第三届地下和空间粒子物理与宇宙物理前沿问题研讨会

Conference on frontiers of underground and space particle physics and cosmophysics

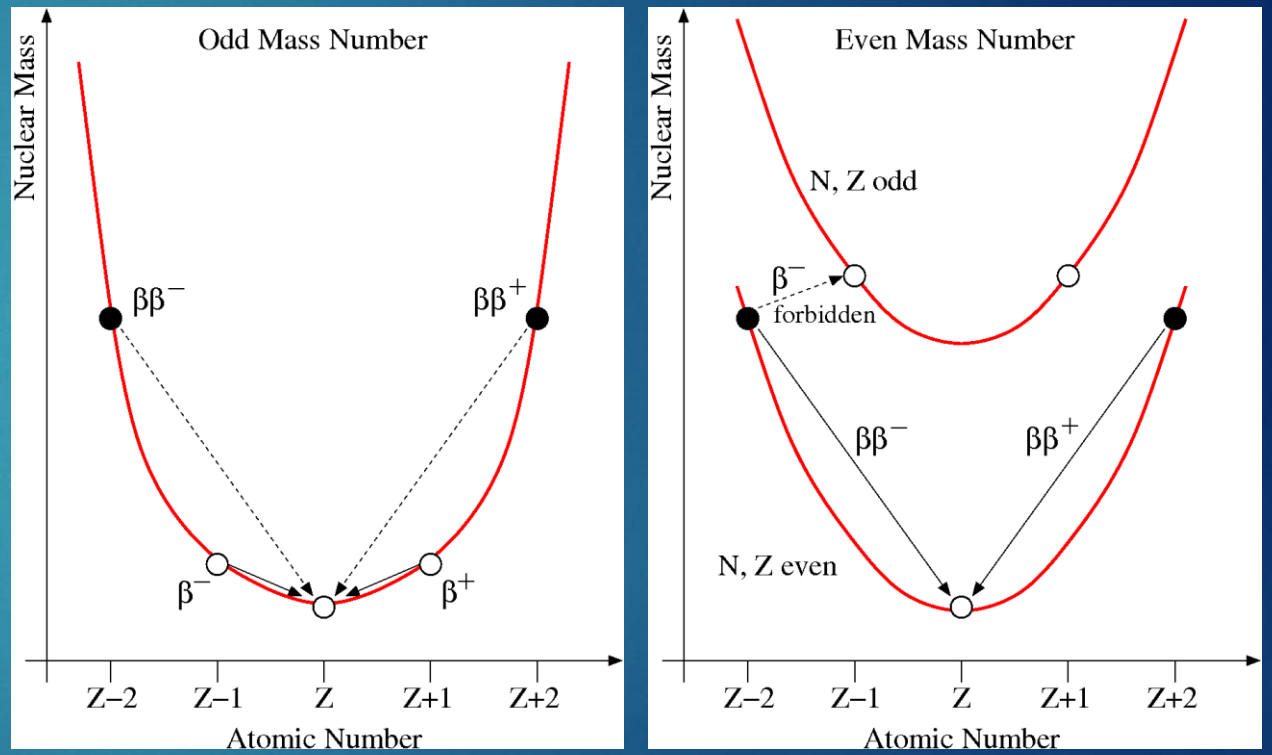
Latest results from the **CUORE** experiment

On behalf of the **CUORE** collaboration

Shihong Fu - Fudan University - COUSP2024, Xichang, China, May 10th, 2024

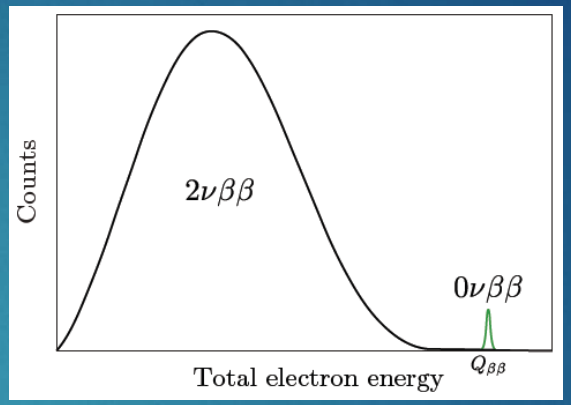
Double Beta Decay ($2\nu\beta\beta$)

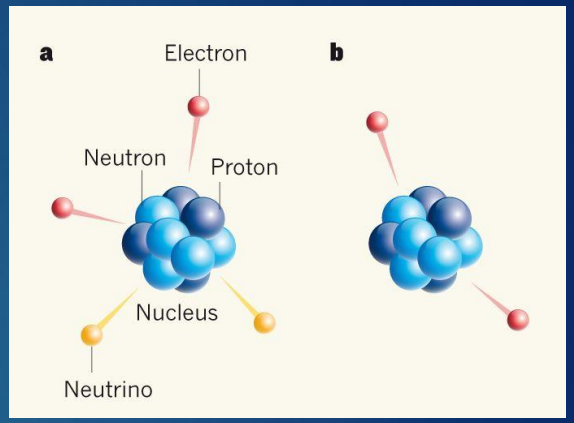
- Same mass number (A), changes the nuclear charge (Z) by two units.
- 2nd order weak transition, allowed by the Standard Model.
- Decay to the intermediate nucleus is forbidden.
- Only even mass number nuclei.
- Half-lives in the order of 10^{18}~10^{21} yr.
- Two-neutrino double beta decay ($2\nu\beta\beta$)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





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

phase space factor

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

experimental observable

nuclear matrix element

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

isotopic abundance

detector mass

measuring time

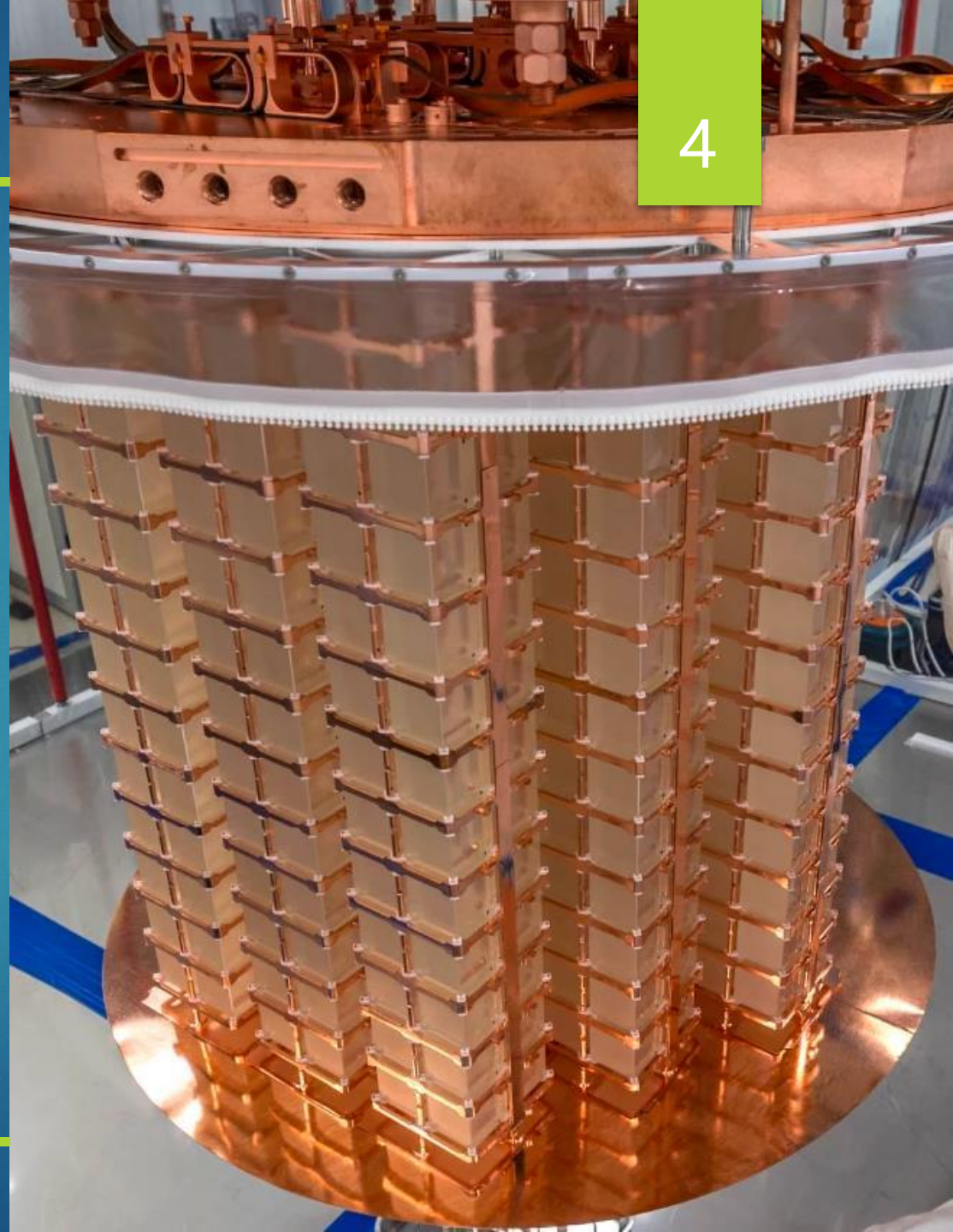
sensitivity

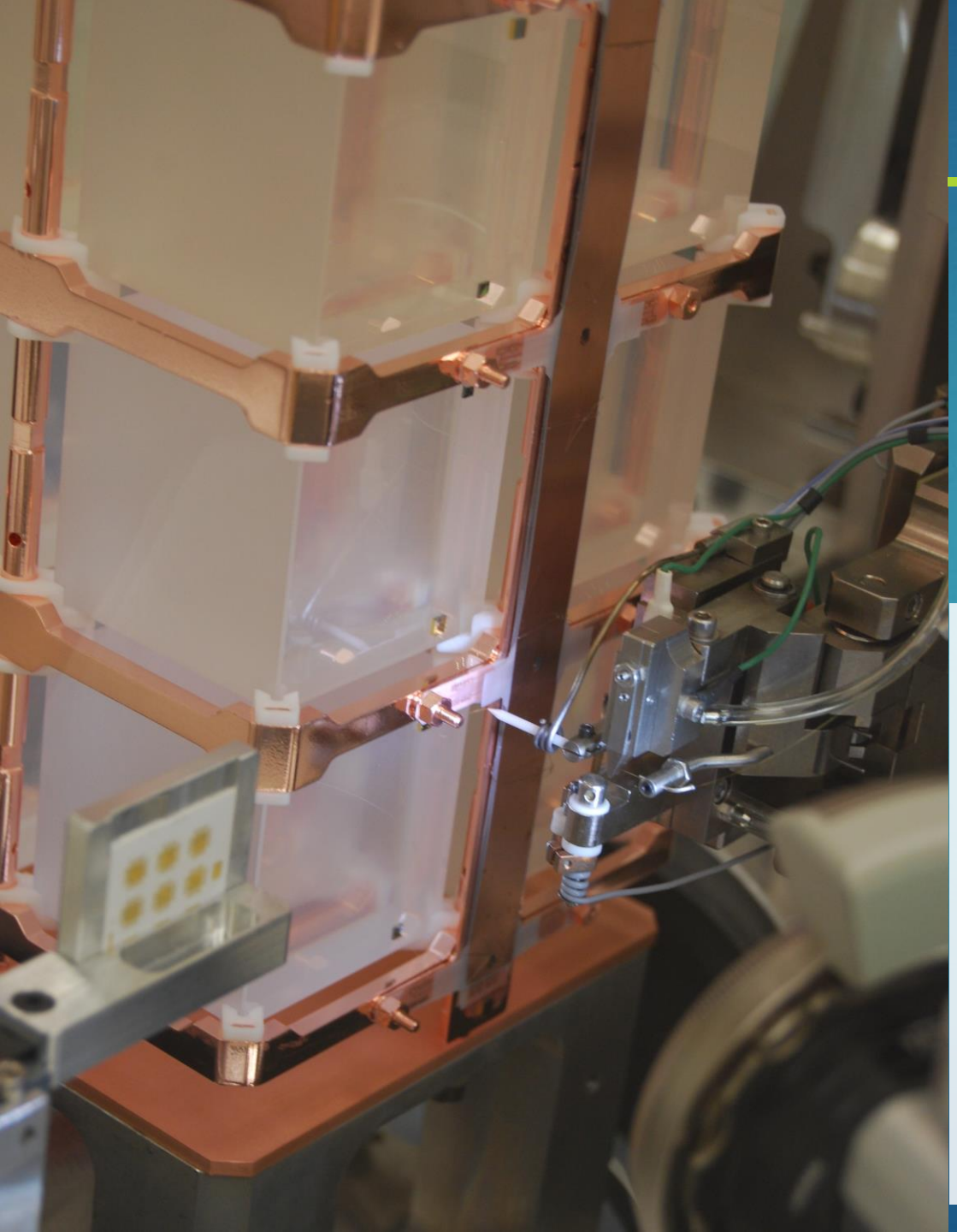
energy resolution

background

CUORE experiment

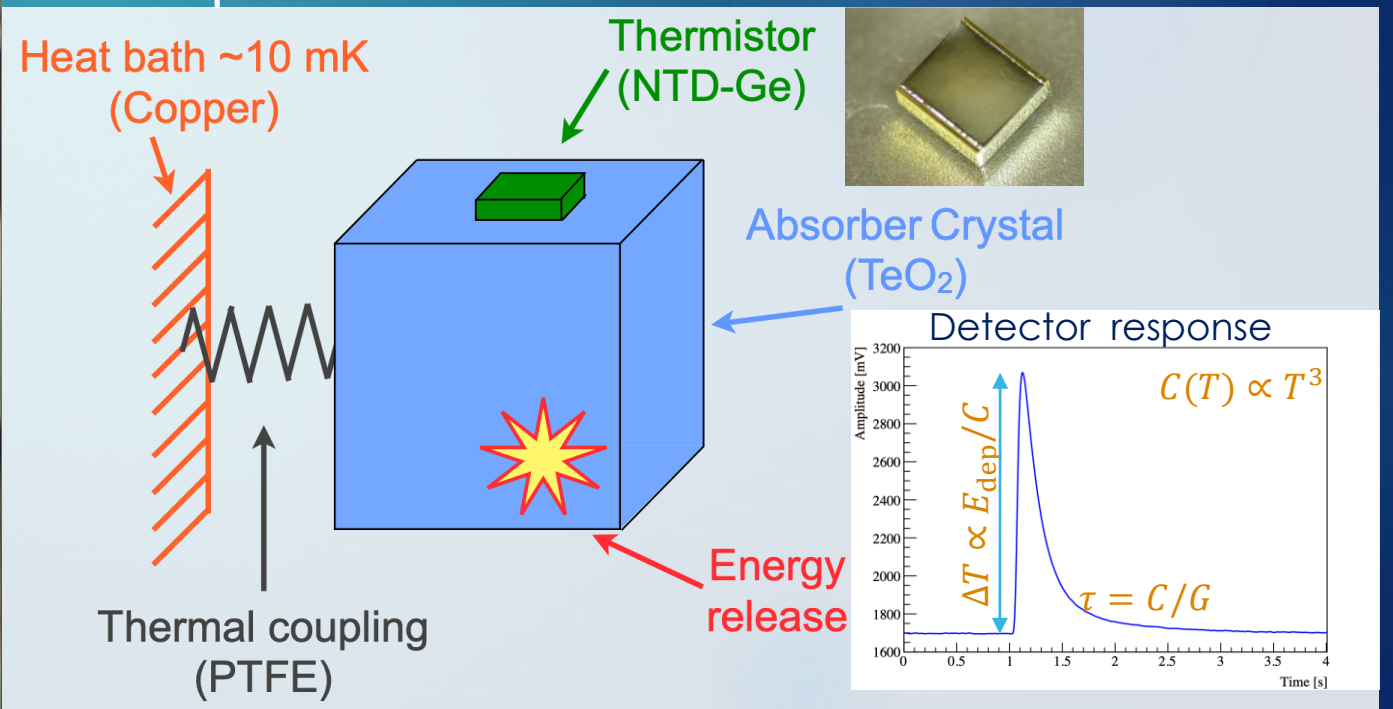
- **C**ryogenic **U**nderground **O**bservatory for **R**are **E**vents
- In operation at the Laboratori Nazionali del Gran Sasso, Italy
- Main objective: observe $0\nu\beta\beta$ in $^{130}\mathrm{Te}$
- The CUORE detector is hosted in a cryogen-free cryostat
  - Operating temperature $\sim 10\ \mathrm{mK}$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



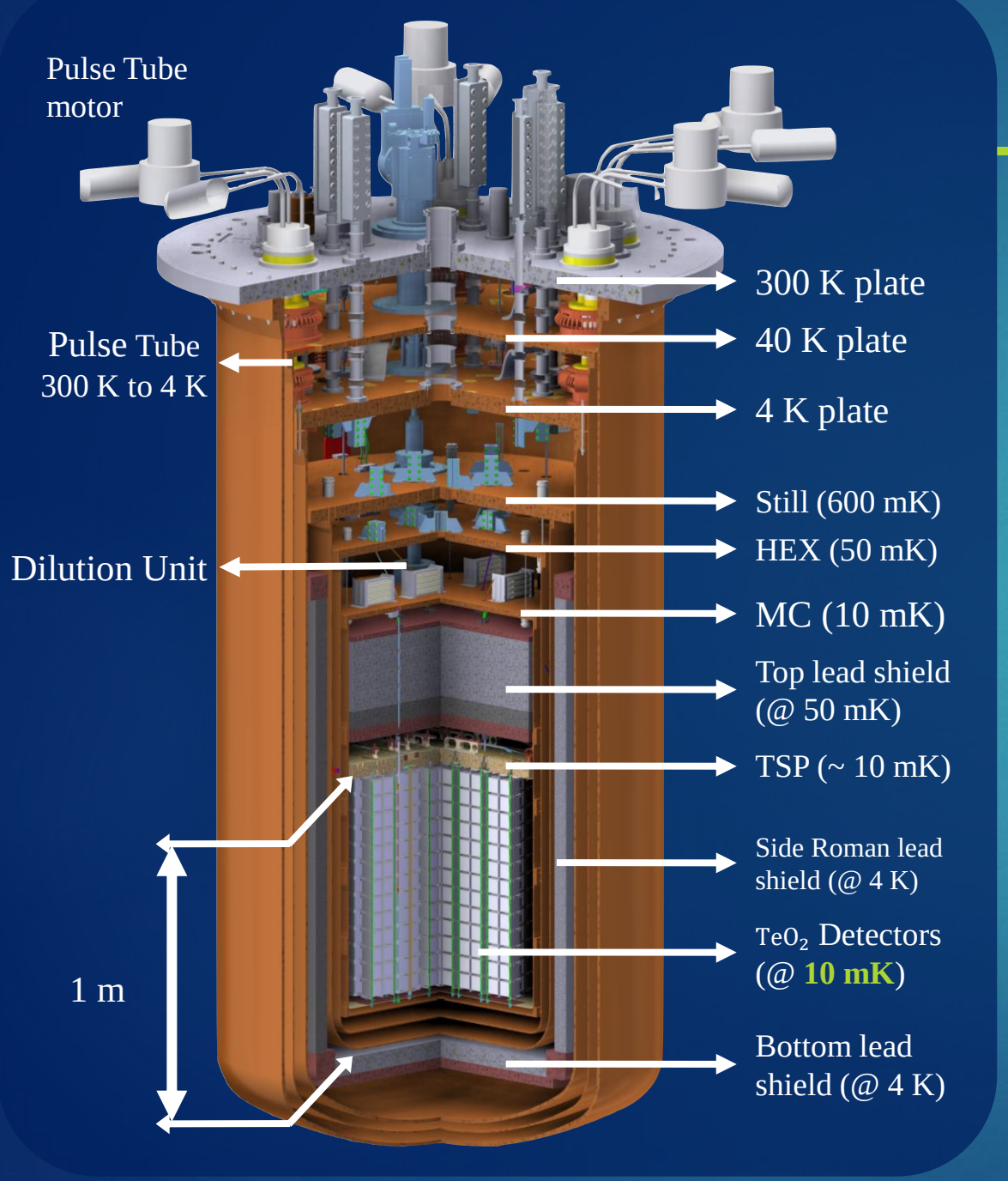


Cryogenic Bolometer

- 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.



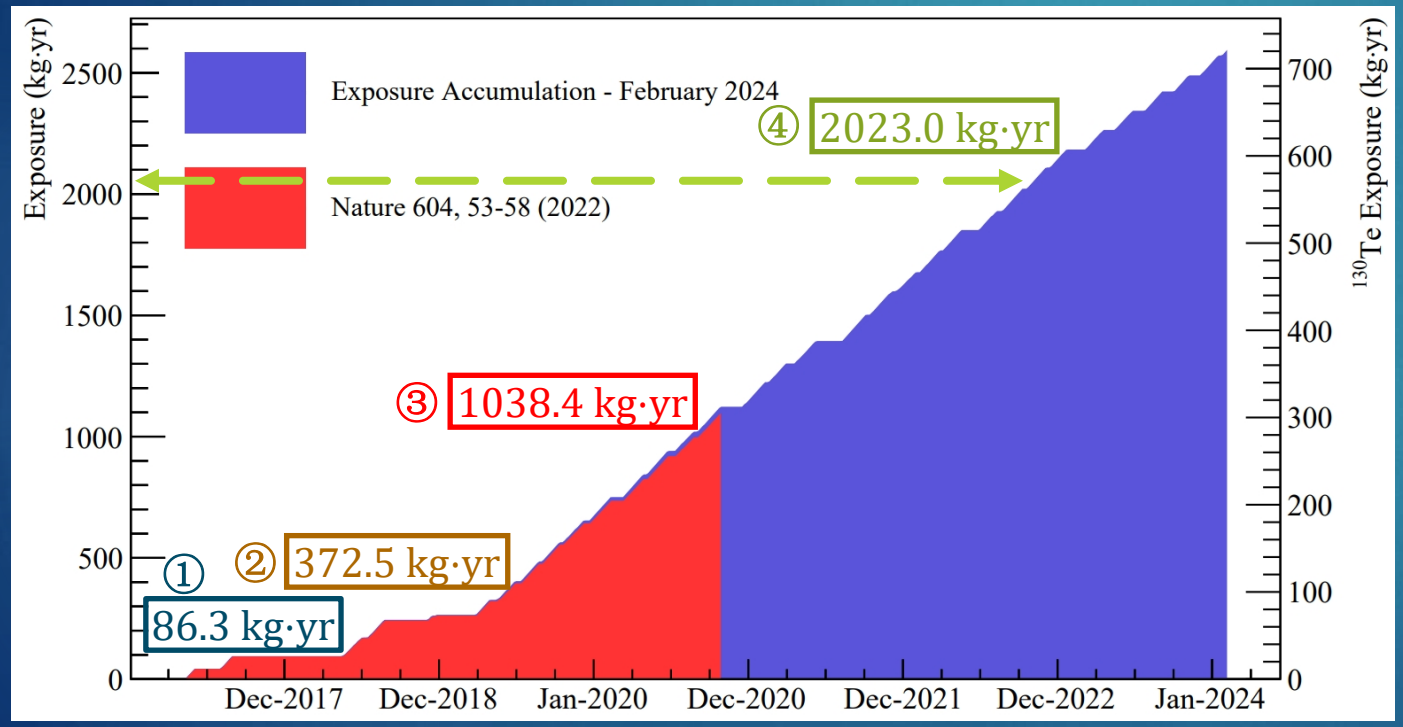
CUORE Cryostat



- 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

Data collection

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

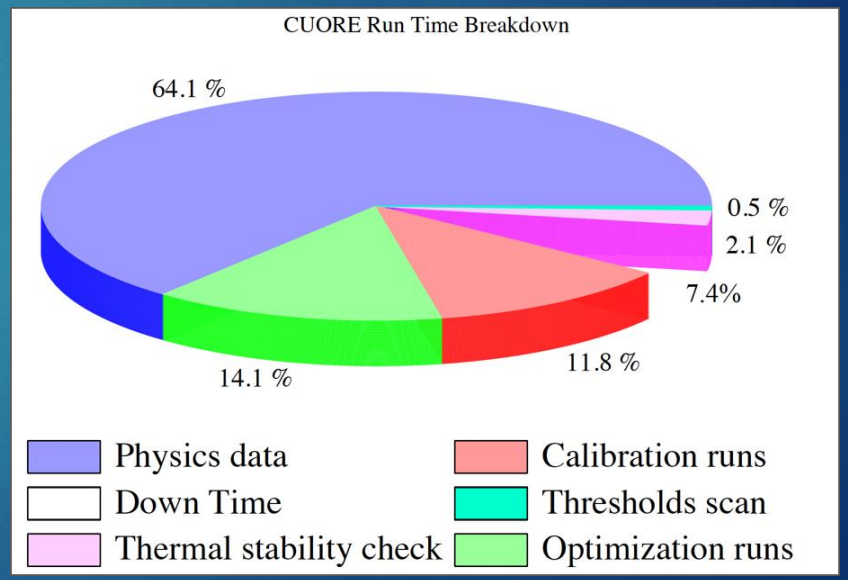


① Alduino, C. et al. (CUORE Collaboration), Phys. Rev. Lett. 120, 132501 (2018)

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

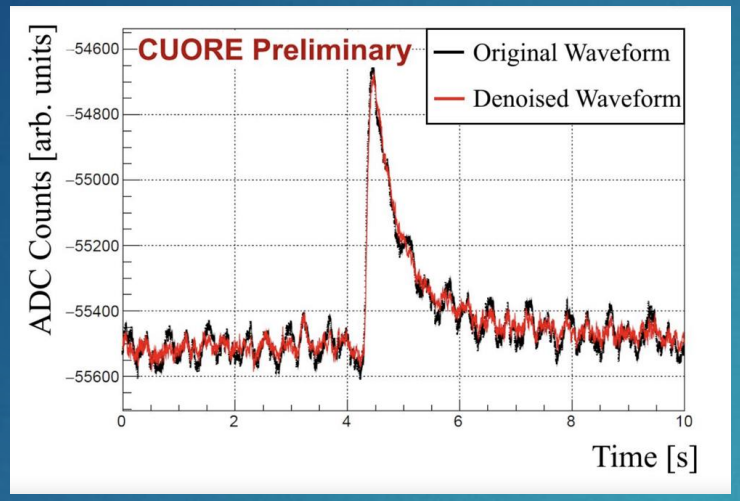
③ Adams, D.Q. et al. (CUORE Collaboration), **Nature** 604, 53-58 (2022)

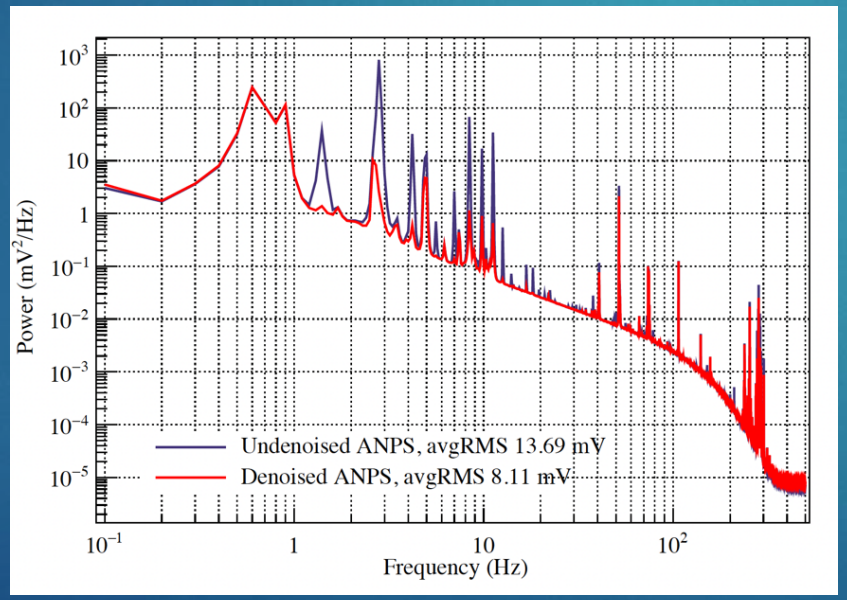
④ **TAUP2023** (CUORE Collaboration)



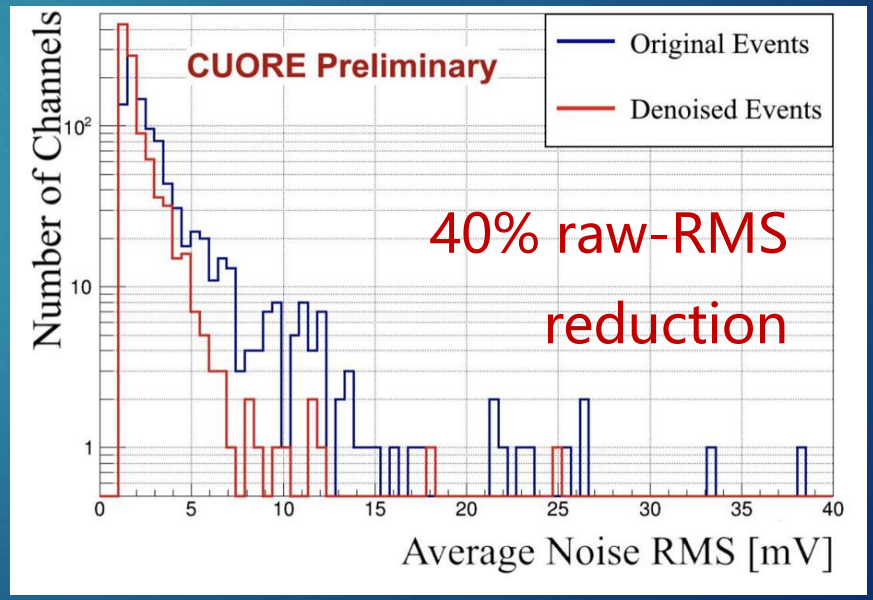
CUORE data analysis

- **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

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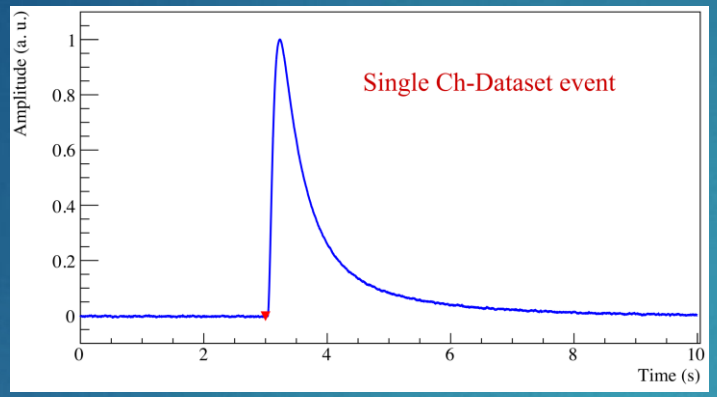
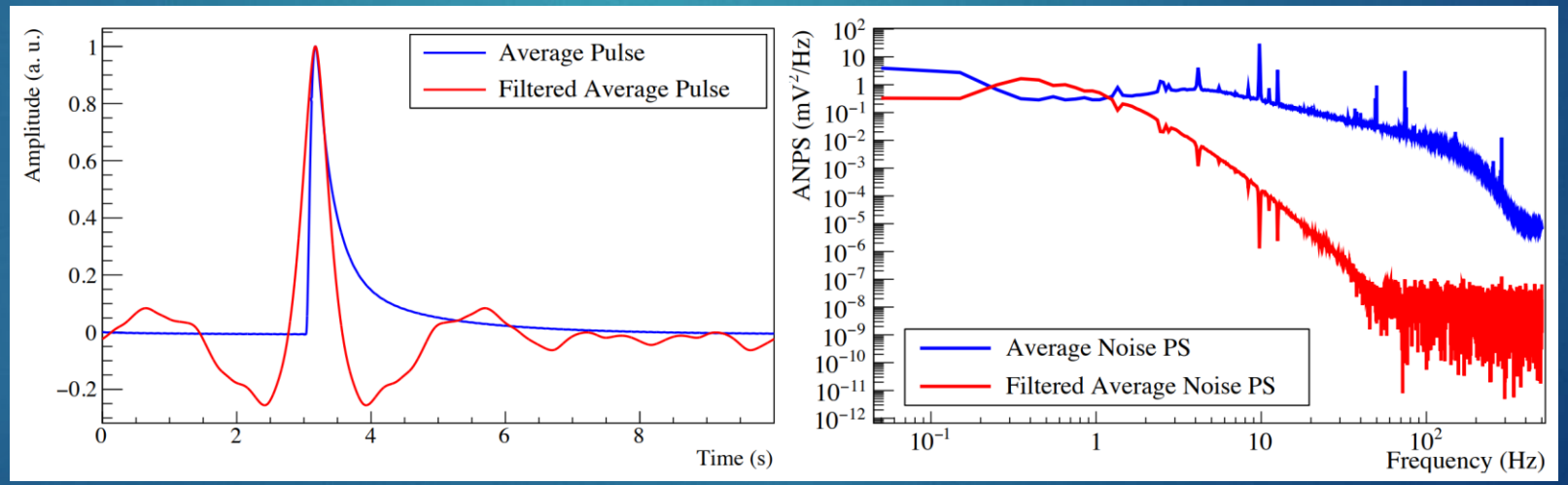
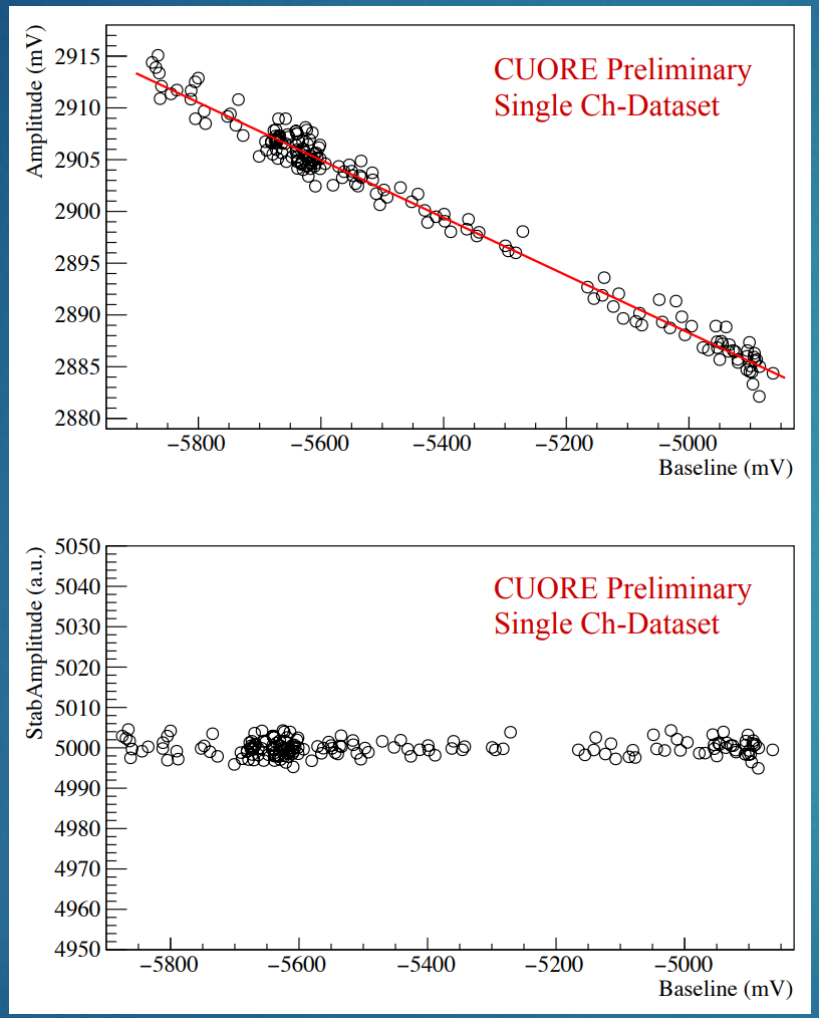


- Derivative trigger: online analysis for quick data quality feedback
- Offline re-triggering (Optimum Trigger)
  - disentangle small signals from noise fluctuations
  - lower threshold

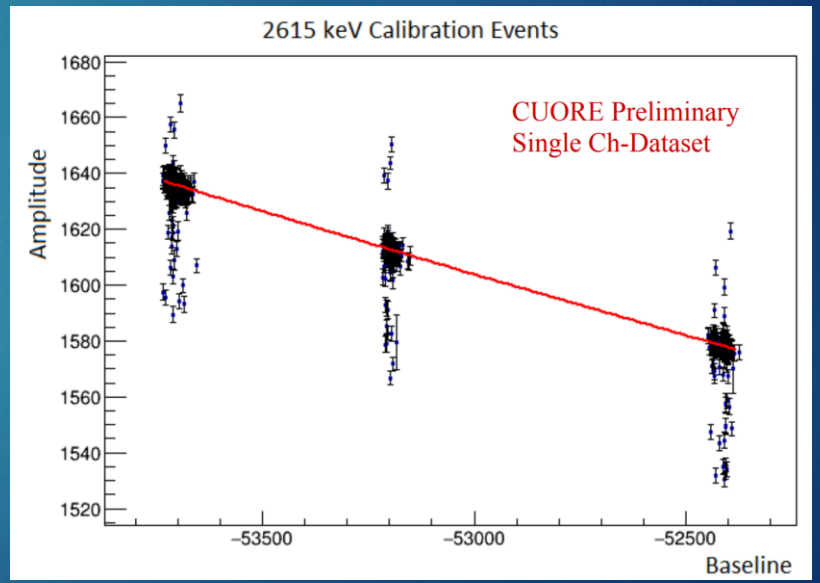


- Matched filter maximizes signal-to-noise ratio

CUORE data analysis



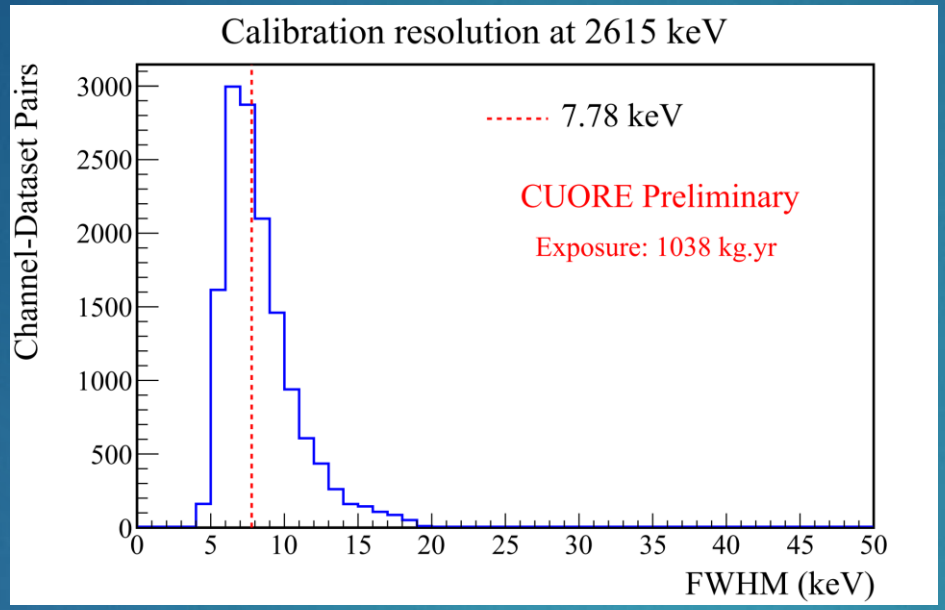
- Use fixed energy heater events to correct amplitude dependence on operating temperature
- Interpolate calibration peak at $2615\ \mathrm{keV}$ for non-functional or underperforming heaters



- Heater pulses for thermal gain stabilization

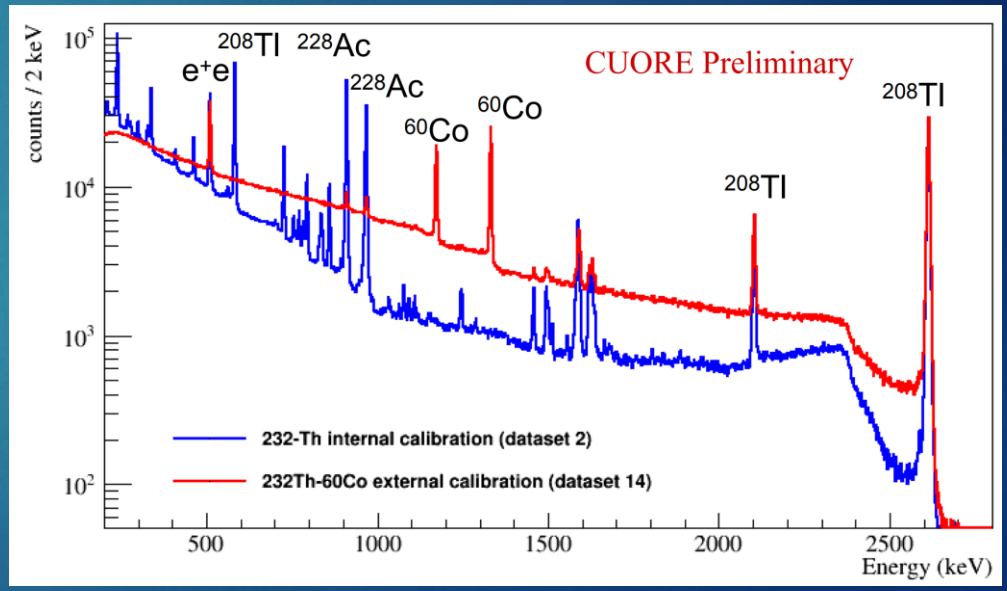
CUORE data analysis

- 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
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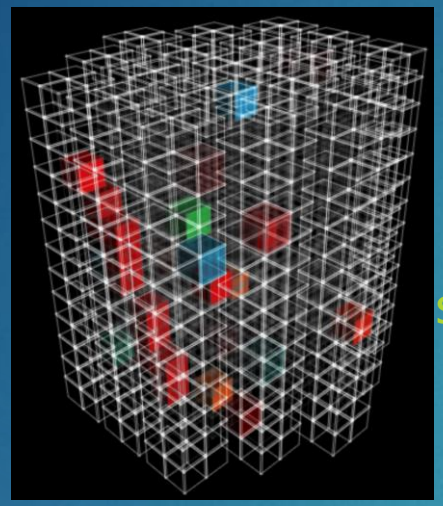
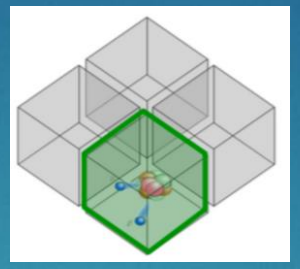
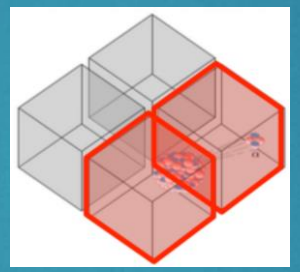
- **Coincidences**
- **Pulse Shape Discrimination (PSD)**
- Blinding





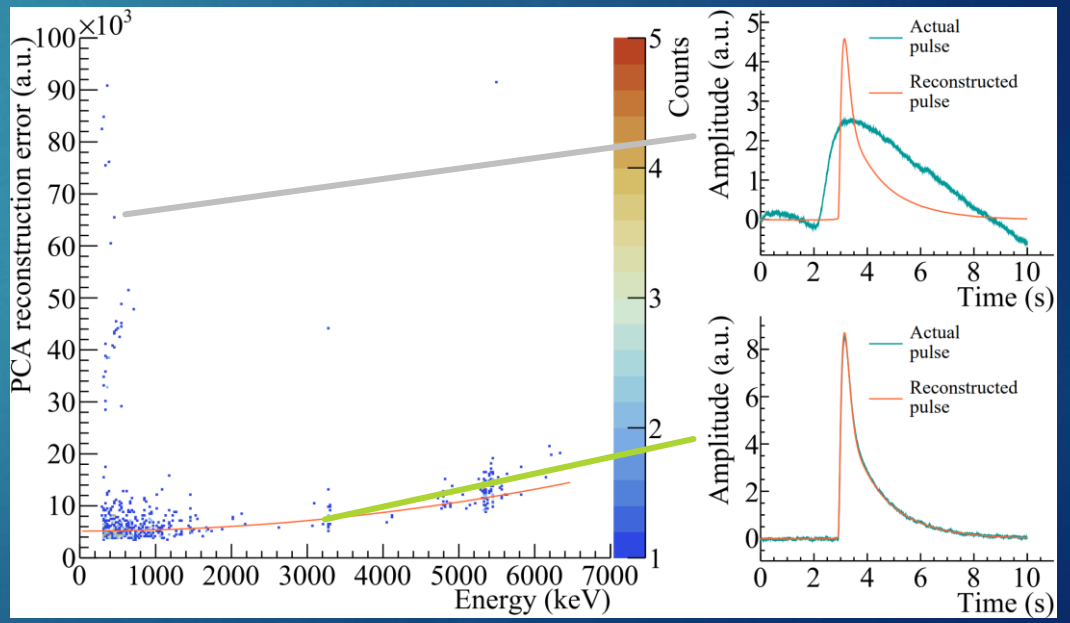
single-site (signal-like)



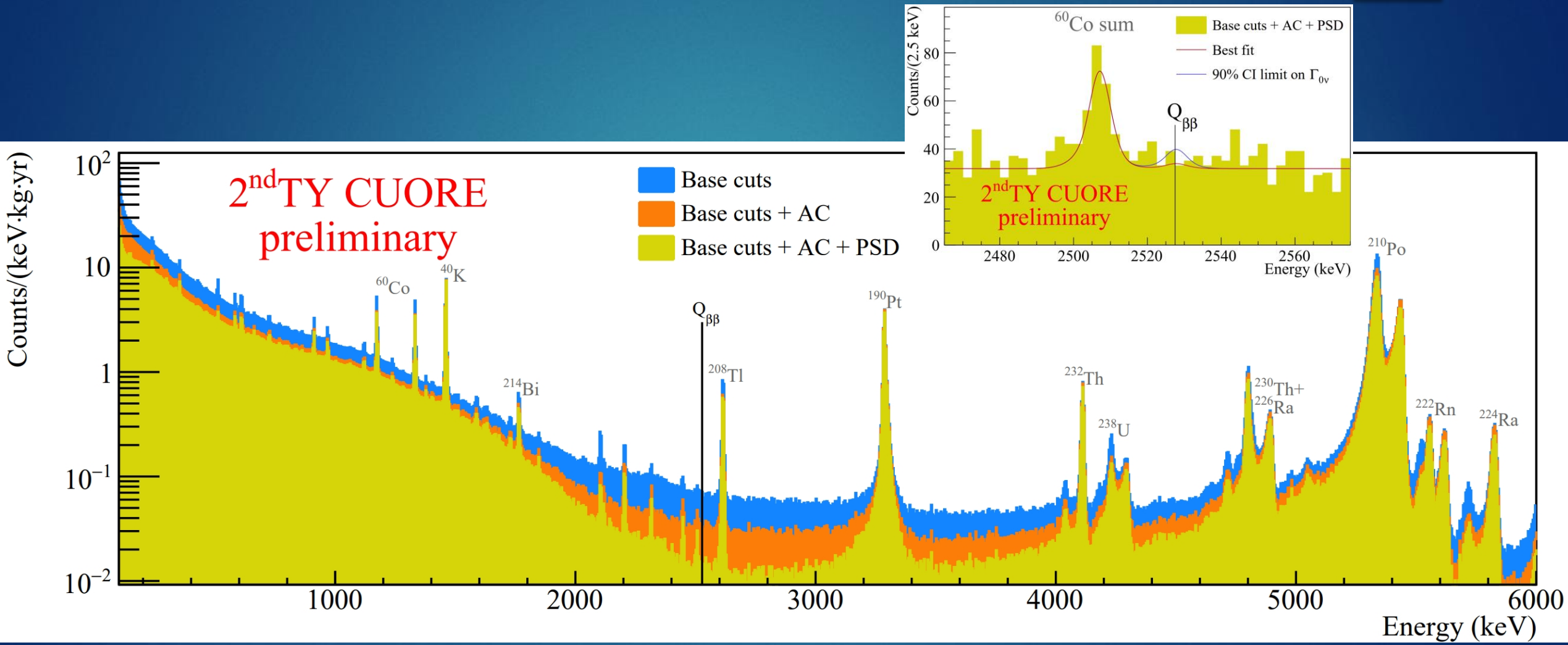
multi-site (background-like)

- 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

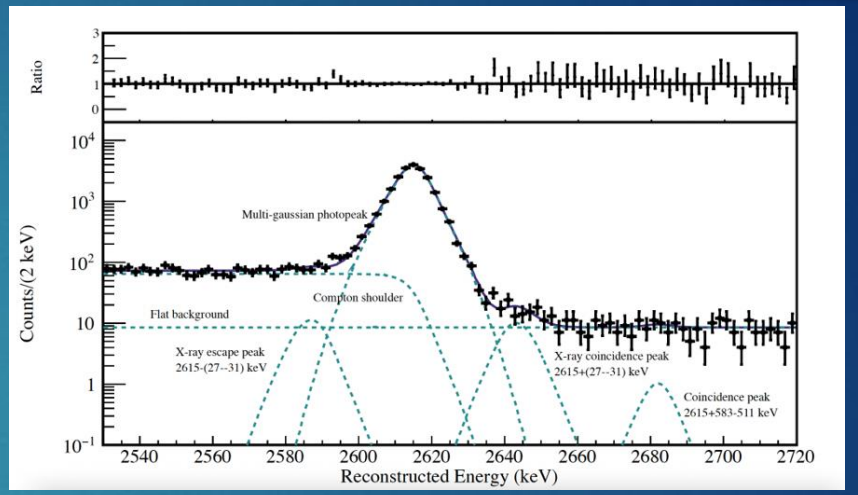


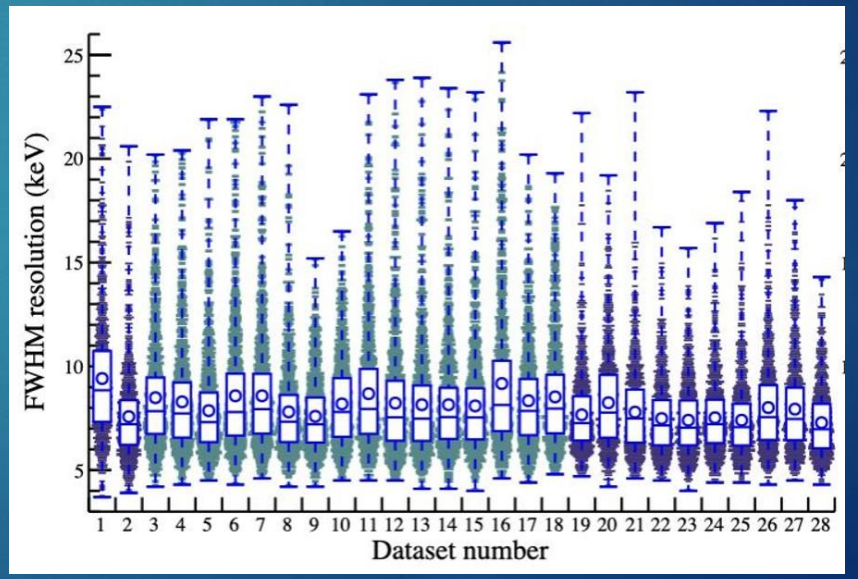
Physics data - 2 ton · yr exposure



Detector performance

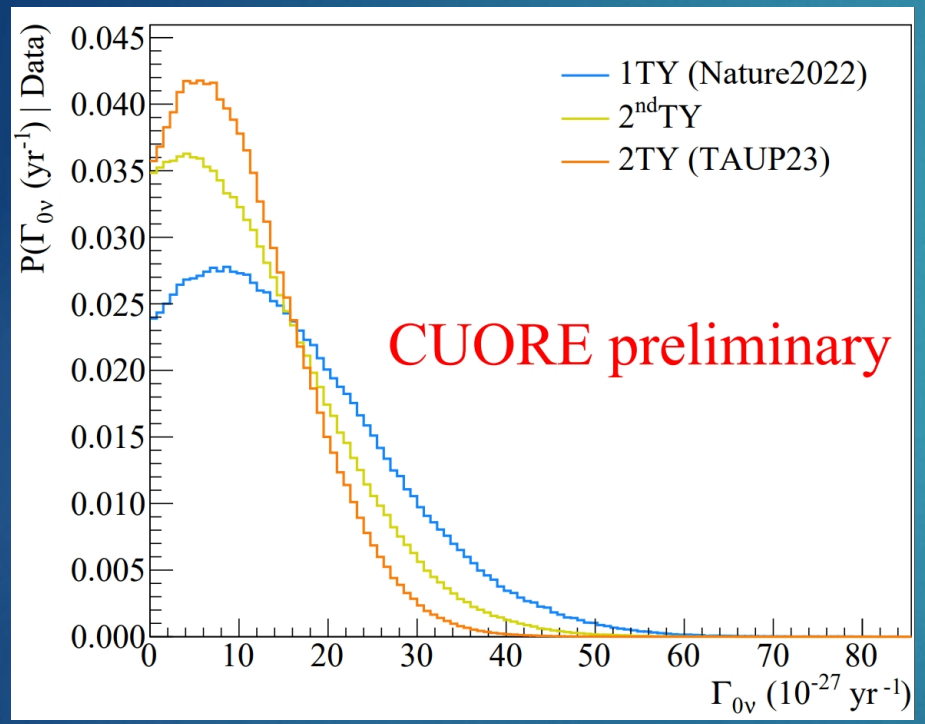
- Peak lineshape:
  - Reference $^{208}\mathrm{Tl}$ gamma peak at $2615\ \mathrm{keV}$ from calibration data
- Fit model:
  - Multi-Gaussian response function
  - Multi-Compton background
  - Flat background
  - Coincidence/escape peaks
- Fit at channel-dataset level
- Energy resolution at $2615\ \mathrm{keV}$
  - FWHM = $(7.550 \pm 0.024)\ \mathrm{keV}$
    - harmonic mean - exposure weighted

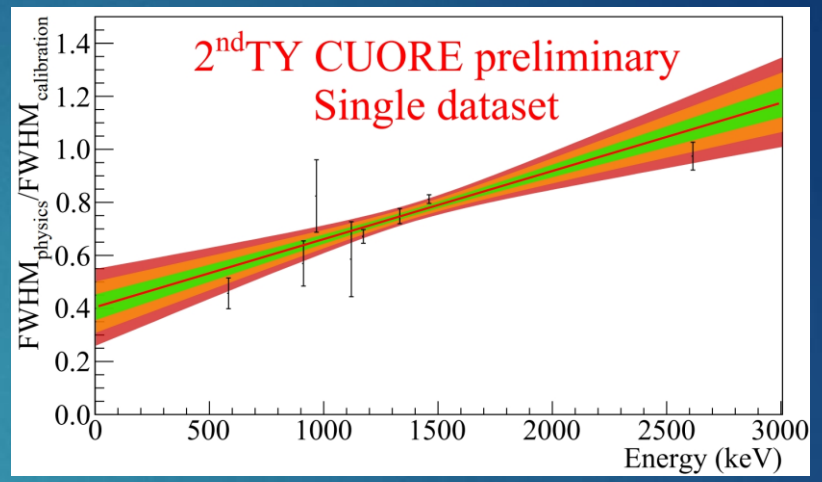


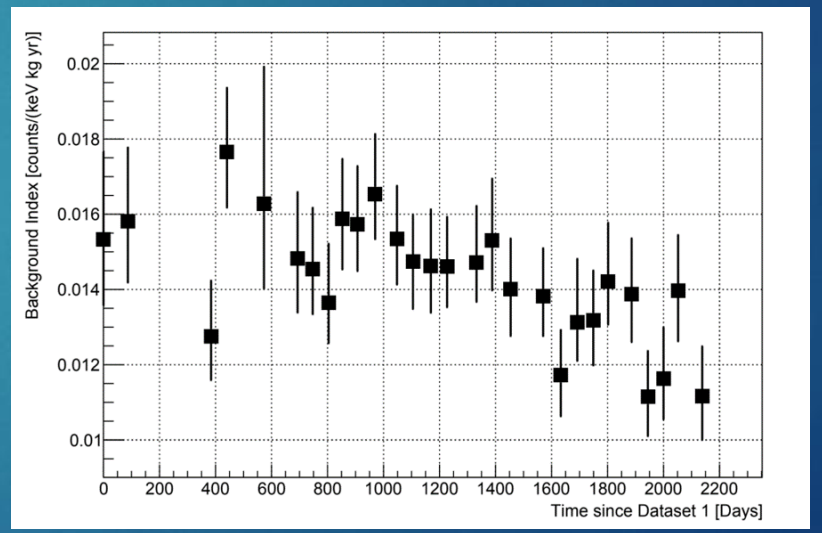


$0\nu\beta\beta$ decay search results

- Resolution scaling
  - FWHM at $Q_{\beta\beta} = 7.525^{+1.45}_{-1.15}$ keV





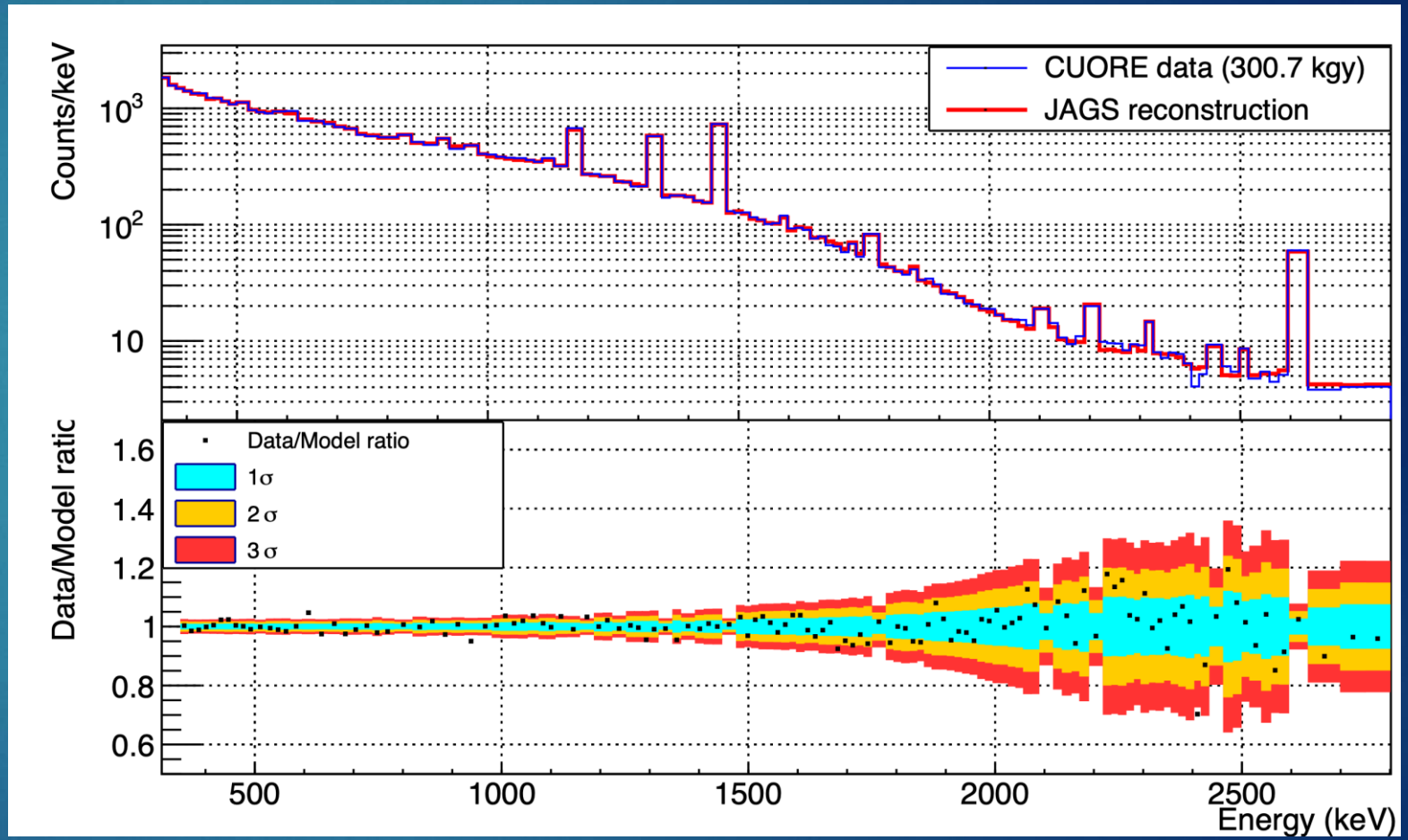


- Bayesian limit: $T_{1/2}^{0\nu} > 3.8 \cdot 10^{25}$ yr @ 90% C.I.
- BI: $(1.42 \pm 0.02) \cdot 10^{-2}$ counts / (keV · kg · yr)

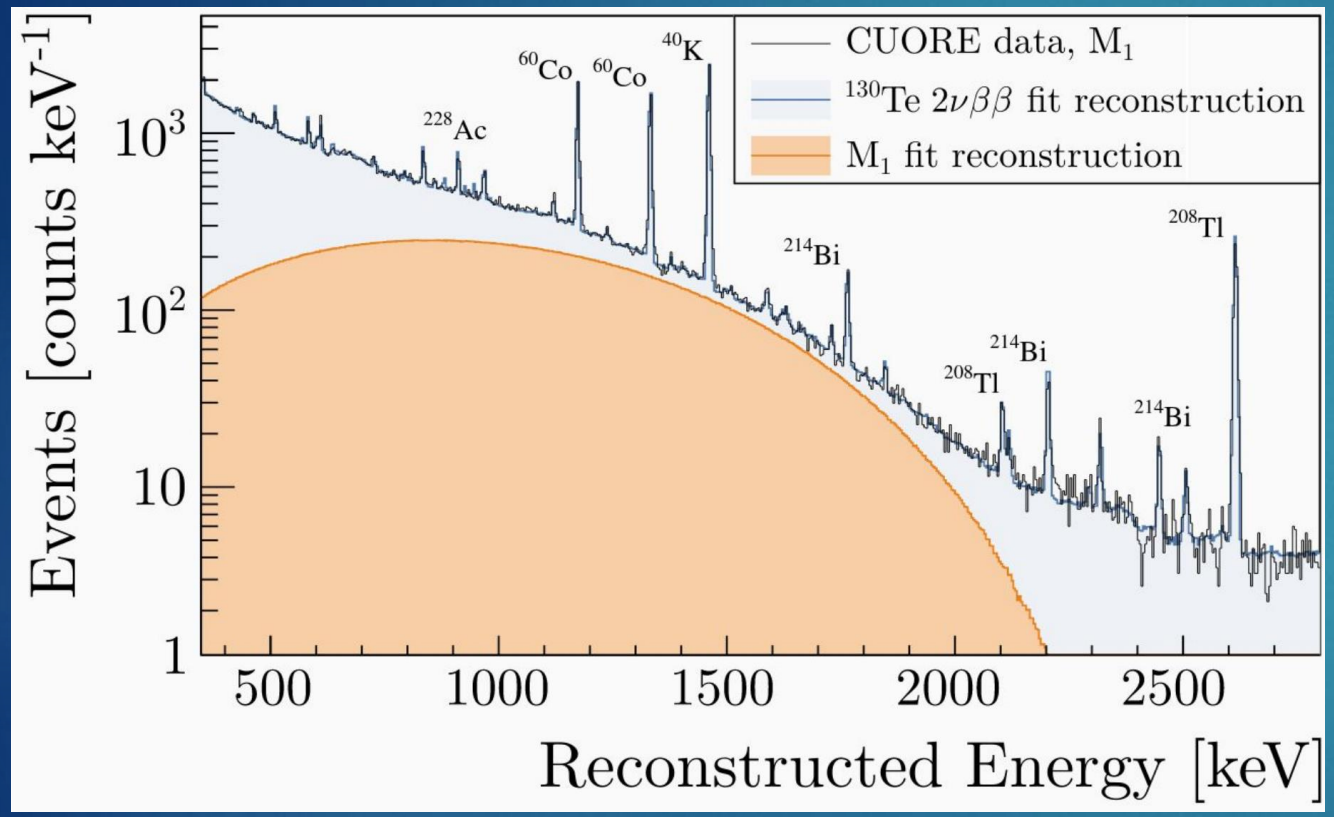
Adams, D.Q. et al. (CUORE Collaboration), arXiv:2404.04453

Background model results

- Full detector geometry and particle interaction implemented in Geant4
- Geant4 output post-processed to include detector response
- 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



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)

What's next?

- CUORE phase-I (current)
  - Run up to mid-2025
  - Reach $> 3\ \mathrm{ton \cdot yr}$ $\mathrm{TeO_2}$, $1\ \mathrm{ton \cdot yr}$ $^{130}\mathrm{Te}$ 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 $10^{-4}\ \mathrm{counts\ /\ (keV \cdot kg \cdot yr)}$
  - Energy resolution: goal of $5\ \mathrm{keV}$ at $Q_{\beta\beta}$

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.

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

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

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

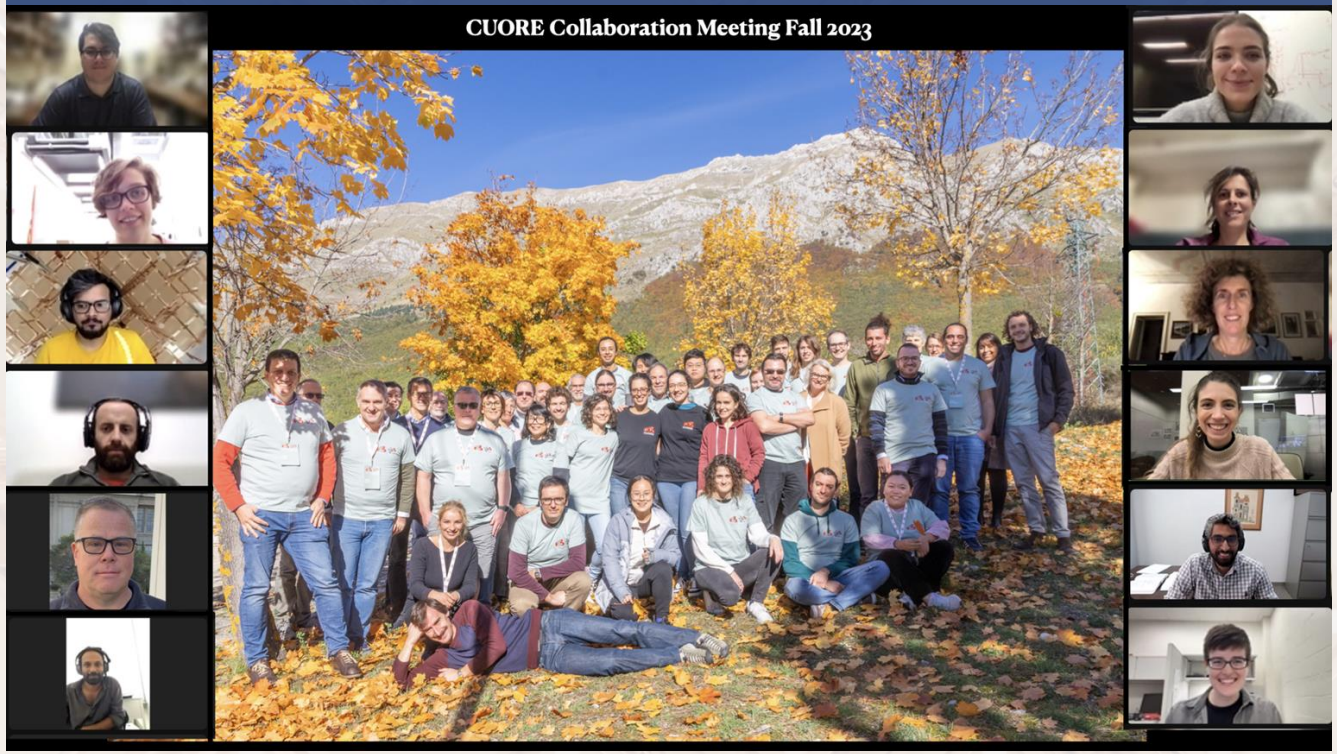
- CUORE will continue to take data until it reaches $^{130}\mathrm{Te}$ exposure of $1\ \mathrm{ton \cdot yr}$, *i.e.*, $3\ \mathrm{ton \cdot yr\ TeO_2}$ exposure.
- Thanks for the unique feature of allow deployment of different isotopes by using the same infrastructure.

CUORE

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

CUPID

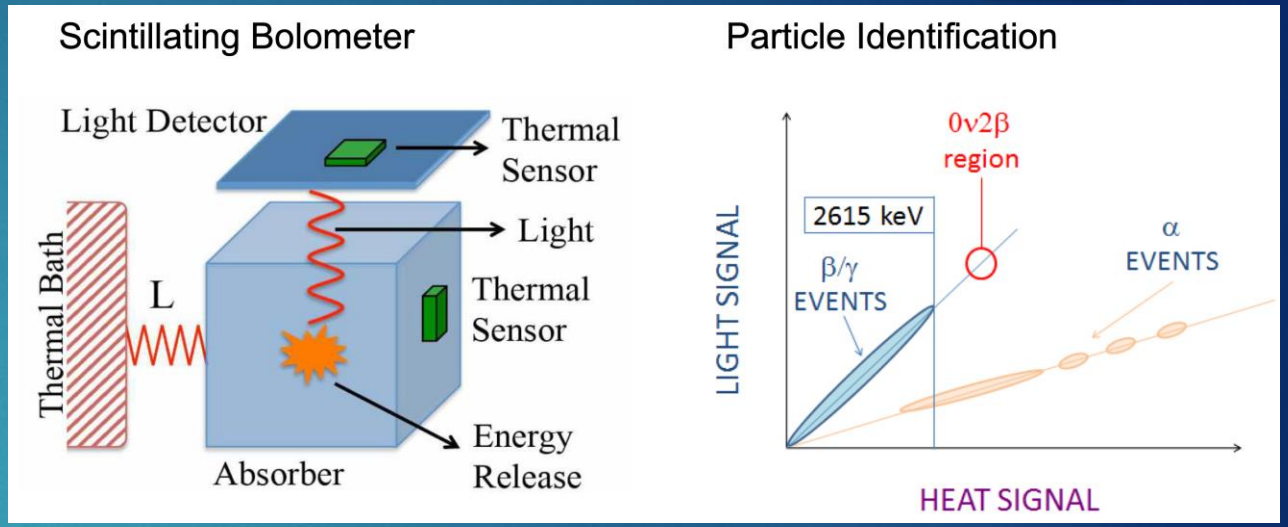
Thank you for your attention!

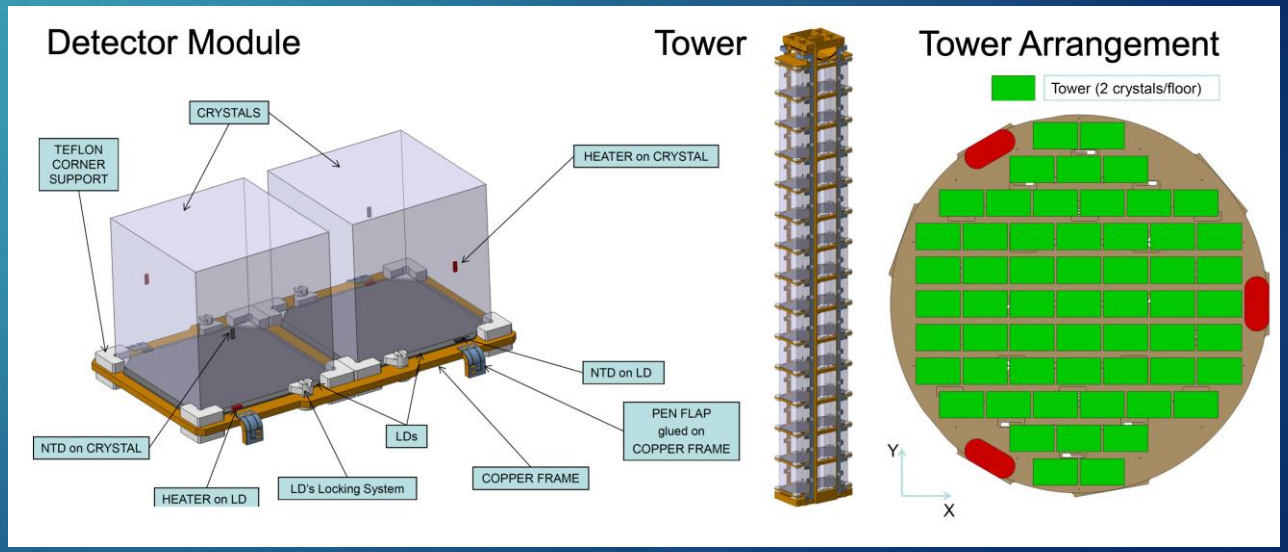


Backup

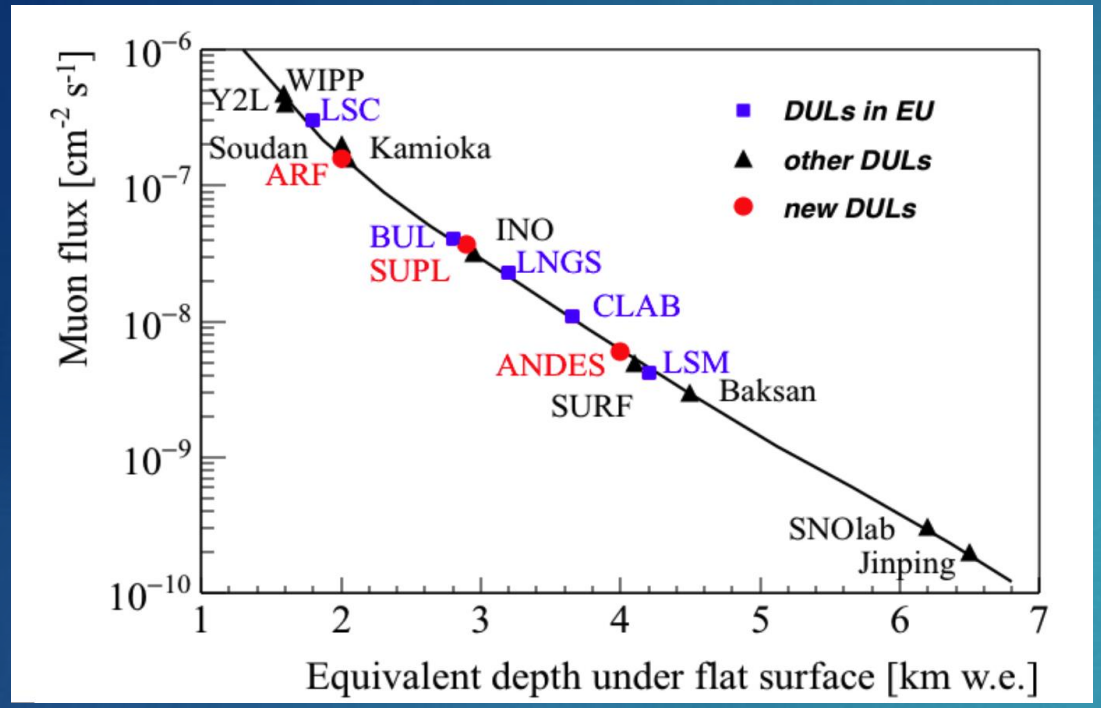
CUPID

- **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)

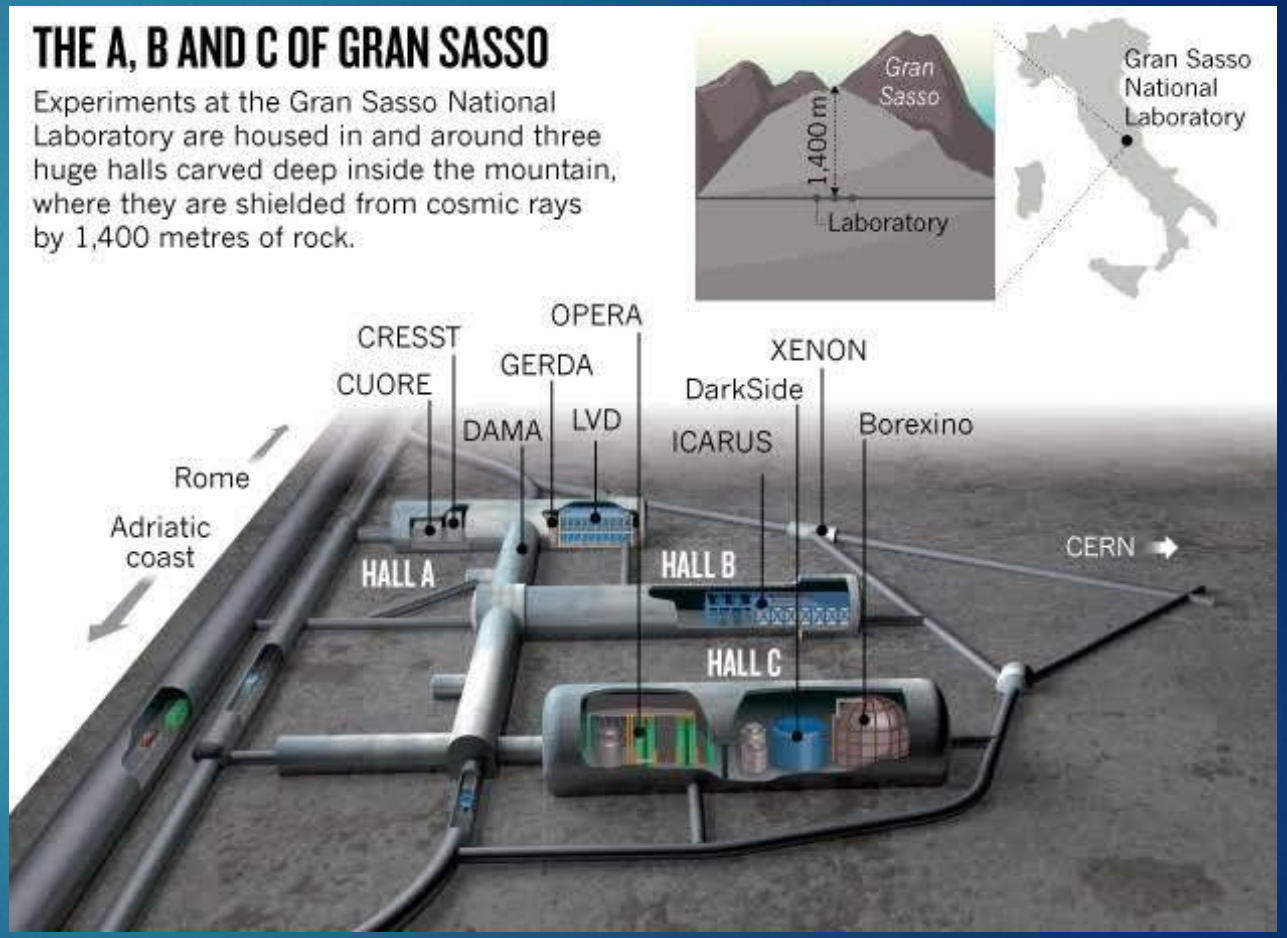




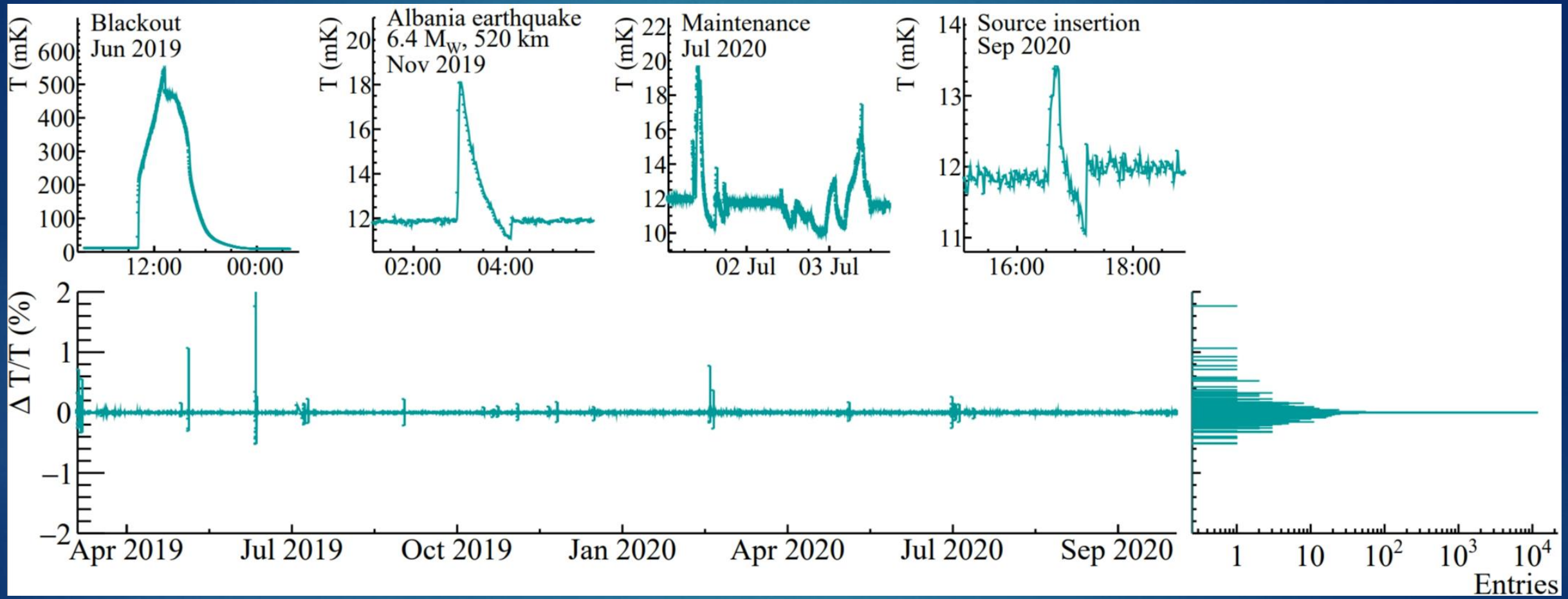
Laboratori Nazionali del Gran Sasso - Italy



- 3600 m.w.e. deep
- μ: ~3x10^{-8}/(s cm^2)
  → 10^6 less than above ground
- γ: ~0.73/(s cm^2)
- neutrons: < 4x10^{-6} n/(s cm^2)



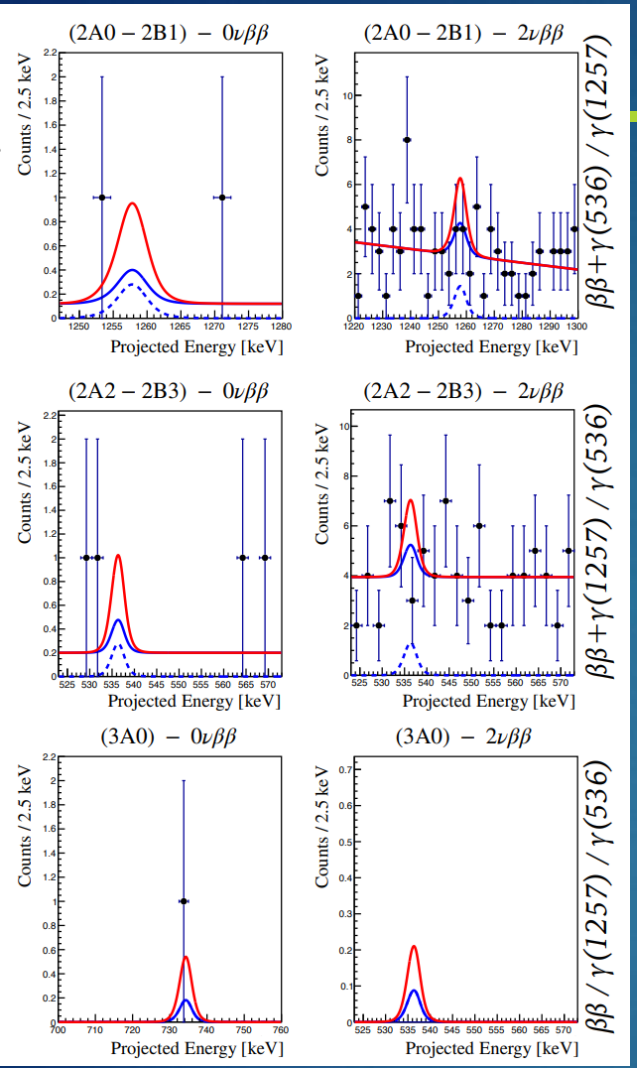
The cryostat performance



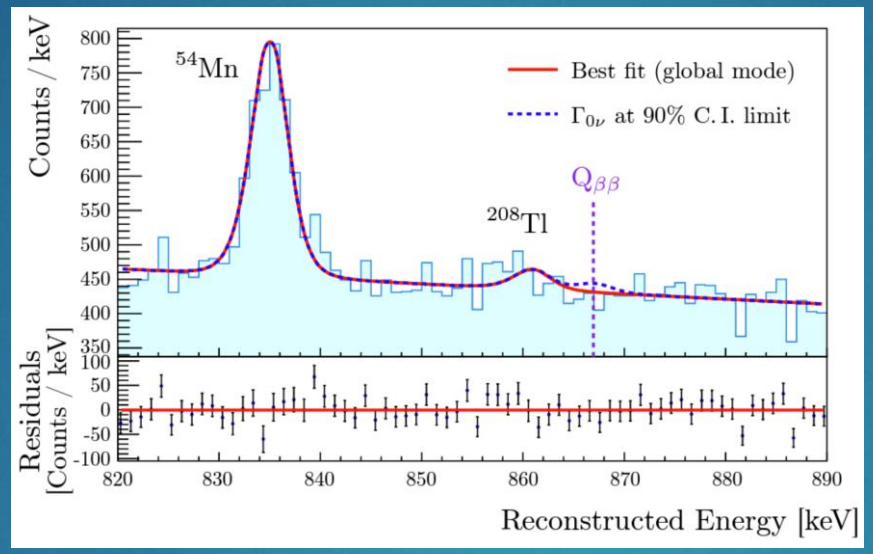
Adams, D.Q. et al. (CUORE Collaboration), **Nature** 604, 53-58 (2022)

Other rare event searches

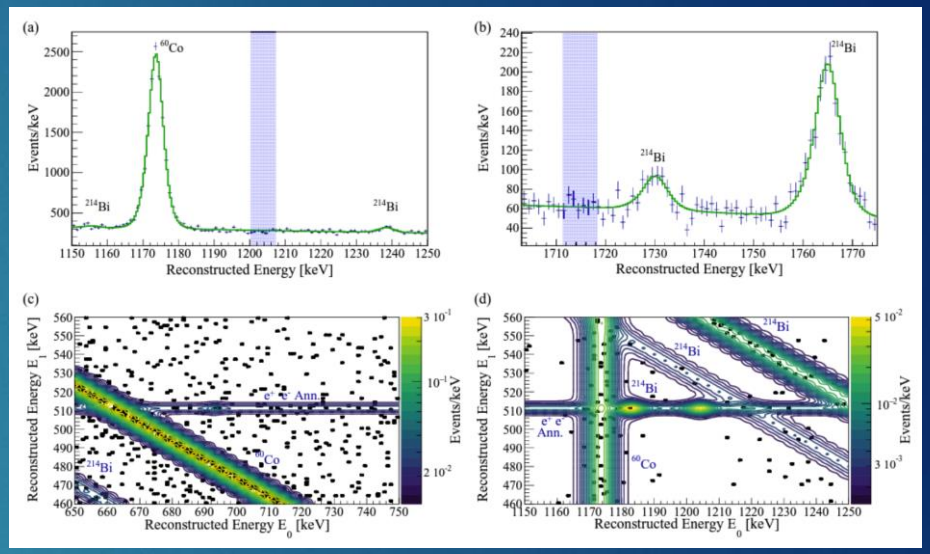
^{130}Te $\beta\beta$ to first 0^+ excited state



^{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)

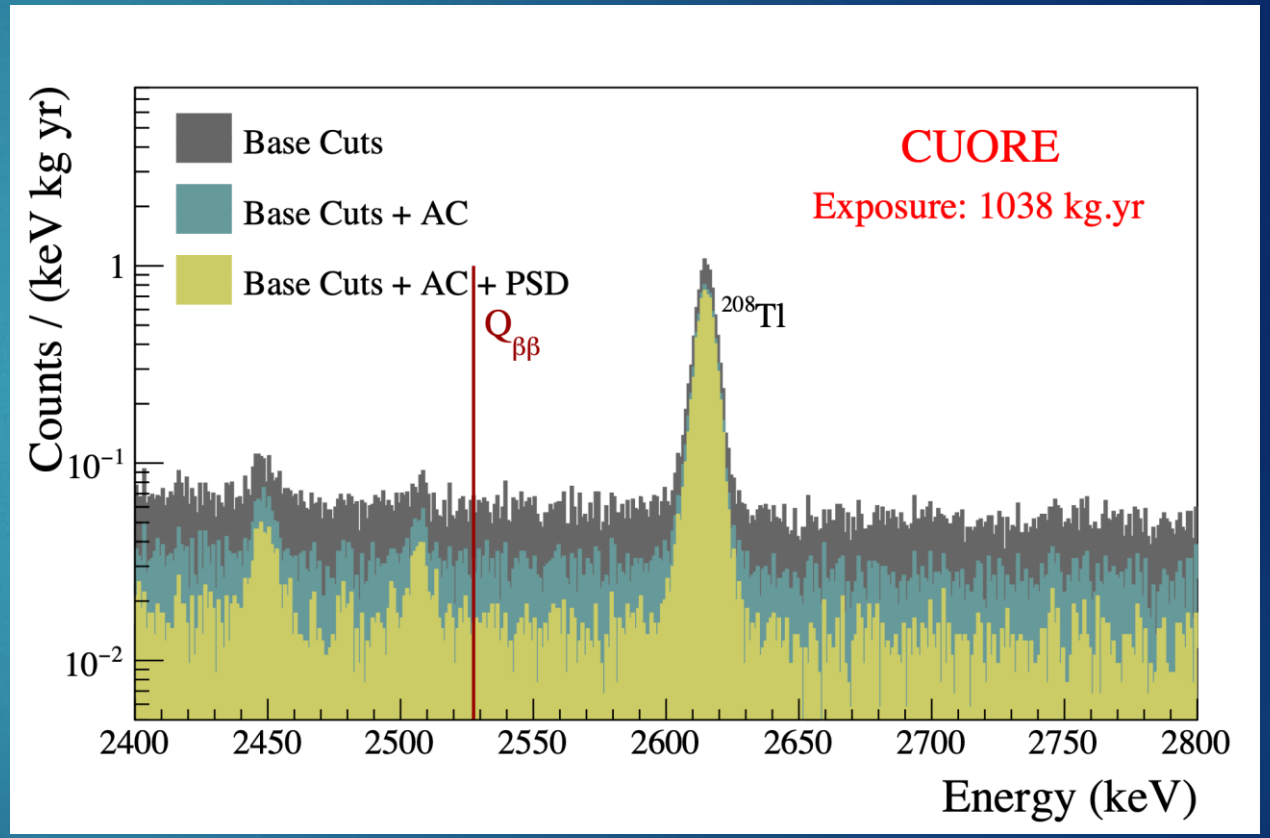
Adams, D.Q. et al. (CUORE Collaboration), Phys.Rev.C 105, 065504 (2022)

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

- 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