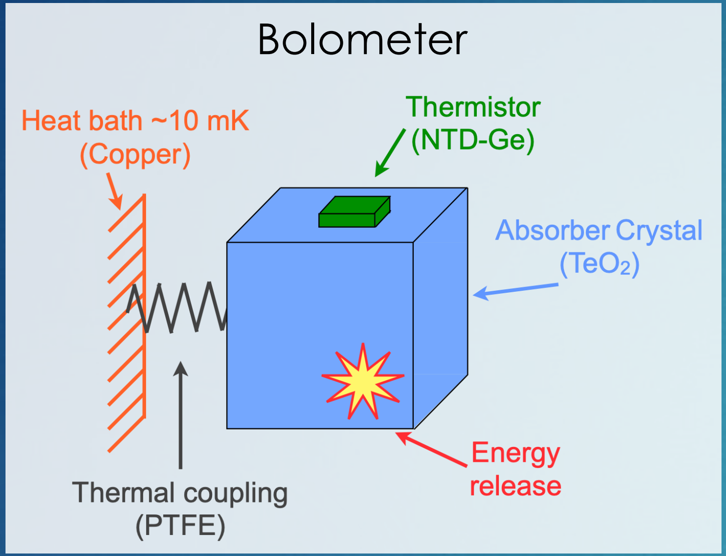


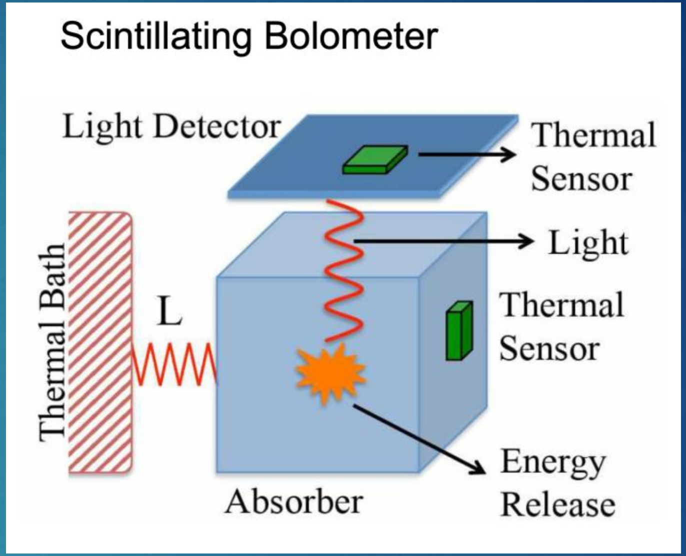




CUPID

arXiv:1907.09376 (CUPID Interest Group)
Alfonso, K. et al. (CUPID Collaboration),
Eur. Phys. J. C **85**, 737 (2025)





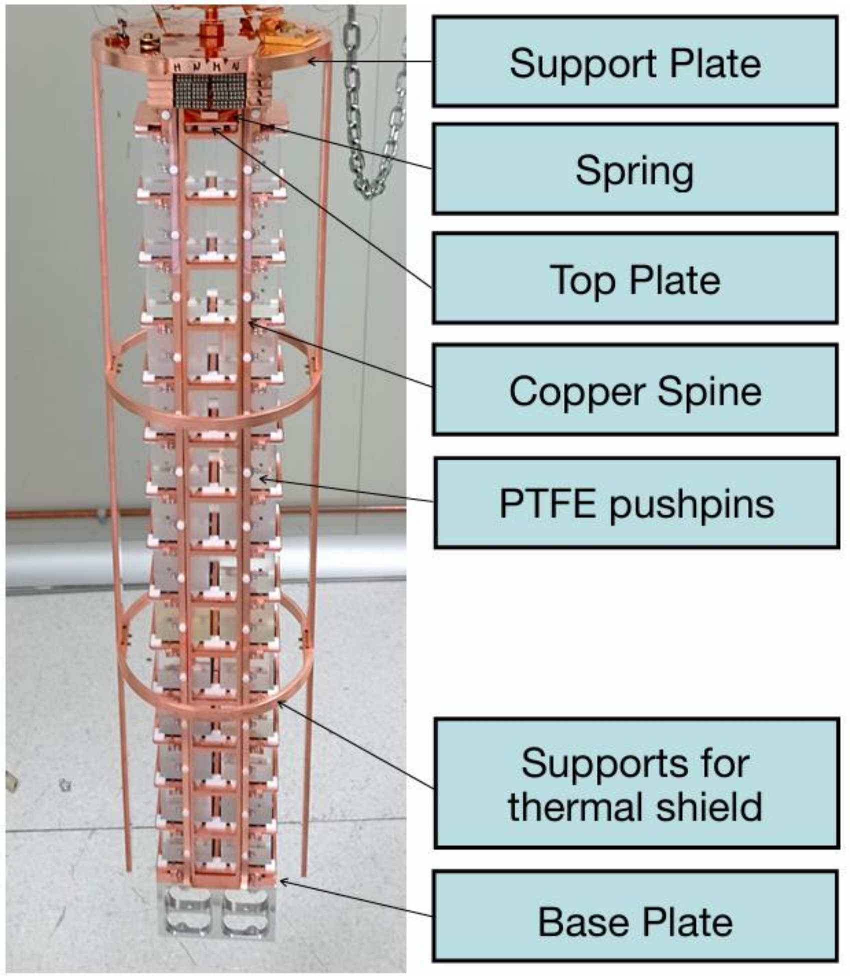
- $Q_{\beta\beta}(^{130}\mathrm{Te})$ $2527.5\ \mathrm{keV} < 2615\ \mathrm{keV}$
- Measure only heat
- No particle ID

- $Q_{\beta\beta}(^{100}\mathrm{Mo})$ $\sim 3034\ \mathrm{keV}$ Most β/γ backgrounds reduced
- Measure both heat + light
- Particle ID to actively discriminate α particles

CUPID Baseline Design

arXiv:2503.04481 (CUPID Collaboration)

- $45 \times 45 \times 45\ \mathrm{mm}^3\ \mathrm{Li_2}{}^{100}\mathrm{MoO_4}$ crystals
  - Crystal mass: 280 g
- 1596 total crystals
- 450 kg of $\mathrm{Li_2}{}^{100}\mathrm{MoO_4}$
- 95% enrichment in ${}^{100}\mathrm{Mo}$: 240 kg of ${}^{100}\mathrm{Mo}$
- 57 towers of 28 crystals. 14-floors of 2x1 crystal pairs. Gravity-assisted design
- Ge light detectors with SiO anti-reflective coating
  - Each crystal has top and bottom light detectors
  - No reflective foils
- Muon veto for muon-induced background suppression



Conclusions

- CUORE demonstrates the feasibility of a tonne-scale experiment employing cryogenic bolometers, for the search of the $0\nu\beta\beta$ decay and some other rare events.
- A raw exposure of more than $2.9\ \mathrm{ton{\cdot}yr}\ \mathrm{TeO_2}$ has been achieved as of today!
  - The data-taking is proceeding with $\gtrsim 85\%$ uptime.
- CUORE released physics results of $^{130}\mathrm{Te}\ 0\nu\beta\beta$ decay, utilizing $2\ \mathrm{ton{\cdot}yr}\ \mathrm{TeO_2}$ data.
- No evidence of $0\nu\beta\beta$ decay with observed data.
  - Bayesian 90% C.I. limit.

$$T_{1/2}^{0\nu} > 3.8 \cdot 10^{25}\ \mathrm{yr}\ @\ 90\%\ \mathrm{C.I.}$$

- CUORE obtained the most precise half-life measurement for the $2\nu\beta\beta$ decay of $^{130}\mathrm{Te}$.

$$T_{1/2}^{2\nu} = 9.32^{+0.05}_{-0.04}(\mathrm{stat.})^{+0.07}_{-0.07}(\mathrm{syst.}) \times 10^{20}\ \mathrm{yr}$$

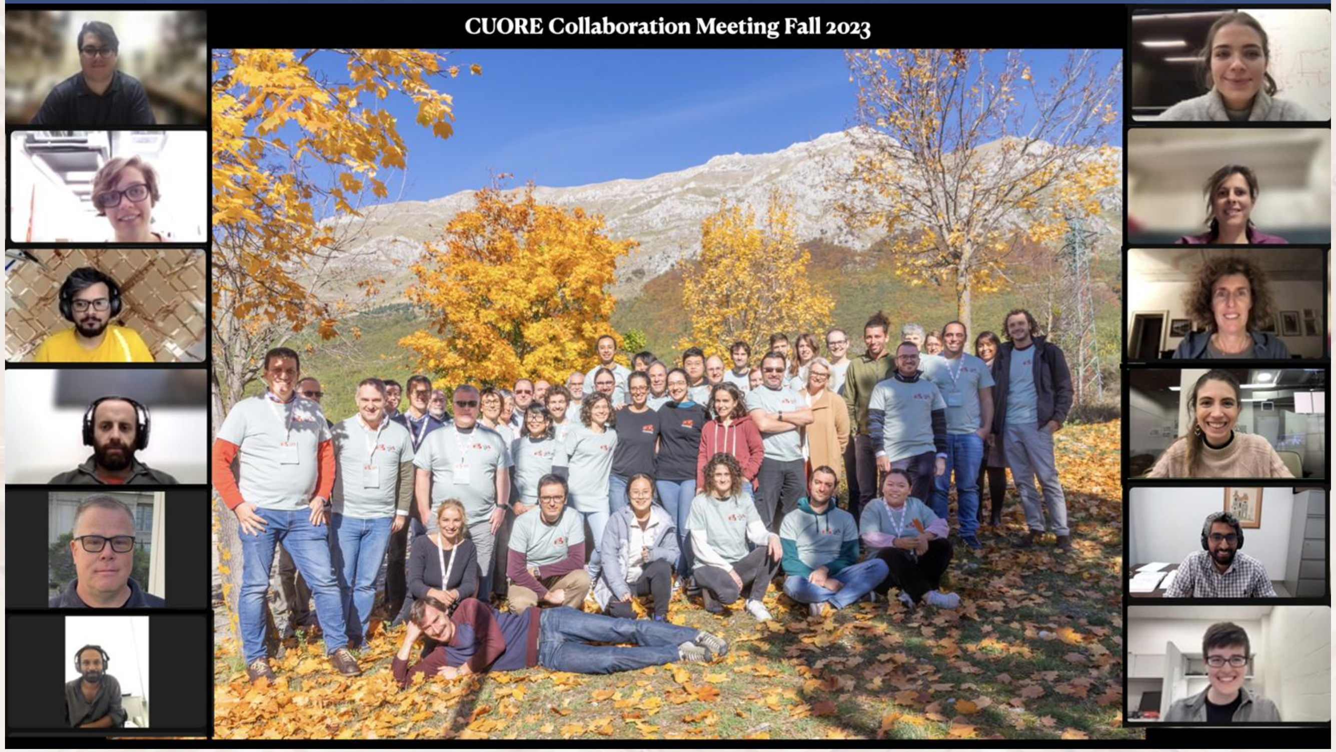
- CUORE will continue to take data until it reaches $^{130}\mathrm{Te}$ exposure of $1\ \mathrm{ton}\cdot\mathrm{yr}$, *i.e.*, $3\ \mathrm{ton}\cdot\mathrm{yr}\ \mathrm{TeO_2}$ exposure.
- Leveraging the unique ability to deploy different isotopes on the same infrastructure.

CUORE

CUORE **U**pgrade with **P**article **ID**entification →

CUPID

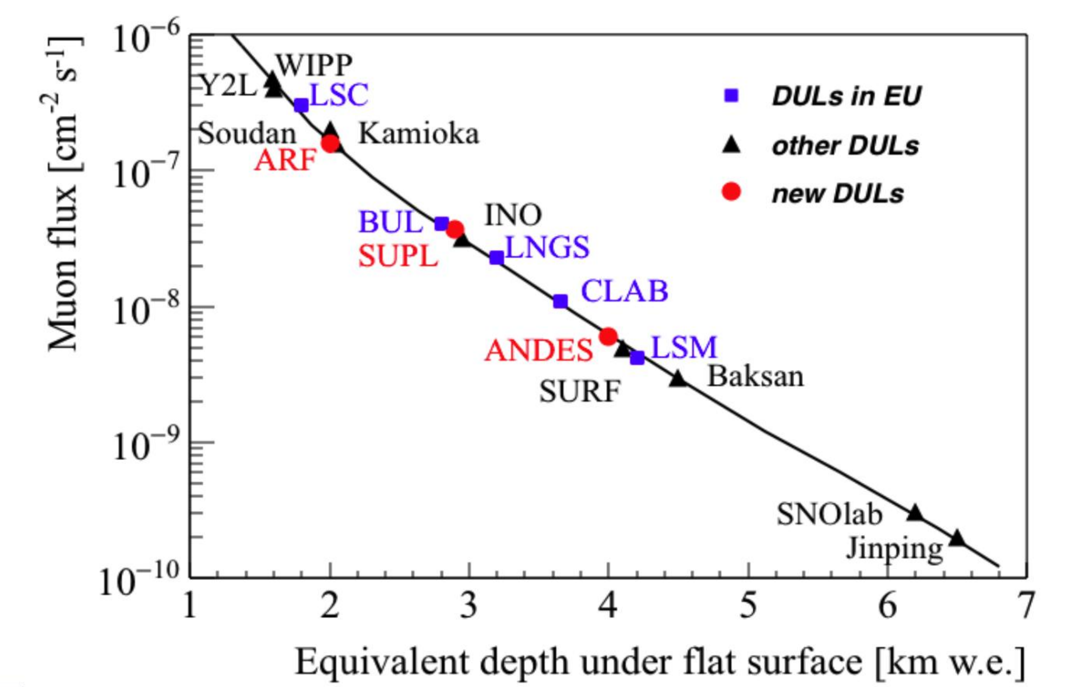
Thank you for your attention!


CUORE Collaboration Meeting Fall 2023

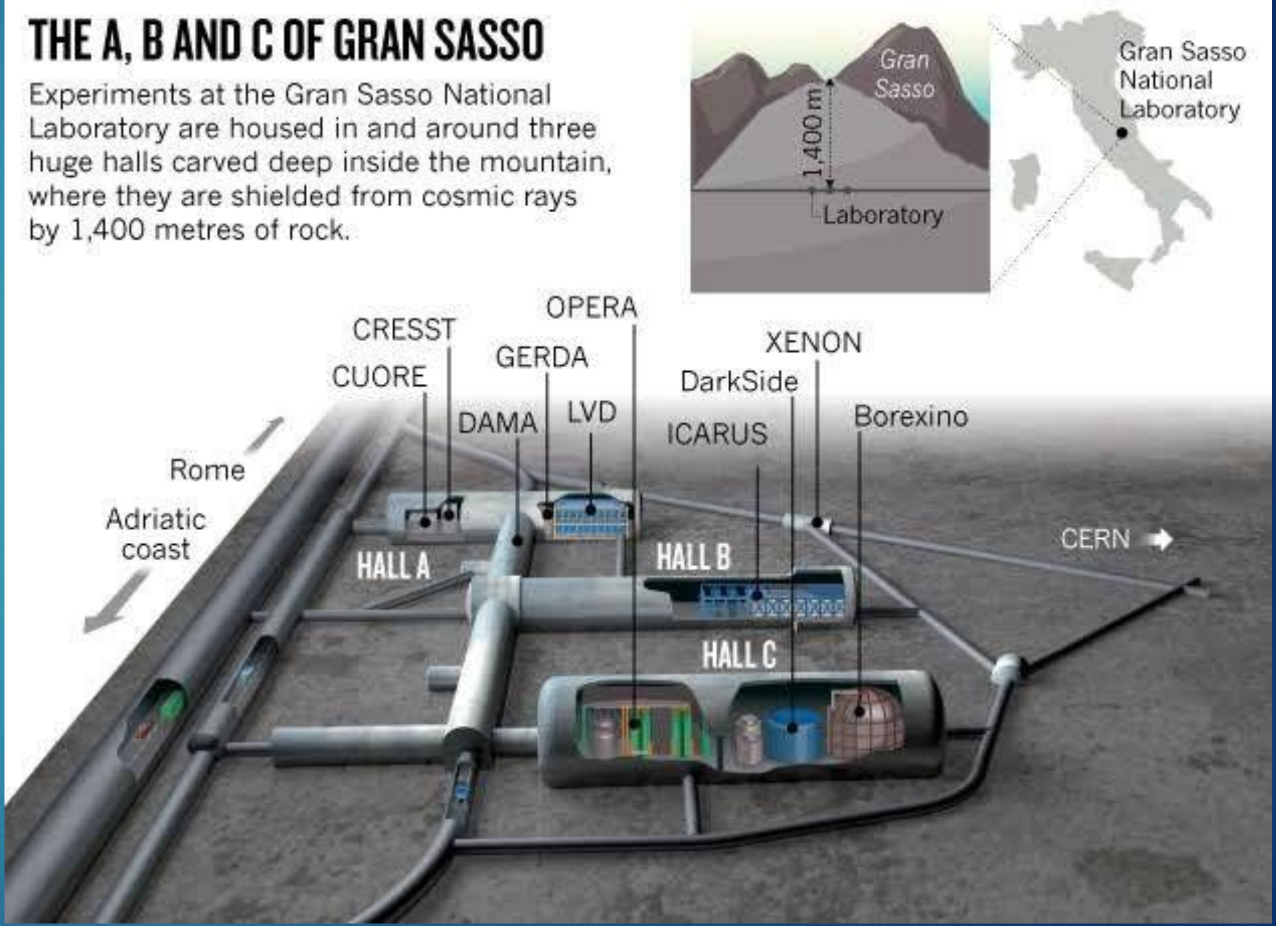
CUORE
CUPID
INFN Istituto Nazionale di Fisica Nucleare
CSNSM Centre de Sciences Nucléaires et de Sciences de la Matière
SINAP
Yale
UCLA
University of South Carolina
GSSI
Università degli Studi di Milano Bicocca
Lawrence Livermore National Laboratory
University of Pittsburgh
Massachusetts Institute of Technology
Johns Hopkins University
Berkeley Lab
Virginia Tech
Berkeley University of California
Sapienza Università di Roma
Cal Poly San Luis Obispo
CUORE

Backup

Laboratori Nazionali del Gran Sasso - Italy



- 3600 m.w.e. deep
- μ: ~3×10^{-8}/(s cm^2)
  → 10^6 less than above ground
- γ: ~0.73/(s cm^2)
- neutrons: < 4×10^{-6} n/(s cm^2)



THE A, B AND C OF GRAN SASSO

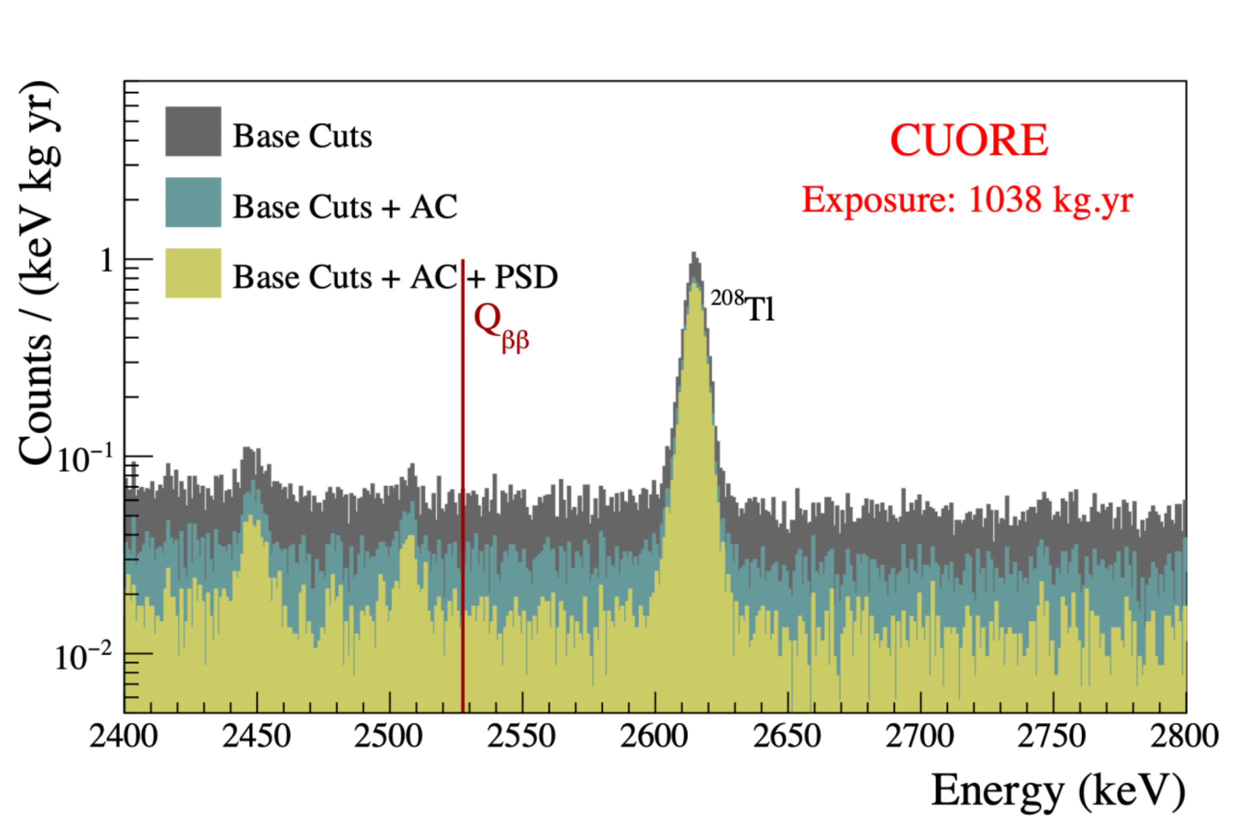
Experiments at the Gran Sasso National Laboratory are housed in and around three huge halls carved deep inside the mountain, where they are shielded from cosmic rays by 1,400 metres of rock.

Efficiencies

Reconstruction Efficiency	Probability that a good event is triggered, reconstructed properly, and not rejected by basic pile-up cuts • Evaluated on heater events
Anti-coincidence Efficiency	Quantifies the probability of that an event is not erroneously cut by being in accidental coincidence with an unrelated event • Calculated on 1460 keV ^{40}K peak
Pulse Shape Discrimination Efficiency	Fraction of signal-like events passing the PSD • Calculated on events in the ^{60}Co, ^{40}K, and ^{208}Tl γ peaks that passed the anti-coincidence cut

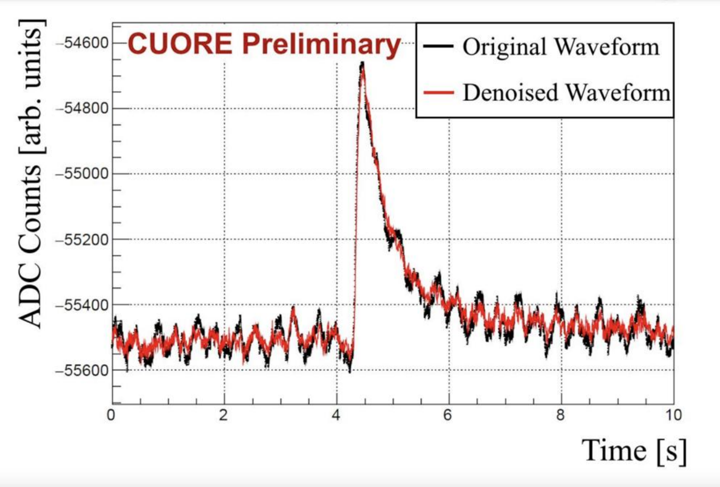
Background in Region of Interest (ROI)

- 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

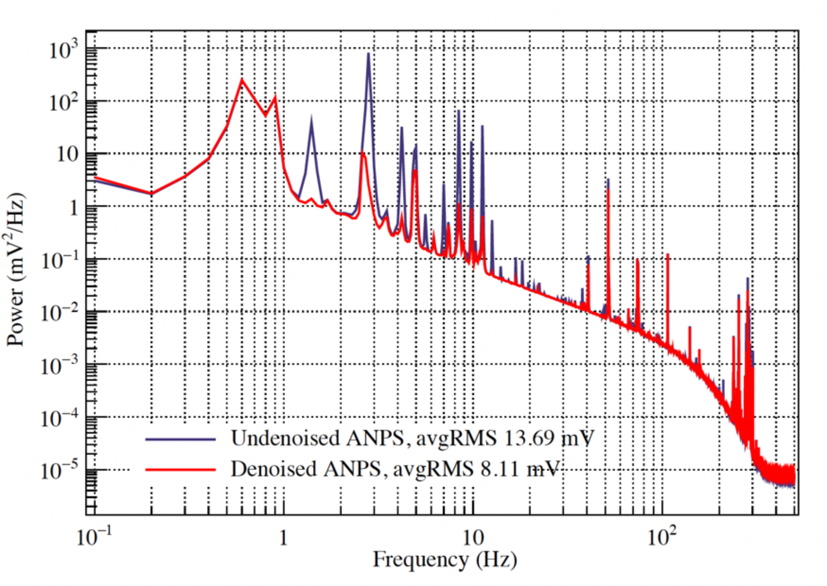


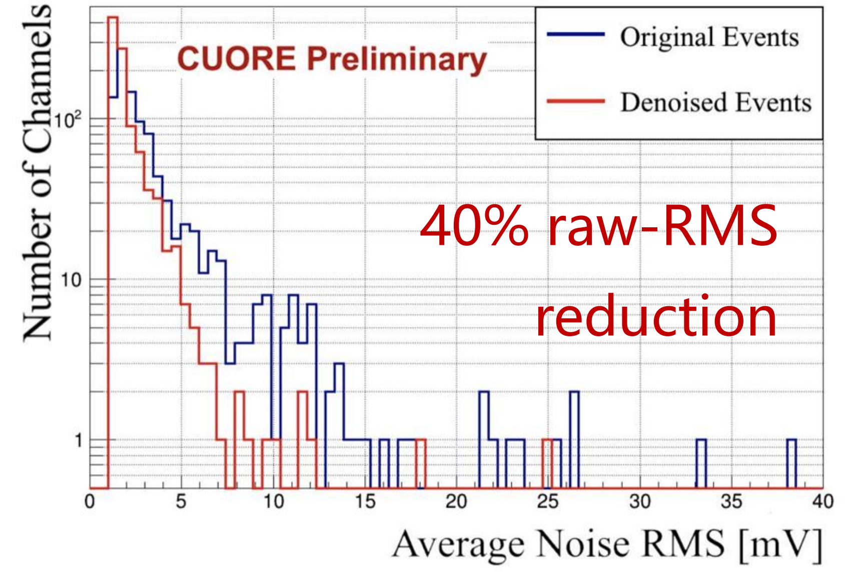
CUORE data analysis

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



- New! of this data release
- Installed diagnostic devices:
  - Seismometers,
  - Accelerometers,
  - Microphones…



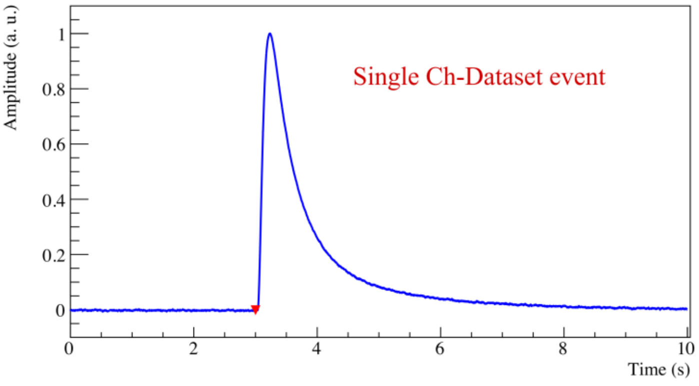


40% raw-RMS reduction

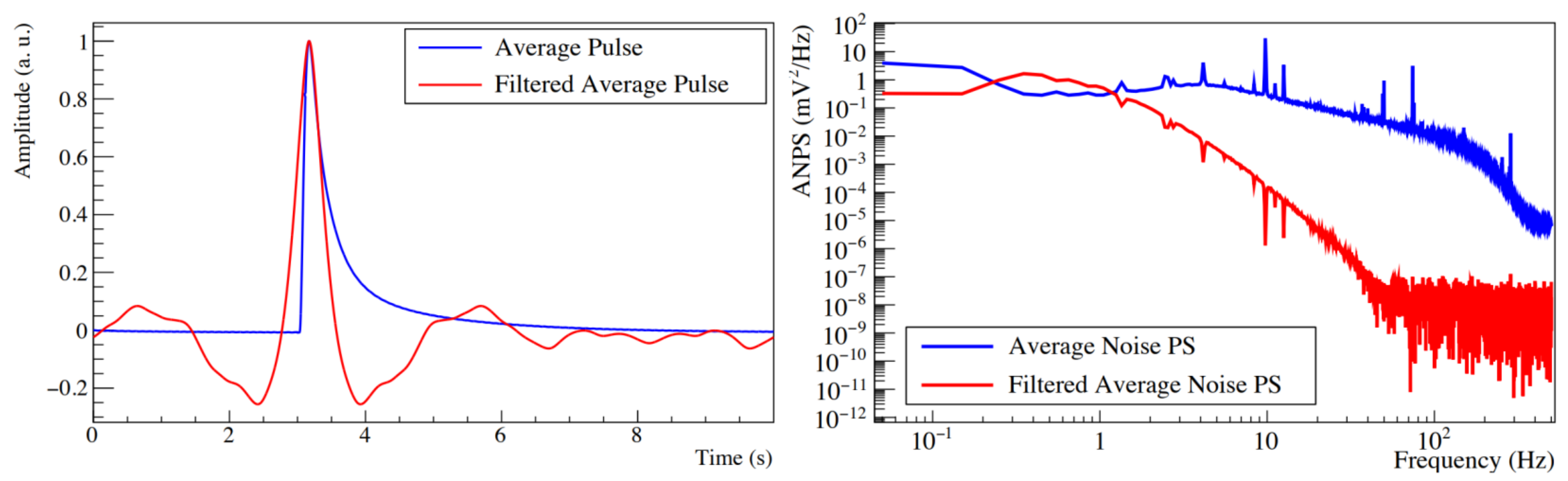
Vetter, K.J., Beretta, M., Capelli, C. et al., Eur. Phys. J. C 84, 243 (2024)

CUORE data analysis

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



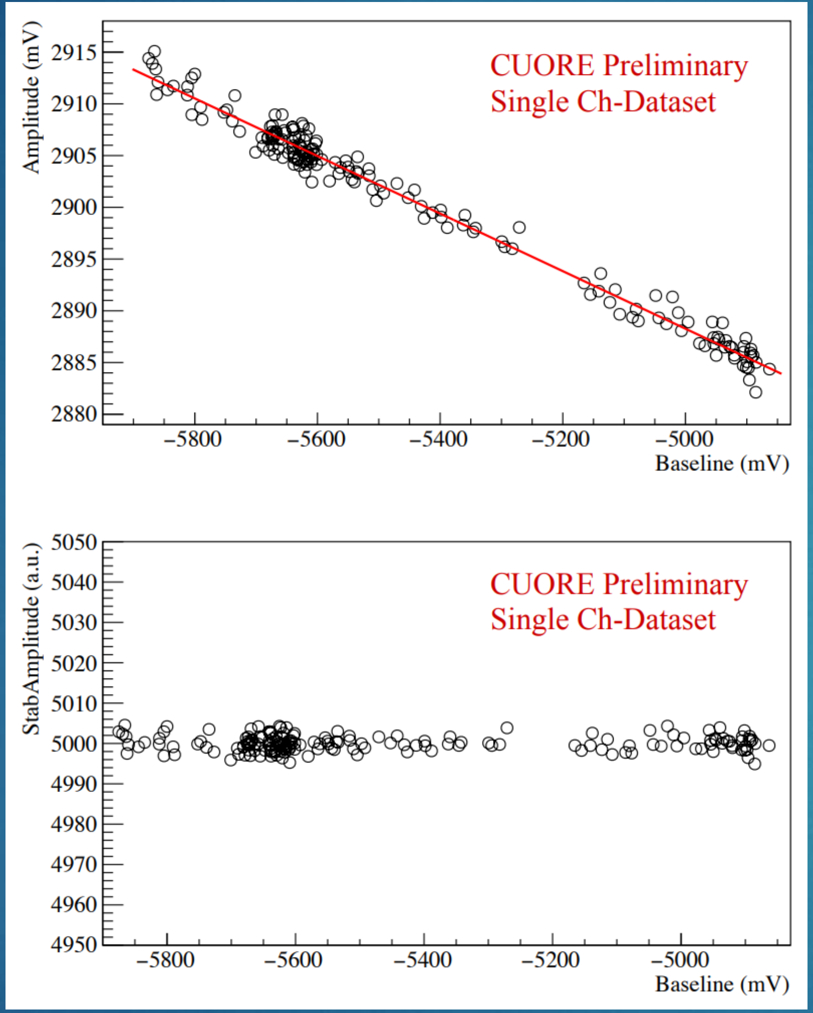
- Derivative trigger: online analysis for quick data quality feedback
- Offline re-triggering (Optimum Trigger)
  - disentangle small signals from noise fluctuations
  - lower threshold



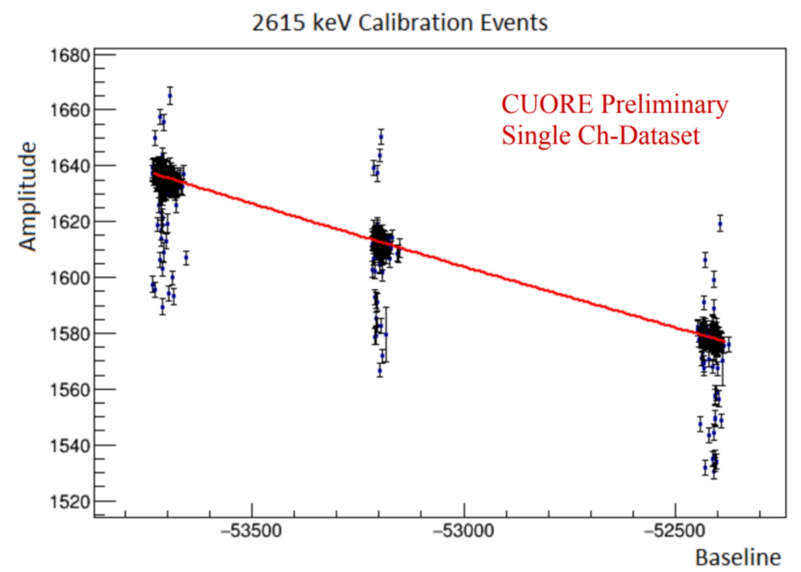
- Matched filter maximizes signal-to-noise ratio

CUORE data analysis

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



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

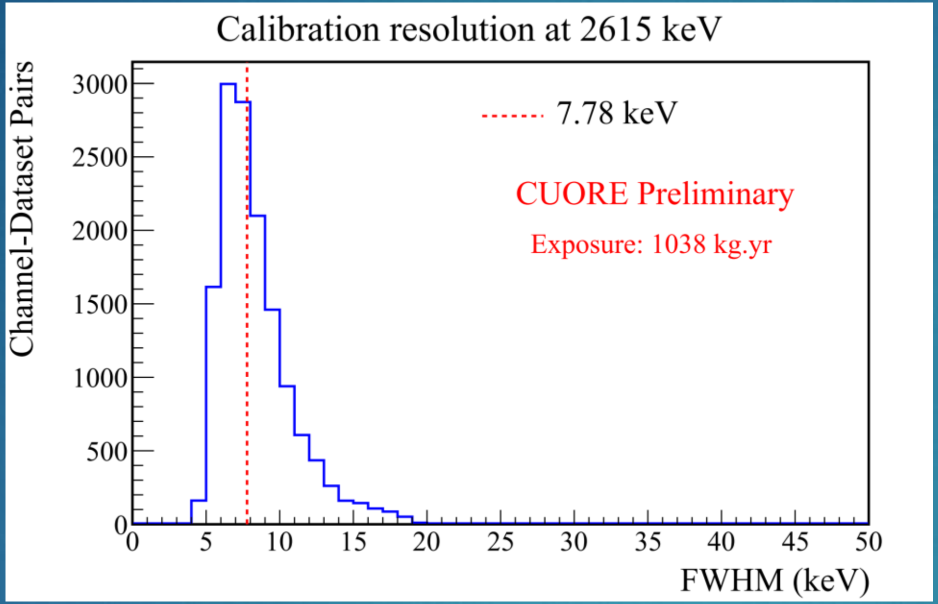


- Heater pulses for thermal gain stabilization

CUORE data analysis

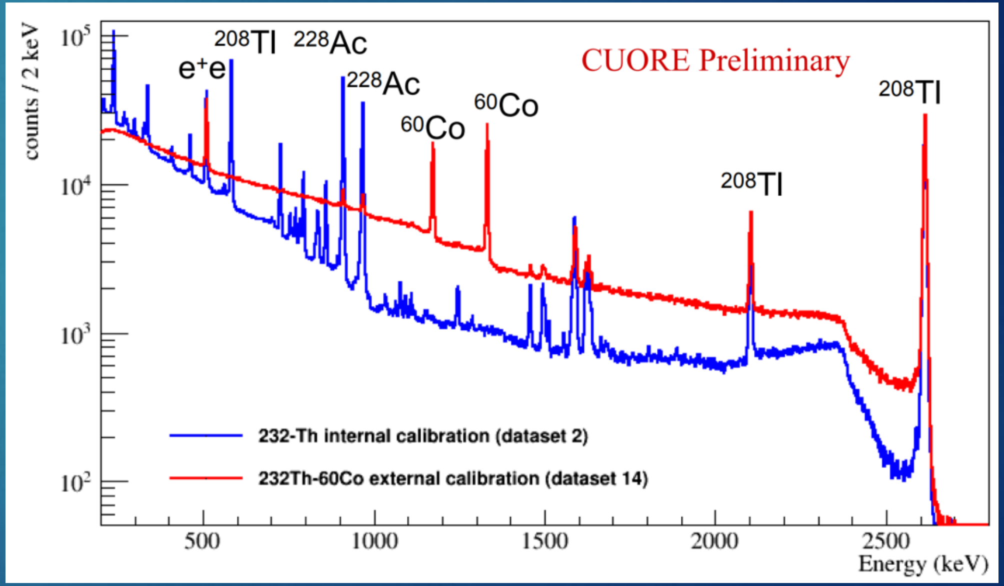
- Denoising
- Trigger
- Optimum Filter
- Gain Correction
- **Energy Calibration**
- Coincidences
- Pulse Shape Discrimination (PSD)
- Blinding

- Calibration performed with external $^{232}\mathrm{Th} - {}^{60}\mathrm{Co}$ source



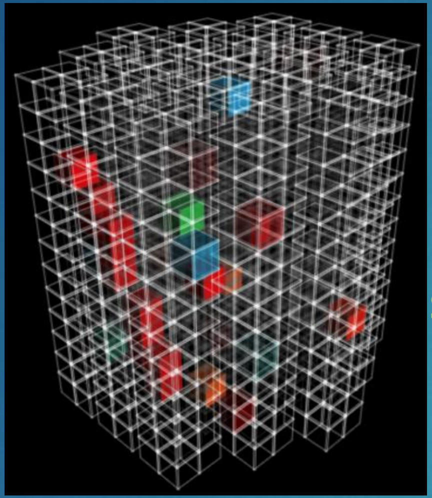
- First 3 datasets used internal $^{232}\mathrm{Th}$ source
- Internal calibration system replaced with simpler external one in later datasets

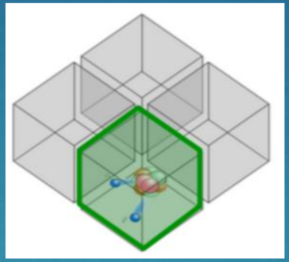
- Detector response modelled on the $2615\ \mathrm{keV}$ line from $^{232}\mathrm{Th}$ chain.
  - Accounts for non idealities.



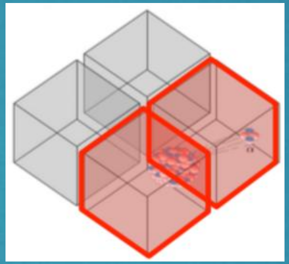
CUORE data analysis

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





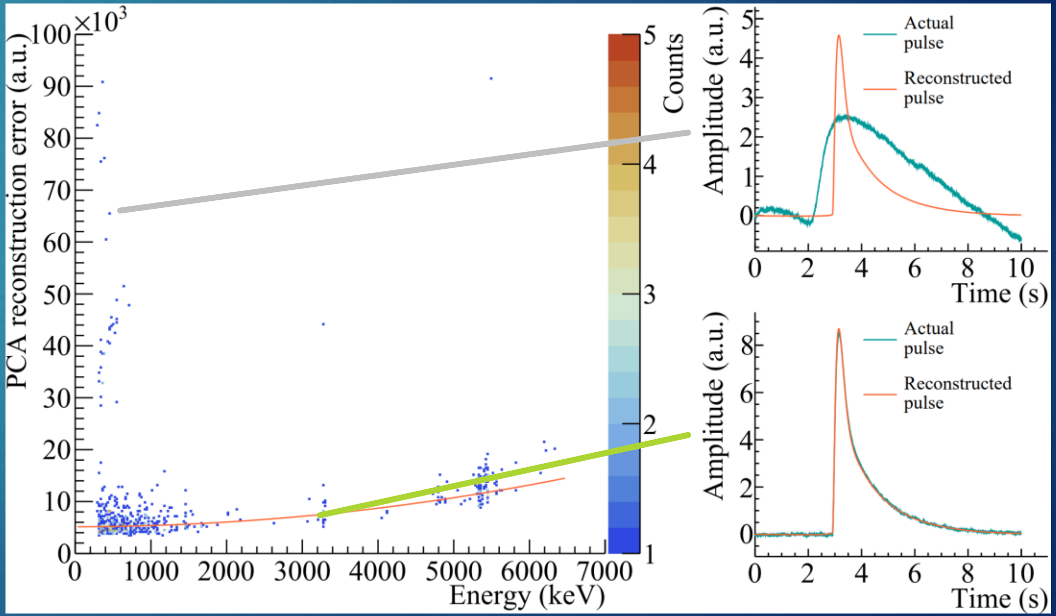
single-site (signal-like)



multi-site (background-like)

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

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



CUORE data analysis

- Denoising
- 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