



17th Topical Seminar on Innovative Particle and Radiation Detectors
(IPRD25) 15-19 September 2025 Siena, Italy

Latest results from CUORE and prospects for CUPID

Kangkang ZHAO

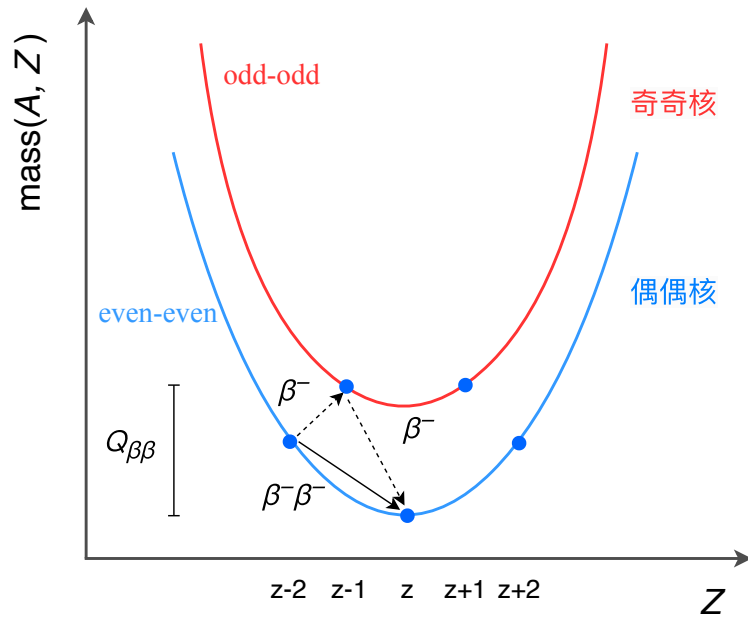
On behalf of the CUORE and CUPID collaborations

Sept. 18th, 2025



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 $T_{2\nu} \sim 10^{18} - 10^{24}$ yr



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



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

- $0\nu\beta\beta$ 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

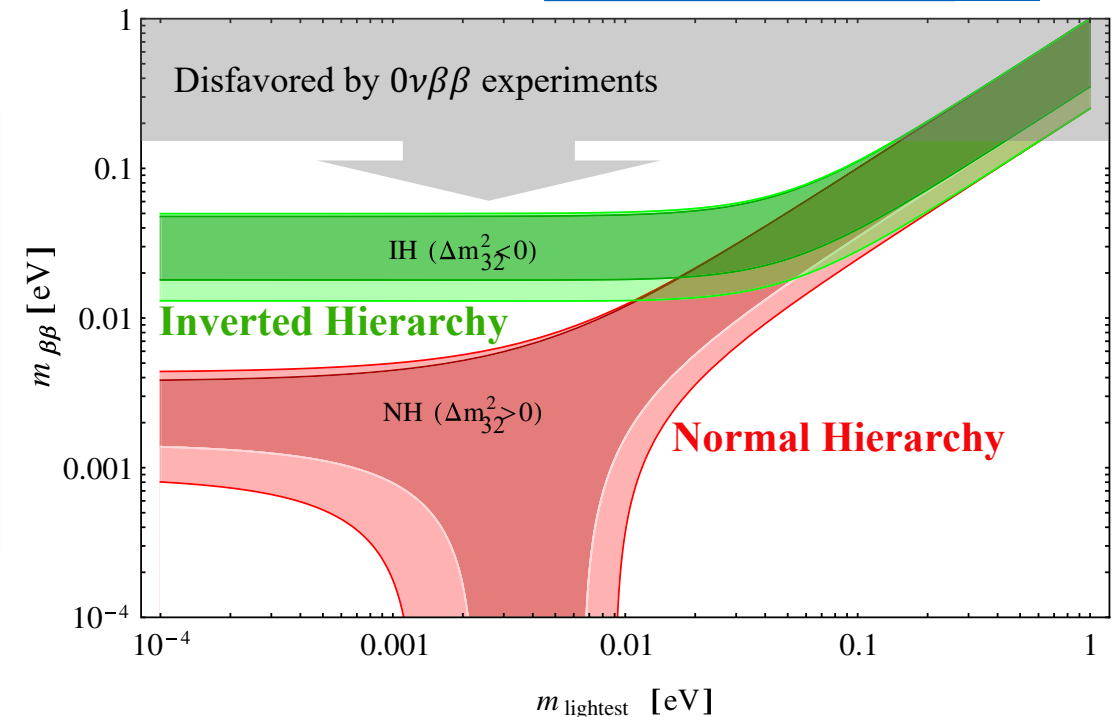
$$[T_{1/2}^{0\nu}]^{-1} = G^{0\nu}(Q_{\beta\beta}, Z) \cdot |M^{0\nu}(A, Z)|^2 \cdot \frac{\langle m_{\beta\beta} \rangle^2}{m_e^2}$$

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

Nuclear Matrix Element

- Lepton number violation ($\Delta L = 2$), beyond SM
- Majorana nature of neutrinos **NEW PHYSICS!**
- Neutrino mass hierarchy
- Absolute neutrino mass scale
- Hints to origin of matter/anti-matter asymmetry

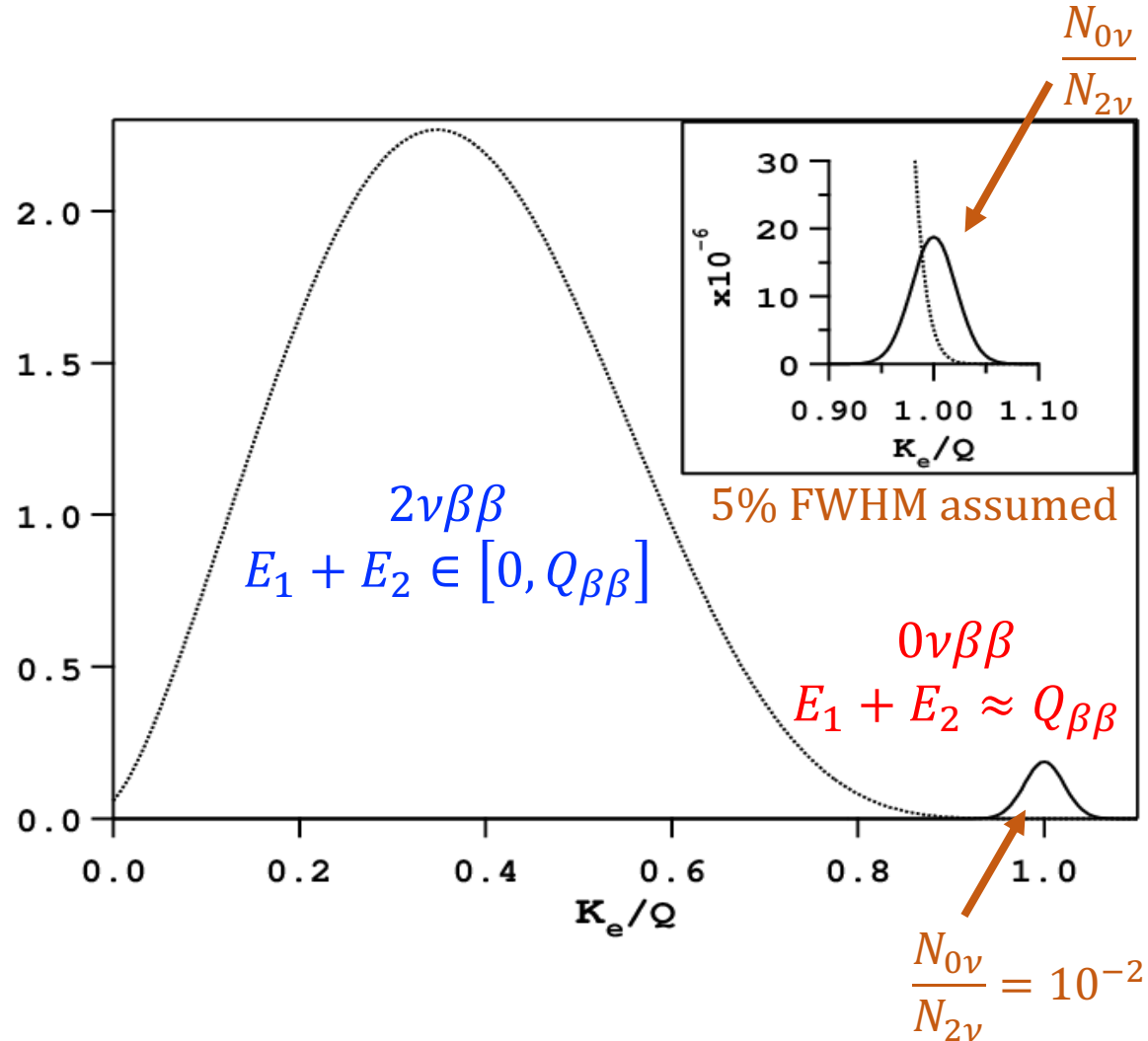
[Stefano Dell'Oro, et al.](#)
[Phys. Rev. D **90**, 033005, 2014](#)



$0\nu\beta\beta$ detection challenges

Compatible detection technique required!

- Experimental signature: two-electron sum-energy spectrum



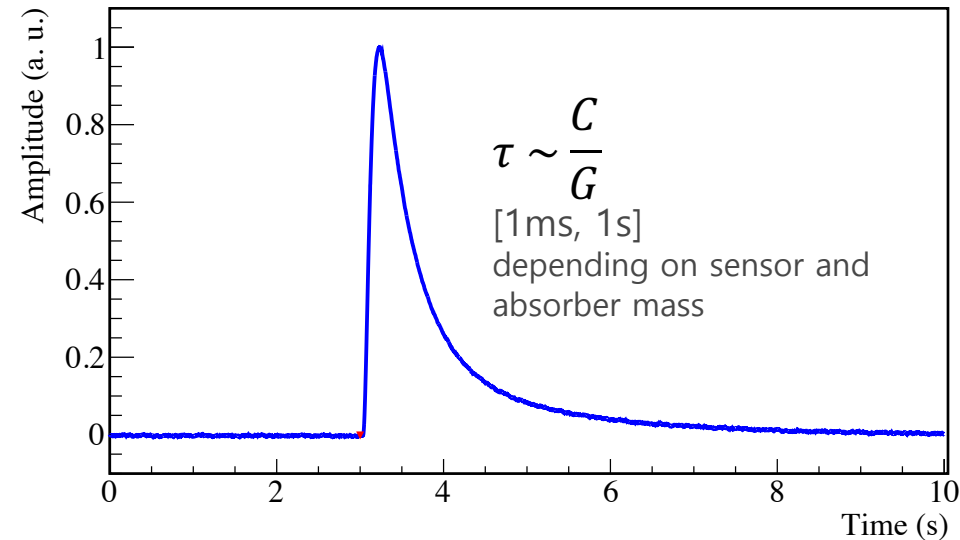
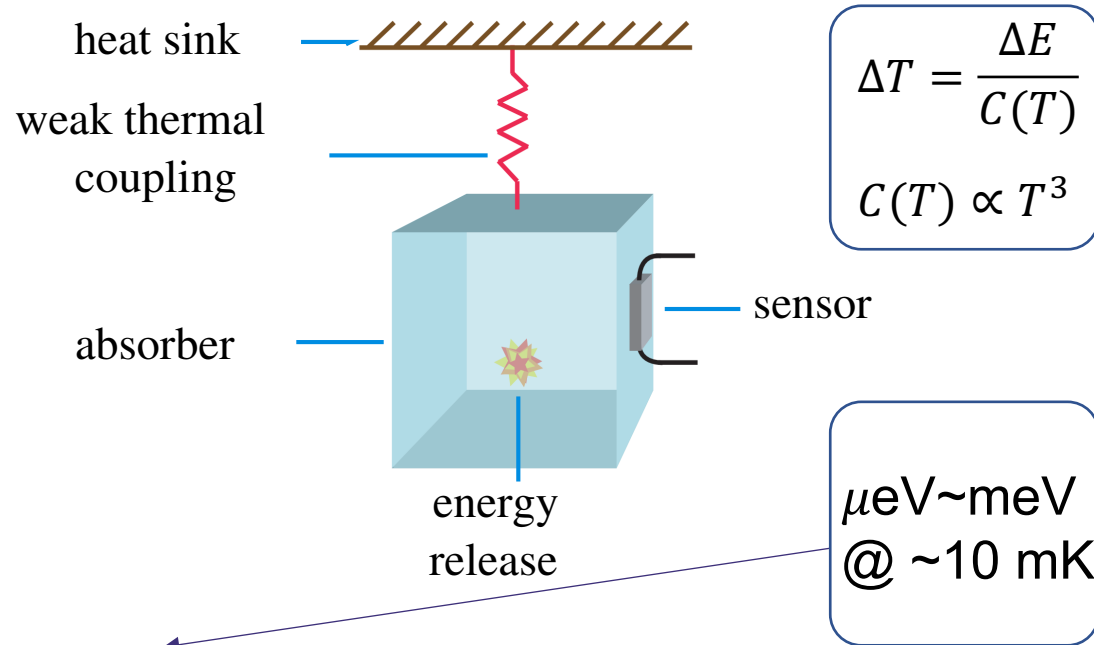
$$S^{0\nu} \propto \epsilon \cdot \frac{\eta}{A} \cdot \sqrt{\frac{M \cdot t}{B \cdot \sigma}}$$

Labels in the diagram:

- $S^{0\nu}$: Sensitivity
- ϵ : detector efficiency
- η : nuclei of interest
- A : target mass
- $M \cdot t$: Live time
- $B \cdot \sigma$: energy resolution
- $\sqrt{\frac{M \cdot t}{B \cdot \sigma}}$: background index

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

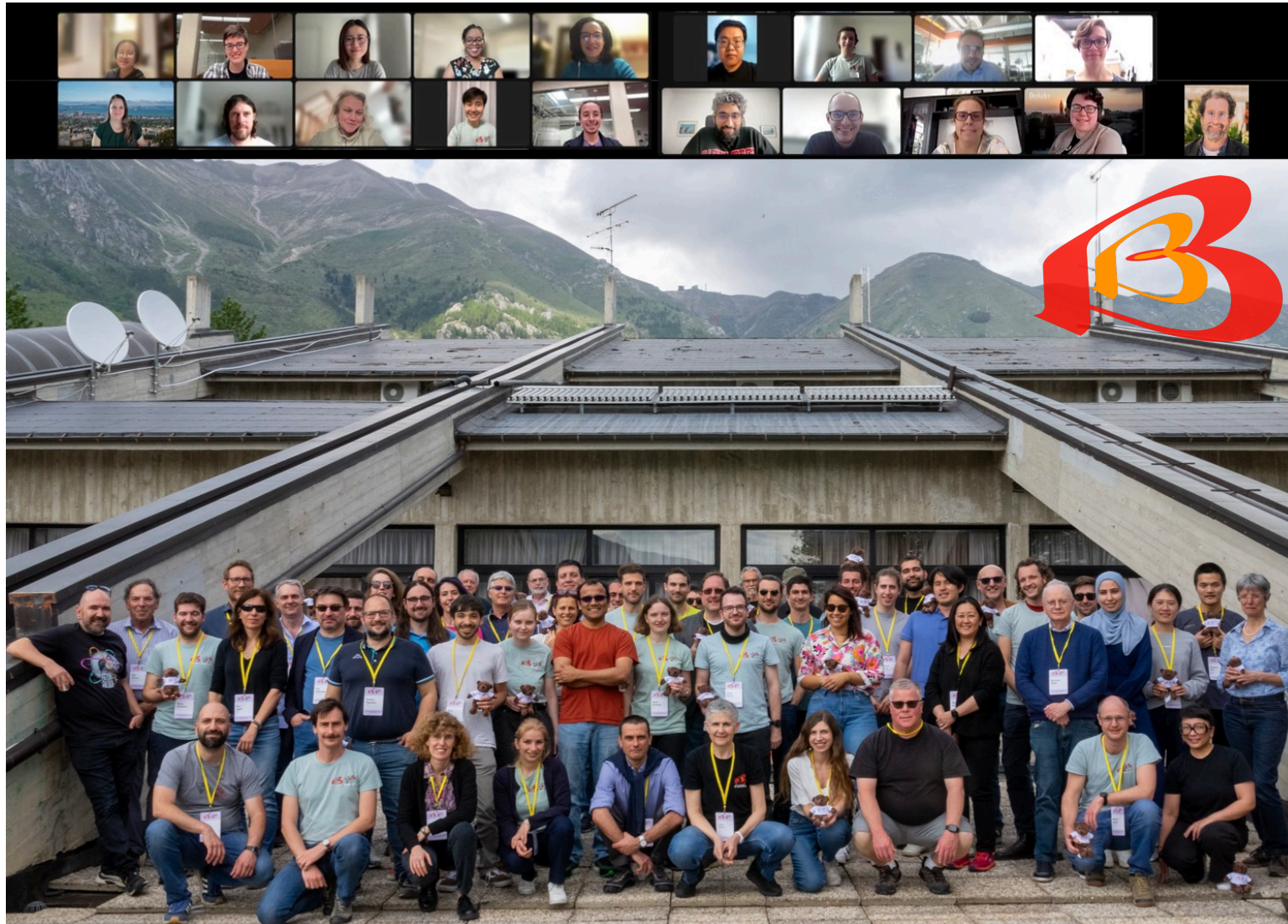
Cryogenic bolometric technique



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

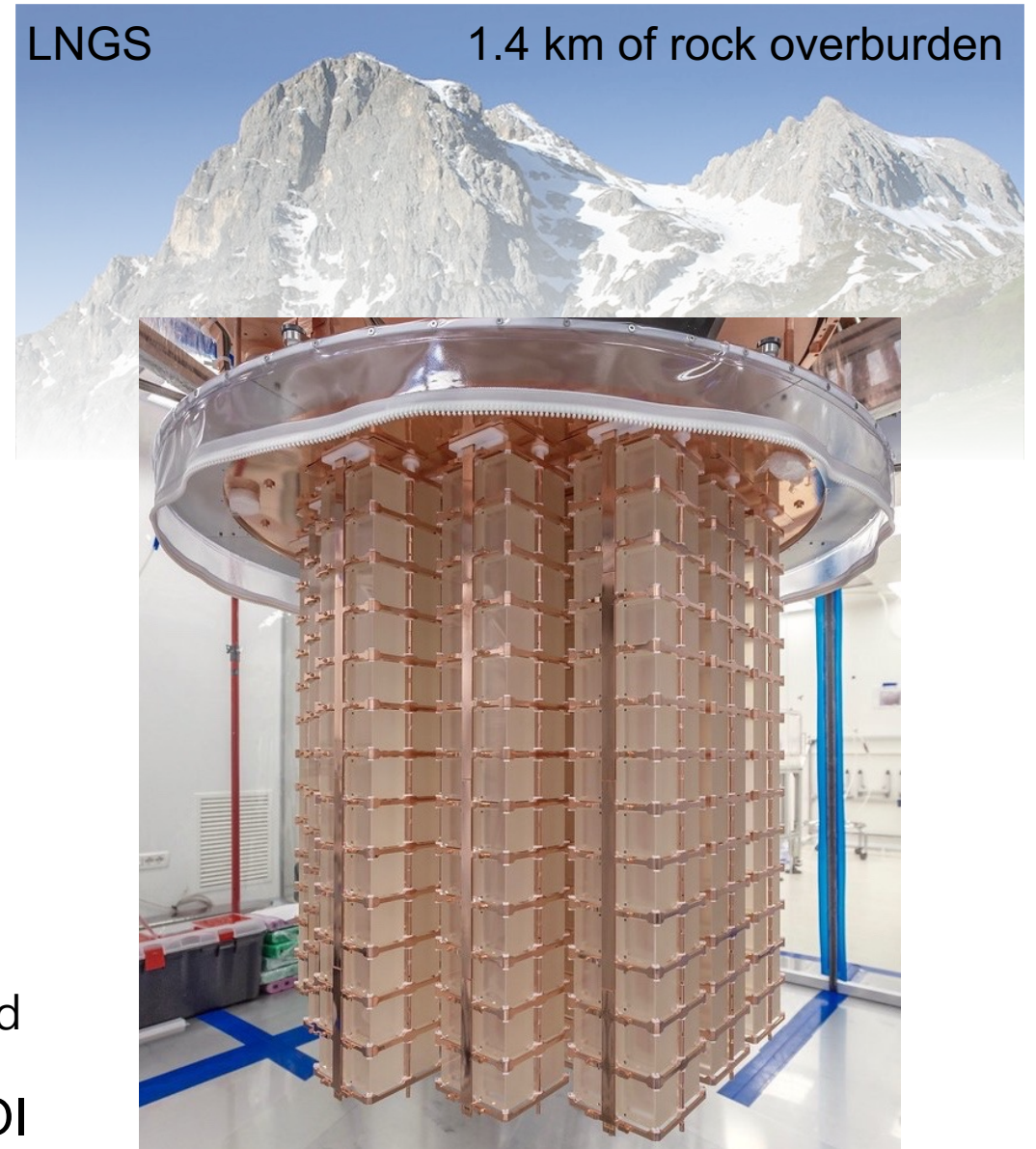
Bolometer matches well with $0\nu\beta\beta$ search!

The CUORE collaboration



Cryogenic U nderground O bservatory for R are E vents

- Largest cryogenic bolometric detector ever built
 - 19 towers of 13 floors of 4 crystals
 - Total of 988 TeO_2 crystals
 - natural abundance, ~ 206 kg of ^{130}Te
- Primary goal: search for $0\nu\beta\beta$ decay of ^{130}Te
 - Q-value of ~ 2527.5 keV
- Located at Gran Sasso National Laboratory (LNGS)
 - ~ 3600 m.w.e. (meter water equivalent)
 - 6 orders of magnitude cosmic ray muon flux reduced
- Design background: $\sim 10^{-2}$ counts / (keV $\cdot$ kg $\cdot$ yr) in ROI



CUORE detector module

Radiopure TeO_2 crystals

Absorber = source

$5.0 \times 5.0 \times 5.0 \text{ cm}^3$

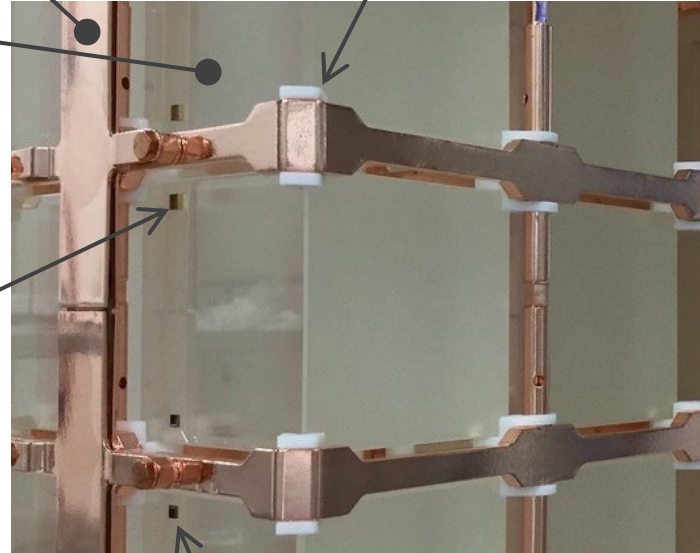
750 g mass

$C(T) \sim 2.3 \times 10^{-9} \text{ J/K}$ (@ 10 mK)

$\Delta T \sim 100 \mu\text{K/MeV}$, $\tau \sim 1\text{s}$

Copper frame:
~10 mK heat sink

PTFE holders:
weak thermal coupling



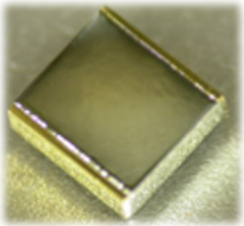
NTD-Ge thermistor

$3.0 \times 2.9 \times 0.9 \text{ mm}^3$

Working impedance:

$R_{\text{work}} \sim 100 \text{ M}\Omega - 1 \text{ G}\Omega$

Comparative easy readout

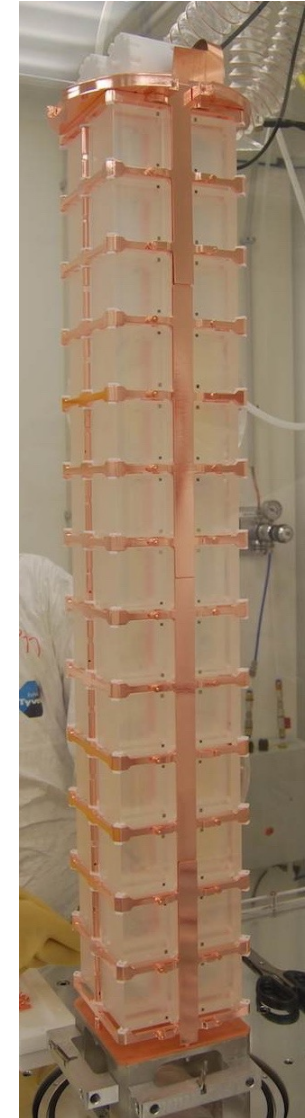


Si Joule heater

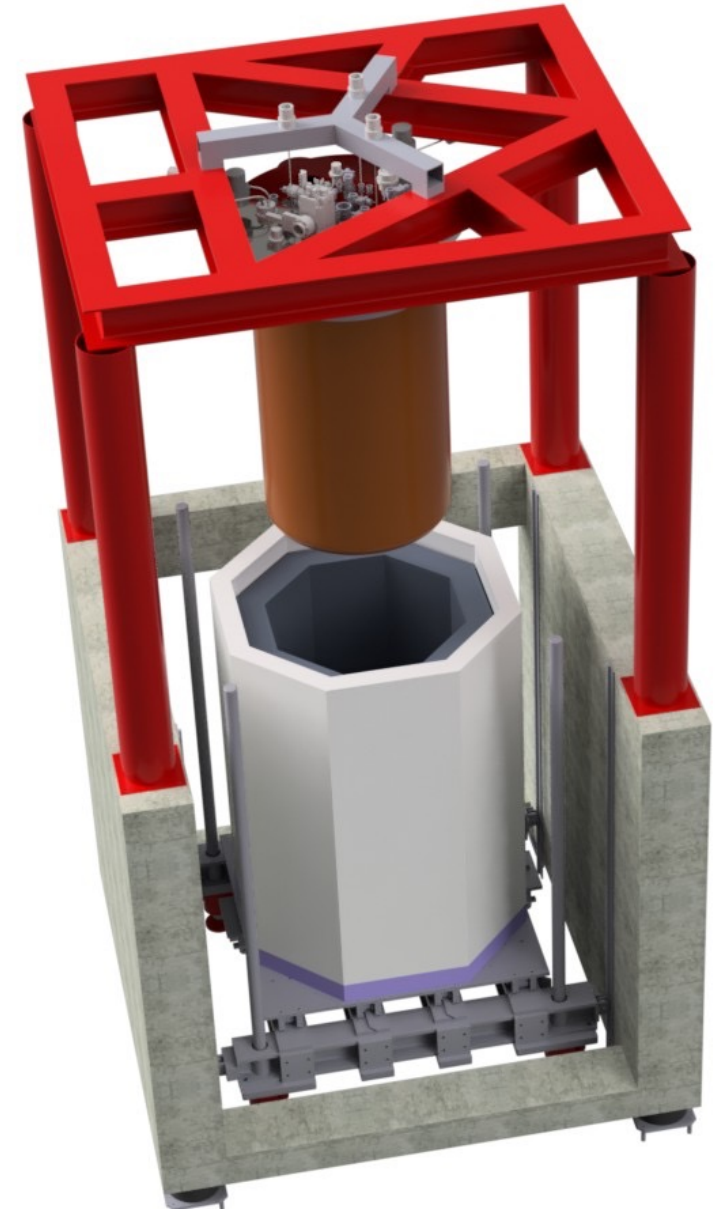
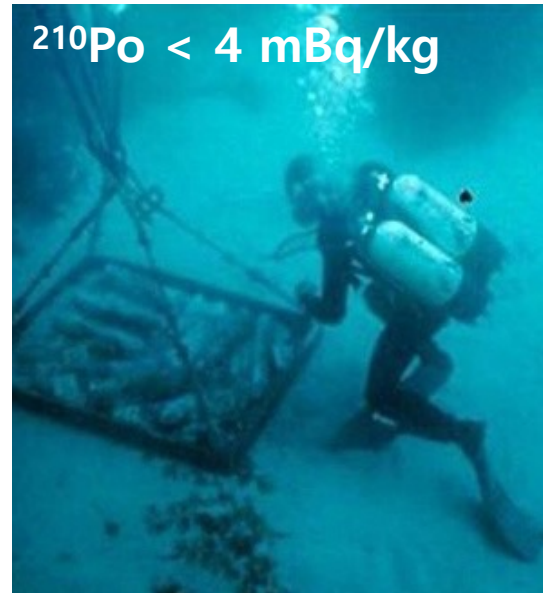
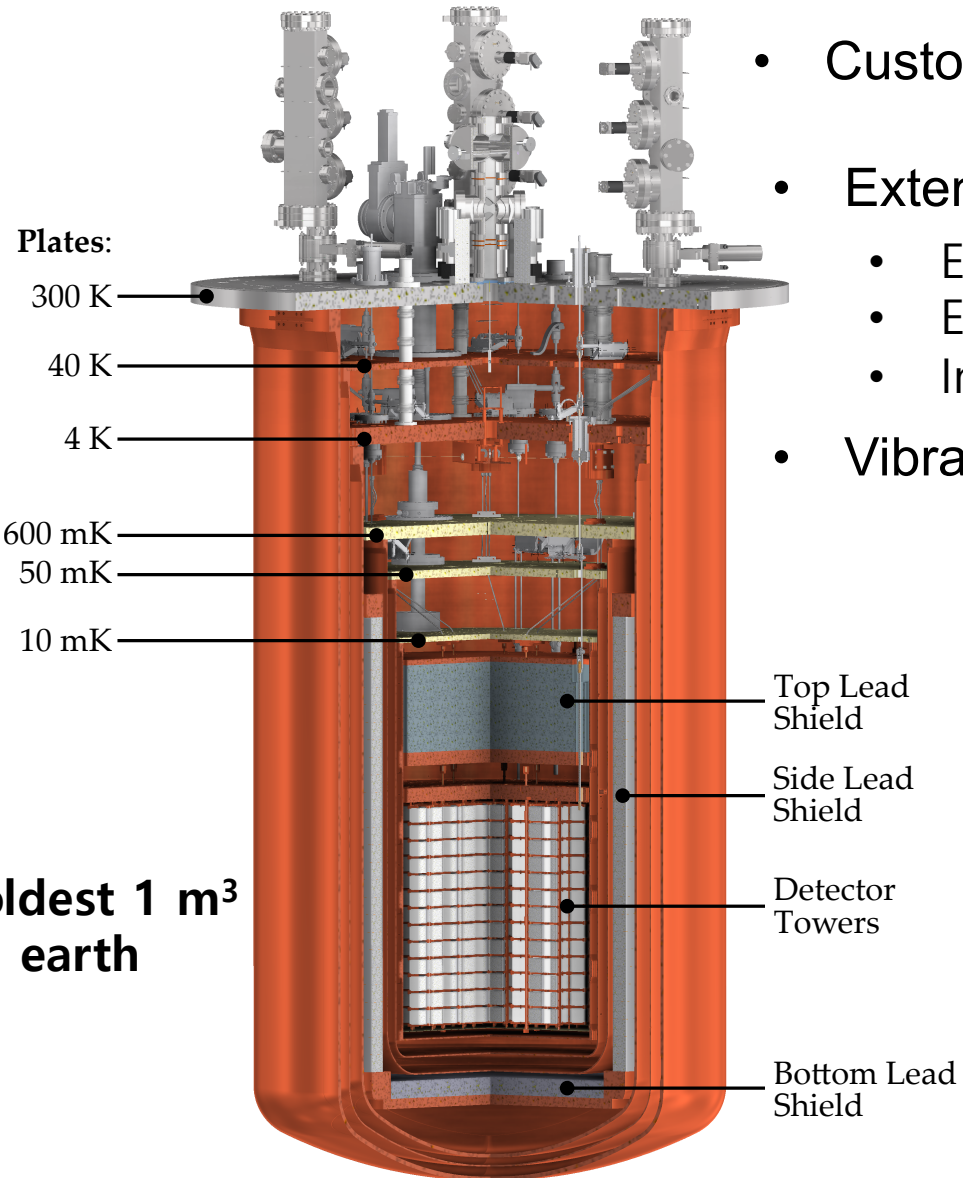
Inject reference pulses for
stabilization of baseline temperature

observes an average resolution of
~8 keV FWHM at 2615 keV

[arXiv:2404.04453](https://arxiv.org/abs/2404.04453)



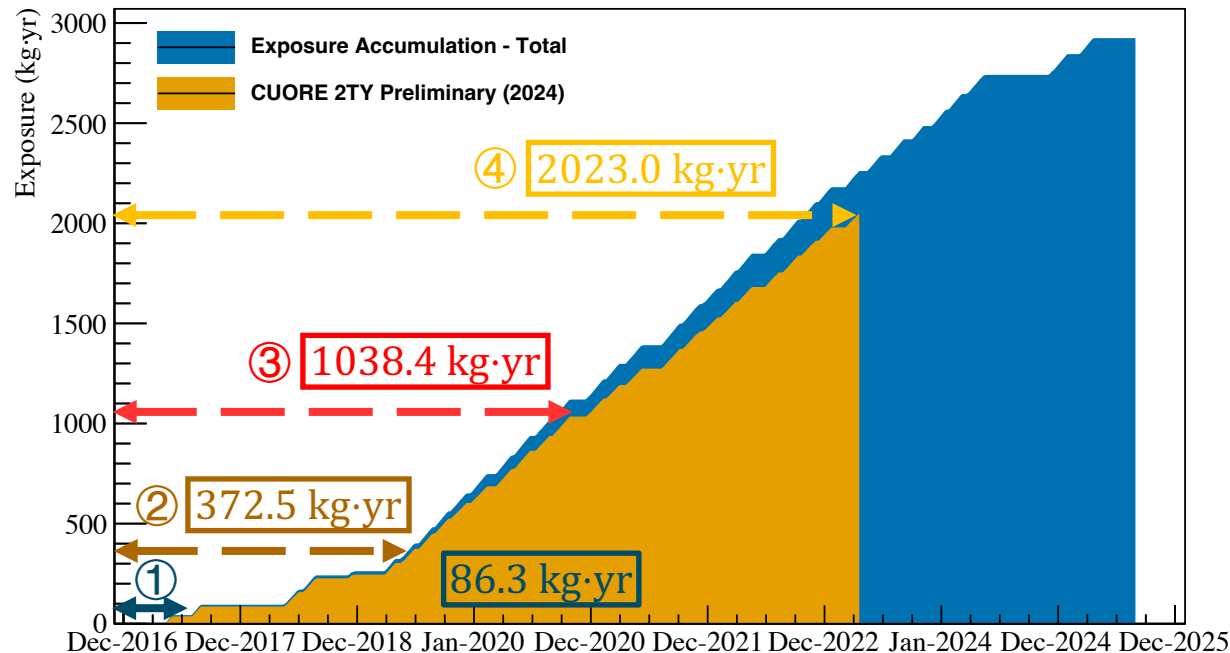
- Customized dry dilution refrigerator
- Extensive shields
 - External PE & borated PE shield
 - External 25 cm-thick lead shield
 - Internal ancient Roman lead
- Vibration damping system



CUORE status

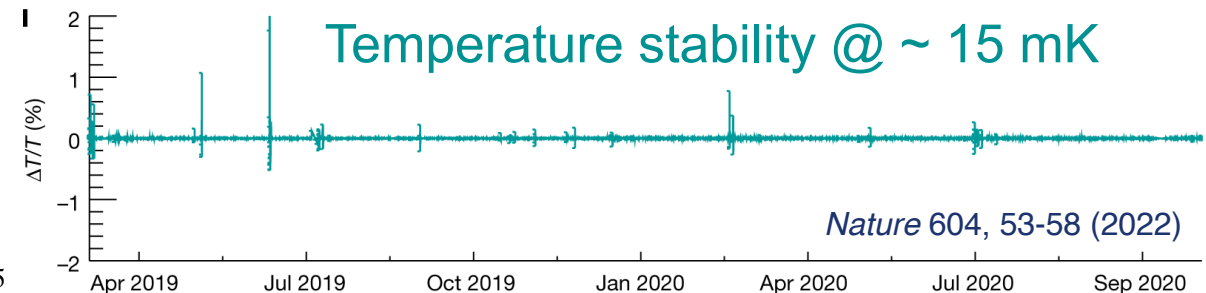
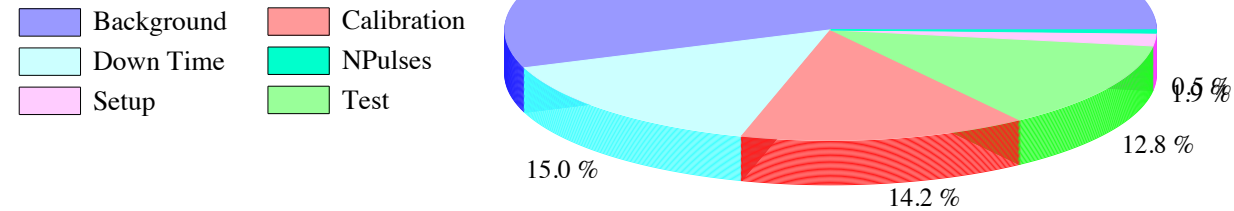


- Data taking started in 2017, with first 2 years for cryostat and detector optimization
- Stable data collection since 2019, with $\geq 85\%$ uptime
- > 2.9 ton $\cdot$ yr of raw TeO₂ exposure accumulated
- Demonstrated stability over years of data taking

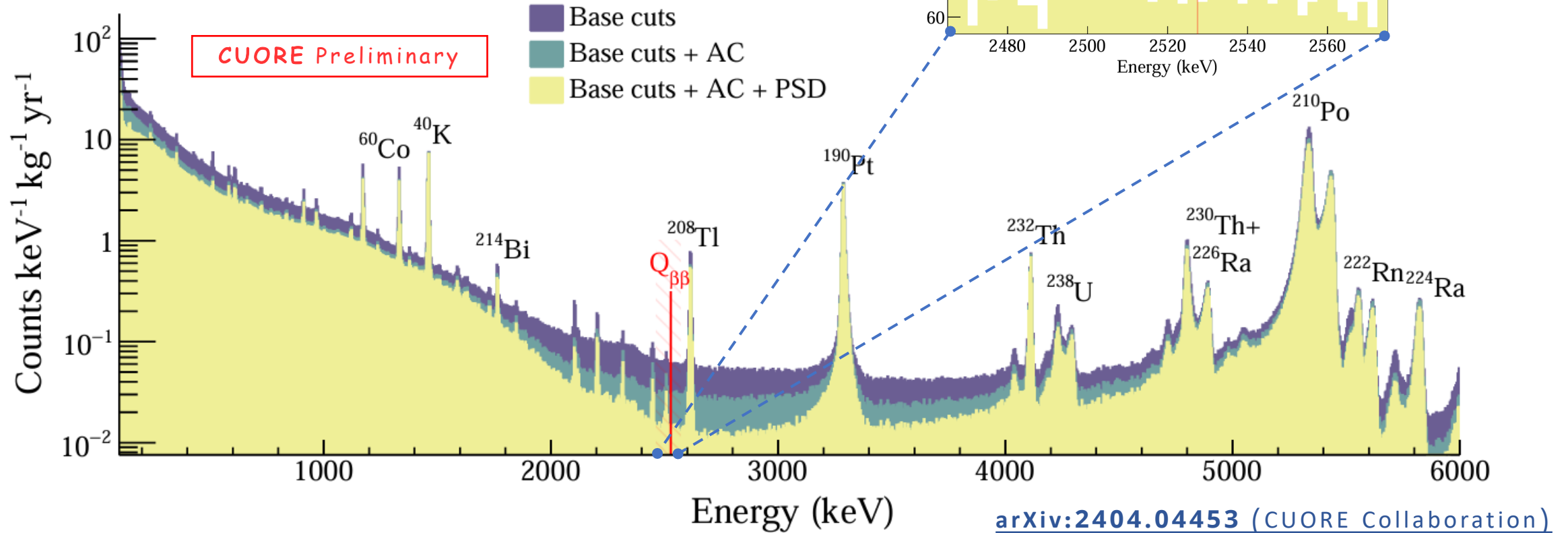


- ① [Alduino, C. et al. \(CUORE Collaboration\), *Phys. Rev. Lett.* **120**, 132501 \(2018\)](#)
- ② [Adams, D.Q. et al. \(CUORE Collaboration\), *Phys. Rev. Lett.* **124**, 122501 \(2020\)](#)
- ③ [Adams, D.Q. et al. \(CUORE Collaboration\), *Nature* **604**, 53-58 \(2022\)](#)
- ④ [arXiv:2404.04453 \(CUORE Collaboration\)](#)

Run Time Breakdown

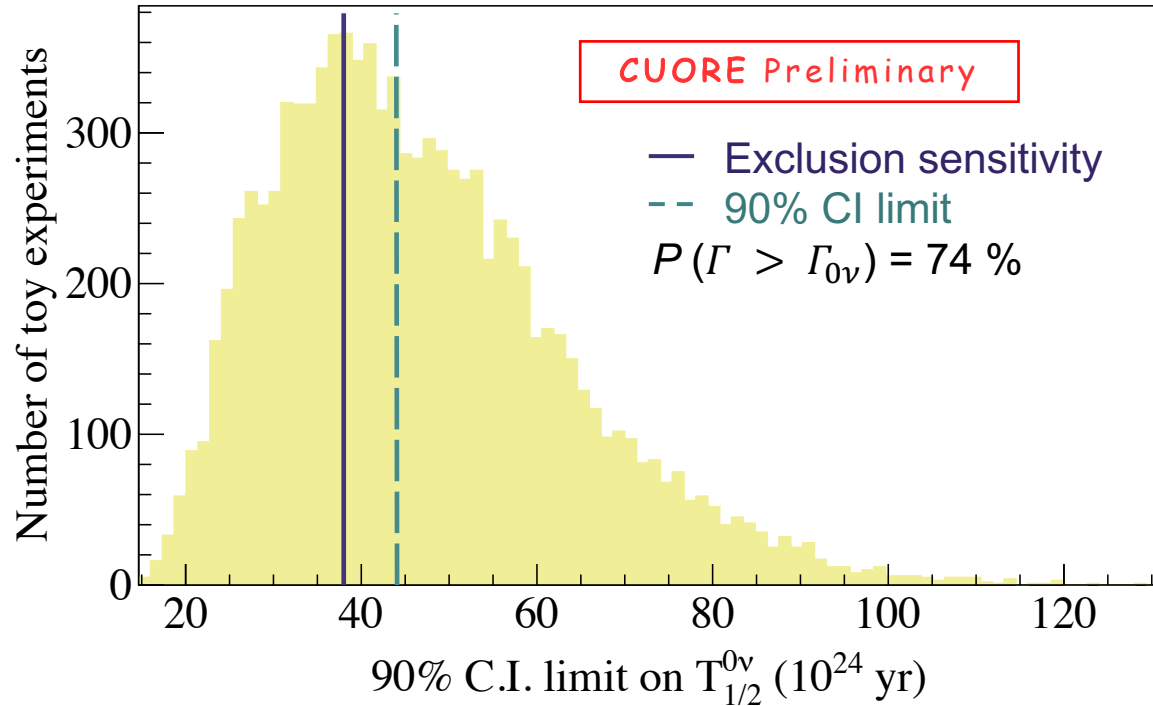


- Total analysis cut efficiency 93.4(18) %
 - Base cuts (trigger, energy reconstruction, pile-up)
 - Anti-coincidence (AC): only single-crystal events
 - Pulse shape discrimination (PSD): only signal-like events

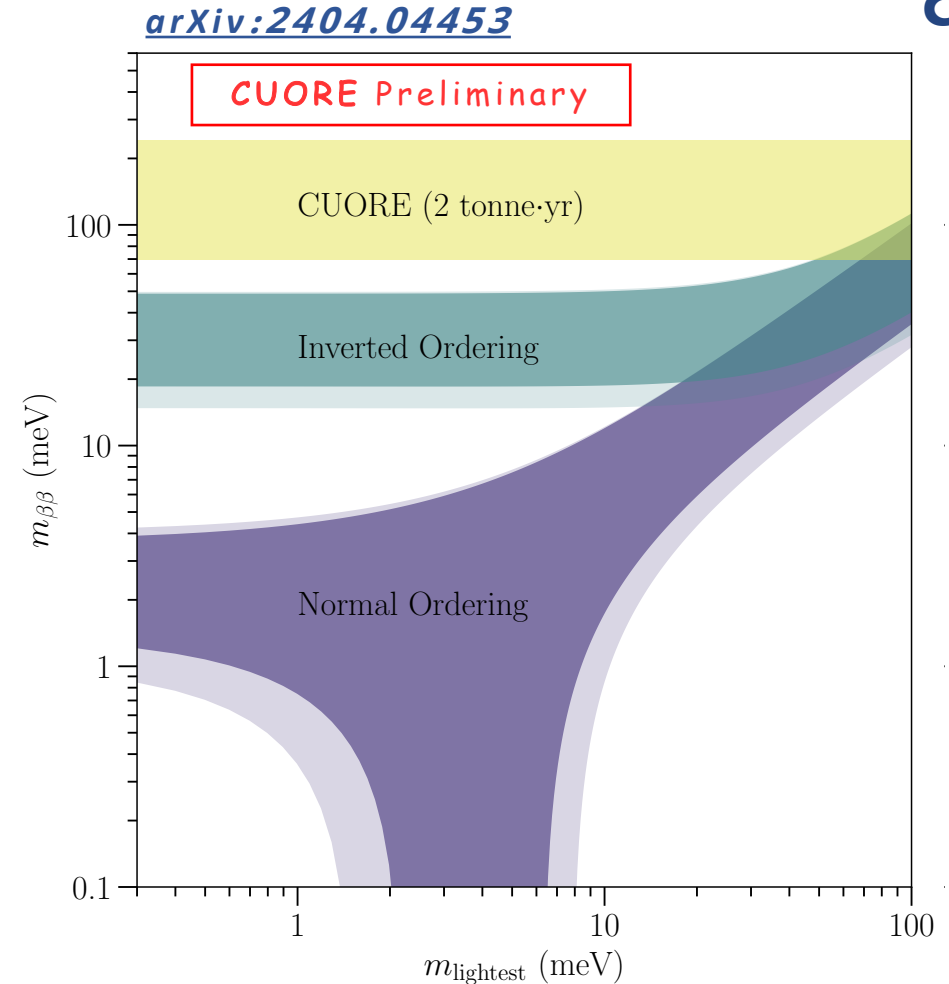


Search for $0\nu\beta\beta$

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



- No evidence, new limit on ^{130}Te $0\nu\beta\beta$ half-life
 $T_{1/2}^{0\nu} > 3.8 \cdot 10^{25}$ yr (90% C. I.)
- Frequentist: $T_{1/2}^{0\nu} > 3.7 \cdot 10^{25}$ yr (90% C. L.)

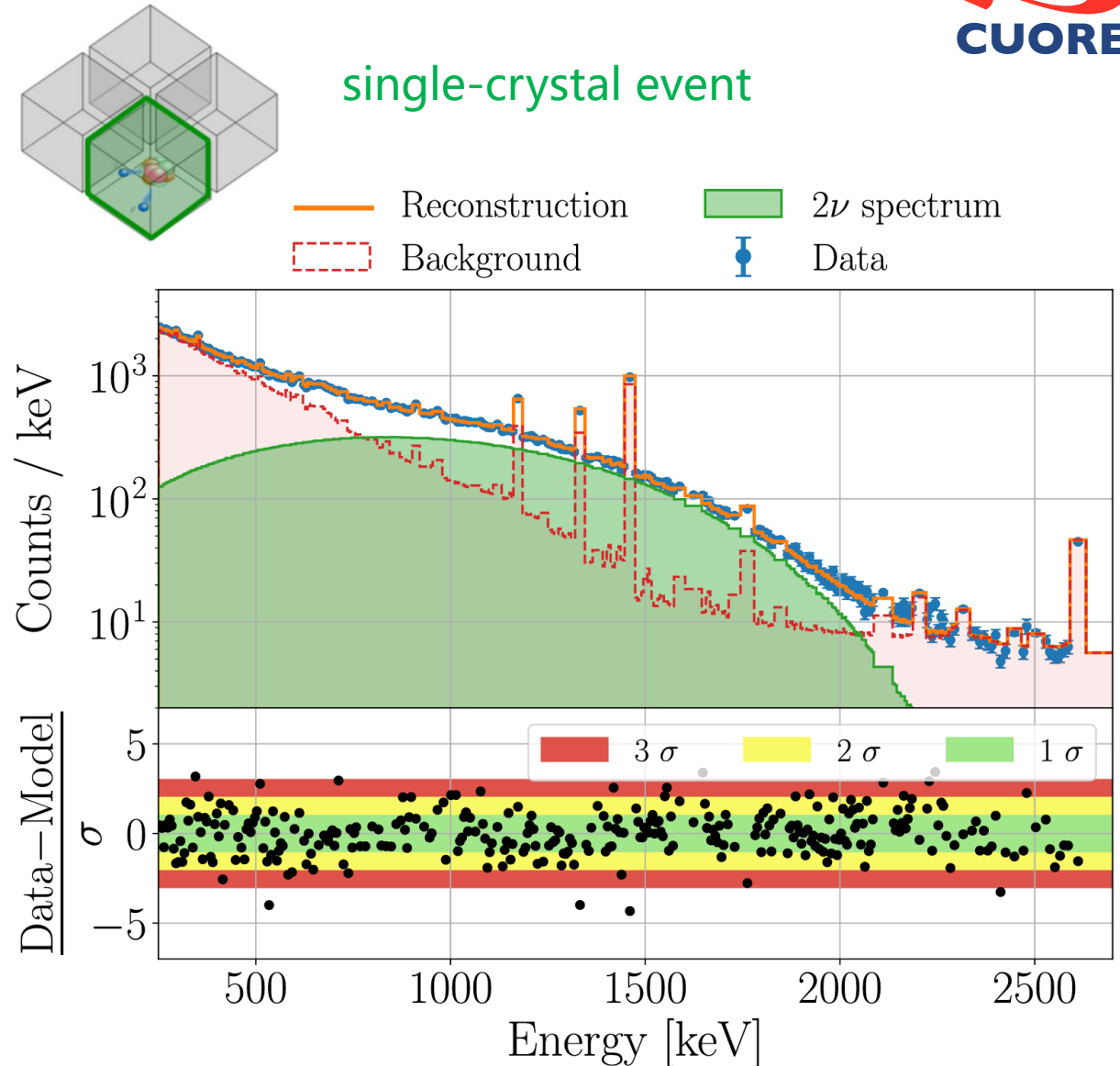


- Assuming light Majorana neutrino exchange
 $m_{\beta\beta} < 70\text{--}240$ meV

$2\nu\beta\beta$ decay measurement

- Exposure: 1038.4 kg·yr of TeO₂
 - 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

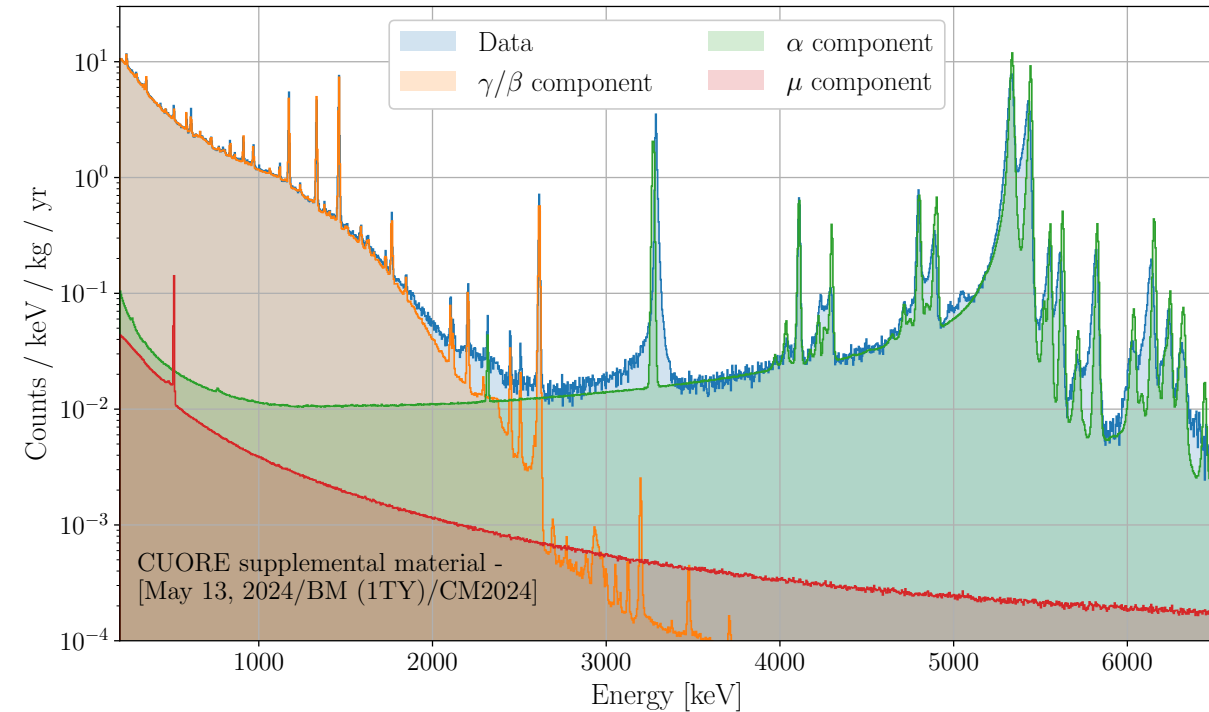
[D. Q. Adams, et al. \(CUORE Collaboration\)
Phys. Rev. Lett. 135, 082501 \(2025\)](#)



CUORE Towards CUPID



- Provided important feedback in term of both the cryogenics and background budget
- CUORE is background limited $(1.42 \pm 0.02) \times 10^{-2}$ counts / (keV·kg·yr)
[arXiv:2404.04453](https://arxiv.org/abs/2404.04453)
- 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



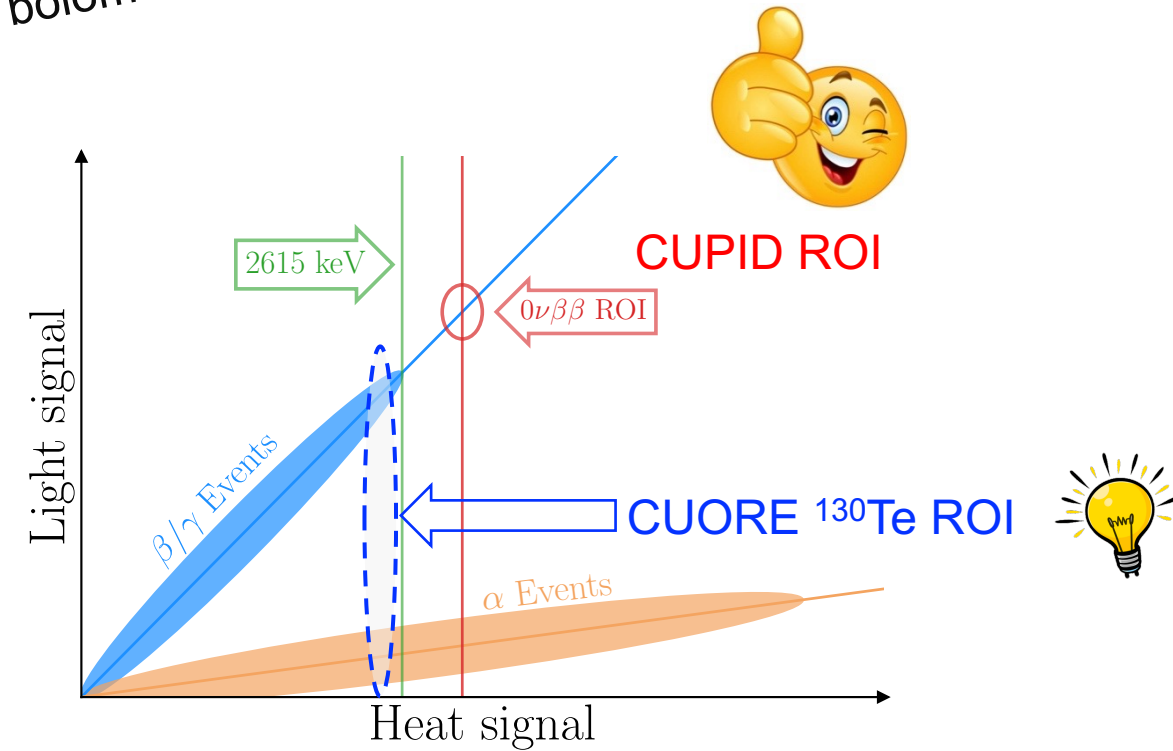
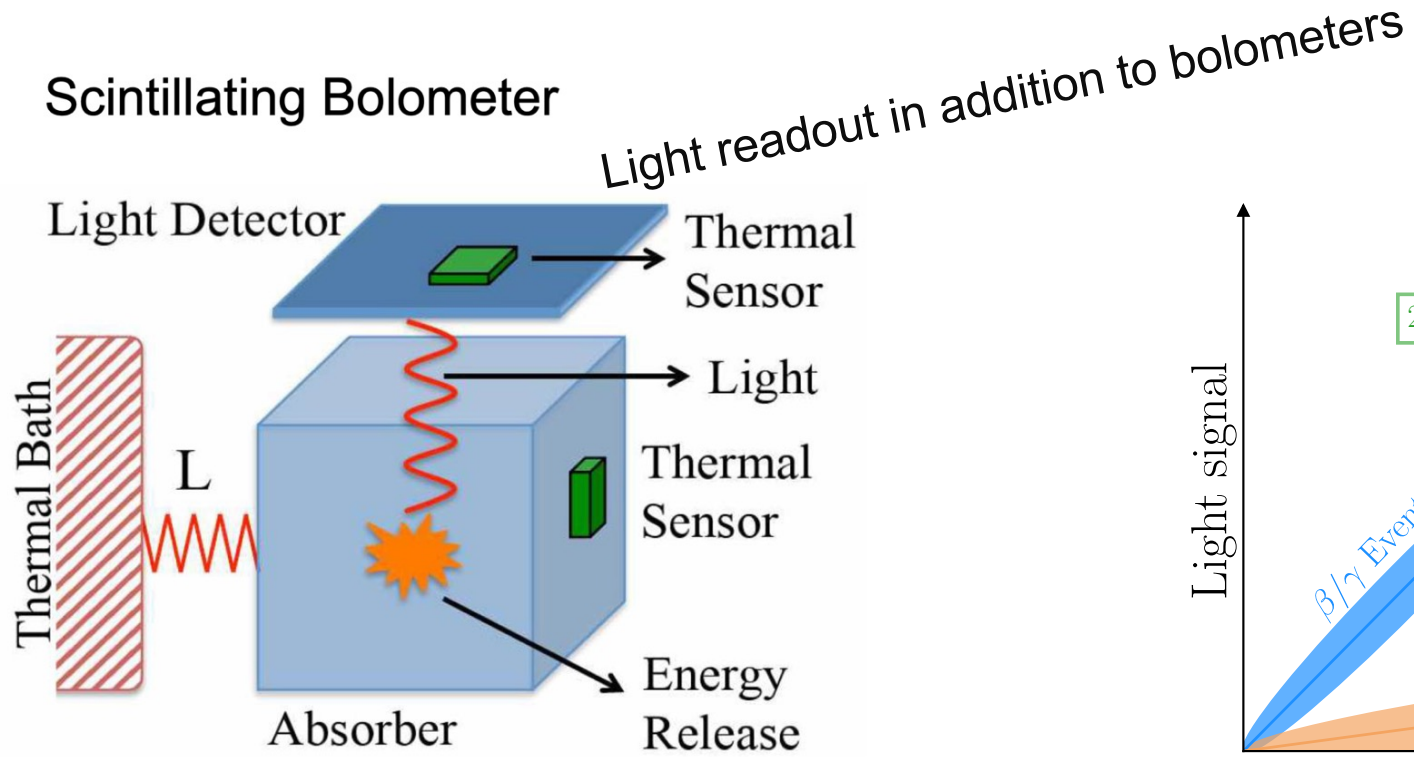
[D. Q. Adams, et al. \(CUORE Collaboration\)
Phys. Rev. D **110**, 052003 \(2024\)](#)



CUORE Upgrade with Particle Identification (CUPID)



CUPID concept

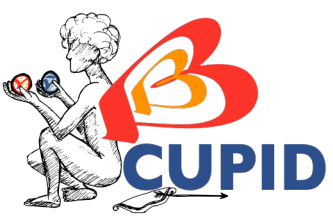


$Q_{\beta\beta}$ greater than 2615 keV: most β/γ backgrounds reduced

Measure both heat and light simultaneously

Particle ID to actively discriminate α particles

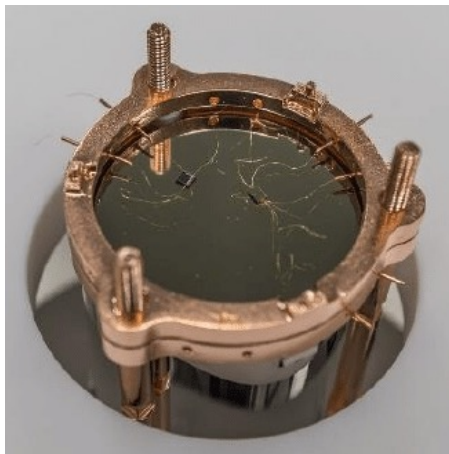
[CUPID pre-CDR arXiv:1907.09376](https://arxiv.org/abs/1907.09376)



CUPID demonstrators



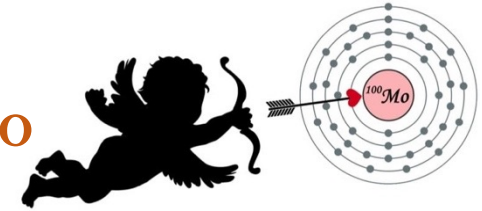
- ZnSe crystals, 95% ^{82}Se enrichment
- (5.17 kg ^{82}Se) at LNGS (Italy)
- α -rejection efficiency > 99.9%
- Background index: 3.5×10^{-3} c/kky
- $\Delta E = 21.8$ keV @ ($Q_{\beta\beta} = 2998$ keV)



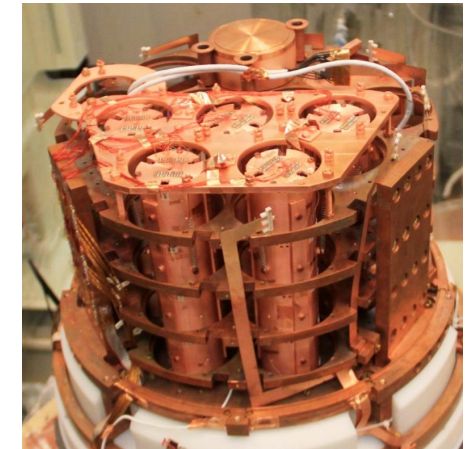
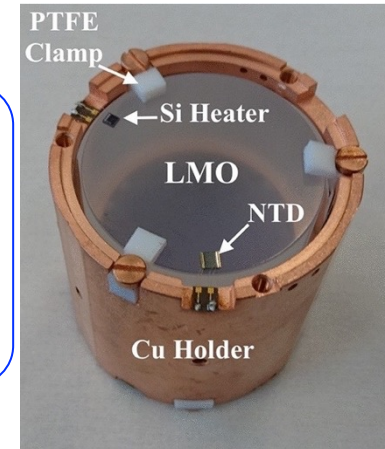
LD: SiO coating
Ge wafer

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
- $\Delta E = 7.4$ keV @ ($Q_{\beta\beta} = 3034$ keV)



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

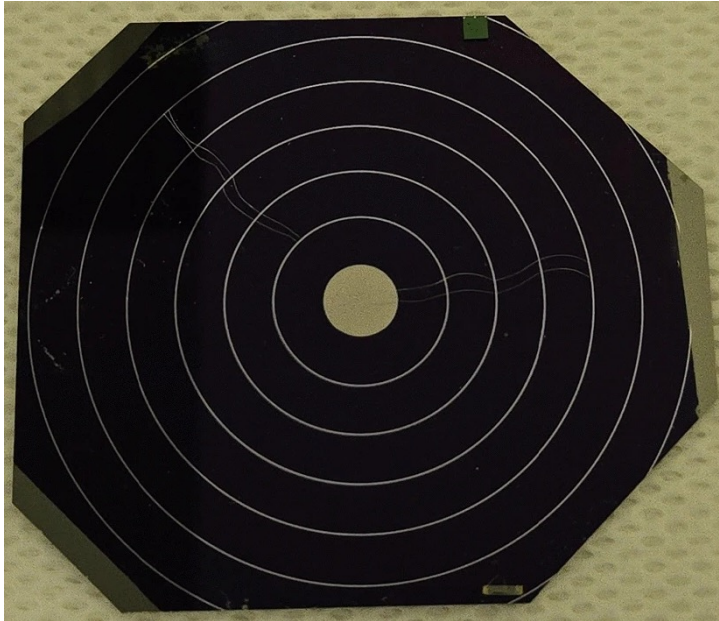
[CUPID-Mo: Eur. Phys. J. C 82, 1033 \(2022\)](#)

Light detector

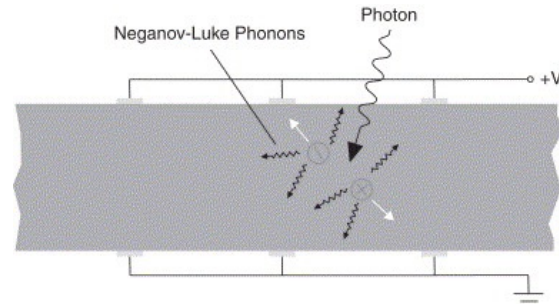
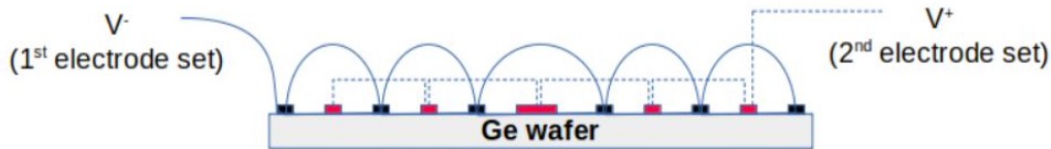
Neganov-Trofimov-Luke (NTL) effect assisted



- 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

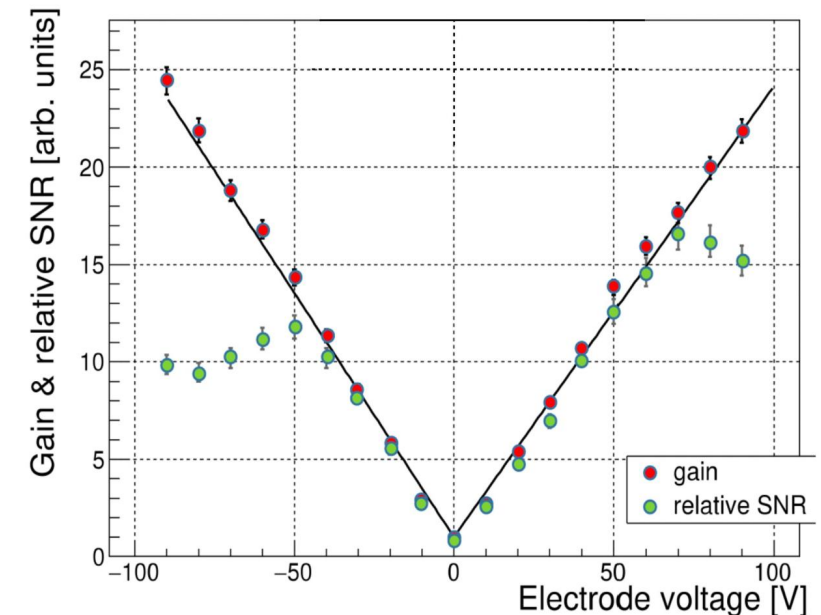


[Eur. Phys. J. C 85, 737 \(2025\).](#)

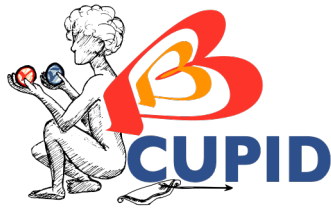


$$E_{tot} = E_0 \left(1 + \frac{q \cdot V_{el} \cdot \eta}{\epsilon} \right)$$

- 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 **2νββ pile-up rejection**



CUPID Baseline Design



45 x 45 x 45 mm³ $\text{Li}_2^{100}\text{MoO}_4$ crystals

- Crystal mass: 280 g

1596 total crystals

- 450 kg of $\text{Li}_2^{100}\text{MoO}_4$
- 95% enrichment in ^{100}Mo : 240 kg of ^{100}Mo
- 57 towers of 28 crystals. 14-floors of 2x1 crystal pairs

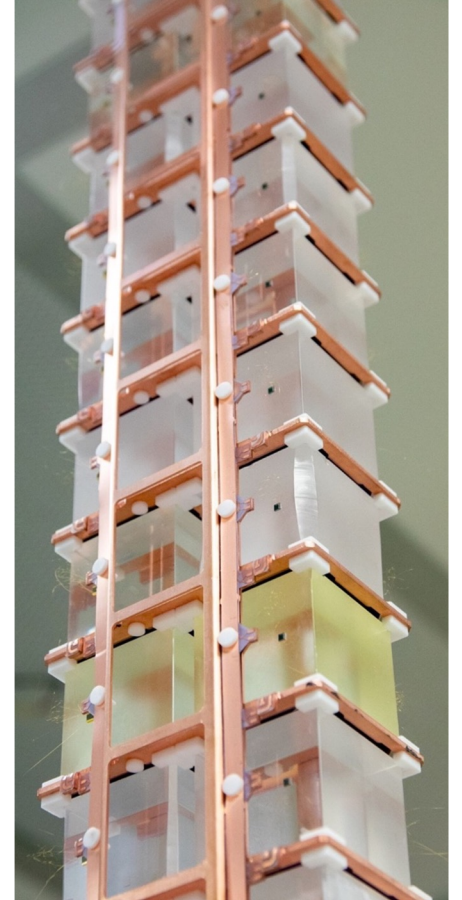
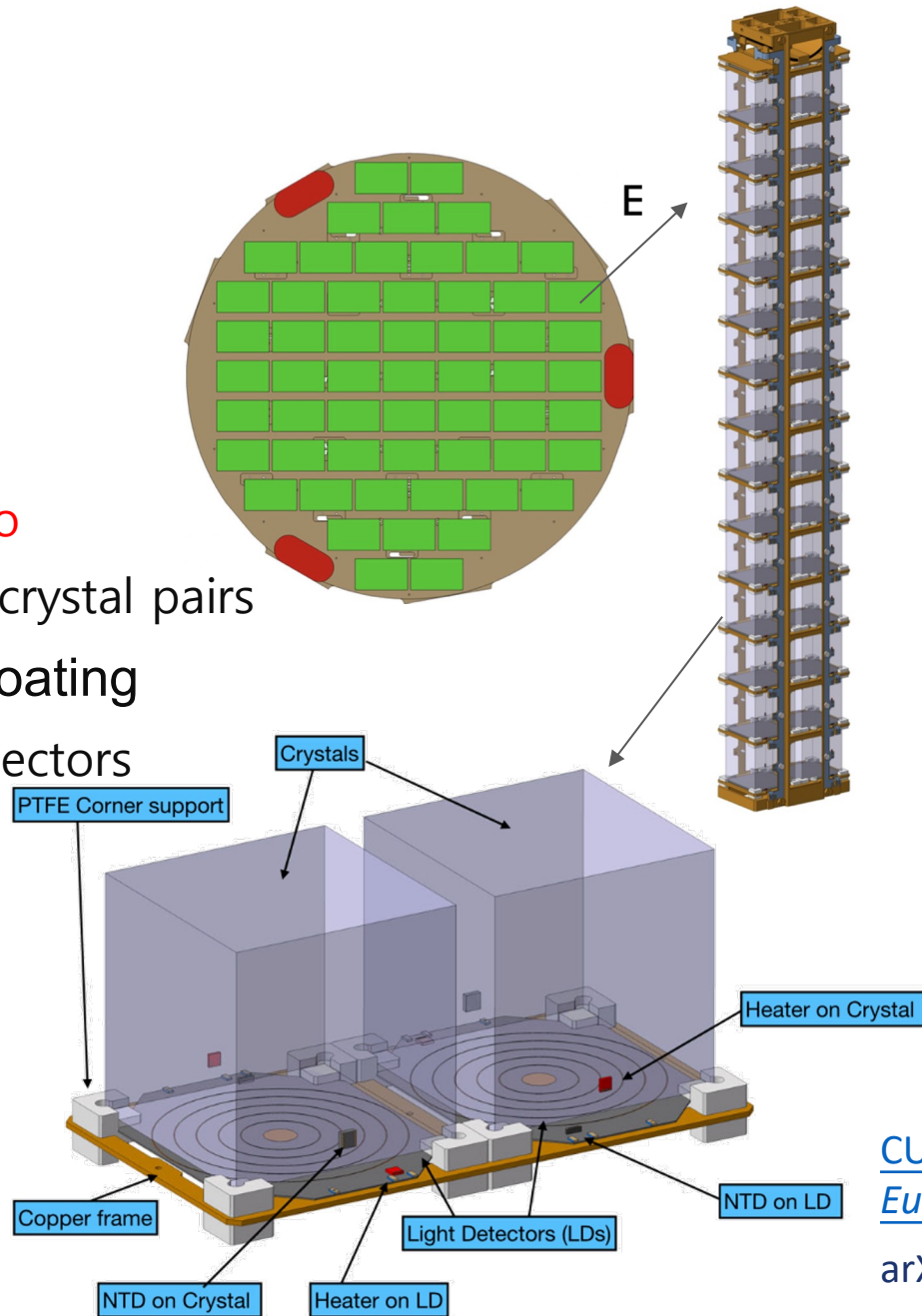
Ge light detectors with SiO anti-reflective coating

- 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

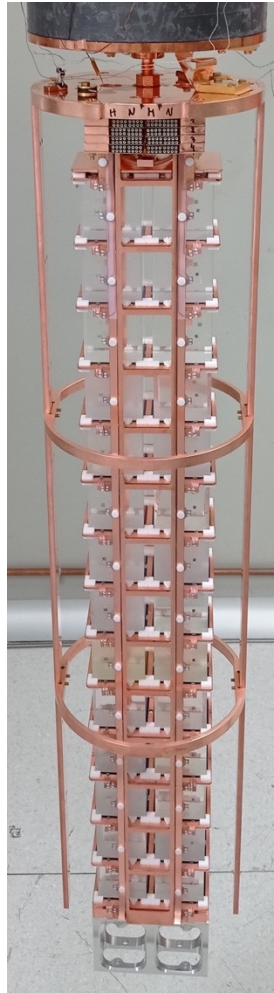
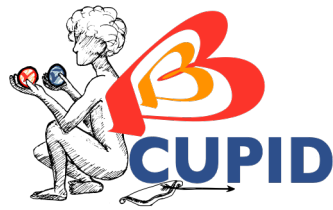


CUPID Collaboration.
[Eur. Phys. J. C 85, 737 \(2025\).](#)

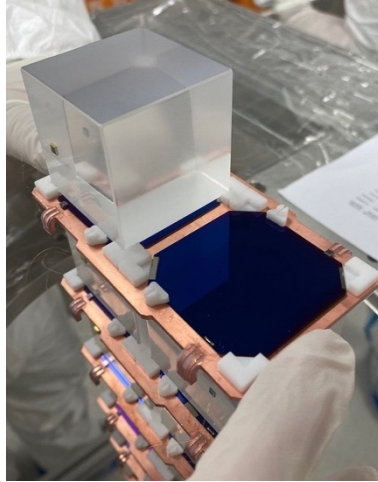
[arXiv:2503.0448](#)

Progress on CUPID prototype towers

CUPID HallA facility @LNGS



GDPT tower



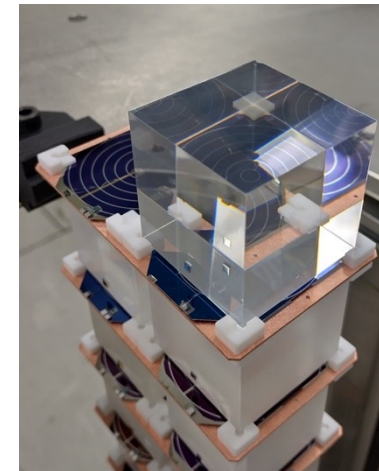
GDPT (Gravity Detector Prototype Tower) (2022)

- **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).

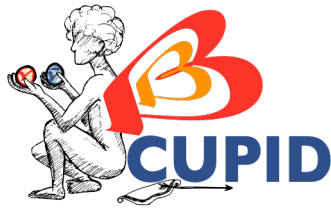
VSTT (Vertical Slice Test Tower) 2025

- Upgraded tower design and assembly-line
- **NTL light detectors**
- **Optical fibers along the tower**
- New electronics and DAQ
- Cooled down in early August 2025 (~ 7 mK)
- Data taking and detectors performance assessment ongoing

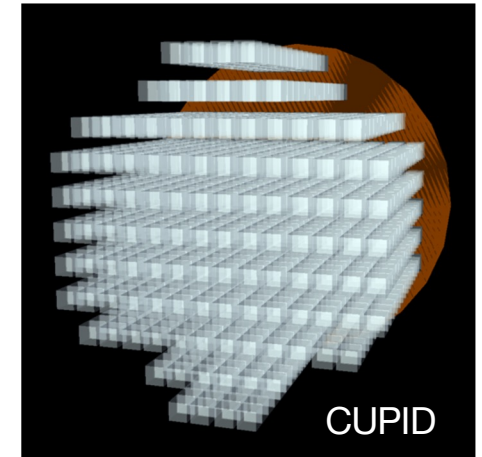
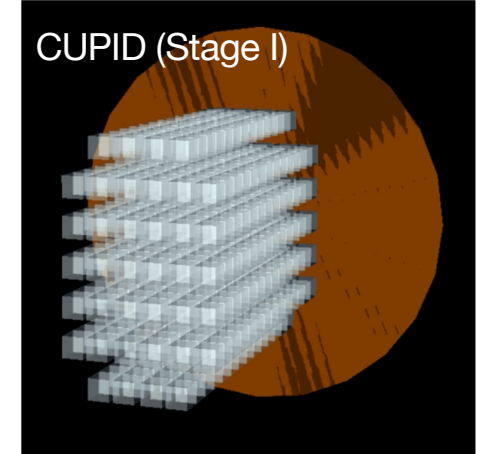
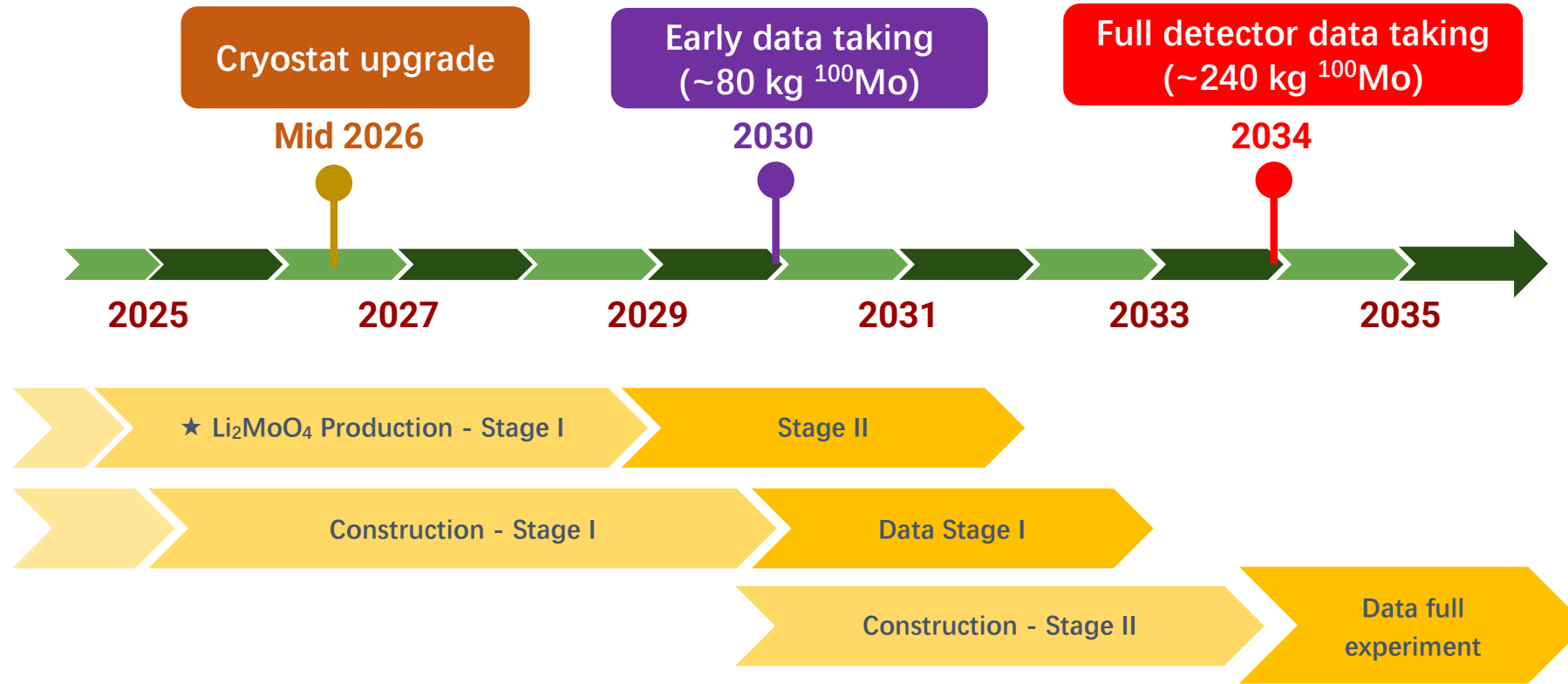


VSTT tower

CUPID timeline



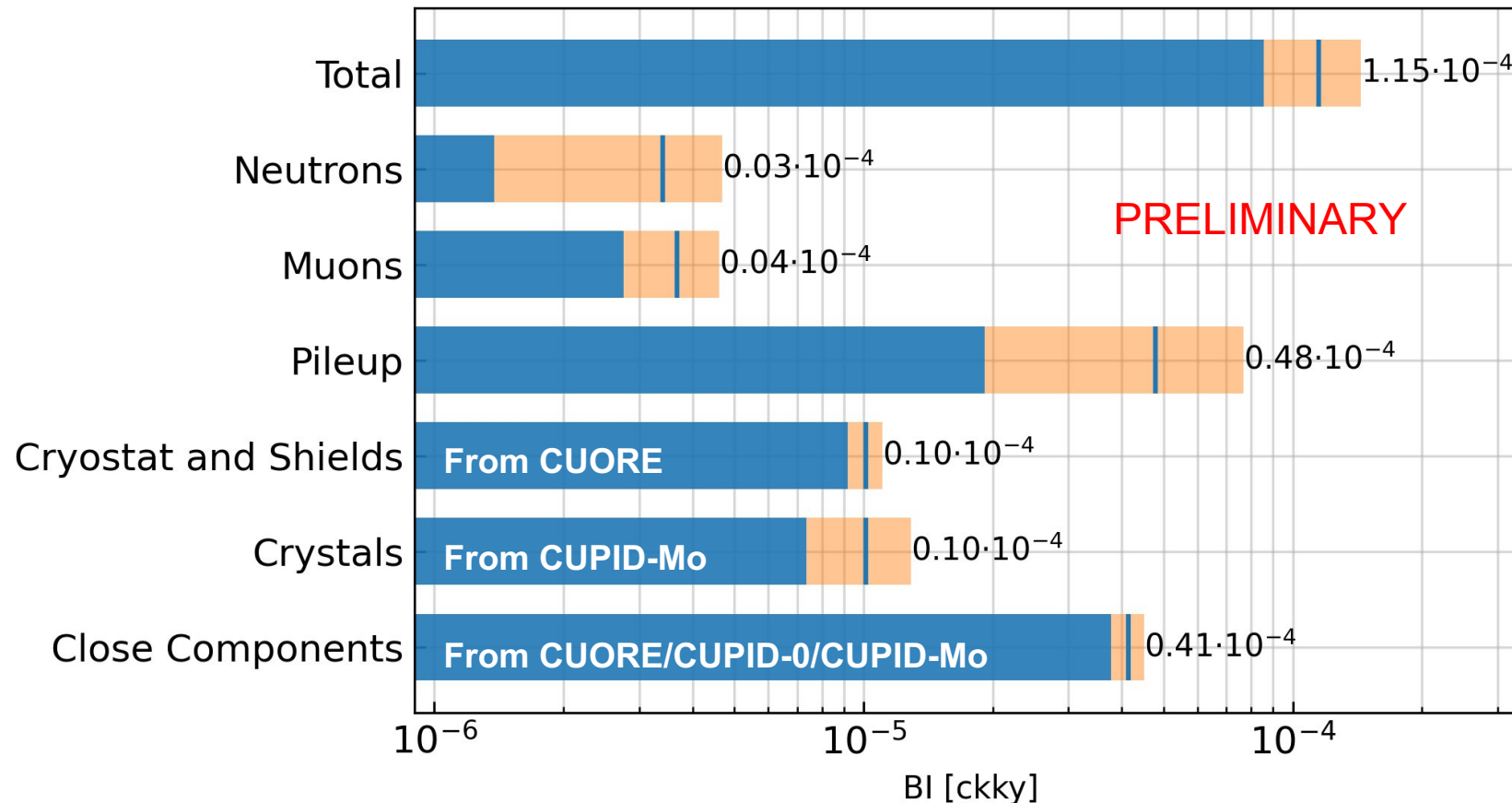
- CUPID Stage-I: 1/3 of the crystals & 3 year data-taking
- CUPID full array: Add the remaining 2/3 of the crystals & full data-taking



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



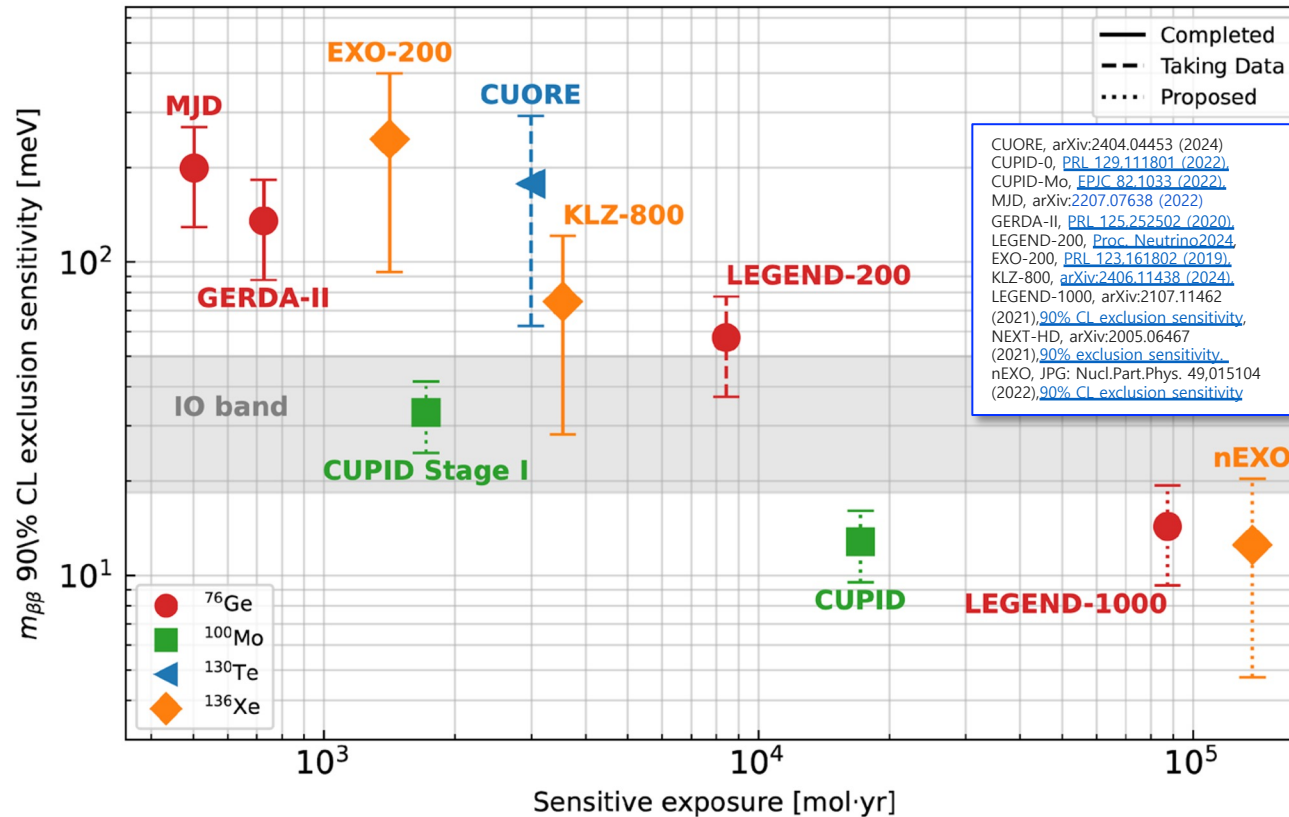
BI Goal: 1.0×10^{-4} c/kky

Figure from Pía Loaiza, *TAUP 2025* conference

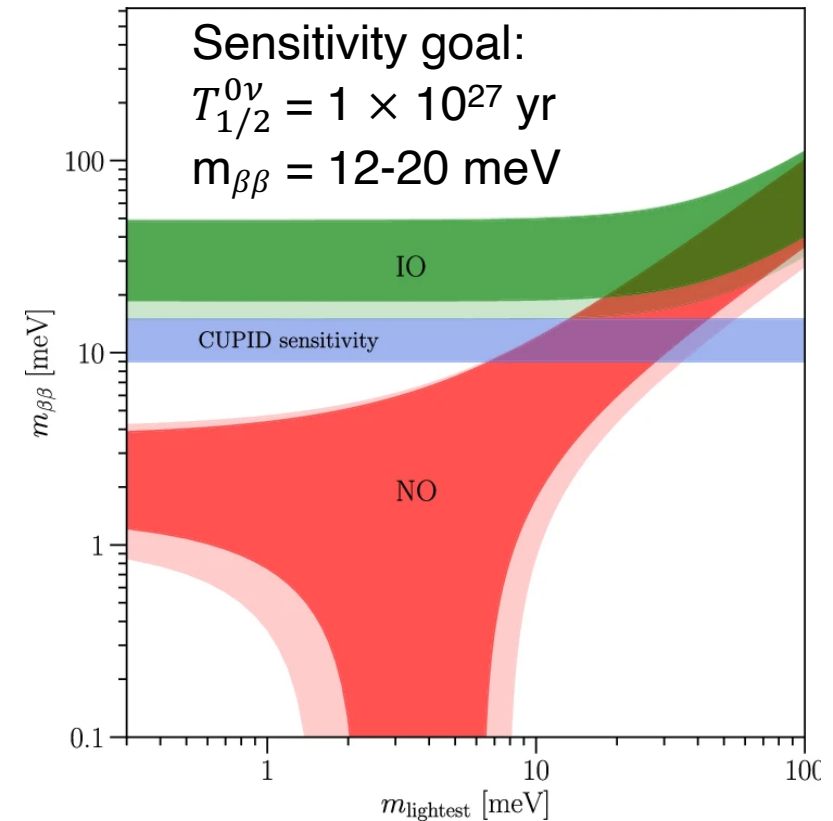
CUPID sensitivity



- 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



with 10 years livetime

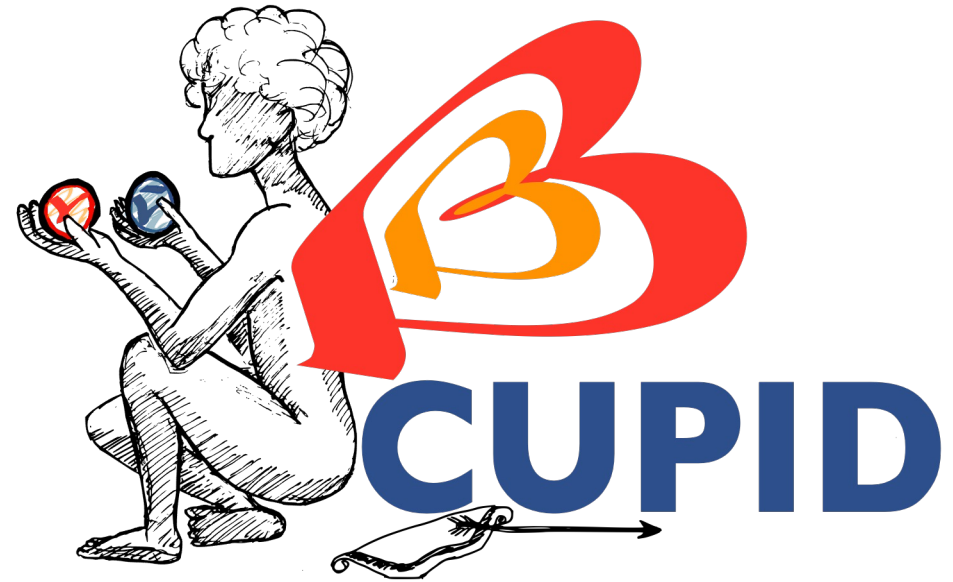


Summary



- 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 . l.)
- 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 and discovery program at LNGS in the next years

Thanks for your attention!

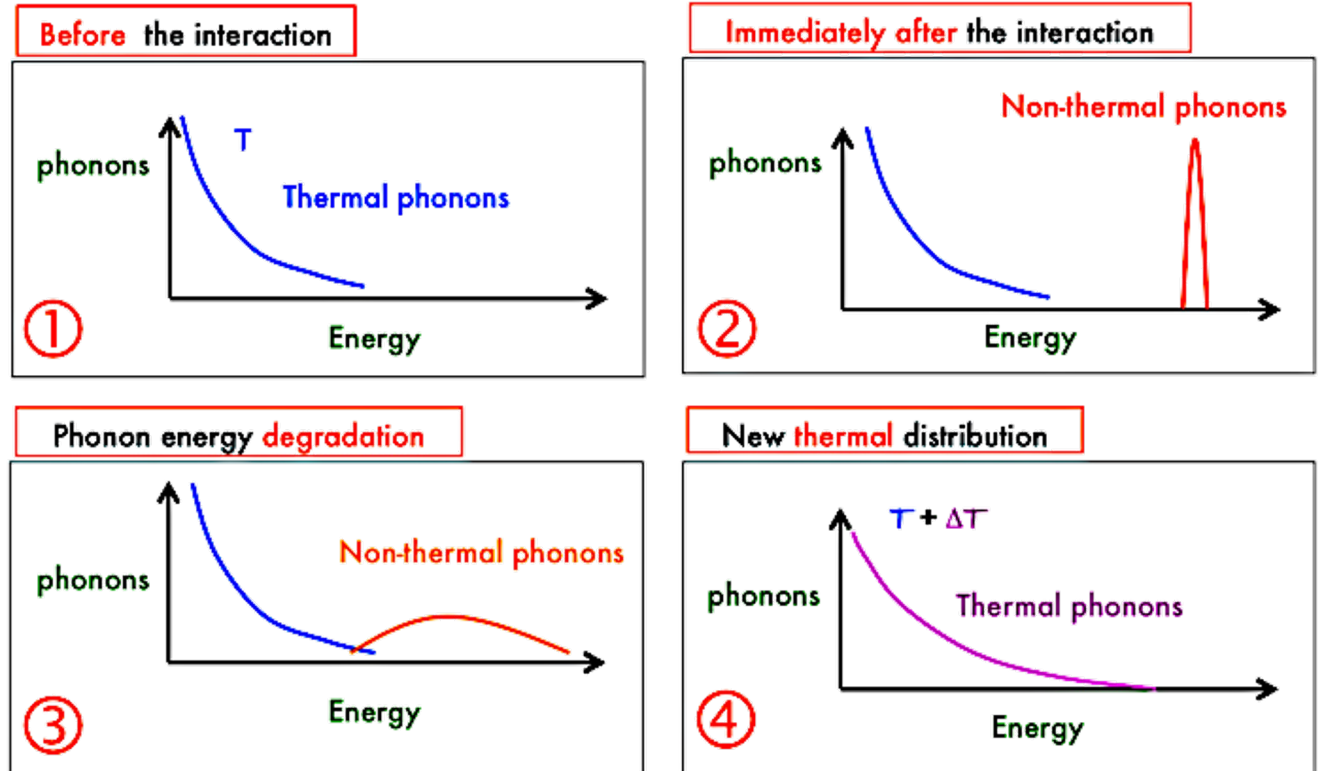
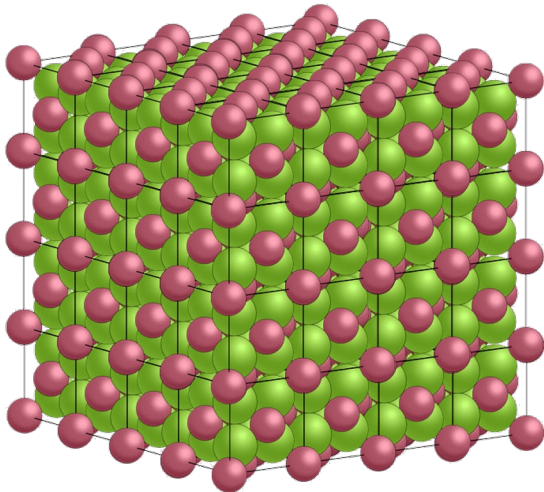


Acknowledgment

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.

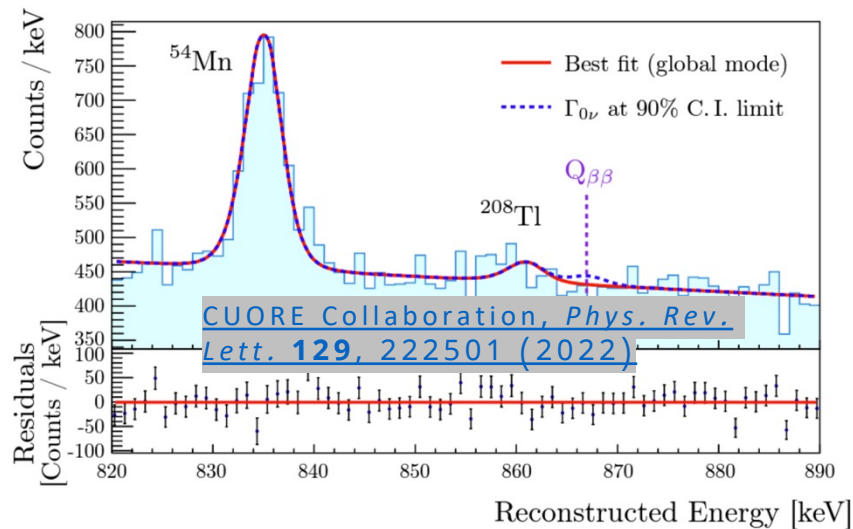
Backup slides

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

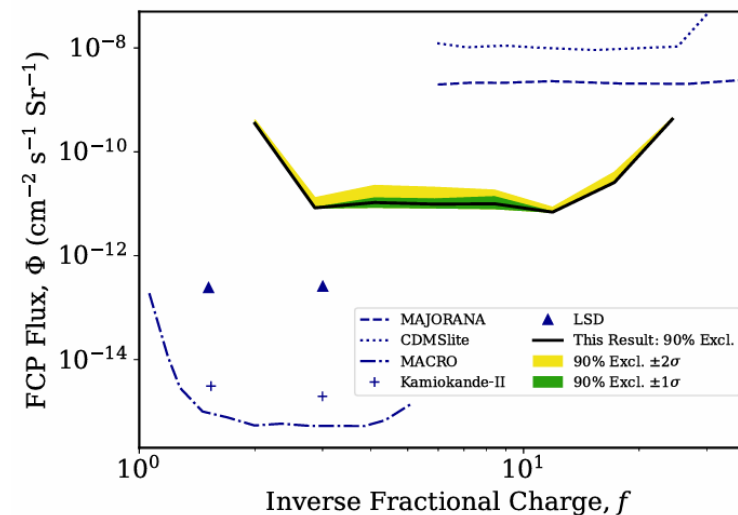


Other searches

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

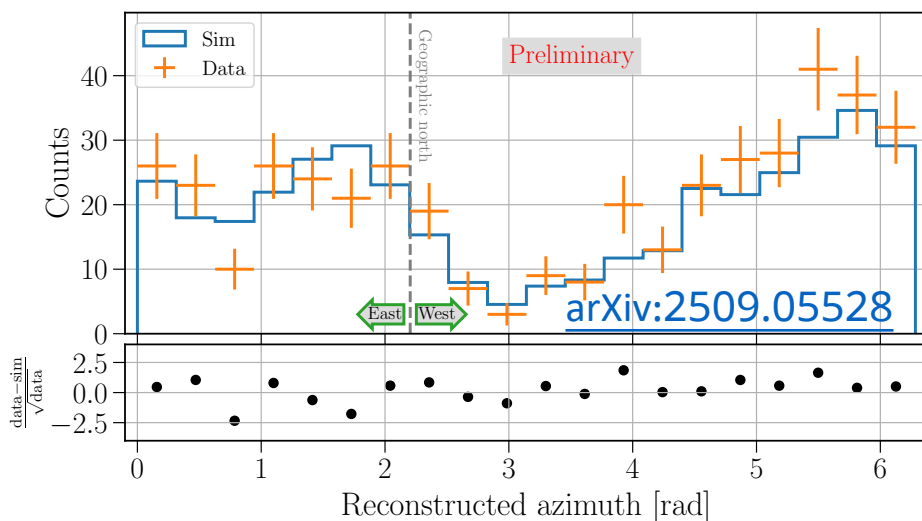


Search for fractionally charged particles

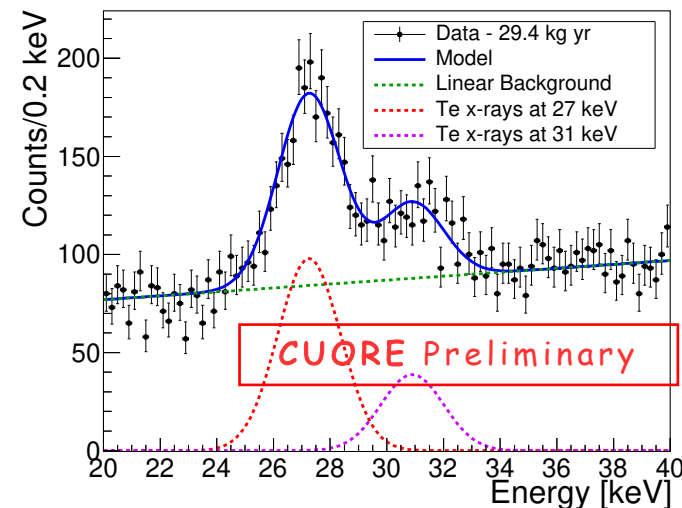


CUORE Collaboration,
Phys. Rev. Lett. **133**,
241801 (2024)

Muon event reconstruction (ongoing)



Low energy studies



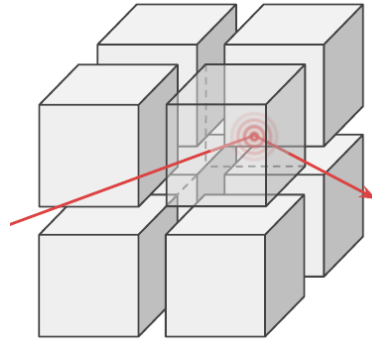
arxiv:2505.23955

Multiplicity selection

Phys. Rev. D 110, 052003

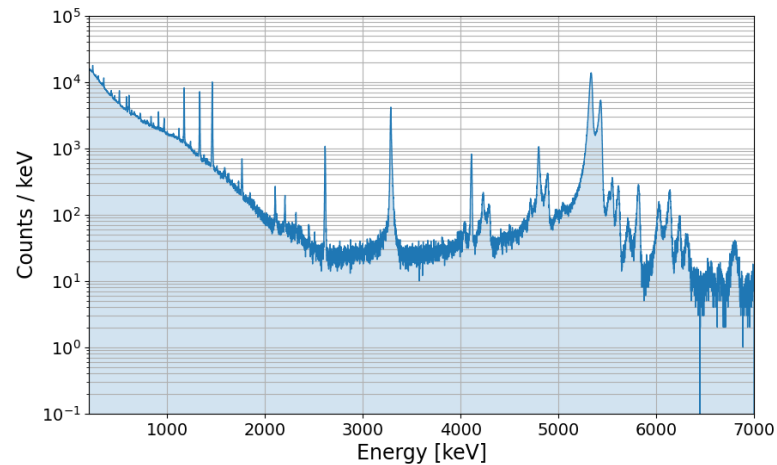


Multiplicity 1

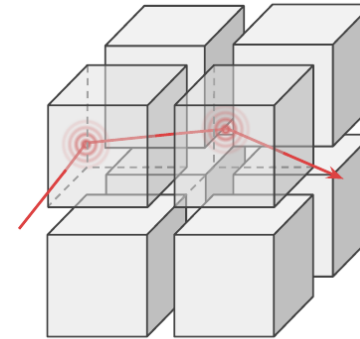


Single spectrum

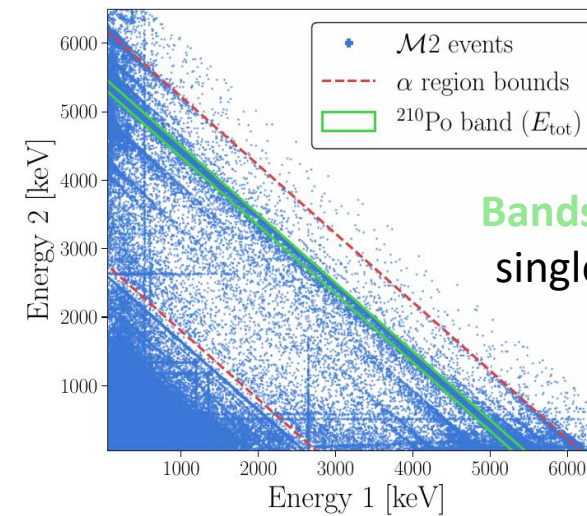
Identical to the $0\nu\beta\beta$



Multiplicity 2



Study correlation
between coincident
energy depositions



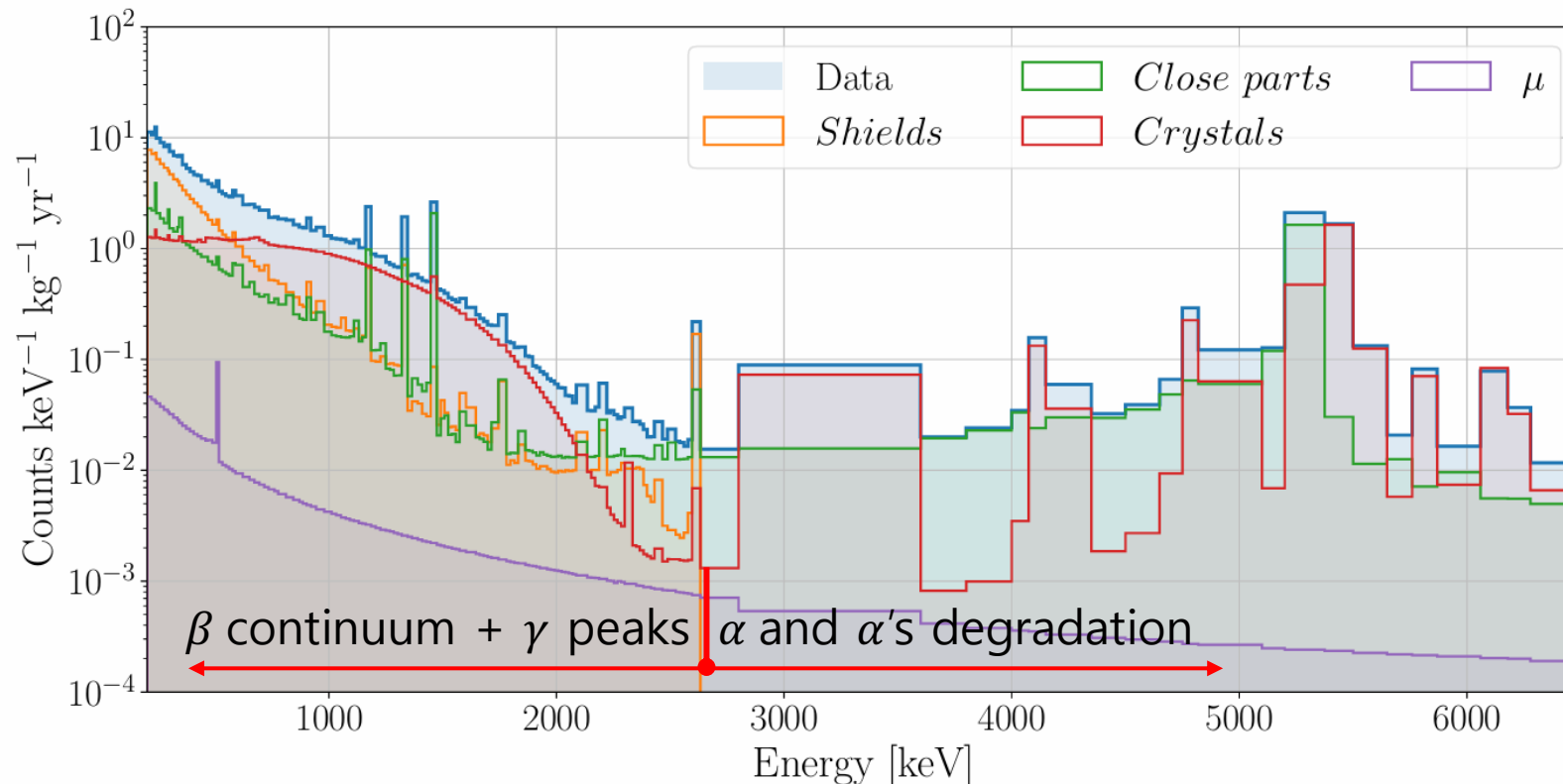
Bands associated to
single total energy

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 \(2024\)](#)



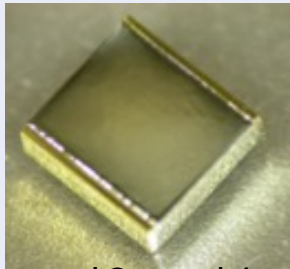
Average background index in the ROI

$1.42 \pm 0.02) \times 10^{-2}$
counts/(keV·kg·yr)

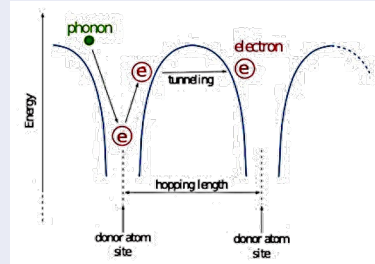
[arXiv:2404.04453](#)

Cryogenic thermal sensors

Neutron Transmutation Doped Germanium, NTD-Ge

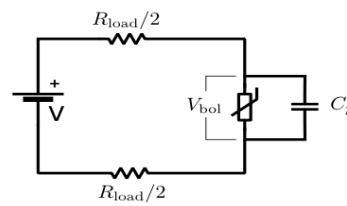
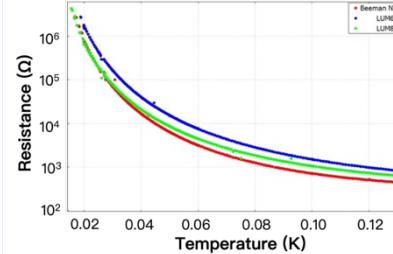


3mm*3mm*1mm



Variable Range Hopping

$$\Delta T \longrightarrow \Delta R \longrightarrow \Delta V$$



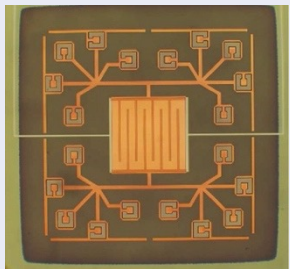
- High sensitivity $A \sim 1-10$
- Large dynamic range
- Relatively easy readout
- Massive production

- Slow response

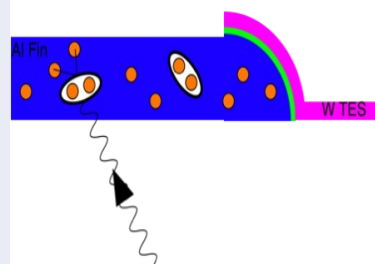
CUORE
($0\nu\beta\beta$)



Transition Edge Sensor, TES

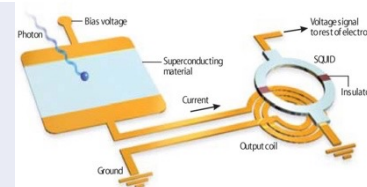
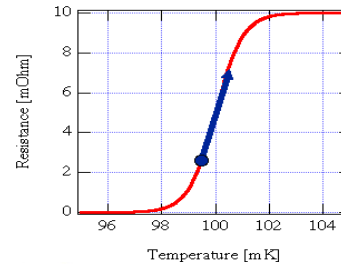


microsize



Phonon-Cooper pair

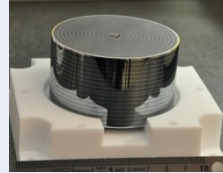
$$\Delta T \longrightarrow \Delta R \longrightarrow \Delta I$$



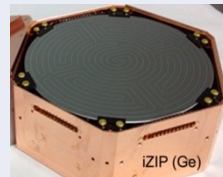
- Very high sensitivity $A \sim 100-1000$
- Multiplex readout
- Fast rising signal

- SQUID readout
- Narrow dynamic range

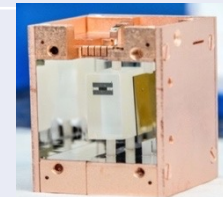
EDELWEISS
(Dark Matter)



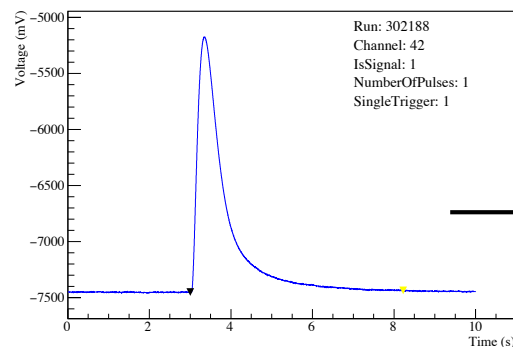
SuperCDMS
(Dark Matter)



CRESST
(Dark Matter)



Data processing

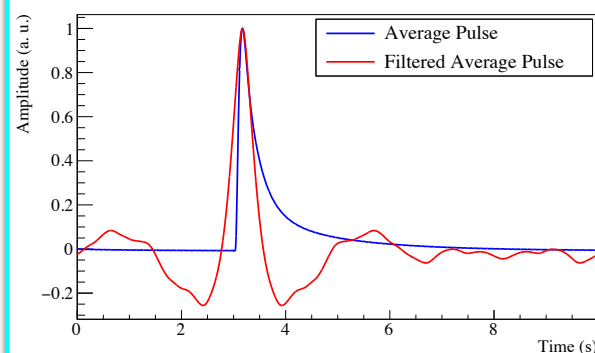


Optimum
Filter

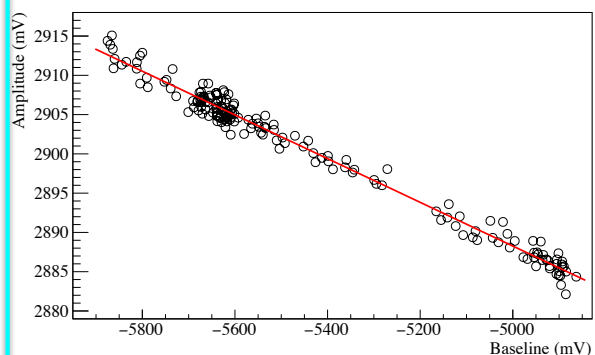
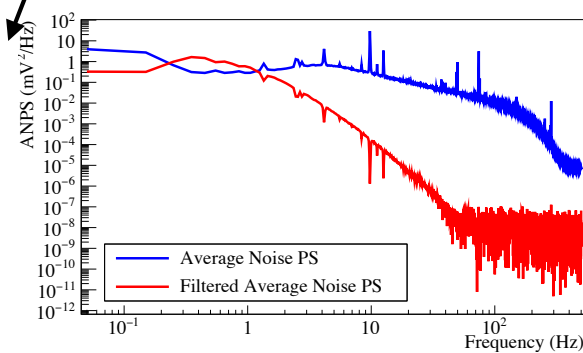
Gain
Correction

Energy
Calibration

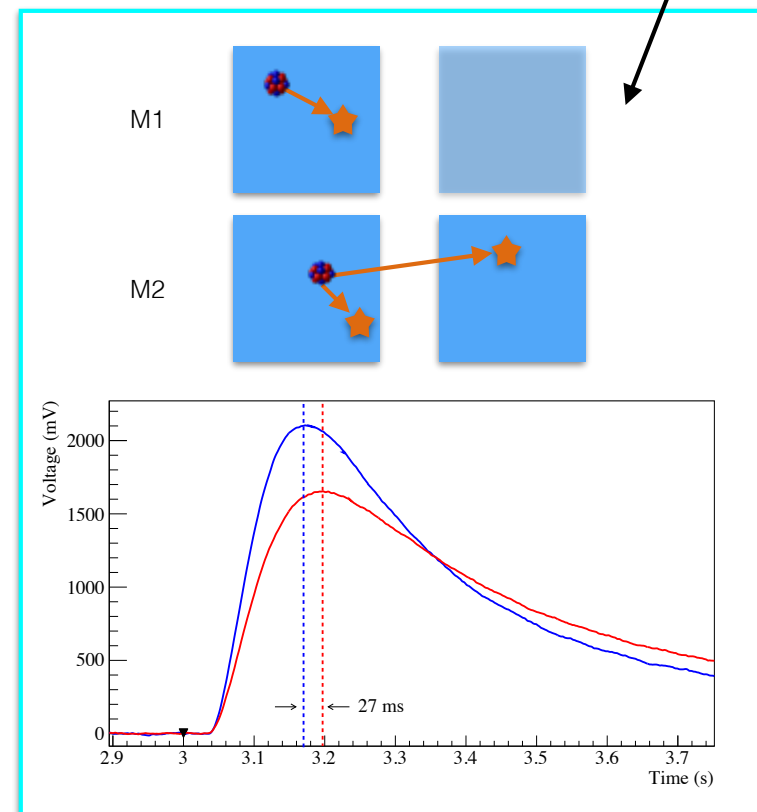
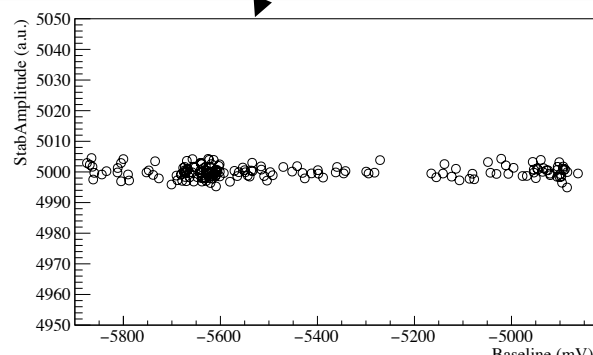
Coincidences



Matched filter that maximizes the signal-to-noise ratio



Heater pulses for thermal gain stabilization

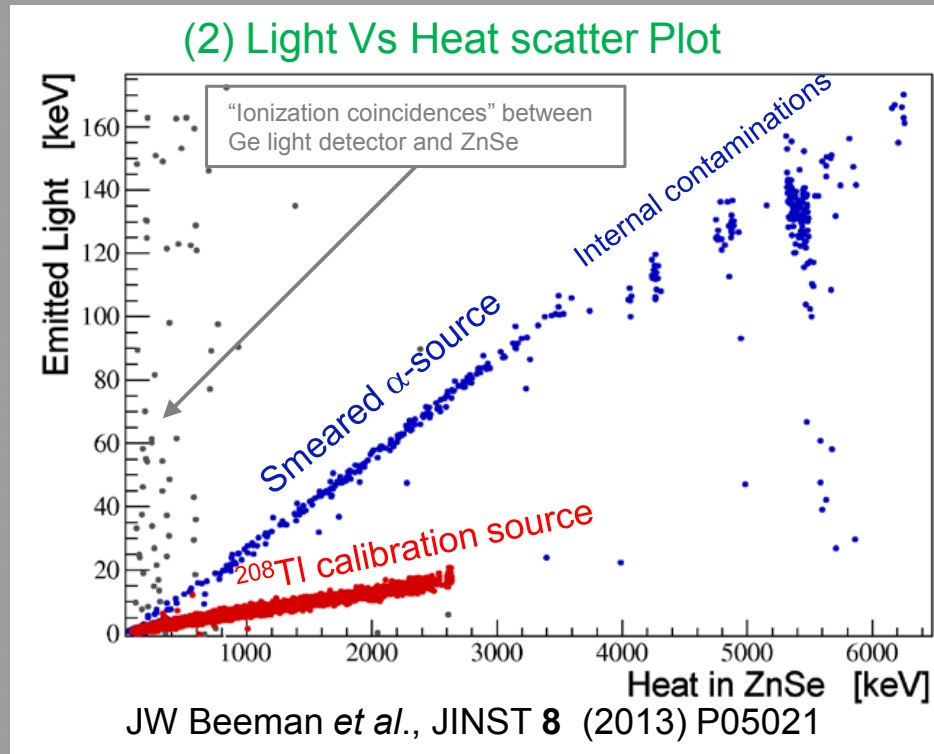


Slide from Irene Nutini, *ICNFP2020* conference

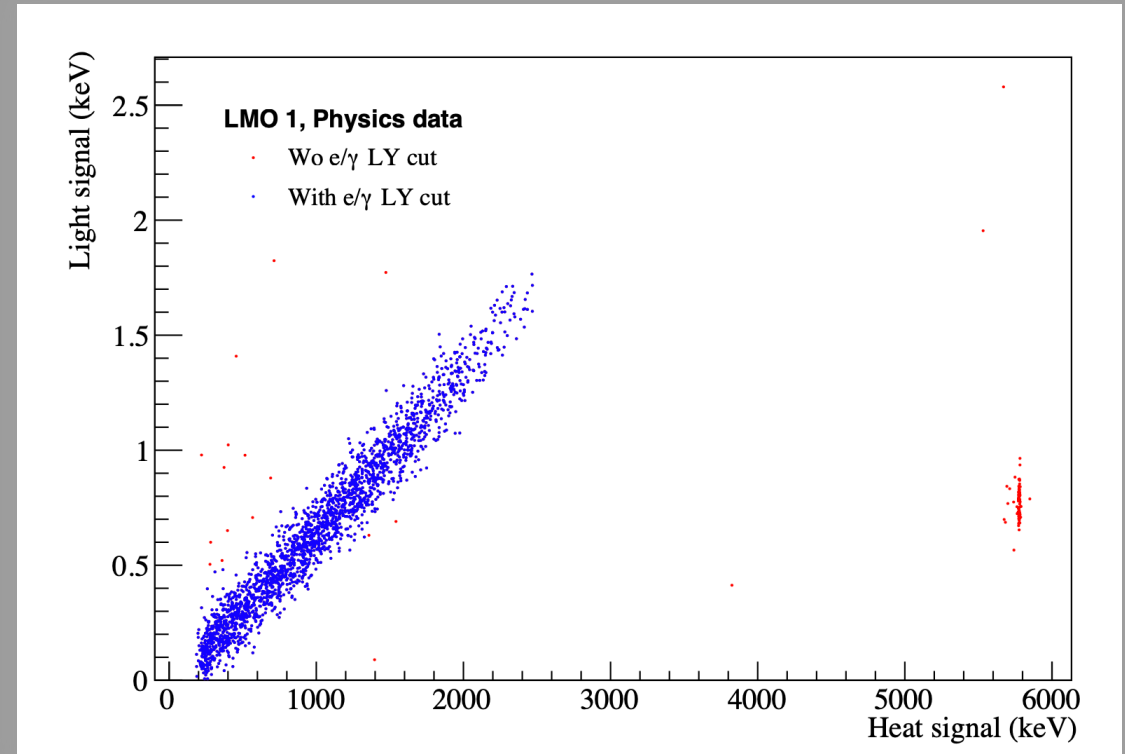
Light heat double readout



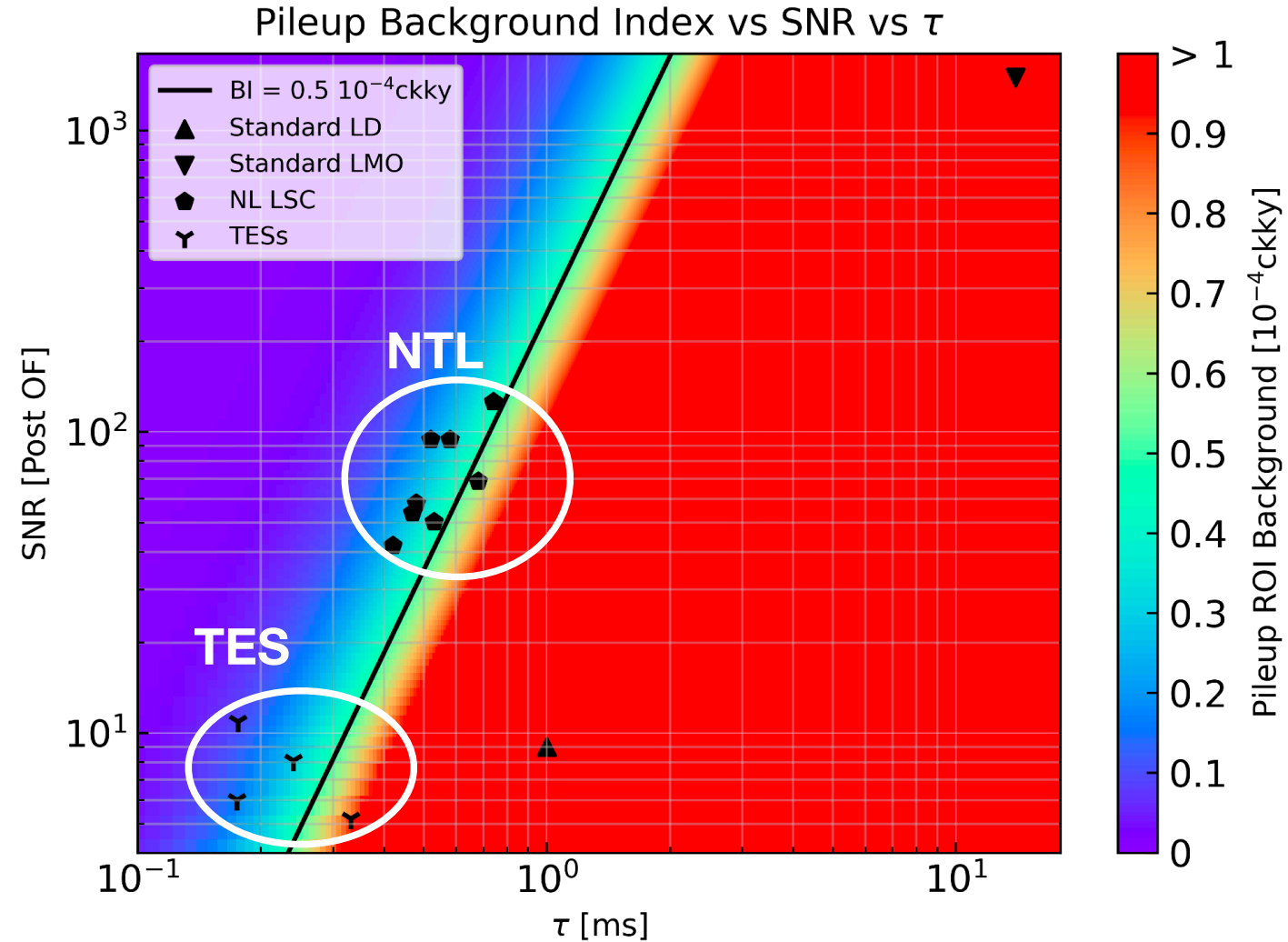
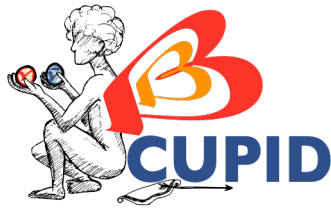
CUPID-0 ZnSe



CUPID-Mo LMO

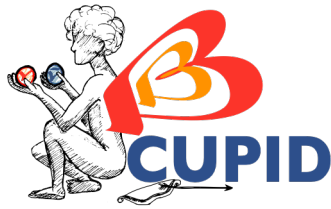


Pileup rejection



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

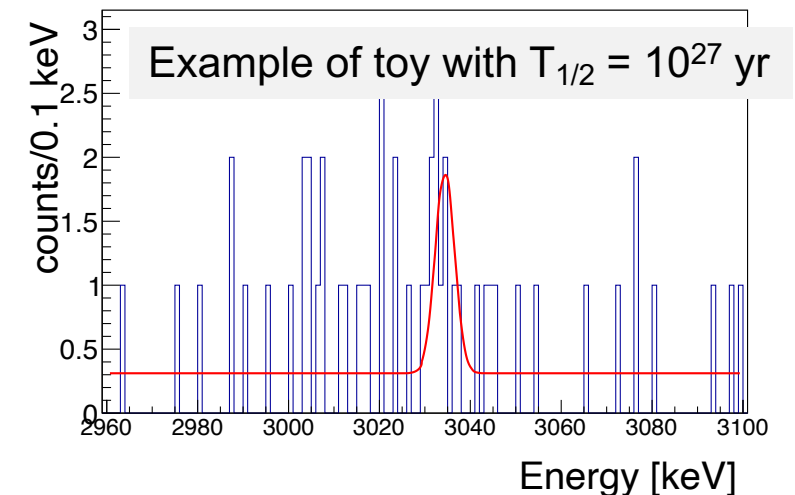
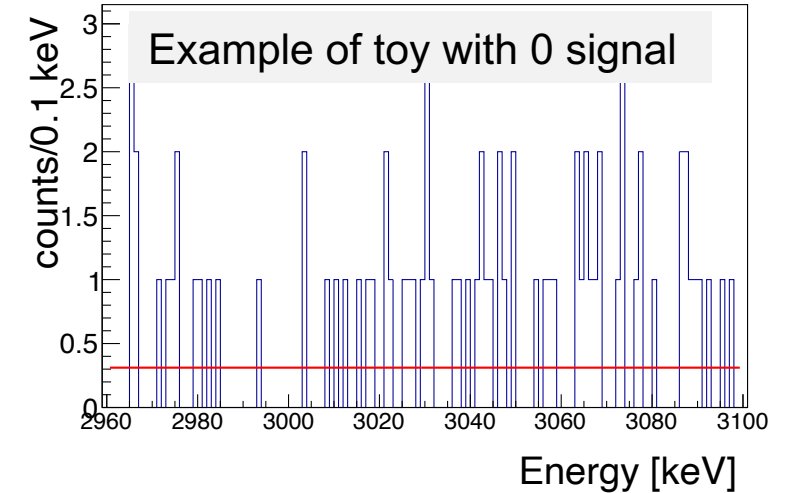
$$t_P(\Gamma = 0) = -2 \ln \frac{H_0}{H_1} = -2 \ln \left(\frac{\mathcal{L}(0)}{\mathcal{L}(\hat{\Gamma})} \right)$$

Background-only

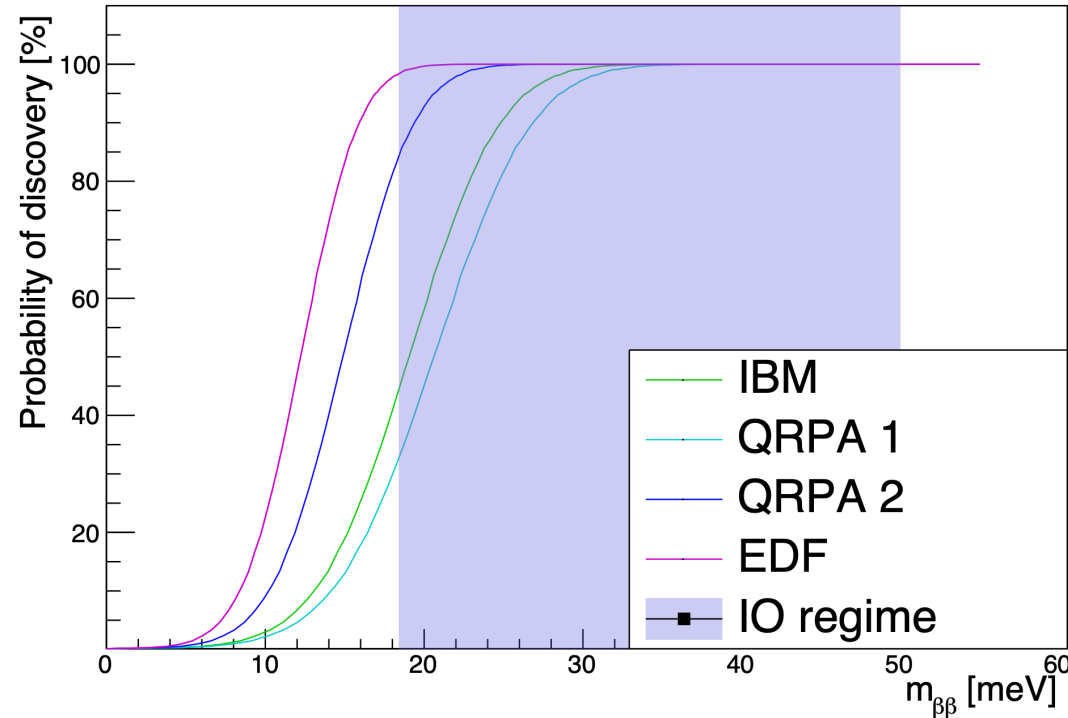
- Generate pseudo-experiments for different values of Γ and compute the background-only p-value. A discovery can be claimed if p is smaller than some cutoff.

- **3σ discovery if $p < 0.14\%$**

- **$T_{1/2} = 1.0 \times 10^{27}$ y**



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

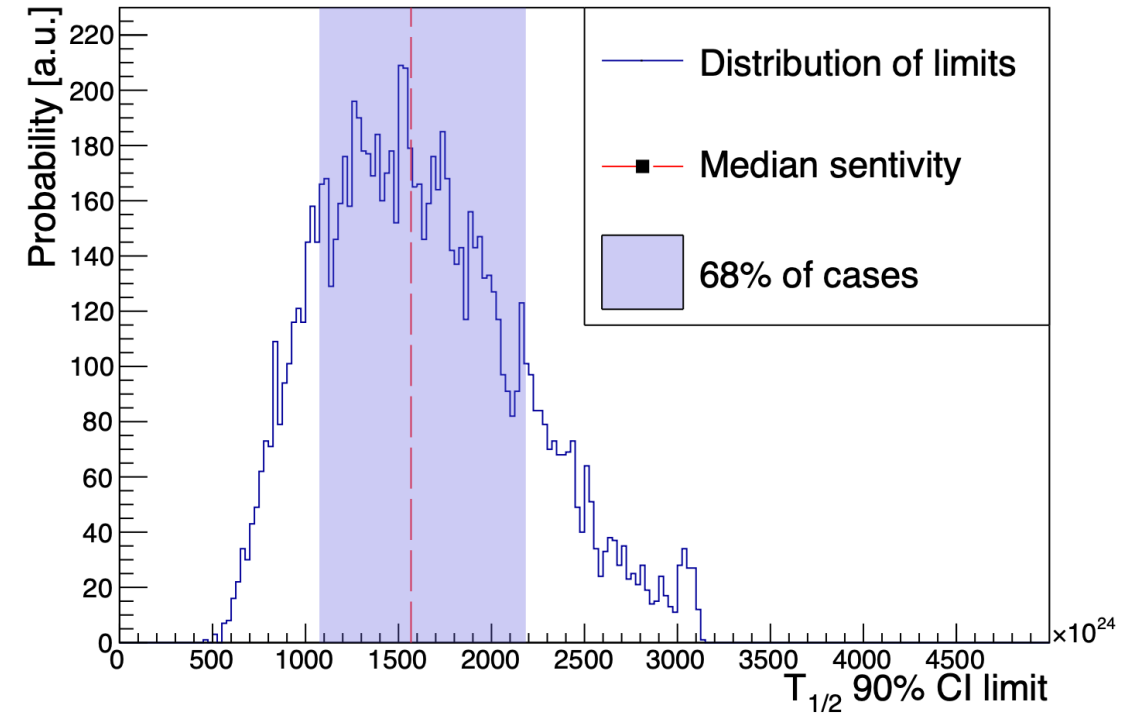


Discovery: Probability = 50%

$$T_{1/2} = 1.0 \times 10^{27} \text{ y}$$

$$m_{\beta\beta} = 12.2 - 20.6 \text{ meV}$$

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



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

$$m_{\beta\beta} < 9.6 - 16.3 \text{ meV}$$

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