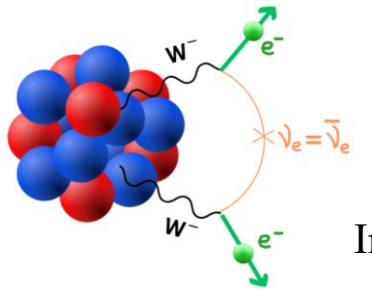
CUPID, the next generation 0νββ decay experiment

Mariia Buchynska on behalf of CUPID collaboration

0νββ decay



$$2n \rightarrow 2p + 2e^-$$

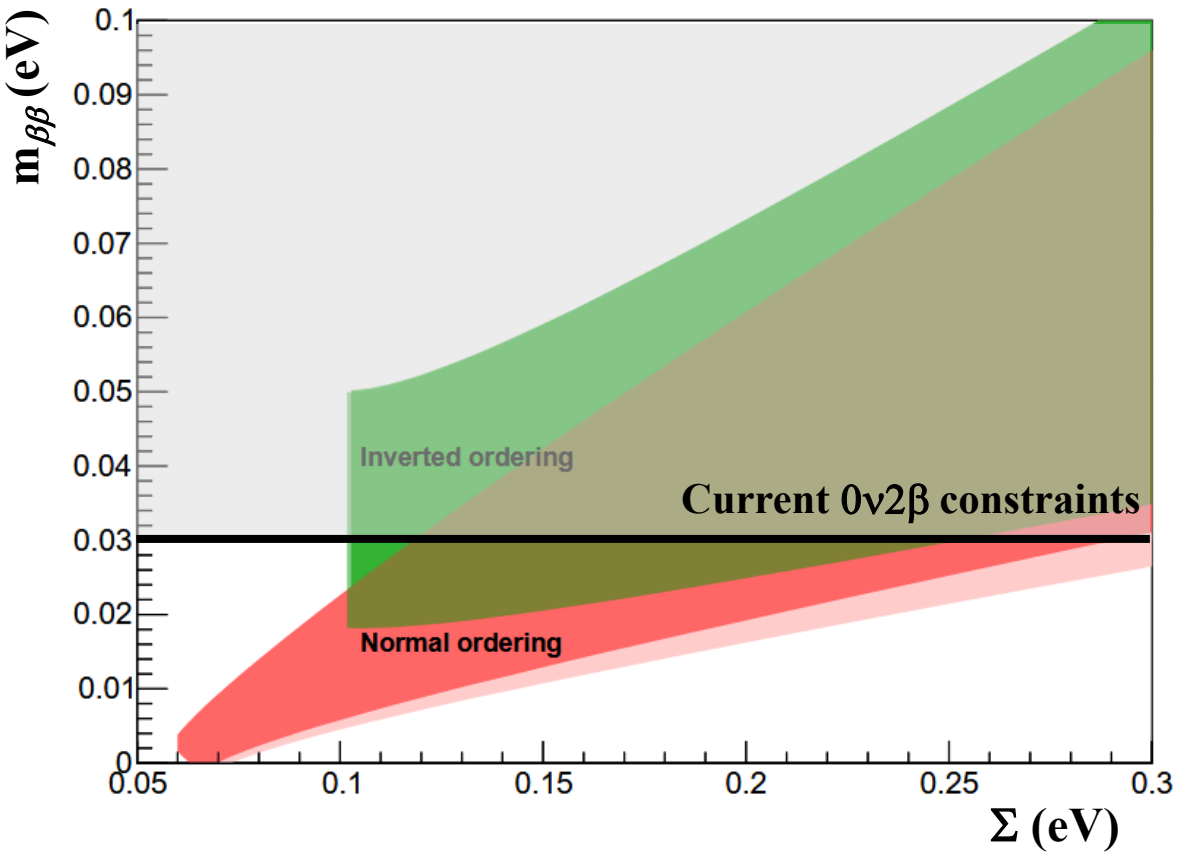
⇩

Lepton number violation
Inclusive test for the "creation of leptons"

Majorana nature of neutrinos

$\Sigma = m_1 + m_2 + m_3$ → **Cosmology**

$\mathbf{m}_{\beta\beta} = \| U_{e1} |^2 m_1 + e^{i\alpha 1} | U_{e2} |^2 m_2 + e^{i\alpha 2} | U_{e3} |^2 m_3 |$ → **0ν2β**



Very rare: $T^{0\nu}_{1/2} > 10^{24}$ -10^{26} yr

Phase-space factor

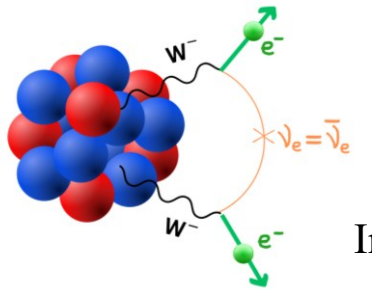
NME

Effective Majorana neutrino mass

Rate: $\frac{1}{T^{0\nu\beta\beta}_{1/2}} \sim G^{0\nu}(Q,Z) \cdot |M^{0\nu}|^2 \cdot \langle m_{\beta\beta} \rangle^2$

(in case of light neutrino exchange mechanism)

0νββ decay



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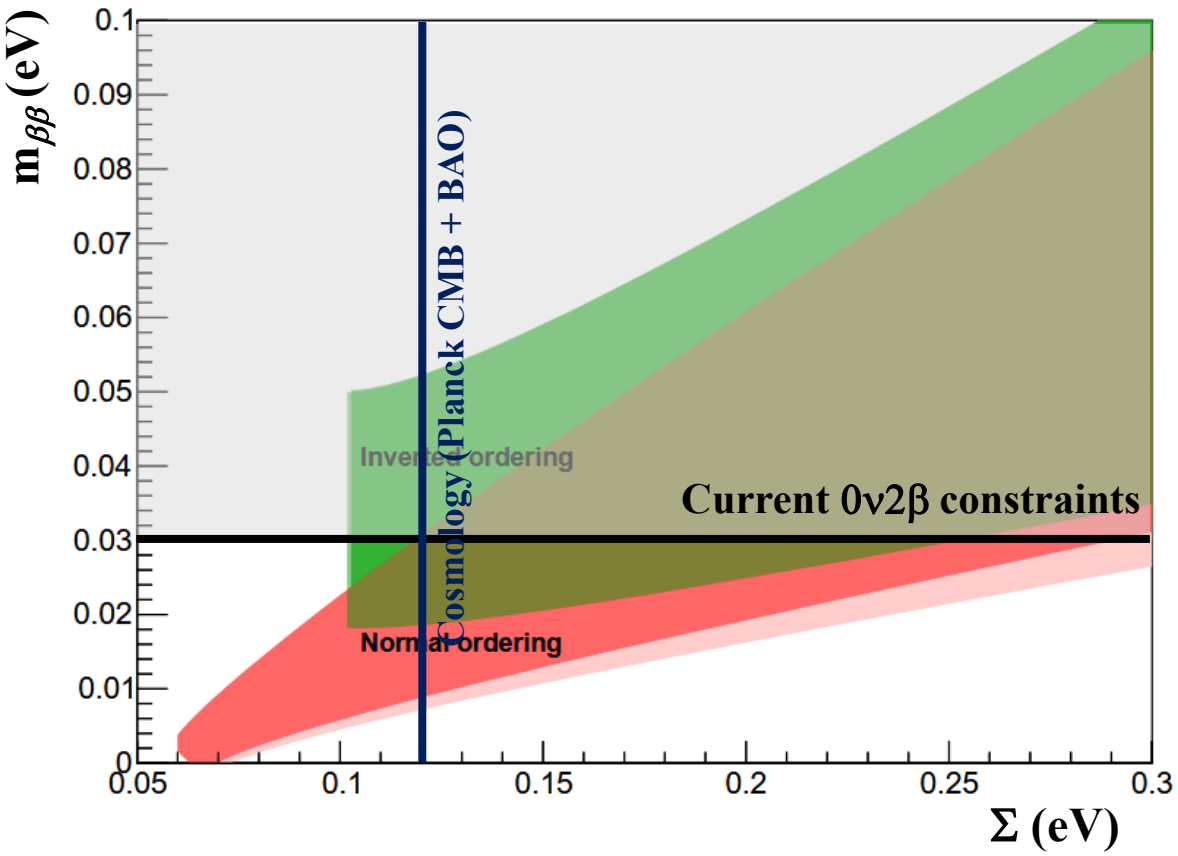

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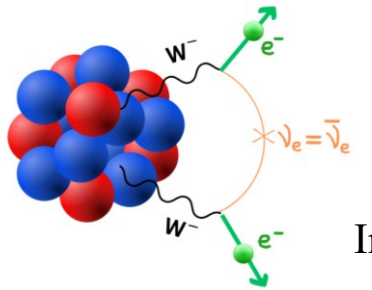
0νββ decay



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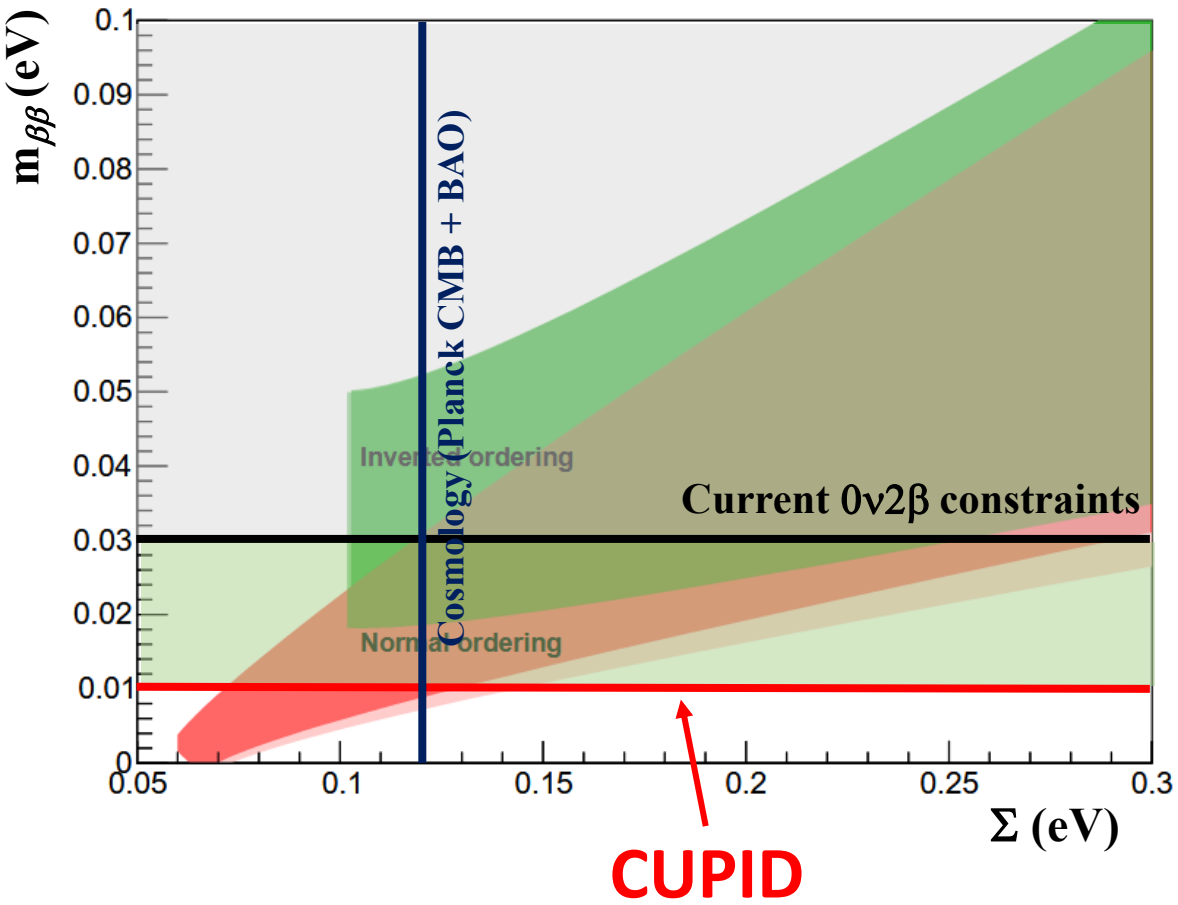
(in case of light neutrino exchange mechanism)

$\Sigma = m_1 + m_2 + m_3$ → Cosmology

$m_{\beta\beta} = ||U_{e1}|^2 m_1 + e^{i\alpha 1}|U_{e2}|^2 m_2 + e^{i\alpha 2}|U_{e3}|^2 m_3|$ → 0ν2β



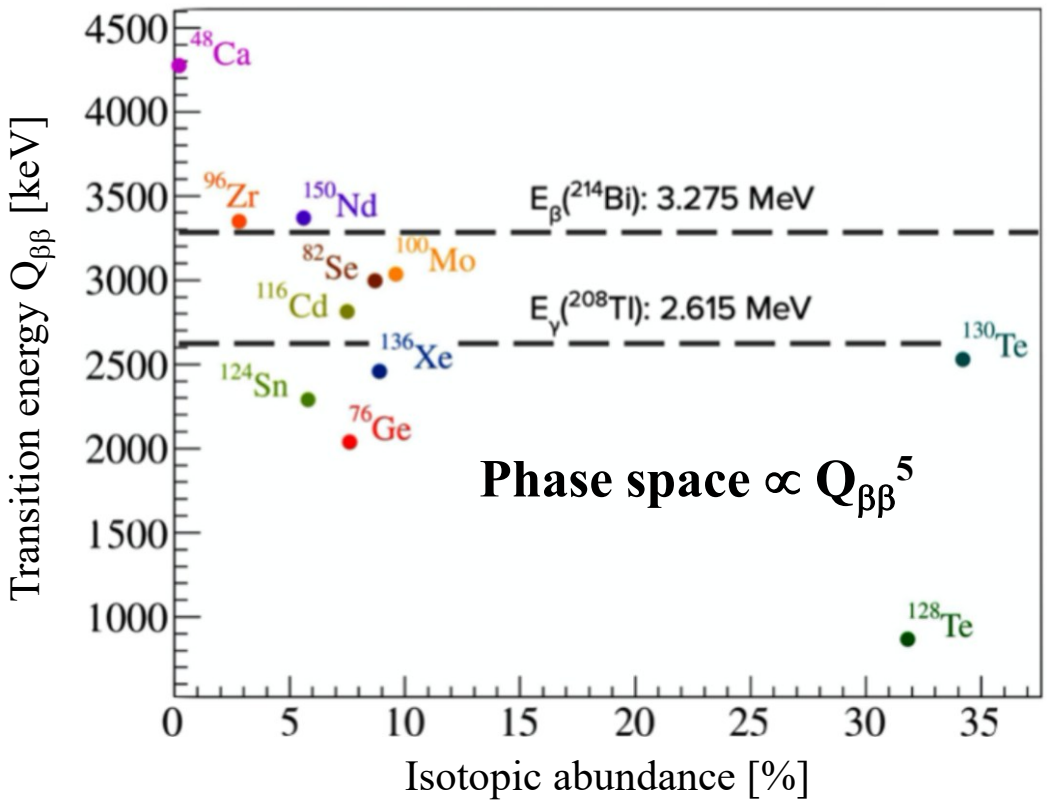
(most favorable matrix elements)

Searching for 0νββ

35 candidates

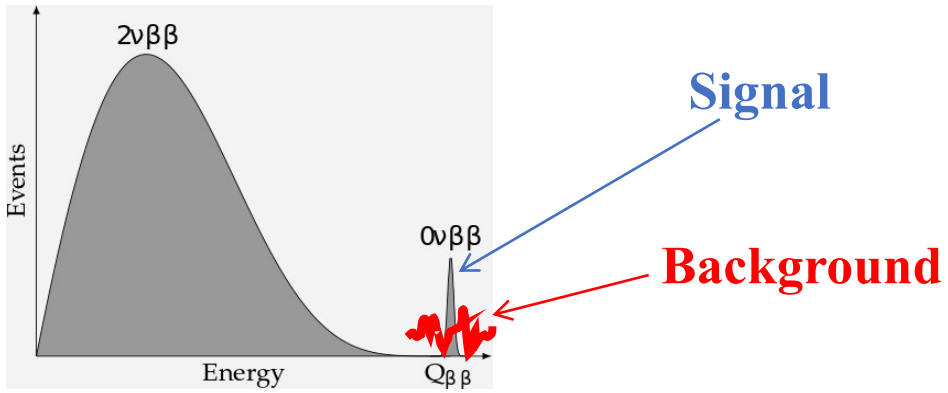
Only ~**10 experimentally relevant**

importance of $Q_{\beta\beta}$



➢ Enrichment is mandatory, with the exception of ^{130}Te

Experimental signature and requirements



Background index:

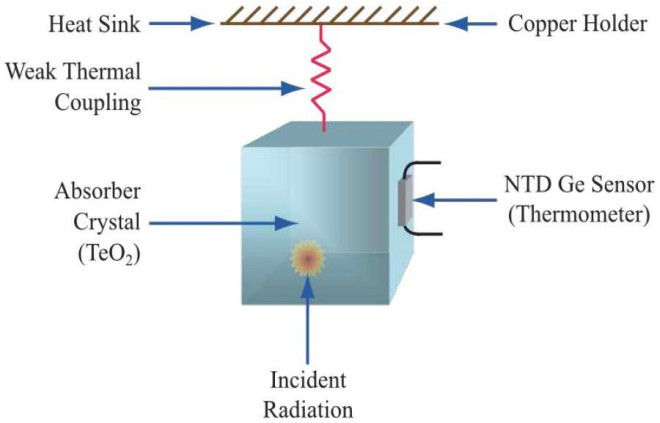
$$BI = \frac{N}{M \cdot t \cdot \Delta E} \text{ [counts/(keV·kg·y)]}$$

$$T_{1/2} \propto \begin{cases} \delta \times \varepsilon \times \sqrt{\frac{M \times t}{BI \times \Delta E}} \rightarrow \text{with background} \\ \delta \times \varepsilon \times M \times t \rightarrow \text{background free } (BI \times \Delta E \times M \times t \ll 1) \end{cases}$$

- $M \times t$ – exposure
- δ – isotopic abundance
- ΔE – energy resolution
- ε – detection efficiency

CUORE experiment

Bolometric technique

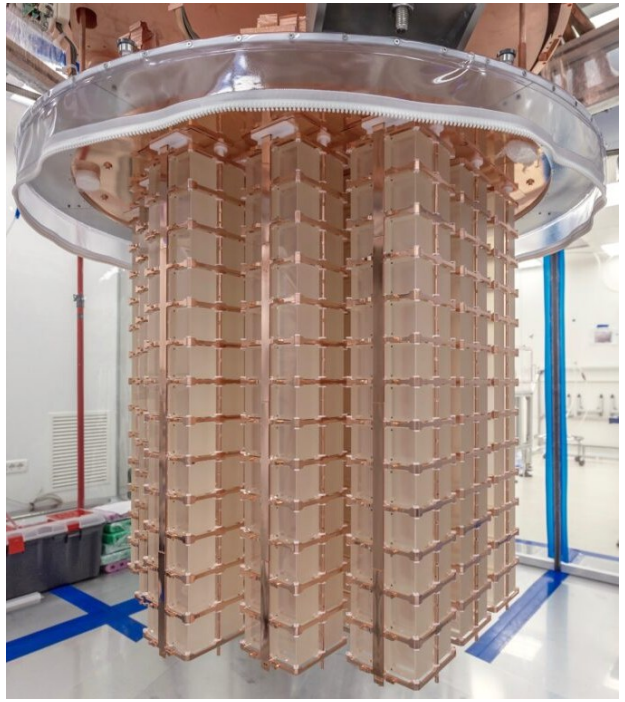


Temperature change:
$\Delta T = \Delta E / C$ (~ 0.1 mK/MeV)
$C(T) \propto T^3$

Operating temperature: ~10 mK

Detector properties:

- Good energy resolution ~ 5-10 keV at Q-value (3 MeV)
- Source = detector: high efficiency



BI = (1.42 ± 0.02) · 10^{-2} counts/keV/kg/year (ckky)

Not background free: **dominated by contributions of surface α**

- located at LNGS ~ 3600 m.w.e.
- 988 TeO_2 crystals (19 towers)
- 742 kg of TeO_2 (natural Te, I.A. ~34%), 206 kg of ^{130}Te
- operation at ~10 mK
- analysed exposure:
  ~ 2.04 ton·yr TeO_2 (~0.6 ton·yr ^{130}Te)

Recent results

No evidence of 0νββ decay

Half life limit: $\mathbf{T^{0\nu}_{1/2} > 3.8 \cdot 10^{25} yr}$ **(90% C.l.)**

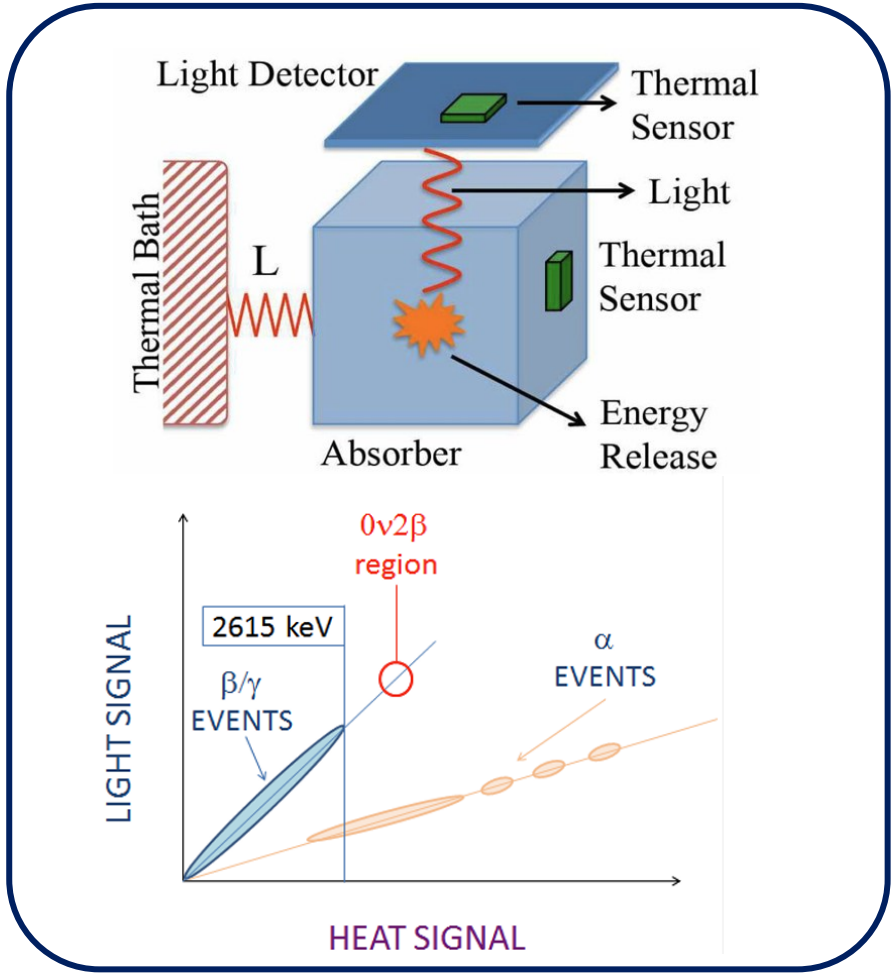
$\mathbf{m_{\beta\beta}}$ **< (70–240) meV** (depending on NME)

arXiv:2404.04453 [nucl-ex]

Scintillating bolometer technique in CUPID to reject α contribution

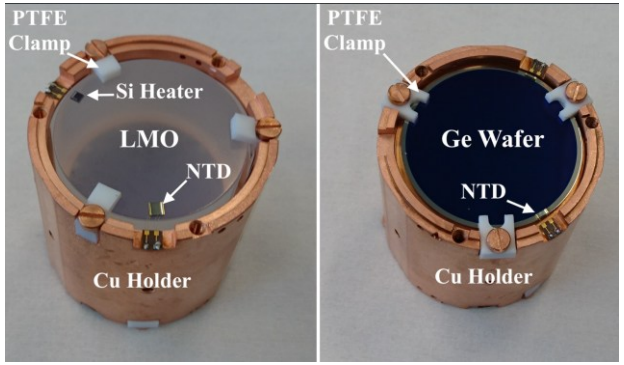
Scintillating bolometer technique

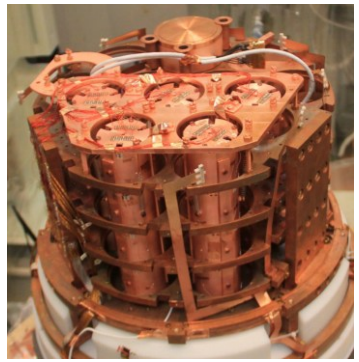
PID with scintillating bolometer



$^{130}Te \rightarrow {}^{100}Mo$ (ROI is above the endpoint of natural γ radioactivity)

CUPID-Mo experiment





EPJC 82 (2022) 1033

EPJC 83 (2023) 675

- located in the Laboratoire Souterrain de Modane (France) ~ 4800 m.w.e.
- 20 scintillating bolometers arranged in 5 towers (single module: $Li_2{}^{100}MoO_4$ (~97% ^{100}Mo) and Ge light detector)
- total mass of crystals is ~ 4.2 kg corresponding to ~ 2.3 kg of ^{100}Mo
- ~ 1.5 years of data taking

0νββ decay limits $T^{0\nu}_{1/2} > 1.8 \cdot 10^{24}$ yr (90% C. l.)
$m_{\beta\beta} < (0.28–0.49)$ eV

Energy resolution (FWHM)
6.6(1) keV @ 2615 keV
7.4(4) keV @ $Q_{\beta\beta}$ (3034 keV)

Total BI: $2.7^{+0.7}_{-0.6}(\text{stat})^{+1.1}_{-0.5}(\text{syst}) \times 10^{-3}$ **counts/keV/kg/yr**

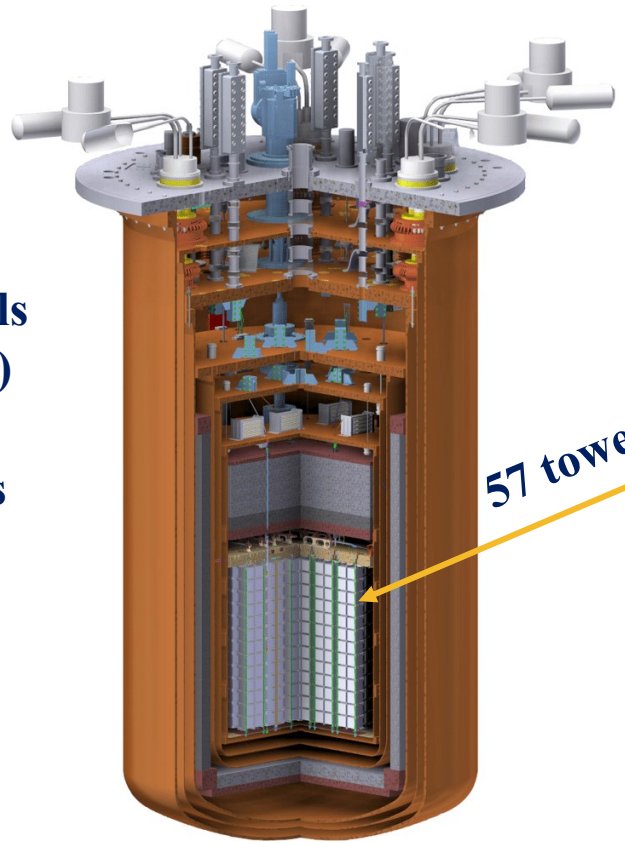
More than 99.9% α particles rejection efficiency

CUPID baseline structure

1596 enriched $Li_2{}^{100}MoO_4$ crystals (>95% enrichment)

1710 light detectors

240 kg of ^{100}Mo



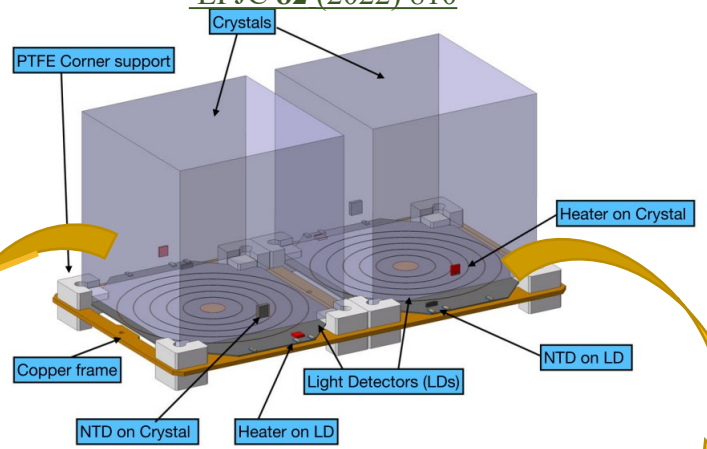
CUORE cryostat and shielding

+ additional muon-veto system & neutron shields

57 towers

14 floors each with 2 crystals

EPJC **82** (2022) 810



$Li_2{}^{100}MoO_4$ crystal

- 45 x 45 x 45 mm^3
- Thermal sensor: NTD Ge thermistor

EPJC **85** (2025) 935

EPJC **85** (2025) 737

Ge light detector

- Thin Ge wafer (<1 mm thickness)
- Thermal sensor: NTD Ge thermistor
- SiO antireflective coating (enhances light collection by ~ 30 %)
- Exploiting Neganov-Trofimov-Luke effect for signal amplification

Single CUPID tower can be tested in LNGS

- GDPT test in the past
- VSTT test now

INFN + CNRS/CEA + DOE

IJCLab CEA/IRFU LP2i IP2I SIMaP

CUPID background

Background model based on

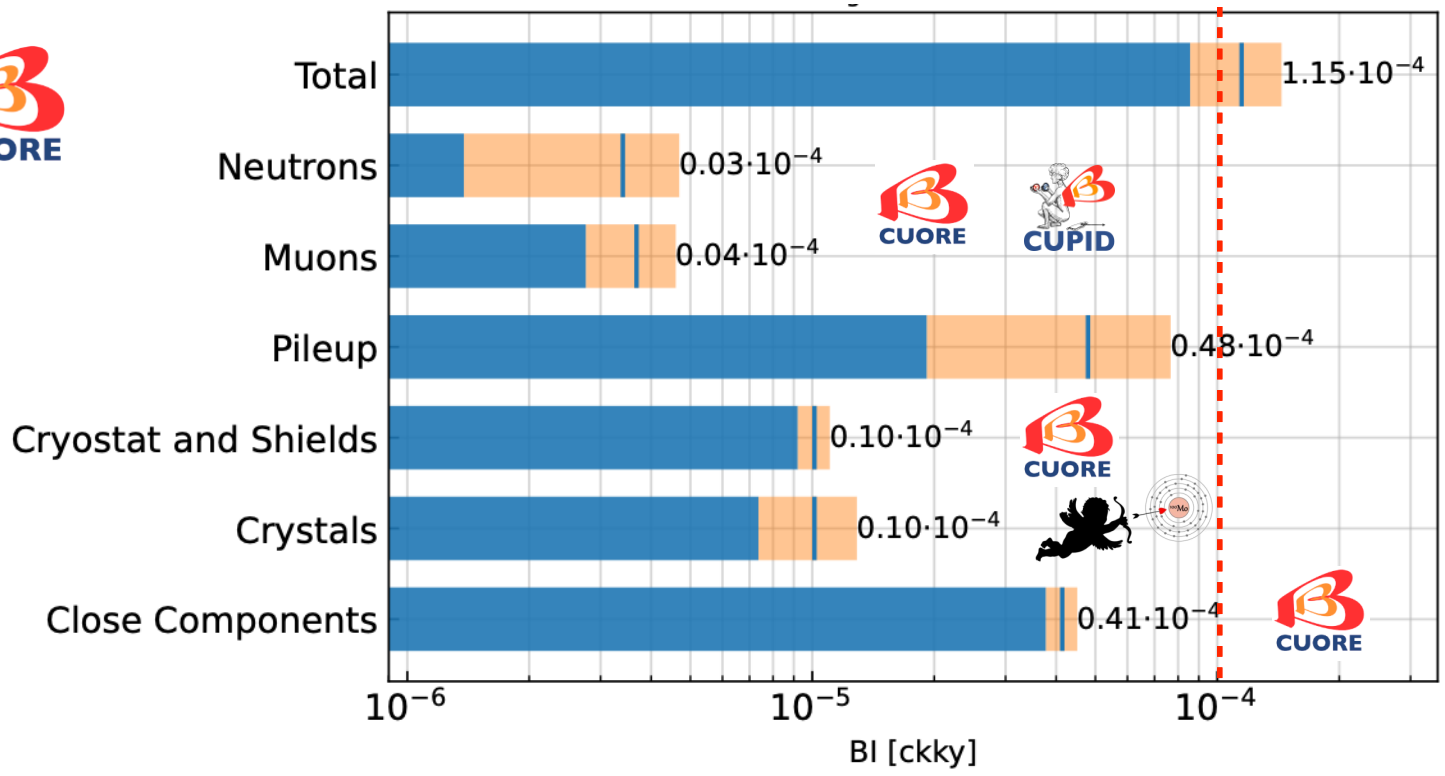
- reconstruction of the background in the cryostat from CUORE analysis
  Phys. Rev. D 110, 052003 (2024)

- results from CUPID-Mo on α particles rejection and radiopurity of Li_2MoO_4 crystals
  EPJC 82 (2022) 1033
  EPJC 83 (2023) 675

- simulations of μ and n shields
  JINST 20 (2025) P08020

- simulations of pile-up rejection efficiency
  EPJC 83 (2023) 373
  arXiv:2507.15732

CUPID background projections



CUPID goal: 10^{-4} ckky

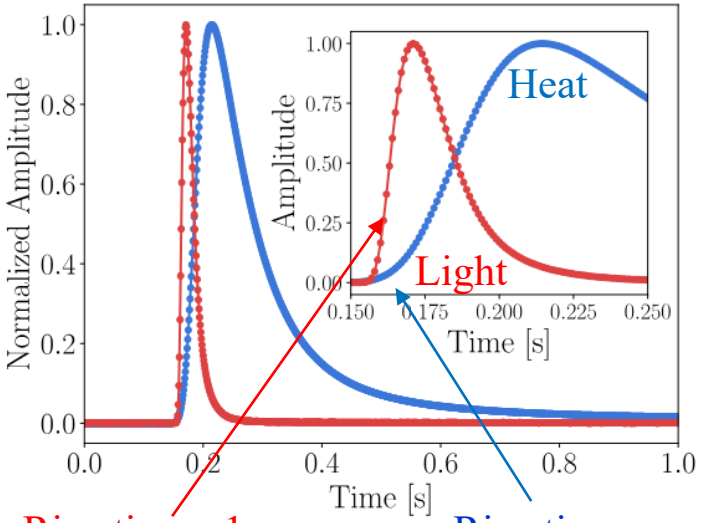
Main contributions to the background: pile-ups and close components

Pile-ups

$T_{1/2}^{2\nu\beta\beta}(^{100}\mathrm{Mo}) = 7.1 \cdot 10^{18}$ years

Δt = 1 ms -> BI $= 3.3 \cdot 10^{-4}$ ckky due to random coincidences of 2ν2β decay

resolving time must be decreased to 0.17 ms to meet CUPID background target



Rise-time ~1 ms (can be decreased to 0.4-0.5 ms)

Rise-time ~ 15 ms

Crucial parameters for pile-up events rejection

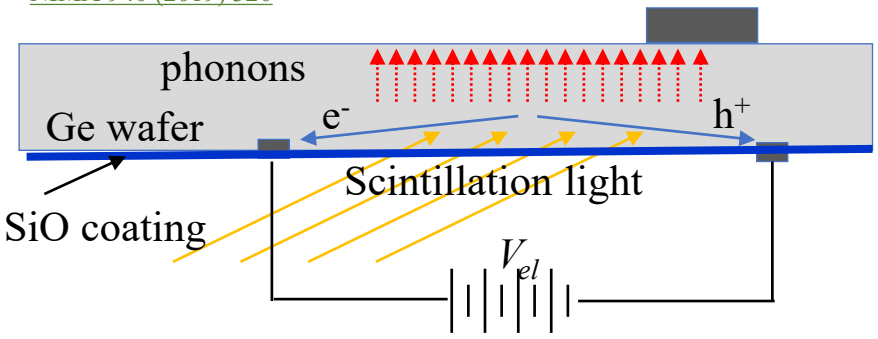
Rise-time → can be decreased to 0.4-0.5 ms

Signal-to-noise ratio → gain in SNR ~10

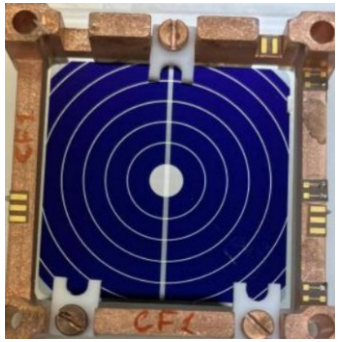
arXiv:2507.15732

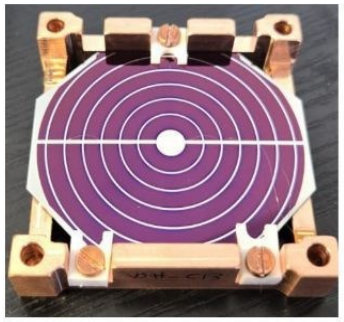
Neganov-Trofimov-Luke light detectors

NIMA 940 (2019) 320



$$E_{tot} = E_0 \cdot G_{NTL}$$
$$G_{NTL} \propto V_{ele}$$



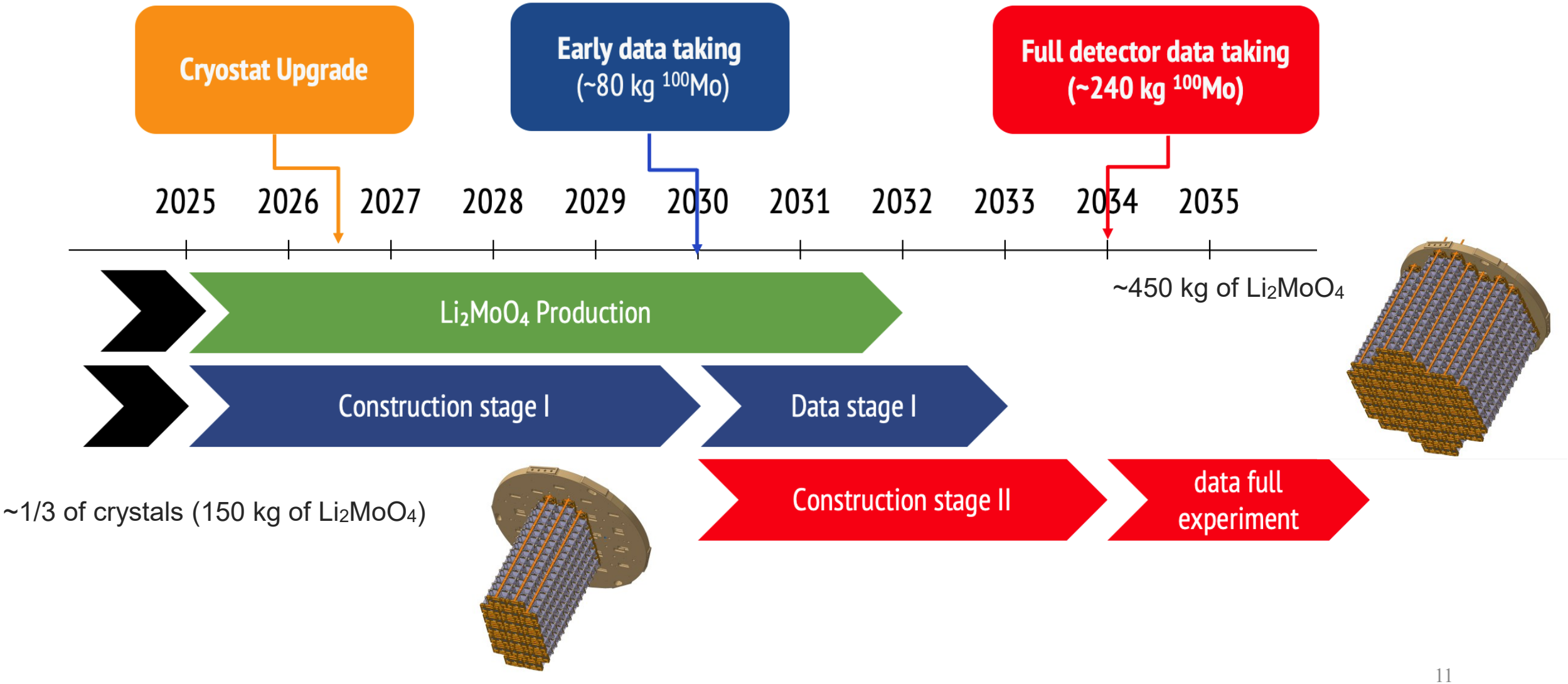


NTL technology developed in France

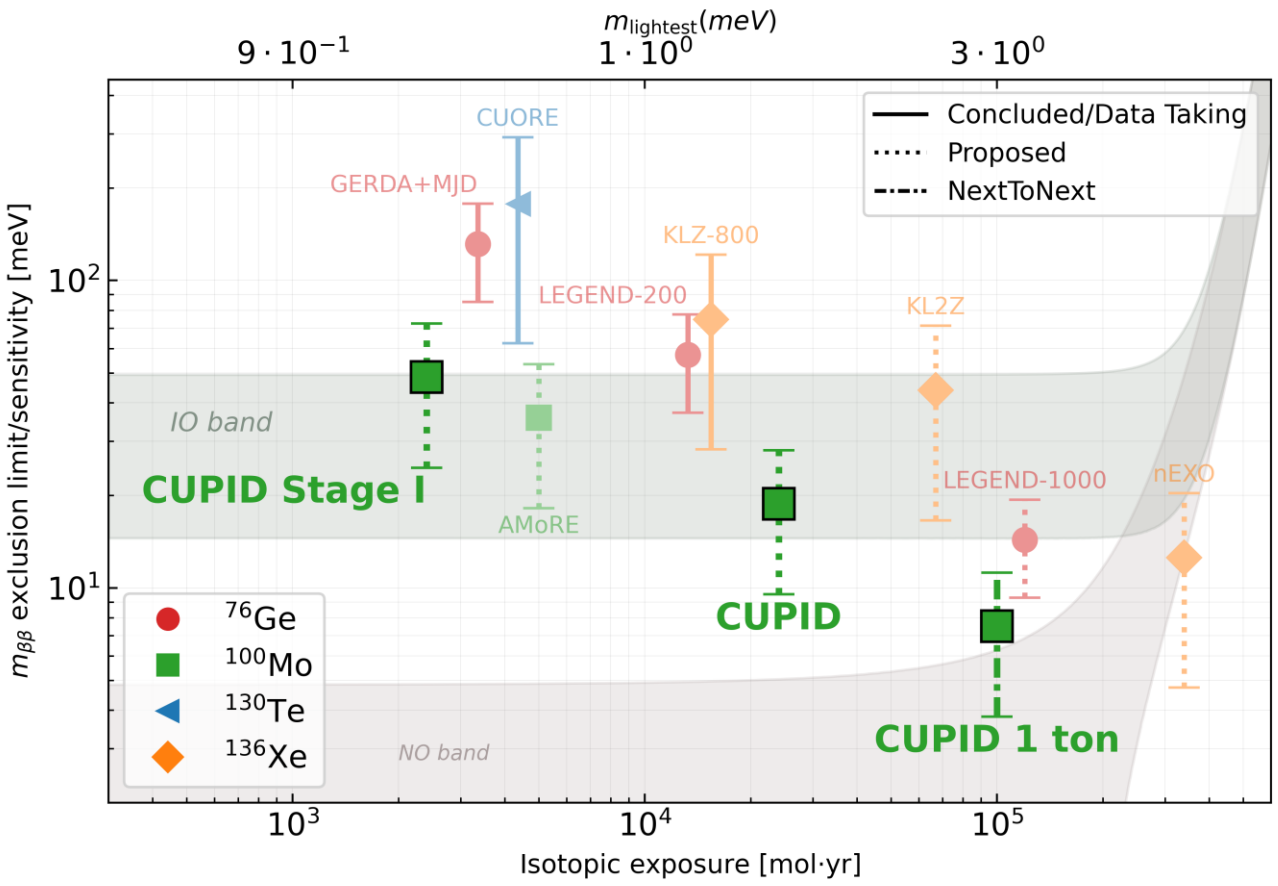
Ongoing tests:

- tests of different electrodes geometries
- tests of Si wafers
- studies on pile-ups rejection efficiency
- gluing procedure of thermal sensors to the wafer

CUPID timeline



CUPID sensitivity



arXiv:2504.14369

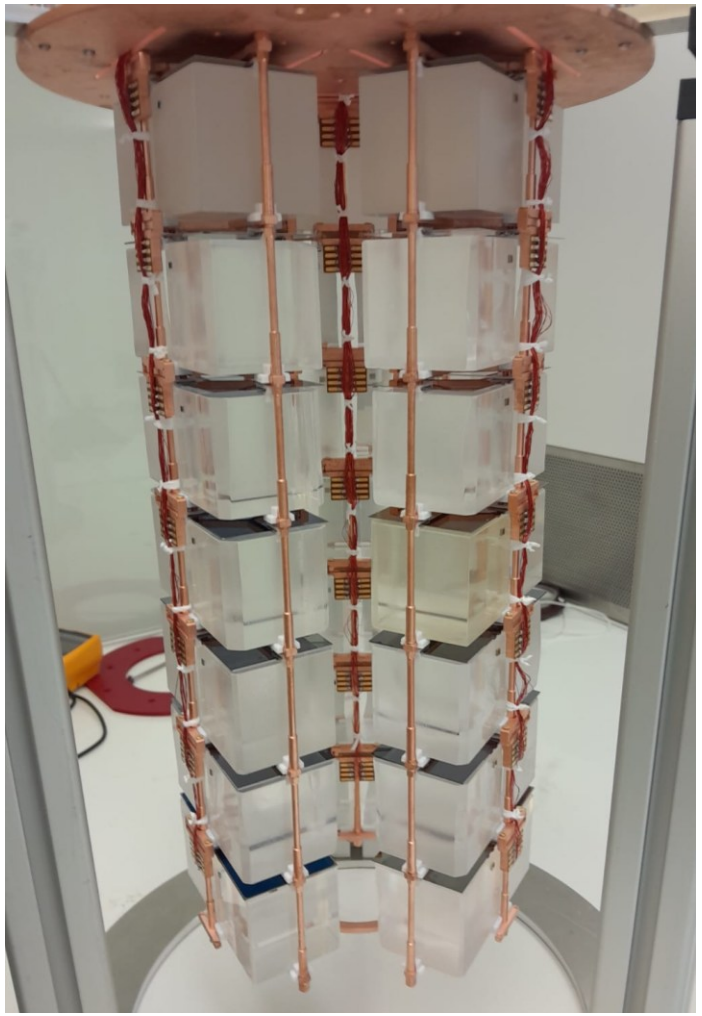
3σ discovery sensitivity: $\mathbf{T_{1/2}^{0\nu\beta\beta} = 1 \cdot 10^{27}yr}$, corresponding to $\mathbf{m_{\beta\beta} = (12.2 - 35.9)\ meV}$

Exclusion sensitivity (at 90% C.L.):
$\mathbf{T_{1/2}^{0\nu\beta\beta} > 1.8 \cdot 10^{27}yr}$,
corresponding to $\mathbf{m_{\beta\beta} < (9.6 - 28.3)\ meV}$

CUPID Stage I has world-leading scientific reach

CUPID is a ton scale experiment with competitive sensitivity and possibility of scaling (CUPID-1T)

CROSS experiment



Location:
Laboratorio Subterráneo de Canfranc (LSC), Spain (2450 m. w. e.)

Detectors structure

3 towers, each with 14 crystals (7 floors)

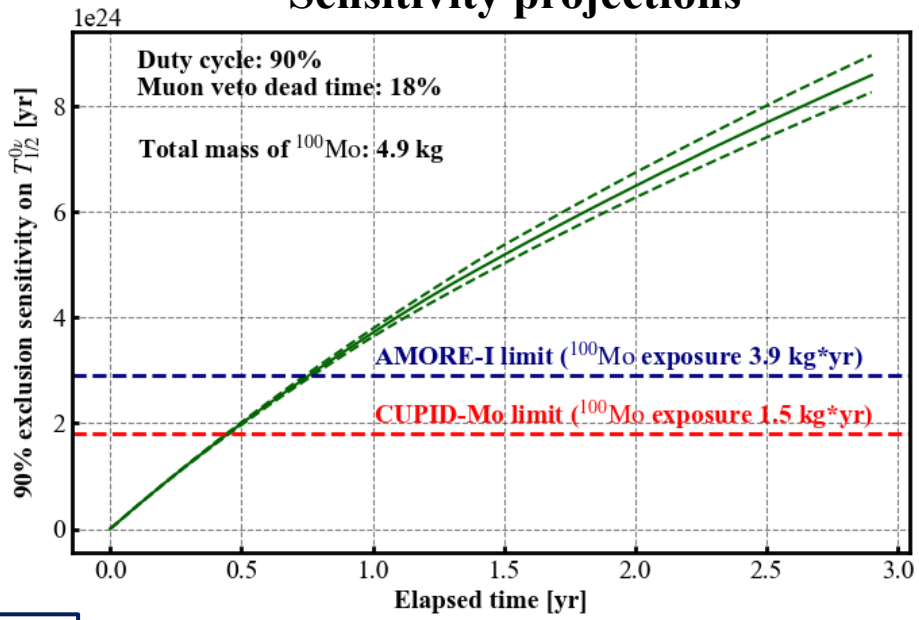
- 6 $^{130}TeO_2$ crystals (enrichment level > 90%)
- 36 Li_2MoO_4 (32 enriched)
- 42 NTL LDs
  - 28 Germanium
  - 16 Silicon

Mass of ^{100}Mo: 4.9 kg

Main objectives

- competitive experiment on the ^{100}Mo $0\nu\beta\beta$
- **high statistics test of NTL LDs (Si and Ge) relevant for CUPID**
- **studies on pile-ups rejection efficiency**
- development of the electronics and DAQ
- probe of the assembly structure

Sensitivity projections



Current status

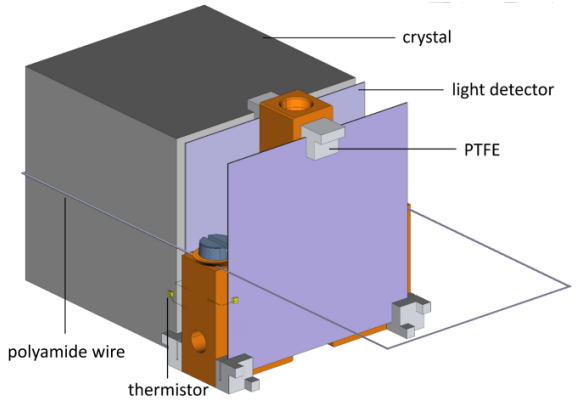
- detectors are installed and at the base temperature
- optimization of the working point of the detectors started

Leadership in IJCLab

Others R&D projects

BINGO (Bi-Isotope 0n2b Next Generation Observatory)

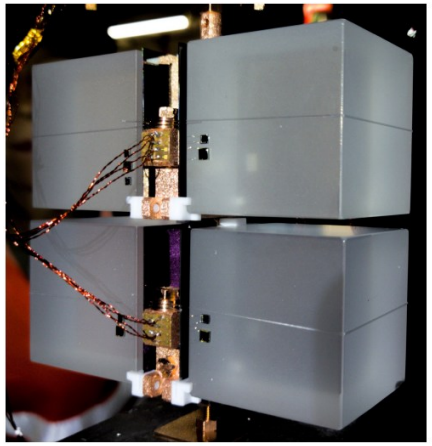
NIMA 1069 (2024) 169936



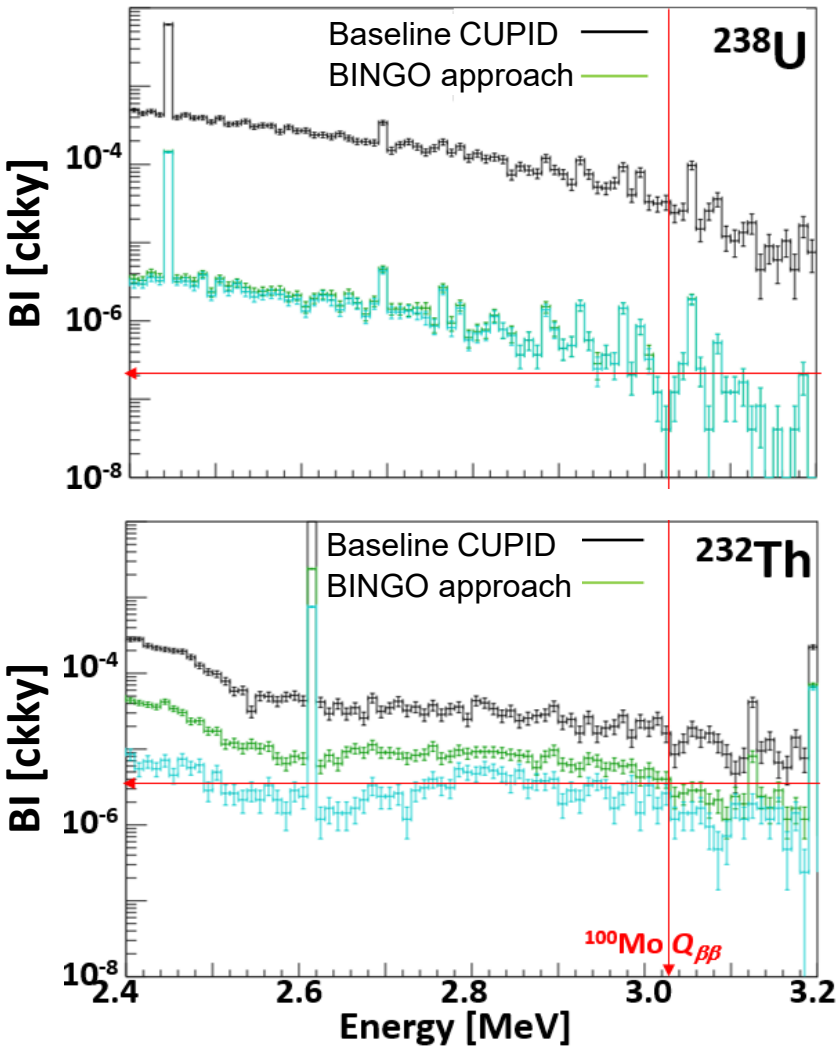
0νββ decay in ^{100}Mo and ^{130}Te

BINGO aims to reduce BI to 10^{-5} ckky using:

- innovative assembly structure reducing contribution from the close components
- active cryogenic veto to suppress background from high energy γ-s
- NTL light detectors for signal amplification



Cryogenic facility is ready in Modane, MINI-BINGO demonstrator to be installed in 2026



TINY (Two Isotopes for Neutrinoless double beta decay)

0νββ decay in ^{96}Zr and ^{150}Nd

- Searching for 0νββ decay in ZrO_2 and $NdGaO_3$ crystals
- Advantage of higher $Q_{\beta\beta}$: larger phase-space, lower background

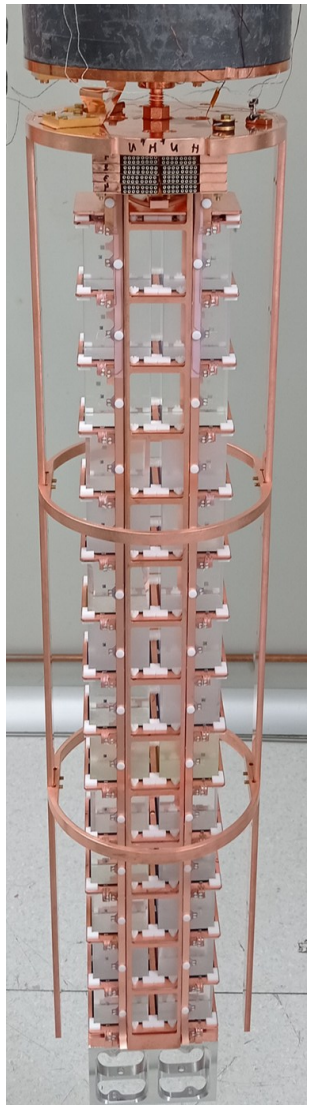
Leadership in CEA

Conclusions

- CUPID is an evolution of CUORE exploiting important innovation achieved in France:
  - Choice of Li_2MoO_4 crystals for the isotope ^{100}Mo
  - development of the NTL technology
- CUPID will be implemented in a staged approach:
  - CUPID-Stage-I has the potential to lead the field at the beginning of the next decade
  - Full CUPID will be a leading experiment with significant discovery potential
- On a longer time scale mass-scaling is possible (CUPID-1T)
  - BINGO approach: new avenues for the background reduction
  - TINY approach: explore the most favorable isotopes

Thank you for your attention!

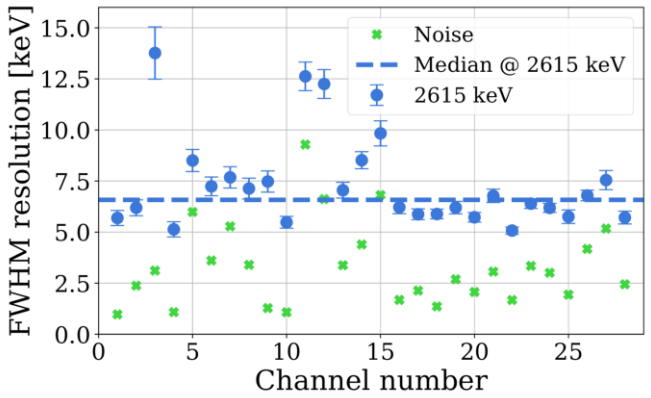
GDPT

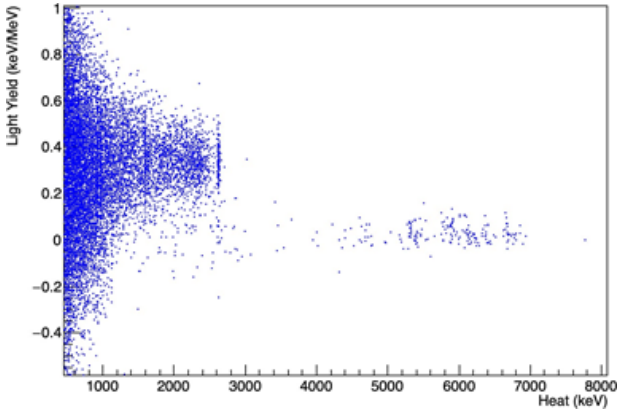


GDPT

(Gravity Design Prototype Tower)

- 28 LMOs
- 30 Ge light detectors without NTL effect
- Tested at LNGS, Italy in July-October, 2022





EPJC **85** (2025) 935

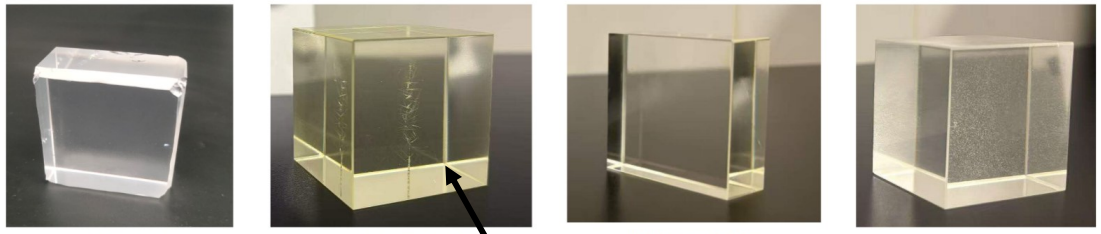
Results:

- Detectors successfully reached baseline temperature ~15 mK
- Baseline stable over the time
- LMO performance:
  median $FWHM_{2615\ keV}$ = 6.2 keV → close to CUPID target: 5 keV @ $Q_{\beta\beta}$
- 0.36 keV/MeV light yield (LY) measured by "close" LD → fulfills the CUPID target: 0.35 keV/MeV
- 0.31 keV/MeV LY measured by "far" LD
- some excess noise on the LD -> changes to the LD assembly structure for the next test

Crystallization in China & crystals result

IPCE + SICCAS: production and experimental tests

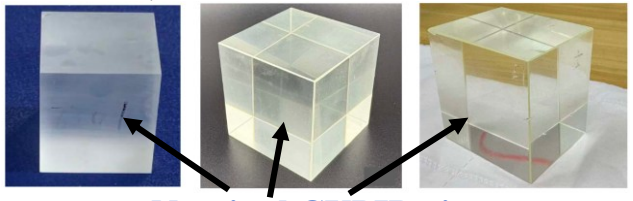
- Pre-production – French + Italian contracts
- **Seven** enriched crystals **produced** so far (**Bridgman method**)



LMO-600 45×45×21 mm³ | LMO-G8382 45×45×45 mm³ | LMO-G8383 45×45×19 mm³ | LMO-G8384 45×45×38 mm³

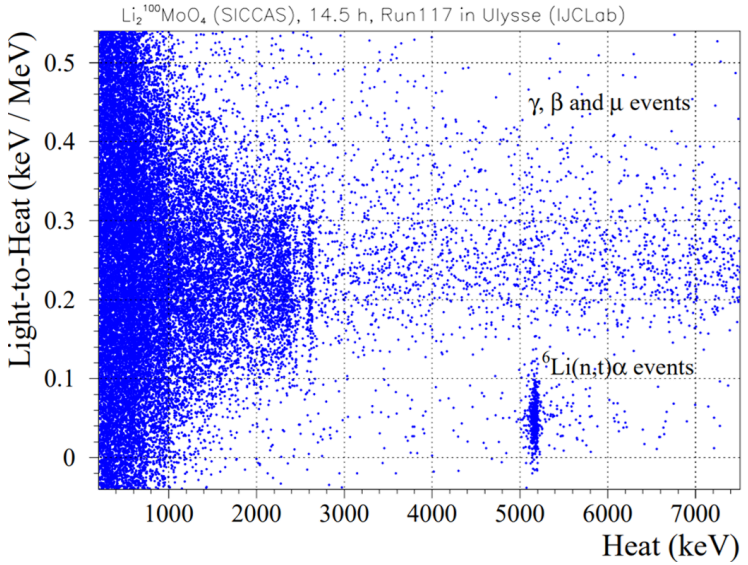
Nominal CUPID size

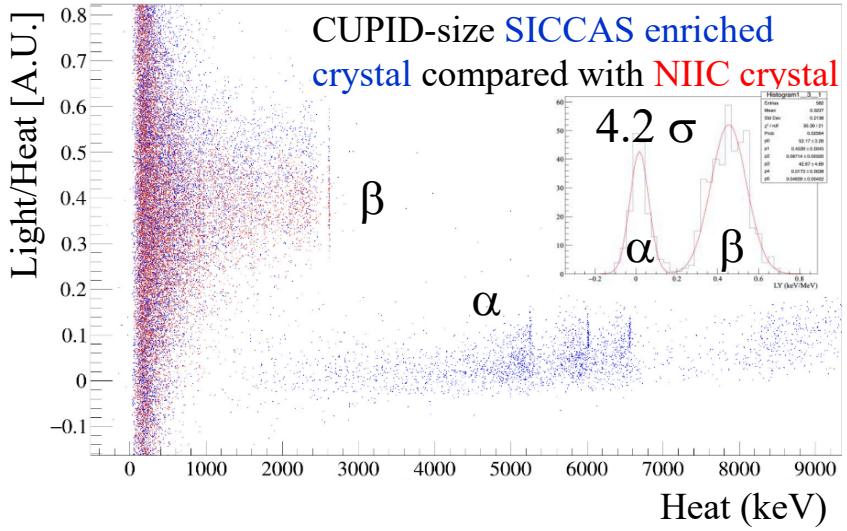
- **Four** crystals have been **tested** in IJCLab, LNGS and CEA/IRFU
- **Three** additional CUPID-size crystals will be tested at LNGS soon



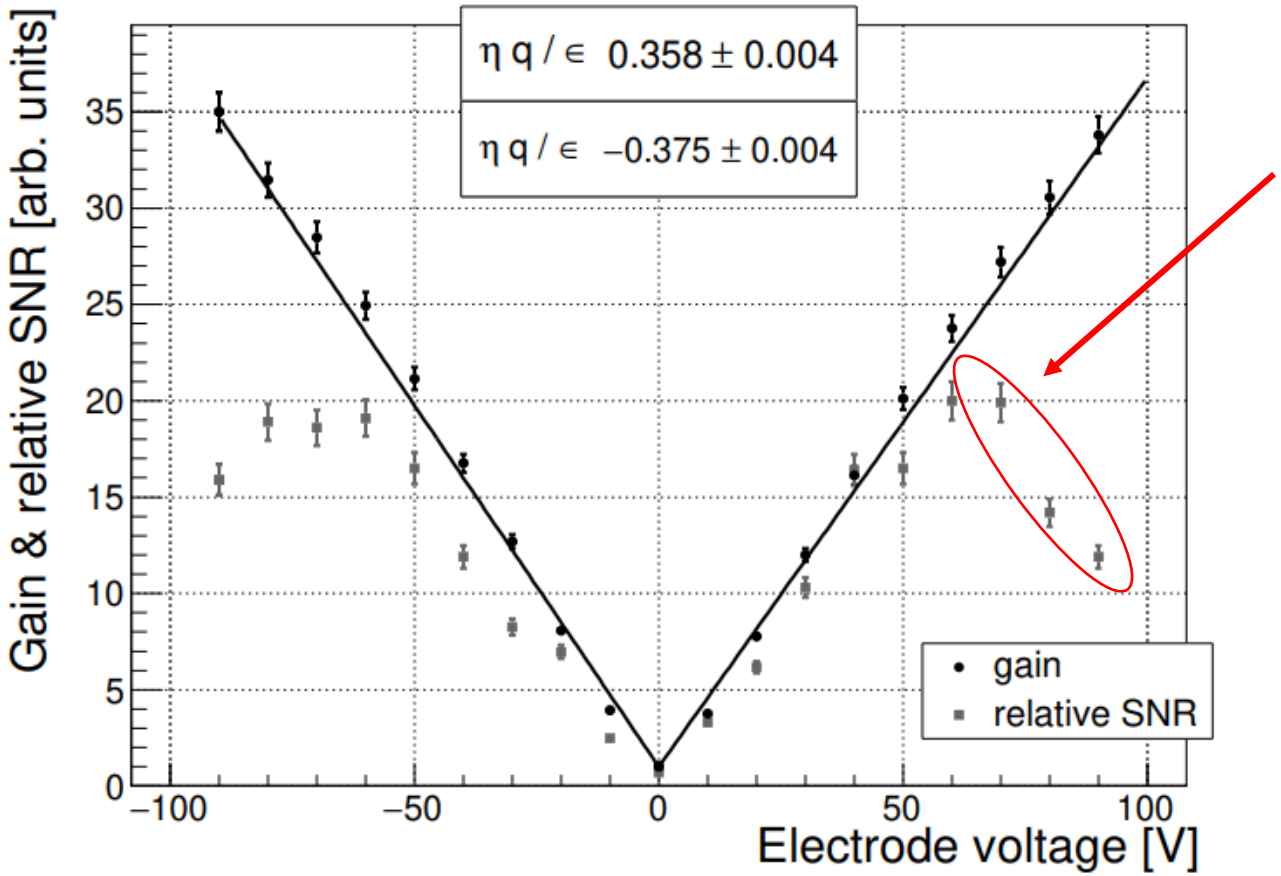
Nominal CUPID size

- **Results** obtained with the tested crystals show that:
  - Sensitivity complies with CUPID goal energy resolution
  - LY is similar or even higher than for Russian crystals (0.24 – 0.45) keV/MeV depending on geometrical configuration)
  - α/β discrimination power is well within CUPID goals
  - Pulse shape is compatible with that obtained with Russian crystals





NTL gain



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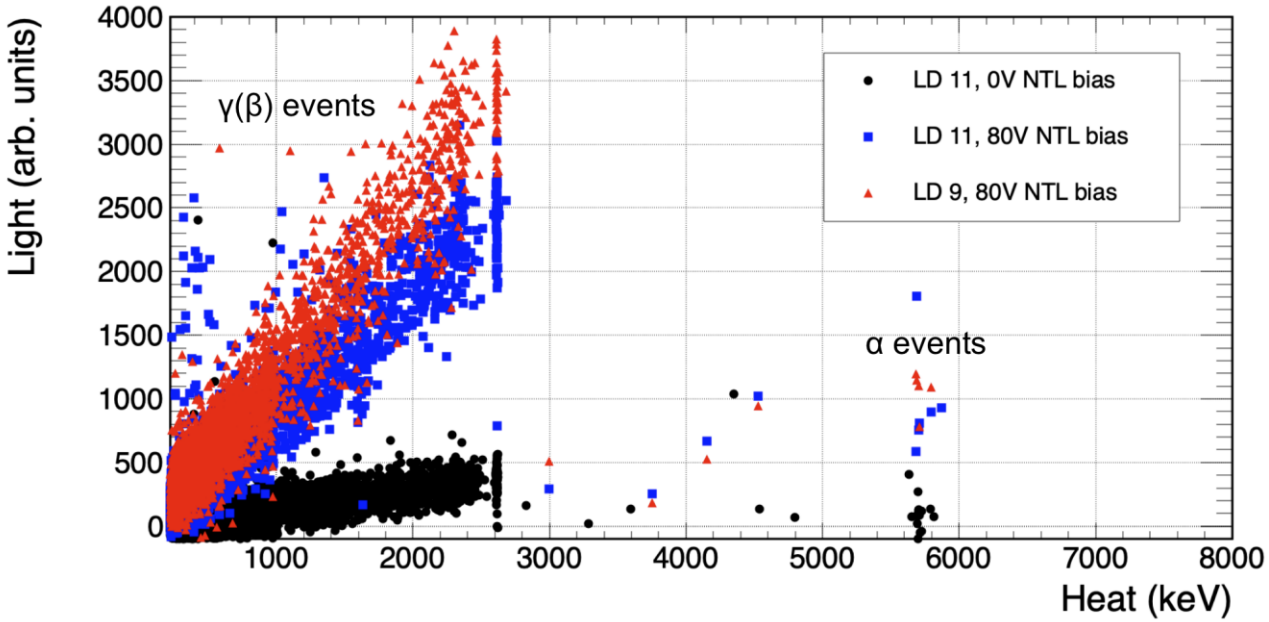
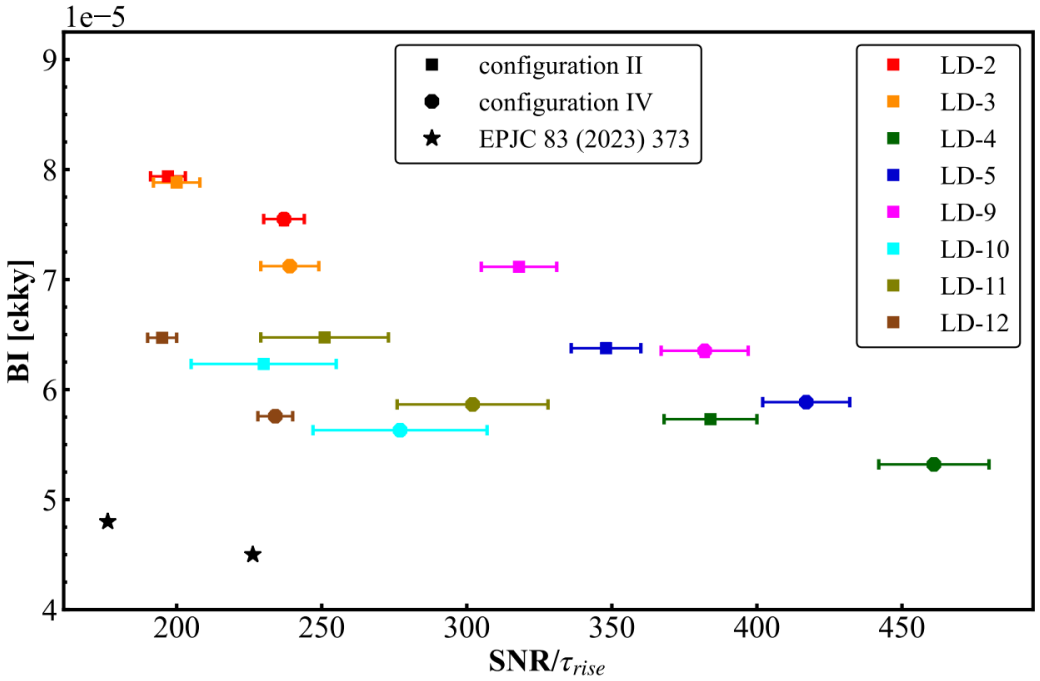
Operation challenges

- Extra noise production after certain voltage threshold → need to search for the optimal V_{el}
- Limitation of the applied voltage: after certain threshold of V_{el} there is leakage current and we heat up the cryostat

NTL amplification





BI from pile-ups contribution for different NTL LDs

arXiv:2507.15732

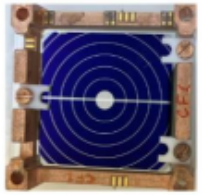
CROSS detectors composition

	Tower 1		Tower 2		Tower 3	
Light detector	Ge Spiral	Ge Spiral	Ge Conc	Ge Conc	Ge Conc	Ge Conc
Crystal	enr TeO2	enr TeO2	enr TeO2	enr TeO2	enr TeO2	enr TeO2
Light detector	Si Spiral	Si Spiral	Si Spiral	Si Spiral	Ge Spiral	Ge Spiral
Crystal	dep LMO	enr LMO	enr LMO	enr LMO	enr LMO	enr LMO
Light detector	Ge Spiral	Ge Spiral	Ge Conc	Ge Conc	Ge Conc	Ge Conc
Crystal	enr LMO	enr LMO	enr LMO	enr LMO	enr LMO	enr LMO
Light detector	Ge Spiral	Ge Spiral	Ge Conc	Ge Conc	Ge Spiral	Ge Spiral
Crystal	enr LMO	enr LMO	enr LMO	SICCAS LMO	SIMaP LMO	enr LMO
Light detector	Si Spiral	Si Spiral	Si Spiral	Si Spiral	Si Spiral	Si Spiral
Crystal	enr LMO	enr LMO	enr LMO	enr LMO	enr LMO	enr LMO
Light detector	Si Spiral	Si Spiral	Si Spiral	Si Spiral	Si Spiral	Si Spiral
Crystal	dep LMO	enr LMO	enr LMO	enr LMO	enr LMO	enr LMO
Light detector	Ge Spiral	Ge Spiral	Ge Conc	Ge Conc	Ge Conc Sq	Ge Spiral
Crystal	enr LMO	enr LMO	enr LMO	enr LMO	enr LMO	enr LMO

5 types of crystals

- 32 Enriched LMOs
- 6 Enriched TeO_2
- 2 Depleted LMO
- 1 LMO SICCAS
- 1 LMO SIMaP

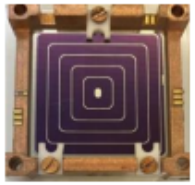
Spiral



Concentric rings

4 types of light detectors

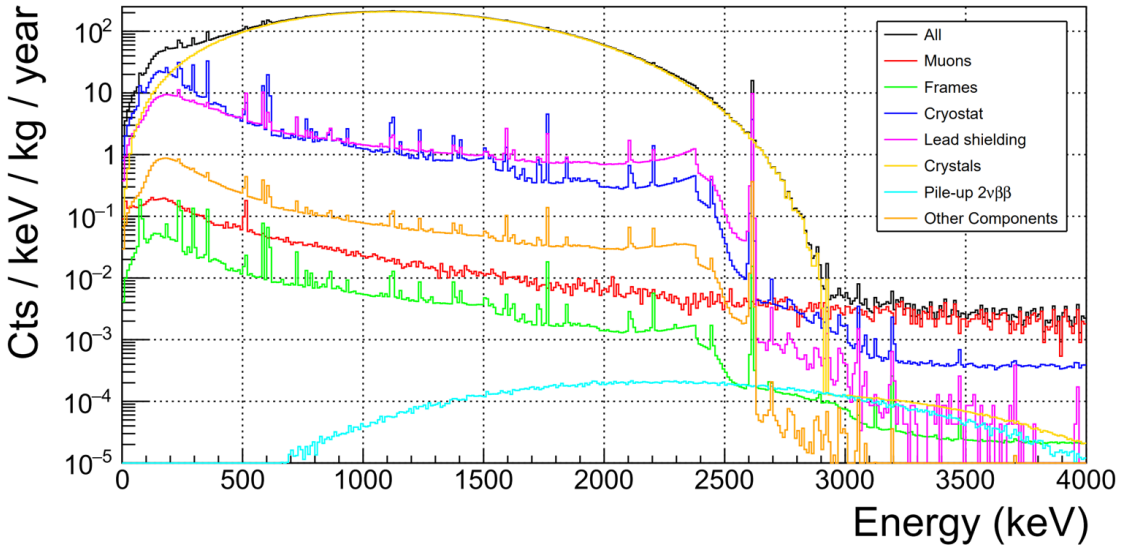
- 13 Ge spiral
- 16 Si spiral
- 12 Ge concentric rings
- 1 Ge concentric square

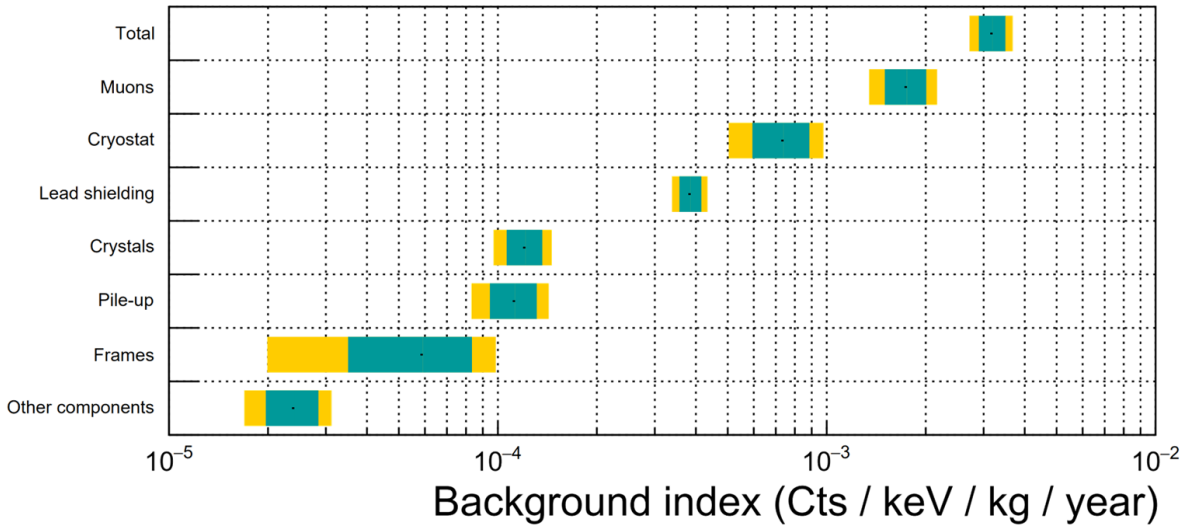


Concentric squares

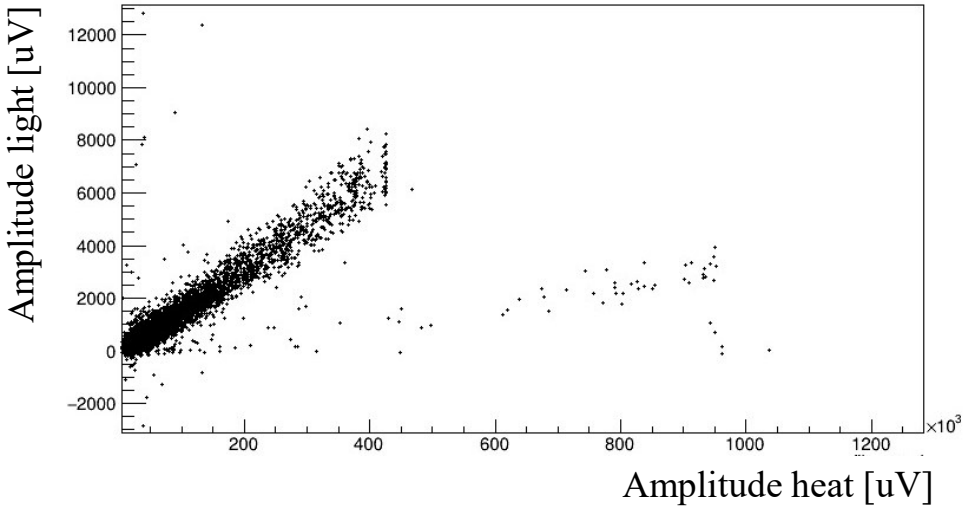
CROSS

Background estimations



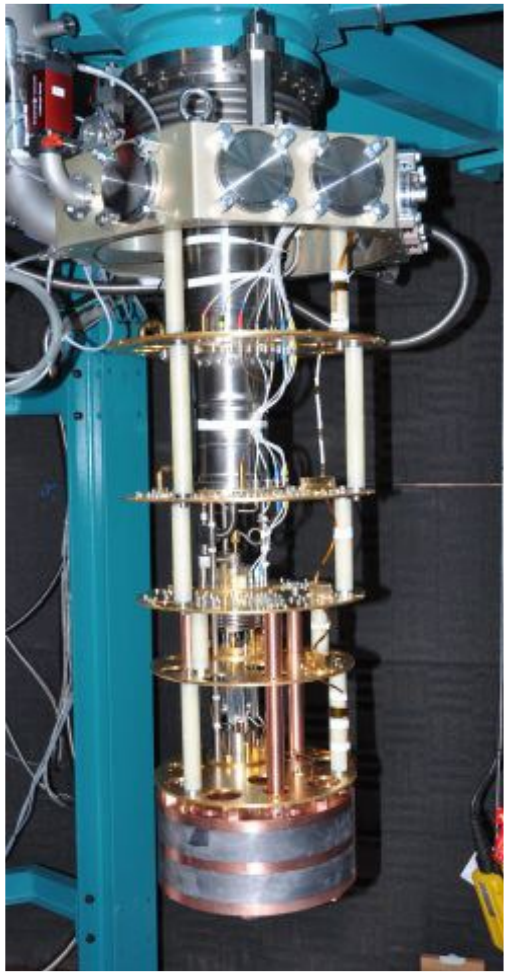


Total BI: $(3.2 \pm 0.5) \cdot 10^{-3}$ counts/keV/kg/year



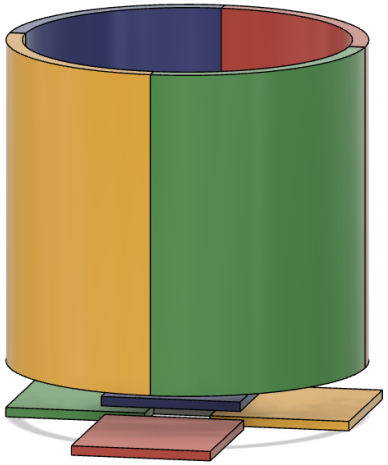
Scatter plot from the first test measurements

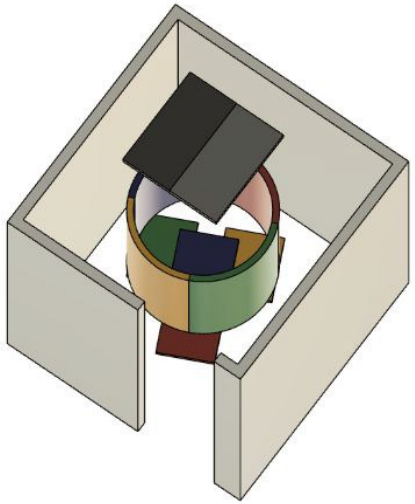
CROSS underground facility



Muon veto

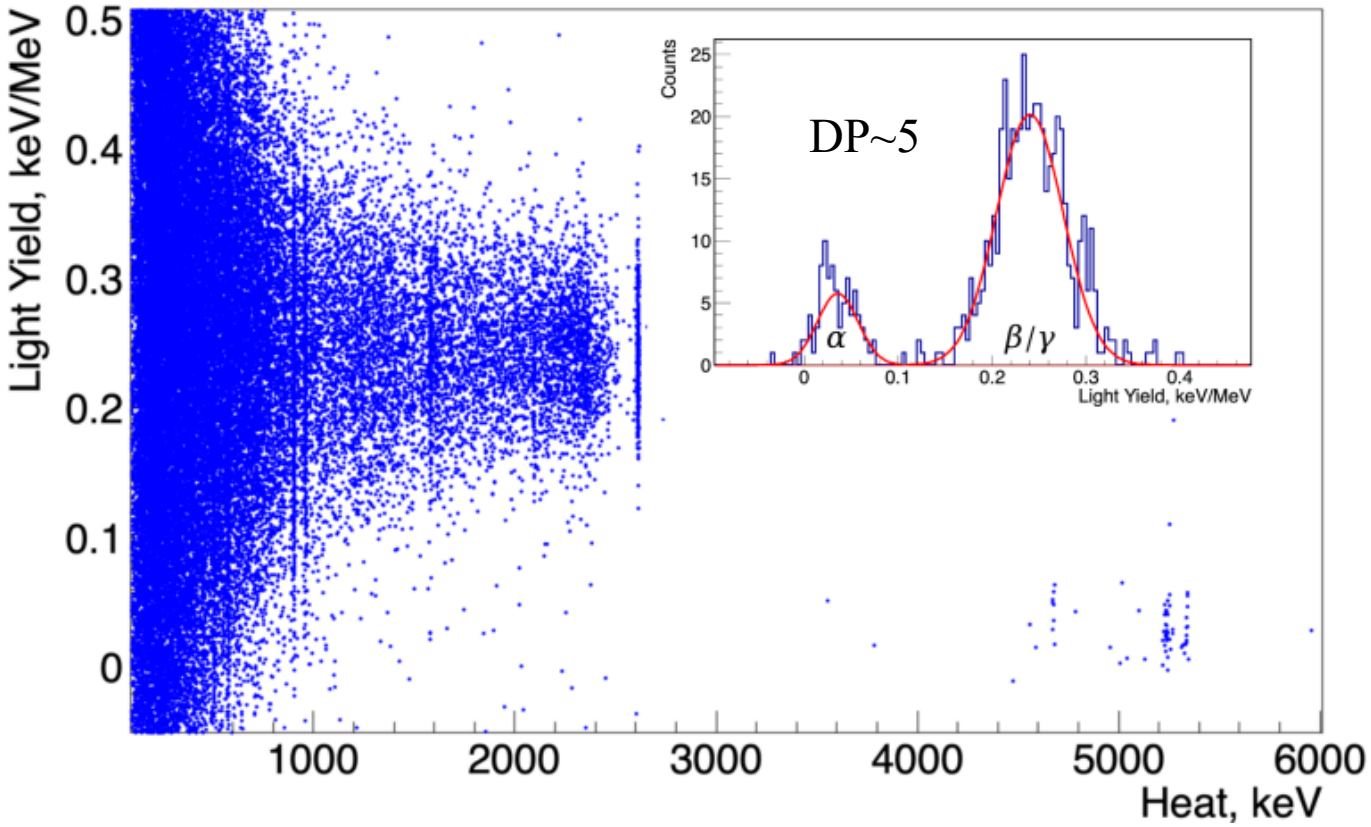
arXiv:2510.27406

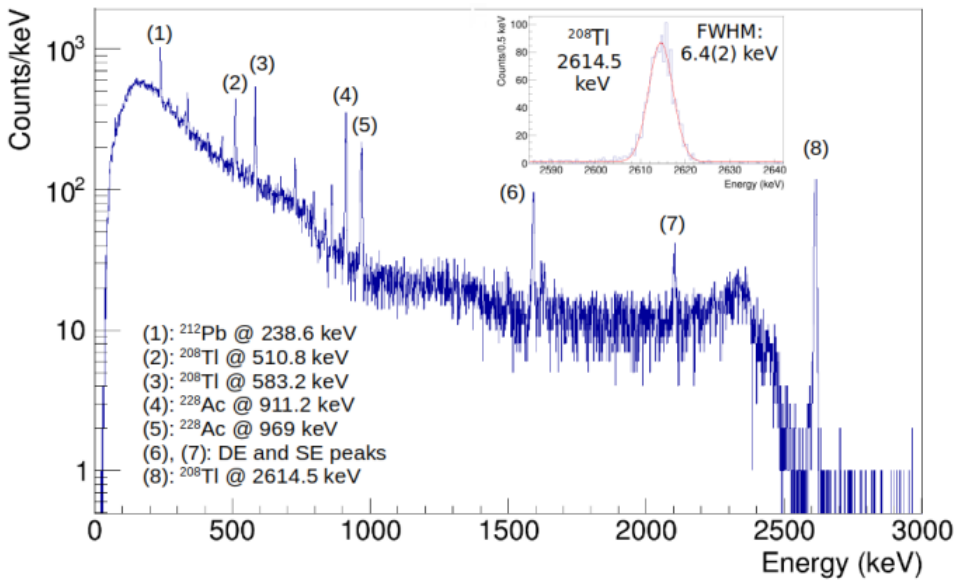




Scheme of the muon veto system

BINGO: recent results





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CUPID maturity

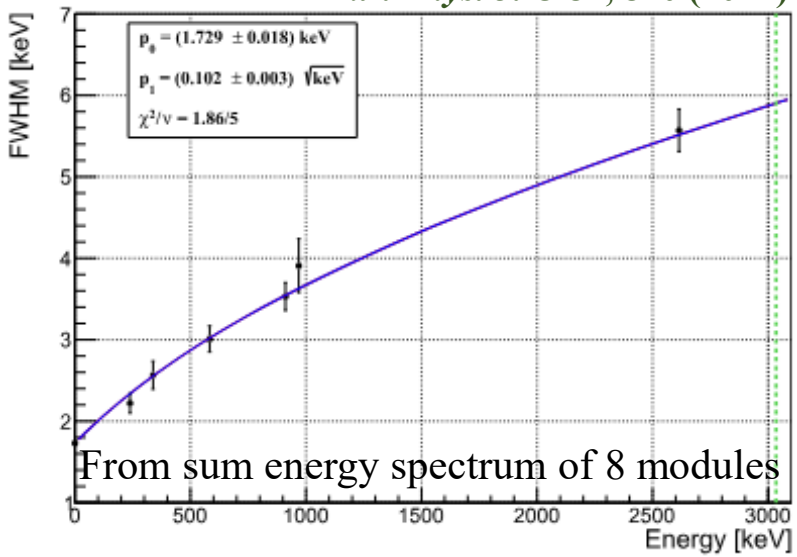
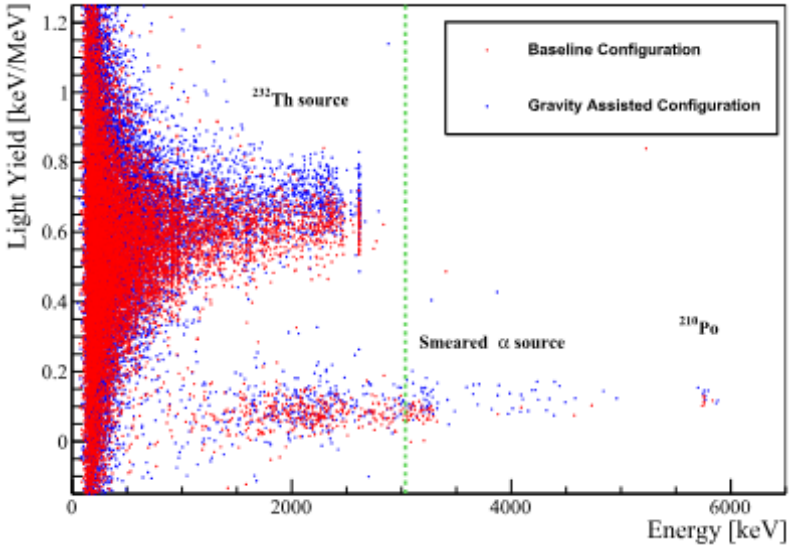
CUPID is a mature experiment, ready for construction

- High energy resolution (**5-7 keV FWHM**)
- Excellent α/β separation (**> 99.9% α rejection**)
- High radiopurity achievable (**≤ 0.5 μBq/kg in U/Th**)

demonstrated in tens of large mass scintillating bolometers based on enriched Li_2MoO_4 crystals

CUPID-Mo, GDPT, CUPID and CROSS prototypes

- **Enhanced-sensitivity light detectors** bring the 2ν2β-induced background down to the desired level

- An **enrichment-purification-crystallization** line is under advanced development in China, replacing the original Russian option

Eur. Phys. J. C 82, 810 (2022)