CUPID: a next generation bolometric 0νββ decay experiment

Giovanni Benato for the CUORE and the CUPID(s) collaborations

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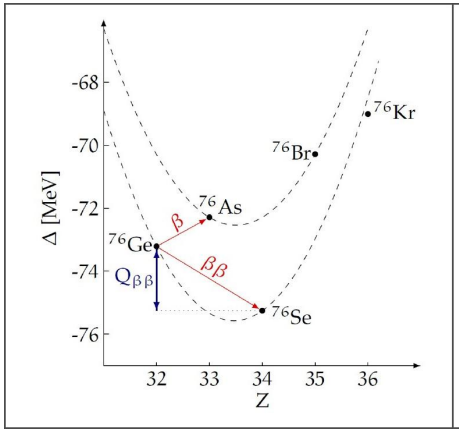
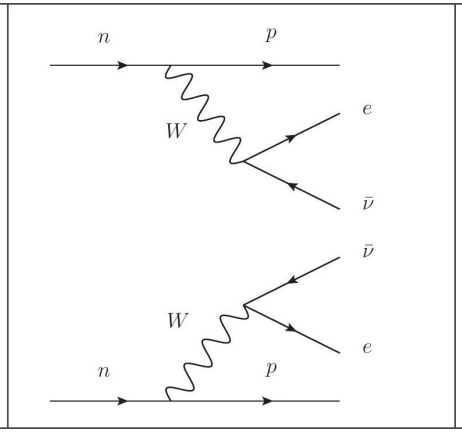
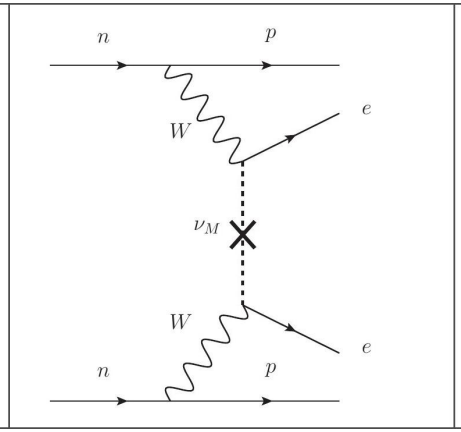
TIPP 2021

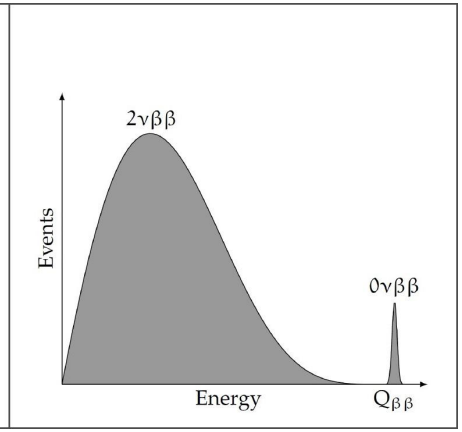
H2020 MSCA COFUND
G.A. 754496

0νββ decay









ββ decay signature

- Continuum for 2νββ decay
- Peak at $Q_{\beta\beta}$ for 0νββ decay
  ⟹ Energy peak is the only necessary and sufficient signature to claim a discovery
- Additional signatures from signal topology, pulse shape discrimination, multiple channel readout, daughter tagging, ...

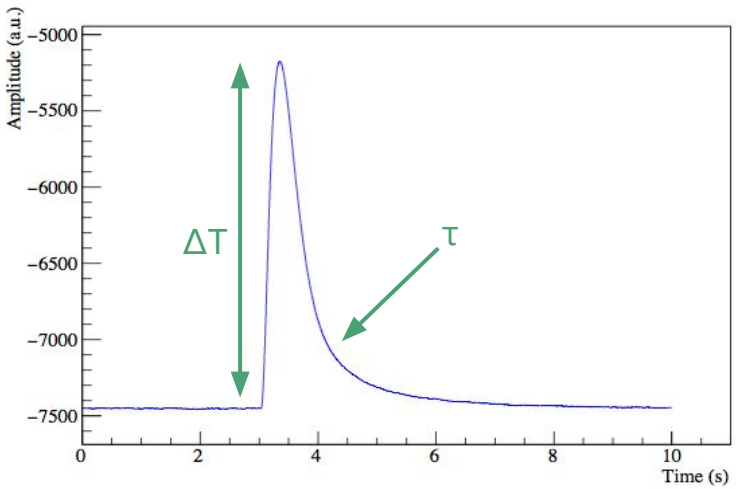
0νββ decay rate

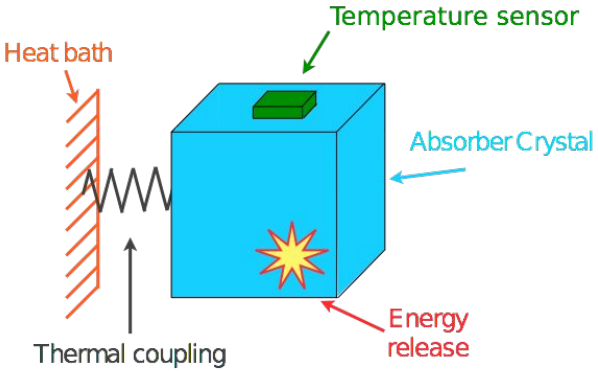
$$(T_{1/2}^{0\nu})^{-1} = G_{0\nu} \cdot |M_{0\nu}|^2 \cdot |f|^2 / m_e^2$$

- $T_{1/2}^{0\nu}$ = 0νββ decay halflife
- $G_{0\nu}$ = phase space (known)
- $M_{0\nu}$ = nuclear matrix element (NME)
- f = new physics term

The bolometric technique

- Low heat capacity @ T ~ 10 mK
- Excellent energy resolution (~0.2% FWHM)
- Detector agnostic to origin of energy deposition
- Detector response of O(1) sec if readout with e.g. Neutron Transmutation Doped (NTD) Ge sensors





Simplified thermal model

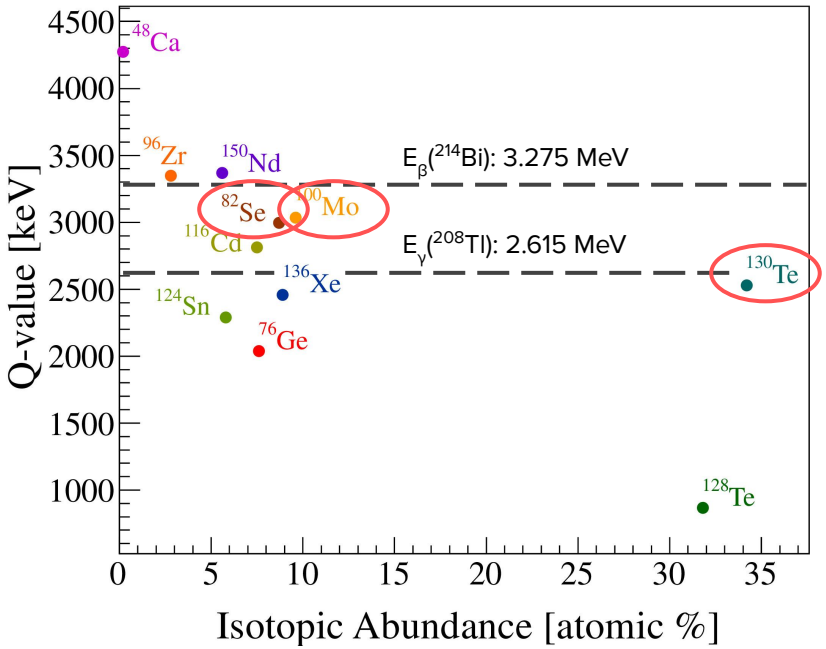
- Crystal heat capacity: C
- Conductivity of coupling to thermal bath: G
- Signal amplitude $\propto \Delta T = E_{dep} / C$
- Decay constant: $\tau = G / C$

Isotope choice for bolometric experiment

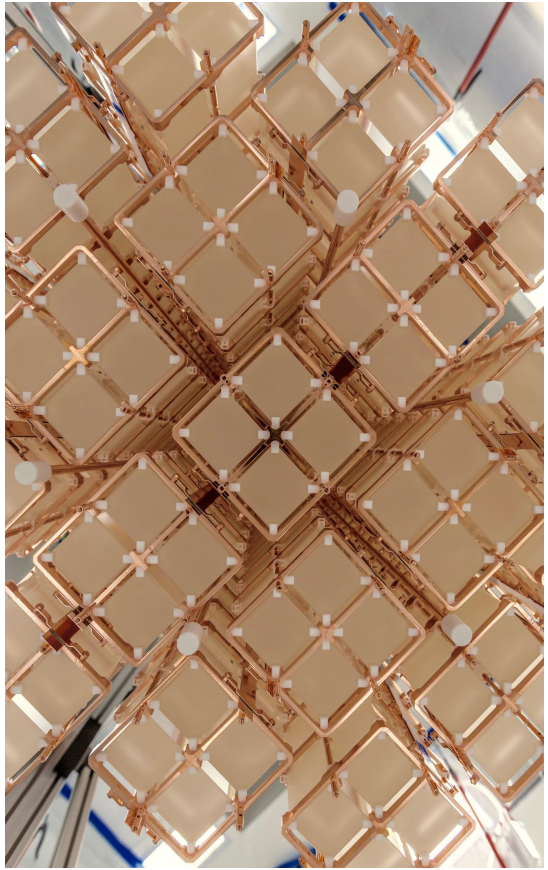
- High isotopic abundance
- Enrichment possible at reasonable cost?
- $Q_{\beta\beta}$ above end point of β or γ radiation?
- Scintillating crystal available?
- Large scale crystal production possible?

Advantages of bolometric approach

- Detectors and infrastructure are decoupled. Same cryogenic infrastructure re-usable with different isotopes and/or crystals
- Perfect for test of discovery or precision measurements



The CUORE experiment



The CUORE experiment

CUORE: the Cryogenic Underground Observatory for Rare Events

- 988 TeO_2 crystals with natural Te composition
  → **742 kg total mass**, 206 kg ^{130}Te mass
- $Q_{\beta\beta}(^{130}Te)$ = 2527.5 keV → Above most natural γ background
- Located in Hall A of the Gran Sasso National Lab
- Background goal: 10^{-2} counts/keV/kg/yr at $Q_{\beta\beta}$
- Sensitivity goal on $T^{0\nu}_{1/2} = 9 \cdot 10^{25}$ yr with 5 yr of live time

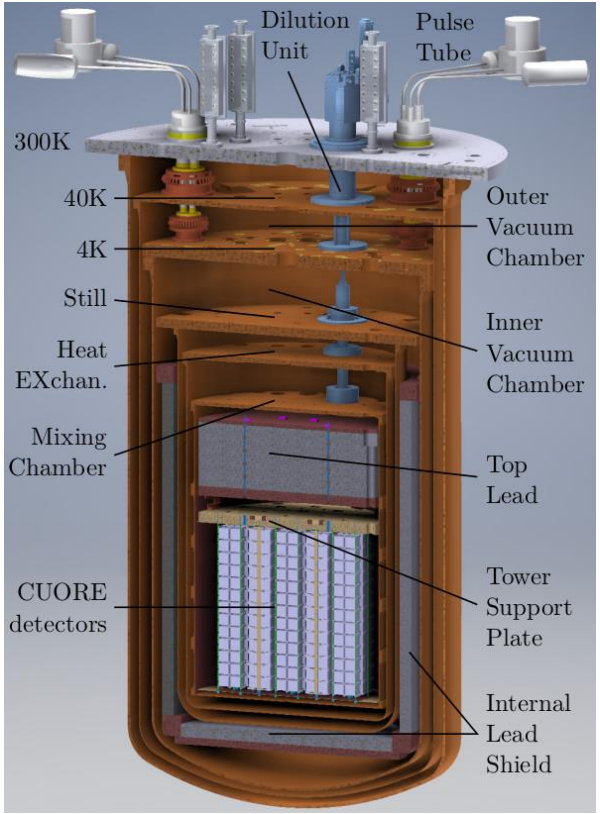
CUORE infrastructure

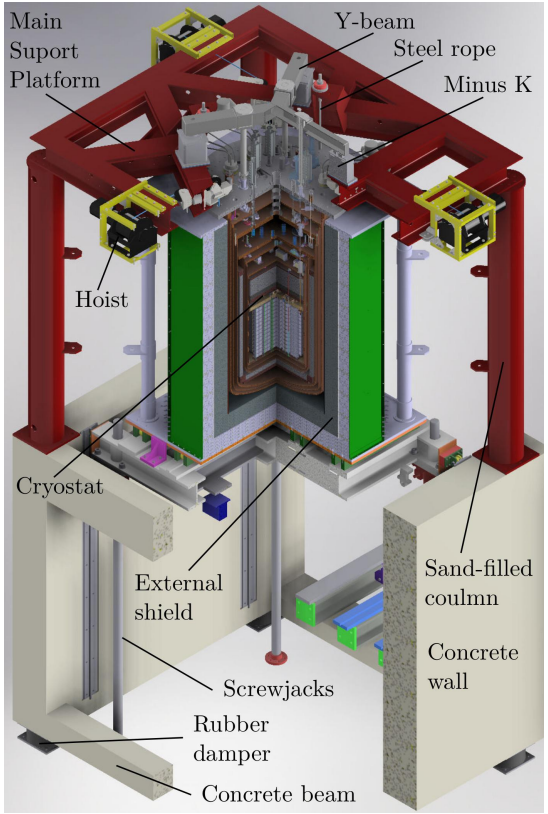
The coldest cubic meter in the known Universe

- Multistage cryogen-free cryostat
- Cooling systems: fast cooling system, Pulse Tubes (PTs), and Dilution Unit (DU)
- ~15 tons @ < 4 K
- ~ 3 tons @ < 50 mK
- Mechanical vibration isolation
- Active noise cancelling

CUORE (passive) shielding

- Roman Pb shielding in cryostat
- External Pb shielding
- H_3BO_3 panels + polyethylene

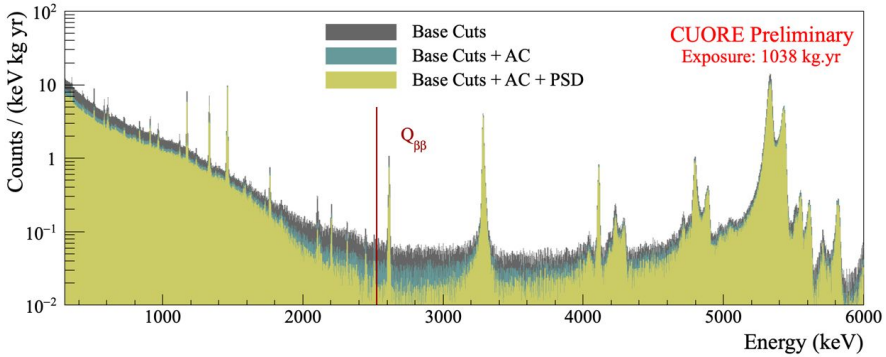




CUORE results

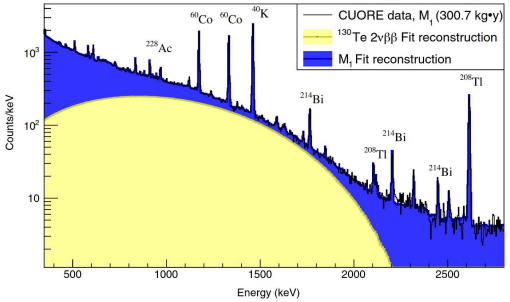
2νββ decay analysis

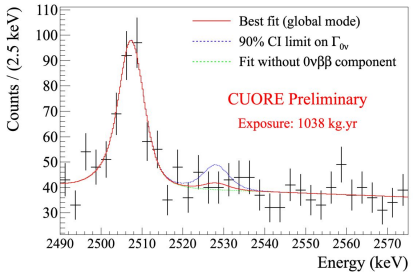
- Exposure: 300.7 kg·yr
- Full background model of γ region
- $T_{1/2}^{2\nu} = 7.71^{+0.08}_{-0.06}(stat)^{+0.12}_{-0.15}(syst) \cdot 10^{20}$ **yr**
  → most precise ^{130}Te half life measurement!
- Refined background model in progress



0νββ decay analysis

- Exposure: **1038.4 kg·yr**
- Fit model: linear bkg + 0νββ + ^{60}Co peak
- Sensitivity: $T_{1/2}^{0\nu} = 2.8 \cdot 10^{25}$ yr
- $T_{1/2}^{0\nu} > 2.2 \cdot 10^{25}$ **yr @ 90% c.i.**
  → $m_{\beta\beta}$ **< 90 - 305 meV** (NME dependent)
- **BI: (1.49±0.04)·10^{-2}** counts/keV/kg/yr

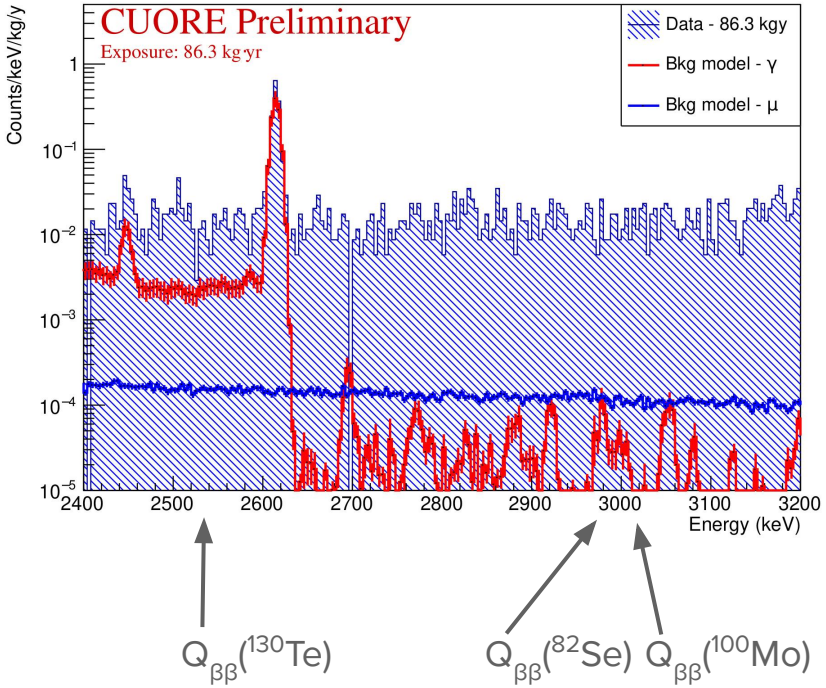




CUORE, PRL 126 (2021) 17, 171801
CUORE, arXiv:2104.06906

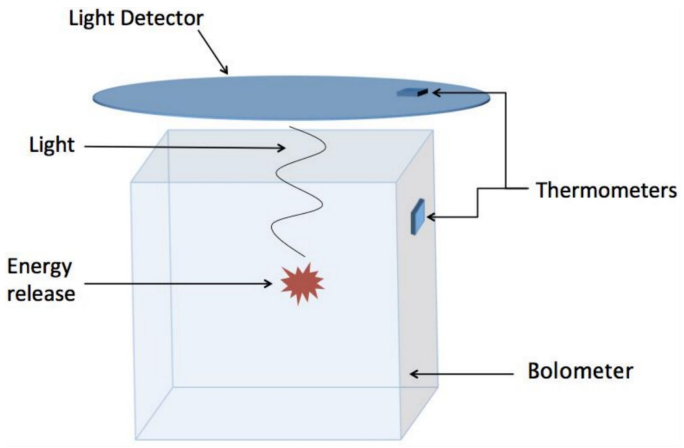
CUORE background: lessons learned for CUPID

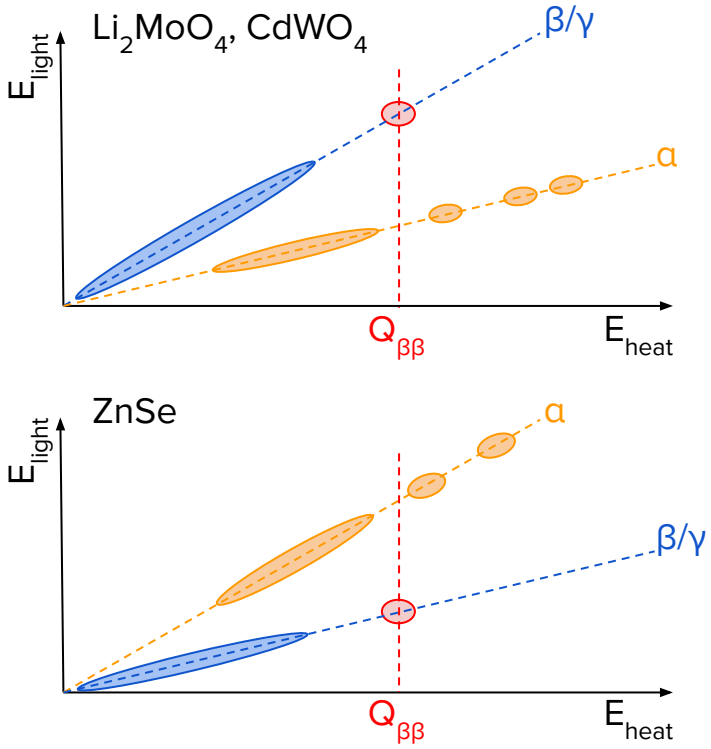
ROI: background model for sources far from detector



- ~90% of measured background is due to α particles (U/Th close to TeO_2 crystals)
  ➔ α/β discrimination would suppress the background by one order of magnitude
- A $Q_{\beta\beta}$ > 2.6 MeV would automatically reduce the remaining non-α background by one order of magnitude
- Muons are the next dominant contribution
  ➔ Implement active muon veto

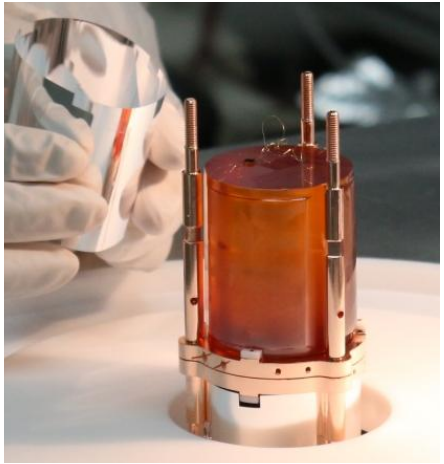
Background suppression via Particle IDentification (PID)

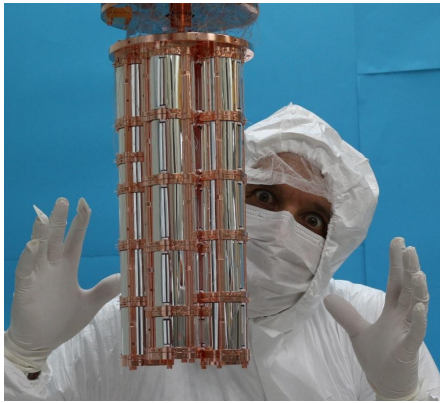




- Couple main crystal with secondary bolometer reading the scintillation light
- Exploit different light yield (LY) of α vs β/γ to actively suppress background
- Typical light detector: thin Ge wafer coupled to thermometer (NTD, TES, KID, MMC)

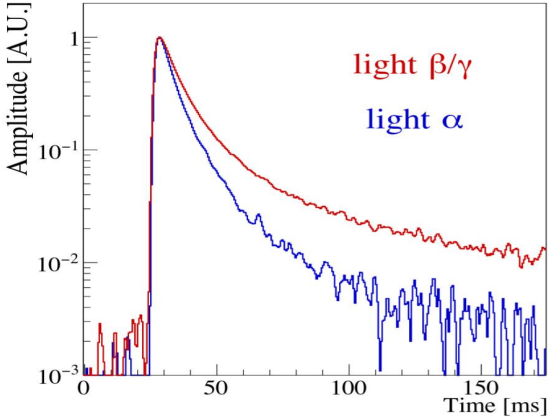
CUPID-0

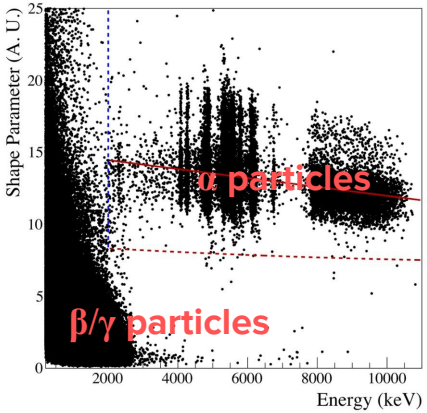




Experiment structure

- 26 **ZnSe** crystals (24 enriched at 95% in ^{82}Se)
- Light detectors: Ge wafer + NTDs
- Crystals + LDs encapsulated in copper + reflector foil
- 5 towers, located in old Cuoricino cryostat at LNGS
- Total Phase-I exposure: **9.95 kg·yr**
- α rejection through pulse shape of light signal





CUPID-0 results

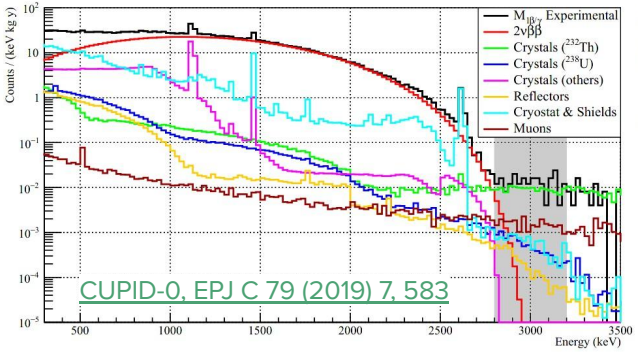
0νββ decay analysis

CUPID-0, PRL 123 (2019) 3, 032501

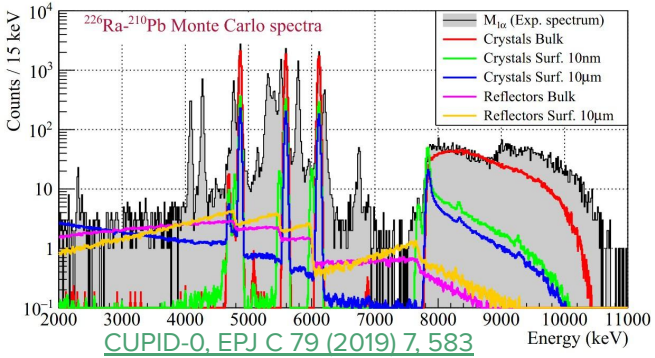
- $T^{0\nu}_{1/2} > 3.5 \cdot 10^{24}$ **yr @ 90% C.I.**
- $m_{\beta\beta} <$ **311-638 meV** (depending on NME)
- Background at $Q_{\beta\beta}$: **$3.5 \cdot 10^{-3}$ counts/keV/kg/yr**
  ➜ Lowest ever in bolometric experiment
- Only ~6% of background from surfaces facing the crystal

2νββ decay and background studies

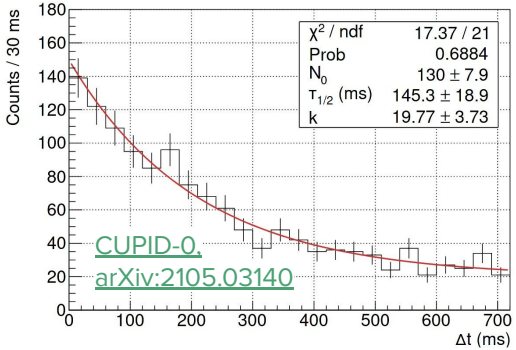
- $T^{2\nu}_{1/2} = [8.6 \pm 0.03(stat)^{+0.17}_{-0.10}(syst)] \cdot 10^{19}$ **yr**
- Tested SSD vs HSD for ^{82}Se ➜ HSD excluded
- Full background model using energy, time and space information
  ➜ Precise understanding of contaminant locations and intensities
  ➜ Novel technique to reconstruct events from the same U/Th decay chain



CUPID-0, EPJ C 79 (2019) 7, 583

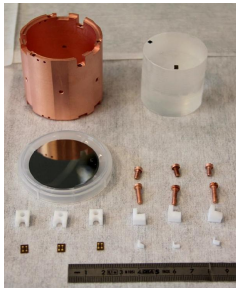


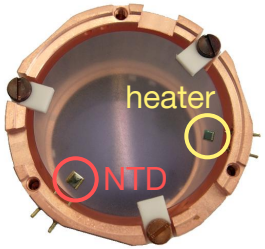
CUPID-0, EPJ C 79 (2019) 7, 583

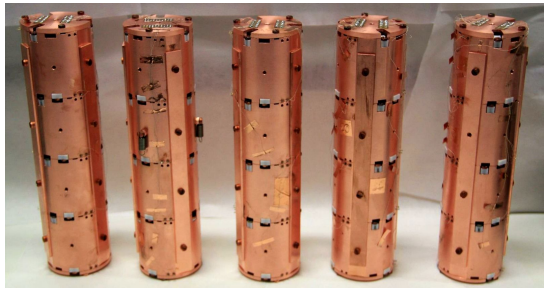


CUPID-0, arXiv:2105.03140

CUPID-Mo





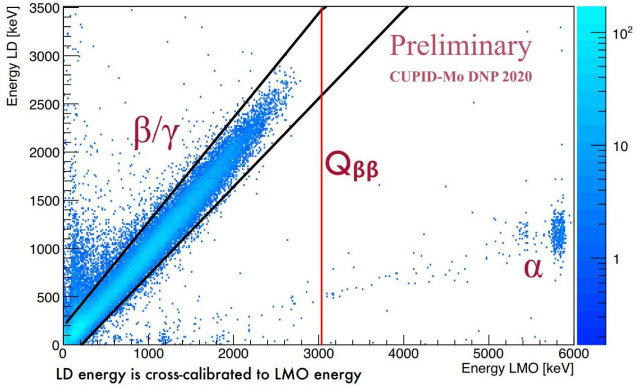


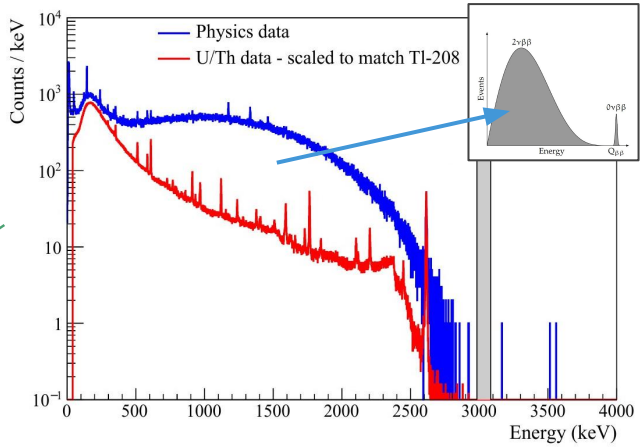
Experiment structure

- Located in Edelweiss cryostat @ Modane
- 20 Li_2MoO_4 crystals of ~210g enriched at 97% in ^{100}Mo
- 20 Ge wafers instrumented as light detectors
- Neutron transmutation doped (NTD) thermistors
- Silicon-based resistors used as heaters for pulser events

Data collection

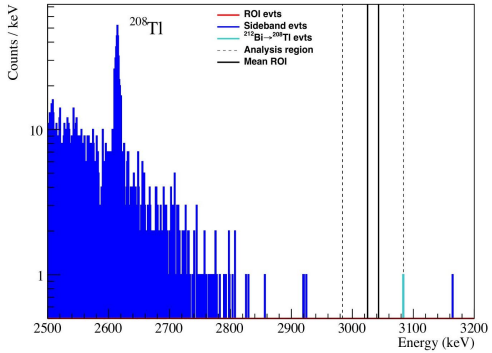
- Physics data: March 2019 - June 2020
- Analysed data: March-2019 - April 2020
  → **Analyzed exposure: 2.16 kg·yr**

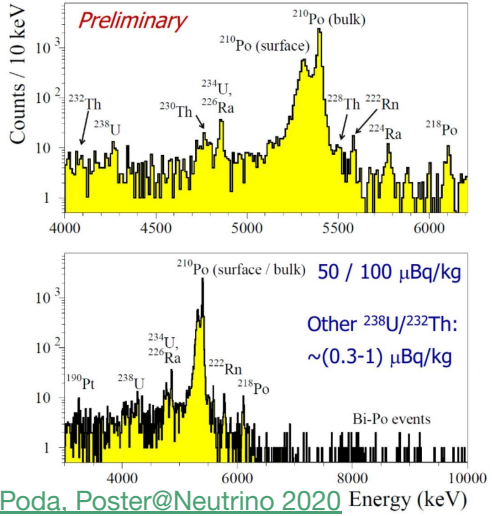




CUPID-Mo, EPJ C80 (2020) 44

CUPID-Mo results





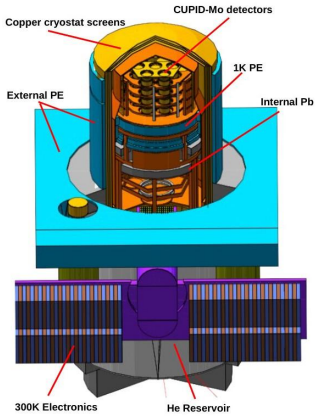
D. Poda, Poster@Neutrino 2020

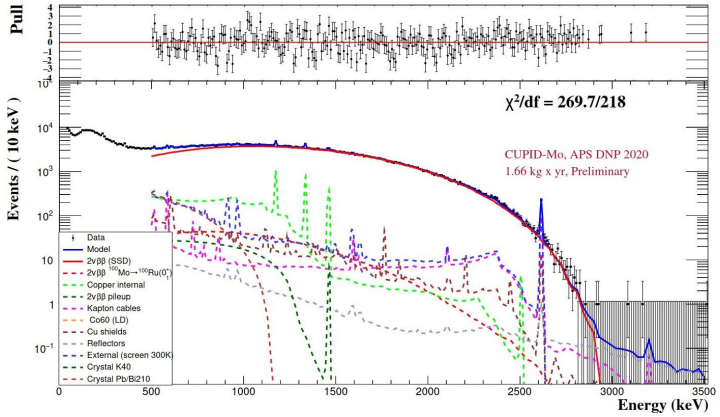
CUPID-Mo, PRL 126 (2021) 18, 181802

0νββ decay analysis

- Bayesian counting analysis in $Q_{\beta\beta}$±50 keV
  $T_{1/2}^{0\nu}$ > 1.5·10^{24} yr @ 90% C.I. ➜ Best result so far in ^{100}Mo!
- **$m_{\beta\beta}$ < 0.3-0.5 eV** (depending on NME)
- BI O(10^{-3}) counts/keV/kg/yr
  ➜ Precise evaluation with background model ongoing

CUPID-Mo is a real experiment, not just a demonstrator!

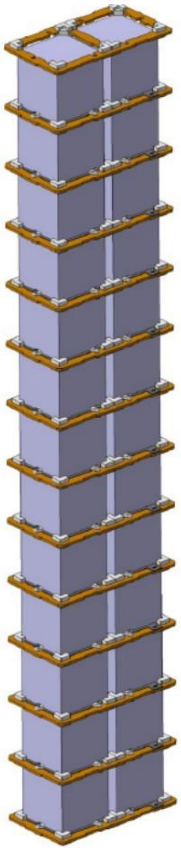


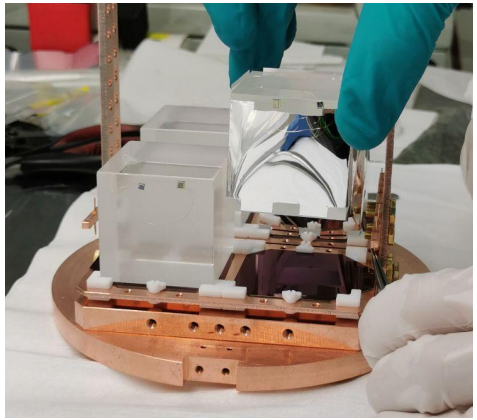


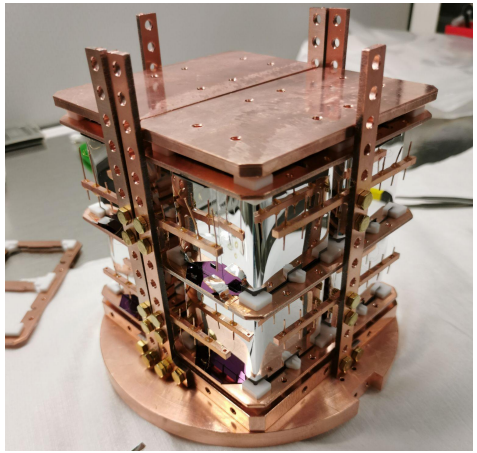
CUPID: CUORE Upgrade with Particle IDentification

- Profits of vast experience from predecessor experiments:
  - ➔ isotope choice
  - ➔ background suppression and active rejection
  - ➔ cryogenic techniques
- Same cryogenic infrastructure of CUORE
- **Li_2MoO_4** scintillating crystals
- ^{100}Mo enrichment > 95%
- 45×45×45 mm^3 crystals
- New, simpler tower structure (under advanced testing)
- ~1500 crystals ➔ **~250 kg of ^{100}Mo**
- Goal FWHM: 5 keV at $Q_{\beta\beta}$
- α rejection via particle identification on light detector
- Goal background: **10^{-4} counts/keV/kg/yr**

CUPID, arXiv:1907.09376
CUPID, EPJ C 81 (2021) 2, 104
CUPID, arXiv:2011.11726
CUPID, JINST 16 (2021) 02, P02037

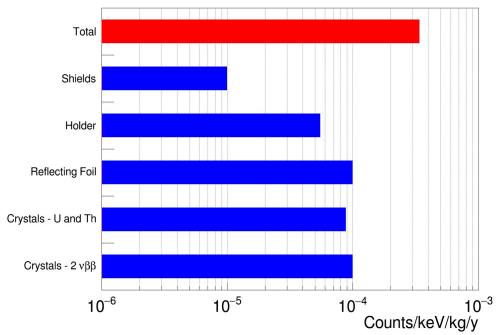


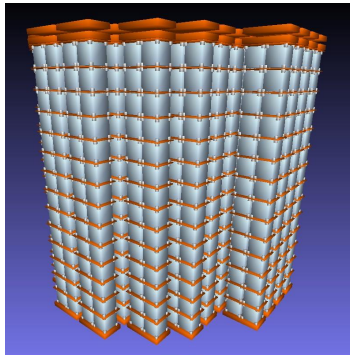




CUPID background projection and sensitivity

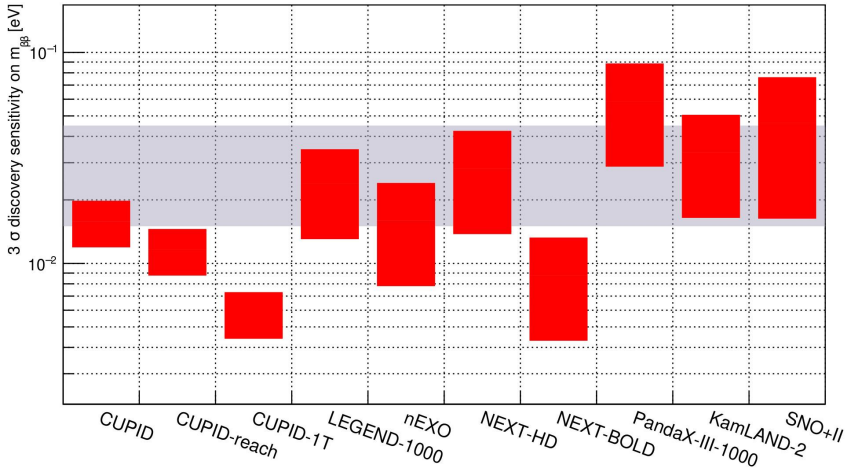
- Crystals
  - U/Th bulk → from CUPID-Mo
  - U/Th surface → from CUORE bkg-model
  - 2νββ pile-up ($T_{1/2}^{2\nu} = 7.1 \times 10^{18}$ yr)
- Crystal holders
  - U/Th surface → CUORE-0 bkg-model
- Reflector foil:
  - U/Th → CUPID-0 bkg-model + BiPo3
- Cryogenic infrastructure and shielding
  - U/Th bulk → CUORE bkg-model
- Muons → Cut by muon veto





Discovery sensitivity

- $T^{0\nu}_{1/2} = 10^{27}$ y
- $m_{\beta\beta} = 12\text{-}20$ meV
  → **Fully cover the inverted ordering region**



THANK YOU!