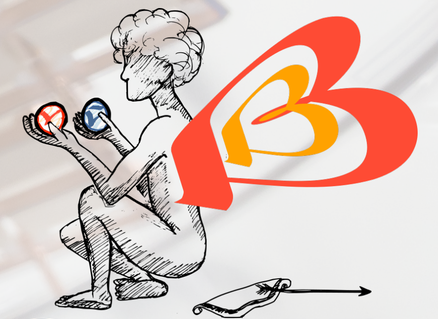
From CUORE to CUPID: Towards a Next Generation Search for Neutrinoless Double Beta Decay

PASCOS 2026 - 23.06.2026

Francesca Pucci
On behalf of the CUORE and CUPID collaborations



Neutrinoless double beta decay (0νββ)

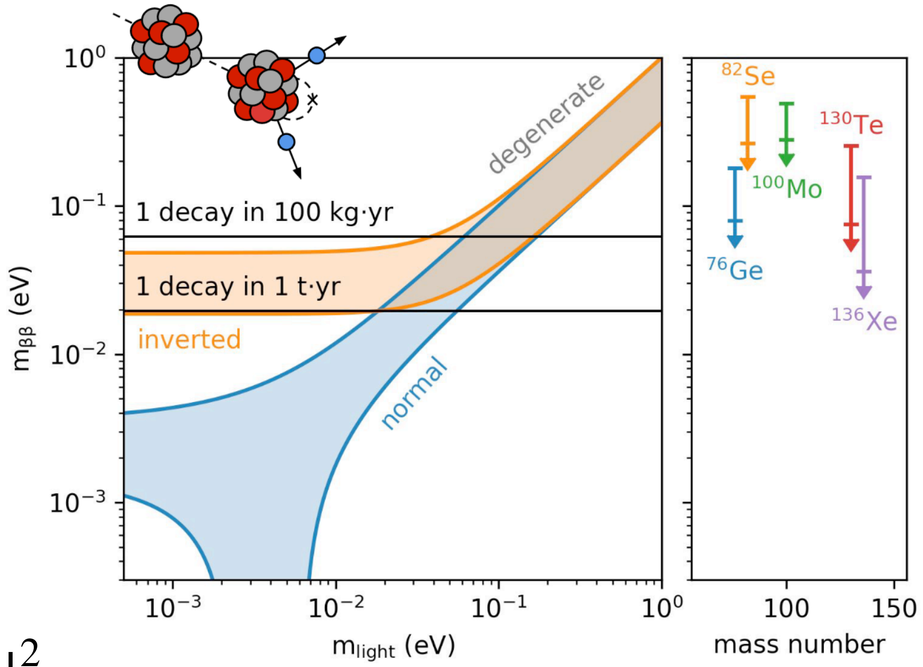
- 2νββ: Standard Model second-order weak transition, observed in 11 nuclei with $T_{1/2} \sim 10^{18} - 10^{24}$ yr

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

- 0νββ: Possible only if neutrinos are Majorana particles

$$(A, Z) \rightarrow (A, Z+2) + 2e^-$$

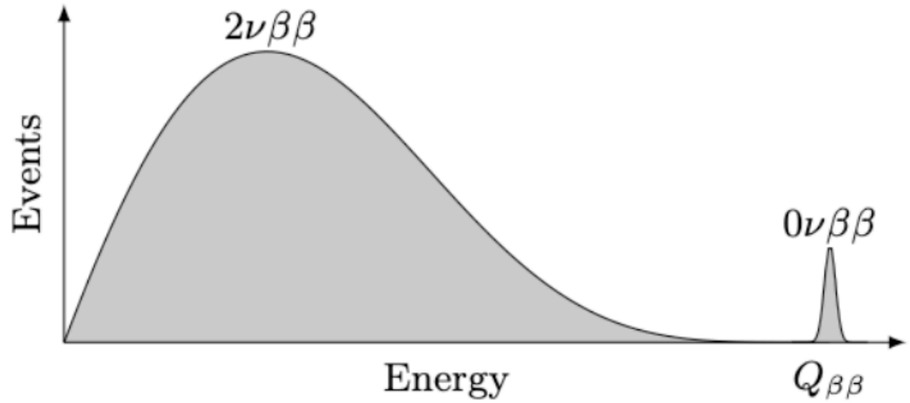
  - Lepton number violating process
  - Potentially impact understanding of matter-antimatter asymmetry in the Universe
  - Constrains neutrino mass hierarchy scale

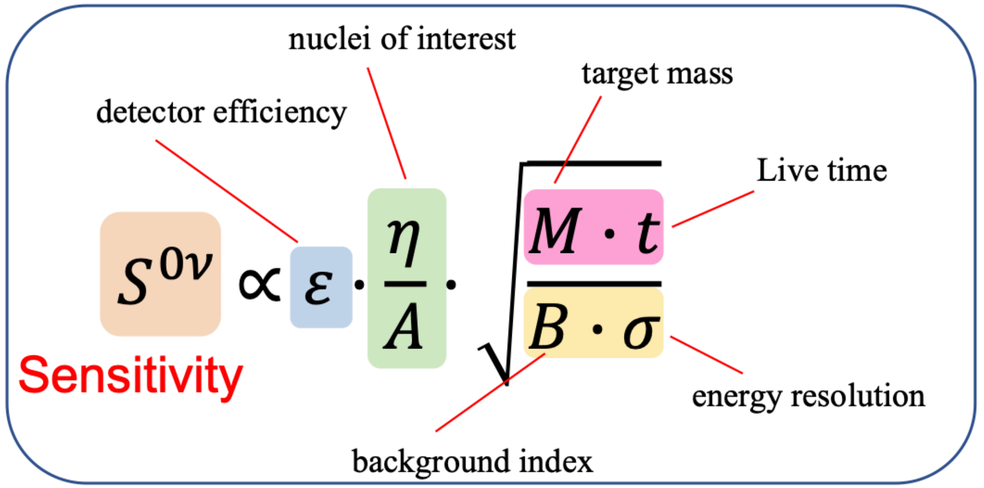


$$\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu}(Q, Z) \, |M_{0\nu}|^2 \frac{|\langle m_{\beta\beta} \rangle|^2}{m_e^2}$$

Neutrinoless double beta decay (0νββ)

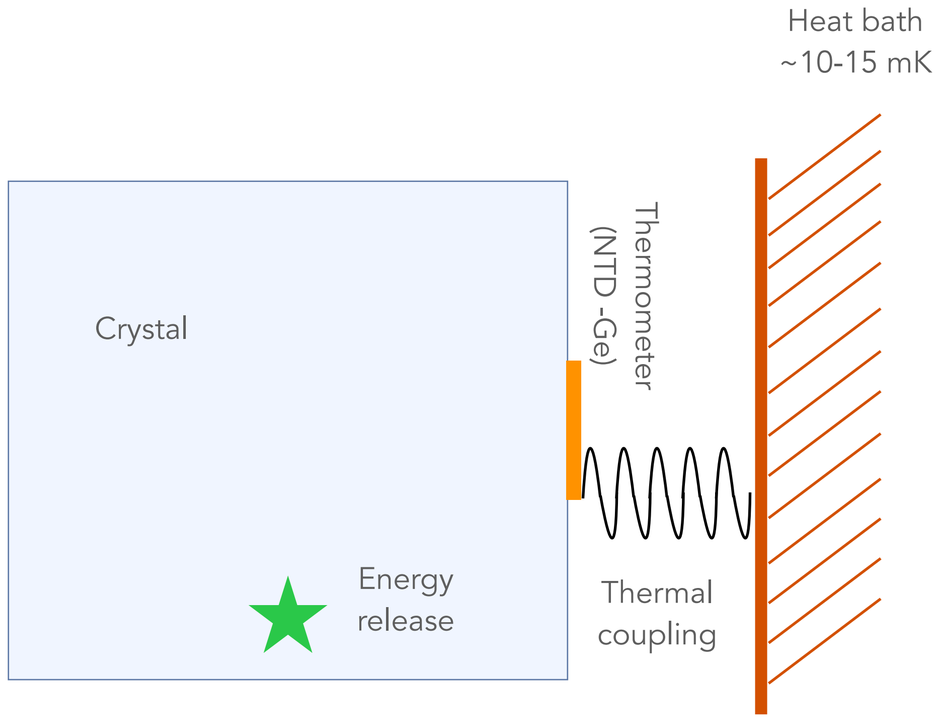
- Experimental signature: a peak over a flat background
- Challenges:
  - High efficiency detectors
  - Good energy resolution
  - Low background in the ROI
    - Underground experiments
    - Active and passive shieldings
    - Background discrimination
  - Long and stable data collection





Cryogenic calorimeters for 0νββ

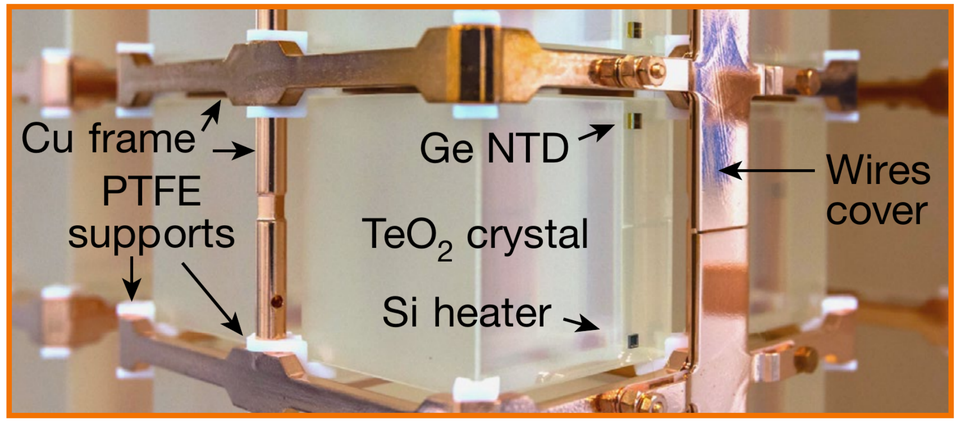
- Energy release measured as a rise in temperature
  $\Delta T \sim \Delta E/C$
  ↳ low temperatures → low heat capacity → high sensitivity
- Variety of thermal sensors and of absorber materials
  ↳ possibility to probe several 0νββ candidates
- Good energy resolution of ~ 5 keV at 2.6 MeV
- Possibility to add a second detector to readout scintillation light
  ↳ particle identification capabilities

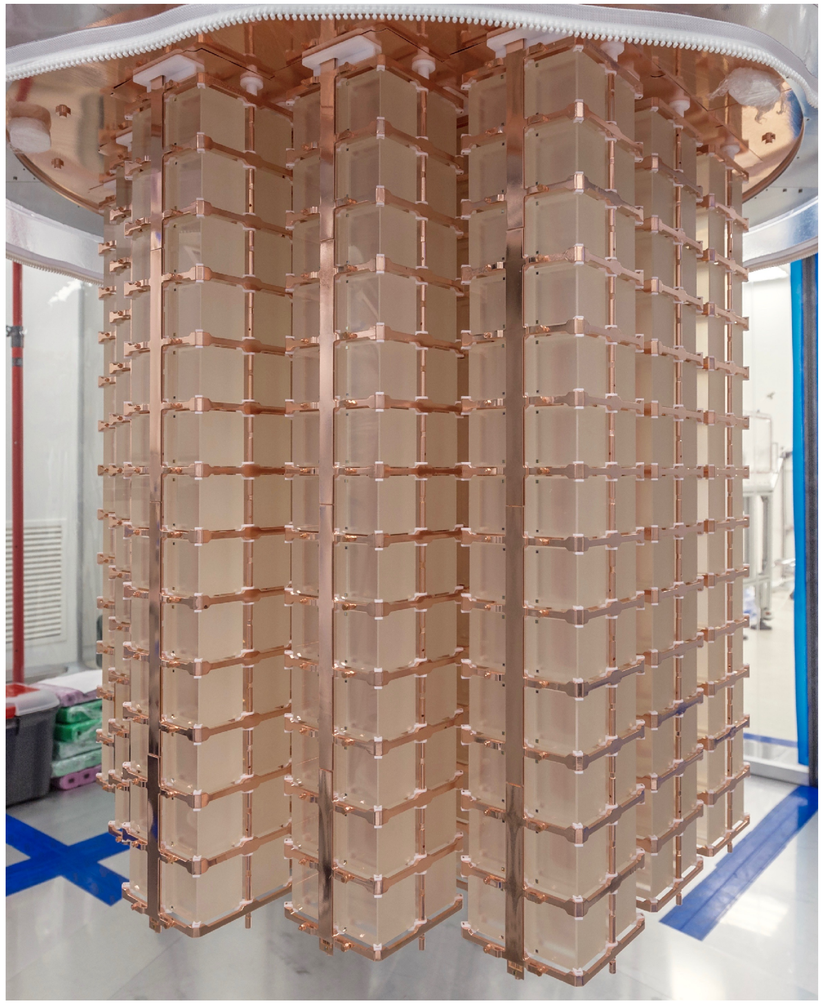


CUORE

Cryogenic Underground Observatory for Rare Events

- Located at LNGS under ~3600 m.w.e.
- 988 TeO_2 crystals arranged in 19 towers
  ↳ search 0νββ decay in ^{130}Te
- Total TeO_2 mass: 742 kg, with 206 kg of ^{130}Te (natural isotopic abundance of ~ 34%)



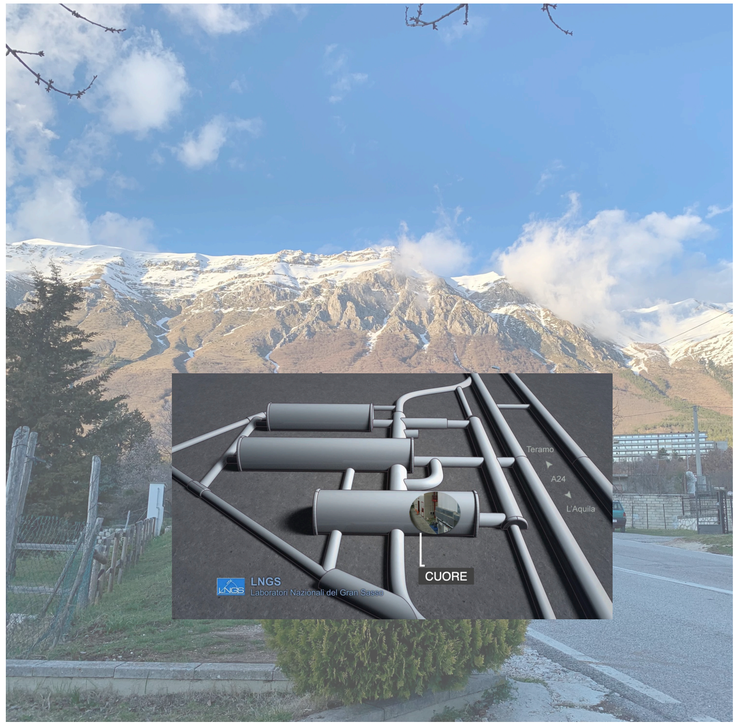


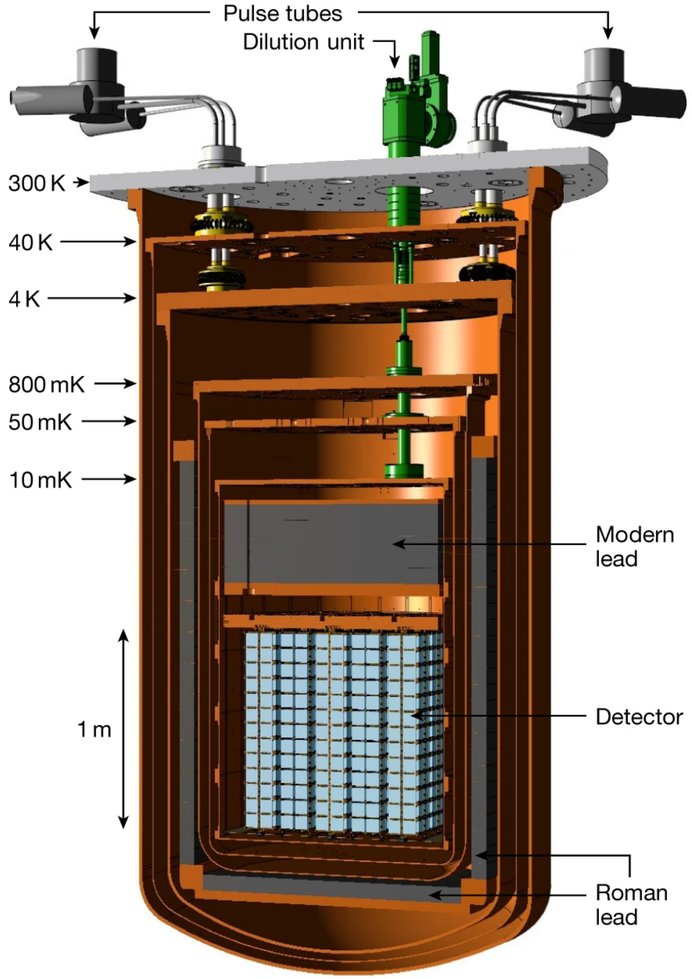
CUORE

Cryogenic Underground Observatory for Rare Events

- Customised dry dilution refrigerator
  - ↳ stable operation at ~10 mK since late 2016
- Low background environment
  - ↳ located underground at LNGS
    - ✙ extensive shieldings with radiopure materials
- Vibrations and noise
  - ↳ mechanical decoupling from the cryostat ✙ passive isolation and active noise mitigation

~3600 m.w.e.
$\gamma s \sim 0.73/(s\ cm^2)$
$\mu s \sim 3 \cdot 10^{-8}/(s\ cm^2)$
Neutrons $4 \cdot 10^{-6}/(s\ cm^2)$





Nature 604, 53–58 (2022)

CUORE

Cryogenic Underground Observatory for Rare Events

- Stable data taking since 2019
- Data-driven background model
- 2-tonne-year data release
- Improved limit for the 0νββ decay of ^{130}Te

$$T_{1/2}^{0\nu} > 3.5 \times 10^{25}\, yr\ (90\,\%\, C.I.)$$

- Many other rare events searches and physics

Detection of marine microseismic activity:
Nat. Commun. Phys volume 9, 121 (2026)
Precision studies of the $2\nu\beta\beta$ decay of ^{130}Te:
Phys. Rev. Lett. 135, 082501 (2025)
Search for Fractionally Charged Particles:
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The environmental low-frequency background:
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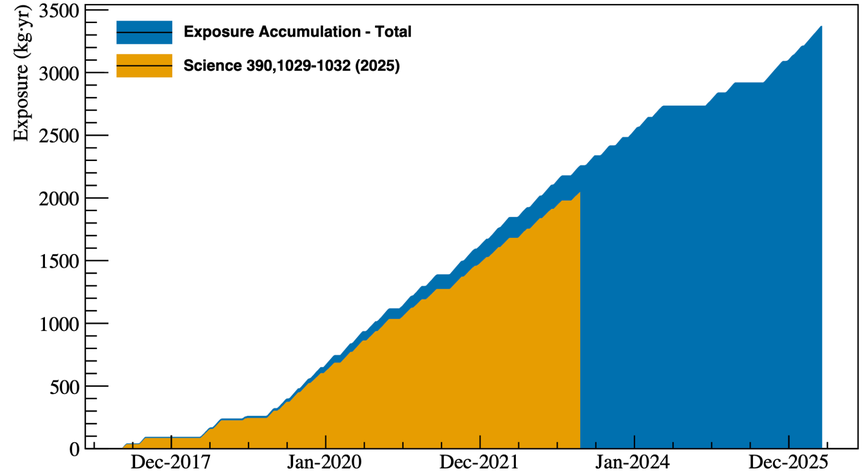
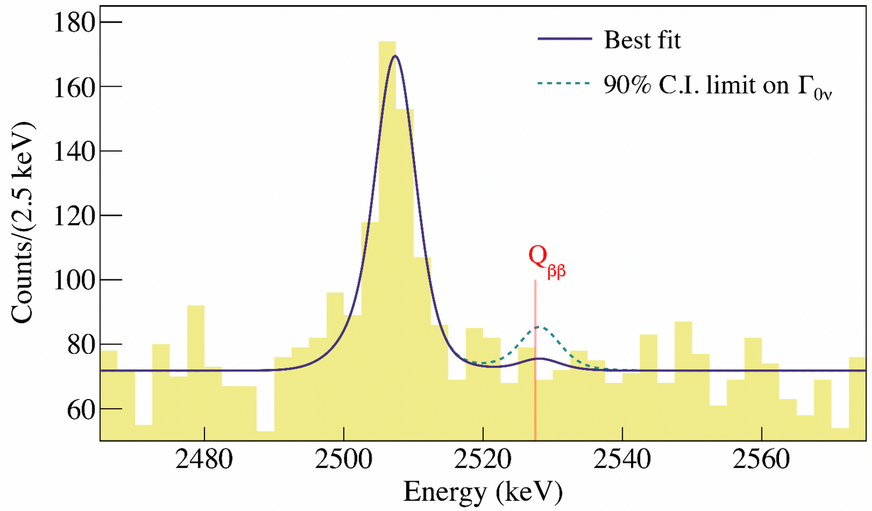
Neutrinoless β^+ decay of ^{120}Te:
Phys. Rev. C 105, 065504 (2022)
..and more





Science 390, 1029–1032 (2025)

CUORE

Cryogenic Underground Observatory for Rare Events

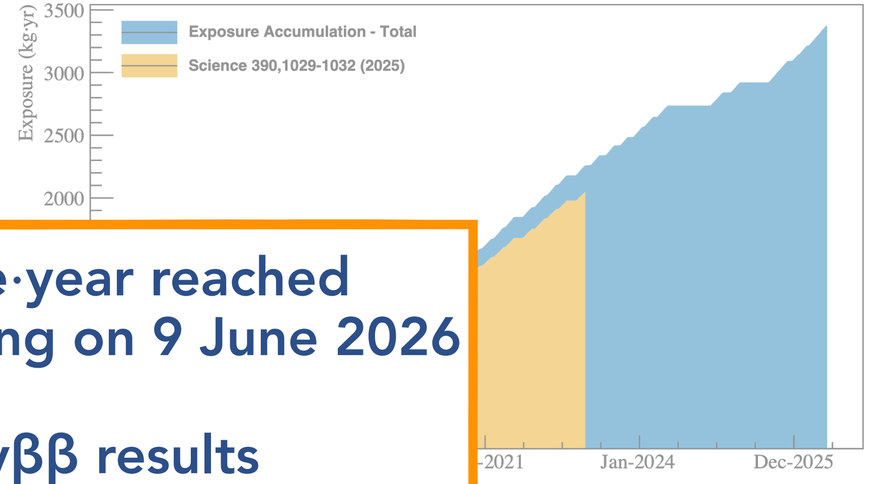
- Stable data taking since 2019
- Data-driven background model
- 2-tonne-year data
- Improved limit fo

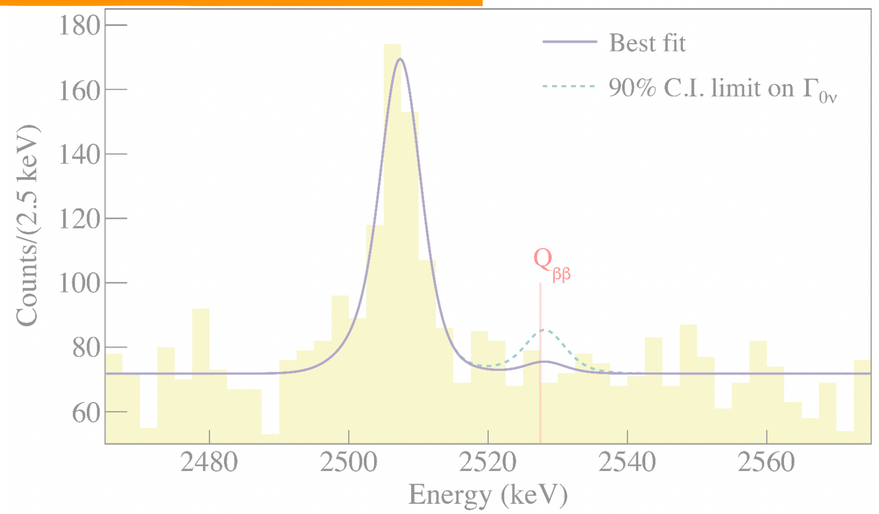
$$T_{1/2}^{0\nu} > 3.5 \times$$

- Many other rare events searches and physics

TeO_2 exposure of 3 tonne·year reached
End of CUORE main data taking on 9 June 2026

Stay tuned for new 0νββ results





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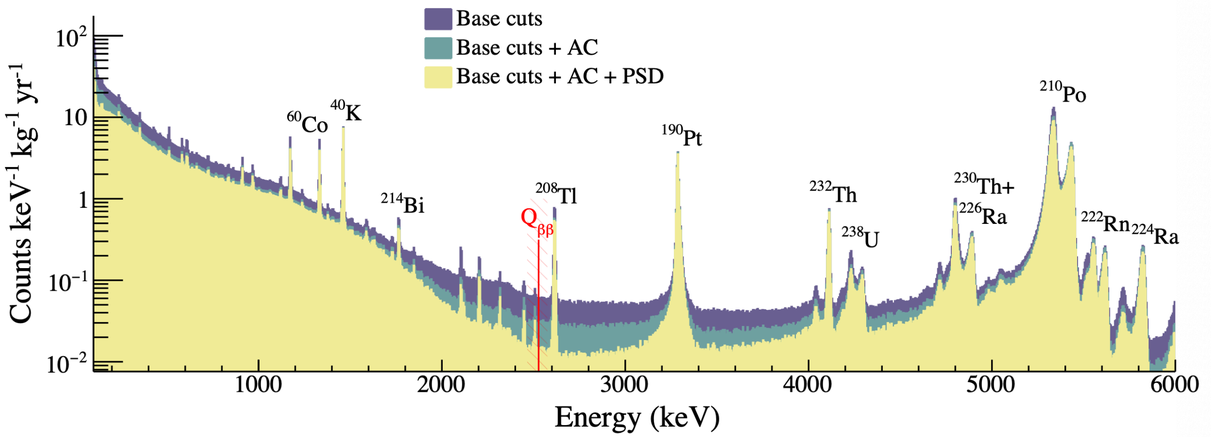
CUORE to CUPID

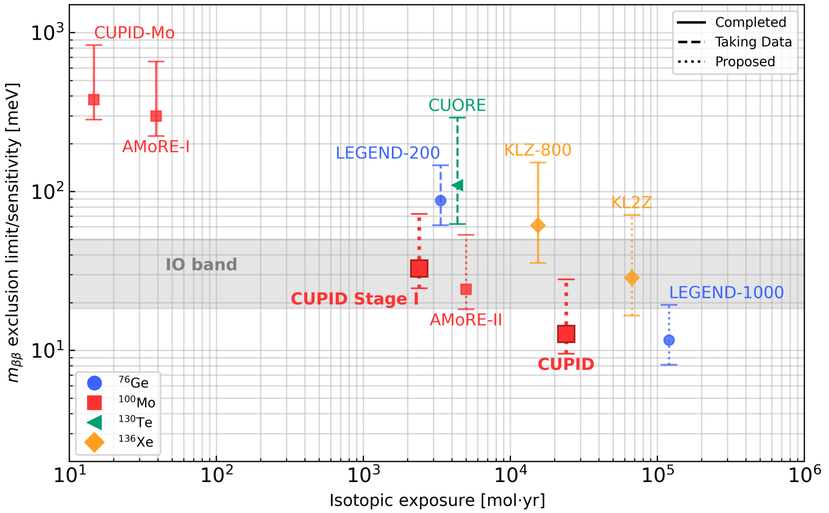
- Background dominated by degraded alphas

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

Science 390, 1029-1032(2025)

- Need to upgrade to CUORE Phase II
  - Cryostat upgrades to mitigate vibrational noise and lower the energy thresholds
  - Prepare the cryostat to host CUPID
- CUPID will probe
  - another isotope with Q > 2.6 MeV
  - $BI \sim 10^{-4}\, counts/(kev \cdot kg \cdot yr)$
  - Scintillating cryogenic calorimeter for PID





CUPID: CUORE Upgrade with Particle IDentification

CUORE

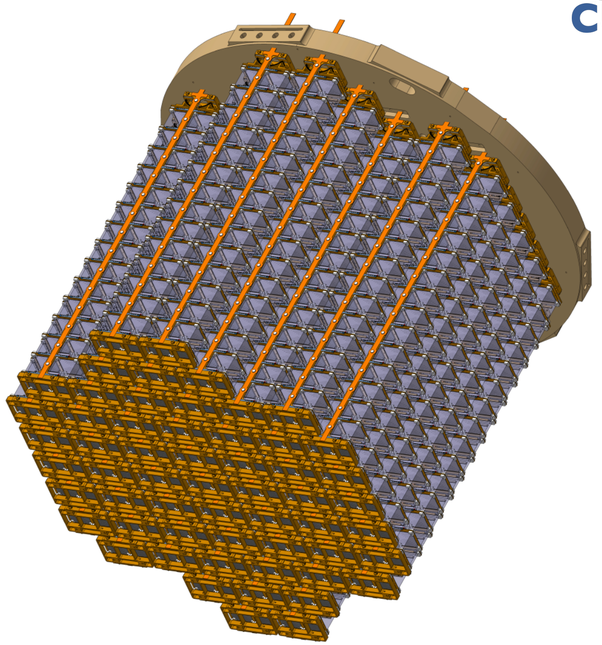
19 towers (4x13 crystals)

988 TeO_2
50x50x50 mm^3

$Q_{\beta\beta}$ = 2528 keV

Operated as calorimeters @ ~10mK

In operation @LNGS since 2016



CUPID

57 towers (2x14 crystals)

1596 $Li_2{}^{100}MoO_4$ (LMO)
45x45x45 mm^3 +

1710 Ge Light Detectors (LD)

$Q_{\beta\beta}$ = 3034 keV

Operated as **scintillating** calorimeters @ ~10mK

In operation @LNGS starting from 2030

CUORE best limits

- ^{130}Te half life: $T_{1/2} > 3.5 \times 10^{25}$ yr (90% C.I.)
- $m_{\beta\beta} < 70\text{-}250$ meV

Science 390, 1029-1032 (2025)

CUPID projections

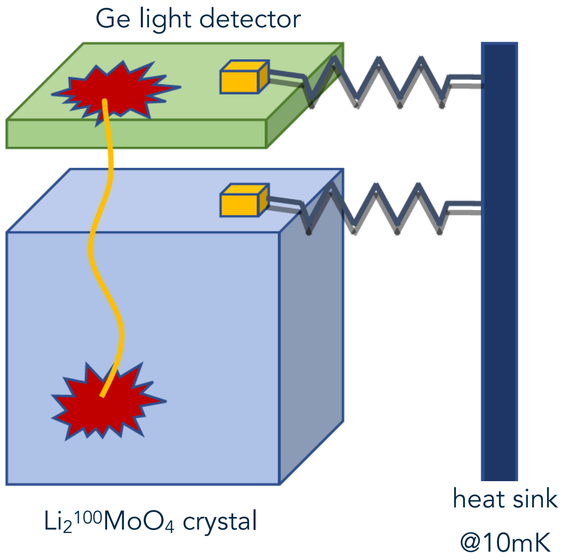
- ^{100}Mo half life: $T_{1/2} > 1.0 \times 10^{27}$ yr
- $m_{\beta\beta} < 12\text{-}21$ meV

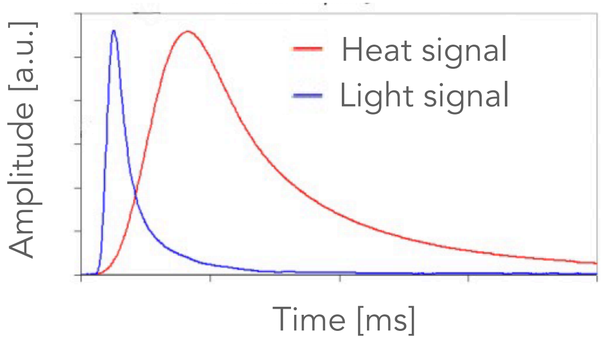
CUPID detectors

CUORE Upgrade with Particle Identification

Dual readout:

- Phonon signal → NTD glued on the LMO crystal
- Light signal → NTD glued on the Ge LD





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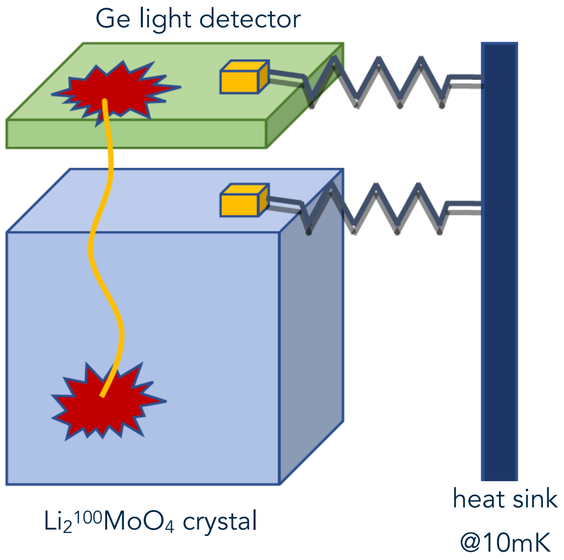
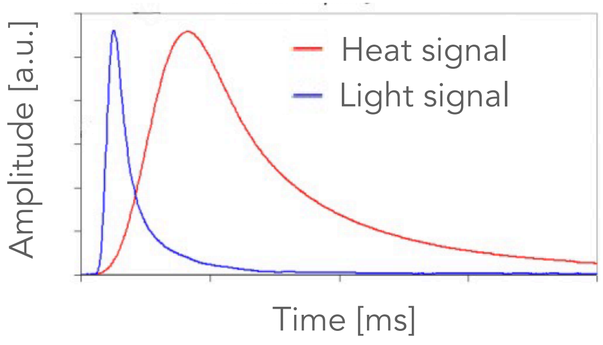
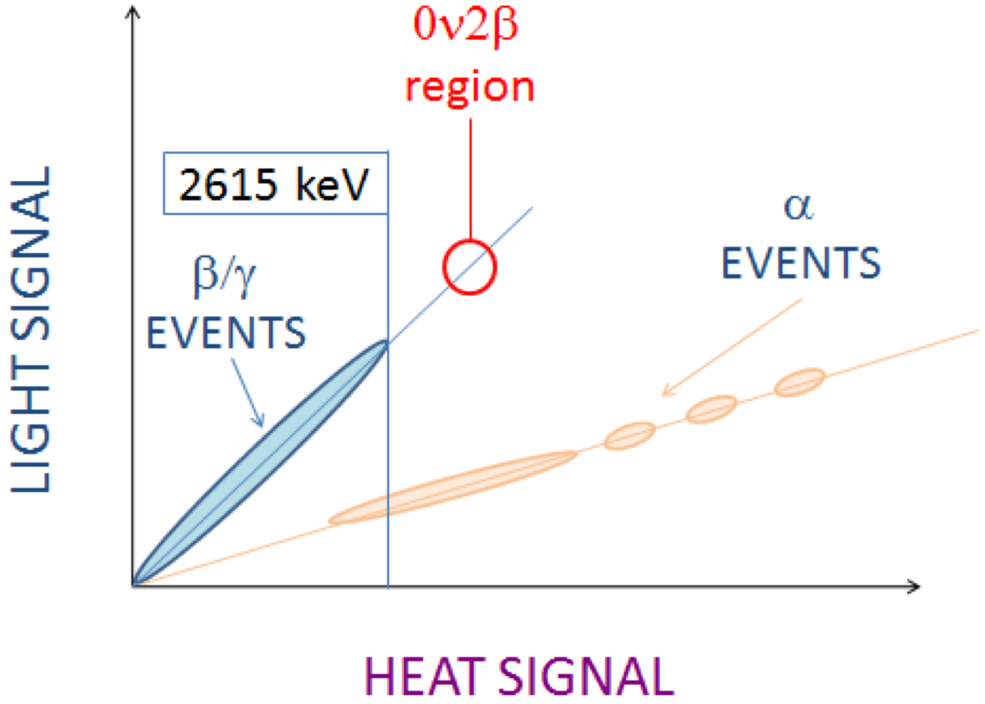




Rejection of α-particles (heat + light)

different amount of scintillation light emitted



CUPID detectors

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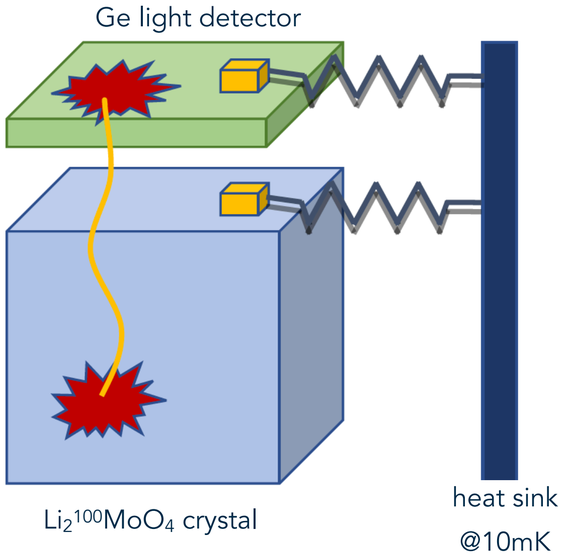
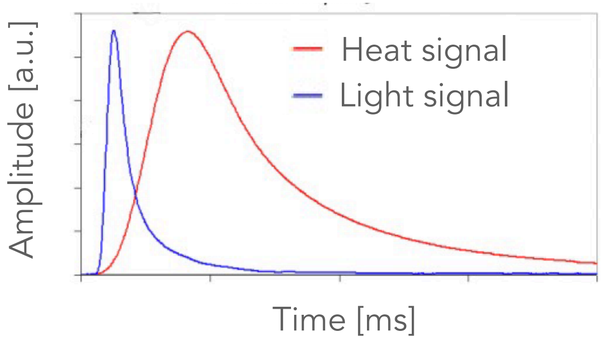


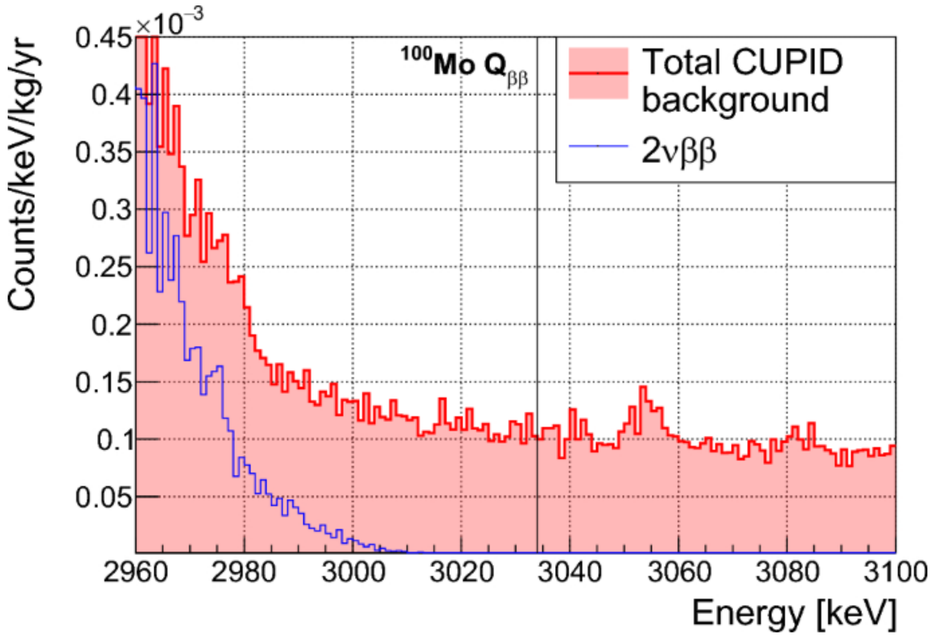


Rejection of α-particles (heat + light)

different amount of scintillation light emitted

Rejection of ^{100}Mo 2νββ pile-up (light only)

deploying LD faster pulses rise time (few ms)



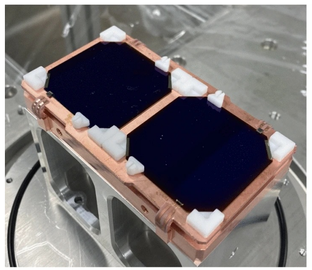
Eur. Phys. J. C 86, 633 (2026)

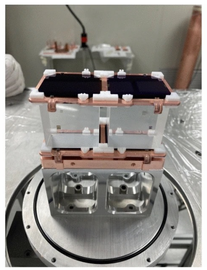
CUPID prototypes

CUORE Upgrade with Particle Identification

GDPT (Gravity Detector Prototype Tower)

- Innovative gravity-assisted design
- Conceptual test in 2022 @ LNGS
- Thermal properties assessment and detector performance
- Light detectors experienced low SNR and correlated noise





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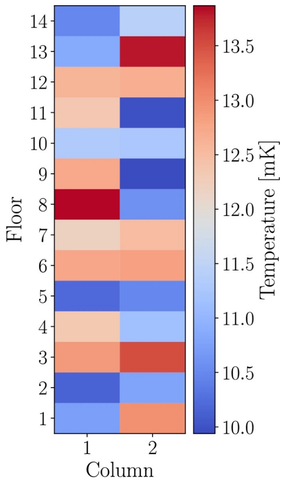
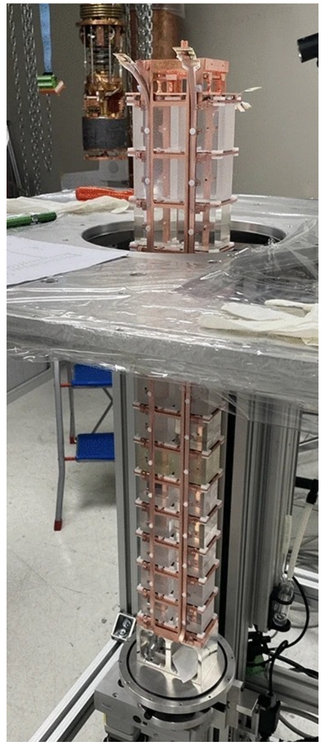
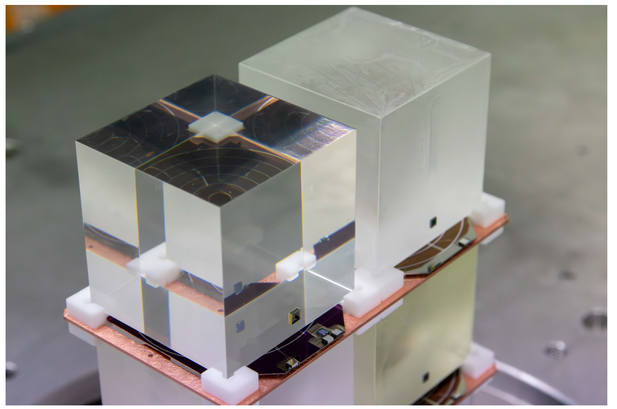




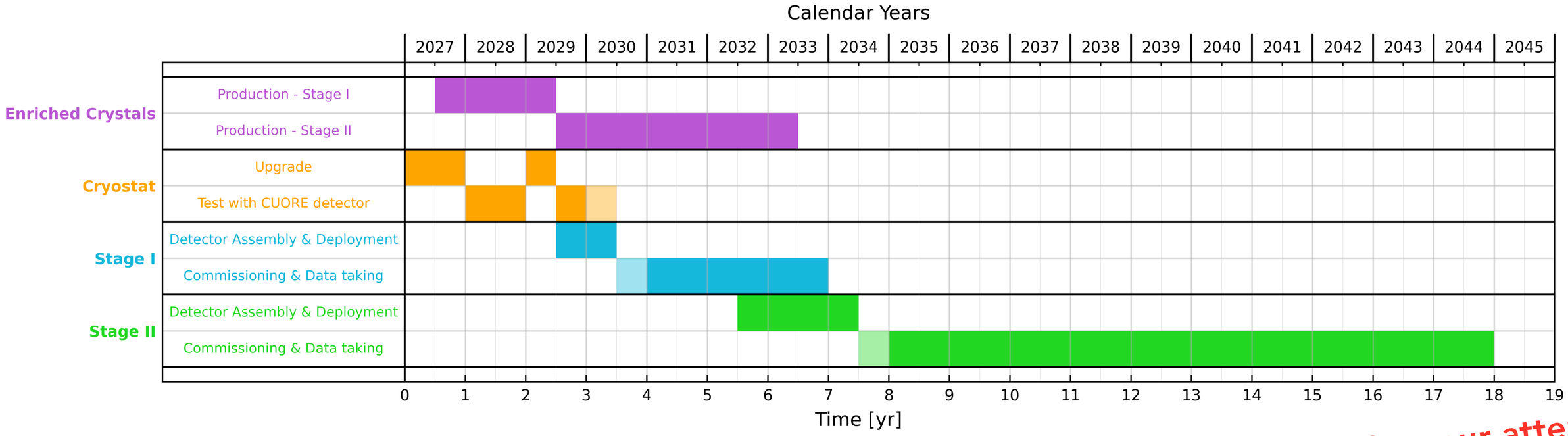
VSTT (Vertically Sliced Test Tower)

- Upgrade on the design and assembly line testing
- NTL light detectors
- Optical fibers for LD calibration
- New DAQ and electronics
- **Currently data taking**



Summary and Outlook

- CUORE demonstrated the feasibility of an array of ~ 1000 cryogenic calorimeters and collected 3 tonne·yr of TeO_2 exposure
- The path towards CUPID has started with full tower prototypes and crystal validation runs
- CUPID will play a central role in the $0\nu\beta\beta$ search in the upcoming years

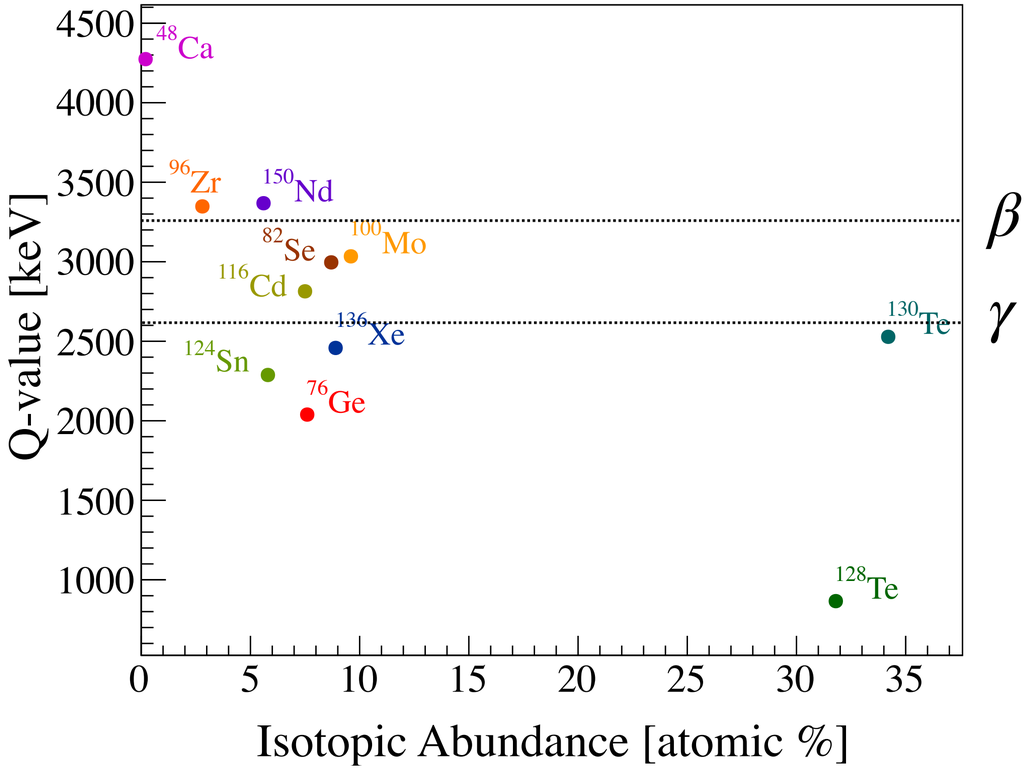


Thank you for your attention

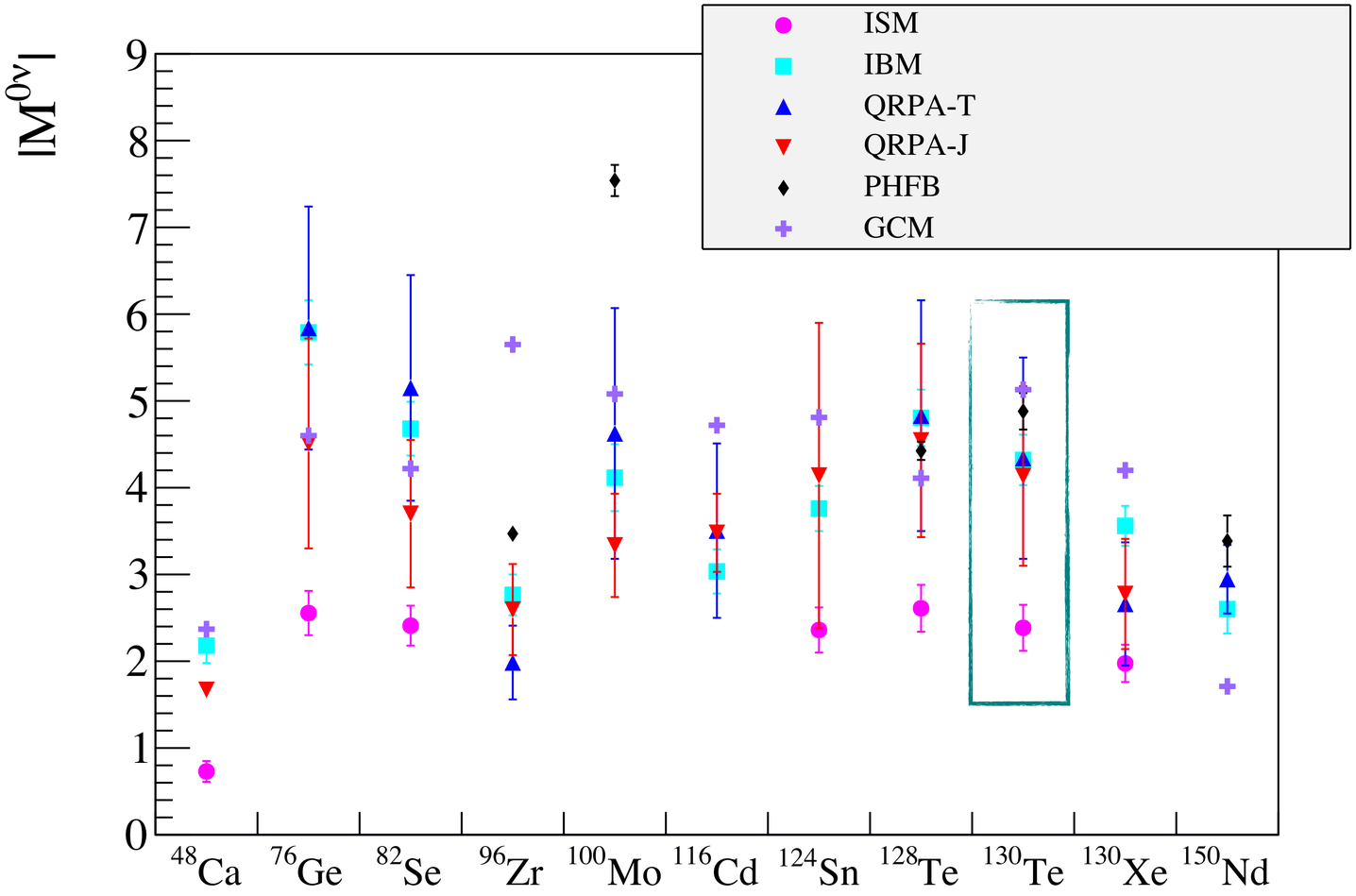
Backup Slides

Isotope choice

- High natural isotopic abundance
- Relatively low β/γ background
- Reproducible growth of high quality crystals



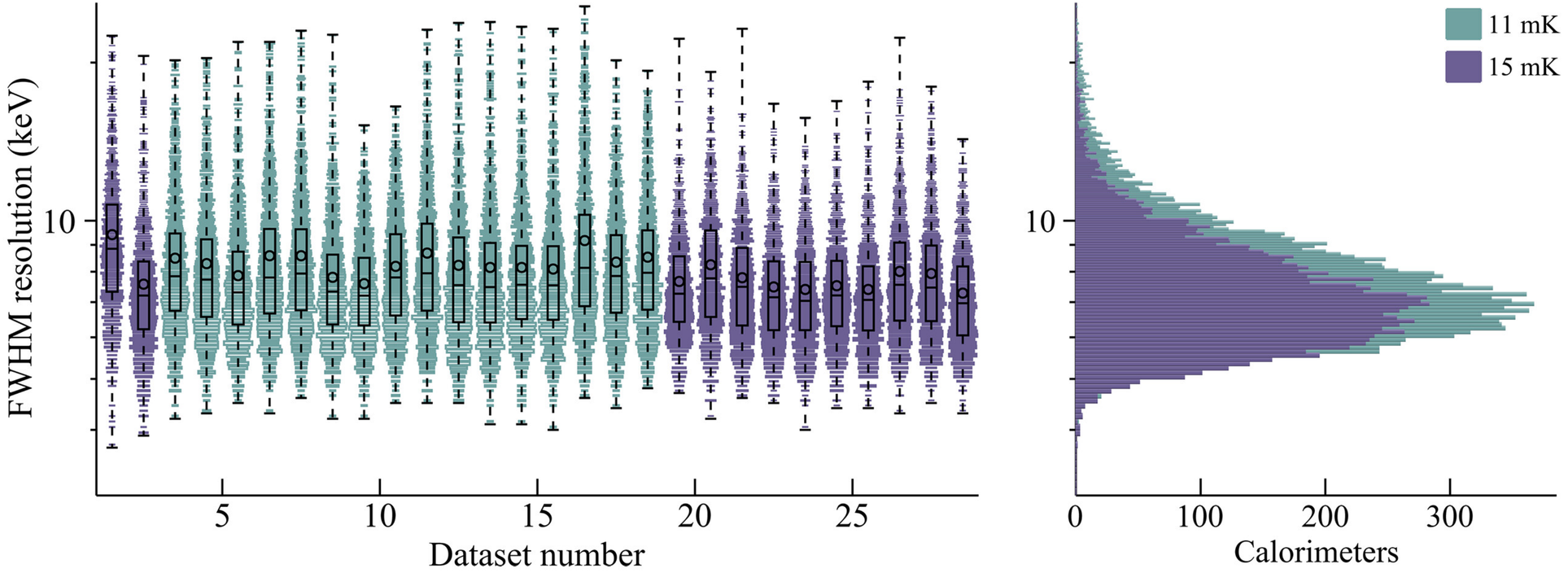
Nuclear Matrix Elements



$$\frac{1}{T^{0\nu}_{1/2}} = G_{0\nu}(Q,Z)\,|M_{0\nu}|^2 \frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$

CUORE Stability

Cryogenic Underground Observatory for Rare Events



CUPID Crystals Validation Runs (CCVRs)

CUORE Upgrade with Particle Identification

- Validation tests of crystals operated as cryogenic detectors to certify vendors
- Certify compliance of precursors radio-purity, and crystal growth processes with our specifications
- Typically 2x2 LMO crystal array with 8 light detectors for particle identification