Latest results from CUORE and progress towards CUPID

B. Schmidt, CUORE-CUPID, Bormio, 2024

CUORE

CUPID

Kangkang ZHAO

On behalf of the CUORE and CUPID collaborations

Jan. 23rd, 2026

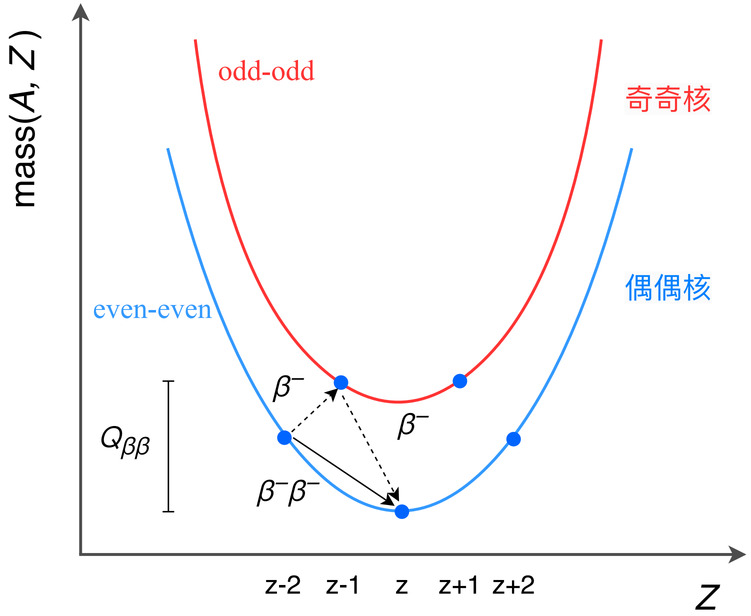
62nd International Winter Meeting on Nuclear Physics
January 19 to 23, 2026 Bormio, Italy

GSSI GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

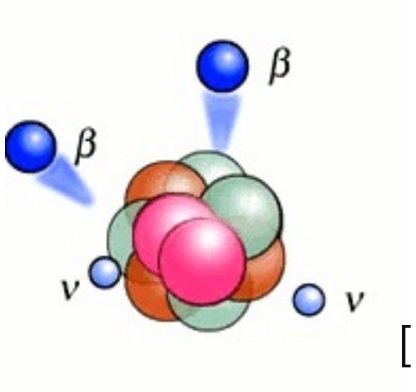
INFN LNGS

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

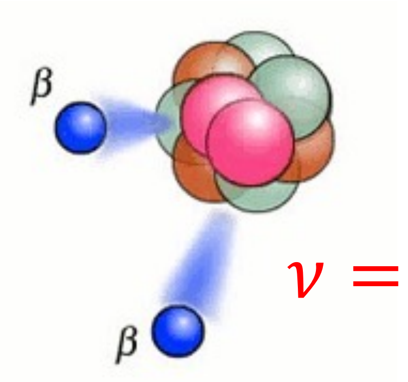
- $2\nu\beta\beta$: Standard Model allowed, 2nd order weak transition
- Possible even-even nuclides when beta decay is forbidden or suppressed
- 35 possible nuclei, 11 observed with half-life $T_{2\nu}$ ~ $10^{18} - 10^{24}$ yr



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



[Ettore Majorana]



$\nu = \bar{\nu}$

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

- $0\nu\beta\beta$ can occur if neutrinos are Majorana particles
- No experimental evidence so far, extremely rare $T_{0\nu}$ > $10^{24} - 10^{26}$ yr

Implications of $0\nu\beta\beta$

Decay rate **Phase space factor** **Effective neutrino mass**

Observable

$$[T_{1/2}^{0\nu}]^{-1} = G^{0\nu}(Q_{\beta\beta}, Z) \cdot |M^{0\nu}(A,Z)|^2 \cdot \frac{\langle m_{\beta\beta} \rangle^2}{m_e^2}$$

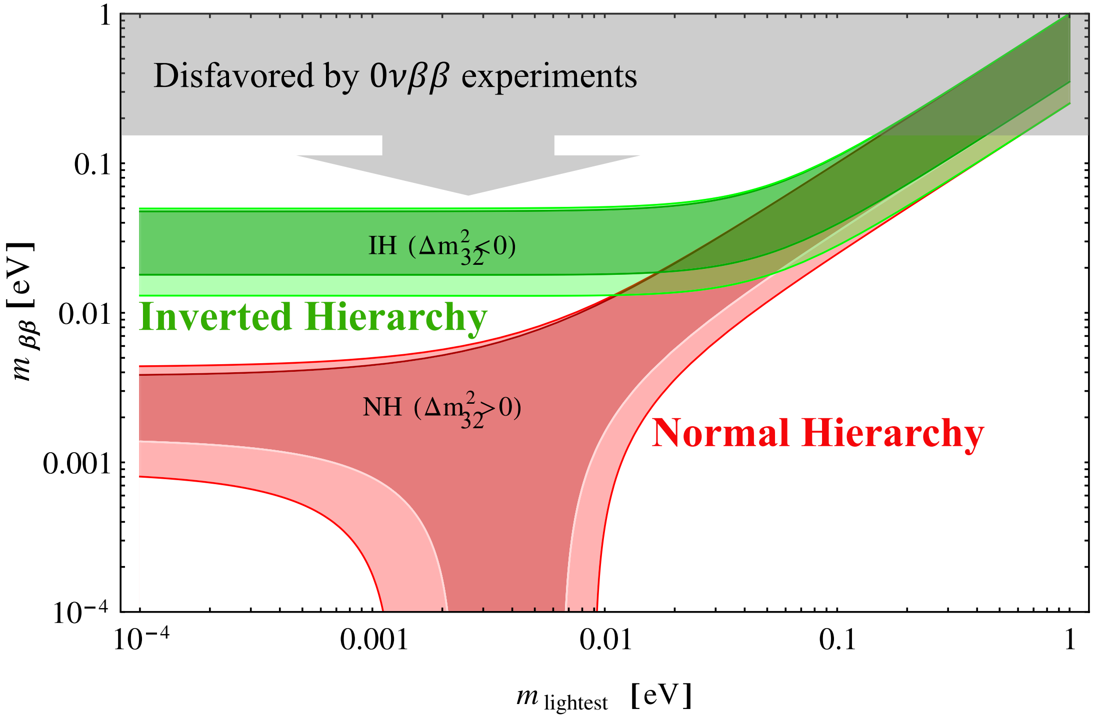
$$\langle m_{\beta\beta} \rangle = \left| \sum_i |U_{ei}|^2 \cdot m_i \right|$$

Nuclear Matrix Element

- Lepton number violation (ΔL = 2), beyond SM
- Majorana nature of neutrinos
- Neutrino mass hierarchy
- Absolute neutrino mass scale
- Hints to origin of matter/anti-matter asymmetry

NEW PHYSICS!

Stefano Dell'Oro, *et al.*
Phys. Rev. D **90**, 033005, 2014

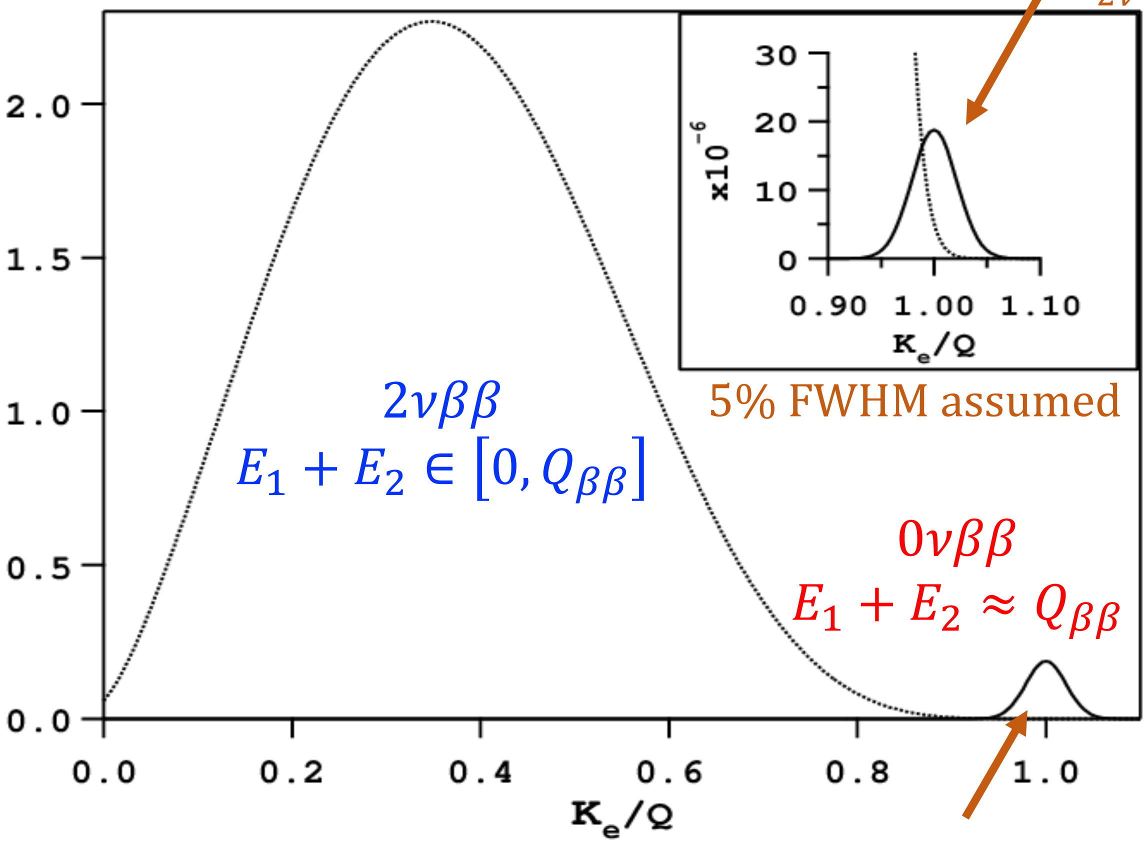


$0\nu\beta\beta$ detection challenges

Compatible detection technique required!

- Experimental signature: two-electron sum-energy spectrum

$\frac{N_{0\nu}}{N_{2\nu}} = 10^{-6}$



5% FWHM assumed

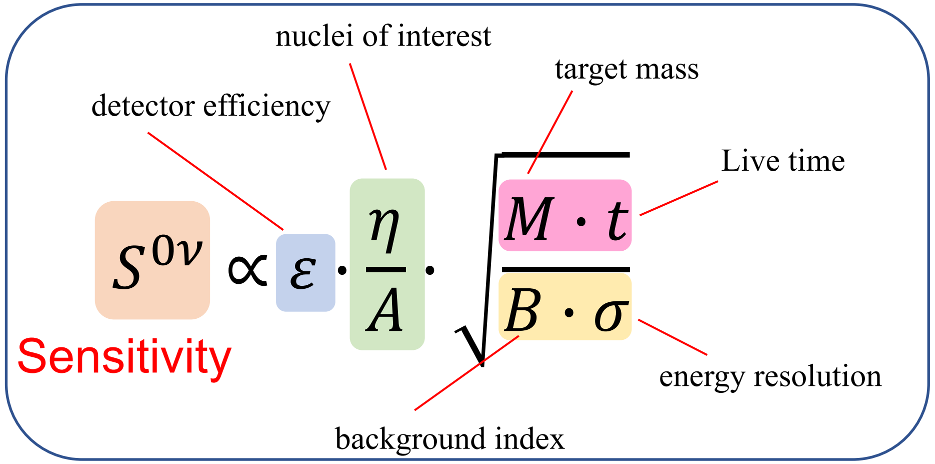
$2\nu\beta\beta$

$E_1 + E_2 \in [0, Q_{\beta\beta}]$

$0\nu\beta\beta$

$E_1 + E_2 \approx Q_{\beta\beta}$

shown in $\frac{N_{0\nu}}{N_{2\nu}} = 10^{-2}$



nuclei of interest

target mass

detector efficiency

Live time

$$S^{0\nu} \propto \varepsilon \cdot \frac{\eta}{A} \cdot \sqrt{\frac{M \cdot t}{B \cdot \sigma}}$$

Sensitivity

energy resolution

background index

- Optimized detector performance
  - Good energy resolution
  - High detection efficiency
- Maximized exposure
  - large detector mass & long livetime
- Minimized background
  - Underground Lab & extensive shield
  - PID, tracking, fiducialization…

The CUORE collaboration

University of Pittsburgh

Fudan University 1905

GSSI

INFN
Istituto Nazionale di Fisica Nucleare

Johns Hopkins University

MIT
Massachusetts Institute of Technology

Sapienza Università di Roma

Università degli Studi di Milano Bicocca

UCLA

Virginia Tech

SINAP

Yale

CSNSM

Cal Poly

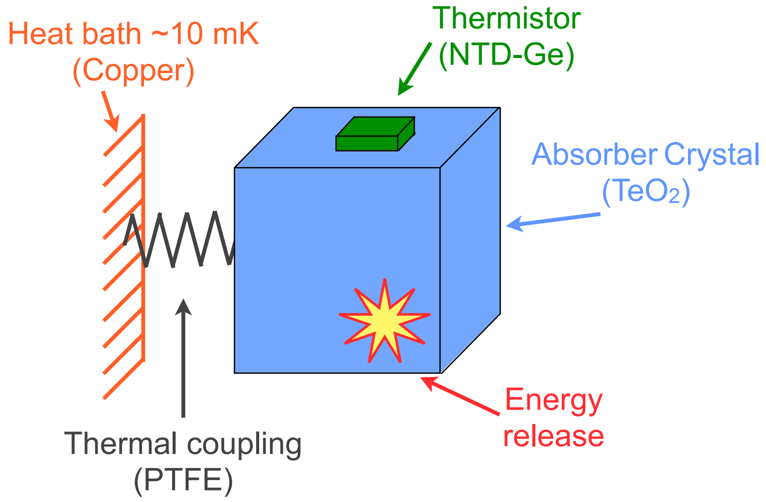
Berkeley Lab

University of South Carolina

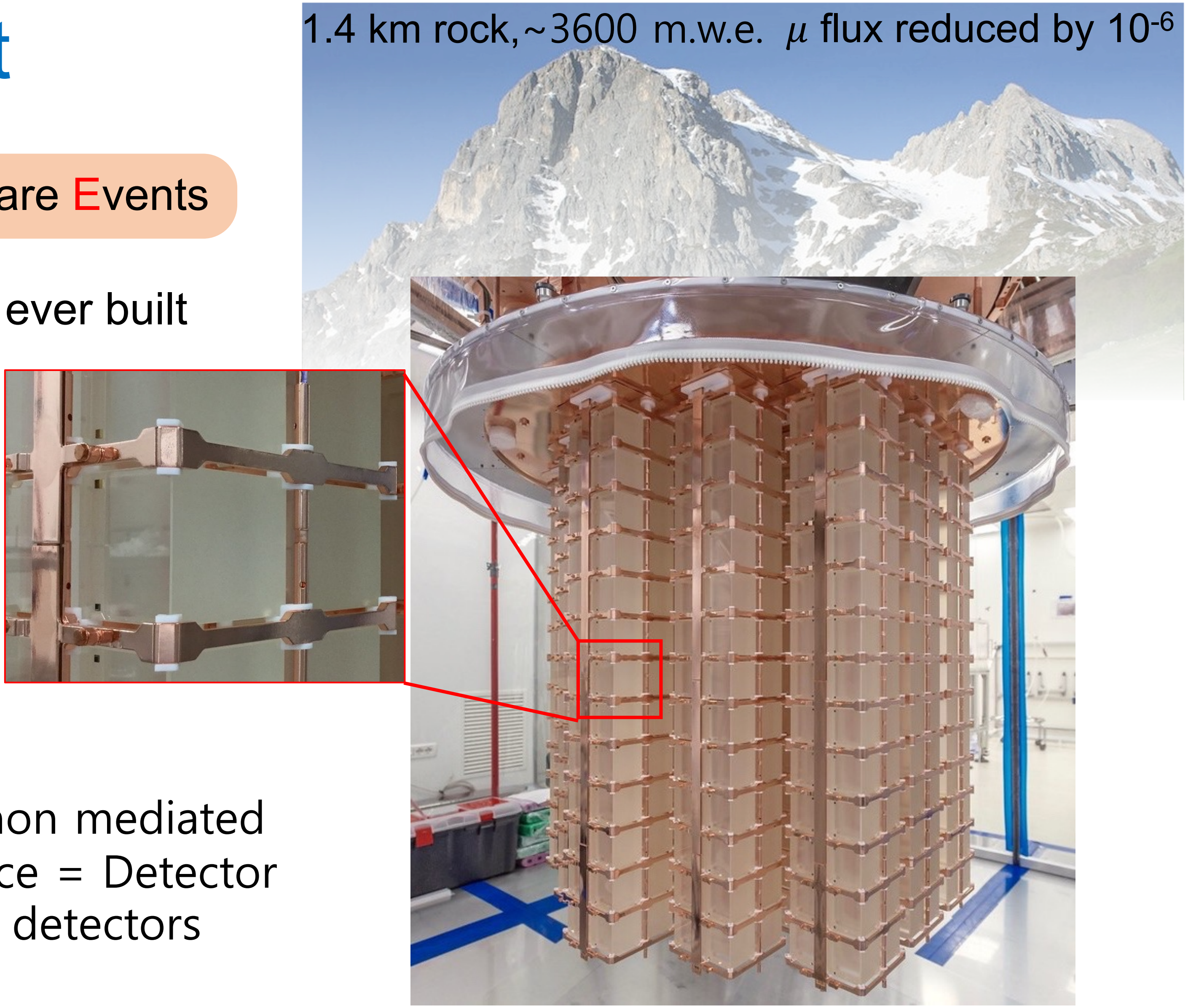
CUORE experiment

Cryogenic Underground Observatory for Rare Events

- Largest **cryogenic bolometric** detector ever built
  - 19 towers of 13 floors of 4 crystals
  - 988 TeO_2 crystals in total
  - natural abundance, ~206 kg of ^{130}Te
- Goal: search for $0\nu\beta\beta$ decay of ^{130}Te
  - Q-value of ~2527.5 keV



- Phonon mediated
- Source = Detector
- Slow detectors

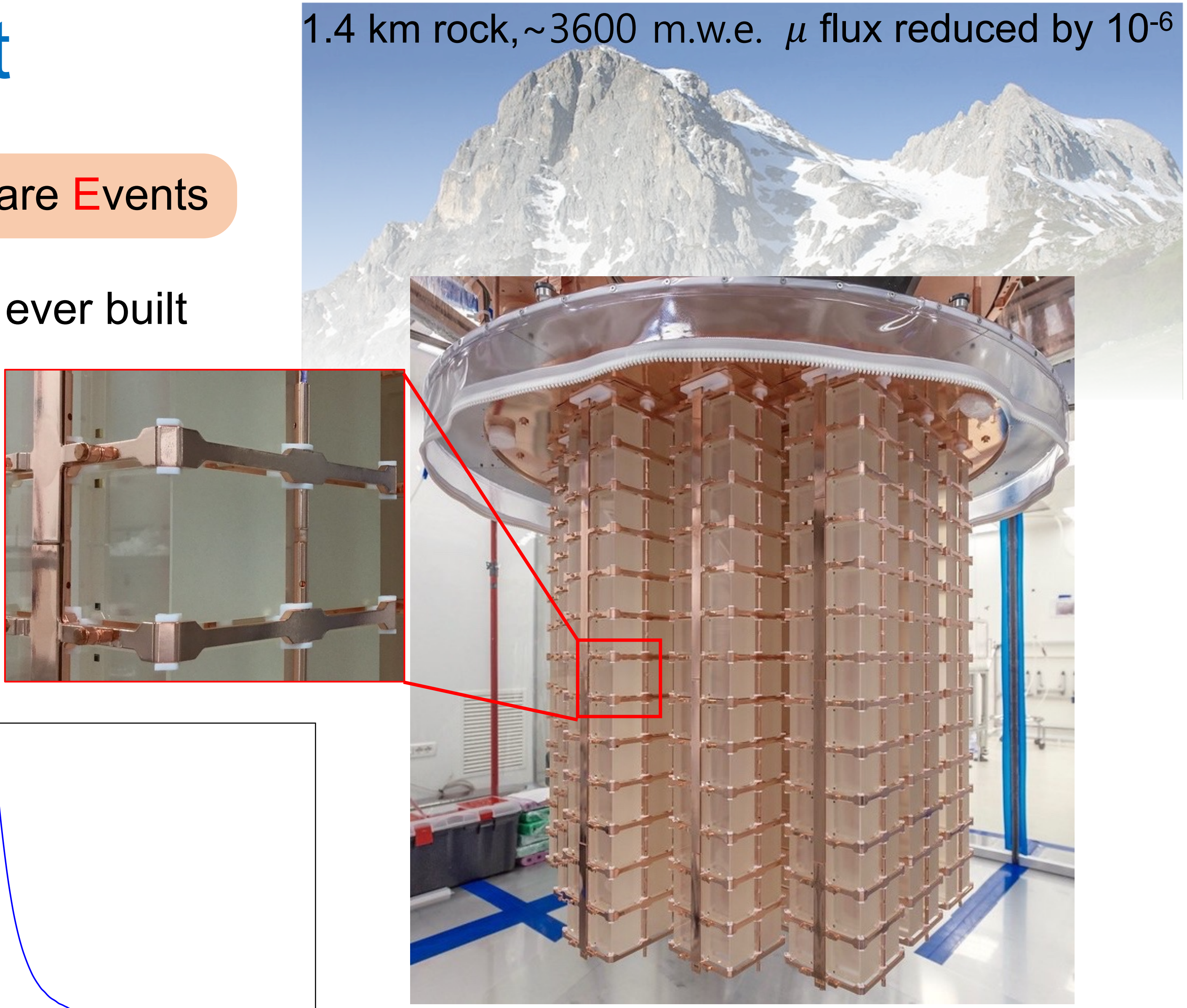

1.4 km rock,~3600 m.w.e. μ flux reduced by 10^{-6}

Gran Sasso National Laboratory (LNGS)

CUORE experiment

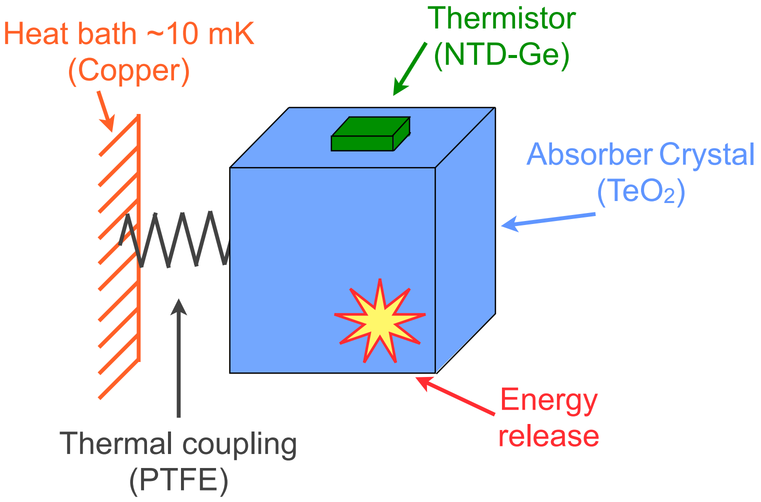
Cryogenic Underground Observatory for Rare Events

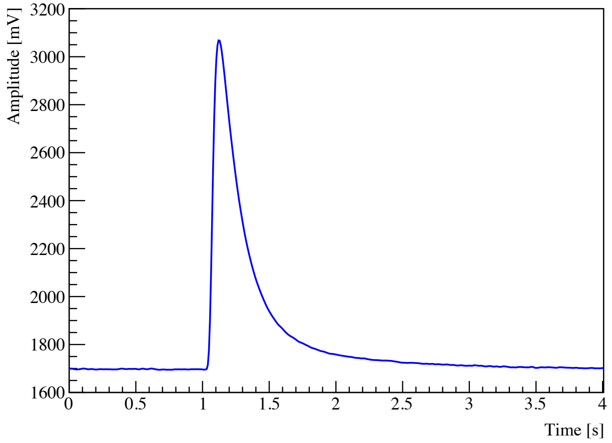
- Largest **cryogenic bolometric** detector ever built
  - 19 towers of 13 floors of 4 crystals
  - 988 TeO_2 crystals in total
  - natural abundance, ~206 kg of ^{130}Te
- Goal: search for $0\nu\beta\beta$ decay of ^{130}Te
  - Q-value of ~2527.5 keV



1.4 km rock,~3600 m.w.e. μ flux reduced by 10^{-6}

Gran Sasso National Laboratory (LNGS)





CUORE status

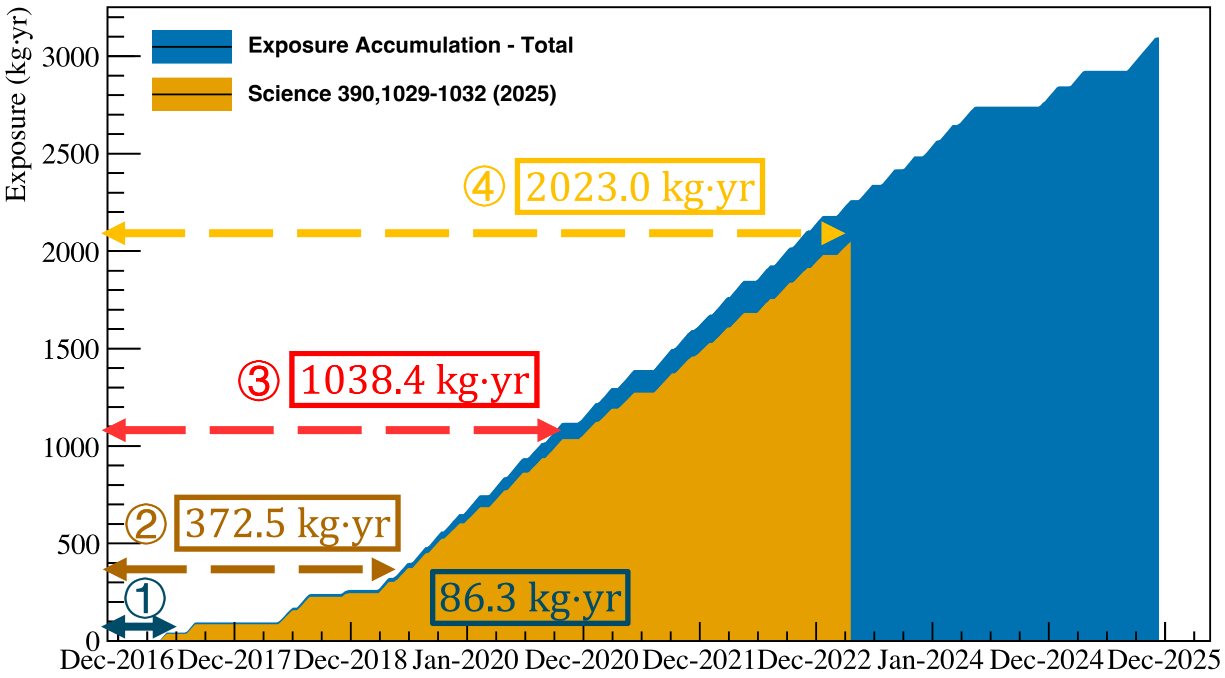
- Data taking started in 2017, with first 2 years for cryostat and detector optimization
- Stable data collection since 2019, with ≳ 85% uptime
- > 2.9 ton·yr of raw TeO_2 exposure accumulated
- Demonstrated stability over years of data taking

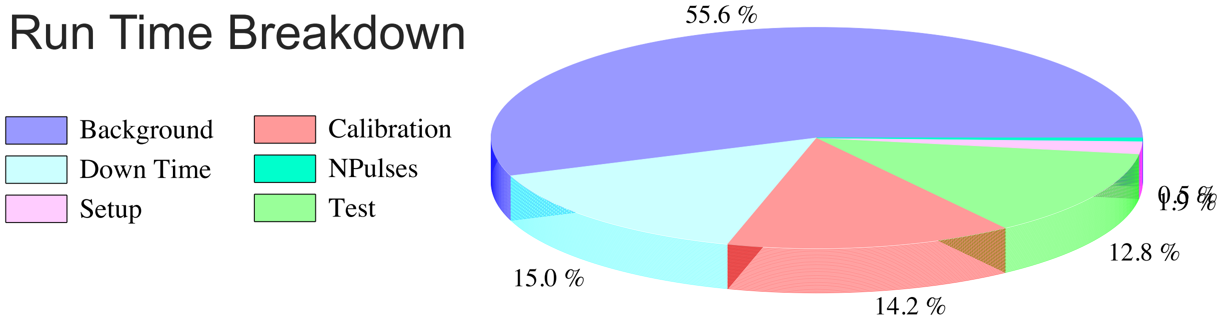
① Alduino, C. et al. (CUORE Collaboration), *Phys. Rev. Lett.* **120**, 132501 (2018)

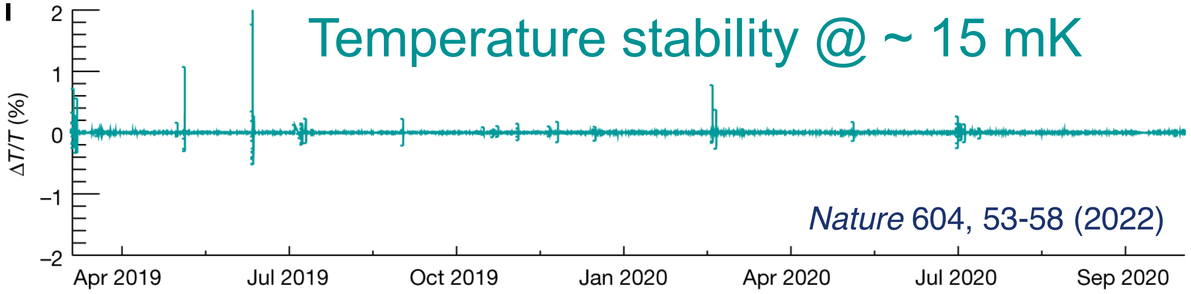
② Adams, D.Q. et al. (CUORE Collaboration), *Phys. Rev. Lett.* **124**, 122501 (2020)

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

④ **arXiv:2404.04453** (CUORE Collaboration)







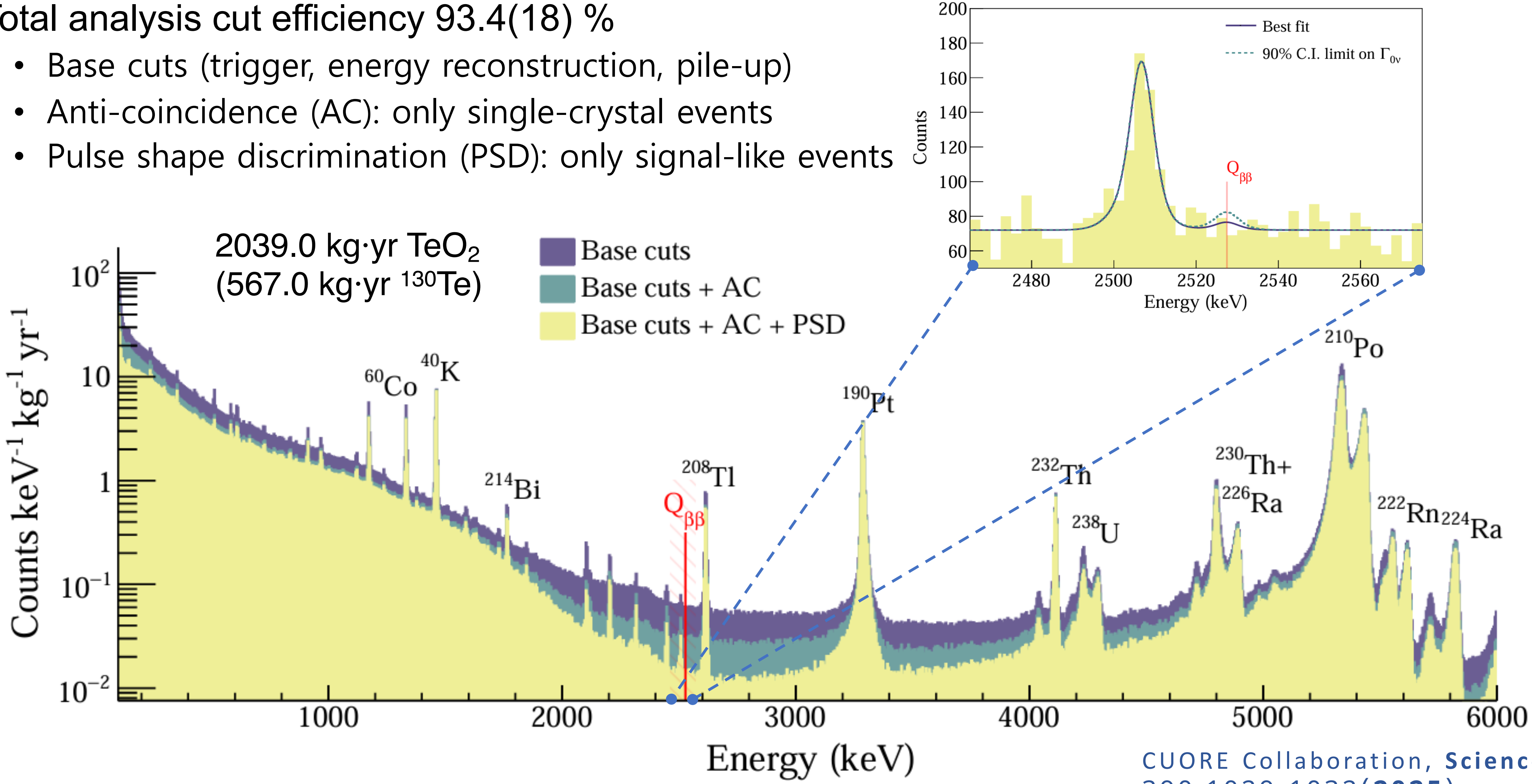
Temperature stability @ ~ 15 mK

Nature 604, 53-58 (2022)

CUORE Spectrum

average resolution of 7.54 keV FWHM at 2615 keV

- Total analysis cut efficiency 93.4(18) %
  - Base cuts (trigger, energy reconstruction, pile-up)
  - Anti-coincidence (AC): only single-crystal events
  - Pulse shape discrimination (PSD): only signal-like events

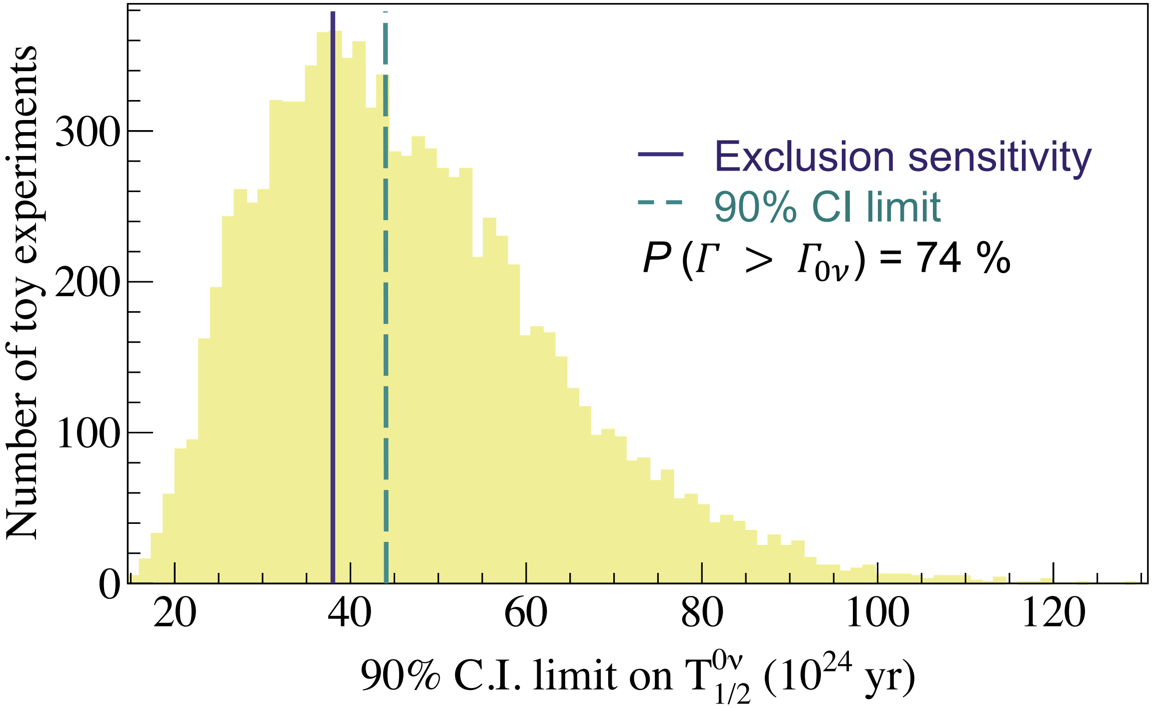


2039.0 kg·yr TeO_2
(567.0 kg·yr ^{130}Te)

CUORE Collaboration, **Science** 390,1029-1032(**2025**)

Search for $0\nu\beta\beta$

- Unbinned Bayesian fit with $\Gamma_{0\nu}$ > 0

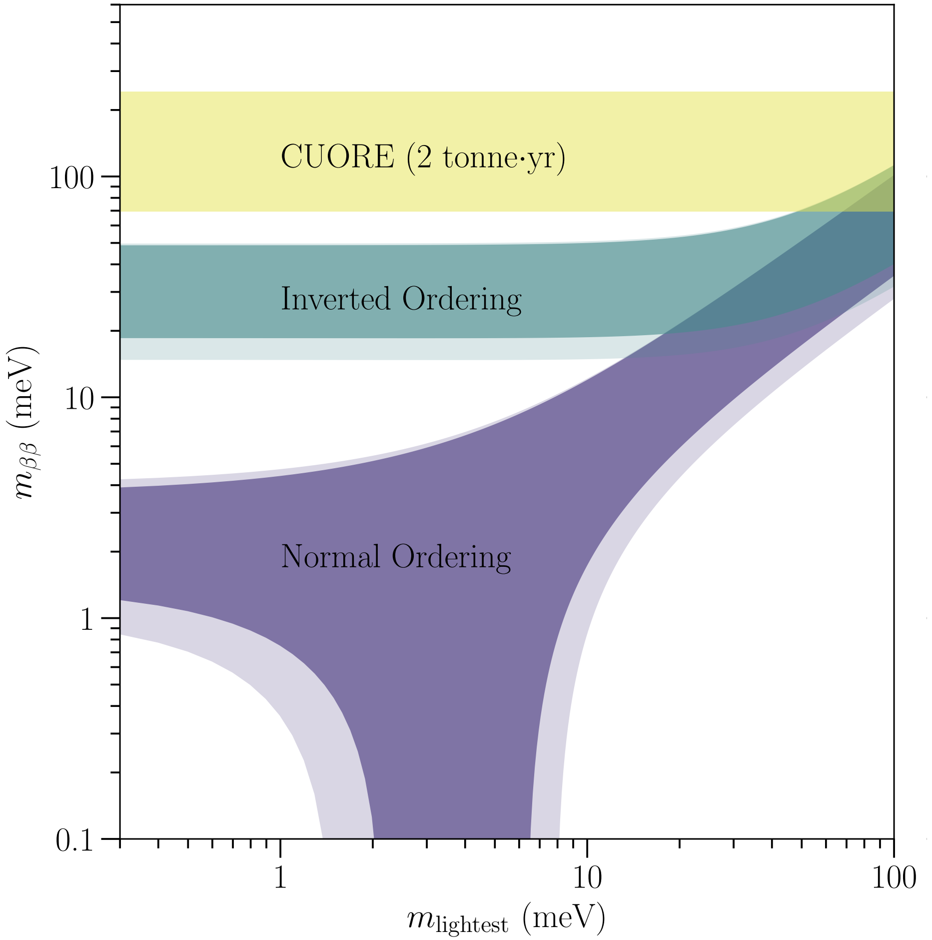


- No evidence, new limit on ^{130}Te $0\nu\beta\beta$ half-life

$$T^{0\nu}_{1/2} > 3.5 \cdot 10^{25} \text{ yr (90\% C. I.)}$$

- Frequentist: $T^{0\nu}_{1/2} > 3.4 \cdot 10^{25}$ yr (90% C. L.)

CUORE Collaboration, **Science** 390,1029-1032(**2025**)



- Assuming light Majorana neutrino exchange

$$m_{\beta\beta} < 70\text{– }250 \text{ meV}$$

$2\nu\beta\beta$ decay measurement

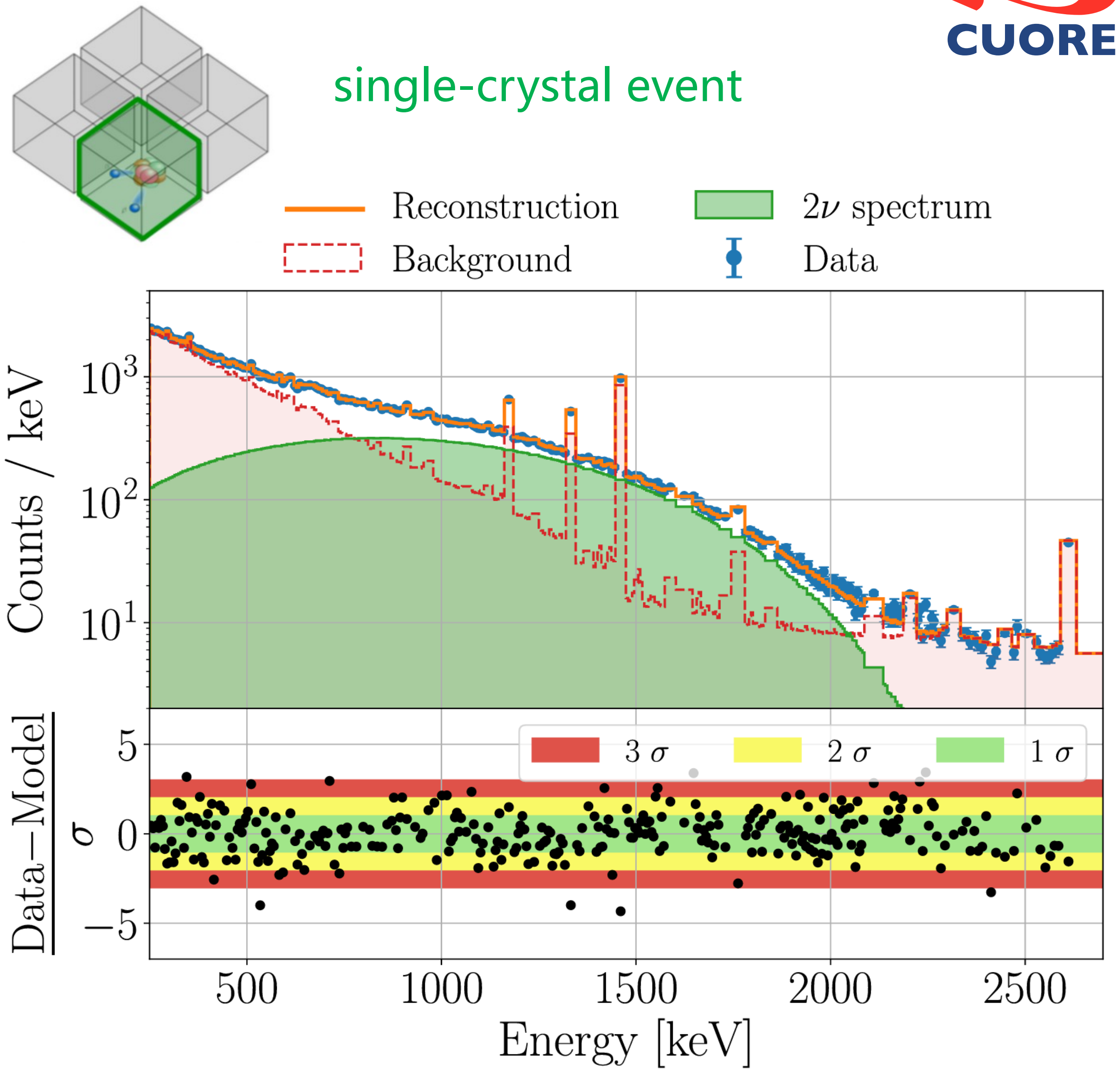
- Exposure: 1038.4 kg·yr of TeO_2

- Spectral fit to the single-crystal-event energy spectrum

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

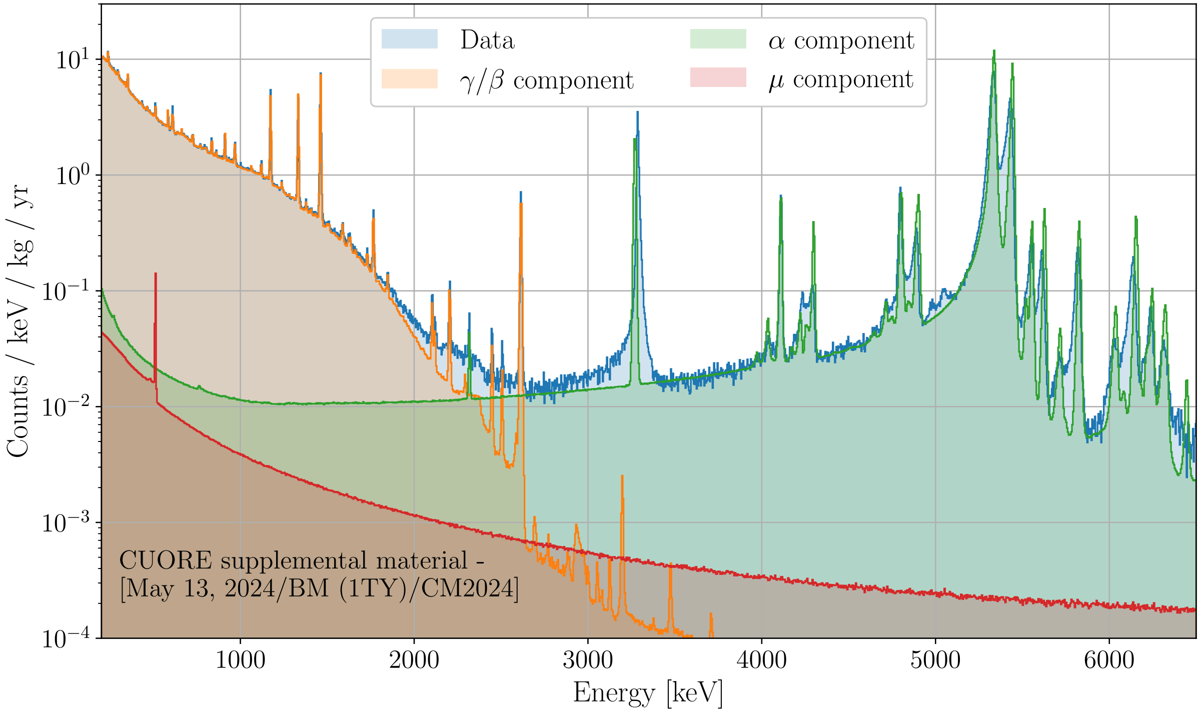
- Most precise measurement of ^{130}Te $2\nu\beta\beta$ decay half-life to date

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



CUORE Towards CUPID

- Provided important feedback in term of both the cryogenics and background budget
- CUORE is background limited (1.42±0.02)×10^{-2} counts / (keV·kg·yr)
- Dominated by (γ/β and degraded α) < 2615 keV
  - β continuum + γ peaks up to 2.7 MeV
  - α region from 4 MeV
  - degraded α extend to γ/β region
- Heat detection is sensitive to all kinds of energy events, additional different channel needed to reject α from γ/β



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

CUORE

CUORE Upgrade with Particle Identification (CUPID)

CUPID

JOHNS HOPKINS UNIVERSITY

VirginiaTech
Invent the Future®

UNIVERSITÉ DE LYON

IJCLab Irène Joliot-Curie

BEIJING NORMAL UNIVERSITY 1902

cnrs IN2P3

CAL POLY

BERKELEY LAB

INFN

NRC KI-ITEP

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

SAPIENZA UNIVERSITÀ DI ROMA

University of Pittsburgh

cea

Irfu

АКАДЕМІЯ НАУК УКРАЇНИ 1918

UGA Université Grenoble Alpes

Argonne NATIONAL LABORATORY

Massachusetts Institute of Technology

UNIVERSITY OF SOUTH CAROLINA

université PARIS-SACLAY

IMM BOLOGNA UNIT

THE UNIVERSITY OF CALIFORNIA 1868

UCLA

SHANGHAI JIAO TONG UNIVERSITY 1896

Yale

NIKOLAEV INSTITUTE OF INORGANIC CHEMISTRY
SIBERIAN BRANCH OF RUSSIAN ACADEMY OF SCIENCES

CAPA
Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza

Northwestern

BOSTON UNIVERSITY

Drexel UNIVERSITY

University of Science and Technology of China 1958

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA A.D. 1088

FUDAN UNIVERSITY 1905

araid
FUNDACIÓN AGENCIA ARAGONESA PARA LA INVESTIGACIÓN Y EL DESARROLLO

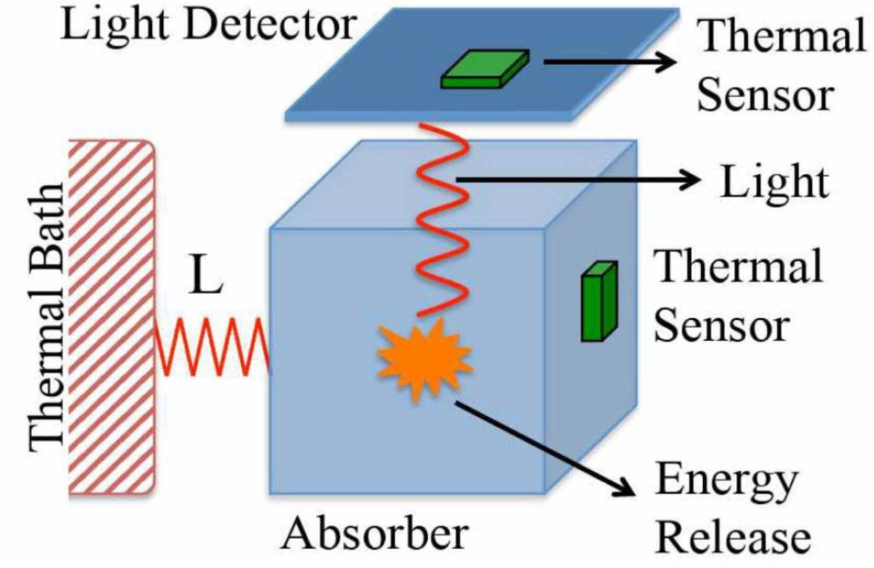
iP2i LES 2 INFINIS LYON

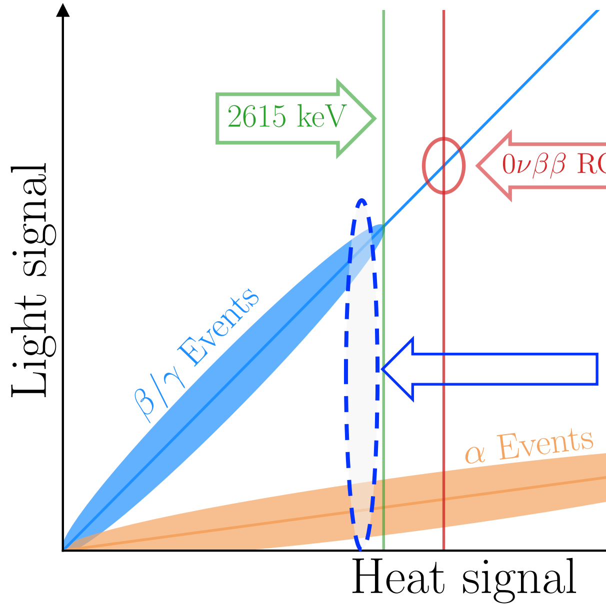
GSSI

CUPID concept

Scintillating Bolometer

Light readout in addition to heat detection





CUPID ROI

CUORE ^{130}Te ROI

$Q_{\beta\beta}$ greater than 2615 keV: most β/γ backgrounds reduced

Measure both heat and light simultaneously

Particle ID to actively discriminate α particles

CUPID pre-CDR *arXiv:1907.09376*

CUPID demonstrators

CUPID-0

- ZnSe crystals, 95% ^{82}Se enrichment
- (5.17 kg ^{82}Se) at LNGS (Italy)
- α-rejection efficiency > 99.9%
- Background index: 3.5×10^{-3} c/kky
- ΔE= 21.8 keV @ ($Q_{\beta\beta}$=2998 keV)

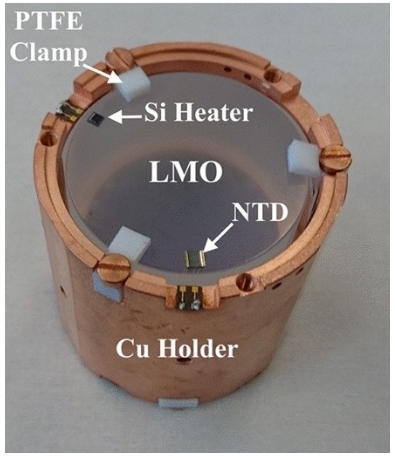
[CUPID-0: *Phys. Rev. Lett.* 129, 111801 (2022)]

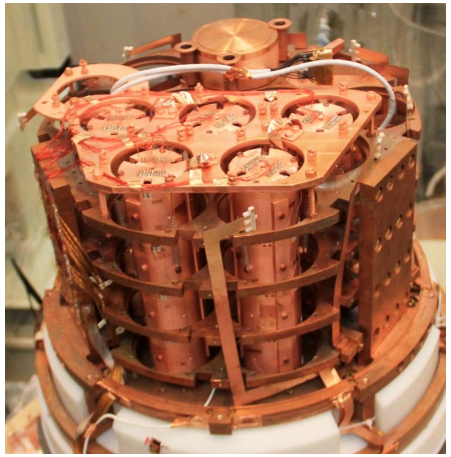
LD: SiO coating
Ge wafer

Reflecting foils
surrounded

CUPID-Mo

- Li_2MoO_4 crystals, 97% ^{100}Mo enrichment
- (2.26 kg ^{100}Mo) at Modane (France)
- α-rejection efficiency > 99.9%
- Background index: 2.7×10^{-3} c/kky
- ΔE = 7.4 keV @ ($Q_{\beta\beta}$=3034 keV)



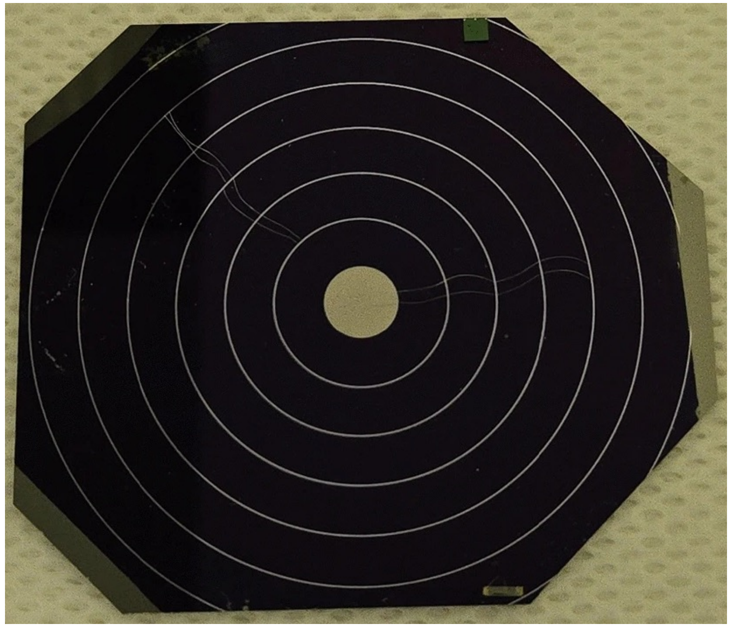


[CUPID-Mo: *Eur. Phys. J. C* 82, 1033 (2022)]

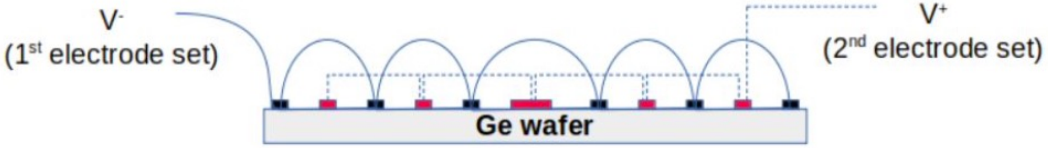
Light detector

Neganov-Trofimov-Luke (NTL) effect assisted

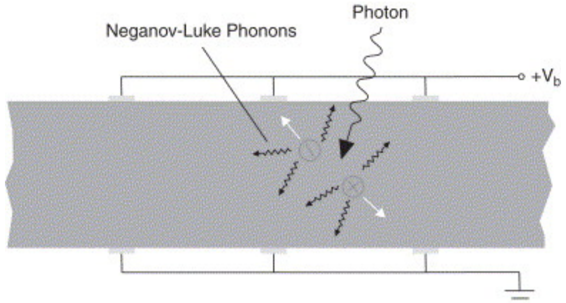
- NTL Light Detector technology now well established:
  - Ge wafer with anti-reflective SiO coating and NTD-Ge readout
  - Establish an electric field via a set of Al electrodes



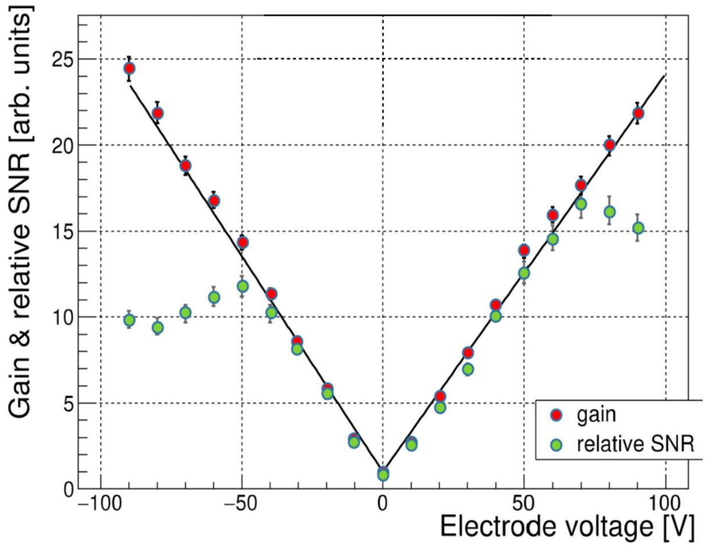
Eur. Phys. J. C 85, 737 (2025).



- NTL effect for signal amplification
  - Electron-hole pairs created by light absorption drift in the field and produce additional heat
  - SNR is increased by an order of magnitude allows for efficient $2\nu\beta\beta$ pile-up rejection



$$E_{tot} = E_0 \left(1 + \frac{q \cdot V_{el} \cdot \eta}{\epsilon}\right)$$



CUPID Baseline Design

45 x 45 x 45 mm³ $Li_2{}^{100}MoO_4$ crystals

- Crystal mass: 280 g

1596 total crystals

- 450 kg of $Li_2{}^{100}MoO_4$
- 95% enrichment in ^{100}Mo: 240 kg of ^{100}Mo
- 57 towers of 28 crystals. 14-floors of 2x1 crystal pairs

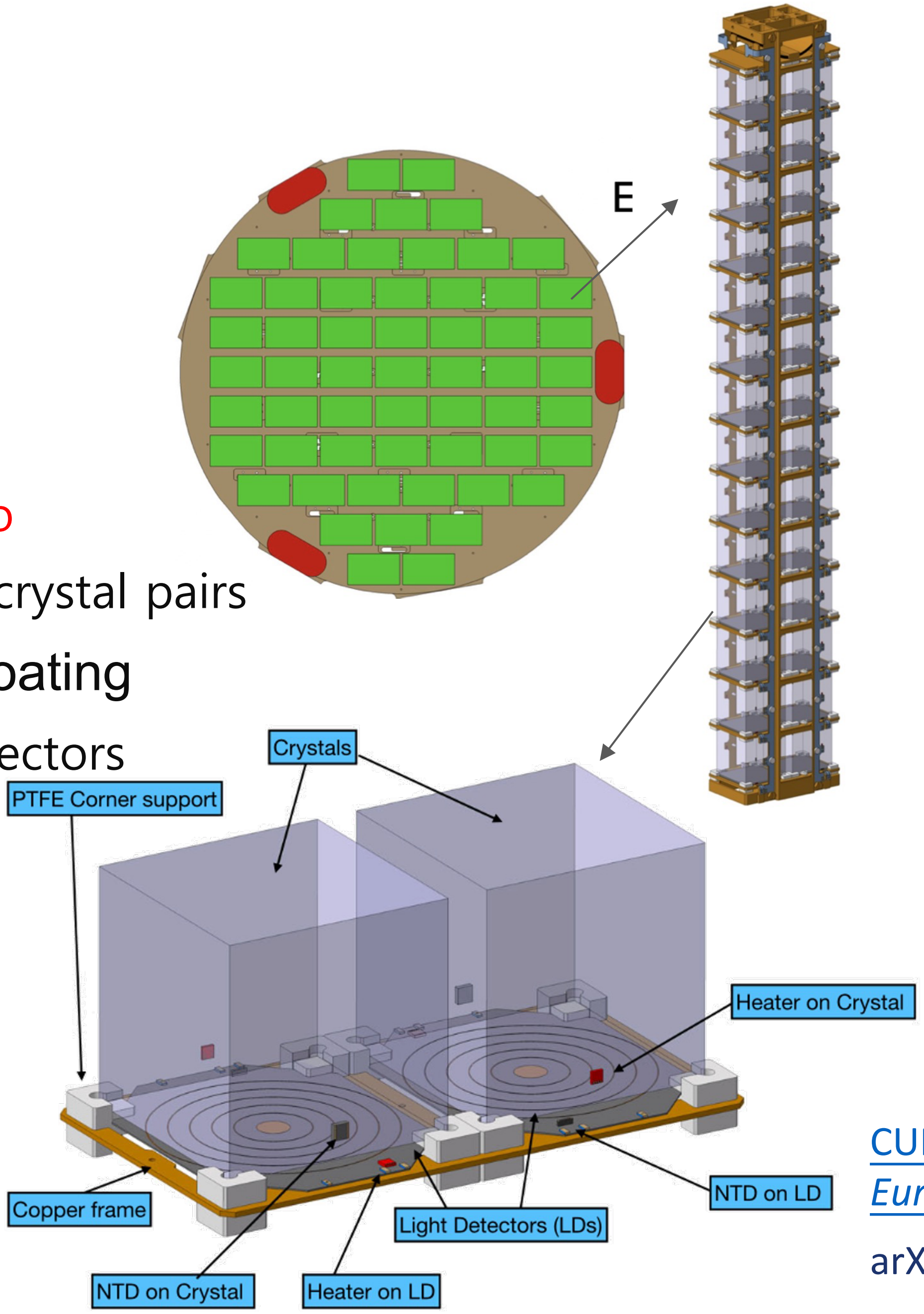
Ge light detectors with SiO anti-reflective coating

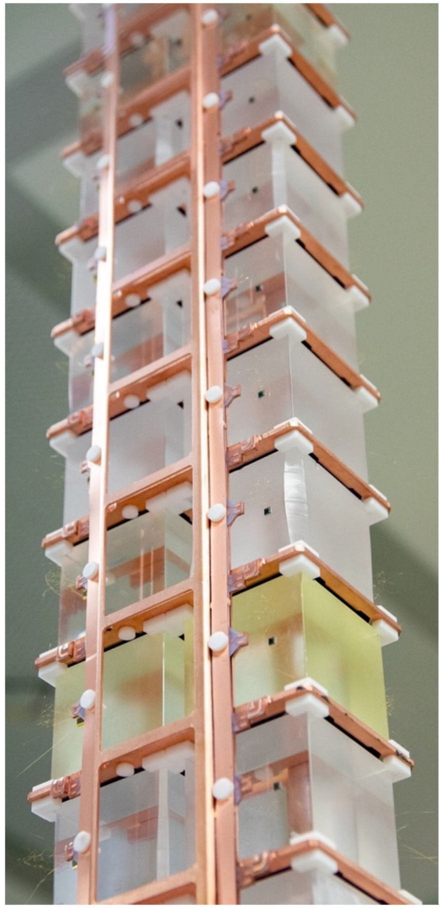
- Each crystal has top and bottom light detectors
- No reflective foils

Energy resolution: 5 keV FWHM @ $Q_{\beta\beta}$

Muon veto for muon-induced background suppression

Planned to use the CUORE's cryostat and infrastructure



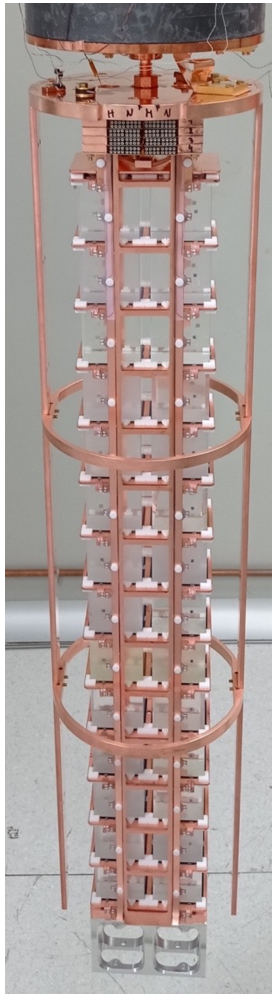


CUPID Collaboration. *Eur. Phys. J. C* 85, 737 (2025).

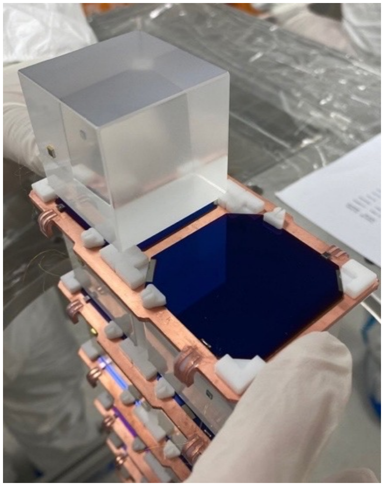
arXiv:2503.0448

Progress on CUPID prototype towers

CUPID HallA facility @LNGS



GDPT tower



GDPT (Gravity Detector Prototype Tower) (2022)

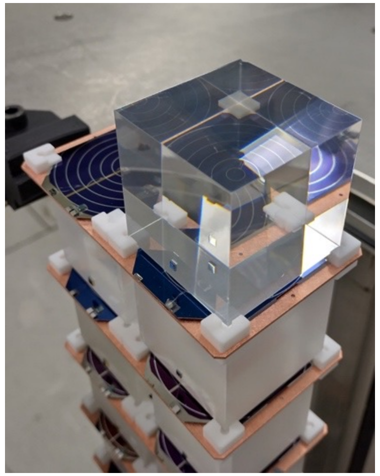
- **Innovative assembly design**, easy for production, cleaning, and detector construction
- Conceptual test of the new mechanical assembly
- **Successful** but limited SNR and correlated noise with LDs
- ~6.6 keV FWHM at 2615 keV, light yield: 0.36 keV/MeV

CUPID Collaboration. *Eur. Phys. J. C* 85, 935 (2025).

VSTT (Vertical Slice Test Tower) 2025

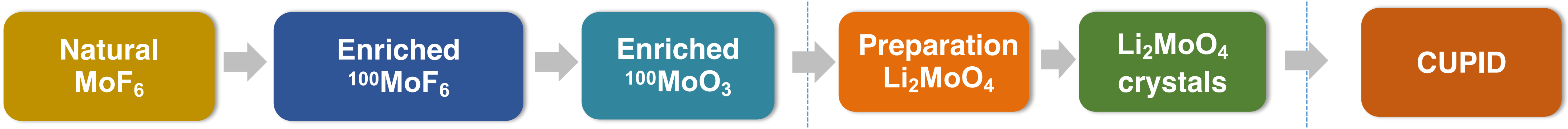
- Upgraded tower design and assembly-line
- **NTL light detectors**
- **Optical fibers along the tower**
- New electronics and DAQ
- Data taking and detectors performance assessment ongoing

WORK IN PROGRESS



VSTT tower

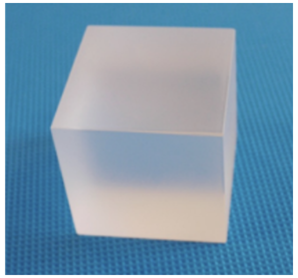
Enriched crystal production



Isotope enrichment, transformation and purification of compounds

Product transformation, purification, crystal growth, cutting, polishing

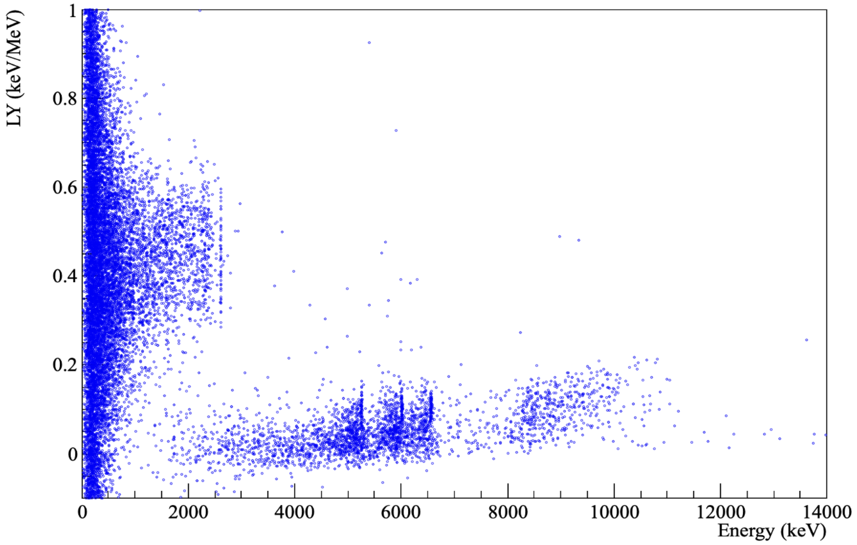
Natural MoF_6 → **Enriched $^{100}MoF_6$** → **Enriched $^{100}MoO_3$** → **Preparation Li_2MoO_4** → **Li_2MoO_4 crystals** → **CUPID**



- Crystal growth: inclusions and cracks are largely under control
  - Inclusions, colored impurities, and precipitates ← Incomplete reaction between Li_2CO_3 and MoO_3,
  - Cracks formation → mostly eliminated by annealing at the end of the growth (before extracting crucibles)
- Working on the optimization of radiopurity and fixing the complete crystal production chain

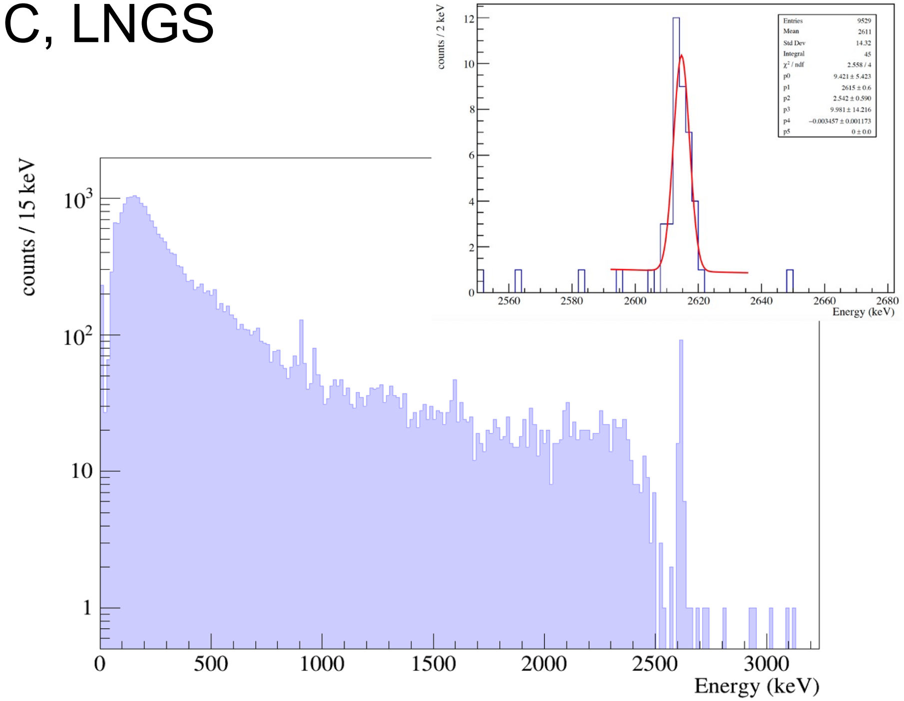
CUPID crystal test

- First CUPID full-size enriched LMO crystal, 45×45×45 mm^3
- Before the optimization of cracks formation
  - Some visible internal cracks and colored impurities
- Cryogenic bolometric test at Hall C, LNGS



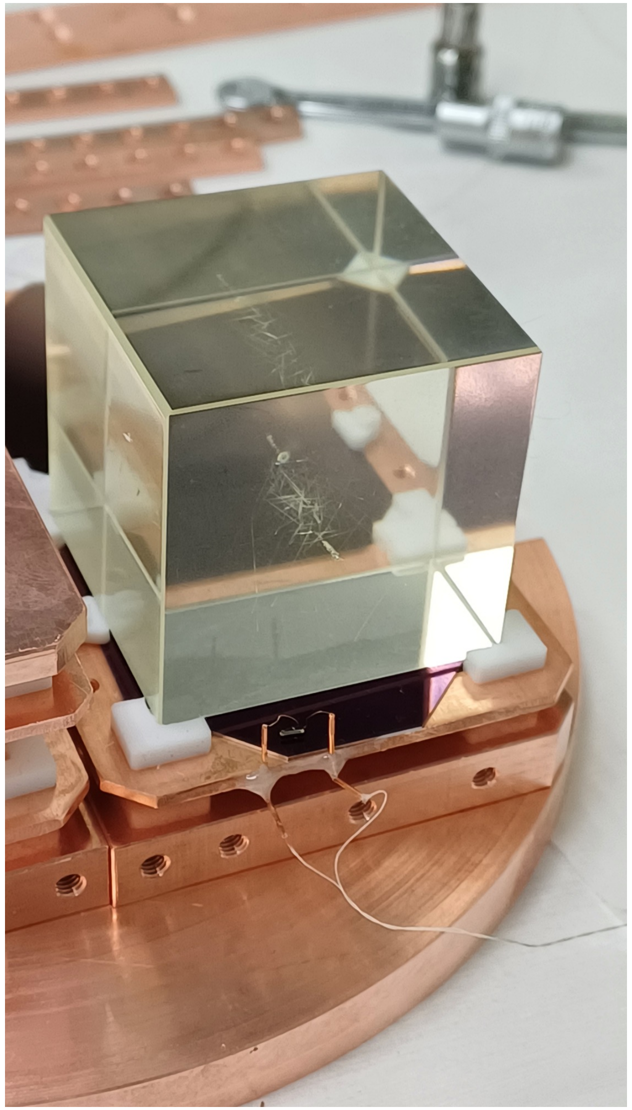
Light yield for beta: ~0.45 keV/MeV

Good scintillating properties



FWHM at 2615 keV: 7.5 ± 1.7 keV

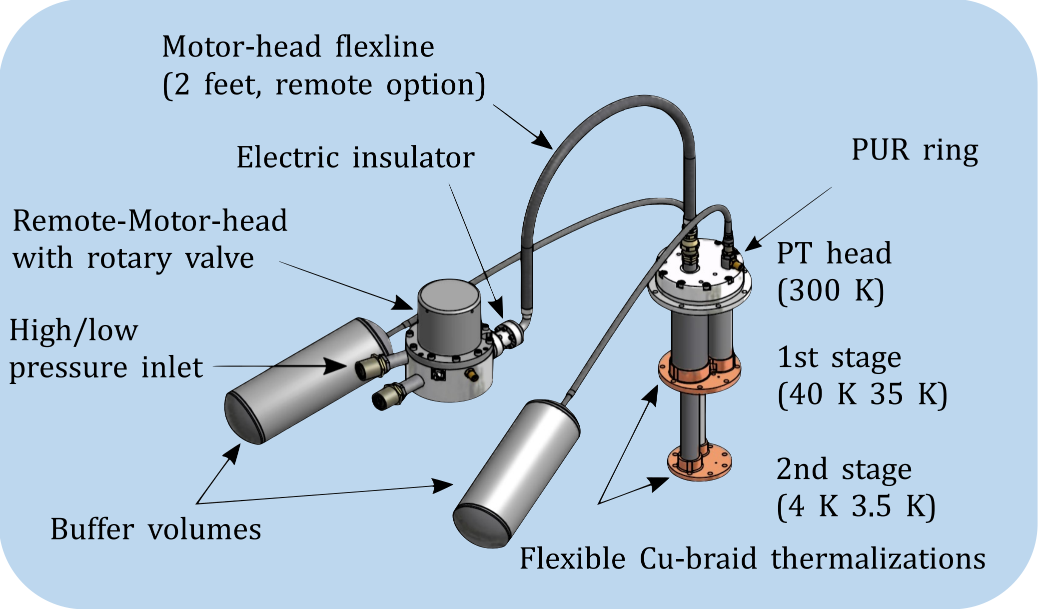
Good resolution after optimized cuts

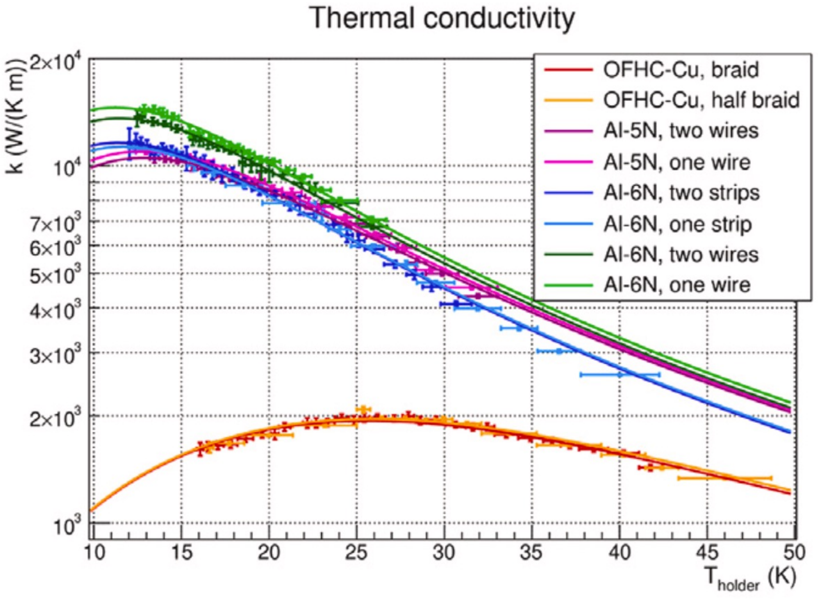


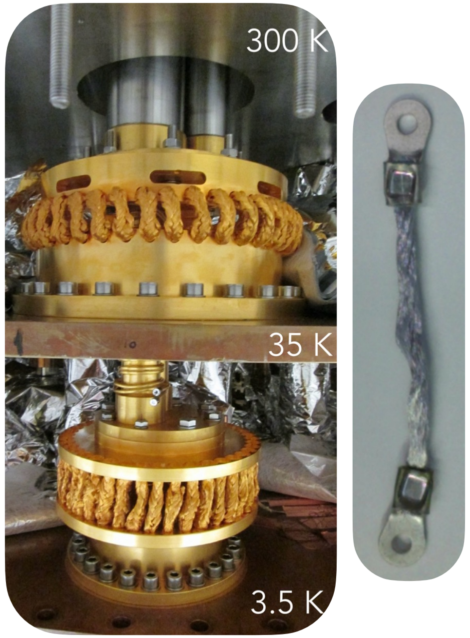
Cryostat upgrades

After CUORE's end

- Pulse Tubes system is an important source of vibrational noise
  - New Pulse Tubes with more cooling power, less PTs required makes better PT phase scan
  - New linear drives for motor head control, refined PT phase scan for noise cancellation
  - New thermalizations: high purity 6N Al, increase thermal link, while reducing mechanical coupling



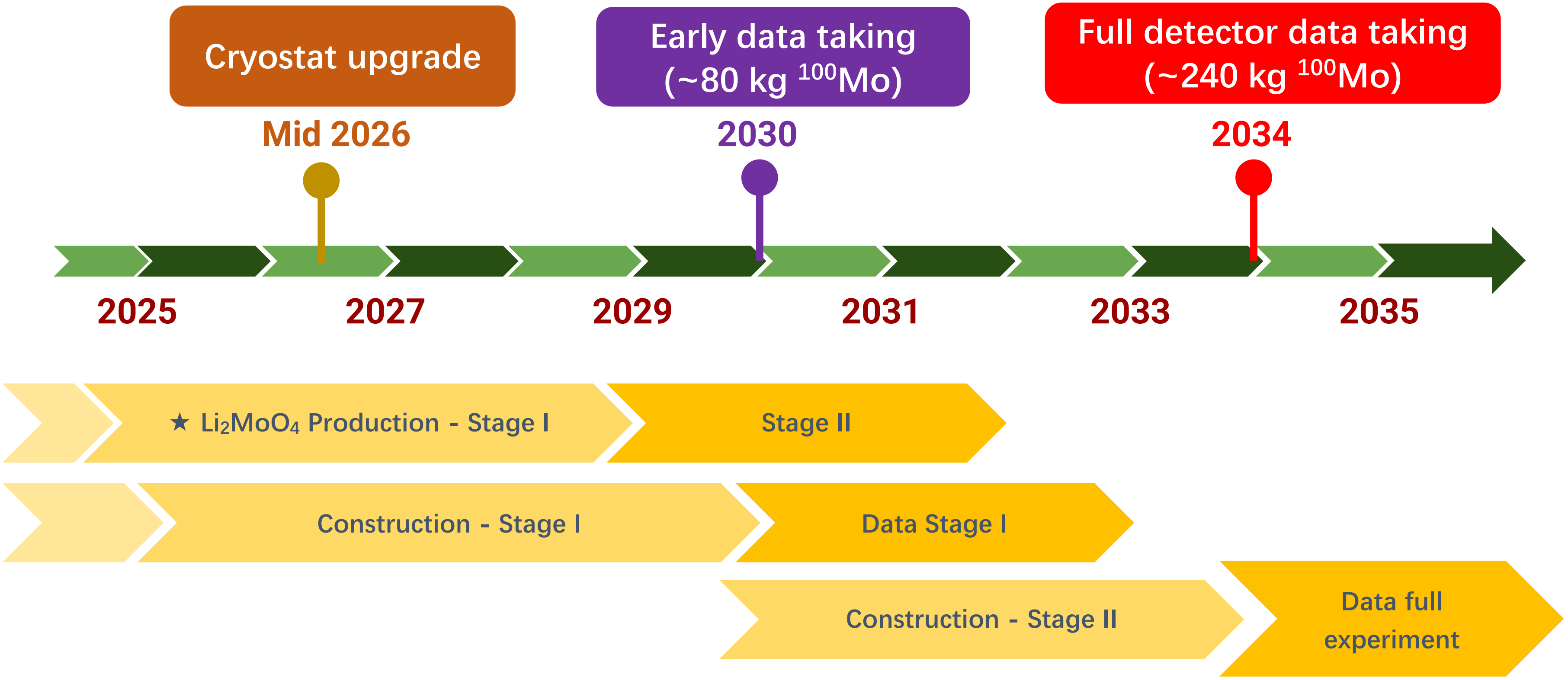




F. Agresti, *at al* Cryogenics 154 (2026) 104276

CUPID timeline

- CUPID Stage-I: 1/3 of the crystals & 3 year data-taking
- CUPID full array: Add the remaining 2/3 of the crystals & full data-taking



Cryostat upgrade

Mid 2026

Early data taking (~80 kg ^{100}Mo)

2030

Full detector data taking (~240 kg ^{100}Mo)

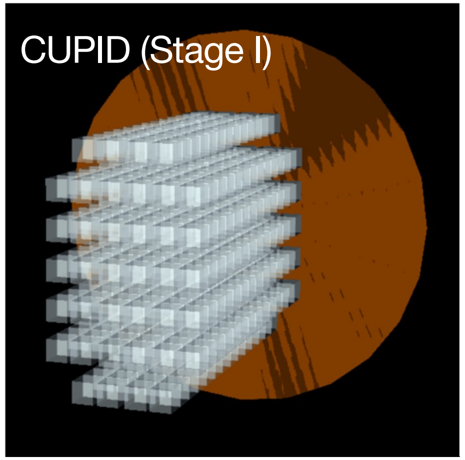
2034

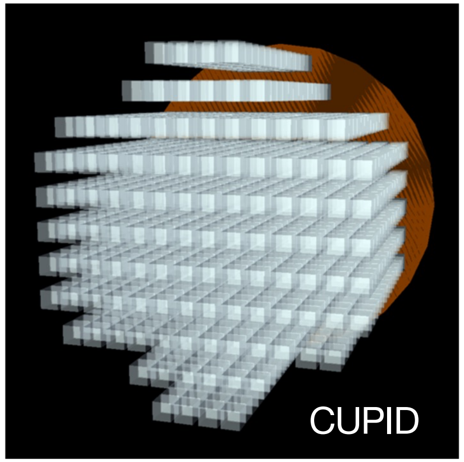
2025 2027 2029 2031 2033 2035

★ Li_2MoO_4 Production - Stage I → Stage II

Construction - Stage I → Data Stage I

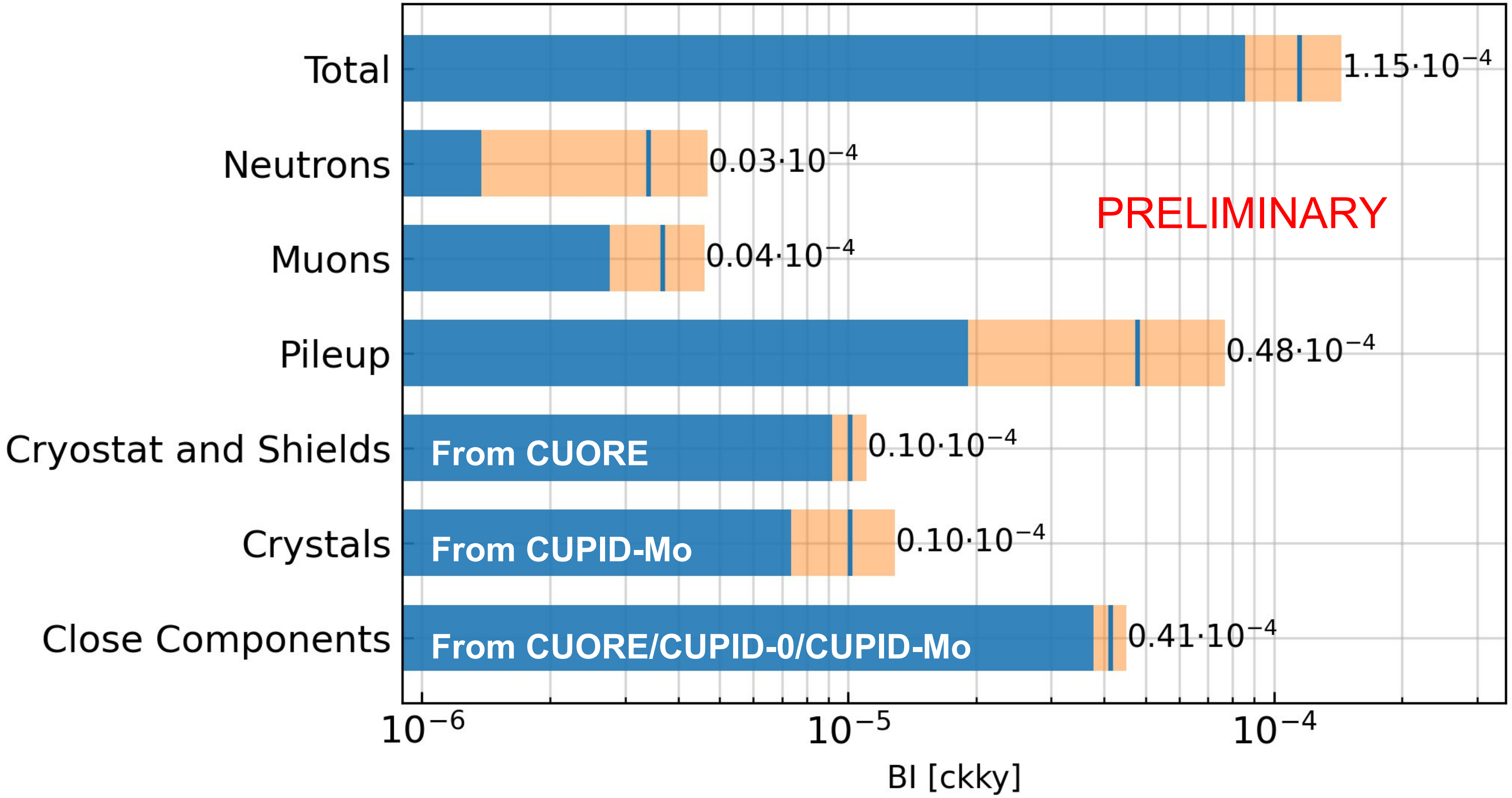
Construction - Stage II → Data full experiment





CUPID background

- A robust background model built using knowledge acquired with **CUORE, CUPID-0 and CUPID-Mo** experiments, pile-up events play a critical role

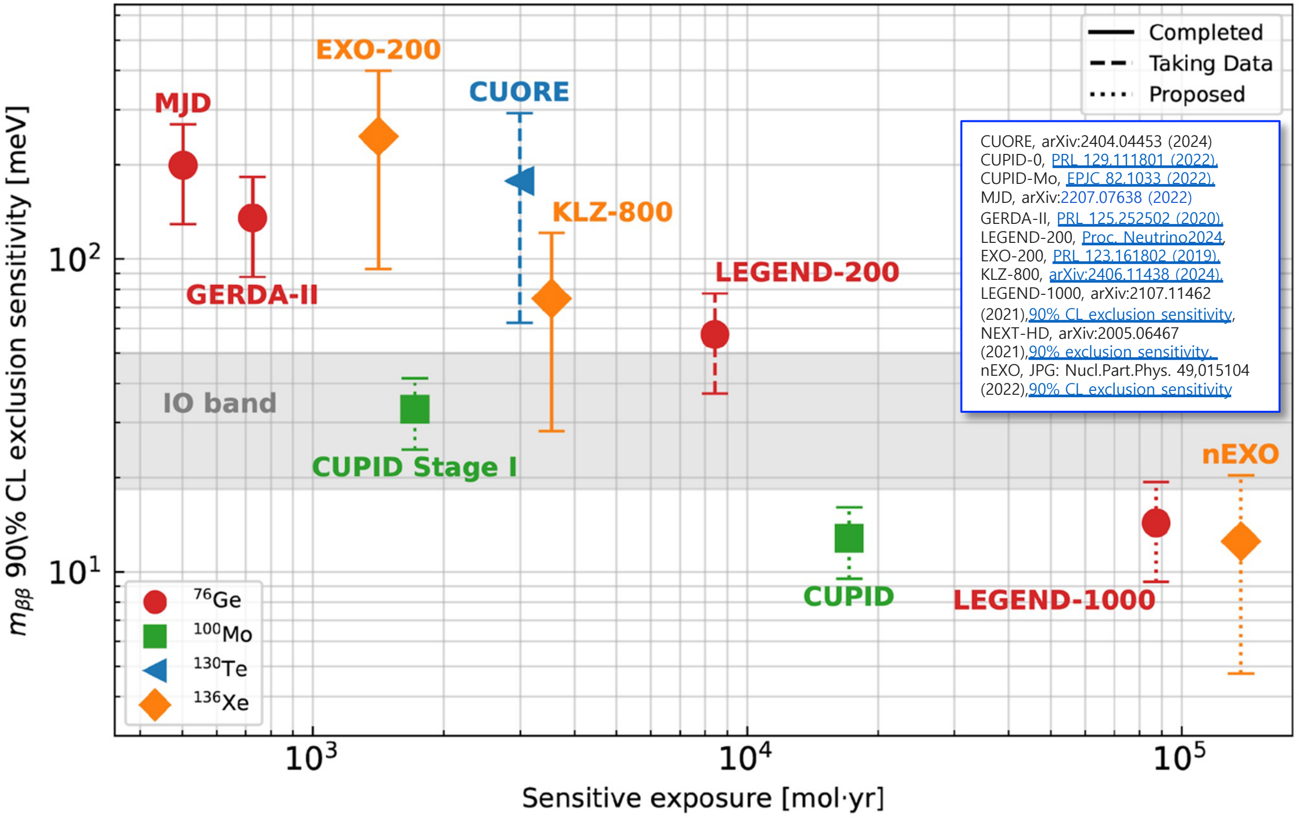


BI Goal: 1.0×10^{-4} c/kky

Figure from Pía Loaiza, *TAUP 2025* conference

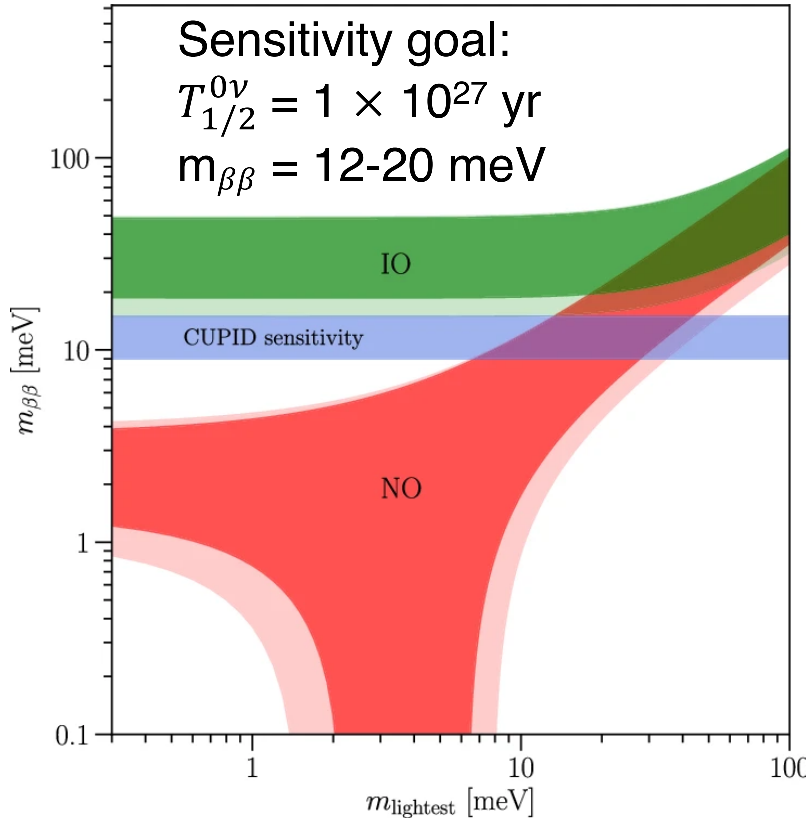
CUPID sensitivity

- CUPID Stage I has world-leading science reach
- Staged deployment enables first science data by 2030 with CUPID Stage I
- Fully explore Inverted Hierarchy and part of Normal Hierarchy region



CUORE, arXiv:2404.04453 (2024)
CUPID-0, PRL 129,111801 (2022),
CUPID-Mo, EPJC 82,1033 (2022),
MJD, arXiv:2207.07638 (2022)
GERDA-II, PRL 125,252502 (2020),
LEGEND-200, Proc. Neutrino2024,
EXO-200, PRL 123,161802 (2019),
KLZ-800, arXiv:2406.11438 (2024),
LEGEND-1000, arXiv:2107.11462 (2021),90% CL exclusion sensitivity,
NEXT-HD, arXiv:2005.06467 (2021),90% exclusion sensitivity,
nEXO, JPG: Nucl.Part.Phys. 49,015104 (2022),90% CL exclusion sensitivity

with 10 years livetime



Sensitivity goal:
$T^{0\nu}_{1/2}$ = 1 × 10^{27} yr
$m_{\beta\beta}$ = 12-20 meV

Summary

- CUORE demonstrated the feasibility of the cryogenic bolometric technique to ton-scale detectors for $0\nu\beta\beta$ searching

- Found no evidence of $0\nu\beta\beta$ decay with 2039.0 kg · yr TeO_2 exposure
- Set a new limit on the half life of ^{130}Te $T_{1/2}^{0\nu} > 3.8 \cdot 10^{25}$ yr (90 % C . I.)
- Data collection is ongoing towards our goal of a final 3 ton·yr TeO_2 exposure (corresponding to 1 ton · yr ^{130}Te)

- Multifaceted efforts are underway for the staged deployment of CUPID
- Leveraging CUORE's expertise, CUPID will play a central role in the $0\nu\beta\beta$ search with discovery potential in the world

Thank you for listening!

CUORE

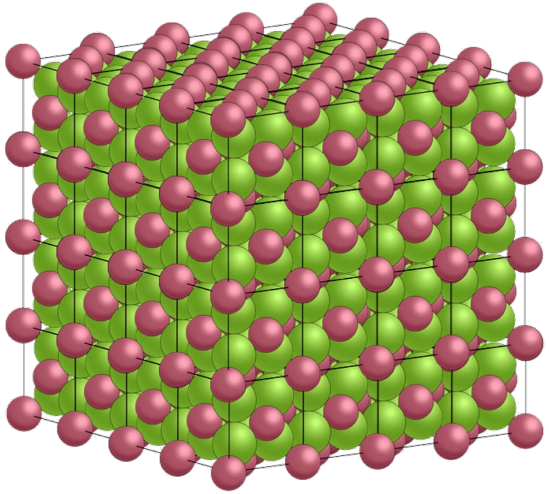
CUPID

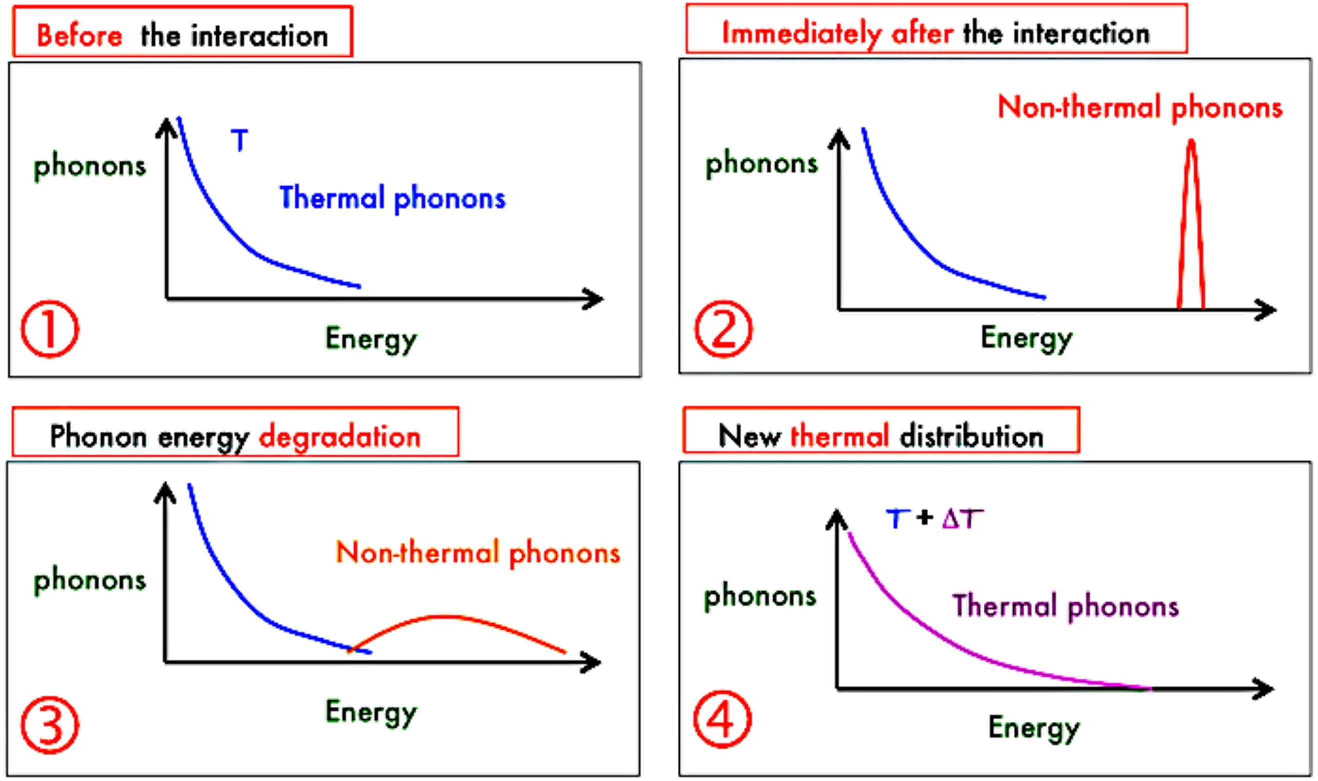
Acknowledgment

The **CUPID** Collaboration thanks the directors and staff of the Laboratori Nazionali del Gran Sasso and the technical staff of our laboratories. This work was supported by the Istituto Nazionale di Fisica Nucleare, the Italian Ministry of University and Research (Italy), the European Research Council and European Commission, the US Department of Energy (DOE) Office of Science, the DOE Office of Science, Office of Nuclear Physics, the National Science Foundation (USA), the Russian Science Foundation (Russia), and the National Research Foundation (Ukraine). This research used resources of the National Energy Research Scientific Computing Center (NERSC). This work makes use of both the DIANA data analysis and APOLLO data acquisition software packages, which were developed by the CUORICINO, CUORE, LUCIFER and CUPID-0 Collaborations.

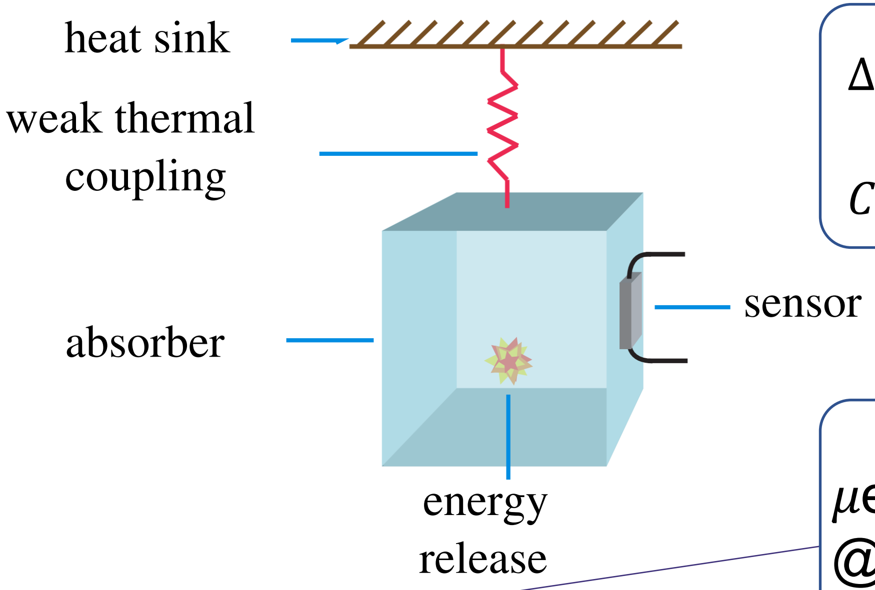
Backup slides

- **Phonon**：quasiparticles, elementary excitation in the quantum mechanical treatment of vibrations in a crystal lattice
- **Athermal/Non-thermal phonon**: ~meV，localized，non-equilibrium
- **Thermal phonon**: ~μeV ($k_B \cdot T$ at 10 mK)，heat equilibrium, equivalent to temperature





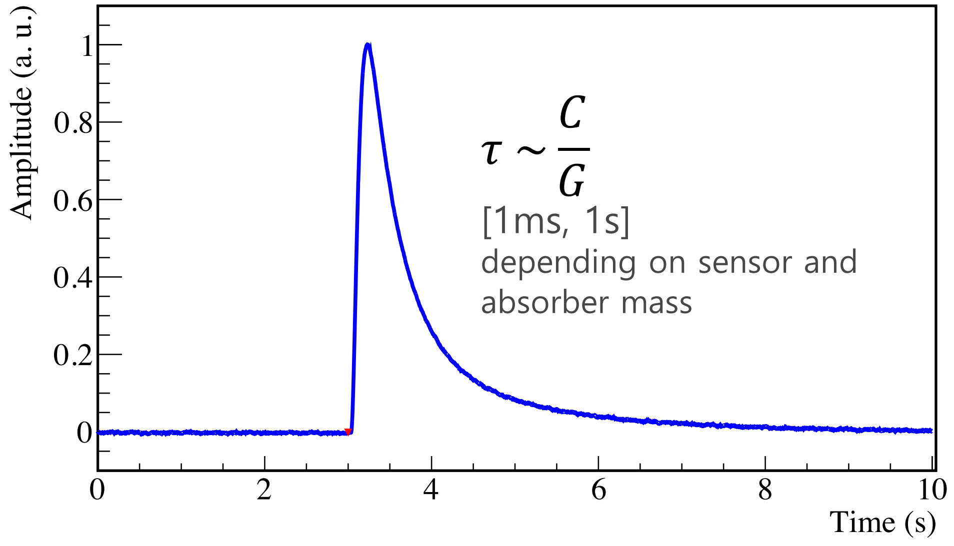
Cryogenic bolometric technique



$$\Delta T = \frac{\Delta E}{C(T)}$$

$$C(T) \propto T^3$$

μeV~meV
@ ~10 mK



$$\tau \sim \frac{C}{G}$$

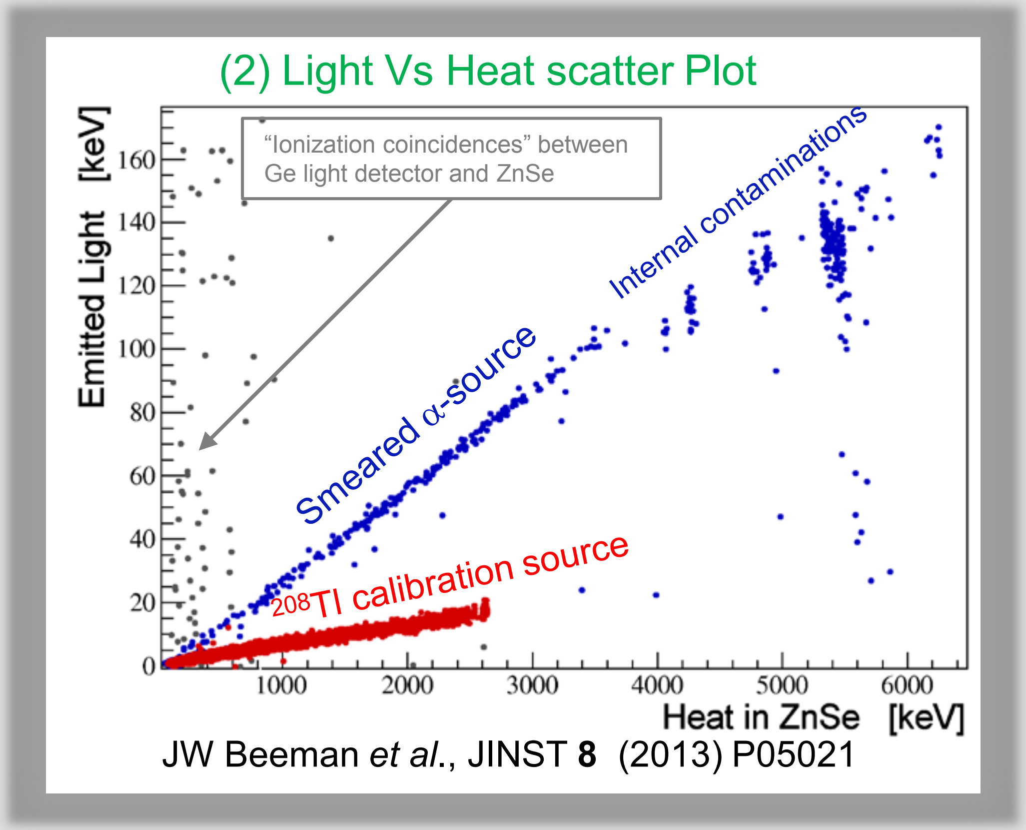
[1ms, 1s]
depending on sensor and absorber mass

- Phonon mediated detection, measure higher portion of the deposited energy
  - Operating at a temperature of ~10 mK, phonon sensor: NTD-Ge, TES, MMC, KID…
  - Good energy resolution, ~5-10 keV at 2.5 MeV
  - Large flexibility in material choice
  - Source = detector, high efficiency
  - Slow detectors suitable only for experiments working at low rates

Bolometer matches well with $0\nu\beta\beta$ search!

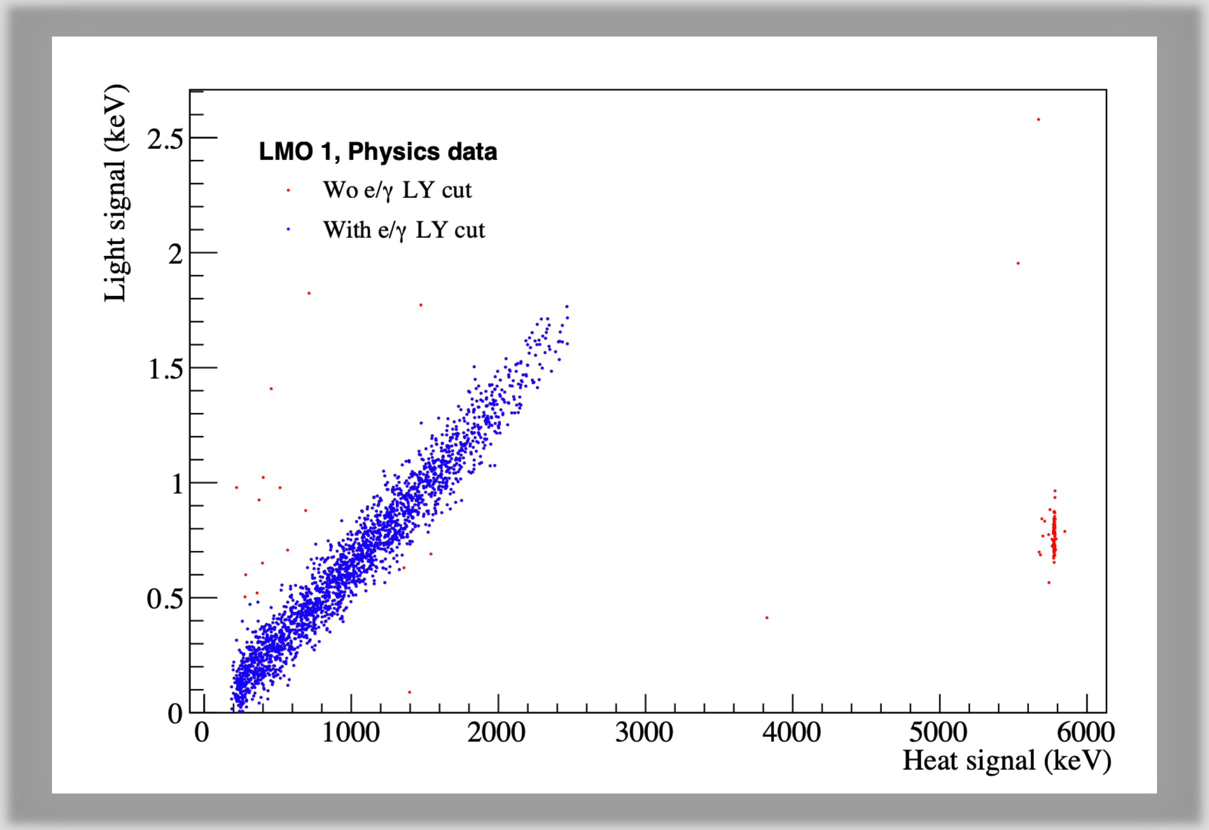
Light heat double readout

CUPID-0 ZnSe

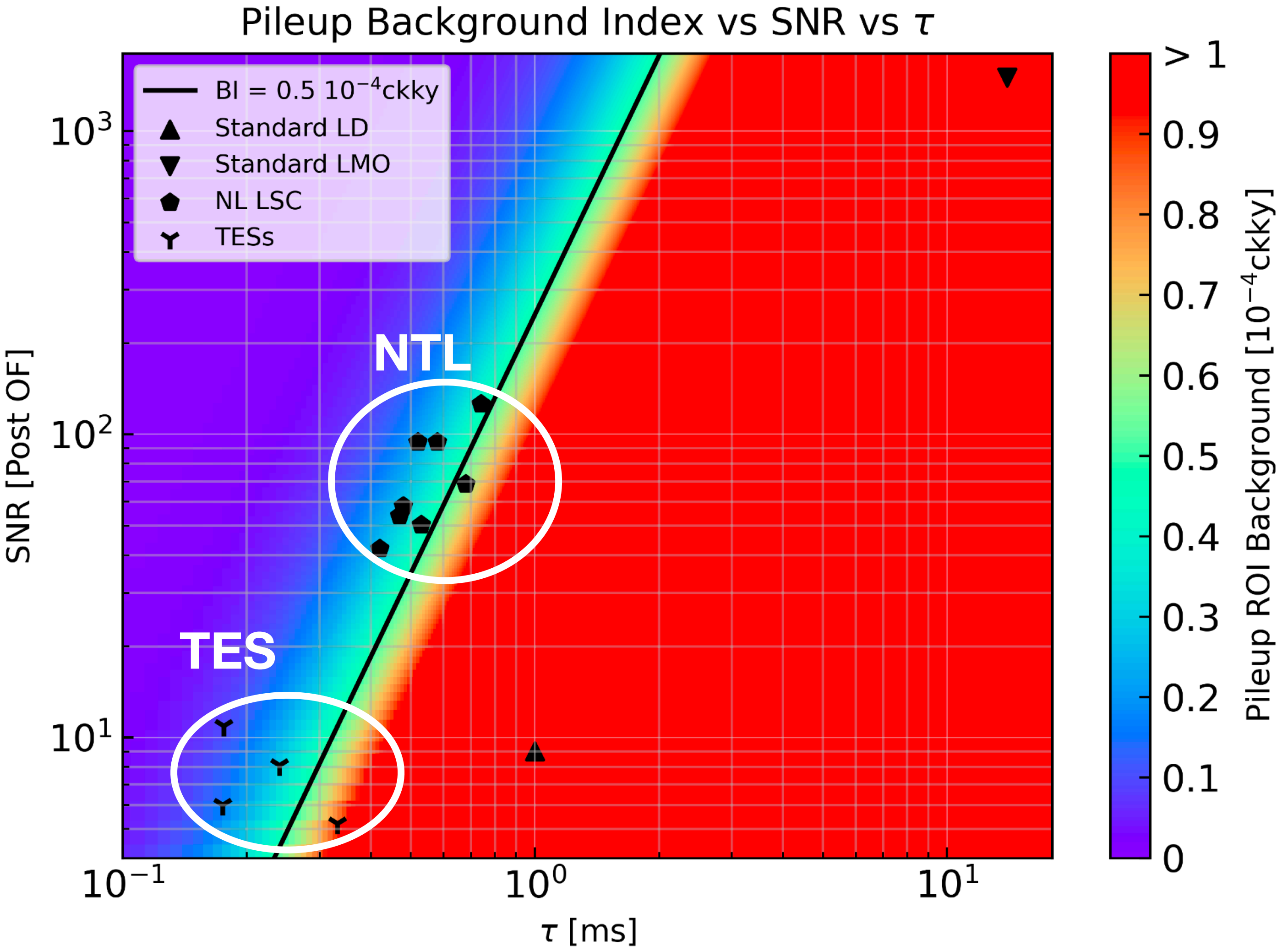


JW Beeman *et al.*, JINST **8** (2013) P05021

CUPID-Mo LMO



Pileup rejection



Sensitivity calculation

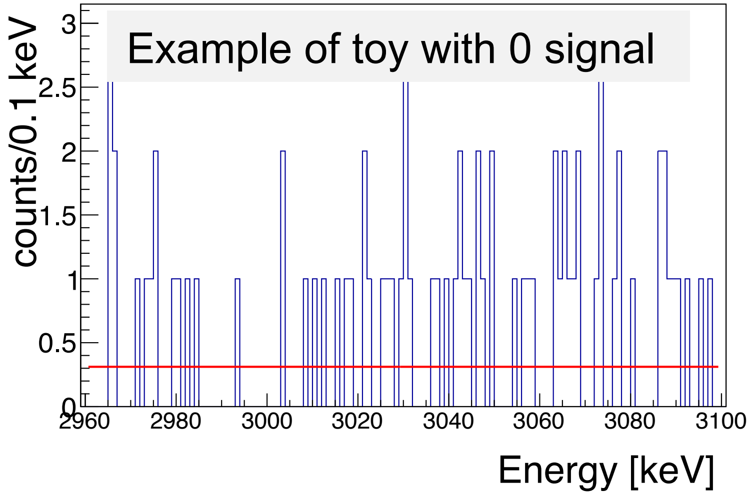
arXiv:2504.14369

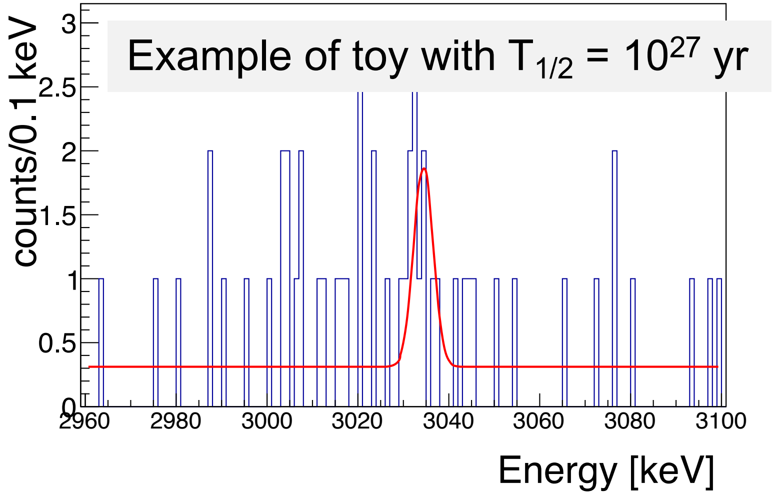
- Method: Frequentist and Bayesian analysis based on likelihood
- Generate pseudo-experiments: Background & Signal
- We have two hypothesis. H_0 : decay rate $\Gamma = 0$ and H_1: $\Gamma > 0$
- Define the test statistic comparing the likelihoods

Background-only

$$t_P(\Gamma = 0) = -2\ln\frac{H_0}{H_1} = -2\ln\left(\frac{\mathcal{L}(0)}{\mathcal{L}(\hat{\Gamma})}\right)$$

- Generate pseudo-experiments for different values of **Γ** and compute the background-only p-value. A discovery can be claimed if p is smaller than some cutoff.
  - **3σ discovery if p < 0.14%**
  - **$T_{1/2} = 1.0 \times 10^{27}$ y**

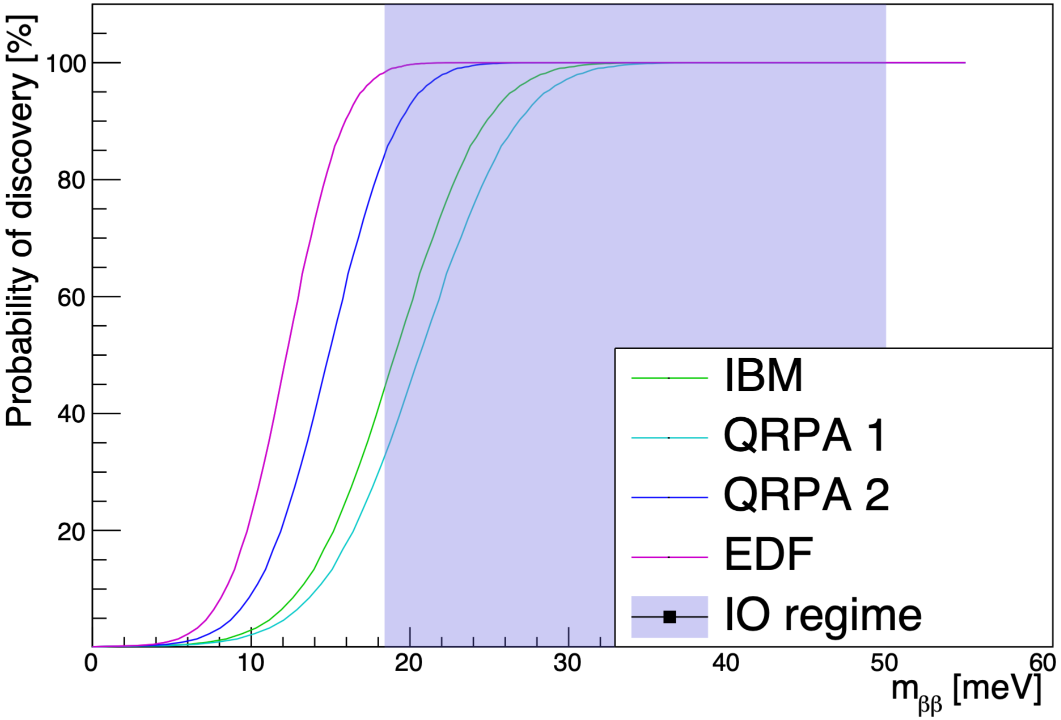




Sensitivity

arXiv:2504.14369

- **Discovery** probability for the CUPID baseline design

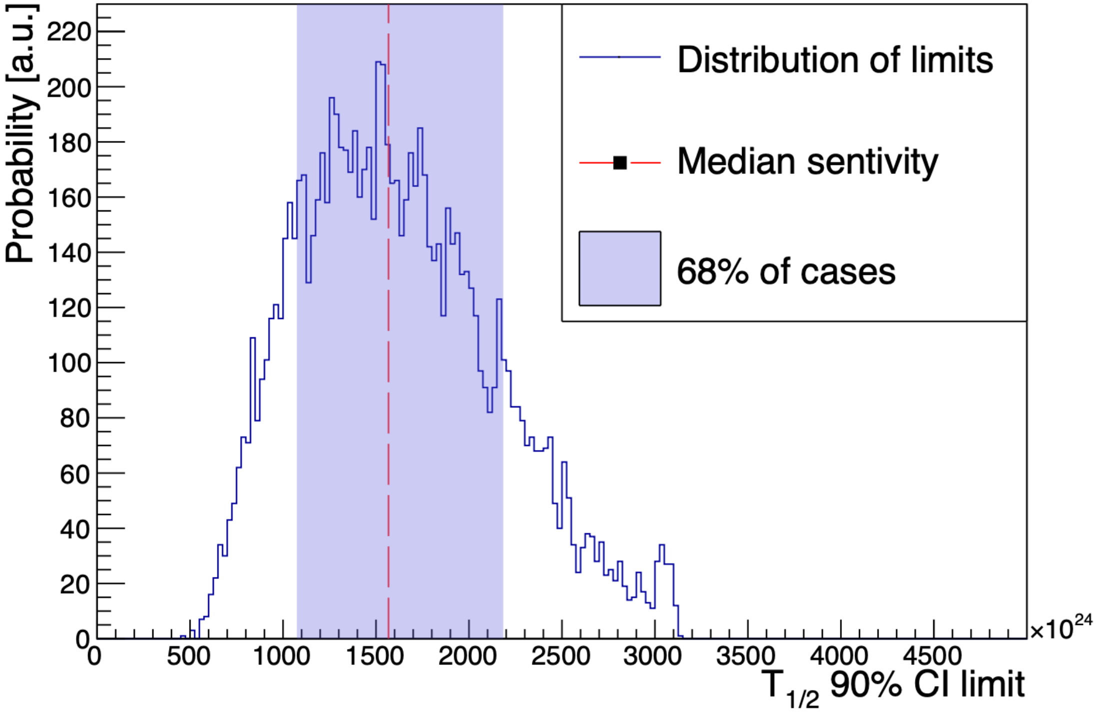


Discovery: Probability = 50%

$T_{1/2}$ = 1.0 × 10^{27} y

$m_{\beta\beta}$ = 12.2 – 20.6 meV

- Probability of 90% **exclusion** limits for CUPID obtained with a Bayesian analysis



$T_{1/2} > 1.6 \times 10^{27}$ y (90% C. I.)

$m_{\beta\beta} < 9.6 – 16.3$ meV

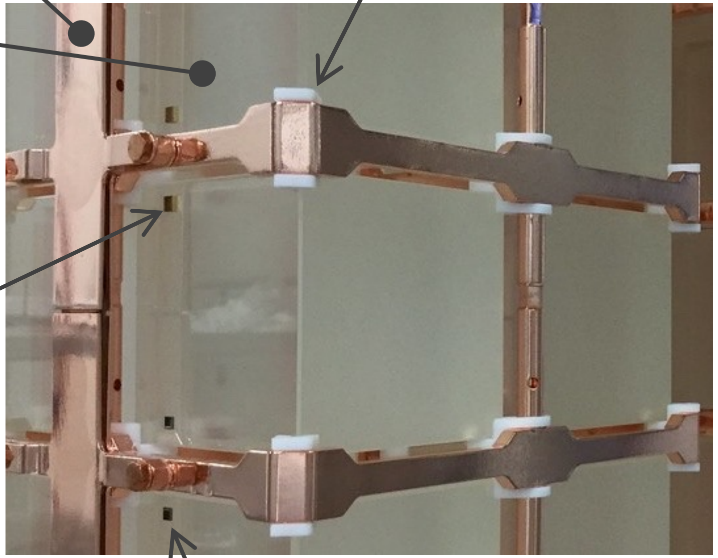
$m_{\beta\beta} < 9.6 – 28.2$ meV (including shell model)

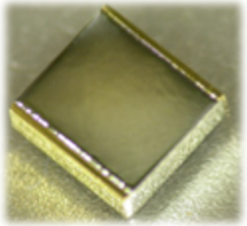
CUORE detector module

Radiopure TeO_2 crystals
Absorber = source
$5.0\times5.0\times5.0\ \mathrm{cm}^3$
750 g mass
$C(T)$ ~ 2.3×10^{-9} J/K (@ 10 mK)
ΔT ~ 100 μK/MeV, τ ~ 1s

Copper frame:
~10 mK heat sink

PTFE holders:
weak thermal coupling



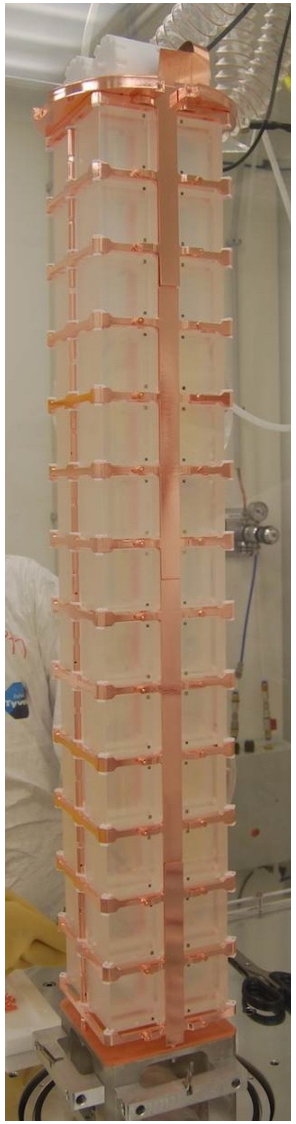


NTD-Ge thermistor
$3.0\times2.9\times0.9\ \mathrm{mm}^3$
Working impedance:
R_{work} ~ 100 MΩ – 1 GΩ
Comparative easy readout

Si Joule heater
Inject reference pulses for
stabilization of baseline temperature

observes an average resolution of
7.54 keV FWHM at 2615 keV

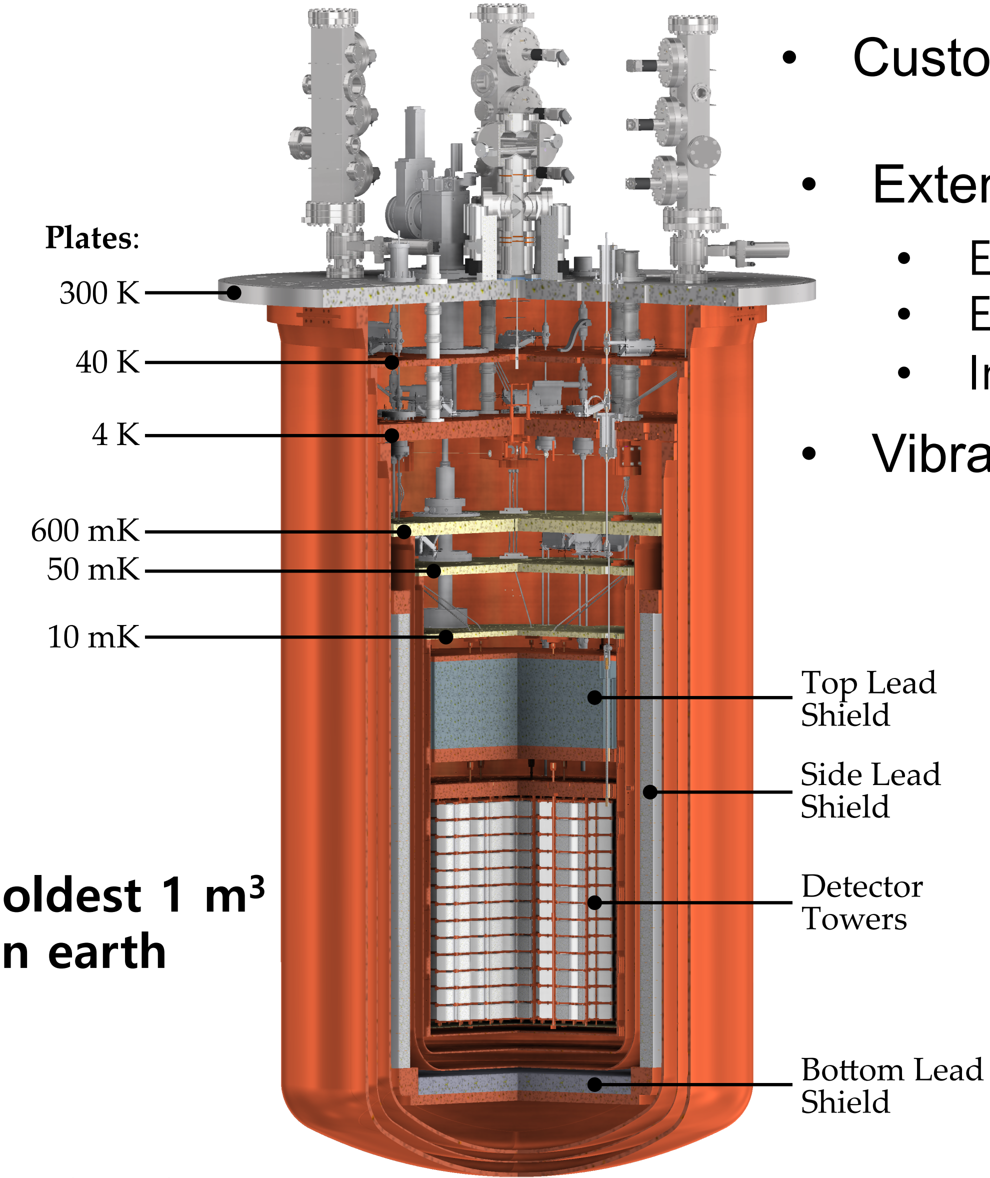
CUORE Collaboration, Science390,1029-1032(2025)



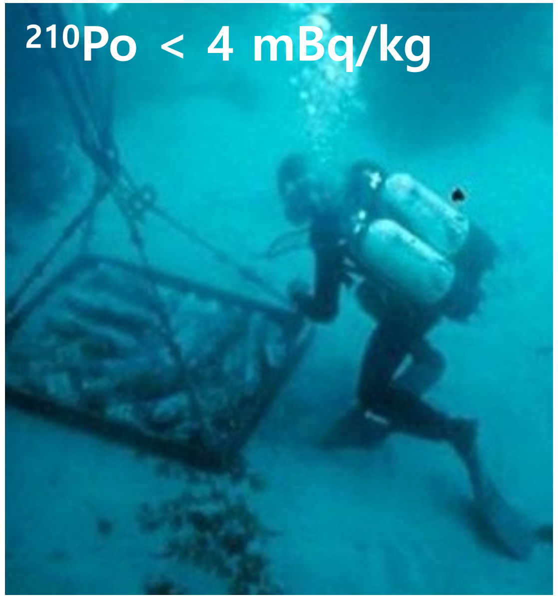
CUORE subsystems

Alduino C, et al.
Cryogenics, 2019, 102: 9-21.

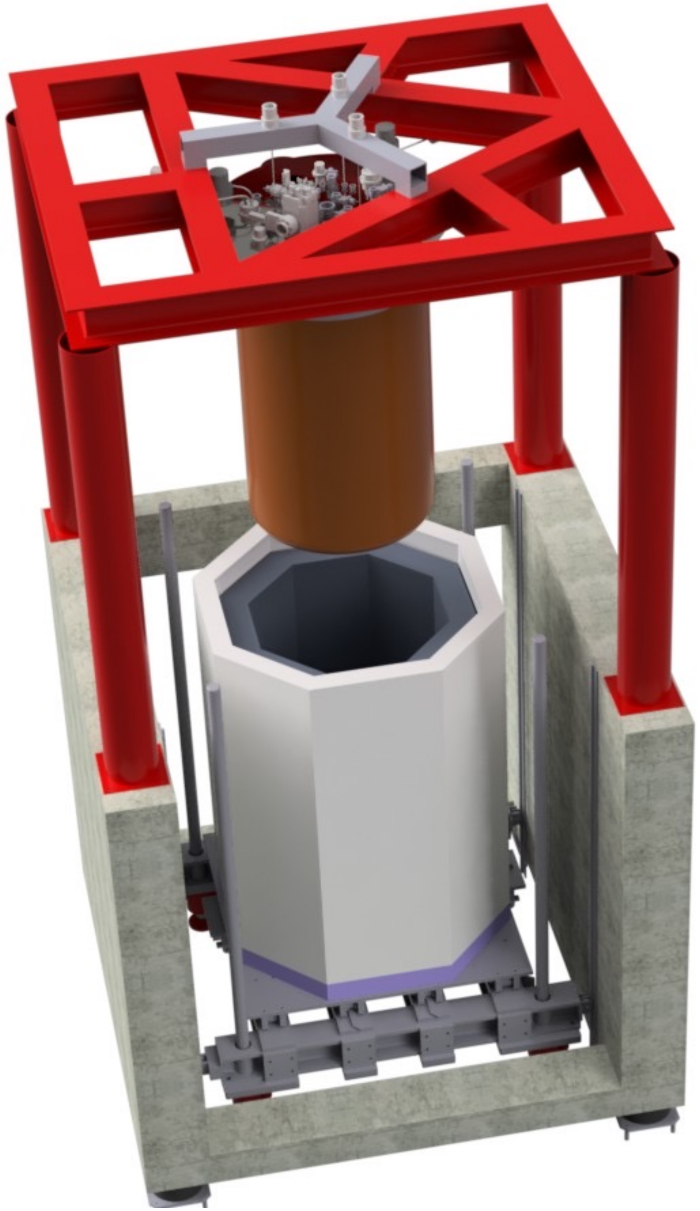
- Customized dry dilution refrigerator
- Extensive shields
  - External PE & borated PE shield
  - External 25 cm-thick lead shield
  - Internal ancient Roman lead
- Vibration damping system



Coldest 1 m^3 on earth

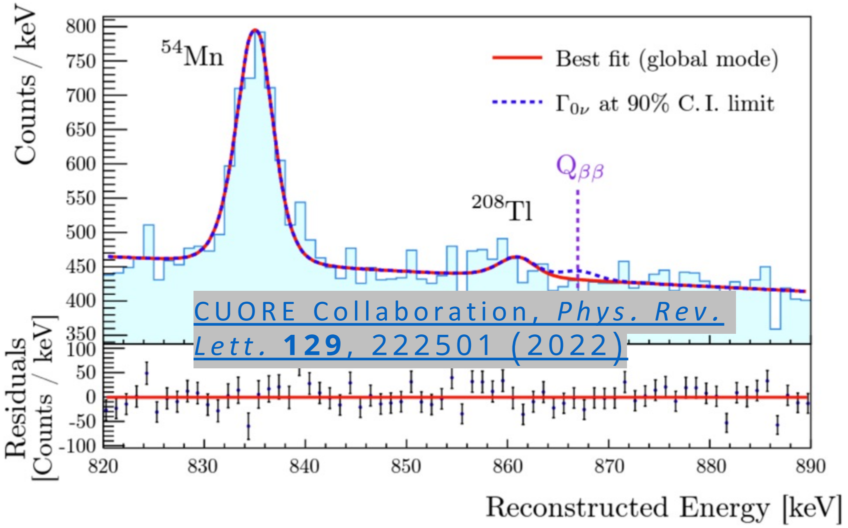


^{210}Po < 4 mBq/kg



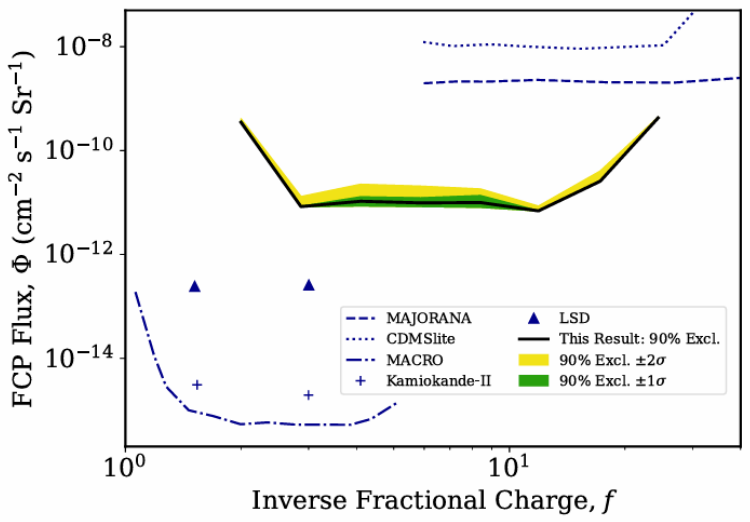
Other searches

^{128}Te $0\nu\beta\beta$ decay to the ground state



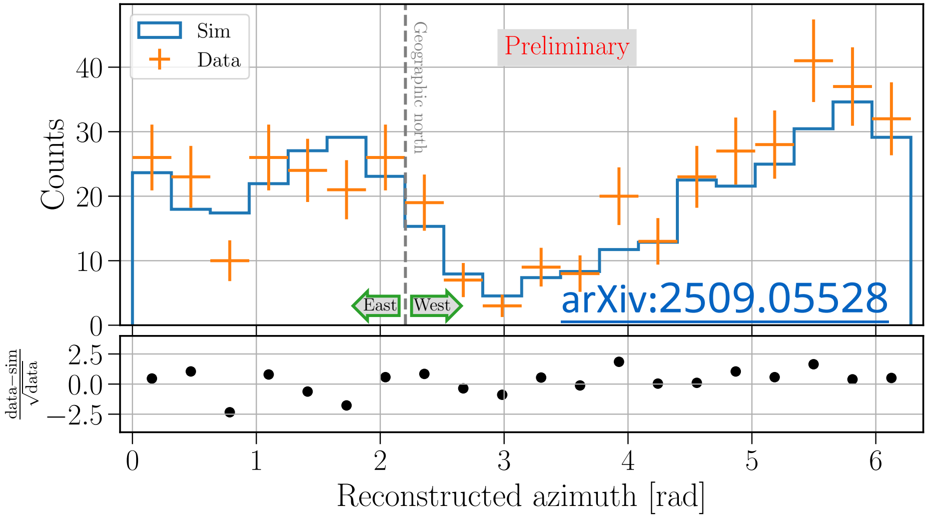
CUORE Collaboration, *Phys. Rev. Lett.* **129**, 222501 (2022)

Search for fractionally charged particles



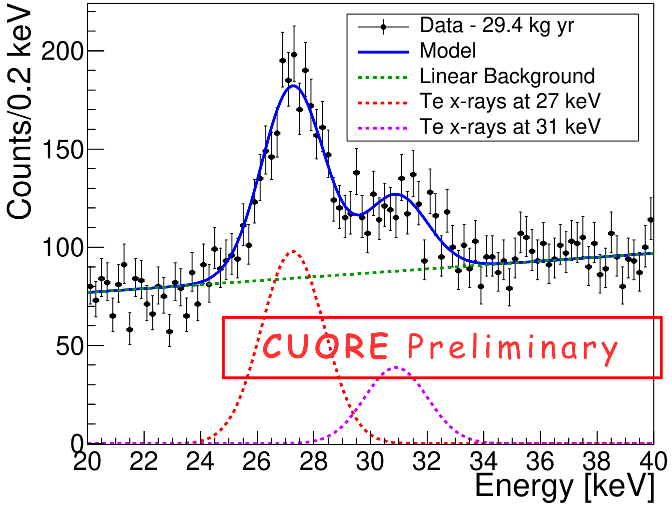
CUORE Collaboration, *Phys. Rev. Lett.* **133**, 241801 (2024)

Muon event reconstruction (ongoing)



arXiv:2509.05528

Low energy studies



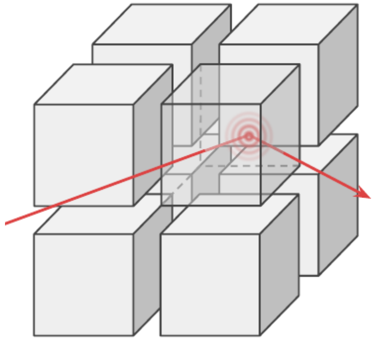
CUORE Preliminary

arxiv:2505.23955

Multiplicity selection

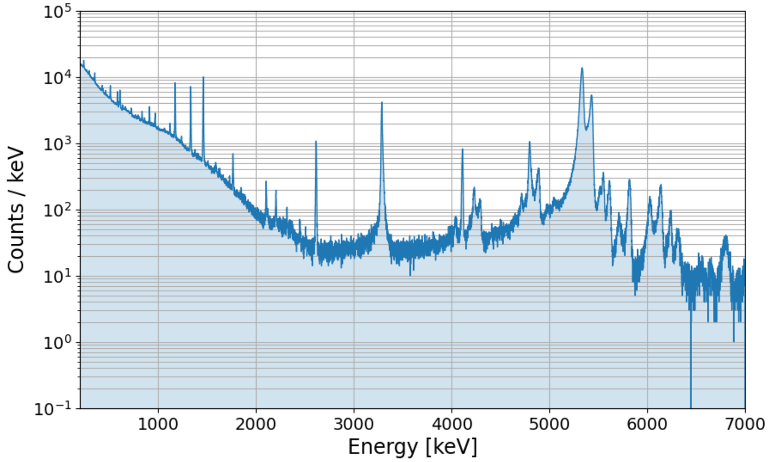
Phys. Rev. D 110, 052003

Multiplicity 1

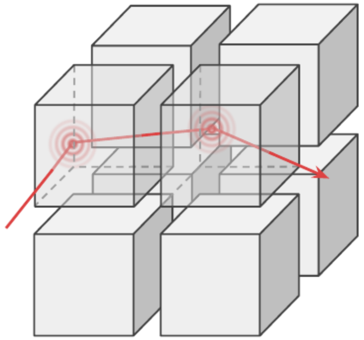


Single spectrum

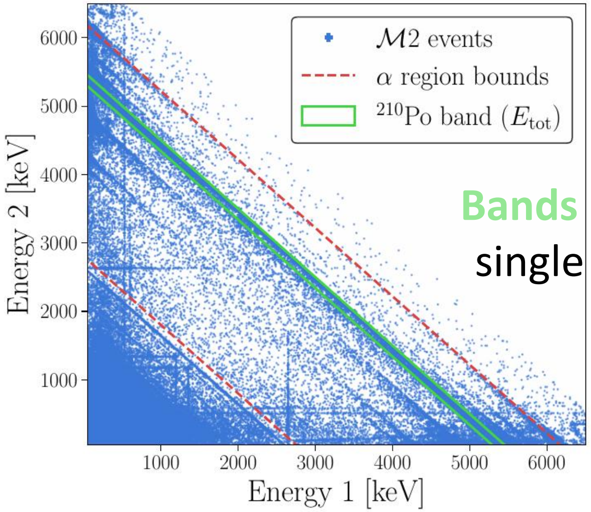
Identical to the 0νββ



Multiplicity 2



Study correlation between coincident energy depositions



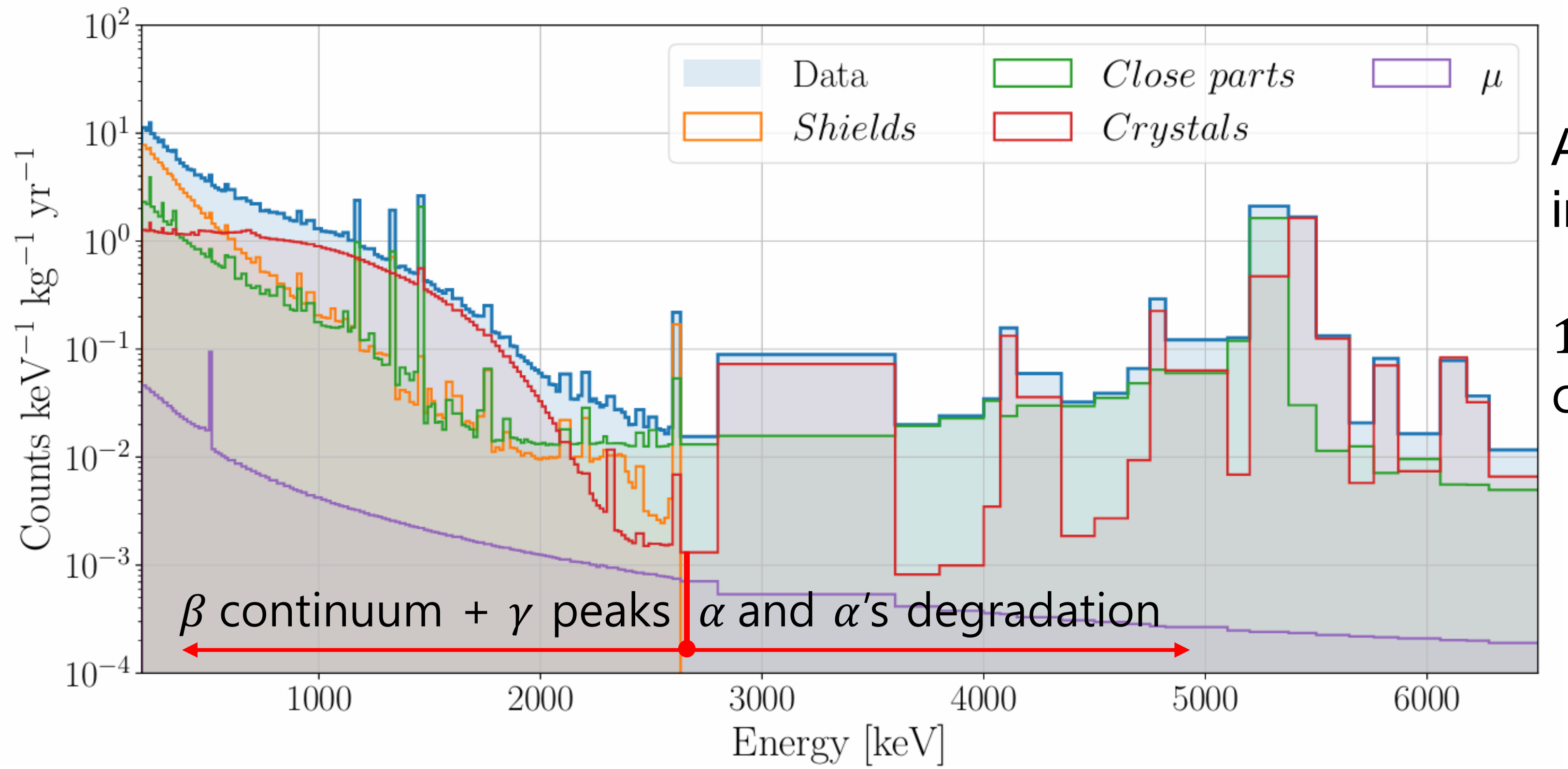
Bands associated to single total energy

Slide from Mattia Beretta, *MEDEX 2025* conference

Background

- Full detector geometry and particle interaction implemented in Geant4
- Geant4 output post-processed to include detector response
- Comprehensive simulated sources (bulk, surface, muons)
- Multiparametric Bayesian fit of 39 spectra encompassing M1 and M2 events across (0.2, 6.8) MeV

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

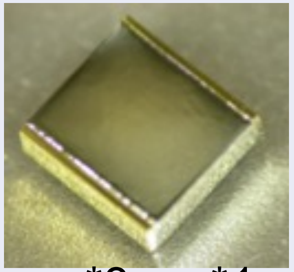
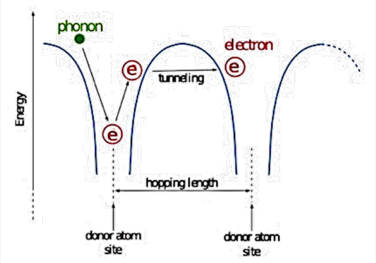
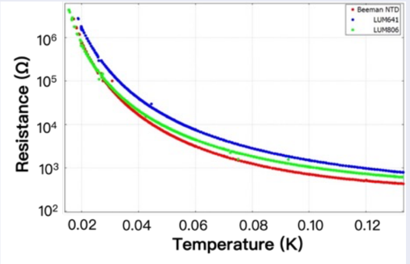
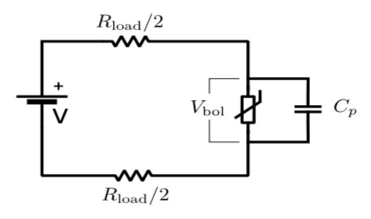
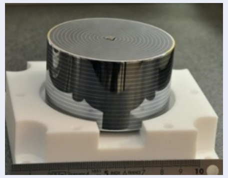
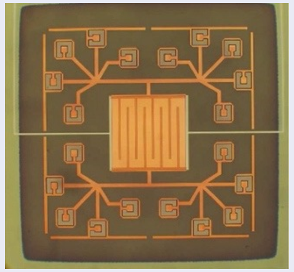
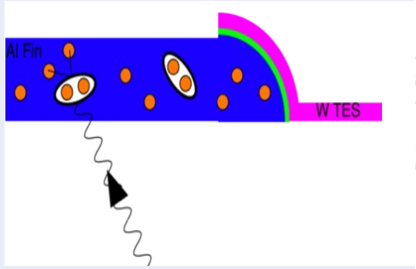
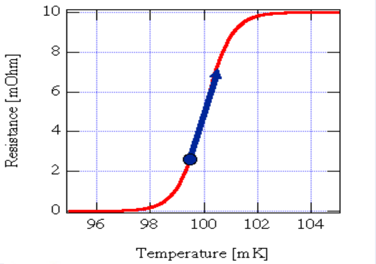
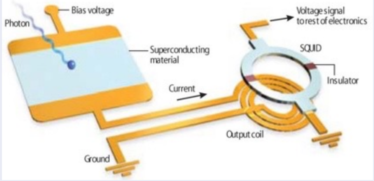
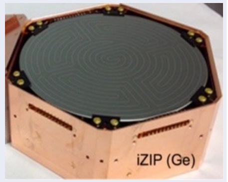
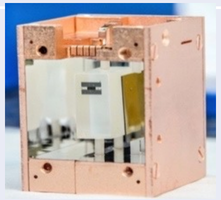


Average background index in the ROI

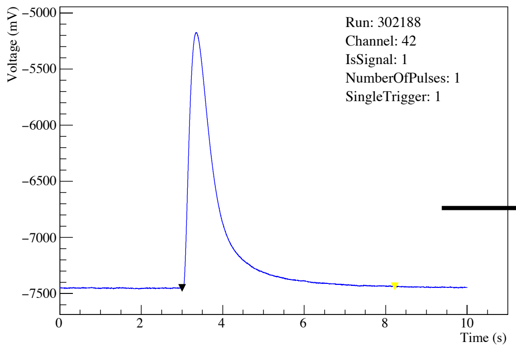
$1.42 \pm 0.02)\times10^{-2}$ counts/(keV·kg·yr)

arXiv:2404.04453

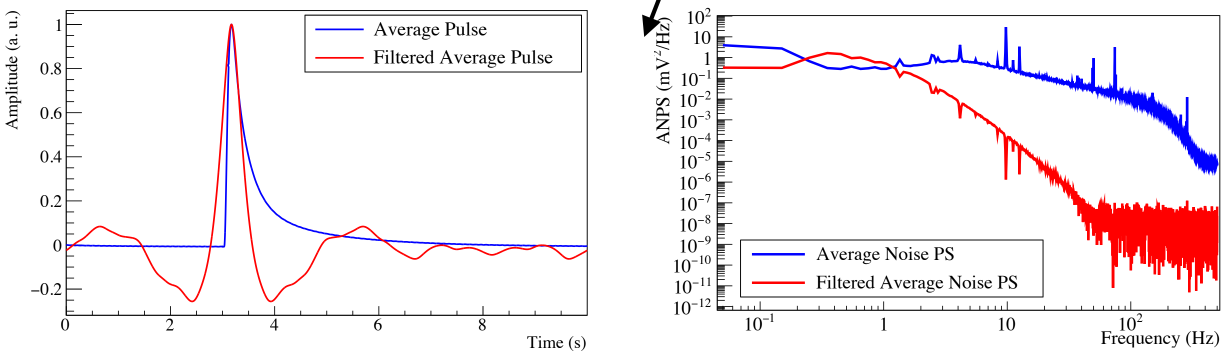
Cryogenic thermal sensors

Neutron Transmutation Doped Germanium, NTD-Ge  3mm*3mm*1mm	  Variable Range Hopping $\Delta T \longrightarrow \Delta R \longrightarrow \Delta V$  	• High sensitivity A~1-10 • Large dynamic range • Relatively easy readout • Massive production • Slow response	CUORE $(0\nu\beta\beta)$  EDELWEISS (Dark Matter) 
Transition Edge Sensor, TES  microsize	  Phonon-Cooper pair $\Delta T \longrightarrow \Delta R \longrightarrow \Delta I$  	• Very high sensitivity A~100-1000 • Multiplex readout • Fast rising signal • SQUID readout • Narrow dynamic range	SuperCDMS (Dark Matter)  CRESST (Dark Matter) 

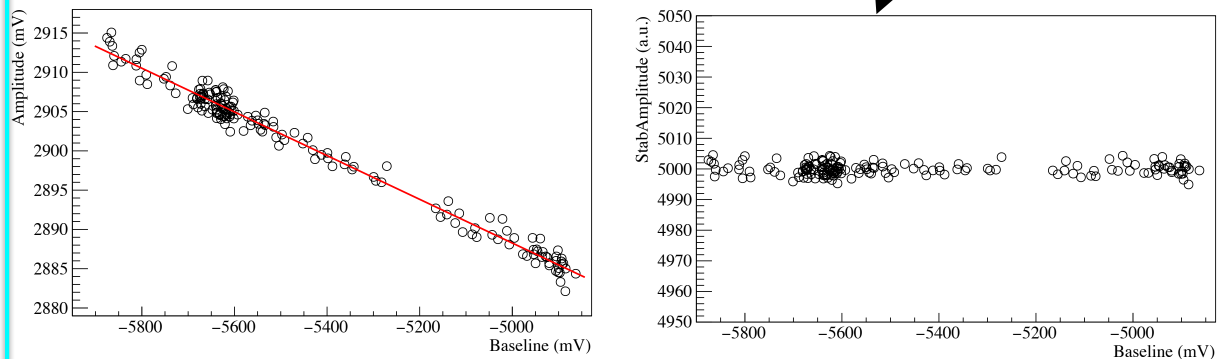
Data processing



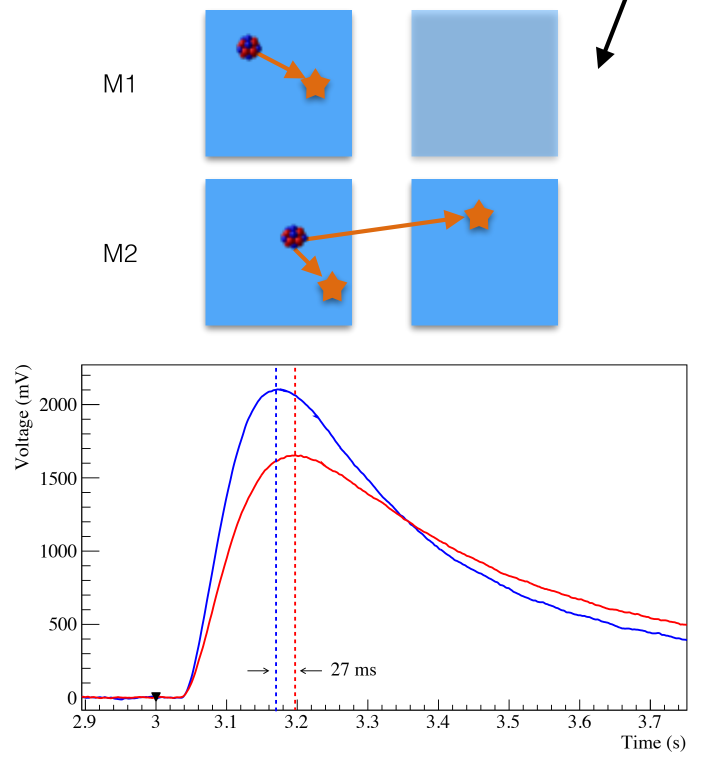
Optimum Filter → Gain Correction → Energy Calibration → Coincidences



Matched filter that maximizes the signal-to-noise ratio



Heater pulses for thermal gain stabilization



Slide from Irene Nutini, *ICNFP2020* conference