GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

Science Fair 2025/2026

CUORE

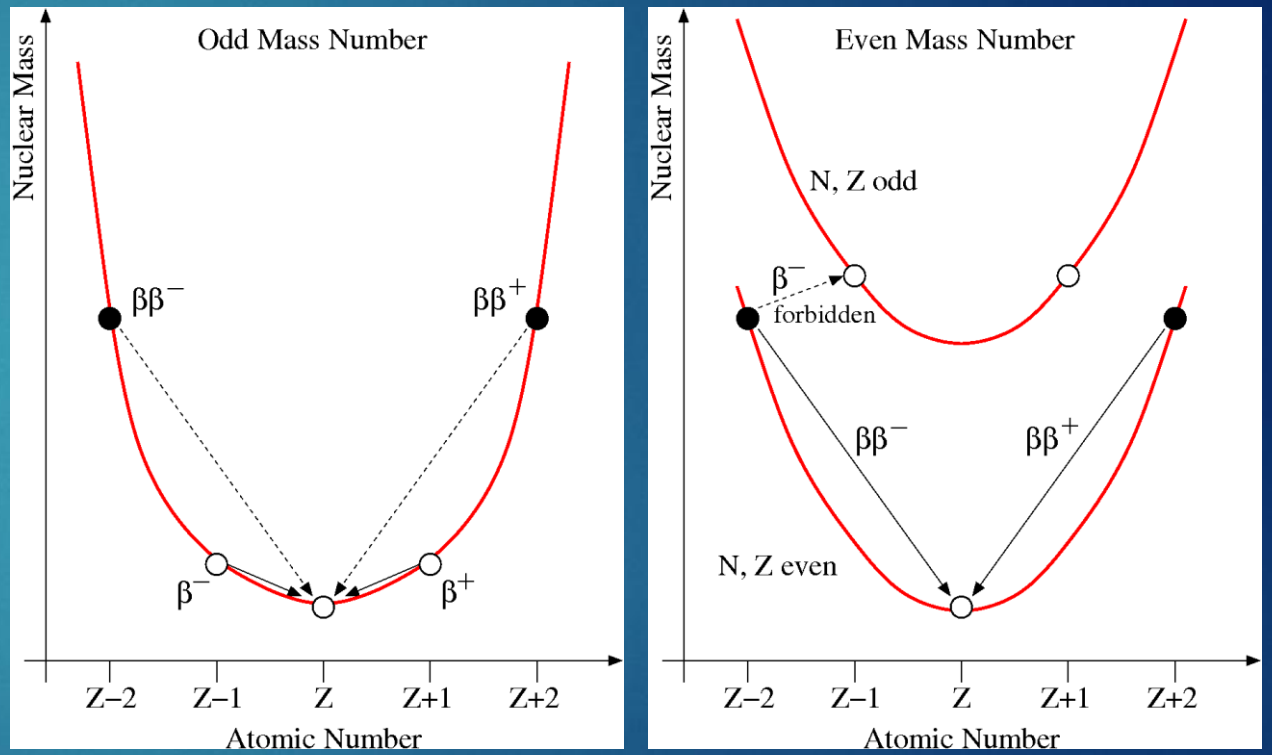
INFN LNGS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Gran Sasso

CUORE – Cryogenic Underground Observatory for Rare Events

On behalf of the **CUORE** collaboration

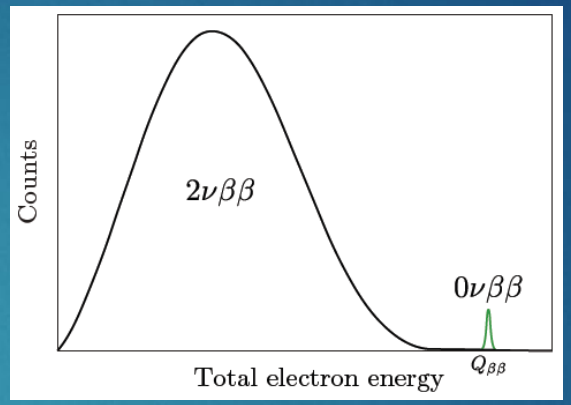
Double Beta Decay ($2\nu\beta\beta$)

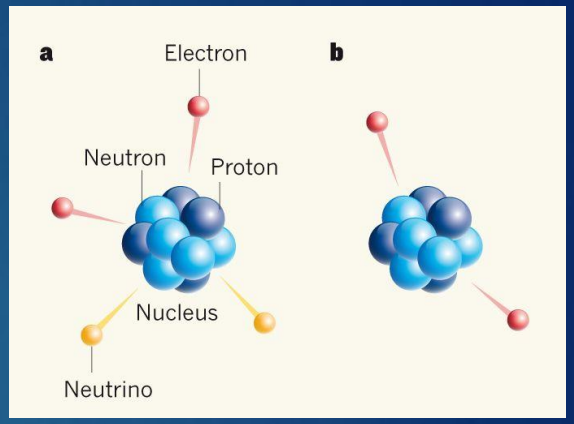
- Same mass number (A), changes the nuclear charge (Z) by two units.
- 2nd order weak transition, allowed by the Standard Model.
- Decay to the intermediate nucleus is forbidden.
- Only even mass number nuclei.
- Half-lives in the order of 10^{18}~10^{21} yr.
- Two-neutrino double beta decay ($2\nu\beta\beta$)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

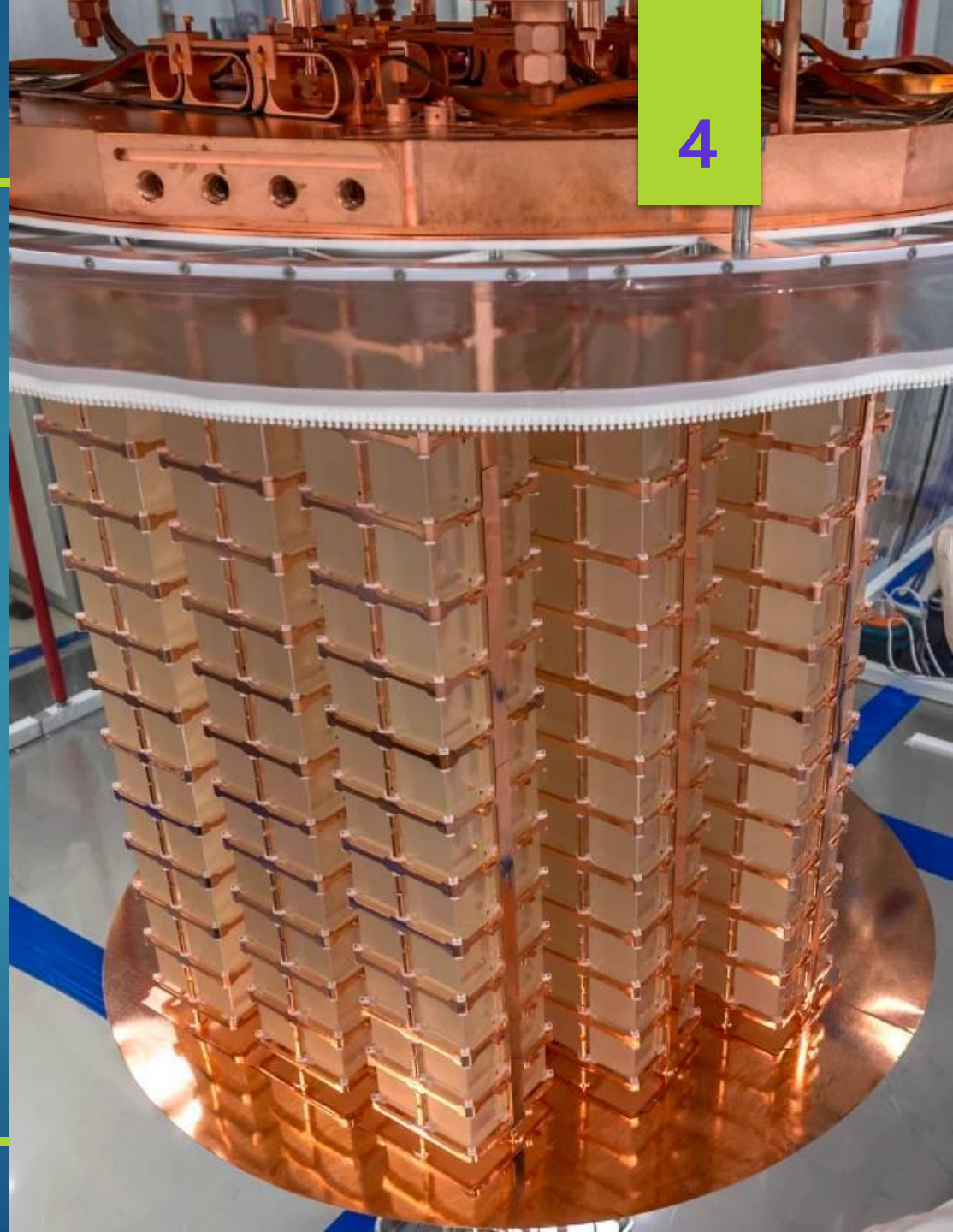
sensitivity

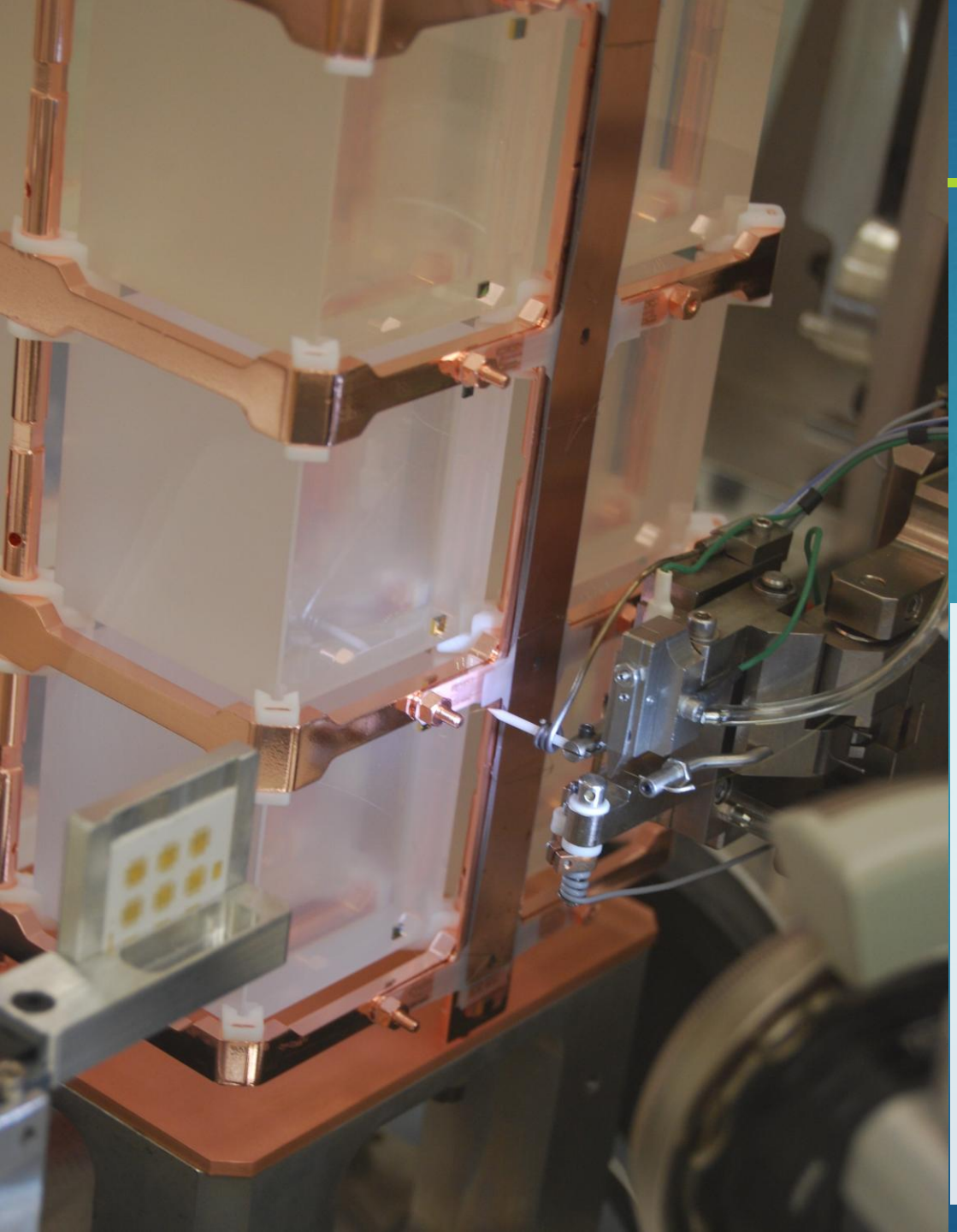
energy resolution

background

CUORE experiment

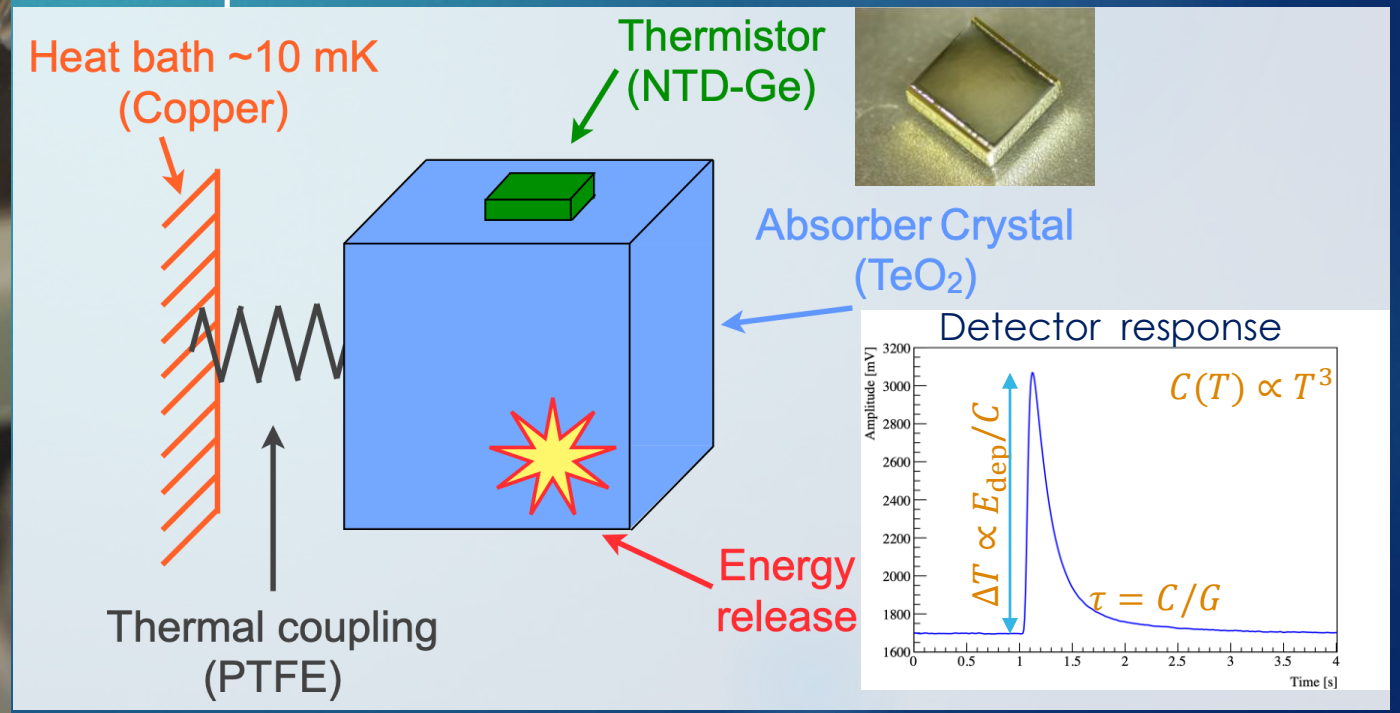
- **C**ryogenic **U**nderground **O**bservatory for **R**are **E**vents
- In operation at the Laboratori Nazionali del Gran Sasso, Italy
- Main objective: observe $0\nu\beta\beta$ in $^{130}\mathrm{Te}$
- The CUORE detector is hosted in a cryogen-free cryostat
  - Operating temperature $\sim 10\ \mathrm{mK}$
  - 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 $Q_{\beta\beta}$





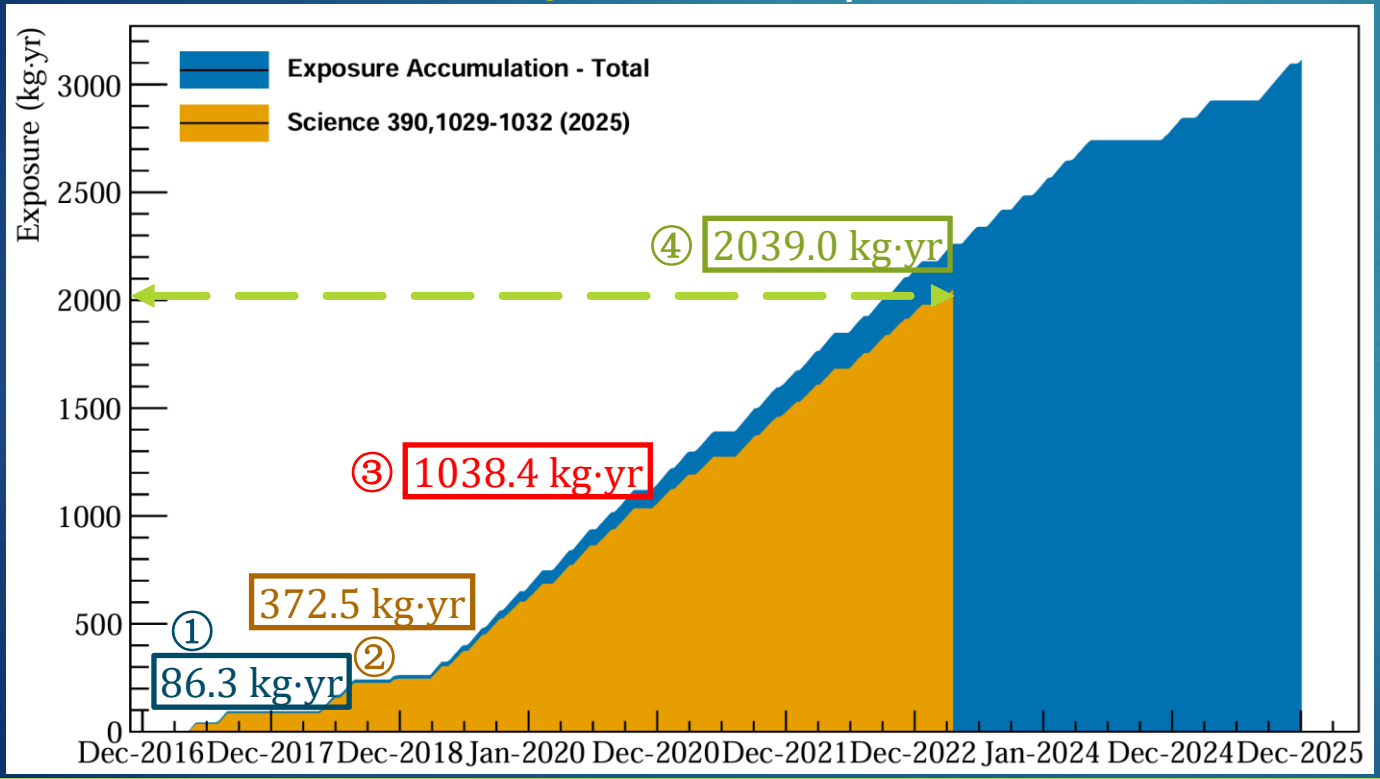
Cryogenic Bolometer

- 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.



Data collection

- Data taking started in 2017, with first 2 years for cryostat and detector optimization
- Stable data collection since 2019, with ≳ 85% uptime
- More than **3.1 ton·yr** of raw exposure accumulated

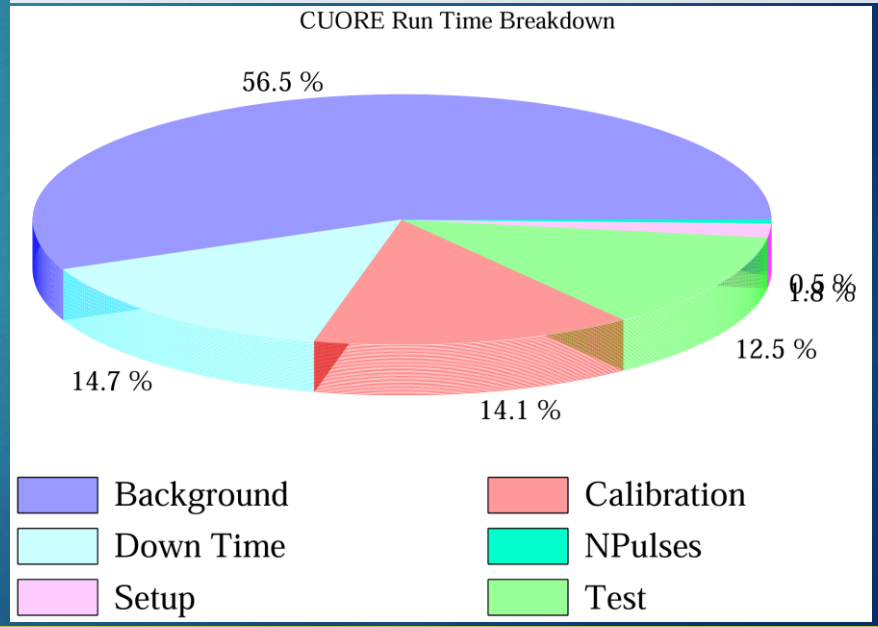


① Alduino, C. et al. (CUORE Collaboration), Phys. Rev. Lett. 120, 132501 (2018)

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)

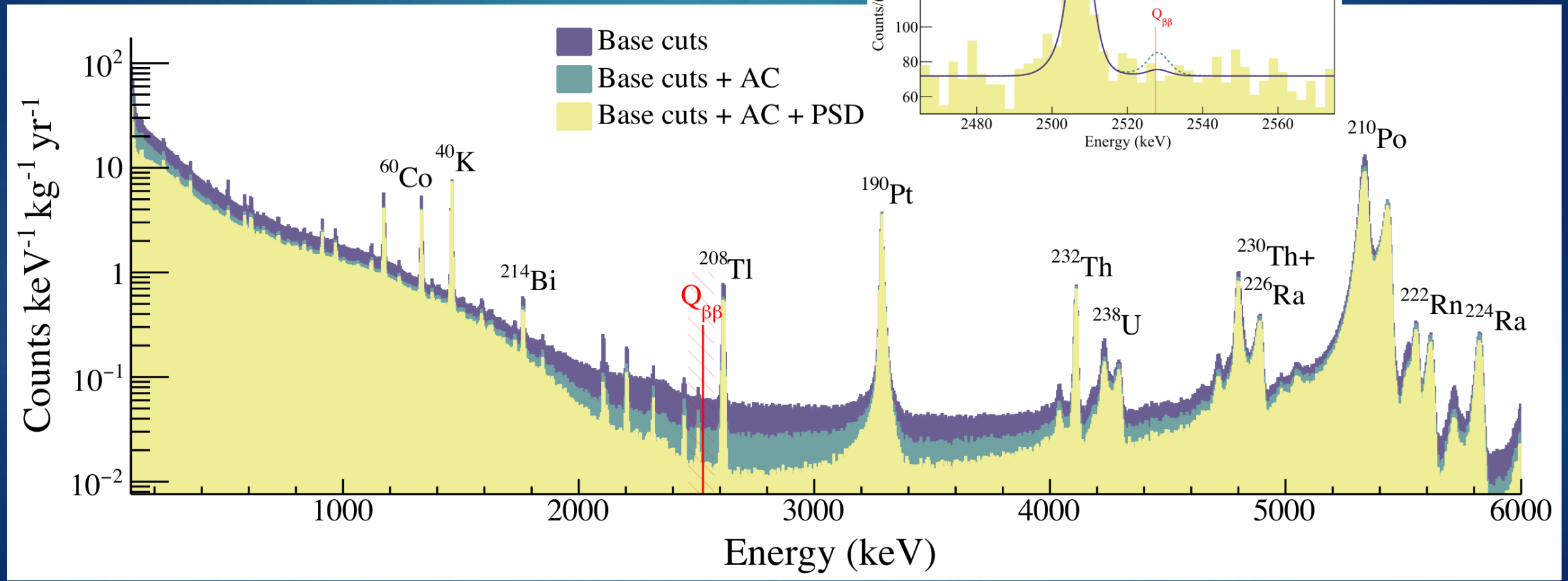
④ Adams, D. Q. et al. (CUORE Collaboration), **Science** 390,1029-1032(2025)



2 ton · yr exposure

- Bayesian limit: $T_{1/2}^{0\nu} > 3.5 \cdot 10^{25}$ yr @ 90% C.I.

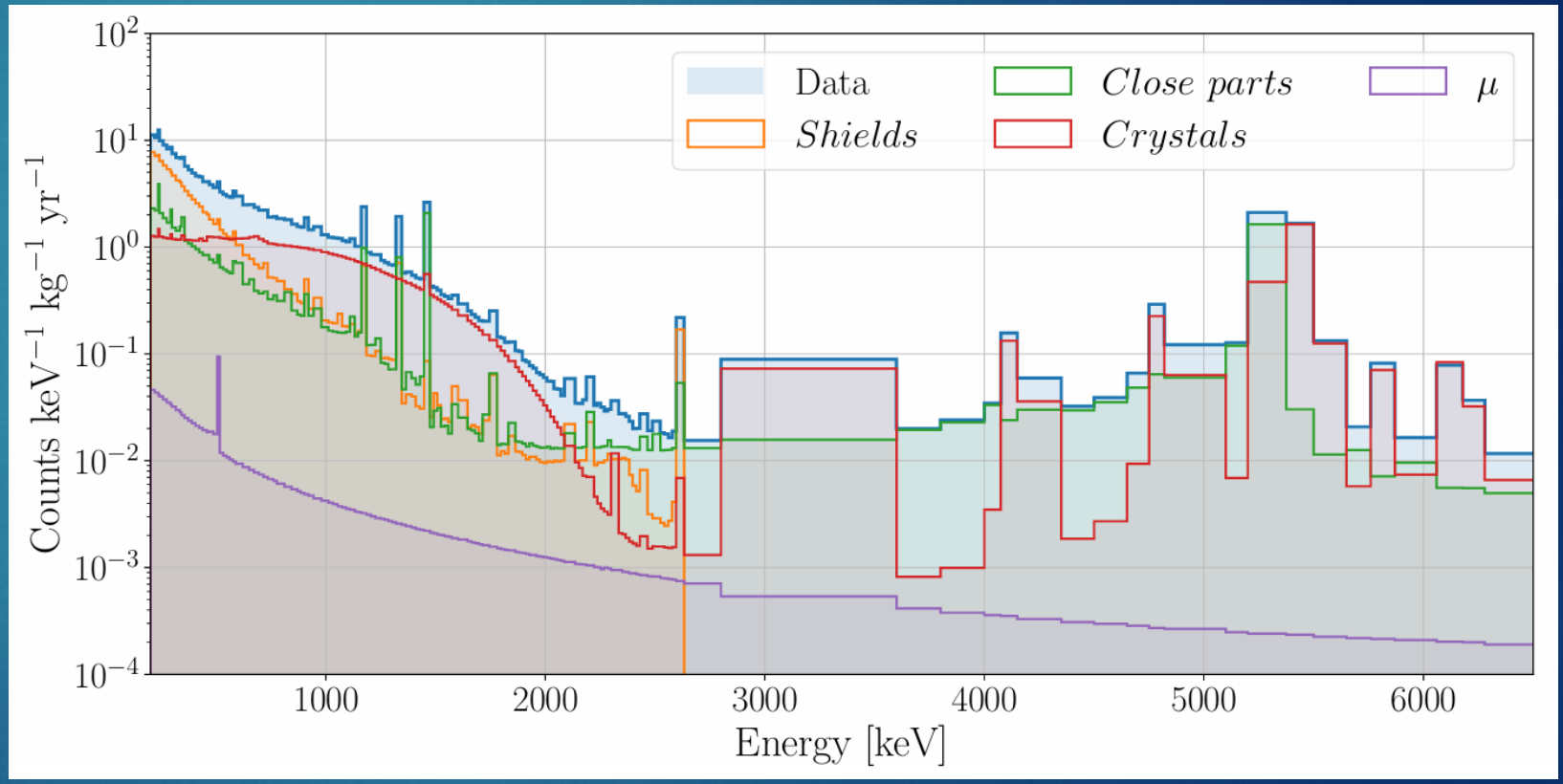
Adams, D. Q. et al. (CUORE Collaboration), **Science** 390,1029-1032(2025)



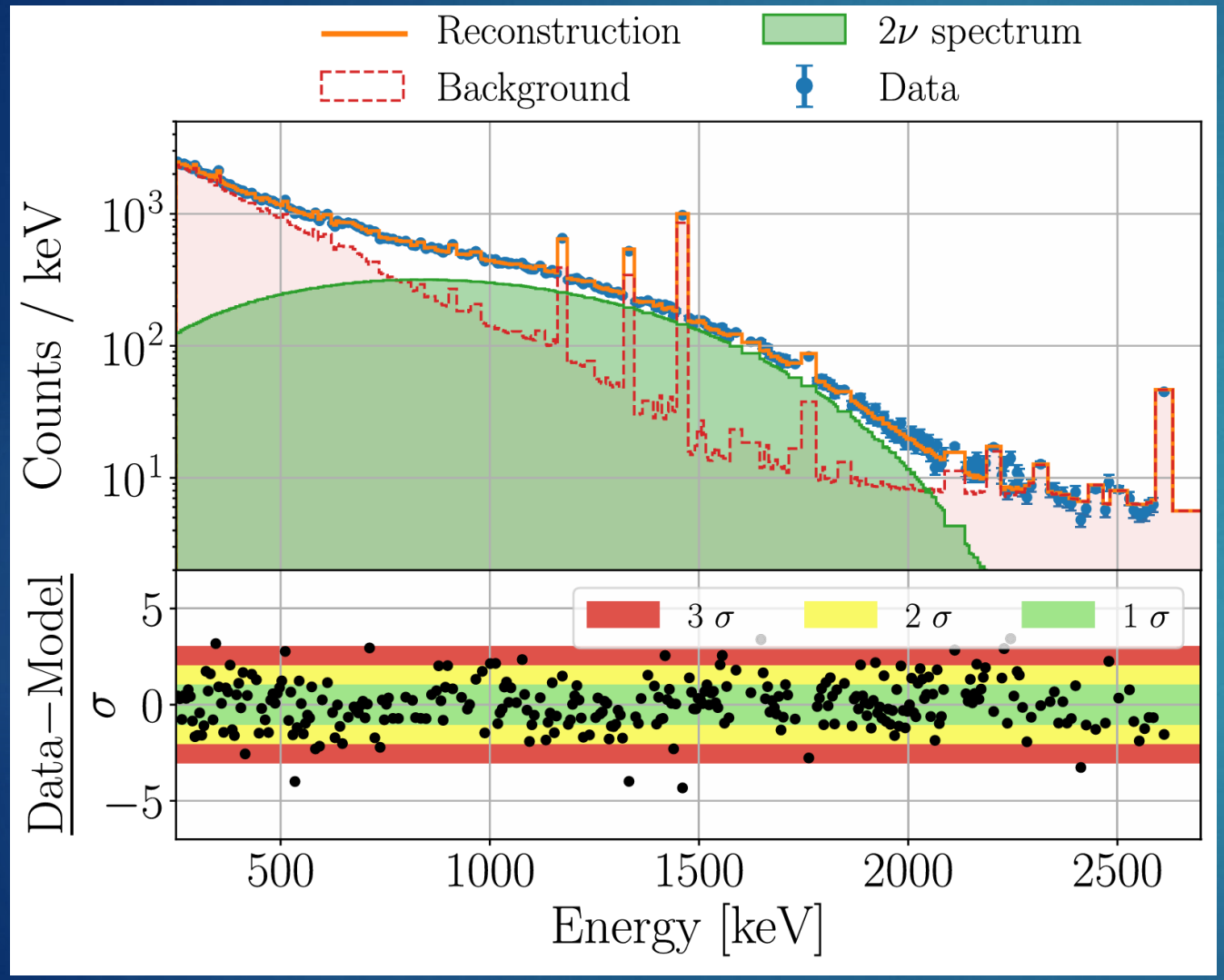
Background model results

- 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

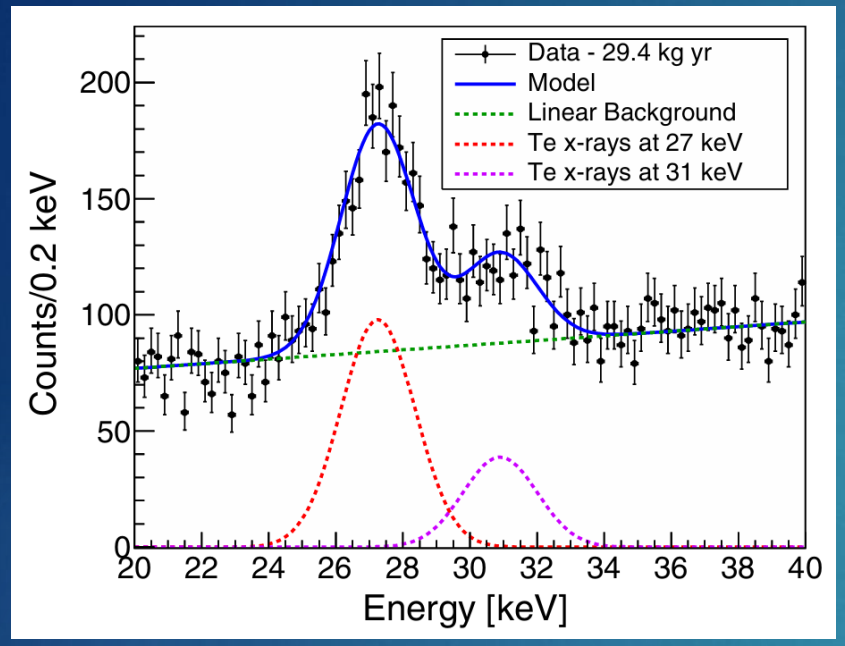


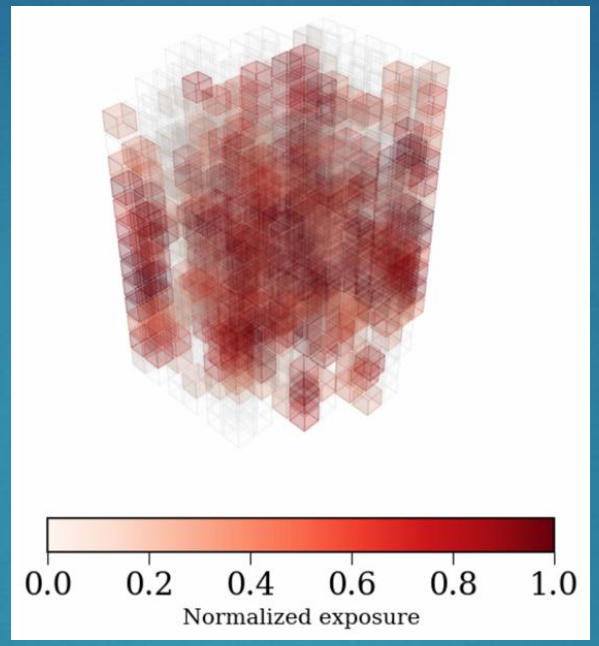
- ^{130}Te 2νββ component from background model fit to single hits (M1) data
- ^{130}Te 2νββ > 50% of events in the 1~2 MeV energy region
- Spectral fit
- $T_{1/2}^{2\nu} = 9.32^{+0.05}_{-0.04}(\text{stat.})^{+0.07}_{-0.07}(\text{syst.}) \times 10^{20}$ yr
- Most precise measurement of ^{130}Te 2νββ decay half-life to date

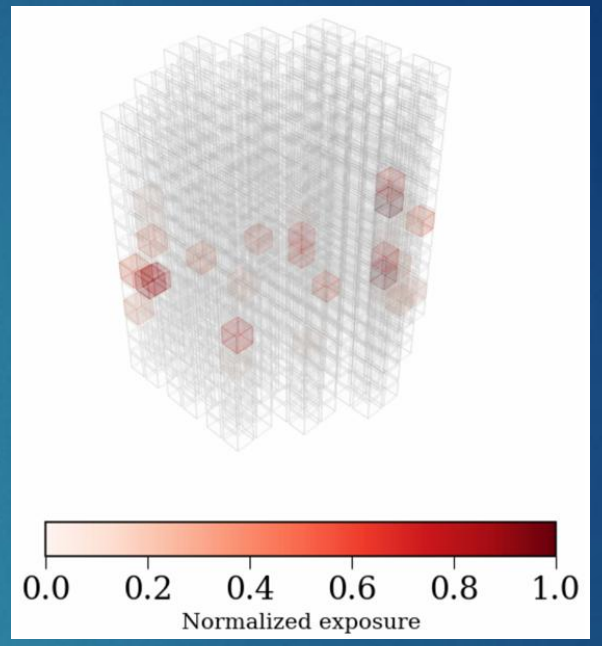
Adams, D.Q. et al. (CUORE Collaboration), Phys. Rev. Lett. 135, 082501 (2025)

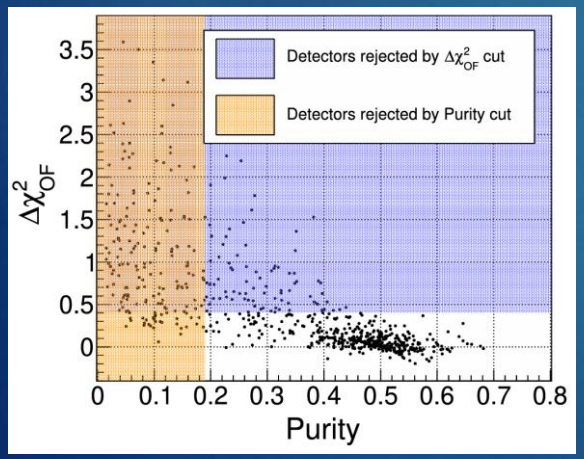
Exploring the keV-scale

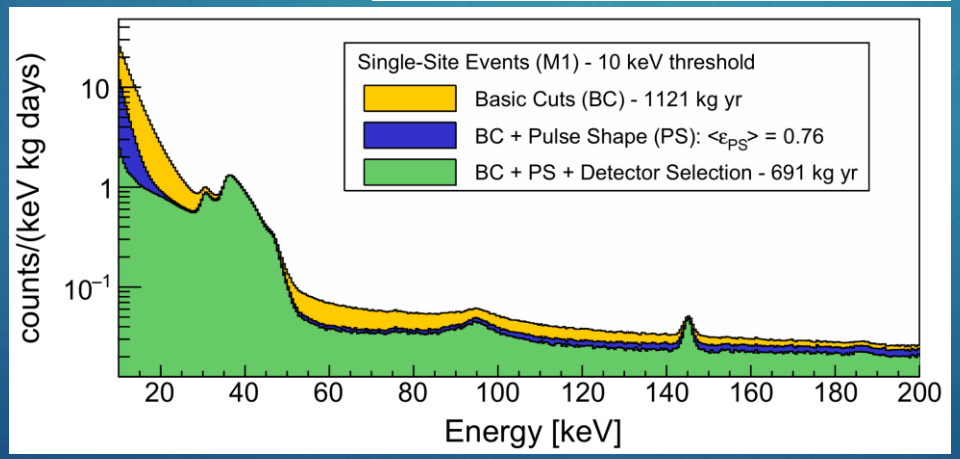
Adams, D.Q. et al. (CUORE Collaboration), Phys. Rev. D 113, 012012 (2026)

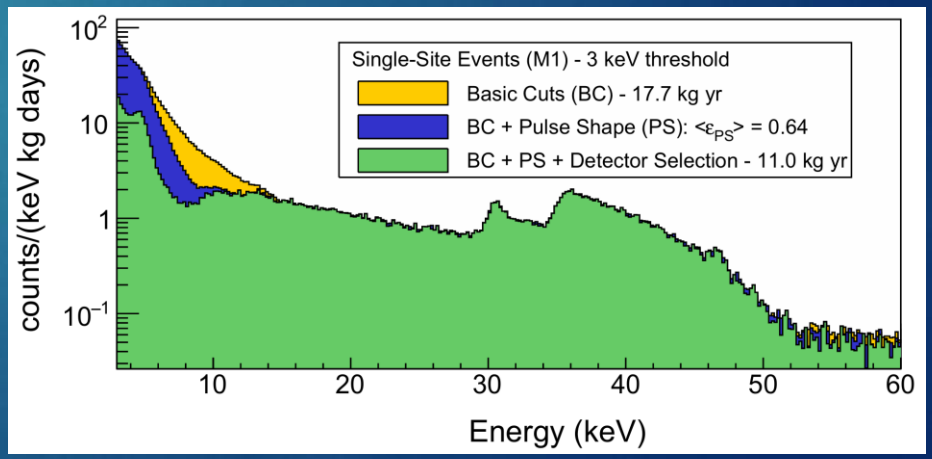






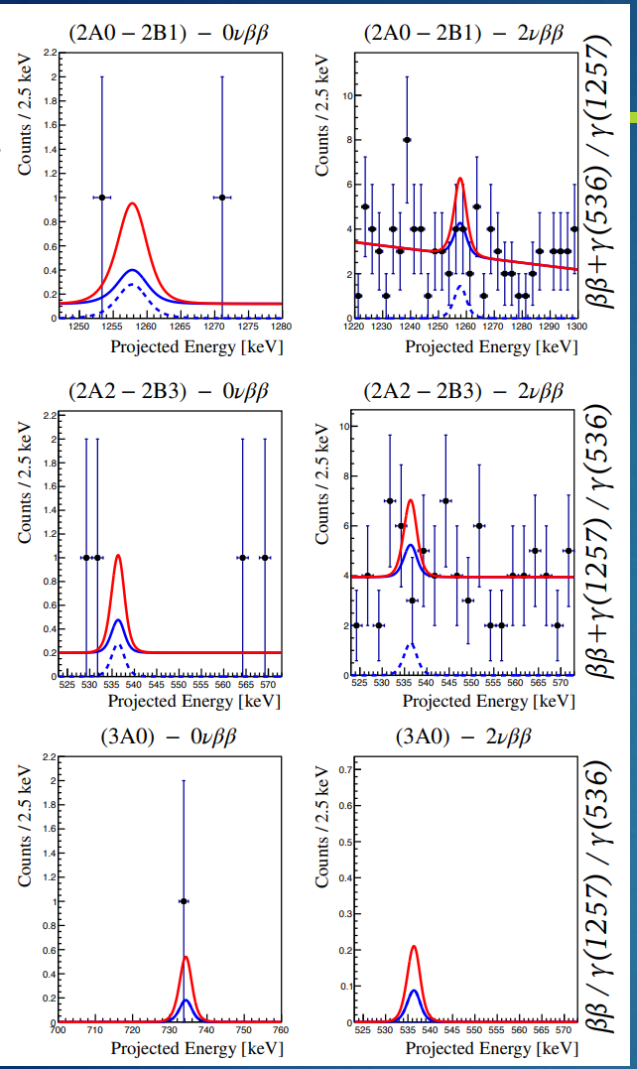




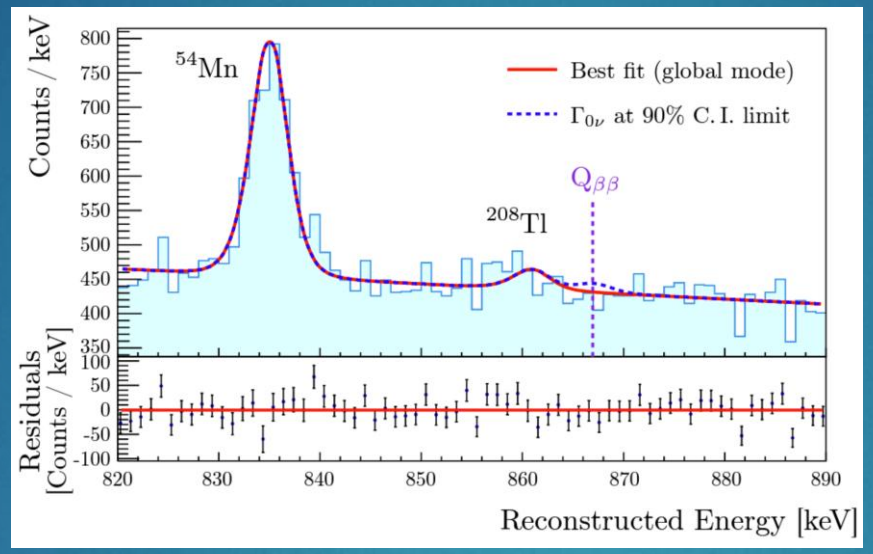


Other rare event searches

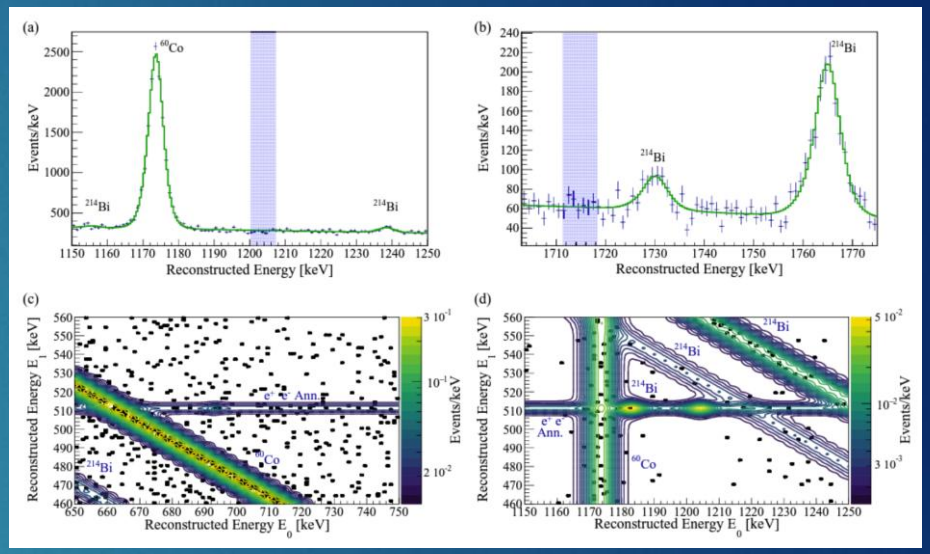
^{130}Te $\beta\beta$ to first 0^+ excited state



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



^{128}Te β^+/EC



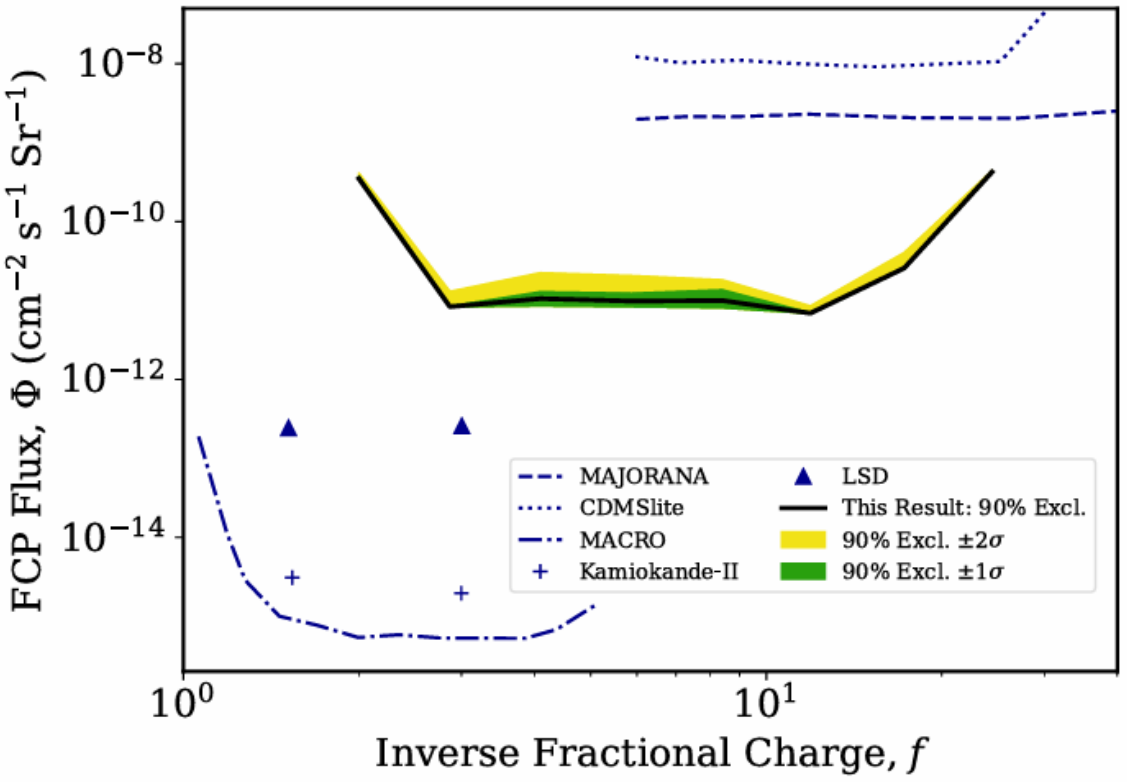
Adams, D.Q. et al. (CUORE Collaboration), Phys. Rev. Lett. 129, 222501 (2022)

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)

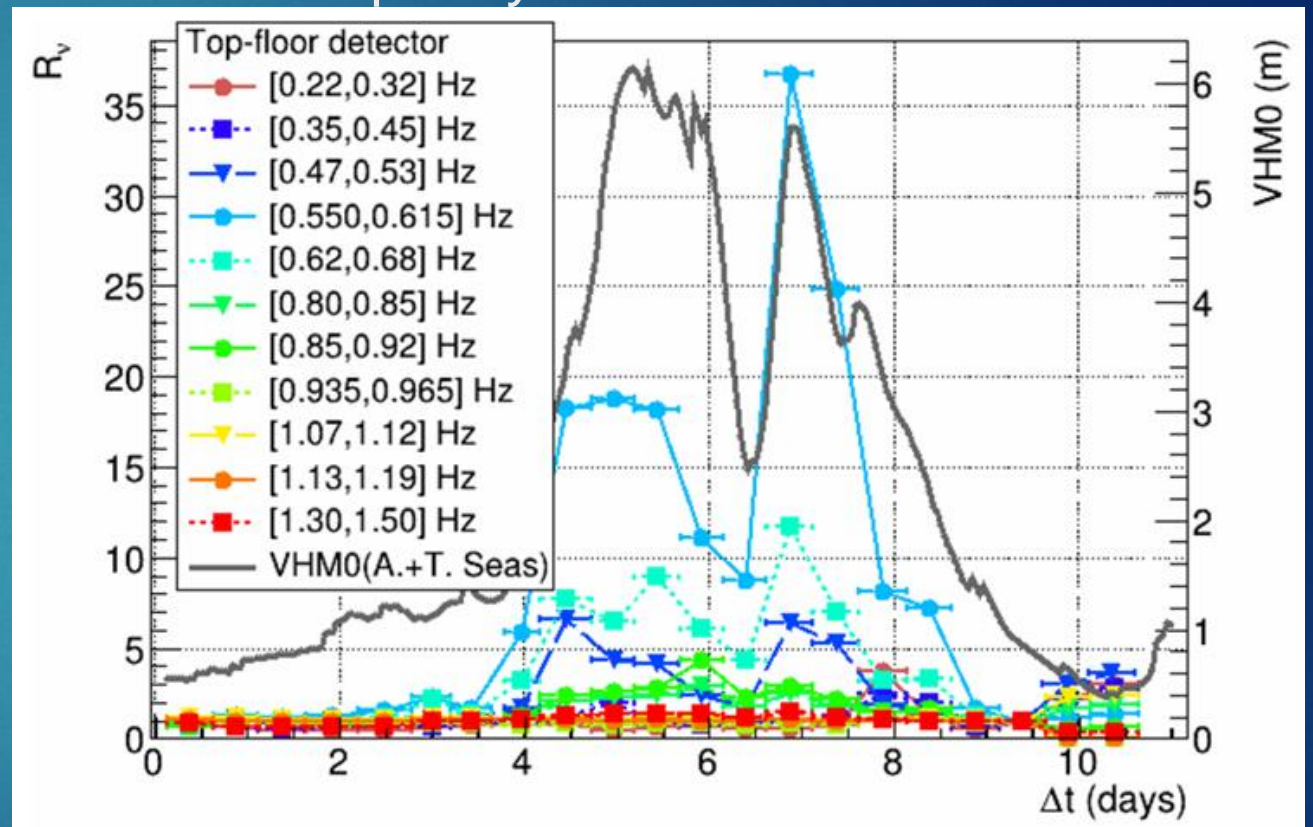
Other searches

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



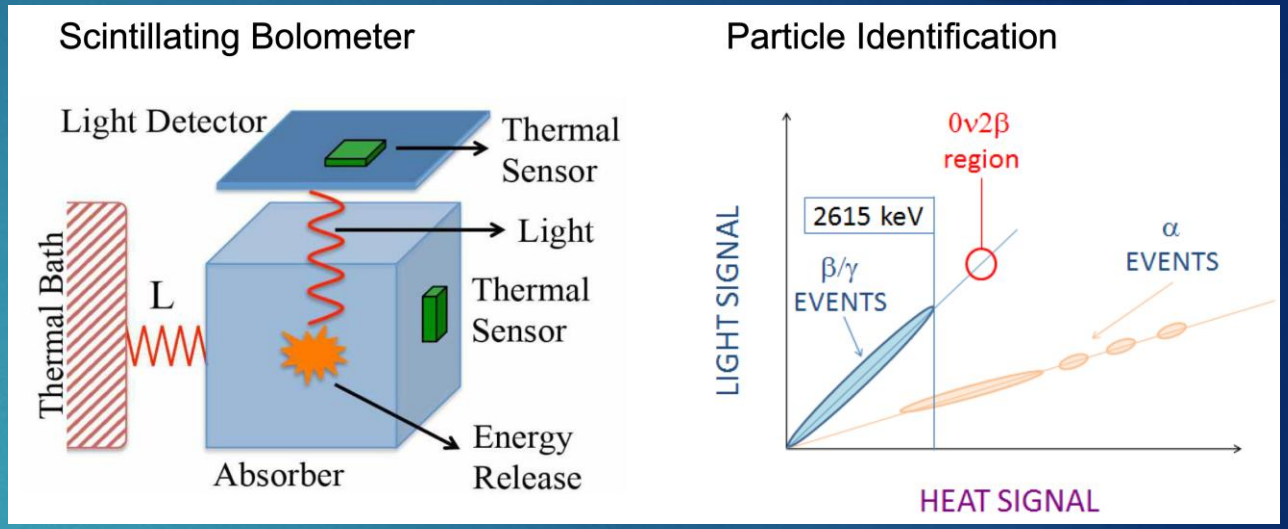
Aragão, L. et al., Eur. Phys. J. C 84, 728 (2024)

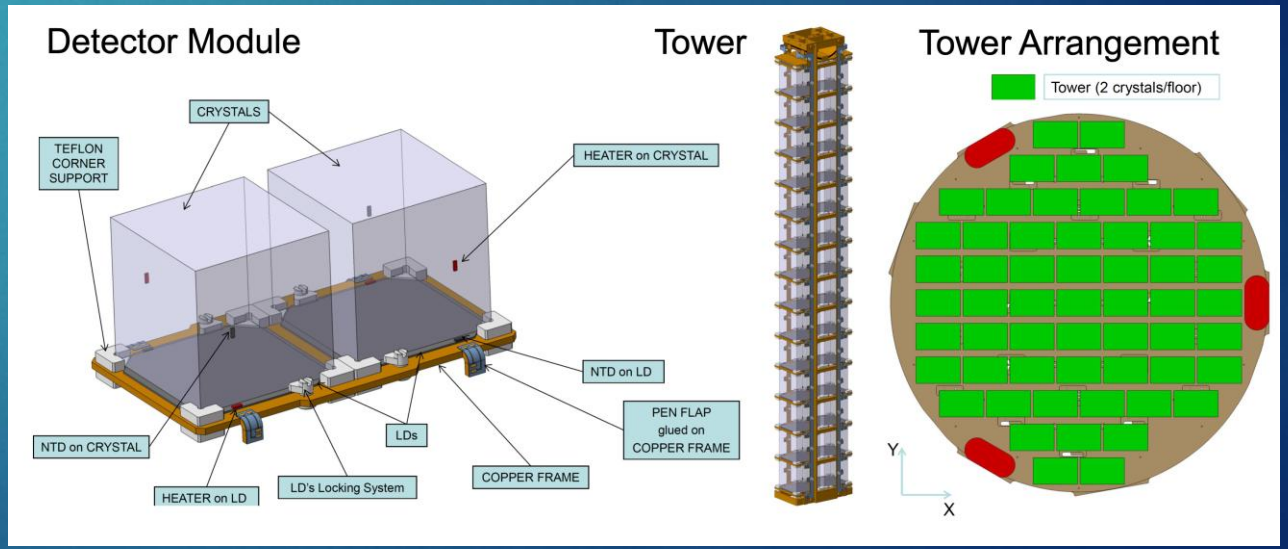
What's next?

- CUORE phase-I (current)
  - Run up to mid-2026
  - 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 $Q_{\beta\beta}$

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)





Proposed thesis topics

- Data Analysis and Processing
  - List of the possible analysis in CUORE (excited states..., on $3\ \mathrm{ton} \cdot \mathrm{yr}$ 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

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 $\mathbf{3.1\ ton{\cdot}yr\ TeO_2}$ 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 $2\ \mathrm{ton{\cdot}yr\ TeO_2}$ data.
- No evidence of $0\nu\beta\beta$ decay with observed data.
  - Bayesian 90% C.I. limit.

$$T_{1/2}^{0\nu} > 3.5 \cdot 10^{25}\ \mathrm{yr}\ @\ 90\%\ \mathrm{C.I.}$$

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

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

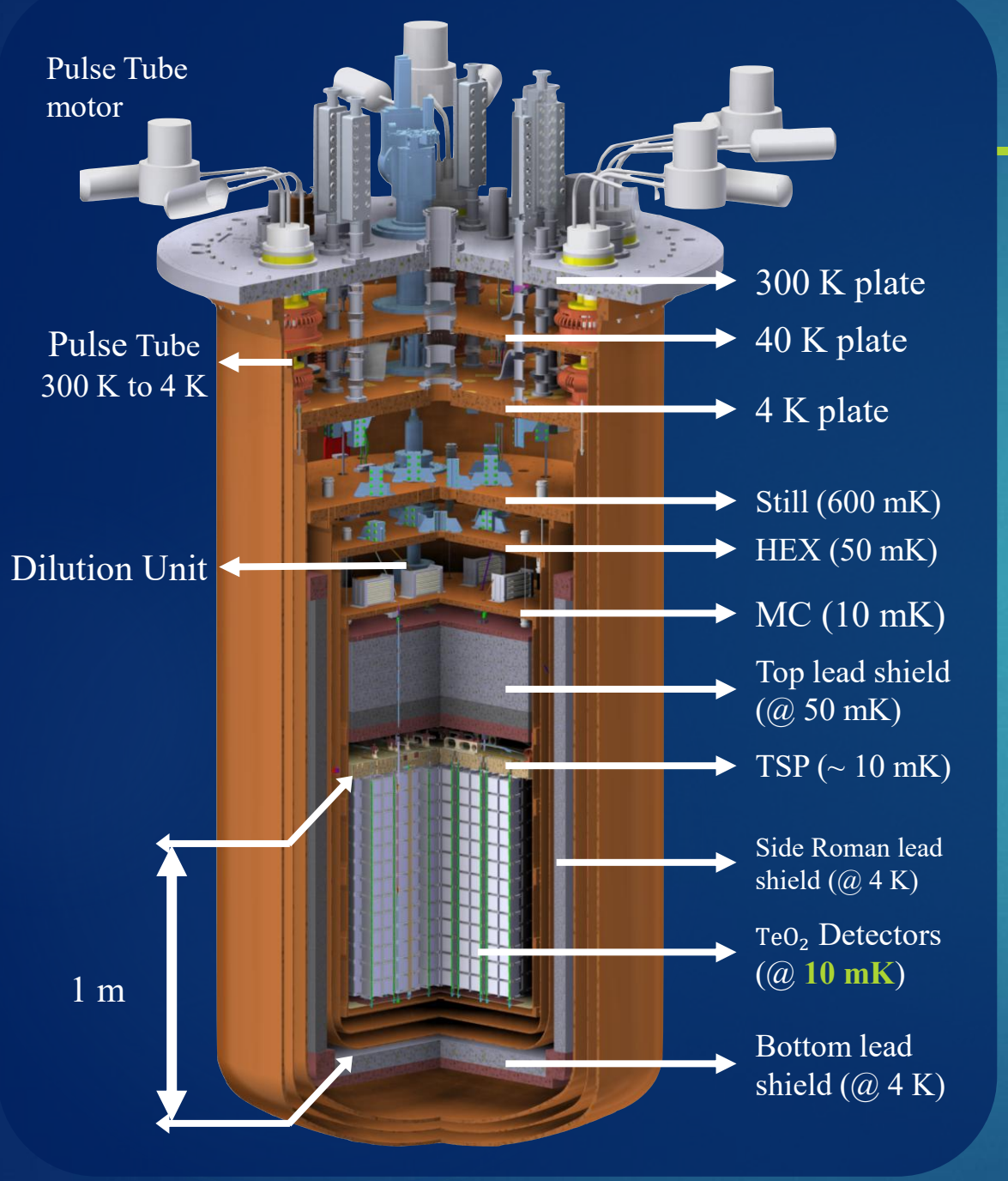
- CUORE will continue to take data until it reaches $^{130}\mathrm{Te}$ exposure of $1\ \mathrm{ton \cdot yr}$, *i.e.*, $3\ \mathrm{ton \cdot yr\ TeO_2}$ exposure.
- Thanks for the unique feature of allow deployment of different isotopes by using the same infrastructure.

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

Thank you for your attention!

Backup

CUORE Cryostat

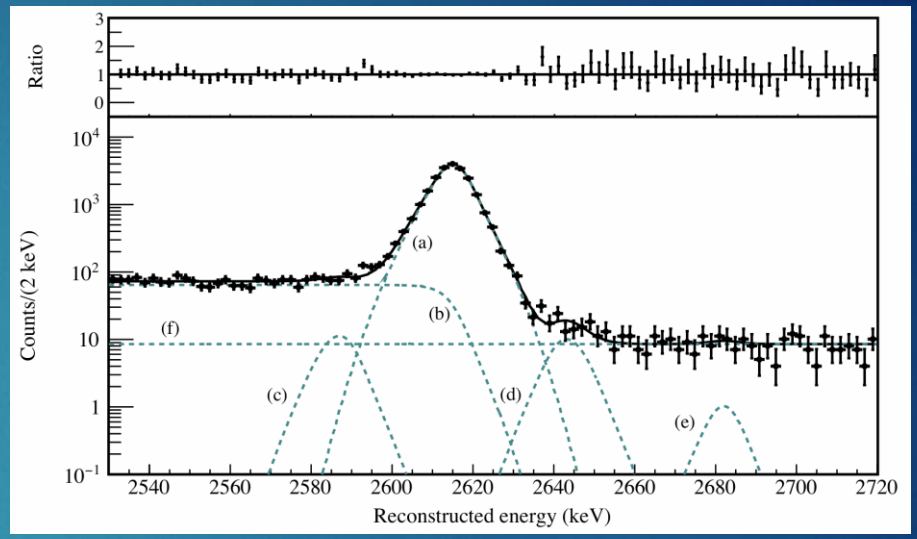


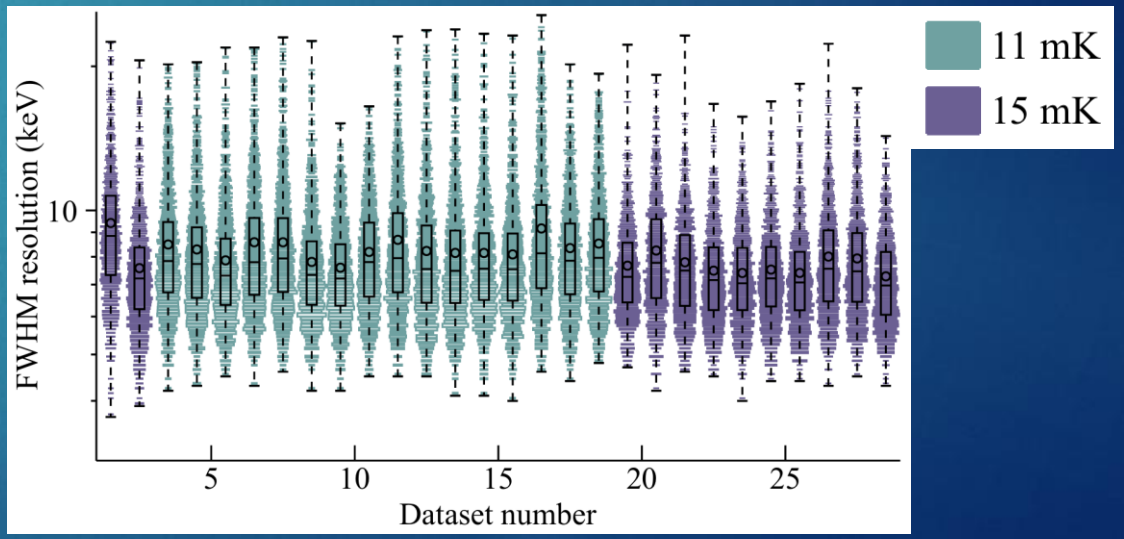
- Custom-made dry dilution refrigerator
- 1.5 t of material at base temperature for ~5 years!
- 5 pulse-tube refrigerators (1 spare)
  - Relative phases tuned for noise cross-canceling
- 6 nested vessels at decreasing temperatures
- Low-temperature lead shielding
  - Modern lead on top of detectors to 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

Adams, D. Q. et al. (CUORE Collaboration), **Science** 390,1029-1032(2025)

- 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 = $(7.540 \pm 0.024)\ \mathrm{keV}$
    - harmonic mean - exposure weighted

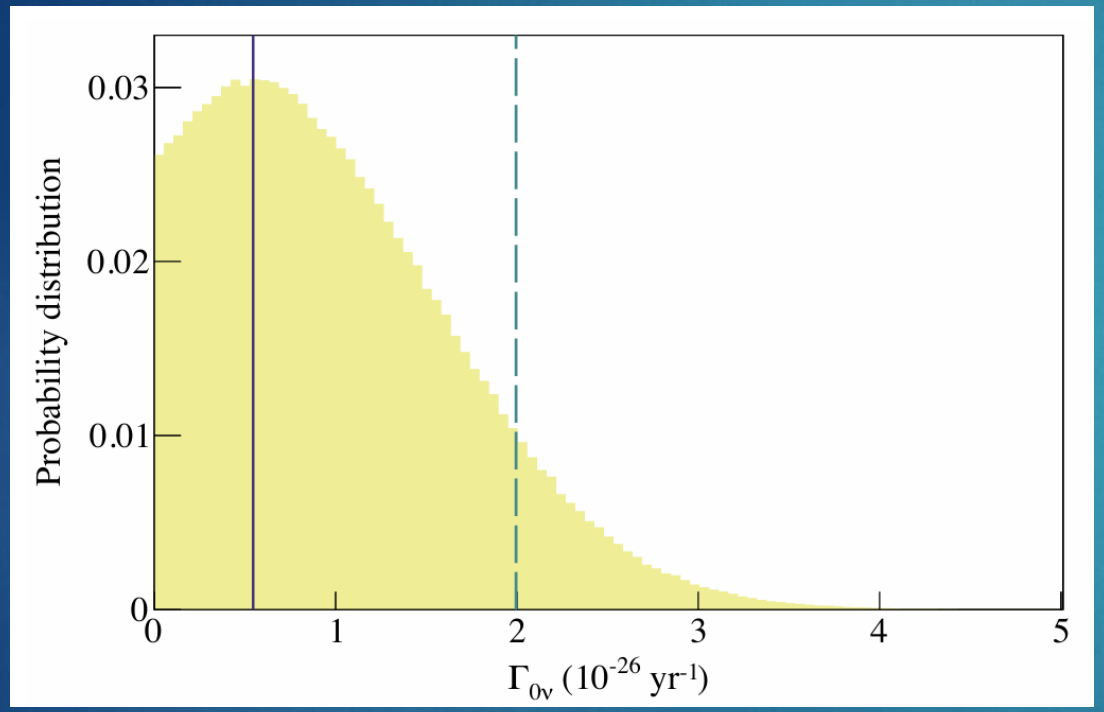




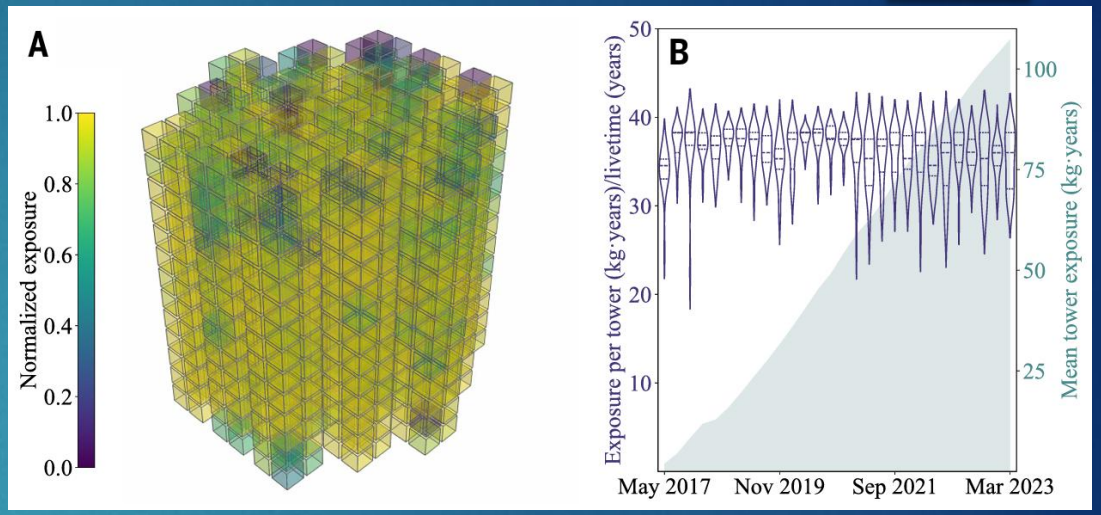
$0\nu\beta\beta$ decay results

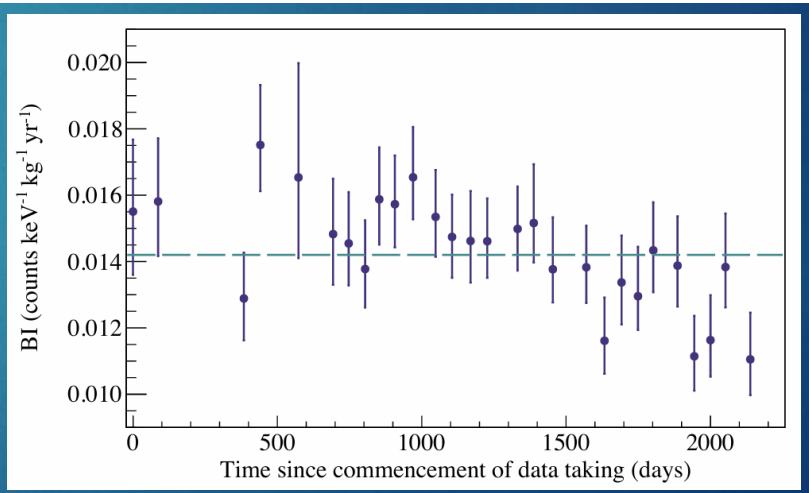
Adams, D. Q. et al. (CUORE Collaboration), **Science** 390,1029-1032(2025)

- Resolution scaling
  - FWHM at $Q_{\beta\beta} = (7.310 \pm 0.024)$ keV



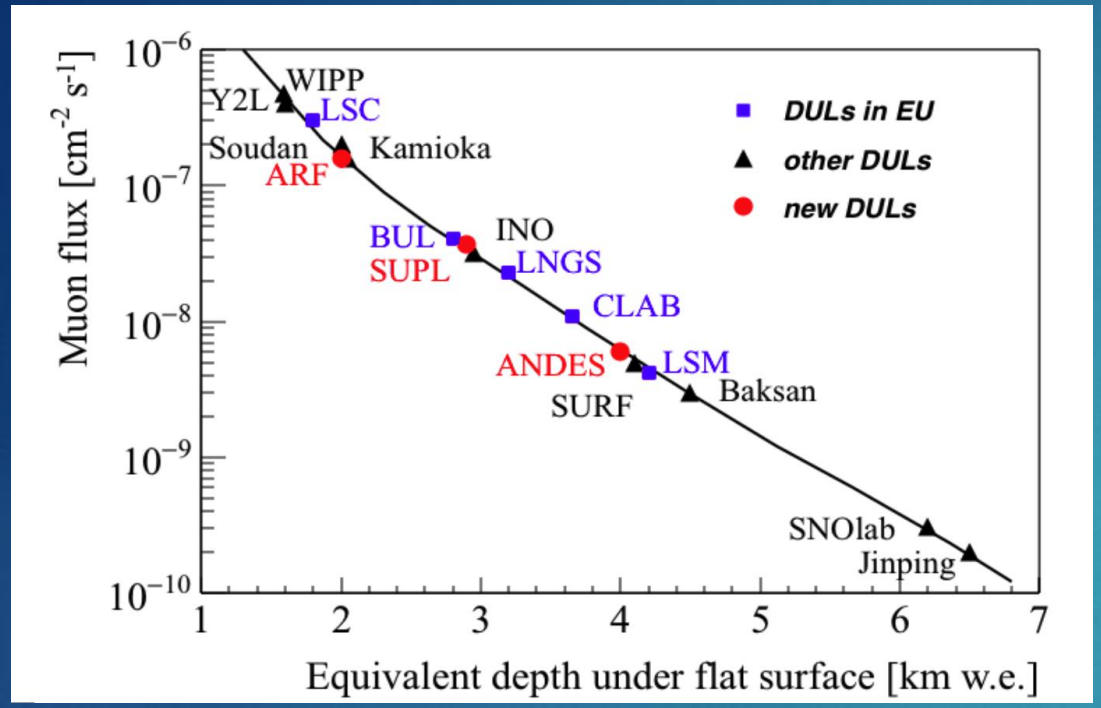
- Bayesian limit: $T_{1/2}^{0\nu} > 3.5 \cdot 10^{25}$ yr @ 90% C.I.



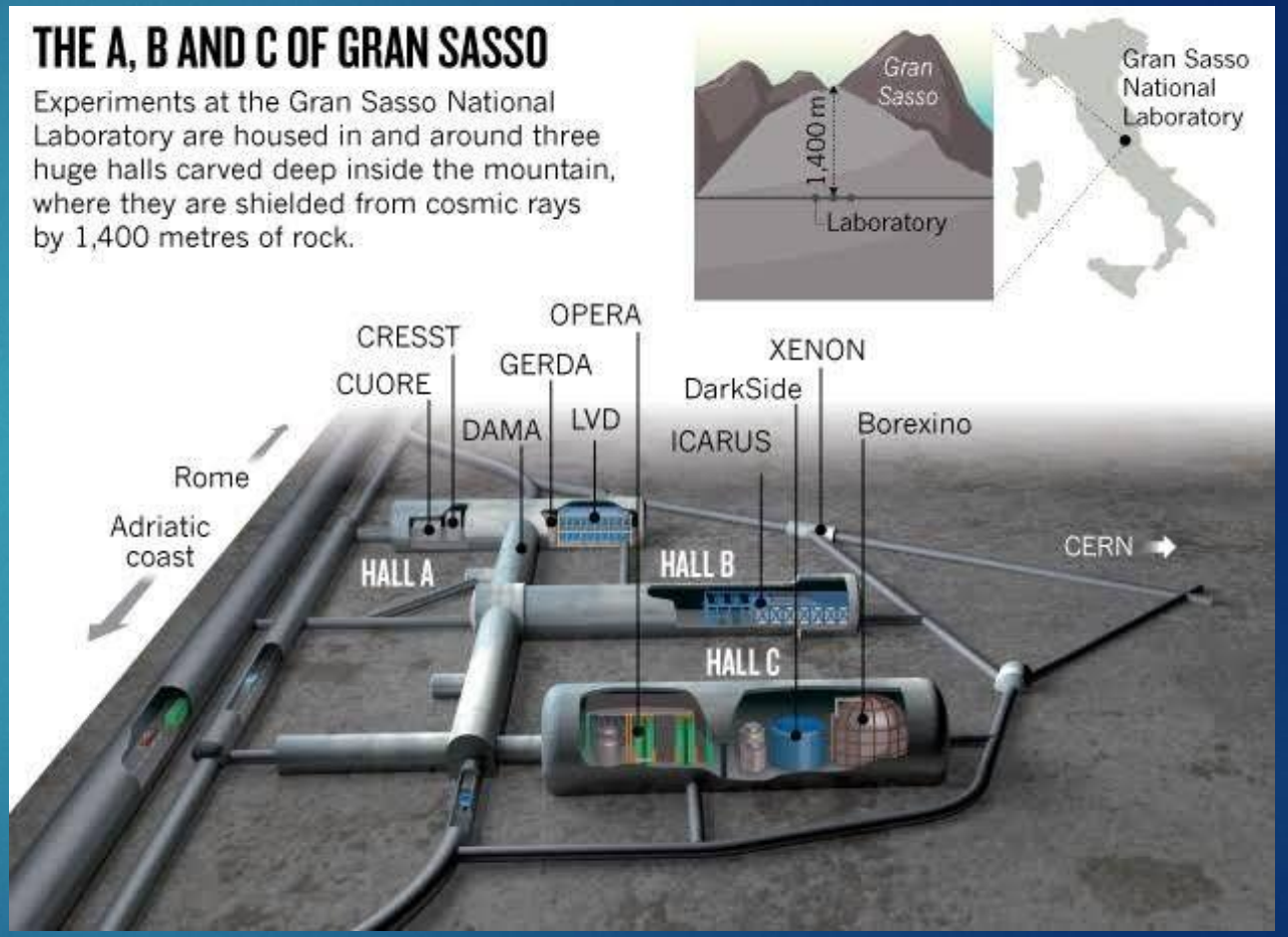


- BI: $(1.42^{+0.03}_{-0.02}) \cdot 10^{-2}$ counts / (keV · kg · yr)

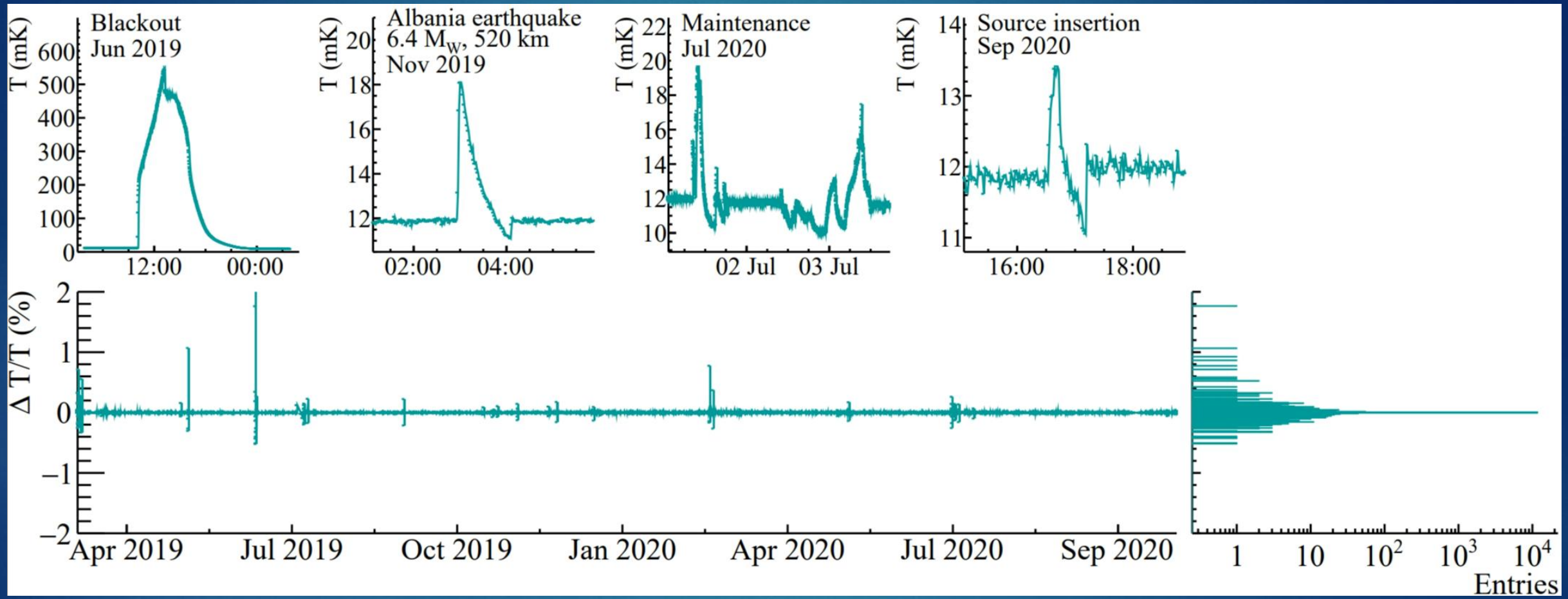
Laboratori Nazionali del Gran Sasso - Italy



- 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)