Latest Results from the CUORE Experiment

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on behalf of the CUORE collaboration

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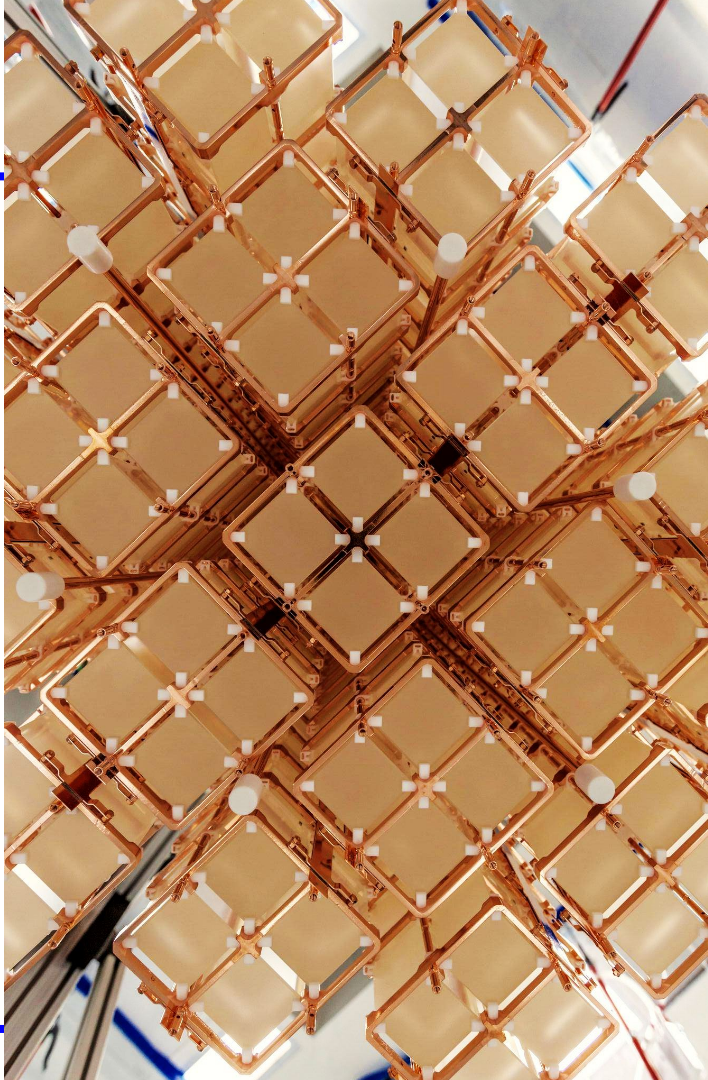
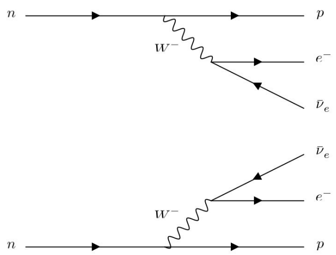
ALPS 2023



Double beta ($2\nu\beta\beta$) decay

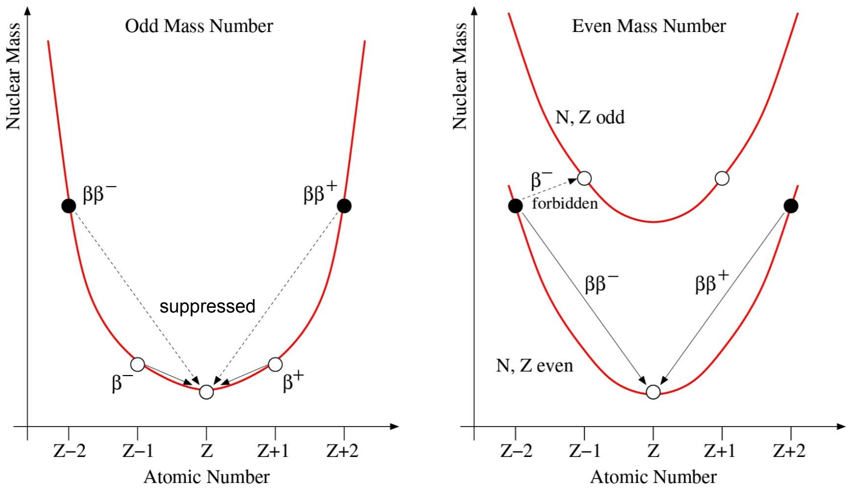
- 2nd order weak process, allowed by the Standard Model:

$$2\nu\beta^-\beta^- : (A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$$
$$2\nu\beta^+\beta^+ : (A,Z) \rightarrow (A,Z-2) + 2e^+ + 2\nu_e$$



- Observed on 14 even-even nuclei for which β decay is energetically forbidden (^{48}Ca, ^{76}Ge, ^{82}Se, ^{100}Mo, ^{128}Te, ^{130}Te, ^{136}Xe, ...).

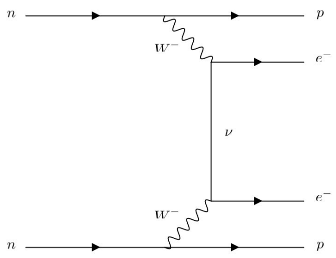
- Half-lives: $T_{1/2}^{2\nu} \sim 10^{18}$ - 10^{22} yr.



Neutrinoless double beta ($0\nu\beta\beta$) decay

- 2^{nd} order weak process, **not allowed by the Standard Model**:

$$0\nu\beta^-\beta^- : (A,Z) \rightarrow (A,Z+2) + 2e^-$$
$$0\nu\beta^+\beta^+ : (A,Z) \rightarrow (A,Z-2) + 2e^+$$

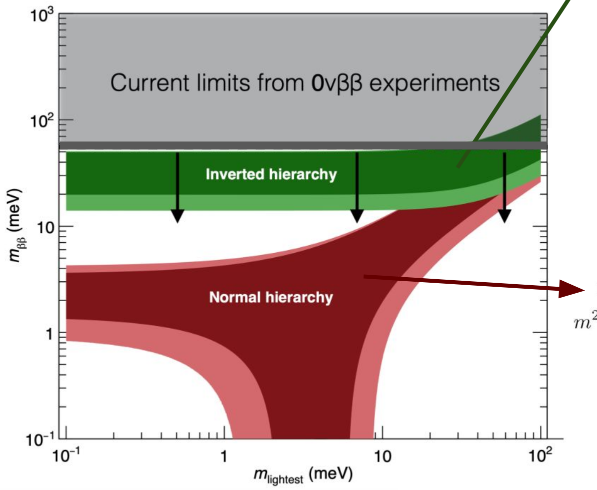


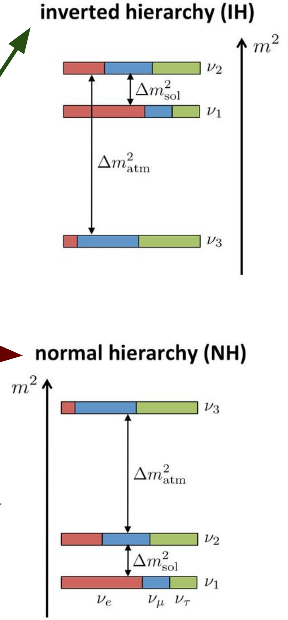
- Never observed → Half-lives: $T_{1/2}^{0\nu} > 10^{24} - 10^{26}$ yr.

- $0\nu\beta\beta$ decay observation would establish:
  - ➢ violation of the lepton number ($\Delta L = 2$);
  - ➢ neutrinos as Majorana particles ($\nu \equiv \bar{\nu}$);
  - ➢ constraints on neutrino mass scale and hierarchy:

$$T_{1/2}^{0\nu} = \left[G_{0\nu} g_A^4 \left| M_{0\nu} \right|^2 \frac{m_{\beta\beta}^2}{m_e^2} \right]^{-1}$$

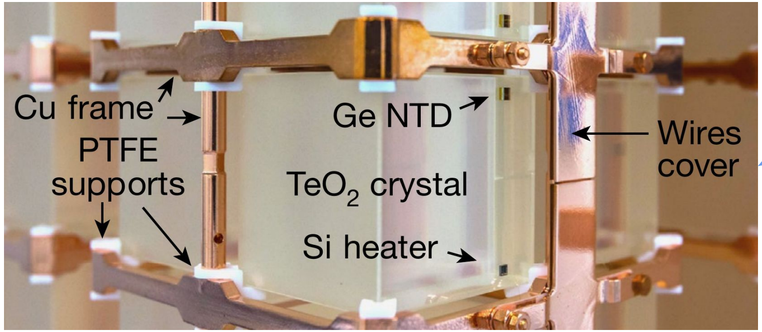
Experimental observable | Phase space factor | Nuclear physics | Effective Majorana mass: $m_{\beta\beta} = \left| \sum_{k=1}^{3} U_{ek}^2 m_k \right|$

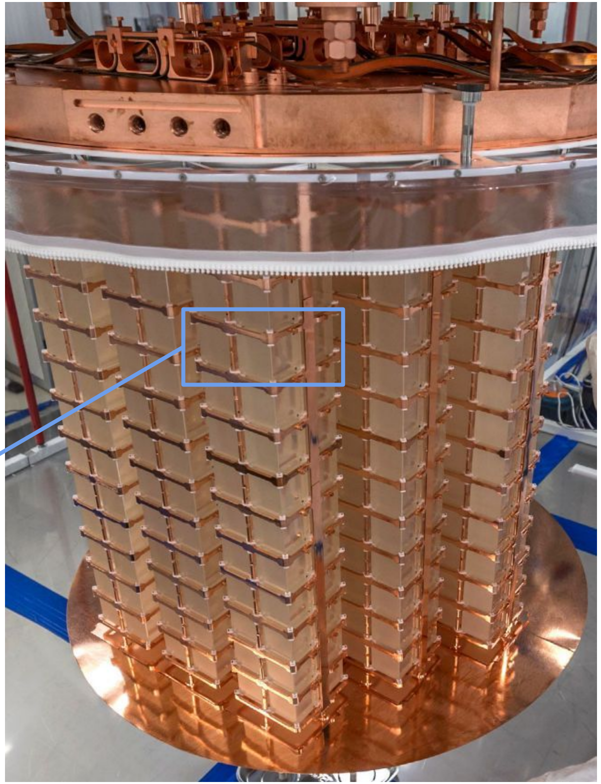




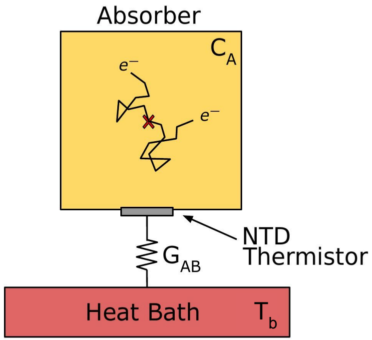
CUORE experiment

- **CUORE** (**C**ryogenic **U**nderground **O**bservatory for **R**are **E**vents):
  - search for $0\nu\beta\beta$ decay of ^{130}Te;
  - 988 TeO_2 crystals (5x5x5 cm^3) with natural ^{130}Te isotopic abundance (34%);
  - total mass: 742 kg of TeO_2 , **206 kg of ^{130}Te**;
  - operated at ≃15 mK;
  - crystals equipped with Ge-NTDs thermal sensors;
  - hosted underground in Gran Sasso National Laboratory (LNGS, Italy) for cosmic rays muons suppression (by factor ~10^6 w.r.t. above-ground).

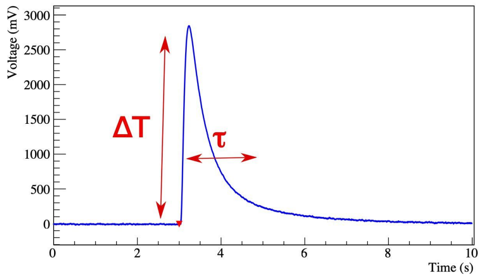




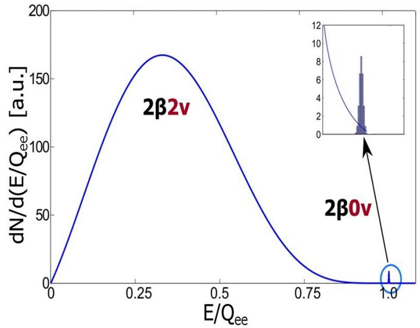
Low-temperature calorimeters



- Working principle of low-temperature calorimeters:
  energy deposition ΔE in the absorber (TeO_2 crystals)
  ↓
  temperature increase proportional to energy deposition:
  $\Delta T \propto \Delta E / C_A(T) \sim 0.1$ mK/MeV
  ↓
  change of the resistance of the thermal sensor: $R_{NTD}(T) = R_0 e^{\sqrt{\frac{T_0}{T}}}$
  ↓
  electric signal generation;
  ↓
  heat dissipation to heat bath (constant T) → restoration of initial temperature ($\tau \sim 1$ s).



- $\beta\beta$-decaying isotope is embedded in the crystals
  ↓
  high containment efficiency of both electrons within a single crystal ($\simeq$ 88%);
  ↓
  experimental signature of $0\nu\beta\beta$ decay:
  peak in the two-electrons sum-energy spectrum,
  at Q-value of the $\beta\beta$ decay: $Q_{\beta\beta}(^{130}Te) = 2527.5$ keV.



Experimental sensitivity to $0\nu\beta\beta$ decay

- Experimental sensitivity $S^{0\nu}$ to $0\nu\beta\beta$ decay:

$$S^{0\nu} = \frac{\ln 2}{n_\sigma} \frac{\varepsilon x \eta N_A}{M_A} \sqrt{\frac{MT}{B\Delta}}$$

experimental efficiency (ε) — isotopic abundance (η) — statistical confidence level (n_σ)

Exposure = $\beta\beta$-isotope mass · measure time

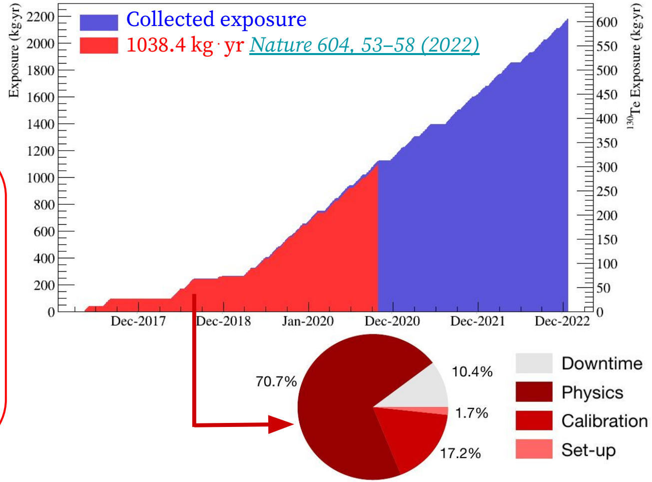
CUORE achievements:

➢ ton-scale cryogenic experiment;

➢ stable and uninterrupted data taking since April 2019;

➢ August 2020: 1 t · yr TeO_2 exposure reached (288.8 kg · yr ^{130}Te exposure) (*Nature 604, 53–58 (2022)*);

➢ October 2022: **2 t · yr TeO_2 exposure** reached (data processing ongoing).



Background index in the ROI

In CUORE:

➢ strict radiopurity selection on crystals and passive materials;

➢ passive shields against external and cryostat radioactivity;

➢ ***B* = 1.49(4)·10^{-2} counts/(keV · kg · yr)**

Energy resolution in the ROI

In CUORE:

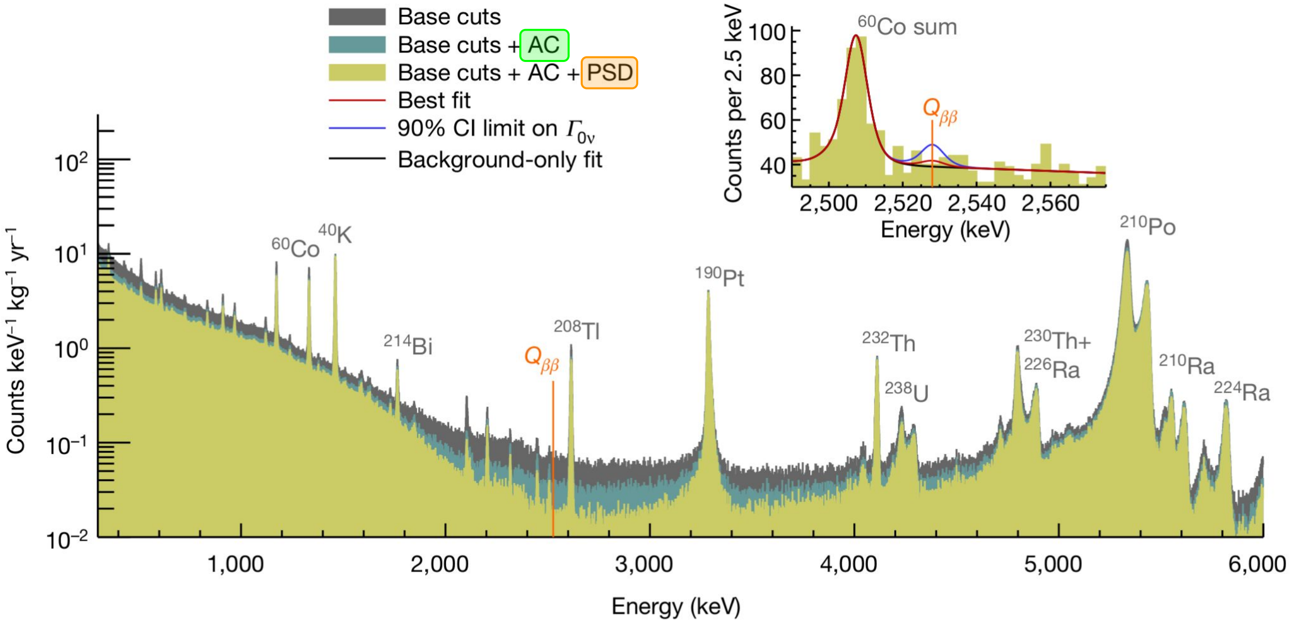
➢ monitor temperature stability;

➢ noise reduction techniques;

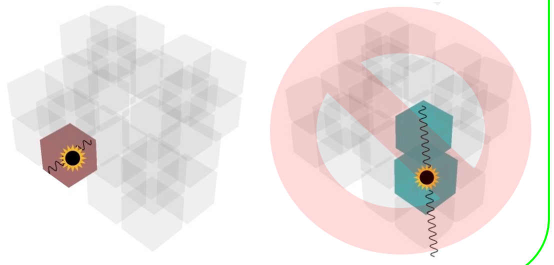
➢ **FWHM($Q_{\beta\beta}$) = (7.8 ± 0.5) keV**
FWHM($Q_{\beta\beta}$)/$Q_{\beta\beta}$ = 0.3%

CUORE energy spectrum

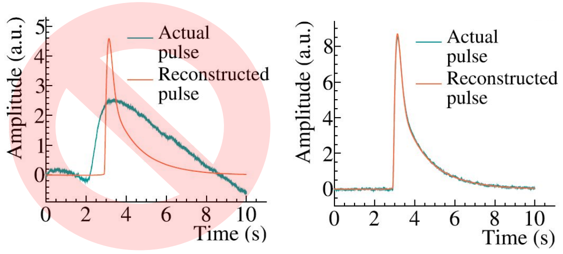
- CUORE energy spectrum at **1038.4 kg·yr TeO_2 (288.8 kg·yr ^{130}Te) exposure** (*Nature 604, 53–58 (2022)*):



Anti-Coincidence (AC) cut:



Pulse Shape Discrimination (PSD):

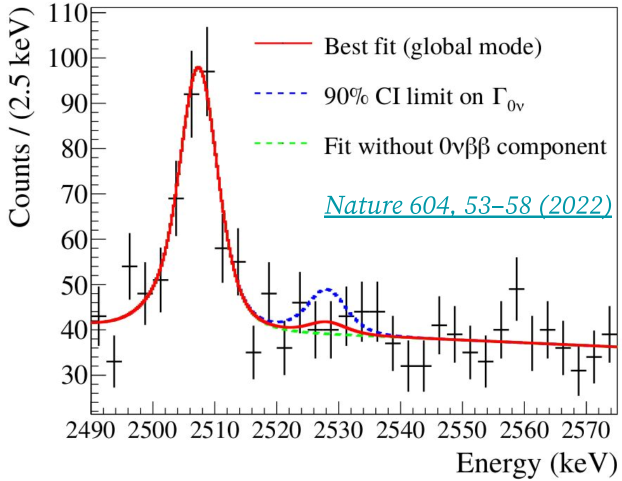


Search for $0\nu\beta\beta$ decay of ^{130}Te

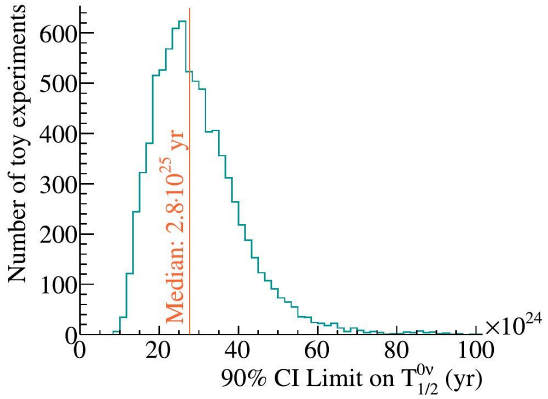
- Model of the ROI = (2490, 2575) keV:
  - ➢ linear background (90% due to degraded-α particles);
  - ➢ ^{60}Co γ-peak @ 2505.7 keV;
  - ➢ $0\nu\beta\beta$ peak @ $Q_{\beta\beta}(^{130}Te)$ = 2527.5 keV.

- Unbinned Bayesian fit of data (**1038.4 kg·yr TeO_2 exposure**):
  - ➢ no evidence of $0\nu\beta\beta$ decay;
  - ➢ world-leading lower limit on half-life of ^{130}Te $0\nu\beta\beta$ decay:

$$T_{1/2}^{0\nu}\,(^{130}\mathrm{Te}) > 2.2\cdot10^{25}\ \mathrm{yr}\ (90\%\ \mathrm{C.I.})$$



- 10^4 toy experiments (background-only model, no $0\nu\beta\beta$ decay):
  - ➢ median exclusion sensitivity:
    $T_{1/2}^{0\nu}\,(^{130}\mathrm{Te}) > 2.8\cdot10^{25}$ yr (90% C.I.);
  - ➢ 72% probability of obtaining a stronger limit.



Limits on $m_{\beta\beta}$

- Assuming $0\nu\beta\beta$ decay mediated by light neutrino exchange:

$$T_{1/2}^{0\nu} = \left[G_{0\nu} g_A^4 \left| M_{0\nu} \right|^2 \frac{m_{\beta\beta}^2}{m_e^2} \right]^{-1}$$

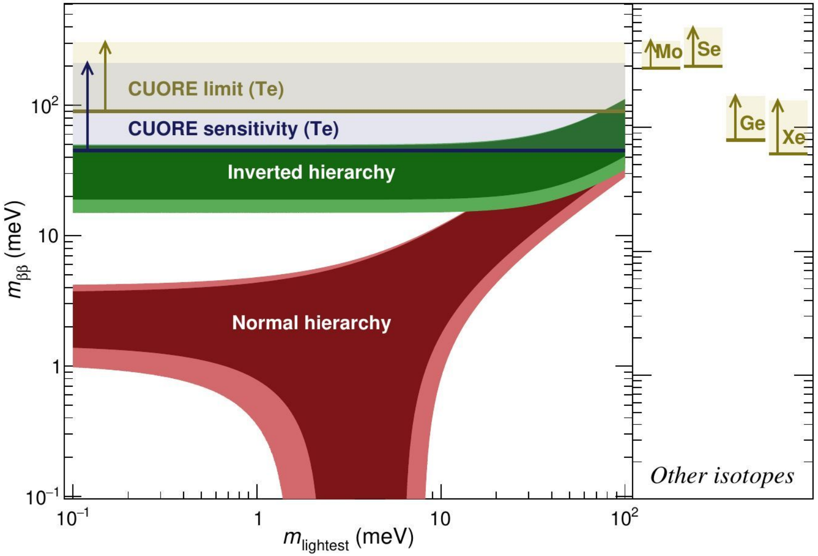
Nuclear matrix element (NME)

↓

upper limit on effective Majorana mass:

➢ **$m_{\beta\beta}$ < 90 - 305 meV (90% C.I.)**

➢ $m_{\beta\beta}$ spread due to uncertainties on Nuclear Matrix Element (NME) calculations.



Measurement of $2\nu\beta\beta$ decay of ^{130}Te

- CUORE background model:
  - ➢ $2\nu\beta\beta$ decay of ^{130}Te;
  - ➢ 60 radioactive contaminants (in crystals and cryostat structure);
  - ➢ cosmogenic muons.

+

- Reproduce CUORE geometry and detectors energy response.

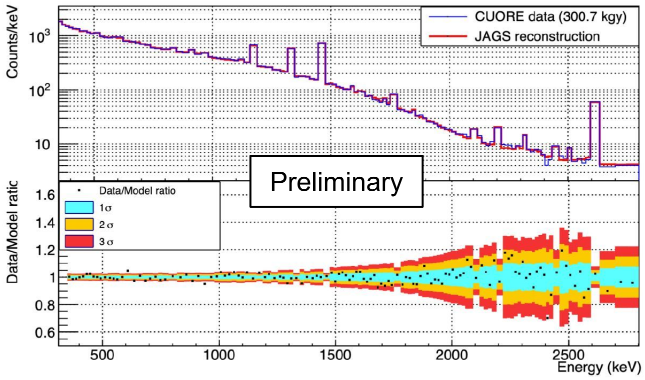
+

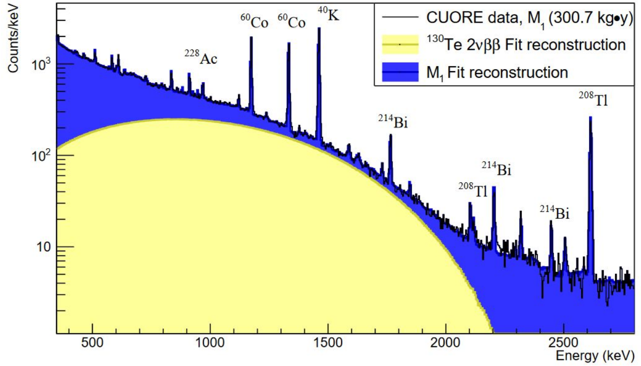
- Markov-Chain Monte Carlo (MCMC) binned Bayesian fit of simulations to experimental data.

↓

- Measurement of $2\nu\beta\beta$ decay of ^{130}Te:
  - ➢ $2\nu\beta\beta$ decay of ^{130}Te accounts for >50% of events in ~1-2 MeV range;
  - ➢ results from **300.7 kg·yr TeO_2 (102.7 kg·yr ^{130}Te) exposure** (*Phys. Rev. Lett. 126, 171801 (2021)*):

$$T_{1/2}^{2\nu}(^{130}\mathrm{Te}) = 7.71^{+0.08}_{-0.06}\,(\mathrm{stat.})^{+0.12}_{-0.15}\,(\mathrm{syst.})\cdot 10^{20}\ \mathrm{yr}$$





Summary

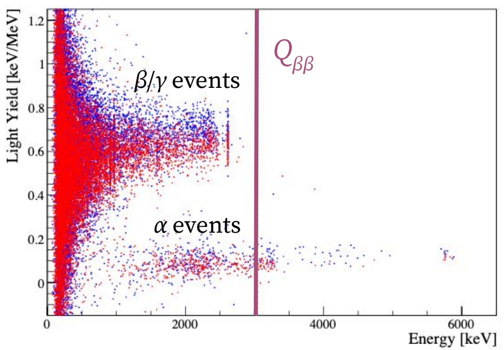
- CUORE demonstrated the feasibility of a ton-scale experiment operating with cryogenic detectors.
- The data collection is ongoing smoothly, accumulating 2 t · yr of TeO_2 exposure.
- No evidence of ^{130}Te $0\nu\beta\beta$ decay (TeO_2 exposure: 1038.4 kg · yr) (Nature 604, 53–58 (2022)):
  - ➢ $T_{1/2}^{0\nu}$ (^{130}Te) > $2.2\cdot10^{25}$ yr (90% C.I.);
  - ➢ $m_{\beta\beta}$ < 90 - 305 meV (90% C.I.).
- Most precise measurement of ^{130}Te $2\nu\beta\beta$ decay half-life (TeO_2 exposure: 300.7 kg · yr) (Phys. Rev. Lett. 126, 171801 (2021)):
  - ➢ $T_{1/2}^{2\nu}$ (^{130}Te) = $7.71_{-0.06}^{+0.08}$ (stat.)$_{-0.15}^{+0.12}$ (syst.)$\cdot10^{20}$ yr.
- Search for other rare processes:

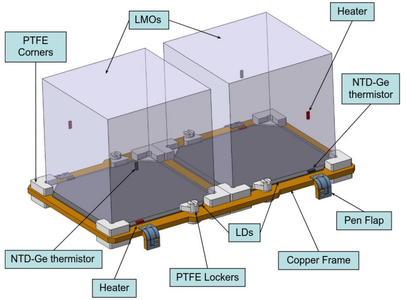
	Exposure (kg · yr)	**Results (90% C.I.)**	**Reference**
$0\nu\beta\beta/2\nu\beta\beta$ decay of ^{130}Te on 0_2^+ excited state of ^{130}Xe	372.5 (TeO_2)	$T_{1/2}^{0\nu}$ (^{130}Te, 0_2^+) > $5.9\cdot10^{24}$ yr $T_{1/2}^{2\nu}$ (^{130}Te, 0_2^+) > $1.3\cdot10^{24}$ yr	Eur. Phys. J. C, 81 57 (2021)
$0\nu\beta\beta$ decay of ^{128}Te	309.3 (TeO_2), 78.6 (^{128}Te)	$T_{1/2}^{0\nu}$ (^{128}Te) > $3.6\cdot10^{24}$ yr	Phys. Rev. Lett. 129, 222501 (2022)
β^+EC decay of ^{120}Te	355.7 (TeO_2), 0.24 (^{120}Te)	$T_{1/2}^{\beta+EC}$ (^{120}Te) > $2.9\cdot10^{22}$ yr	Phys. Rev. C 105, 065504 (2022)

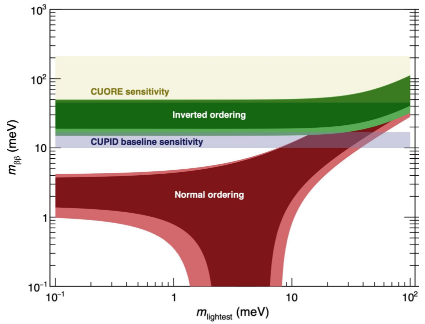
Next-generation experiment: CUPID

- **CUPID** (**C**UORE **U**pgrade with **P**article **ID**entification):
  - search for $0\nu\beta\beta$ decay of ^{100}Mo → $Q_{\beta\beta}(^{100}Mo)$ = 3034 keV;
  - scintillating crystals for heat-light double read-out
    ↓
    99% α vs β/γ discrimination → α rejection (main bkg. in CUORE ROI);
  - baseline design:
    - > 1500 $Li_2{}^{100}MoO_4$ crystals enriched in ^{100}Mo (≃ 95%);
    - total mass: 450 kg of $Li_2{}^{100}MoO_4$, **240 kg of ^{100}Mo**;
    - Ge bolometric light detectors;
  - target parameters (*arXiv:1907.09376v1*):
    - background index in ROI: $\boldsymbol{B \sim 10^{-4}}$ **counts/(keV·kg·yr)** (factor ~100 better than CUORE);
    - $0\nu\beta\beta$ decay sensitivity: $T_{1/2}^{0\nu}$ (^{100}Mo) > $1.0 \cdot 10^{27}$ yr (10 yr);
    - effective Majorana mass: $m_{\beta\beta}$ ~ 12 - 20 meV;
      ↓

explore the entire inverted hierarchy region.







Thanks for the attention!

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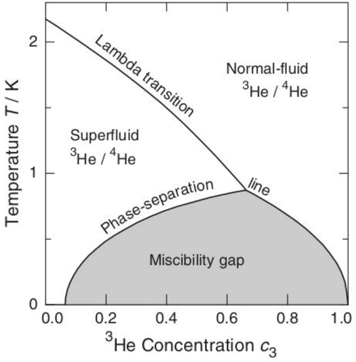
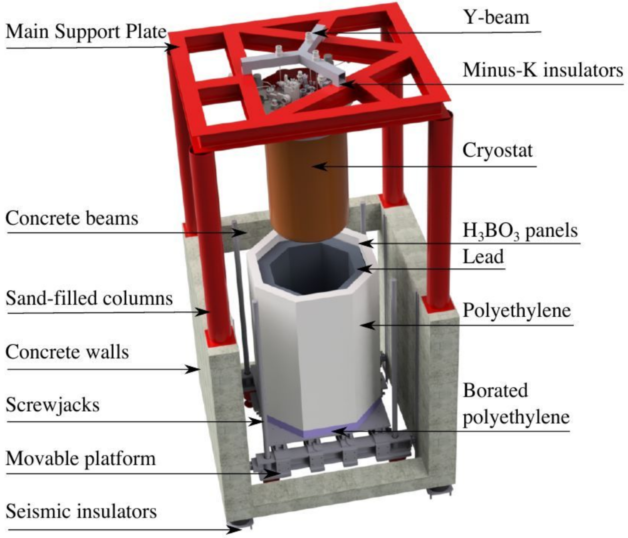
CUORE

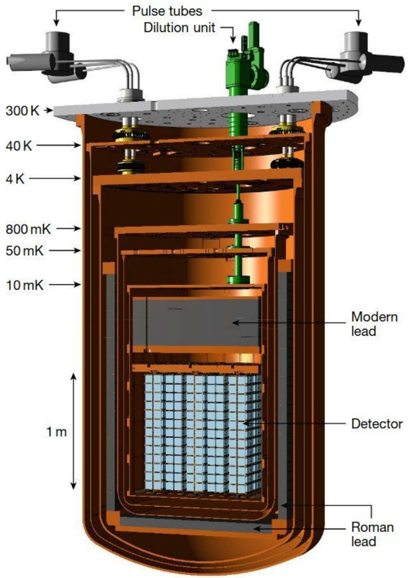
Backup slides

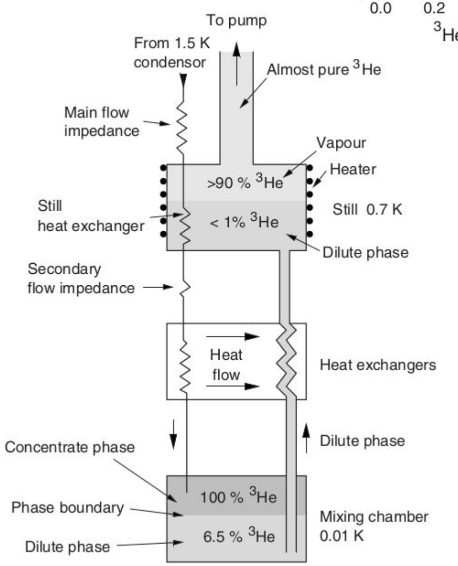
CUORE cryostat

- ^3He-^4He dilution cryostat (Cryogenics 102 (2019) 9-21):
  - ➢ suspension system to decouple from external vibrations;
  - ➢ pulse tubes pre-cooling system;
  - ➢ shieldings: Roman ^{arch}Pb, modern Pb, H_3BO_3 neutron shield;
  - ➢ radiopurity constraints on materials.



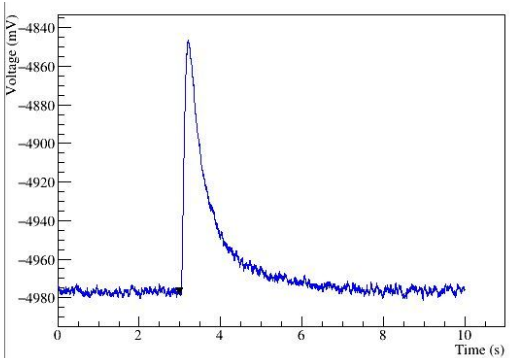


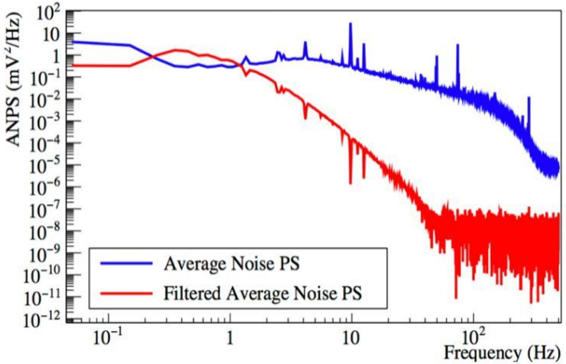


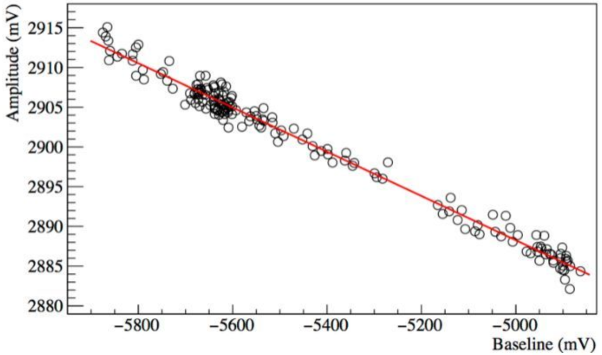


$0\nu\beta\beta$ decay data analysis

Trigger events from continuous data stream → Create pulse and noise templates for amplitude evaluation with optimum filter technique → Thermal gain stabilization by means of artificial fixed-energy pulses →





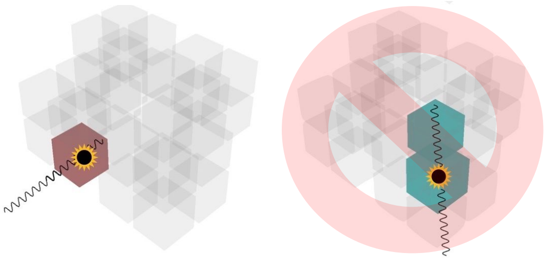


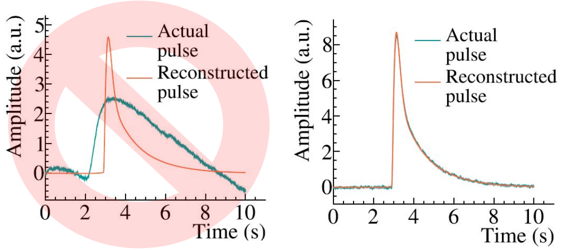
$0\nu\beta\beta$ decay data analysis

Energy calibration with external ^{232}Th-^{60}Co sources

Coincidences: identify simultaneous (± 5 ms) events on multiple crystals

Pulse Shape Discrimination (PSD): reject unphysical/noisy/pile-up pulses



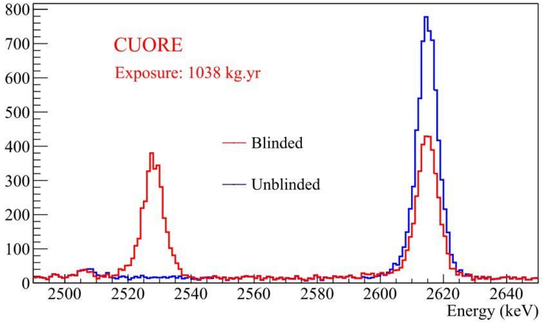


$0\nu\beta\beta$ decay data analysis

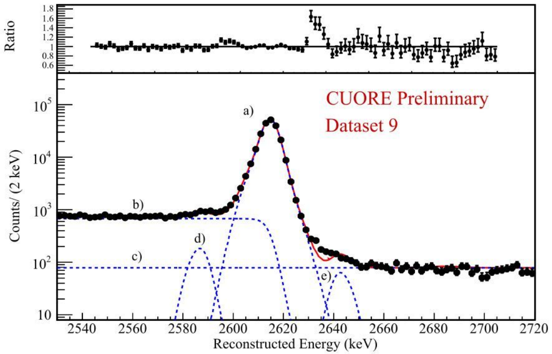
ROI blinding:
move a random fraction of events from ^{208}Tl peak to ROI

→ Efficiency evaluation

→ Model the detector response from ^{208}Tl peak.
Fit ROI energy spectrum



Total analysis efficiency (data)	92.4(2)%
Reconstruction efficiency	96.418(2)%
Anticoincidence efficiency	99.3(1)%
PSD efficiency	96.4(2)%
Containment efficiency (Monte Carlo)	88.35(9)%



a) ^{208}Tl 3-guassians peak;
b) multi-Compton;
c) flat background;
d) 30 keV x-ray escape peak;
e) 30 keV x-ray coincidence peak.