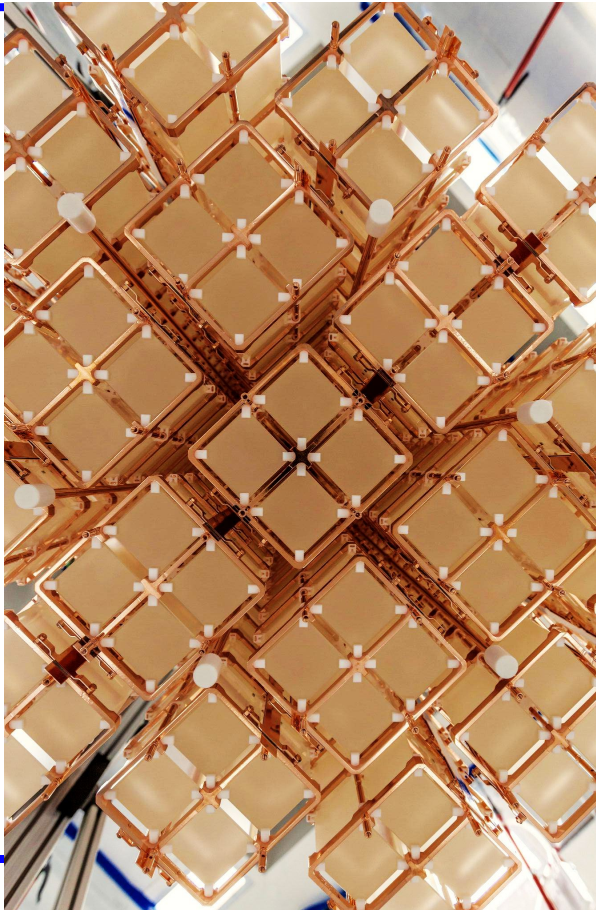
Latest Results from the CUORE Experiment



Simone Quitadamo

on behalf of the CUORE collaboration

NOW 2024 - Neutrino Oscillation Workshop

September 2nd - 8th 2024

Otranto, Italy

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

- 2^{nd} order weak process, **beyond Standard Model**:

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

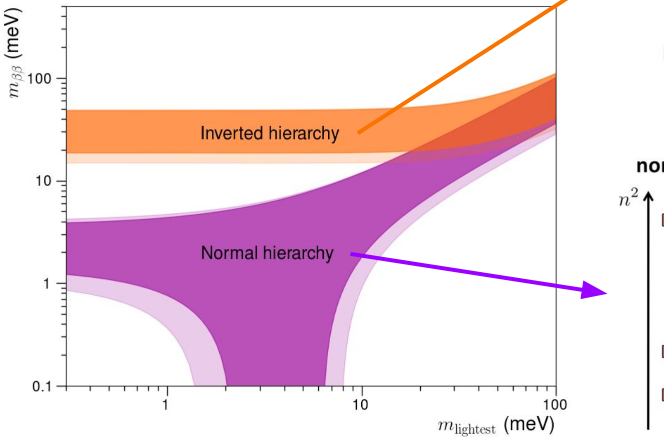
- Broad experimental program to search for $0\nu\beta\beta$ decay with various isotopes with energetically forbidden β decay (^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd).

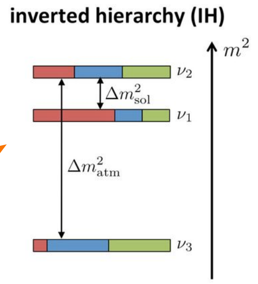
- Not yet observed → Half-lives: $T_{1/2}^{0\nu} > 10^{22}$ - 10^{26} yr.

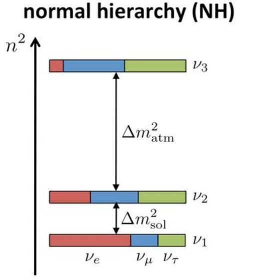
- $0\nu\beta\beta$ decay observation would establish:
  - ➢ violation of the lepton number ($\Delta L = 2$);
  - ➢ neutrinos as Majorana particles ($\nu \equiv \bar{\nu}$);
  - ➢ constraints on neutrinos mass scale and hierarchy:

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

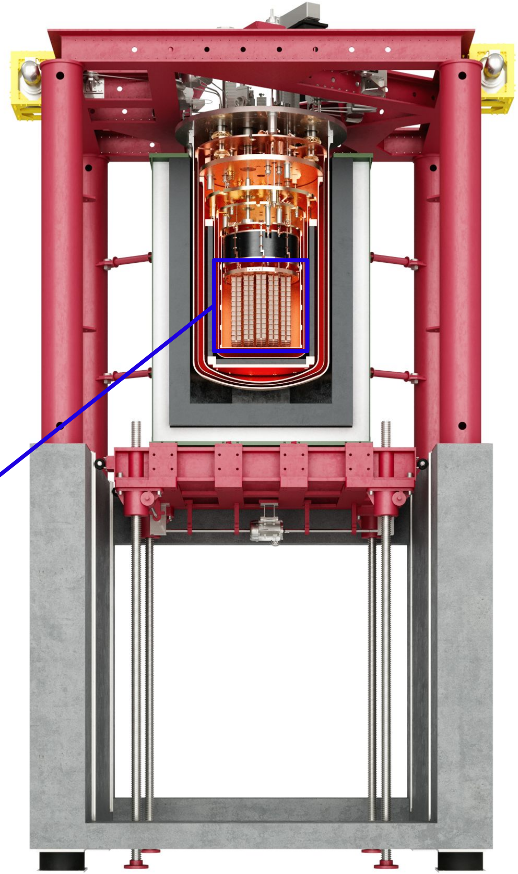
Experimental observable | Phase space factor | Nuclear physics | Effective Majorana mass: $m_{\beta\beta} = \left| \sum_{k=1}^{3} U_{ek}^2 m_k \right|$



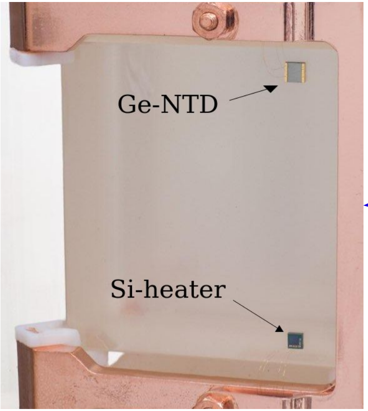


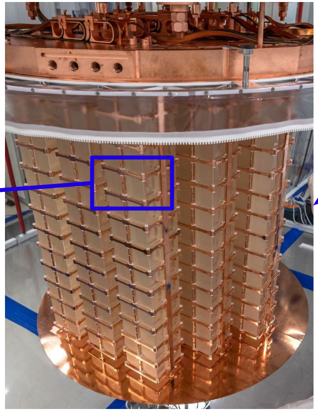


CUORE experiment



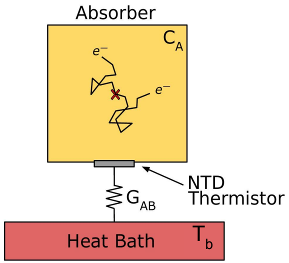
- **CUORE** (**C**ryogenic **U**nderground **O**bservatory for **R**are **E**vents):
  - ➢ search for $0\nu\beta\beta$ decay of ^{130}Te;
  - ➢ 988 TeO_2 crystals (5x5x5 cm^3) with natural ^{130}Te isotopic abundance (34%);
  - ➢ total active mass: 742 kg of TeO_2 → **206 kg of ^{130}Te**;
  - ➢ crystals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

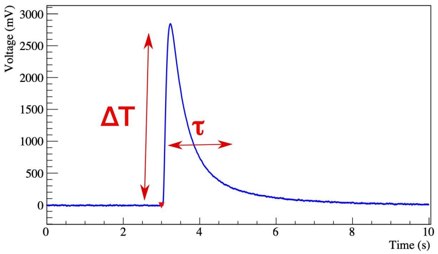




Low-temperature calorimeters for $0\nu\beta\beta$ decay

- Working principle of low-temperature calorimeters:
  - ➢ the energy E released in the crystal induces a temperature variation: $\Delta T \propto E/C_A(T)$ ~ 0.1 mK/MeV
  - ➢ the temperature variation is converted into an electric signal by the thermal sensor.





- $\beta\beta$-decaying isotope is embedded in the crystals

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  high containment efficiency of both electrons within a single crystal

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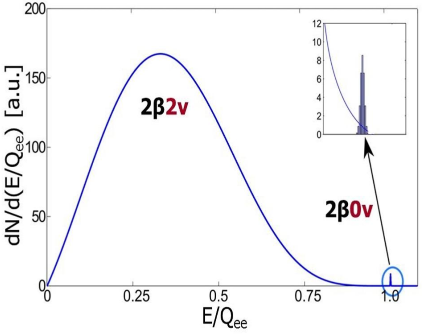
  experimental signature of $0\nu\beta\beta$ decay: peak in the energy spectrum at $\beta\beta$ decay Q-value.



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

- Experimental sensitivity $S^{0\nu}$ to $0\nu\beta\beta$ decay for a background-limited experiment:

experimental efficiency

$$S^{0\nu} \propto \varepsilon\, \eta \sqrt{\frac{M\,T}{B\,\Delta E}}$$

isotopic abundance

Exposure = active mass · measure time

CUORE achievements:

- ➢ ton-scale mk-scale experiment;
- ➢ stable data taking since April 2019;
- ➢ Analyzed exposure:
  2039 kg · yr TeO_2 (567.0 kg · yr ^{130}Te) (arxiv:2404.04453);
- ➢ Raw accumulated exposure: > 2.5 t · yr TeO_2.

Background index in the ROI

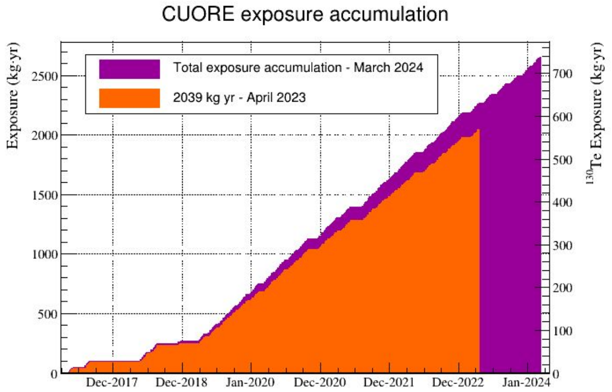
In CUORE:

- ➢ strict radiopurity selection of crystals and passive materials;
- ➢ shields and analysis cuts against radioactive contamination;
- ➢ ***B* = 1.42(2)·10^{-2} counts/(keV · kg · yr)**

Energy resolution in the ROI

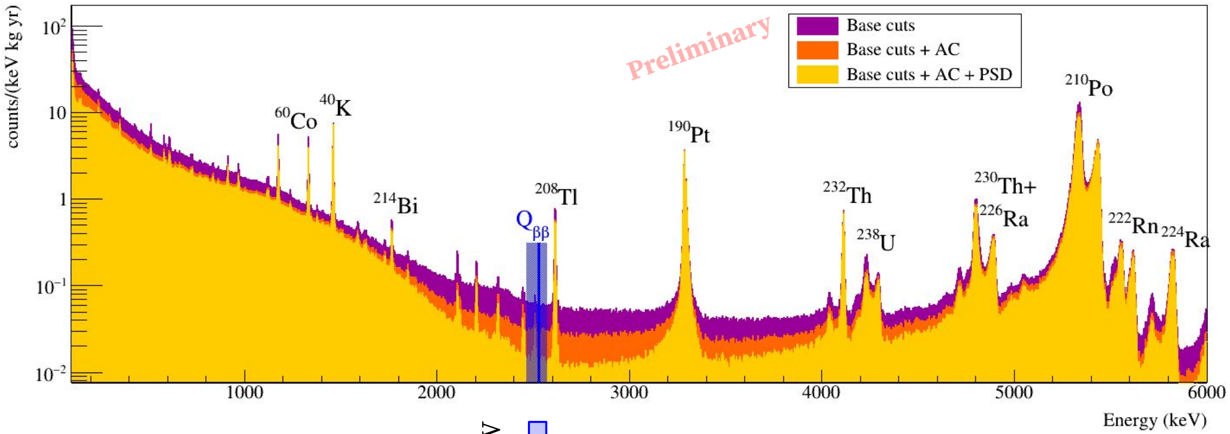
In CUORE:

- ➢ monitor detectors stability;
- ➢ noise reduction techniques;
- ➢ $Q_{\beta\beta}(^{130}Te)$ = 2527.5 keV
  FWHM($Q_{\beta\beta}$) = (7.320 ± 0.024) keV
  FWHM($Q_{\beta\beta}$)/$Q_{\beta\beta}$ ≃ 0.3%

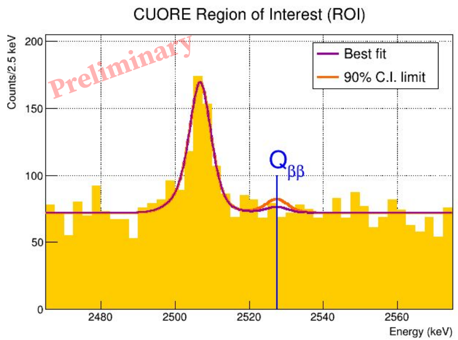


CUORE energy spectrum

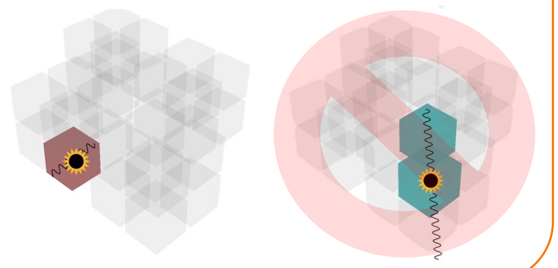
- CUORE energy spectrum at 2039 kg·yr TeO_2 analyzed exposure (arxiv:2404.04453):



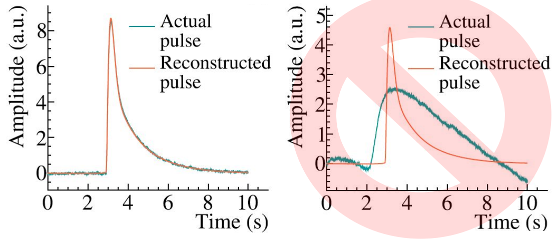
ROI = (2465, 2575) keV



Anti-Coincidence (AC) cut:



Pulse Shape Discrimination (PSD):



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

- Model of the ROI = (2465, 2575) keV:
  - ➢ flat background (≃90% due to degraded-α particles);
  - ➢ ^{60}Co γ-peak @ 2505.7 keV;
  - ➢ $0\nu\beta\beta$ decay peak @ $Q_{\beta\beta}(^{130}Te)$ = 2527.5 keV.

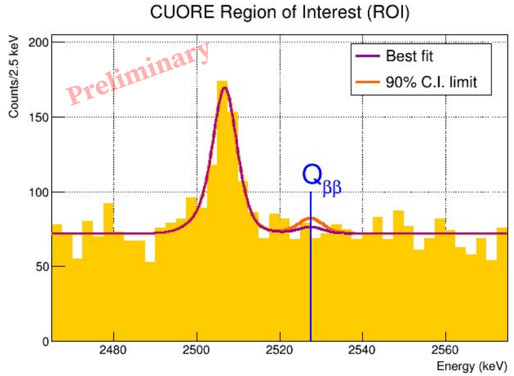
- No evidence of $0\nu\beta\beta$ decay of ^{130}Te at 2039 kg · yr TeO_2 (567.0 kg · yr ^{130}Te) exposure;

$T_{1/2}^{0\nu}$ (^{130}Te) > $3.8 \cdot 10^{25}$ yr (90% C.I.)

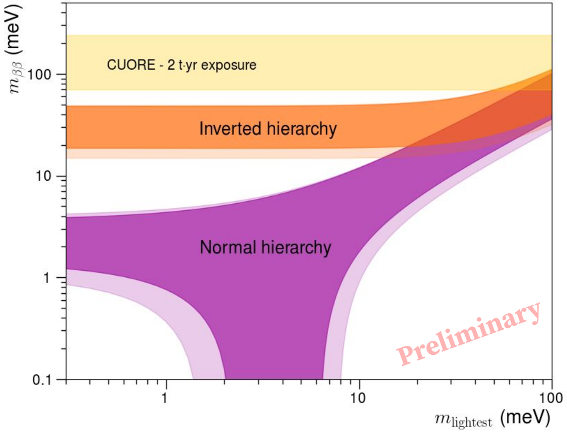
- Upper limit on effective Majorana mass, assuming $0\nu\beta\beta$ decay mediated by light neutrino exchange:

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

$m_{\beta\beta}$ < 70 - 240 meV

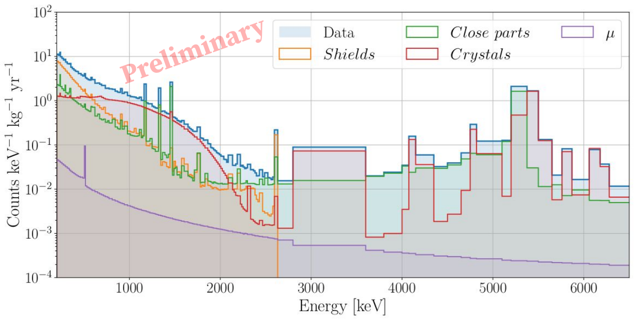


arxiv:2404.04453

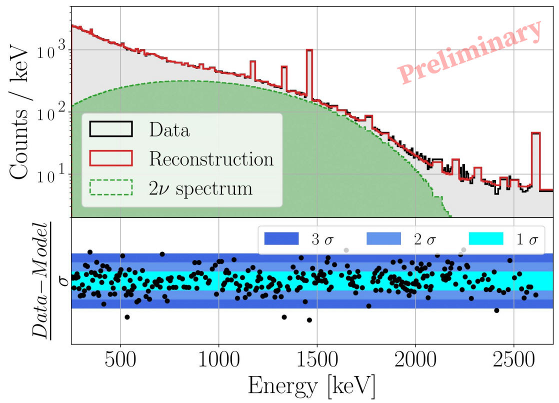


Background model & $2\nu\beta\beta$ decay of ^{130}Te

- CUORE background model (arxiv:2405.17937):
  - ➢ improved exploiting 1038.4 kg·yr TeO_2 exposure;
  - ➢ accounts for:
    - $2\nu\beta\beta$ decay of ^{130}Te;
    - ≃80 background sources;
    - detector geometry and granularity.



- Accurate background model allows for precise measurement of ^{130}Te $2\nu\beta\beta$ decay:
  - ➢ exploiting 1038.4 kg·yr TeO_2 exposure;
  - ➢ analysis under finalisation;
  - ➢ foreseen uncertainties within ~1%.

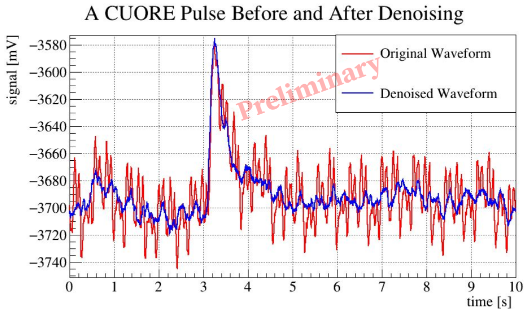


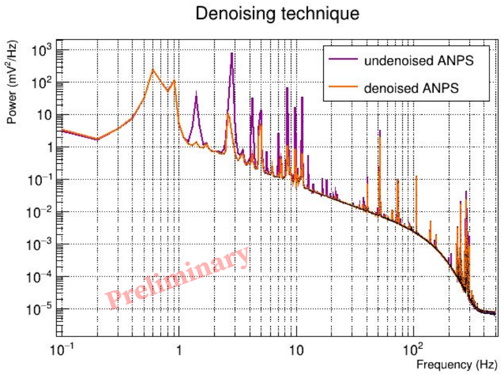
Denoising technique

- Vibrational noise must be suppressed to enhance the detectors energy resolution.

- Vibrations mitigation through:
  - ➢ suspension and insulation systems;
  - ➢ active noise cancellation technique for vibrations from the cryogenic system;
  - ➢ denoising technique.

- Denoising technique (EPJC:10.1140/s10052-024-12595-y , arxiv:2404.04453):
  - ➢ algorithm for noise decorrelation between CUORE and auxiliary devices (microphones, accelerometers, seismometers, antennas);
  - ➢ ≃40% reduction of total RMS_{noise} of CUORE;
  - ➢ implemented in the $0\nu\beta\beta$ decay analysis at 2 t·yr TeO_2 exposure.





Detection of marine activity with low-T calorimeters

- Multiple noise reduction techniques make CUORE sensitive to otherwise subdominant sources of noise

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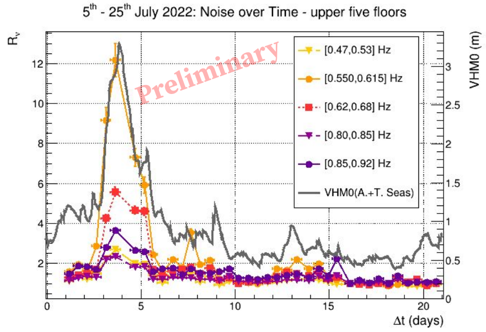
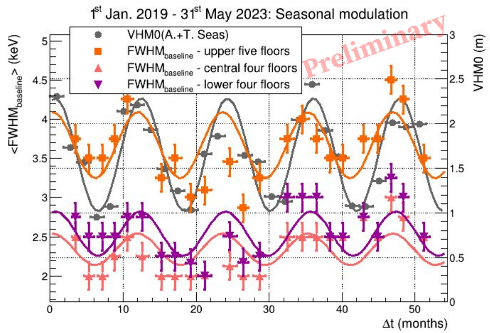
  first ever detection of marine microseismic activity with low-temperature calorimeters (EPJC:10.1140/s10052-024-13065-1).

- Marine microseisms: faint seisms caused by the motion of sea swells.

- Strong correlations between:
  - ➢ Mediterranean Sea waves amplitude (VHM0),
    from Copernicus (E.U. Earth Observation space programme);
  - ➢ seismic activity at LNGS, from seismometers;
  - ➢ CUORE sub-Hz noise.



- Seasonal modulation of sea activity → seasonal modulation of CUORE energy resolution:
  - ➢ ≃1 yr modulation period;
  - ➢ summer: minimum sea activity → better energy resolution;
  - ➢ winter: maximum sea activity → worse energy resolution.



Summary & future plans

- CUORE demonstrated the feasibility of a ton-scale experiment based on low-temperature calorimeters at mK-scale.

- Steady data acquisition:
  - ➢ 2 t · yr of TeO_2 exposure analized → no evidence of $0\nu\beta\beta$ decay of ^{130}Te;
  - ➢ > 2.5 t · yr TeO_2 exposure accumulated;
  - ➢ plan to accumulate 3 t · yr of TeO_2 exposure (around end of 2025);
  - ➢ many analysis ongoing.

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- CUORE phase II:
  - ➢ upgrade of the cryogenic system to decrease the vibrational noise;
  - ➢ data acquisition with lower energy threshold to search for low-energy signatures (axion, WIMP, ...).

⇩

- CUPID.

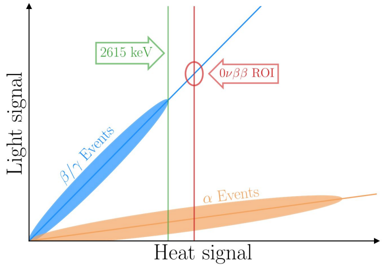
Next-generation: CUPID

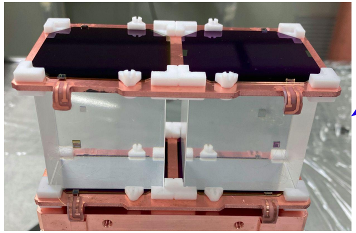
- **CUPID** (**C**UORE **U**pgrade with **P**article **ID**entification):
  - ➢ next-gen. experiment to overcome CUORE limitations;
  - ➢ search for $0\nu\beta\beta$ decay of ^{100}Mo:
    - ■ $Q_{\beta\beta}(^{100}\text{Mo}) = 3034$ keV → reduced γ background w.r.t. CUORE;
  - ➢ $Li_2{}^{100}MoO_4$ scintillating crystals for heat-light double read-out:
    - ■ α vs β/γ discrimination → α rejection (main bkg. in CUORE ROI).

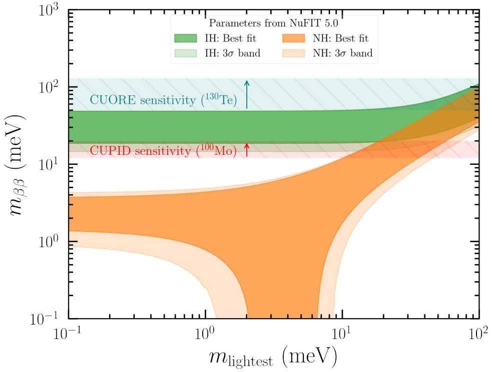
- Baseline design:
  - ➢ 1596 $Li_2{}^{100}MoO_4$ crystals enriched in ^{100}Mo (≃95%);
  - ➢ total active mass: 450 kg of $Li_2{}^{100}MoO_4$ → **240 kg of ^{100}Mo;**
  - ➢ crystals equipped with Ge-NTDs thermal sensors;
  - ➢ 1710 Ge light detectors with Neganov-Trofimov-Luke amplification;

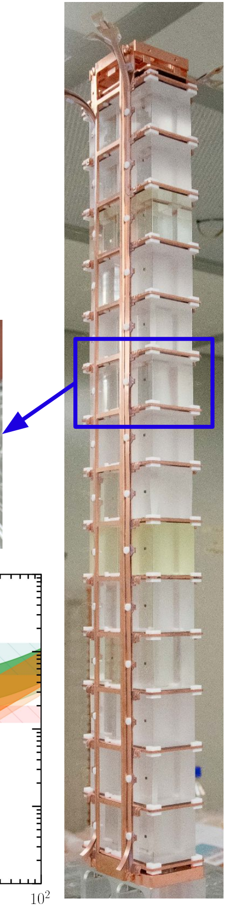
↓

  - ➢ background index at ROI: $\boldsymbol{B \lesssim 10^{-4}}$ **counts/(keV · kg · yr)**;
  - ➢ $0\nu\beta\beta$ decay sensitivity:
    - ■ $T_{1/2}^{0\nu}(^{100}\text{Mo}) > 1.0 \cdot 10^{27}$ yr (10 yr)
    - ■ effective Majorana mass: $m_{\beta\beta} \sim 12 - 20$ meV;
    - ■ **explore the entire inverted hierarchy region of neutrino masses.**







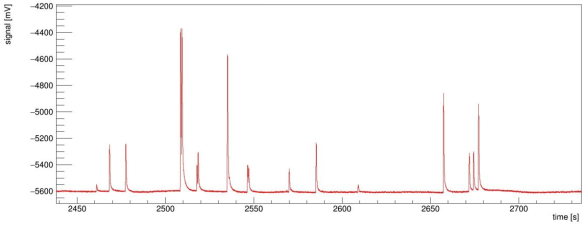


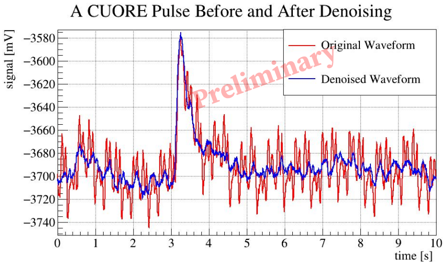
Thanks for the attention!

Backup slides

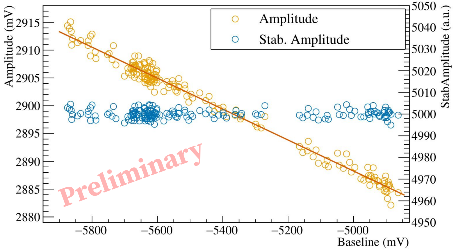
$0\nu\beta\beta$ decay data analysis

Continuous data stream → Denoising → Optimum trigger of thermal pulses →



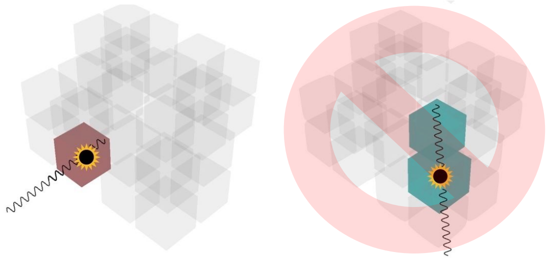


→ Average pulse, avg. noise power spectrum, optimum filter → Thermal gain stabilization → Energy calibration with external ^{232}Th-^{60}Co sources →

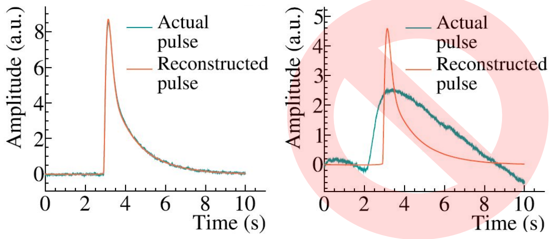


$0\nu\beta\beta$ decay data analysis

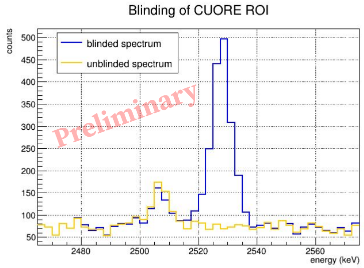
Anti-coincidence (AC) cut



Pulse shape discrimination (PSD)



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

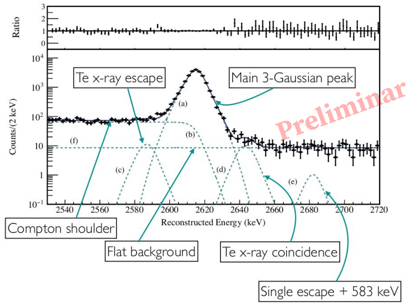


Evaluate efficiency of analysis cuts

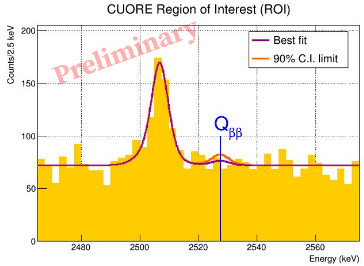
Total analysis efficiency (data)	93.4(18)%
Reconstruction efficiency	95.624(16)%
Anti-coincidence efficiency	99.80(5)%
PSD efficiency	97.9(18)%
Containment efficiency (MC)	88.35(9)%

arxiv:2404.04453

Model the detector response at ^{208}Tl peak.

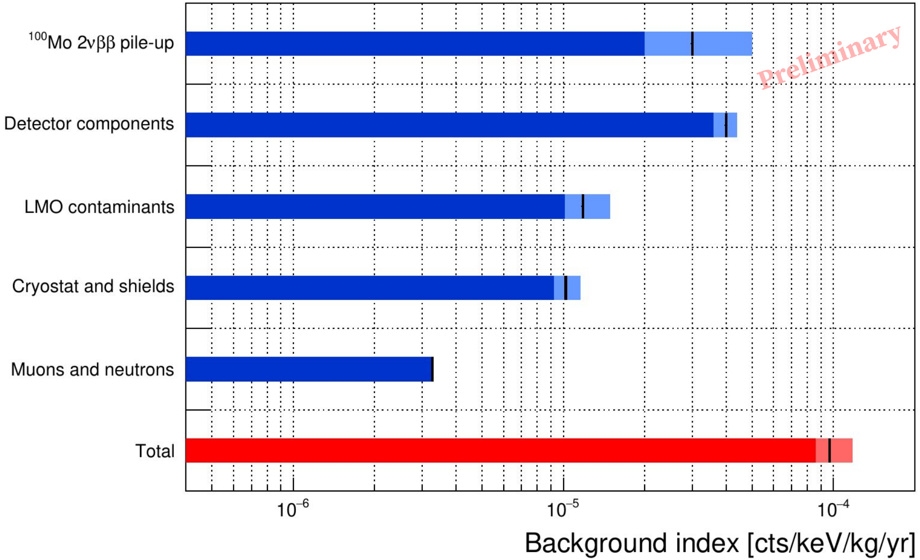


Blinded fit of ROI, unblinding, unblinded fit of ROI



CUPID background budget

- CUPID background budget:



From CUORE-0 & CUORE

From CUPID-Mo

From CUORE

- Major background contribution from random pile-up of $2\nu\beta\beta$ decay of ^{100}Mo
  ↓
  exploit the scintillation light channel to resolve pile-up in the heat channel
  ↓
  Ge light detectors with Neganov-Trofimov-Luke amplification for enhanced signal-to-noise ratio.