GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

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

Science Fair 2024/2025

CUORE

CUPID

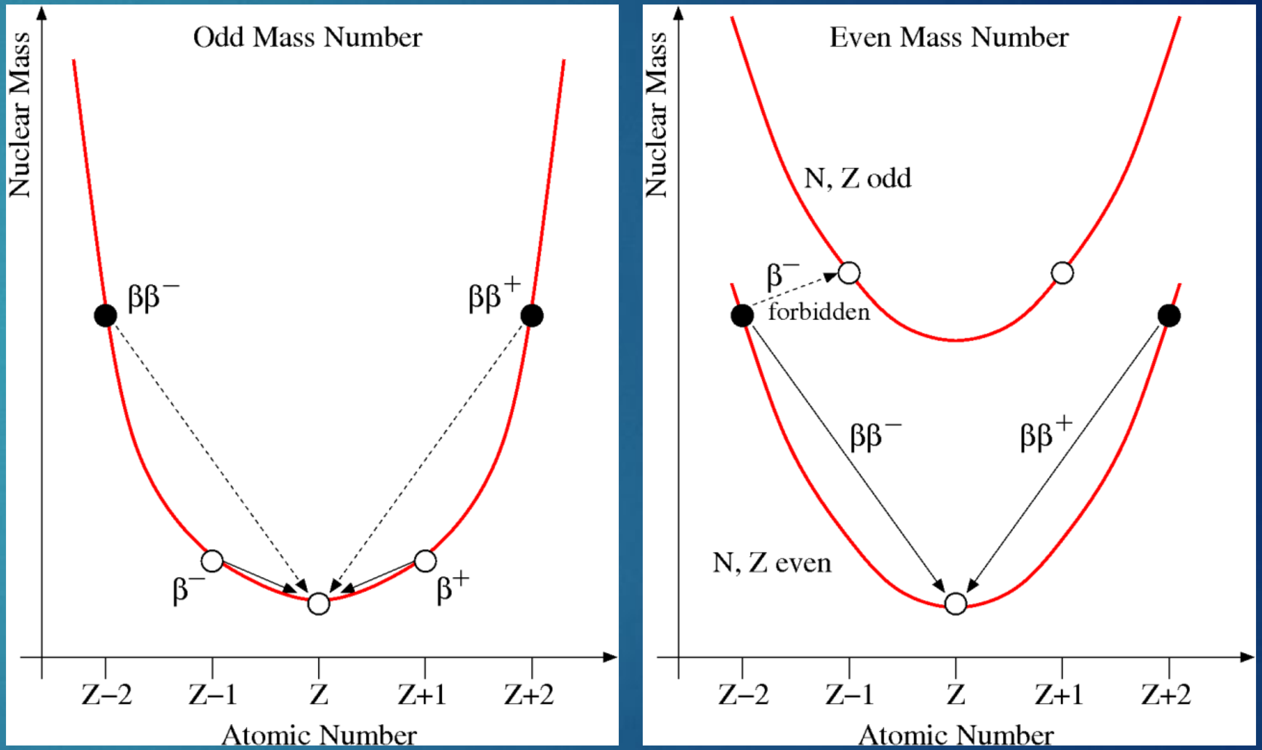
CUORE, **CUPID**, and searching for $0\nu\beta\beta$

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

Shihong Fu · INFN-LNGS · 11th Astroparticle Physics Science Fair 2024/2025, February 24th, 2025

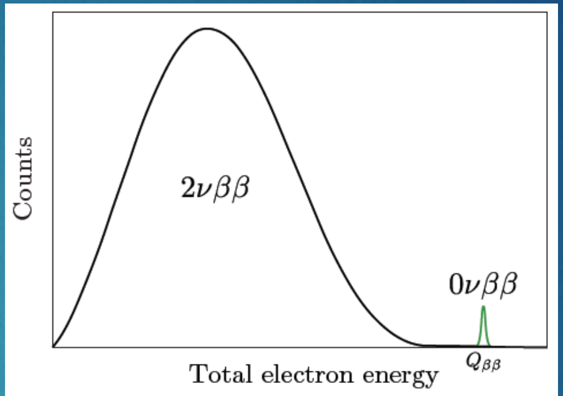
Double Beta Decay ($2\nu\beta\beta$)

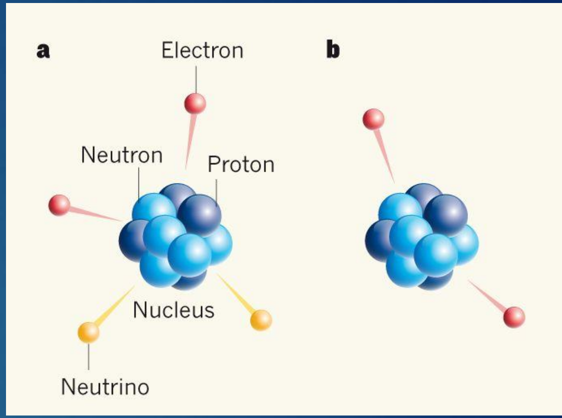
- Same mass number (A), changes the nuclear charge (Z) by two units.
- 2nd order weak transition, allowed by the Standard Model.
- Decay to the intermediate nucleus is forbidden.
- Only even mass number nuclei.
- Half-lives in the order of $10^{18} \sim 10^{21}$ yr.
- Two-neutrino double beta decay ($2\nu\beta\beta$) candidate isotopes:
  - ^{48}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 ($0\nu\beta\beta$)

- 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





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

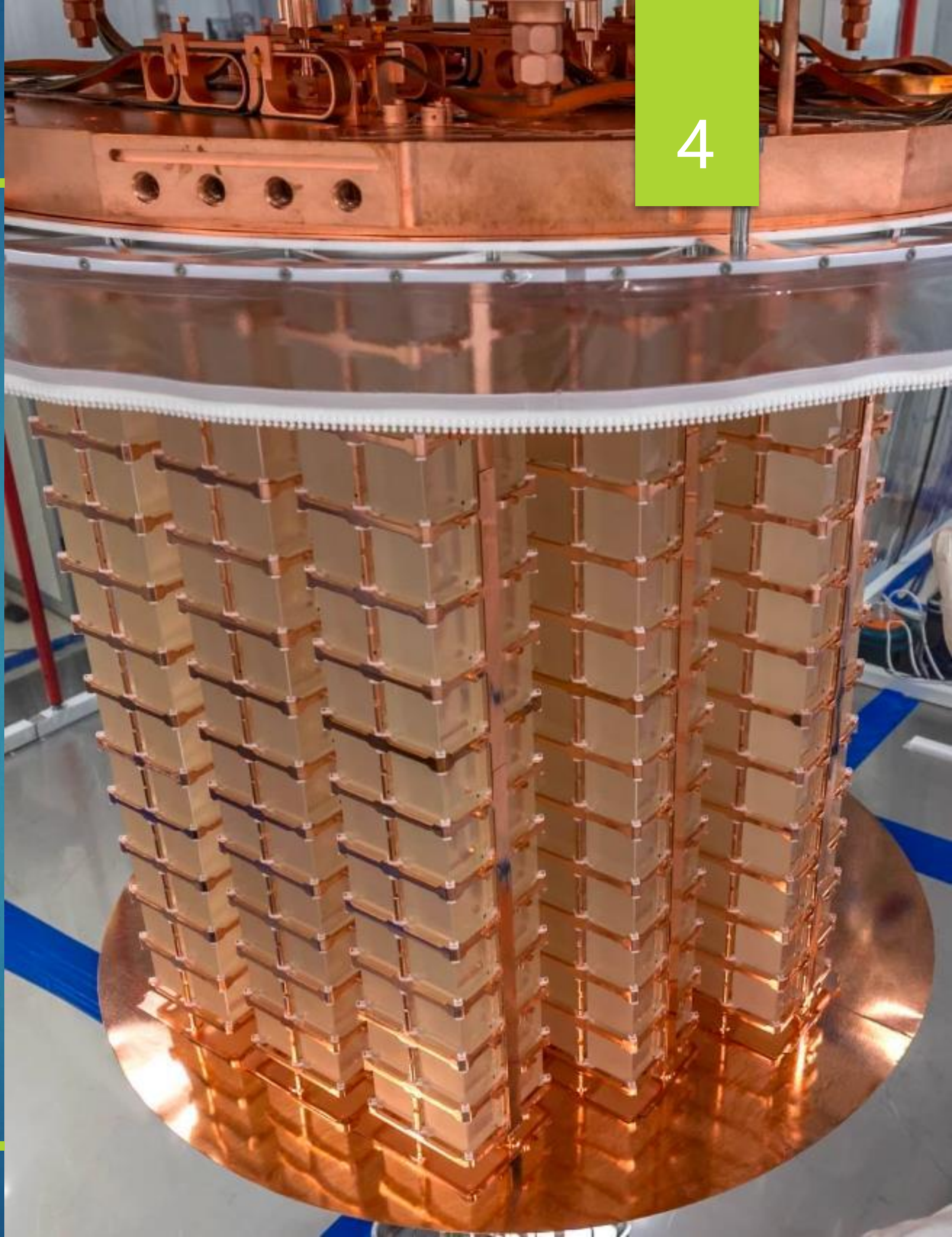
- $T_{1/2}^{0\nu}$: experimental observable
- $G^{0\nu}$: phase space factor
- $|\mathcal{M}^{0\nu}|^2$: nuclear matrix element
- $\langle m_{\beta\beta} \rangle$: effective $\nu_{\beta\beta}$ mass

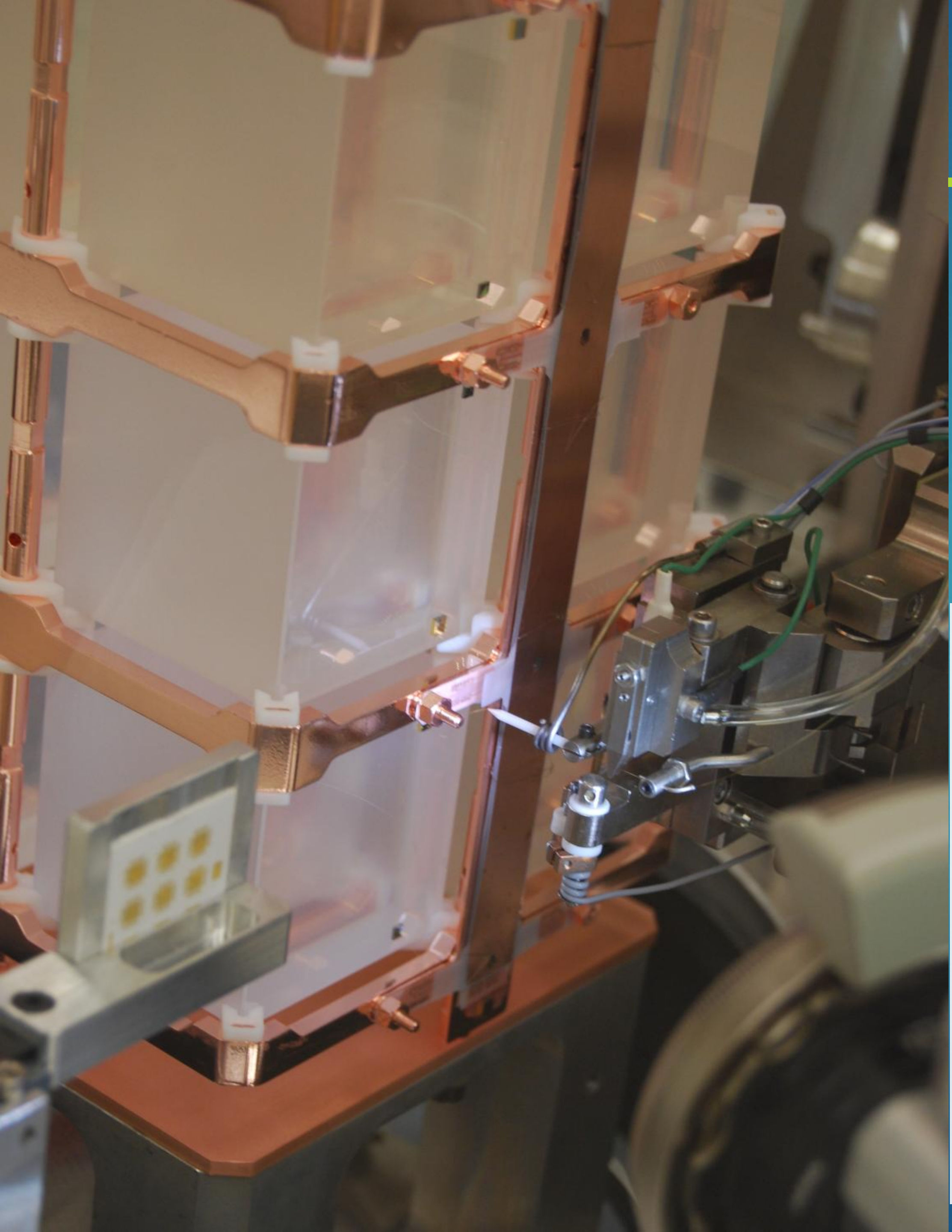
$$S^{0\nu} \propto \text{i.a.} \cdot \sqrt{\frac{M \cdot T}{\Delta E \cdot B}}$$

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

CUORE experiment

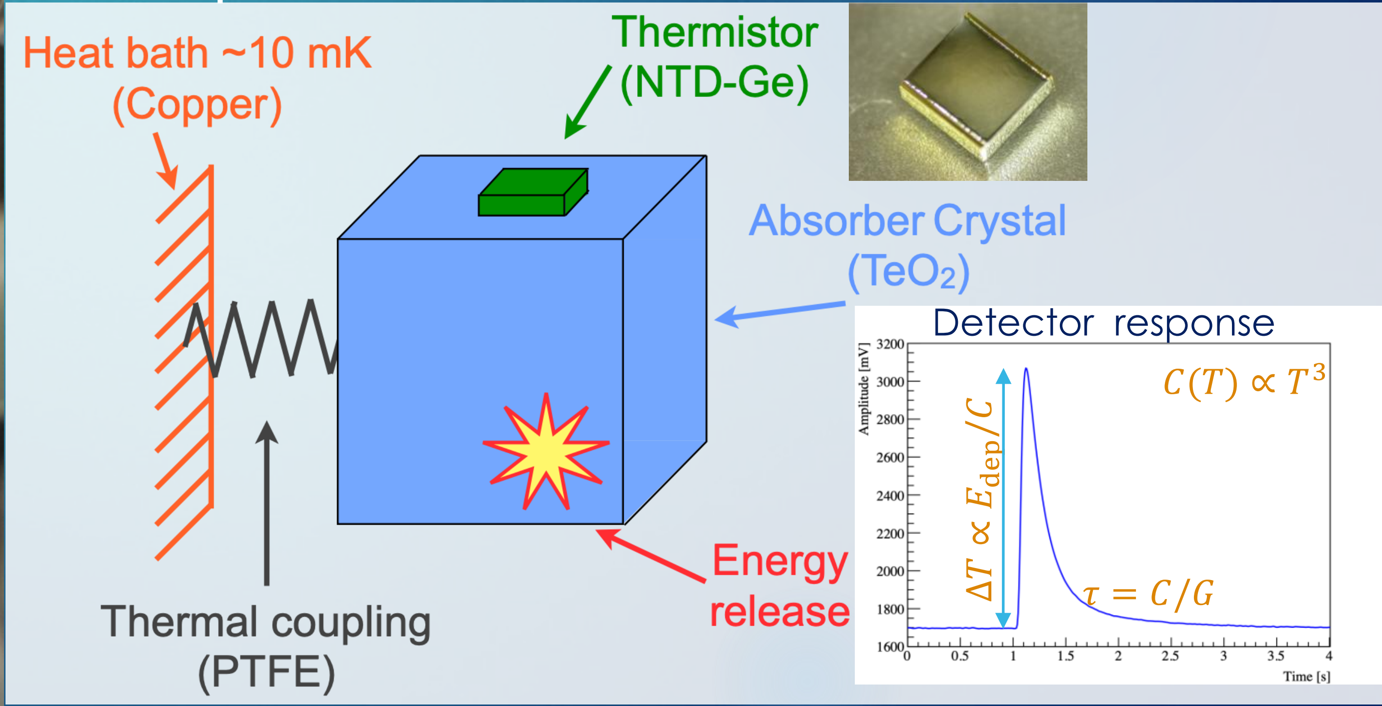
- **C**ryogenic **U**nderground **O**bservatory for **R**are **E**vents
- In operation at the Laboratori Nazionali del Gran Sasso, Italy
- Main objective: observe $0\nu\beta\beta$ in $^{130}\mathrm{Te}$
- The CUORE detector is hosted in a cryogen-free cryostat
  - Operating temperature $\sim 10\ \mathrm{mK}$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



Data collection

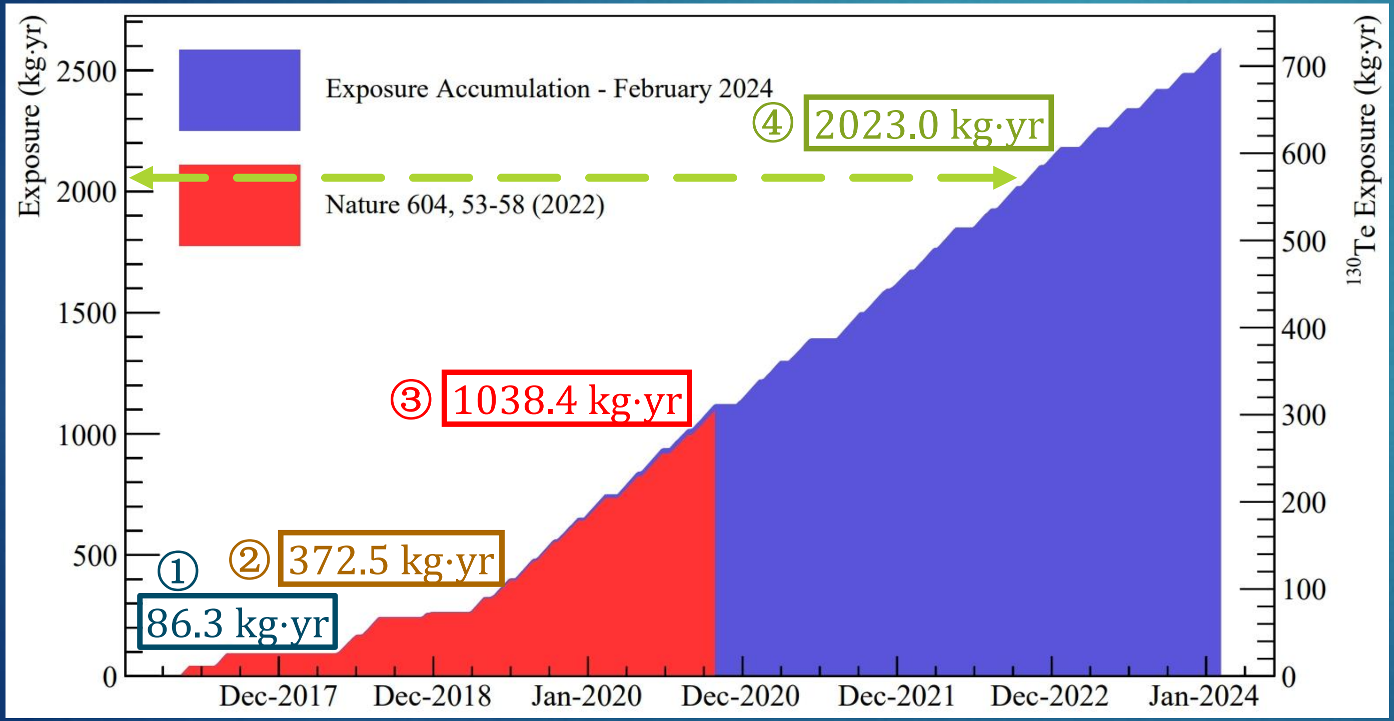
- Data taking started in 2017, with first 2 years for cryostat and detector optimization
- Stable data collection since 2019, with $\gtrsim 90\%$ uptime
- More than 2.5 ton·yr of raw exposure accumulated

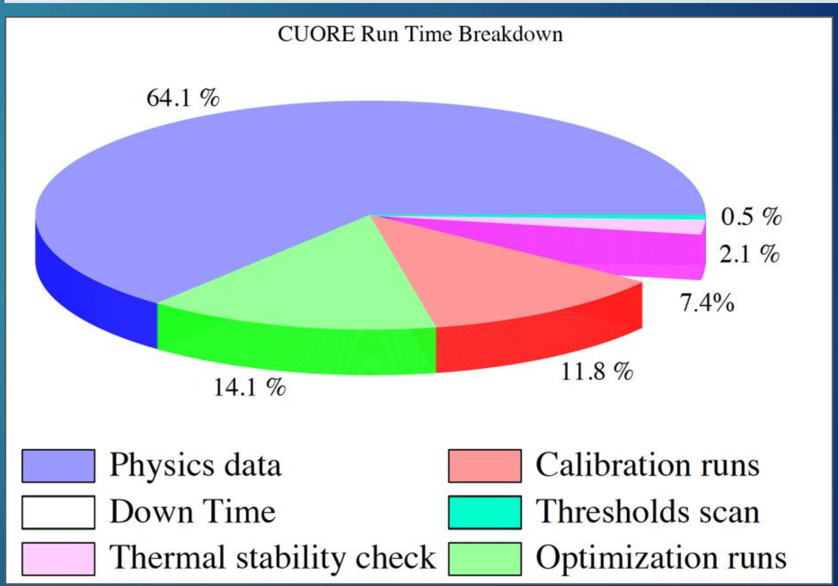
① Alduino, C. et al. (CUORE Collaboration), Phys. Rev. Lett. 120, 132501 (2018)

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)

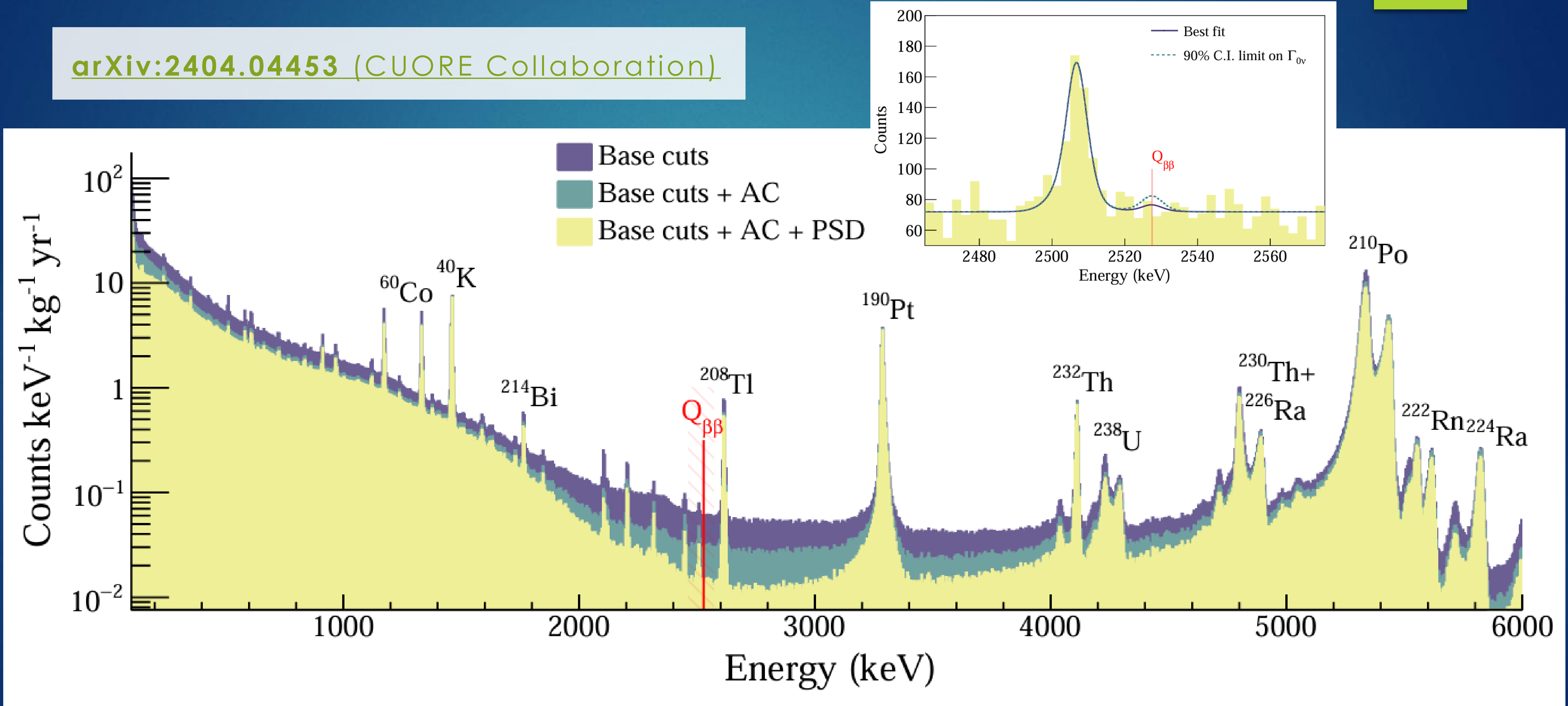




2 ton · yr exposure

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

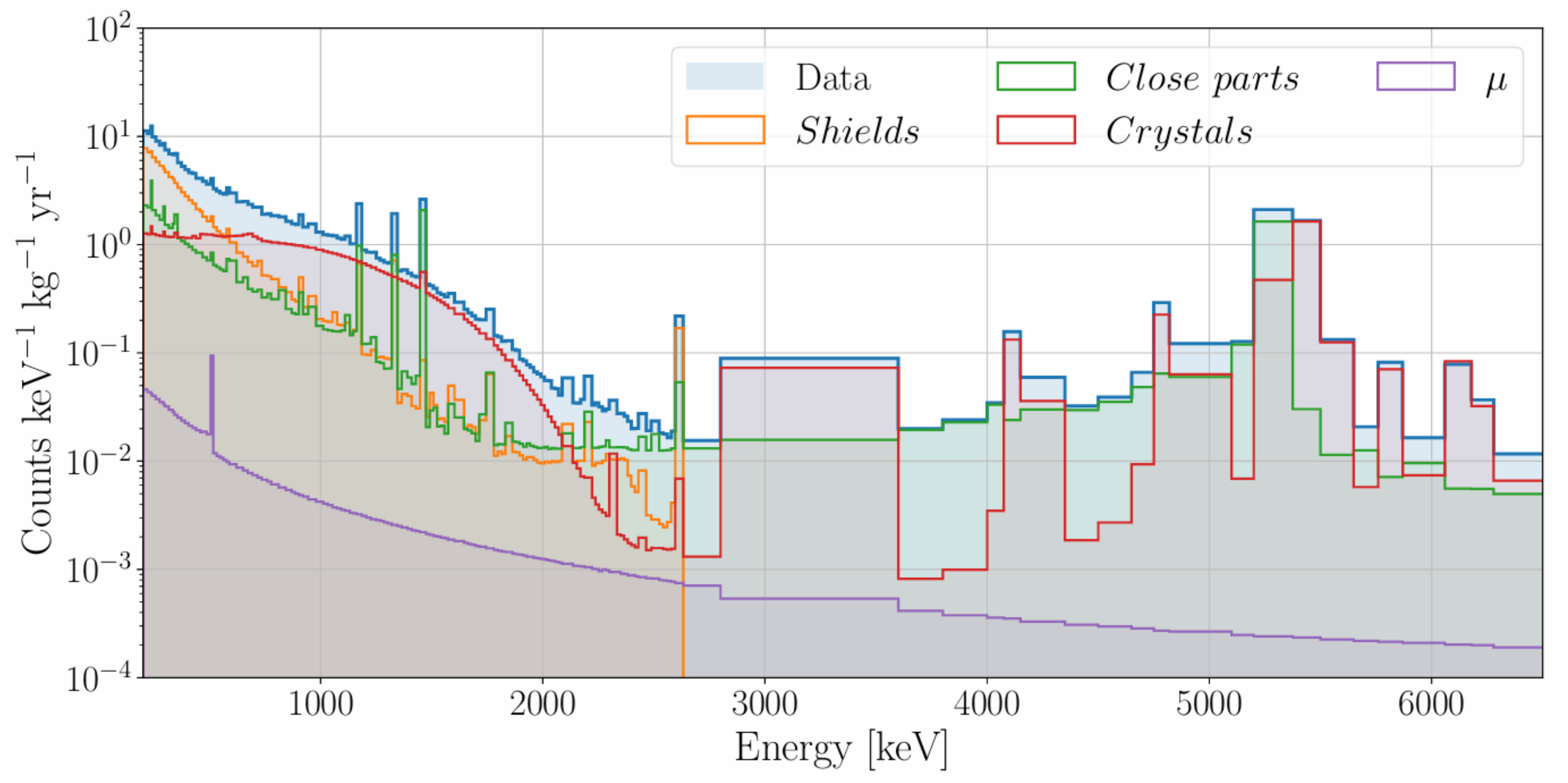
arXiv:2404.04453 (CUORE Collaboration)



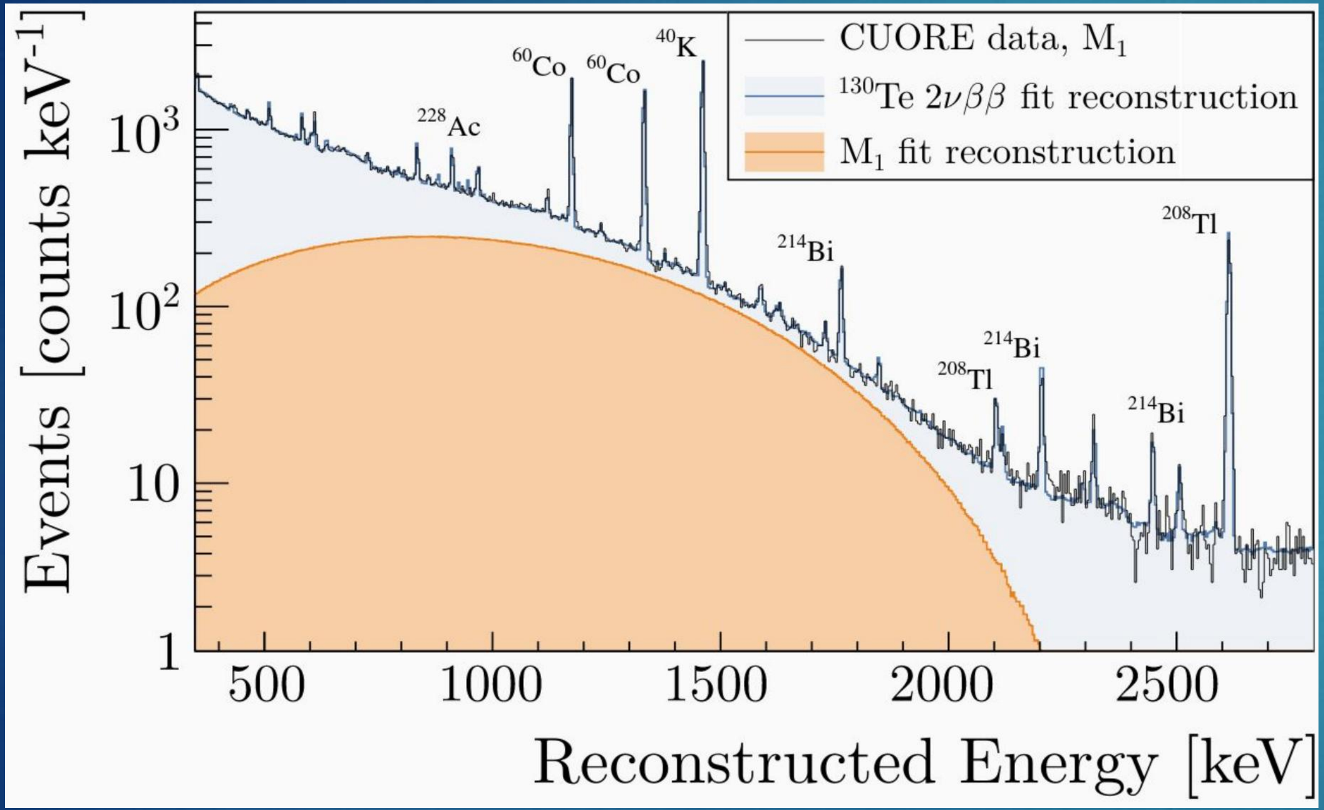
Background model results

- Full detector geometry and particle interaction implemented in Geant4
- Geant4 output post-processed to include detector response
- 62 simulated sources (bulk, surface, muons)
- Coincidence events used to constrain source location
- JAGS-based MCMC binned Bayesian fit
- Uniform priors for all components, except muons

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



2νββ decay measurement

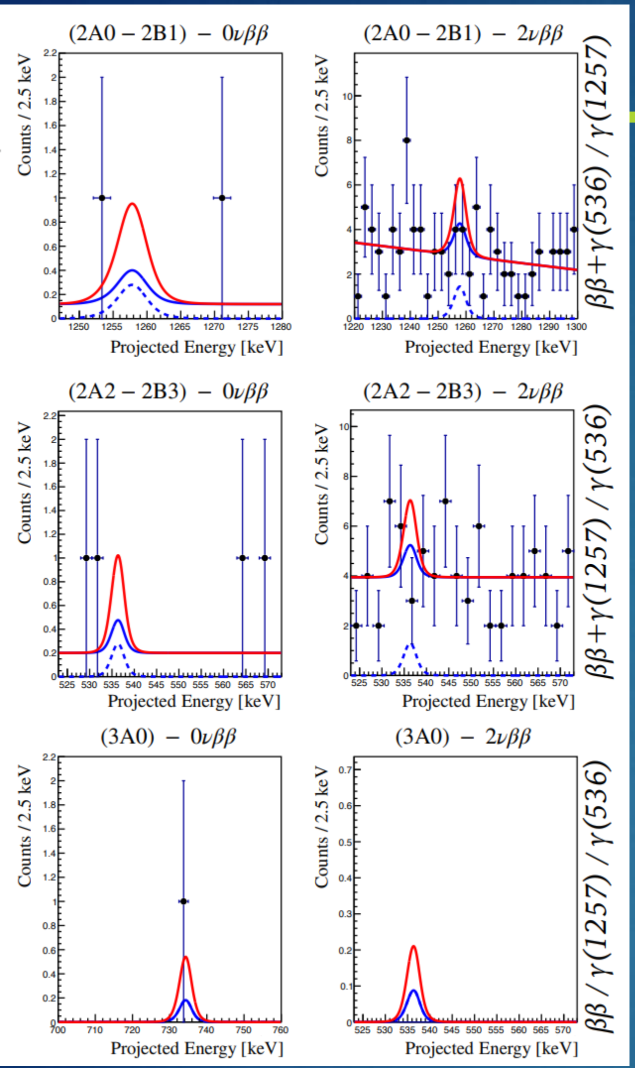


- ^{130}Te 2νββ component from background model fit to single hits (M1) data
- ^{130}Te 2νββ > 50% of events in the 1~2 MeV energy region
- Spectral fit
- $T_{1/2}^{2\nu} = 7.71^{+0.08}_{-0.06}(\text{stat.})^{+0.12}_{-0.15}(\text{syst.}) \times 10^{20}$ yr
- Most precise measurement of ^{130}Te 2νββ decay half-life to date

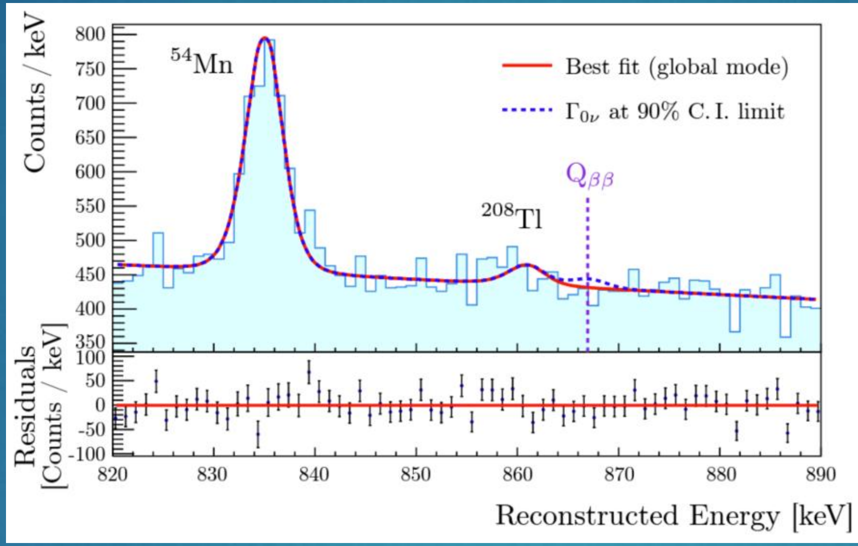
Adams, D.Q. et al. (CUORE Collaboration), Phys. Rev. Lett. 126, 171801 (2021)

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

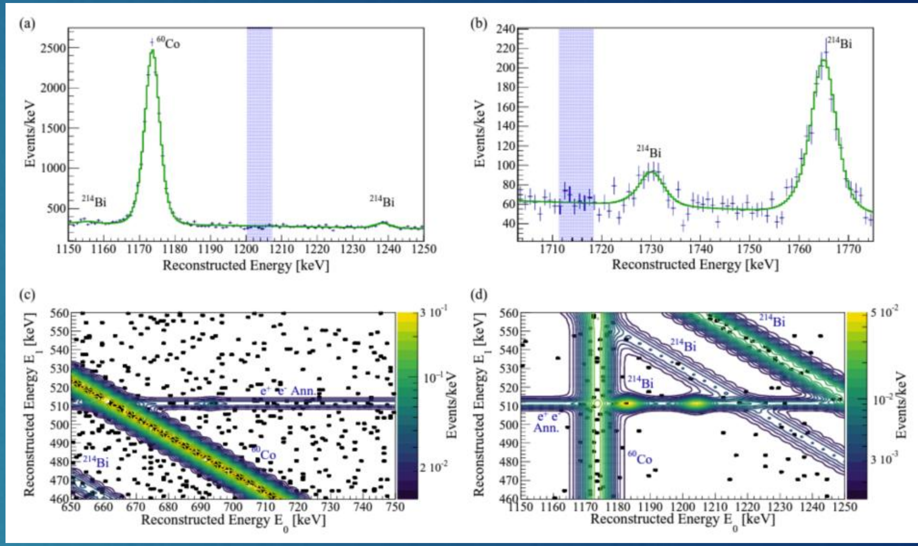
Other rare event searches



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



^{128}Te β^+/EC



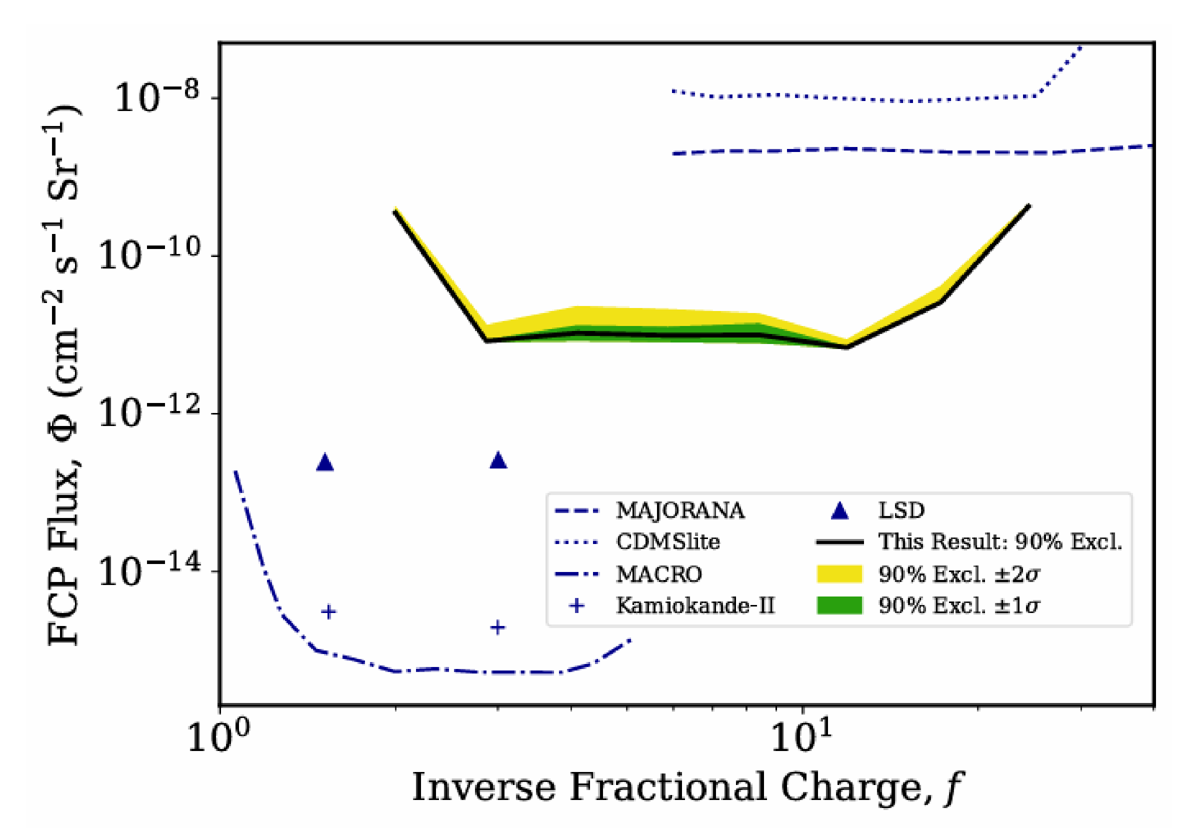
Adams, D.Q. et al. (CUORE Collaboration), Phys. Rev. Lett. 129, 222501 (2022)

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)

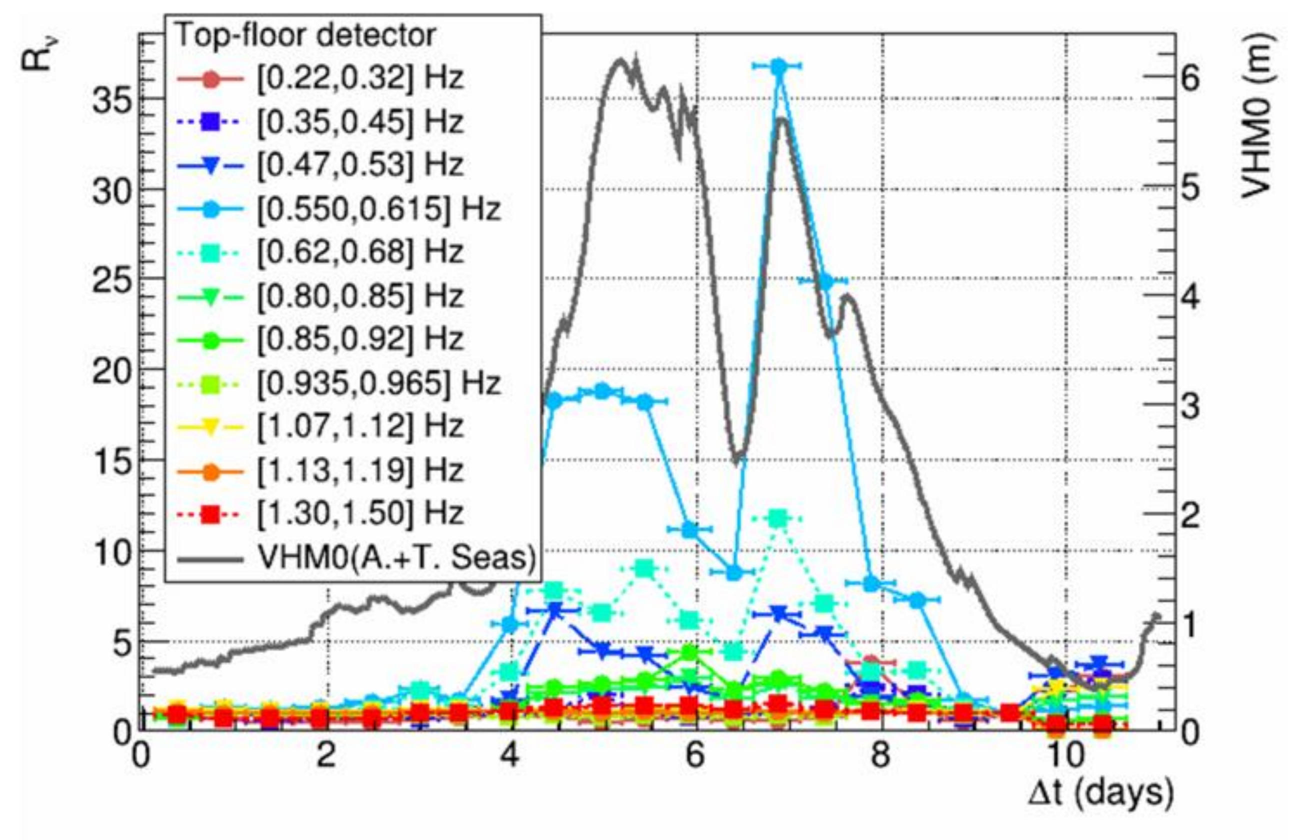
Other searches

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



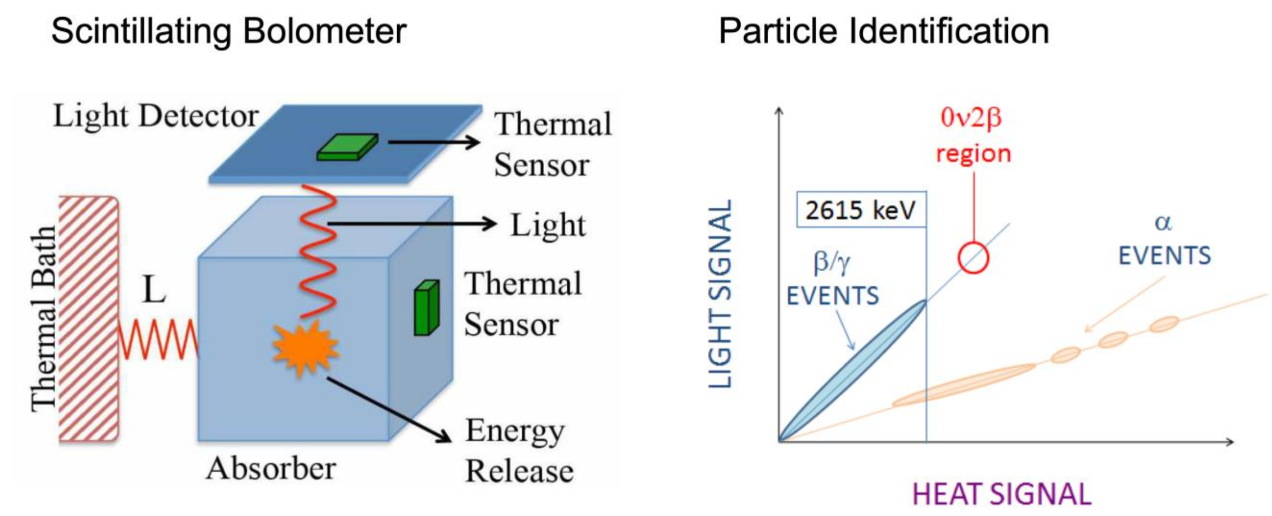
Aragão, L. et al., Eur. Phys. J. C 84, 728 (2024)

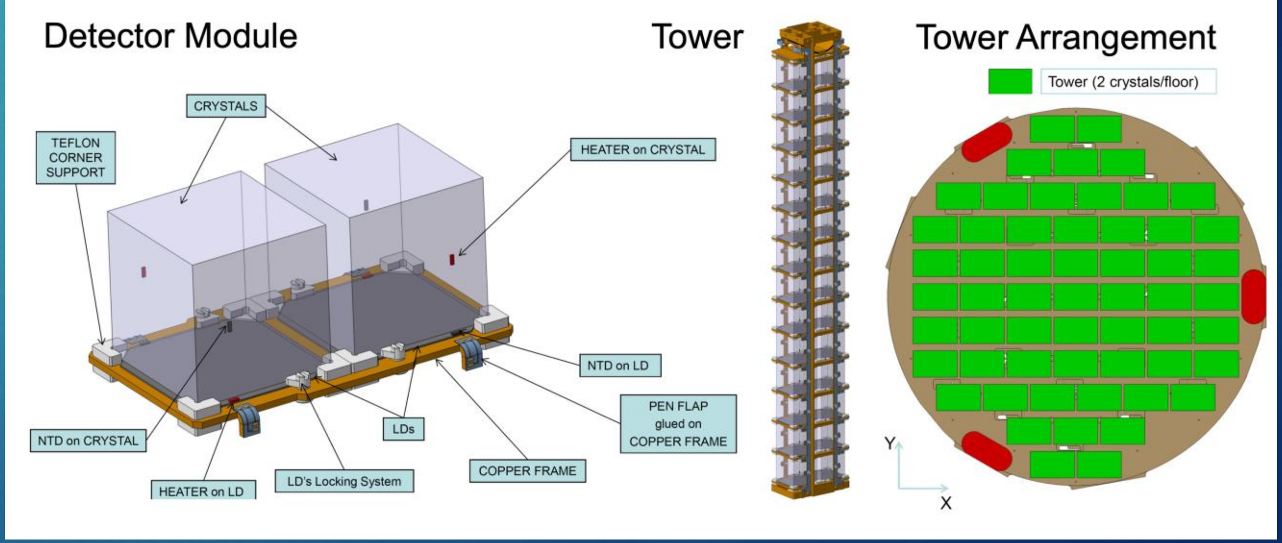
What's next?

- CUORE phase-I (current)
  - Run up to mid-2025
  - Reach $> 3\ \mathrm{ton} \cdot \mathrm{yr}\ \ \mathrm{TeO_2}$, $1\ \mathrm{ton} \cdot \mathrm{yr}\ \ {}^{130}\mathrm{Te}$ 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 improve noise and push towards low energy studies
  - 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} counts / (keV · kg · yr)
  - Energy resolution: goal of $5\ \mathrm{keV}$ at $Q_{\beta\beta}$

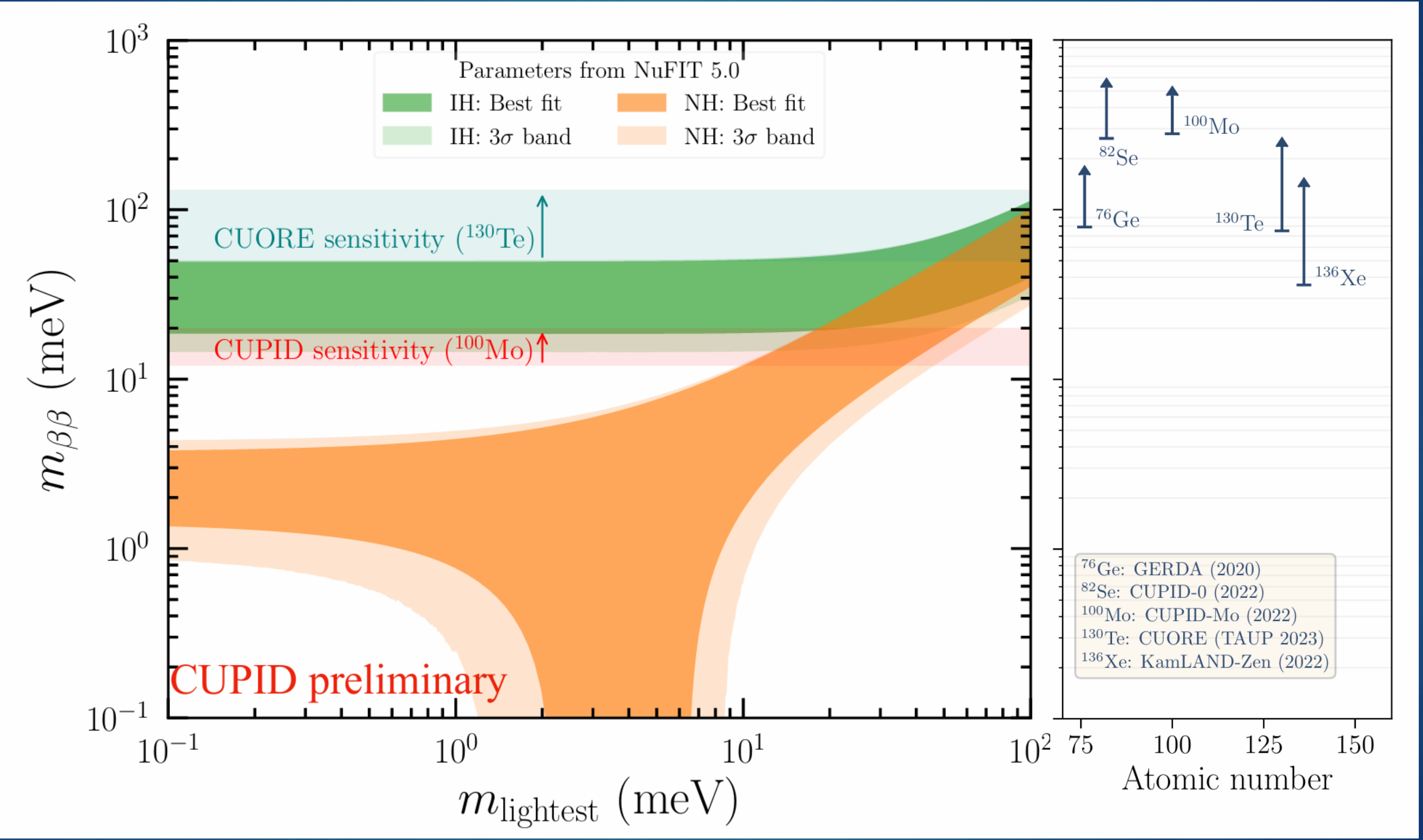
CUPID

- **CU**ORE **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)





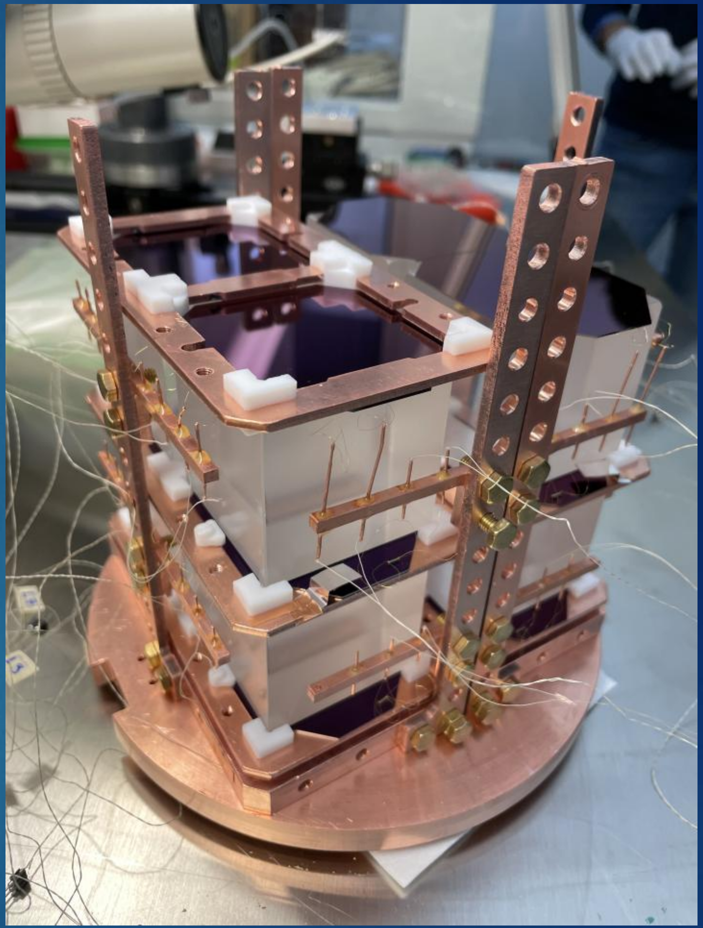
CUPID



Parameters from NuFIT 5.0
IH: Best fit
NH: Best fit
IH: 3σ band
NH: 3σ band
CUORE sensitivity (130Te)
CUPID sensitivity (100Mo)
CUPID preliminary
$m_{\beta\beta}$ (meV)
m_{lightest} (meV)
82Se
100Mo
76Ge
130Te
136Xe
76Ge: GERDA (2020)
82Se: CUPID-0 (2022)
100Mo: CUPID-Mo (2022)
130Te: CUORE (TAUP 2023)
136Xe: KamLAND-Zen (2022)
Atomic number

Proposed thesis topics

- Data Analysis and Processing (CUORE / CUPID)
  - List of the possible analysis in CUORE (excited states..., on 3T data)
  - Background model and sensitivity studies
  - Search for Beyond Standard Model processes in CUORE
  - Discovery Potential for Supernova Neutrinos
  - Dark Matter searches
  - Development of algorithm for pileup-rejection in CUPID
  - Pulse shape studies for alpha tagging in CUPID
- CUPID detector design
  - Optimization of the sensor performance (sensitivity, time response)
  - Design and test of the CUPID prototypes
  - Design and optimization of the CUPID (active and passive) shielding



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 $2.5\ \mathrm{ton{\cdot}yr\ TeO_2}$ has been achieved as of today!
  - The data-taking is proceeding with $\gtrsim 90\%$ uptime.
- CUORE released physics results of $^{130}\mathrm{Te}\ 0\nu\beta\beta$ decay, utilizing $2\ \mathrm{ton{\cdot}yr\ TeO_2}$ data.
- No evidence of $0\nu\beta\beta$ decay with observed data.
  - Bayesian 90% C.I. limit.

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

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

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

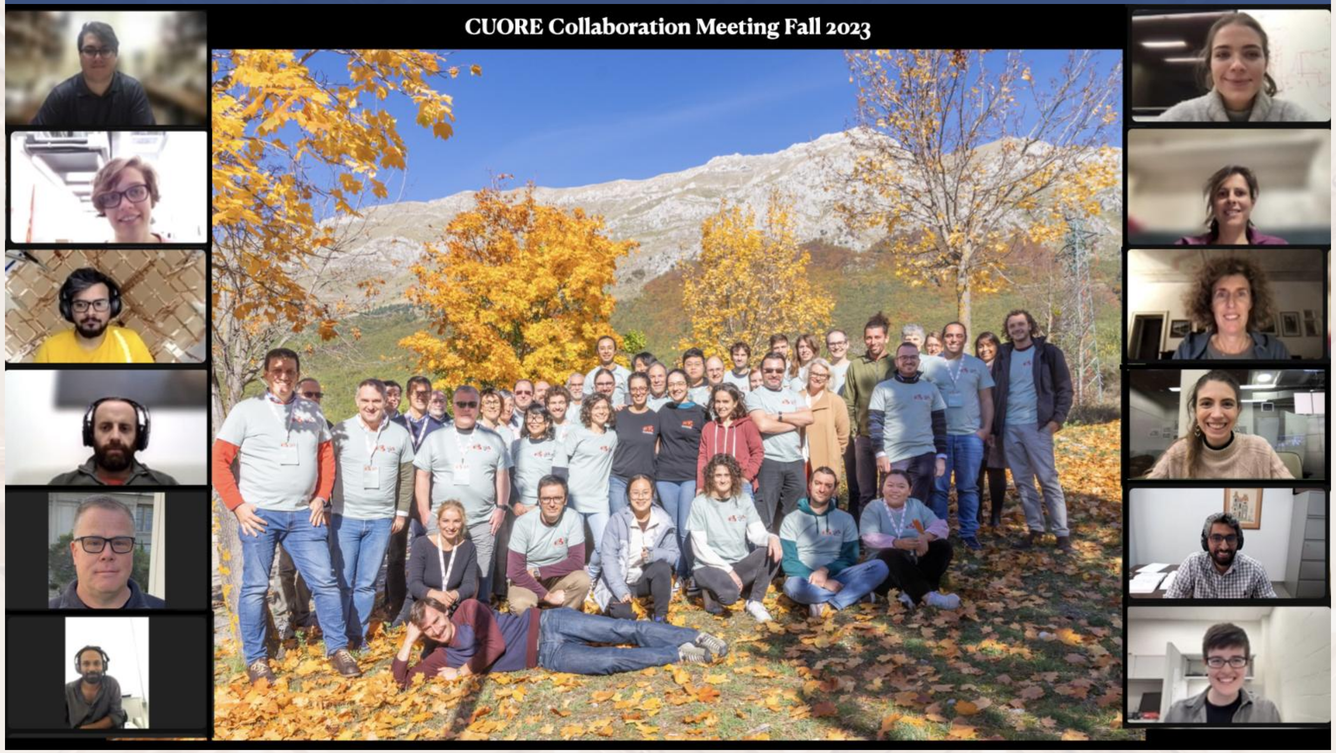
- CUORE will continue to take data until it reaches $^{130}\mathrm{Te}$ exposure of $1\ \mathrm{ton \cdot yr}$, *i.e.*, $3\ \mathrm{ton \cdot yr\ TeO_2}$ exposure.
- Thanks for the unique feature of allow deployment of different isotopes by using the same infrastructure.

CUORE

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

CUPID

Thank you for your attention!



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Cal Poly San Luis Obispo
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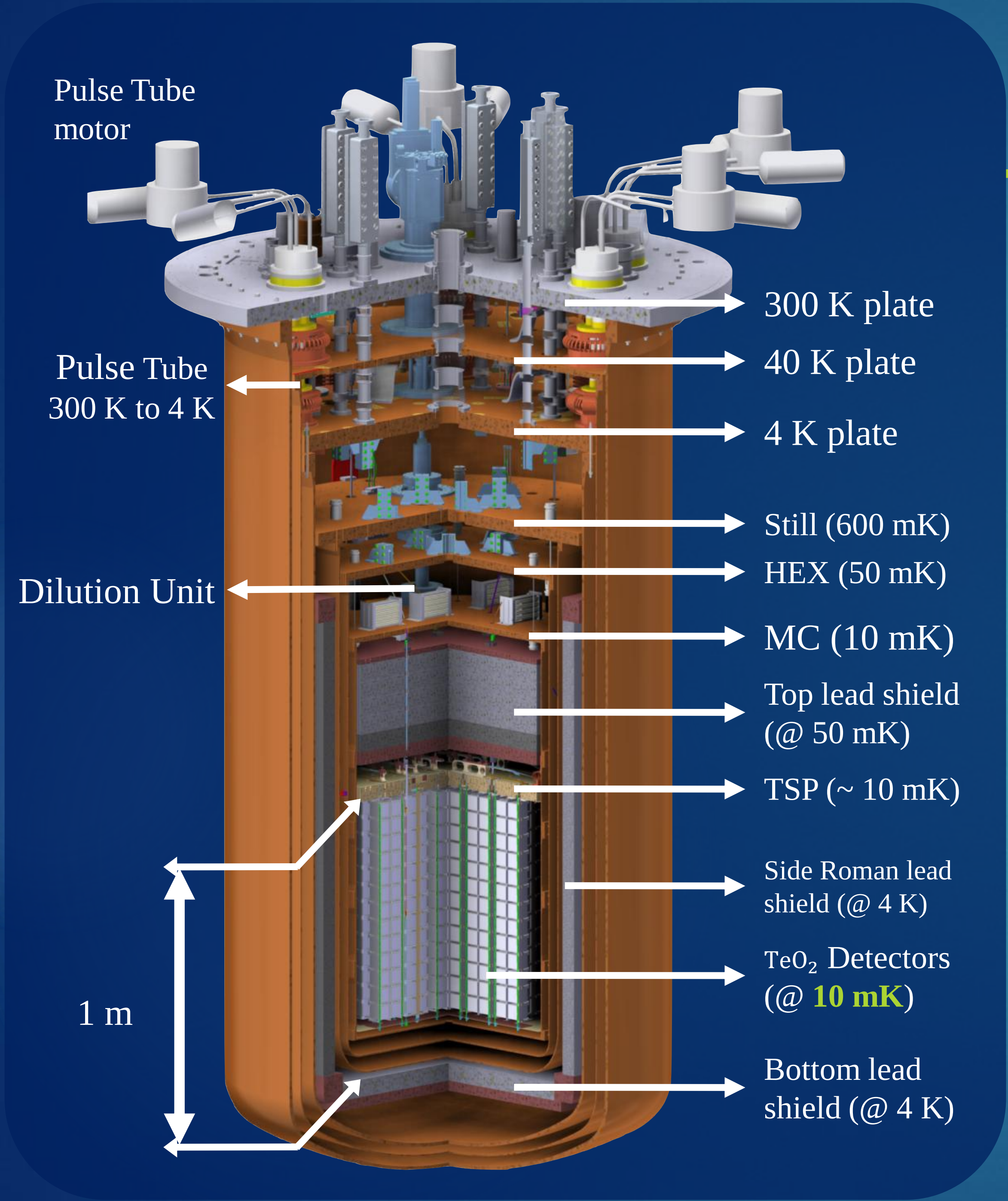
Università degli Studi di Milano Bicocca
Lawrence Livermore National Laboratory
University of Pittsburgh
Massachusetts Institute of Technology
Johns Hopkins University
CUORE

Backup

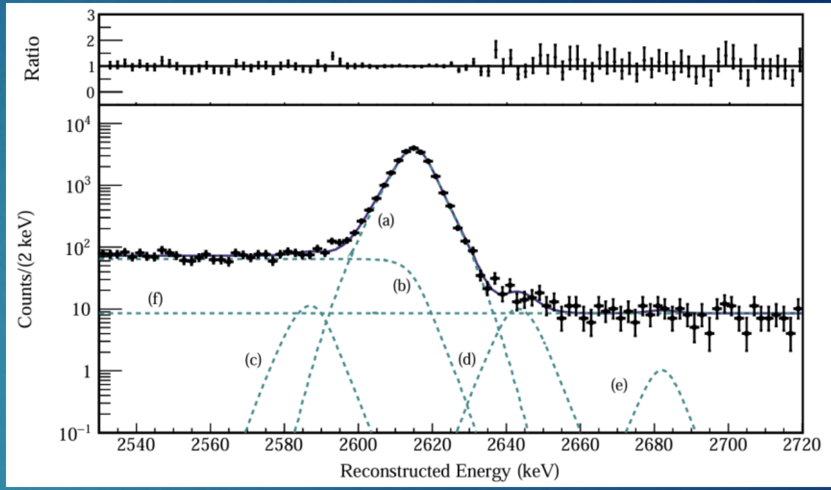


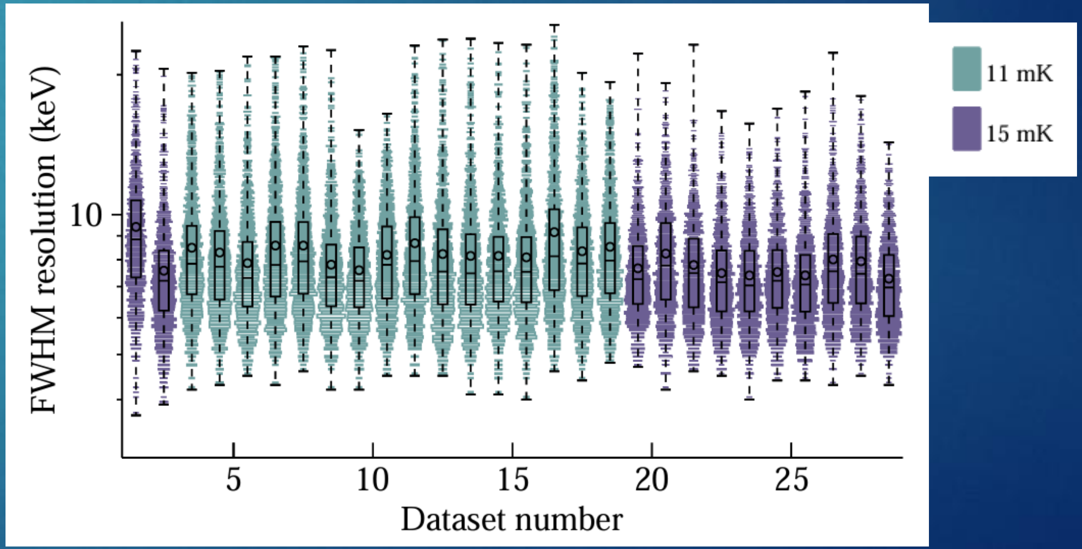
CUORE Cryostat

- Custom-made dry dilution refrigerator
- 1.5 t of material at base temperature for ~5 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

Detector performance

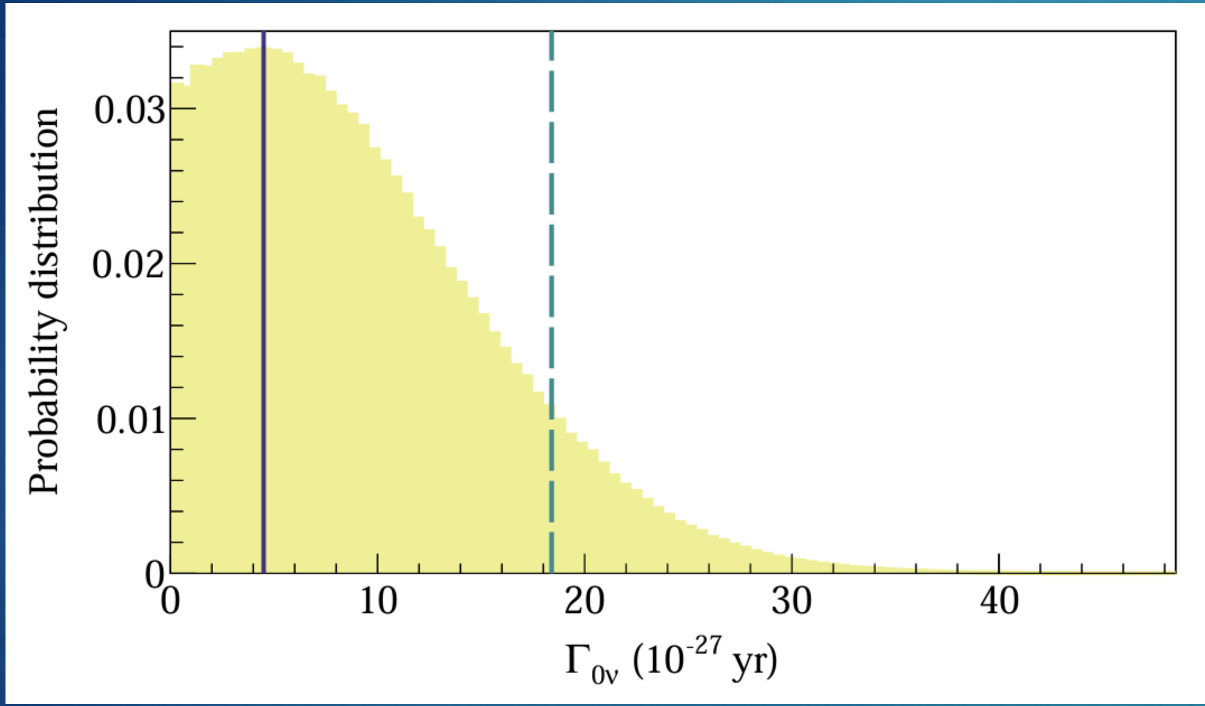
- Peak lineshape:
  - Reference ^{208}Tl gamma peak at 2615 keV from calibration data
- Fit model:
  - Multi-Gaussian response function
  - Multi-Compton background
  - Flat background
  - Coincidence/escape peaks
- Fit at channel-dataset level
- Energy resolution at 2615 keV
  - FWHM = (7.540 ± 0.024) keV
    - harmonic mean - exposure weighted



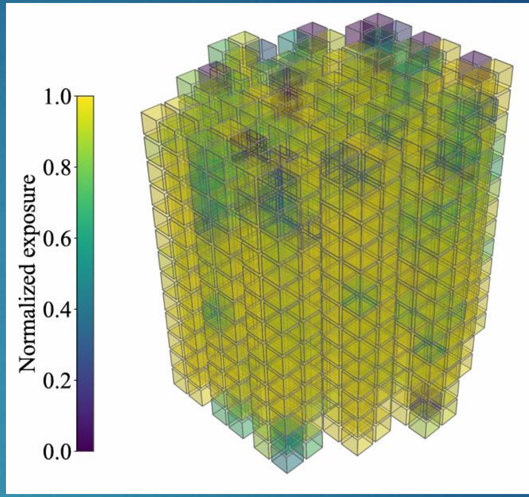


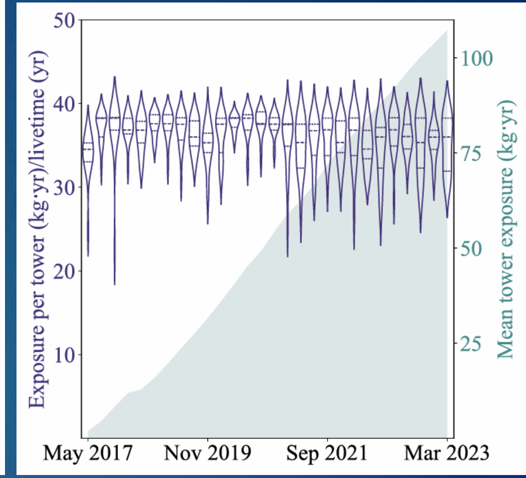
$0\nu\beta\beta$ decay search results

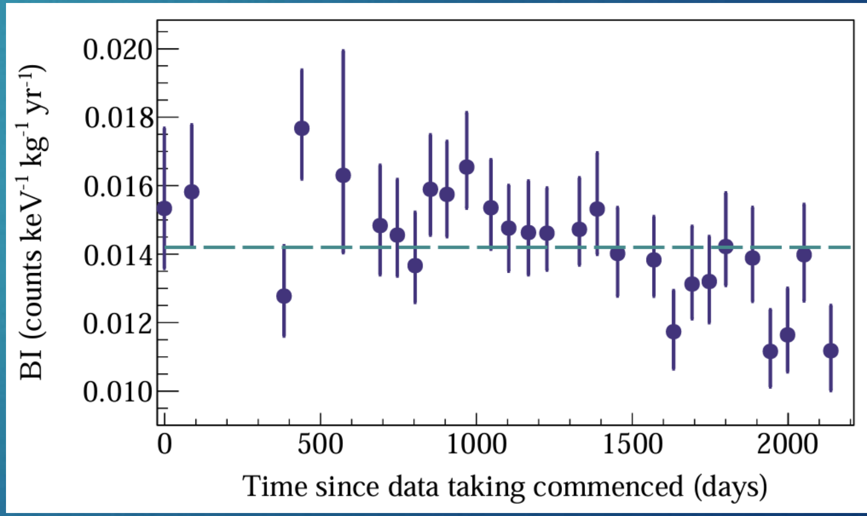
- Resolution scaling
  - FWHM at $Q_{\beta\beta} = (7.320 \pm 0.024)$ keV



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



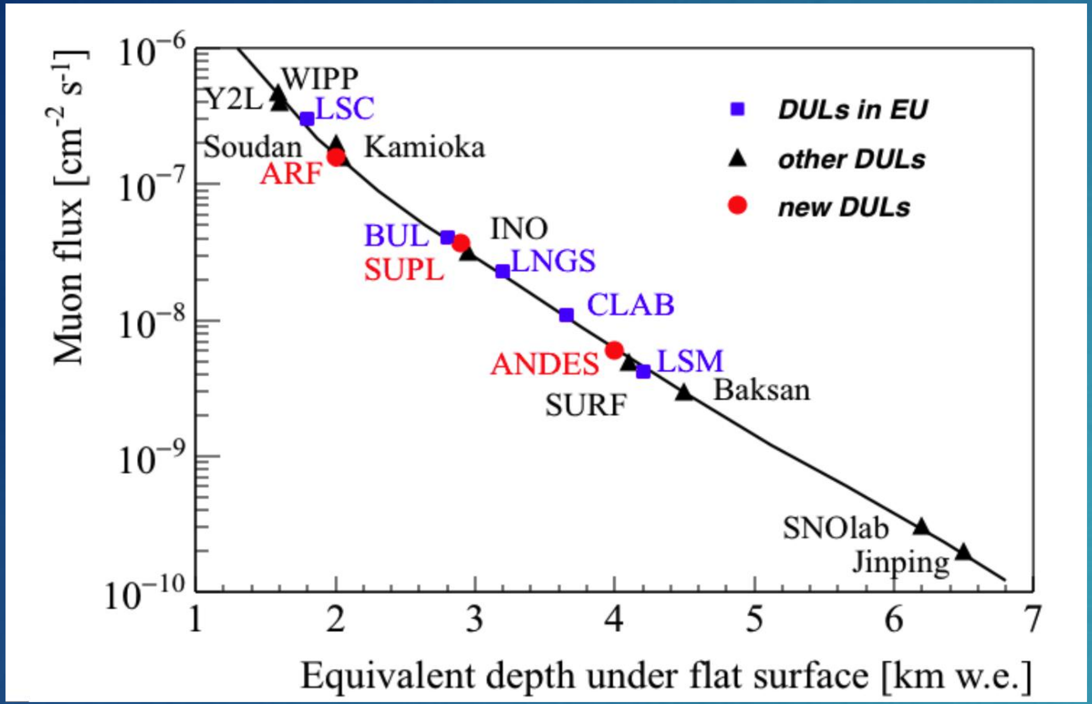


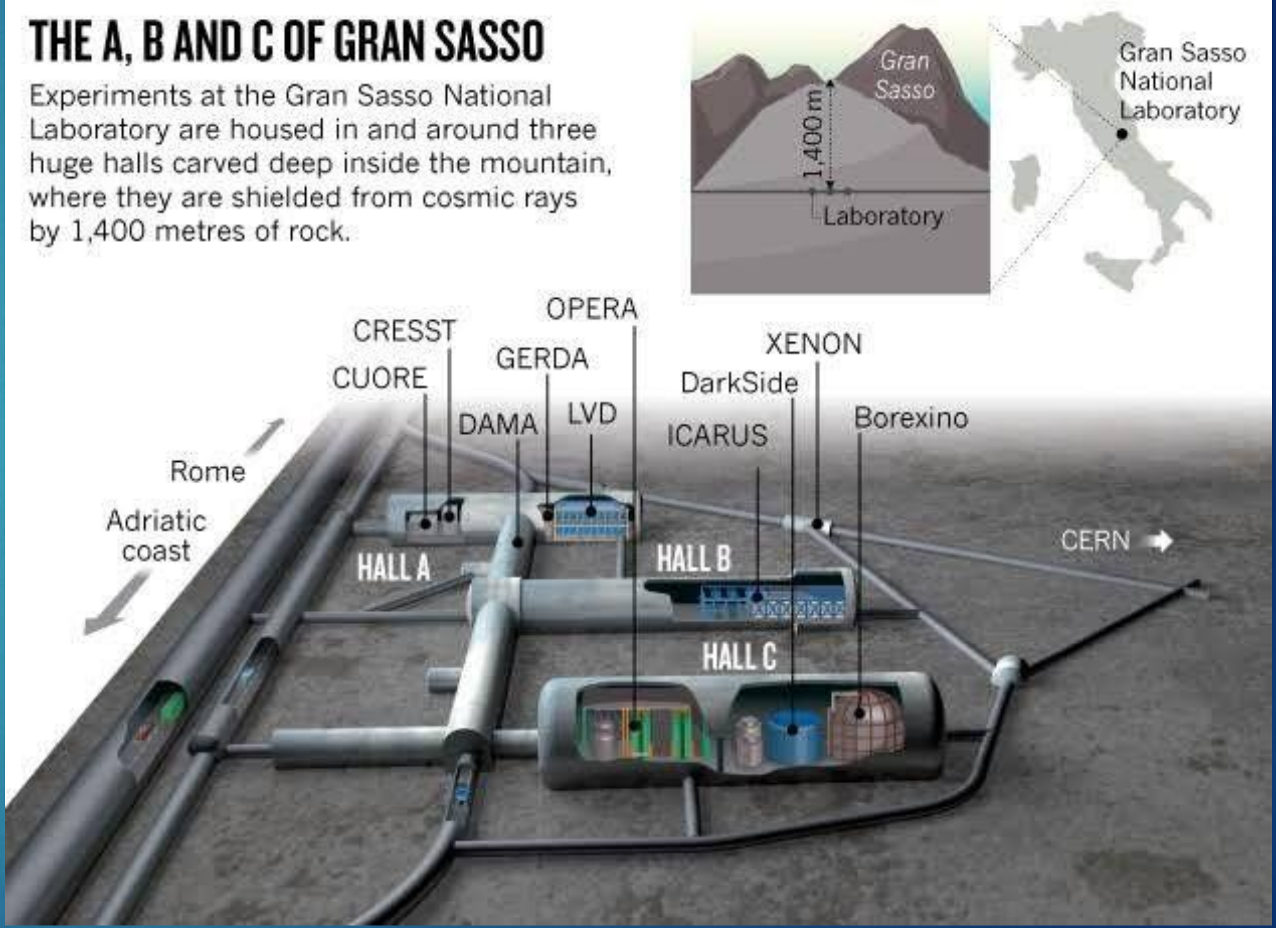


- BI: $(1.42 \pm 0.02) \cdot 10^{-2}$ counts / (keV · kg · yr)

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

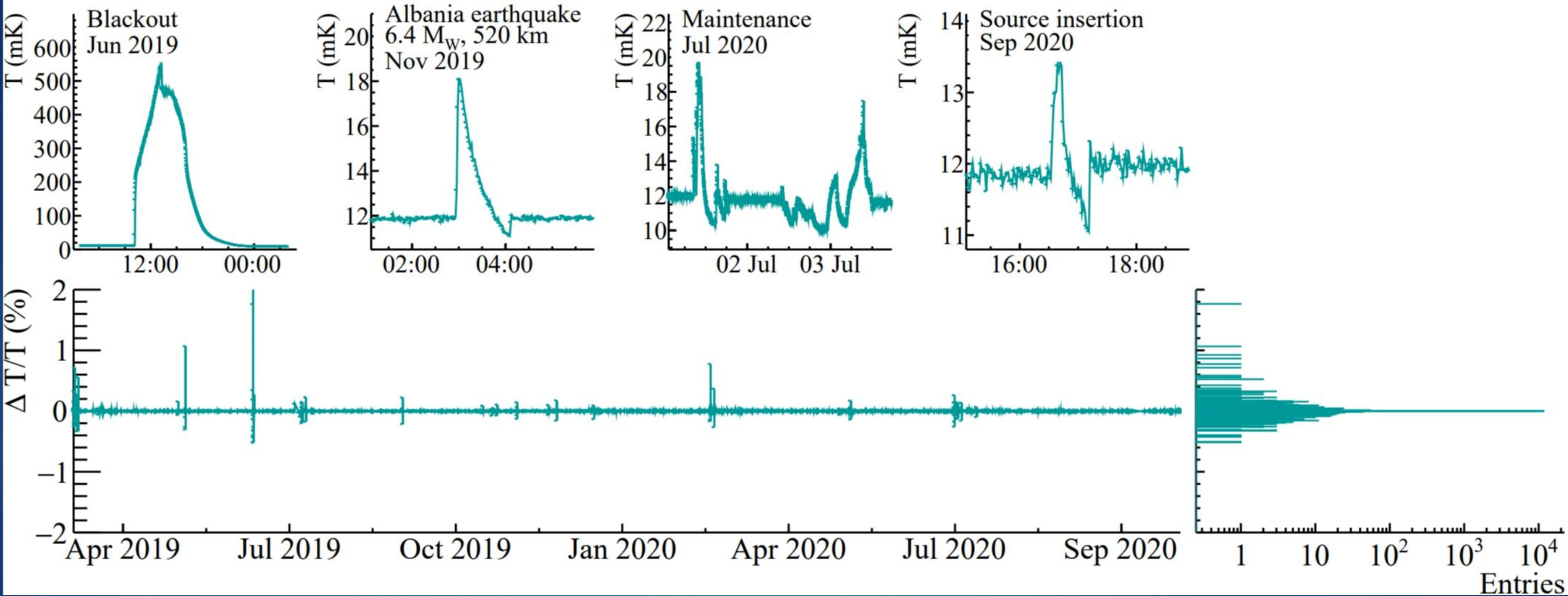
Laboratori Nazionali del Gran Sasso - Italy





- 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 cryostat performance



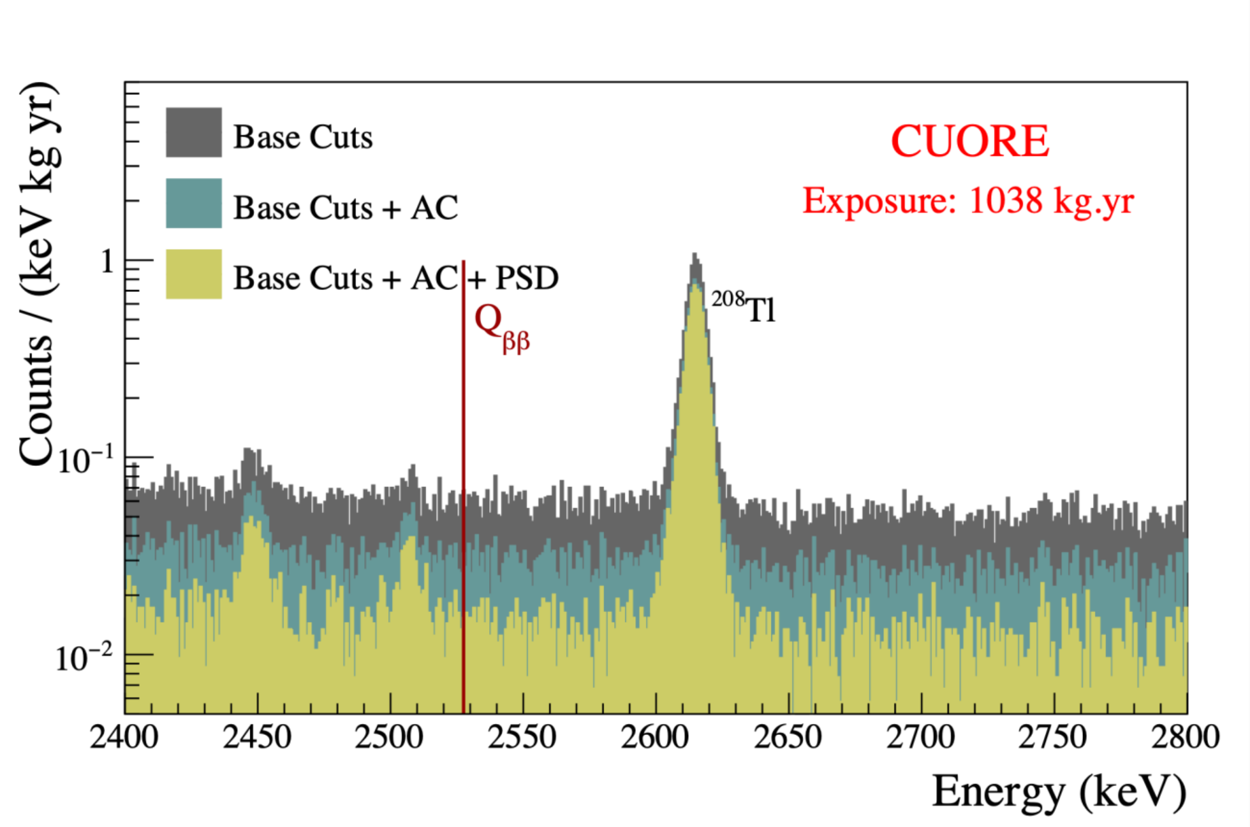
Adams, D.Q. et al. (CUORE Collaboration), **Nature** 604, 53-58 (2022)

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

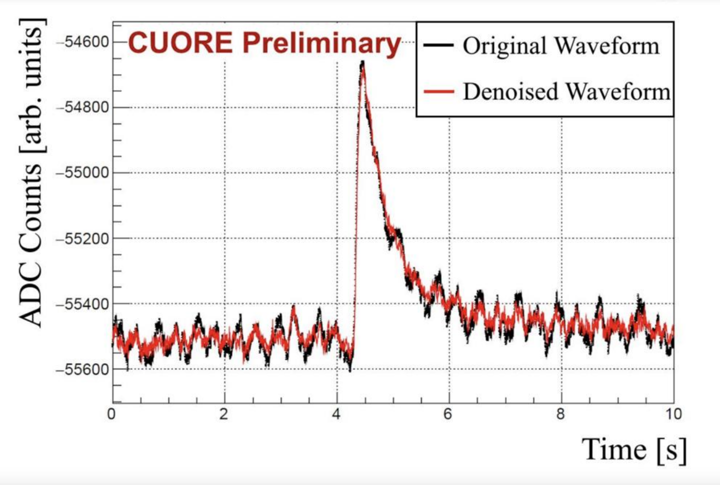
Background in Region of Interest (ROI)

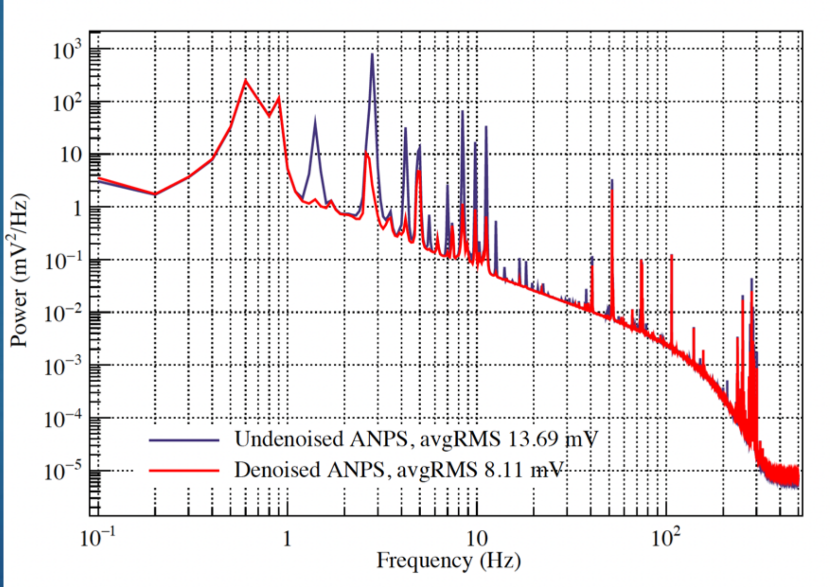
- α region
  - fit flat background in [2650, 3100] keV
  - $1.40(2) \times 10^{-2}$ counts/(keV kg yr)
- $Q_{\beta\beta}$ region
  - fit background + ^{60}Co peak in [2490, 2575] keV
  - $1.49(4) \times 10^{-2}$ counts/(keV kg yr)
- source
  - ~90% of the background in the ROI is given by degraded alpha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



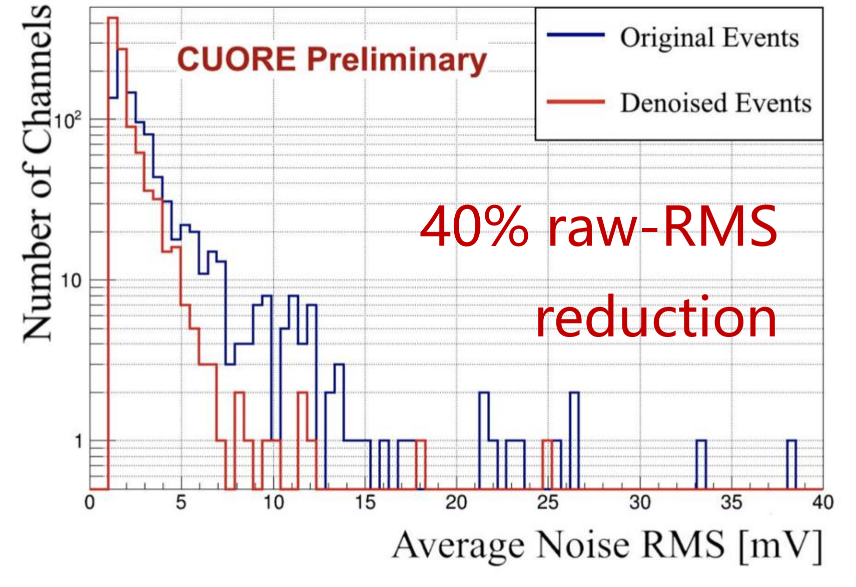
CUORE data analysis

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





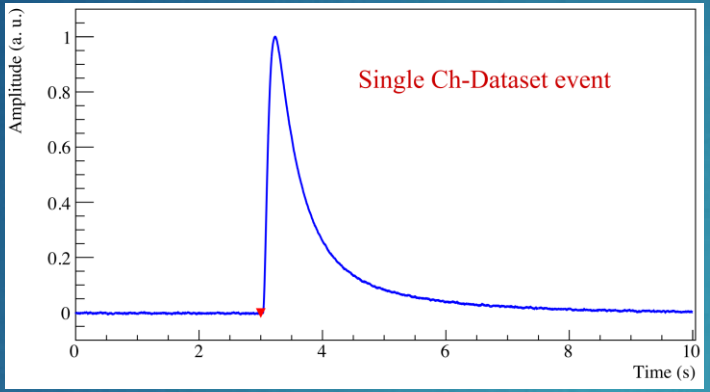
- New! of this data release
- Installed diagnostic devices:
  - Seismometers,
  - Accelerometers,
  - Microphones…



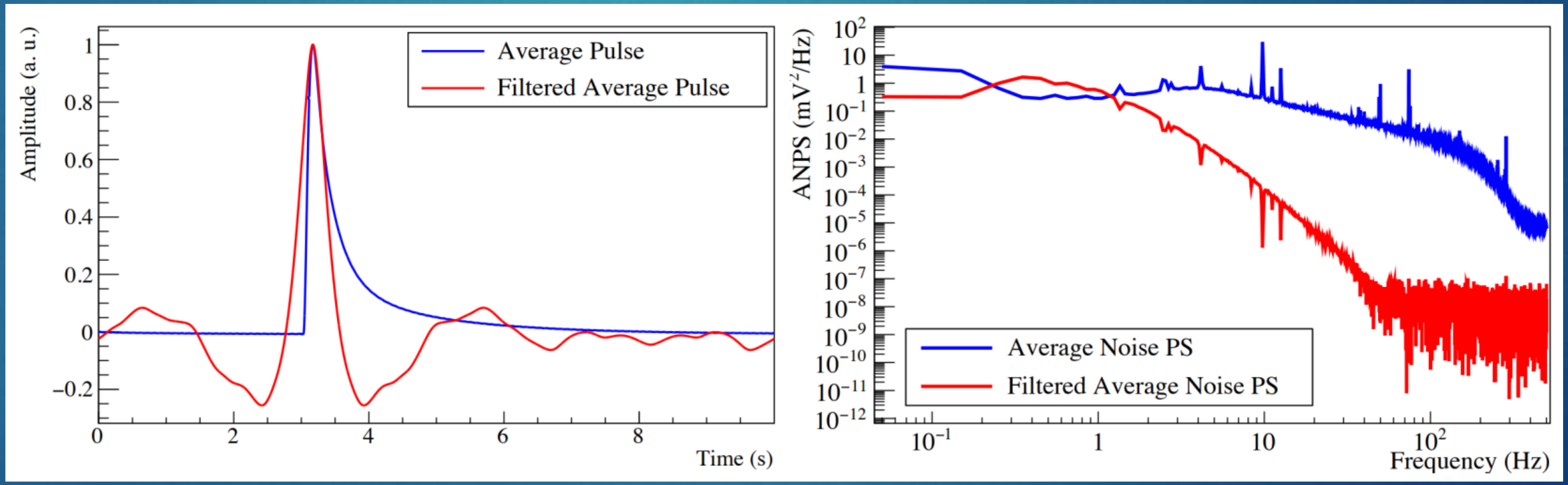
Vetter, K.J., Beretta, M., Capelli, C. et al., Eur. Phys. J. C 84, 243 (2024)

CUORE data analysis

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



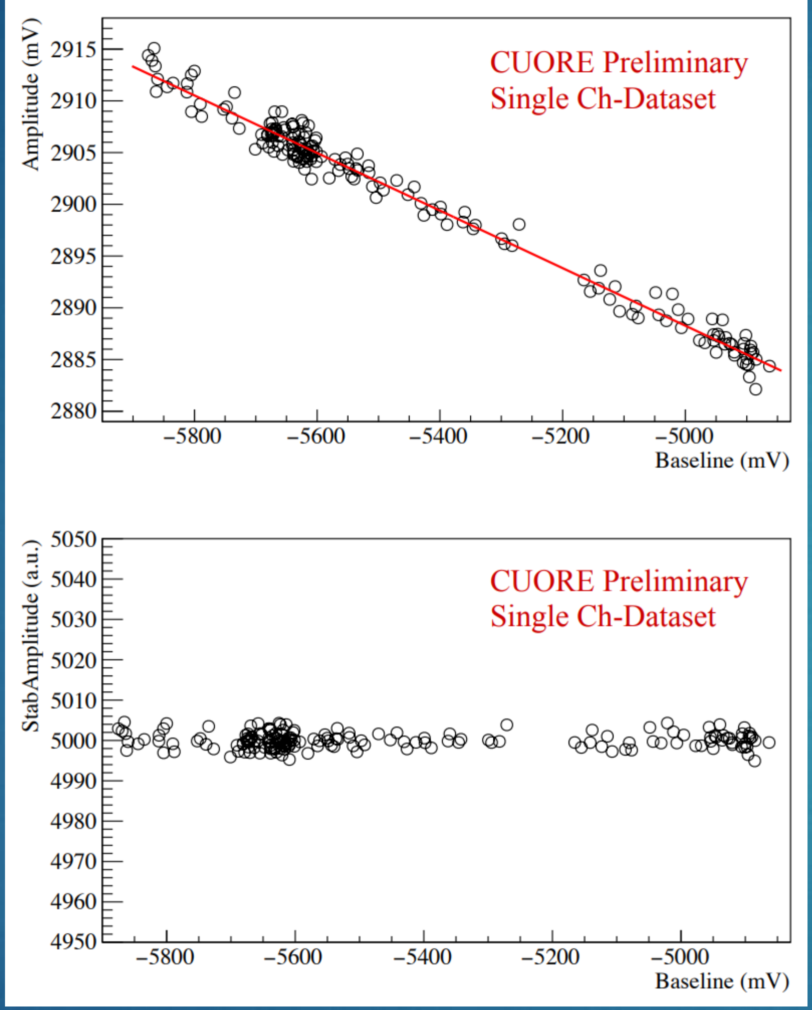
- Derivative trigger: online analysis for quick data quality feedback
- Offline re-triggering (Optimum Trigger)
  - disentangle small signals from noise fluctuations
  - lower threshold



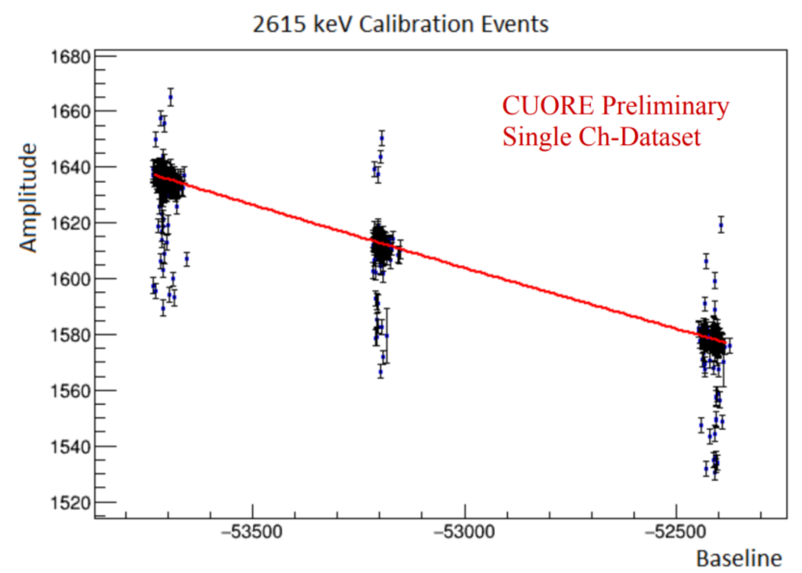
- Matched filter maximizes signal-to-noise ratio

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 keV for non-functional or underperforming heaters

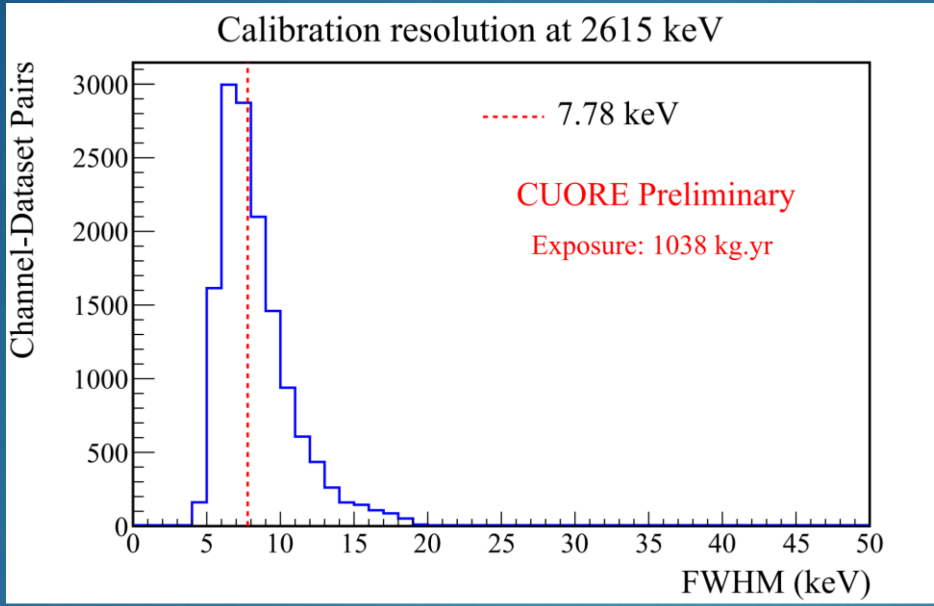


- Heater pulses for thermal gain stabilization

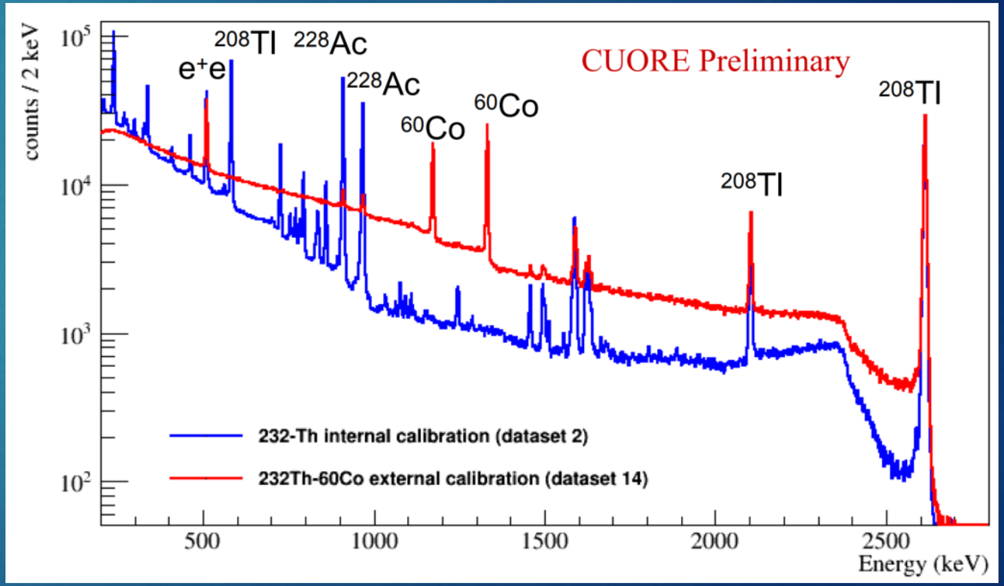
CUORE data analysis

- 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



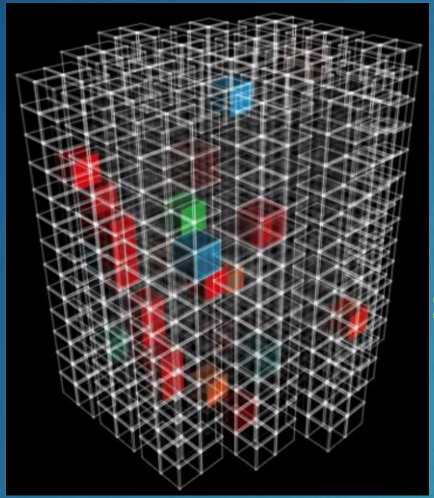
- Detector response modelled on the 2615 keV line from $^{232}\mathrm{Th}$ chain.
  - Accounts for non idealities.

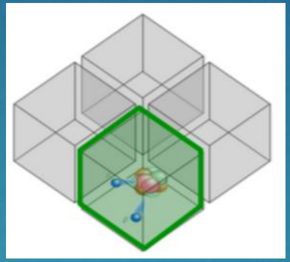


- First 3 datasets used internal $^{232}\mathrm{Th}$ source
- Internal calibration system replaced with simpler external one in later datasets

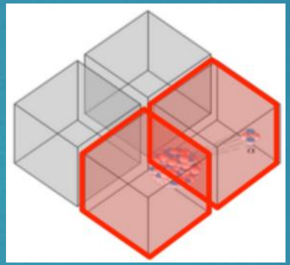
CUORE data analysis

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





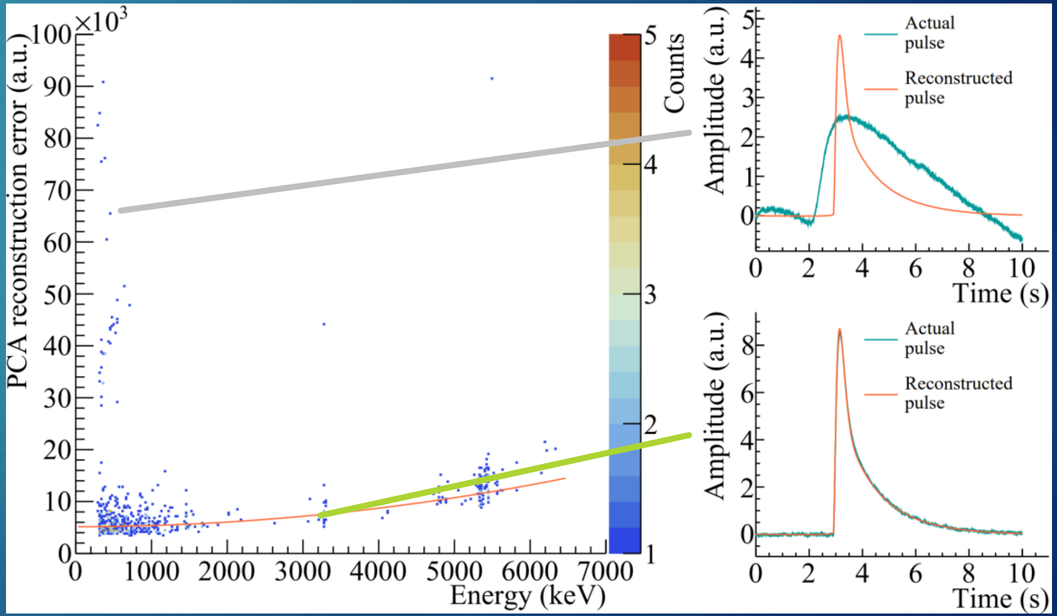
single-site (signal-like)



multi-site (background-like)

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