Towards a next-generation 0νββ search in ^{100}Mo with CUPID

Sonja Schneidewind on behalf of the CUPID collaboration

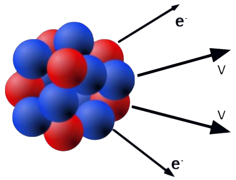
La Thuile 2026 - Les Rencontres de Physique de la Vallée d'Aoste

CUPID

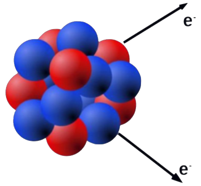
INFN
MILANO BICOCCA

Double-β decay

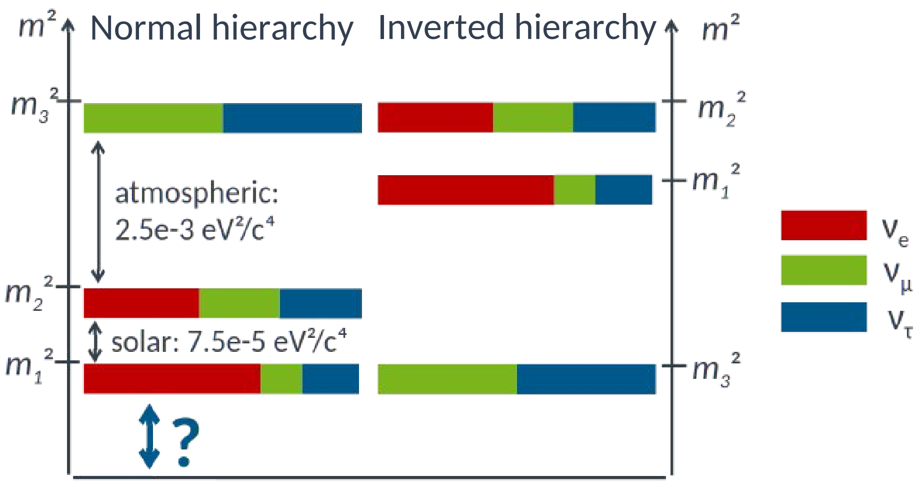
- $2\nu\beta\beta$: (A, Z) → (A, Z+2) + $2e^-$ + $2\bar{\nu}$ $T_{1/2} > 10^{18}$ y
  $0\nu\beta\beta$: (A, Z) → (A, Z+2) + $2e^-$ $T_{1/2} > 10^{25}$ y
- Key tool to study neutrinos:
  - Majorana or Dirac particles?
    $(\nu = \bar{\nu}?)$
  - Mass scale and mass ordering?
    (inverted vs. normal hierarchy)
  - CP violation in the lepton sector?



ΔL = 0



ΔL = 2



Particle Data Group, Phys. Rev. D 110 (2024) 030001

Double-β decay

Detection: Energy of 2 emitted electrons

- Monochromatic peak at Q-value of $Q_{\beta\beta}$ of the decay
- Smearing due to finite energy resolution

Observable: decay half-life $T_{1/2}$ of the isotope

Sensitivity:

$$S_{1/2} \propto \begin{cases} aM\varepsilon t & \text{, background-free} \\ a\varepsilon \sqrt{Mt/b\Delta E} & \text{, with background } b \end{cases}$$

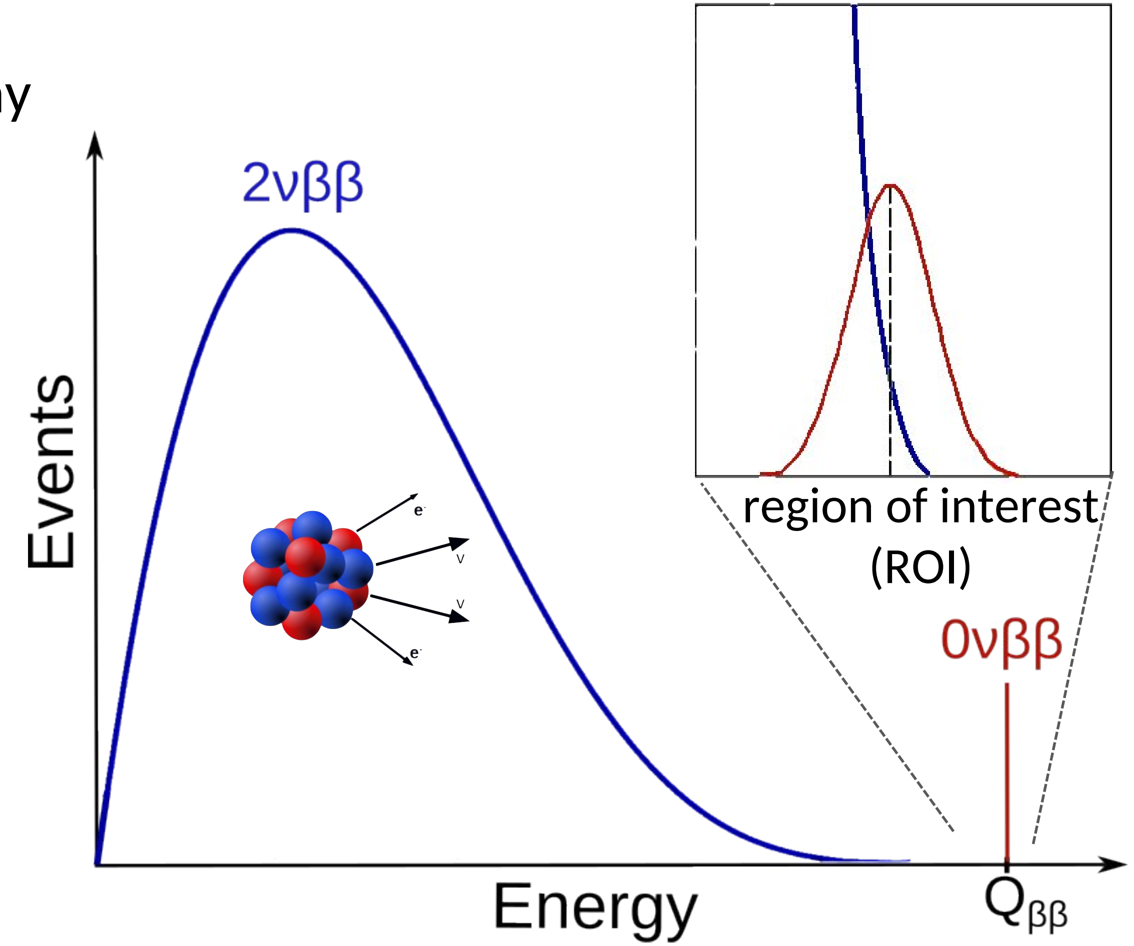
with

a: isotopic abundance of parent isotope

ε: signal-detection efficiency in ROI

M: detector mass

ΔE: energy resolution



Double-β decay

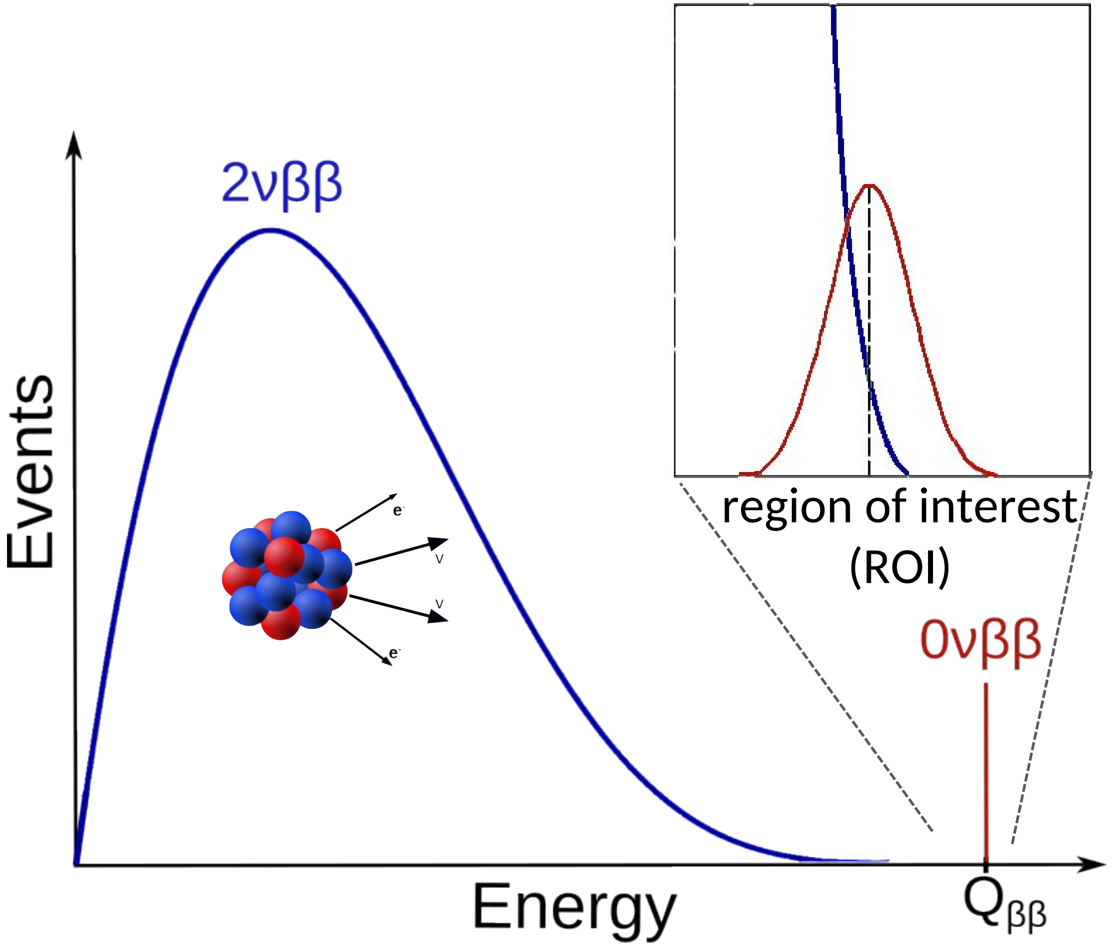
Sensitivity:

$$T_{1/2} \propto \begin{cases} aM\varepsilon t & \text{, background-free} \\ a\varepsilon\sqrt{Mt/b\Delta E} & \text{, with background } b \end{cases}$$

$$T_{1/2}^{0\beta} = \left(G|\mathcal{M}|^2\langle m_{\beta\beta}\rangle^2\right)^{-1}$$

with $\langle m_{\beta\beta}\rangle = \sum_i |U_{ei}^2 m_i|$ ← neutrino-mass eigenstate

and phase-space factor $G \propto Q_{\beta\beta}^5$ ← Q value



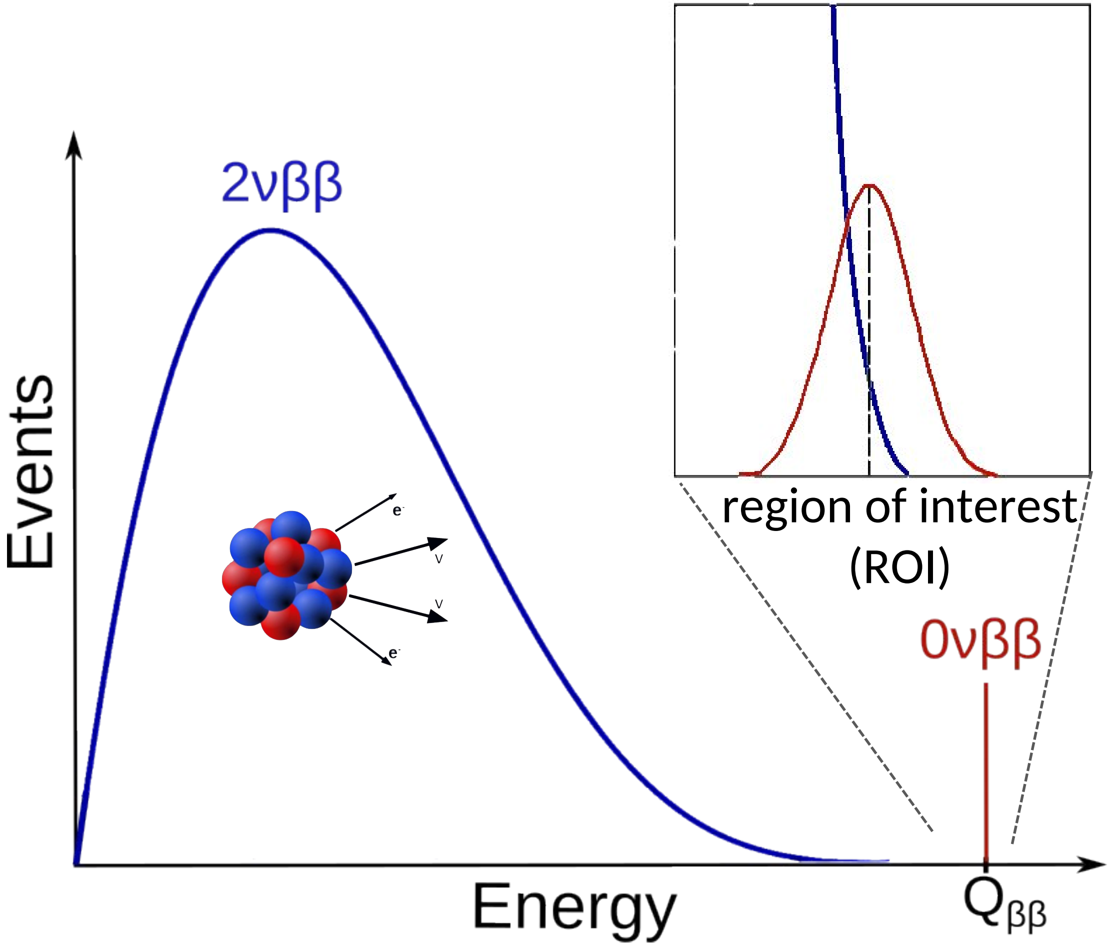
Double-β decay

Sensitivity:

$$T_{1/2} \propto \begin{cases} a M \varepsilon t & \text{, background-free} \\ a\varepsilon \sqrt{\frac{Mt}{b \Delta E}} & \text{, with background } b \end{cases}$$

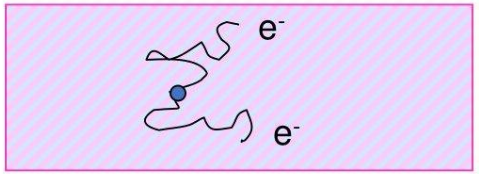
Requirements for highly sensitive measurement:

- Good energy resolution ΔE
  - ➞protection from 2νββ background!
- Very low background level b
  - ➞ underground location and shielding
  - ➞ radiopure materials
  - ➞ analysis-rejection techniques
- Large detector mass M & isotope abundance a



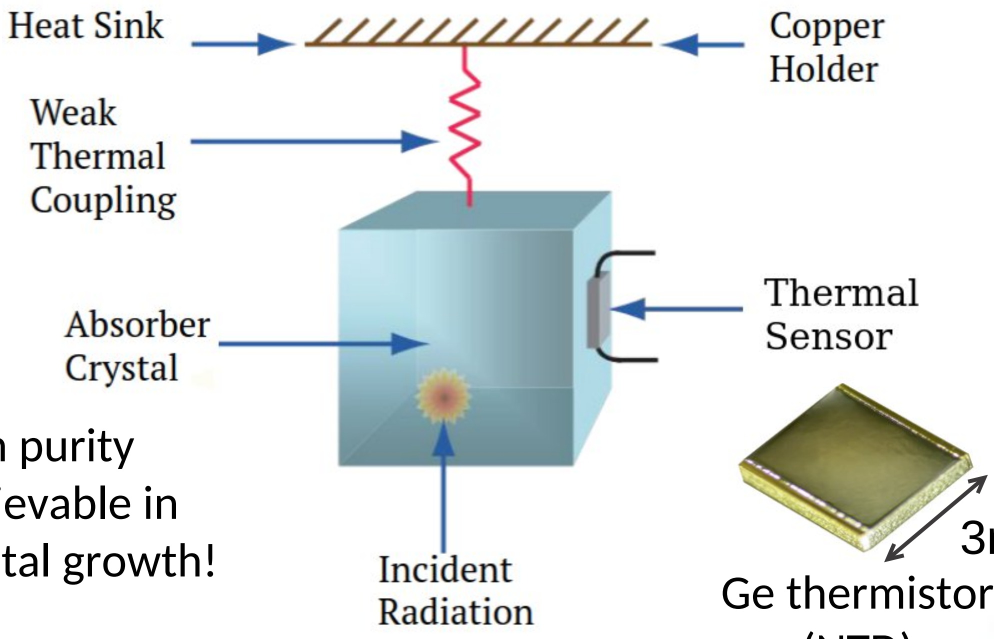
Double-β decay detection with cryogenic bolometers

- Measurement of temperature change $\Delta T = \Delta E/C$ induced by energy deposit ΔE in detector with heat capacity C
- Since $C\downarrow \rightarrow \Delta T\uparrow$ and $C \propto T^3$: low temperature needed! Typical: T~10mK



Source ≡ Detector

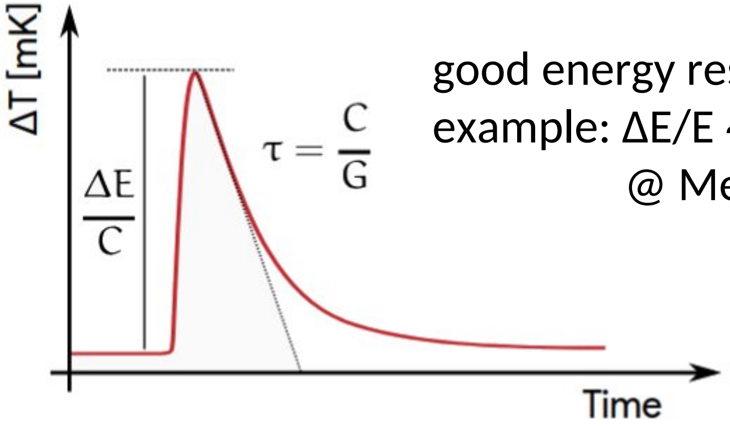
good efficiency!



high purity achievable in crystal growth!

3mm

Ge thermistor (NTD)

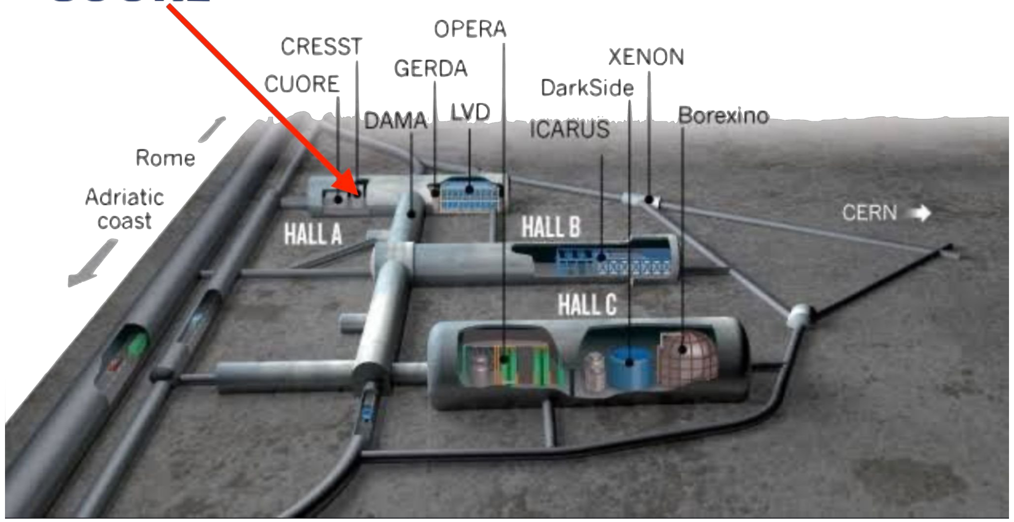


good energy resolution!
example: $\Delta E/E \sim 0.1\%$ @ MeV energies

CUORE Experiment

- CUORE (Cryogenic Underground Observatory for Rare Events): experiment at Gran Sasso National Laboraties (LNGS) Abruzzo, Italy, 1.4 km underground
- $0\nu\beta\beta$ search in ^{130}Te with 988 TeO_2 crystals used as cryogenic calorimeters (with ~206 kg ^{130}Te)
- Successfully running since 2017, 2 tonne · years exposure so far

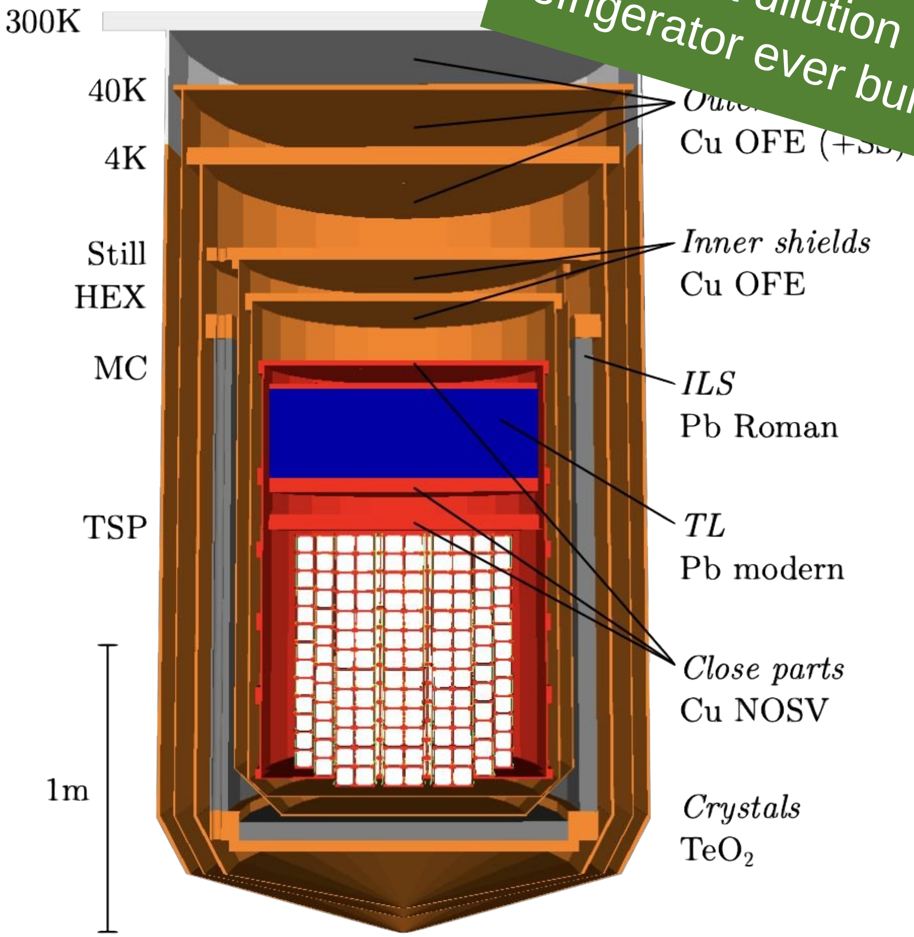
  CUORE Coll., Science **390** 1029-1032 (2025)



CUORE Infrastructure

- Custom-made dry dilution cryostat with $1 m^3$ experimental volume & T ~ 10 mK
- External shielding: room-temperature lead shield + neutron shield
- Internal shielding: Modern + ancient Roman lead on top, sides and bottom

Largest dilution refrigerator ever built



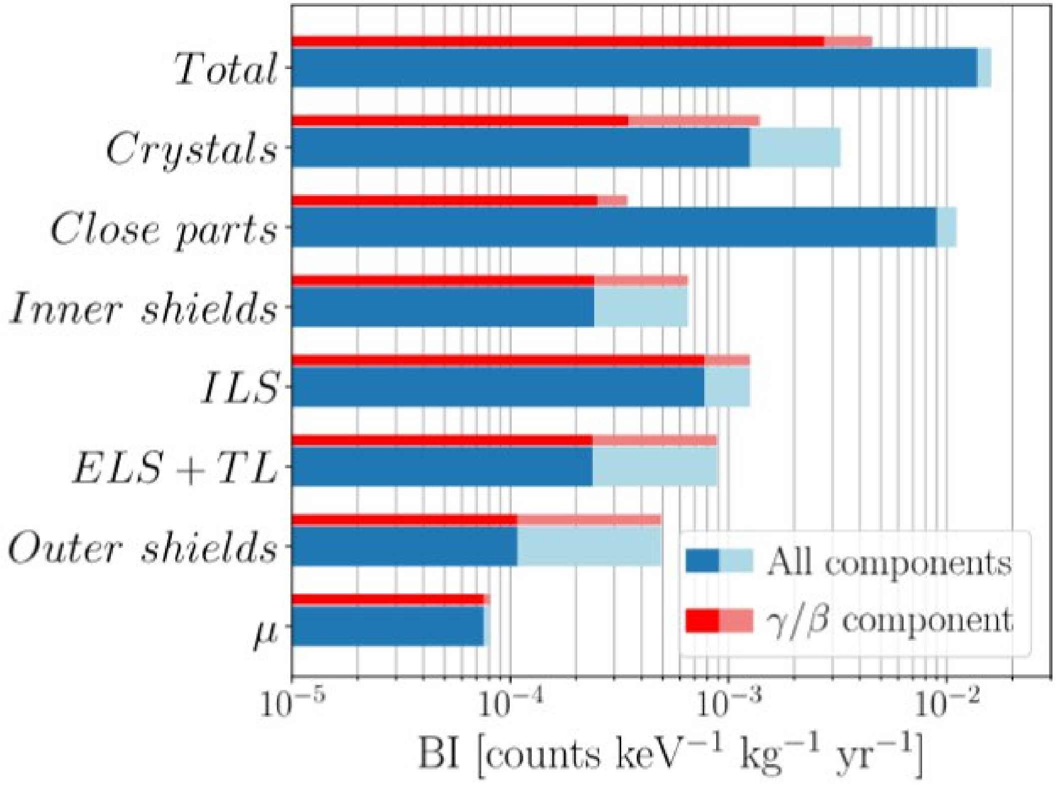
Cryogenics 102 9-21 (2019)

CUPID CUORE Upgrade with Particle IDentification

- CUORE sensitivity limited by background level in region of interest of ~10^{-2} counts/keV/kg/yr (ckky)

CUORE Coll., Phys. Rev. D **110**, 052003 (2024)

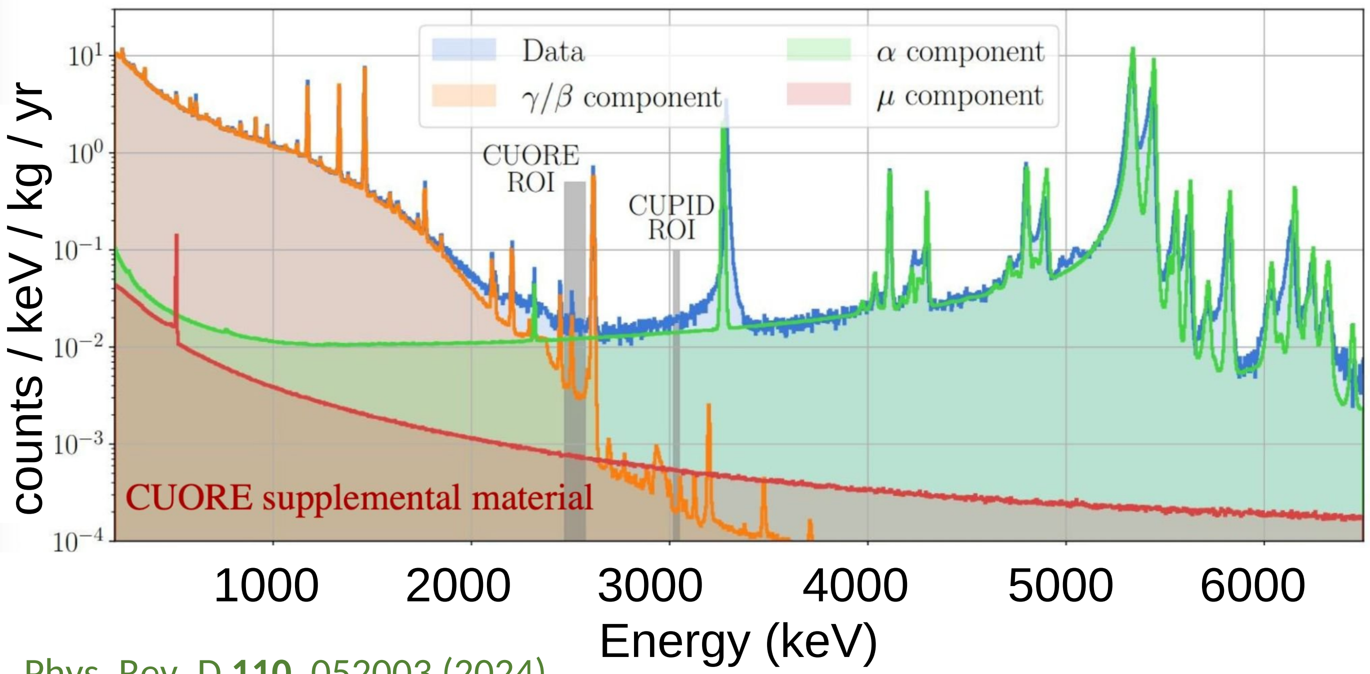
Cuore background contributions



CUPID CUORE Upgrade with Particle IDentification

- CUORE sensitivity limited by background level in region of interest of ~10^{-2} counts/keV/kg/yr (ckky)
- CUPID: Sensitivity improvement by background reduction to **~10^{-4} ckky** via
  - Particle identification
  - Muon veto
  - Isotope with increased Q value for reduced γ/β background

Cuore background



CUORE Coll., Phys. Rev. D **110**, 052003 (2024)

CUPID Goal: Factor 100 background reduction → Factor 5 improvement of exclusion sensitivity to neutrino mass $m_{\beta\beta}$ → Fully probe „Inverted Hierarchy“ region

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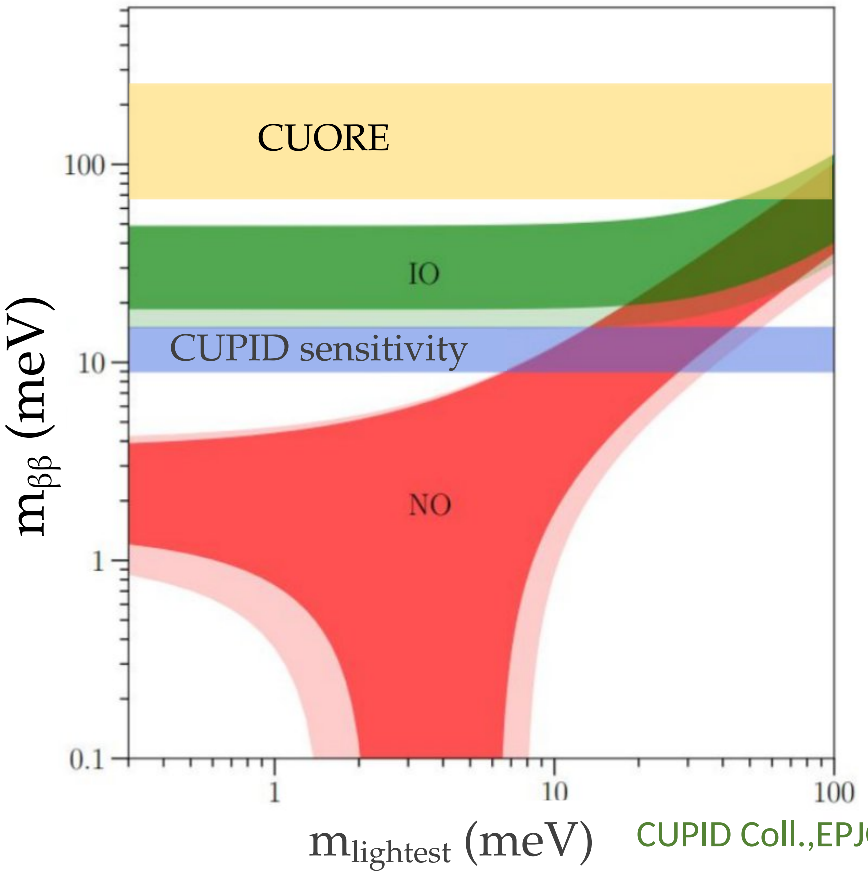
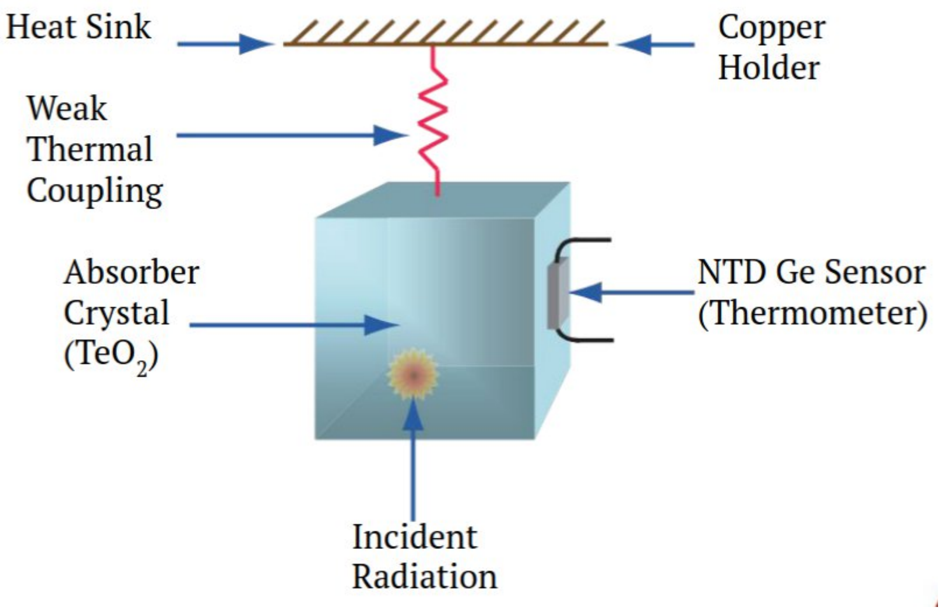


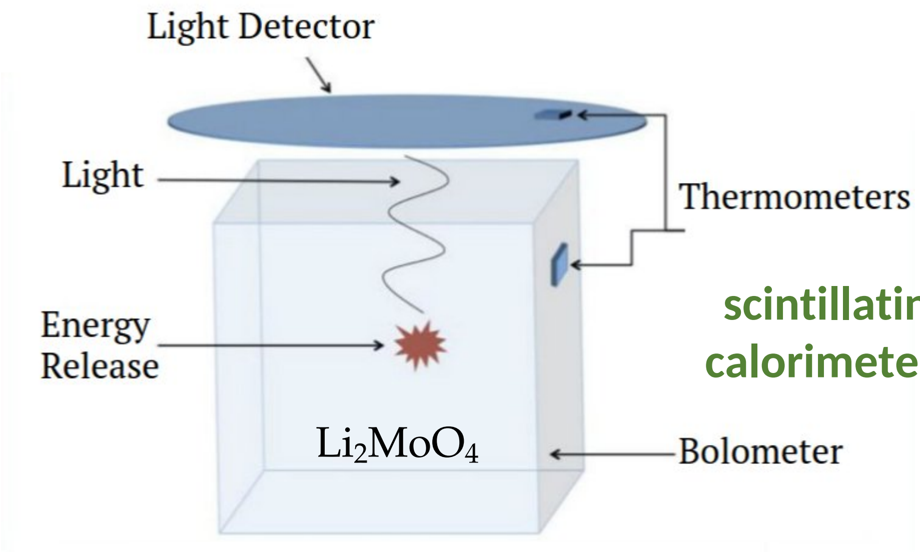
CUPID Coll.,EPJC 85 737 (2025)

CUPID Goal: Factor 100 background reduction → Factor 5 improvement of exclusion sensitivity to neutrino mass $m_{\beta\beta}$ → Fully probe „Inverted Hierarchy“ region

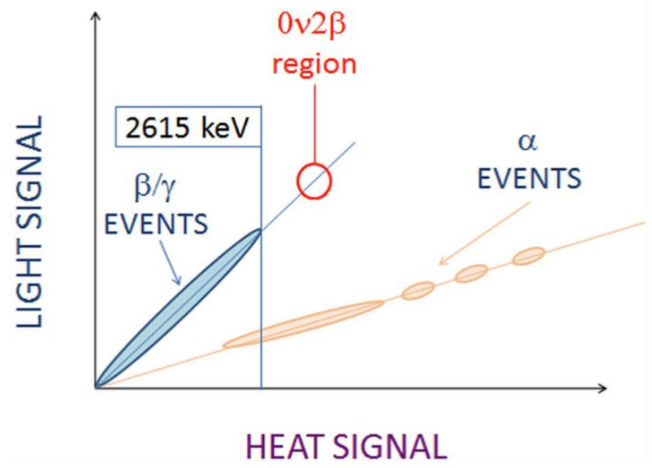
CUPID CUORE Upgrade with Particle IDentification

Will be hosted in CUORE cryogenic infrastructure
→ Profit from experience gained during CUORE operation





scintillating calorimeters!



CUPID CUORE Upgrade with Particle IDentification

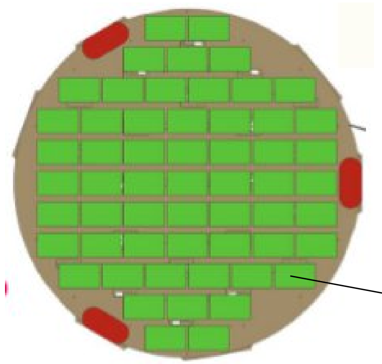
Sensitivity: $S_{1/2} \propto a\varepsilon \sqrt{Mt/b\Delta E}$

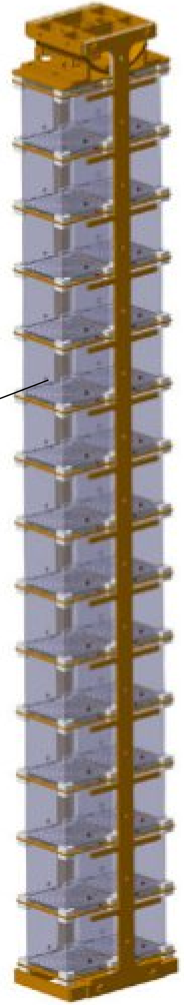
	CUPID goal	CUORE performance
Isotope enrichment *a*	>95% ^{100}Mo	~34% ^{130}Te
Isotope mass *M*	240kg ^{100}Mo	206kg ^{130}Te
$Q_{\beta\beta}$	3034 keV	2528 keV
Energy resolution *ΔE* at $Q_{\beta\beta}$ (FWHM)	5 keV	7.3 keV
Background index *b*	$<10^{-4}$ ckky	$1.42\text{x}10^{-2}$ ckky
Live time *t*	10 y	8 y

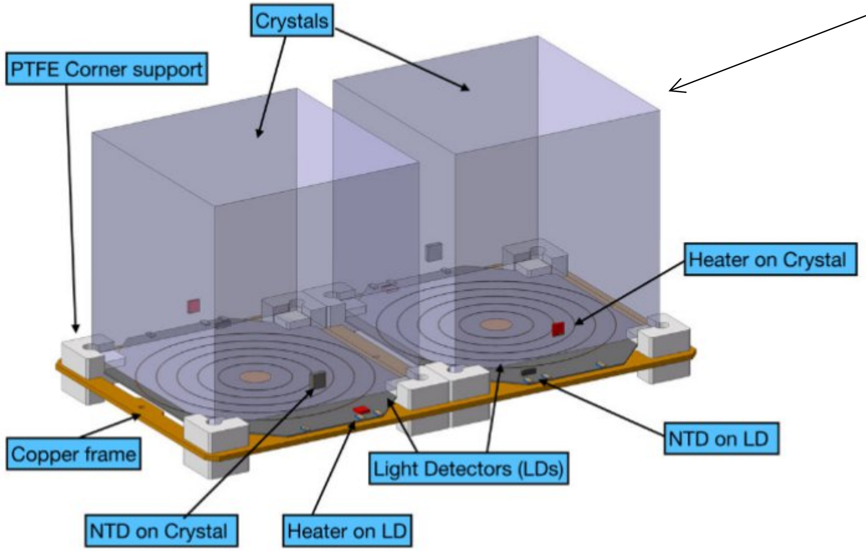
CUPID Baseline Design

CUPID Coll., EPJC 85 737 (2025)

- (45x45x45) mm³ $Li_2{}^{100}MoO_4$ crystals, 280g each
- 1596 crystals on 57 towers
- 14 floors per tower, 2 crystals per floor
- Ge light detectors on top + bottom of each crystal







Detector performance was successfully tested in mid-scale CUPID demonstrators like Cupid-0, Cupid-Mo

EPJC 78 428 (2018)
EPJC 80 44 (2020)
EPJC 85 935 (2025)

CUPID Test Towers

K. Alfonso et al., Eur. Phys. J. C (2025) 85:935

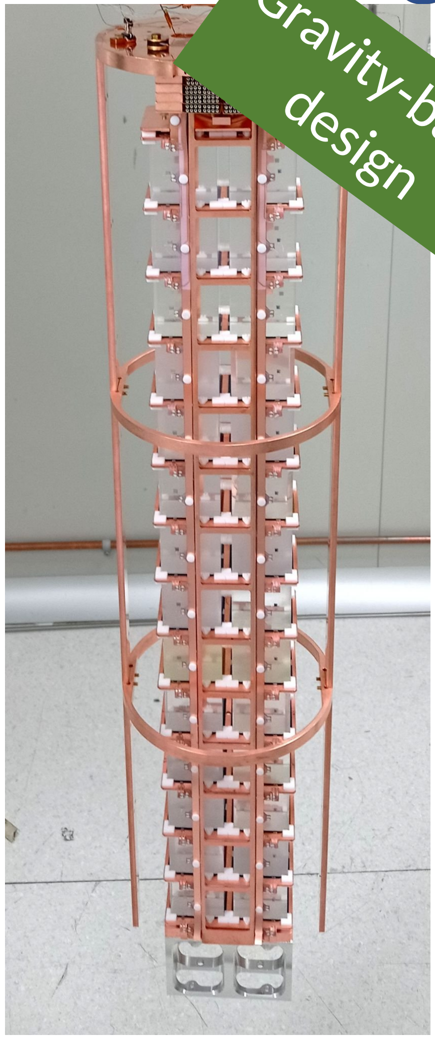
July – October 2022: Test of 1 full prototype tower @ LNGS

- 28 LMO crystals
- 30 LDs
- copper/LMO ratio <20%

Results:

- Stable operation at 10mK ± 0.5mK
- Energy resolution: (6.6 ± 2.2)keV@2615keV (FWHM)
- Light Yield (LD signal/heat signal): 0.36 keV/MeV

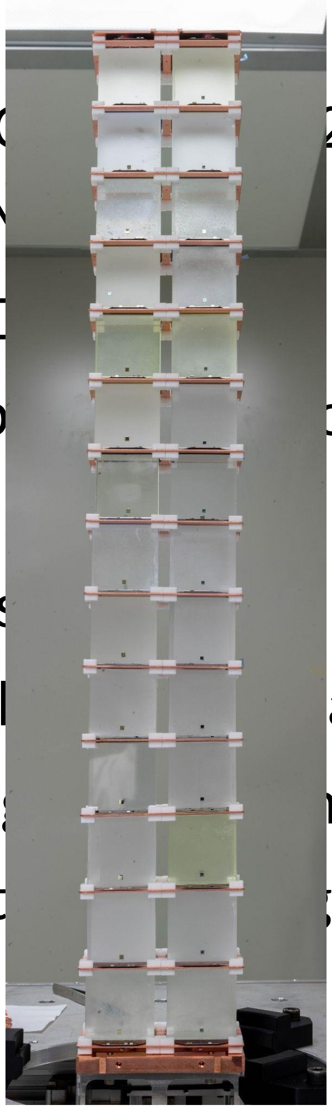
Close to CUPID goal!



Gravity-based design

CUPID Test Towers

K. Alfonso et al., Eur. Phys. J. C (2025) 85:935



July – C 2: Test of 1 full prototype tower @ LNGS

- 28 LN
- 30 LD
- copp o <

Currently ongoing:
Test measurements of
refined test tower with improved LD holder
and amplified LD signal @ LNGS

Results

- Stabl at 10mK ± 0.5mK
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- Light gnal/heat signal): 0.36 keV/MeV

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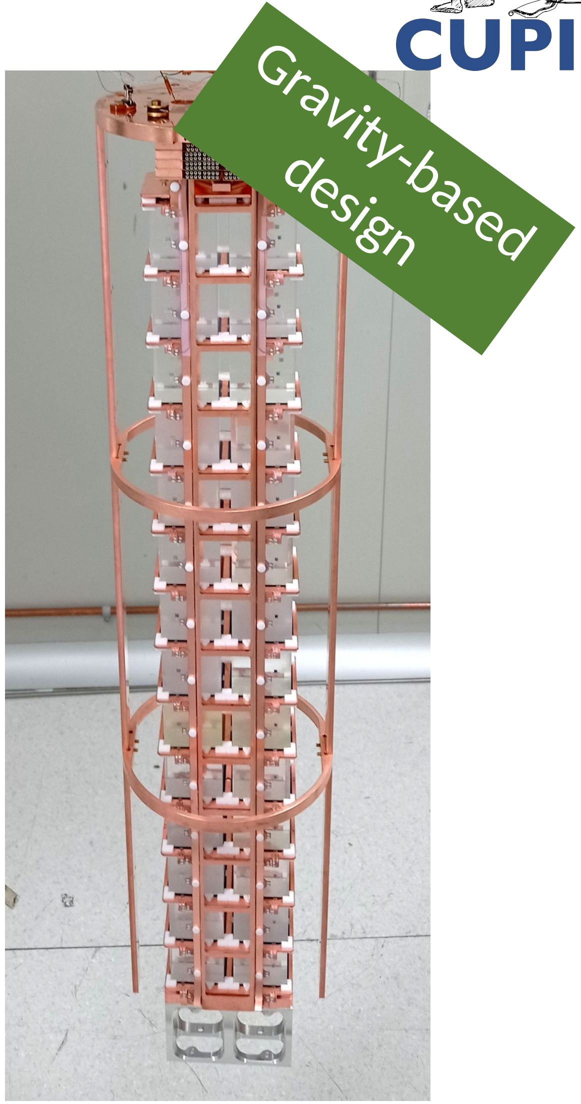


Light Detection: Particle discrimination

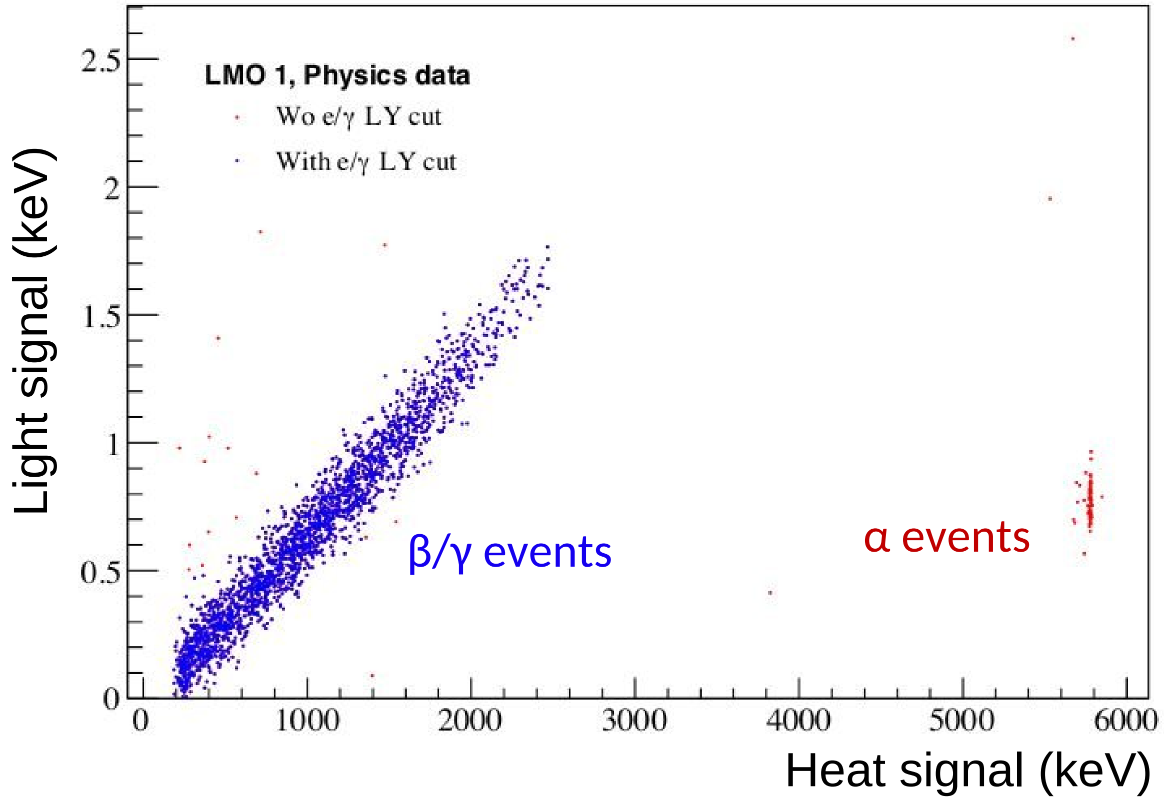
- Particle discrimination capability with light detectors shown in mid-scale demonstrator Cupid-Mo

E. Armengauf et al., EPJC 80 44 (2020)

Light Yield = $\frac{\text{LD signal}}{\text{heat signal}}$

β/γ events clearly distinguishable from α events by light yield

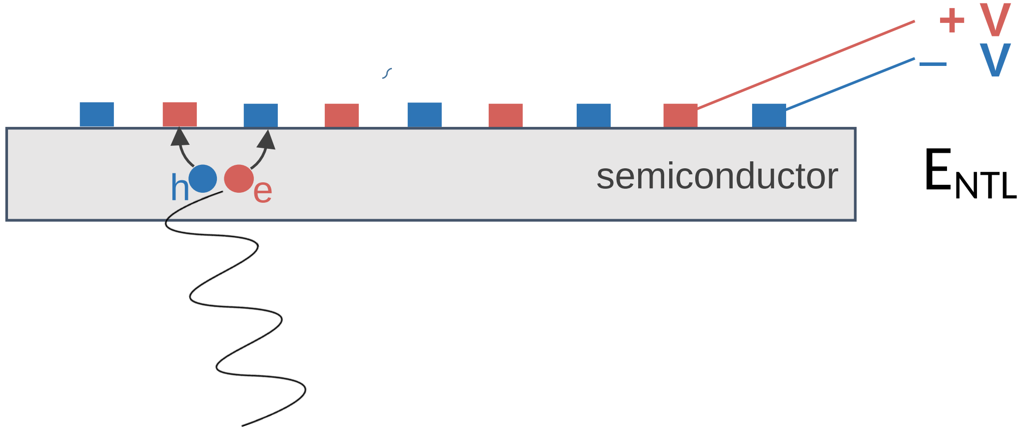
Particle discrimination without amplification



Light Detection with signal amplification

- Light detectors (LDs) are covered with Al electrodes on one side
  → bias voltage V_{NTL} applied (up to $\mathcal{O}$(100V))

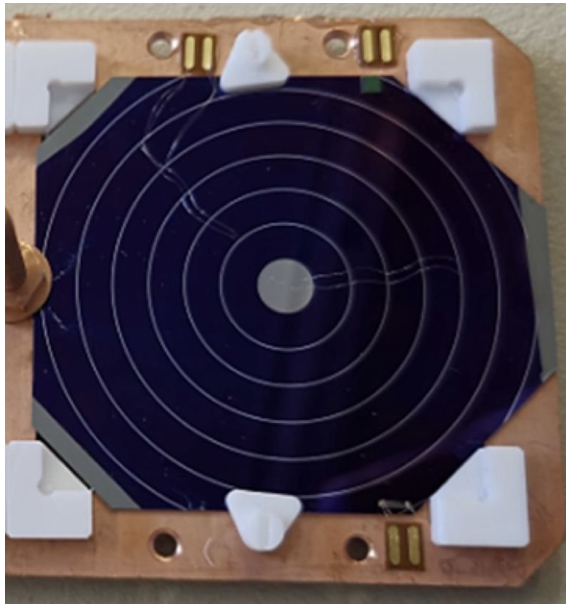
➡ Signal-to-Noise ratio enhanced by **Neganov-Trofimov-Luke (NTL)** amplification: extra heat by drift of e/h pairs in electric field



$$E_{NTL} = E_0 \cdot (1+e \cdot V_{NTL} \cdot \eta/\varepsilon)$$

efficiency factor

energy for e/h creation



Prototype LD with Al electrodes

A. Armatol et al JINST 21 P01035 (2026)

Light Detection with signal amplification

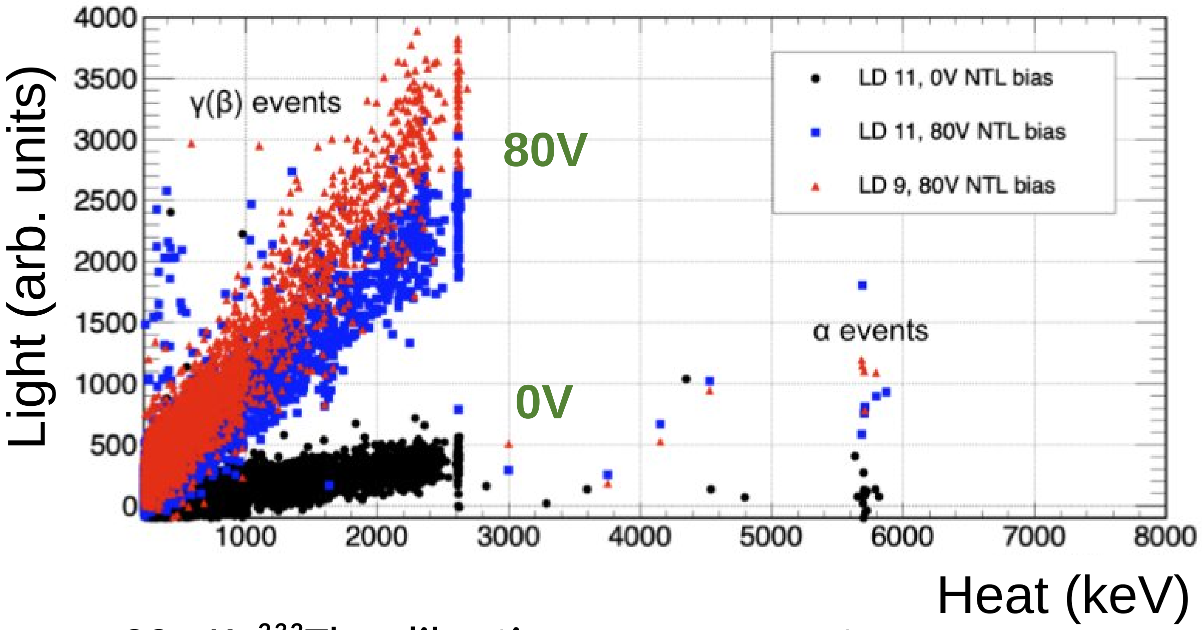
- Investigation of LD performance with/without amplification studied with 10 LDs at CROSS facility (Canfranc underground laboratory, Spain)

A. Armatol et al JINST 21 P01035 (2026)

- Sensitivity enhancement by factor 4-10 achieved with NTL amplification
- Further improvements expected by electrode-geometry adjustments

>99.9% rejection of α-particles in ROI expected

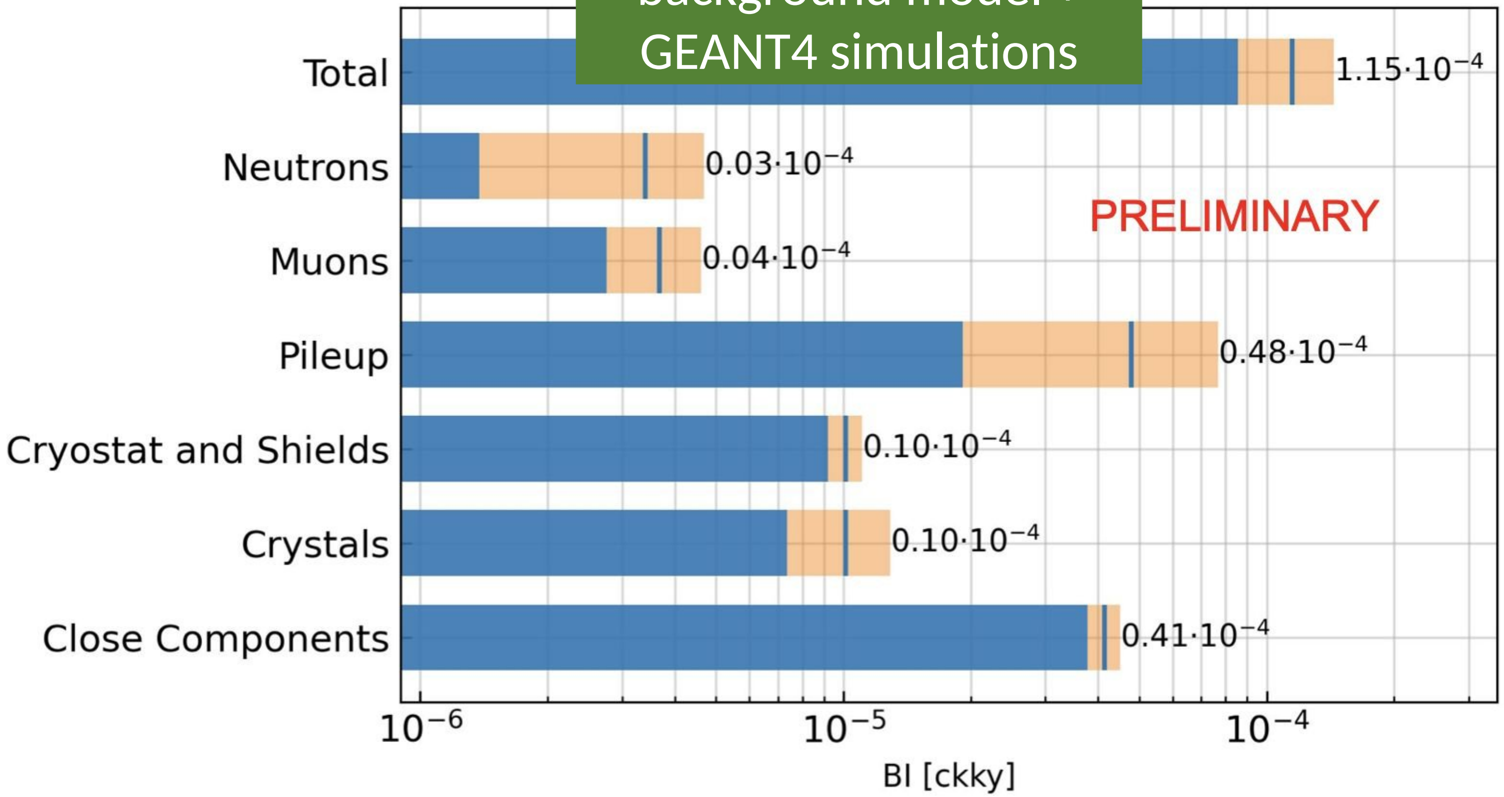
Impact of amplification on light yield



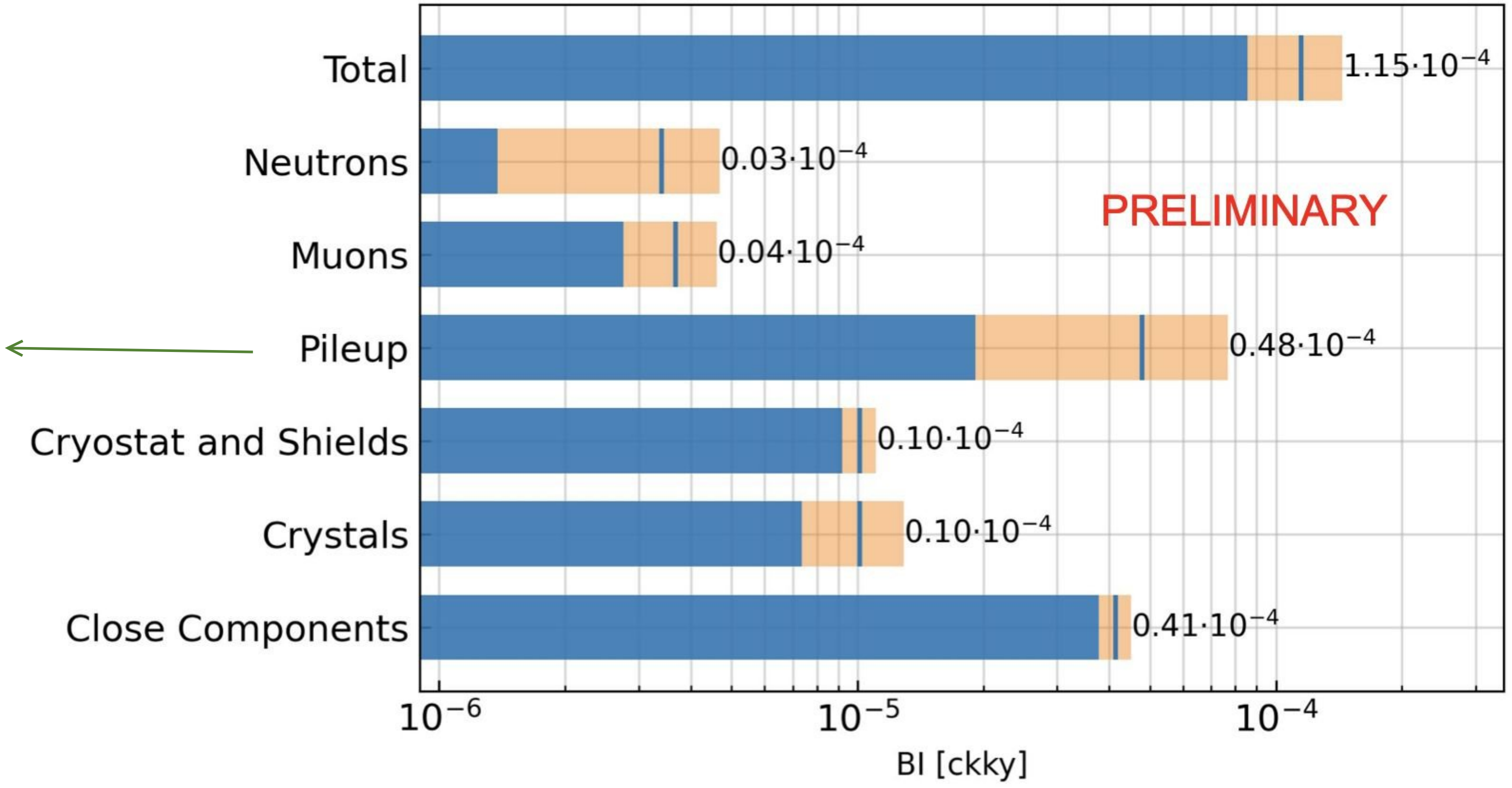
22mK, ^{232}Th calibration measurement

Background Projection

Based on CUORE background model + GEANT4 simulations

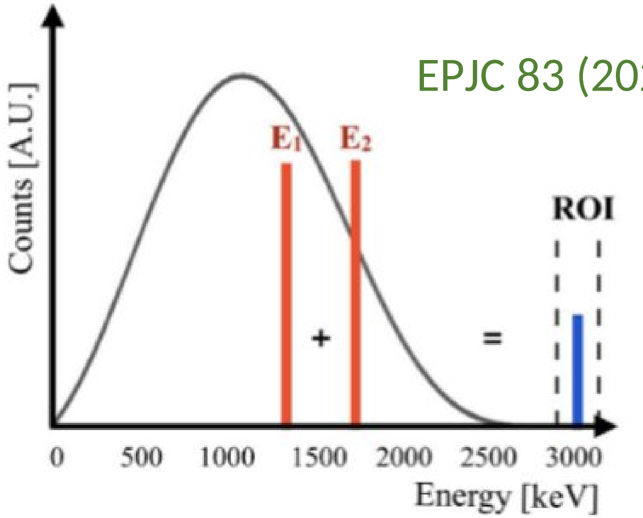


Background Projection



coincidences of 2νββ events - suppressed by pulse-shape analysis of NTL-amplified LDs

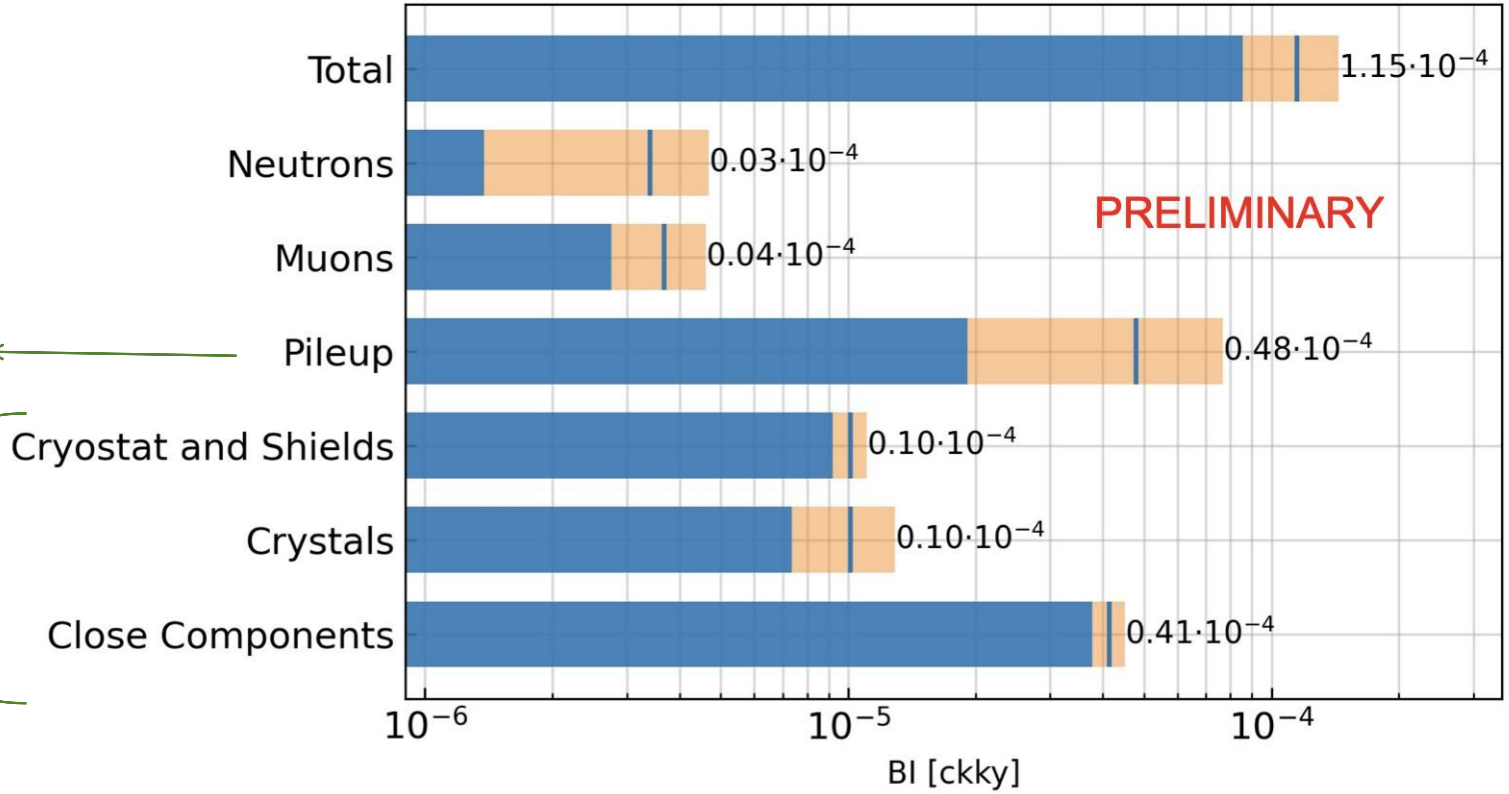
EPJC 83 (2023) 5, 373



Background Projection

coincidences of 2νββ events - suppressed by pulse-shape analysis of NTL-amplified LDs

reduced by using high-radiopurity materials

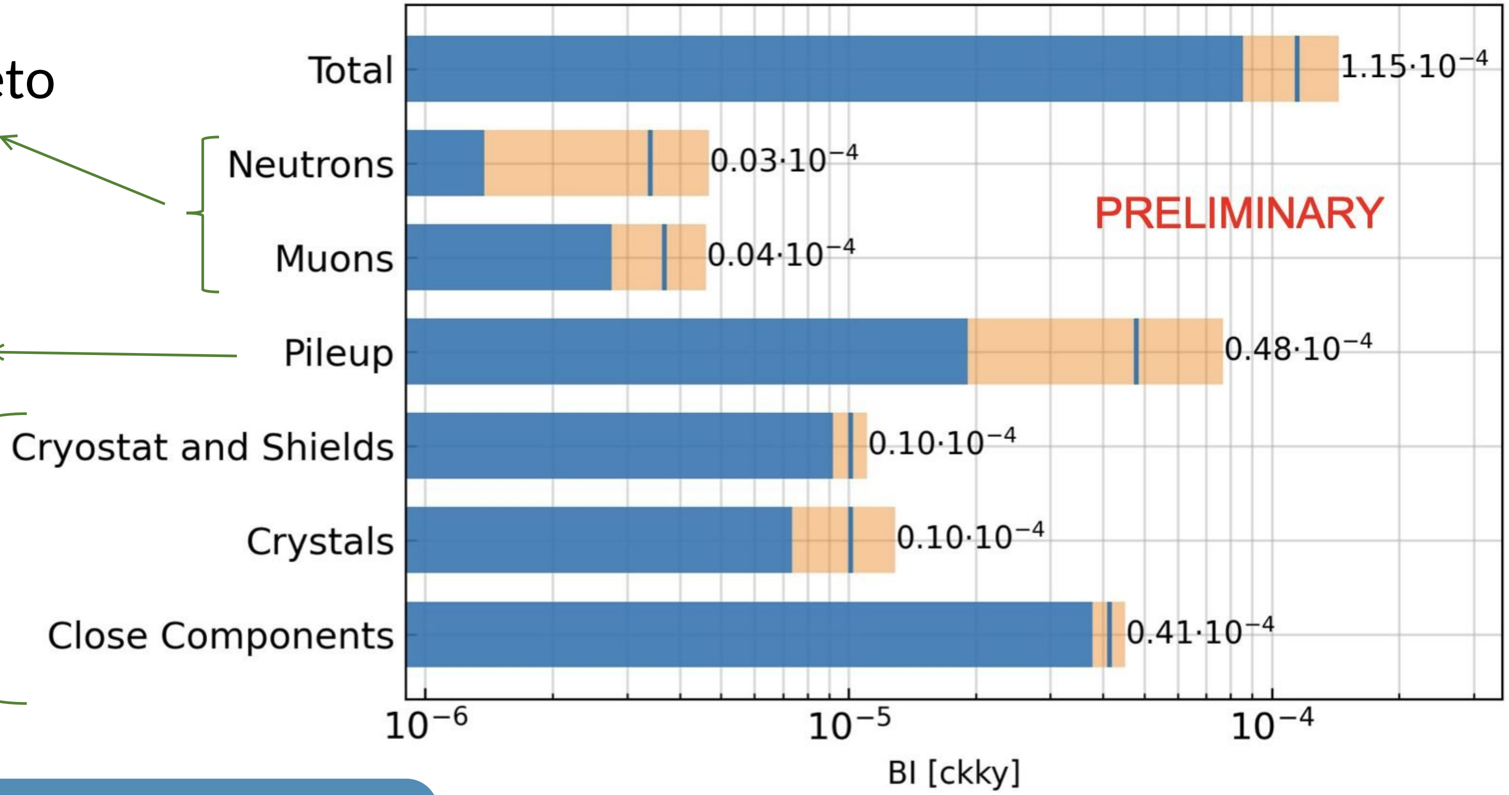


Background Projection

mitigated by muon veto
+ neutron shielding

coincidences of 2νββ events - suppressed by pulse-shape analysis of NTL-amplified LDs

reduced by using high-radiopurity materials

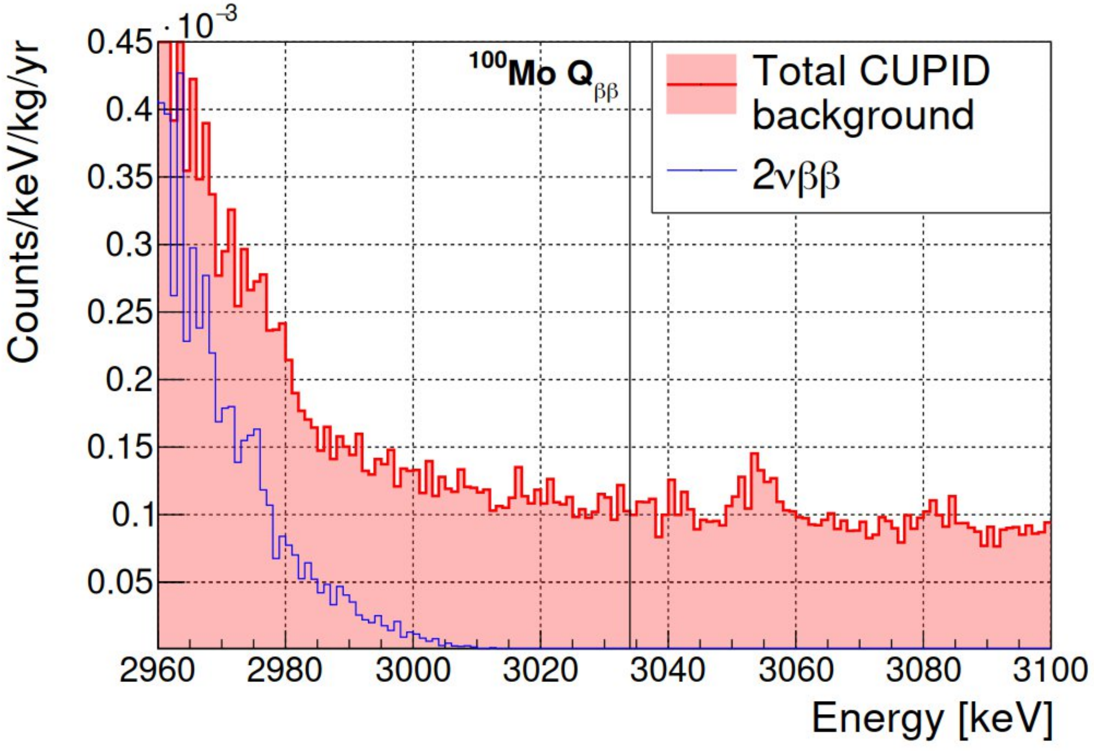


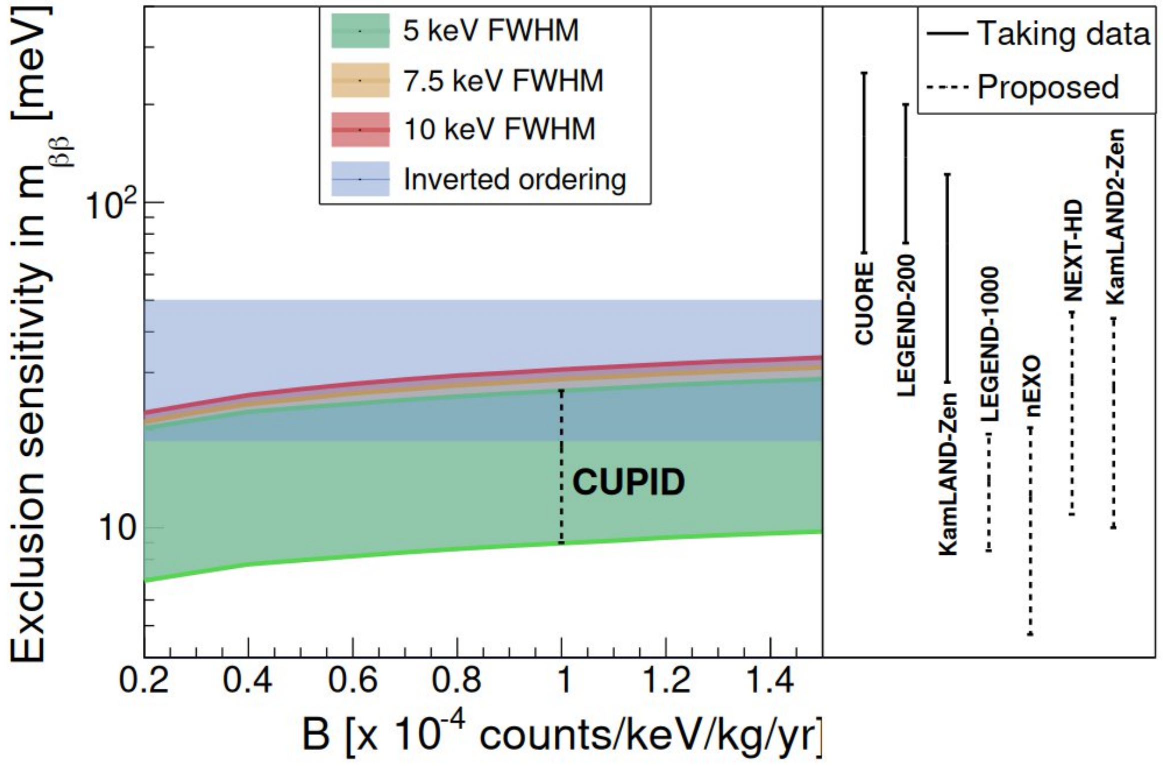
Background goal of $1x10^{-4}$ counts/keV/kg/y seems realistic

Projected Sensitivity

arXiv:2504.14369
Accepted by EPJC

Expected total CUPID background





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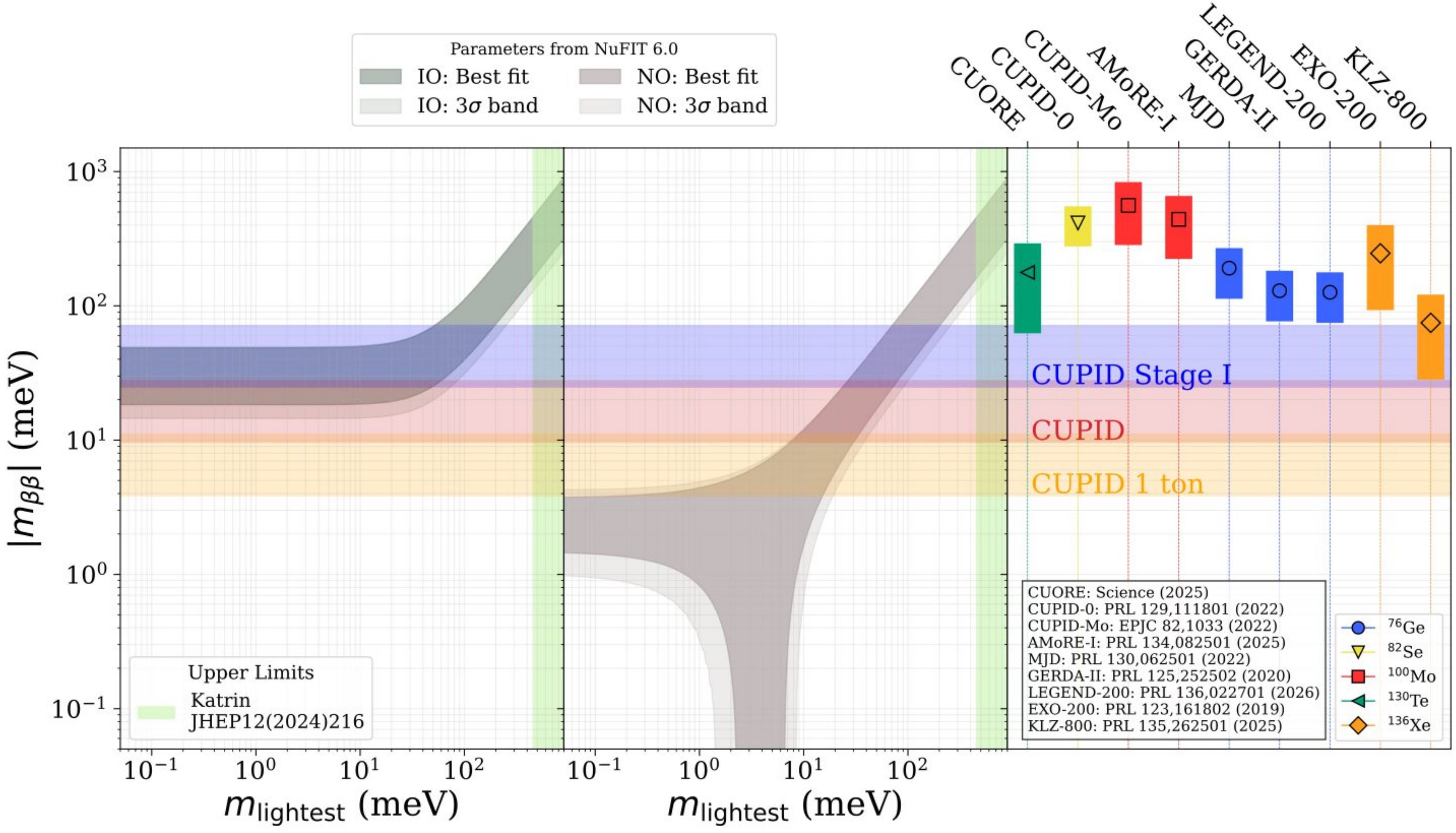
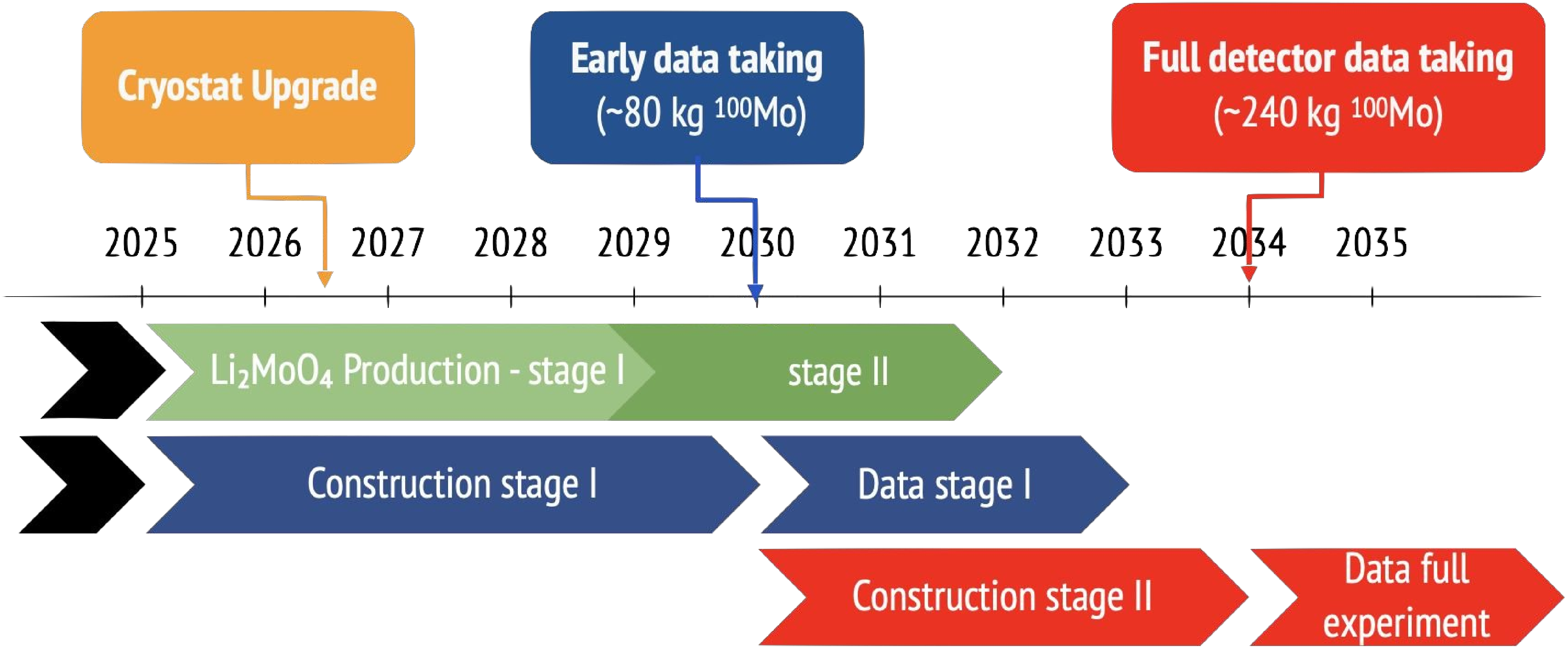


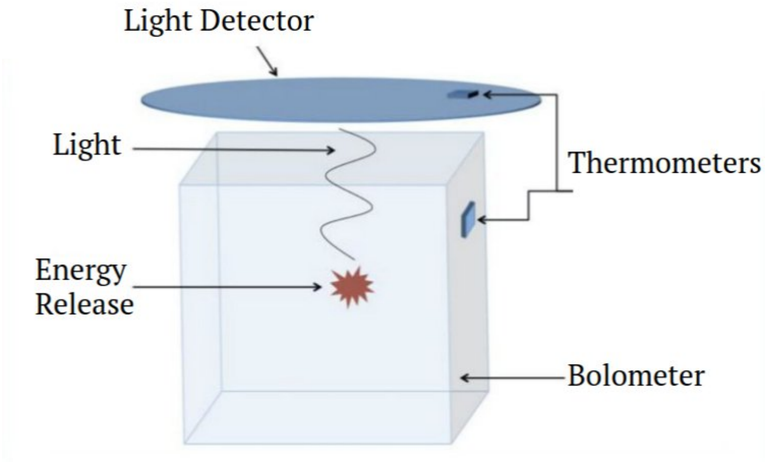
Timeline

PRELIMINARY

CUPID



Summary & Outlook



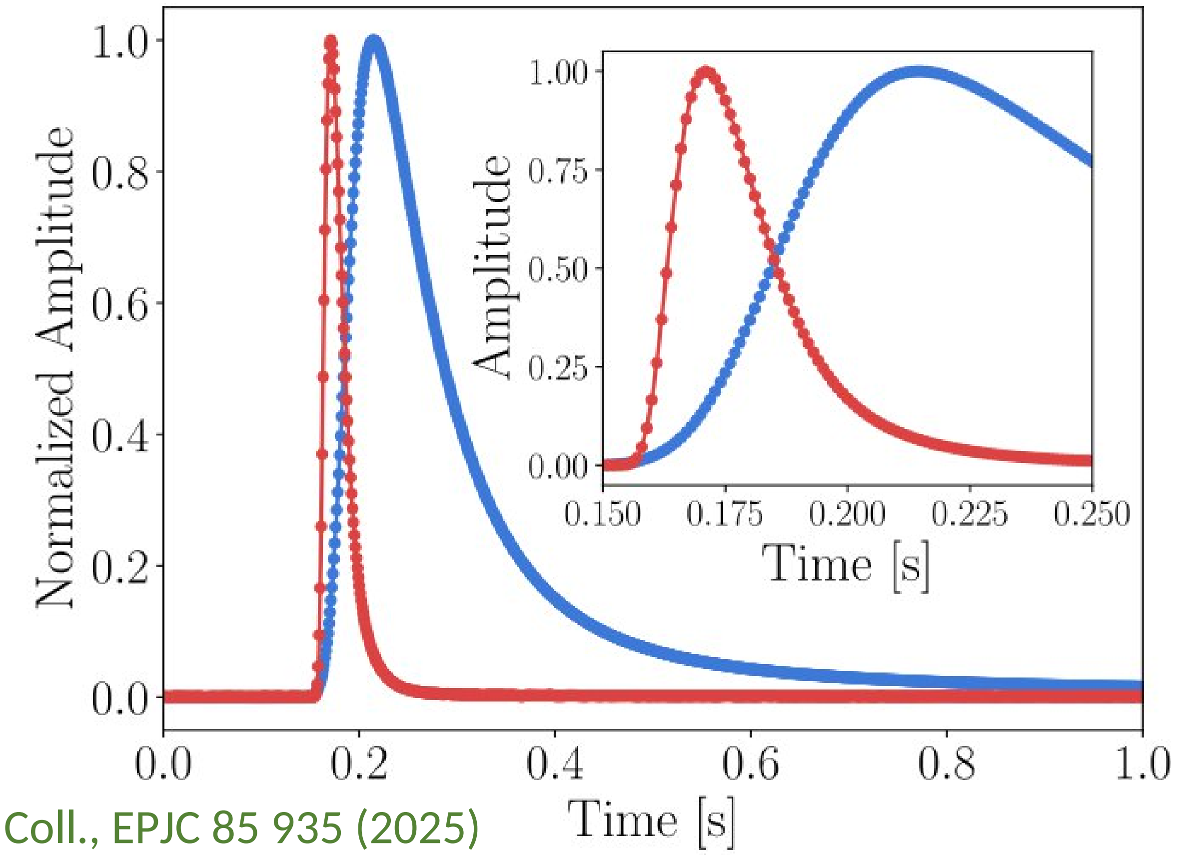
CUPID

- aims to measure 0νββ in ^{100}Mo using both heat and scintillation-light signals
- profits from well-established infrastructure of CUORE@LNGS
- has a predicted background index of 1x10^{-4} counts/(keV·kg·y) to cover the full inverted-hierarchy neutrino-mass region
- preparations for CUPID Stage-I ongoing
  – early data taking expected to start around 2030

Projection:
10y exclusion sensitivity (90% CI)
$m_{\beta\beta}$=(9.6-28)meV
$T_{1/2}$=(1.6+0.6-0.5)x10^{27} y

Backup

Comparison of LMO and LD pulses



blue: LMO crystal
red: light detector

CUPID Coll., EPJC 85 935 (2025)

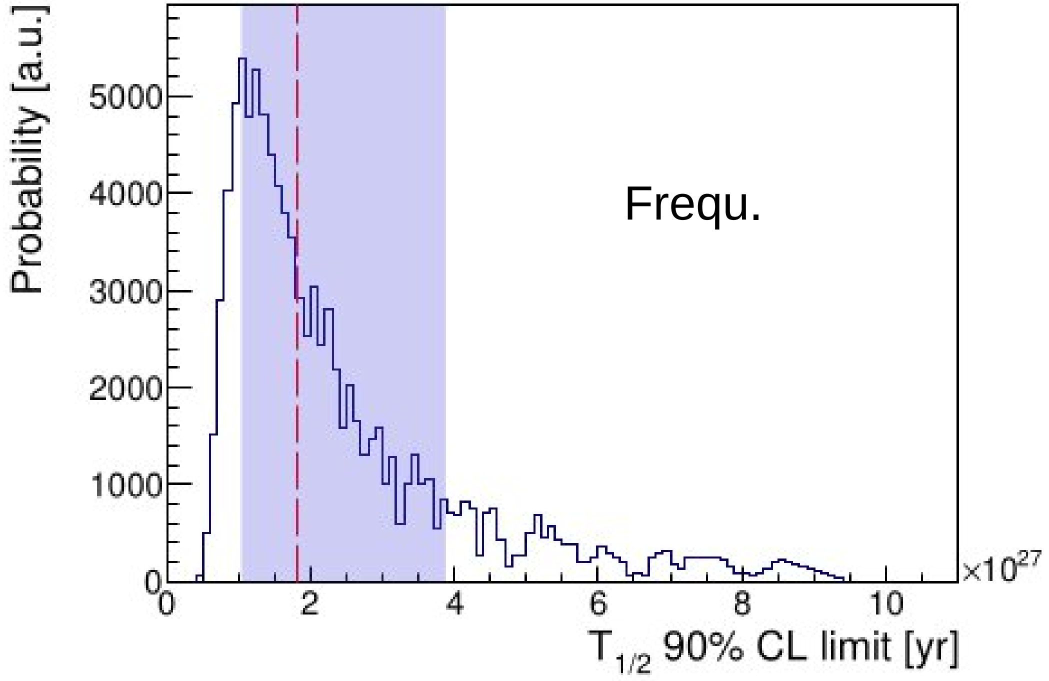
Sensitivity for various scenarios

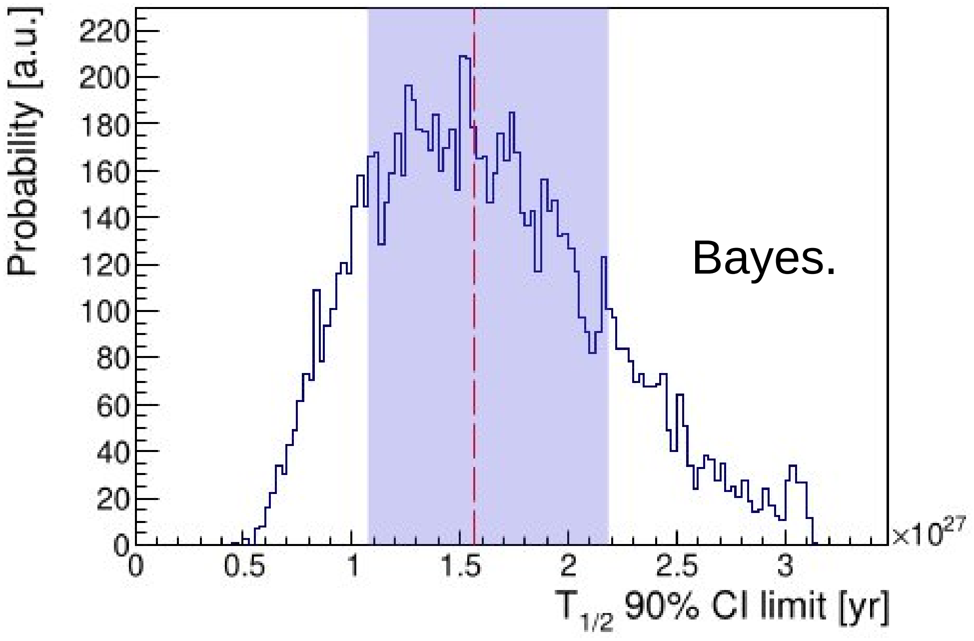
CUPID

B [ckky]	ΔE [keV]	$\hat{T}_{1/2}$ 10^{27} [yr]		$\hat{m}_{\beta\beta}$ [meV]	
		Bay.	Freq.	Bay.	Freq.
1.5×10^{-4}	5	1.4	1.5	10–30	9.7–29
1.0×10^{-4}	5	1.6	1.8	9.6–28	9.0–26
	7.5	1.4	1.5	10–30	9.7–29
	10	1.2	1.3	11–32	10–31
0.6×10^{-4}	5	1.8	2.2	8.9–26	8.2–24
0.2×10^{-4}	5	2.3	3.1	7.9–23	6.9–20

arXiv:2504.14369
Accepted by EPJC

Sensitivity for various scenarios





arXiv:2504.14369
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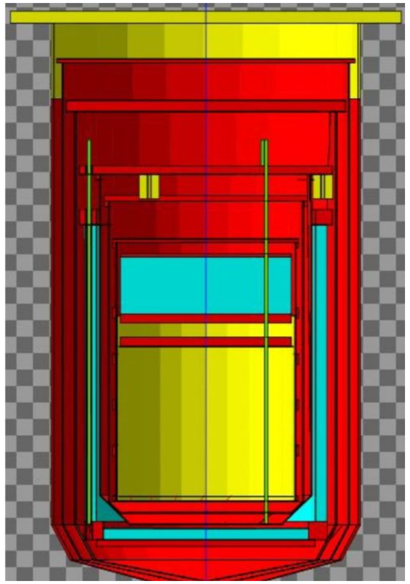
Nuclear-Matrix Elements for $m_{\beta\beta}$ determination

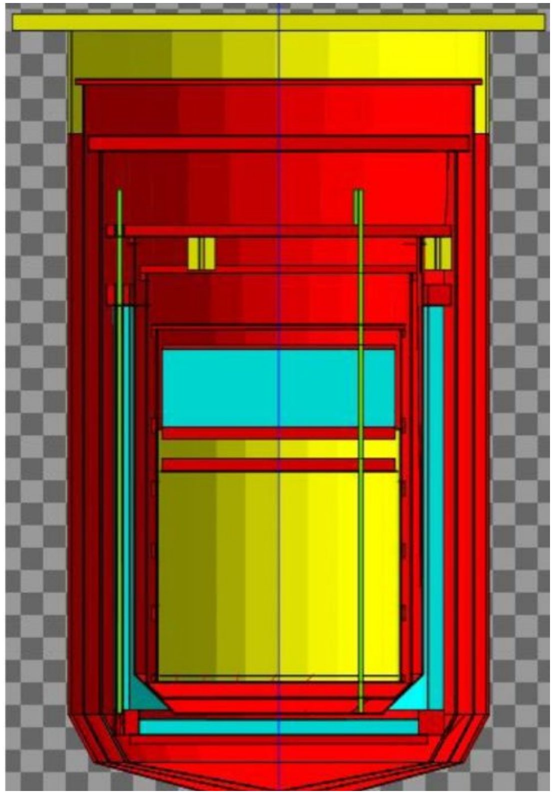
Model	NME	Reference
pn-QRPA	3.90	[45]
pn-QRPA	5.868	[57]
IBM-2	5.077	[46]
EDF	6.588	[47]
EDF	5.08	[58]
EDF	6.48	[59]
Shell	2.24	[43]

[45]: DOI 10.1103/PhysRevC.91.024613
[57]: DOI 10.1103/PhysRevC.98.064325
[46]: DOI 10.1103/PhysRevD.102.095016
[47]: DOI 10.1103/PhysRevLett.111.142501
[58]: DOI 10.1103/PhysRevLett.105.252503
[59]: DOI 10.1103/PhysRevC.95.024305
[43]: DOI 10.1103/PhysRevC.105.034312

Outlook: Towards CUPID1T



- 240kg Mo
- CUORE cryostat
- Background ~10^{-4} ckky
- T1/2 > 1e27 y
- $m_{\beta\beta}$~ (13-21) meV



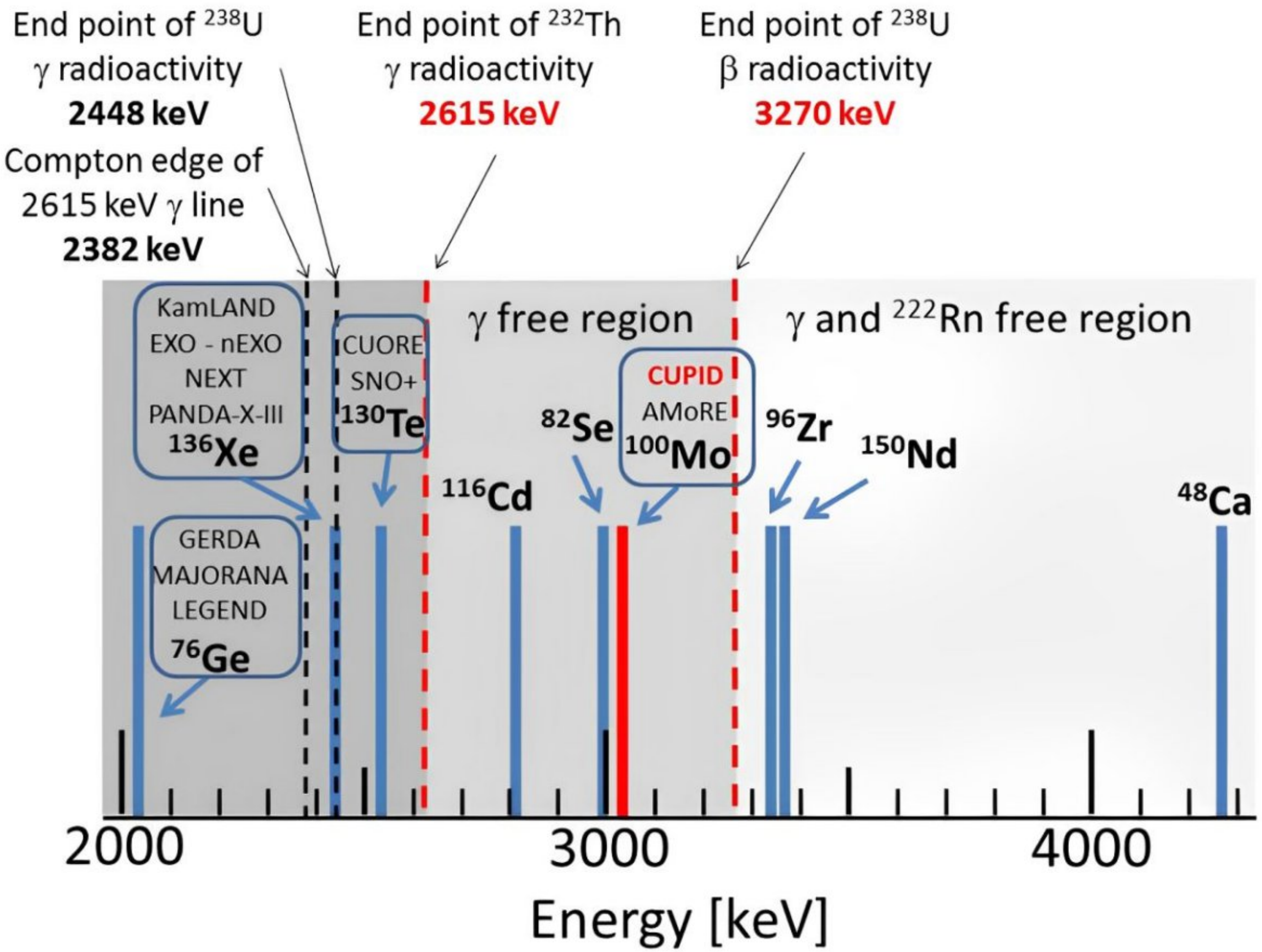
- 1000kg Mo
- New cryostat
- Background ~10^{-6} ckky
- T1/2 > 9e27 y
- $m_{\beta\beta}$~ (4-7) meV

White Paper: https://doi.org/10.48550/arXiv.2203.08386

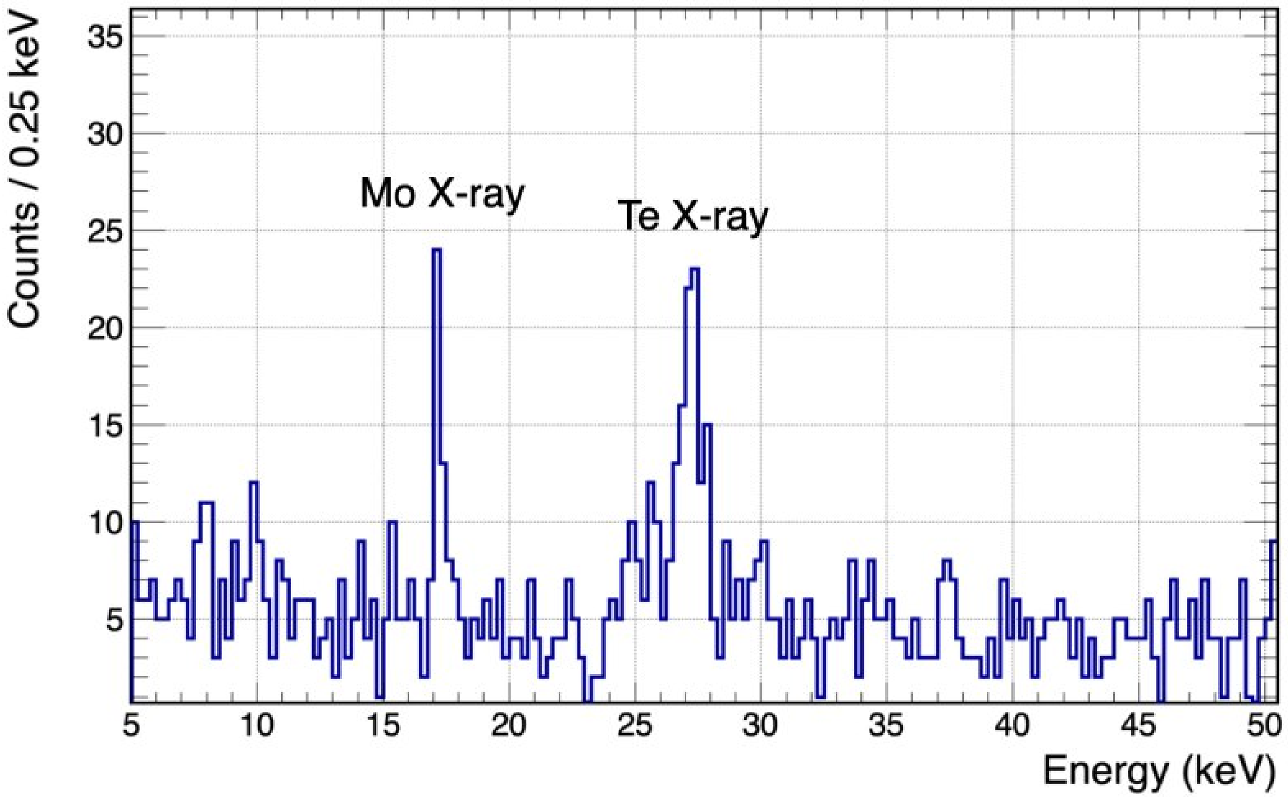
Cryostat upgrade

- More detectors & factor 3 more readout channels —> increased heat load —> increase of cooling power required
- Impact of vibrations on noise experienced during CUORE operation —> Vibration cancellation required
- Installation of Muon-Veto: Plastic scintillators with SiPM readout on sides, final design for top to be defined

Q values of different ββ isotopes



LD calibration @ CROSS facility



A. Armatol et al JINST 21 P01035 (2026)

LD calibration with 232Th source at 17mK
X-rays induced by neighbouring crystals by γ-rays