CUPID: bolometric searches for neutrinoless double beta decay

GDR Neutrino 2019

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CENTRE DE SCIENCES NUCLÉAIRES ET DE SCIENCES DE LA MATIÈRE

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Outline

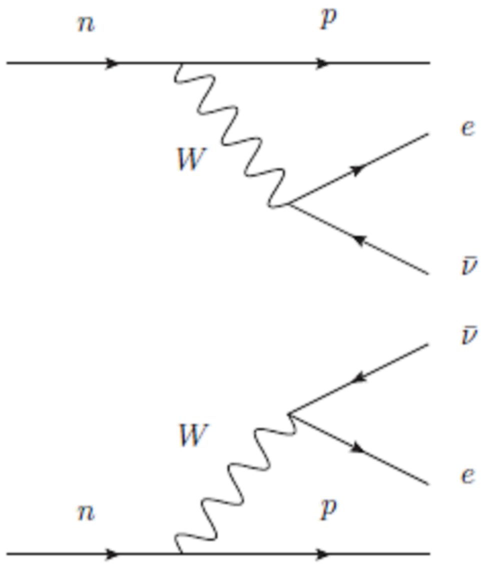
- **Neutrinoless double beta decay**
- **Signal and background**
- **Bolometric approach: from CUORE to CUPID**
- **CUPID-0 experiment**
- **CUPID-Mo experiment**
- **CUPID baseline configuration**
- **CROSS experiment**
- **Summary**

Double beta decay

$$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\nu_e$$

- One of the rarest observed nuclear decays
- Takes place between two even-even isobars
- Energetically allowed in 35 nuclei
- Experimentally observed in 11 isotopes with

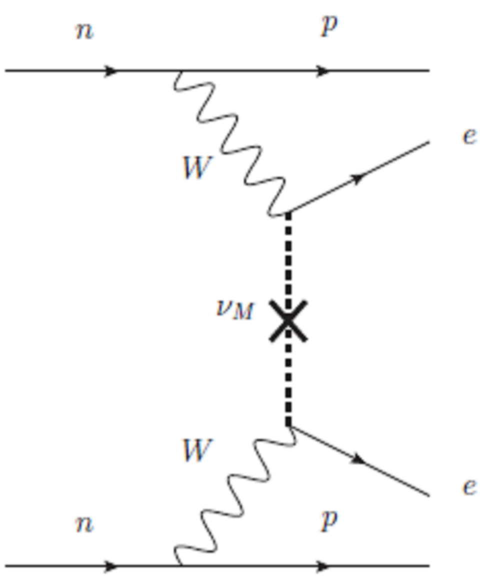
$T_{1/2}$ ($2\nu\beta\beta$): ~ 10^{18}-10^{24} years



$$(A,Z) \rightarrow (A,Z+2) + 2e^-$$

- $\Delta L=2$: total lepton number violation (LNV)
- This process would imply new physics beyond SM
- Never observed, half-life limits:

$T_{1/2}$ ($0\nu\beta\beta$) > 10^{25}-10^{26} years



Physics of $0\nu2\beta$

- If observed, neutrino is Majorana particle

$$\nu \equiv \bar{\nu}$$

- See-saw mechanism explains naturally small neutrino masses

- Lepton number violation gives clues on leptogenesis (matter and antimatter asymmetry)

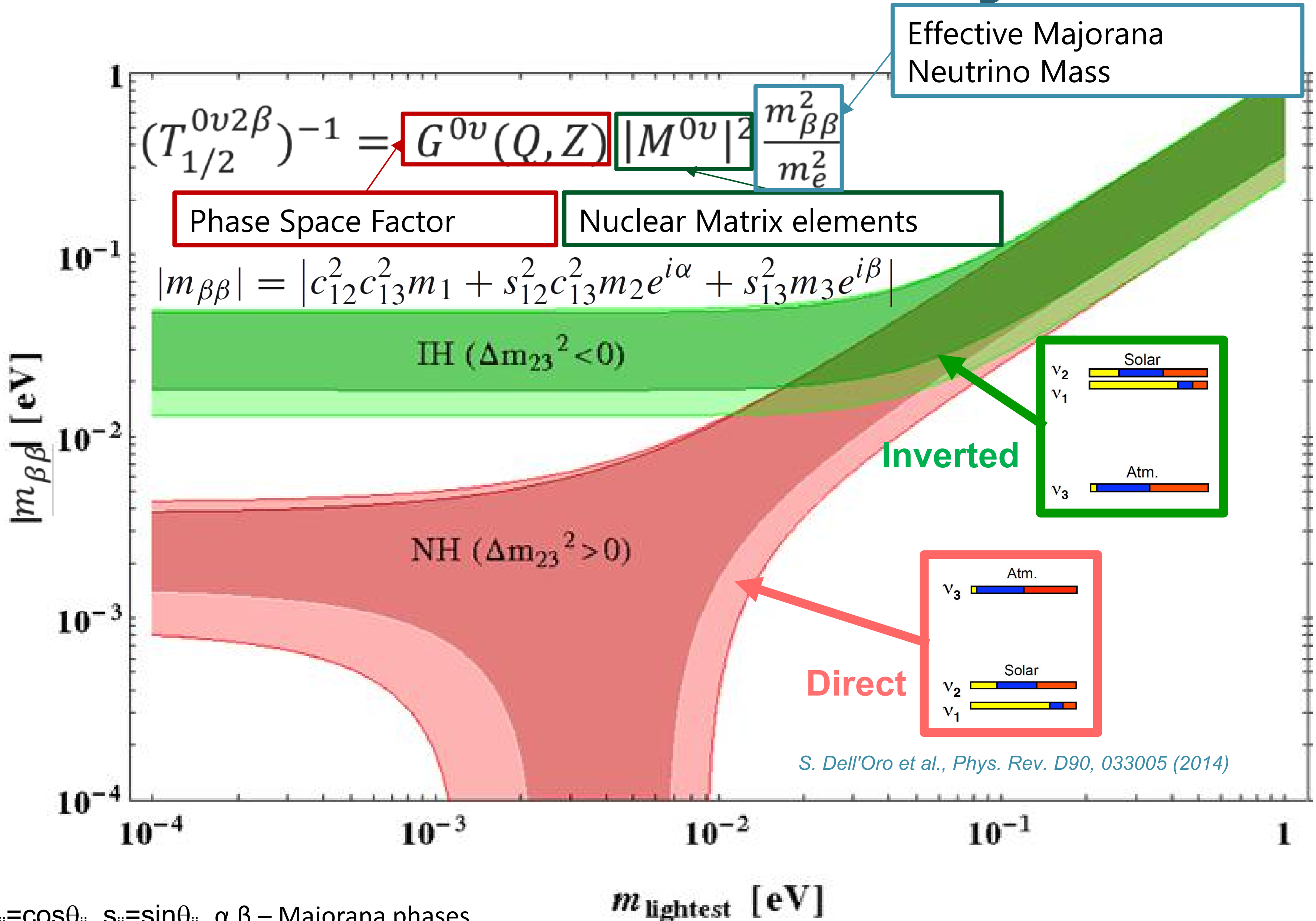
- Absolute neutrino mass scale determination and information on mass hierarchy

$0\nu2\beta$ mechanisms

Standard: require minimal extension of SM, $0\nu2\beta$ is mediated by light massive Majorana neutrinos

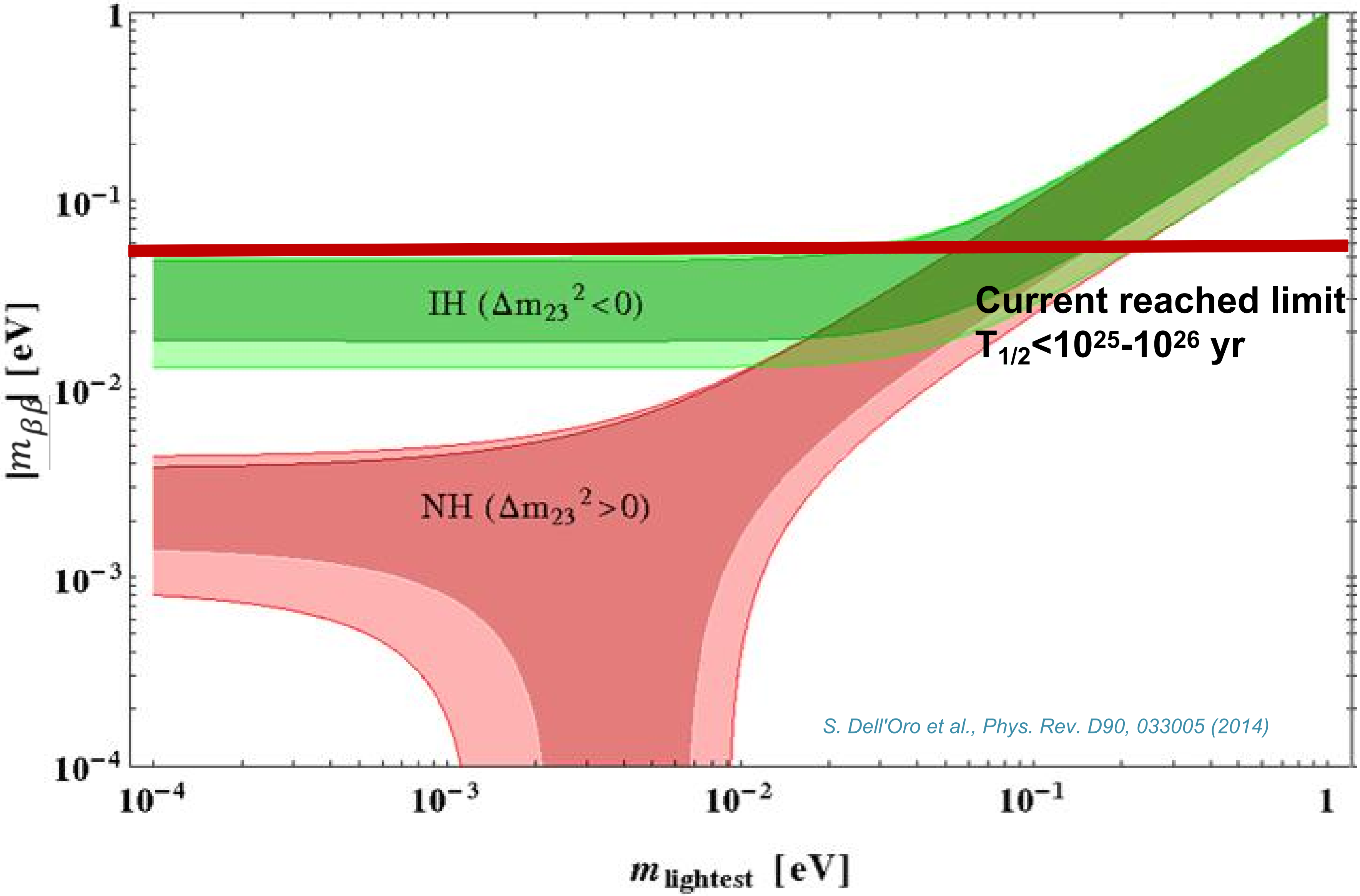
Non-standard: non necessarily neutrino physics

Neutrino mass hierarchy

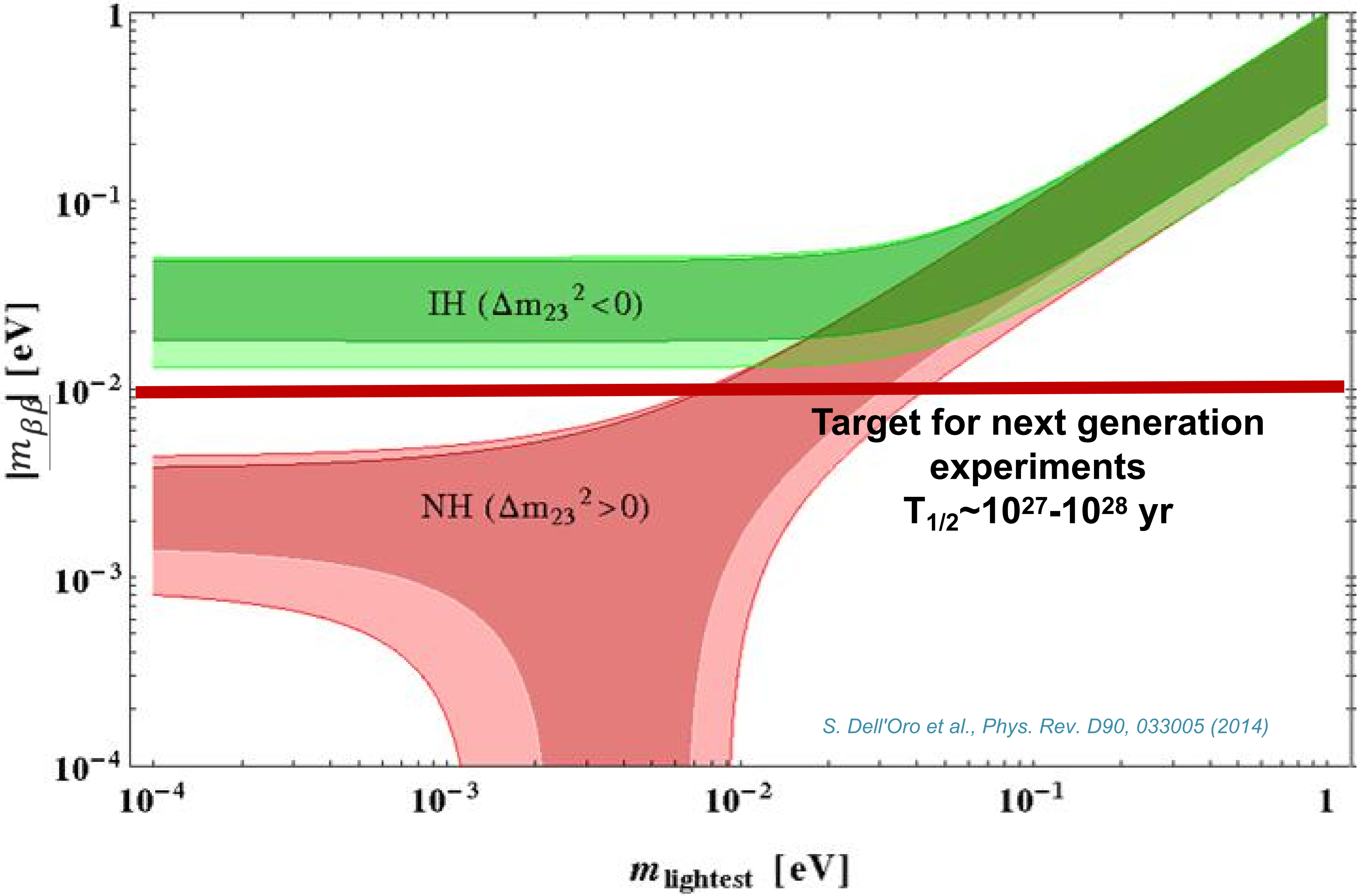


$c_{ij}=\cos\theta_{ij}$, $s_{ij}=\sin\theta_{ij}$, α,β – Majorana phases

Neutrino mass hierarchy



Neutrino mass hierarchy



Outline

- Neutrinoless double beta decay and sensitivity
- **Signal and background**
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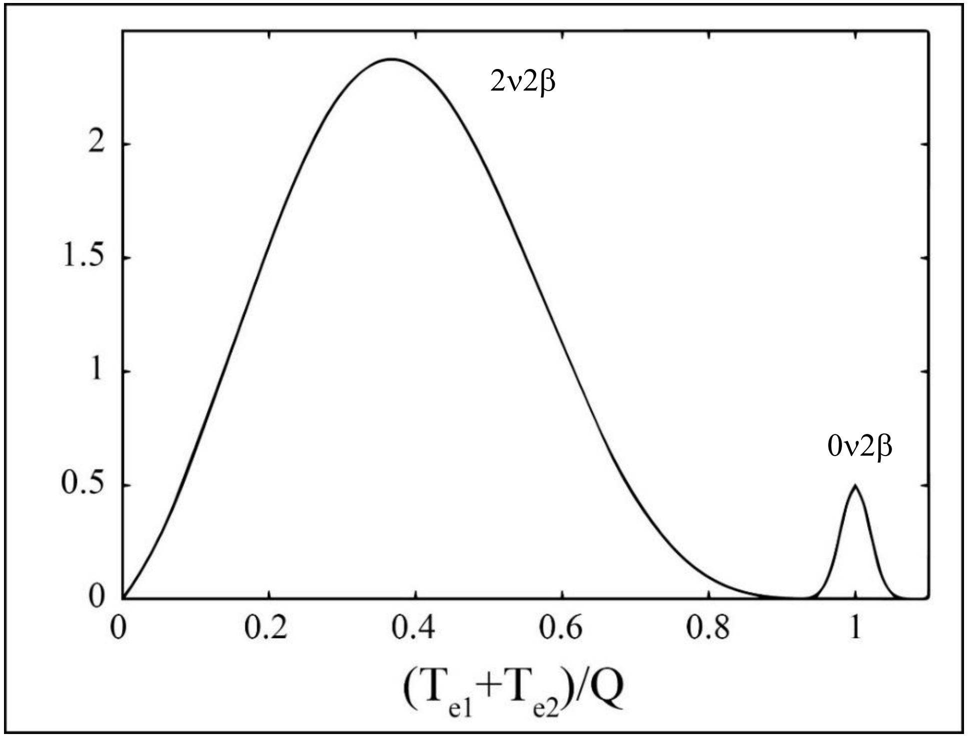
Experimental signature

- The shape of the two-electron sum-energy spectrum enables possibility to distinguish between the 0ν (new physics) and the 2ν decay modes



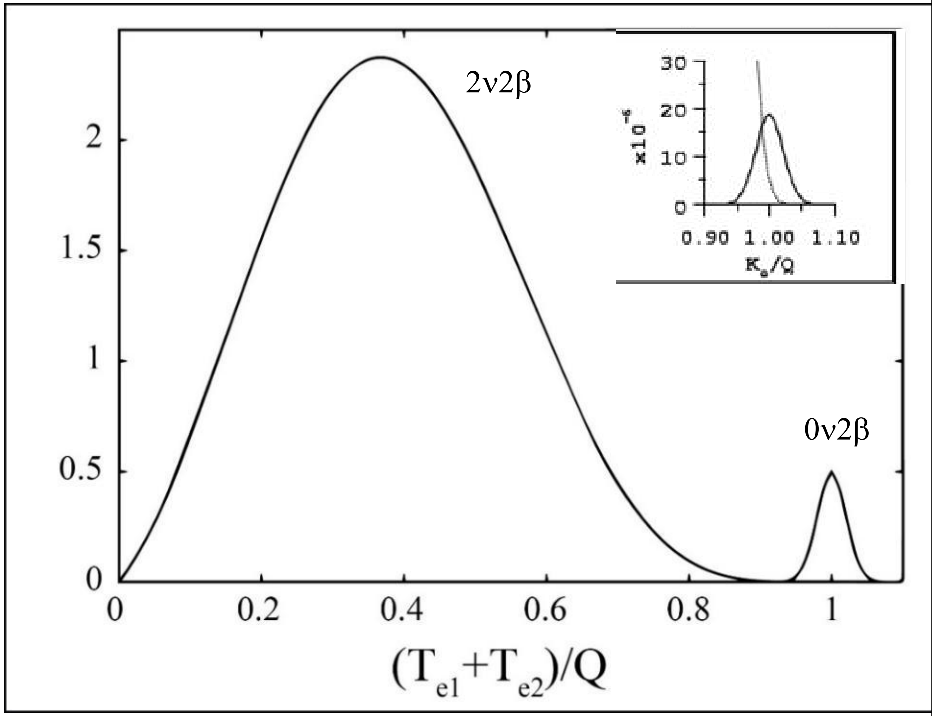
$Q_{\beta\beta}$~2-3 MeV for the most promising candidates

$2\nu2\beta$: continuum with maximum at ~1/3 $Q_{\beta\beta}$

$0\nu2\beta$: peak enlarged only by the detector energy resolution

Signal and background

- **Background sources:**
  - Natural radioactivity of materials: detectors themself, surrounding structures, radon
  - Cosmogenic induced activity
  - Neutrons
  - $2\nu2\beta$ decay
- **How to reduce:**
  - underground conditions
  - massive passive / active shields
  - high radiopurity of detectors



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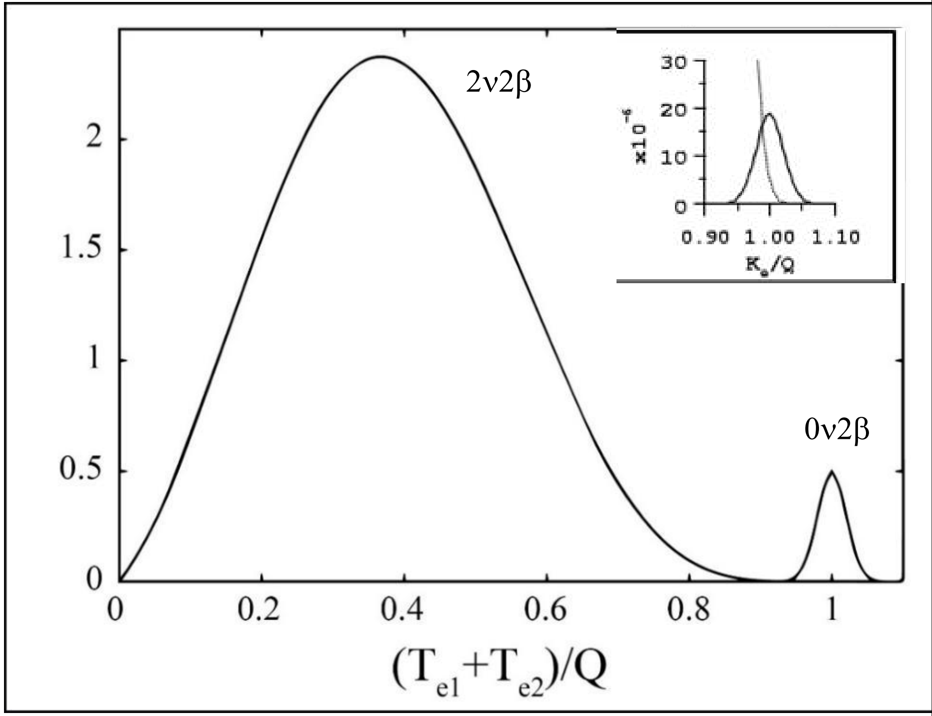


Background index: **b ≤ 10^{-4} *counts/(keV kg yr)* is mandatory** to cover completely inverted hierarchy with a **high energy resolution (<10 keV FWHM)** experiment as CUPID - even lower background levels are required for experiments with lower energy resolution.

Background index

$$T_{1/2}^{0\nu 2\beta} \propto \mathbf{a} \cdot \epsilon \cdot \sqrt{\frac{\mathbf{M} \cdot t}{\mathbf{b} \cdot \delta E}}$$

What if there is no background?

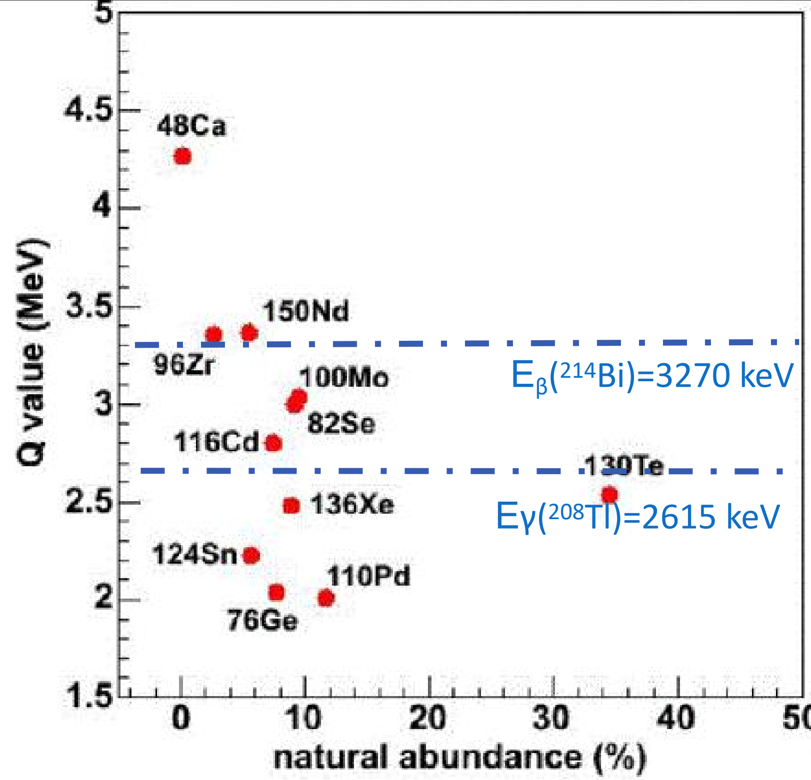
Background index can be
so small that background is
actually zero with high C.L. for
a given exposure real experiment

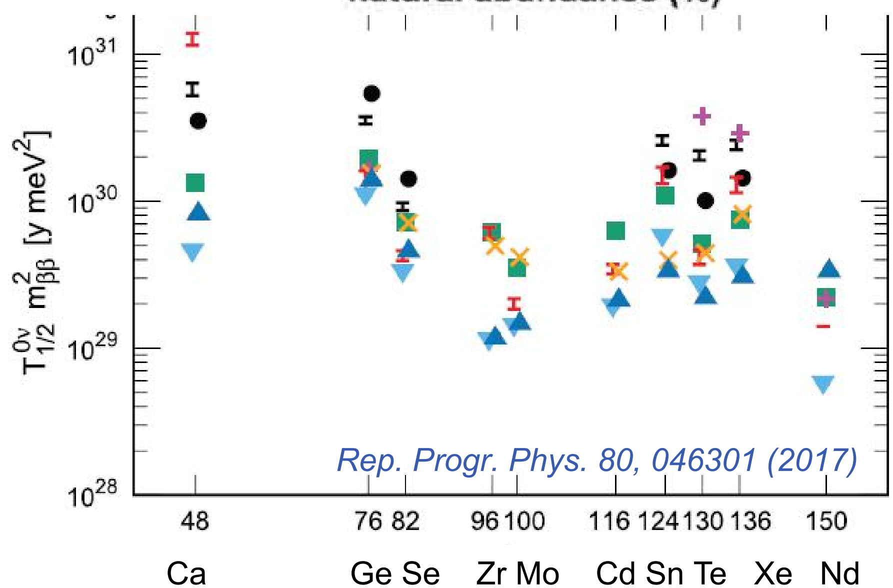
In case of $\mathbf{b} \cdot \Delta\mathbf{E} \cdot \mathbf{M} \cdot \mathbf{t} \ll 1$:

$$T_{1/2}^{0\nu 2\beta} \propto \mathbf{a} \cdot \epsilon \cdot M \cdot t$$

Isotopes selection

- Energetically allowed only for 35 nuclei
- Q-value is the crucial factor:
  - Phase space factor: $G(Q,Z) \sim Q^5$
  - Natural background level
- Natural abundance and enrichment possibility are essential
- Theoretical predictions on half-life are important





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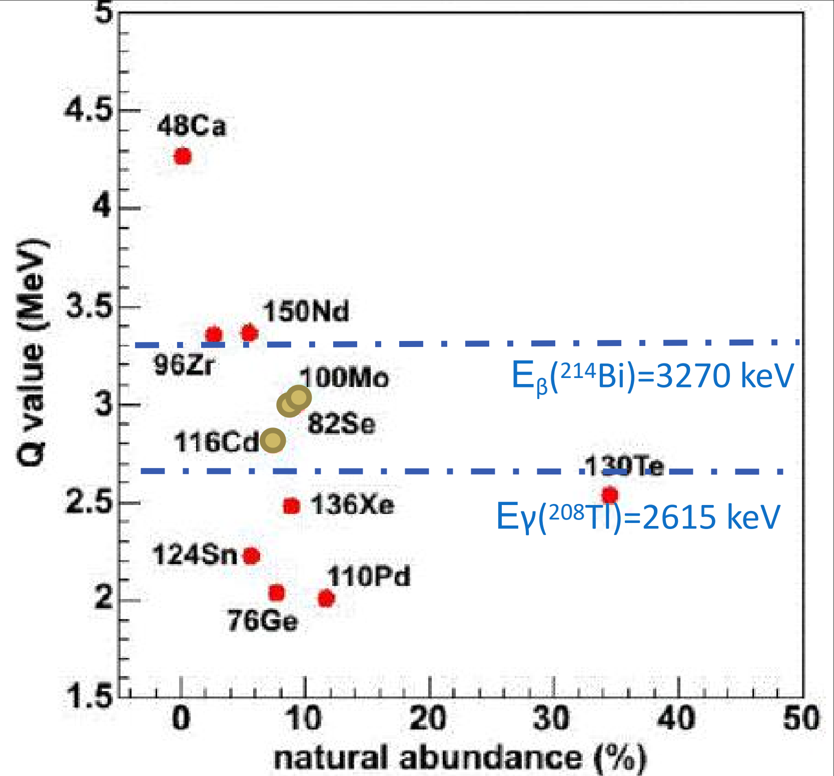
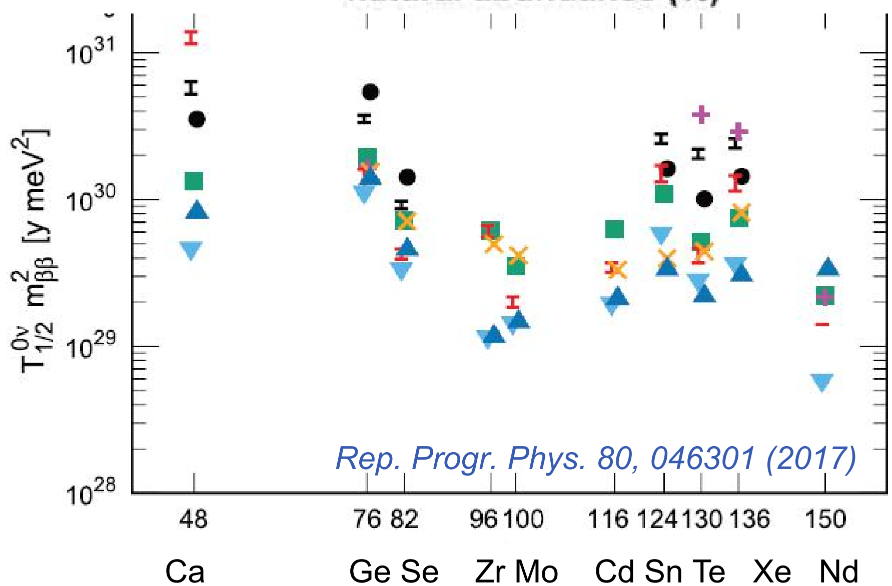
“Golden isotopes”:
^{100}Mo, ^{82}Se, ^{116}Cd





Rep. Progr. Phys. 80, 046301 (2017)

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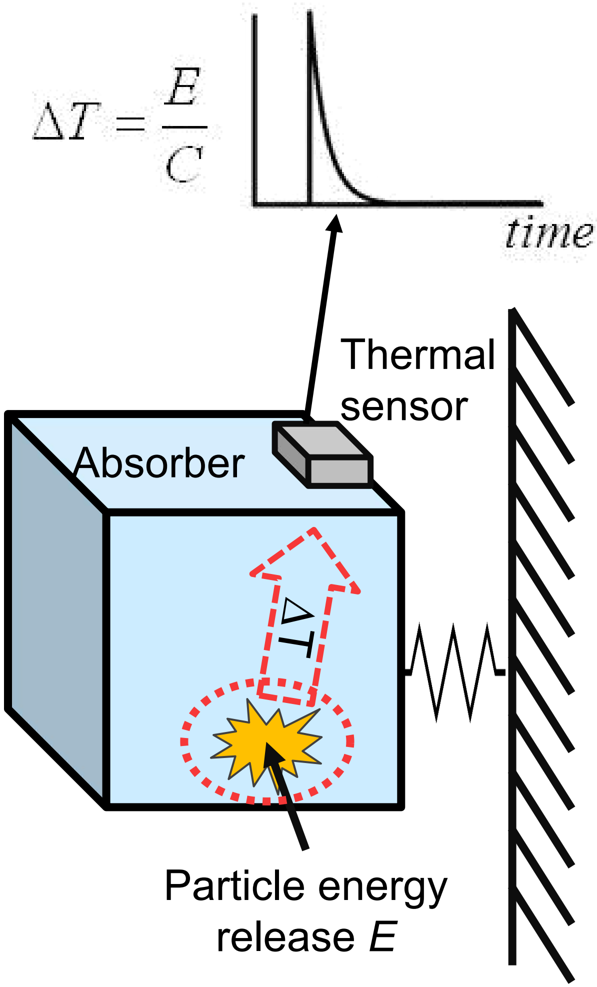
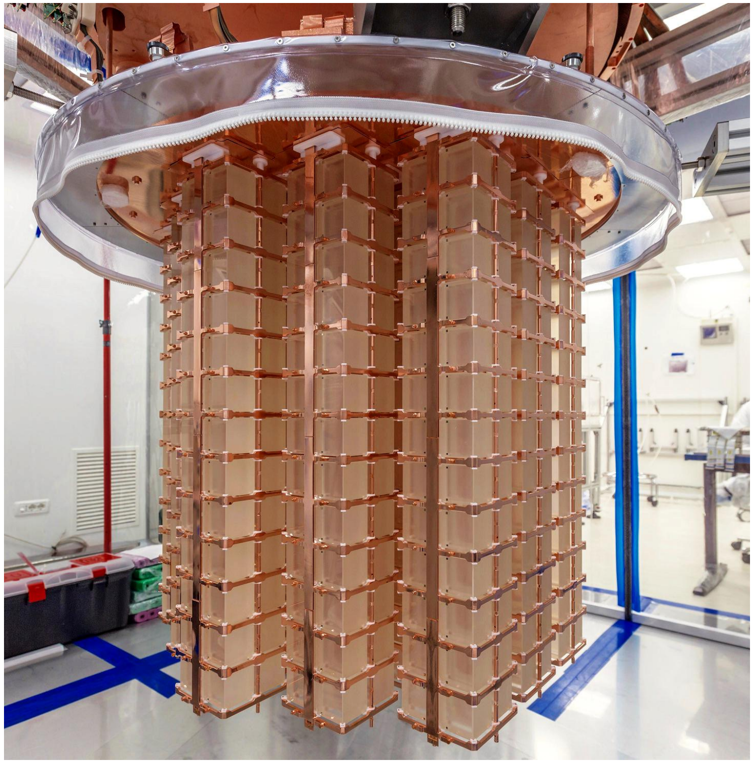
Bolometers in a nutshell

- **Isotope of interest is embedded** in a crystal → High detection efficiency
- **0.1-1 kg** typical crystal mass: scalability to large masses is possible through arrays
- The deposited **energy is measured as a temperature increase** in a crystal; detectors are operated at ~10 mK
- High energy resolution: **5-10 keV (~0.2%) FWHM** in the ROI



CUORE: the largest bolometric experiment

- **CUORE:** the Cryogenic Underground Observatory for Rare Events
- **First ton scale** array of cryogenic calorimeters: **988 TeO_2 crystals** (0.75 kg each)
- CUORE cryogenic facility is an unprecendented techological challenge, which is now **taking data in steady and reliable conditions** (after 1 yr of optimization)



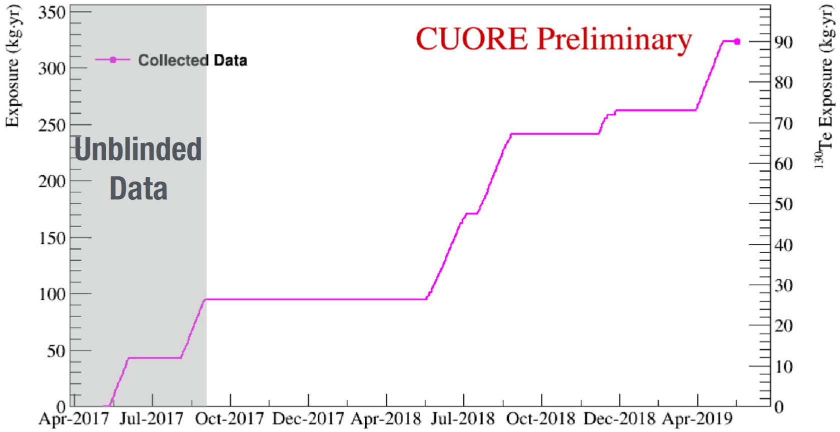
- Limit on half-life of ^{130}Te:

$$T_{1/2}^{0\nu} > 1.5 \times 10^{25} \text{ yr (90\% C.I.)}$$

- Limit on effective mass:

$m_{\beta\beta}$ < (110 - 520) meV (90% C.I.)

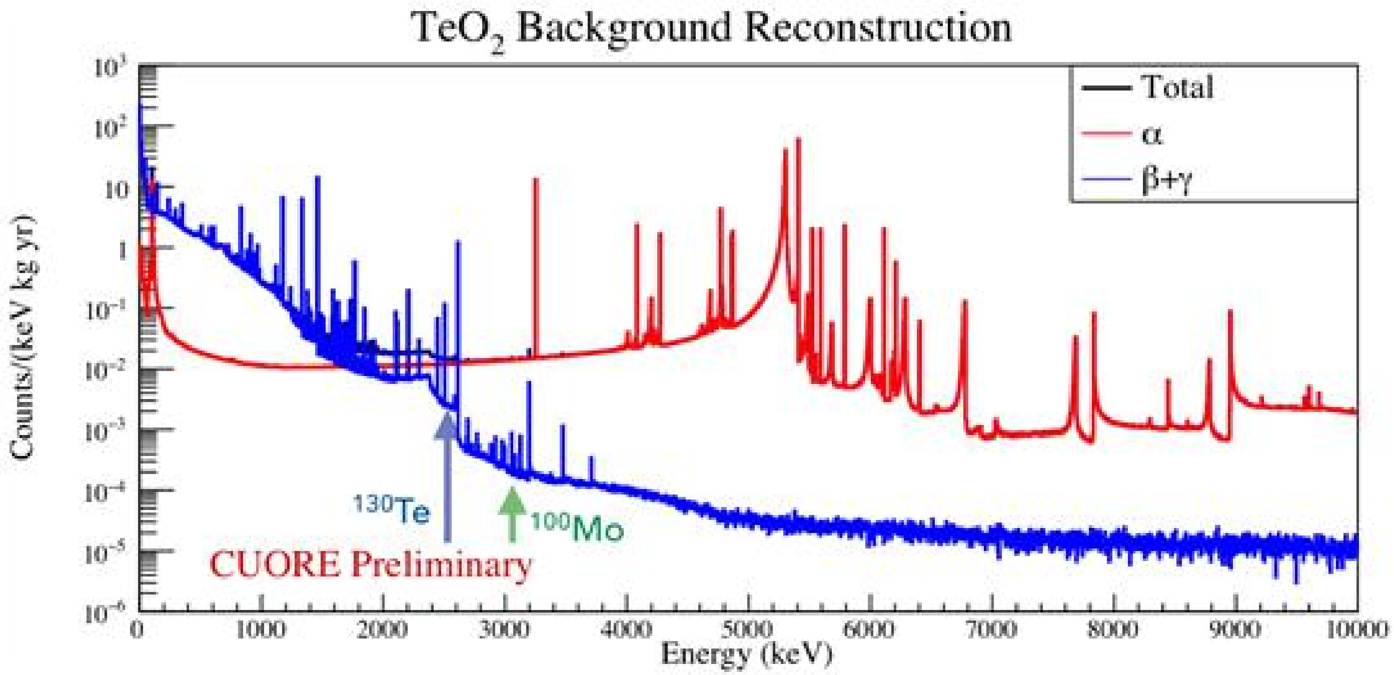
Preliminary



G. Fantini, "Results from the CUORE experiment" presented at rencontres du Blois 2019

CUORE lessons

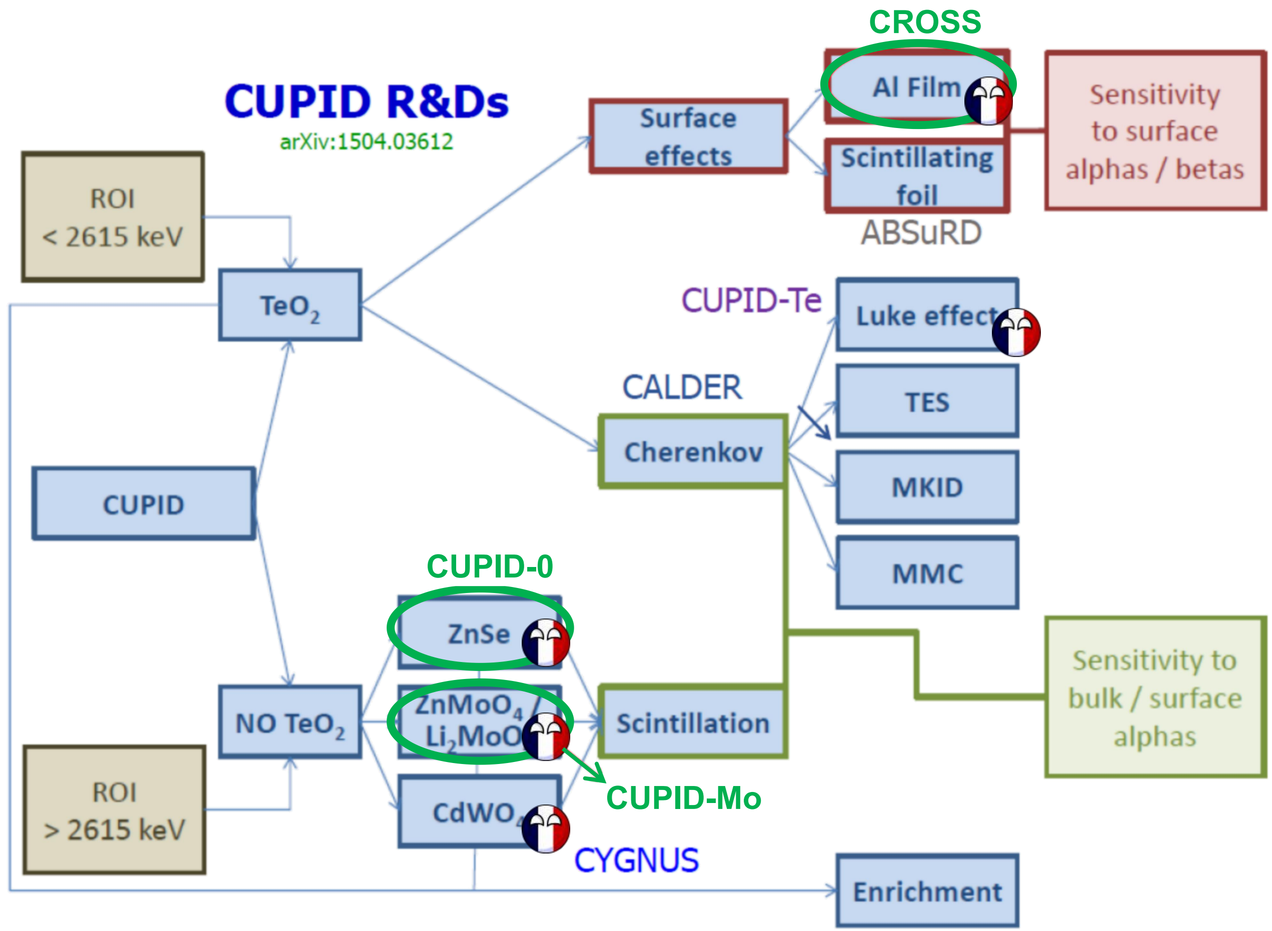
- 90% of background at ^{130}Te $Q_{\beta\beta}$ induced by degraded α from surrounding surfaces
- Need to discriminate between α and β/γ or between surface and bulk
- β/γ background “naturally” lower above the ^{208}Tl line at 2615 keV
- **If an isotope with $Q_{\beta\beta}$> 2615 keV is used, a background ~10^{-4} counts/(keV kg yr) is achievable with the CUORE infrastructure**



G. Benato, ”Status and results of CUORE experiment” presented at MEDEX2019

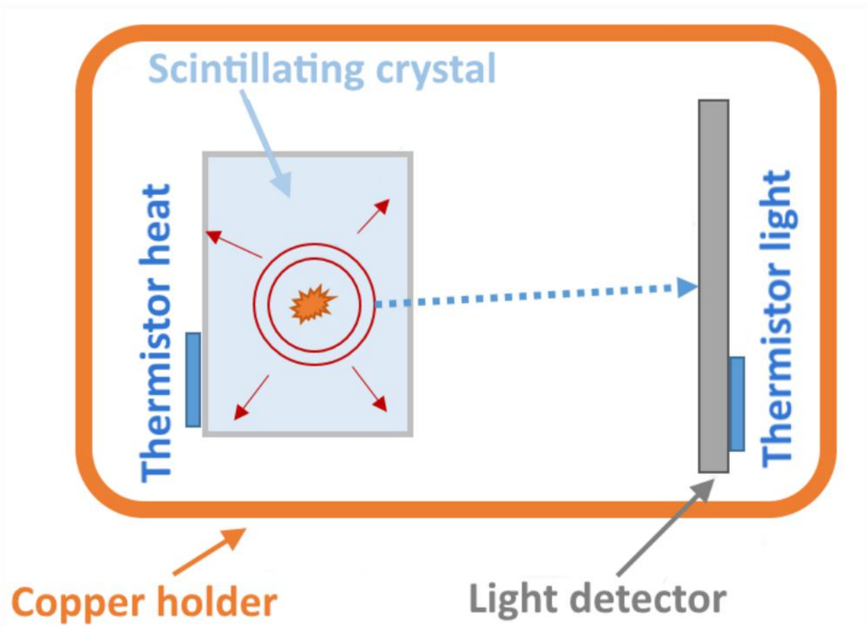
From CUORE to CUPID: R&Ds

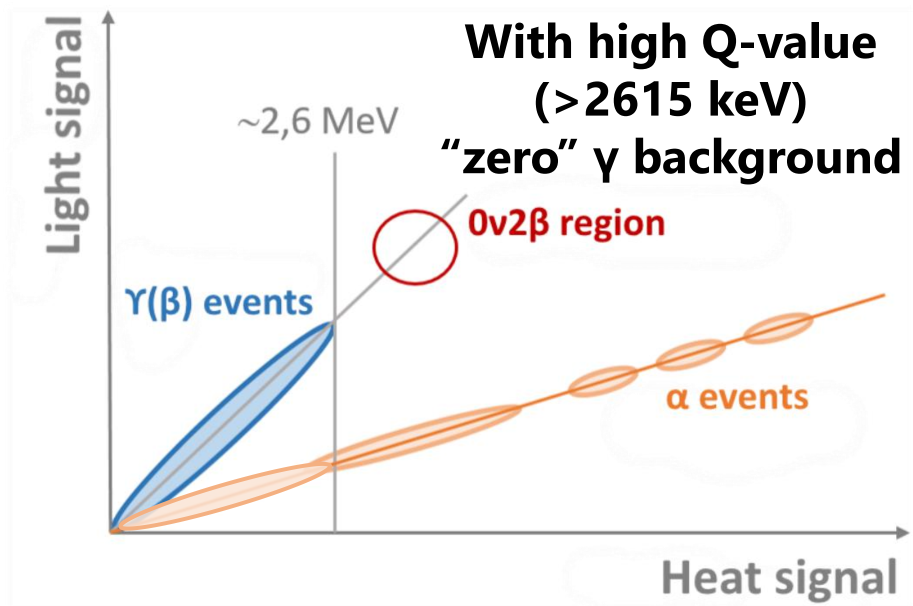
- **CUPID (CUORE Upgrade with Particle IDentification):** Follow-up using CUORE facility with background improved by a factor 100: **~10^{-4} counts/(keV kg yr)**



Particle ID:scintillation light

- Particle identification is a powerful tool for background rejection
- Flash of light is produced by the absorption of a particle
- Different particles produce different amount of light
- Full discrimination of α particles from ROI





With use of scintillation light for α/γ discrimination: "zero" α background

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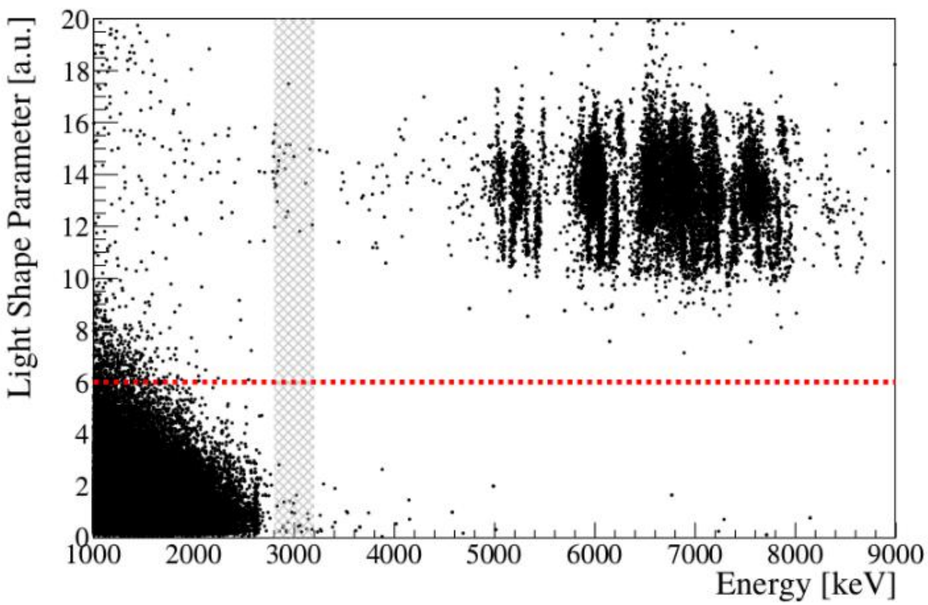
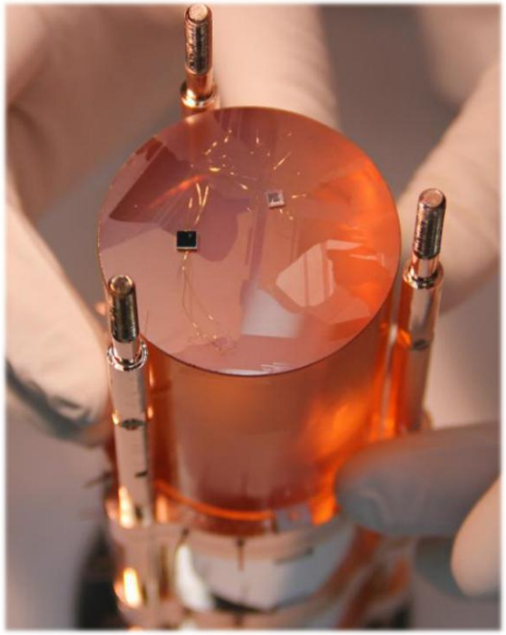
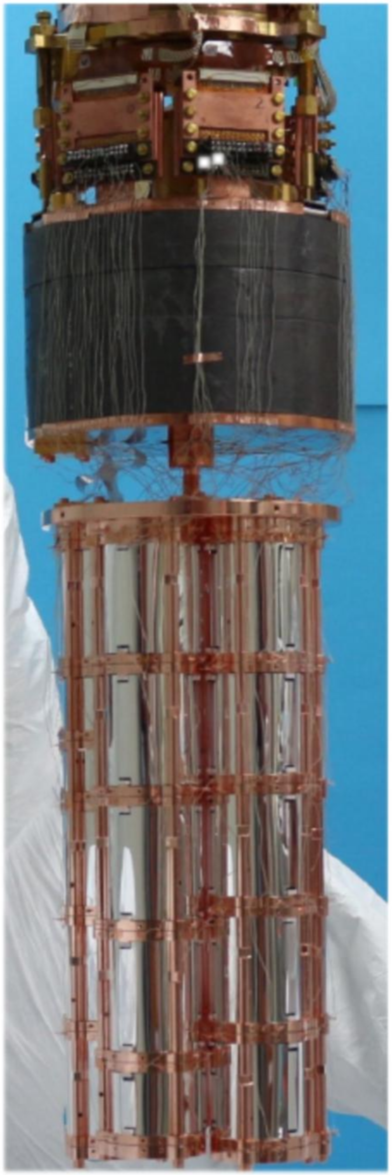
CUPID-0 experiment

- 24 95%-enriched **$Zn^{82}Se$** crystals + 2 natural ones
- 31 Ge light detectors (Provided by CSNSM-CEA)
- Hosted in the CUORE-0 cryostat (LNGS, Italy)
- Total Mass: 10.5 kg (ZnSe) - **5.17 kg (^{82}Se)**
- Total signal detection efficiency: **(75 ± 2)%**
- $Q_{\beta\beta}$ = (2997.9 ± 0.3) keV



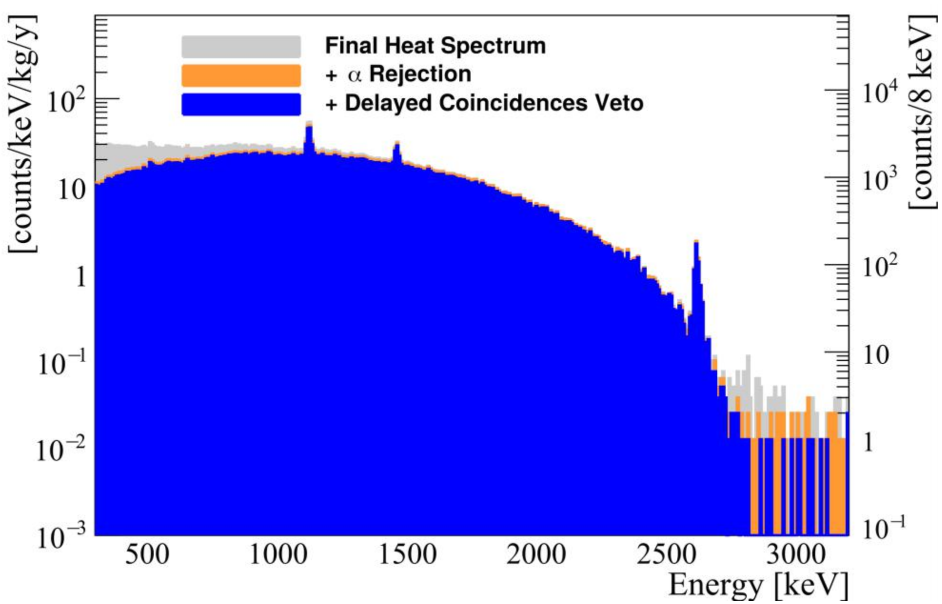


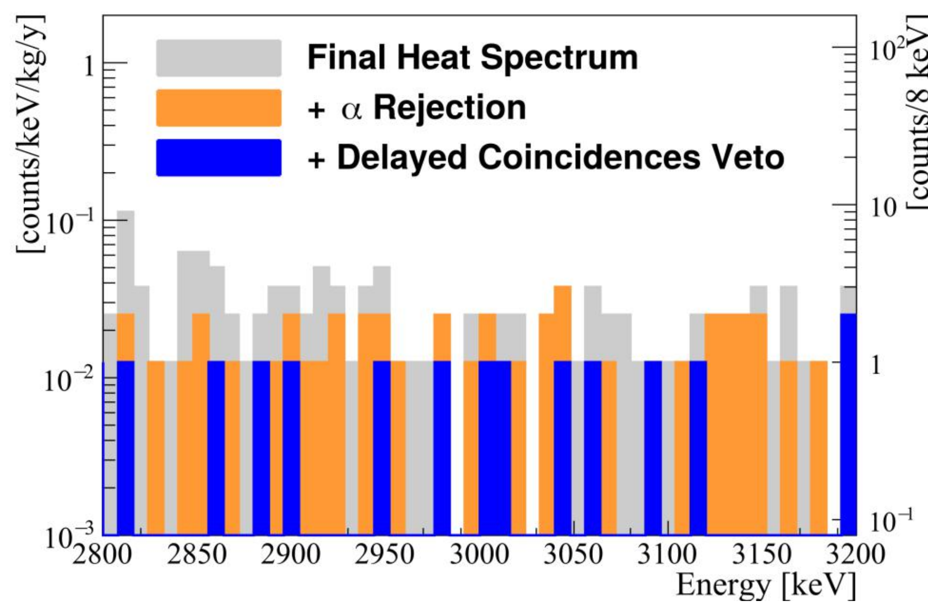


CUPID-0 experiment: results

- Final Exposure (Phase I): 9.95 kg × yr (22 $Zn^{82}Se$)
- ^{82}Se atoms: $(3.41 \pm 0.03)\times10^{25}$
- Resolution at $Q_{\beta\beta}$: (20.05 ± 0.34) keV
- Background: **3.5×10^{-3}** counts/(keV kg yr)
- **$T_{1/2}$ ($0\nu2\beta$ ^{82}Se) > 3.5×10^{24} yr** (90% C.I. Limit)
- **$m_{\beta\beta}$ < (311 - 638) eV**

7 articles published in 2018-2019!
And more to be produced...

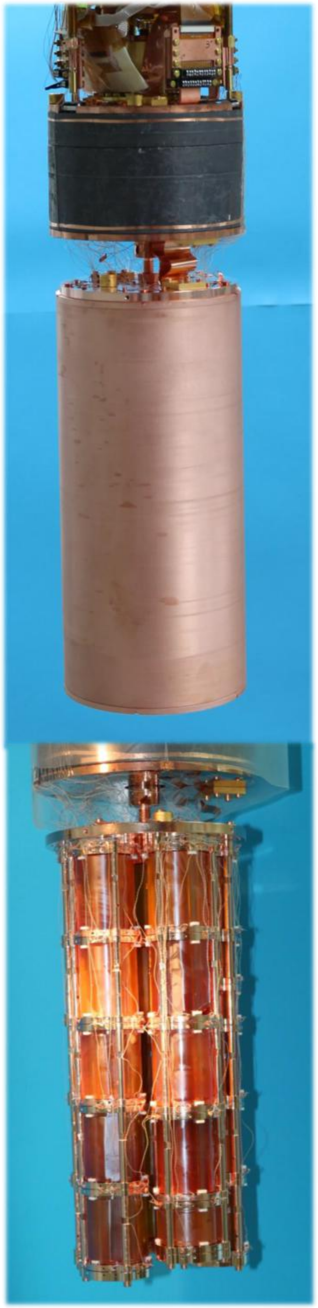




L. Gironi, "Final results of the CUPID0 Phase I experiment" presented at Rencontres de Blois 2019

CUPID-0 lessons

- First demonstrator with enriched scintillating bolometers technique in the CUPID framework
- Excellent α rejection
- Long measurement with good stability and large statistics
- Best limit on $0\nu2\beta$ and best measurement of $2\nu2\beta$ of ^{82}Se
- Measurements are ongoing with upgraded detector
- ZnSe is interesting material for $0\nu2\beta$ searches, but not the best option for full CUPID experiment: complicated crystal growth, high internal contamination, good but not excellent energy resolution (~20 keV FWHM)



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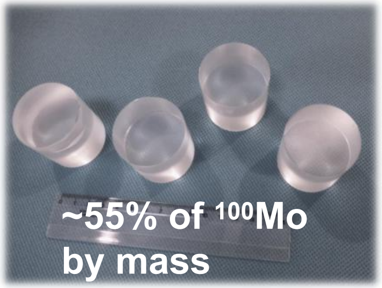
CUPID-Mo project

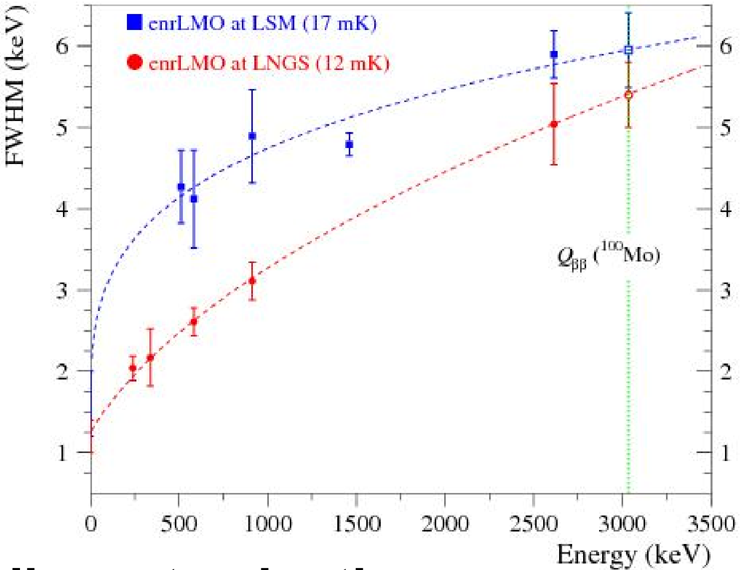


LUMINEU

ANR AGENCE NATIONALE DE LA RECHERCHE

$Li_2{}^{100}MoO_4$ scintillating bolometers technology
was developed by LUMINEU project with promising results:

- High optical quality and scintillation properties
- High energy resolution: 5-6 keV in ROI
- Discrimination power of $\alpha/\beta(\gamma)$>99.9%
- Excellent internal radiopurity: <6 μBq/kg in ^{232}Th, ^{238}U; < 5 mBq/kg in ^{40}K



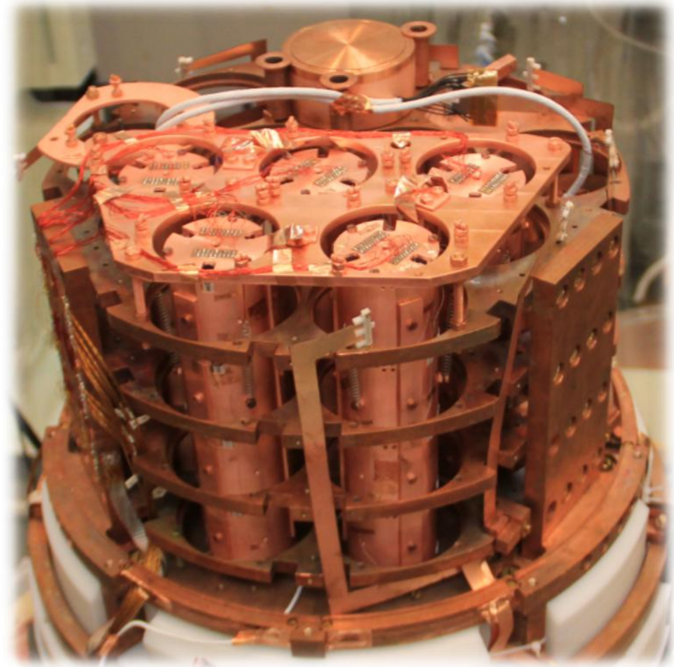
Contribution from the crystal bulk contamination less than 10^{-4} counts/(keV kg yr)!

The European Physical Journal C
November 2017, 77:785 | Cite as

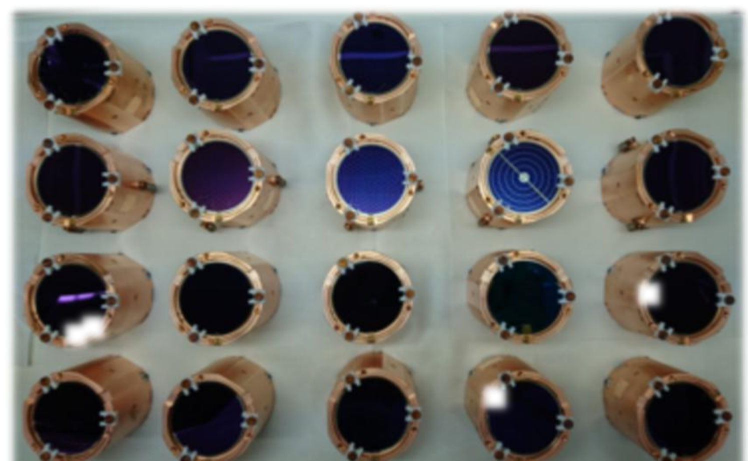
Development of ^{100}Mo-containing scintillating bolometers for a high-sensitivity neutrinoless double-beta decay search

CUPID-Mo experiment

- 20 $\mathbf{Li_2{}^{100}MoO_4}$ (2.34 kg of ^{100}Mo)
- 20 Ge light detectors
- EDELWEISS set-up (LSM, France)
- Commissioned in winter 2019
- Data taking is ongoing

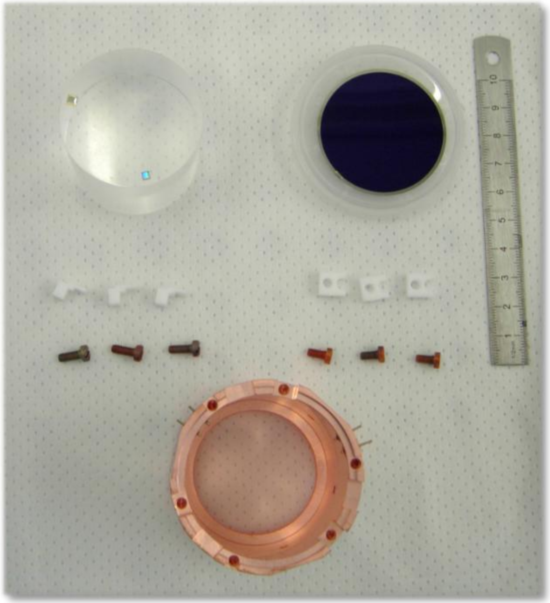


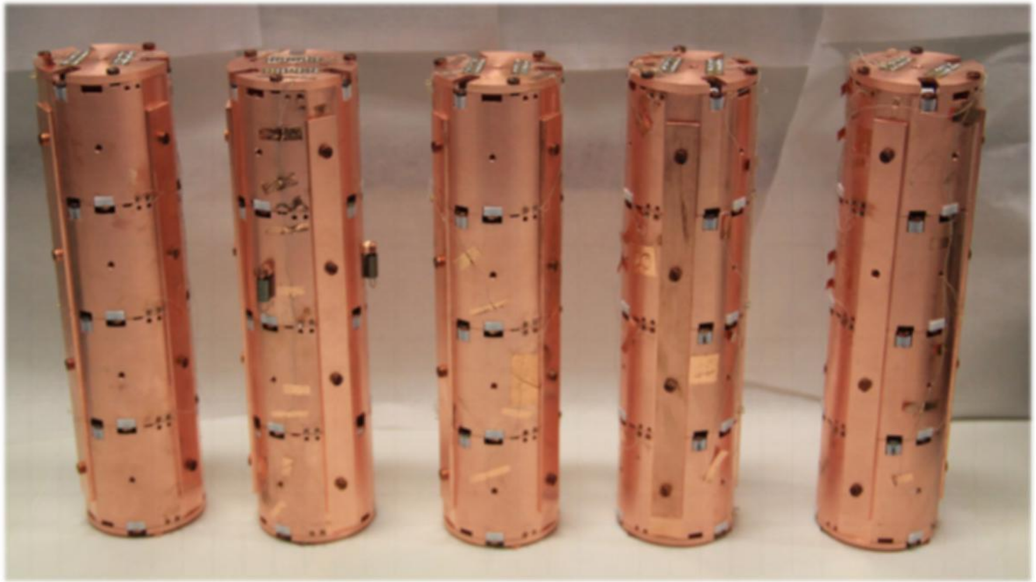
http://cupid-mo.mit.edu

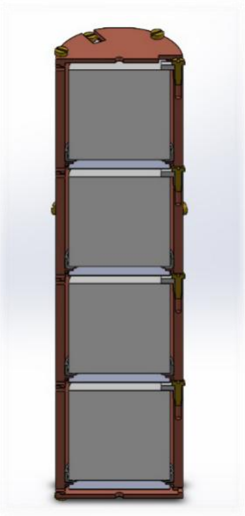


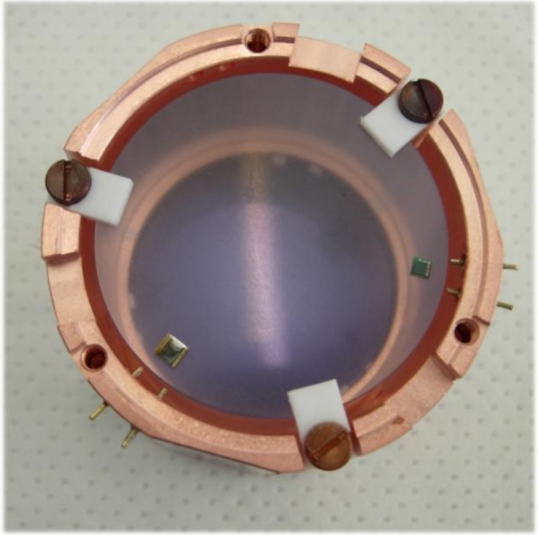
CUPID-Mo detectors

- Absorber: $Li_2{}^{100}MoO_4$ - Ø 43.8×45 mm, ~210 g mass
- Light detector: Ge wafer Ø 44.5 mm x 170 µm with SiO coating on both sides
- NOSV copper holders
- PTFE for thermal and mechanical coupling
- 4 modules in each tower, 5 towers





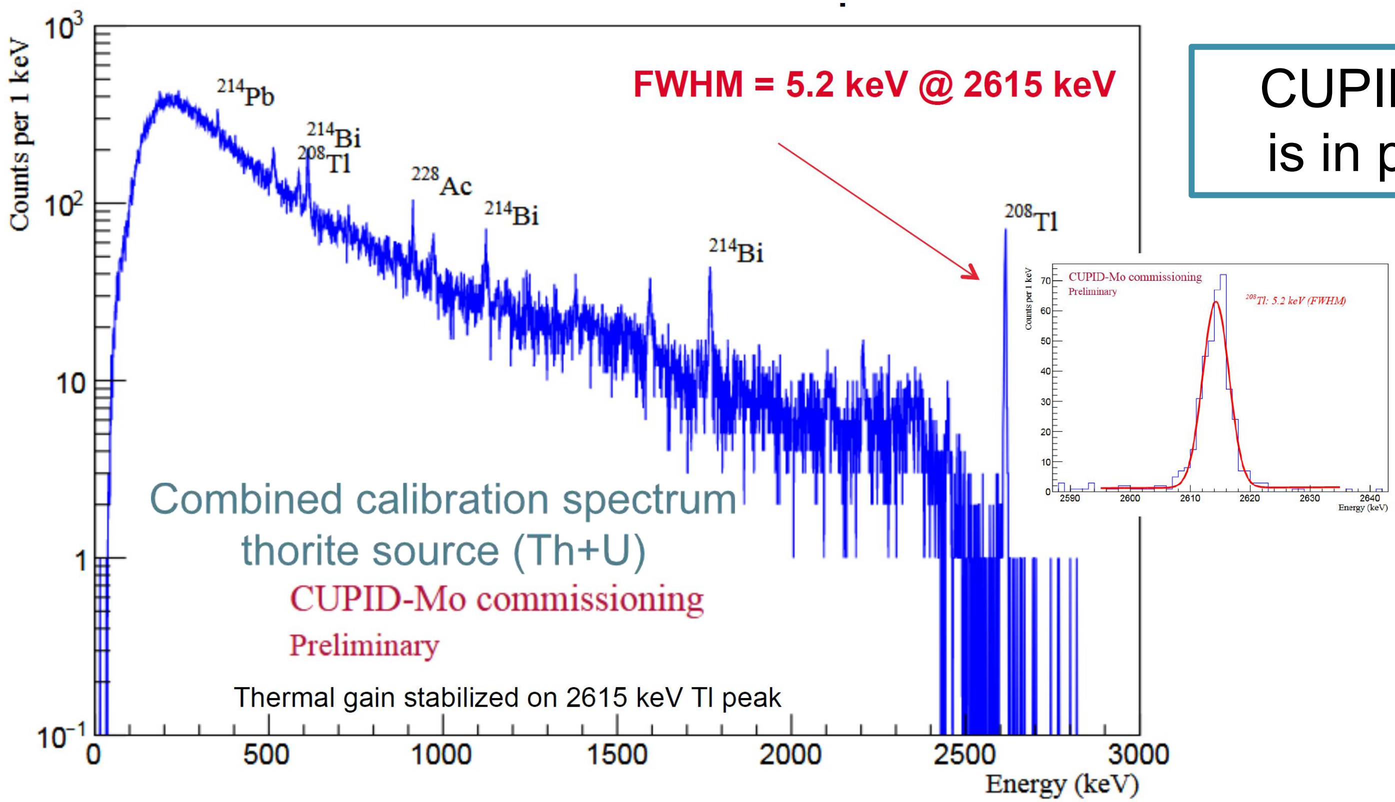




CUPID-Mo: performance

Preliminary

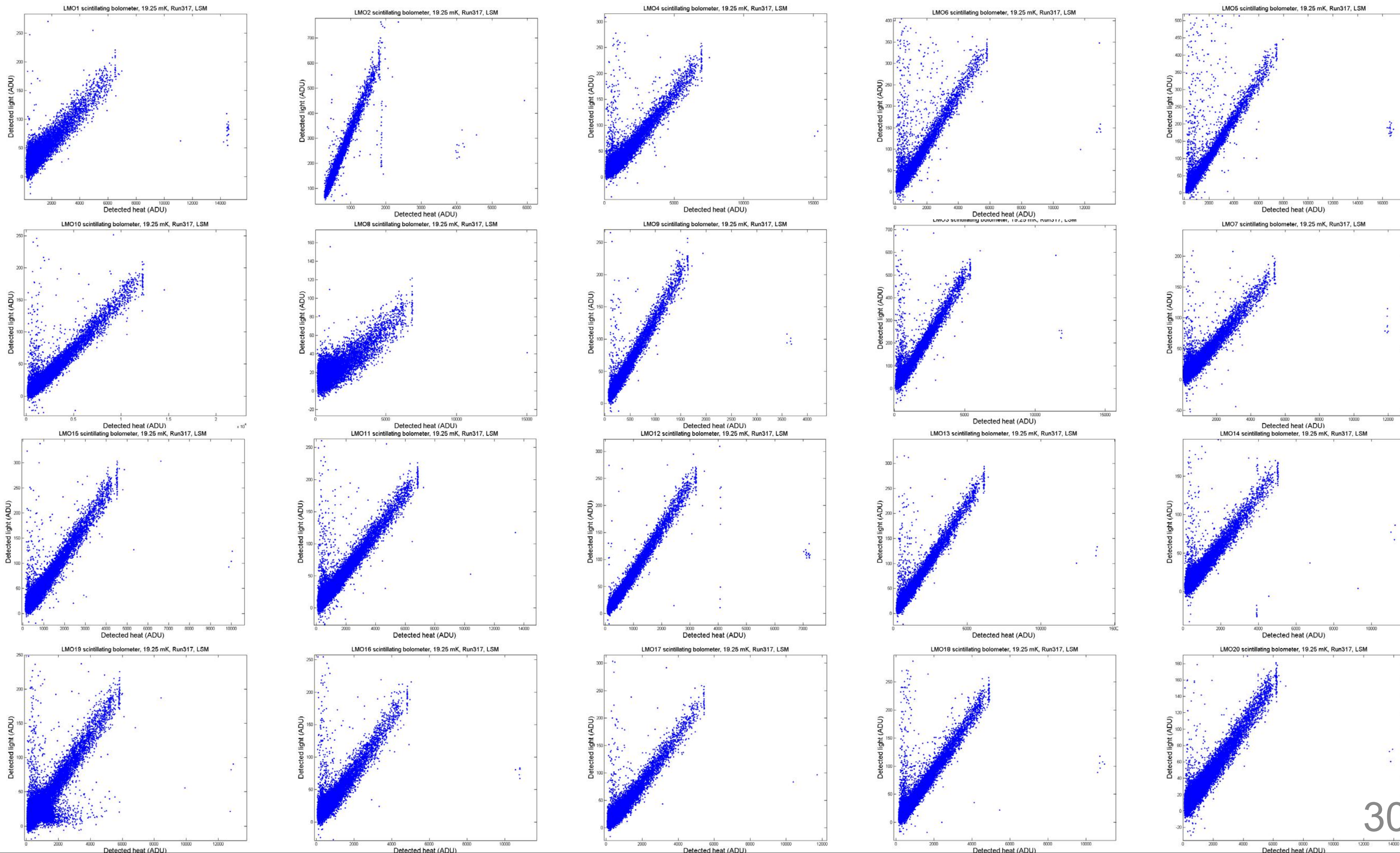
- **High energy resolution** (0.2 % FWHM)
- **Stable data taking @20.7 mK** since April 2019 (after some cryogenic issues)
- **Analyzed ~32 days of background** (~126 kg×day of $Li_2{}^{100}MoO_4$)
- **Total live time ~ 93 days** (62 days of bkg + various calibrations)



CUPID-Mo paper is in preparation!

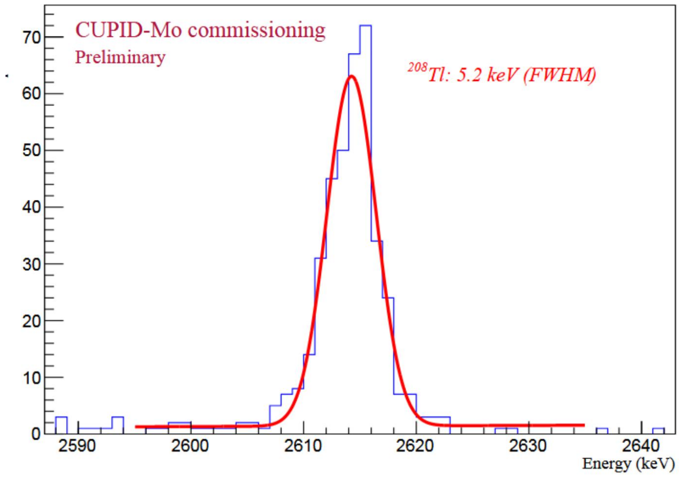
CUPID-Mo: performance

- Full α/γ discrimination with scintillation light for all channels



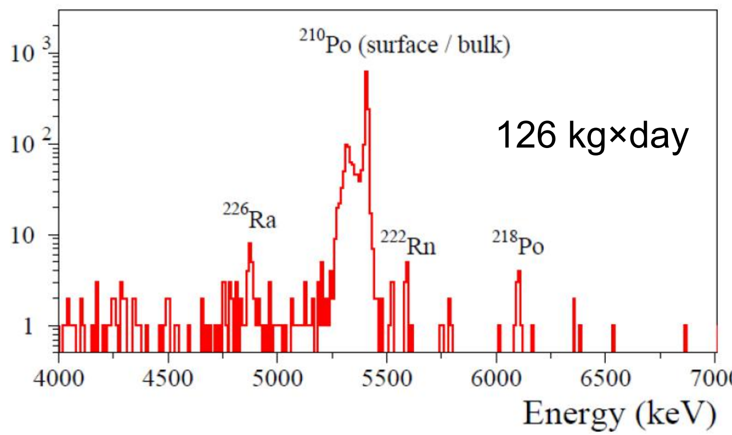
Goals for CUPID-Mo

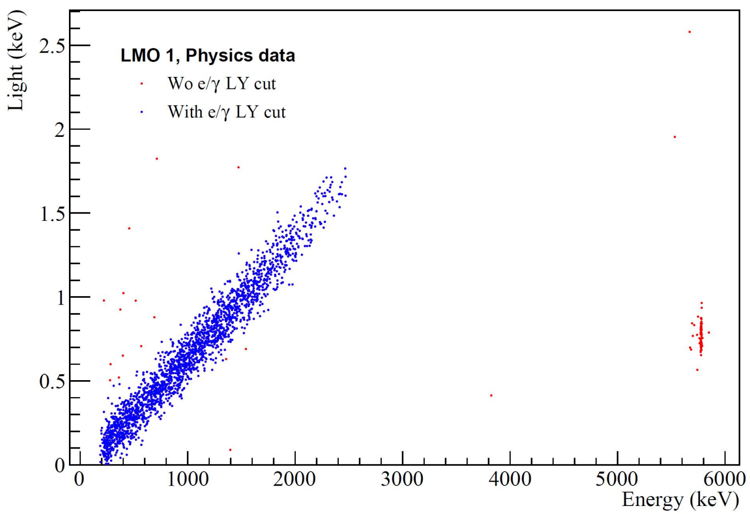
☑ **High energy resolution**: ~5 keV FWHM



☑ **Full α/β(γ) discrimination**: DP ~14σ

☑ **High internal radiopurity**: <2 uBq/kg (Th/U), ~100 uBq/kg ^{210}Po

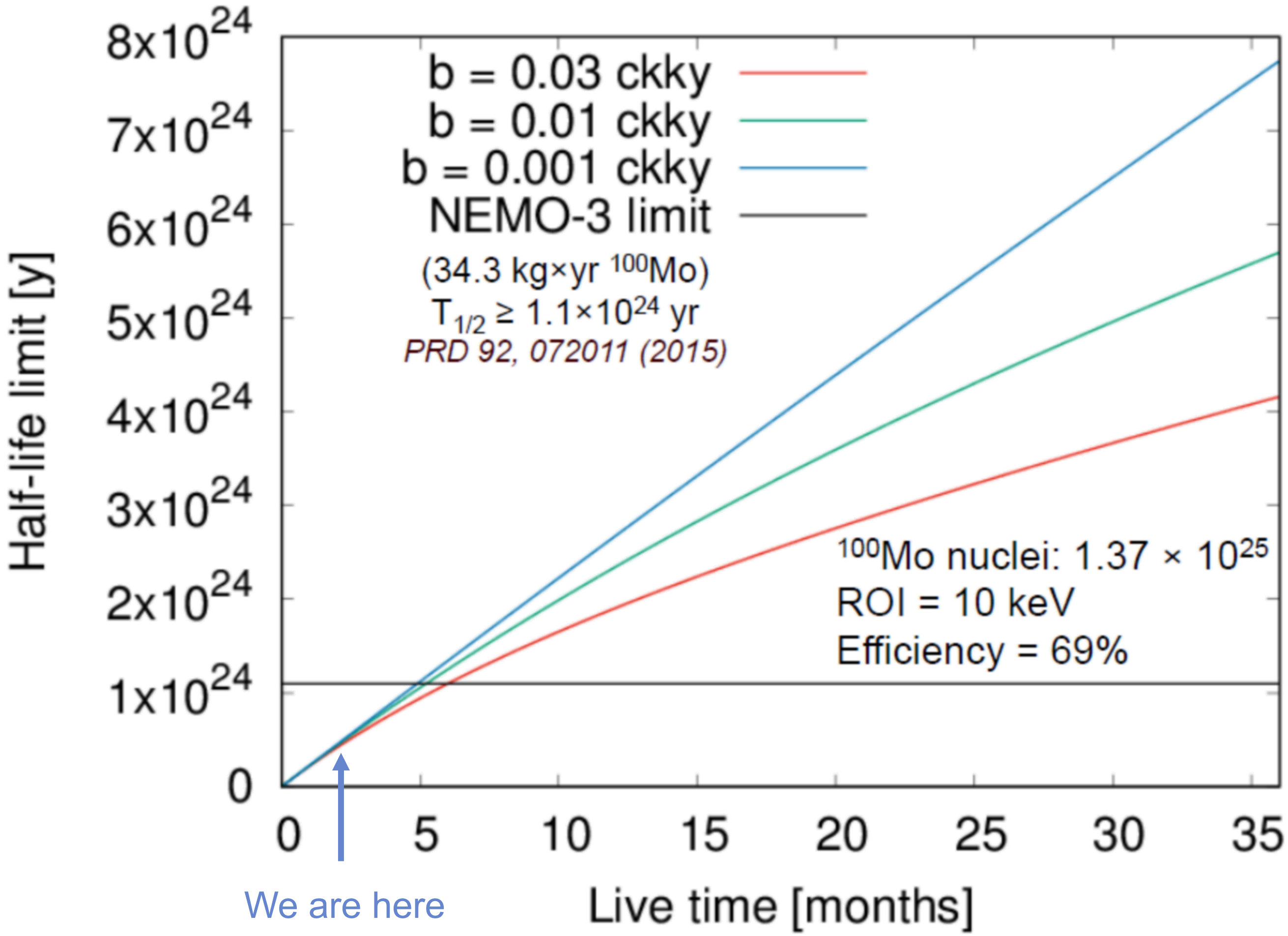




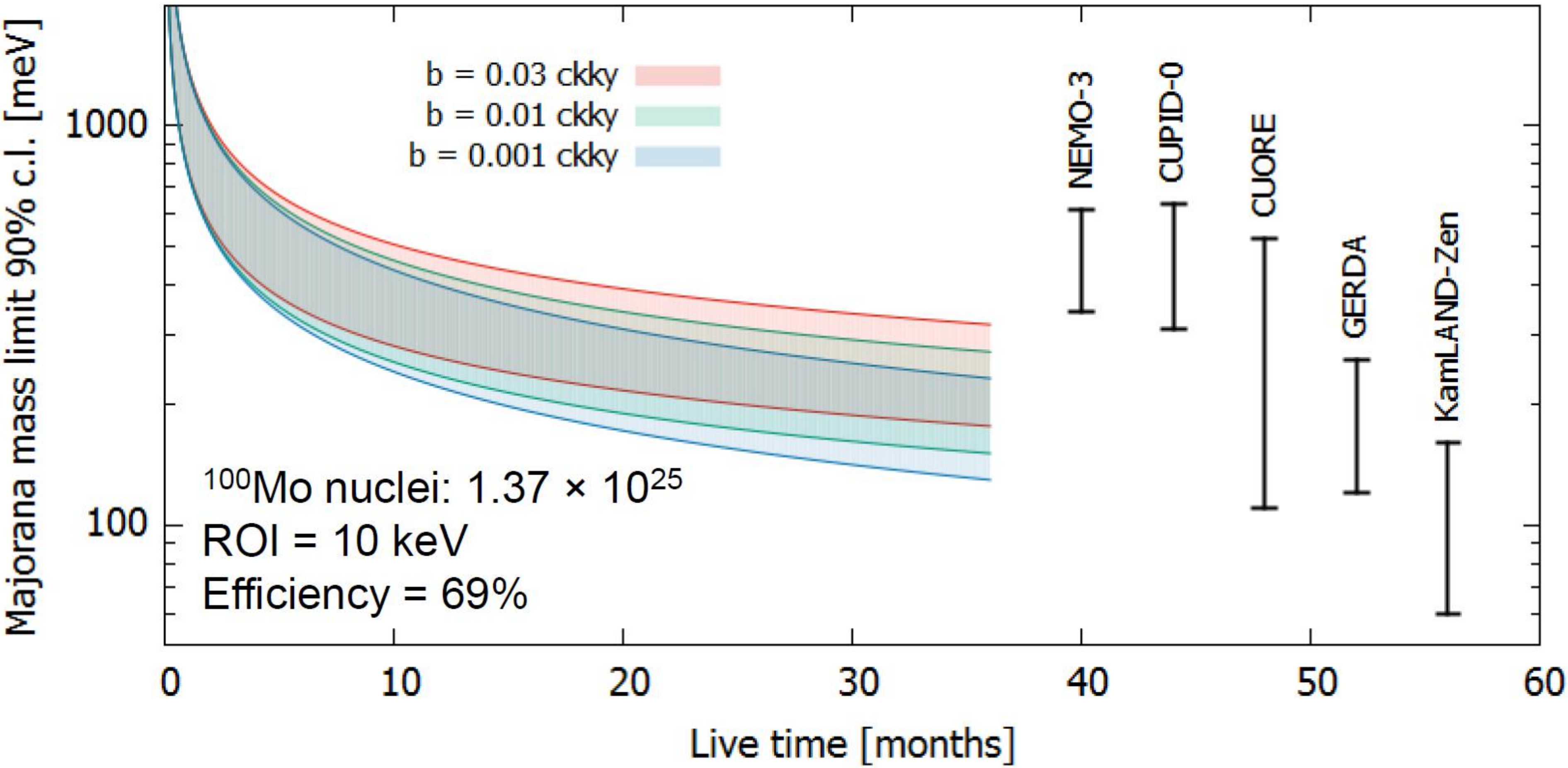
All CUPID-Mo goals are achieved with the demonstrator: mature techology for ton-scale experiment!

CUPID-Mo sensitivity

- In less than one year of measurements CUPID-Mo can establish new limit on $0\nu2\beta$ decay half-life of ^{100}Mo



CUPID-Mo sensitivity



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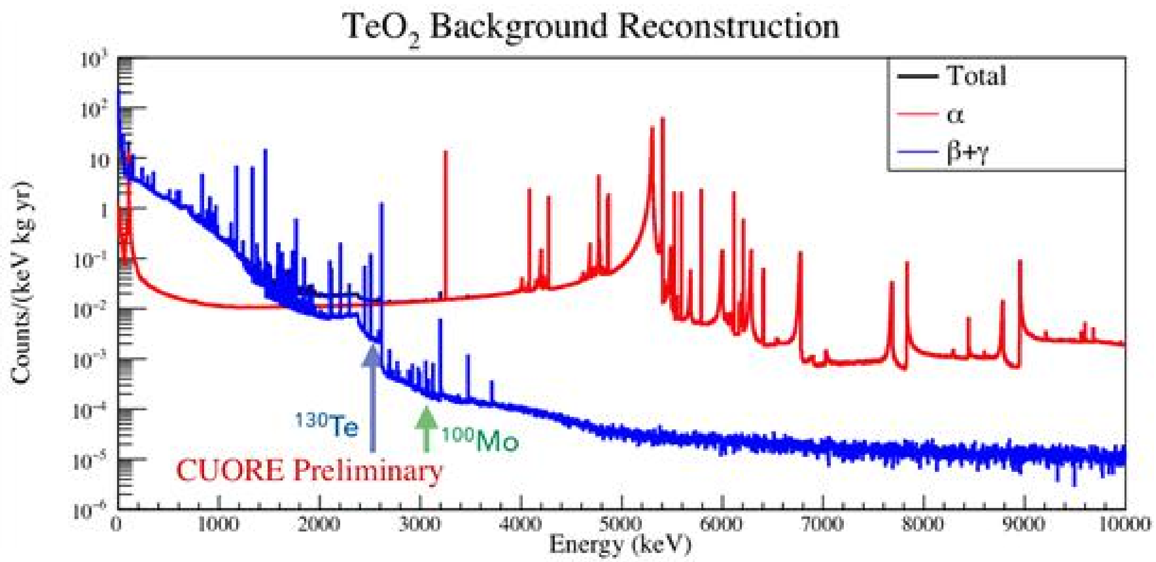
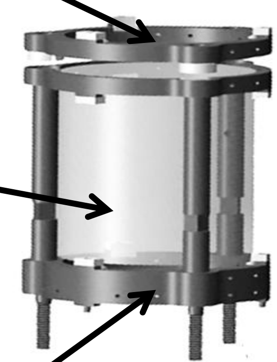
CUPID baseline configuration

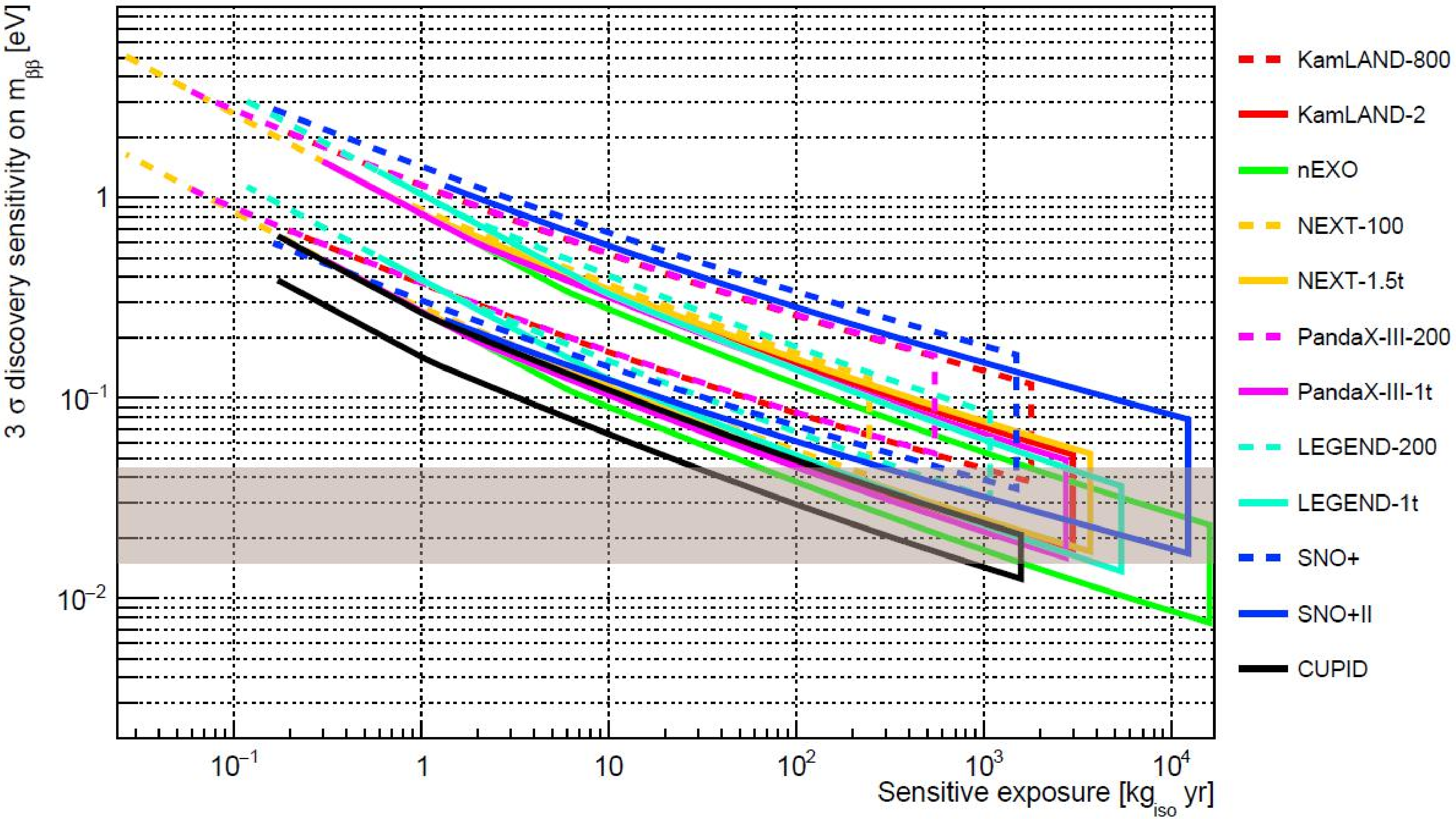
- Single module: $Li_2{}^{100}MoO_4$ Ø50×50 mm
- 118 towers of 13 floors each - 1534 crystals
- ~250 kg of ^{100}Mo for >95% enrichment
- 1.6×10^{27} ^{100}Mo atoms





b ~ 10^{-4} counts/(keV kg yr) in the ROI of ^{100}Mo (~ 3 MeV) supported by detailed Monte Carlo simulation with LMO crystals (CDR in preparation)

Discovery potential



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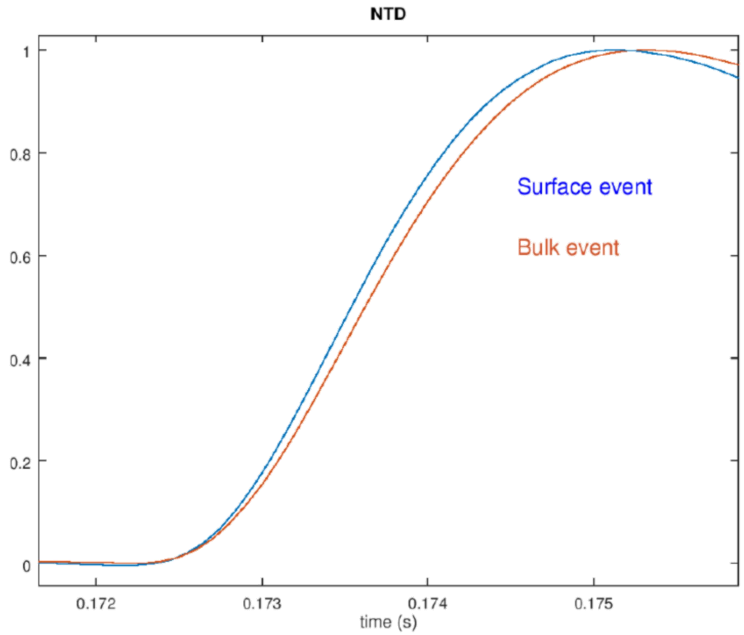
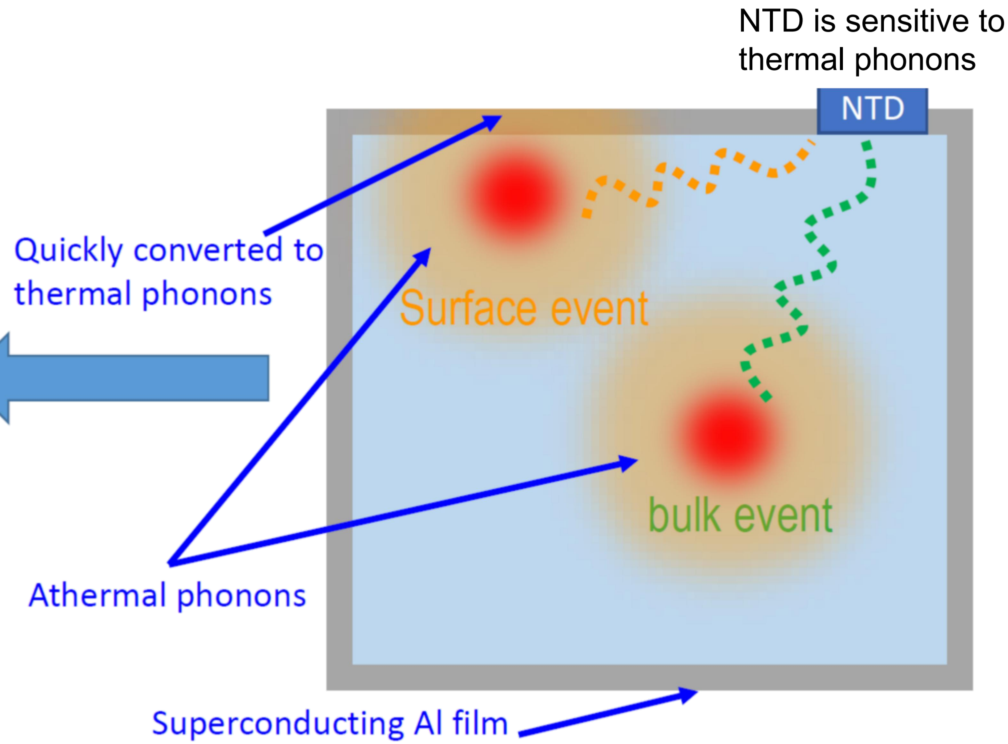
CROSS: surface sensitivity

- **C**ryogenic **R**are-event **O**bservatory with **S**urface **S**ensitivity
- Bolometers with superconducting films to identify near surface events (No light detector is needed)

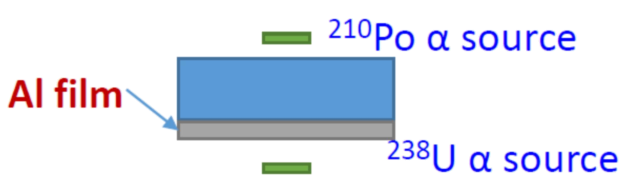


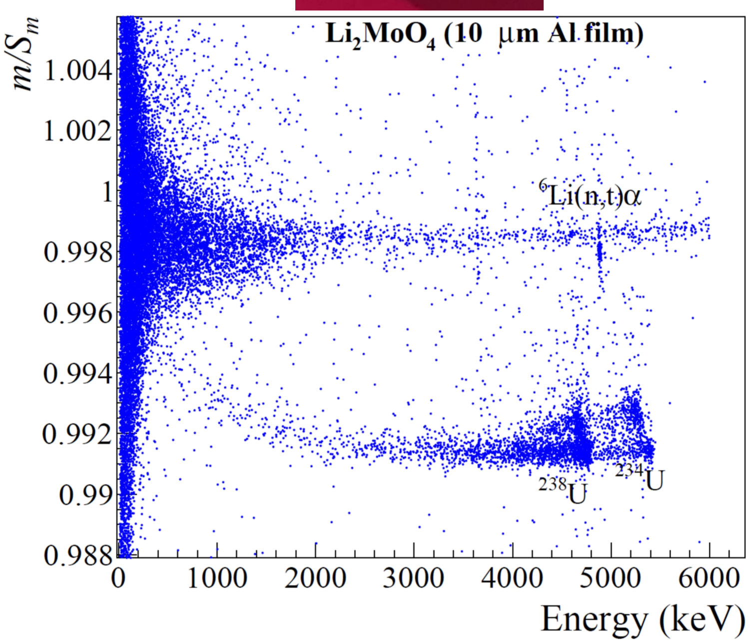


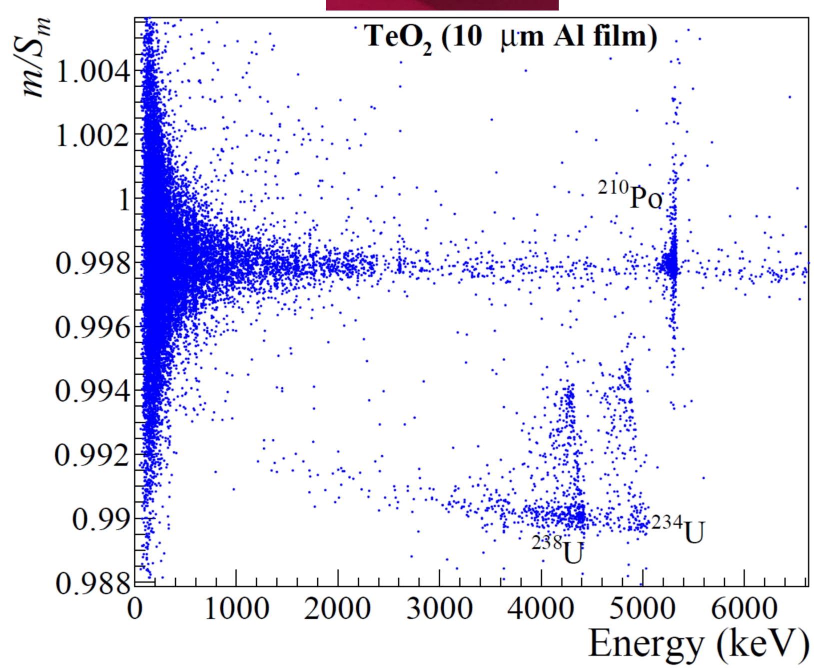
CROSS prototypes

Article is already on arxiv:
http://arxiv.org/abs/1906.10233

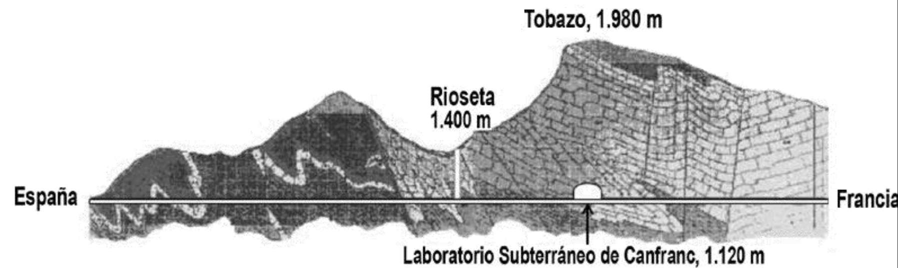
- Prototype tests of Al coated TeO_2 & Li_2MoO_4 crystals are in process
- CROSS with up to 60 crystal array of enriched $^{130}TeO_2$ & $Li_2{}^{100}MoO_4$ bolometers is in preparation





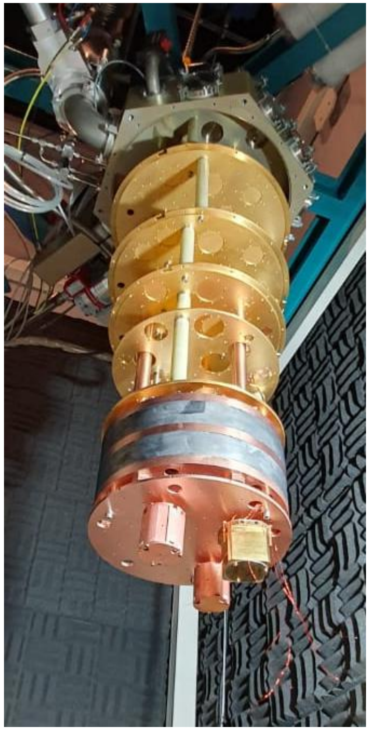


LSC: CROSS underground facility



- Cryostat installed and commissionned in April 2019
- Three detectors are installed for performance check and background estimations, data acquisition is ongoing
- This facility will be used also for the final definition of the CUPID structure
- The CROSS method could be used in second phase of CUPID
- A mixed configuration with Al film replacing the reflector is under study

LSC
Laboratorio Subterráneo Canfranc

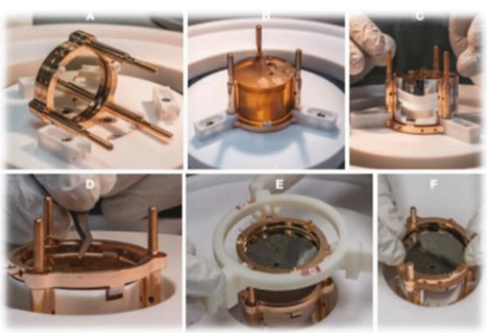
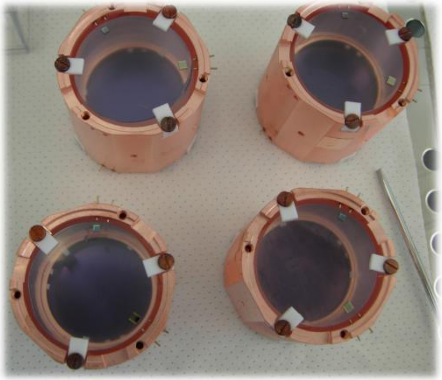


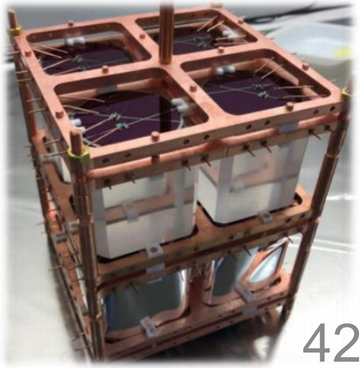
Outline

- Neutrinoless double beta decay
- Signal and background
- Bolometric approach: from CUORE to CUPID
- CUPID-0 experiment
- CUPID-Mo experiment
- CUPID baseline configuration
- CROSS experiment
- **Summary**

Summary:CUPID R&Ds

- $0\nu2\beta$ **decay is a key process** in particle physics, neutrino physics and cosmology
- The **bolometric approach is extremely competitive** (CUORE), new technologies are developed for sensitivity improvement → **CUPID tests are ongoing:**
  - **CUPID-0** demonstrated excellent results with **$Zn^{82}Se$** scintillating bolometers
  - **CUPID-Mo** provided **$Li_2{}^{100}MoO_4$** technology, chosen for **CUPID** baseline configuration
  - The **CROSS** project is developing **surface sensitive bolometers**, with possibility to use this technology for CUPID



Summary: CUPID

CUPID is an outstanding next-generation experiment, whose core technology was conceived, developed and verified in France. It is:

- **technologically ready:** $Li_2{}^{100}MoO_4$ detectors are well-studied and ready for mass production, including enrichment process;
- **data driven:** precise background model of the cryostat; significant experience with data analysis of large arrays of bolometers;
- **based on existing infrastructure**, which is already optimized and well-tested in CUORE;
- **cost effective**

CUPID aims to cover completely inverted and part of normal hiearchy regions

Thank you for attention...

And you are welcome to join!

BACKUPS

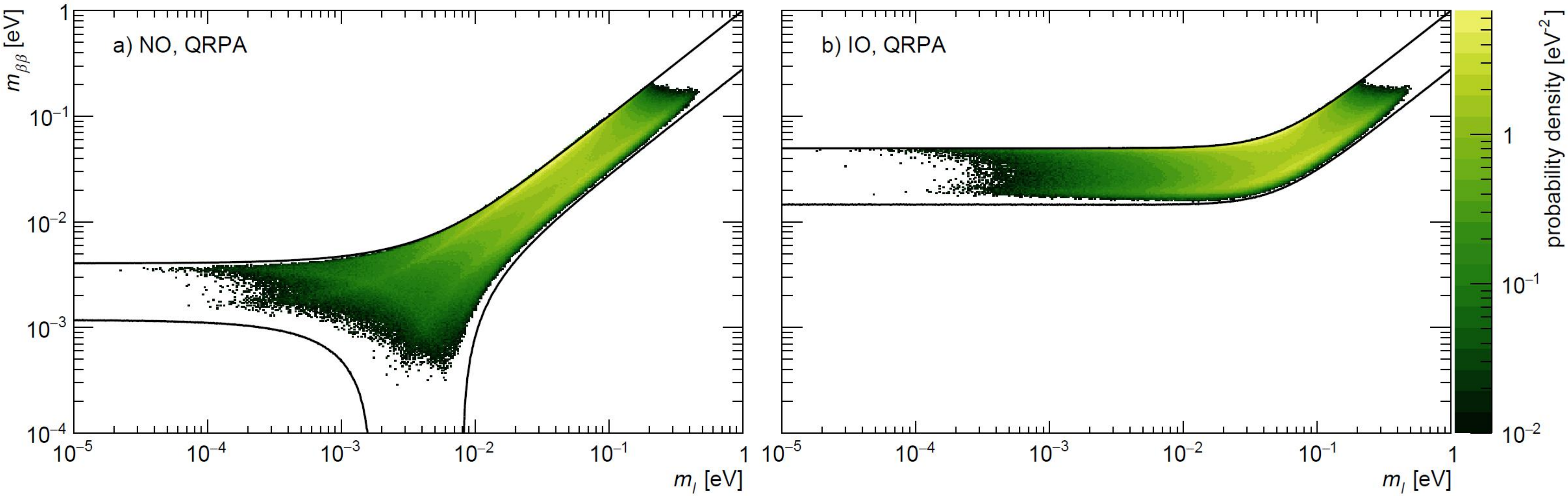


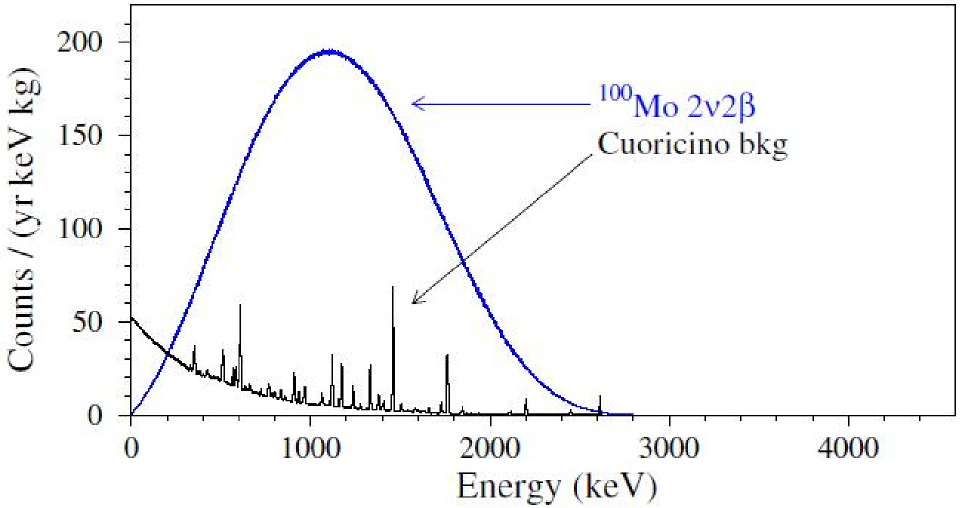
FIG. 1. Marginalized posterior distributions for $m_{\beta\beta}$ and m_l for NO (a) and IO (b). The solid lines show the allowed parameter space assuming 3σ intervals of the neutrino oscillation observables from nu-fit [12]. The plot is produced assuming QRPA NMEs and the absence of mechanisms that drive m_l or $m_{\beta\beta}$ to zero. The probability density is normalized by the logarithm of $m_{\beta\beta}$ and of m_l.

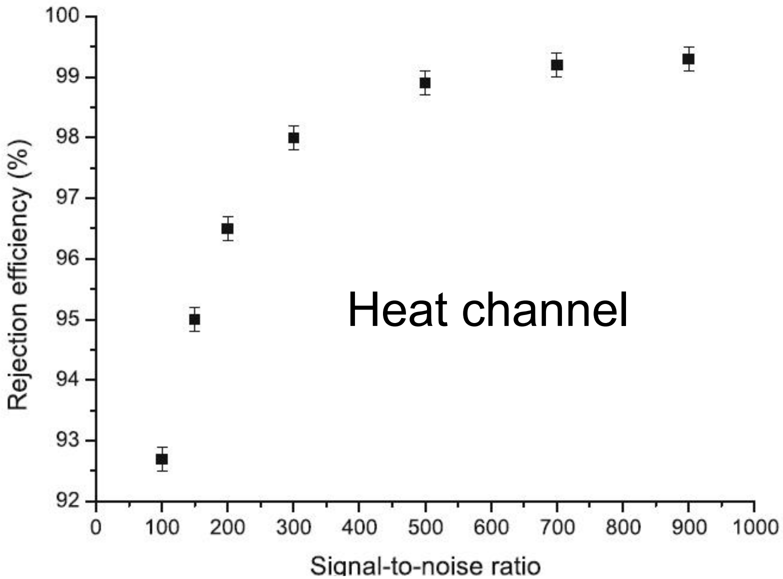
Activities for next 2-3 years

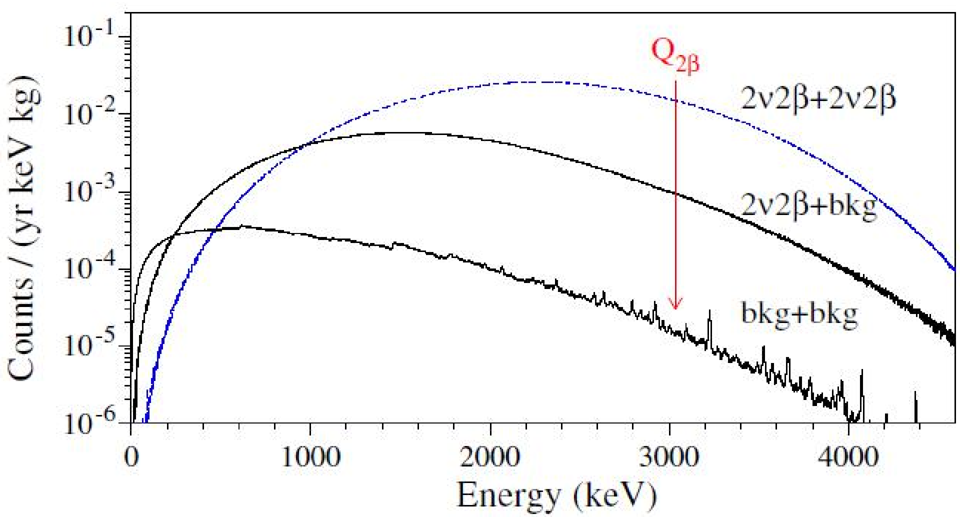
- LNGS test with 8 crystals (summer 2019)
- Light detectors production
- NTD production
- Crystal growth
- Optimization of detectors design
- Pile-ups rejection

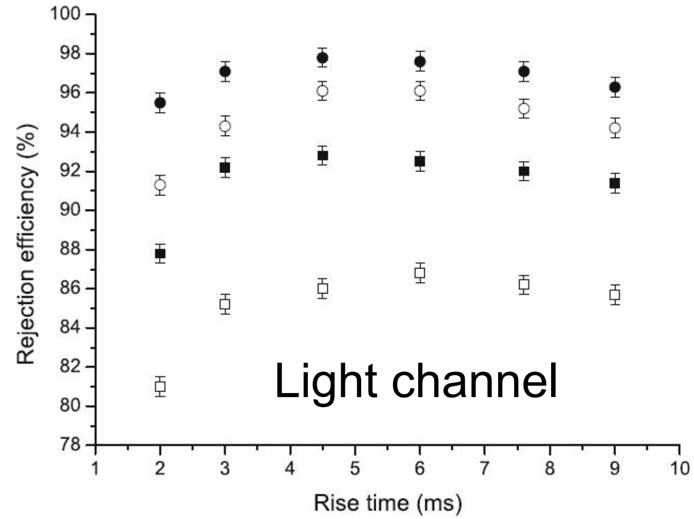
Pile-ups from 2ν2β

- Irreducible background, but can be rejected by pulse-shape or li







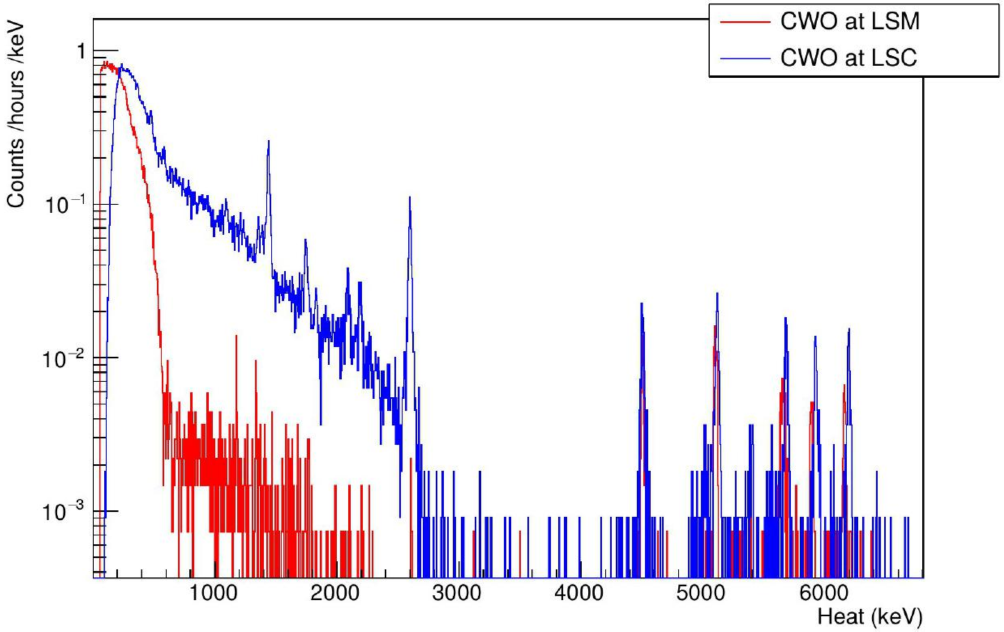


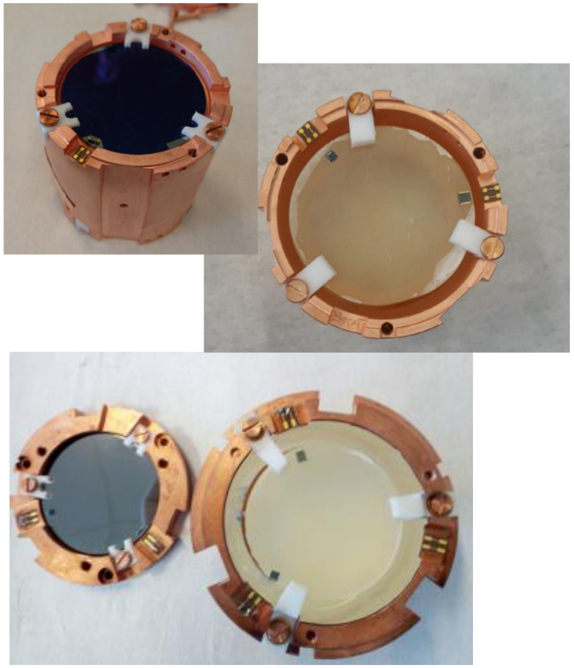
CYGNUS

- Using existing radiopure $^{116}CdWO_4$ crystals

- One crystal is installed in LSM
- One crystal is installed in LSC

Both crystals were used as scintillators in the Aurora experiment Phys. Rev. D 98, 092007 (2018) [1]



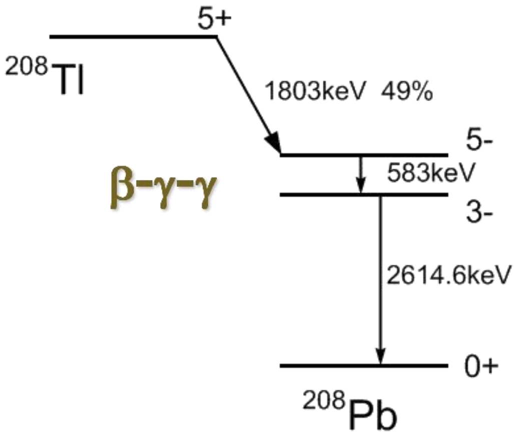


Zero-background bolometric experiment

In scintillating bolometers, dangerous bulk contaminants are high energy β decays

^{214}Bi → Q -value 3.270 MeV
(progenitors: ^{238}U, ^{226}Ra, ^{228}Th)

^{208}Tl → Q -value 4.999 MeV
(progenitors: ^{232}Th, ^{228}Th)



Target for internal contamination in ton-scale experiment with high energy resolution (~ 0.2%):

A(^{228}Th) ≤ 10 μBq/kg → **b ~ 10^{-4} counts/keV/kg/yr**