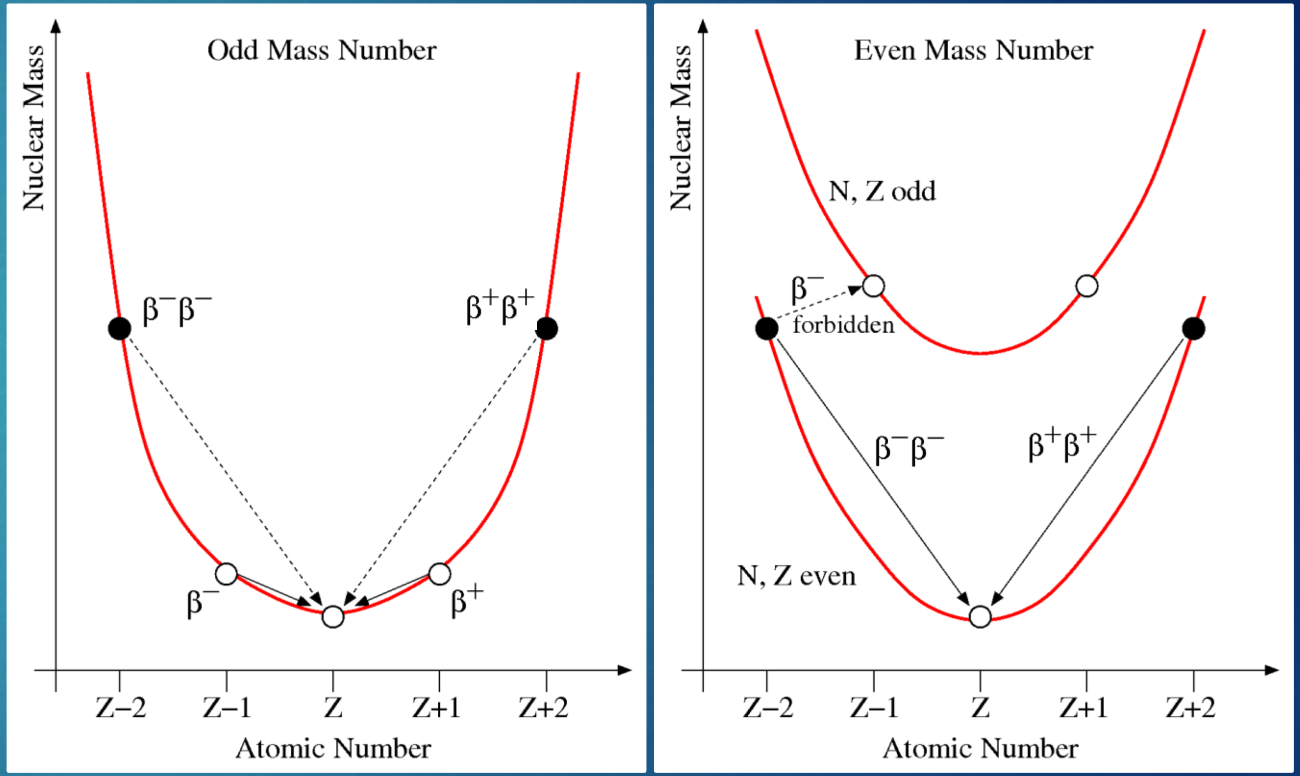
The CUPID $0\nu\beta\beta$ experiment

On behalf of the **CUPID** collaborations

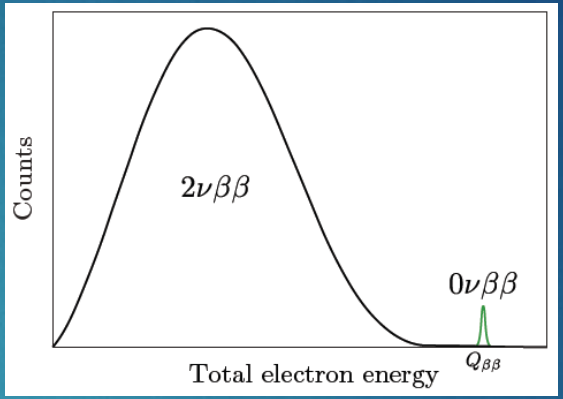
Double Beta Decay ($2\nu\beta\beta$)

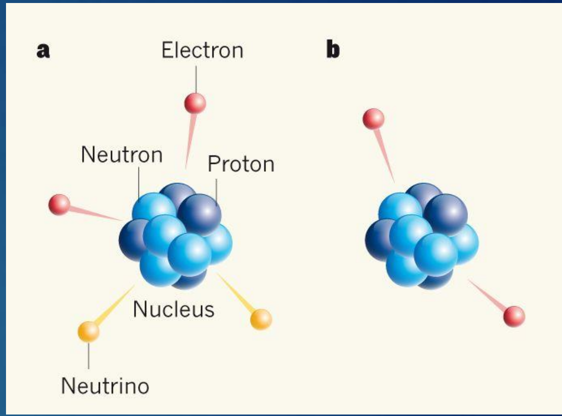
- Same mass number (A), changes the nuclear charge (Z) by two units.
- 2nd order weak transition, allowed by the Standard Model.
- Decay to the intermediate nucleus is forbidden.
- Only even mass number nuclei.
- Half-lives in the order of $10^{18} \sim 10^{21}$ yr.
- Two-neutrino double beta decay ($2\nu\beta\beta$)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





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

experimental observable ($T_{1/2}^{0\nu}$); phase space factor ($G^{0\nu}$); nuclear matrix element ($\mathcal{M}^{0\nu}$); effective $\nu_{\beta\beta}$ mass ($\langle m_{\beta\beta} \rangle$)

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

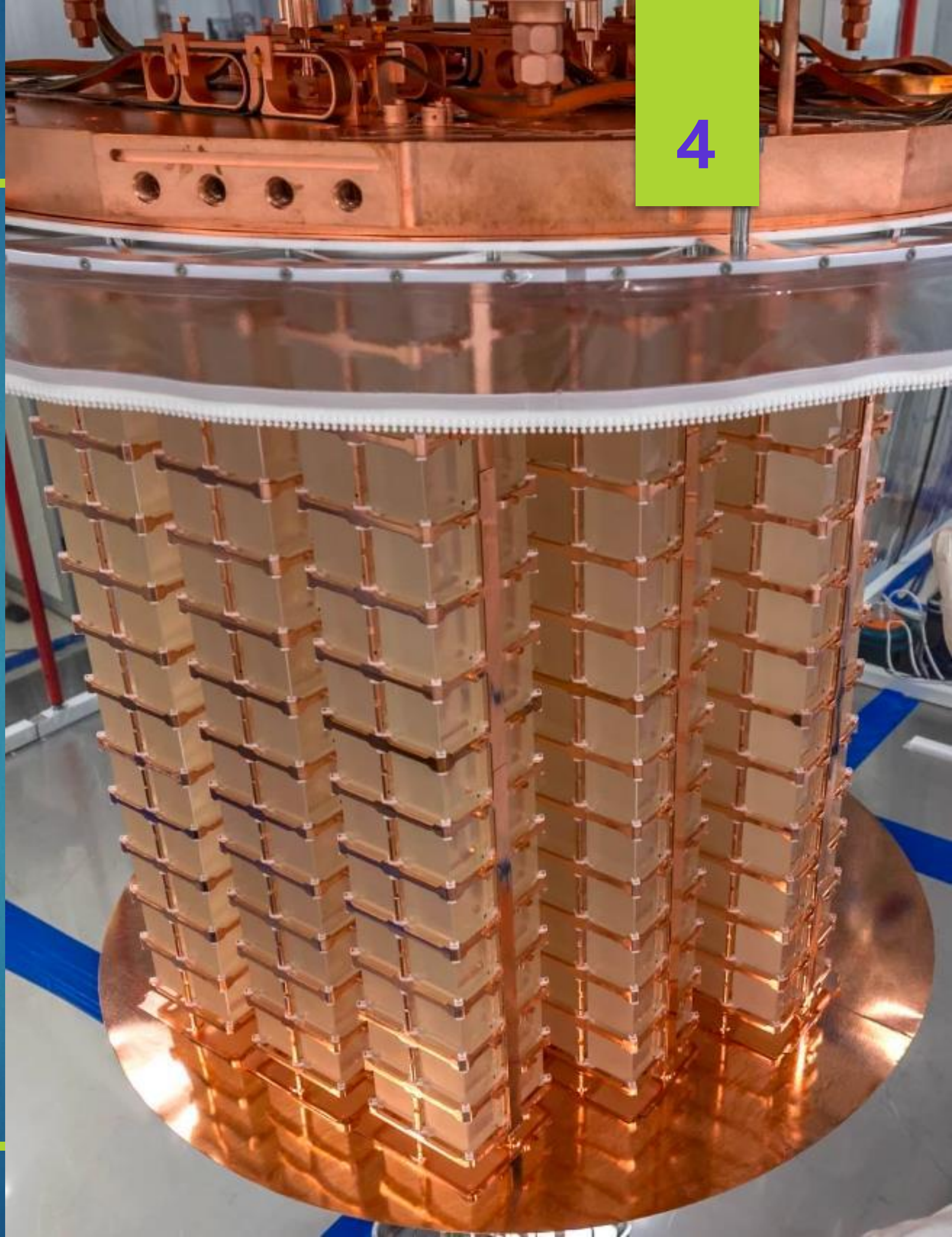
sensitivity ($S^{0\nu}$); isotopic abundance (i.a.); detector mass (M); measuring time (T); energy resolution (ΔE); background (B)

CUORE Experiment (P. Gorla)

- **C**ryogenic **U**nderground **O**bservatory for **R**are **E**vents
- In operation at the Laboratori Nazionali del Gran Sasso, Italy

INFN LNGS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Gran Sasso

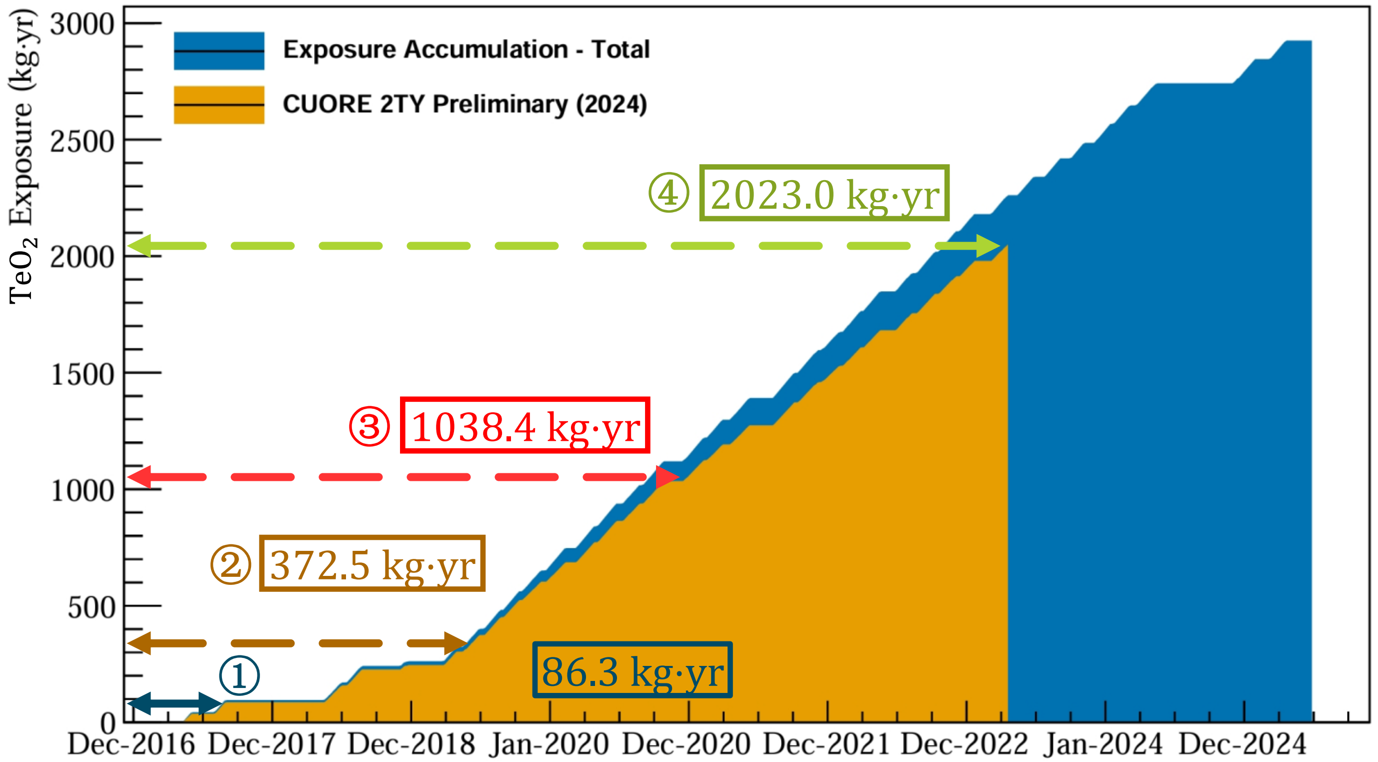
- Main objective: observe $0\nu\beta\beta$ in $^{130}\mathrm{Te}$
- The CUORE detector is hosted in a cryogen-free cryostat
  - Operating temperature $\sim 10\ \mathrm{mK}$
  - Designed for low radioactivity and low vibrations environment
- Energy resolution: goal of $\sim 5\ \mathrm{keV}$ at $Q_{\beta\beta}$ $(2527.5\ \mathrm{keV})$
- Low background: goal of $\sim 10^{-2}\ \mathrm{counts}\ /\ (\mathrm{keV}\cdot\mathrm{kg}\cdot\mathrm{yr})$ at $Q_{\beta\beta}$



CUORE Data Collection

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

- 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 TeO_2 exposure accumulated

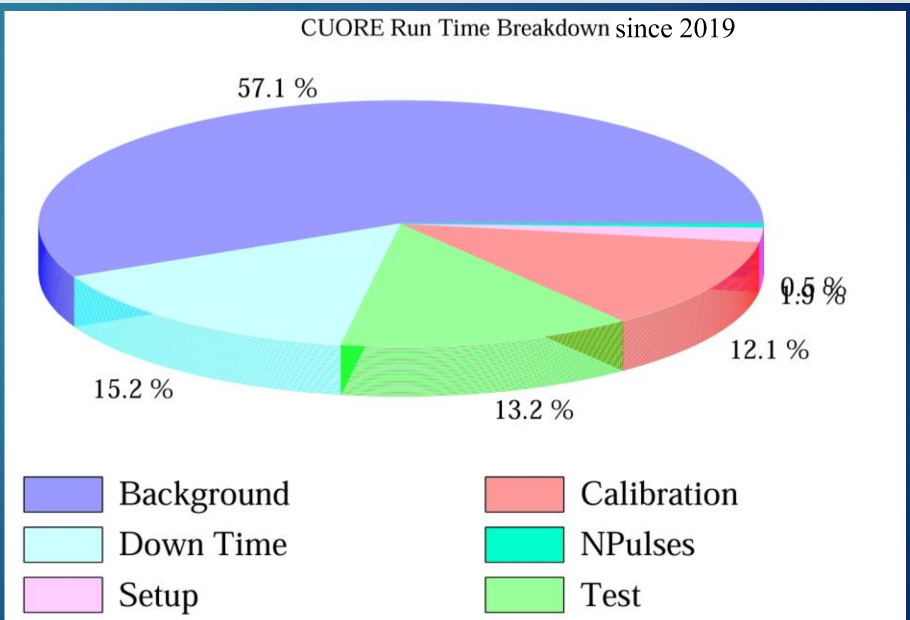


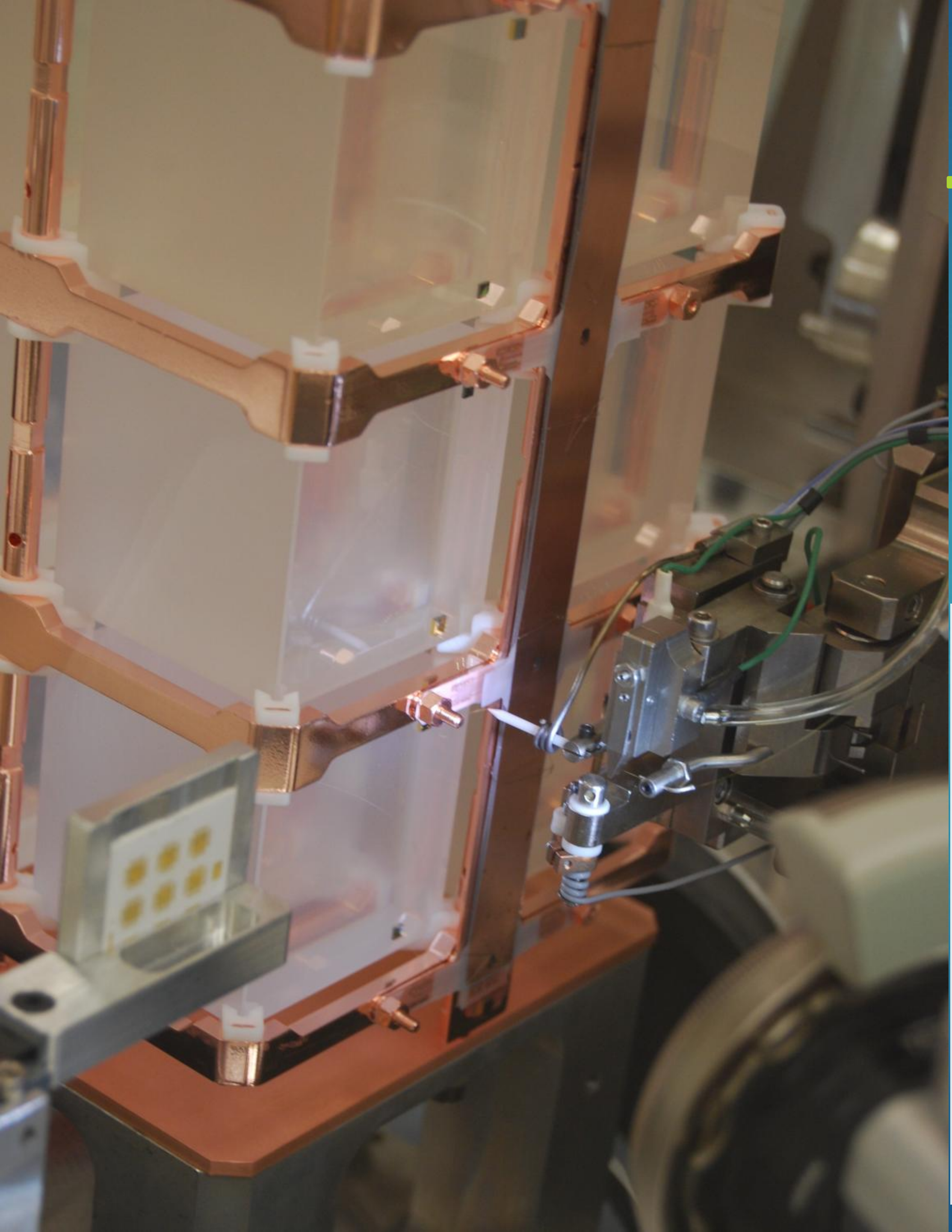
① Alduino, C. *et al.* (CUORE Collaboration), *Phys. Rev. Lett.* **120**, 132501 (2018)

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)



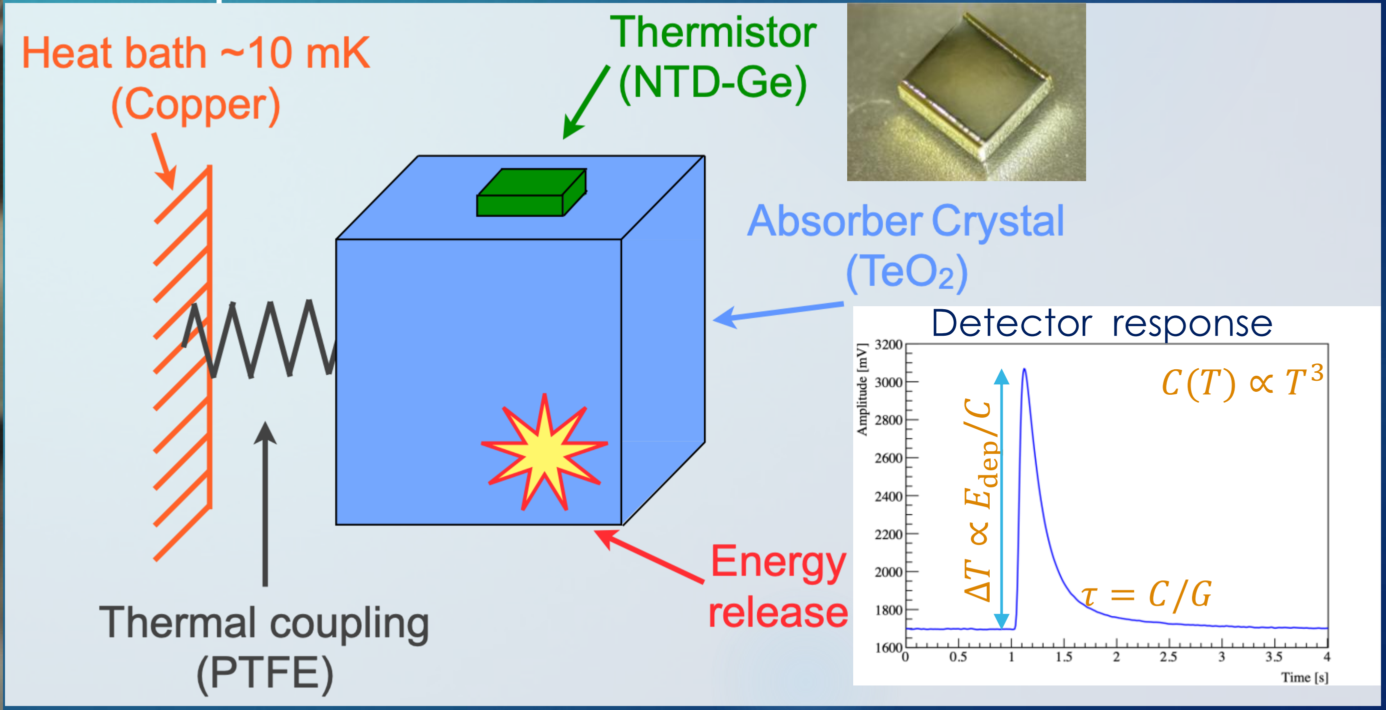


Bolometer

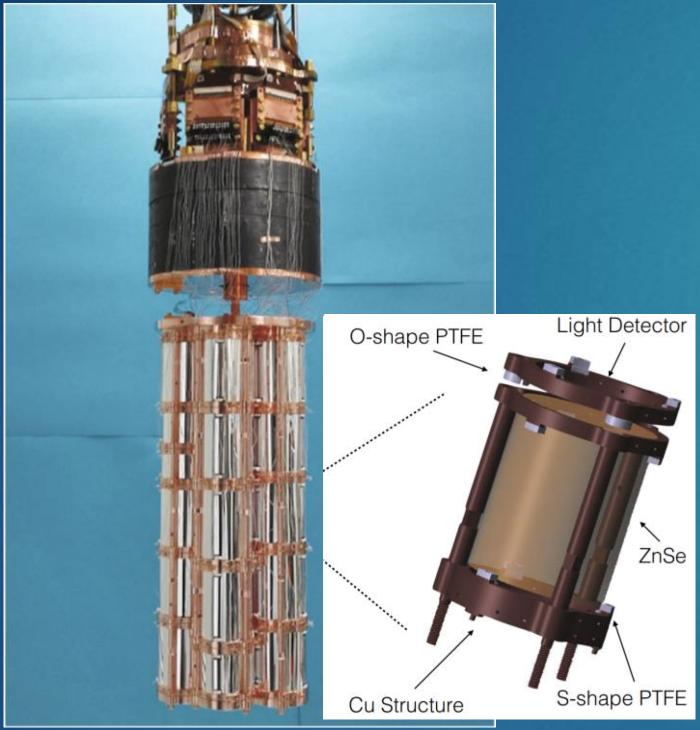
$$S^{0\nu} \propto \text{i.a.} \cdot \sqrt{\frac{M \cdot T}{\Delta E \cdot B}}$$

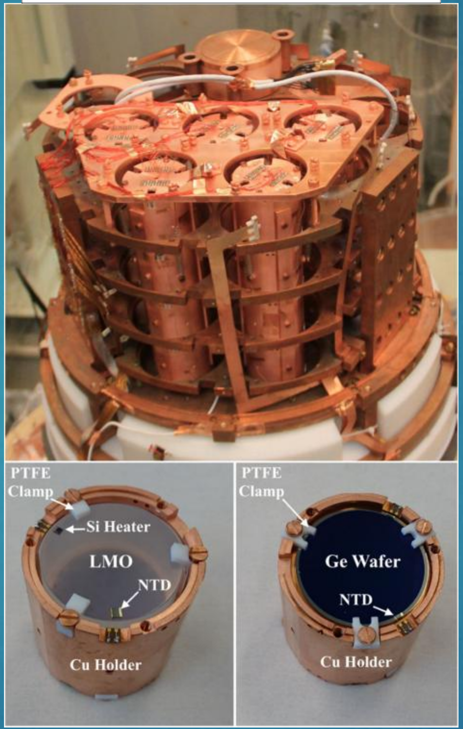
CUORE

- 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.



CUPID-0 & CUPID-Mo





- **CUPID-0** (2017-2020 @LNGS) and **CUPID-Mo** (2019-2021 @Modane) demonstrated that the **technology of scintillating calorimeters** is mature to be implemented on large scale!

O. Azzolini *et al.* (CUPID-0), *Phys. Rev. Lett.* **129**, 111801 (2022)

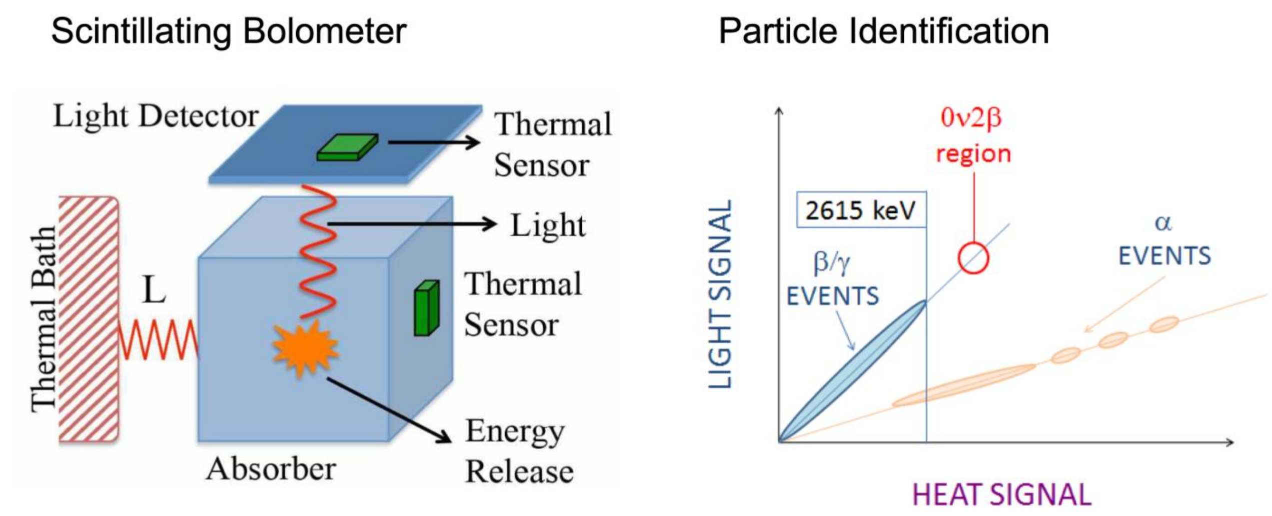
Augier, C. *et al.* (CUPID-Mo), *Eur. Phys. J. C* **82**, 1033 (2022)

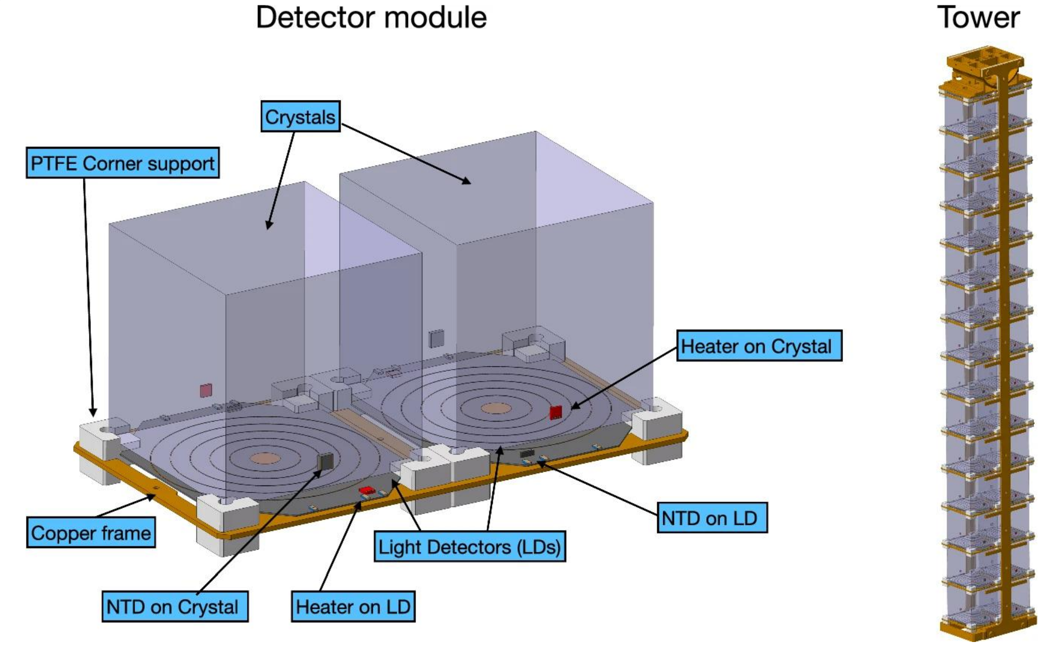
CUPID

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

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

- **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 $\mathrm{Li_2}^{100}\mathrm{MoO_4}$ crystals
- High energy resolution (~5 keV)

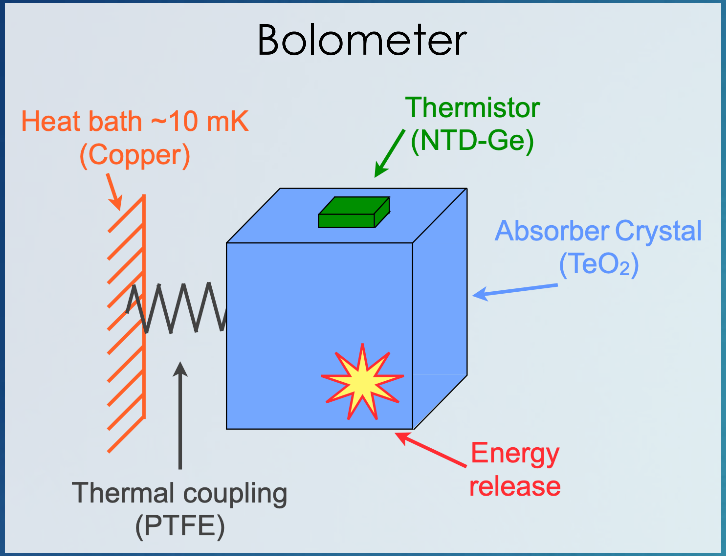


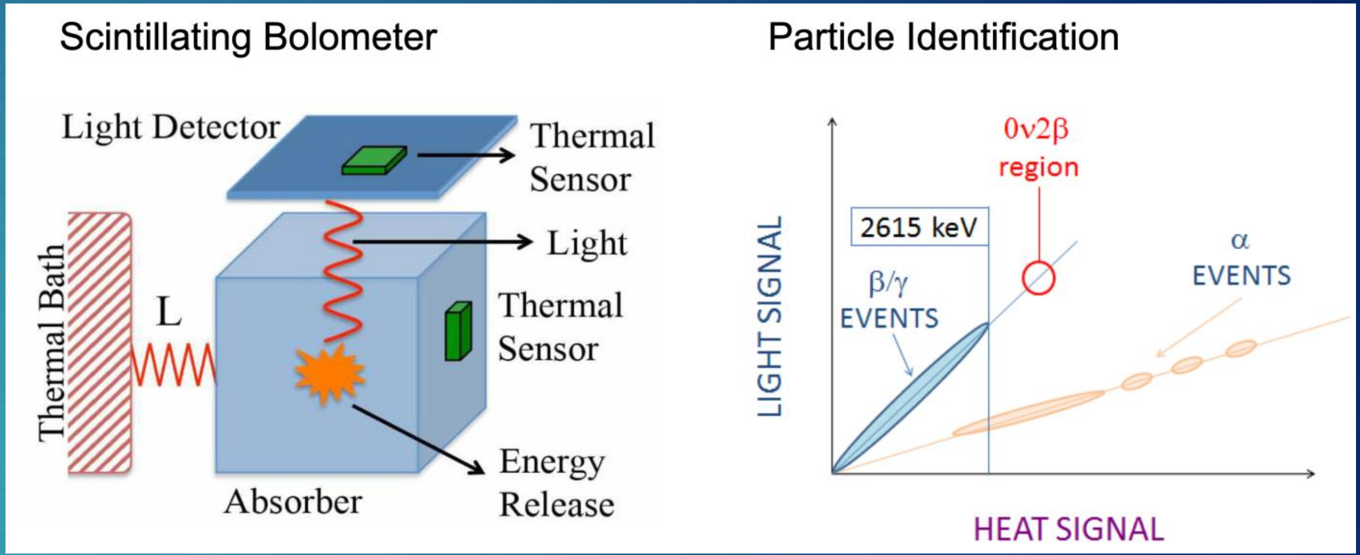


CUPID

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

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





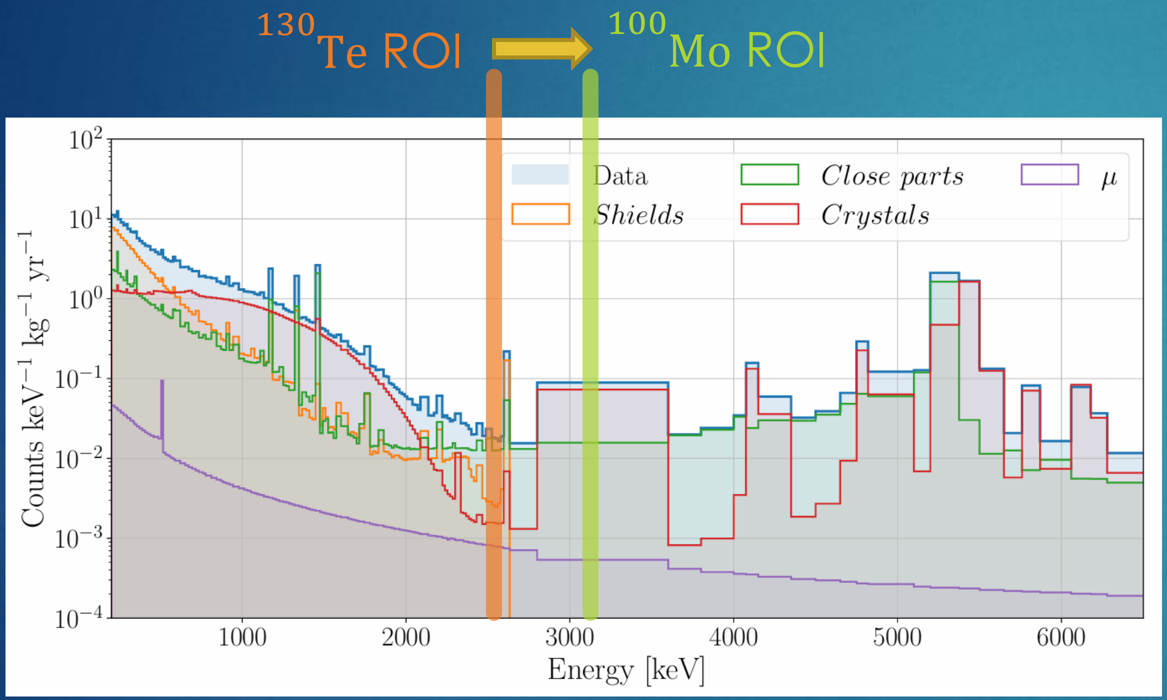
- $Q_{\beta\beta}(^{130}\text{Te})$ 2527.5 keV < 2615 keV
- Measure only heat
- No particle ID

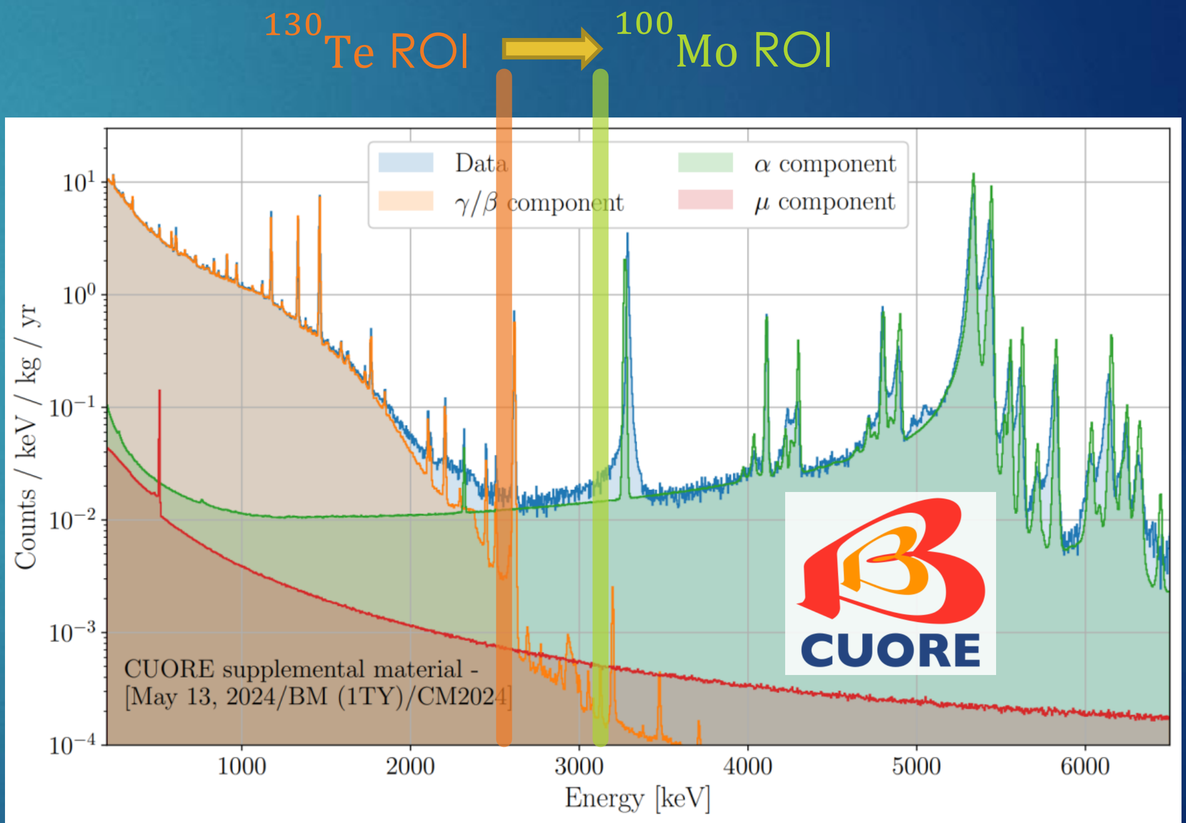
- $Q_{\beta\beta}(^{100}\text{Mo})$ ~3034 keV Most β/γ backgrounds reduced
- Measure both heat + light
- Particle ID to actively discriminate α particles

Lessons from Background Model

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

- CUORE background in the ^{100}Mo region,
- once α and μ are removed, is close to ~10^{-4} cts/(keV kg yr)





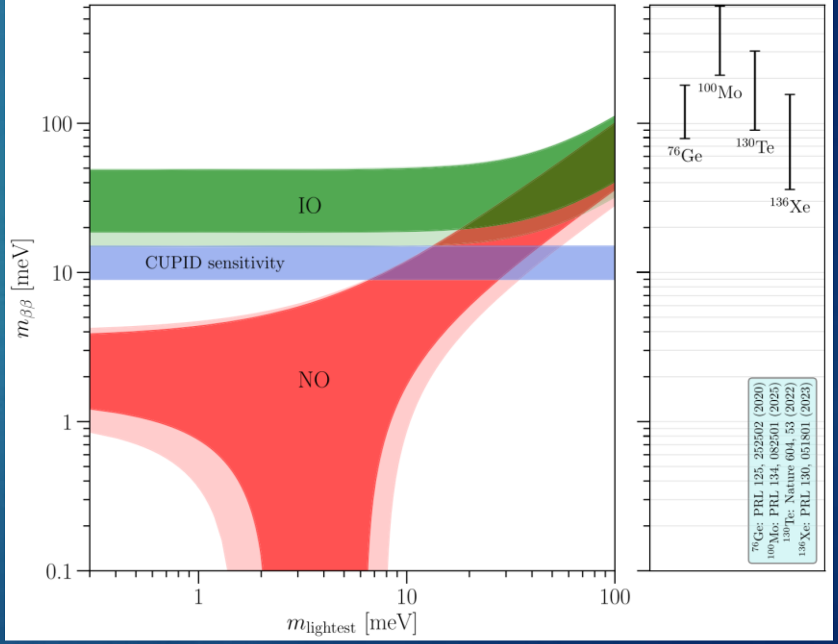
Adams, D.Q. *et al.* (CUORE Collaboration), *Phys. Rev. D* **110**, 052003 (2024)

CUPID Sensitivity

arXiv:2504.14369 (CUPID Collaboration)
Alfonso, K. *et al.* (CUPID Collaboration), *Eur. Phys. J. C* **85**, 737 (2025)

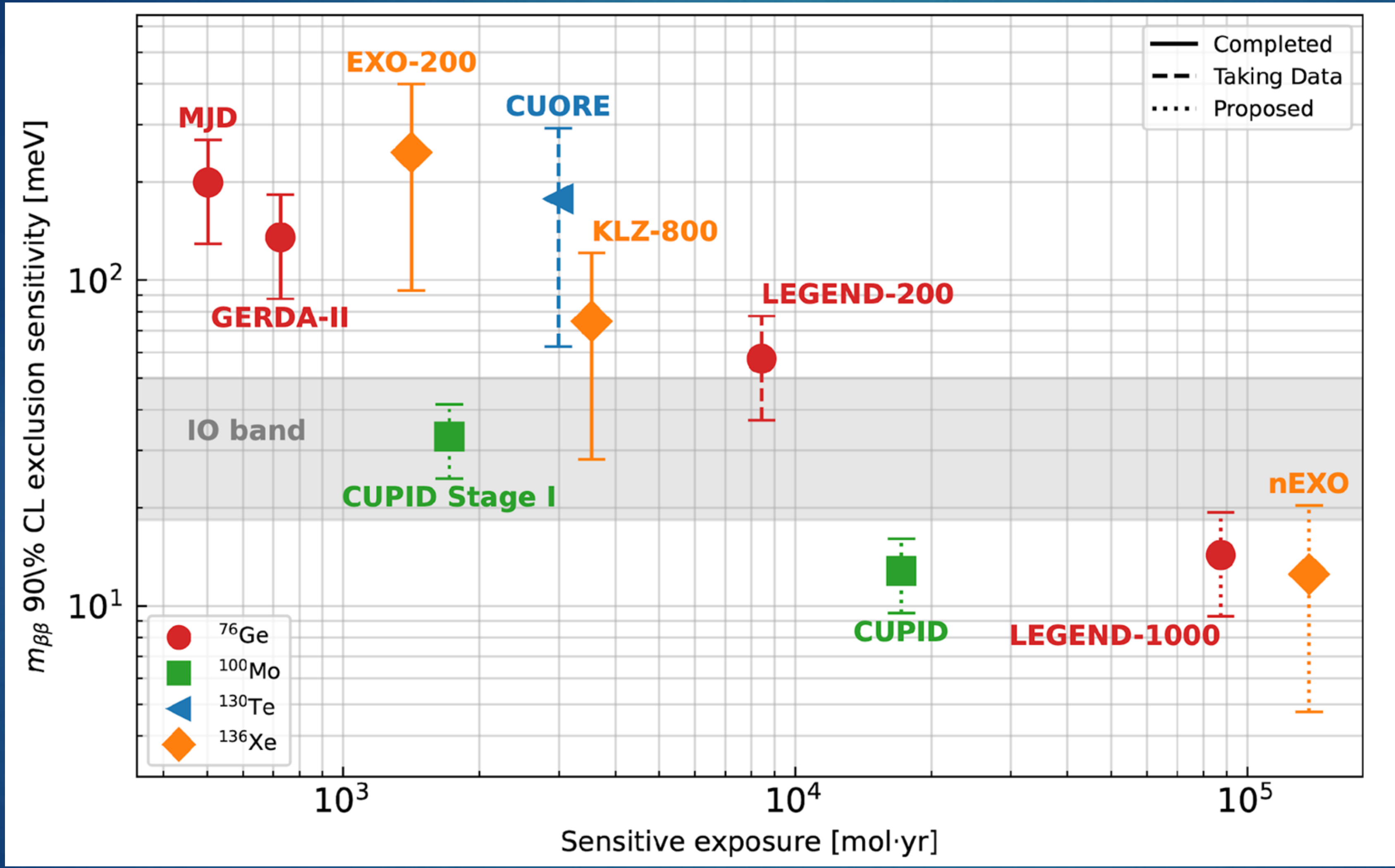
- $45 \times 45 \times 45\ \mathrm{mm}^3\ \mathrm{Li_2{}^{100}MoO_4}$ crystals
  - Crystal mass: 280 g
- 1596 total crystals
  - 450 kg of $\mathrm{Li_2{}^{100}MoO_4}$
  - 95% enrichment in $^{100}\mathrm{Mo}$: 240 kg of $^{100}\mathrm{Mo}$
  - 57 towers of 28 crystals. 14-floors of 2x1 crystal pairs.
- 1710 Ge NTL light detectors
  - Each crystal has top and bottom light detectors
- Muon veto for muon-induced background suppression

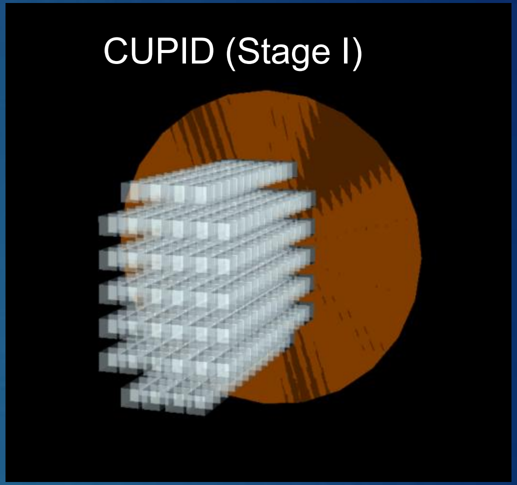
- Physics goal:
  - $\tau_{1/2} \sim 10^{27}$ years
  - → Discovery sensitivity in $m_{\beta\beta} \sim 10$ meV
- Requirements:
  - Background Index: $<10^{-4}$ cts/(keV kg yr)
  - Energy Resolution: ~ 5 keV FWHM at $Q_{\beta\beta}$

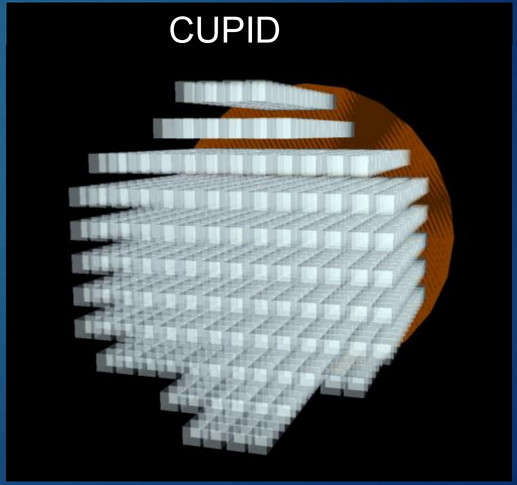


CUPID Sensitivity

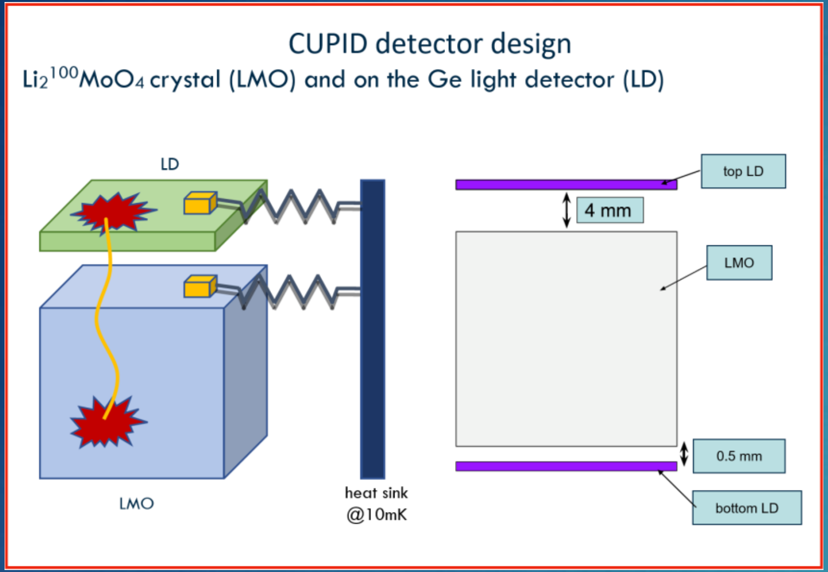
arXiv:2504.14369 (CUPID Collaboration)
Alfonso, K. *et al.* (CUPID Collaboration), *Eur. Phys. J. C* **85**, 737 (2025)



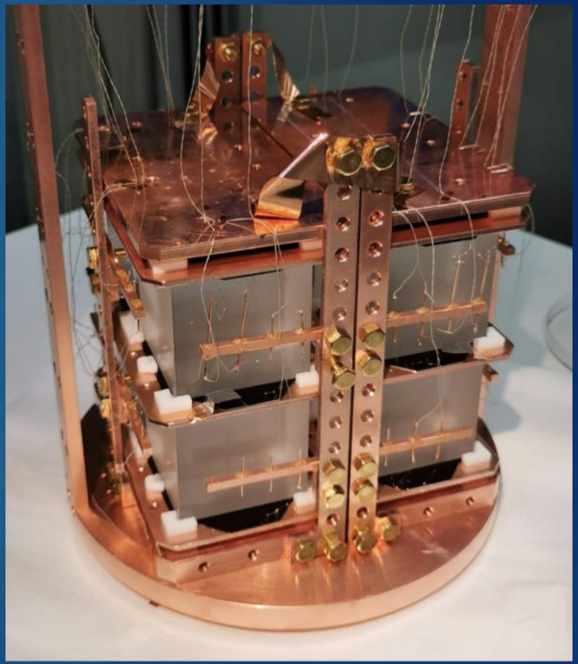




CUPID Detector performance



- CUPID detector small scale prototype tested in LNGS:
- Ge Light Detectors:
  - Average noise energy resolution: 57 ± 6 eV RMS
  - Light Yield:
    - (0.28 ± 0.02) keV/MeV [top LD]
    - (0.33 ± 0.03) keV/MeV [bottom LD]
  - α-discrimination: > 99.9 %
- LMO crystals:
  - Average energy resolution:
    - noise: (0.69 ± 0.06) keV RMS
    - @3034 keV: (5.9 ± 0.2) keV FWHM



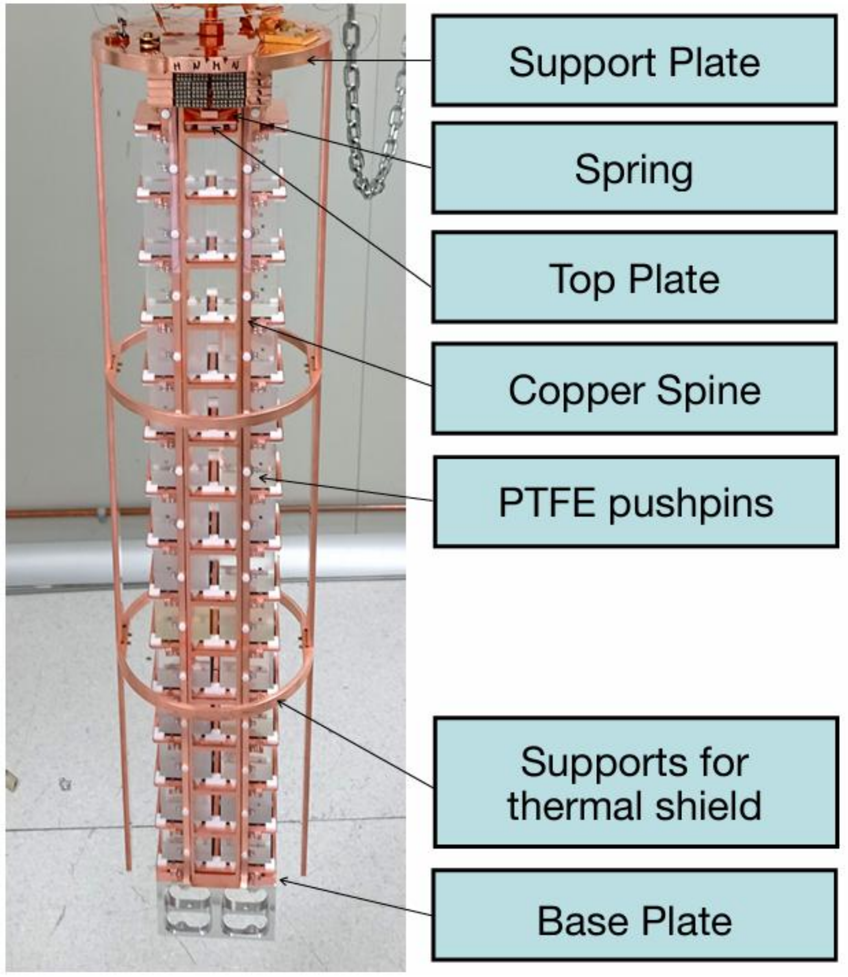
Alfonso, K. *et al.* (CUPID Collaboration), *Eur. Phys. J. C* **82**, 810 (2022)
K. Alfonso *et al.* (CUPID Collaboration), *JINST* **18** P06033 (2023)

Gravity Detector Prototype Tower

(CUPID Collaboration), *Eur. Phys. J. C* **85**, 935 (2025)

CUPID

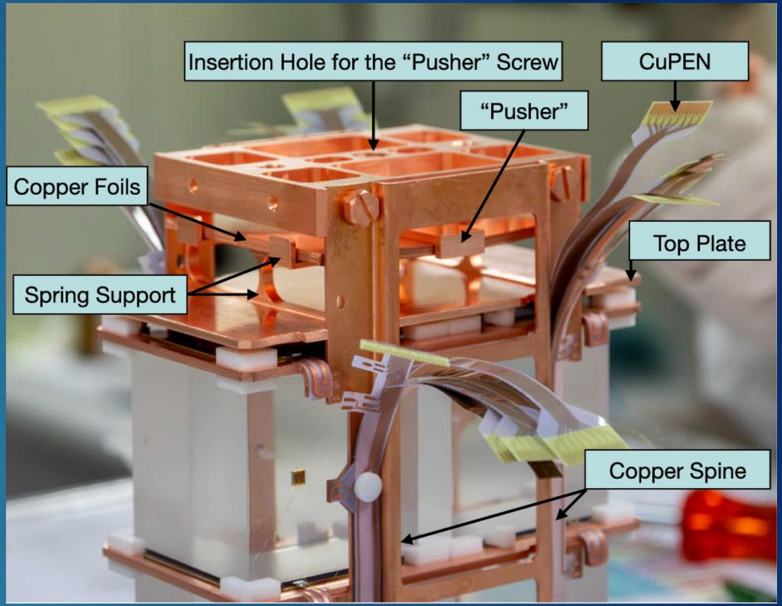
- $45 \times 45 \times 45\ \mathrm{mm}^3\ \mathrm{Li_2{}^{100}MoO_4}$ crystals
  - Crystal mass: 280 g
- 1596 total crystals
- 450 kg of $\mathrm{Li_2{}^{100}MoO_4}$
- 95% enrichment in $^{100}\mathrm{Mo}$: 240 kg of $^{100}\mathrm{Mo}$
- 57 towers of 28 crystals.
- 14-floors of 2x1 crystal pairs. Gravity-assisted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

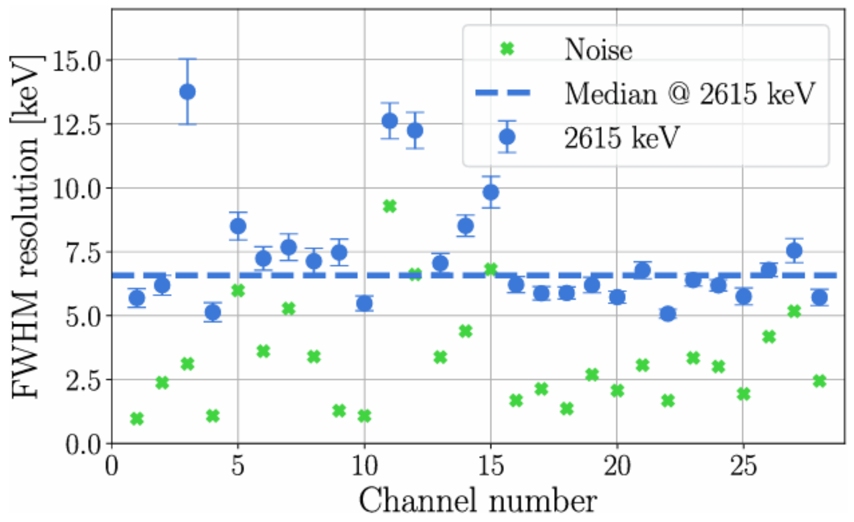


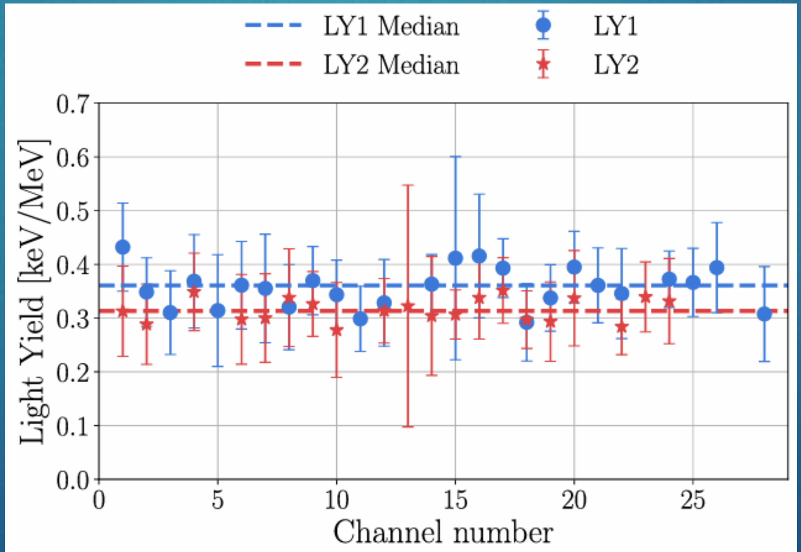
Gravity Detector Prototype Tower

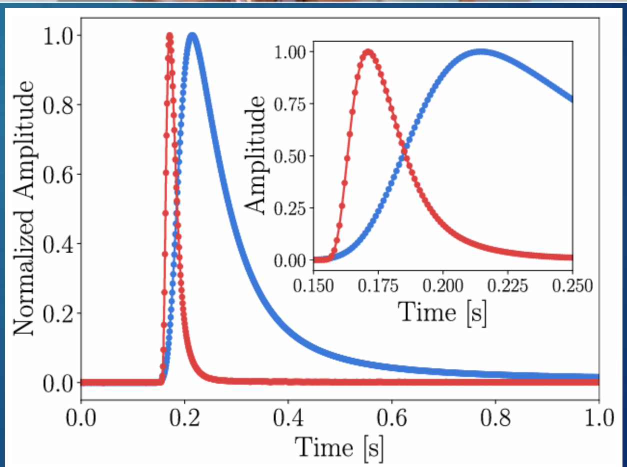
(CUPID Collaboration), *Eur. Phys. J. C* **85**, 935 (2025)

- Conceptual test of the new mechanical assembly of the tower (GDPT). Run in CUPID Hall-A facility @LNGS (2022)
- Showed a stable base temperature at better than ±0.5 mK stability at 10 mK.
- The first full tower test was successful, but LDs experienced limited SNR and correlated noise.







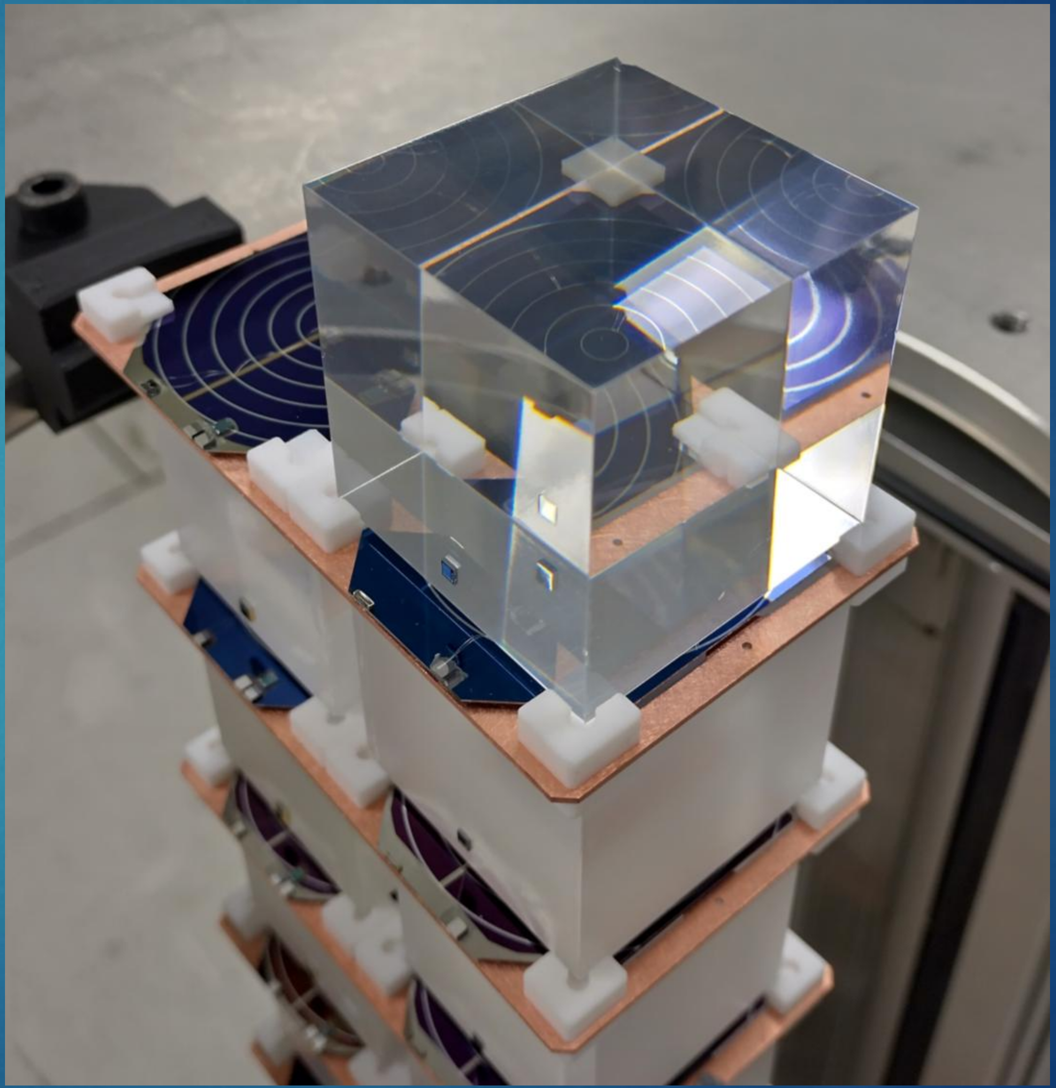


Vertical Slice Test Tower (VSTT)

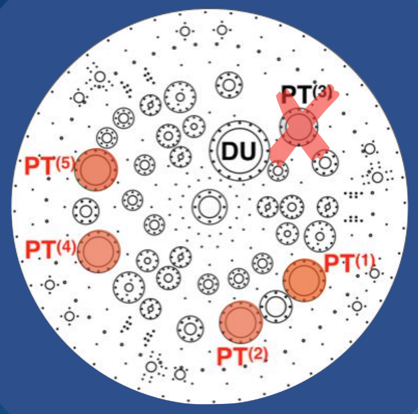
(CUPID Collaboration), *Eur. Phys. J. C* **85**, 935 (2025)

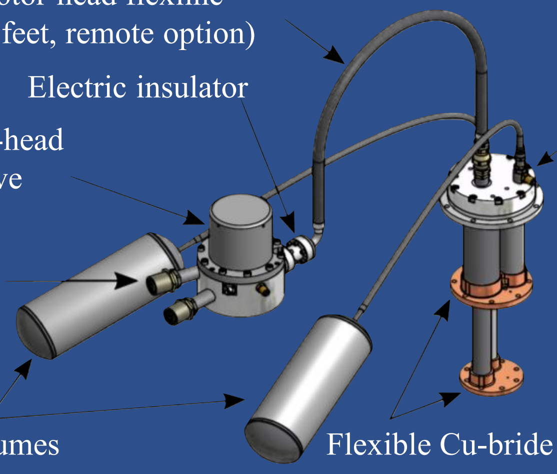
- 28 Li_2MoO_4 crystals
  - (3 enriched in ^{100}Mo)
- 30 Ge NTL amplification light detectors
- Refined copper holders
- Extended Cu-PEN readout wiring
- Optimized bonding for light detectors
- Optical fibers
- New Front End and DAQ electronics

- Assembled last week @ National Laboratory of Gran Sasso (INFN)
- Cooldown and validation of performance by summer 2025… stay tuned!



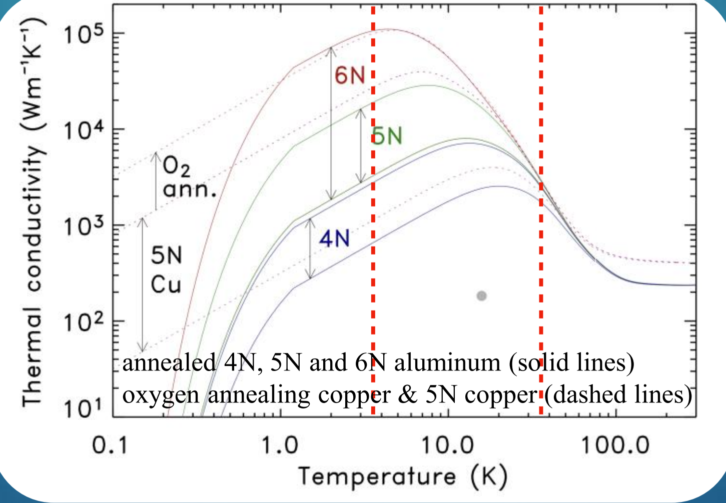
Cryostat: performance and future upgrades





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

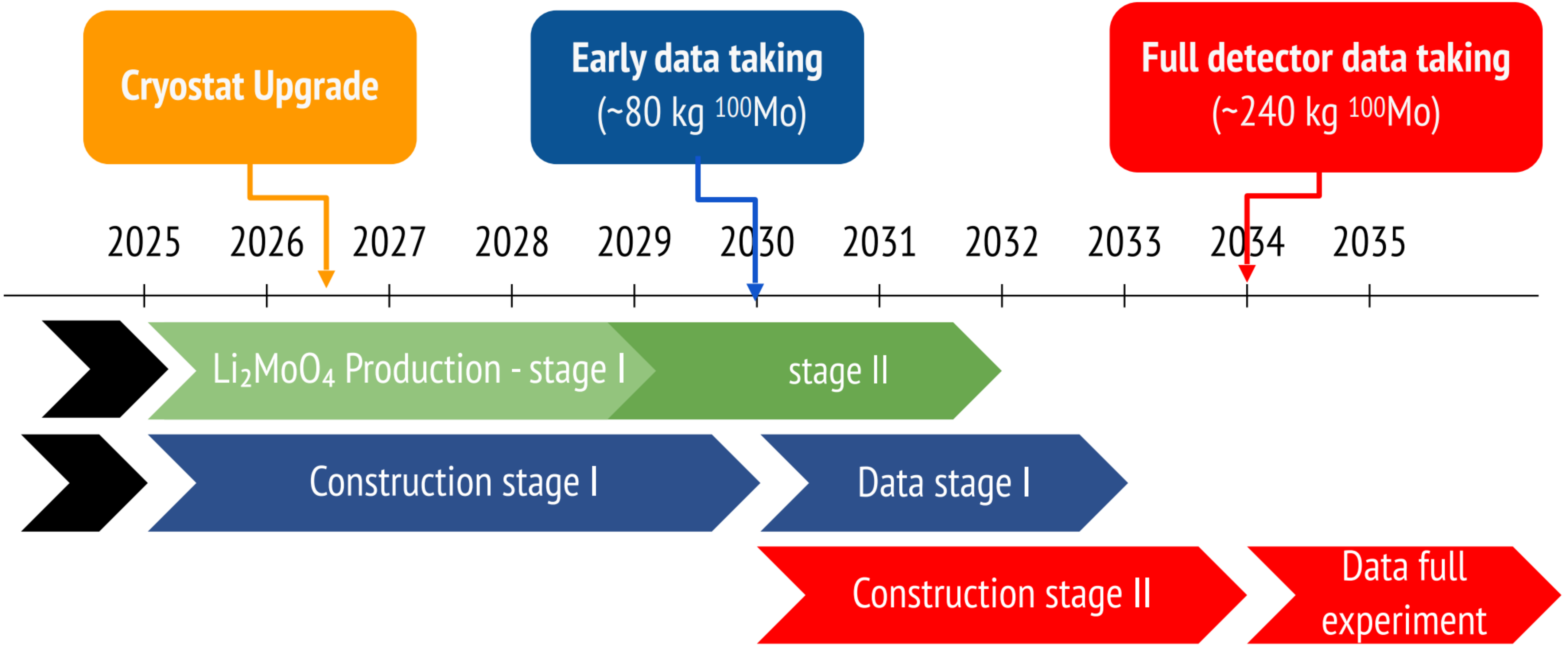


Adam L. Woodcraft, *Cryogenics* **45**, 626-636 (2005)

Pulse Tube Thermalization

- Good thermal conductivity
- Strong mechanical coupling
- More flexible
- Foresee vibration transmission reduction

CUPID timeline



Conclusions and Outlook

- 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.
- Next-generation $0\nu\beta\beta$ experiments aim to probe lepton number violation and to extend sensitivity to fully cover the inverted hierarchy region of neutrino mass.
- CUPID will be leveraging the unique ability to deploy different isotopes on the same infrastructure.
  - CUPID has a path for isotope enrichment, procurement and crystal growth
  - Final technical integration tests are underway at LNGS
  - CUPID is ready to start construction
  - Preparations for cryostat upgrade are underway at LNGS
  - CUPID will pursue a staged deployment
- CUPID will play a central role in the $0\nu\beta\beta$ search and discovery program at LNGS in the next years

CUORE → **C**UORE **U**pgrade with **P**article **ID**entification → CUPID

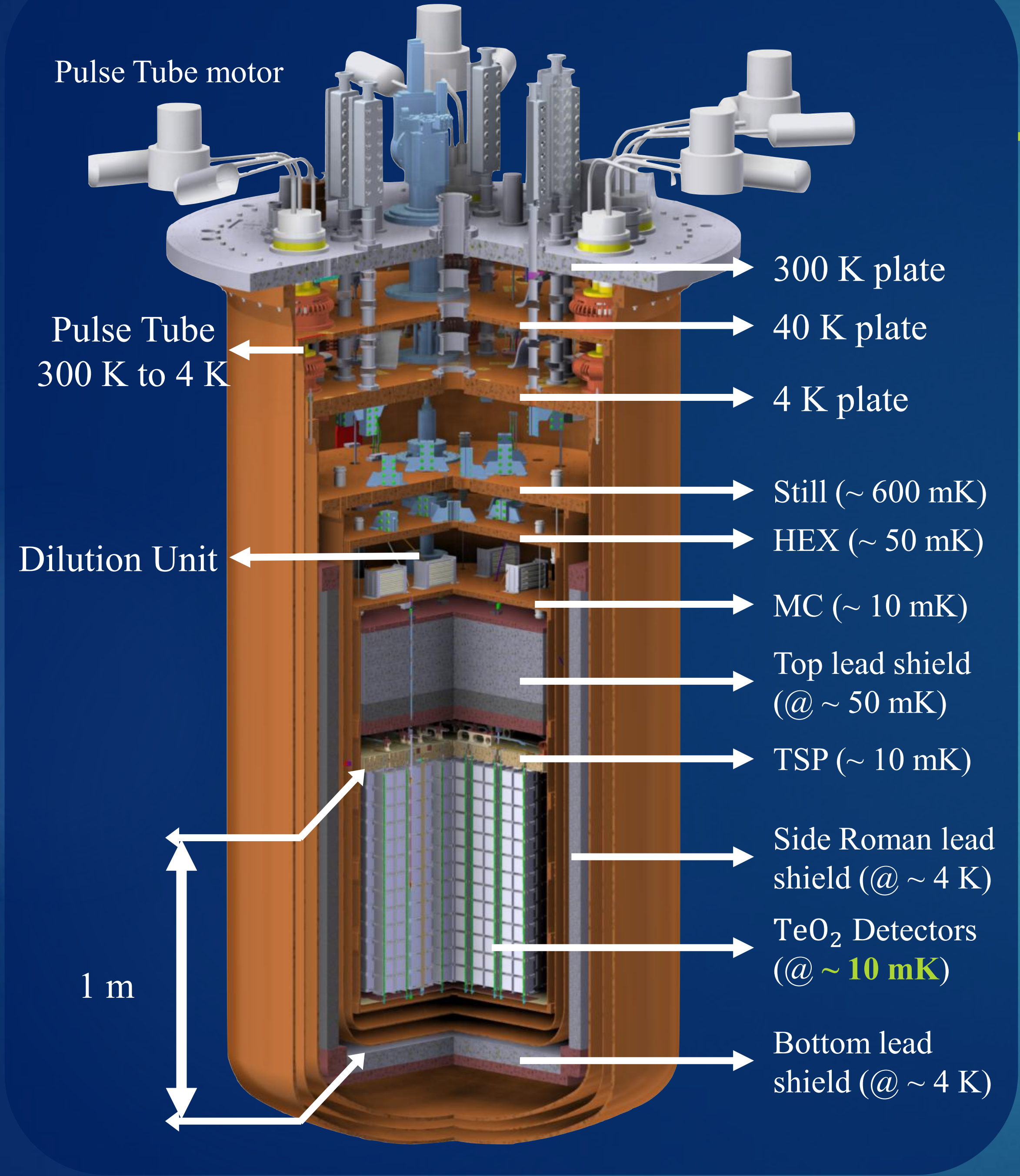
Acknowledgements

- The CUPID Collaboration thanks the directors and staff of the Laboratori Nazionali del Gran Sasso and the technical staff of our laboratories. This work was supported by the Istituto Nazionale di Fisica Nucleare (INFN); by the European Research Council (ERC) under the European Union Horizon 2020 program (H2020/2014-2020) with the ERC Advanced Grant no. 742345 (ERC-2016-ADG, project CROSS) and the Marie Sklodowska-Curie Grant Agreement No. 754496; by the Italian Ministry of University and Research (MIUR) through the grant Progetti di ricerca di Rilevante Interesse Nazionale (PRIN) grant no. 2017FJZMCJ and grant no. 2020H5L338; by the US National Science Foundation under Grant Nos. NSF-PHY-1401832, NSF-PHY-1614611, NSF-PHY-2412377 and NSF-PHY-1913374; by the French Agence Nationale de la Recherche (ANR) through the ANR-21-CE31-0014-CUPID-1; by the National Research Foundation of Ukraine (Grant No. 2023.03/0213). This material is also based upon work supported by the US Department of Energy (DOE) Office of Science under Contract Nos. DE-AC02-05CH11231 and DE-AC02-06CH11357; and by the DOE Office of Science, Office of Nuclear Physics under Contract Nos. DE-FG02-08ER41551, DE-SC0011091, DE-SC0012654, DE-SC0019316, DE-SC0019368, and DE-SC0020423. This work was also supported by the Russian Science Foundation under grant No. 18-12-00003. This research used resources of the National Energy Research Scientific Computing Center (NERSC). This work makes use of both the DIANA data analysis and APOLLO data acquisition software packages, which were developed by the CUORICINO, CUORE, LUCIFER and CUPID-0 Collaborations.

Thank you for your attention!

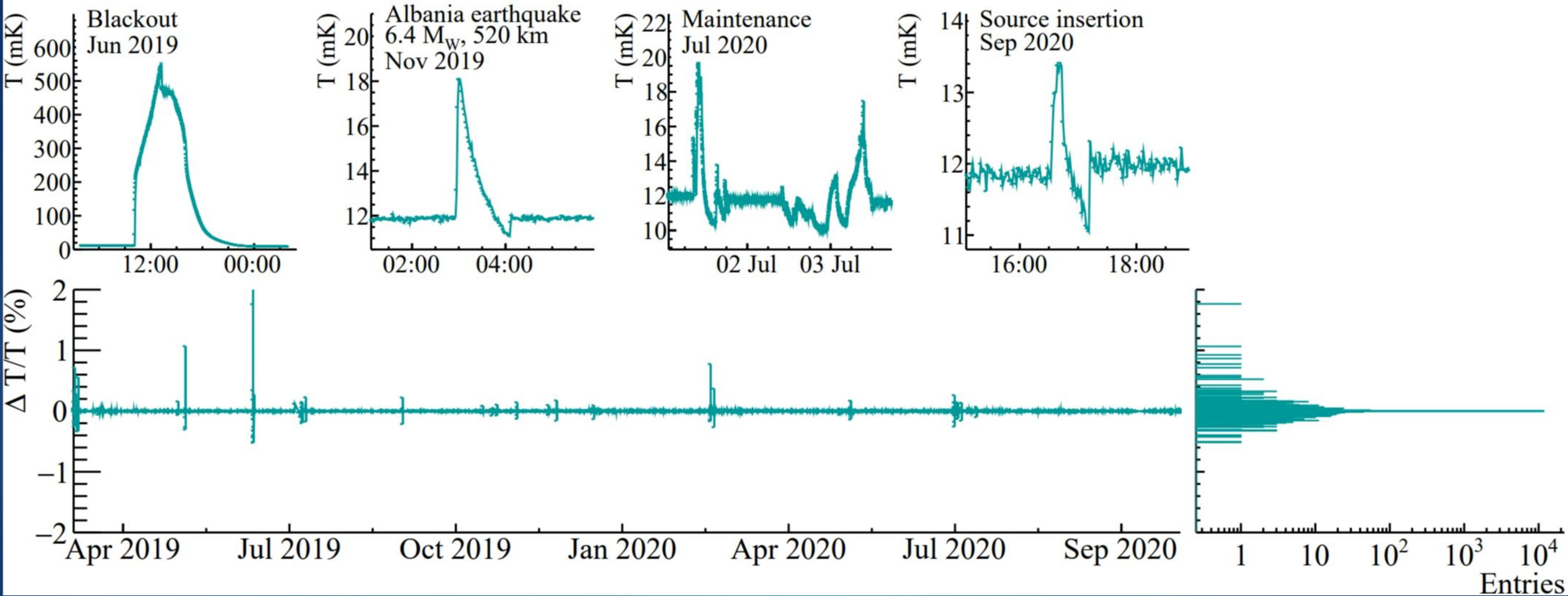
Backup

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

The cryostat performance

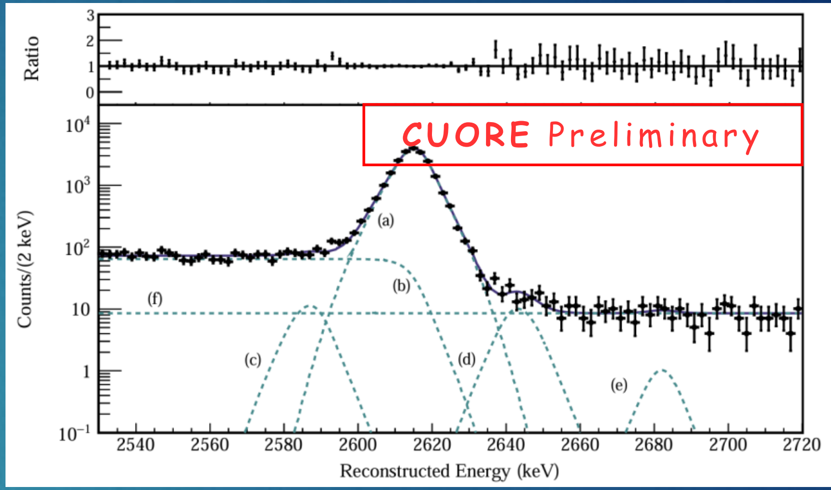


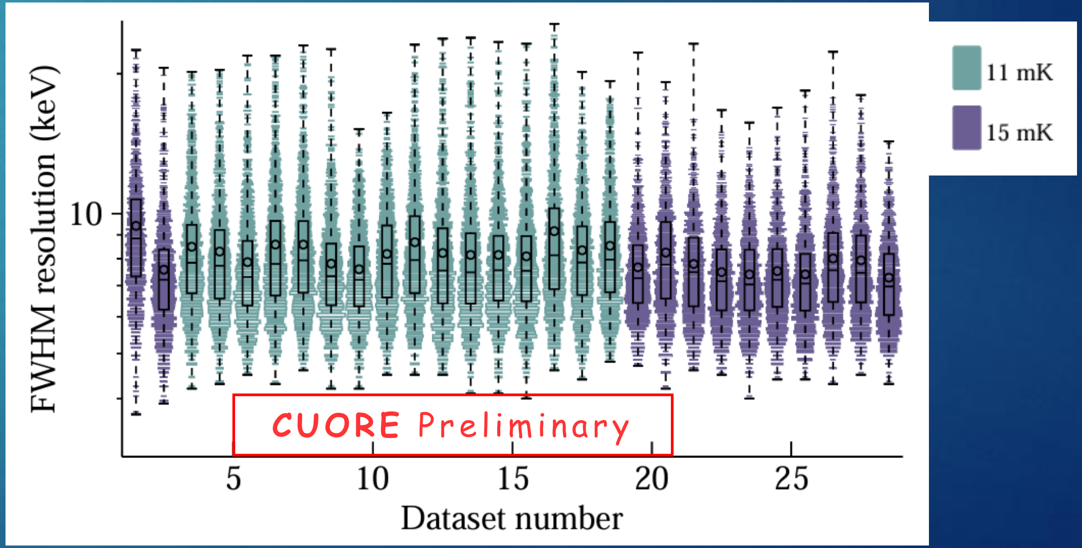
Adams, D.Q. et al. (CUORE Collaboration), ***Nature* 604**, 53-58 (2022)

Detector performance

arXiv:2404.04453 (CUORE Collaboration)

- Peak lineshape:
  - Reference ^{208}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

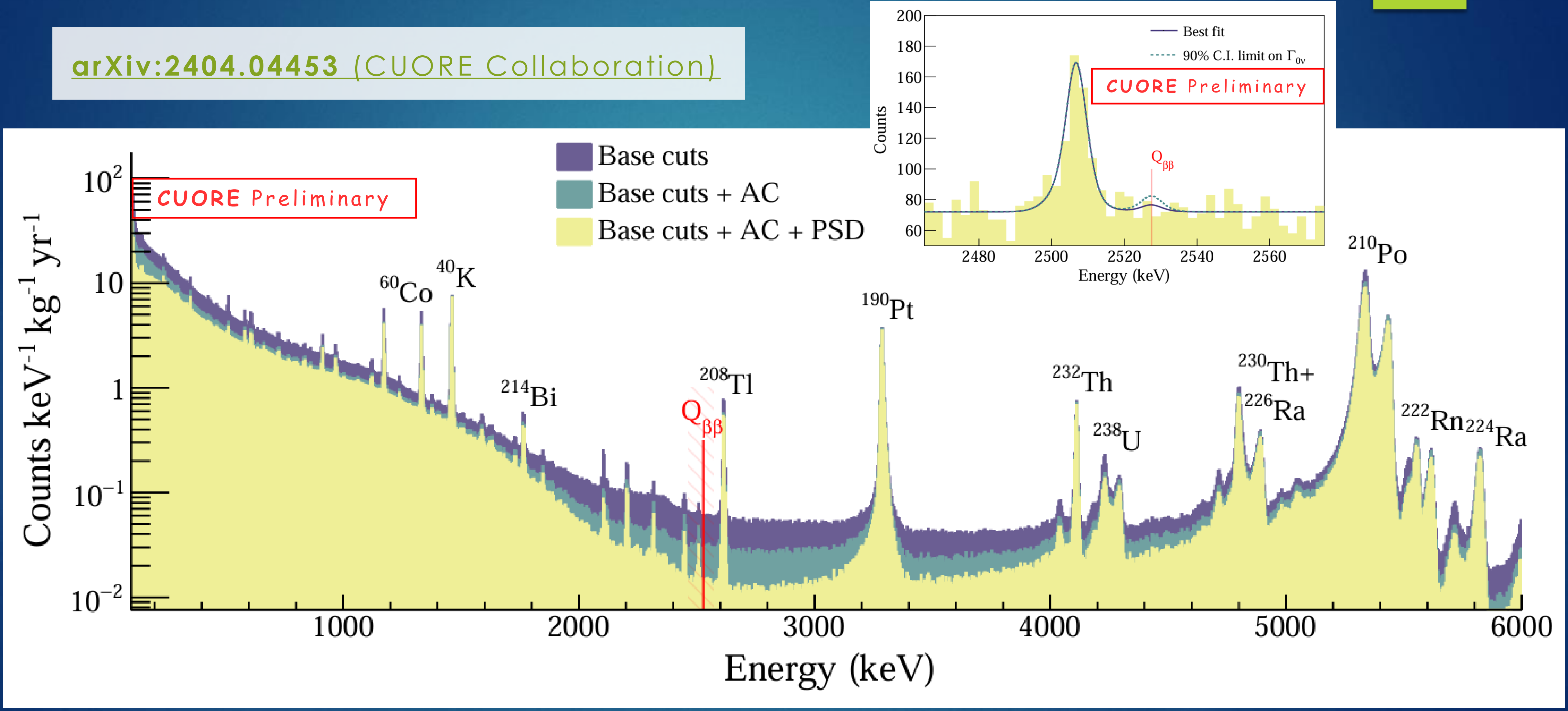




2 ton · yr exposure

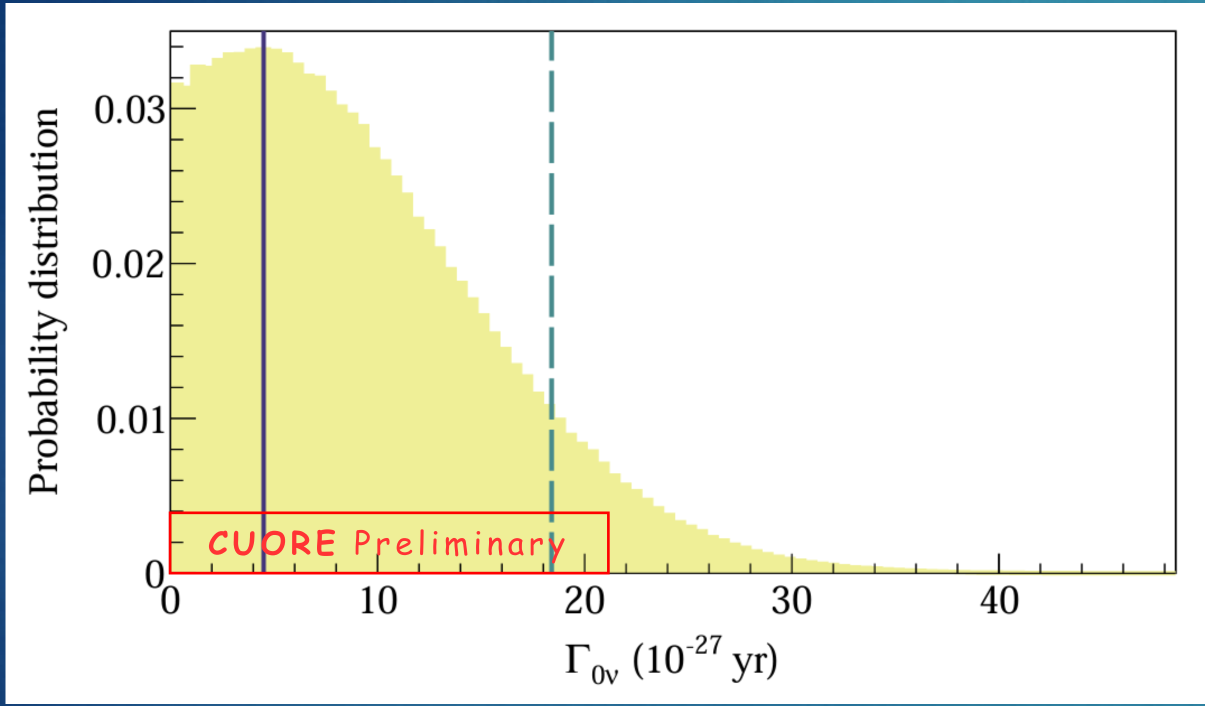
CUORE

arXiv:2404.04453 (CUORE Collaboration)

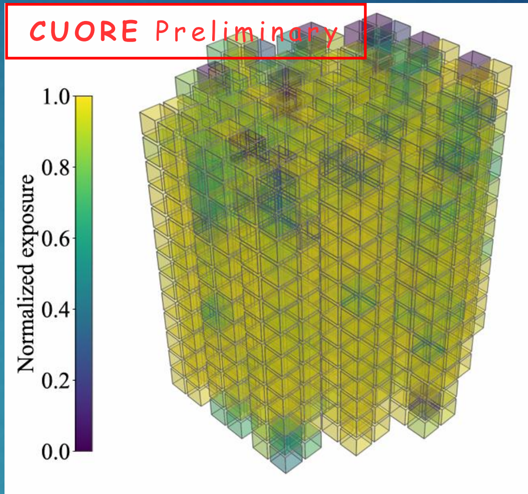


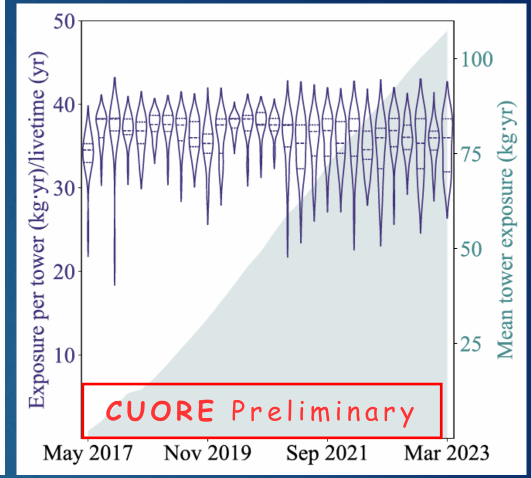
$0\nu\beta\beta$ decay search results

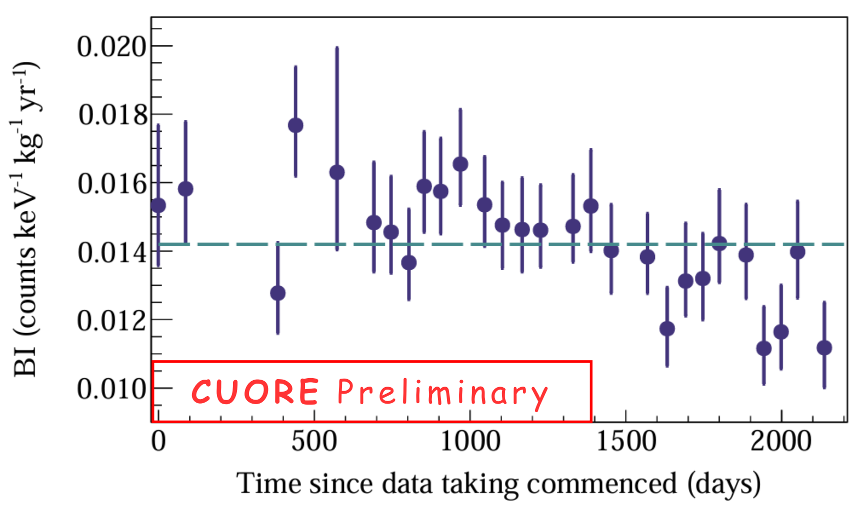
- Resolution scaling
  - FWHM at $Q_{\beta\beta} = (7.320 \pm 0.024)$ keV



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



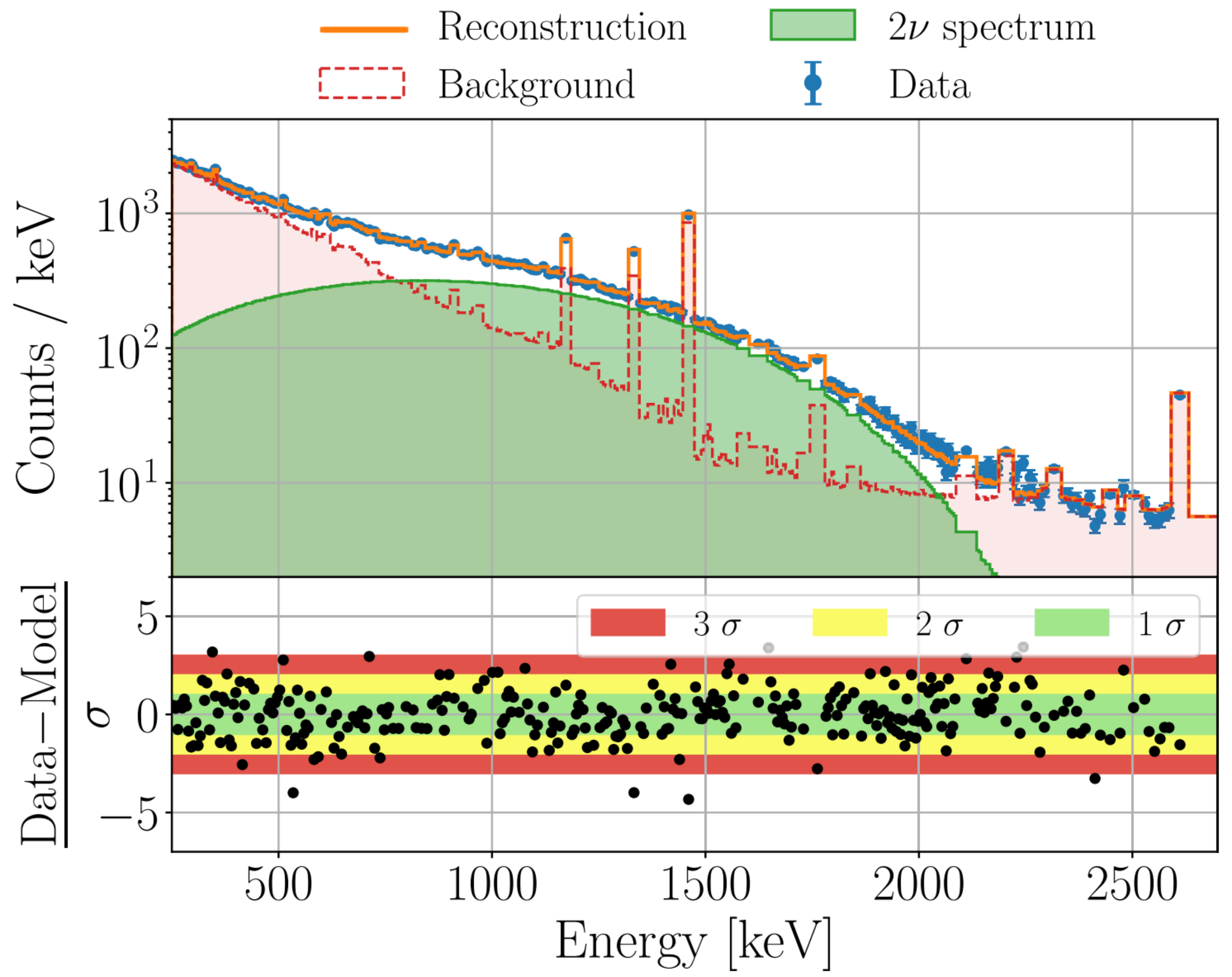




- BI: $(1.42 \pm 0.02) \cdot 10^{-2}$ counts / (keV · kg · yr)

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

2νββ decay measurement

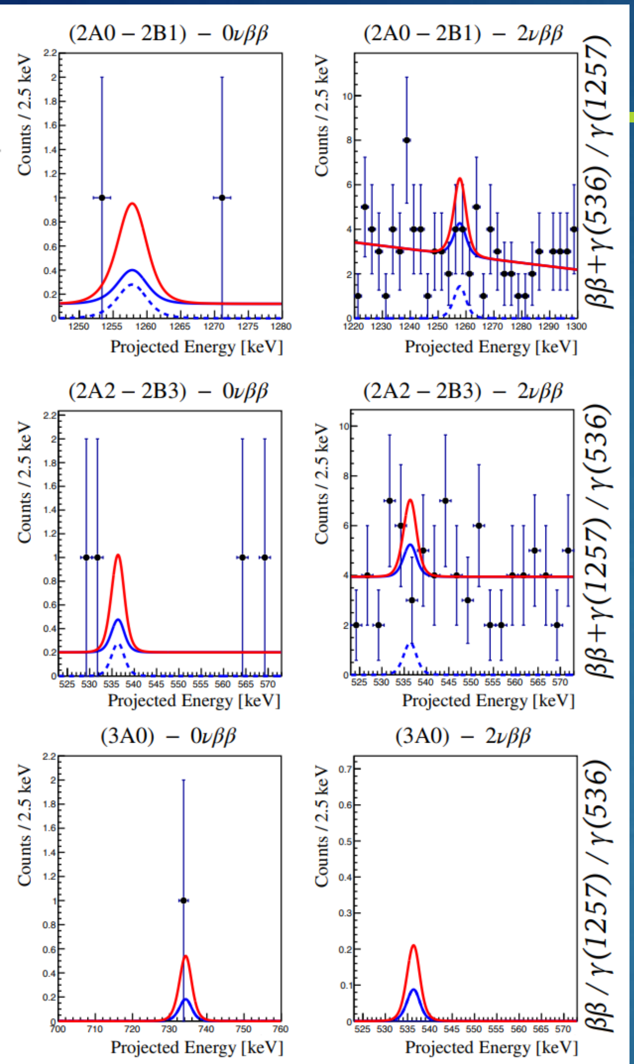


- ^{130}Te 2νββ component from best fit to the single-crystal-event energy spectrum with CUORE 1038.4 kg·yr TeO_2 exposure.
- Spectral fit
- $T^{2\nu}_{1/2} = 9.32^{+0.05}_{-0.04}(\text{stat.})^{+0.07}_{-0.07}(\text{syst.}) \times 10^{20}$ yr
- Most precise measurement of ^{130}Te 2νββ decay half-life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

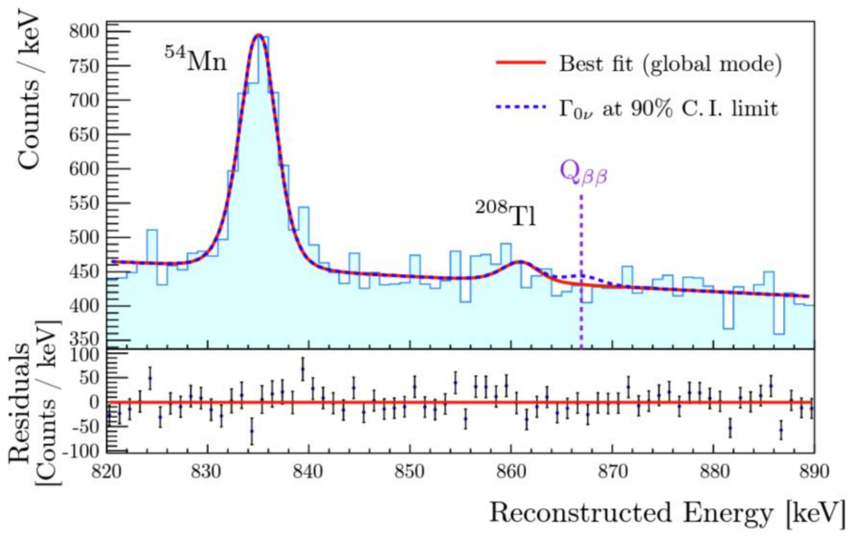
D. Q. Adams *et al.* (CUORE Collaboration), *Phys. Rev. Lett.* **135**, 082501 (2025)

Other rare event searches

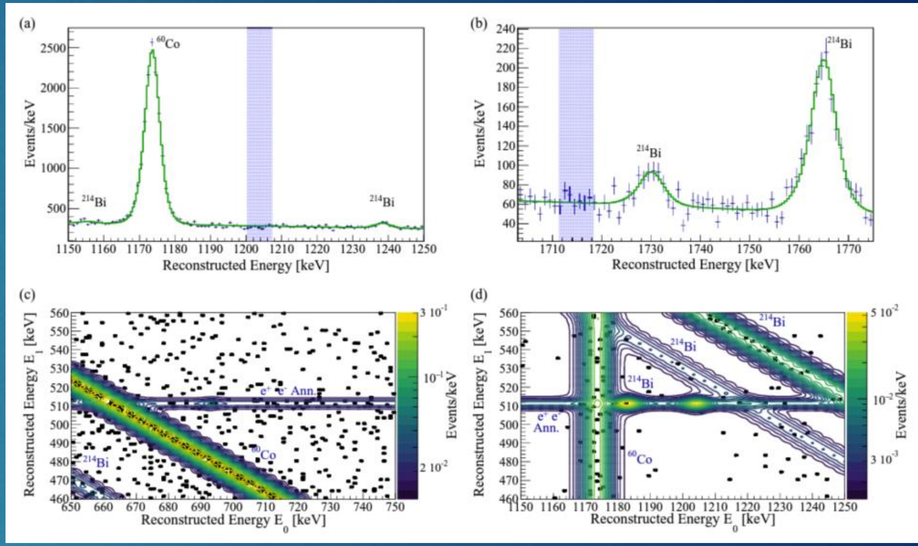
^{130}Te $\beta\beta$ to first 0^+ excited state



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



^{128}Te β^+/EC



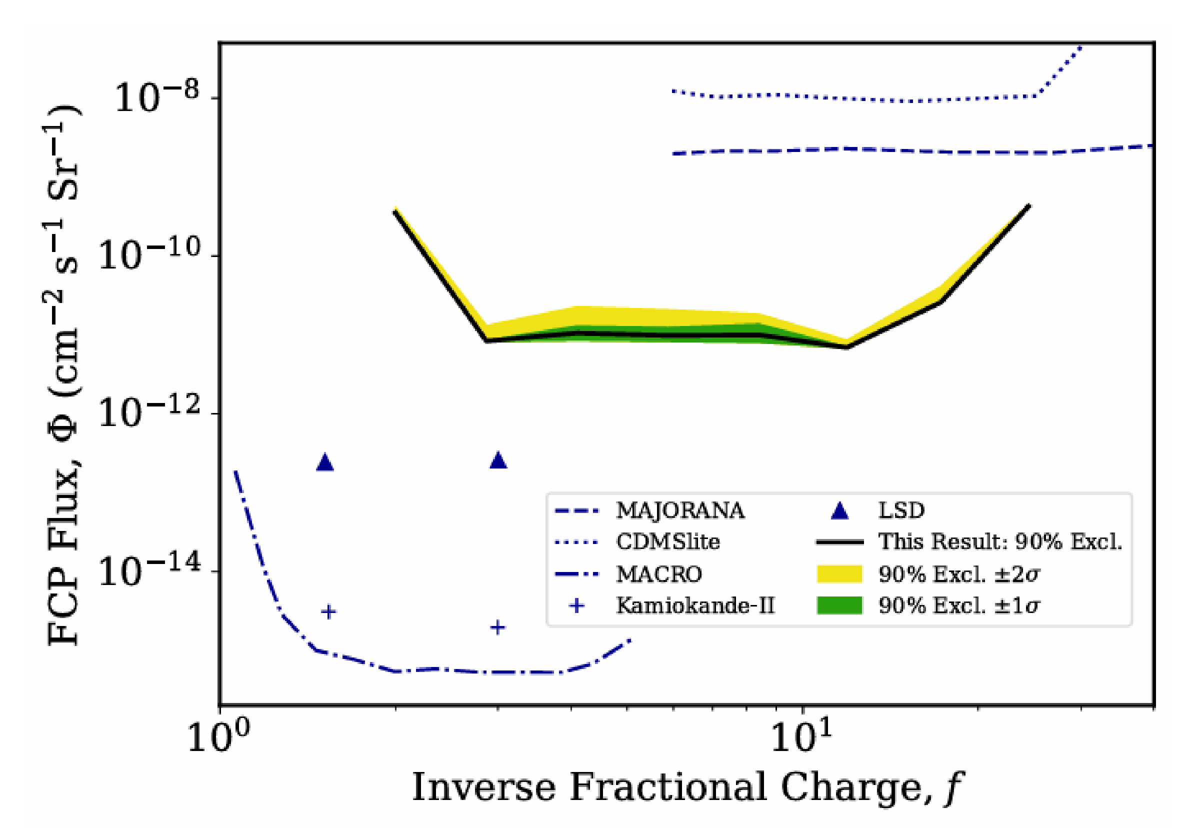
Adams, D.Q. et al. (CUORE Collaboration), *Phys. Rev. Lett.* **129**, 222501 (2022)

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)

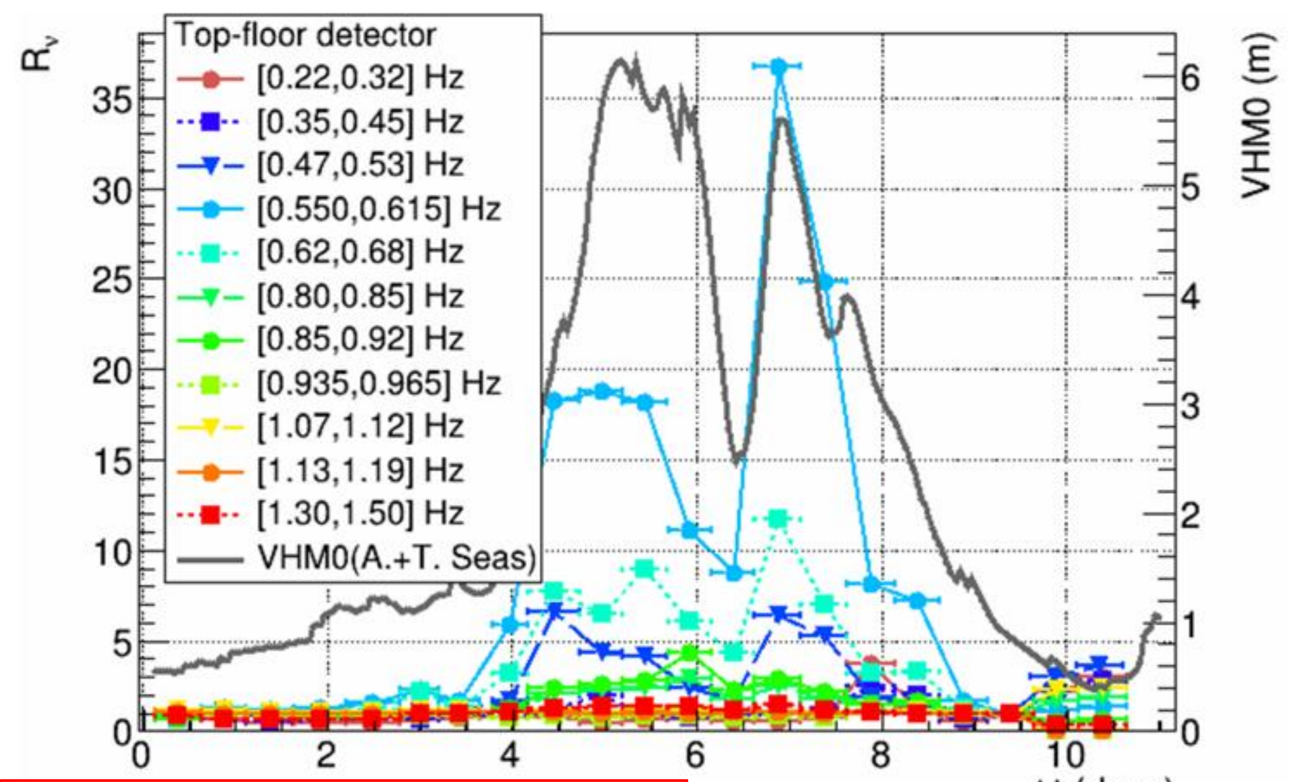
Other searches

Fractionally Charged Particles



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

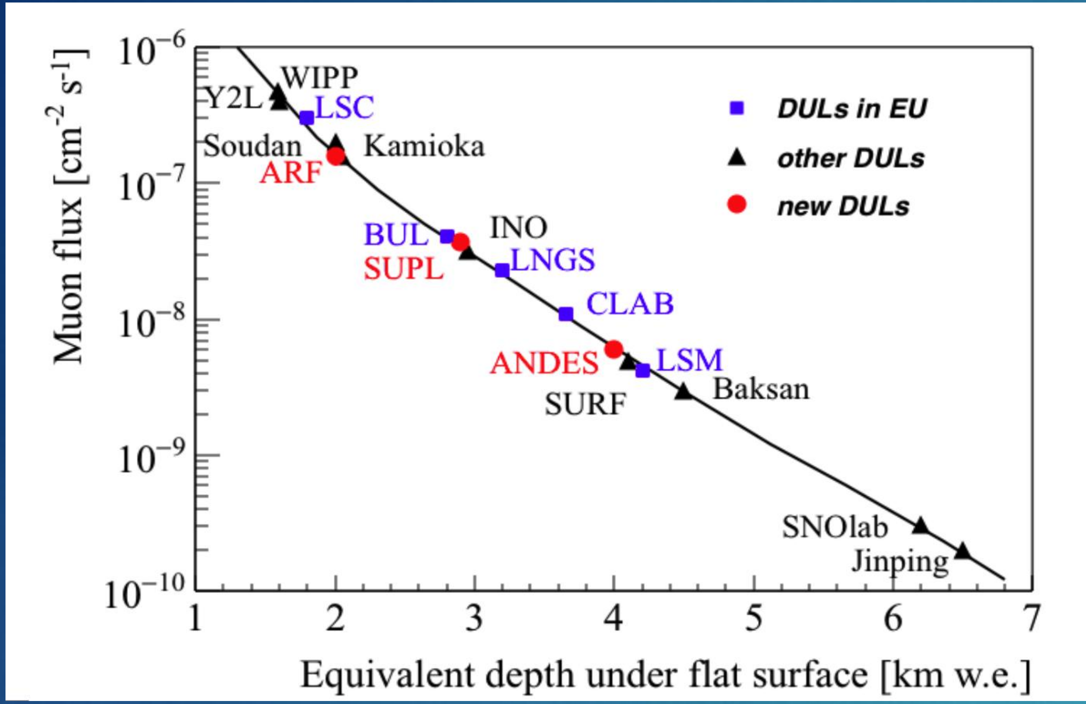
Correlations between CUORE low frequency noise and sea waves



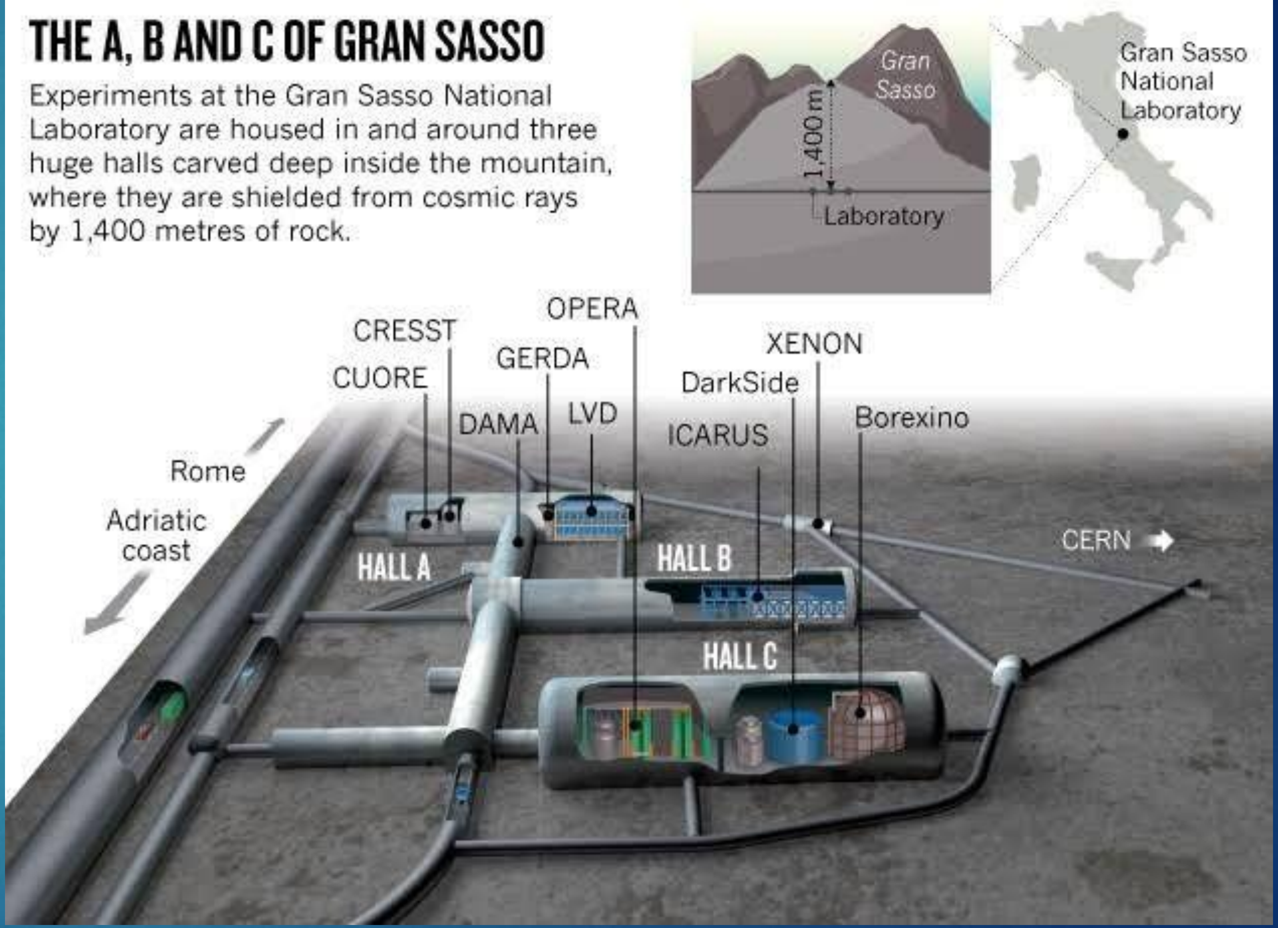
8.PS2.10.5: S. Quitadamo's talk

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

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)

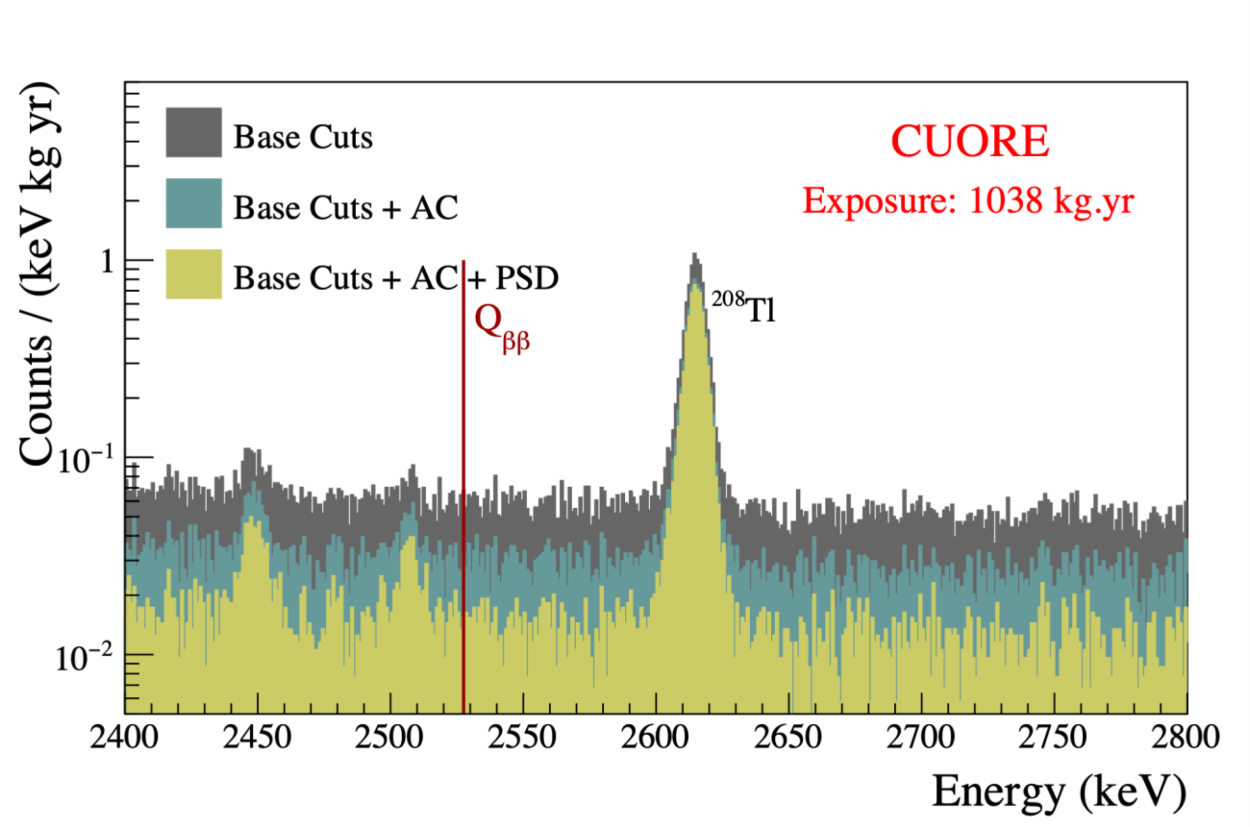


Efficiencies

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)

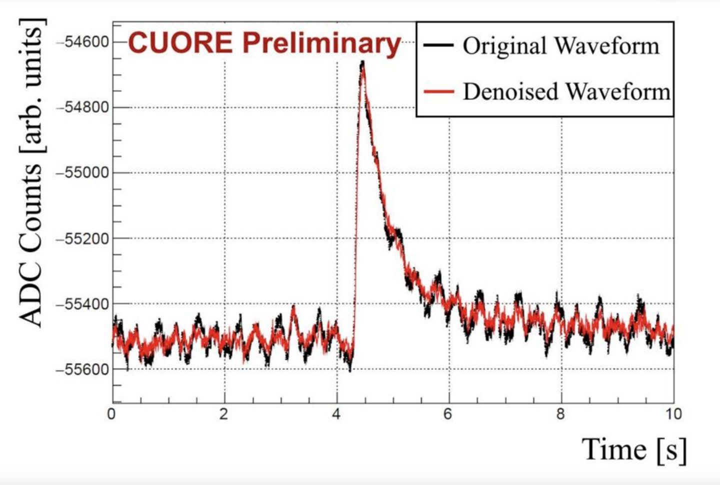
- α region
  - fit flat background in [2650, 3100] keV
  - 1.40(2) × 10^{-2} counts/(keV kg yr)
- $Q_{\beta\beta}$ region
  - fit background + ^{60}Co peak in [2490, 2575] keV
  - 1.49(4) × 10^{-2} counts/(keV kg yr)
- source
  - ~90% of the background in the ROI is given by degraded alpha interactions

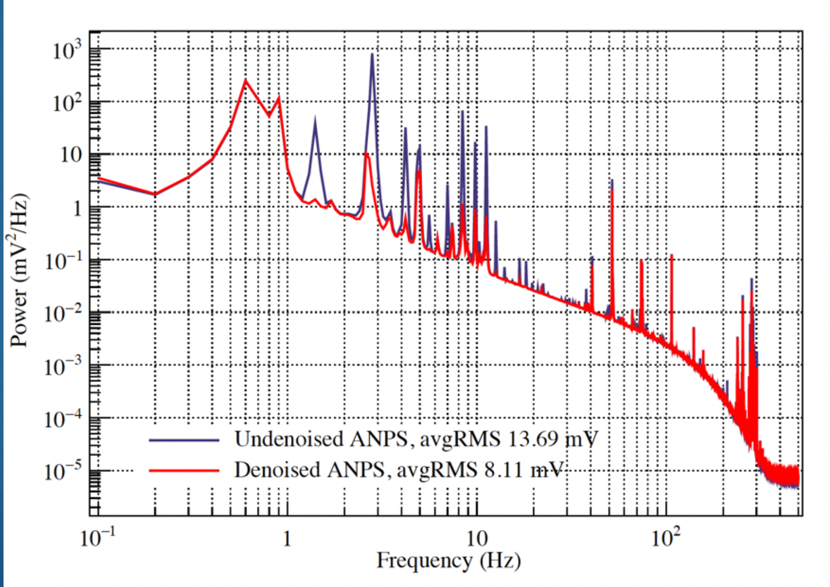


CUORE data analysis

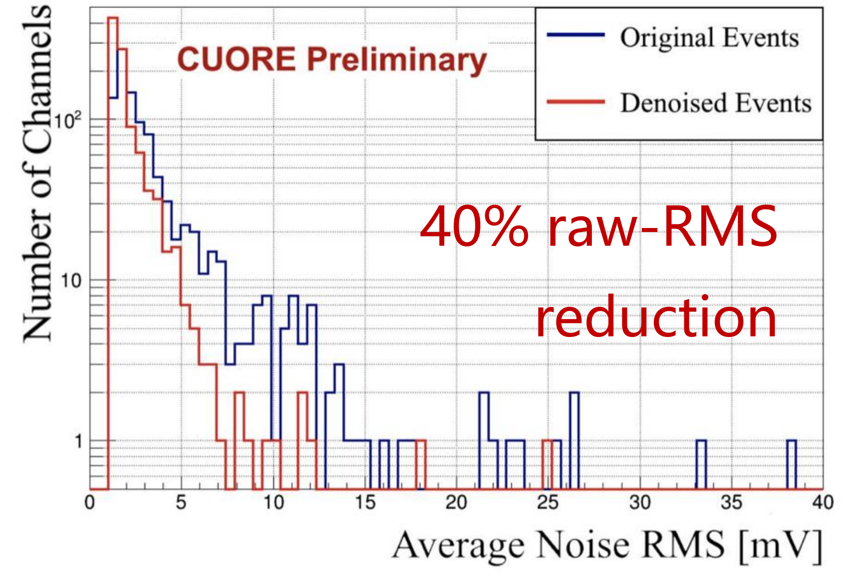
CUORE

- **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…

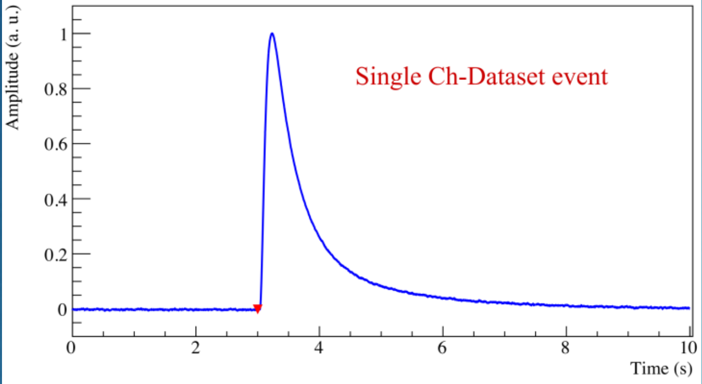


Vetter, K.J., Beretta, M., Capelli, C. et al., Eur. Phys. J. C 84, 243 (2024)

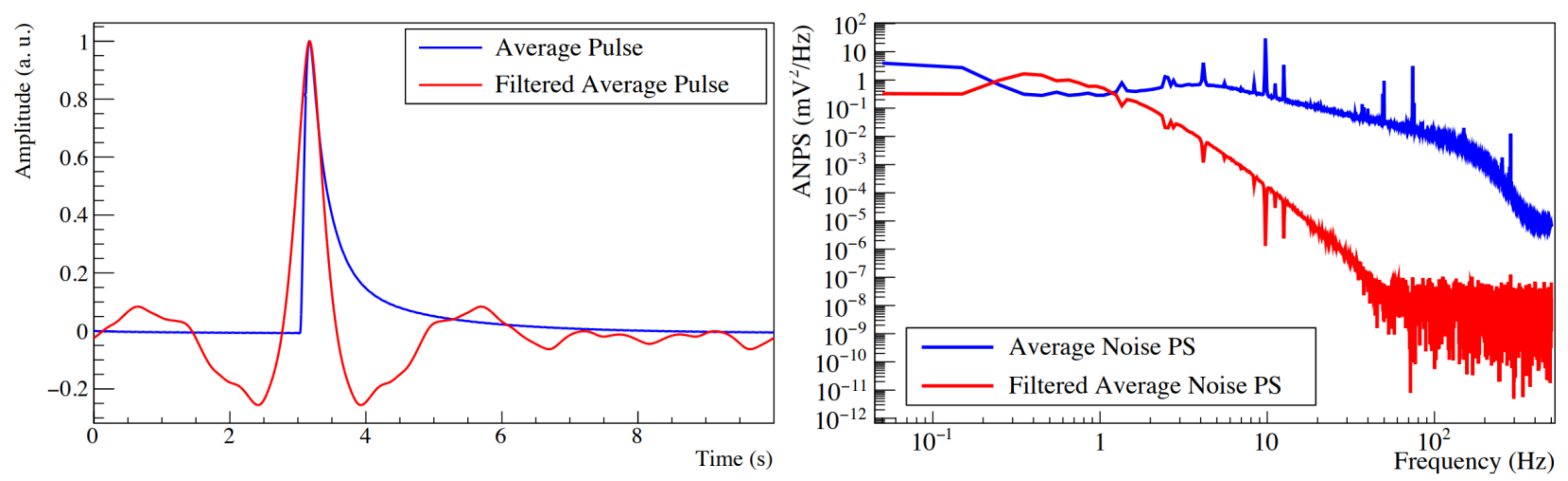
CUORE data analysis

CUORE

- 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)
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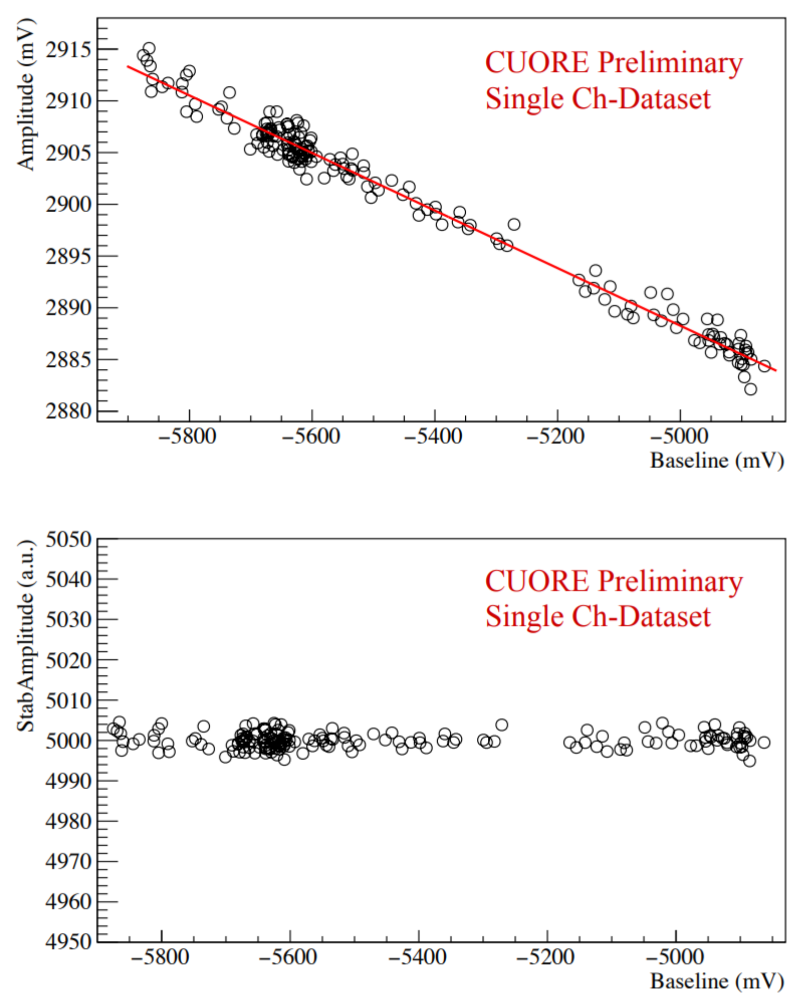
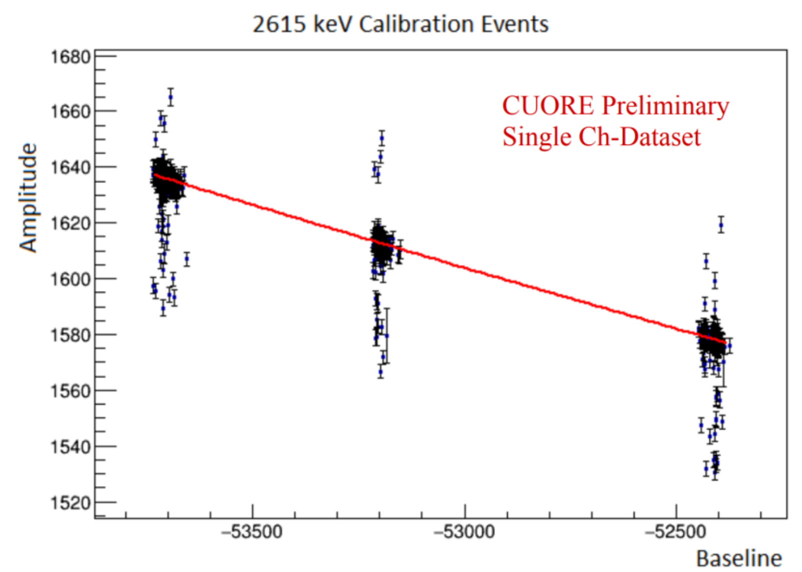


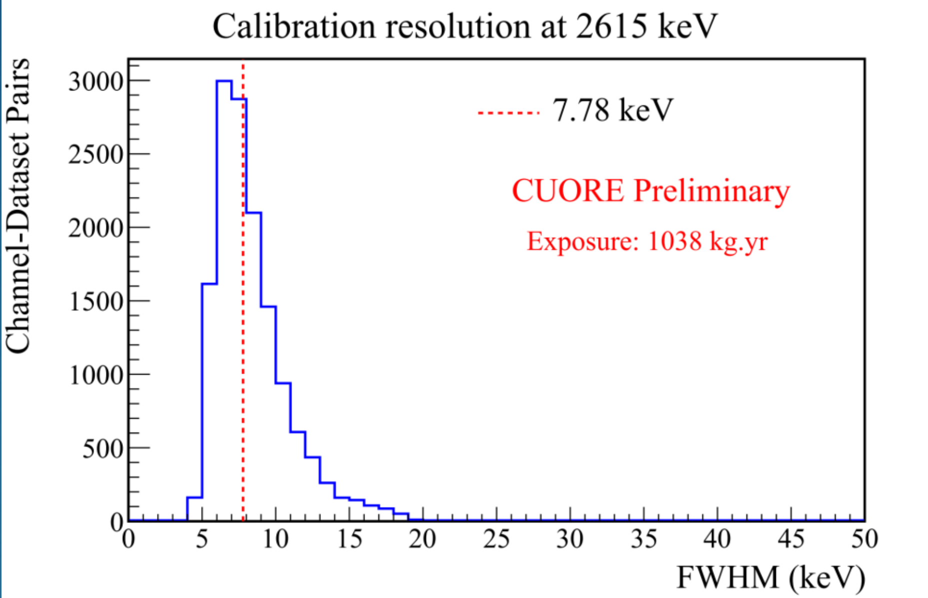
- Use fixed energy heater events to correct amplitude dependence on operating temperature
- Interpolate calibration peak at 2615 keV for non-functional or underperforming heaters



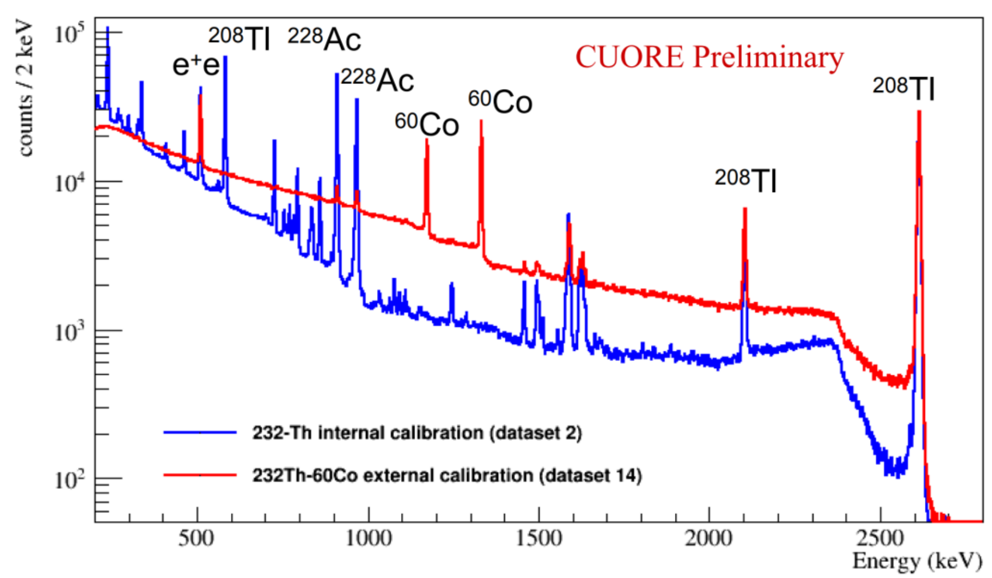
- Heater pulses for thermal gain stabilization

CUORE data analysis

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



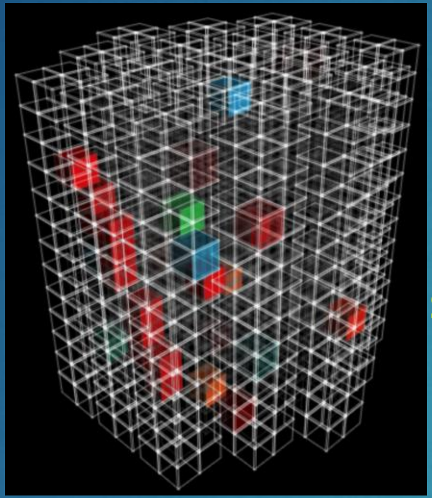
- Detector response modelled on the $2615\ \mathrm{keV}$ line from $^{232}\mathrm{Th}$ chain.
  - Accounts for non idealities.

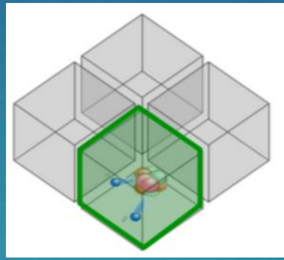


- First 3 datasets used internal $^{232}\mathrm{Th}$ source
- Internal calibration system replaced with simpler external one in later datasets

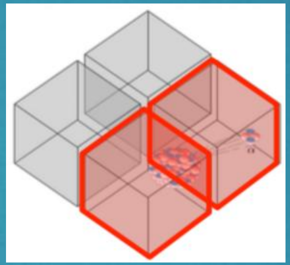
CUORE data analysis

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





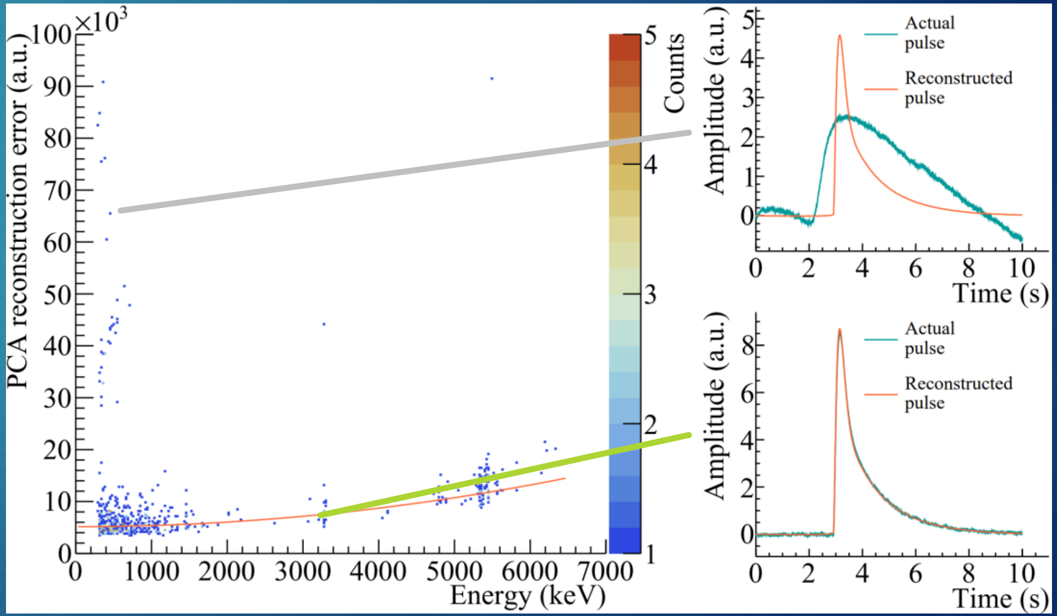
single-site (signal-like)



multi-site (background-like)

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

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



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